Flavor Mixing and CP Violation

1. CKM Matrix
2. Mixing of neutral mesons
3. CP violation

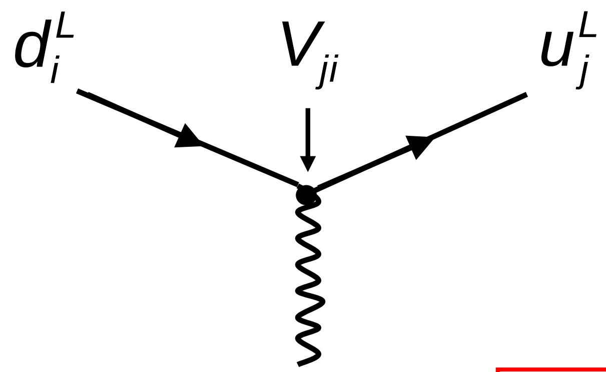
1. CKM Matrix

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

weak eigenstates | **CKM matrix** | **mass eigenstates**

Unitarity

$$V_{CKM} V_{CKM}^{+} = 1$$



Charged currents:

$$J_\mu^+ \propto (\bar{u}, \bar{c}, \bar{t})\, \gamma_\mu (1 - \gamma_5) \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = (\bar{u}, \bar{c}, \bar{t})\, \gamma_\mu (1 - \gamma_5)\, \mathbf{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak | **mass/ flavor**

1.1 Parameters of CKM matrix

Number of independent parameters:

18 parameter (9 complex elements)

-5 relative quark phases (unobservable)

-9 unitarity conditions

=4 independent parameters: 3 angles + 1 phase

PDG parametrization

3 Euler angles

$\theta_{23}, \theta_{13}, \theta_{12}$

1 Phase

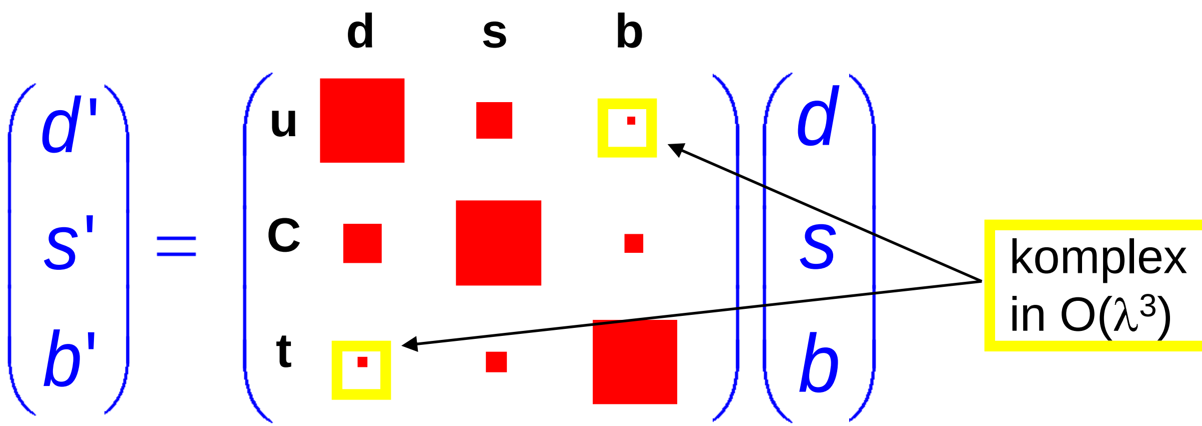
δ

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

where $c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$

Magnitude of elements



Wolfenstein parametrization: reflects hierarchical structure of CKM matrix

λ, A, ρ, η with $\lambda = 0.22$

$|V_{ub}| \times e^{-i\gamma}$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

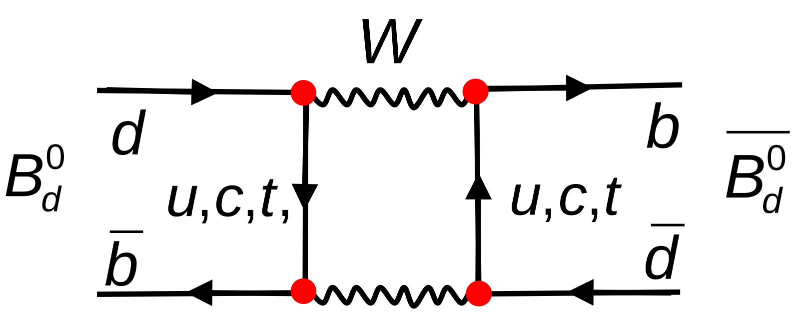
$|V_{td}| \times e^{-i\beta}$

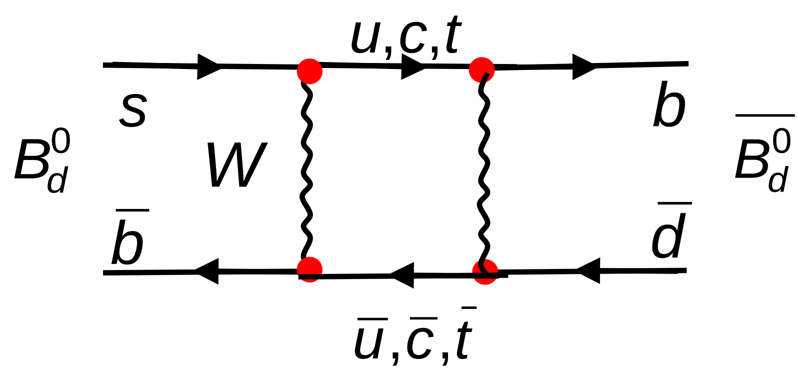
2. Mixing of neutral mesons

The quark mixing results into several interesting “loop” effects:

➡ Standard Model predicts at loop-level Flavor Changing Neutral Currents

Mixing of neutral mesons, e.g.: $B_d^0 \Leftrightarrow \overline{B_d^0}$





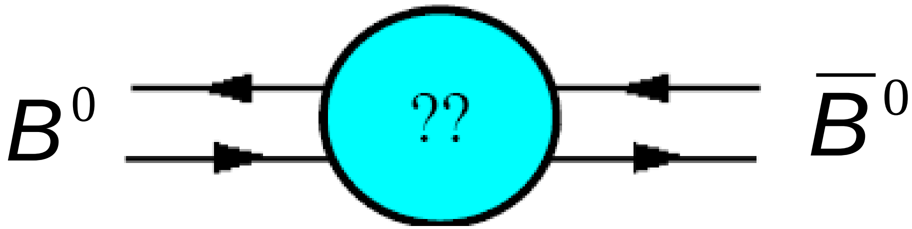
Neutral mesons: $|P^0\rangle$: $K^0 = |d\bar{s}\rangle$ $D^0 = |\bar{u}c\rangle$ $B_d^0 = |d\bar{b}\rangle$ $B_s^0 = |s\bar{b}\rangle$

$|\overline{P^0}\rangle$: $\overline{K^0} = |\bar{d}s\rangle$ $\overline{D^0} = |\bar{u}c\rangle$ $\overline{B_d^0} = |d\bar{b}\rangle$ $\overline{B_s^0} = |s\bar{b}\rangle$

discovery of mixing: 1960 2007 1987 2006

2.1 Mixing Phenomenology

Applies to all neutral mesons!



$$i\frac{d}{dt}\begin{pmatrix} B^0(t) \\ \overline{B}^0(t) \end{pmatrix} = \underbrace{\left(\mathbf{M} - \frac{i}{2}\Gamma\right)}_{\mathbf{H}} \begin{pmatrix} B^0(t) \\ \overline{B}^0(t) \end{pmatrix}$$

Flavor states = No mass eigenstates

Diagonalizing H:

Mass eigenstates: $|B_L\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$ with $m_{L,}\Gamma_L$ light

$|B_H\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$ with $m_{H,}\Gamma_H$ heavy

complex coefficients

$|p|^2 + |q|^2 = 1$

$$|B_{H,L}(t)\rangle = |B_{H,L}(0)\rangle \cdot e^{-im_{H,L}t} \cdot e^{-\frac{1}{2}\Gamma_{H,L}t}$$

Flavor eigenstates: $|B^0\rangle = \frac{1}{2p}(|B_L\rangle + |B_H\rangle)$ $|\overline{B}^0\rangle = \frac{1}{2q}(|B_L\rangle - |B_H\rangle)$

Mixing of neutral mesons

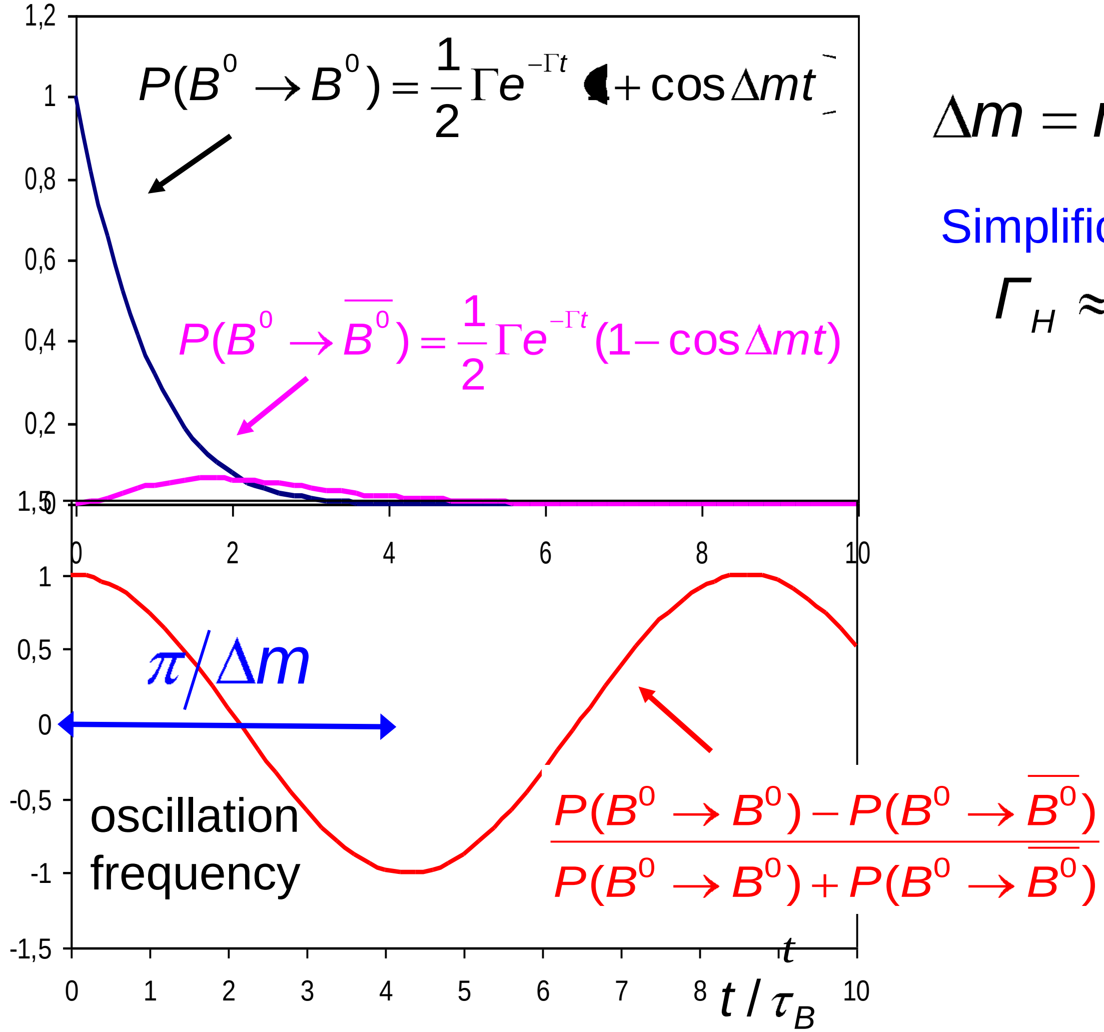
$$\underbrace{P(B^0 \to B^0) = P(\overline{B^0} \to \overline{B^0})}_{\text{CPT}} = \frac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} + 2e^{-(\Gamma_L + \Gamma_H)t/2}\cos\Delta m t\right]$$

$$P(B^0 \to \overline{B^0}) = \frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L + \Gamma_H)t/2}\cos\Delta m t\right] \qquad \Delta m = m_H - m_L$$

$$P(\overline{B^0} \to B^0) = \frac{1}{4}\left|\frac{p}{q}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L + \Gamma_H)t/2}\cos\Delta m t\right]$$

CP, T- violation in mixing: $P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0) \Rightarrow \left|\frac{q}{p}\right| \neq 1$

B^0-B^0 Mixing



$$\Delta m = m_H - m_L$$

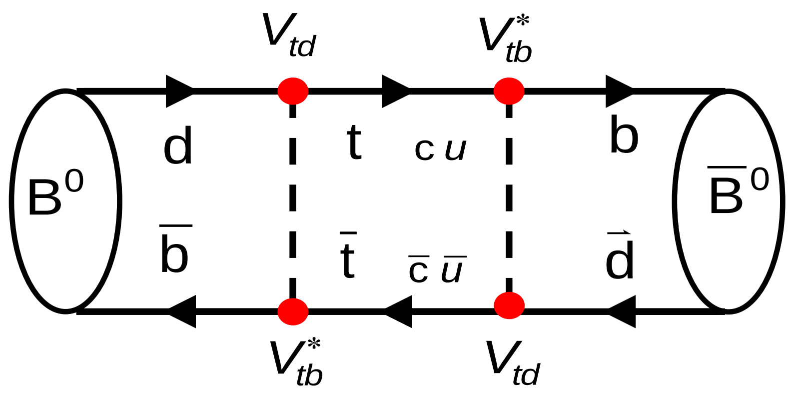
Simplification for

$$\Gamma_H \approx \Gamma_L \approx \Gamma$$

Mixing asymmetry

2.2 Standard Model Prediction

$B_d^0 - \overline{B}_d^0$



$\Delta m_d \sim m_t^2 \cdot O(\lambda^6)$

Dominant contribution from top-loop:

$\eta_B = 0.55 \pm 0.01$

NLO QCD

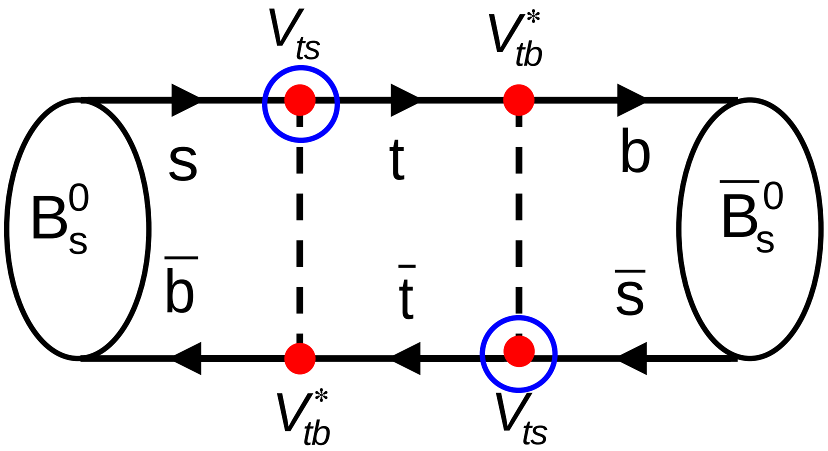
$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B f_B^2 B_B (V_{td}^* V_{tb})^2 m_W^2 \, \eta_B \, F\left(\frac{m_t^2}{m_W^2}\right)$$

← e.w. correction

$f_B^2 B_B = (235 \pm 33 \pm 12)^2 MeV^2$ from lattice QCD

Describes the binding of the quarks to a meson

$B_s^0 - \overline{B}_s^0$



$\Delta m_s \sim m_t^2 \cdot O(\lambda^4)$

$$\Delta m_s \sim (V_{ts}^* V_{tb})^2$$

Oscillation is about 35 times stronger than in the case of B_d
(V_{ts} much larger than V_{td})

B oscillation:

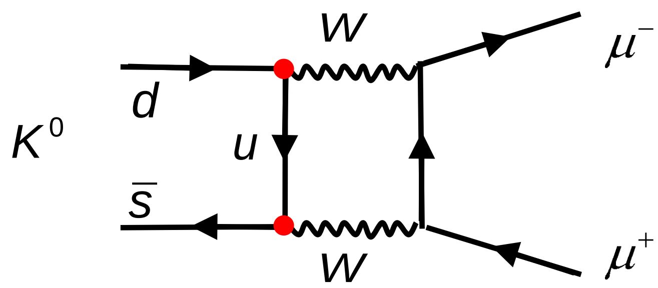
Deactivation of GIM suppression because of large mass splitting:

What would be the mixing if all quarks had the same masses?
(Unitarity of CKM matrix -> cancellation of FCNC!)

Non-observed FCNC and GIM mechanism

Historical retrospect

FCNC in the 3 quark model: $K^0 \rightarrow \mu^+\mu^-$



$$M \sim \sin\theta_c \cos\theta_c$$

Theoretically one predicts large BR, in contradiction with experimental limits for this decay:

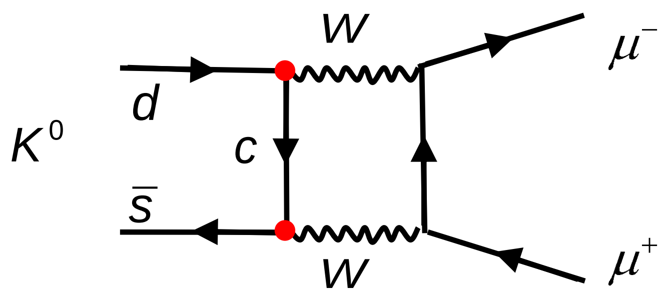
$$\frac{BR(K_L \rightarrow \mu^+\mu^-)}{BR(K_L \rightarrow all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

Proposal by Glashow, Iliopoulos, Maiani, 1970:

GIM

There exists a fourth quark which builds together with the s quark a second doublet:

$$\begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ -\sin\theta_c \cdot d + \cos\theta_c \cdot s \end{pmatrix}$$



$$M \sim -\sin\theta_c \cos\theta_c$$

→ Additional Feynman-Graph for $K^0 \rightarrow \mu\mu$ which compensates the first one:

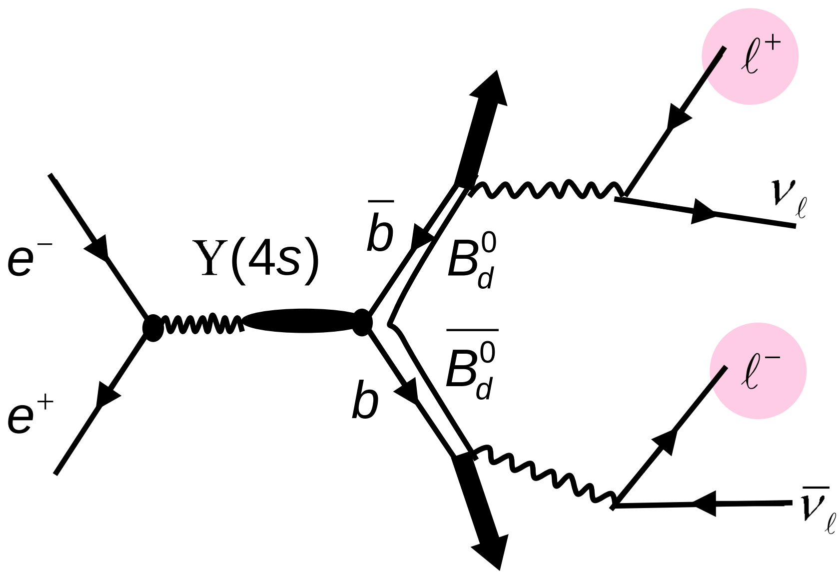
Prediction of a fourth quark:
Mass prediction BR=f(m_c,…)

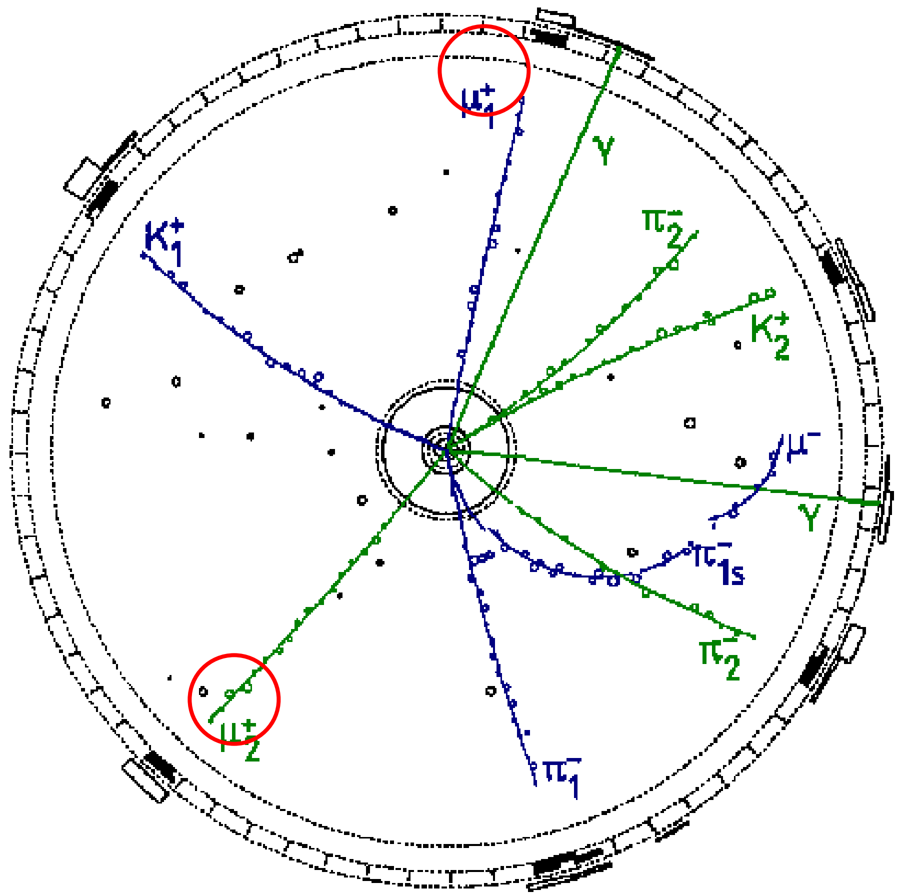
2.3 Discovery of B^0 mixing

ARGUS 1987

First e^+e^- B factory at DESY:

$$\left.\begin{array}{l} \text{at } \sqrt{s} = 10.58\text{ GeV}: \\ e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0 \end{array}\right\} \sigma(B\overline{B}) \approx 1\text{nb}$$





$B^0 \to D^{*-}\mu^+\nu_\mu$
$\quad \hookrightarrow \overline{D}^0\pi_s^-$
$\quad\quad \hookrightarrow K^+\pi^-$

$B^0 \to D^{*-}\mu^+\nu_\mu$
$\quad \hookrightarrow D^-\pi^0$
$\quad\quad \hookrightarrow \gamma\gamma$
$\quad\quad \hookrightarrow K^+\pi^-\pi^-$

Unmixed: $B^0\overline{B}^0 \to \ell^+\ell^-$

Mixed:
$$\left.\begin{array}{l} B^0B^0 \to \ell^+\ell^+ \\ \overline{B}^0\overline{B}^0 \to \ell^-\ell^- \end{array}\right\} \text{Same charge}$$

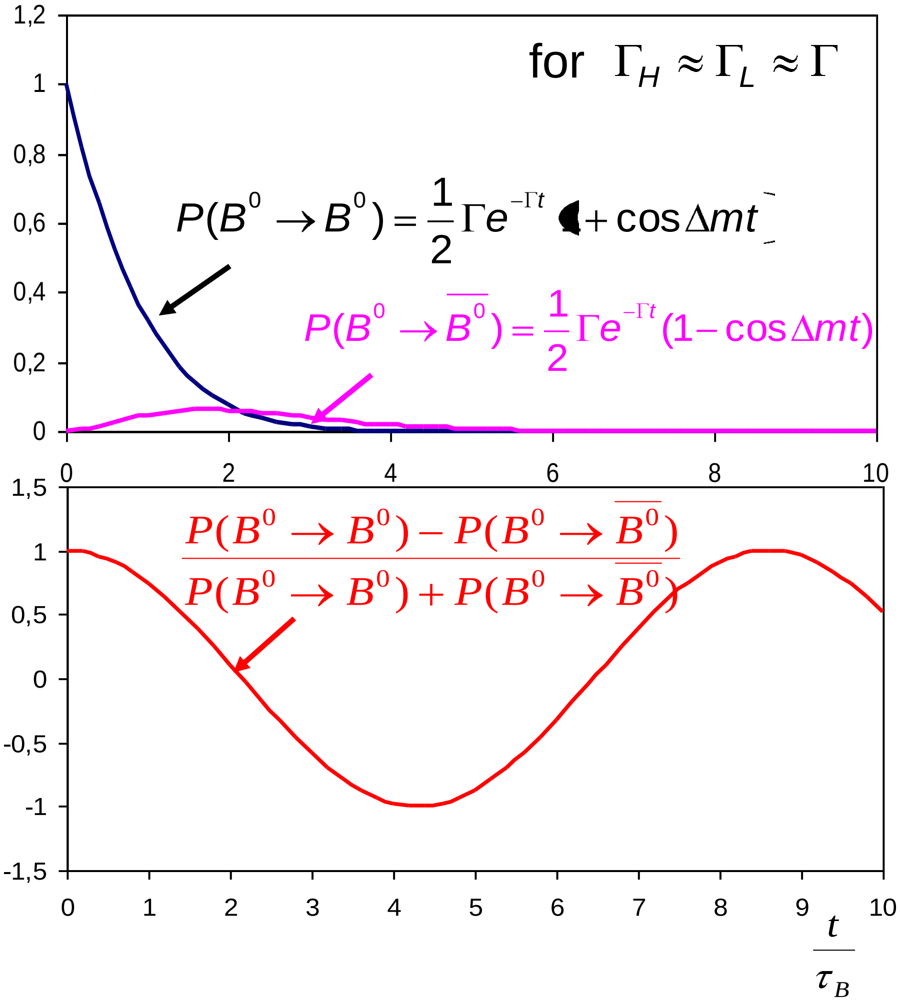
Historical remark:

The observation of the B_d meson mixing put the first lower limit on the top mass: $m_{top} > 50$ GeV.

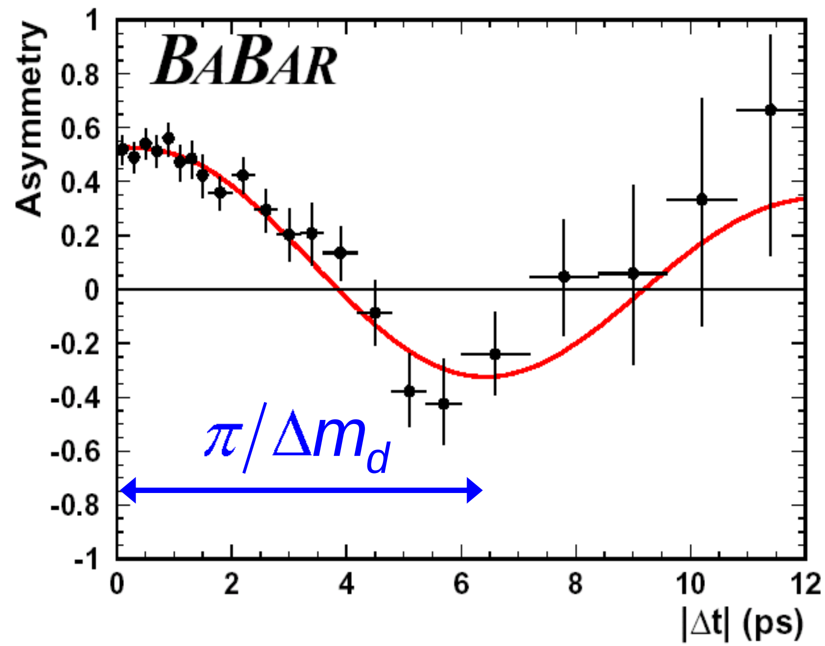
If the top mass was lower the GIM mechanism would in a small Δm, i.e. the B would oscillate very slowly and would decay before mixing.

The GIM mechanism is a result of the unitarity of the CKM matrix. Only different quark masses lead to a non-perfect cancellation and are the soruces of observable FCNCs at loop level.

Experimental Status of B meson mixing

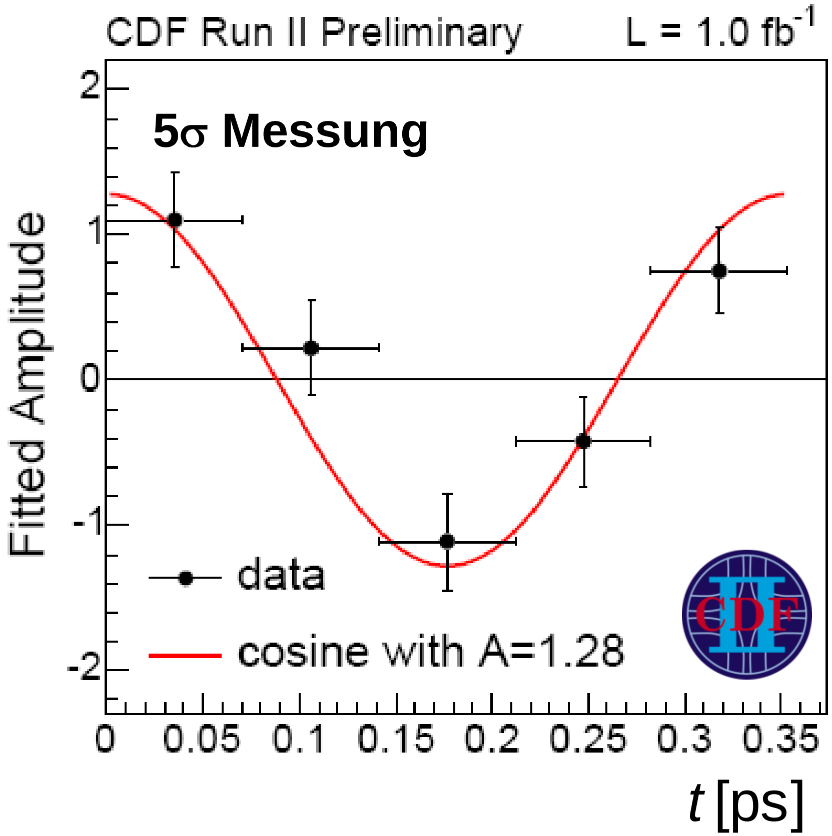


$$A = \frac{unmixed - mixed}{unmixed + mixed}$$



$$\Delta m_d = 0.506 \pm 0.006 \pm 0.004\,\text{ps}^{-1}$$

$$\approx \frac{0.774}{\tau_B}$$



Observation:

Spring 2006

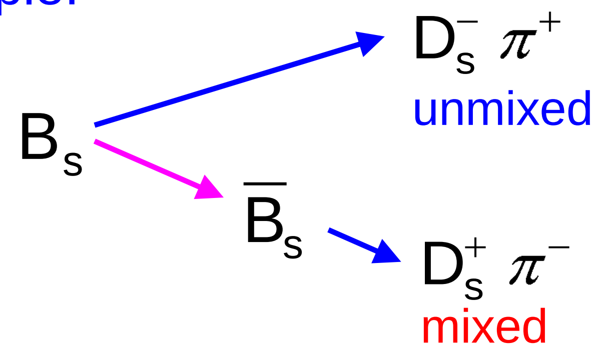
$$\Delta m_s = 17.77 \pm 0.10(\text{stat.}) \pm 0.07(\text{syst.})\ \text{ps}^{-1} = \frac{26}{\tau}$$

(CDF Collaboration, September 2006)

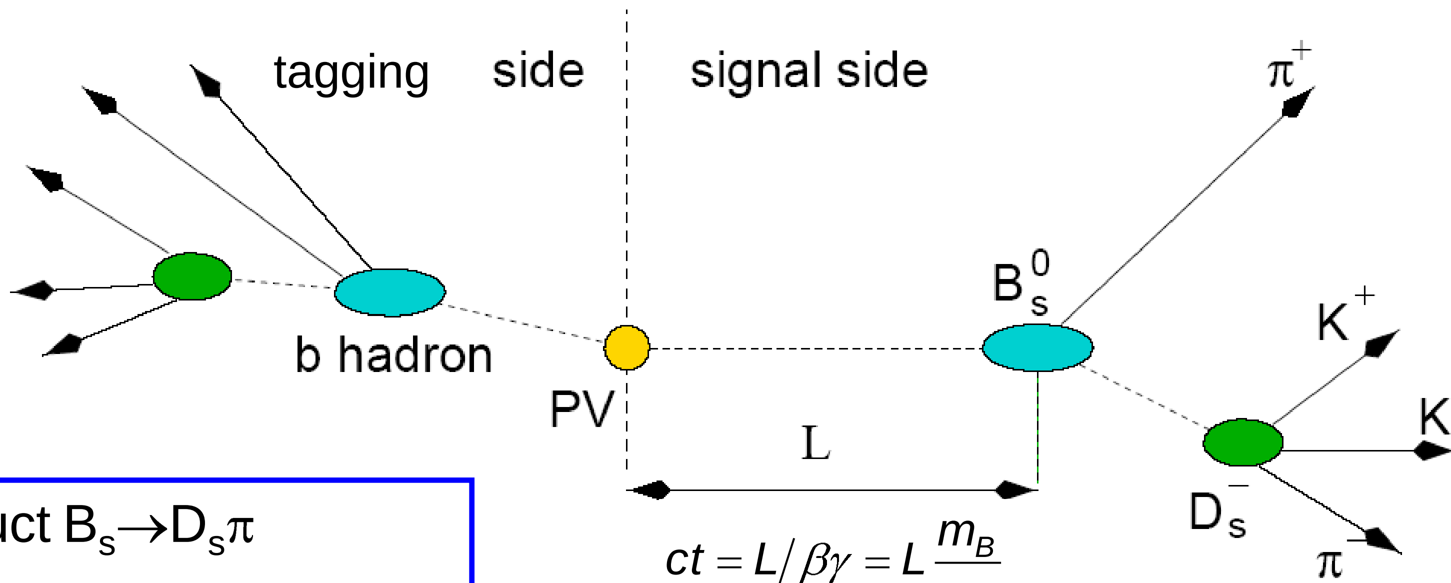
35 times faster than B^0

Measuring B_s Mixing

Principle:



$$A(t) = \frac{unmixed(t) - mixed(t)}{unmixed(t) + mixed(t)} = \cos(\Delta m t)$$



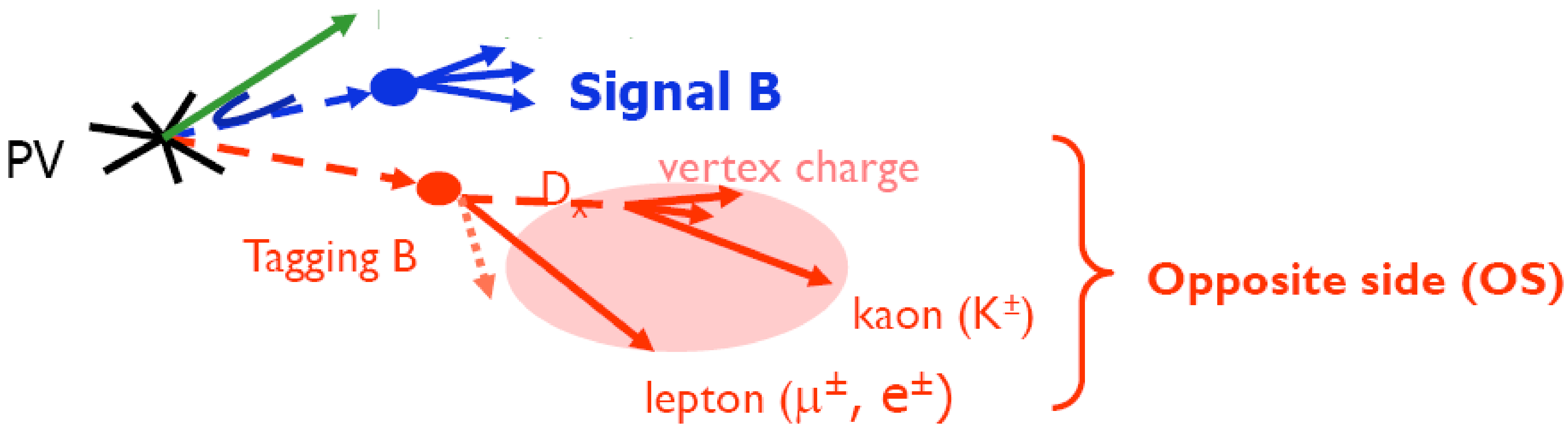
$$ct = L/\beta\gamma = L\frac{m_B}{p}$$

Reconstruct $B_s \rightarrow D_s \pi$

Determine decay time

Determine production flavor

Determination of Production Flavor = Tagging



Flavour tagging algorithms are not perfect!

- Backgrounds in tagger selections
- The *tagging B* can oscillate incoherently (unlike in B-factories):
  - **40% $B^{\pm}$, 10% baryons :** no oscillation ☺
  - **40% B_d:** $\Delta m_d \sim \Gamma_d \Rightarrow$ oscillated 17.5% ☺
  - **10% B_s:** $\Delta m_s >> \Gamma_s \Rightarrow$ oscillated 50% ☹

at LHC

Characterization:

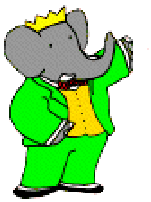
ε_{tag} = tagging effi.

ω = wrong tag fraction

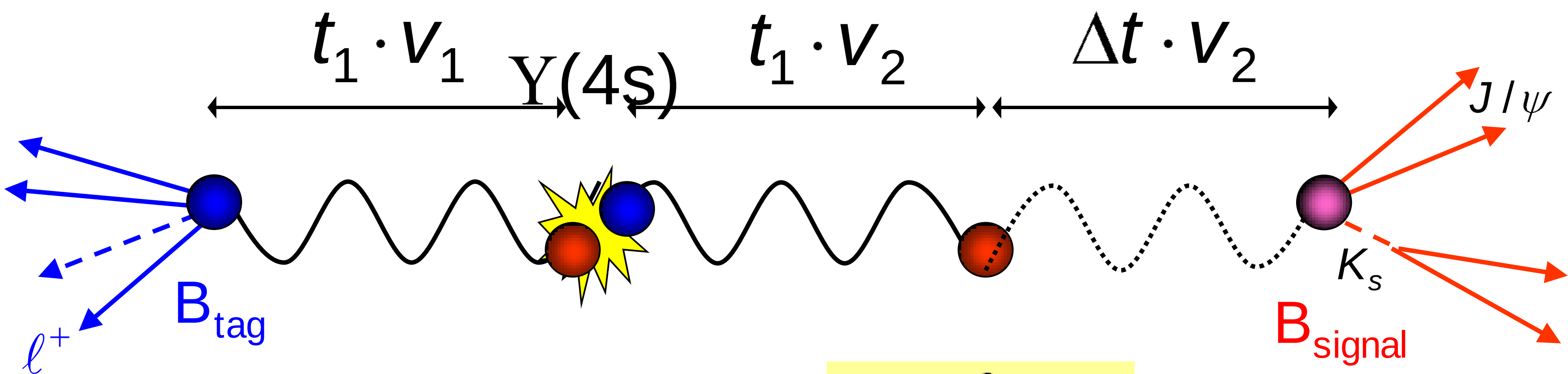
➡ Advantage of e+e- B-factories

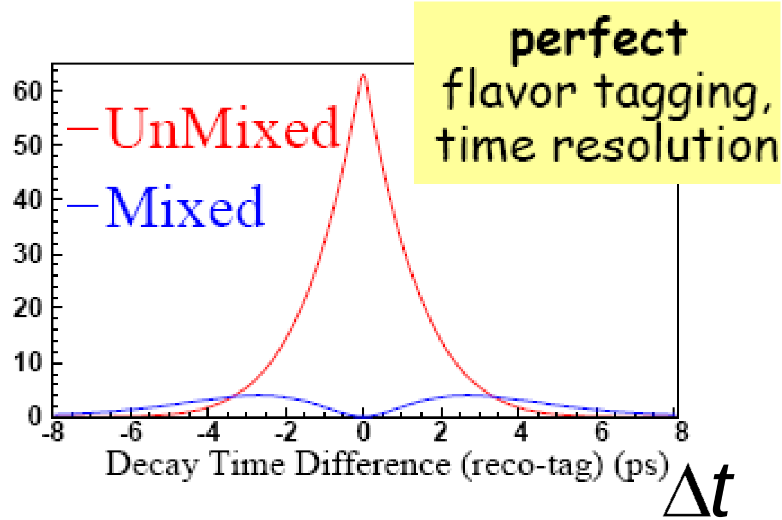
Interlude: $\Upsilon(4S)\to B^0B^0$

Coherent state!



$$\Upsilon(4S)\to\frac{1}{\sqrt{2}}\left(\left|B^0\bar{B}^0\right\rangle-\left|\bar{B}^0B^0\right\rangle\right)$$

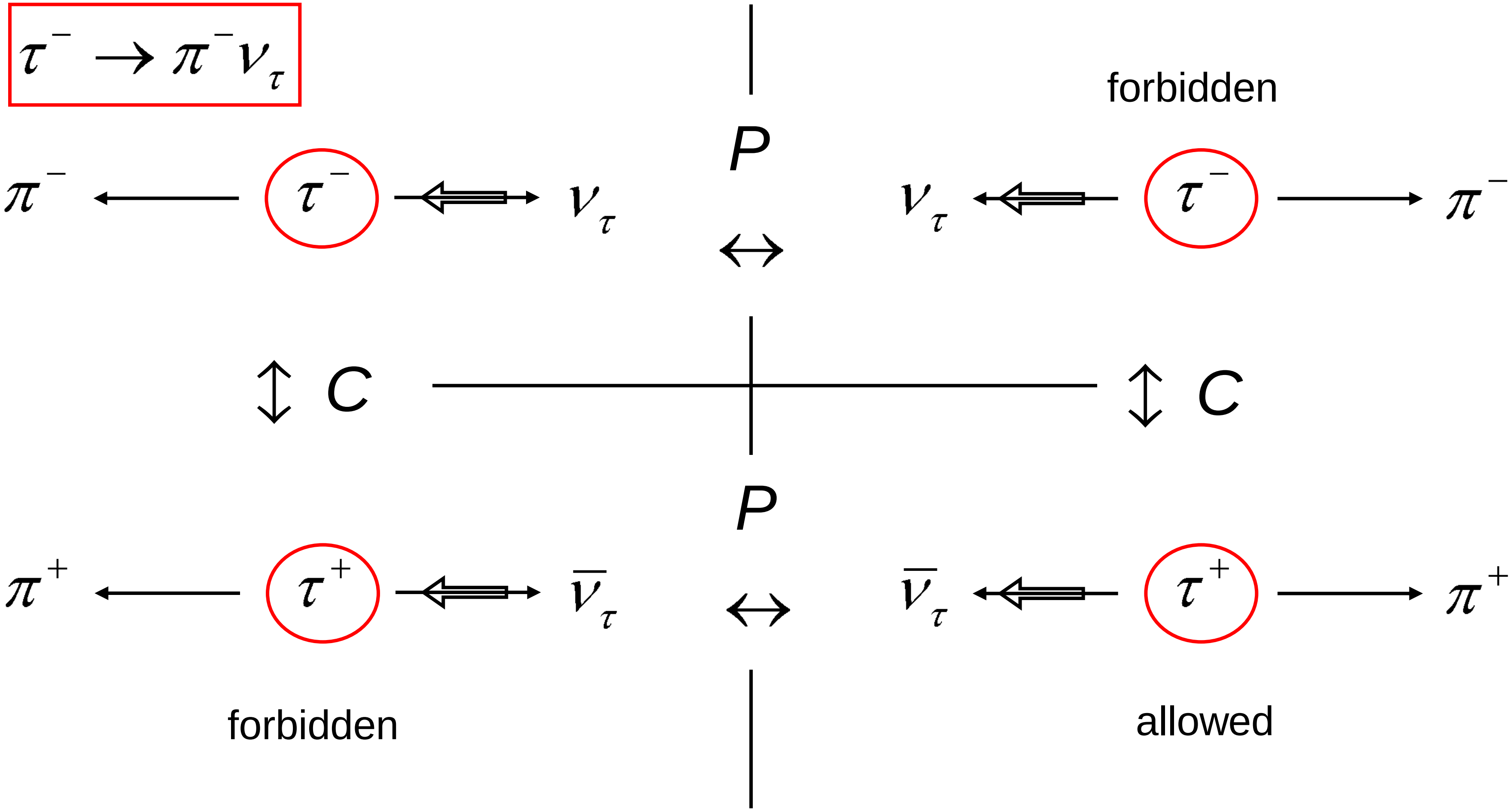




3. CP Violation

Reminder: Maximum C and P violation in weak decays:

$$\tau^- \rightarrow \pi^- \nu_\tau$$



- C and P violated in weak decays
- CP conserved in weak interaction ? $\rightarrow$ No !

3.1 Discovery of CP Violation in Kaon Decays

Observation of two neutral kaons $\mathbf{K_L}$ (long) and $\mathbf{K_S}$ (short) with different lifetimes:

$$\tau(K_L^0) = (51.7 \pm 0.4)\,\text{ns} \;>>\; \tau(K_S^0) = (0.089 \pm 0.001)\,\text{ns}$$

$$K^0 = |d\,\bar{s}\rangle$$

$$\overline{K}^0 = |\bar{d}\,s\rangle$$

$K_L^0 \to 3\pi$ $\quad$ $K_S^0 \to 2\pi$

$CP = -1$ $\quad$ $CP = +1$

Interpretation: (neglecting possible CP violation)

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

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

$CP|K_2\rangle = -|K_2\rangle$

$CP|K_1\rangle = +|K_1\rangle$

Phase convention:

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

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

Large differences between lifetimes

$$\Delta m = (0.5303 \pm 0.0009) \cdot 10^{10}\,\hbar s^{-1}$$

$$= (3.49 \pm 0.006) \cdot 10^{-12}\,\text{MeV}$$

$$\Delta\Gamma = -11.182 \cdot 10^{9}\,\hbar s^{-1}$$

If no CPV:

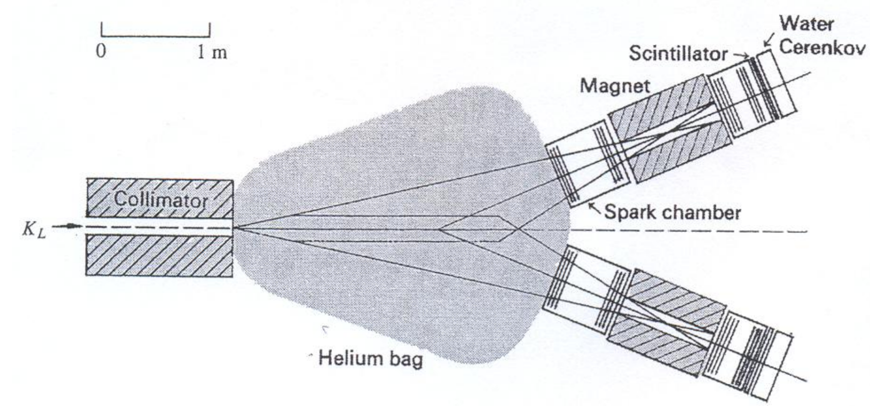
$$|K_L\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right) \quad CP = -1$$

Christenson, Cronin, Fitch, Turlay, 1964

should always decay into 3π:

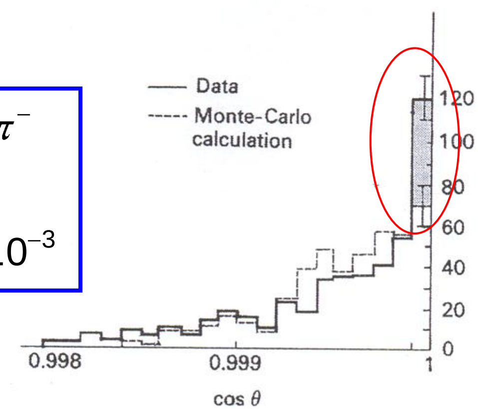
$CP(|3\pi\rangle) = -1$

and never into 2π $CP(|2\pi\rangle) = +1$



(a)

$$K_L \to \pi^+\pi^-$$
$$CP = +1$$
$$BR \sim 2 \cdot 10^{-3}$$



(b)

$$\theta = \angle(\vec{p}_K, (\vec{p}_{\pi+} + \vec{p}_{\pi-}))$$

Explanation:

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

Not a CP eigenstate: CP violation !

After 35 years of kaon physics:

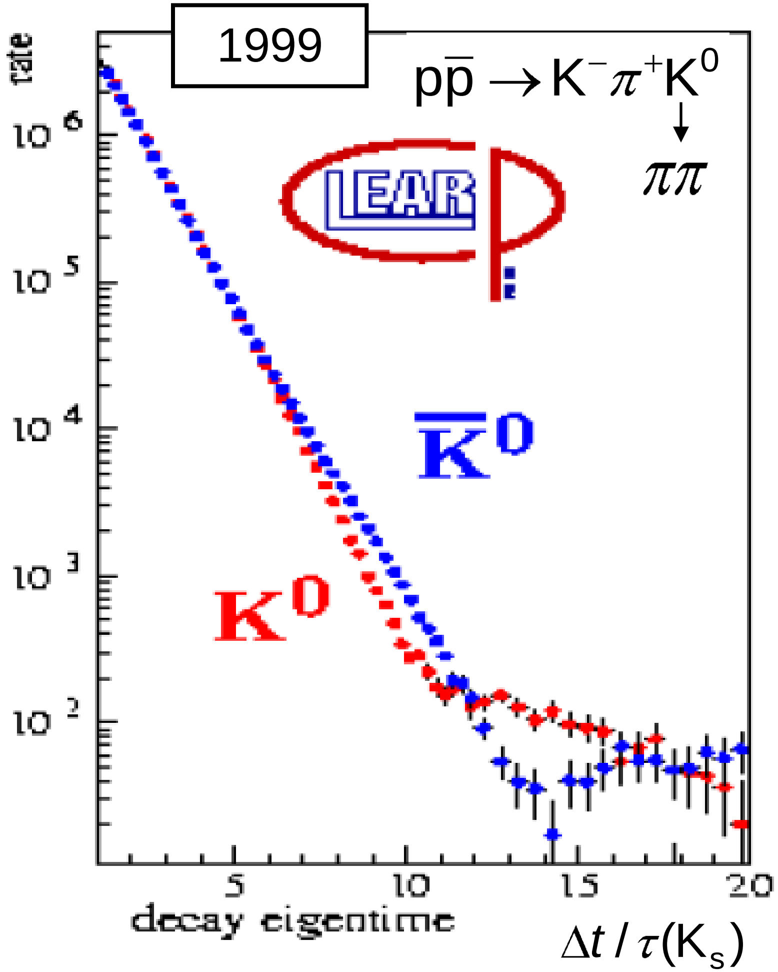
$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_2\rangle + \varepsilon|K_1\rangle\right)$$

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

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

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

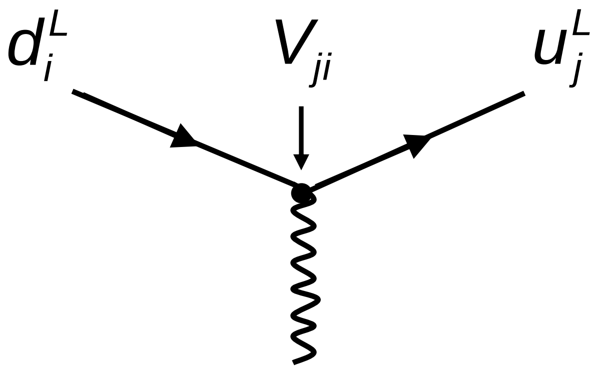
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1.67 \pm 0.26)\cdot 10^{-3}$$



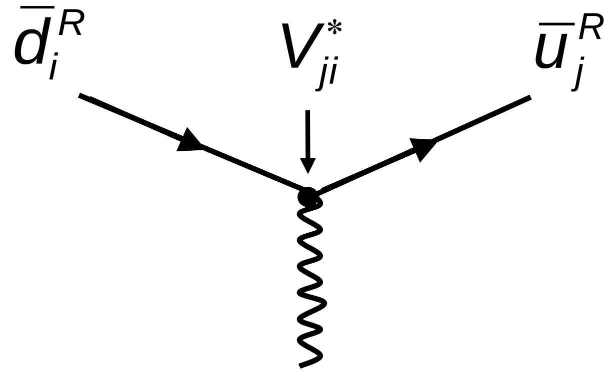
The measured CP violation in the kaon system is small – theoretical interpretation is quiet difficult !

In the B meson system effects are much larger, easier to understand and they can be calculated in the Standard Model. CPV in the B^0 system was observed in 2000.

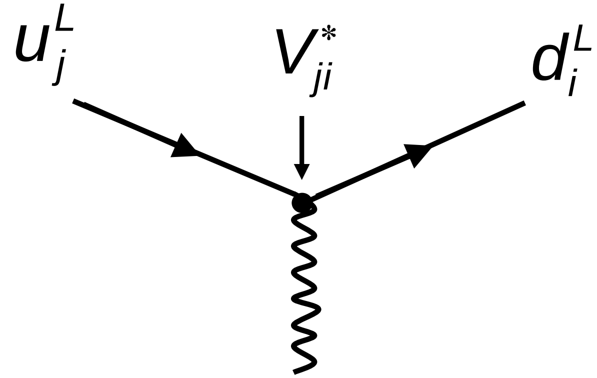
3.2 CP Violation in Standard Model: complex CKM elements



CP



T



CP (T) violation $\Leftrightarrow$ $V_{ji} \neq V_{ji}^*$

i.e. Complex elements

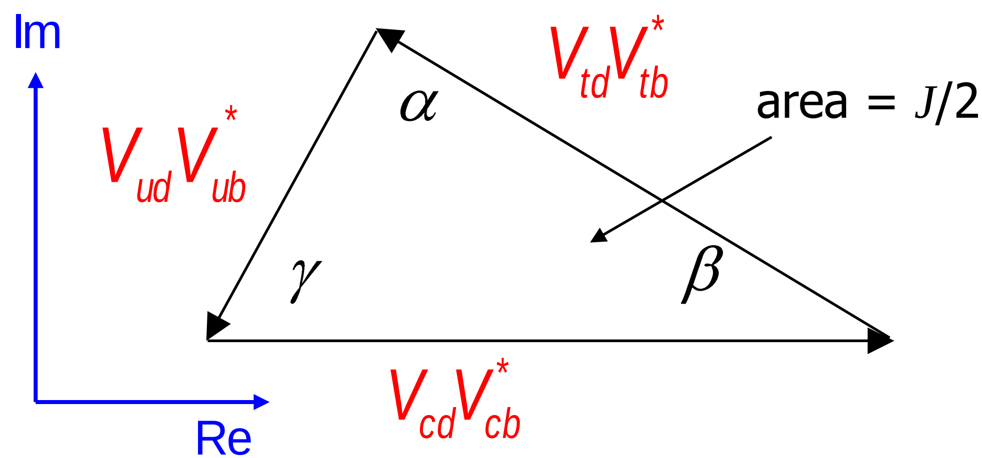
Remark: For 2 quark generations the mixing is described by the **real 2x2** Cabbibo matrix $\rightarrow$ **no CP violation** !!. To explain **CPV** in the SM Kobayashi and Maskawa have predicted a **third quark generation**.

Moreover, as can be shown, CPV requires that all **u-type and all d-type quarks have different masses.**

CKM Matrix and Unitarity Triangle

Unitary CKM matrix: $\mathbf{VV}^{\dagger} = \mathbf{1}$ $\rightarrow$ 6 “triangle” relations in complex plane:

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



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

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

$$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0$$

Important for $\mathbf{B_d}$ and $\mathbf{B_s}$ decays

Non degenerated “triangles” only in case of CP violation: Tip / triangle area defines the amount/strength of CPV!

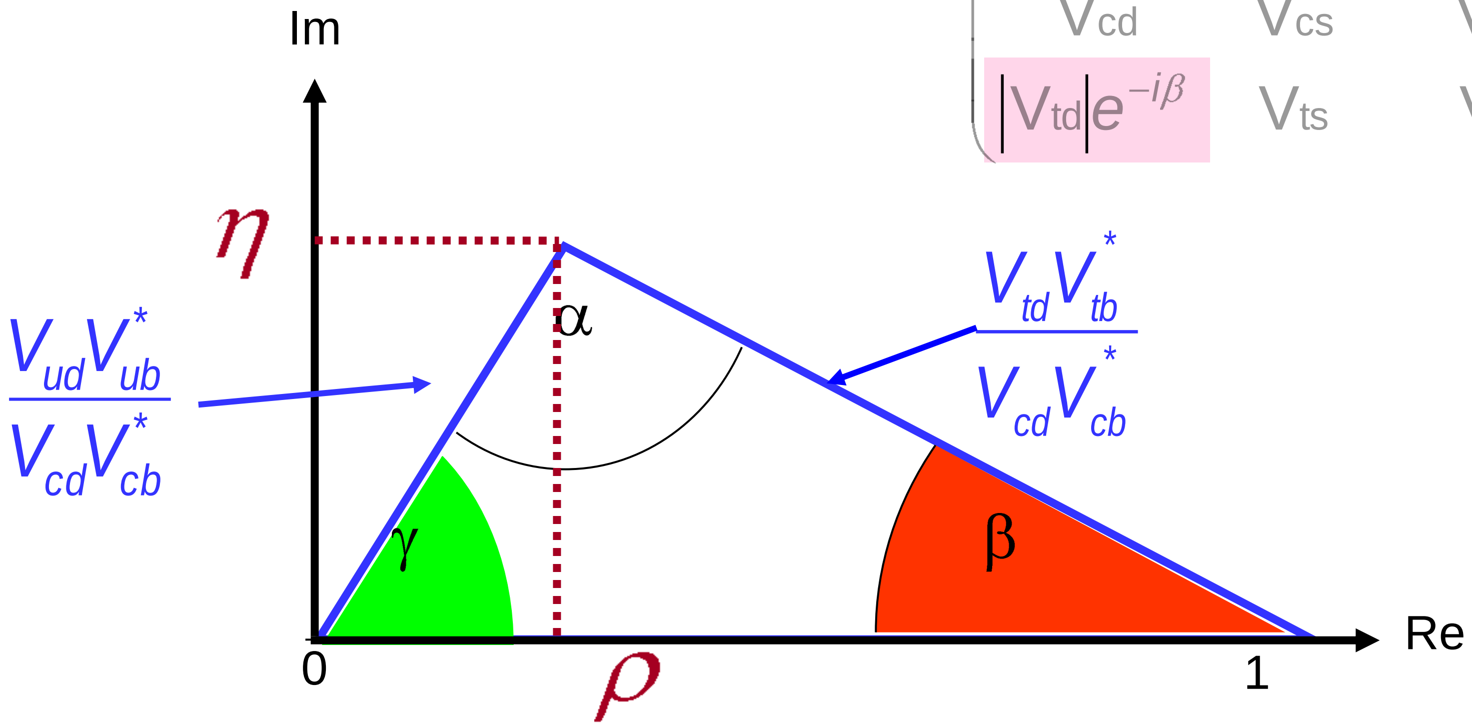
Strength of CPV characterized by Jarlskog invariant (area) $J = \mathrm{Im}\left(V_{ij}V_{kl}V_{il}^*V_{kj}^*\right)$

In SM: $J = \mathrm{Im}[V_{us}V_{cb}V_{ub}^*V_{cs}^*] = A^2\lambda^6\eta\left(-\lambda^2/2\right) + O(\lambda^{10}) \sim 10^{-5}$

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

"The Unitarity Triangle"

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



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

Experimental confirmation of UT:

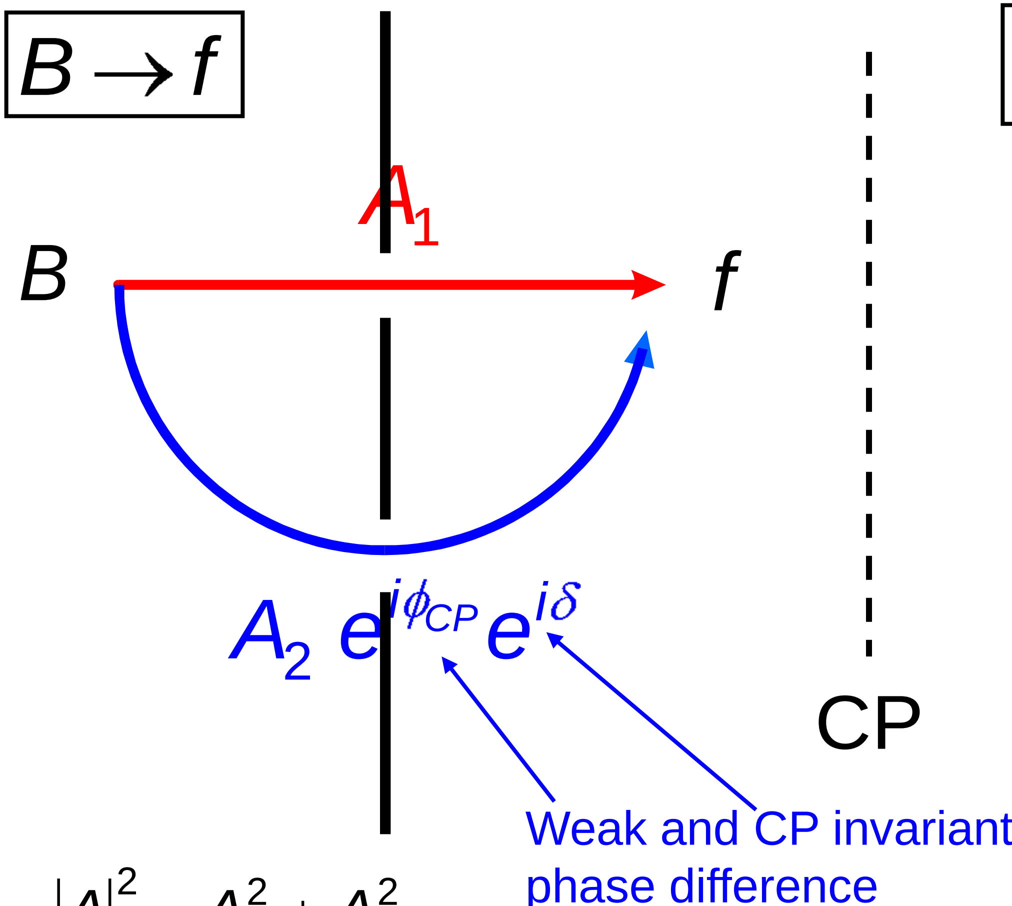
The sides of the UT can be measured via

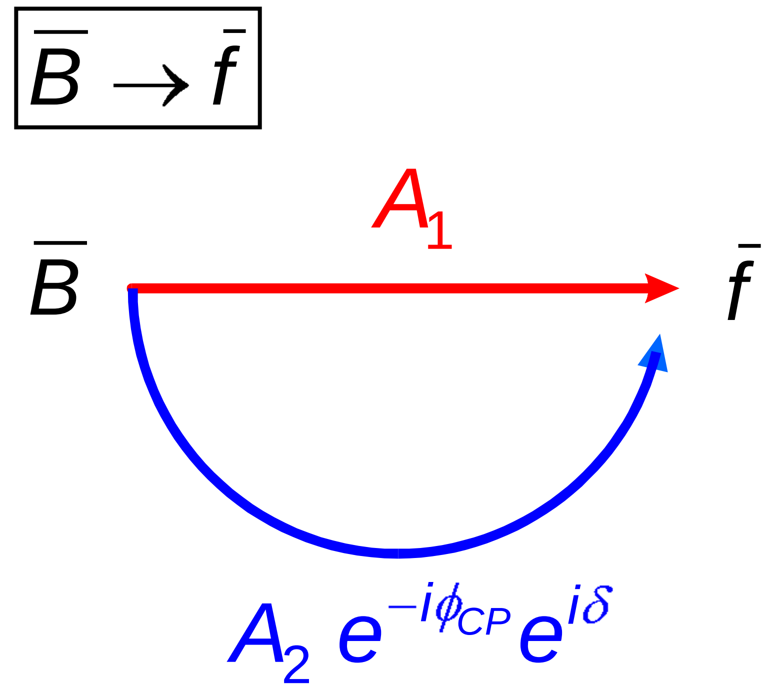
- B_d and B_s oscillation
- Semileptonic B decays with a $b\rightarrow c$ or $b\rightarrow u$ quark transition.

The angles (phases) can be determined from CP asymmetries in B decays! Observation of CP violating phases require presence of interfering amplitudes!

3.3 Observation of CP Violation

→ Phase measurement
→ Interference experiment





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

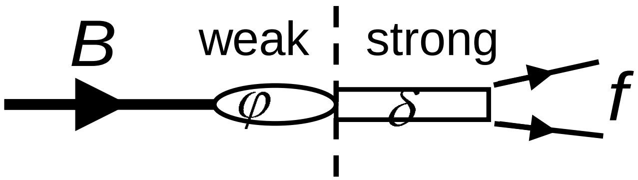
$$|\bar{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} - \delta)$$

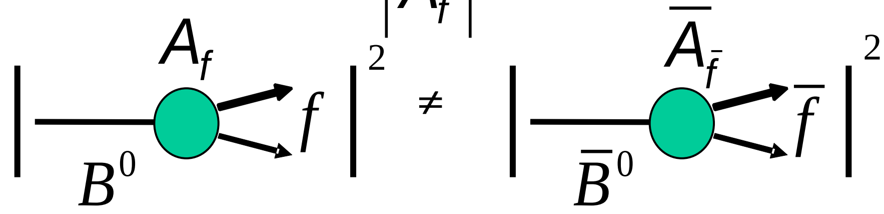
Need two phase differences between A_1 and A_2: Weak difference which changes sign under CP and another phase difference (strong) which is unchanged.

"3 Ways" of CP violation in meson decays

a) Direct CP violation

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



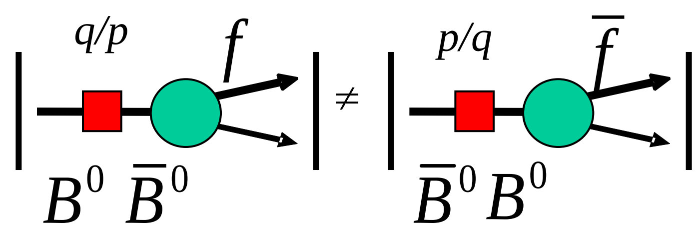


$$A(B \rightarrow f) = |A|\, e^{i\varphi}\, e^{i\delta}$$

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

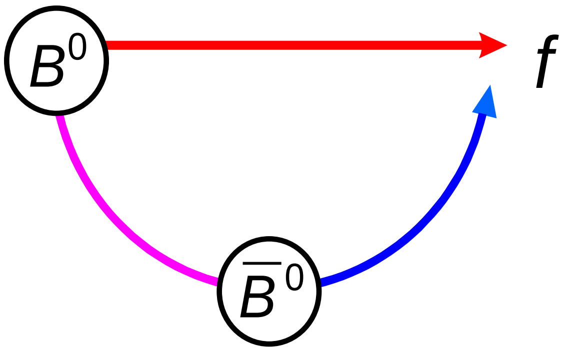
b) CP violation in mixing

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



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

c) CP violation through interference of mixed and unmixed amplitudes

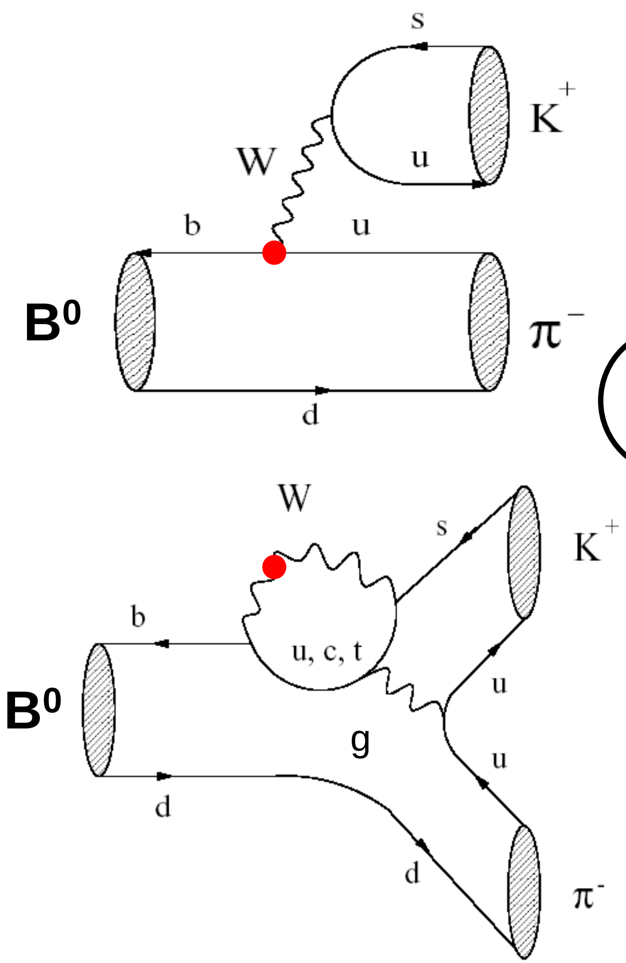


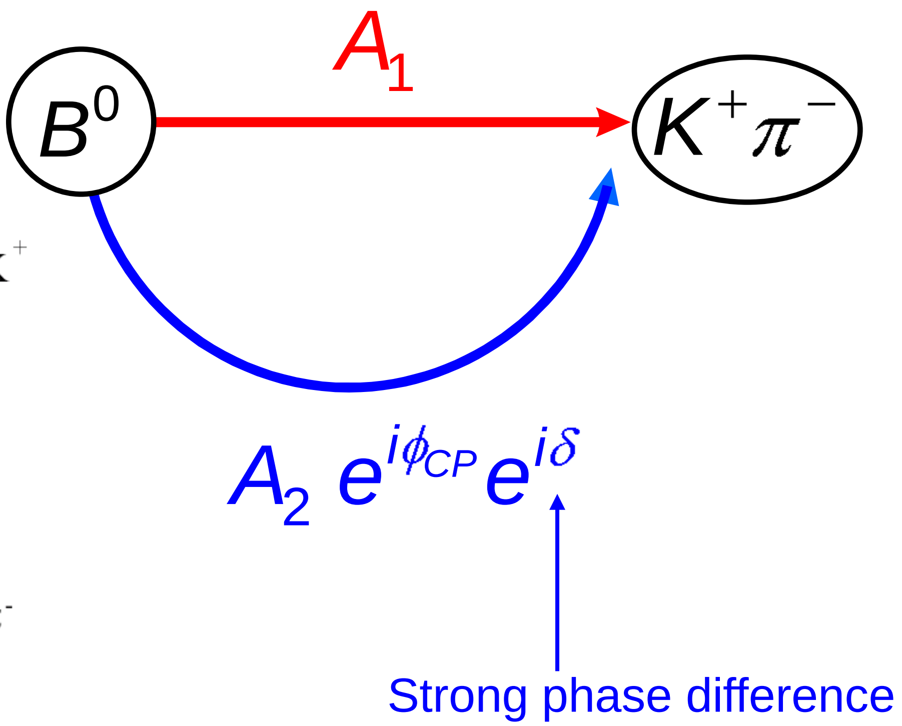
$$\Gamma(B^0_{t=0} \to f)(t) \neq \Gamma(\overline{B}^0_{t=0} \to f)(t)$$

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

Combinations of the 3 ways are possible!

ad a) Direct CP violation (B system)





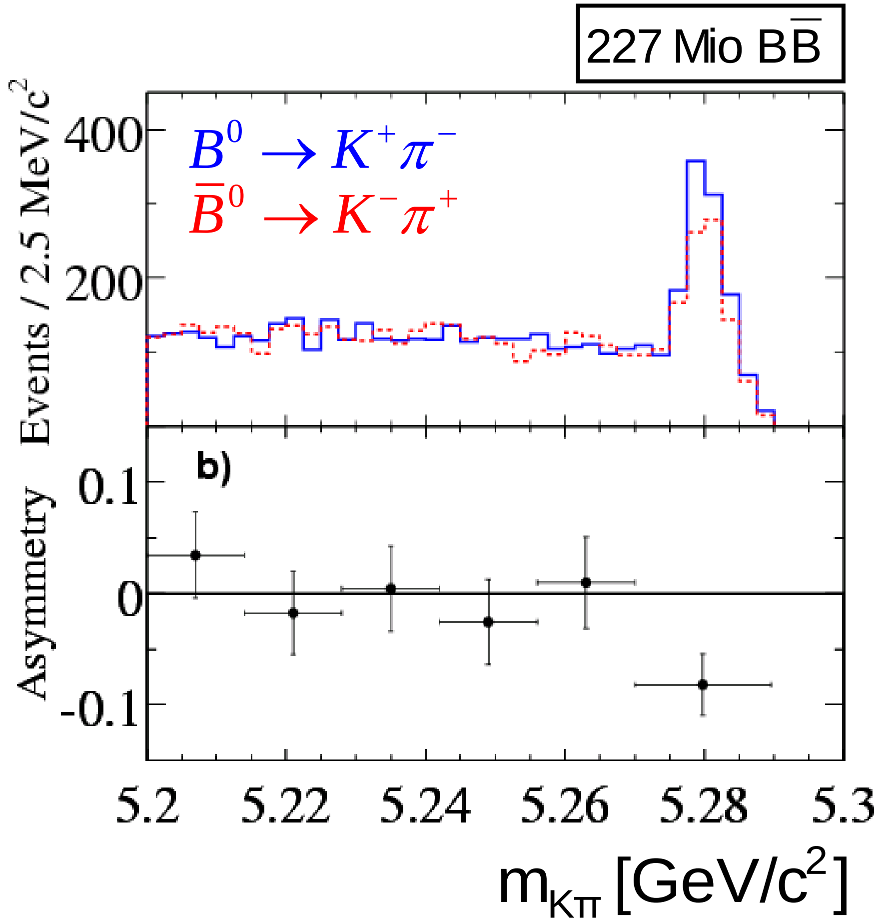
CP Asymmetrie $$|\bar{A}|^2 - |A|^2 = 4|A_1||A_2|\sin\varphi\sin\delta$$

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

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

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

4.2σ



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b) CP (T) violation in mixing

T violation

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

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 $p\bar{p}$ 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: $A^b_{sl} = -0.00957 \pm 0.00251$ (stat) ± 0.00146 (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.

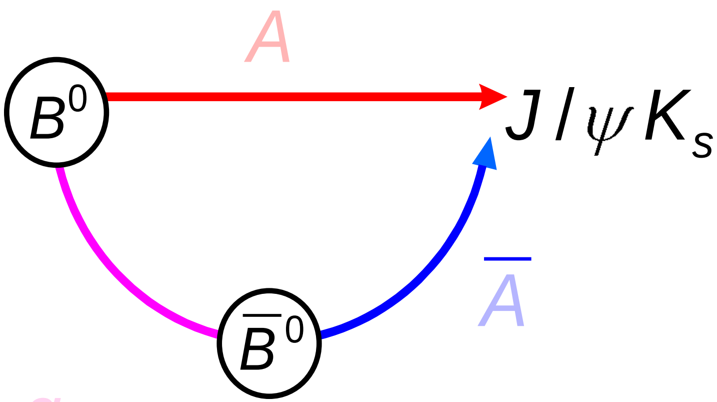
arXiv:1005.2757v1 [hep-ex] 16 May 2010

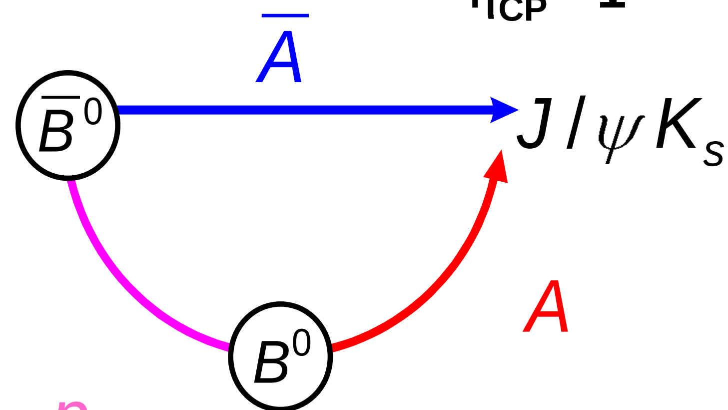
Skipped.

c) CP violation in interference between mixing and decay

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

$\eta_{CP}=-1$





$$\frac{q}{p} e^{i\pi/2} \sim e^{i2\beta} \boxed{e^{i\pi/2}} \quad = -1$$

$= \eta_{CP}(J/\psi K_s)$

$$\frac{p}{q} e^{i\pi/2} \sim e^{-i2\beta} \boxed{e^{i\pi/2}} \quad = -1$$

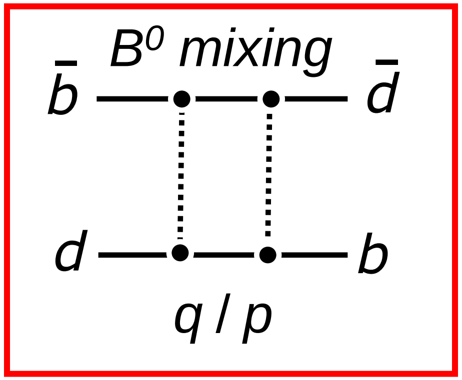
$= \eta_{CP}(J/\psi K_s)$

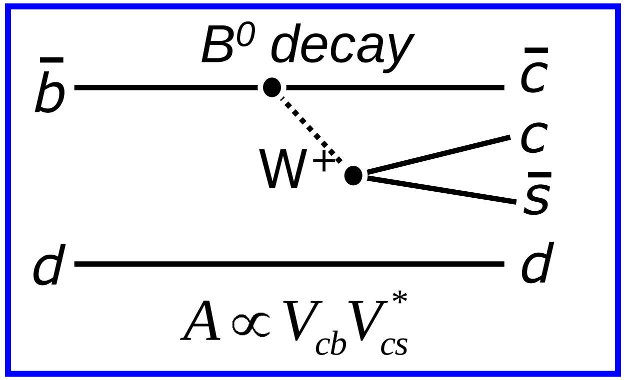
$$\Gamma(t) \sim e^{-\Gamma t}\left[1 - \sin 2\beta \sin(\Delta m t)\right]$$

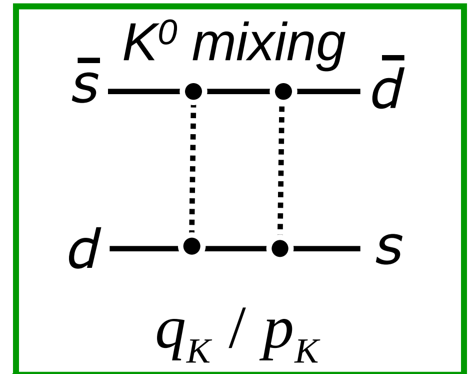
$$\Gamma(t) \sim e^{-\Gamma t}\left[1 + \sin 2\beta \sin(\Delta m t)\right]$$

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

SM prediction for $\lambda = A_1 / A_2$ (amplitude ratio)







Same for all $c\bar{c}K^0$ channels

$\frac{q}{p} \sim e^{2i\beta}$

$$\text{Ratio } A_1 / A_2 = \lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}} = -e^{-2i\beta}$$

Beside V_{td} all other CKM elements are real

$$V_{td} \approx |V_{td}| e^{-i\beta} \quad \Rightarrow \quad |\lambda_{CP}| = 1, \quad \mathrm{Im}(\lambda_{CP}) = \sin(2\beta)$$

no direct CPV, no CPV in mixing

Calculation of the time-dependent CP asymmetry

$$\Gamma(B^0 \to f_{CP})(t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} - \mathrm{Im}\left(\lambda_{CP}\right)\sin\left(\Delta m_d t\right) + \frac{1-|\lambda_{CP}|^2}{2}\cos\left(\Delta m_d t\right)\right]$$

$$\neq$$

$$\Gamma(\overline{B}^0 \to f_{CP})(t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} + \mathrm{Im}\left(\lambda_{CP}\right)\sin\left(\Delta m_d t\right) - \frac{1-|\lambda_{CP}|^2}{2}\cos\left(\Delta m_d t\right)\right]$$

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = S_f \sin\left(\Delta m_d t\right) - \underbrace{C_f \cos\left(\Delta m_d t\right)}_{\text{negligible}}$$

Time resolved

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_{CP}}{1+|\lambda_{CP}|^2} \qquad C_f = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$$

Interference
= $\sin 2\beta$ for $B^0 \to J/\psi K_S$

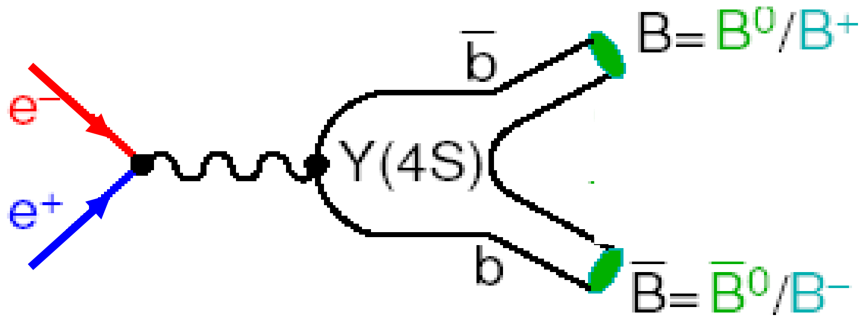
indicates direct CP violation
if $|q/p|=1$

To measure CP violation in B_d system:

- Need many B (several 100×10^9)
- Need to know the flavor of the B at t=0
- Need to reconstruct the decay length to measure t

3.4 Measurement of sin2β: Asymmetric $e^+ e^-$ B factory

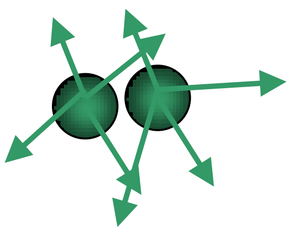
$E_{CMS} = 10.58\,\mathrm{GeV}$



Υ(4S) resonance decays
entirely to B pairs

Symmetric:

e^- 5.3 GeV → ← 5.3 GeV e^+

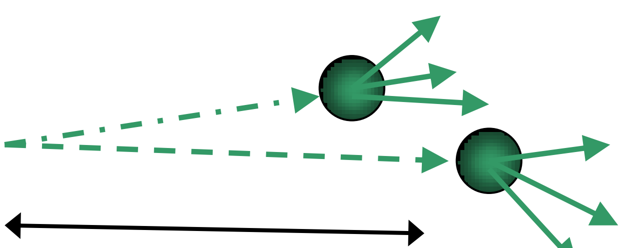


B mesons decay at rest
→ decay length $z \approx 0$

Asymmetric:

e^- 9 GeV → ← 3.1 GeV e^+

Boost β = 0.56

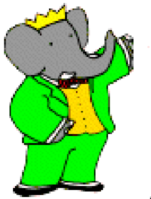


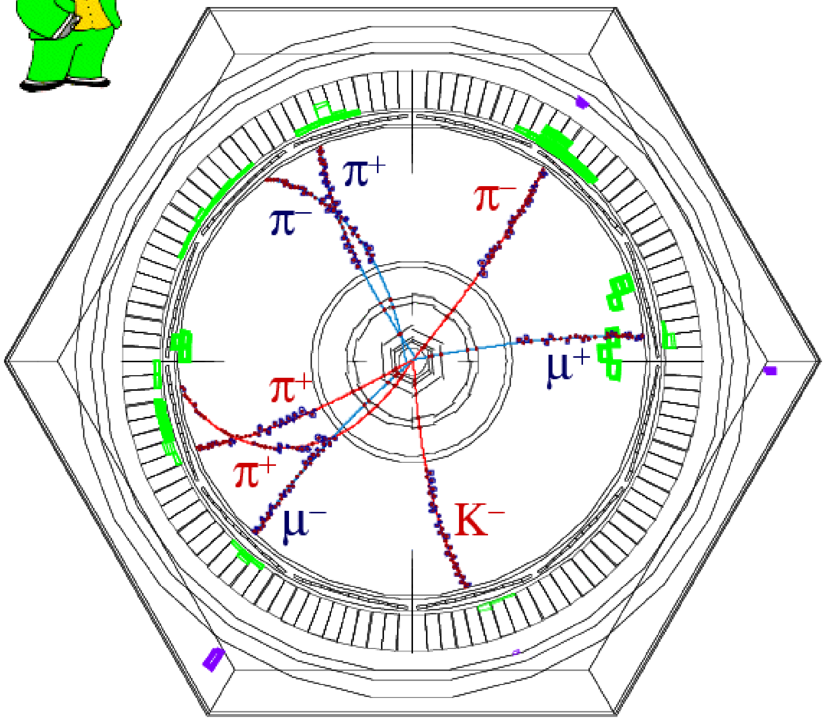
$z = c\beta\gamma\, t$

decay length
$z \approx 250\,\mu m$

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

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





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

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

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

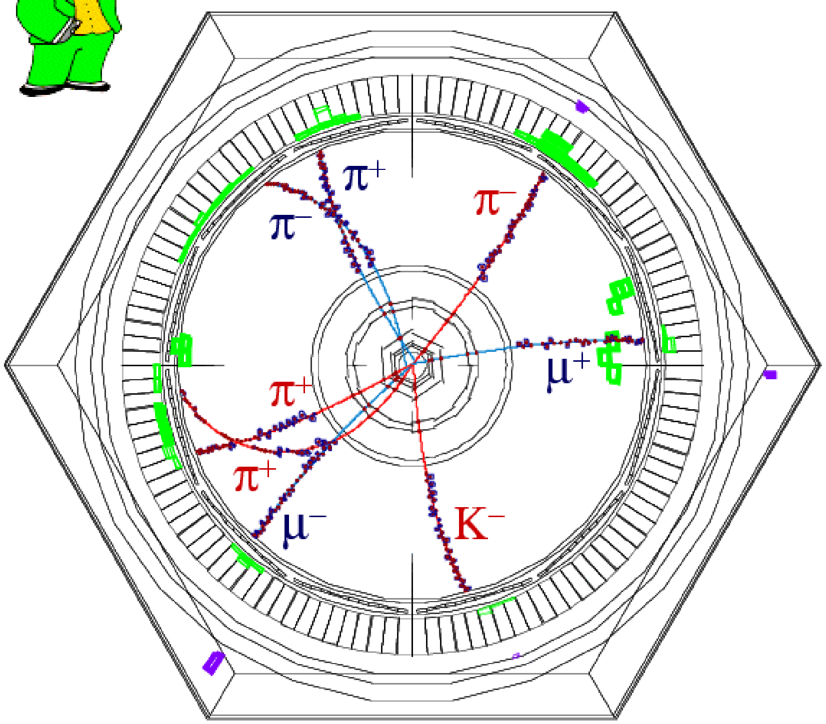
B_{CP} $B^0(\Delta t)$

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

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

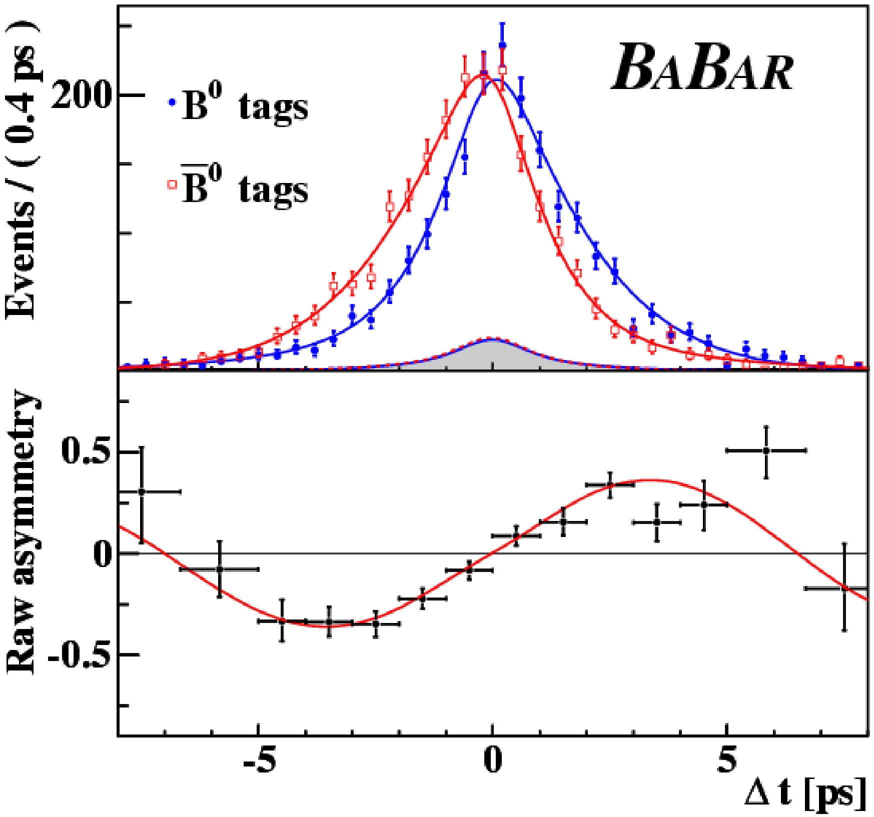
Measurement of sin2β: Golden decay channel $B^0 \to \psi K_s$

$B^0 \to \psi K_s$



PRL 94, 161803.

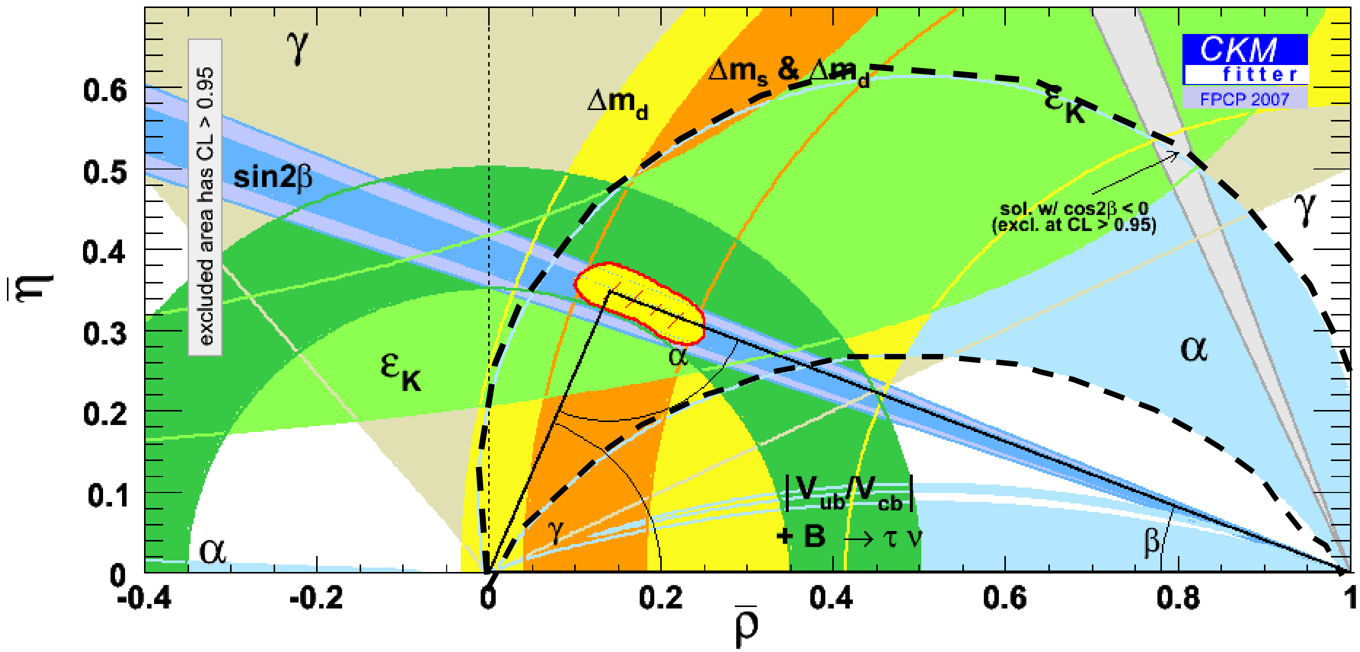
227 Mio $B\bar{B}$



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

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

3.5 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