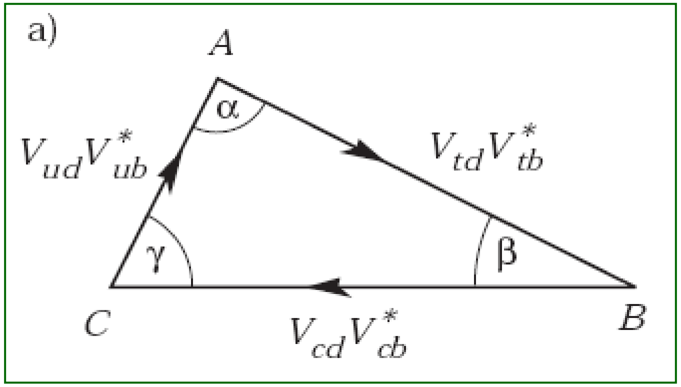
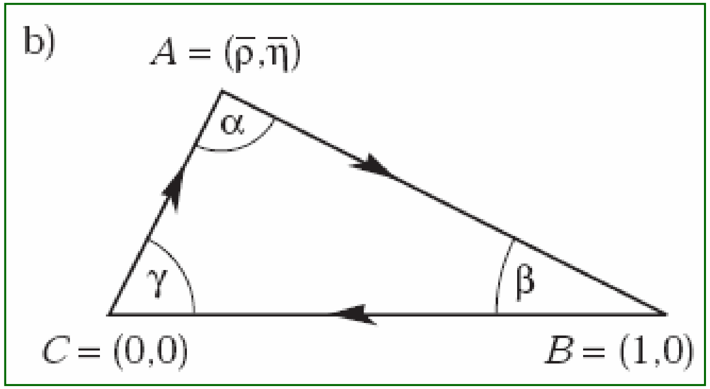
CP-Verletzung und Unitaritätsdreieck

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

Unitarity applied to the first and third columns yields

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



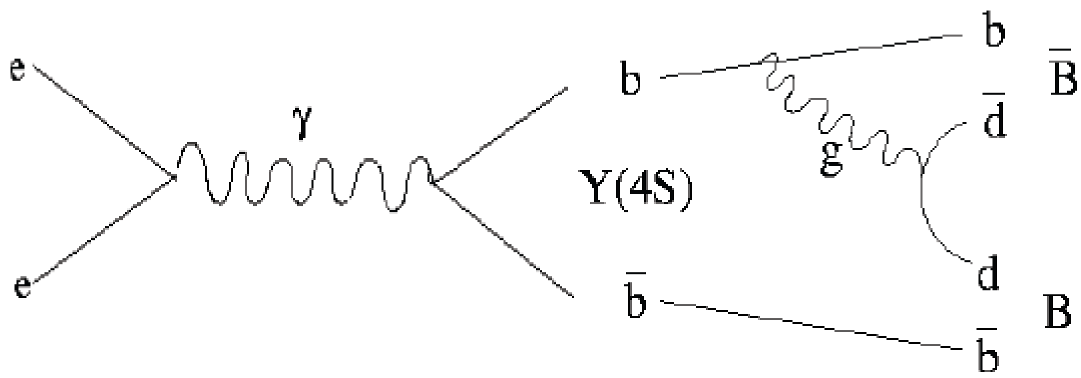


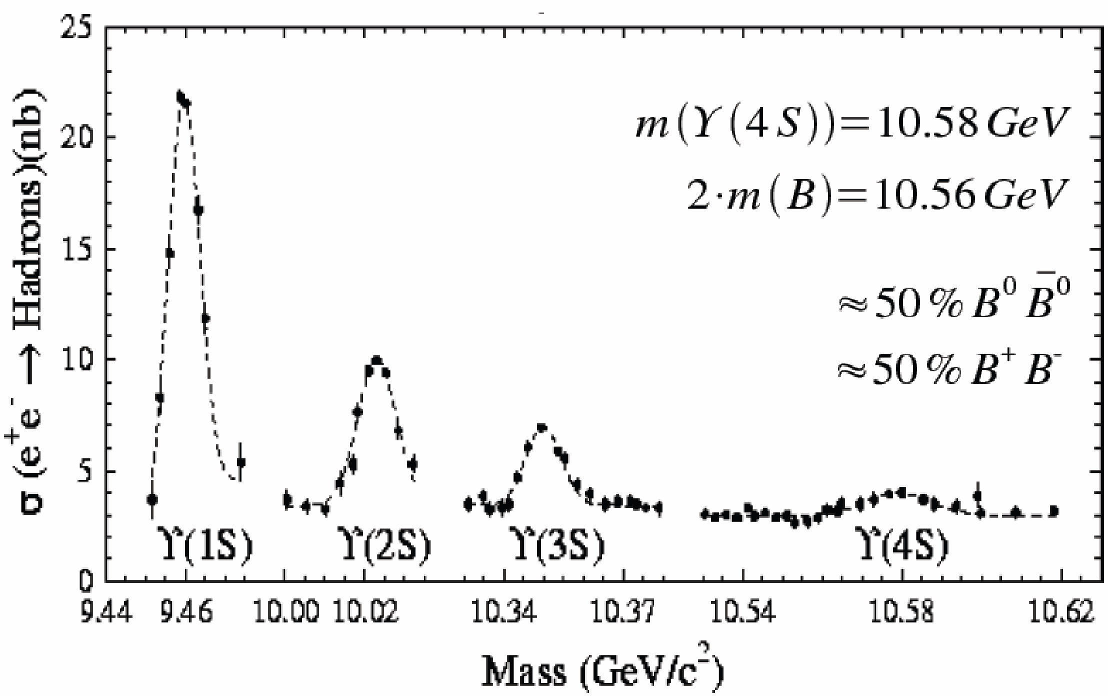
Fläche $\neq 0 \Rightarrow$ Phase $\neq 0 \Rightarrow$ CP-Verletzung:

$$\left.\begin{array}{l} q_{di} \rightarrow q_{uj} \sim V_{ji} \\ \bar{q}_{di} \rightarrow \bar{q}_{uj} \sim V_{ji}^* \end{array}\right\} \text{CP-Verletzung}$$

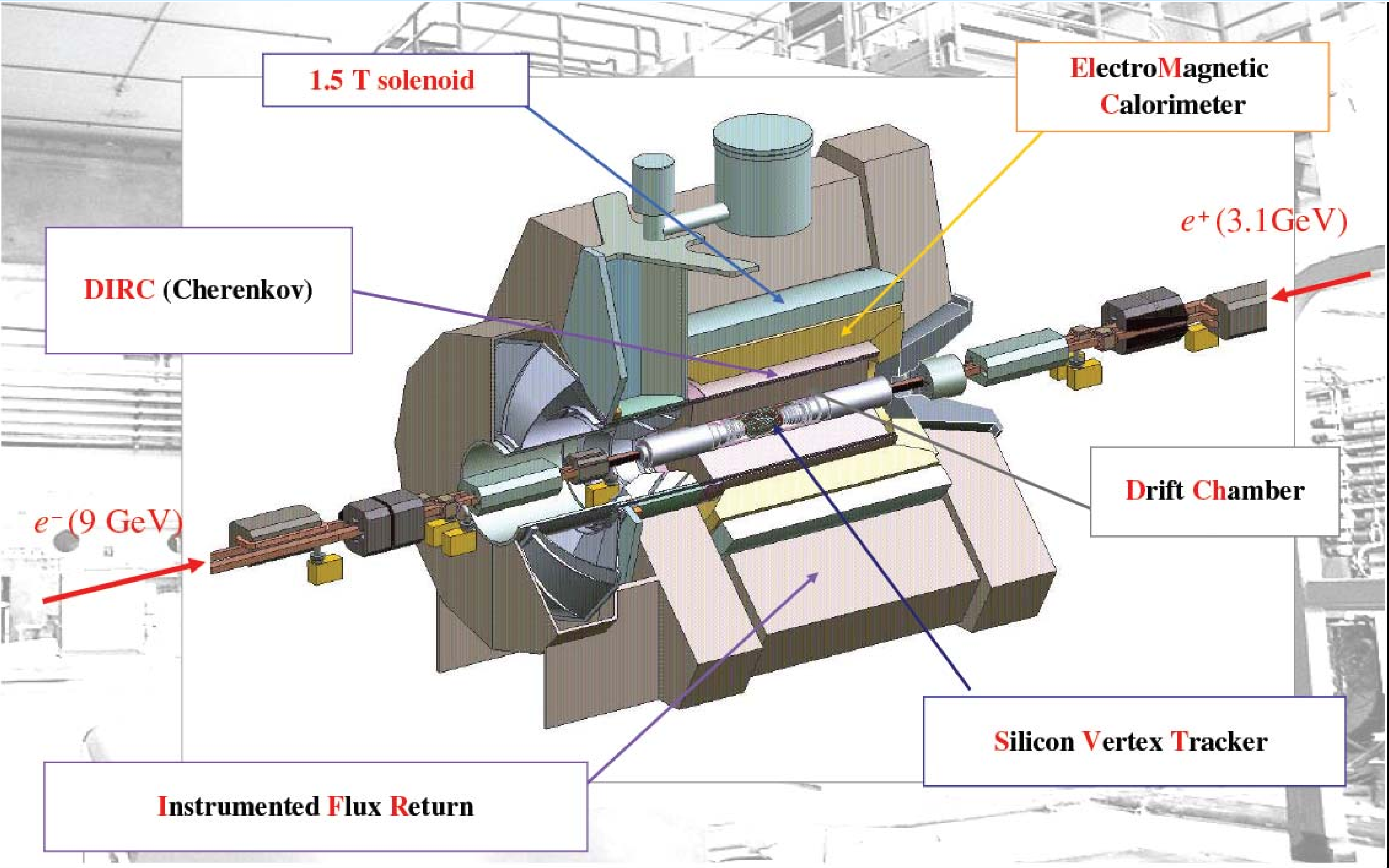
$$\left.\begin{array}{l} \bar{q}_{di} \rightarrow \bar{q}_{uj} \sim V_{ji}^* \\ q_{uj} \rightarrow q_{di} \sim V_{ji}^* \end{array}\right\} \text{T-Verletzung}$$

B-Fabriken: Υ(4s)



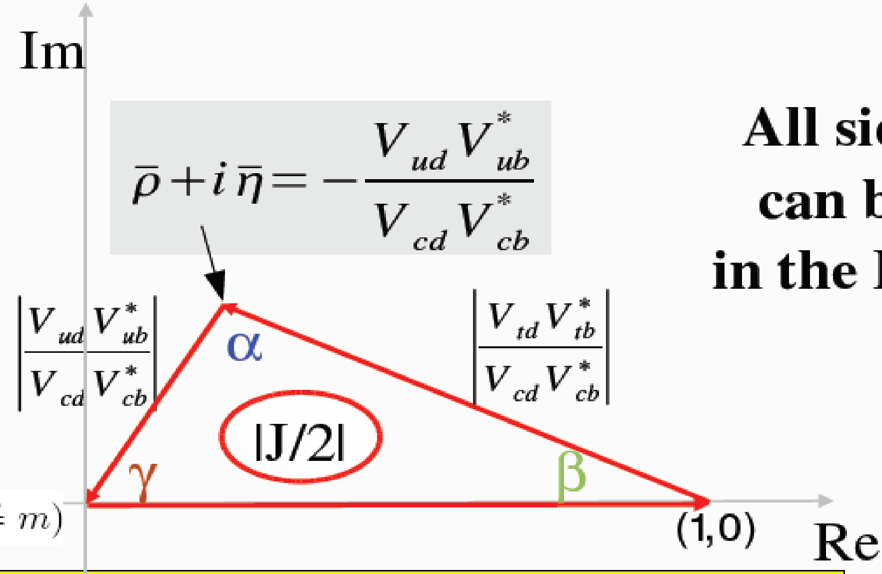


BABAR Detector



CP violation quantitatively: Unitarity Triangle

$$\frac{1}{V_{cd}V_{cb}^{*}}\left(V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}\right)=0$$



All sides & angles can be determined in the B-meson system!

J: Jarlskog parameter

$$\mathcal{J}=\mathrm{Im}\left[V_{il}V_{jm}V_{im}^{*}V_{jl}^{*}\right]\quad(i\neq j,\ l\neq m)$$

All data compatible with CKM ?

Yes → **Precise determination of CKM parameters**

No → **New Physics beyond SM (Higgs sector, SUSY, ...)**

11

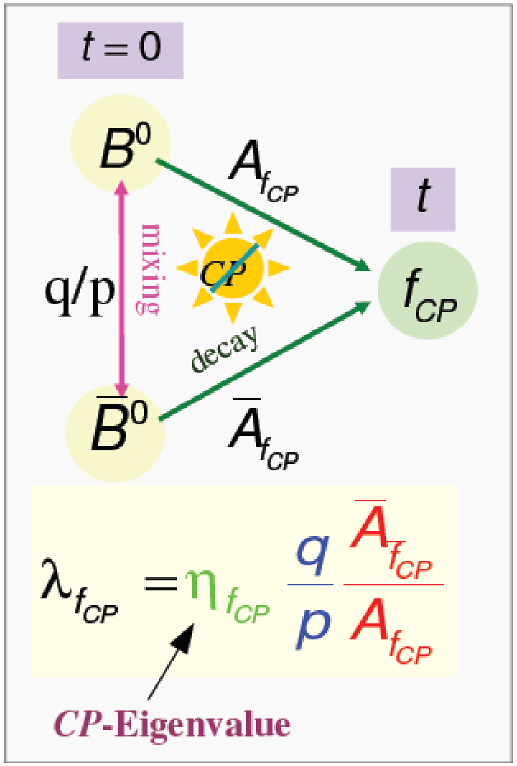
Different manifestations of *CP* violation

Neutral B-meson mass eigenstates:

$$|B_L> \propto p|B^0> + q|\bar{B}^0>$$
$$|B_H> \propto p|B^0> - q|\bar{B}^0>$$

Mass difference between heavy and light B meson:

$$\Delta m_d \equiv M_H - M_L$$

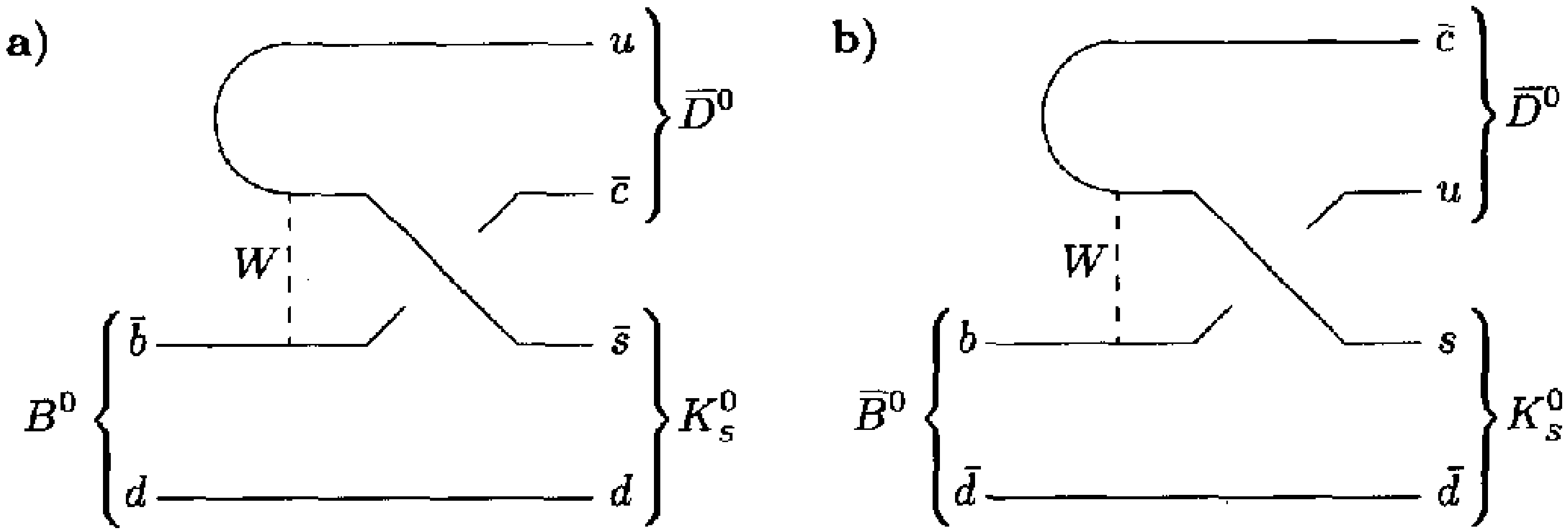


$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

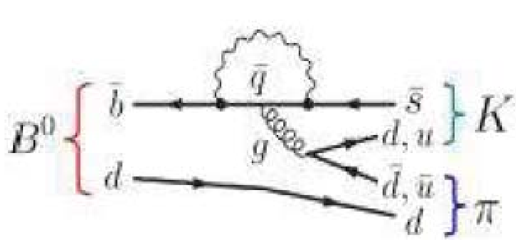
$$= \frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2} \sin(\Delta m_d t) - \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m_d t)$$

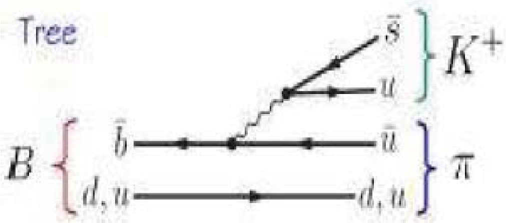
- *CP* violation in *Mixing*: $|q/p| \neq 1$
- *CP* violation in *Decay*: $|\bar{A}_{f_{CP}} / A_{f_{CP}}| \neq 1$
- *CP* violation in *Interference between decay with and without Mixing:* $\mathrm{Im}\,\lambda_{f_{CP}} \neq 0$

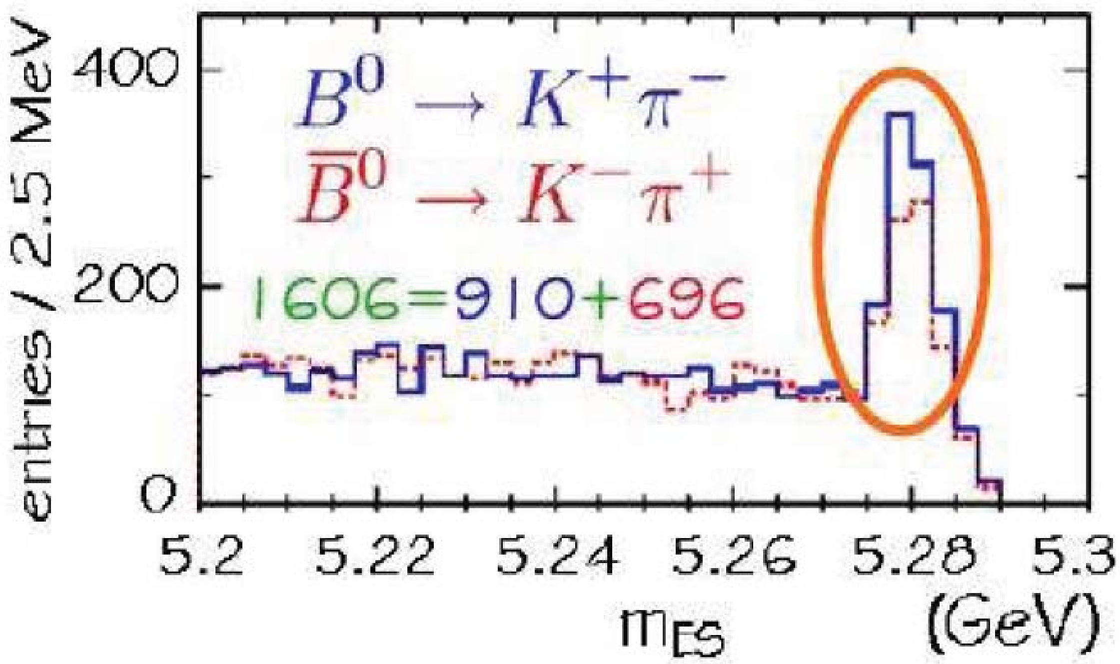
CP-Verletzung im Zerfall



CP violation in decay in the B system







$$\mathcal{A}_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

(a 4.2 sigma effect)

CP-Asymmetrie in $B^0 \to J/\psi\, K_s$

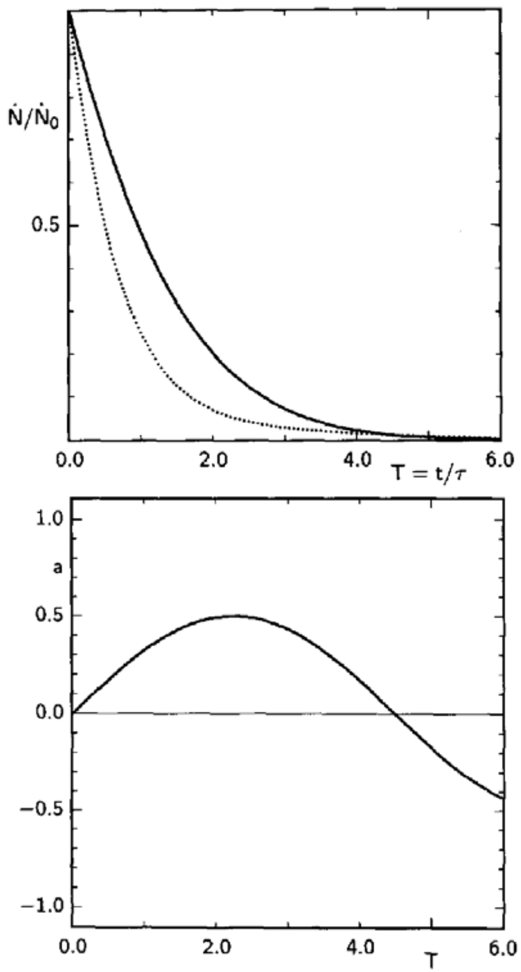
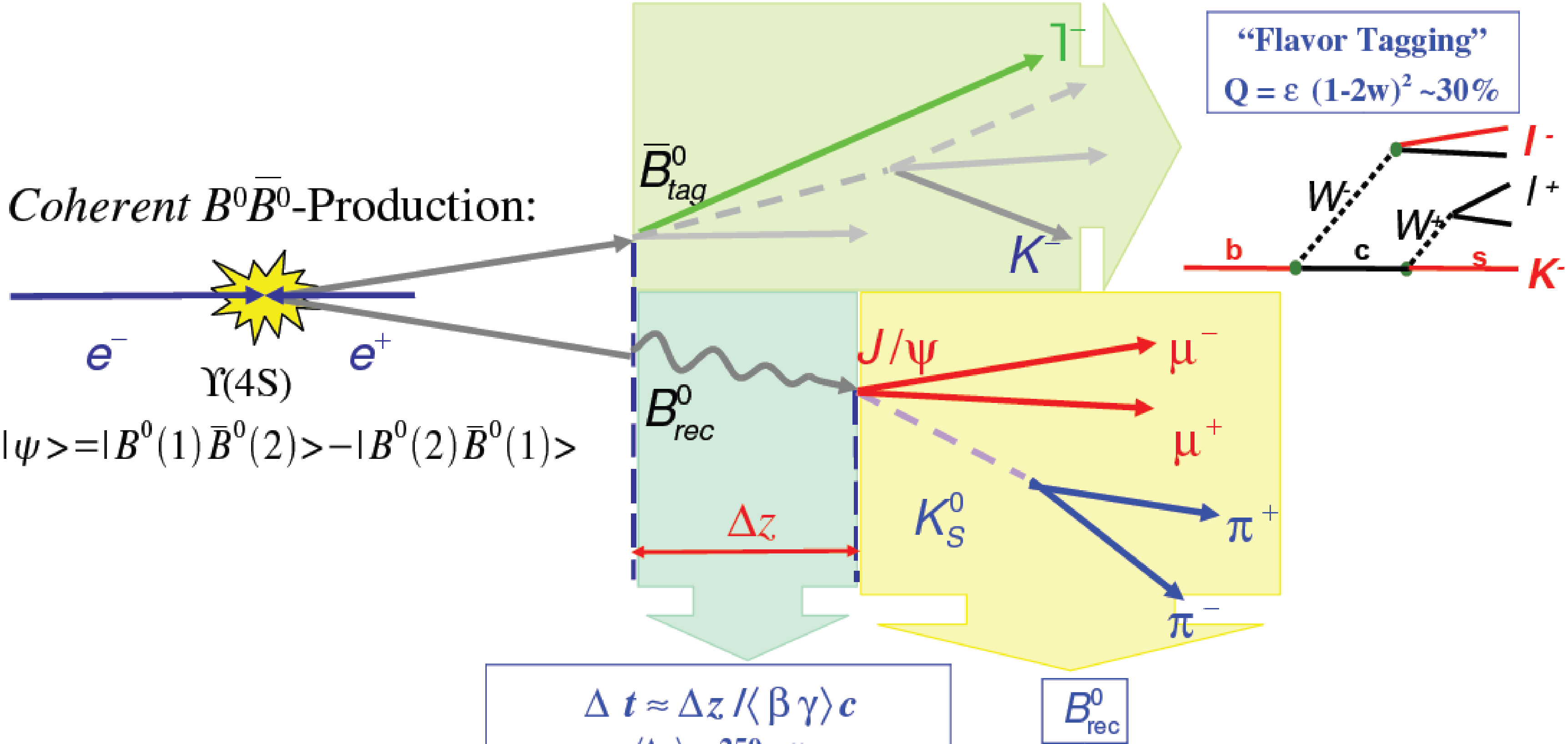


Figure 10: Time dependent rate of $\overline{B}^0 \to J/\psi K_S^0$ (——) and $B^0 \to J/\psi K_S^0$ (········) for $\Lambda_0 = \sin 2\beta = 0.5$ and $x = 0.70$. The lower plot shows the asymmetry $a(T)$.

Time dependent CP violation: Experimental Technique



$\Delta t \approx \Delta z / \langle \beta\gamma \rangle c$

$\langle \Delta z \rangle \approx 250\ \mu m$

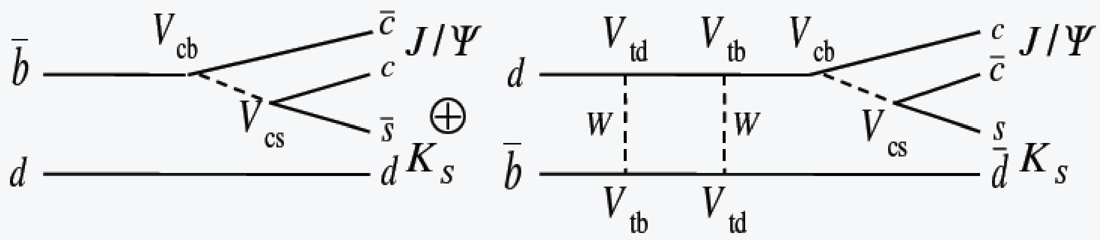
($\beta\gamma = 0.56$(BABAR), 0.42 (Belle))

$\langle \Delta z \rangle \approx 30\ \mu m$ without Boost

$B^0_{rec} = B^0_{flav}$ **(Flavor eigenstate)** ➡ **Oscillation, life time, ...**

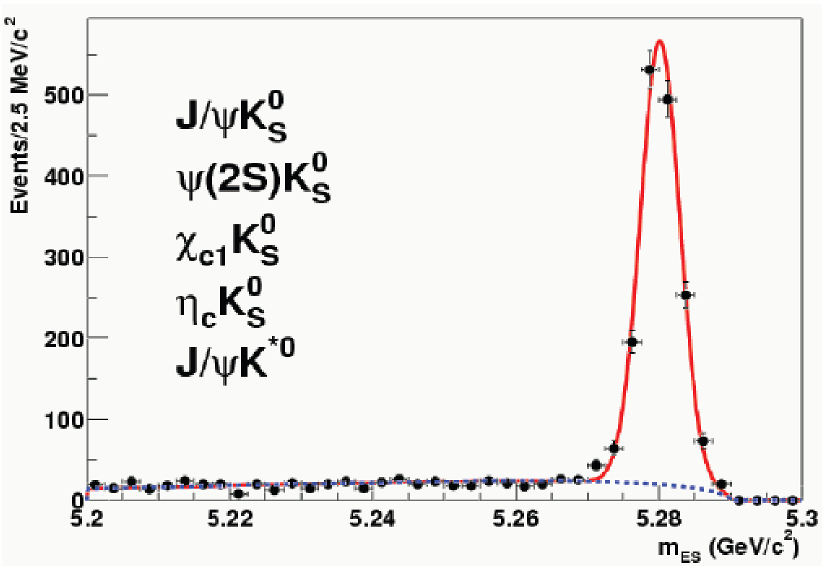
$B^0_{rec} = B^0_{CP}$ **(*CP* eigenstate)** ➡ ***CP* asymmetries**

Time dependent CP violation: Results



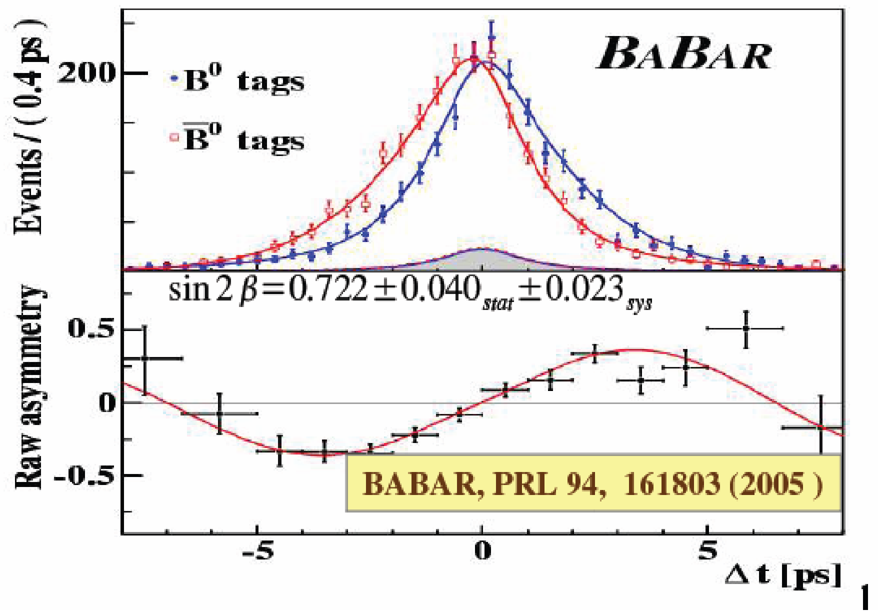
$$\left(\frac{q}{p}\right)_B \frac{\bar{A}}{A} = e^{-2 \cdot i\beta}$$

A clean measurement:

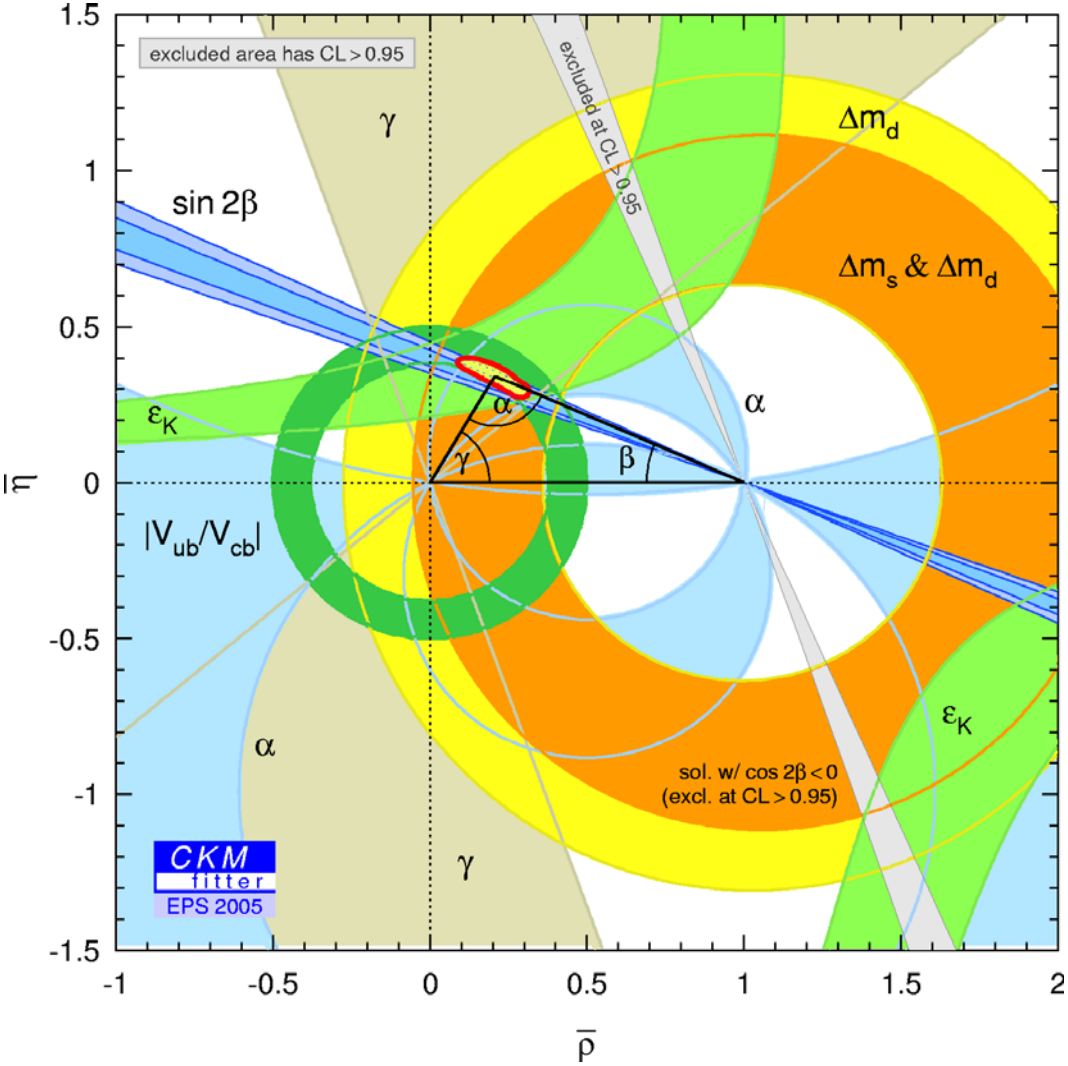


Expected CP asymmetry:

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



CP violation & CKM matrix 2006: a new era



CP violation in SM (CKMfitter):

$$J = (3.11\,^{+0.48}_{-0.57}) \cdot 10^{-5} \text{ @95\%CL}$$

CP violation too small | **Higgs mass too large**

to explain baryon asymmetry in universe by means of SM

=> Indirect hint for NP ... but where ?

$B_s - B_s$ - Oscillation @ CDF II

Stephanie Menzemer

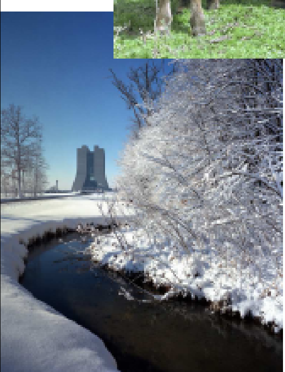
Physikalisches Institut, Heidelberg

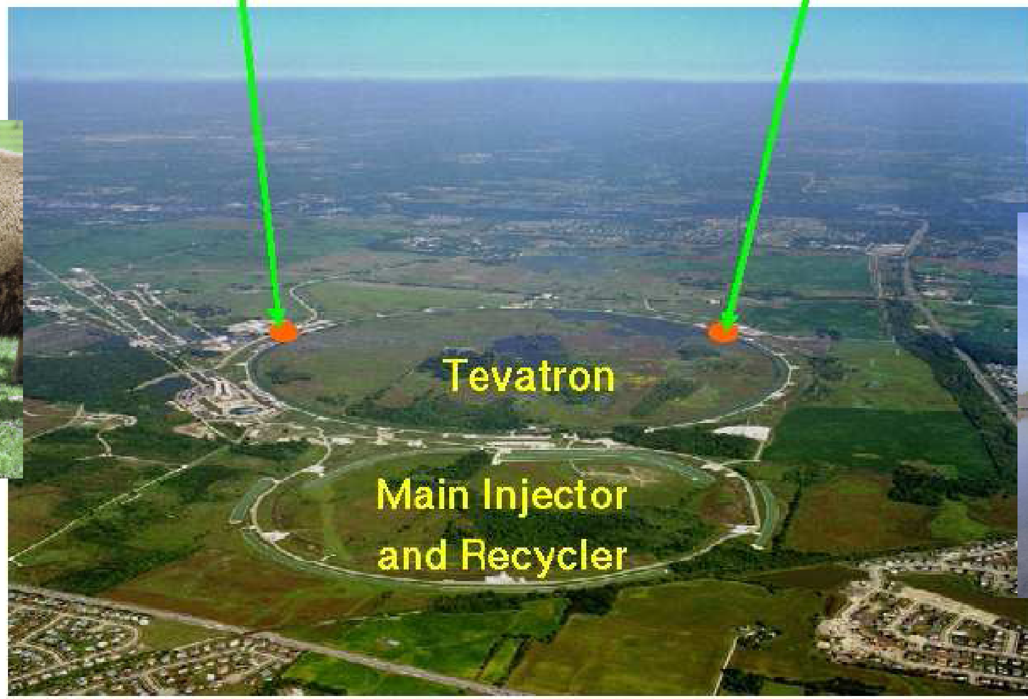
for the CDF Collaboration

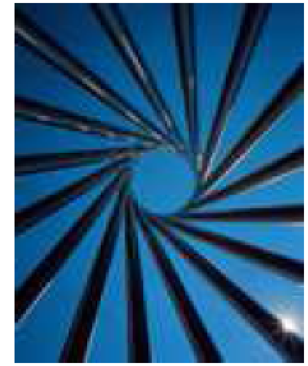
DESY, 13/14th June 2006

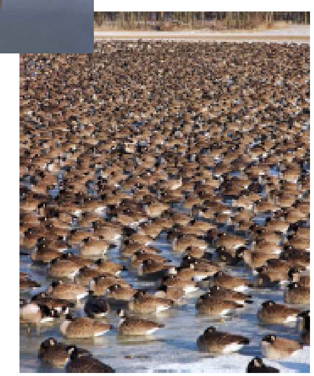
Seminar gestern in Zeuthen!

Tevatron









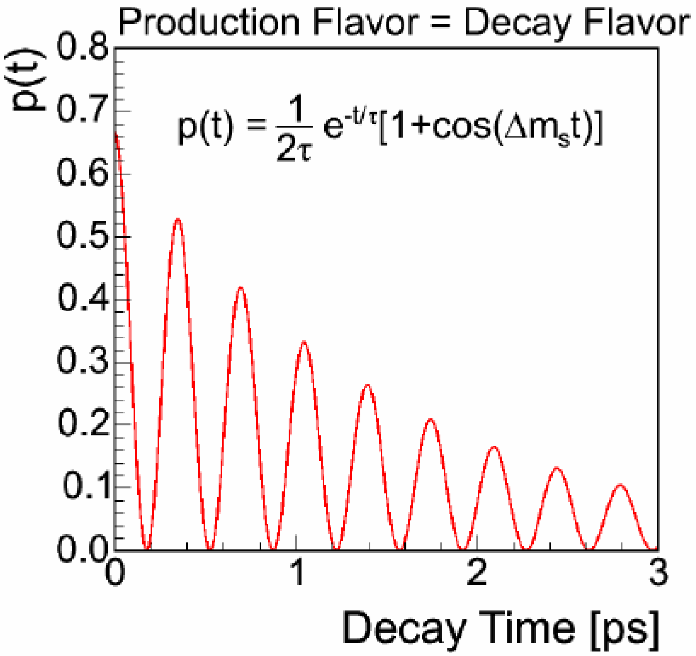
$p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV observed by two experiments

CDF & D0

Neutral B Meson Mixing

Two-state mixing system:

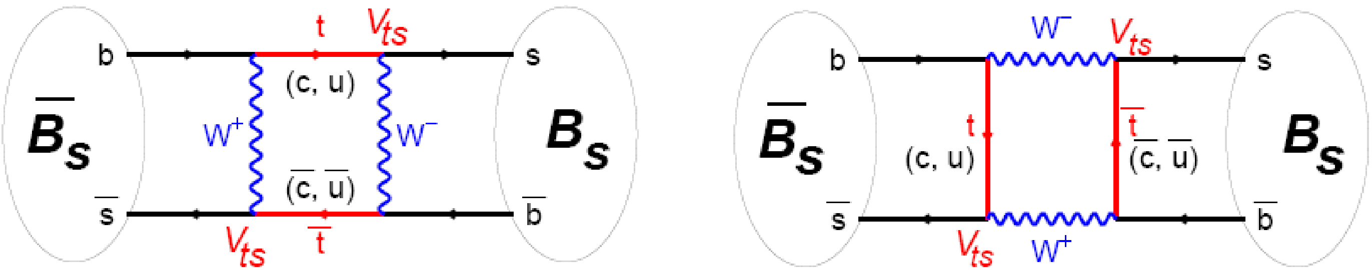
- "heavy" and "light" mass eigenstates
- $B\ (\bar{b}s)$ and $\overline{B}\ (b\bar{s})$ weak eigenstates:
  $$|B_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$$
  $$|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$$
- B_H and B_L may have different mass and decay width
  - $\Delta m = M_H - M_L$
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$
- Solution in proper time ($\Delta\Gamma = 0$)
  $$P(t)_{B_s \to B_s} = \frac{1}{2\tau} e^{-t/\tau}(1 + \cos \Delta m_s t)$$
  $$P(t)_{B_s \to \overline{B}_s} = \frac{1}{2\tau} e^{-t/\tau}(1 - \cos \Delta m_s t)$$



Standard Model Prediction

CKM Matrix: transformation from mass to weak quark eigenstates

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



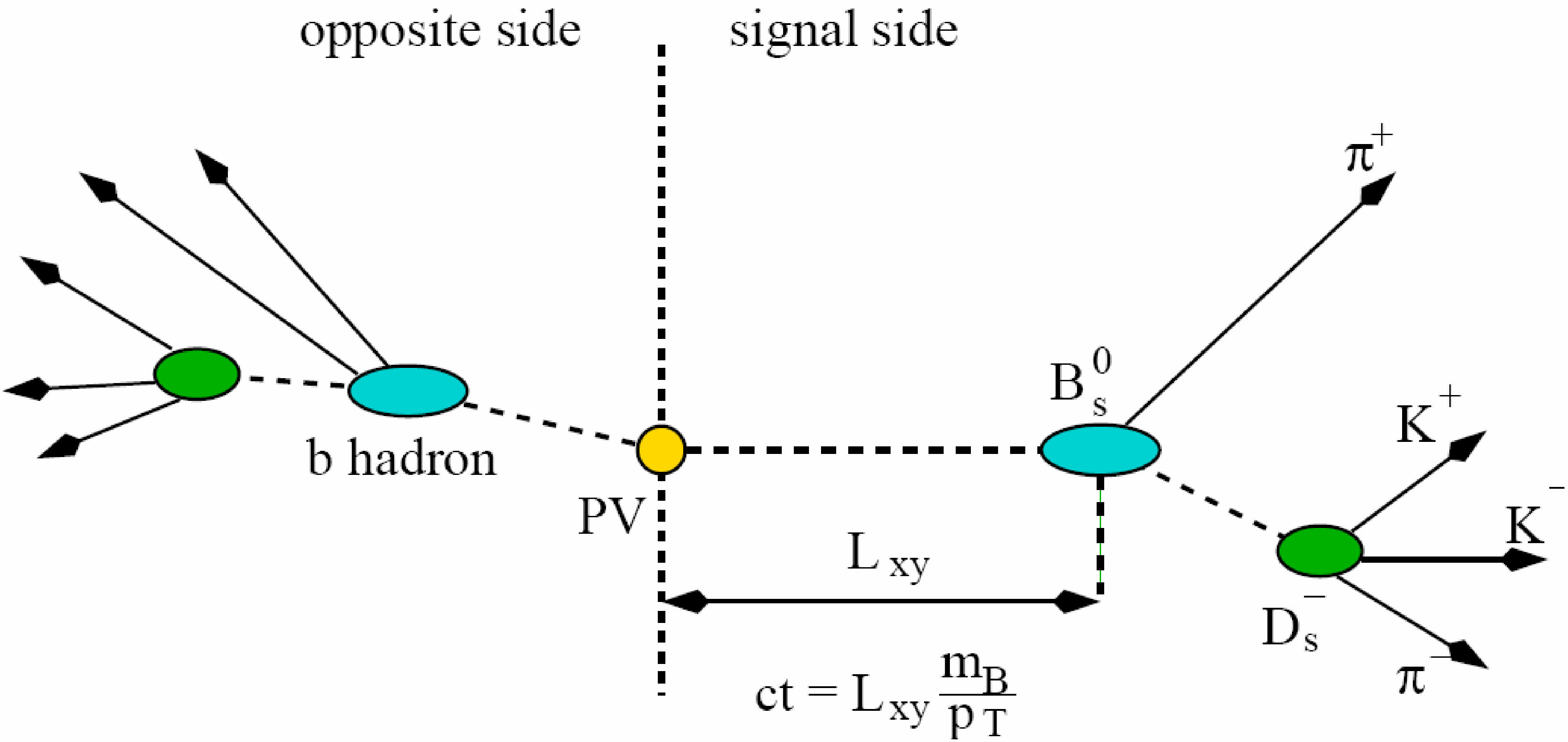
- Access to fundamental SM Parameters:

$$\Delta m_s = \frac{G_F^2 M_W^2 \eta S(m_t^2/m_W^2)}{6\pi^2} m_{B_s} f_{B_{B_s}}^2 |V_{ts}^* V_{tb}|^2$$

- Hadronic uncertainties cancel in ratio: $\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$

improved lattice QCD: ξ = 1.210 $^{+0.047}_{-0.035}$ (hep/lat-0510113)

$B_s - \bar{B}_s$ Mixing Analysis



1) B_s selection & reconstruction

2) Measurement of proper decay time ct & ct resolution

3) Flavor tagging (main challenge at hadron colliders)

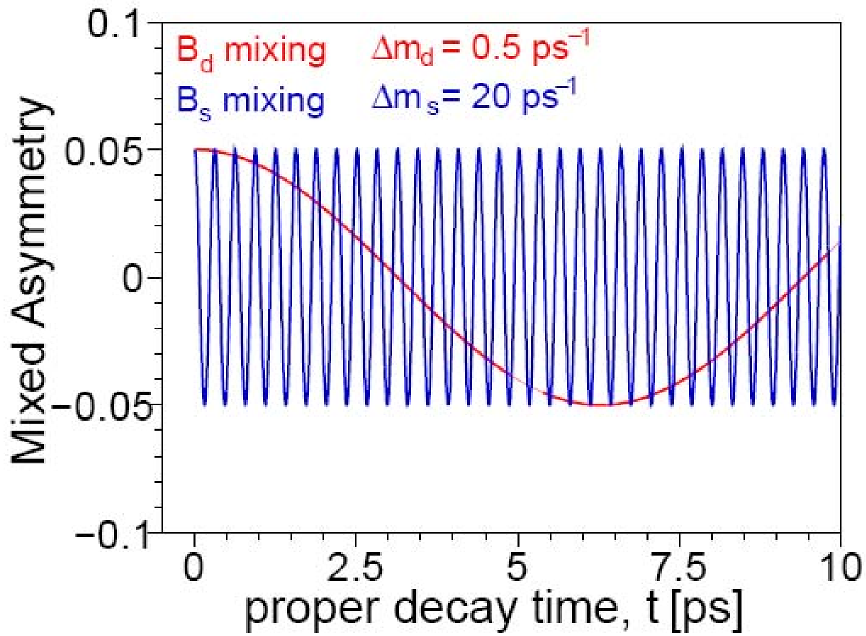
Why is it so difficult?

B_s Mixing is very very fast!

Challenges:

- High vertex resolution
- High momentum resolution
- Large statistics
- Good tagging

Very complex analysis!



$$\text{significance} = \sqrt{\frac{S\epsilon D^2}{2}}\frac{S}{S+B}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$$

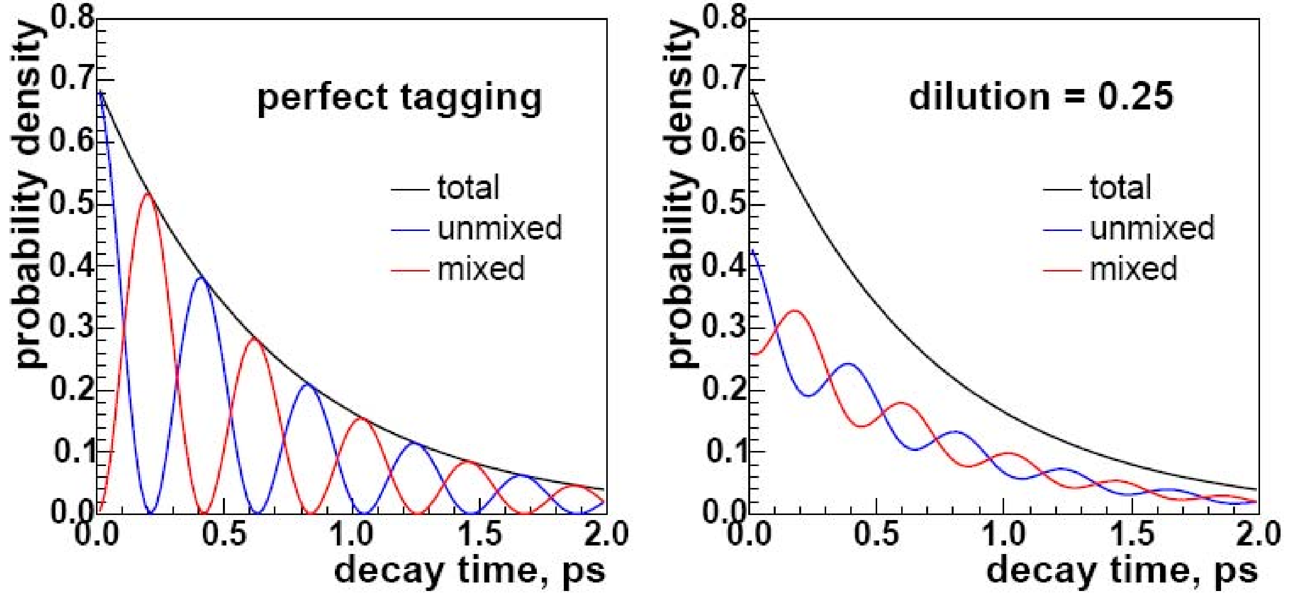
ϵD^2: tagging performance (efficiency ϵ and dilution D = 1-2*P$_{mistag}$),

$\sigma(ct)$: proper time resolution, for high Δm_s, $\sigma(ct)$ is crucial!

S,B: signal and background yields

Effect of Imperfect Tagging

Dilution dampens the observed oscillation!



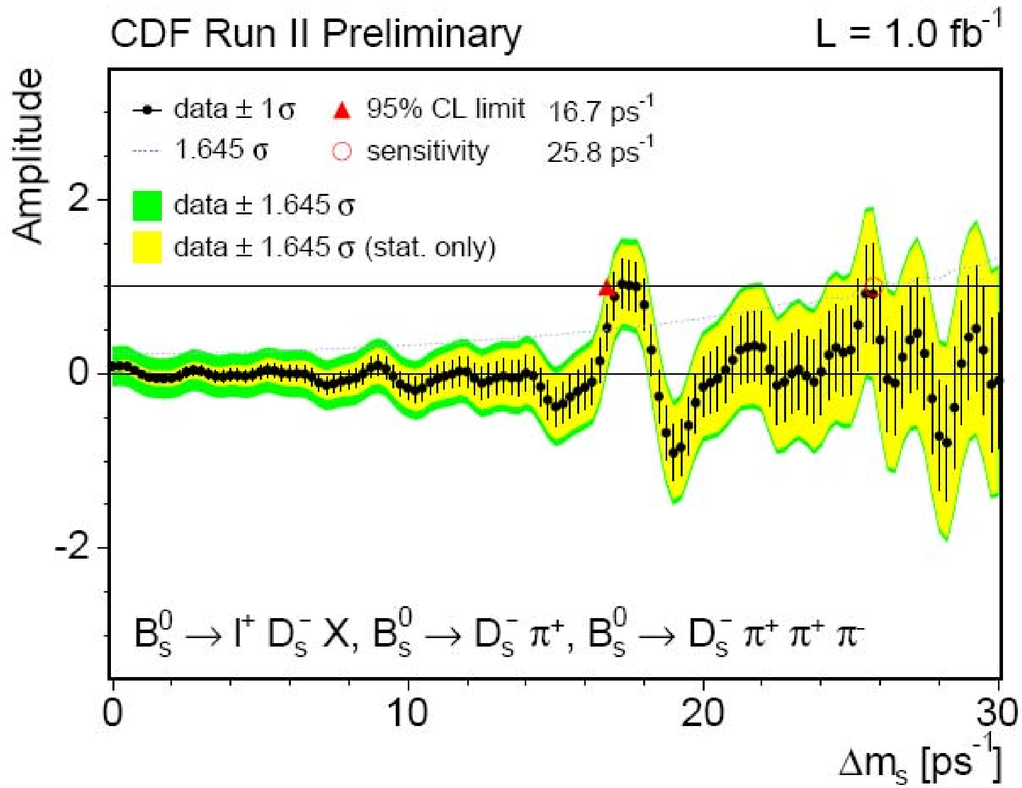
$\mathcal{D}$ = 25% $\longrightarrow$ 62.5% of the events are correctly tagged.

$$\mathcal{A}(t) \equiv \frac{N(t)_{mixed} - N(t)_{unmixed}}{N(t)_{mixed} + N(t)_{unmixed}} = \mathcal{D}\cos(\Delta m_s t)$$

(in this example: Δm_s = 2.5 ps $^{-1}$)

Combined Amplitude Scan

$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim 17.25$ ps^{-1}!

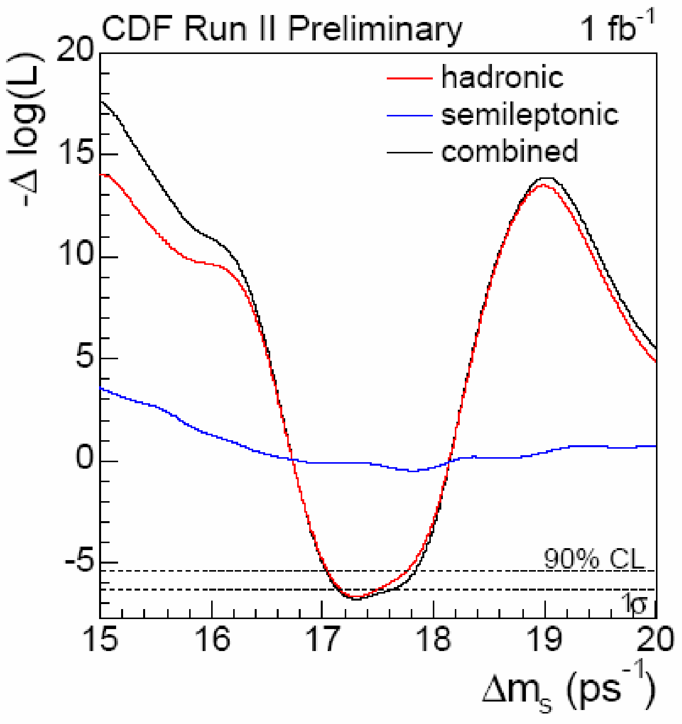


$$\mathcal{A}/\sigma_{\mathcal{A}}(\Delta m_s = 17.25\ \text{ps}^{-1}) \sim 3.7$$

Δm_s Measurement

Δm_s in [17.01, 17.84] ps^{-1} @ 90% C.L.

Δm_s in [16.96, 17.91] ps^{-1} @ 95% C.L.



$$\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)\text{ps}^{-1}$$

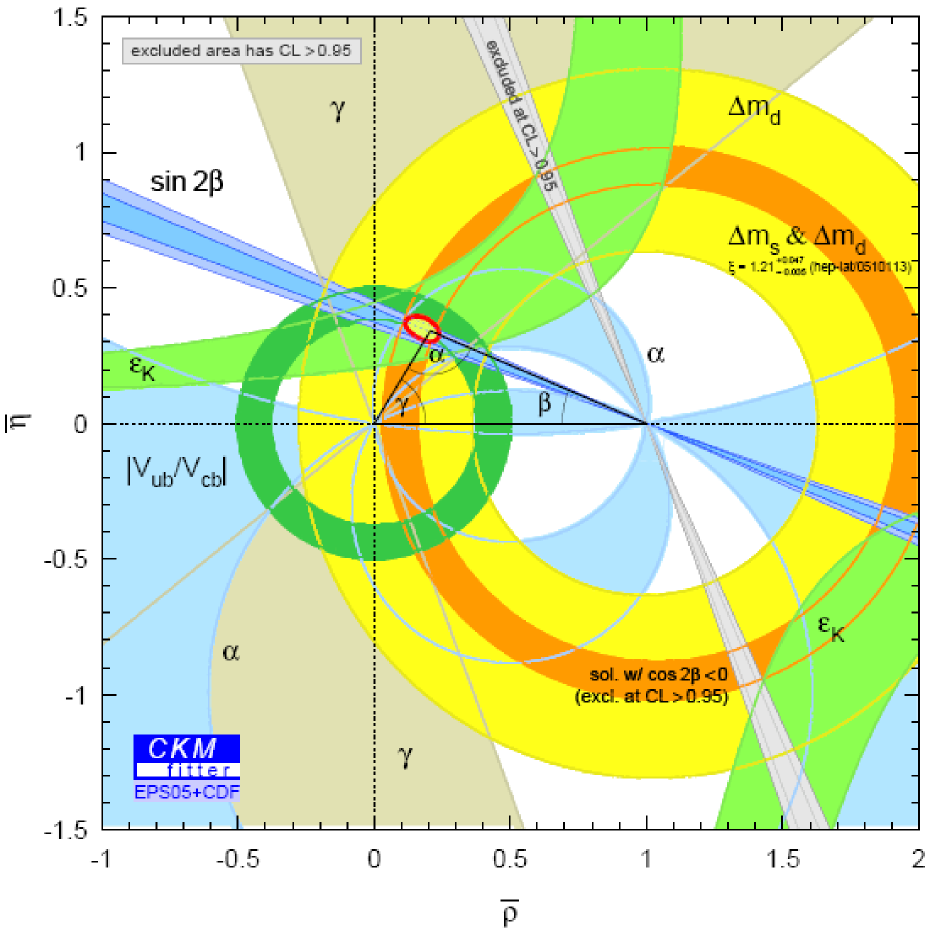
Systematic dominated by uncertainties on ct.

$|V_{td}|/|V_{ts}|$ Measurement

Input	Value	Source
$\frac{m(B^0)}{m(B_s)}$	0.98320	PDG
ξ	$1.21^{+0.047}_{-0.035}$	Lattice 2005
Δm_d	0.505 ± 0.005	PDG
Δm_s	$17.310^{+0.34}_{-0.19}$	this analysis

$|V_{td}|/|V_{ts}| =$

$0.208\ ^{+0.001}_{-0.002}$(exp.) $^{+0.008}_{-0.006}$ (theo.)



Belle measurement $b \to d\gamma$:

$|V_{td}|/|V_{ts}| = 0.199\ ^{+0.026}_{-0.025}$(exp.) $^{+0.018}_{-0.015}$(theo.)