Experimental aspects of the CP violation.

S. Monteil,
LPC – Université Blaise Pascal – in2p3.
[LHCb experiment – CKMfitter group]

Some authoritative literature about the lecture :

- BaBar physics book: http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- LHCb performance TDR: http://cdsweb.cern.ch/record/630827?ln=en
- A. Höcker and Z. Ligeti: CP Violation and the CKM Matrix. hep-ph/0605217

World Averages and Global Fits:

- Heavy Flavour Averaging Group: http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter: http://ckmfitter.in2p3.fr/
- UTFit: http://www.utfit.org/

Disclaimers

- This is an experimentalist point of view on a subject which is all about intrications between experiment and theory.

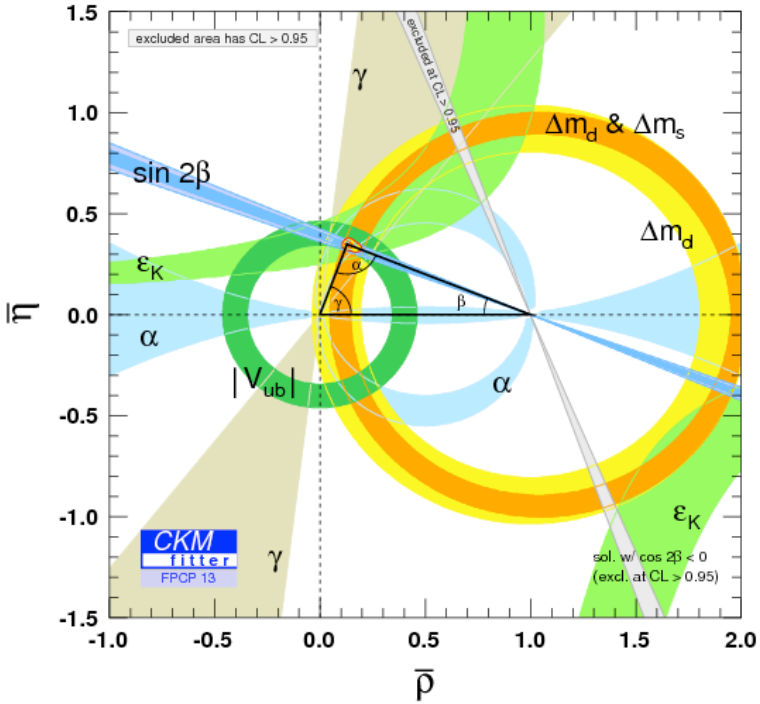
- I won't discuss (at all) CP violation in the lepton sector.

- The main machines in question here are the TeVatron (Fermilab, US), PEPII (SLAC, US), KEKB (KEK, Japan) and LHC (CERN, EU). Former experiments played a pioneering role: LEP (CERN, EU) and CLEO (CESR, US).

- Most of the material concerning global tests of the SM and above is taken from the CKMfitter group results (assumed bias) and Heavy Flavour Averaging Group (and hence the experiments themselves). I borrowed materials in presentations from colleagues which I tried to cite correctly.

Motivation

- In any HEP physics conference summary talk, you will find this plot, stating that (heavy) flavours and CP violation physics is a pillar of the Standard Model.



- One objective of these series of lectures is to undress this plot.

A more detailed outline

1. Introduction: setting the scene. History and recent past of the parity violation experiments. The discovery of the CP violation. Few elements about CKM. Machine and experiments.

2. Main observables and measurements relevant to study CP violation.

3. The global fit of the SM: CKM profile.

4. New Physics exploration with current data: two examples.

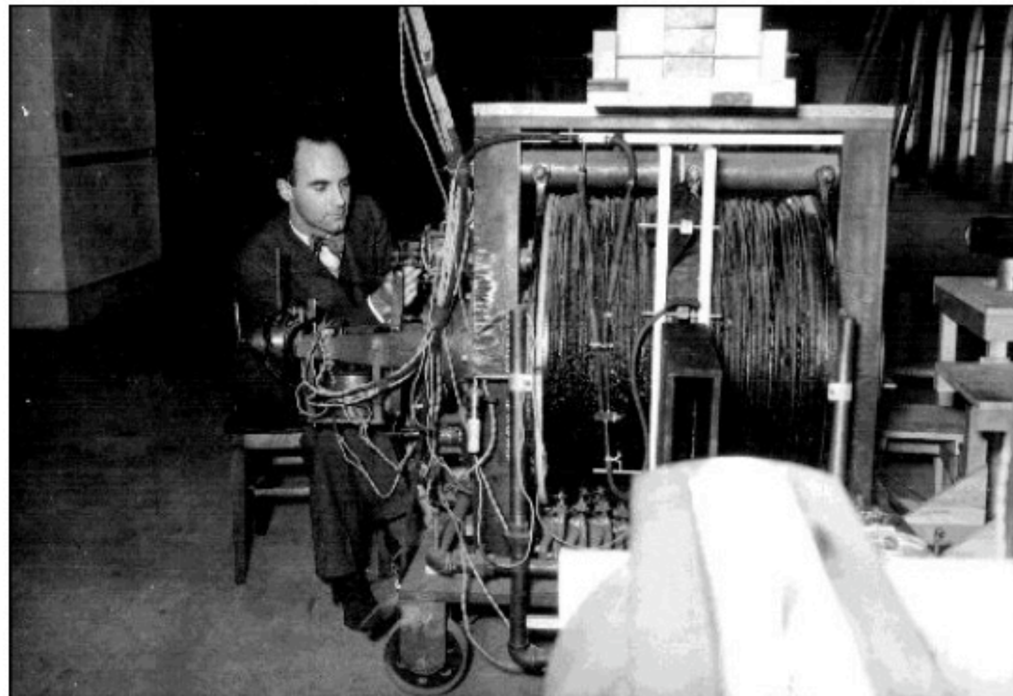
1.1 Introduction: founding experiments

1. Antimatter discovery – C. Anderson.
2. The parity violation measurement – Madame Wu.
3. The parity violation measurement – Goldhaber et al.
4. Recent parity violation measurements at LEP/SLD.
5. The discovery of CP violation – Cronin et al.
6. Recent CP violation discoveries

1.1 Introduction: antimatter exists.

In 1929, P.A.M Dirac solves the free motion of a relativistic spin 1/2 particle (electron or proton). It happened that there should exist a solution of negative energy, which he interpreted as an antiparticle.

$$\text{Dirac spin } 1/2 : \ (i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$$



Anderson at work: discovery of the positron in 1932.

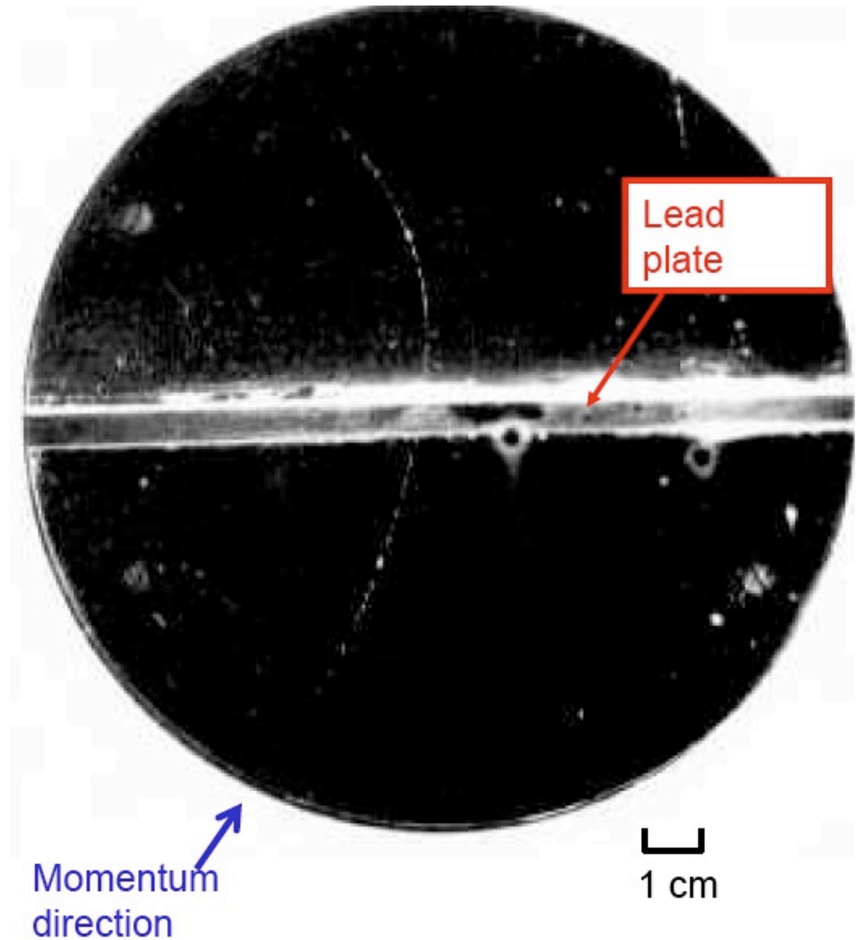
1.1 Introduction: antimatter exists .

- The radius of curvature is smaller above the plate. The particle is slowed down in the lead ⇒ the particle in incoming from the bottom.

- The magnetic field direction is known
  ⇒ positive charge

- From the density of the drops one can measure the ionizing power of the particle
  ⇒ minimum ionizing particle

- Similar ionizing power before and after the plate ⇒ same particle on the 2 sides
- Curvature measurement after the lead : particle of ~23MeV).



1.1 Introduction: evidence for P violation

The Wu experiment:

- Before 1956 : all interactions were thought to be invariant under parity operation
- It was (quite comprehensively) tested for strong and electromagnetic interactions.
- Lee and Yang proposed an experiment to test it for weak interaction
- Designed and performed in 1957 by C.S. Wu and collaborators
- The Co^{60} experiment : Phys. Rev. 105, 1413-1414 (1957)

1.1 Introduction: evidence for P violation

The Wu experiment: $$\mathrm{Co}^{60}(J=5) \to \mathrm{Ni}^{60*}(J=4)\; e^- \; \bar{\nu}_e$$

- Study the beta decay of Co^{60} atoms.
- The spins of the Co^{60} atoms are aligned towards the direction of a magnetic field able to flip polarity.
- The electrons are detected and their direction is measured: 2 possibilities related by parity transformation:

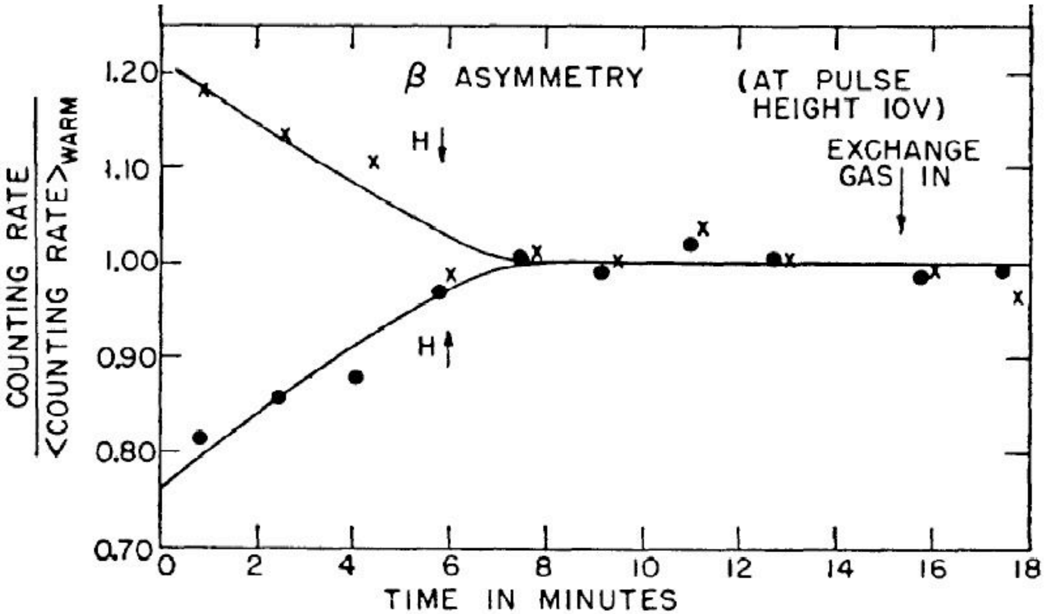
Sketch that on the black board

The result of the experiment is that the electrons are preferentially produced in the opposite direction of the spins of the Co^{60} atoms: PARITY SYMMETRY IS VIOLATED.

1.1 Introduction: evidence for P violation

The Wu experiment:

- The magnetic field direction is changed and the rate for the electrons emission is measured in the two configurations. The asymmetry is reversed.

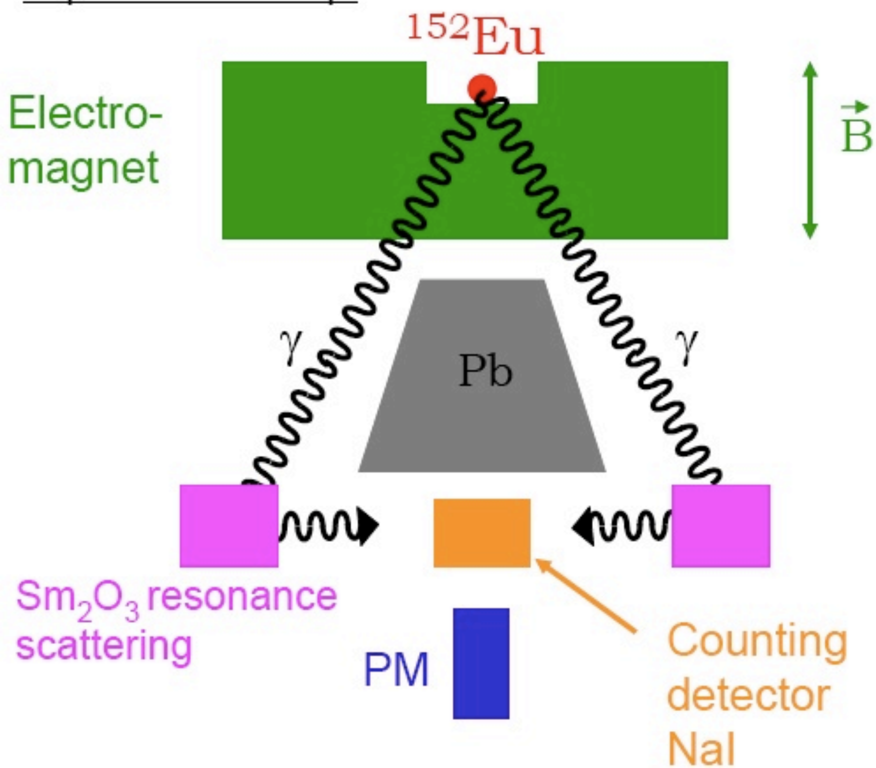


- The preferred chiral state is a right-handed anti-neutrino (left-handed electron).

1.1 Introduction: neutrinos are left-handed

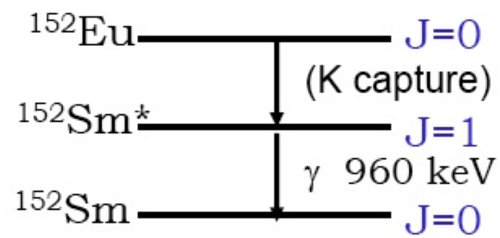
The Goldhaber experiment:

Experimental set-up:



γ emitted in the direction of the momentum of the Sm* are selected

$$^{152}Eu(J=0) + e^- \rightarrow {}^{152}Sm^*(J=1) + \nu$$
(K capture)
$$\hookrightarrow {}^{152}Sm(J=0) + \gamma$$



The spins of all final states particles are constrained. The gammas aligned with the ^{152}Sm are selected and their polarization is measured.

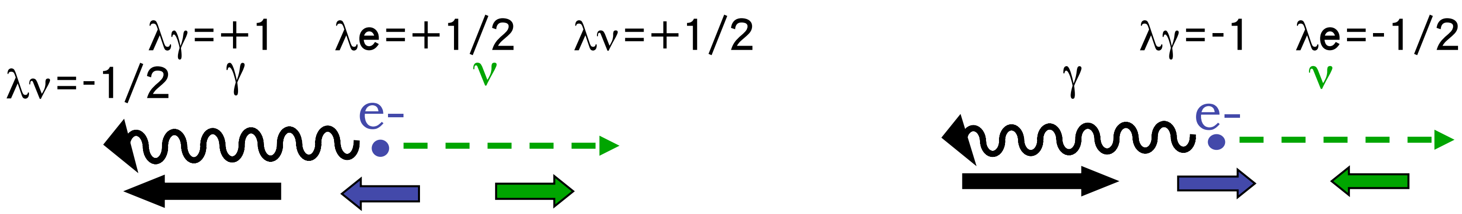
1.1 Introduction: neutrinos are left-handed

The Goldhaber experiment:

We write down the spin constraints: the spin of the electron defines the initial and the final states. We shall end up with a one-half spin projection. Two configurations are possible:

Putting the gamma in the game: $^{152}Sm^*(J=1) \to {}^{152}Sm(J=0) + \gamma$

And writing the helicities of the particles, two possible configurations emerge:



From the gamma polarization measurement, Goldhaber et al. show that only left-handed neutrinos are found (i.e, the second configuration) in β decays. Goldhaber, Grodzins, Sunyar, Phys. Rev. 109, 1015 (1958)

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓QFT: requirement of Lorentz Invariance (LI) of the matrix elements strongly constrains the form of the interaction vertices. We learnt QED and QCD to have vector currents. In general, 5 and only 5 combinations of 2 spinors and γ-matrices complies with Lorentz Invariance. They are called covariant bilinears:

Type	Expression	Components	Mediating Boson
Scalar	$\bar{\Psi}\Phi$	1	Spin 0
PseudoScalar	$\bar{\Psi}\gamma^5\Phi$	1	Spin 0
Vector	$\bar{\Psi}\gamma^\mu\Phi$	4	Spin 1
Axial Vector	$\bar{\Psi}\gamma^\mu\gamma^5\Phi$	4	Spin 1
Tensor	$\bar{\Psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\Phi$	6	Spin 2

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓WE, have to find which form or combination of forms would fit the experimental observation that parity symmetry is maximally violated in weak interaction and that left-handed helicity neutrinos seem to be the only authorized state in that scope.

✓ First a reminder on chirality states. Let's consider a spin-half particle:

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0.$$

$$\Psi = \Psi_L + \Psi_R, \Psi_L = P_L\Psi, \Psi_R = P_R\Psi,$$

$$P_{L,R} = \frac{(1 \pm \gamma^5)}{2},$$

$$\gamma^5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}.$$

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓There are two vertex interaction form complient with our objectives: these are the Vector-AxialVector interaction:

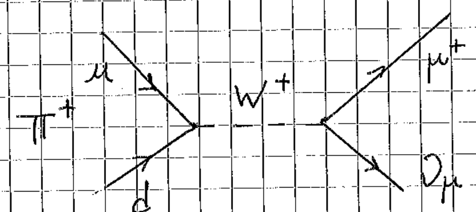
$$
\begin{aligned}
\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi &= \bar{\Psi}(P_L+P_R)\gamma^{\mu}(1-\gamma^{5})(P_L+P_R)\Psi \\
\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi &= 2\bar{\Psi}(P_L+P_R)\gamma^{\mu}(P_L^2+P_LP_R)\Psi \\
\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi &= 2\bar{\Psi}_L\gamma^{\mu}\Psi_L
\end{aligned}
$$

✓Selection of chirality states. Only LL couplings allowed for particles. Maximal violation of the parity symmetry. A natural candidate for the weak interaction.

✓*Homework 1: show that vectorial interactions selects democratically LL and RR interaction vertices. Show as well that [V+A] does the same as [V-A].*

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration

π Decay - Decay width and related matters
Hands out.



$$d\Gamma = \frac{1}{2E}\,\frac{1}{(2S_\pi+1)}\sum_{spins}|\mathcal{M}|^2\,dQ.$$

(1) HADRONIC MATRIX ELEMENT $j_q^\mu = \bar{u}(u)\,\gamma^\mu(1-\gamma^5)\,v(\bar{d})$

Since quarks, cannot be calculated perturbatively for the strong interaction $\rightarrow$ $j_q^\mu = f_\pi p^\mu$. p = momentum of π.

(2) LEPTONIC MATRIX ELEMENT AND $\mathcal{M}$.

$j_{l\mu} = \bar{u}(\mu^+)\,\gamma_\mu(1-\gamma^5)\,u(\nu_\mu)$ and $\mathcal{M} = \frac{G_F}{\sqrt{2}}[j^\mu_q][j_{l\mu}]$.

$$\rightarrow \mathcal{M} = \frac{G_F}{\sqrt{2}} f_\pi m_\mu \left[\bar{u}(\mu^+)(1-\gamma^5)u(\nu_\mu)\right]$$

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration

(3) SUM OVER FINAL STATES SPINS

$$|\bar{\mathcal{M}}|^2 = \sum_{spins} \mathcal{M}\mathcal{M}^* = 4 G_F^2 f_\pi^2 m_\mu^2 P(\mu) \cdot P(\nu_\mu)$$

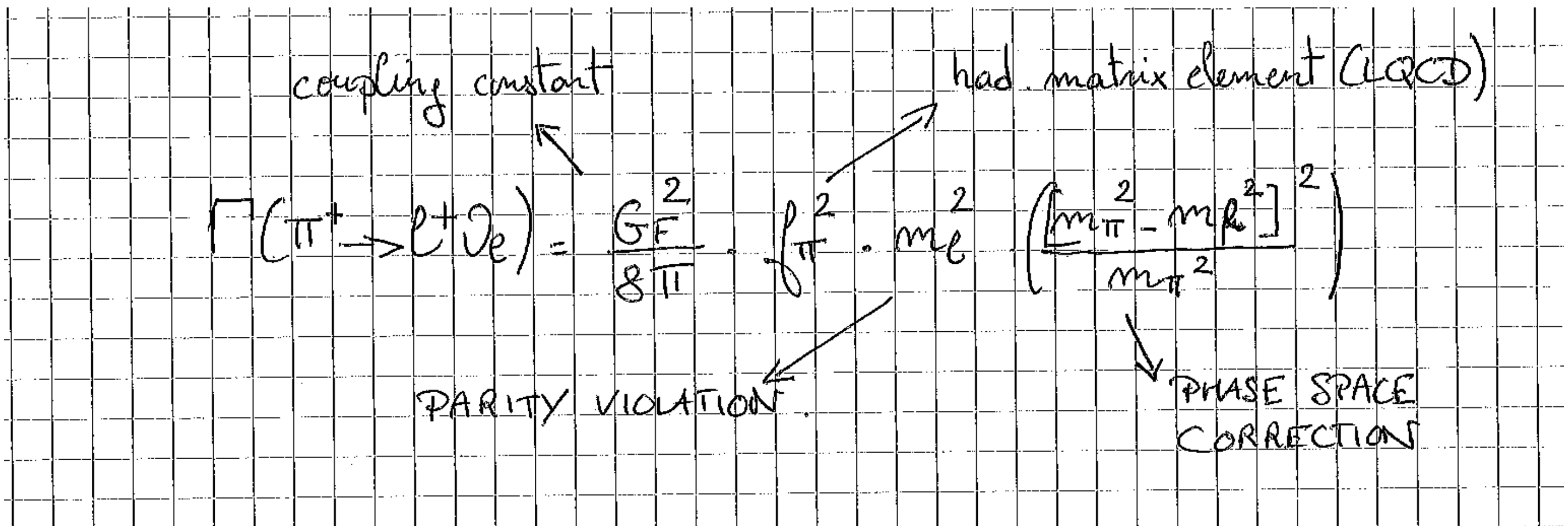
(4) PHASE SPACE INTEGRATION

$$dQ = \frac{d^3p(\mu)}{(2\pi)^3 \cdot 2E(\mu)} \cdot \frac{d^3p(\nu_\mu)}{(2\pi)^3 \cdot 2E(\nu_\mu)} (2\pi)^4 \delta^{(4)}(P - p(\mu) - p(\nu_\mu))$$

(5) BOTTOMLINE

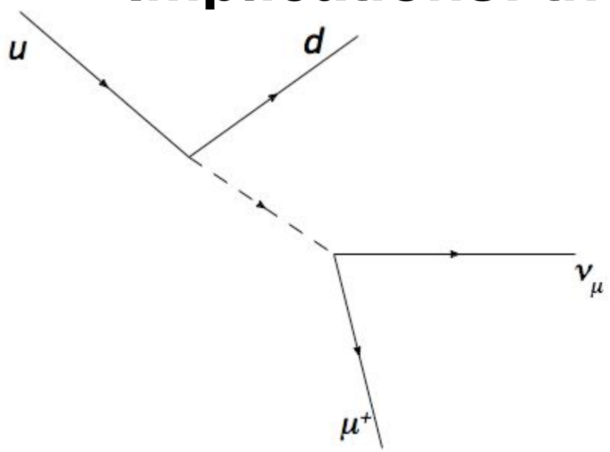
$$\Gamma = \frac{G_F^2}{8\pi} f_\pi^2 \cdot \frac{m_\mu^2}{m_\pi^2} \left(m_\pi^2 - m_\mu^2\right)^2$$

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration



✓Interpretation: you force the lepton to be in its wrong helicity state (chirality is definitely right-handed). Electrons must hate you more than muons (at least in the ratio of the squared masses).

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration



To remove the QCD part of the decay width which is badly determined, it is relevant to consider a ratio of decay widths in leptons.

Again, we can compare the predictions with the different allowed Lorentz Invariant structures of the interaction to the measurement.

$$\frac{\Gamma(\pi^+ \to \mu^+\nu_\mu)}{\Gamma(\pi^+ \to e^+\nu_e)} = (0.813 \pm 0.004).10^4,$$

$$\frac{\Gamma(\pi^+ \to \mu^+\nu_\mu)}{\Gamma(\pi^+ \to e^+\nu_e)} = 0.2 \ \ (\mathrm{S\ or\ P\ prediction}),$$

$$\frac{\Gamma(\pi^+ \to \mu^+\nu_\mu)}{\Gamma(\pi^+ \to e^+\nu_e)} = 0.78\ 10^4 \ \ (\mathrm{V-A\ prediction}).$$

1.1 Introduction: neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓Final notes on the subject:

✓ If the electron and muon decay widths differ a lot, lepton and antilepton decay widths are the same within experimental uncertainties, making CP a good symmetry of the weak interaction.

✓In the actual calculation (which I strongly encourage you to perform), you will observe a slight tension between the prediction and the measurement. Anticipating a bit the following elements of this lecture, this disagreement is related to the probability of the $d \rightarrow u$ transition which is not amounting to unity.

1.1 Introduction: modern parity violation experiments:LEP/SLD

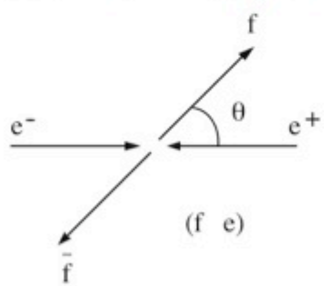
The Standard Model Tests (Part II)

3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Parity is maximally violated in weak interactions. This induces the fermion particle in the final state to be produced preferentially in the direction of the initial electron.

$$\frac{d\sigma^f}{d\cos\theta} = \sigma^f_{\rm tot} \cdot [\frac{3}{8}(1+\cos^2\theta) + A^{f\bar{f}}_{\rm FB}\cos\theta]$$

- The experimentalist's job is to identify the nature of the fermion and count how many times it is find forward (i.e in the electron direction)



$$A^{f\bar{f}}_{\rm FB} = \frac{N_F - N_B}{N_F + N_B} \text{ with } N_F = \int_0^1 \frac{d\sigma_{f\bar{f}}}{d\cos\theta}\cdot d\cos\theta$$

$$A^{f\bar{f}}_{\rm FB} \propto A_e \cdot A_f \propto \frac{g^e_V g^e_A}{(g^e_V)^2 + (g^e_A)^2} \cdot \frac{g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

Hence depends primarily to $\sin^2\theta_{eff}$

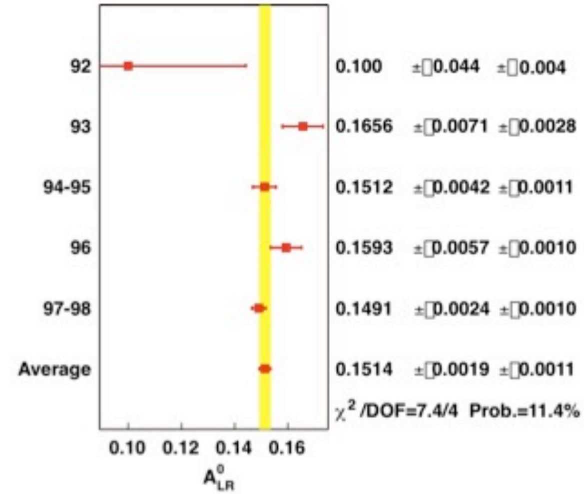
S.Monteil TESchool of High Energy Physics 2

1.1 Introduction: modern parity violation experiments: SLD

The Standard Model Tests (Part II)

3.4 The Parity-Violating Left-Right asymmetry from SLD

- We have seen in 3.3 that A_e was an excellent laboratory.
- SLC machine polarized the electron beam.
- Hence, knowing the polarization and just measuring the LL and RR production of Z boson yields A_e :



$$A_{\mathrm{LR}} = \frac{N_L - N_R}{N_L + N_R} \cdot \frac{1}{\langle P_e \rangle}$$

$$\langle P_e \rangle_{1998} = 0.7292 \pm 0.0038$$

$$A^0_{\mathrm{LR}} = 0.1514 \pm 0.0022$$

$$\sin^2\theta_{\mathrm{eff}} = 0.23097 \pm 0.00027.$$

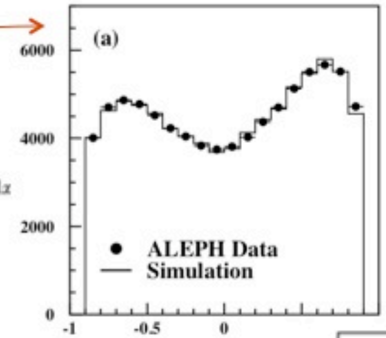
1.1 Introduction: modern parity violation experiments: LEP

The Standard Model Tests (Part II)

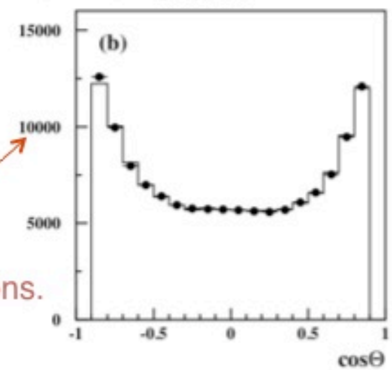
3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Then we fit the asymmetries to these data:

$$
\begin{aligned}
f_{ijkl} = {} & (F^{rs}_{\ell,b})_{ijkl} \int_l [1+x^2+\frac{8}{3}A^b_{FB}(1-2\overline{\chi}_{ijkl})\,x]dx \\
& + (F^{ws}_{\ell,b})_{ijkl} \int_l [1+x^2-\frac{8}{3}A^b_{FB}(1-2\overline{\chi}_{ijkl})\,x]dx \\
& + (F^{asym}_{bkg,b})_{ijkl} \int_l [1+x^2+\frac{8}{3}A^b_{FB}(1-2\overline{\chi}_{ijkl})(2\eta^b_{ijk}-1)\,x]dx \\
& + (F_{\ell,c})_{ijkl} \int_l (1+x^2-\frac{8}{3}A^c_{FB}\,x)dx \\
& + (F^{asym}_{c\to bkg})_{ijkl} \int_l [1+x^2-\frac{8}{3}A^c_{FB}(2\eta^c_{ijk}-1)\,x]dx \\
& + (F^{asym}_{s\to bkg})_{ijkl} \int_l [1+x^2+\frac{8}{3}A^s_{FB}(2\eta^s_{ijk}-1)\,x]dx \\
& + (F^{asym}_{d\to bkg})_{ijkl} \int_l [1+x^2+\frac{8}{3}A^d_{FB}(2\eta^d_{ijk}-1)\,x]dx \\
& + (F^{asym}_{u\to bkg})_{ijkl} \int_l [1+x^2-\frac{8}{3}A^u_{FB}(2\eta^u_{ijk}-1)\,x]dx \\
& + (F^{sym}_{bkg})_{ijkl} \int_l (1+x^2)dx,
\end{aligned}
$$



Parity violation even seen for charm.



Includes QED and QCD effects.

Measuring simultaneously the mixing parameter w/ leptons.

S.Monteil TESchool of High Energy Physics

1.1 Introduction: discovery of CP violation.

- With simple quantum mechanics, one can show that in absence of CP violation:

$$
\begin{aligned}
CP|K_1\rangle &= \frac{1}{\sqrt{2}}(CP|K^0\rangle + CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) = +|K_1\rangle \\
CP|K_2\rangle &= \frac{1}{\sqrt{2}}(CP|K^0\rangle - CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle - |K^0\rangle) = -|K_2\rangle
\end{aligned}
$$

- Final states CP eigenvalues are +1 ($\pi\pi$) and -1 ($\pi\pi\pi$). If CP is a conserved quantity, one then should have:

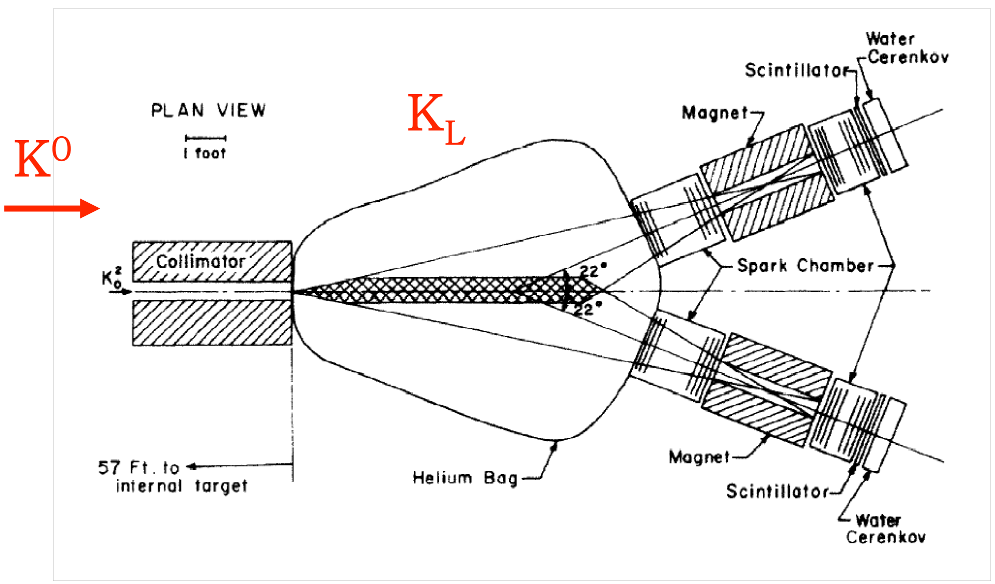
$$
\begin{aligned}
K_1 &\rightarrow \pi\pi \\
K_2 &\rightarrow \pi\pi\pi.
\end{aligned}
$$

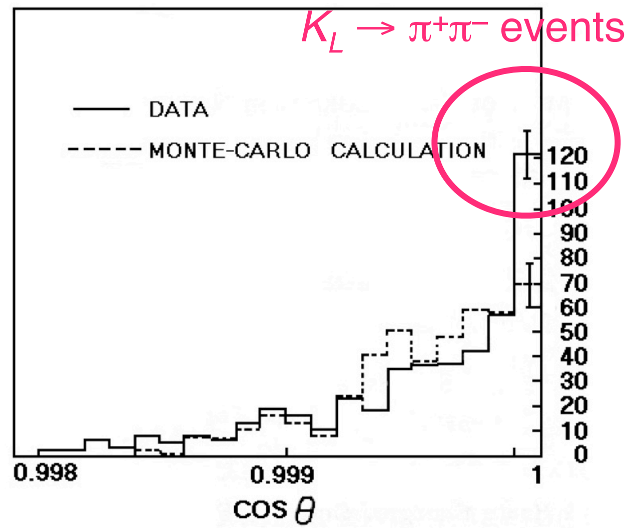
  Which we'll identify as K^0_S and K^0_L respectively.

- measuring K^0_L decays into two pions ? Proof that CP symmetry is violated in weak interaction.

1.1 Introduction: discovery of CP violation.

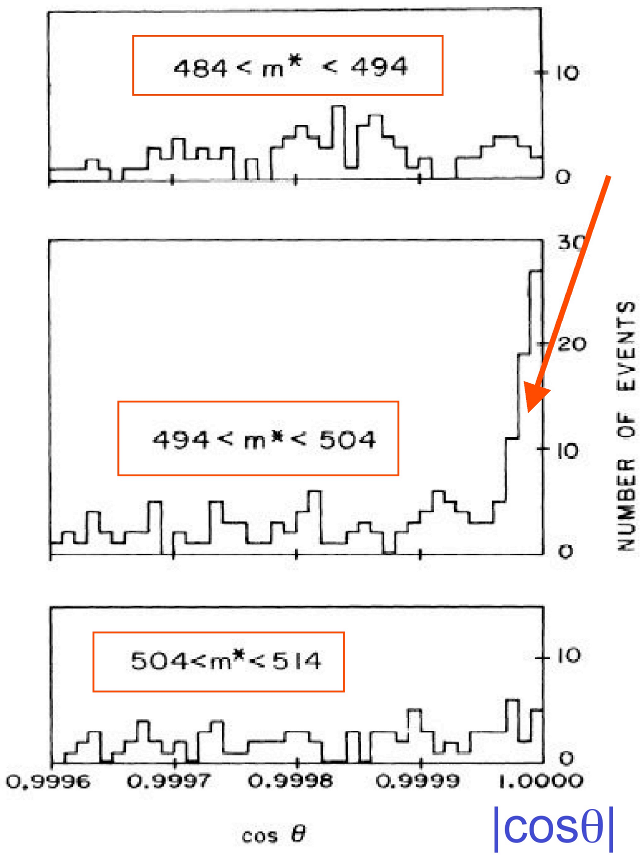
- The CP violation in kaon system: Christenson, Cronin, Fitch , Turlay. Phys. Rev. Lett. 13 (1964) 138.
- Far after the target, only the long species of K^0 survive. They measured:





$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)}$$

1.1 Introduction: discovery of CP violation.



•Two body decay : in the *K⁰* center of mass system the two π are back to back : |cosθ|=1.

•Today's more precise measurement for the ratio of amplitudes:

$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)} = (2.271 \pm 0.017)10^{-3}.$$

1.1 Introduction: discovery of CP violation.

Message Number 1:

The CP symmetry is violated in the mixing of neutral kaons K^0, a pure electroweak phenomenon.

$$K^0 \longrightarrow \bar{K}^0 \neq \bar{K}^0 \longrightarrow K^0$$

1.1 Introduction: other discoveries of CP violation.

- At LHC, compare the decay rates of $B^0_{d,s}$ and *anti*$B^0_{d,s}$ into self-tagged final states $K\pi$

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

$$A_{CP}(B^0_s \to \pi K) = \frac{\Gamma(\bar{B}^0_s \to \pi^- K^+) - \Gamma(B^0_s \to \pi^+ K^-)}{\Gamma(\bar{B}^0_s \to \pi^- K^+) + \Gamma(B^0_s \to \pi^+ K^-)}.$$

- These raw asymmetries must be corrected from detection asymmetry and B production asymmetry:

$$A_\Delta(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)} \to K\pi)$$

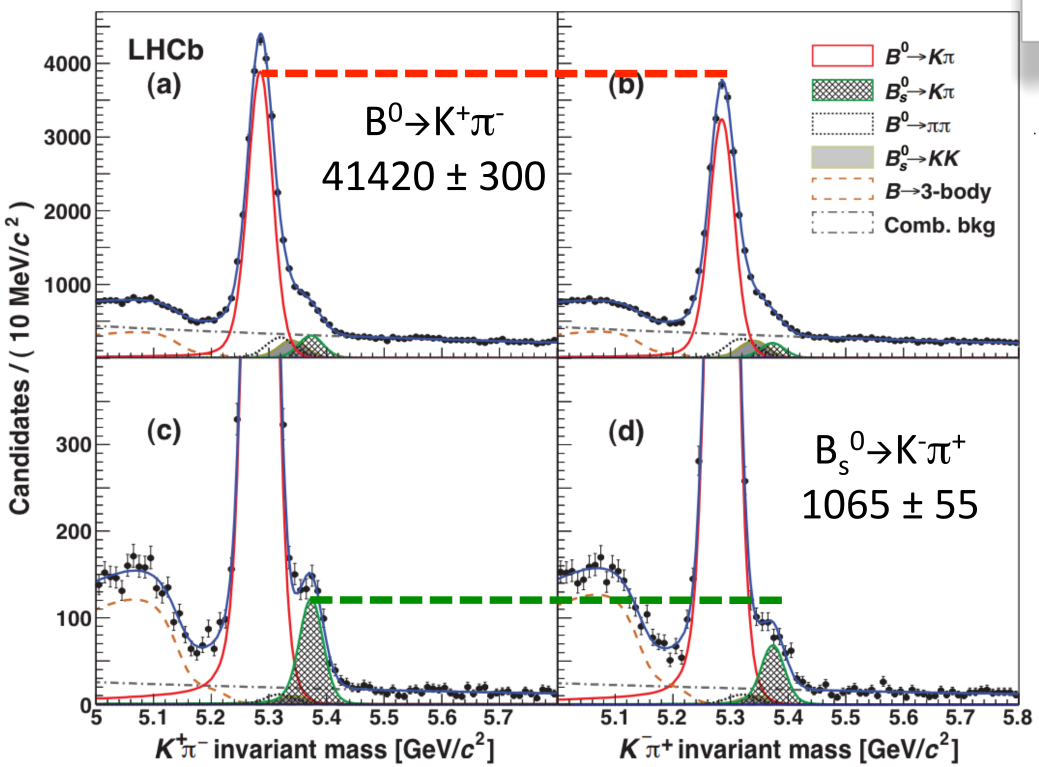
- Ingredients: these analyses are heavily relying on Particle Identification performance. It is also necessary to master the *B* production asymmetry and the differences of charged particle detection efficiencies (data-driven estimates).

1.1 Introduction: other discoveries of CP violation.

- Compare the decay rates of self-tagged modes $K\pi$

$\mathcal{L}$ = (1/fb @ √s = 7 TeV)

$$A_{\rm raw}(B^0 \to K^-\pi^+) = -0.091 \pm 0.006,$$
$$A_{\rm raw}(B_s \to K^+\pi^-) = 0.28 \pm 0.04,$$



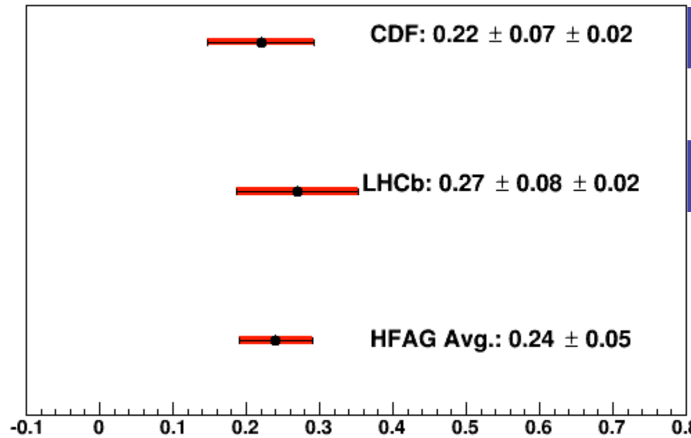
- Data-driven control of PID efficiencies thanks to the self-tagged mode $D^{*+} \to D^0 (K^-\pi^+) \pi^+$
- Raw asymmetries corrected from detection asymmetry (also D^{*+} control sample.
- *B* production asymmetry simultaneously measured from decay time distribution.

1.1 Introduction: other discoveries of CP violation.

$$A_{\rm CP}(B^0 \to K^-\pi^+) = -0.080 \pm 0.007\,({\rm stat.})\ \pm 0.003\,({\rm syst.}),$$
$$A_{\rm CP}(B_s \to K^+\pi^-) = 0.27 \pm 0.04\,({\rm stat.})\ \pm 0.01\,({\rm syst.}).$$

LHCB-PAPER-2013-018

- World best measurement for the B^0
- Former results for B_s



CDF-PUBLIC-10726

Phys. Rev. Lett. 108 (2012)

- **First observation of CPV in the *Bs* system.**

1.1 Introduction: other discoveries of CP violation.

Message Number 2:

The CP symmetry is violated in the decay of beautiful particles, pure electroweak phenomenon.

$$B^0 \longrightarrow K^+\pi^- \neq \bar{B}^0 \longrightarrow K^-\pi^+$$

1.1 Concluding the first part of the introduction

- C, P and CP are (so far) conserved in electromagnetic and strong interactions.
- C and P symmetries are maximally violated by the weak interaction.
- CP symmetry is slightly violated in the electroweak interaction.

- There are three ways of CP violation to manifest in the Nature so far:

  1) In the mixing of neutral particles (observed solely in neutral kaon mixing - 1964).

  2) In the decay of the beautiful and strange mesons (*K* and $B_{d,s}$, 2001 and 2004,2013 resp.).

  3) In the interference between decay and mixing of the beautiful particles (2001, see next chapters) .

  And that's all.

1.2 Introduction: the unitarity triangle.

• You have been taught by Louis that the Higgs boson gives mass to bosons and fermions (quarks and leptons) through the Yukawa couplings but this is not the end of the story:

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger [\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5)V_{ij}d_j] + \text{h.c}$$

• After spontaneous symmetry breaking, and once the mass matrices are diagonalized, it determines also how the mass and weak eigenstates are related. This is the CKM matrix. As for the (fermion) masses, nothing is predicted except the mass matrix must be unitary and complex.

$$\begin{pmatrix} u \\ s \\ b \end{pmatrix}_{EW} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} u \\ s \\ b \end{pmatrix}_{MASS}$$

1.2 Introduction: the unitarity triangle.

• Weak eigentates are therefore a mixture of mass eigenstates, controlled by the Cabibbo-Kobayashi-Maskawa elements V_{ij}: flavour changing charged currents between quark generations.

• This matrix is a 3X3, unitary, complex, and hence described by means of four parameters: 3 rotation angles and a phase. The latter makes possible the CP symmetry violation in the Standard Model.

• These four parameters are free parameters of the SM. As for electroweak gauge precision tests, they must be measured with some redundancy and the SM hypothesis is to be falsified by a consistency test. We will review in this lecture this overall test. But let's define first the parameters.

1.2 Introduction: the unitarity triangle.

- *Homework 2:*

Prove that a 3x3 unitary complex quark mixing matrix is described by four parameters: three real parameters, one complex.

Hint: the phase of each quark field can be redefined relative to a global phase.

1.2 Introduction: the unitarity triangle. Parametrization.

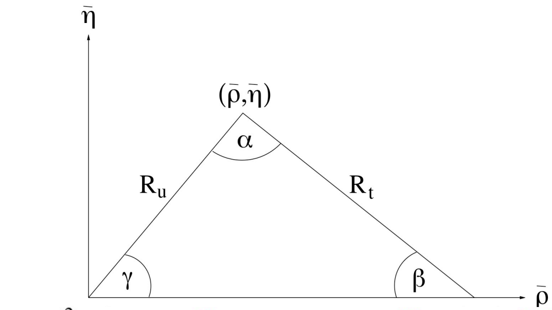
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Consider the Wolfenstein parametrization as in EPJ C41:1-131,2005 : unitary-exact and phase convention independent:

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad \text{and} \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- λ is measured from $|V_{ud}|$ and $|V_{us}|$ in superallowed beta decays and semileptonic kaon decays, respectively.
- *A* is further determined from $|V_{cb}|$, measured from semileptonic charmed B decays.
- The last two parameters are to be determined from angles and sides measurements of the CKM unitarity triangle.

1.2 Introduction: the unitarity triangle. Representation.



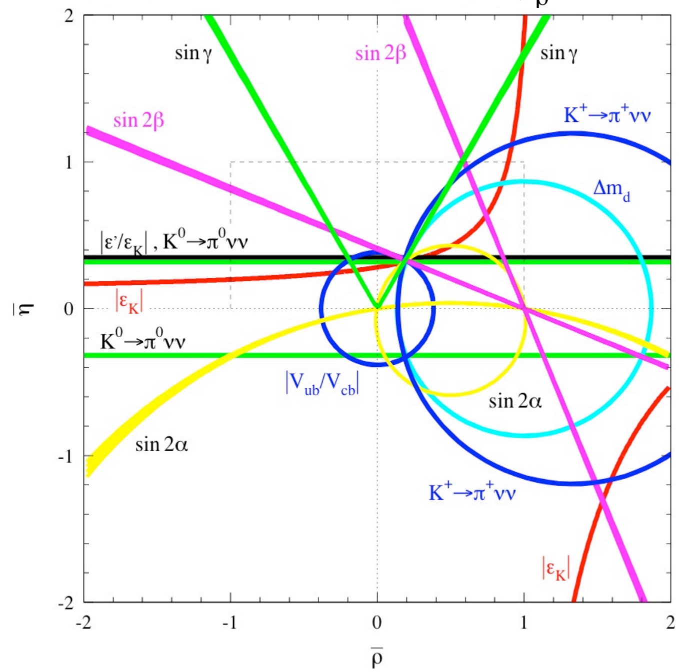
- An elegant way to represent the unitarity relations is to display them in the complex plane.

- $$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0.$$

- The area of the triangle is half the Jarlkog invariant and measures the magnitude of the CP violation:

$$J \sum_{\sigma\gamma=1}^{3} \epsilon_{\mu\nu\sigma}\epsilon_{\alpha\beta\gamma} = \mathrm{Im}(V_{\mu\alpha}V_{\nu\beta}V_{\mu\beta}^*V_{\nu\alpha}^*) \; ,$$

$$J = A^2\lambda^6\eta(1-\lambda^2/2) \simeq 10^{-5}$$



1.2 Introduction: the unitarity triangle. Definitions.

- Sides and angles of the unitarity triangle.
- Normalization given by the matrix element $V_{cd}.V_{cb}^*$.

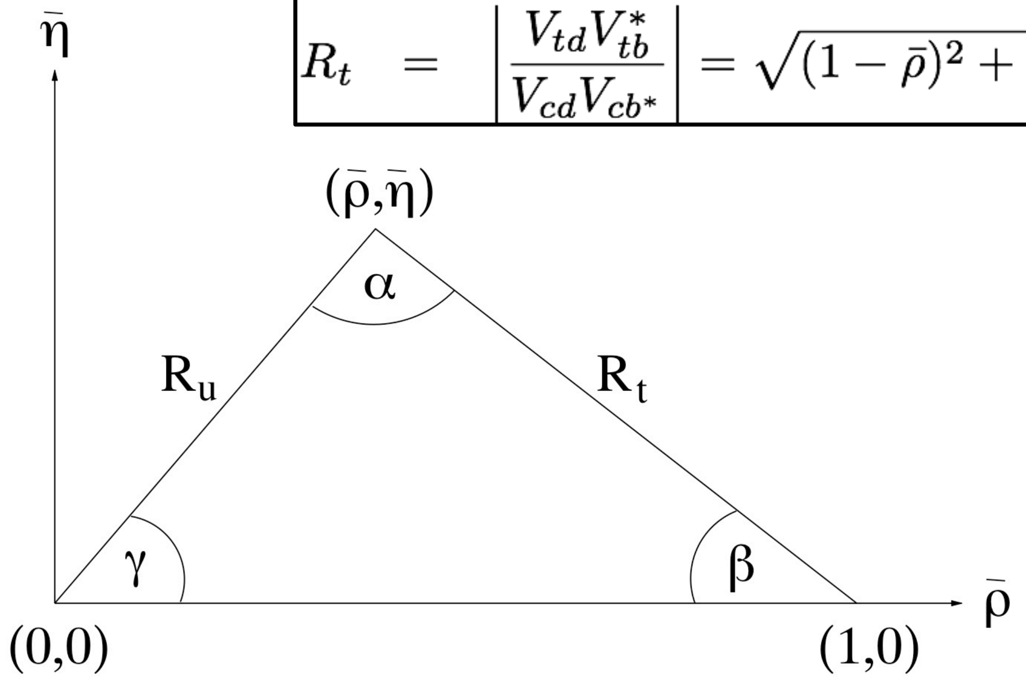
$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar{\rho}^2+\bar{\eta}^2} \, ,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} \, .$$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

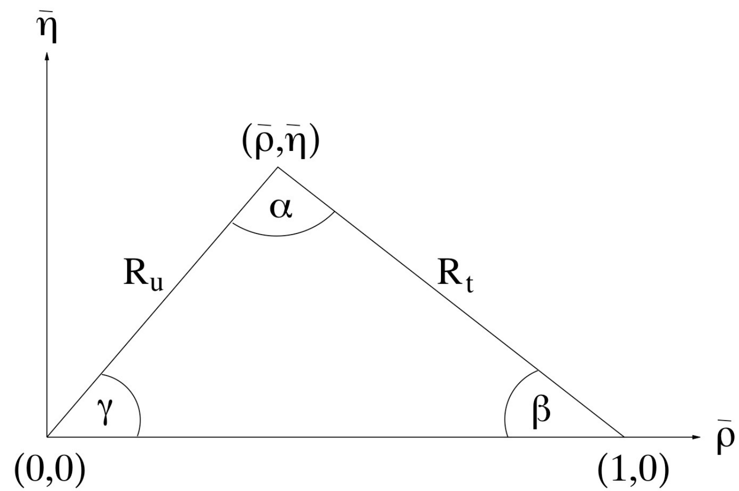


1.2 Introduction: the unitarity triangle. Definitions.

- Sides of the unitarity triangle. Towards the experimental constraints:

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar\rho^2+\bar\eta^2}\ ,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^2}\ .$$



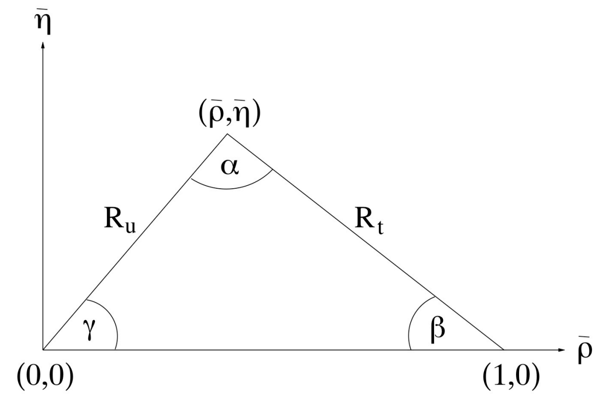
- R_u is measured by the matrix elements V_{ub} and V_{cb} extracted from the semileptonic decays of b-hadrons.

- R_t implies the matrix element V_{td} and hence can be measured from the mixing of B^0 mesons.

1.2 Introduction: the unitarity triangle. Definitions.

• Angles of the unitarity triangle. Towards the experimental constraints:

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$
$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$



• The angle β is directly the weak mixing phase of the of B^0 mixing.

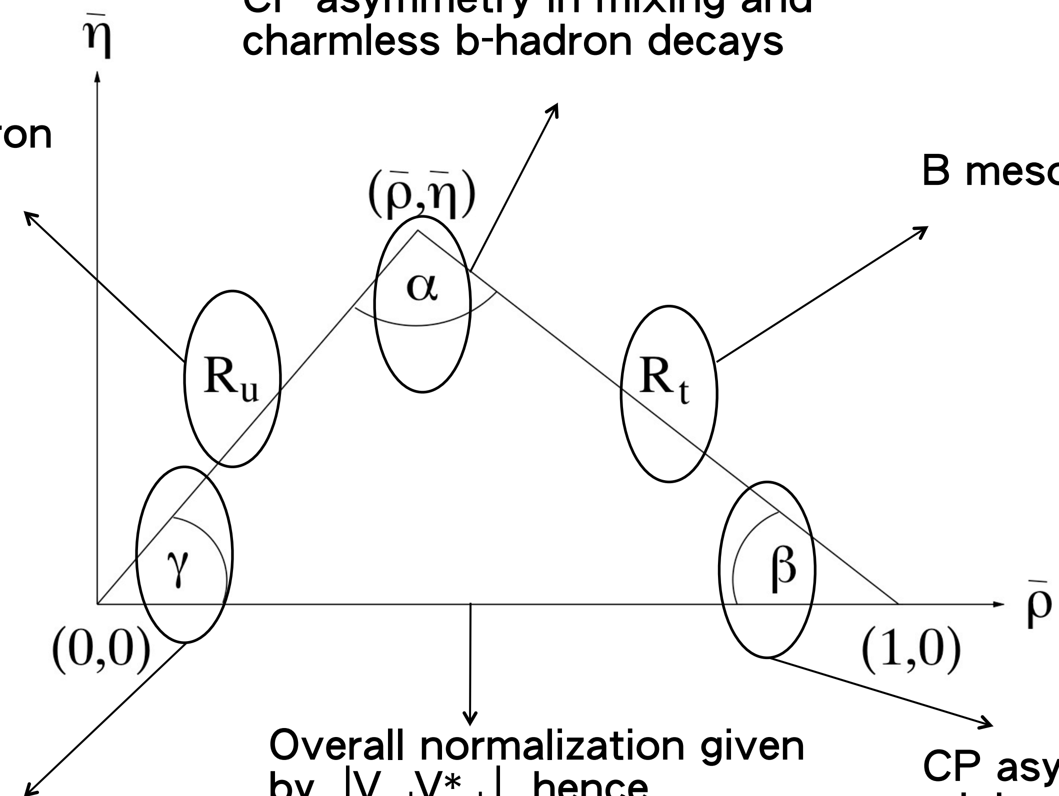
• The angle γ is the weak phase at work in the charmless decays of b-hadrons.

• The angle α is nothing else than (π–β–γ) and can be exhibited in processes where both charmless decays and mixing are present.

•Note: a phase is not an observable. Only phase difference can be measured.

1.2 Introduction: the unitarity triangle. Experiments.

- Summary:



CP asymmetry in mixing and charmless b-hadron decays

Semileptonic b-hadron decays

B meson mixing

CP asymmetry in $b \rightarrow u$ b-hadron decays (LHCb in)

Overall normalization given by $|V_{cd}V^{*}_{cb}|$, hence semileptonic b decays

CP asymmetry in mixing processes

1.3 Introduction: machine and experiments.

There are many machines and experiments which are interested in the flavour physics and CP violation. As for their pioneering role, we'll mention ARGUS (DESY, Ge), CLEO (Cornell,US) and LEP (CERN, EU) experiments. The kaon sector is not in the scope of this lecture. Major results came from NA48 (CERN, EU) and KTeV (FNAL, US). Japan and Cern projects for kaon physics should bring extremely valuable results. Tevatron used to provide as well world class measurements in heavy flavours physics.

But the B factories definitely dominate the landscape. And LHC through LHCb experiment already acts on their playground. Let's concentrate on this.

1.3 Introduction: machine and experiments.

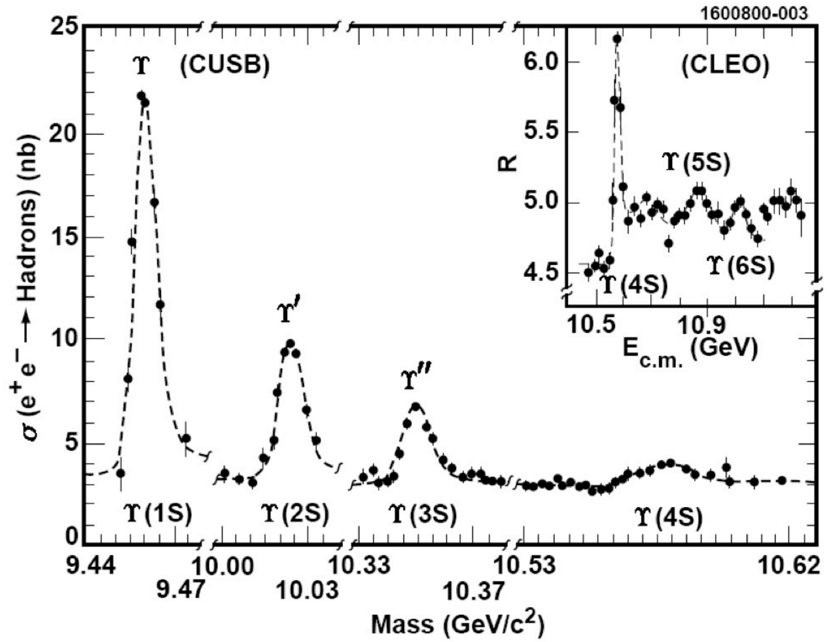
1. Coherent b quarks pair production: the B factories.

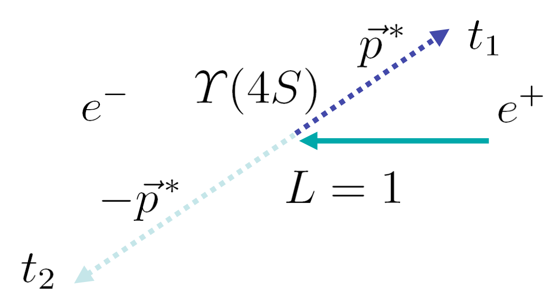
2. Incoherent b quarks pair production: the Tevatron, LEP and LHC experiments.

1.3 Introduction: machine and experiments.

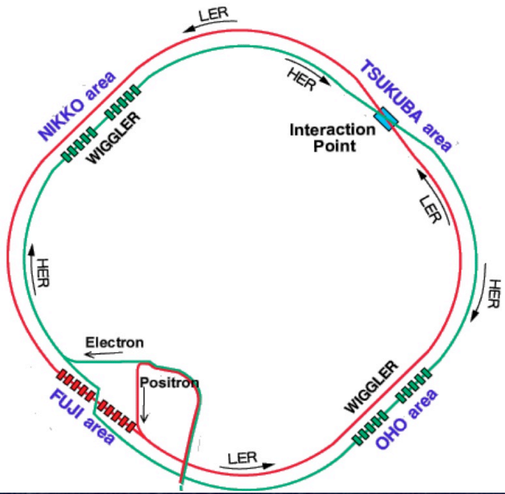
The physics characteristics of the B factories at the Υ(4s):

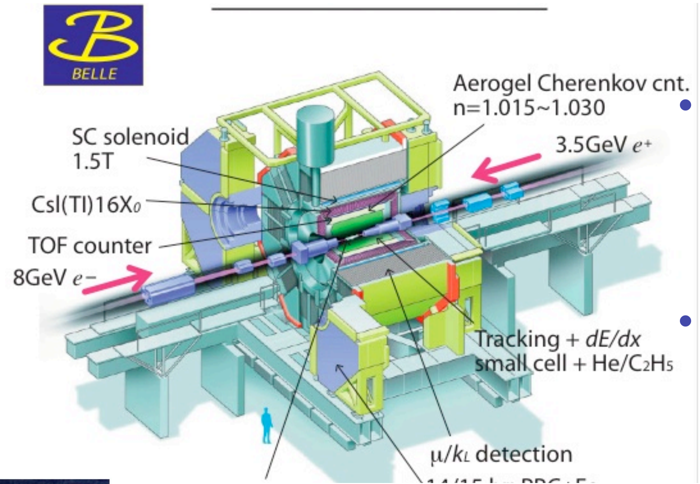
- The series of Υ contains the Υ(4s), above the production threshold of BB pairs. Almost all (~96%) of the Υ(4s) decays.
- Coherent B-anti(B) production: when one decays, you know the flavour of the other at the same time. Ideal flavour tagging.
- Beams are asymmetric. The Υ(4s) is boosted allowing time separation between the B.
- No hadronization. Very clean experimental environment.



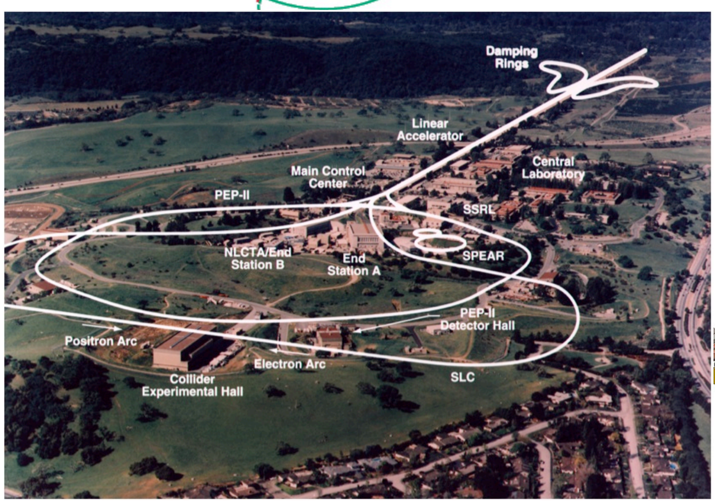


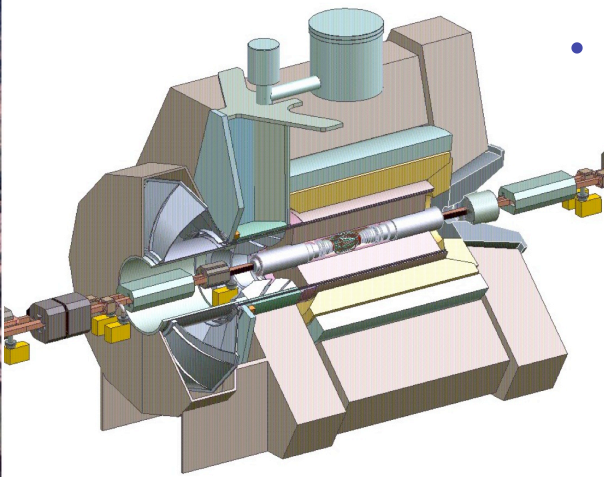
1.3 Introduction: machine and experiments.





- KEKB – Belle – Japan. 8 vs 3.5 GeV. βγ=0.425
- PEPII – BaBar – US. 9 vs 3.1 GeV. βγ=0.56.

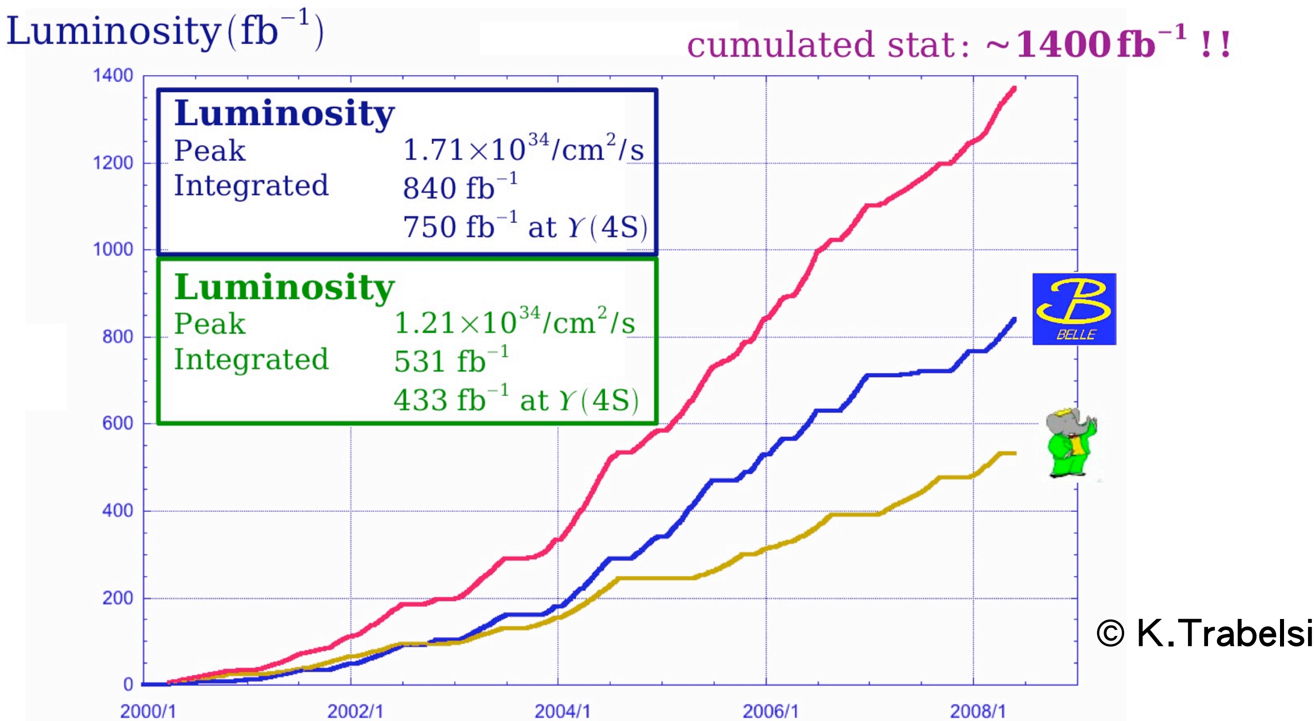




- Common detector characteristics: excellent vertexing and particle identification w/ Cerenkov imaging detectors.

1.3 Introduction: machine and experiments:performance

B factories: BaBar and Belle



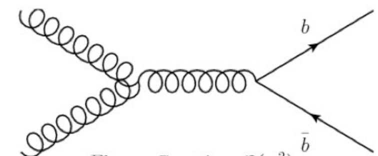
$>$ 250 publications for each experiment

BaBar: $\sim 465\times10^6 B\bar{B}$ pairs = final sample
Belle: $\sim 657\times10^6 B\bar{B}$ pairs = max. current sample (final sample will probably be $\sim 800\times10^6 B\bar{B}$ pairs)

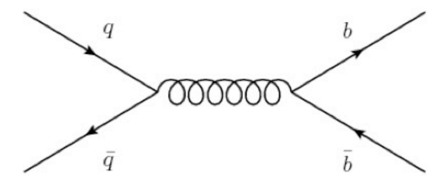
1.3 Introduction: machine and experiments.

The physics characteristics of the hadron colliders at high energy (some are playing at electron colliders):

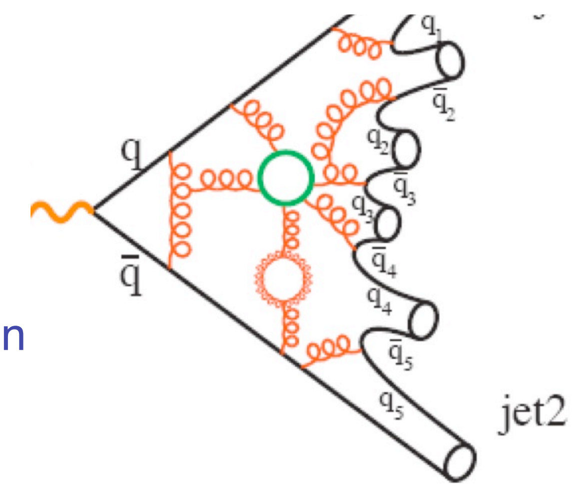
- There is hadronization. Busy hadronic environment.
- Incoherent b quarks pair production. Flavour tagging is (much) less efficient than at B factories.
- All the b-hadrons species can be produced. Unique laboratory for b baryons and charm B meson.
- High production cross-sections and hence high (but a trigger strategy is required).
- Energy: b-hadrons do receive an important boost. Facilitates vertexing capability to identify the b-hadron decay vertex.



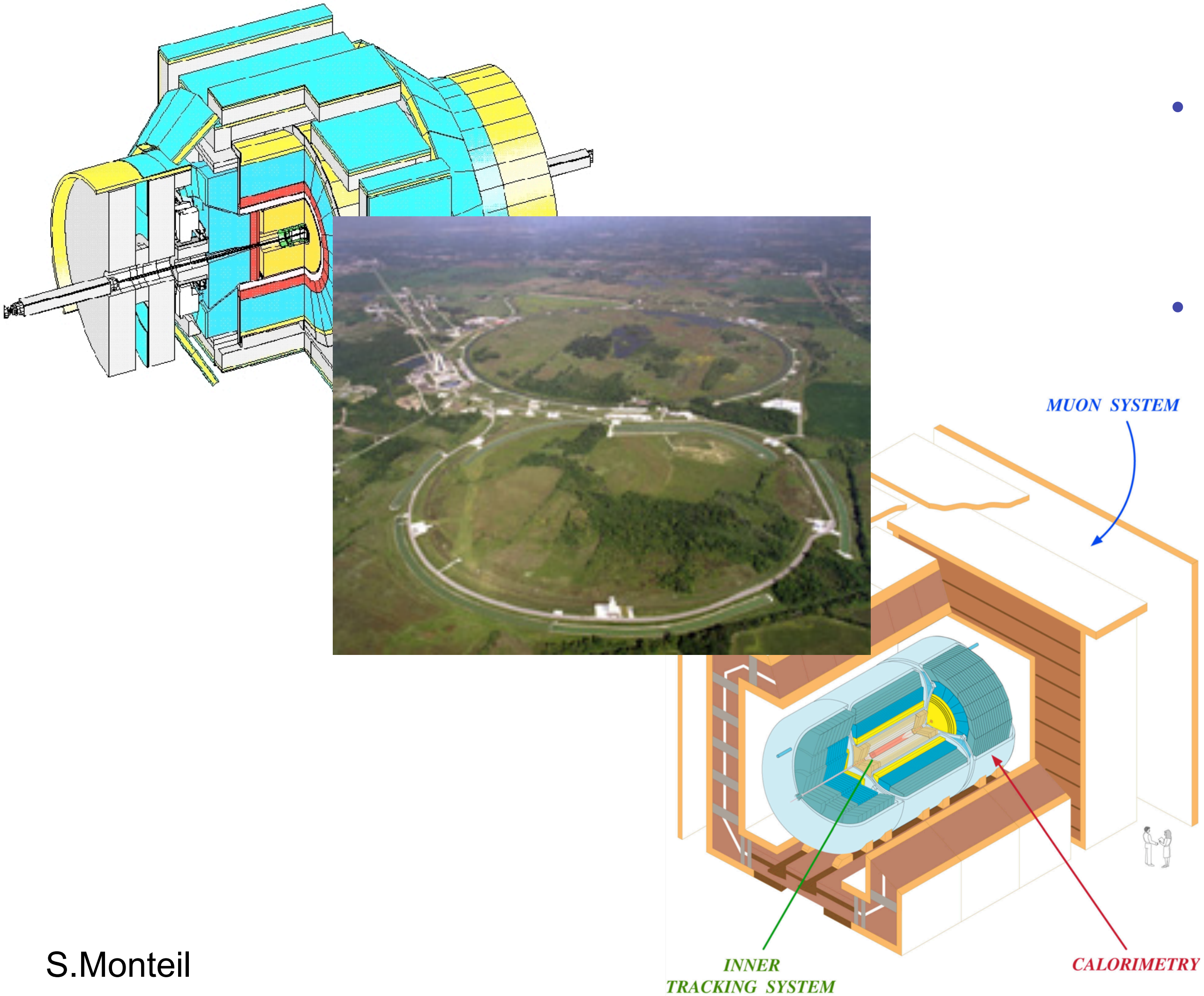
Flavor Creation $\mathcal{O}(\alpha_s^2)$



Flavor Creation $\mathcal{O}(\alpha_s^2)$



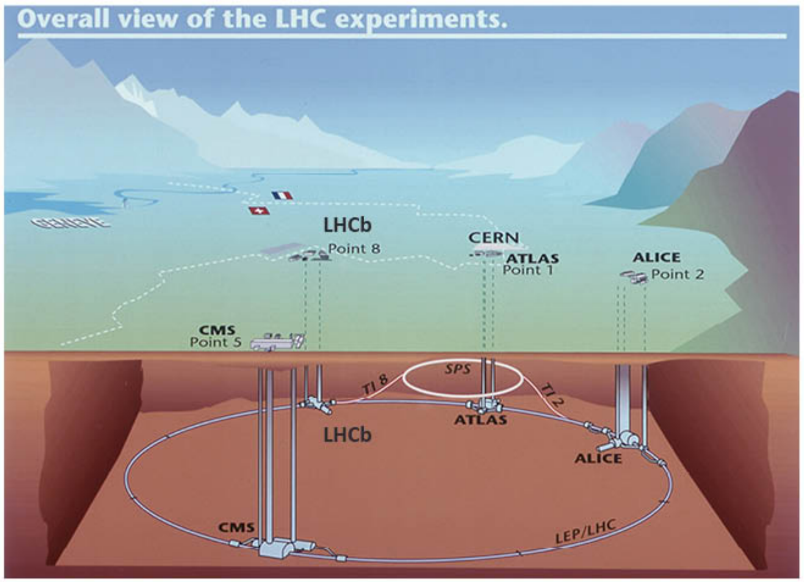
1.3 Introduction: machine and experiments.



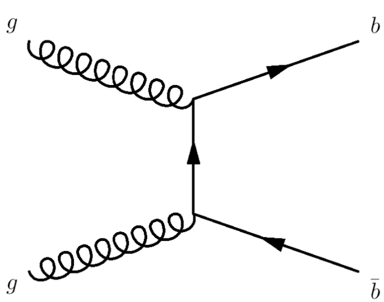
- CDF and D0 are multipurpose experiments.
- D0 has an excellent muon coverage.

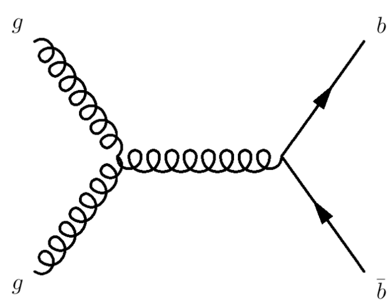
CDF has a flexible trigger and excellent tracking for b physics.

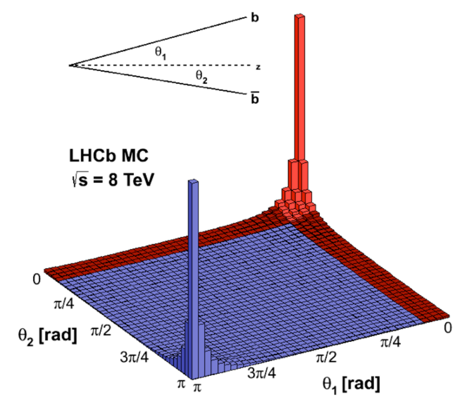
1.3 Introduction: machine and experiments: LHC



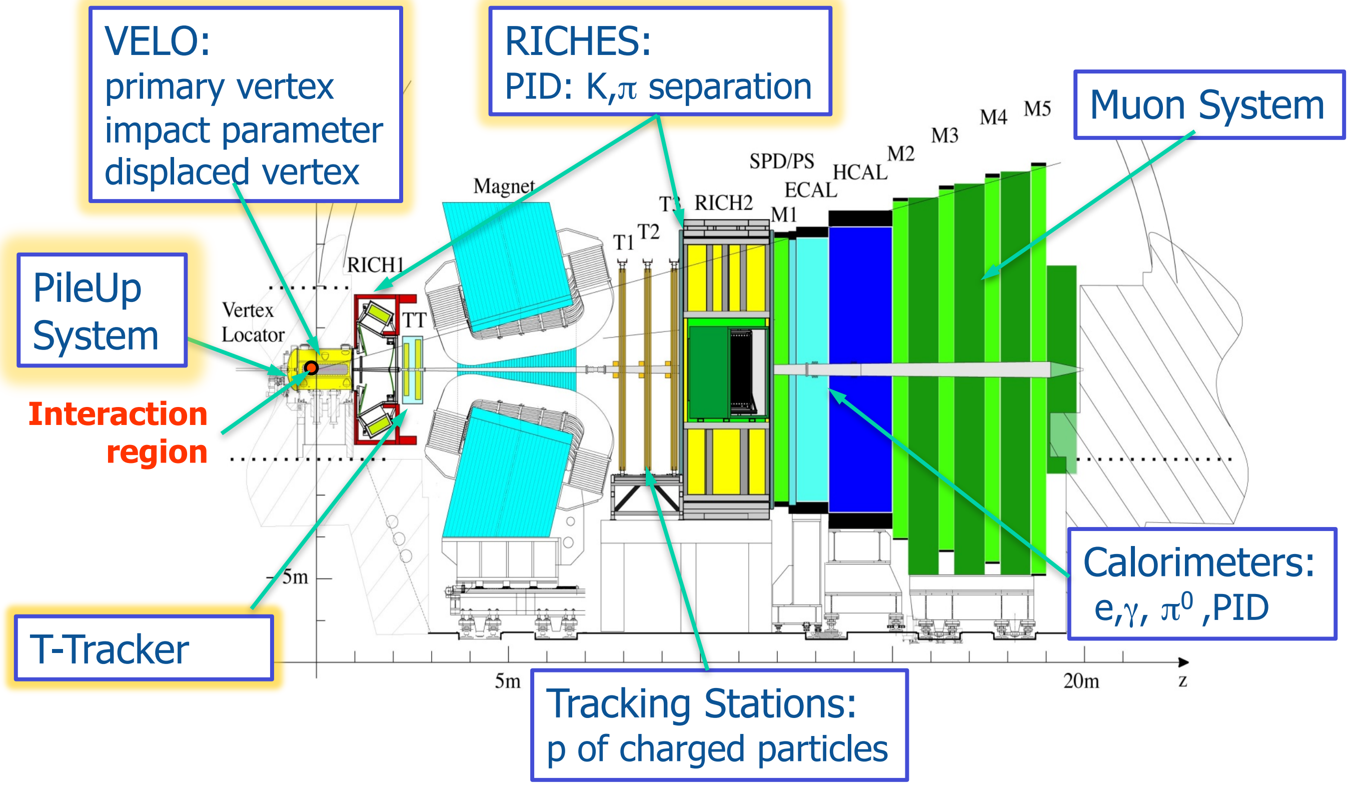
- ATLAS and CMS are general purpose experiments w/ 4π coverage. Flavour physics program however.
- LHCb is on the contrary a spectrometer. The shape of it is driven by the angular distribution of the beautiful quarks pair.







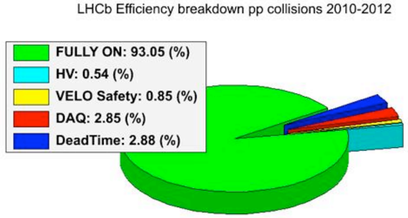
1.3 Introduction: machine and experiments: LHC

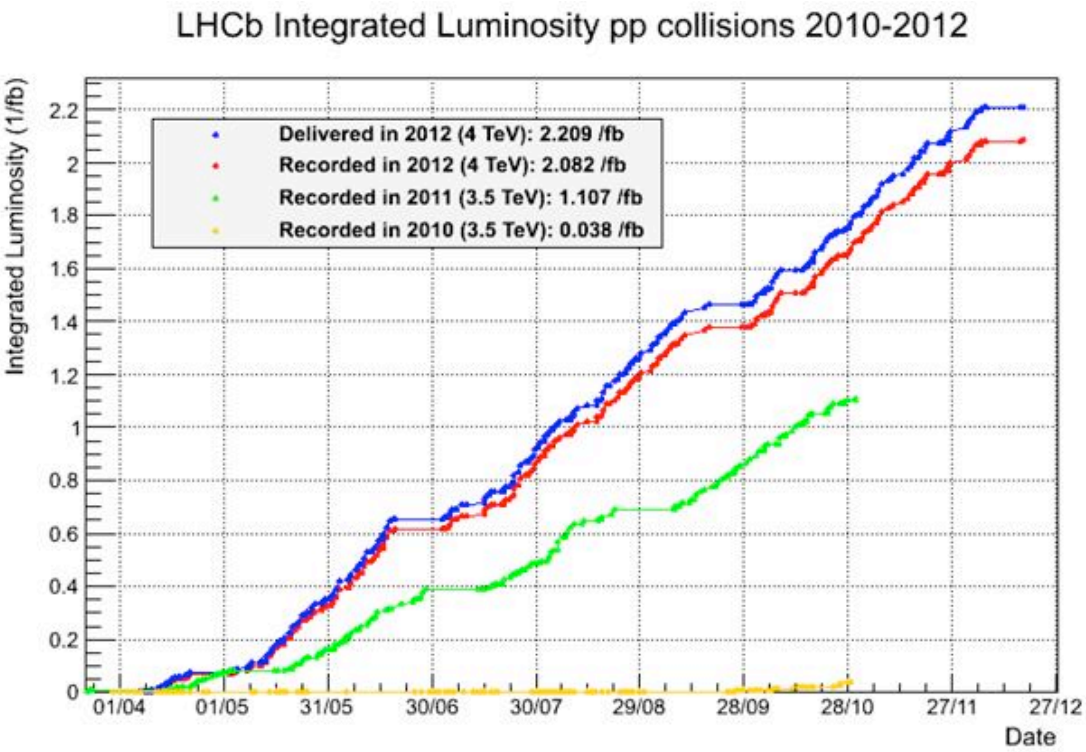


Design: excellent vertexing, excellent particle identification, flexible trigger. All this advertised in the success story relation prepared by Yasmine.

1.3 Introduction: machine and experiments. LHC and LHCb performance.

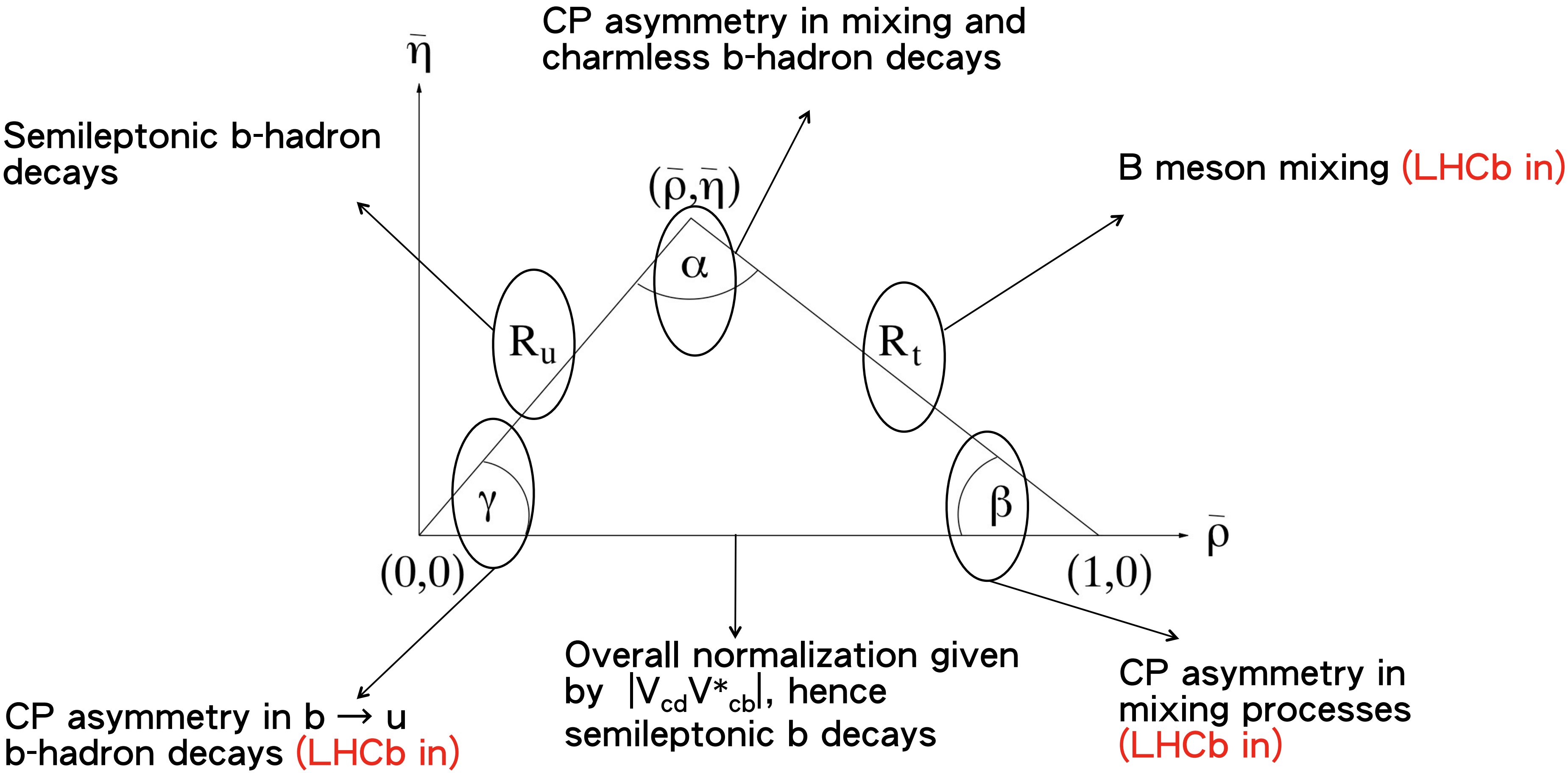
For those of you working on Atlas and CMS, the luminosity is lowered in LHCb by displacing the beams. On another hand the luminosity is levelled constantly. Ideas to generalize this to all LHC experiments in 2015.





1.4 Introduction: which measurements and where?

- B factories: all ! As far as UT is concerned.



1.4 Introduction: which measurements and where?

The following lectures will hence essentially concentrate on observables which were measured at the B-factories and established the SM KM paradigm as the dominant source of the observed CP violation.

LHC and especially LHCb now works in the very same playground:

- Precise the CKM profile (and further contrain or discover New Physics) by improving some of the angle measurements and the Bs properties.

- Unique laboratory for B_s, B_c and b-baryons.

- The high statistics allows to search for rare decays where NP could/should naturally exhibit (a part of Yasmine's seminar).