CP Violation in B- and K-Meson Systems

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Outline

- Motivation
- CP violation in the standard model
- Types of CP violation
- CP violation in the B^0-System
  - Comparison with K^0-System
- Determination of ε'/ε, δ
- B-Factories
- Determination of $\sin 2\beta$, $\sin 2\alpha_{eff}$, $Re(\varepsilon_B)$
- Conclusion and Outlook

CP-Violation in the Standard Model

Standard model: Origin of CP-Violation: Higgs-Sector!

⇨ Quark-Mass-Mixing matrix

⇨ Cabibbo Kobayashi Maskawa (CKM) Matrix

Relates mass eigenstates to weak eigenstates

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

~~CP~~

- complex
- unitary
  - 4 parameters: 3 real Euler angles, 1 Phase

~~CP~~

- characterized by J (Jarlskog invariant)

$$J = \operatorname{Im}\left(V_{ik} V_{jk}^{*} V_{j\ell} V_{i\ell}^{*}\right) \neq 0$$

$$J_{\max} = \frac{1}{6\sqrt{3}} \approx 0.1 \qquad J_{SM} \leq 4 \cdot 10^{-5} \Rightarrow$$

~~CP~~$_{CKM}$ **small**

Too small to explain matter-antimatter asymmetry in the universe($O(10^8)$)

Origin of CP-Violation?

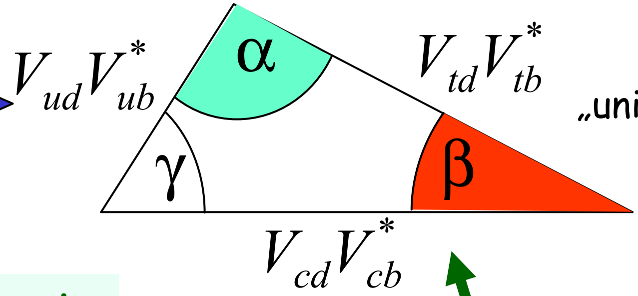
Standard Model: Phase of CKM-matrix
⇒Test Standard Model: determine phase
⇒Test unitarity of CKM matrix
⇒Test for New Physics

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

Unitarity: derive 6 relations → 6 triangles in complex plane with area J/2

e.g.

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

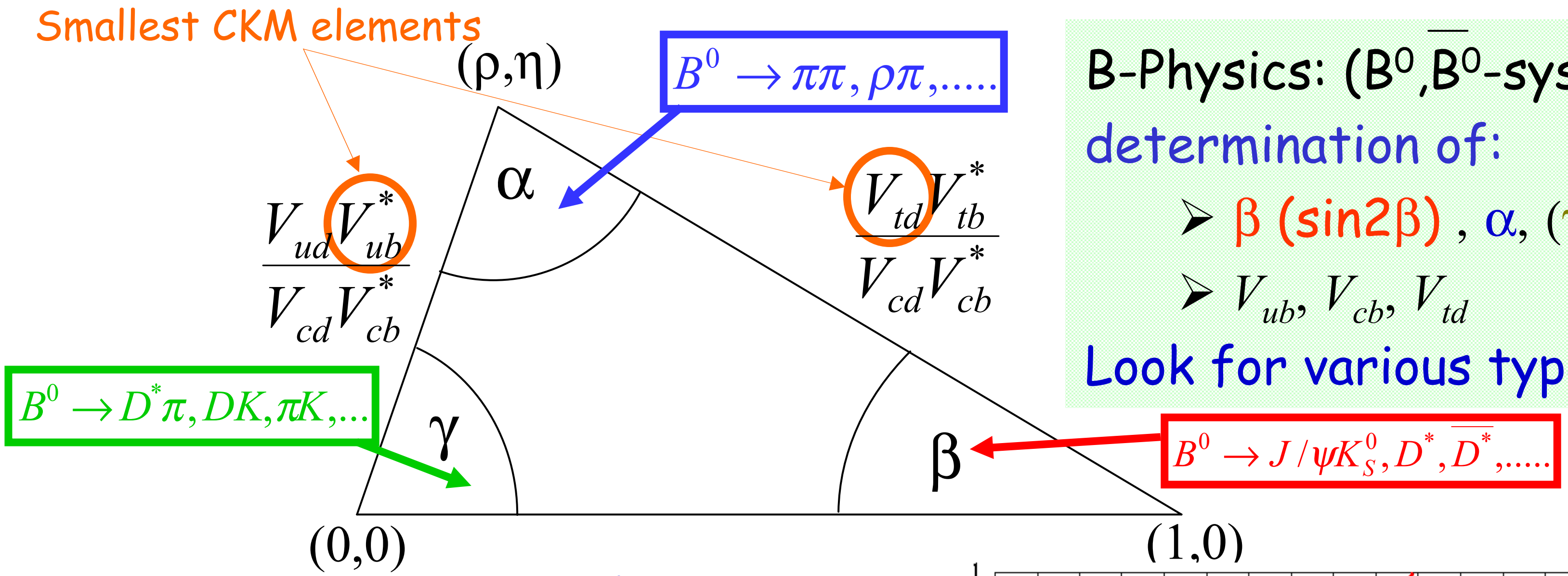


„unitarity triangle"

Unitarity Test ⇒ overconstrain triangle
- measure sides and angles
- need triangle with ≈ equal side length ⇒ large angles
- only 2 triangles qualify
  - not fully accessible to K-Physics
  - 1 fully accessible to B-Physics

„B"-triangle

CP-Violation and B-Physics



B-Physics: (B^0,$\overline{B^0}$-system, $B^\pm$)

determination of:

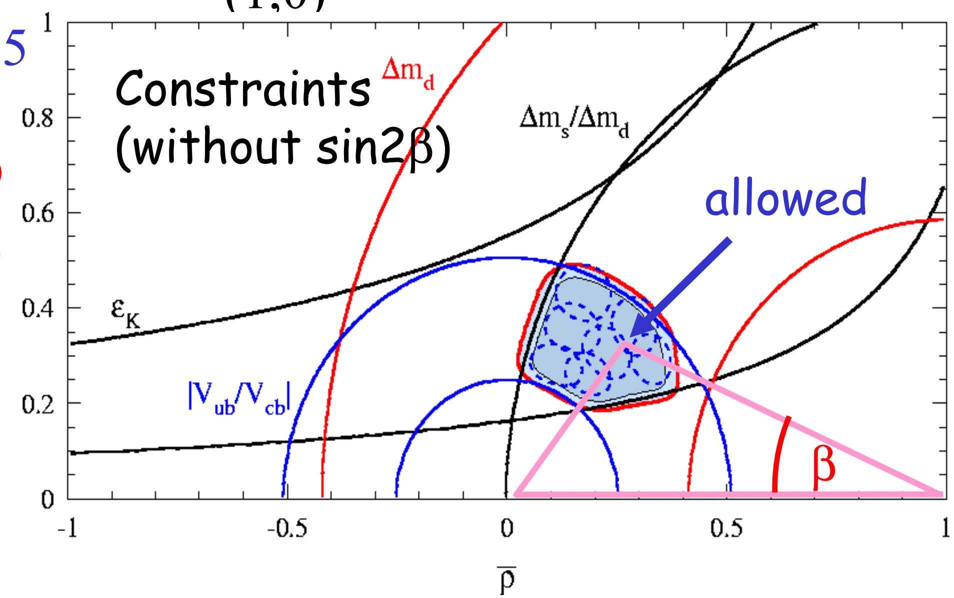
- β (sin2β) , α, (γ)
- V_{ub}, V_{cb}, V_{td}

Look for various types of ~~CP~~

Wolfenstein parametrisation: $\lambda \approx \sin\theta_C$, $A \approx 0.85$

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

$$\bar{\rho} = \left(1-\lambda^2/2\right)\rho\,, \quad \bar{\eta} = \left(1-\lambda^2/2\right)\eta$$



Assume **CPT** is conserved

CP Violation

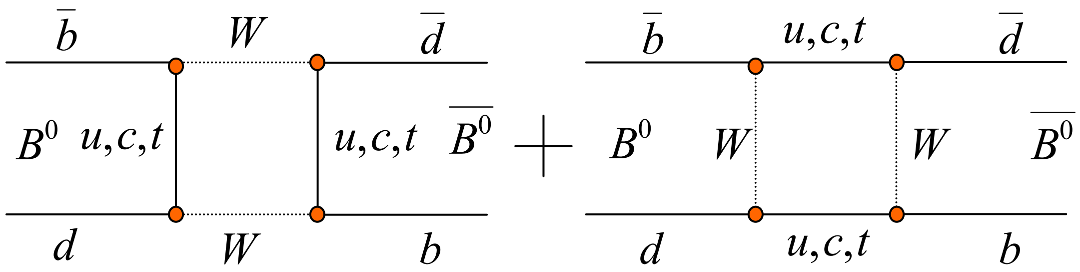
Three types of CP-Violation:

- CP-Violation in Decay → „Direct“ CP Violation
  - ⇨ Charged and neutral decays

K^0 – System $\frac{\varepsilon'}{\varepsilon}$

$$\Gamma(A \rightarrow B) \neq \Gamma(\overline{A} \rightarrow \overline{B})$$

- CP-Violation in Mixing → „Indirect“ CP Violation
  - ⇨ Neutral decays K^0, B^0 ⇒ particle ⇔ antiparticle oscillations



$$\Gamma(K^0 \rightarrow \overline{K^0}) \neq \Gamma(\overline{K^0} \rightarrow K^0)$$

- CP-Violation in Interference between Decays with and without Mixing
  - ⇨ neutral B-meson-system: e.g. sin2β measurement with BABAR

Note on the K-System

$K^0, \overline{K^0}$ Decay amplitudes dominated by the 2π decay.
⇒ i.e. by the the I=0 amplitude
⇒ mixing dominated by same decay mode $K^0 \longrightarrow \pi\pi \longrightarrow \overline{K^0}$
⇒ CP violation in mixing, interference mixing ↔ decay ⇒ε

Note: I=0 and I=2 amplitude have different phases
⇒ direct CP-violation ⇒ε' <<ε

⇒ ~~C~~P in K-system described by two parameters

⇒ ε, ε'

ε: komplex, arg(ε)≈45^0 (unitarity, I=0 dominates)

$$\varepsilon = \frac{\langle \pi\pi, I=0 | T | K_L \rangle}{\langle \pi\pi, I=0 | T | K_S \rangle}$$

$$\eta_{+-} = \frac{\langle \pi^+\pi^- | T | K_L \rangle}{\langle \pi^+\pi^- | T | K_S \rangle} \approx \varepsilon + \varepsilon'$$

$$\eta_{00} = \frac{\langle \pi^0\pi^0 | T | K_L \rangle}{\langle \pi^0\pi^0 | T | K_S \rangle} \approx \varepsilon - 2\varepsilon'$$

$$\delta_L \approx 2\mathrm{Re}(\varepsilon) = \frac{\Gamma(K_L \to e^+\pi^-\nu_e) - \Gamma(K_L \to e^-\pi^+\overline{\nu_e})}{\Gamma(K_L \to e^+\pi^-\nu_e) - \Gamma(K_L \to e^-\pi^+\overline{\nu_e})}$$

Oscillations/Mixing

$B^0\overline{B^0}$ – Oscillations :

⇒ mass eigenstates:

$$\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\overline{B^0}\right\rangle$$
$$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B^0}\right\rangle$$

$$\left|K_S\right\rangle = p\left|K^0\right\rangle + q\left|\overline{K^0}\right\rangle \equiv \text{"}\left|K_L\right\rangle\text{"}$$
$$\left|K_L\right\rangle = p\left|K^0\right\rangle - q\left|\overline{K^0}\right\rangle \equiv \text{"}\left|K_H\right\rangle\text{"}$$

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

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

$\Rightarrow B_H$ and B_L with Δm and $\Delta\Gamma$ ($m_H > m_L$, sign of $\Delta\Gamma$ not defined)

up to here, formalism is identical for K and B-systems:
BUT: $\Delta\Gamma$ is negligible in the B system but significant in the K-system!
⇒Kaons: define eigenstates by lifetime: K_S, K_L

CP Violation in Mixing

Since 1964 known: $\left|\frac{q}{p}\right| \neq 1 \quad \Rightarrow$ CP violation (very small effect)

Mass eigenstates:
$$\left|K_S^0\right\rangle = \frac{1}{\sqrt{1+\left|\varepsilon_m\right|^2}}\left(\left|K_1^0\right\rangle + \varepsilon_m\left|K_2^0\right\rangle\right)$$
$$\left|K_L^0\right\rangle = \frac{1}{\sqrt{1+\left|\varepsilon_m\right|^2}}\left(\left|K_2^0\right\rangle + \varepsilon_m\left|K_1^0\right\rangle\right)$$

with $\boxed{\varepsilon_m = \frac{p-q}{p+q}, \quad \frac{q}{p} = \frac{1-\varepsilon_m}{1+\varepsilon_m}}$ $\mathrm{Im}\,\varepsilon_m, \frac{q}{p}$: unobservable

K-system: CP violation: small effect $\Rightarrow \mathrm{Re}\,\varepsilon_m << 1 \Rightarrow \left|\frac{q}{p}\right| \cong 1 - 2\mathrm{Re}(\varepsilon_m)$

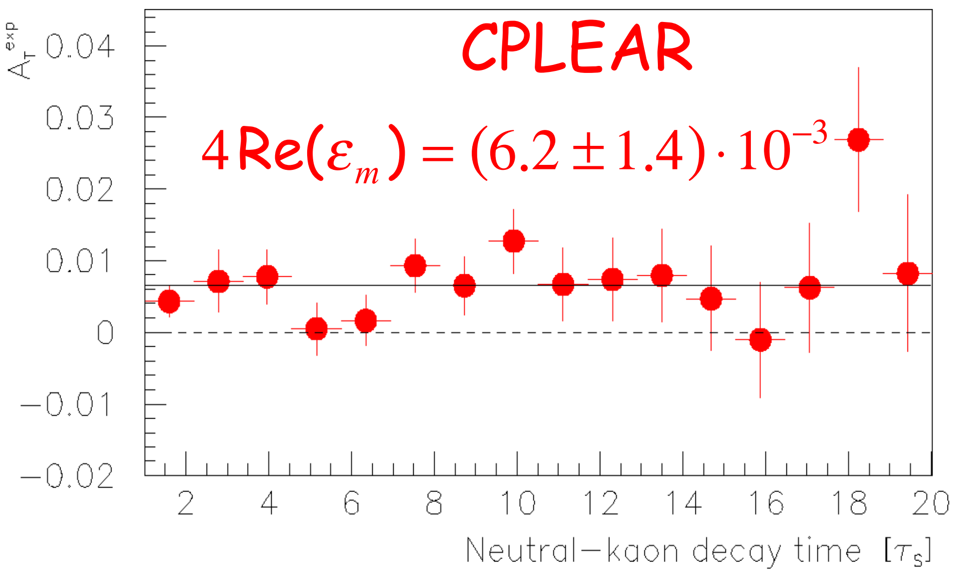
$\boxed{\mathrm{Re}(\varepsilon) = \mathrm{Re}(\varepsilon_m)}$

observable

CP-Violation in $K^0\overline{K^0}$ -Mixing

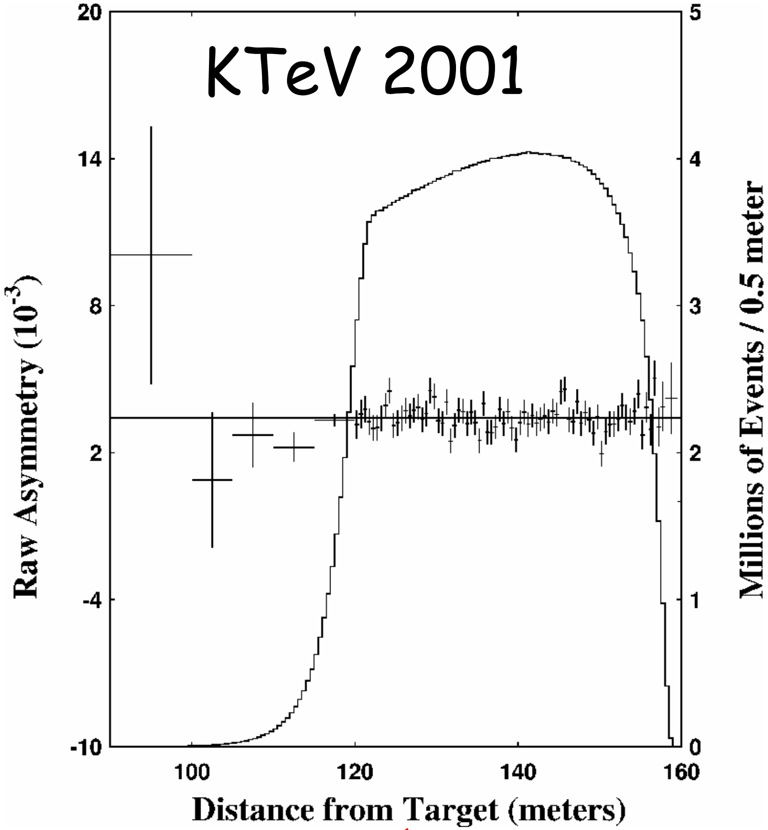
$$\frac{P(\overline{K^0}\rightarrow K^0)-P(K^0\rightarrow\overline{K^0})}{P(\overline{K^0}\rightarrow K^0)+P(K^0\rightarrow\overline{K^0})}\cong\frac{4\mathrm{Re}(\varepsilon_m)}{1+|\varepsilon_m|^2}\cong 4\mathrm{Re}(\varepsilon_m)$$

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

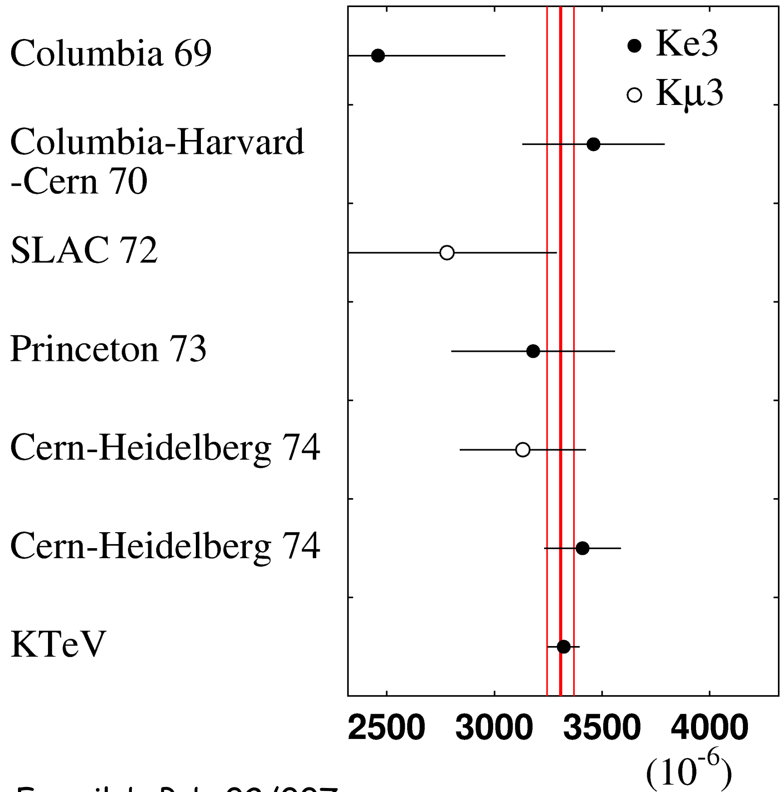


CP-Violation in $K^0\overline{K^0}$ -Mixing

$$A_{CP} = \frac{\Gamma(K_L \to e^+\pi^-\nu_e) - \Gamma(K_L \to e^-\pi^+\overline{\nu_e})}{\Gamma(K_L \to e^+\pi^-\nu_e) - \Gamma(K_L \to e^-\pi^+\overline{\nu_e})} = \delta_L \approx 2\,\mathrm{Re}(\varepsilon)$$



$$2\,\mathrm{Re}(\varepsilon_m) = \delta_L\left(3.322 \pm 0.074\right)\cdot 10^{-3}$$



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Direct CP Violation

Consider decay amplitudes for a decays into final state f

e.g. $B \to f \Rightarrow$ amplitude A
$\overline{B} \to \overline{f} \Rightarrow$ amplitude $\overline{A}_{\overline{f}}$

$\Rightarrow$ if $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$ $\Rightarrow$ CP violation
$\Rightarrow$ Prob$(\overline{B} \to \bar{f}) \neq$ Prob$(B \to f)$

Several possible contributions i to A_f and $\overline{A}_{\overline{f}}$
with magnitude A_i, weak phase $e^{i\phi}$ and strong phase $e^{i\delta}$
Transformations under CP: $e^{i\phi} \to e^{-i\phi}$ and $e^{i\delta} \to e^{i\delta}$

$$\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| = \left|\frac{\sum_i A_i e^{i(\delta_i - \phi_i)}}{\sum_i A_i e^{i(\delta_i + \phi_i)}}\right| \Rightarrow \left|A_f\right|^2 - \left|\overline{A}_{\overline{f}}\right|^2 = -2\sum_{i,j} A_i A_j \underbrace{\sin(\phi_i - \phi_j)}\underbrace{\sin(\delta_i - \delta_j)}$$

weak & strong phases

Direct CP violation requires ≥ 2 different contributions with different weak phases and different strong phases

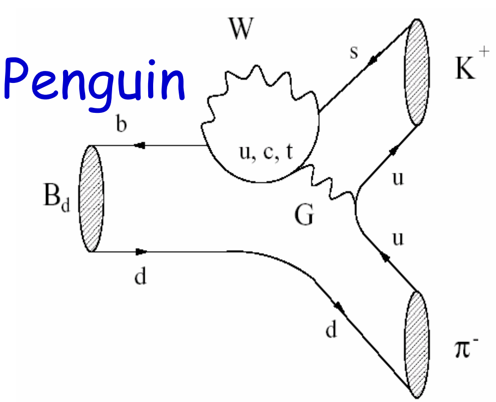
For neutral modes, direct ~~CP~~ competes with other types of CP violation

Direct CP Violation

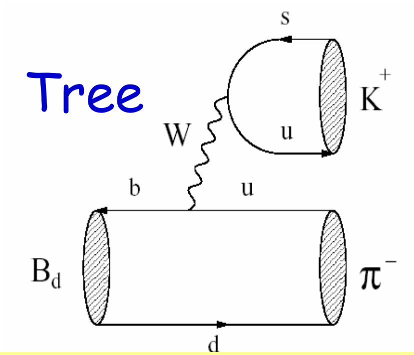
Example: $B \to K^+\pi^-$

$$A_{CP} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \propto 2 A_1 A_2 \sin(\phi_1 - \phi_2) \sin\underbrace{(\delta_1 - \delta_2)}_{\text{Tough to calculate}}$$

Penguin



Tree



Expect significant interference of tree and penguin amplitudes

Similar diagrams for $B \to \pi^+\pi^-$

Status: in B-System, direkt CP-violation not yet observed big challenge!!

in K-System, direkt CP-violation observed $\Rightarrow \frac{\varepsilon'}{\varepsilon}$ NA31, NA48, KTeV

(note, that difference between I=0 and I=2 amplitudes is here responsible for direct $\not{C}$P)

Measurement of ε'/ε

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

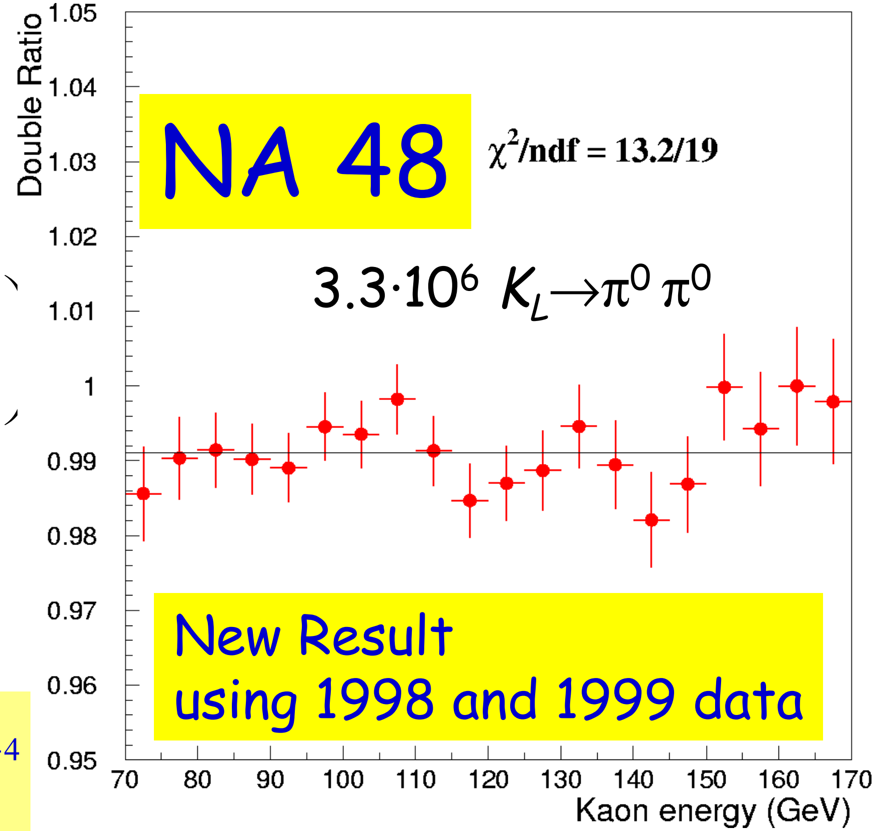
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

Measure

$$R = \frac{\dfrac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)}}{\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} \cong 1 - 6 \cdot \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

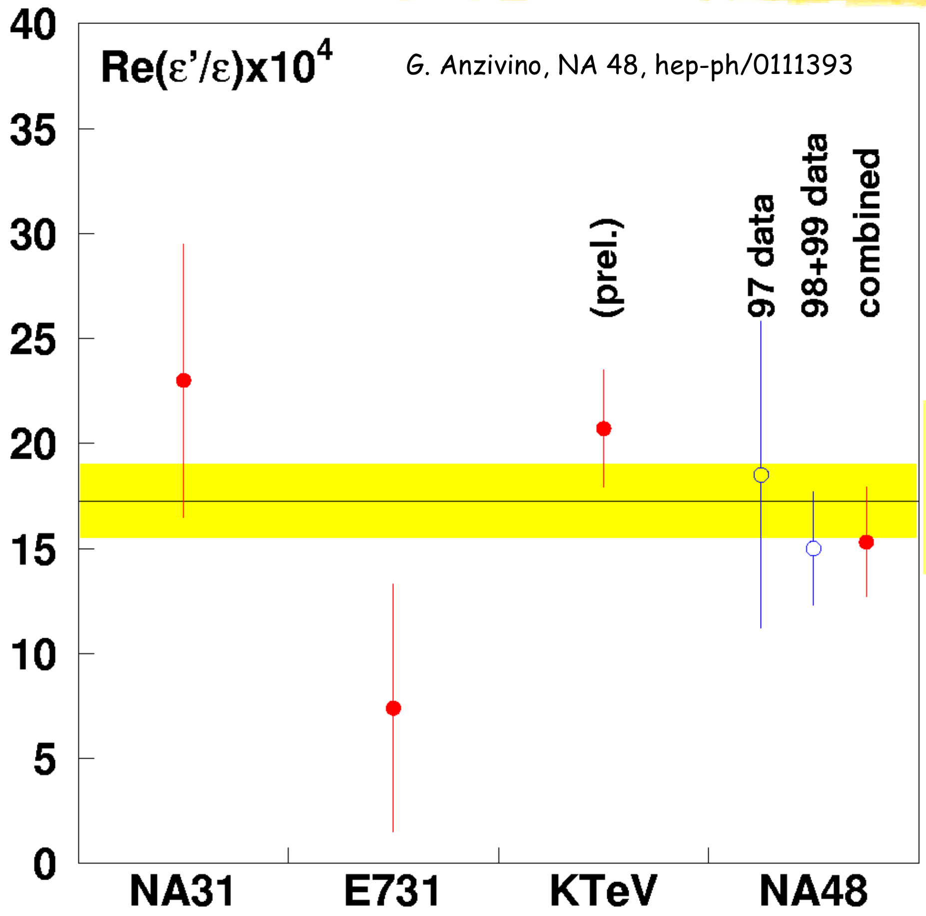
$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (15.0 \pm 1.7 \pm 2.1) \cdot 10^{-4}$$

$$\Rightarrow \langle \text{NA 48} \rangle: \quad \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (15.3 \pm 2.6) \cdot 10^{-4}$$



Eur. Phys. J C 22, 231 (2001)

Measurements of ε'/ε



KTeV 2001: Lepton Photon (2001)
„reanalysis of 1997 data"

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (20.7 \pm 2.8) \cdot 10^{-4}$$

$$\Rightarrow \mathrm{WA}: \quad \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (17.2 \pm 1.8) \cdot 10^{-4}$$

- Long standing discrepancy settled
- Direct CP-violation established

However:
Further conclusions wrt to SM hardly possible.

~~CP~~ in Interference between Mixing and Decay

Consider decays into CP-eigenstates $f_{CP} \Rightarrow$ define $\lambda_{CP} = \dfrac{q}{p}\dfrac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{CP}\,\dfrac{q}{p}\dfrac{\overline{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$

Oscillation

Decay

CP-eigenvalue of f_{CP}

λ_{CP} : Observable in modulus and phase !

$$
\begin{tikzcd}
 & \overline{B}^0 \arrow[dr] & \\
B^0 \arrow[ur] \arrow[rr] & & f
\end{tikzcd}
$$

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

$$A_{f_{CP}} = |A| e^{i\phi_A} e^{i\delta_A}$$

$$\overline{A}_{\bar{f}_{CP}} = \eta_{CP} \left|\overline{A}\right| e^{-i\phi_A} e^{i\delta_A}$$

Mixing Phase

Weak Decay Phase

$$\boxed{\lambda_{CP} = -\eta_{CP} \cdot \left|\frac{q}{p}\right| \cdot \left|\frac{\overline{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right| \cdot e^{2i(\phi_M - \phi_A)}}$$

$\cancel{CP}$ in Interference between Mixing and Decay

Define:

$$\varepsilon_f = \frac{1-\lambda_{CP}}{1+\lambda_{CP}} \quad \Leftrightarrow \quad \lambda_{CP} = \frac{1-\varepsilon_f}{1+\varepsilon_f}$$

K-Language

$$A_{CP}(t) = \frac{\dot{N}\left(K^0 \to f_{CP}\right) - \dot{N}\left(\overline{K^0} \to f_{CP}\right)}{\dot{N}\left(K^0 \to f_{CP}\right) + \dot{N}\left(\overline{K^0} \to f_{CP}\right)}$$

$$= \frac{2e^{\frac{-(\Gamma_S+\Gamma_L)}{2}t} \cdot \left(\mathrm{Re}(\varepsilon_f)\cos(\Delta m t) + \mathrm{Im}(\varepsilon_f)\sin(\Delta m t)\right)}{e^{-\Gamma_S t} + \left|\varepsilon_f\right|^2 e^{-\Gamma_L t}}$$

$$= \frac{2e^{\frac{-(\Gamma_S+\Gamma_L)}{2}t} \cdot \left(\left|\varepsilon_f\right| \cos(\Delta m t - \phi(\varepsilon_f))\right)}{e^{-\Gamma_S t} + \left|\varepsilon_f\right|^2 e^{-\Gamma_L t}}$$

~~CP~~ in Interference between Mixing and Decay

$$A_{CP}(t) = -A_{+-} = \frac{\dot{N}\left(K^0 \to \pi^+\pi^-\right) - \dot{N}\left(\overline{K^0} \to \pi^+\pi^-\right)}{\dot{N}\left(K^0 \to \pi^+\pi^-\right) + \dot{N}\left(\overline{K^0} \to \pi^+\pi^-\right)}$$

here: K-System

with $\lambda_{CP} \neq 1$

$$= \frac{2|\eta_{+-}| e^{\frac{-(\Gamma_S+\Gamma_L)}{2}t} \cdot (\cos(\Delta m t - \varphi_{+-}))}{e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t}}$$

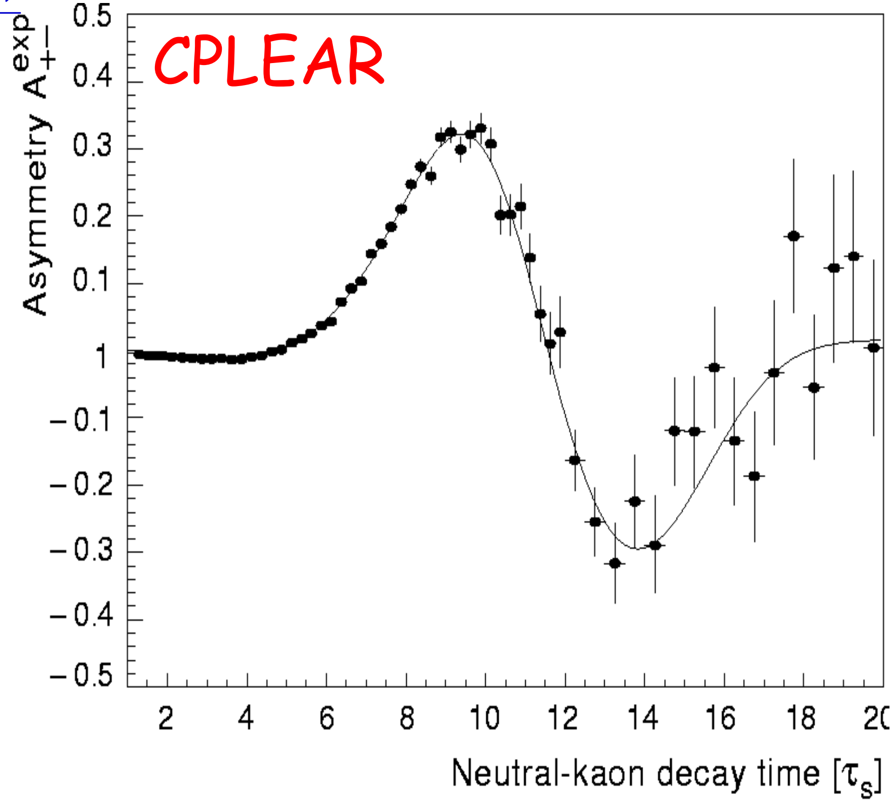
$$\varepsilon_f = \eta_{+-} \checkmark$$

$$\eta_{+-} = |\eta_{+-}| \cdot e^{i\varphi_{+-}} = \frac{\langle \pi^+\pi^- | T | K_L \rangle}{\langle \pi^+\pi^- | T | K_S \rangle}$$

PDG 2000:

$$|\eta_{+-}| = (2.276 \pm 0.017) \cdot 10^{-3}$$

$$\phi_{+-} = (43.3 \pm 0.5)^0$$



$\cancel{CP}$ in Interference between Mixing and Decay

B-Language

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

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

$$A_{CP}(t) = \frac{\dot{N}\left(\overline{B^0} \to f_{CP}\right) - \dot{N}\left(B^0 \to f_{CP}\right)}{\dot{N}\left(\overline{B^0} \to f_{CP}\right) + \dot{N}\left(B^0 \to f_{CP}\right)} = \frac{\left(1-|\lambda_{CP}|^2\right)\cos(\Delta m_d t) - 2\,\mathrm{Im}(\lambda_{CP})\sin(\Delta m_d t)}{\left(1+|\lambda_{CP}|^2\right)}$$

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

Interference

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

$$\lambda_{CP} = -\eta_{CP} \cdot \underbrace{\left|\frac{q}{p}\right| \cdot \left|\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right|}_{\approx 1} \cdot e^{2i(\phi_M - \phi_A)} \approx -\eta_{CP} \cdot e^{2i(\phi_M - \phi_A)}$$

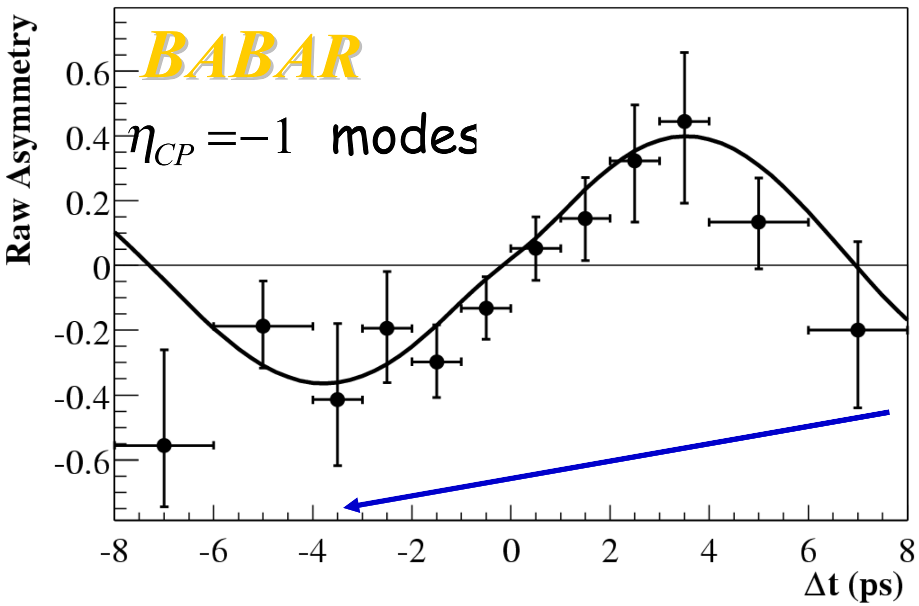
$$\varepsilon_f = \frac{1-\lambda_{CP}}{1+\lambda_{CP}} \quad \Rightarrow \mathrm{Re}(\varepsilon_f) = 0$$

$$A_{CP}(t) = \frac{\dot{N}\left(\overline{B^0} \to J/\psi K_S^0\right) - \dot{N}\left(B^0 \to J/\psi K_S^0\right)}{\dot{N}\left(\overline{B^0} \to J/\psi K_S^0\right) + \dot{N}\left(B^0 \to J/\psi K_S^0\right)}$$

$$= -\eta_{CP} \sin 2\underbrace{(\phi_M - \phi_A)}\sin(\Delta m t)$$

$B^0 \to J/\psi K_S$: β

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$



$\Delta t<0$!

due to $\Upsilon(4S)$ properties!

$B^0 \to J/\psi K_S \leftrightarrow K^0 \to \pi\pi$

$B^0 \to J/\psi K_S$: „golden channel", more channels available

CP Violation ($\lambda_{CP} \neq 1$): 3 possible mechanisms

1. $|q/p| \neq 1$
   Kaons: small effect (ε_m) – described by ε
   B-Mesons: small effect in SM ($|q/p| \approx 1$)
2. $|\bar{A}/A| \neq 1$
   Kaons: very small effect (ε')
   B-Mesons: 0 (diagrams for $B^0 \to J/\psi K_S$ have same phase)
3. $\phi_M - \phi_A \neq 0$
   Kaons: small effect ($Re(\varepsilon_0) = Re(\varepsilon_m) \approx Re(\varepsilon_f)$) - described by ε
   B-Mesons: SM: large phase difference ($\phi_M - \phi_{A\beta}$) $\to \beta$

Kaons: All 3 effects: small but contribute – described by ε, ε'
Branching ratio large

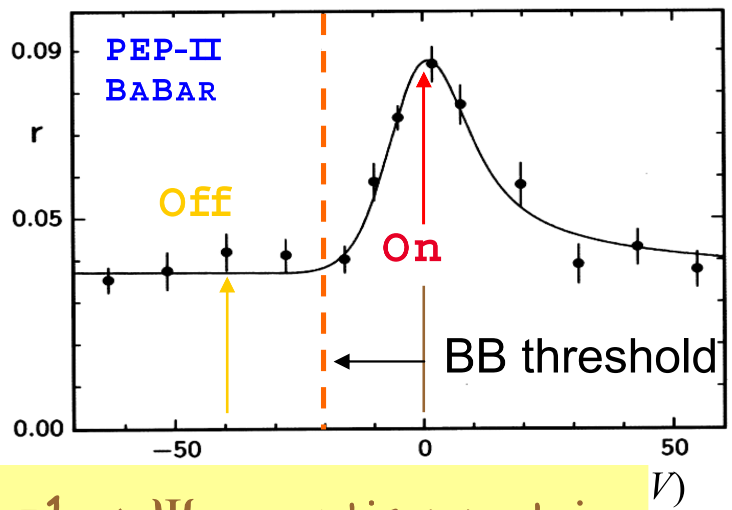
B-Mesons: dominated by interference between mixing and decay
Branching ratio tiny ($BR \approx 4 \cdot 10^{-4}$)

B-Mesons at the Υ(4S)

production: $b\bar{b}$-resonance, m $\approx 10.58\,\mathrm{GeV}$

$$e^+e^- \to \Upsilon(4S) \to B^+B^-(50\%)$$
$$B^0\overline{B^0}(50\%)$$

Υ(4S) Energy Scan



Υ(4S) restframe: p(B) ≈ 0 (approx. 340 MeV)
⇒coherent BB system with L=1

2 bosons ⇒ symmetric wavefunction

$$\Psi = \Psi_{Flavour} \cdot \Psi_{space}$$

L=1 ⇒ Ψ_{space} antisymmetric

$$\Psi_{Flavour} = \frac{1}{\sqrt{2}}\left(B^0\overline{B^0} - \overline{B^0}B^0\right)$$

cannot distinguish between B and $\overline{\mathrm{B}}$ until a B decays into non CP eigenstate!
⇒ decay defines t_0=0!

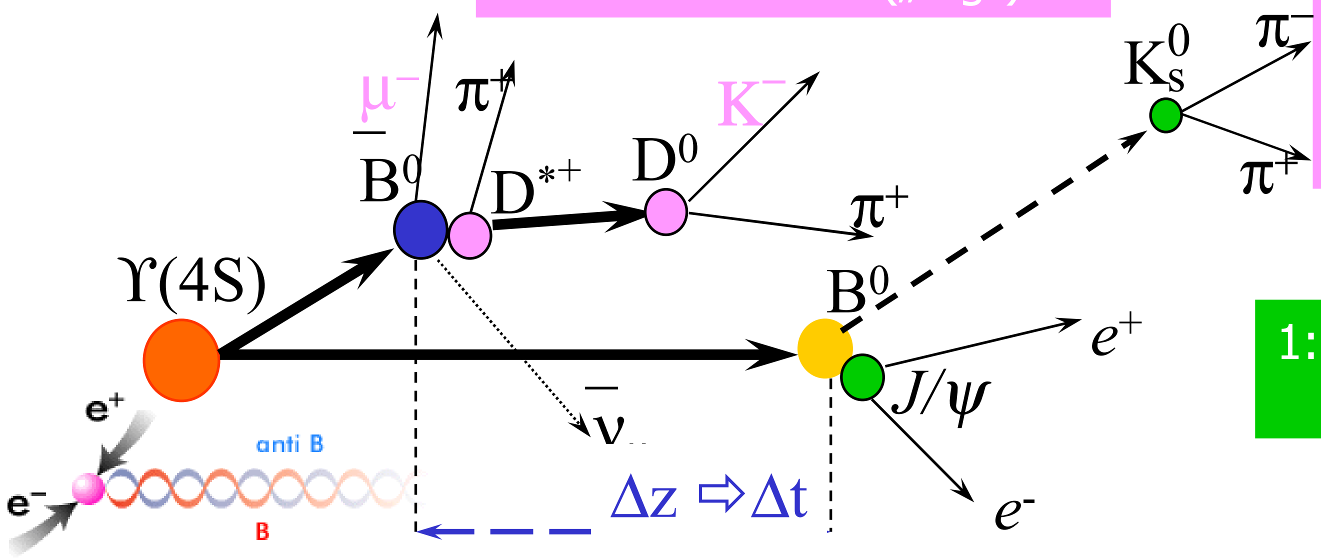
Δt may be positive or negative. With $|\lambda_{CP}|\approx 1 \Rightarrow \int A_{CP}dt = -\eta_{CP}\int \sin 2\beta \sin(\Delta m t)dt = 0$
⇒time resolved asymmetry measurement necessary!
⇒Boost of Υ(4S) system! ⇒determine Δt from Δz (in boost direction)
PEP-II/BABAR: βγ=0,55 ⇒ $\beta\gamma c\,\tau_B \approx 260\ \mu m \Rightarrow \langle\Delta z\rangle \approx 260\mu m$

Measurement of sin2β

$$\tilde{A}(\Delta\tilde{t}) = \frac{\Gamma\left(\overline{B^0} \to J/\psi K_S^0\right) - \Gamma\left(B^0 \to J/\psi K_S^0\right)}{\Gamma\left(\overline{B^0} \to J/\psi K_S^0\right) + \Gamma\left(B^0 \to J/\psi K_S^0\right)} = \mathrm{D} \cdot \sin 2\beta \cdot \int \sin(\Delta m \Delta t) \cdot \mathrm{R}\,(\Delta\tilde{t} - \Delta t)\, d\Delta t$$

2: Flavour-determination of other B meson („tag")

3: Determination of mistag fraction w
$\Rightarrow$Dilution D: D = $(1-2w)$ reduces visible asymmetry



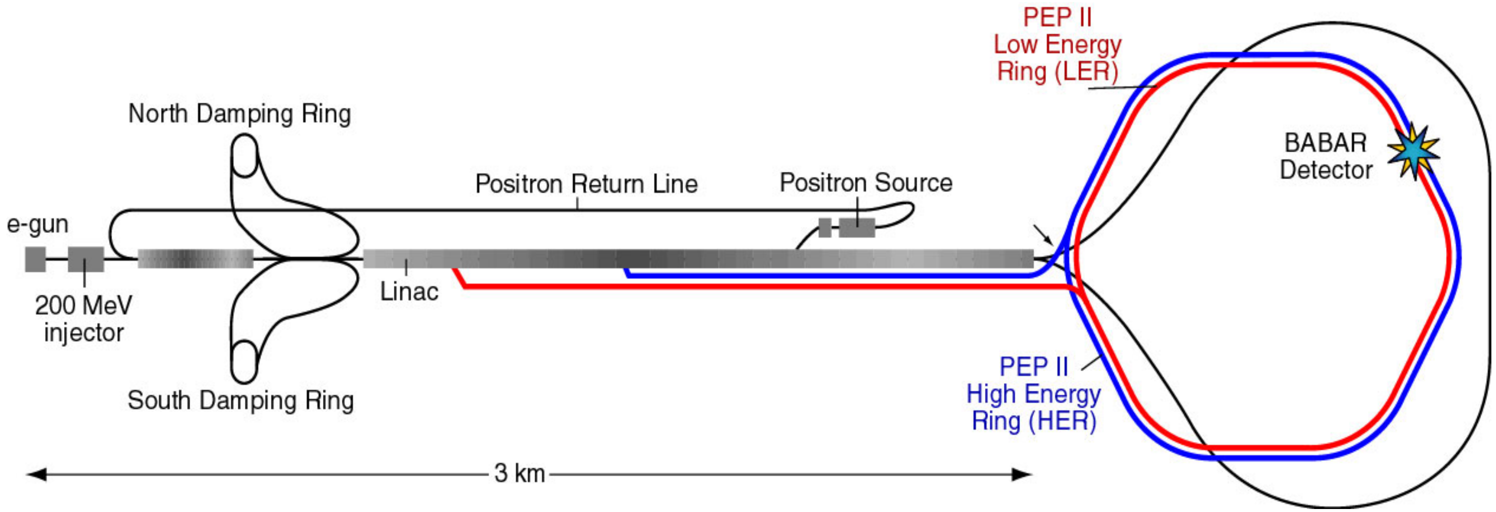
1: Reconstruction of CP eigenstates

4: Determination of $\Delta t = \Delta z/\beta\gamma c$

5: Determination of Δz (Δt) resolution funktion R

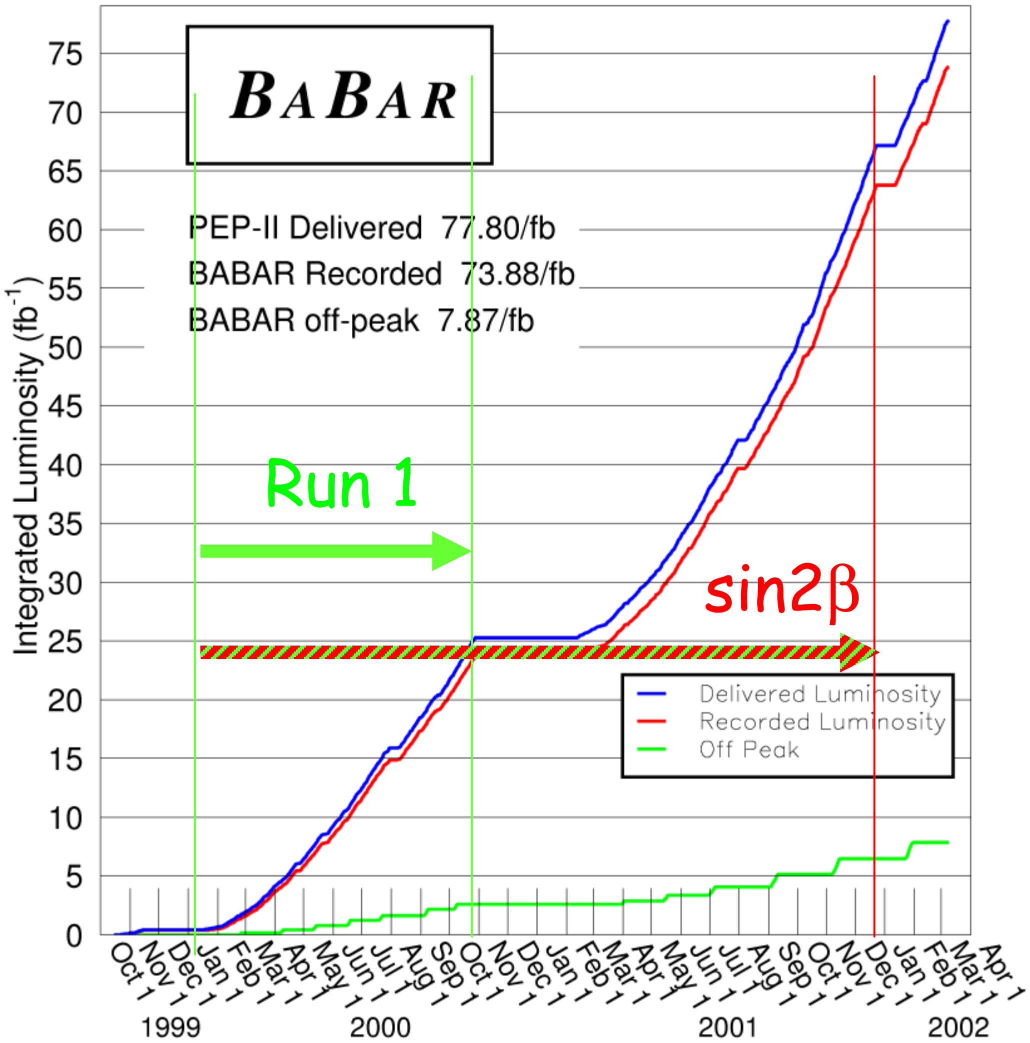
6: sin2β fit to Δt distribution for B^0 and $\overline{B}{}^0$ tags

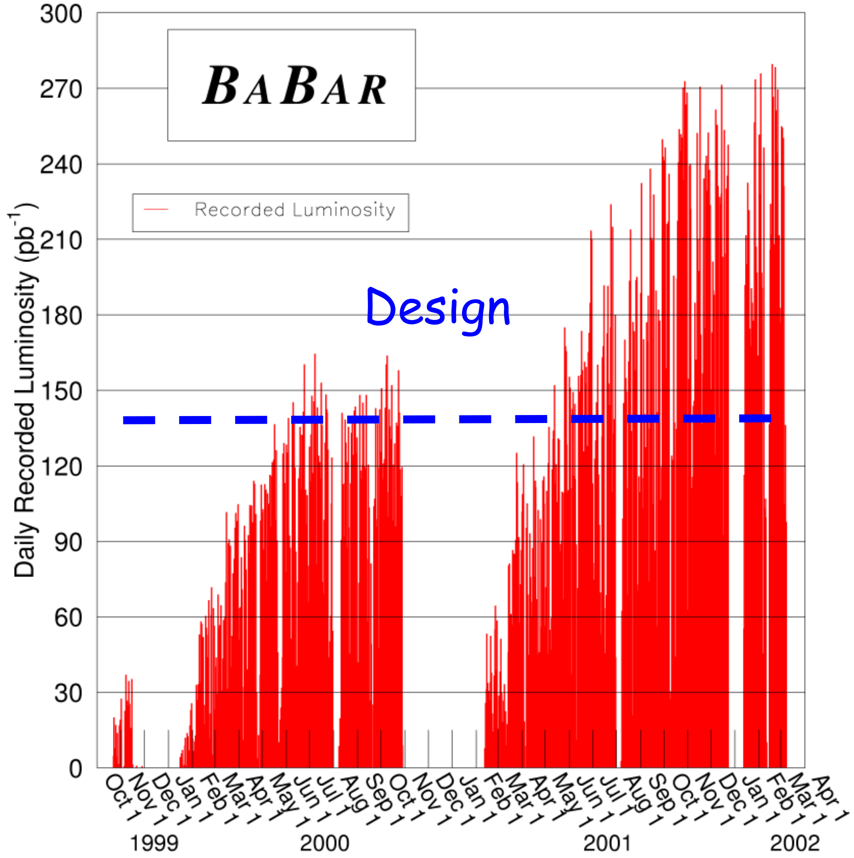
B-Factory PEP-II at SLAC



	Design	Reached
E [GeV] e^- / e^+	9.0 / 3.1	✓
L [$cm^{-2}\ s^{-1}$]	3×10^{33}	4.6×10^{33}
L_{int} [pb^{-1}/day]	135	309

BABAR: Luminosity and Data Sample





$\int L/\text{day}$

sin2β measurement:

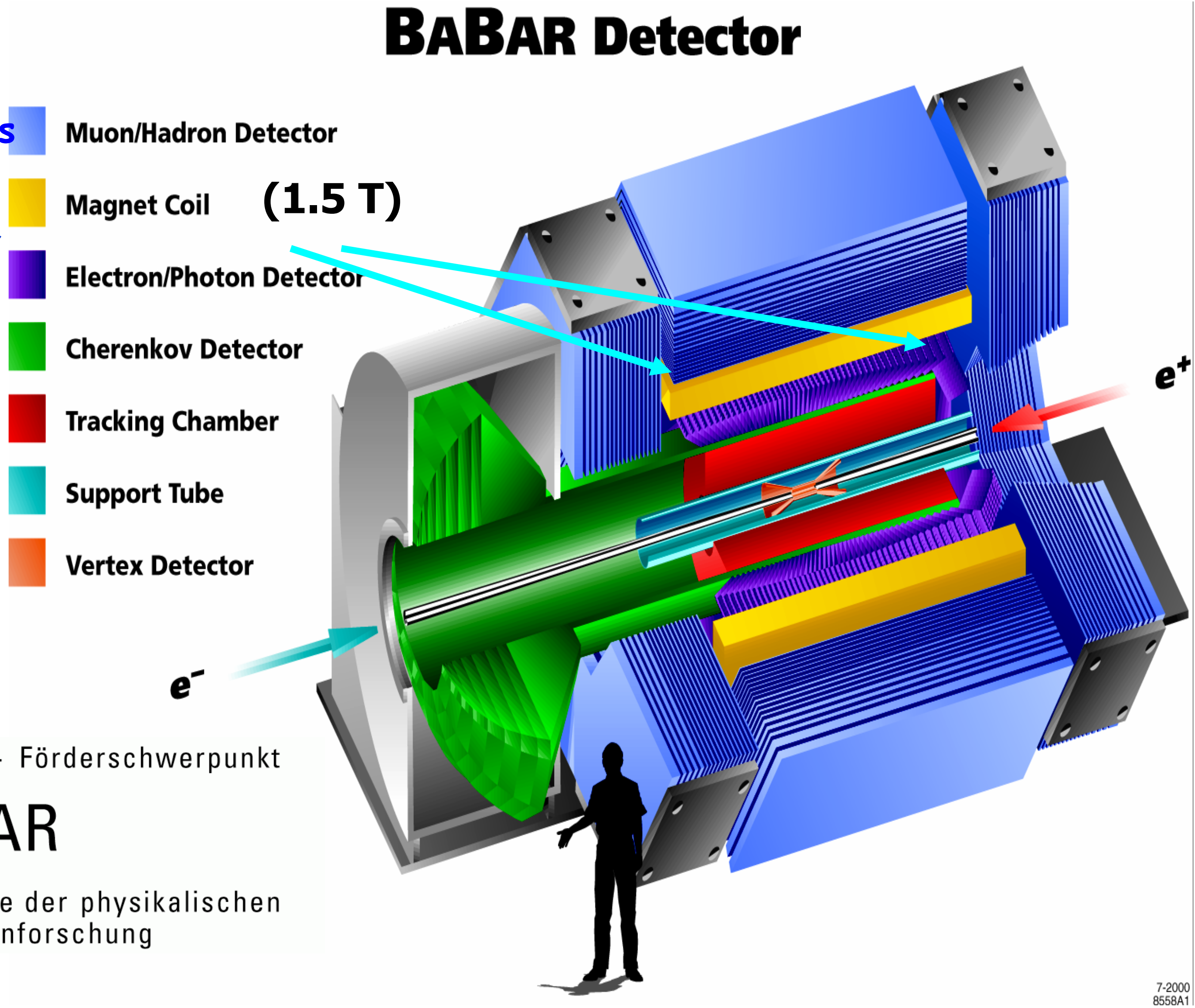
$\Rightarrow \approx 62 \cdot 10^6$ $B\bar{B}$-Pairs

BABAR

BABAR collaboration:
9 countries, 73 institutes
German institutes::
Bochum
Dresden
Rostock

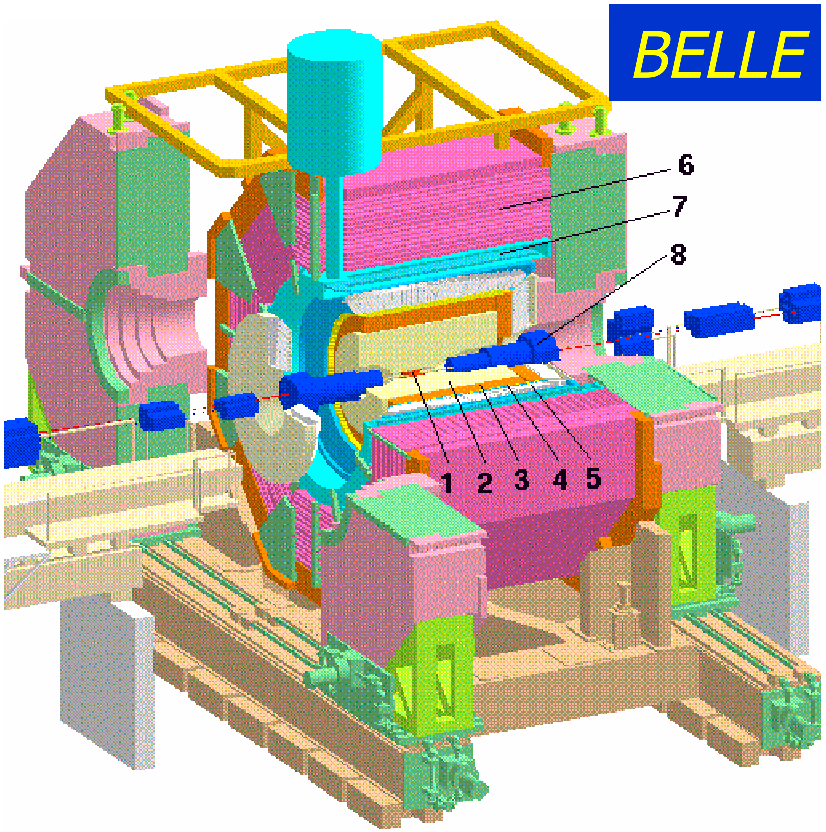
516 physicists

Calorimeter:
6580 CsI(Tl) crystals
photodiode readout
(2 per crystal)

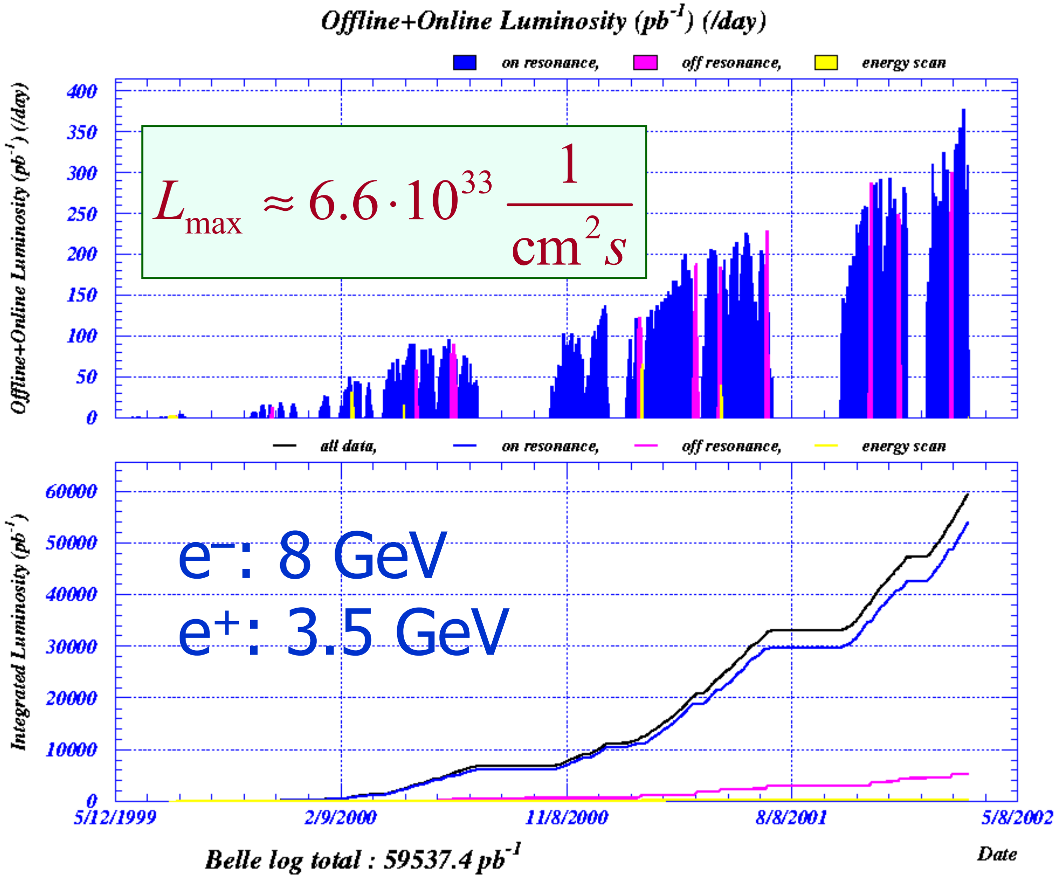


bmb+f - Förderschwerpunkt
BABAR
Großgeräte der physikalischen
Grundlagenforschung

KEKB and BELLE

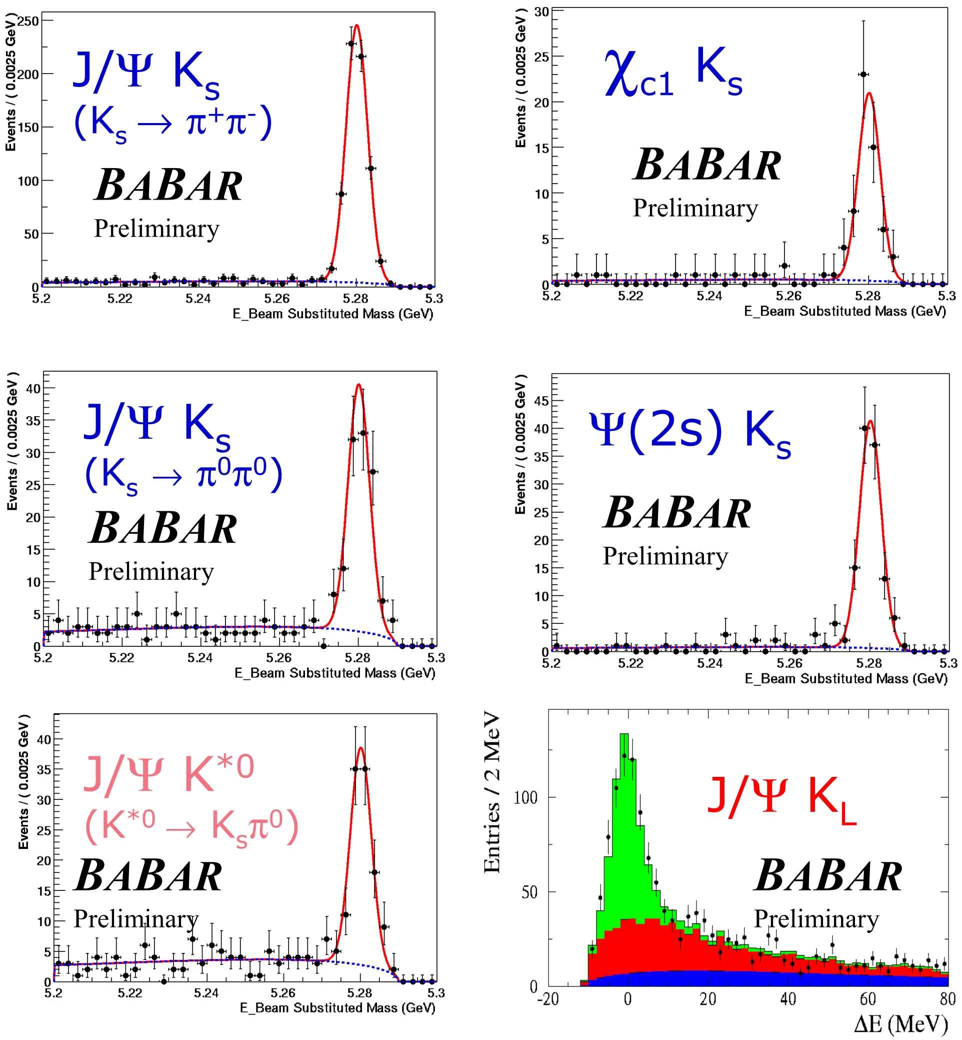


1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System



Results based on $\int L = 42.8\ fb^{-1}$ on resonance

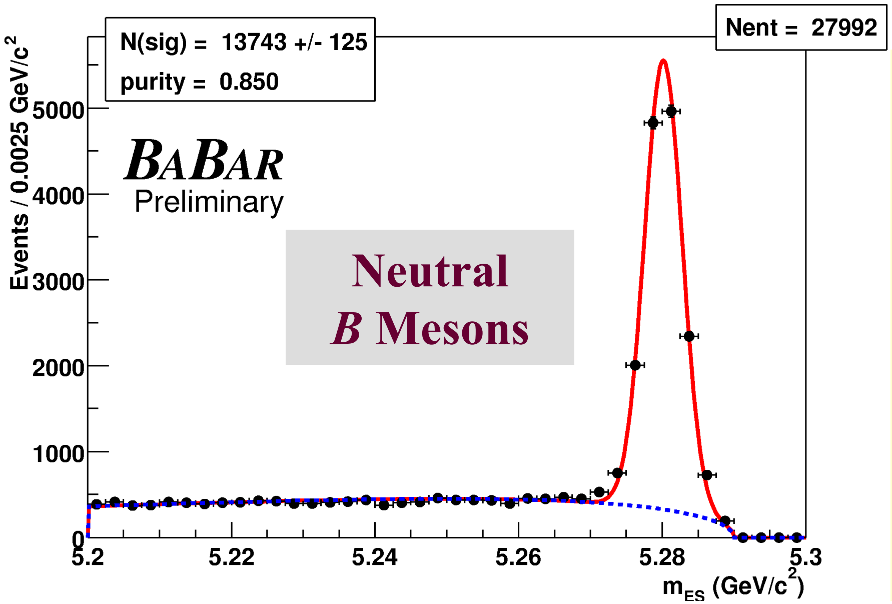
Reconstruction of CP Eigenstates

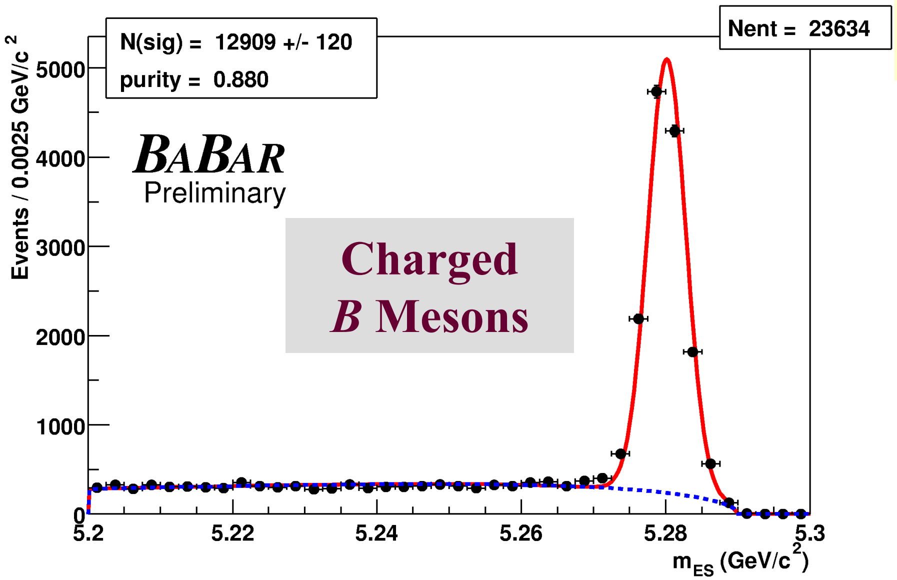


Mode	N_{tag}	Purity	CP
$(c\bar{c})K_s$	995	94%	–1
J/Ψ K$_L$	742	57%	+1
J/Ψ K^{*0}	113	83%	+0.68
All CP	**1,850**	**79%**	
B_{flav}	17,634	85%	Flav. ES

$$B \to J/\psi\, K, \quad J/\psi \to e^+e^-, \mu^+\mu^-$$

„Flavour" Sample





These samples are used to measure:

- B^0, B^+ lifetimes
- Δm (mixing) of neutral B
- Δz resolution and tagging performance for the $\sin(2\beta)$ measurement

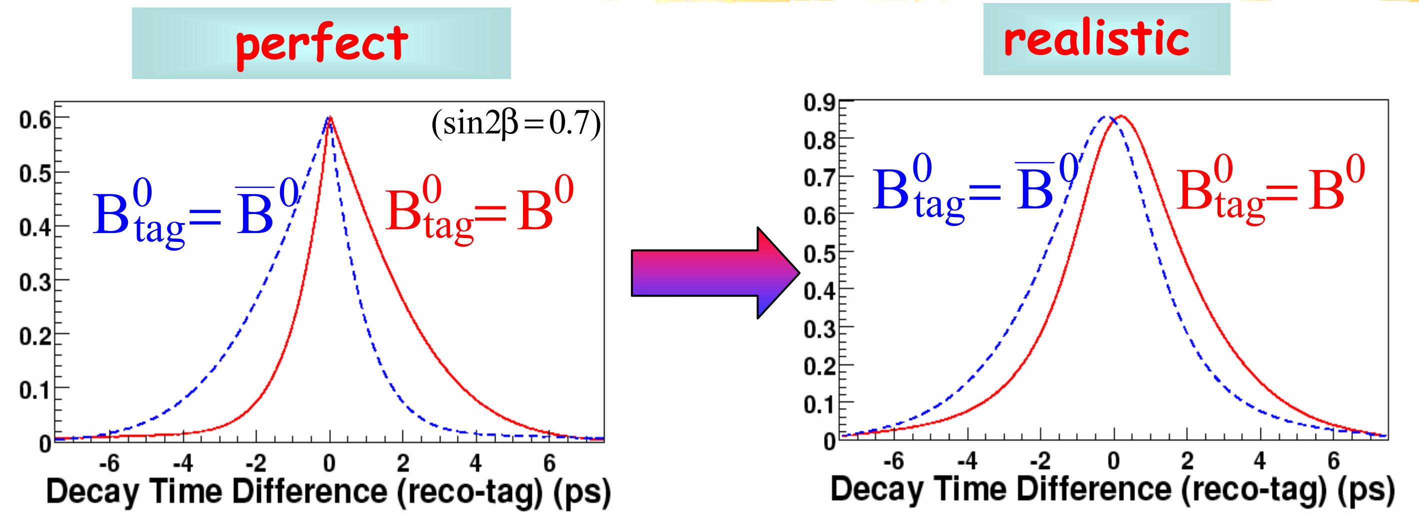
  (are parameters in combined fit for $\sin 2\beta$ to CP, Flavour, and Background samples.)

- B-Flavour known by decay
  - ⇒Determination of w
  - ⇒Determination of efficiency ε

    (via fit to Flavour & CP Data)

Δt distributions

perfect → realistic



$$f_{\pm}^{CP}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{2\tau_{B_d}} \times \left(1 \mp \eta_f . (1-2\omega) \sin 2\beta \cdot \sin(\Delta m_{B_d} \Delta t)\right) \right\} \otimes R$$

$"f_{+}^{CP}" \Leftrightarrow B^0_{tag} = B^0$

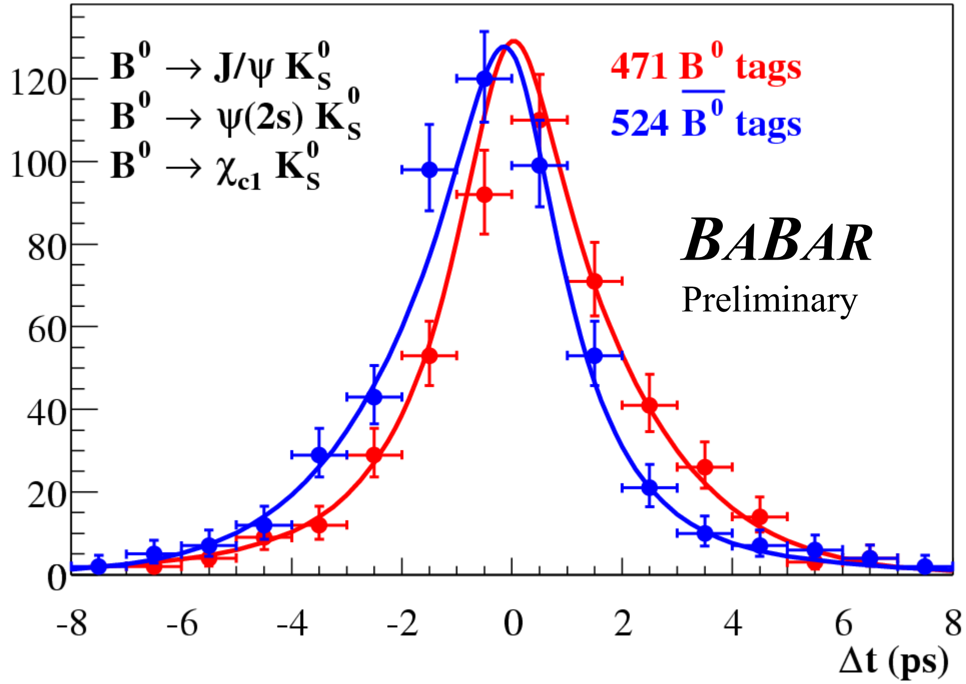
$"f_{-}^{CP}" \Leftrightarrow B^0_{tag} = \overline{B}^0$

ω: mis-tagging probability

$R(\Delta t)$: time-resolution function

Fit

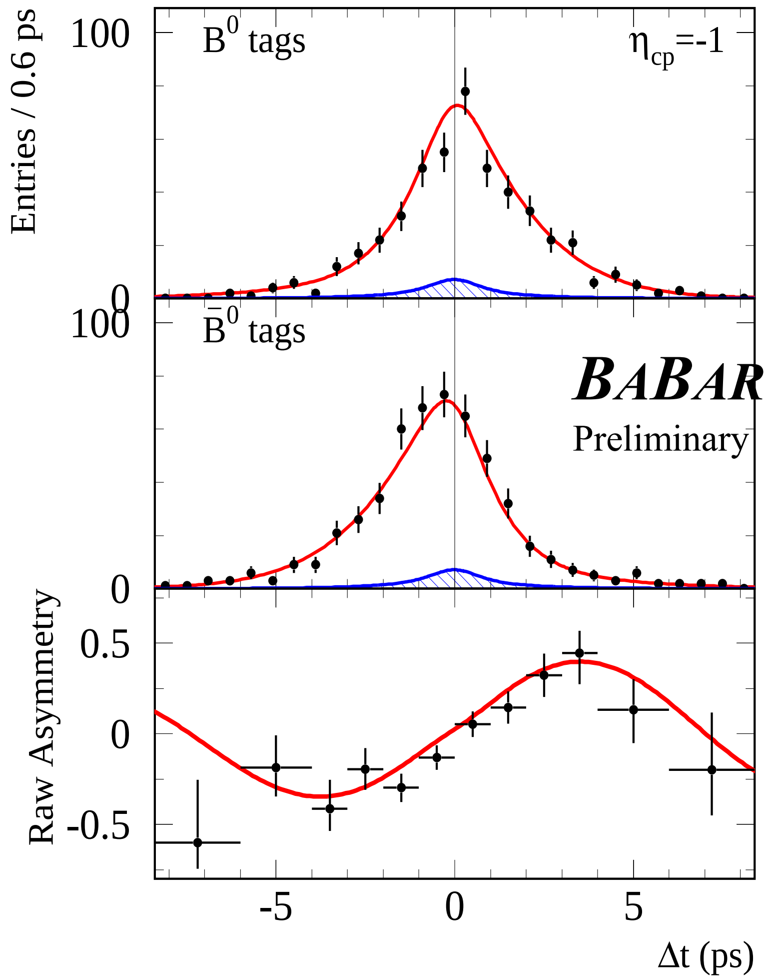
Combined unbinned maximum likelihood fit for:
CP, Flavour and Background samples

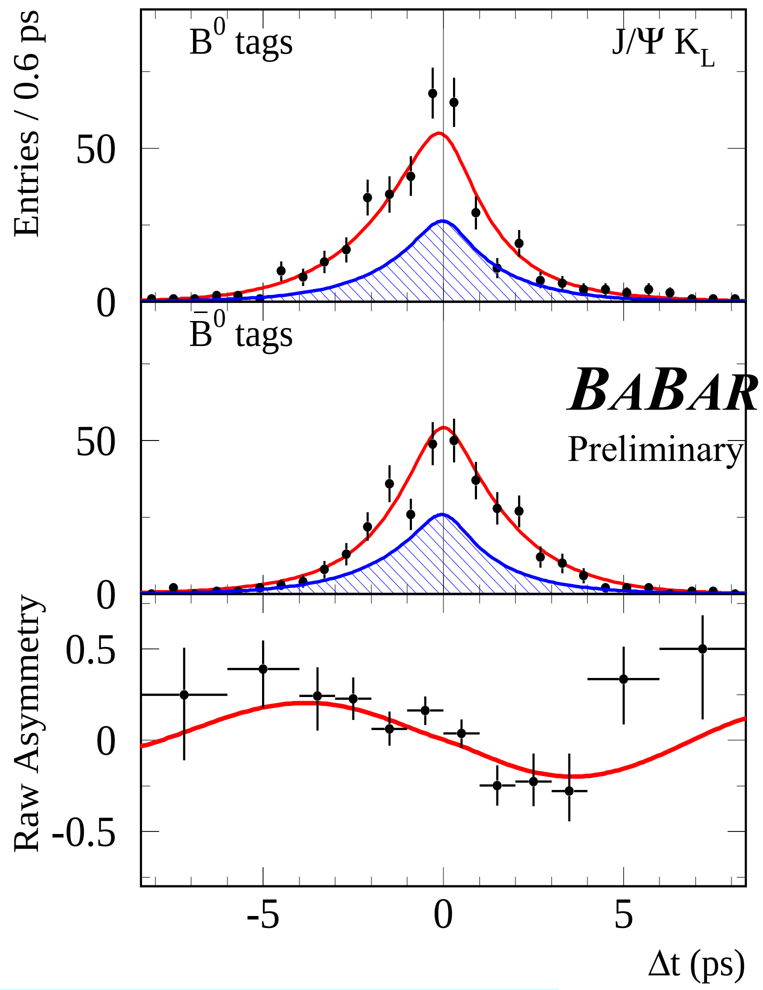


- Mistag, resolution determination dominated by large B_{FLAV} sample
- Background parameters from m_{ES} sideband
- B^0 Δm: fixed to 0.472 $\hbar$ ps^{-1}
- B^0 lifetime: fixed to 1.548 ps

PDG values

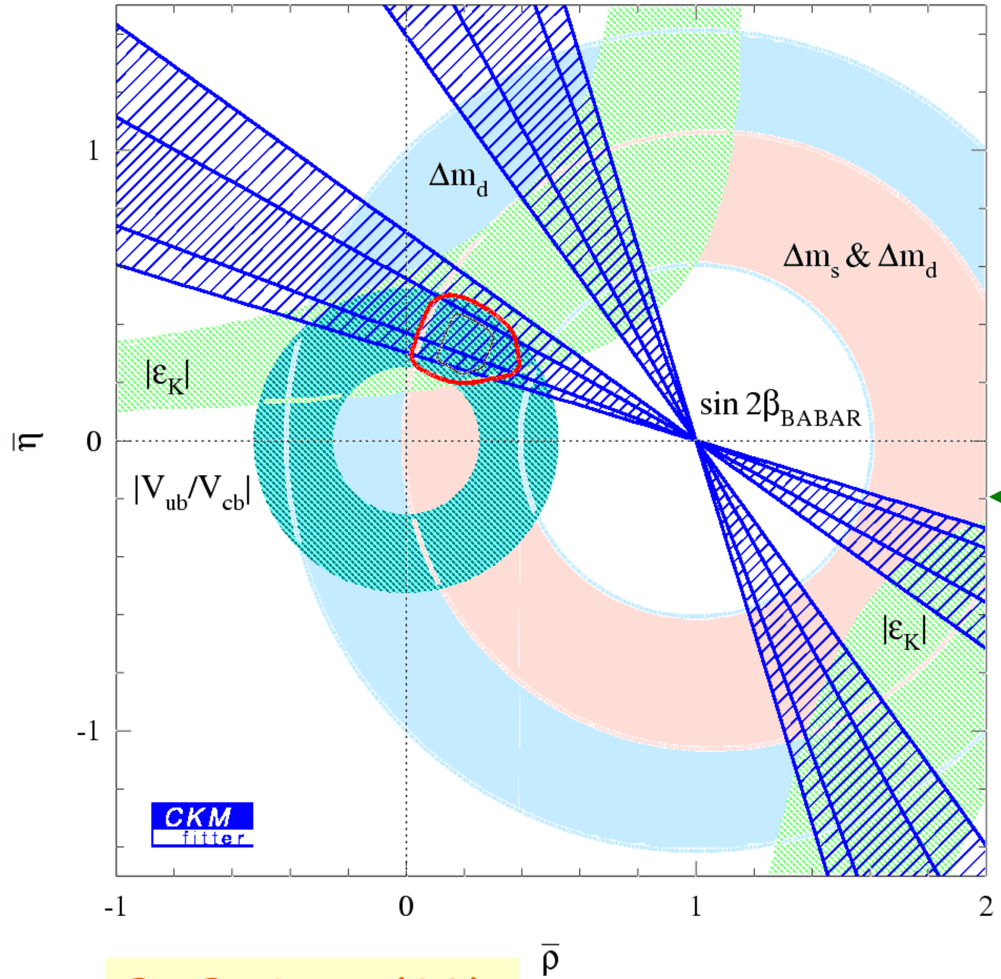
sin2β-Fit to Δt Distributions





preliminary $\sin(2\beta) = \pm_{\text{stat}} \pm_{\text{syst}}$

sin2β and Unitarity Triangle



BABAR sin(2β)

There is $\not{C}P$ outside the K-system!
Consistent with the SM :
precision test requires more data.
i.e better determination of V_{ub}

à la Höcker et al,
Eur.Phys.J.C21:225-59,2001

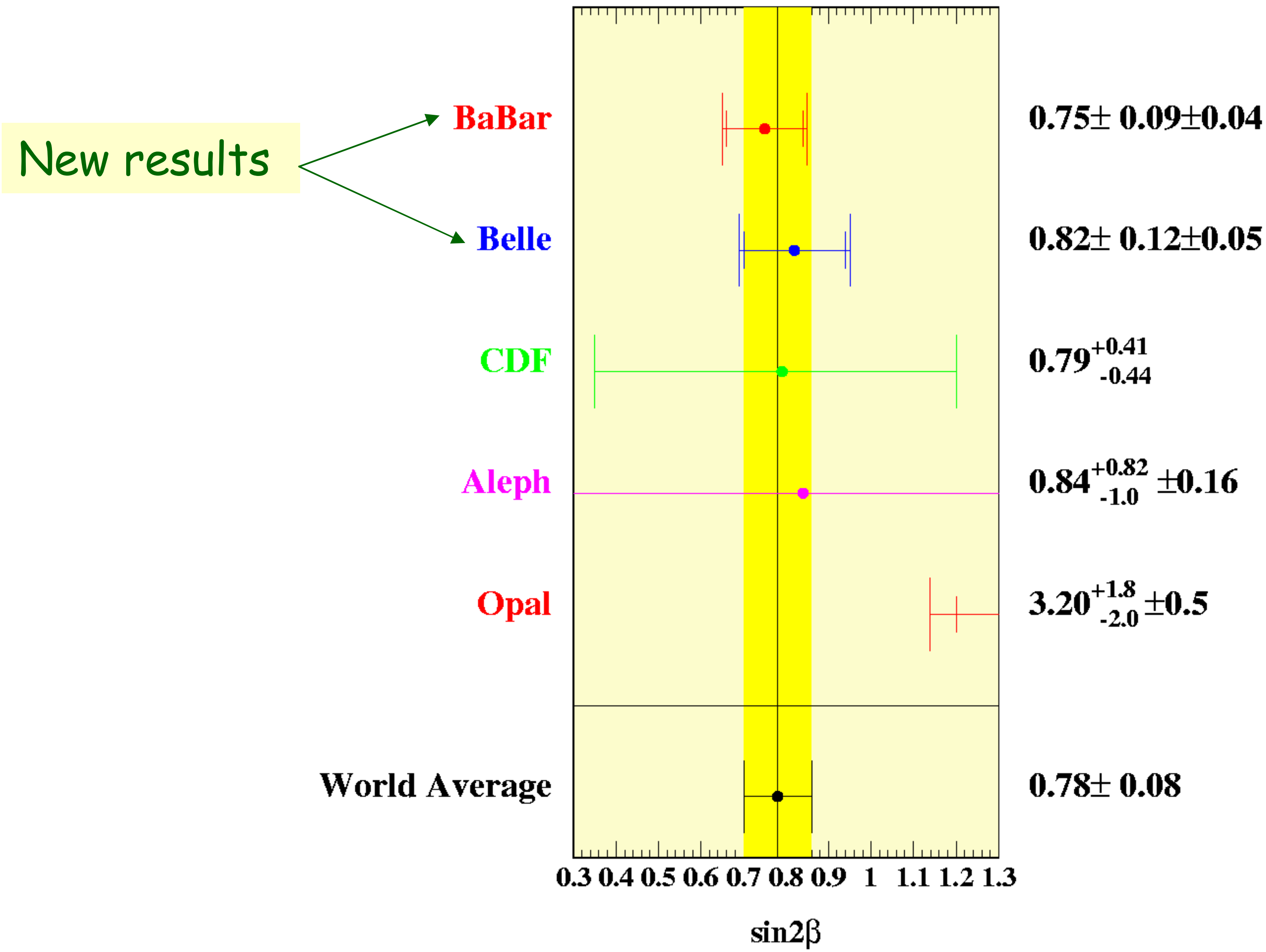
Is there direct $\not{C}P$?

$\Rightarrow$Fit for $|\lambda_{CP}|$ too:

$$|\lambda_{CP}| = 0.92 \pm 0.06 \pm 0.03$$

$\Rightarrow$Consistent with no direct $\not{C}P$

sin2β - World Measurements



CP-Violation in Mixing

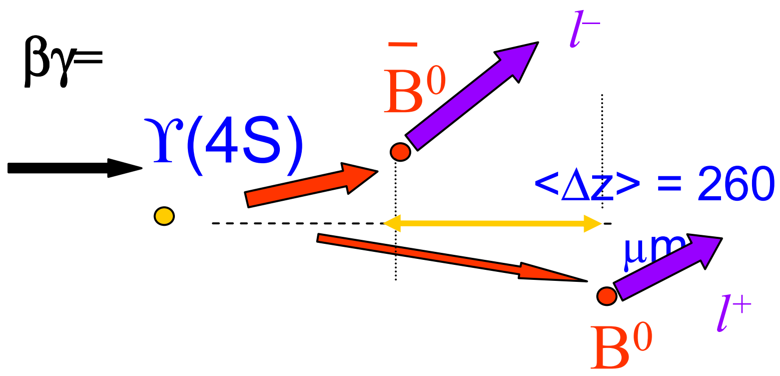
Using Dileptons

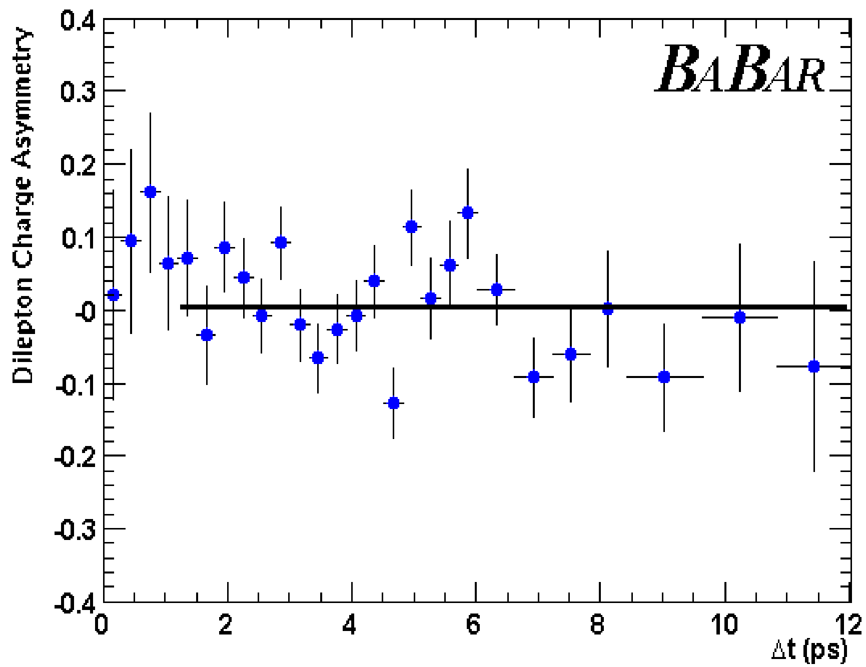
CP/T violation (ε_B):

$$A_{CP}(\Delta t) = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} \approx \frac{4\,\mathrm{Re}(\varepsilon_B)}{1+|\varepsilon_B|^2}$$

SM expectation:

$A_{CP} \approx (0.5 - 5)\cdot 10^{-3}$



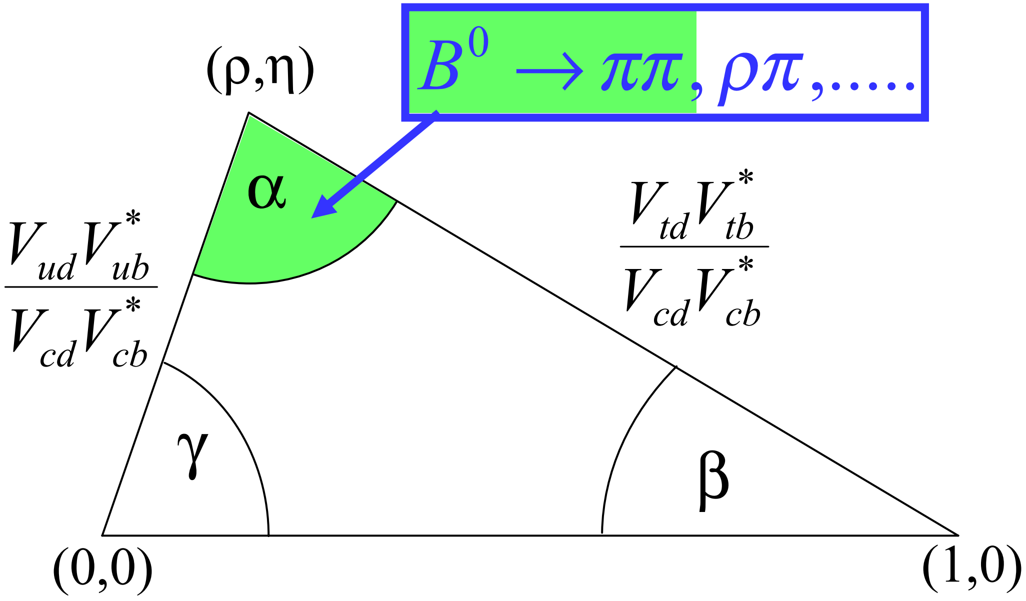


$$A_{CP} = (0.5 \pm 1.2 \pm 1.4)\%$$

$$\Rightarrow \left|\frac{q}{p}\right| = 0.998 \pm 0.006 \pm 0.007$$

$\mathrm{Re}(\varepsilon_B)/(1+|\varepsilon_B|^2) = (1.2 \pm 2.9 \pm 3.6)\cdot 10^{-3}$

CP Asymmetries in $B^0 \to \pi^+\pi^-$



Tree and Penguin:

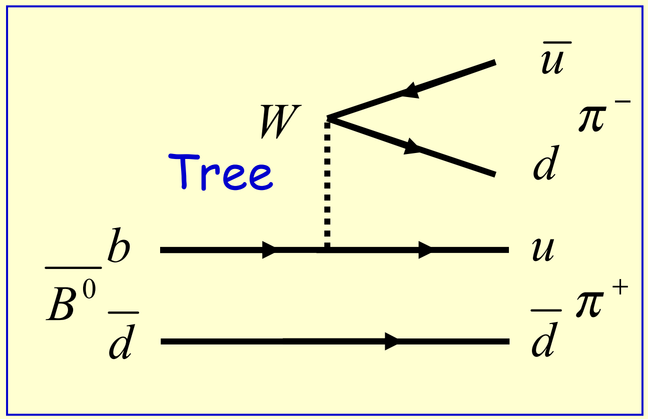
⇒ different weak phases

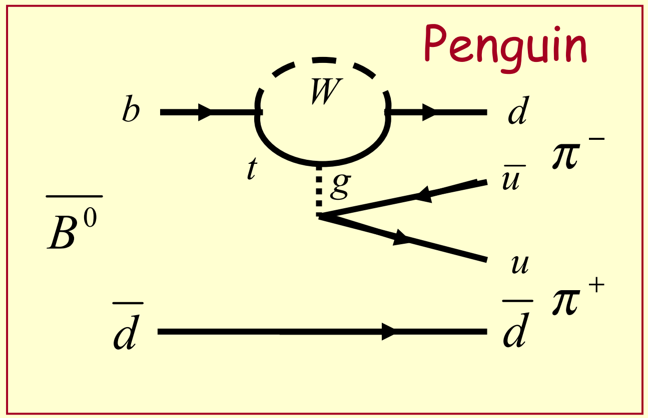
⇒ sin2α only from Tree diagram!

⇒ A_{CP} measures $\sin 2\alpha_{eff}$

⇒ need to disentangle Penguin pollution!

Diagrams





CP Asymmetries in $B^0 \to \pi^+\pi^-, K\pi$

Time dependent asymmetry measurement:
$\Rightarrow$ very similar to $\sin 2\beta$ measurement
BUT: $\mathrm{Re}(\varepsilon_f)$ not necessarily 0! (see Kaon case)

$$f_\pm = \frac{e^{-|\Delta t|/\tau}}{4\tau} \cdot \left[1 \pm S_{\pi\pi} \sin(\Delta m \Delta t) \mp C_{\pi\pi} \cos(\Delta m \Delta t)\right]$$

$$S_{\pi\pi} = \frac{2\,\mathrm{Im}(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$C_{\pi\pi} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$$

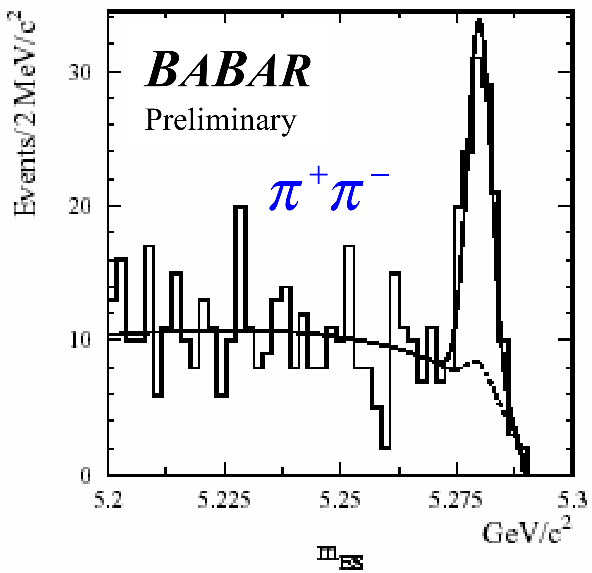
BABAR: measure $B^0 \to h^+, h^-$, $h = \pi, K$ (global max. Lhood fit)

$B(\pi^+\pi^-) = (5.4 \pm 0.7 \pm 0.4) \cdot 10^{-6}$

$B(K^+\pi^-) = (17.8 \pm 1.1 \pm 0.8) \cdot 10^{-6}$

$B(K^+K^-) < 1.1 \cdot 10^{-6}$ (90% C.L.)

Mode	N_S
$\pi^+\pi^-$	$124.3^{+15.8}_{-15.3}$
$K^+\pi^-$	$402.7^{+24.3}_{-23.9}$
K^+K^-	$0.6^{+8.0}_{-7.4}$ (< 15



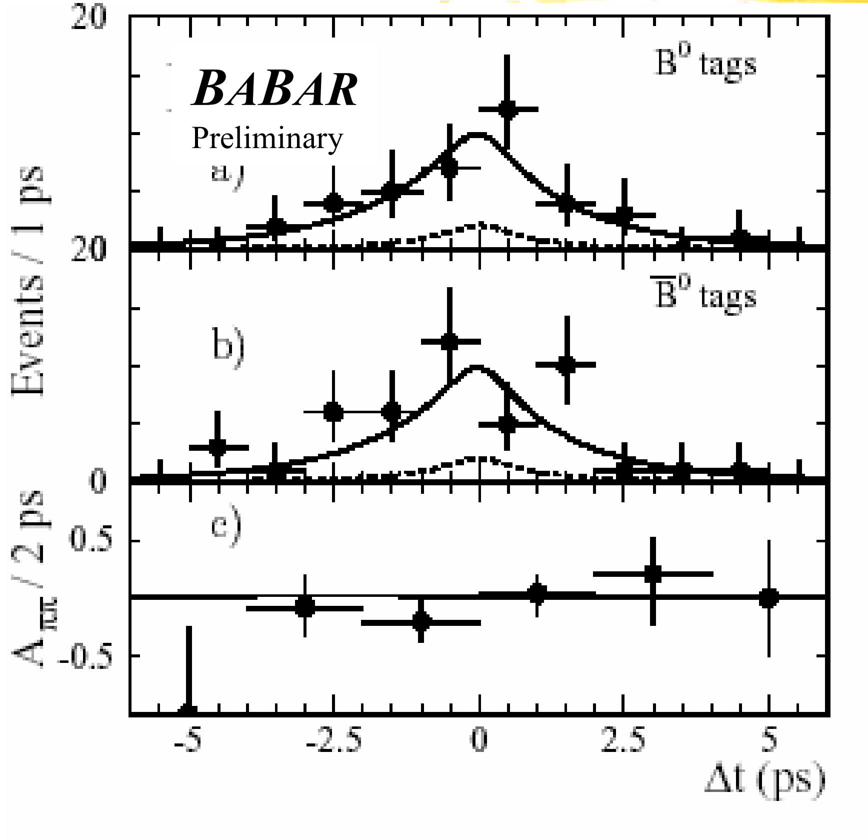
Direct CP violation:

$$A_{K\pi} = \frac{N_{K^-\pi^+} - N_{K^+\pi^-}}{N_{K^-\pi^+} + N_{K^+\pi^-}} = (0.05 \pm 0.06 \pm 0.01)$$

$$[-0.15 \leftrightarrow +0.05] @ 90\% CL$$

preliminary

$\sin 2\alpha_{eff}$



$S_{\pi\pi}$=-0.01 ± 0.37 ± 0.07

[-0.66, +0.62] 90%CL

$C_{\pi\pi}$=-0.02 ± 0.29 ± 0.07

[-0.54, +0.48] 90%CL

preliminary

$\sin 2\alpha_{eff}$

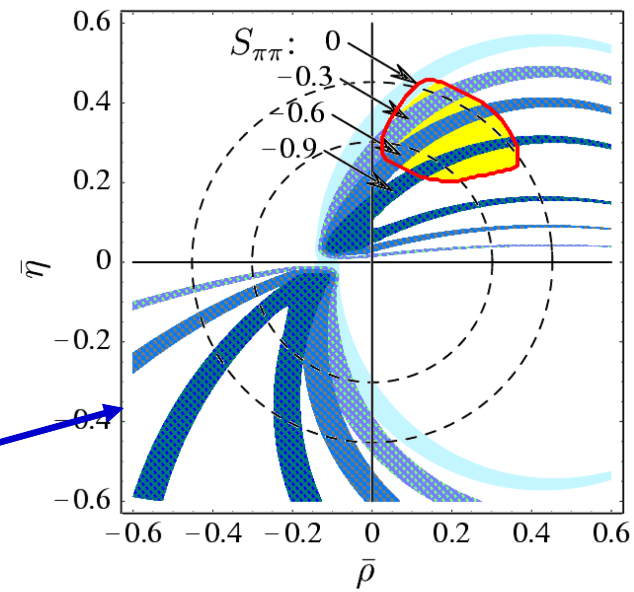
$\sigma(\alpha_{eff})\approx 12^0$

background

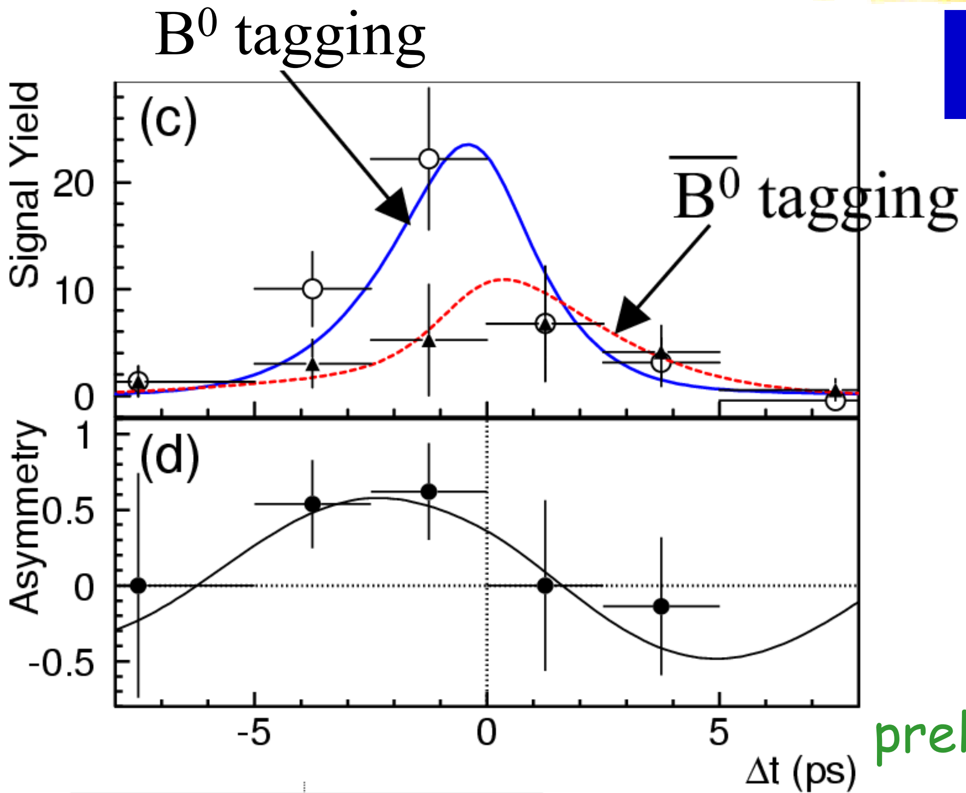
Determination of $\sin 2\alpha$:

- Isospin analysis ⇒ measure $B \to \pi^0\pi^0$
- or use models?

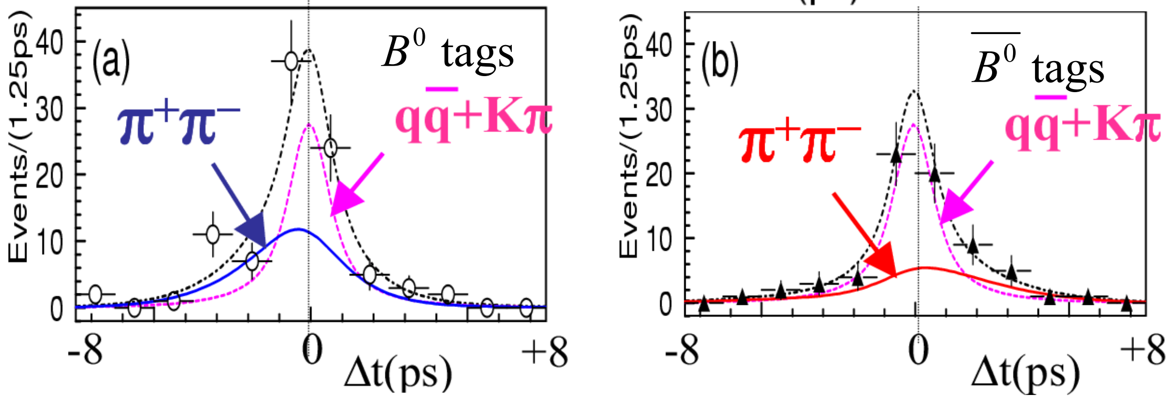
e.g. M.Beneke, G.Buchalla, M.Neubert, and C.T.Sachrajda, Nucl.Phys.B606:245-321,2001
see talk by M. Beneke on Thursday, 12:15h



$\sin 2\alpha_{eff}$



preliminary



BELLE

Moriond

$N_{\pi\pi}$=73.5±13.8 events

$$S_{\pi\pi} = -1.21 \begin{matrix} +0.38 \\ -0.27 \end{matrix} \begin{matrix} +0.16 \\ -0.13 \end{matrix}$$

$$-C_{\pi\pi} = +0.94 \begin{matrix} +0.25 \\ -0.31 \end{matrix} \pm 0.09$$

Indication for direct CP-violation in B-System?

BABAR: similar errors, $S_{\pi\pi}$, $C_{\pi\pi}$, consistent with 0!

Conclusion and Outlook

- CP Violation in K-System well studied
  - All three types of CP violation discovered
  - Many CPT tests performed

- Study of CP-Violation in the B-System and measurement of CKM-parameter will provide sensitive tests on the origin of CP-violation
- CP violation has been observed in the B system
  - first observation of CP violation outside the K-system!
  - Providing a relevant constraint in the ρ-η plane
- Many more measurements on CP violation in B-system: $\sin\alpha_{eff}$, $\mathrm{Re}(\varepsilon_B)$,...
- Already a rich variety of CKM tests and more in the near future
- CP-Violation measurements in the B-System just started
  - expect productive long term future even after BABAR, BELLE completion! (LHCb, BTeV, ...)

    $\Rightarrow$high precision measurements on angles, sides, direct CP violation...