Experimental aspects of the CP violation.

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[LHCb experiment – CKMfitter group]

Some authoritative literature about the lecture :

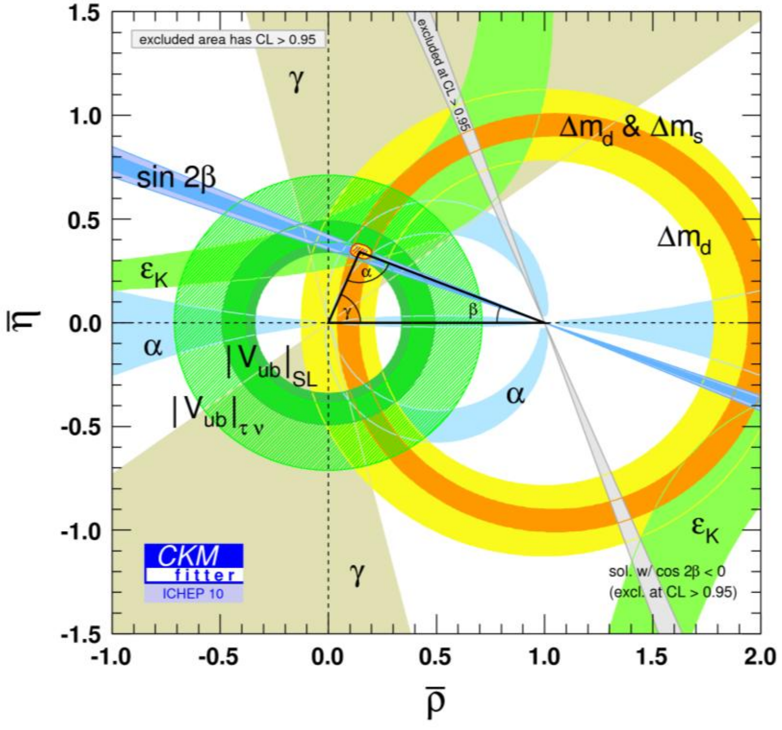
- BaBar physics book: http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- LHCb performance TDR: http://cdsweb.cern.ch/record/630827?ln=en
- A. Höcker and Z. Ligeti: *CP Violation and the CKM Matrix. hep-ph/0605217*

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/

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 this serie of lectures is to undress this plot.

Disclaimers

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

• The main machines in question here are the TeVatron (Fermilab, US), PEPII (SLAC, US) and KEKB (KEK, Japan). 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 and ideas in presentations from colleagues which I tried to cite correctly.

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.

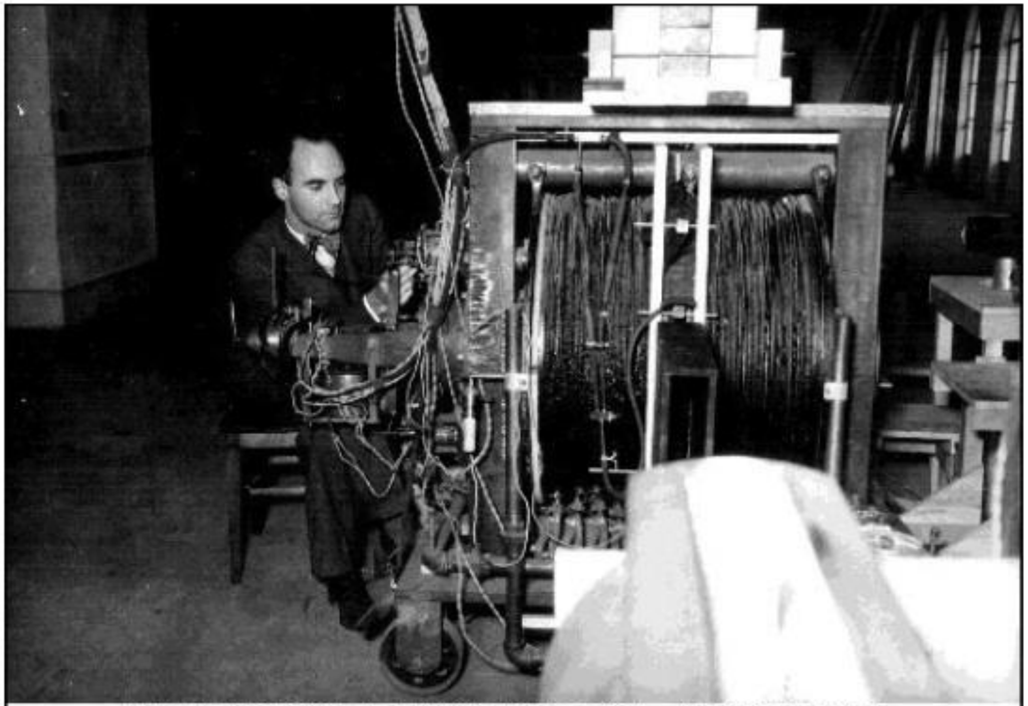
1.1 Introduction: founding experiments

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

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.

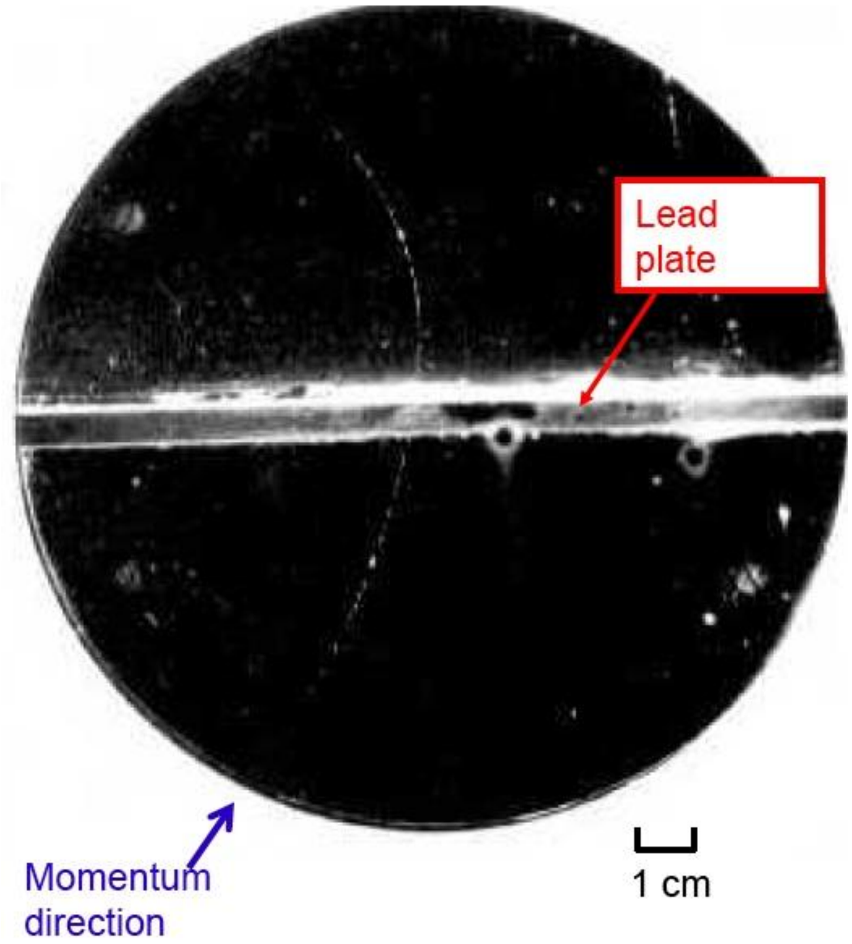
Dirac spin 1/2 : $(i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$



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 slow down in the lead $\Rightarrow$ the particle in incoming from the bottom.
- The magnetic field direction is known
  $\Rightarrow$ positive charge
- From the density of the drops one can measure the ionizing power of the particle $\Rightarrow$ minimum ionizing particle
- Similar ionizing power before and after the plate $\Rightarrow$ same particle on the 2 sides
- Curvature measurement after the lead : particle of ~23MeV).



1.1 Introduction: evidence for P violation

The Wu experiment:

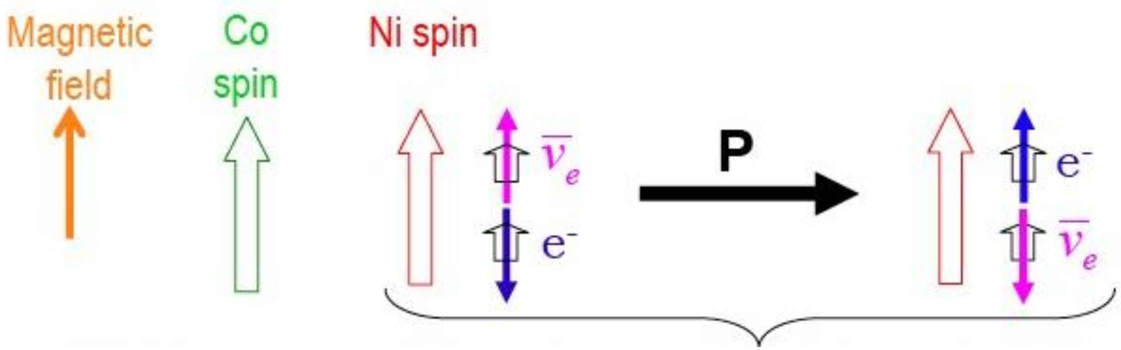
- Before 1956 : all interactions were thought to be invariant under parity operation
- It was (quite comprehensively) tested for strong and electromagnetic interactions.
- Lee and Yang proposed an experiment to test it for weak interaction
- Designed and performed in 1957 by C.S. Wu and collaborators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

1.1 Introduction: evidence for P violation

The Wu experiment:

$$Co^{60}\ (J=5) \rightarrow Ni^{60*}\ (J=4)\, e^{-}\, \overline{\nu_e}$$

- 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.

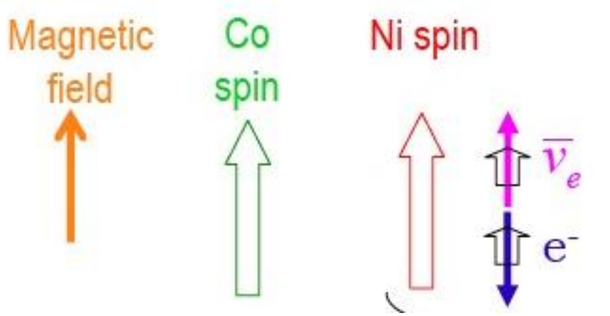


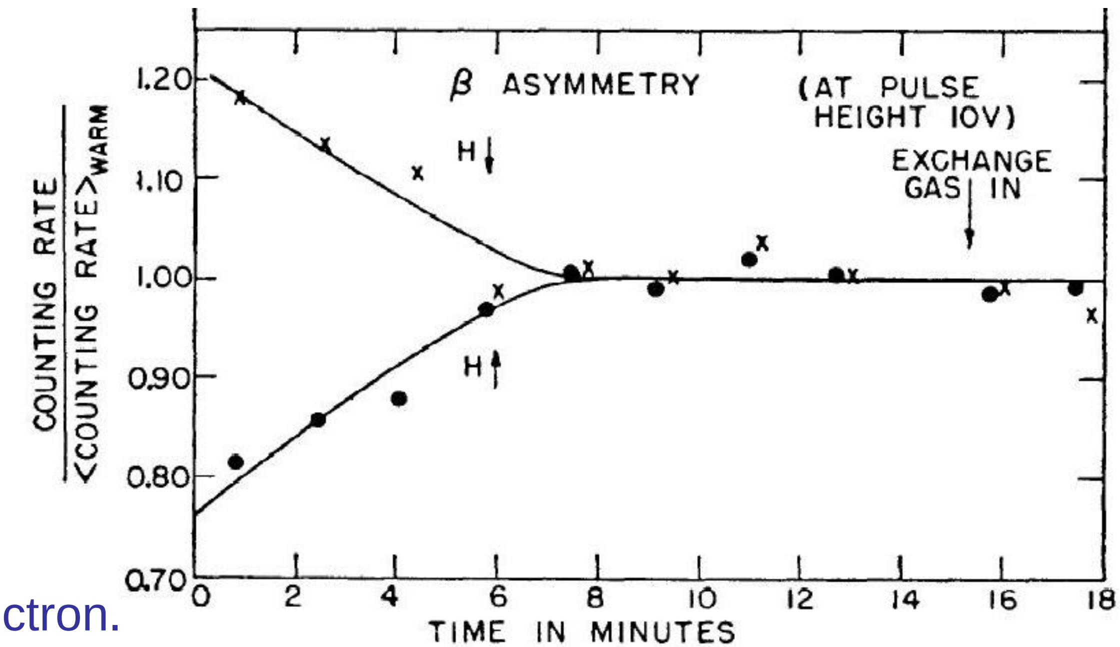
The result of the experiment is that the electrons are preferentially produced in the opposite direction of the spins of the Co^{60} atoms: PARITY SYMMETRY IS VIOLATED.

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.



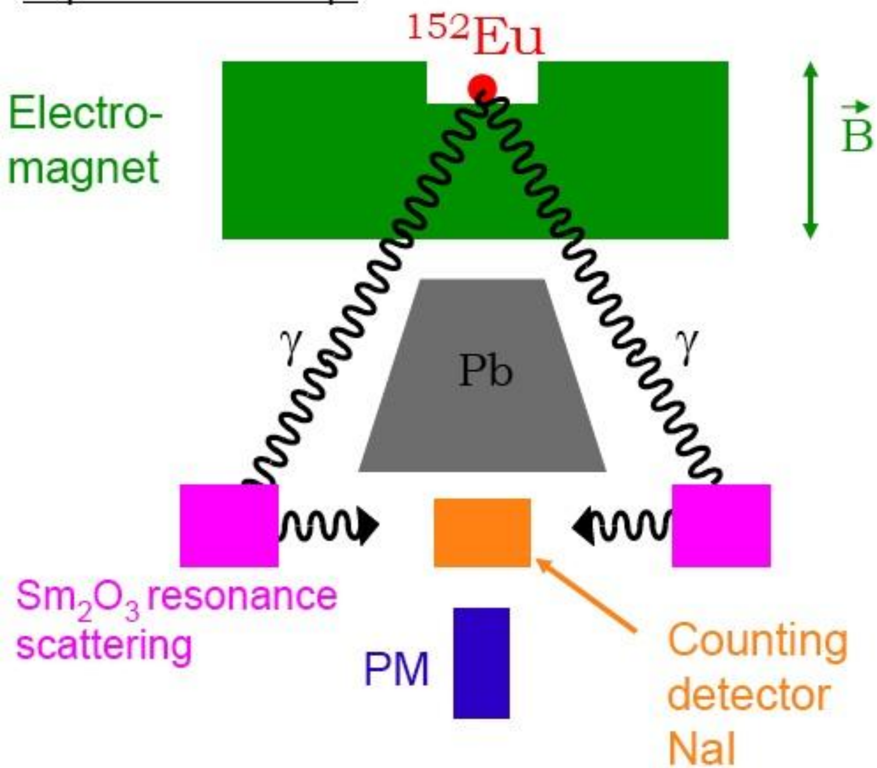


The prefered chiral state is a left electron.

1.1 Introduction: neutrinos are left-handed

The Goldhaber experiment:

Experimental set-up:

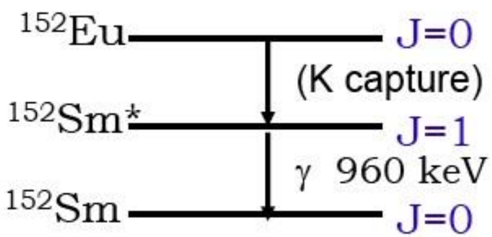


γ emitted in the direction of the momentum of the Sm* are selected

$$^{152}Eu(J=0) + e^- \to {}^{152}Sm^*(J=1) + \nu$$

(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: $^{152}Sm^*(J=1) \rightarrow {}^{152}Sm(J=0) + \gamma$

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: modern parity violation experiments:LEP/SLD

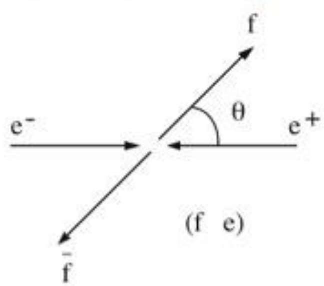
The Standard Model Tests (Part II)

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.

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

- 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)



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

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

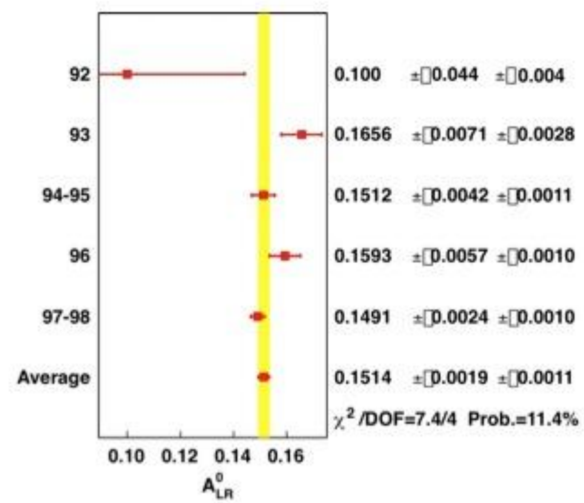
Hence depends primarily to $\sin^2\theta_{\mathrm{eff}}$

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 :



$$A_{\mathrm{LR}} = \frac{N_L - N_R}{N_L + N_R} \cdot \frac{1}{\langle P_e \rangle}$$
$$\langle P_e \rangle_{1998} = 0.7292 \pm 0.0038$$

$$\boxed{\begin{aligned} A^0_{\mathrm{LR}} &= 0.1514 \pm 0.0022 \\ \sin^2\theta_{\mathrm{eff}} &= 0.23097 \pm 0.00027. \end{aligned}}$$

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Experimental aspects of the CP violation.

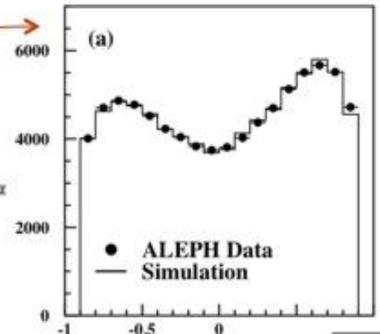
1.1 Introduction: modern parity violation experiments: LEP

The Standard Model Tests (Part II)

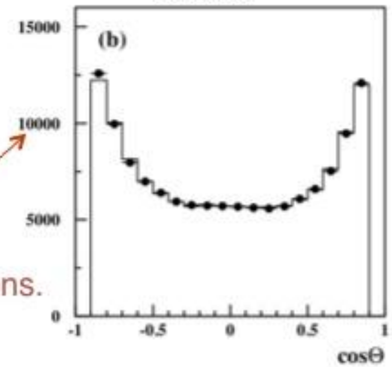
3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Then we fit the asymmetries to these data:

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



Parity violation even seen for charm.



Includes QED and QCD effects.

Measuring simultaneously the mixing parameter w/ leptons.

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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:

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

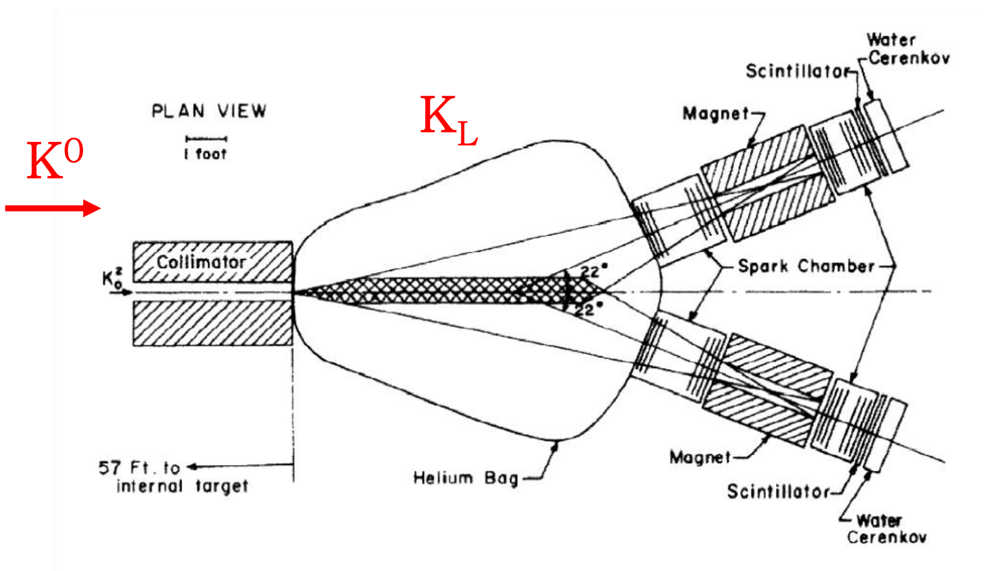
  Which we'll identify as $K^0{}_S$ and $K^0{}_L$ respectively.

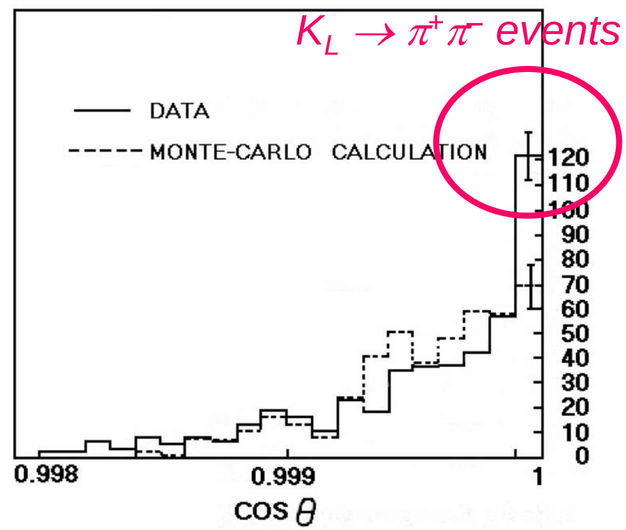
- measuring $K^0{}_L$ decays into two pions ? Proof that CP symmetry is violated in weak interaction.

1.1 Introduction: discovery of CP violation.

- The CP violation in kaon system: Christenson, Cronin, Fitch , Turlay. Phys. Rev. Lett. 13 (1964) 138.

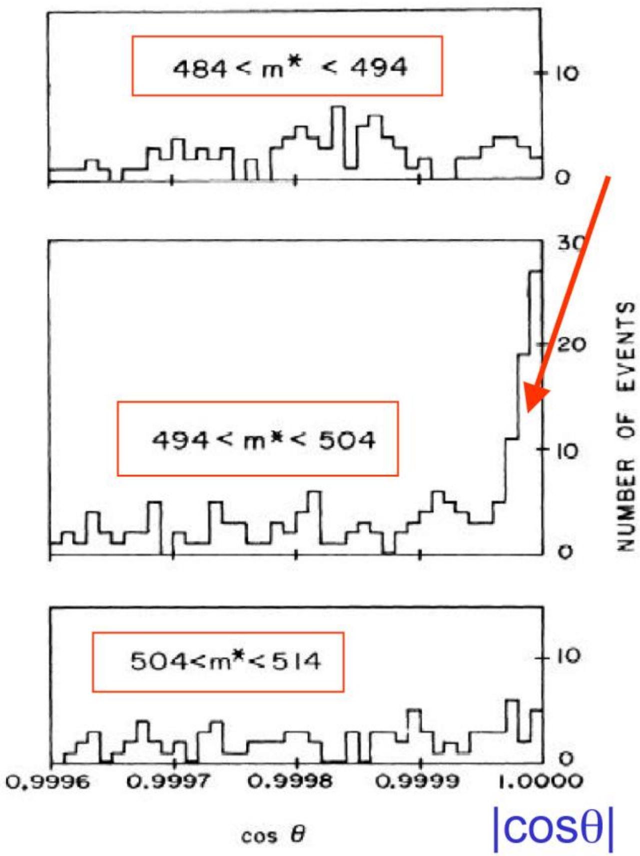
- Far after the target, only K long survive. They measured:





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

1.1 Introduction: discovery of CP violation.



•Two body decay : in the K^0 center of mass system the two π are back to back : $|\cos\theta|=1$.

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

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

1.2 Introduction: the unitarity triangle. Reminder from Zoltan's lecture.

• We have been taught 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:

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

• Once the mass matrix is diagonalized, it determines also how the mass and weak eigenstates are related. This is the CKM matrix. As for the 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 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. Parametrization.

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

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

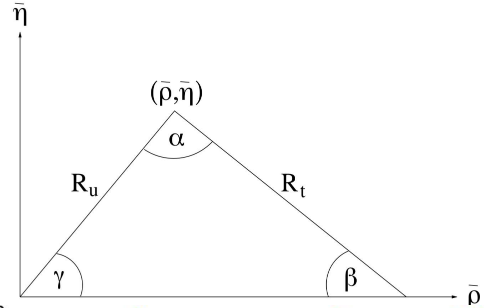
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad \text{and} \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- 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.

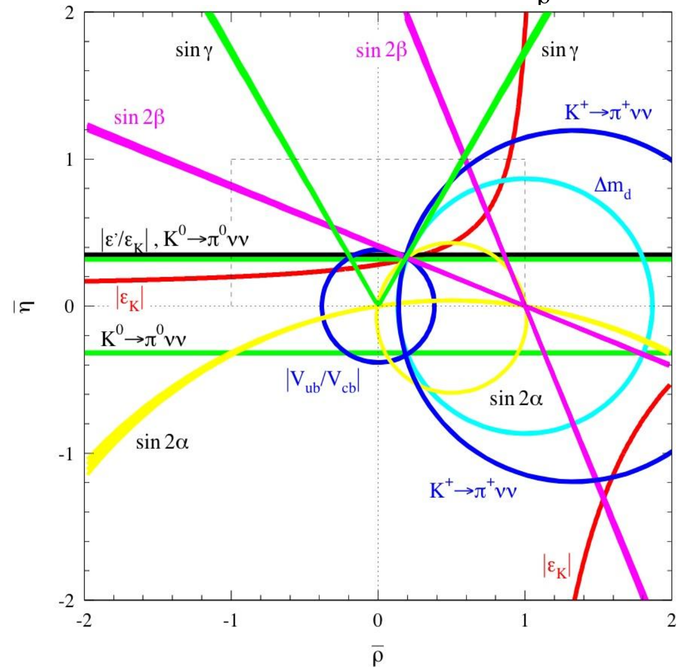
- The last two parameters are to be determined from angles and sides measurements of the CKM unitarity triangle.

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:

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

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

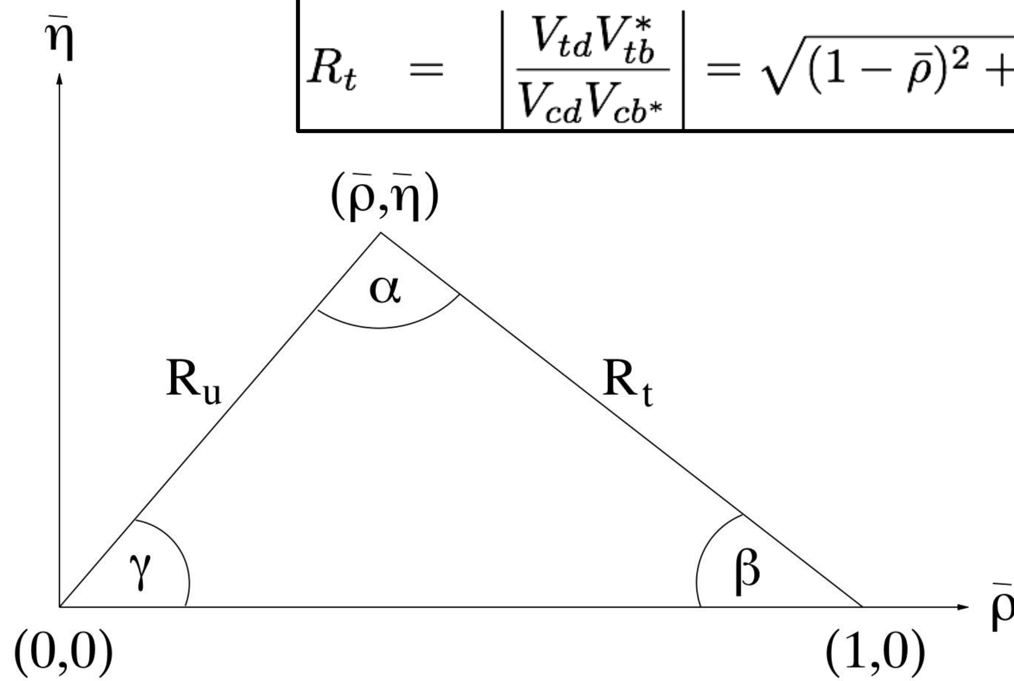
1.2 Introduction: the unitarity triangle. Definitions.

- Sides and angles of the unitarity triangle.

- Normalization given by the matrix element V_{cb}.

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

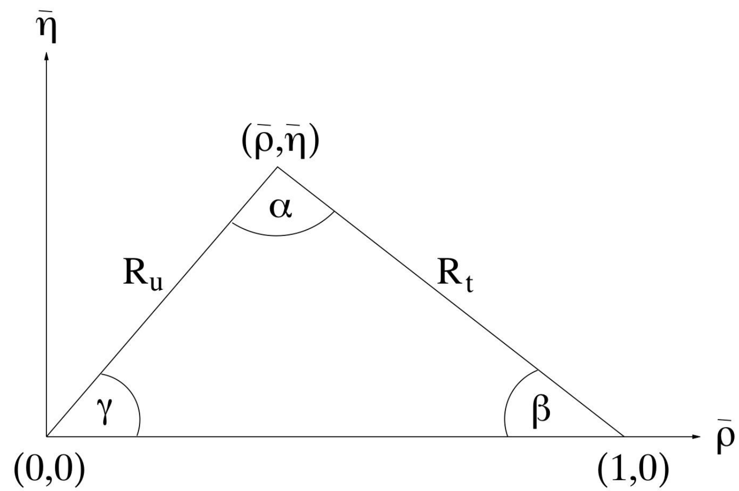
$$
\begin{aligned}
\alpha &= \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \\
\beta &= \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right), \\
\gamma &= \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).
\end{aligned}
$$



1.2 Introduction: the unitarity triangle. Definitions.

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

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



- 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.

•

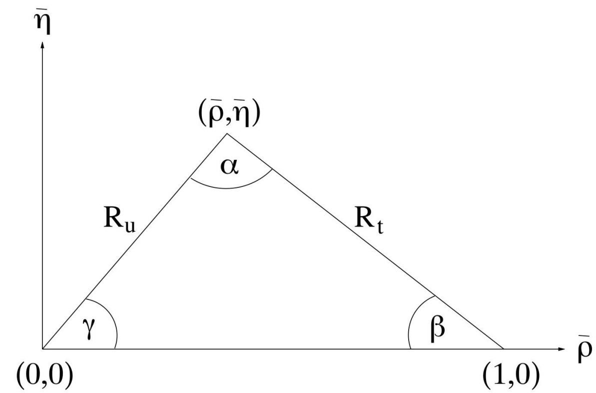
1.2 Introduction: the unitarity triangle. Definitions.

• 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.

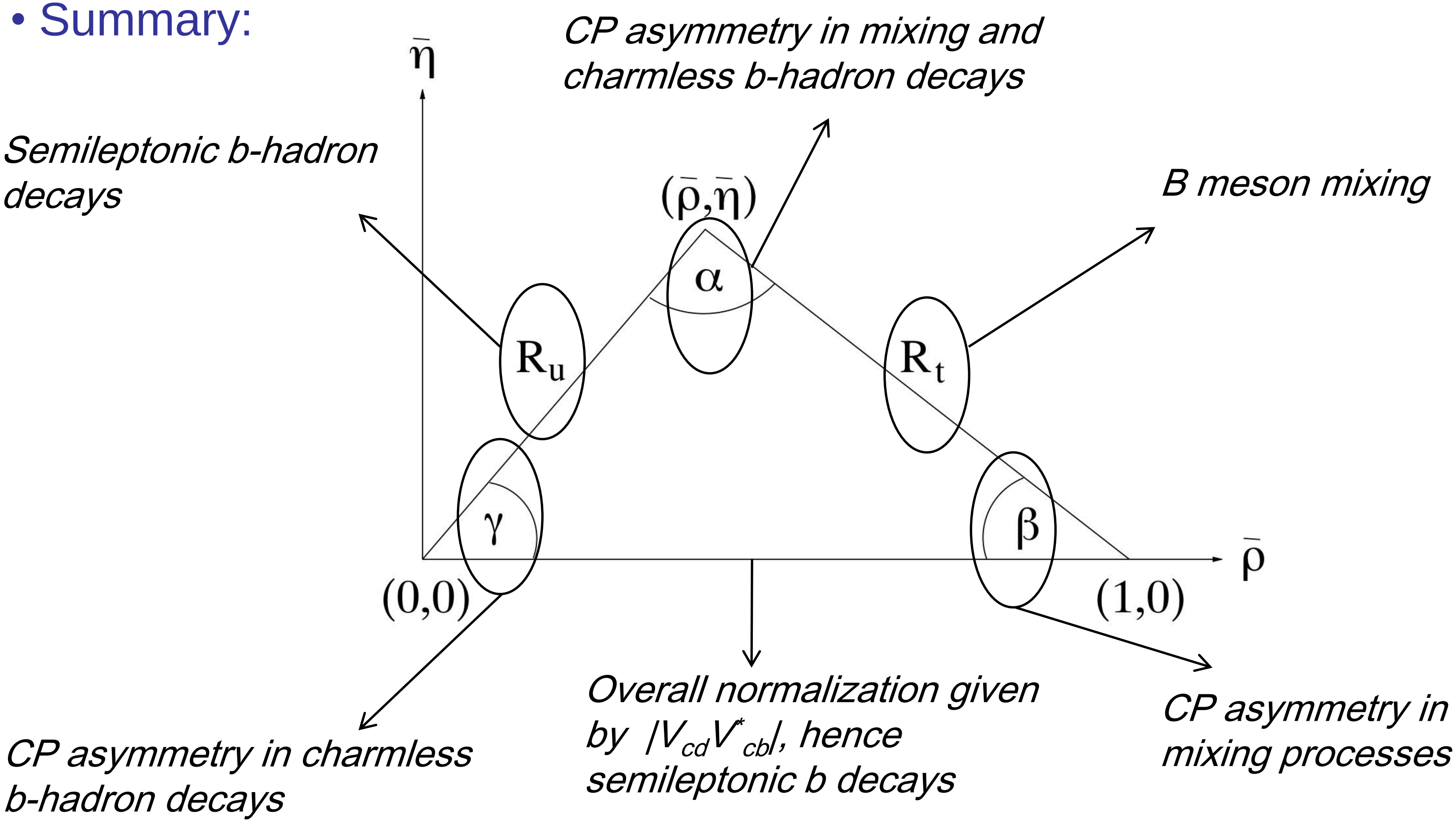
• The angle γ is the weak phase at work in the charmless decays of b-hadrons.

• The angle α is nothing else than $(\pi-\beta-\gamma)$ 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:



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 projects. We all hope that LHC will be successful.

But for the time being, B factories dominate. And Tevatron expriments provided very nice measurements.

1.3 Introduction: machine and experiments.

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

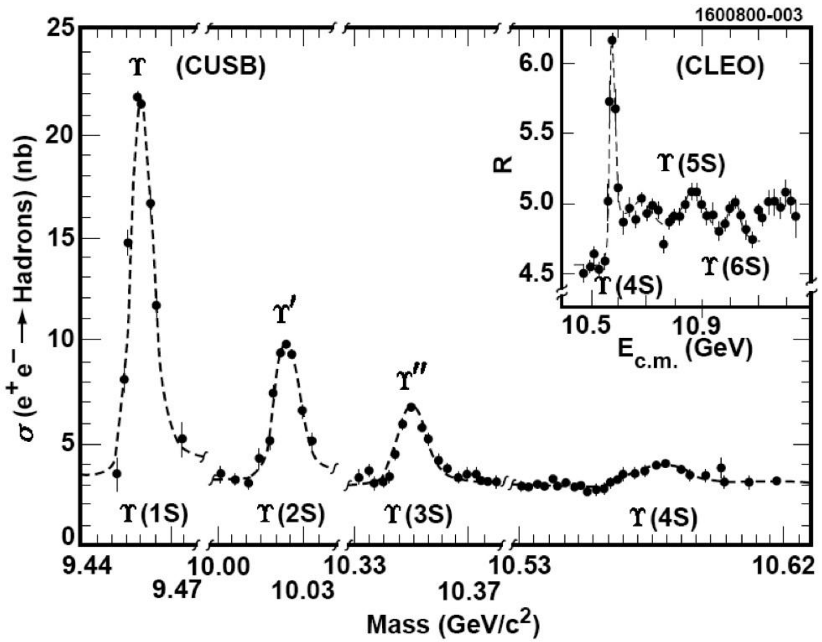
2. Incoherent b quarks pair production: the Tevatron, LEP and LHC experiments.

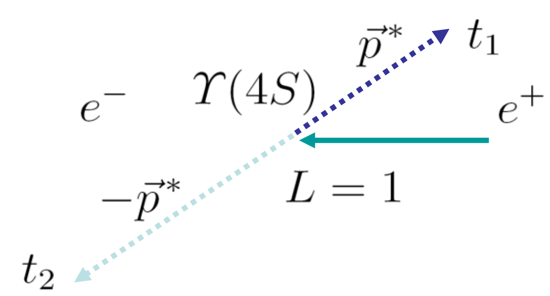
3. See Jacques's lecture for details.

1.3 Introduction: machine and experiments.

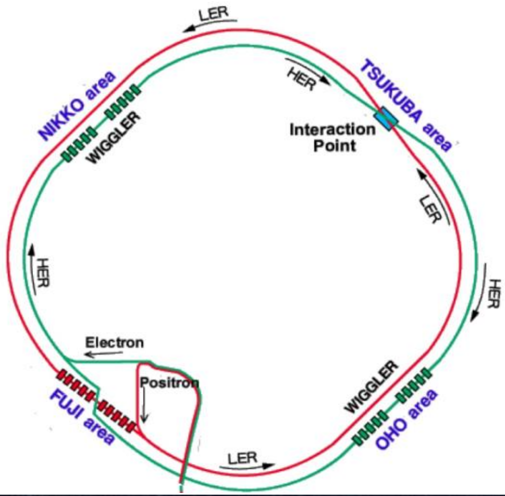
The physics characteristics of the B factories at the Υ(4s):

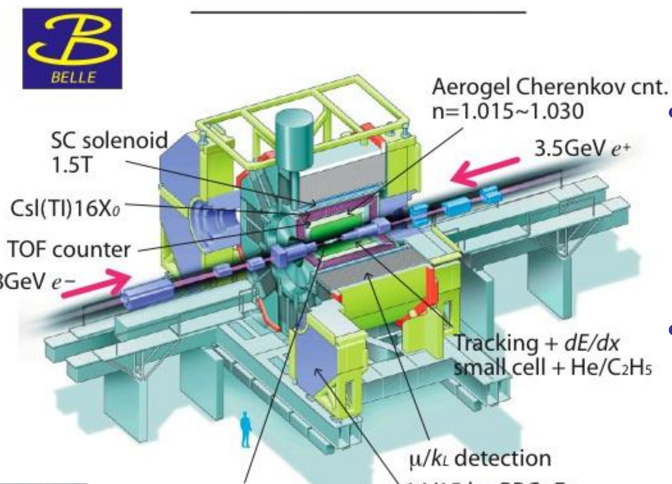
- The series of Υ contains the Υ(4s), above the production threshold of BB pairs. Almost 100% of the Υ(4s) decays.
- Coherent B-ANTI(B) production: when one decays, you know the flavour of the other at the same time. Ideal flavour tagging.
- Beams are asymmetric. The Υ(4s) is boosted allowing time separation between the B.
- No hadronization. Very clean experimental environment.



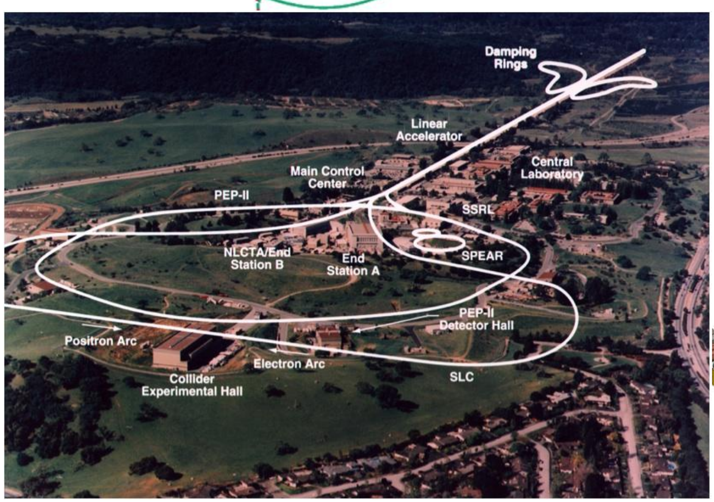


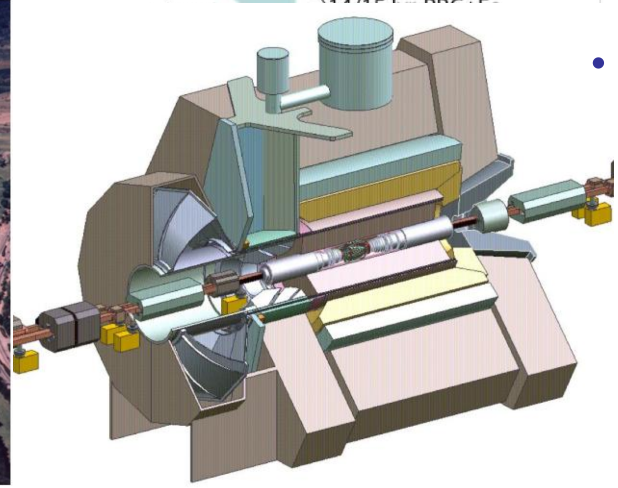
1.3 Introduction: machine and experiments.





- KEKB – Belle – Japan. 8 vs 3.5 GeV. $\beta\gamma$=0.425
- PEPII – BaBar – US. 9 vs 3.1 GeV. $\beta\gamma$=0.56.
- Common detector characteristics: excellent vertexing and particle identification w/ Cerenkov imaging detectors.



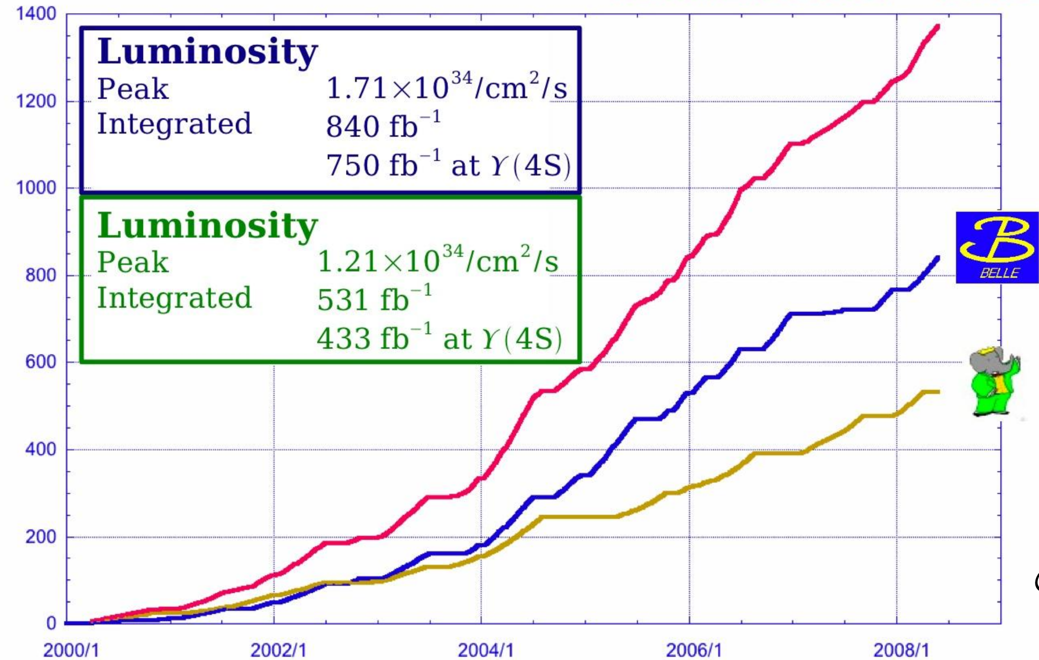


1.3 Introduction: machine and experiments:performance

B factories: BaBar and Belle

Luminosity (fb^{-1})

cumulated stat: **$\sim 1400\,\mathrm{fb}^{-1}$!!**



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$>$ 250 publications for each experiment

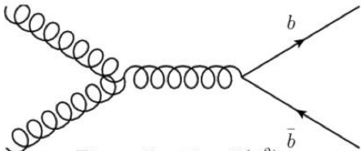
BaBar: $\sim 465\times10^6\,B\bar{B}$ pairs = final sample

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)

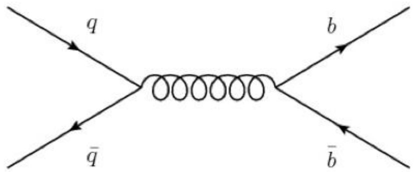
1.3 Introduction: machine and experiments.

The physics characteristics of the Tevatron proton vs antiproton at 2 TeV in c.m:

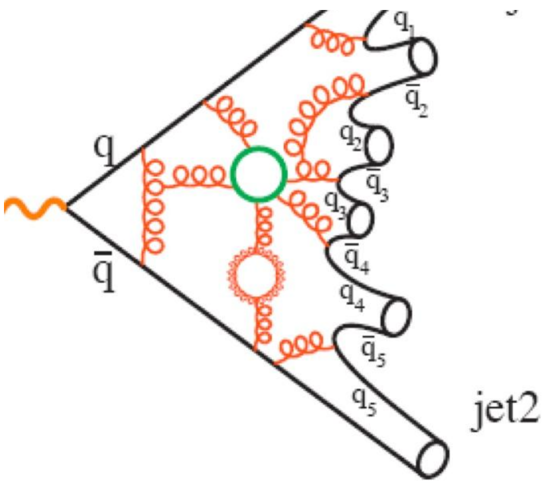
- There is hadronization. Busy hadronic environment.
- Incoherent b quarks pair production. Flavour tagging is much less efficient than at B factories.
- All the b-hadrons species can be produced. Unique laboratory for b baryons and charm B meson.
- Huge production cross-sections and hence large statistics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



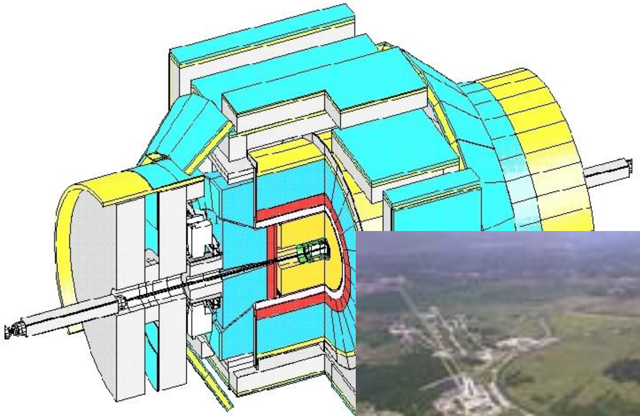
Flavor Creation $\mathcal{O}(\alpha_s^2)$

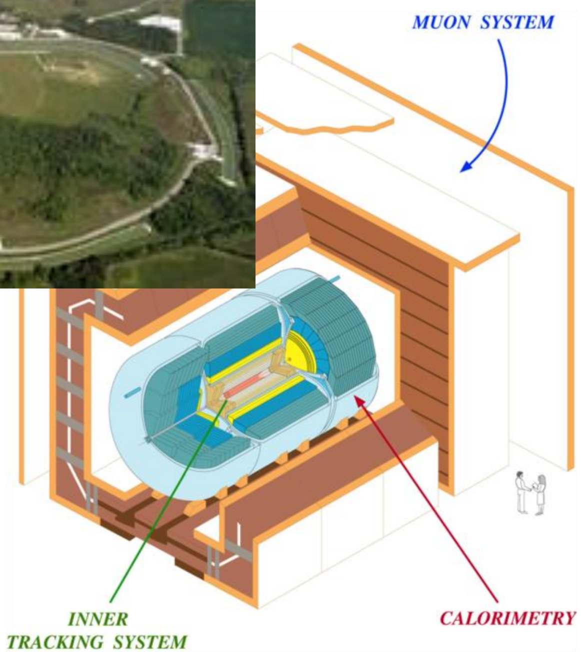


Flavor Creation $\mathcal{O}(\alpha_s^2)$



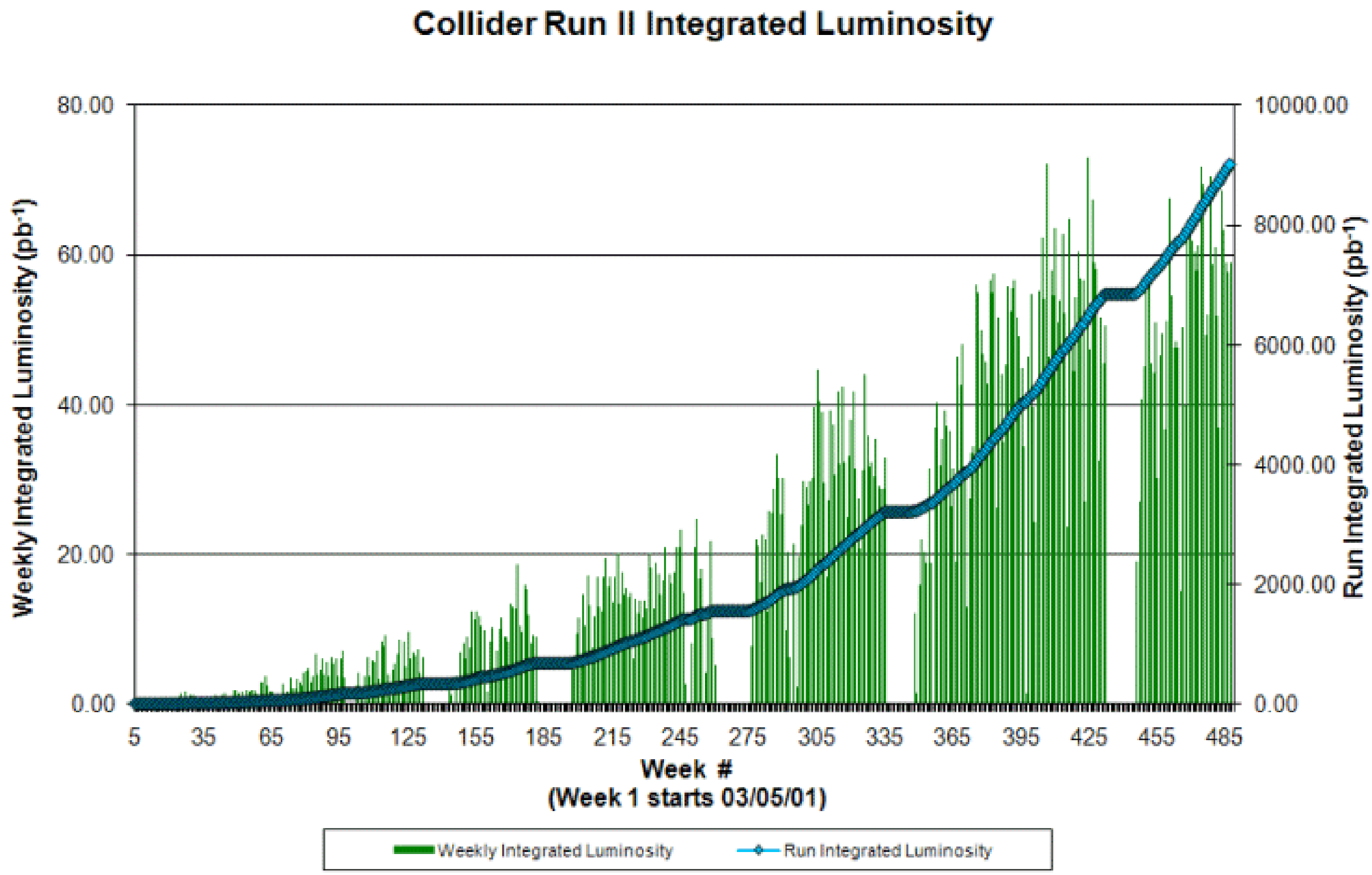
1.3 Introduction: machine and experiments.





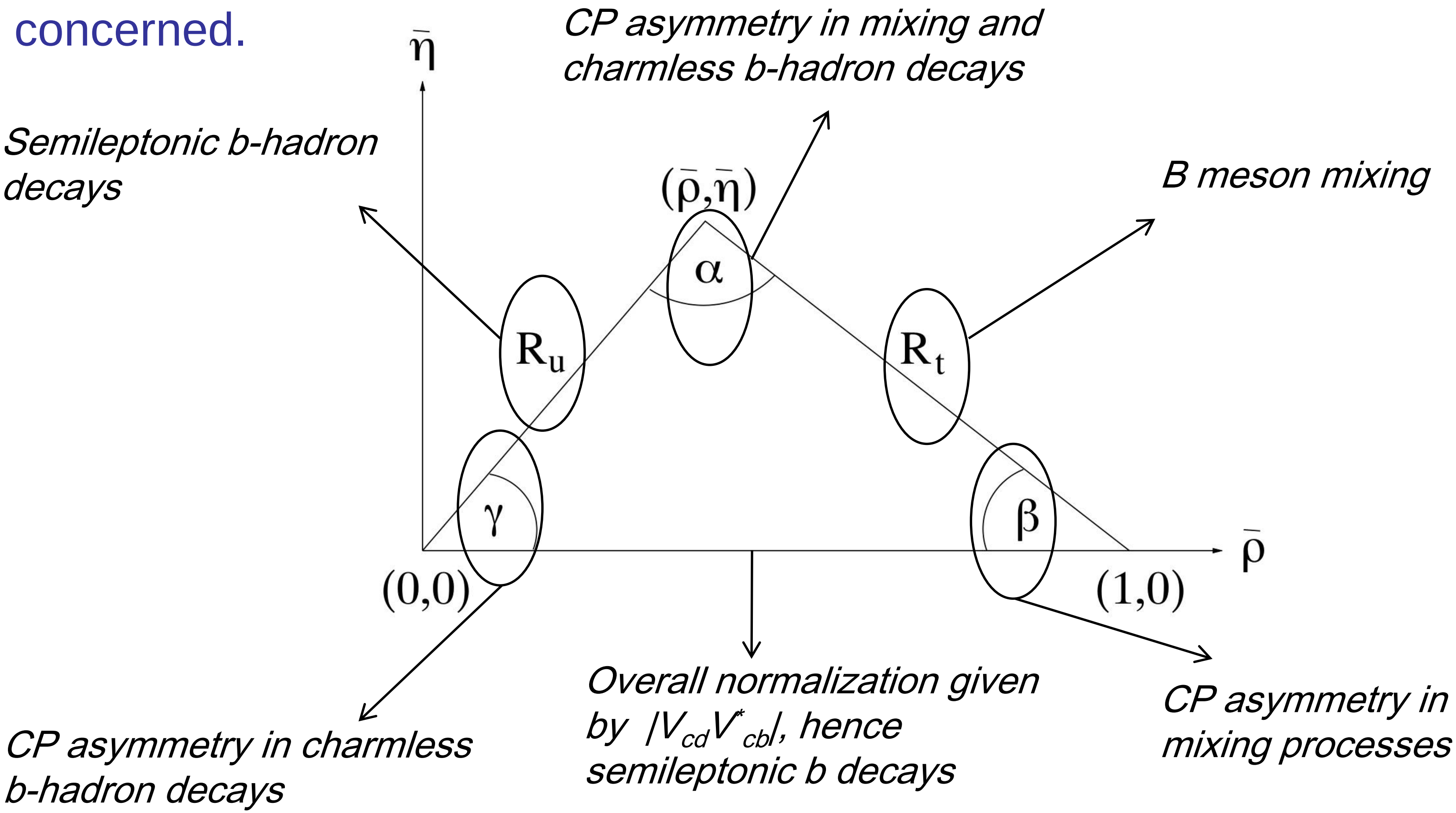
- CDF and D0 are multipurpose experiments.
- D0 has an excellent muon coverage.
- CDF has a flexible trigger and excellent tracking for b physics.

1.3 Introduction: machine and experiments. Performance.



1.4 Introduction: which measurements and where?

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



1.4 Introduction: which measurements and where?

Hadron machines (Tevatron of course, but I am more thinking to LHC…):

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

- Unique laboratory for Bs, Bc and b-baryons.

- The high statistics allows to search for rare decays where NP could/should naturally exhibit.

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.

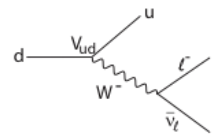
4. New Physics exploration with current data: two examples.

Main observables and measurements relevant to study CP violation.

2.0 The matrix elements Vud and Vus.

- These matrix elements do not exhibit dependencies to the CKM weak phase.

- They however play a role in the global fit through the determination of the two others parameters λ and *A*.



The magnitudes: $|V_{ud}|$

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

2008 RPP $|V_{ud}| = 0.97418 \pm 0.00027$

Best determinations in superallowed $0^+ \to 0^+$ nuclear β decays.

Recent analysis from Hardy and Towner PRC **79** (2009) 055502 yields:

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

$|V_{ud}| = 0.97425 \pm 0.00022$

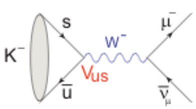
The magnitudes: $|V_{us}|$

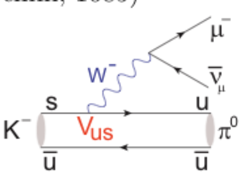
2008 RPP $|V_{us}| = 0.2255 \pm 0.0019$

$|V_{us}|$ from kaon decays

Porter in ICHEP'10

- New averages from FlaviaNet Kaon Working Group, arXiv:1005.2323 [hep-ph] (2010), see also KLOE (Archilli, 1085)





– $K_{\ell 3}$: $|V_{us}|f_+(0) = 0.2163(5)$ or $|V_{us}| = 0.2254 \pm 0.0013$ with $f_+(0) = 0.959(5)$ (lattice, Boyle et al., arXiv1004:0886 (2010))

– $K_{\ell 2}$: $\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = 0.2758(5)$ or $\frac{|V_{us}|}{|V_{ud}|} = 0.2312 \pm 0.0013$ with $f_K/f_\pi = 1.193(6)$ (lattice average)

– Combining, obtain $|V_{us}|(K) = 0.02253 \pm 0.0009$

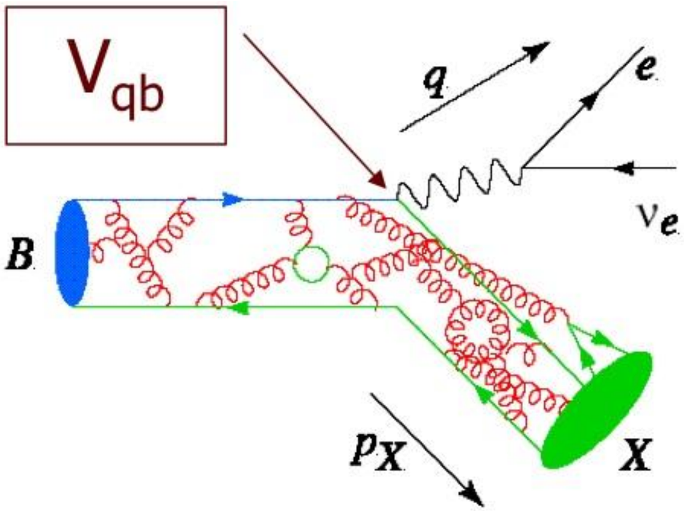
2.1 The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.

• The magnitude $|V_{ub}|$ is key observable in constraining the CKM profile. It basically determines the side R_u of the CKM triangle.

• Pioneered in CLEO and LEP experiments. Nowadays B factories results dominate by far.

• The matrix element V_{cb} enters everywhere in the triangle: as a normalization and in dependencies in some observables.

• There are two ways to access the matrix elements: the inclusive (whatever the charmless X is) and exclusive (specific decays – mainly [B $\rightarrow \pi$ l ν]]) decay rates.



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

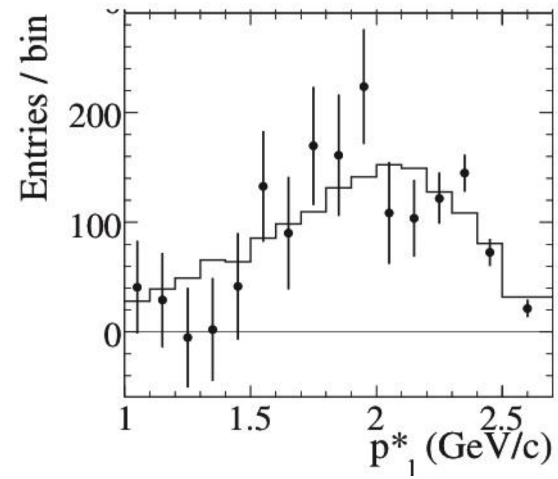
2.1 The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.

- The experimental technique shared by most of the analyses is to fully reconstruct one B decay (hadronic mode) and look at the other B of the event.

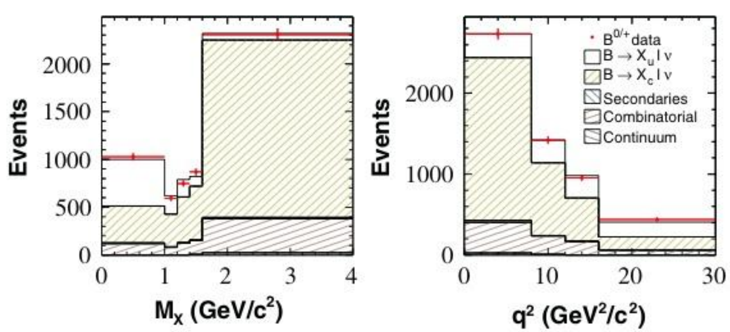
- Though the branching fractions of the fully reconstructed mode is small, the full kinematics of the other decay is constrained.

- Apply to exclusive and inclusive modes.

- It's in general crucial (at least for Vub) that the background is measured in off-peak data.



Top: Babar p_l bkgd subtracted
Bottom: Belle M_X and q^2



2.1 The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.

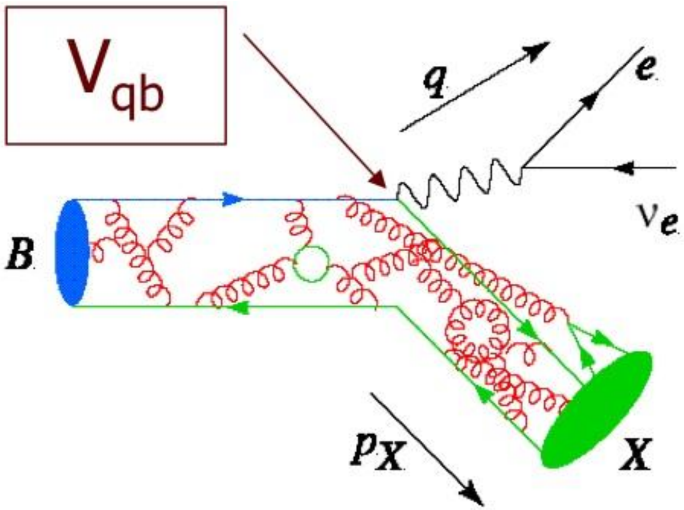
- The measurement of the branching fraction relies on the lepton detection and identification above a given threshold.

- To relate the measurements to the theoretical prediction, one has to extrapolate the experimental spectra and hence rely on models.

- As suggested by the diagram on the right, the hadronic content of the decay is rich. Several theoretical techniques (cf Sebastien's lecture).

- From the experimental point of view, charmless semileptonic are very difficult to separate from charm (in a ratio 1/150) .

- Very intense activity in this field of theory/experiment collaboration.



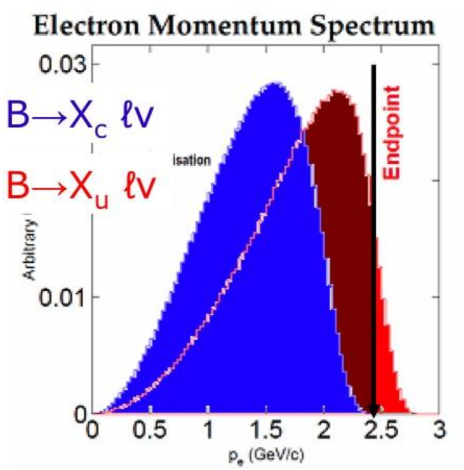
The decay rate from the parton level:

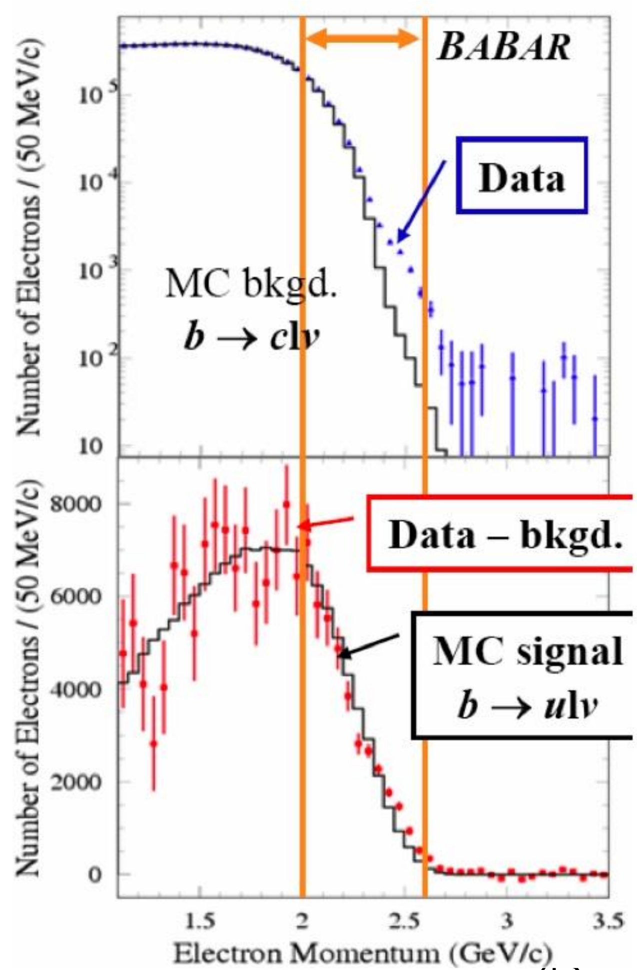
$$\Gamma_0 \equiv \Gamma\left(b \to c[u]\ell\bar{\nu}\right) = \frac{G_F^2 \left|V_{c[u]b}\right|^2}{192\pi^3} m_b^5$$

to the hadron level:

$$\frac{\partial^3\Gamma}{\partial E_l \partial q^2 \partial m_X} = \underbrace{\Gamma_0}_{\text{free quark decay}} \times f(E_l, q^2, m_X) \times \underbrace{\left(1 + \sum_n C_n \left(\frac{\Lambda_{QCD}}{m_b}\right)^n\right)}_{\text{Perturbative +non-perturbative corrections}}$$

2.1 The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.

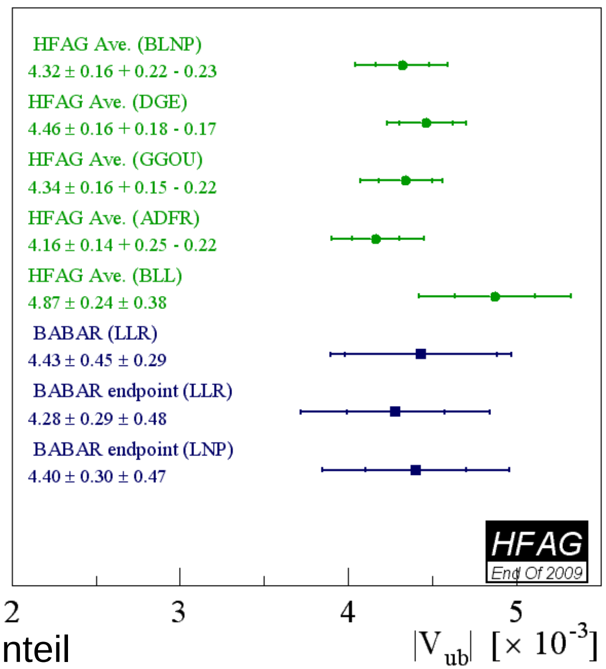
- Incluvive $|V_{ub}|$ measurements: lepton endpoint.
- It's tempting to consider the pure b→u region.
- But for higher signal efficiency, the theoretical error is smaller. Get a compromise. Typically the cut is defined larger than 2 GeV.
- 

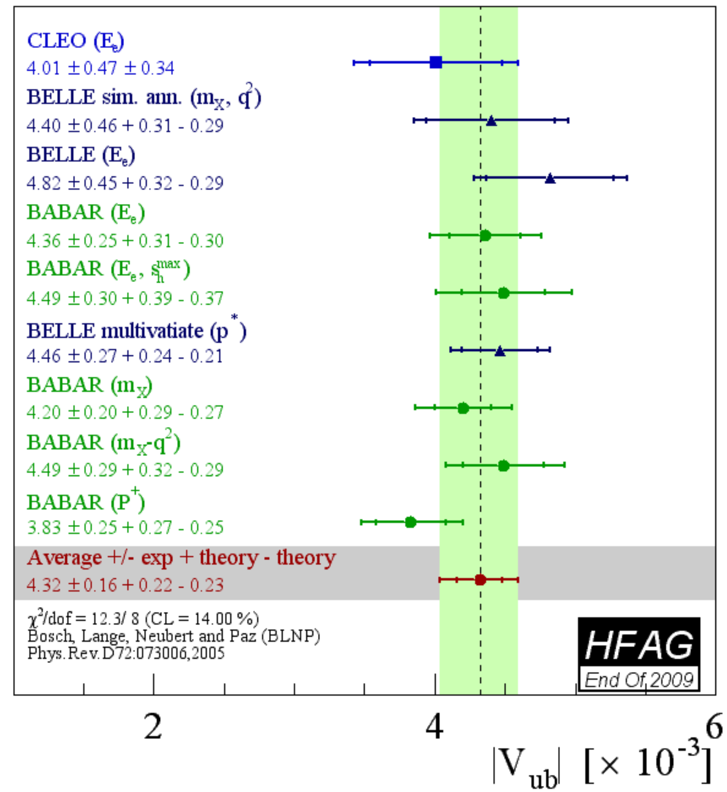


2.1 The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.

- Summary of inclusive $|V_{ub}|$ determinations:

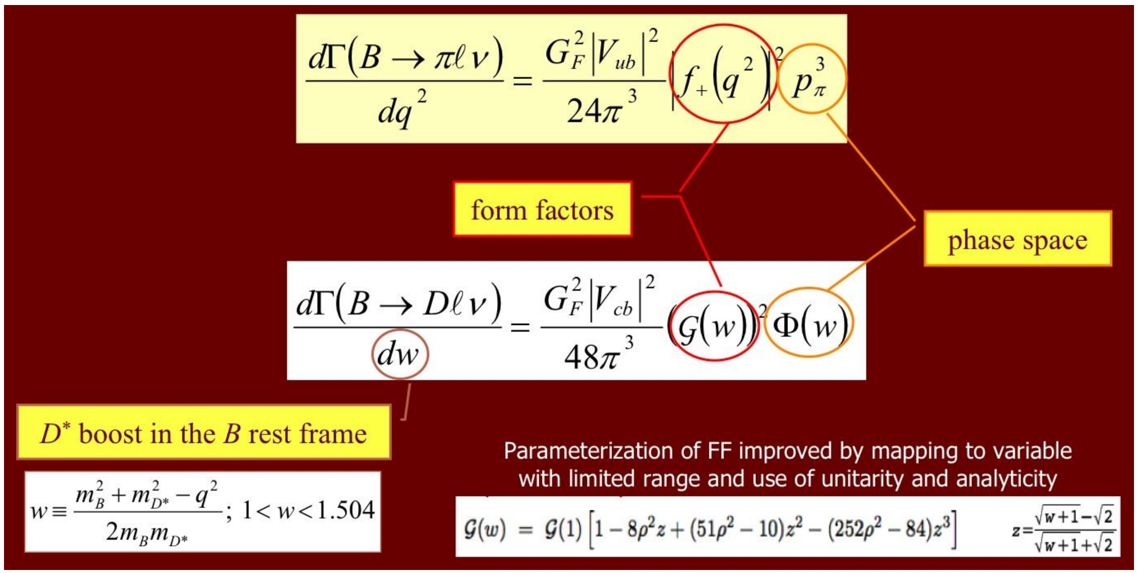
- Shown are the extrapolation within the BLNP scheme. BLNP PRD 72 (2005), DGE arXiv:0806.4524, GGOU JHEP 0710 (2007) 058, ADFR Eur Phys J C 59 (2009) 831





2.1 The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.

• Summary of exclusive $|V_{ub}|$ determinations:



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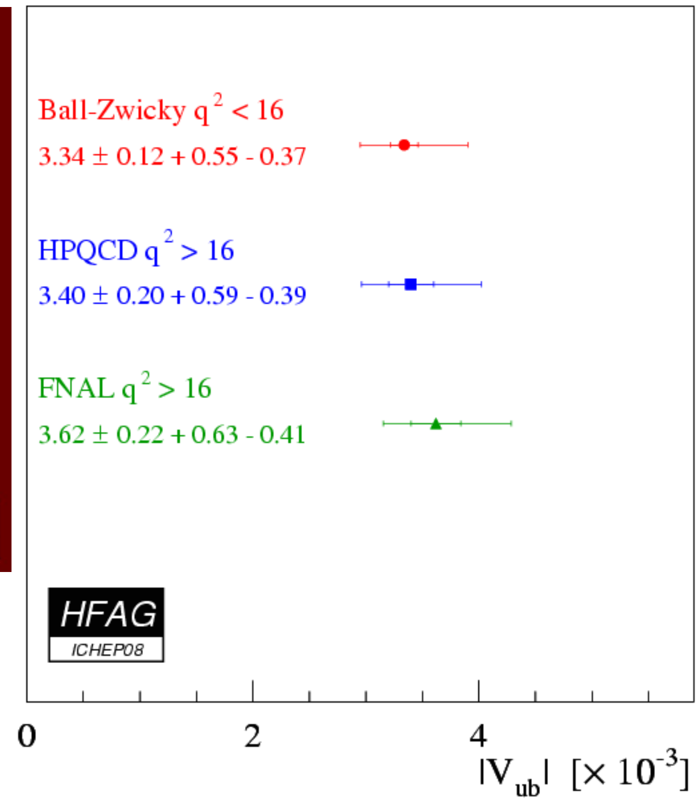
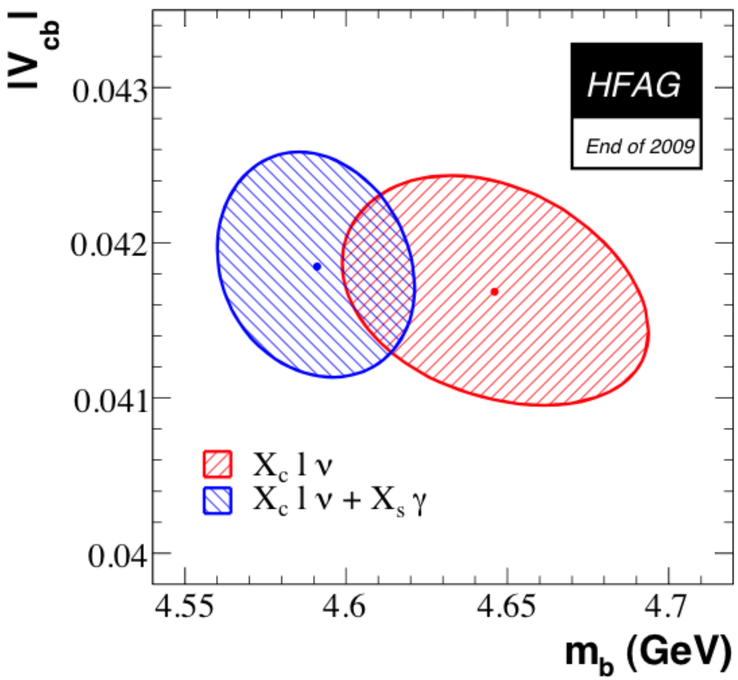
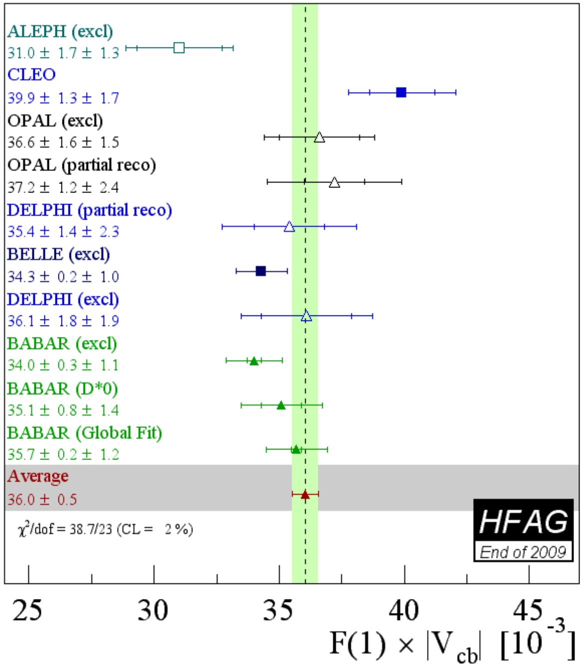


• FF can be calculated on the lattice (See Olivier's lecture. Significant progresses made recently.

2.1 *The Semileptonic branching ratios: the |Vub| and |Vcb| matrix elements.*

- Summary of inclusive and exclusive $|V_{cb}|$ determinations:



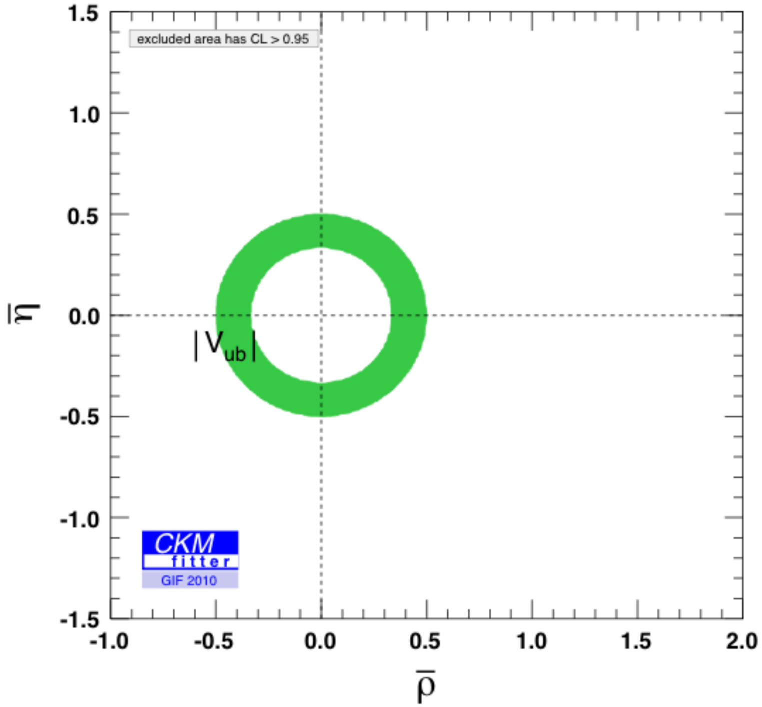


2.1 The Semileptonic branching ratios: the Vub and Vcb matrix elements.

© F.Porter Recent measurements

Measurement	Experiment	V_{ub}
Inclusive	Belle	0.00441 ± 0.00024
Inclusive	*BABAR*	0.00431 ± 0.00035
Exclusive $\pi\ell\nu$	Belle	0.00343 ± 0.00033
Exclusive $\pi\ell\nu$	*BABAR*	0.00326 ± 0.00054

$$|V_{ub}| = (3.92 \pm 0.09 \pm 0.45).10^{-3}.$$



$$|V_{cb}| = (40.89 \pm 0.38 \pm 0.59).10^{-3}.$$

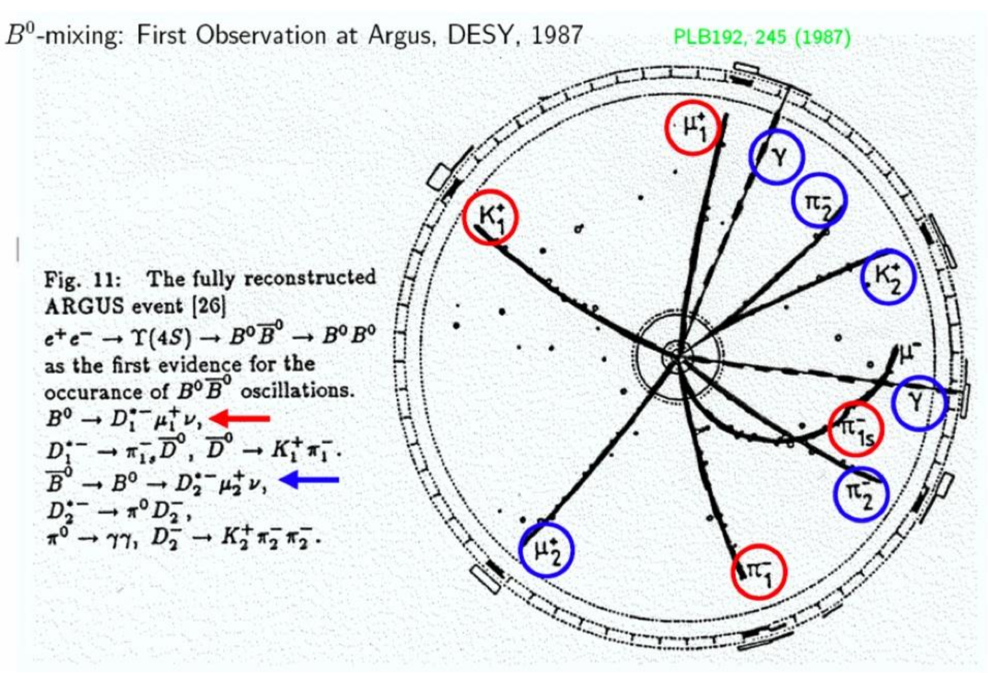
- A typical theoretical uncertainty of 10% on the $|V_{ub}|$ measurement/extraction.

- Inclusive and exclusive determinations of $|V_{ub}|$ marginally agree (the trend is the same for $|V_{cb}|$.

- Intense theoretical effort undergoing in the field.

2.2 The oscillation frequencies: Δm_d and Δm_s.

- As we have seen in the kaon system, weakly decaying neutral mesons can mix.
- The B^0 mixing first observation was in 1987 by the Argus collaboration:



$B^0 \to D^{*-}\mu^+\nu$

$B^0 \to D^{*-}\mu^+\nu$

2.2 The oscillation frequencies: Δm_d and Δm_s.

• In the case of weakly decaying neutral mesons (K^0, D^0, B^0, B_s), the mass eigenstates (which propagate) are a superposition of the flavour states. The example of the B^0 in presence of CP violation:

$$|B_L\rangle = \frac{1}{\sqrt{2}}(p|B^0\rangle + q|\bar{B}^0\rangle)$$
$$|B_H\rangle = \frac{1}{\sqrt{2}}(p|B^0\rangle - q|\bar{B}^0\rangle)$$

• The time evolution of these mass states is derived by solving the Schrödinger equation for the hamiltonian $H=M-i\Gamma/2$:

$$|B_{L,H}\rangle = e^{-i(M_{L,H}-i\frac{\Gamma_{L,H}}{2})t} \cdot |B_{L,H}(t=0)\rangle$$

2.2 The oscillation frequencies: Δm_d and Δm_s.

- Intermediate calculation and definitions:

$$|B^0(t)\rangle = (g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\bar{B}^0\rangle)$$
$$|B^0(t)\rangle = (\frac{p}{q}g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle)$$

$$\begin{aligned} g_+(t) &= e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[\cosh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} - i\,\sinh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right], \\ g_-(t) &= e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[-\sinh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} + i\,\cosh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right] \end{aligned}$$

- We defined here the mass difference $\Delta m_d = M_H - M_L$ and width (lifetime) difference $\Delta\Gamma_d = \Gamma_H - \Gamma_L$. Δm_d governs the speed of the oscillations.

2.2 The oscillation frequencies: Δm_d and Δm_s.

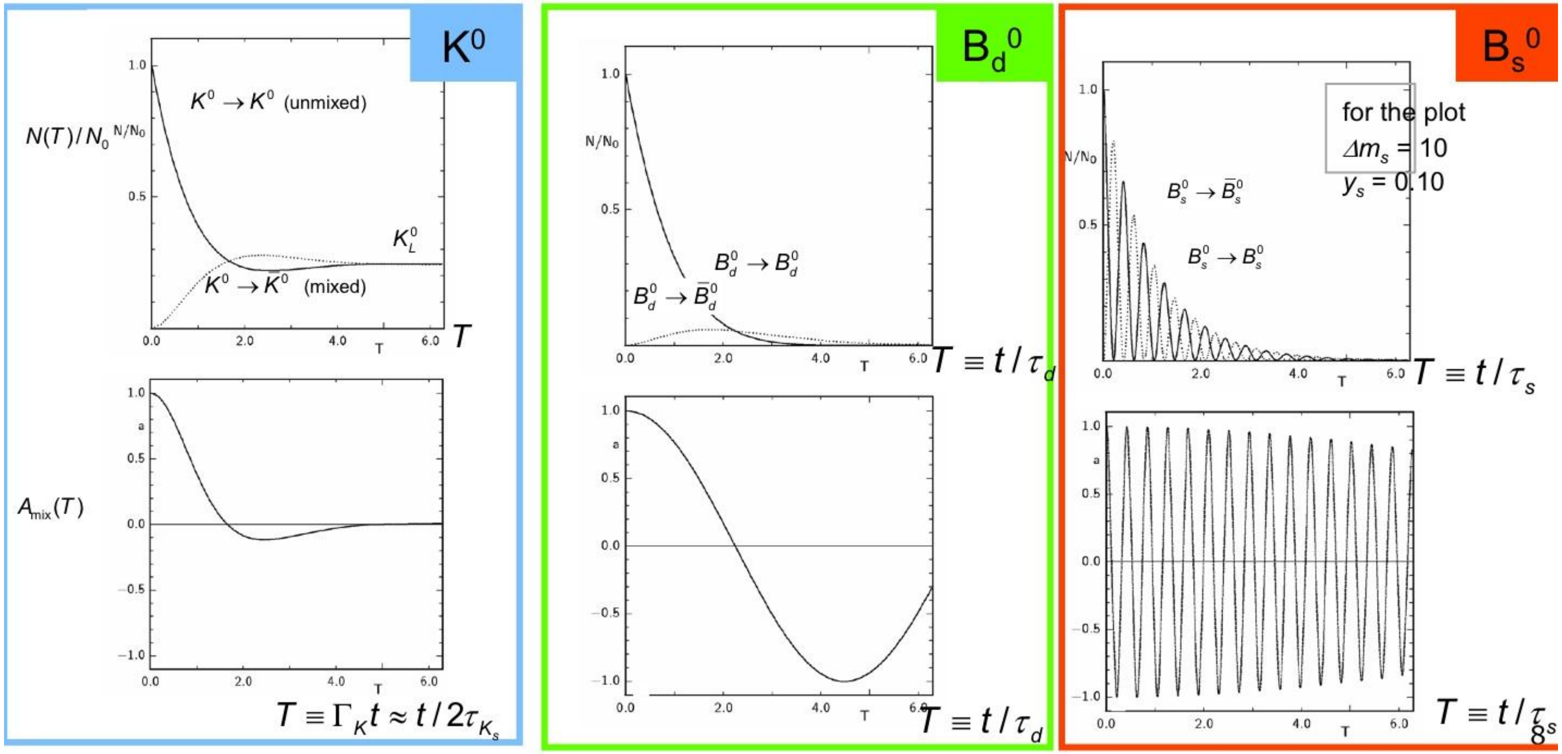
• The master formulae to get a B^0 produced at t=0 decaying in a final state *f* (neglecting $\Delta\Gamma$ in case of the B^0):

$$\begin{aligned} P(B^0(0) \to f) &= \frac{e^{-\Gamma\tau}}{2}[(1+\cos\Delta mt)\left|\langle f\left|H\right|B^0\rangle\right|^2) \\ &+ (1-\cos\Delta mt)\left|\frac{q}{p}\right|^2\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^2) \\ &- 2\sin\Delta mt\cdot\mathcal{I}m(\left|\frac{q}{p}\right|\left|\langle f\left|H\right|B^0\rangle\right|\cdot\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^*)]. \end{aligned}$$

$$\begin{aligned} P(\bar{B}^0(0) \to f) &= \frac{e^{-\Gamma\tau}}{2}[(1+\cos\Delta mt)\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^2) \\ &+ (1-\cos\Delta mt)\left|\frac{p}{q}\right|^2\left|\langle f\left|H\right|B^0\rangle\right|^2) \\ &- 2\sin\Delta mt\cdot\mathcal{I}m(\left|\frac{p}{q}\right|\left|\langle f\left|H\right|B^0\rangle\right|\cdot\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^*)]. \end{aligned}$$

2.2 The oscillation frequencies: Δm_d and Δm_s.

- Time evolution in plots:



2.2 The oscillation frequencies: Δm_d and Δm_s.

• Which observable to look at the time evolution ?

•If we only consider the B^0 mixing in absence of CP violation (we'll see what happens in presence of CP violation in the Chapter 4:

$$\left|\langle B^0 |H| \bar{B}^0(t)\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1+\cos\Delta m t)$$

$$\left|\langle \bar{B}^0 |H| B^0(t)\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1-\cos\Delta m t)$$

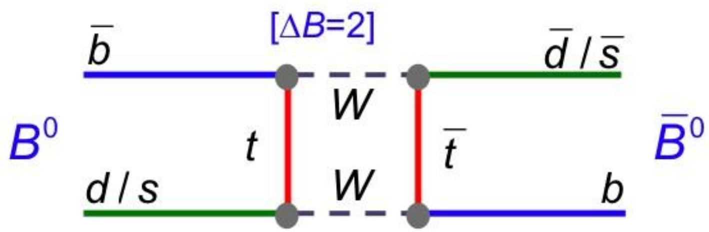
•We want to compare the number of mixed and unmixed events along the evolution. Define the time dependent asymmetry:

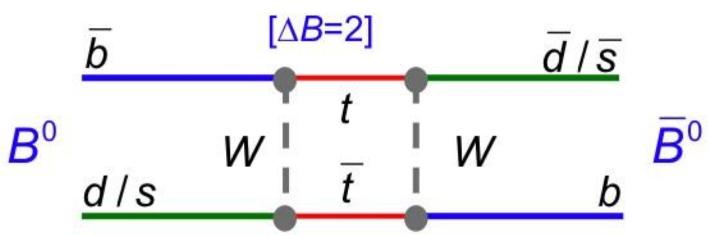
$$A_{\rm mix} = \frac{N(B^0 \to B^0) - N(B^0 \to \bar{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \bar{B}^0)} = \cos(\Delta m_d t)$$

•Note: in the case of Bs, the width difference is no more negligible. Complete treatment in LHCb TDR.

2.2 The oscillation frequencies: Δm_d and Δm_s.

• In the Standard Model the short distance contribution is given by the following diagrams dominated in the loop by the top quark contribution.





• and Δm_d is given by:

Non pert. QCD correction. Main uncertainty.

The weak part we are searching for.

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\eta_B m_{B_d} f_{B_d}^2 B_d m_W^2 S(x_t) |V_{td}V_{tb}^*|^2$$

Pert. QCD correction to Inami-Lim function.

Inami-Lim function describing the content of the box. Top quark dominating.

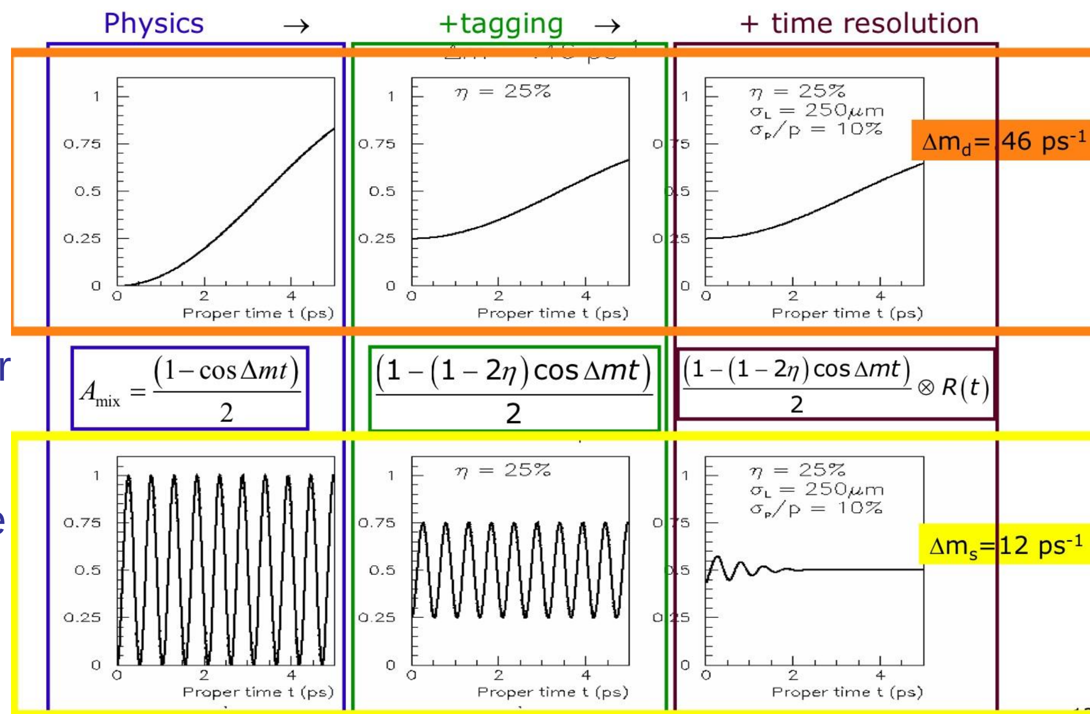
2.2 The oscillation frequencies: Δm_d and Δm_s.

The measurements requires several ingredients:

• Reconstruct the flavour at the decay time Either use a fully flavour specific hadronic mode or a tag the charge with direct semileptonic decays.

• Reconstruct the decay time. Requires excellent vertexing capabilities (in particular to reconstruct the fast B_s oscillations.

• Reconstruct the flavour at production time (see Jacques's lecture). This is the key ingredient. Made easiest at the B factories where the B mesons are coherently evolving. The flavour of one B at its decay time gives the flavour of the companion at the same time.



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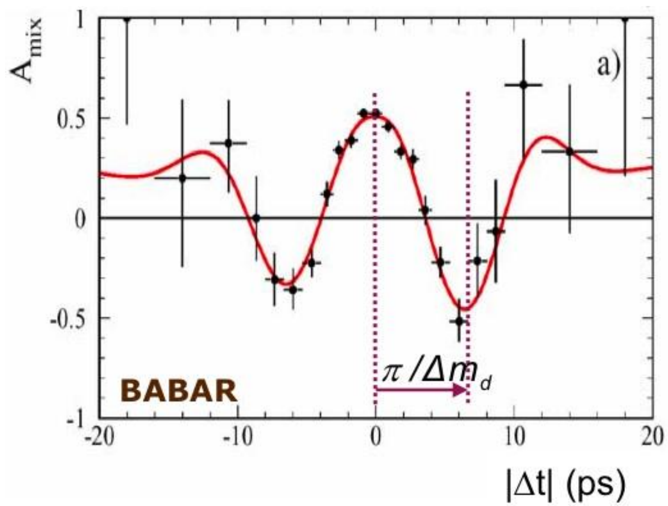
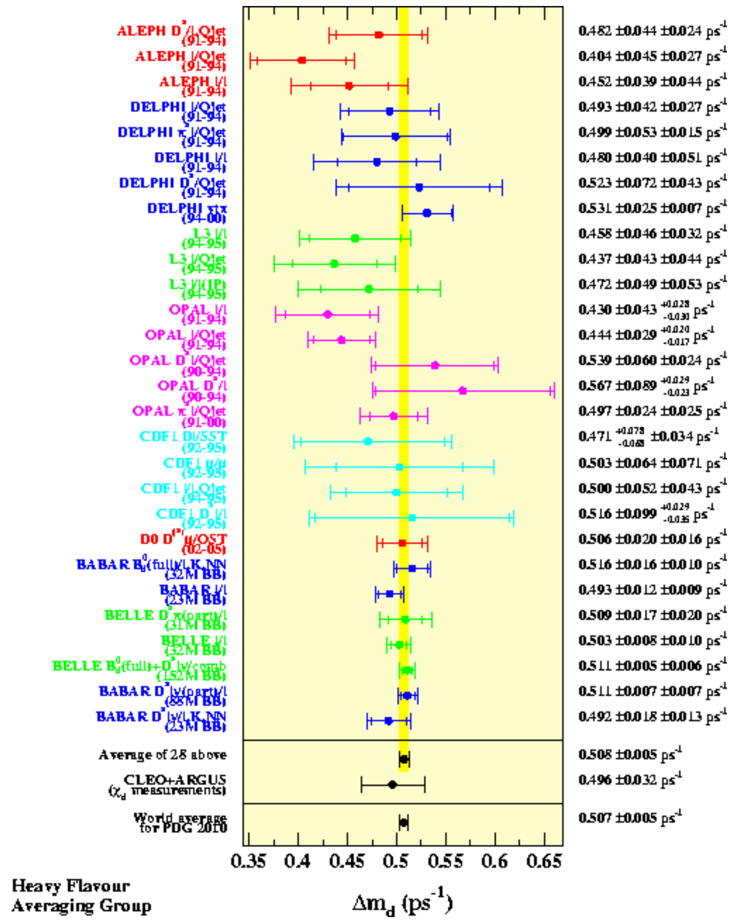
2.2 The oscillation frequencies: Δm_d and Δm_s.

Results for the oscillation frequency measurements:

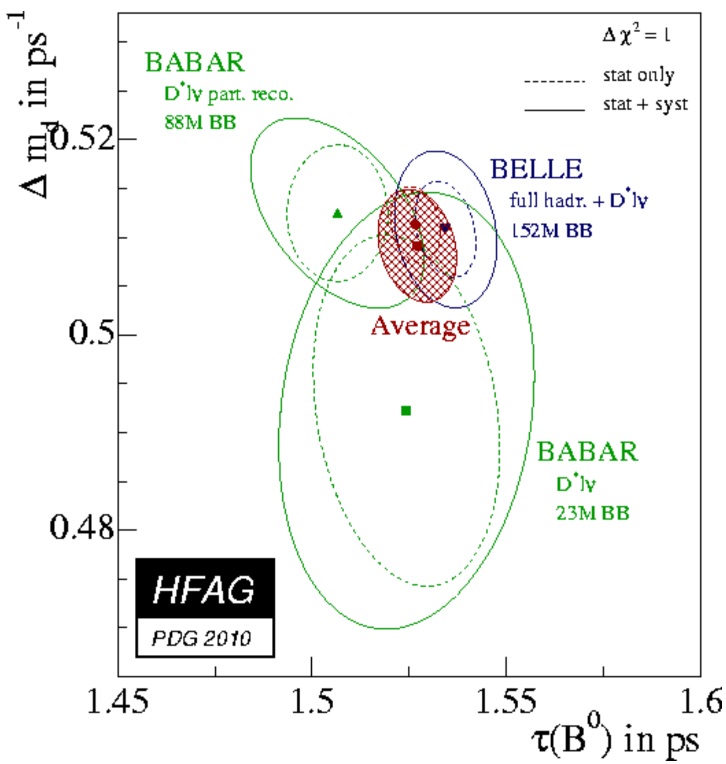
- The BaBar example: this is a fantastic measurement among thirty !

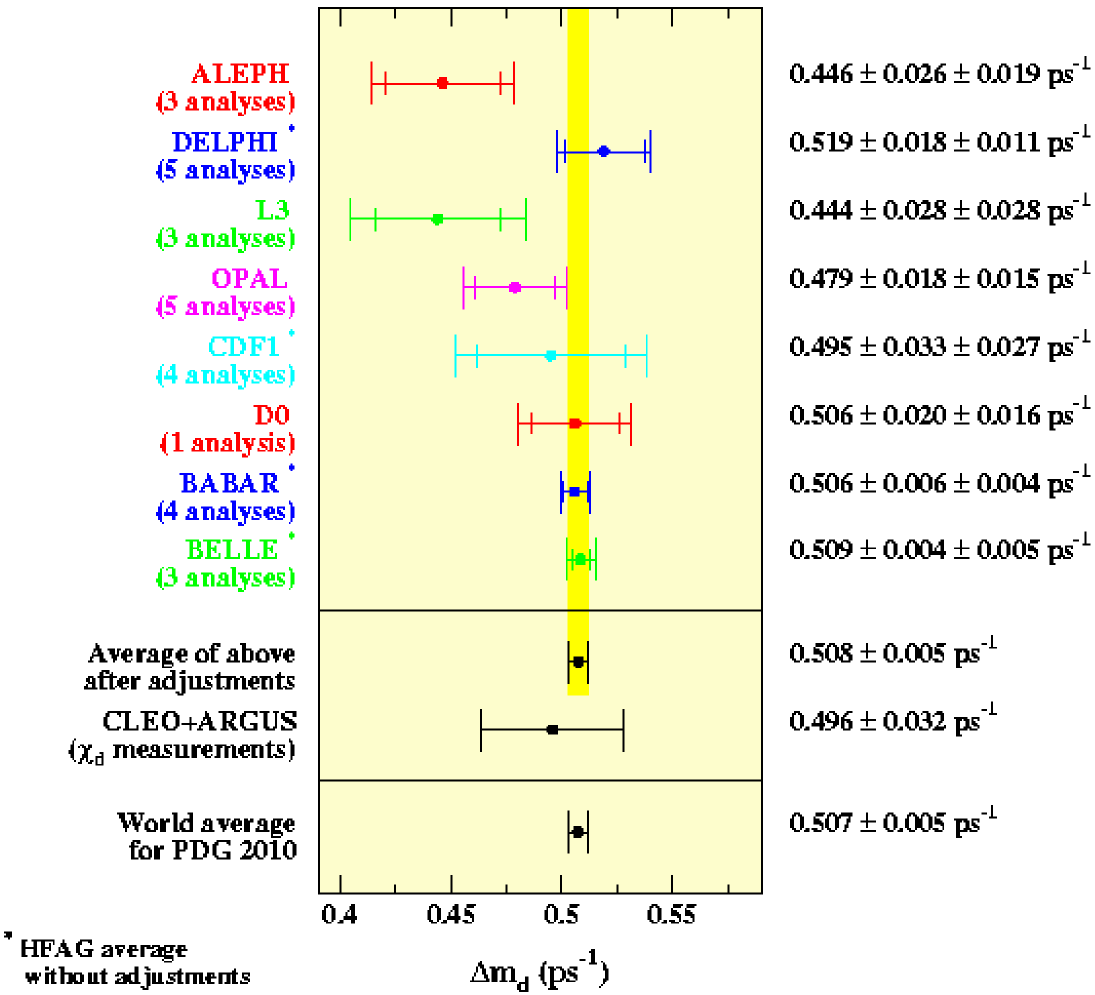




2.2 The oscillation frequencies: Δm_d and Δm_s.

Sorting the results by experiments, it becomes obvious that B factories are dominating the WA.





2.2 The oscillation frequencies: Δm_d and Δm_s.

Non pert. QCD correction.
Main uncertainty.

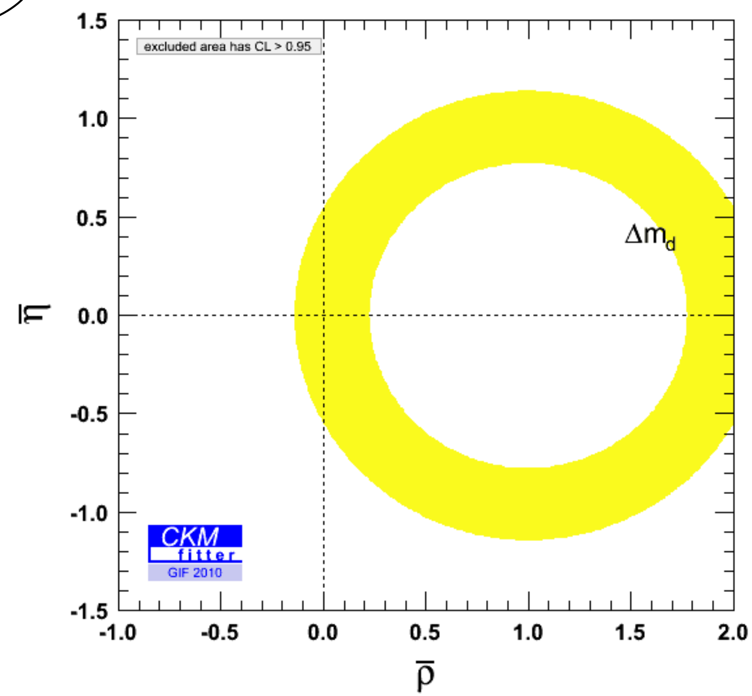
The weak part we are searching for.

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\eta_B m_{B_d} f_{B_d}^2 B_d m_W^2 S(x_t)\,|V_{td}V_{tb}^*|^2$$

Pert. QCD correction to Inami-Lim function.

Inami-Lim function.

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



•The constraint on the Wolfenstein parameters is entirely dominated by the calculation on the Lattice of the product decayconstant*bagfactor.

•There is a way out to improve the precision with the Bs mixing measurement.

2.2 The oscillation frequencies: Δm_d and Δm_s.

• Though Δm_s only depends marginally on the Wolfenstein parameters, it helps a lot in reducing the LQCD uncertainty. Actually, the ratio:

$$\xi = \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$$

is much better determined (better than 5 %) than each of its argument. Δm_s is improving the knowledge we have on the Bd product decayconstant x bag factor.

.

• Note: in the global fit, we don't use anymore the xi parameter but directly the ratios of decay constants and bag factors per species.

2.2 The oscillation frequencies: Δm_d and Δm_s.

- The CDF experiment managed to resolve the fast oscillations of the B_s and measured the oscillation frequency Δm_s in 2006 with a remarkable accuracy. It was the end of a long search starting at LEP in the early nineties.

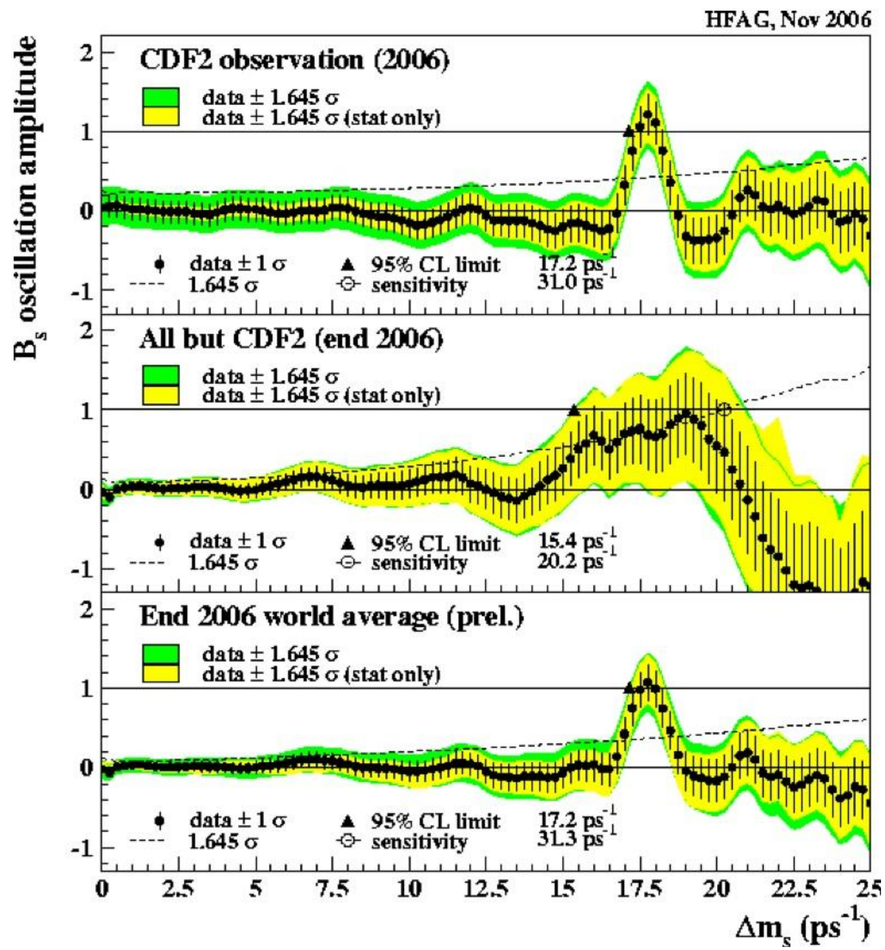
- Amplitude method for combining limits:

$$P(B_s^0 \to \bar{B}_s^0) = \frac{e^{-t/\tau}}{2} \cdot (1 + \mathcal{A}\cos(\Delta m_s t))$$

  - A is measured at each Δm_s hypothesis.

  - A=0: no oscillation is seen.

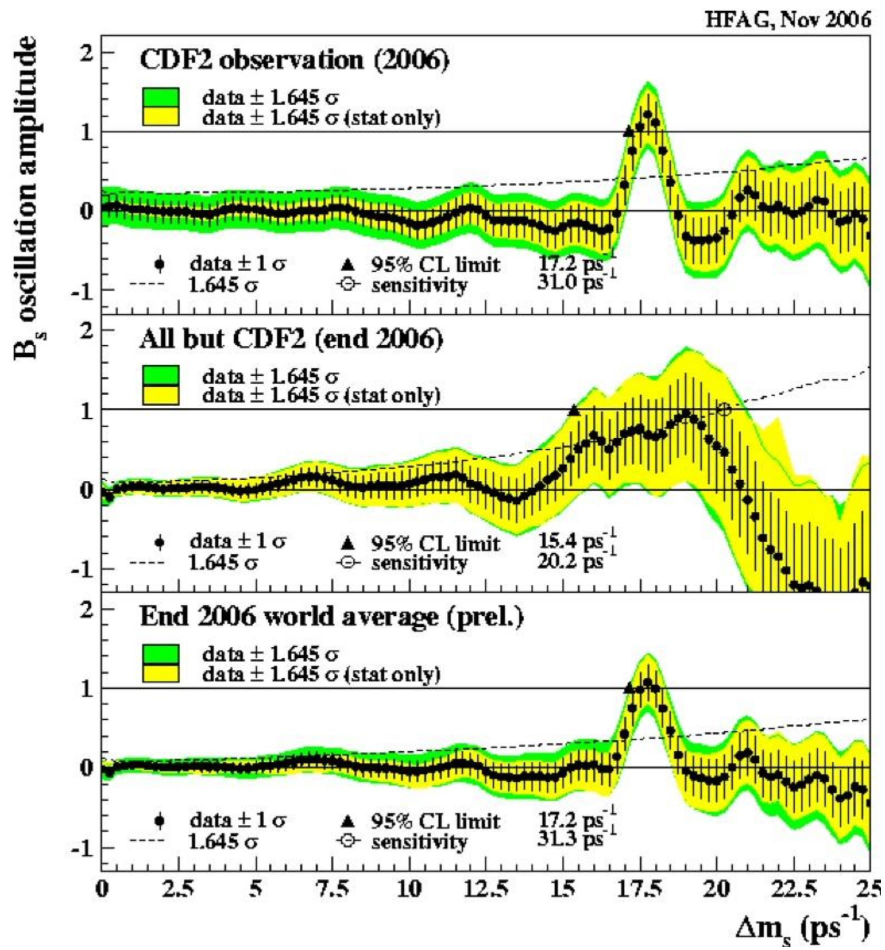
  - A=1: oscillation are observed.



2.2 The oscillation frequencies: Δm_d and Δm_s.

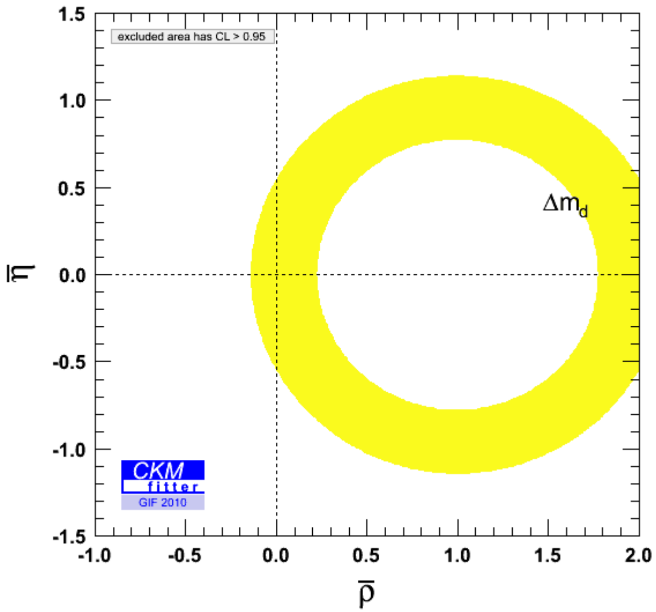
• Digression: looking at the intermediate plot (all experiments but CDF), one sees a structure of the amplitude, yielding to set a limit very close to the CDF measurement.

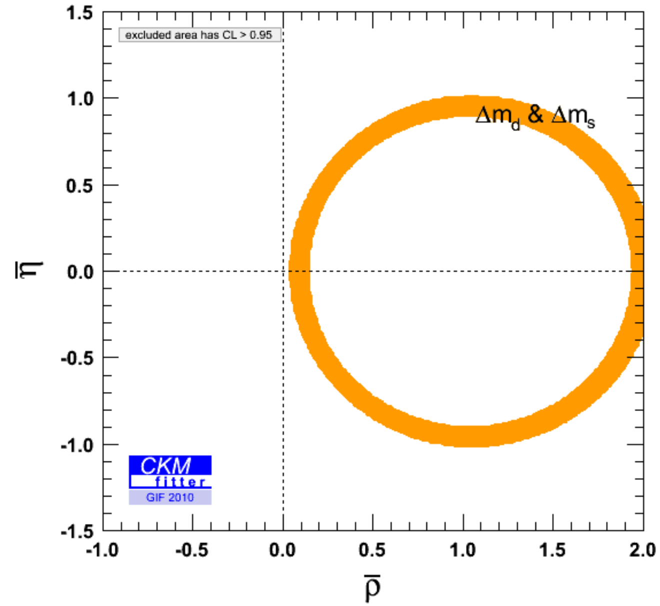
• This was basically driven by the LEP experiments constraints, very close eventually to resolve the Bs oscillations. It was a 2 σ effect which was confirmed … That happens also …. [Never take 2 σ effects too seriously !]



2.2 The oscillation frequencies: Δm_d and Δm_s.

• The simultaneous fit of the two oscillation frequencies yield a dramatic improvement in the constraint.





2.3 The neutral kaon mixing $|\varepsilon_K|$.

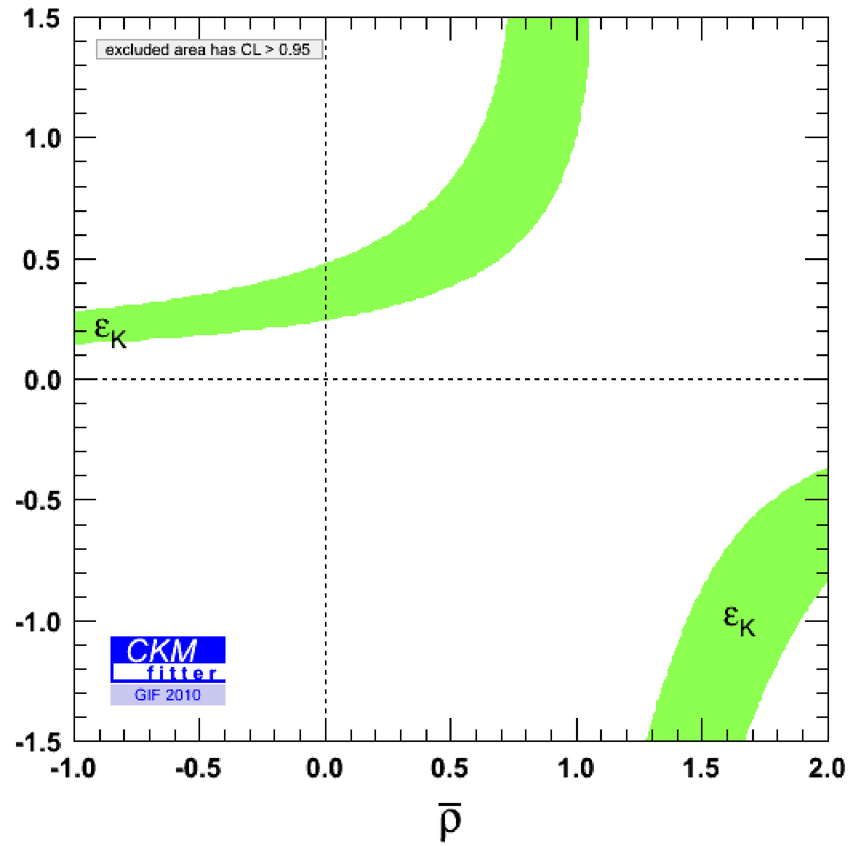
$$|\varepsilon_K| = \frac{G_F^2 m_W^2 m_K f_K^2}{12\sqrt{2}\pi^2 \Delta m_K} B_K \Big(\eta_{cc} S(x_c, x_c) \mathrm{Im}\big[(V_{cs} V$$

$$+ 2\eta_{ct} S(x_c, x_t) \mathrm{Im}$$

• Here again the weak interaction part is ovewhelmed by theoretical hadronic uncertainties.

• Yet, it deserves some interest as the only kaon observables considered in the global fit.

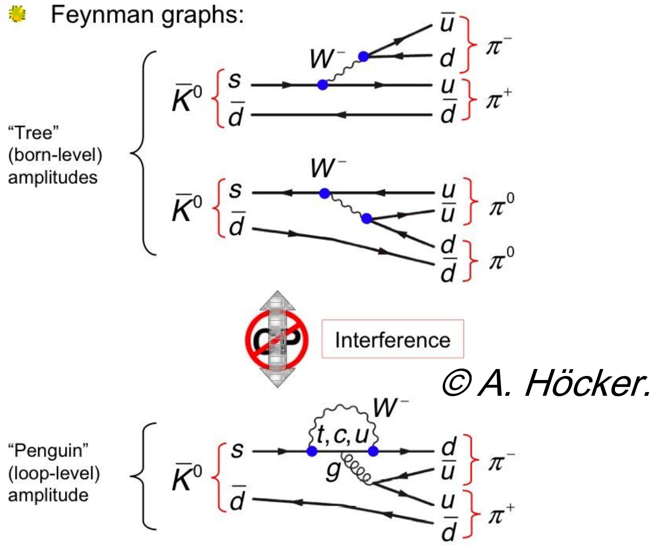
• This CP-violating observable yields a complementary constraint to for instance the weak phase of the B mixing.

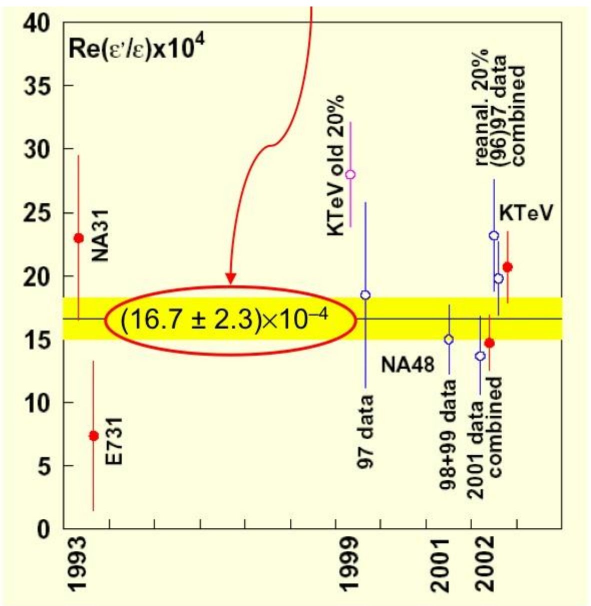


2.3 Aparté: direct CP violation in K decays.

• Not only the CP violation in the kaon mixing has been measured but also the direct CP violation in the kaon decay.

•Modify slightly the ε_K definition to account for the interference between penguin and tree decays to two pions.





•This is a very small effect and the first observation was reported in 2001 by NA48 and KTeV experiments, after 30 years of efforts.

• It happens that the SM prediction is plagued by hadronic uncertainties and makes unuseful for the global fit this (in principle) very valuable information.

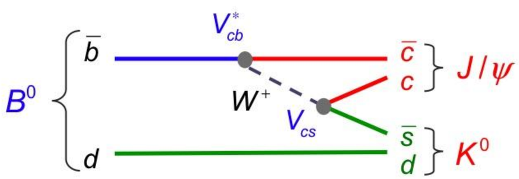
2.4 The measurement of sin(2*β*).

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

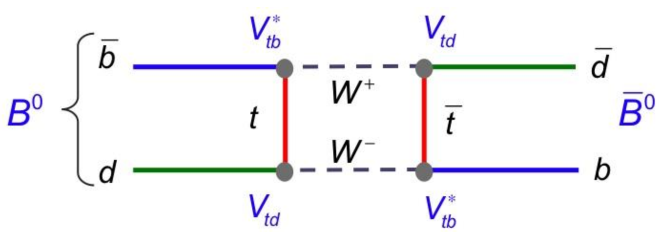
- Sketch of the method: double slit experiment.

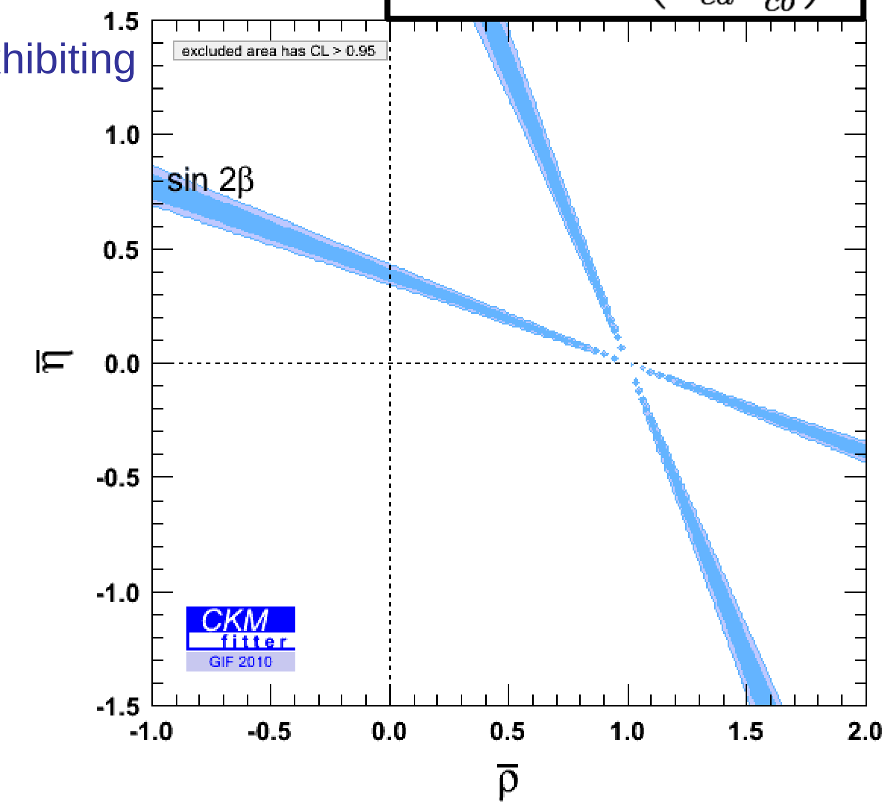
- An interference between processes exhibiting V_{td} and V_{cb} matrix element:

  - The b→c process: $V^*_{cb}V_{cs}$



  - The mixing process: $V^*_{tb}V_{td}$





  - And additonally the K0 mix: $V_{cd}V^*_{cs}$:

$$\arg\left[\frac{A(B^0\to J/\psi K^0)}{A(B^0 \underset{\text{mix}}{\to} \bar{B}^0 \to J/\psi \bar{K}^0 \underset{\text{mix}}{\to} J/\psi K^0)}\right] = \arg\left[\frac{V_{cs}V^*_{cb}}{(V_{td}V^*_{tb})^2\cdot V^*_{cs}V_{cb}\cdot(V^*_{cd}V_{cs})^2}\right] = \arg\left[\frac{(V_{cd}V^*_{cb})^2}{(V_{td}V^*_{tb})^2}\right] = -2\beta$$

2.4 The measurement of sin(2β).

• Sketch of the method: some definitions.

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

• The CP asymmetry:

$$A_{\rm CP}(f,t) = \frac{N(\bar{B}^0(t)\to f) - N(B^0(t)\to f)}{N(\bar{B}^0(t)\to f) + N(B^0(t)\to f)}$$

• can be expressed as a function of the S and C observables:

$$A_{\rm CP}(f,t) = S\sin(\Delta m_d t) - C\cos(\Delta m_d t)$$

• which can be related to CP violating phase β:

$$\lambda = \frac{q}{p}\frac{A(\bar{B}^0\to f)}{A(B^0\to f)} = e^{-i2\beta}\frac{\bar{A}_f}{A_f}$$

$$S = \frac{2\mathcal{I}m\lambda}{1+|\lambda|^2}$$

$$S = -\eta_{CP}\sin(2\beta)$$

• Let's notice (anticipating the next section) that the charmless CP final state $\pi\pi$ would receive S = sin (2α) in absence of penguin diagrams.

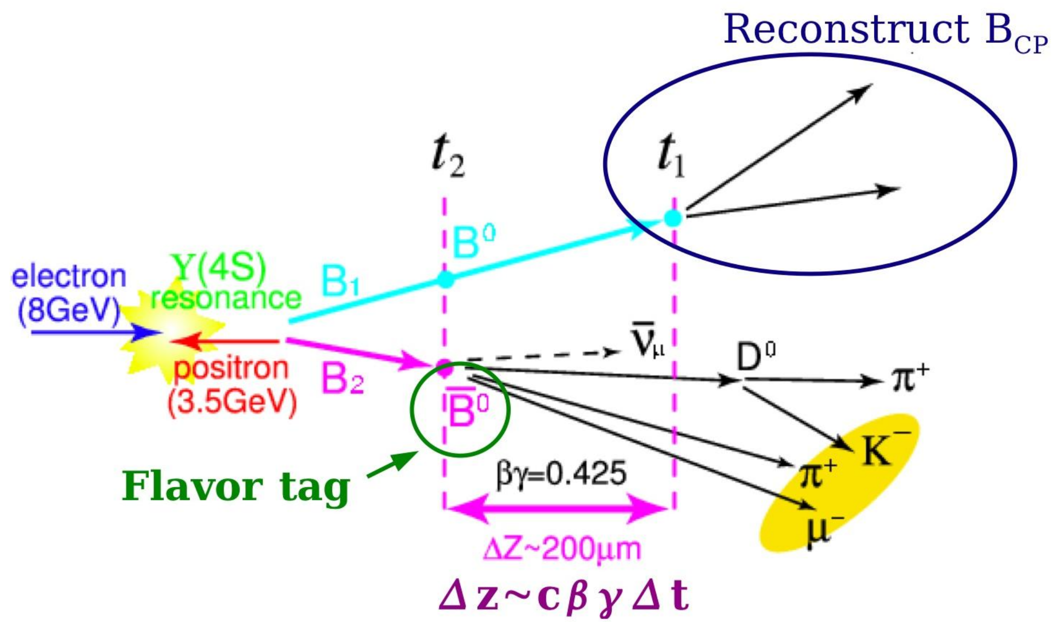
2.4 The measurement of sin(2β).

- The experimental method to measure S and C parameters:

- Fully reconstruct the bccs CP decay .

- Tag the flavour with the other B of the event.

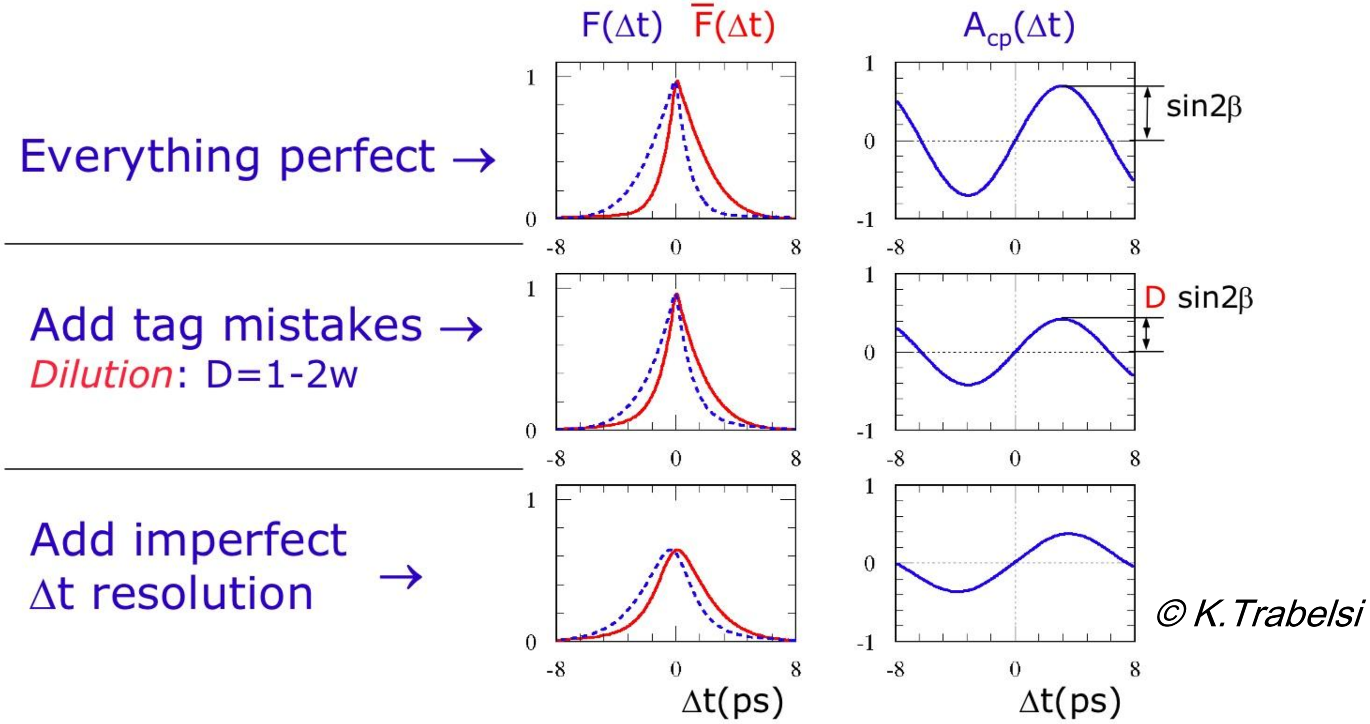
- Reconstruct the time difference between the decays from the vertex seperation.



$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left(1 + q\left(S\sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)\right)\right)$$

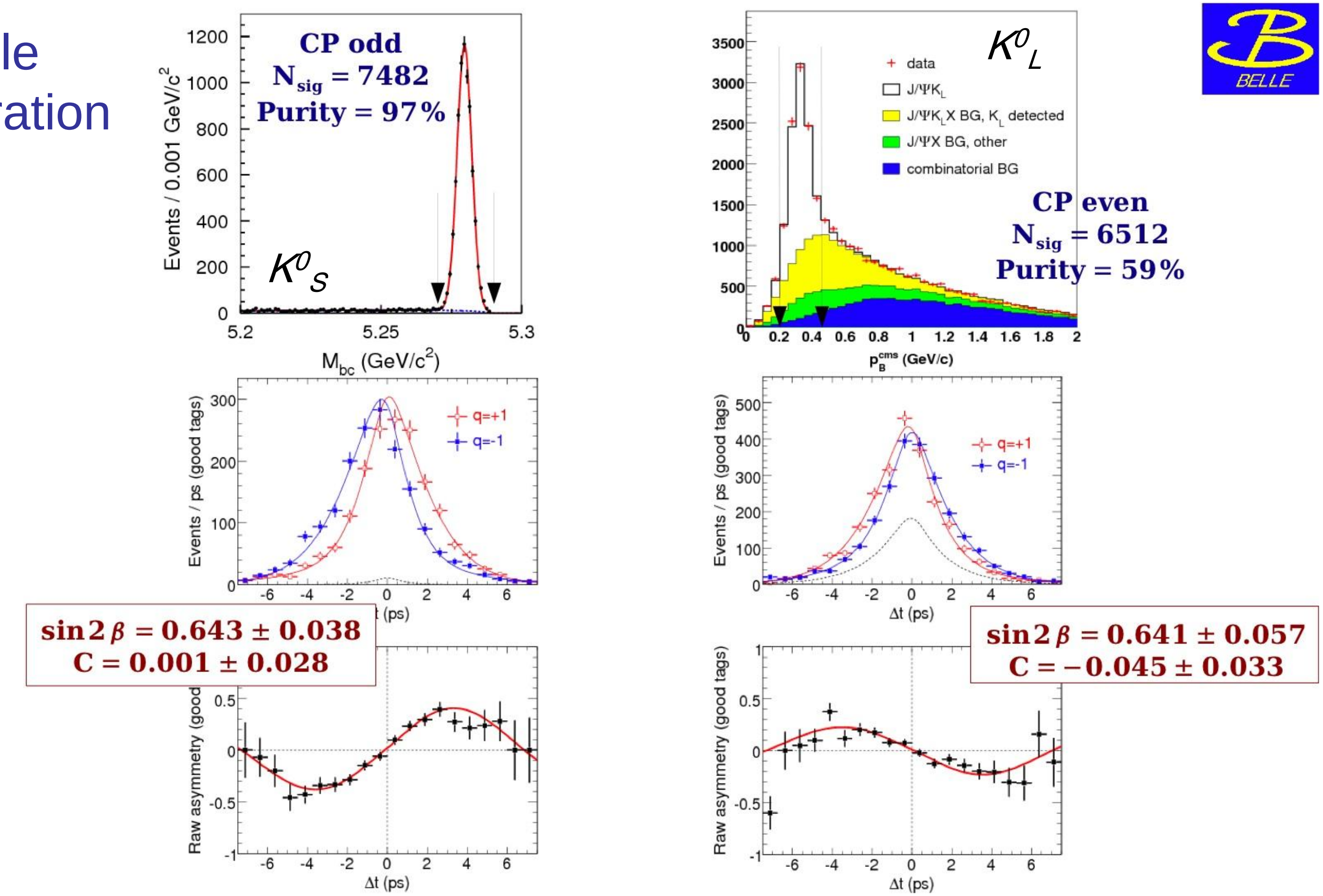
2.4 The measurement of sin(2β).

- Dilution factors: mistag rate and vertexing resolution.



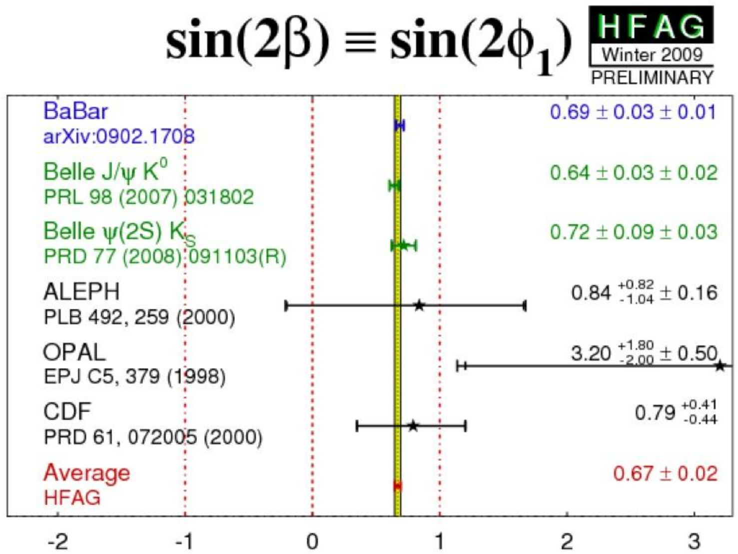
2.4 The measurement of sin(2β).

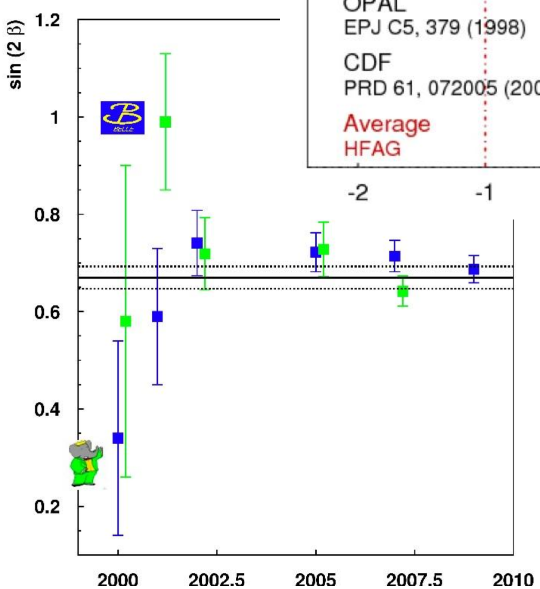
- A selection of Belle results as an illustration of this fantastic achievement.

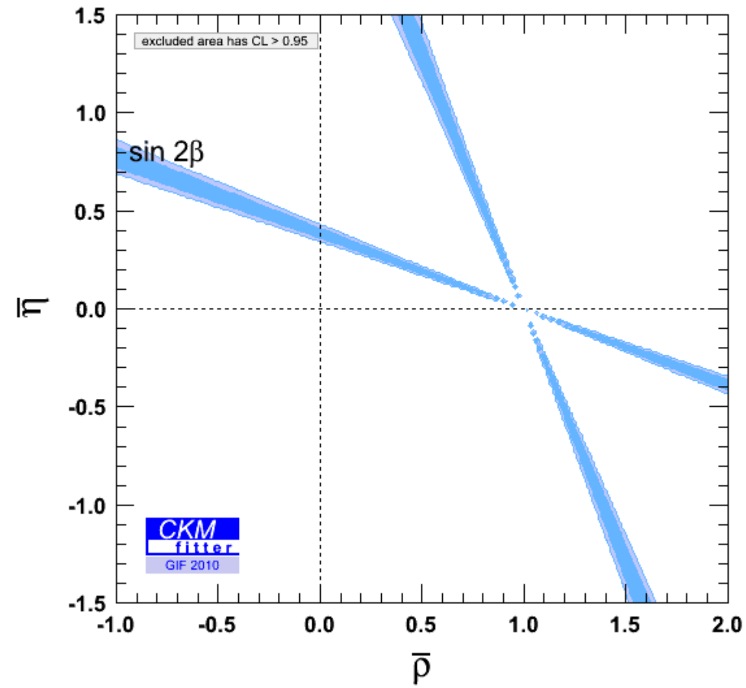


2.4 The measurement of sin(2*β*).

- This measurement was the highlight of the physics case of the B factories and the accuracy of their measurements is a tremendous success…

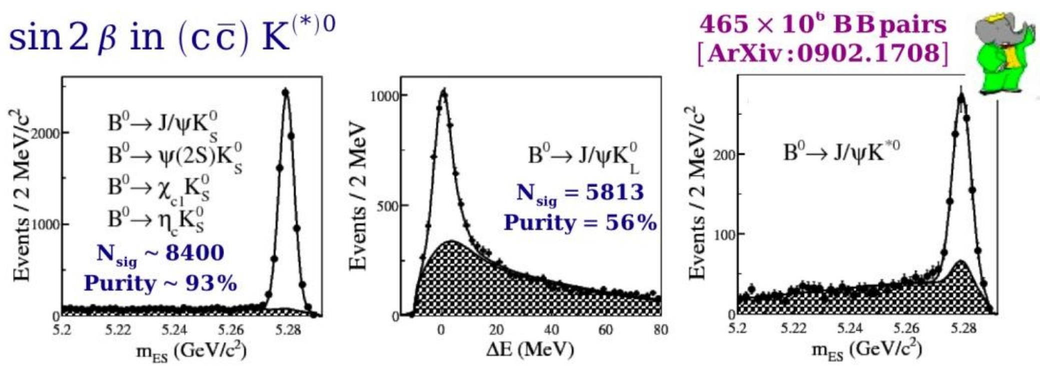


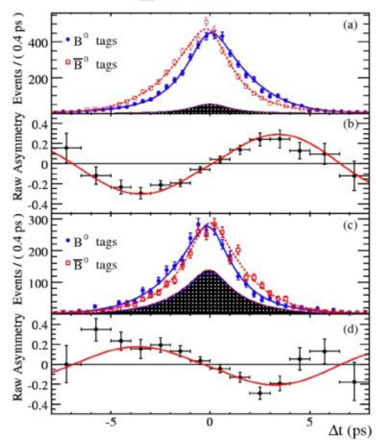




2.4 The measurement of sin(2β).

• Other charmonia modes are measured with good precision and nice consitency :





Mode	$\sin 2\beta$
$J/\psi K_S$	$0.657 \pm 0.036 \pm 0.012$
$J/\psi K_L$	$0.694 \pm 0.061 \pm 0.031$
$\mathbf{J/\psi K^0}$	$\mathbf{0.666 \pm 0.031 \pm 0.013}$
$\psi(2S) K_S$	$0.897 \pm 0.100 \pm 0.036$
$\chi_{c1} K_S$	$0.614 \pm 0.160 \pm 0.040$
$\eta_c K_S$	$0.925 \pm 0.160 \pm 0.057$
$J/\psi K^{*0}$	$0.601 \pm 0.239 \pm 0.087$
$\mathbf{c\bar{c}K^{(*)0}}$	$\mathbf{0.687 \pm 0.028 \pm 0.012}$

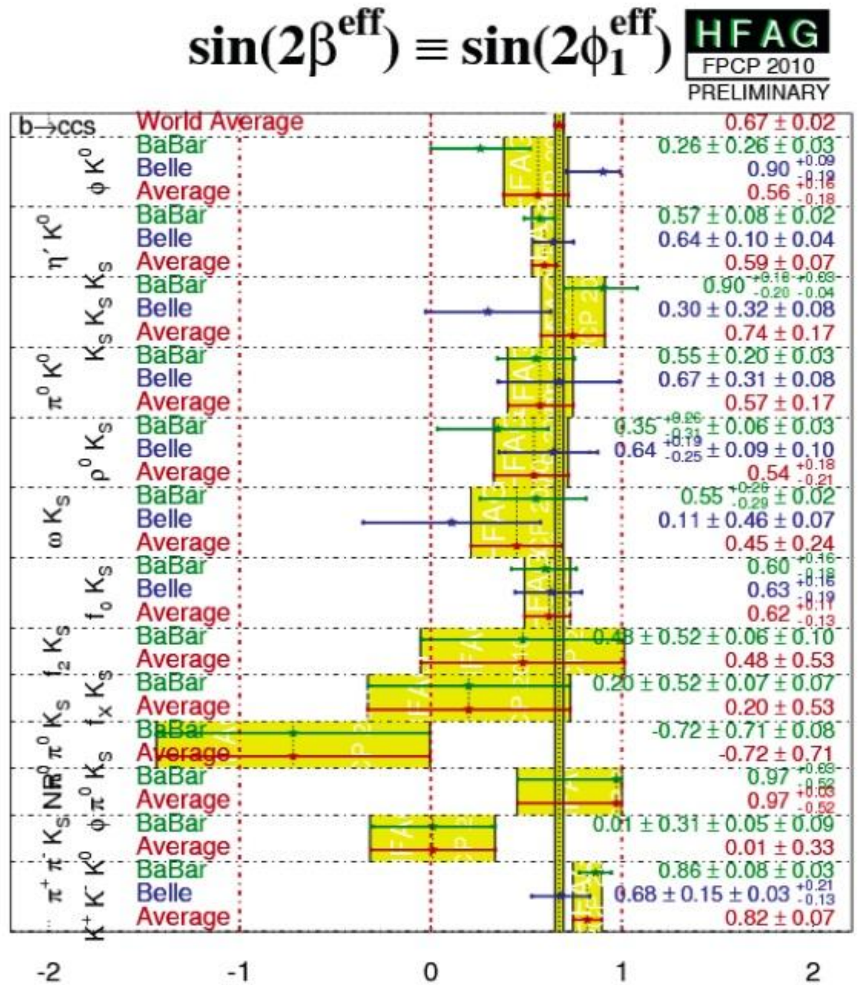
2.4 The measurement of sin(2β).

• An active search for β measurements concern the charmless decays proceeding through penguins (bsss).

• Probing a difference with sin (2β) measured in (bccs) would indicate New Physics (see Tobias lecture).

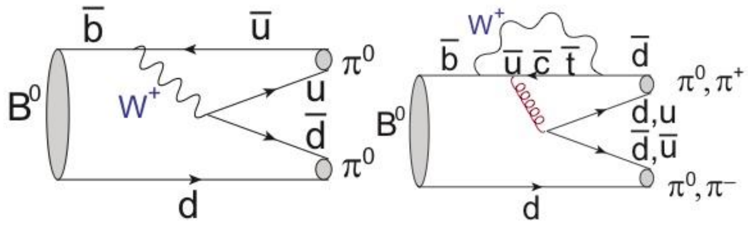
•The precision starts to be interesting but more statistics is crucial since each mode receives its own hadronic correction.

• The consistency is so far acceptable.



2.5 The angle α from B→ππ, B→ρρ and B→ρπ

• The angle α can be analogously to β measured in the time dependent interference between the mixing and the decay of buud processes.



$$A(B^0 \to \pi^+\pi^-) = T^{+-}e^{i\gamma} + P$$

• The situation is further complicated by the presence of penguin diagram exhibiting a different CKM phase. The CP asymmetry is modified as:

$$\begin{aligned} A(t) &= S_{\pi^+\pi^-}\sin(\Delta m t) - C_{\pi^+\pi^-}\cos(\Delta m t) \\ &= \sqrt{1-C^2_{\pi^+\pi^-}}\,\sin 2\alpha_{\mathrm{eff}}\,\sin(\Delta m t) - C_{\pi^+\pi^-}\cos(\Delta m t) \end{aligned}$$

$$\mathbf{S}_{\pi^+\pi^-} = \mathbf{\sin 2\alpha} + 2r\cos\delta\,\sin(\beta+\alpha)\cos 2\alpha + O(r^2)$$

$$r = |P|/|T|$$

• Additional information is required.

2.5 The angle α from $B\rightarrow\pi\pi$

• Use companion modes ($\pi\pi$) and isospin symmetry to disentangle penguin contributions:

Gronau, London (1990)

- completely general isospin decomposition

$$A_{+-} = \langle \pi^+\pi^- | H | B^0 \rangle = -A_{1/2} + \frac{1}{\sqrt{2}} A_{3/2} - \frac{1}{\sqrt{2}} A_{5/2}$$
$$A_{00} = \langle \pi^0\pi^0 | H | B^0 \rangle = \frac{1}{\sqrt{2}} A_{1/2} + A_{3/2} - A_{5/2}$$
$$A_{+0} = \langle \pi^+\pi^0 | H | B^+ \rangle = \frac{3}{2} A_{3/2} + A_{5/2}$$

• Tree and EWP contribute to $|\Delta I|=1/2$ and $3/2$ amplitudes
• QCD penguins contribute to $|\Delta I|=1/2$ amplitudes
• $|\Delta I|=5/2$ induced by Isospin Symmetry Breaking (not present in H_W)

• Neglecting $|\Delta I|=5/2$ transition and EWP, A+0 is pure Tree.

• Isospin triangular relation :

$$A_{+-} + \sqrt{2} A_{00} = \sqrt{2} A_{+0}$$
$$\bar{A}_{+-} + \sqrt{2} \bar{A}_{00} = \sqrt{2} \bar{A}_{+0}$$

2.5 The angle α from $B \to \pi\pi$

• Use companion modes ($\pi\pi$) and isospin symmetry to disentangle penguin contributions.

• In addition to the time dependant analysis parameters S and C, consider the BR of the companion modes.

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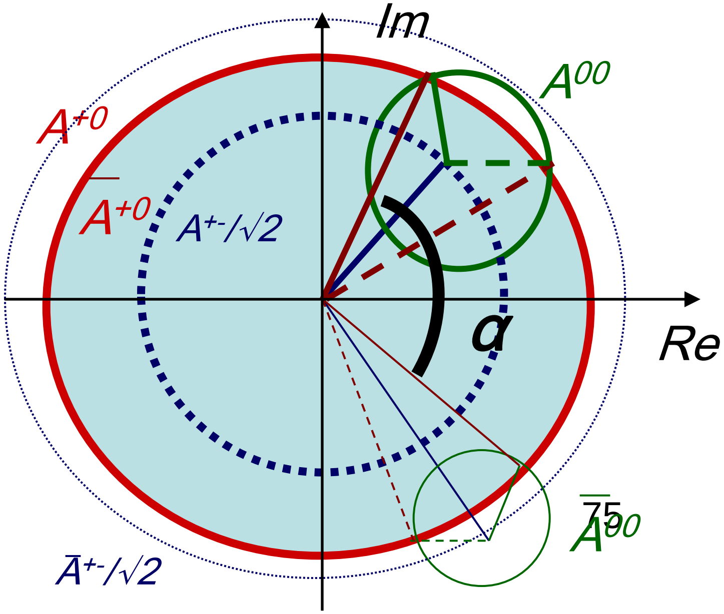
•Geometrical resolution:

- B^{+0} $\rightarrow |A^{+0}| = |\bar{A}^{+0}|$
- B^{+-}, C^{+-} $\rightarrow |A^{+-}|, |\bar{A}^{+-}|$
- S^{+-} $\rightarrow \sin(2\alpha_{eff}) \rightarrow$ 2-fold α_{eff} in $[0,\pi]$
- B^{00}, C^{00} $\rightarrow |A^{00}|, |\bar{A}^{00}|$

Closing SU(2) triangle ☐ 8-fold α

- S^{00} $\rightarrow$ relative phase between A^{00} & $\bar{A}^{00}$



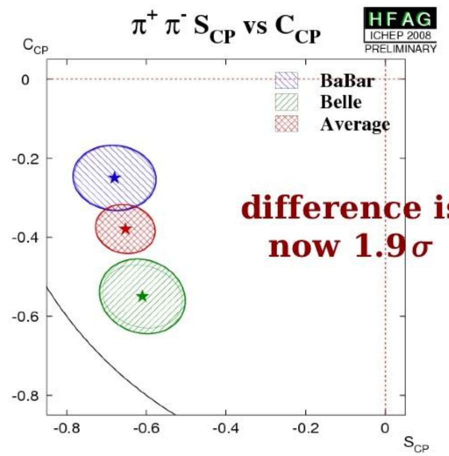
2.5 The angle α from $B \to \pi\pi$

$535 \times 10^6\ B\bar{B}$ pairs
PRL98, 221801(2007)

$C = -0.55 \pm 0.08 \pm 0.05$

$S = -0.61 \pm 0.10 \pm 0.04$

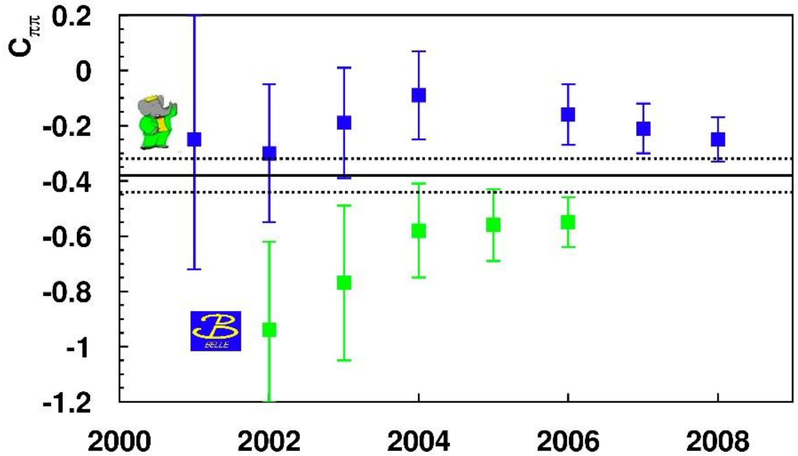
direct CPV @ 5.5σ



$467 \times 10^6\ B\bar{B}$ pairs
ArXiv:0807.4226

$C = -0.25 \pm 0.08 \pm 0.02$

$S = -0.68 \pm 0.10 \pm 0.03$



2.5 The angle α from $B \to \pi\pi$

α : $\pi\pi$ system (6 observables for 6 parameters)

$Br(B \to \pi^+\pi^-)$, $S_{\pi^+\pi^-}$, $C_{\pi^+\pi^-}$, $Br(B \to \pi^+\pi^0)$, $Br(B \to \pi^0\pi^0)$, $C_{\pi^0\pi^0}$

535×10^6 $B\bar{B}$ pairs
PRL 98, 221801 (2007)

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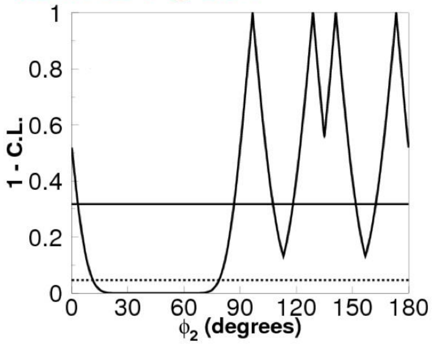
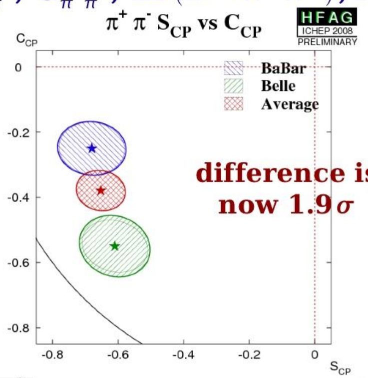


standard peak
$[86^\circ, 108^\circ]$ @ 68% C.L.



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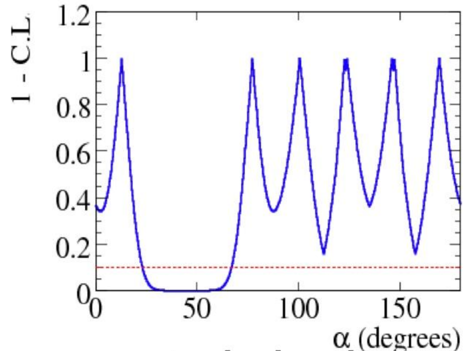


standard peak
$[71^\circ, 109^\circ]$ @ 68% C.L.

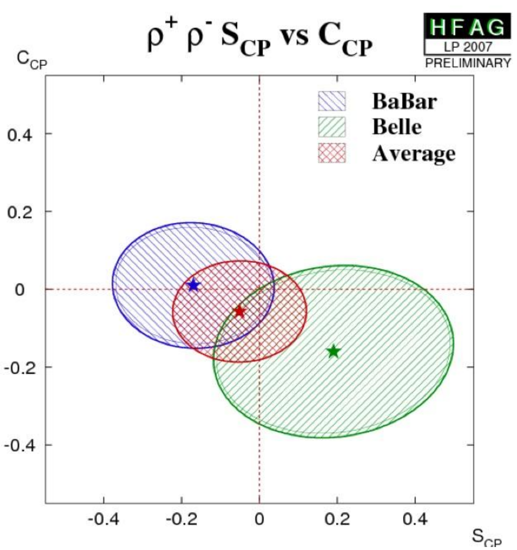
Note: the eightfold solutions are reduced to four because one isospin triangle is not closing.

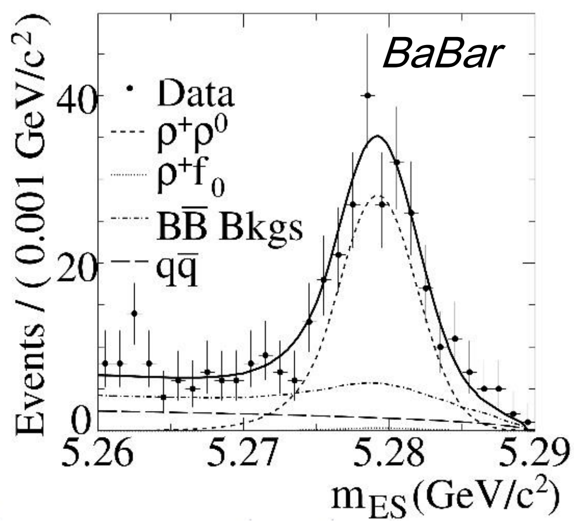
2.5 The angle α from B$\rightarrow\rho\rho$

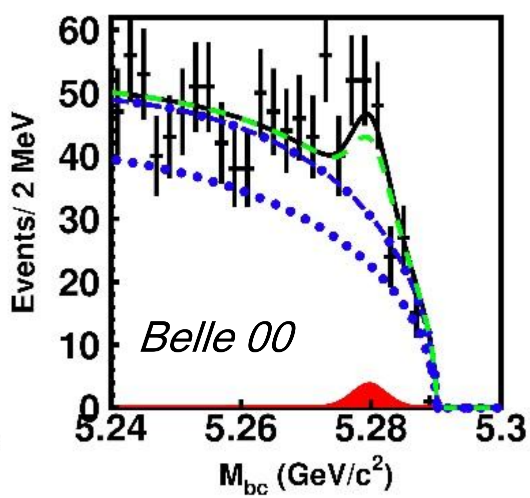
• B$\rightarrow$*VV* process but final state almost pure CP state as the decay is saturated with longitudinally saturated ρ's.

• Isospin decomposition same as B$\rightarrow\pi\pi$ at first order.

• The inputs of the analysis: $(\mathrm{Br}(B\rightarrow\rho^+\rho^-),\ S_{\rho^+\rho^-},\ C_{\rho^+\rho^-},\ \mathrm{Br}(B\rightarrow\rho^+\rho^0), \mathrm{Br}(B\rightarrow\rho^0\rho^0)) + f_L$



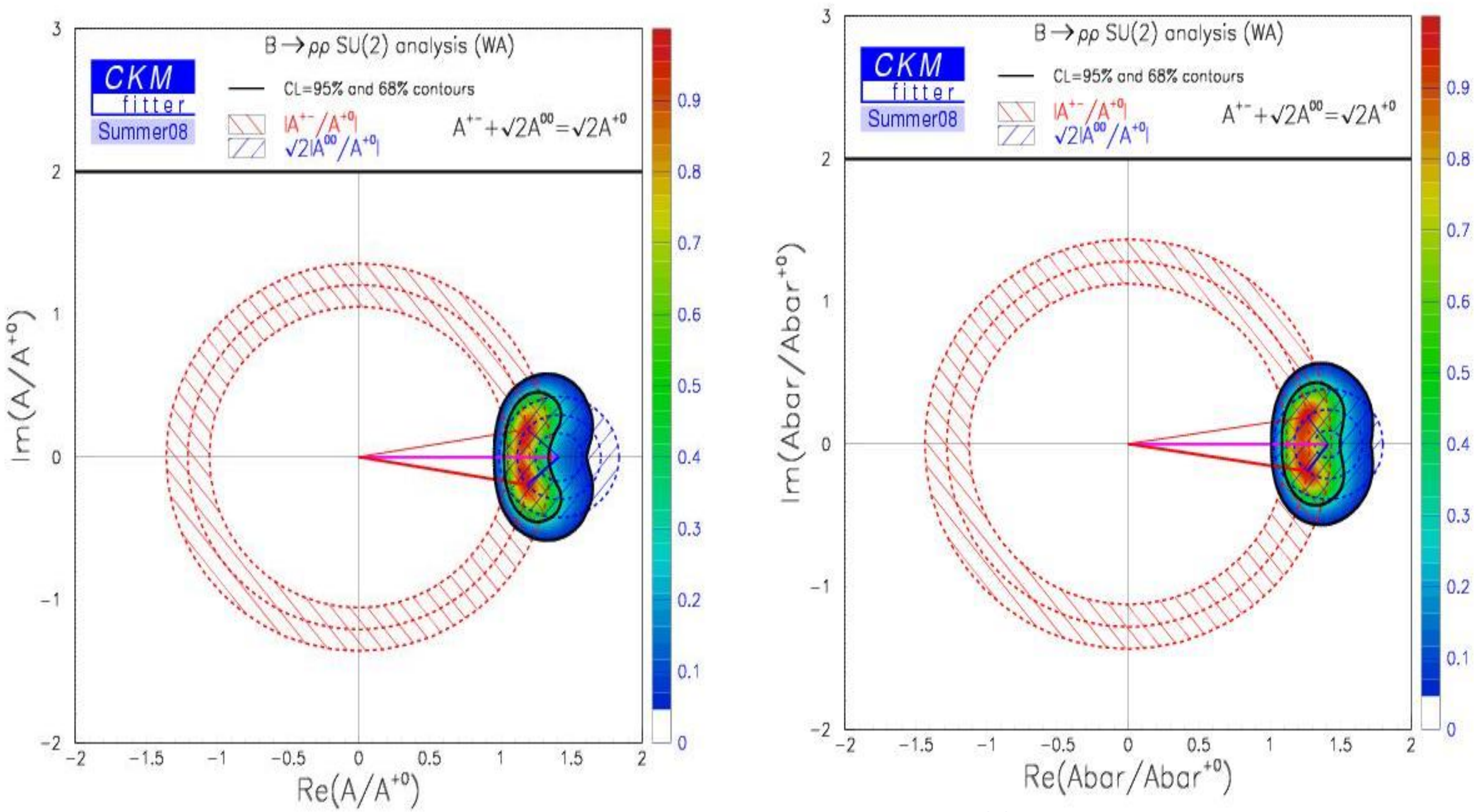




2.5 The angle α from $B \to \rho\rho$

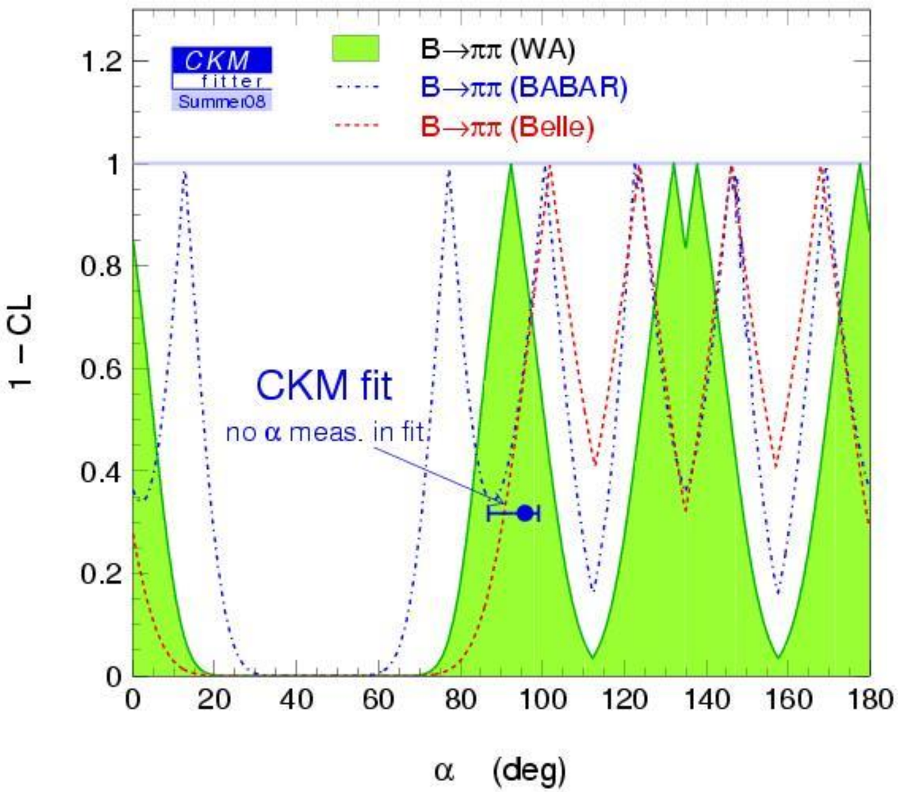
- *Inputs :*

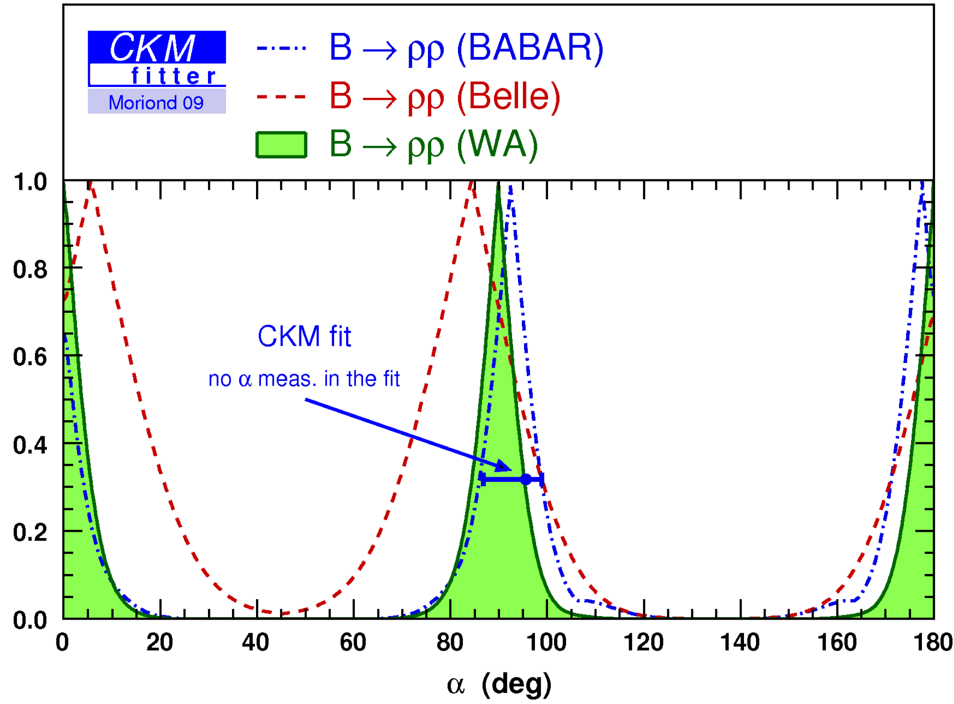
B^{+-}
B^{0+}
B^{00}
C^{+-}
S^{+-}
C^{00}
S^{00}
f_L^{+-}
f_L^{0+}
f_L^{00}



Both triangles (squashed because of the smallness of B^{00}) do close $\rightarrow$ 8-fold solution for alpha but S^{00} breaks the degeneracy.

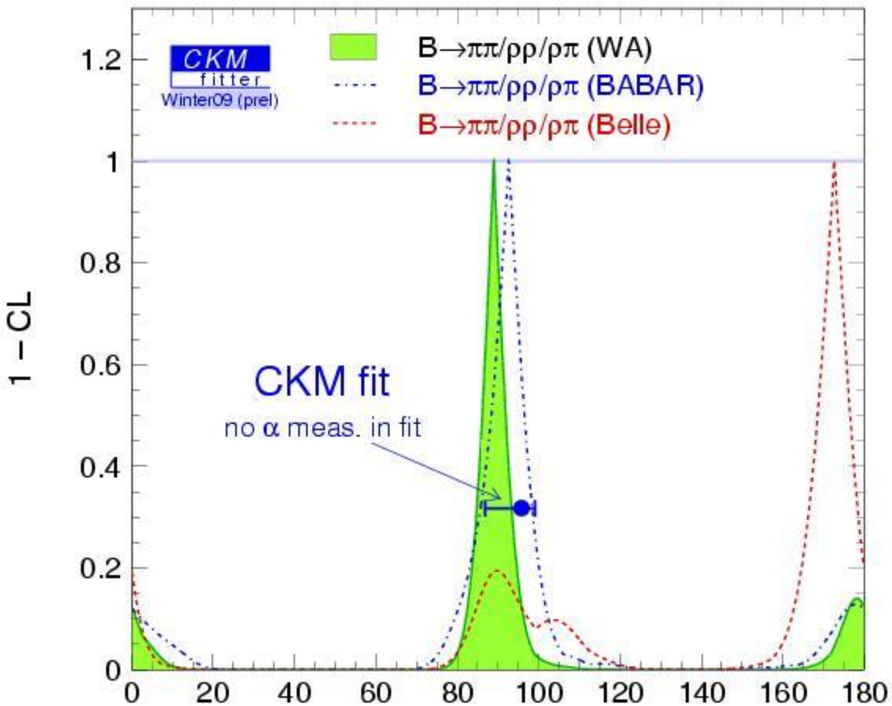
2.5 The angle α: WA



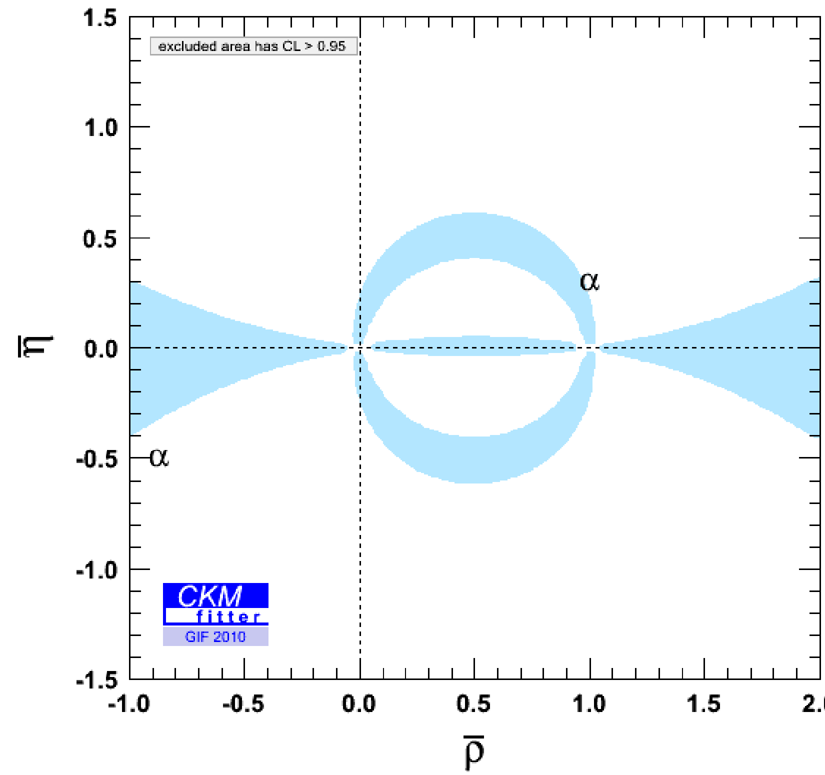


Nice consistency between BaBar and Belle measurements.

2.5 The angle α: WA



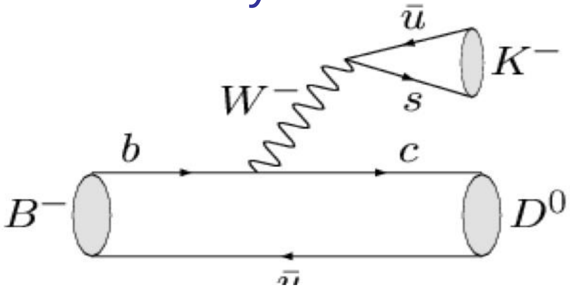
$$\alpha_{WA} = (89.0^{+4.4}_{-4.2})\ \mathrm{deg.}$$



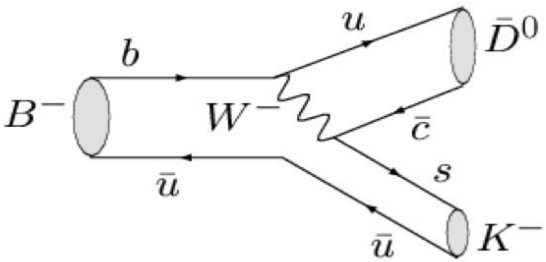
$B \to \rho\rho$ dominates the average. 5% (!) precision measurements.

2.6 The angle γ: principle of the measurement

• The determination of the angle γ requires interferences between charmless $b \to u$ transition and another weak phase, say for instance $b \to c$. This interference is realized in decays $B \to DK$.



$$
\begin{aligned}
A(B^- \to D^0 K^-) &= a \\
&\downarrow CP \\
\bar{A}(B^+ \to \bar{D}^0 K^+) &= a
\end{aligned}
$$



$$
\begin{aligned}
A(B^- \to D^0 K^-) &= a e^{-i\gamma} r_B e^{i\delta_B} \\
&\downarrow CP \\
\bar{A}(B^+ \to D^0 K^+) &= a e^{+i\gamma} r_B e^{i\delta_B}
\end{aligned}
$$

• The interference level between $b \to u$ and $b \to c$ transitions is controlled by the parameter r_B:

$$
r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|
$$

• No penguin: theoretically clean. But one has to reach through undistinguisble paths the same final state !

2.6 The angle γ: the methods

• We hence have to reconstruct the D mesons in final states accessible to both D^0 and anti-D^0. There are three main techniques which have been undertaken at B factories:

1. GLW (Gronau, London, Wyler): search for *D* mesons decays into 2-body CP eigenstates, *e.g* K^+K^-, $\pi^+\pi^-$ (CP=+) or $K_S\pi^0$, ϕK_S (CP=-). Somehow natural but very low branching fractions.

2. ADS (Atwood, Dunietz, Soni): Use anti-$D^0 \rightarrow K^-\pi^+$ for $b \rightarrow u$ transitions (Cabibbo allowed) and $D^0 \rightarrow K^-\pi^+$ (Doubly Cabibbo suppressed) for $b \rightarrow c$ transitions. Again low branching fractions and additonally one has to know the strong phase of the *D* decay.

3. GGSZ (Giri, Grossman, Sofer, Zupan): use 3-body CP eigenstates of the *D* to be resolved in the Dalitz plane. $D \rightarrow K_S\pi^+\pi^-$. So far the only way to get the angle gamma.

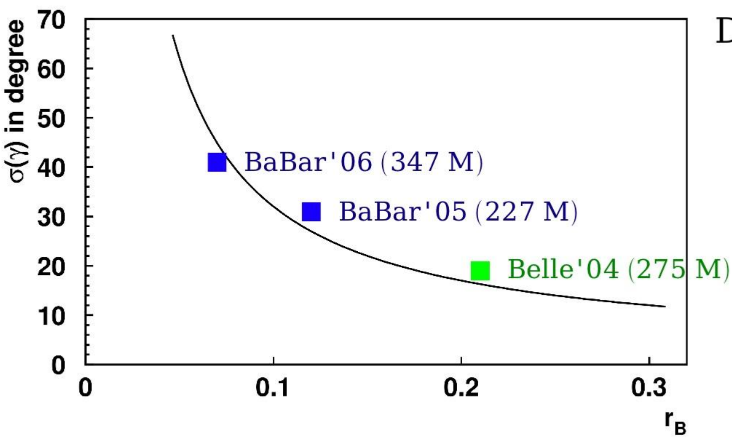
   Note: I used D^0K for illustration. The same stands for D*K and DK*. The hadronic factors (r_B, δ_B) are however different in each case.

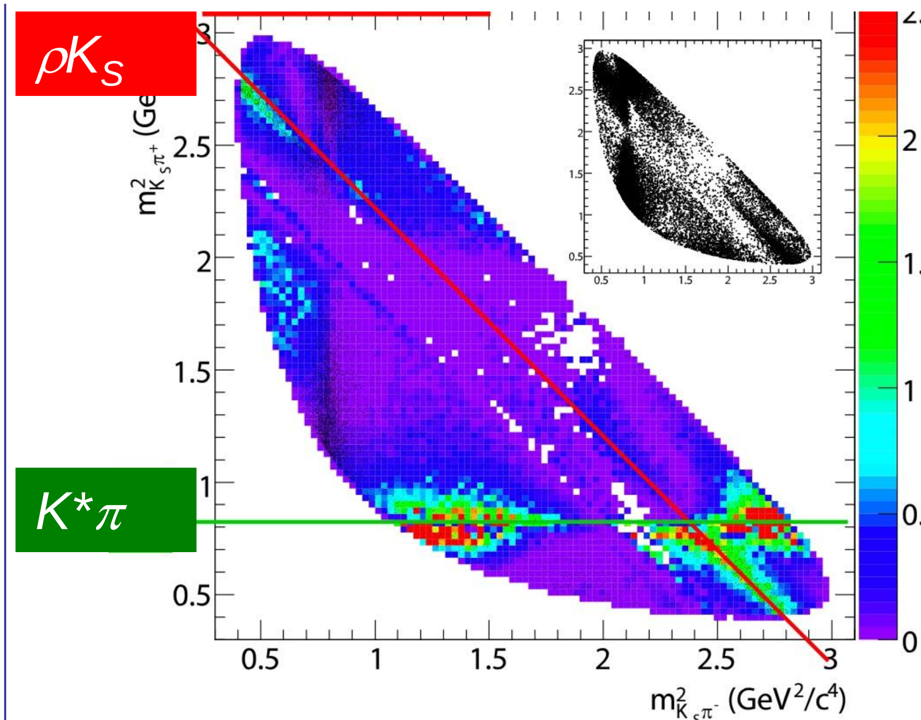
2.6 The angle γ: sensitivity GGSZ

- In the Dalitz plane, the level of interference is controlled by the cartesian coordinates (they are the experimental inputs for gamma extraction):

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$
$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

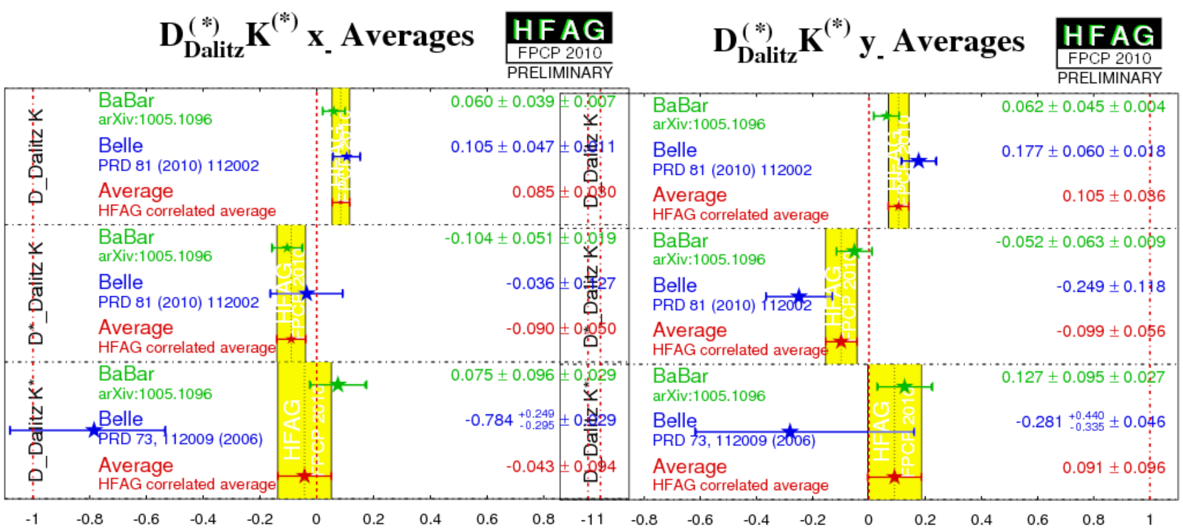
- How does the uncertainty on γ scales with r_B? $1/r_B$ …

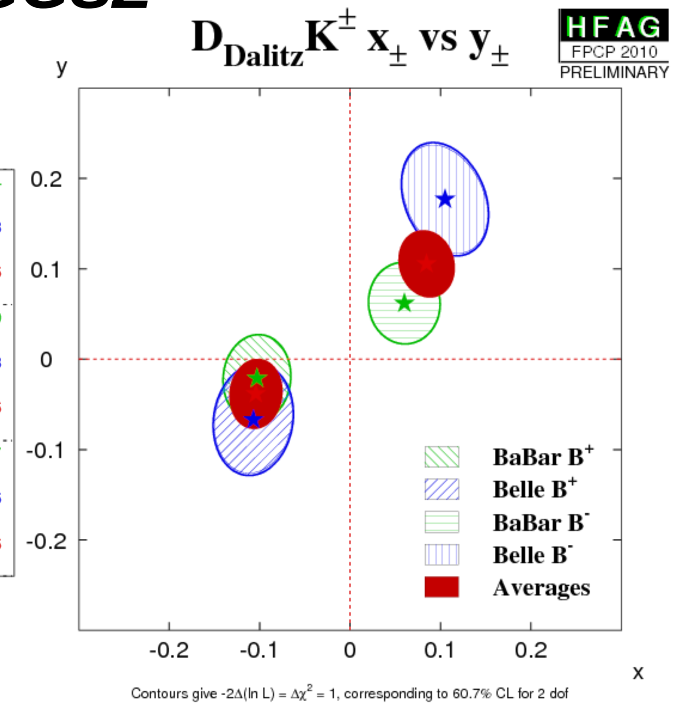




- Sensitivity plot. Which regions of the Dalitz plane do contribute the more to the gamma precision: $K^*\pi$ and ρK_S bands.

2.6 The angle γ: results GGSZ





- Best precision for DK mode.

- The BaBar and Belle experiments extracted gamma using a frequentist scheme:

$$\gamma_{\rm BaBar} = 69\ ^{+15}_{-14}\ ({\rm stat.}) \pm 4\ ({\rm syst.}) \pm 3(\ {\rm mod.})\ {\rm deg}$$
$$\gamma_{\rm Belle} = 78\ ^{+11}_{-12}\ ({\rm stat.}) \pm 4\ ({\rm syst.}) \pm 9(\ {\rm mod.})\ {\rm deg}$$

2.6 The angle γ: WA

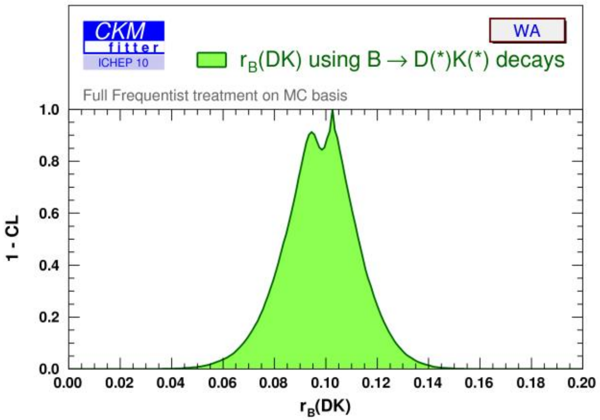
• GGSZ method is nowadays the best way to extract the γ angle. Other methods provide very valuable constraints on r_B and hence contribute to the overall precision.

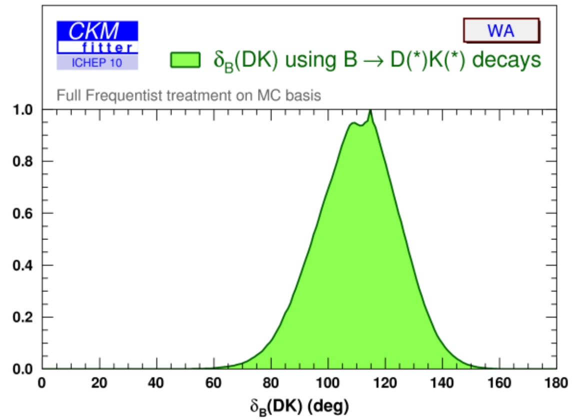
• The high statistics expected at the LHC will allow to measure the γ angle with a precision comparable to what is achieved with α.

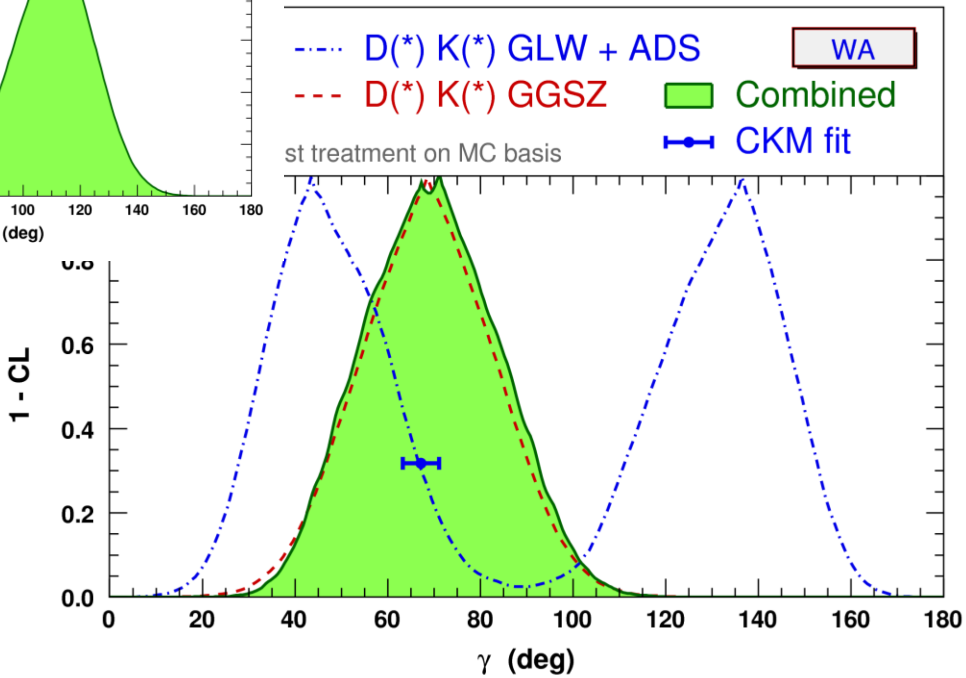
• Though the less well determined angle of the Unitarity triangle, the γ angle measurement is a tremendous achievement of the B factories: was not foreseen at the beginning of their operation.

• CKMfitter extraction of the γ angle makes use a full frequentist treatment (MC based) to ensure all the possible values of nuisance parameters (r_B in particular) are tested in the evaluation of the coverage. Significant variation on the global uncertainty w.r.t less sophisticated method.

2.6 The angle γ: WA





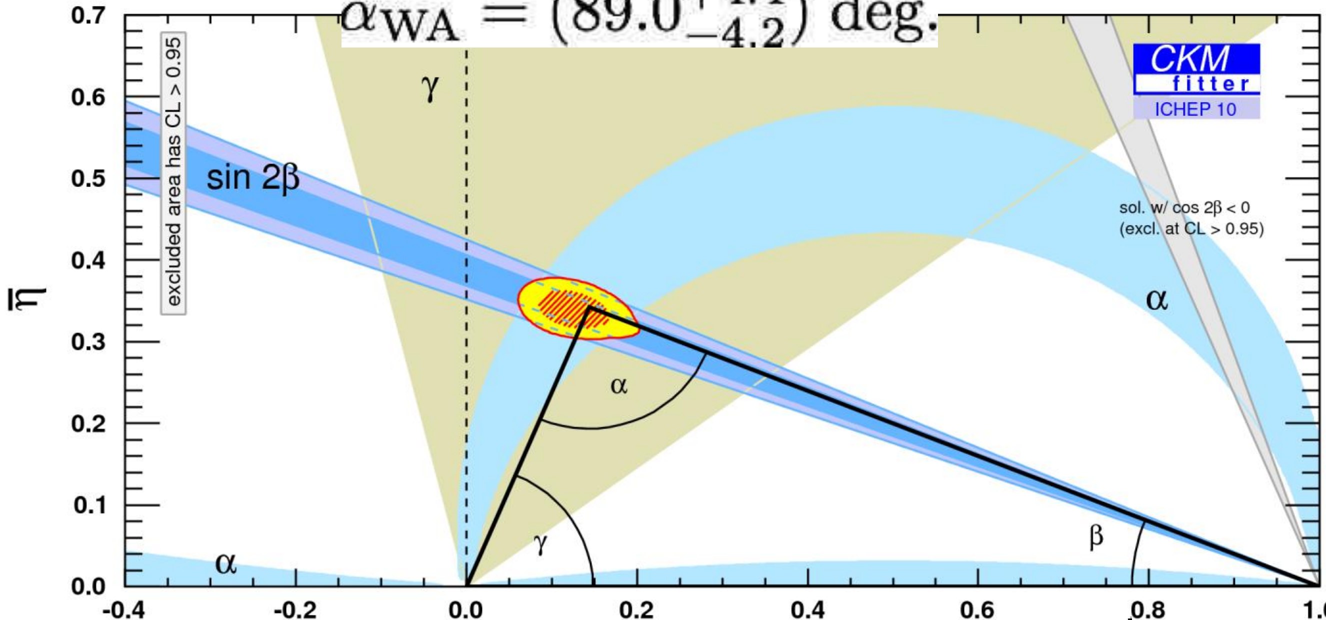


$$\gamma_{\mathrm{WA}} = 71\,^{+21}_{-25}\ \mathrm{deg}$$

2.7 Conclusion of Chapter 2 and introduction to Chapter 3

• We have now all the relevant experimental ingredients to produce the consistency check of all observables in the Standard Model and hence test the KM mechanism. By anticipation, we can produce a unitarity triangle with angles only:

$$\alpha_{\rm WA} = (89.0^{+4.4}_{-4.2})\ \text{deg.}$$



$$\gamma_{\rm WA} = (71\ ^{+21}_{-25})\ \text{deg} \qquad \bar{\rho} \qquad \beta_{\rm WA} = (21.1 \pm 0.9)\ \text{deg}$$