CP Violation in meson decays

Only source of CP violation in the SM are non-trivial phases of CKM matrix:

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & V_{ts} & V_{tb} \end{pmatrix}$$ at $O(\lambda^4)$.

<u>CP violation was first observed in the system of neutral Kaons:</u>

Observation of decay $K_L \rightarrow \pi\pi$ (CP=+1) with BR~2×10^{-3}.
As the K_L was believed to be a pure CP=-1 state,
the observed decay violates CP symmetry.
A intense program to study CPV in kaon decays followed.

Christenson, Cronin, Fitch, Turlay, 1964

Effects in kaon decays are small and difficult to explain.
From a didactic point of view B mesons are much easier and exhibit much larger CPV. Interpretation of CKM phases also easier.

Observation of CP violation in K_L decays

Reminder:

If no CPV:

$$|K_L\rangle = "|K_2\rangle" \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right)$$

$$|K_S\rangle = "|K_1\rangle" \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right)$$

$$\mathrm{CP}|K_2\rangle = -|K_2\rangle$$

$$\mathrm{CP}|K_1\rangle = +|K_1\rangle$$

Phase convention:

$$CP|K^0\rangle = |\overline{K^0}\rangle$$

$$CP|\overline{K^0}\rangle = |K^0\rangle$$

One can show that the 2π final state is CP=+1:
The observation of $K_L \to \pi\pi$ thus violates CP.

Explanation:

K_L is not a pure K_s state.

$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(\underbrace{|K_2\rangle}_{CP=-1} - \varepsilon\underbrace{|K_1\rangle}_{CP=+1}\right)$$

Not a CP eigenstate: CP violation !

Today's knowledge

After 35 years of kaon physics:

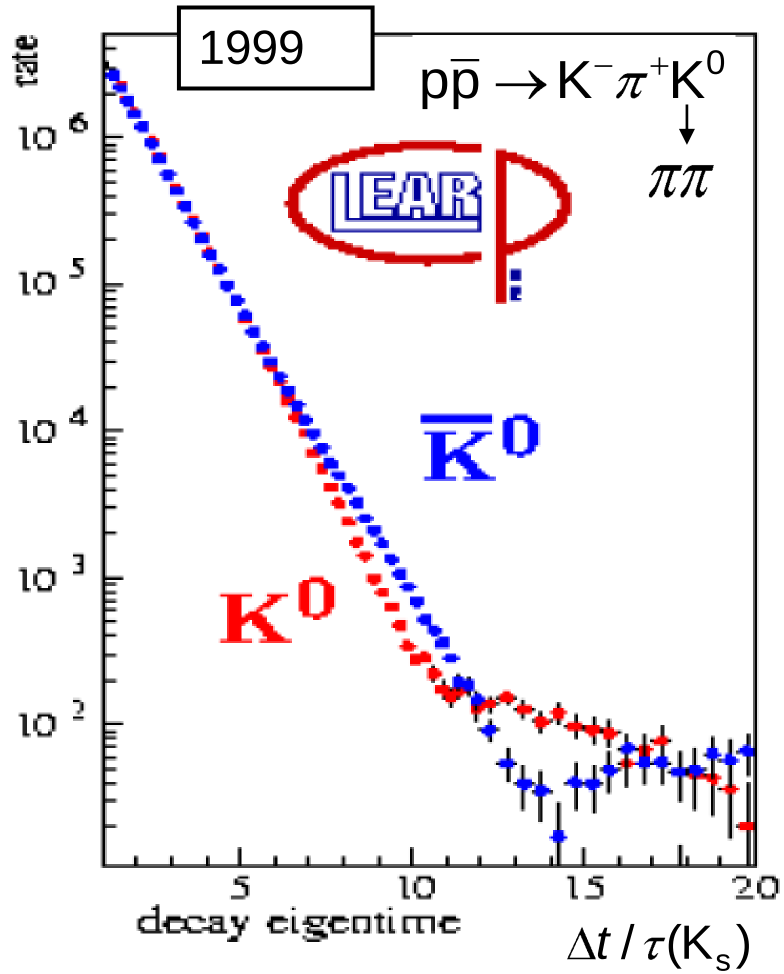
$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_2\rangle + \varepsilon|K_1\rangle\right)$$

$|K_2\rangle \rightarrow \varepsilon' \rightarrow \pi\pi$ (Direct CPV)

$\varepsilon|K_1\rangle \rightarrow \pi\pi$ (mixing)

$$|\varepsilon| = (2.284 \pm 0.014)\cdot 10^{-3}$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1.67 \pm 0.26)\cdot 10^{-3}$$



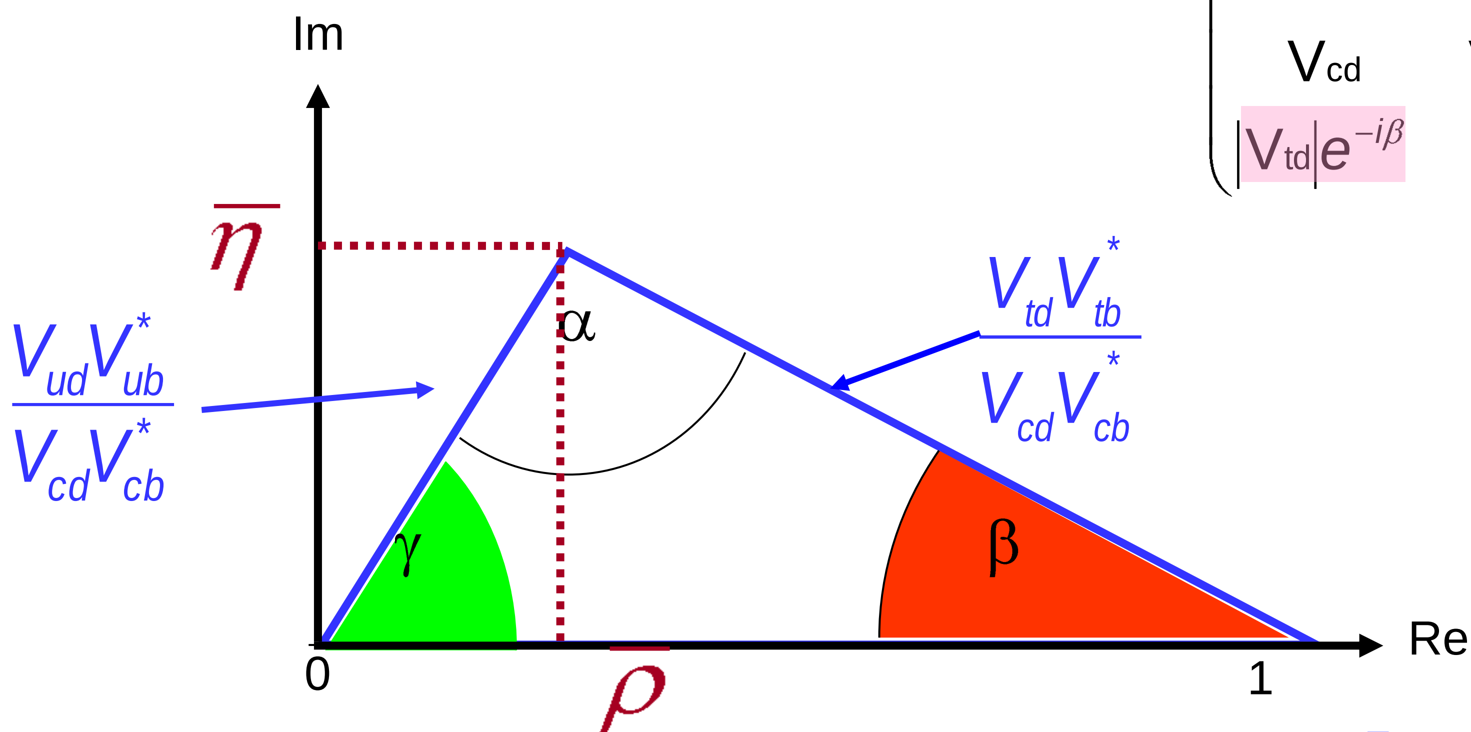
Interpretation of CPV measured in the kaon system is difficult.

"The Unitarity triangle"

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

(Division by $V_{cd}\,V_{cb}^*$)

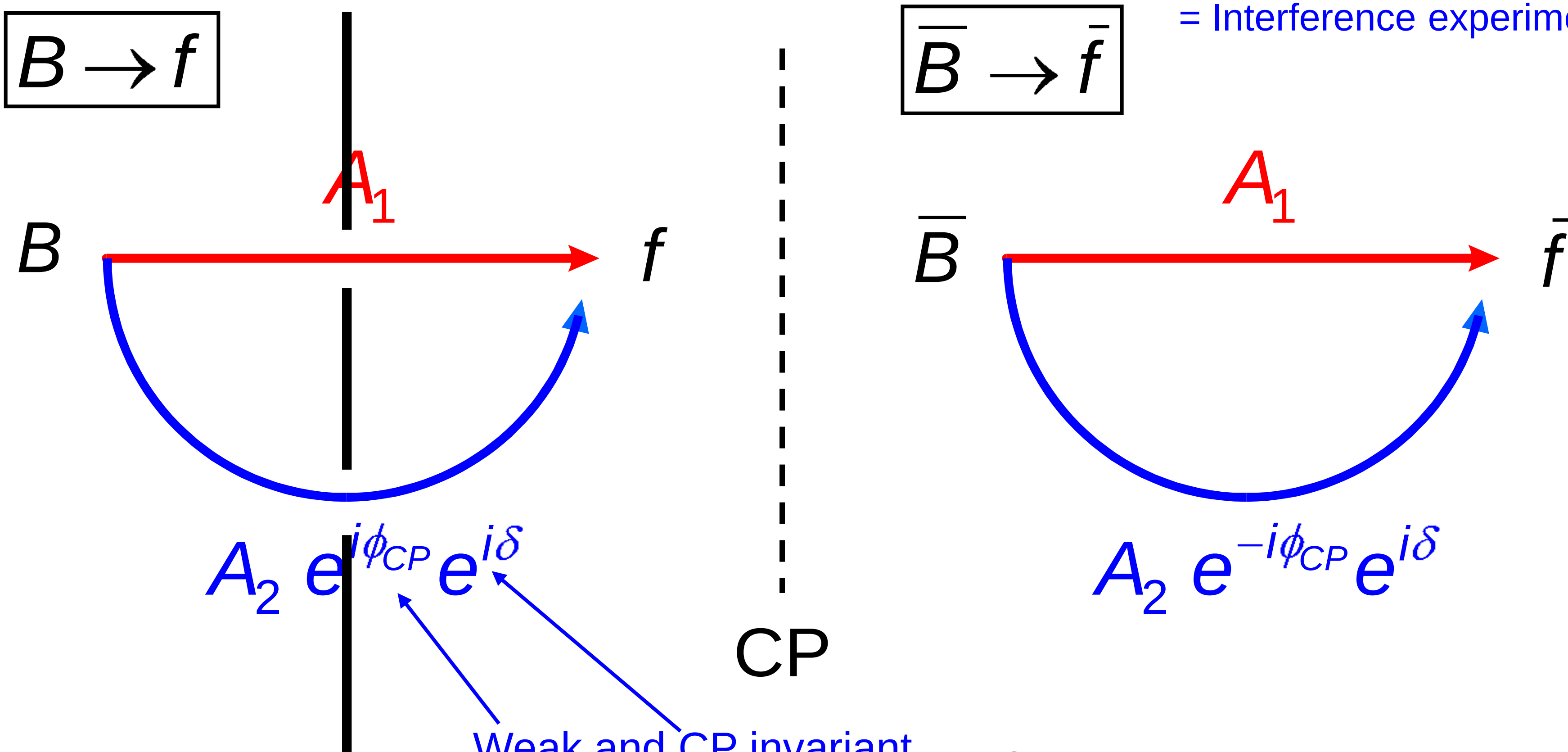
$$\begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & V_{ts} & V_{tb} \end{pmatrix}$$



$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Observation of CP Violating Phases

→ Phase measurement
= Interference experiment



$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} + \delta)$$

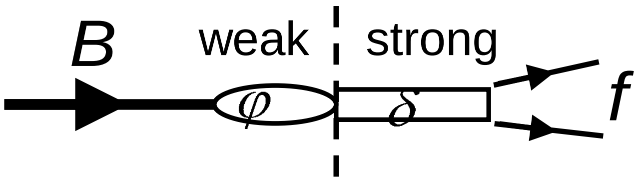
$$|\bar{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} - \delta)$$

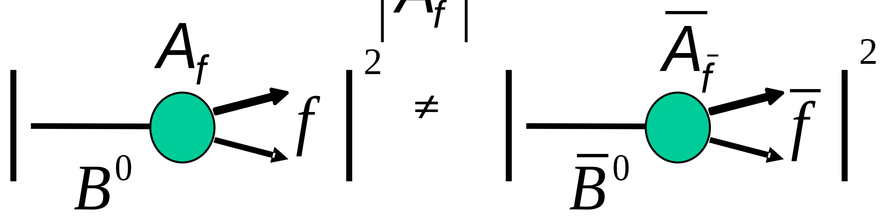
Need two phase differences between A_1 and A_2: Weak difference which changes sign under CP and another phase difference (strong) which is unchanged.

"3 Ways" of CP violation in meson decays

a) Direct CP violation

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



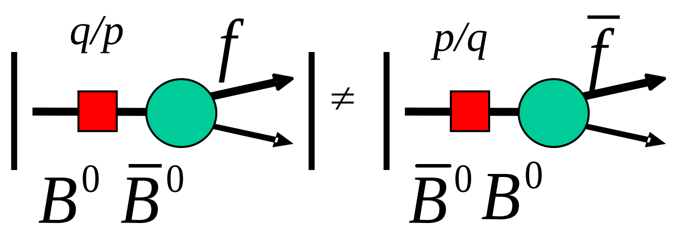


$$A(B \to f) = |A|\, e^{i\varphi}\, e^{i\delta}$$

$$P(\bar{B} \to \bar{f}) \neq P(B \to f)$$

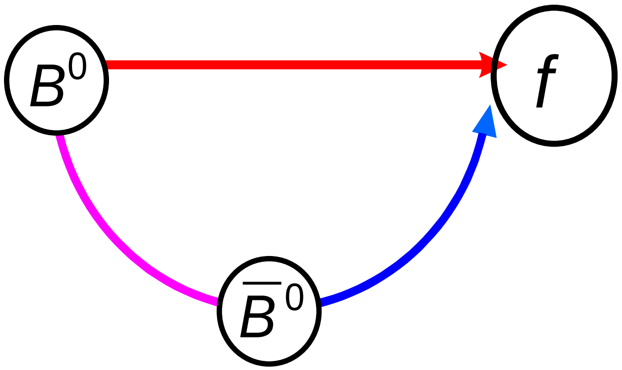
b) CP violation in mixing

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



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

c) CP violation through interference of mixed and unmixed amplitudes



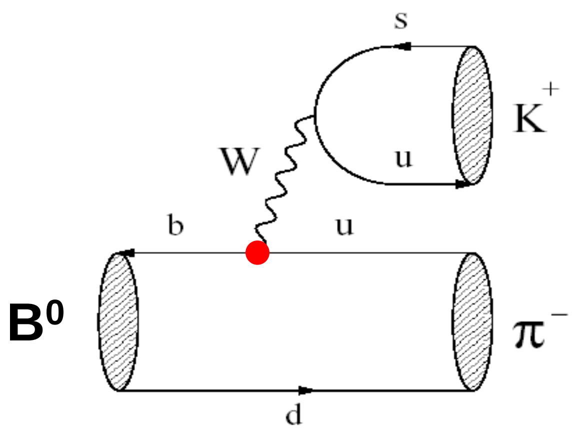
f = CP eigenzustand!

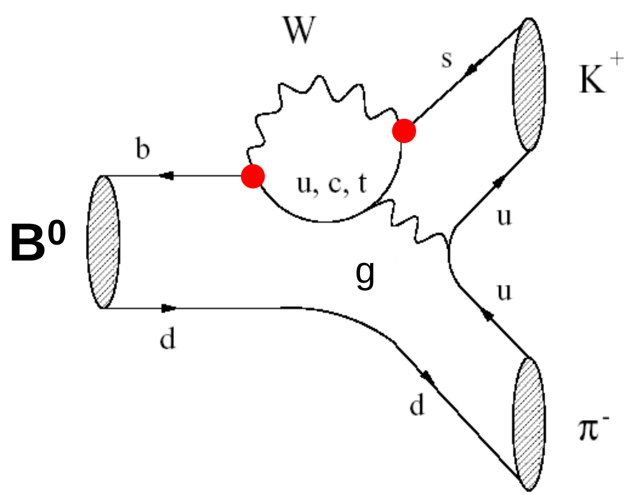
$$\Gamma(B^0_{t=0} \to f)(t) \neq \Gamma(\overline{B}^0_{t=0} \to f)(t)$$

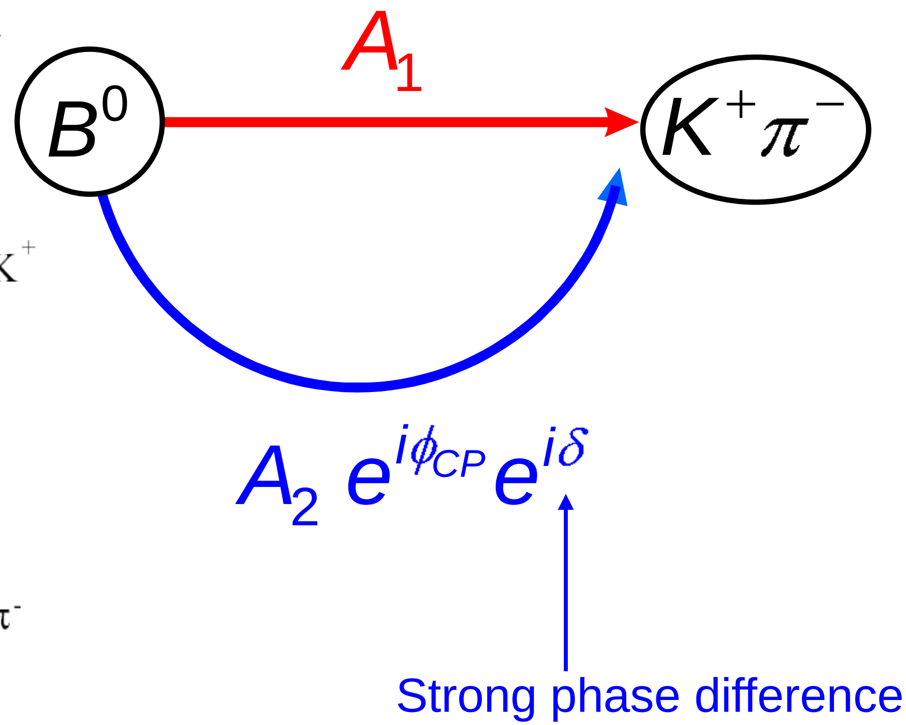
Asymmetrie modulated by $\sim \sin \Delta m t$

Combinations of the 3 ways are possible!

ad a) Direct CP violation (B system)







CP Asymmetrie

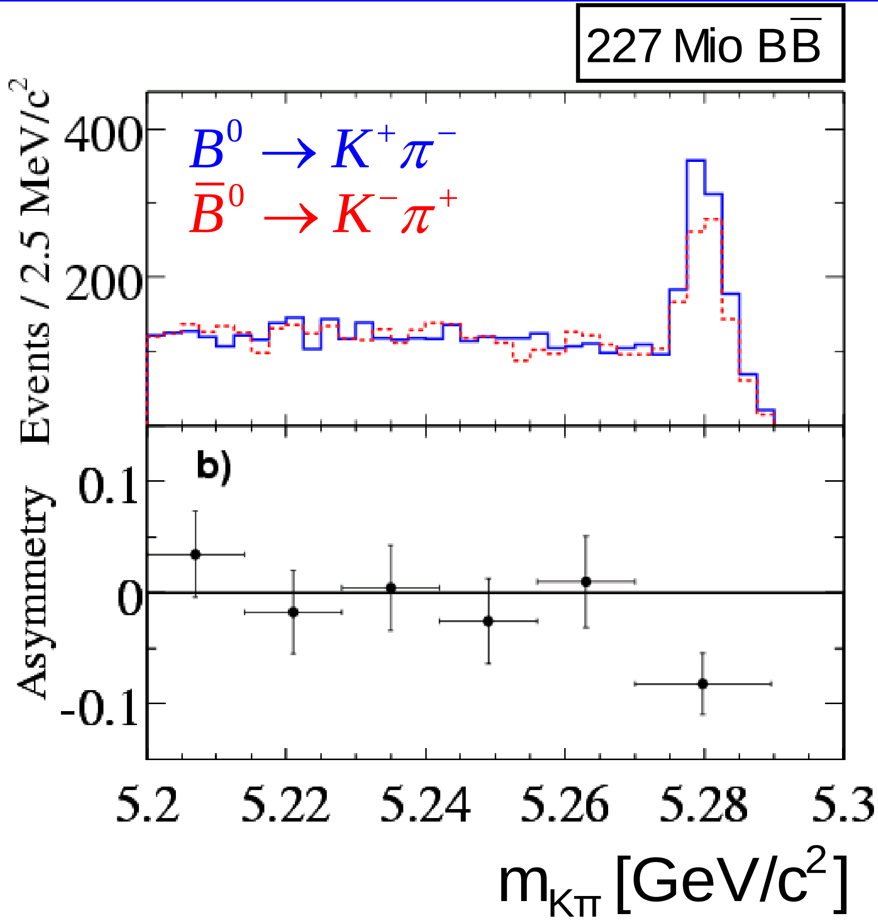
$$\left|\bar{A}\right|^2 - \left|A\right|^2 = 4\left|A_1\right|\left|A_2\right| \sin\varphi \sin\delta$$

$$N(B^0/\bar{B}^0 \to K^{\pm}\pi^{\mp}) = 1606 \pm 51$$

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

$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

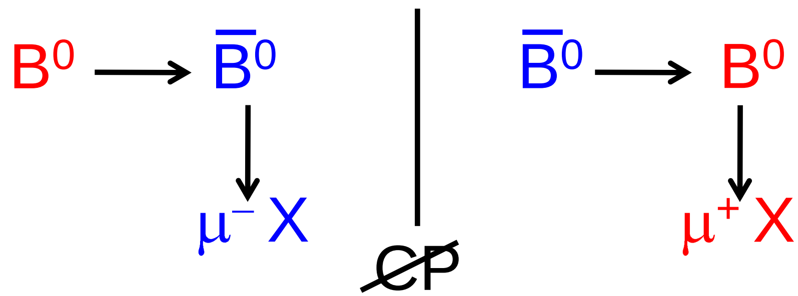
4.2σ



PRL93(2004) 131801.

b) CP violation in mixing

$$\left|\frac{q}{p}\right| \neq 1 \qquad P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0)$$



$$a_{sl}^{q} \equiv \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}; \quad q = d, s$$

CP violation in mixing

Evidence of anomalous CP-violation in the mixing of neutral B mesons:

Evidence for an anomalous like-sign dimuon charge asymmetry

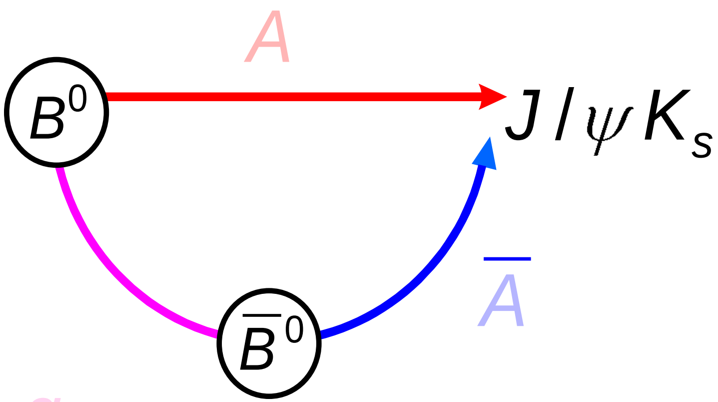
We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\overline{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A, we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{sl} = -0.00957 \pm 0.00251\ \text{(stat)} \pm 0.00146\ \text{(syst)}$. This result differs by 3.2 standard deviations from the standard model prediction $A^b_{sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP-violation in the mixing of neutral B mesons.

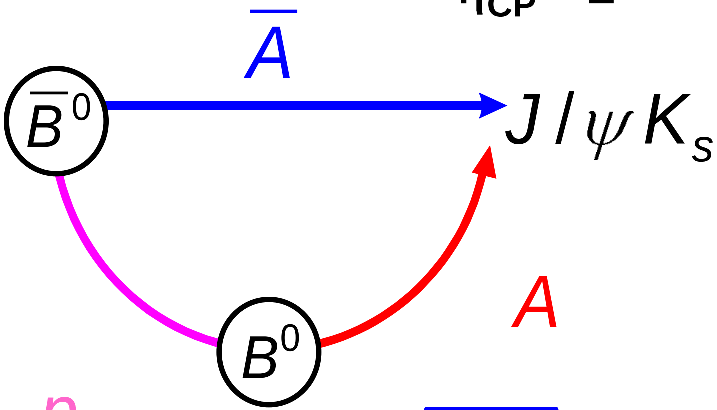
arXiv:1005.2757v1 [hep-ex] 16 May 2010

c) CP violation in interference between mixing and decay

$B^0 \to J/\psi K_s$ **CP** ⟹ $\overline{B}^0 \to J/\psi K_s$

$\eta_{CP} = -1$





$\frac{q}{p} e^{i\pi/2} \sim e^{i2\beta} e^{i\pi/2}$ = -1 $= \eta_{CP}(J/\psi K_s)$

$\frac{p}{q} e^{i\pi/2} \sim e^{-i2\beta} e^{i\pi/2}$ = -1 $= \eta_{CP}(J/\psi K_s)$

$$\Gamma(t) \sim e^{-\Gamma t} \left[- \sin 2\beta \sin(\Delta m t) \right]$$

$$\Gamma(t) \sim e^{-\Gamma t} \left[+ \sin 2\beta \sin(\Delta m t) \right]$$

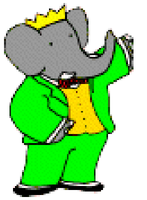
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to f)(t) - \Gamma(B^0 \to f)(t)}{\Gamma(\overline{B}^0 \to f)(t) + \Gamma(B^0 \to f)(t)} = \sin 2\beta \sin(\Delta m t)$$

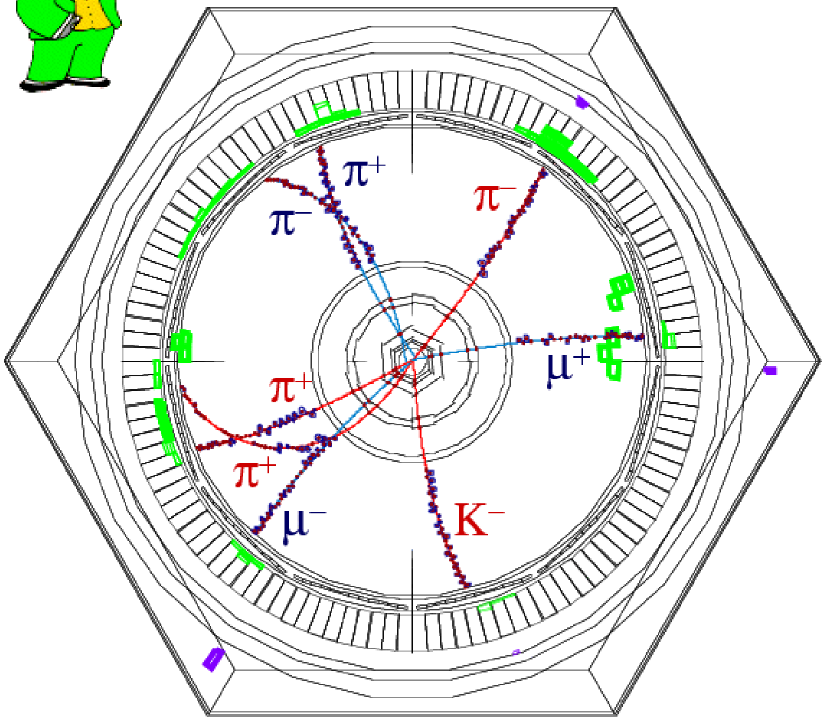
To measure CP violation in B_d system:

- Need many B (several 100×10^6)
- Need to know the flavor of the B at t=0
- Need to reconstruct the decay length to measure t

Measurement of sin2β in $B_d \to J/\psi\ K_s$

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





B_{tag} $\bar{B}^0 \to D^{*+} \pi^-_{fast}$

$\quad \hookrightarrow D^0 \pi^+_{soft}$

$\quad\quad \hookrightarrow K^- \pi^+$

⇕

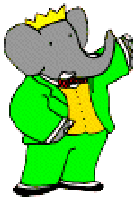
B_{CP} $B^0(\Delta t)$

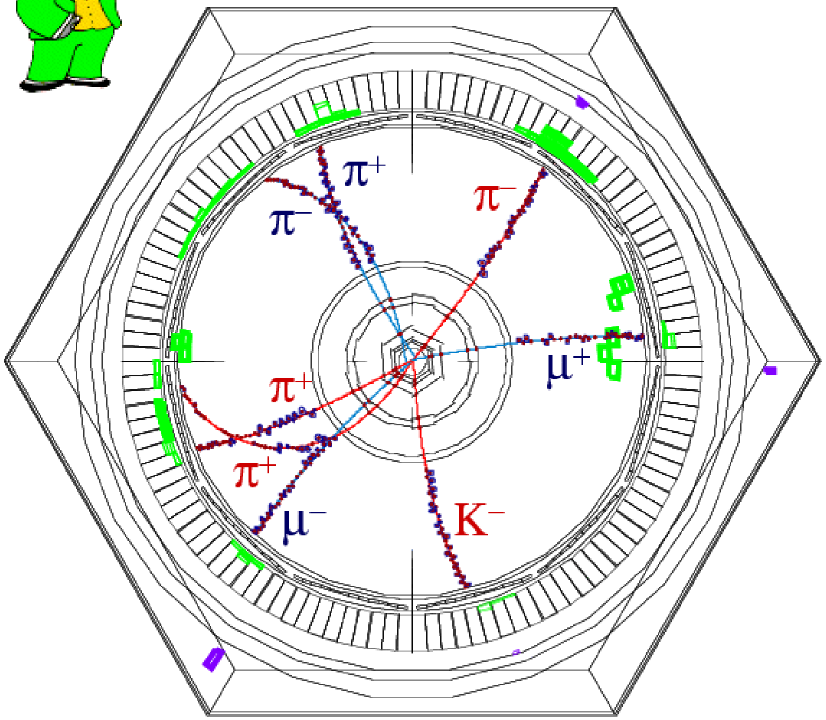
$\quad \hookrightarrow \psi(2S)\ K_s$

$\quad\quad \hookrightarrow \mu^+\mu^-$ $\hookrightarrow \pi^+\pi^-$

Measurement of sin2β: Golden decay channel $B^0 \to \psi K_s$

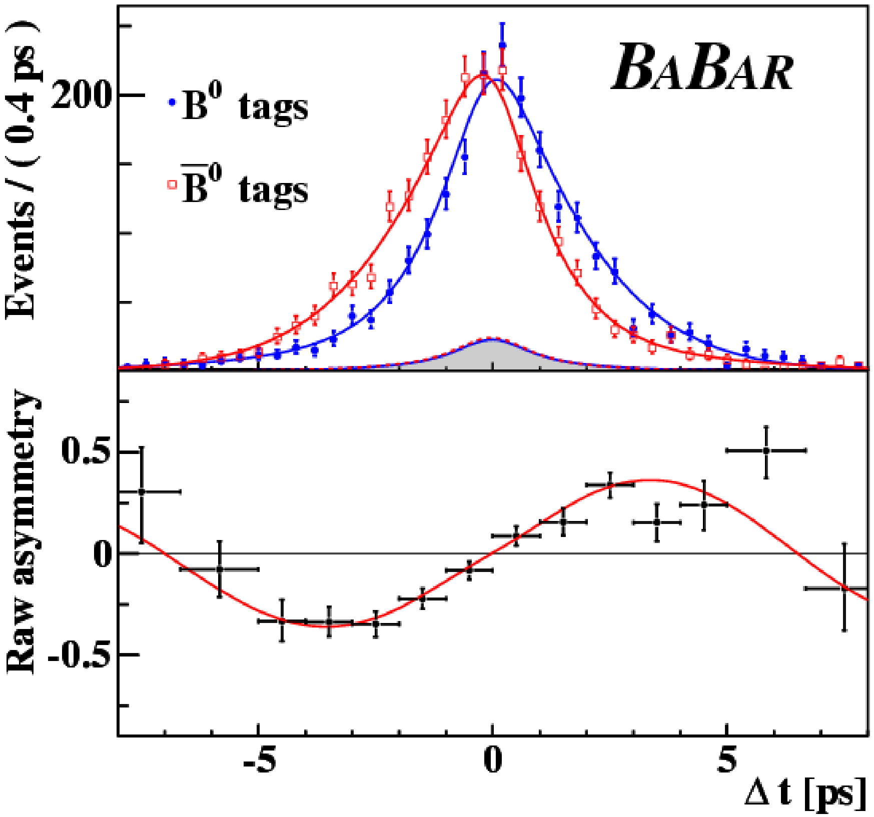
$B^0 \to \psi K_s$





PRL 94, 161803.

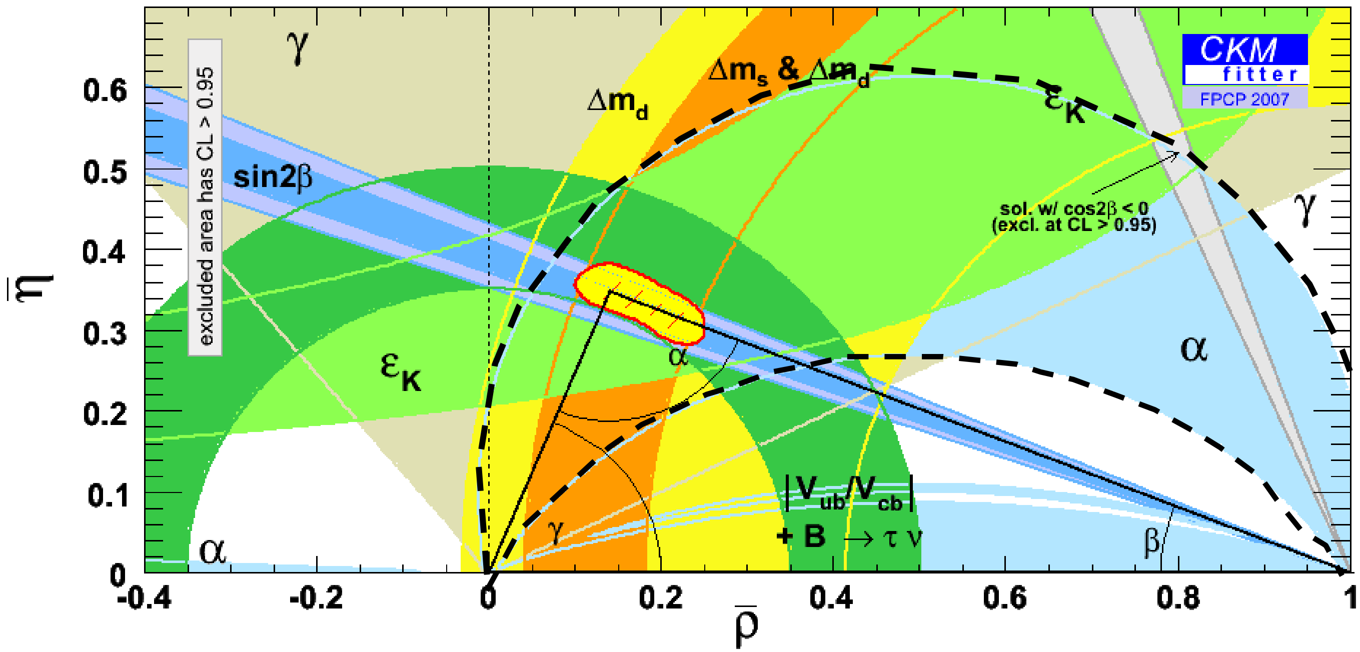
227 Mio $B\bar{B}$



$A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$

$\sin 2\beta = \ 0.722 \pm 0.040 \pm 0.023$

Experimental status of the Unitarity Triangle



Standard Model CKM mechanism confirmed

1. Large CP Violation in B decays
2. Large direct CP violation observed
3. CPV parameter related to magnitude of non-CP observables