IX. Flavor oscillation and CP violation

1. Quark mixing and the CKM matrix
2. Flavor oscillations: Mixing of neutral mesons
3. CP violation
4. Neutrino oscillations

1. Quark mixing and CKM matrix

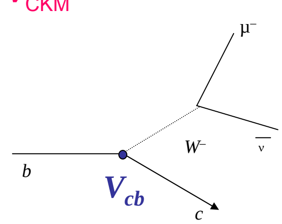
1.1 Quark mixing:

Mass eigen-states are not equal to the weak eigen-states: **Quark-mixing** described by unitary **CKM matrix**,

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

For weak charged current one obtains:

$$J^{+}_{\mu} \propto (\bar{u},\bar{c},\bar{t})(1-\gamma_5)\,\gamma_\mu\, V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Weak states u' d' s' are orthogonal: V_{CKM} is unitary.

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

1.2 Cabbibo-Kobayashi-Maskawa 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
1 Phase

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

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

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

Wolfenstein Parametrization λ, A, ρ, η

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

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

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

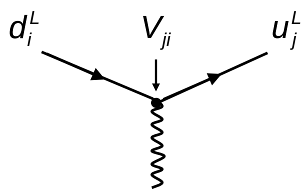
→ hierarchy expressed by orders of λ = **$\sin\theta_c \approx$ 0.22**

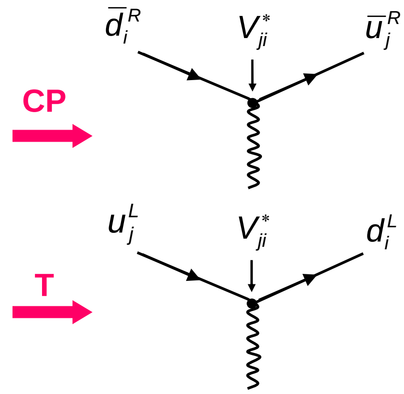
Magnitude of the elements:

$$\begin{pmatrix} 0.9739 \text{ to } 0.9751 & 0.221 \text{ to } 0.227 & 0.0029 \text{ to } 0.0045 \\ 0.221 \text{ to } 0.227 & 0.9730 \text{ to } 0.9744 & 0.039 \text{ to } 0.044 \\ 0.0048 \text{ to } 0.014 & 0.037 \text{ to } 0.043 & 0.9990 \text{ to } 0.9992 \end{pmatrix}$$

PDG 2004
90% C.L>

Komplex CKM elements and CP violation





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.

2. Flavor oscillation: Mixing of neutral mesons

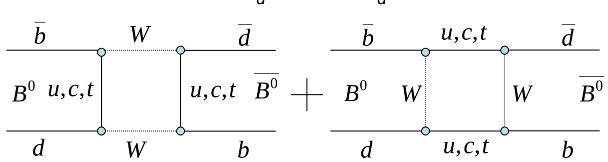
Neutral mesons:

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

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

Standard Model predicts oscillations of neutral Mesons:

$$B_d^0 \Leftrightarrow \overline{B_d^0}$$



Transition can be described by matrix element: $\left\langle \overline{B_d^0} \middle| H_W \middle| B_d^0 \right\rangle$

2.1 Phenomenological description of mixing

Schrödinger equation for unstable meson:

$$i\frac{d}{dt}|\psi\rangle = H|\psi\rangle = \left(m - \frac{i}{2}\Gamma\right)|\psi\rangle \quad \Rightarrow \quad \begin{cases} |\psi(t)\rangle = |\psi_0\rangle \cdot e^{-imt} \cdot e^{-\frac{1}{2}\Gamma t} \\ \| \psi(t)\rangle|^2 = \| \psi_0\rangle|^2 \cdot e^{-\Gamma t} \end{cases}$$

For neutral mesons $(K^0,\overline{K}^0),(D^0,\overline{D}^0),(B^0,\overline{B}^0),(B_s^0,\overline{B}_s^0)$ consider 2 compon.

$$i\frac{d}{dt}\begin{pmatrix} P^0 \\ \overline{P}^0 \end{pmatrix} = \mathbf{H}\begin{pmatrix} P^0 \\ \overline{P}^0 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{21} \\ H_{12} & H_{22} \end{pmatrix}\begin{pmatrix} P^0 \\ \overline{P}^0 \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix} P^0 \\ \overline{P}^0 \end{pmatrix} = \begin{pmatrix} m_{11} - \frac{i}{2}\Gamma_{11} & m_{12}^* - \frac{i}{2}\Gamma_{12}^* \\ m_{12} - \frac{i}{2}\Gamma_{12} & m_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} P^0 \\ \overline{P}^0 \end{pmatrix}$$

$\langle B^0|\mathbf{H}_w|\overline{B}^0\rangle$

M and Γ hermitian:

$$m_{21} = m_{12}^*$$
$$\Gamma_{21} = \Gamma_{12}^*$$

CP $\Rightarrow H_{12} = H_{21}$

CPT $\Rightarrow$ $H_{11} = H_{22} = H$, $m_{11} = m_{22} = m$, $\Gamma_{11} = \Gamma_{22} = \Gamma$

Mass eigenstates (by diagonalizing matrix)

Heavy and light mass eigenstate:

$|P_L\rangle = p|P^0\rangle + q|\overline{P}^0\rangle$ with m_L, Γ_L

$|P_H\rangle = p|P^0\rangle - q|\overline{P}^0\rangle$ with m_H, Γ_H

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

$$|P^0\rangle = \frac{1}{2p}(|P_L\rangle + |P_H\rangle)$$
$$|\overline{P}^0\rangle = \frac{1}{2q}(|P_L\rangle - |P_H\rangle)$$

Flavor / weak eigenstates

Parameters of the mass states

$$m_{H,L} = m \pm \mathrm{Re}\sqrt{H_{12}H_{21}}$$
$$\Gamma_{H,L} = \Gamma \mp 2\,\mathrm{Im}\sqrt{H_{12}H_{21}}$$
$$\Delta m = m_H - m_L = 2\,\mathrm{Re}\sqrt{H_{12}H_{21}}$$
$$\Delta\Gamma = \Gamma_H - \Gamma_L = -4\,\mathrm{Im}\sqrt{H_{12}H_{21}}$$

$x \equiv \frac{\Delta m}{\Gamma}$ und $y \equiv \frac{\Delta\Gamma}{2\Gamma}$

Neutral B mesons

$\Delta m_d = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$ (PDG)

$\Delta m_s > 14.4\ \mathrm{ps}^{-1}$ (PDG)

$\Delta\Gamma / \Gamma < 0.07$ (90% *CL*)

$\Delta\Gamma_s / \Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$ (ICHEP04)

Time evolution

Generic particle (before P)

$$|B_{H,L},t\rangle = b_{H,L}(t)|B_{H,L}\rangle \quad \text{mit} \quad b_{H,L}(t) = e^{-\Gamma_{H,L}t}e^{-im_{H,L}t}$$

$$|\psi_{B^0}(t)\rangle = \frac{|B_L,t\rangle + |B_H,t\rangle}{2p} = \frac{1}{2p}\left(b_L(t)\cdot\left(p|B^0\rangle + q|\overline{B^0}\rangle\right) + b_H(t)\cdot\left(p|B^0\rangle - q|\overline{B^0}\rangle\right)\right)$$

$$= f_+(t)\cdot|B^0\rangle - \frac{q}{p}f_-(t)\cdot|\overline{B^0}\rangle \qquad f_\pm(t) = \frac{1}{2}\cdot\left[e^{-im_H t}e^{-\Gamma_H t/2} \pm e^{-im_L t}e^{-\Gamma_L t/2}\right]$$

$$|\psi_{\overline{B}^0}(t)\rangle = f_+(t)\cdot|\overline{B}^0\rangle + \frac{p}{q}f_-(t)\cdot|B^0\rangle$$

B^0

$$P\left(B^0 \to B^0, t\right) = |f_+(t)|^2$$

$$P\left(B^0 \to \overline{B}^0, t\right) = \left|\frac{q}{p}\right|^2 |f_-(t)|^2$$

$\overline{B}^0$

$$P\left(\overline{B}^0 \to \overline{B}^0, t\right) = |f_+(t)|^2$$

$$P\left(\overline{B}^0 \to B^0, t\right) = \left|\frac{p}{q}\right|^2 |f_-(t)|^2$$

Mixing of neutral mesons

Time evolution of rates:

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

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

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

Two mixing mechanisms:

- Mixing through decays → $y = \frac{\Delta\Gamma}{2\Gamma} \approx O(1)$
- Mixing through oscillation → $x = \frac{\Delta m}{\Gamma} \approx O(1)$

$(K^0,\overline{K}^0),(D^0,\overline{D}^0),(B^0,\overline{B}^0),(B^0_s,\overline{B}^0_s)$ show different oscillation behavior

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

2.2 Neutral kaons

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

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

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

$$\text{CP} = -1 \qquad\qquad \text{CP} = +1$$

$\mathbf{K_L}$ and $\mathbf{K_S}$ can be identified with the mass eigenstates:

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

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

$$\text{CP}|K_{Heavy}\rangle = -|K_{Heavy}\rangle$$

$$\text{CP}|K_{Light}\rangle = +|K_{Light}\rangle$$

Phase convention:

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

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

Large differences between lifetimes

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

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

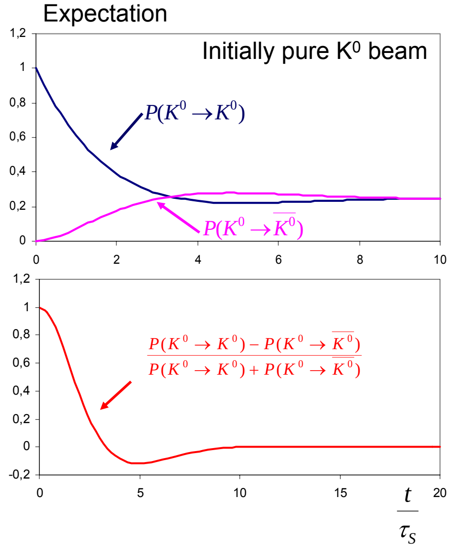
$$\Delta\Gamma = -11.182 \cdot 10^{9}\,\hbar\text{s}^{-1}$$

$$x = \frac{\Delta m}{\Gamma} = 0.942 \pm 0.007$$

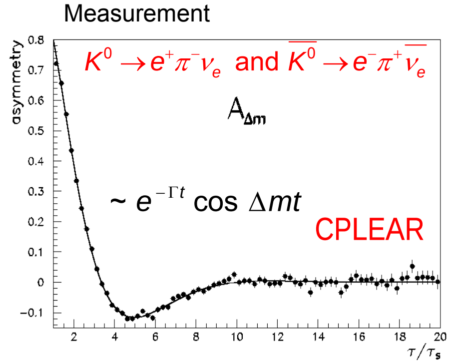
$$y = \frac{\Delta\Gamma}{2\Gamma} = \text{-}0.9966$$

Neutral kaon system

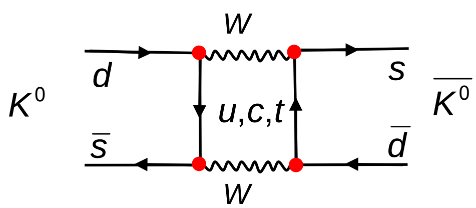
Expectation

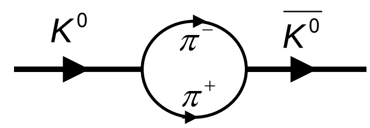


Measurement



K^0 - $\overline{K}^0$ (strangeness) oscillation in the SM





Short range effects

Long range effects

Oscillation frequency Δm:

$$\Delta m \sim \frac{G_F^2}{4\pi} m_K f_K^2 \sum_{q=u,c,t} m_q^2 \left|V_{qs} V_{qd}\right|^2 \approx \frac{G_F^2}{4\pi} m_K f_K^2 m_c^2 \left|V_{cs} V_{cd}\right|^2$$

c quark contribution dominant: although m_t^2 is very large, the factor $|V_{ts}V_{td}|^2 \sim \lambda^5$ is very small !

2.3 Neutral B Meson

2 neutral B mesons:

$B_d^0 = |d\ \bar{b}>$ - oscillations precisely measured

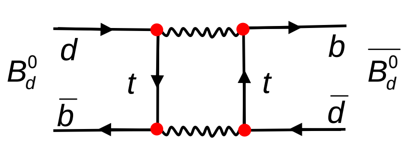
$B_s^0 = |s\ \bar{b}>$ - oscillations not yet observed

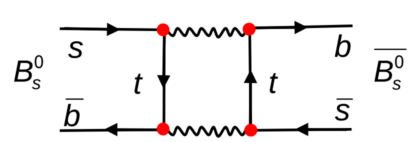
Mixing mechanisms:

- **Mixing through decay:** many possible hadronic decays $\rightarrow \Gamma$ is large

$$\Rightarrow y = \frac{\Delta\Gamma}{2\Gamma} \text{ is small} = \begin{cases} \approx 0 \text{ for } B_d^0 \\ \approx O(0.1) \text{ for } B_s^0 \end{cases} \Rightarrow \text{no mixing via decay}$$

- **Mixing through oscillation** $\rightarrow$ Significant contribution only from top loop





$$\Delta m \sim m_t^2 \left|V_{tb} V_{td}\right|^2 \sim m_t^2 \cdot O(\lambda^6) \qquad \Delta m \sim m_t^2 \left|V_{tb} V_{ts}\right|^2 \sim m_t^2 \cdot O(\lambda^4)$$

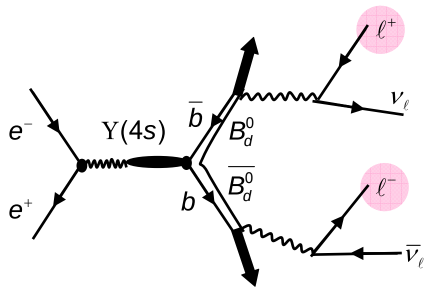
Large $\Delta m_{s,d}$: $\Delta m_s \sim 1/\lambda^2 \Delta m_d \rightarrow B_s$ osc. is about 20 times faster than B_d osc.

Discovery of B^0 mixing

ARGUS 1987

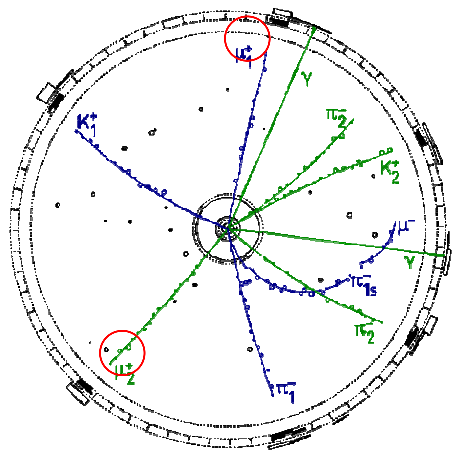
First e^+e^- B factory at DESY:

at $\sqrt{s} = 10.58$ GeV :
$e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0$ } $\sigma(B\overline{B}) \approx 1$nb



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

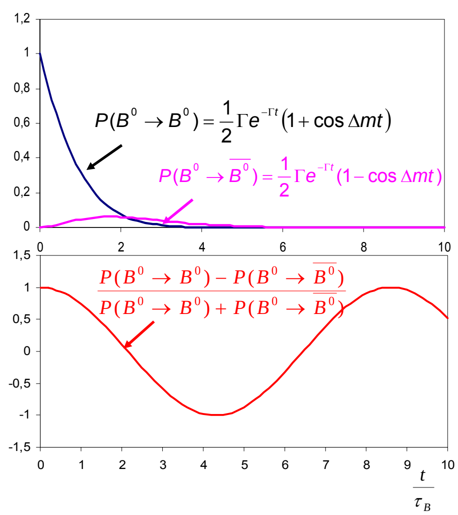
$B^0B^0 \to \ell^+\ell^+$ }
$\overline{B}^0\overline{B}^0 \to \ell^-\ell^-$ } mixed



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

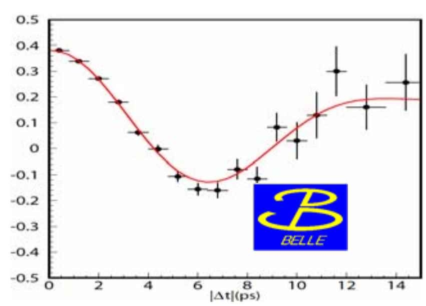
$B^0 \to D^{*-}\mu^+\nu_\mu$
$\quad \hookrightarrow D^-\pi^0$
$\qquad \hookrightarrow \gamma\gamma$
$\quad \hookrightarrow K^+\pi^-\pi^-$

Mixing of neutral B mesons



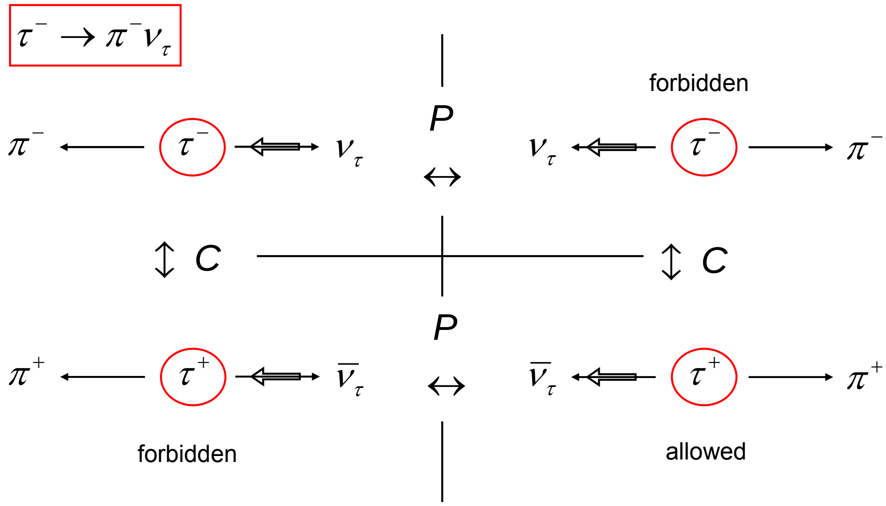
$$A = \frac{unmixed - mixed}{unmixed + mixed}$$

$\Delta m_d = 0.511 \pm 0.005 \pm 0.006$ ps^{-1}



3. CP violation in the K^0 and B^0 system

$\tau^- \to \pi^- \nu_\tau$



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

3.1 Observation of CP violation (CPV) in K_L decays

$|K_L\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$ CP = −1 should decay into 3π w/ CP(|3π>)= -1

and not into 2π w/ CP(|2π>)= +1

Christenson et al., 1967

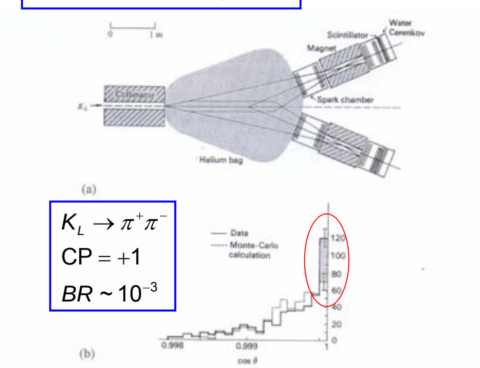


Fig. 7.22. (a) Arrangement of Christenson *et al.* (1964) demonstrating the *CP*-violating decay $K_L \to \pi^+\pi^-$. K_L decays are observed in a helium bag, the charged products being analysed by two magnet spectrometers instrumented with spark chambers and scintillators. (b) Rare two-pion decays are distinguished from the common three-pion decays by the invariant mass of the pair (490 MeV $< M_{\pi\pi} <$ 510 MeV) and the direction, θ, of the resultant momentum vector. The $\cos\theta$ distribution is that expected from three-body decays, plus 50 events (shaded) collinear with the beam and attributed to the two-pion decay mode.

- Until the year 2000 the K^0 was the only system in which CPV was observed
- In 2000, CPV was observed in the B^0 system
- So far the observed CPV is consistent with the SM prediction. But it is too small to explain the baryon asymmetry of the universe.

3.2 CP Violation in the Standard Modell

$V_{ub} = |V_{ub}|e^{-i\gamma}$ ← see Wolfenstein parametrization

Quarks

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

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

Antiquarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

Phase angle≠0: complex CKM matrix
⬇
Different mixing for quarks and anti-quarks
⬇
Origin of CP Violation (CPV)

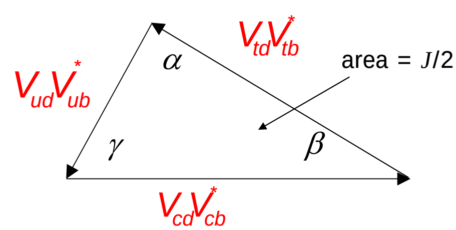
Strength of CPV: Characterized by Jarlskog invariant: $J = \text{Im}\left(V_{ij} V_{kl} V^*_{il} V^*_{kj}\right) \neq 0$

In SM: $J = \text{Im}[V_{us}V_{cb}V^*_{ub}V^*_{cs}] = A^2\lambda^6\eta\left(1-\lambda^2/2\right) + O(\lambda^{10}) \sim 10^{-5}$

3.3 Unitarity Triangle

Unitary CKM matrix: $\mathbf{VV^\dagger = 1}$

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



6 "triangle" relations:

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

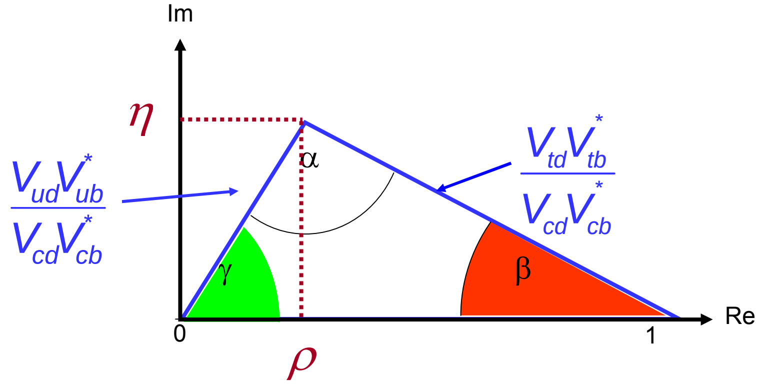
$V_{td}V^*_{ud} + V_{ts}V^*_{us} + V_{tb}V^*_{ub} = 0$

"Real" triangles w/ similar sides:
→ expect large CPV effects
Important for $\mathbf{B_d}$ and $\mathbf{B_s}$ decays

Row 1x2, 2x3
Column 1x2, 2x3

Degenerated triangles (same area):
→ small CPV effect (Kaon decays)

Rescaled Unitarity Triangle

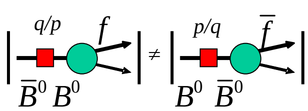


$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

3.4 “3 Ways” of CP violation in meson decays

1. CP Violation in mixing:

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



Standard model prediction for B

$$\left|\frac{q}{p}\right| - 1 \approx 4\pi \frac{m_c^2}{m_t^2} \sin\beta \approx 5 \times 10^{-4}$$

Kaon system:

CP eigenstates are not identical with mass/lifetime eigenstates

admixture

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right) \quad \text{CP } +1 \qquad |K_S^0\rangle = \frac{1}{\sqrt{1+|\varepsilon_m|^2}}\left(|K_1^0\rangle + \varepsilon_m |K_2^0\rangle\right)$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right) \quad \text{CP } -1 \qquad |K_L^0\rangle = \frac{1}{\sqrt{1+|\varepsilon_m|^2}}\left(|K_2^0\rangle + \varepsilon_m |K_1^0\rangle\right)$$

$$\left|\frac{q}{p}\right| \cong 1 - 2\mathrm{Re}(\varepsilon_m)$$

CPLEAR 2001: $4\mathrm{Re}(\varepsilon_m) = (6.2 \pm 1.7) \cdot 10^{-3}$

CP (T) Violation in mixing

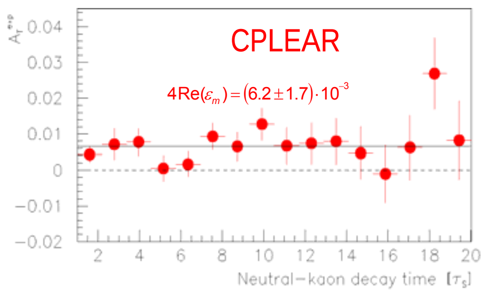
K^0 $\bar{K}^0$ System:

$$\frac{P(\overline{K^0}\to K^0)-P(K^0\to\overline{K^0})}{P(\overline{K^0}\to K^0)+P(K^0\to\overline{K^0})}\cong\frac{4\mathrm{Re}(\varepsilon_m)}{1+|\varepsilon_m|^2}\cong 4\mathrm{Re}(\varepsilon_m)$$

$$A^{\exp}(t)=\frac{\Gamma(\overline{K}^0_{t=0}\to e^+\pi^-\nu_e)-\Gamma(K^0_{t=0}\to e^-\pi^+\overline{\nu}_{e})}{\Gamma(\overline{K}^0_{t=0}\to e^+\pi^-\nu_e)-\Gamma(K^0_{t=0}\to e^-\pi^+\overline{\nu}_{e})}(t)$$

In principal the ratio measures the T invariance:

$$\overline{K^0}\to K^0 \quad \overset{T}{\leftrightarrow} \quad \overline{K^0}\leftarrow K^0$$



B^0 $\bar{B}^0$ System:

$$A_{SL}=-0.0026\pm0.0067$$

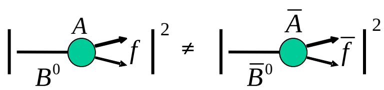
$$\left|\frac{q}{p}\right|=1.0013\pm0.0034$$

$$\frac{4\,\mathrm{Re}\,\varepsilon_B}{(1+|\varepsilon_B|^2)}=-0.0007\pm0.0017$$

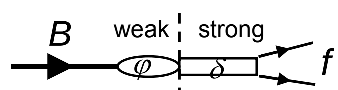
HFAG 2004

2. Direct CPV

$$\mathrm{Prob}(\bar{B}\to\bar{f})\neq\mathrm{Prob}(B\to f)$$



$$\left|\cdots\right|^2\neq\left|\cdots\right|^2 \qquad \left|\frac{\bar{A}}{A}\right|\neq1$$



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

Standard Model:

$$A(B^0\to X)=|A_1|e^{i\varphi_1+i\delta_1}+|A_2|e^{i\varphi_2+i\delta_2}$$

$$\bar{A}(B^0\to X)=|A_1|e^{-i\varphi_1+i\delta_1}+|A_2|e^{-i\varphi_2+i\delta_2}$$

Two interfering amplitudes A_1, A_2:

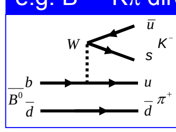
–with diff. CKM phases φ_1 , φ_2

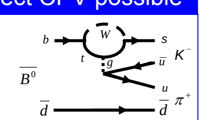
–with diff. strong phases δ_1 , δ_2

$$|\bar{A}|^2-|A|^2=4|A_1||A_2|\sin(\varphi_1-\varphi_2)\sin(\delta_1-\delta_2)$$

$$\left|\frac{\bar{A}}{A}\right|\neq1 \quad\Leftrightarrow\quad \underbrace{\neq0}_{\text{weak}} \quad \underbrace{\neq0}_{\text{strong}}$$

e.g: $B^0\to K\pi$ direct CPV possible





First observation of direct CPV in B decays

Summer 2004

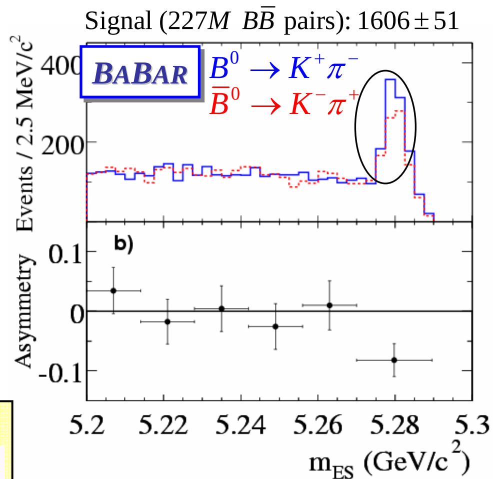
$B^0 \to K^+\pi^-$

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

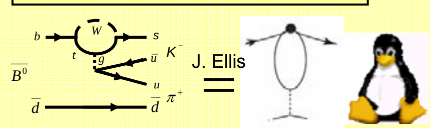
BABAR *hep-ex/0408057,*

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

4.2σ



Effect of "penguin" contribution

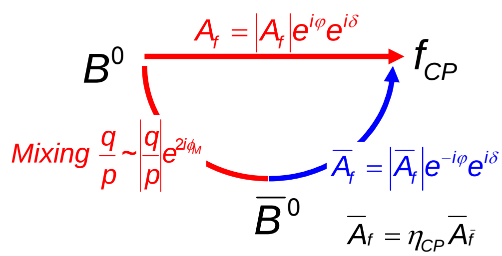


3. CPV in interference between mixing and decay

$B^0 \to f_{CP}$

CP eigenstate:

$CP|f_{CP}\rangle = \eta_{CP}|f_{CP}\rangle$



CPV if there is a phase difference λ_{CP} between the direct path and the path with mixing:

$$\lambda_{CP} \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = \eta_{CP} \cdot \left|\frac{q}{p}\right| \cdot \left|\frac{\overline{A}_{\bar{f}}}{A_f}\right| \cdot e^{2i(\phi_M - \phi_f)}$$

Mixing: $\frac{q}{p} = \left|\frac{q}{p}\right| e^{2i\phi_M}$

=1 if no CPV in decay

If no CPV in mixing and decay:

$\lambda_{CP} = -\eta_{CP}\, e^{2i(\varphi_M - \varphi_f)}$

good approximation for $B_0 \to J/\psi K_s$

Calculation of the time-dependent CP asymmetry

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

$$\neq$$

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

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

Time resolved

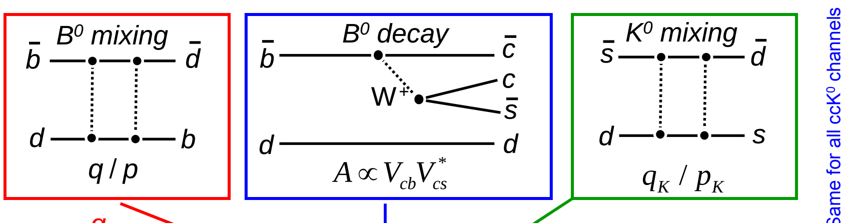
$$S_f = \frac{2\,\mathrm{Im}\,\lambda_{CP}}{1+|\lambda_{CP}|^2} \qquad C_f = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$$

Interference
= $\sin 2\beta$ for e.g. $B^0 \to J/\psi K_S$
≈ $\sin 2\alpha_{(eff)}$ for e.g. $B^0 \to \pi^+\pi^-$

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

3.5 SM prediction for the decay $B^0 \to J/\psi K_S$

$\eta_{CP} = -1$



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

$$\lambda_{\psi K_S} = \frac{q}{p}\frac{\overline{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}} = -e^{-2i\beta}$$

Beside V_{td} all other CKM elements are real

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

no direct CPV, no CPV in mixing

Phase of decay amplitude $\varphi_f = 0$

Mixing phase $\varphi_M = \beta$

3.6 Time dependent A_{CP} for $B^0 \to J/\psi K_s$

$$A_{CP}(t) = \frac{\dot{N}\left(\overline{B^0} \to J/\psi K_S^0\right) - \dot{N}\left(B^0 \to J/\psi K_S^0\right)}{\dot{N}\left(\overline{B^0} \to J/\psi K_S^0\right) + \dot{N}\left(B^0 \to J/\psi K_S^0\right)} = -\eta_{CP} \sin 2(\varphi_M - \varphi_f) \sin(\Delta m t)$$

$B^0 \to J/\psi K_S: \ = \beta$

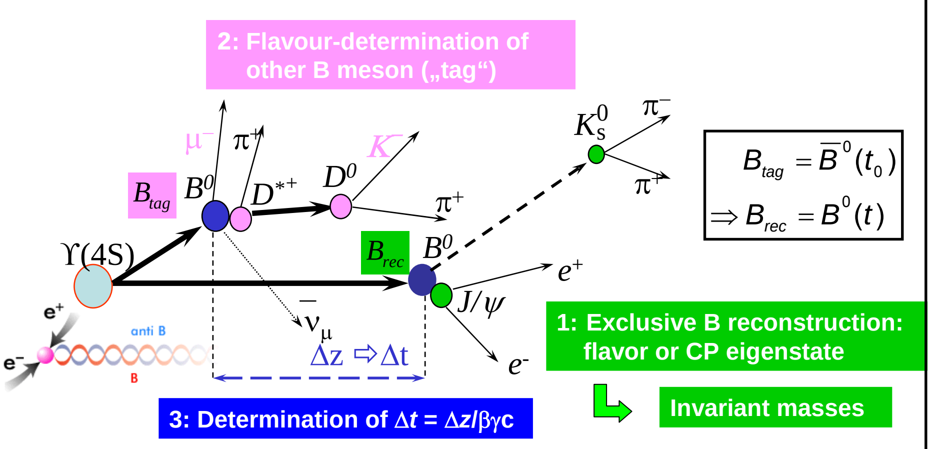
$$\Rightarrow \quad A_{CP}(t) = -\eta_{CP} \sin 2\beta \sin(\Delta m t)$$

Oscillation with Δm_d

If $A_{CP} \neq 0$:

- CP violation
- Measurement of the angle $\beta = \arg(V_{td})$

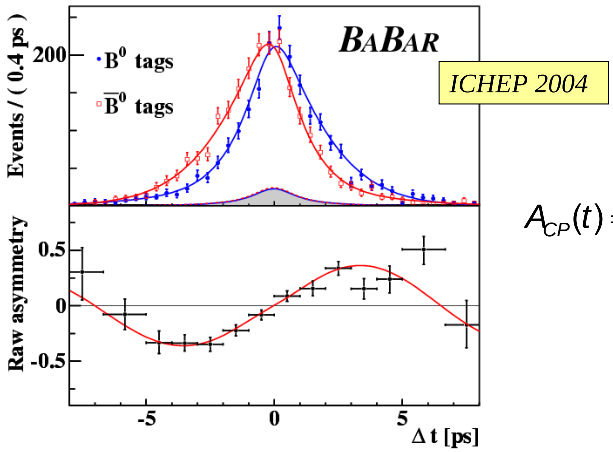
Time dependent CP asymmetry measurement for $B^0 \to J/\psi K_s$



$B^0_{rec} = B^0_{flav}$ (flavor eigenstates) ➡ lifetime, mixing analyses

$B^0_{rec} = B^0_{CP}$ (CP eigenstates) ➡ CP analysis

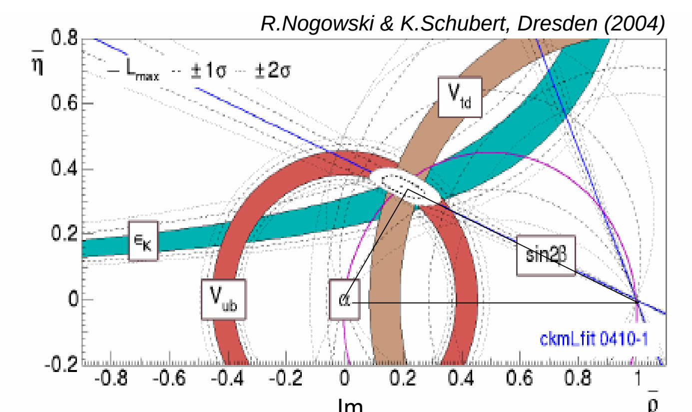
CP asymmetry in $B^0 \to J/\psi K_s$



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

sin2β = 0.722 ± 0.040 (stat) ± 0.023 (sys)
|λ| = 0.950 ± 0.031 (stat.) ± 0.013 (sys)

3.7 Status of the Unitarity Triangle



With the current precision the CKM phases behave as predicted by the Standard Model → high precision measurements necessary