The Higgs boson one year later: theoretical issues

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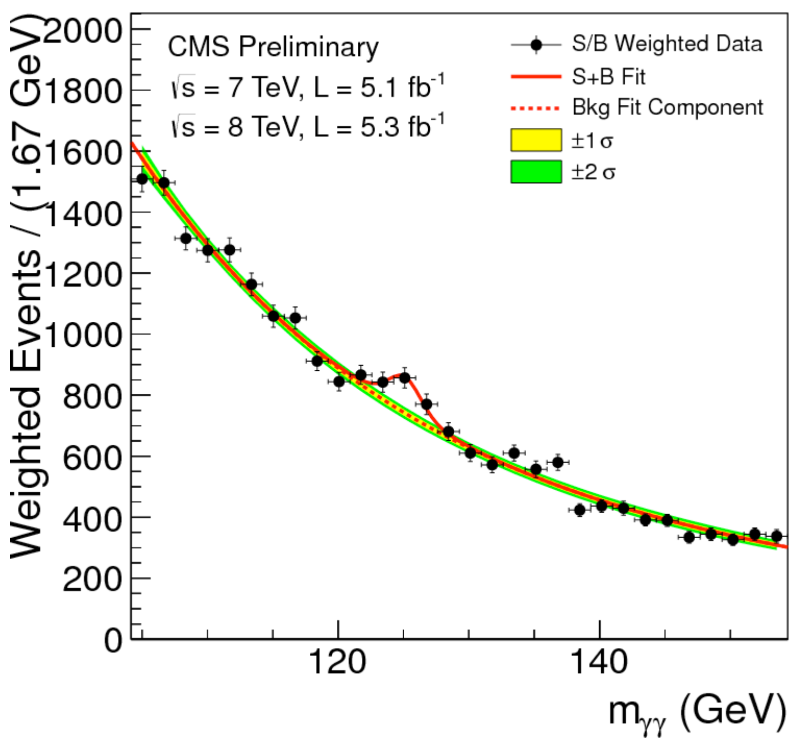
Lyon, october 29 2013

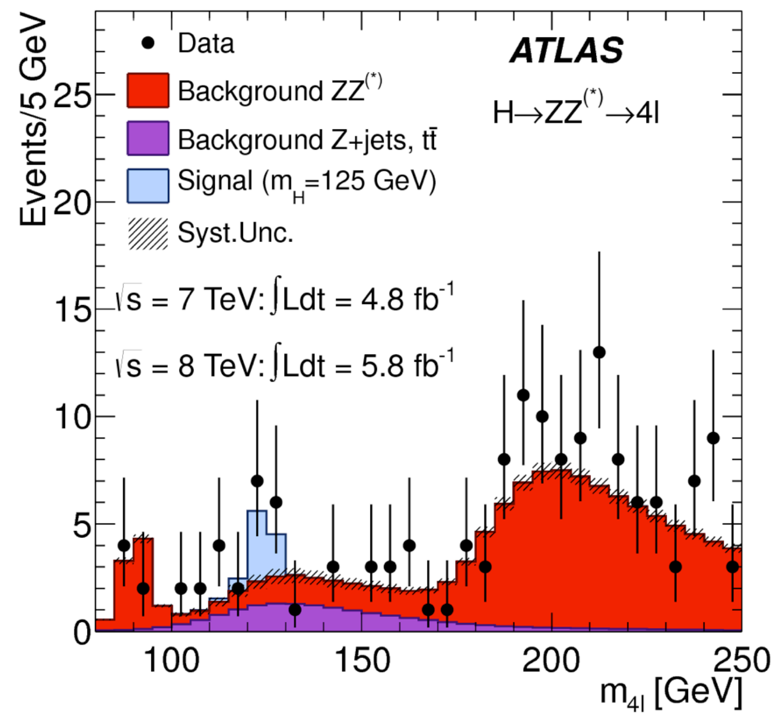
Outline

- Introduction
- Higgs boson production in the SM: $gg \rightarrow H$
  - Benchmark cross sections and uncertainties
  - Going differential: p_T spectrum and jet-bins
- Higgs boson production in the SM: VBF and VH
- Higgs properties
  - Spin/CP properties and TH frameworks
  - Coupling extraction
  - Beyond interim recommendations
- Summary and Outlook

Introduction

- On July 4th 2012 ATLAS and CMS have announced the observation of a new neutral state with mass $m_H \sim 125$ GeV compatible with the production and decay of the Standard Model Higgs boson





- Right where precision tests like the SM model Higgs to be !

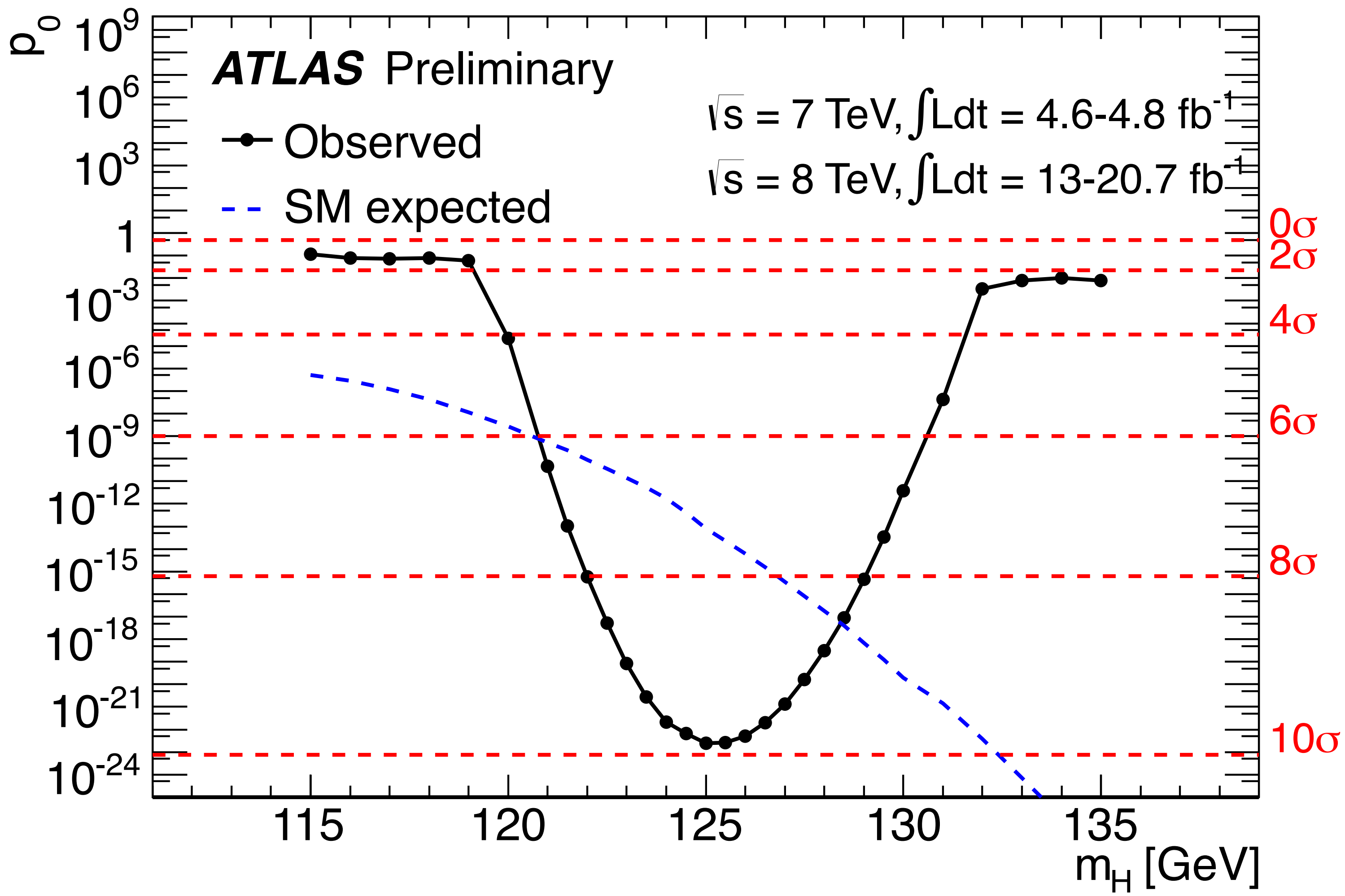
- Probably the most difficult and long sought discovery in the history of particle physics: search for very rare events with tiny cross sections

- Clever analyses to isolate signal over huge backgrounds

Introduction

One year later:

the existence of a new particle established beyond any doubt



CMS

Channel	Expected, σ	Observed, σ
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
$b\bar{b}$	2.2	2.0
$\tau\tau$	2.6	2.8
$b\bar{b}+\tau\tau$	3.4	3.4

The discovery driven by high-resolution channels: H→ZZ, H→γγ is now confirmed in the other channels

Introduction

- ZZ is the most sensitive high-resolution channel: high S/B ratio

ATLAS	$\mu = 1.43^{+0.40}_{-0.35}$	$m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV
CMS	$\mu = 0.91^{+0.30}_{-0.24}$	$m_H = 125.8 \pm 0.4 \pm 0.2$ GeV

- γγ is the second most sensitive high-resolution channel: low S/B ratio but high signal yield

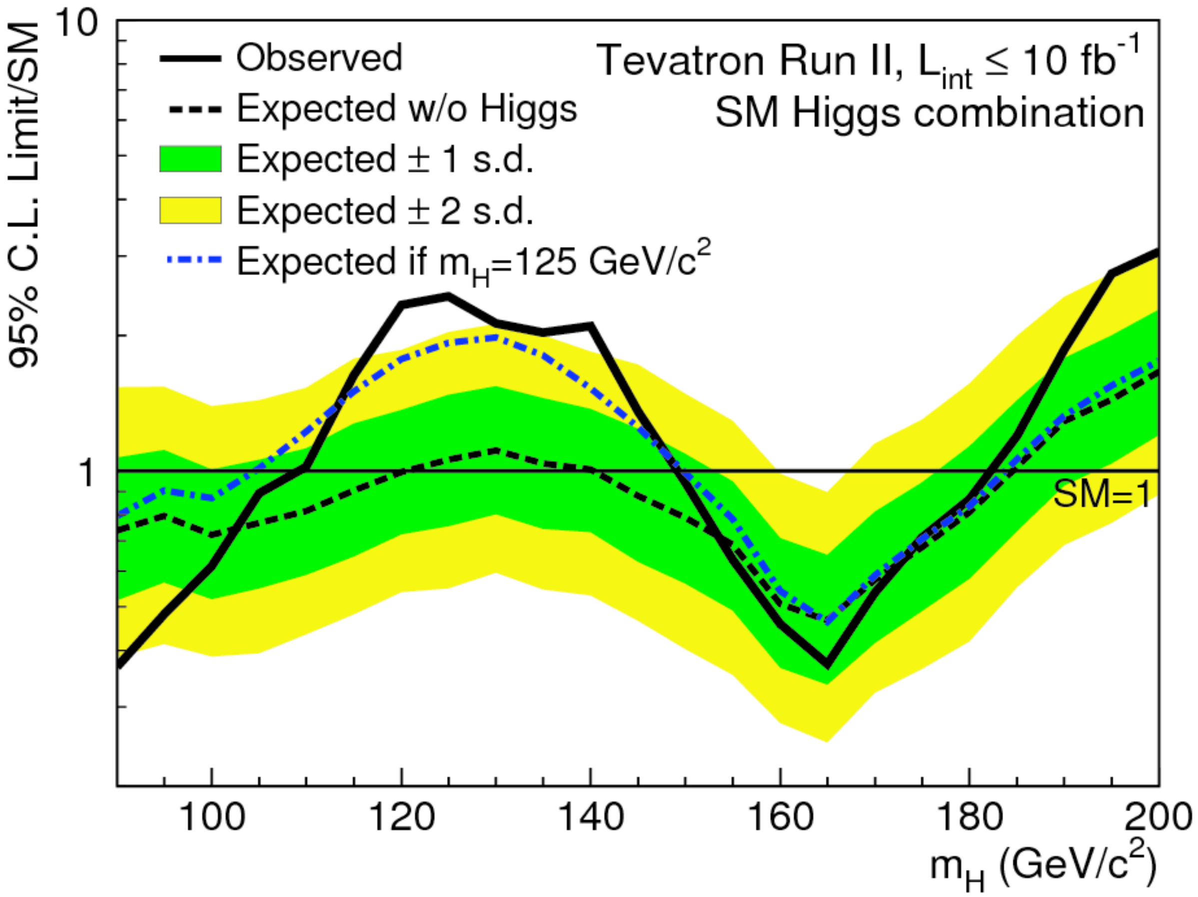
ATLAS	$\mu = 1.55^{+0.33}_{-0.28}$	$m_H = 126.8 \pm 0.2 \pm 0.7$ GeV
CMS	$\mu = 0.78^{+0.28}_{-0.26}$	$m_H = 125.4 \pm 0.8$ GeV

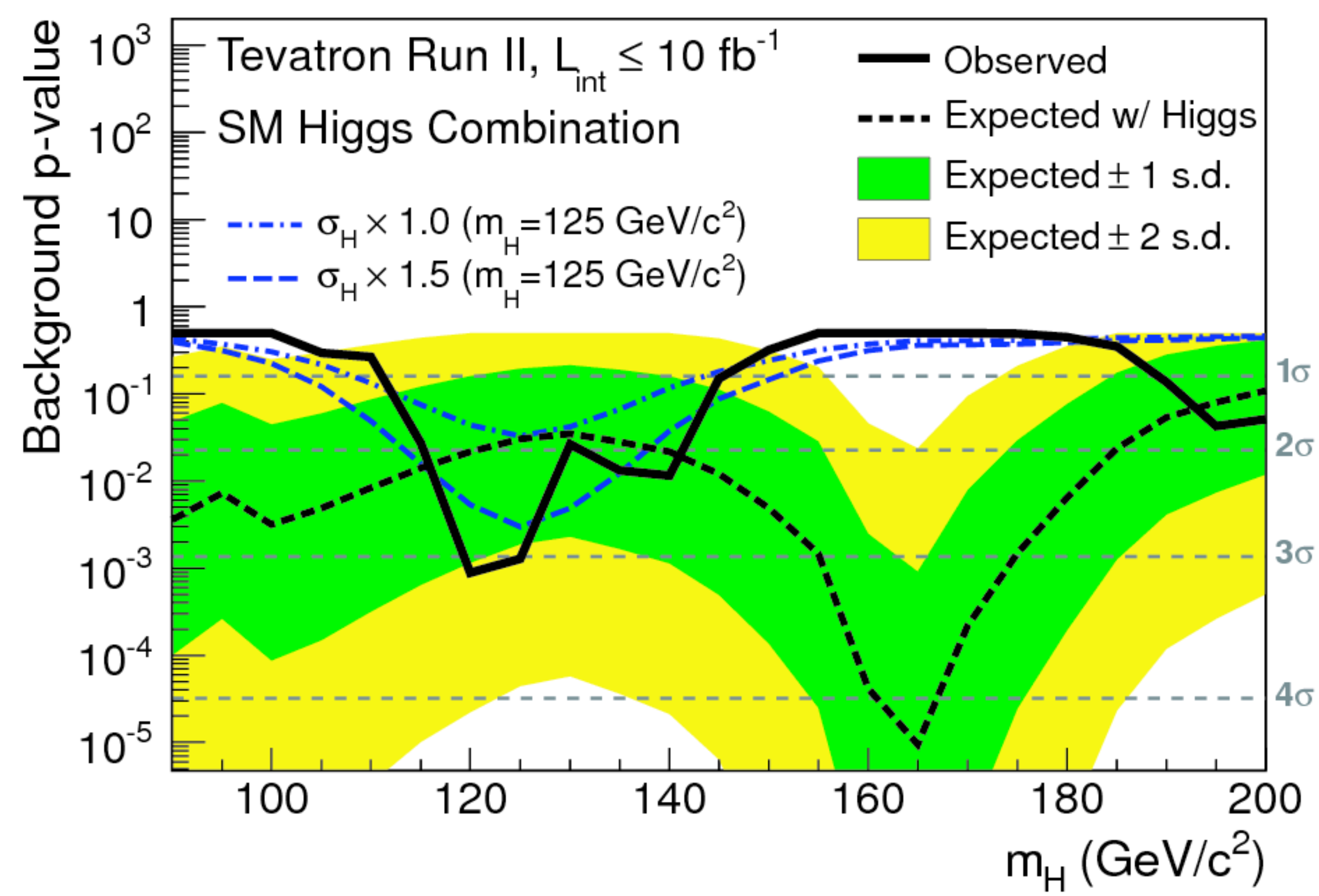
ATLAS tends to have a higher signal yield ($\mu>1$) with respect to CMS ($\mu<1$)

CMS mass measurements perfectly consistent but 2.4σ tension between ATLAS ZZ and γγ measurements

Introduction

These results are further corroborated by the broad excess seen at the Tevatron (but with poor mass resolution)



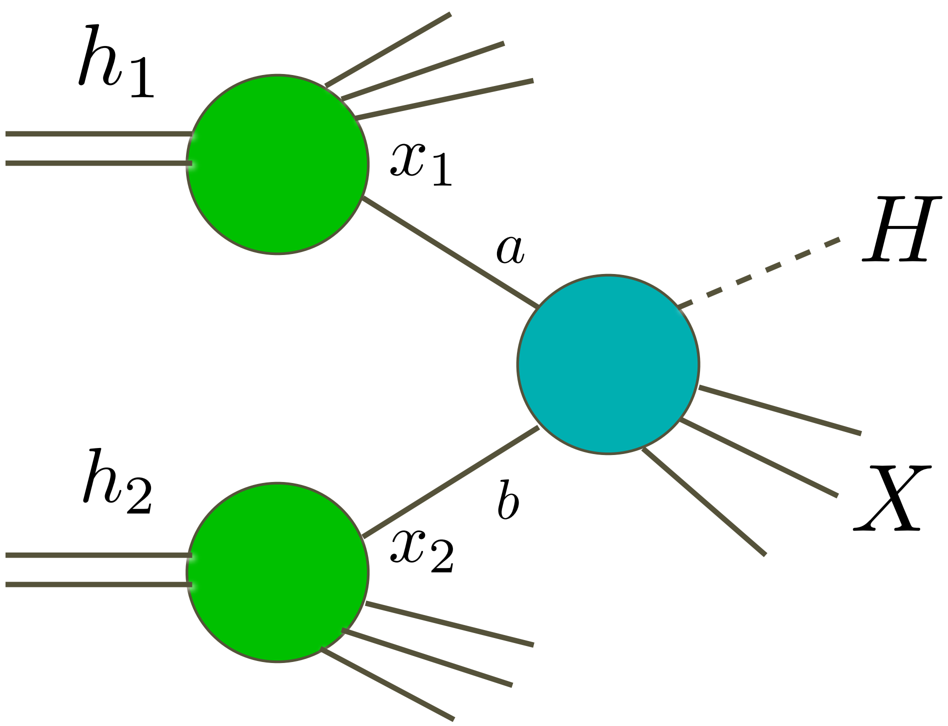


CDF and D0 claim a global significance in the range m_H=115-150 GeV of 3.0 σ

Important because it is in the H→bbar channel
on which LHC is poorly sensitive at present

Theoretical predictions

The framework: QCD factorization theorem



Parton distributions

Partonic cross section

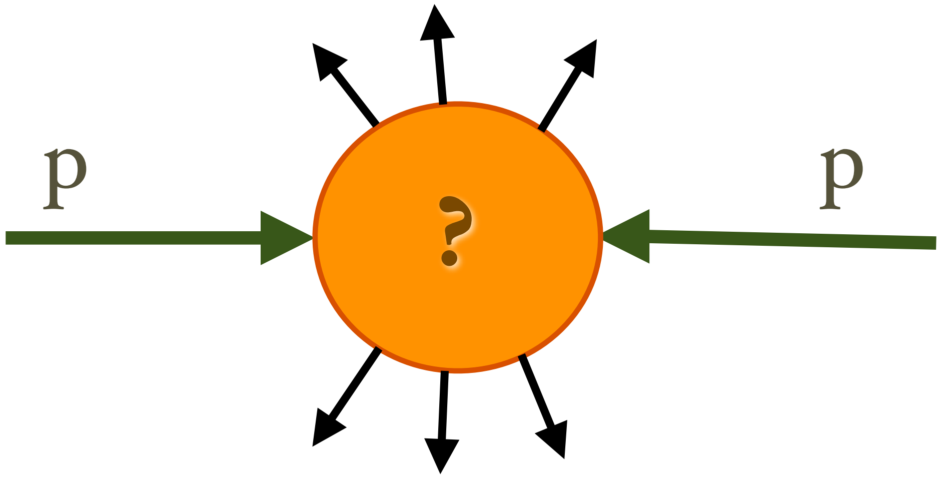
$$\sigma(p_1, p_2; M_H) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1, \mu_F^2)\, f_{h_2,b}(x_2, \mu_F^2) \times \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_S(\mu_R^2); \mu_F^2)$$

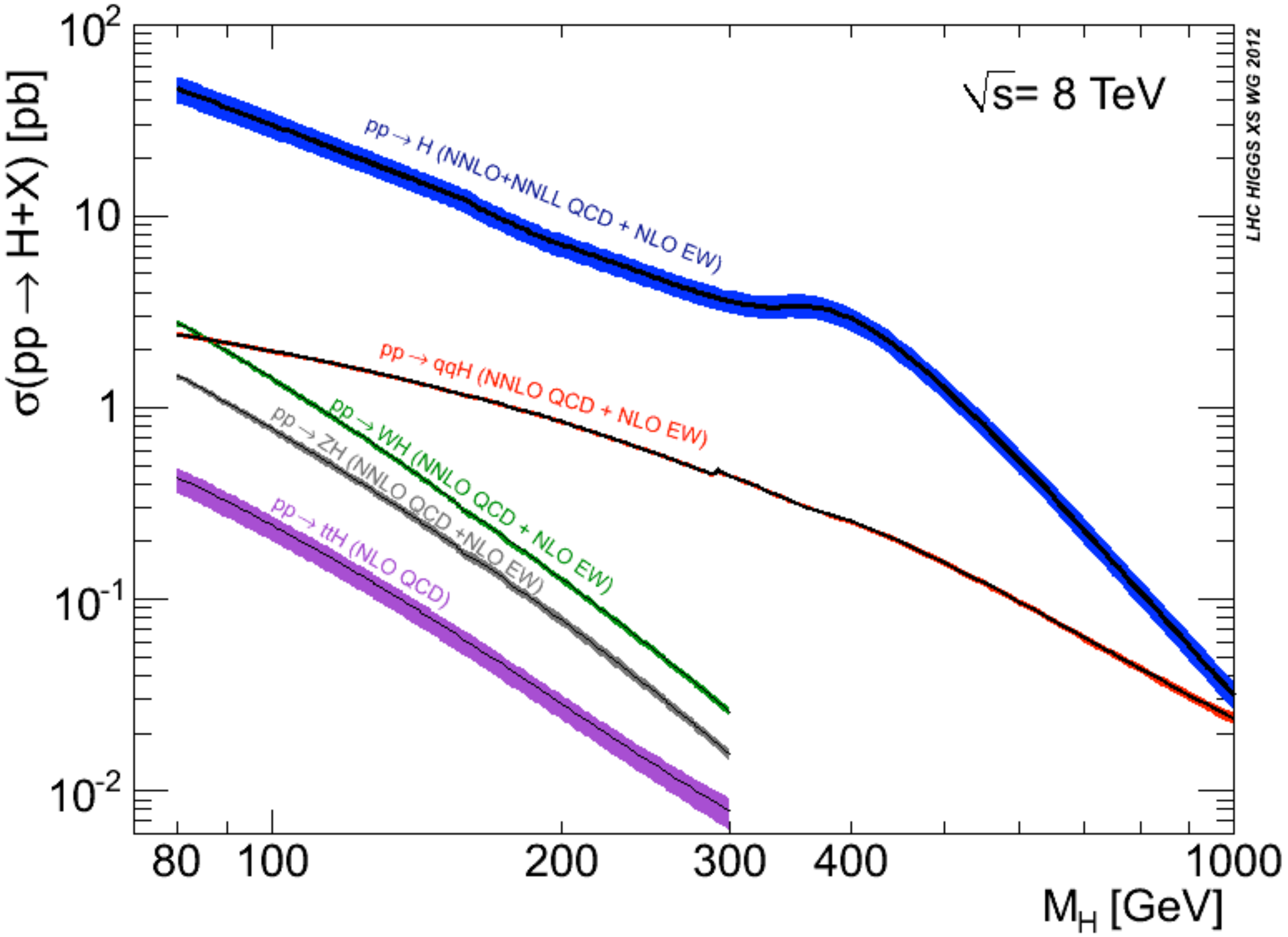
Precise predictions for σ depend on good knowledge of BOTH $\hat{\sigma}_{ab}$ and $f_{h,a}(x, \mu_F^2)$

Introduction

QCD ubiquitous at hadron colliders

This applies also to Higgs production



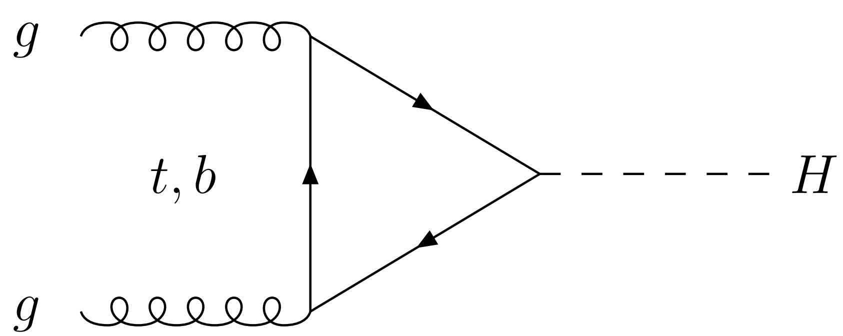


Large gluon luminosity:

gg fusion is the dominant production channel over the whole range of m_H

→ Focus on gg fusion in this talk

gg fusion



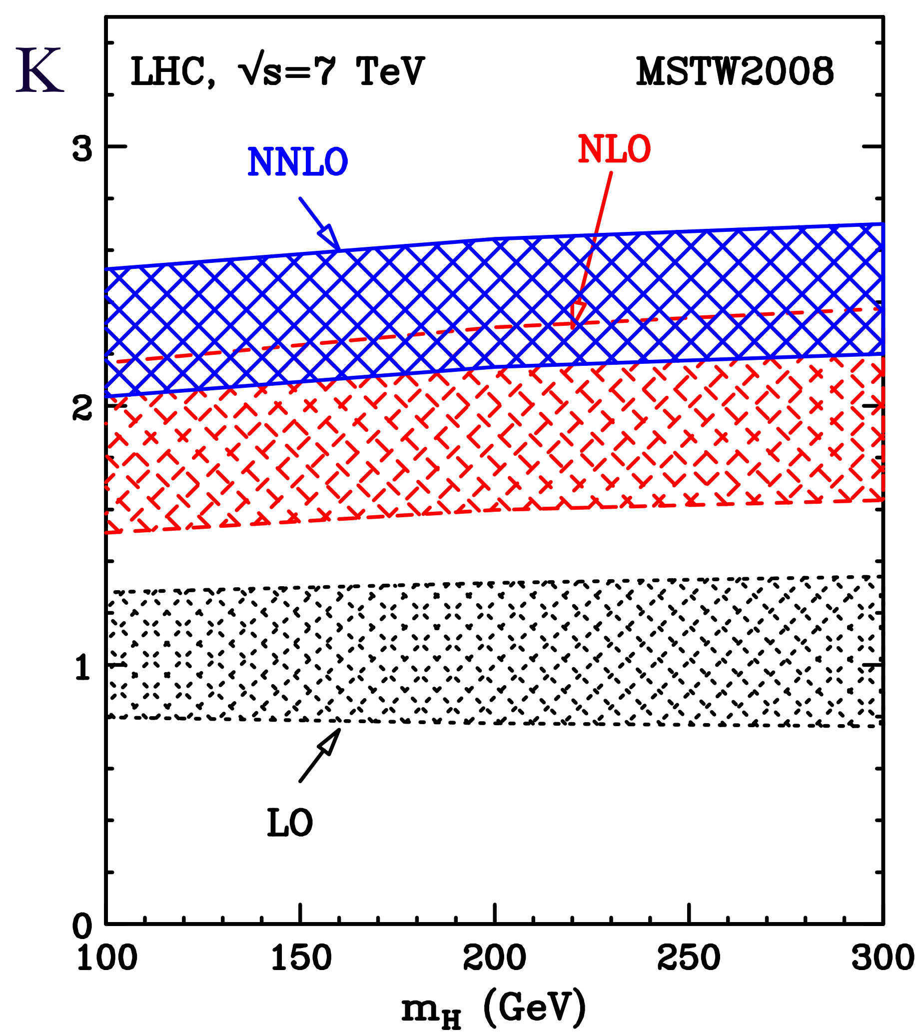
The Higgs coupling is proportional to the quark mass

→ top-loop dominates

$O(\alpha_S^2)$ process already at Born level

QCD corrections to the total rate computed 20 years ago and found to be large → O(100 %) effect !

A. Djouadi, D. Graudenz, M. Spira, P. Zerwas (1991)



Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit (+25 % at the LHC, +30 % at the Tevatron)

R.Harlander (2000); S. Catani, D. De Florian, MG (2001)
R.Harlander, W.B. Kilgore (2001,2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

scale uncertainty computed with
$m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

The large-m_{top} approximation

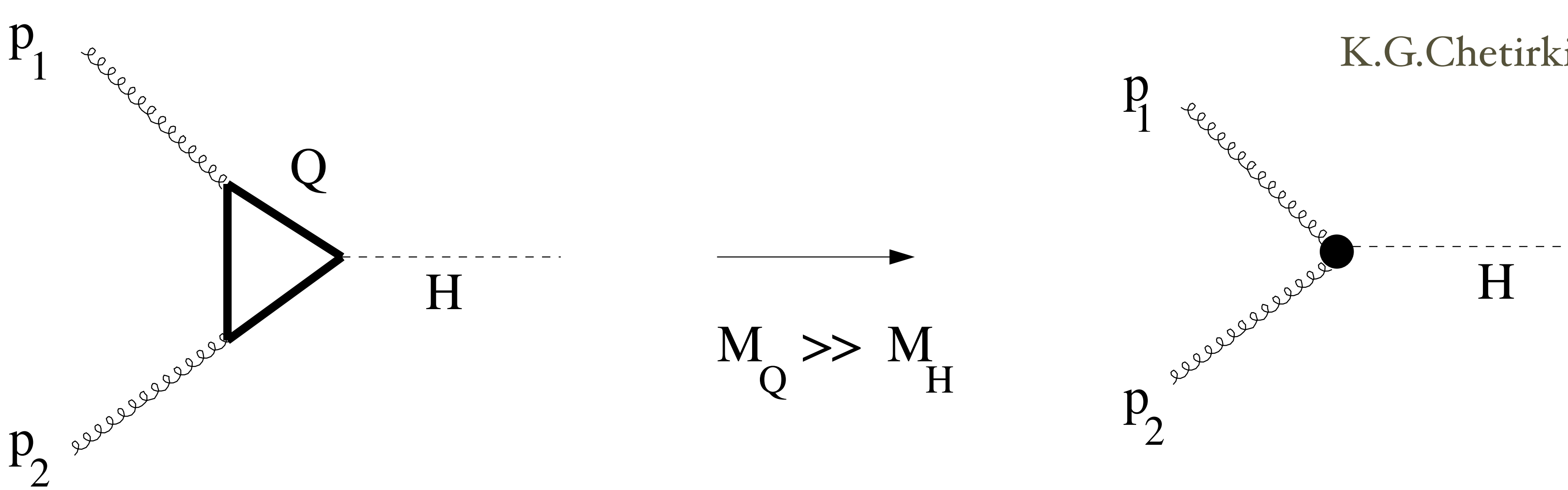
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1976)
M.Voloshin, V.Zakharov, M.Shifman (1979)

$$\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$$

Known to $\mathcal{O}(\alpha_S^3)$

K.G.Chetirkin, M.Steinhauser, B.A.Kniehl (1997)



Effective vertex: one loop less !

Recently the subleading terms in large-m_{top} limit at NNLO have been evaluated

S.Marzani et al. (2008)
R.Harlander et al. (2009,2010)
M.Steinhauser et al. (2009)

➡ **The approximation works to better than 0.5 % for $m_H < 300$ GeV**

gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about +9-10% at the LHC, +13% at the Tevatron, with slight reduction of scale unc.)

S. Catani, D. De Florian, P. Nason, MG (2003)

→ Nicely confirmed by computation of soft terms at N^3LO

S. Moch, A. Vogt (2005), E. Laenen, L. Magnea (2005)

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach (effect O(1%))

Anastasiou et al. (2008)

→ support “complete factorization”: EW correction multiplies the full QCD corrected cross section

EW effects for real radiation (effect O(1%))

W.Keung, F.Petriello, (2009)
O.Brein (2010)
C.Anastasiou et al. (2011)

Results

Quite an amount of work has been done in the last few years to provide updated results that include all the available theoretical information

- NNLO Calculation implemented in iHixs

C.Anastasiou et. al. (2012)

  - Start from exact NLO and include NNLO in the large-m_{top} limit
  - Effect of resummation is mimicked by choosing $\mu_F = \mu_R = m_H/2$ as central scale (choice motivated by apparent better convergence of the perturbative series)
  - Includes EFT estimate of mixed QCD-EW effects and some effects from EW corrections to real radiation (at the percent level or smaller)

- Our NNLL+NNLO calculation:

D. de Florian, MG (2009)

  - Improvement of the calculation by Catani et al. (2003)
  - Start from exact NLO result and add soft-gluon resummation at NLL
  - Perform NNLL+NNLO calculation in the large-m_{top} limit
  - Include two-loop EW effects

→ **Recommended result by the LHC Higgs XS WG and used as reference theoretical prediction by ATLAS and CMS**

(corresponding results for the Tevatron still used by CDF+D0)

Our latest update (2012)

- Effect of the charm quark included (typically neglected so far)

D. de Florian, MG (2012)

This is a -2.5 % effect at Born level (reduced to -1.2% at NNLL+NNLO) !

Finite width effects according to complex-mass scheme included (irrelevant for m_H=125 GeV)

G. Passarino et al. (2011)

PDF uncertainties computed with PDF4LHC recommendation (roughly equivalent to consider 90% CL)

Scale uncertainties computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

$$\sigma = 19.27^{+7.2\%}_{-7.8\%}\,(\text{scale})^{+7.5\%}_{-6.9\%}\,(\text{PDF} + \alpha_S)\ \text{pb}$$

- Compare with result by iHixs

Anastasiou et al. (2012)

$$\sigma = 20.69^{+8.4\%}_{-9.3\%}\,(\text{scale})^{+7.8\%}_{-7.5\%}\,(\text{PDF} + \alpha_S)\ \text{pb}$$

→ 7% higher than our result but still compatible within scale uncertainties

The issue of the scale choice

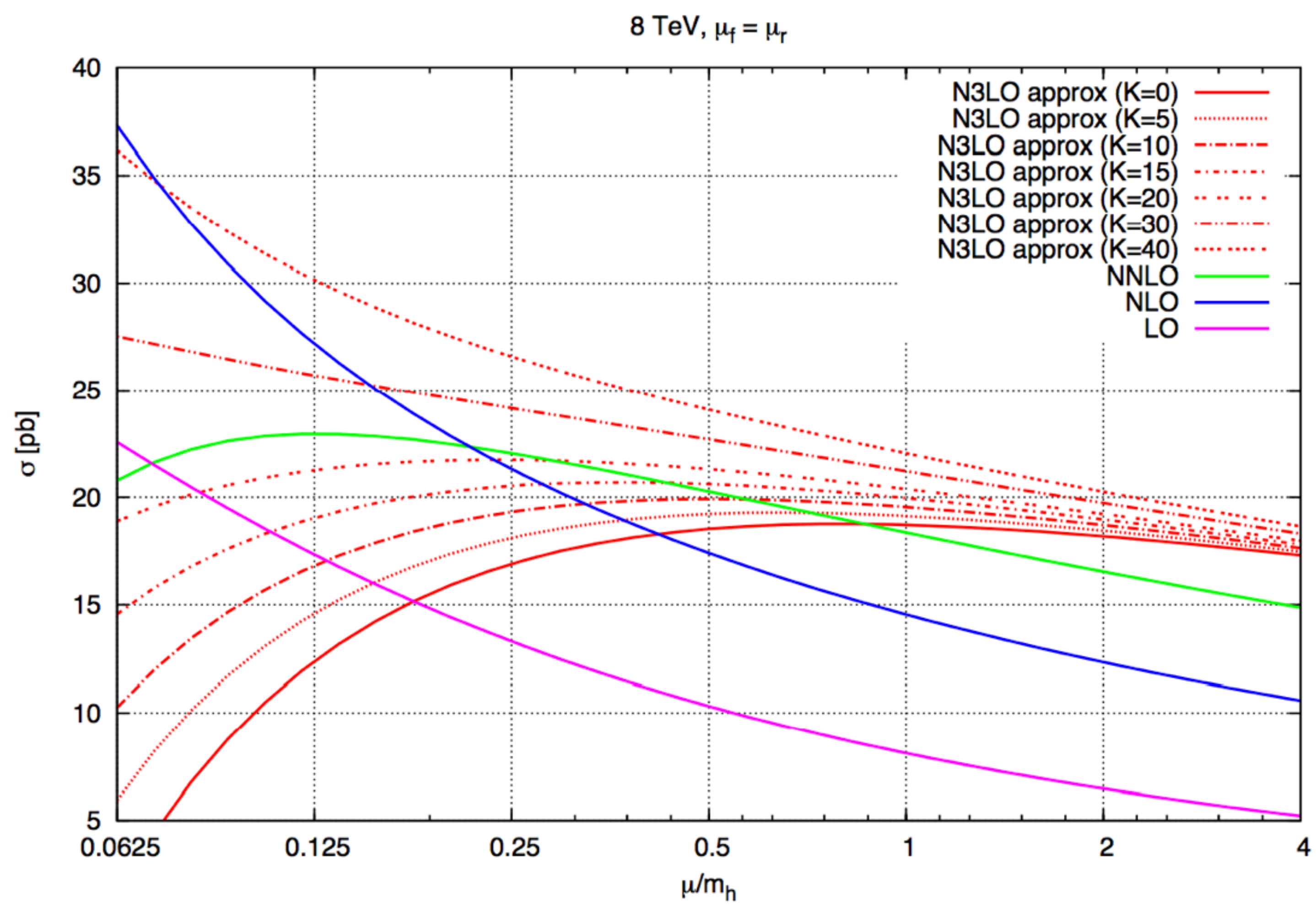
Our calculation uses $\mu_F=\mu_R=m_H$ as central value for the renormalization and factorization scales whereas Anastasiou and collaborators use $\mu_F=\mu_R=m_H/2$

The central scale choice is somewhat arbitrary and both choices make sense

One argument that has been used to support the choice of $m_H/2$ is that the NNLO is stationary for $\mu \sim 0.1-0.2\ m_H$

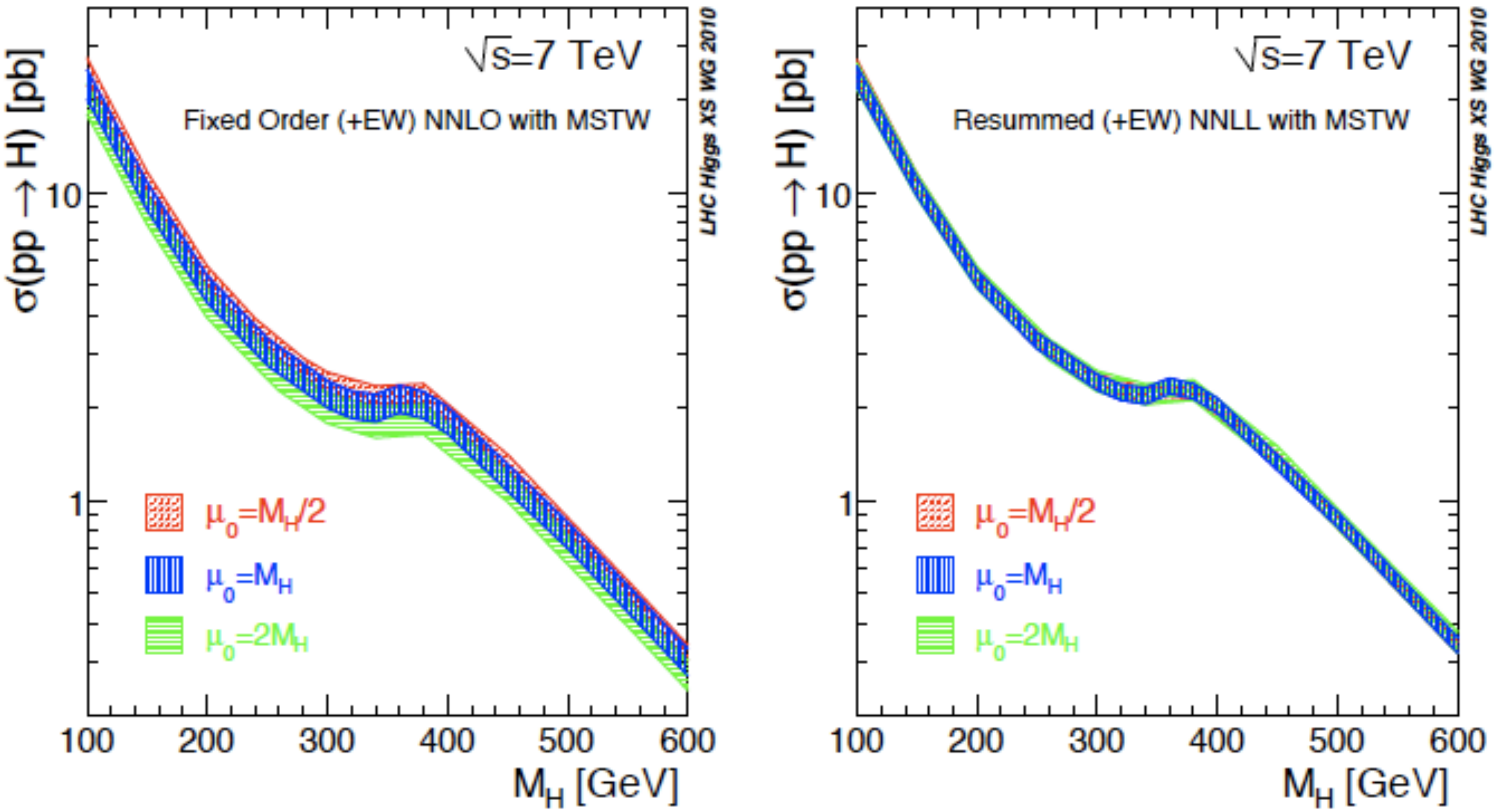
Scale dependence at N3LO recently estimated

Note that at N3LO the stationary point could move up to $\mu \sim m_H$ (depending on the parameter K which controls the size of the corrections)



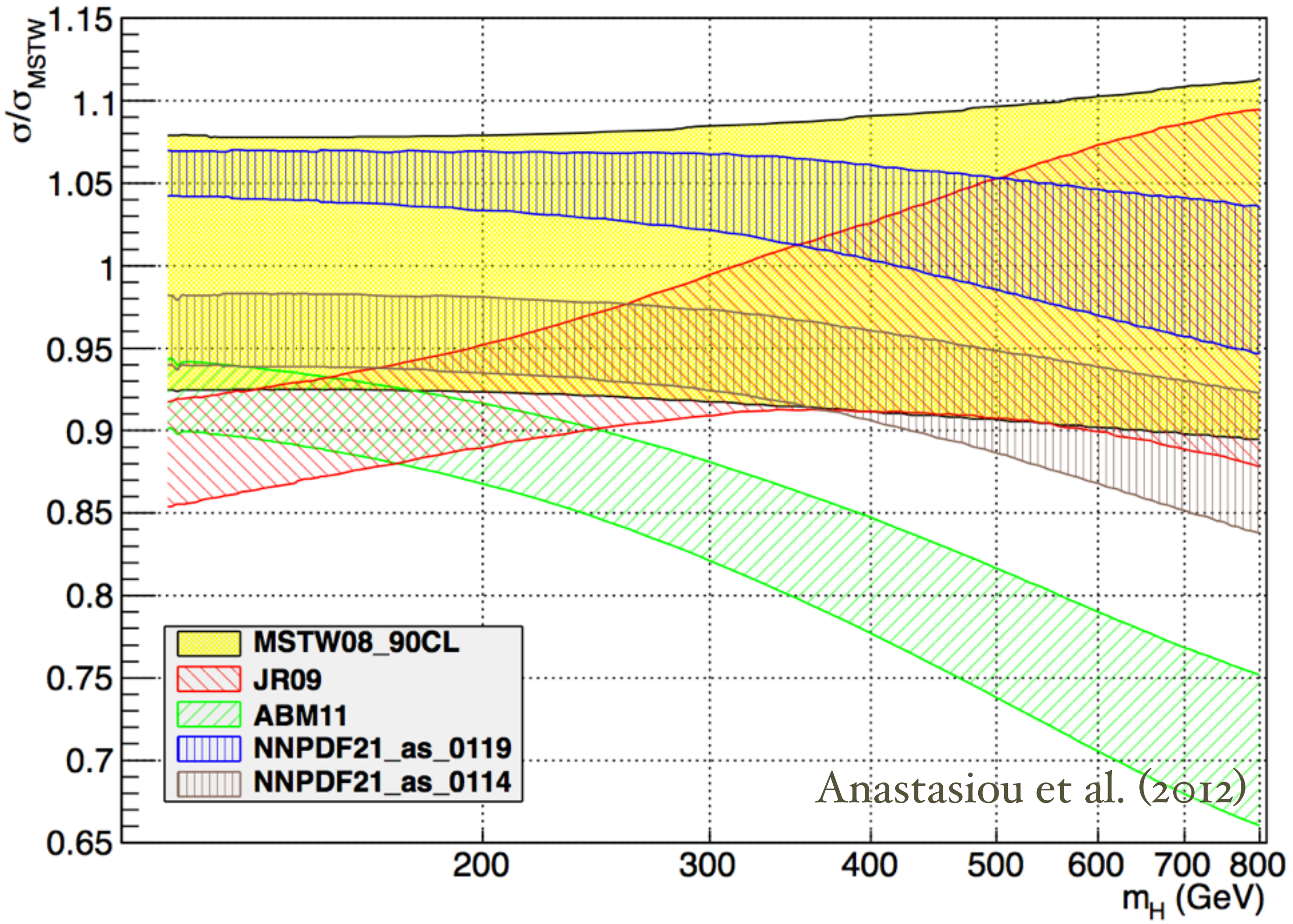
S.Buehler, A.Lazopoulos (2013)

The issue of the scale choice



It is remarkable that the NNLL resummed calculation is basically insensitive to the central scale choice !

The gluon density and α_S



Various NNLO sets have become available in the last few years

New CT10 NNLO fit agrees with MSTW within 5 %

At m_H=125 GeV things appear under control

ABM11 set does not include Tevatron jet data and it has α_S much smaller than the world average

Jet data give important constraint on the gluon distribution but known only at NLO at present

NNLO calculation in progress: gg channel just completed

A.Gehrmann et al. (2013)

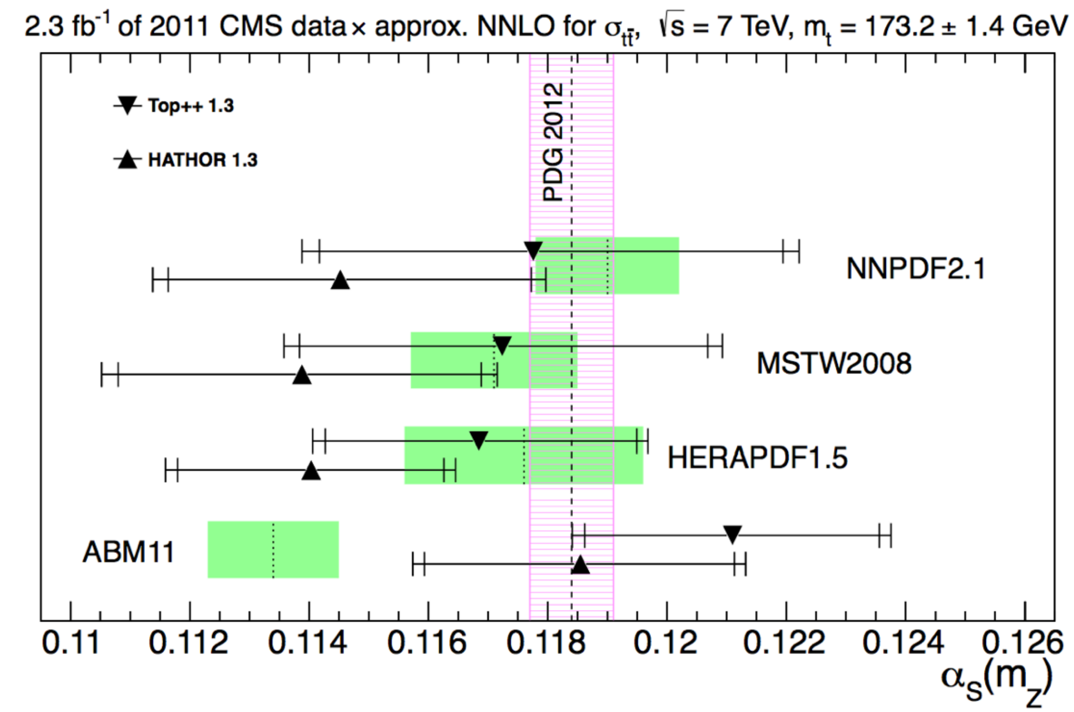
The gluon density and α_S

The ttbar cross section is also sensitive to the gluon density

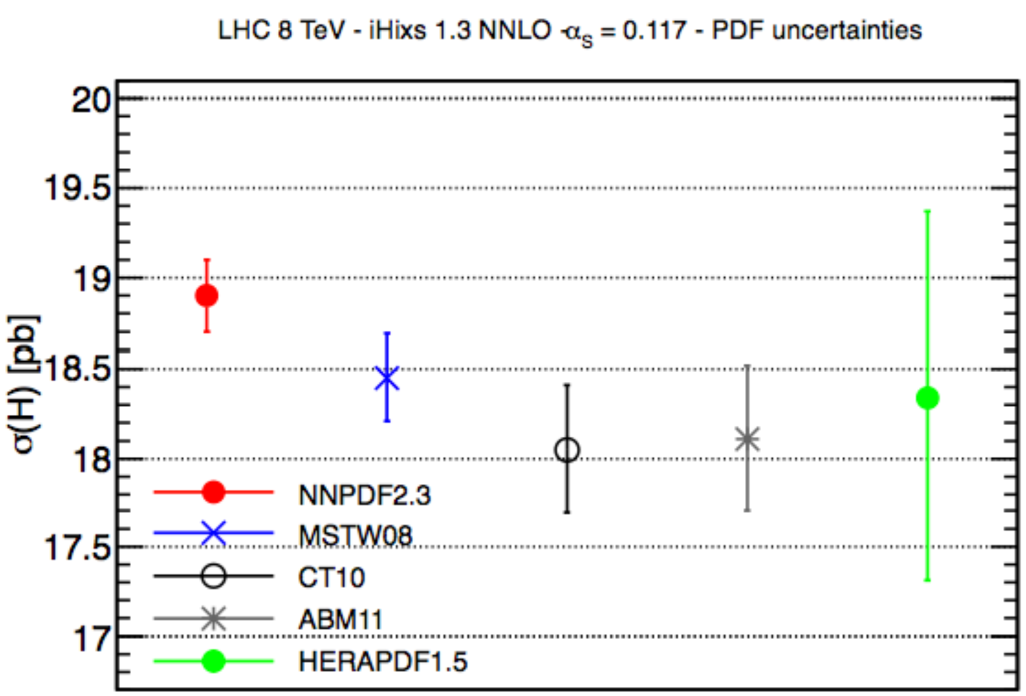
CMS-PAS-TOP-12-022

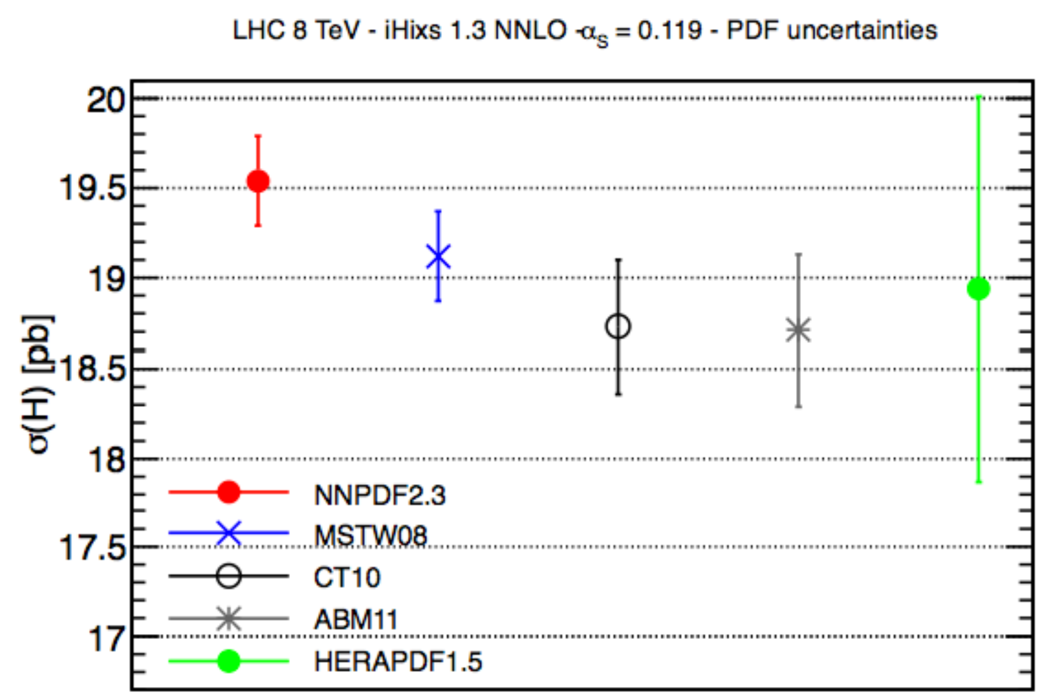
Once m_{top} is fixed it is possible to extract α_S from the measured cross section and compare it with the preferred value for the set

→ Consistency check for the PDFs !



NNLO predictions are compatible if a common value of α_S is used





J.Rojo et al. (2012)

The gluon density and α_S

ABM12 global fit recently released: it includes for the first time Drell-Yan and somewhat accounts for heavy quark data from the LHC
(jet data still not included)

Results consistent with previous fits

→ $\alpha_S(m_Z)=0.1132\pm0.0011$

For comparison the PDG world average is $\alpha_S(m_Z)=0.1184\pm0.0007$

- ABM: differences are due to incorrect treatment of higher-twist ?
- Others: differences due to use of FFS for quark masses ?

S.Forte et al. (2013)

It leads to a cross section which is 8% smaller than the one obtained with MSTW

Most reliable determinations (EW precision fit and τ decays, both N^3LO) lead to $\alpha_S(m_Z)=0.1196\pm0.0014$

N^3LO ?

Some brave colleagues are working to extend the calculation to N^3LO

Consistent N^3LO calculation would require N^3LO PDFs.....

but...... N^3LO result would be an impressive achievement anyway !

Collinear and UV counterterms at N^3LO S.Buehrer, A.Lazopoulos (2013)

→ Scale uncertainty will be between 2 and 8% (most likely about 5%)

Experience at NNLO tells us that the first step would be to compute the soft-virtual part first

W. van Neerven et al. (1988)

S.Catani, D. de Florian, MG (2001)
R.Harlander, B.Kilgore (2001)

- NNLO Partonic cross section to $O(\varepsilon)$

M.Steinhauser et al . (2012)

- NNLO master integrals to $O(\varepsilon)$ and to all orders in ε at threshold

C.Anastasiou et al . (2012)

N^3LO ?

First two terms of the threshold expansion for triple-real contribution (SV plus its first correction)

$$\sigma_{i\,j\to H+X}(s,\bar{z}) = \bar{z}^{-1-6\epsilon} s^{3\epsilon} \sum_{k=0}^{\infty} \bar{z}^k \sigma^{S(k)}_{i\,j\to H+X} \qquad \bar{z} = 1 - z \qquad z = m_H^2/s$$

C.Anastasiou. C. Duhr, F.Dulat, B.Mistlberger (2013)

Note that soft-gluon resummation predicts the first term in the soft expansion $\sigma^{S(0)}_{ij\to H+X}$ (except its δ(1-z) part)

S.Catani, D. de Florian, P. Nason, MG (2003)
S.Moch, A. Vogt (2005)

Two-loop contribution for H+1 parton now feasible (two-loop soft current computed at all orders in ε)

C.Duhr, T.Gehrmann (2013)
Y.Li, X.Zhu (2013)

Still missing: contribution from one-loop H+2 parton amplitudes

L.Dixon, Y.Sofianatos (2009)
S.Badger et al. (2009)

To be combined with known three-loop result to get a finite cross section

→ Result seems within reach !

P.A.Baikov et al. (2009)
R.N.Lee, A.V.Smirnov and V.A.Smirnov (2010)
T.Gehrmann et al . (2010)

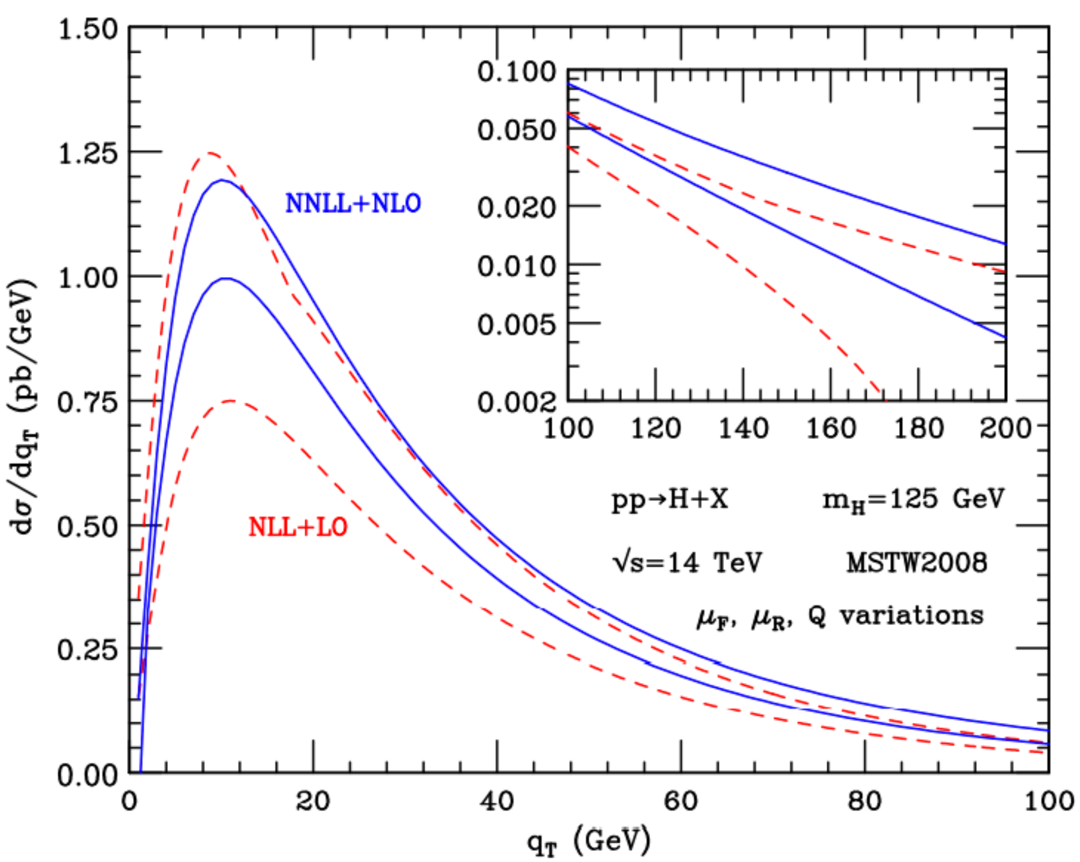
Going differential: p_T spectrum

Among the various distributions an important role is played by the transverse momentum spectrum of the Higgs boson

Transverse momentum (p_T) and rapidity (y) identify the Higgs kinematics

The shape of rapidity distribution mainly determined by PDFs

→ Effect of QCD radiation mainly encoded in the p_T spectrum



HqT: soft gluon resummation at $p_T \ll m_H$ matched to fixed order result at $p_T \sim m_H$

In the last few years HqT became the reference tool to compare with

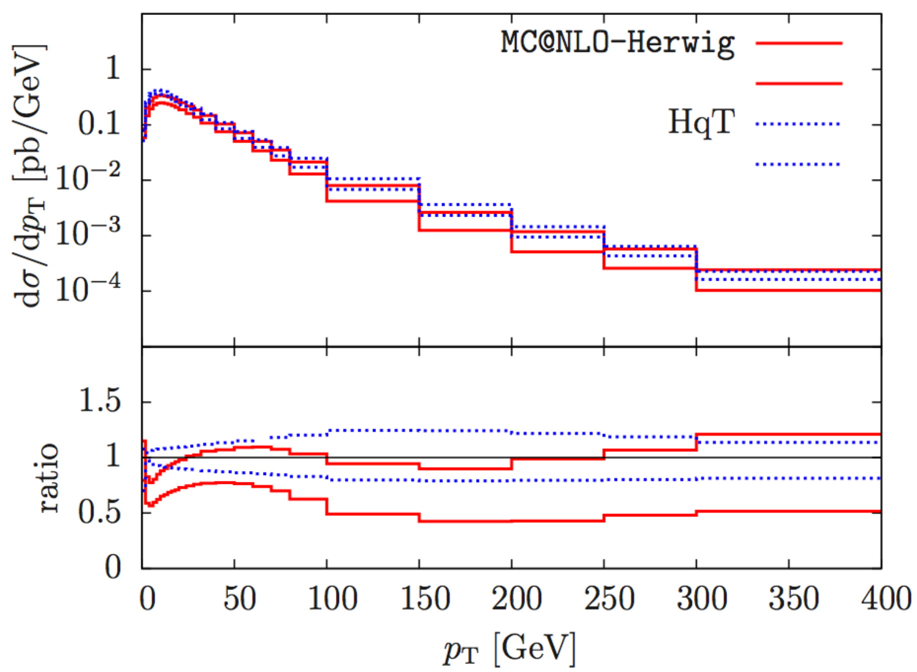
New program HRes includes Higgs decay

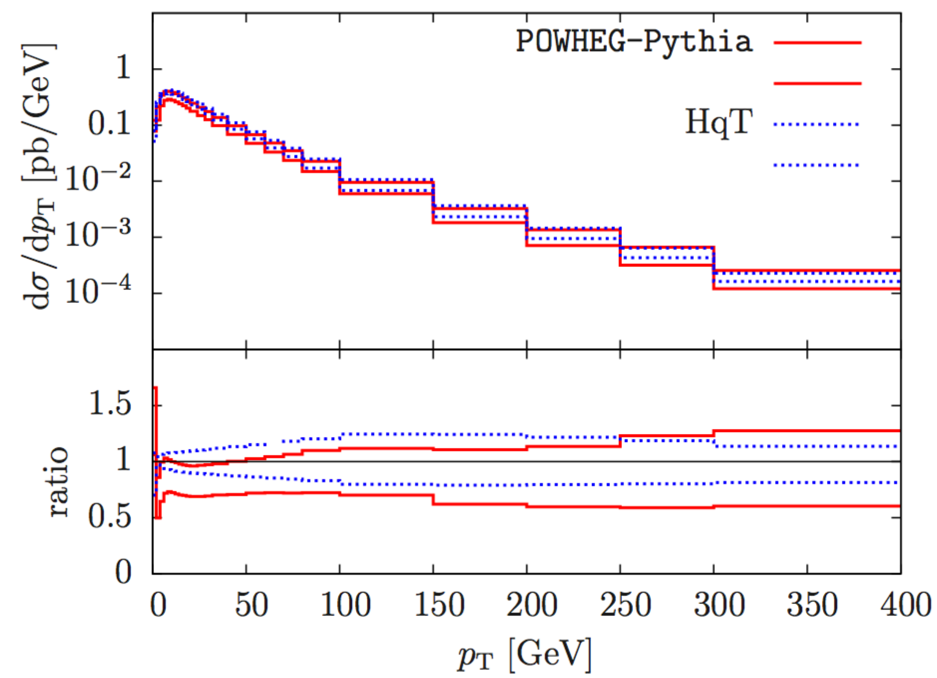
G. Bozzi, S.Catani, D. de Florian, MG (2005,2007)
D. de Florian, G.Ferrera, D.Tommasini, MG (2011,2012)

Going differential: p_T spectrum

Resummation “effectively” performed (less accurately) by standard MC event generators

Reasonably good agreement with MC@NLO and now also POWHEG (with h=1.2)





h controls amount of real radiation that is exponentiated ($h=\infty$ in default POWHEG)

C.Oleari, Higgs Hunting 2012

But the spectrum is still in the large-mtop limit: bound to fail when p_T is very large

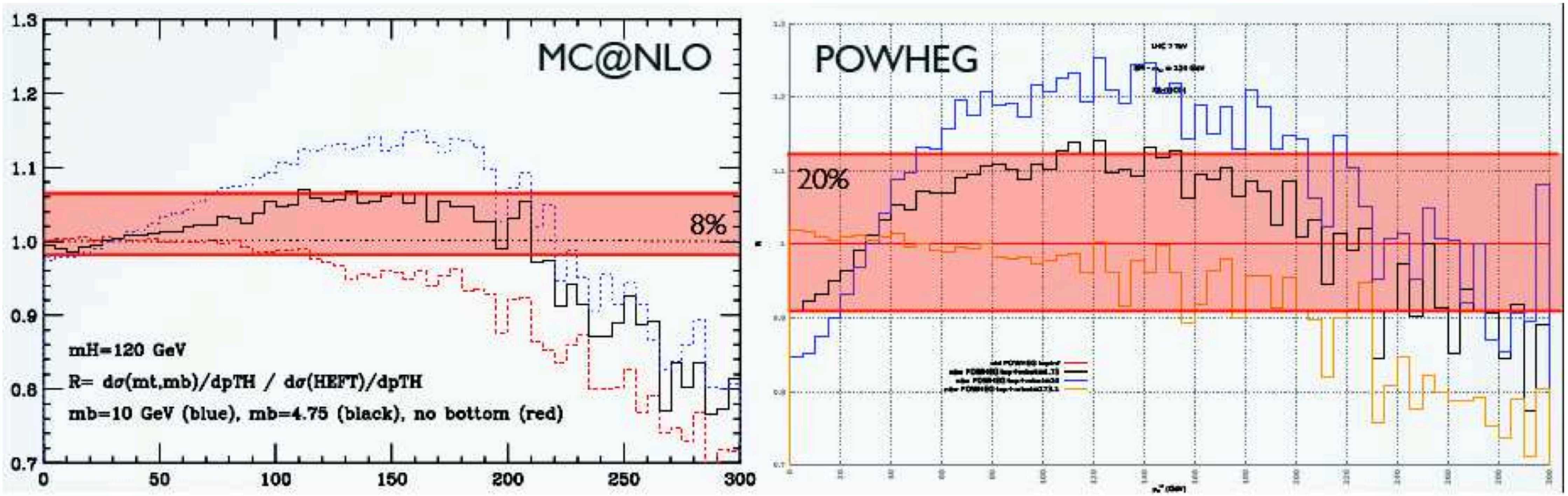
Exact dependence on the masses of top and bottom quarks known up to NLO

M. Spira et al. (1995)
K.Ellis, Hinchliffe, van der Bij (1988)

Heavy quark mass effects now included in POWHEG and MC@NLO

E.Bagnaschi et al. (2012)
S.Frixione (2012)

Mass effects



S.Frixione, LHC Higgs XS Meeting (december, 2012)

But what seems a trivial implementation of the exact real and virtual NLO matrix elements lead to large differences in MC@NLO vs POWHEG

MC@NLO agrees rather well with analytic resummation whereas POWHEG appears to "amplify" the effect of the bottom mass

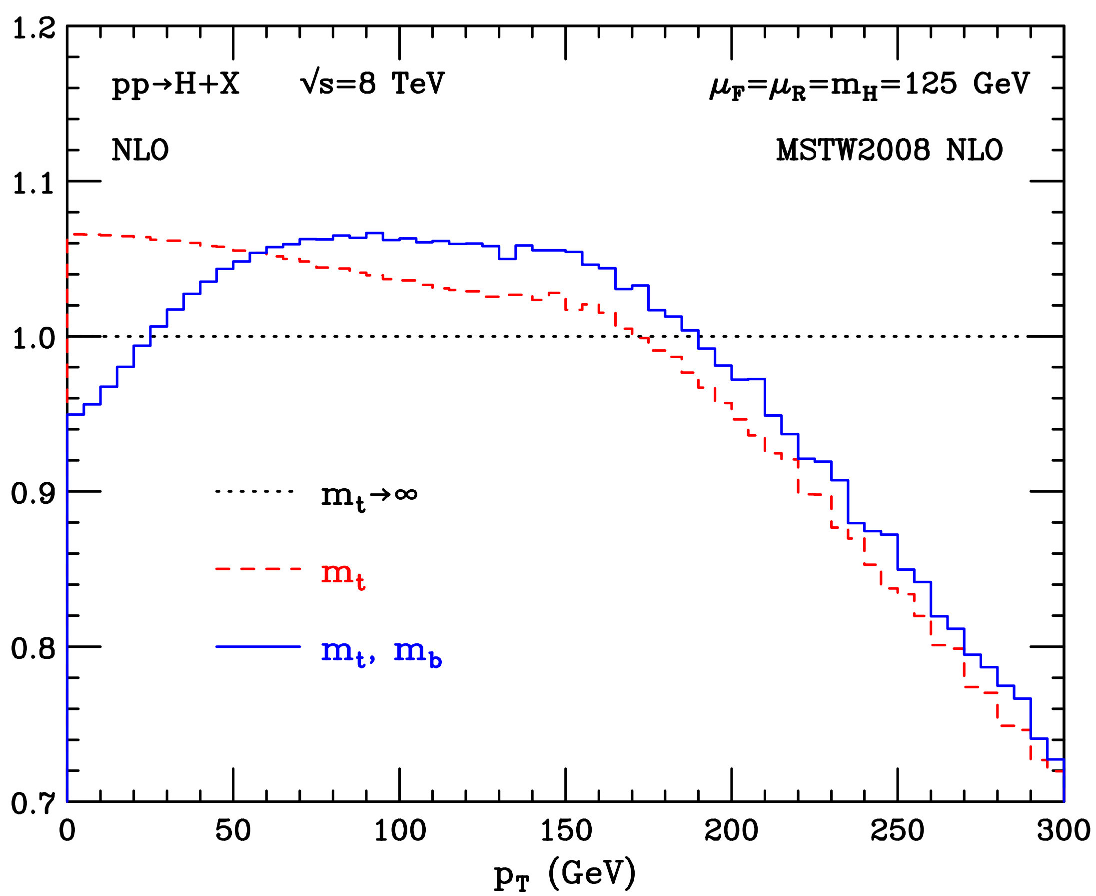
- Without bottom $p_T << m_H \sim m_{top}$ still 2-scale problem
- With bottom p_T, m_b, $m_H \sim m_{top}$ 3-scale problem !

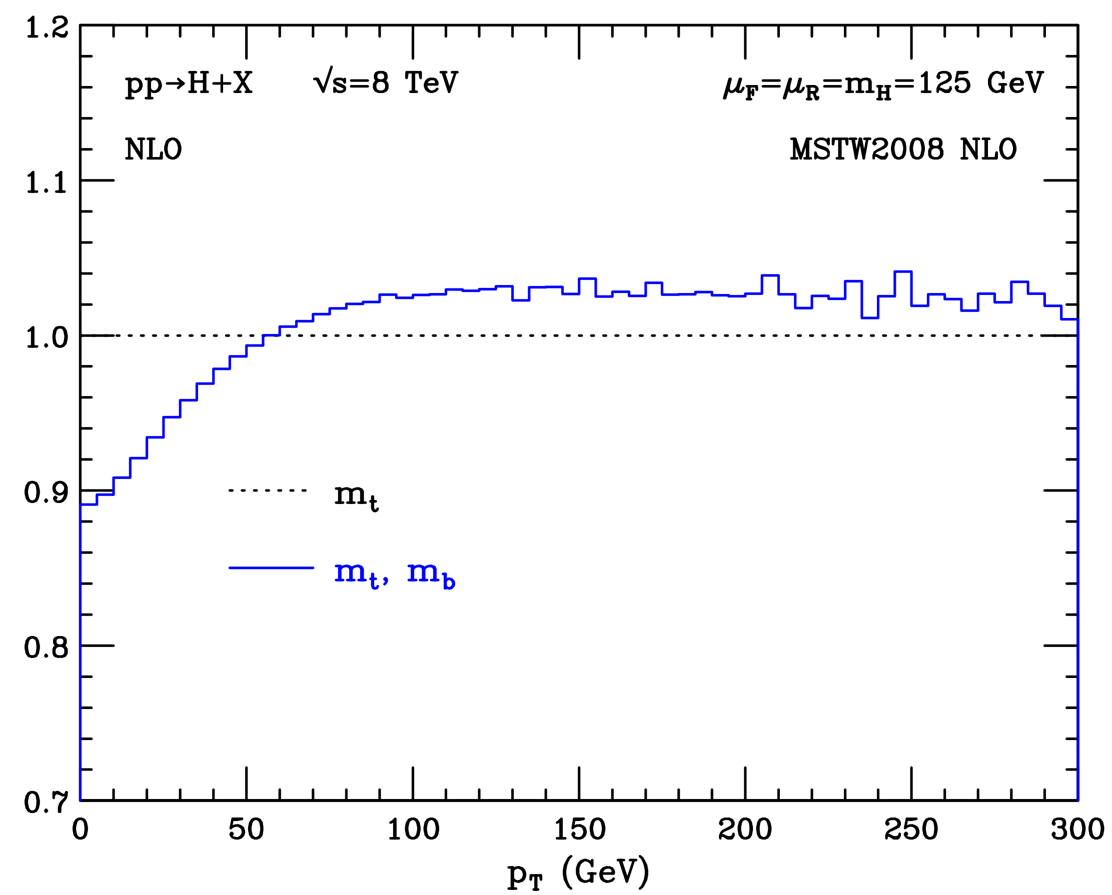
The implementation of the bottom quark in the spectrum is non trivial

Mass effects

H.Sargsyan, MG (2013)

Let us look at the mass effects in the NLO p_T spectrum





When only the top contribution is considered the shape of the spectrum in the small and intermediate p_T region is similar to the $m_t \to \infty$ result

The bottom contribution significantly distorts the spectrum in the low p_T region

Mass effects

H.Sargsyan, MG (2013)

Studying the analytic behavior of the QCD matrix elements we find that collinear factorization is a good approximation only when $p_T << 2m_b$

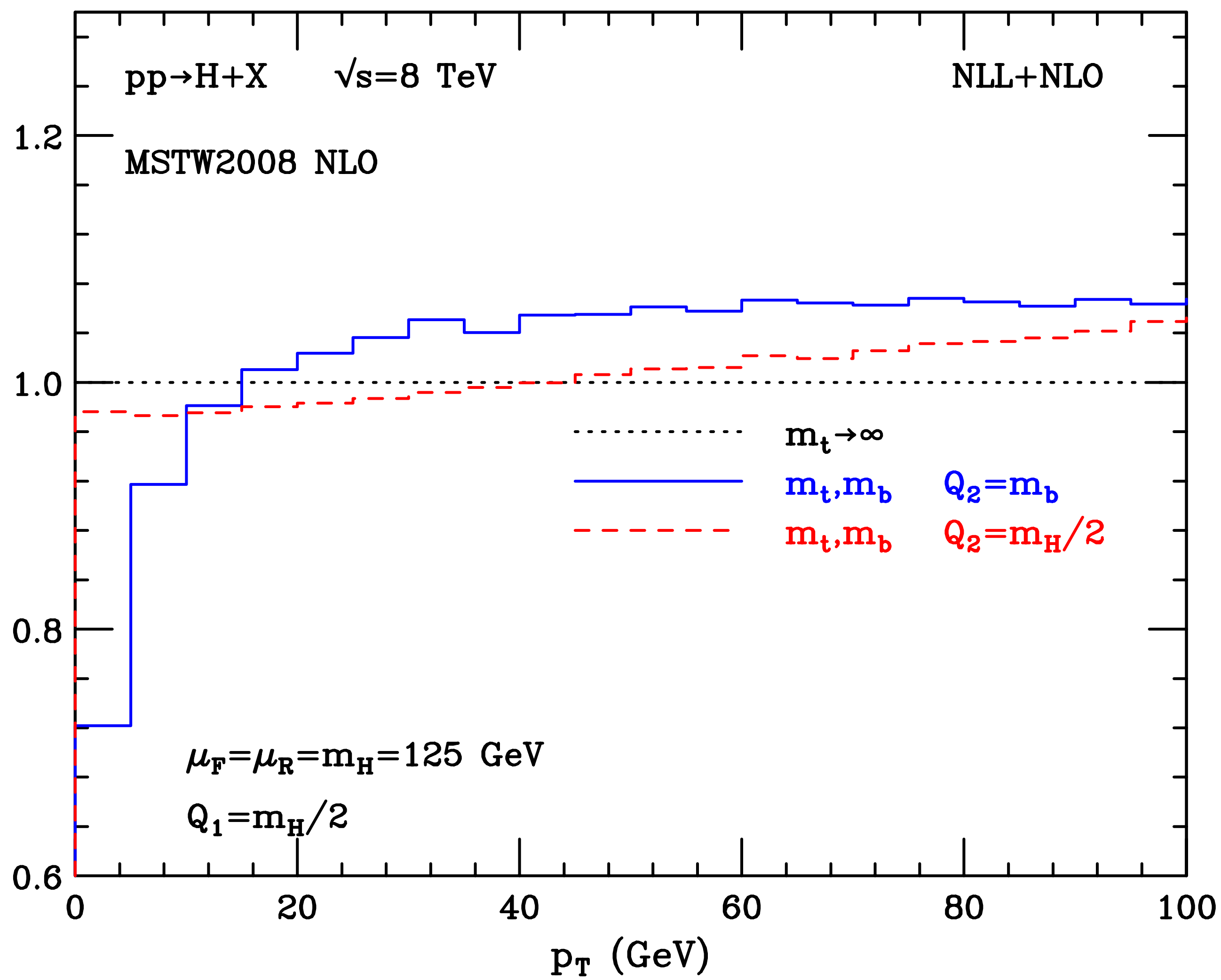
→ the standard resummation procedure cannot be straightforwardly applied to the bottom quark contribution

Our solution:

- the top quark gives the dominant contribution to the p_T cross section and we treat it as usual with a resummation scale Q_1
- the bottom contributions (and the top-bottom interference) are controlled by an additional resummation scale Q_2 that we choose of the order of the b-mass

In this way we limit the resummation for the bottom contribution only to the region in which it is really justified (and needed)

Mass effects



Comparison of the results obtained with $Q_2=m_b$ and $Q_2=m_H/2$

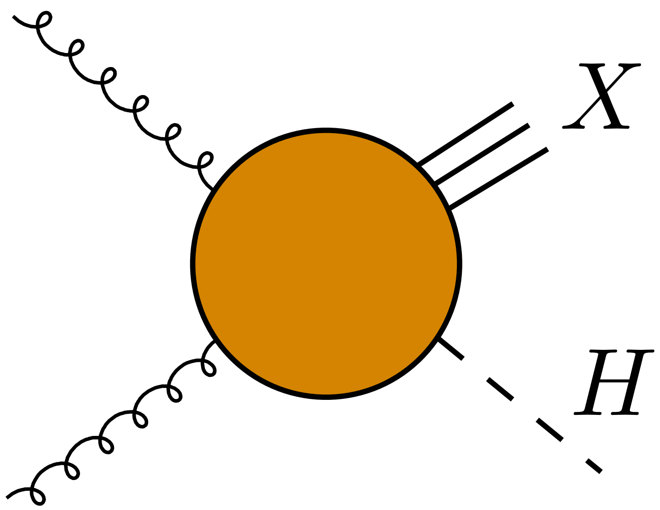
Significant differences in the low-p_T region

The result with $Q_2=m_H/2$ is in agreement with independent calculation by Mantler-Wiesemann (and with MC@NLO)

Our calculation is now implemented in updated versions of the HNNLO and HRes numerical programs

Following our work the possibility of a lower shower scale for the bottom contribution is now implemented in MC@NLO and similar results are found with POWHEG

p_T spectrum: what else ?



Higgs production at high-p_T can be useful to test new physics scenarios

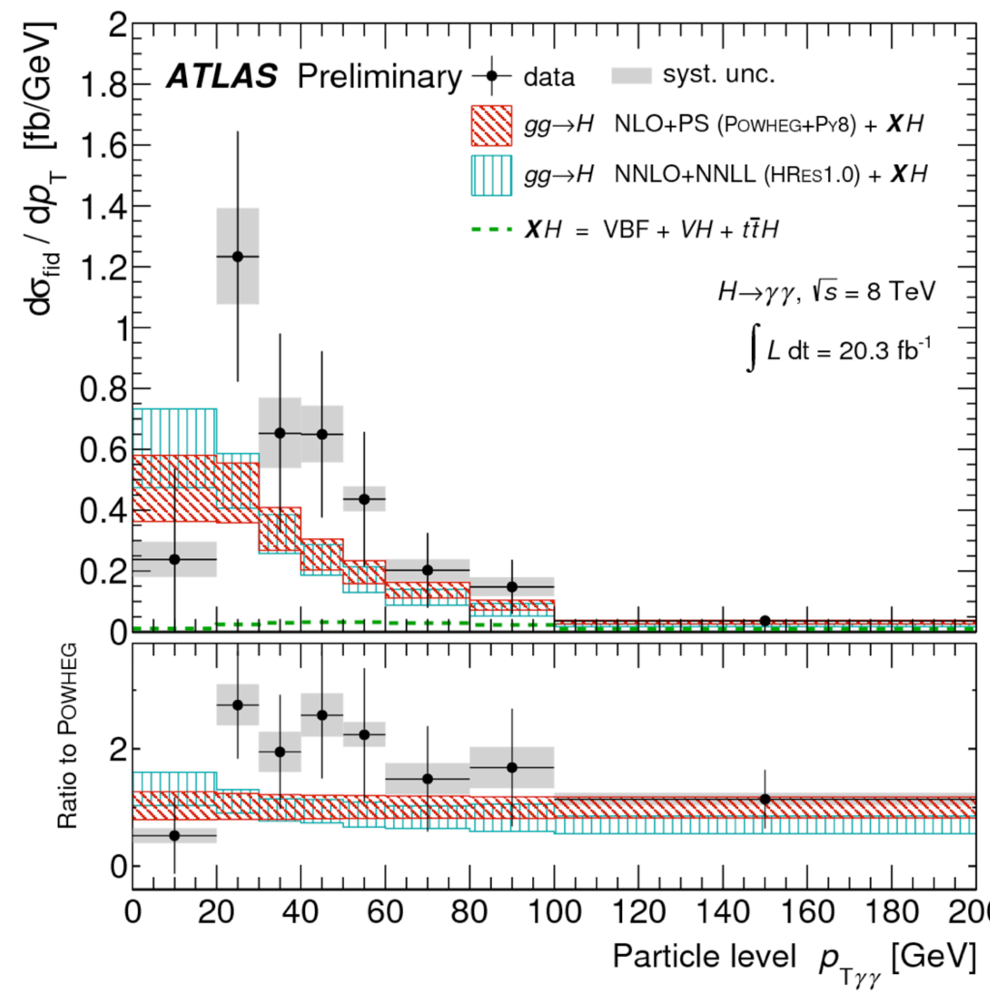
- models with modified couplings to gluons and top quark
- models with fermionic top partners — A.Azatov, A.Paul (2013)

.... A.Banfi et al. (2013)

...and now data !

First measurement of p_T spectrum presented by ATLAS: it is compatible with TH predictions but suggests a possibly harder spectrum

If ATLAS is sitting on a statistic fluctuation of the background (driven by qbarq annihilation) I would expect a softer spectrum !



Going differential: jet bins

NNLO fully differential calculations for $gg \to H$ available

C.Anastasiou et al. (2005)
S.Catani, MG (2007)

The HNNLO numerical code includes $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to WW \to 4l$ decay modes

MG (2008)

It allows realistic studies accounting for the selection cuts applied in the experiment

Experimental analysis often split into jet bins in order to optimize the sensitivity → Introduce a scale p_{Tveto} Large logarithmic terms could spoil perturbative convergence

Is theoretical description under control ?

It is known that uncertainties obtained from naive scale variations of the jet vetoed cross section are typically too small to be realistic

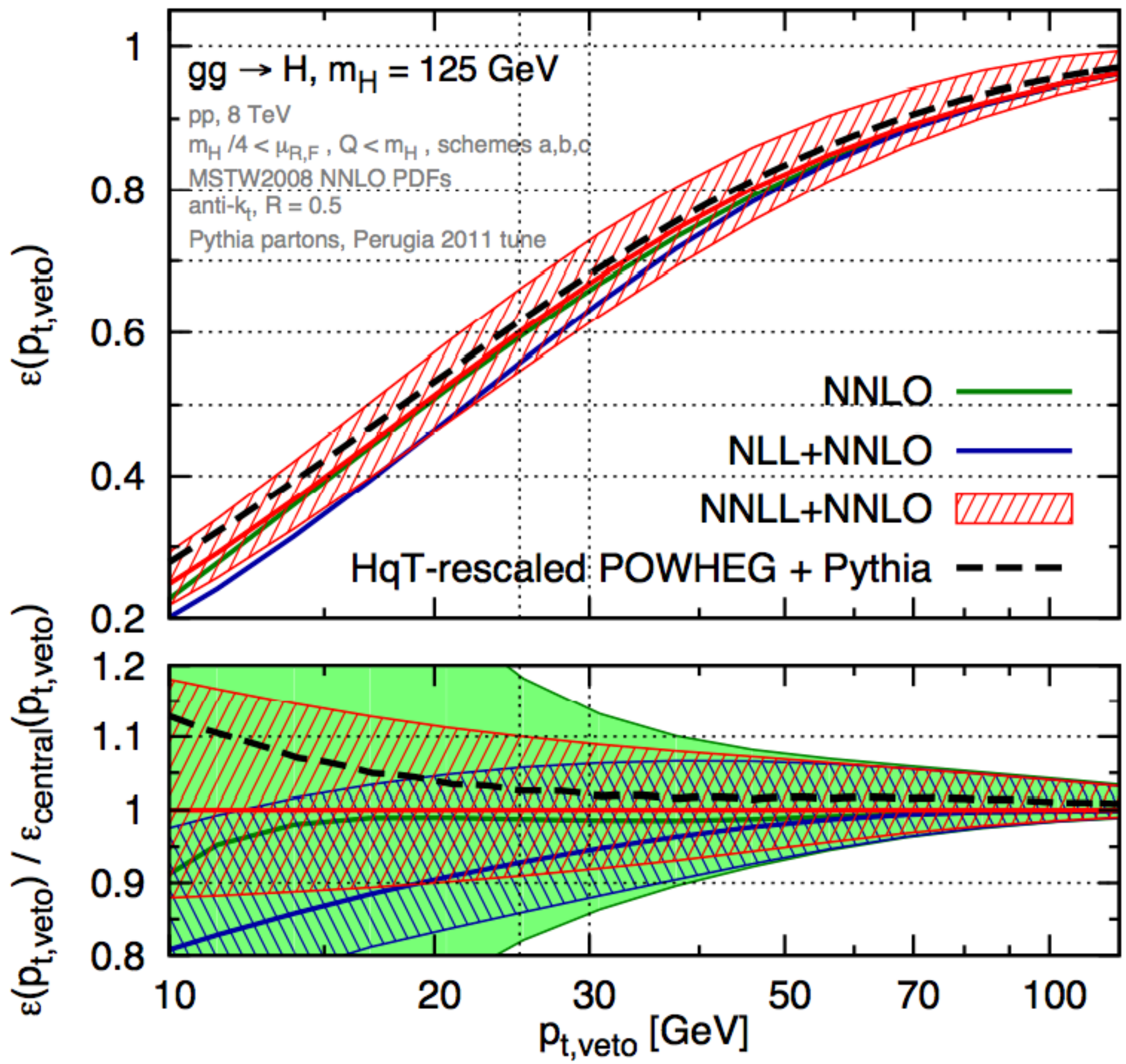
I.Stewart, F.Tackmann (2011)

Going differential: jet bins

Quite an amount of work recently done in this direction and now resummation for jet vetoed cross section is available !

Good agreement obtained by using naive rescaling with NNLL +NNLO calculation of p_T spectrum with HqT

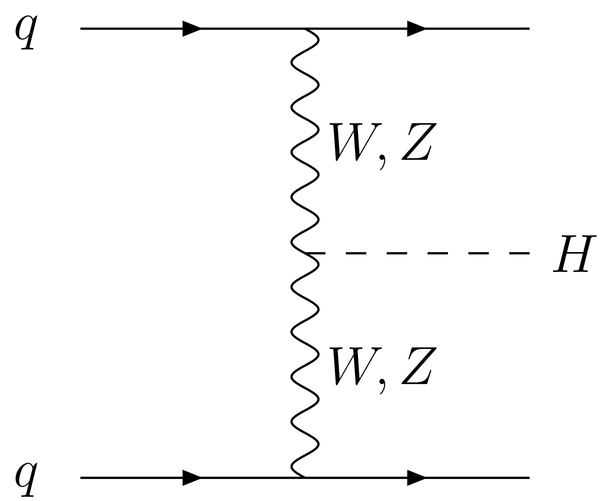
For values of p_{Tveto} used by ATLAS and CMS the large logs are not so large !



A.Banfi, P.Monni, G.Salam, G.Zanderighi (2012)

(see also related work by Becher-Neubert and Tackmann et al.)

Vector boson fusion



Valence quarks pdf peaked around $x \sim 0.1 - 0.2$

Transverse momentum of final state quarks of order of a fraction of the W(Z) mass

→ Tends to produce two highly energetic jets with a large rapidity interval between them

Since the exchanged boson is colourless, there is no hadronic activity between the quark jets

QCD corrections to the total rate increase the LO result by $5 - 10\%$

T. Han, S. Willenbrock (1991)

Implemented for distributions in VBFNLO

T. Figy, C. Oleari, D. Zeppenfeld (2003)
J. Campbell, K. Ellis (2003)

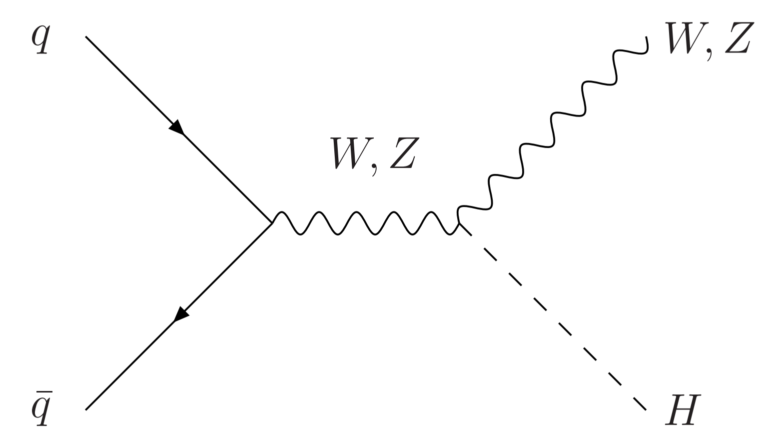
EW+QCD corrections have also been evaluated

M.Ciccolini, A.Denner, S.Dittmaier (2007)

→ even if the cross section is almost one order of magnitude smaller than for gg fusion this channel is very attractive both for discovery and for precision measurements of the Higgs couplings (but wait for RunII !)

Associated VH production

Most important channel for low mass at the Tevatron



→ lepton(s) provide the necessary background rejection

Would provide unique information on the HWW and HZZ couplings

Considered not promising at the LHC due to the large backgrounds

- small VH invariant mass: decay products can often go outside the detector acceptance
- Identifying H→bbar possible only if b produced at sufficiently high p_T
- Typical energy of b quarks from ttbar background close to $m_H/2$

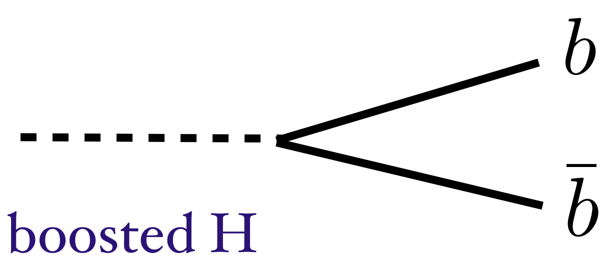
ATLAS TDR: *"The extraction of a signal for H→bbar decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions...."*

Associated VH production

Resurrected through boosted analysis

J.Butterworth et al. (2008)

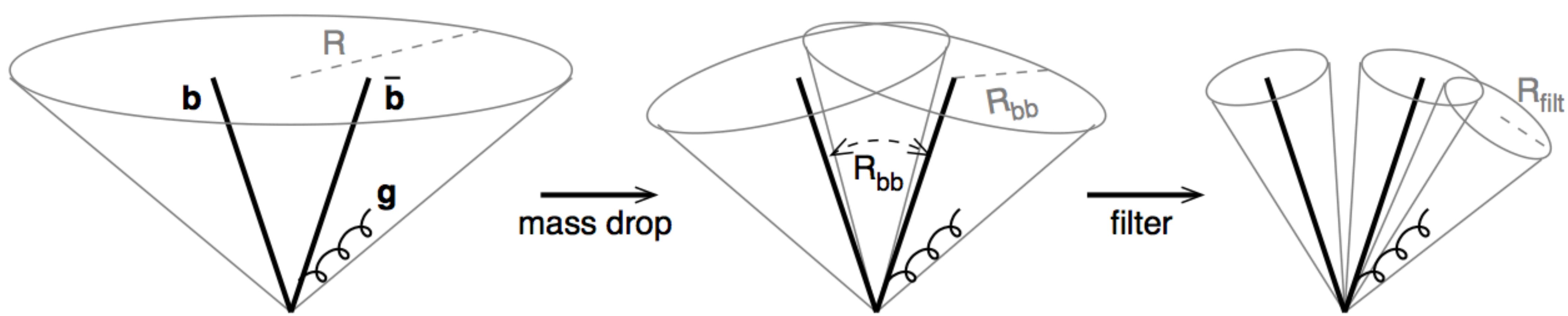
Look for events with high-p_T (> 200 GeV): loose 95 % of the signal !



FAT jet with $R_{b\bar{b}} \sim \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_T}$ $p_T \gg m_H$

- Undo the last stage of clustering with $j \rightarrow j_1 + j_2$

- Require mass drop: $m_{j1} < \mu\, m_j$

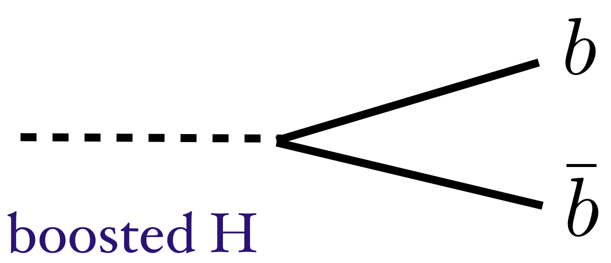


- Finally filter (cluster with smaller resolution) and require 2 b-tags

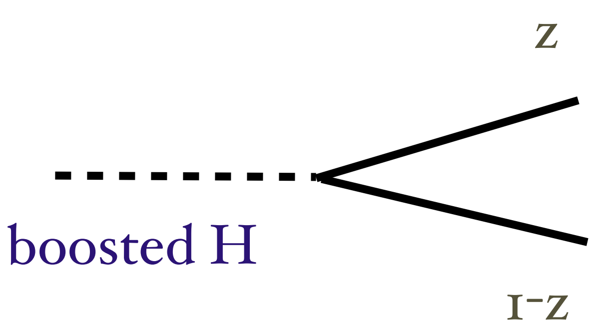
Associated VH production

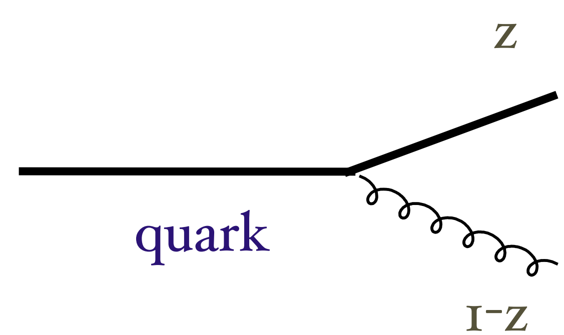
Resurrected through boosted analysis J.Butterworth et al. (2008)

Look for events with high-p_T (> 200 GeV): loose 95 % of the signal !



FAT jet with $R_{b\bar{b}} \sim \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_T}$ $p_T \gg m_H$





$$P(z) \sim 1$$

$$P(z) \sim \frac{1+z^2}{1-z}$$

The background is enhanced at z→1

choose cut on z to maximize S/√B

	g→gg	q→qg	g→bbar	H→bbar
softer prong z	soft	soft	hard	hard
prong colour factors	$2C_A$	C_F+C_A	$2C_F$	$2C_F$
system colour factors	C_A	C_F	C_A	0

Higgs properties

Spin/CP properties

What do we know about the newly discovered resonance ?

It manifested itself first clearly in the ZZ and $\gamma\gamma$ high resolution channels (and then also in WW, bb and $\tau\tau$)

Its width is consistent with being smaller than the experimental resolution

$H \to \gamma\gamma$ ➡ J ≠ 1 (Landau-Yang) and C=+ (barring C violation in the Higgs sector)

It has significant decay fraction in WW and ZZ

➡ what we expect from the agent of EW symmetry breaking

➡ must have a significant CP even component, since the couplings of a pseudoscalar to VV are loop induced, and thus expected to be small.........

but difficult to rule out the existence of a (small) CP odd component ! (fermionic couplings are more democratic)

Spin/CP properties

The methods to determine the properties of a resonance through its decays to gauge bosons and then into four leptons date back to more than 50 years ago

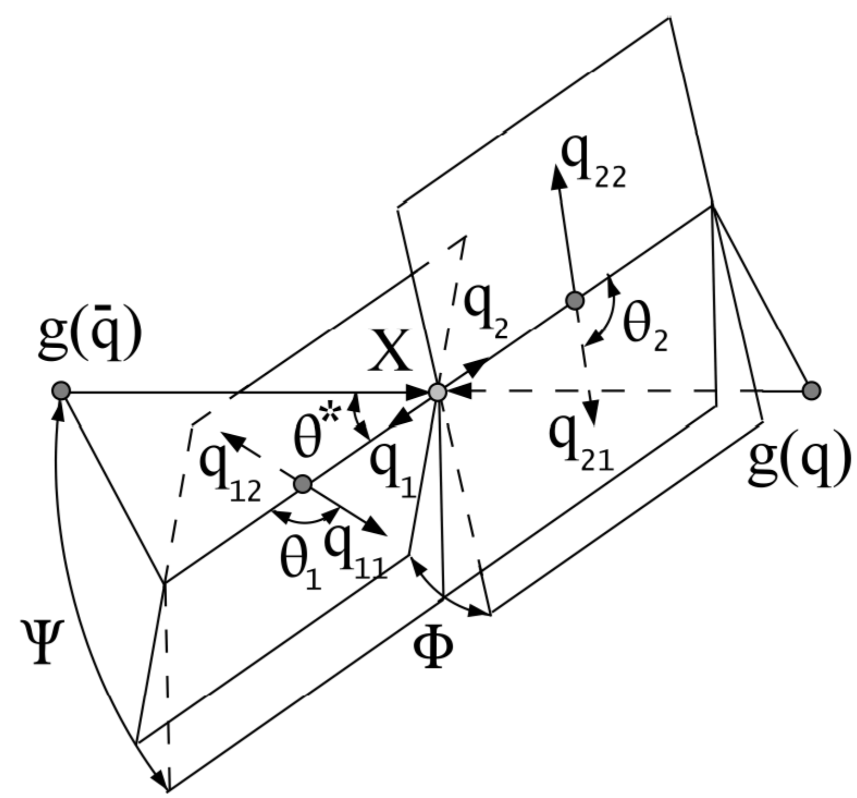
Photon polarization can be used to determine π^0 parity in $\pi^0 \rightarrow \gamma\gamma$

C.N. Yang (1950)

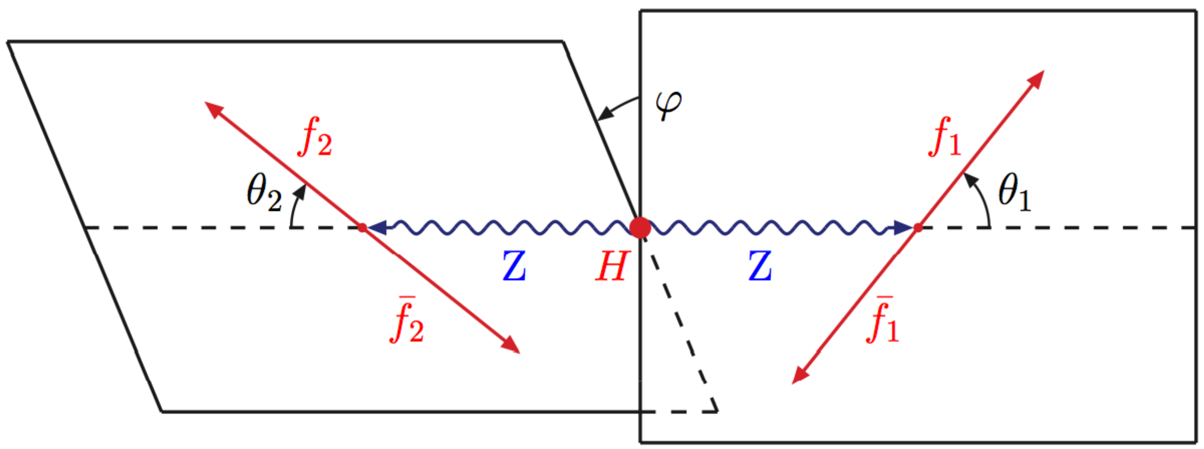
Easier to use orientation in Dalitz pairs in $\pi^0 \rightarrow e^+ e^- e^+ e^-$

R.H. Dalitz (1951)

Analogously the $H \rightarrow ZZ \rightarrow 4l$ channel where the final state can be fully reconstructed makes possible to study the JCP properties almost independently on the production process



The golden channel



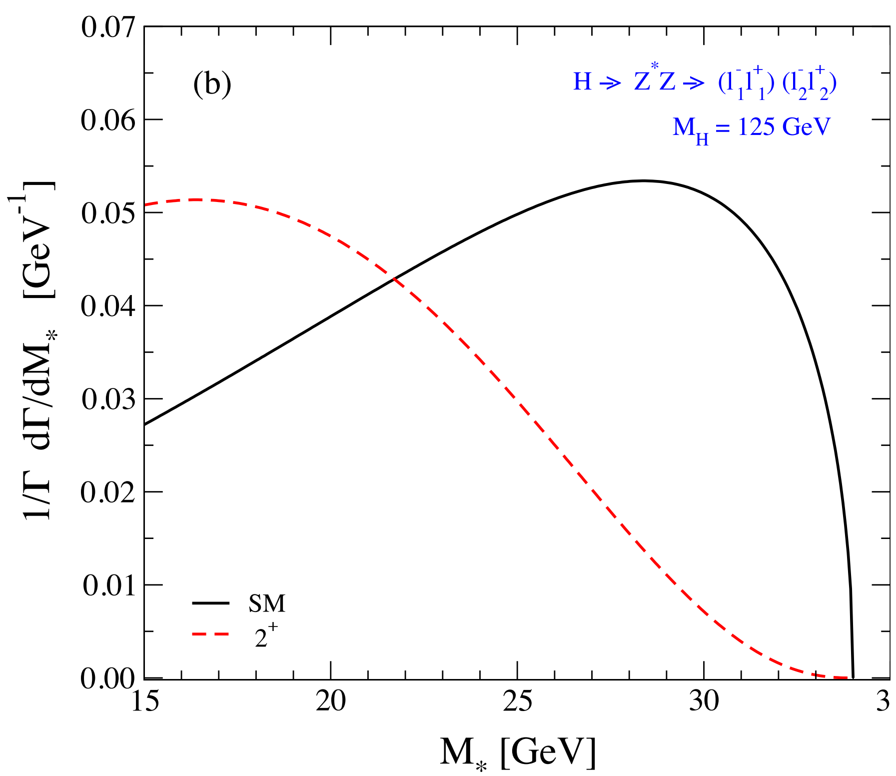
For $m_H \sim 125$ GeV and H→ZZ→4l one of the two Z is virtual

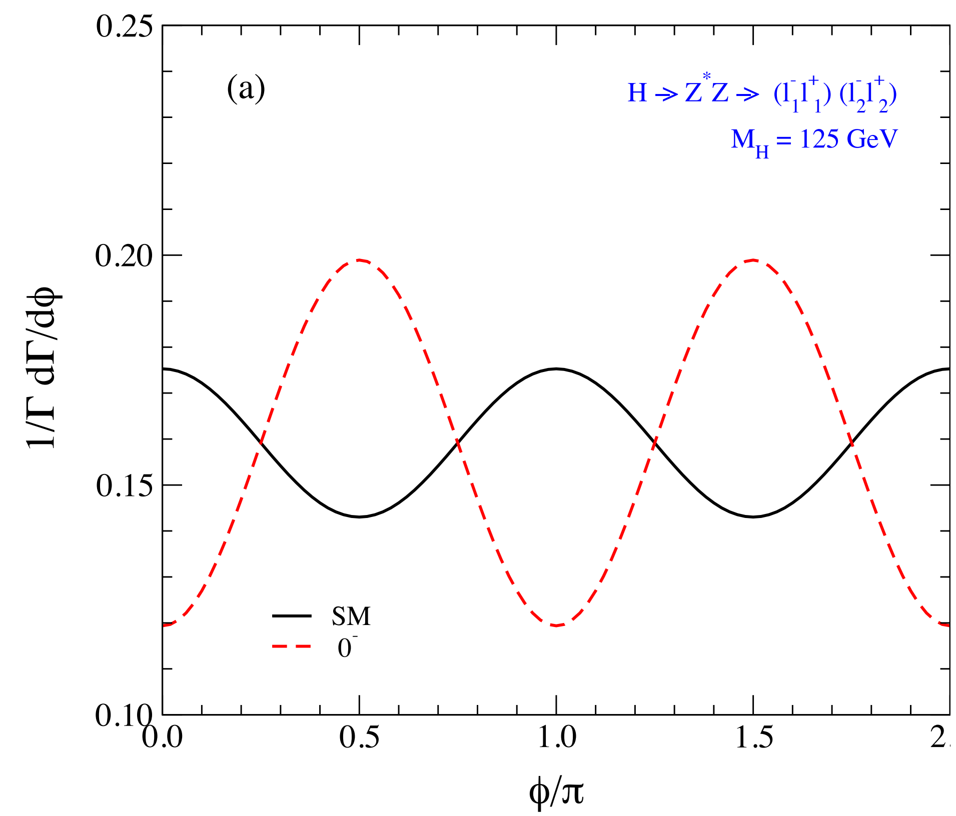
J. Dell'Aquila, C.Nelson (1986)
A.Djouadi et al. (1994)
S.Choi, D.J.Miller, P.Zerwas, M.Muehlleitner (2002)

Classical discriminating variables are the invariant mass of the off shell Z M* and the angle ϕ

$$\beta \sim \sqrt{(m_H - m_Z)^2 - M_*^2}$$

Threshold behavior $d\Gamma/dM_*^2 \sim \beta^{2J+1}$





plots courtesy of Margarete Muehlleitner

Matrix element method

Instead of relying on specific kinematical variables, one can try to exploit the full information of the event

The MEM starts from a tree level amplitude to construct a likelihood

$$\mathcal{P}(\mathbf{x}|\Omega) = \frac{1}{\sigma_\Omega^{LO}} \int dx_a dx_b \, d\mathbf{y} \sum_{ij} \frac{f_i(x_a) f_j(x_b)}{x_a x_b s} \mathcal{B}_\Omega^{ij}(p_a, p_b, \mathbf{y}) \, W(\mathbf{x}, \mathbf{y})$$

integration over phase space

PDFs

squared amplitude

transfer function from parton to detector level

The amplitude should describe the interaction of the X resonance with the gauge bosons

Recently there have been attempts to extend MEM to NLO

J.Campbell, W.Giele, C.Williams (2012)

Effective lagrangian or anomalous couplings ?

How do we parametrize the amplitude ?

There are essentially two strategies:

- Effective lagrangian

Write the most general effective lagrangian compatible with Lorentz and gauge invariance

- Anomalous couplings

Write the most general amplitude compatible with Lorentz and gauge invariance: couplings become momentum dependent form factors

Effective lagrangian (EFT)

- + Clear ordering between relevant and subdominant operators
- + Consistent beyond LO

Anomalous couplings (AC)

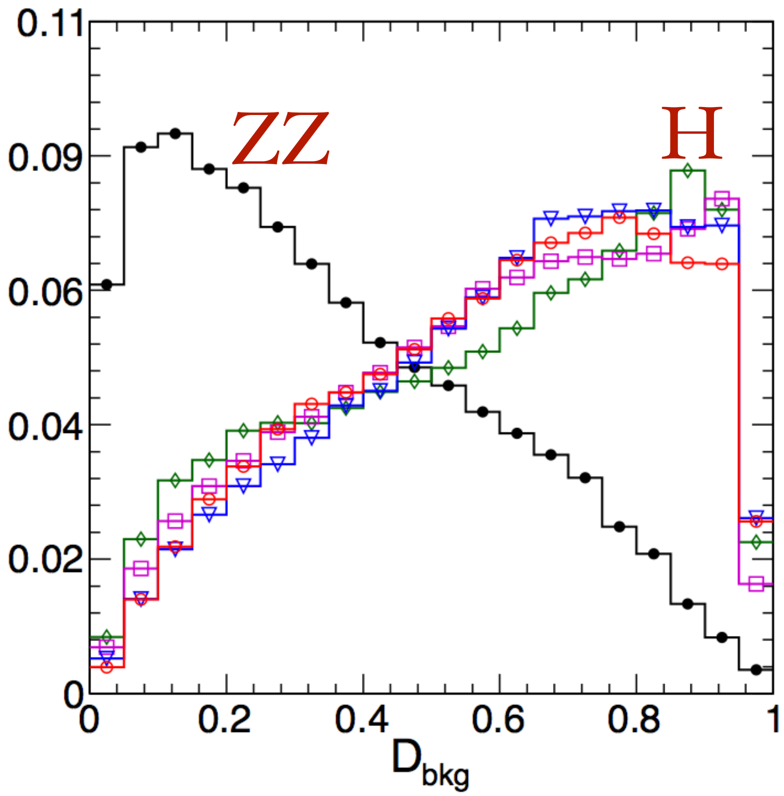
- + Somewhat more “general” but....
- - “Agnostic” approach (more parameters)
- - Inconsistent beyond LO

My opinion: the only reasons why you could prefer AC to EFT are:

- if you believe that there can still be relatively light and weakly coupled degrees of freedom that can circulate in the loops (but then why have they not been observed ?)
- if you don’t have a clue on how a consistent model looks like (spin 2 case ?)

MELA

MELA (Matrix Element Likelihood Analysis)

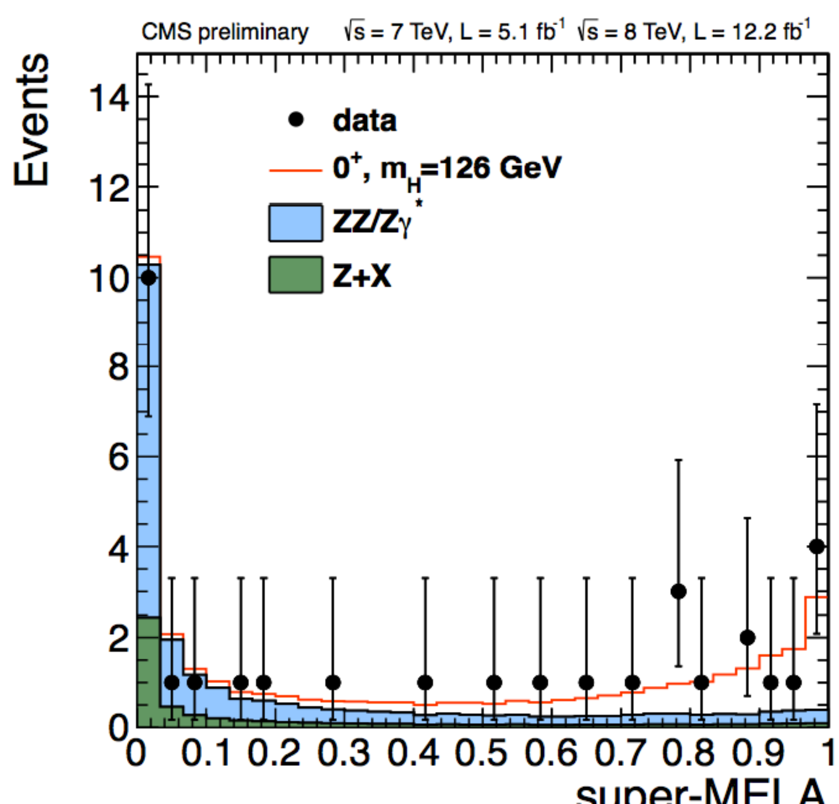


simplest MEM (no PS integration, no transfer function)

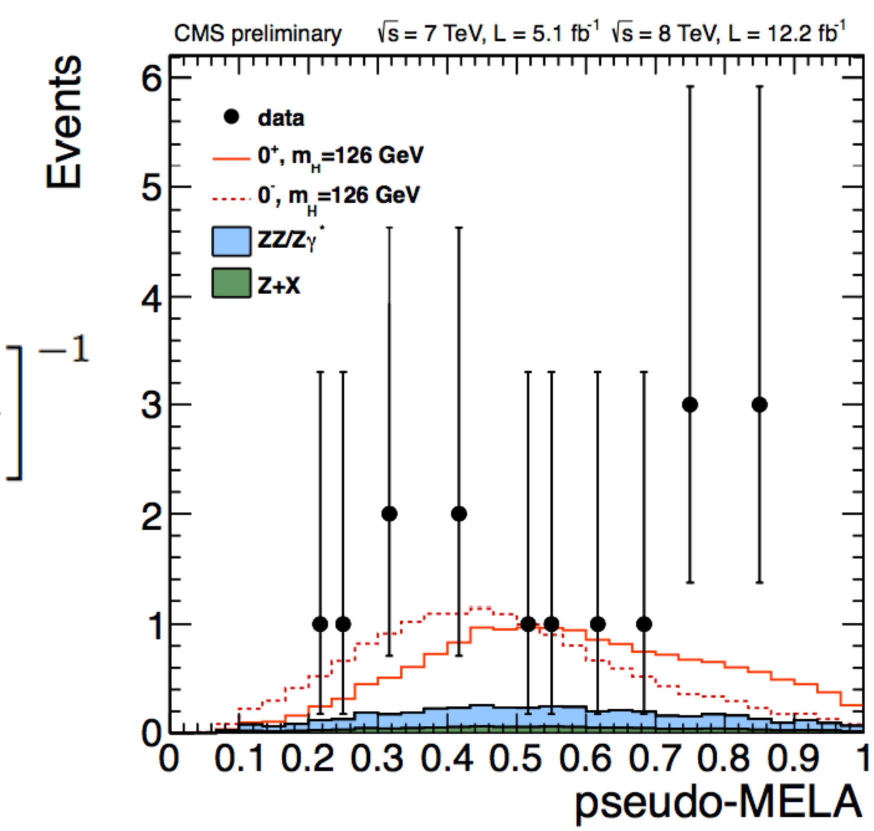
$$D_{\text{bkg}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}\right]^{-1}$$

kinematic discriminant constructed from the ratio of probabilities for signal and backgrounds (superMELA)

the discriminant can be extended to discriminate two different JCP hypothesis



$$D_{J^P_x} = \left[1 + \frac{\mathcal{P}_2(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}{\mathcal{P}_1(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}\right]^{-1}$$



JHU

K.Melnikov et al. (2009, 2012)

Model independent production of a resonance X followed by its decay in two vector bosons and in four fermions

See also:
De Rujula, Lykken, Pierini, Rogan, Spiropulu (2010)
MEKD, Avery et al. (2012)

→ The approach is the one of anomalous couplings

spin 0

$$A(X \to V_1 V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

spin 2

$$\begin{aligned} A(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)} \right) \\ & + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big], \end{aligned} \quad (18)$$

Used by ATLAS and CMS through MELA

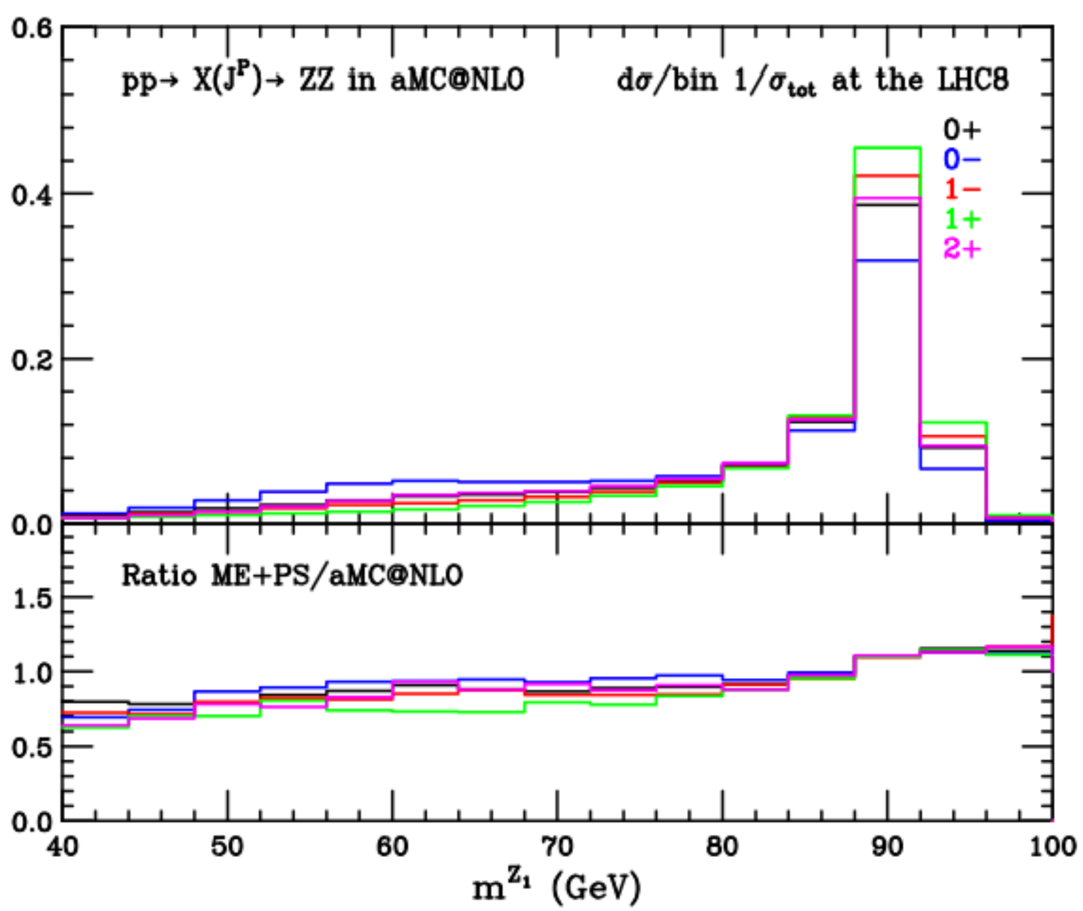
The Higgs Characterization model

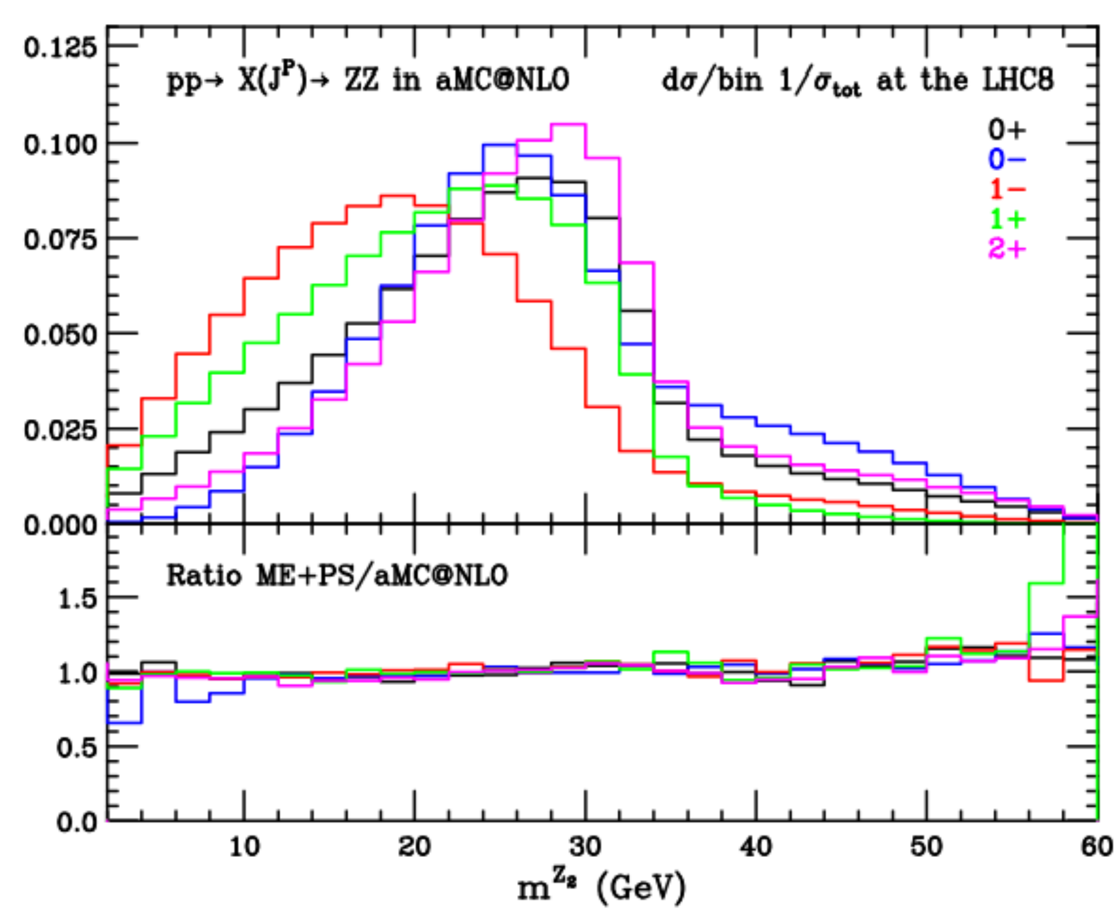
P.Artoisenet et al (2013)

A complete EFT framework to describe the production of a $X(J^{CP})$ resonance in hadronic collisions ➡ consistent description of spin-0, 1 and 2 possibilities

Embedded in the MADGRAPH5 framework

It allows to include QCD radiative corrections either by ME+PS or (when virtual corrections are available) through the aMC@NLO method

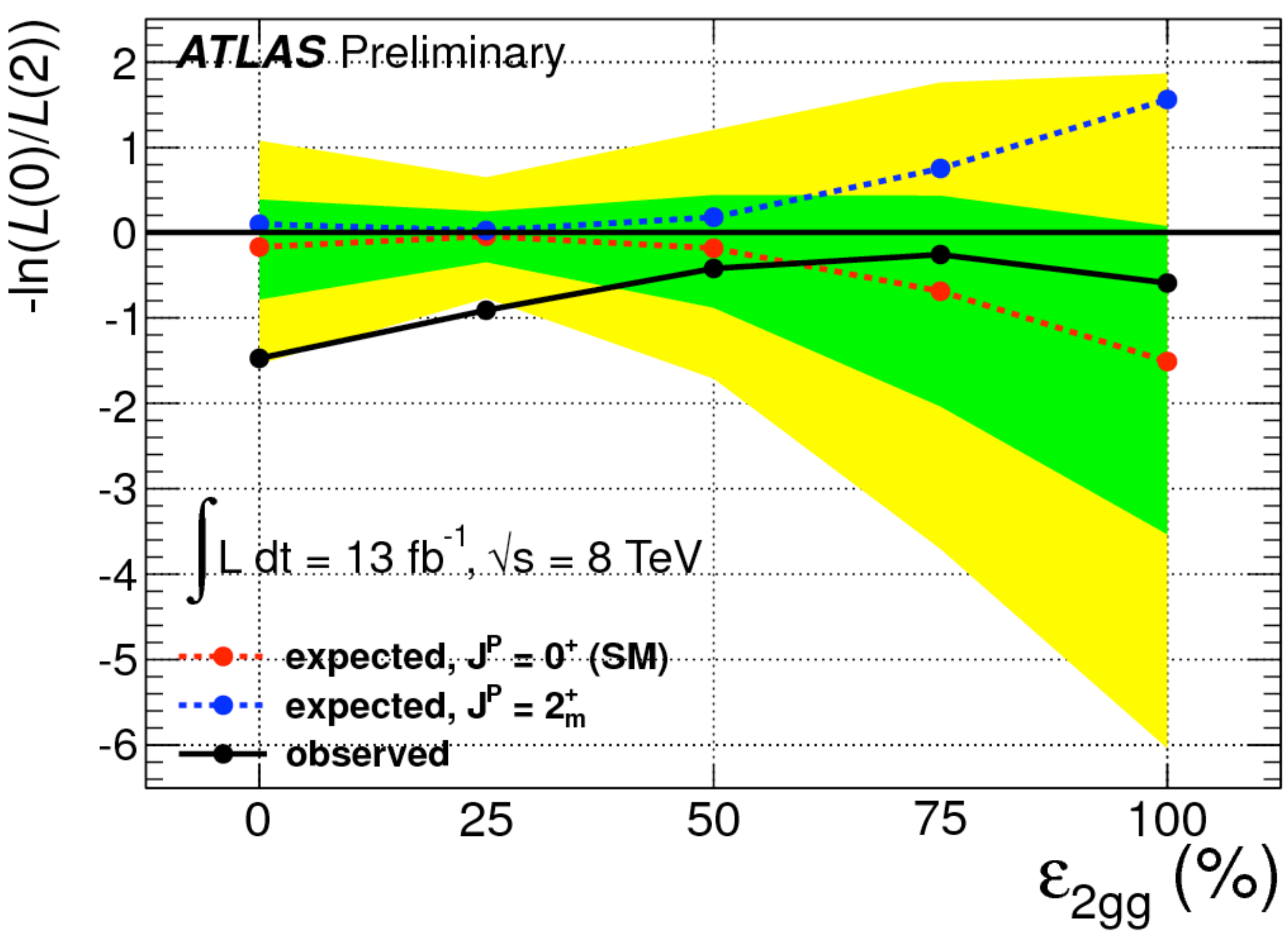


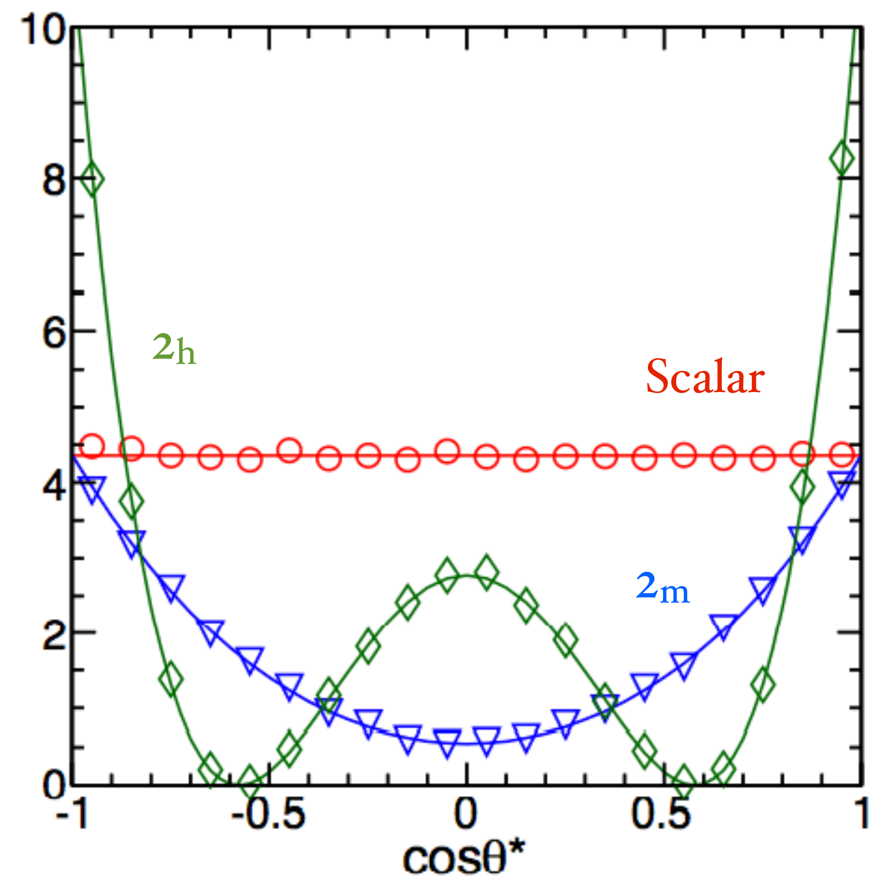


$X \to \gamma\gamma$

In $X \to \gamma\gamma$ the final state is fully reconstructed but there is only one distribution: $\cos\theta^*$ which is flat in the scalar case

Dependence on the production model comes from spin correlations

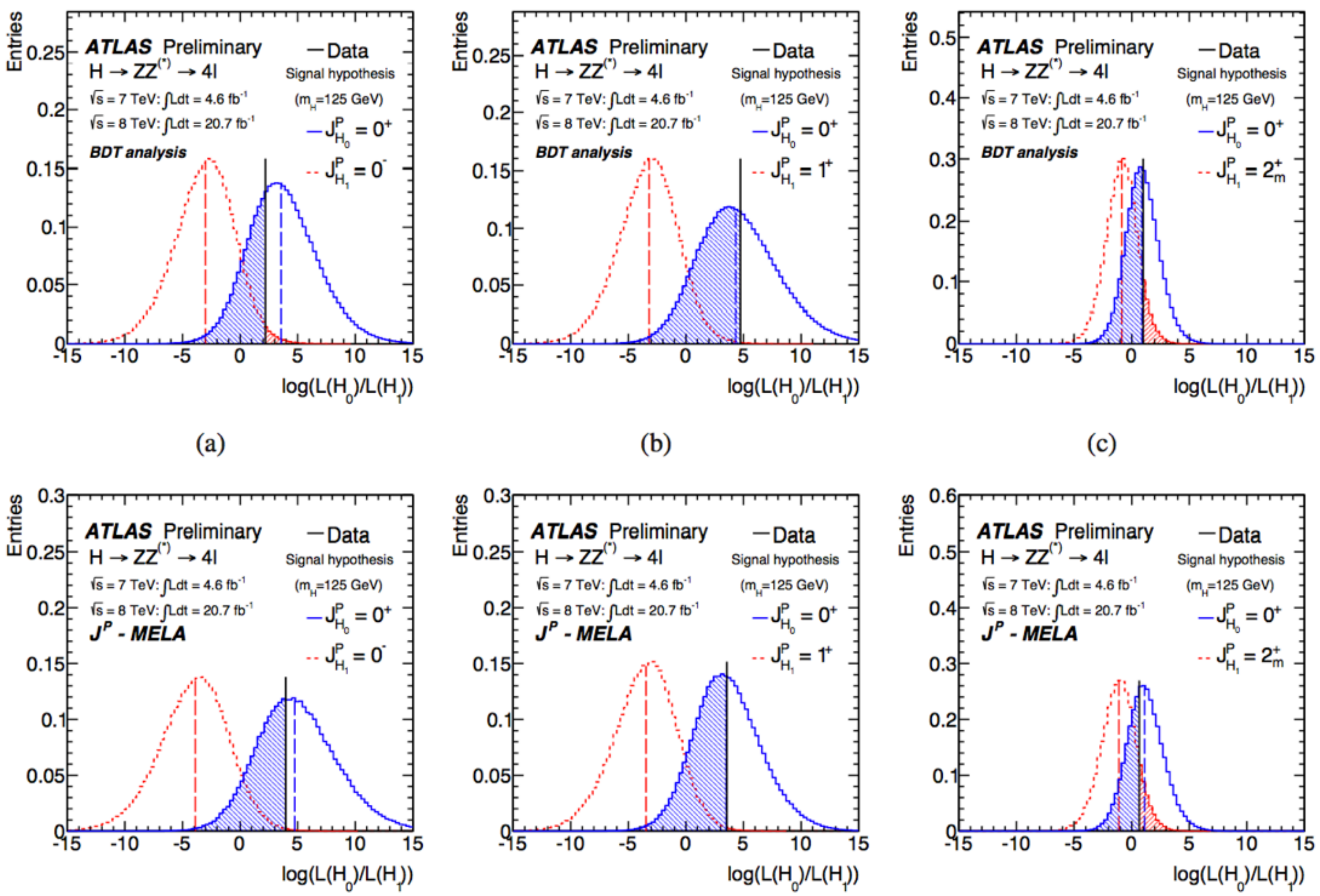




K.Melnikov et al. (2009, 2012)

Discrimination only if the spin 2 is produced in the gg channel

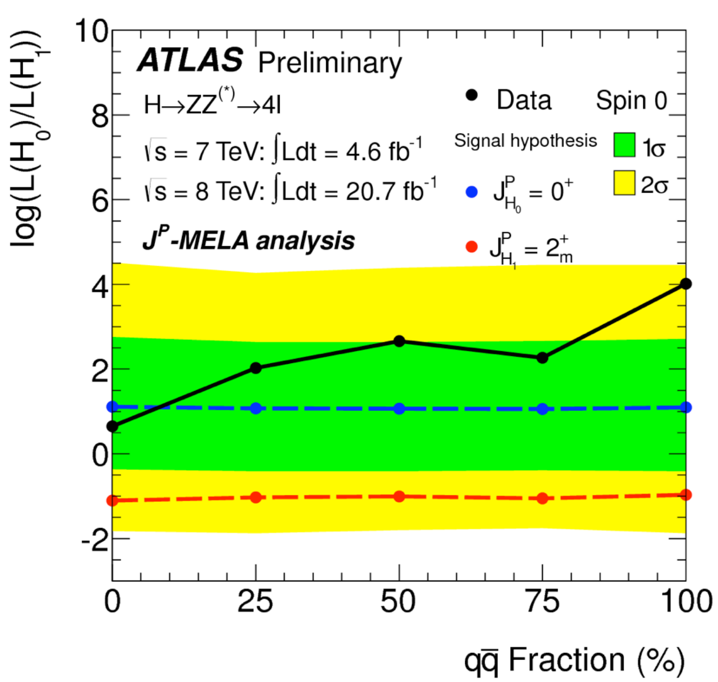
ATLAS H→ZZ→4l

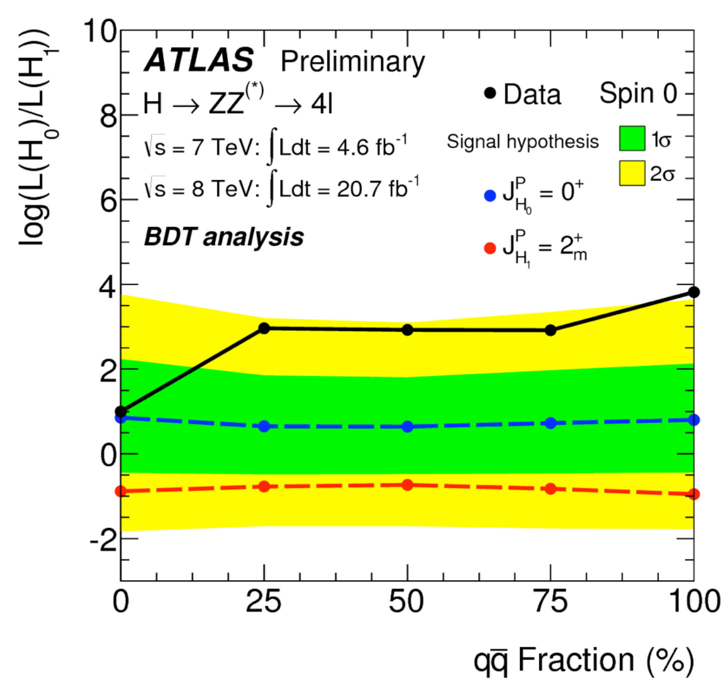


ATLAS uses MELA and BDT

results look consistent

Effect of p_T reweighting very small (1% level)





Production independent !

Spin-Parity ATLAS - CMS Overview

F.Cerutti , EPS2013

CMS ZZ*(4ℓ)

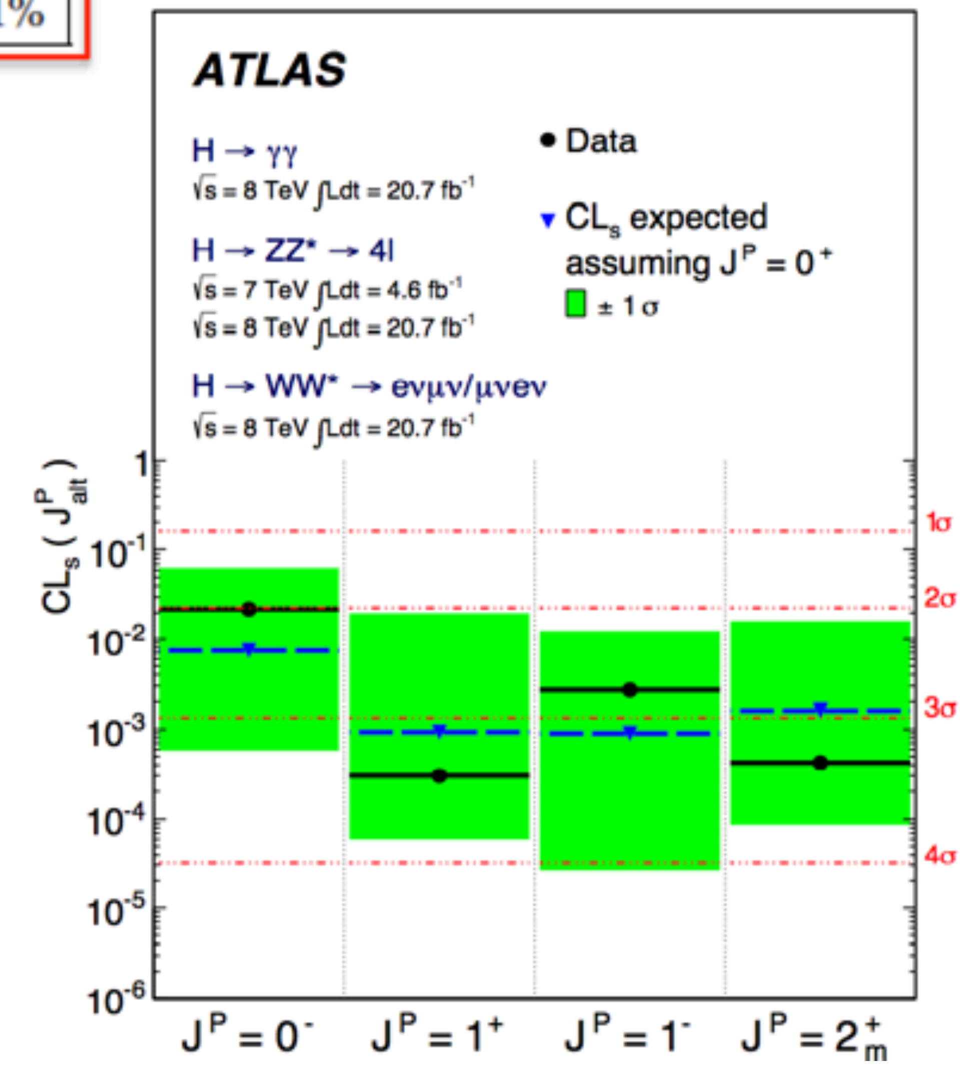
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

ATLAS and CMS: *"bosonic"* decay modes

Strongly favor J^P = 0^+ SM quantum numbers

All alternative J^P models tested:

Excluded @ >95% CL



Higgs couplings

Interim framework for coupling exploration

LHCHXSWG, A. David et al (2012)

Assumptions:

- The signal observed originate from a single narrow resonance of mass around 125 GeV
- The width of the resonance can be neglected (i.e. the narrow width approximation can be used)
- Only (small) modifications of the coupling strength are taken into account, while the tensor structure is assumed to be the same as in the SM

Predicted SM cross sections (including all available radiative corrections) are dressed with scale factors $\varkappa_i$

Higgs couplings

- Simplest approach: one common scale factor $\varkappa$

→ Equivalent to fit overall signal strength

ATLAS finds $\mu=1.33 \pm 0.20$ at $m_H=125.5$

CMS finds $\mu=0.80 \pm 0.14$ at $m_H=125.7$

- Scaling of vector ($\varkappa_V=\varkappa_W=\varkappa_Z$) and fermion couplings ($\varkappa_f=\varkappa_t=\varkappa_b$)

$(\sigma \times BR)(gg \to H \to \gamma\gamma) = \varkappa_f^2 \varkappa_\gamma^2 / \varkappa_H^2$

$\varkappa_\gamma = \varkappa_\gamma(\varkappa_f, \varkappa_V)$ loop coupling to the photons (involves W, heavy quarks)

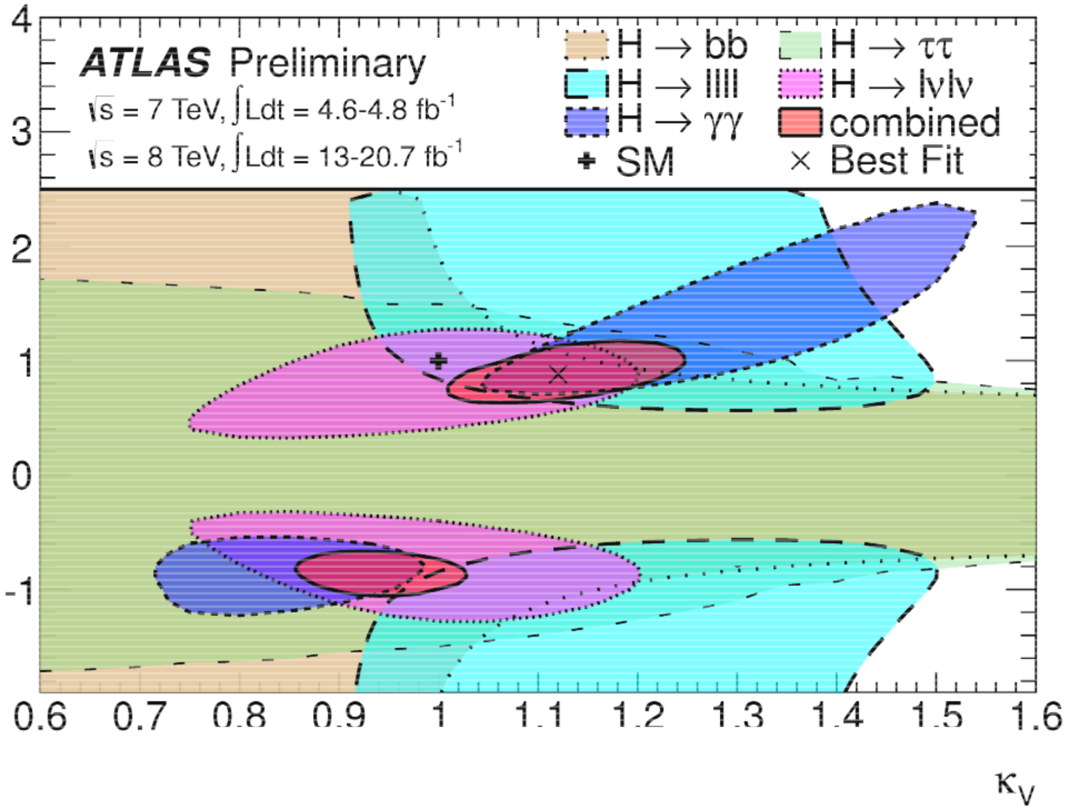
$\varkappa_H = \varkappa_H(\varkappa_f, \varkappa_V)$ scaling factor for the total width

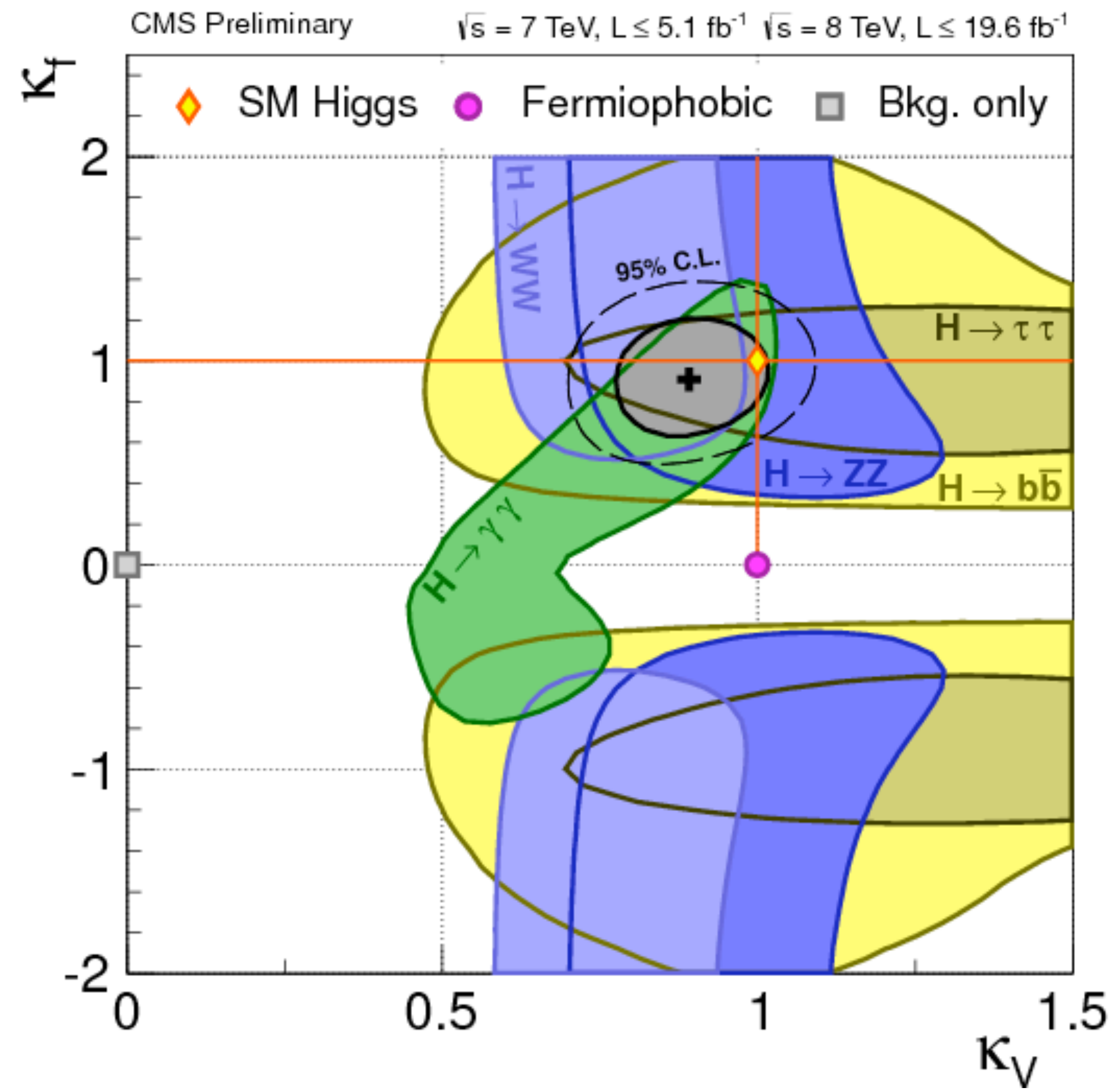
→ implies no invisible or undetectable widths

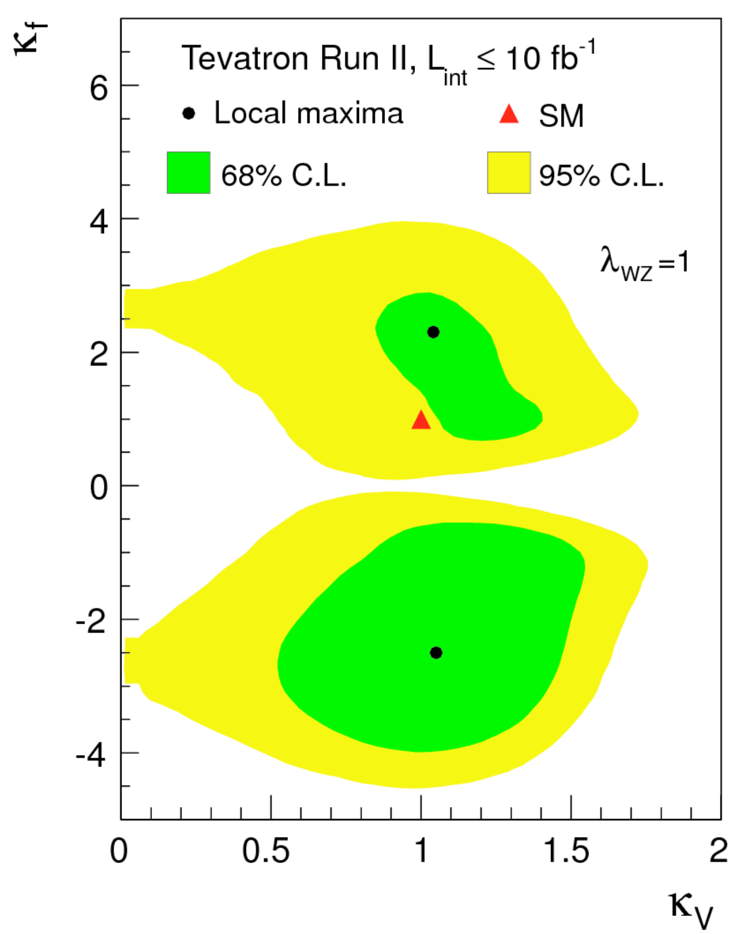
this assumption can be relaxed and the width treated as a free parameter

Increasing the number of parameters the model becomes more realistic but experimental uncertainties in the fit will rapidly grow

$\varkappa_F$ vs $\varkappa_V$







Results compatible with the SM predictions

Note that also the Tevatron was able to produce this fit !
(though with much larger uncertainties)

Beyond the interim framework

The interim framework outlined before was proposed within the LHCHXSWG as a first step to explore the coupling structure of the newly discovered resonance

Besides possible deviations in the absolute values of the couplings from their SM value one should consider also possible deviation in the tensor structures

→ This implies that coupling and JCP properties should be studied within the same framework

If we assume that at the scale $m_H \sim 125$ GeV the SM with a Higgs doublet is a good description of the data

→ Use SM fields to build up an effective lagrangian with higher dimensional gauge invariant effective operators

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \dots$$

W.Buchmuller, D.Wyler (1986)
B. Grzadkowski et al. (2010)

Beyond the interim framework

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi) \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi) \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi}) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi) \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi}) B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi) \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$

34 operators involving Higgs or gauge boson fields+25 four-fermion operators

→ 59 operators

Alternative approach: non linear lagrangian

R.Contino, M.Ghezzi,C.Grojean, M.Muhlleitner (2013)
G.Giudice, C.Grojean,A.Pomarol,R.Rattazzi (2007)

Does not assume that H is part of a EW doublet (could also describe a dilaton...)

Somewhat more general (though it seems more difficult to include radiative corrections)

Summary & Outlook

It is a very exciting moment for particle physics: a new particle consistent with the long sought Higgs boson has been discovered

Difficult to overstate the importance of this discovery for a generation of physicists !

15 months after the discovery from the EXP side we can say that:

- It is now clearly seen in the ZZ, $\gamma\gamma$ and WW channels
- The mass has been determined with rather good precision (but still tension between the ZZ and $\gamma\gamma$ ATLAS measurements)
- Evidence for coupling to fermions (indirect 5σ, direct 3σ)
- Evidence for VBF
- The Spin/CP studies definitely support the 0^{++} hypothesis

→ It looks more and more like the SM Higgs !

Summary & Outlook

From the TH side:

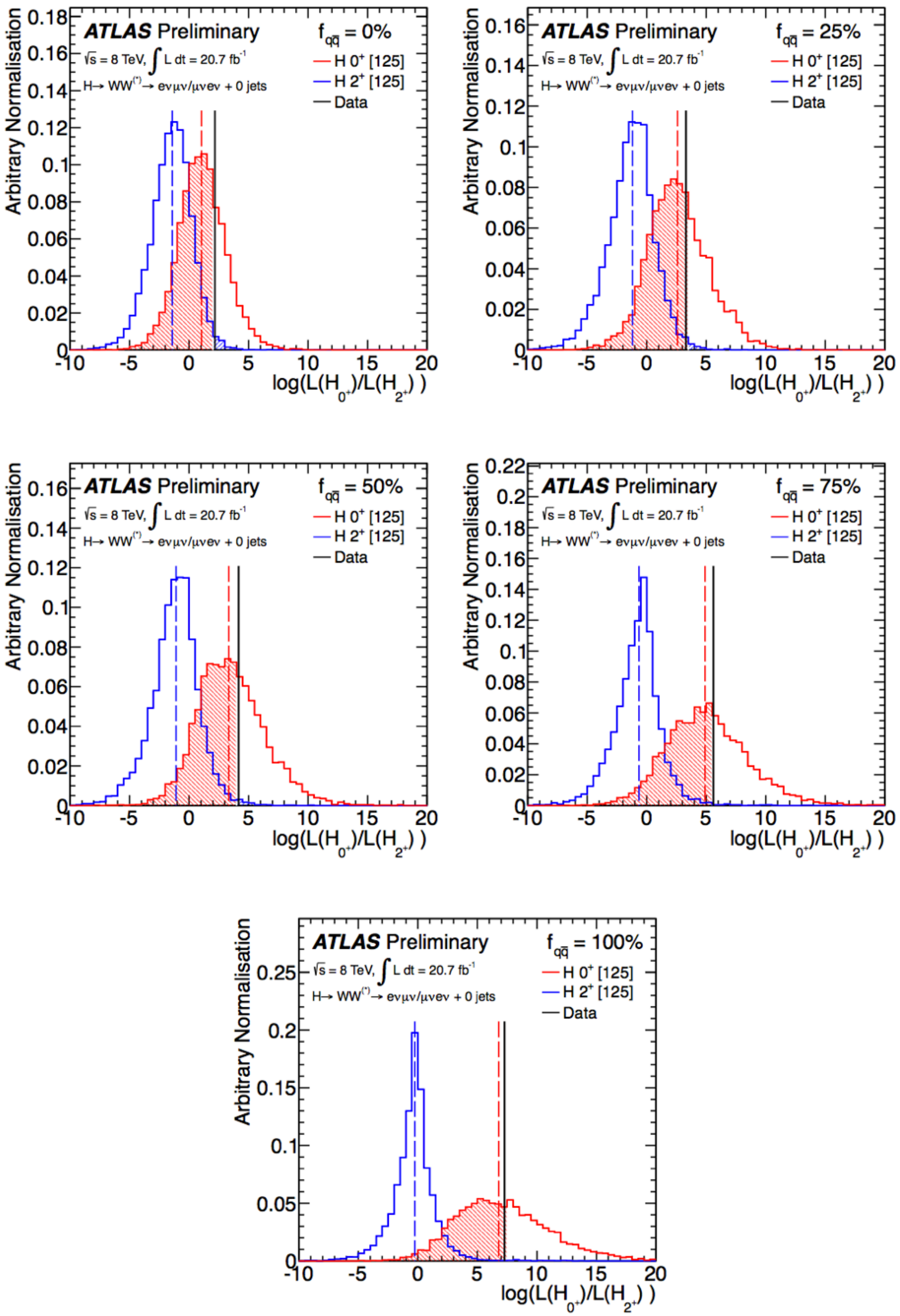
- Perturbative predictions seem in good shape and it is unlikely that big higher order effects have been missed
- Nonetheless a renewed effort is being put in extending the calculation for the leading $gg \to H$ channel to N^3LO (but precision still limited by PDFs and α_S)
- The study of Higgs properties from the 7 and 8 TeV data did not require particularly sophisticated tools from the theory side

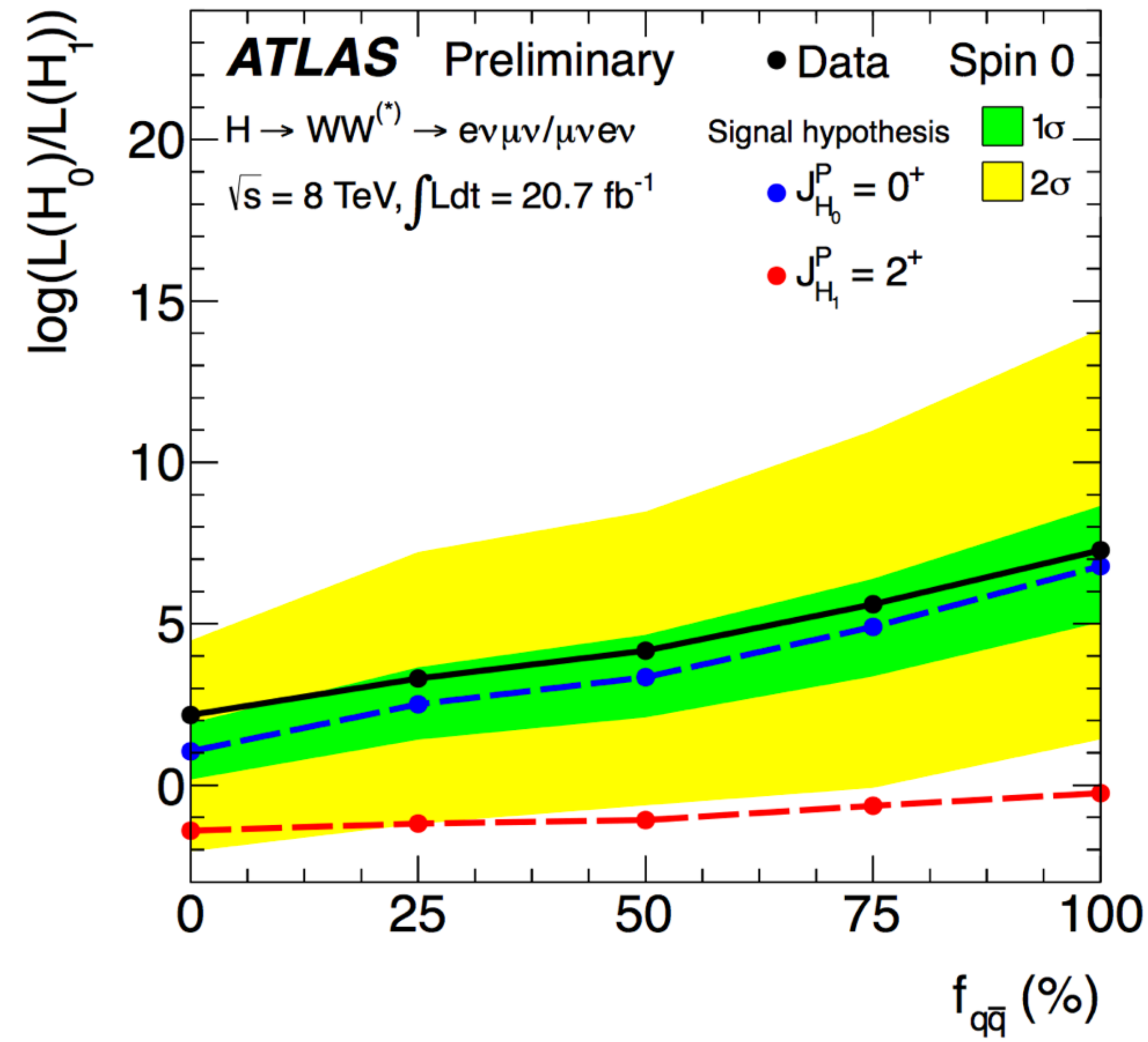
  - the MELA approach is based on tree-level matrix elements
  - coupling studies based on naive rescalings of SM couplings

- With more data more sophisticated frameworks will be required and work in this direction is being carried out

BACKUP SLIDES

ATLAS H→WW





2^+ with f_{qq}=100 % is more WW background like

→ better discrimination with respect to 0^+ but worse with respect to background

TH Intermezzo: Spin 2

The Spin 2 possibility seems so unlikely that everybody would like to discard it

- Minimal coupling of Pauli-Fierz lagrangian to U(1) leads to the Velo-Zwanziger problem

→ acausality/superluminality

M.Porrati, R.Rahman (2008)

The model turns out to have a cut off $\Lambda \sim m/e^{1/3}$

A consistent effective description (with a cut off $\Lambda \sim O(m)$) could be obtained by interpreting the spin 2 particle as a KK graviton (but then how about the corresponding W and Z modes that should also be around 100 GeV ?)

However:

A graviton-like massive spin 2 with a warped extra dimension of AdS type will have too small couplings to WW and ZZ with respect to $\gamma\gamma$

J.Ellis et al. (2012)

$c_{W,Z} / c_\gamma < O(35)$ effective volume of the extra dimension: $\log(M_{Plank}/TeV)$

Couplings to gg and $\gamma\gamma$ equal in many models with a compactified extra dimension

→ $\Gamma(H \to gg) = 8\, \Gamma(H \to \gamma\gamma)$

But this seems very different from what the data tell us: $\Gamma(H \to gg) >> 8\, \Gamma(H \to \gamma\gamma)$