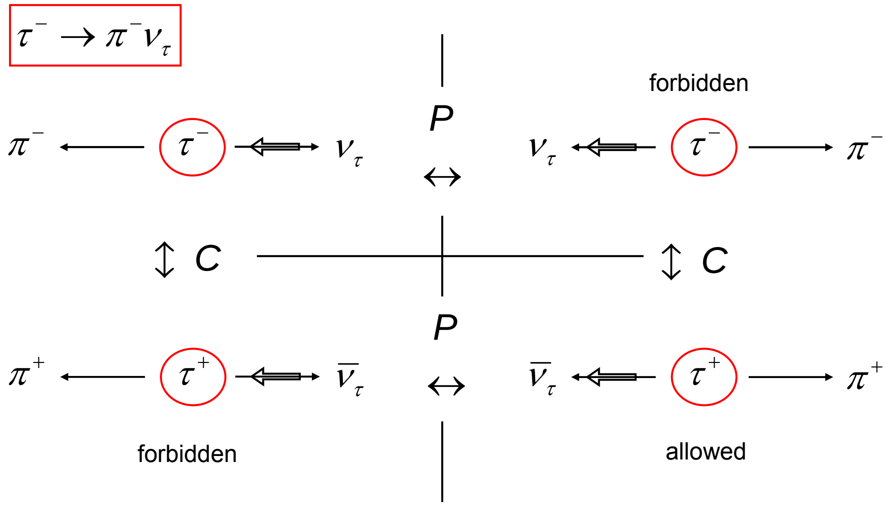
3. CP violation in the K^0 and B^0 system

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



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

3.1 Observation of CP violation (CPV) in K_L decays

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

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

should always decay into 3π:

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

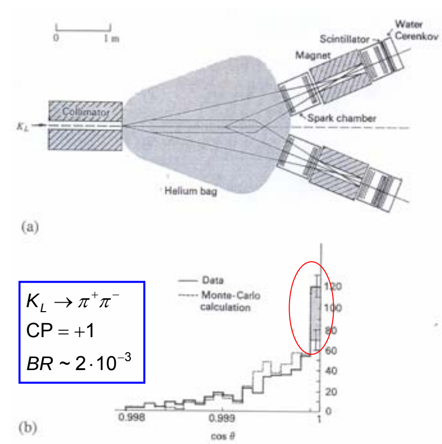
and never into 2π CP($|2\pi\rangle$)= +1

Explanation:

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

Not a CP eigenstate: CP violation !

Christenson, Cronin, Fitch, Turlay, 1964



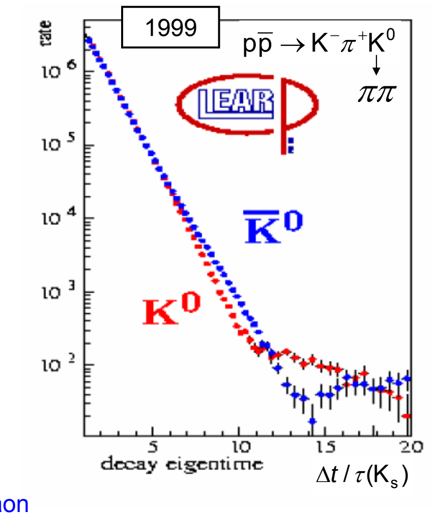
After 35 years of kaon physics:

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

$|K_2\rangle$ → ε' → $\pi\pi$ (Direct CPV)

$|K_1\rangle$ → $\pi\pi$ (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. Much easier to understand and to predict in the SM is the B meson system:

CPV in the B^0 system was observed in 2000.

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)

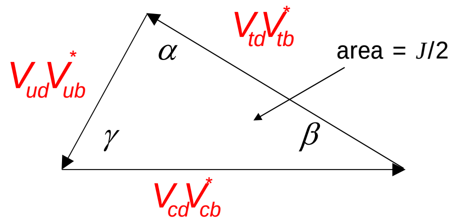
Strength of CPV: Characterized by Jarlskog invariant: $J = \mathrm{Im}\left(V_{ij}V_{kl}V^*_{il}V^*_{kj}\right) \neq 0$

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

3.3 Unitarity Triangle

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

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



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

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

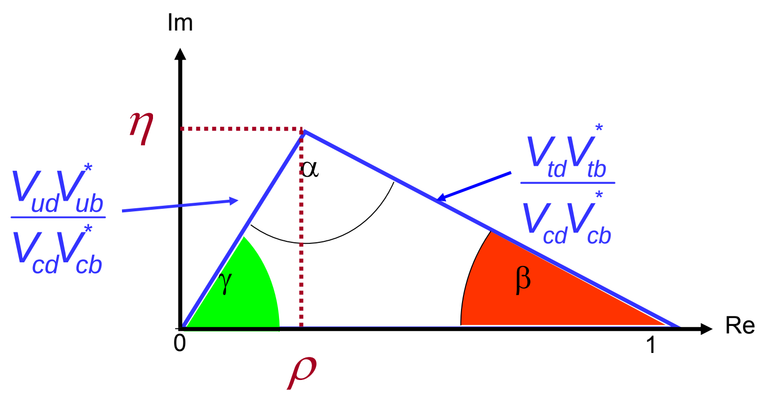
$$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0$$

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

Remaining 4 relations lead to degenerated triangles: same area (J/2) but very different sides.

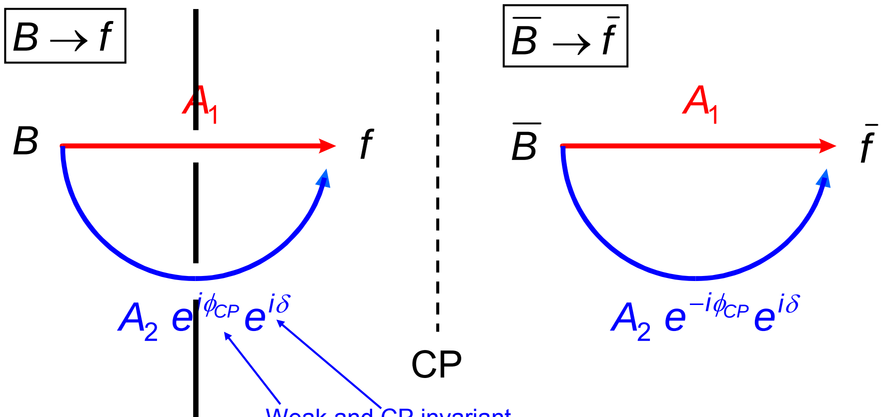
Rescaled Unitarity Triangle

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



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

3.4 Observation of CP Violation



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

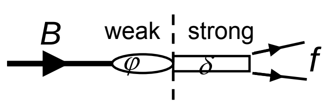
$$|\bar{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} - \delta)$$

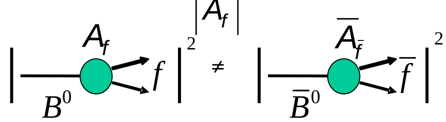
Need two phase differences between A_1 and A_2: Weak difference which changes sign under CP and another phase difference (strong) which is unchanged.

"3 Ways" of CP violation in meson decays

a) Direct CP violation

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



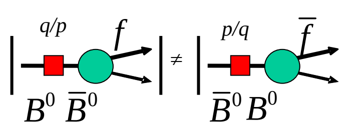


$$A(B \to f) = |A|\, e^{i\varphi}\, e^{i\delta}$$

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

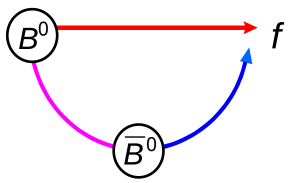
b) CP violation in mixing

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



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

c) CP violation through interference of mixed and unmixed amplitudes

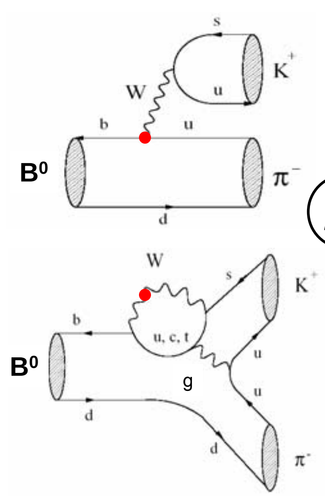


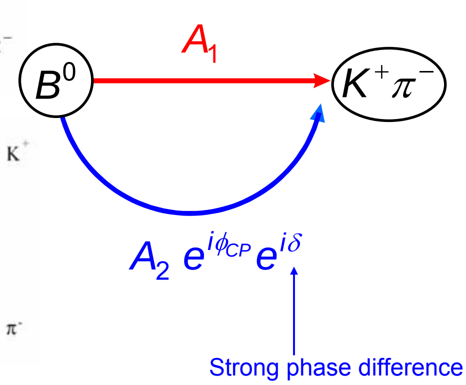
$$\Gamma(B^0_{t=0} \to f)(t) \neq \Gamma(\overline{B}^0_{t=0} \to f)(t)$$

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

Combinations of the 3 ways are possible!

a) Direct CP violation (B system)





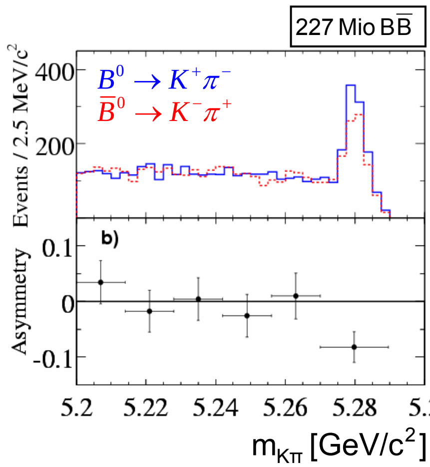
CP Asymmetrie $\quad |\overline{A}|^2 - |A|^2 = 4|A_1||A_2| \sin\varphi \sin\delta$

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

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

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

4.2σ



PRL93(2004) 131801.

b) CP (T) violation in mixing

T violation

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

$$\eta_m \equiv \frac{q}{p} = \frac{1-\varepsilon}{1+\varepsilon}$$

Reminder:

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

$$A(t) = \frac{P(\overline{B}^0 \to B^0)(t) - P(B^0 \to \overline{B}^0)(t)}{P(\overline{B}^0 \to B^0)(t) + P(B^0 \to \overline{B}^0)(t)} = \frac{1-|q/p|^4}{1+|q/p|^4} \approx \frac{4\,\mathrm{Re}\,\varepsilon}{1+|\varepsilon|^2} \approx 4\,\mathrm{Re}\,\varepsilon$$

Measured using semileptonic decays

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

$$A_{SL}(t) = \frac{\Gamma(\overline{B}^0_{t=0} \to \overset{B^0}{X\ell^+\nu})(t) - \Gamma(B^0_{t=0} \to \overset{\overline{B}^0}{X\ell^-\overline{\nu}})(t)}{\Gamma(\overline{B}^0_{t=0} \to X\ell^+\nu)(t) + \Gamma(B^0_{t=0} \to X\ell^-\overline{\nu})(t)}$$

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

HFAG 2004

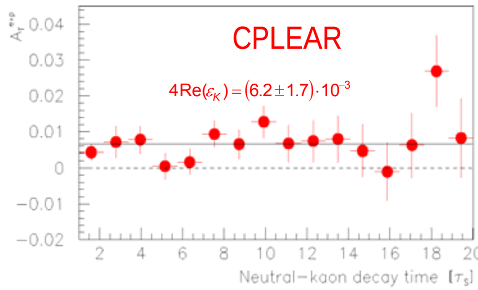
$$A_{SL} = -0.0026 \pm 0.0067$$
$$\left|\frac{q}{p}\right| = 1.0013 \pm 0.0034$$
$$4\,\mathrm{Re}\,\varepsilon_B = -0.0007 \pm 0.0017$$

Standard model prediction for B

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

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

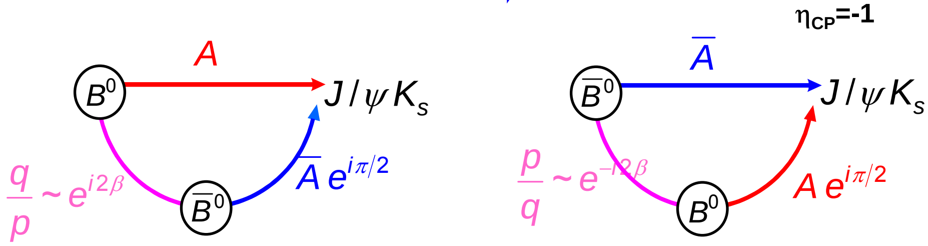
$$A^{exp}(t) = \frac{\Gamma(\bar{K}^0_{t=0} \to e^+\pi^-\nu_e) - \Gamma(\overbrace{K^0_{t=0}}^{K^0} \to e^-\pi^+\bar{\nu}_e)}{\Gamma(\bar{K}^0_{t=0} \to e^+\pi^-\nu_e) - \Gamma(K^0_{t=0} \to e^-\pi^+\bar{\nu}_e)}(t)$$



c) CP violation in interference between mixing and decay

$$B^0 \to J/\psi K_s \quad \xrightarrow{CP} \quad \bar{B}^0 \to J/\psi K_s$$

η_{CP}=-1

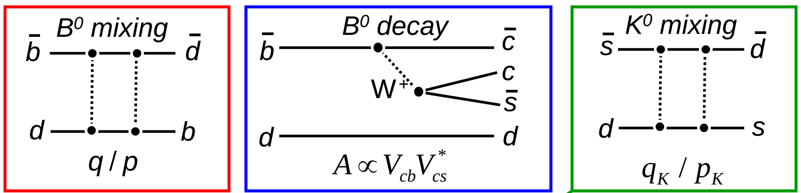


$$\Gamma(B^0 \to J/\psi K_s)(t) \neq \Gamma(\bar{B}^0 \to J/\psi K_s)(t)$$

Important variable: $\lambda_{CP} \equiv \frac{q}{p}\cdot\frac{\bar{A}}{A}$

SM prediction of λ_{CP} for $B^0 \to J/\psi K_S$

$\eta_{CP} = -1$



Same for all ccK⁰ channels

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

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

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

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

$$\neq$$

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

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

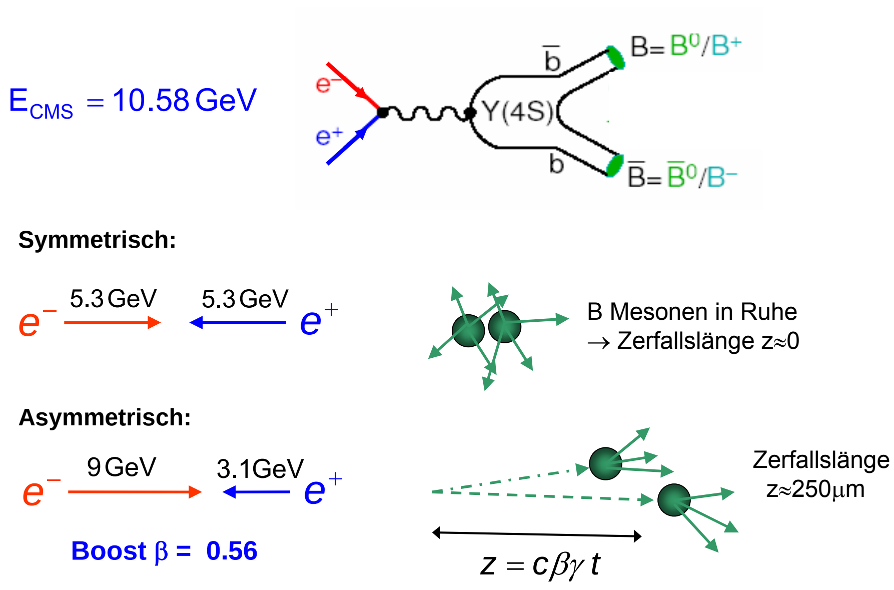
Time resolved

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

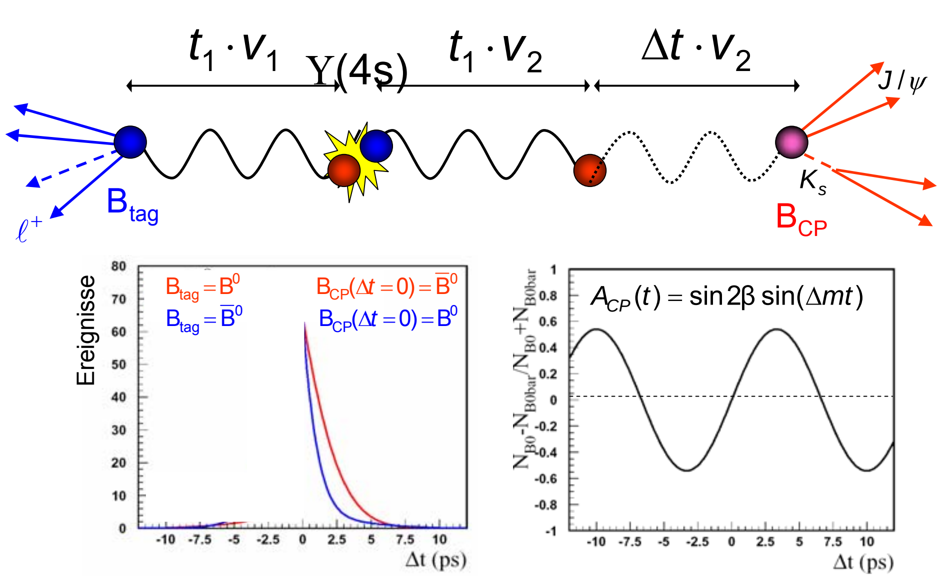
Interference = $\sin 2\beta$ for $B^0 \to J/\psi K_S$

indicates direct CP violation if $|q/p| \neq 1$

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

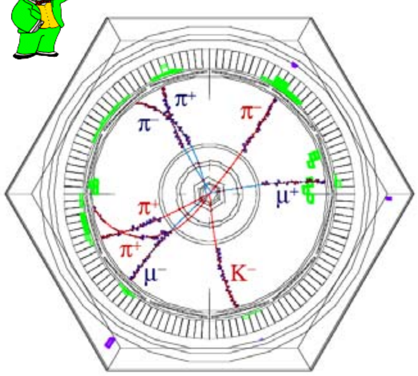


Measurement of sin2β: Coherent oszillation



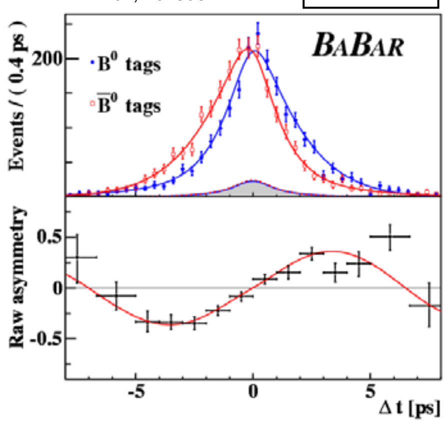
Measurement of sin2β: Golden decay channel

$B^0 \rightarrow \psi K_s$



PRL 94, 161803.

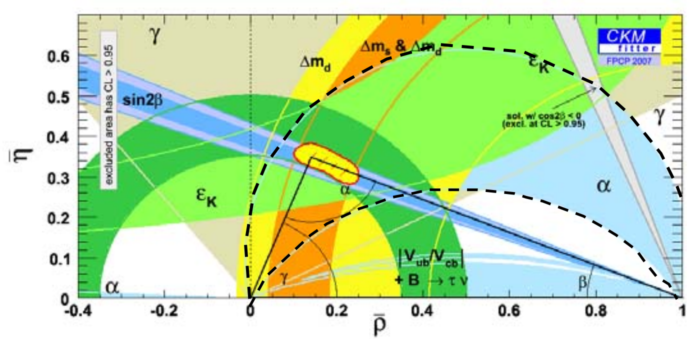
227 Mio $B\bar{B}$



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

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

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

A triple triumph

3.6 Baryon asymmetry in the universe

Does the Standard Model explain the baryon symmetry in universe?

Andrei D. Sakharov, 1967

- **Baryon number violation** **No**
- **C and CP Violation** **No**
- **Departure from thermal equilibrium**

- **CP violation in quark sector is a factor ~10^{10} to small.**
- **for M_{Higgs}> 114 GeV: Symmetry breaking = 2nd order phase transition**

Attractive: Super-symmetric extensions of Standard Model

- **Additional CP violation through supersymmetric particles**
- **Extended Higgs-sector → strong phase transition**

Alternative: Lepto-genesis