CP Violation and CKM Physics at the B Factories

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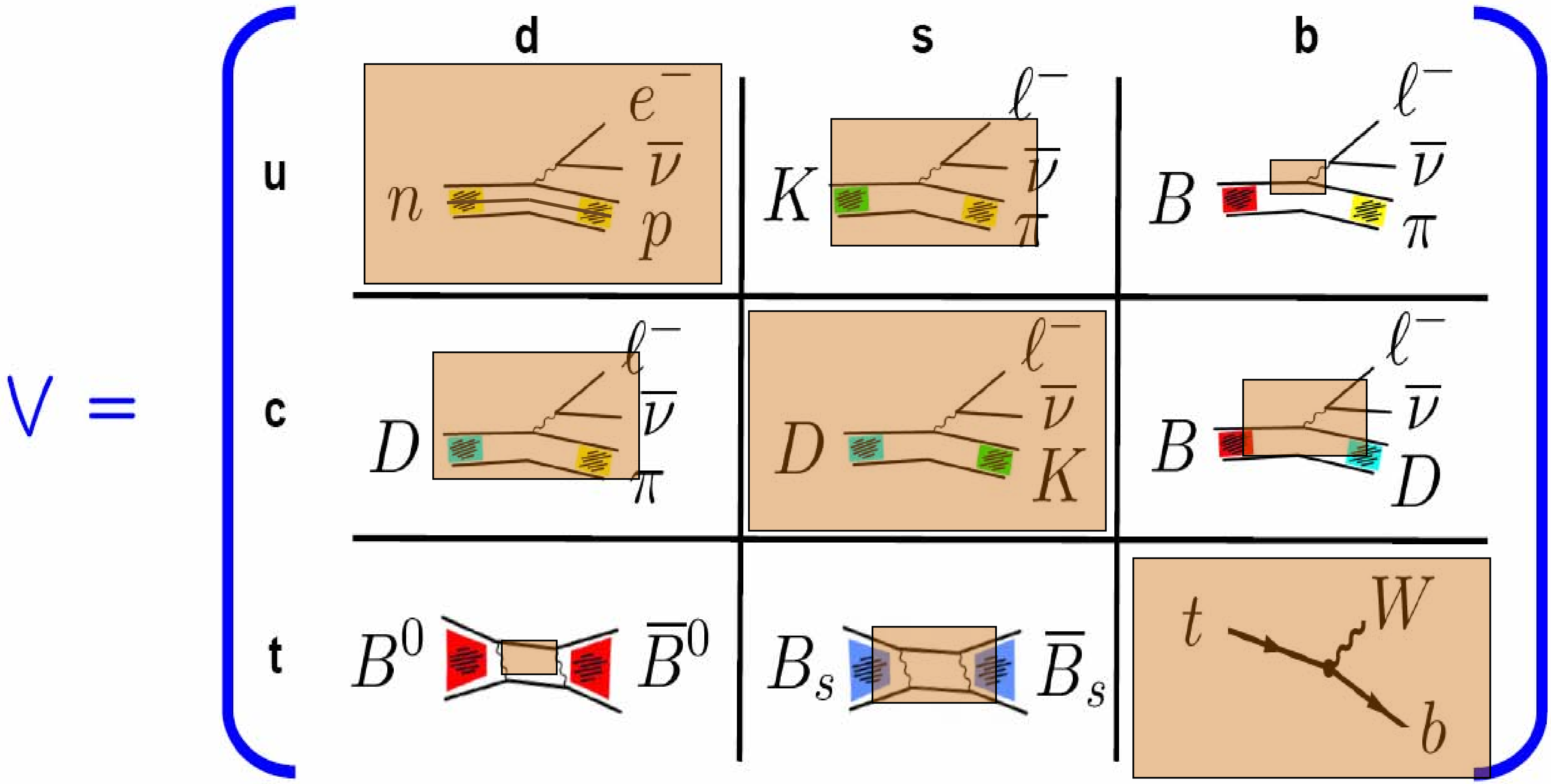
(for Belle & BaBar Collaborations)

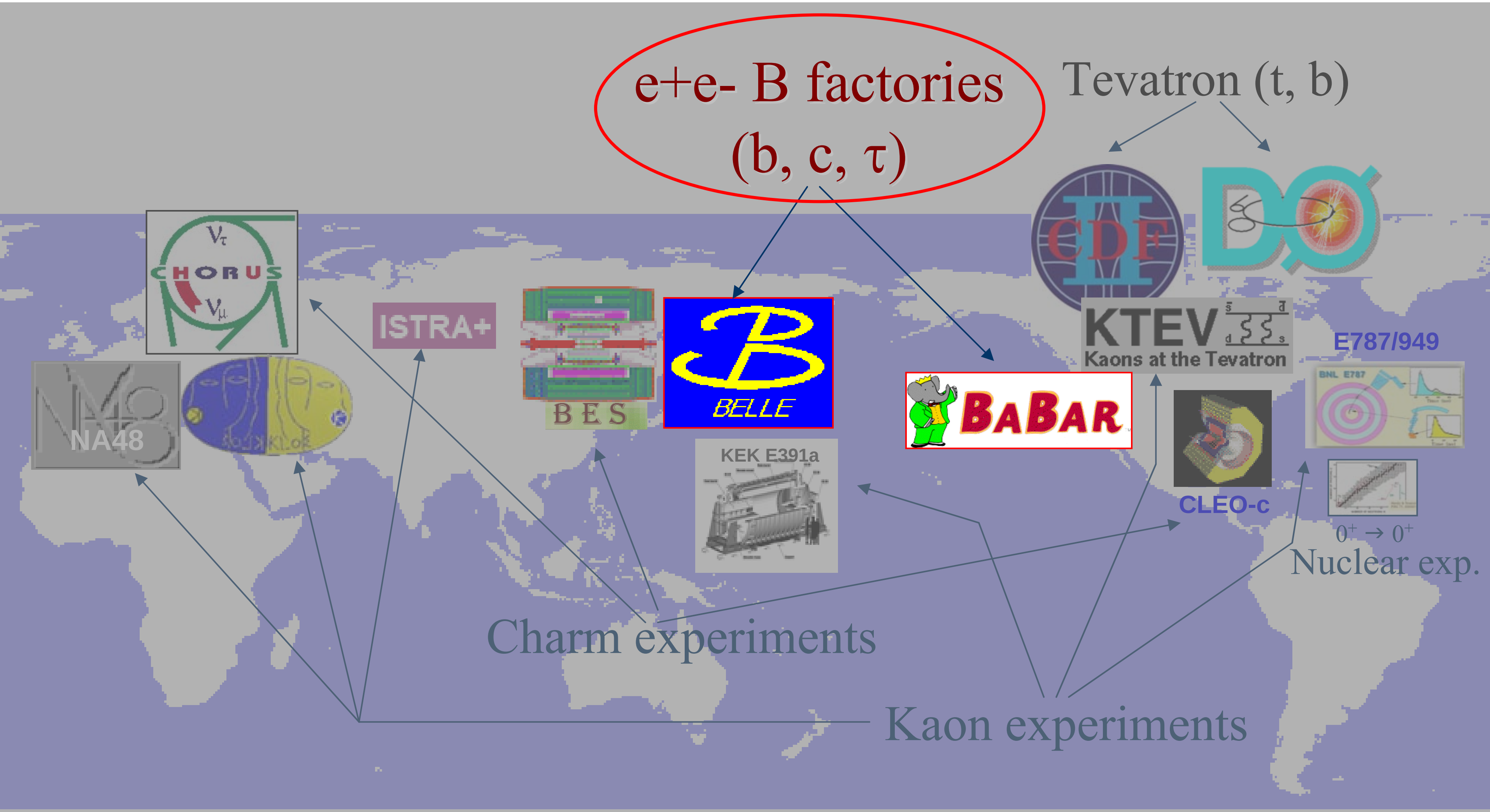
CKM Matrix

Elements of the Cabibbo-Kobayashi-Maskawa matrix describe transitions between up and down quarks



CKM & CPV Around The World

Major experiments, ongoing or recently ended



Asymmetric-Energy B Factories

$e^+e^- \Rightarrow \Upsilon(4S) \Rightarrow B\bar{B}$

- $2M_B \approx M_{\Upsilon(4S)}$ ⇨ B mesons are (almost) at rest in the Y(4S) rest frame.

- Must be able to measure time difference between B and $\bar{B}$ decays (distance between B and $\bar{B}$ decay vertices).
  ⇨ asymmetric energy collisions
  ⇨ good vertex detector

- Must be able to distinguish between B and B decays (flavor tag)
  ⇨ good particle identification capability

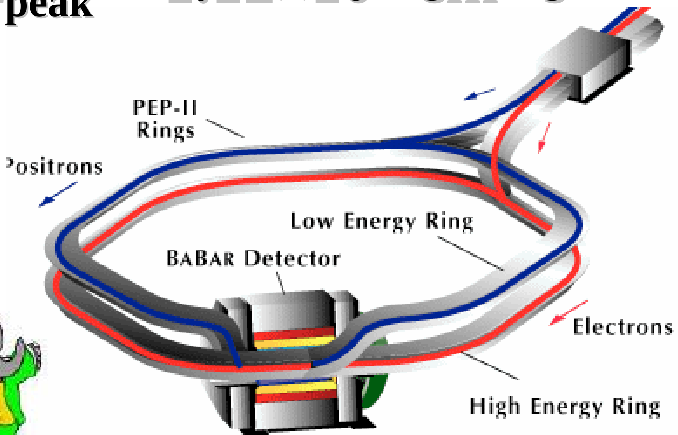
- The goal is to measure asymmetry in decays of B and $\bar{B}$ mesons (~10%) with reasonable accuracy (~10%). The relevant BF~10^{-6} with reconstruction efficiency of ~20%
  ⇨ ~10^8 of B mesons required

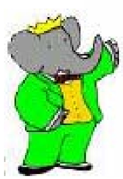
Asymmetric-Energy B Factories

PEP-II at SLAC

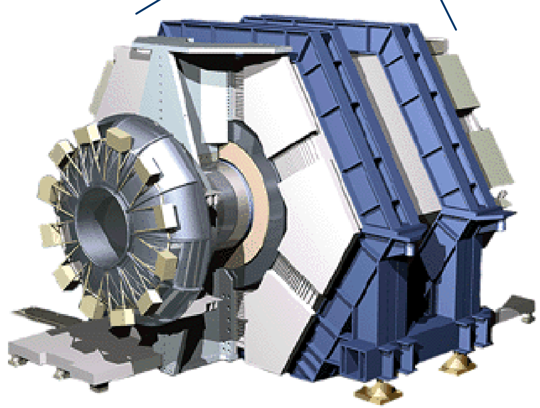
9GeV (e^-) × 3.1GeV (e^+)

$L_{peak} = 1.12\times10^{34}\text{cm}^{-2}\text{s}^{-1}$





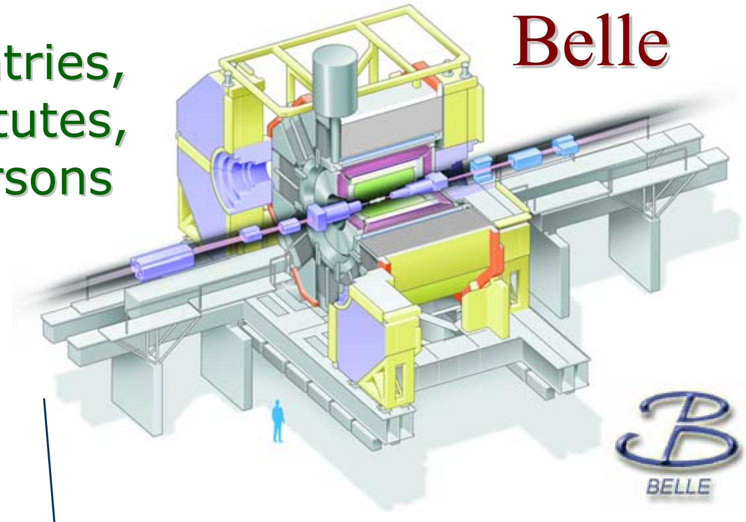
BABAR

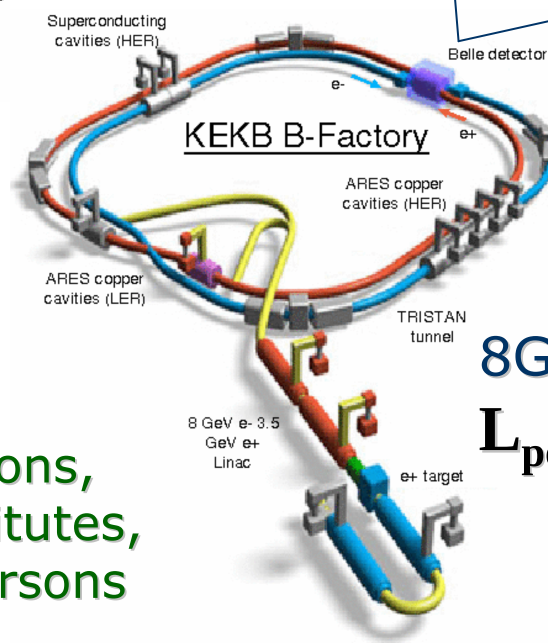


11 nations,
80 institutes,
~600 persons

13 countries,
57 institutes,
~400 persons

Belle





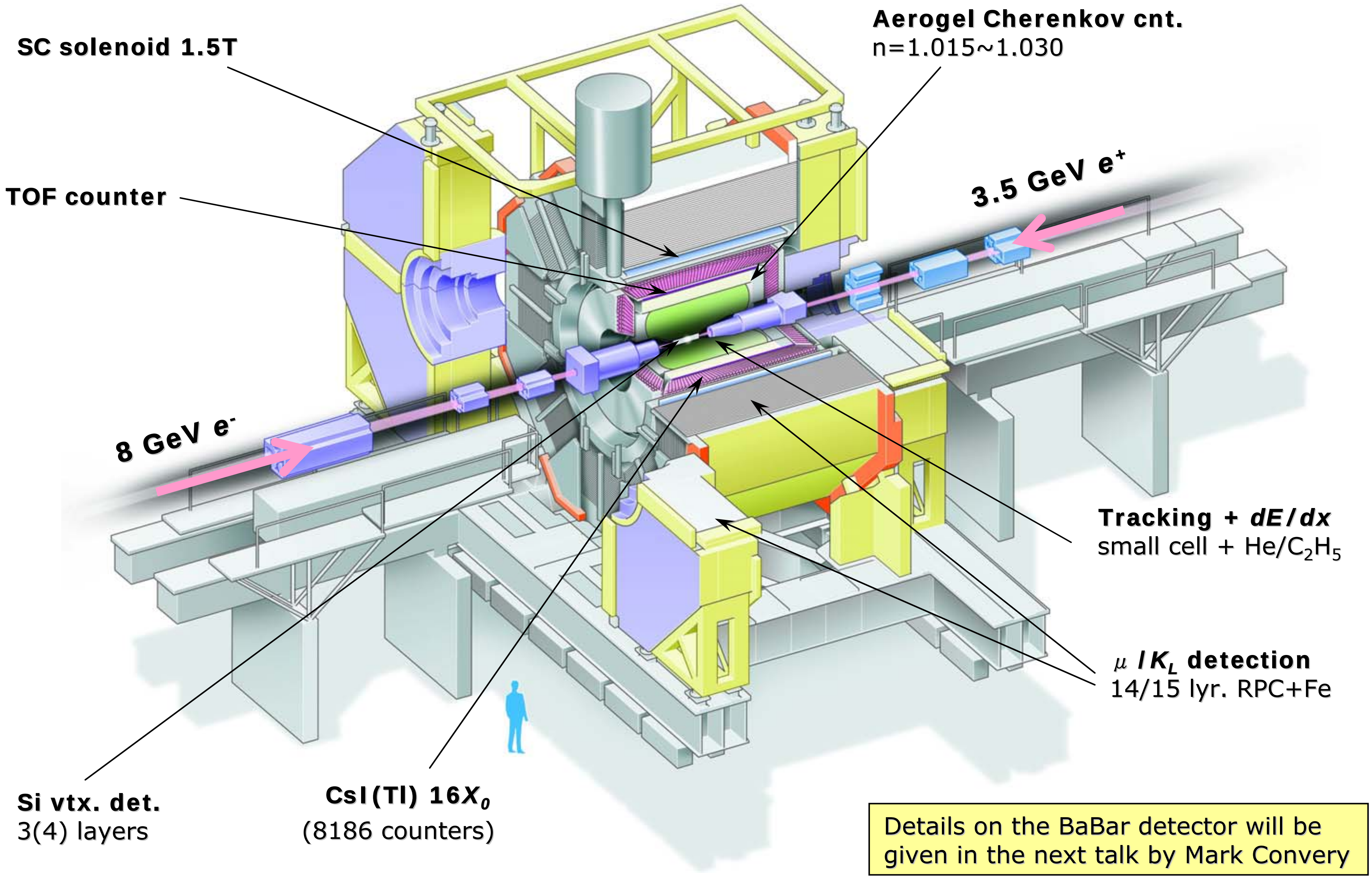
KEKB at KEK

8GeV (e^-) × 3.5GeV (e^+)

$L_{peak} = 1.71\times10^{34}\text{cm}^{-2}\text{s}^{-1}$

world record !

Belle Detector

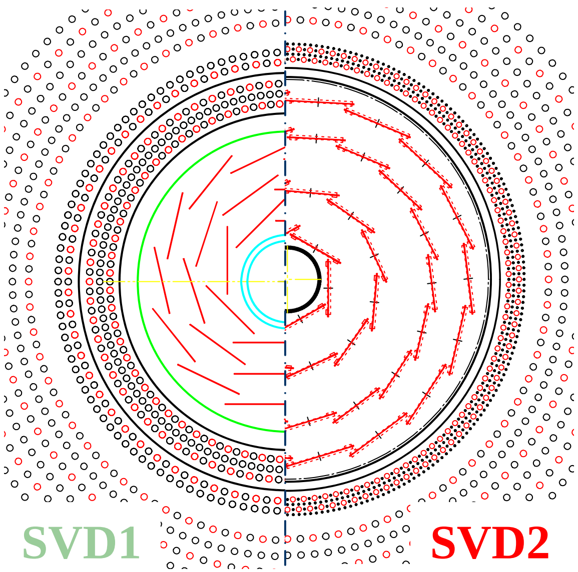


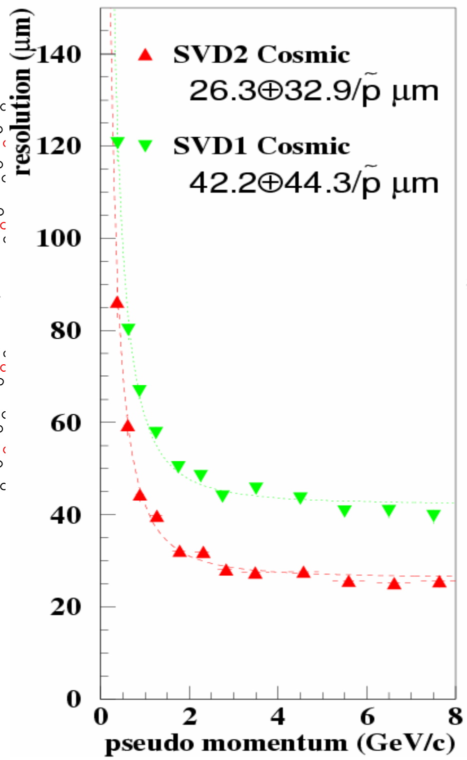
Details on the BaBar detector will be given in the next talk by Mark Convery

Belle Vertex Detector

Belle's SVD

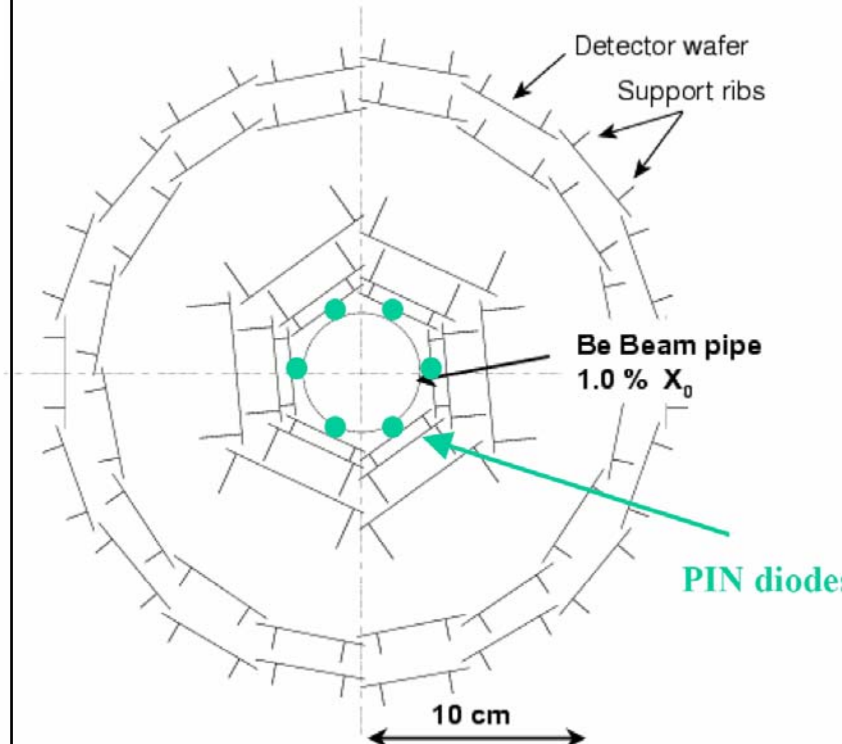
In 2004 SVD has been upgraded from 3 to 4 layer setup.





Vertex resolution:
$\sigma_Z \approx 150$um

BaBar's SVT

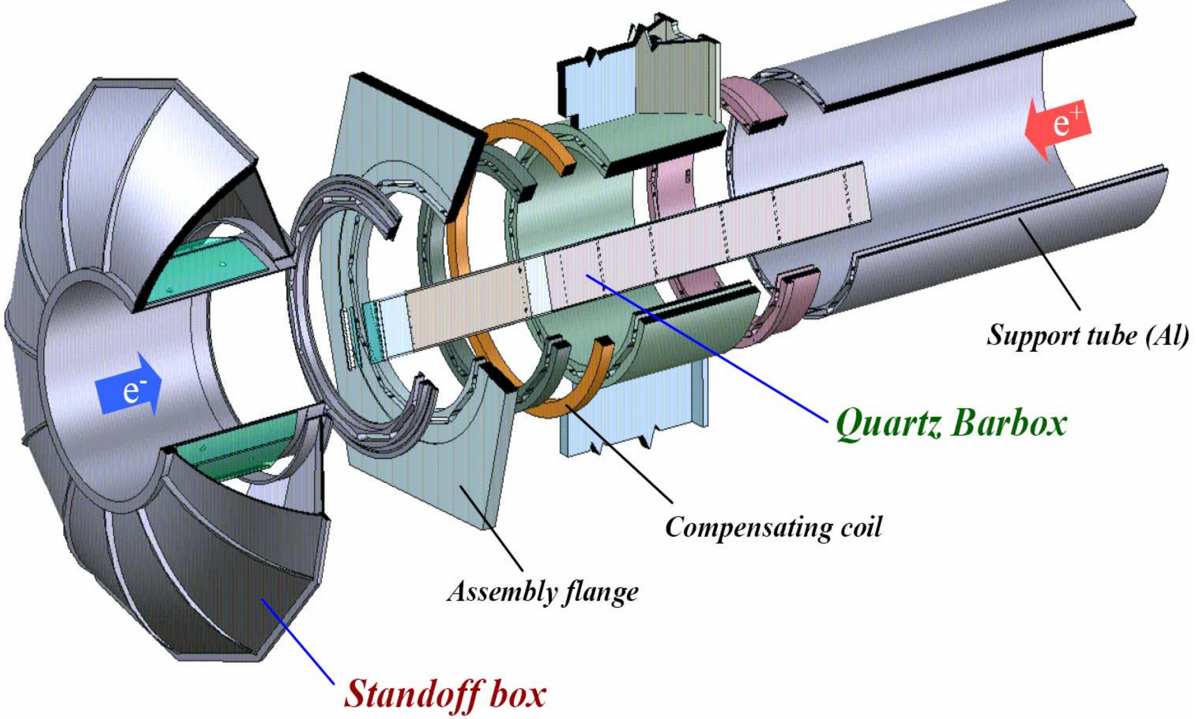


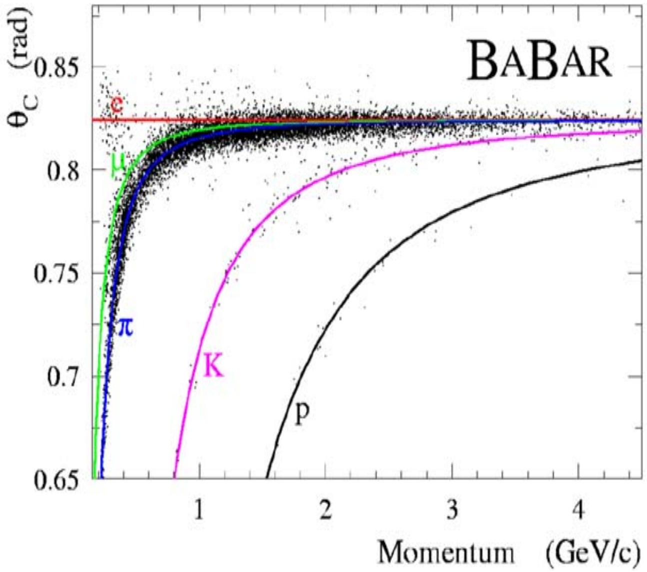
Vertex resolution:
$\sigma_Z \approx 120$um

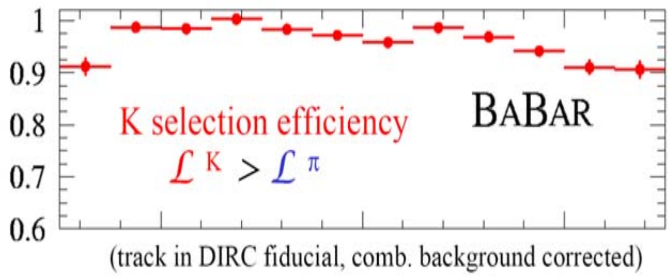
Average B flight: $\tau\beta\gamma \sim 200\mu$m

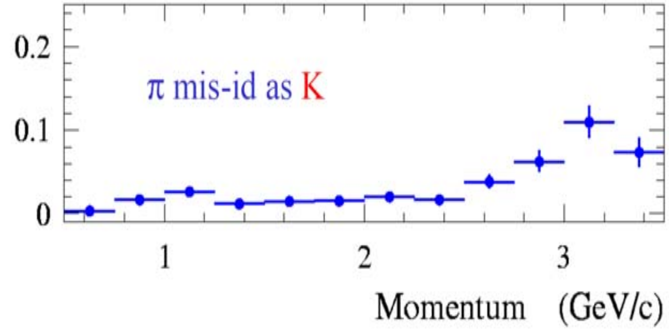
Particle Identification: BaBar

D ETECTION OF
I NTERNALLY
R EFLECTED
C HERENKOV LIGHT

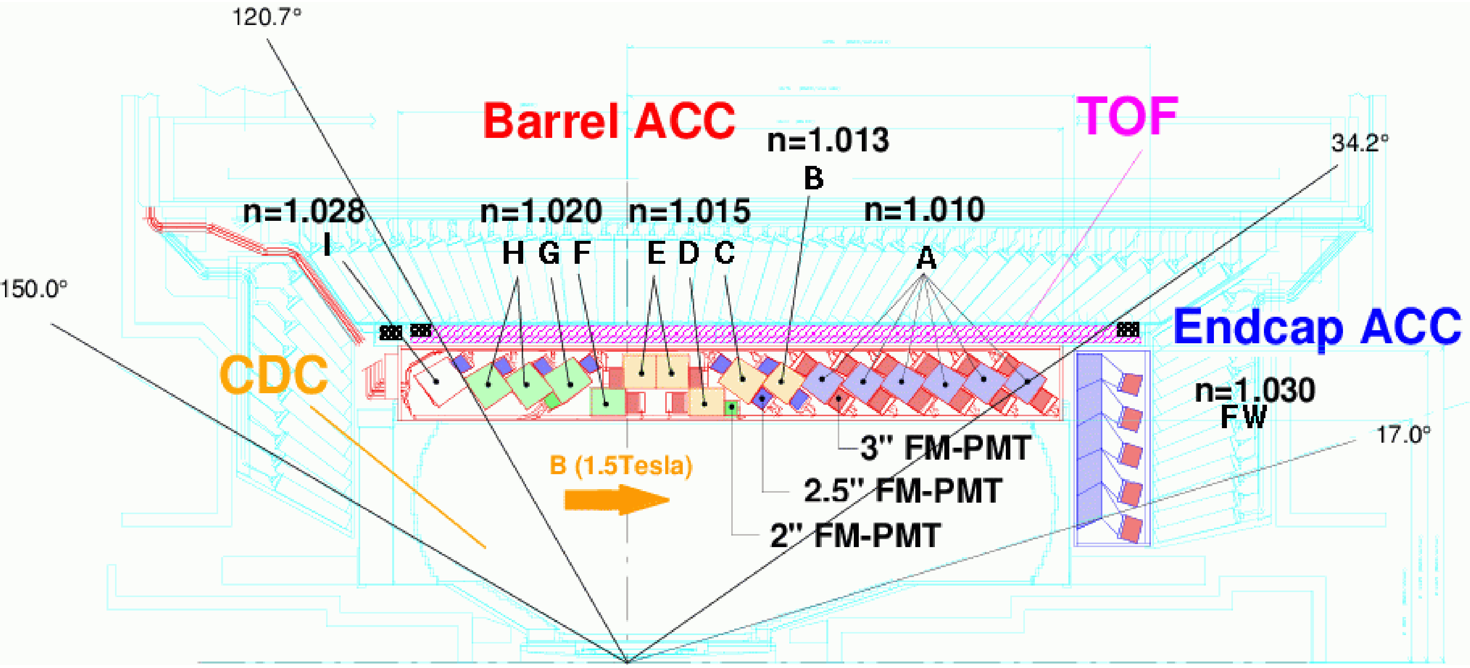






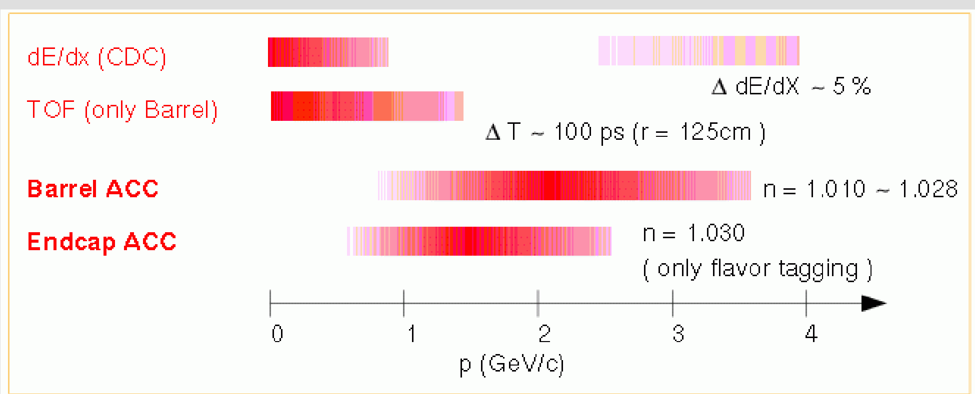


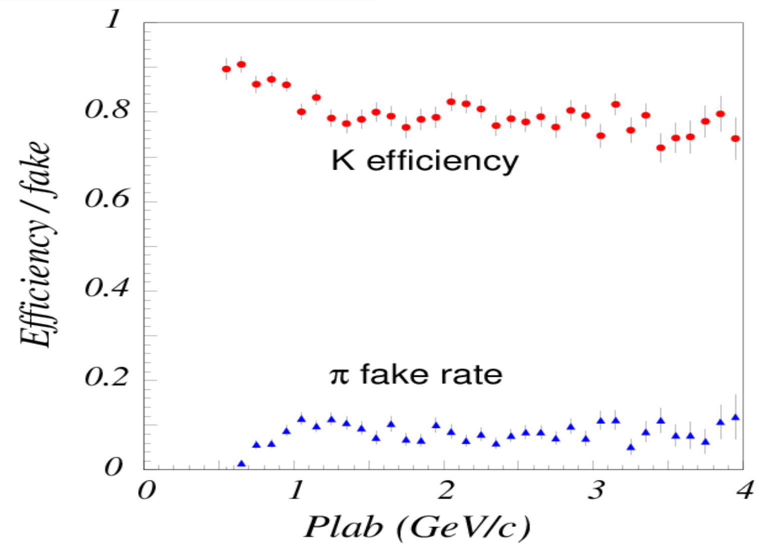
Particle Identification: Belle



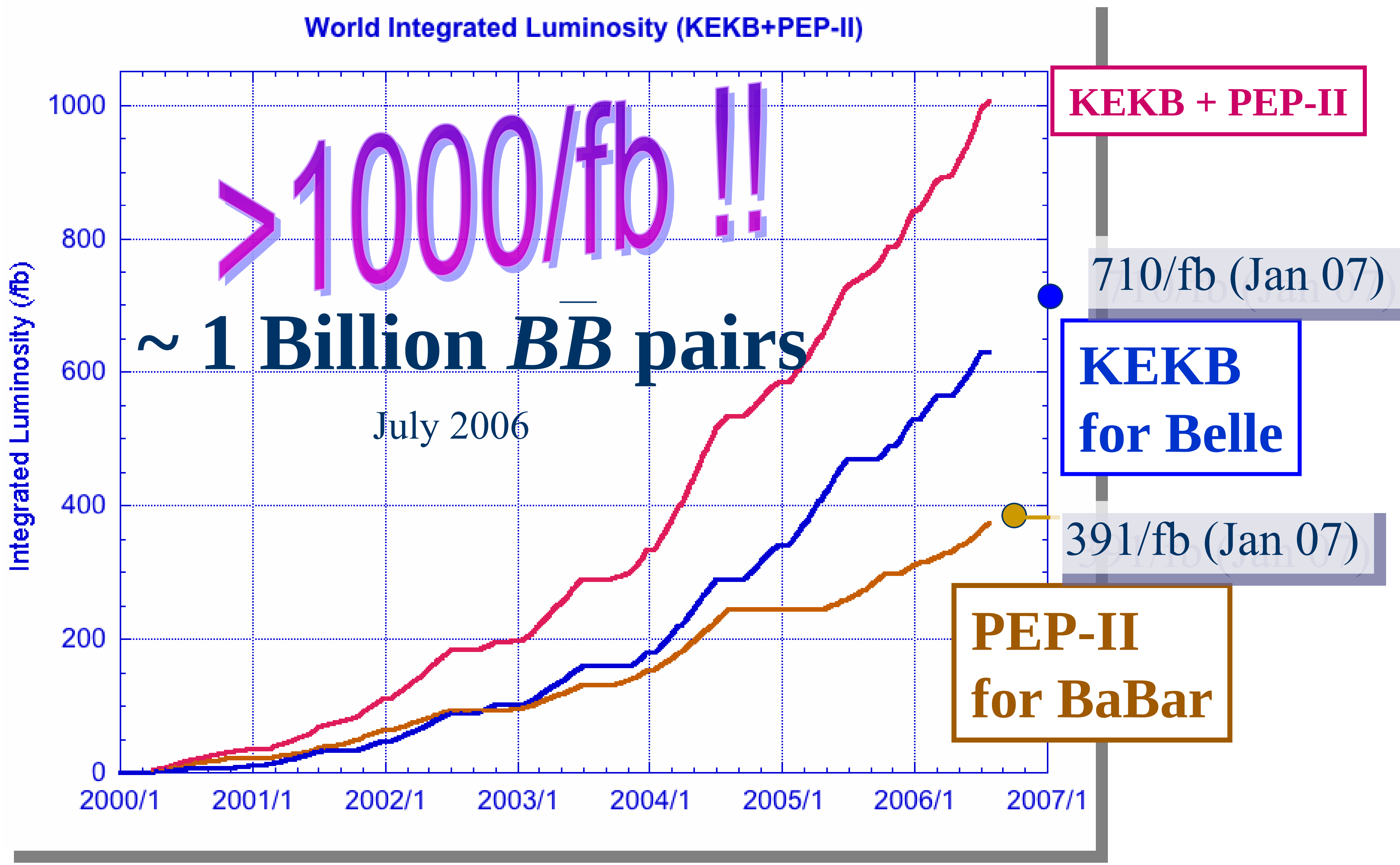
p/K/π separation is based on Likelihood ratio:

$$LR(K) = \frac{L(K)}{L(K)+L(\pi)}$$





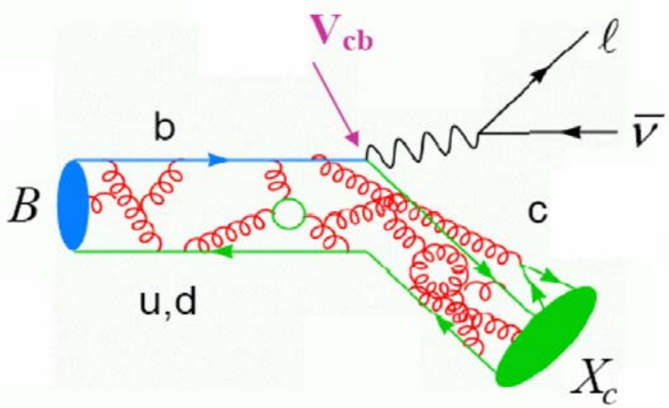
B Factories


World Integrated Luminosity (KEKB+PEP-II)
Integrated Luminosity (/fb)
1000
800
600
400
200
0
2000/1
2001/1
2002/1
2003/1
2004/1
2005/1
2006/1
2007/1
>1000/fb !!
~ 1 Billion $B\bar{B}$ pairs
July 2006
KEKB + PEP-II
710/fb (Jan 07)
KEKB
for Belle
391/fb (Jan 07)
PEP-II
for BaBar

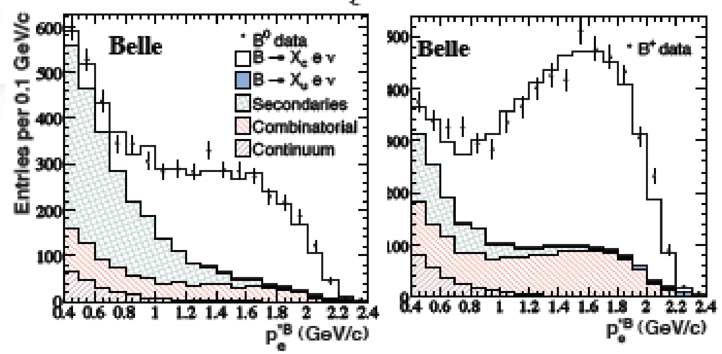
$|V_{ij}|$ Results

$|V_{cb}|$

Inclusive/Exclusive semileptonic B decays: $B \to X_c l\nu$



Inclusive E_ℓ spectrum



rate

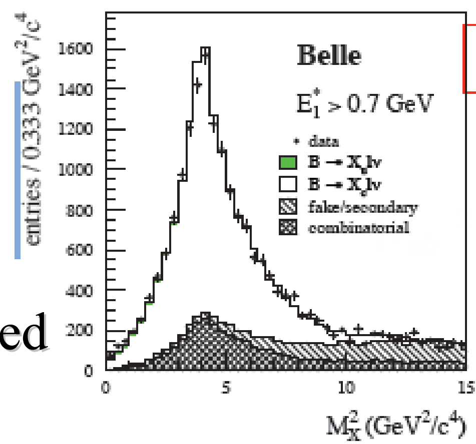
shape

$|V_{cb}|$

m_b, m_c

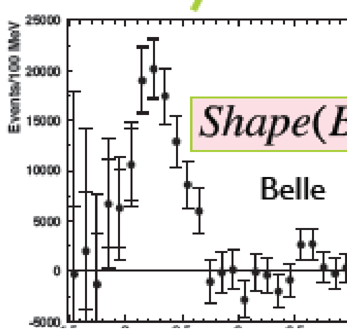
μ^2_G, μ^2_π

Inclusive M_X spectrum



shape

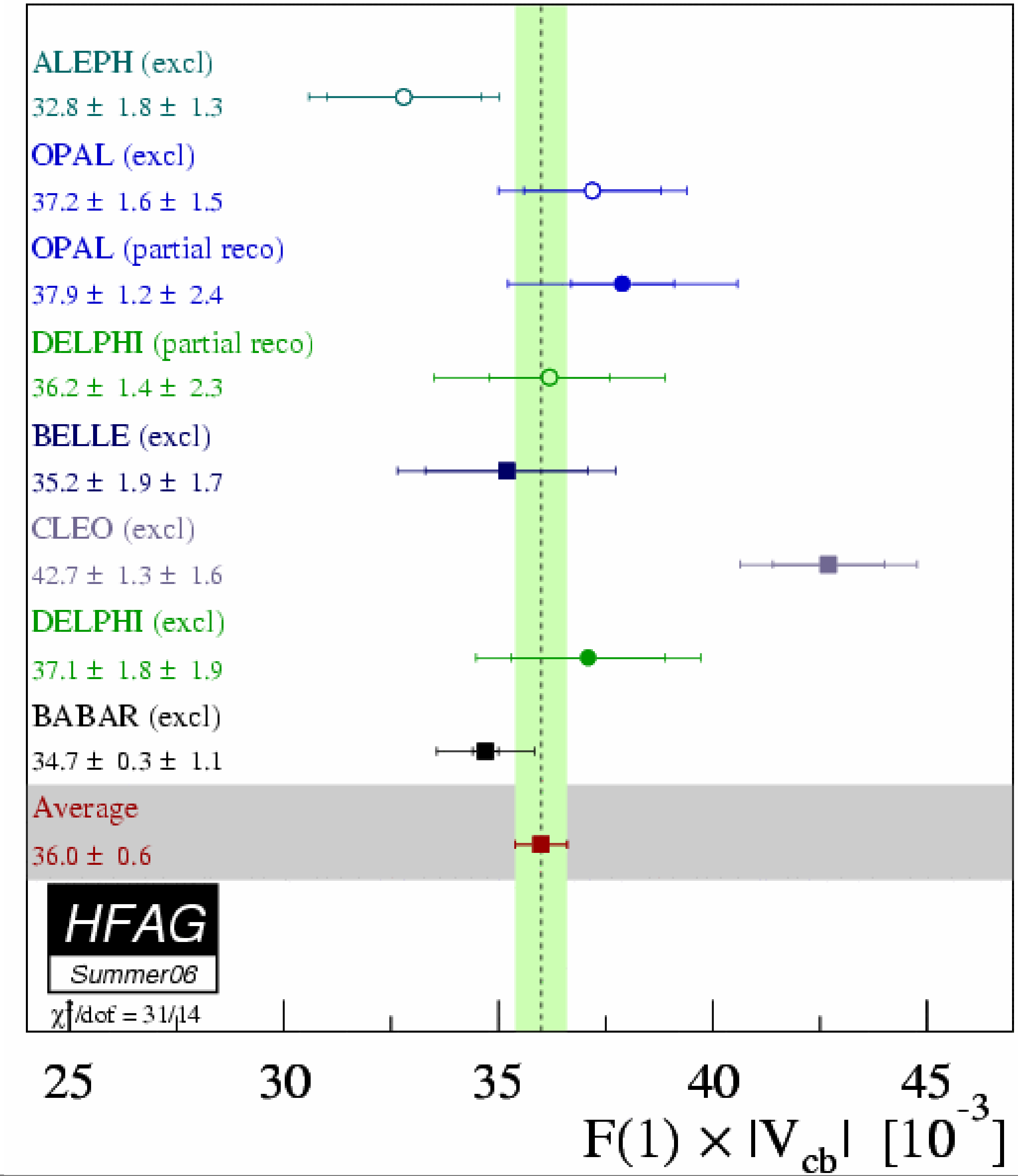
$|V_{ub}|$



3 independent parameters

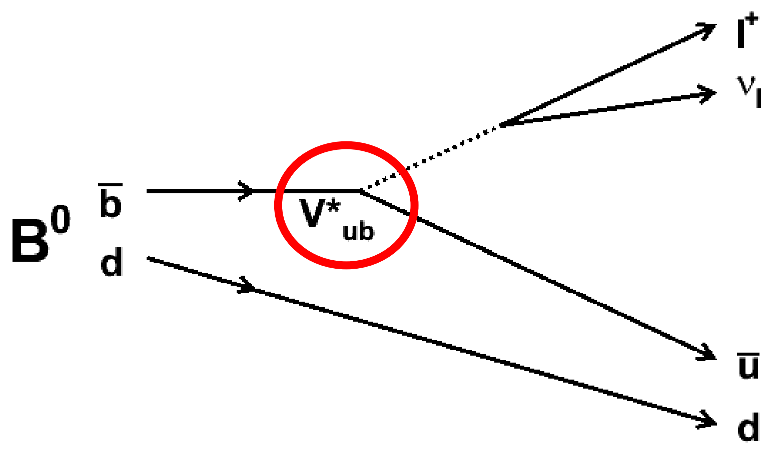
- E_l: lepton energy
- q^2: lepton-neutrino mass squared
- M_x: hadronic mass

$|V_{cb}|$: Summary



ALEPH (excl)
32.8 ± 1.8 ± 1.3
OPAL (excl)
37.2 ± 1.6 ± 1.5
OPAL (partial reco)
37.9 ± 1.2 ± 2.4
DELPHI (partial reco)
36.2 ± 1.4 ± 2.3
BELLE (excl)
35.2 ± 1.9 ± 1.7
CLEO (excl)
42.7 ± 1.3 ± 1.6
DELPHI (excl)
37.1 ± 1.8 ± 1.9
BABAR (excl)
34.7 ± 0.3 ± 1.1
Average
36.0 ± 0.6
HFAG
Summer06
χ²/dof = 31/14
25
30
35
40
45
F(1) × |V_cb| [10^-3]

| V_{ub} | Method

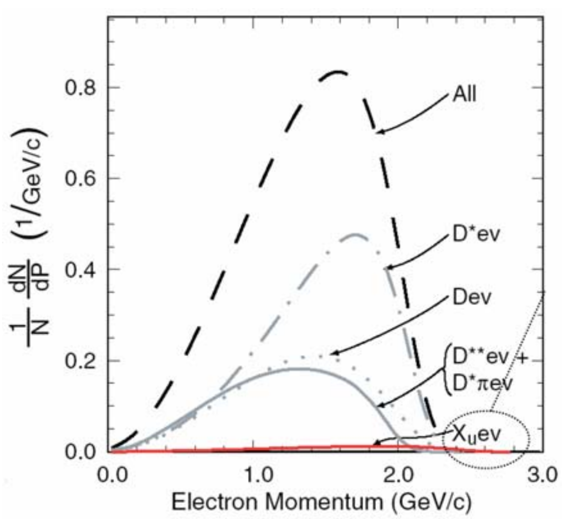


In principle, simple measurement of rate $\propto |V_{ub}|^2$

- But huge rate of semileptonic $b \to c$

Inclusive $B \to X_u l^+ \nu_l$

- Use high momentum lepton ("endpoint"), X_u mass (or both)
- Need to correct for missing parts of spectra



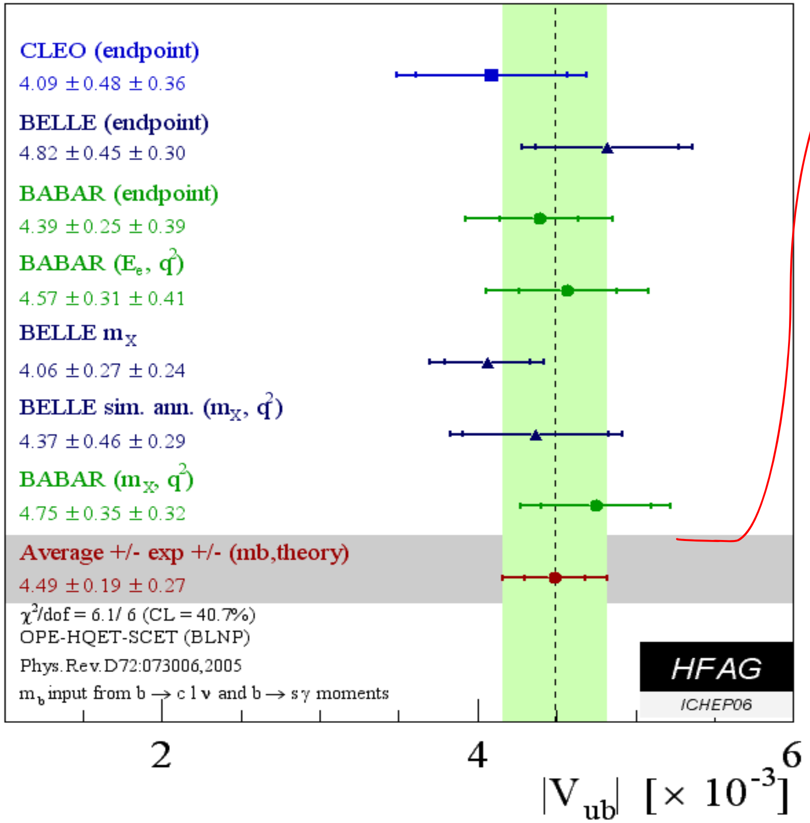
Exclusive $B^{0/+} \to \pi^{-/0} l^+ \nu_l$

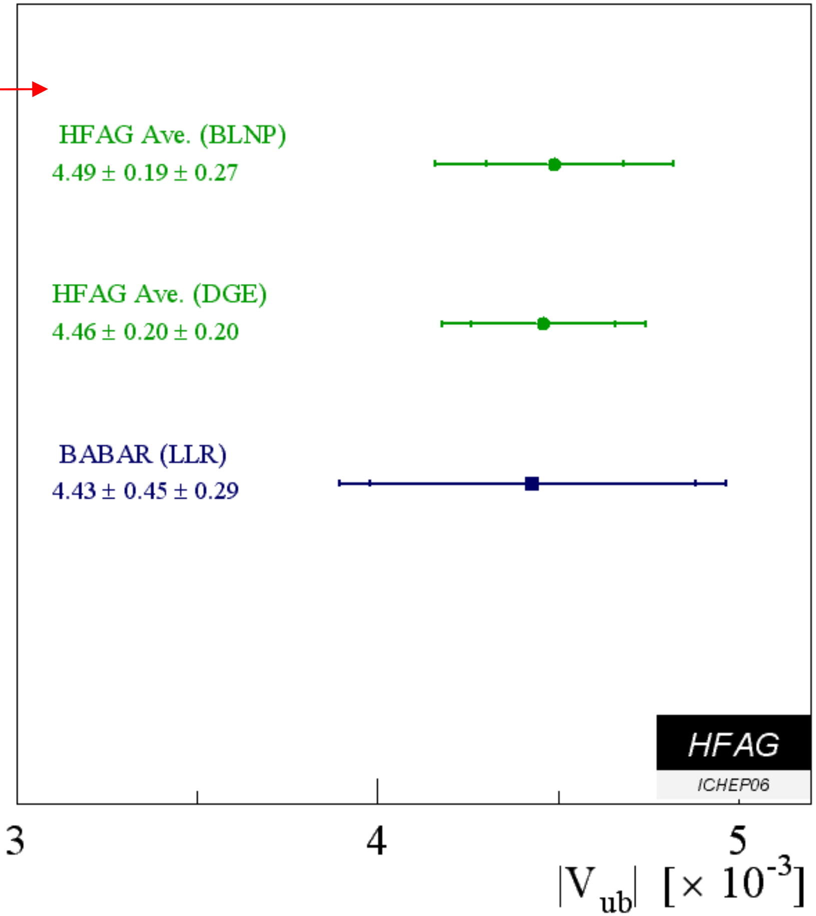
- Correct B^+ decays for lifetime difference
- Need to include form factor $f^+(q^2 = m_{l\nu}^2)$ for $B \to \pi$ transition

| V_{ub} | Inclusive

BLNP: Lange, Neubert, Paz (2005)
DGE: Anderson, Gardi (2006)
LLR: Leibovich, Low, Rothstein (2006)

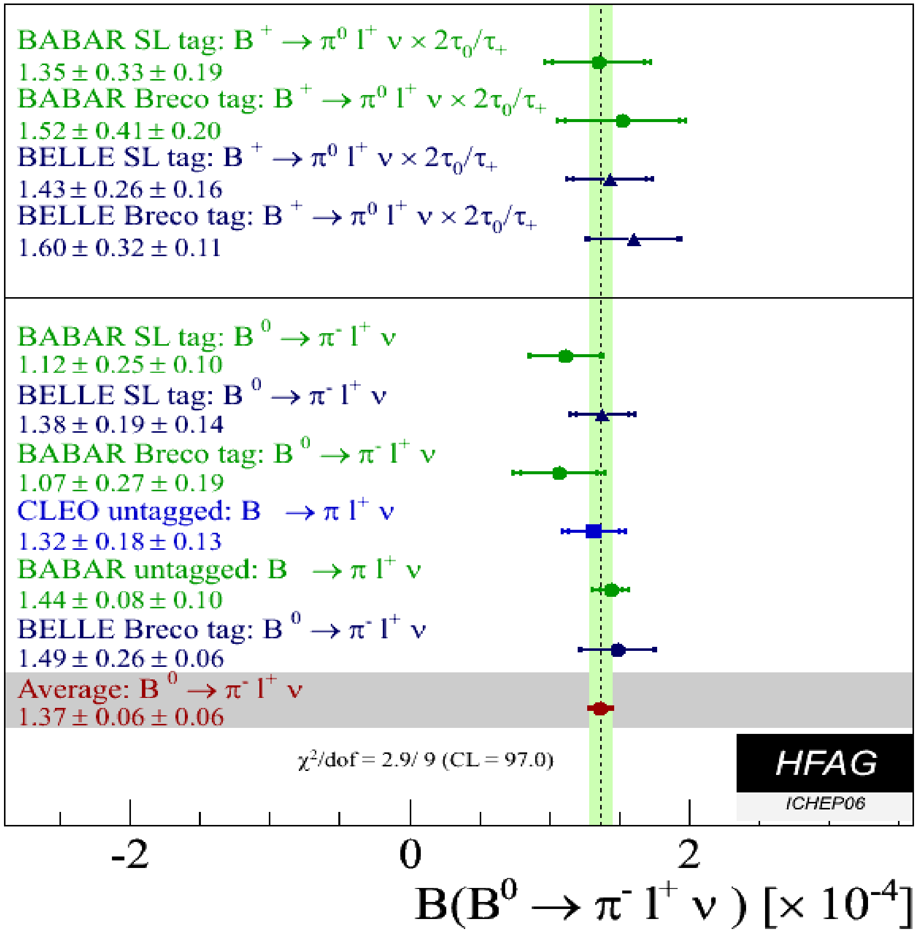
Representative theory example (BLNP)



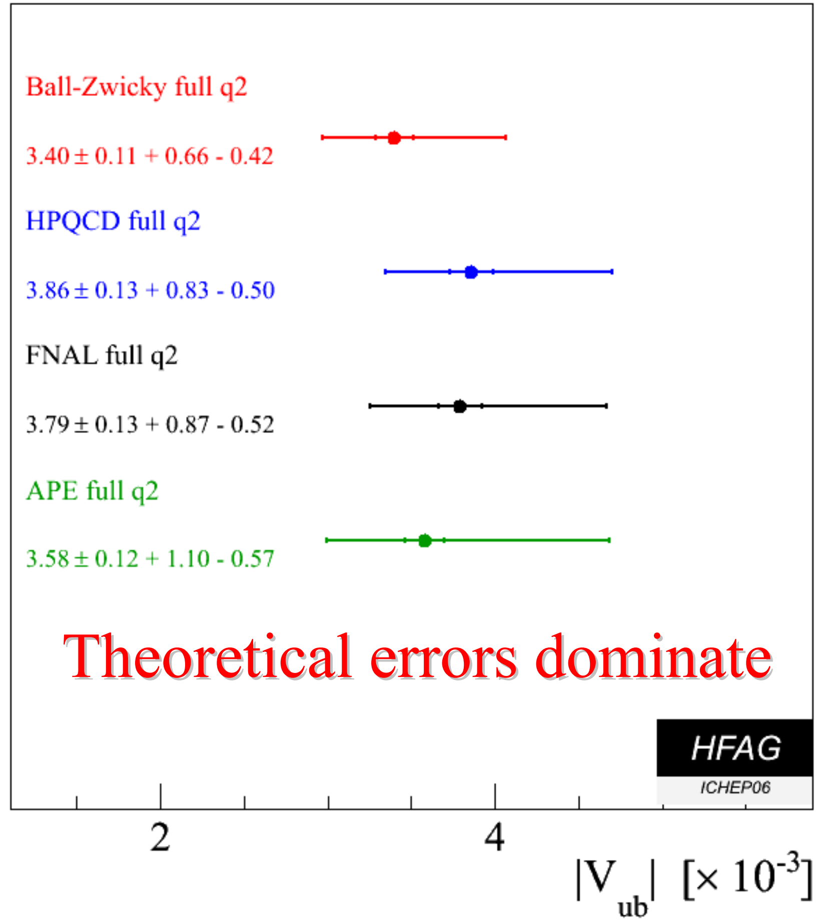


Room for some experimental statistical improvement

$|V_{ub}|$ Exclusive



Using theoretical form factors

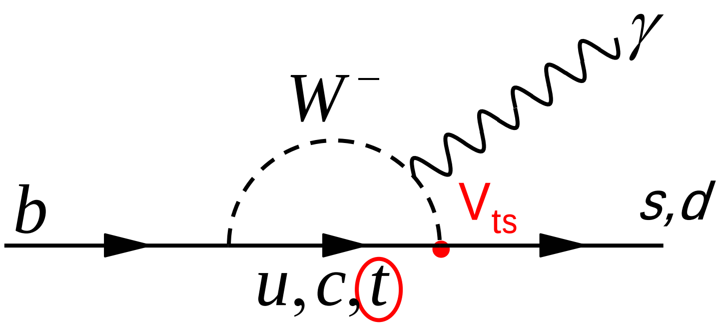


Experiments starting to measure form factor shape from data; allows elimination of some theory models

$|V_{td}|$ & $|V_{ts}|$

METHOD 1

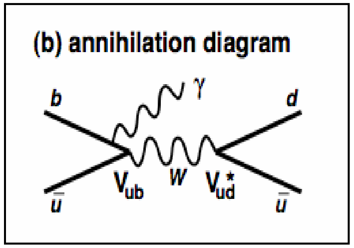
Loop diagram



Light Cone Sum Rules

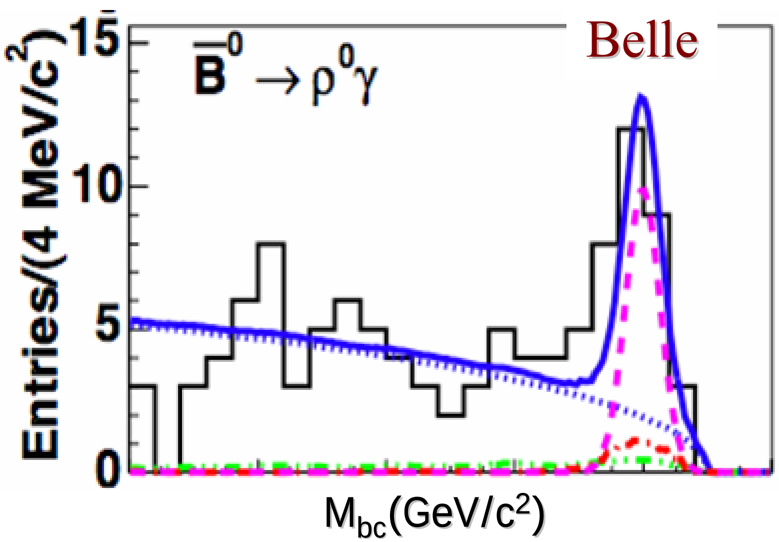
$$\frac{BF(B\to(\rho/\omega)\gamma)}{BF(B\to K^{*}\gamma)}=\left|\frac{V_{td}}{V_{ts}}\right|^2\left(\frac{m_B^2-m_\rho^2}{m_B^2-m_{K*}^2}\right)^3\zeta^2(1+\Delta R)$$

well measured
by BaBar & Belle



$\Delta R = 0.1 \pm 0.1$

Ali, Lunghi, Parkhomenko, PLB 595, 323 (2004)



BaBar + Belle (10^{-6}): $1.22^{+0.23}_{-0.21}\pm0.05$

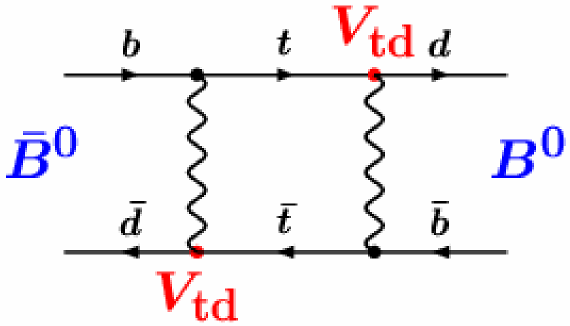
$$\left|\frac{V_{td}}{V_{ts}}\right|_{\rho\gamma}=0.197^{+0.019}_{-0.018}(\text{exp})\pm0.015(\text{th})$$

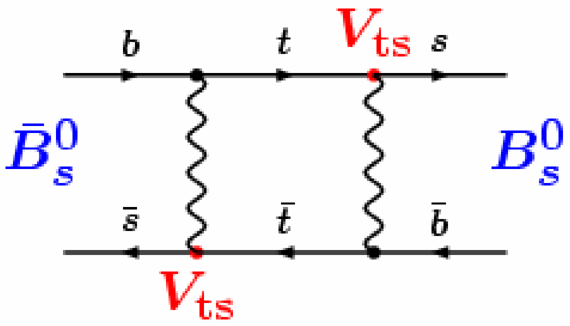
Caveat: Assumes unitarity

$|V_{td}|$ & $|V_{ts}|$

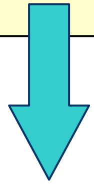
METHOD 2

Box diagrams





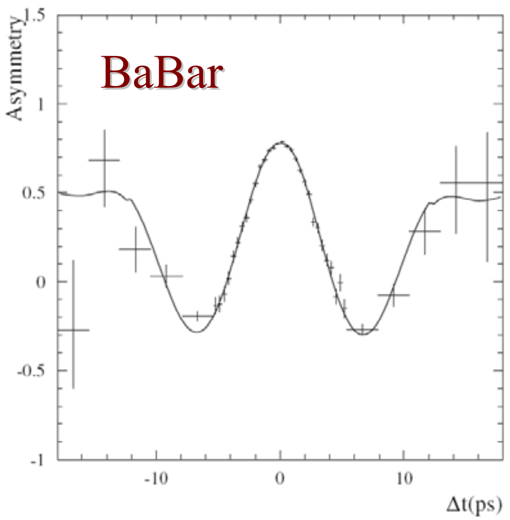
$$\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2 \quad q = d, s$$

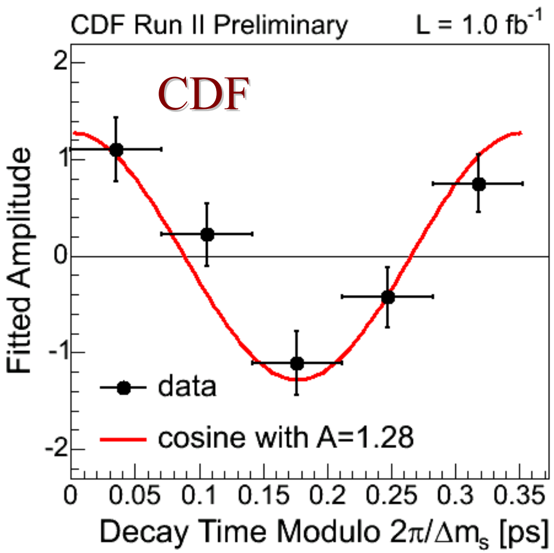


LQCD

$$\sqrt{B_{B_d}} f_{B_d} = 244 \pm 26 \text{ MeV}$$

(Okamoto, hep-lat/0510113)





Limits precision on $|V_{td}|$, $|V_{ts}|$ to ~ 10%

$$|V_{td}| = (7.4 \pm 0.8) \times 10^{-3}$$

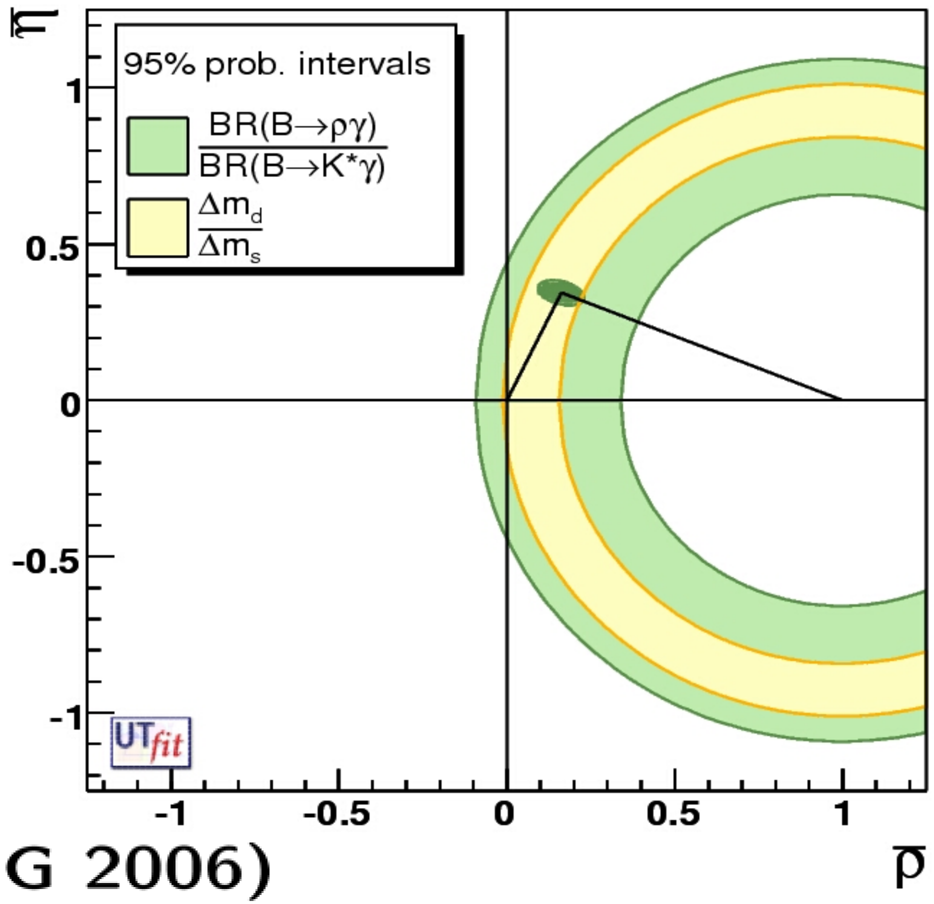
$|V_{td}|$ & $|V_{ts}|$

METHOD 2: Box diagrams

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

$$\xi = \frac{B_{B_s}\sqrt{f_{B_s}}}{B_{B_d}\sqrt{f_{B_d}}} = 1.210^{+0.047}_{-0.035}$$

(~4% accuracy)



$$\Delta m_d = 0.507 \pm 0.005 (1\%) \text{ (PDG 2006)}$$

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

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.2060 \pm 0.0007 \,(\text{exp.})^{+0.0081}_{-0.0060} \,(\text{theo.})$$

CDF (2006)

CPV Results

Unitarity Triangle

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

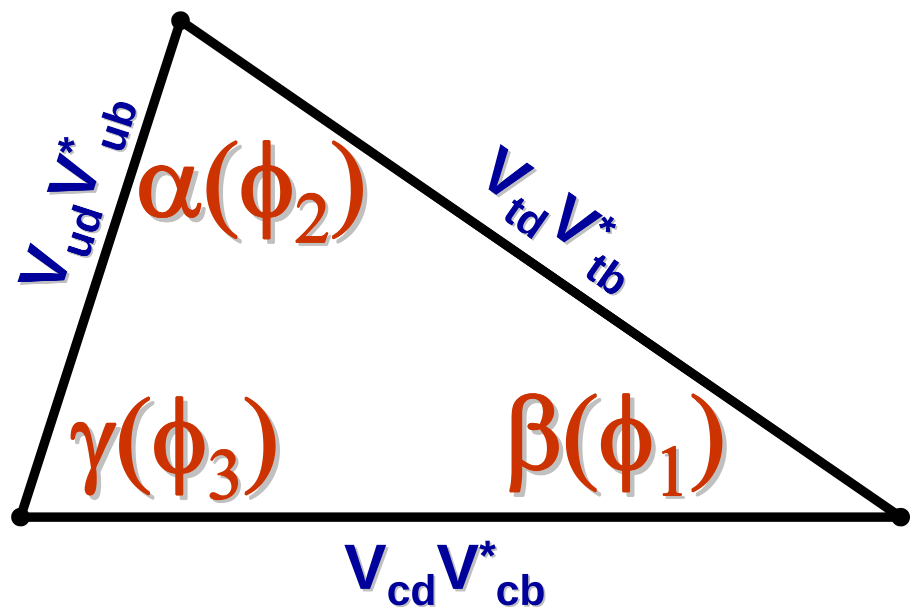
from **Unitarity**

λ^3 λ^3 λ^3

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

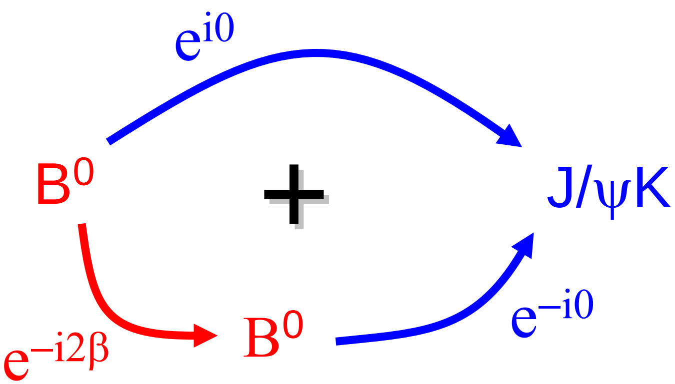
Triangle on a complex plane

(B) **Unitarity Triangle**



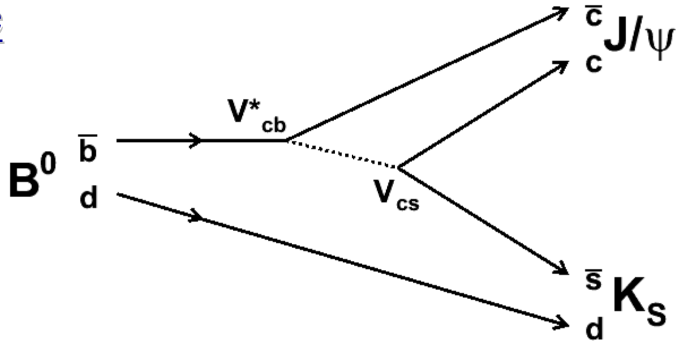
Time-dependent CP violation (tCPV)

Golden mode: **$B^0 \to J/\psi K$**; high rate, theoretically clean



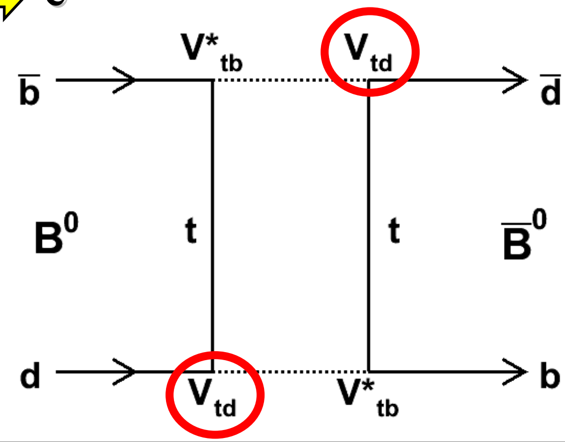
Decay amplitude

No weak phase



Mixing amplitude

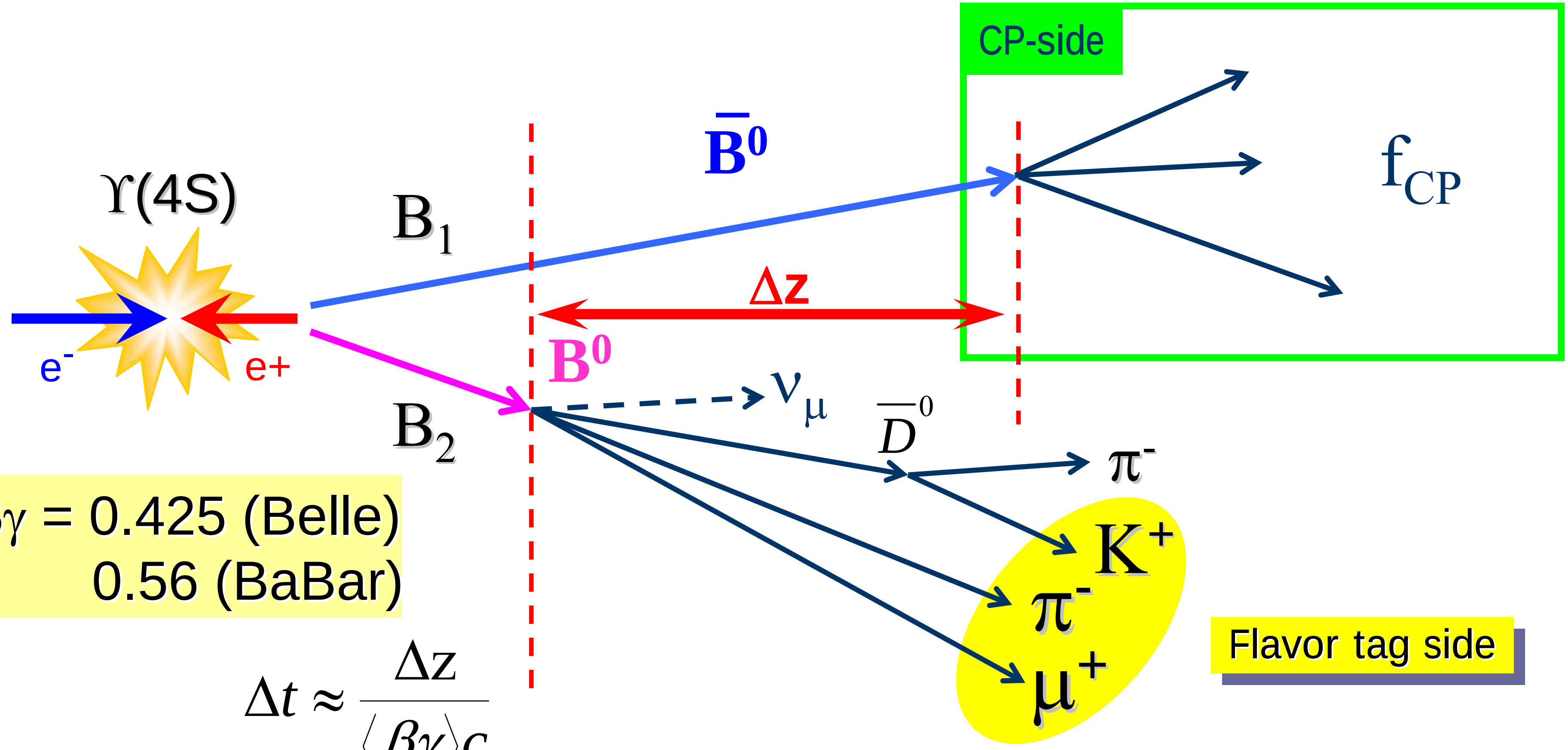
Two V_{td} vertices ⇨ $e^{-i2\beta}$



Measurable relative phase = $e^{i2\beta}$

Note: true for **any** B^0 decay with no phase from decay amplitude

Time-dependent CP violation



$\beta\gamma$ = 0.425 (Belle)
0.56 (BaBar)

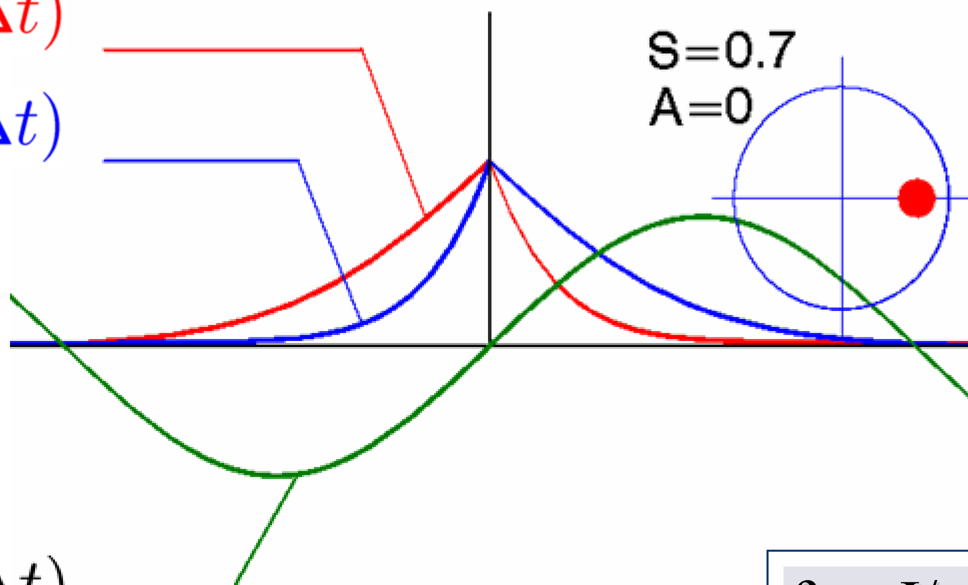
$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

1. Fully reconstruct one B-meson which decays to CP eigenstate f_{CP}
2. Tag-side determines its flavor (effective efficiency = 30%)
3. Proper time (Δt) is measured from decay-vertex difference (Δz)

Time-dependent CP violation

$\Gamma_{B^0}(\Delta t)$

$\Gamma_{\bar{B}^0}(\Delta t)$



$$A_{CP}(\Delta t)$$
$$\equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)}$$
$$= \mathcal{S} \sin \Delta m \Delta t + \mathcal{A} \cos \Delta m \Delta t$$

Mixing-induced CPV

Direct CPV

for J/ψ Ks:

$\mathcal{S} = -\xi_{CP} \sin 2\phi_1 = +\sin 2\phi_1$

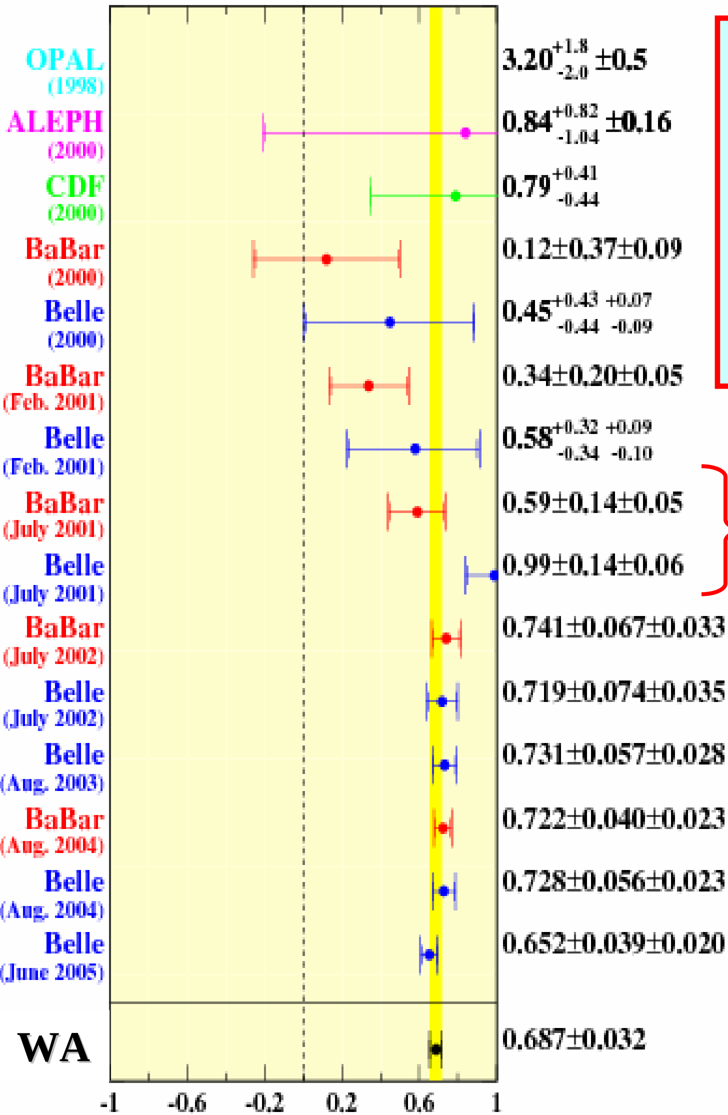
$\mathcal{A} = 0$

to a very good approximation

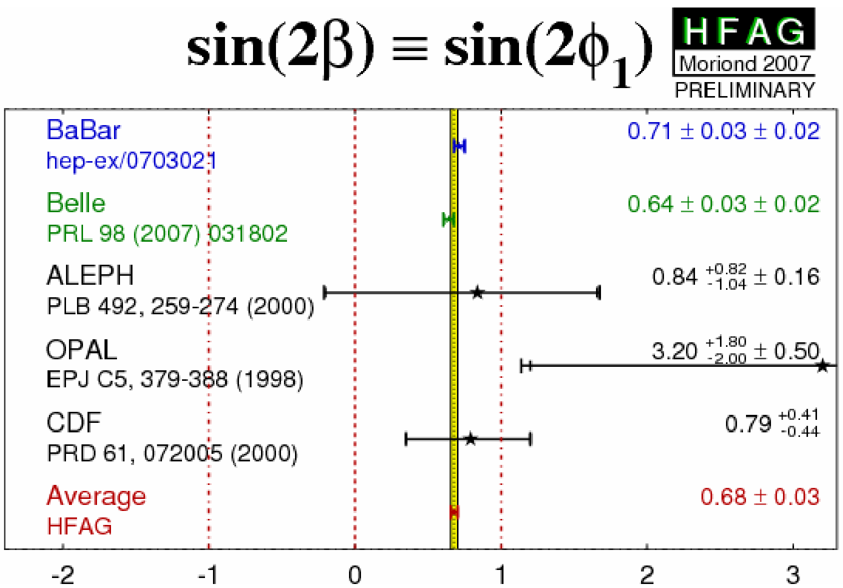
(ξ_{CP} : CP eigenvalue)

β: b→cc̄s

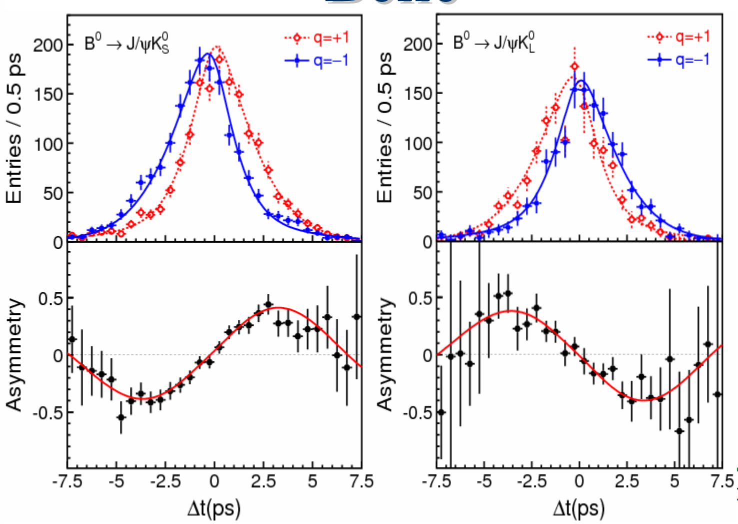
sin2β history (1998-2005)



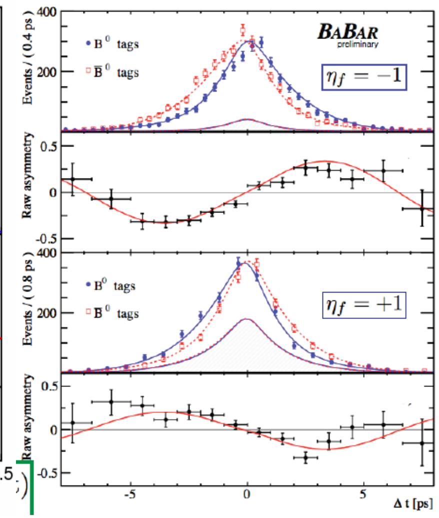
Discovery of CPV in the B system



Belle



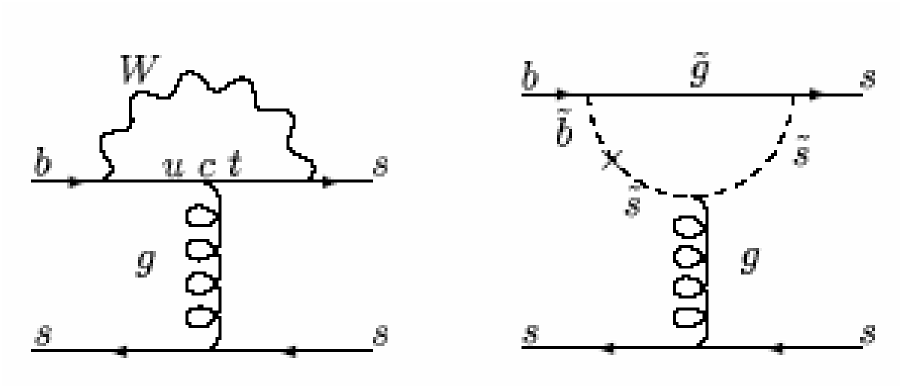
BaBar



β: b→sq̄q

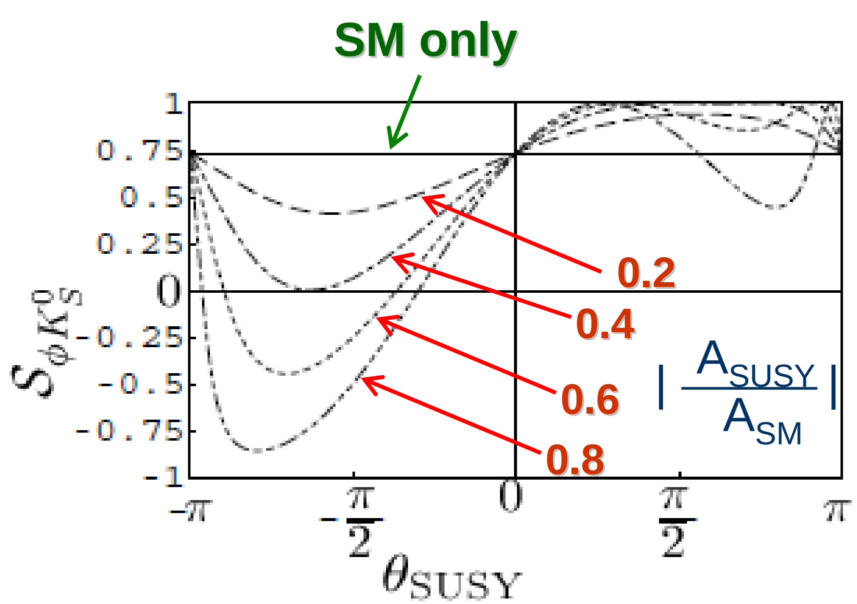
In general, new physics contains new sources of flavor mixing and CP violation.

- In SUSY models, for example, SUSY particles contribute to the *b*→*s* transition, and their CP phases change CPV observed in *B*→φ*K*, η'*K* etc.



SM **SUSY contribution**

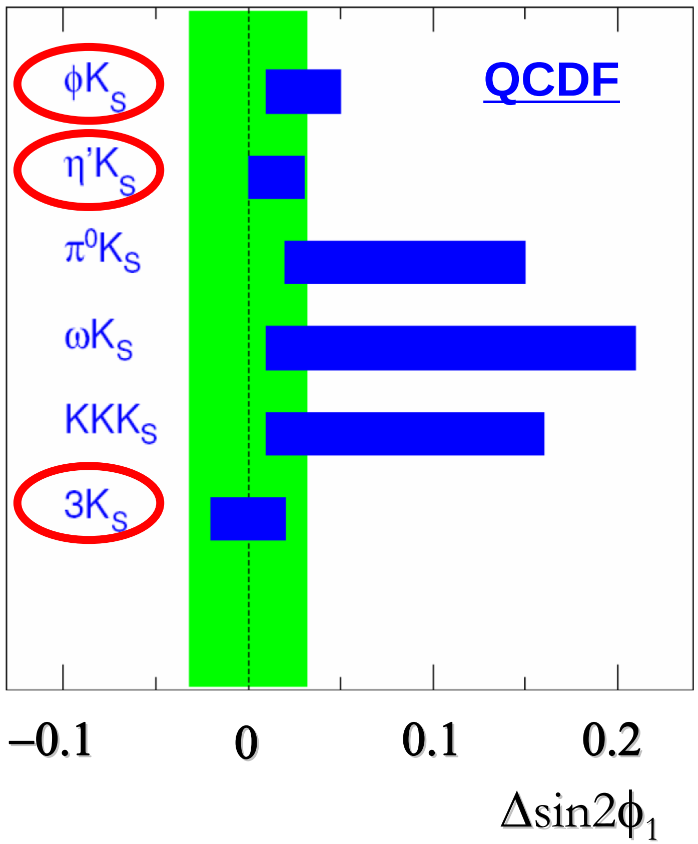
In general, if SUSY is present, the squark mixing matrix contains complex phases just as in the Kobayashi-Maskawa matrix.



β: b→sq$\bar{q}$

Even in the SM slight shift in sin2β measured in b→s dominated decays is expected due to

- b→u tree contamination
- Im(V_{ts}) ≠ 0 at $O(\lambda^4)$
- final state rescattering



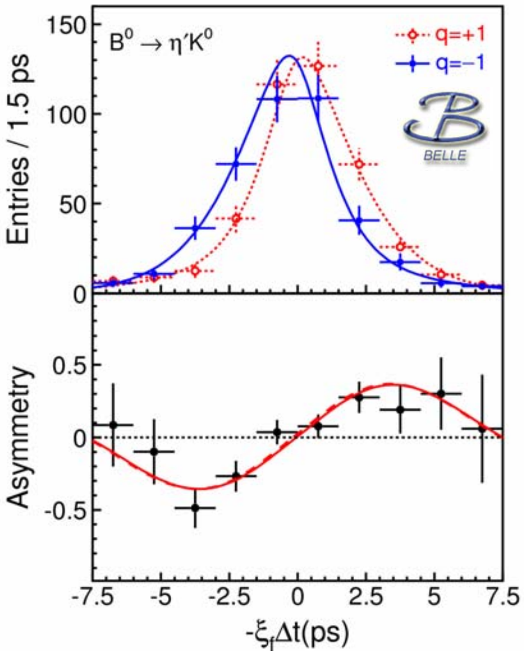
<u>Short distance effect</u>

QCDF:
Beneke, PLB 620, 143 (2005)
Cheng, Chua, Yang, PRD 73, 014017 (2006)
pQCD:
Mishima, Sanda, PRD 72, 114005 (2005)
SCET:
Williamson, Zupan, PRD 74, 014003 (2006)

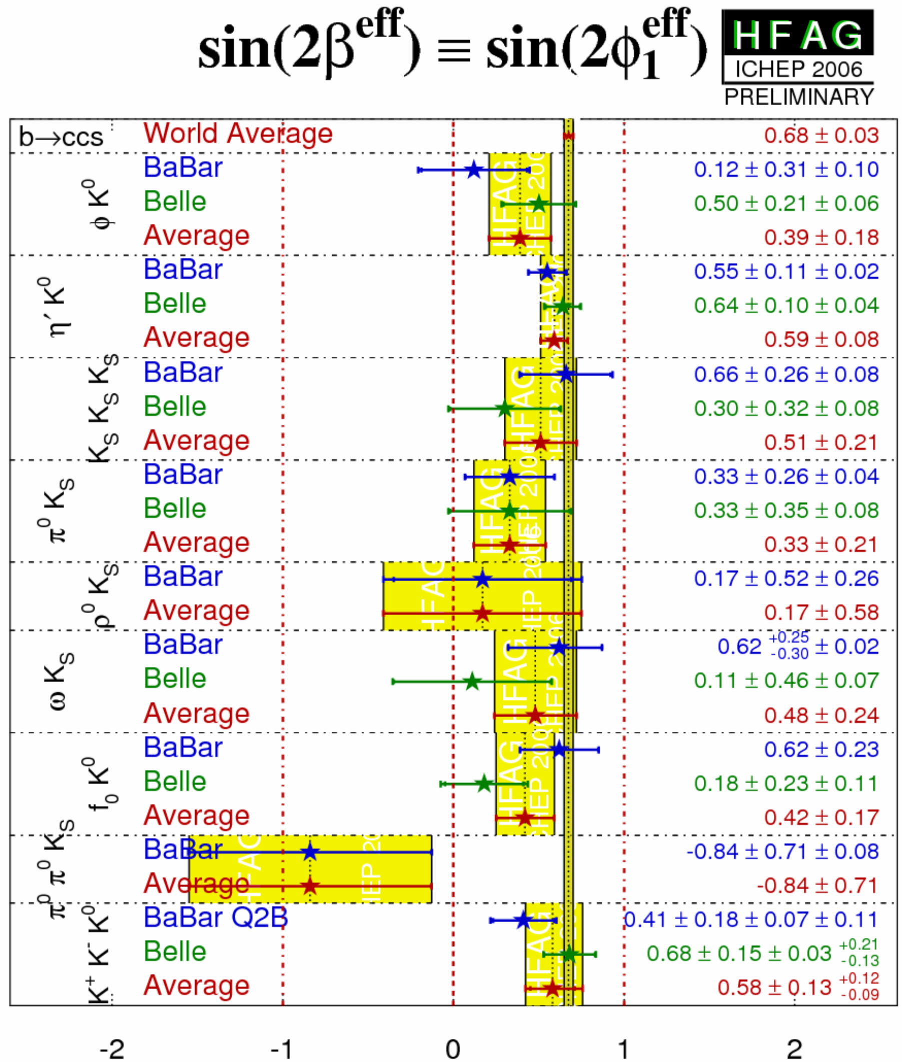
Long distance effect (is small)

Cheng, Chua, Soni, PRD 72, 014006 (2005)

β: b→sq$\bar{q}$



Smaller than in b→ccs in all 9 modes while theory predicts positive shift



Naïve average of all b → s modes

$\sin 2\beta^{eff} = 0.52 \pm 0.05$

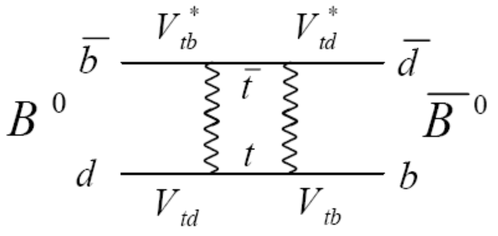
2.6 σ deviation between penguin and tree

(b → s) (b → c)

More statistics crucial for mode-by-mode studies

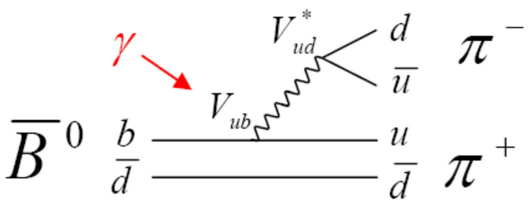
α: B→ππ

$B^0\bar{B}^0$ mixing



$q/p \propto V_{tb}^{*}V_{td} / V_{tb}V_{td}^{*}$

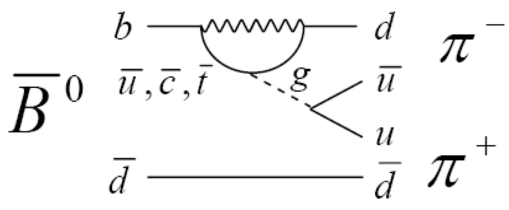
Tree decay



$A \propto V_{ud}^{*}V_{ub}$

⊕

Penguin decay



$A \approx V_{td}^{*}V_{tb}$

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

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t)\to\pi^+\pi^-) - \Gamma(B^0(t)\to\pi^+\pi^-)}{\Gamma(\bar{B}^0(t)\to\pi^+\pi^-) + \Gamma(B^0(t)\to\pi^+\pi^-)} = S_{\pi\pi}\cdot\sin(\Delta m_d t) + C_{\pi\pi}\cdot\cos(\Delta m_d t)$$

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

$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = e^{-i2\beta}e^{-i2\gamma} = e^{i2\alpha}$$

$$S = \sin(2\alpha)$$

$$C = 0$$

If Penguin pollution ⇒

$$\lambda = e^{i2\alpha}\frac{T + P e^{+i\gamma}e^{i\delta}}{T + P e^{-i\gamma}e^{i\delta}}$$

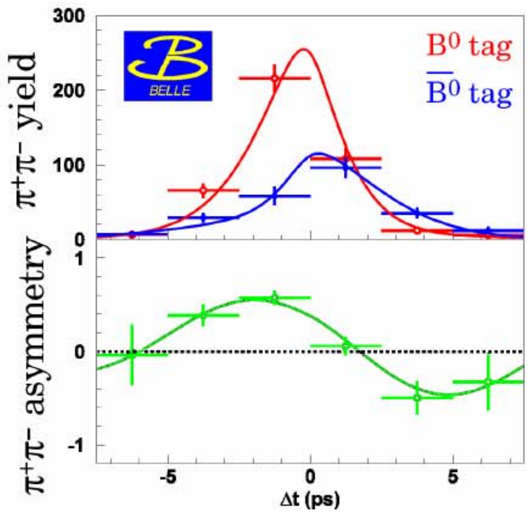
$$S = \sqrt{1-C^2}\,\sin(2\alpha_{eff})$$

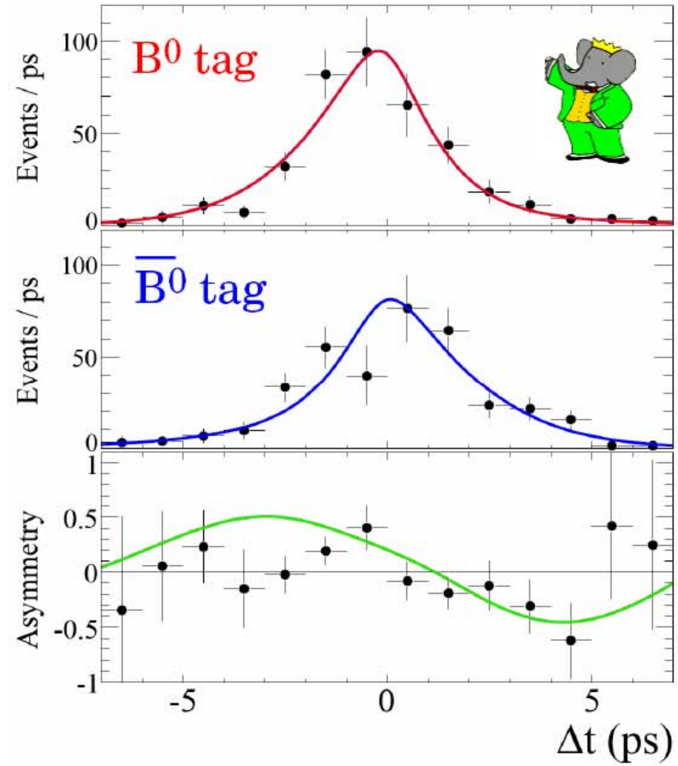
$$C \propto \sin\delta$$

α: B→ππ

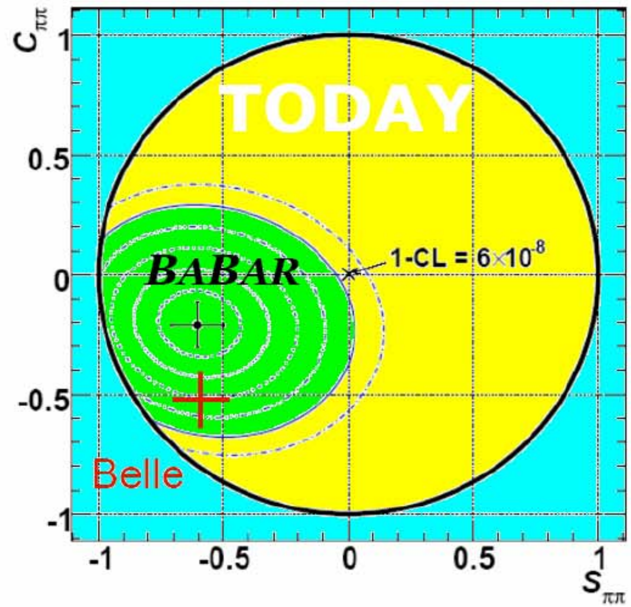
Two types of *CP* Violation are observed:

- direct *CP* V
- mixing-induced *CP* V



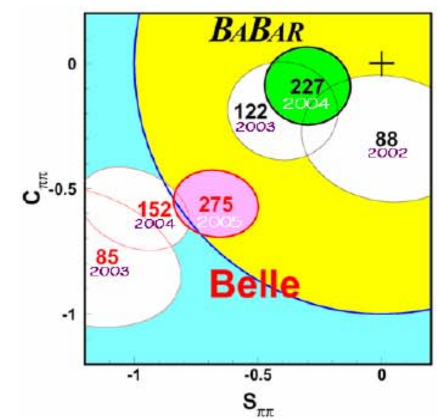


BABAR and BELLE now in better agreement



BABAR prelim. (347M BB) – hep-ex/0607106
BELLE prelim. (535M BB) – hep-ex/0608035

evolution

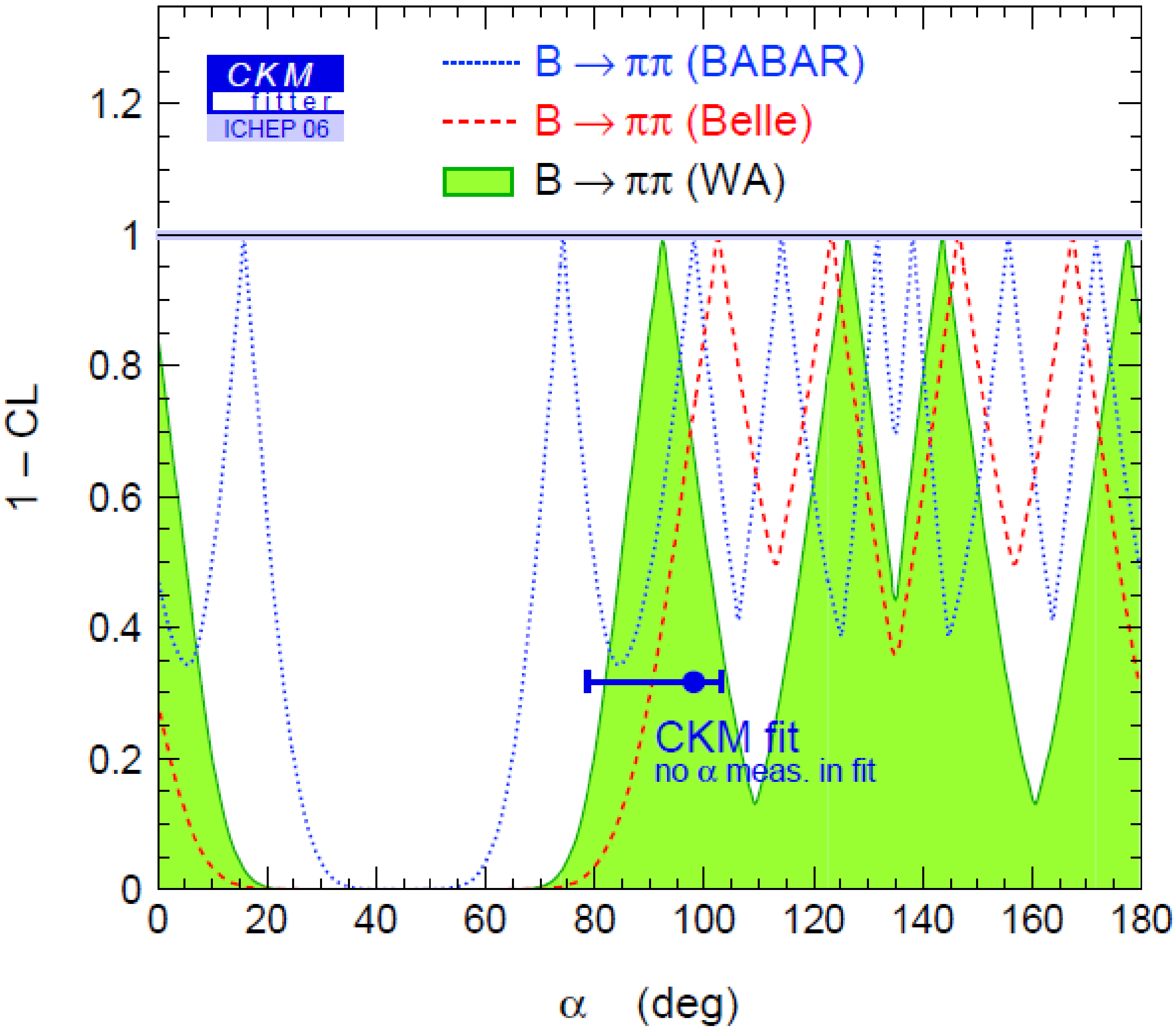


$$C_{\pi^+\pi^-} \neq 0 \quad \text{and} \quad S_{\pi^+\pi^-} = \sqrt{1 - C^2_{\pi^+\pi^-}}\ \sin 2\alpha_{\rm eff}$$

need to estimate $\Delta\alpha \equiv \alpha_{\rm eff} - \alpha$

→ isospin analysis (Gronau-London)

α: $B \to \pi\pi$



inputs

$\mathcal{B}(\pi^+\pi^0) = (5.75 \pm 0.42) \times 10^{-6}$

$\mathcal{B}(\pi^+\pi^-) = (5.20 \pm 0.25) \times 10^{-6}$

$\mathcal{B}(\pi^0\pi^0) = (1.30 \pm 0.21) \times 10^{-6}$

$\mathcal{A}(\pi^0\pi^0) = +0.35 \pm 0.33$

$\mathcal{S}(\pi^+\pi^-) = -0.59 \pm 0.09$

$\mathcal{A}(\pi^+\pi^-) = +0.39 \pm 0.07$

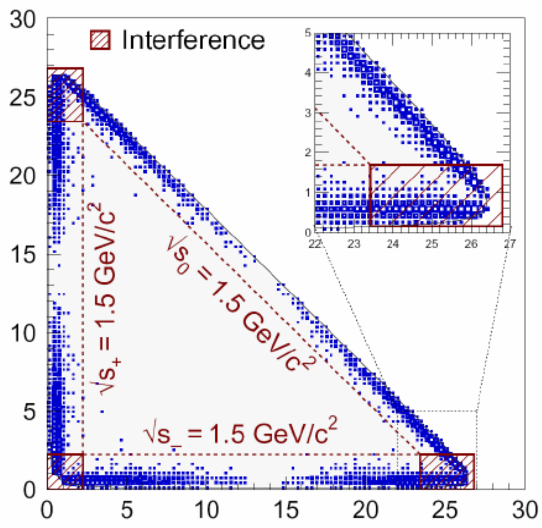
No useful constraint is obtained with $\pi\pi$ system alone

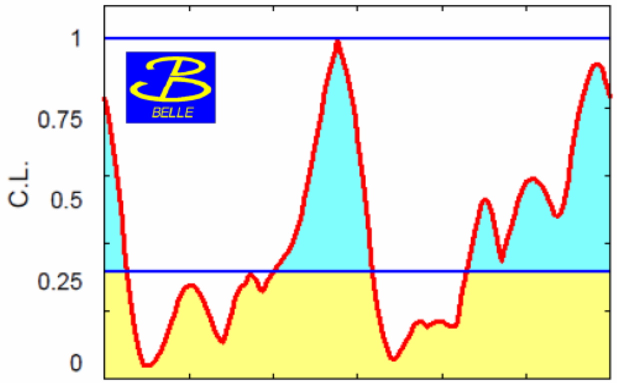
→ need $\rho\rho$ and $\rho\pi$

α: B→ρπ→πππ

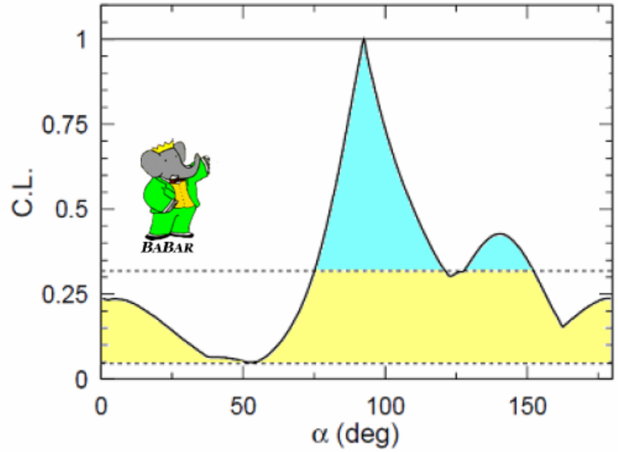
★ three-pion final state: dominated by transitions through ρ mesons

interfering contributions from $\rho^+\pi^-$, $\pi^+\rho^-$ (and $\rho^0\pi^0$)





$\alpha \in [60, 95]^\circ$ at the 68.3% C.L.



$\alpha \in [75, 152]^\circ$ at the 68.3% C.L.

(no constraint at the 2σ level)

★ Snyder-Quinn method:
time-dependent Dalitz analysis

➡ BW phase variations break degeneracy in solutions

BELLE prelim. (449M BB) – hep-ex/0609003
BABAR prelim. (347M BB) – hep-ex/0608002

α: $B \to \rho\rho$

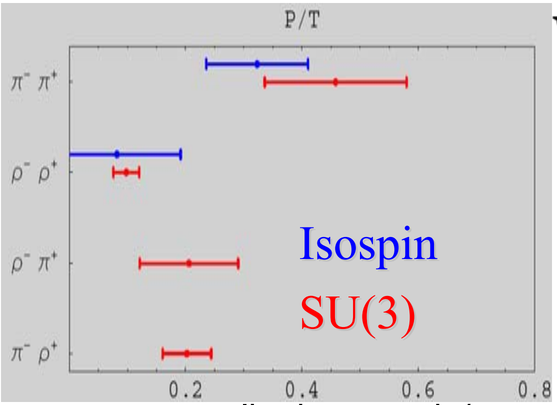
- Relatively large BF with

$\pi^+\pi^-$	5.2±0.2	$\rho^+\rho^-$	23±4
$\pi^+\pi^0$	5.7±0.4	$\rho^+\rho^0$	18±3
$\pi^0\pi^0$	1.3±0.2	$\rho^0\rho^0$	1.2±0.5

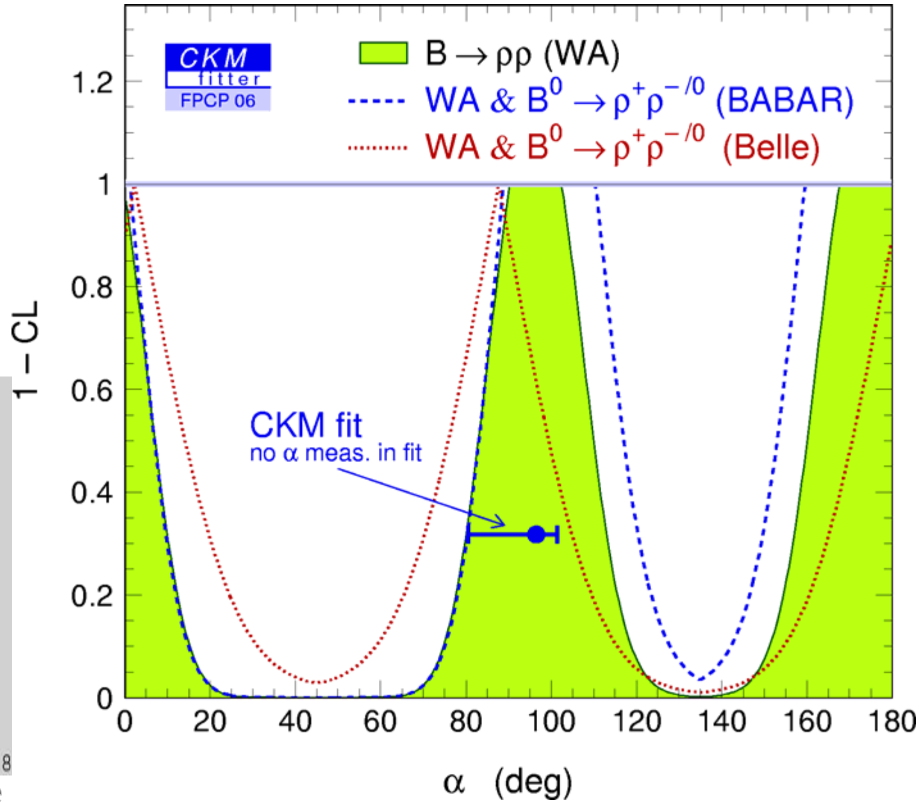
Branching fractions ($\times 10^6$)

- Small b->d penguin contribution:

Zupan, hep-ph/0701004



Amplitude Penguin/Tree



- fortunately, longitudinal polarization dominates

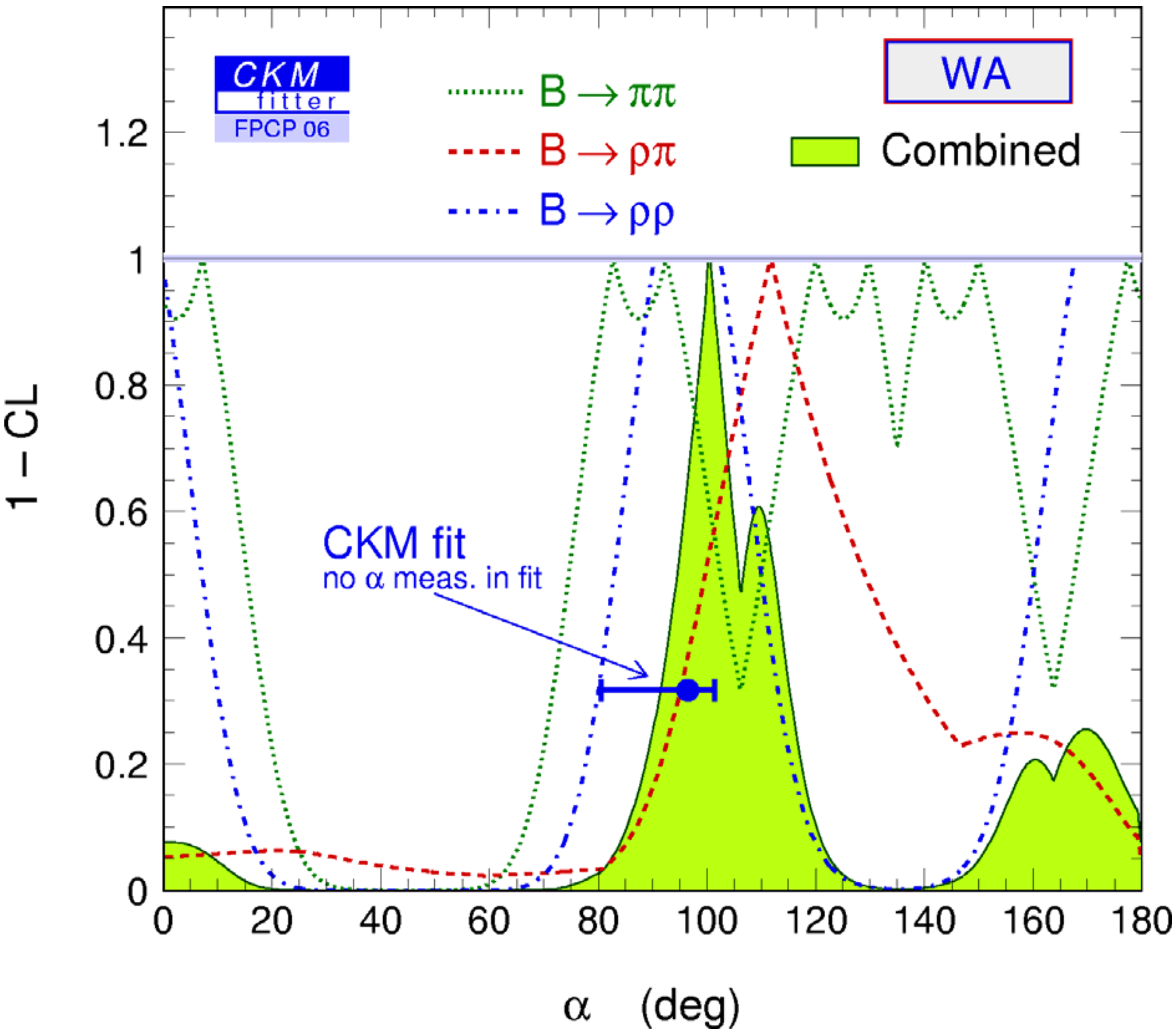
$$f_{long} = 0.977 \pm 0.024^{+0.015}_{-0.013} \quad \text{BaBar}$$

$$0.941^{+0.034}_{-0.040} \pm 0.030 \quad \text{Belle}$$

$CP(\rho^+\rho^-) = +1$

α: Summary

BaBar + Belle



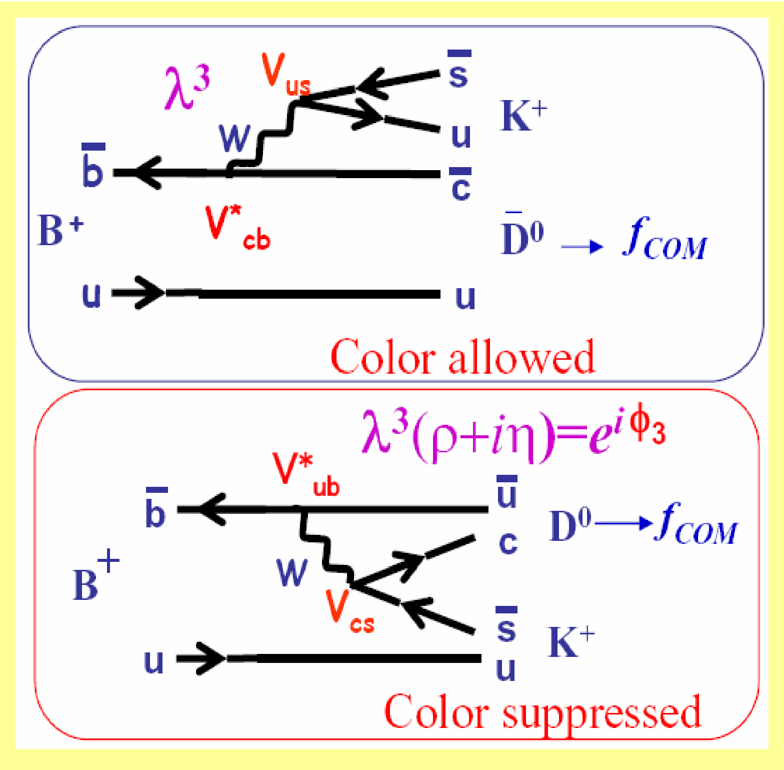
$$\alpha/\phi_2 = [100^{+15}_{-\ 9}]^\circ$$

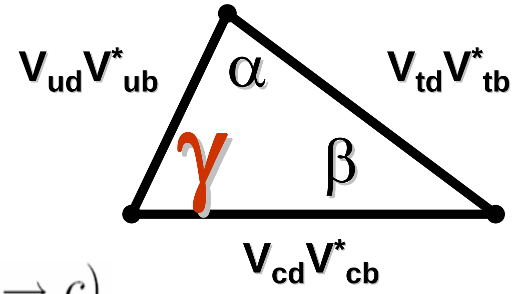
Consistent with a global fit w/o α/ϕ_2

$$\alpha_{Fit} = [98^{+\ 5}_{-19}]^\circ$$

γ : Method

Interference between two tree level amplitudes





$$r_B \equiv A(b \rightarrow u)/A(b \rightarrow c)$$
$$\approx 0.39 f_c \sim 0.1 - 0.3$$

interference parameter

$$R = r_B \frac{A(D^0 \rightarrow f)}{A(\bar{D}^0 \rightarrow f)}$$

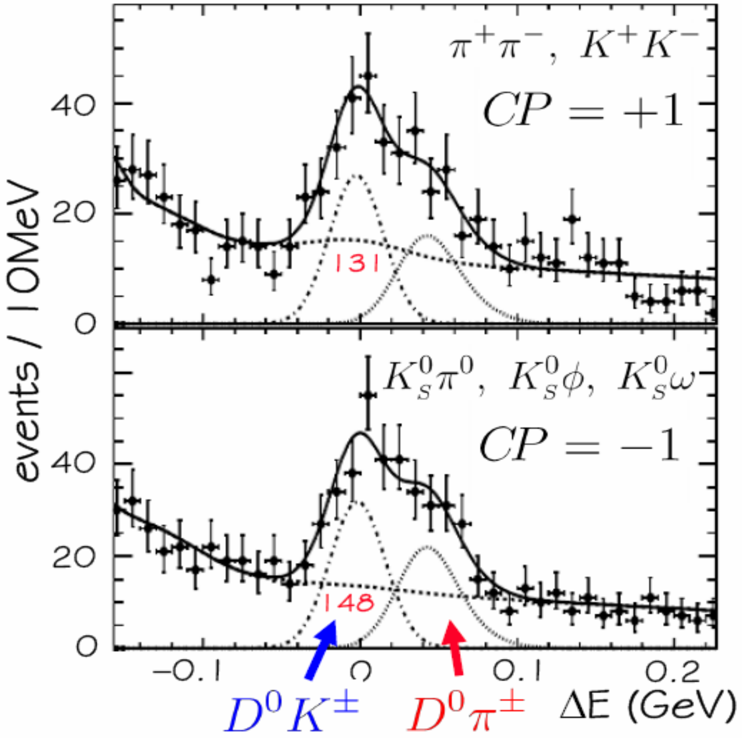
- **GWL** (Gronau-Wyler-London): f_{COM} – CP eigenstates ($\pi^+\pi^-$, $K^0\pi^0$, K^+K^-, ...)
- **ADS** (Atwood-Dunietz-Soni): f_{COM} – flavor specific ($K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, ...)
- **GGSZ** (Giri-Grossman-Soffer-Zupan): f_{COM} – multibody ($K^0\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, ...)

γ: GWL & ADS

★ Gronau-Wyler-London (GWL)

$$B \to D_{CP} K$$

- small interference
- sensitivity to γ
- no sensitivity to r_B



BABAR (232M BB) – PR D73, 051105 (2006)

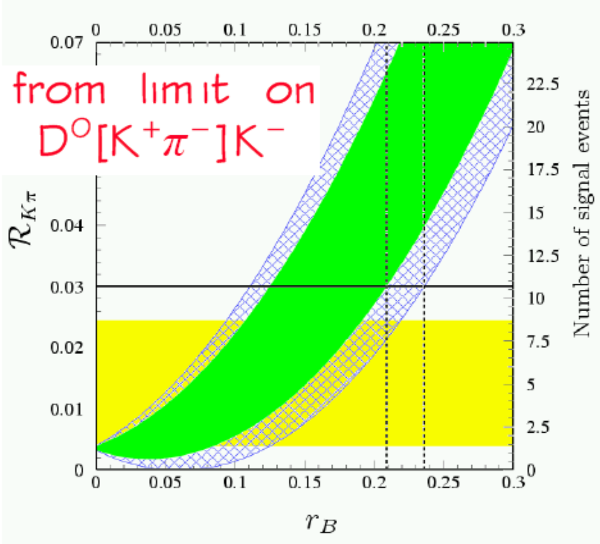
★ Atwood-Dunietz-Soni (ADS)

- larger interference
- unknown D relative strong phase
- sensitivity to r_B

$$R_{K\pi} = \frac{Br(D^0[K^+\pi^-]K^- + c.c.)}{Br(D^0[K^-\pi^+]K^- + c.c.)} \sim r_B^2$$

➡ no observation yet – set limits

$r_B^2 < 0.23$ (90 % C.L)

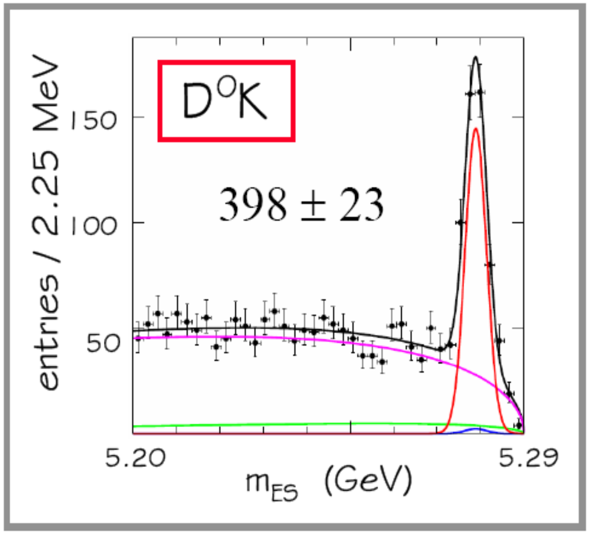


BABAR (232M BB) – PR D72, 032004 (2005)

γ: GGSZ

★ Giri-Grossman-Soffer-Zupan (GGSZ)

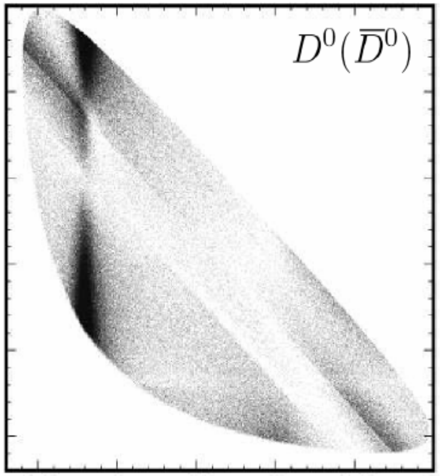
- exploit interference pattern in Dalitz plot
- sensitivity to both γ and r_B
- a two-fold ambiguity remains in the extraction of γ



➡ *schematic* view of the interference

$$|A_\mp|^2 = \Big|$$

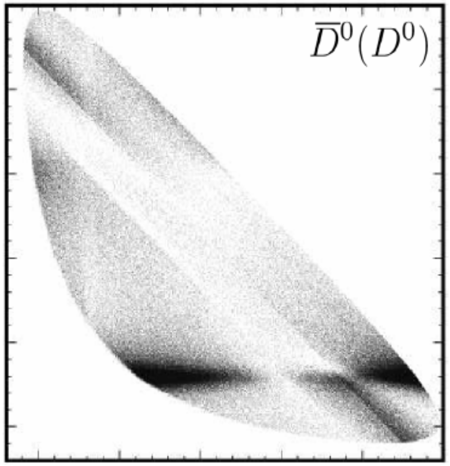
$m_\mp^2$



$m_\pm^2$

$$+\, r_B\, e^{i(\gamma\pm\delta)}$$

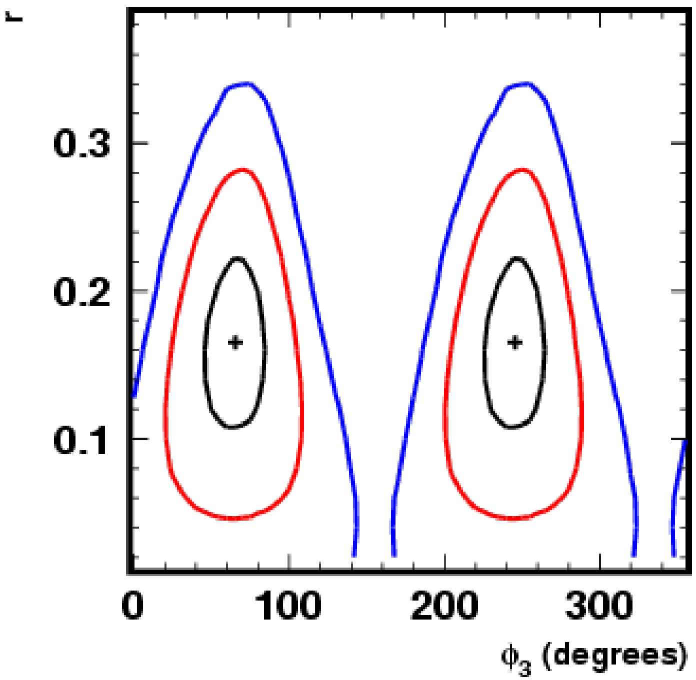
$m_\mp^2$



$m_\pm^2$

$$\Big|^2$$

γ: GGSZ



$B^{\pm} \to D K^{\pm}$

$\varphi_3 = 66^{+19}_{-20}{}^{\circ}$(stat)

$B^{\pm} \to D^{*} K^{\pm}$

$\varphi_3 = 86^{+37}_{-93}{}^{\circ}$(stat)

$B^{\pm} \to D K^{*\pm}$

$\varphi_3 = 11^{+23}_{-57}{}^{\circ}$(stat)

3 modes combined:
CPV significance: 78%

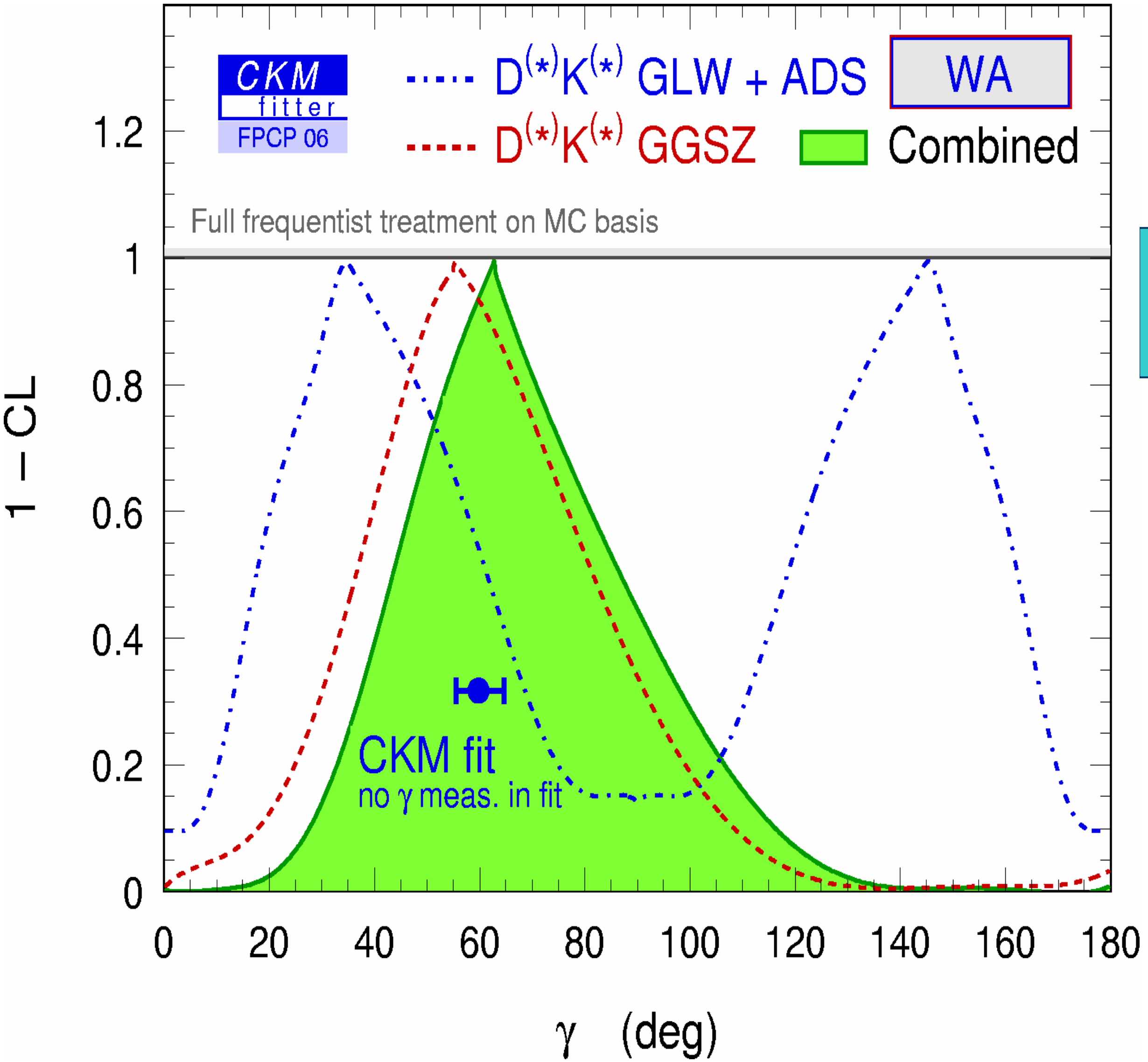
$\gamma = \mathbf{53}^{+15}_{-18} \pm \mathbf{3}$(syst)$\pm \mathbf{9}$(model)$^{\circ}$

$8^{\circ} < \gamma < 111^{\circ}$ (2σ interval)

DK: $r_B = 0.159^{+0.054}_{-0.050} \pm 0.012$(syst)$\pm 0.049$(model); $\delta = (146^{+19}_{-20})^{\circ}$
D*K: $r_B = 0.175^{+0.108}_{-0.099} \pm 0.013$(syst)$\pm 0.049$(model); $\delta = (302^{+34}_{-35})^{\circ}$
DK*: $r_B = 0.564^{+0.216}_{-0.155} \pm 0.041$(syst)$\pm 0.084$(model); $\delta = (243^{+20}_{-23})^{\circ}$

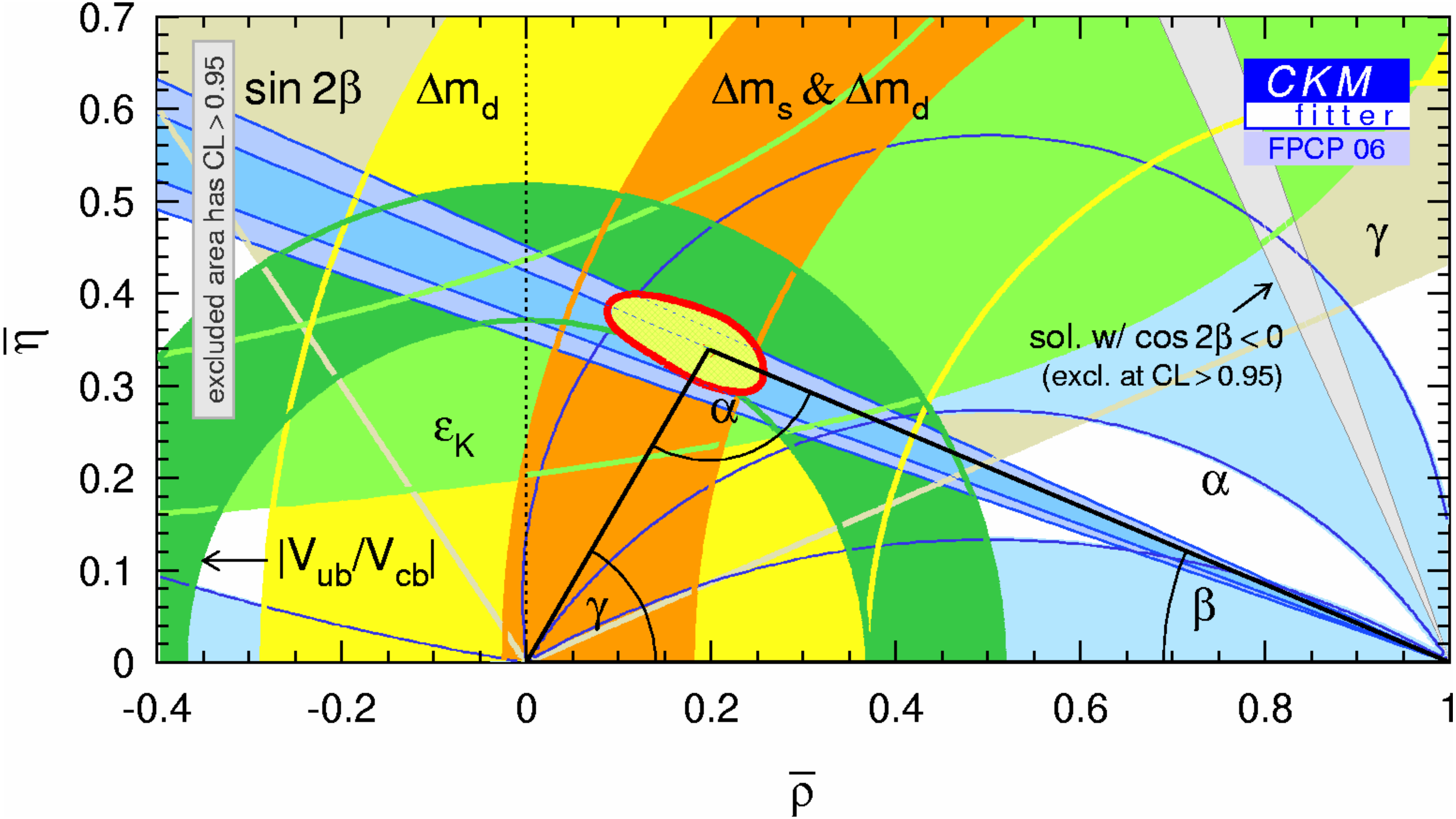
BELLE

γ: Summary



$$\gamma/\phi_3 = [62^{+35}_{-25}]^\circ$$

UT: Global Fit (2006)



Good overall agreement. O(1) new physics unlikely.

Need to be able to detect O(0.1) effects as the next step.

Prospects for The Future

- BaBar and Belle only half way
  - Both aiming for around $1ab^{-1}$ each over next two years
- Some measurements are clearly statistics limited
  - $\sin 2\beta/\phi_1$ $b \to c\bar{c}s$ vs. $b \to s\bar{s}s$ comparison
  - other angle measurements
- V_{ub} is mainly theory limited
  - Some experimental improvements possible
  - Theory error can be reduced but with substantial work
- More data also brings new techniques and decay modes
  - Improvements better than $\sqrt{N}$ can be expected