Particle Physics II – CP violation

(also known as "Physics of Anti-matter")

Lecture 6

N. Tuning

Plan

1) Wed 12 Feb: Anti-matter + SM
2) Mon 17 Feb: CKM matrix + Unitarity Triangle
3) Wed 19 Feb: Mixing + Master eqs. + $B^0 \to J/\psi K_s$
4) Mon 9 Mar: CP violation in $B_{(s)}$ decays (I)
5) Wed 11 Mar: CP violation in $B_{(s)}$ and K decays (II)
6) Mon 16 Mar: Rare decays + Flavour Anomalies
7) ~~Wed 18 Mar:~~ Exam postponed...

- Final Mark:
  - if (mark > 5.5) mark = max(exam, 0.85*exam + 0.15*homework)
  - else mark = exam
- In parallel: Lectures on Flavour Physics by prof.dr. R. Fleischer

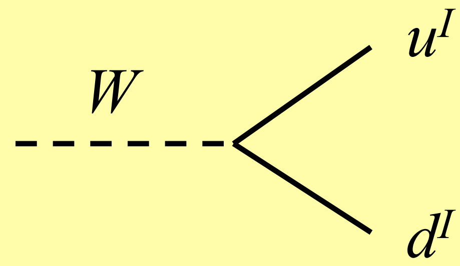
Table of contents

$$L_{SM} = L_{Kinetic} + L_{Higgs} + L_{Yukawa}$$

Recap

$$-L_{Yuk} = Y^{d}_{ij}\,(\overline{u^I_L},\overline{d^I_L})_i \begin{pmatrix}\varphi^+\\ \varphi^0\end{pmatrix} d^I_{Rj} + \ldots$$

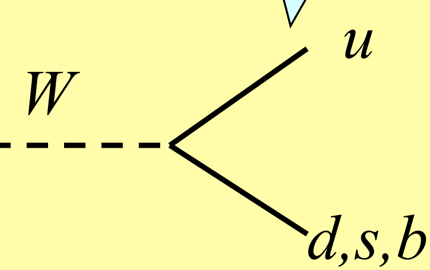
$$L_{Kinetic} = \frac{g}{\sqrt{2}}\overline{u^I_{Li}}\gamma^\mu W^-_\mu d^I_{Li} + \frac{g}{\sqrt{2}}\overline{d^I_{Li}}\gamma^\mu W^+_\mu u^I_{Li} + \ldots$$



Diagonalize Yukawa matrix Y_{ij}

- Mass terms
- Quarks rotate
- Off diagonal terms in charged current couplings

$$\begin{pmatrix}d^I\\ s^I\\ b^I\end{pmatrix} \rightarrow V_{CKM}\begin{pmatrix}d\\ s\\ b\end{pmatrix}$$



$$-L_{Mass} = \left(\bar{d},\bar{s},\bar{b}\right)_L \begin{pmatrix}m_d & & \\ & m_s & \\ & & m_b\end{pmatrix}\begin{pmatrix}d\\ s\\ b\end{pmatrix}_R + \left(\bar{u},\bar{c},\bar{t}\right)_L \begin{pmatrix}m_u & & \\ & m_c & \\ & & m_t\end{pmatrix}\begin{pmatrix}u\\ c\\ t\end{pmatrix}_R + \ldots$$

$$L_{CKM} = \frac{g}{\sqrt{2}}\overline{u_i}\gamma^\mu W^-_\mu V_{ij}\left(1-\gamma^5\right)d_j + \frac{g}{\sqrt{2}}\overline{d_j}\gamma^\mu W^+_\mu V^*_{ij}\left(1-\gamma^5\right)u_i + \ldots$$

$$L_{SM} = L_{CKM} + L_{Higgs} + L_{Mass}$$

Why bother with all this?

- CKM matrix has origin in L_{Yukawa}
  - Intricately related to quark massed…
- Both quark masses and CKM elements show intriguing hierarchy
- There is a whole industry of theorist trying to postdict the CKM matrix based on arguments on the mass matrix in L_{Yukawa}…

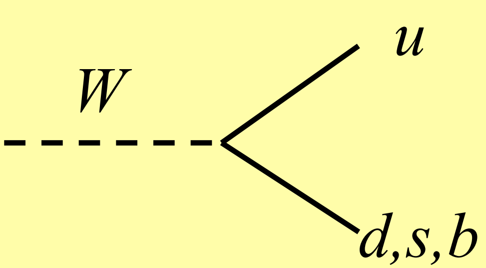
CKM-matrix: where are the phases?

- Possibility 1: simply 3 ‘rotations’, and put phase on smallest:

$$V_{CKM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} =$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

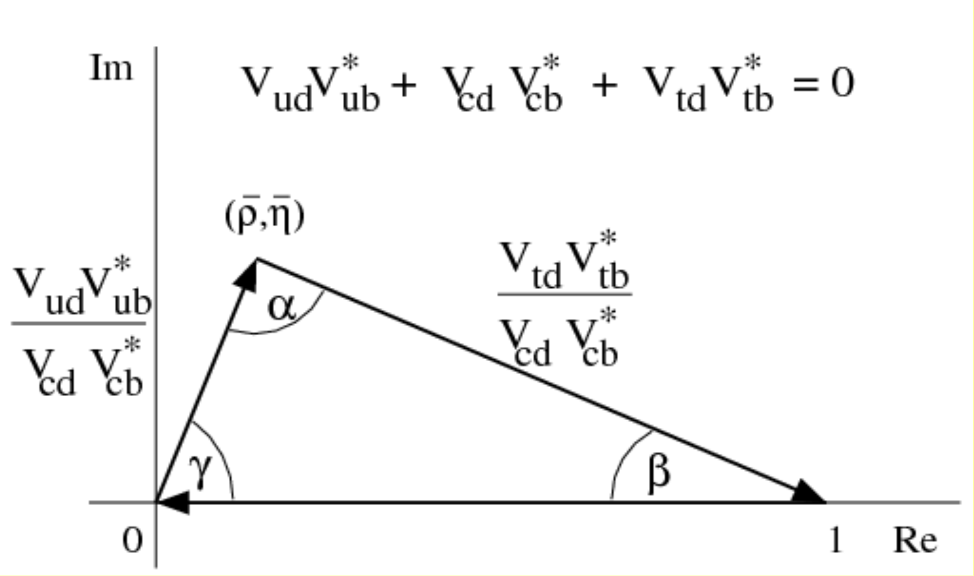
- Possibility 2: parameterize according to magnitude, in O(λ):



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

This was theory, now comes experiment

- We already saw how the moduli $|V_{ij}|$ are determined
- Now we will work towards the measurement of the imaginary part
  - Parameter: η
  - Equivalent: angles α, β, γ .



- To measure this, we need the formalism of neutral meson oscillations…

Meson Decays

- Formalism of meson *oscillations*:

$$\left|P^0(t)\right\rangle = \frac{1}{2}\left(e^{-im_Ht-\frac{1}{2}\Gamma_Ht}+e^{-im_Lt-\frac{1}{2}\Gamma_Lt}\right)|P^0\rangle+\frac{q}{2p}\left(e^{-im_Ht-\frac{1}{2}\Gamma_Ht}-e^{-im_Lt-\frac{1}{2}\Gamma_Lt}\right)|\bar{P}^0\rangle$$

- Subsequent: *decay*

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \left(|g_+(t)|^2+|\lambda_f|^2|g_-(t)|^2+2\Re[\lambda_f g_+^*(t)g_-(t)]\right)$$

$P^0 \to f$ | $P^0 \to \bar{P}^0 \to f$ | Interference

$$A(f) = \langle f|T|P^0\rangle$$

$$\bar{A}(f) = \langle f|T|\bar{P}^0\rangle$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Interference

$$\Gamma_{P^0\to f}(t) = |A_f|^2\frac{e^{-\Gamma t}}{2}\left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t+2\Re\lambda_f\sinh\frac{1}{2}\Delta\Gamma t+(1-|\lambda_f|^2)\cos\Delta mt-2\Im\lambda_f\sin\Delta mt\right)$$

('direct') Decay

Interference

Classification of CP Violating effects

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

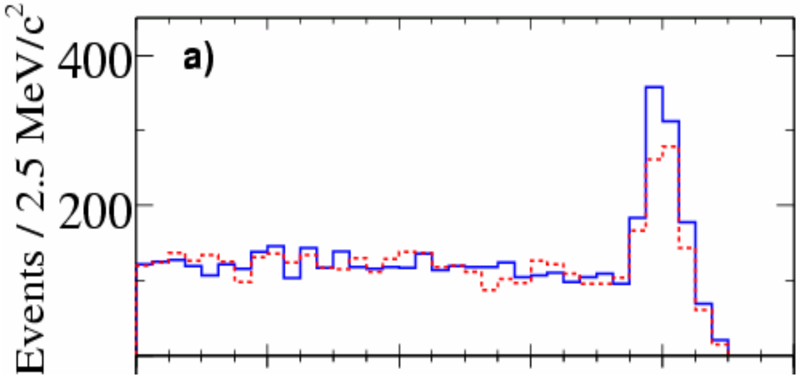
$$\Im \lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

Classification of CP Violating effects

1. CP violation in decay

Example: $B^0 \to K^+\pi^-$

$\overline{B}^0 \to K^-\pi^+$

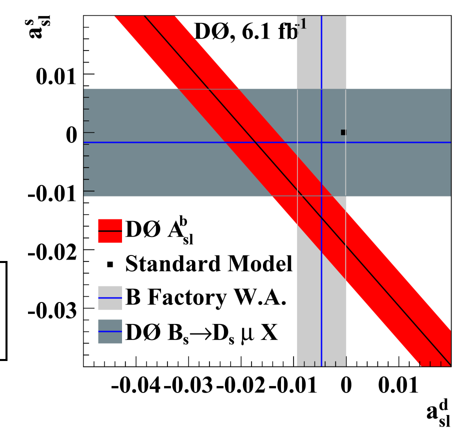


2. CP violation in mixing

Example: $$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$A_{\rm sl}^b({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

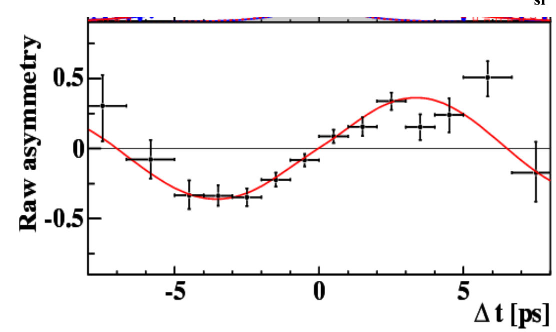
$$A_{\rm sl}^b = -0.00957 \pm 0.00251\ ({\rm stat}) \pm 0.00146\ ({\rm syst})$$



3. CP violation in interference

Example: $B^0 \to J/\psi K_s$

$$A_{CP}(t) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)\sin(\Delta m t)$$



Remember!

Necessary ingredients for CP violation:

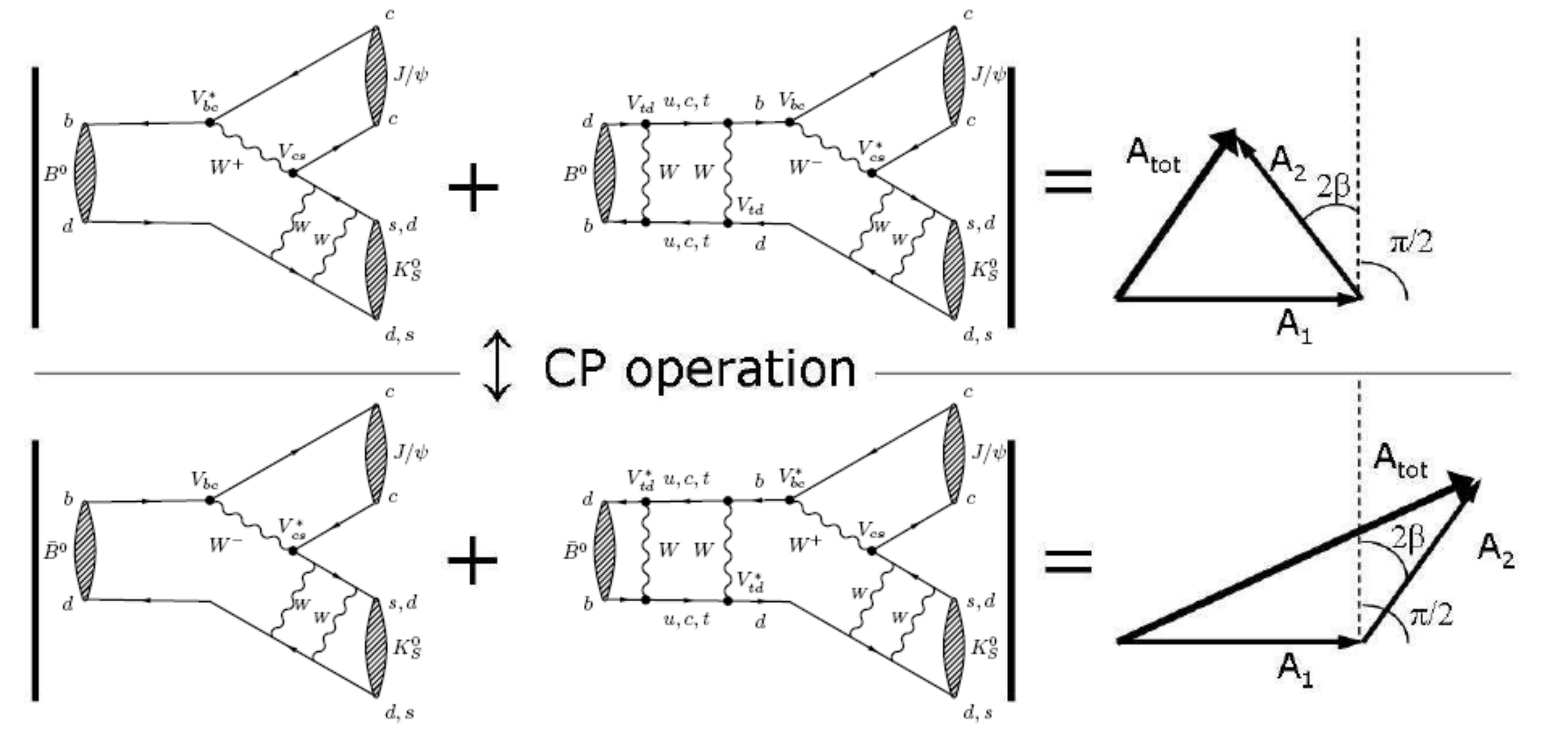
1) Two (interfering) amplitudes

2) Phase difference between amplitudes

   – one CP conserving phase ('strong' phase)
   – one CP violating phase ('weak' phase)

2 amplitudes
2 phases

Remember!



2 amplitudes
2 phases

CKM Angle measurements from $B_{d,u}$ decays

- Sources of phases in $B_{d,u}$ amplitudes*

Amplitude	Rel. Magnitude	Weak phase
b→c	Dominant	0
b→u	Suppressed	γ
t→d (x2, mixing)	Time dependent	2β

In Wolfenstein phase convention.

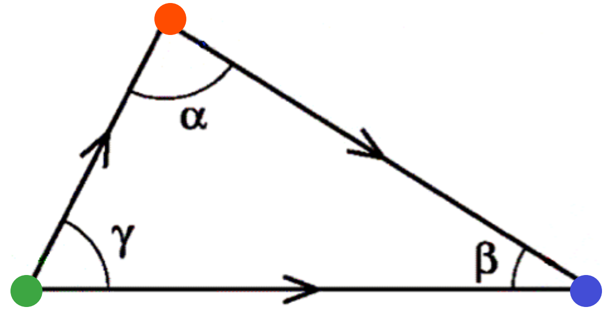
b→u

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

t→d

- The standard techniques for the angles:

B^0 mixing + single b→u decay



B^0 mixing + single b→c decay

Interfere b→c and b→u in $B^{\pm}$ decay.

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$$\text{Prob}(P^0 \to \bar{P}^0) \neq \text{Prob}(\bar{P}^0 \to P^0)$$

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$$\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

$$\Im \lambda_f = \Im \left(\frac{q}{p} \frac{\bar{A}_f}{A_f} \right) \neq 0$$

Next… Something completely different? No, just K

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$$\Gamma(P^0{}_{(\leadsto \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\leadsto P^0)} \to f)(t)$$

$$\Im \lambda_f = \Im \left(\frac{q}{p} \frac{\bar{A}_f}{A_f} \right) \neq 0$$

Kaons…

- Different notation: confusing!

$K_1, K_2, K_L, K_S, K_+, K_-, K^0$

$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$
$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

$$|K_L\rangle = p\,|K^0\rangle - q\,|\overline{K^0}\rangle$$
$$|K_S\rangle = p\,|K^0\rangle + q\,|\overline{K^0}\rangle$$

- Smaller CP violating effects

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

$$\delta V = \begin{pmatrix} -\frac{1}{8}\lambda^4 & 0 & 0 \\ \frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) & -\frac{1}{8}\lambda^4(1+4A^2) & 0 \\ \frac{1}{2}A\lambda^5(\rho+i\eta) & \frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) & -\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

- But historically important!
  - Concepts same as in B-system, so you have a chance to understand…

Kaons…

- Different notation: confusing!

$K_1, K_2, K_L = K_S, K_+, K_-, K^0$

CP eigenstates

$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$
$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

$$|K_L\rangle = p\,|K^0\rangle - q\,|\overline{K^0}\rangle$$
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Mass/lifetime eigenstates

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$$|K_L\rangle = p\,|K^0\rangle - q\,|\overline{K^0}\rangle$$
$$|K_S\rangle = p\,|K^0\rangle + q\,|\overline{K^0}\rangle$$

- Smaller CP violating effects

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

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- ➢ But historically important!
  - Concepts same as in B-system, so you have a chance to understand…

Kaons…

- Different notation: confusing!

$K_1, K_2, K_L, K_S, K_+, K_-, K^0$

Flavour eigenstates

$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$
$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

$$|K_L\rangle = p\,|K^0\rangle - q\,|\overline{K^0}\rangle$$
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- Smaller CP violating effects

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

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➢ But historically important!

- Concepts same as in B-system, so you have a chance to understand…

Neutral kaons – 60 years of history

1947 : First K^0 observation in cloud chamber *("V particle")*
1955 : Introduction of Strangeness (Gell-Mann & Nishijima)
K^0, $\overline{K^0}$ are two distinct particles (Gell-Mann & Pais)

> *... the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions.*

1956 : Parity violation observation of long lived K_L (BNL Cosmotron)
1960 : $\Delta m = m_L - m_S$ measured from regeneration
1964 : Discovery of CP violation (Cronin & Fitch)

1970 : Suppression of FCNC, $K_L \rightarrow \mu\mu$ - GIM mechanism/charm hypothesis
1972 : 6-quark model; CP violation explained in SM (Kobayashi & Maskawa)

1992-2000 : K^0, $\overline{K^0}$ time evolution, decays, asymmetries (CPLear)
1999-2003 : Direct CP violation measured: $\varepsilon'/\varepsilon \neq 0$ (KTeV and NA48)

From G.Capon

Intermezzo: CP eigenvalue

- Remember:
  - $P^2 = 1$ ($x \rightarrow -x \rightarrow x$)
  - $C^2 = 1$ ($\psi \rightarrow \overline{\psi} \rightarrow \psi$)
  - $\rightarrow CP^2 = 1$
- $CP \mid f \rangle = \pm \mid f \rangle$
- Knowing this we can evaluate the effect of CP on the K^0
- Mass/Lifetime eigenstates: *almost* CP eigenstates!

  $|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$

  $|K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$

($S(K)=0 \rightarrow L(\pi\pi)=0$)

$|K_s\rangle$ *(CP=+1)* $\longrightarrow \pi\,\pi$ *(CP= (-1)(-1)(-1)$^{l=0}$ =+1)*

$|K_L\rangle$ *(CP=-1)* $\longrightarrow \pi\,\pi\,\pi$ *(CP = (-1)(-1)(-1)(-1)$^{l=0}$ = -1)*

Decays of neutral kaons

- Neutral kaons is the lightest strange particle → it must decay through the weak interaction
- **If** weak force conserves CP then
  - **decay products of K_1 can only be a CP=+1 state**, i.e.

    $|K_1\rangle$ (CP=+1) $\longrightarrow \pi\,\pi$ (CP= $(-1)(-1)(-1)^{l=0}$ =+1)

    (S(K)=0 → L(ππ)=0)

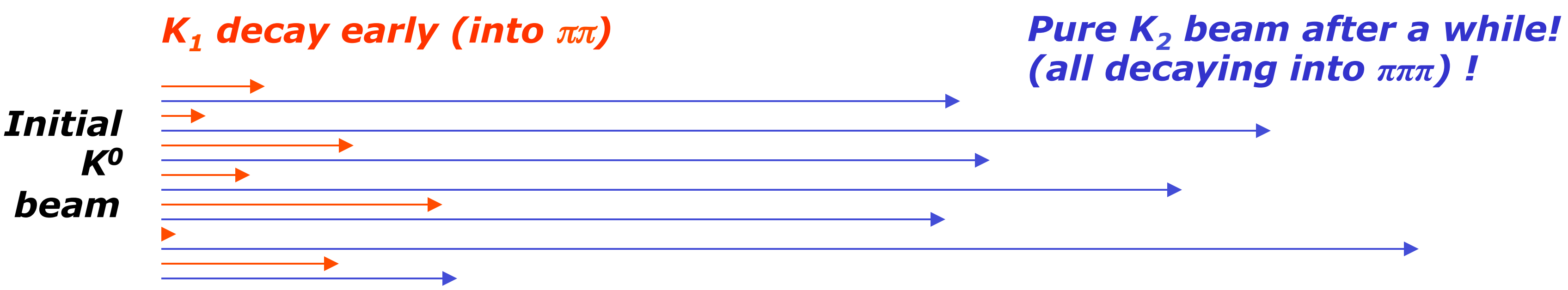
  - **decay products of K_2 can only be a CP=-1 state, i.e.**

    $|K_2\rangle$ (CP=-1) $\longrightarrow \pi\,\pi\,\pi$ (CP = $(-1)(-1)(-1)(-1)^{l=0}$ = -1)

- You can use neutral kaons to *precisely test* that the weak force preserves CP (or not)
  - If you (somehow) have a pure CP=-1 K_2 state and you observe it decaying into 2 pions (with CP=+1) then you know that the weak decay violates CP…

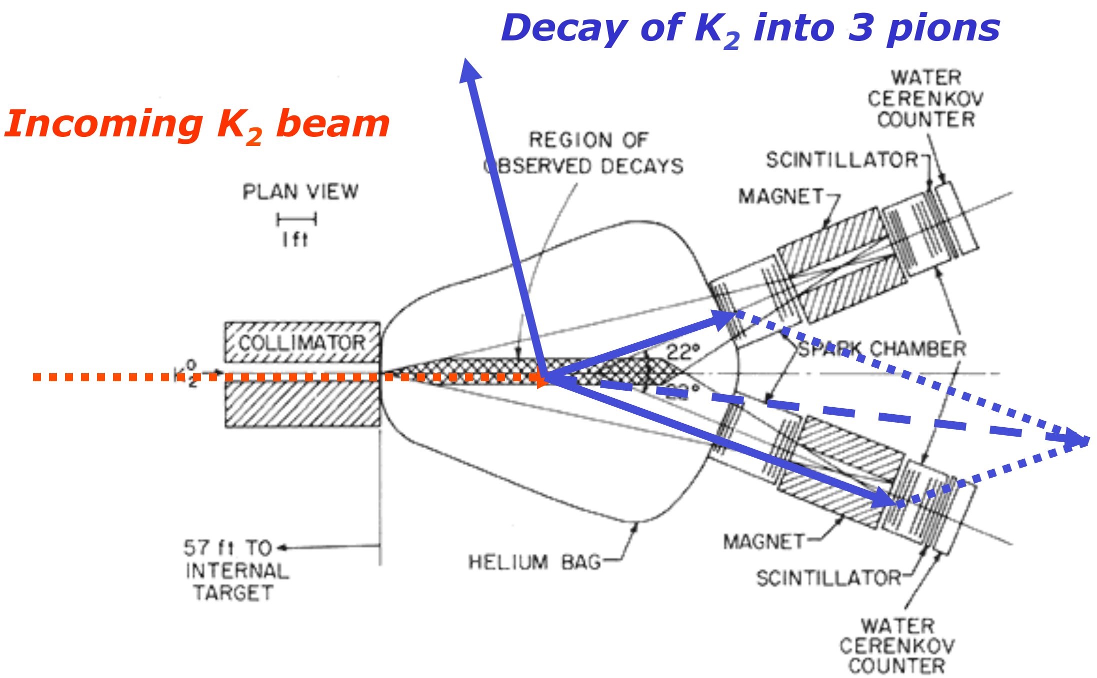
Designing a CP violation experiment

- How do you obtain a pure 'beam' of K_2 particles?
  - It turns out that you can do that through clever use of kinematics
- Exploit that decay of K into two pions is *much* faster than decay of K into three pions
  - Related to fact that energy of pions are large in 2-body decay
  - τ_1 = 0.89 x 10^{-10} sec
  - τ_2 = 5.2 x 10^{-8} sec (~600 times larger!)
- Beam of neutral Kaons automatically becomes beam of $|K_2\rangle$ as all $|K_1\rangle$ decay very early on…

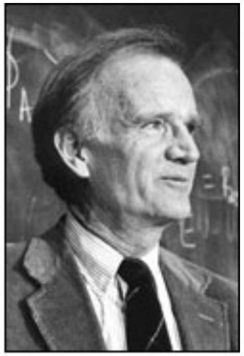


The Cronin & Fitch experiment

Essential idea: Look for (CP violating) $K_2 \rightarrow \pi\pi$ decays 20 meters away from K^0 production point



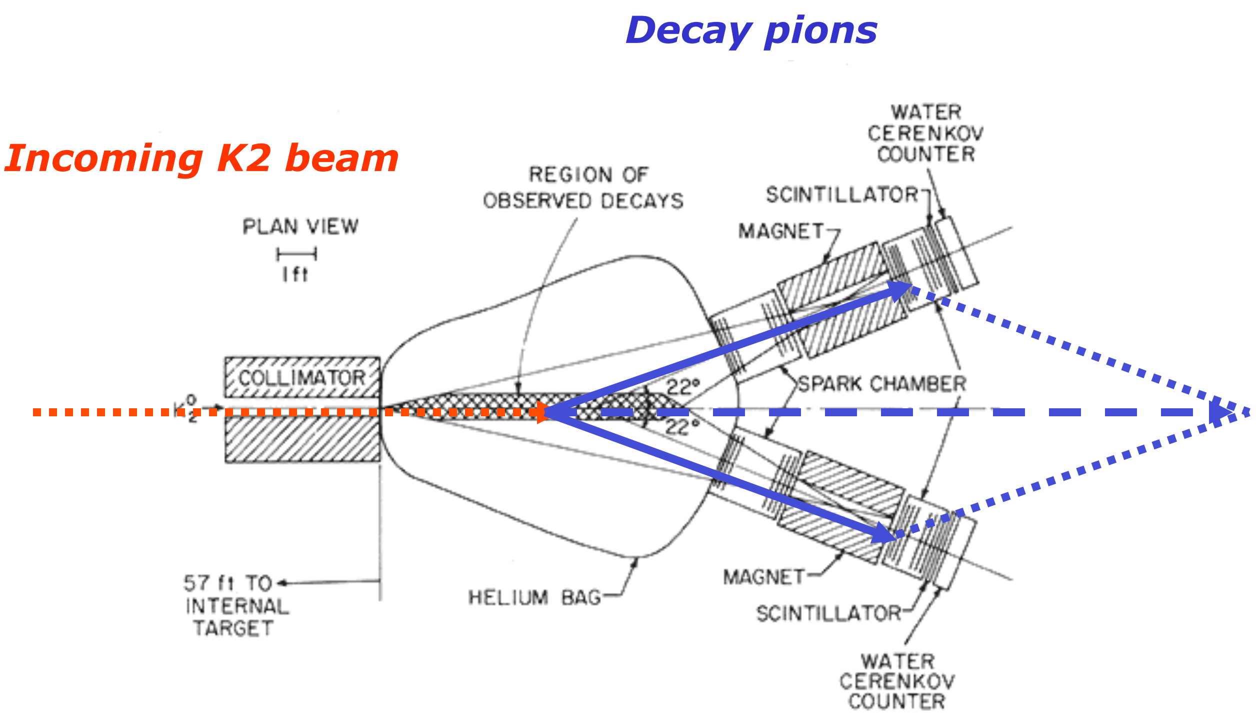

James Cronin

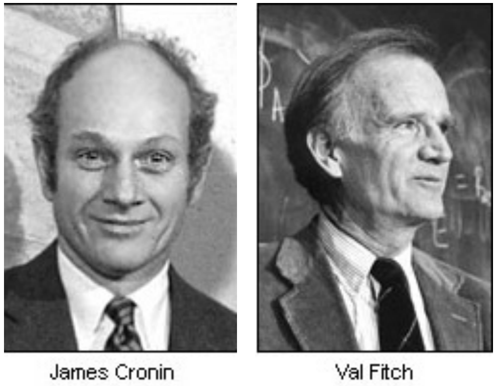

Val Fitch

If you detect two of the three pions of a $K_2 \rightarrow \pi\pi\pi$ decay they will generally not point along the beam line

The Cronin & Fitch experiment

Essential idea: Look for $K_2 \rightarrow \pi\pi$ decays
20 meters away from K^0 production point





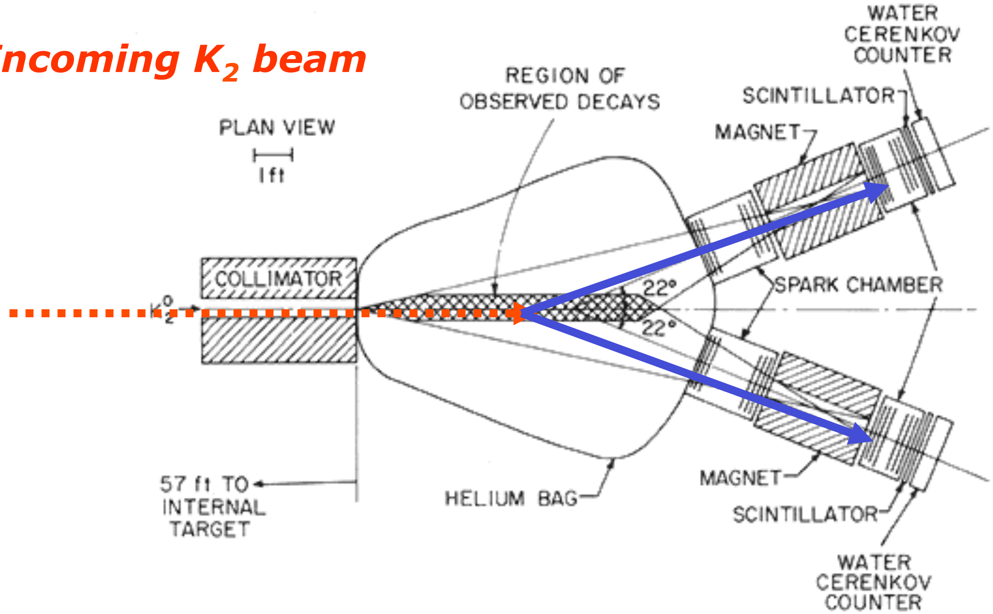
If K_2 decays into two pions instead of three both the reconstructed direction should be exactly along the beamline (conservation of momentum in $K_2 \rightarrow \pi\pi$ decay)

The Cronin & Fitch experiment

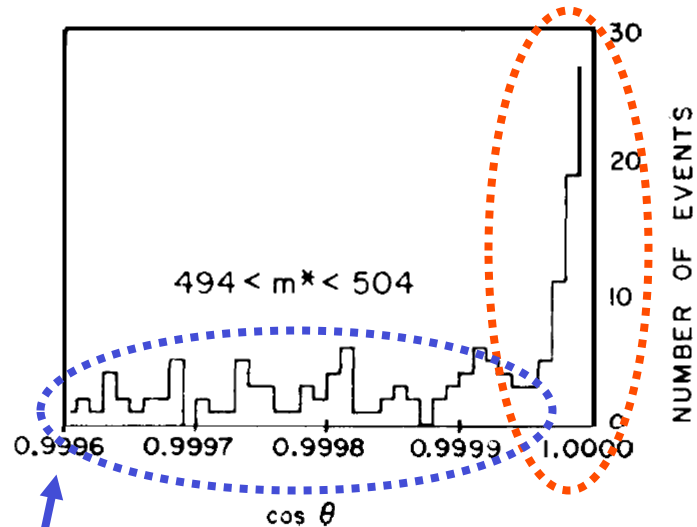
Essential idea: Look for $K_2 \rightarrow \pi\pi$ decays
20 meters away from K^0 production point

Decay pions

Incoming K_2 beam



$K_2 \rightarrow \pi\pi$ decays (CP Violation!)



$K_2 \rightarrow \pi\pi\pi$ decays

Result: an excess of events at Θ=0 degrees!

- CP violation, because K_2 (CP=-1) changed into K_1 (CP=+1)

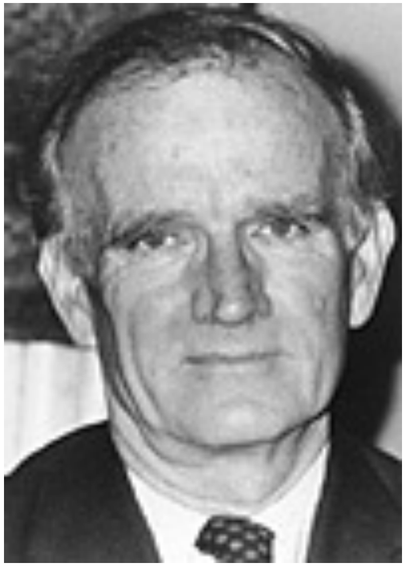
Note scale: 99.99% of $K \rightarrow \pi\pi\pi$ decays are left of plot boundary

Nobel Prize 1980

James Watson Cronin
1/2 of the prize
University of Chicago
Chicago, IL, USA
b. 1931

"for the discovery of violations of fundamental symmetry principles in the decay of neutral *K* mesons"

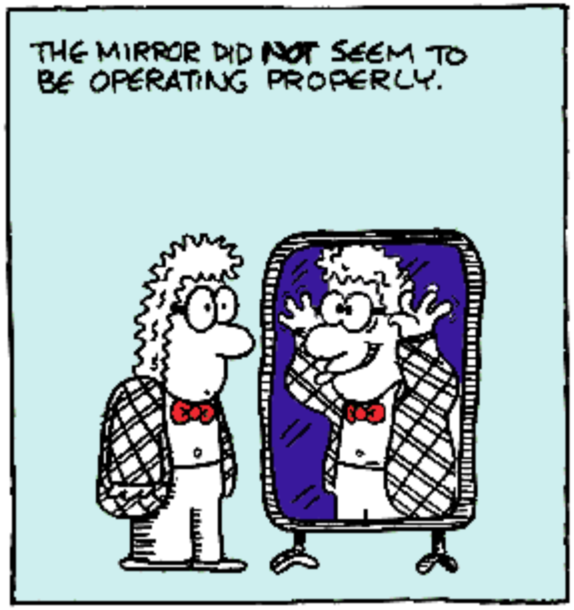
The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments.



Val Logsdon Fitch
1/2 of the prize
Princeton University
Princeton, NJ, USA
b. 1923

Cronin & Fitch – Discovery of CP violation

- Conclusion: **weak decay violates CP** (as well as C and P)
  - But effect is tiny! (~0.05%)
  - Maximal (100%) violation of P symmetry easily follows from absence of right-handed neutrino, but how would you construct a physics law that violates a symmetry just a tiny little bit?



- Results also provides us with *convention-free* definition of matter vs anti-matter.
  - If there is no CP violation, the K_2 decays in equal amounts to
    $\pi^+ e^- \nu_e$ (a)
    $\pi^- e^+ \nu_e$ (b)
  - Just like CPV introduces $K_2 \rightarrow \pi\pi$ decays, it also introduces a slight asymmetry in the above decays (b) happens more often than (a)
  - *"Positive charge is the charged carried by the lepton preferentially produced in the decay of the long-lived neutral K meson"*

Intermezzo: Regeneration

- Different cross section for $\sigma(p\ K^0)$ than $\sigma(p\ \overline{K^0})$
  - Elastic scattering: same
  - Charge exchange : same → $K^0 + p \to K^+ + n$, $\overline{K}^0 + n \to K^- + p$
  - Hyperon production: more for [?] K^0 !

$$\overline{K}^0 + p \to \Lambda^0 + \pi^+$$

$$K_2 = \frac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right)$$

$$K^0 + p \to \Lambda^0 + \underbrace{K^0 + K^+}$$

strong interactions: must conserve strangeness

leave little free energy – unlikely!

- What happens when K_L-beam hits a wall ??
- Then admixture changes...: $|K_L\rangle = p|K^0\rangle - q|\overline{K^0}\rangle$

→ Regeneration of K_S !

- Could fake CP violation due to $K_S \to \pi^+\pi^-$...

K_S and K_L

Usual (historical) notation in kaon physics:

$$|K_S\rangle = \frac{|K_+\rangle + \varepsilon |K_-\rangle}{\sqrt{1+|\varepsilon|^2}}, \qquad |K_S(t)\rangle = e^{-i\omega_S t}|K_S\rangle,$$

$$|K_L\rangle = \frac{|K_-\rangle + \varepsilon |K_+\rangle}{\sqrt{1+|\varepsilon|^2}}. \qquad |K_L(t)\rangle = e^{-i\omega_L t}|K_L\rangle.$$

Modern notation used in B physics:

$$|K_S\rangle = p|K^0\rangle + q|\overline{K^0}\rangle, \qquad p = (1+\varepsilon)\Big/\left(\sqrt{2}\sqrt{1+|\varepsilon|^2}\right),$$

$$|K_L\rangle = p|K^0\rangle - q|\overline{K^0}\rangle. \qquad q = (1-\varepsilon)\Big/\left(\sqrt{2}\sqrt{1+|\varepsilon|^2}\right).$$

Regardless of notation:

K_L and K_S *are not orthogonal*:

$$\langle K_S|K_L\rangle = \frac{\varepsilon+\varepsilon^*}{1+|\varepsilon|^2} = \frac{2\Re\varepsilon}{1+|\varepsilon|^2} = \left|\frac{p}{q}\right|^2 - 1$$

Three ways to break CP; e.g. in $K^0 \to \pi^+\pi^-$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) = \left|A_{\pi^+\pi^-}\left(g_+(t) + \lambda g_-(t)\right)\right|^2$$

$$\Gamma\left(\bar{K}^0 \to \pi^+\pi^-\right) = \left|\bar{A}_{\pi^+\pi^-}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)\right|^2$$

$$\lambda_{\pi^+\pi^-} = \frac{q}{p}\frac{\bar{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto \left|A_{+-}\right|^2 \left[\left|g_+(t)\right|^2 + \left|\lambda_{+-}\right|^2 \left|g_-(t)\right|^2 + 2\Re\left(\lambda_{+-} g_+^*(t) g_-(t)\right)\right]$$

$$\Gamma\left(\overline{K}^0 \to \pi^+\pi^-\right) \propto \left|\bar{A}_{+-}\right|^2 \left[\left|g_+(t)\right|^2 + \frac{1}{\left|\lambda_{+-}\right|^2}\left|g_-(t)\right|^2 + \frac{2}{\left|\lambda_{+-}\right|^2}\Re\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right)\right]$$

CP violation in decay: $\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$

CP violation in mixing: $\left|\frac{q}{p}\right| \neq 1$

CP violation in interference mixing/decay: $\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

Classification of CP Violating effects

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\leadsto \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\leadsto P^0)} \to f)(t)$$

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

Time evolution

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto \left[\begin{array}{l} e^{-\Gamma_S t} + \left|\frac{1-\lambda}{1+\lambda}\right|^2 e^{-\Gamma_L t} \\ +2e^{-\Gamma t}\left[\Re\left(\frac{1-\lambda}{1+\lambda}\right)\cos\left(\Delta m\cdot t\right) - \Im\left(\frac{1-\lambda}{1+\lambda}\right)\sin\left(\Delta m\cdot t\right)\right] \end{array} \right]$$

$$\Gamma\left(\overline{K}^0 \to \pi^+\pi^-\right) \propto \left[\begin{array}{l} e^{-\Gamma_S t} + \left|\frac{1-\lambda}{1+\lambda}\right|^2 e^{-\Gamma_L t} \\ -2e^{-\Gamma t}\left[\Re\left(\frac{1-\lambda}{1+\lambda}\right)\cos\left(\Delta m\cdot t\right) - \Im\left(\frac{1-\lambda}{1+\lambda}\right)\sin\left(\Delta m\cdot t\right)\right] \end{array} \right]$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) = N\left[e^{-\Gamma_S t} + \left|\eta_{+-}\right|^2 e^{-\Gamma_L t} + 2e^{-\Gamma t}\left|\eta_{+-}\right|\cos\left(\Delta m\cdot t - \phi_{+-}\right)\right]$$

$$\Gamma\left(\overline{K}^0 \to \pi^+\pi^-\right) = \bar{N}\left[e^{-\Gamma_S t} + \left|\eta_{+-}\right|^2 e^{-\Gamma_L t} - 2e^{-\Gamma t}\left|\eta_{+-}\right|\cos\left(\Delta m\cdot t - \phi_{+-}\right)\right]$$

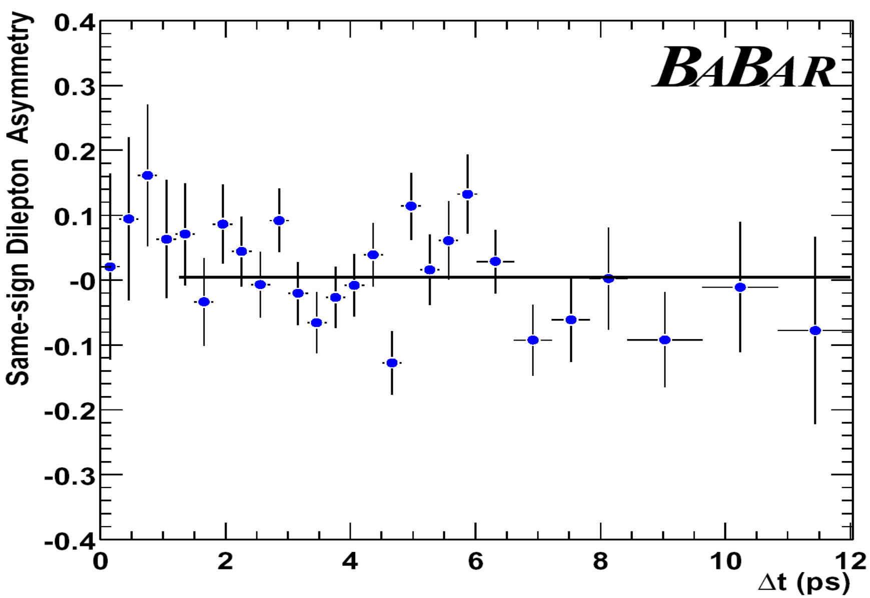
$$\eta_{+-} = \frac{1-\lambda}{1+\lambda} = \frac{pA - q\bar{A}}{pA + q\bar{A}} = \frac{\left\langle \pi^+\pi^- \middle| K_L \right\rangle}{\left\langle \pi^+\pi^- \middle| K_S \right\rangle} \qquad \eta_{+-} = \left|\eta_{+-}\right| e^{i\phi_{+-}}$$

B-system 2. CP violation in mixing K-system

$$A_{CP} = \frac{P(\bar{B}^0 \to B^0) - P(B^0 \to \bar{B}^0)}{P(\bar{B}^0 \to B^0) + P(B^0 \to \bar{B}^0)} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

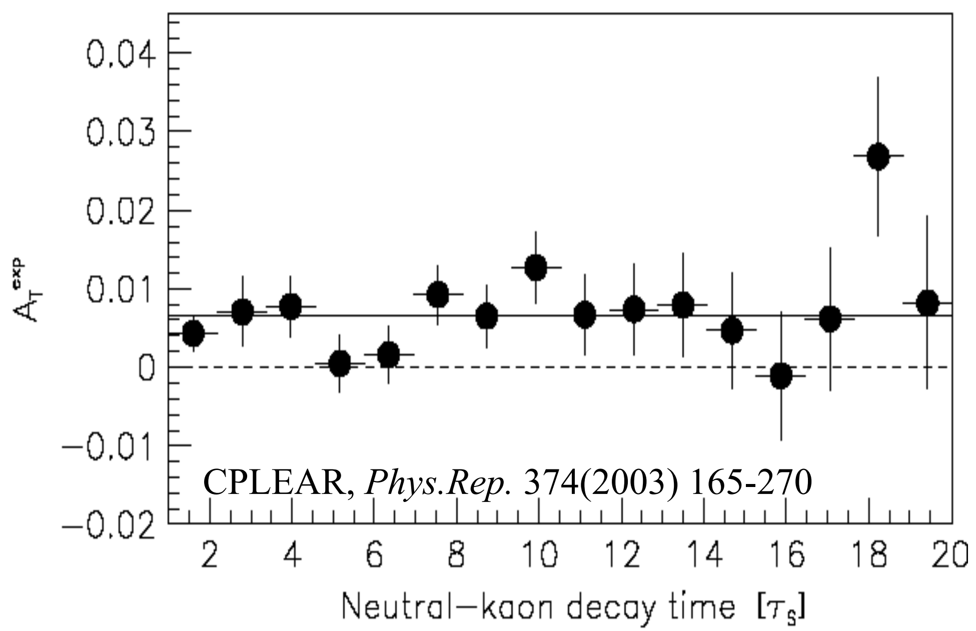
$$A_T(\Delta t) = \frac{N_{++}(\Delta t) - N_{--}(\Delta t)}{N_{++}(\Delta t) + N_{--}(\Delta t)} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

$$A_T(t) = \frac{\bar{I}_{e^+\nu\pi^-}(t) - I_{e^-\bar{\nu}\pi^+}(t)}{\bar{I}_{e^+\nu\pi^-}(t) + I_{e^-\bar{\nu}\pi^+}(t)} = \frac{1-|q/p|^4}{1+|q/p|^4} = 4\Re\varepsilon$$



BaBar, (2002)

$$\left|\frac{q}{p}\right|_{B^0} = 1.0024 \pm 0.0023$$



CPLear (2003)

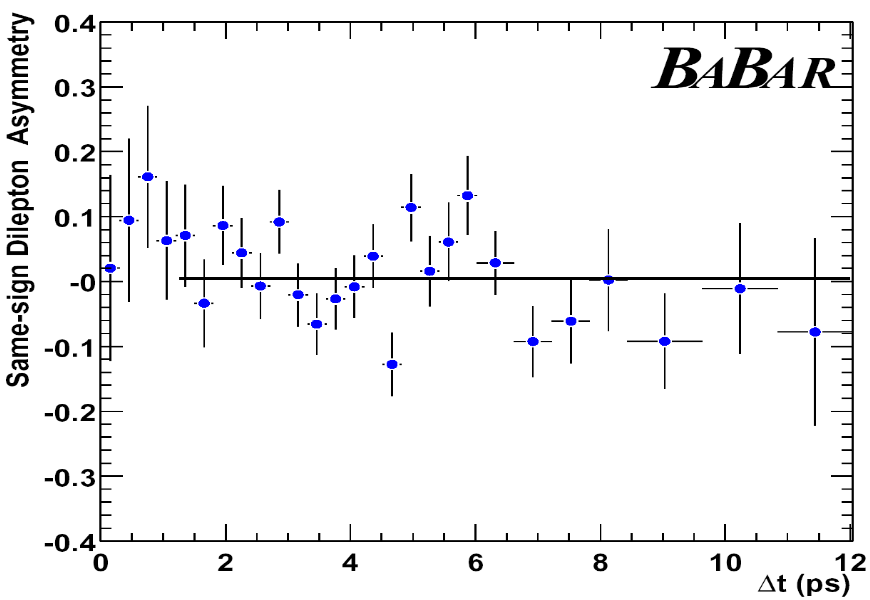
$$A_T(t) = (6.6 \pm 1.6)10^{-3}$$

$$\Rightarrow |q/p| = 0.9967 \pm 0.0008 \neq 1$$

B-system 2. CP violation in mixing K-system

$$A_{CP} = \frac{P(\bar{B}^0 \to B^0) - P(B^0 \to \bar{B}^0)}{P(\bar{B}^0 \to B^0) + P(B^0 \to \bar{B}^0)} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

$$A_T(\Delta t) = \frac{N_{++}(\Delta t) - N_{--}(\Delta t)}{N_{++}(\Delta t) + N_{--}(\Delta t)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$



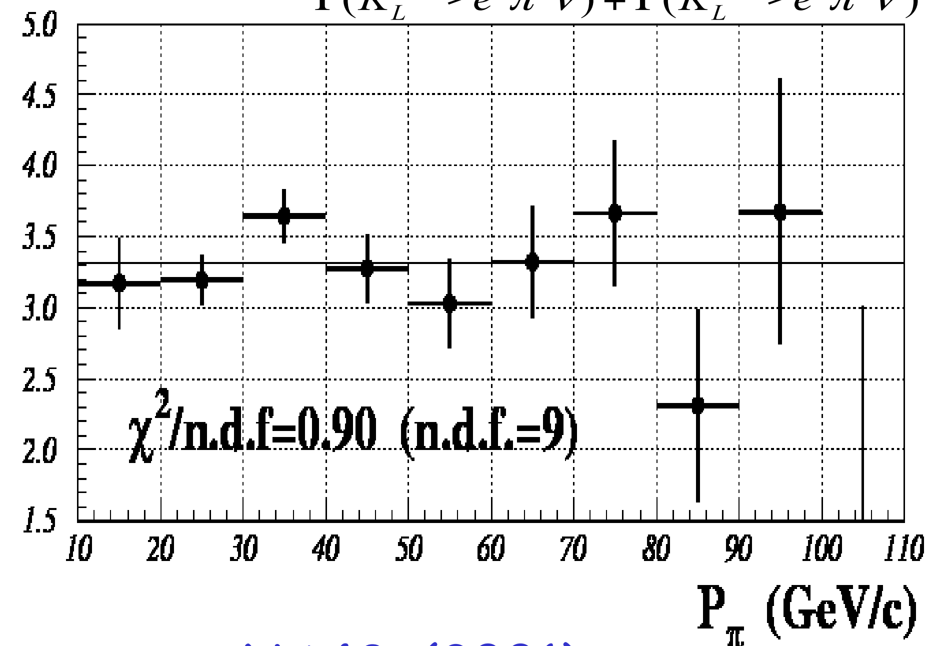
BaBar, (2002)

$$\left|\frac{q}{p}\right|_{B^0} = 1.0024 \pm 0.0023$$

$$A_{+-} = \frac{\Gamma(K_L^0 \to e^+\pi^-\nu_e) - \Gamma(K_L^0 \to e^-\pi^+\bar{\nu}_e)}{\Gamma(K_L^0 \to e^+\pi^-\nu_e) + \Gamma(K_L^0 \to e^-\pi^+\bar{\nu}_e)} = \frac{|1+\epsilon|^2 - |1-\epsilon|^2}{|1+\epsilon|^2 + |1-\epsilon|^2}$$

$\delta \cdot 10^{-3}$

$$\delta_L(e) = \frac{\Gamma(K_L \to e^+\pi^-\nu) - \Gamma(K_L \to e^-\pi^+\bar{\nu})}{\Gamma(K_L \to e^+\pi^-\nu) + \Gamma(K_L \to e^-\pi^+\bar{\nu})}$$



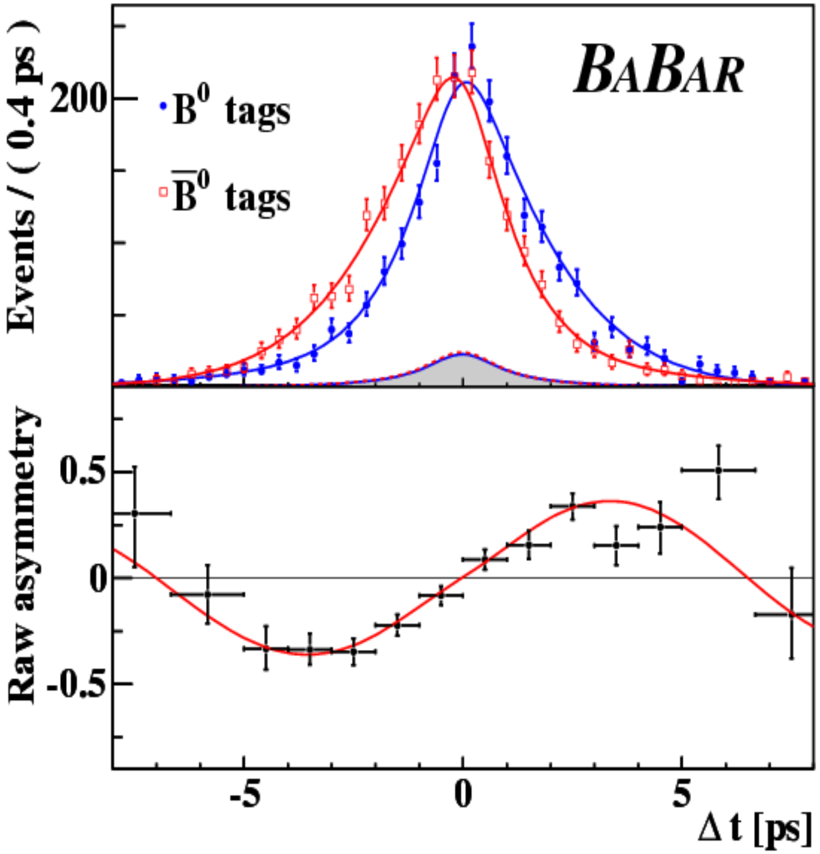
NA48, (2001)

$\delta_L(e) = (3.317 \pm 0.070 \pm 0.072) \times 10^{-3}$

B-system 3.Time-dependent CP asymmetry

$$B^0 \rightarrow J/\psi K_s$$

$$A_{CP}(t) = \frac{N_{\overline{B^0}\rightarrow f} - N_{B^0\rightarrow f}}{N_{B^0\rightarrow f} + N_{\overline{B^0}\rightarrow f}} = \sin(2\beta)\sin(\Delta m t)$$

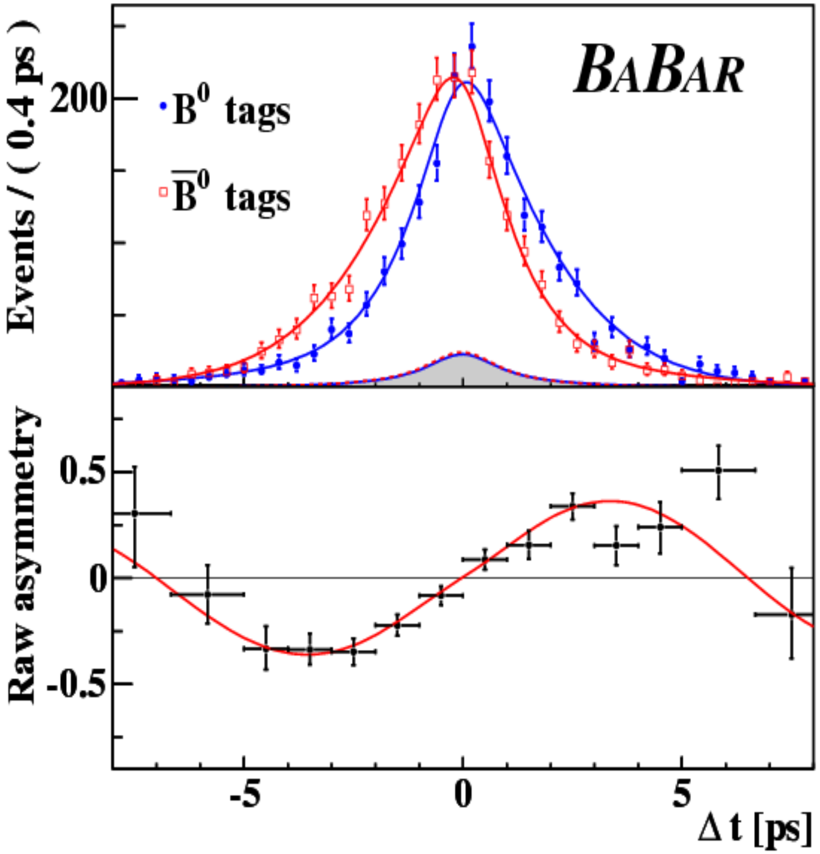


BaBar (2002)

B-system 3.Time-dependent CP asymmetry K-system

$B^0 \to J/\psi K_s$

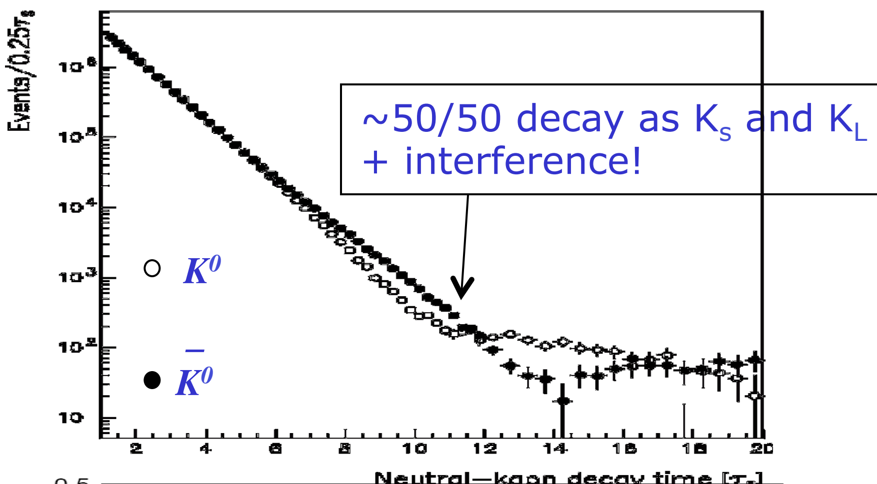
$$A_{CP}(t) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)\sin(\Delta m t)$$

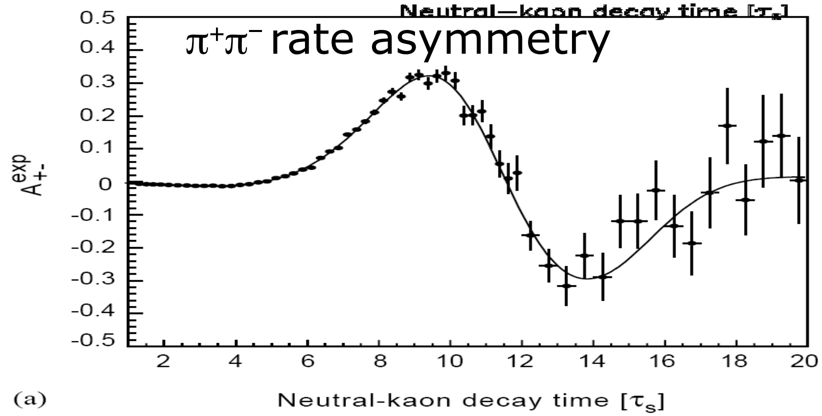


BaBar (2002)

$K^0 \to \pi^- \pi^+$

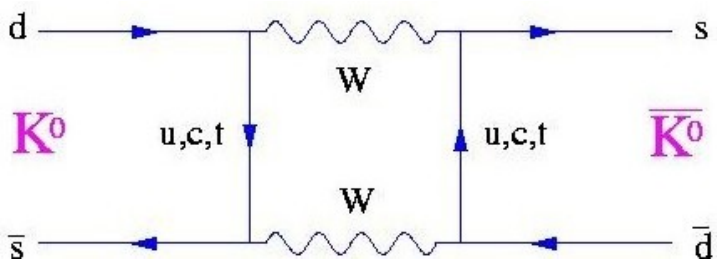
$$A_f(t) = \frac{R(k^0 \to f,t) - R(\bar{k}^0 \to f,t)}{R(k^0 \to f,t) + R(\bar{k}^0 \to f,t)}$$





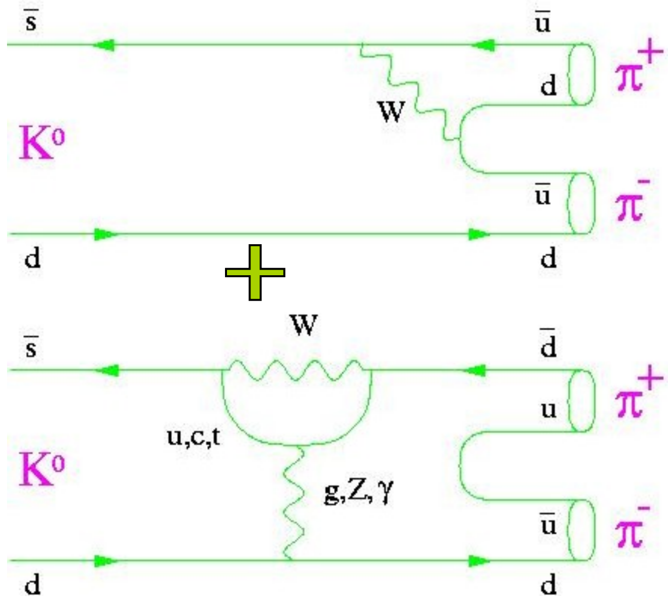
CPLear (PLB 1999)

The Quest for Direct CP Violation



Indirect CP violation in the mixing: ε

Direct CP violation in the decay: ε'



A fascinating 30-year long enterprise: "Is CP violation a peculiarity of kaons? Is it induced by a new superweak interaction?"

B system 1. Direct CP violation K system

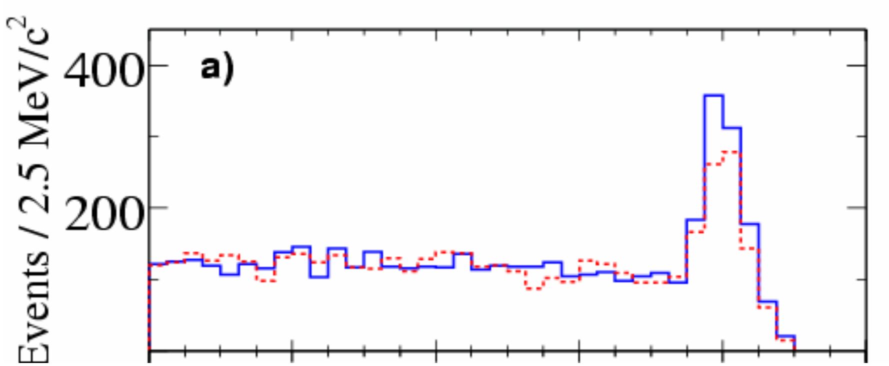
$B^0 \to K^+\pi^-$ $\bar{B}^0 \to K^-\pi^+$

$K^0 \to \pi^-\pi^+$ $\bar{K}^0 \to \pi^-\pi^+$

$K^0 \to \pi^0\pi^0$ $\bar{K}^0 \to \pi^0\pi^0$

$$\eta_{+-} \equiv \frac{Amp(k_L \to \pi^+\pi^-)}{Amp(k_s \to \pi^+\pi^-)} \qquad \eta_{oo} \equiv \frac{Amp(k_L \to \pi^o\pi^o)}{Amp(k_s \to \pi^o\pi^o)}$$

Different CP violation for the two decays → Some CP violation in the decay!

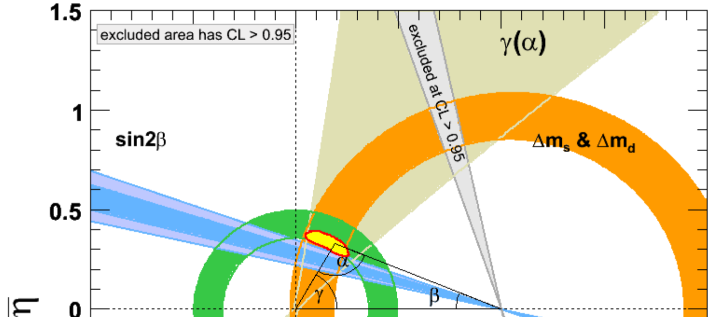


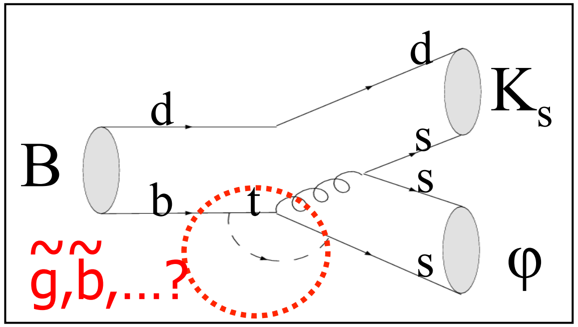
$$\frac{\dfrac{BR(K_L \to \pi^+\pi^-)}{BR(K_s \to \pi^+\pi^-)}}{\dfrac{BR(K_L \to \pi^o\pi^o)}{BR(K_s \to \pi^o\pi^o)}} = \left|\frac{\eta_{+-}}{\eta_{oo}}\right|^2 = \frac{|\varepsilon + \varepsilon'|^2}{|\varepsilon - 2\varepsilon'|^2} \approx 1 + 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$\varepsilon' \neq 0$$

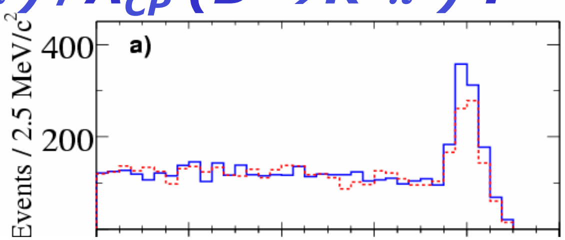
Hints for new physics?

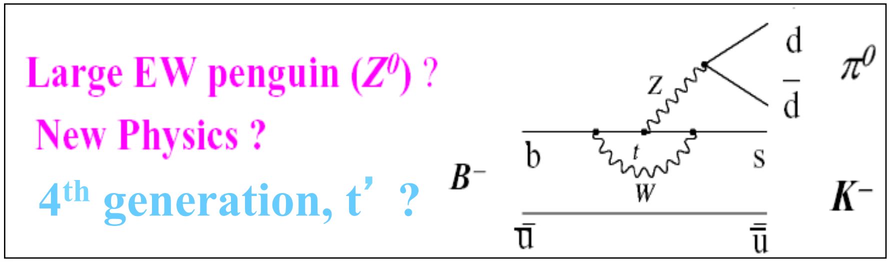
1) $\sin 2\beta \neq \sin 2\beta$?



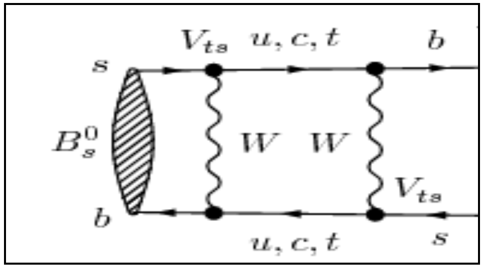


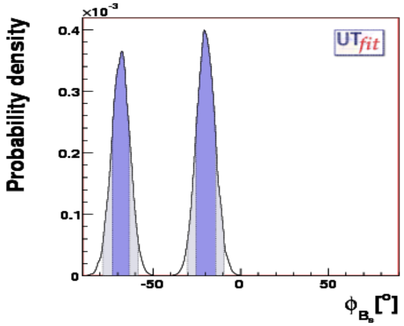
2) $A_{CP}(B^0 \to K^+\pi^-) \neq A_{CP}(B^+ \to K^+\pi^0)$?



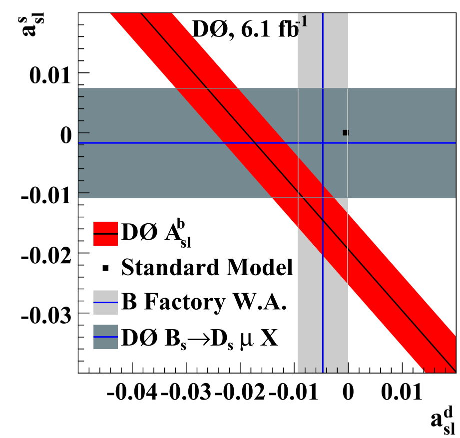


3) $\beta_s \neq 0.04$?

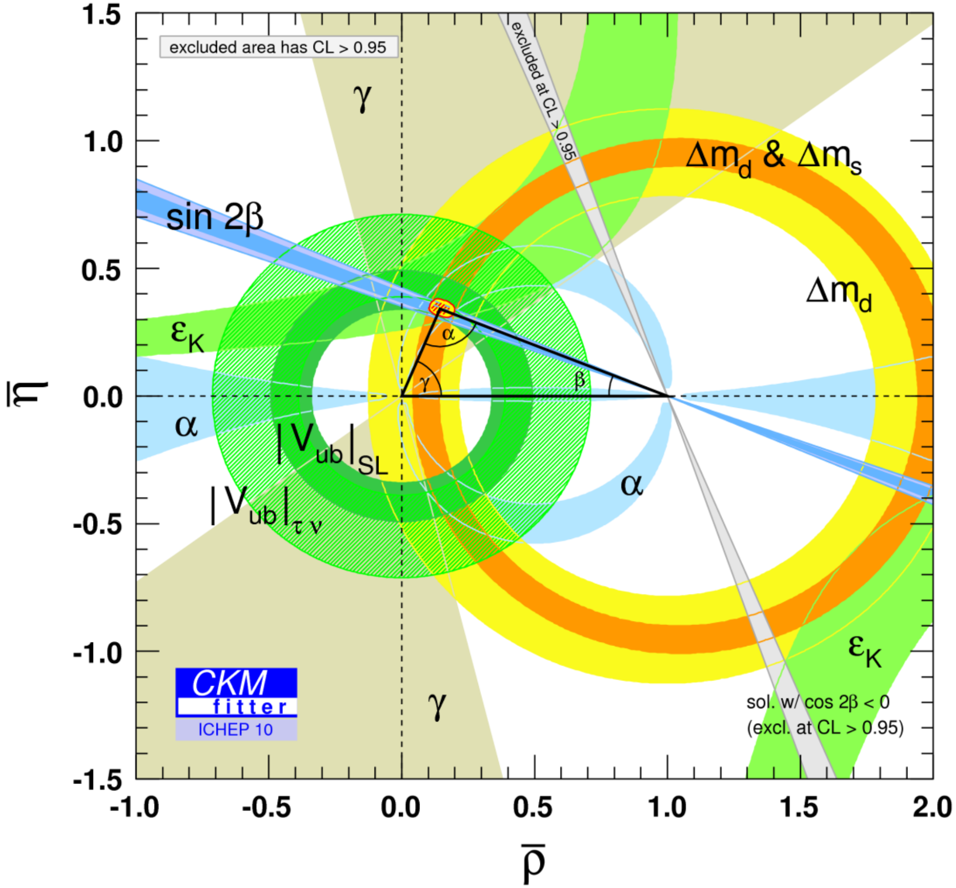


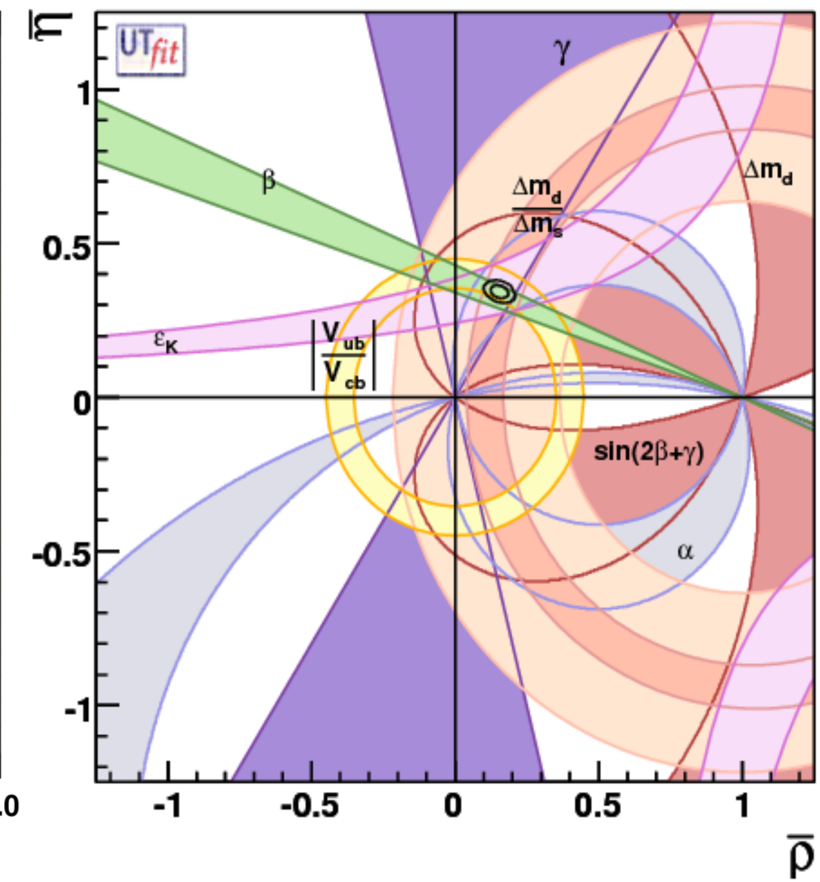


4) $P(B^0_s \to \overline{B^0}_s) \neq P(B^0_s \leftarrow \overline{B^0}_s)$



Present knowledge of unitarity triangle

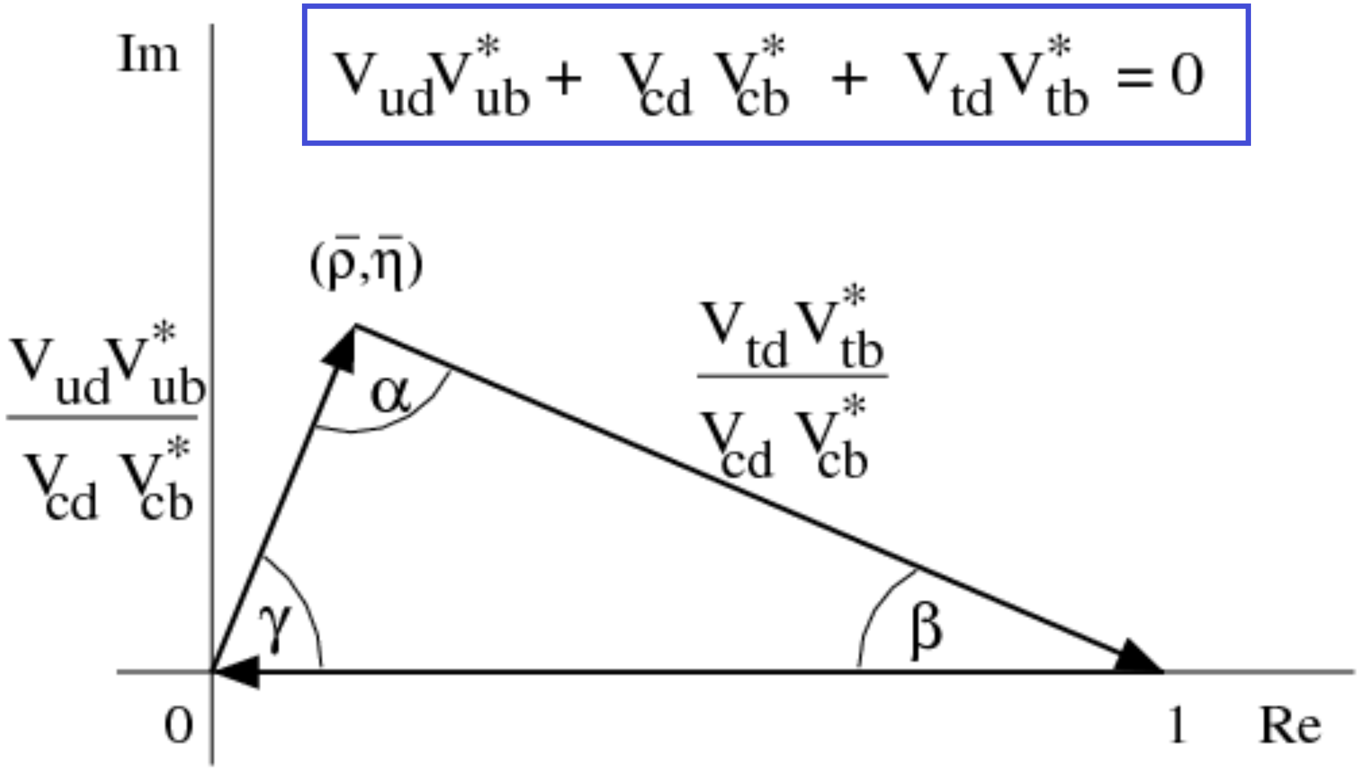




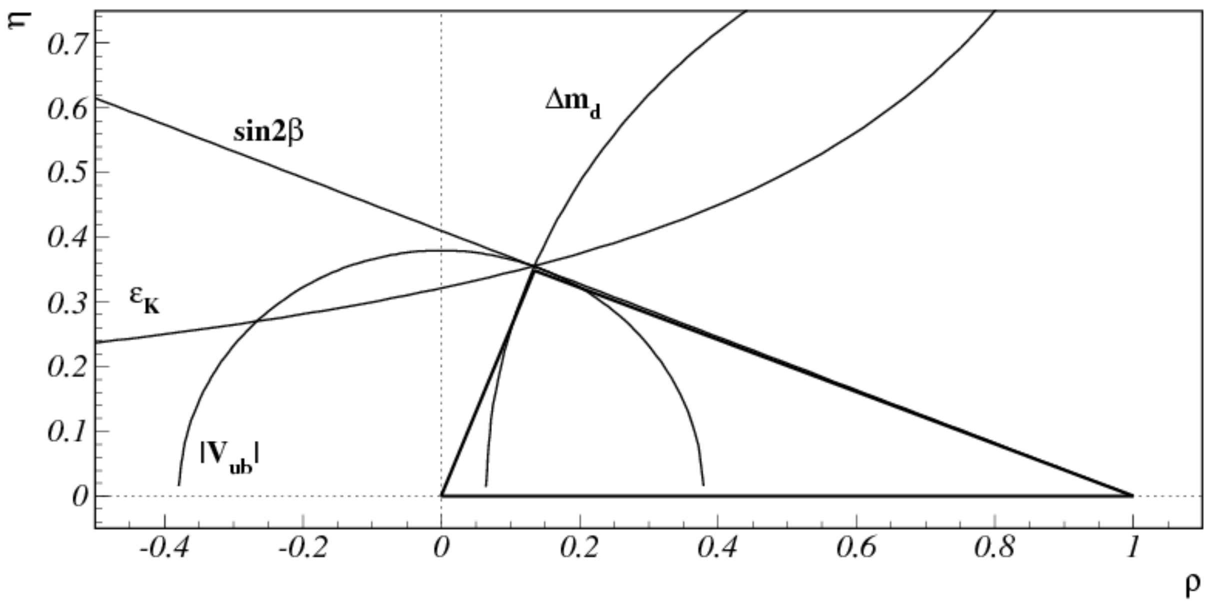
“The” Unitarity triangle

- We can visualize the CKM-constraints in (ρ,η) plane

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Present knowledge of unitarity triangle



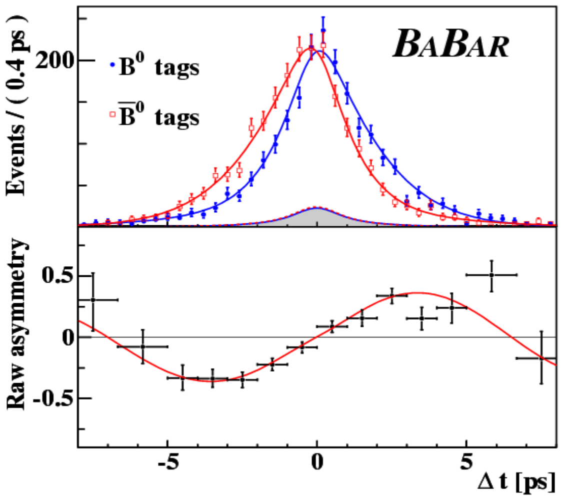
I **sin2**β The measurement of $\sin 2\beta$ constrains one of the three angles of the triangle.

II $\epsilon_{\mathbf{K}}$ The measurement of ϵ_K provides a constraint that follows a hyperbola in the (ρ, η) plane.

III $|\mathbf{V_{ub}}|$ The measurement of $|V_{ub}/V_{cb}|$ constrains one side of the triangle as it is proportional to $\sqrt{\rho^2 + \eta^2}$.

IV $\mathbf{\Delta m}$ The measurements of Δm_d and Δm_s for the B^0 and B_s^0 systems constrain another side, as it is proportional to $((1-\rho)^2 + \eta^2)$.

I) sin 2β



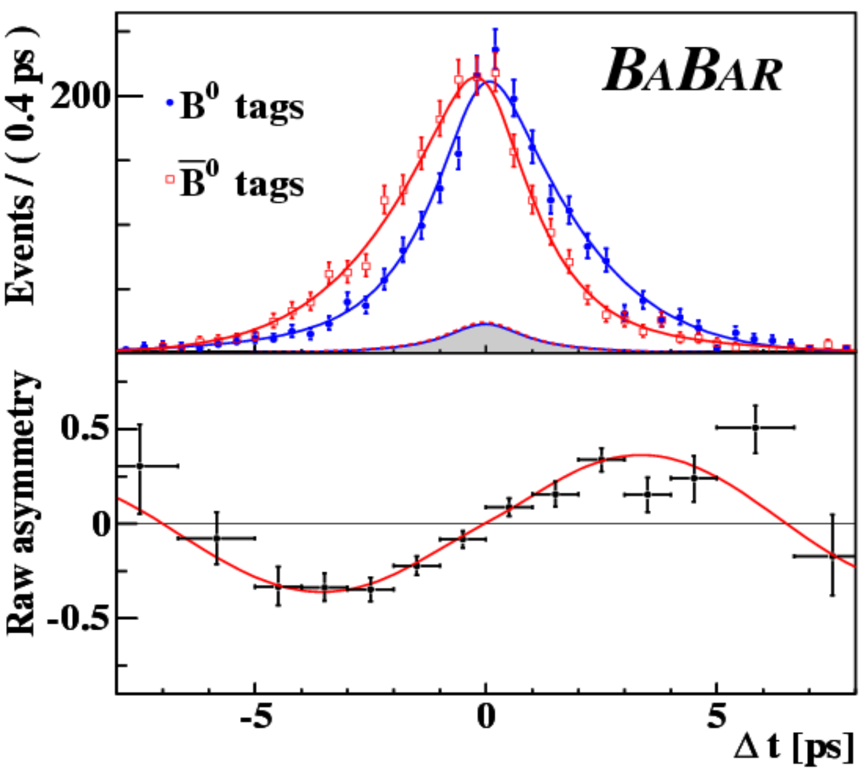
$$\Gamma_{P^0\to f}(t) = |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f \sin\Delta m t\right)$$

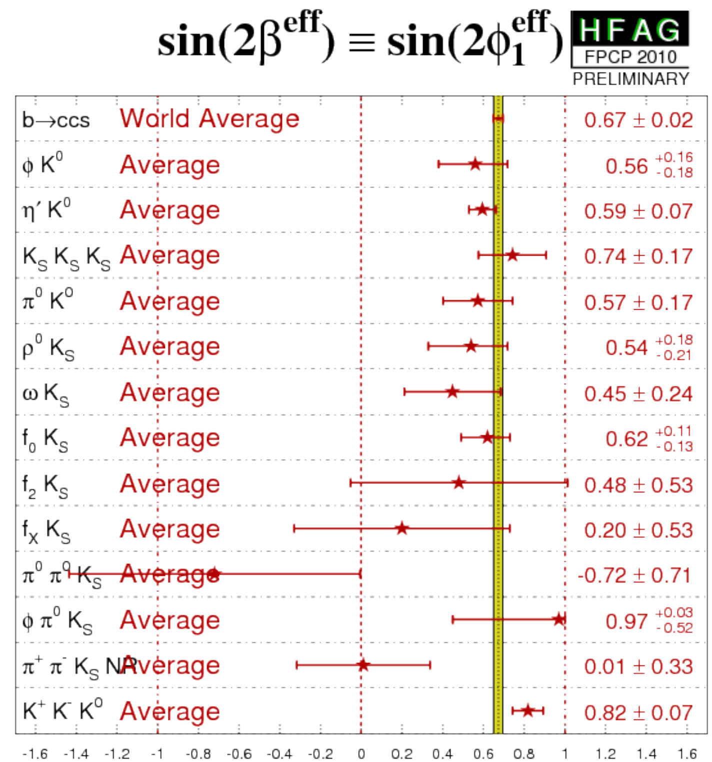
$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f \sin\Delta m t\right)$$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f\cos\Delta m t - 2S_f\sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f\sinh\frac{1}{2}\Delta\Gamma t}$$

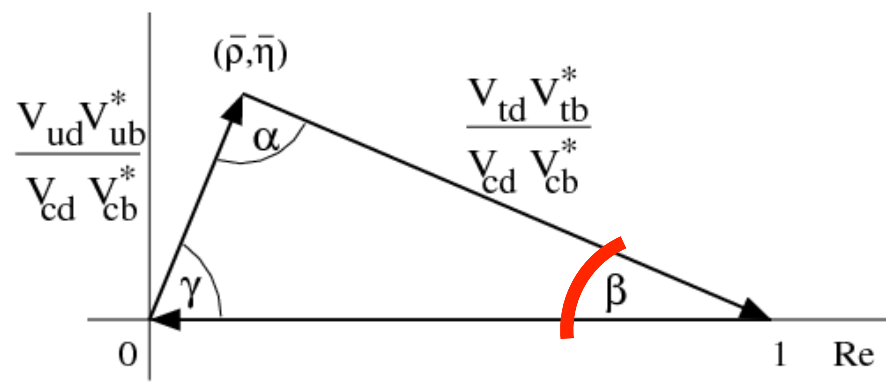
$$A_{CP}(t) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)\sin(\Delta m t)$$

I) sin 2β

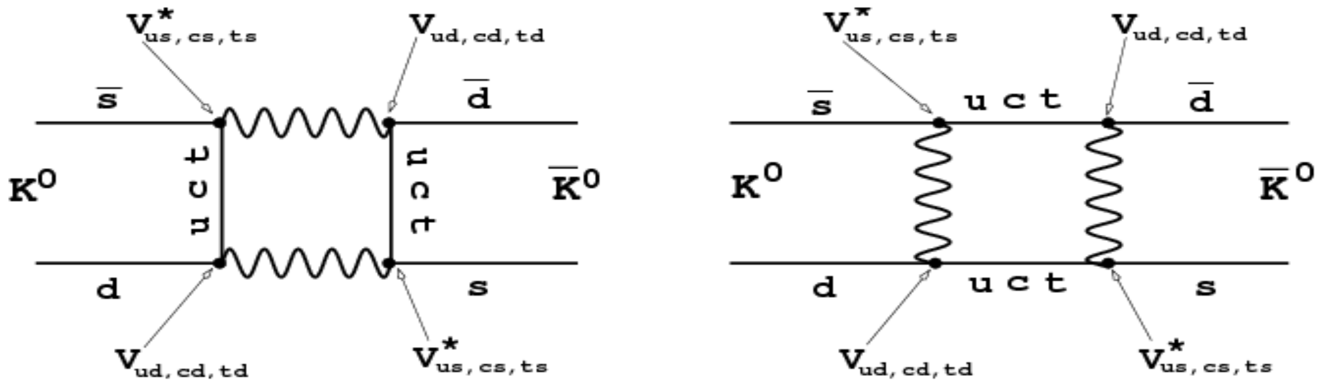




$$A_{CP}(t) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)\sin(\Delta m t)$$



II) ε and the unitarity triangle: box diagram



$$|K_S\rangle = \frac{|K_+\rangle + \varepsilon |K_-\rangle}{\sqrt{1+|\varepsilon|^2}},$$

$$|K_L\rangle = \frac{|K_-\rangle + \varepsilon |K_+\rangle}{\sqrt{1+|\varepsilon|^2}}.$$

CP violation in mixing

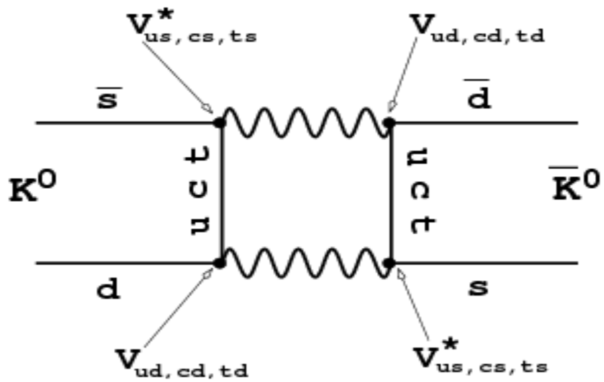
$$\boxed{\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)}$$

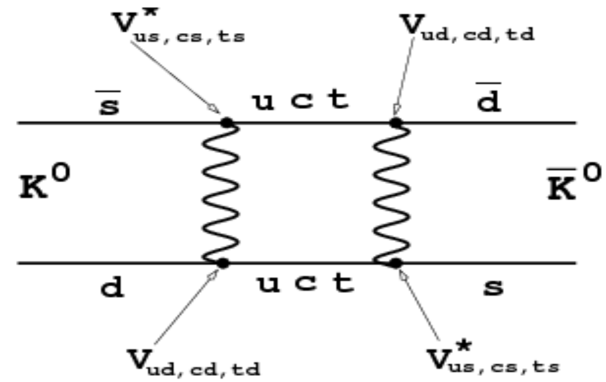
$$\left|\frac{q}{p}\right| \neq 1.$$

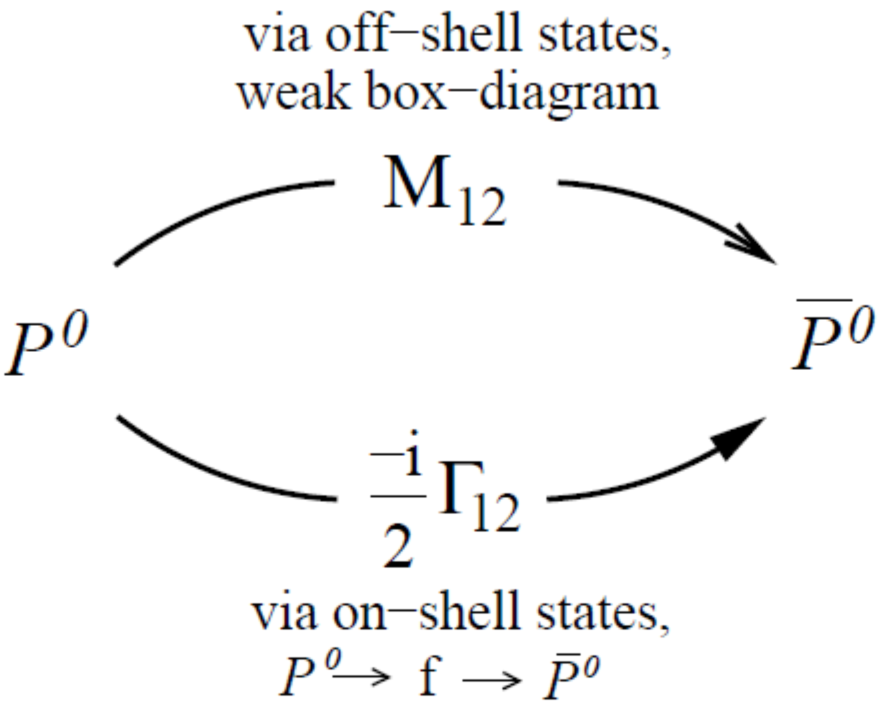
$$|K_S\rangle = p|K^0\rangle + q|\overline{K^0}\rangle, \qquad p = (1+\varepsilon)\Big/\left(\sqrt{2}\sqrt{1+|\varepsilon|^2}\right),$$

$$|K_L\rangle = p|K^0\rangle - q|\overline{K^0}\rangle. \qquad q = (1-\varepsilon)\Big/\left(\sqrt{2}\sqrt{1+|\varepsilon|^2}\right).$$

II) ε and the unitarity triangle: box diagram



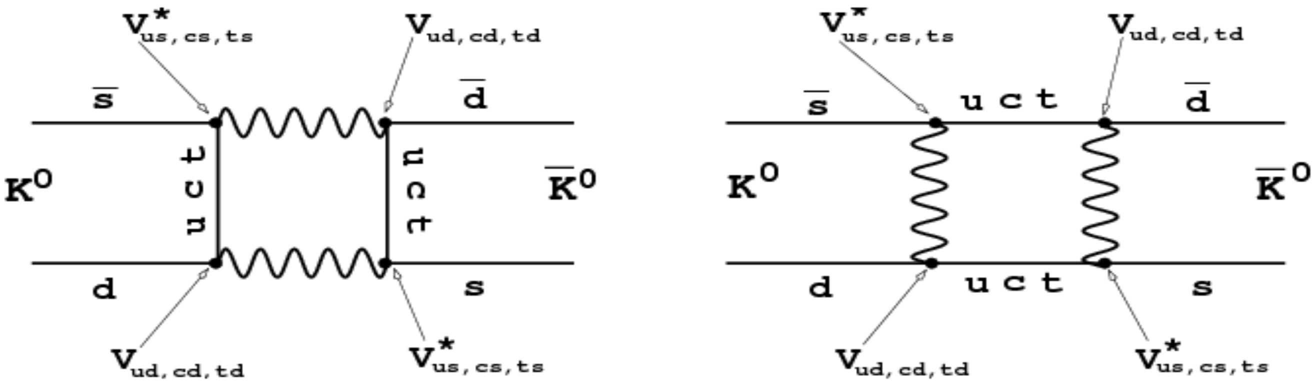




$$\phi = arg\left(-\frac{M_{12}}{\Gamma_{12}} \right)$$

$$\begin{aligned} \Delta m &= 2|M_{12}| \\ \Delta\Gamma &= 2|\Gamma_{12}|\cos\phi. \end{aligned}$$

II) ε and the unitarity triangle: box diagram



$$\Delta m_K = \frac{G_F^2 m_W^2}{6\pi^2}\eta_{QCD} B_K f_K^2 m_K \left[S_0(m_c^2/m_W^2)|V_{cd}V_{cs}|^2\right]$$

$$\begin{aligned}|\epsilon_K| &= \frac{G_F^2 m_W^2}{12\sqrt{2}\pi^2}\frac{m_K f_K^2 B_K}{\Delta m_K} \quad \Im\left[\eta_c S(x_c)(V_{cs}^* V_{cd})^2 + \eta_t S(x_t)(V_{ts}^* V_{td})^2 + 2\eta_{ct} S(x_c, x_t)(V_{cs}^* V_{cd} V_{ts}^* V_{td})\right] \\ &= \frac{G_F^2 m_W^2}{12\sqrt{2}\pi^2}\frac{m_K f_K^2 B_K}{\Delta m_K} \quad [\eta_c S(x_c) 2\Re(V_{cs}^* V_{cd})\Im(V_{cs}^* V_{cd})) + \eta_t S(x_t) 2\Re(V_{ts}^* V_{td})\Im(V_{ts}^* V_{td})) - \\ &\quad \eta_{ct} S(x_c, x_t)\Re(V_{cs}^* V_{cd})\Im(V_{cs}^* V_{cd})]\end{aligned}$$

$Im(z^2)=Im((Rez+iImz)^2)=2RezImz$

third term is evaluated as follows: $(V_{cs}^* V_{cd} V_{ts}^* V_{td}) \equiv (\lambda_c \lambda_t) = (\Re\lambda_c + i\Im\lambda_c)(\Re\lambda_t + i\Im\lambda_t)$. Using $\Im\lambda_c \approx -\Im\lambda_t$ and $\Re\lambda_t \ll \Re\lambda_c$, we then find $\Im(V_{cs}^* V_{cd} V_{ts}^* V_{td}) \approx -\Re(V_{cs}^* V_{cd})\Im(V_{cs}^* V_{cd})$.

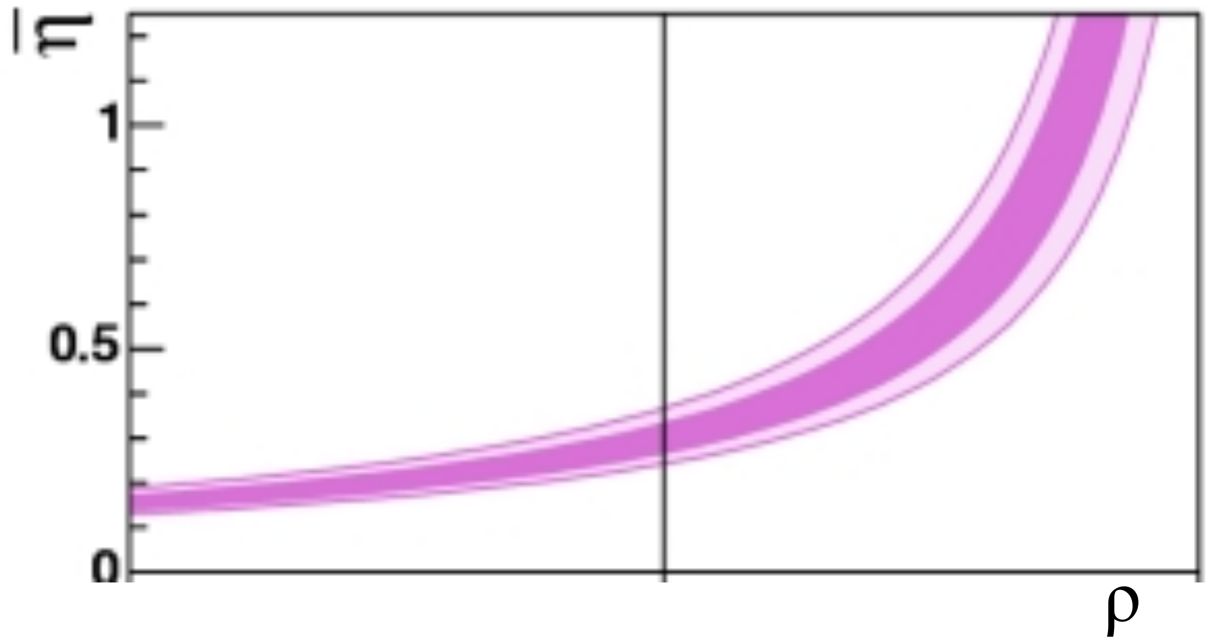
II) ε and the unitarity triangle

Using the Wolfenstein parameterization we find [2]:

$$
\begin{aligned}
|\epsilon_K| &= \frac{G_F^2 m_W^2}{12\sqrt{2}\pi^2}\frac{m_K f_K^2 B_K}{\Delta m_K} A^2\lambda^6\eta\left[\eta_c S(x_c) - \eta_t S(x_t) A^2\lambda^4(1-\rho) - \eta_{ct} S(x_c, x_t)\right] \\
&\approx 10^4\, A^2\lambda^6\eta\left[\eta_c S(x_c) - \eta_t S(x_t) A^2\lambda^4(1-\rho) - \eta_{ct} S(x_c, x_t)\right].
\end{aligned}
$$

With $|V_{cb}| = A\lambda^2$ and $|V_{us}| = \lambda$ and the evaluation of the Inami-Lim functions $S(x_c) \approx 2.4 \times 10^{-4}$, $S(x_t) \approx 2.6$ and $S(x_c, x_t) = 2.2 \times 10^{-3}$ [20] we can rewrite as:

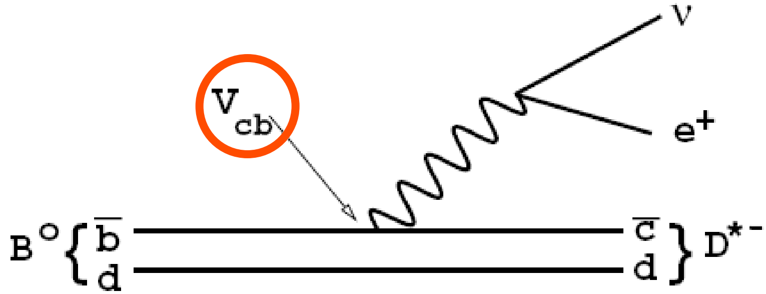
$$
\begin{aligned}
|\epsilon_K| &\approx 10^4\, \eta |V_{cb}|^2 |V_{us}|^2 \left[2.4 \times 10^{-4} + 2.6 |V_{cb}|^2 (1-\rho) - 2.2 \times 10^{-3}\right] \\
&\approx 10^{-3}\, \eta\left[(1-\rho)\right]
\end{aligned}
$$

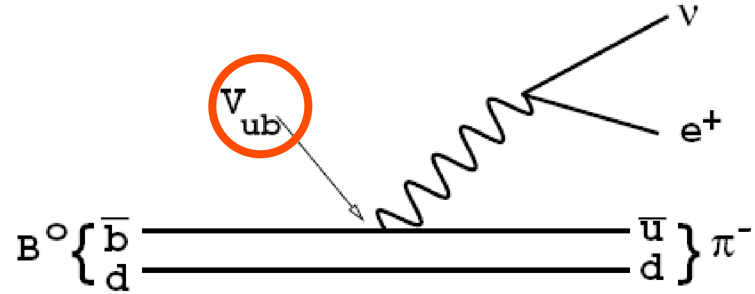


III.) $|V_{ub}|$ / $|V_{cb}|$

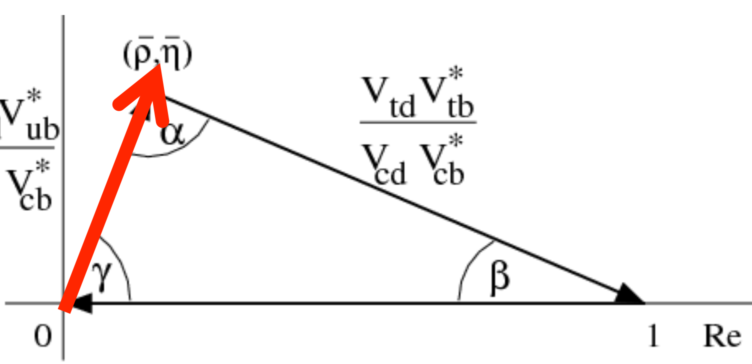
- Measurement of V_{ub}
  - Compare decay rates of $B^0 \to D^{*-} l^+ \nu$ and $B^0 \to \pi^- l^+ \nu$
  - Ratio proportional to $(V_{ub}/V_{cb})^2$
  - $|V_{ub}/V_{cb}| = 0.090 \pm 0.025$
  - V_{ub} is of order $\sin(\theta_c)^3$ [= 0.01]

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





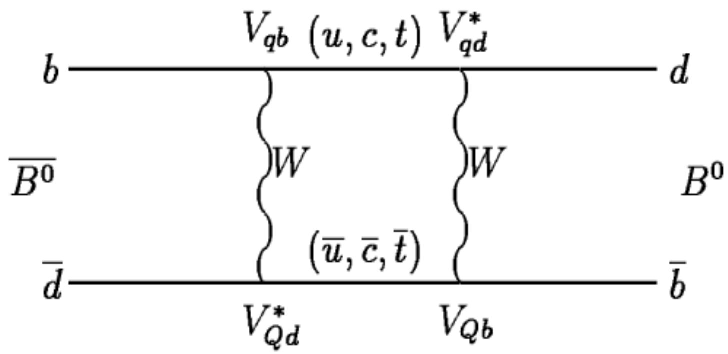
$$\frac{\Gamma(b \to u l^- \overline{\nu}_l)}{\Gamma(b \to c l^- \overline{\nu}_l)} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \left(\frac{f(m_u^2 / m_b^2)}{f(m_c^2 / m_b^2)} \right)$$

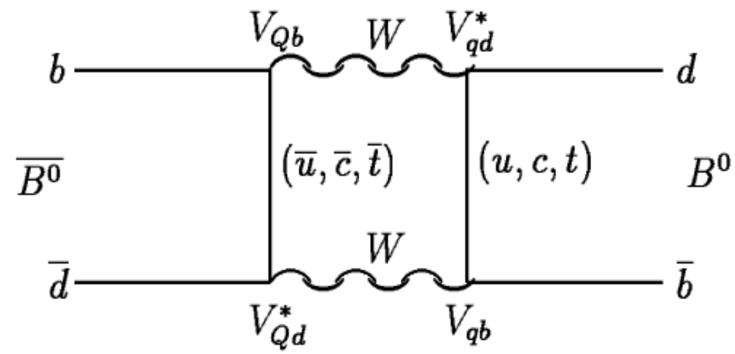


$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \qquad \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$$

IV.) Δm_d and Δm_s

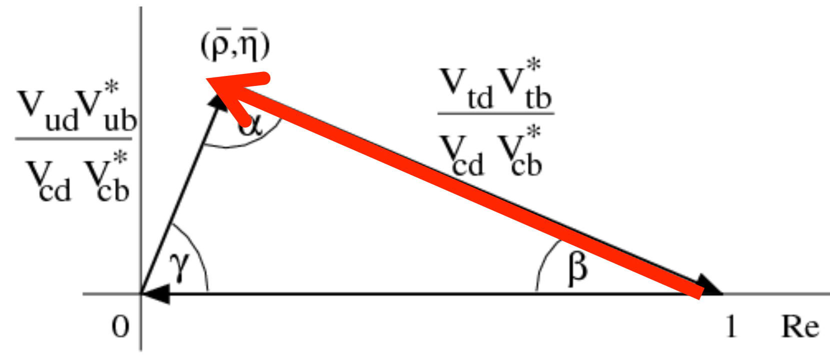
$$\Delta m_B = \frac{G_F^2 m_W^2}{6\pi^2}\eta_{QCD} B_B f_B^2 m_B \left[S_0(m_t^2/m_W^2)|V_{td}V_{tb}|^2\right]$$



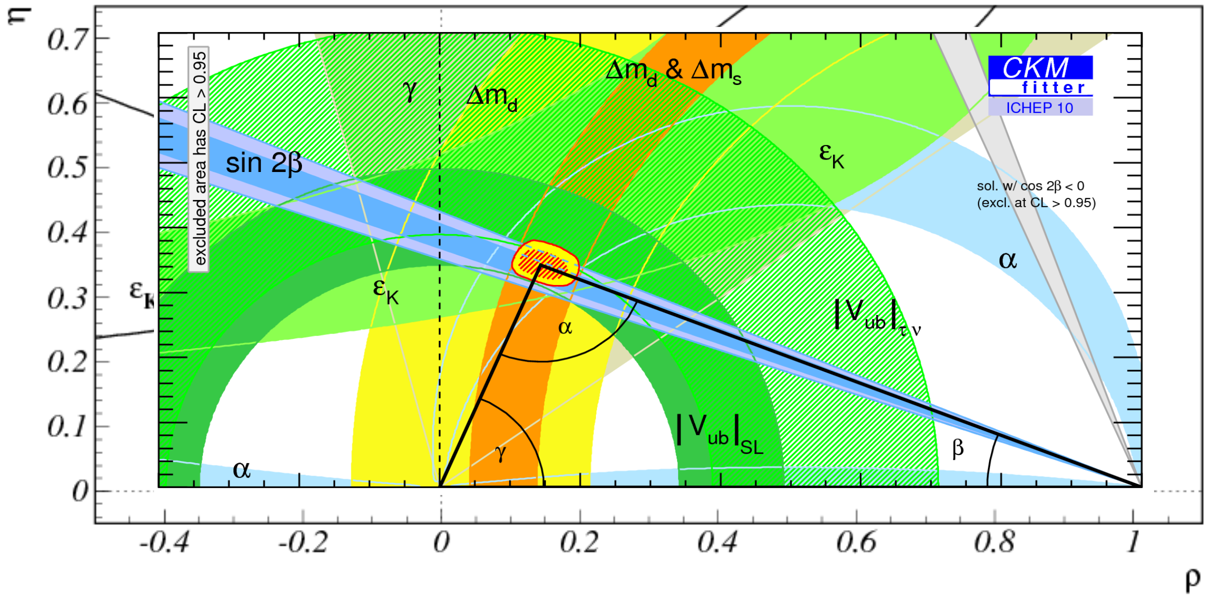


- Δm depends on V_{td}
- V_{ts} constraints hadronic uncertainties

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}}\frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}}\frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{Bs}}{m_{Bd}}\xi^2\frac{|V_{ts}|^2}{|V_{td}|^2}$$



Present knowledge of unitarity triangle



I **sin2**β The measurement of $\sin 2\beta$ constrains one of the three angles of the triangle.

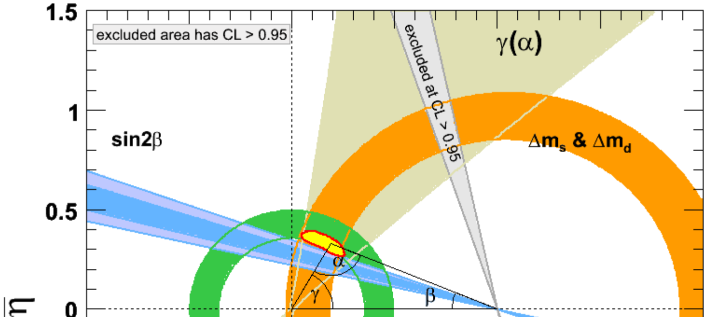
II $\boldsymbol{\epsilon_K}$ The measurement of ϵ_K provides a constraint that follows a hyperbola in the (ρ, η) plane.

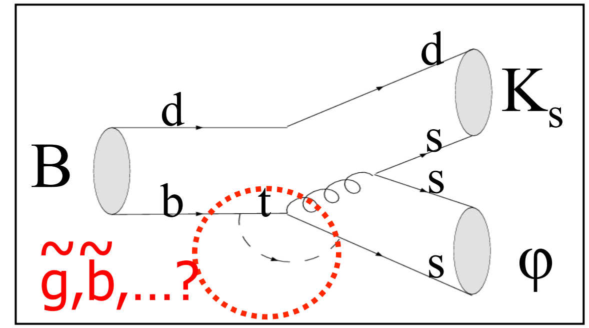
III $|\mathbf{V_{ub}}|$ The measurement of $|V_{ub}/V_{cb}|$ constrains one side of the triangle as it is proportional to $\sqrt{\rho^2 + \eta^2}$.

IV $\mathbf{\Delta m}$ The measurements of Δm_d and Δm_s for the B^0 and B_s^0 systems constrain another side, as it is proportional to $((1-\rho)^2 + \eta^2)$.

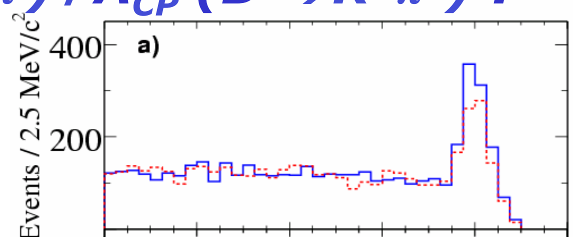
Hints for new physics?

1) $\sin 2\beta \neq \sin 2\beta$?





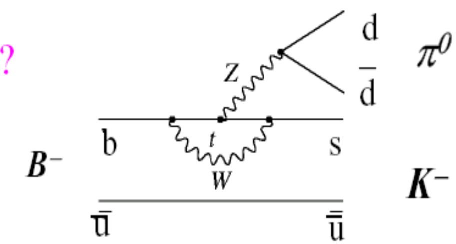
2) $A_{CP}(B^0 \rightarrow K^+\pi^-) \neq A_{CP}(B^+ \rightarrow K^+\pi^0)$?



Large EW penguin (Z^0) ?

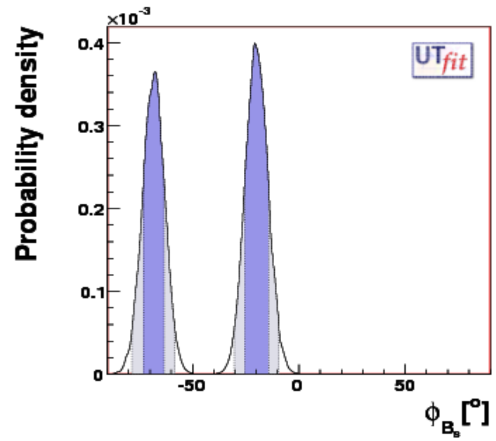
New Physics ?

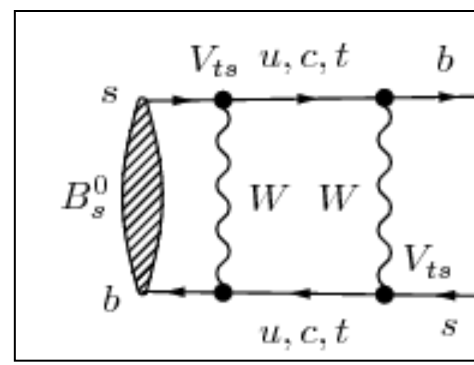
4^{th} generation, t' ?



3) $\beta_s \neq 0.04$?

4) $P(B^0_s \rightarrow ?B^0_s) \neq P(B^0_s \leftarrow ?B^0_s)$



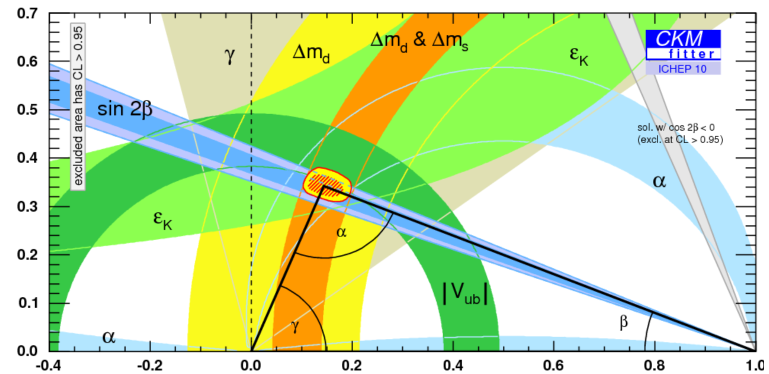


More hints for new physics?

5) ε_K ? $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$

- *Treatment of errors…*
- *Input from Lattice QCD B_K*
- *Strong dependence on V_{cb}*

Inputs from Lunghi (FPCP2010) and Gaussian errors: $10^3|\epsilon_K| = 1.77^{+0.18}_{-0.16}\ (2.4\,\sigma)$



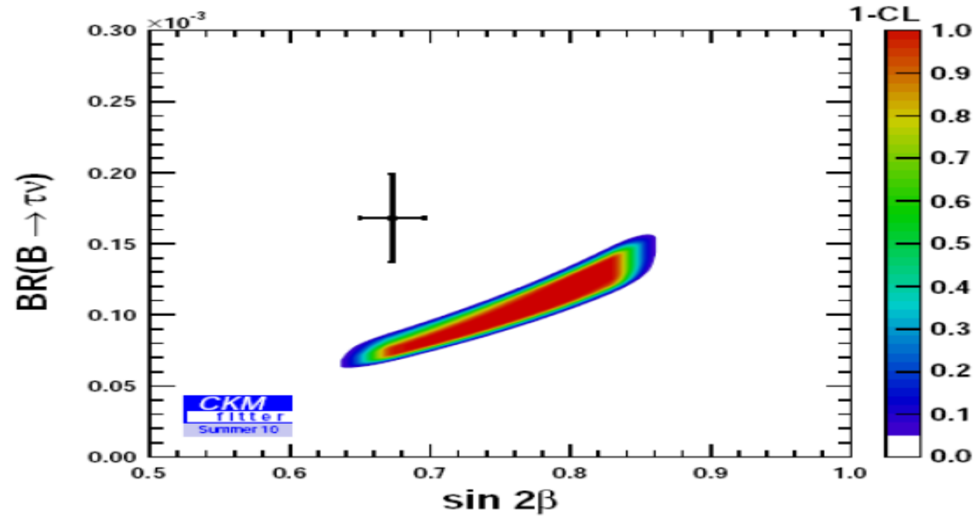
More hints for new physics?

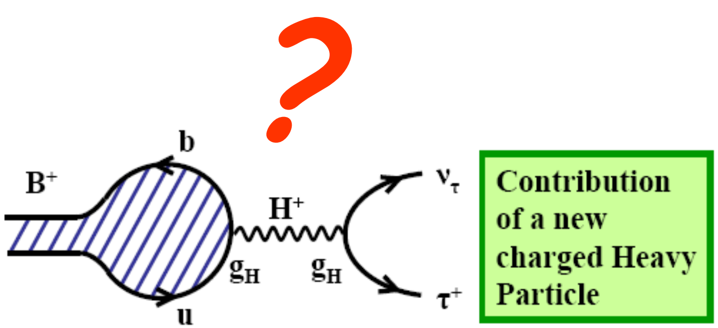
6) V_{ub}: 2.9σ ??

$BR(B^+ \to \tau\upsilon) = 1.68 \pm 0.31 \quad 10^{-4}$
Predicted: $0.764 \pm 0.087 \quad 10^{-4}$

$$\mathcal{B}(B \to \tau\nu) = \frac{G_F^2 m_{B^+} m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 |V_{ub}|^2 f_B^2 \tau_{B^+}$$

(If f_{Bd} off, then B_{Bd} needs to be off too, to make Δm_d agree)





From:
H.Lacker, and A.Buras, Beauty2011, Amsterdam

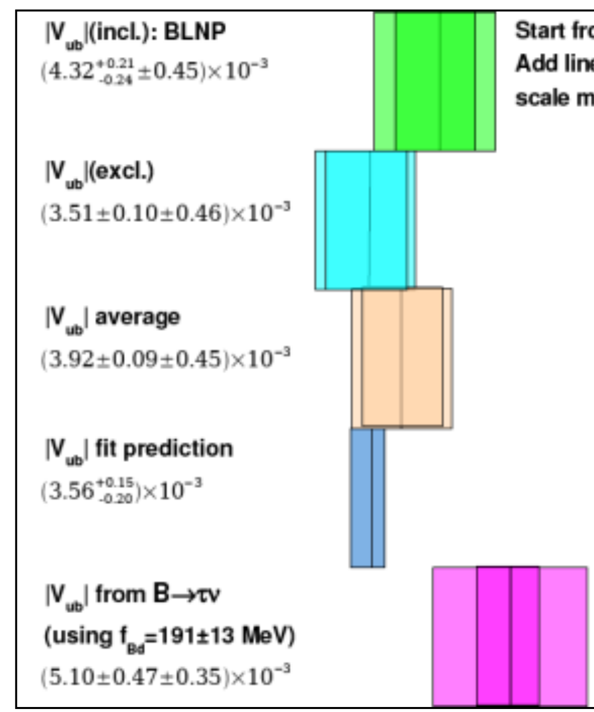
$|V_{ub}|$ from b → ulν decays

$|V_{ub}|$ from B → πlν decays

$|V_{ub}|$ avg from semi-lep

$|V_{ub}|$ from *fit*

$|V_{ub}|$ from $B \to \tau\nu$



A.Buras, Beauty2011:

Most popular BSM Directions

NEW **MFV** (NMFV) (GMFV)

CMFV (constrained MFV)

NEW **2HDM**

NEW **RHMFV**

LHT (Littlest Higgs with T-parity)

SUSY (flavour models)

Z´ (Langacker…)

RS (Randall-Sundrum) (Warped Extra Dimensions)

NEW **4th G** (Hou.., Soni.., Lenz.., Melic) Munich

Vector-Like Quarks (Branco…, del Aguila)

Non-Decoupling

New gauge bosons, fermions, scalars in loops and even trees with often non-CKM interactions.

A.Buras, Beauty2011:

ABGPS

DNA Tests of Flavour Models

0909.1333

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS	4G
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?	★★
ϵ_K	★	★★★	★★★	★	★	★★	★★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?	★★
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?	★
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?	★★
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?	★★
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★	★★★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★	★
d_e	★★★	★★★	★★	★	★★★	★	★★★	★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?	★

Standard Model: 25 free parameters

Elementary particle masses (MeV):

$m_e \approx$	0.51099890	$m_{\nu e} <$	0.000003	$m_u \approx$	3	$m_d \approx$	7
$m_\mu \approx$	105.658357	$m_\nu^\mu <$	0.19	$m_c \approx$	1200	$m_s \approx$	120
$m_\tau \approx$	1777.0	$m_\nu^\tau <$	18.2	$m_t \approx$	174000	$m_b \approx$	4300

Electro-weak interaction:

$\alpha_e(0) \approx 1/137.036$

$m_W \approx 80.42$ GeV

$m_Z \approx 91.188$ GeV

$m_H > 114.3$ GeV

CMS

quark mixing (4)

$$\begin{pmatrix} u' \\ d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ij}^q \end{pmatrix} \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

LHCb

neutrino mixing (4)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{ij}^l \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

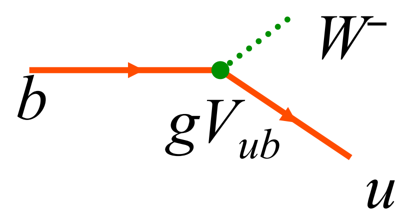
Strong interaction:

$\alpha_s(m_Z) \approx 0.117$

The CKM matrix

- *Couplings* of the charged current:

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



- Wolfenstein *parametrization*:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

- Magnitude:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.9738 \pm 0.0002 & 0.227 \pm 0.001 & 0.00396 \pm 0.00009 \\ 0.227 \pm 0.001 & 0.9730 \pm 0.0002 & 0.0422 \pm 0.0005 \\ 0.0081 \pm 0.0005 & 0.0416 \pm 0.0005 & 0.99910 \pm 0.00004 \end{pmatrix}$$

- Complex phases:

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

The CKM matrix

- *Couplings* of the charged current:

$$1)\quad -\mathcal{L}_{Yuk} = Y_{ij}^{d}\,(\overline{u_L^I}, \overline{d_L^I})_i \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_{Rj}^I + Y_{ij}^{u}(\ldots) + Y_{ij}^{l}(\ldots)$$

$$2)\quad -\mathcal{L}_{W^+} = \frac{g}{\sqrt{2}}\,\overline{u_{Li}^I}\,\gamma^\mu\, d_{Li}^I\, W_\mu^+$$

$$3)\quad -\mathcal{L}_{W^+} = \frac{g}{\sqrt{2}}\,(\bar{u}, \bar{c}, \bar{t})_L \,(V_{CKM}) \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \gamma^\mu W_\mu^+$$

- Wolfenstein *parametrization*

- Magnitude:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.9738 \pm 0.0002 & 0.227 \pm 0.001 & 0.00396 \pm 0.00009 \\ 0.227 \pm 0.001 & 0.9730 \pm 0.0002 & 0.0422 \pm 0.0005 \\ 0.0081 \pm 0.0005 & 0.0416 \pm 0.0005 & 0.99910 \pm 0.00004 \end{pmatrix}$$

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The CKM matrix

- *Couplings* of the charged current:
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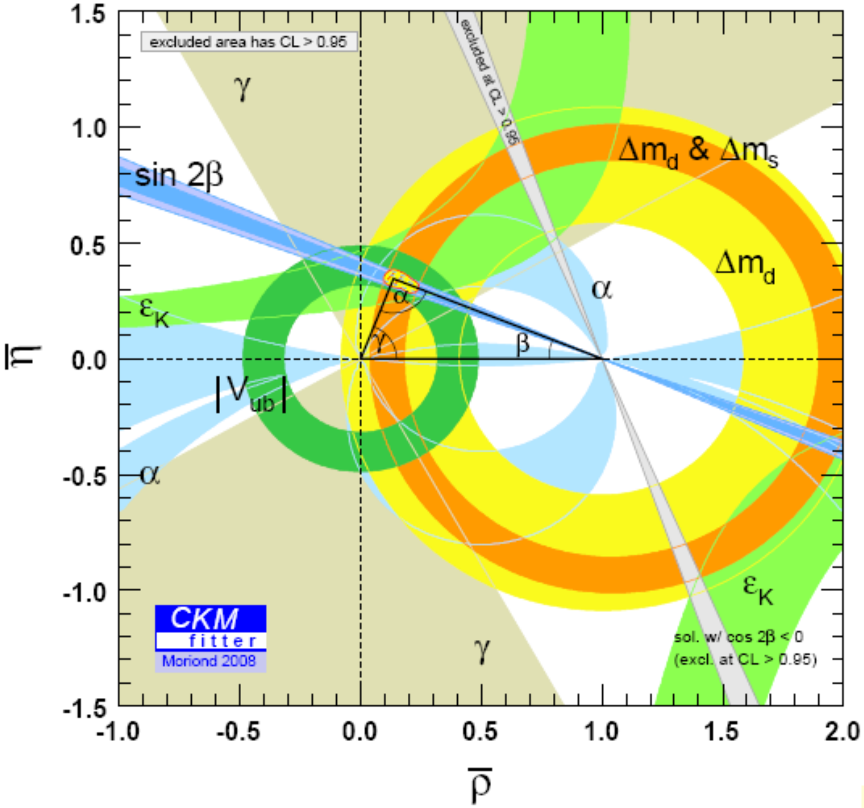

- Magnitude:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.9738 \pm 0.0002 & 0.227 \pm 0.001 & 0.00396 \pm 0.00009 \\ 0.227 \pm 0.001 & 0.9730 \pm 0.0002 & 0.0422 \pm 0.0005 \\ 0.0081 \pm 0.0005 & 0.0416 \pm 0.0005 & 0.99910 \pm 0.00004 \end{pmatrix}$$

- Complex phases:

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

Remember the following:

- CP violation is discovered in the K-system
- CP violation is naturally included if there are 3 generations or more
  - 3x3 unitary matrix has 1 free complex parameter
- CP violation manifests itself as a complex phase in the CKM matrix
- The CKM matrix gives the strengths and phases of the weak couplings
- CP violation is apparent in experiments/processes with 2 interfering amplitudes with different strong and weak phase
  - Often using "mixing" to get the 2nd decay process
- Flavour physics is powerful for finding new physics in loops!
  - Complementary to Atlas/CMS

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Thank you

Personal impression:

- People think it is a complicated part of the Standard Model (me too:-). Why?

1) Non-intuitive concepts?

- *Imaginary phase* in transition amplitude, T ~ $e^{i\varphi}$
- *Different bases* to express quark states, d' =0.97 d + 0.22 s + 0.003 b
- *Oscillations* (mixing) of mesons: $|K^0\rangle \leftrightarrow |\bar{K}^0\rangle$

2) Complicated calculations?

$$\Gamma\left(B^0 \to f\right) \propto \left|A_f\right|^2 \left[\left|g_+(t)\right|^2 + \left|\lambda\right|^2 \left|g_-(t)\right|^2 + 2\Re\left(\lambda g_+^*(t) g_-(t)\right)\right]$$

$$\Gamma\left(\bar{B}^0 \to f\right) \propto \left|\bar{A}_f\right|^2 \left[\left|g_+(t)\right|^2 + \frac{1}{\left|\lambda\right|^2} \left|g_-(t)\right|^2 + \frac{2}{\left|\lambda\right|^2}\Re\left(\lambda^* g_+^*(t) g_-(t)\right)\right]$$

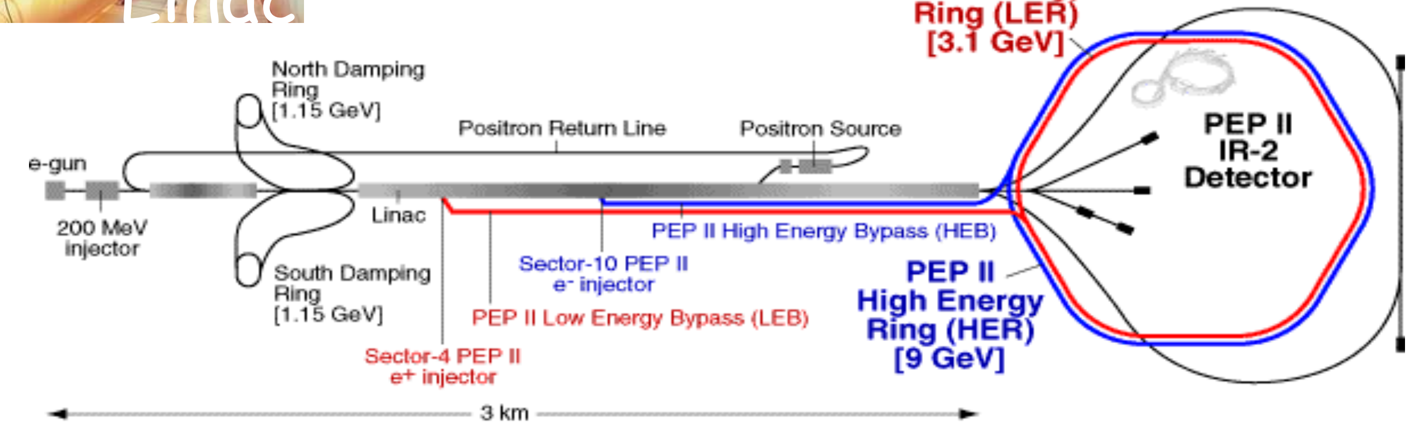
3) Many decay modes? *"Beetopaipaigamma…"*

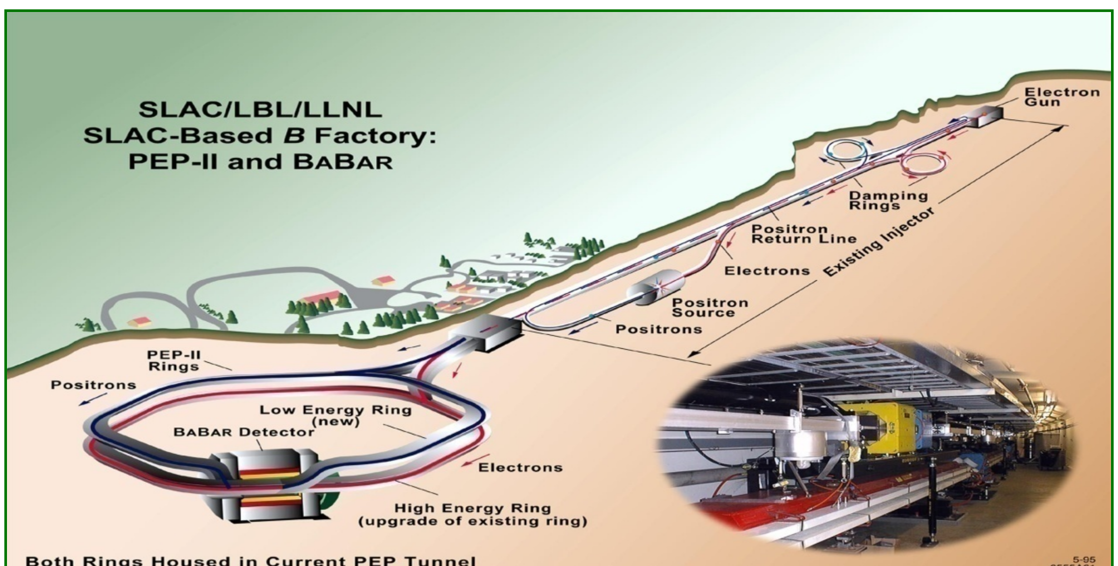
- PDG reports 347 decay modes of the B^0-meson:
  - Γ_1 $l^+ \nu_l$ *anything* (10.33 ± 0.28) × 10^{-2}
  - Γ_{347} $\nu \nu \gamma$ $<4.7 \times 10^{-5}$ *CL=90%*
- And for one decay there are often more than one decay *amplitudes*…

Backup

SLAC: LINAC + PEPII

$$\left.\begin{array}{l} E_{e^+} = 3.1 \text{ GeV} \\ E_{e^-} = 9 \quad \text{GeV} \end{array}\right\} \beta\gamma = 0.56, \sqrt{s} = M\left(\Upsilon_{4S}\right)$$





PEP-II accelerator schematic and tunnel view

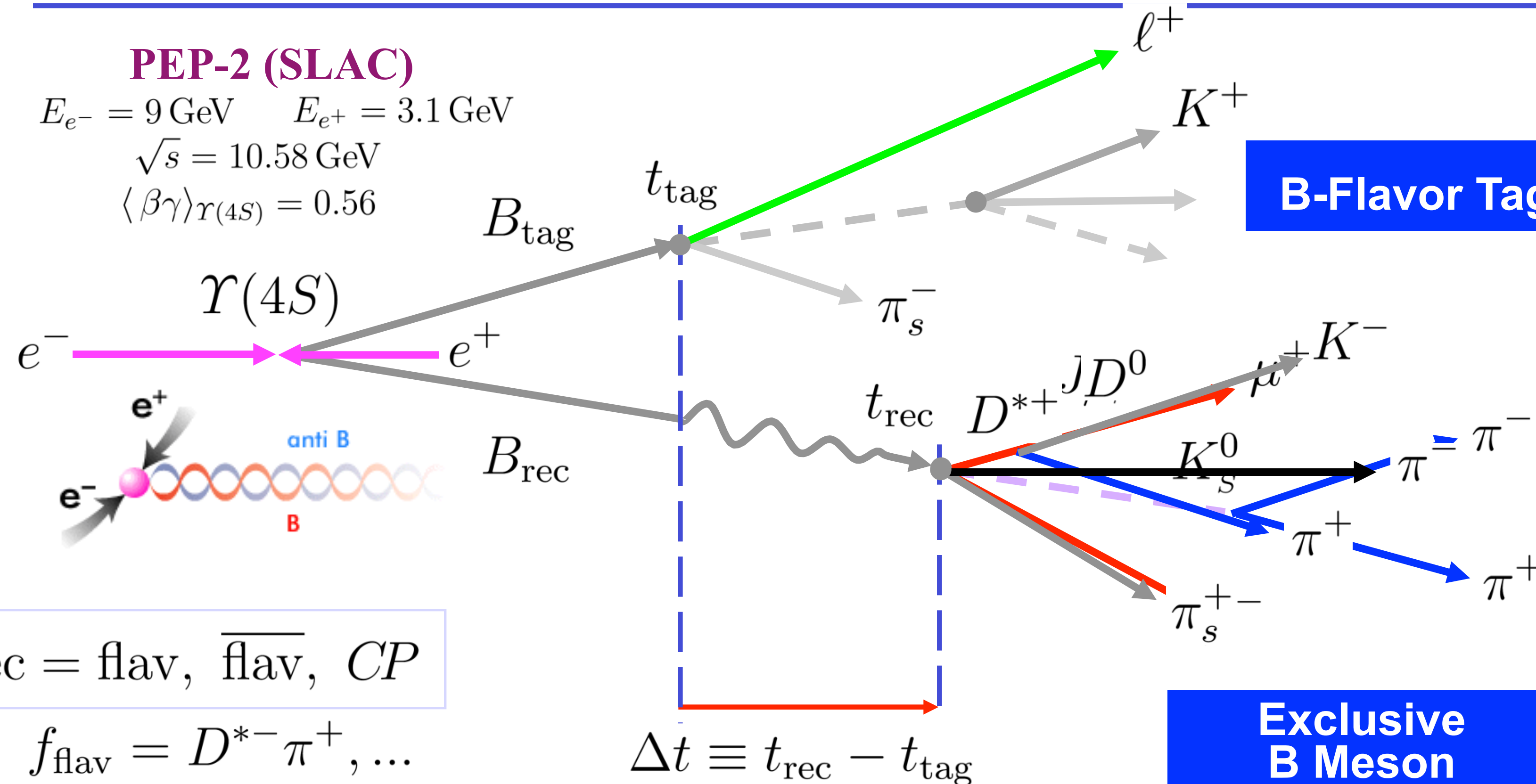
Coherent Time Evolution at the $\Upsilon(4S)$

PEP-2 (SLAC)

$E_{e^-} = 9\,\mathrm{GeV} \qquad E_{e^+} = 3.1\,\mathrm{GeV}$

$\sqrt{s} = 10.58\,\mathrm{GeV}$

$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.56$



B-Flavor Tagging

$\mathrm{rec} = \mathrm{flav},\ \overline{\mathrm{flav}},\ CP$

$f_{\mathrm{flav}} = D^{*-}\pi^+, \ldots$

$f_{CP} = J/\psi\, K_S^0,\ J/\psi\, K_L^0, \ldots$

$\mathrm{tag} = B^0,\ \overline{B}^0$

$f_{B^0} = X\ell^+\nu,\ X K^+,\ X\pi_s^-, \ldots$

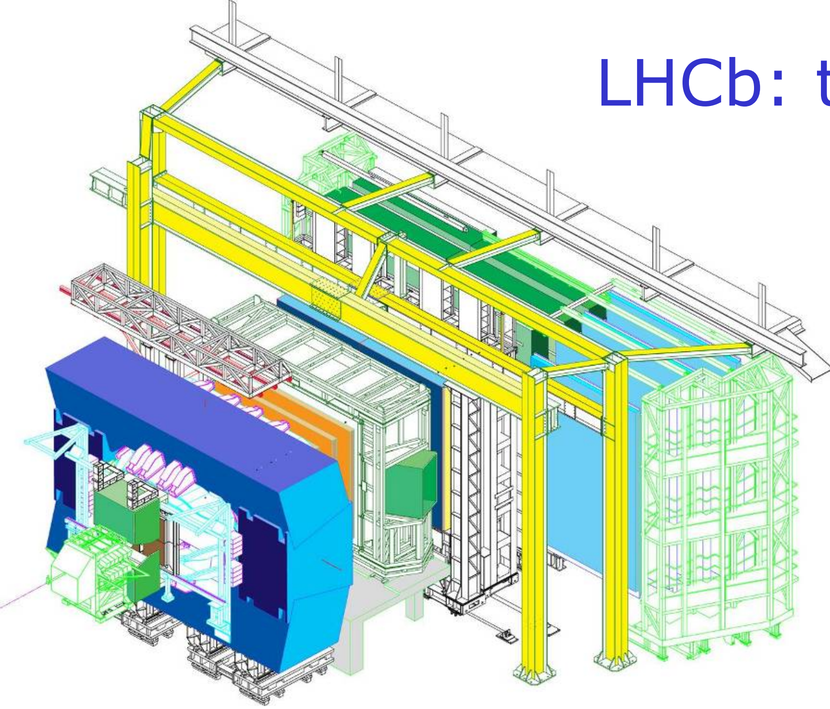
Exclusive B Meson Reconstruction

Vertexing & Time Difference Determination

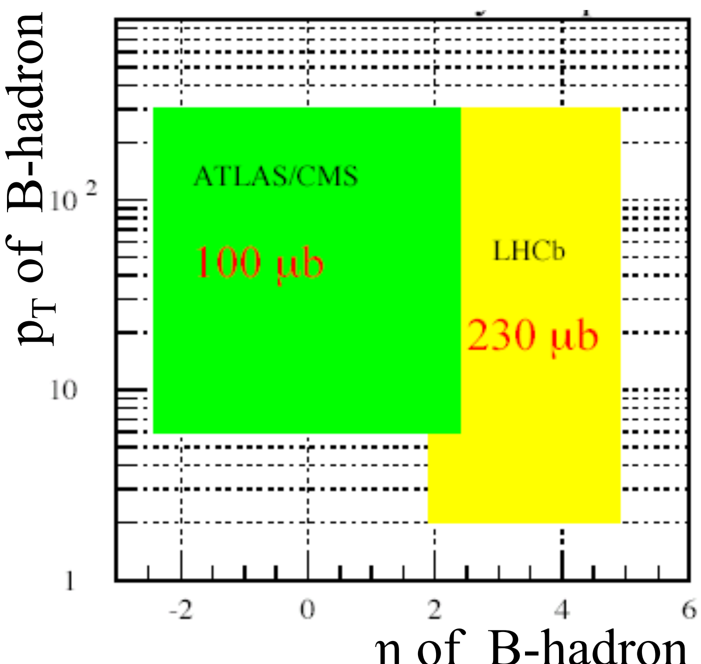
$\Delta t \approx \Delta z / c \langle \beta\gamma \rangle_{\Upsilon(4S)}$

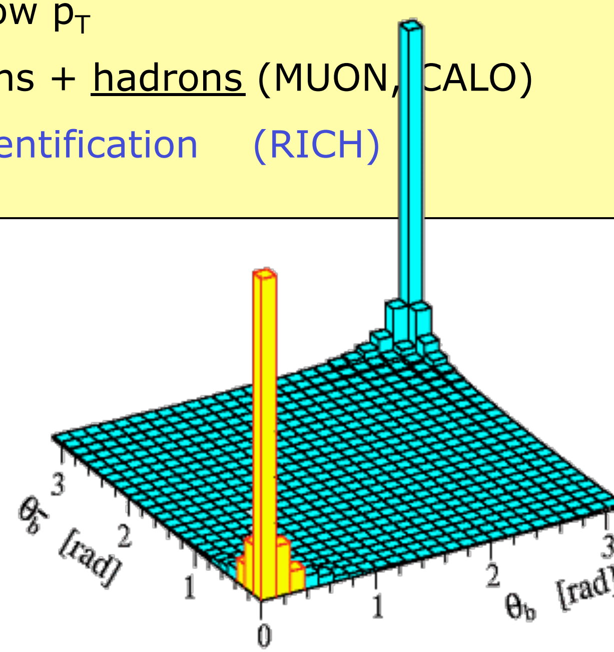
$\langle \Delta z \rangle_{B\overline{B}} \approx 260\,\mu\mathrm{m}$

LHCb: the Detector



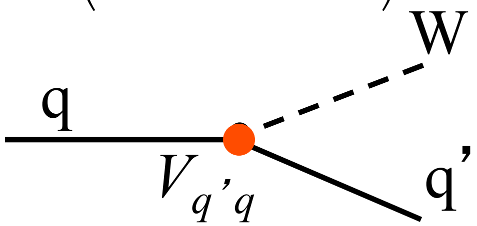
- High cross section
  - LHC energy
    - B_s produced in large quantities
- Large acceptance
  - b’s produced forward
- Small multiple scattering
  - Large boost of b’s
- Trigger
  - ↓ Low p_T
  - Leptons + <u>hadrons</u> (MUON, CALO)
- Particle identification (RICH)





Measuring the Quark Couplings

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

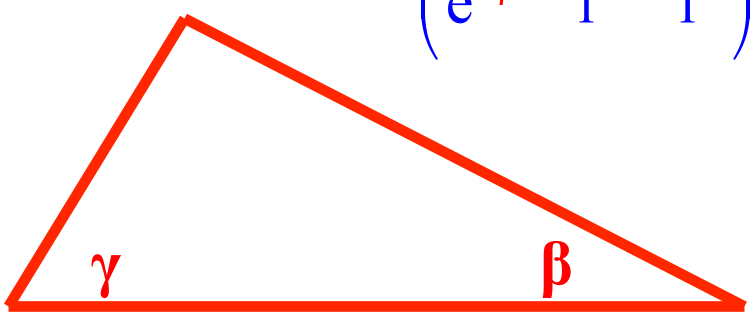


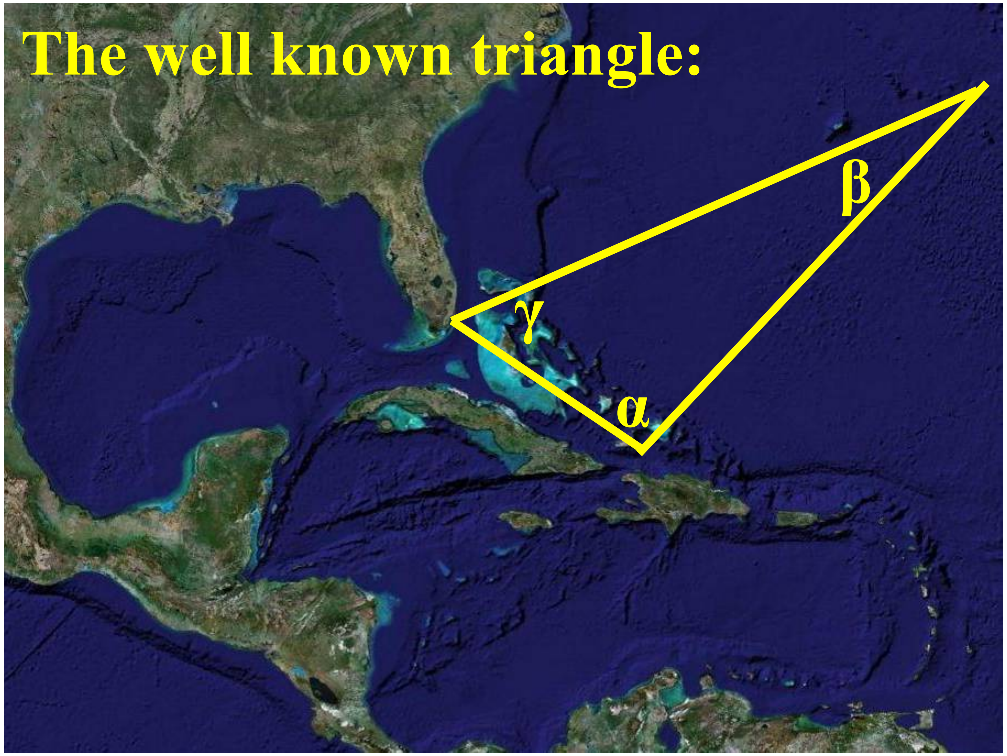
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- Measure the CKM triangle to unprecedented precision
- Measure very small Branching Ratios

CP phases:

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$





LHCb

- https://wiki.nikhef.nl/lhcb/Master_student_Projects

Master projects in the Nikhef B-physics group

1) Measurement of BR(Lb->p Ds-)

Supervisors: Niels Tuning (staff), Lennaert Bel (PhD) , Mick Mulder (PhD)

Research description:

This project aims to measure the branching fraction of the decay Lb->p Ds+. The decay Lb->p Ds+ is quite rare, because it occurs through the transition of a b-quark to a u-quark. It has not been measured yet (although some LHCXb colleagues claim to have seen it in the past).

This decay is interesting, because
1) It is sensitive to the CKM-element Vub, which determination is heavily debated.
2) It can quantify non-factorisable QCD effects in b-baryon decays.

The decay is closely related to B0->pi-Ds+, which proceeds through a similar Feynman diagram. Also the final state of B0->pi-Ds+ is almost identical to Lb->p Ds+. The aim is to determine the relative branching fraction of Lb->pDs+ with respect to B0->D+pi- decays, in close collaboration with the PhD (who will study BR(B0->pi-Ds+)/BR(B0->D+pi-)).

The aim is that this project results in a journal publication on behalf of the LHCb collaboration. For this project computer skills are needed. The ROOT programme and C++ and/or Python macros are used. This is a project that is closely related to previous analyses in the group. Weekly video meetings with CERN coordinate the efforts with in the LHCb collaboration.

Relevant information:

[1] R.Aaij et al. [LHCb Collaboration], ``Study of the kinematic dependences of Lambda_b production in pp collisions and a measurement of the Lambda_b->Lambda_c pi branching fraction, JHEP 08 (2014) 143 [arXiv:1405.6842 [hep-ex]].

[2] R.Aaij et al. [LHCb Collaboration], ``Determination of the branching fractions of B0s->DsK and B0->DsK, JHEP 05 (2015) 019 [arXiv:1412.7654 [hep-ex]].

[3] R. Fleischer, N. Serra and N. Tuning, ``Tests of Factorization and SU(3) Relations in B Decays into Heavy-Light Final States, Phys. Rev. D 83, 014017 (2011) [arXiv:1012.2784 [hep-ph]].

[4] K. de Bruyn, R. Fleischer, R. Knegjens, M. Merk, M. Schiller and N. Tuning, ``Exploring Bs -> Ds(*)K Decays in the Presence of a Sizable Width Difference Delta Gamma_s, Nucl. Phys. B 868, 351 (2013) [arXiv:1208.6463 [hep-ph]].

File:Lb-pDs.pdf

2) A search for heavy neutrinos in the decay of W at LHCb

Supervisors: Wouter Hulsbergen (staff), Elena Dall'Occo (PhD)

Research description:

Neutrinos are arguably the most mysterious of all known fundamental fermions as they are both much lighter than all others and only weakly interacting. It is thought that the tiny mass of neutrinos can be explained by their mixing with so-far unknown, much heavier, neutrino-like particles. In this research proposal we look for these new neutrinos in the decay of the SM W-boson using data with the LHCb experiment at CERN. The W boson is assumed to decay to a heavy neutrino and a muon. The heavy neutrino subsequently decays to a muon and a pair of quarks. Both like-sign and opposite-sign muon pairs will be studied. The result of the analysis will either be a limit on the production of the new neutrinos or the discovery of something entirely new.

3) A Scintillator Fibers Tracker

Supervisors: Antonio Pellegrino

Research description:

The LHCb collaboration is upgrading the present tracking system constructing a new tracker based on scintillating fibers combined with silicon photo-multipliers (SiPM): the SciFi Tracker! Nikhef plays a key role in the project, as we will build the SciFi fibers modules, the cold-box enclosure housing the SiPMs, and a large part of the on-detector electronics. In all these areas, interesting test hardware and software has to be realized, and several research topics for a Master project are available, taking the student in contact with state-of-the-art particle detectors, in a large team of physicists and engineers. Possible collaborations with the Nikhef R&D group can also be envisaged.

4) A search for Majorana neutrino's in Bc decays

Supervisors : P. Koppenburg and F. Archilli.

Research Description:

Neutrinos can either be their own anti-particles, in which case they are called "Majorana" particles, or Dirac fermions. It is thought that the tiny mass of neutrinos can be explained by their mixing with so-far unknown, much heavier, neutrino-like particles. LHCb has looked for off-shell Majorana neutrinos in the decays B+->pi-mu+mu+ and B+->D(*)-mu+mu+. Both decays suffer from suppression from Cabibbo-Kobayashi-Maskawa matrix elements, or from low reconstruction efficiencies. Although its production rate is much lower, the Bc meson provides a potentially more promising decay channel: Bc->J/psimu+mu+pi-. The Master student will design and optimise a selection, study potential backgrounds and perform a search in view of setting a stringent limit, or an observation of new physics.

arXiv:1401.5361 [hep-ex]. arXiv:1201.5600 [hep-ex]. arXiv:11602.09112 [hep-ph]

LHCb

- $\Lambda_b^0 \rightarrow D_s p$
  - Never observed
  - Background to others
  - Sensitivity to Vub?
  - Measure factorization

- Heavy neutrino's
  - Holy grail

- Scintillator Fiber tracker
  - New detector for LHCb
  - Constructed at Nikhef, to be installed in 2019

- Majorana neutrino in B_c^+ decays
  - Hole grail