Ecole Internationale de Physique Subatomique (EIPS)

Physics with the scalar boson(s)

Louis Fayard
LAL Orsay
lfayard@in2p3.fr

please ask questions if you want

and detectors

- ♥ **Historical introduction of the boson and of the LHC**

- ♥ **Some phenomenological comments**

see also seminar by *Massimiliano Grazzini*

- ♥ **Rapid overview of the detectors** **and LHC**

- ♥ **The discovery**

and the description of the analysis in the various channels , and the searches for additional bosons

- ♥ **The first measurements of the properties**

- ♥ **The future of the physics with the scalar boson(s)**

- ♥ **Backup (with references)**

references
I made the effort of compiling (almost) all the references from ATLAS and CMS in the appendix going from 36pb-1 to the full 5+25 fb-1 full analysis

Phys.Lett.B699:25-47,2011 arXiv:1102.5429
Measurement of W+W- Production and Search for the Higgs Boson in pp Collisions at sqrt(s) = 7 TeV (36 pb-1)

PAS HIG-11-003
Search for the Higgs Boson in the Fully Leptonic W+ W- Final State (1 fb-1)

PAS HIG-11-014
Search for the Higgs Boson in the Fully Leptonic W+W- Final State (1.5 fb-1)

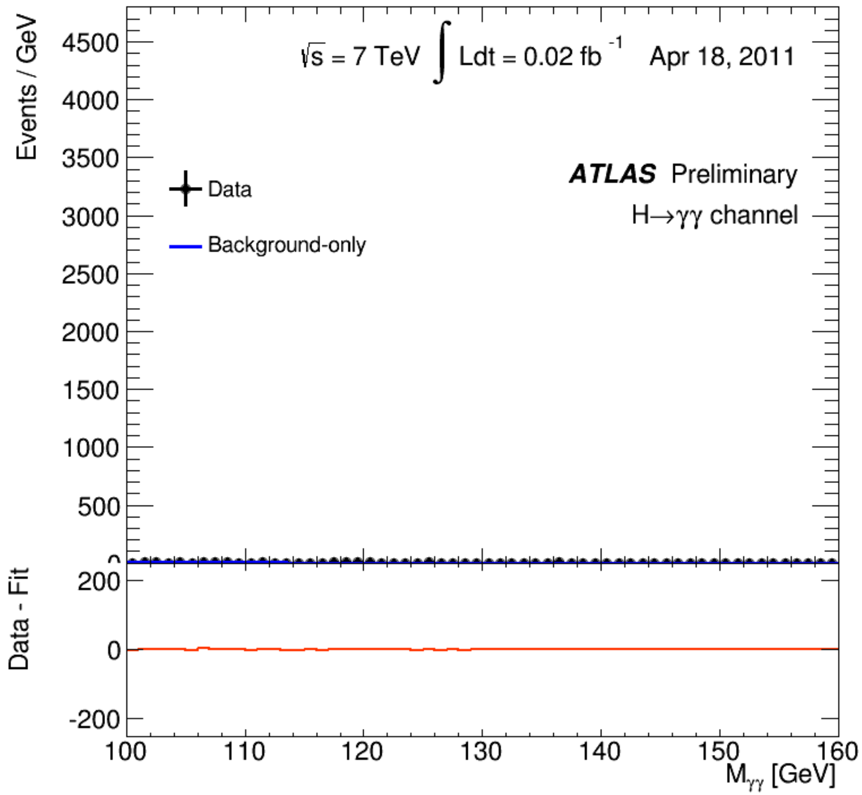
PAS HIG-11-024
Search for the Higgs Boson in the Fully Leptonic W+W- Final State (5 fb-1)

Phys.Lett. B710 (2012) 91-113 arXiv:1202.1489
Search for the standard model Higgs boson decaying to a W pair in the fully leptonic final state in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

There are 2 important results at the LHC

the discovery of the boson at 125 GeV

very standard !



and no new physics !

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

THE NOBEL PRIZE IN PHYSICS 2013

POPULAR SCIENCE BACKGROUND

Here, at last!

***François Englert** and **Peter W. Higgs** are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other (Englert together with his now deceased colleague Robert Brout). In 2012, their ideas were confirmed by the discovery of a so called* Higgs particle *at the CERN laboratory outside Geneva in Switzerland.*

Disclaimer

This is not a course on the whole LHC physics !

I probably do not have everywhere all the most recent results !

I will be detector-oriented (not statistics oriented)

It is a course
$\Rightarrow$ I will try to be simple and not be able to show the '*state of the art*'

Do not hesitate to interrupt me and to ask questions

I will often take $H \rightarrow \gamma\gamma$ as an example

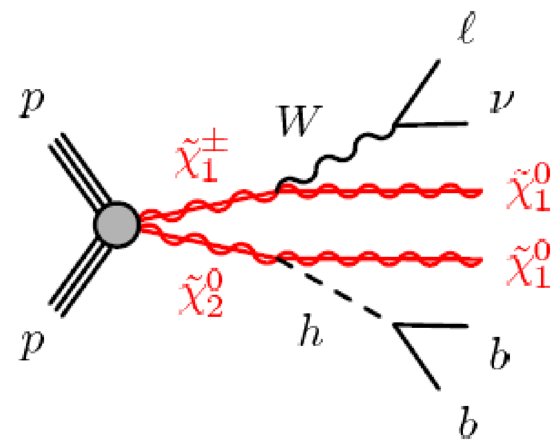
I will not discuss very exotic models/ideas but they are in the references

examples

ATLAS-CONF-2013-018
Search for heavy top-like quarks decaying to a Higgs boson and a top quark in the lepton plus jets final state in pp collisions at sqrt(s) =8 TeV with the ATLAS detector (14 fb-1)

$$t' \to Ht$$

ATLAS-CONF-2013-093
Search for chargino and neutralino production in final states with one lepton, two b-jets consistent with a Higgs boson, and missing transverse momentum with the ATLAS detector in 20.3 fb-1 of √s = 8 TeV pp collisions

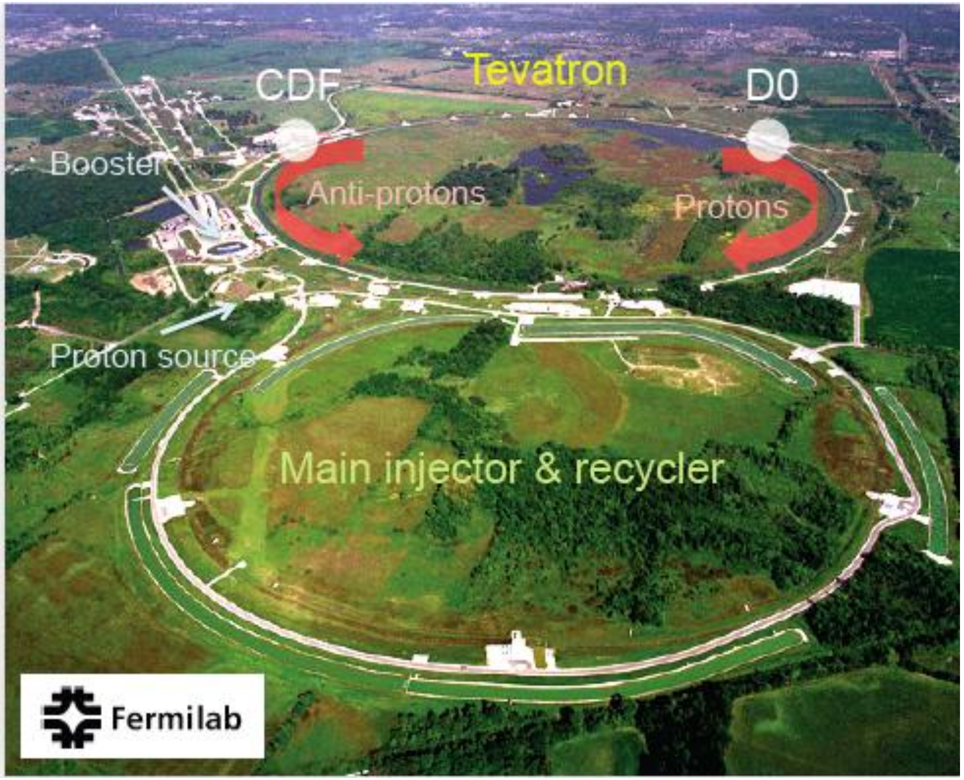


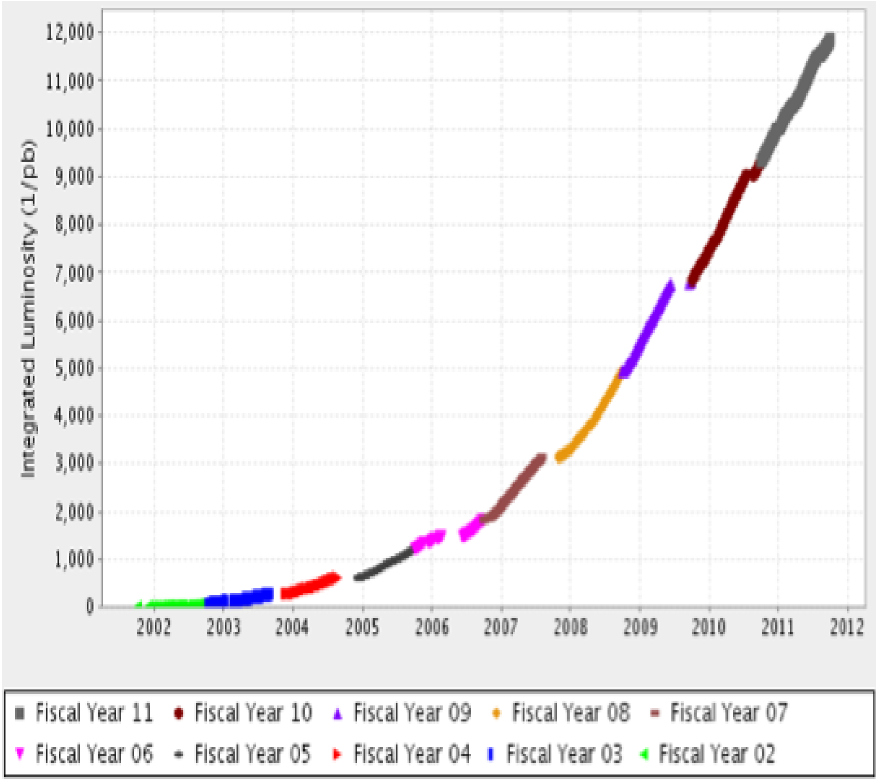
But I will still discuss extensions of the SM (SUSY , MSSM, … , FCNC)

I will not give full justice to the Tevatron

But we cannot overestimate what the LHC experiments owe to the Tevatron , in particular in term of analysis methods !

- Proton-antiproton collider at $\sqrt{s}$=1.96 TeV
  - Tevatron accelerator: 6.5 km circumference
  - Two general-purpose experiments: CDF and DØ
  - 10-year long Run II ended Sept. 30th, 2011
  - Total integrated luminosity delivered in Run II: ~12 fb^{-1} (per experiment)





Rien n’est cru si fermement que ce que l’on sait le moins

Nothing is believed more strongly that which we know the least

Montaigne , Essais

and detectors

- **Historical introduction of the boson and of the LHC**
- **Some phenomenological comments**
- **Rapid overview of the detectors**
- **The discovery**
- **The first measurements of the properties**
- **The future of the physics with the scalar boson(s)**
- **Backup (with references)**

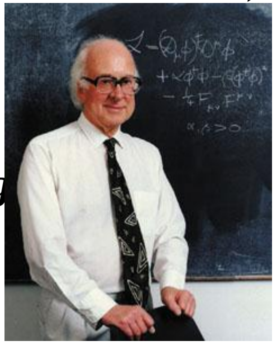
Spontaneous Symmetry breaking

The Brout-Englert-Higgs mechanism

The LHC

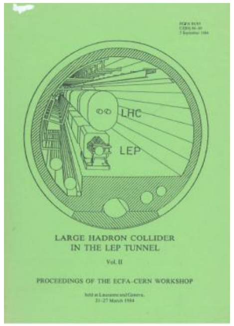
in a

1950 Ginzburg-Landau (*Meissner-Ochsenfeld effect → London penetration length ~ W mass*
1959 Nambu *→ Pippard coherence length ~ H mass)*
1960 Goldstone
1961 Schwinger
1962 Anderson *related to sort of*
1964 Brout, Englert, Higgs, Guralnik,Hagen,Kibble *(Anderson) Brout-Englert-Hig*



1967 Weinberg, Salam Faddeev,Popov
1970 Glashow, Iliopoulos,
Maiani, 't Hooft, Veltman…..

1983 Rubbia, van der Meer, Spiro, Banner, *discovery of W and Z at CERN*
1984 , Darriulat, Di Lella, Repellin, …… Lausanne



1989 construction of the LEP (e+ e- collider) tunnel finished
beginning of the R & D of LHC experiments

1992 ← LOI of 'large' LHC experiments
1994 ← TP of ATLAS andCMS approval of LHC (december)
1995 *discovery of top by CDF and D0 (following evidence in 1994 by CDF)*
1996 ← approval of LHC in one step (december)
1998 ← approval of the 4 largest LHC experiments (ATLAS,CMS, *LHCb, ALICE*)
1999 ← ATLAS Physics TDR CERN/LHCC/99-14 CERN/LHCC/99-15

2006 ← CMS Physics TDR J. Phys. G: Nucl. Part. Phys. 34 (2007) 995–1579
2008 ← ATLAS *Expected Performance* arXiv:0901.0512
2010 ← start-up at 3.5 + 3.5 TeV
2012 ← 4th July discovery of boson
2013 ← boson like properties

2008

10th september 2008 : first beams around
19th september 2008 : incident

14 months of major repairs and consolidation
New Quench Protection system

2009

20th november 2009 : first beams around (*again*)
december 2009 : collisions at 2.36 TeV cms

January 2010 : decided scenario 2010-11 7 TeV cms instead of 14 TeV

2010

30th march 2010 : first collisions at 7 TeV cms
august 2010 : luminosity of 10^{31} cm^{-2} s^{-1}

2011

may 2011 : luminosity > 10^{33} cm^{-2} s^{-1}
november 2011 : integrated luminosity ~ 5 fb^{-1}
13^{th} december 2011 : first 'signal' around 126 GeV

2012

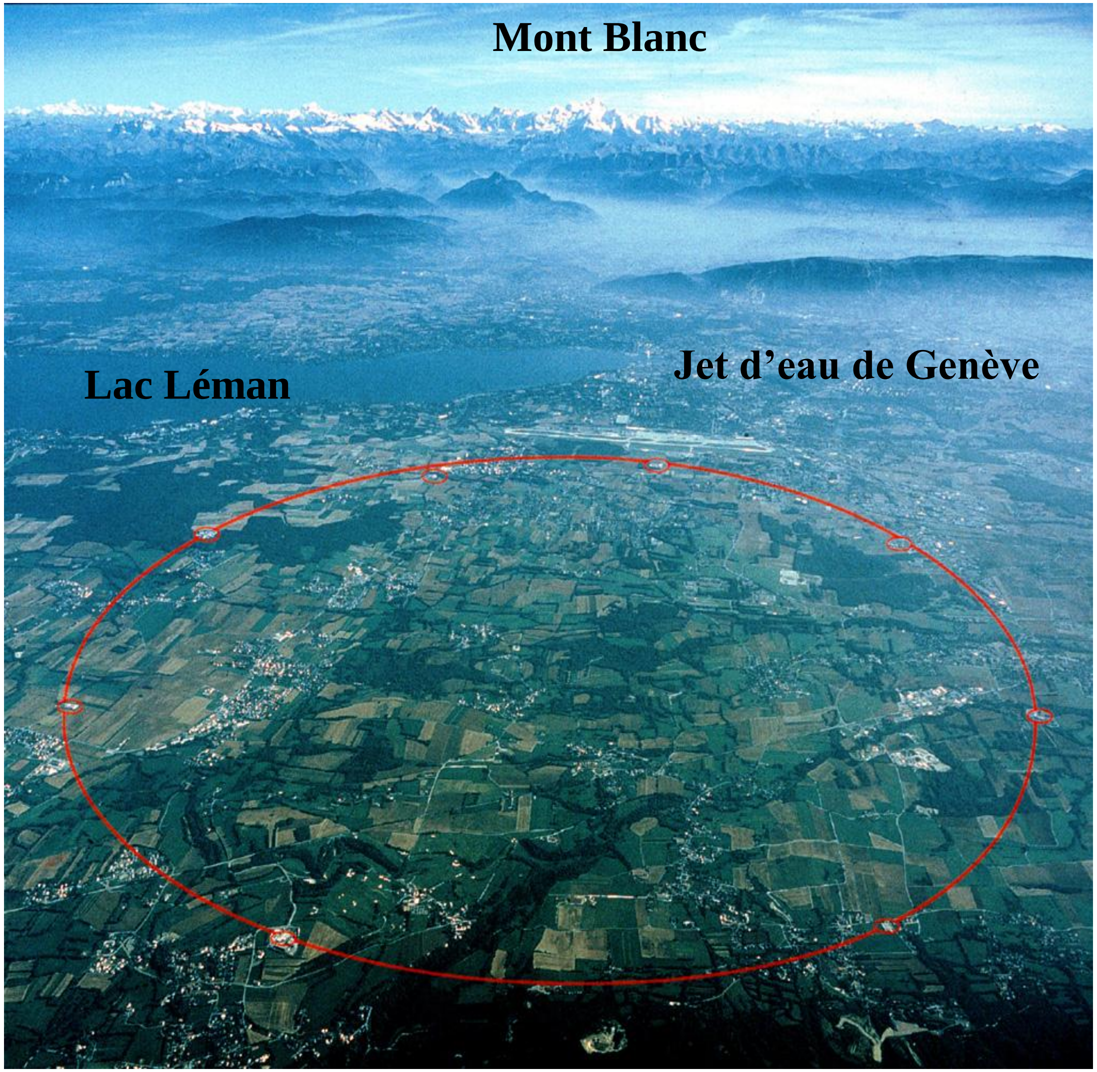
march 2012 : start again at 8 TeV
4^{th} July 2012 : evidence for a new boson
(*integrated luminosity ~ 6 fb^{-1}*)

2013

(Standard-Model) boson-like properties
peak luminosity 7 10^{33} cm^{-2} s^{-1}

► The LHC

The LHC is a (mainly) pp superconducting collider of 27 km long in a tunnel ~ 100 m underground close to Geneva (tunnel already used by LEP) which should work with a *design* centre-of-mass energy of 14 TeV



CERN
(Centre
Europeen
de
Recherche
(sub)Nucleaire)

in fact world center

LHC = Large Hadron Collider

αδρός, hadrós = strong

for particles sensitive to strong interaction

hadrons are opposed to leptons

λεπτός = thin

In fact it accelerates mainly protons but also ions

luminosity is a property of beams

event rate [events s^{-1}]
= luminosity [nb^{-1} s^{-1}] * cross section [nb]

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

Number of protons in A bunch

Number of bunches in collision

energy

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} E}{m_p 4\pi\beta^*\epsilon} F$$

Transverse size of the beams

Important parameters

(instantaneous) luminosity

LHC : currently

peak luminosity is $7\ 10^{33}\ cm^{-2}\ s^{-1}$

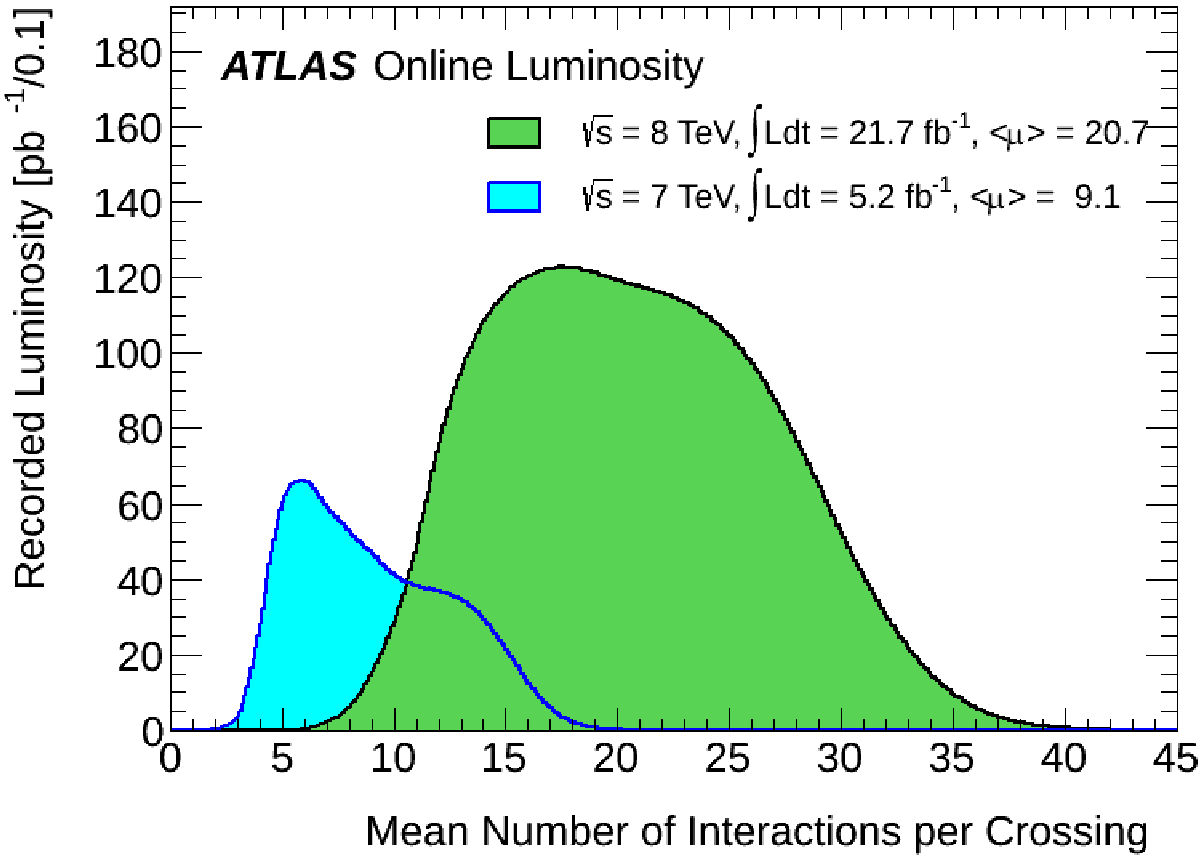
other unit = $nb^{-1}\ s^{-1}$

Integrated luminosity

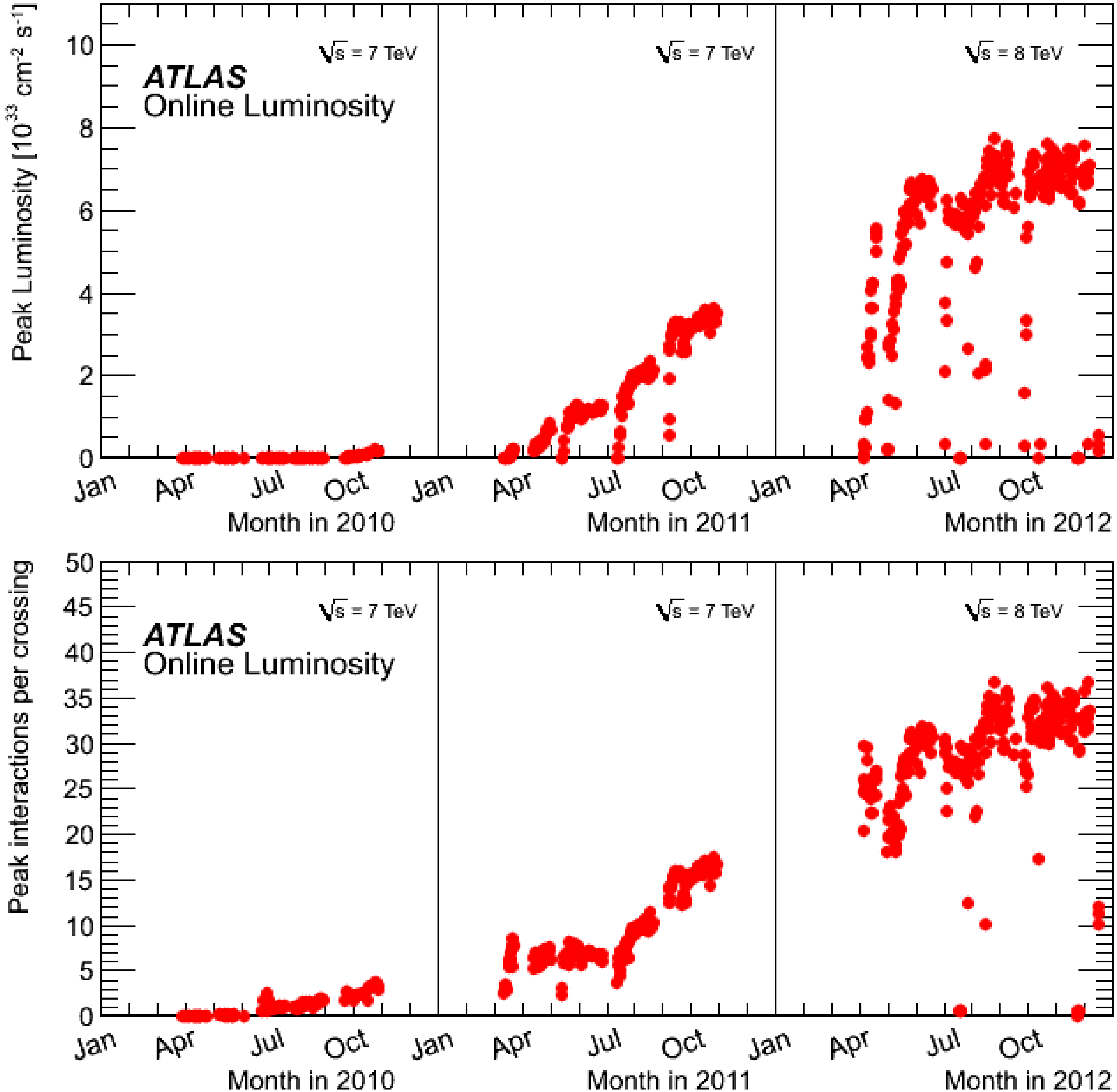
for ATLAS and CMS each

it was ~ 5 fb^{-1} at $\sqrt{s}$ = 7 TeV and ~ 20 fb^{-1} at $\sqrt{s}$ = 8 TeV

Notion of pile-up : in a bunch-crossing , in addition to the 'nice' event there are additional p-p interactions (~35 for $7\ 10^{33}\ cm^{-2}\ s^{-1}$) which make the 'nice' event more complicated to analyze



ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 21.7 fb-1, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb-1, <μ> = 9.1
Recorded Luminosity [pb -1/0.1]
Mean Number of Interactions per Crossing
0
20
40
60
80
100
120
140
160
180
0
5
10
15
20
25
30
35
40
45


ATLAS
Online Luminosity
√s = 7 TeV
√s = 7 TeV
√s = 8 TeV
Peak Luminosity [10^33 cm^-2 s^-1]
Month in 2010
Month in 2011
Month in 2012
Jan
Apr
Jul
Oct
Peak interactions per crossing

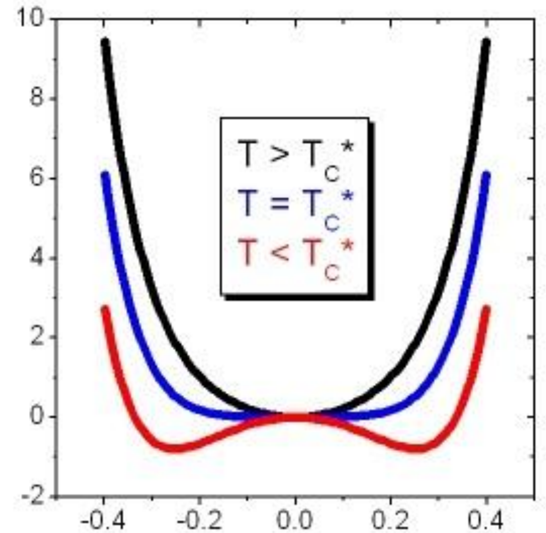
Condensed matter physics

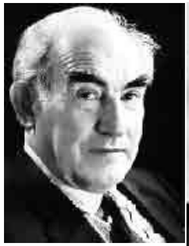
SSB = Spontaneous Symmetry Breaking :There are symmetries of the Lagrangian that are not symmetries of the fundamental state (vacuum)

1928 (Heisenberg) For $T<T_C$ dipoles are aligned in some arbitrary direction

1950 (Ginzburg Landau) : phase transition in superconductivity

1957 (Bardeen, Cooper, Schrieffer) SSB of EM gauge invariance





Particle physics - strong interaction (global symmetry)

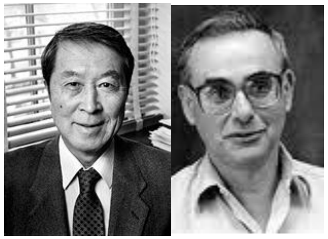
1959 (Nambu Jona-Lasinio) **: SSB transmitted from condensed matter to particle physics**
SSB of (global) chiral symmetry $\rightarrow$ pseudoscalar boson π^0
massless boson if exact symmetry

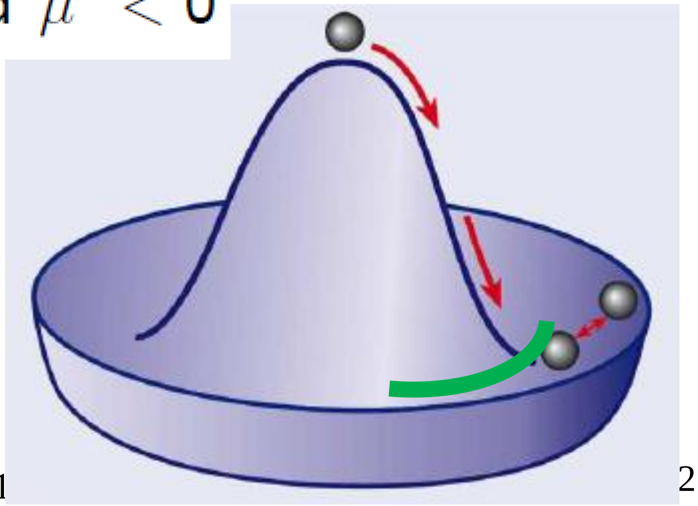
1960 (Goldstone) : generalization : SSB of continuous global symmetry $\rightarrow$ massless (Nambu-Goldstone) bosons

$$L = \partial^\mu \phi^\dagger \partial_\mu \phi - V(\phi^\dagger \phi)$$

$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2; \ \lambda > 0 \text{ and } \mu^2 < 0$$

and massive boson mass $\sqrt{(-2\mu^2)}$
$\sigma = f_0(600)$





Particle physics - strong interaction (local symmetry)

1964 (Brout,Englert, Higgs, Guralnik, Hagen,Kibble)

SSB of gauge symmetries

The BEH mechanism : no massless particles
massive gauge bosons

mass of gauge boson acquired by 'eating' the N-G boson

one massive particle $\sqrt{(-2\mu^2)}$: BEH boson (or Higgs boson)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

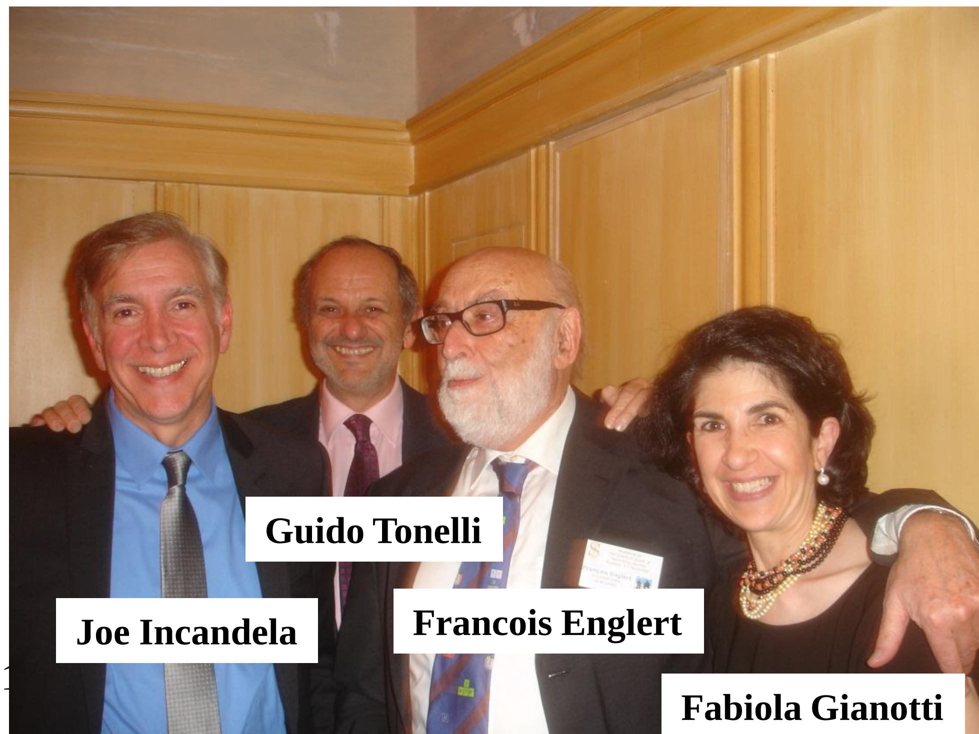
The interaction between the φ and the A_μ fields is

$$H_{\text{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu,$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$.

and causes the A_μ field to acquire a mass

$$\mu^2 = e^2 \langle\varphi_1\rangle^2.$$



Field Theories with «Superconductor» Solutions.

J. GOLDSTONE
CERN - Geneva

(ricevuto l'8 Settembre 1960)

Plasmons, Gauge Invariance, and Mass

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

Symmetry Breaking in Non-Abelian Gauge Theories*

T. W. B. KIBBLE
Department of Physics, Imperial College, London, England
(Received 24 October 1966)

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Particle physics - weak interaction (local symmetry)

1967 (Weinberg Salam) Electroweak theory of leptons

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

**** Three massive bosons : W and Z***

**** One massless vector boson : photon*** γ

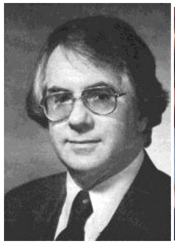
**** One massive scalar boson : BEH boson H***

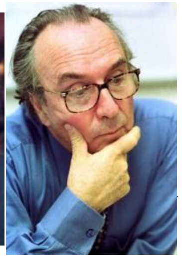
**** massive leptons by Yukawa couplings to BEH boson***

1970 (Glashow, Iliopoulos, Maiani) introduction of quarks in theory

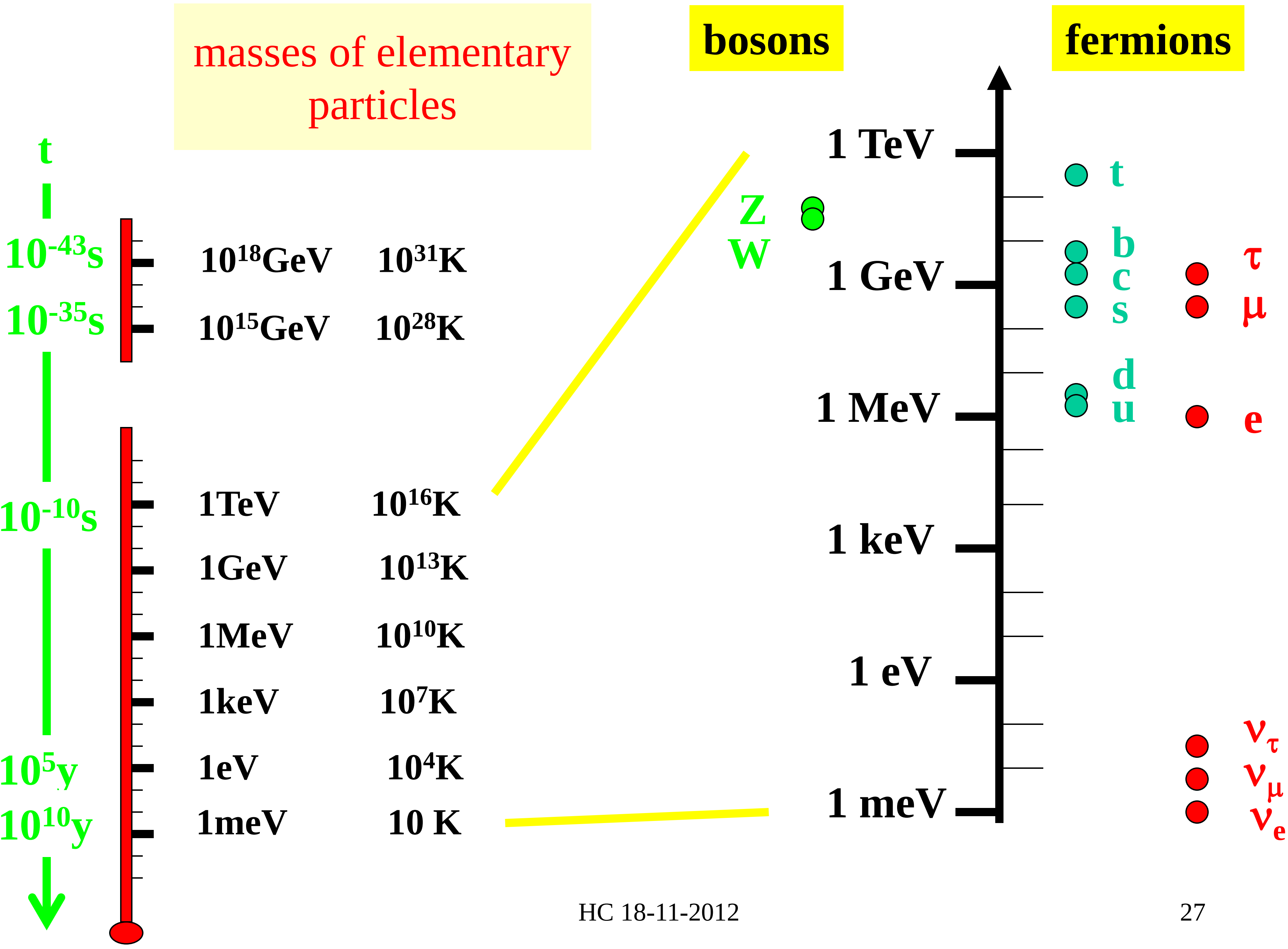
Faddeev,Popov,'t Hooft,Veltman,Lee,Zinn-Justin,Becchi, Rouet,Stora,Tyutin : renormalizable theory







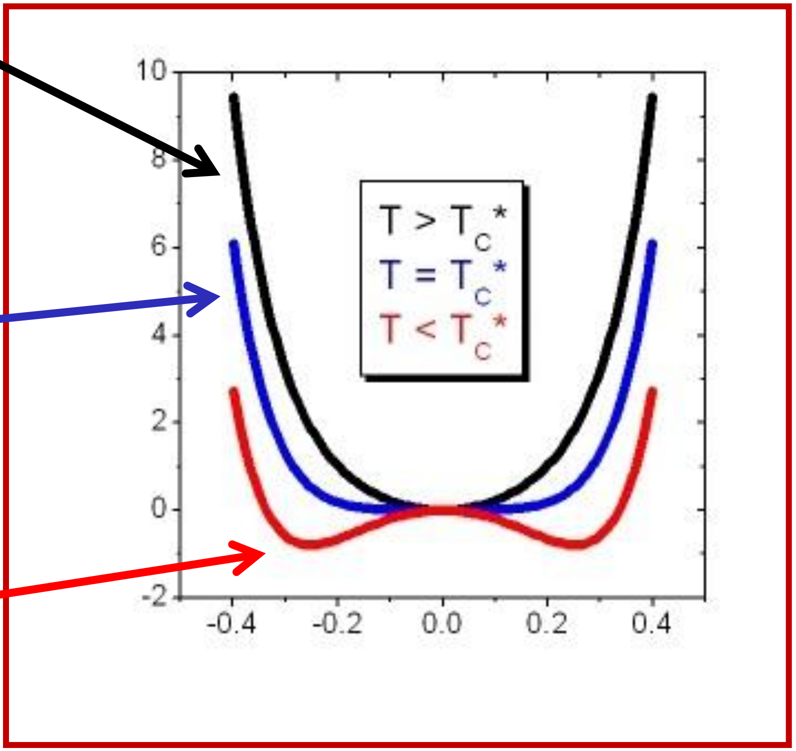
masses of elementary particles



Mass of the 4 scalar bosons positive
W and Z mass = 0
fermion masses =0

10^{-10} s

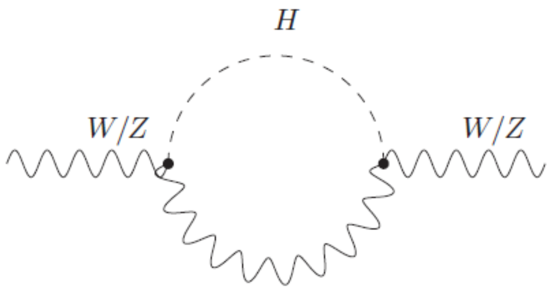
Mass of one scalar (BEH) boson positive
W and Z mass positive
fermion have their masses

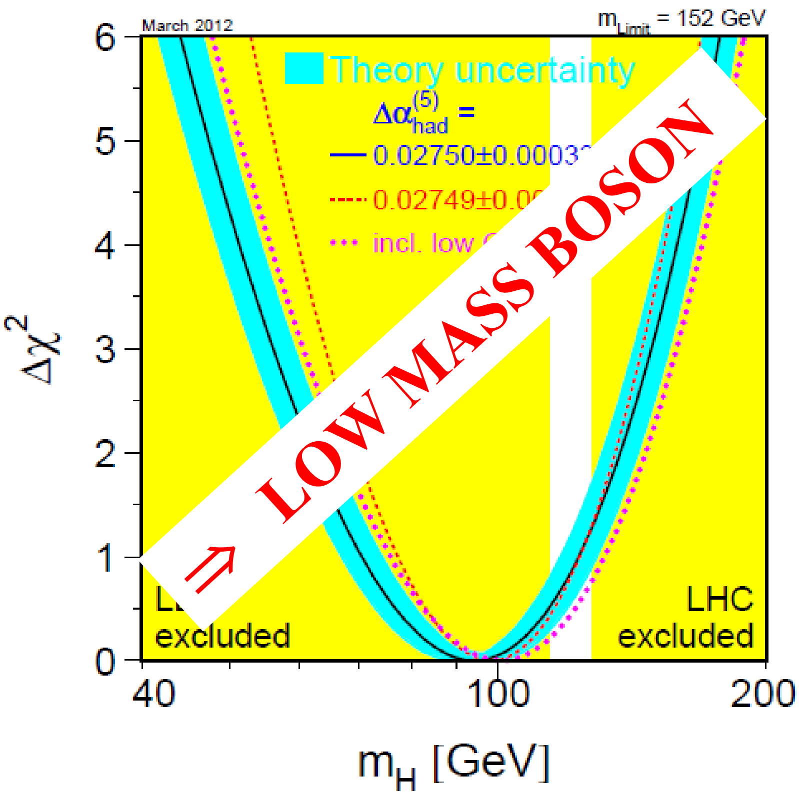


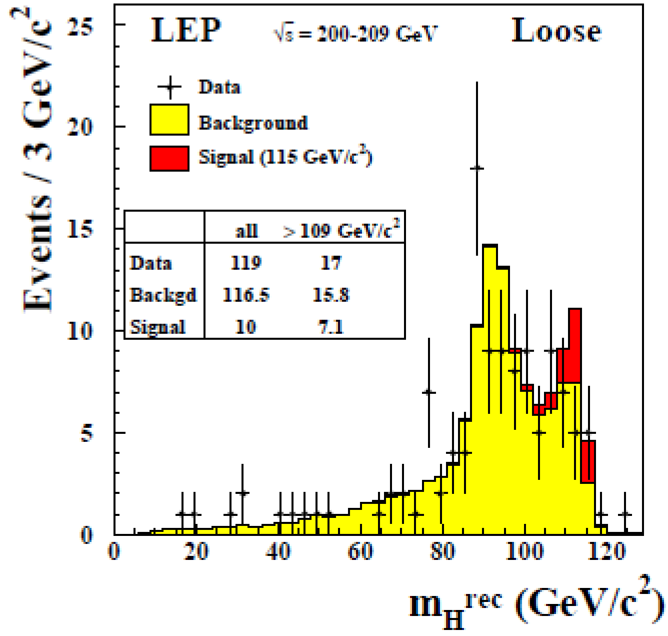
LEP legacy **Mainly e+e- → ZH**

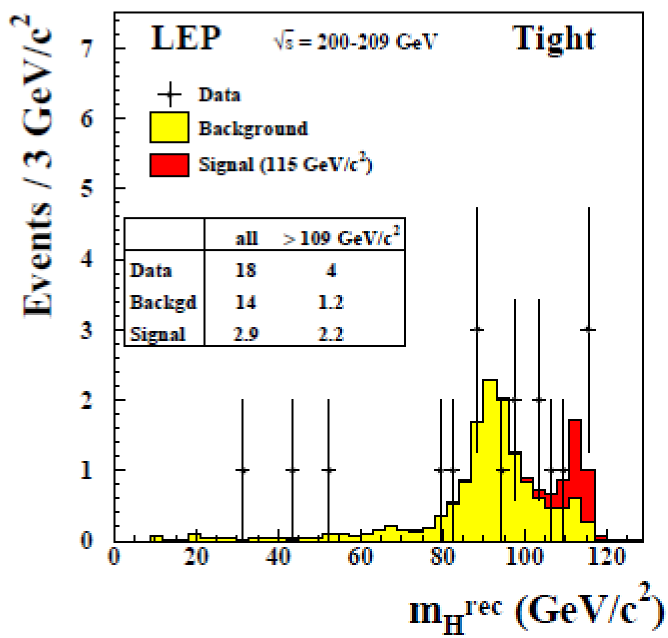
mH > 114.4 GeV 95% CL

tests of radiative corrections









Theorists and SUSY (SUperSYmmetry) prefer(ed) low mass boson

$m_h < m_Z$ at lowest order . But was realized that this prediction is subject to important radiative corrections that could push m_h up to ~130 GeV in simple supersymmetric models

Y. Okada, M. Yamaguchi and T. Yanagida, *Upper bound of the lightest Higgs boson mass in the minimal supersymmetric standard model*, Prog. Theor. Phys. **85** (1991) 1.

J. R. Ellis, G. Ridolfi and F. Zwirner, *Radiative corrections to the masses of supersymmetric Higgs bosons*, Phys. Lett. B **257** (1991) 83; H. E. Haber and R. Hempfling, *Can the mass of the lightest Higgs boson of the minimal supersymmetric model be larger than m(Z)?*

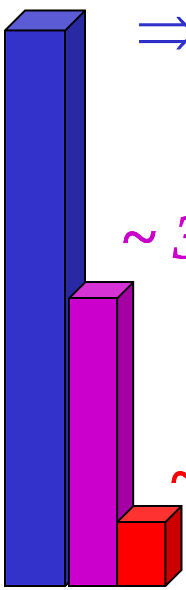
A lot of things are not known ! SM not ultimate theory

Energy of Universe

Hierarchy problem
$m_H << m_{Planck}$

~ 65 % of dark energy (vacuum energy)

⇒ expansion of Universe accelerating



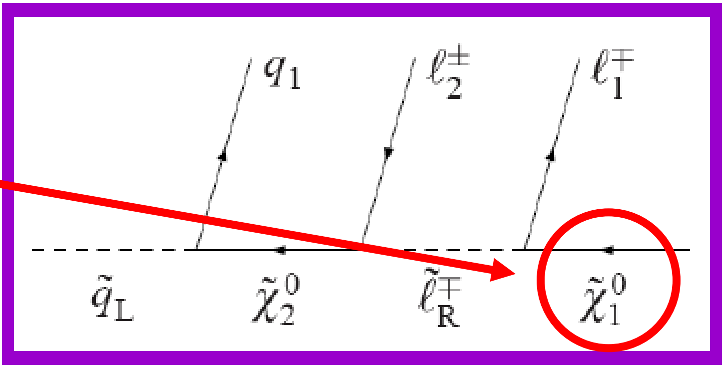
~ 30 % of dark matter (not yet observed) ⇒ rotation of galaxies

~ 5 % of "known" matter

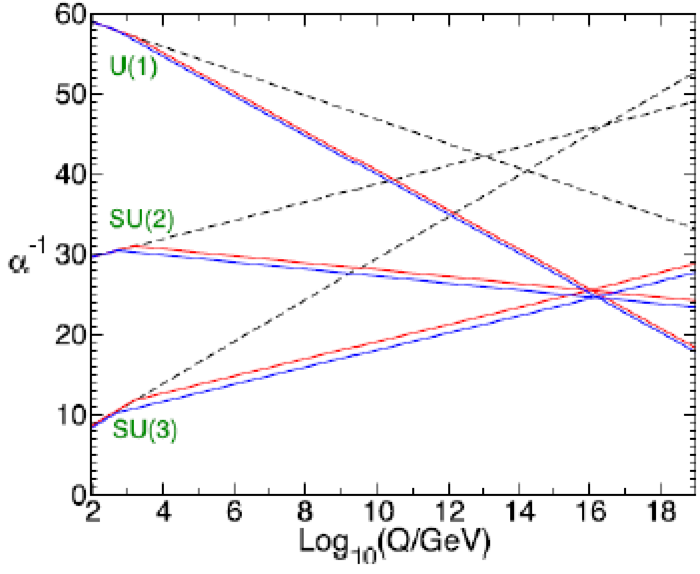
Connection with gravity

Supersymmetry (SUSY) is a popular candidate in order to 'explain' this

** Multiplies by ~2 the number of particles*
** Allows the stabilisation of the Higgs mass*
** Local SUSY incorporates gravity*
** Gives a natural candidate to dark matter : the* ***LSP***



In addition better unification



CHAPTER XII: NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES, *J. Ellis et al.*

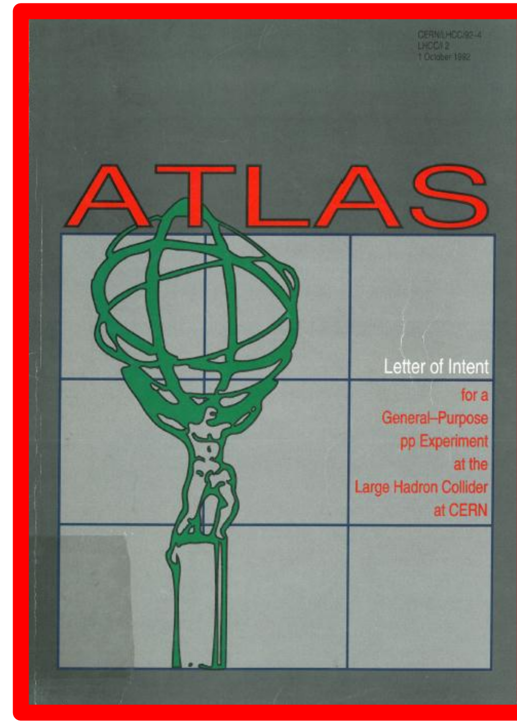
CONTENTS

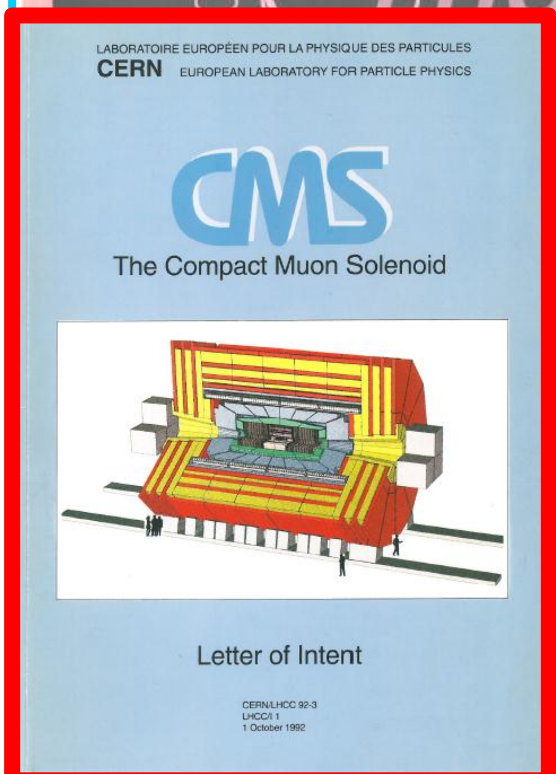
I. INTRODUCTION

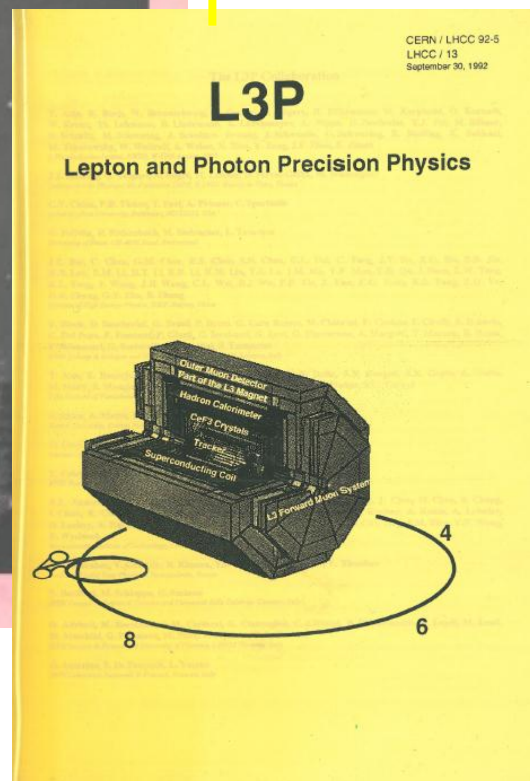
The phys… undergone a remarka… …st decade. A host of ne… accessible by a new gen… …ors and the accompanying ra… …oretical ideas have brought to the …erence. Our current outlook has been … identification of quarks and leptons as fun… …l constituents of matter and by the gauge theory …nesis of the fundamental interactions.[1] These developments represent an important simplification of

…rgy scale in elementary
… beam energies between
number of conventional
…grounds to more exotic
…s for several new phe-
…point for the choice of

cancellation of Superconducting SuperCollider by US congress in 1993


ATLAS
Letter of Intent
for a
General–Purpose
pp Experiment
at the
Large Hadron Collider
at CERN


LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CMS
The Compact Muon Solenoid
Letter of Intent
CERN/LHCC 92-3
LHCC/I 1
1 October 1992

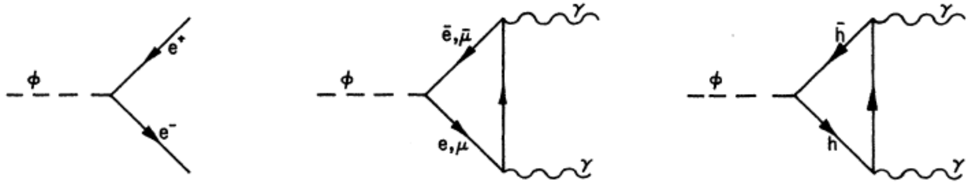

CERN / LHCC 92-5
September 30, 1992
L3P
Lepton and Photon Precision Physics
Outer Muon Detector
Hadron Calorimeter
CeF3 Crystals
Superconducting Coil
L3 Forward Muon System
4
6
8

chosen

Phenomenology of scalar boson (theory)

Is There a Light Scalar Boson?

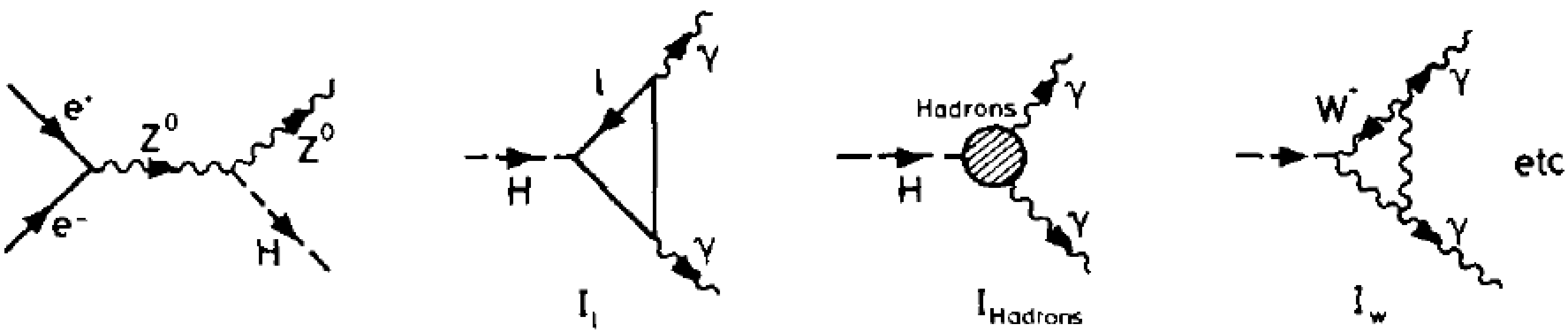
L. Resnick, M. K. Sundaresan, and P. J. S. Watson
Department of Physics, Carleton University, Ottawa, Canada
(Received 28 July 1972; revised manuscript received 2 January 1973)



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975



Phenomenology of scalar boson (theory)

Higgs Bosons from Two-Gluon Annihilation in Proton-Proton Collisions

H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 27 December 1977)

We estimate the cross section for Higgs-boson production in proton-proton collisions. We find that most of the cross section comes from a two-gluon annihilation process, in which the gluons couple to Higgs bosons via heavy-quark loops.

Low-energy theorems for Higgs meson interaction with photons

A. I. Vaĭnshteĭn, M. B. Voloshin, V. I. Zakharov, and M. A. Shifman
Institute of Theoretical and Experimental Physics of the State Committee on Atomic Energy
(Submitted 21 May 1979)
Yad. Fiz. **30**, 1368–1378 (November 1979)

First experimental note on scalar boson search at LEP

DESY 79/27
May 1979

THE PRODUCTION AND DETECTION OF HIGGS PARTICLES AT LEP

ECFA/LEP Specialized Study Group 9 "Exotic Particles"

G. Barbiellini	–	*INFN, Frascati and CERN*
G. Bonneaud	–	*Strasbourg and CERN*
G. Coignet	–	*LAPP, Annecy-le-vieux*
J. Ellis	–	*CERN*
M. K. Gaillard	–	*LAPP, Annecy-le-vieux*
J. F. Grivaz	–	*LAL, Orsay*
C. Matteuzzi	–	*CERN*
B. H. Wiik	–	*DESY*

$H \rightarrow \gamma\gamma$ (historical mode)

Photon decay modes of the intermediate mass Higgs

ECFA Higgs working group
C.Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

A report is given of studies of:
(a) H -> γγ (work done by C. Seez and T. Virdee)
(b) W H -> γγ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_H < 150$ GeV/c^2).
The study of the two photon decay mode is described in detail.

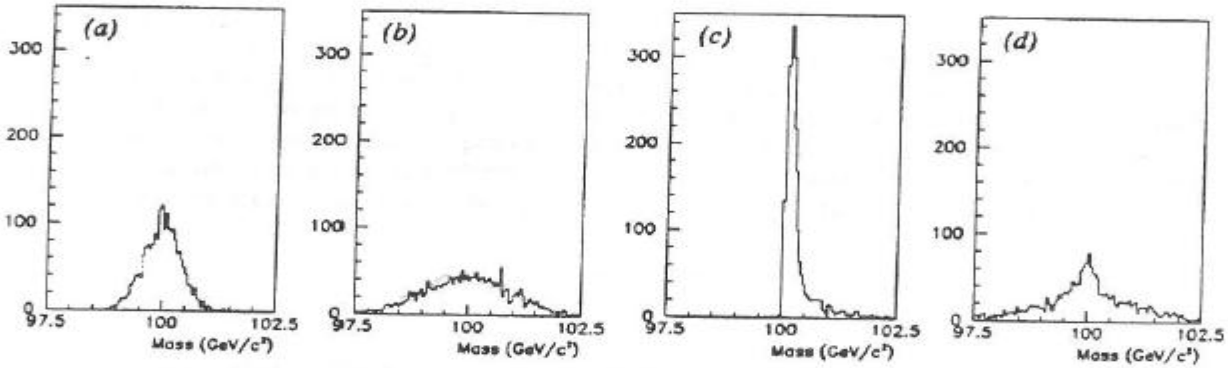


Figure 4: Reconstructed mass plots for Higgs boson, m_H=100GeV/c^2
(a) smeared by: calorimeter energy resolution of $\Delta E/E = 2\%/\sqrt{E} \oplus 0.5\%$
(b) smeared by: calorimeter energy resolution of $\Delta E/E = 7\%/\sqrt{E} \oplus 1.0\%$
(c) smeared by: pileup energy from, on average, 10 interactions
(d) smeared by: loss of knowledge of the vertex position (σ_{vtx}=5.5 cm)



C.Seez **J.Virdee** **G.Unal**

was studied at the LHC
for more than 20 years
(and even before at the SSC)

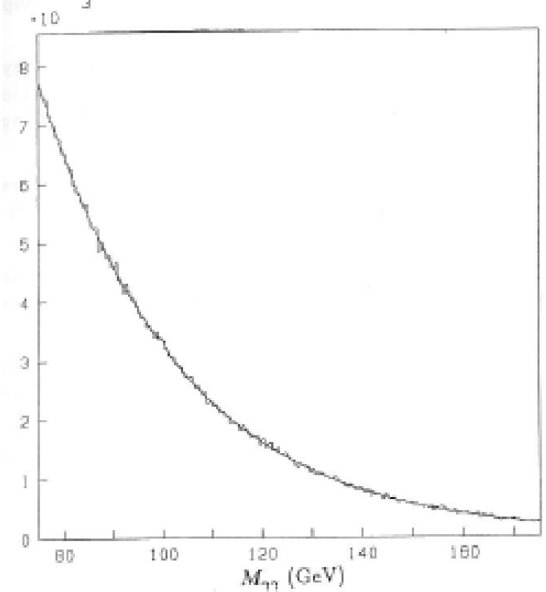


FIG. 6. Simulated mass distribution for 100 GeV Higgs in detector with extraordinary resolution.

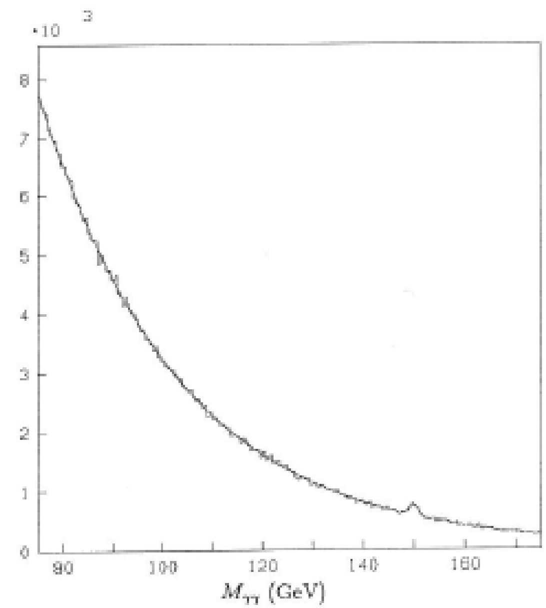


FIG. 7. Simulated mass distribution for 150 GeV Higgs in detector with extraordinary resolution.

DETECTION OF $H^0 \to \gamma\gamma$ AT THE SSC

C. Barter and R. Partridge
Brown University, Providence, Rhode Island 02912

A. Bay and A. Spadafora
Lawrence Berkeley Laboratory, Berkeley, California 94720

S. Whitaker
Boston University, Boston, Massachusetts 02215

A. Abashian
University of Virginia, Chalottesville, Virginia 22901

R. Kass
Ohio State University, Columbus, Ohio 43210

Proceedings of the Summer Study on High Energy Physics in the 1990s

June 27 – July 15, 1988
Snowmass, Colorado

Editor
Sharon Jensen

SSC-SDC-90-00113

PRODUCTION OF $WH \to W\gamma\gamma \to e/\mu\gamma\gamma$

Michelangelo L. MANGANO

Istituto Nazionaledi FisicaNucleare
Scuola NormaleSuperioreand
Dipartimento di Fisica, Pisa, ITALY

H → 4l (gold plated mode)

Proceedings of the Summer Study on High Energy Physics in the 1990s

June 27 – July 15, 1988
Snowmass, Colorado

Editor
Sharon Jensen

Effect of Lepton Energy Resolution on Higgs Searches at the SSC.*

Ian Hinchliffe

Edward M. Wang

Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, California 94720

Abstract

We discuss the effects of realistic detector resolutions on the processes $H \to ZZ \to e^+e^-e^+e^-$ and $H \to ZZ \to e^+e^-\mu^+\mu^-$ at the SSC. The background from $Zt\bar{t}$ where the $t\bar{t}$ system produces two isolated leptons in its decays is discussed.

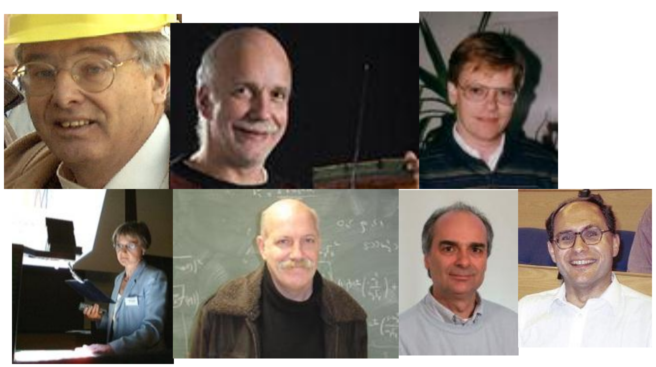
SEARCH FOR H → Z*Z* → 4 LEPTONS AT LHC

Higgs Study Group

M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen, R. Kleiss, A. Nisati and T. Sjöstrand

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

In Section 2, we discuss the simulation of the Higgs signal, and we study the backgrounds from $t\bar{t}$, $Zb\bar{b}$ and Z^*Z^*, γ^*Z^*, in Section 3. Finally, in Section 4, we present and discuss the results, and we conclude in Section 5.



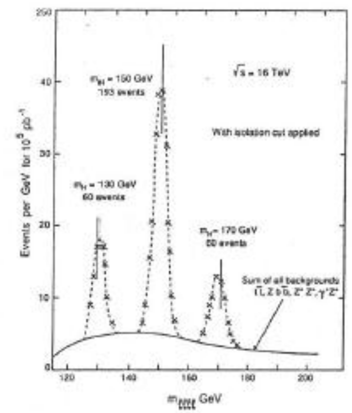


Fig. 10

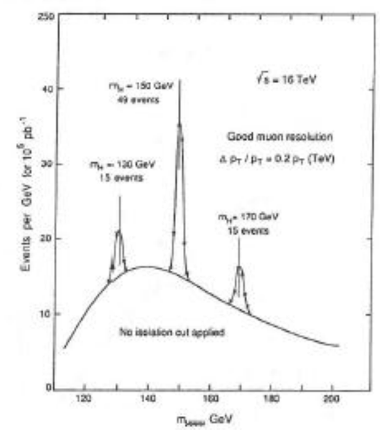
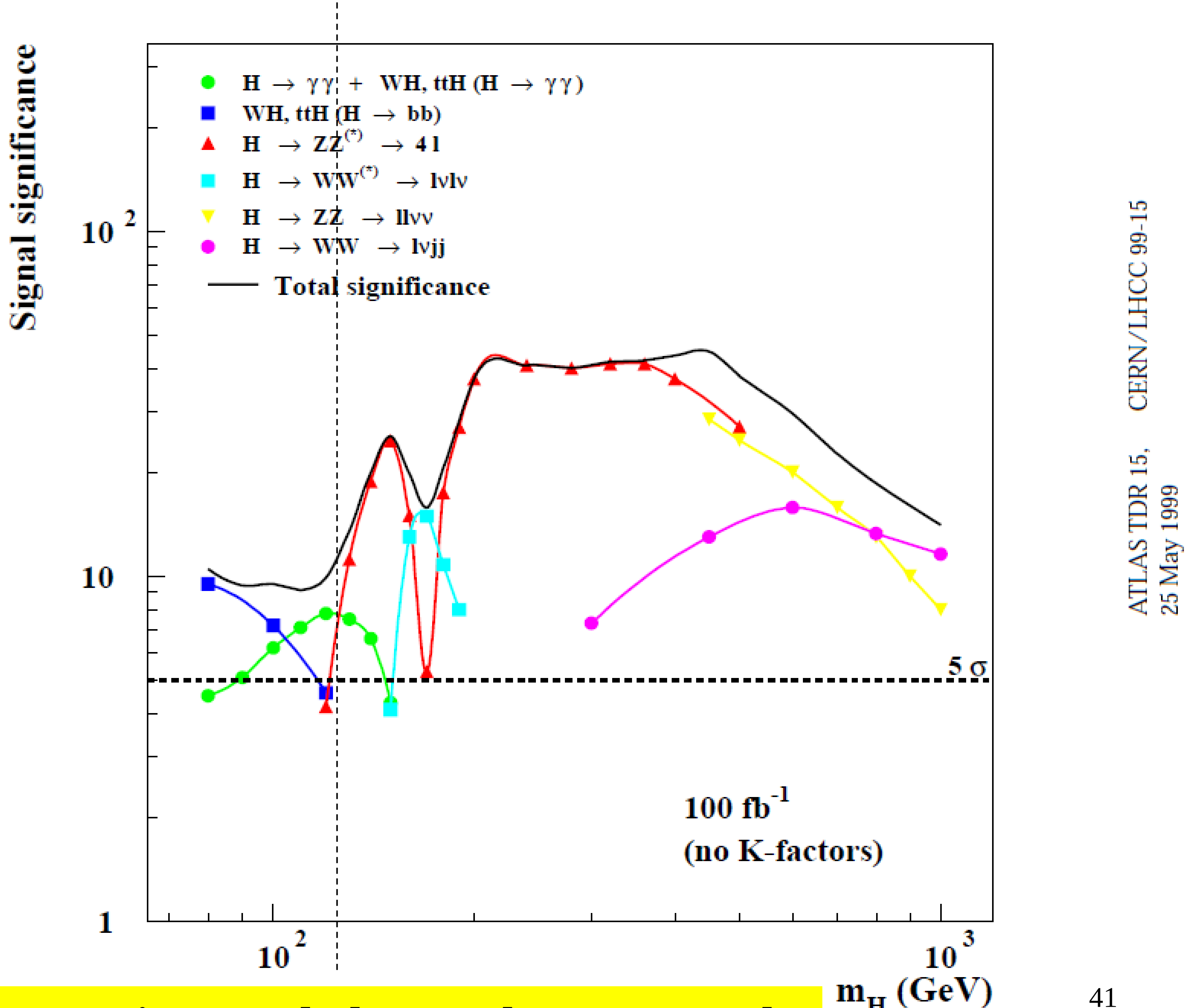
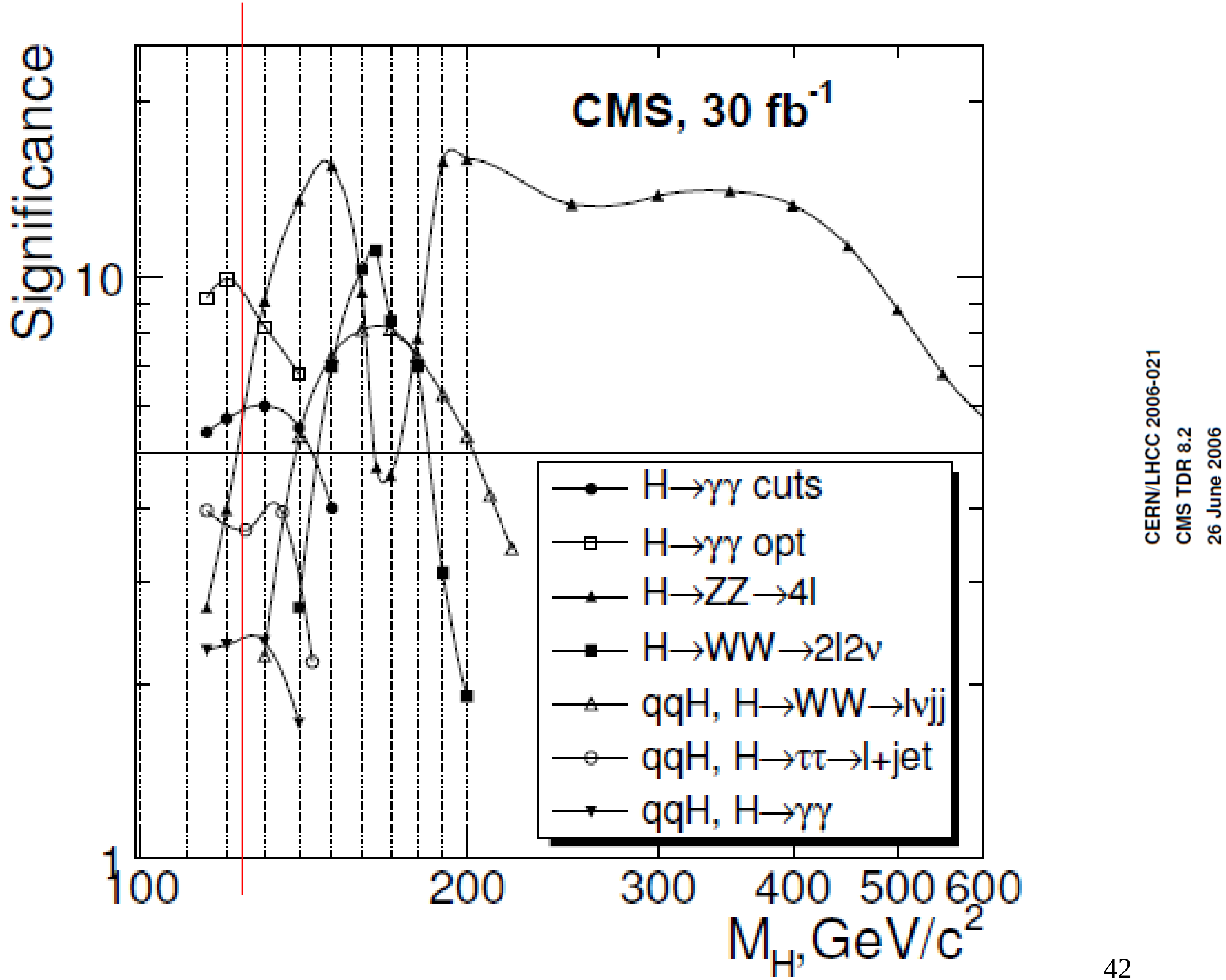


Fig. 11



as often , experiments do better than expected



CMS, 30 fb-1
Significance
10
1
100
200
300
400
500
600
M_H, GeV/c2
H→γγ cuts
H→γγ opt
H→ZZ→4l
H→WW→2l2ν
qqH, H→WW→lνjj
qqH, H→ττ→l+jet
qqH, H→γγ
CERN/LHCC 2006-021
CMS TDR 8.2
26 June 2006

MSSM

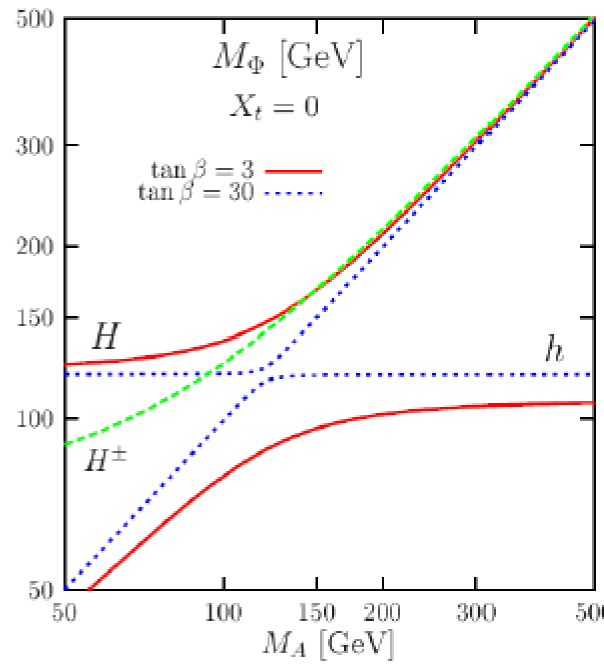
5 Higgs bosons
(3 neutrals A,H,h and 2 charged H±)

couplings to down part of doublets (b , τ , μ) enhanced at high *tan(β)*

D.Rainwater hep-ph/0702124

	Φ	$\frac{g_{\Phi u\bar{u}}}{g_f}$	$\frac{g_{\Phi d\bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
	h	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
	H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta-\alpha)$
	A	$-i\gamma_5\cot\beta$	$i\gamma_5\cot\beta$	0	0
MSSM	h	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
MSSM	H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta-\alpha)$
MSSM	A	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$	0	0

Type I (upper) and II (lower) 2HDMs



at LO MSSM Higgs sector depends of 2 parameters M_A tan(β) (= v2/ v1) at NLO more SUSY parameters

A (0^-) does not give ZZ and WW)

Testing the Higgs sector of t
supersymmetric standard mc
hadron colliders

Z. Kunszt
Institute of Theoretical Physics, ETH, Zurich

F. Zwirner *
Theory Division, CERN, Geneva, Swit.

Received 31 March 1992
Accepted for publication 8 July 1

m_A tan(β)   plane

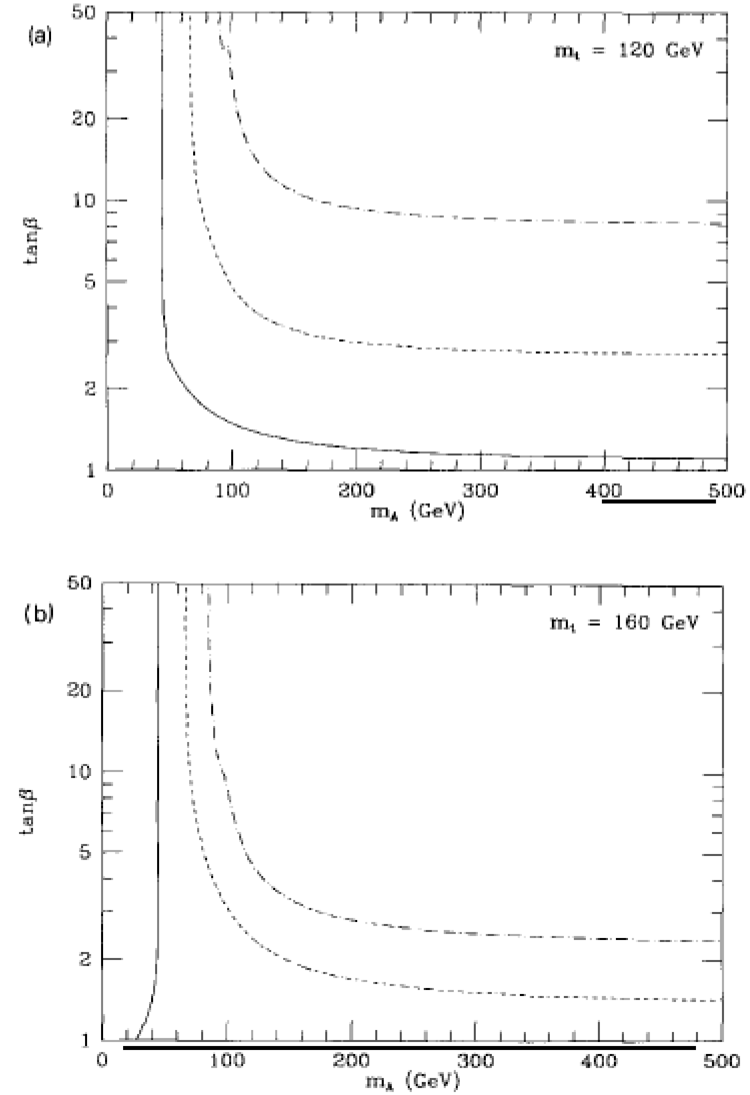


Fig. 8. Schematic representation of the present LEP I limits and of the future LEP II sensitivity in the (m_A, tan β) plane, for $m_{\tilde{q}} = 1$ TeV and (a) $m_t = 120$ GeV, (b) $m_t = 160$ GeV. The solid lines correspond to the present LEP I limits. The dashed lines correspond to $\sigma(e^+e^- \to hZ, HZ, hA, HA) = 0.2$ pb at $\sqrt{s} = 175$ GeV, which could be seen as a rather conservative estimate of the LEP II sensitivity. The dash-dotted lines correspond to $\sigma(e^+e^- \to hZ, HZ, hA, HA) = 0.05$ pb at $\sqrt{s} = 190$ GeV, which could be seen as a rather optimistic estimate of the LEP II sensitivity.

- **Historical introduction of the boson and of the LHC**
- **Some phenomenological comments**

see also seminar by *Massimiliano Grazzini*

- **Rapid overview of the detectors**
- **The discovery**
- **The first measurements of the properties**
- **The future of the physics with the scalar boson(s)**
- **Backup (with references)**

We have to produce the Brout-Englert-Higgs boson

The production rate is small !

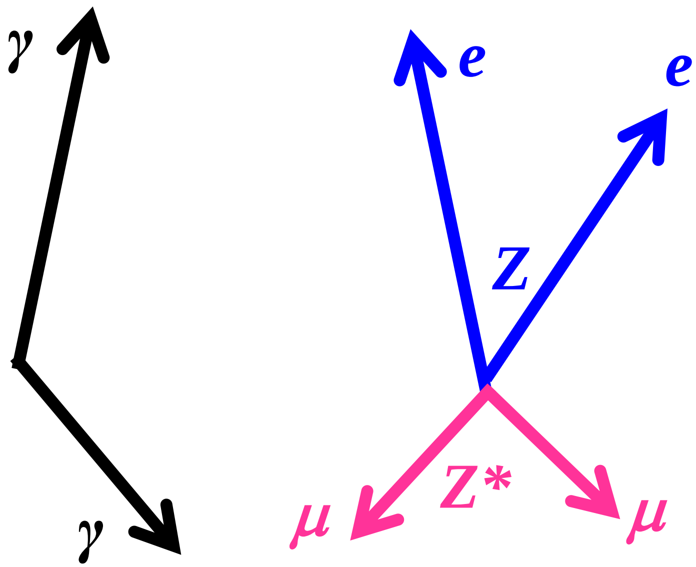
1 BEH boson produced for 10^9 collisions !

But LHC is still the only place where one can discover it (there are however indications at Tevatron)

LHC has produced 10^6 bosons !

The production rate of the boson is predicted with a very good precision (~ 10%) by the Standard Model (strong interactions with quarks and gluons + couplings to BEH boson) ….. if it is correct

We can measure the boson only through its decay products !



We can reconstruct its mass m_H by measuring the sum of the energies (** *in the center of mass* **) of its decay products

E

then $E = m_H c^2$

The Brout-Englert-Higgs boson decays very early !

in ~ 10^{-22} s

(corresponding to ~100 fm ~ 10^{-3} Å)

We can reconstruct its mass m_H ***by measuring the sum of the energies (*** *in the center of mass* ***) of its decay products***

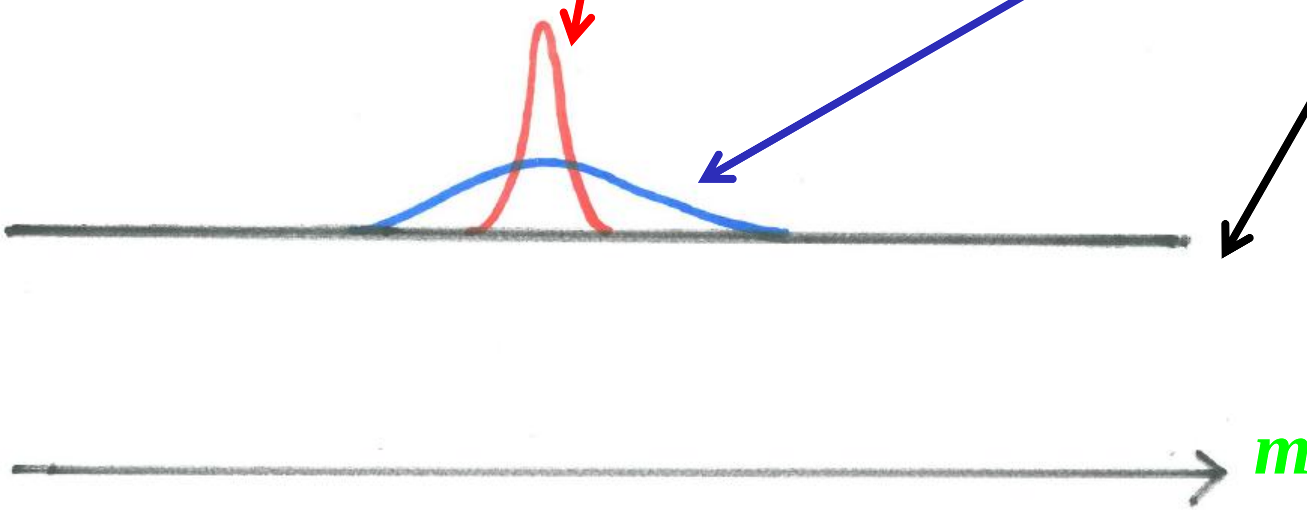
E

then $E = m_H c^2$

Considering the mass distribution m ***of events 'candidates BEH'***

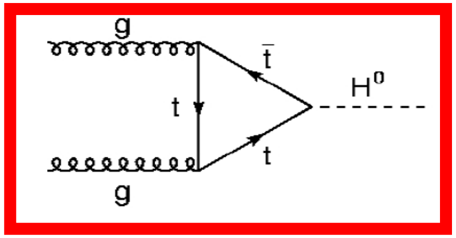
We have background events

A signal with a good resolution will be better seen than a signal with a bad resolution

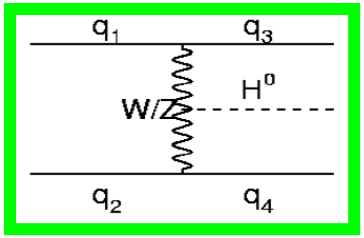


We need detectors with a good resolution

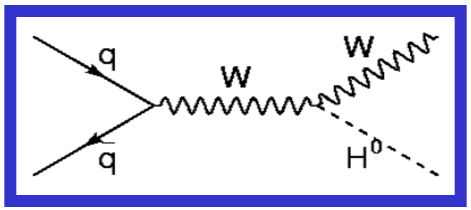
A.Djouadi Phys.Rept.457:1-216



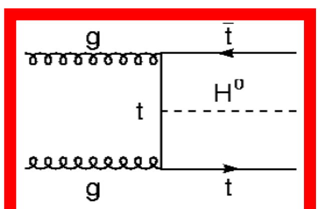
GF H → WW , ZZ , γγ , bb,ττ



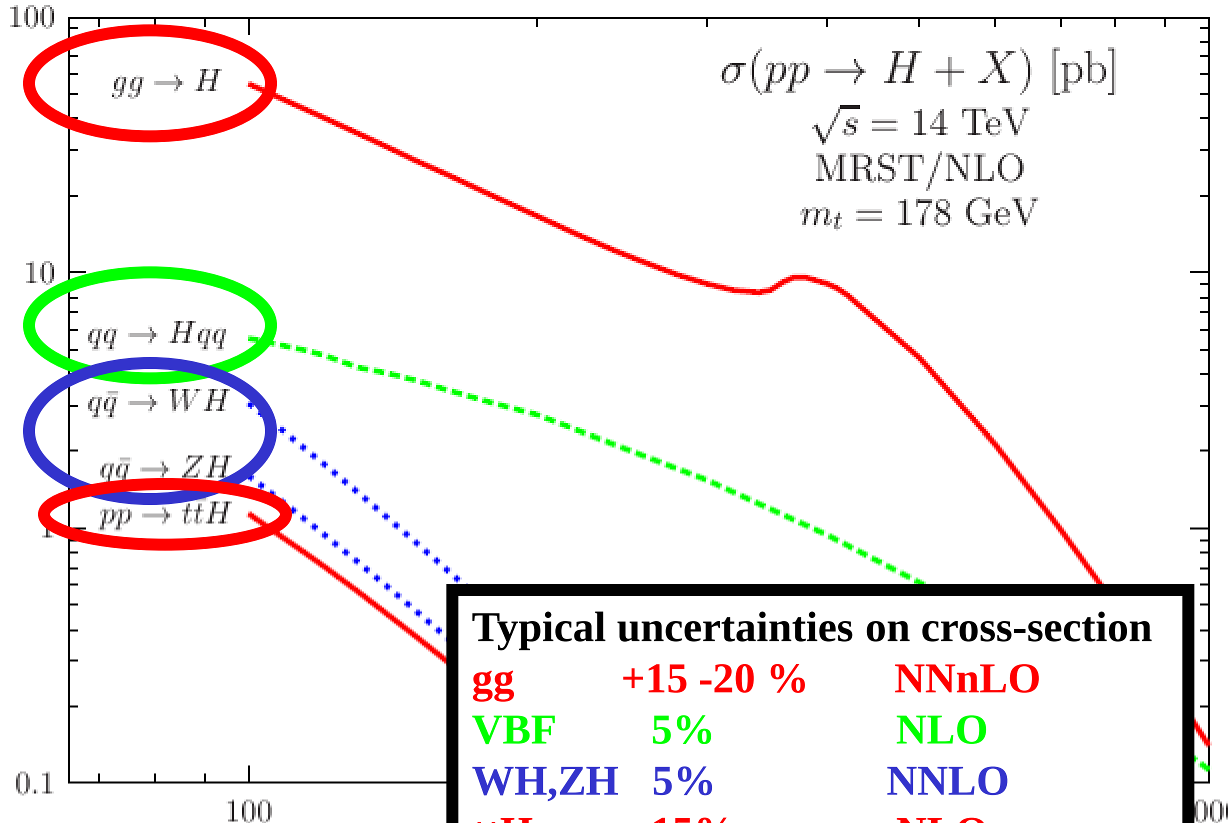
VBF H → WW, ZZ , γγ , ττ



H → WW, γγ, bb



H → WW, γγ, bb

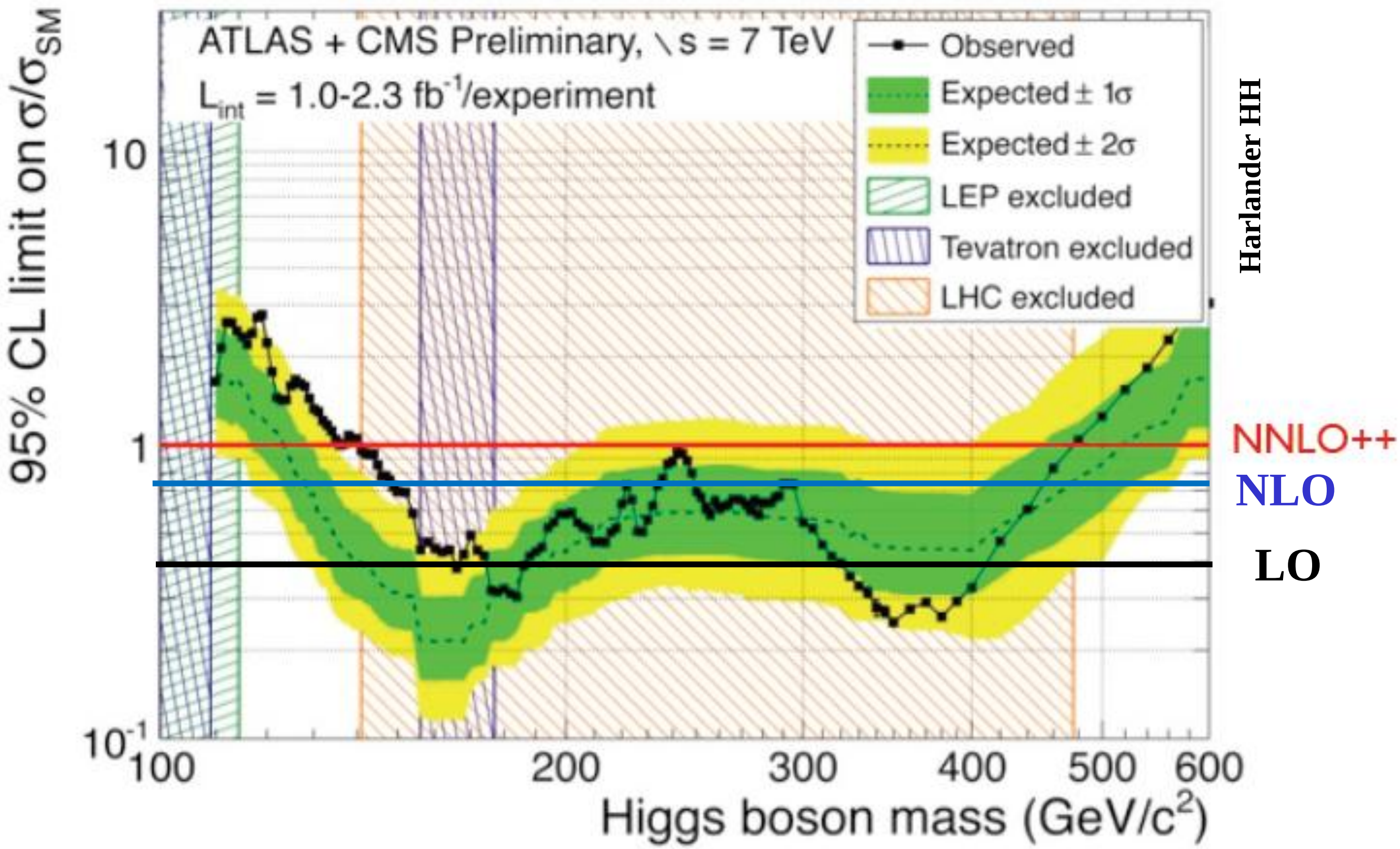


Typical uncertainties on cross-section		
gg	+15 -20 %	NNnLO
VBF	5%	NLO
WH,ZH	5%	NNLO
ttH	15%	NLO

These production cross sections have to be used with the decays **bb , ττ , WW , ZZ , γγ**

channels with good mass resolution

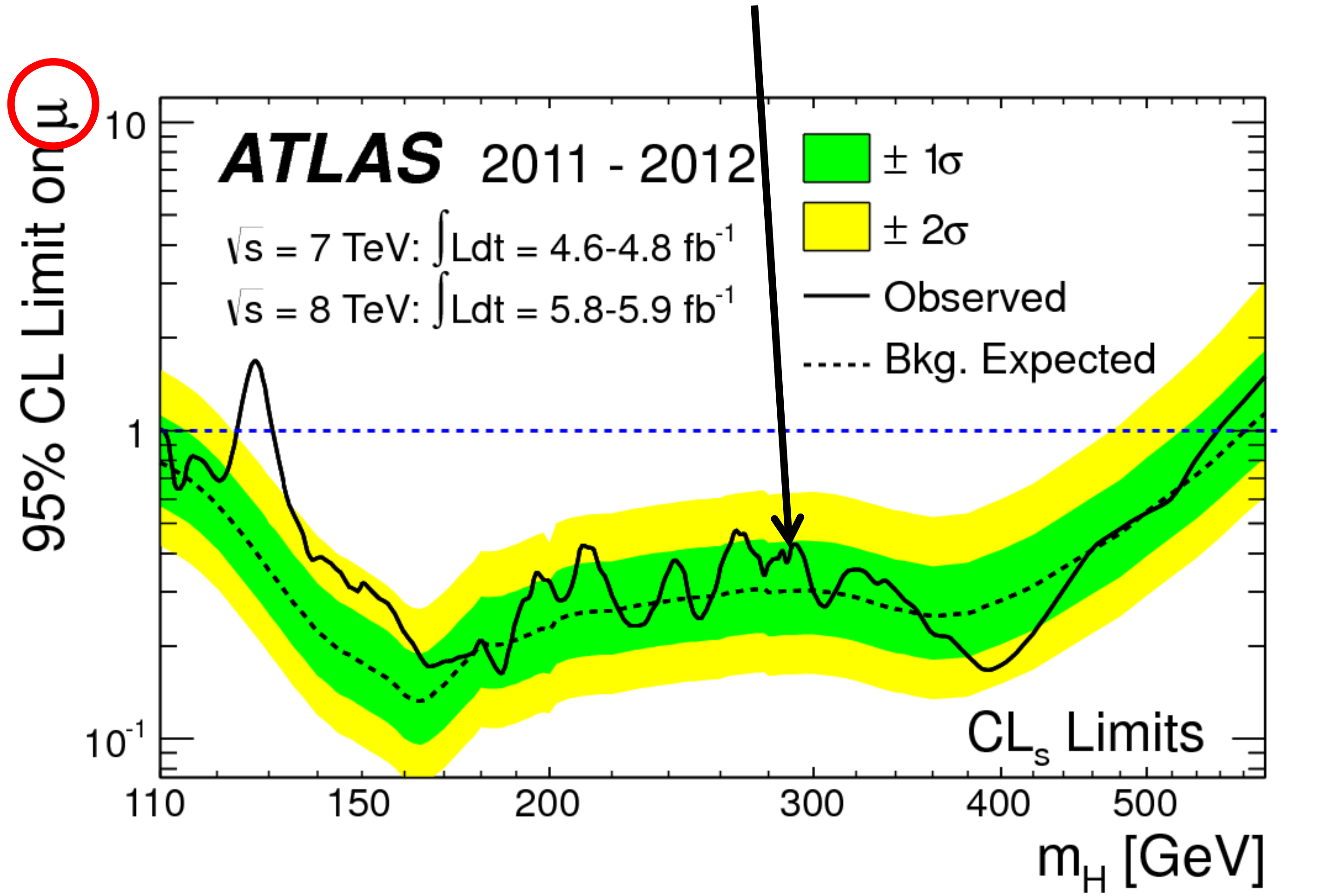
Importance of theory !



Digression on brazil limit plots

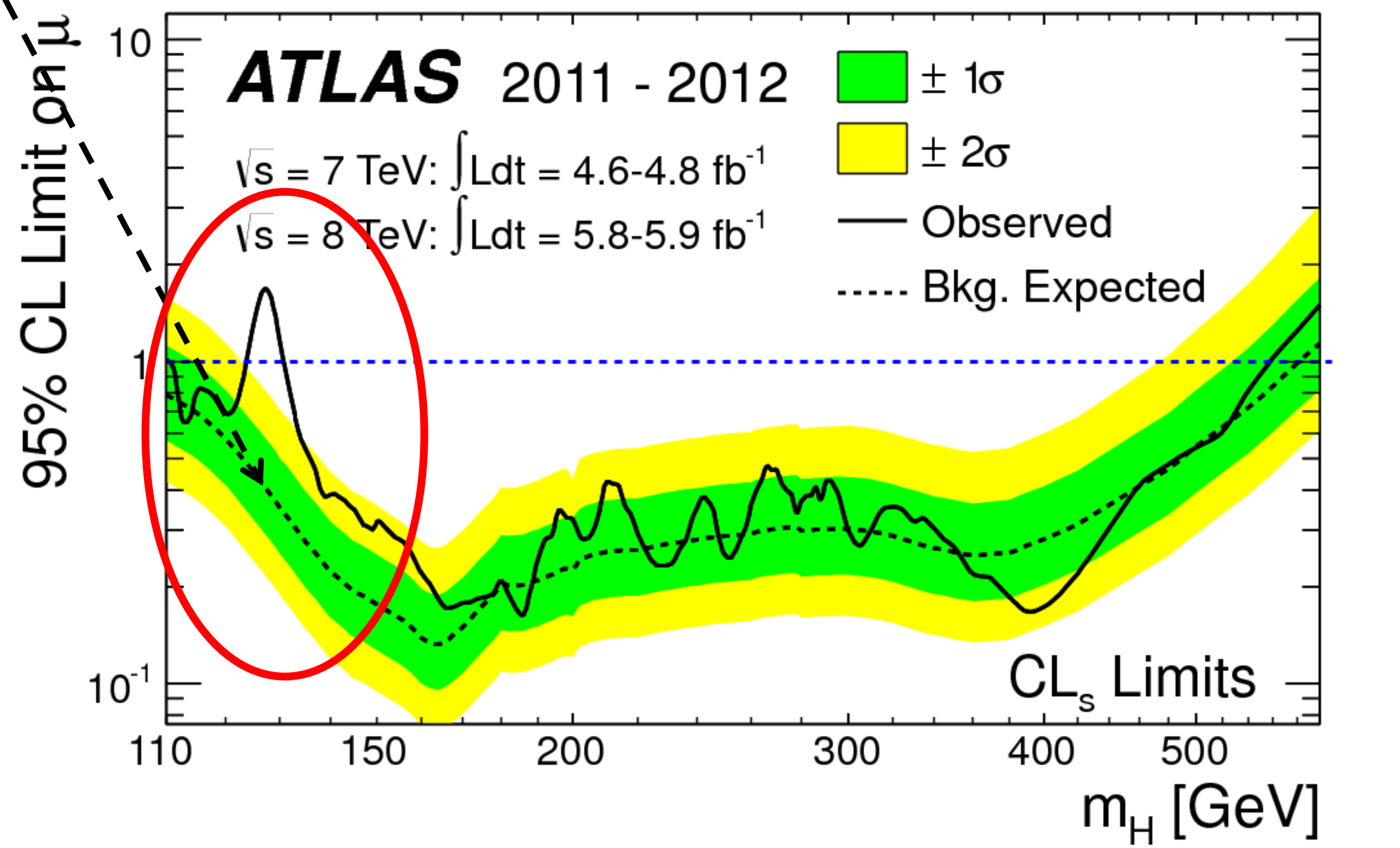
Exclusion on $\mu = \sigma / \sigma_{SM}$ SM = SM boson

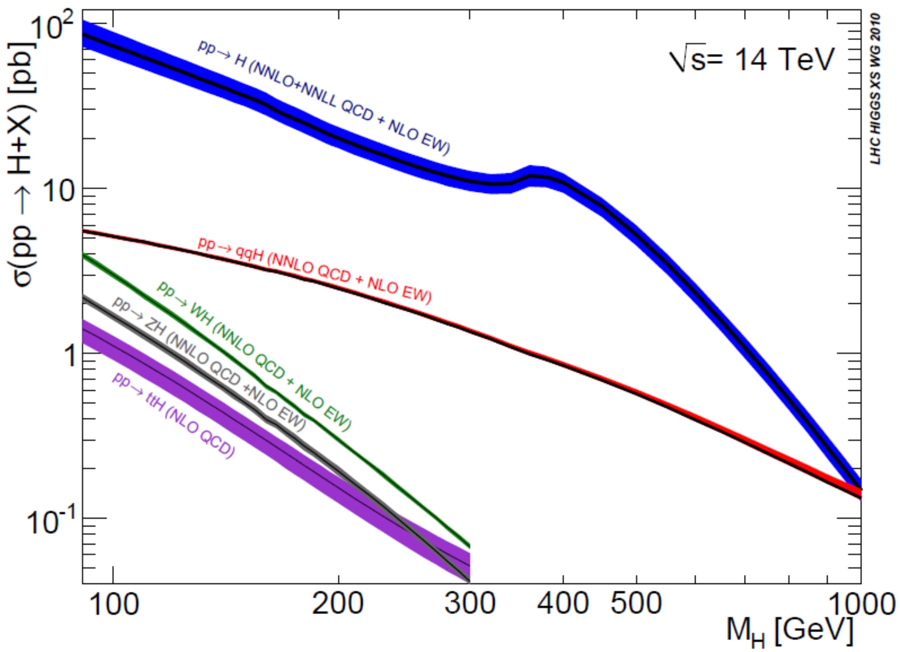
Everything above the black line is excluded

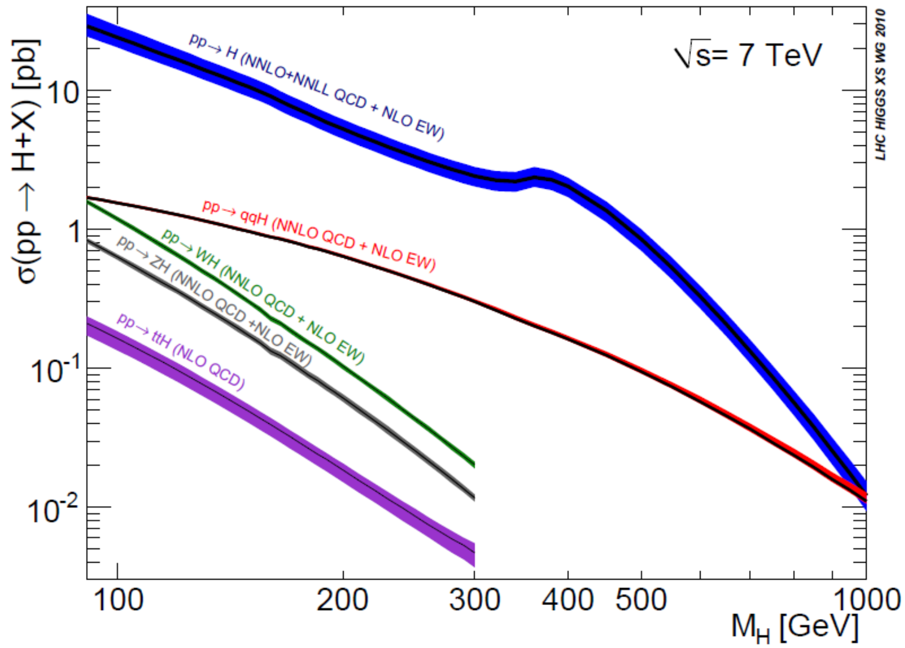


The dashed line show the limit we would expect if the data would be without any boson . The green and yellow bands show where , without any boson , the limits would be allowed to move at the 1 σ or 2 σ level (depending of the statistical fluctations of the background)

The fact that the observed limit is above the expected + 2σ limit is a hint that the data are not well simulated by the backgrounds (stat fluctuation , mismodeling , signal)





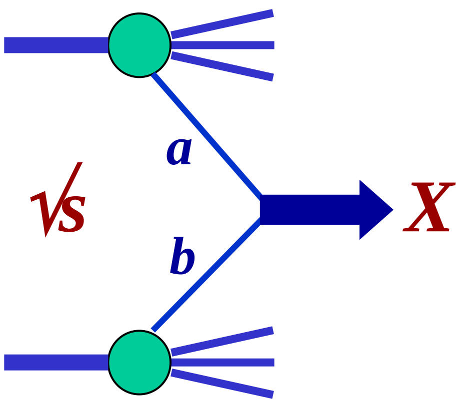


Detailed study of cross-sections ….
arXiv:1101.0593

VBF is important for high m_H

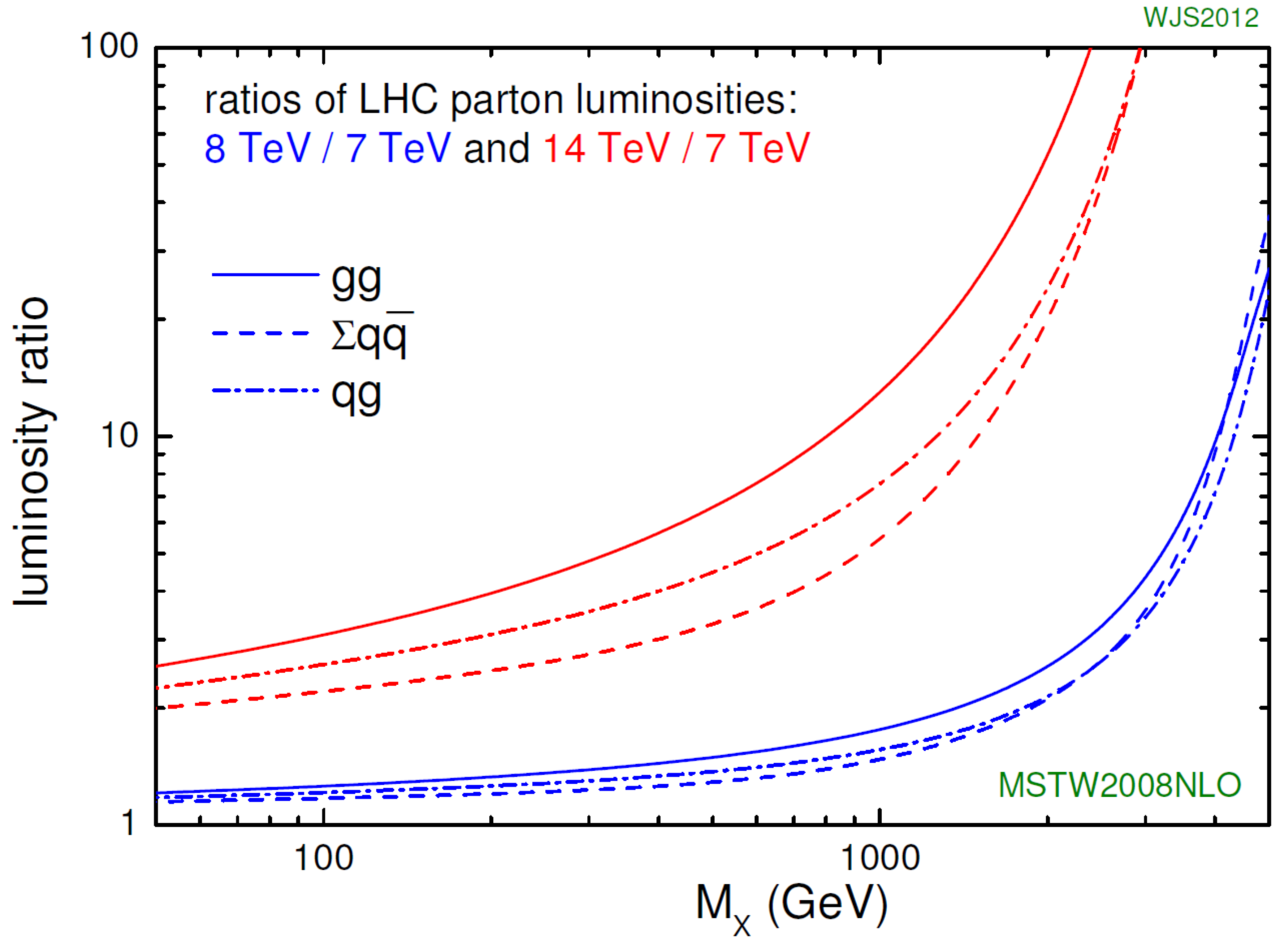
parton luminosity functions

- ***a quick and easy way to assess the mass and collider energy dependence of production cross sections, and to compare different PDF sets***

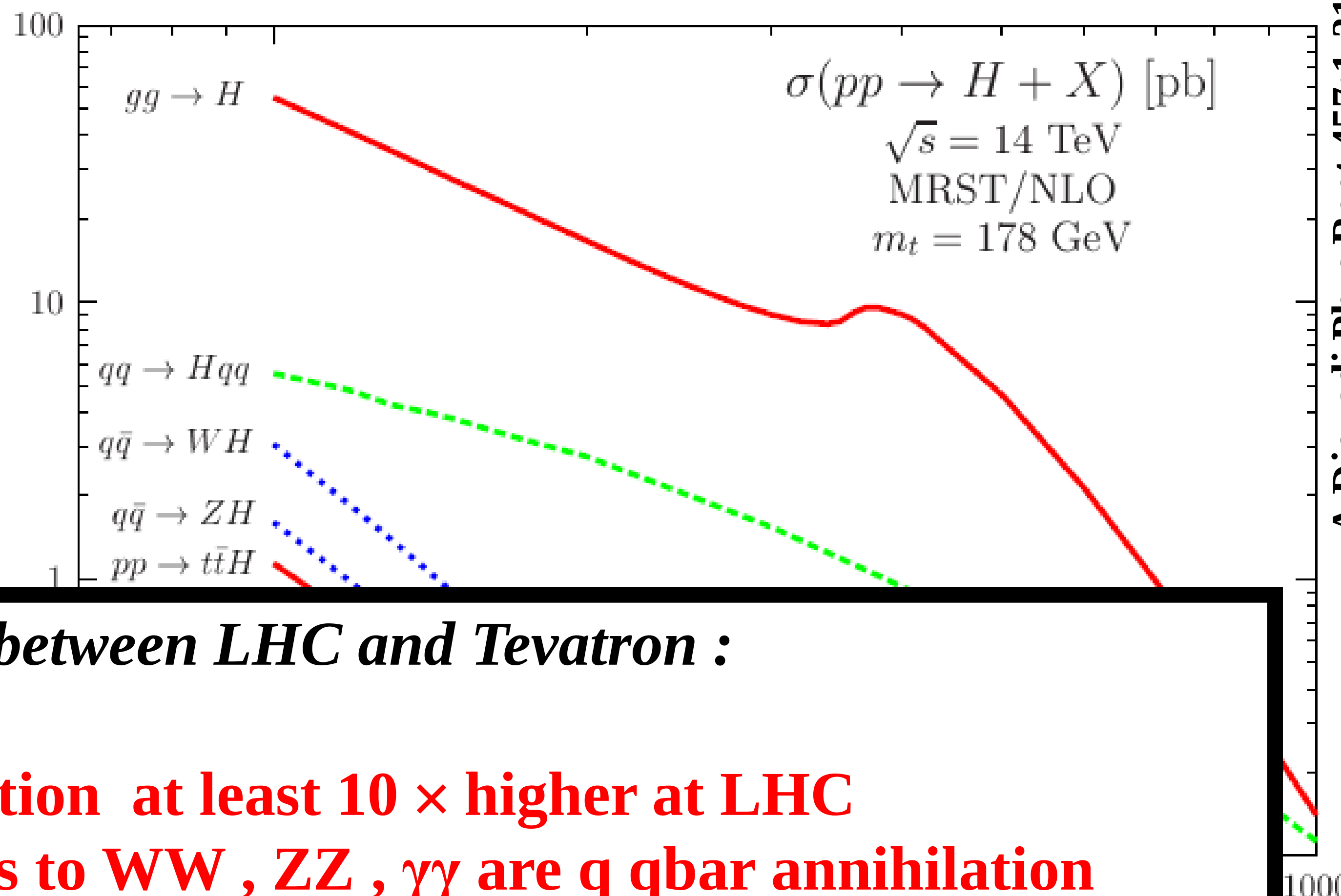


$$
\begin{aligned}
\hat{\sigma}_{ab\to X} &= C_X \delta(\hat{s} - M_X^2) \\
\sigma_X &= \int_0^1 dx_a dx_b \; f_a(x_a, M_X^2) f_b(x_b, M_X^2) \; C_X \; \delta(x_a x_b - \tau) \\
&\equiv C_X \left[\frac{1}{s} \frac{\partial \mathcal{L}_{ab}}{\partial \tau} \right] \qquad\qquad (\tau = M_X^2/s) \\
\frac{\partial \mathcal{L}_{ab}}{\partial \tau} &= \int_0^1 dx_a dx_b \; f_a(x_a, M_X^2) f_b(x_b, M_X^2) \; \delta(x_a x_b - \tau)
\end{aligned}
$$

- ***i.e. all the mass and energy dependence is contained in the X-independent parton luminosity function in [ ]***
- ***useful combinations are*** $ab = gg, \sum_q q\bar{q}, \ldots$
- ***and also useful for assessing the uncertainty on cross sections due to uncertainties in the PDFs***



$r_{gg}(8/7) = 1.28$ for $M_X = 125$ GeV, cf. $r_Z(8/7) = 1.17$



A.Djouadi Phys.Rept.457:1-216

comparison between LHC and Tevatron :

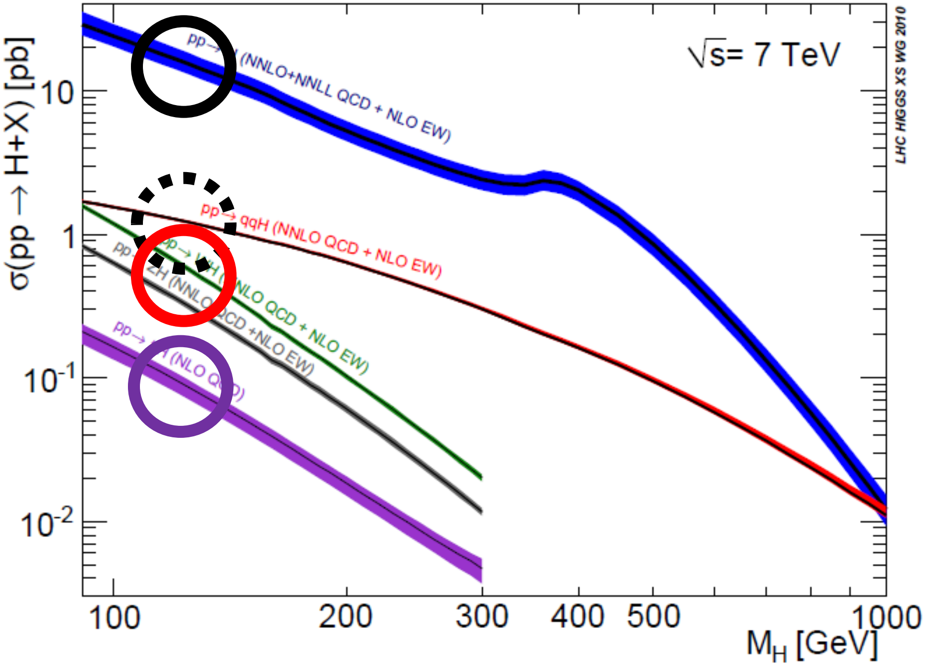
gg cross section at least 10 × higher at LHC

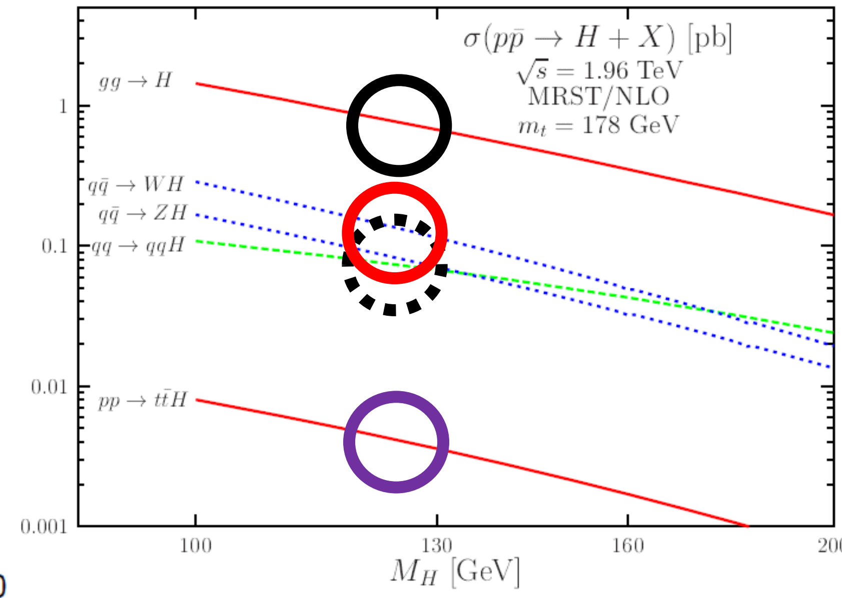
backgrounds to WW , ZZ , γγ are q qbar annihilation

(Remember Tevatron was a p pbar collider)

→ S/B better in these channels at LHC than at Tevatron

however it is worse in associated modes





comparison between LHC and Tevatron :

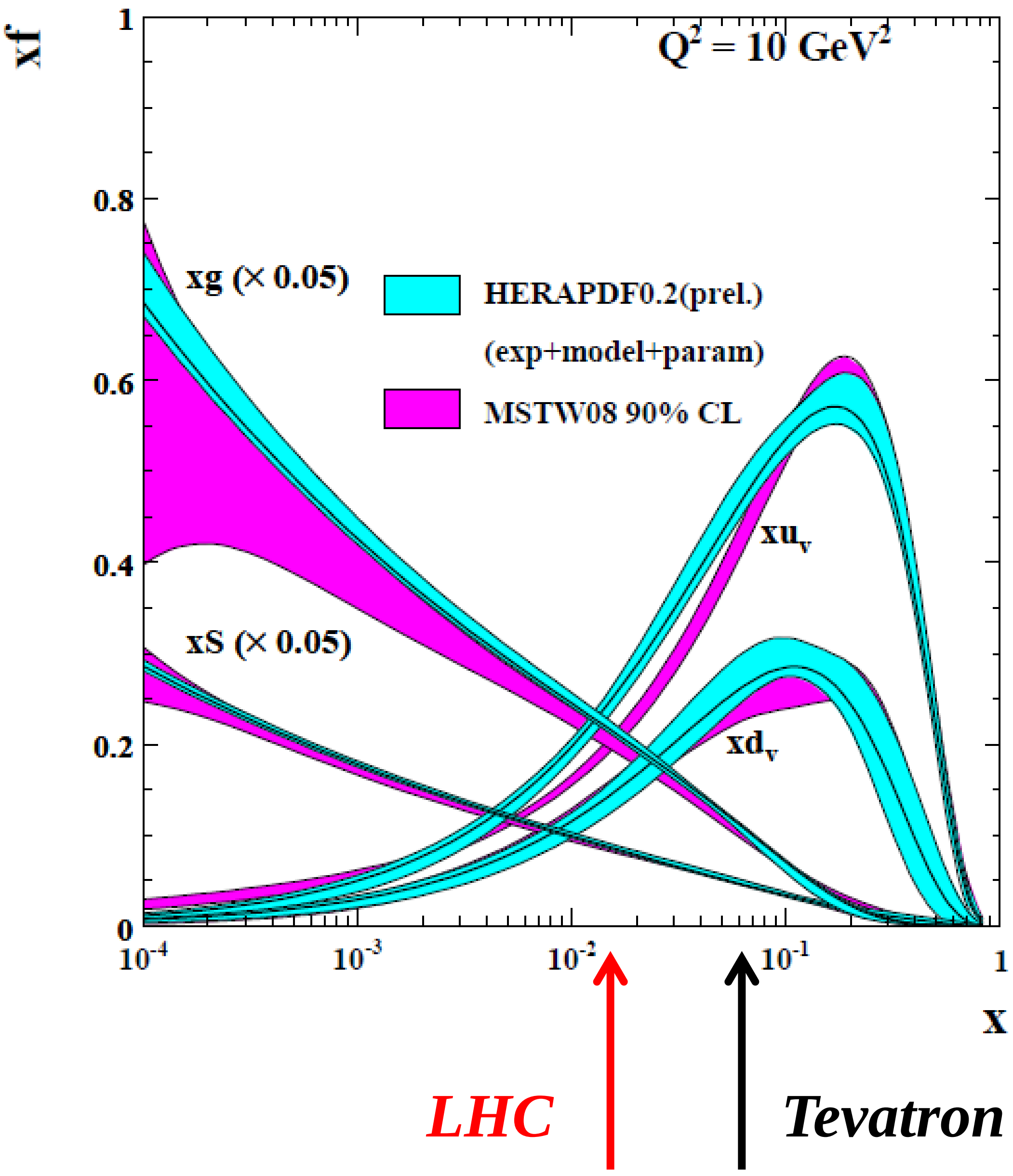
gg cross section at least 10 × higher at LHC

backgrounds to WW , ZZ , γγ are q qbar annihilation

(Remember Tevatron was a p pbar collider)

→ S/B better in these channels at LHC than at Tevatron

however it is worse in associated modes


xf
Q² = 10 GeV²
xg (× 0.05)
HERAPDF0.2(prel.)
(exp+model+param)
MSTW08 90% CL
xu_v
xS (× 0.05)
xd_v
x
LHC
Tevatron

number of events in one experiment produced/detected for 5 fb^{-1} (7 TeV)

and S/B

700 / 50

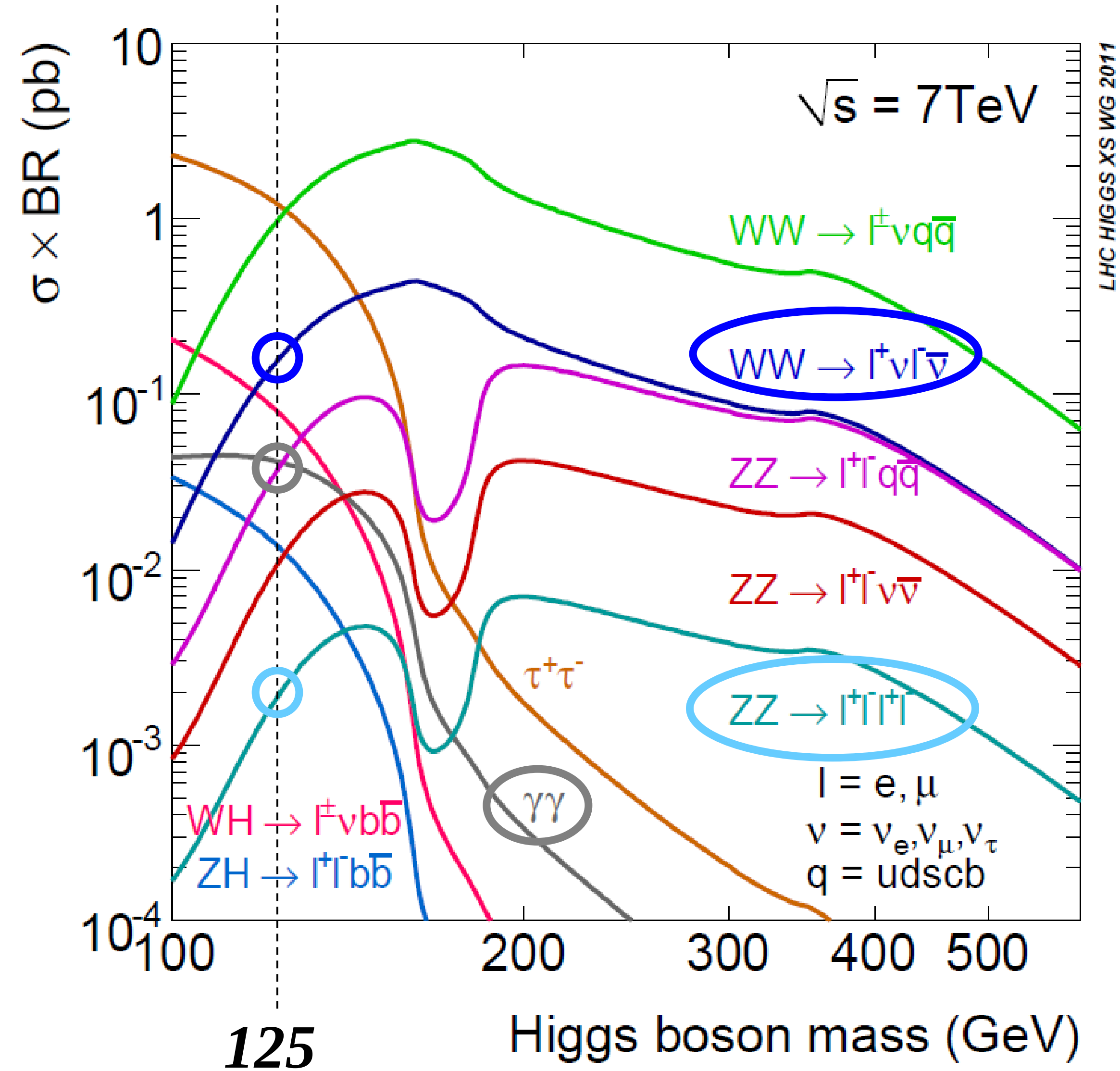
S/B ~.3

200 / 70

S/B ~ .02

10 / 2

S/B ~ 1.5



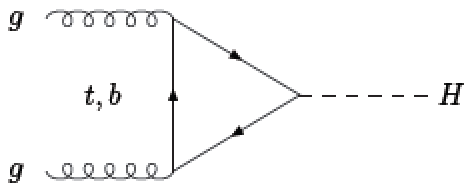
higher order computations (NNLO)

R. Harlander, W.B. Kilgore, *Next-to-next-to-leading order Higgs production at hadron colliders*, Phys.Rev.Lett.88:201801, 2002, hep-ph/0201206.

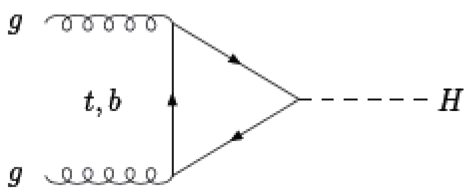
C. Anastasiou, K. Melnikov, *Higgs boson production at hadron colliders in NNLO QCD*, Nucl.Phys.B646:220-256, 2002, hep-ph/0207004.

V. Ravindran, J. Smith, W.L. van Neerven, *NNLO corrections to the total cross-section for Higgs boson production in hadron hadron collisions*, Nucl.Phys.B665:325-366, 2003, hep-ph/0302135.

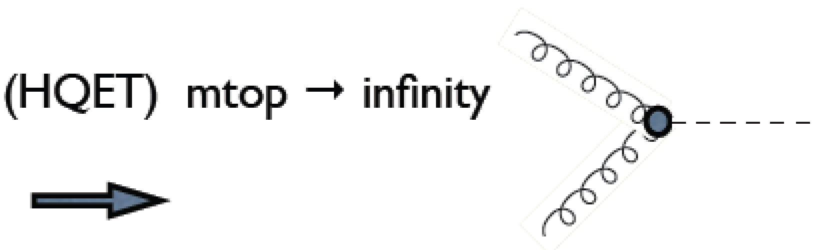
see seminar of Massimiliano



LO-QCD



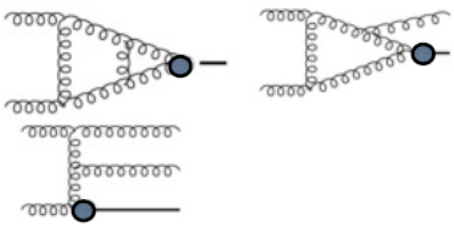
Effective theory (HQET) mtop → infinity



in the effective lagrangian approach, one loop less to be computed

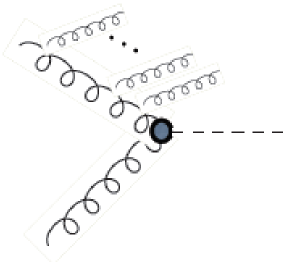
delicate is the effective lagrangian approach:

in presence of light particles in the loop, in the high-energy limit



NNLO-QCD
HQET

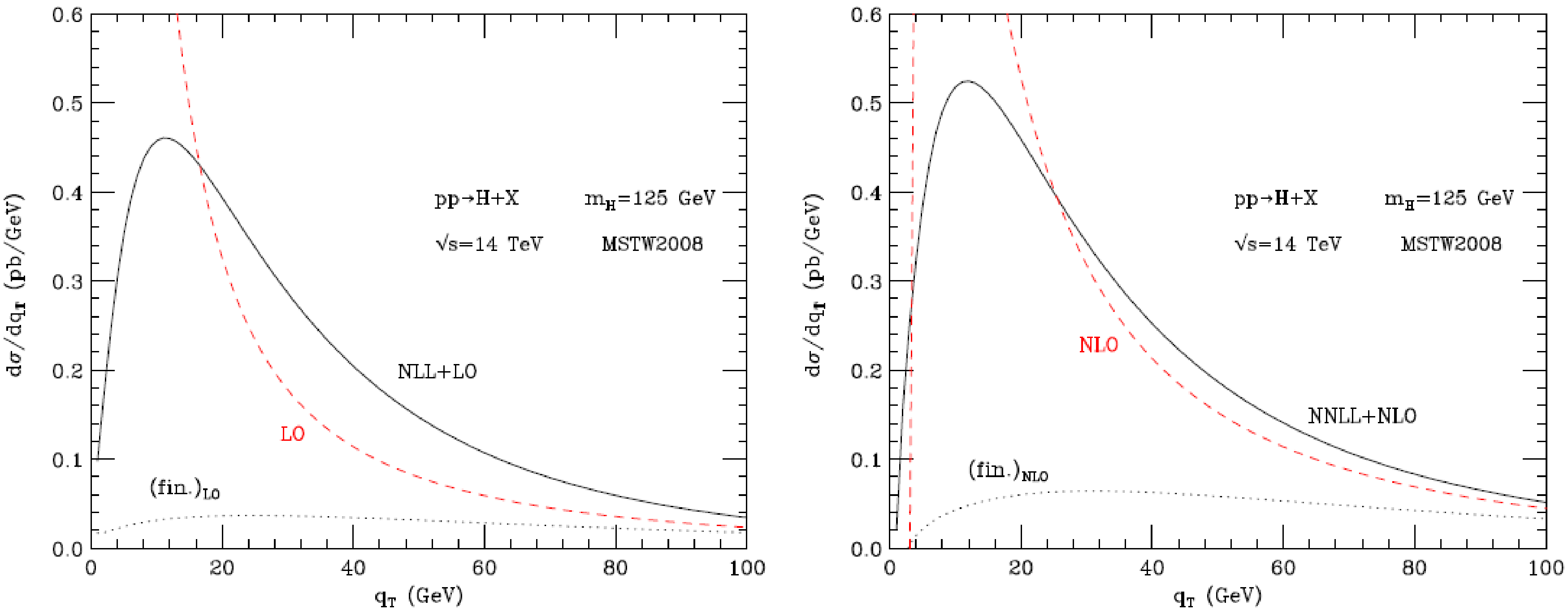
Anastasiou Melnikov 2002
Harlander Kilgore 2002
Ravindran Smith van Neerven 2003



NNLO-QCD + soft gluon resummation NNLL-QCD
HQET

Catani De Florian Grazzini Nason 2003
Moch Vogt 2005 Idilbi Ji Yuan 2006
Ravindran Smith van Neerven 2007

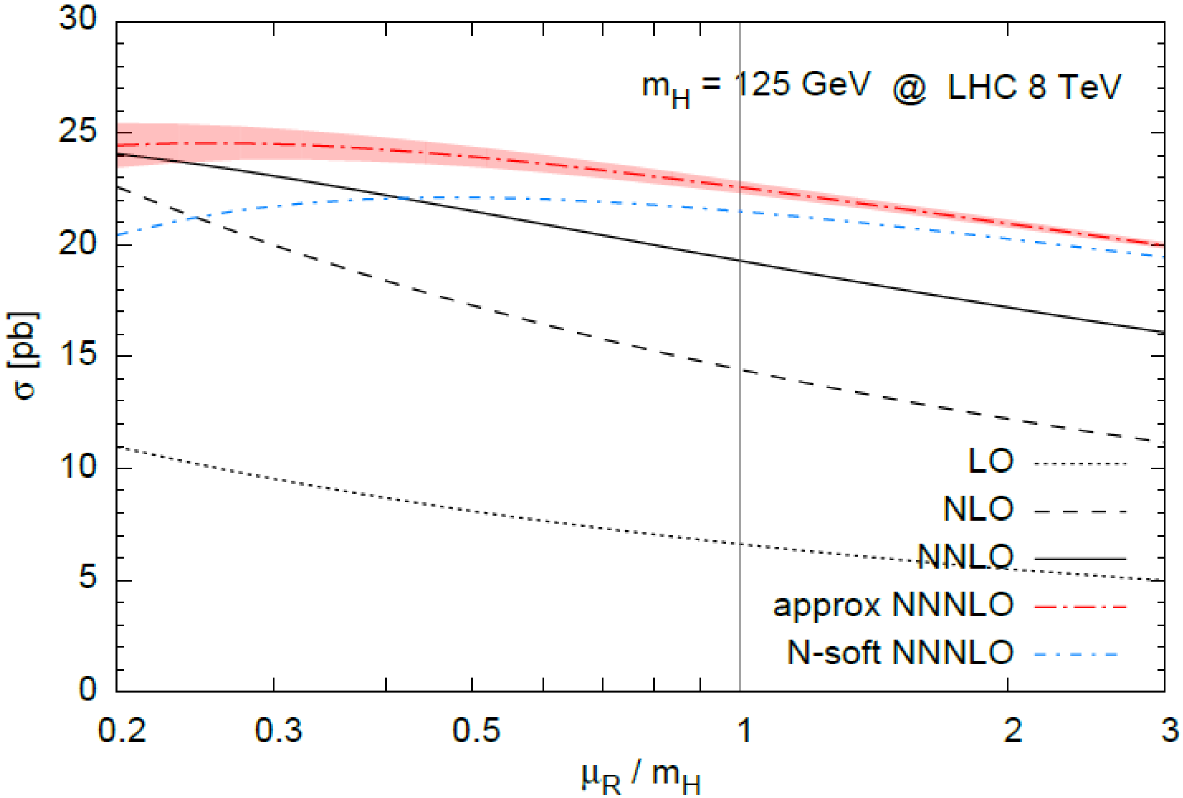
S. Catani, D. de Florian, M. Grazzini, P. Nason, *Soft gluon resummation for Higgs boson production at hadron colliders*, JHEP.0307:028, 2003, hep-ph/0306211.



de Florian et al. JHEP 1111 (2011) 064

Fixed order (LO,NLO) computations diverge at q_T(H)→0
⇒ resummation

approximate NNNLO cross section computation

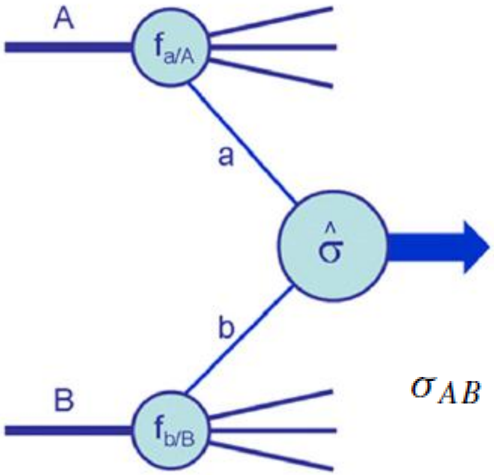


Nuclear Physics B 874 (2013) 746–772

Richard D. Ball [a], Marco Bonvini [b], Stefano Forte [c,*], Simone Marzani [d], Giovanni Ridolfi [e]

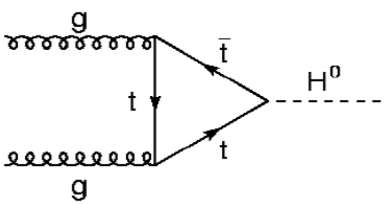
small(er) dependence w.r.t μ_R

'full' NNNLO computation soon (useful for H cross section measurement) by Anastasiou et al.



$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b \; f_{a/A}(x_a) f_{b/B}(x_b) \; \hat{\sigma}_{ab\to X}$$

$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b \; f_{a/A}(x_a, \mu_F^2) \; f_{b/B}(x_b, \mu_F^2) \; \times \; [\, \hat{\sigma}_0 \; + \; \alpha_S(\mu_R^2)\, \hat{\sigma}_1 \; + \; \cdots \,]_{ab\to X}$$



first term in expansion above in $\alpha_S{}^2(\mu_R{}^2)$

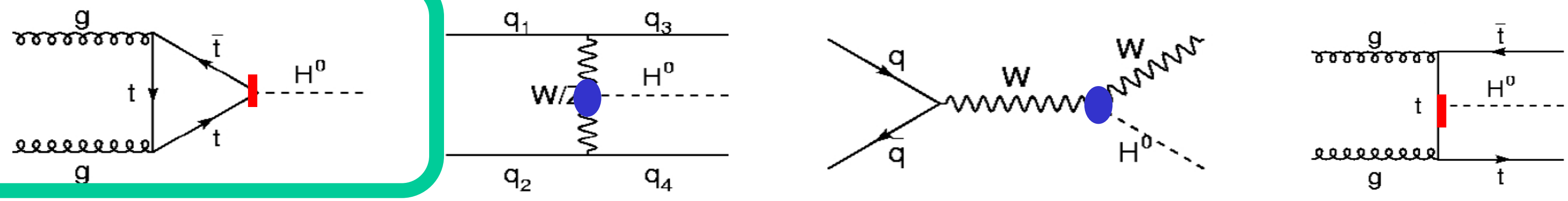
2 gtt vertices

Formally, the cross section calculated to all orders in perturbation theory is invariant under changes in these parameters, the μ_F^2 and μ_R^2 dependence of the coefficients, e.g. $\hat{\sigma}_1$, exactly compensating the explicit scale dependence of the parton distributions and the coupling constant. This compensation becomes more exact as more terms are included in the perturbation series

J M Campbell[1], J W Huston[2] and W J Stirling[3]

Rep. Prog. Phys. **70** (2007) 89–193

couplings



A way to have access to H couplings to bosons ● and fermions ▮

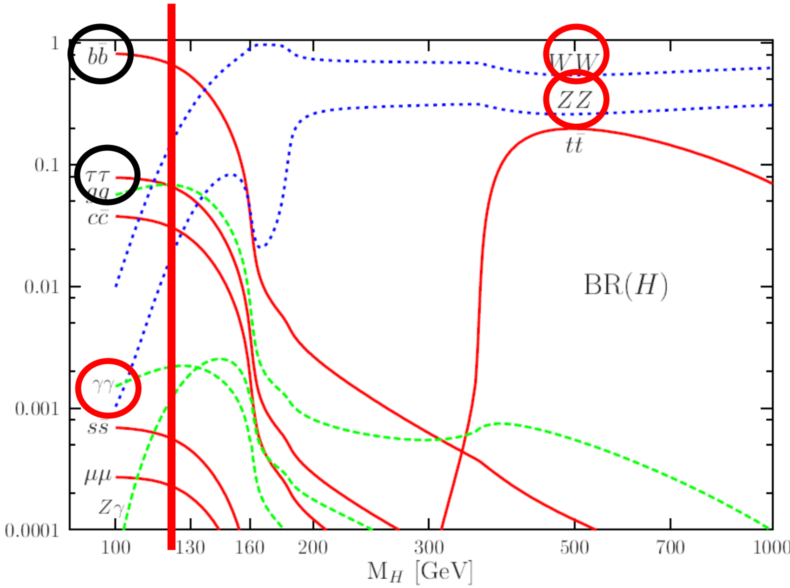
We are looking $\mu = \sigma / \sigma_{SM}$ SM = SM boson
and we can study

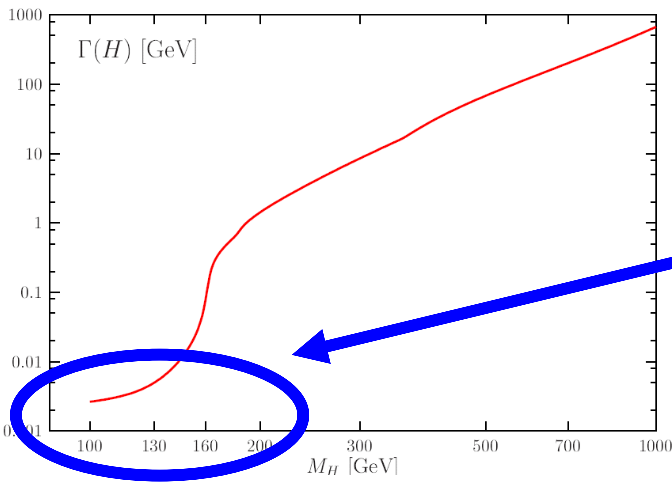
$\mu ggH = \sigma ggH / \sigma ggH_{SM}$
$\mu VBFH = \sigma VBFH / \sigma VBFH_{SM}$
$\mu WH = \sigma WH / \sigma WH_{SM}$
…..

In fact $\mu = (\sigma . B) / (\sigma . B)_{SM}$

decay

A.Djouadi Phys.Rept.457:1-216





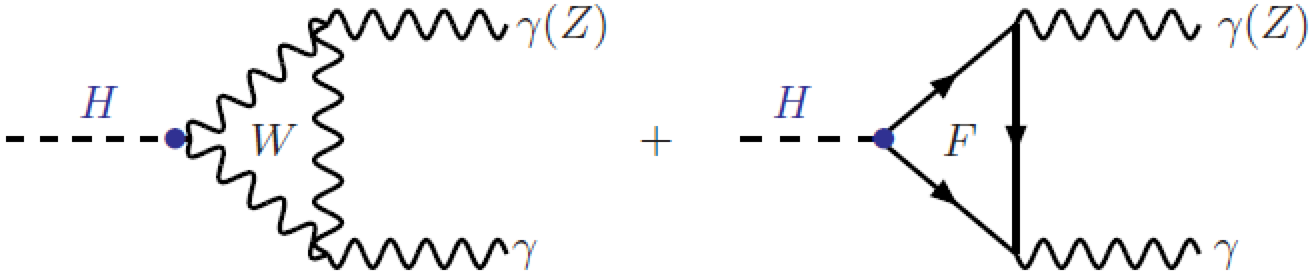
Width smaller than 'leptonic/γ resolution'

zone favored by *(pre-LHC)* data

For m_H ~ 125 GeV the width is about 4 MeV corresponding to ~ 10^{-22} s and ~100 fm

Scalar boson decays : example of $H\rightarrow\gamma\gamma$

A.Djouadi Phys.Rept.457:1-216



Interference between

W loop ***top loop***

$$\Gamma\,(H\to\gamma\gamma)=\frac{G_\mu\,\alpha^2\,M_H^3}{128\,\sqrt{2}\,\pi^3}\left|\sum_f N_c Q_f^2 A_{1/2}^H(\tau_f)+A_1^H(\tau_W)\right|^2$$

$\propto$ **-.28** **+ 1.28**

invisible decay

Up to now we supposed that there is some modification (by μ) of the SM cross sections

But we can have DM particles ….

If the DM particles are light enough, $M_{\mathrm{DM}} \leqslant \frac{1}{2} m_h$, they will appear as invisible decay products of the Higgs boson

"Higgs portal dark matter model"

in these models Higgs interacts with dark matter via the Lagrangian term of the form c DM DM |H|^2

The coupling c has to be large to enable thermal annihilation of dark matter in the early universe.

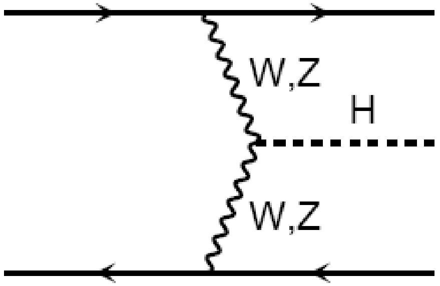
Thus, if 2 m_DM < m_H, the invisible branching fraction should be large

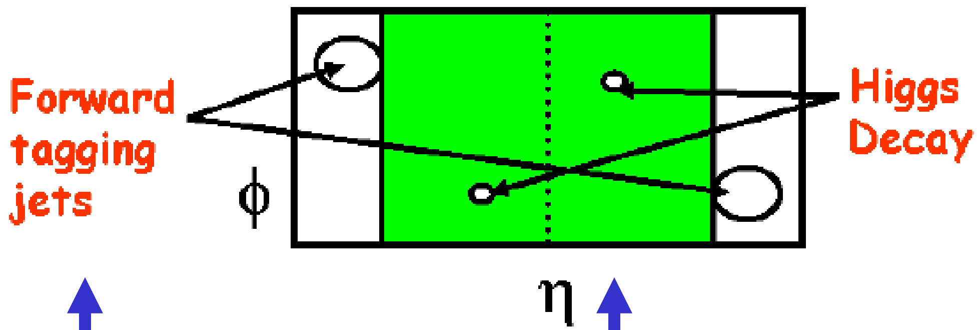
A. Djouadi et al. / Physics Letters B 709 (2012) 65–69

You can also have invisible decays in the MSSM (h -> 2 neutralinos)
if the lightest neutralino is below 60 GeV
and has a sizable Higgsino component

A.Djouadi Phys.Rept. 459 (2008) 1-241

Low mass VBF



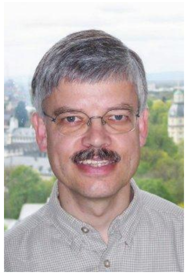


2 high p_T tag jets at large rapidity

no color flow between tag jets ⇒ rapidity gap
central jet veto effective to reduce backgrounds

VBF was used for high mass searches since the start of LHC studies but was used (on Monte-Carlos) at low mass at the end of the 90's

D.Rainwater and D.Zeppenfeld JHEP 9712 (1997) 005



Interlude : definition of (pseudo) **rapidity**

$$y = \frac{1}{2} ln \left[\frac{E + p_z}{E - p_z} \right]$$ rapidity

in the limit of massless objects

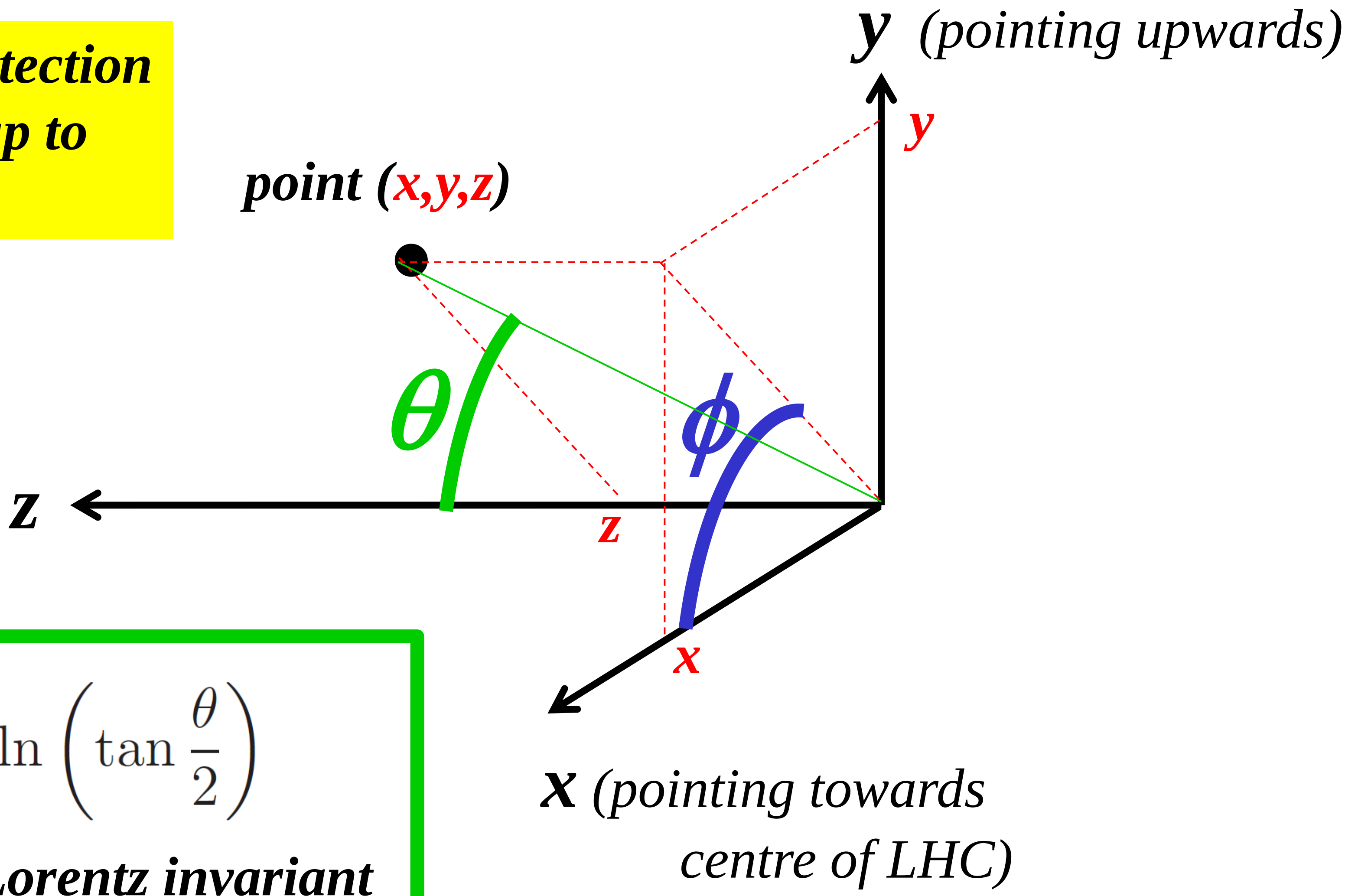
$$\eta = -ln(tan(\theta/2))$$ pseudorapidity

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Δy is Lorentz invariant (along the z axis)

and ΔR too

precise detection (e, γ, μ) up to $|\eta| \sim 2.5$



$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

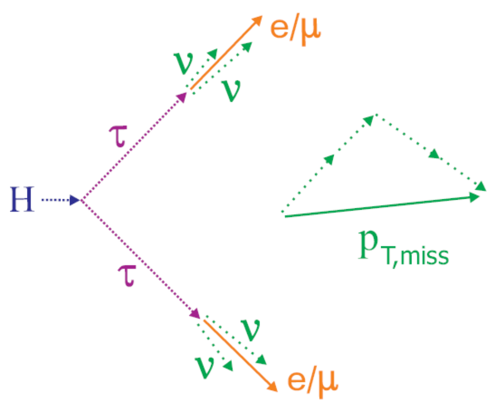
Δη is a Lorentz invariant

(w.r.t z axis)

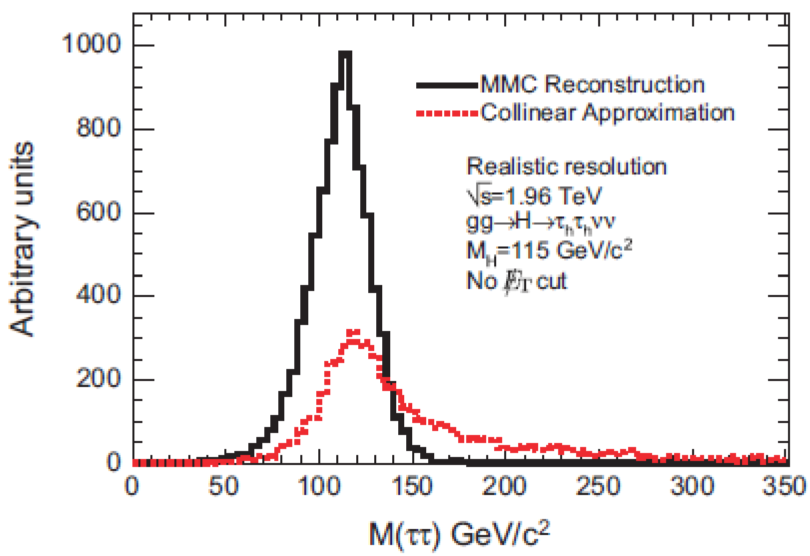
(for mass = 0)

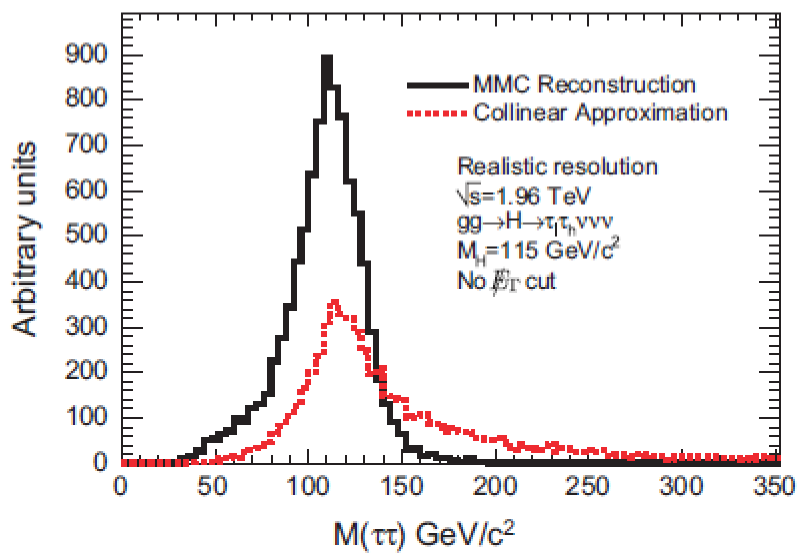
B of solenoid along z

Tau reconstruction



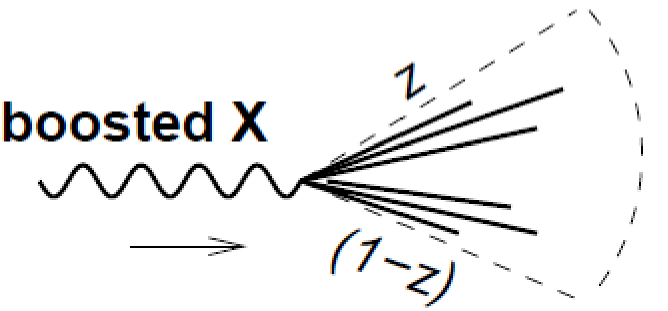
reconstruction of Higgs mass with collinear approximation and angle between the two τ



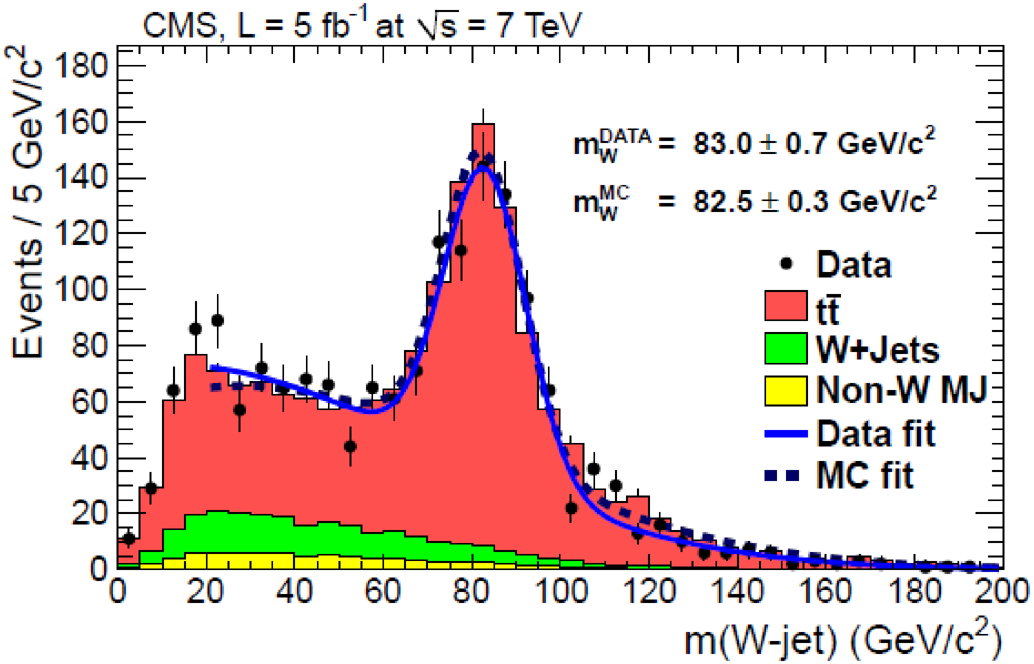


Improvement comes from requiring that the relative orientations of the neutrinos and other decay products are consistent with the mass and kinematics of a τ lepton decay

Boosted massive particles (Fat jets)



Happens for $p_t \gtrsim 2m/R$

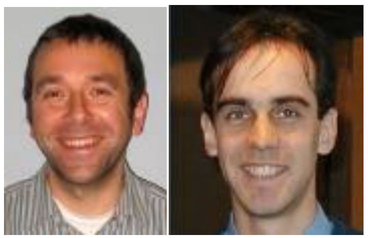


highest mass jet in Semileptonic top sample

arXiv:1204.2488

Futur : boosted Higgs in bb

J.Butterworth G.Salam

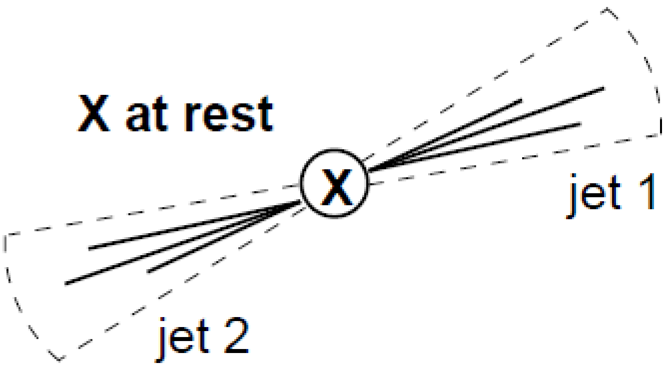


Butterworh,Davison,Rubin,Salam
Phys.Rev.Lett. 100 (2008) 242001
Jet substructure as a new Higgs search channel at the LHC

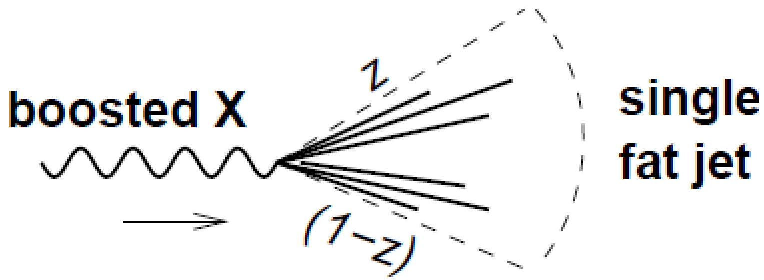
Boosted massive particles (Fat jets)

angle between the 2 jets ~ $2m/p_T$

Normal analyses: two quarks from $X \to q\bar{q}$ reconstructed as two jets



High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



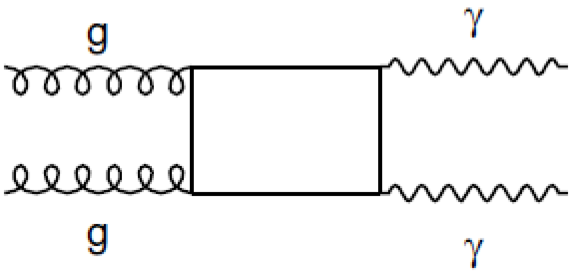
Happens for $p_t \gtrsim 2m/R$

$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

As LHC explores far above EW scale, such configurations become of interest

Could be used for H→ bb search at high luminosity/energy (t t increases)

interferometry



Dixon Siu Phys.Rev.Lett. 90 (2003) 252001

Expected (destructive) interference between gg→γγ and gg →H→γγ

⇒ reduction of the production rate

the effect is 'confined' within Γ_H (~ few MeV)

PHYSICAL REVIEW D **86,** 073016 (2012)

Shift in the LHC Higgs diphoton mass peak from interference with background

Stephen P. Martin

The Higgs diphoton amplitude from gluon fusion at the LHC interferes with the continuum background induced by quark loops. I investigate the effect of this interference on the position of the diphoton invariant mass peak used to help determine the Higgs mass. At leading order, the interference shifts the peak towards lower mass by an amount of order 150 MeV or more, with the precise value dependent on the methods used to analyze and fit the data.

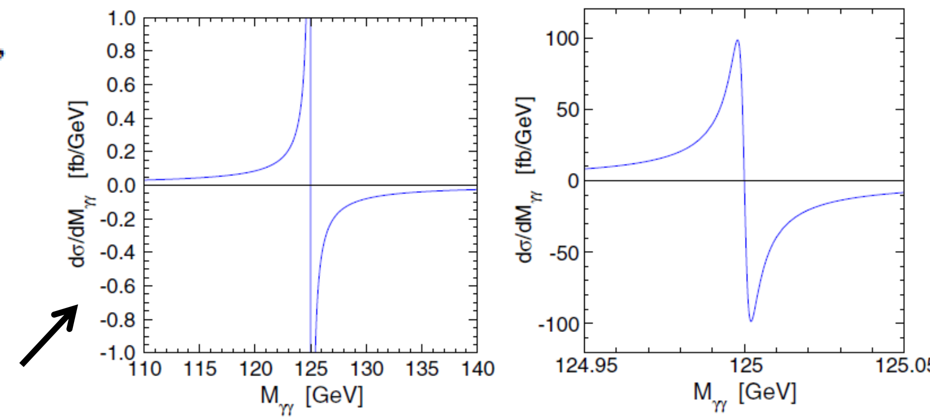
$$\frac{d^2\sigma_{pp\to\gamma\gamma}}{d(\sqrt{\hat{s}})dz} = \frac{G(\hat{s})}{128\pi\sqrt{\hat{s}}D(\hat{s})}(N_H + N_{\mathrm{int,Re}} + N_{\mathrm{int,Im}}),$$

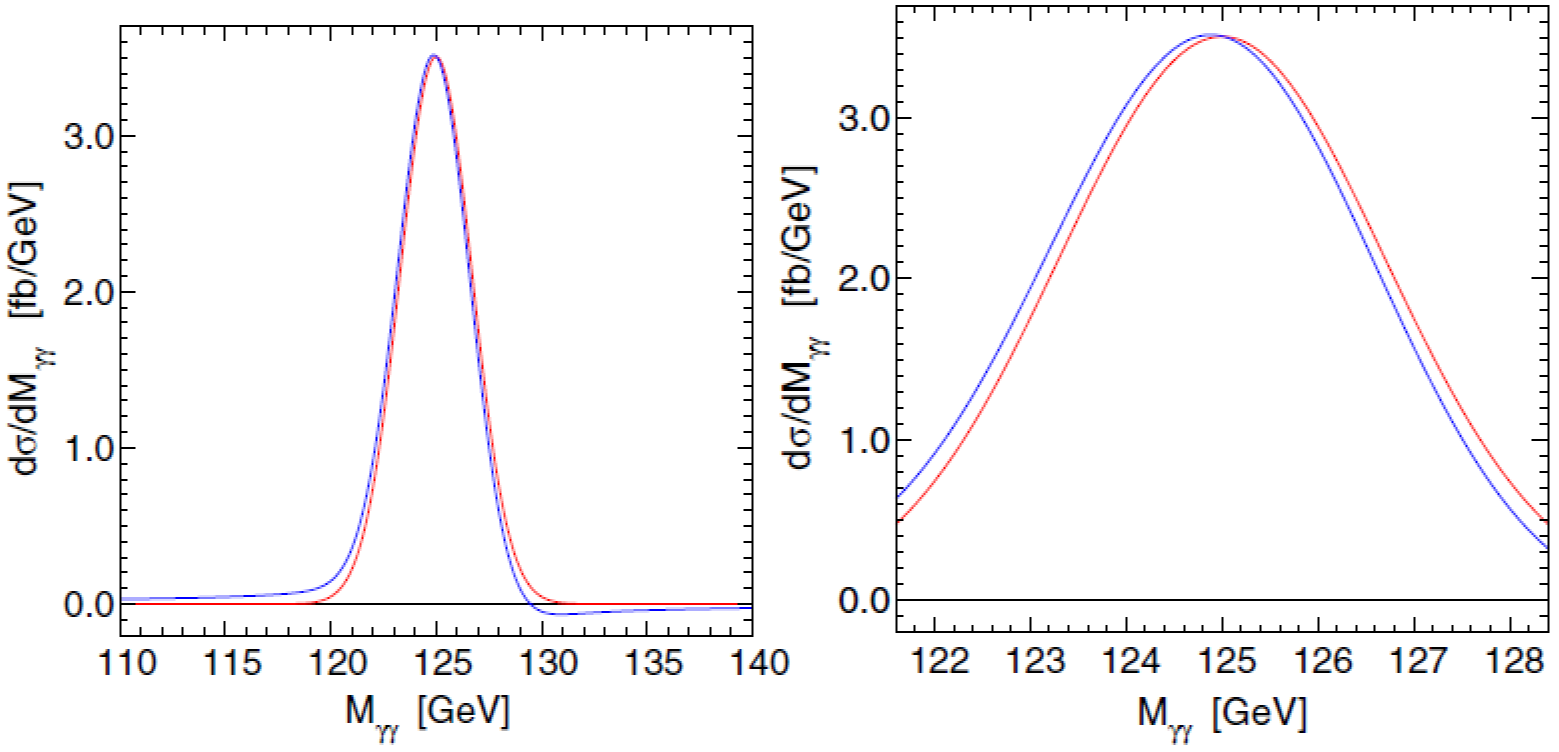
where

$$N_H = |A_{ggH}A_{\gamma\gamma H}|^2,$$

$$N_{\mathrm{int,Re}} = -(\hat{s} - M_H)2\mathrm{Re}[A_{ggH}A_{\gamma\gamma H}A^*_{gg\gamma\gamma}],$$

$$N_{\mathrm{int,Im}} = -M_H\Gamma_H 2\mathrm{Im}[A_{ggH}A_{\gamma\gamma H}A^*_{gg\gamma\gamma}],$$

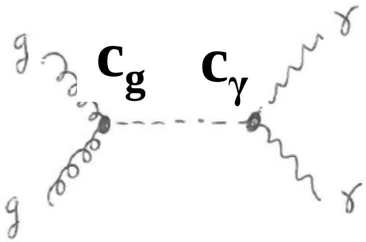




dσ/dMγγ [fb/GeV]
3.0
2.0
1.0
0.0
110
115
120
125
130
135
140
Mγγ [GeV]
dσ/dMγγ [fb/GeV]
3.0
2.0
1.0
0.0
122
123
124
125
126
127
128
Mγγ [GeV]

Dixon Li Phys.Rev.Lett. 111 (2013) 111802

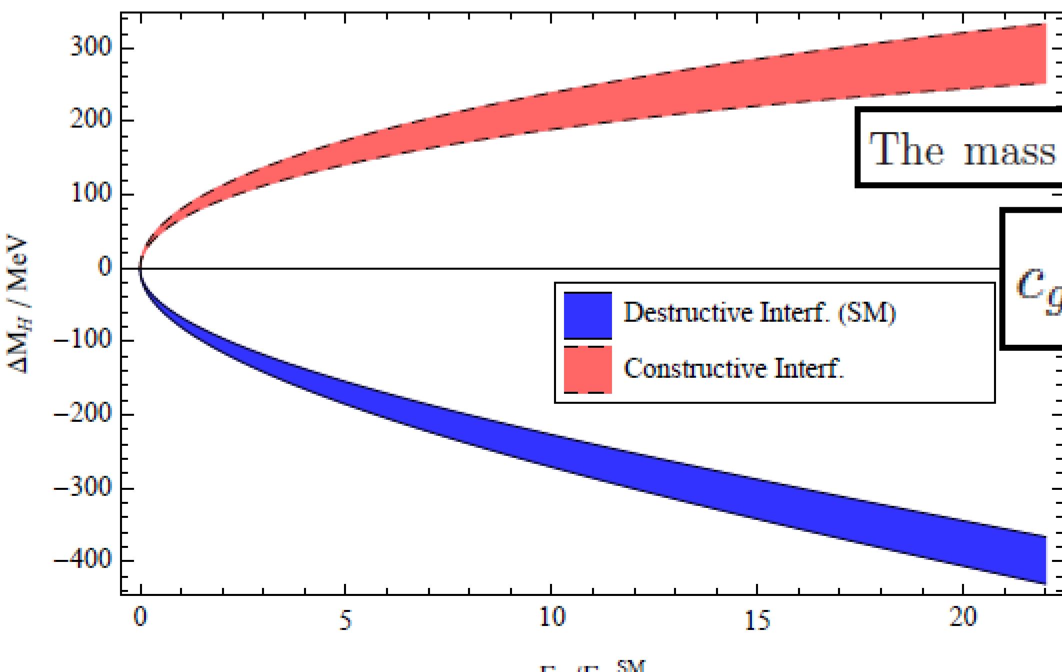
We study the change in the di-photon invariant mass distribution for Higgs boson decays to two photons, due to interference between the Higgs resonance in gluon fusion and the continuum background amplitude for $gg \to \gamma\gamma$. Previously, the apparent Higgs mass was found to shift by around 100 MeV in the Standard Model in the leading order approximation, which may potentially be experimentally observable. We compute the next-to-leading order QCD corrections to the apparent mass shift, which reduce it by about 40%. The apparent mass shift may provide a way to measure, or at least bound, the Higgs boson width at the Large Hadron Collider through "interferometry". We investigate how the shift depends on the Higgs width, in a model that maintains constant Higgs boson signal yields. At Higgs widths above 30 MeV the mass shift is over 200 MeV and increases almost linearly with the width. The apparent mass shift could be measured by comparing with the ZZ^* channel, where the shift should be much smaller. It might be possible to measure the shift more accurately by exploiting its strong dependence on the Higgs transverse momentum.



The signal factor S is proportional to $c_g^2 c_\gamma^2$, while the real and imaginary parts of the interference terms, R and I, are proportional to $c_g c_\gamma$.

The Higgs couplings to gluons, photons, and other observed final states should then change accordingly, in order to maintain roughly SM signal yields, as is in reasonable agreement with current LHC measurements. In particular, for the product $c_g c_\gamma = c_{g\gamma}$ entering the dominant gluon fusion contribution to the $\gamma\gamma$ yield, we solve the following equation,

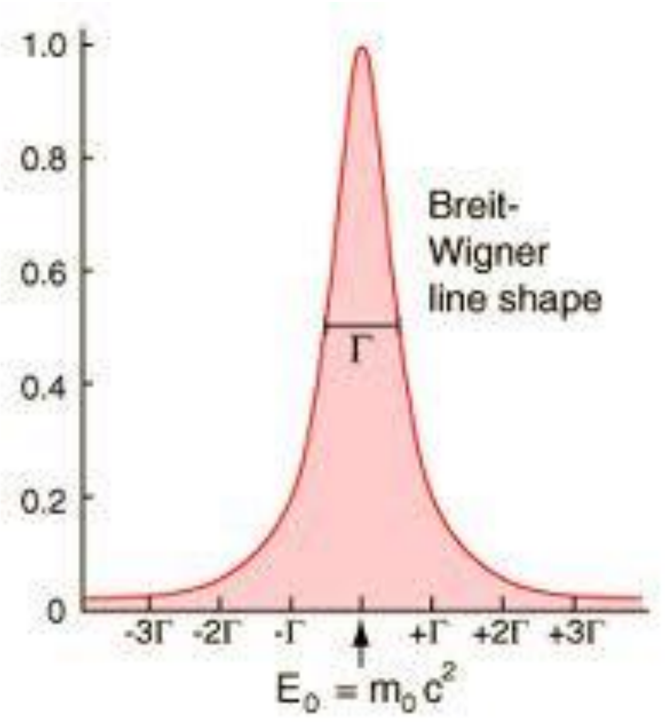
$$\frac{c_{g\gamma}^2 S}{m_H \Gamma_H} + c_{g\gamma} I = \left(\frac{S}{m_H \Gamma_H^{\rm SM}} + I \right) \mu_{\gamma\gamma}$$



The mass shift is directly proportional to $c_{g\gamma}$

$$c_{g\gamma} = \sqrt{\Gamma_H / \Gamma_H^{SM}}$$

The mass uncertainty of the experiments will be < .3 GeV


1.0
0.8
0.6
0.4
0.2
0
Breit-
Wigner
line shape
Γ
-3Γ -2Γ -Γ +Γ +2Γ +3Γ
E0 = m0 c2

SM cross section **SM integral**

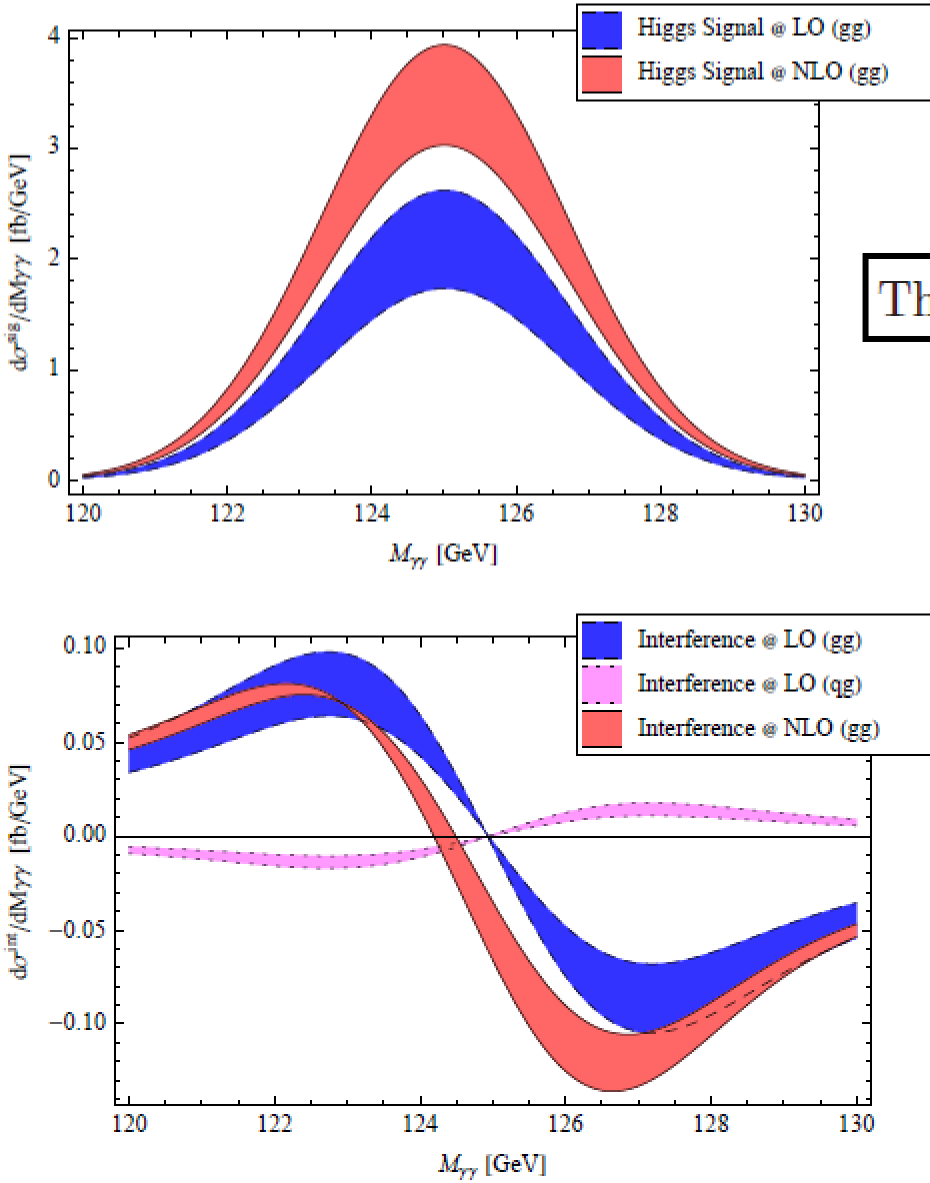
$$\frac{d\sigma^{sig}}{dM_{\gamma\gamma}} = \frac{S}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \qquad \pi S/(2m_H^2\Gamma_H)$$

$$\frac{d\sigma^{int}}{dM_{\gamma\gamma}} = \frac{(M_{\gamma\gamma}^2 - m_H^2)R + m_H\Gamma_H I}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \qquad \pi I/(2m_H)$$

We assume the event rate is ~ the SM event rate and if we neglect I we have

$$\frac{c_{g\gamma}^2 S}{\Gamma_H} = \frac{S}{\Gamma_H^{SM}}$$

$$\boxed{c_{g\gamma} = \sqrt{\Gamma_H/\Gamma_H^{SM}}}$$



The mass shift is directly proportional to $c_{g\gamma}$

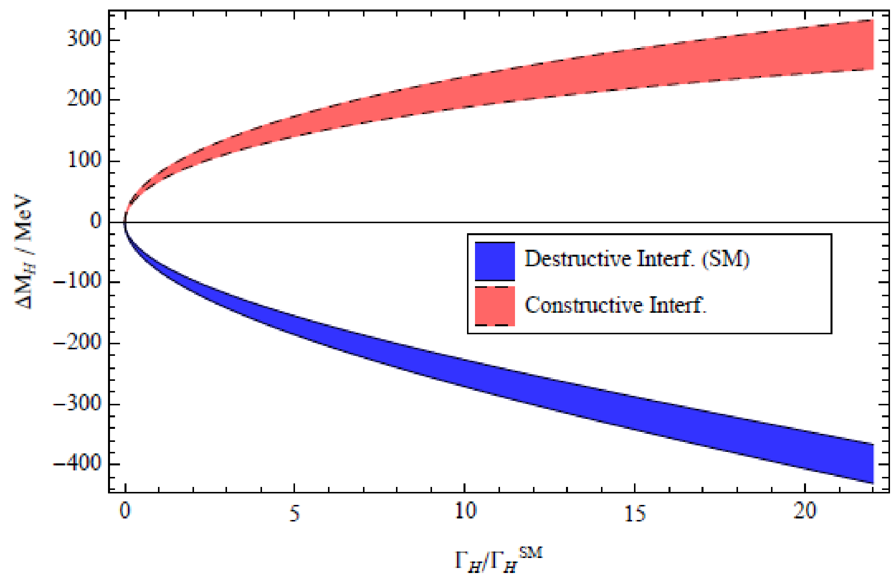


FIG. 2. Diphoton invariant mass $M_{\gamma\gamma}$ distribution for pure signal (top panel) and interference term (bottom panel) after Gaussian smearing.

F.Caola and K.Melnikov Phys.Rev. D88 (2013) 054024

Constraining the Higgs boson width with ZZ production at the LHC

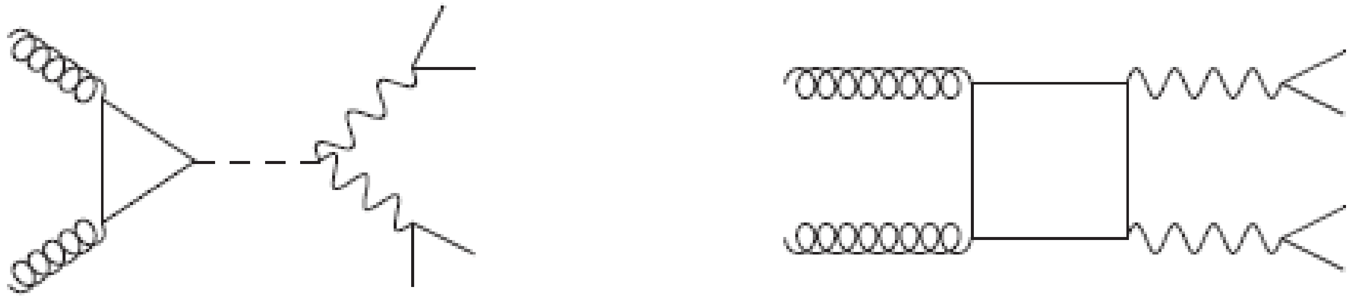


FIG. 1: Sample signal (left) and background $gg \to ZZ$ (right) diagrams for the process $pp \to ZZ \to 4l$. The two amplitudes can interfere.

interference important off-peak

$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM^2_{4l}} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{(M^2_{4l}-m^2_H)^2+m^2_H\Gamma^2_H}$$

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

Energy	$\sigma^{\rm H}_{\rm peak}$	$\sigma^{H}_{\rm off}$	$\sigma^{\rm int}_{\rm off}$
7 TeV	0.203	0.044	-0.108
8 TeV	0.255	0.061	-0.166
$N^{\rm SM}_{2e2\mu}$	9.8	1.73	-4.6
$N^{\rm SM}_{\rm tot}$	21.1	3.72	-9.91

$$N^{\rm off}_{4l} = 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$

TABLE I: Fiducial cross-sections for $pp \to H \to ZZ \to 2e2\mu$ in fb, and the corresponding number of events expected for integrated luminosity $L_7 = 5.1$ fb^{-1} at 7 TeV and $L_8 = 19.6$ fb^{-1} at 8 TeV. All cross-sections are computed with leading order MSTW 2008 parton distribution functions [23]. The renormalization and factorization scales are set to $\mu = m_H/2$. The peak cross-section is defined with the cut $M_{4l} < 130$ GeV, while off-peak and the interference cross-sections are defined with the cut $M_{4l} > 130$ GeV. The total number of events in the last row includes contributions from $4e$ and 4μ channels. The number of events are obtained using procedures outlined in the text.

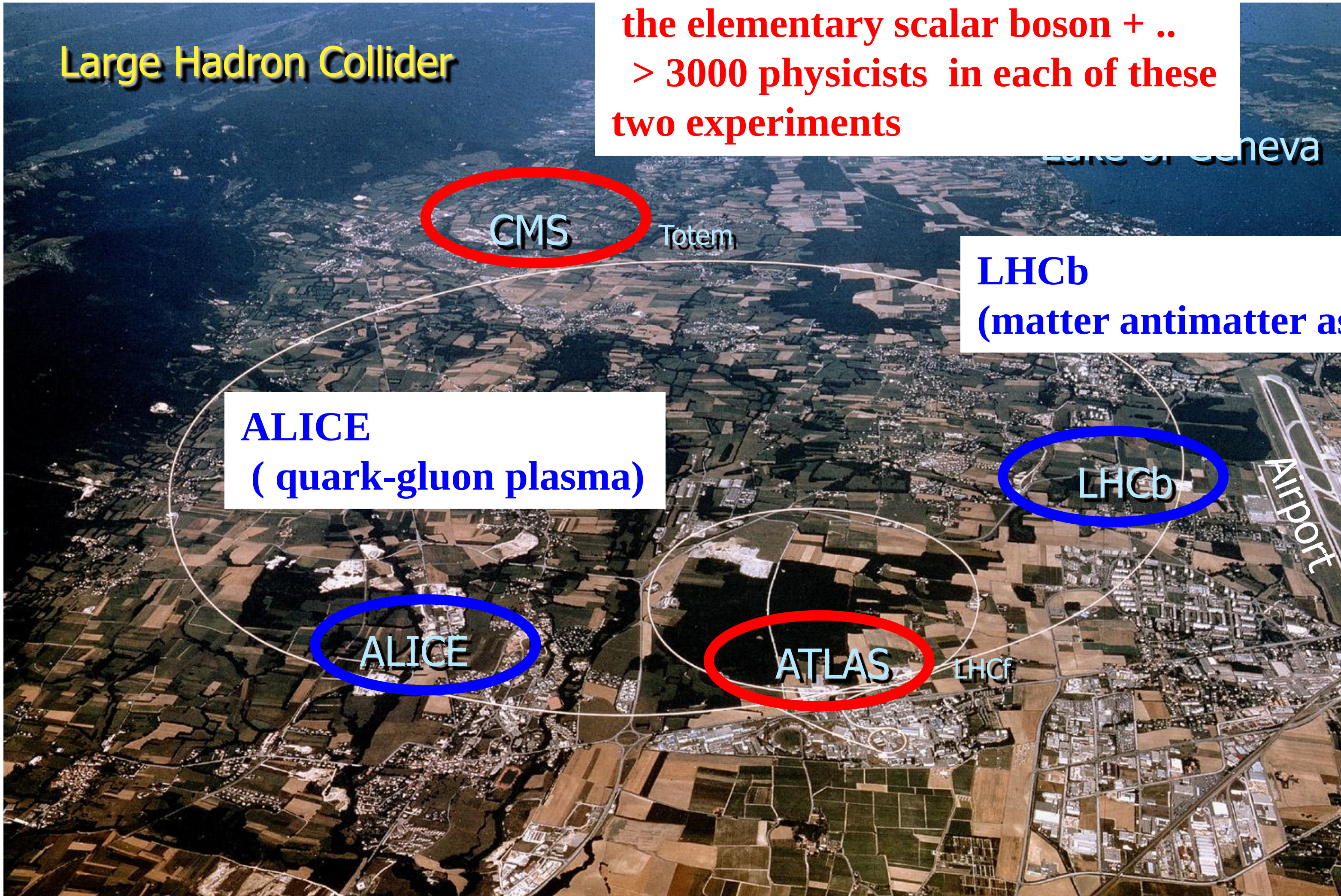
~ important additional source of ZZ events in current data constraint boson width to <~ 40 SM width

- ♥ Historical introduction of the boson and of the LHC
- ♥ Some phenomenological comments
- ♥ **Rapid overview of the detectors** **and LHC**
- ♥ The discovery
- ♥ The first measurements of the properties
- ♥ The future of the physics with the scalar boson(s)
- ♥ Backup (with references)

The LHC

experiments at the LHC

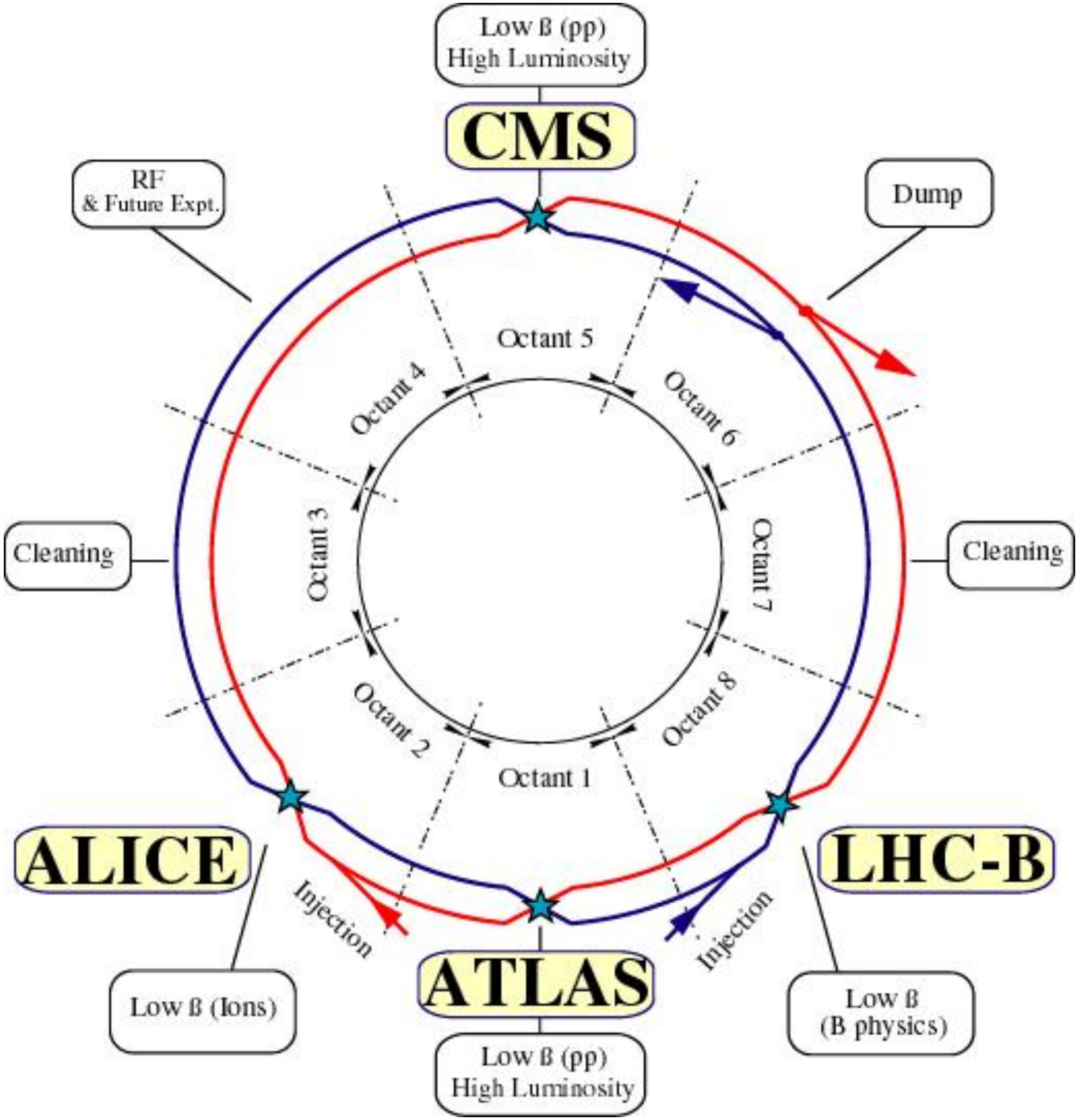
ATLAS and CMS look for
the elementary scalar boson + ..
> 3000 physicists in each of these two experiments



LHCb
(matter antimatter asymmetry)

ALICE
(quark-gluon plasma)

LHC: highest energy *pp*, *AA*, and *pA* collider



design parameters

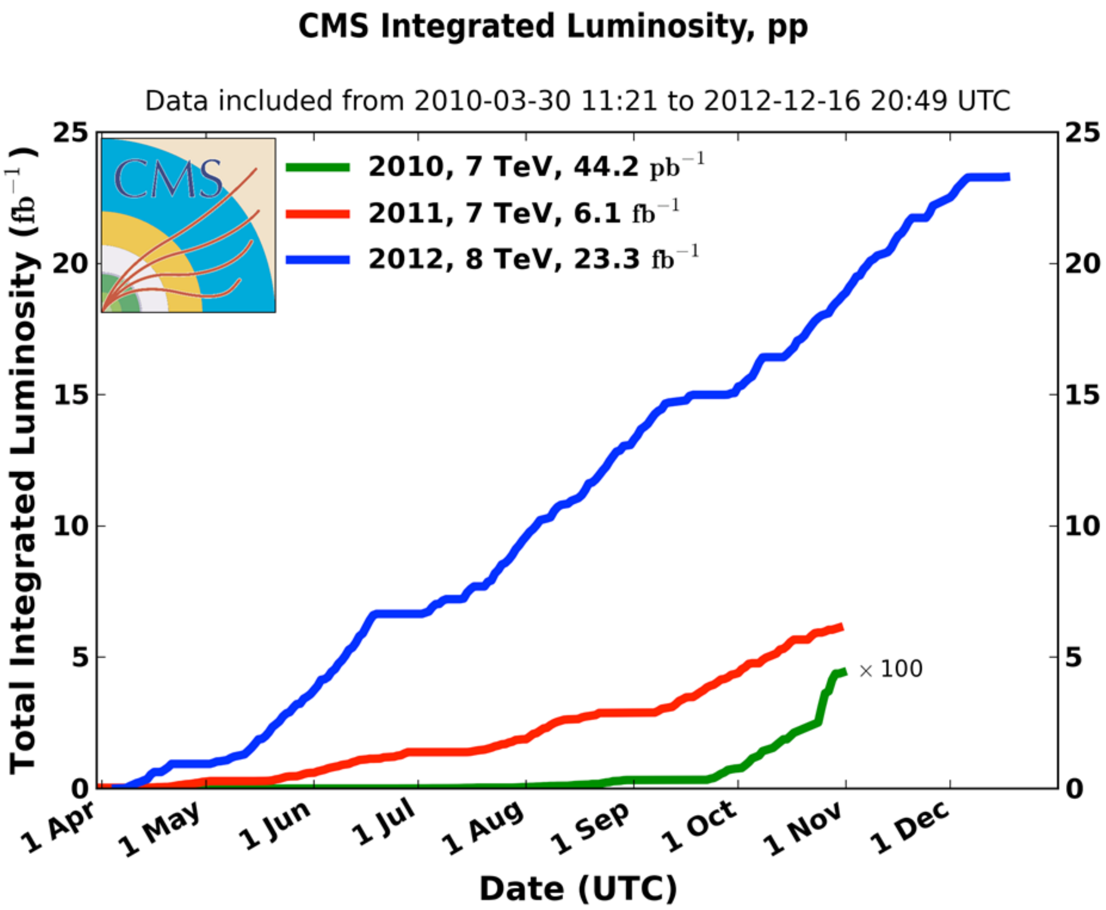
c.m. energy = 14 TeV (*p*)
luminosity =10^{34} $cm^{-2}s^{-1}$

1.15×10^{11} p/bunch
2808 bunches/beam

360 MJ/beam

$\gamma\varepsilon$=3.75 μm
β^*=0.55 m
θ_c=285 μrad
σ_z=7.55 cm
σ^*=16.6μm

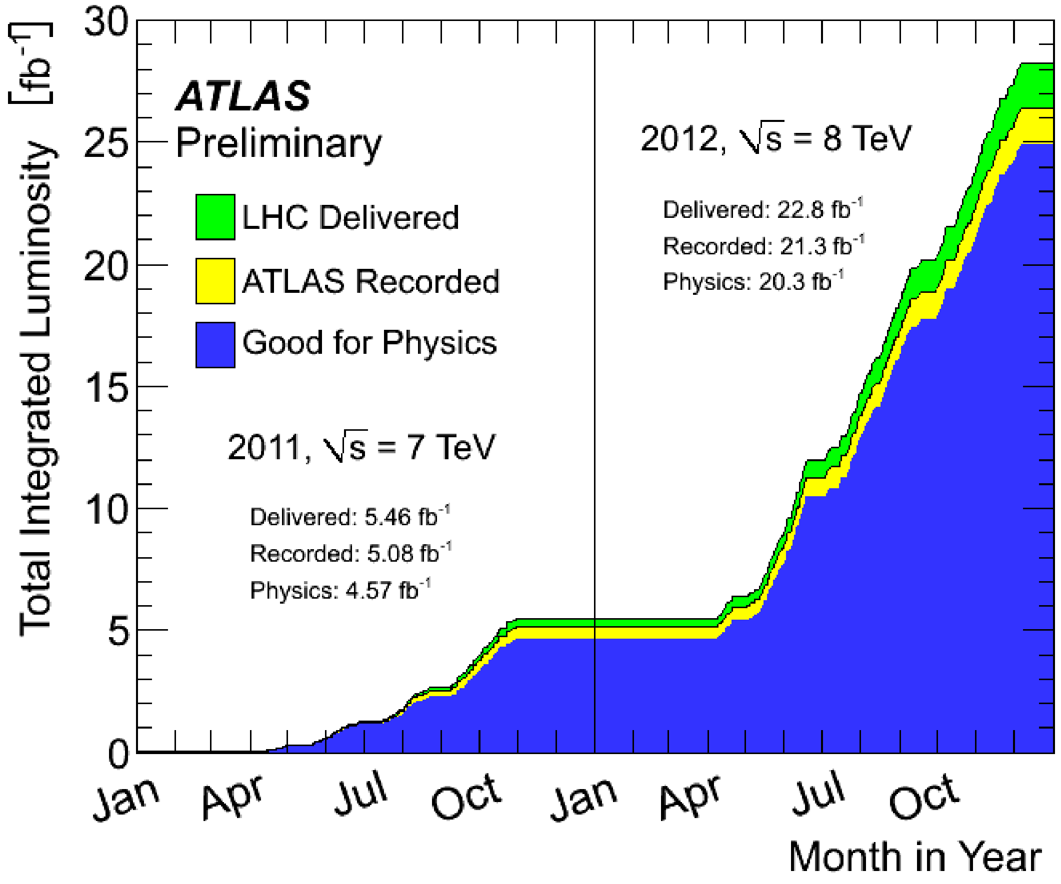
integrated *pp* luminosity 2010-12



- **2010: 0.04 fb^{-1}**
  - **7 TeV CoM**
  - **Commissioning**
- **2011: 6.1 fb^{-1}**
  - **7 TeV CoM**
  - **Exploring the limits**
- **2012: 23.3 fb^{-1}**
  - **8 TeV CoM**
  - **Production**

M. Lamont, IPAC'13

very good efficiency of the experiments

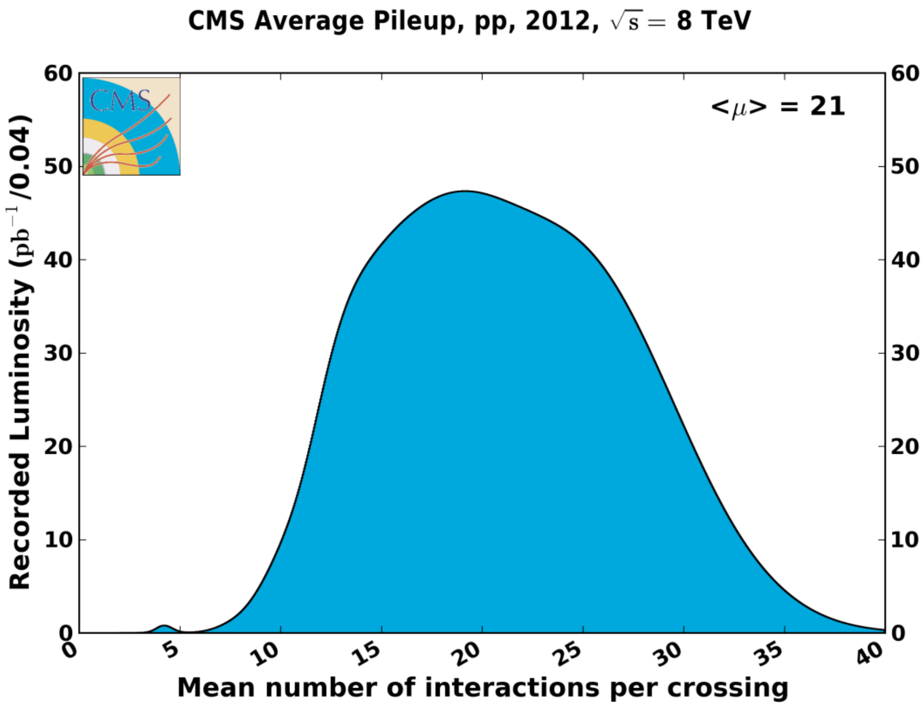


peak performance through the years

	2010	2011	2012	Nominal
bunch spacing [ns]	150	50	50	25
no. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
max. **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
normalized **emittance** [mm-mrad]	~2.0	~2.4	~2.5	3.75
peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

>2x design when scaled to 7 TeV!

M. Lamont, IPAC'13

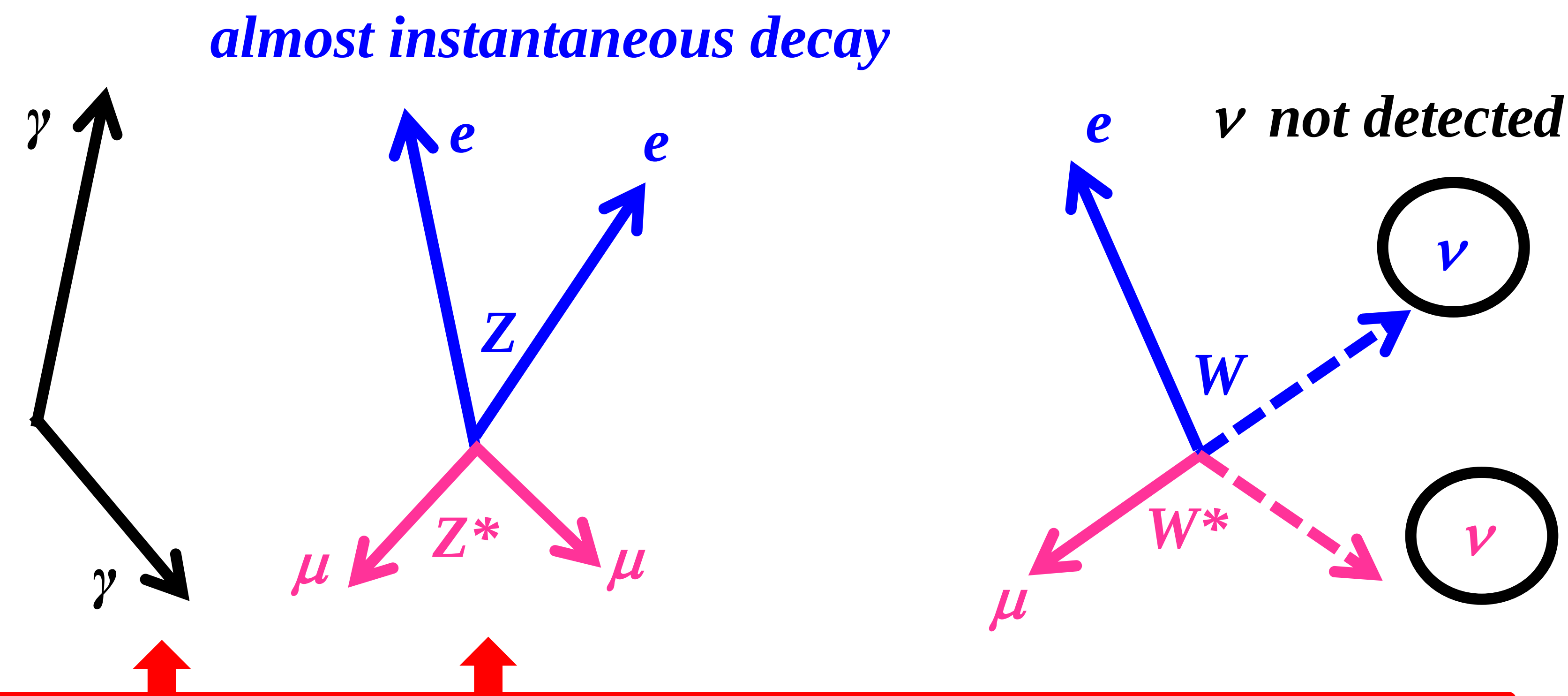


pile up
will increase
at higher energy
→
experiments
request
25 ns
operation
in 2015

M. Lamont, IPAC'13

back to detectors

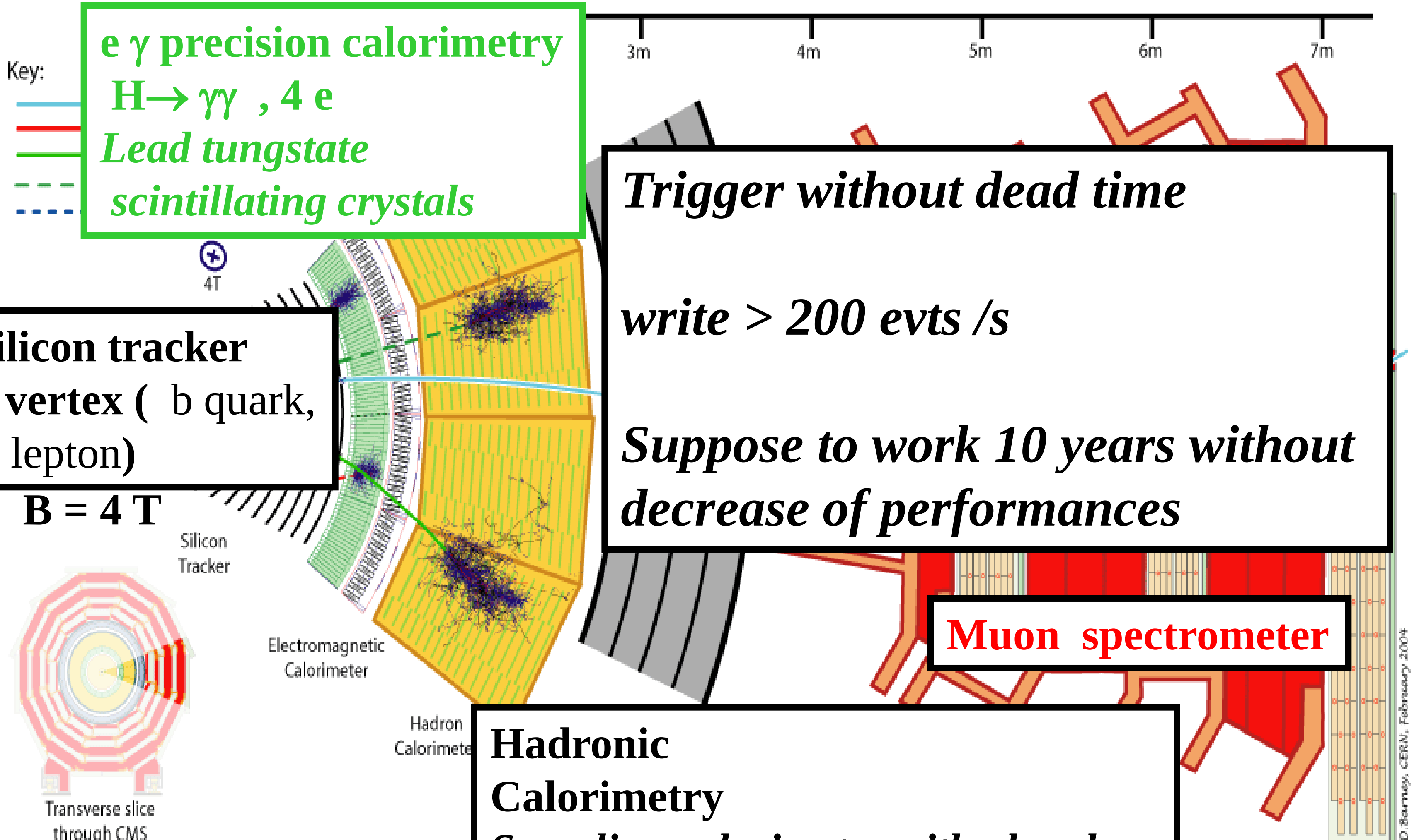
Fundamental scalar (Higgs) boson searches have guided the conception, design and technological choices of ATLAS and CMS



In these 2 cases the boson mass is computed reconstructing the invariant mass of the decay products

⇒ the mass resolution (and E and p) is very important in order to have a good significance S/√ B, **often** ∝ 1/√(resolution) **since the natural width of the boson is (**almost always**) negligible**

CMS = (Compact Muon Solenoid)



e γ precision calorimetry
H→ γγ , 4 e
Lead tungstate scintillating crystals

Trigger without dead time

write > 200 evts /s

Suppose to work 10 years without decrease of performances

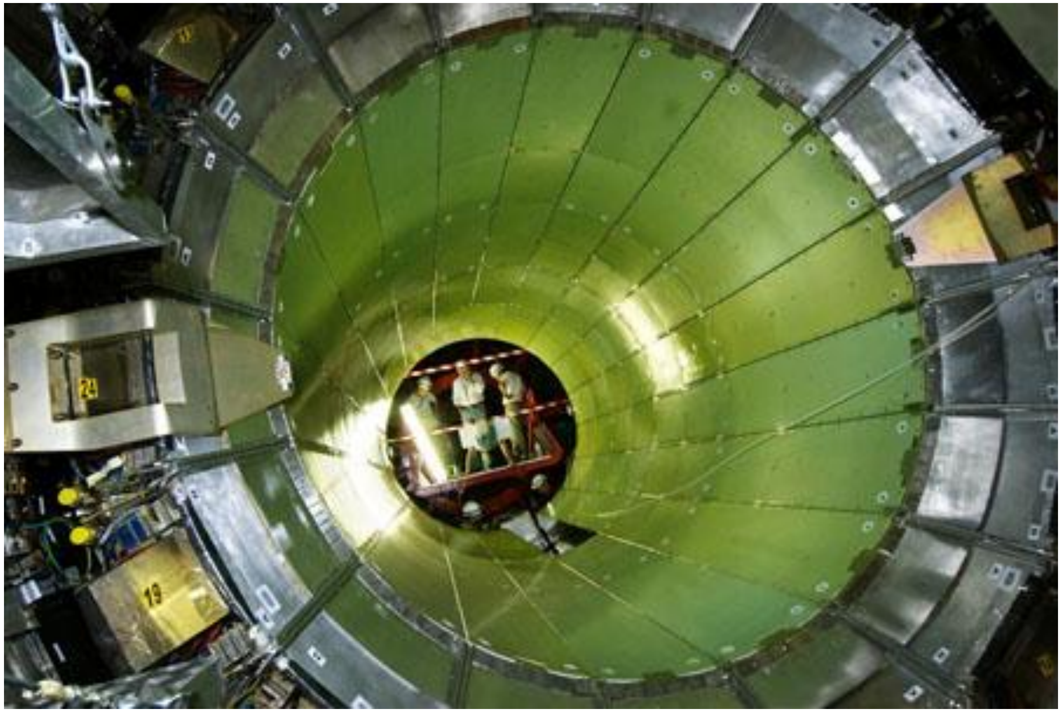
Silicon tracker
+ vertex (b quark, τ lepton**)**

B = 4 T

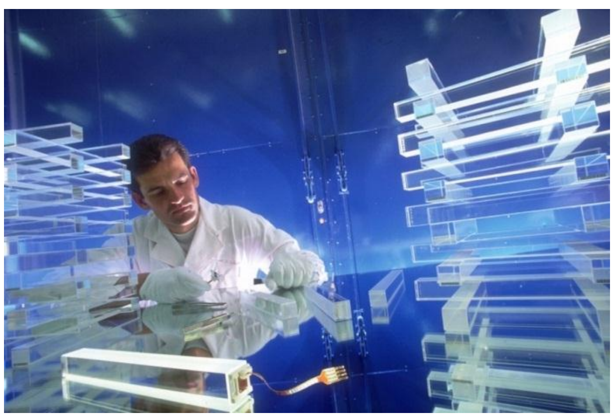
Muon spectrometer

Hadronic Calorimetry
Sampling calorimeter with absorber (brass) and plastic scintillators
Jets and $E_T$miss

« 4 π » detector
up to η=5
(from θ = 1.35°)



CMS EM calorimeter
more than 75000 cristals of $PbW0_4$



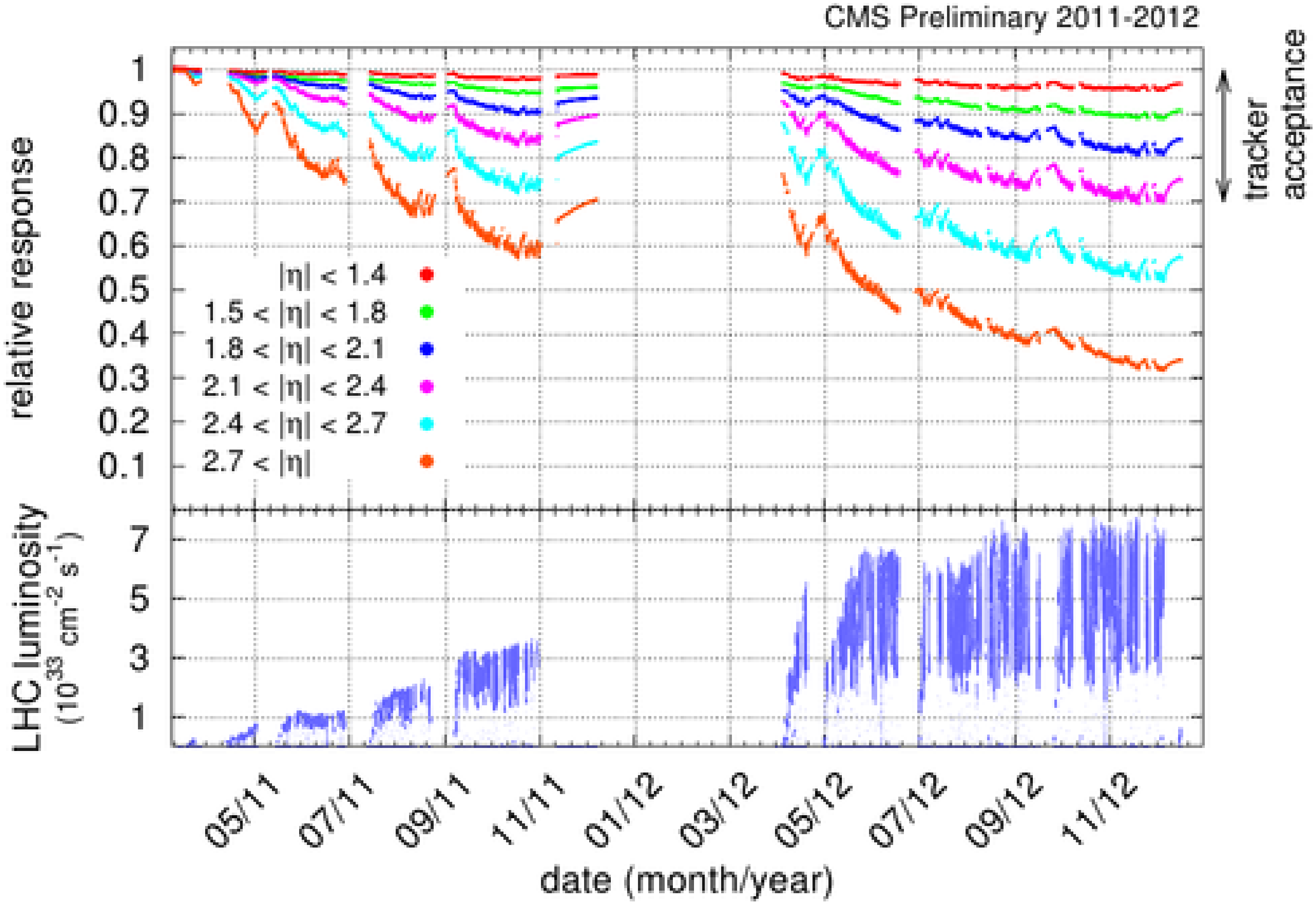
$$\sigma(E)/E = 3\%/\sqrt{E_{GeV}} \oplus 0.7\ \%$$

High level quality control !

e and γ

fixed size (different between e,γconverted and γ unconverted) in ATLAS clusters

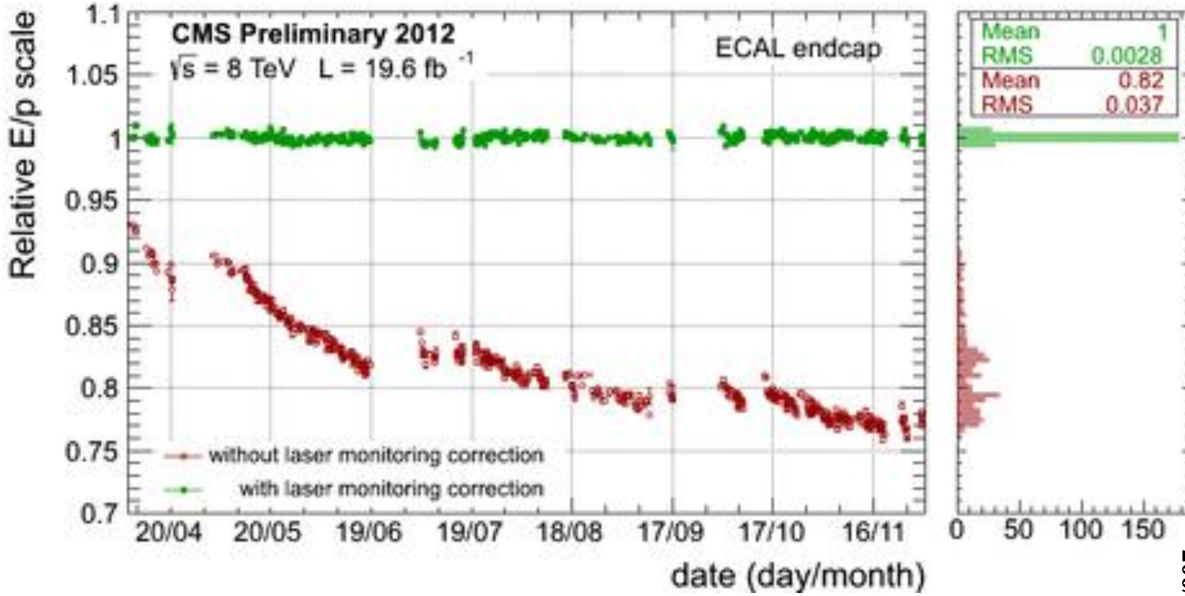
variable size (mainly in φ)in CMS (superclusters)
because B ~ 4 T (and the charged particles turn in the field)



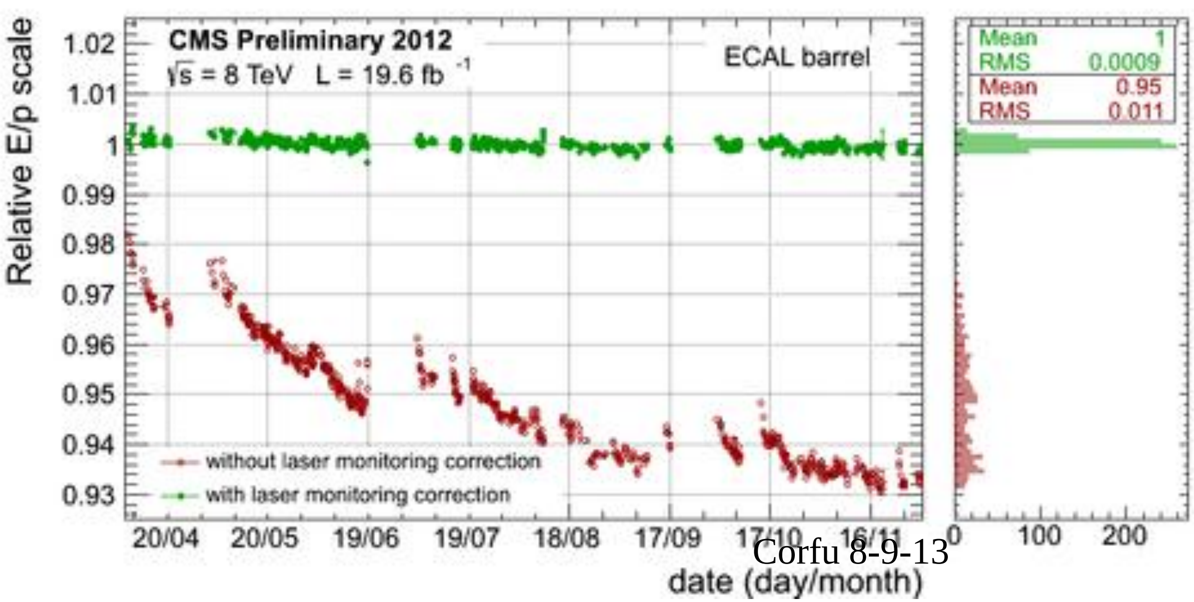
CMS-DP-2013/007

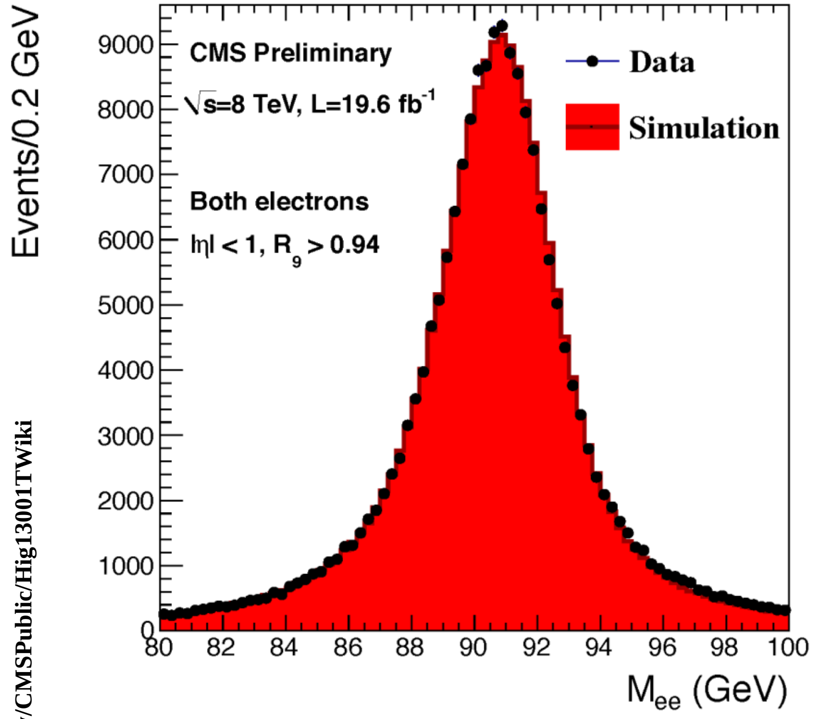
history of relative response

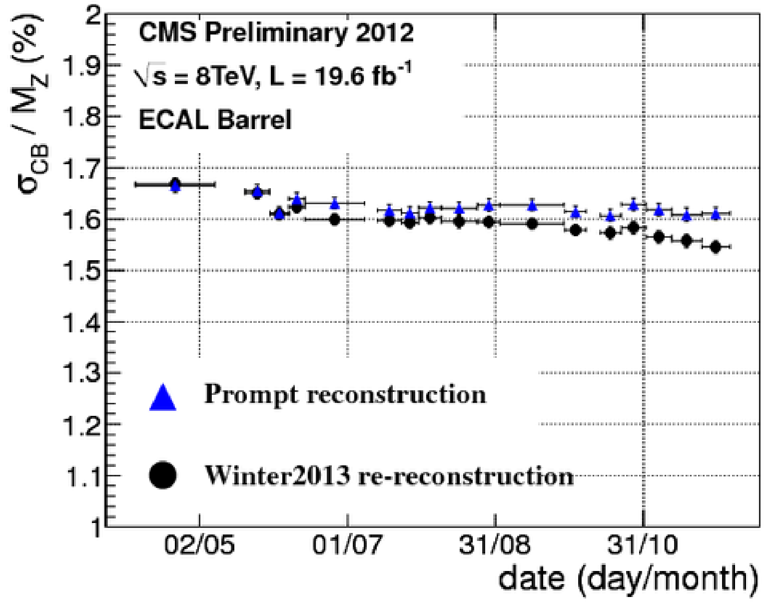
E/p history



CMS-DP-2013/007







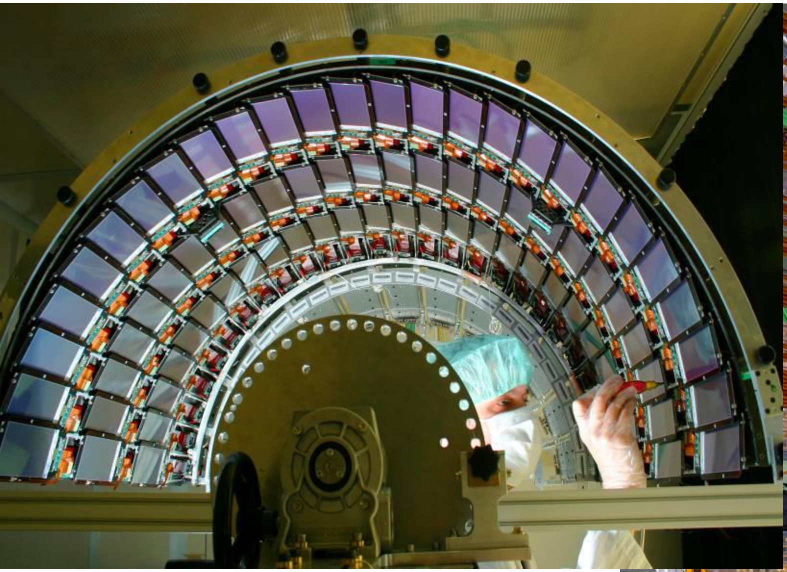
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13001TWiki

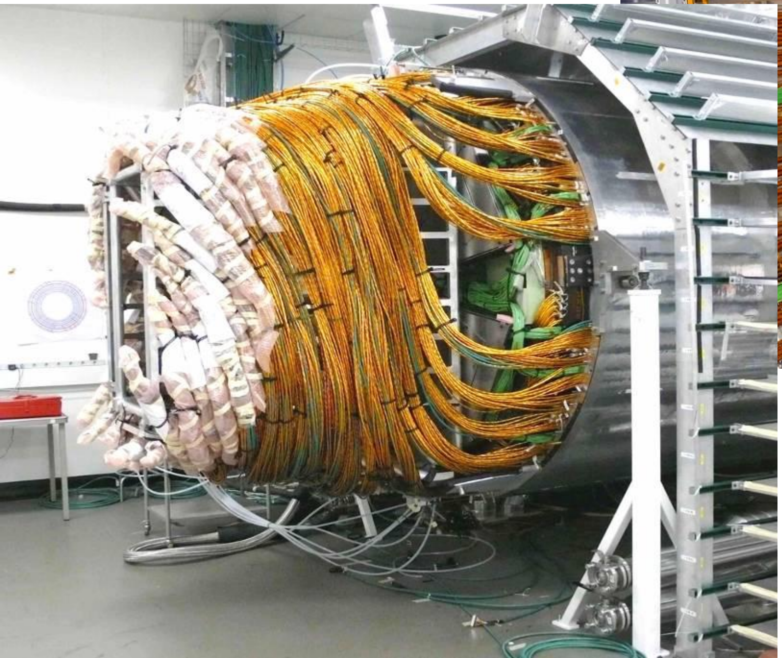
CMS-DP-2013/007

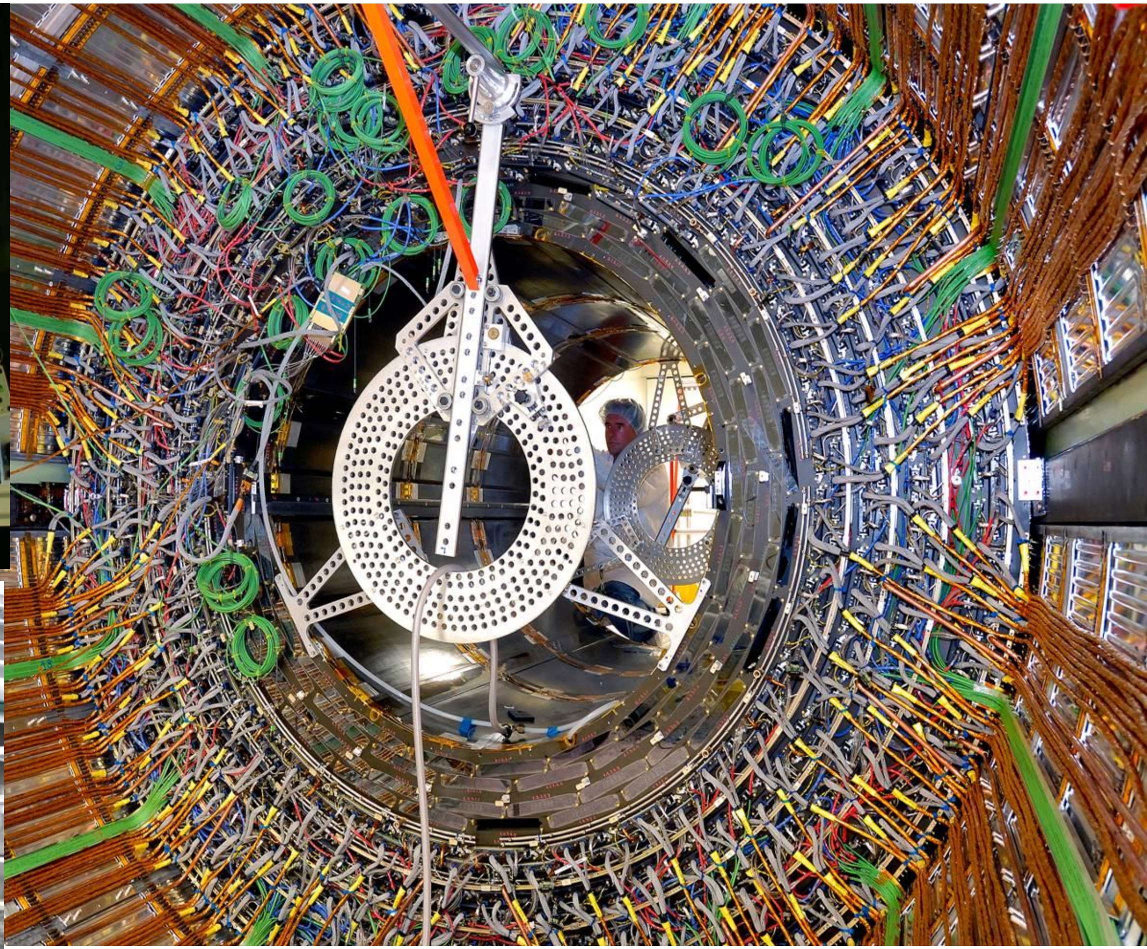
Validation and tests with Z → ee

the energy (and the response) of γ from H→ γγ is different from the energy (and response) of e from Z→ ee

CMS Silicon Tracker

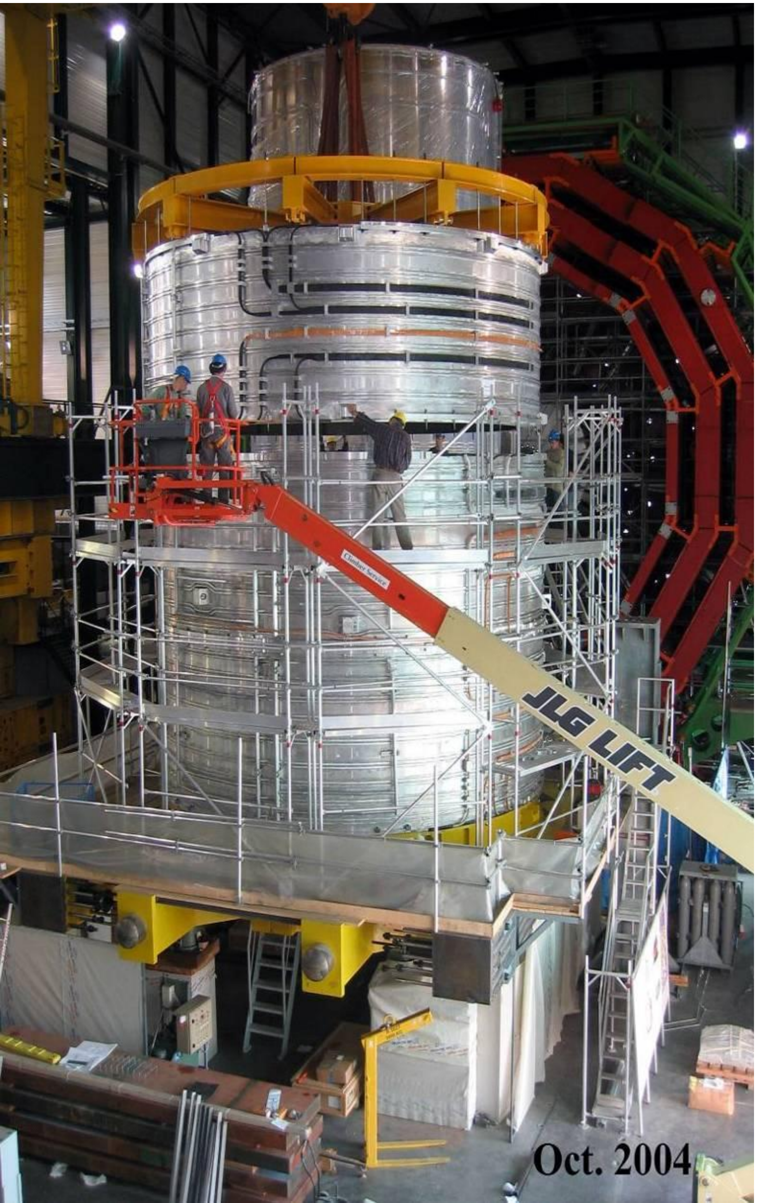




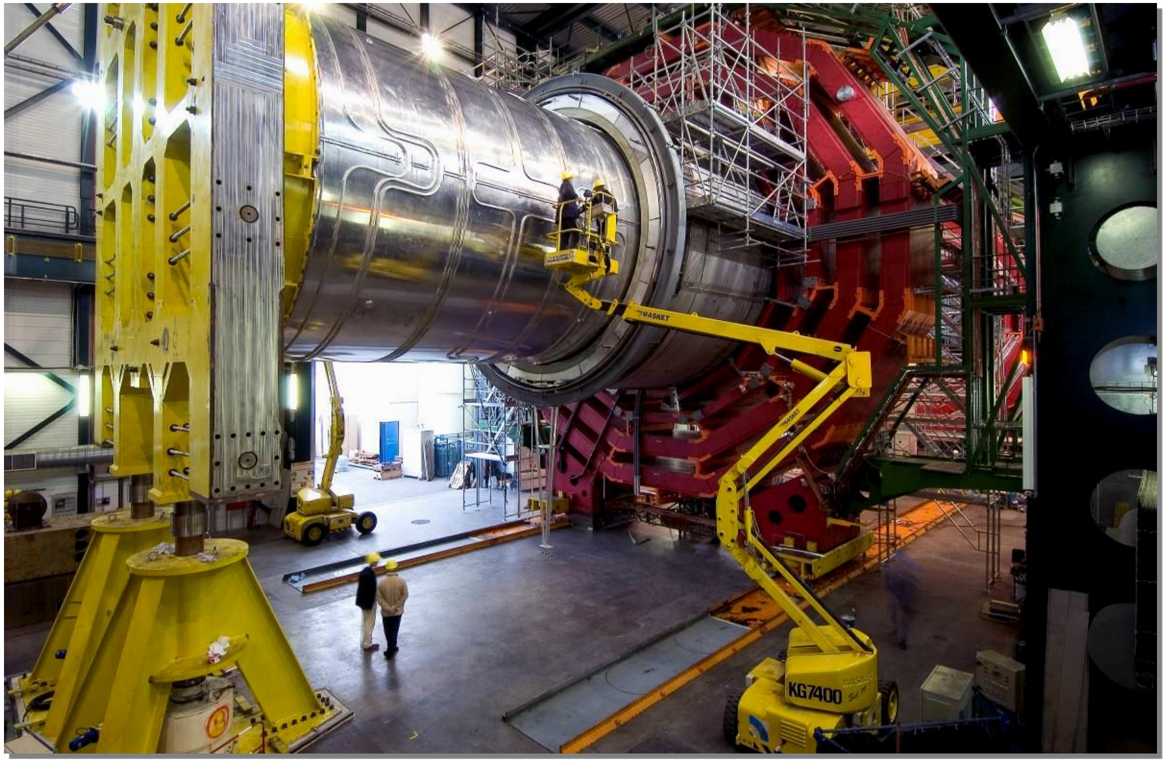


The Silicon tracker (200m^2) has 10 M channels
Operating temperature -15°C

CMS solenoid



B= 3.8 T
Diameter = 6m
Stored energy = 2.6 GJ
Magnetic length = 12.5 m



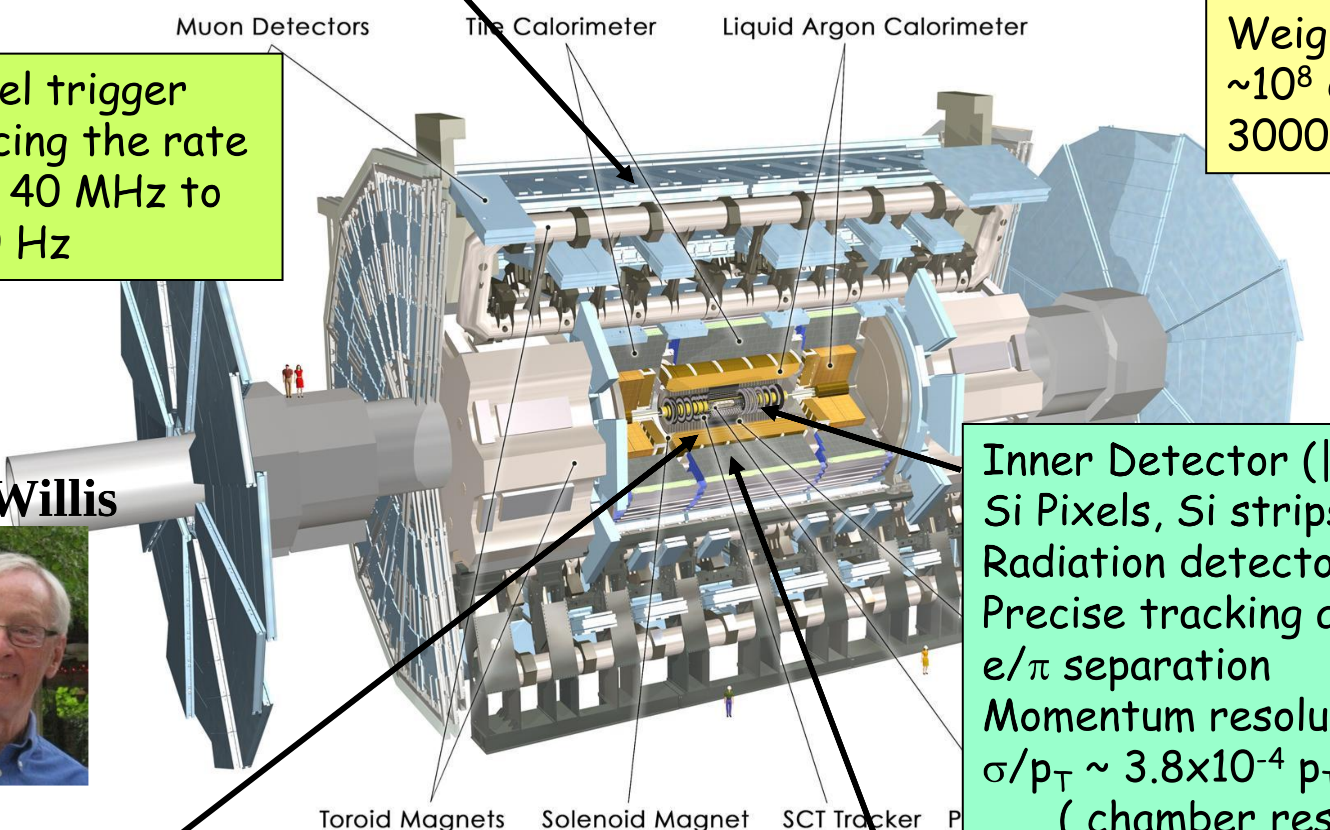
Forward CMS hadronic calorimeter going down

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids (B ~ 0.5 / 1T in barrel/ end-cap) with gas-based muon chambers Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

ATLAS detector

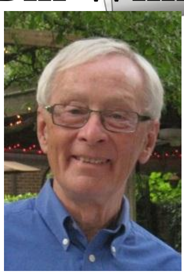
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Boris Dolgoshein

Bill Willis



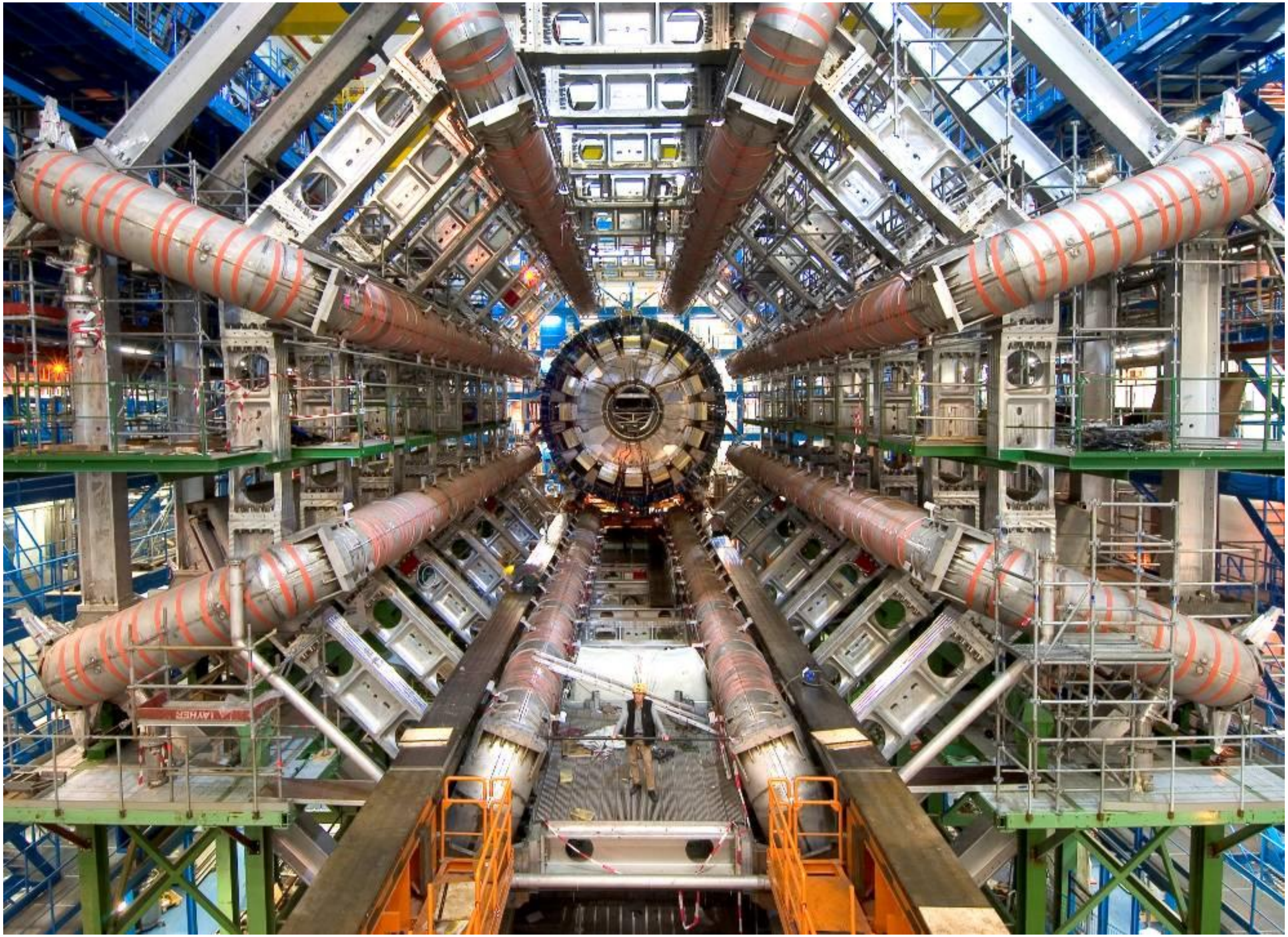
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$
(chamber resolution $\oplus$ MS)

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

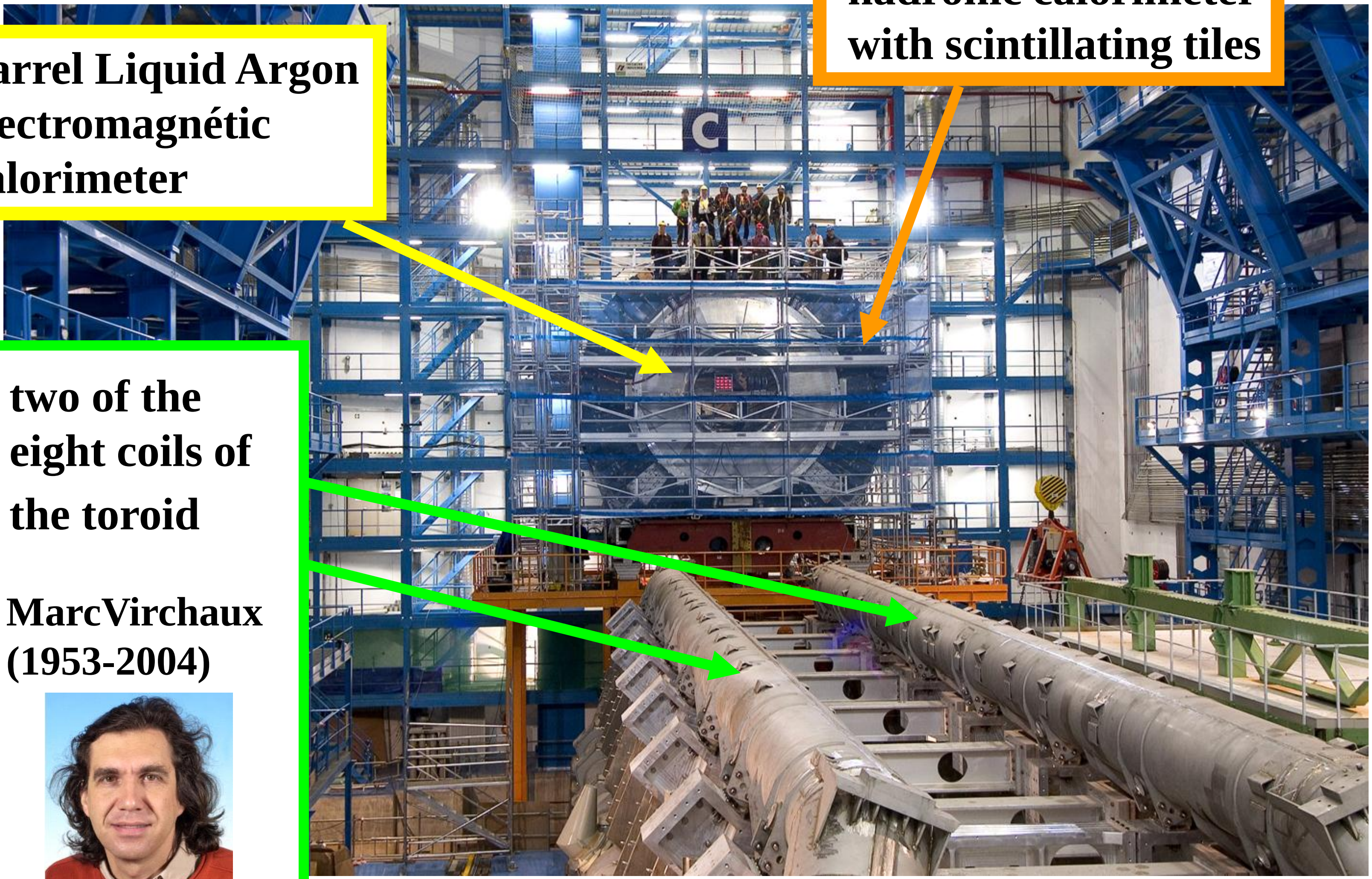
Daniel Fournier

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The barrel superconducting toroid of ATLAS (A Toroidal LHC ApparatuS)



ATLAS end of 2004

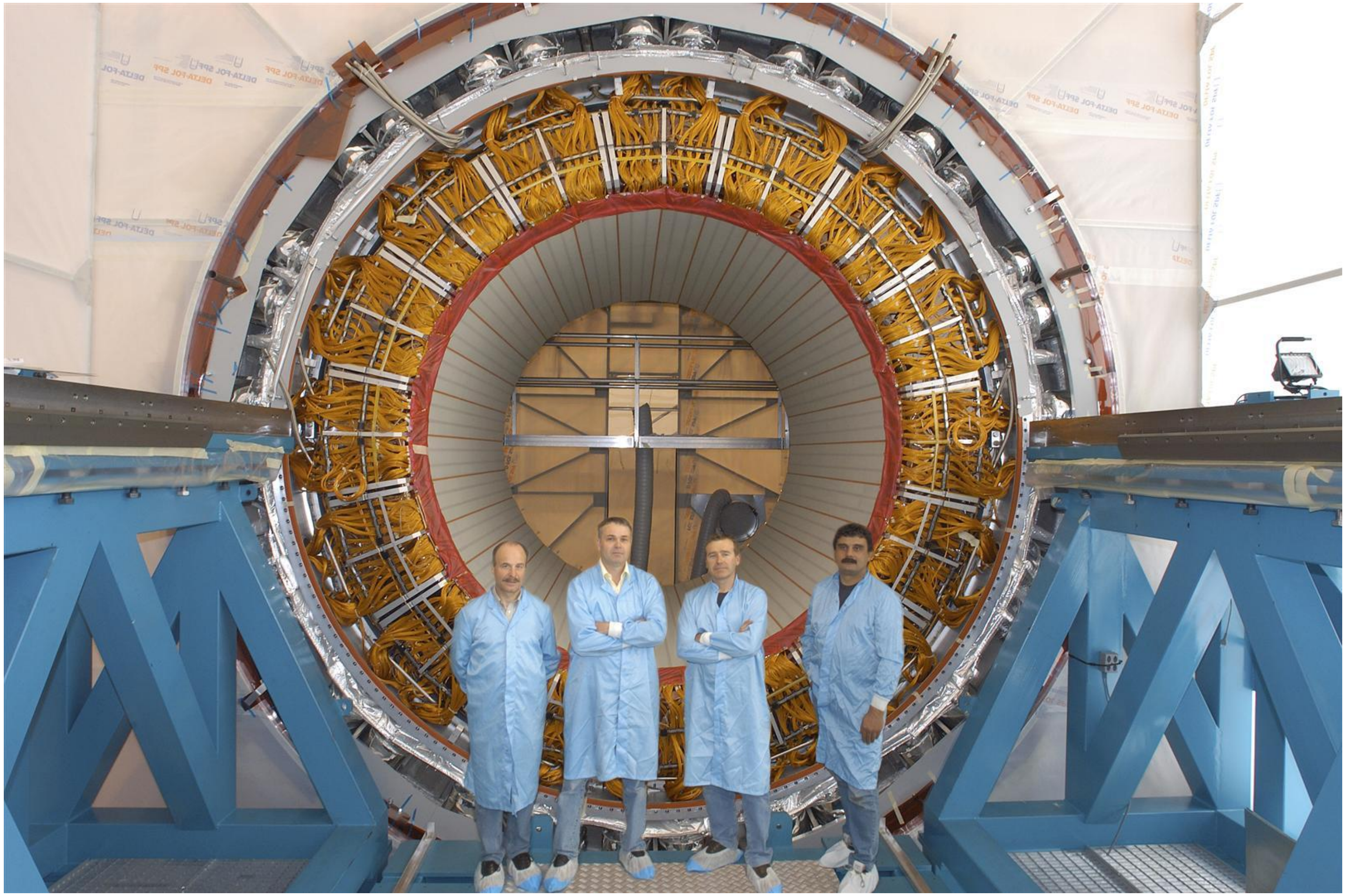


hadronic calorimeter with scintillating tiles

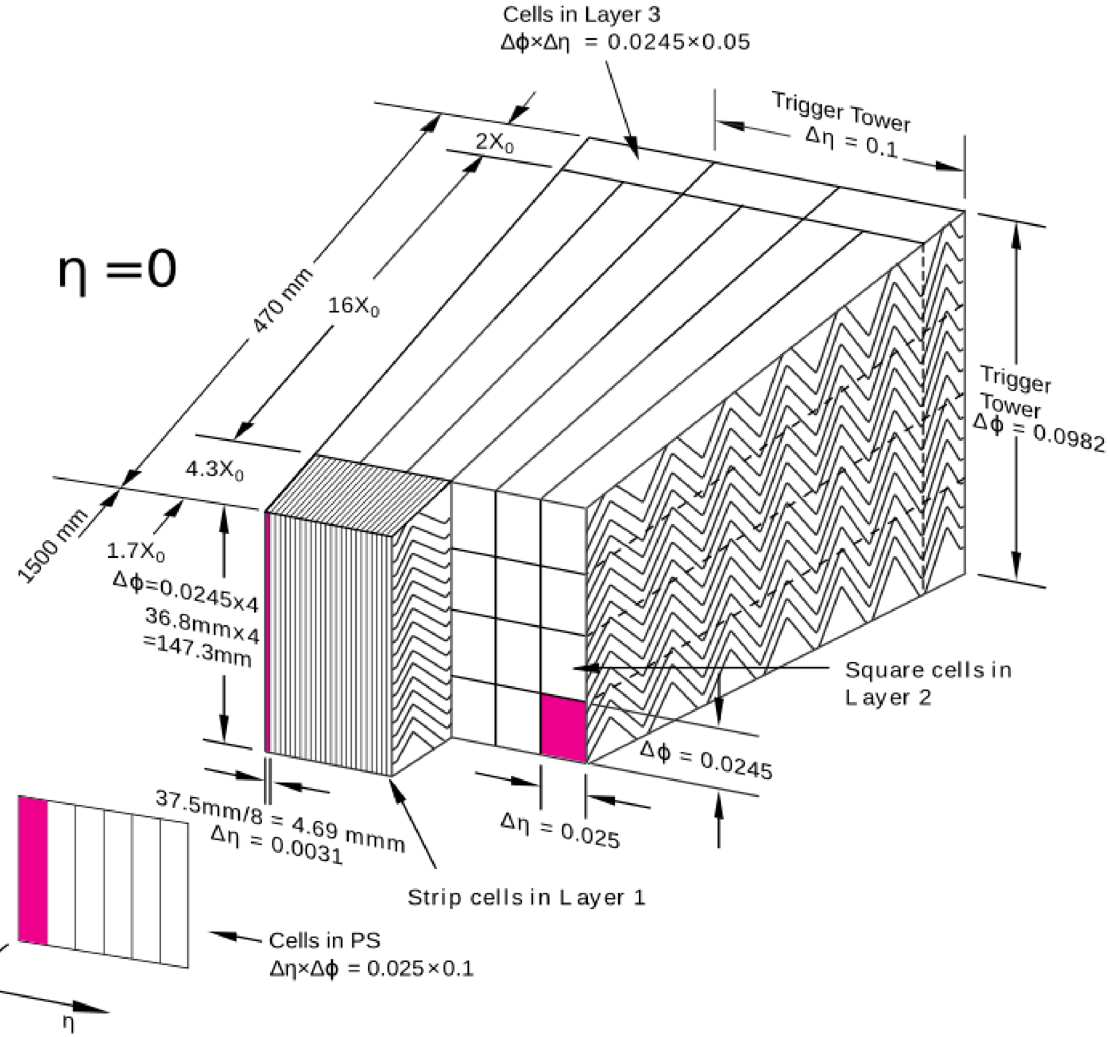
barrel Liquid Argon electromagnétic calorimeter

two of the eight coils of the toroid

MarcVirchaux (1953-2004)



ATLAS Liquid Argon (accordion) calorimeter
about 200000 channels
transverse and longitudinal segmentation

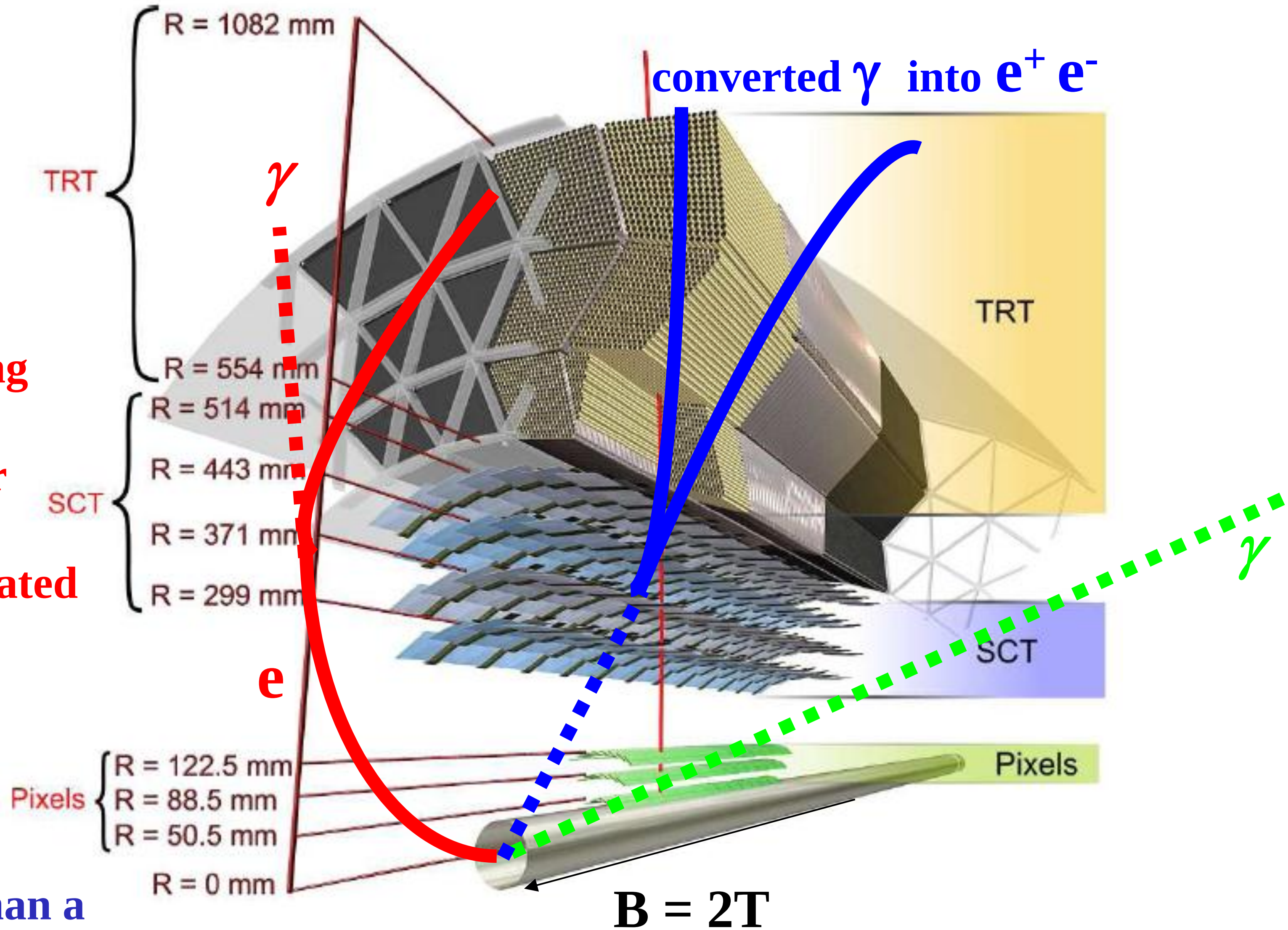


presampler and longitudinal segmentation of the EM (*Liquid Argon*) accordion calorimeter

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

ATLAS inner detector

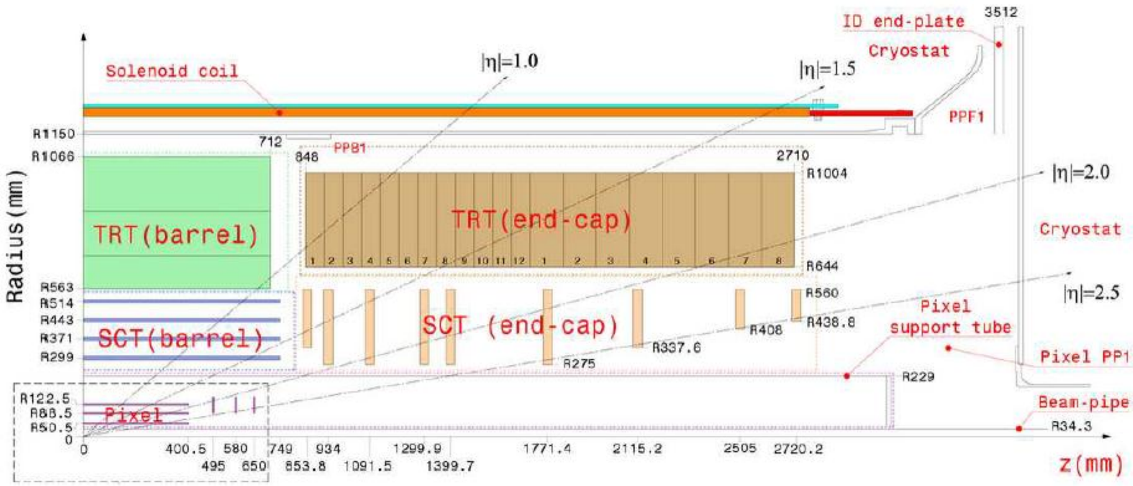
Outside you have the calorimeters and the muon detector



electrons can do some bremsstrahlung in the Inner Detector ⇒ response more complicated

photons can convert ⇒ more complicated than a non converted photon

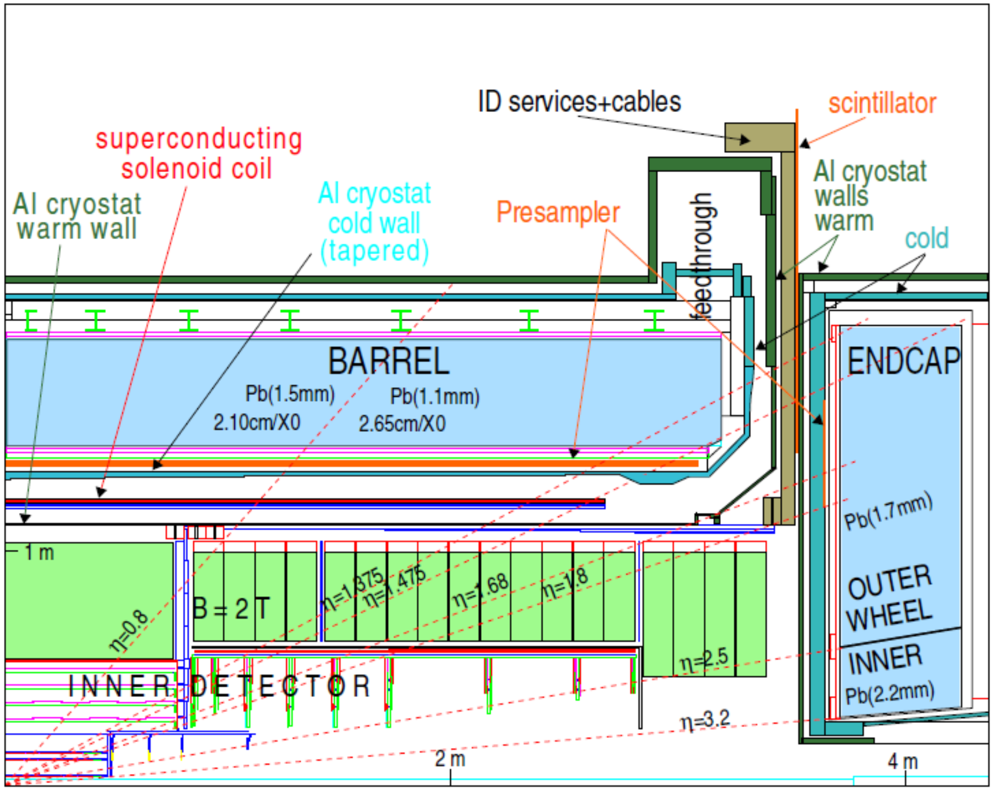
ATLAS



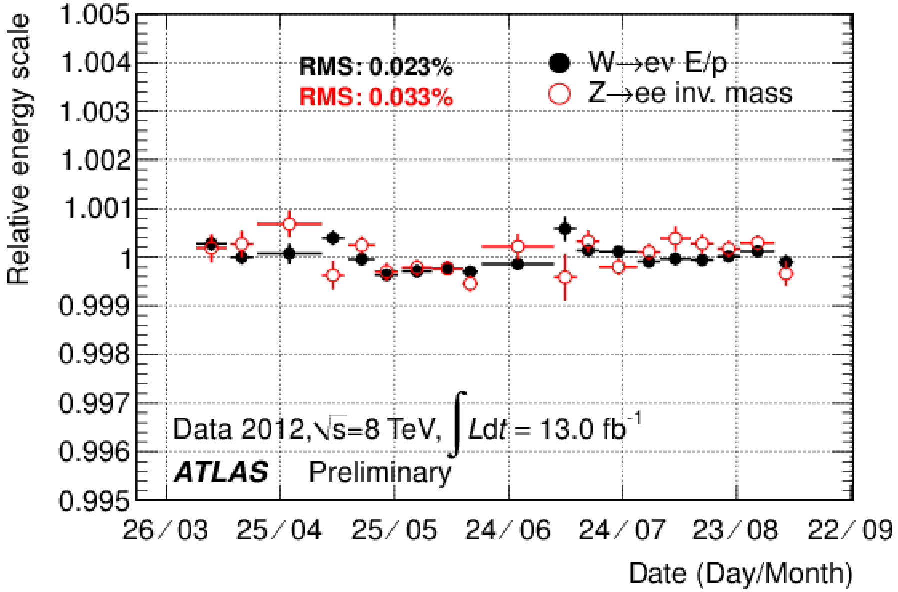
inner tracker up to η ~ 2.5

EM calorimeter up to η ~ 3

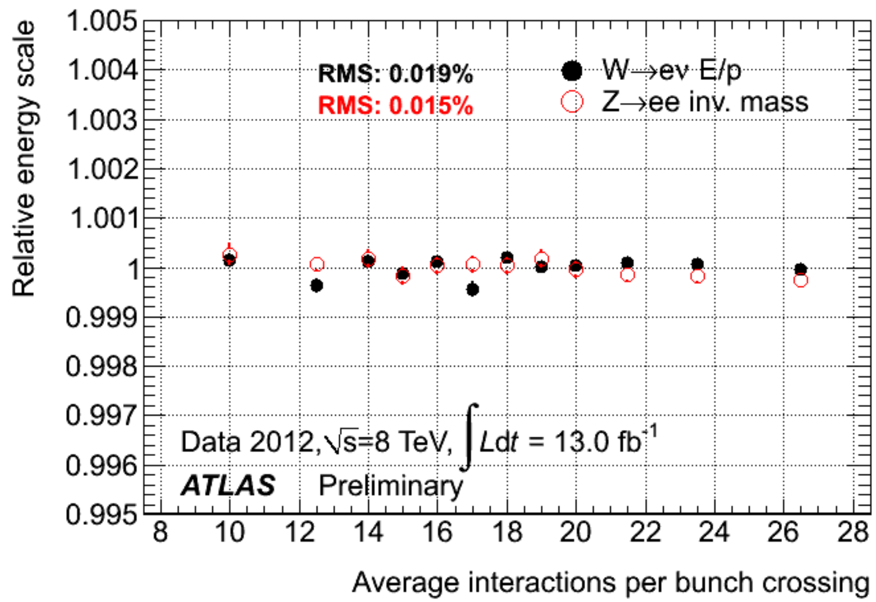
HAD calorimeter up to η ~ 5



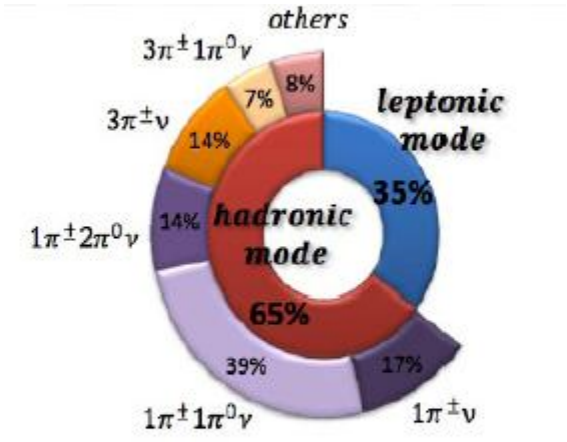
Lyon 28-29 oct 13



very good stability

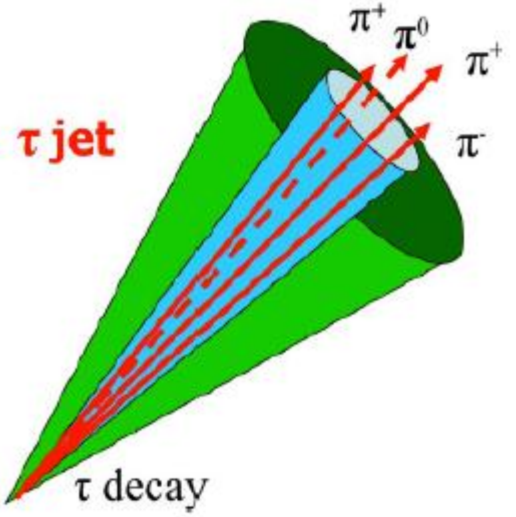


τ signature



2-4 neutrinos in final state , mass reconstruction difficult (see above)

hadronic τ decays : challenging signature
⇒ use multivariate techniques to separate τ decays from jets



b signature

b (and c) hadrons have relatively large masses, long lifetimes and daughter particles with hard momentum spectra. Their semileptonic decays can be exploited as well

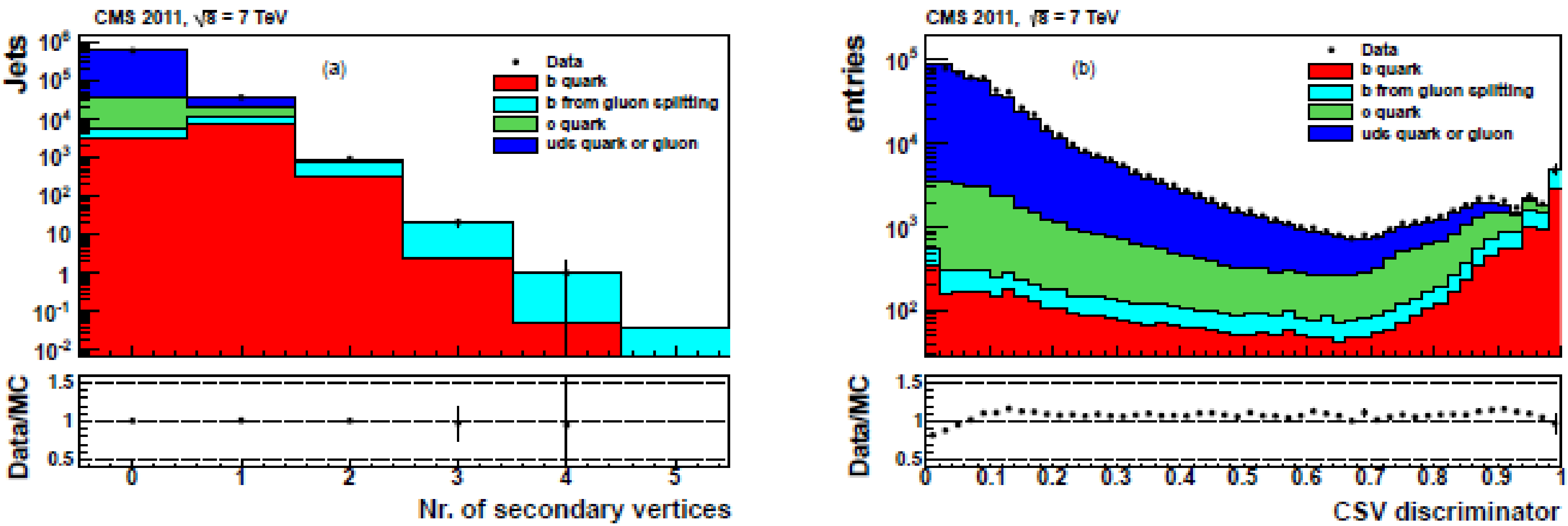
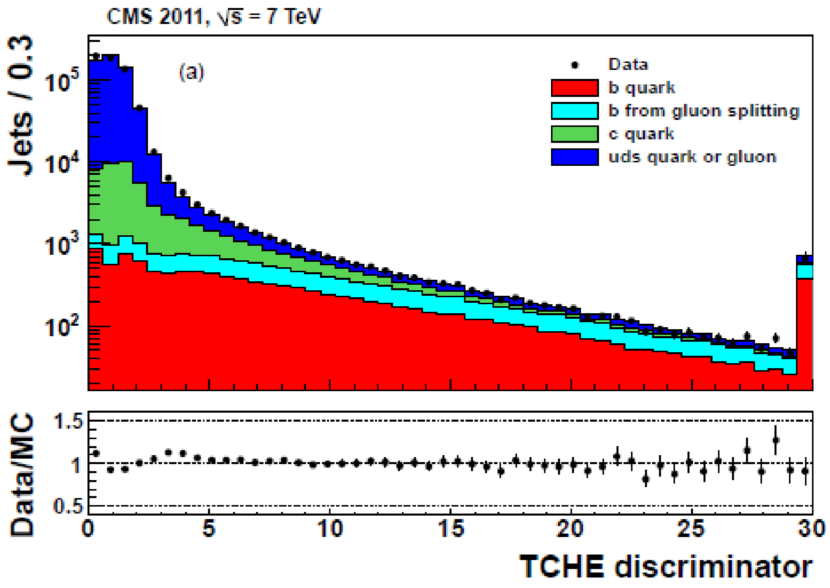
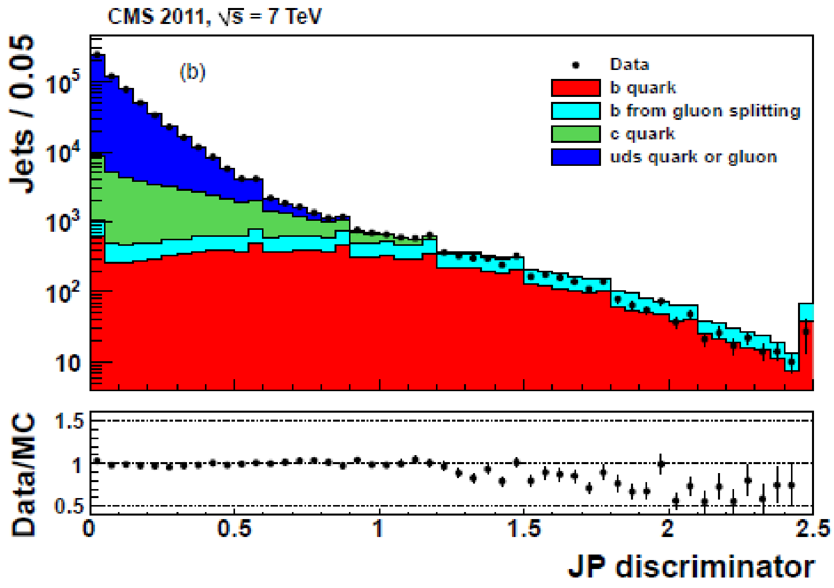


Figure 5: Distributions of (a) the secondary vertex multiplicity and (b) the CSV discriminator.

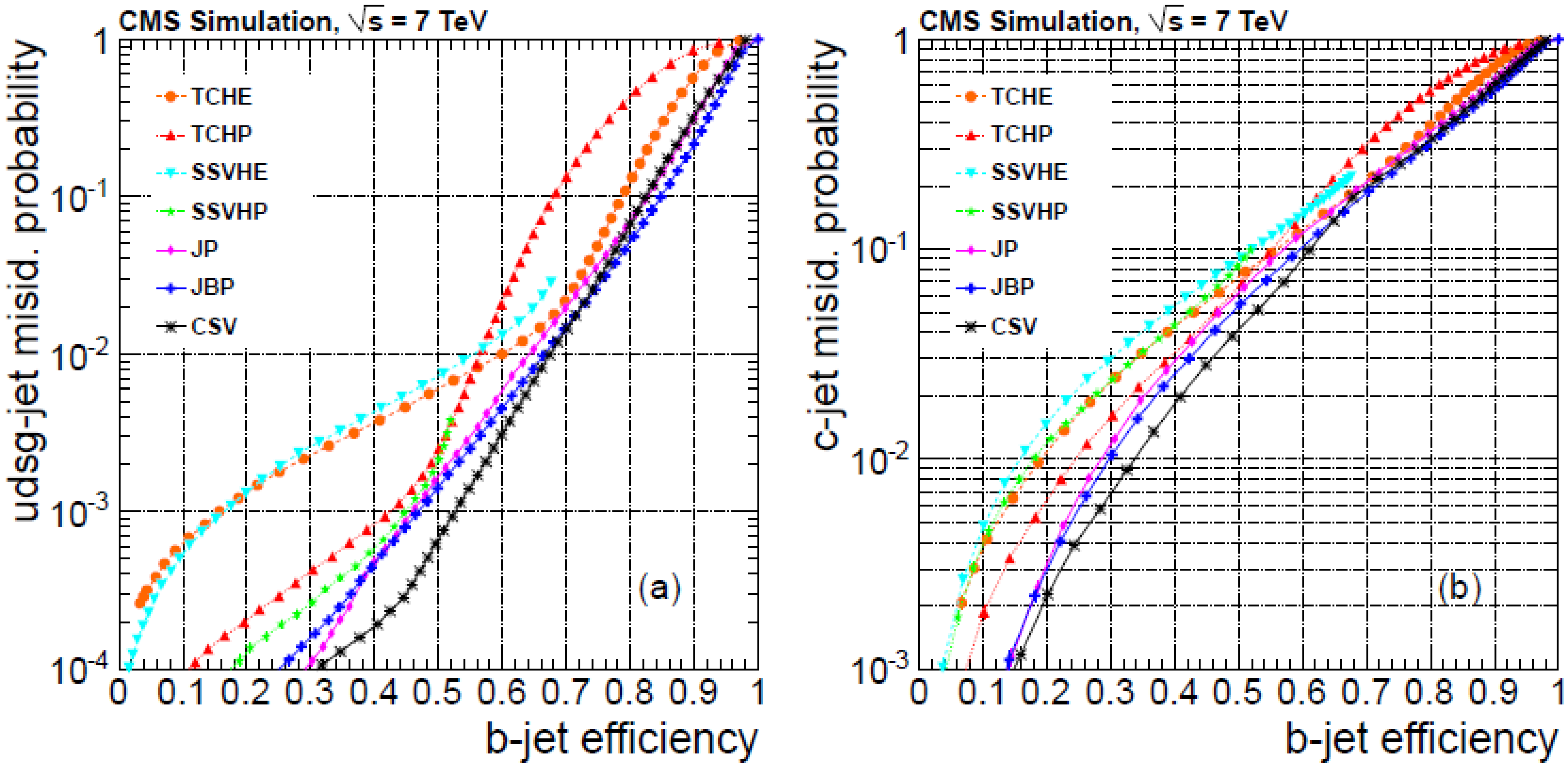
Combined Secondary Vertex (CSV)

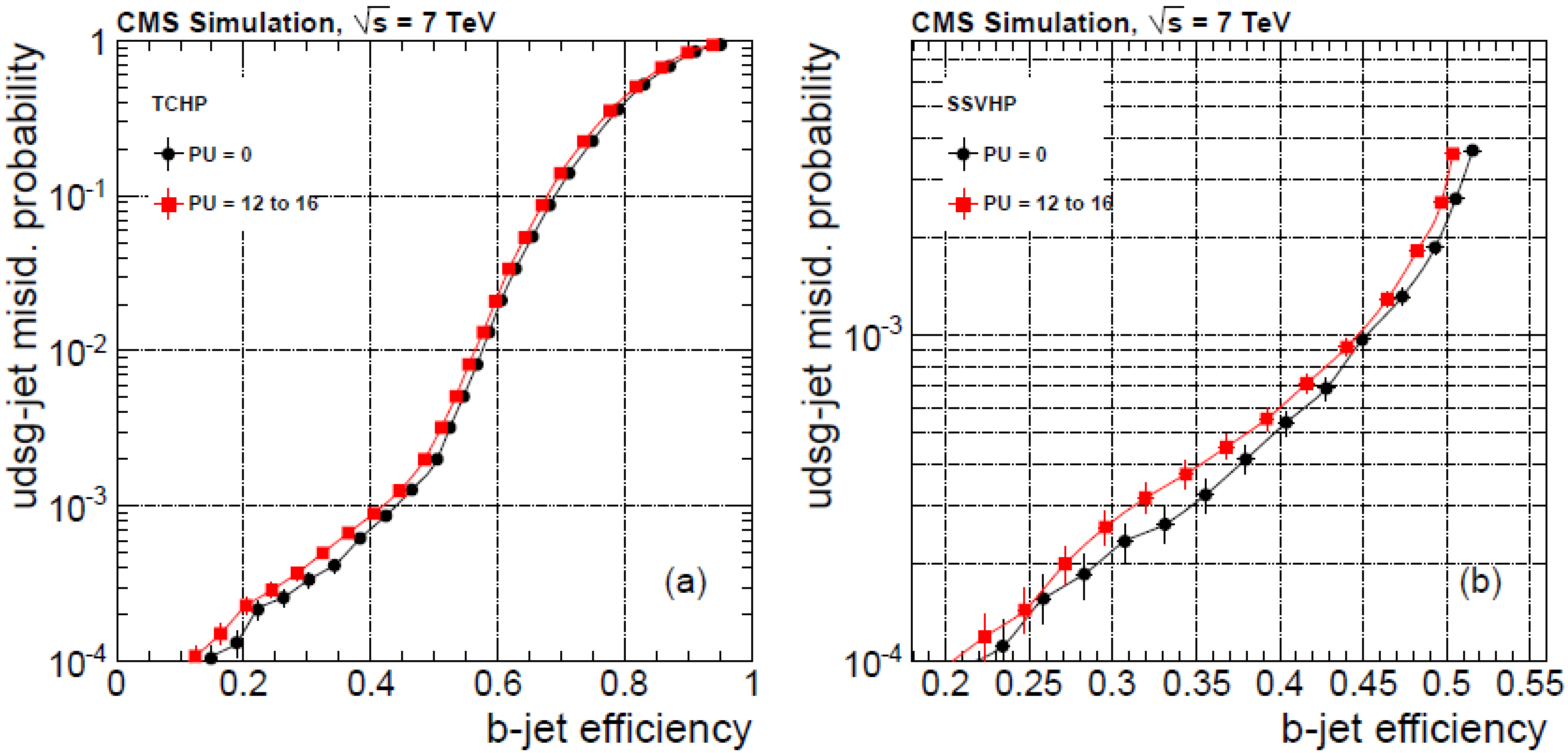


Track Counting High Efficiency (TCHE)



Jet B Probability (JBP)


CMS Simulation, $\sqrt{s}$ = 7 TeV
udsg-jet misid. probability
b-jet efficiency
TCHE
TCHP
SSVHE
SSVHP
JP
JBP
CSV
(a)
CMS Simulation, $\sqrt{s}$ = 7 TeV
c-jet misid. probability
b-jet efficiency
(b)



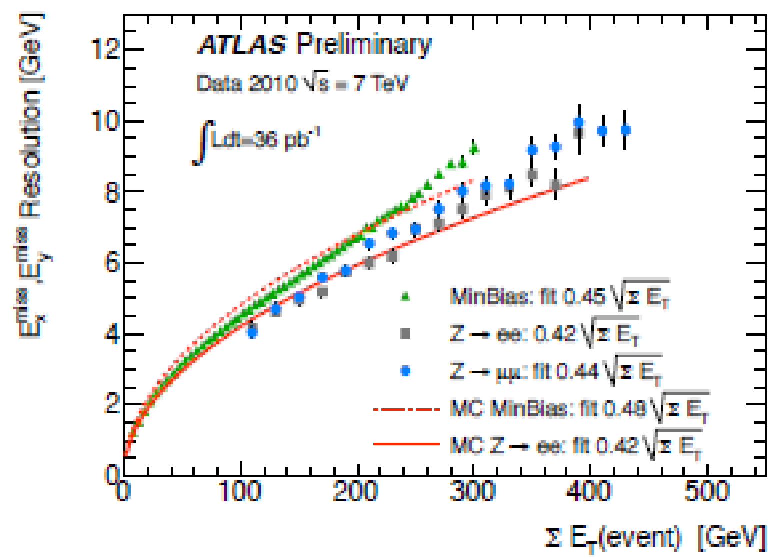
A lot of ‘data driven’ checks …

Missing E_T

It is a key signature for many measurements

Calculated by summing all energy deposits in the calorimeter (based on identified objects: e, γ, τ, jets >20 GeV, soft energy depositions incl. tracks, and muons

$$E^{\text{miss}}_{x(y)} = E^{\text{miss},e}_{x(y)} + E^{\text{miss},\gamma}_{x(y)} + E^{\text{miss},\tau}_{x(y)} + E^{\text{miss,jets}}_{x(y)} + E^{\text{miss,SoftTerm}}_{x(y)} + E^{\text{miss},\mu}_{x(y)},$$



Resolution depends on total transverse energy (and also on pile-up
⇒ need pile-up suppression

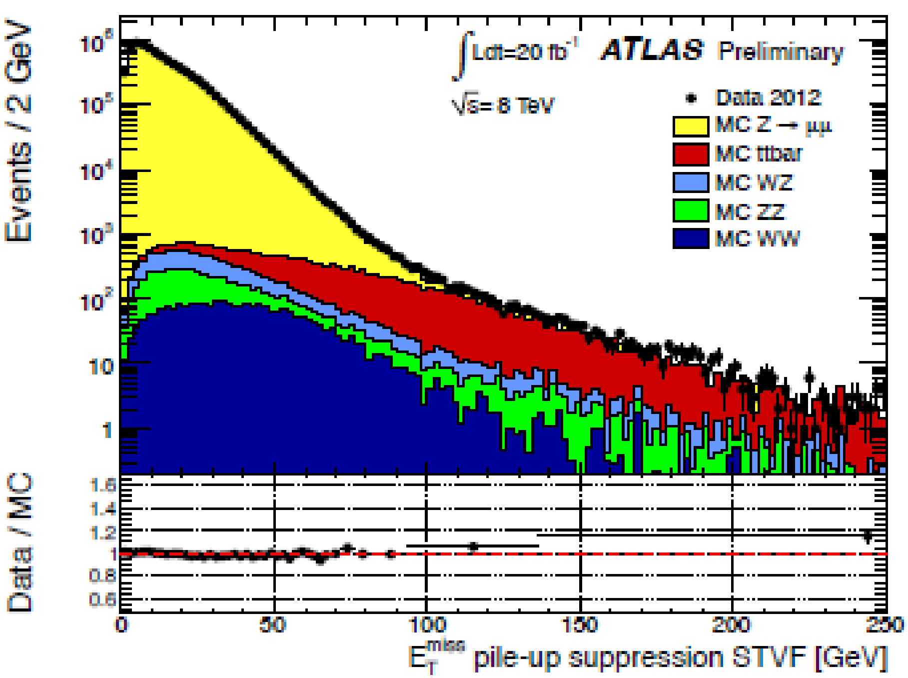
Suppress pile-up contributions using tracking detector

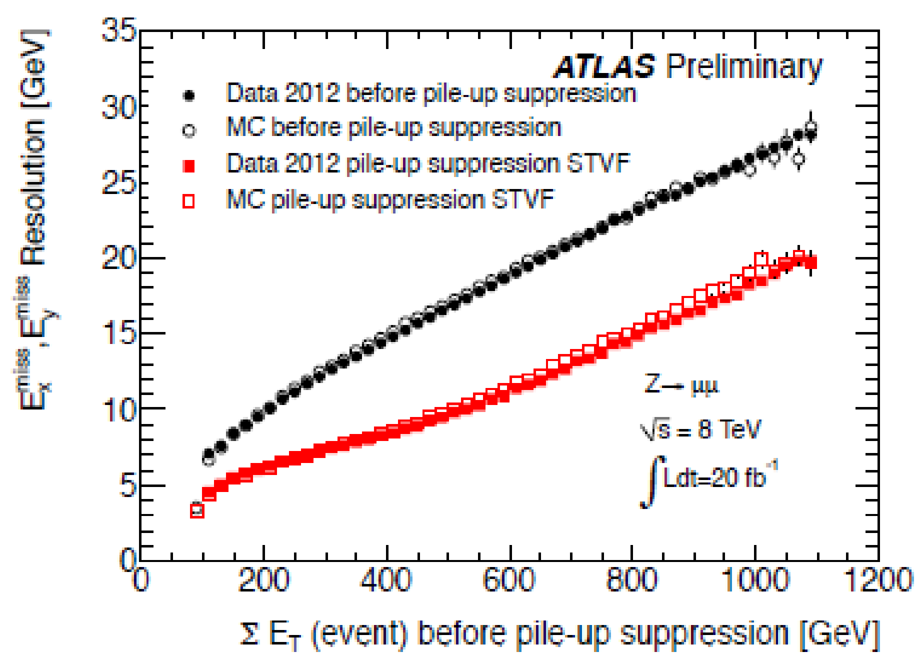
Include only jets whose tracks have a high vertex fraction

$$\mathrm{JVF} = \sum_{\mathrm{tracks_{jet}},\mathrm{PV}} p_{\mathrm{T}} / \sum_{\mathrm{tracks_{jet}}} p_{\mathrm{T}}$$

Scale Soft Term by Vertex Fraction

$$\mathrm{STVF} = \sum_{\mathrm{tracks_{SoftTerm}},\mathrm{PV}} p_{\mathrm{T}} / \sum_{\mathrm{tracks_{SoftTerm}}} p_{\mathrm{T}}$$





Good description of the missing transverse energy distribution/resolution by the Monte Carlo simulation

♥ **Historical introduction of the boson and of the LHC**

♥ **Some phenomenological comments**

♥ **Rapid overview of the detectors**

♥ **The discovery**

and the description of the analysis in the various channels , and the searches for additional bosons

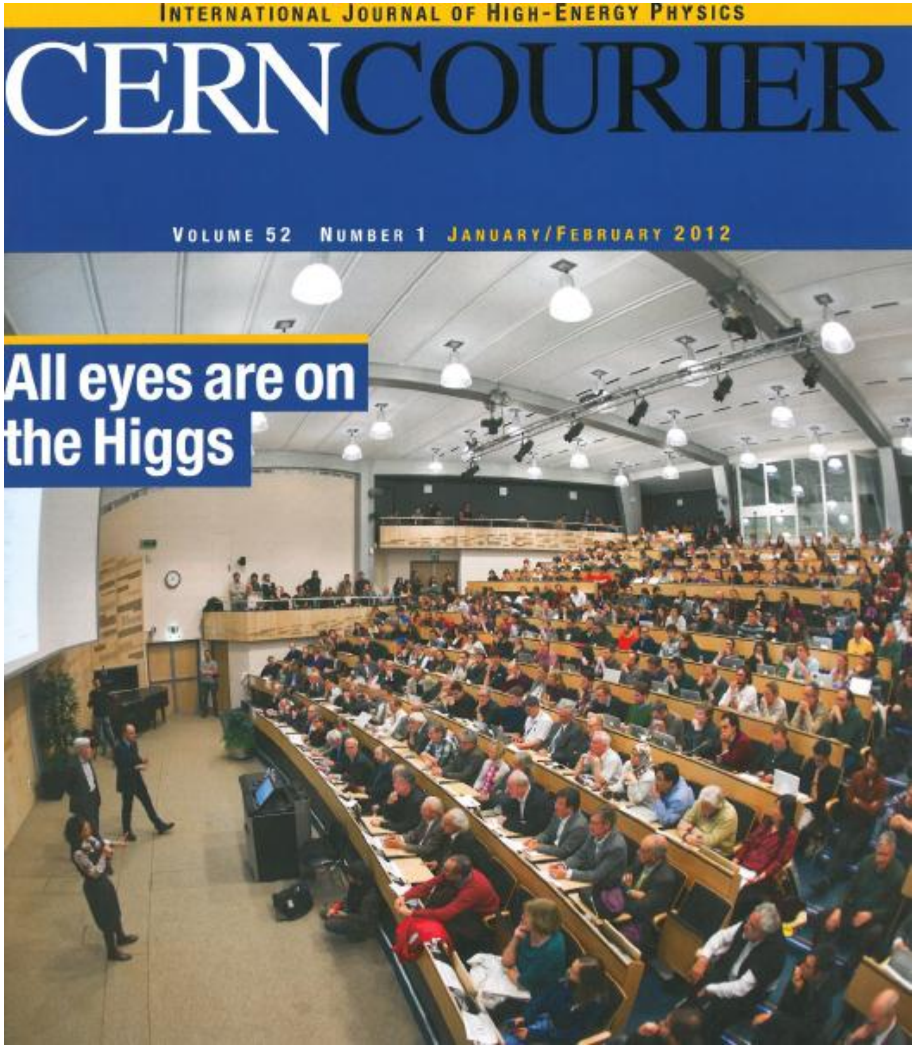
♥ **The first measurements of the properties**

♥ **The future of the physics with the scalar boson(s)**

♥ **Backup (with references)**

The discovery

Hints of signal were already there in 13th december 2011



The 4th July (2012) seminar

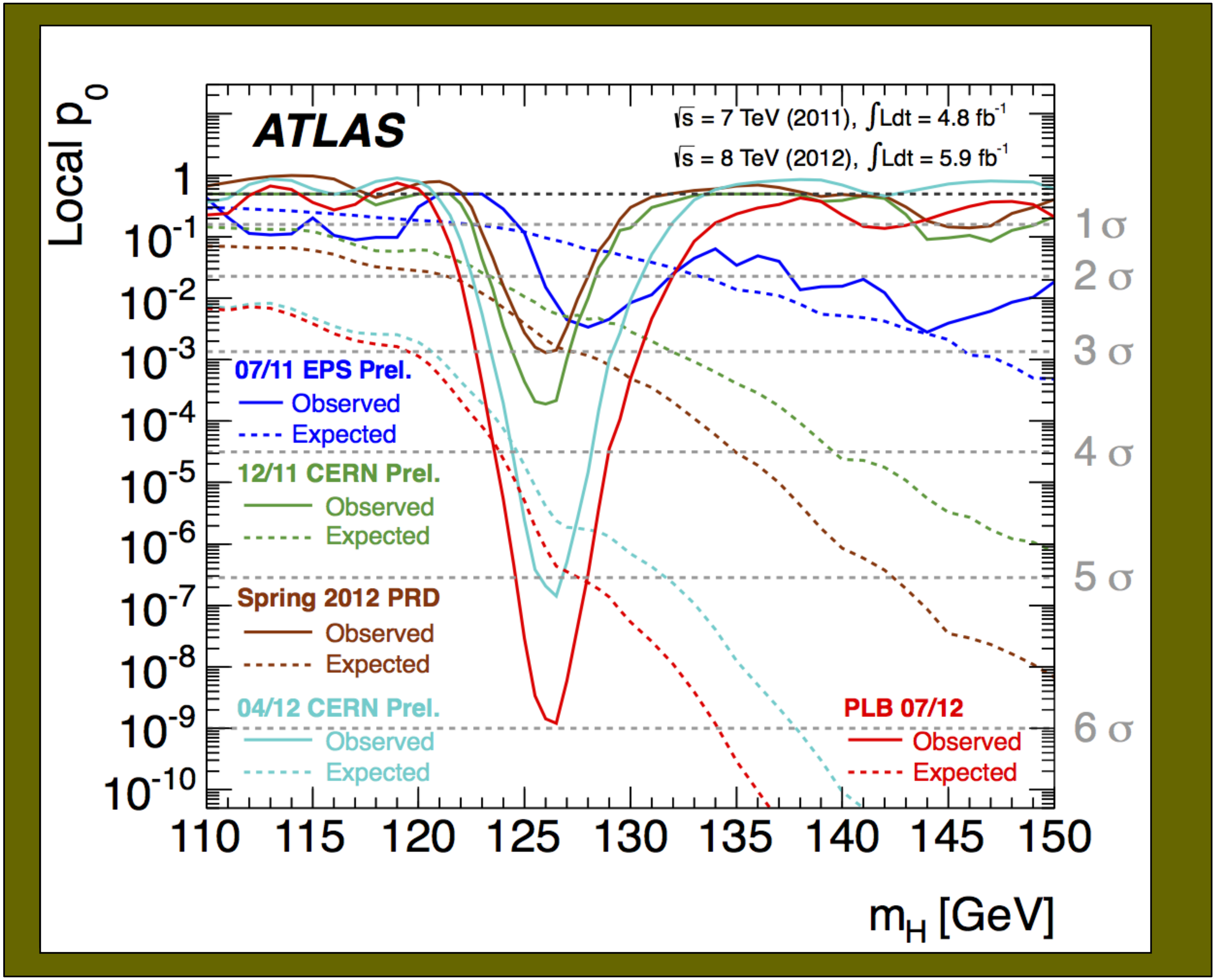
before

after

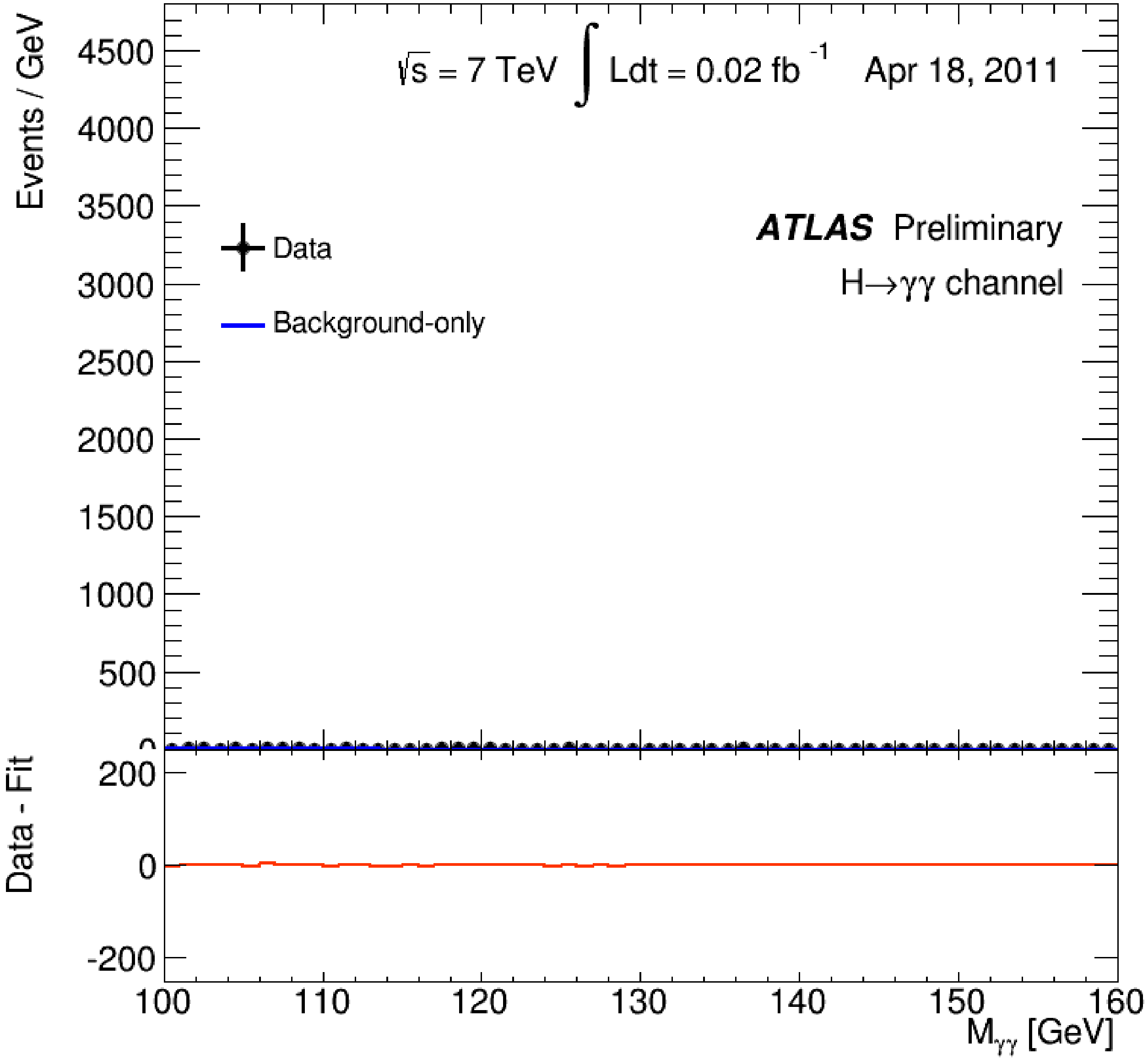
during


accelerators – experiments – Grid computing
Observation of a new particle consistent with a Higgs Boson (but which one…?)
Historic Milestone but only the beginning
Global Implications for the future
CERN
R-D Heuer

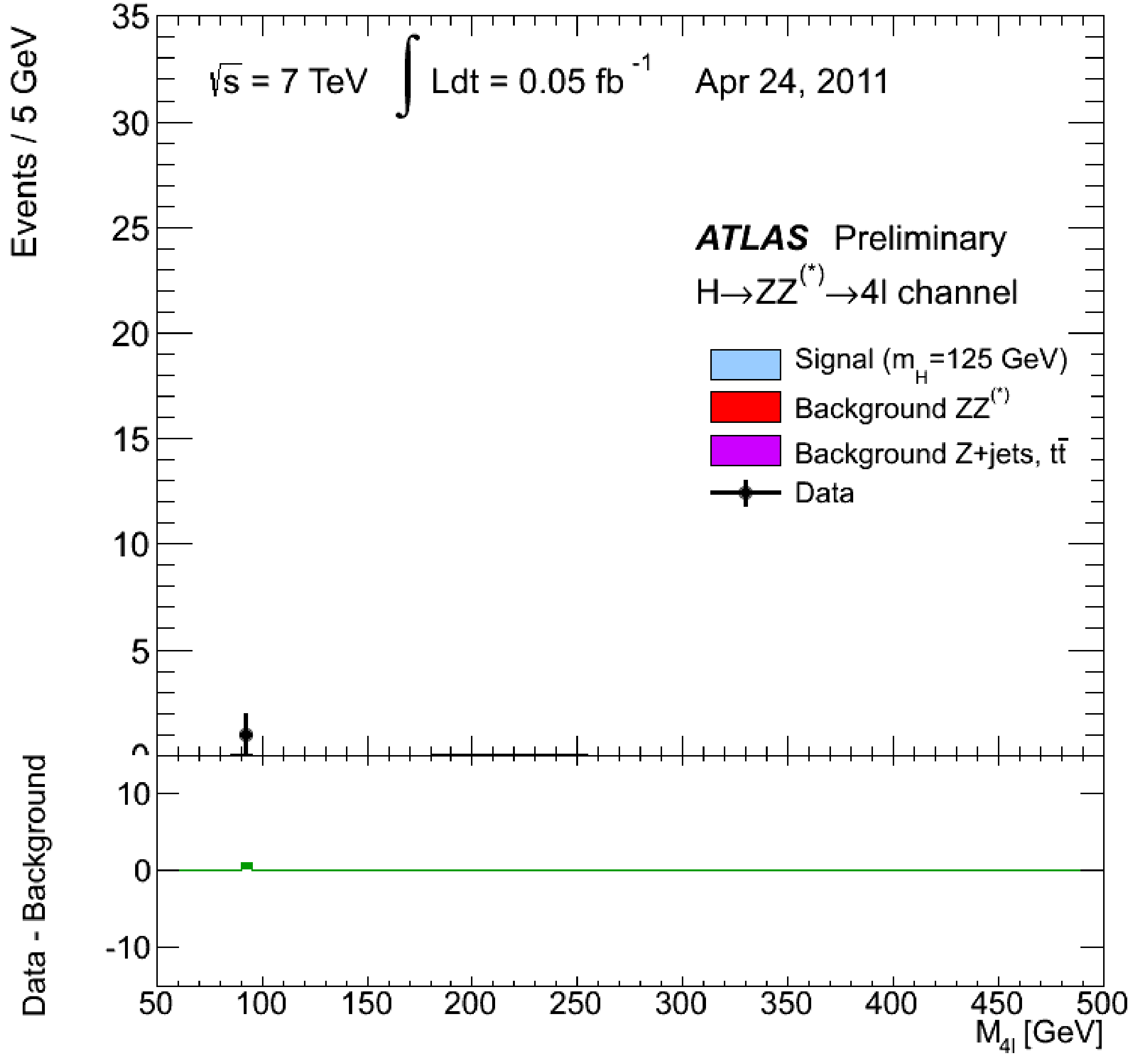
Evolution of the excess with time



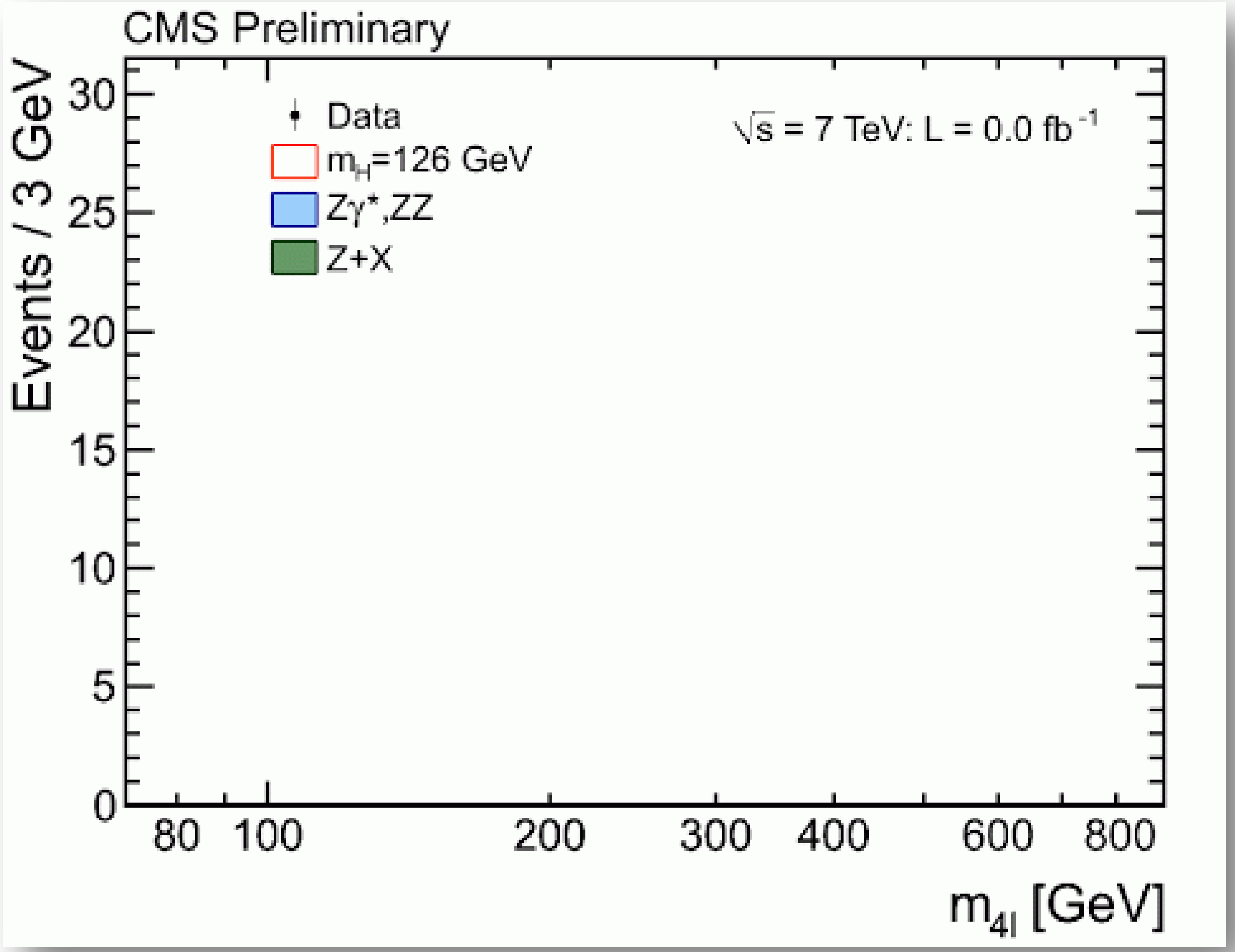
p_0= probability that the background fluctuates more than the observed excess



channel with good resolution (FWHM ~4 GeV) , large background

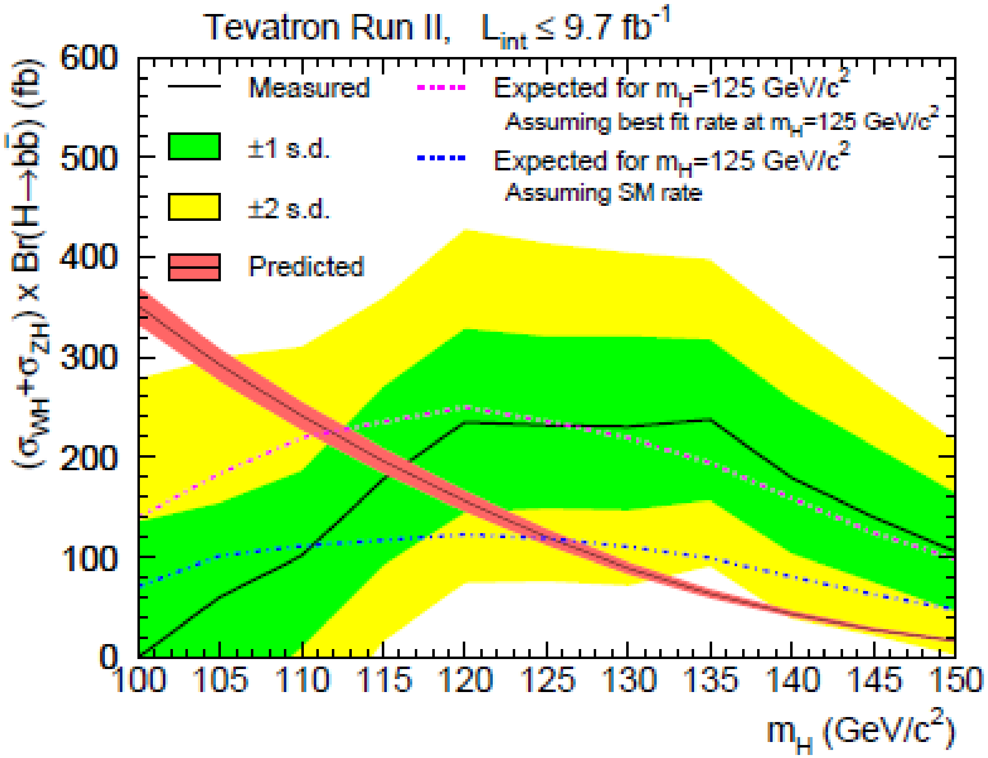


(similar) good resolution , small background


CMS Preliminary
Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
√s = 7 TeV: L = 0.0 fb -1
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m_4l [GeV]

(*Tevatron data (proton –antiproton √s =1.96 TeV) ended in september 2011*)

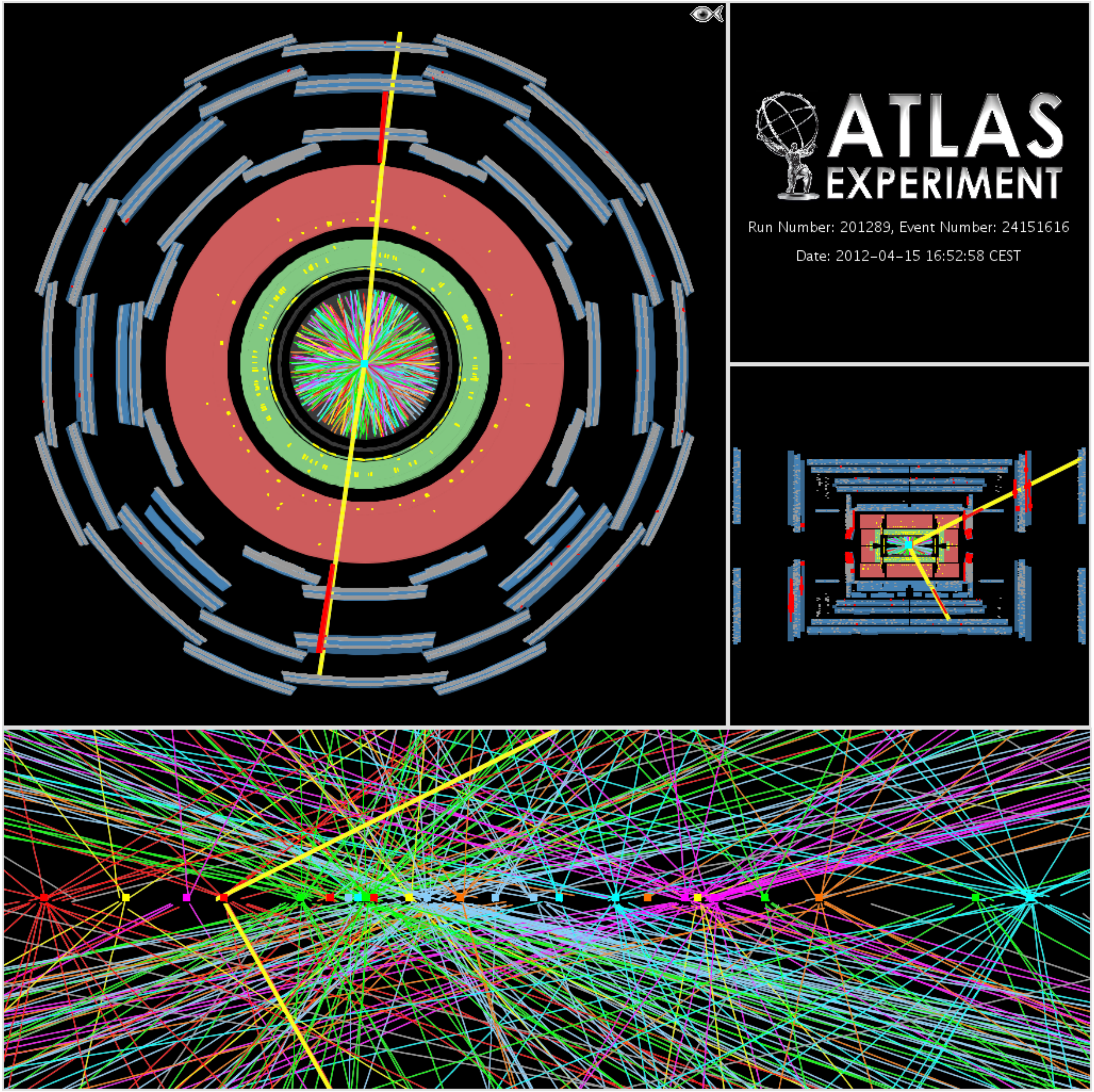
CDF and D0 (at Tevatron) have paved the way and brought sophistication and maturity into Higgs boson searches at hadron colliders



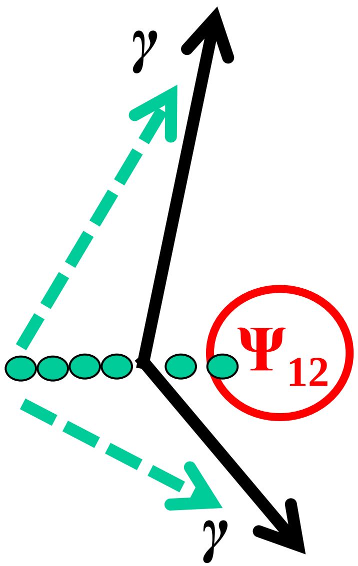
We combine searches by the CDF and D0 Collaborations for the associated production of a Higgs boson with a W or Z boson and subsequent decay of the Higgs boson to a bottom-antibottom quark pair. The data, originating from Fermilab Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, correspond to integrated luminosities of up to 9.7 fb^{-1}. The searches are conducted for a Higgs boson with mass in the range 100–150 GeV/c^2. We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 120 and 135 GeV/c^2. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations. We interpret this as evidence for the presence of a new particle consistent with the standard model Higgs boson, which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair.

Back to the description of the analysis …

H $\rightarrow \gamma\gamma$



Event display with a $Z \rightarrow \mu^+\mu^-$ with 25 reconstructed vertices recorded April 15th 2012



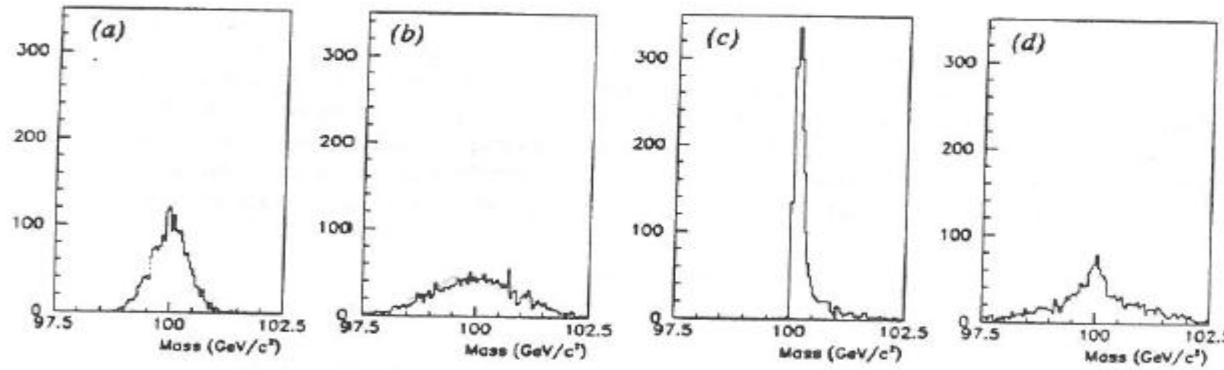


Figure 4: Reconstructed mass plots for Higgs boson, m_H=100GeV/c2
(a) smeared by: calorimeter energy resolution of $\Delta E/E=2\%/\sqrt{E}\oplus0.5\%$
(b) smeared by: calorimeter energy resolution of $\Delta E/E=7\%/\sqrt{E}\oplus1.0\%$
(c) smeared by: pileup energy from, on average, 10 interactions
(d) smeared by: loss of knowledge of the vertex position (σ_{vtx}=5.5 cm)

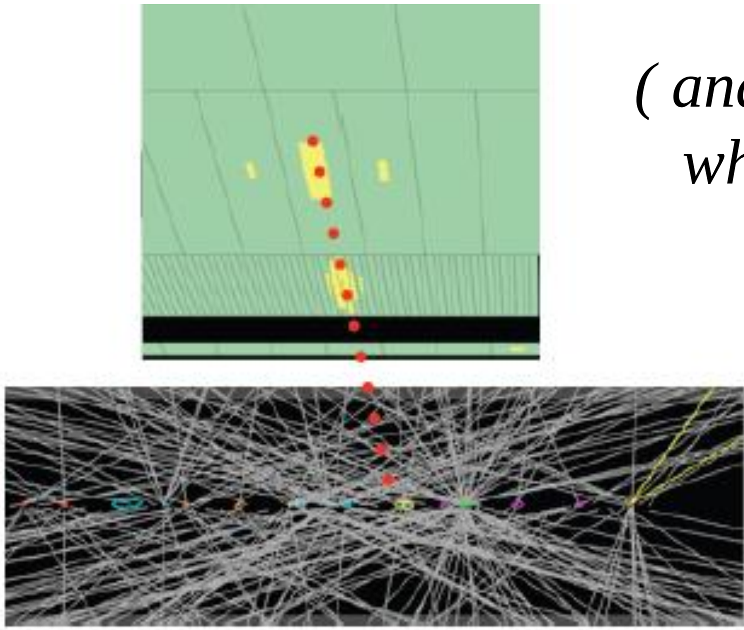
$$M^2 = 2\, E\gamma_1\, E\gamma_2\, (1 - \cos \Psi_{12})$$

A lot of vertex $\Rightarrow$ ***(if the wrong vertex is taken)***

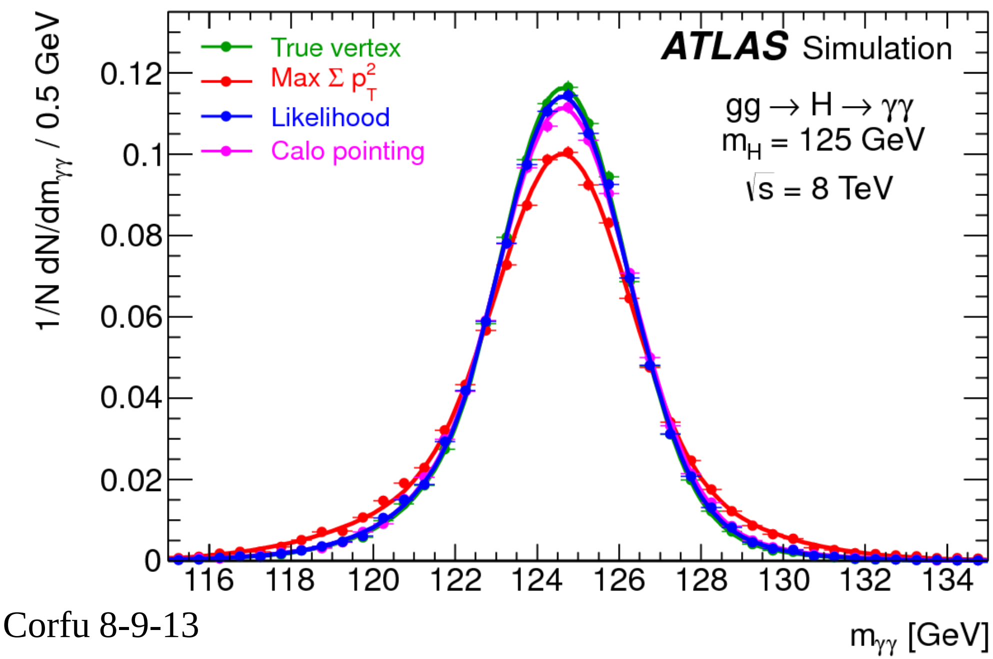
impact on Ψ_{12}

ATLAS : uses the longitudinal segmentation in order to get the vertex

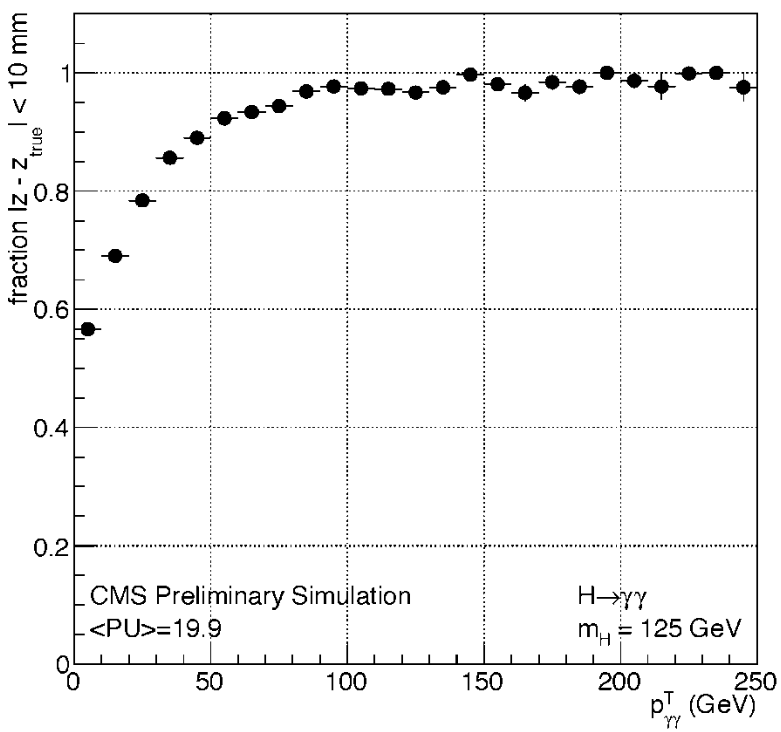
(and also the track conversion(s) when the photon is converted)

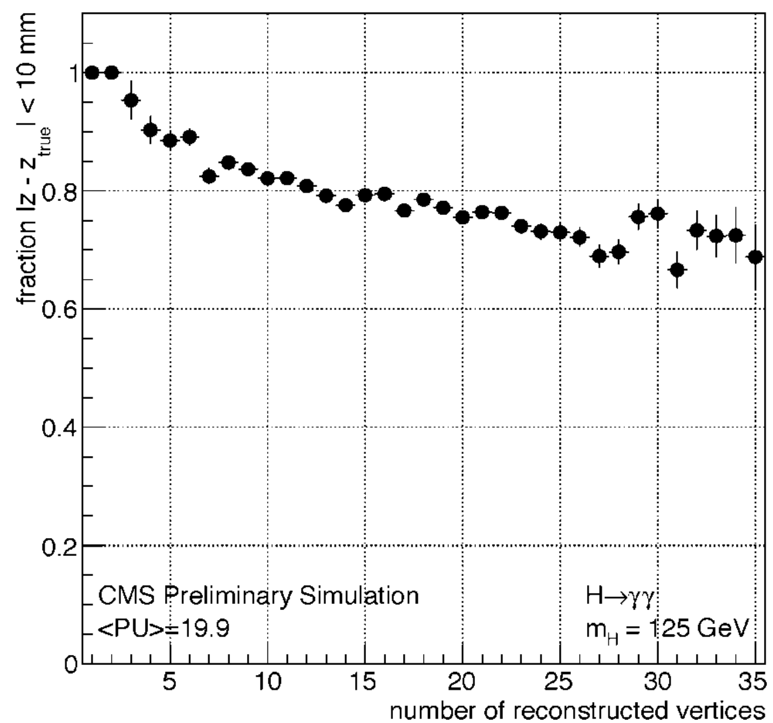


⇒ No degradation of the resolution

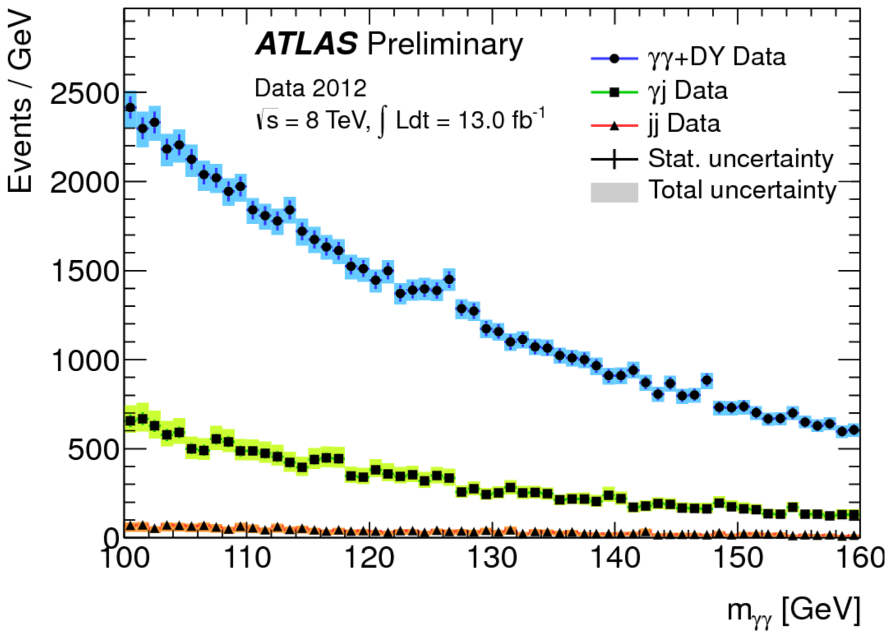


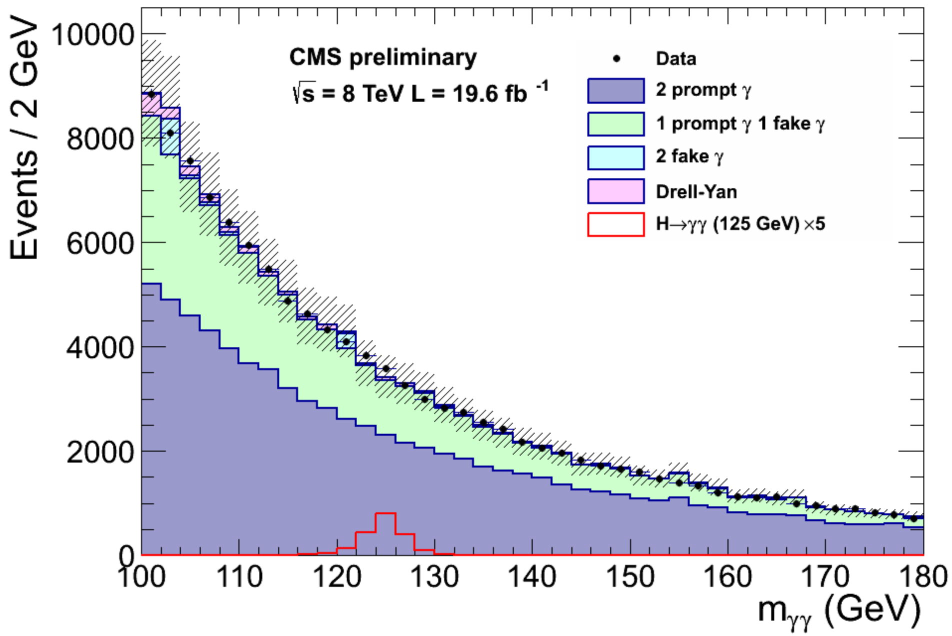
CMS : sophisticated kinematical cuts *(and the conversions)* in order to get 'the' vertex





Fraction of 'good' vertices

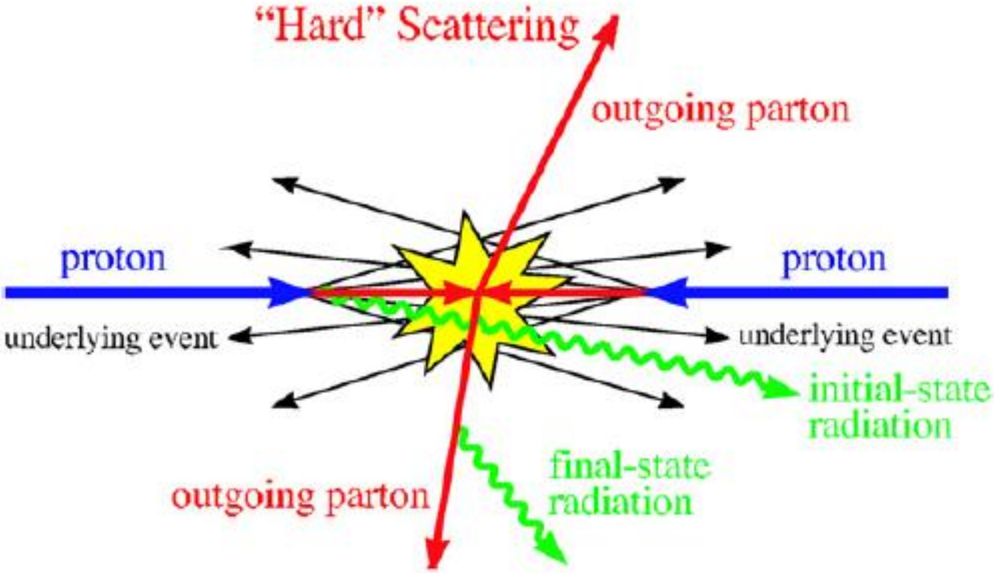




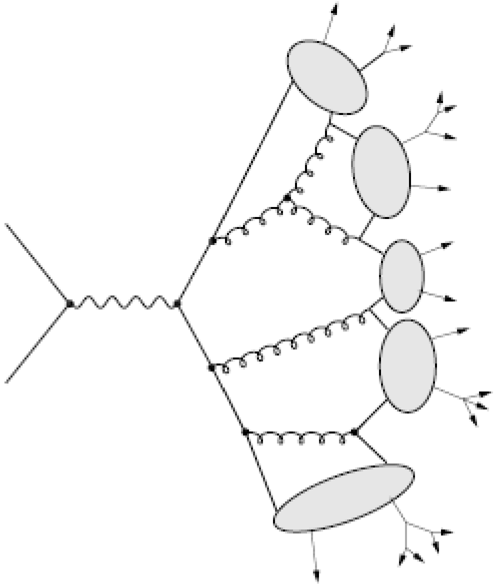
large (non photon) background

due to jets fragmenting mainly into π^0 's

background 'photon candidates' coming from jets are less isolated than real photons



too schematic

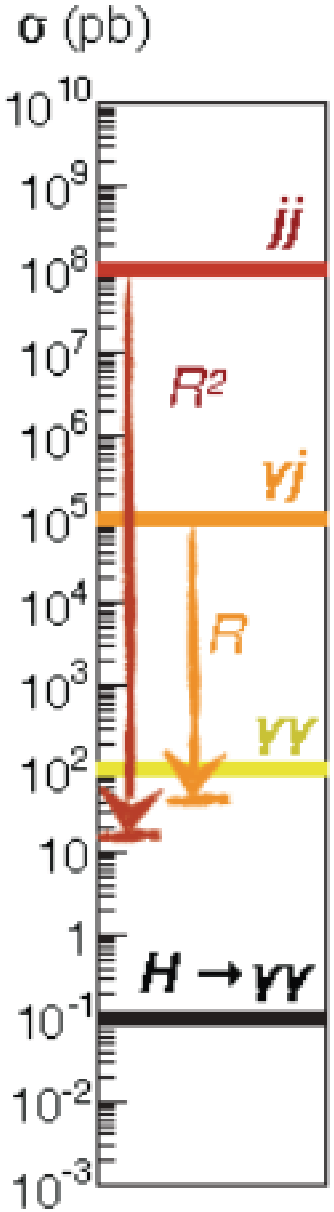


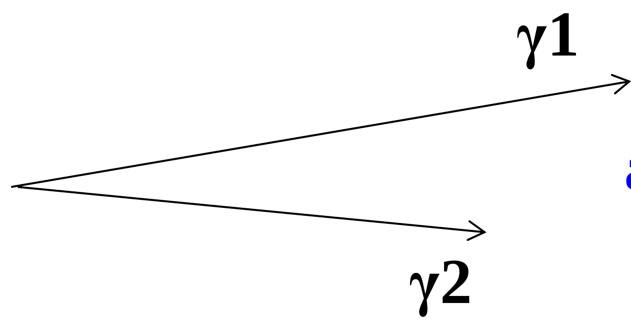
Connection between jets

jet definition is very complicated

γ/π^0 discrimination

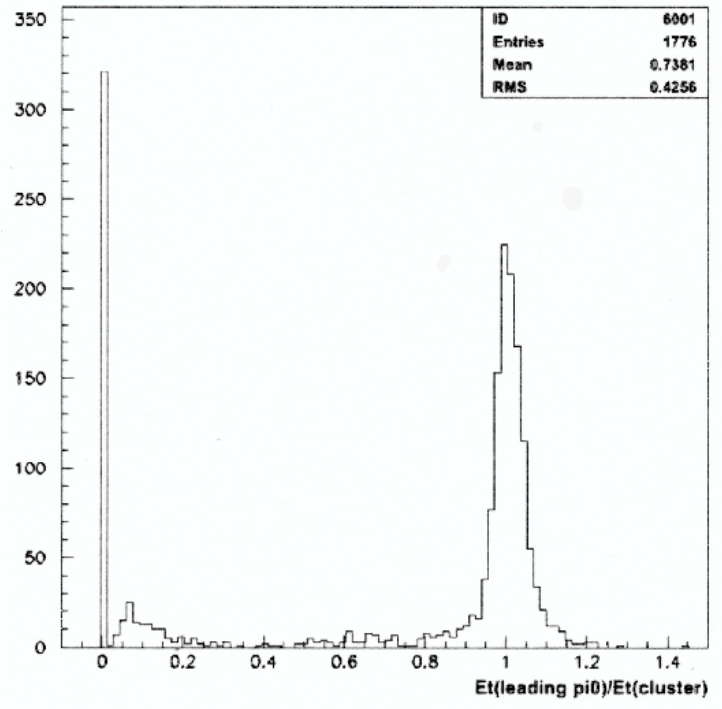
$R_j \sim 10^4$
$\varepsilon(\gamma) \sim 90\%$



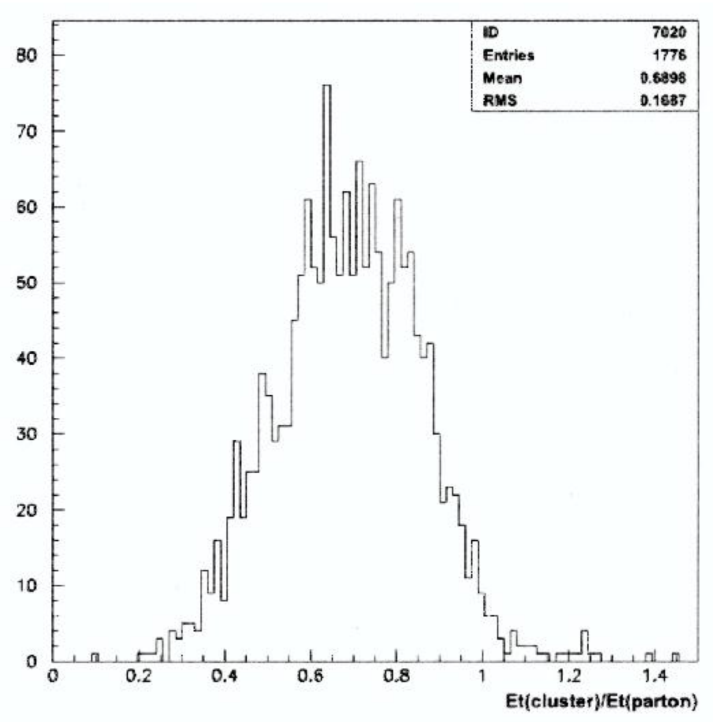


$\pi^0 \rightarrow \gamma 1\ \gamma 2$

angle between γ1 and γ2 $\geq\ 2\, m(\pi^0) / p_T(\pi^0)$



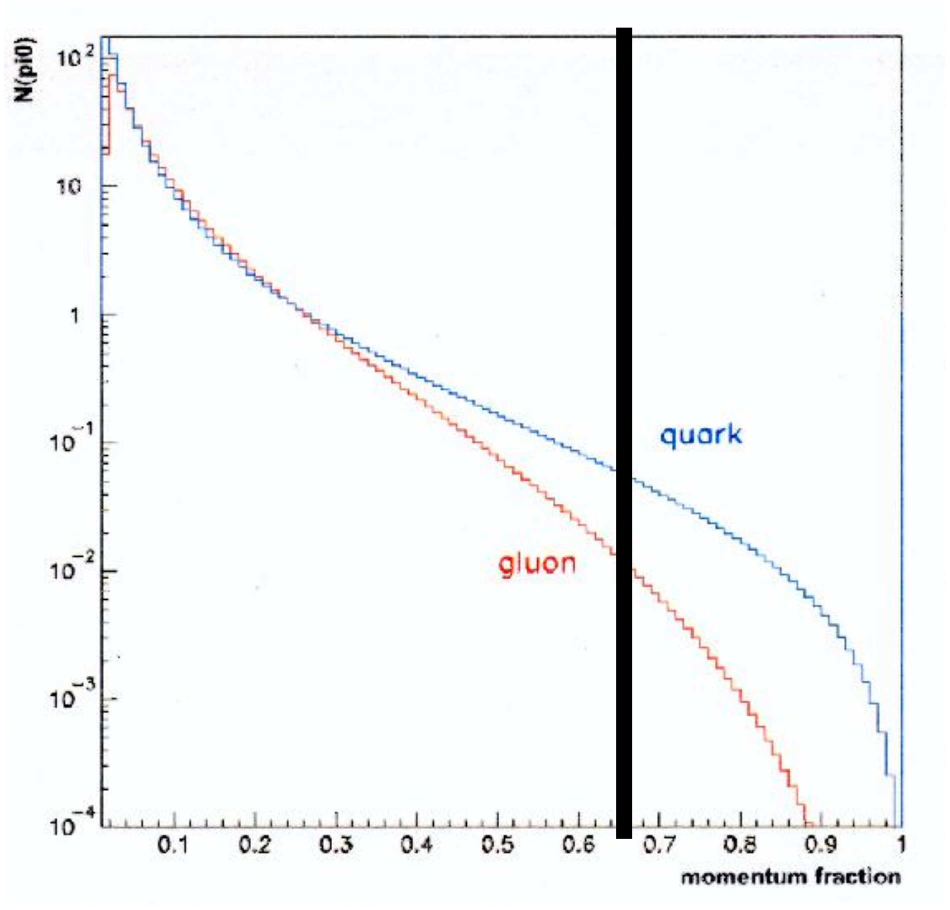
after the analysis cuts the reconstructed electromagnetic cluster is mainly the π^0



However the cluster (or the π^0) does not take the whole energy of the jet

$\Rightarrow$ Isolation is an important discriminating variable

fragmentation functions

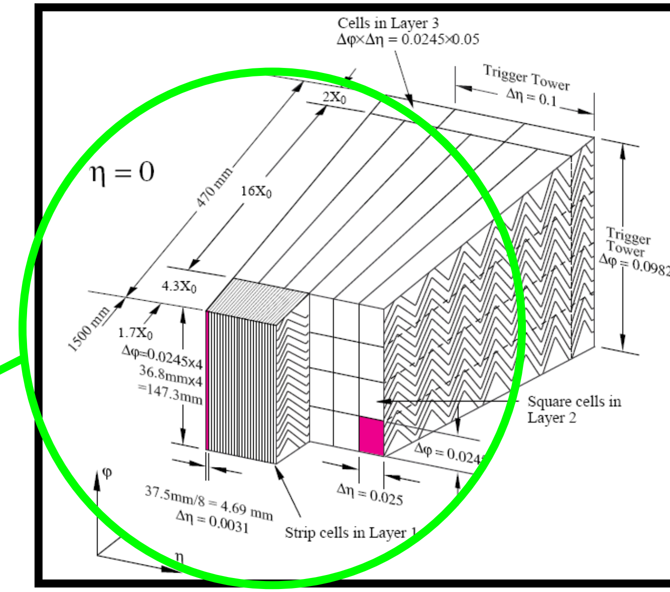


Rejection better for gluon jets than for quark jets

QCD (DGLAP)splitting function $g \rightarrow gg \sim 9/4 \quad q \rightarrow qg$

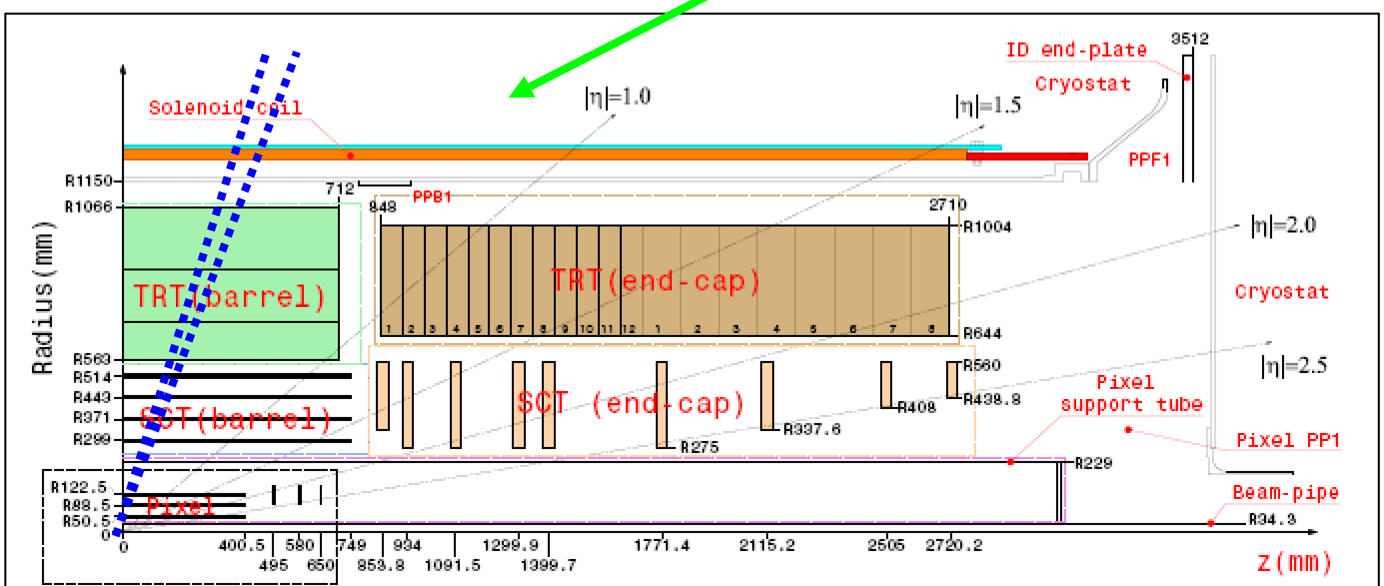
♦ **good jet rejection essential (to reduce γj and jj backgrounds)**

The granularity of the electromagnetic ATLAS detector is very useful to reject the π^0 bakground



opening of photons coming from a π^0 (p_T=40 GeV)

$\Delta R > .007$

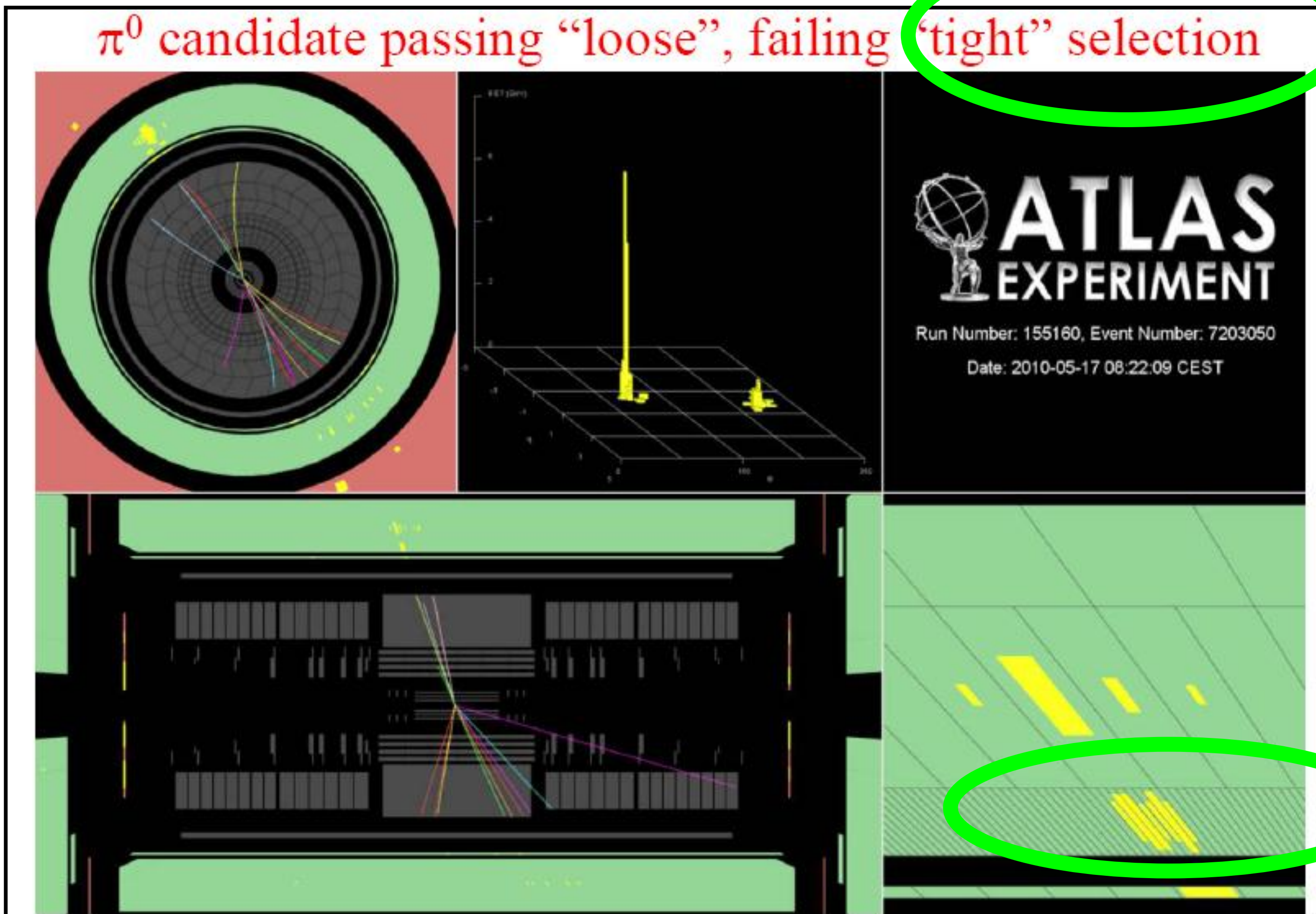


granularity of 1st sampling of calorimeter

$\Delta\eta \sim .003$

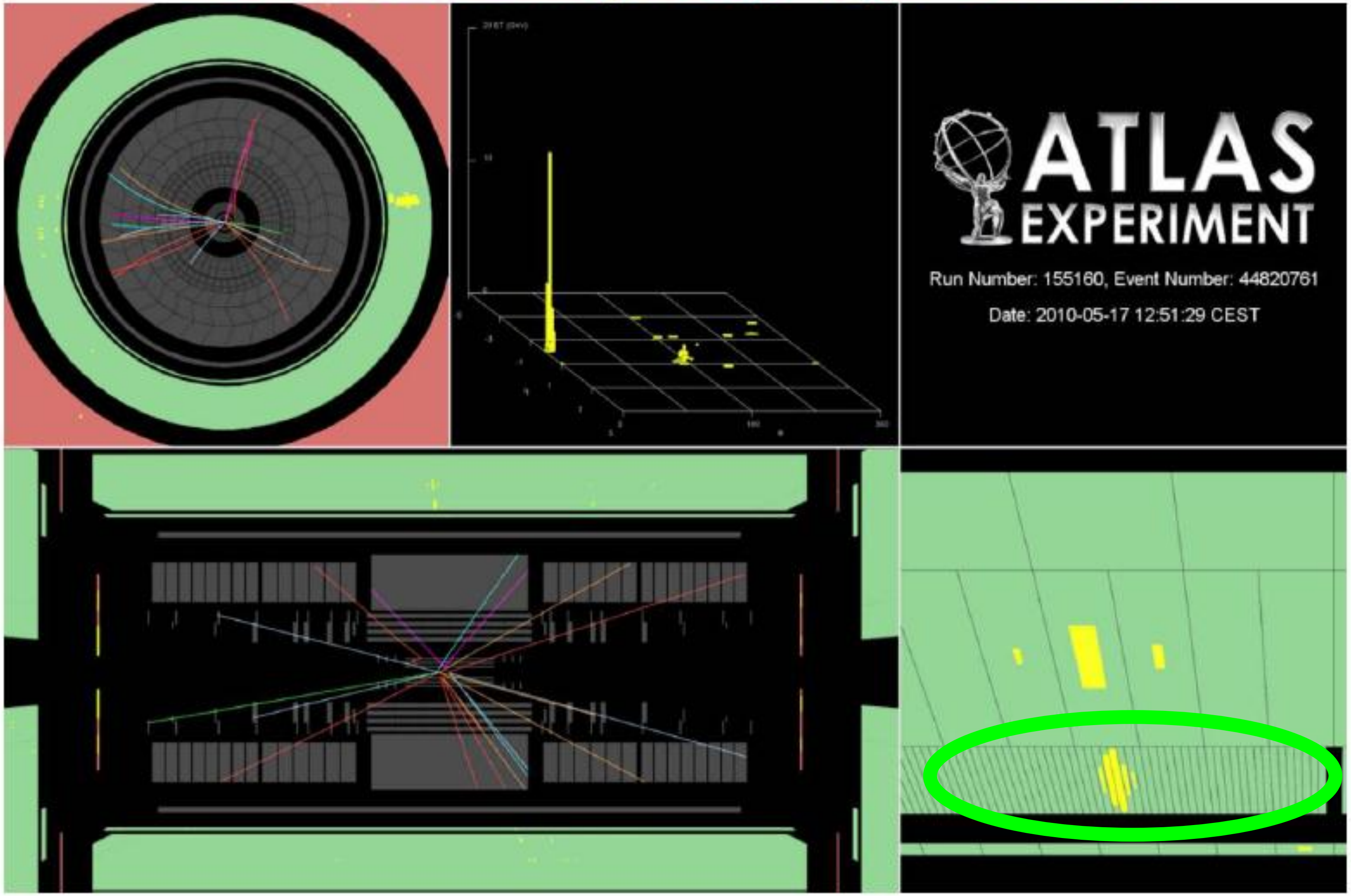
Photon identification with shower shapes

reminder: opening angle between the two photons of a π^0 of p_T =40 GeV ***is > 0.007 to be compared with size of strip calo 1st sampling ~0.003***



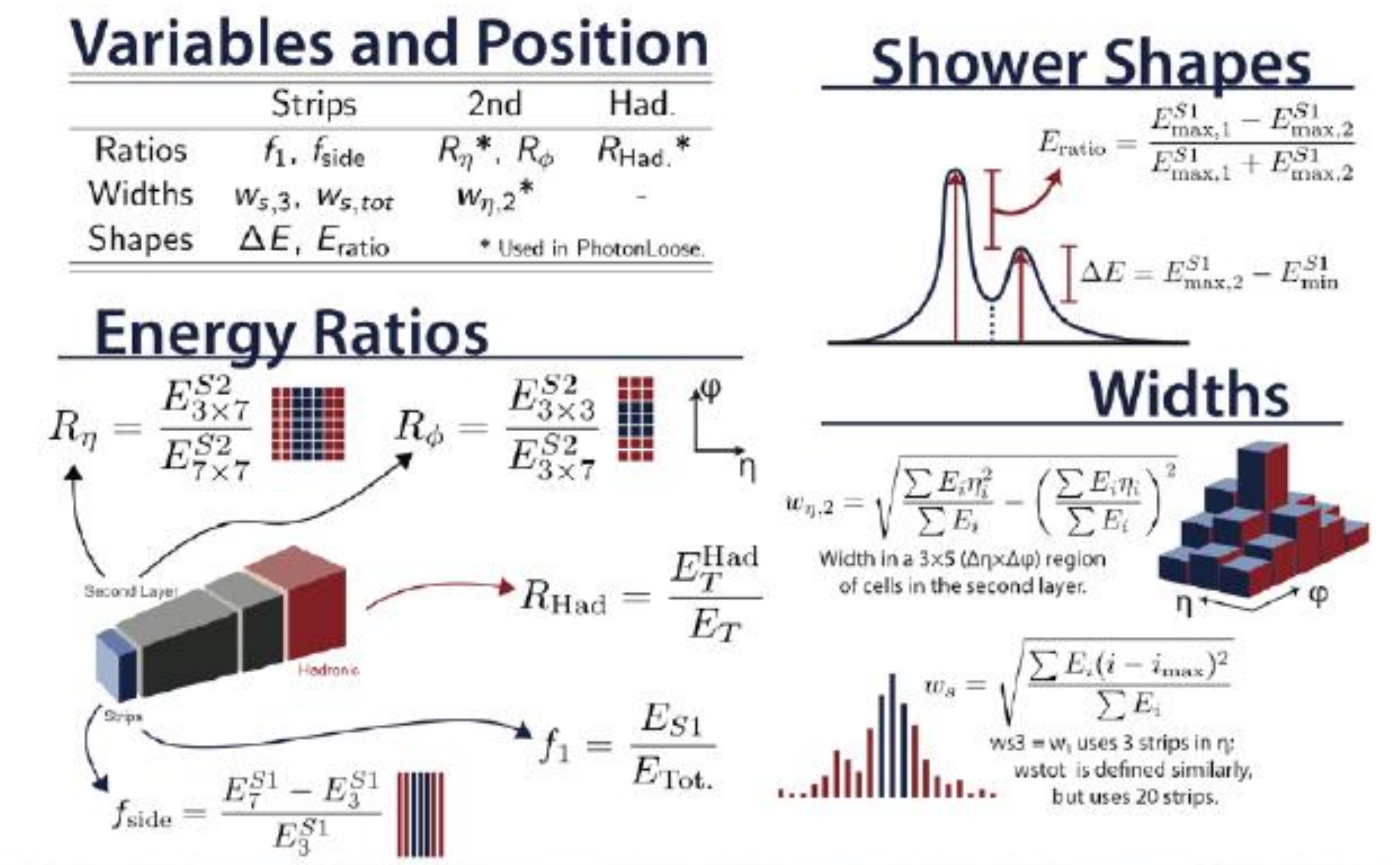
tight selection uses mainly calo 1st sampling

Photon candidate passing "tight" selection



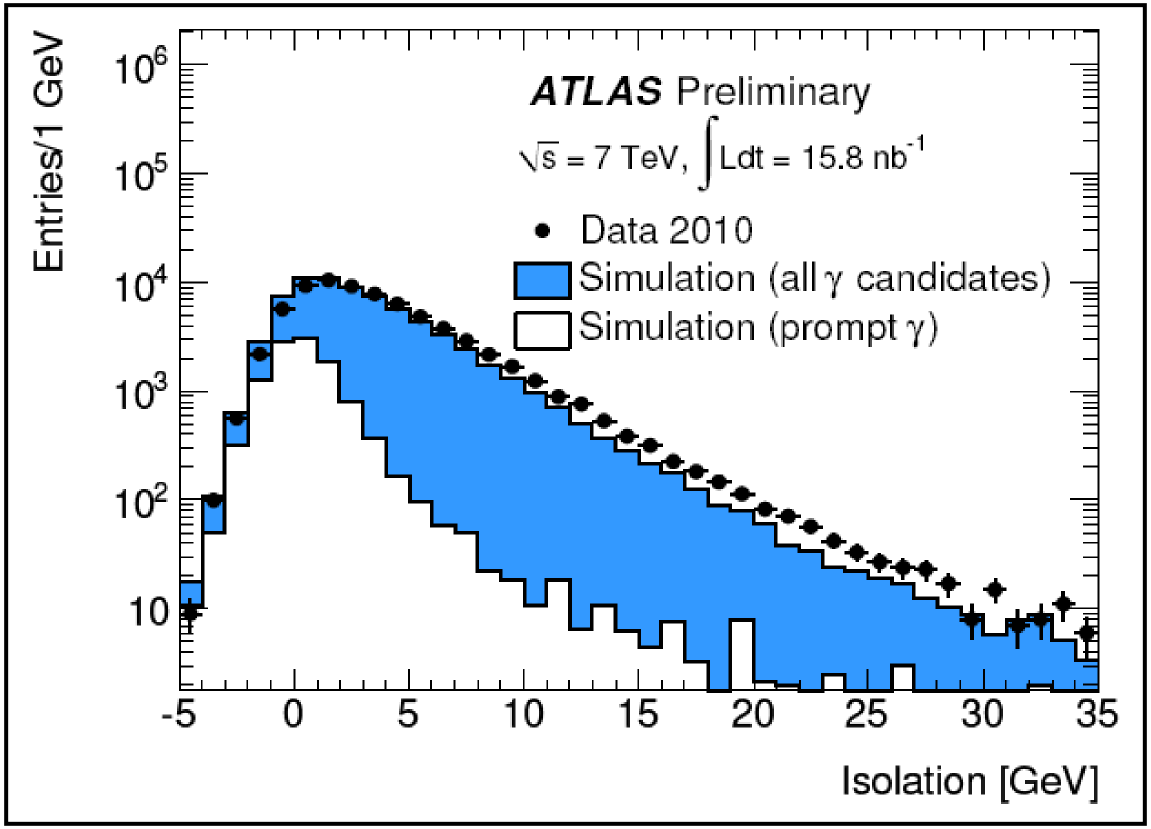
Nice shape in first sampling of EM calormeter

Graphical representation of shower shape variables used in the ATLAS photon identification:



Digression on background estimation (and purity estimation)

Important discrimination variable is isolation variable



isolated

non isolated

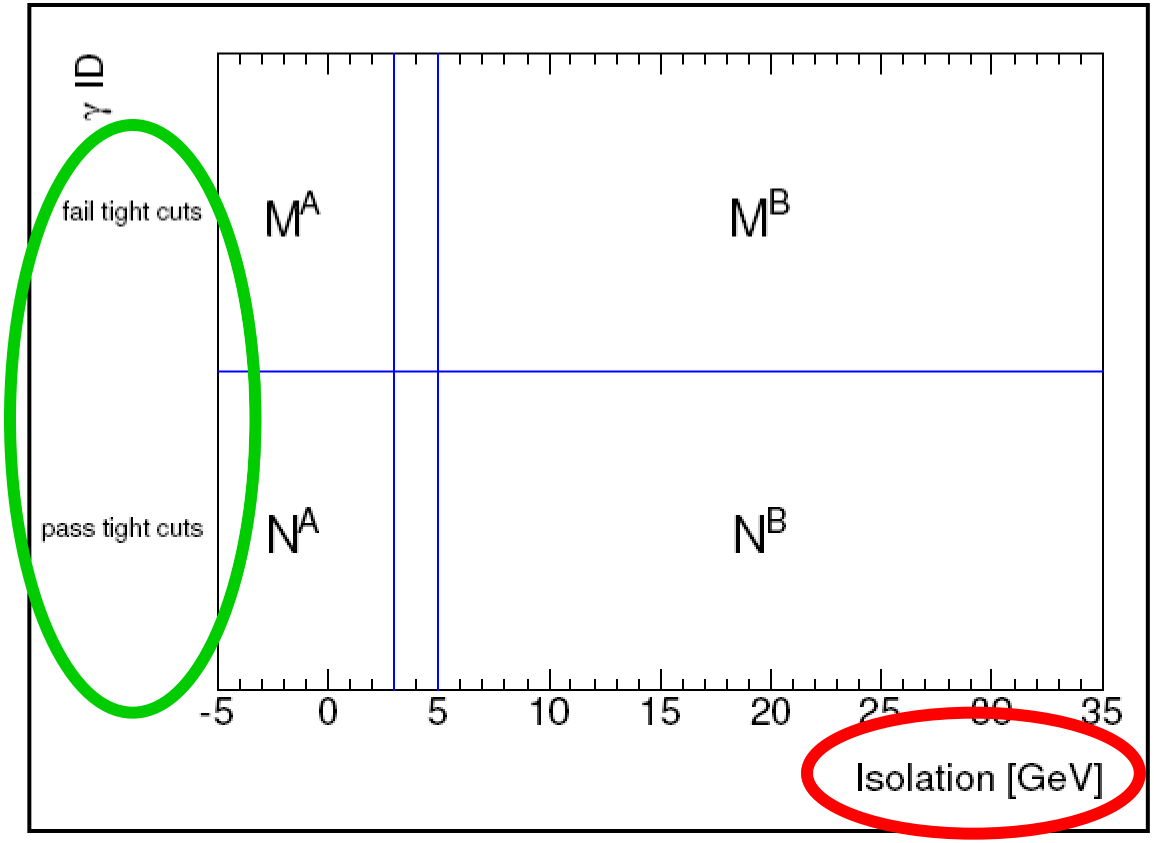
keyword *(pedantic)* ***in the LHC experiments***

data driven background estimation

I will give an example below with photons

It is a way to compute the background trying to use *as less as possible* ***the simulation (which may not be correct)***

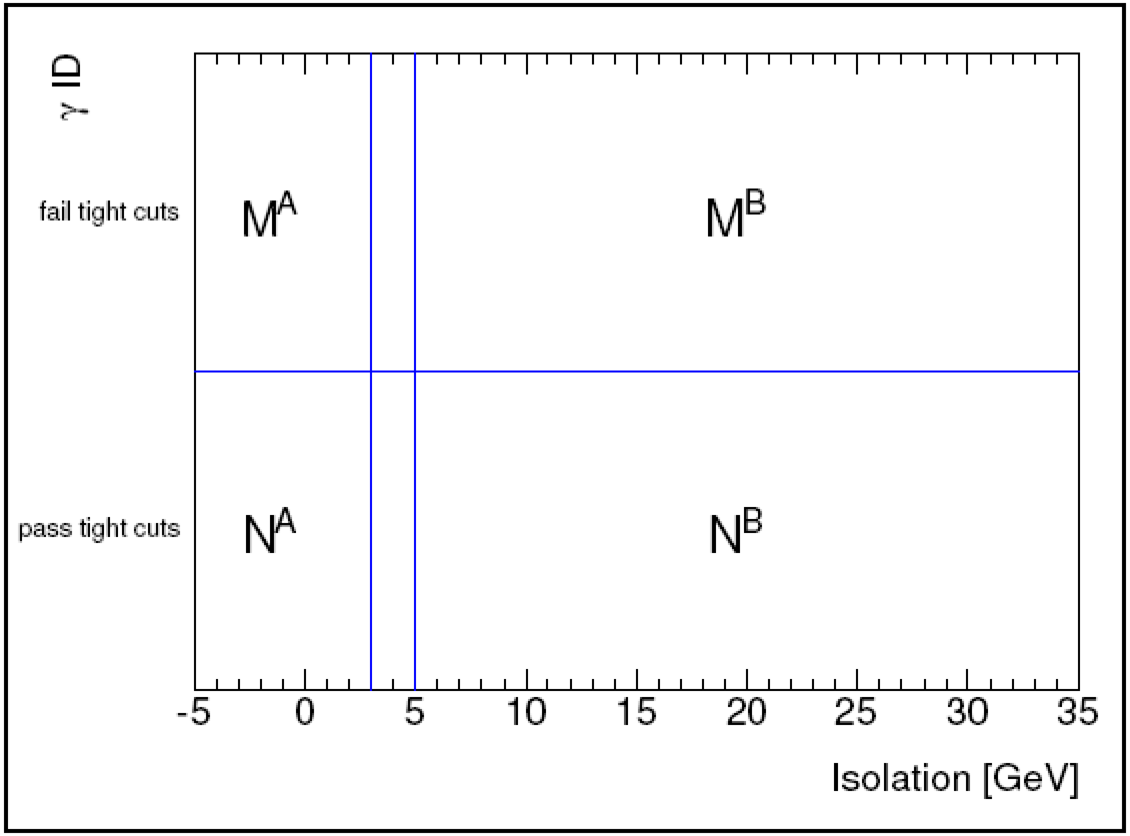
Signal and purity extraction



We define cuts on isolation and on shower shape variables in the electromagnetic calorimeter such that the γ signal will concentrate in N^A where the background (of π^0) will be small (but not zero)

The background is present everywhere

Signal and purity extraction



we suppose the γ signal is only in N^A and the background is everywhere

we suppose also that the isolation is the same for tight and non tight events for background events

$N^A/N^B = M^A/M^B$

i.e the 2 variables are not correlated

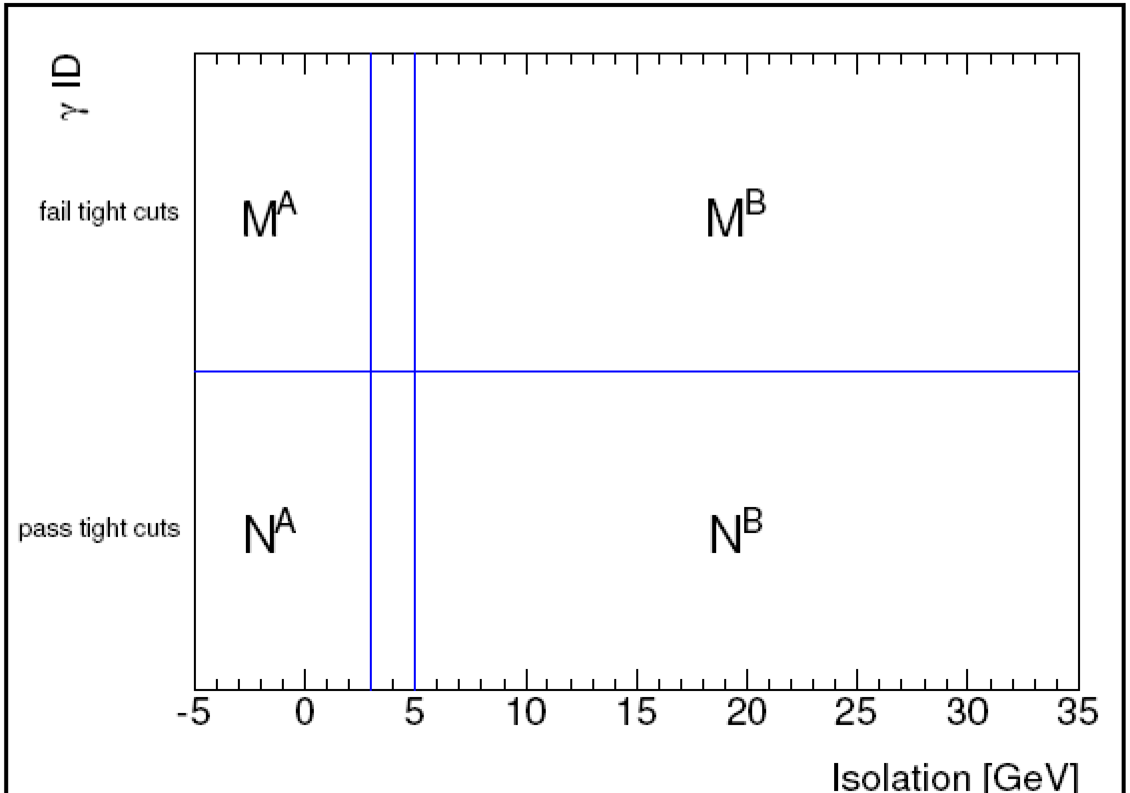
$$N^A_{\mathrm{sig}} = N^A - N^B \frac{M^A}{M^B}$$

$$P = 1 - \frac{N^B}{N^A}\frac{M^A}{M^B}$$

approximate formula

ABCD method « data driven »

Signal and purity extraction

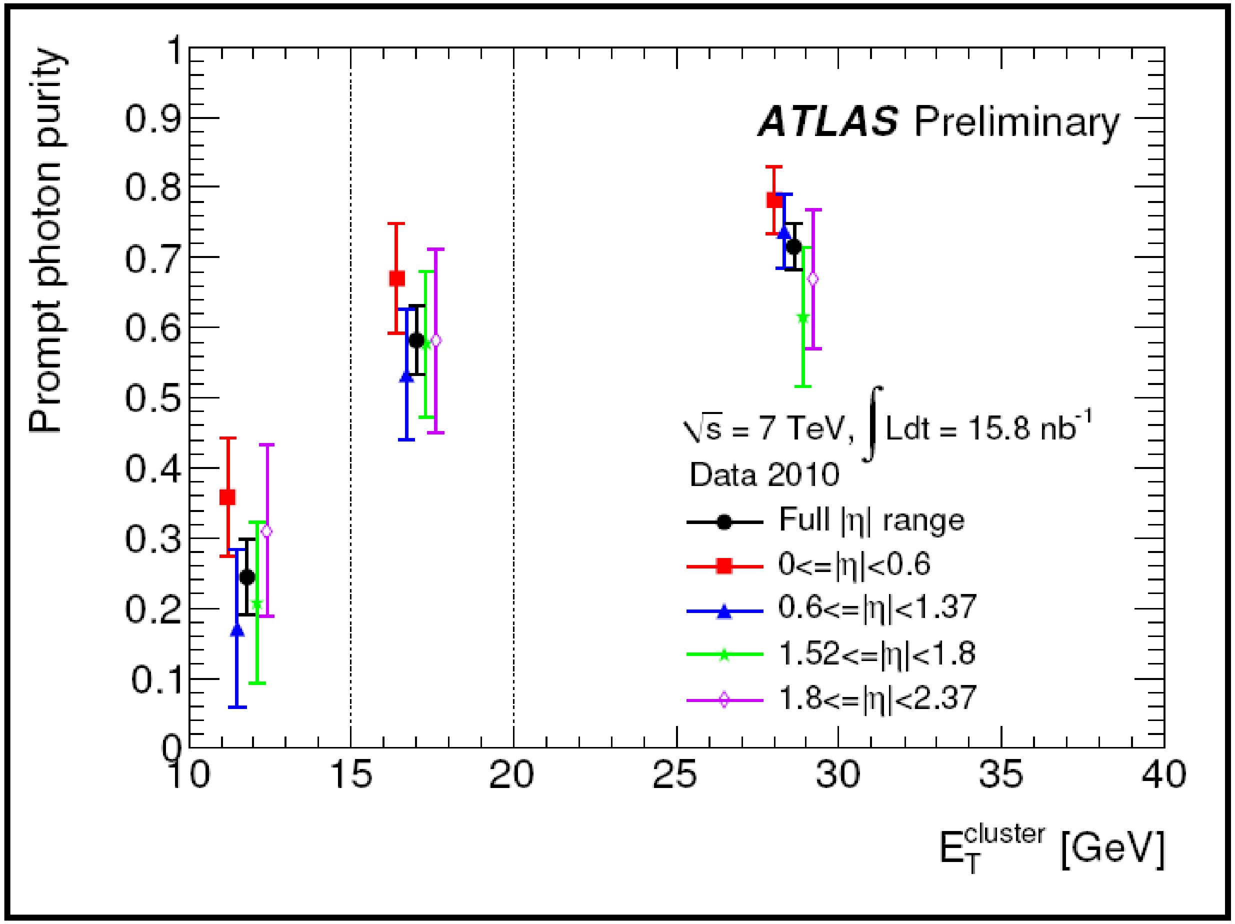


Modified ABCD method → needs Monte-Carlo to *extrapolate* (sometimes in a *non trivial* way)

better formula

$$N_A^{\text{sig}} = N_A - \left[\left(N_B - c_{\text{B}} N_A^{\text{sig}}\right) \frac{\left(N_C - c_{\text{C}} N_A^{\text{sig}}\right)}{\left(N_D - c_{\text{D}} N_A^{\text{sig}}\right)}\right] \left(\frac{N_A^{\text{bkg}}}{N_B^{\text{bkg}}} \frac{N_D^{\text{bkg}}}{N_C^{\text{bkg}}}\right)$$

$$P = \frac{N_A^{\text{sig}}}{N}$$



ATLAS-CONF-2010-077

If one makes a mistake in the extrapolation giving the background then the estimation of the signal will be wrong

The previous method was supposing that the extrapolation of the background in data was given by some (other) data

Sometimes the extrapolation cannot be done with data and it is done through this formula

$$N_{data}^{S.R.} = \alpha \times N_{data}^{C.R.}, \qquad \alpha = \frac{N_{MC}^{S.R.}}{N_{MC}^{C.R.}}$$

S.R = Signal Region

(what we want to know)

CR = Control Region

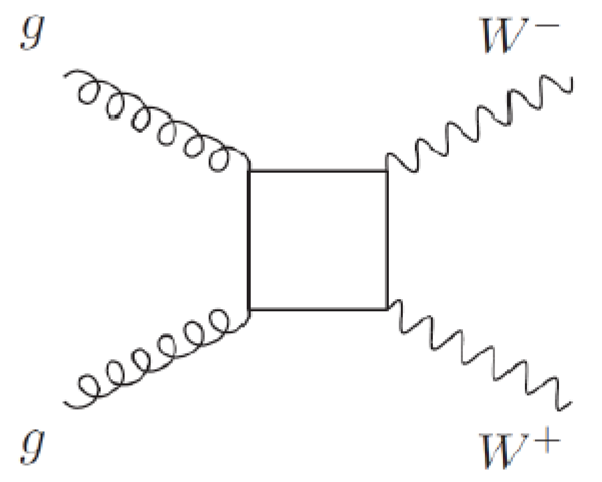
(the 'measured' input)

But be careful !

E.James HH2011

Also need to concern oneself about potential background events in odd regions of phase space that could mimic a Higgs signal

Classic example is WW production through box diagram (small Tevatron cross section but events are more signal-like)

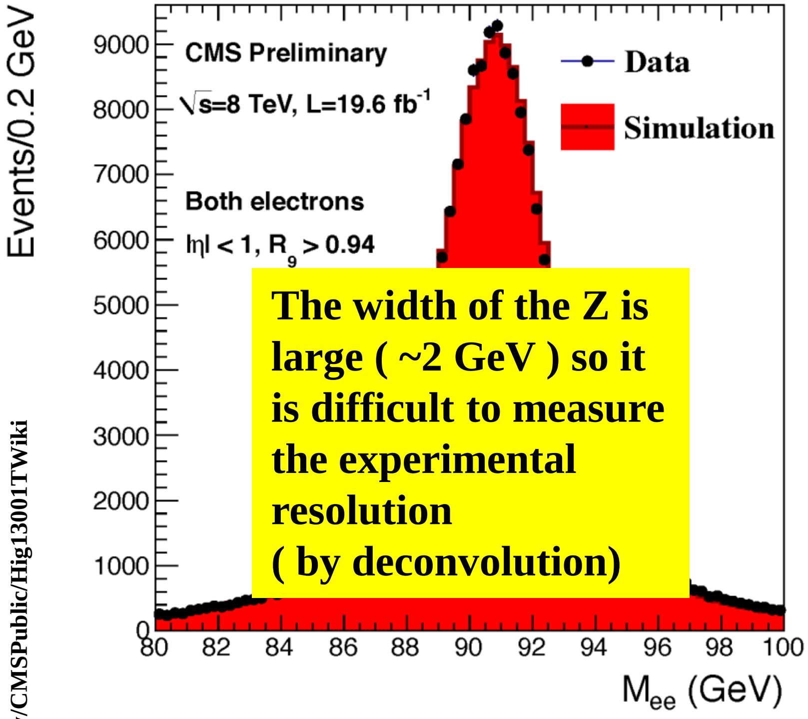


Back to (***energy*** **,** ***mass*** **) resolution**

We do not have pure (with fixed energy/mass) photons (except from $Z \rightarrow e\ e\ \gamma$ $Z \rightarrow \mu\ \mu\ \gamma$)

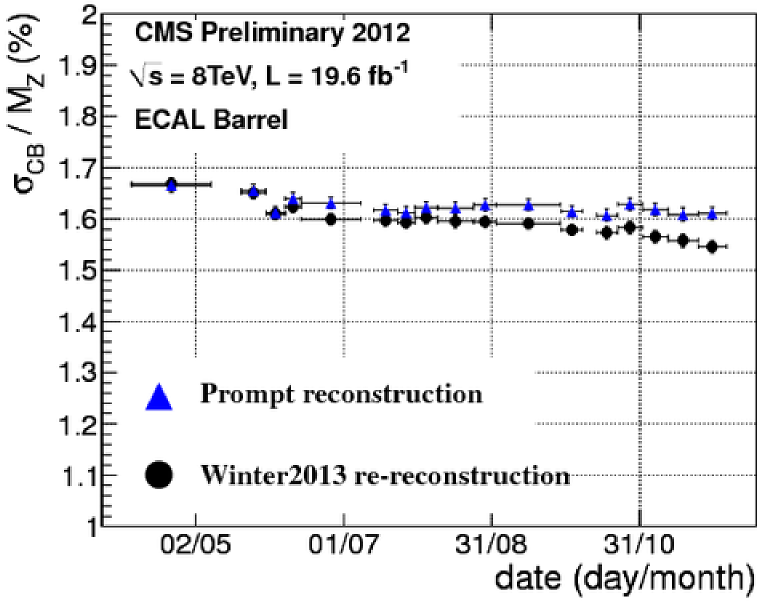
$\Rightarrow$ use e from $Z \rightarrow e\ e$

Reminder (transparency already shown) :



The width of the Z is large (~2 GeV) so it is difficult to measure the experimental resolution (by deconvolution)

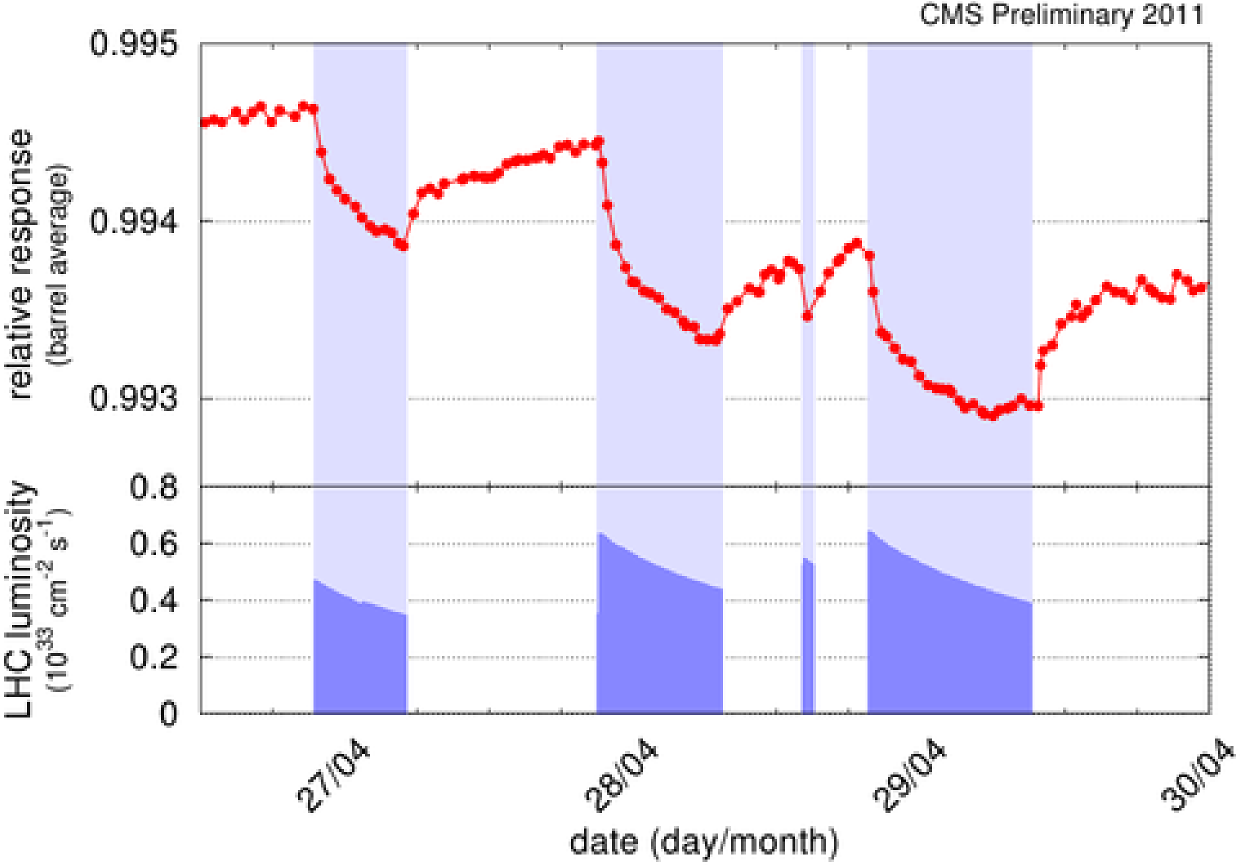
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13001TWiki



CMS-DP-2013/007

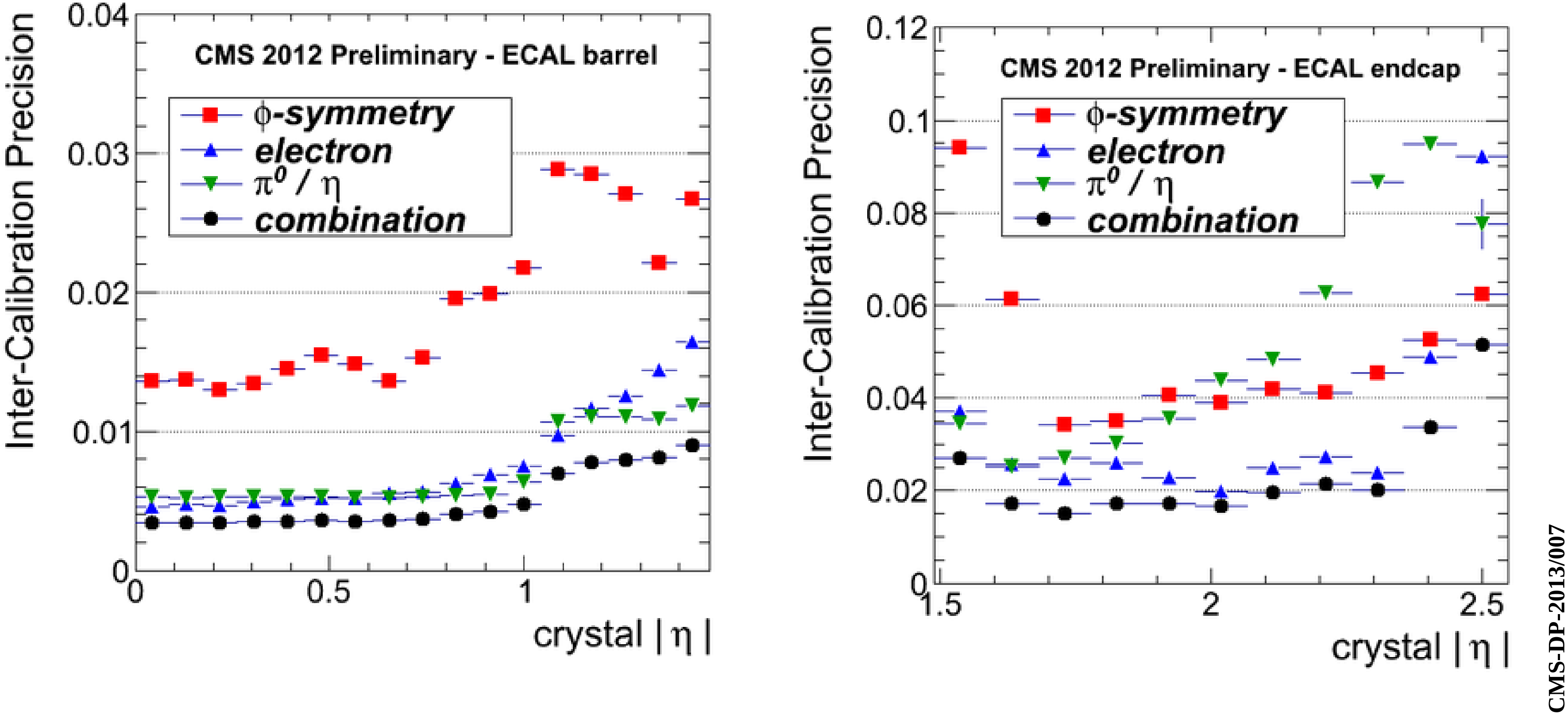
Validation and tests with Z → ee

the energy (and the response) of γ from H→ γγ is different from the energy (and response) of e from Z→ ee

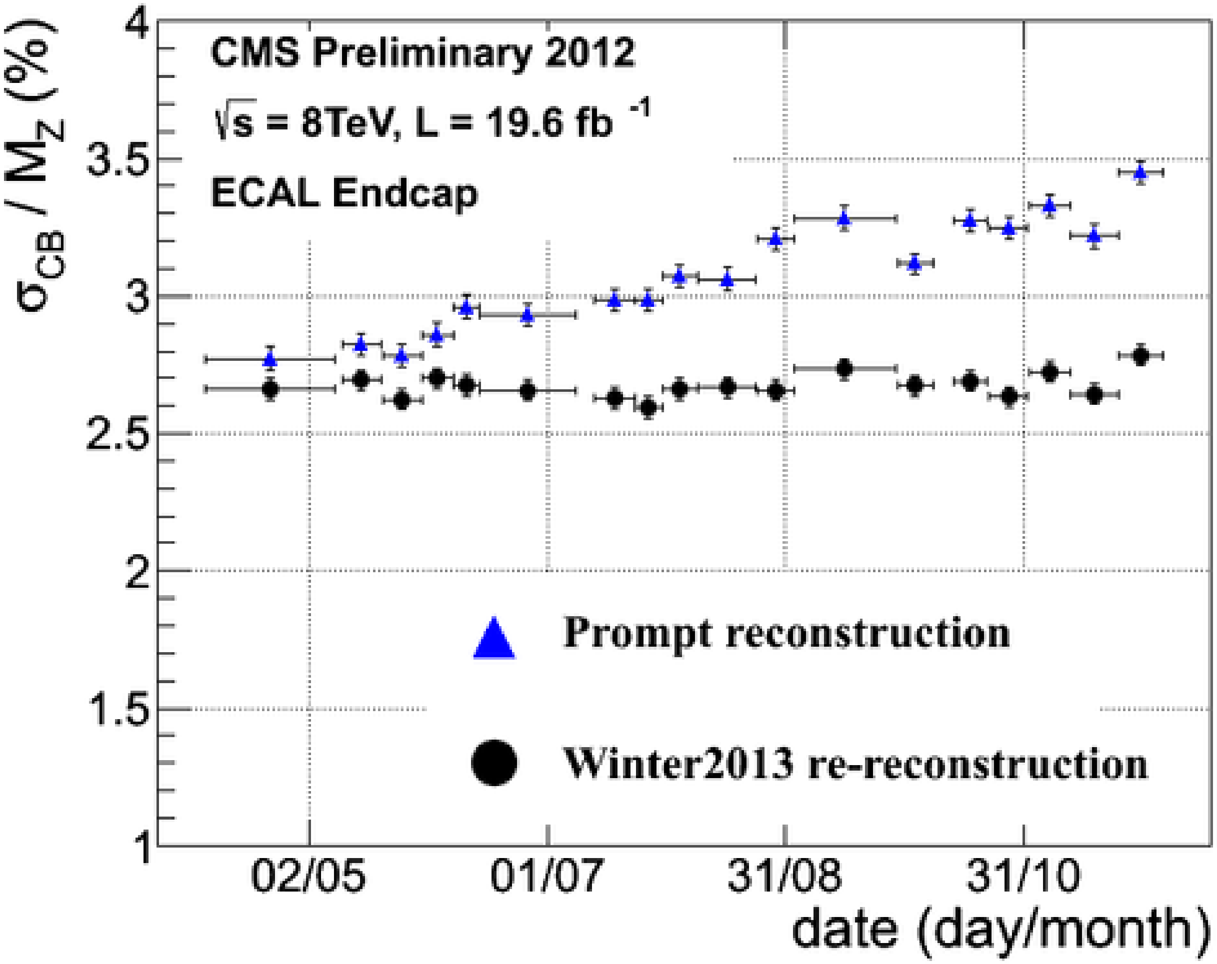


CMS-DP-2013/007

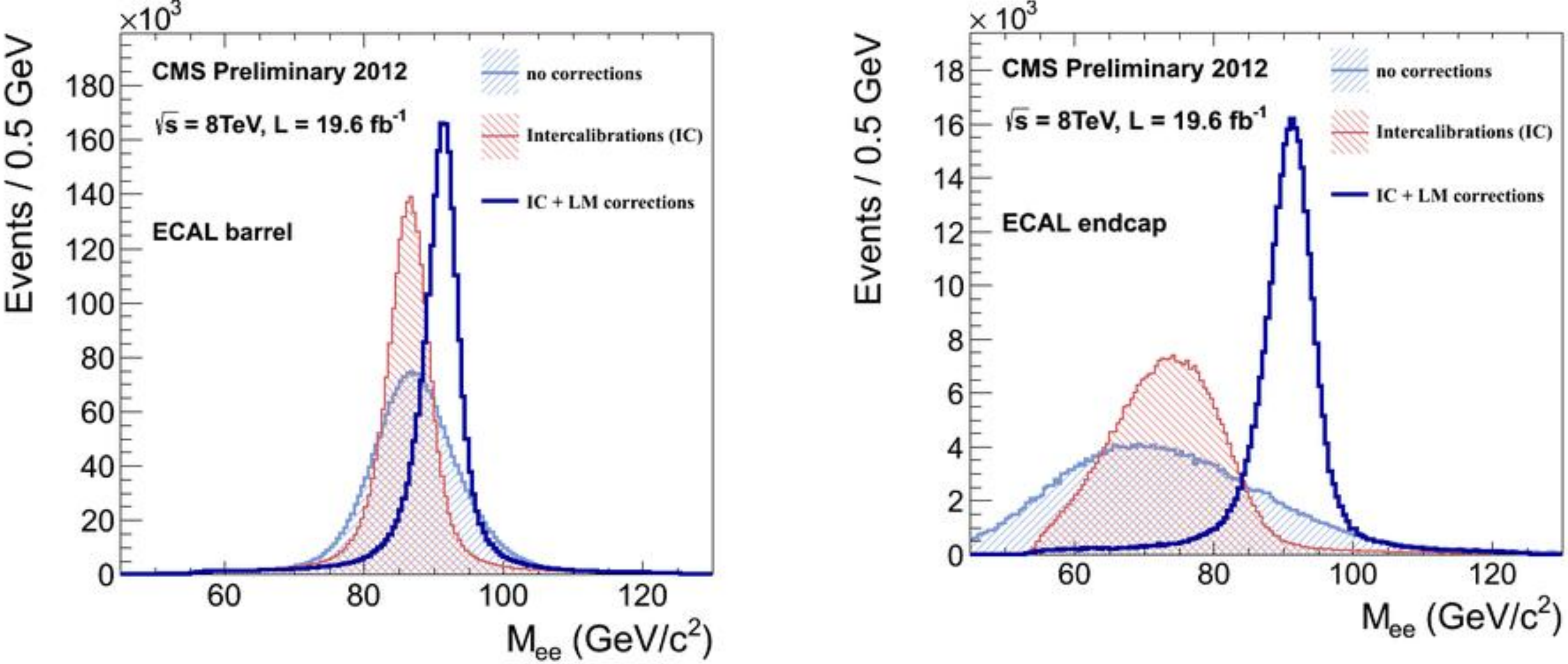
loss in a fill and recovery in interfill



2012 intercalibration precision

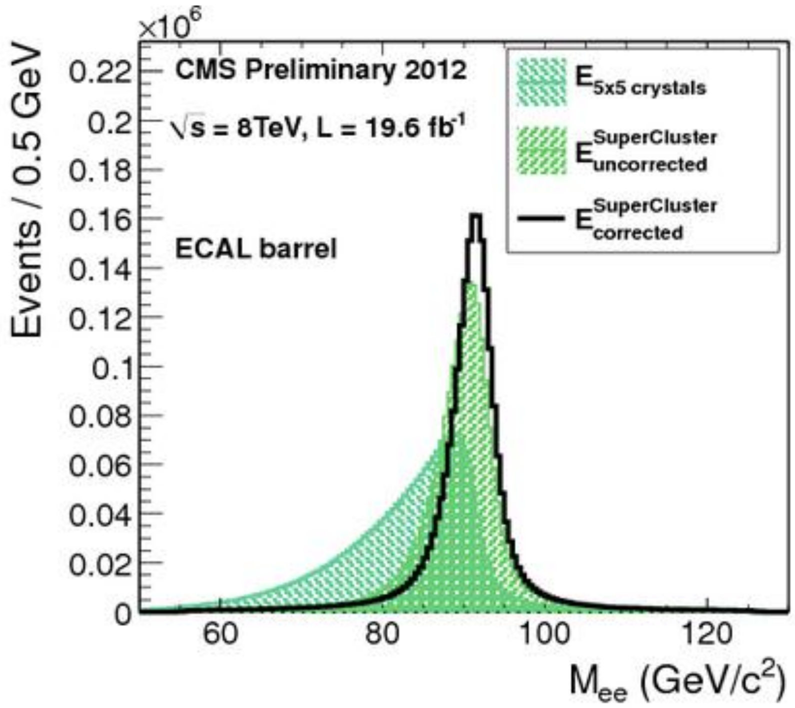


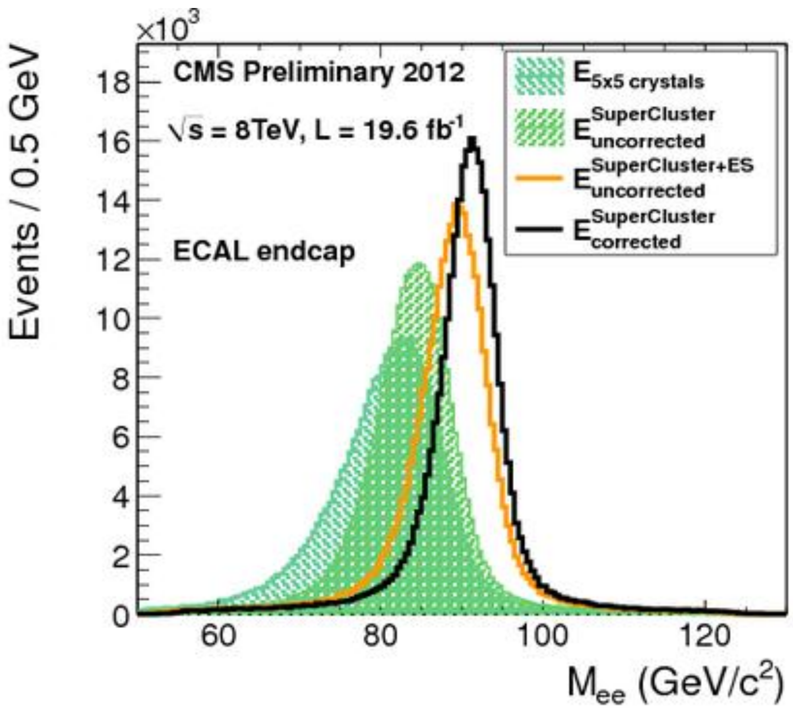
CMS-DP-2013/007



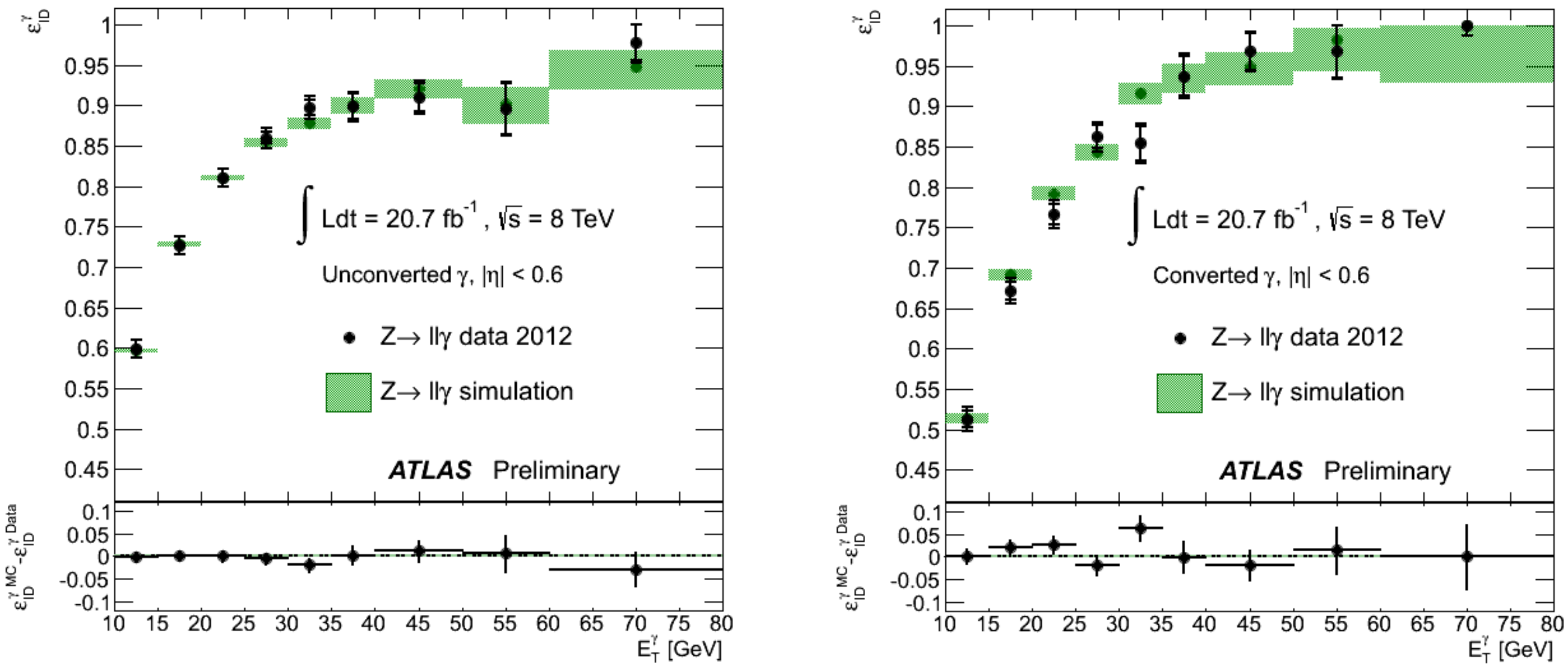
CMS-DP-2013/007

energy scale corrections



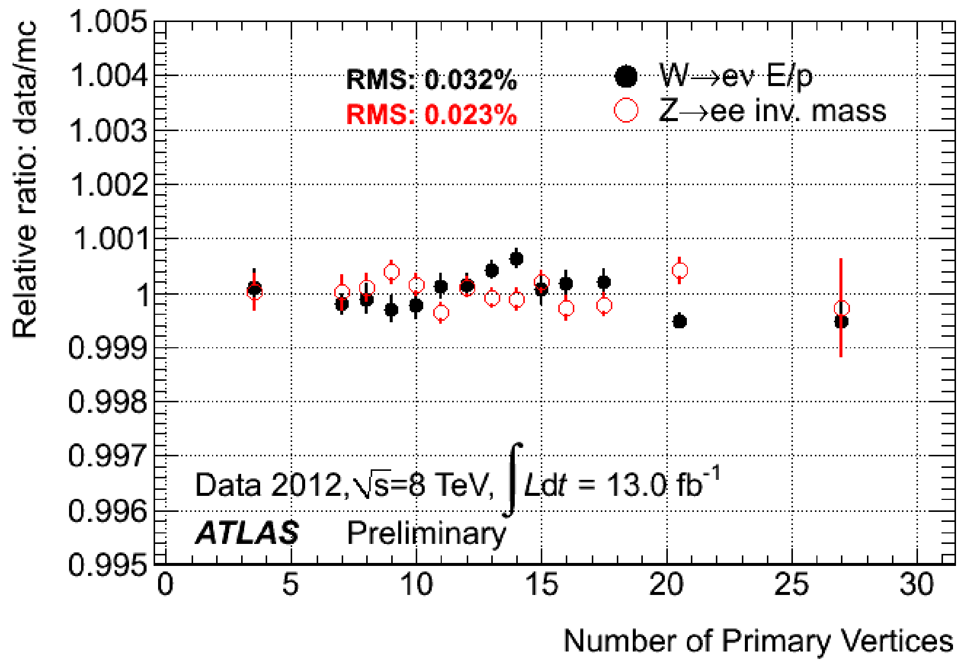


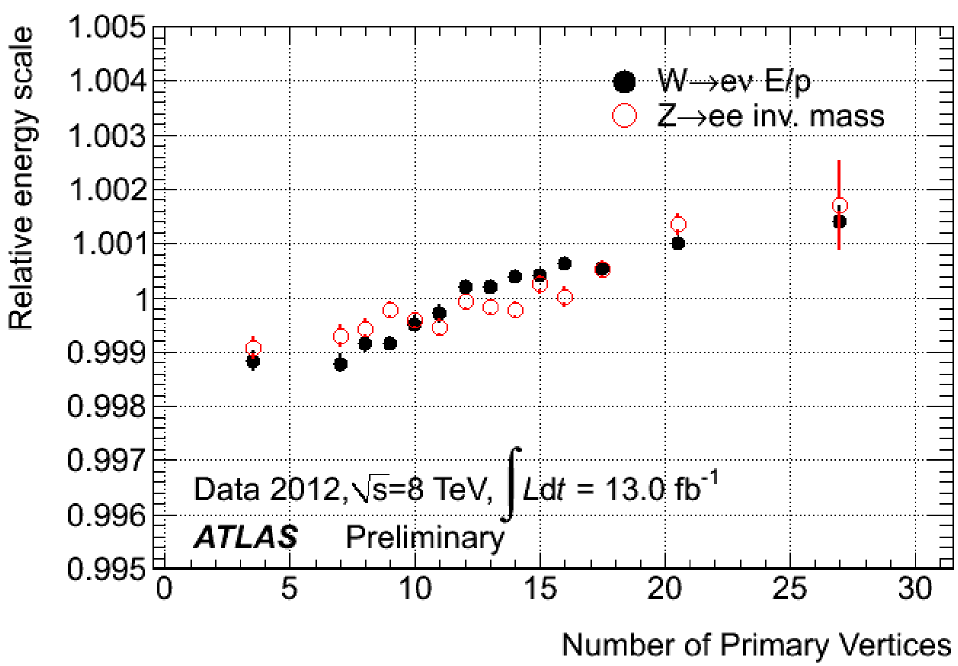
ECAL supercluster energy



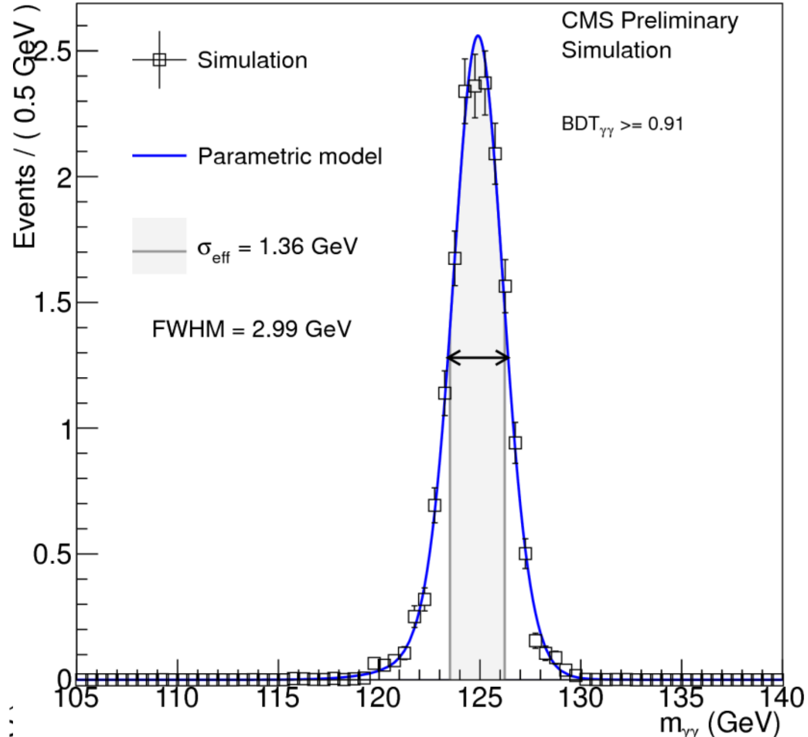
efficiency of photons

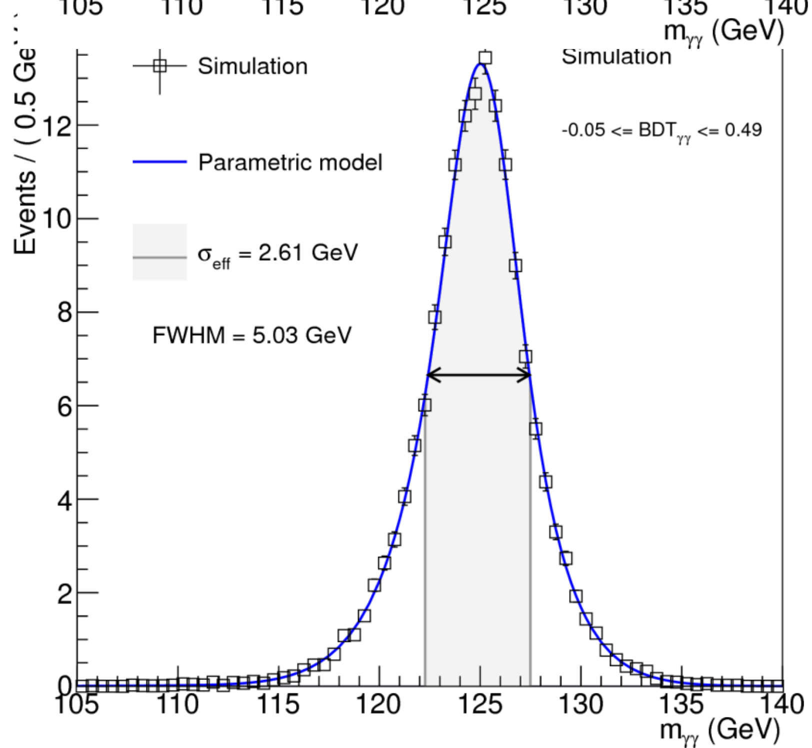
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20130304/ATL-COM-PHYS-2013-244/index.html

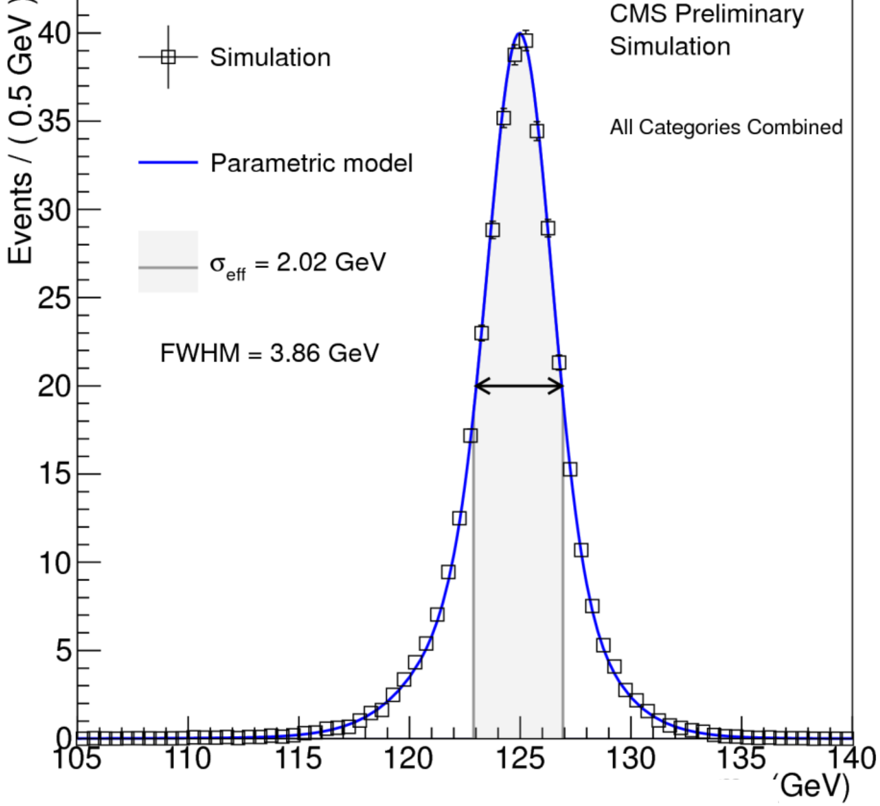


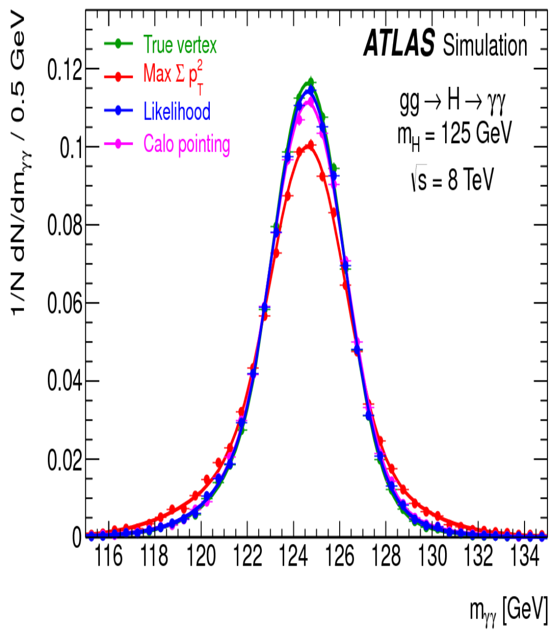


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121129/ATL-COM-PHYS-2012-1668/index.html


CMS Preliminary
Simulation
Simulation
Parametric model
σ_{eff} = 1.36 GeV
FWHM = 2.99 GeV
$BDT_{\gamma\gamma}$ >= 0.91
Events / (0.5 GeV)
$m_{\gamma\gamma}$ (GeV)


Simulation
Simulation
Parametric model
σ_{eff} = 2.61 GeV
FWHM = 5.03 GeV
-0.05 <= $BDT_{\gamma\gamma}$ <= 0.49
$m_{\gamma\gamma}$ (GeV)





slightly better resolution in CMS but more tails

but there are different categories

very similar 'effective' resolutions

Several categories are made in order to enhance the sensitivity in order to have different S/B , based on

- number of jets

- different resolutions

- different kinematics giving different S/B

S/B has to be different for various categories

This is needed if we want to gain in statistical significance

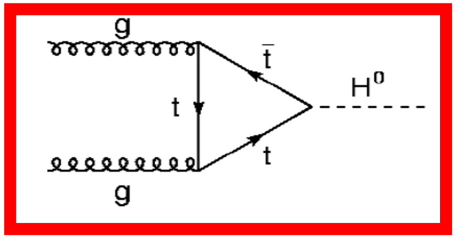
if $S_1 / B_1 = S_2 / B_2$

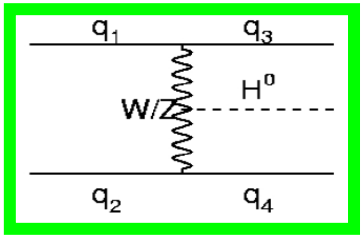
then $S_1 / \sqrt{B_1} \oplus S_2 / \sqrt{B_2} = (S_1+S_2) / \sqrt{(B_1+B_2)}$

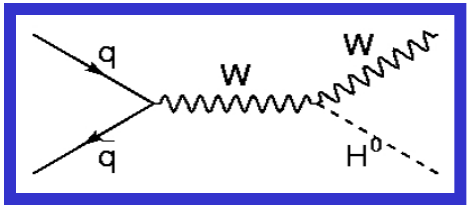
and one does not gain making categories

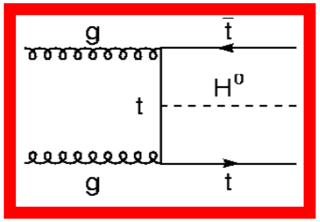
(one of) the work of the experimentalist is to find categories with different S/B !

In fact finding and using different categories allows us to « see » the various production modes

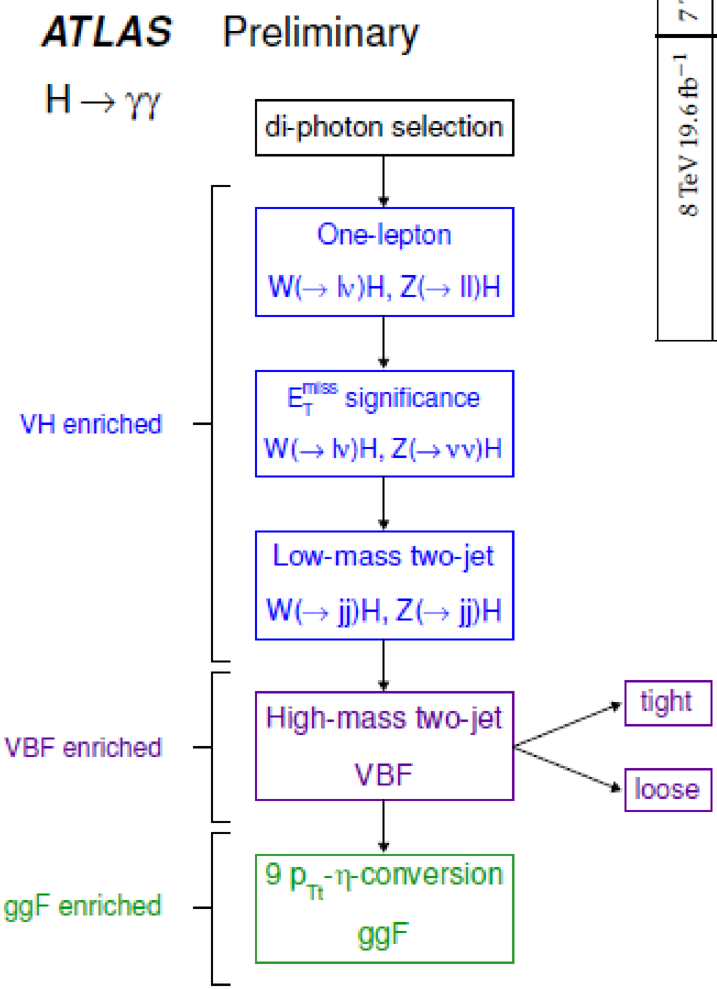


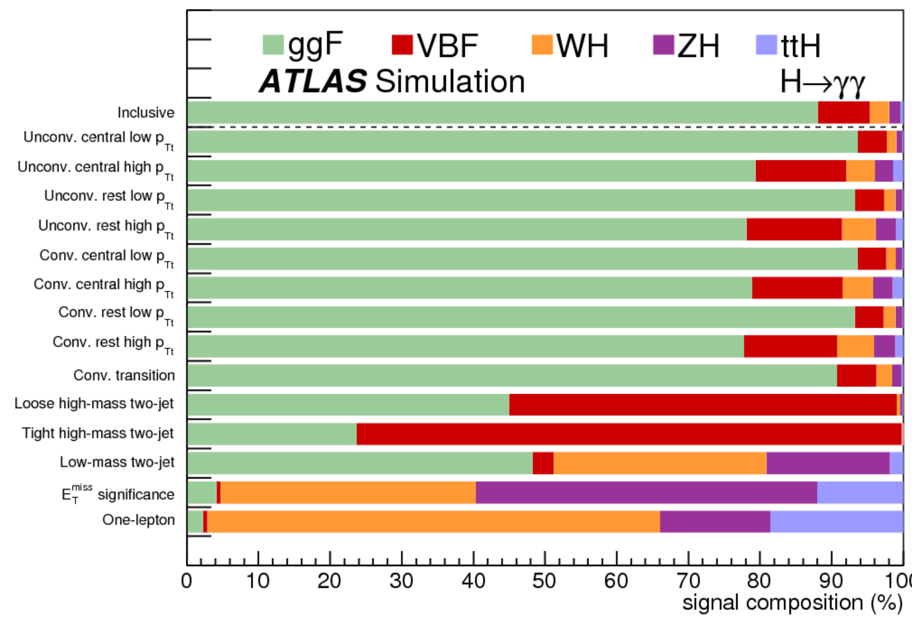




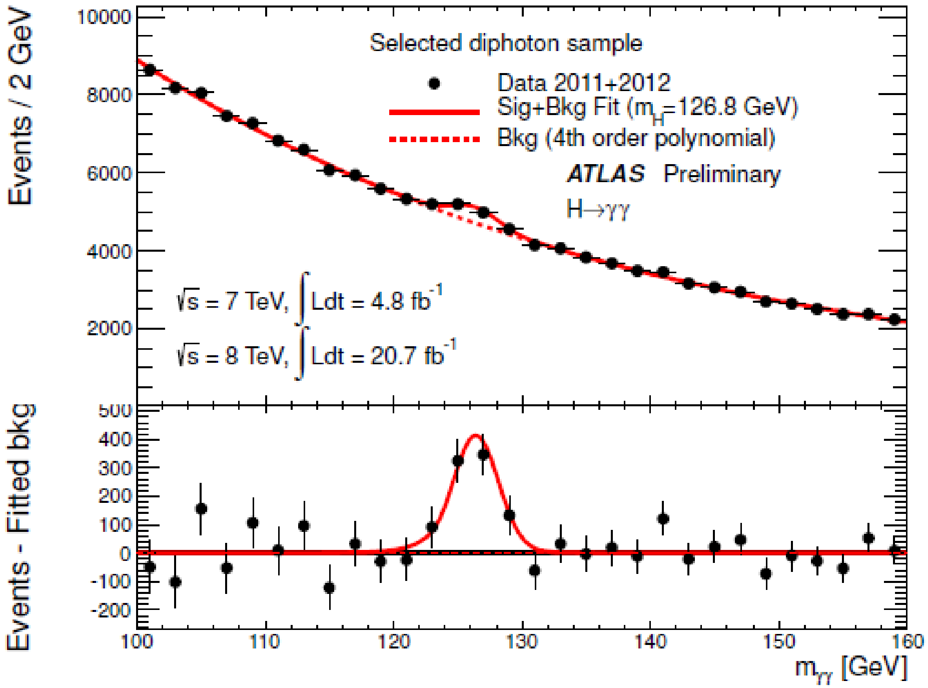


Expected signal and estimated background									
Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1





Flow-chart of the event categorisation, giving the order of selection of the different categories.



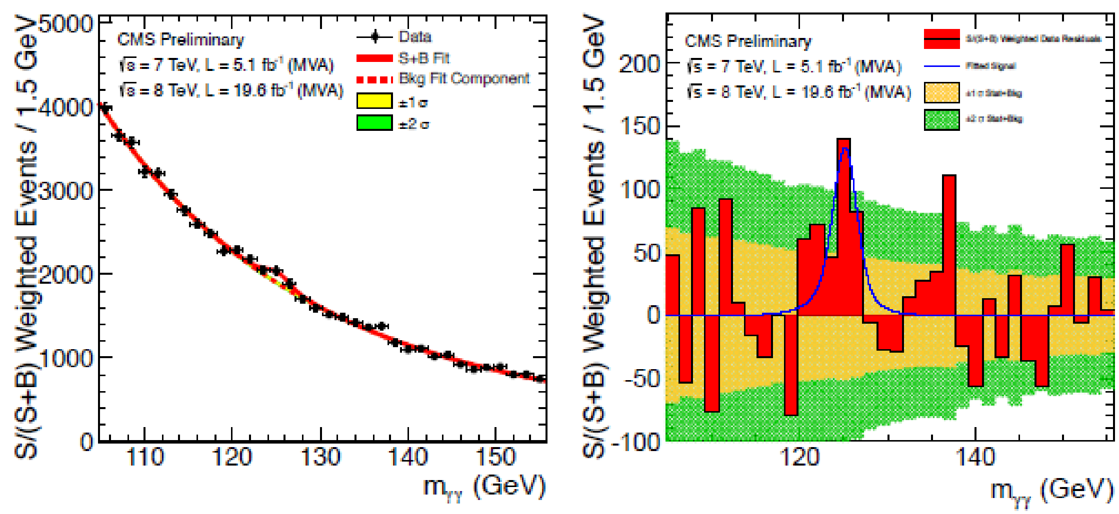
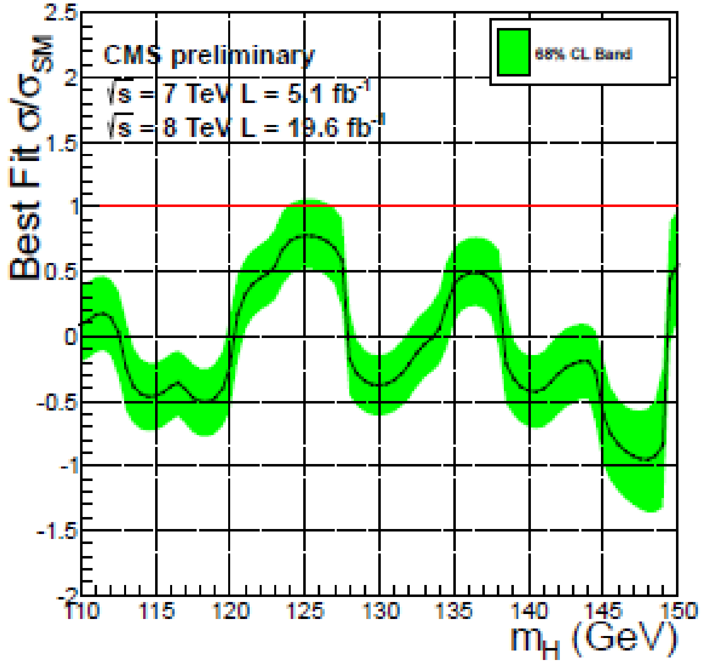
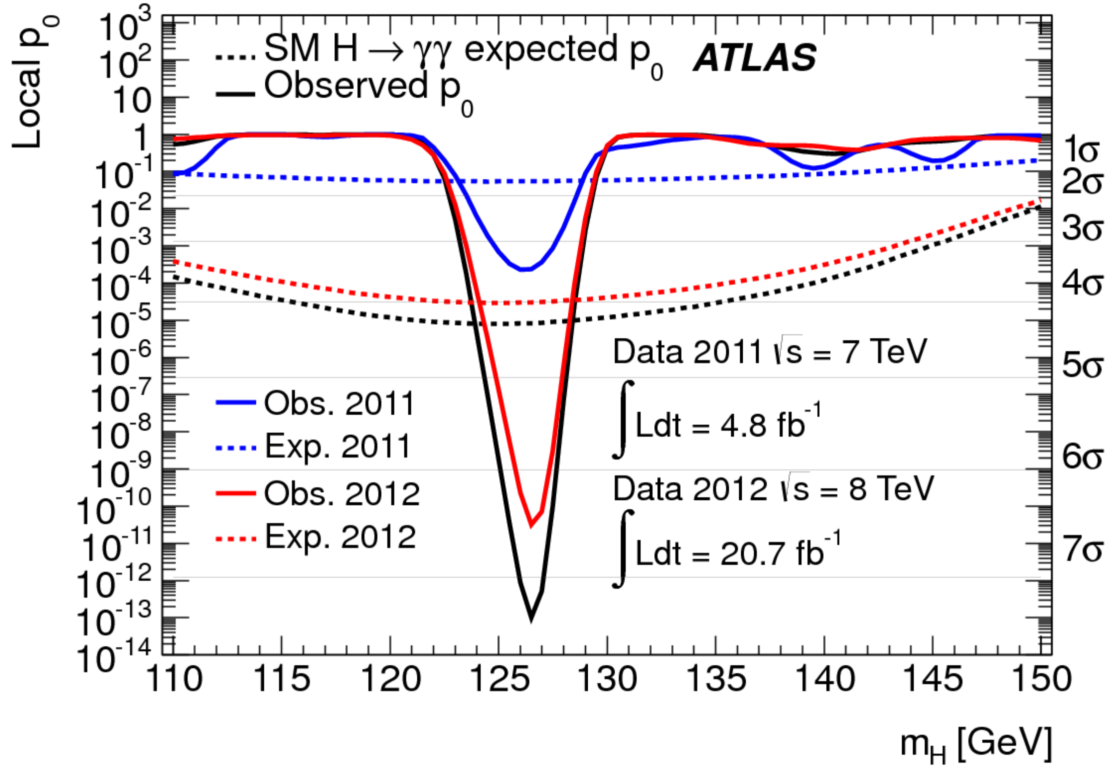
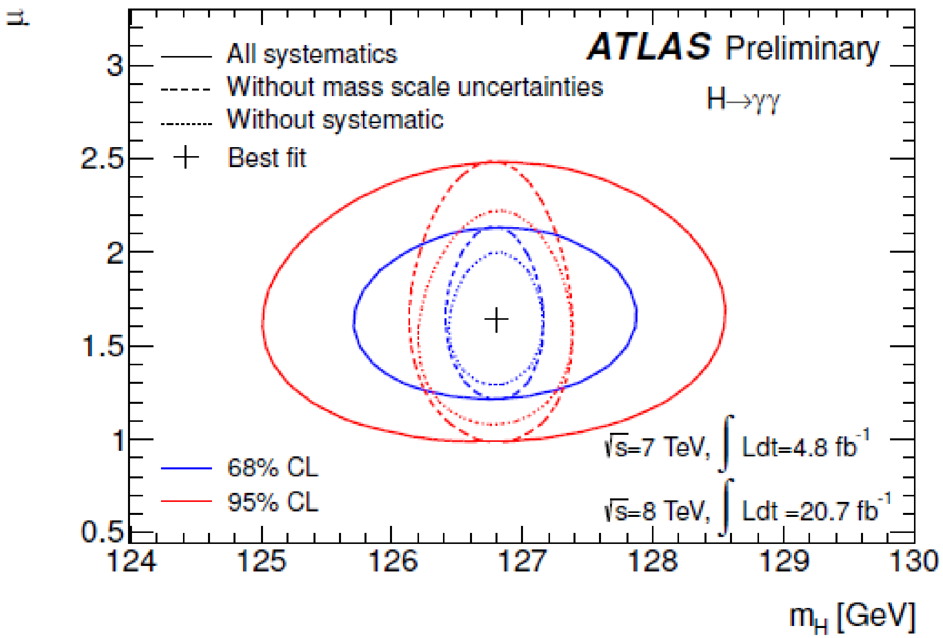
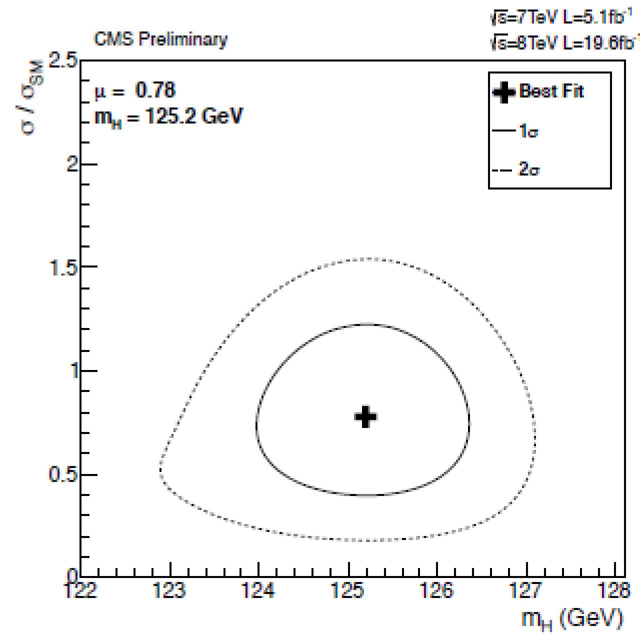


Figure 10: (left) The diphoton mass spectrum weighted by the ratio of signal-to-background in each event class for the mass-fit-MVA analysis. (right) The background-subtracted weighted mass spectrum.


CMS preliminary
√s = 7 TeV L = 5.1 fb-1
√s = 8 TeV L = 19.6 fb-1
68% CL Band
Best Fit σ/σSM
mH (GeV)


SM H → γγ expected p0
Observed p0
ATLAS
Obs. 2011
Exp. 2011
Obs. 2012
Exp. 2012
Data 2011 √s = 7 TeV
∫Ldt = 4.8 fb-1
Data 2012 √s = 8 TeV
∫Ldt = 20.7 fb-1
Local p0
mH [GeV]





μ slightly above SM

$\mu = 1.55^{+.33}_{-.28}$

7.4 σ

mH = 126.8 ± .2 ± .7 GeV

μ slightly below SM

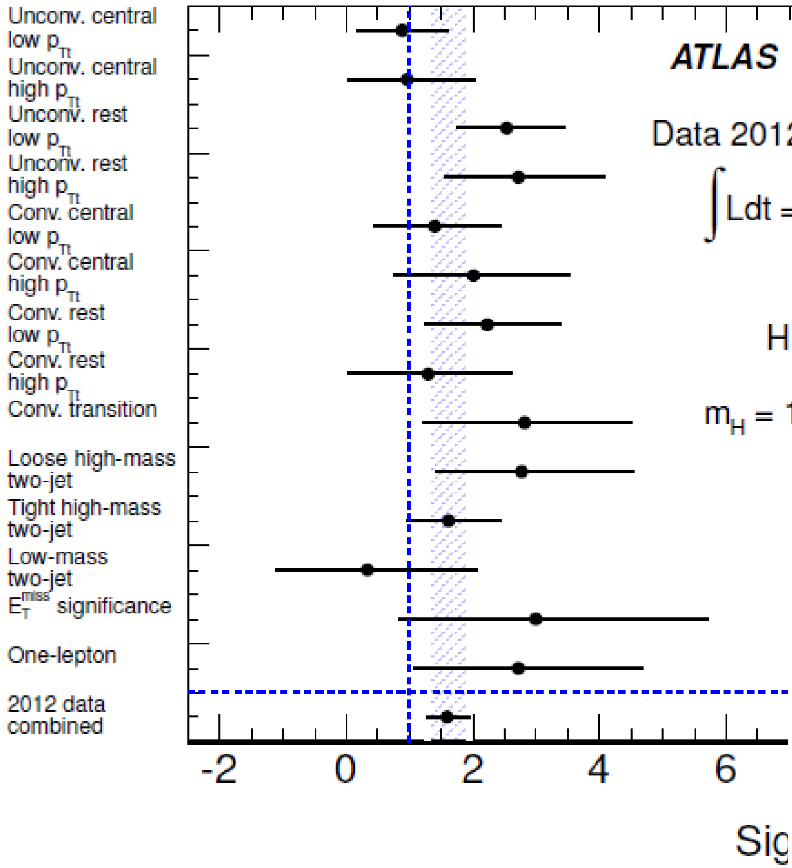
$\mu = .78^{+.28}_{-.26}$

3.2 σ

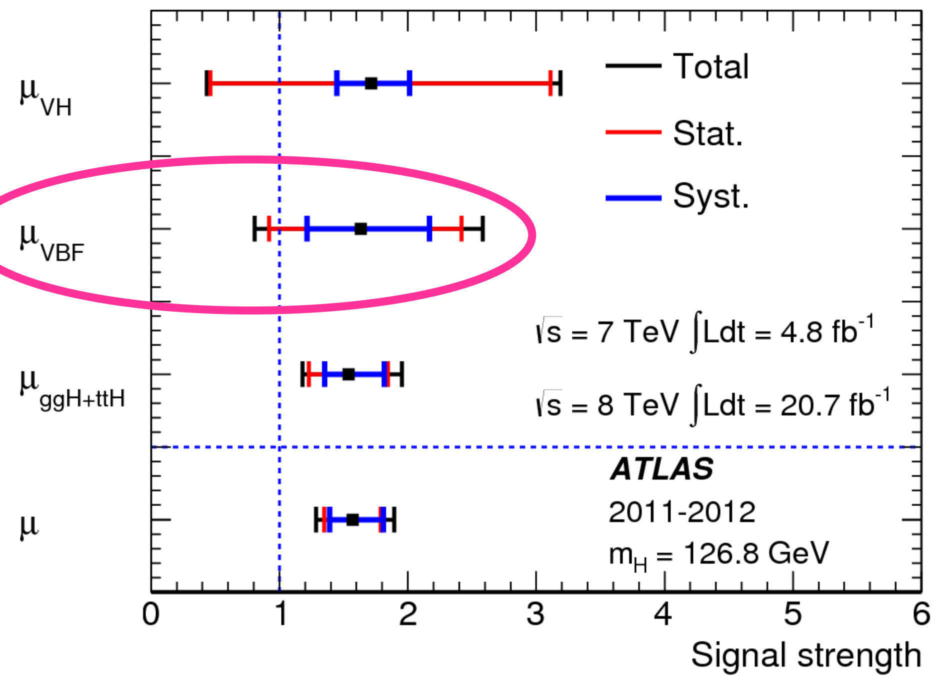
mH = 125.4 ± .5 ± .6 GeV

syst uncertainty : non linearity between Z and H energies and difference between e and γ

errors : ± .23(stat) ± .15(syst) ±. 15 (th) *similar errors*



couplings measured in all categories

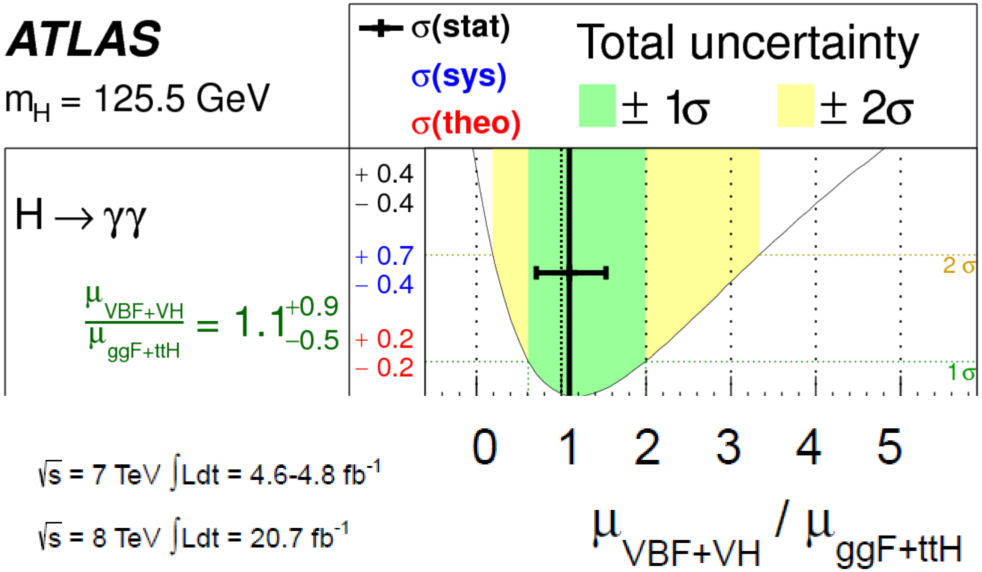


signal strengths for different subprocesses

start to see evidence for VBF

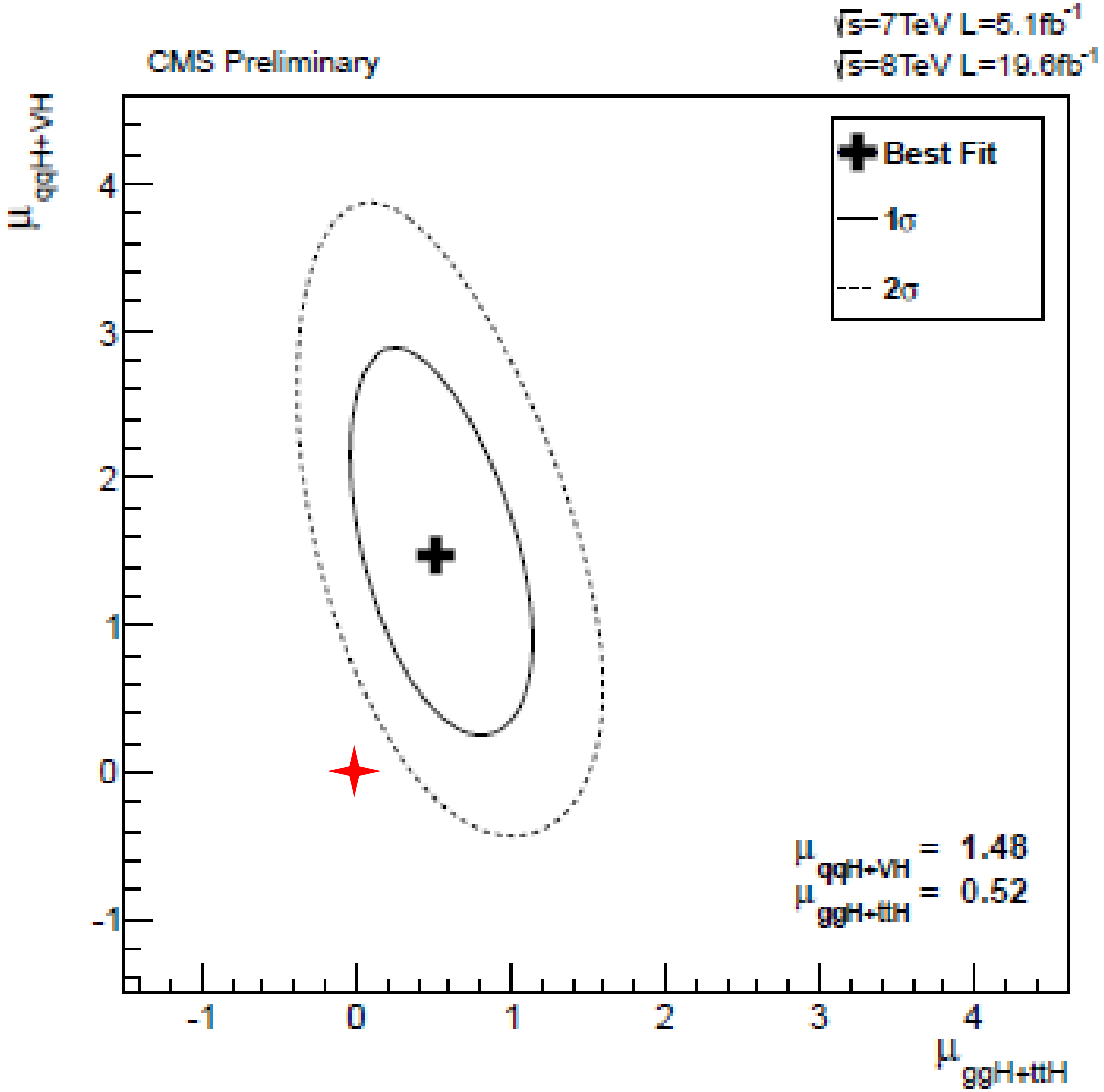
$$\mu_{\text{VBF}} / \mu_{\text{ggF}+ttH}$$

$$\mu_{\text{VBF}} / \mu_{\text{ggF}+ttH} = 1.4^{+0.4}_{-0.3}\,(\text{stat})\,^{+0.6}_{-0.4}\,(\text{sys})$$

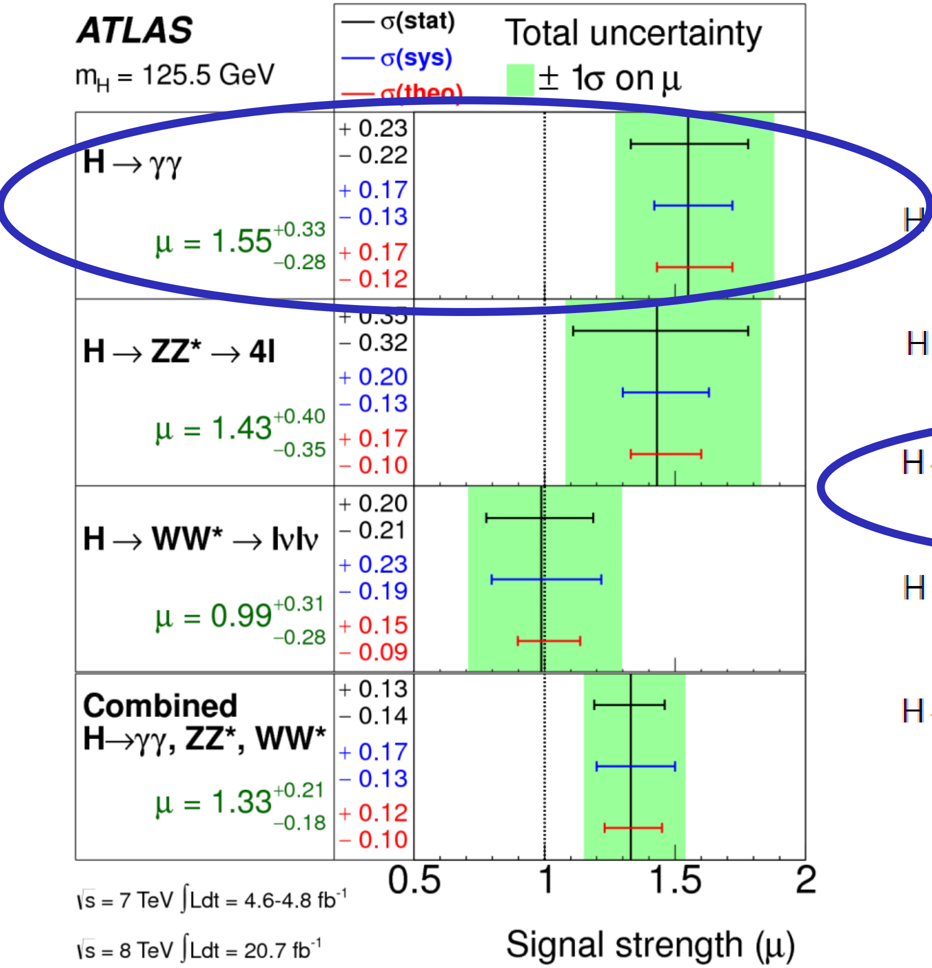


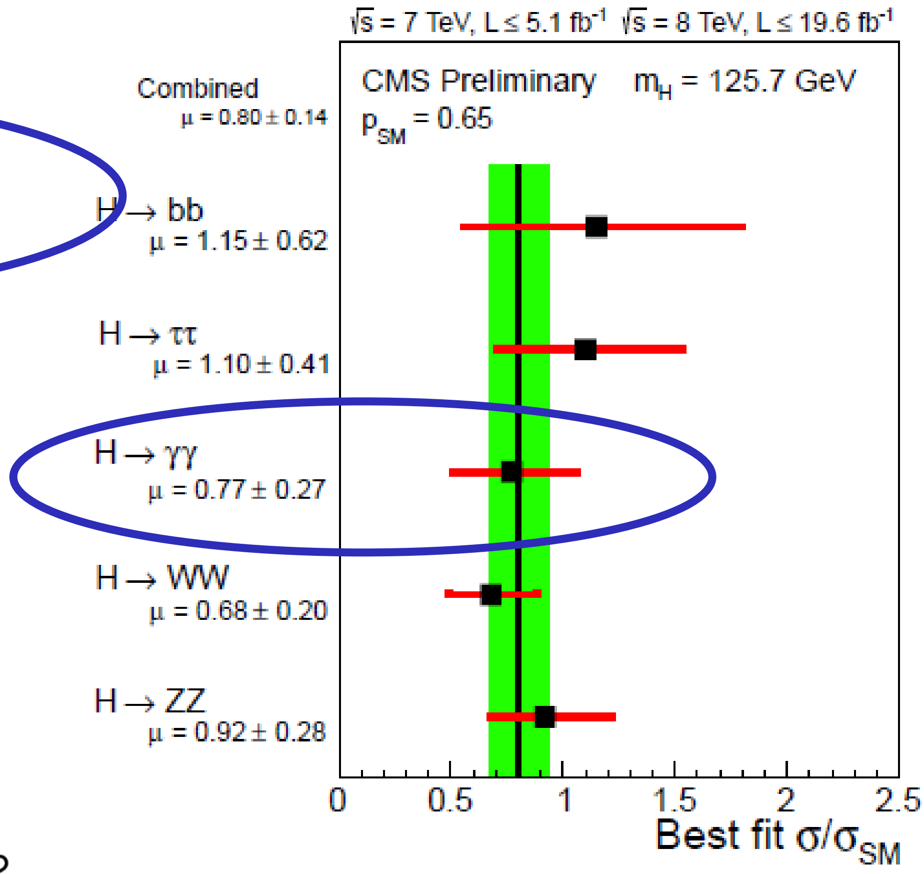
3.3 σ effect ⟶

CMS too



CMS Preliminary
√s=7TeV L=5.1fb⁻¹
√s=8TeV L=19.6fb⁻¹
Best Fit
1σ
2σ
μ qqH+VH = 1.48
μ ggH+ttH = 0.52
μ qqH+VH
μ ggH+ttH
-1
0
1
2
3
4

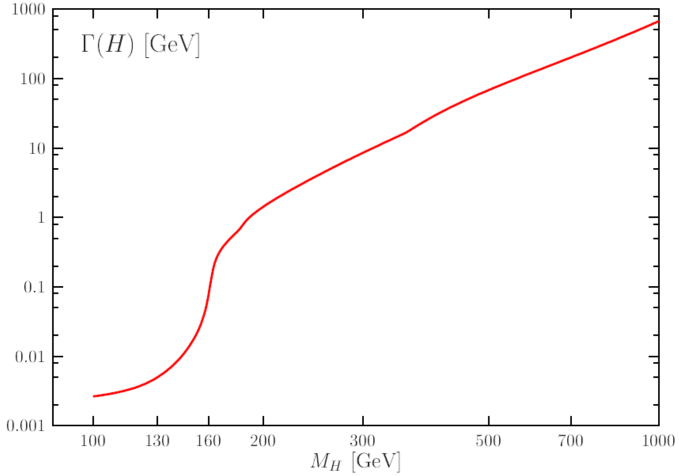




General good agreement with the Standard Model in particular γγ

width

A.Djouadi Phys.Rept.457:1-216

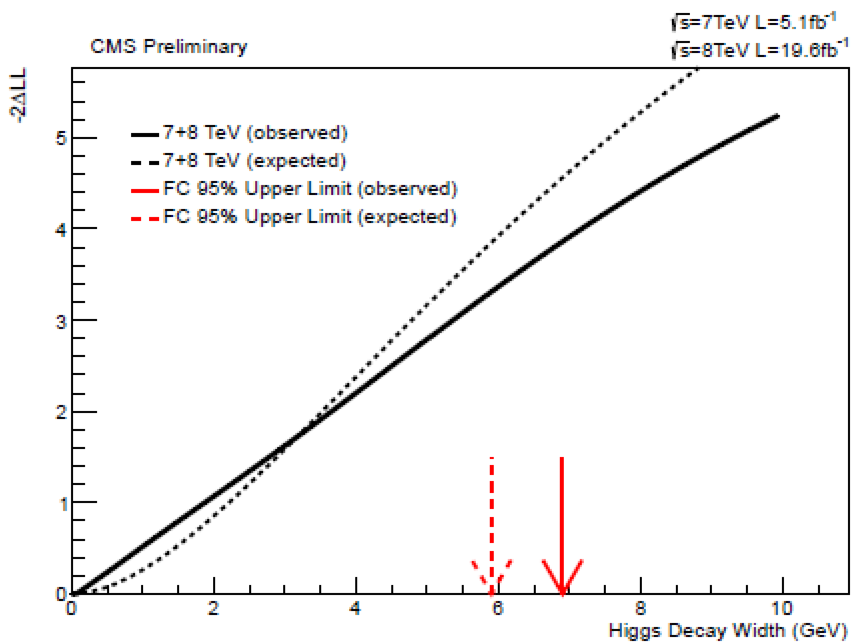


the width of the SM scalar is small (Γ =4.2 MeV)

compared to the experimental resolution FWHM ~ 4 GeV

and it is very difficult to obtain
$\Gamma \sim \sqrt{(FWHM_{(meas)}^2 - FWHM_{(pred)}^2)}$

CMS PAS HIG-13-006



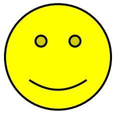
still a limit is set for Γ at 6.9 GeV 95%CL

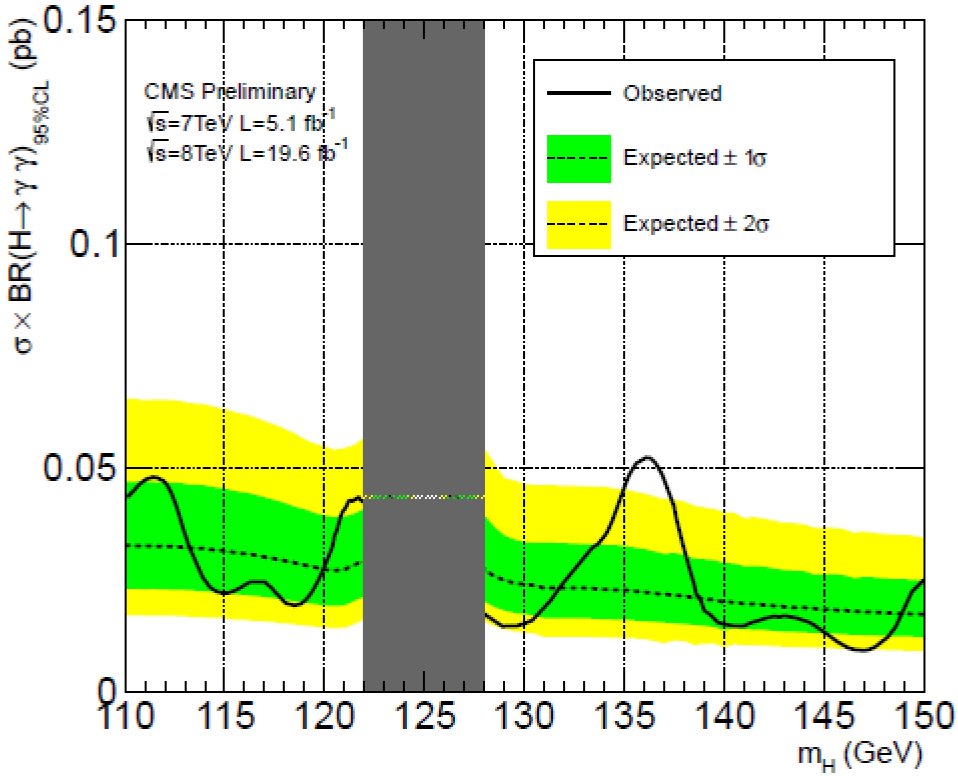
There are other (indirect) ways of putting limits (with few hypothesis) on invisible width or invisible branching ratio

- ♥ **ZH , H → inv**
- ♥ **couplings analysis**

search for additional scalar-boson-like states

In this search the observed state around 125 GeV is considered as part of the 'background'





Once sufficiently away from 125 GeV, we recover the same limit as in the search for a single SM Higgs boson. The p-value at the most significant excess, where m_H=136.5 GeV, is found to be 2.93σ.

ATLAS-CONF-2013-072

differential cross sections

relatively high signal yield (~ 620 fitted in ATLAS at $\sqrt{s}$=8 TeV)

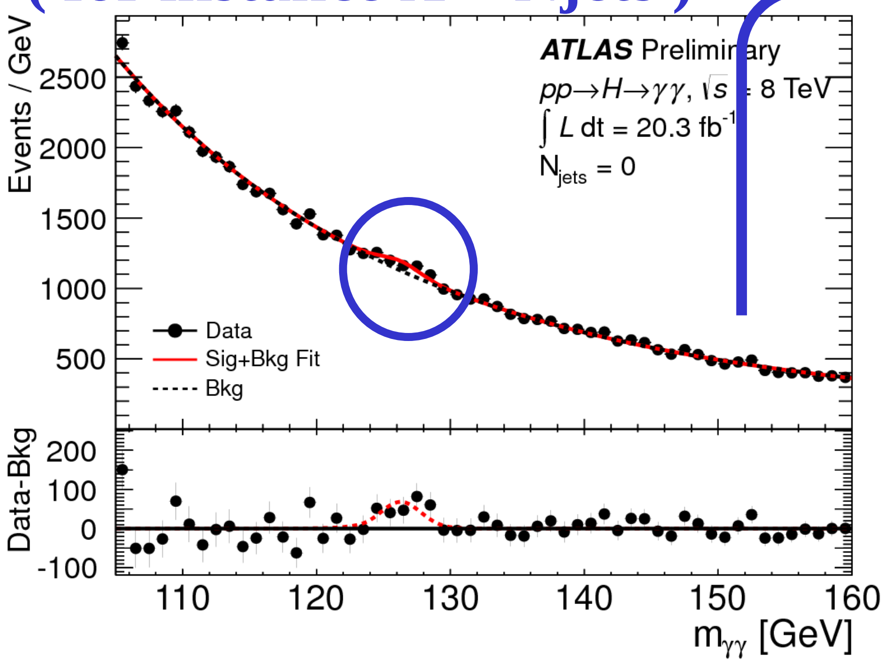
⇒ can be used to probe the underlying kinematic properties of production and decay

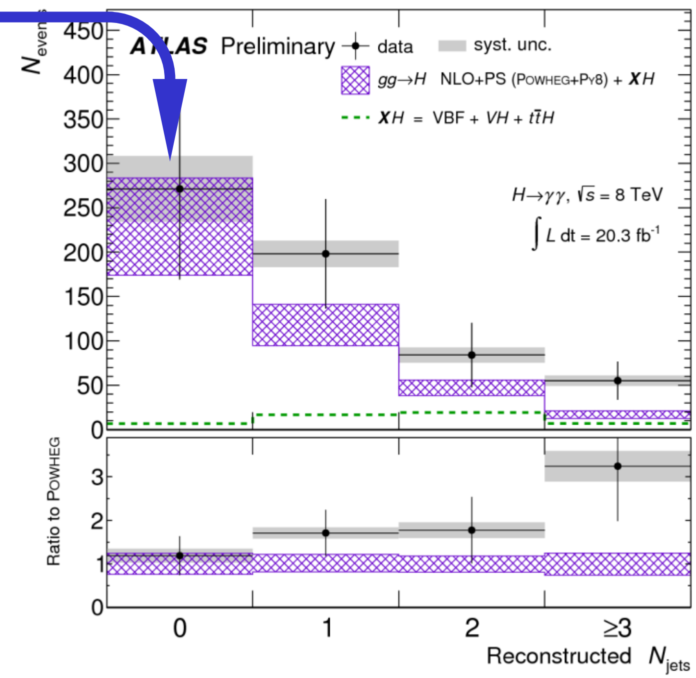
Inclusive	$p_T^{\gamma\gamma}$	Fundamental kinematics, H.O.
	$\|y^{\gamma\gamma}\|$	Fundamental kinematics, pdf
	N_{jets}	VH, VBF, $t\bar{t}H$ vs ggH, H.O.
	$\sigma_i/\sigma_{\geq i}$	H.O.
	$\|\cos\theta^*\|$	Spin
1-jet	$p_T^{leading\ jet}$	H.O.
2-jet	$\Delta\phi_{jj}$	Spin-Parity, VBF, H.O.
	$p_T^{\gamma\gamma jj}$	VBF, H.O.

Methodology :

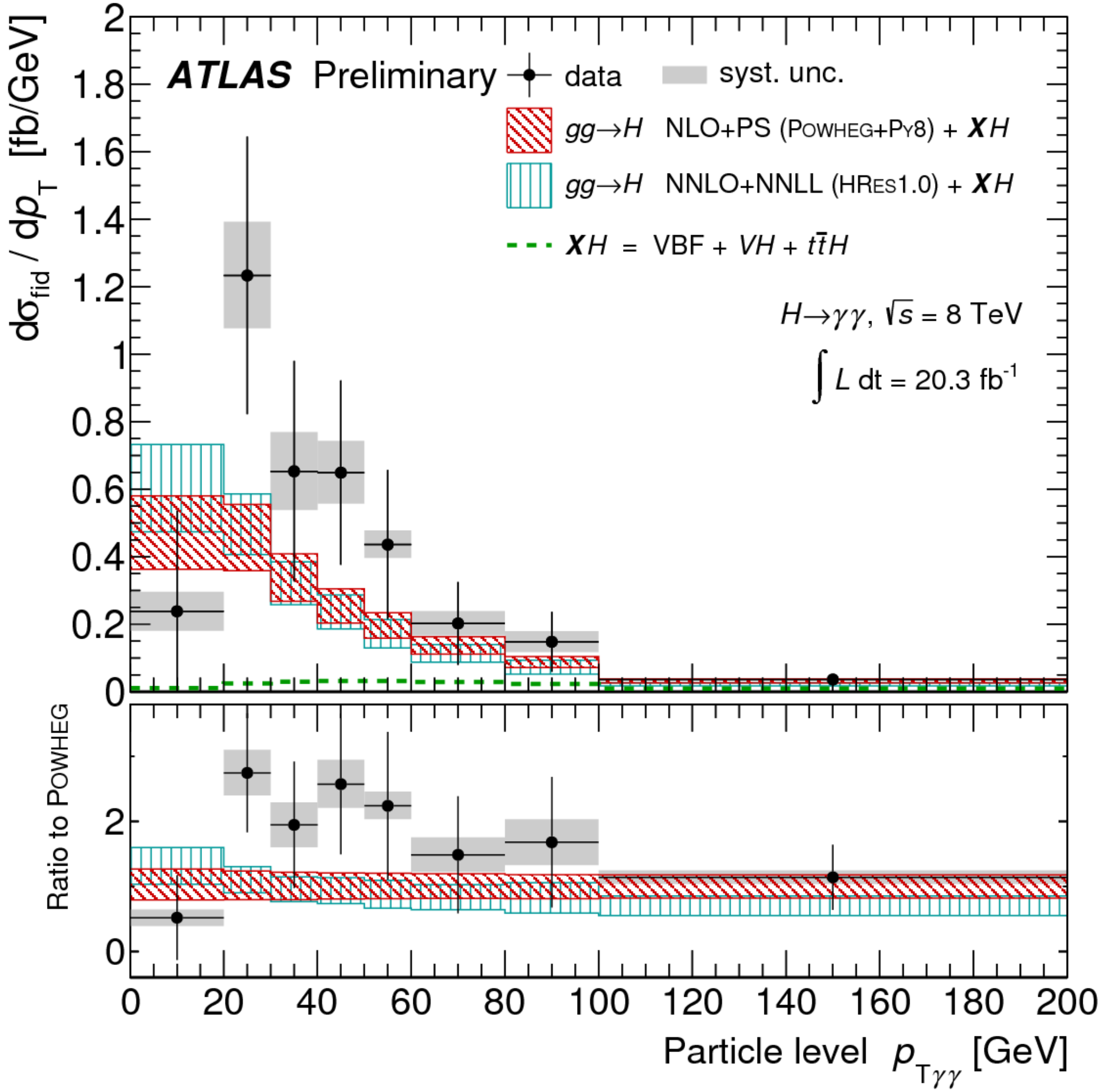
- Choose a binning for variable X
- For each bin get signal yield from $m_{\gamma\gamma}$ distribution
- Bin-by-bin unfolding (correct yields for acceptance, eff, resolution) ⇒ $d\sigma/dX$

(for instance X = Njets)





No significant deviation from SM predictions



still large uncertainties

$P(\chi^2) = 0.55$
(POWHEG)

$P(\chi^2) = 0.39$
(HRES)

$H \rightarrow Z\ Z(*) \rightarrow 4\ l$

Mass can be fully reconstructed

4 leptons with cuts on pT and on the mass (*second mass ~ Z** *resolution 1.5 to 3 GeV* **)**

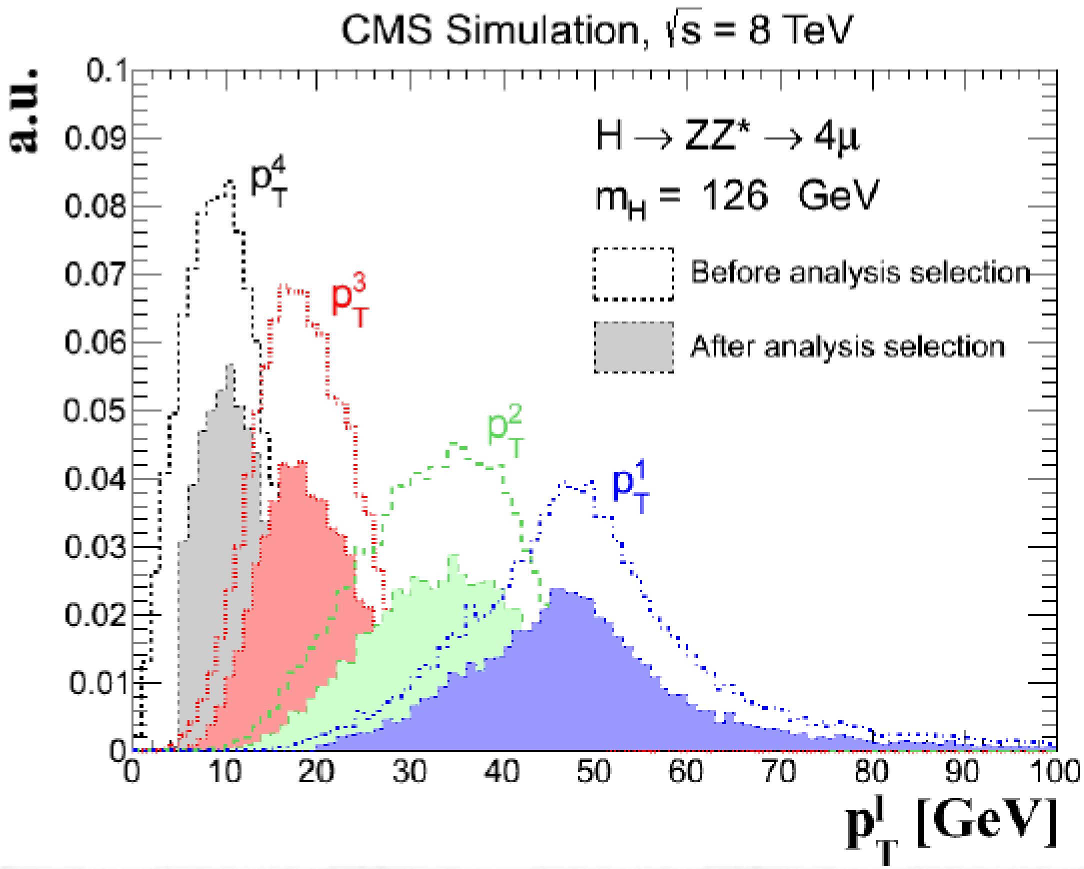
However low rate at low mass → low p_T leptons (down to 5 GeV)

Main backgrounds

- ♠ **Z Z* (irreducible)**
- ♠ **$m_H < 2\ m_Z$: Z bb , t t**

Crucial experimental aspects

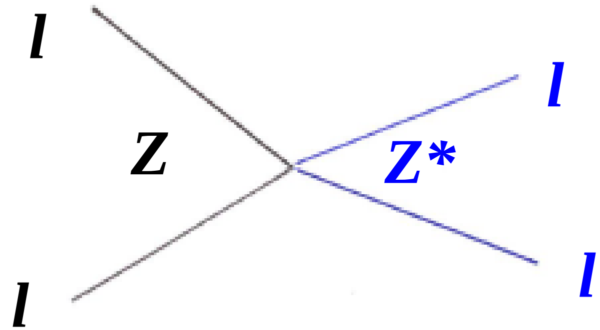
- ♠ **High lepton efficiency (***even at low p_T***)**
- ♠ **Good lepton energy/momentum resolution (** *special fits of electrons with bremsstrahlung* **)**
- ♠ **Good control of reducible background (** *MC normalised in background enriched control regions* **)**

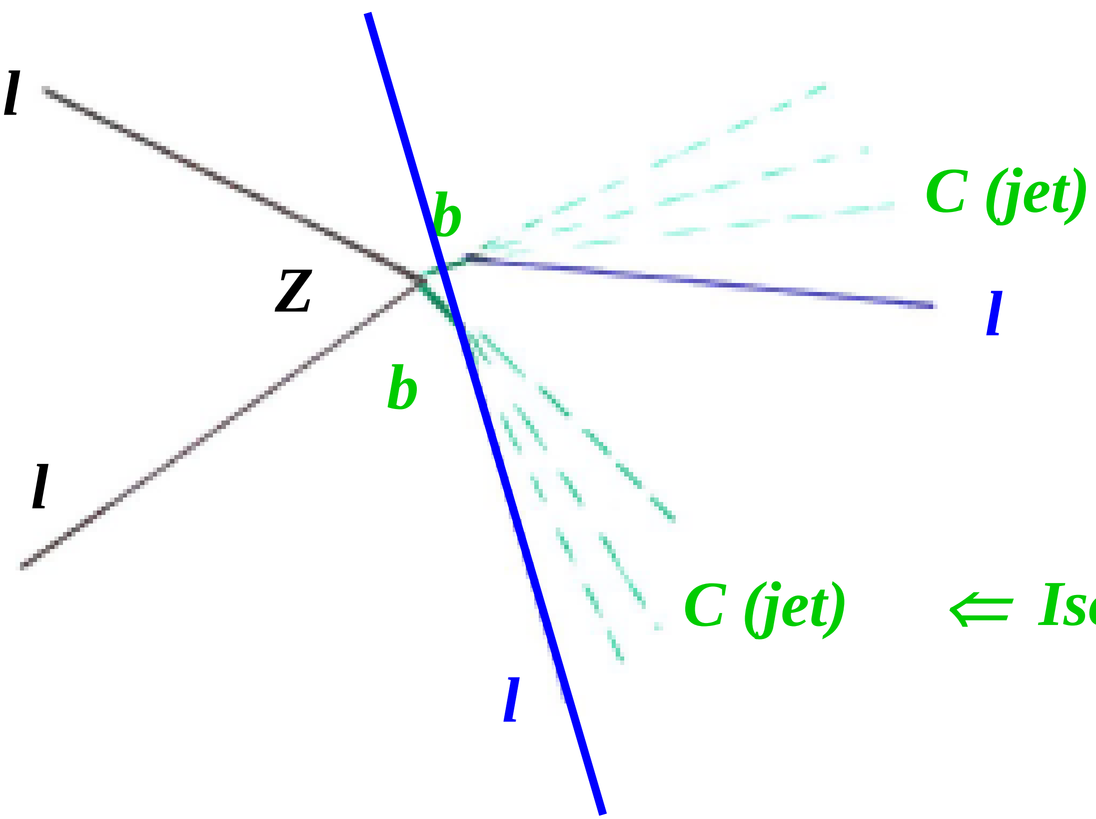


CMS Simulation, √s = 8 TeV
a.u.
H → ZZ* → 4μ
m_H = 126 GeV
Before analysis selection
After analysis selection
p_T^4
p_T^3
p_T^2
p_T^1
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 10 20 30 40 50 60 70 80 90 100
p_T^l [GeV]

Main backgrounds

- ♠ **Z Z* (irreducible)**
- ♠ **$m_H < 2\ m_Z$: Z bb , t t**



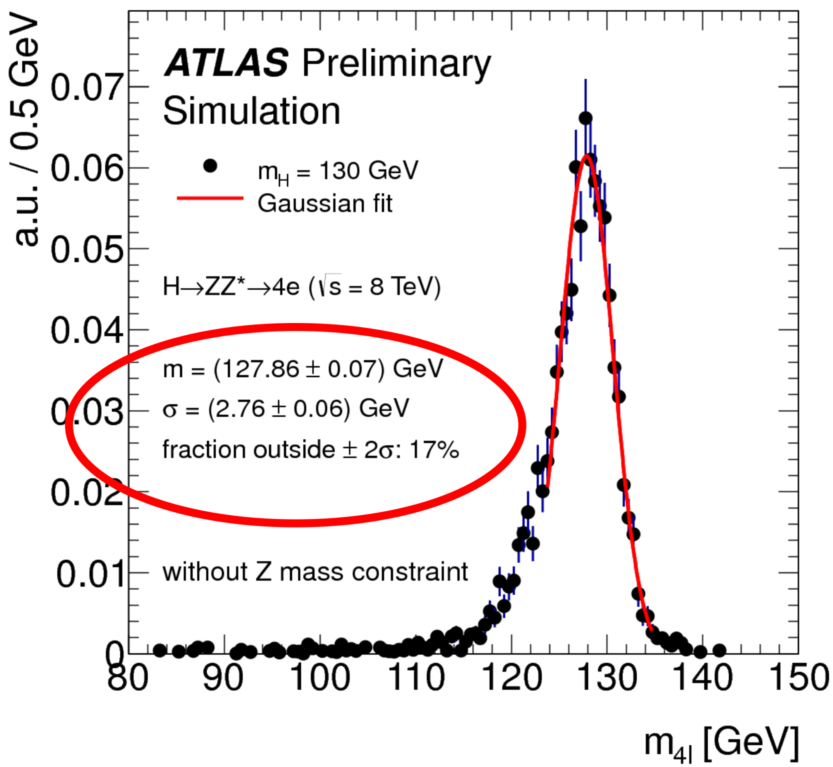


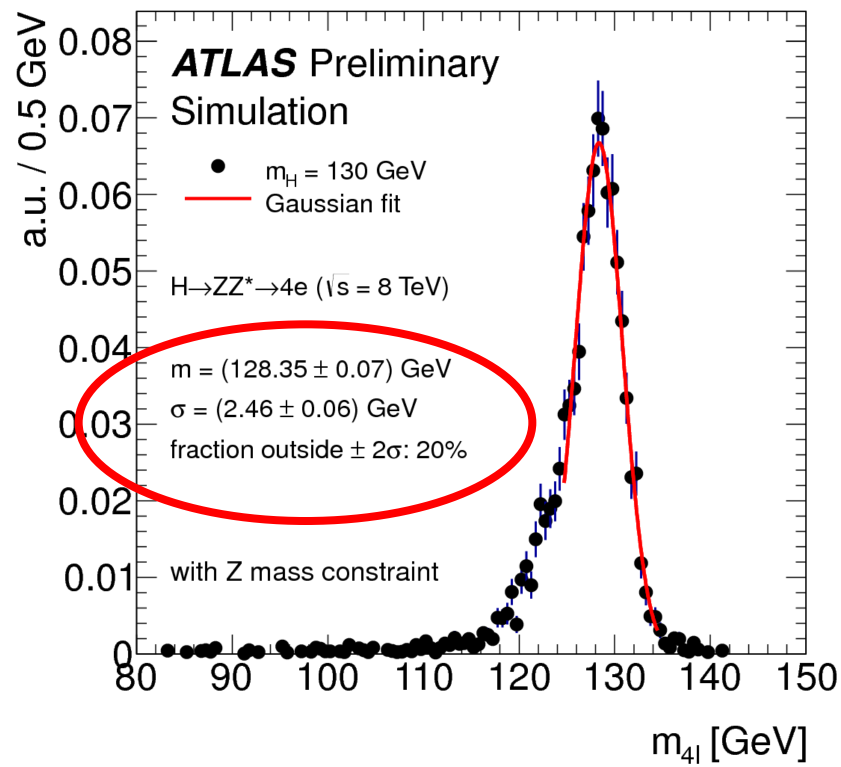
Impact parameter cut

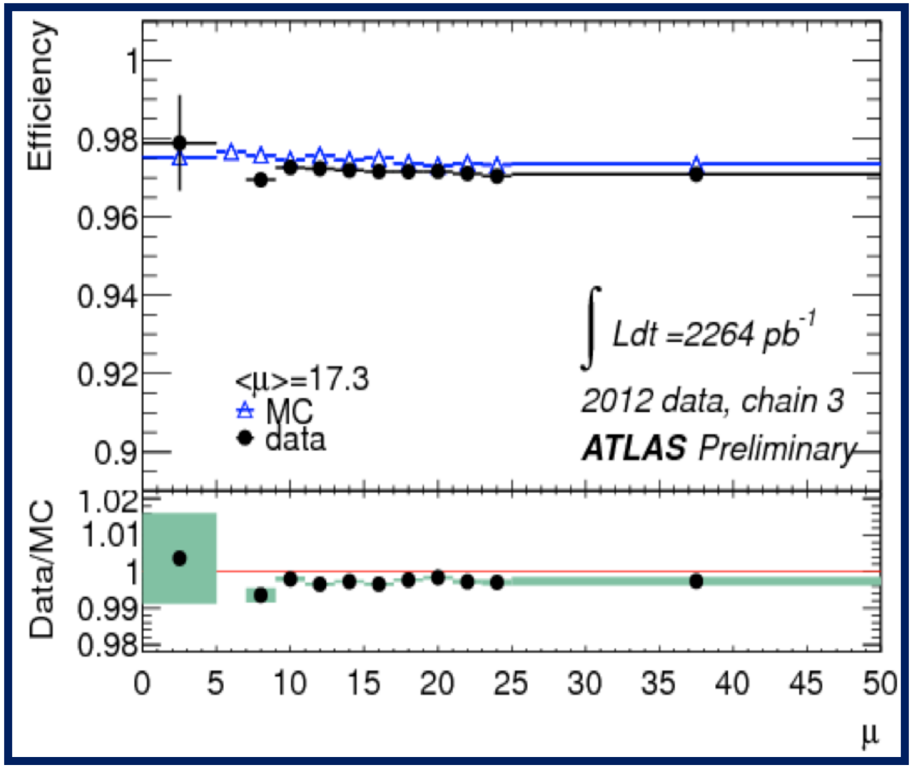
⇐ Isolation cuts

The mass resolution is crucial for the sensitivity

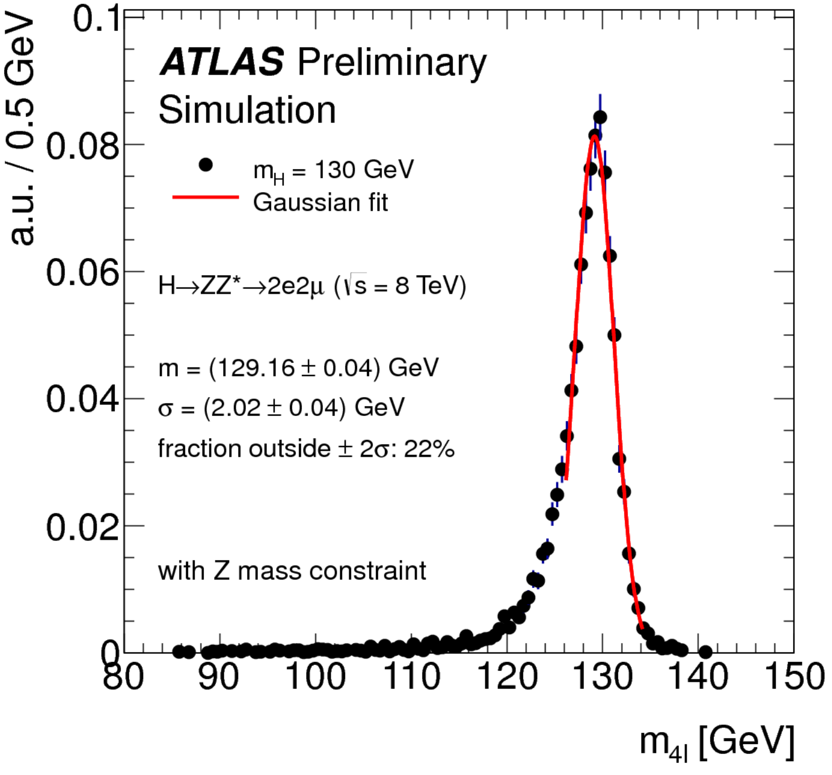
Correct m_{12} applying Z mass constraint using the event uncertainty







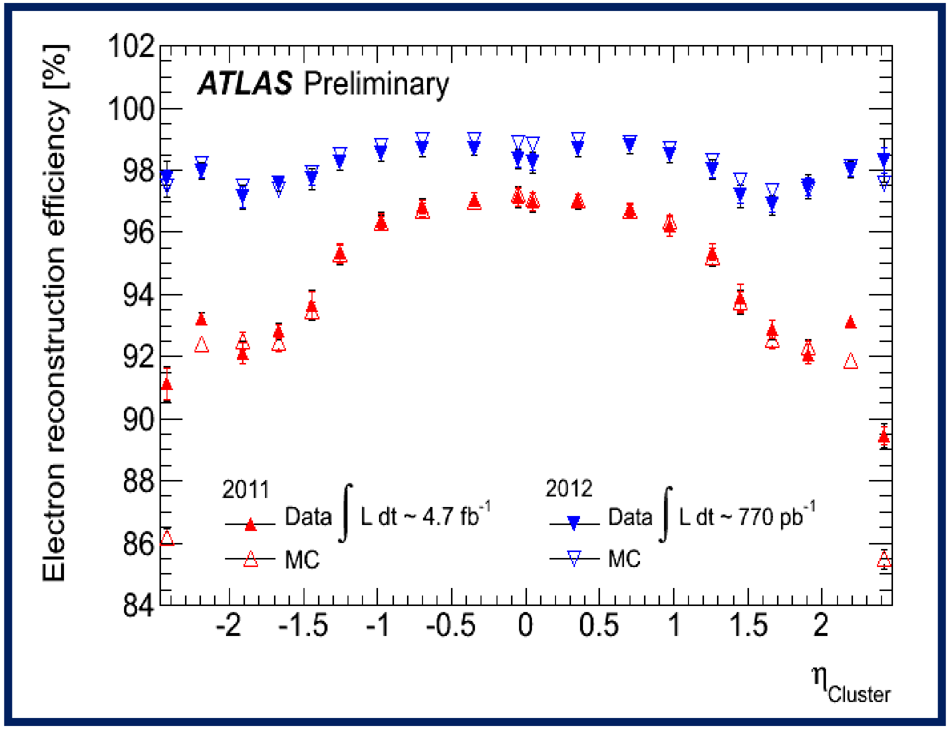
*good **muon** reconstruction efficiency*

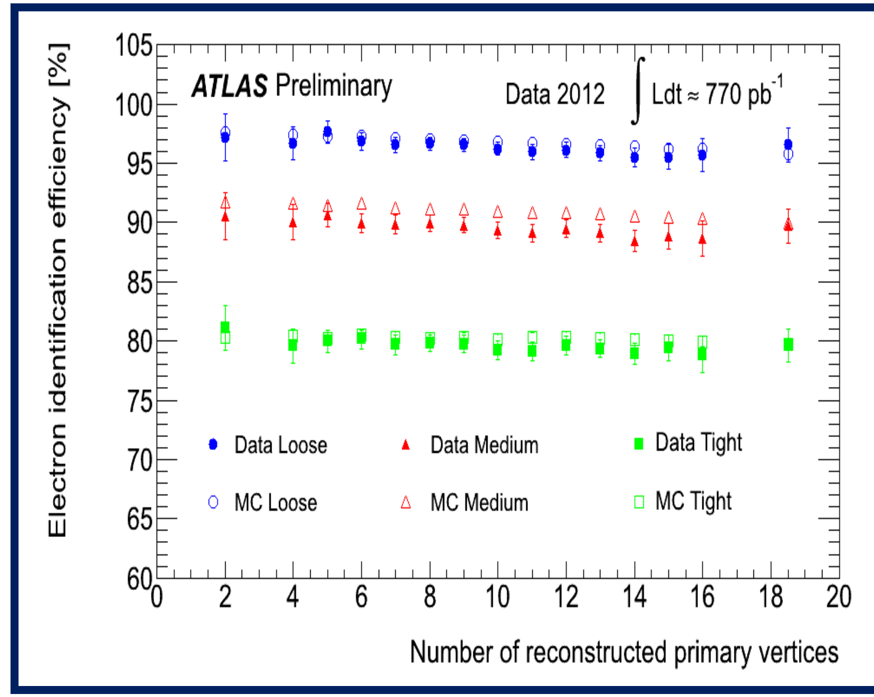


Very good resolution

small mass(momentum) energy scale uncertainty

Improvements in 2012 electron analysis



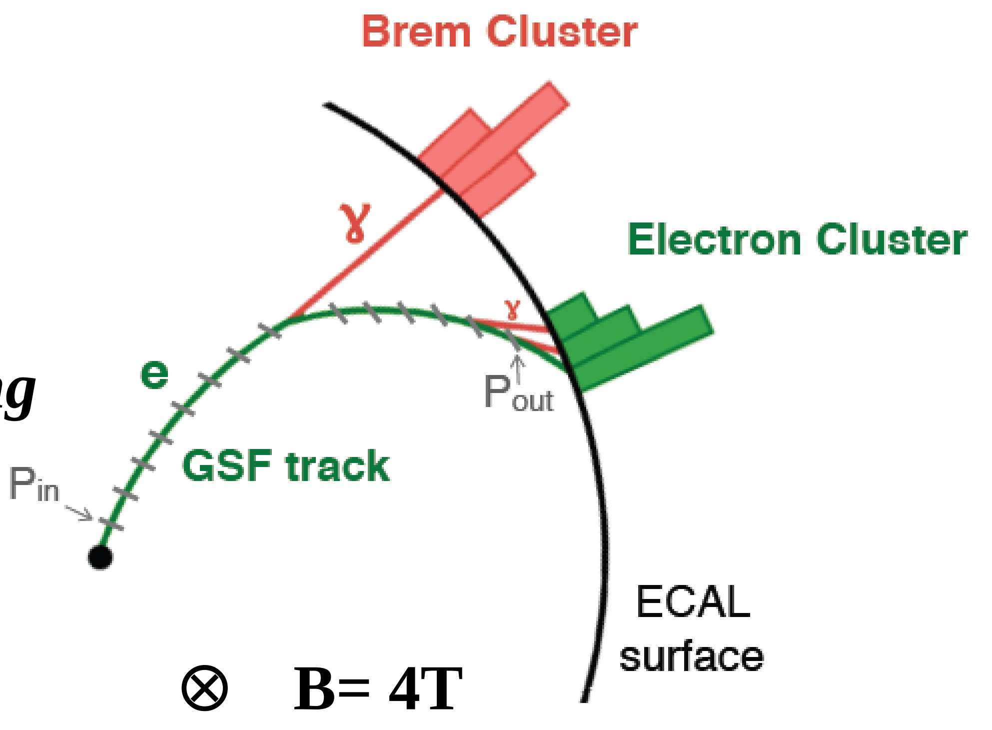


new electron reconstruction with brem recovery

new pile-up robust identification

Electron ID in CMS

superclusters in ECAL +
dedicated track finding and GSF fit

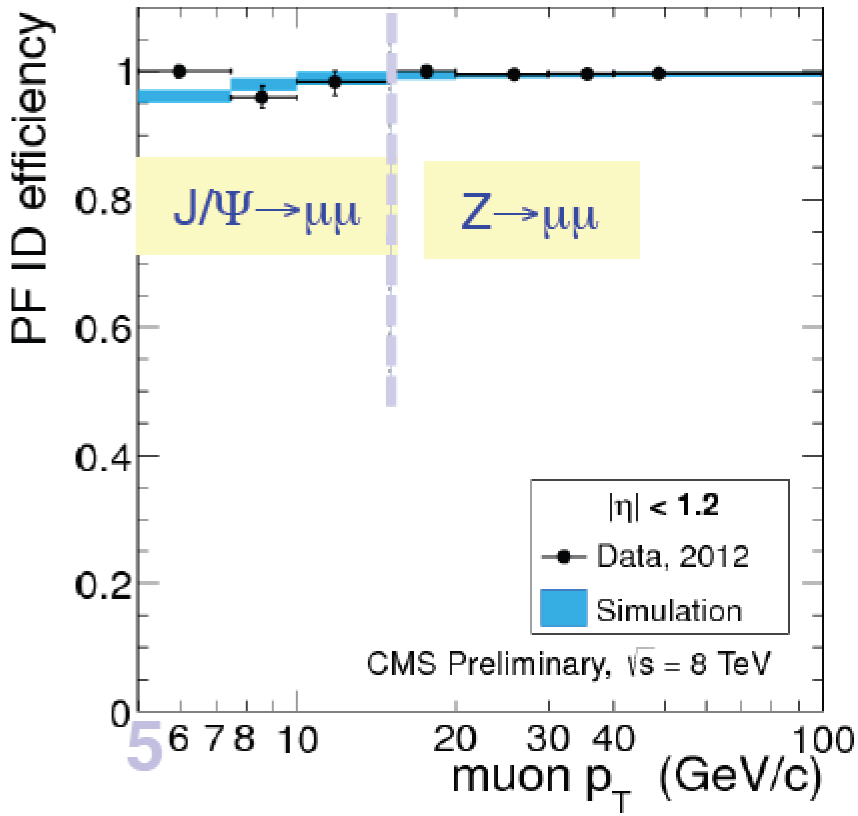


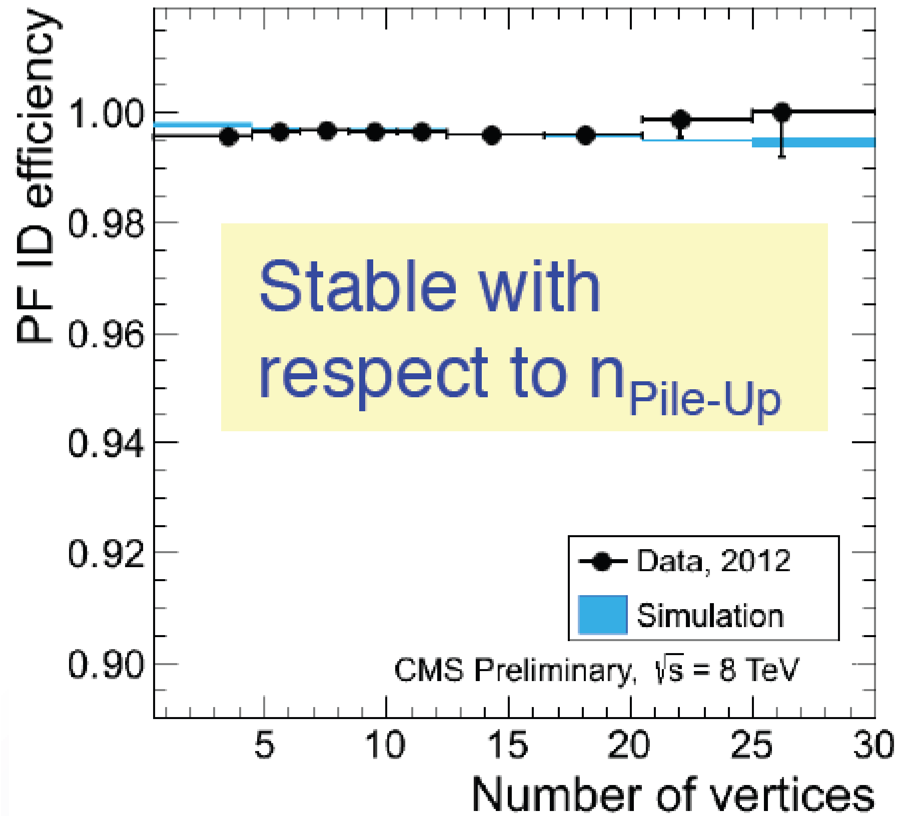
Baffioni HH

Optimisation of electron ID using multivariate analysis
30% efficiency gain wrt 2011 (at same fake rate)

Muon ID CMS

5% efficiency gain in 4μ (same fake rate) wrt 2011 effficiency measured via Z and J/Ψ tag and probe

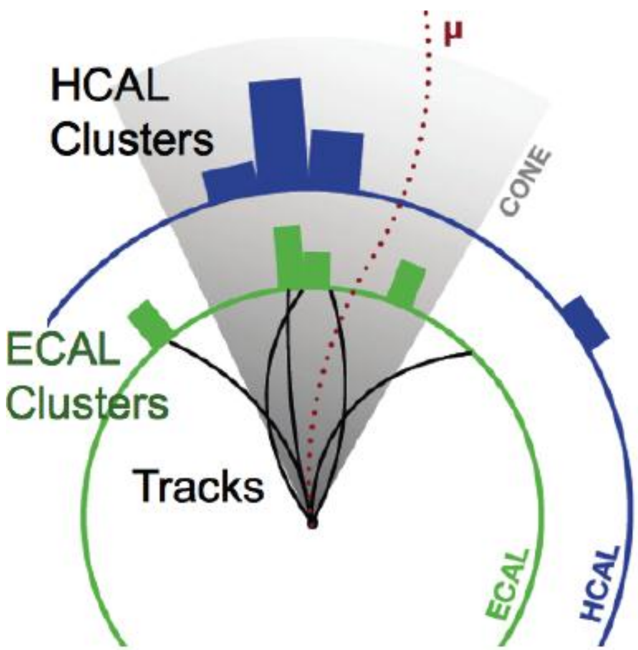


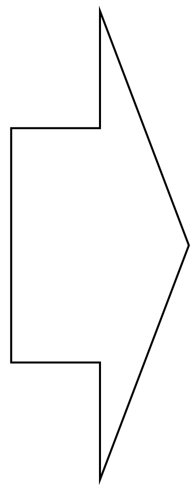


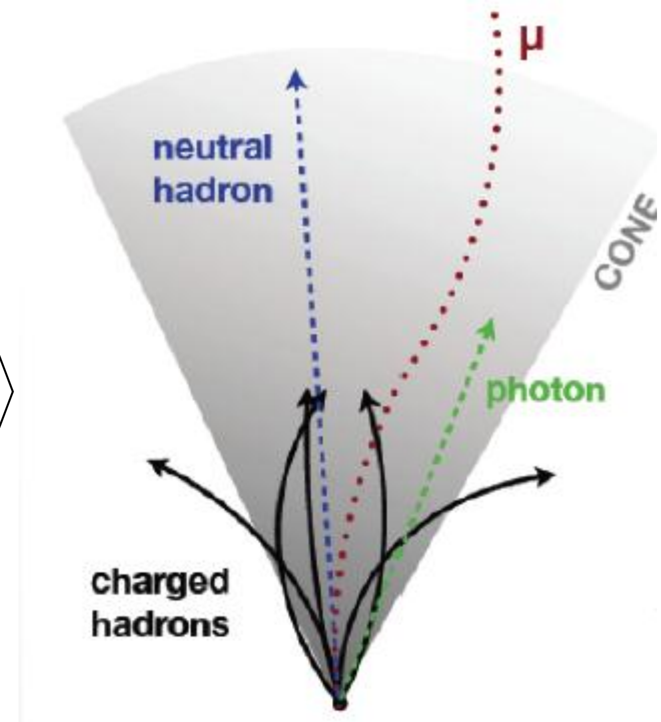
isolation

used to be detector isolation

now particle flow isolation

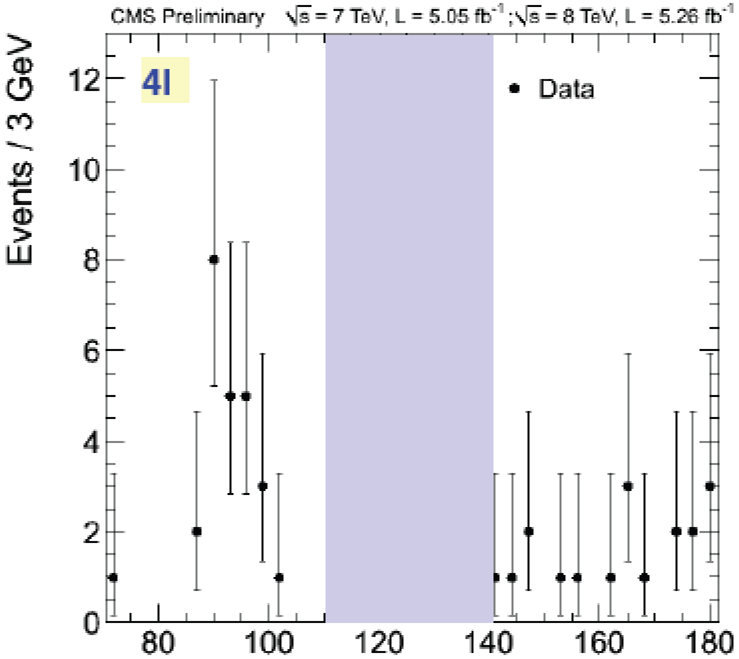


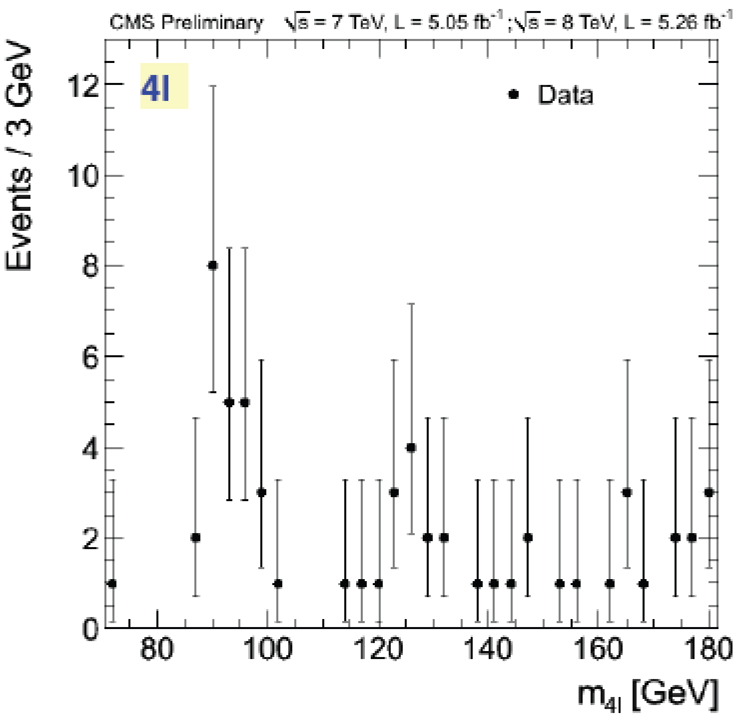


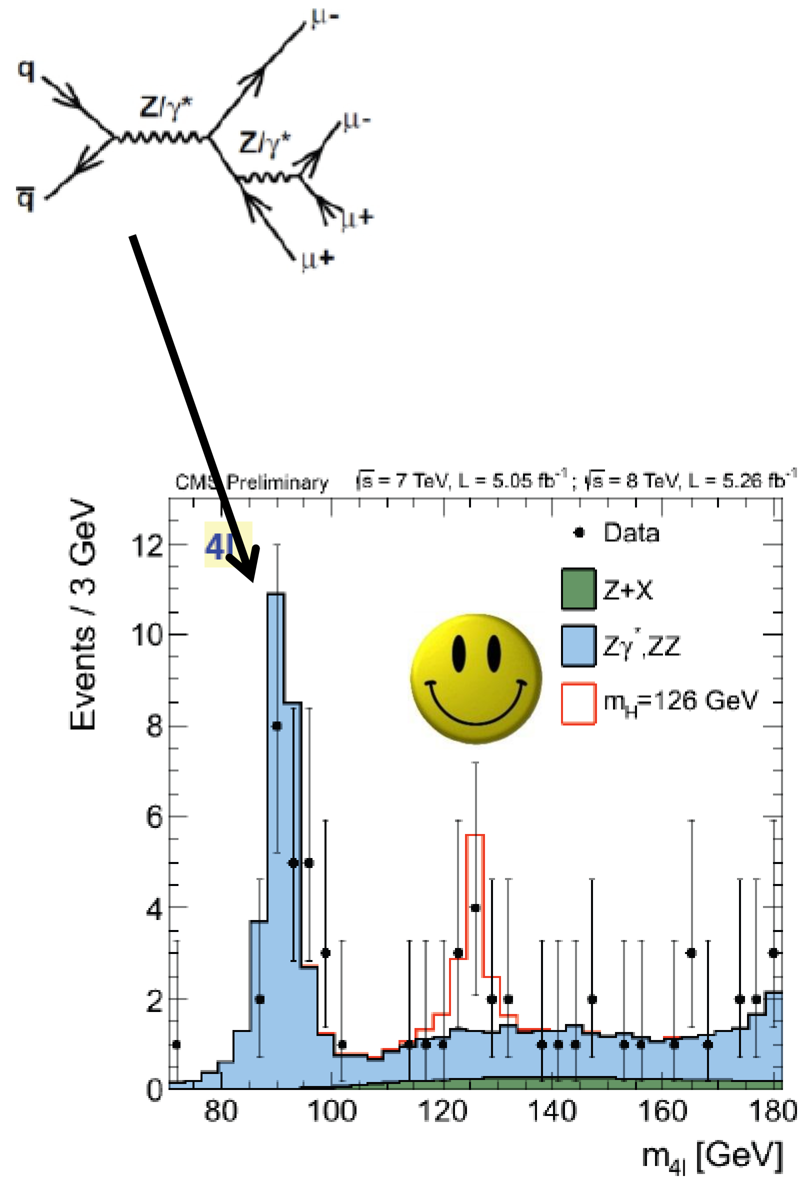


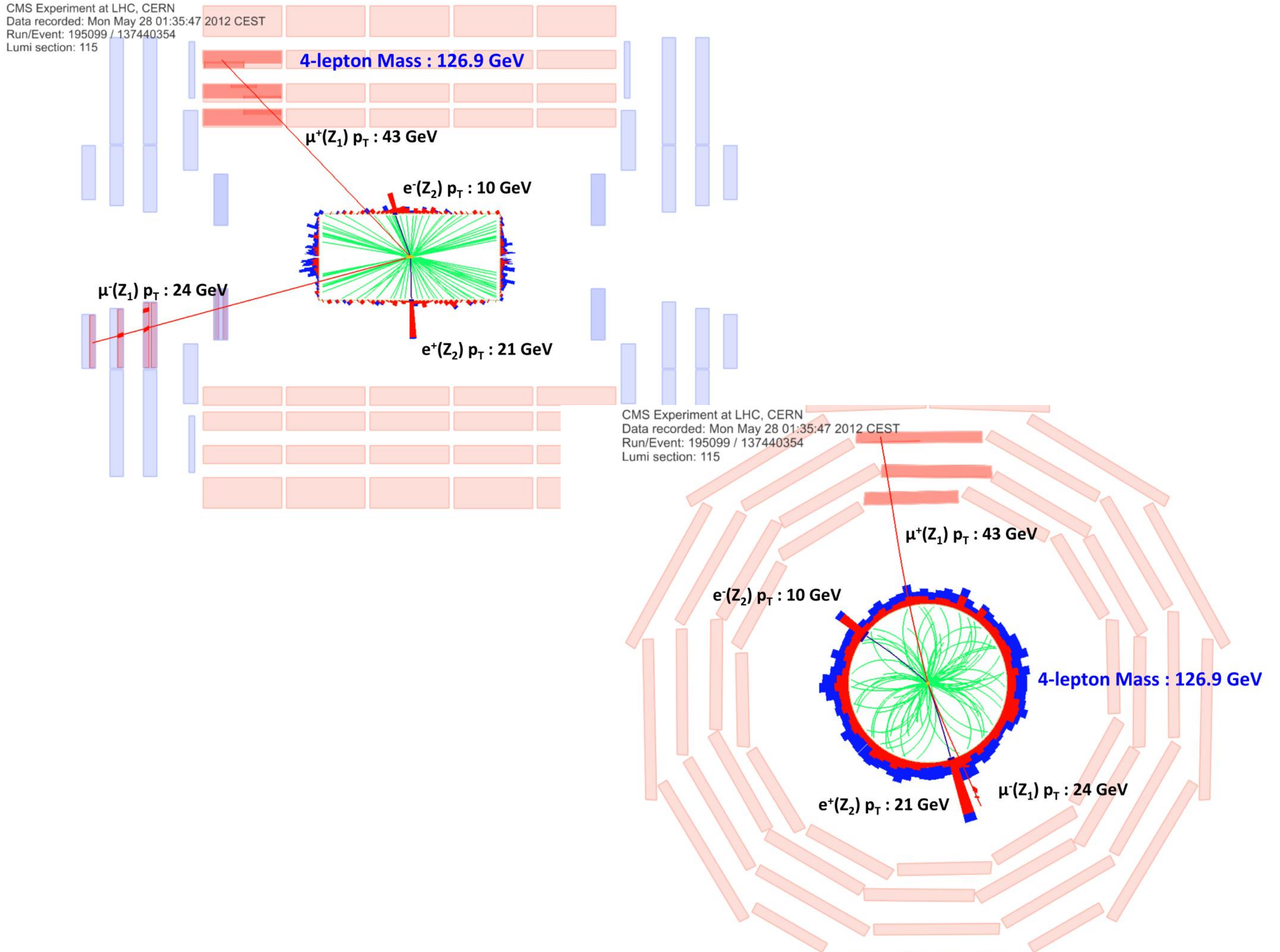
10% efficiency gain per lepton (same fake rate) wrt 2011

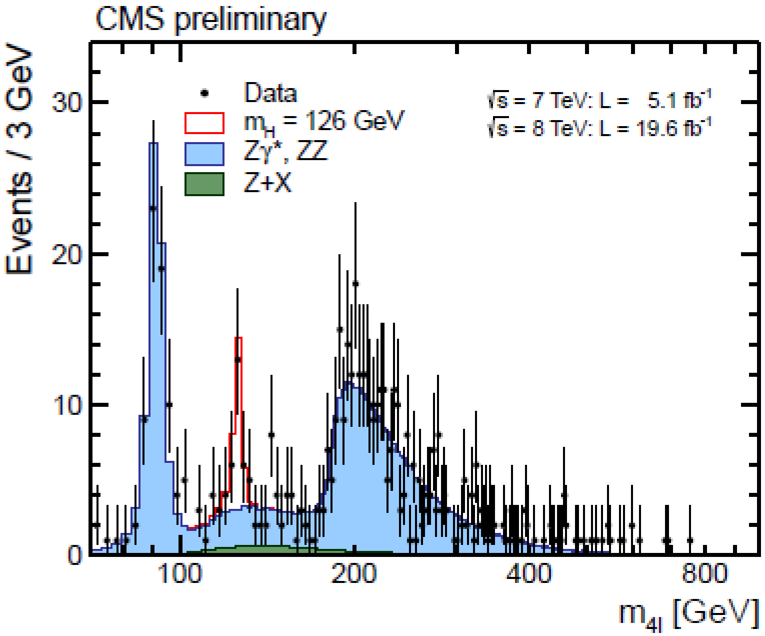
Blind analysis







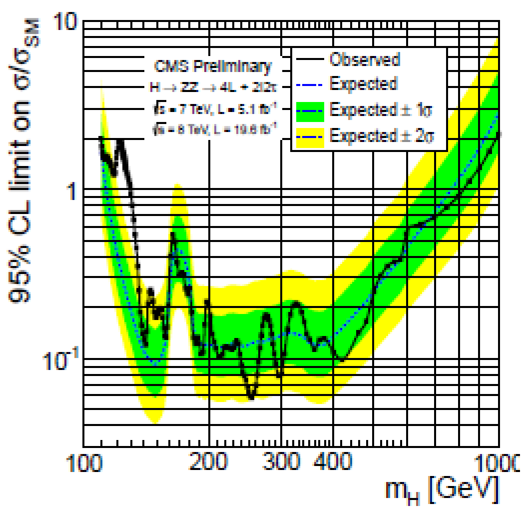

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
4-lepton Mass : 126.9 GeV
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
4-lepton Mass : 126.9 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV

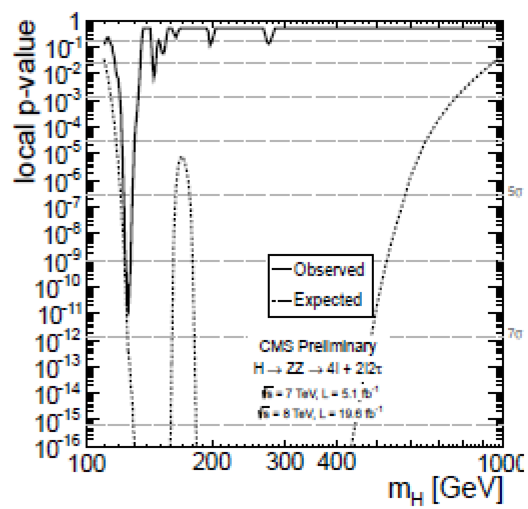


use of kinematic discriminant

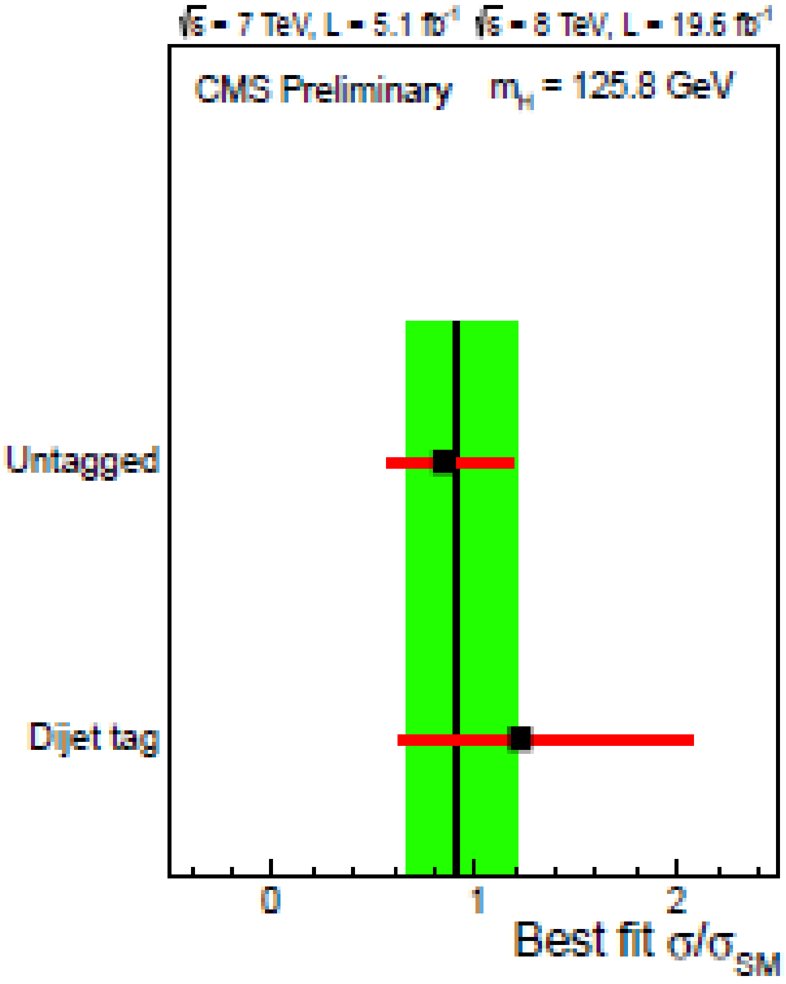
6.7 σ observed

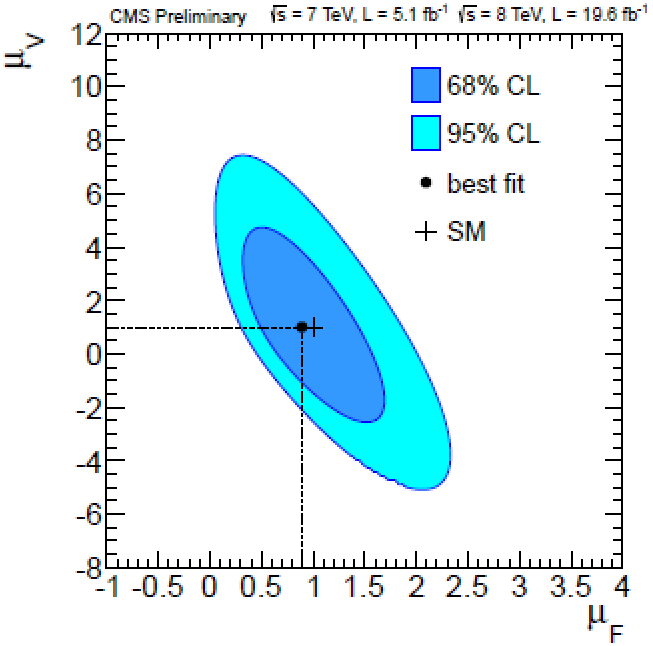
(7.2 σ expected)





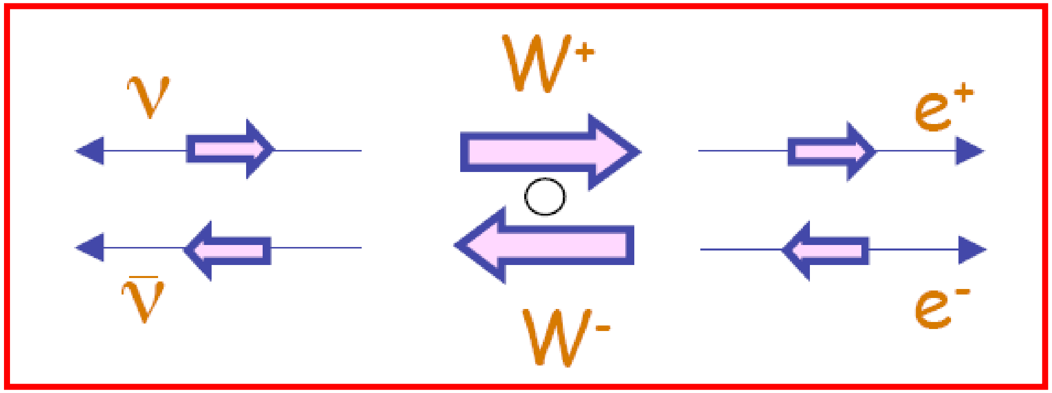
jet category



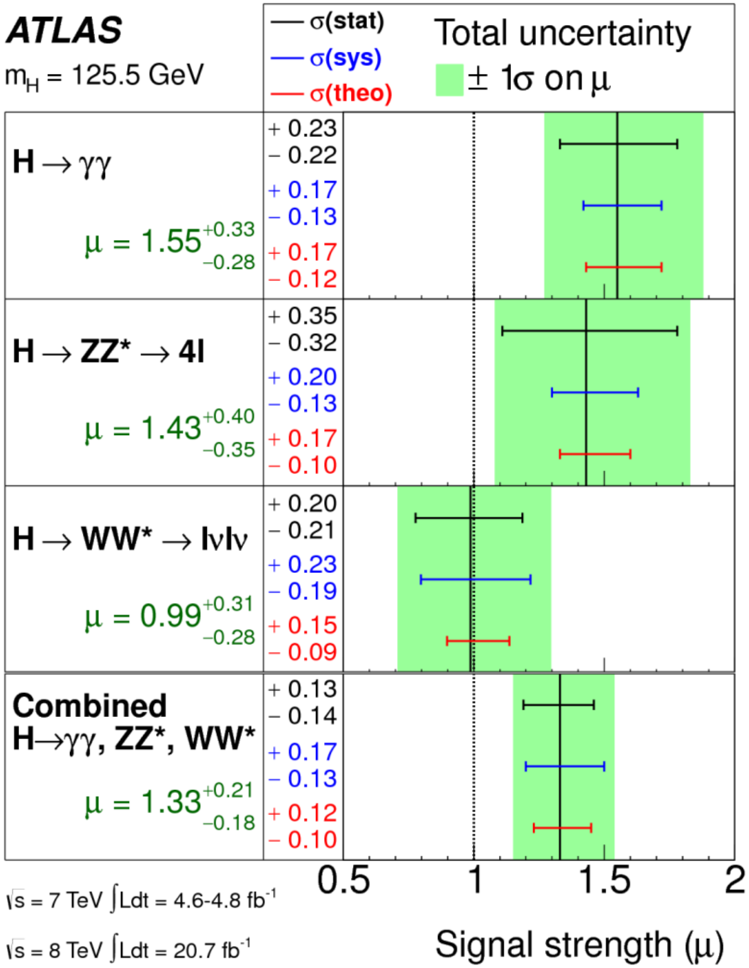


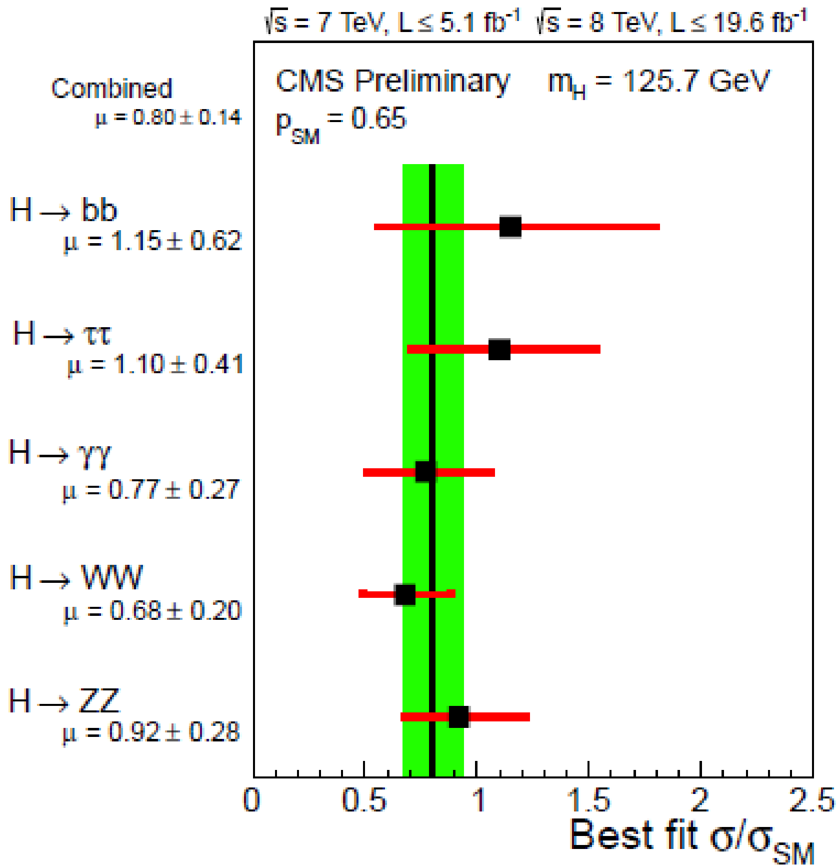
$H \rightarrow WW \rightarrow l\, \nu\, l\, \nu$

- ***Look at leptonic decays (e, μ)***
- ***2 neutrinos $\rightarrow$ no accurate mass information***
- ***Counting experiment : background understanding is critical***
  $\rightarrow$ control regions
- ***Analysis optimised for spin 0 :***
  cut on $\Delta\phi^{ll}$ + kinematical variables



all channels





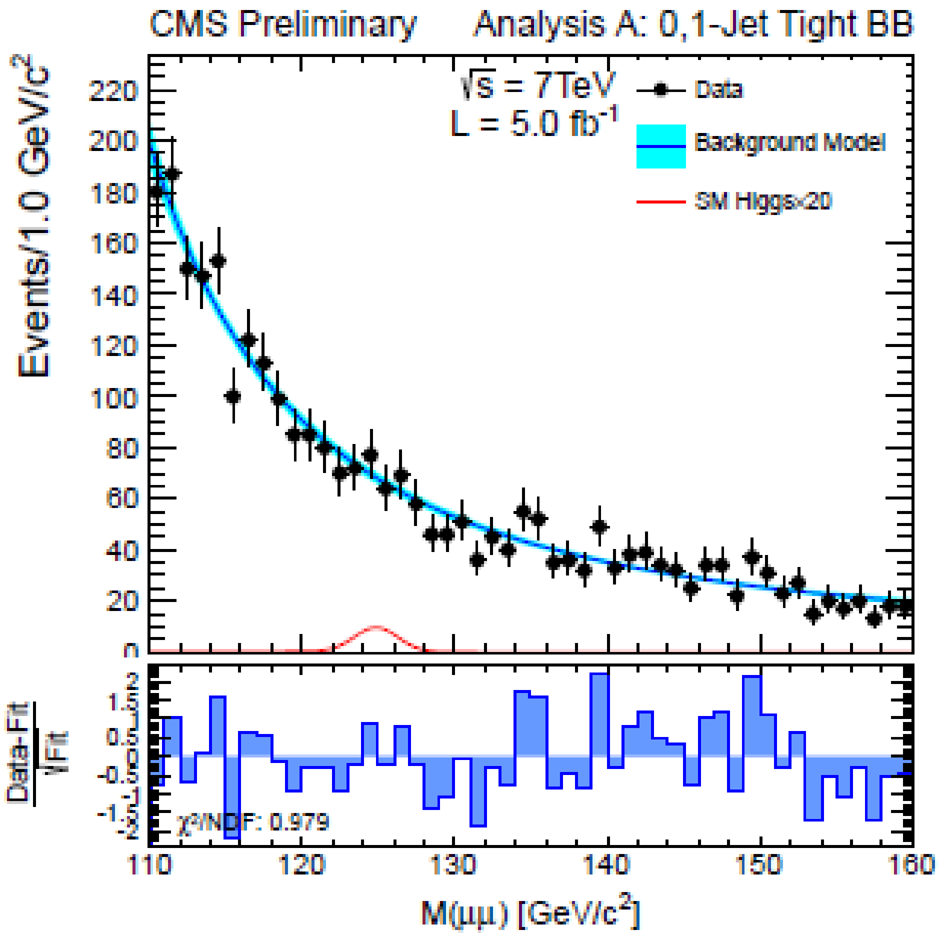
$\mu = \sigma / \sigma_{SM}$ **SM = SM boson**

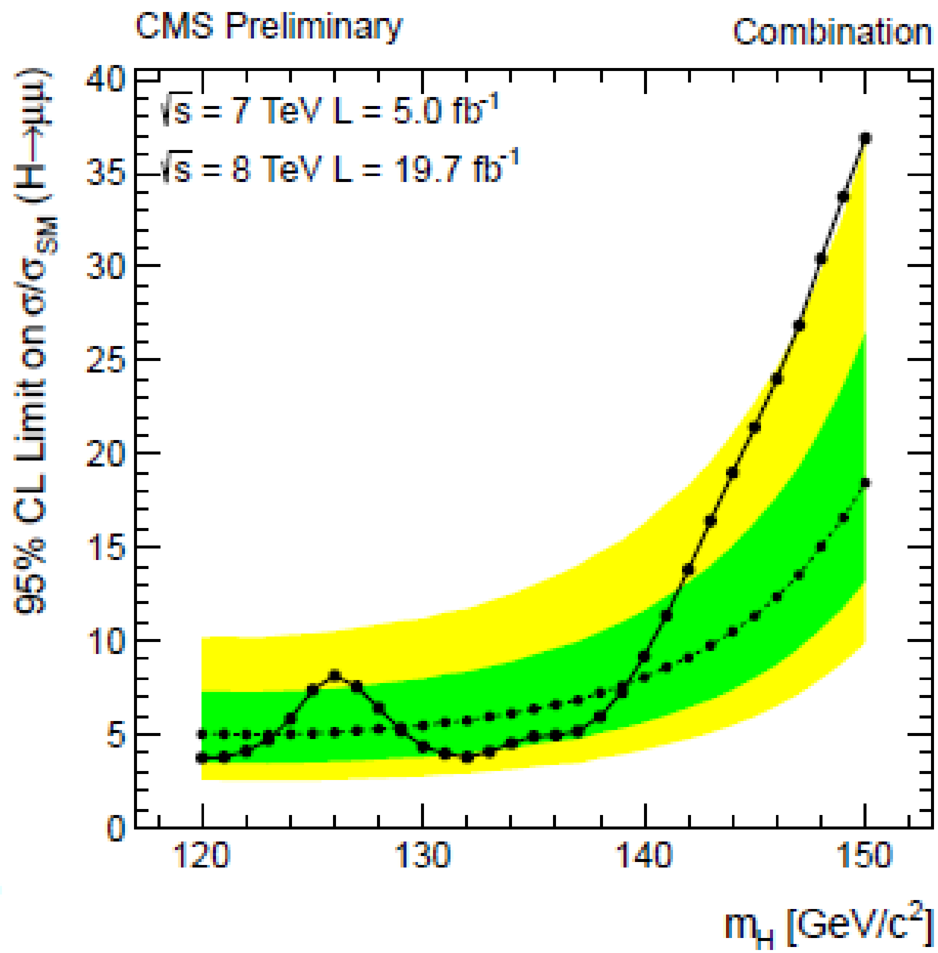
Cross sections are in agreement with the Standard Model

H→μμ

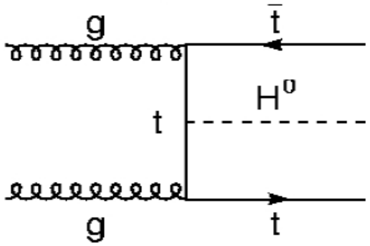
Table 1: Optimized event categories used in Analysis A and Analysis B.

A	**0,1-Jet**	**Tight** $p_T(\mu\mu) \geq 10$ GeV/c	**BB** (Barrel-Barrel)
			BO (Barrel-Overlap)
			BE (Barrel-Endcap)
			OO (Overlap-Overlap)
			OE (Overlap-Endcap)
			EE (Endcap-Endcap)
		Loose $p_T(\mu\mu) < 10$ GeV/c	**BB**
			BO
			BE
			OO
			OE
			EE
	2-Jet	**VBF Tight** $M(jj) > 650$ GeV/c^2 and $\lvert\Delta\eta(jj)\rvert > 3.5$	
		GF Tight (not VBF Tight selected) $M(jj) > 250$ GeV/c^2 and $p_T(\mu\mu) > 50$ GeV/c	
		Loose (not VBF Tight and not GF Tight selected)	
B	**0-Jet**	**Tight** ($p_T(\mu\mu) \geq 15$ GeV/c)	
		Loose ($p_T(\mu\mu) < 15$ GeV/c)	
	1-Jet	no subcategories	
	2-Jet	**VBF Tight** $M(jj) > 500$ GeV/c^2 and $\lvert\Delta\eta(jj)\rvert > 4$, **for 7 TeV** $\lvert\Delta\eta(jj)\rvert > 3$	
		VBF Loose (not VBF Tight selected) $M(jj) > 300$ GeV/c^2 and $\lvert\Delta\eta(jj)\rvert > 3$ **category used only for** $\sqrt{s} = 8$ **TeV**	
		non-VBF (not VBF Tight and not VBF Loose selected)	


CMS Preliminary
Analysis A: 0,1-Jet Tight BB
√s = 7TeV
L = 5.0 fb-1
Data
Background Model
SM Higgs×20
Events/1.0 GeV/c2
Data-Fit
√Fit
χ2/NDF: 0.979
M(μμ) [GeV/c2]


CMS Preliminary
Combination
√s = 7 TeV L = 5.0 fb-1
√s = 8 TeV L = 19.7 fb-1
95% CL Limit on σ/σSM (H→μμ)
mH [GeV/c2]

ttH

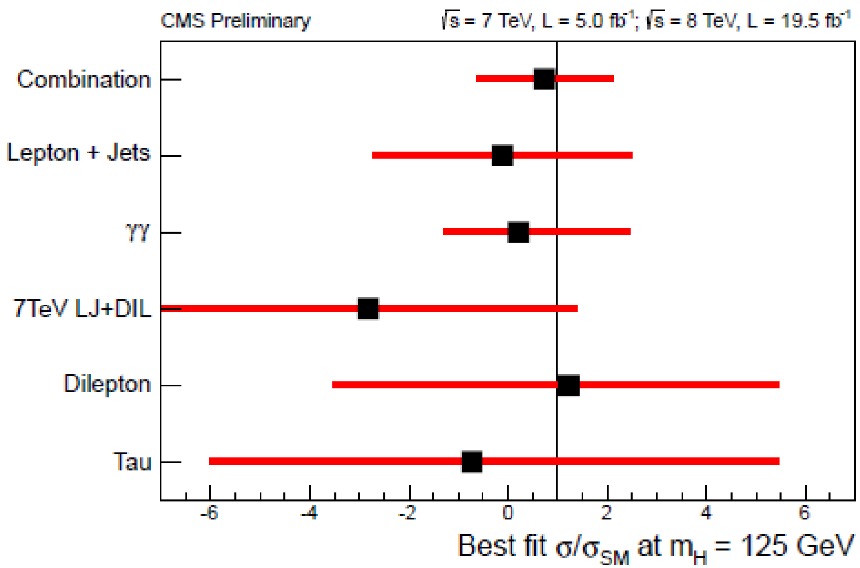


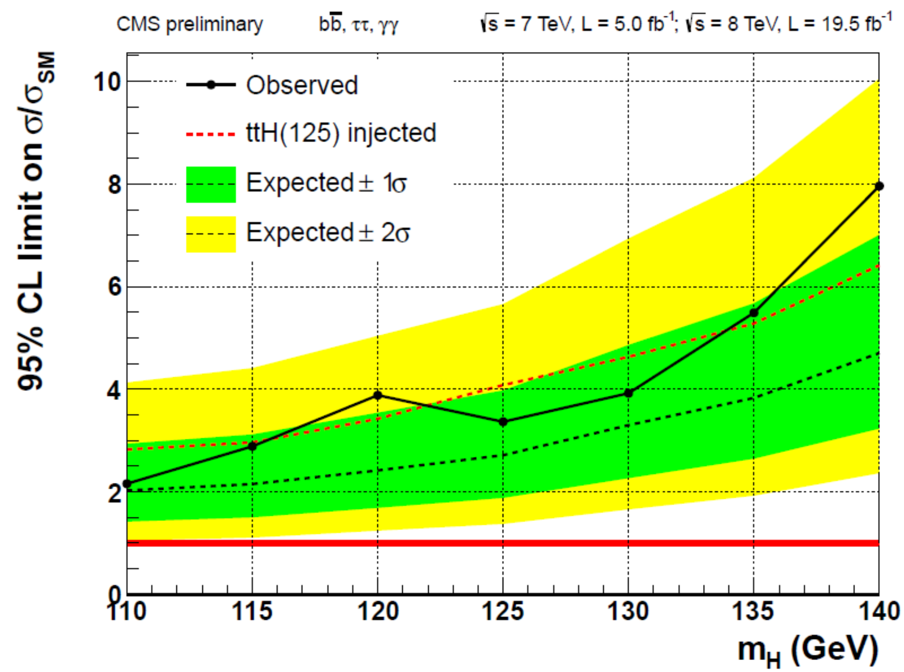
$$(t\bar{t} \to \ell\nu q\bar{q}'b\bar{b},\ H \to b\bar{b})$$

$$(t\bar{t} \to \ell^+\nu\ell^-\bar{\nu}b\bar{b},\ H \to b\bar{b})$$

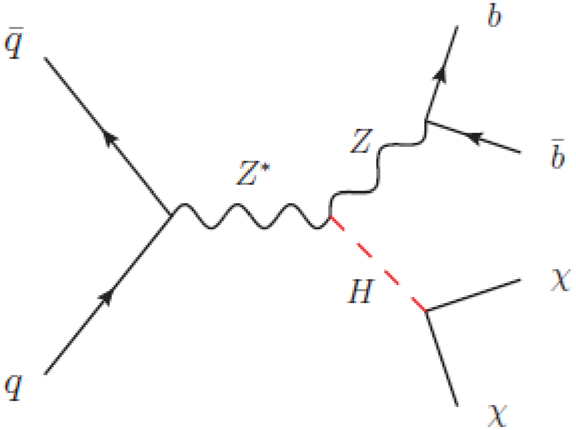
$$(t\bar{t} \to \ell\nu q\bar{q}'b\bar{b},\ H \to \tau^+\tau^-)$$

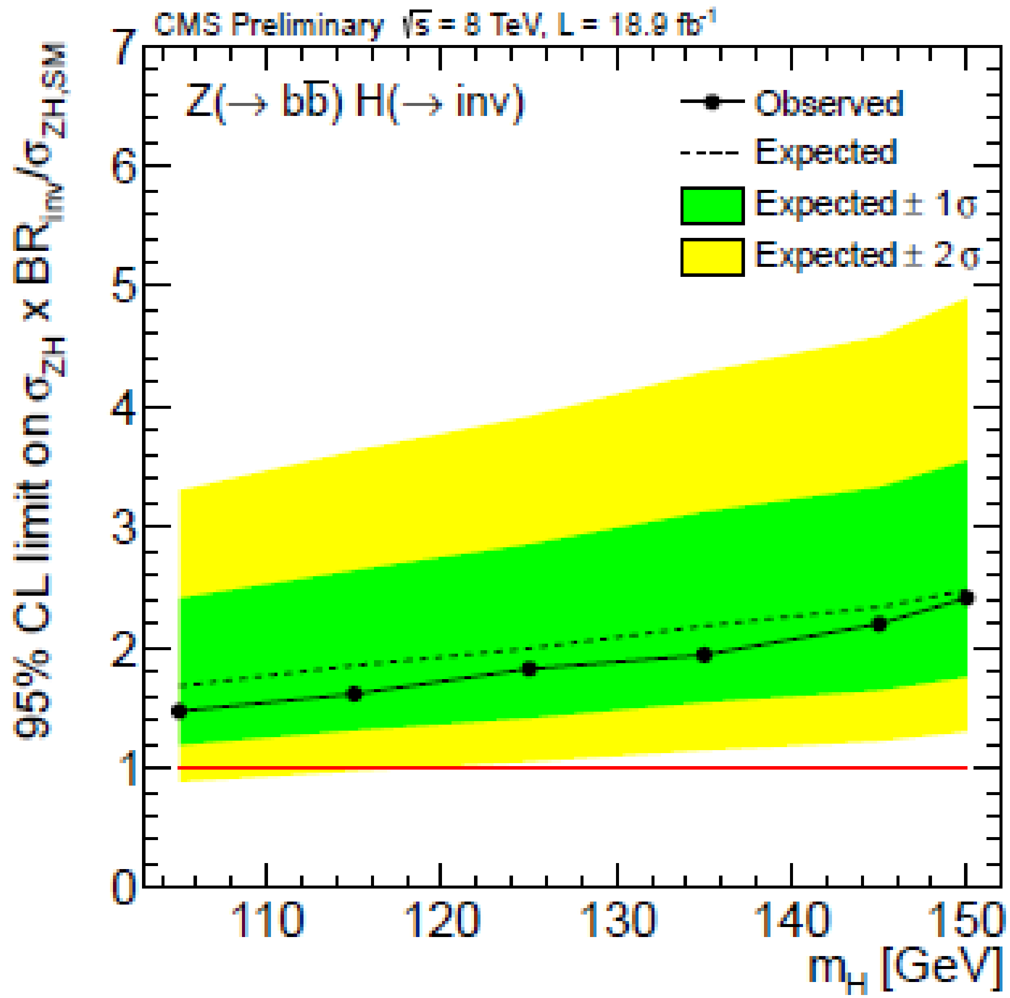
MVA techniques





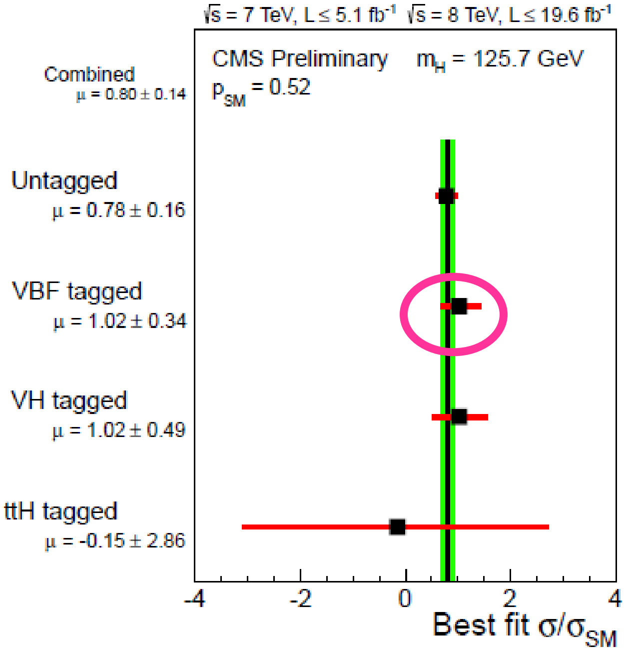
Inivisible H decays



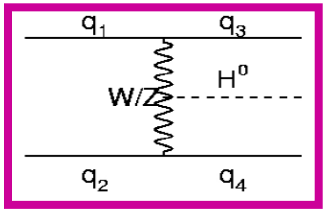


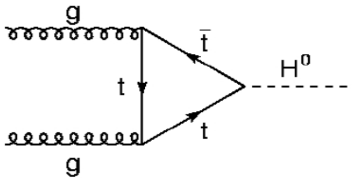
different production modes

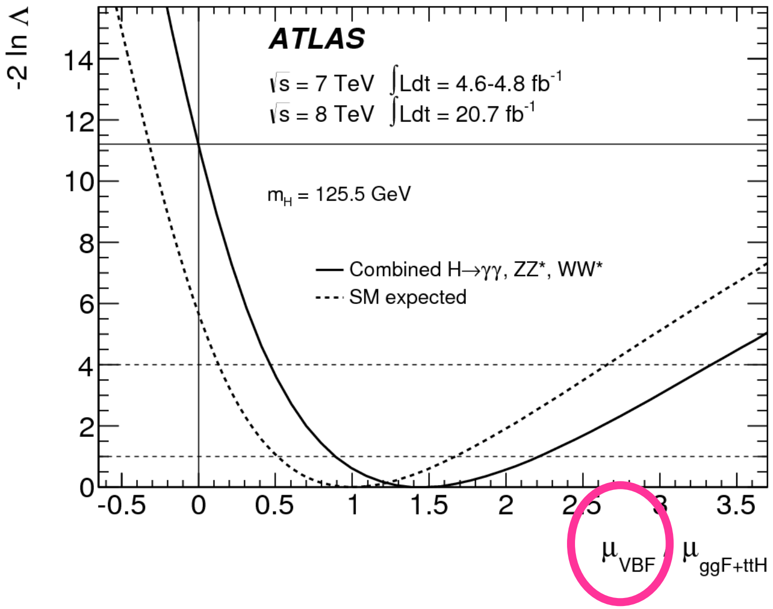
Measure of the ratios μ of the Cross sections w.r.t Standard Model cross sections for the different production modes of the boson



Good agreement with Standard Model

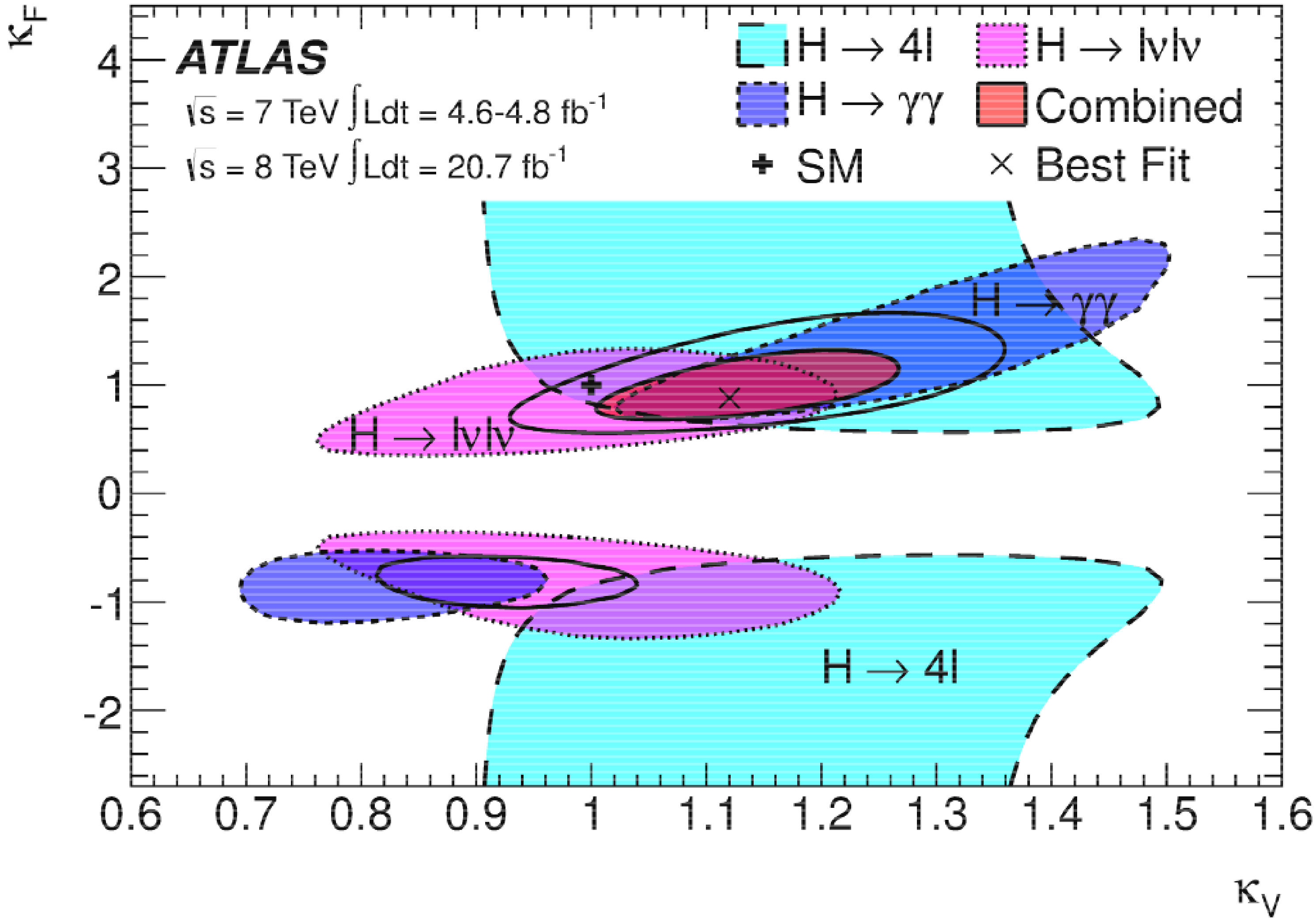




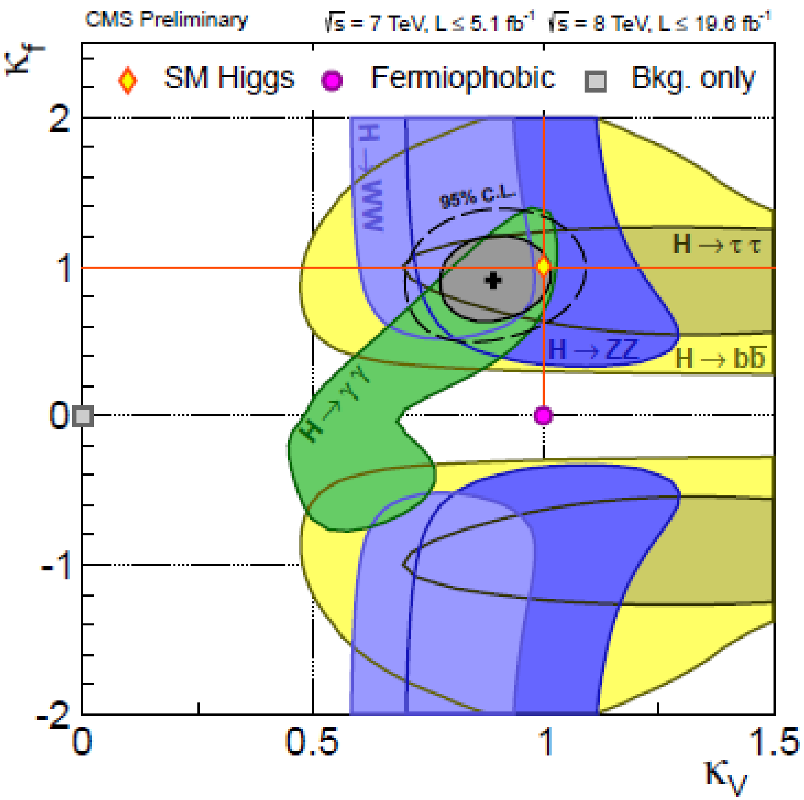


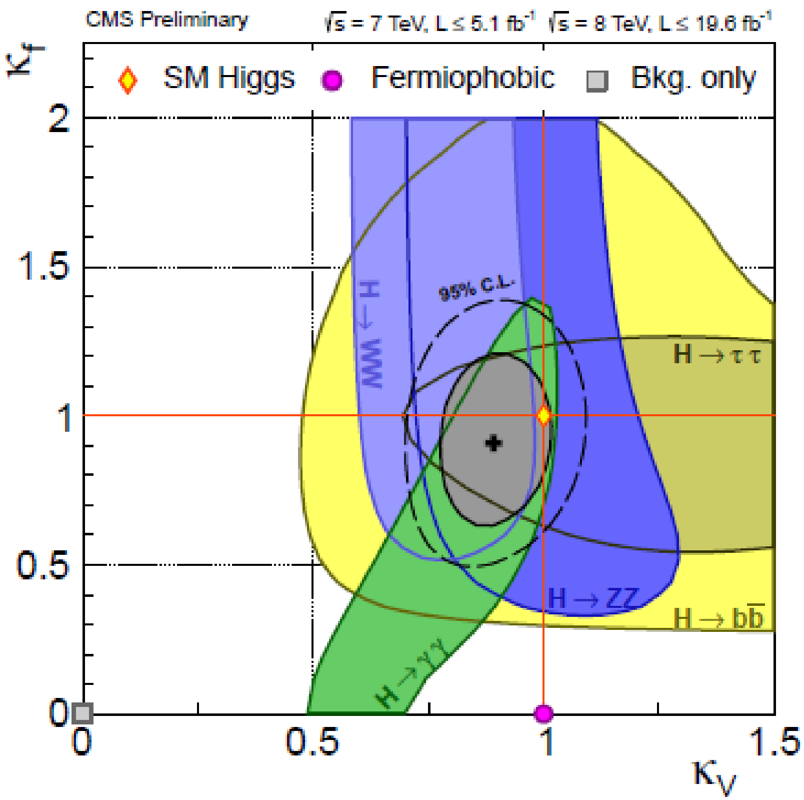
coupling scale factors

$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot B_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$


ATLAS
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
H → 4l
H → lνlν
H → γγ
Combined
SM
Best Fit
H → γγ
H → lνlν
H → 4l
κF
κV
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
4
3
2
1
0
-1
-2

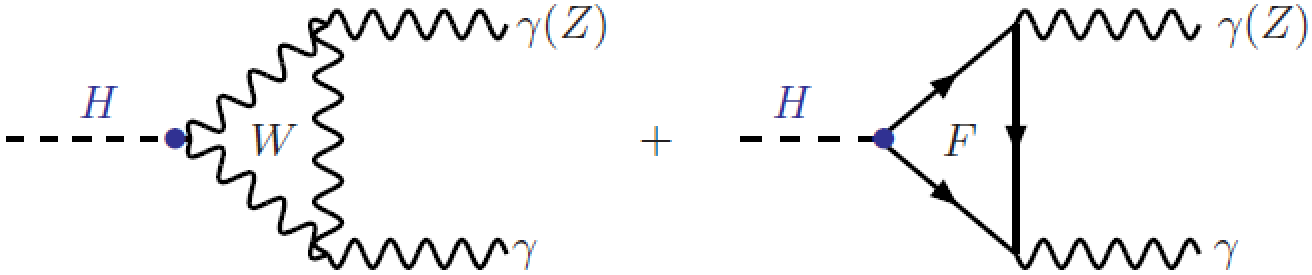
asymetry


CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
SM Higgs
Fermiophobic
Bkg. only
95% C.L.
H → WW
H → ττ
H → ZZ
H → bb̄
H → γγ
κ_f
κ_V


CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
SM Higgs
Fermiophobic
Bkg. only
95% C.L.
H → WW
H → ττ
H → ZZ
H → bb̄
H → γγ
κ_f
κ_V

Scalar boson decays : example of $H \rightarrow \gamma\gamma$

A.Djouadi Phys.Rept.457:1-216



Interference between

W loop ***top loop***

$$\Gamma\left(H \rightarrow \gamma\gamma\right) = \frac{G_\mu\, \alpha^2\, M_H^3}{128\, \sqrt{2}\, \pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

$\propto$ ***-.28*** ***+ 1.28***

No assumption on the total width

free parameters are κ_g, κ_γ and $BR_{inv.,undet.}$

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})} \Gamma_H^{SM}$$

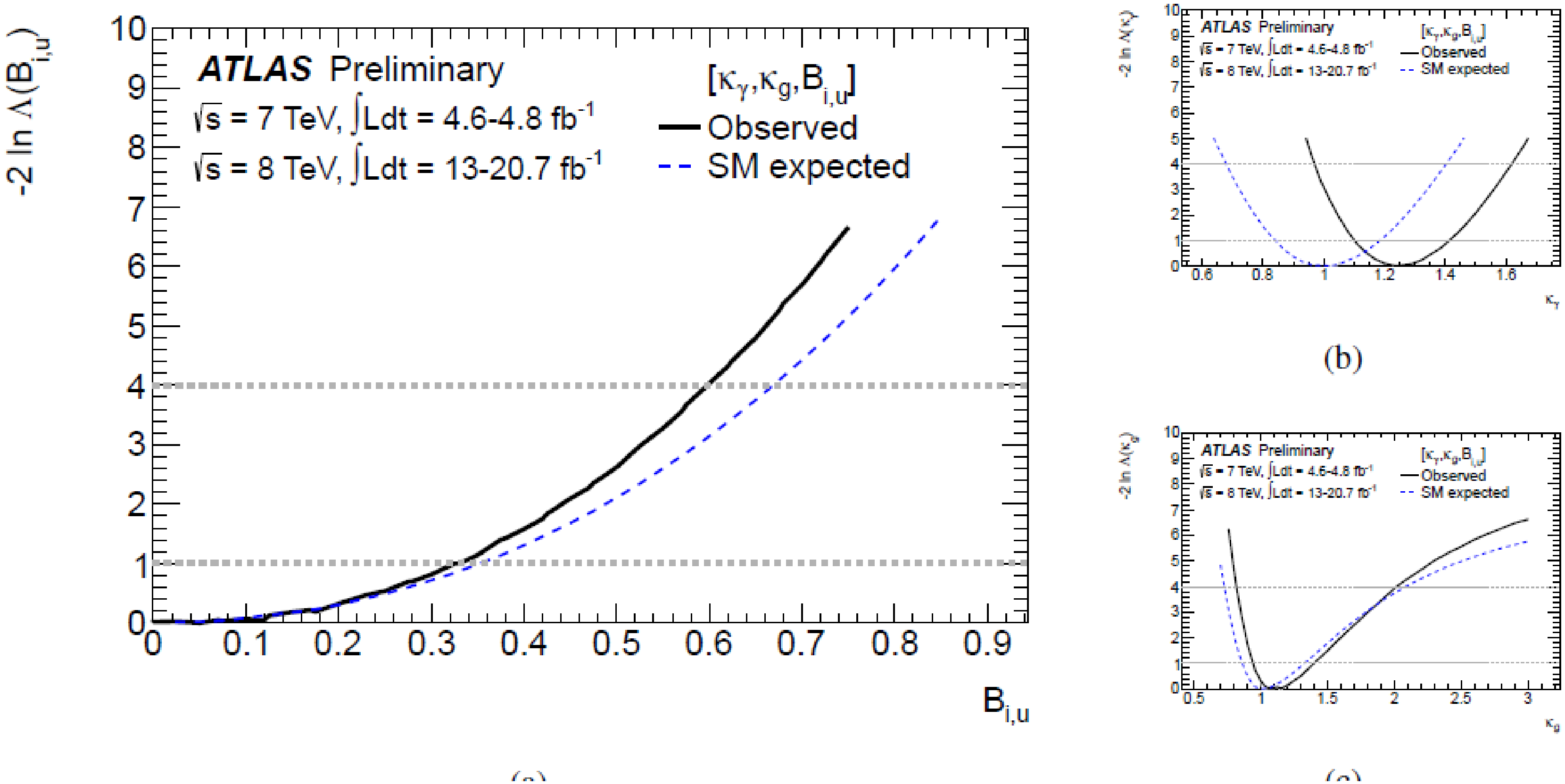
$$\sigma(gg \to H) * BR(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - BR_{inv.,undet.})$$

$$\sigma(qq' \to qq'H) * BR(H \to \gamma\gamma) \sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - BR_{inv.,undet.})$$

$$\sigma(gg \to H) * BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - BR_{inv.,undet.})$$

$$\sigma(qq' \to qq'H) * BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - BR_{inv.,undet.})$$

$$\sigma(qq' \to qq'H, VH) * BR(H \to \tau\tau, H \to b\bar{b}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - BR_{inv.,undet.})$$



$$\kappa_g = 1.08^{+0.32}_{-0.14}$$

$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$

$$BR_{inv.,undet.} < 0.33$$

mass

The two 'high precision' (ZZ , $\gamma\gamma$) channels give the mass

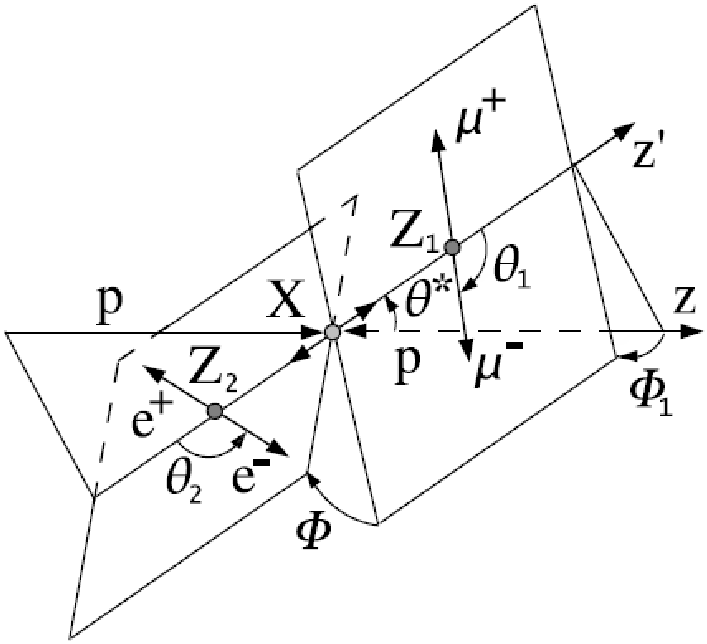
ATLAS : m = 125.5 $\pm$ .2 (stat) $^{+.5}_{-.6}$ (syst) GeV

CMS : m = 125.7 $\pm$ .3 (stat) $\pm$ .3 (syst) GeV

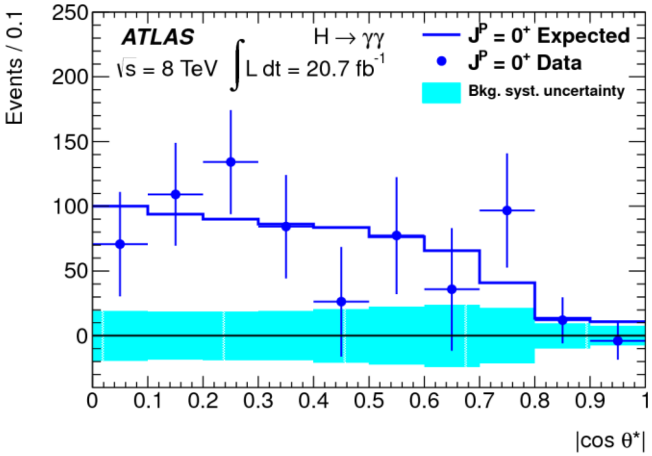
spin parity

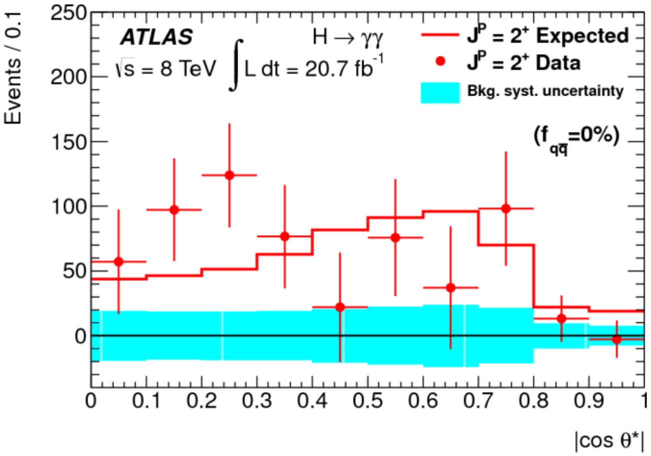
spin (and parity)

Everybody expected
spin 0 and
parity (*mainly*) +



Study of angular distributions



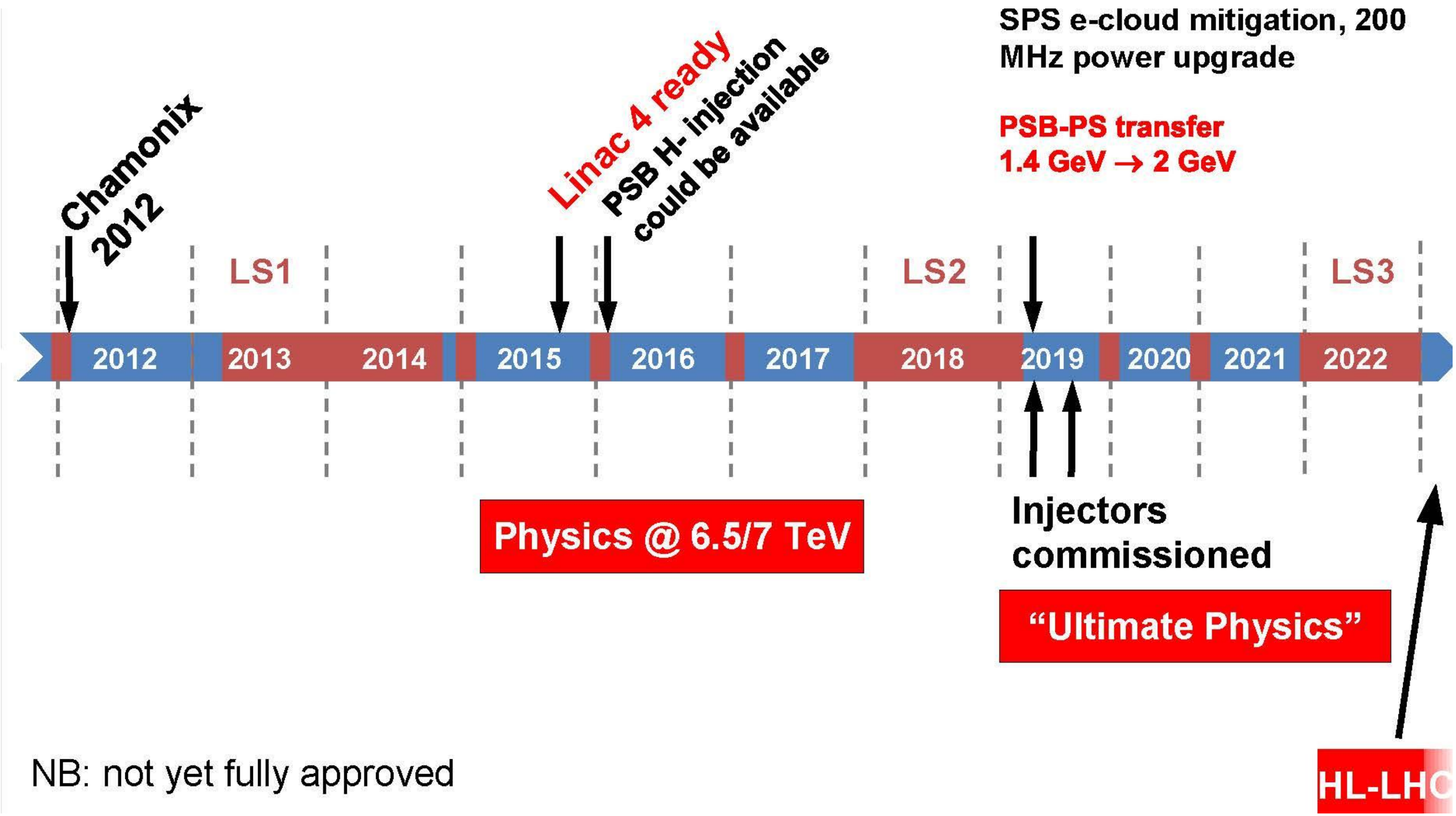


0+ well favorised w.r.t à 0- and 2+

(1 excluded : Landau-Yang theorem)

- ♥ Historical introduction of the boson and of the LHC
- ♥ Some phenomenological comments
- ♥ Rapid overview of the detectors
- ♥ The discovery
- ♥ The first measurements of the properties
- ♥ **The future of the physics with the scalar boson(s)**
- ♥ Backup (with references)

example LHC time line – next ten years



Ralph Steinhagen, ICHEP2012

LHC luminosity forecast

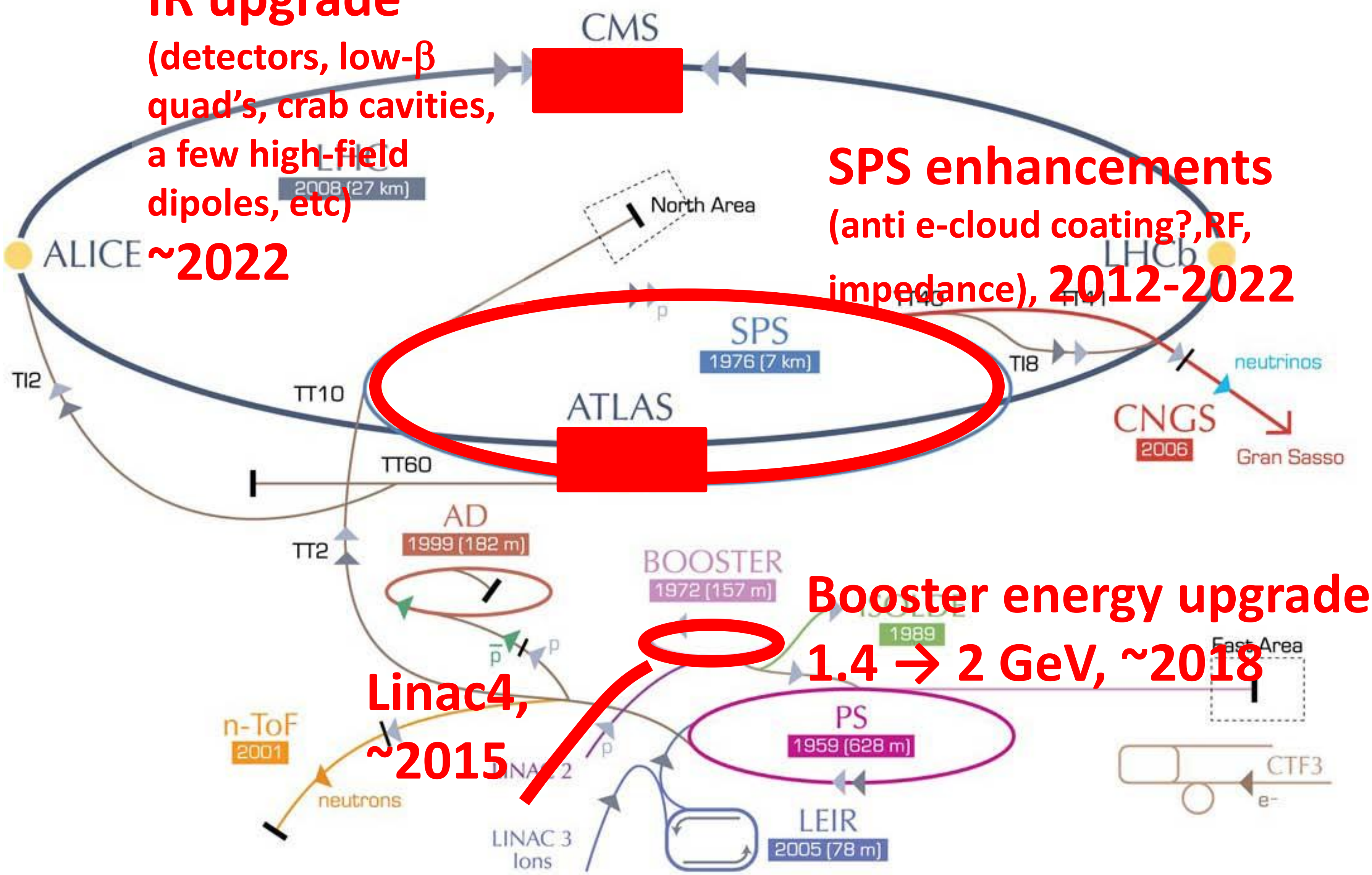
~30/fb at 3.5 & 4 TeV **2012 DONE**

~400/fb at 6.5-7 TeV **2021 goal (?)**

~3000/fb at 7 TeV **2035 goal (??)**

to obtain 3000/**fb** ***by 2035***
we need the HL-LHC

HL-LHC – modifications



IR upgrade
(detectors, low-β quad's, crab cavities, a few high-field dipoles, etc)
~2022

SPS enhancements
(anti e-cloud coating?,RF, impedance), **2012-2022**

Booster energy upgrade
1.4 → 2 GeV, ~2018

Linac4, ~2015

HL-LHC Official Beam Parameters

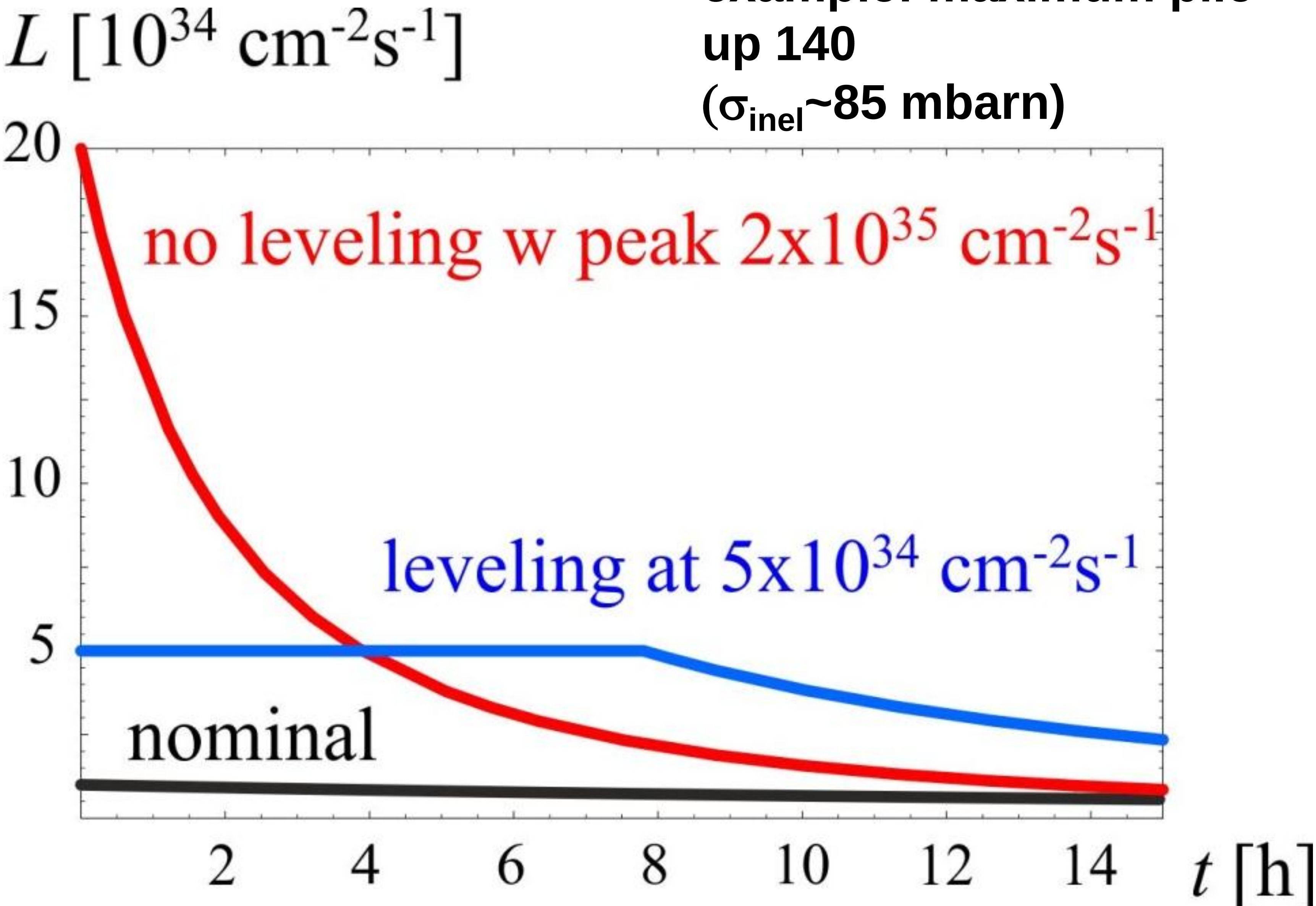
Parameter	nominal	25ns	50ns		
N	1.15E+11	**2.2E+11**	**3.5E+11**		
n_b	2808	2808	1404		
beam current [A]	0.58	**1.12**	**0.89**		
x-ing angle [μrad]	300	590	590		
beam separation [σ]	10	12.5	11.4		
β* [m]	0.55	**0.15**	**0.15**		
ε_n [μm]	3.75	2.5	3.0		
ε_L [eVs]	2.51	2.5	2.5		
energy spread	1.20E-04	1.20E-04	1.20E-04		
bunch length [m]	7.50E-02	7.50E-02	7.50E-02		
IBS horizontal [h]	106	**20.0**	**20.7**		
IBS longitudinal [h]	60	**15.8**	**13.2**		
Piwinski parameter	0.68	**3.1**	**2.9**		
geom. reduction	0.83	**0.35**	**0.33**		
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**		
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**		
Virtual Luminosity	$1.2\ 10^{?4}$	**$21\ 10^{34}$**	**$26\ 10^{34}$**		
Events / crossing (peak & leveled L	[illegible]	**210**	**475**	**140**	**140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

(Leveled to $5\ 10^{34}$ cm^{-2} s^{-1} and $2.5\ 10^{34}$ cm^{-2} s^{-1})

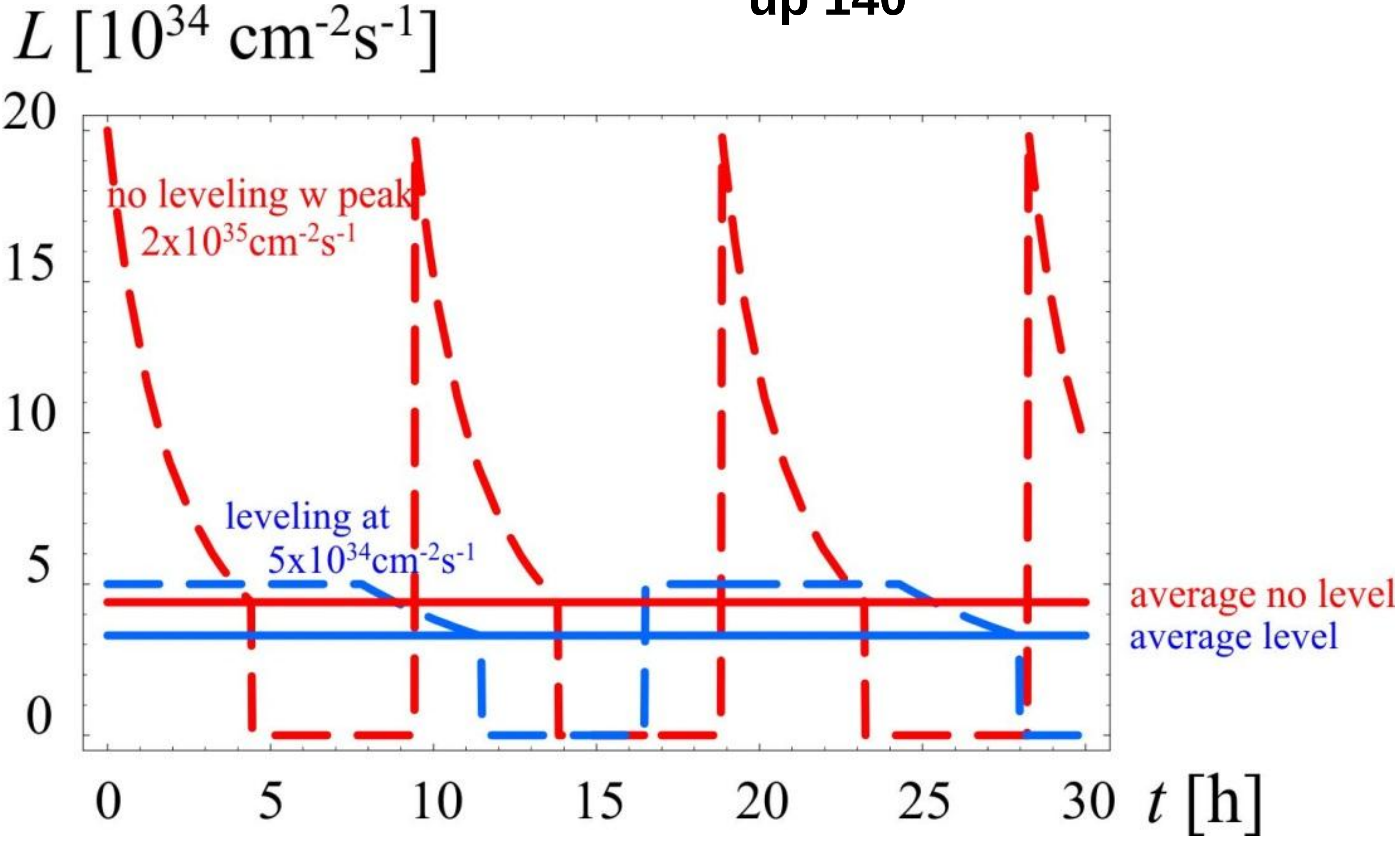
luminosity leveling at the HL-LHC

example: maximum pile up 140 (σ_{inel}~85 mbarn)



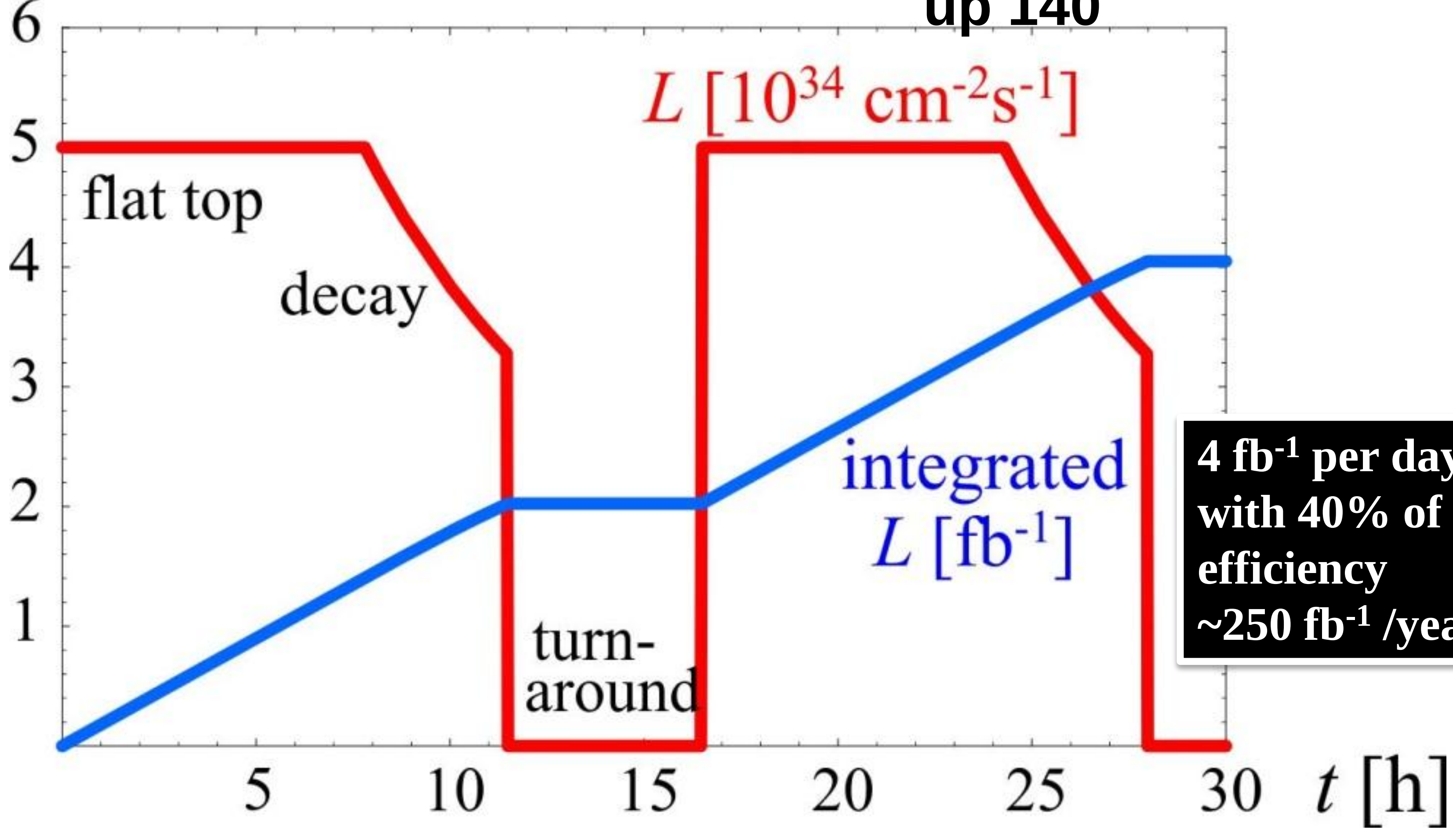
luminosity leveling at the HL-LHC

example: maximum pile up 140



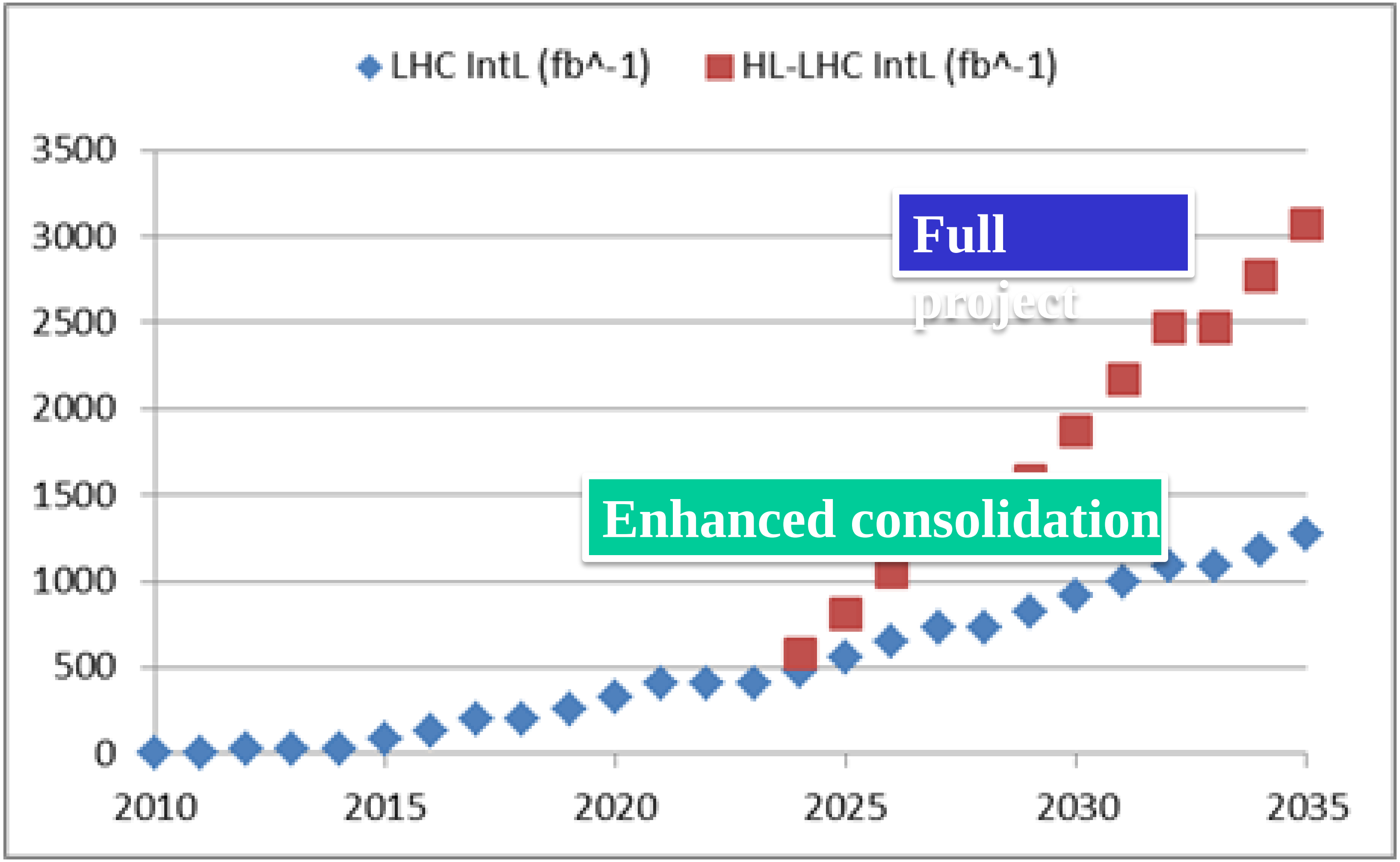
luminosity & integrated luminosity during 30 h at the HL-LHC

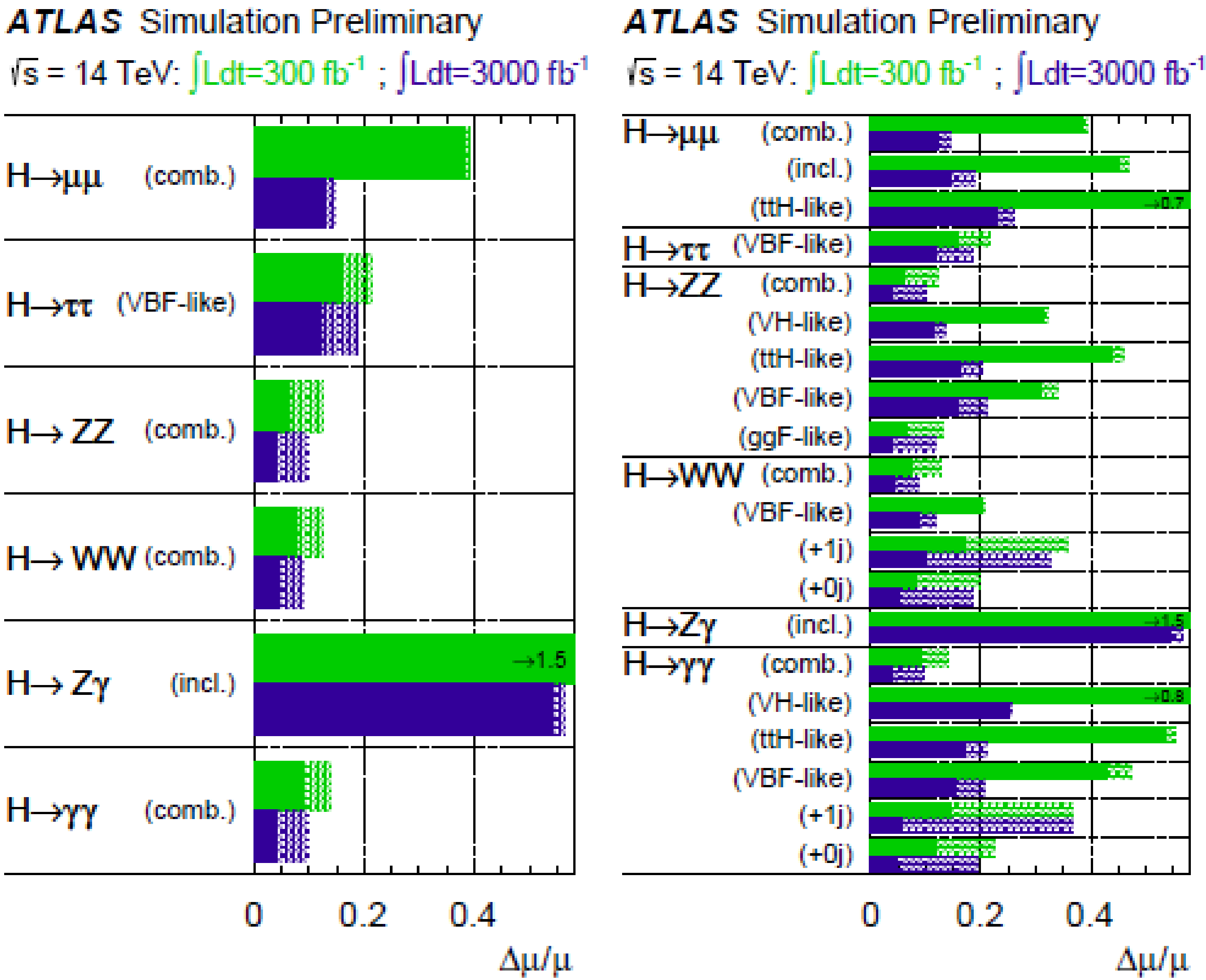
example: maximum pile up 140



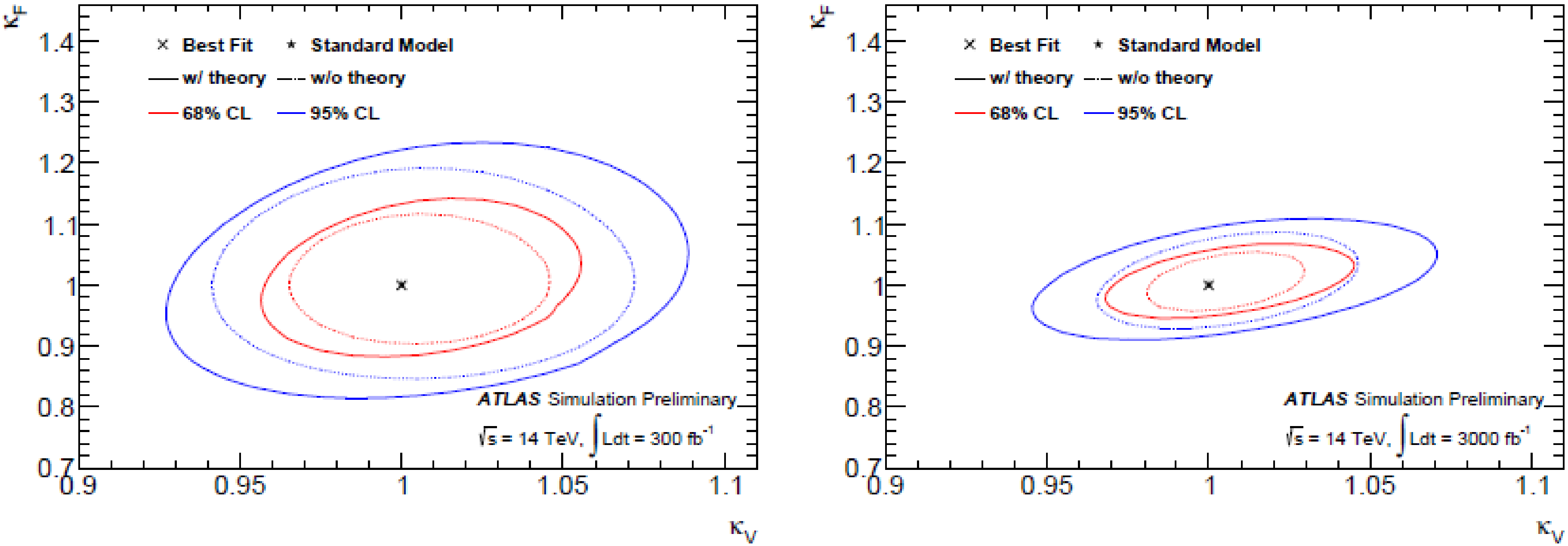
4 fb^{-1} per day, with 40% of efficiency ~250 fb^{-1} /year

final goal : 3000 fb^{-1} by 2030's…



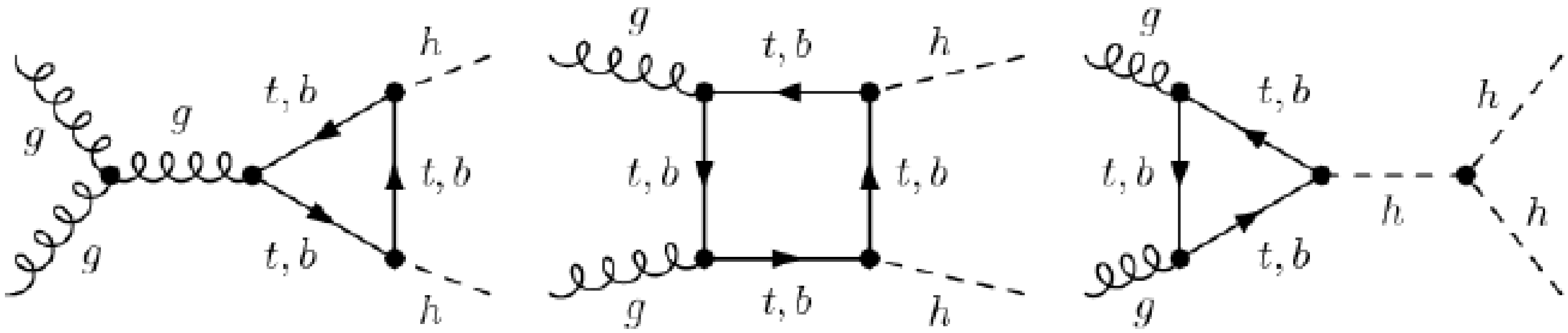


ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb⁻¹ ; ∫Ldt=3000 fb⁻¹
H→μμ (comb.)
H→ττ (VBF-like)
H→ZZ (comb.)
H→WW (comb.)
H→Zγ (incl.)
H→γγ (comb.)
→1.5
0
0.2
0.4
Δμ/μ
ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb⁻¹ ; ∫Ldt=3000 fb⁻¹
H→μμ (comb.)
(incl.)
(ttH-like)
→0.7
H→ττ (VBF-like)
H→ZZ (comb.)
(VH-like)
(ttH-like)
(VBF-like)
(ggF-like)
H→WW (comb.)
(VBF-like)
(+1j)
(+0j)
H→Zγ (incl.)
→1.5
H→γγ (comb.)
(VH-like)
→0.8
(ttH-like)
(VBF-like)
(+1j)
(+0j)
0
0.2
0.4
Δμ/μ



κF
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.9
0.95
1
1.05
1.1
κV
Best Fit
Standard Model
w/ theory
w/o theory
68% CL
95% CL
ATLAS Simulation Preliminary
√s = 14 TeV, ∫Ldt = 300 fb⁻¹
√s = 14 TeV, ∫Ldt = 3000 fb⁻¹

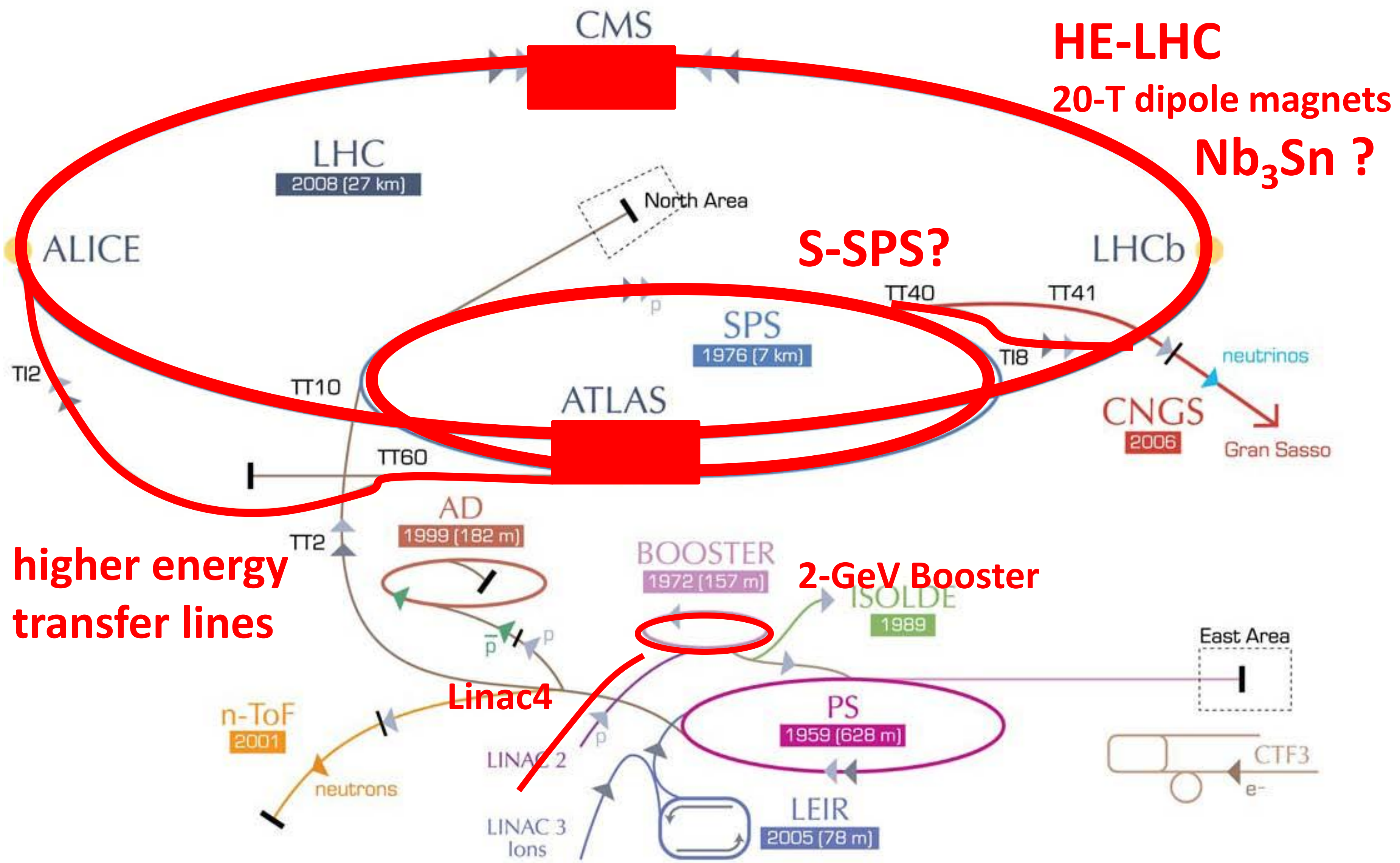
H pair production



last diagram, the only one that depends on λ_{HHH}, interferes destructively with the first two. The cross section is therefore enhanced at lower values of λ_{HHH}. For $\lambda_{HHH}/\lambda_{HHH}^{SM} = 0$ (2) the cross section is 71 (16) fb. Studies using Higgs pair decays to $b\bar{b}\gamma\gamma$ and $b\bar{b}W^+W^-$ are in progress.


beyond HL-LHC?

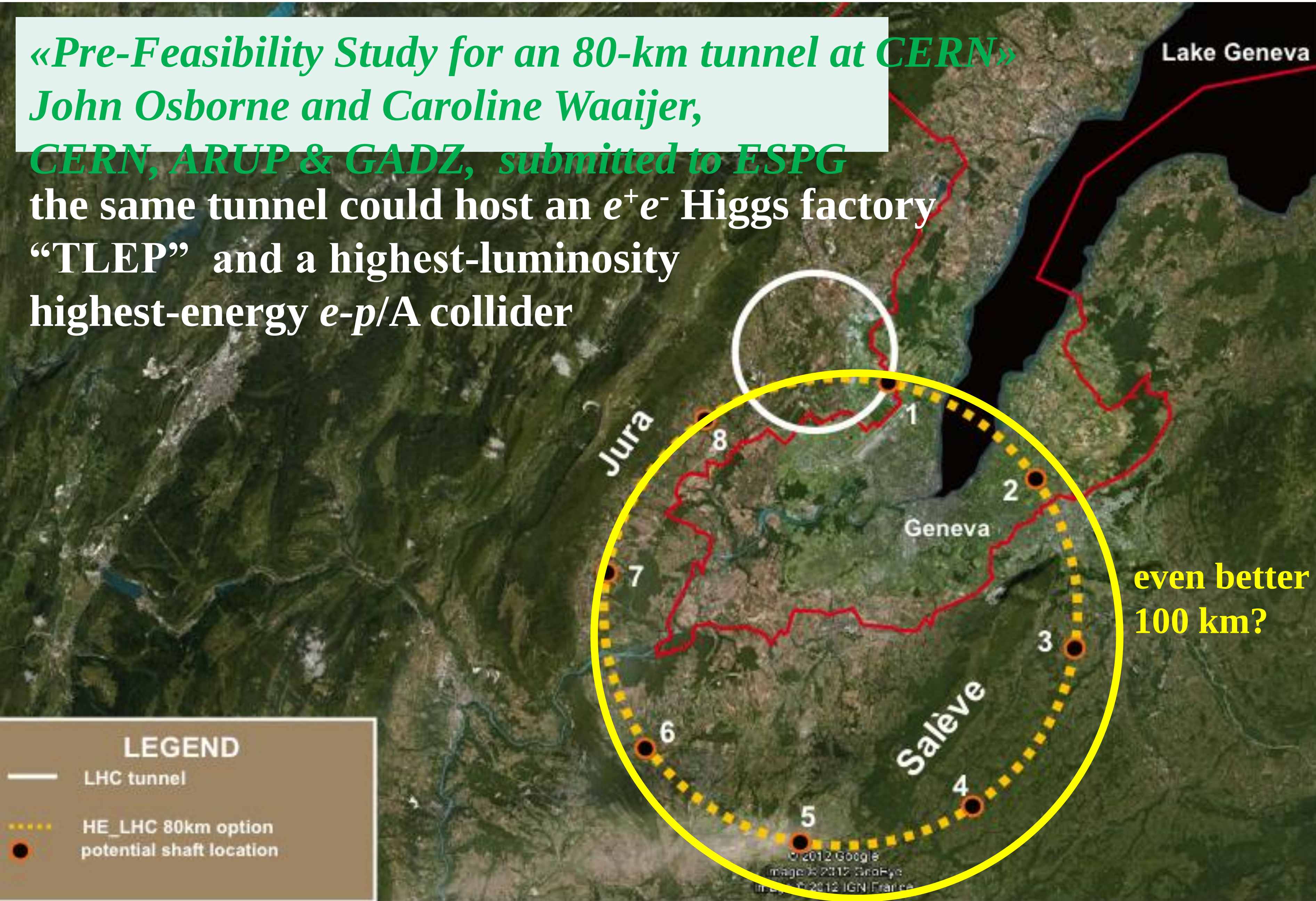
High-Energy LHC



80-km tunnel for VHE-LHC – “best” option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG

the same tunnel could host an e^+e^- Higgs factory “TLEP” and a highest-luminosity highest-energy *e-p*/A collider



even better 100 km?

HE-LHC & VHE-LHC parameters

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	≤ 40
beam half aperture [cm]	~ 2	~ 2	1.3	≤ 1.3
injection energy [TeV]	0.45	0.45	>1.0	>3.0
no. of bunches n_b	2808	2808	2808	8420
bunch population N_b [10^{11}]	1.15	2.2	0.94	0.97
init. transv. norm. emit. [μm]	3.75	2.5	1.38	2.15
initial longitudinal emit. [eVs]	2.5	2.5	3.8	13.5
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.478	0.492
rms bunch length [cm]	7.55	7.55	7.55	7.55
IP beta function [m]	0.55	0.15 (min.)	0.35	1.1
rms IP spot size [μm]	16.7	7.1 (min.)	5.2	6.7
full crossing angle [μrad]	285	590	185	72
stored beam energy [MJ]	362	694	701	6610

O. Dominguez, L. Rossi, F.Z.

HE-LHC & VHE-LHC parameters

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
SR power per ring [kW]	3.6	7.3	96.2	2900
arc SR heat load [W/m/aperture]	0.17	0.33	4.35	43.3
energy loss per turn [keV]	6.7	6.7	201	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	2.0	1.9	2.0
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	23.3	40	396
init. horiz. IBS emit. rise time [h]	103	10.4	20	157
peak events per crossing	27	135 (lev.)	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
beam lifetime due to burn off [h]	45	15.4	5.7	14.8
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.4	2.1

O. Dominguez, L. Rossi, F.Z

pp Higgs factories

LHC is the 1st Higgs factory!
E_{CM}=8-14 TeV, $\widehat{L}\sim10^{34}cm^{-2}s^{-1}$

1 M Higgs produced so far – more to come!
15 H bosons / min – and more to come

HL-LHC (~2022-2030):
E_{CM}=14 TeV, $L\sim5x10^{34}cm^{-2}s^{-1}$ (leveled)

10x more Higgs

HE-LHC: in LHC tunnel (2035-?)
E_{CM}=33 TeV, L = $5x10^{34}cm^{-2}s^{-1}$

6x higher cross section for *H* self coupling

VHE-LHC in new 80-100 km tunnel (2040?)
E_{CM}=84-104 TeV, L = $5x10^{34}cm^{-2}s^{-1}$

42x higher cross section for *H* self coupling

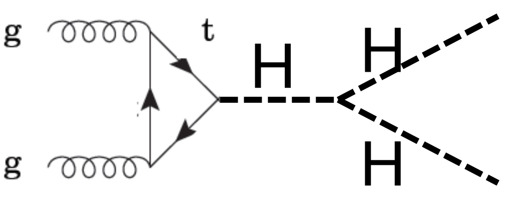
pp Higgs coupling cross sections vs c.m. energy

M. Mangano

HE-LHC VHE-LHC

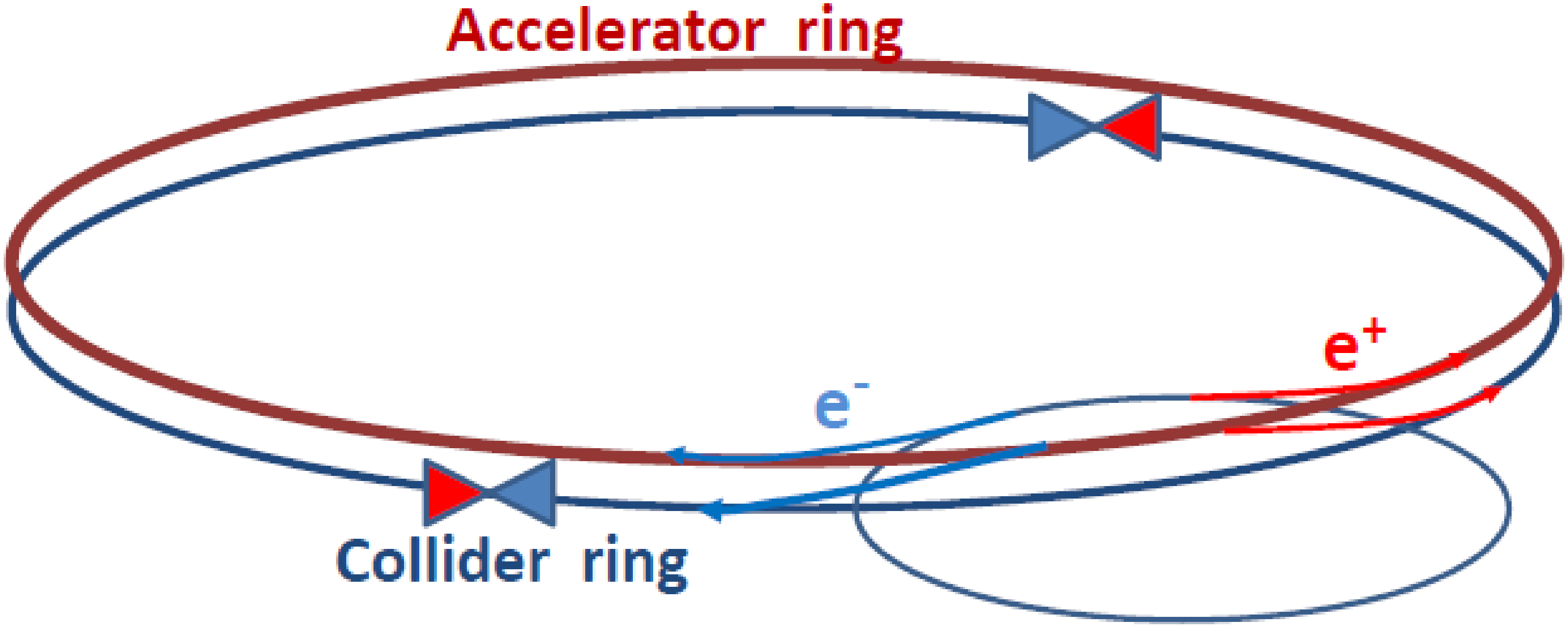
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

➔ **high statistics studies of ttH**
… and, at long last, HHH couplings



VHE-LHC is ultimate machine to measure Higgs self coupling! (~2-5% level)

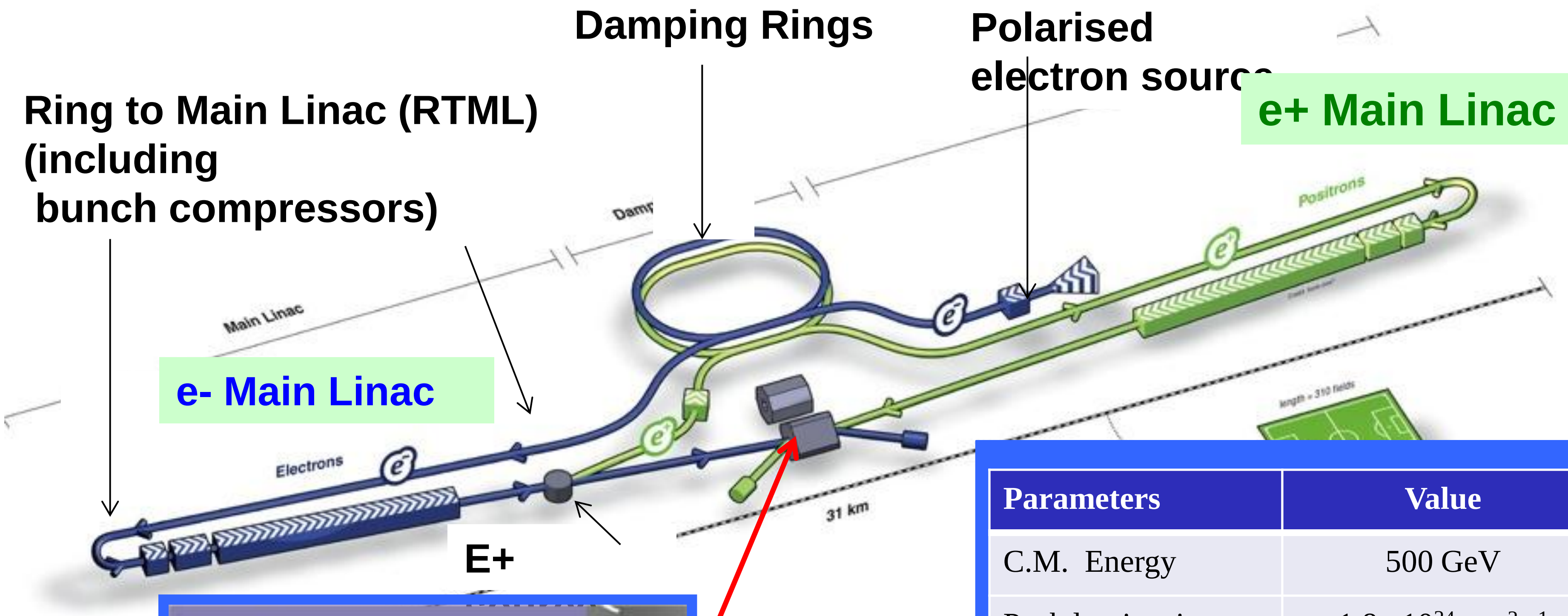
TLEP - circular e^+e^- colliders to study the «Higgs boson» X(126)

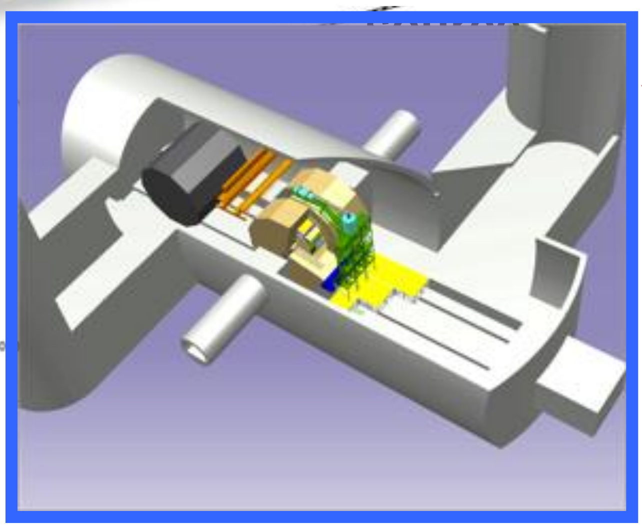


A. Blondel

a relatively young concept (2011)

ILC TDR Layout





Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /exp	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

(*) The total luminosity is the sum of the integrated luminosity a

TLEP Circular e^+e^- Higgs Factory goes to precision at few permil level.

conclusions

Discovery in 2012 of the (Brout-Englert) Higgs boson

Culmination of the work of more than 20 years at the LHC

- **conception of the detectors**
- **research and development**
- **construction**
- **analysis**

Important work of theorists

He looks standard

Start of a new era
detailed studies of the boson to do

LHC stops during 2 years then starts at higher energy
We hope to increase by 10 (even 100) the number of bosons detected

A lot of questions :
how standard is he ?
how many bosons ?

Why there is no antimatter in the universe
Understand the neutrino masses
Undertand dark matter
Understand unification of the 3/4 forces

1. What is the origin of the great disparity in the energy scales associated with the weak and gravitational forces? This is the hierarchy problem. It has two pieces: 1) why is there such a large disparity 2) the problem of fine tuning: any new energy threshold much above the masses of the W and Z bosons, such as the Planck scale or unification scale, tends to destabilize the Higgs boson mass through quantum corrections.
2. Where do the parameters of the SM originate?
3. Do the strong and electroweak forces unify at some energy scale?
4. Why is the strong interaction CP conserving? Is this accounted for by an axion field, and does this axion constitute some or all of the dark matter?
5. The quarks and leptons present many mysteries. Why are there repetitive generations? What accounts for the hierarchical structure of the masses and mixings of the quarks and charged leptons?
6. The discovery of neutrino mass has raised new questions. What is the energy scale associated with the generation of neutrino mass? Are neutrinos their own anti-particles?
7. The observed CP violation in the SM is insufficient to account for the baryon asymmetry of the Universe. What phenomena might account for this? Might they be accessible to experiments at the Energy or Intensity Frontiers?
8. What is the identity of the dark matter which makes up 25% of the energy density of the Universe?
9. What is the origin of the dark energy which makes up 70% of the energy density? Why is it just becoming important at the present epoch of the Universe?
10. What caused the inflationary epoch, and how did the Universe end up in its current state?
11. What is the nature of the quantum theory of gravitation?
12. From what set of principles or structures do the laws of nature originate?

arXiv:1310.6111 M. Dine; K. Babu, C. Csaki, S. Dawson, L. Dixon, S. Gottlieb, J. Harvey, D. Whiteson

Some publicity

Thank you for your attention

- ♥ **Historical introduction of the boson and of the LHC**
- ♥ **Some phenomenological comments**
- ♥ **Rapid overview of the detectors**
- ♥ **The discovery**
- ♥ **The first measurements of the properties**
- ♥ **The future of the physics with the scalar boson(s)**
- ♥ **Backup (with references)**

references

(some) Tevatron references

CDF , D0 Phys.Rev.Lett. 109 (2012) 071804 arXiv:1207.6436
Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom
quark pair in Higgs boson searches at the Tevatron

CDF,D0 Phys.Rev. D88 (2013) 052014 arXiv:1303.6346
Higgs Boson Studies at the Tevatron

D0 note 6406
Constraints on the JP = 0- hypothesis for the Higgs boson in W/Z + bb final states at the D0 Experiment
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H139/H139.pdf

D0 note 6387
Constraints on the JP = 2+ hypothesis for the 125 GeV boson in W/Z + bb final states
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H138/H138.pdf

G.Bernardi at Higgs couplings 2013
https://indico.cern.ch/getFile.py/access?contribId=35&sessionId=1&resId=0&materialId=slides&confId=253774

Historical references

For a list of historical references see

Frank Close The Infinity Puzzle
Oxford University Press

Nansi Andari (Orsay, LAL) CERN-THESIS-2012-144
Observation of a BEH-like boson decaying into two photons with the ATLAS detector at the LHC

Nobel prize information
http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

J.Ellis et al.   arXiv:1201.6045
A historical profile of the Higgs boson

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.[7,8] We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons φ_A which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reasonable.

(1) Lest the simplicity of the argument be shrouded in a cloud of indices, we first consider a one-parameter Abelian group, representing, for example, the phase transformation of a charged boson; we then present the generalization to an arbitrary compact Lie group.

The interaction between the φ and the A_μ fields is

$$H_{\rm int} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \tag{1}$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$.

We shall assume that the application of the theorem of Goldstone, Salam, and Weinberg[7] is straightforward and thus that the propagator of the field φ_2, which is "orthogonal" to φ_1, has a pole at $q = 0$ which is not isolated.

We calculate the vacuum polarization loop $\Pi_{\mu\nu}$ for the field A_μ in lowest order perturbation theory about the self-consistent vacuum. We take into consideration only the broken-symmetry diagrams (Fig. 1). The conventional terms do not lead to a mass in this approximation if gauge invariance is carefully maintained. One evaluates directly

$$\Pi_{\mu\nu}(q) = (2\pi)^4 ie^2[g_{\mu\nu}\langle\varphi_1\rangle^2 - (q_\mu q_\nu/q^2)\langle\varphi_1\rangle^2]. \quad (2)$$

Here we have used for the propagator of φ_2 the value $[i/(2\pi)^4]/q^2$; the fact that the renormalization constant is 1 is consistent with our approximation.[9] We then note that Eq. (2) both maintains gauge invariance ($\Pi_{\mu\nu}q_\nu = 0$) and causes the A_μ field to acquire a mass

$$\mu^2 = e^2\langle\varphi_1\rangle^2. \quad (3)$$

We have not yet constructed a proof in arbitrary order; however, the similar appearance of higher order graphs leads one to surmise the general truth of the theorem.

Consider now, in general, a set of boson-field operators φ_A (which we may always choose to be Hermitian) and the associated Yang-Mills field $A_{a,\mu}$. The Lagrangian is invariant under the transformation[10]

$$\delta\varphi_A = \sum\nolimits_{a,A}\epsilon_a(x)T_{a,AB}\varphi_B,$$

$$\delta A_{a,\mu} = \sum\nolimits_{c,b}\epsilon_c(x)c_{acb}A_{b,\mu} + \partial_\mu\epsilon_a(x), \quad (4)$$

where c_{abc} are the structure constants of a compact Lie group and $T_{a,AB}$ the antisymmetric generators of the group in the representation defined by the φ_B.

Suppose that in the vacuum $\langle\varphi_{B'}\rangle \neq 0$ for some B'. Then the propagator of $\sum_{A,B'}T_{a,AB'}\varphi_A$

FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2(q_\mu q_\nu/q^2) \times\langle\varphi_1\rangle^2$.

$\times\langle\varphi_{B'}\rangle$ is, in the lowest order,

$$\left[\frac{i}{(2\pi)^4}\right]\sum_{A,B',C'}\frac{T_{a,AB'}\langle\varphi_{B'}\rangle T_{a,AC'}\langle\varphi_{C'}\rangle}{q^2}$$

$$= \left[\frac{-i}{(2\pi)^4}\right]\frac{(\langle\varphi\rangle T_a T_a\langle\varphi\rangle)}{q^2}.$$

With λ the coupling constant of the Yang-Mills field, the same calculation as before yields

$$\Pi_{\mu\nu}^{a}(q) = -i(2\pi)^4\lambda^2(\langle\varphi\rangle T_a T_a\langle\varphi\rangle)$$

$$\times[g_{\mu\nu} - q_\mu q_\nu/q^2],$$

giving a value for the mass

$$\mu_a^2 = -(\langle\varphi\rangle T_a T_a\langle\varphi\rangle). \quad (6)$$

(2) Consider the interaction Hamiltonian

$$H_{\rm int} = -\eta\bar{\psi}\gamma_\mu\gamma_5\psi B_\mu - \epsilon\bar{\psi}\gamma_\mu\psi A_\mu, \quad (7)$$

where A_μ and B_μ are vector and pseudovector gauge fields. The vector field causes attraction whereas the pseudovector leads to repulsion between particle and antiparticle. For a suitable choice of ϵ and η there exists, as in Johnson's model,[11] a broken-symmetry solution corresponding to an arbitrary mass m for the ψ field fixing the scale of the problem. Thus the fermion propagator $S(p)$ is

$$S^{-1}(p) = \gamma p - \Sigma(p) = \gamma p[1 - \Sigma_2(p^2)] - \Sigma_1(p^2), \quad (8)$$

with

$$\Sigma_1(p^2) \neq 0$$

and

$$m[1 - \Sigma_2(m^2)] - \Sigma_1(m^2) = 0.$$

We define the gauage-invariant current J_μ^5 by using Johnson's method[12]:

$$J_\mu^5 = -\eta \lim_{\xi\to 0}\bar{\psi}'(x+\xi)\gamma_\mu\gamma_5\psi'(x),$$

$$\psi'(x) = \exp[-i\int_{-\infty}^{x}\eta B_\mu(y)dy^\mu\gamma_5]\psi(x). \quad (9)$$

This gives for the polarization tensor of the pseudovector field

$$\Pi_{\mu\nu}{}^{5}(q)=\eta^2\frac{i}{(2\pi)^4}\int \mathrm{Tr}\{S(p-\tfrac{1}{2}q)\Gamma_{\nu 5}(p-\tfrac{1}{2}q;p+\tfrac{1}{2}q)\times S(p+\tfrac{1}{2}q)\gamma_\mu\gamma_5 -S(p)[\partial S^{-1}(p)/\partial p_\nu]S(p)\gamma_\mu\}d^4p, \quad (10)$$

where the vertex function $\Gamma_{\nu 5}=\gamma_\nu\gamma_5+\Lambda_{\nu 5}$ satisfies the Ward identity[5]

$$q_\nu\Lambda_{\nu 5}(p-\tfrac{1}{2}q;p+\tfrac{1}{2}q)=\Sigma(p-\tfrac{1}{2}q)\gamma_5+\gamma_5\Sigma(p+\tfrac{1}{2}q), \quad (11)$$

which for low q reads

$$q_\nu\Gamma_{\nu 5}=q_\nu\gamma_\nu\gamma_5[1-\Sigma_2]+2\Sigma_1\gamma_5 -2(q_\nu p_\nu)(\gamma_\lambda p_\lambda)(\partial\Sigma_2/\partial p^2)\gamma_5. \quad (12)$$

The singularity in the longitudinal $\Gamma_{\nu 5}$ vertex due to the broken-symmetry term $2\Sigma_1\gamma_5$ in the Ward identity leads to a nonvanishing gauge-invariant $\Pi_{\mu\nu}{}^5(q)$ in the limit $q\to 0$, while the usual spurious "photon mass" drops because of the second term in (10). The mass of the pseudovector field is roughly $\eta^2 m^2$ as can be checked by inserting into (10) the lowest approximation for $\Gamma_{\nu 5}$ consistant with the Ward identity.

Thus, in this case the general feature of the phenomenological boson system survives. We would like to emphasize that here the symmetry is broken through the gauge fields themselves. One might hope that such a feature is quite general and is possibly instrumental in the realization of Sakurai's program.[3]

(3) We present below a simple argument which indicates why the gauge vector field need not have zero mass in the presence of broken symmetry. Let us recall that these fields were introduced in the first place in order to extend the symmetry group to transformations which were different at various space-time points. Thus one expects that when the group transformations become homogeneous in space-time, that is $q\to 0$, no dynamical manifestation of these fields should appear. This means that it should cost no energy to create a Yang-Mills quantum at $q=0$ and thus the mass is zero. However, if we break gauge invariance of the first kind and still maintain gauge invariance of the second kind this reasoning is obviously incorrect. Indeed, in Fig. 1, one sees that the A_μ propagator connects to intermediate states, which are "rotated" vacua. This is seen most clearly by writing $\langle\varphi_1\rangle=\langle[Q\varphi_2]\rangle$ where Q is the group generator. This effect cannot vanish in the limit $q\to 0$.

*This work has been supported in part by the U. S. Air Force under grant No. AFEOAR 63-51 and monitored by the European Office of Aerospace Research.

[1]J. Schwinger, Phys. Rev. 125, 397 (1962).
[2]C. N. Yang and R. L. Mills, Phys. Rev. 96, 191 (1954).
[3]J. J. Sakurai, Ann. Phys. (N.Y.) 11, 1 (1960).
[4]Y. Nambu, Phys. Rev. Letters 4, 380 (1960).
[5]Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345 (1961).
[6]"Broken symmetry" has been extensively discussed by various authors in the Proceedings of the Seminar on Unified Theories of Elementary Particles, University of Rochester, Rochester, New York, 1963 (unpublished).
[7]J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).
[8]S. A. Bludman and A. Klein, Phys. Rev. 131, 2364 (1963).
[9]A. Klein, reference 6.
[10]R. Utiyama, Phys. Rev. 101, 1597 (1956).
[11]K. A. Johnson, reference 6.
[12]K. A. Johnson, reference 6.

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem [1,2]: that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee [3] showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert [4], however, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert [4], let us consider a theory of two hermitian scalar fields $\varphi_1(x)$, $\varphi_2(x)$ which is invariant under the phase transformation

$$\begin{aligned}\varphi_1 &\to \varphi_1 \cos\alpha + \varphi_2 \sin\alpha\,,\\ \varphi_2 &\to -\varphi_1 \sin\alpha + \varphi_2 \cos\alpha\,.\end{aligned} \qquad (1)$$

Then there is a conserved current j_μ such that

$$i[\int d^3x\, j_0(x),\ \varphi_1(y)] = \varphi_2(y). \qquad (2)$$

We assume that the Lagrangian is such that symmetry is broken by the nonvanishing of the vacuum expectation value of φ_2. Goldstone's theorem is proved by showing that the Fourier transform of $\langle[j_\mu(x),\ \varphi_1(y)]\rangle$ contains a term $2\pi\langle\varphi_2\rangle\epsilon(k_0)k_\mu\,\delta(k^2)$, where k_μ is the momentum, as a consequence of Lorentz-covariance, the conservation law and eq. (2).

Klein and Lee [3] avoided this result in the non-relativistic case by showing that the most general form of this Fourier transform is now, in Gilbert's notation,

$$\text{F.T.} = k_\mu \rho_1(k^2, nk) + n_\mu \rho_2(k^2, nk) + C_3 n_\mu \delta^4(k)\,, \qquad (3)$$

where n_μ, which may be taken as (1, 0, 0, 0), picks out a special Lorentz frame. The conservation law then reduces eq. (3) to the less general form

$$\text{F.T.} = k_\mu \delta(k^2)\rho_4(nk) + [k^2 n_\mu - k_\mu(nk)]\rho_5(k^2, nk) + C_3 n_\mu \delta^4(k)\,. \qquad (4)$$

It turns out, on applying eq. (2), that all three terms in eq. (4) can contribute to $\langle\varphi_2\rangle$. Thus the Goldstone theorem fails if $\rho_4 = 0$, which is possible only if the other terms exist. Gilbert's remark that no special timelike vector n_μ is available in a Lorentz-covariant theory appears to rule out this possibility in such a theory.

There is however a class of relativistic field theories in which a vector n_μ does indeed play a part. This is the class of gauge theories, where an auxiliary unit timelike vector n_μ must be introduced in order to define a radiation gauge in which the vector gauge fields are well defined operators. Such theories are nevertheless Lorentz-covariant, as has been shown by Schwinger [5]. (This has, of course, long been known of the simplest such theory, quantum electrodynamics.) There seems to be no reason why the vector n_μ should not appear in the Fourier transform under consideration.

It is characteristic of gauge theories that the conservation laws hold in the strong sense, as a consequence of field equations of the form

$$j^\mu = \partial_\nu F'^{\mu\nu}\,,$$

$$F_{\mu\nu}' = \partial_\mu A_\nu' - \partial_\nu A_\mu'\,. \qquad (5)$$

Except in the case of abelian gauge theories, the fields A_μ', $F_{\mu\nu}'$ are not simply the gauge field variables A_μ, $F_{\mu\nu}$, but contain additional terms with combinations of the structure constants of the group as coefficients. Now the structure of the Fourier transform of $\langle[A_\mu'(x),\ \varphi_1(y)]\rangle$ must be given by eq. (3). Applying eq. (5) to this commutator gives us as the Fourier transform of $\langle[j_\mu(x),\ \varphi_1(y)]\rangle$ the single term $[k^2 n_\mu - k_\mu(nk)]\rho(k^2, nk)$. We have thus exorcised both Goldstone's zero-mass bosons and the "spurion" state (at $k_\mu = 0$) proposed by Klein and Lee.

In a subsequent note it will be shown, by considering some classical field theories which display broken symmetries, that the introduction of gauge fields may be expected to produce qualitative changes in the nature of the particles described by such theories after quantization.

References

1) J. Goldstone, Nuovo Cimento 19 (1961) 154.
2) J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. 127 (1962) 965.
3) A. Klein and B. W. Lee, Phys. Rev. Letters 12 (1964) 266.
4) W. Gilbert, Phys. Rev. Letters 12 (1964) 713.
5) J. Schwinger, Phys. Rev. 127 (1962) 324.

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2 + \varphi_2^2) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2) = 0$, $V''(\varphi_0^2) > 0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \qquad (3)$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \qquad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e = 0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y = 0$, $I_3 = 0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe massive vector bosons. There are two $I=\frac{1}{2}$ vector doublets, degenerate in mass between $Y=\pm1$ but with an electromagnetic mass splitting between $I_3=\pm\frac{1}{2}$, and the $I_3=\pm1$ components of a $Y=0$, $I=1$ triplet whose mass is entirely electromagnetic. The two $Y=0$, $I=0$ gauge fields remain massless: This is associated with the residual unbroken symmetry under the Abelian group generated by Y and I_3. It may be expected that when a further mechanism (presumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

---

[1]P. W. Higgs, to be published.

[2]J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3]P. W. Anderson, Phys. Rev. 130, 439 (1963).

[4]In the present note the model is discussed mainly in classical terms; nothing is proved about the quantized theory. It should be understood, therefore, that the conclusions which are presented concerning the masses of particles are conjectures based on the quantization of linearized classical field equations. However, essentially the same conclusions have been reached independently by F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964): These authors discuss the same model quantum mechanically in lowest order perturbation theory about the self-consistent vacuum.

[5]In the theory of superconductivity such a term arises from collective excitations of the Fermi gas.

[6]See, for example, S. L. Glashow and M. Gell-Mann, Ann. Phys. (N.Y.) 15, 437 (1961).

[7]These are just the parameters which, if the scalar octet interacts with baryons and mesons, lead to the Gell-Mann–Okubo and electromagnetic mass splittings: See S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).

[8]Tentative proposals that incomplete SU(3) octets of scalar particles exist have been made by a number of people. Such a rôle, as an isolated $Y=\pm1$, $I=\frac{1}{2}$ state, was proposed for the κ meson (725 MeV) by Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 11, 42 (1963). More recently the possibility that the σ meson (385 MeV) may be the $Y=I=0$ member of an incomplete octet has been considered by L. M. Brown, Phys. Rev. Letters 13, 42 (1964).

[9]In the theory of superconductivity the scalar fields are associated with fermion pairs; the doubly charged excitation responsible for the quantization of magnetic flux is then the surviving member of a U(1) doublet.

$H \rightarrow \gamma\gamma$ (and Z γ) (and combination)

Early H$\rightarrow\gamma\gamma$ theory references

L. Resnick, M.K. Sundaresan and P.J.S. Watson, *Is there a light scalar boson*, Phys.Rev.D8:172-178, 1973.

J. Ellis, M. K. Gaillard and D. Nanopoulos, *A Phenomenological Profile of the Higgs Boson*, Nucl.Phys.B106:292, 1976.

M. Shifman, A. Vainshtein, M. Voloshin, and V. Zakharov, *Low-energy theorems for Higgs boson couplings to photons*, Sov.J.Nucl.Phys.30:711-716, 1979 [Yad.Fiz.30:1368-1378, 1979]

Early phenomelogical/experimental references (pre-LHC)

J. Gunion et al., *Searching For The Intermediate Mass Higgs Boson*, Phys.Rev.D34:101, 1986.

J. Gunion, G. Kane and J. Wudka, *Search Techniques for Charged and Neutral Intermediate Mass Higgs Bosons*, Nucl.Phys.B299:231, 1988.

C. Barter et al., *Detection of $H \rightarrow \gamma\gamma$ at the SSC*, Proceedings of the Summer Study on HEP in the 1990's, june 1988, Snowmass, Colorado

M. Mangano, *Production of $WH \rightarrow W\gamma\gamma$*, SSC-SDC-90-00113.

Early phenomelogical/experimental references (LHC)

C. Seez and J. Virdee, *Photon decay modes of the intermediate masss Higgs*, Large Hadron Collider Workshop, Aachen October 1990 (ed by G. Jarlskog and D. Rein), vol 2 report CERN 90-10 ECFA 90-133 page 474

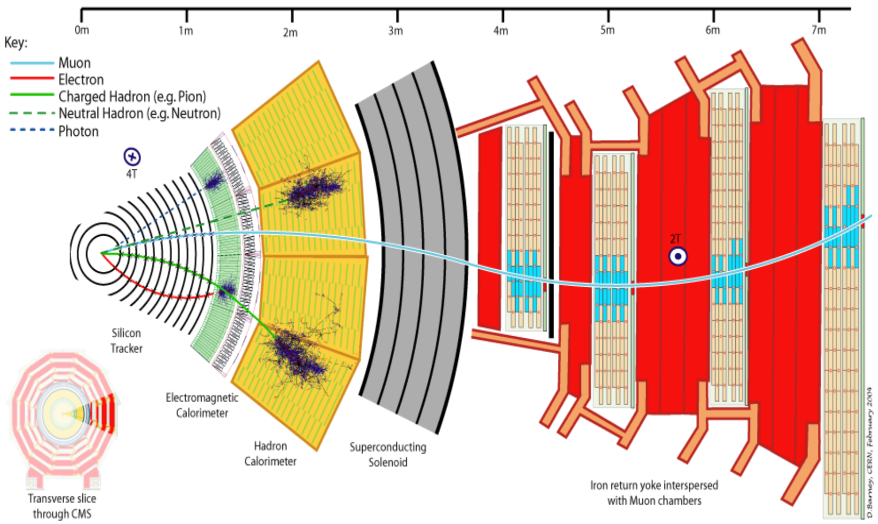
D. Fournier, *Liquid Argon Calorimetry*, Large Hadron Collider Workshop, Aachen, October 1990, vol 3, CERN-90-10, ECFA90-133 page 356.

L. Fayard and G. Unal, *Search for Higgs decay into photons with EAGLE*, ATL-PHYS-92-001.

The LOI's of ATLAS,CMS and L3P

B.Mansoulié et al. ATL-CAL-92-008
Study of the rejection of pi-zeros by a cold preshower behind, the coil and cryostat (Dice-A): rapidity dependance, noise dependance

CMS references



CMS-PAS-EGM-10-005
Photon reconstruction and identification at sqrt(s) = 7 TeV

CMS-PAS-EGM-10-006
Isolated Photon Reconstruction and Identification at $\sqrt{s}$ = 7 TeV

CMS-PAS-HIG-11-010
Search for a Higgs boson decaying into two photons in the CMS detector *(1 fb-1*
8 categories : pT - converted , non-converted - Barrel , End-Cap)

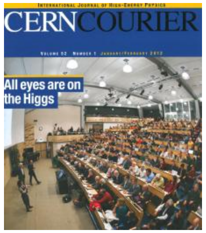
CMS-PAS-HIG-11-011
SM Higgs Combination *(1 fb-1)*

CMS-PAS-HIG-11-022
Combination of Higgs Searches (1.7 fb-1)

CMS-PAS-HIG-11-021
Search for a Higgs boson decaying into two photons in the CMS detector *(1.7 fb-1)*

CMS-PAS-HIG-11-023
Combined Standard Model Higgs boson searches with up to 2.3 inverse femtobarns of pp collision data at sqrt(s)=7 TeV at the LHC (ATLAS + CMS)

CMS-PAS-HIG-11-030
Search for a Higgs boson decaying into two photons in the CMS detector *(5 fb-1*
4 categories : converted , non converted - Barrel , Endcap , local significance of 2.3 σ)



CMS-PAS-HIG-11-032
Combination of SM Higgs Searches *(5 fb-1)*

Phys.Lett. B710 (2012) 26-48
Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV

Phys.Lett. B710 (2012) 403-425
Search for the standard model Higgs boson decaying into two photons in pp collisions at $\sqrt{s} = 7$ TeV *(5 categories , in addition dijet à la VBF , local significance of 3.1 σ)*

CMS-PAS-HIG-12-001
A search using multivariate techniques for a standard model Higgs boson decaying into two photons *(7 TeV , MVA , local significance of 2.9 σ , 5 categories : 4 from BDT and a dijet one à la VBF)*

CMS-PAS-HIG-12-008
Combination of SM, SM4, FP Higgs boson searches *(like 12-001 , 7 TeV , excludes fermiophobic)*

CMS-PAS-HIG-12-002
Search for the fermiophobic model Higgs boson decaying into two photons
(7 categories : 4 from converted, non converted – barrel , endcap a dijet tag à la VBF , an electron tag one and a muon tag one)

JHEP 1209 (2012) 111
Search for a fermiophobic Higgs boson in pp collisions at $\sqrt{s}$ =7 TeV
($\gamma\gamma$ like 12-002, ZZ,WW)

CMS-PAS-HIG-12-015

Evidence for a new state decaying into two photons in the search for the standard model Higgs boson in pp collisions *(local significance = 4.1 σ , 5 categories at 7 TeV , 6 at 8 TeV , 4 by BDT at 7 and 8 TeV , 1 additional dijet category at 7 TeV , 2 additional dijet categories at 8 TeV)*

CMS-PAS-HIG-12-020

Observation of a new boson with a mass near 125 GeV

CMS-PAS-HIG-12-022

Higgs to gamma gamma, Fermiophobic *(5+ 5 fb-1*
2011 : 7 categories like in JHEP 1209 (2012) 111
2012 : 9 categories : converted, unconverted –
Barrel-Endcap , 2 dijet categories , 1 e category , 1 μ category and 1 Etmiss category)

Phys.Lett. B716 (2012) 30-61

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
(uses 12-015 for $\gamma\gamma$ mH comb = 125.3 $\pm$ .4 $\pm$ .5 GeV)

CMS-PAS-HIG-12-045
Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV *(5 + 13 fb-1 , but $H \to \gamma\gamma$ 5 + 5 fb-1 uses Phys.Lett. B716 (2012) 30-61)*

CMS-PAS-HIG-12-049
Search for a Light Higgs boson in the Z boson plus a Photon Decay Channel *(5 + 5 fb-1)*

Phys.Lett. B725 (2013) 36-59
Searches for Higgs bosons in pp collisions at sqrt(s) = 7 and 8 TeV in the context of four-generation and fermiophobic models *($\gamma\gamma$ like in Phys.Lett. B716 (2012) 30-61 5 + 5 fb-1)*

CMS-PAS-HIG-13-006
Search for the standard model Higgs boson in the Z boson plus a photon channel in pp collisions at $\sqrt{s}$ = 7 and 8 TeV *(5 + 20 fb-1)*

JHEP 06 (2013) 081
Observation of a new boson with mass near 125 GeV in pp collisions at sqrt(s) = 7 and 8 TeV

CMS-PAS-HIG-13-001

Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel

(3.2 σ mH = 125.4 $\pm$ .5 $\pm$ .6 GeV

MVA analysis : 5 categories at 7 TeV , 9 at 8 TeV ,

4 by BDT at 7 and 8 TeV , 1 additional dijet category at 7 TeV ,

2 additional dijet categories , 1 muon-tag, 1 e-tag and 1 Etmiss tag at 8 TeV

There is also a cut-based analysis described)

CMS-PAS-HIG-13-005

Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV *($\gamma\gamma$ uses 13-001 , mH comb = 125.7 $\pm$ .3 $\pm$ .3 GeV)*

CMS-PAS-HIG-13-015

Search for ttH production in events where H decays to photons at 8 TeV collisions

(2 analysis : 2 top hadronic

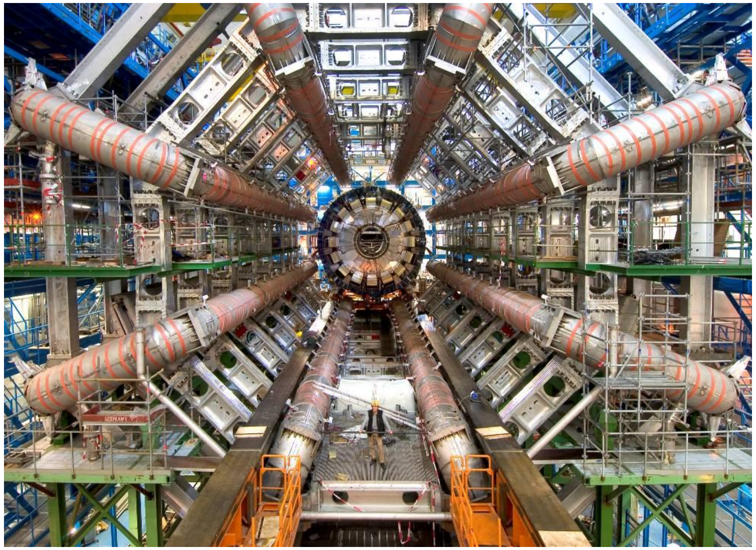
1 hadronic and 1 leptonic)

arXiv:1306.2016
Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7$ TeV

CMS-PAS-HIG-13-016
Properties of the observed Higgs-like resonance using the diphoton channel **S**
(like 13-001 . natural width and second Higgs scenario uses MVA analysis , spin uses cut based analysis)

arXiv:1307.5515
Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV

ATLAS references



Lampl, W ; Laplace, S ; Lelas, D ; Loch, P ; Ma, H ; Menke, S ; Rajagopalan, S ; Rousseau, D ; Snyder, S ; Unal, G

ATL-LARG-PUB-2008-002

Calorimeter Clustering Algorithms : Description and Performance

ATLAS-CONF-2011-004
Measurement of the backgrounds to the Higgs To gammagamma search and reappraisal of its sensitivity with 37 pb-1 of data recorded by the ATLAS detector

ATLAS-CONF-2011-025
Search for the Higgs boson in the diphoton final state with 38 ipb of data recorded by the ATLAS detector in proton-proton collisions at sqrt(s)=7 TeV *PCL*

ATL-PHYS-PUB-2011-007
Expected photon performance in the ATLAS experiment

ATLAS-CONF-2011-085

Search for the Higgs Boson in the Diphoton Channel with the ATLAS Detector using 209 pb-1 of 7 TeV Data taken in 2011 *PCL*

Eur.Phys.J. C71 (2011) 1728

Limits on the production of the Standard Model Higgs Boson in pp collisions at √s =7 TeV with the ATLAS detector *1st combination H 40* pb^{-1}

ATLAS-CONF-2011-112

Combined Standard Model Higgs Boson Searches in pp Collisions at sqrt(s) = 7 TeV with the ATLAS Experiment at the LHC (1 fb-1)

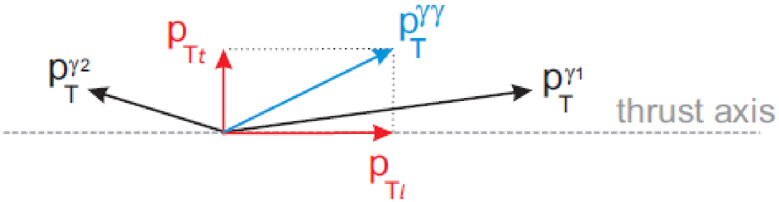
ATLAS-CONF-2011-135

Update of the Combination of Higgs Boson Searches in 1.0 to 2.3 fb−1 of pp Collisions Data Taken at √s = 7 TeV with the ATLAS Experiment at the LHC

Phys.Lett. B705 (2011) 452-470
Search for the Standard Model Higgs boson in the two photon decay channel with the ATLAS detector at the LHC *(1 fb^{-1})*

ATLAS-CONF-2011-149
Search for a fermiophobic Higgs boson in the diphoton channel with the ATLAS detector *(1 fb^{-1} , pT categories)*

ATLAS-CONF-2011-157
Combined Standard Model Higgs boson searches with up to 2.3 fb-1 of pp collision data at sqrt{s} = 7 TeV at the LHC (ATLAS+CMS)



ATLAS-CONF-2011-161
Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb-1 of ATLAS data at sqrt(s)=7 TeV *(PTt and conversion categories : 9 categories local significance = 2.8 σ)*

ATLAS-CONF-2011-163
Combination of Higgs Boson Searches with up to 4.9 fb-1 of pp Collision Data Taken at sqrt(s)=7 TeV with the ATLAS Experiment at the LHC

Phys.Lett. B710 (2012) 49-66
Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s}$ =7 TeV with the ATLAS detector at the LHC

Phys.Rev.Lett. 108 (2012) 111803
Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb^{-1} of pp collisions at $\sqrt{s}$ =7 TeV with ATLAS *(local significance = 2.8 σ)*

ATLAS-CONF-2012-013
Search for a fermiophobic Higgs boson in the diphoton decay channel with 4.9/fb of ATLAS data at sqrt(s)= 7 TeV *(using 9 categories)*

ATLAS-CONF-2012-019
An update to the combined search for the Standard Model Higgs boson with the ATLAS detector at the LHC using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s}$ = 7 TeV

Eur.Phys.J. C72 (2012) 2157
Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector (5 fb-1)

ATLAS-CONF-2012-048

Performance of the ATLAS Electron and Photon Trigger in p-p Collisions at sqrt{s} = 7 TeV in 2011

Phys.Rev. D86 (2012) 032003 arXiv:1207.0319

Combined search for the Standard Model Higgs boson in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector (5 fb-1)

ATLAS-CONF-2012-091

Observation of an excess of events in the search for the Standard Model Higgs boson in the gamma-gamma channel with the ATLAS detector *(10 categories , including a 2 jet – à la VBF – one , 5 (2011) + 6 (2012) fb^{-1} local significance = 4.5 σ)*

ATLAS-CONF-2012-093

Observation of an Excess of Events in the Search for the Standard Model Higgs boson with the ATLAS detector at the LHC *(WW only 2011)*

Phys.Lett. B716 (2012) 1-29

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC *(with WW 2012 mH comb = 126.0 $\pm$.4 $\pm$.4 GeV)*

ATLAS-CONF-2012-123

Measurements of the photon identification efficiency with the ATLAS detector using 4.9 fb−1 of pp collision data collected in 2011

ATLAS-CONF-2012-127
Coupling properties of the new Higgs-like boson observed with the ATLAS detector at the LHC *(5+6 fb^{-1})*

ATLAS-CONF-2012-162
Updated ATLAS results on the signal strength of the Higgs-like boson for decays into WW and heavy fermion final states *(includes 13fb^{-1} of 2012 except $\gamma\gamma$ 5+6 fb^{-1})*

ATLAS-CONF-2012-168
Observation and study of the Higgs boson candidate in the two photon decay channel with the ATLAS detector at the LHC *(mH = 126.6 ± .3 ± .7 GeV local significance = 6.1 σ 5+ 13 fb^{-1} 12 categories in 2012 with two 2-jet categories and a one-lepton category)*

ATLAS-CONF-2012-170
An update of combined measurements of the new Higgs-like boson with high mass resolution channels *(mH comb = 125.2 ± .3 ± .6 GeV 5+13 fb^{-1})*

ATLAS-CONF-2013-009
Search for the Standard Model Higgs boson in the $H \rightarrow Z\gamma$ decay mode with pp collisions at $\sqrt{s}$ = 7 and 8 TeV *(5+ 20 fb^{-1})*

ATLAS-CONF-2013-012

Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb−1 of proton-proton collision data **S**

(14 categories including two 2-jet high mass , one 2-jet low mass , lepton , ETmiss local significance = 7.4 σ , mH=126.8 $\pm$.2 $\pm$.7 GeV)

ATLAS-CONF-2013-014

Combined measurements of the mass and signal strength of the Higgs-like boson with the ATLAS detector using up to 25 fb-1 of proton-proton collision data

(mH comb= 125.5 $\pm$.2 $^{+.5}_{-.6}$ GeV)

ATLAS-CONF-2013-029

Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7 fb-1 of pp collisions collected at sqrt(s) = 8 TeV with the ATLAS detector **S**

ATLAS-CONF-2013-034

Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb-1 of proton-proton collision data *(10 σ)*

ATLAS-CONF-2013-040

Study of the spin of the new boson with up to 25 fb−1 of ATLAS data **S**

Phys.Lett. B726 (2013) 88-119 arXiv:1307.1427
Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-02/

Phys.Lett. B726 (2013) 120-144 arXiv:1307.1432
Evidence for the spin-0 nature of the Higgs boson using ATLAS data **S**
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-01/

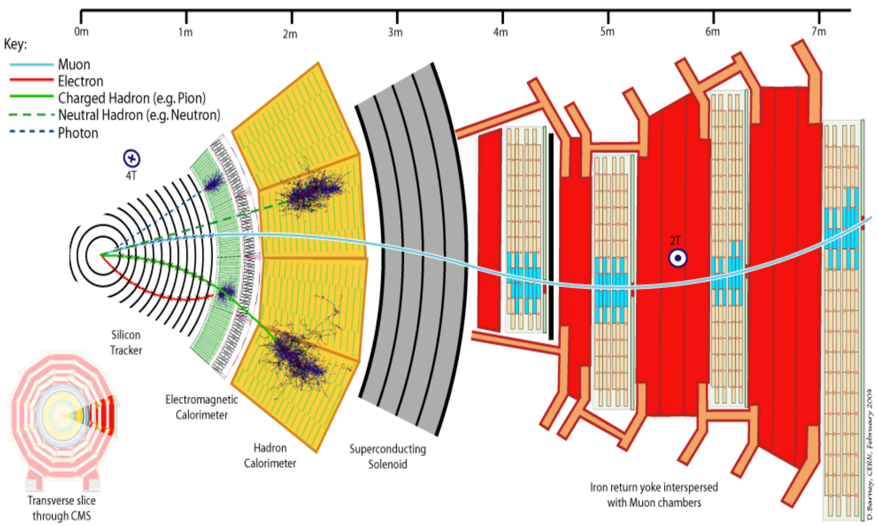
ATLAS-CONF-2013-072
Differential cross sections of the Higgs boson measured in the diphoton decay channel with the ATLAS detector using 8 TeV proton-proton collision data

ATLAS-CONF-2013-080
Search for ttH production in the $H \rightarrow \gamma\gamma$ channel at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS-CONF-2013-081
Search for flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC

$H \rightarrow ZZ \rightarrow 4l$

CMS references



PAS HIG-11-004
Search for a Standard Model Higgs boson produced in the decay channel 4l (1 fb-1)

PAS HIG-11-015
Search for a Standard Model Higgs boson produced in the decay channel 4l (1.7 fb-1)

PAS HIG-11-025
Search for a Higgs boson produced in the decay channel 4l (5 fb-1)

Phys.Rev.Lett. 108 (2012) 111804 arXiv:1202.1997
Search for the standard model Higgs boson in the decay channel H to ZZ to 4 leptons in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

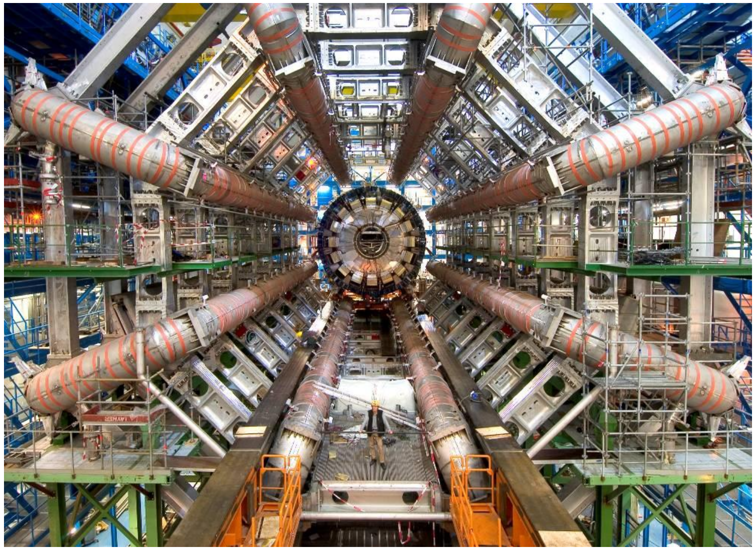
PAS HIG-12-016
Evidence for a new state in the search for the standard model Higgs boson in the H to ZZ to 4 leptons channel in pp collisions at sqrt(s) = 7 and 8 TeV (5 fb-1)

PAS HIG-12-041
Updated results on the new boson discovered in the search for the standard model Higgs boson in the ZZ to 4 leptons channel in pp collisions at sqrt(s) = 7 and 8 TeV (5 + 12 fb-1)

Phys.Rev.Lett. 110 (2013) 081803 arXiv:1212.6639
On the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs (5 + 12 fb-1)

PAS HIG-13-002
Properties of the Higgs-like boson in the decay H to ZZ to 4l in pp collisions at sqrt s =7 and 8 TeV (5 + 20 fb-1)

ATLAS references



ATLAS-CONF-2011-048
Search for the Standard Model Higgs boson in the decay channel H->ZZ*->4l with 40 pb-1 of pp collisions at sqrt(s)= 7 TeV

ATLAS-CONF-2011-131
Search for the Standard Model Higgs boson in the decay channel H to ZZ to llll with the ATLAS detector (1 fb-1)

Phys.Lett. B705 (2011) 435-451 arXiv:1109.5945
Search for the Standard Model Higgs boson in the decay channel
H->ZZ(*)->4l with the ATLAS detector (2 fb-1)

ATLAS-CONF-2011-162
Search for the Standard Model Higgs boson in the decay channel H->ZZ*->4ll with
4.8 fb-1 of pp collisions at sqrt{s} = 7 TeV

Phys.Lett. B710 (2012) 383-402 arXiv:1202.1415
Search for the Standard Model Higgs boson in the decay channel H->ZZ(*)->4l with 4.8 fb-1 of pp collisions at sqrt(s)=7 TeV with ATLAS

ATLAS-CONF-2012-092

Observation of an excess of events in the search for the Standard Model Higgs boson in the H-> ZZ(*) -> 4l channel with the ATLAS detector (5 + 6 fb-1)

ATLAS-CONF-2012-169

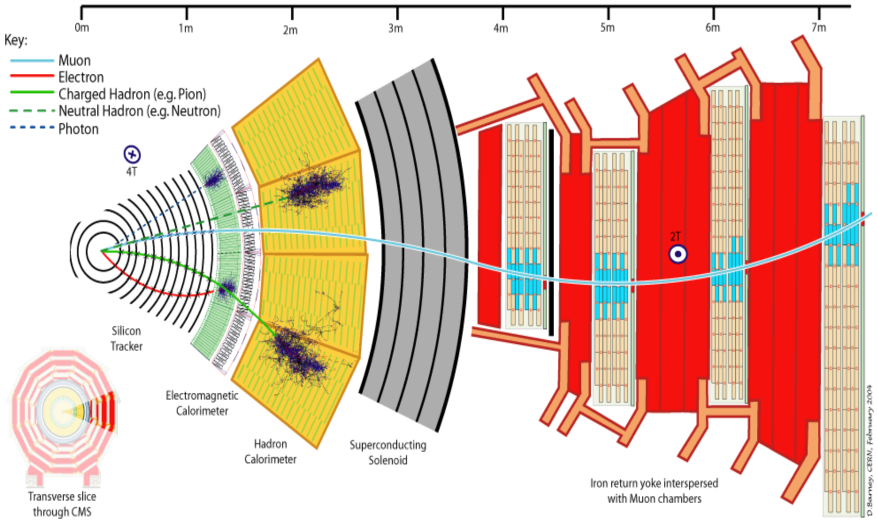
Updated results and measurements of properties of the new Higgs-like particle in the four lepton decay channel with the ATLAS detector (5 + 13 fb-1)

ATLAS-CONF-2013-013

Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb-1 of proton-proton collision data

$H \to ZZ \to l\,l\,\tau\tau$

CMS references

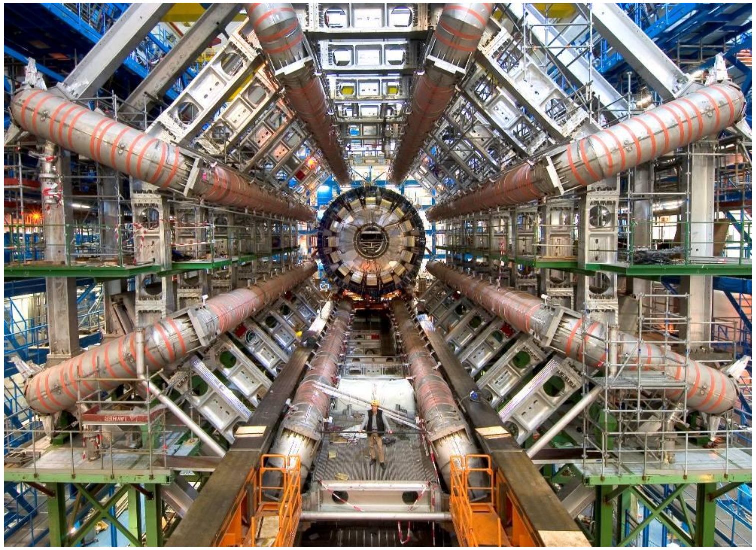


PAS HIG-11-013
Study of the Higgs to ZZ to 2l + 2 tau final state with CMS detector (1 fb-1)

PAS HIG-11-028
Study of the Higgs to ZZ to 2l + 2 tau final state with CMS detector (5 fb-1)

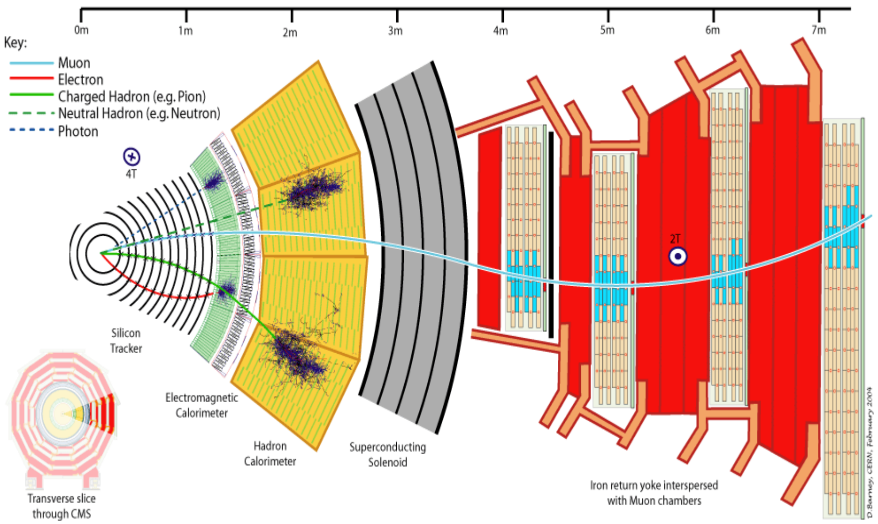
JHEP 1203 (2012) 081 arXiv:1202.3617
Search for the standard model Higgs boson in the H to ZZ to ll tau tau decay channel in pp collisions at sqrt(s)=7 TeV (5 fb-1)

ATLAS references



$H \rightarrow ZZ \rightarrow l\, l\, \nu\nu$

CMS references



PAS HIG-11-005
H to ZZ to 2l2nu (1 fb-1)

PAS HIG-11-016
H to ZZ to 2l2nu (1.7 fb-1)

HIG-11-026
H to ZZ to 2l 2nu (5 fb-1)

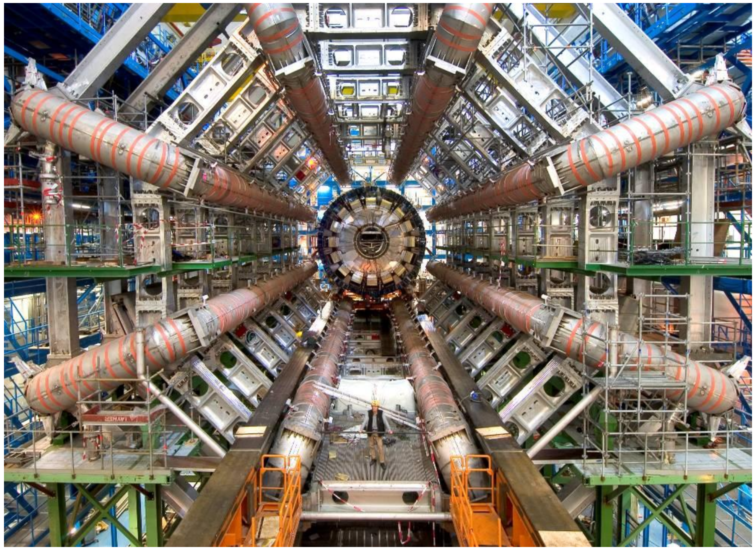
JHEP 1203 (2012) 040 arXiv:1202.3478
Search for the standard model Higgs boson in the H to ZZ to 2l 2nu channel in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

PAS HIG-12-023
Higgs to ZZ to 2l 2nu at 7 and 8 TeV (5 + 5 fb-1)

PAS HIG-13-014

Search for a heavy Higgs boson in the H to ZZ to 2l2nu channel in pp collisions at sqrt(s)= 7 and 8 TeV (5 + 20 fb-1)

ATLAS references



ATLAS-CONF-2011-026
Search for a Standard Model Higgs Boson in the Mass Range 200-600 GeV in the Channels H -> ZZ -> llnunu and H -> ZZ -> llqq with the ATLAS Detector (36 pb-1)

Phys.Rev.Lett. 107 (2011) 221802 arXiv:1109.3357
Search for a Standard Model Higgs boson in the H->ZZ->llnunu decay channel with the ATLAS detector (1 fb-1)

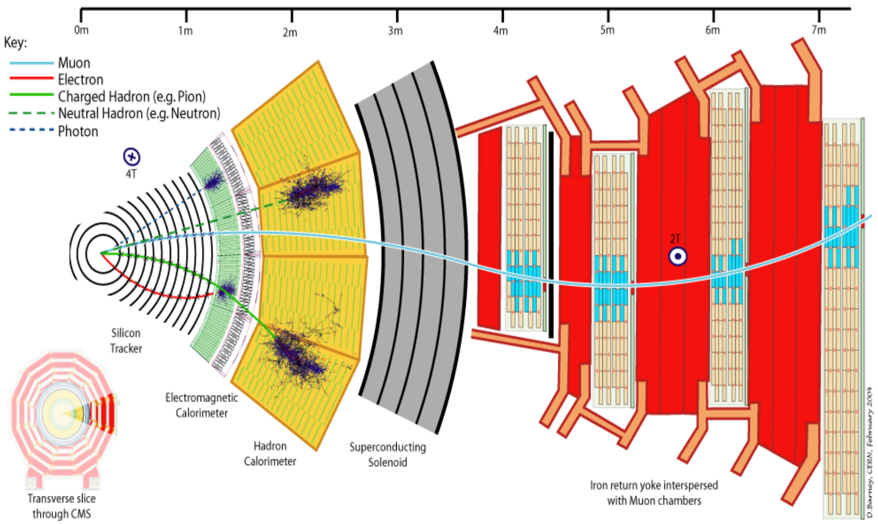
ATLAS-CONF-2011-148
Search for a Standard Model Higgs boson in the H -> ZZ -> llnunu decay channel with 2.05 fb-1 of ATLAS data

ATLAS-CONF-2012-016
Search for a Standard Model Higgs boson in the H -> ZZ -> llnunu decay channel using 4.7 fb-1 of sqrt(s) = 7 TeV data with the ATLAS Detector

Phys.Lett. B717 (2012) 29-48 arXiv:1205.6744
Search for a Standard Model Higgs boson in the H -> ZZ -> llnunu decay channel using 4.7 fb-1 of sqrt(s) = 7 TeV data with the ATLAS detector

$H \rightarrow ZZ \rightarrow l\, l\, qq$

CMS references



PAS HIG-11-006

Search for the standard model Higgs Boson in the decay channel H to ZZ to llqq at CMS (1 fb-1)

PAS HIG-11-017

Search for the standard model Higgs Boson in the decay channel H to ZZ to llqq at CMS (1.6 fb-1)

PAS HIG-11-027

Search for the standard model Higgs Boson in the decay channel H to ZZ(*) to q qbar l-l+ at CMS (5 fb-1)

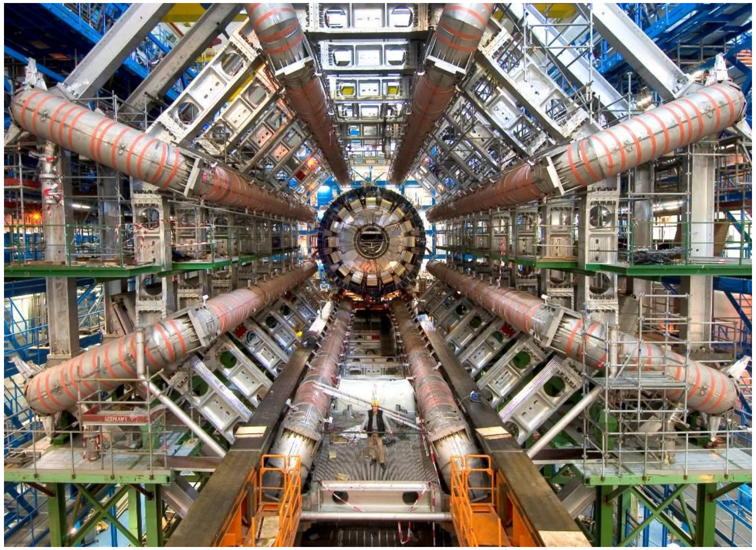
JHEP 1204 (2012) 036 arXiv:1202.1416

Search for a Higgs boson in the decay channel H to ZZ(*) to q qbar l-l+ in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

PAS HIG-12-024

Search for a standard model like Higgs boson in the H -> ZZ -> 2l2q decay channel at sqrts=8 TeV (20 fb-1)

ATLAS references



ATLAS-CONF-2011-026
Search for a Standard Model Higgs Boson in the Mass Range 200-600 GeV in the Channels H -> ZZ -> llnunu and H -> ZZ -> llqq with the ATLAS Detector (36 pb-1)

Phys.Lett. B707 (2012) 27-45 arXiv:1108.5064
Search for a heavy Standard Model Higgs boson in the channel H->ZZ->llqq using the ATLAS detector (1 fb-1)

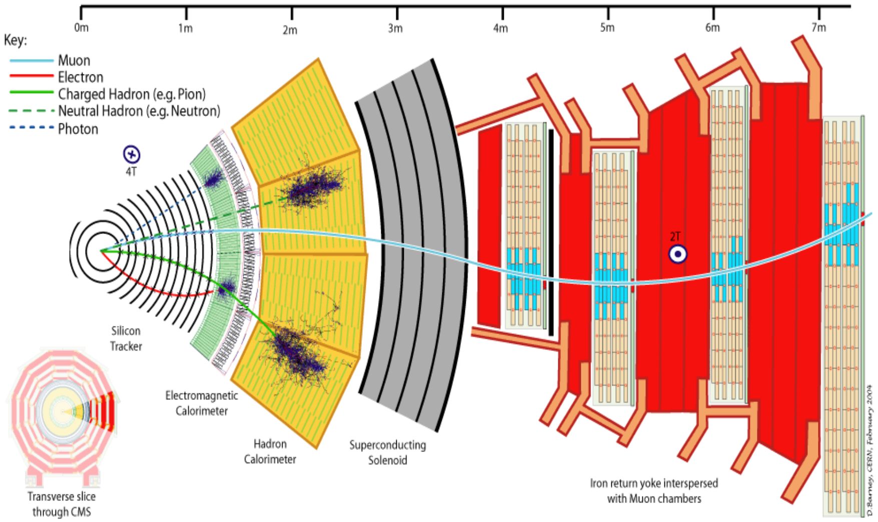
ATLAS-CONF-2011-150
Search for a Standard Model Higgs Boson in the mass range 200-600 GeV in the channel H -> ZZ -> llqq using the ATLAS Detector (2 fb-1)

ATLAS-CONF-2012-017
Search for a Standard Model Higgs boson in the mass range 200--600 GeV in the H->ZZ->llqq decay channel with the ATLAS Detector (7 TeV 5 fb-1)

Phys.Lett. B717 (2012) 70-88 arXiv:1206.2443
Search for a Standard Model Higgs boson in the mass range 200-600 GeV in the H->ZZ->llqq decay channel (5 fb-1)

$H \rightarrow WW \rightarrow l\,\nu\,l\,\nu$

CMS references



Phys.Lett.B699:25-47,2011 arXiv:1102.5429
Measurement of W+W- Production and Search for the Higgs Boson in pp Collisions at sqrt(s) = 7 TeV (36 pb-1)

PAS HIG-11-003
Search for the Higgs Boson in the Fully Leptonic W+ W- Final State (1 fb-1)

PAS HIG-11-014
Search for the Higgs Boson in the Fully Leptonic W+W- Final State (1.5 fb-1)

PAS HIG-11-024
Search for the Higgs Boson in the Fully Leptonic W+W- Final State (5 fb-1)

Phys.Lett. B710 (2012) 91-113 arXiv:1202.1489
Search for the standard model Higgs boson decaying to a W pair in the fully leptonic final state in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

PAS HIG-12-014
VH with H->WW->lnulnu and V->jj at sqrt(s)=7 TeV (5 fb-1)

PAS HIG-12-017
Search for the standard model Higgs boson decaying to a W pair in the fully leptonic final state in pp collisions at sqrt(s) = 8 TeV (5 fb-1)

PAS HIG-12-038
Search for the standard model Higgs boson decaying to a W pair in the fully leptonic final state in pp collisions at sqrt(s) = 8 TeV (5 fb-1)

PAS HIG-12-039
Search for SM Higgs in WH to WWW to 3l 3nu (7 +8 TeV 5+5 fb-1)

PAS HIG-12-042
Evidence for a particle decaying to W+W- in the fully leptonic final state in a standard model Higgs boson search in pp collisions at the LHC (8TeV 12 fb-1)

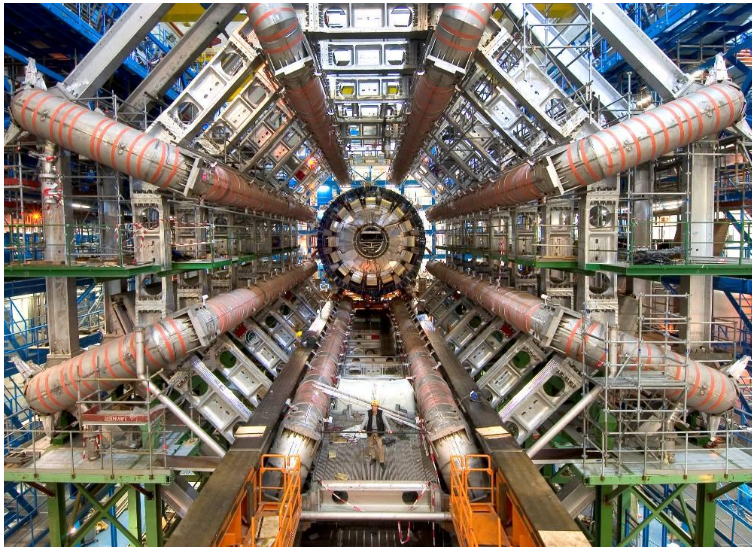
PAS HIG-13-003
Evidence for a particle decaying to W+W- in the fully leptonic final state in a standard model Higgs boson search in pp collisions at the LHC (5 + 20 fb-1)

PAS HIG-13-009
Search for SM Higgs in WH to WWW to 3l 3nu (5 + 20 fb-1)

PAS HIG-13-017
VH with H-> WW->lnulnu and V-> jj (5 + 20 fb-1)

PAS HIG-13-022
Update of the search for the Standard Model Higgs boson decaying into WW in the vector boson fusion production channel (5 + 20 fb-1)

ATLAS references



ATLAS-CONF-2011-005

Higgs Boson Searches using the H -> WW(*)-> l nu l nu Decay Mode with the ATLAS Detector at 7 TeV (36 pb-1)

ATLAS-CONF-2011-111

Search for the Standard Model Higgs boson in the H->WW*->l nu l nu decay mode with the ATLAS detector (1 fb-1)

ATLAS-CONF-2011-134

Search for the Standard Model Higgs boson in the H->WW->llnunu decay mode using 1.7 fb-1 of data collected with the ATLAS detector at sqrt(s)=7 TeV

Phys.Rev.Lett. 108 (2012) 111802 arXiv:1112.2577
Search for the Higgs boson in the H->WW(*)->lvlv decay channel in pp collisions at sqrt{s} = 7 TeV with the ATLAS detector (2 fb-1)

ATLAS-CONF-2012-012
Search for the Standard Model Higgs boson in the H->WW(*)-> lnulnu decay mode with 4.7 fb-1 of ATLAS data at sqrt(s) = 7 TeV

Phys.Lett. B716 (2012) 62-81 arXiv:1206.0756
Search for the Standard Model Higgs boson in the H -> WW(*) -> l nu l nu decay mode with 4.7 /fb of ATLAS data at sqrt(s) = 7 TeV

ATLAS-CONF-2012-060

Search for the Standard Model Higgs boson in the H->WW(*)->lvlv decay mode using Multivariate Techniques with 4.7 fb-1 of ATLAS data at sqrt{s}=7 TeV

ATLAS-CONF-2012-078

Search for the Higgs boson in the associated mode WH->WWW(*)->lnu lnu with the ATLAS detector at sqrt{s}=7TeV (5 fb-1)

ATLAS-CONF-2012-098

Observation of an Excess of Events in the Search for the Standard Model Higgs Boson in the H->WW(*)->lnulnu Channel with the ATLAS Detector (6 fb-1 8TeV ,ajouté aux 5 fb-1 7 TeV)

ATLAS-CONF-2013-027

Search for Higgs bosons in Two-Higgs-Doublet models in the H -> WW -> e nu µ nu channel with the ATLAS detector

ATLAS-CONF-2013-030

Measurements of the properties of the Higgs-like boson in the WW(*) -> lnu lnu decay channel with the ATLAS detector using 25 fb-1 of proton-proton collision data

ATLAS-CONF-2013-031

Study of the spin properties of the Higgs-like boson in the H -> WW(*) -> enu µnu channel with 21 fb-1 of $\sqrt{s}$ = 8 TeV data collected with the ATLAS detector

ATLAS-CONF-2013-067

Search for a high-mass Higgs boson in the H->WW->lnulnu decay channel with the ATLAS detector using 21 fb -1   of proton-proton collision data (8 TeV)

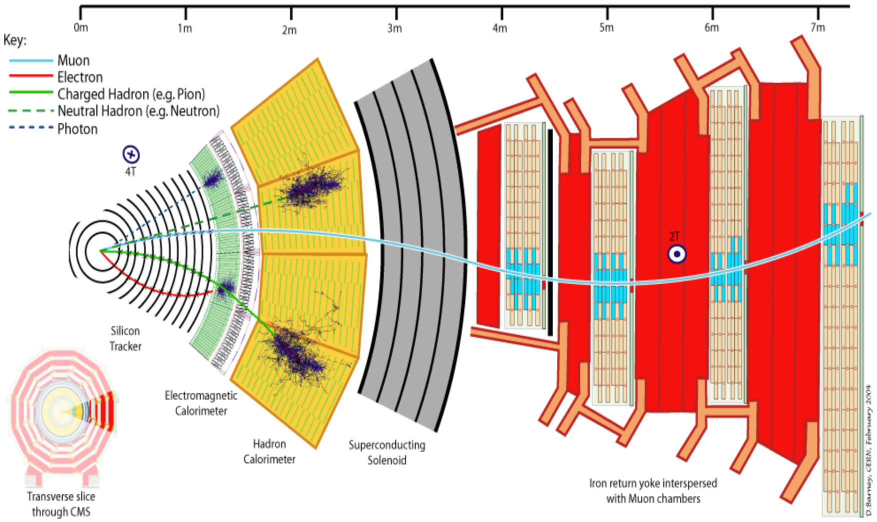
ATLAS-CONF-2013-075

Search for associated production of the Higgs boson in the WH->WWW(*)->lnulnulnu and ZH->ZWW(*)->lllnulnu channels with the ATLAS detector at the LHC

(8 Tev 20 fb-1 auxquels on ajoute 5 fb-1 de 7 TeV)

$H \rightarrow WW \rightarrow l\,\nu\,qq$

CMS references



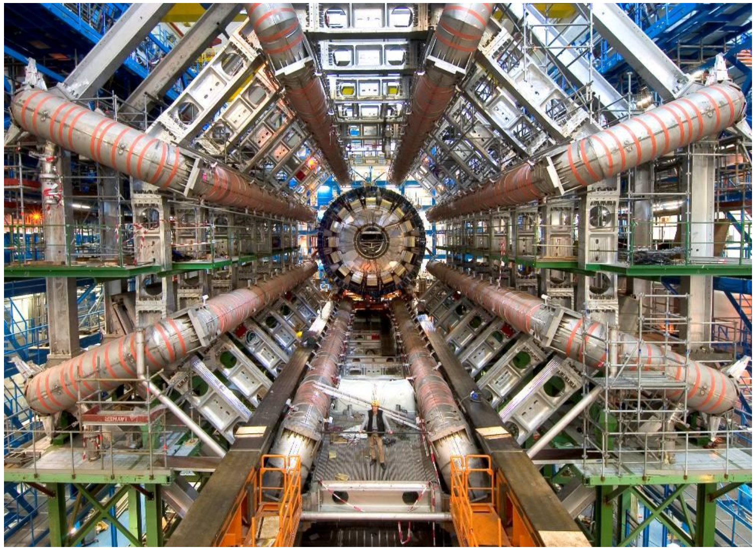
PAS HIG-12-003
Search for the Standard Model Higgs boson in the H -> WW -> l nu jj decay channel (5 fb-1)

PAS HIG-12-021
Search for the Standard Model Higgs boson in the H to WW to lvjj decay channel at 8 TeV (5 fb-1)

PAS HIG-12-046
Search for the Standard Model Higgs boson in the H to WW to lnujj decay channel in pp collisions at the LHC (5 + 12 fb-1)

PAS HIG-13-008
Search for a Standard Model-like Higgs boson decaying into WW to l nu qqbar in pp collisions at sqrt s = 8 TeV (20 fb-1)

ATLAS references



ATLAS-CONF-2011-052
Search for Higgs Boson Production in pp Collisions at sqrt{s}=7 TeV using the H->WW->lvqq Decay Channel and the ATLAS Detector (36 pb-1)

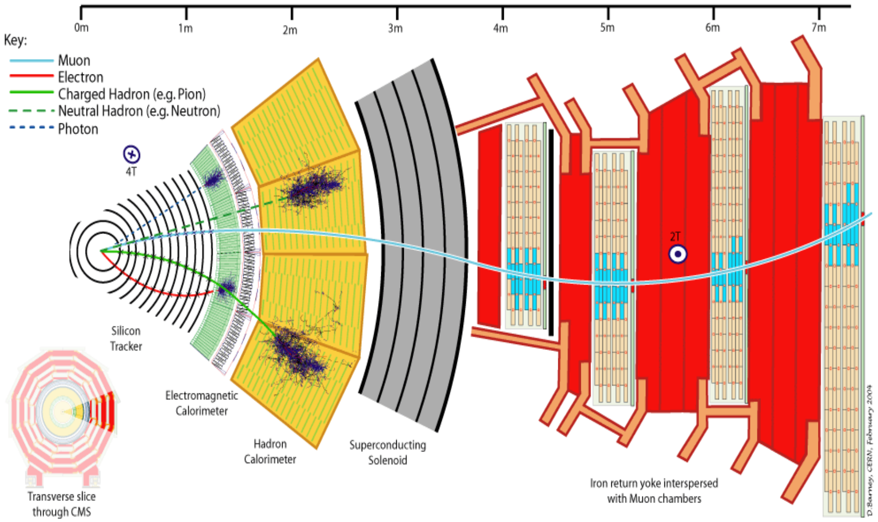
Phys.Rev.Lett. 107 (2011) 231801 arXiv:1109.3615
Search for the Higgs boson in the H->WW->lvjj decay channel in pp collisions at sqrt{s} = 7 TeV with the ATLAS detector (1 fb-1)

ATLAS-CONF-2012-018
Search for the Higgs boson in the H->WW->lvjj decay channel using 4.7 fb-1 of pp collisions at sqrt(s)= 7 TeV with the ATLAS detector

Phys.Lett. B718 (2012) 391-410 arXiv:1206.6074
Search for the Higgs boson in the H->WW->lnujj decay channel at sqrt(s) = 7 TeV with the ATLAS detector (5 fb-1)

$H \rightarrow bb$

CMS references



PAS HIG-11-012

Search for Higgs Boson in VH Production with H to bb (1 fb-1)

PAS HIG-11-031

Search for Higgs Boson in VH Production with H to bb (5 fb-1)

Phys.Lett. B710 (2012) 284-306 arXiv:1202.4195

Search for the standard model Higgs boson decaying to bottom quarks in pp collisions at sqrt(s)=7 TeV (VH , 5 fb-1)

PAS HIG-12-019

Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks for ICHEP 2012 (5 + 5 fb-1)

PAS HIG-12-025
Search for Higgs boson production in association with top quark pairs in pp collisions
(7 TeV 5fb-1)

PAS HIG-12-026
Search for a Higgs boson produced in association with b
quarks and decaying into a b-quark pair (7 TeV 4 fb-1)

PAS HIG-12-027
Search for SuperSymmetric Higgs boson states decaying into b b and produced in association with b-quarks in events collected by semi-leptonic triggers in pp collisions at sqrts = 7TeV (5 fb-1)

JINST 8 (2013) P04013 arXiv:1211.4462
Identification of b-quark jets with the CMS experiment

Phys.Lett. B722 (2013) 207-232 arXiv:1302.2892
Search for a Higgs boson decaying into a b-quark pair and produced in association with b quarks in proton-proton collisions at 7 TeV (5 fb-1)

PAS HIG-12-044
Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks for HCP 2012 (5+12 fb-1)

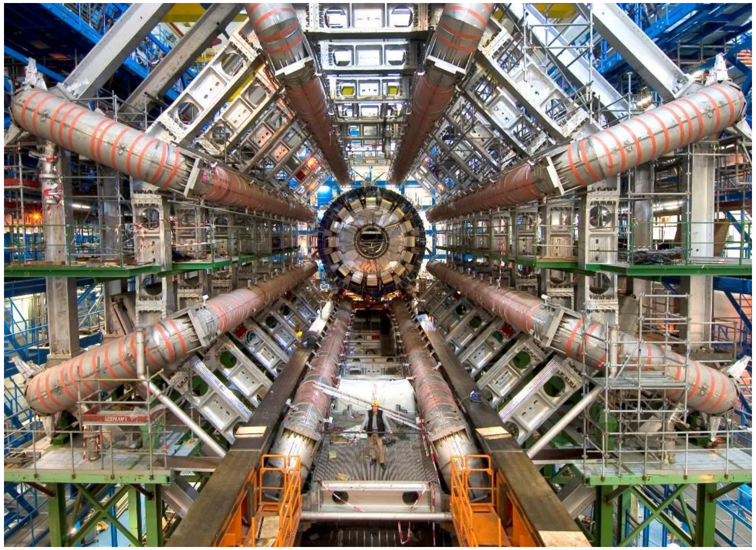
JHEP 1305 (2013) 145 arXiv:1303.0763
Search for the standard model Higgs boson produced in association with a top-quark pair in pp collisions at the LHC (5 + 5 fb-1)

PAS HIG-13-011
Higgs to bb in the VBF channel (8 TeV 19 fb-1)

PAS HIG-13-012
Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks for LHCp 2013 (5 + 19 fb-1)

arXiv:1310.3687
Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks (5 + 19 fb-1)

ATLAS references



ATLAS-CONF-2011-103
Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector at the LHC (1 fb-1)

ATLAS-CONF-2012-015
Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair using up to 4.7/fb of pp collision data at sqrt(s) = 7 TeV with the ATLAS detector at the LHC

Phys.Lett. B718 (2012) 369-390 arXiv:1207.0210
Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector (5 fb-1)

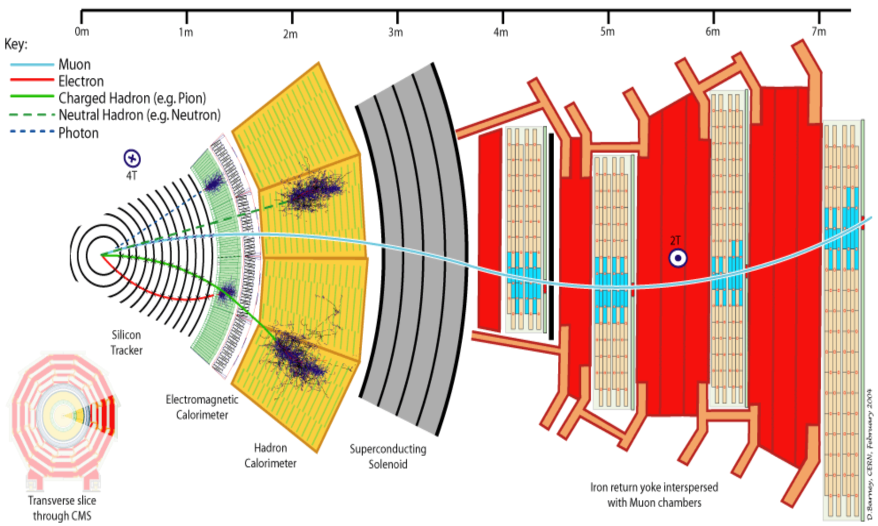
ATLAS-CONF-2012-135
Search for a Higgs boson produced in association with a top-quark pair and decaying to b¯b in pp collisions at $\sqrt{s}$ = 7 TeV using the ATLAS Detector (5 fb-1)

ATLAS-CONF-2012-161
Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to bottom quarks with the ATLAS detector (5+ 13 fb-1)

ATLAS-CONF-2013-079
Search for the bb decay of the Standard Model Higgs boson in associated W/ZH producti on with the ATLAS detector (5 + 20 fb-1)

H→ ττ

CMS references



PAS HIG-10-002
Search for Neutral Higgs Boson Production and Decay to Tau Pairs (36 pb-1)

Phys.Rev.Lett. 106 (2011) 231801 arXiv:1104.1619
Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions at sqrt(s)=7 TeV (36 pb-1)

PAS HIG-11-009
Search for Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s}$=7 TeV (1 fb-1)

PAS HIG-11-020
Search for Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s}$=7 TeV (1.6 fb-1)

PAS HIG-11-029
Search for Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s}$=7 TeV (5 fb-1)

PAS HIG-12-007

Search for Neutral Higgs Bosons Decaying into Tau Leptons in the Dimuon Channel with CMS in pp Collisions at 7 TeV (5 fb-1)

Phys.Lett. B713 (2012) 68-90 arXiv:1202.4083

Search for neutral Higgs bosons decaying to tau pairs in pp collisions at sqrt(s)=7 TeV (5 fb-1)

PAS HIG-12-018

Search for a standard model Higgs bosons decaying to tau pairs in pp collisions (5+5 fb-1)

PAS HIG-12-043

Higgs to tau tau (SM) (HCP) (5 + 12 fb-1)

PAS HIG-12-050

Search for MSSM Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions (5 + 12 fb-1)

PAS HIG-12-051

Search for the standard model Higgs boson decaying to tau pairs produced in association with a W or Z boson (5 +12 fb-1)

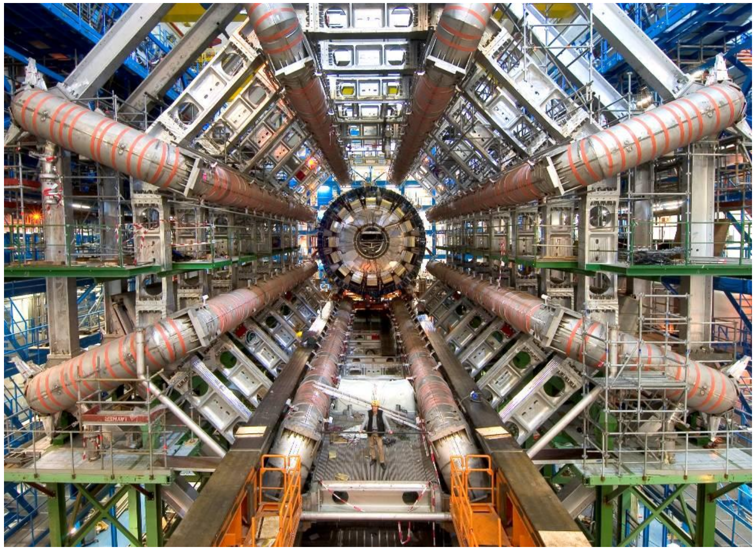
PAS HIG-12-053

Search for the standard model Higgs boson decaying to tau pairs produced in association with a W or Z boson (5 + 20 fb-1)

PAS HIG-13-004

Search for the Standard-Model Higgs boson decaying to tau pairs in proton-proton collisions at sqrt(s) = 7 and 8 TeV (5 + 20 fb-1)

ATLAS references



ATLAS-CONF-2011-024

Search for neutral MSSM Higgs bosons decaying to tau+tau- pairs in proton-proton collisions at sqrt(s)=7 TeV with the ATLAS Experiment (36 pb-1)

Phys.Lett. B705 (2011) 174-192 arXiv:1107.5003

Search for neutral MSSM Higgs bosons decaying to tau+ tau- pairs in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector (36 pb-1)

ATLAS-CONF-2011-132

Search for neutral MSSM Higgs bosons decaying to tau+tau- pairs in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector (1 fb-1)

ATLAS-CONF-2011-133

Search for the Standard Model Higgs boson in the decay mode H -> tau+ tau- -> ll + 4 neutrinos in Association with jets in Proton-Proton Collisions at sqrt(s) =7 TeV with the ATLAS detector (1 fb-1)

ATLAS-CONF-2012-014

Search for the Standard Model Higgs boson in the H->tau tau decay mode with 4.7 fb^-1 of ATLAS data at sqrt(s)=7TeV

JHEP 1209 (2012) 070 arXiv:1206.5971

Search for the Standard Model Higgs boson in the H to tau+ tau- decay mode in sqrt(s) = 7 TeV pp collisions with ATLAS (5 fb-1)

JHEP 1302 (2013) 095 arXiv:1211.6956

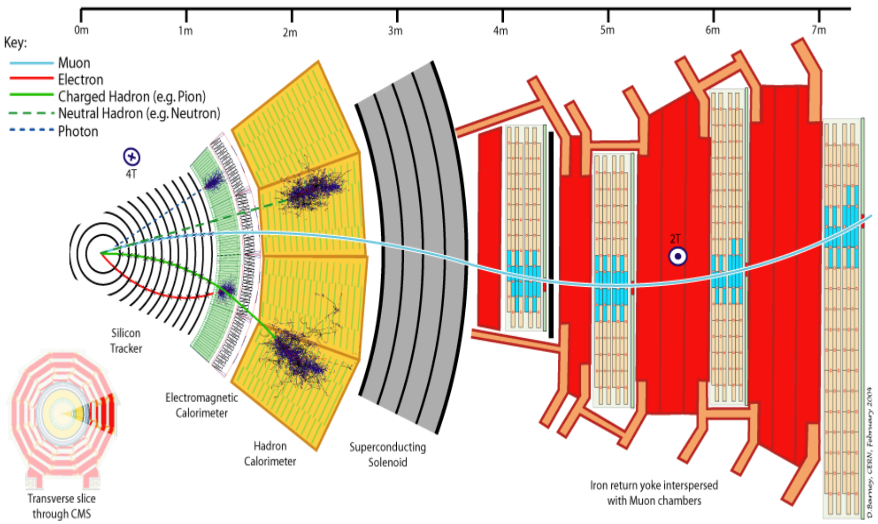
Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at sqrt(s)=7 TeV with the ATLAS detector (5 fb-1)

ATLAS-CONF-2012-160

Search for the Standard Model Higgs boson in H->tau+tau- decays in proton-proton collisions with the ATLAS detector (5 + 13 fb-1)

H→ $\mu\mu$

CMS references



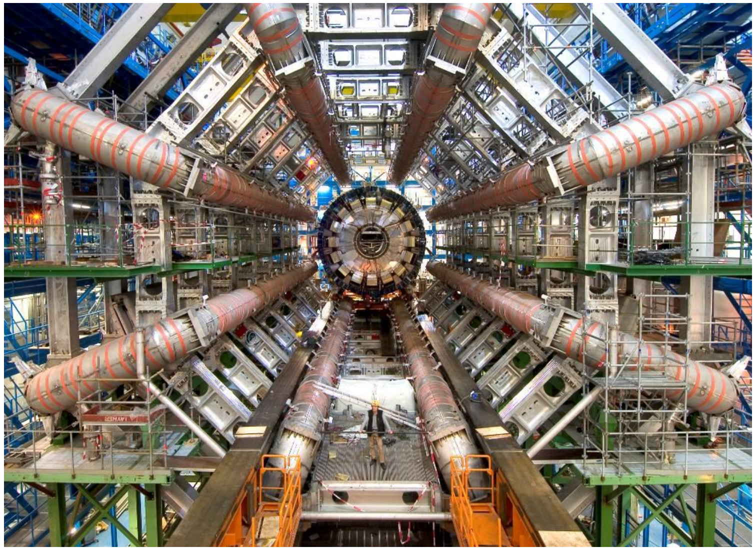
PAS HIG-12-004
Search for a light pseudoscalar boson in the dimuon channel (1.3 fb-1)

Phys.Rev.Lett. 109 (2012) 121801 arXiv:1206.6326
Search for a light pseudoscalar Higgs boson in the dimuon decay channel in pp collisions at sqrt(s) = 7 TeV (1.3 fb-1)

PAS HIG-12-011
Search for Neutral MSSM Higgs Bosons in the mu+mu- final state with the CMS experiment in pp Collisions at sqrt s =7 TeV (5 fb-1)

PAS HIG-13-007
Search for the standard model Higgs boson in the dimuon decay channel in pp collisions at sqrt(s)= 7 and 8 TeV (5 + 20 fb-1)

ATLAS references

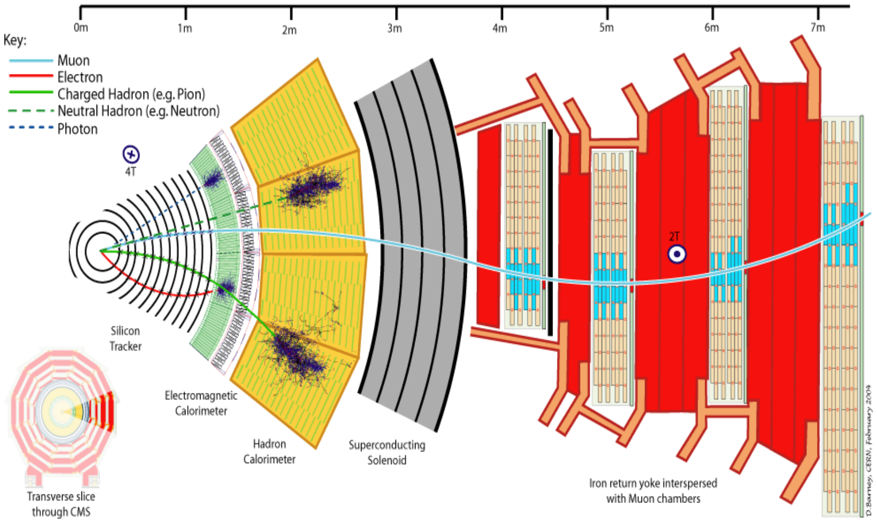


ATLAS-CONF-2011-020
A Search for a Light CP-Odd Higgs Boson Decaying to mu^+ mu^- in ATLAS
(36 pb-1)

ATLAS-CONF-2013-010
Search for a Standard Model Higgs boson in H->μμ decays with the ATLAS detector
(8 TeV 21 fb-1)

Other combinations

CMS references

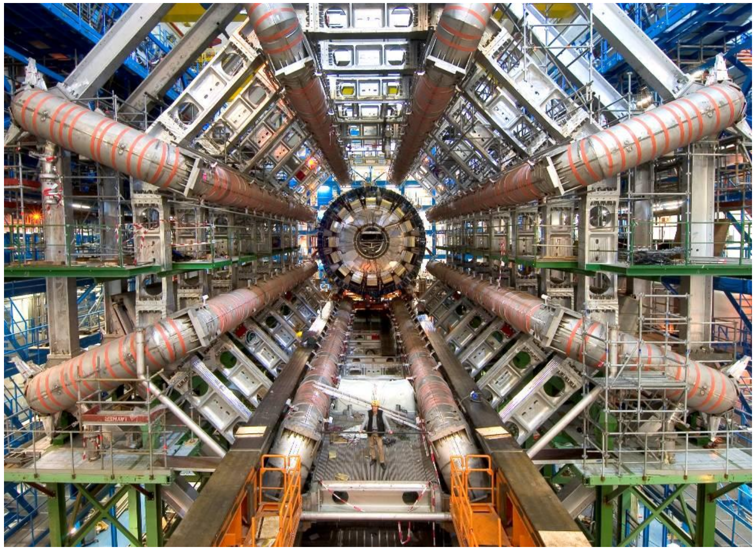


Eur.Phys.J. C73 (2013) 2469 arXiv:1304.0213

Search for a standard-model-like Higgs boson with a mass of up to 1 TeV at the LHC

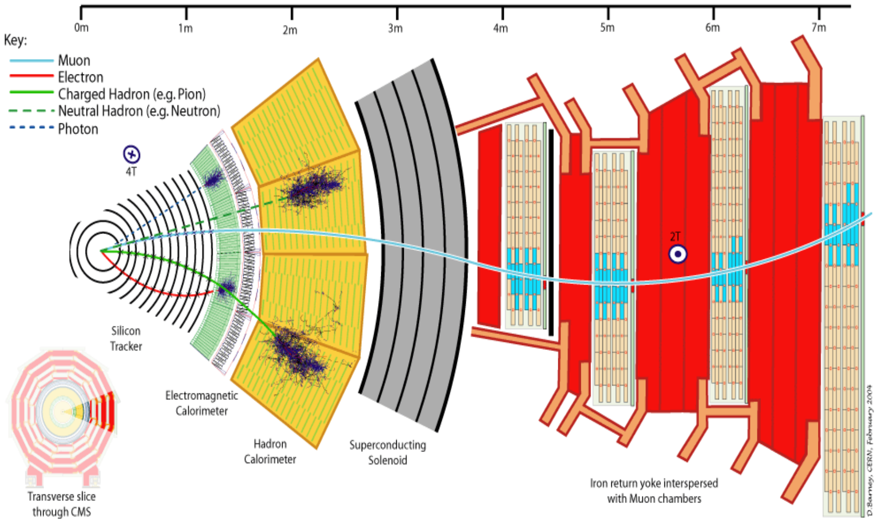
(WW , ZZ 5 + 5 fb-1)

ATLAS references



VH   t t H

CMS references



PAS HIG-11-034
Search for WH to 3 leptons (5 fb-1)

PAS HIG-12-006
Search for WH in Final States with Electrons, Muons, Taus (5 fb-1)

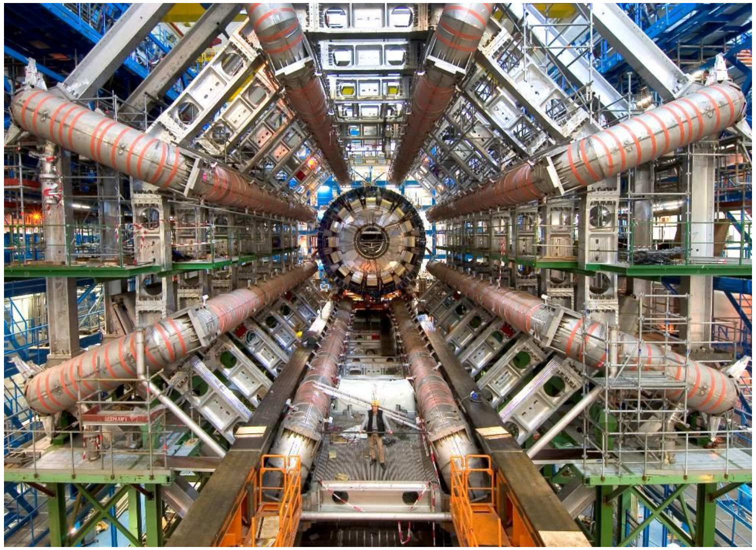
JHEP 1211 (2012) 088 arXiv:1209.3937
Search for the standard model Higgs boson produced in association with W and Z bosons in pp collisions at sqrt(s)=7 TeV (5 fb-1)

PAS HIG-13-019
Search for Higgs Boson Production in Association with a Top-Quark Pair and Decaying to Bottom Quarks or Tau Leptons (8 TeV 20 fb-1)

PAS HIG-13-020

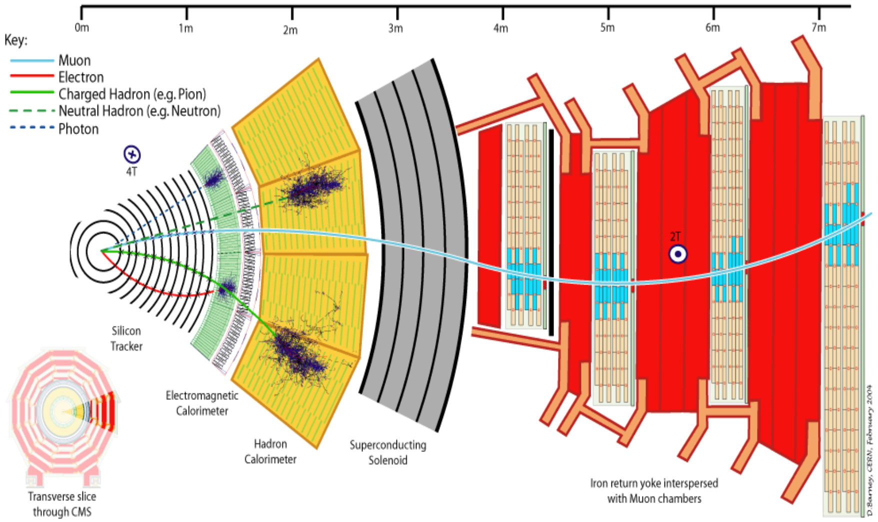
Search for the standard model Higgs boson produced in association with top quarks in multilepton final states (8 TeV 20 fb-1)

ATLAS references



H±

CMS references



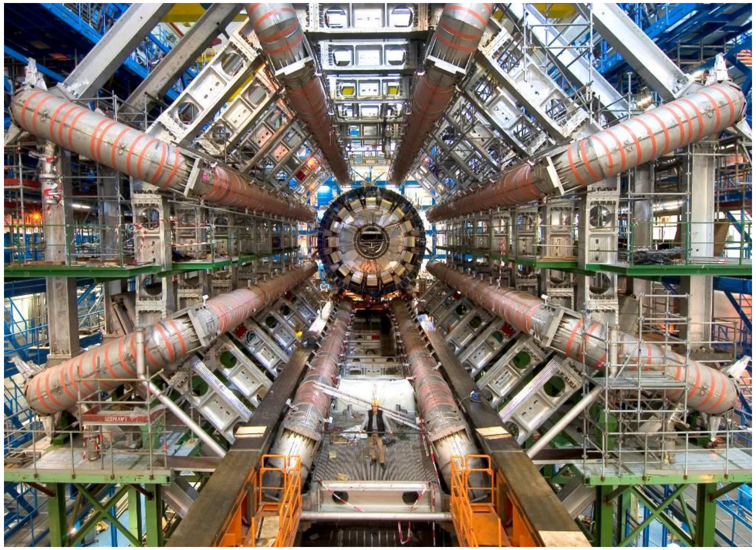
PAS HIG-11-002
Search for the charged Higgs boson in the etau and mutau dilepton channels of top quark pair decays (36 pb-1)

PAS HIG-11-008
H+ -> Tau in Top quark decays (1 fb-1)

JHEP 1207 (2012) 143 arXiv:1205.5736
Search for a light charged Higgs boson in top quark decays in pp collisions at sqrt(s) = 7 TeV (2 fb-1)

PAS HIG-12-052
Updated search for a light charged Higgs boson in top quark decays in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

ATLAS references



ATLAS-CONF-2011-018
Study of discriminating variables for charged Higgs boson searches in ttbar events with leptons, using 35/pb of data from the ATLAS detector

ATLAS-CONF-2011-094
A search for a light charged Higgs boson decaying to cs in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector (36 pb-1)

ATLAS-CONF-2011-138
Search for Charged Higgs Bosons in the tau+jets Final State in t-tbar Decays with 1.03 fb-1 of pp Collision Data Recorded at sqrt{s} = 7TeV with the ATLAS Experiment

ATLAS-CONF-2012-011
Search for charged Higgs bosons decaying via H->tau nu in ttbar events using 4.6 fb^-1 of collision data at sqrt(s)=7 TeV with the ATLAS detector

JHEP 1206 (2012) 039 arXiv:1204.2760
Search for charged Higgs bosons decaying via H+ -> tau nu in top quark pair events using pp collision (5 fb-1)

ATLAS-CONF-2011-151
Search for a charged Higgs boson decaying via H+ to tau(lep)+nu in ttbar events with one or two light leptons in the final state using 1.03/fb of pp collision data recorded at sqrt(s) = 7 TeV with the ATLAS detector

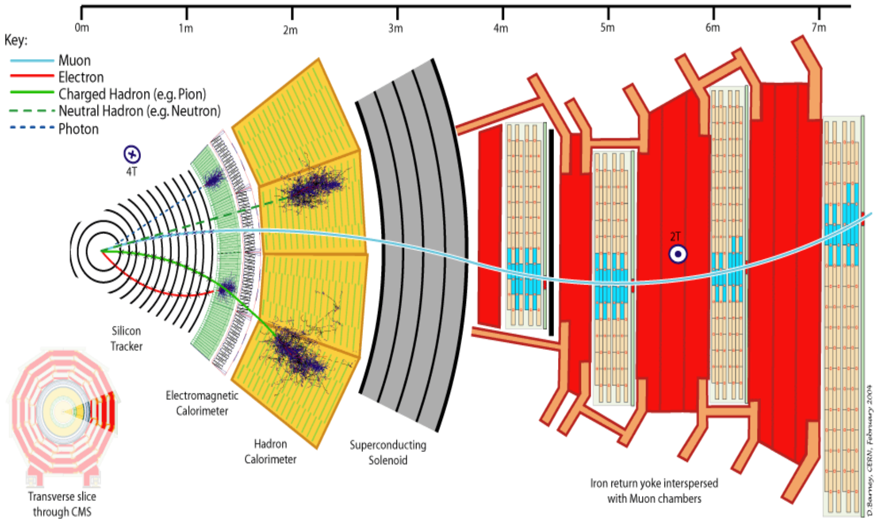
JHEP 1303 (2013) 076 arXiv:1212.3572
Search for charged Higgs bosons through the violation of lepton universality in ttbar events using pp collision data at sqrt(s) = 7 TeV with the ATLAS experiment (5 fb-1)

Eur.Phys.J. C73 (2013) 2465 arXiv:1302.3694
Search for a light charged Higgs boson in the decay channel H+->csbar in ttbar events using pp collisions at sqrt(s) = 7 TeV with the ATLAS detector (5 fb-1)

ATLAS-CONF-2013-090
Search for charged Higgs bosons in the tau +jets final state with pp collision data recorded at sqrt(s) =8 TeV with the ATLAS experiment (20 fb-1)

invisible H

CMS references



PAS HIG-13-013

Search for an Invisible Higgs Boson in VBF channels (8 TeV 20 fb-1)

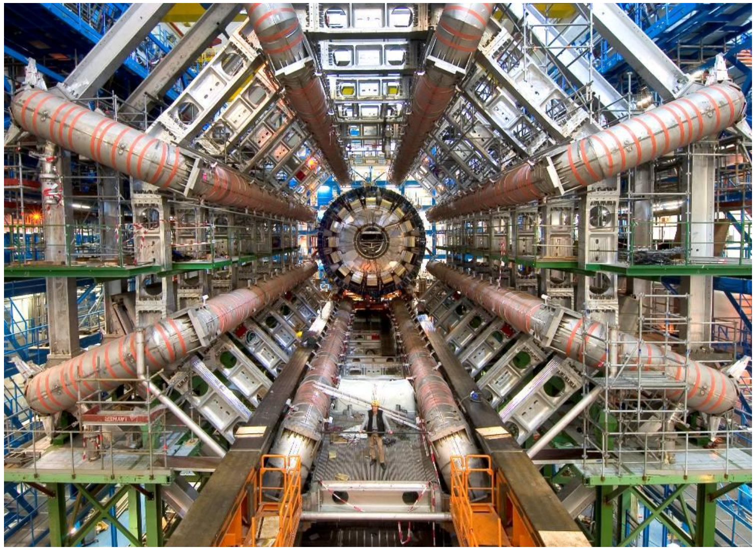
PAS HIG-13-018

Search for invisible Higgs produced in association with a Z boson (5 + 20 fb-1)

PAS HIG-13-028

Search for Higgs boson decaying to invisible particles and produced in association with a Z boson decaying to bottom quarks (8 TeV 20 fb-1)

ATLAS references

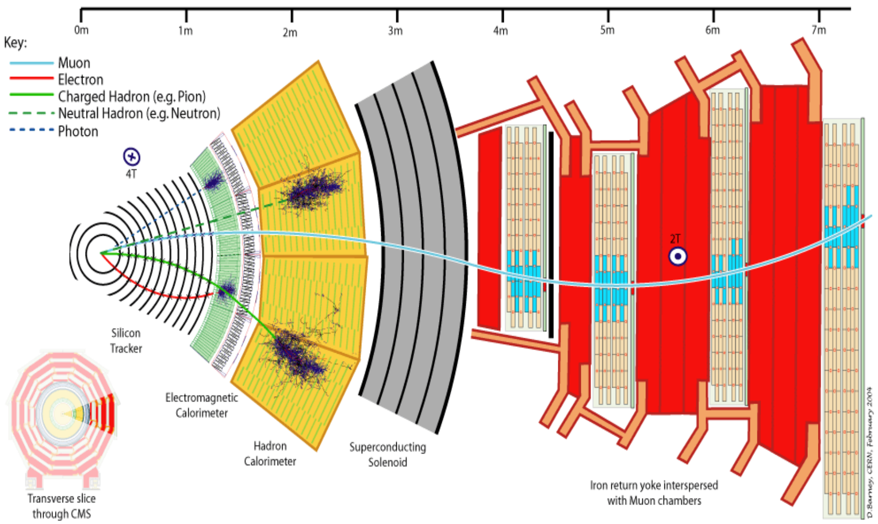


ATLAS-CONF-2013-011

Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS (5 + 13 fb-1)

BSM (MSSM, NMSSM) H

CMS references



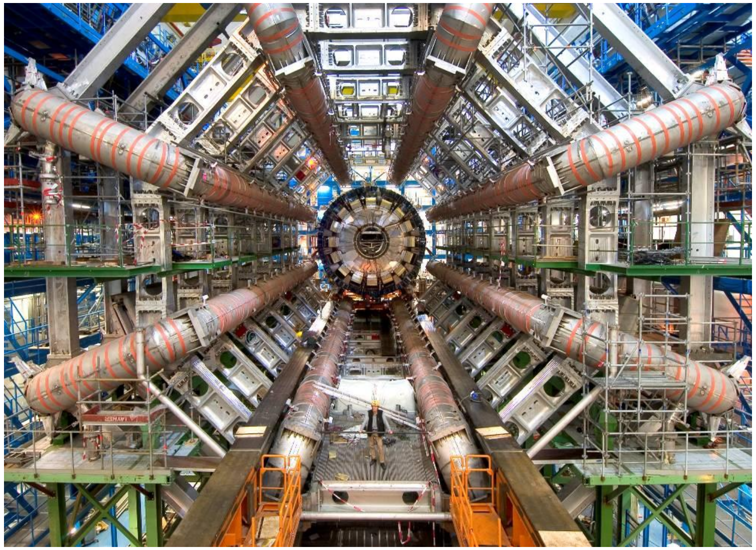
arXiv:1210.7619

Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states (5 fb-1)

PAS HIG-13-010

Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states (8 TeV 20 fb-1)

ATLAS references



ATLAS-CONF-2012-079

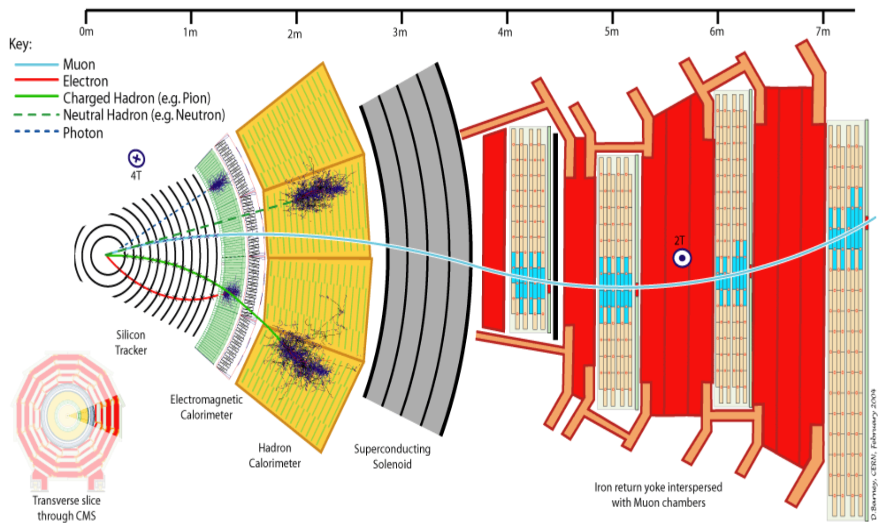
Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb-1 of 7 TeV pp collision data taken with ATLAS detector at the LHC

ATLAS-CONF-2012-094

Search for neutral MSSM Higgs bosons in sqrt{s}=7 TeV pp collisions with the ATLAS detector (5 fb-1 $\mu\mu$ $\tau\tau$)

very exotic H   associated production

CMS references



PAS HIG-11-001
Inclusive search for doubly charged higgs in leptonic final states at sqrt s=7 TeV (36 pb-1)

PAS HIG-11-007
Inclusive search for doubly charged higgs in leptonic final states at sqrt s=7 TeV (1 fb-1)

JHEP 1209 (2012) 111 arXiv:1207.1130
Search for a fermiophobic Higgs boson in pp collisions at sqrt(s)=7 TeV (5 fb-1)

PAS HIG-12-005
Inclusive search for a doubly charged Higgs boson in leptonic final states with CMS at sqrts=7 TeV (5 fb-1)

Eur.Phys.J. C72 (2012) 2189 arXiv:1207.2666
A search for a doubly-charged Higgs boson in pp collisions at sqrt(s) = 7 TeV (5 fb-1)

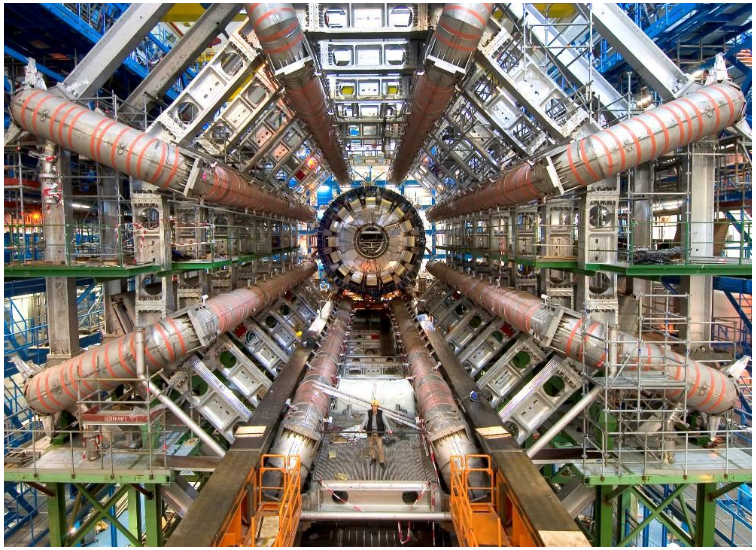
PAS SUS-13-002
A search for anomalous production of events with three or more leptons using 19.5 fb-1 of sqrts=8 TeV LHC data (FCNC t $\rightarrow$cH)

Phys.Lett. B725 (2013) 36-59 arXiv:1302.1764
Searches for Higgs bosons in pp collisions at sqrt(s) = 7 and 8 TeV in the context of four-generation and fermiophobic models (5 + 5 fb-1)

PAS SUS-13-014
Search for SUSY Partners of Top and Higgs Using Diphoton Higgs Decays (8TeV 20 fb-1)

PAS SUS-13-017
Search for electroweak production of charginos and neutralinos in final states with a Higgs boson in pp collisions at 8 TeV (8 fb-1)

ATLAS references



ATLAS-CONF-2011-127

Search for Doubly Charged Higgs Boson Production in Like-sign Muon Pairs in pp Collisions at sqrt(s)=7 TeV (1.6 fb-1)

Phys.Rev.Lett. 108 (2012) 251801 arXiv:1203.1303

Search for a light Higgs boson decaying to long-lived weakly-interacting particles in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector (2 fb-1)

ATLAS-CONF-2012-089

Search for Displaced Muon Jets from light Higgs boson decay in proton-proton collisions at sqrt(s) = 7 Tev with the ATLAS detector (2 fb-1)

Phys.Lett. B721 (2013) 32-50 arXiv:1210.0435

Search for displaced muonic lepton jets from light Higgs boson decay in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector (2 fb-1)

Eur.Phys.J. C72 (2012) 2244 arXiv:1210.5070

Search for doubly-charged Higgs bosons in like-sign dilepton final states at sqrt(s) = 7 TeV with the ATLAS detector (5 fb-1)

New J.Phys. 15 (2013) 043009 arXiv:1302.4403

Search for WH production with a light Higgs boson decaying to prompt electron-jets in proton-proton collisions at sqrt(s)=7 TeV with the ATLAS detector (2 fb-1)

ATLAS-CONF-2013-018

Search for heavy top-like quarks decaying to a Higgs boson and a top quark in the lepton plus jets final state in pp collisions at sqrt(s) =8 TeV with the ATLAS detector (14 fb-1)

ATLAS-CONF-2013-093

Search for chargino and neutralino production in final states with one lepton, two b-jets consistent with a Higgs boson, and missing transverse momentum with the ATLAS detector in 20.3 fb-1 of √s = 8 TeV pp collisions

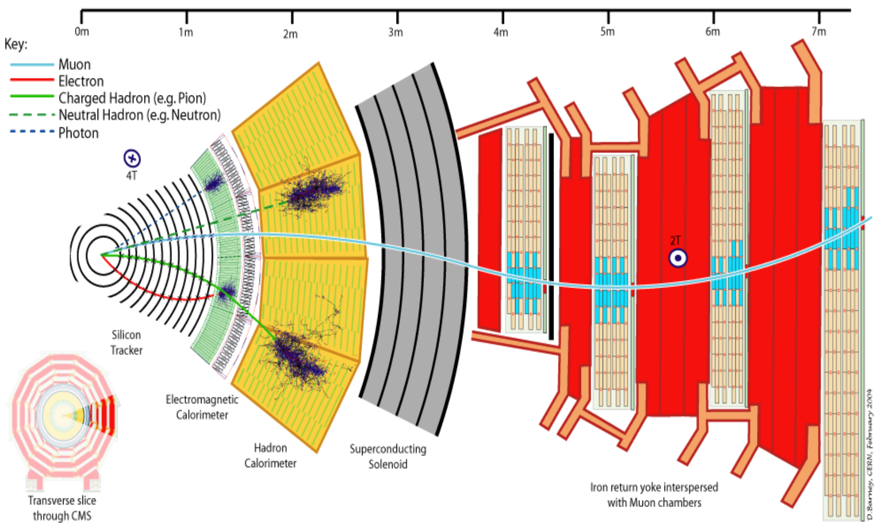
future

general references

R.Aleksan et al. CERN-ESG-005
Physics Briefing Book (Input for the Strategy Group to draft the update of the European Strategy for Particle Physics)

M.Bicer et al. arXiv:1308.6176
First Look at the Physics Case of TLEP

CMS references



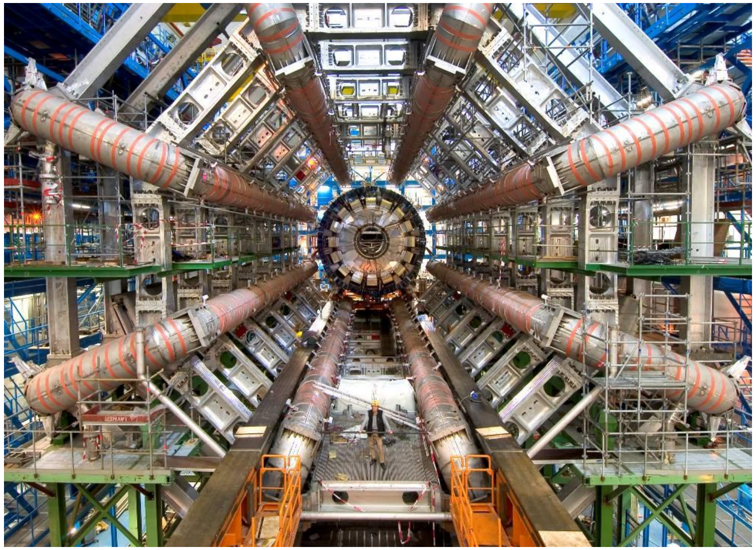
CMS NOTE 2012-006
CMS at the High-Energy Frontier. Contribution to the Update of the European Strategy for Particle Physics

CMS NOTE 2013-002 arXiv:1307.7135
Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process

CMS PAS FTR-13-003
H to ZZ to 4l

CMS PAS FTR-13-024
2HDM Neutral Higgs Future Analysis Studies

ATLAS (…) references



ATL-PHYS-PUB-2012-004
Physics at a High-Luminosity LHC with ATLAS

ATL-PHYS-PUB-2012-005
Studies of Vector Boson Scattering with an Upgraded ATLAS Detector at a High-Luminosity LHC

ATL-PHYS-PUB-2013-001
Studies of the ATLAS potential for Higgs self-coupling measurements at a High Luminosity LHC

ATL-PHYS-PUB-2013-004
Performance assumptions for an upgraded ATLAS detector at a High-Luminosity LHC

ATL-PHYS-PUB-2013-006
Studies of Vector Boson Scattering And Triboson Production with an Upgraded ATLAS Detector at a High-Luminosity LHC

ATL-PHYS-PUB-2013-007
Physics at a High-Luminosity LHC with ATLAS

ATL-PHYS-PUB-2013-009
Performance assumptions based on full simulation for an upgraded ATLAS detector at a High-Luminosity LHC

ATL-UPGRADE-PUB-2013-014
Expected pileup values at the HL-LHC

ATL-PHYS-PUB-2013-012
Sensitivity of ATLAS at HL-LHC to flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$

ATL-PHYS-PUB-2013-014
Projections for measurements of Higgs boson cross sections, branching ratios and coupling parameters with the ATLAS detector at a HL-LHC

ATL-PHYS-PUB-2013-015
Sensitivity to New Phenomena via Higgs Couplings with the ATLAS Detector
at a High-Luminosity LHC

ATL-PHYS-PUB-2013-016
Beyond-the-Standard-Model Higgs boson searches at a High-Luminosity LHC with ATLAS

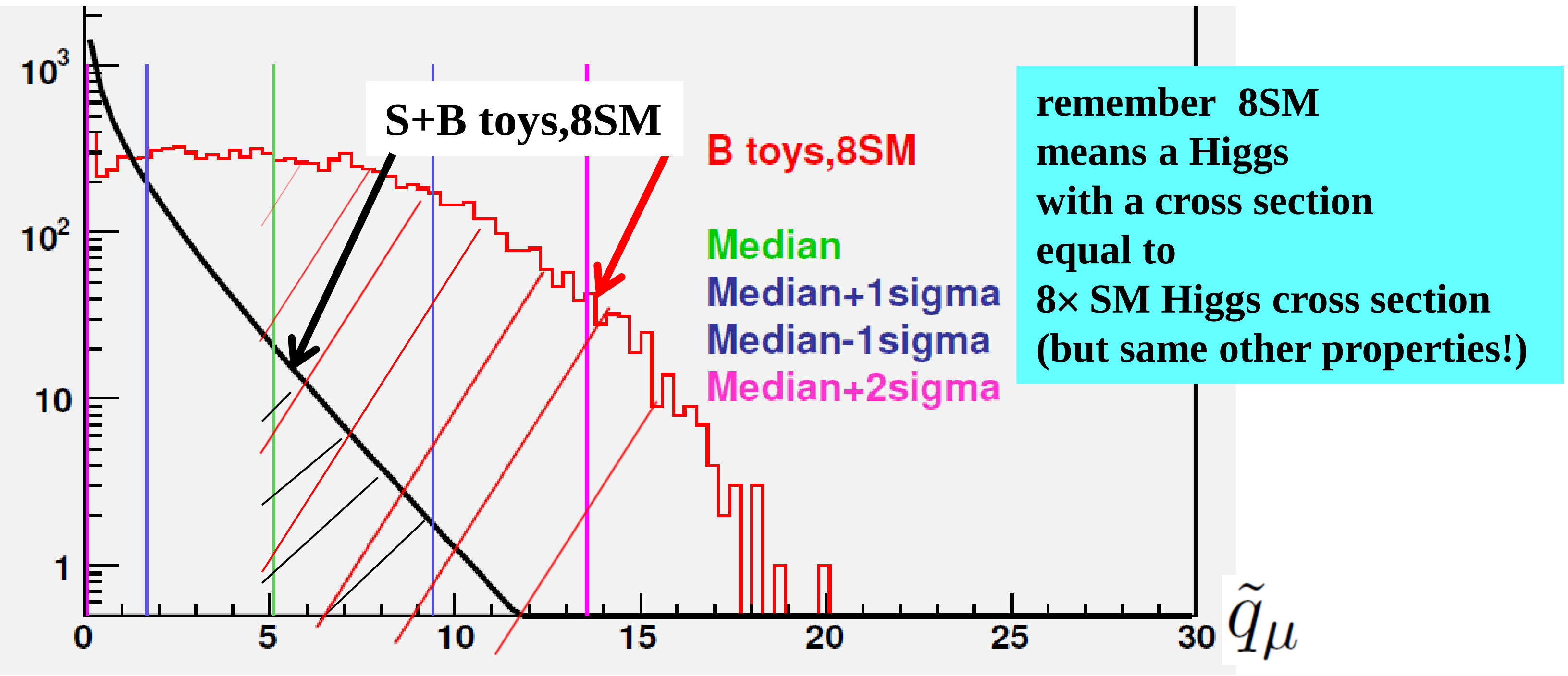
R.Goncalo,S.Guindon,V.Jain arXiv:1310.0292
Sensitivity of LHC experiments to the t t H final state,
with $H \rightarrow bb$ at center of mass energy of 14 TeV

J.Vasquez,J.Adelman,A.Loginov and P.Tipton arXiv:1310.1132
Study of ttH (H -> mu mu) in the three lepton channel
at sqrt(s) = 14 TeV; A Snowmass white paper

additional transparencies

Collateral problems : movements of magnets

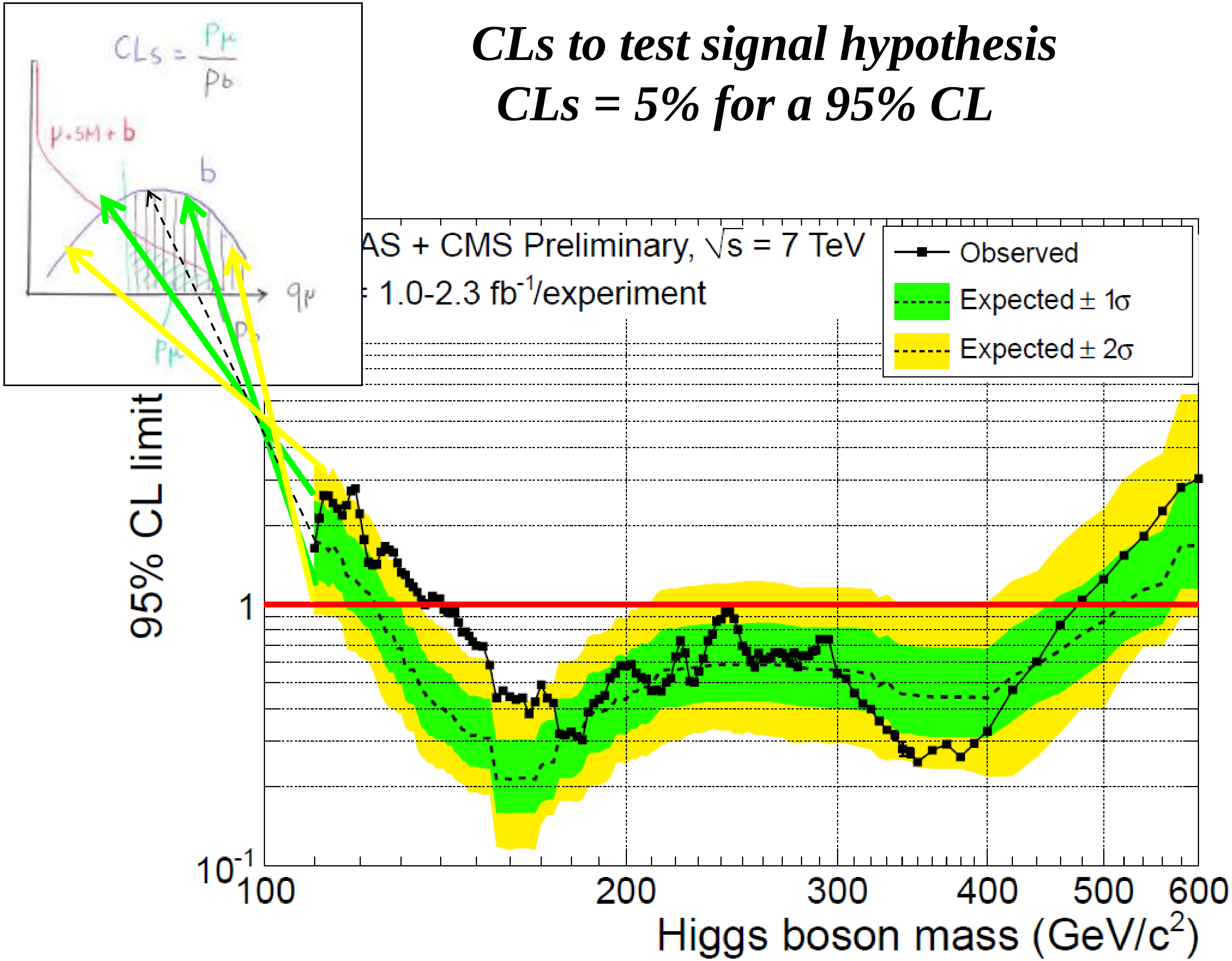
Parenthesis on limits (and the green – yellow bands)



In fact 8SM is excluded (median here) at 95%CL if the ratio of the black hatched area divided by the red hatched area is (smaller than) 5% (CL$_S$ definition)

Alex Read

CLs to test signal hypothesis
CLs = 5% for a 95% CL



p_0 to test background hypothesis