CP Violation in B Meson Decays: Experimental Results

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“Greatest Puzzle” n.8: Why is the Universe made of Matter and not Anti-Matter?

- Matter and Anti-Matter: the CP Violation connection
- The Standard Model CKM paradigm and Unitarity Triangles
- CP Violation in B meson decays: experimental challenges
- Experimental results on Unitarity Angles: $\beta(\phi_1)$, $\alpha(\phi_2)$, and $\gamma(\phi_3)$
- Interpretation: the CKM fitting industry
- Outlook and Conclusions

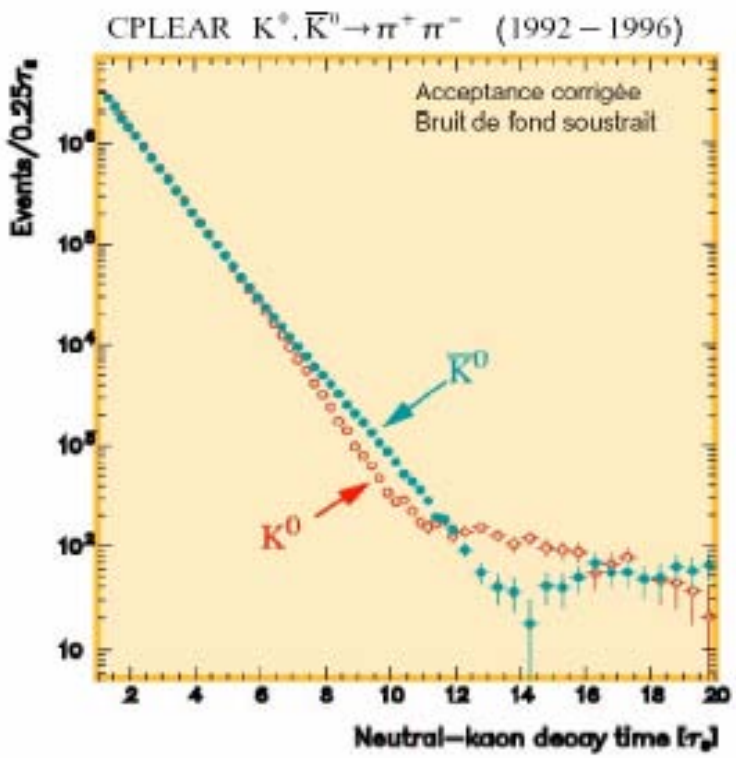
Disclaimer

- New results from B-Factories are timed for ICHEP 2004
  - BaBar will present ~60 new results at ICHEP
  - Belle expected to have a similar yield

- Only one new result in this talk!

CP Violation

- Combined Particle-Antiparticle Exchange (C) and Space Reflection (P): is it a good symmetry of nature?
- 1964 (Christensen et al.): CP is violated in weak decays of neutral kaons
- CP violation allows to distinguish a world of matter from a world of anti-matter in an absolute way
- CPT is an exact symmetry for local quantum field theories; T (time reversal) violation is also experimentally seen



Standard Model CP Violation: is it enough?

- **Cosmology**:

  CP violation is one of the three necessary conditions for generating a global excess of matter in the evolution of our Universe (Andrei Sakharov, 1967)

- **Standard Model (SM)**

  CP violation is generated entirely by a phase in the quark sector (Kobayashi & Maskawa mechanism). Not sufficient to explain the observed baryon asymmetry ! (see other talks, today)

- **Non-SM CP violation sources?**

  A thorough experimental investigation of CP violation is needed to test the SM predictions in the heavy quark sector, and to look for evidence of new physics and possible new CP violation sources

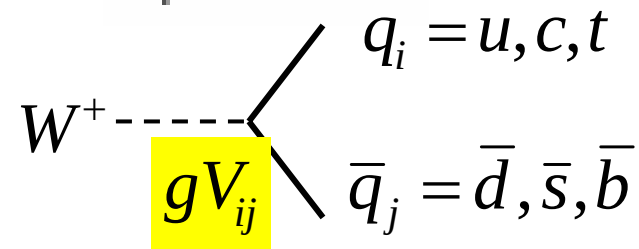
The CKM paradigm in the SM

(1973) M.Kobayashi and T.Maskawa

- CP violation $\Rightarrow$ third generation of quarks

u	c	t
d	s	b

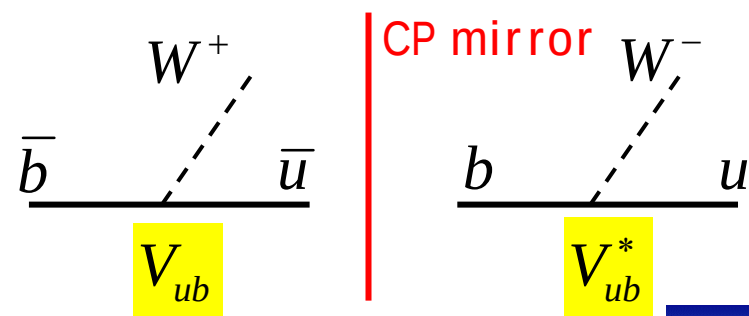
quark doublets



Cabibbo-Kobayashi-Maskawa matrix V

- couples quark charged currents to $W^{\pm}$
- mixes the left-handed (q_j=d,s,b) quark mass eigenstates to give weak eigenstates;
- unitary, with 4 independent parameters (e.g., 3 angles and 1 phase)
- complex elements: phase changes sign under CP
- interfering amplitudes can give observable CP-violating rate asymmetries

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



CKM matrix: Wolfenstein parameterization

- Explicitely shows hierarchy of couplings in terms of powers of $\lambda = \sin\theta_C$

$$V \cong \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

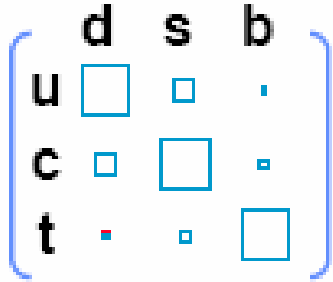
- CKM matrix: 4 of the 18 free parameters of the SM
- From experiments:

$$\lambda \approx 0.22 \qquad A \approx 0.82 \qquad \sqrt{\rho^2+\eta^2} \approx 0.4$$

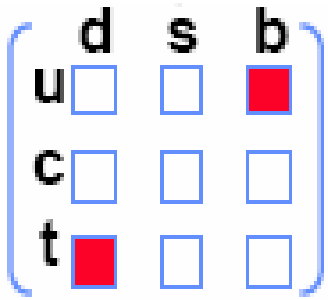
$$\eta/\rho \equiv \tan\gamma = ?$$

- CP violation in the SM $\Leftrightarrow \eta \neq 0$

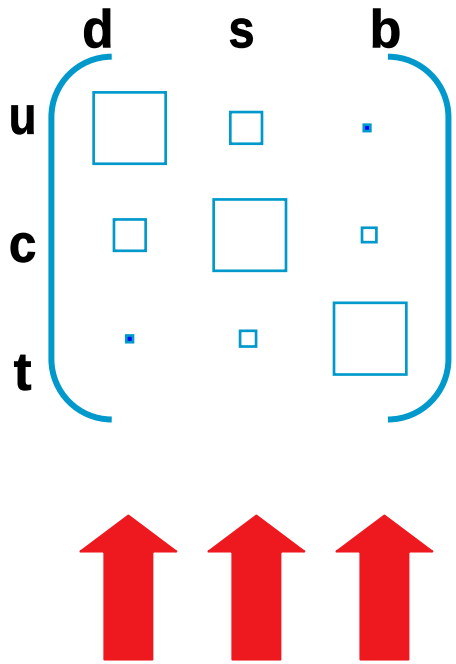
Magnitudes:



Phase
in this parameterization:



The Unitarity Triangles



apply unitarity constraint to pairs of columns

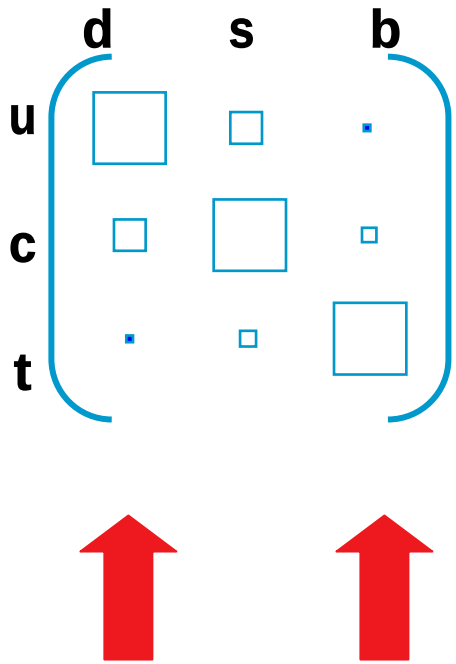
$\mathbf{d} \bullet \mathbf{s}^* = 0$ (K system)

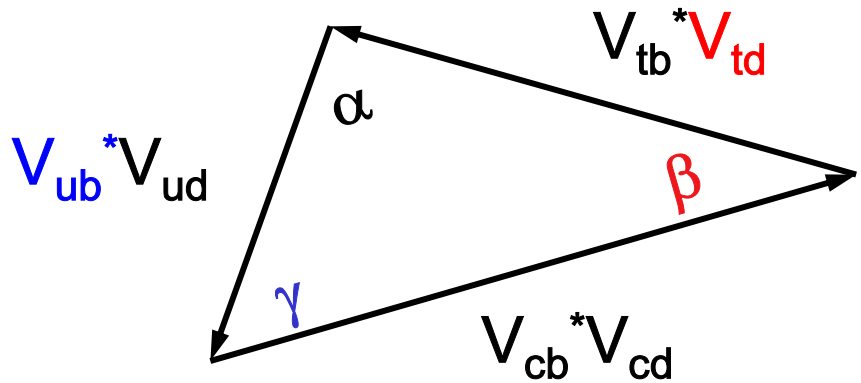
$\mathbf{s} \bullet \mathbf{b}^* = 0$ (B_s system)

$\mathbf{d} \bullet \mathbf{b}^* = 0$ (B_d system)

These three triangles (and the three triangles corresponding to the rows) all have the same area. A nonzero area is a measure of CP violation and is an invariant of the CKM matrix.

The Unitarity Triangle

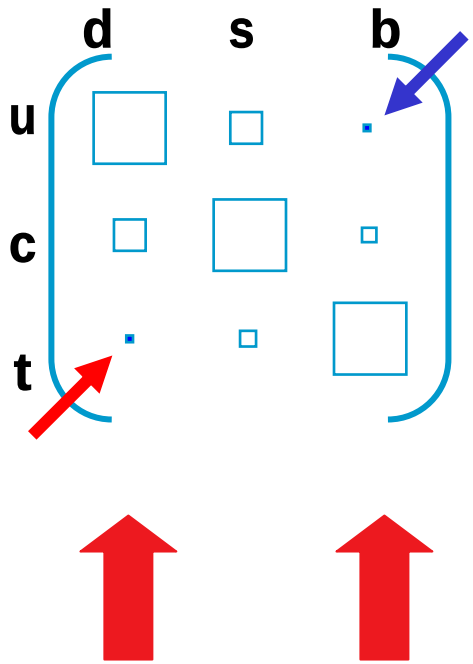


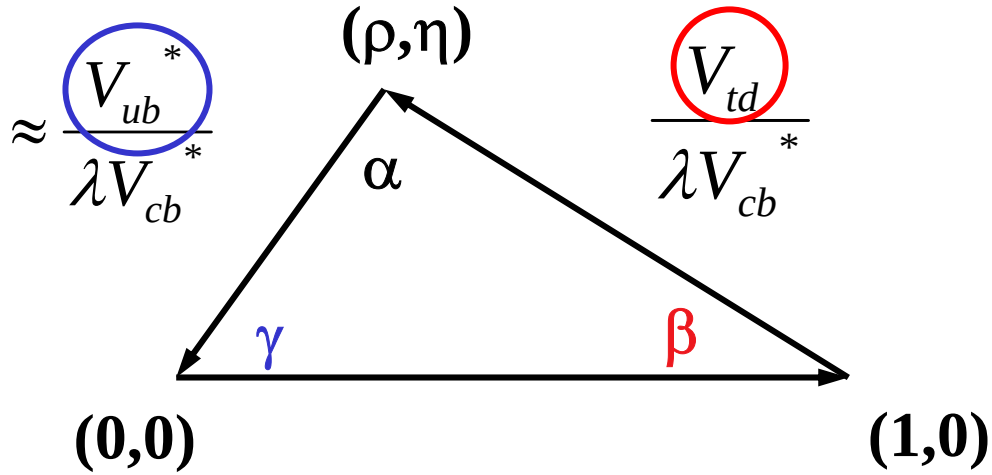


apply unitarity constraint to these two columns

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

The Unitarity Triangle





$$\gamma \approx \arg V_{ub}^* \qquad \beta \approx -\arg V_{td} \qquad \alpha = \pi - \beta - \gamma$$

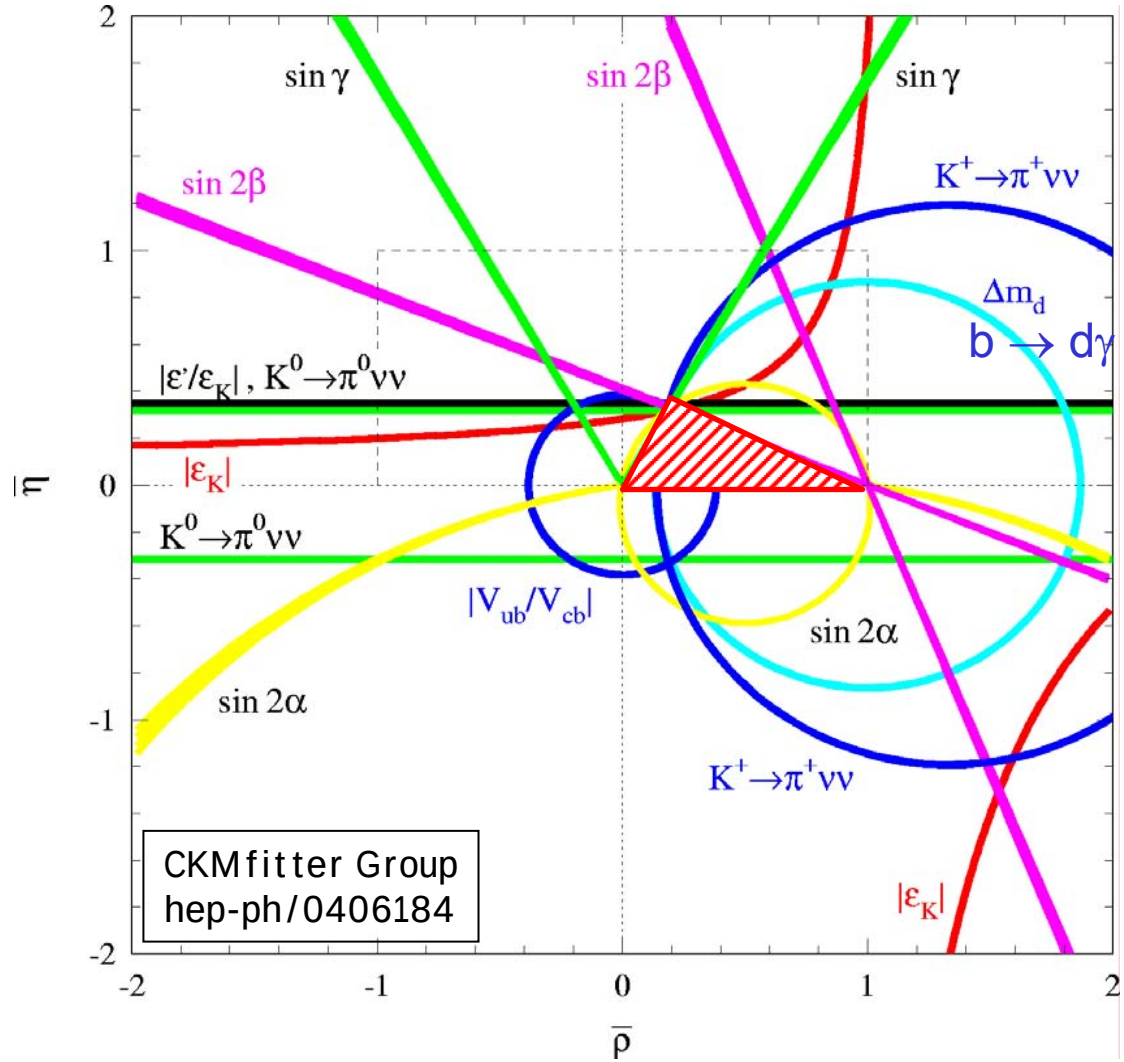
apply unitarity constraint to these two columns

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

$$V_{cd} = \lambda\,, \qquad V_{ud} \approx V_{tb} \approx 1$$

Experimental paths to the Unitarity Triangle

B meson mixing and decays probe 5 of the 9 elements of the CKM matrix



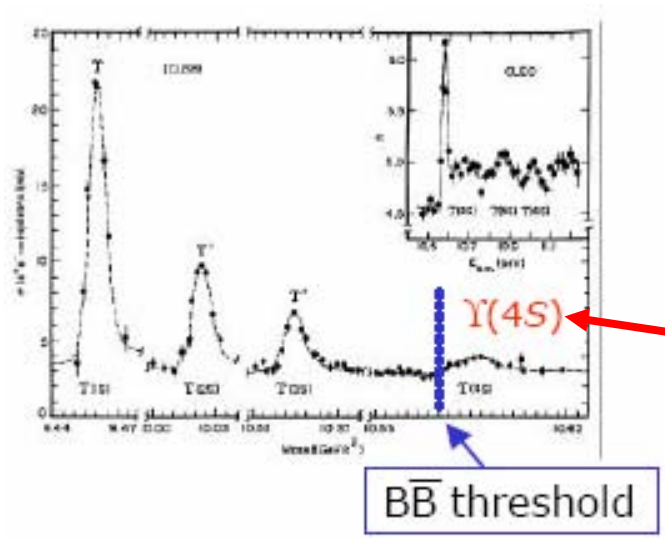
$$\bar{\rho} = \rho\left(1-\lambda^2/2\right)$$
$$\bar{\eta} = \eta\left(1-\lambda^2/2\right)$$

B physics: experimental facilities

- Asymmetric Energy B-factories:
  - $e^+e^- \rightarrow \Upsilon(4s) \rightarrow \overline{B^0_d} B^0_d$: clean environment, low backgrounds, high efficiency; small cross section !
  - Luminosity is the key factor;
  - asymmetric energies boost the B mesons to separate their decay vertices and measure decay time differences
- Hadron colliders:
  - Much higher cross sections ($\times 10^5$)
  - Also larger backgrounds and lower efficiency
  - Unique for B_s production and decays !
- For a quantitative comparison:
  - See table in a backup slide

The B-factory approach

- CM energy = 10.580 GeV



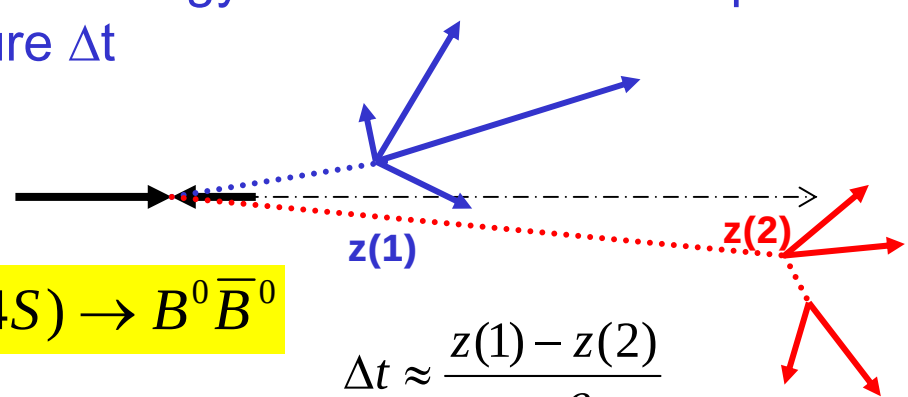
Favorable
Signal / Background:

$$\frac{\sigma_{b\bar{b}}}{\sigma_{had}} \cong 0.28$$

Effective cross sections:

$e^+e^- \rightarrow$	σ (nb)
bb	1.05
cc	1.30
ss	0.35
uu	1.39
dd	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	≈ 40

- Asymmetric energy beams: boost the B pair to measure Δt



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

$$\Delta t \approx \frac{z(1)-z(2)}{c\gamma\beta}$$

boost :

$$\gamma\beta \approx 0.56$$

for :

$$E(e^-) \approx 9\,\text{GeV},$$

$$E(e^+) \approx 3\,\text{GeV},$$

Asymmetric Energy B-Factories

PEP-II :

Delivered Luminosity 256 fb^{-1}

At LP 2003: 115 fb^{-1}

(~10% off-resonance)

> 240 M BB pairs recorded

Peak L.: $9.2 \times 10^{33} cm^{-2} s^{-1}$

(design: $3.0 \times 10^{33} cm^{-2} s^{-1}$)

LER: 3.1 GeV HER: 9.0 GeV

$$\gamma\beta = 0.56$$

$$\gamma\beta c\tau_B \approx 270\,\mu m$$

KEK-B :

Integrated Luminosity 287 fb^{-1}

At LP 2003: 140 fb^{-1}

(~10% off-resonance)

~ 280 M BB pairs recorded

Peak L.: $13.9 \times 10^{33} cm^{-2} s^{-1}$

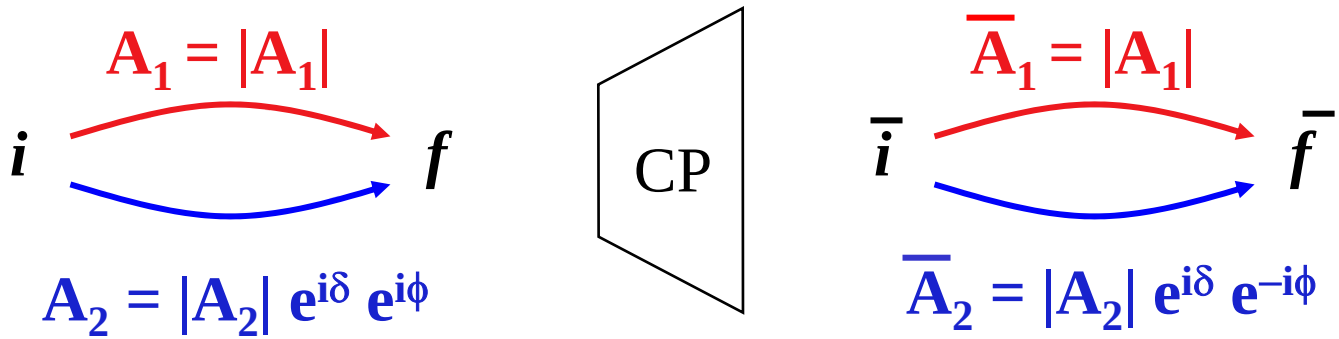
(design: $10.0 \times 10^{33} cm^{-2} s^{-1}$)

LER: 3.5 GeV HER: 8.0 GeV

$$\gamma\beta = 0.43$$

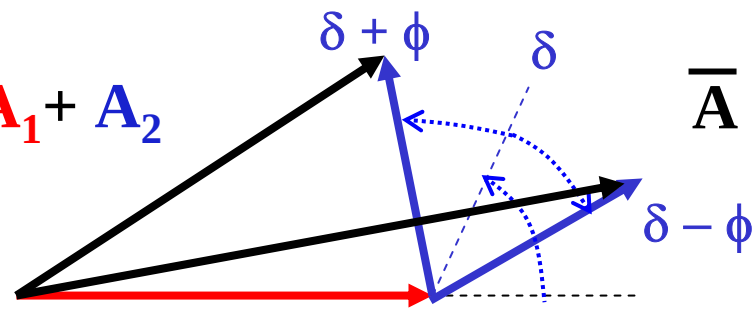
$$\gamma\beta c\tau_B \approx 210\,\mu m$$

Observables: "direct" CP asymmetry



$\delta \to \delta$ (CP-conserving)
$\phi \to -\phi$ (CP-violating)

$$A = A_1 + A_2$$

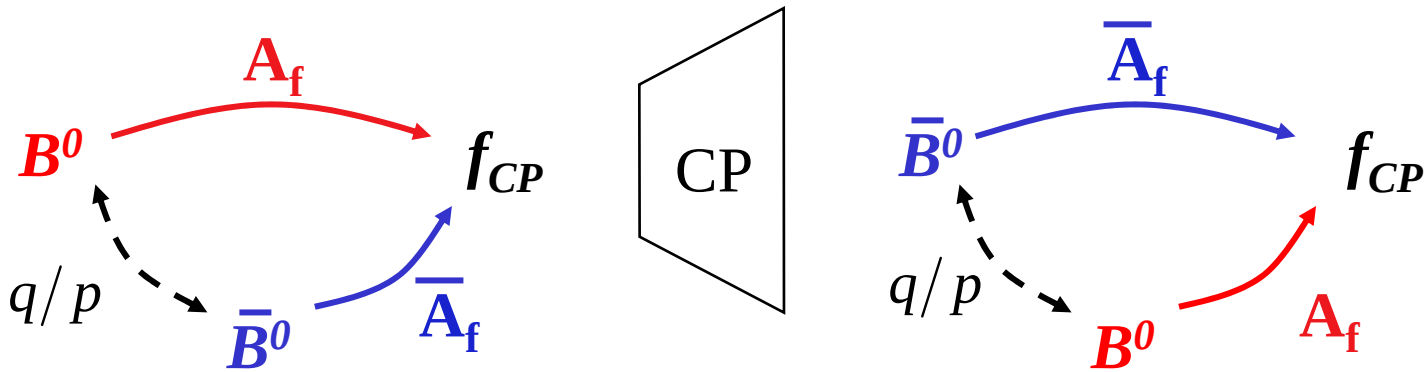


$$\bar{A} = \bar{A}_1 + \bar{A}_2 \neq A$$

Time-integrated "direct" CP asymmetry requires two amplitudes and $\delta \neq 0$:

$$A_{CP} = \frac{P(i \to f) - P(\bar{i} \to \bar{f})}{P(i \to f) + P(\bar{i} \to \bar{f})} \propto 2|A_1||A_2| \sin\delta \sin\phi \quad (\delta = 0 \Rightarrow A_{CP} = 0)$$

Time-dependent CP asymmetry



Interference between mixing and decay to a CP eigenstate

$$\Rightarrow \quad \Gamma\left(B^0_{phys}(t) \to f_{CP}\right) \neq \Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right)$$

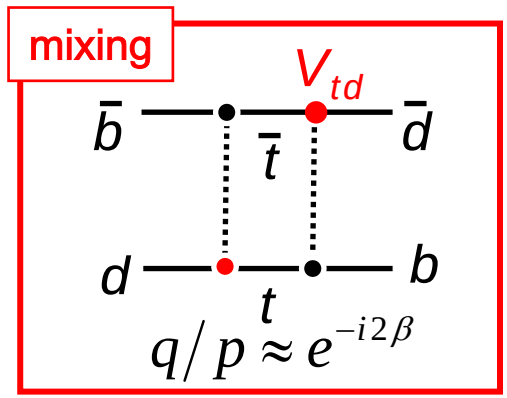
Flavor-tagged time-dependent decay rates are different!
they are governed by the "CP parameter":

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

CP eigenvalue

$\approx e^{-i2\beta}$ from mixing

Amplitude ratio



$$\left|B^0_{1,2}\right\rangle = p\left|B^0\right\rangle \pm q\left|\bar{B}^0\right\rangle$$

Time-dependent CP asymmetry

Decay distributions $f_+(f_-)$ when tag = $B^0(\bar{B}^0)$

$$f_{CP,\pm}(\Delta t) = \frac{\Gamma}{4} e^{-\Gamma \Delta t} [1 \pm S_{f_{CP}} \sin \Delta m_d \Delta t \mp C_{f_{CP}} \cos \Delta m_d \Delta t]$$

Asymmetry

$$A_{f_{CP}}(\Delta t) = C_{f_{CP}} \cos(\Delta m_d \Delta t) - S_{f_{CP}} \sin(\Delta m_d \Delta t)$$

CP parameter

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

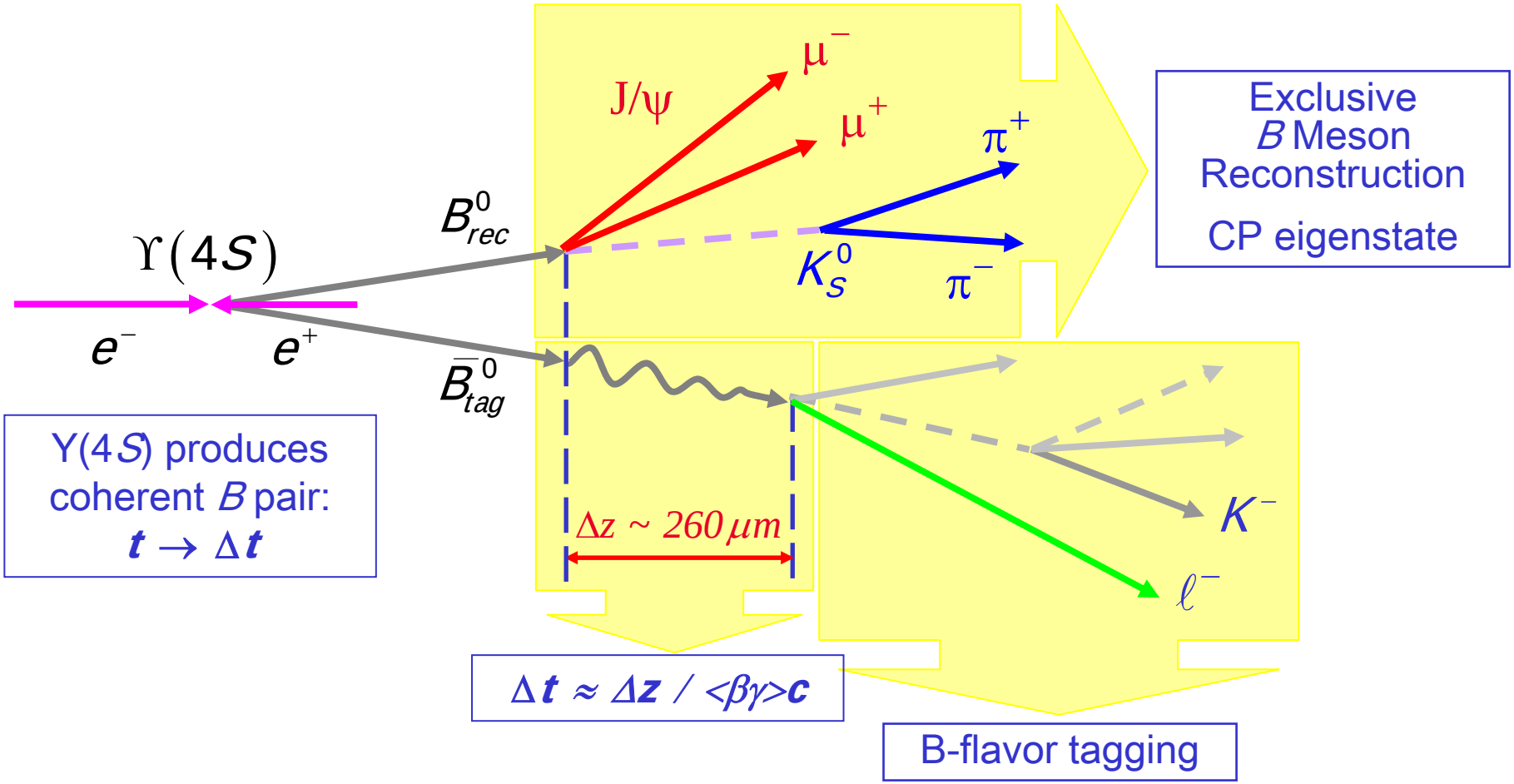
$$\boxed{\begin{aligned} C_{f_{CP}} &= \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \\ S_{f_{CP}} &= \frac{-2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \end{aligned}}$$

For single decay amplitude

$= 0$

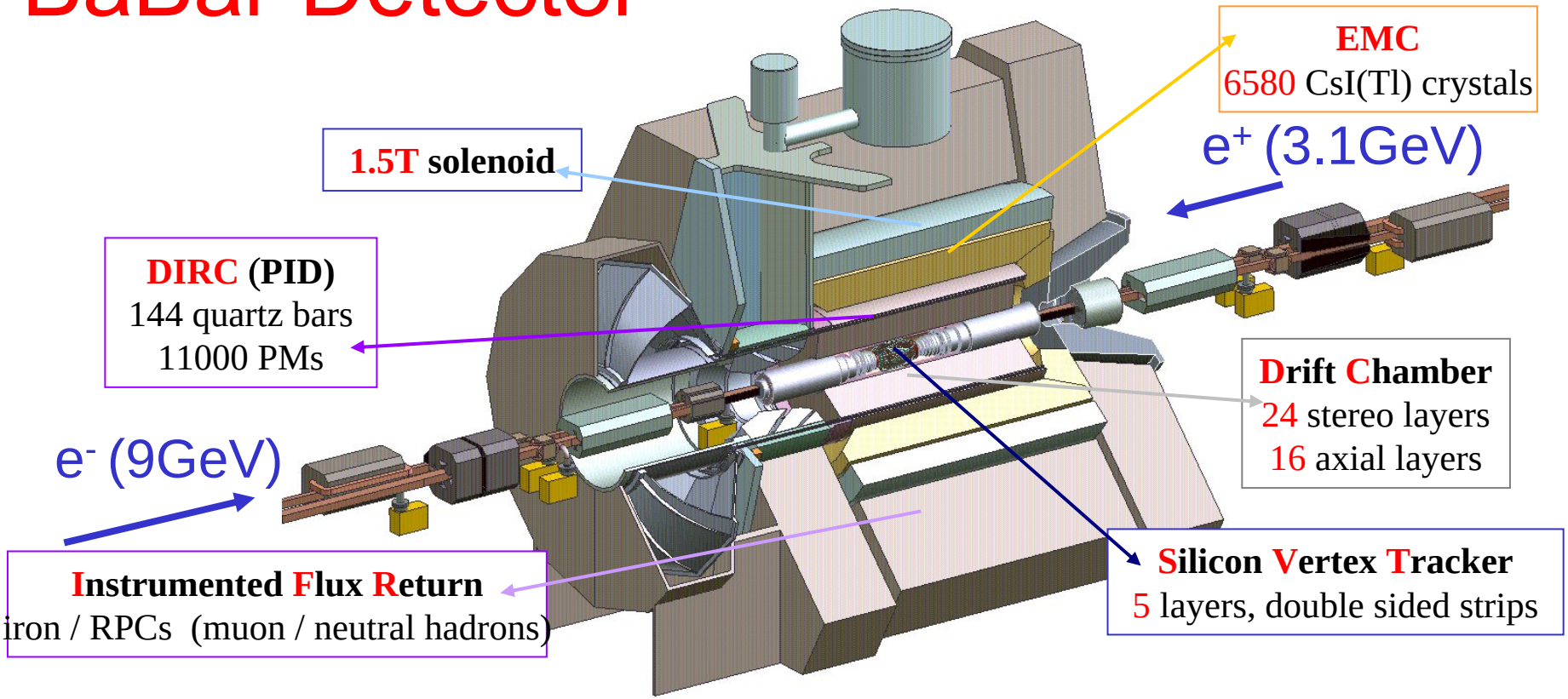
$= -\,\mathrm{Im}\,\lambda_{f_{CP}}$

Time-Dependent CP Asymmetry Measurement



B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging flavor states)

BaBar Detector



SVT: vertexing and tracking: crucial for Δt and low p_T tracks

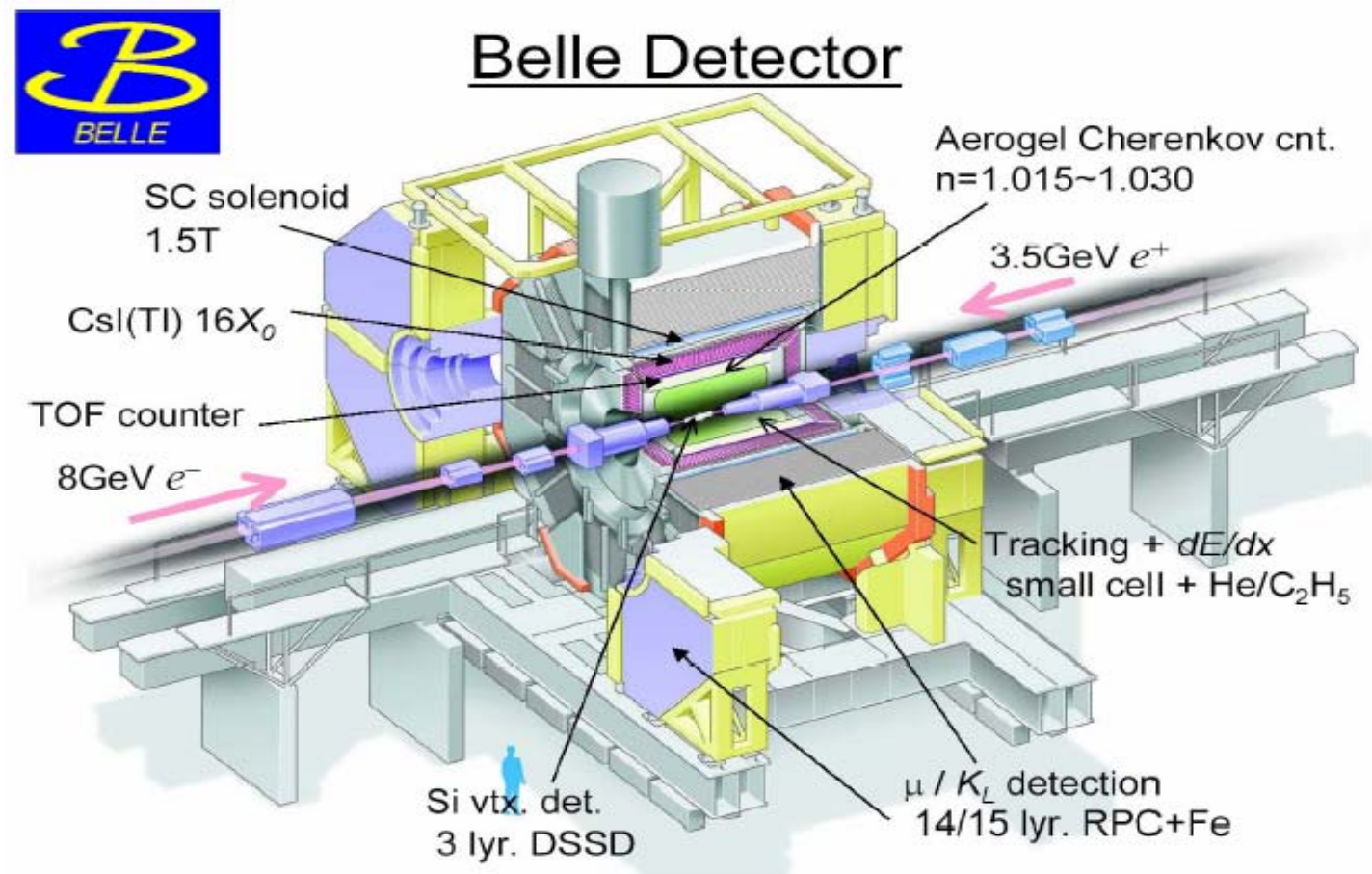
DCH: main tracking device, also dE/dx for particle ID

DIRC: K-π separation > 3.4σ for P < 3.5GeV/c

EMC: very good energy resolution; electron ID, π^0 and γ reco.

IFR: Muon and neutral hadrons (K^0_L) ID

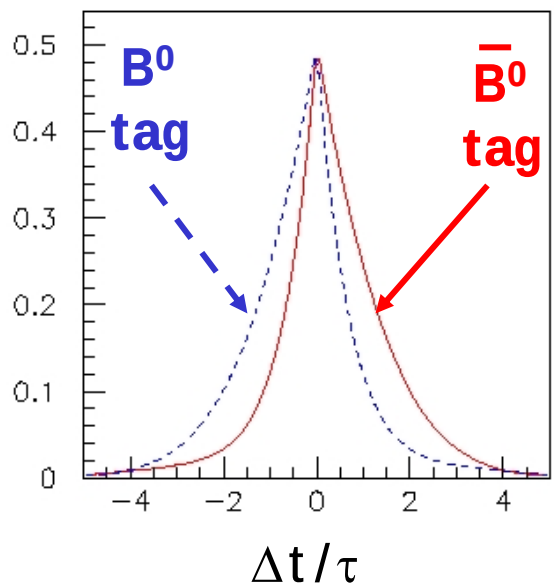
Belle detector at KEK



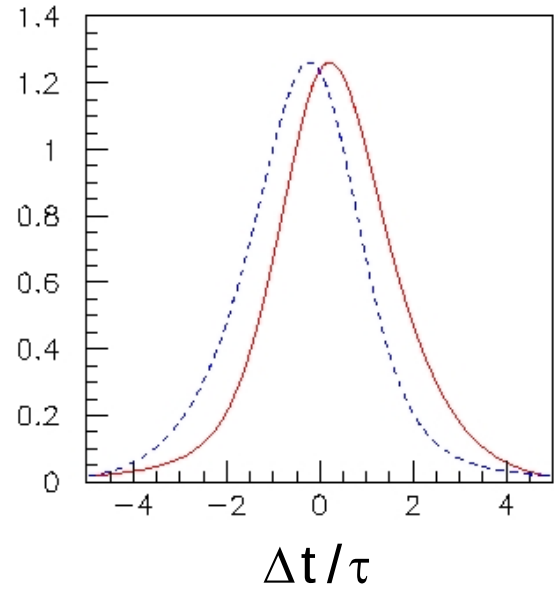
Both BaBar and Belle: optimized for CP asymmetries

Δt resolution effect

CP time-dependent asymmetry (C=0, S≠0)



perfect resolution



smeared resolution

Time-integrated asymmetry = 0
⇒ Need both Δt and tag !

Δt resolution dominated by tag side:

~1 ps ⇔ 170 μm

τ_B ~ 1.6 ps ⇔ 250 μm

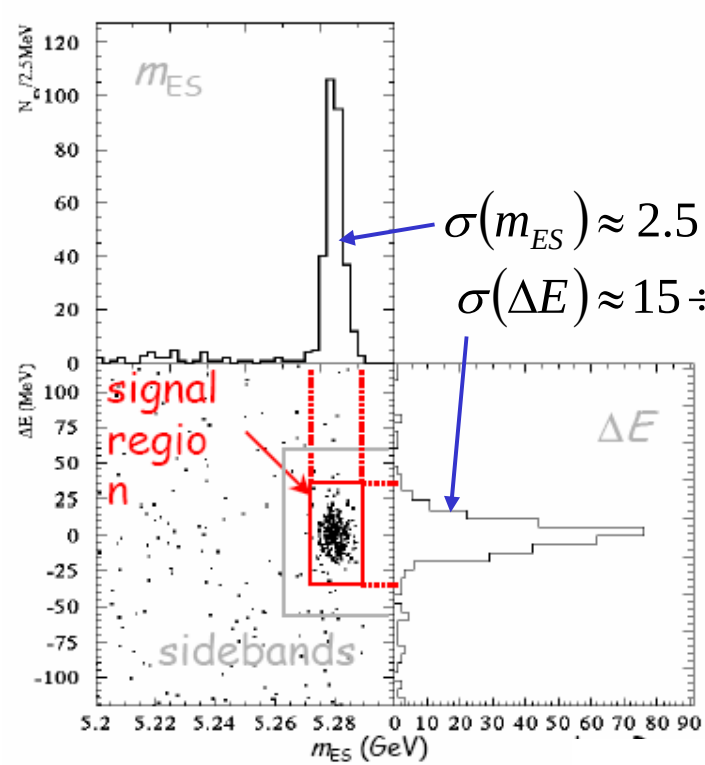
Exclusive B decay reconstruction

- Likelihood fits with discriminating variables:
  - Kinematics:

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

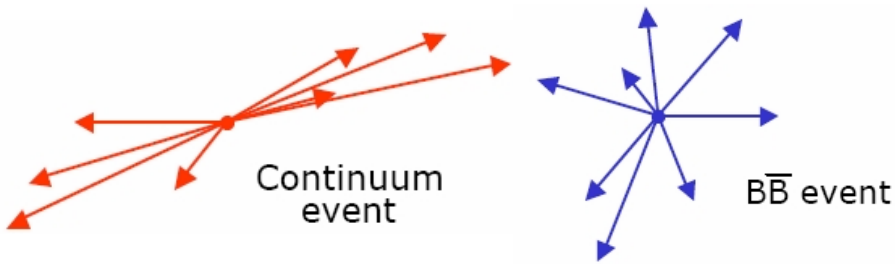
$$\Delta E = E_B^* - E_{beam}^*$$

  - Particle ID
  - Event shape variables, to separate the continuum bkgd
- Efficiency
  - Typically $\varepsilon \approx 15 \div 40\%$
- Purity
  - Up to 97% (for $J/\psi K_S$)



$$\sigma(m_{ES}) \approx 2.5 \text{ MeV}$$

$$\sigma(\Delta E) \approx 15 \div 30 \text{ MeV}$$



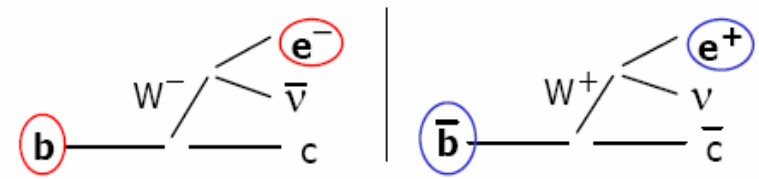
B Flavour Tagging

CP asymmetry is between $B^0 \to f$ and $\overline{B^0} \to f$

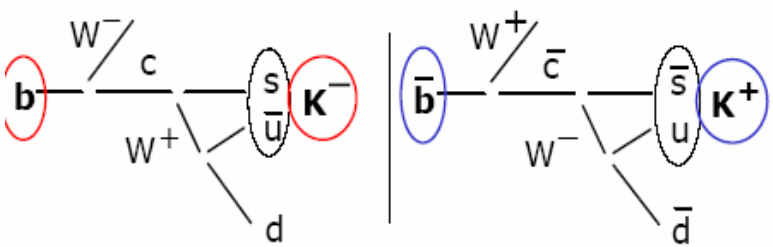
Must tag flavor at $\Delta t=0$ (when we know flavor of two Bs is opposite).

Use decay products of *other* (tag) B.

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Soft and hard pion tagging

$$\overline{B}^0 \to D^{*+}\boxed{\pi^-}$$

$$\hookrightarrow D^0\boxed{\pi^+}$$

$\overline{B}^0$: fast π^-, soft π^+

B^0: fast π^+, soft π^-

Overall tagging performance

$$\sum_i \varepsilon_i (1-2\omega_i)^2 \approx 28\%$$

recently improved to 30.5%

BaBar

ε_i tag efficiency

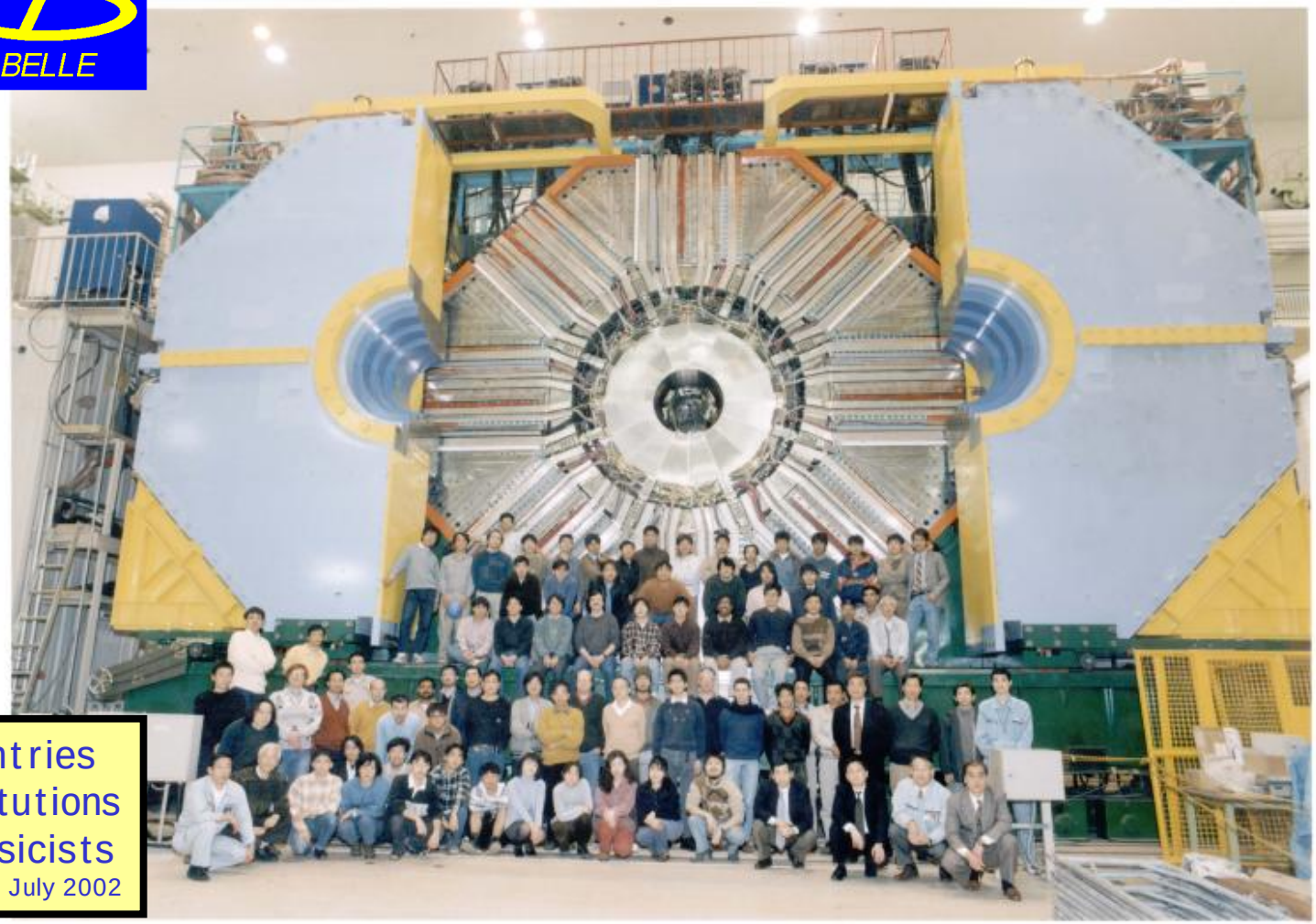
ω_i wrong tag probability

BABAR Collaboration

Gathering at SLAC, July 2004

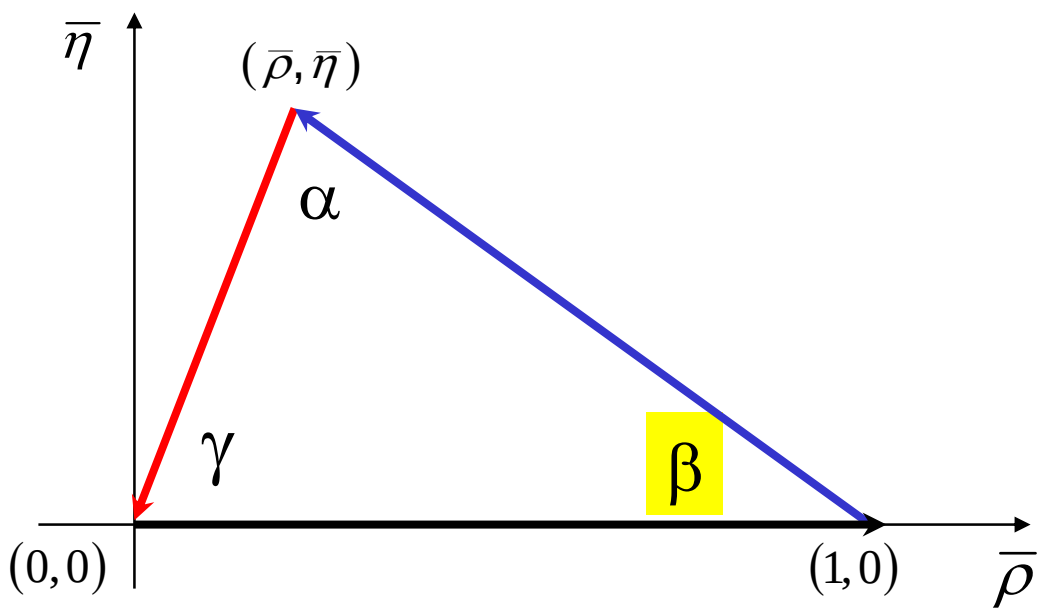
10 Countries
77 Institutions
593 Physicists
May 2004

Belle Collaboration

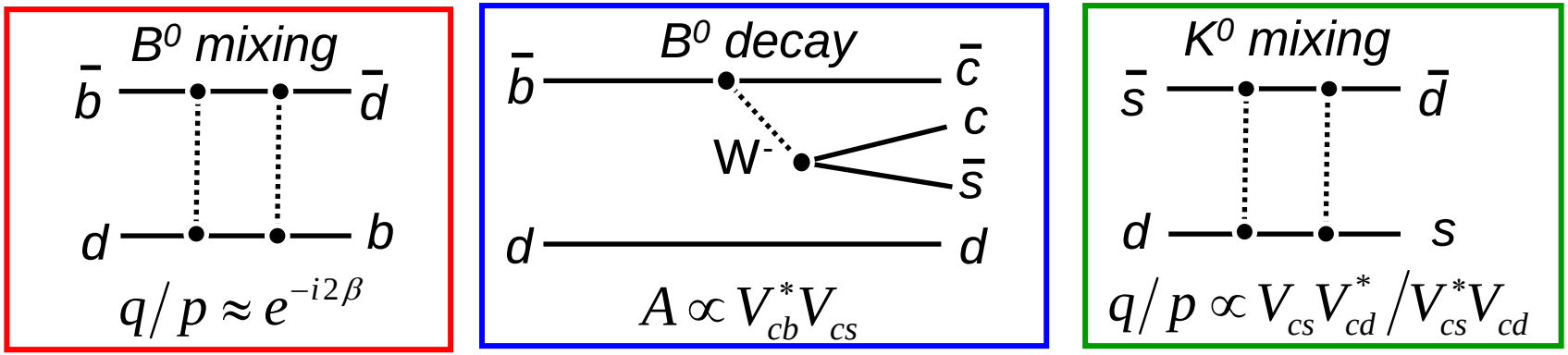


12 Countries
54 Institutions
285 Physicists
July 2002

beta (ϕ_1)



sin2β from mixing & $b \to c\bar{c}s$ "tree" amplitudes



Clean!

$$\lambda_f = \eta_f \left(\frac{q}{p}\right)_B \frac{\bar{A}_f}{A_f} \left(\frac{q}{p}\right)_K = \eta_f e^{-i2\beta}$$

THEORY:

- all decay amplitudes have the same weak phase ⇒ clean prediction

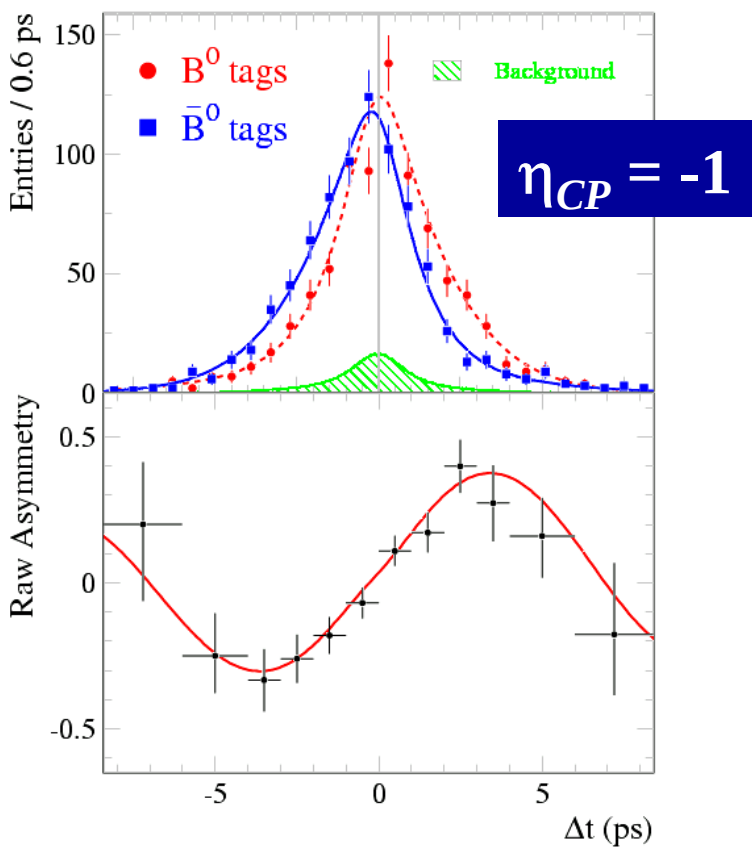
$$\mathrm{Im}(\lambda_{\psi K_S}) = -\mathrm{Im}(\lambda_{\psi K_L}) = \sin(2\beta) = S$$

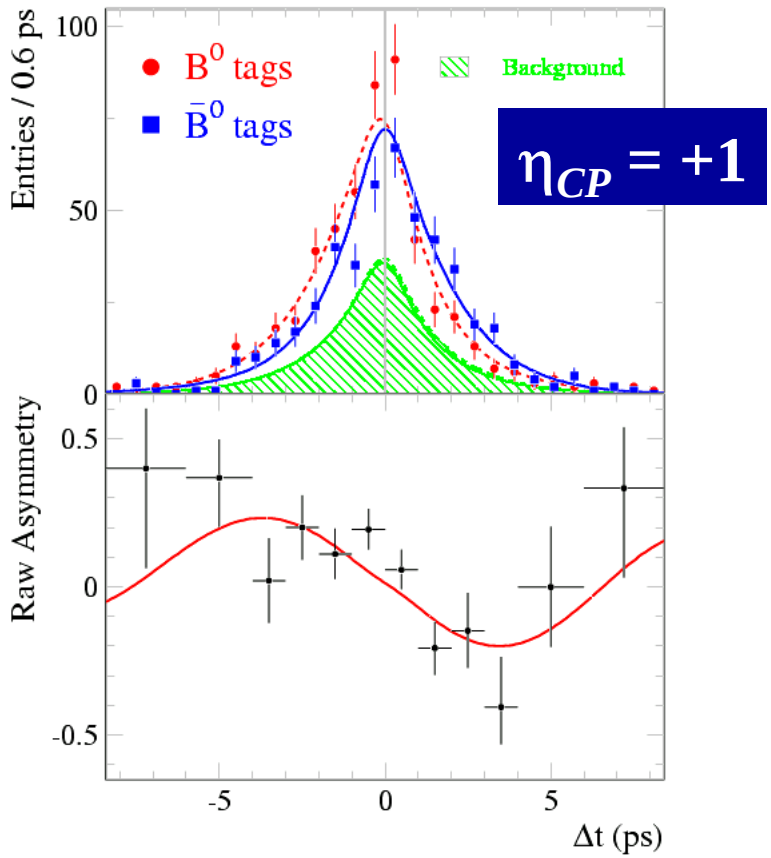
$$C = 0 \qquad |\lambda_{\psi K_S}| = 1$$

EXPERIMENT:

- Large branching fractions, i.e.: $BF(\psi(l^+l^-)K_S(\pi^+\pi^-)) = 3.5 \times 10^{-4}$
- High purity: 97% for $J/\psi K_S$, somewhat less for other charmonium modes

BABAR Result for sin2β





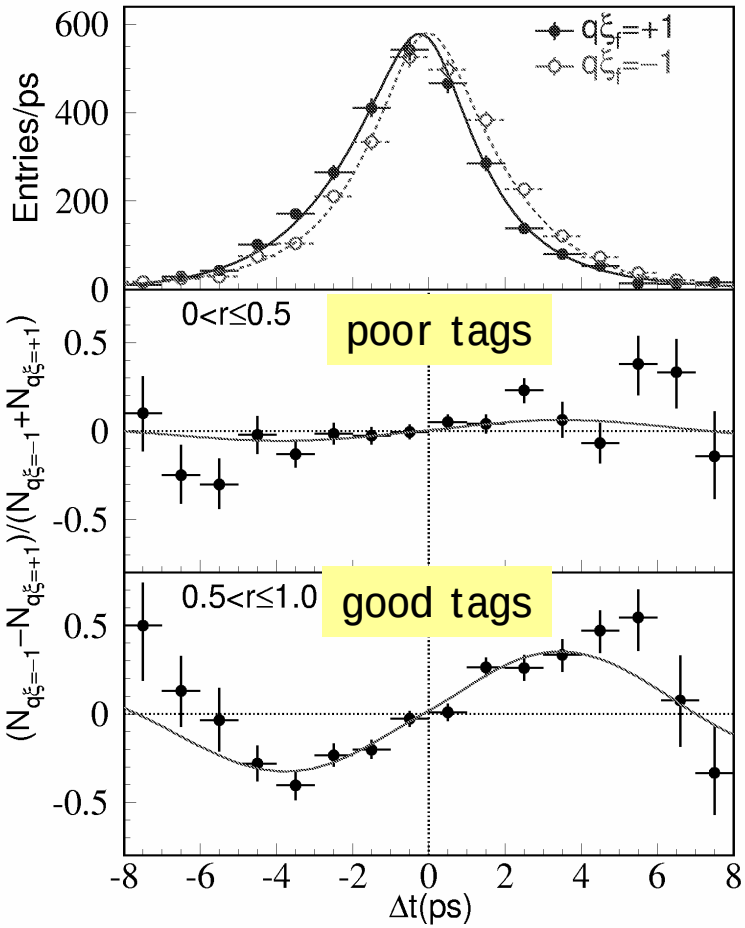
BABAR
88M BB

$$\sin 2\beta = 0.741 \pm 0.067_{(stat)} \pm 0.033_{(syst)}$$

PRL **89** (2002) 201802

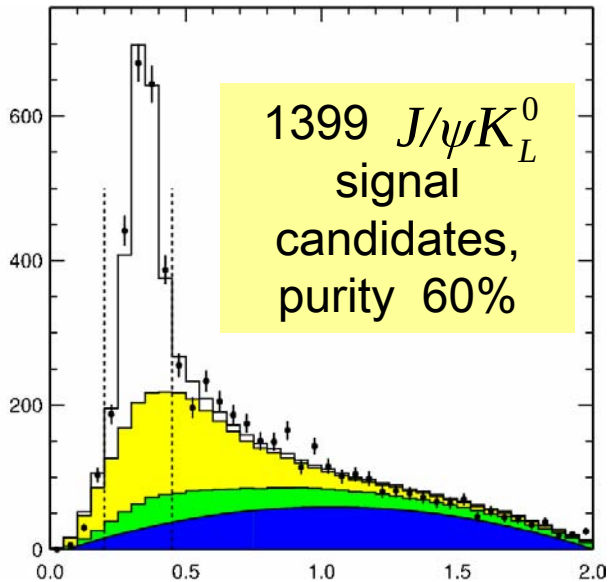
$|\lambda| = 0.948 \pm 0.051 \pm 0.030$ (consistent with unity, no direct CPV)

Belle Result for sin2β



Preliminary, 140 fb^{-1}

2716 charmonium signal events, 93% purity, and:

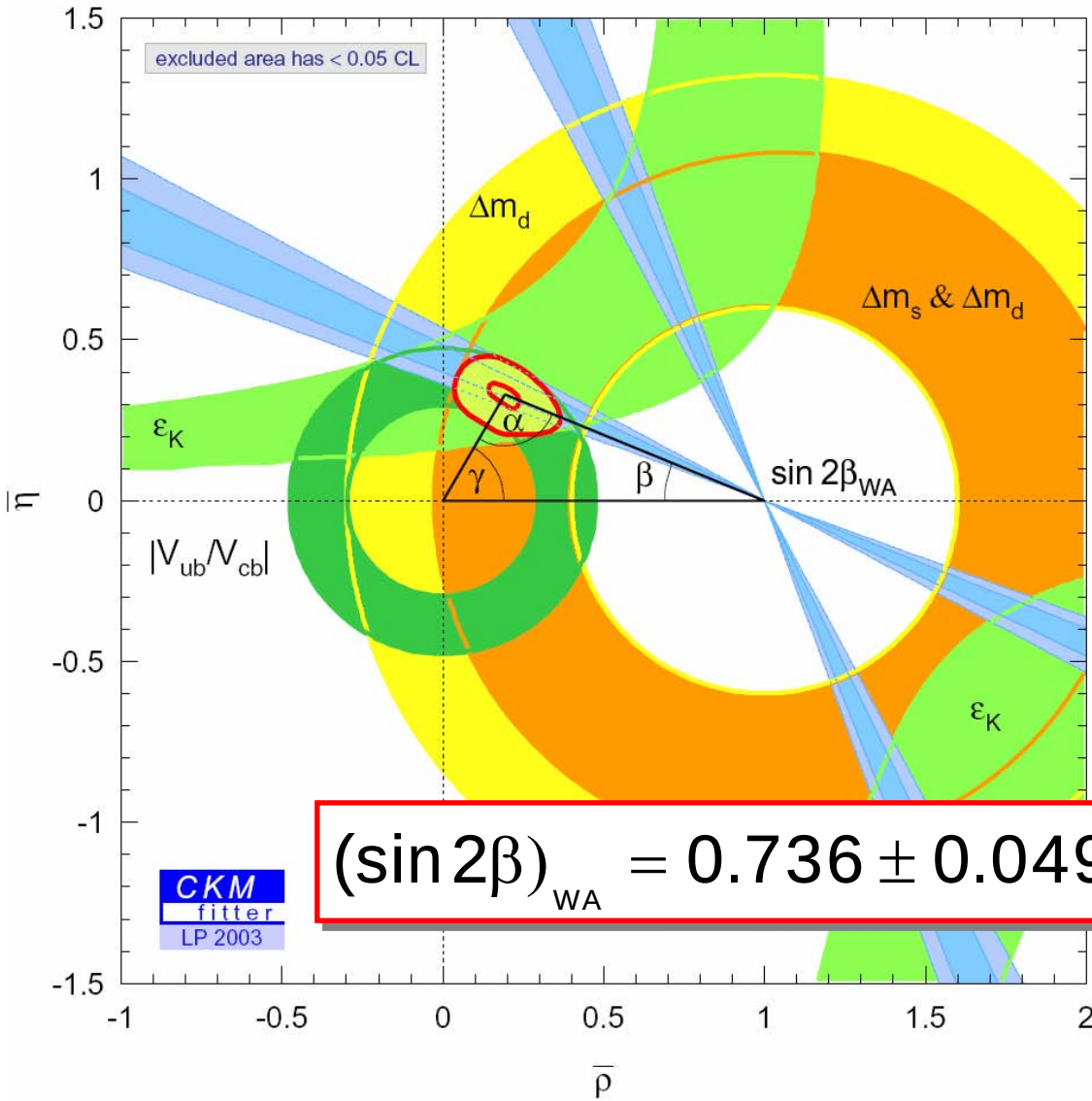


1399 $J/\psi K_L^0$ signal candidates, purity 60%

$$\sin 2\beta = 0.733 \pm 0.057_{(stat)} \pm 0.028_{(syst)}$$

Reported at LP03, hep-ex/0308040

Standard Model Constraints



Indirect constraints vs direct measurement

At 95% CL:

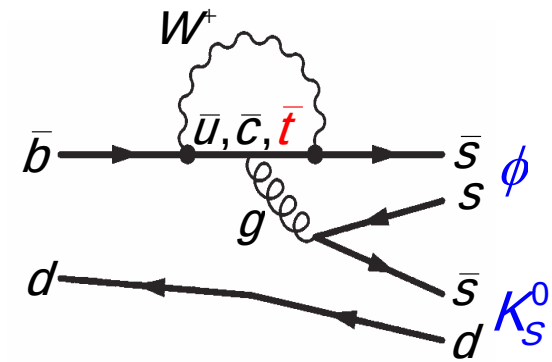
$$19.4 < \beta < 26.5^{o}$$
$$77 < \alpha < 122^{o}$$
$$37 < \gamma < 80^{o}$$

$$(\sin 2\beta)_{WA} = 0.736 \pm 0.049 \quad \text{(stat+syst)}$$

A.Hoecker et al.

sin2β from mixing & b→s "penguin" amplitudes

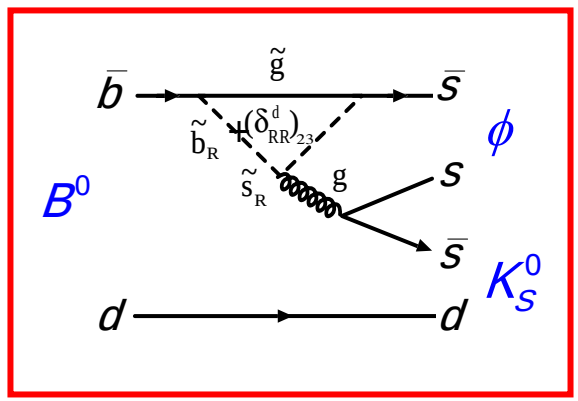
- The CKM model passed its first precision test !
  - The determination of (ρ,η) is now dominated by the measurement of sin2β: what next ?
- Start looking for non-SM effects
  - Best candidates: decays with the same (zero) weak phase, but loop ("penguin") diagrams
  - Look for effects of virtual non-SM particles in the loop
  - Experimentally, the best modes are ϕK_S, $\eta' K_S$; recently BaBar started also to study $\pi^0 K_S$, $f^0 K_S$, $K^*\gamma$
  - non-SM signature: pattern of different asymmetries for these channels



SM expectation:

$$\mathrm{Im}(\lambda_{\phi K_S}) = \sin(2\beta) = S$$

$$C = 0$$

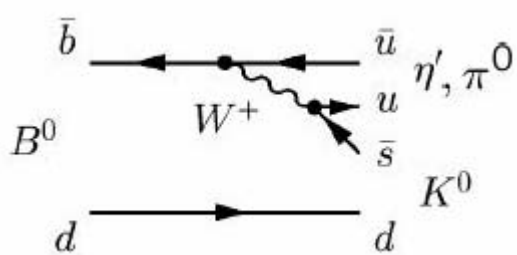


sin2β from mixing & b→s "penguin" amplitudes

- Experimental challenge of b→s "penguins" :
  - Smaller branching fractions
  - smaller purities

Mode	BF(B→f) x10^{-6}	$\Pi_i BF_i$ x10^{-6}	Reco. Efficiency	Purity
$J/\psi K_s$	440	36.0	44%	97%
$\eta' K_s$	33	10.6	23%	~60%
ϕK_s	4	1.4	42%	~80%
$\pi^0 K_s$	6	4.1	17%	~50%

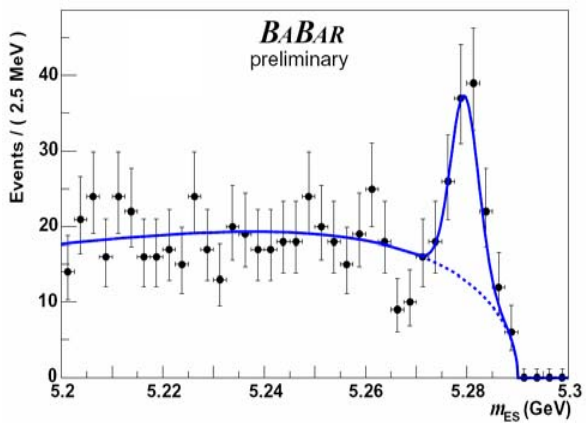
- Theoretical problems:
  - Sub-dominant SM contributions with non-zero weak phase
  - "u-quark penguin" is CKM-suppressed (~0.02), but $\eta' K_S$ and $\pi^0 K_S$ also have "b → u tree"

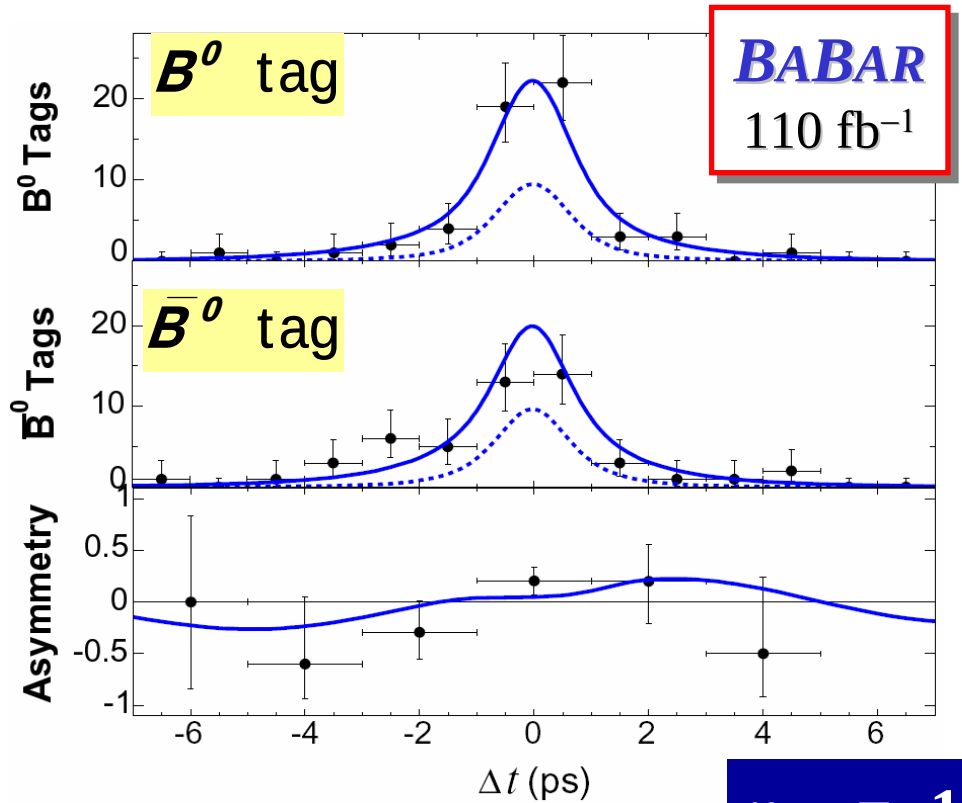


SM breaking of S=sin2β		
Mode	Reasonable expectation	Bounds* from SU(3)
ϕK_s	<0.05	<0.25
$\eta' K_s$	~0.08	<0.35
$\pi^0 K_s$	~0.08?	<0.20

*Grossman, Ligeti, Nir, Quinn. PRD 68, 015004 (2003)
Gronau, Grossman, Rosner hep-ph/0310020

BABAR Results for $B \to \phi K^0_S$





Signal

$$N\left(\phi K_S^0\left(\to \pi^+\pi^-\right)\right) = 70 \pm 9$$

hep-ex/0403026

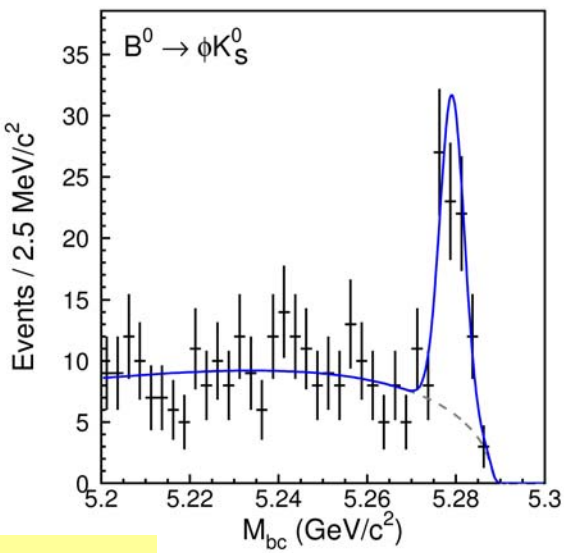
Accepted by PRL

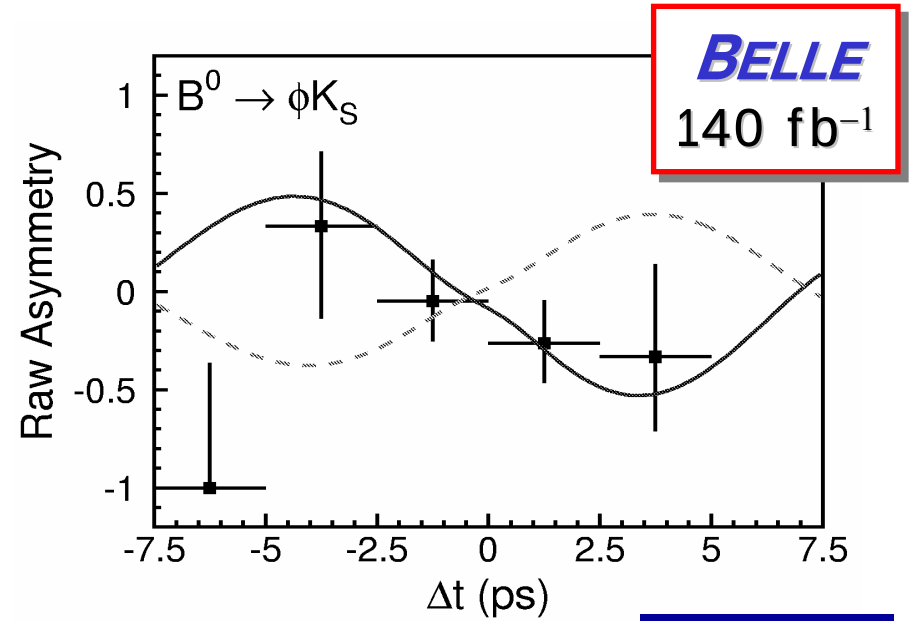
Consistent with Standard Model expectation.

$\eta_{CP} = -1$

$$S_{\phi K_S^0} = +0.45 \pm 0.43_{(stat)} \pm 0.07_{(syst)}$$
$$C_{\phi K_S^0} = -0.38 \pm 0.37_{(stat)} \pm 0.12_{(syst)}$$

Belle Results for $B \to \phi K^0_S$





Signal

$$N\left(\phi K_S^0\left(\to \pi^+\pi^-\right)\right) = 68 \pm 11$$

PRL **91** (2003) 261602

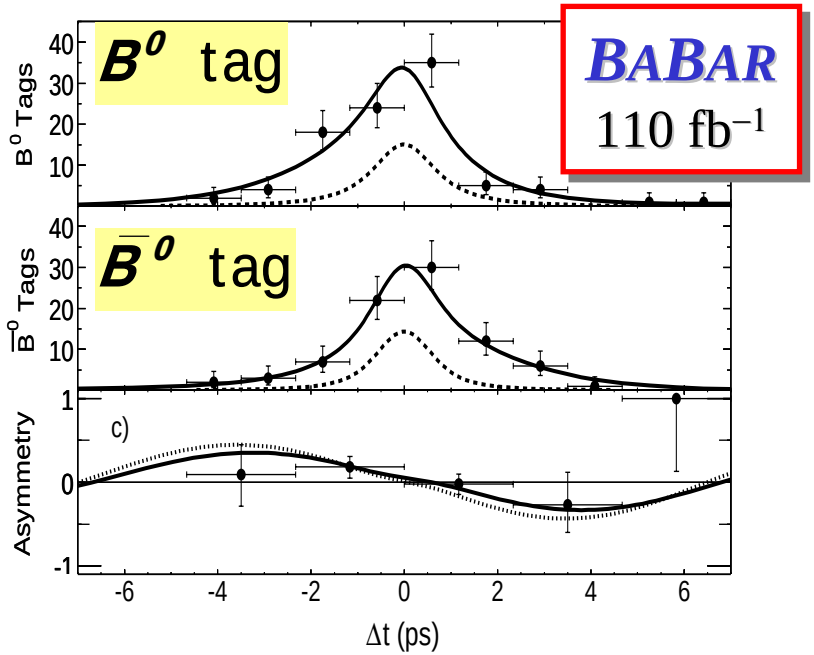
$\eta_{CP} = -1$

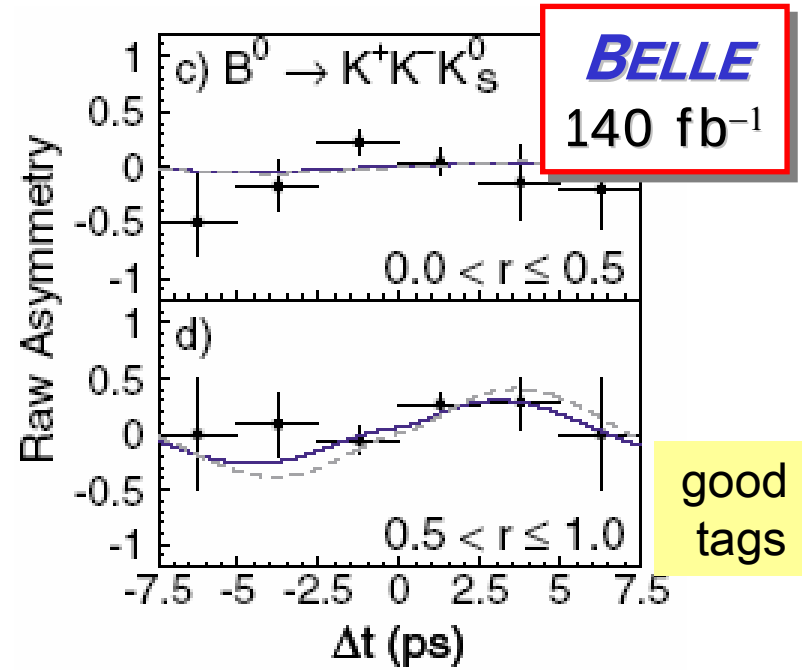
$$S_{\phi K_S^0} = -0.96 \pm 0.50_{(stat)} \; {}^{+0.09}_{-0.11}{}_{(syst)}$$

$$C_{\phi K_S^0} = +0.15 \pm 0.29_{(stat)} \pm 0.07_{(syst)}$$

"We find that the observed CP asymmetry (…) differs from the standard model (SM) expectation by 3.5 standard deviations."

BaBar and Belle: $B \to K^+K^-K^0_S$





good tags

$S = -0.56 \pm 0.25 \pm 0.04$
$C = -0.10 \pm 0.19 \pm 0.10$

$\approx -\sin 2\beta$

$S = -0.51 \pm 0.26 \pm 0.05$
$C = 0.17 \pm 0.16 \pm 0.04$

hep-ex/0406005

$\eta_{CP} = +1$

PRL 91 (2003) 261602

Non-resonant $K^+K^-K_S$: almost completely CP-even (isospin analysis). Both BaBar and Belle consistent with Standard Model expectation.

sin2β: charmonium vs penguins

World average for charmonium modes

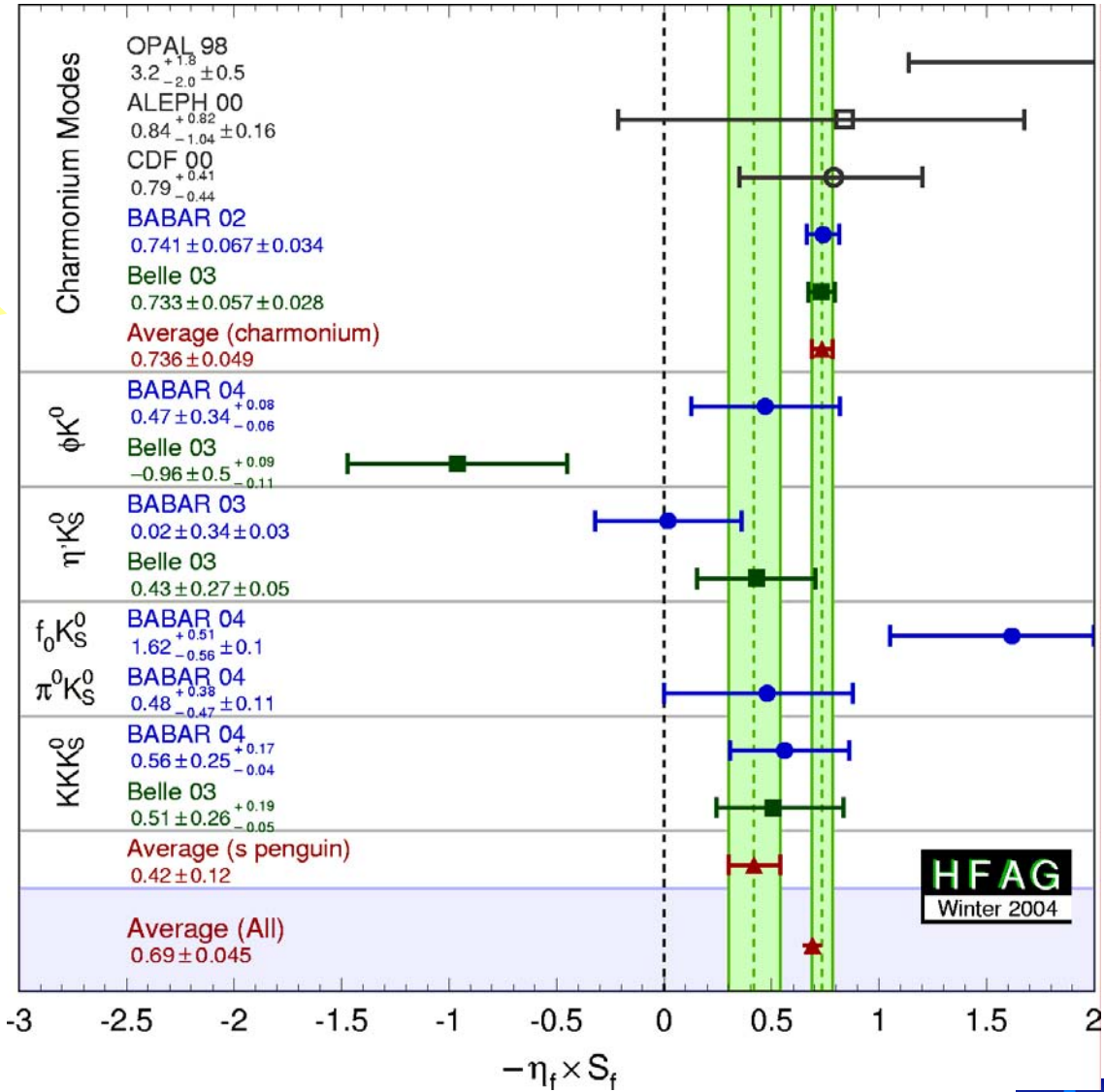
0.736 ± 0.049

ϕK^0:
BaBar and Belle ~2.6σ apart

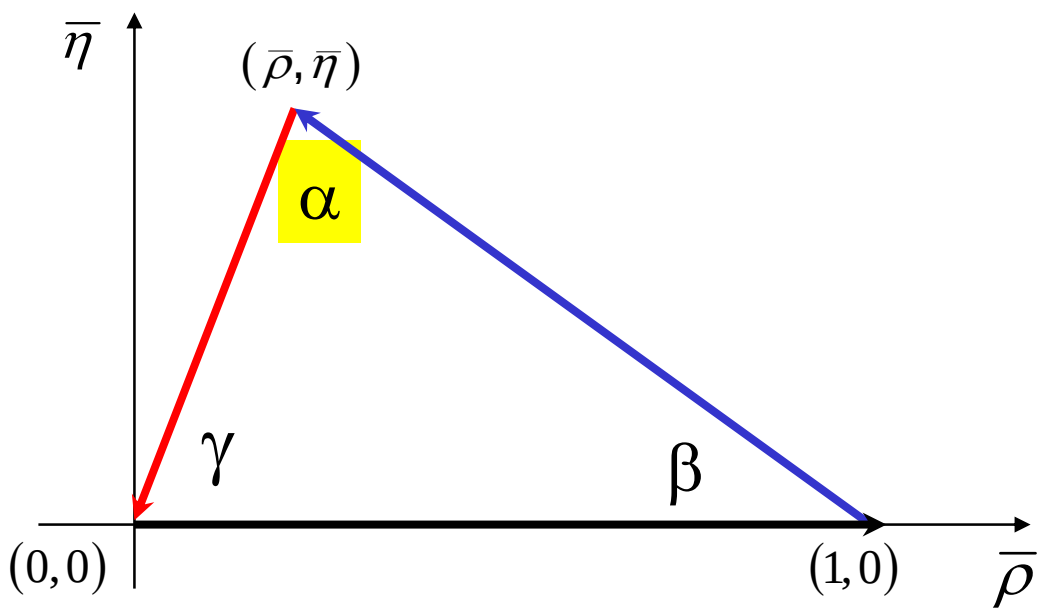
Present average for $b \to s\bar{s}s$

0.42 ± 0.12

~2.4 sigma below charmonium modes



alpha (ϕ_2)

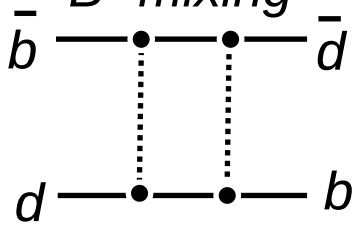


$\sin 2\alpha$ from $B \to \pi\pi, \rho\pi, \rho\rho$

Interference of suppressed $b \to u$ "tree" decay with mixing

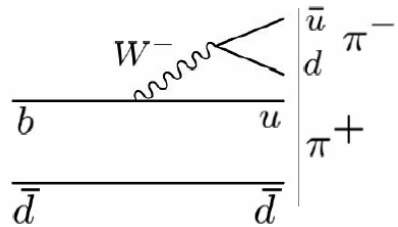
but: "penguin" is sizeable!

B^0 mixing



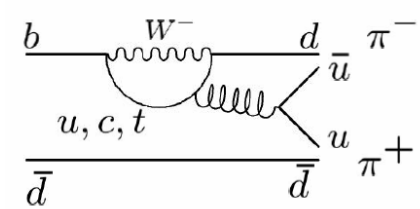
$$q/p \propto V_{tb}^* V_{td} / V_{tb} V_{td}^*$$

B^0 decay: tree



$$A \propto V_{ub}^* V_{ud} \quad \propto \lambda^3$$

B^0 decay: penguin



$$A \propto V_{td}^* V_{tb} \quad \propto \lambda^3$$

$$\lambda_{\pi\pi} = \frac{q}{p}\frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$\lambda_{\pi\pi} = e^{i2\alpha} \frac{T + Pe^{+i\gamma} e^{i\delta}}{T + Pe^{-i\gamma} e^{i\delta}}$$

→ Coefficients in time-dependent CP Asymmetry:

Neglecting penguins:

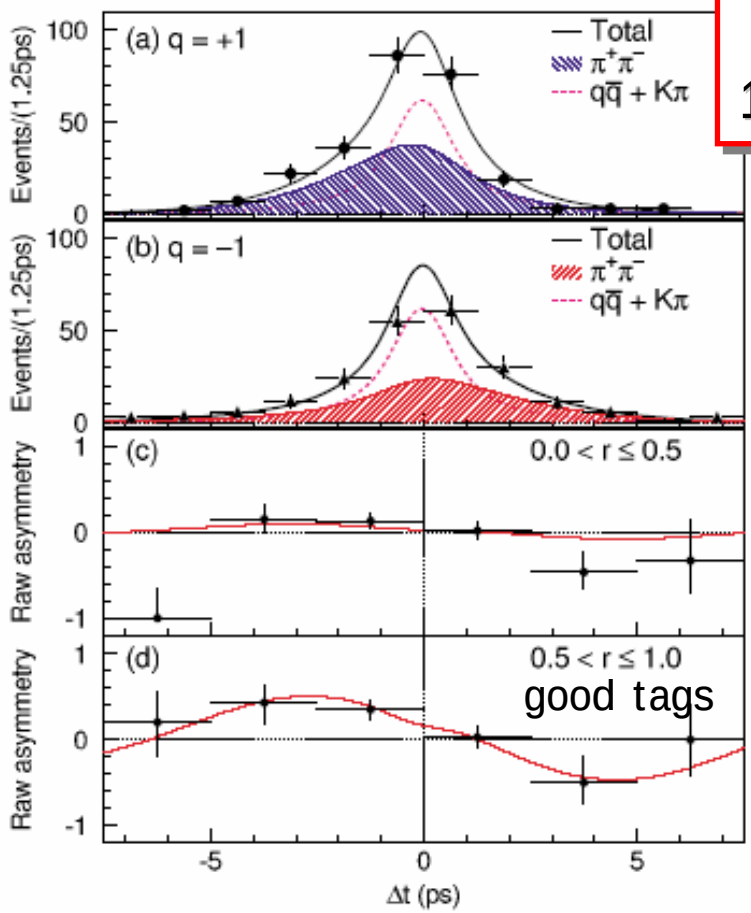
$$S_{\pi\pi} = \sin 2\alpha$$
$$C_{\pi\pi} = 0$$

But: large penguins expected !
|P/T| ~ 0.3 ⇒

$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2} \sin 2\alpha_{eff}$$
$$C_{\pi\pi} \propto \sin\delta$$

NB: Experimental challenge: BFs down to ~ 10^{-6} ; purities also are lower!

Belle results on $S_{\pi\pi}$ and $A_{\pi\pi} = -C_{\pi\pi}$



Belle
140 fb^{-1}

1529 candidates
(801 B^0- and 728 B^0-tags)
(372 ± 32) $\pi^+\pi^-$ signal ev.ts

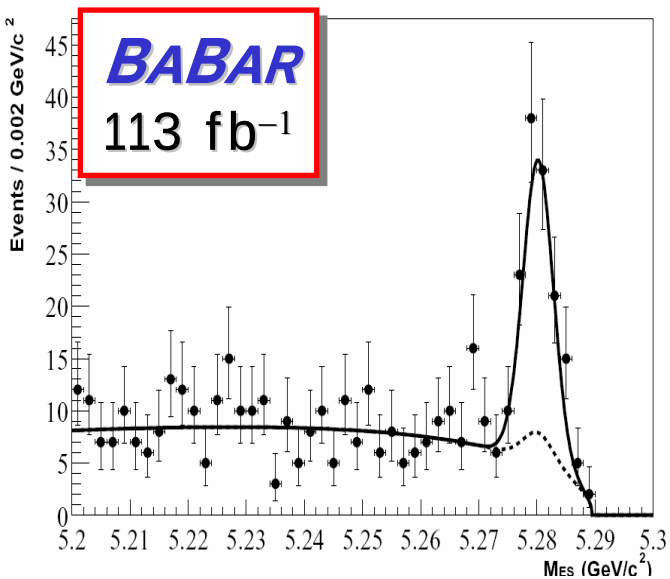
$$S_{\pi\pi} = -1.00 \pm 0.15_{(stat)} \pm 0.07_{(syst)}$$
$$A_{\pi\pi} = +0.58 \pm 0.15_{(stat)} \pm 0.07_{(syst)}$$

PRL **93** (2004) 021601

"We rule out the CP-conserving case, A = S = 0, at a level of 5.2 σ."

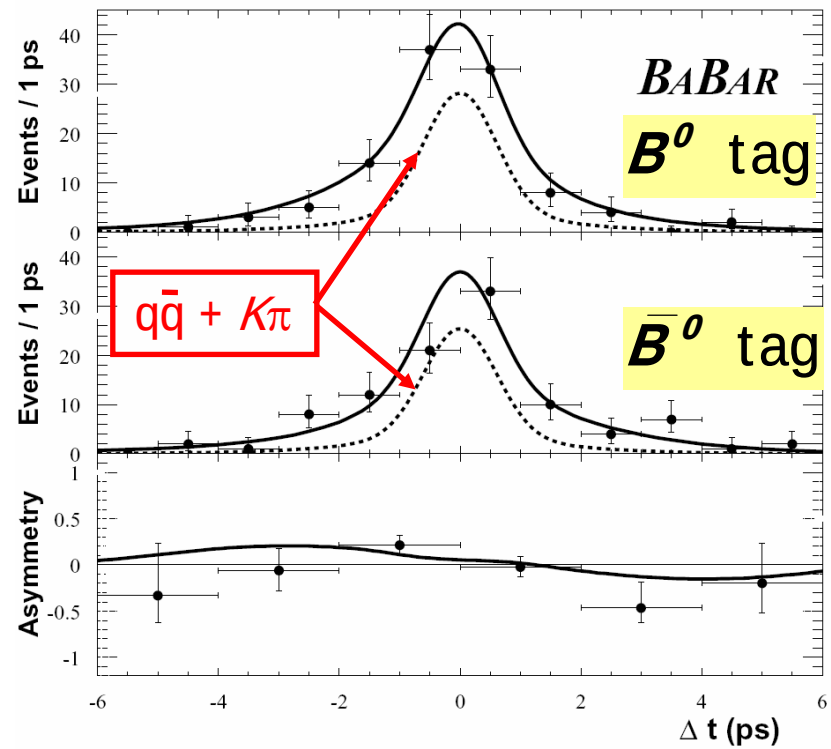
"We also find evidence for direct CP violation with a significance at or greater than 3.2 σ for any S value."

BaBar results on $S_{\pi\pi}$ and $C_{\pi\pi}$



266 ± 24 $\pi^+\pi^-$ candidates

Fit projections in sample of $\pi\pi$-enriched events

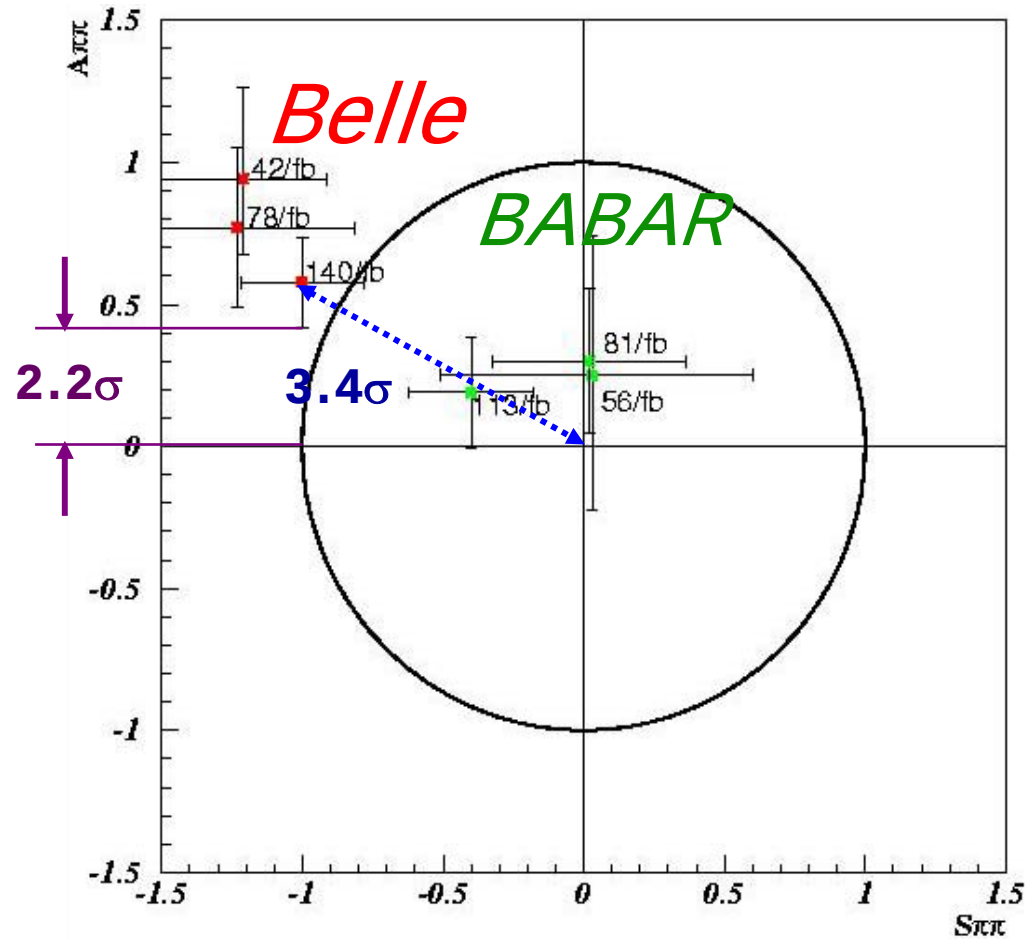


$$\sin 2\alpha_{eff} = \boxed{\begin{aligned} S_{\pi\pi} &= -0.40 \pm 0.22_{(stat)} \pm 0.03_{(syst)} \\ C_{\pi\pi} &= -0.19 \pm 0.19_{(stat)} \pm 0.05_{(syst)} \end{aligned}}$$

Reported at LP03

Comparison of $A_{\pi\pi} = -C_{\pi\pi}$ and $S_{\pi\pi}$

$A_{\pi\pi} = - C_{\pi\pi}$



$S_{\pi\pi}$

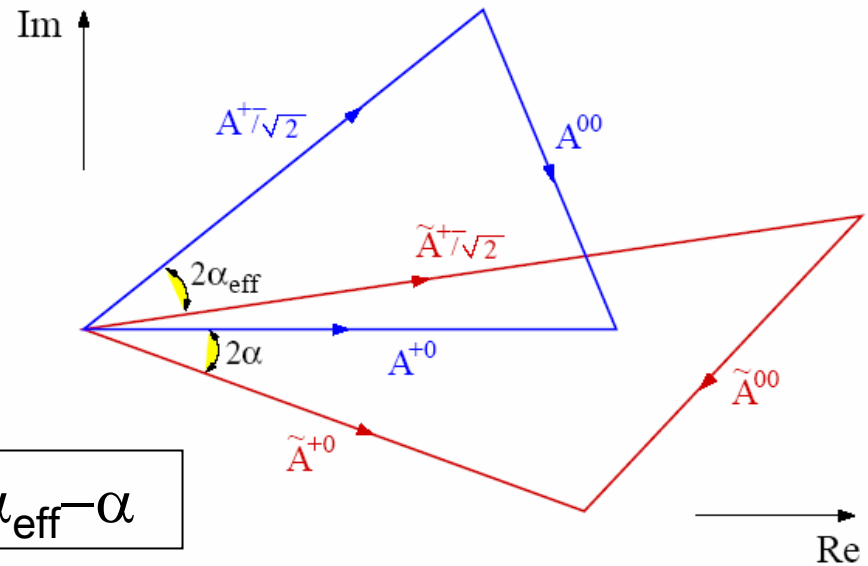
Belle (140 fb-1) vs
BaBar (113 fb-1):
~2 σ difference

Coping with penguins: isospin analysis

To correct for penguin contribution:

$$2\alpha_{\text{eff}} = 2\alpha + 2\kappa$$

Gronau-London method (isospin triangles). From flavor-tagged decay rates of $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$



$$A^{+0} = A^{00} + \frac{1}{\sqrt{2}} A^{+-}$$

$$\overline{A}^{+0} = \overline{A}^{00} + \frac{1}{\sqrt{2}} \overline{A}^{+-}$$

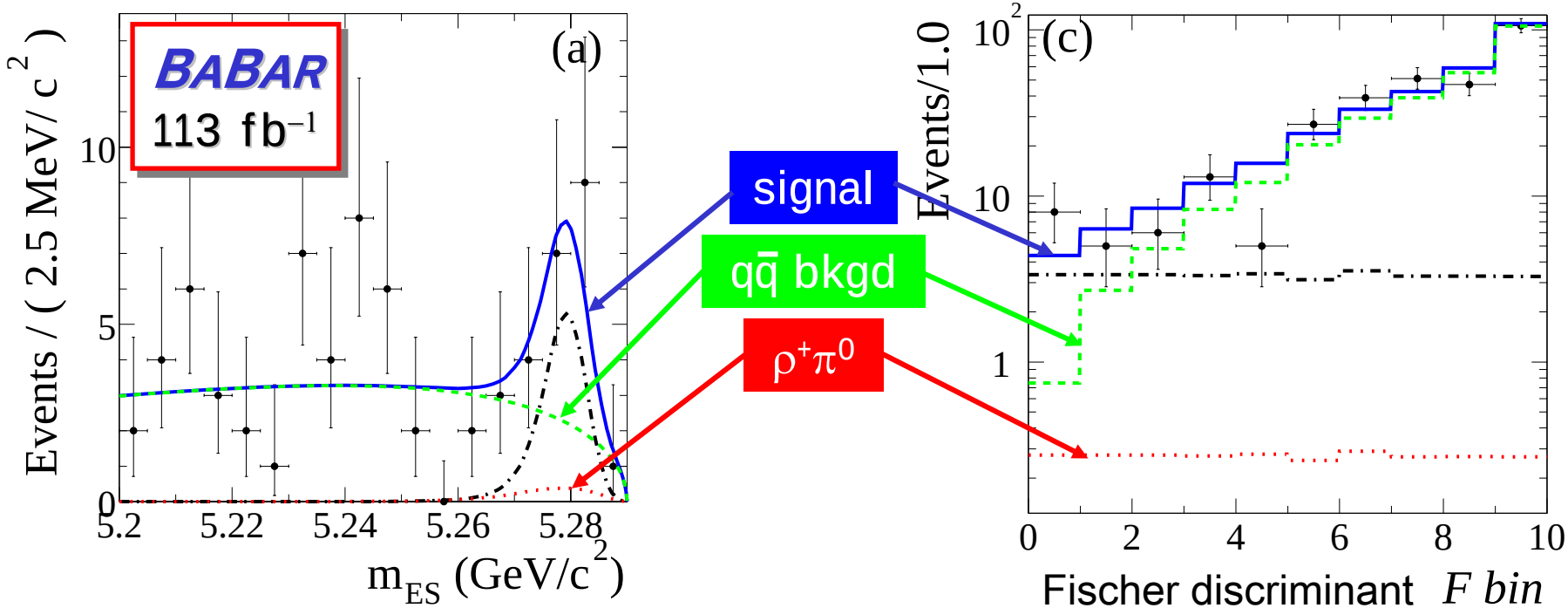
→ $\kappa = \alpha_{\text{eff}} - \alpha$

Upper limit on the correction κ: Grossman-Quinn bound

$$\sin^2(\alpha - \alpha_{\text{eff}}) \leq \frac{\mathcal{B}(B^0 \to \pi^0\pi^0) + \mathcal{B}(\overline{B}^0 \to \pi^0\pi^0)}{\mathcal{B}(B^+ \to \pi^+\pi^0) + \mathcal{B}(B^- \to \pi^-\pi^0)}$$

→ Look for $\pi^0\pi^0$

Observation of $B^0 \to \pi^0\pi^0$



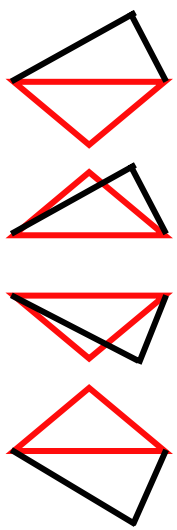
	Signal	BF x 10^{-6}	σ	
BABAR	46^{+14+2}_{-13-3}	$2.1 \pm 0.6 \pm 0.3$	4.2	PRL **91** (2003) 241801
BELLE	$25.6^{+9.3}_{-8.4}$	$1.7 \pm 0.6 \pm 0.3$	3.4	PRL **91** (2003) 262001

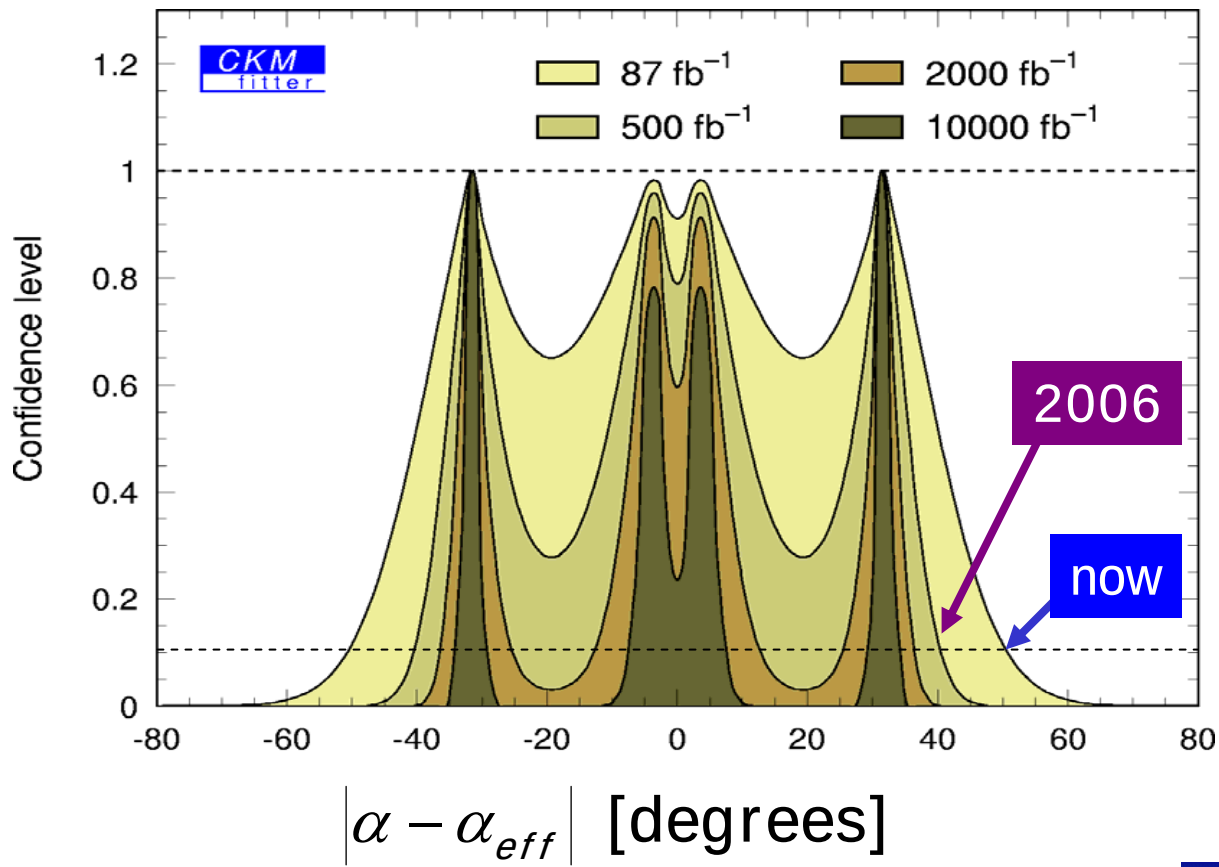
Projections of $\pi\pi$ Isospin Analysis

$\mathrm{B}\left(B^0 \to \pi^0\pi^0\right) = 2\times10^{-6}$ → Grossman-Quinn bound not very effective:

$$|\alpha - \alpha_{\mathrm{eff}}|_{\pi\pi} \leq 47^0 \ (90\%).$$

Projection of the full isospin analysis, with 4-fold ambiguity (CKMfitter group):





$B^0 \to \rho^+\rho^-$: a breakthrough ?

- Vector-vector final state, but:
  - From angular analysis:

$$f_L(\rho^+\rho^-) = (99\,^{+1}_{-7} \pm 3)\%$$ hep-ex/0308024

  - CP-even state!

- Same CP formalism as $\pi^+\pi^-$

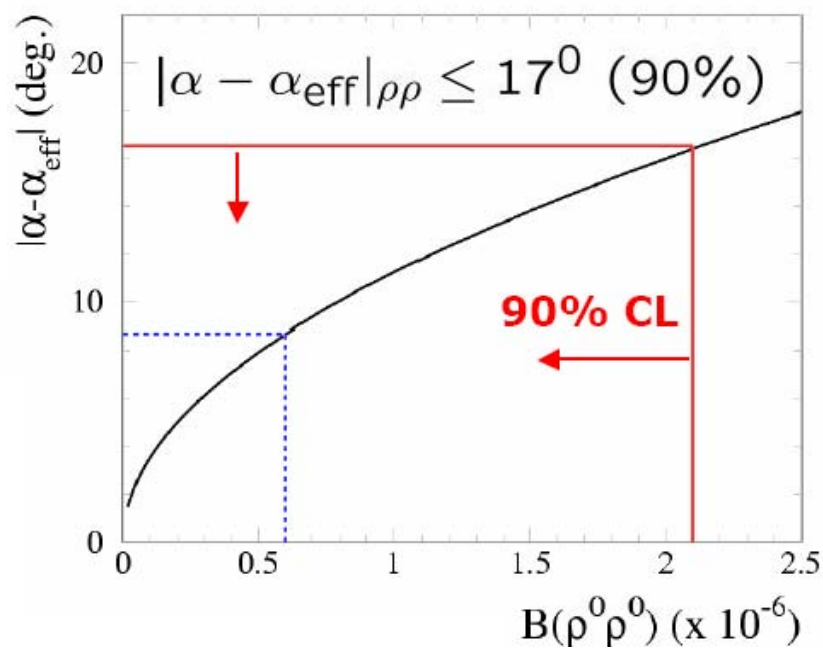
- Grossman-Quinn bound:
  - more favorable!

$$\sin^2(\alpha-\alpha_{\rm eff}) \leq \frac{\mathcal{B}(B^0 \to \rho^0\rho^0) + \mathcal{B}(\overline{B}^0 \to \rho^0\rho^0)}{\mathcal{B}(B^+ \to \rho^+\rho^0) + \mathcal{B}(B^- \to \rho^-\rho^0)}$$

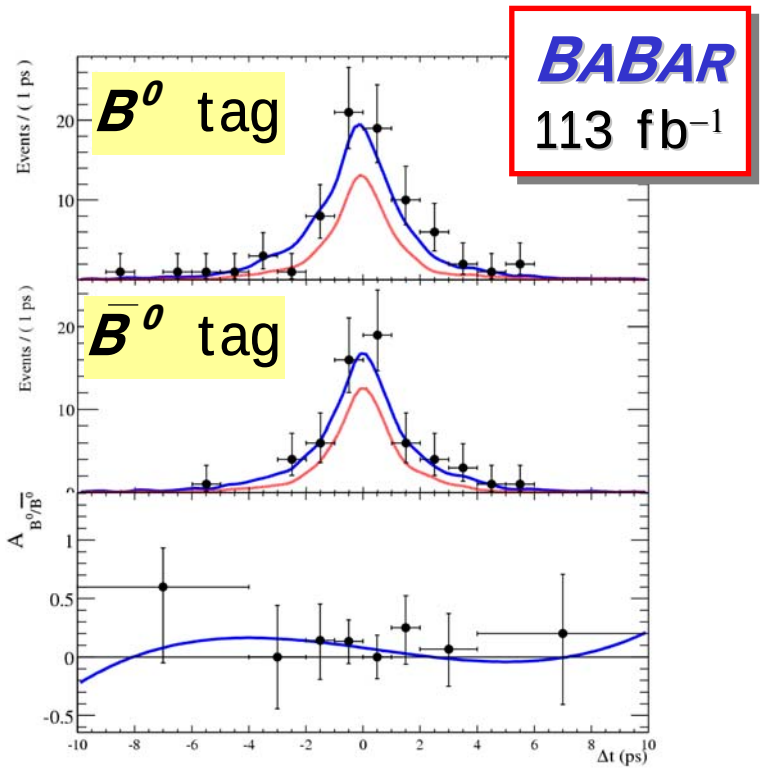
Babar hep-ex/0307026

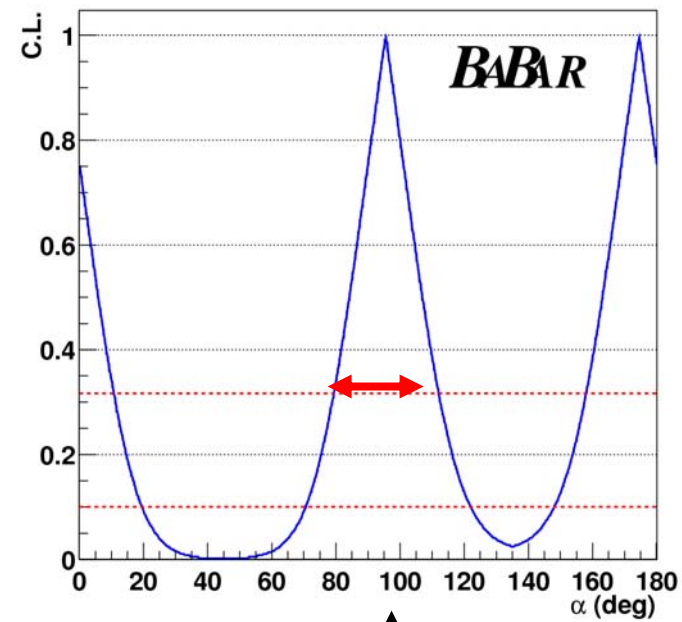
$$\mathcal{B}(\rho^0\rho^0) < 2.1 \times 10^{-6}\ (90\%)$$

$$\mathcal{B}(\rho^\pm\rho^0) = (22.5 \pm 5.6 \pm 5.8) \times 10^{-6}$$



New BaBar result on $B^0 \to \rho^+\rho^-$





$$S_{long} = -0.19 \pm 0.33_{(stat)} \pm 0.11_{(syst)}$$
$$C_{long} = -0.23 \pm 0.24_{(stat)} \pm 0.14_{(syst)}$$

$$\alpha = (96 \pm 10_{stat} \pm 4_{syst} \pm 13_{peng})^\circ$$

Preliminary isospin analysis

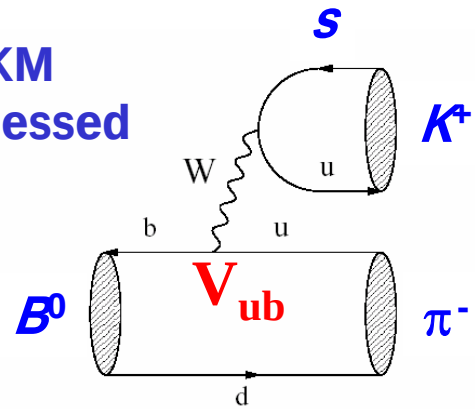
New: Winter 04

Intermezzo:
Direct CP Violation

Back to $B^0 \to h^+h^-$: direct CPV ?

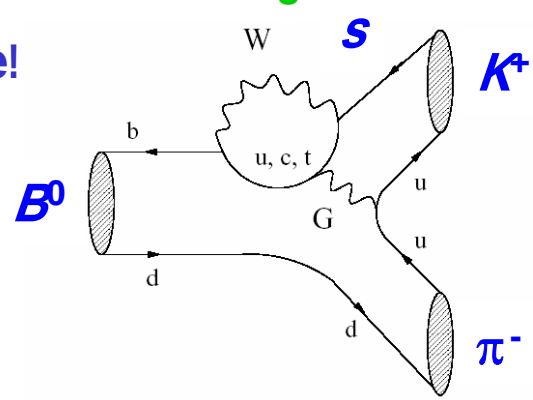
Tree-level $b \to u$ = T

CKM suppressed



Internal Penguin = P

Large!



$$BF(B^0 \to K^+\pi^-) = (18.5 \pm 1.0) \times 10^{-6}$$

Penguin dominated:

$$A_{K\pi} = \lambda^2 e^{i\gamma} T + P$$

Potentially: direct *CPV* asymmetry and constraints on γ

$$A = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \propto$$

$$\propto 2|T||P| \sin\delta \sin\gamma$$

(where δ = CP-conserving strong phase complicated by long-distance & re-scattering)

Look for direct CPV!

Direct CP asymmetry in $B^0 \to K^+\pi^-$?

- BaBar analysis
  - 227 M $B\bar{B}$ events
  - 68030 selected events
- Extended ML fit:
  - discriminating variables:

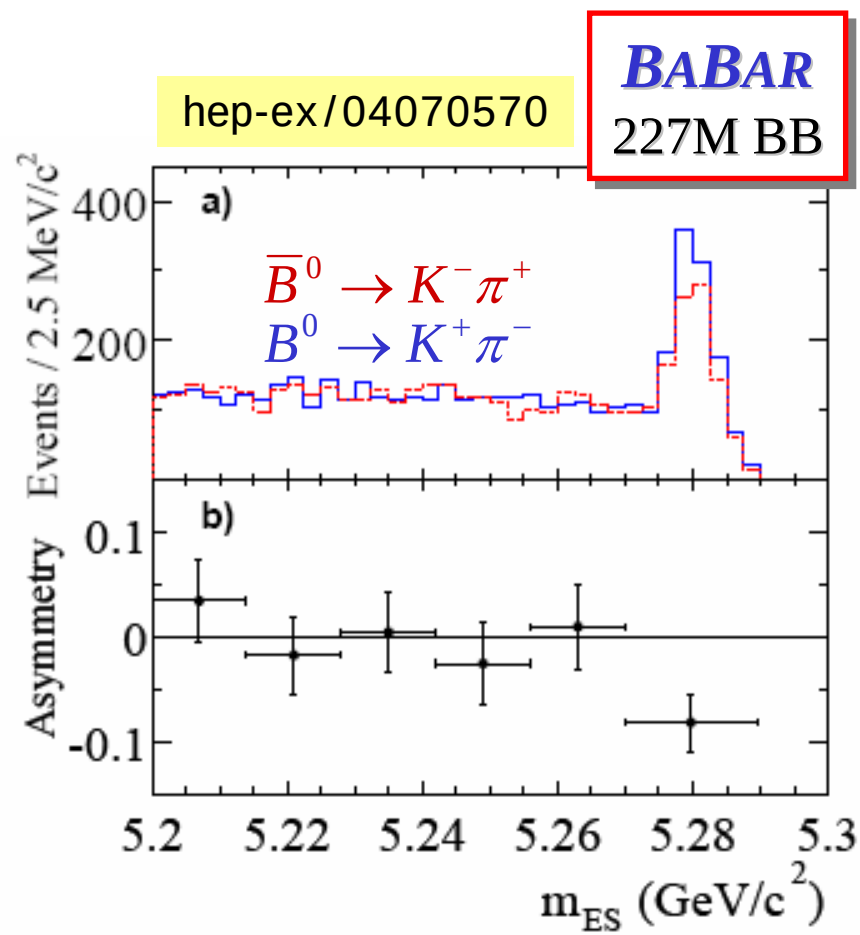
$$\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-\}$$

  - Fisher, Cherenkov angles
- Fitted parameters
  - Yields for $K\pi$, $\pi\pi$, KK

$$n_{K\pi} = 1606 \pm 51$$
$$n_{\pi\pi} = 467 \pm 33$$
$$n_{KK} = 3 \pm 12$$

  - asymmetries for signal and background $A_{K\pi}$, $A_{K\pi}^{b}$

(Likelihood Projection)



Breaking news… *direct CPV observed by BaBar !*

- BaBar result (significance: 4.3σ) hep-ex/04070570 submitted to PRL

$$A_{K\pi} = \frac{n(K^-\pi^+) - n(K^+\pi^-)}{n(K^-\pi^+) + n(K^+\pi^-)} = -0.133 \pm 0.030\,(\text{stat}) \pm 0.009\,(\text{syst})$$

- Belle (140 fb^{-1}, hep-ex/0407025) $A_{K\pi}^{Belle} = -0.088 \pm 0.035 \pm 0.013$
- Systematic uncertainty
  - Dominated by the asymmetry of identified charged tracks
  - Controlled by the background asymmetry, compatible with zero; the bkgd is from real K and π with the correct kinematics, from opposite jets of continuum cc events

$$A_{K\pi}^{b} = -0.001 \pm 0.008$$

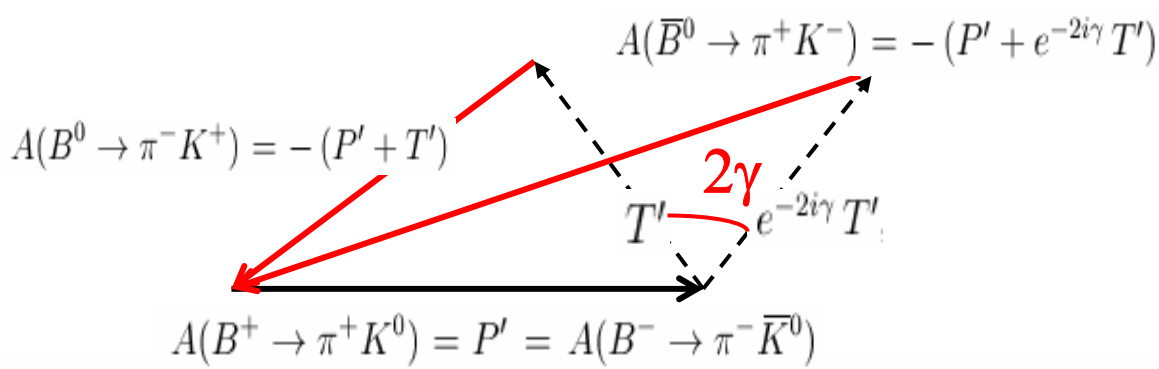
- Coherent results in all subsamples

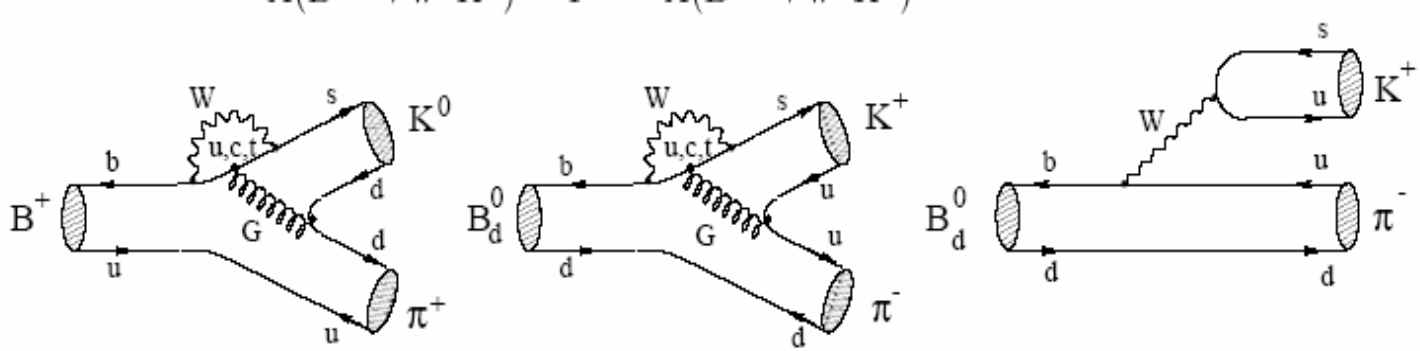
Sample	$N_{B\bar{B}}$	$n_{K\pi}$	$\mathcal{A}_{K\pi}$	$\mathcal{A}^{b}_{K\pi}$
1999–2001	21.1	142 ± 15	-0.240 ± 0.102	0.006 ± 0.026
2002	66.4	479 ± 27	-0.102 ± 0.055	-0.008 ± 0.015
2003	34.1	241 ± 19	-0.109 ± 0.079	0.007 ± 0.021
2004	104.9	743 ± 33	-0.142 ± 0.044	0.004 ± 0.012

Why so exciting?

- Not unexpected: strikingly larger than direct CPV in K decays: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.7 \pm 1.6)\times 10^{-4}$
- Naïve picture (neglecting EW penguins and other effects):

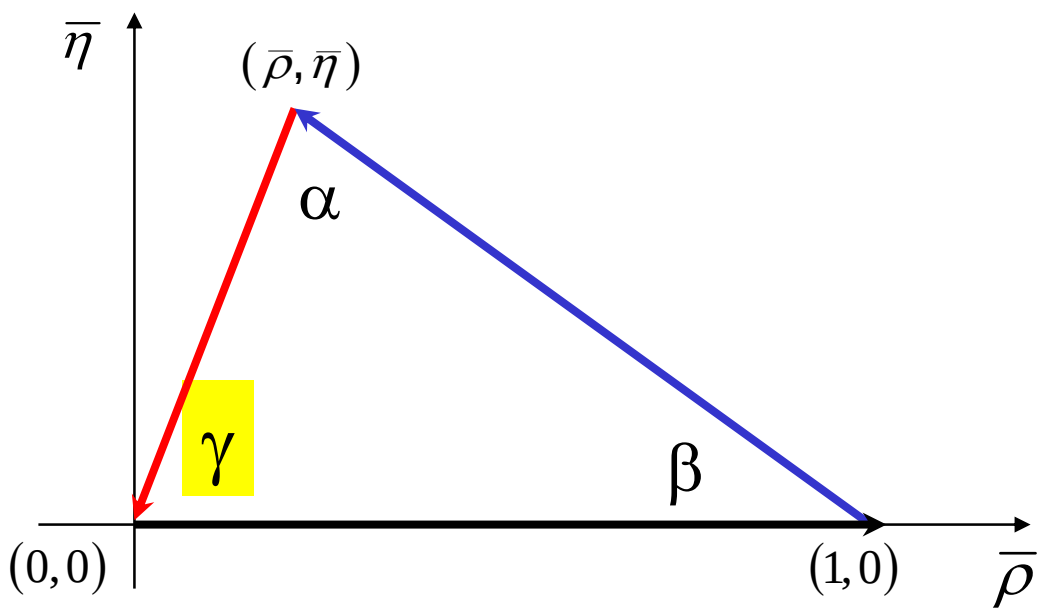
  Observed CP asymmetry:





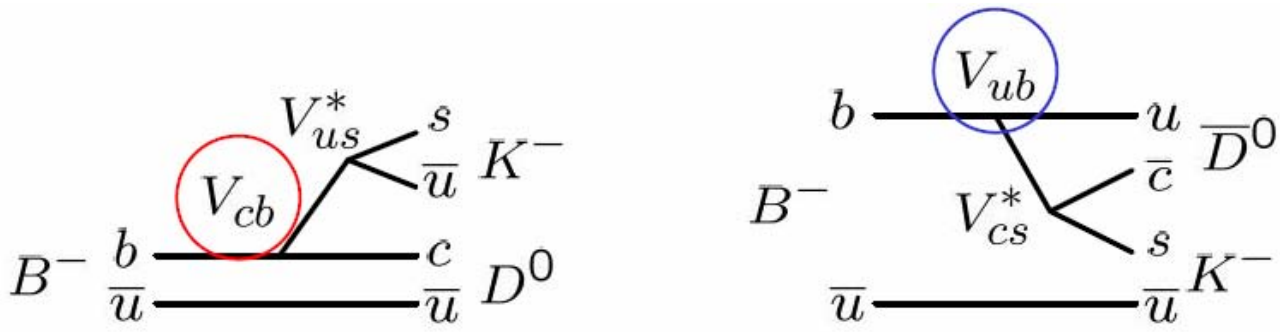
- Real life more complicated (EW penguins etc), but CP asymmetries give a very important clue to disentangle P, T and constrain γ.

Gamma (ϕ_3)



Methods to measure γ

- *The challenge*: directly measure the b→u phase (γ) relative to the b→c phase (0).



- These amplitudes *interfere* for D final states that both D^0 and $\overline{D}^0$ can decay to.

$$r_b \equiv \frac{A(b \to u)}{A(b \to c)} = R_u \, F_{cs}$$

larger $r_b \Rightarrow$ larger interference term
$\Rightarrow$ more sensitivity to γ

F_{cs} is an *unknown* color-suppression factor. Expected to be in the range [0.2,0.5].

R_u is the left side of the Unitarity Triangle (~0.4).

$r_b \approx 0.1 \div 0.2$

Methods to measure γ

- $B^- \to D^{(*)0} K^{(*)-}$, $B^- \to \bar{D}^{(*)0} K^{(*)-}$
  - $D^{(*)0}$, $\bar{D}^{(*)0}$ decay to same final state.
    - D^0_{CP} — Gronau-London-Wyler (*GLW*)
    - $D^0_{Non\text{-}CP}$ — Atwood-Dunietz-Soni (*ADS*)
    - $D^0 \to K_s \pi^+ \pi^-$ Dalitz — Giri-Grossman-Soffer-Zupan

The best results at present

Problems:
Squashed triangles!
Small triangles!
Model dependence!

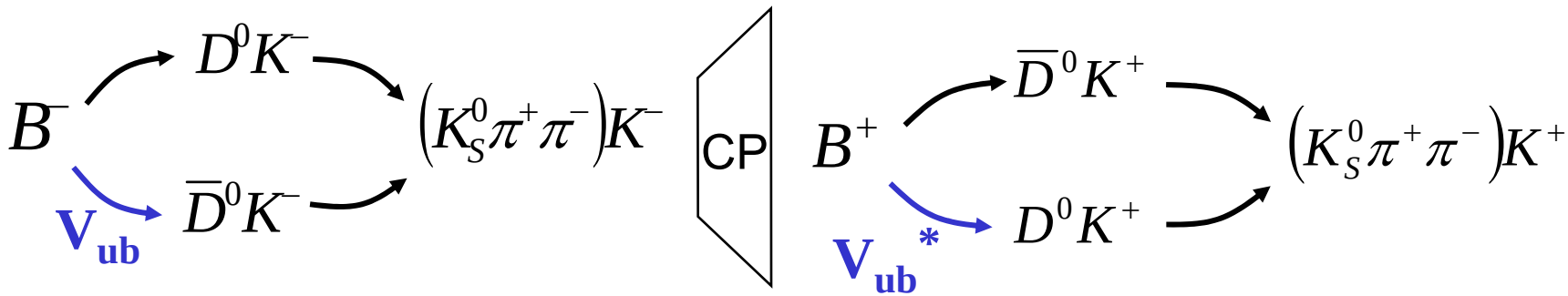
- $\sin(2\beta + \gamma)$ in $B^0 \to D^{(*)\pm} \pi^{\mp}$
  - Via $B\bar{B}$ mixing.

Alternative interference method:
2β from mixing,
γ from suppressed $b \to u$ decays

Large number of events, but: small asymmetry

$B^- \to D^{(*)0}K^-$ Dalitz

- Interference since both $D^0 \to K^0_S\pi^+\pi^-$ and $\overline{D}^0 \to K^0_S\pi^+\pi^-$



- Sensitivity to γ enters via amplitude $\propto V_{ub}$; interference occurs in Dalitz plot for $D^0(\overline{D}^0) \to K^0_S\pi^+\pi^-$

$$M_+ = f\left(m_+^2, m_-^2\right) + re^{i(\delta+\gamma)} f\left(m_-^2, m_+^2\right)$$
$$M_- = f\left(m_-^2, m_+^2\right) + re^{i(\delta-\gamma)} f\left(m_+^2, m_-^2\right)$$

$$r = \frac{A(b \to u)}{A(b \to c)} = \frac{A\left(B^- \to \overline{D}^0 K^-\right)}{A\left(B^- \to D^0 K^-\right)}$$

- Dalitz plot characterized with large sample of $D^0(\overline{D}^0) \to K^0_S\pi^+\pi^-$

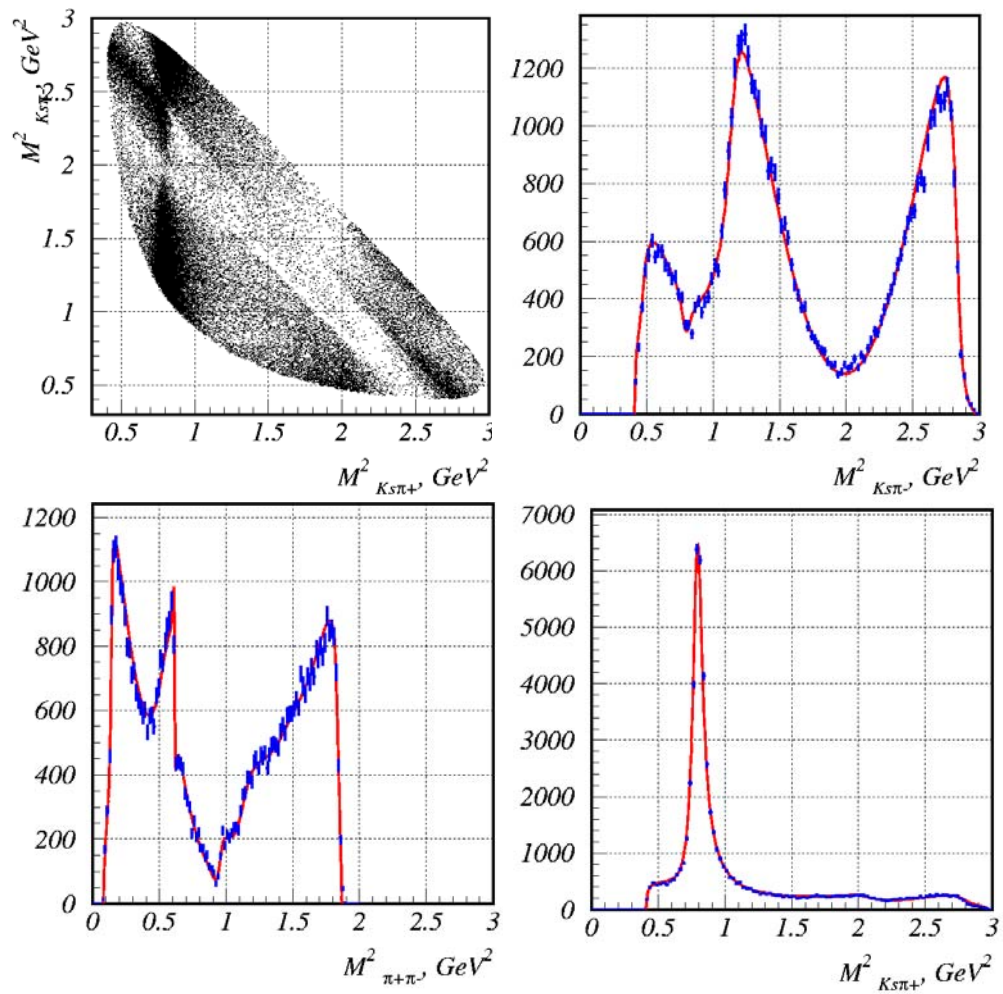
D^0 Dalitz Plot Model

Select D^0 sample from

$$D^{*+} \to D^0 \left[\to K_S^0 \pi^+ \pi^- \right] \pi^+$$

101800 events, 3% background

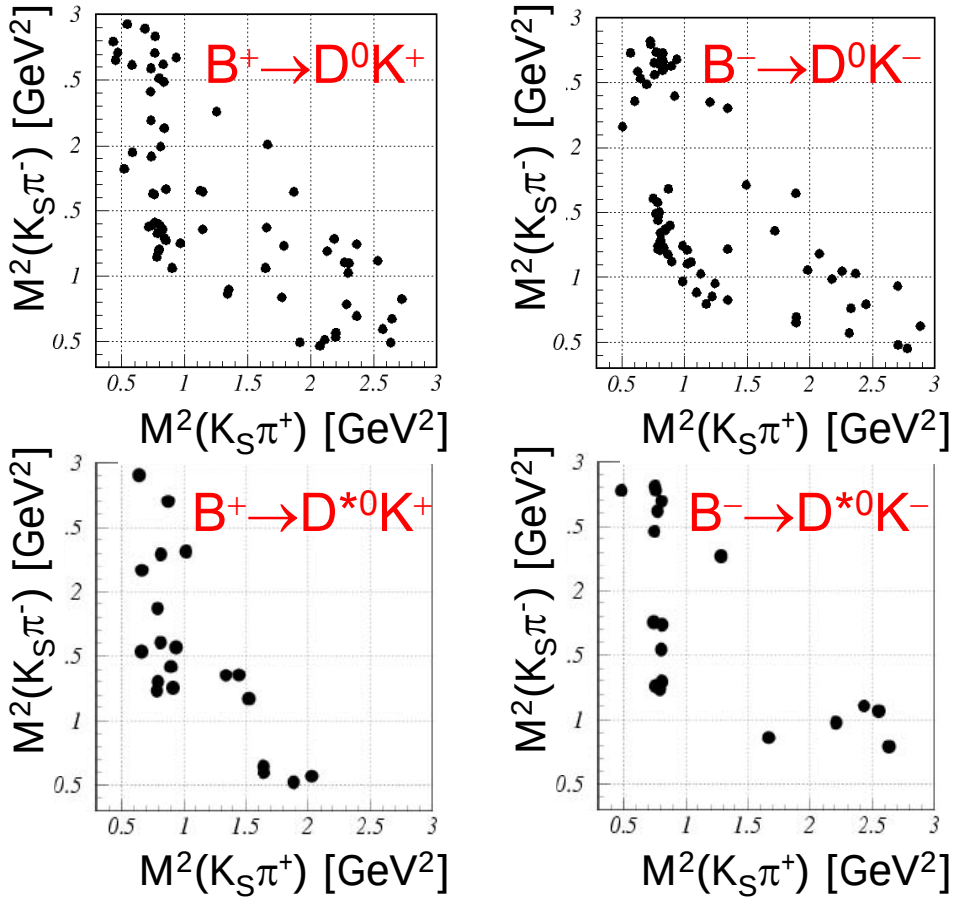
Resonance	Our fit		
	Amplitude	Phase, °	Fit fraction
$\sigma_1 K_s$	1.66±0.11	218.0±3.8	11%
$\rho(770) K_S$	1	0	21%
ωK_s	$(3.30\pm1.13)\cdot10^{-2}$	114.3±2.3	0.4%
$f_0(980) K_s$	0.405±0.008	212.9±2.3	4.8%
$\sigma_2 K_s$	0.31±0.05	236±11	0.9%
$f_2(1270) K_s$	1.36±0.06	352±3	1.5%
$f_0(1370) K_s$	0.82±0.10	308±8	0.9%
$K^*(892)^-\pi^+$	1.656±0.012	137.6±0.6	60%
$K^*(892)^+\pi^-$	0.149±0.007	325.2±2.2	0.5%
$K^*_0(1430)^-\pi^+$	1.96±0.04	357.3±1.5	5.8%
$K^*_0(1430)^+\pi^-$	0.30±0.05	128±8	0.1%
$K^*_2(1430)^-\pi^+$	1.32±0.03	313.5±1.8	2.8%
$K^*_2(1430)^+\pi^-$	0.21±0.03	281.5±9	0.07%
$K^*(1680)^+\pi^-$	2.56±0.22	70±6	0.4%
$K^*(1680)^-\pi^+$	1.02±0.22	102±11	0.07%
Non resonant	6.1±0.3	146±3	24%



$B^- \to D^{(*)0} K^-$ Dalitz

hep-ex/0406067

If no CP violation, plots should be same:



Belle
140 fb^{-1}

$B^- \to D^{(*)0} K^-$ Dalitz: fit results (Belle)

hep-ex/0406067

Parameters:
$\gamma, r_D, r_{D^*}, \delta_D, \delta_{D^*}$

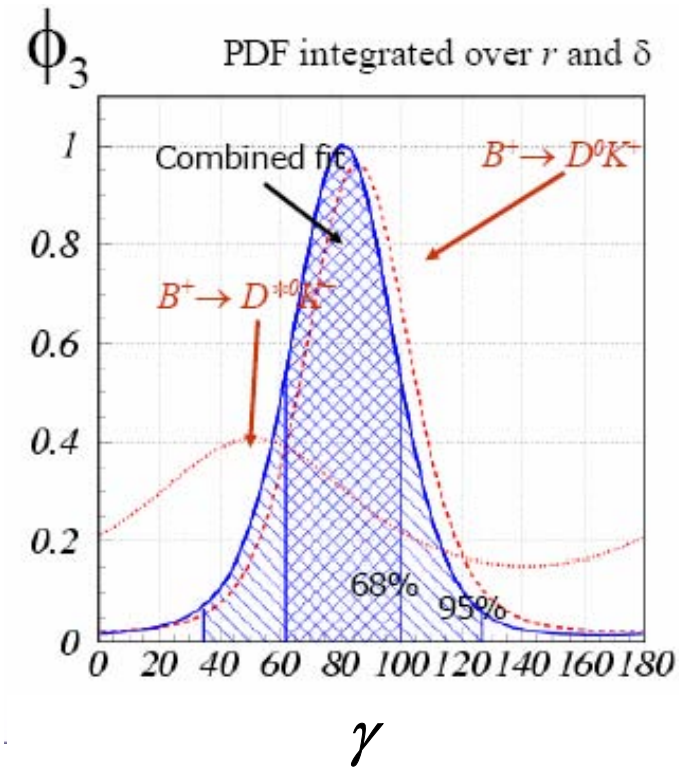
Belle
140 fb^{-1}

$$\gamma = 77^{\circ}\,{}^{+17}_{-19}{}_{(stat)} \pm 13_{(sys)} \pm 11_{(model)}$$

$$26 < \gamma < 126^{\circ} \quad [95\%\ \mathrm{CL}]$$

$$r_D = 0.26^{+0.10}_{-0.14} \pm 0.03 \pm 0.04$$

$$r_{D^*} = 0.20^{+0.19}_{-0.17} \pm 0.02 \pm 0.04$$



…lucky ?

outlook

CKMfitter

hep-ph/0406184

Global fit including the observables "quantitatively under control": $|V_{us}|$, $|V_{ud}|$, $|V_{ub}|$, $|V_{cb}|$, $|\varepsilon_K|$, Δm_d, Δm_s, $\sin 2\beta$**[$c\bar{c}$]**, $\sin 2\alpha$**[$\rho\rho$]**

Detailed separate study of other observables, including constraints related to γ, penguins, factorization models etc.

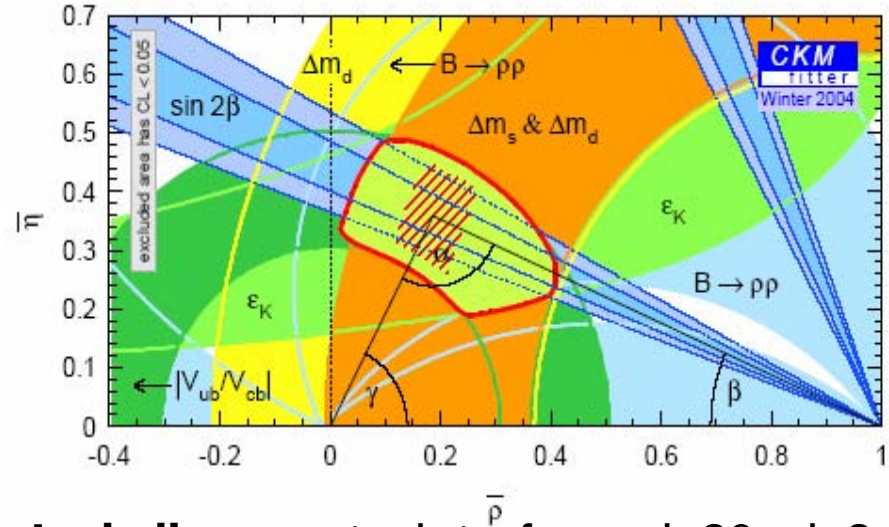
Conclusions:

Standard Model OK;

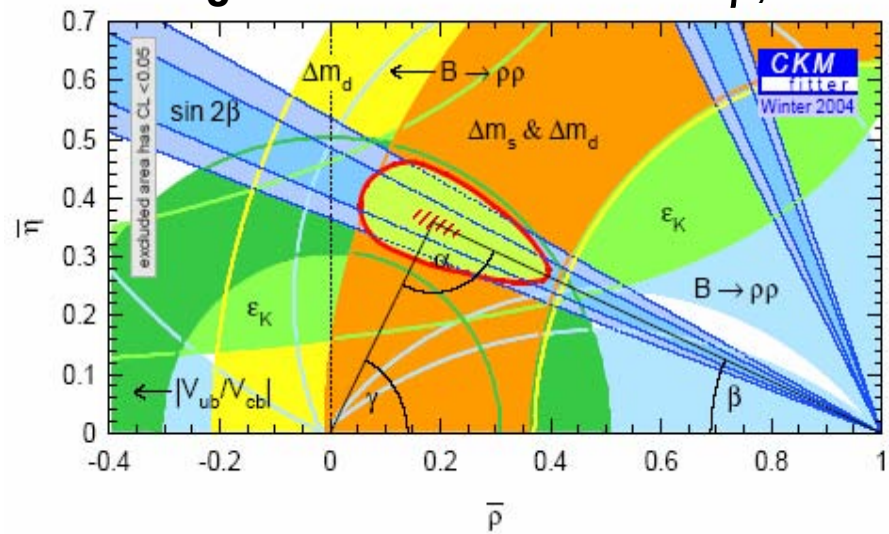
constraints from γ measurements not yet effective;

significant non-SM corrections cannot be excluded yet, however SM solutions are favored in most cases

Excluding constraints from $\sin 2\beta$, $\sin 2\alpha$

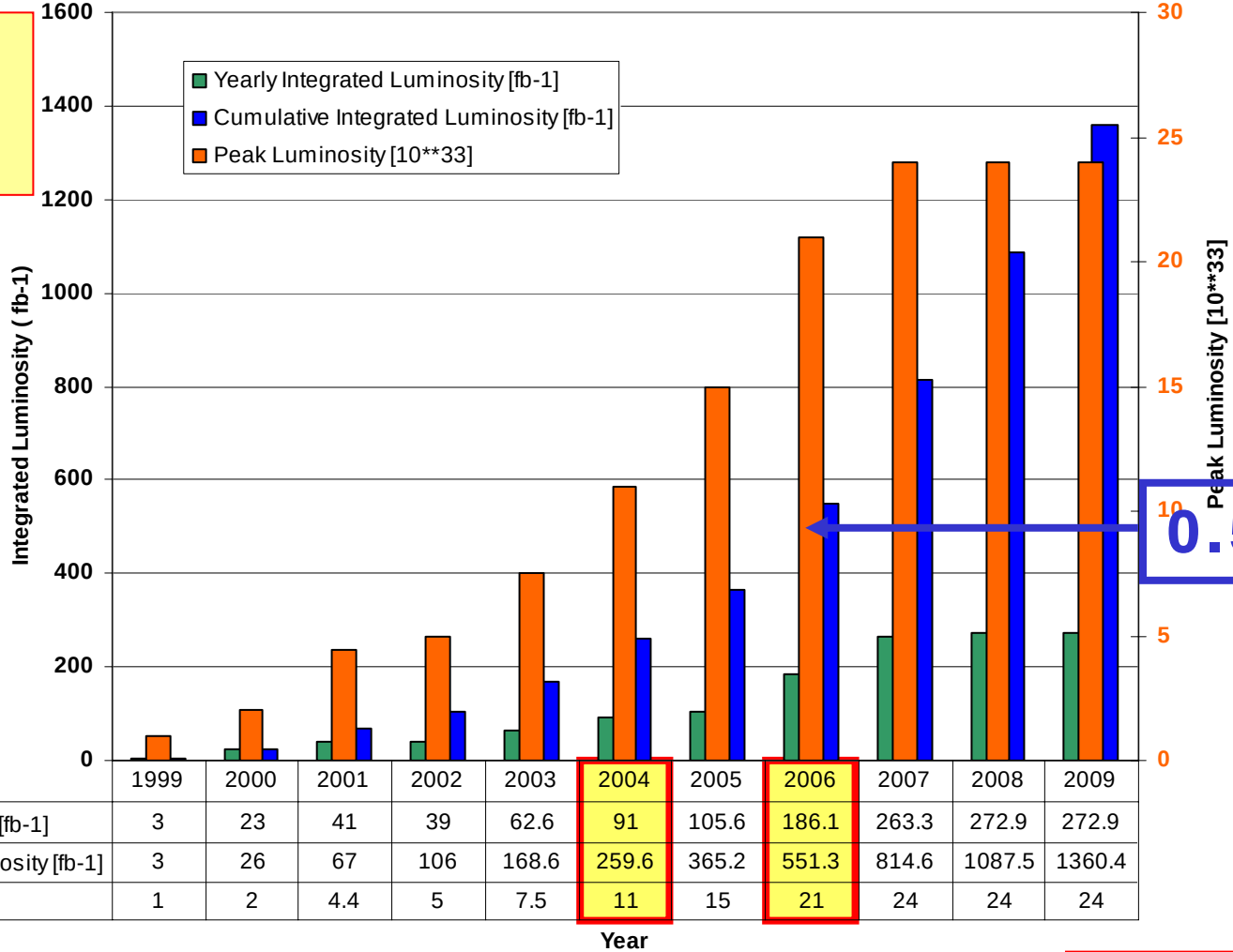


Including constraints from $\sin 2\beta$, $\sin 2\alpha$



PEP-II Luminosity Projections

KEKB plans are comparable or better!

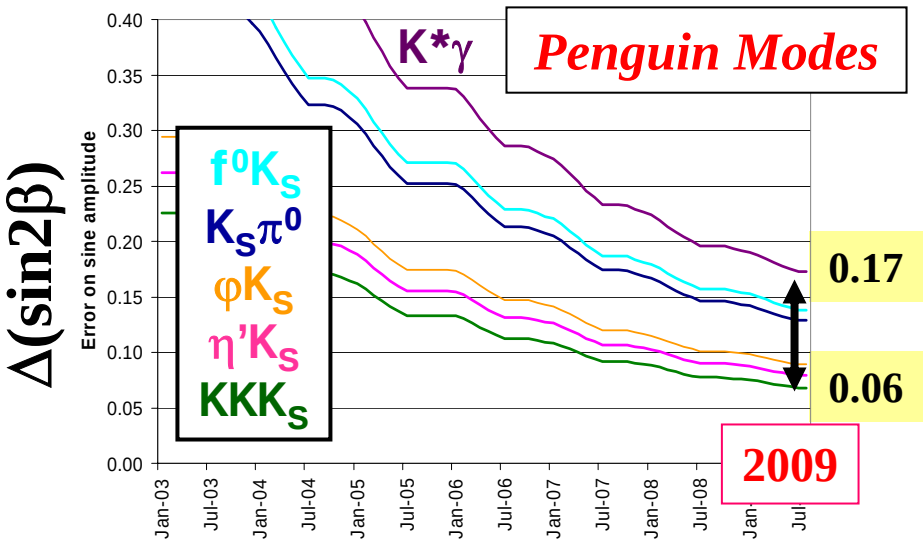


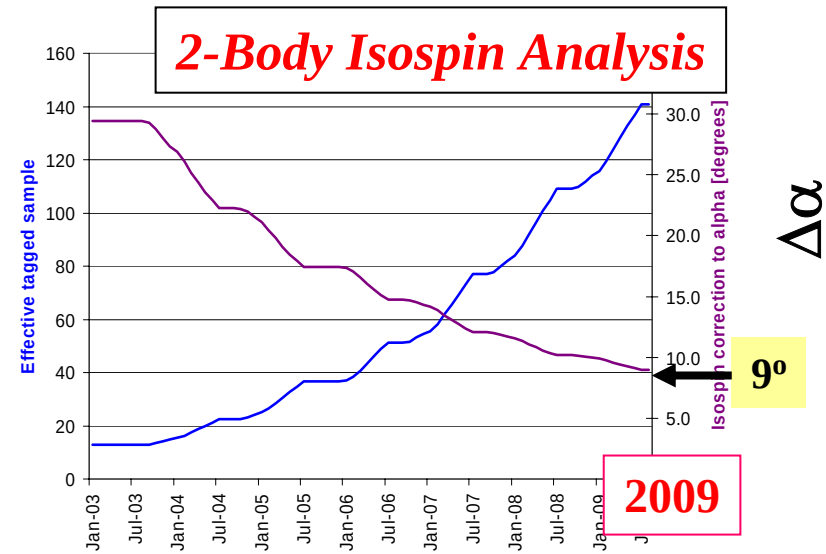
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Yearly Integrated Luminosity [fb-1]	3	23	41	39	62.6	91	105.6	186.1	263.3	272.9	272.9
Cumulative Integrated Luminosity [fb-1]	3	26	67	106	168.6	259.6	365.2	551.3	814.6	1087.5	1360.4
Peak Luminosity [10**33]	1	2	4.4	5	7.5	11	15	21	24	24	24

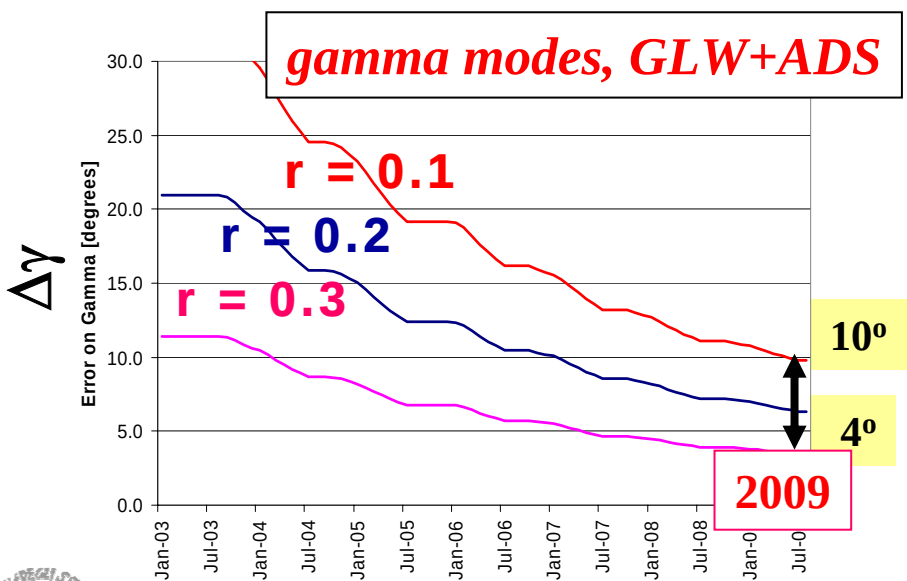
0.5 ab^{-1}

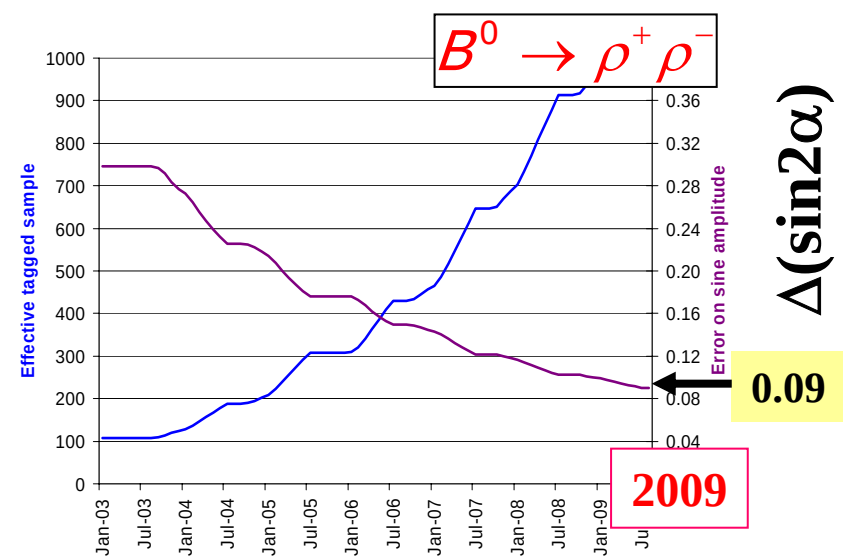
2004 2006 ← **2.1×10^{34}**

Some sensitivity projections









Outlook, hadron colliders

- Tevatron (CDF/D0):
  - Luminosity now approaching design value
  - Trigger on tracks impact parameter – study of hadronic B decays feasible at an hadron collider !
  - Preliminary results on the selection of final states for the very important B_s mixing constraint on the Unitarity Triangle
  - B_d mixing measurements: are used to tune the essential tagging tools, needed also for B_s mixing

- Future dedicated experiments:
  - LHC-B at LHC: expected on-line in 2007
  - BTeV, recently approved: expected on-line in 2009

Conclusions - 1

- $\sin 2\beta$
  - Precision measurement with charmonium modes dominate now CKM fits
  - Look at $b \to s$ penguins for spicy non-SM effects !
- $\sin 2\alpha$
  - $\pi^+\pi^-$ suffers from penguins $\Rightarrow$ isospin analysis, but few $\pi^0\pi^0$
  - $\rho^+\pi^-$ BF and asymmetries measured in "quasi-two-body" approach; Dalitz analyses in progress, complicated
  - $\rho^+\rho^-$ very promising, already an impact on CKM fits
- γ
  - DK and $D\pi$ methods: few events, sensitivities depend on $\mathbf{r_b}$ (CKM and color suppression factor of interfering amplitudes) $\Rightarrow$ combine many analyses and hope for the best

Conclusions - 2

- Short term prospects for the B factories
  - Double the integrated luminosity at least twice with the present detectors:

    ~ 500fb^{-1} per experiment by 2006

    > 1 ab^{-1} per experiment by 2008-09
  - This will not exhaust completely the B physics program…

- Special purpose hadron collider experiments expected in 2007-09
  - Specially suited for B_s, gamma, very rare decays

- Long term future of B-factories ?
  - Community interested in joining efforts for a Super B-Factory

Backup slides

B physics: experimental facilities

- Asymmetric B-factories:
  - $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0_d \overline{B^0_d}$: clean environment, low backgrounds, high efficiency; small cross section
  - Luminosity is the key factor; asymmetric energies boost the B mesons
- Hadron colliders:
  - higher cross sections, larger backgrounds and lower efficiency
  - Also B_s production and decays !

Design Luminosity

Expt.	Collider	Beams	Sqrt(s) (GeV)	Year Online	Lumi(10^{33} cm^{-2} s^{-1})	σ(b-bbar) (nb)	bb pairs (10^7/yr)	βγcτ (μm)	σ(b-bbar)/ σ(q-qbar)
BaBar	PEP-II	e^+e^-	10	1999	3	1	3-10	270	3×10^{-1}
Belle	KEK-B	asymm	10	1999	10	1	3-10	200	3×10^{-1}
CDF-II	Tevatron	ppbar	1800	2001	0.2-1.0	100000	20000	500	1×10^{-3}
D0									
BTeV				2009	0.2			5000	
LHC-B	LHC	pp	14000	2007	0.15	500000	75000	7000	5×10^{-3}