Overview of CP Violation in the Quark Sector

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Outline

- Introduction to CP violation
  - Definitions and Background
  - CP Violation in the Flavor sector of Standard Model:
    CKM Matrix, Unitarity Triangle
  - Experimental Physics Goals

- How do we do measurements?
- A few Major Experimental Results

- Conclusion
  - What do we know today?
  - Future

Definitions and Background

- **Symmetry:** Transformation of a system that does not change the physics laws formulation for this system

CP: the two applied consec-utively

- **The Parity P:** Inversion of the spatial coordinates, image in a mirror $$\vec{x} \to -\vec{x}$$
- **The Charge conjugation C:** Change of all the charge quantum numbers into their opposite, transforms a particle into its anti-particle $$q_i \to -q_i$$

CP Violation ⇔ the world is not symmetric under CP transformation

In the **Standard Model** of Particle Physics (**SM**):

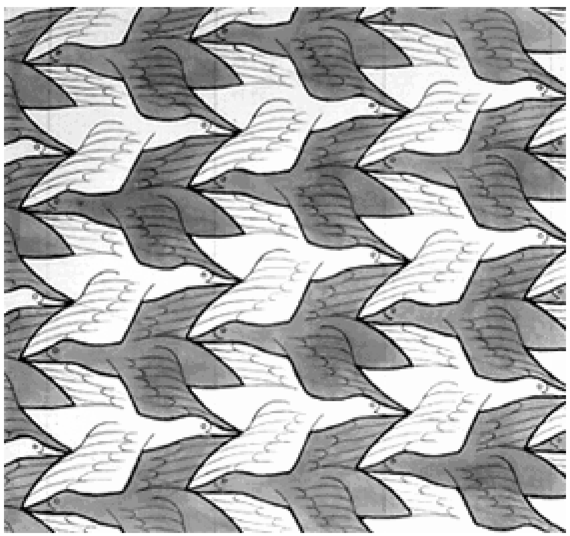
- **C** and **P** are symmetries of strong and electromagnetic interactions.
- **C** and **P** symmetries are violated by weak interaction
- **CP** symmetry is **slightly violated by weak interaction**

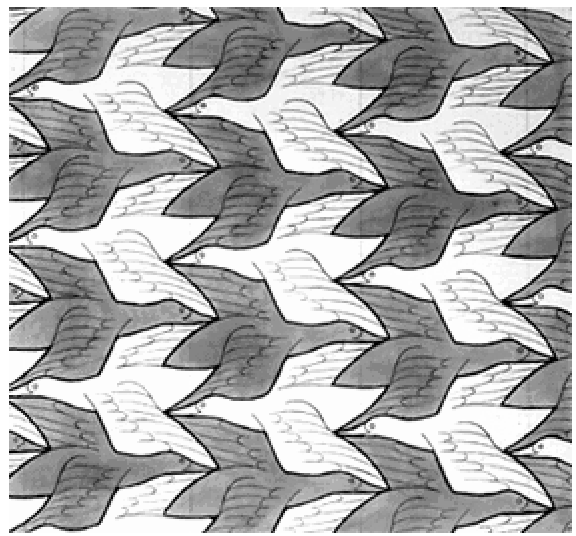
CP Violation with Escher's Images

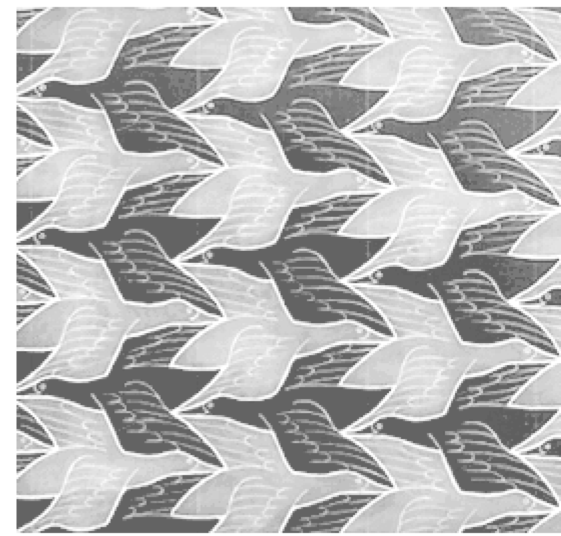
CP (anti-matter in a mirror)

P (mirror) **C** (anti-matter)

White geese fly right | White geese fly left | White geese fly right







Slight breaking of CP (look at the tails…)

Analogy to weak interaction in the Standard Model.

The CKM Matrix

In the Quark sector: Week Int. eigenstates ≠ Mass eigenstates

⇔ Quarks that participate in weak processes are linear combinations of mass eigenstates

⇔ Existence of 3X3 unitary matrix describing the **mixing of quarks**: the **CKM Matrix**

The CKM Matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_J = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_M$$

CKM matrix — Wolfenstein parameterization:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Expansion in powers of λ at the order λ^3 with $\lambda = \sin(\theta_{cabibbo}) \approx 0.22$

~ half of the SM

10 free parameters in the Flavor sector of the SM

6 quark masses

4 CKM parameters (Wolfenstein : λ ,A, ρ, η)

From CKM Matrix to Unitarity Triangle

CKM matrix Wolfenstein parameterization:

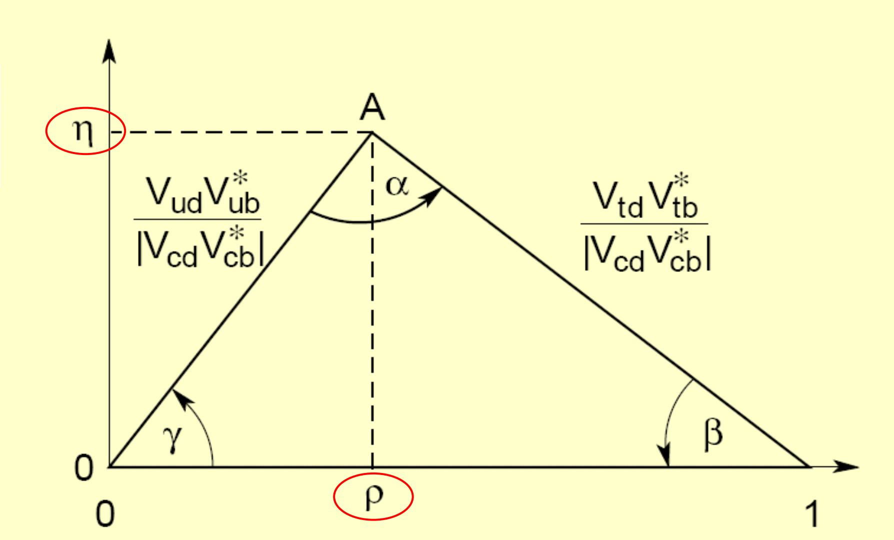
$$\begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

V_{CKM} Unitarity $\Rightarrow$

$$\underbrace{V_{ud}V_{ub}^*}_{\propto\lambda^3} + \underbrace{V_{cd}V_{cb}^*}_{\propto\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{\propto\lambda^3} = 0$$

Other unitarity conditions (triangles) are difficult to use: Sides are very different.

Try it with second and third columns…



CP Violation is possible in the Standard Model only if

V_{CKM} is complex $\Leftrightarrow$ $\eta \neq 0$ $\Leftrightarrow$ Unitarity Triangle is not flat

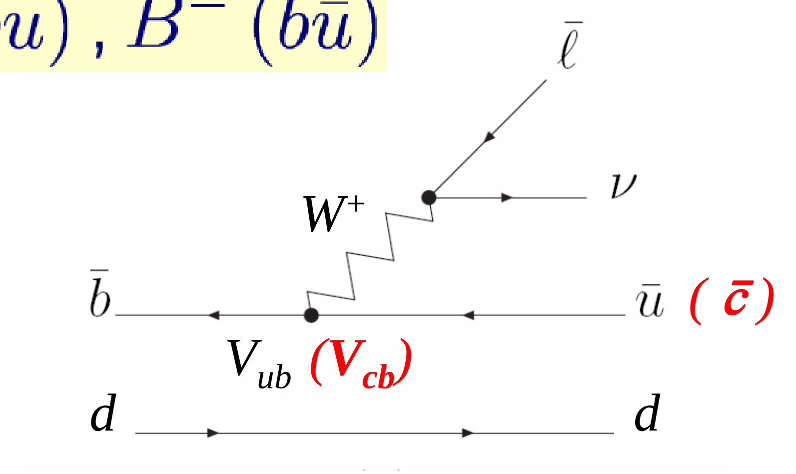
We want to determine ρ and η experimentally

Examples of Weak Processes

$$B^0\,(\bar{b}d)\;,\;\bar{B}^0(b\bar{d})\;,\;B^+\,(\bar{b}u)\;,\;B^-\,(b\bar{u})$$

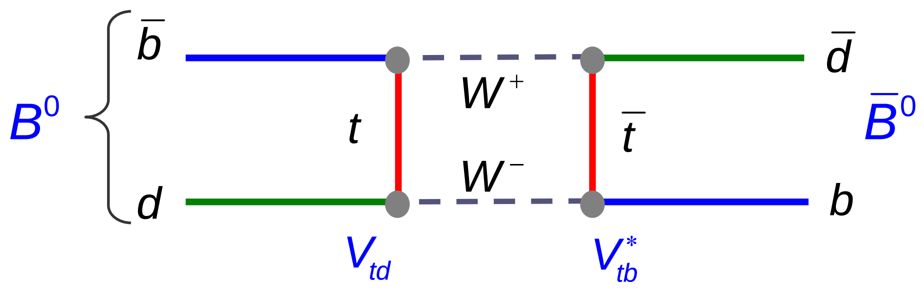
- **Semileptonic Decay of B^0**

Provide information on V_{ub} (V_{cb})



- **$B^0 \leftrightarrow \bar{B}^0$ Oscillations**

$\propto$ $(V_{td}\, V^*_{tb})^2$



More on B Oscillations

With the weak int. eigenstates:

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

Oscillation frequency, width difference:

$$\Delta M_d = m_{B_H} - m_{B_L}$$
$$\Gamma_d = \Gamma_{B_H} - \Gamma_{B_L}$$

Time evolution of a B meson that was a B^0 at t=0:

$$|B^0(t)\rangle = e^{-im_B t} e^{-\Gamma_d t/2} \left[\cos\left(\frac{\Delta m_d t}{2}\right)|B^0\rangle + i\frac{q}{p}\sin\left(\frac{\Delta m_d t}{2}\right)|\overline{B}^0\rangle\right]$$

Decay term

Oscillation term

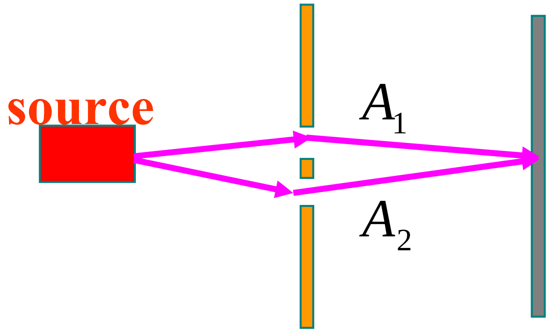
Competition between oscillation and decay

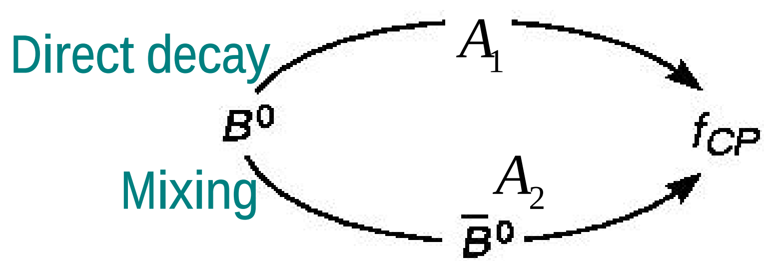
To study oscillations, need to identify the species of the *B* meson at time t=0.
To follow its time evolution, need to measure time.

Two Types of CP Violation

- **Direct CP Violation:** $B \to f \neq \bar{B} \to \bar{f}$, with $f \neq \bar{f}$
  - To measure it, only need to count events.
    Rates are different ⇔ CP is violated
  - Only type of CP violation for charged B mesons
- **CP violation in the interference between decay and mixing:** $B^0 \to f \neq \bar{B}^0 \to f$

Analogy to "Double-Slit" experiment

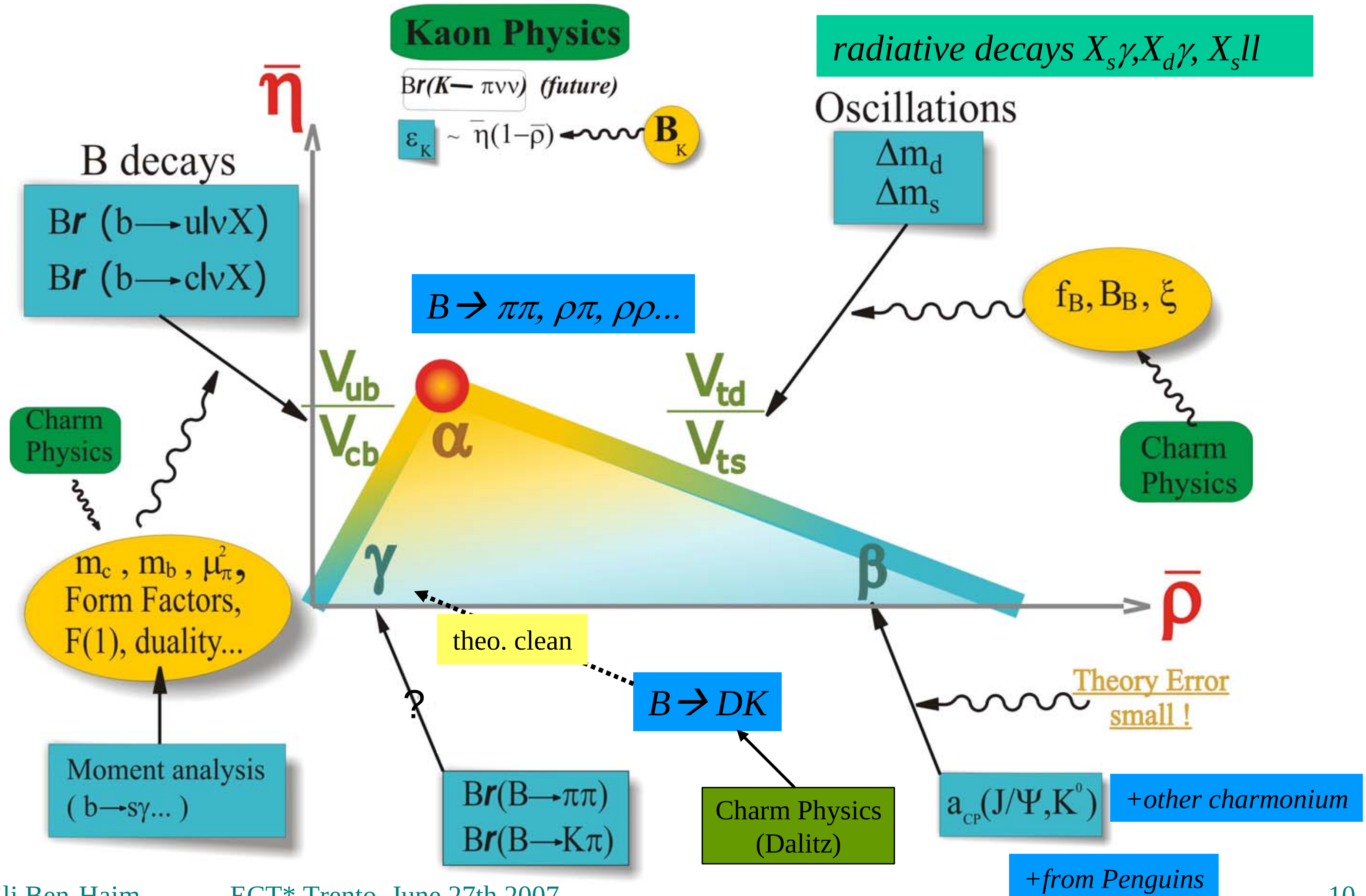




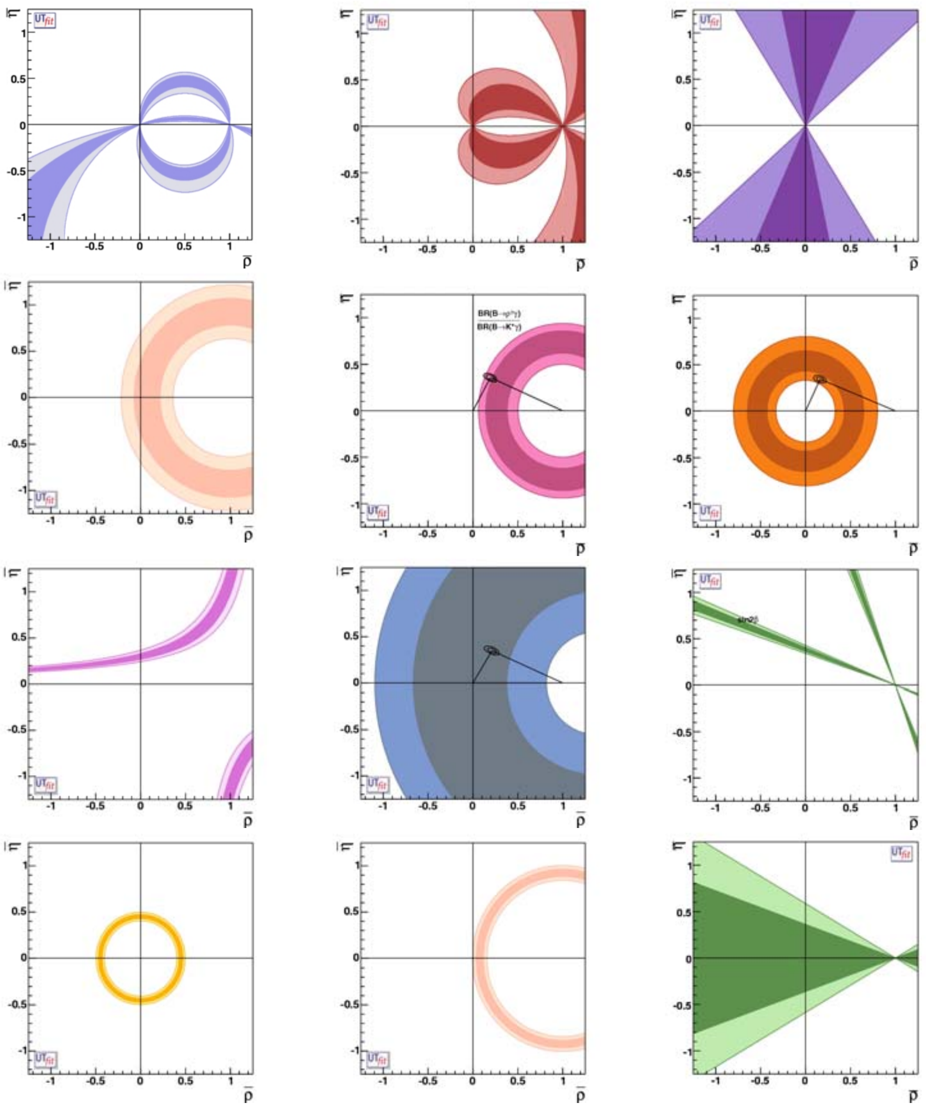
In the double-slit experiment, there are two paths to the same point on the screen.

In the B experiment, we must choose final states into which both a $\bar{B}^0$ and a B^0 can decay. *We perform the B experiment twice* (starting from B^0 and from $\bar{B}^0$). We then compare the results.

How to Get ρ and η from Experiments?



The Unitarity Triangle Fit



- Quantify CP Violation within the Standard Model with precision measurements of its angles and sides

- Test the Standard Model, by over- constraining the Unitarity Triangle with redundant measurements. If there is New Physics (not described by the Standard Model), we might see some incompatibilities between several independent measurements of the same parameter of the UT.

Intermediate Summary, What do We know by Now?

- CP and CP violation
- CKM Matrix and the Unitarity Triangle
- B mixing

- Goals and motivations for studying CP violation:
  - Constrain the Standard Model by measuring its free parameters. Flavor sector in one of its less known parts before B-Factories
  - Test the Standard Model and eventually challenge it by showing discrepancies between several measurements of the same parameters → a window for discovery of New Physics

  - It is also one of the necessary conditions to explain matter-antimatter asymmetry in the universe

Sakharov, JETP Lett. **5**, 24 (1967).

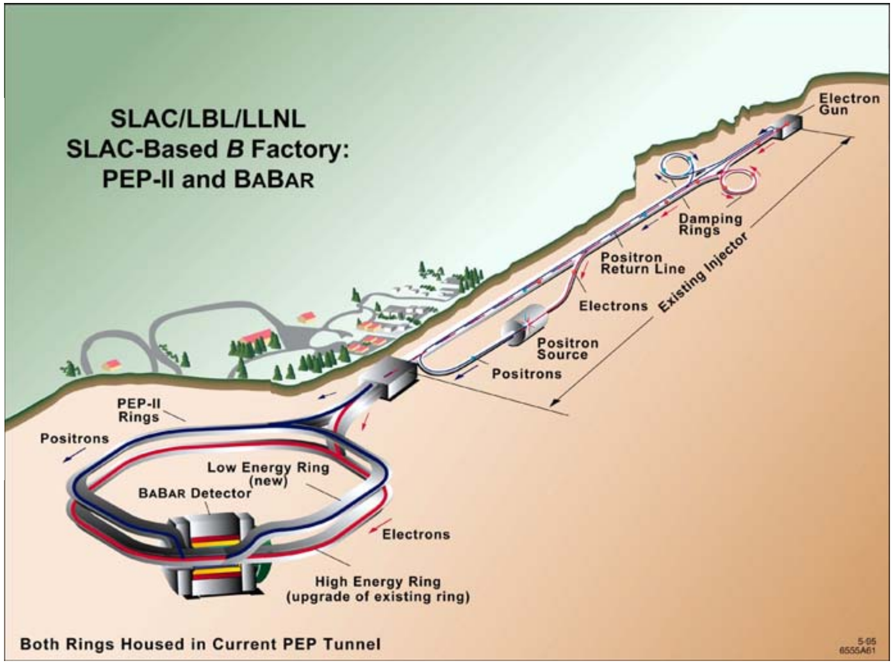
B-Factories

- Experiments designed for precision measurements of CP violation in the B meson (and Charm) sector

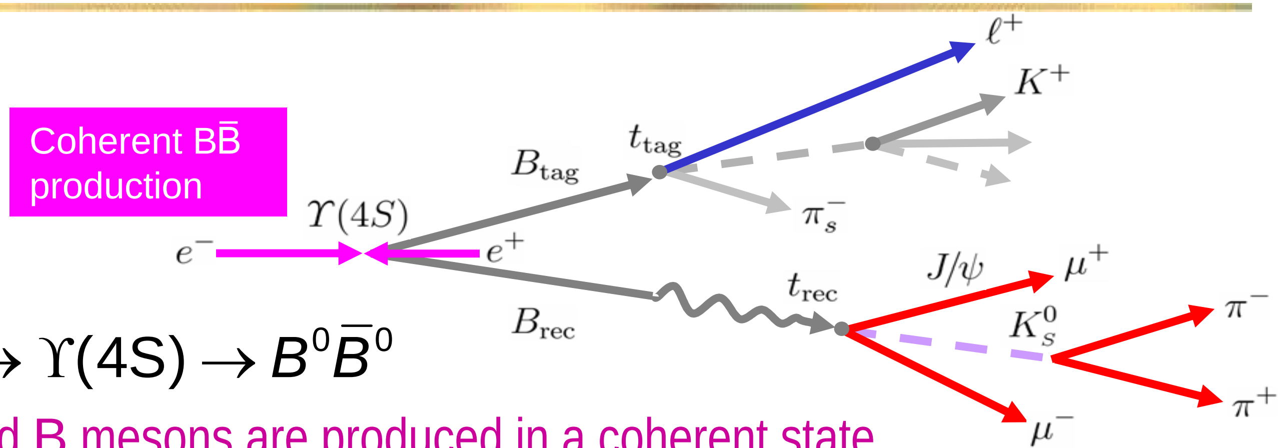
- Two active B-Factories experiments:
  - BaBar, in Stanford Linear Accelerator Center (California)
  - Belle, in KEKB (Japan)

- The BaBar experiment:

$e^-(9\,\mathrm{GeV})/e^+(3.1\,\mathrm{GeV})$ collision
$E_{CM} = m(\Upsilon(4S)) = 10.58\,\mathrm{GeV}$
$e^+e^- \to \Upsilon(4S) \to B/\bar{B}$
almost at rest in the CM frame
boost of $\Upsilon(4S)$ with $\beta\gamma = 0.56$



Time Dependent Measurements, Flavor Tagging



$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$$

Two boosted B mesons are produced in a coherent state

$\Rightarrow$ until the first B decay, there is exactly one B^0 and one $\bar{B}^0$

$\beta\gamma \sim 0.56$
$\Delta t = 1.6$ ps $\Leftrightarrow$ $\Delta z \approx 200, 250\ \mu$m

Problem:

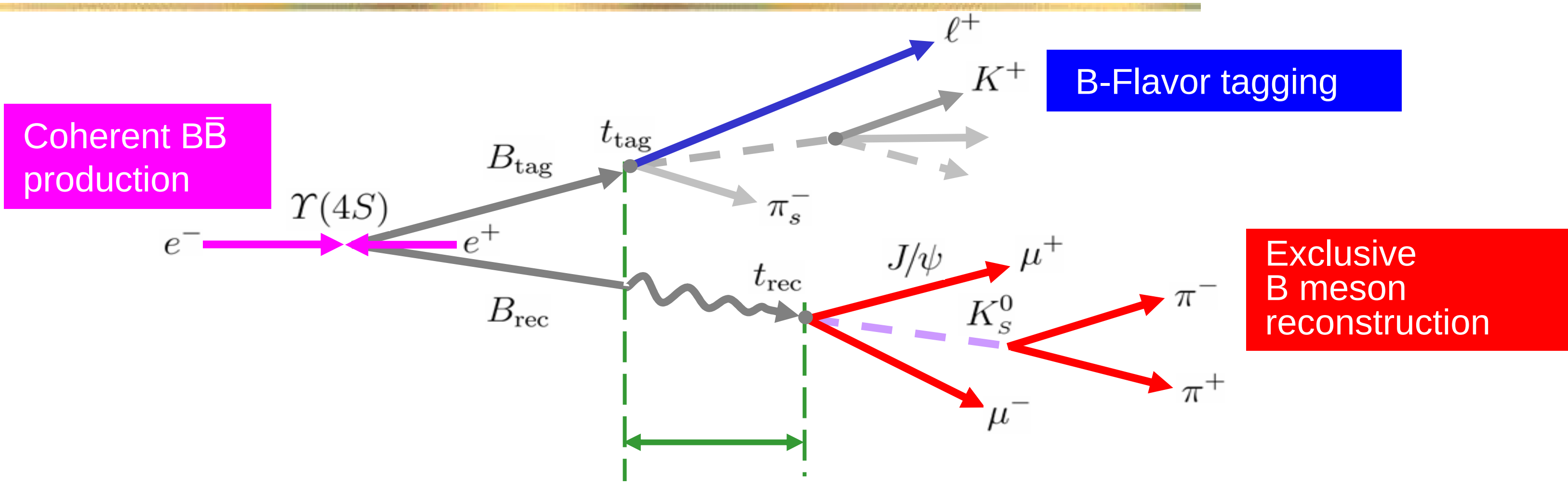
If we want to study a decay $B^0 \to f$

Where f is also accessible by an anti-B^0 $\bar{B}^0 \to f$

And we want to see if $B^0 \to f \neq \bar{B}^0 \to f$

We need to find a clever way to know the B flavor

Time Dependent Measurements, Flavor Tagging



$$\Delta t \equiv t_{rec} - t_{tag} \approx \Delta z / \beta\gamma c$$

Solution:

- There is coherent evolution until B_{tag} decays
- At t_{tag} the flavor of B_{reco} is the opposite of the B_{tag}'s flavor
- B_{reco}'s flavor determined from B_{tag}'s flavor and Δt
- Boost: Δt measured via space length measurement between B_{tag} and B_{reco} Δz
- Flavor of the B_{tag} determined by its decay product: charge of leptons, K, π

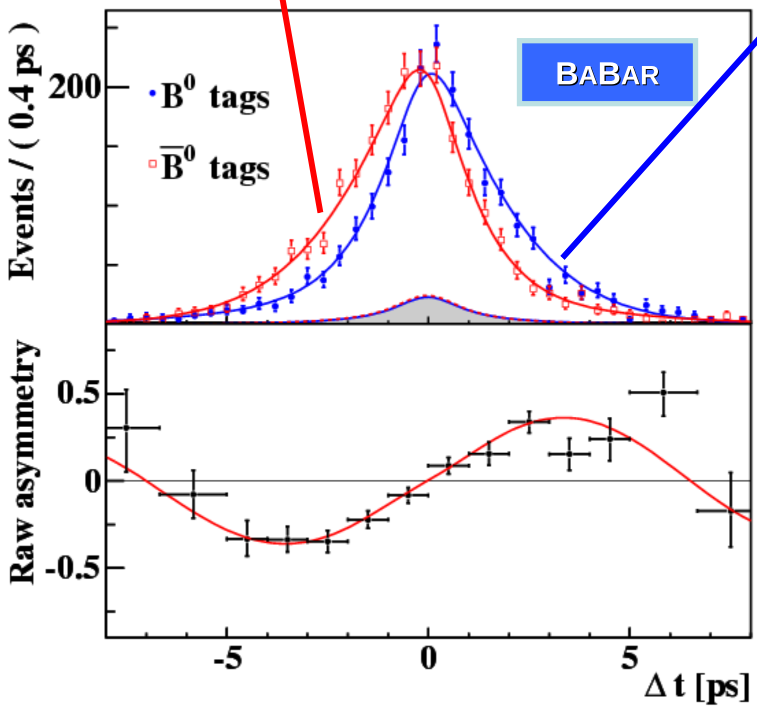
Measurement of sin(2β) with $B^0 \to J/\psi\, K^0_S$

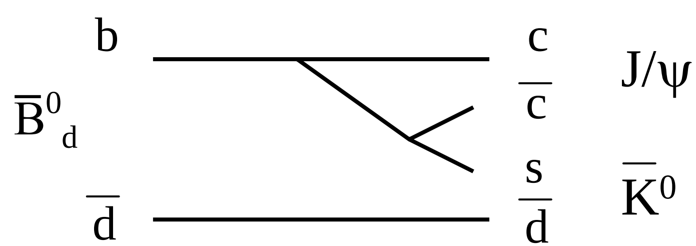
- Final state accessible to B^0 and $\bar{B}^0$ → Time dependent asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)} = \boxed{S}\sin(\Delta m_d t) - \boxed{C}\cos(\Delta m_d t)$$

indirect

direct





~only one amplitude

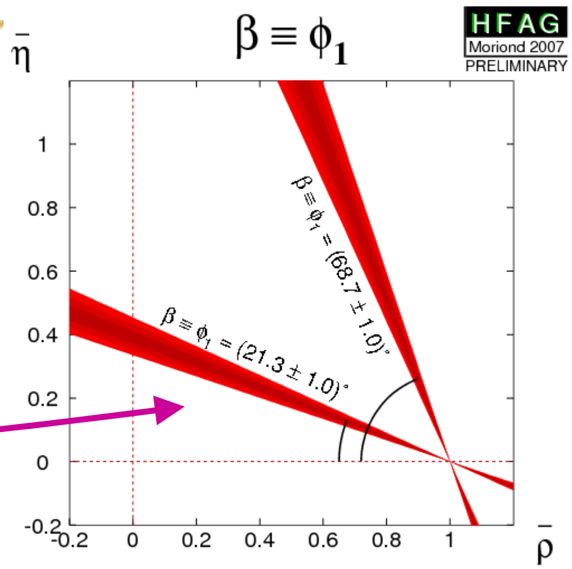
$$C_f = 0$$

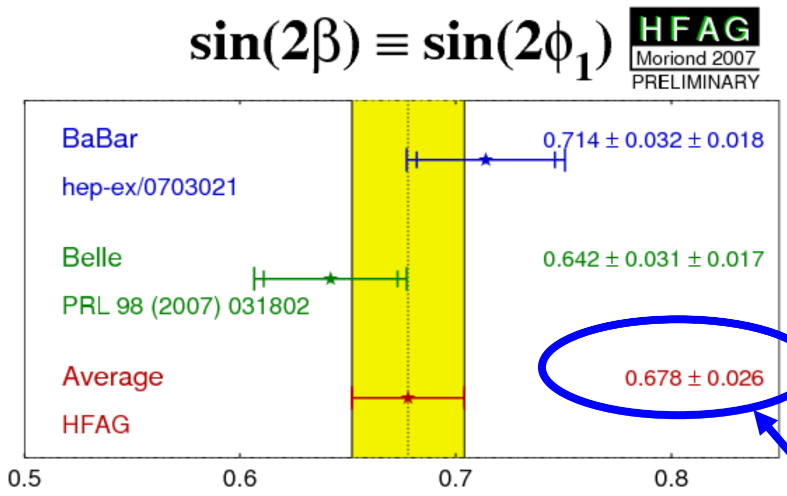
$$S_f = -\eta_{CP} \sin 2\beta$$

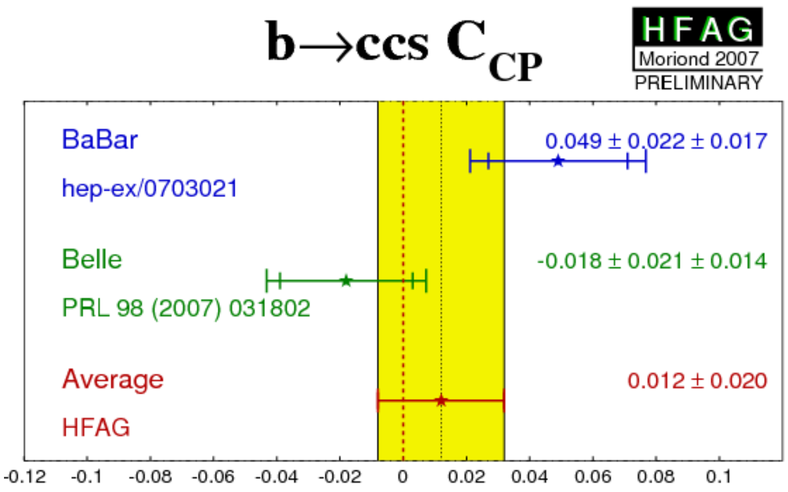
⇒ Extraction of sin(2β) from A_{cp}

Measurement of sin(2β) with $B^0 \rightarrow J/\psi\, K^0_S$

- This measurement is theoretically clean (at 1%)
- Benefits from a large data sample
- Sin(2β) gives the best **constraint on ρ-η plane**

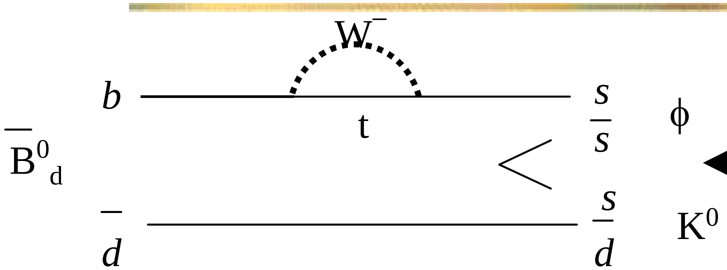




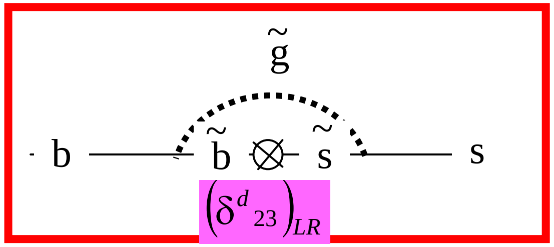


$\boxed{\sin(2\beta) \neq 0 \quad \Rightarrow \text{non flat triangle i.e. CP violation}}$

Measurement of sin(2β) with "s Penguins"

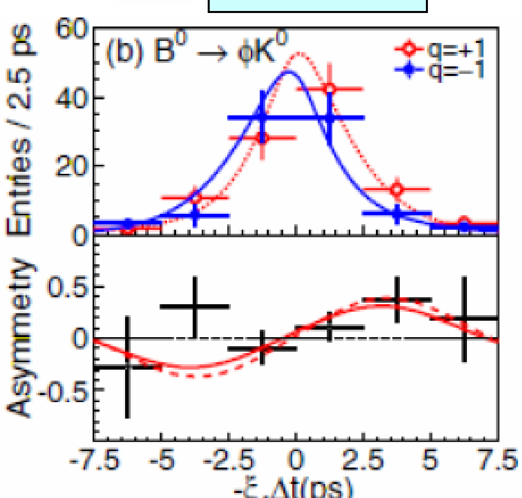


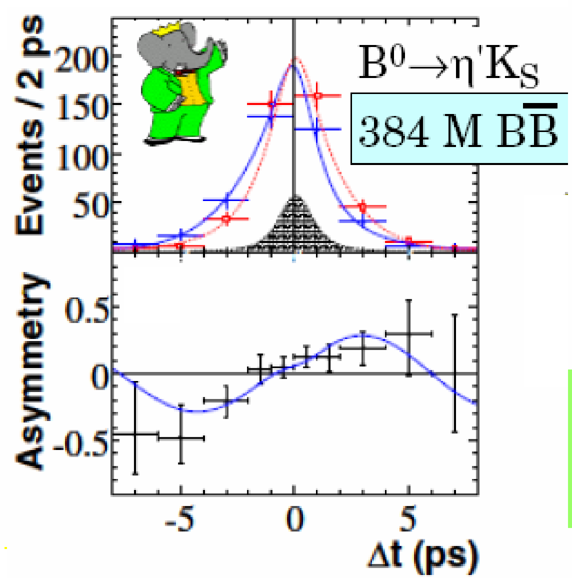
Standard Model contribution

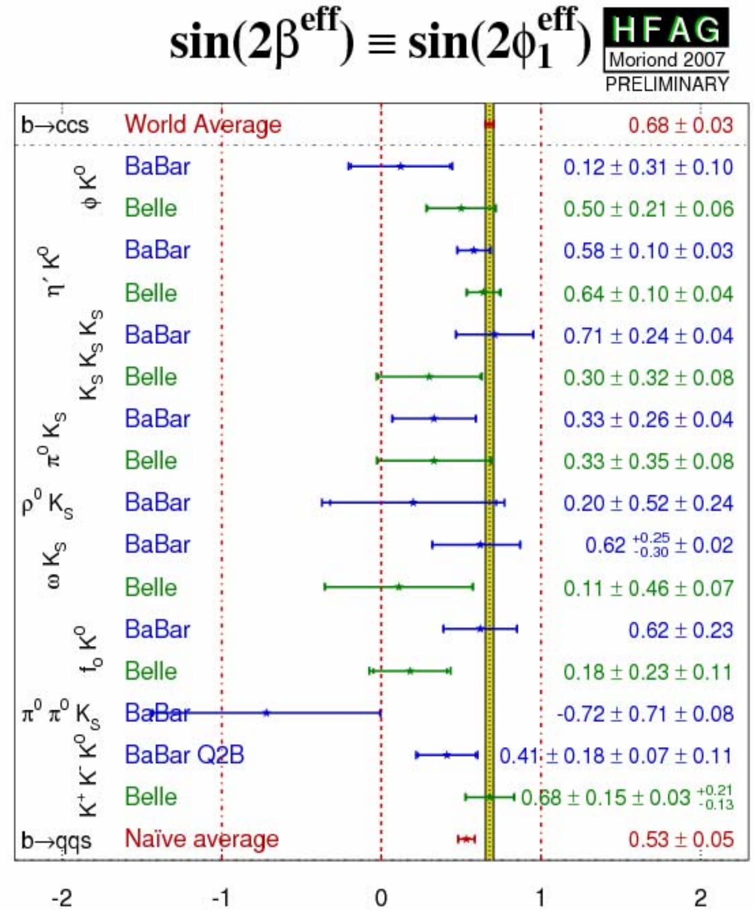


New Physics contribution

535 M $B\bar{B}$







Tensions between sin2β from b→ccs and b→qqs

B^0_s Oscillations: Δm_s Measurement at the TeVatron

$\Delta m_d = 0.509 \pm 0.006\ ps^{-1}$
$\Delta m_s \sim 30 \times \Delta m_d$
$\Rightarrow$ **Rapid oscillations for B^0_s**

Behavior in proper time

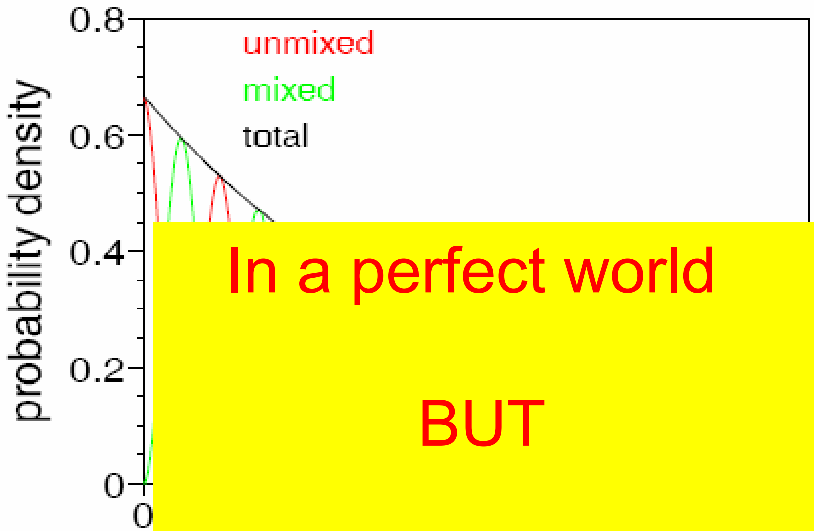
$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

In this case, they are able to determine the flavor at decay and at production

Determine asymmetry

$$A_0(t) = \frac{N(t)_{unmixed}-N(t)_{mixed}}{N(t)_{unmixed}+N(t)_{mixed}} = \cos\Delta m\, t$$

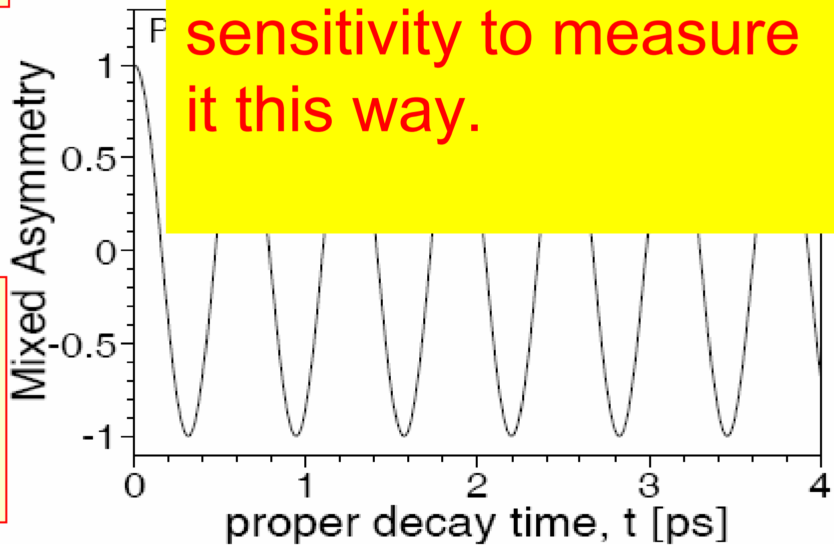
- "unmixed": same flavor at decay and at production
- "mixed": different flavor



In a perfect world

BUT

They do not have the sensitivity to measure it this way.



Δm_s Measurement: Fourier Analysis

Two domains to fit for oscillation:

Time domain:

- fit for Δm_s in $P(t) \sim (1 \pm D \cos \Delta m_s t)$

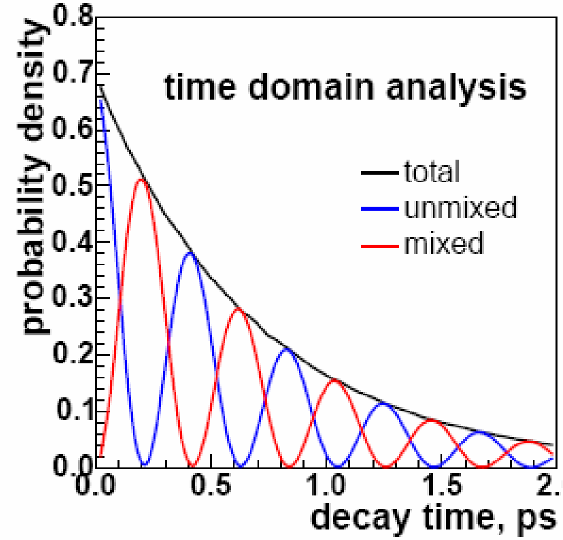
Frequency domain: amplitude scan

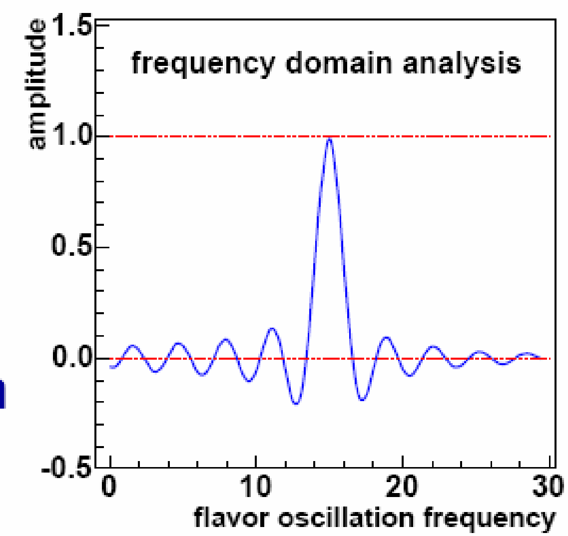
- introduce amplitude:
  $P(t) \sim (1 \pm \mathcal{A} D \cos \Delta m_s t)$
- fit for $\mathcal{A}$ at different Δm_s

$\Rightarrow$ obtain frequency spectrum

- true $\Delta m_s \Rightarrow \mathcal{A} = 1$, else $\mathcal{A} = 0$
- traditionally used for B_s^0 mixing search

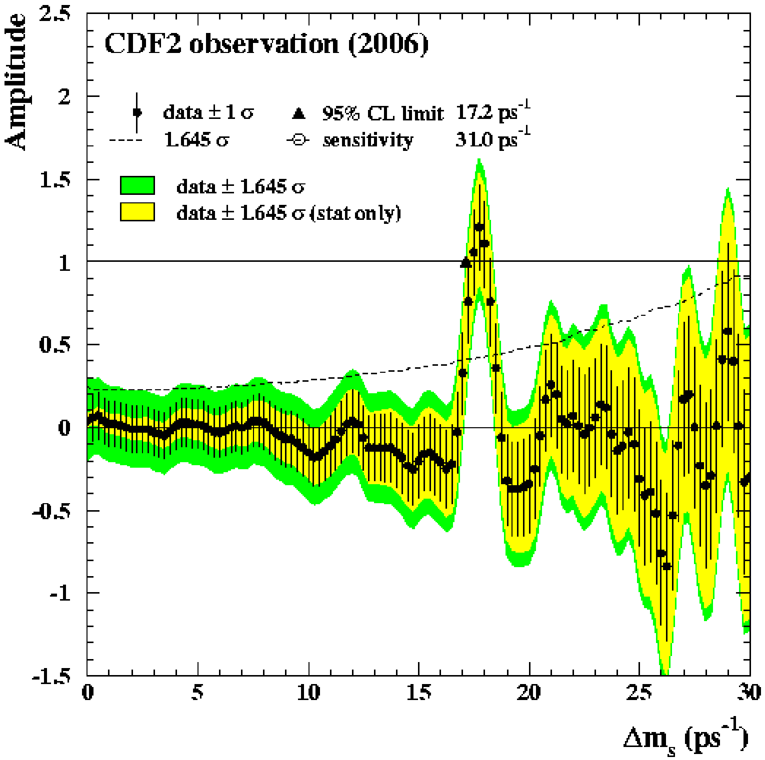
$\Rightarrow$ easy to combine experiments



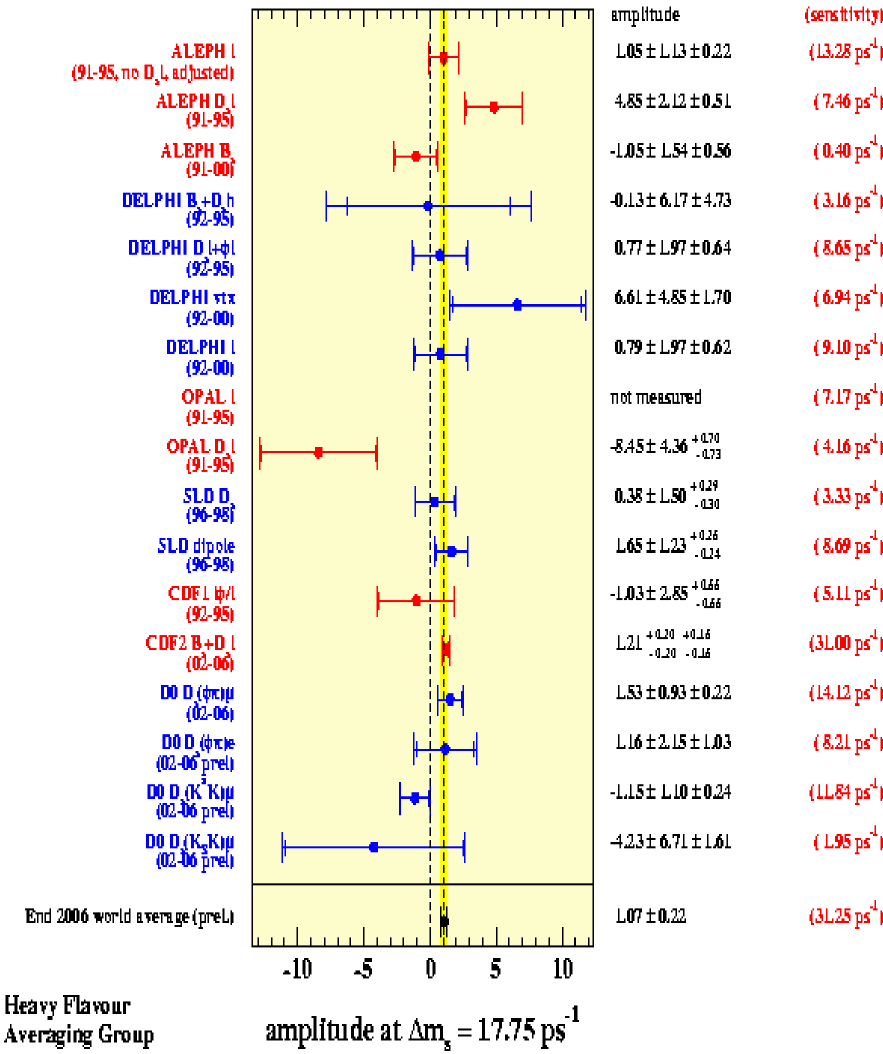


Courtesy of G. Gomes-Ceballos, FPCP 2006, Vancouver, Canada

Δm_s Measurement at the TeVatron: Result



CDF obtained the first direct evidence of Δm_s!



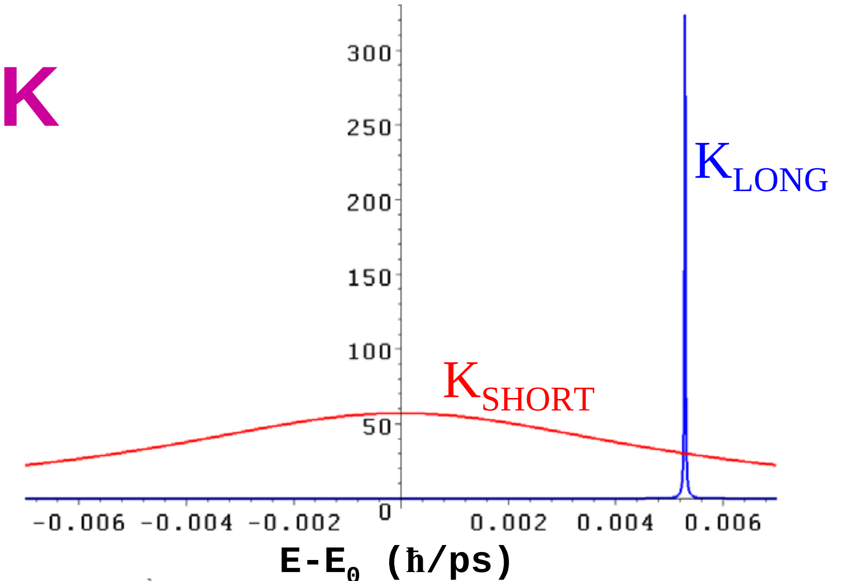
$\Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ ps}^{-1}$

Comparison of K, B_d and B_s Oscillations

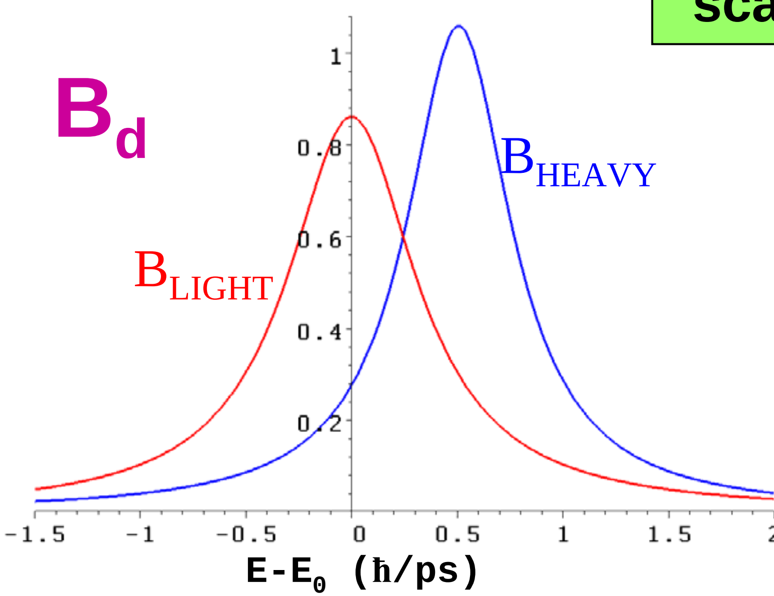
- Analogy: coupled Harmonic Oscillator
- Oscillations (mixing) characterized by mass and lifetime differences between the two eigenstates of weak interaction.
- Differences between flavors:
  - K: very different states
  - B_d: Oscillation and decay are comparable
  - B_s: Rapid oscillations

Mind the scales!

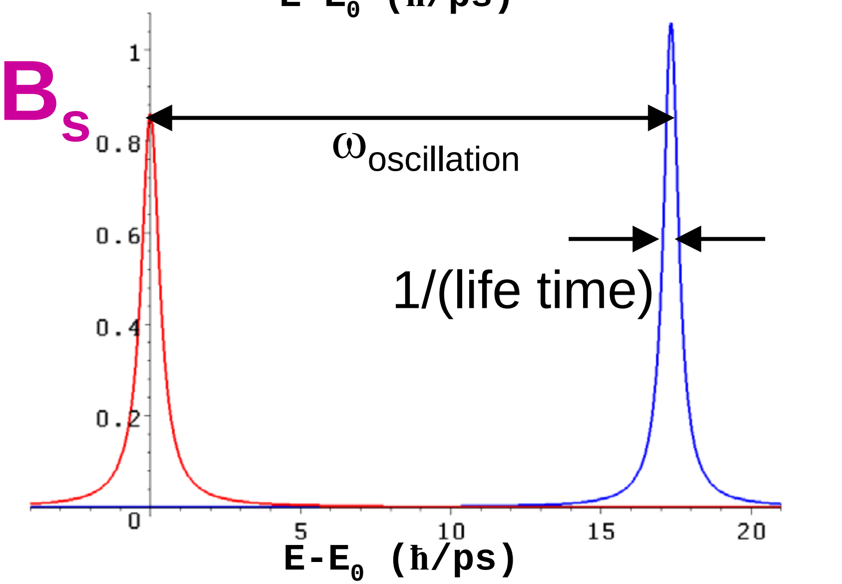
K



B_d



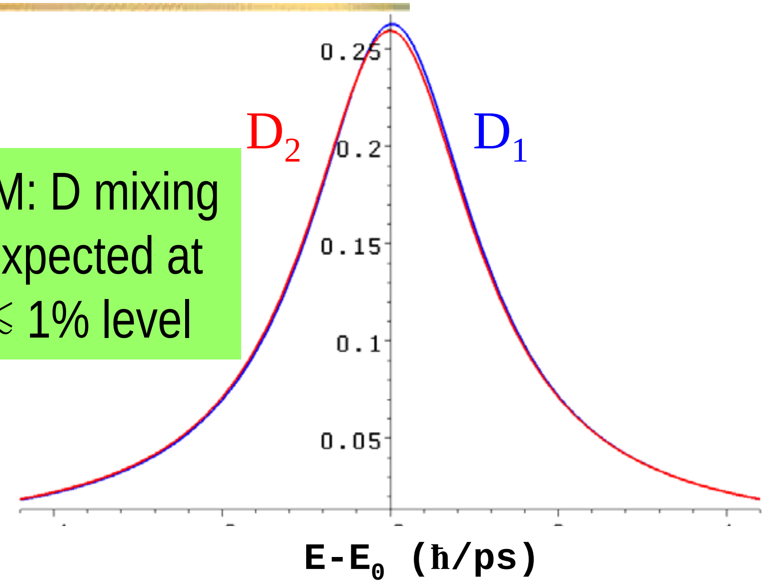
B_s



D-Oscillations are now Measured

- An experimental challenge!
- Both BaBar and Belle observed mixing (Winter 2007)
- Results are consistent with SM
- Charm: only place where CP violation with down-type quarks in the mixing diagram can be explored.

SM: D mixing expected at $\lesssim$ 1% level

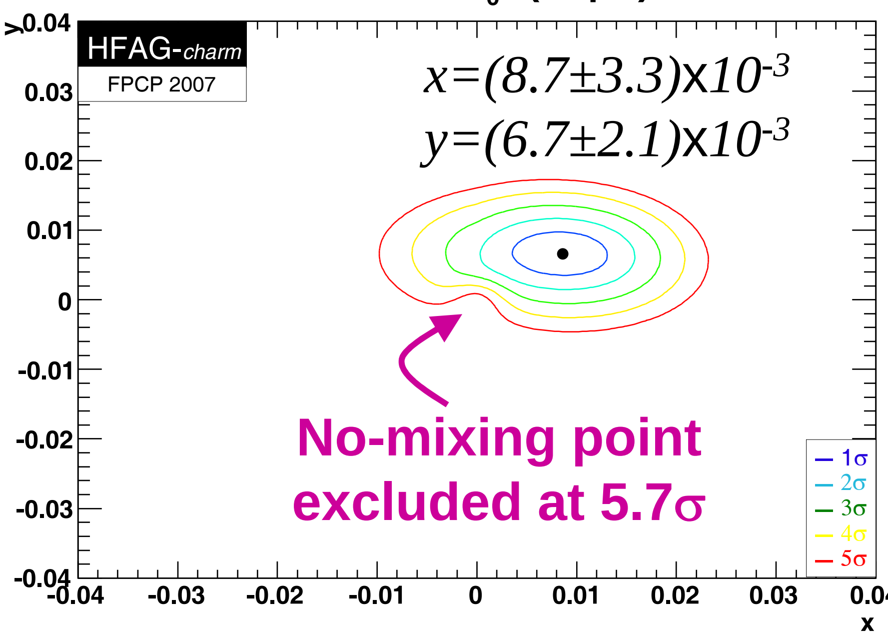


- No evidence for CP violation
- We need more Measurements with different techniques to get x and y parameters.

$$x = \frac{m_1 - m_2}{\Gamma}$$

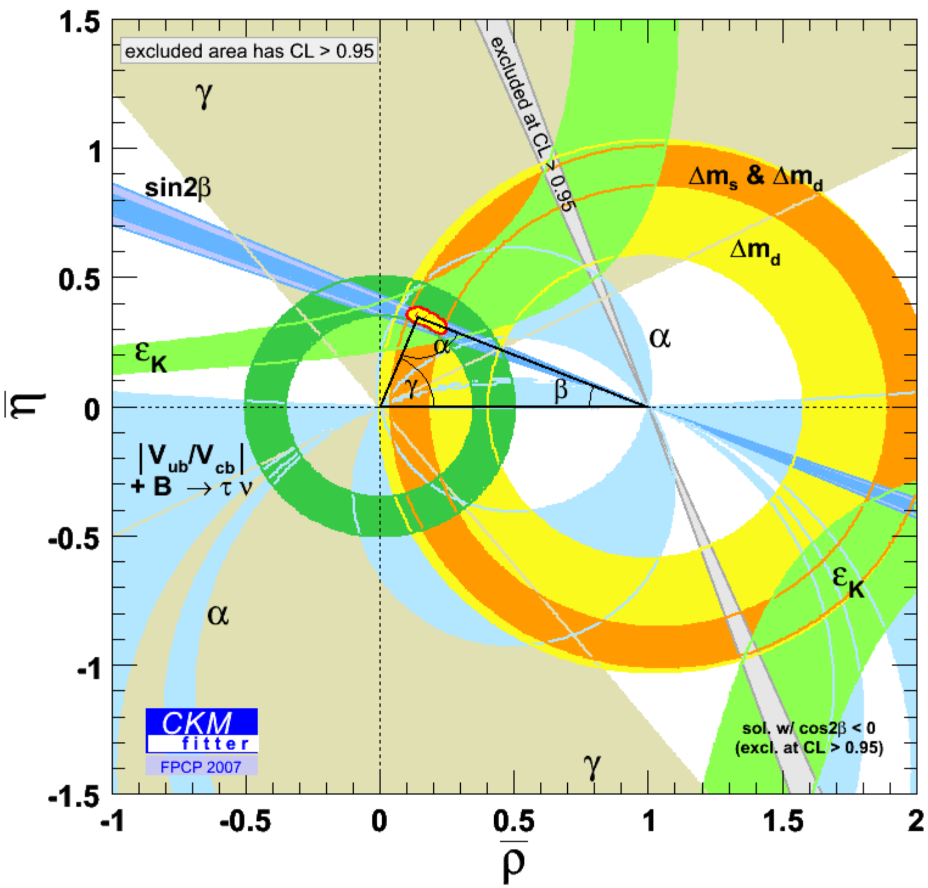
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$\Gamma = \frac{1}{2}\left(\Gamma_1 + \Gamma_2\right)$$



Summary and Conclusions (I)

Back to the Unitarity Triangle Fit



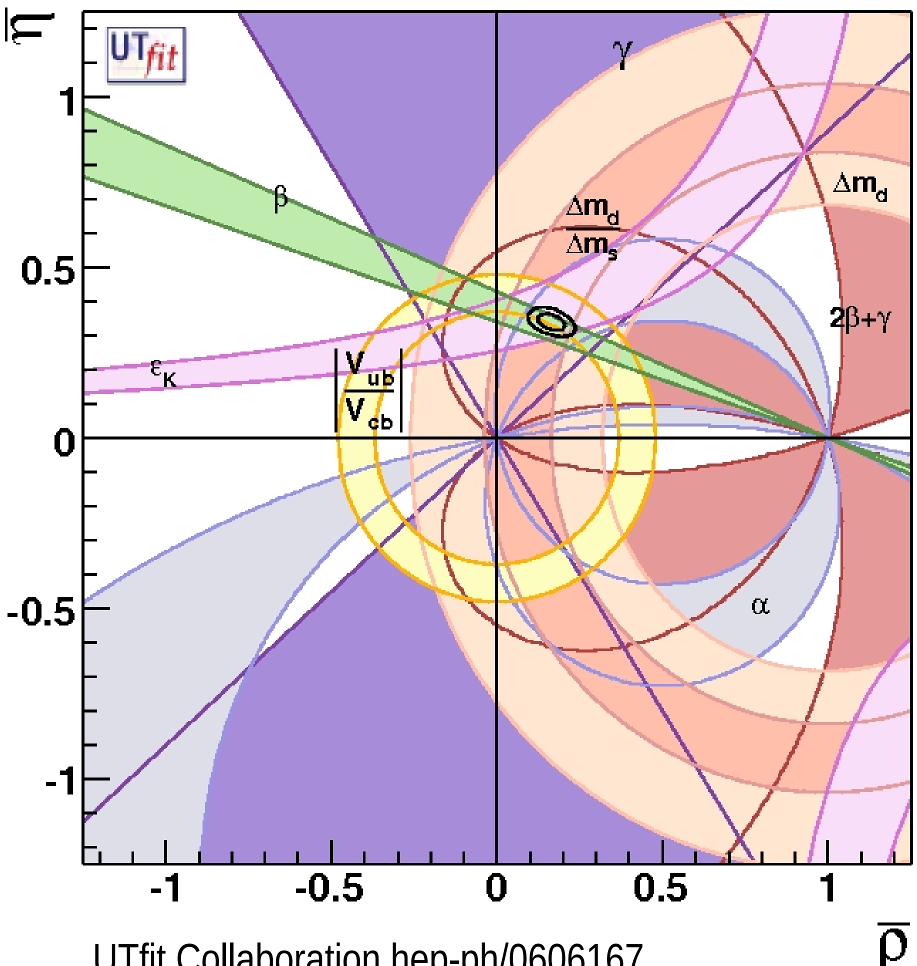
CKMfitter Group Eur. Phys. J. C41, 1-131 (2005)

$$\rho = 0.141\,^{+0.043}_{-0.016} \;||\; 0.213\,^{+0.014}_{-0.024}$$
$$\eta = 0.311\,^{+0.015}_{-0.012} \;||\; 0.348\,^{+0.012}_{-0.021}$$

- In this talk I have only focused of a few recent results on CP violation
- After many results from B-Factories and measurement of Δm_s by CDF All the independent constraints superimpose in a small region of the (ρ,η) plane!
- Great success of the Standard Model and the CKM Picture

Summary and Conclusions (II)

Back to the Unitarity Triangle Fit



UTfit Collaboration hep-ph/0606167

$\rho = 0.164 \pm 0.029$
$\eta = 0.340 \pm 0.017$

- There are still small tensions in the fit
- However, if there is physics beyond the Standard Model, the present results constrain it strongly
- Possible New Physics scenarios are likely to have a similar flavor structure similar to the one of the SM (MFV models).
- Eventual New physics should appear as “corrections” to the CKM picture.

There is room for additional effort in the Flavor sector

Super-B Factory?

I would like to thank Julie Malcles and Achille Stocchi, who authorized me to use materiel which has greatly benefited this talk