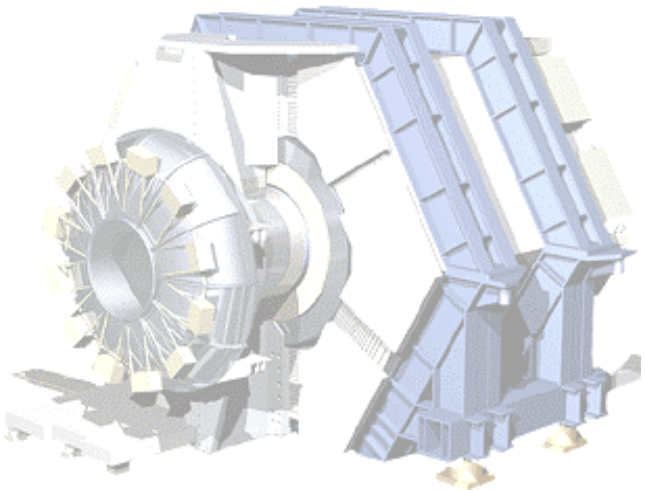
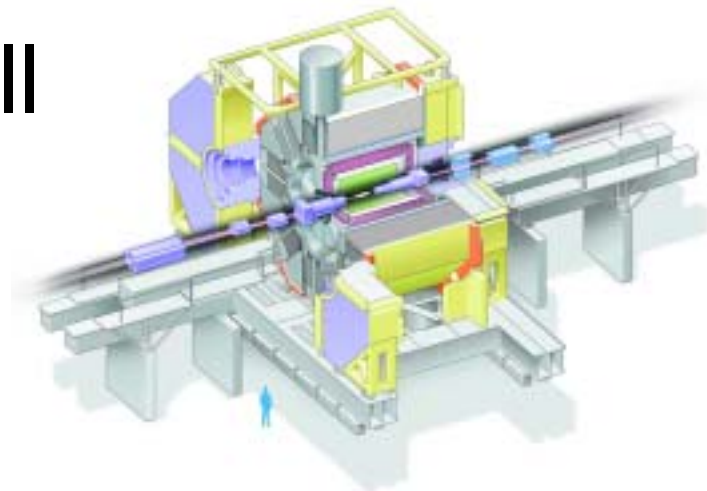
CP Violation at BaBar & Belle

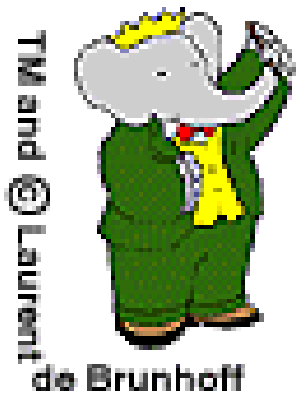


Sören Prell

Iowa State University



31st SLAC Summer Institute
Topical Conference
August 6-8, 2003



Outline

- CP violation in the Standard Model
- The BaBar and Belle detectors
- CP violation measurements
  - β / ϕ_1
    - **$B \rightarrow J/\psi\ K_s$**
    - **$B \rightarrow J/\psi\ \pi^0$, D^*D, D^*D^***
    - **$B \rightarrow \phi\ K_s$, $\eta'\ K_s$**
  - α / ϕ_2
    - **$B \rightarrow \pi\pi$**
    - **$B \rightarrow \rho\pi$**
  - γ / ϕ_3
    - **$B \rightarrow DK$**
    - **$B \rightarrow D^{(*)}\pi$**
- Summary and Conclusion

Macroscopic CP Violation

- Universe is matter dominated
  - Where has the anti-matter gone?

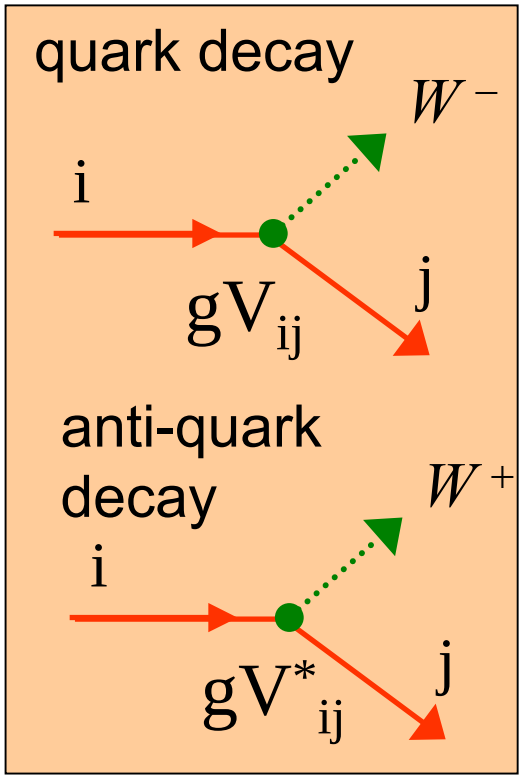
$$\Rightarrow \quad \frac{N(\text{anti-Baryon})}{N(\text{Baryon})} \leq 10^{-4}\text{-}10^{-6}$$

- Generation of a net baryon number requires (Sakharov conditions):
  1. Baryon number violating processes (*e.g.* proton decay)
  2. Non-equilibrium state during the expansion
  3. C and CP symmetry violation (different decay rates for particles and antiparticles)

- How is CP violation described in the Standard Model and how do we measure it?

The Weak Interactions of Quarks

- Coupling strength at vertex is gV_{ij}
  - universal Fermi weak coupling g
  - V_{ij} depends on quark flavors i,j
  - complex phase η leads to different b→u and t →d amplitudes for quarks and anti-quarks



$$\mathbf{V}_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |\mathbf{V_{ub}}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |\mathbf{V_{td}}|e^{-i\beta} & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

Cabbibo-Kobayashi-Maskawa matrix

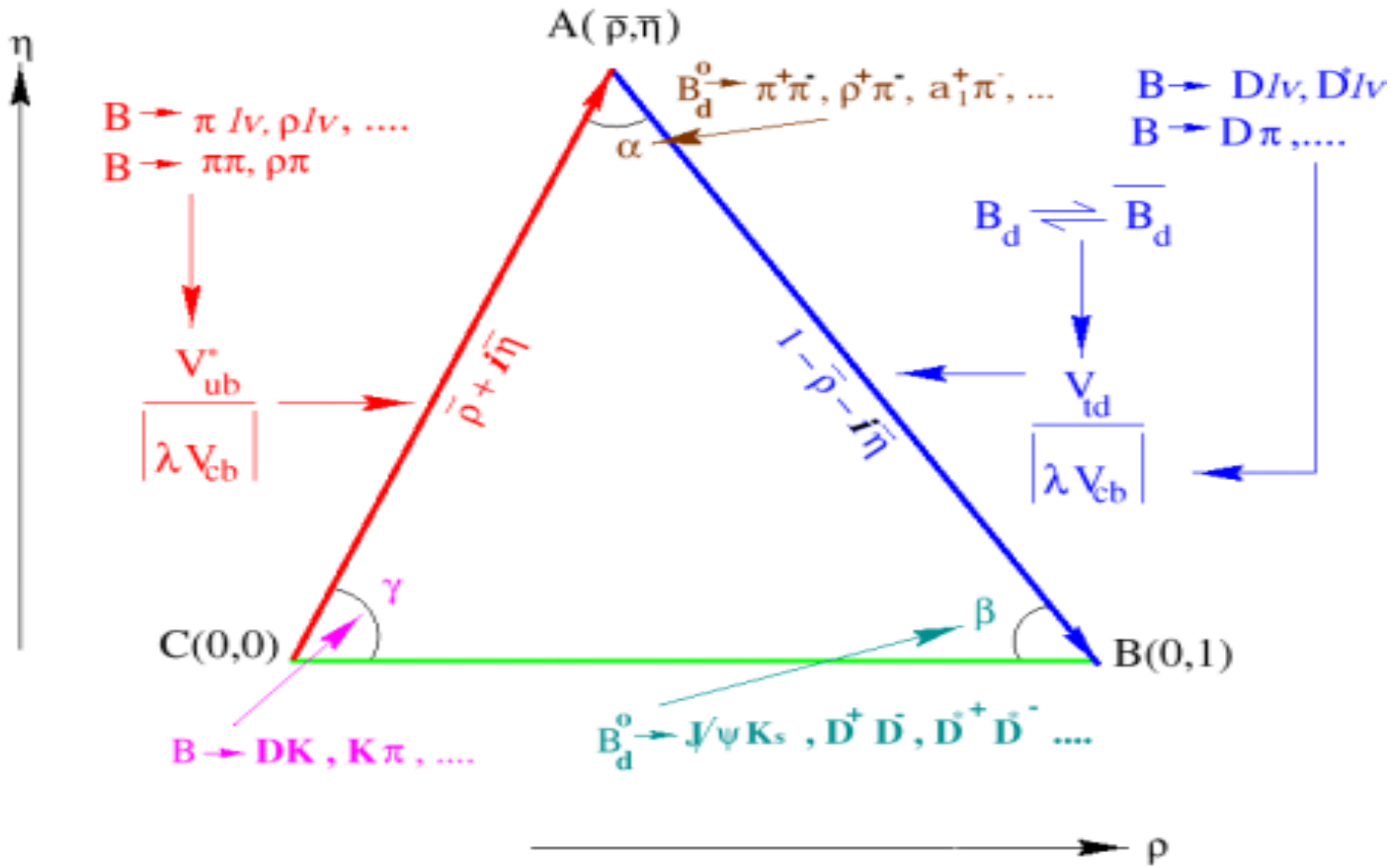
$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

(Wolfenstein parameterization)

λ = 0.221 ± 0.002
A = 0.83 ± 0.06
$\bar{\rho}$ = 0.22 ± 0.10
$\bar{\eta}$ = 0.35 ± 0.05

The B Unitarity Triangle

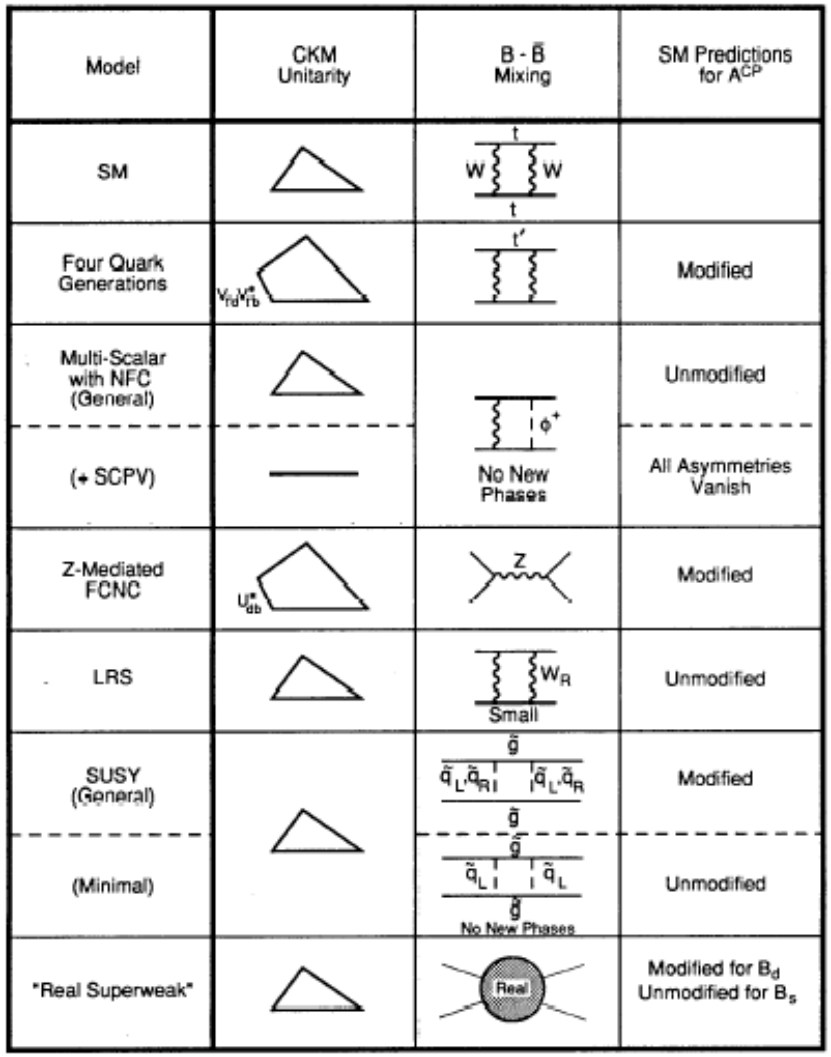
$$V^{\dagger}V = 1 \rightarrow V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



- angles α, β and γ in SM related to single weak phase η
- test SM by over-constraining the Unitarity Triangle

Is CKM matrix the (only) source of $\not{CP}$?

- Why should we expect other (New Physics) mechanisms for $\not{CP}$?
  - difficult for CKM CP violation to generate the observed matter/anti-matter asymmetry in the universe
- **There must be something else !**



CP Observable

- Need non-zero expectation value of a CP odd observable
  - requires two interfering amplitudes

- CP violation in B decays manifests itself in
  - Different (time-integrated or time-dependent) rates of decay for B and $\bar{B}$ for specific final states

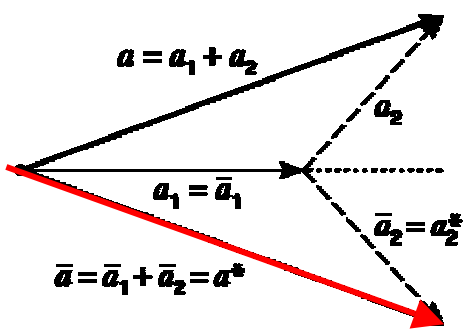
- Sometimes easy to interpret as some weak phase, sometimes interpretation hard (direct CP violation, penguin pollution, etc.)

~~CP~~ in Decay (direct ~~CP~~)

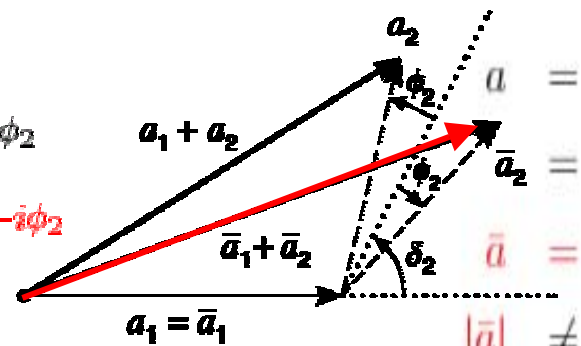
- Different decay rates for B → f and $\bar{B}$ → $\bar{f}$

$$A_{CP} = \frac{N(B \to f) - N(\bar{B} \to \bar{f})}{N(B \to f) + N(\bar{B} \to \bar{f})}$$

- need 2 decay amplitudes with different weak phase **and** different strong phase:



$$\begin{aligned} a &= a_1 + a_2 \\ &= |a_1| + |a_2| e^{i\phi_2} \\ \bar{a} &= |a_1| + |a_2| e^{-i\phi_2} \\ |\bar{a}| &= |a| \end{aligned}$$



$$\begin{aligned} a &= a_1 + a_2 \\ \bar{a}_2 &= |a_1| + |a_2| e^{i(\phi_2 + \delta_2)} \\ \bar{a} &= |a_1| + |a_2| e^{i(-\phi_2 + \delta_2)} \\ |\bar{a}| &\neq |a| \end{aligned}$$

No CP violation

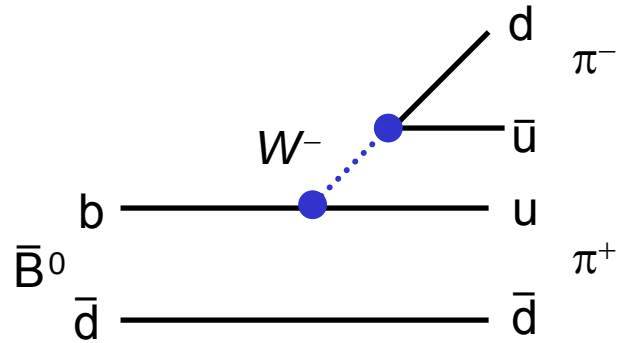
Direct CP violation !

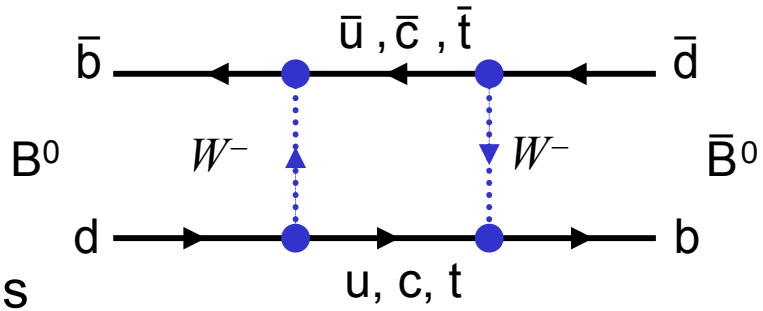
Difficult to interpret: measure a and $\bar{a}$, but need a_1, a_2, ϕ, δ

CP-violating observables for B mesons

CP violation arises from interference of 2 amplitudes with different phases

- In B decays, we have 2 types of amplitudes:
  - **Decay amplitudes**
  - **Mixing amplitudes**



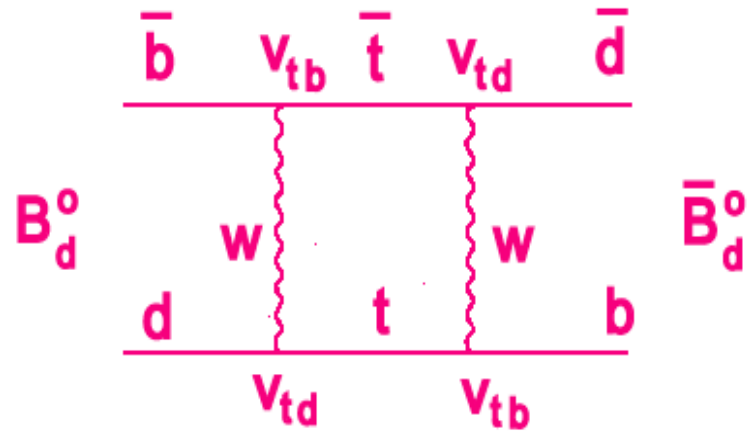


- 3 possible manifestations of CP violation:
  - Interference between 2 decay amplitudes **(Direct *CP* violation)**
  - Interference between 2 mixing amplitudes
  - Interference between mixed and unmixed decays

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

$B^0 \leftrightarrow \bar{B}^0$ Oscillation via 2nd order weak transition

- Involve $\mathbf{V_{td} = |V_{td}|\, e^{i\beta}}$

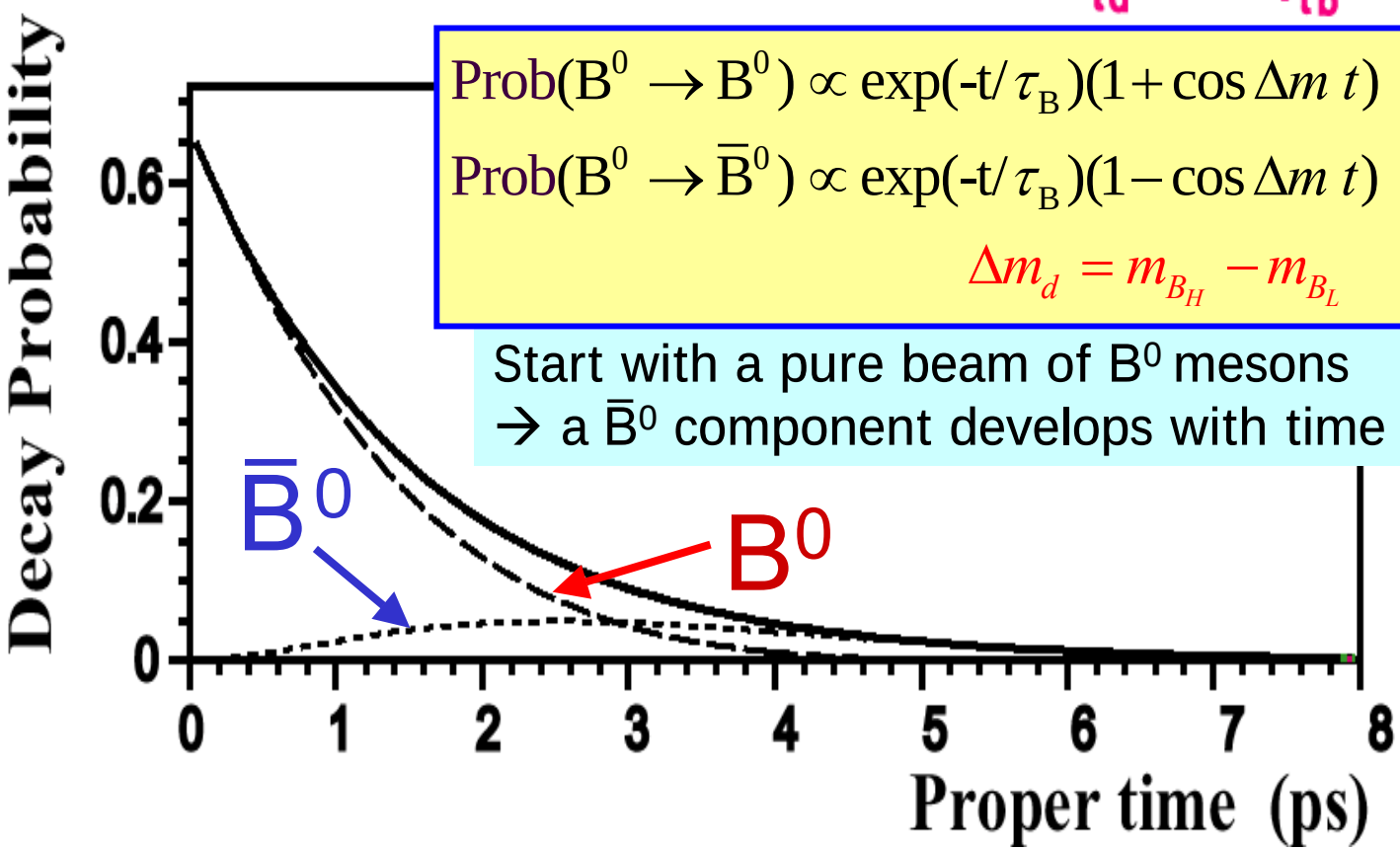


$$\mathrm{Prob}(B^0 \to B^0) \propto \exp(-t/\tau_B)(1+\cos\Delta m\, t)$$

$$\mathrm{Prob}(B^0 \to \bar{B}^0) \propto \exp(-t/\tau_B)(1-\cos\Delta m\, t)$$

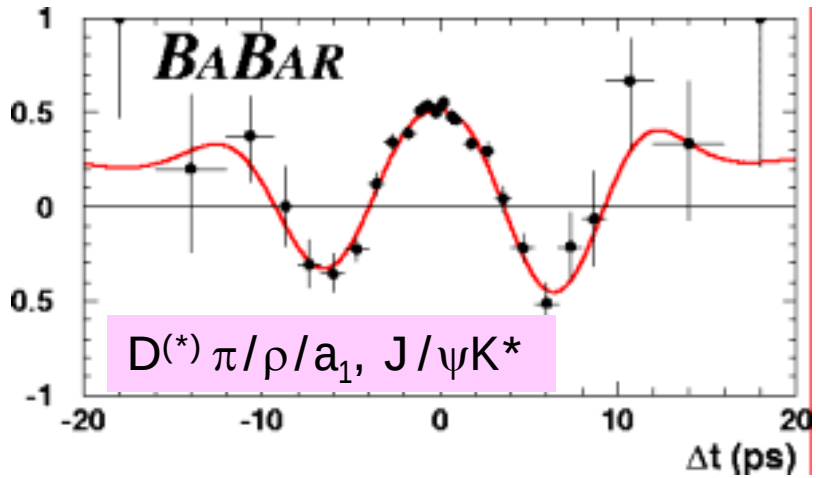
$$\Delta m_d = m_{B_H} - m_{B_L}$$

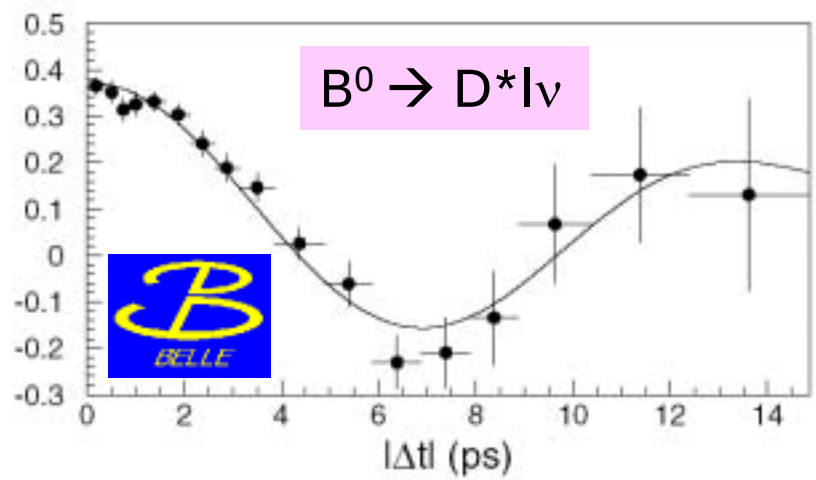
Start with a pure beam of B^0 mesons
→ a $\bar{B}^0$ component develops with time

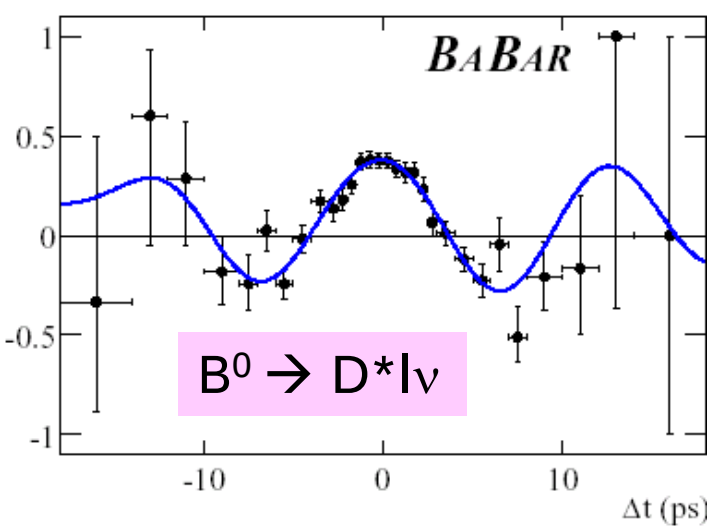


$B^0\bar{B}^0$ Oscillation Measurements

$$A_{\text{mixing}}(\Delta t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \approx \left(1 - 2\langle w \rangle\right) \times \cos(\Delta m \Delta t)$$





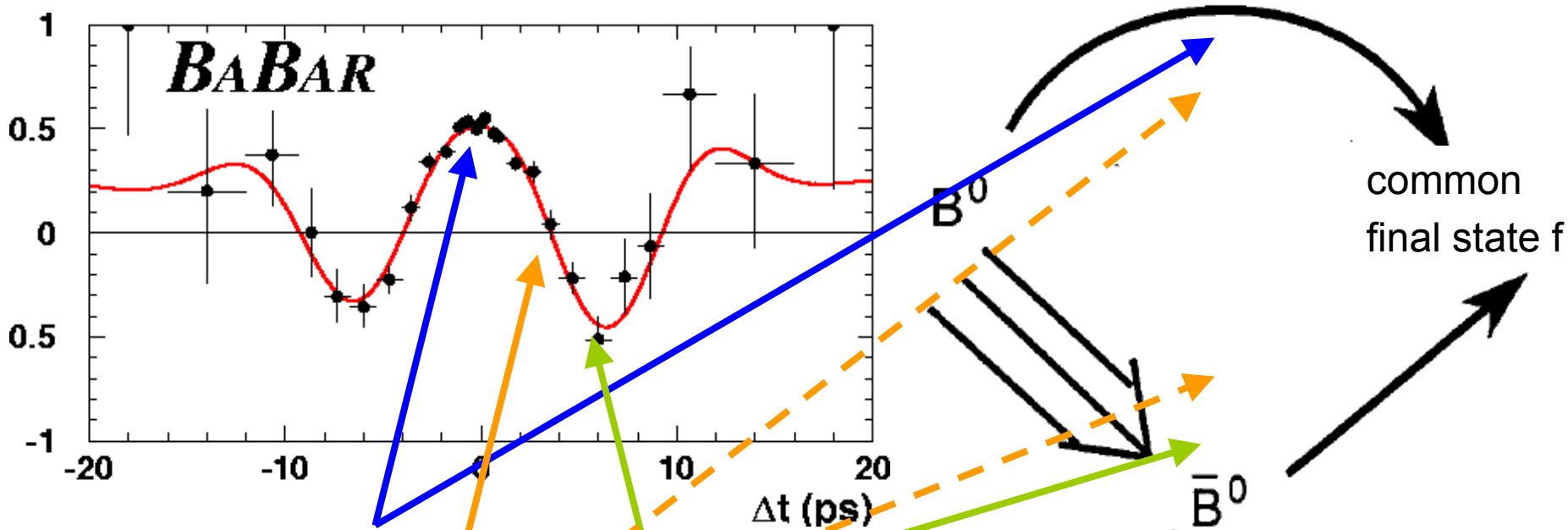


$B^0\bar{B}^0$ oscillation frequency precisely determined from flavor specific final states:

$\Delta m = 0.502 \pm 0.006\ \text{ps}^{-1}$
(HFAG average)

Interference of 2 different Paths to the same Final State induced by B Mixing

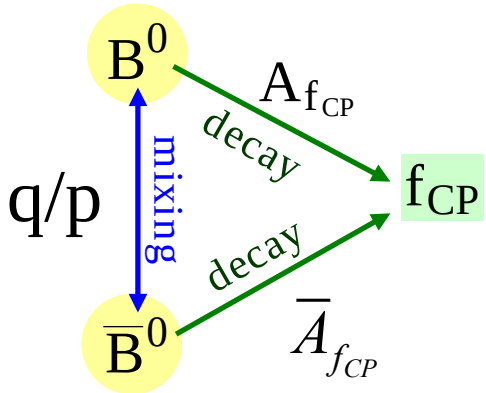
- Consider pure B^0 initial state ($\bar{B}^0$ is the same)



- $\Delta m \Delta t = 0$: $P(B^0 \rightarrow B^0) = 0 \rightarrow$ no mixing, no interference
- $\Delta m \Delta t = \pi$: $P(B^0 \rightarrow \bar{B}^0) = 1 \rightarrow$ full mixing, no interference
- $\Delta m \Delta t = \pi/2$: $P(B^0 \rightarrow \bar{B}^0) = 1/2 \rightarrow$ maximal interference, resulting in CP violation !

$\not{C}\not{P}$ from Interference of Mixing and Decay

CP violation results from interference between decays with and without mixing



$$\lambda_{f_{CP}} = \underbrace{\frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}}_{=|\lambda_{f_{CP}}| e^{-i2\varphi_{CP}}}$$

Time-dependent CP asymmetry:

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

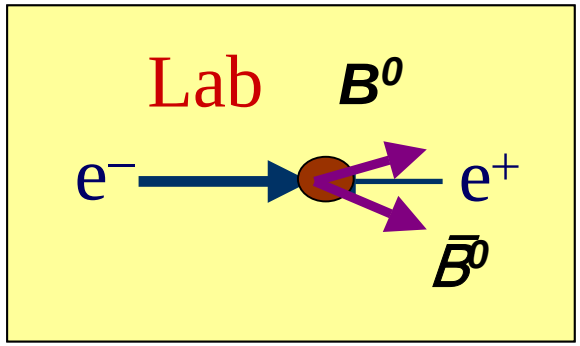
$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

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

$$\lambda_{f_{CP}} \neq \pm 1 \Rightarrow \mathrm{Prob}(\bar{B}^0_{phys}(t) \to f_{CP}) \neq \mathrm{Prob}(B^0_{phys}(t) \to f_{CP})$$

PEP-II & KEKB Asymmetric B Factories

- Decay time determined from decay distance between B decays $\Delta z = \Delta t\ (c\ \beta\gamma)$
- In $\Upsilon(4S)$ CMS daughter B's travel only $\Delta z \sim 20\ \mu m$
- Boost at PEP-II / KEKB decay gives much larger separation $<|\Delta z|> \sim 250/200\ \mu m$ (BaBar/Belle)
  - measurable with high resolution Silicon Vertex Detectors (typical resolution 200 μm)

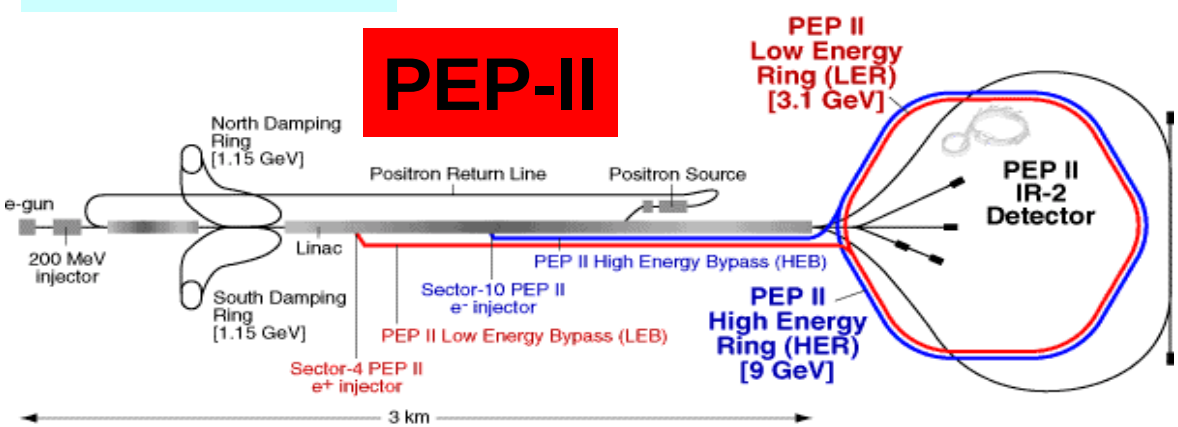


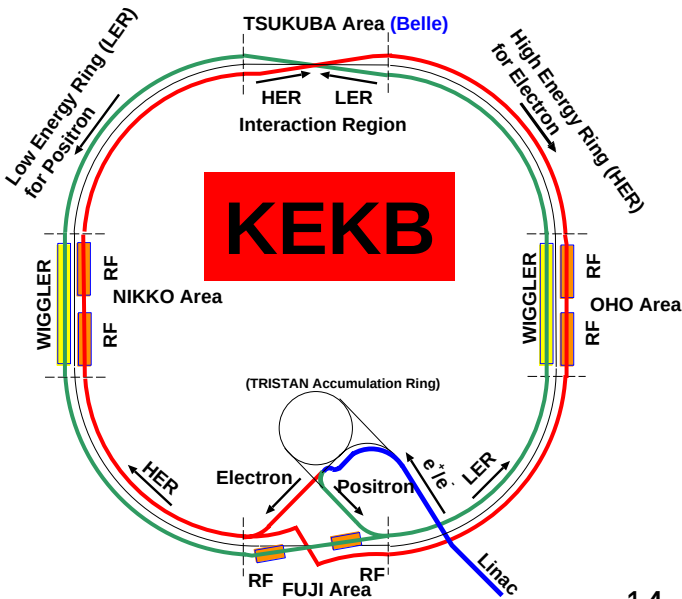
$E_+ = 3.5$ GeV
$E_- = 8$ GeV

$\beta\gamma = 0.43$

$E_+ = 3$ GeV
$E_- = 9.1$ GeV

$\beta\gamma = 0.56$



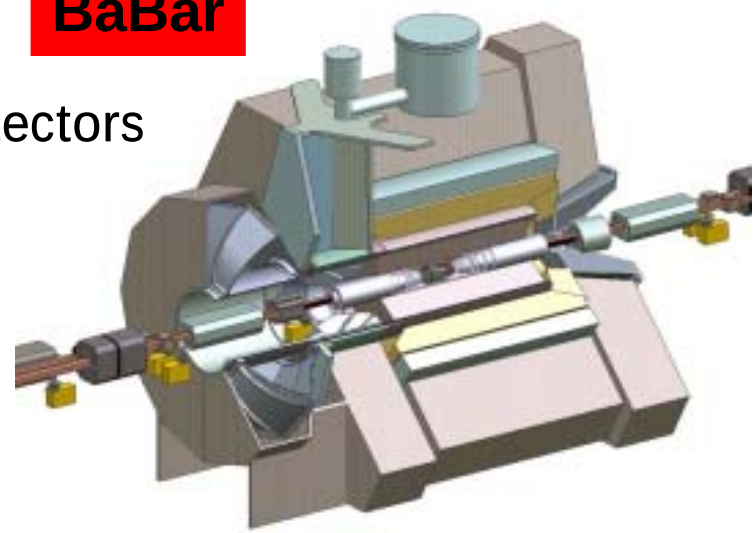


The BaBar & Belle Detectors

Multi-purpose 4π detectors

- Precision vertexing with silicon strip detectors
- Tracking with central drift chamber
- PID (BaBar: DIRC, Belle: Aerogel+TOF)
- Super-conducting coil
- EM CsI calorimeter
- Muon detection with RPCs

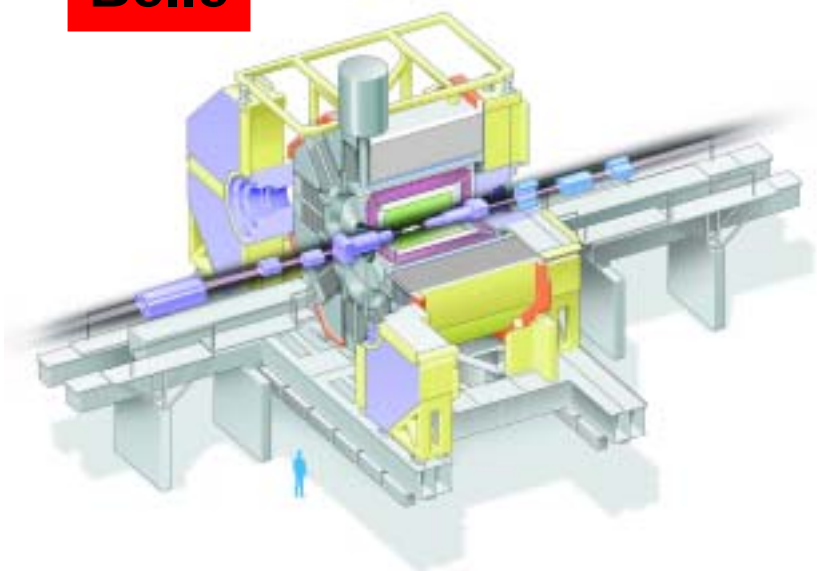
BaBar



Integrated Luminosity

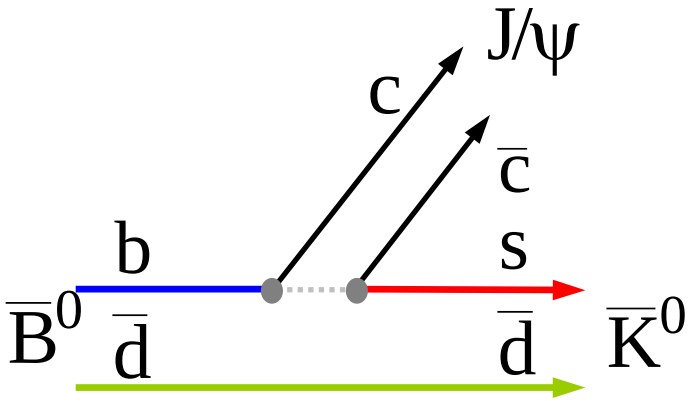
- BaBar 131/fb, Belle 159/fb
- ~ 80/fb analyzed per experiment (1/fb ~ 1.15 million $B\bar{B}$ events)

Belle



Golden Decay Mode: $B^0 \to J/\psi\, K^0_S$

- Relatively 'large' branching fraction ie. $O(10^{-4})$
- Clear experimental signature
- Theoretically clean way to measure $\sin 2\beta$



$\bar{B}^0 \to J/\psi\, \bar{K}^0$
$B^0 \to J/\psi\, K^0$

K^0 mixing

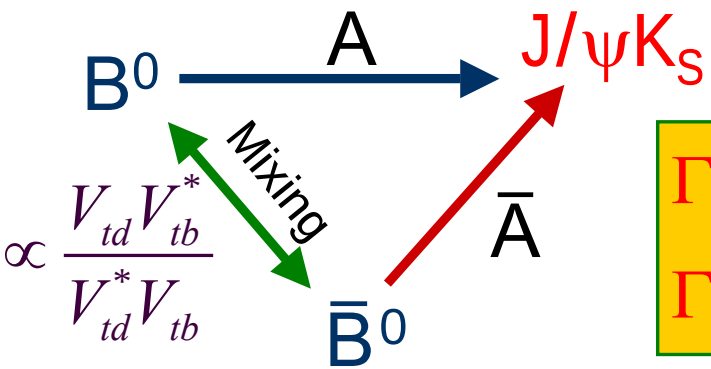
$B^0_{CP=-1} \to J/\psi K^0_S$
$B^0_{CP=+1} \to J/\psi K^0_L$

$$\lambda_{J/\psi K^0_{L,S}} = \eta\, e^{-i2\beta}$$

η = -1 (+1) for $J/\psi\, K^0_{S(L)}$

Single weak phase = no direct $\not{CP}$

$$C = 0, \quad S = \sin 2\beta$$



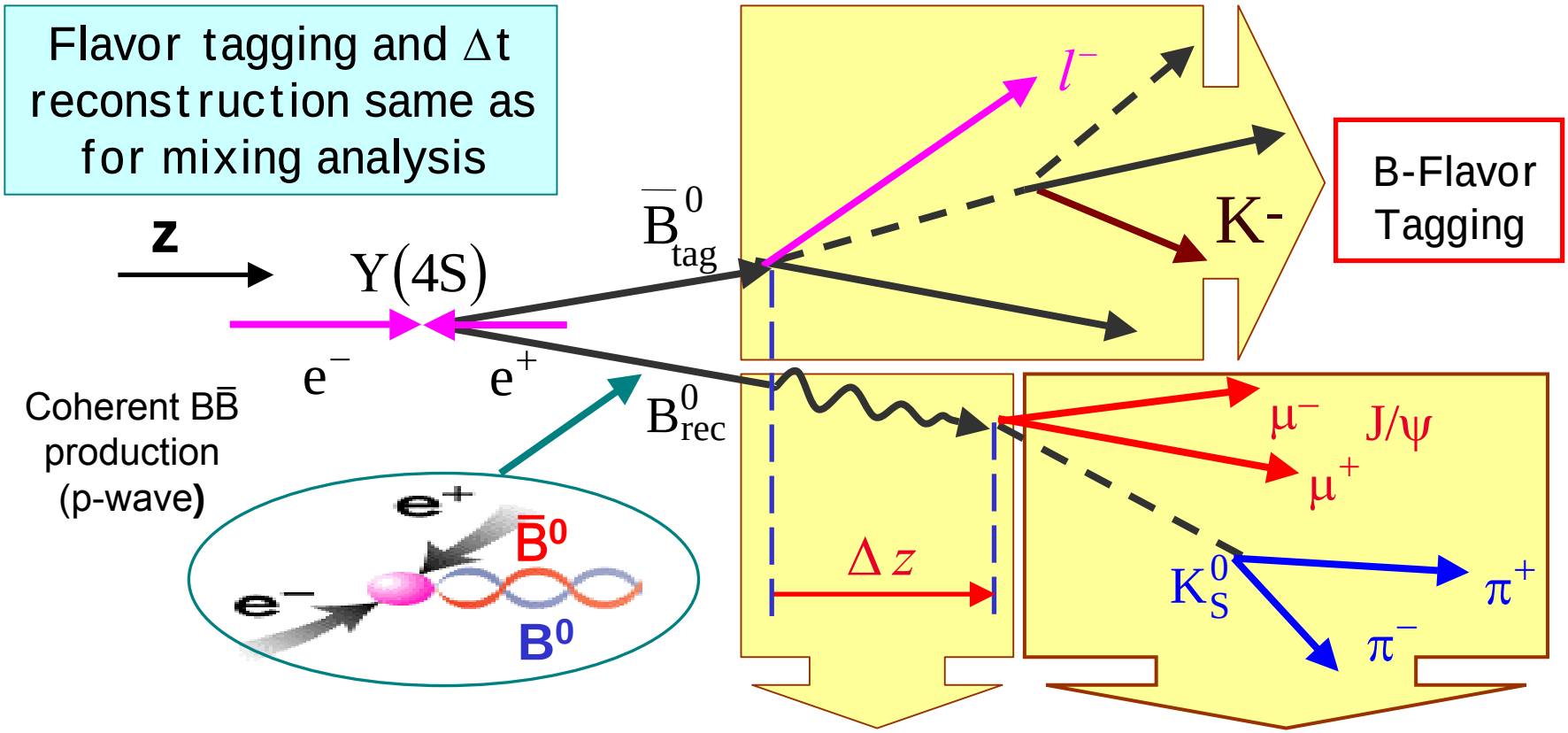
$$\propto \frac{V_{td}V^*_{tb}}{V^*_{td}V_{tb}}$$

$$\Gamma(B^0 \to f_{CP}) \propto e^{-t/\tau}[1 + \eta \sin 2\beta \sin \Delta m \Delta t]$$
$$\Gamma(\bar{B}^0 \to f_{CP}) \propto e^{-t/\tau}[1 - \eta \sin 2\beta \sin \Delta m \Delta t]$$

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

Measurement of sin2β

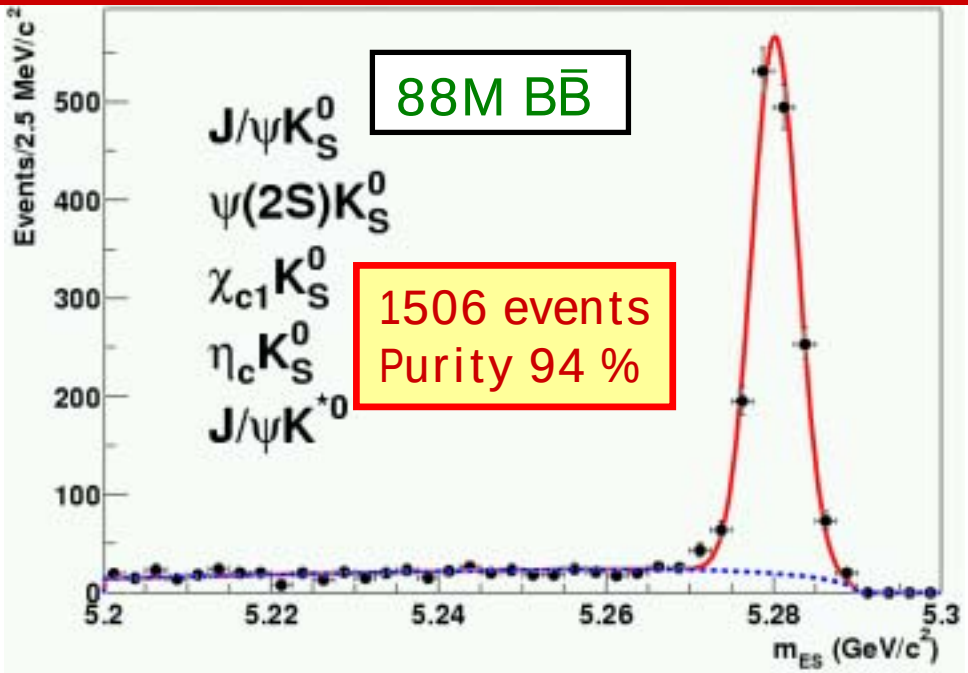
Flavor tagging and Δt reconstruction same as for mixing analysis

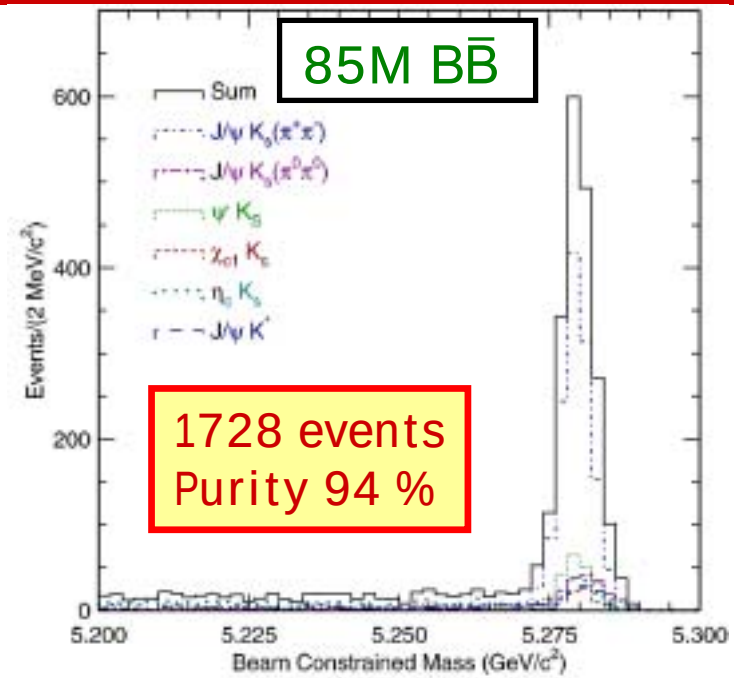


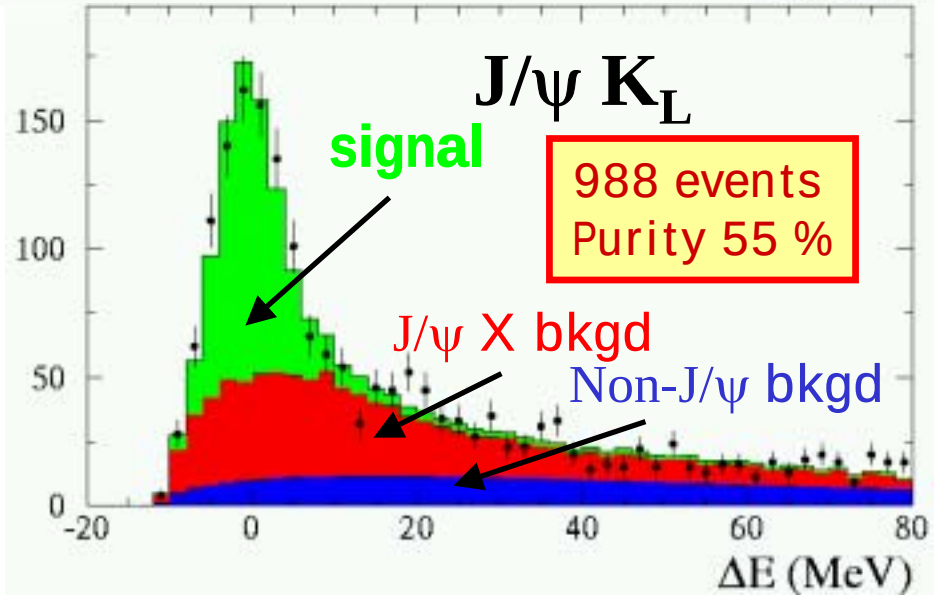
$$\Delta t = t_{rec} - t_{tag}$$
$$\approx \Delta z / \langle \beta\gamma \rangle c$$

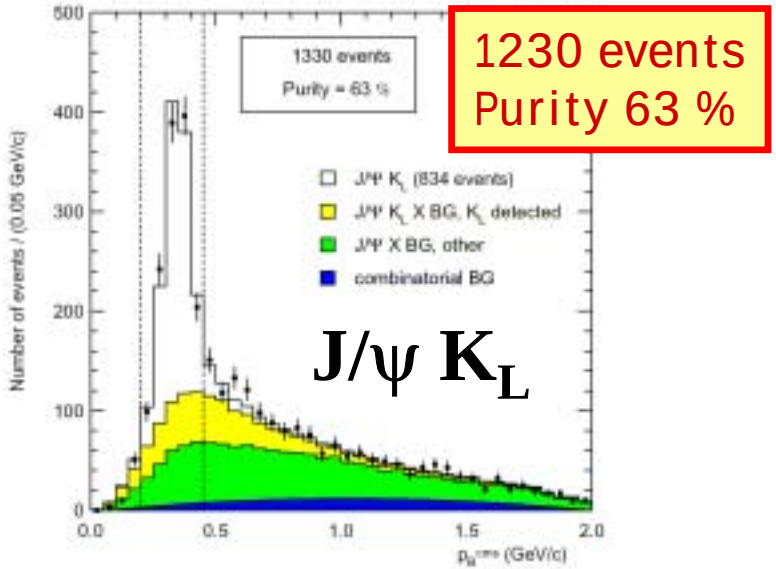
Reconstruction of B decays to CP eigenstates

Tagged B_{CP} candidates





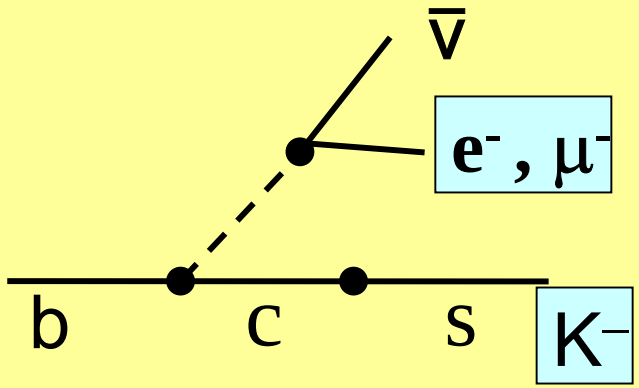




B^0 Flavor Tagging

- Reconstruct one B in a decay mode accessible to B^0 and $\bar{B}^0$ e.g $J/\psi K_S$
  - Need to know B flavor at production !
- determine flavor of other B (tag B) from its charged decay products
  - lepton, Kaons, soft π^+ from $D^{*+} \rightarrow D^0\pi^+$, high p tracks
  - Correlations exploited by multivariate techniques

Lepton, Kaon tagging



$\bar{B}^0(b \rightarrow l^-, K^-)$, $B^0(\bar{b} \rightarrow l^+, K^+)$

Soft and hard pion tagging

$$\bar{B}^0 \rightarrow D^{*+}\pi^-$$

$$\hookrightarrow D^0\pi^+$$

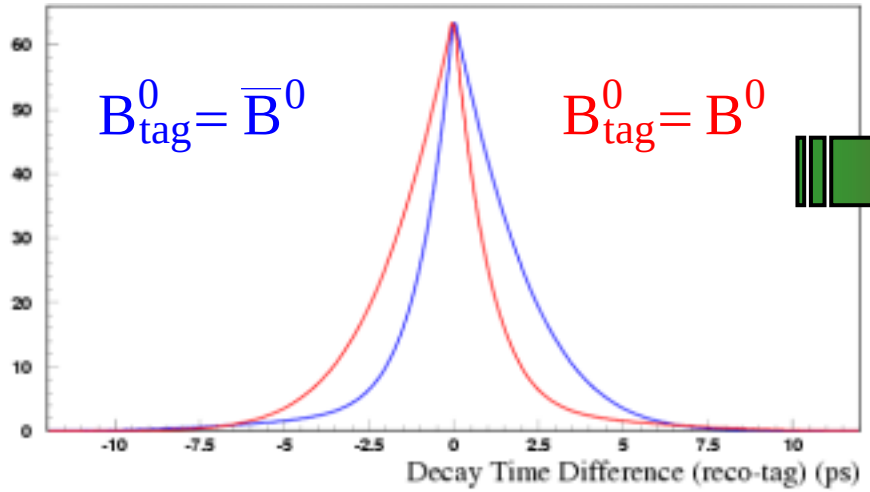
$\bar{B}^0$: fast π^-, soft π^+

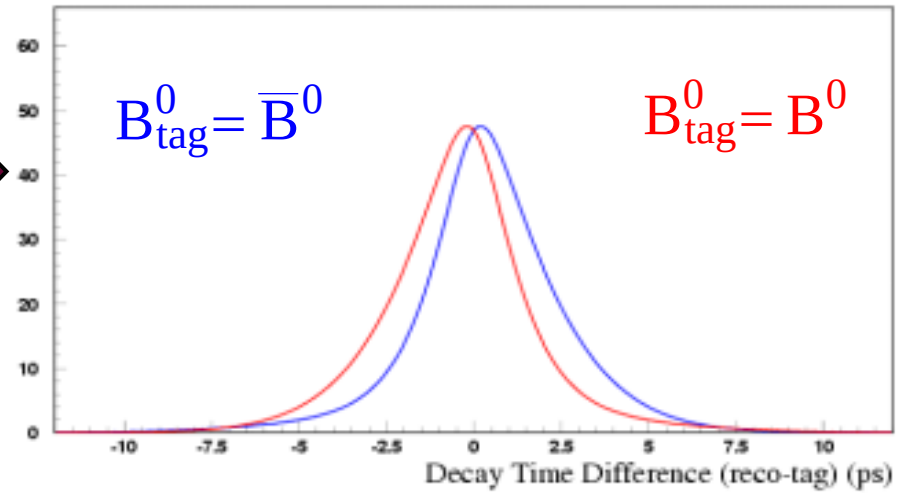
B^0: fast π^+, soft π^-

CP Analysis: Δt Distributions

perfect
flavor tagging & time resolution

realistic
mis-tagging & finite time resolution





Determine **flavor mis- tag rates w** and **Δt resolution function R** from large control samples of $B^0 \rightarrow D^{(*)}\pi/\rho/a_1$, $J/\psi K^*$, $D^* l \nu$

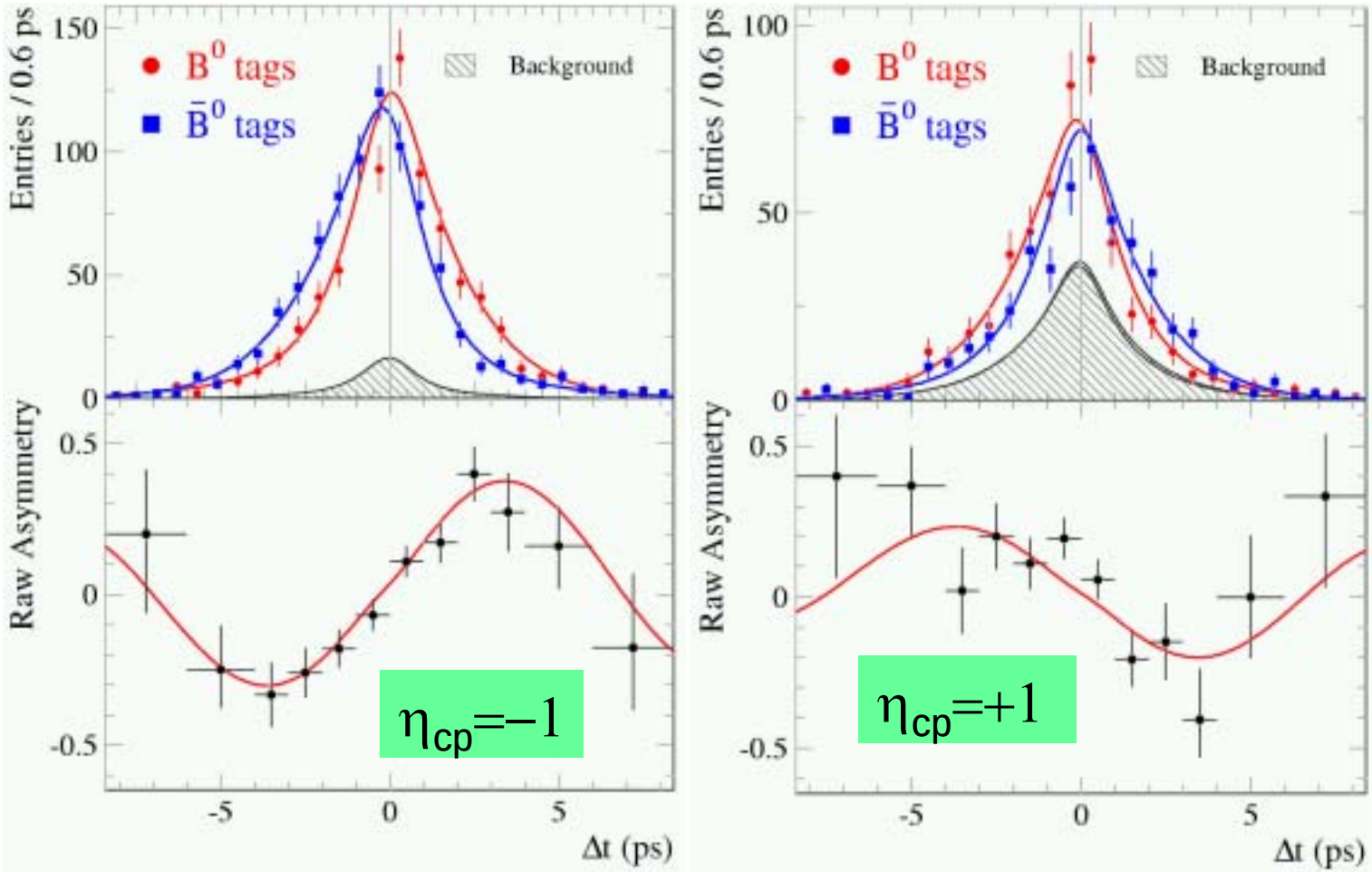
CP PDF

$$f_{CP,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{4\,\tau_{B_d}} \times \left(1 \mp \eta_f \, \sin 2\beta \, (\mathbf{1\text{-}2w}) \, \sin(\Delta m_d \Delta t) \right) \right\} \otimes \boldsymbol{R}$$

Mixing PDF

$$f_{mixing,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{4\,\tau_{B_d}} \times \left(1 \pm (\mathbf{1\text{-}2w}) \, \cos(\Delta m_d \Delta t) \right) \right\} \otimes \boldsymbol{R}$$

Sin2β from BaBar



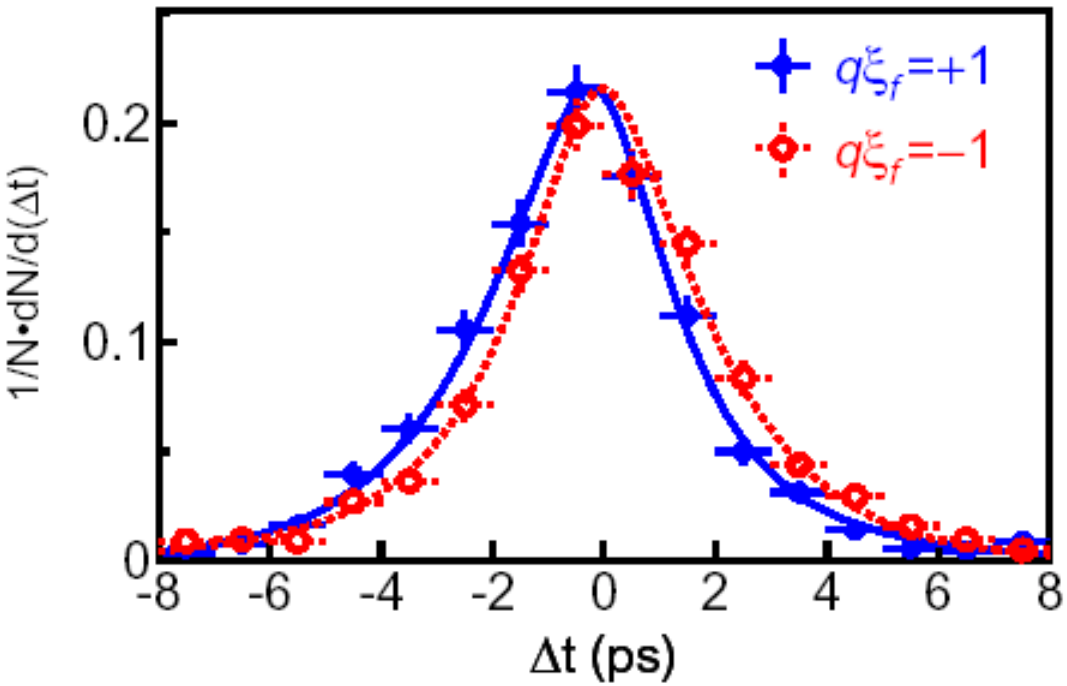
sin2β = 0.755 ± 0.074 **sin2β = 0.723 ± 0.158**

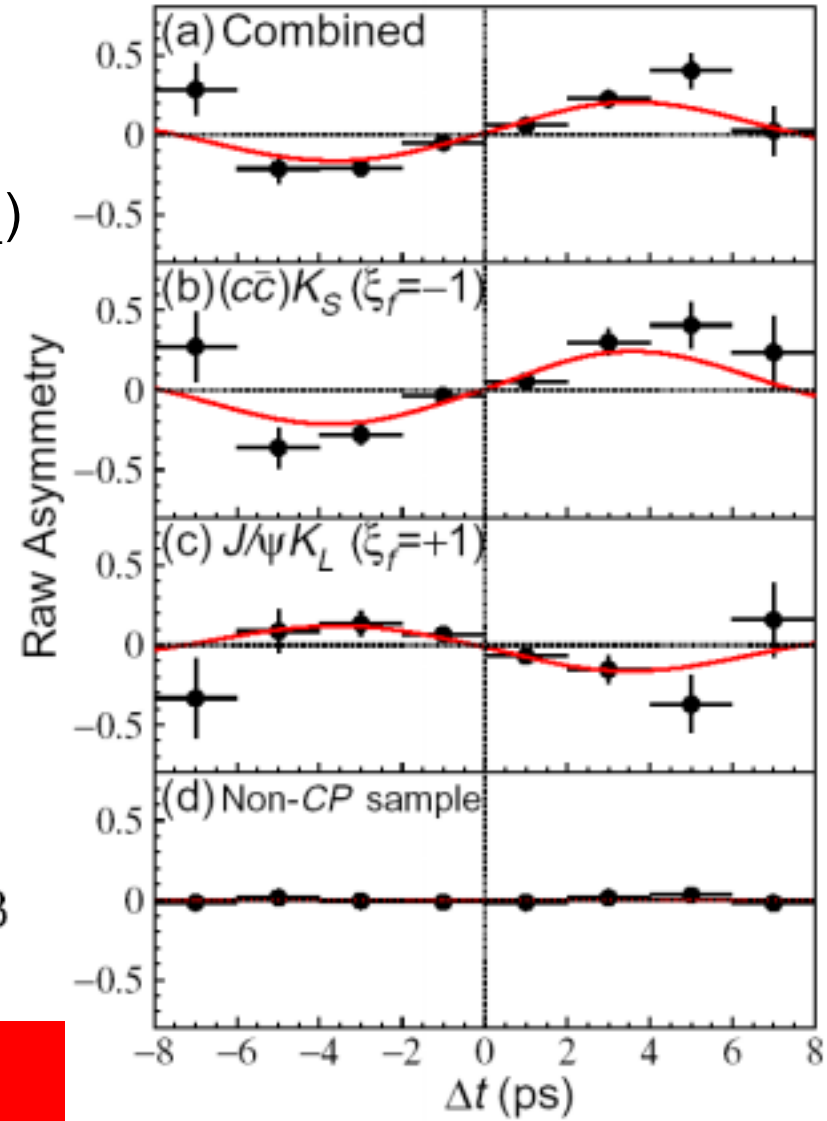
sin2β = 0.741 ± 0.067 ± 0.034

Sin2β from Belle

q = +1 → B^0 tag ξ = CP eigenvalue

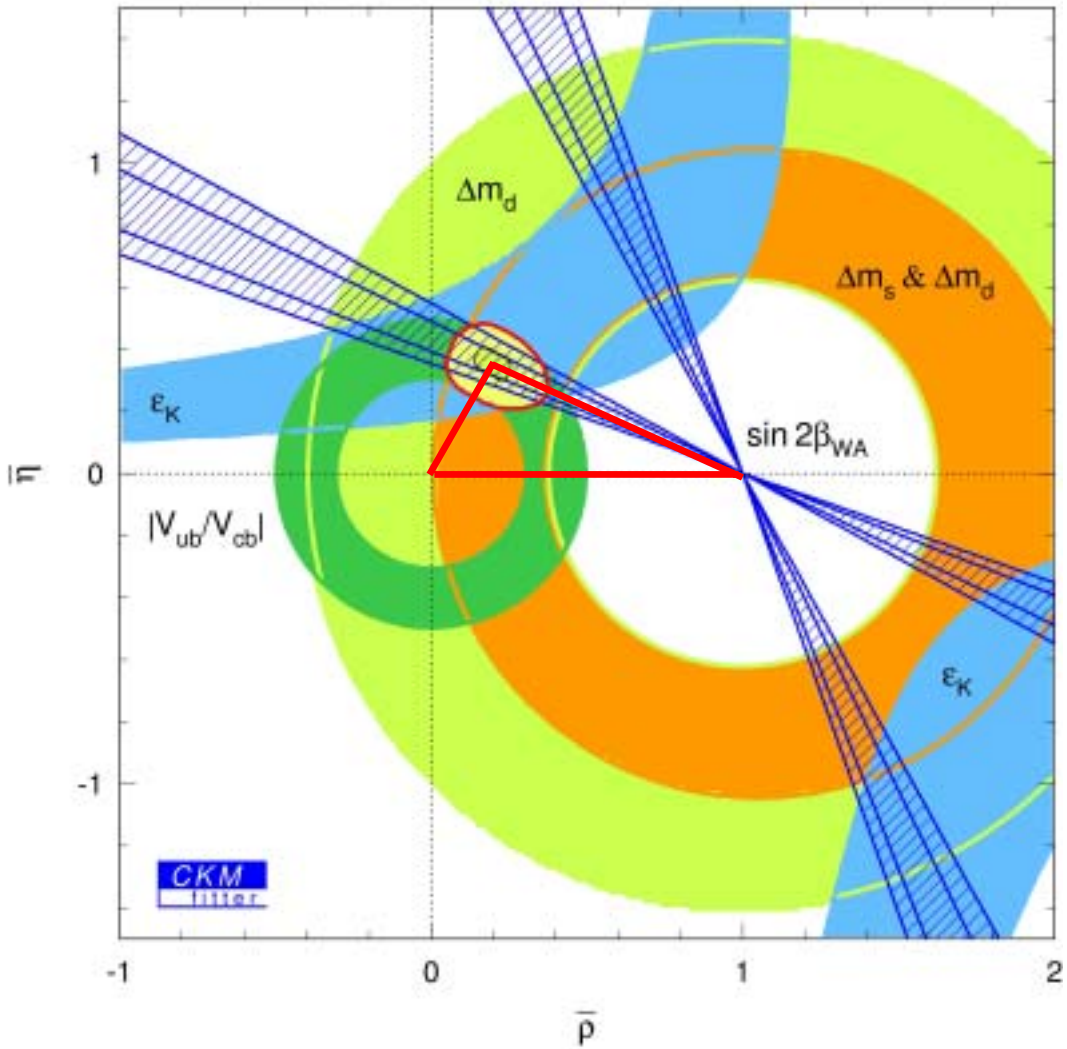
q = - 1 → $\bar{B}^0$ tag (-1 for J/ψ K_S,+1 for J/ψK_L)





sin2β = 0.719 ± 0.074 ± 0.035

Consistency with Indirect Measurements



One solution for β is in good agreement with measurements of sides of Unitarity Triangle

Error on sin2β is dominated by statistics → will decrease ~1/√Luminosity for a while

sin2β = 0.731 ± 0.056 (BaBar & Belle)

Beyond the Standard Model

If at least 2 amplitudes with a weak phase difference contribute |λ| could be different from 1

(tree amplitude and leading penguin amplitude for B→ $J/\psi\ K_S$ have same weak phase in SM)

$$\underbrace{\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}}_{=|\lambda_{f_{CP}}| e^{-i2\varphi_{CP}}}$$

$$A_{CP} = C_{f_{CP}} \cos \Delta m_d \Delta t + S_{f_{CP}} \sin \Delta m_d \Delta t$$

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

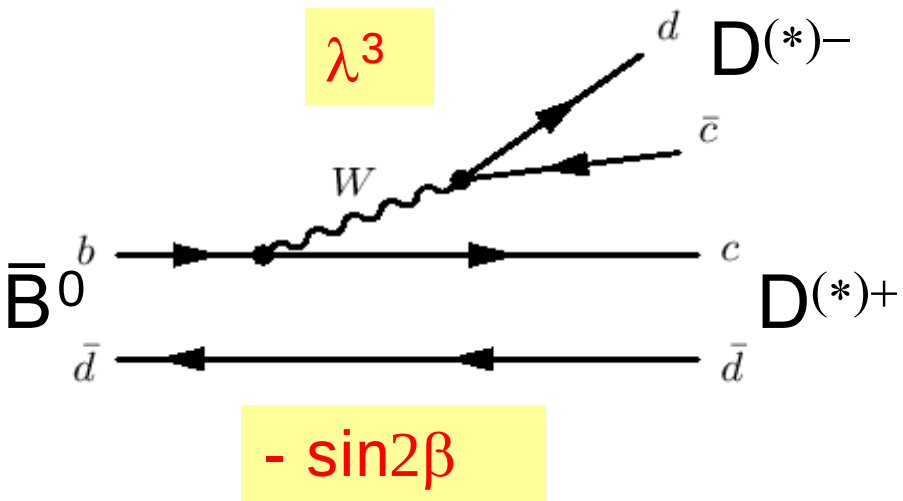
$$S_{f_{CP}} = \frac{-2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

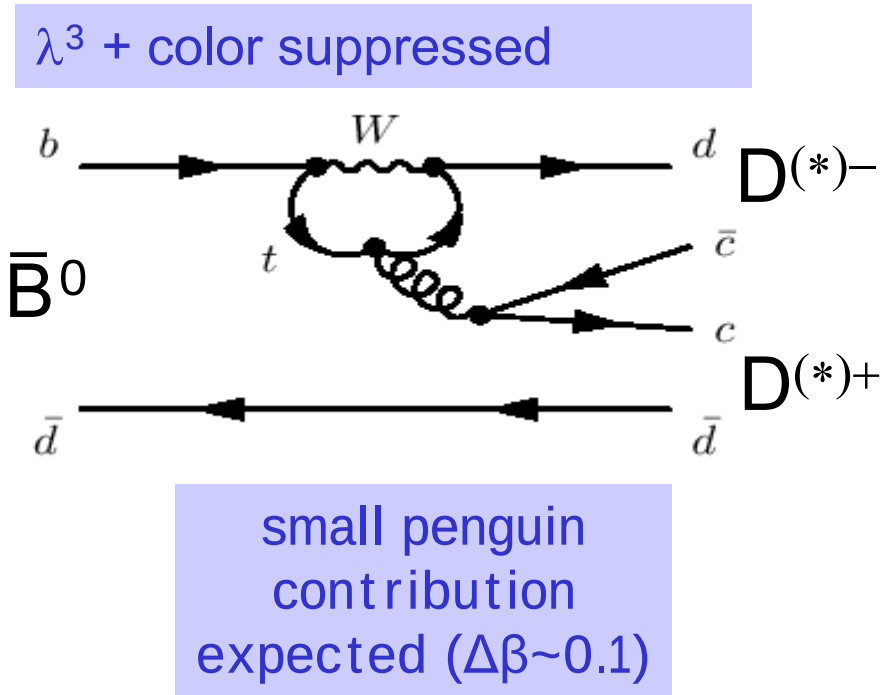
|λ| = 0.949 ± 0.045 (BaBar & Belle)

No evidence of direct CP violation due to decay amplitude interference !

sin2β from $B^0 \to D^{*+} D^{*-}$ and $B^0 \to D^{*+} D^-$

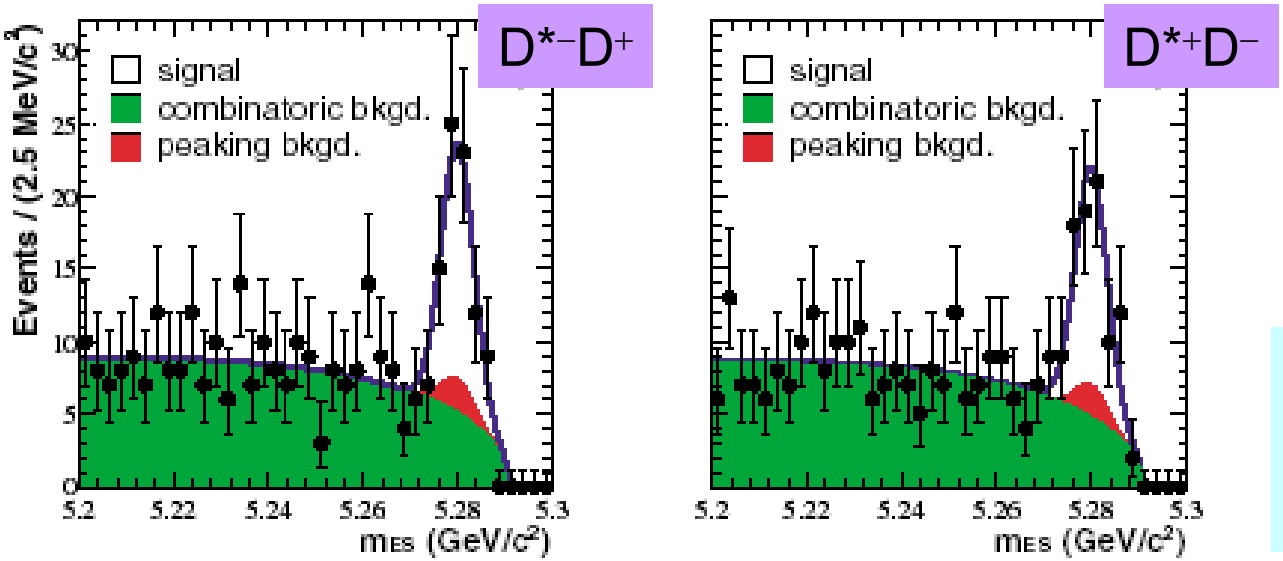
- Tree amplitude dominant, top or up penguin diagram (internal loop) with different phases are color-suppressed





S and C in $B^0 \to D^{*+} D^-$ (BaBar)

133 ± 13 signal events (81/fb)



Not a CP eigenstate!

Separate C and S for $D^{*+}D^-$ and $D^{*-}D^+$

$D^{*-}D^+ / D^{*+}D^-$ rate asymmetry
$A = -0.03 \pm 0.11 \pm 0.05$

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

$S_{-+} = -0.24 \pm 0.69 \pm 0.12$

$C_{-+} = -0.22 \pm 0.37 \pm 0.10$

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

$S_{+-} = -0.82 \pm 0.75 \pm 0.14$

$C_{+-} = -0.47 \pm 0.40 \pm 0.12$

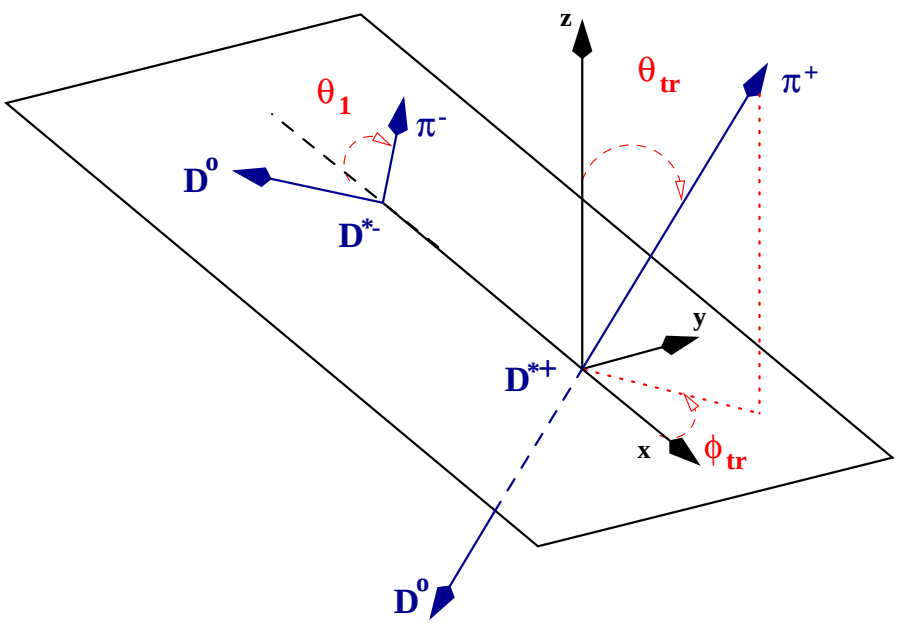
If penguins negligible, expect
$C_{-+} = C_{+-} = 0$
$S_{-+} = S_{+-} = -\sin 2\beta$

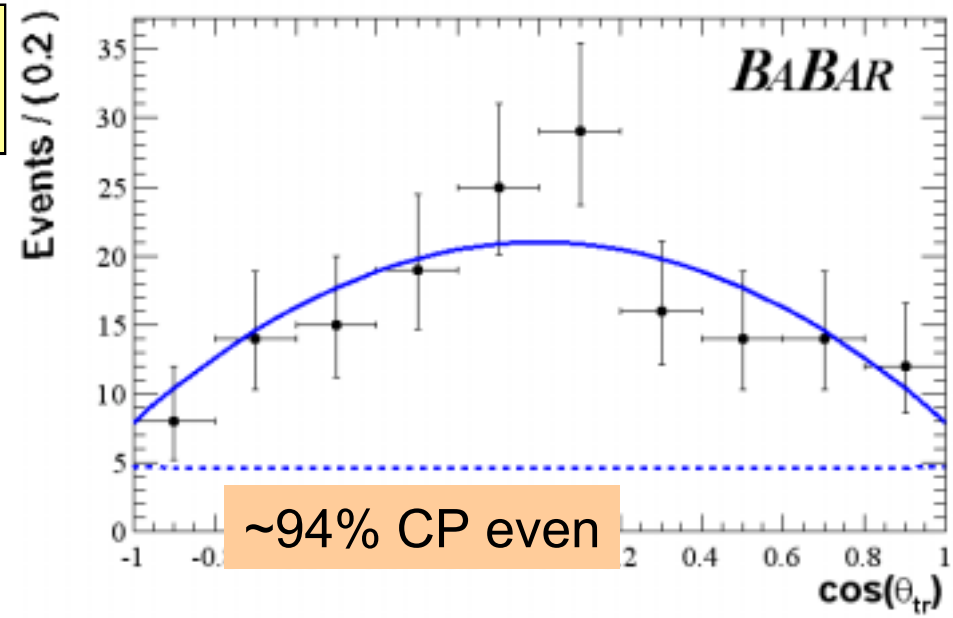
More data needed, to see penguin effect!

$\sin 2\beta$ in $B^0 \to D^{*+} D^{*-}$ (BaBar)

- $D^{*+}D^{*-}$ is vector-vector final state with CP-even (S- and D-wave) and CP-odd (P-wave) contributions
- Get CP-odd fraction $R_\perp$ from θ_{tr} distribution

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{tr}} = \frac{3}{4}(1-R_\perp)\sin^2\theta_{tr} + \frac{3}{2}R_\perp\cos^2\theta_{tr}$$





~94% CP even

$R_\perp = 0.063 \pm 0.055 \pm 0.009$

sin2β from $B^0 \to D^{*+} D^{*-}$ (BaBar, 81/fb)

156 ± 14 signal events (88M $B\bar{B}$)

Measure CP-parameter λ_+ for CP-even component:

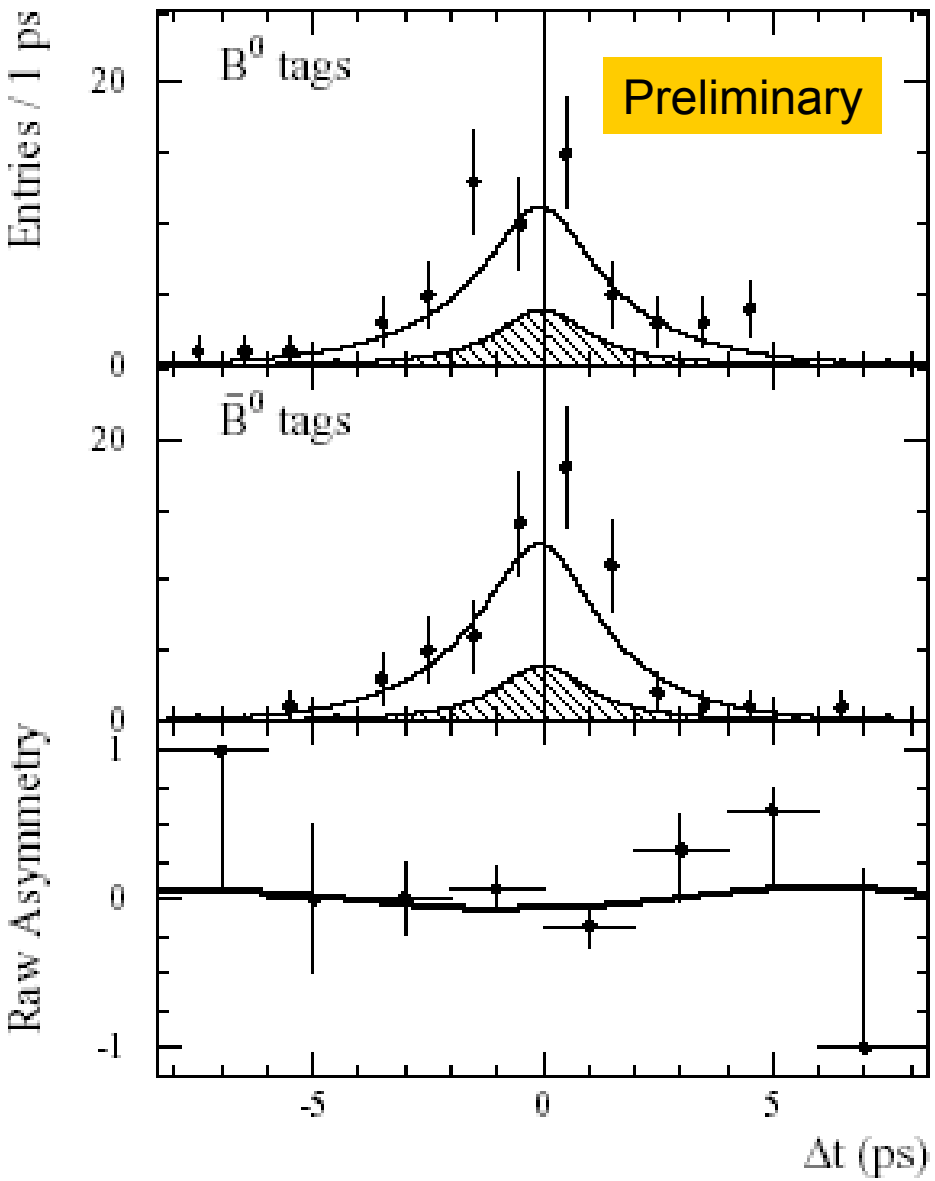
$$\mathrm{Im}(\lambda_+) = 0.05 \pm 0.29 \pm 0.10$$

$$|\lambda_+| = 0.75 \pm 0.19 \pm 0.02$$

If no penguin contribution, expect:

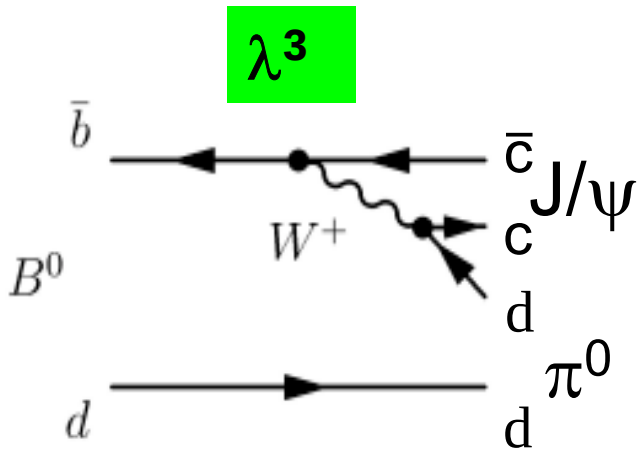
$$\mathrm{Im}(\lambda_+) = -\sin 2\beta, \quad |\lambda_+| = 1$$

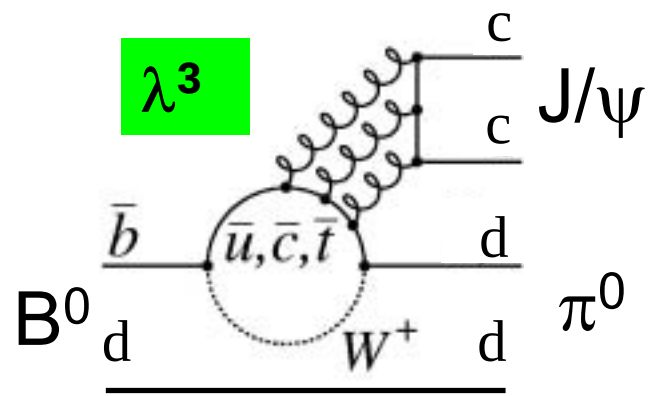
2.5 σ away from 'no penguin' SM



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

Tree and penguin contributions

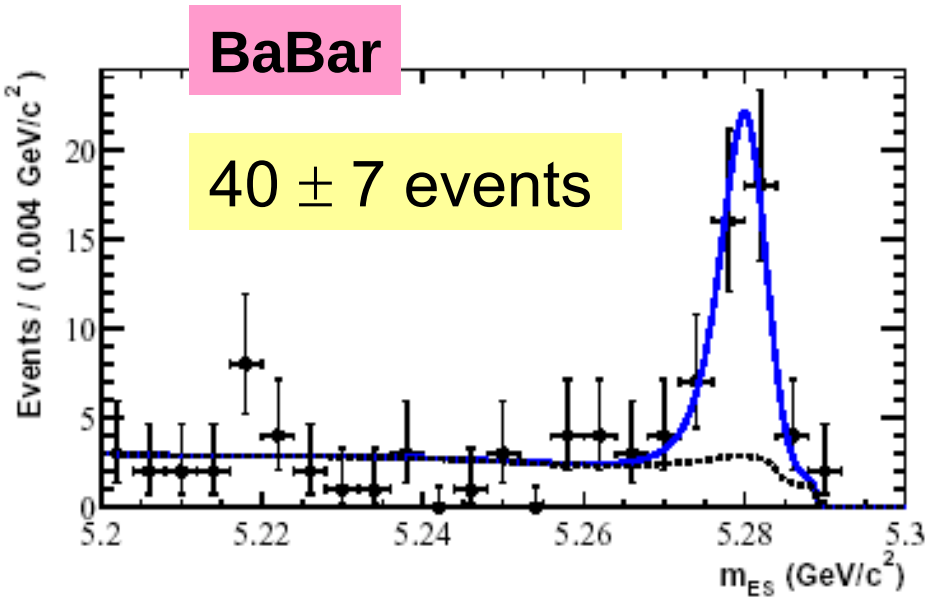




	BaBar	Belle
S	0.05 ±0.49 ±0.16	–0.93 ±0.49 ±0.08
C	0.38 ±0.41 ±0.09	+0.25 ±0.39 ±0.06

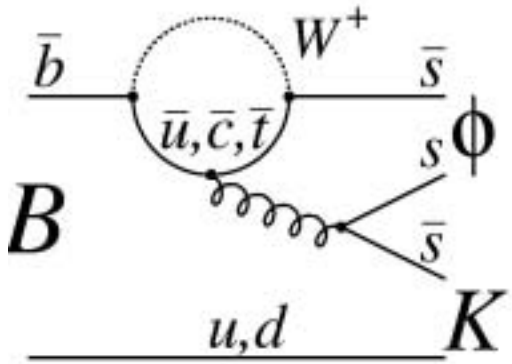
If no penguins, expect S = -sin2β, C = 0

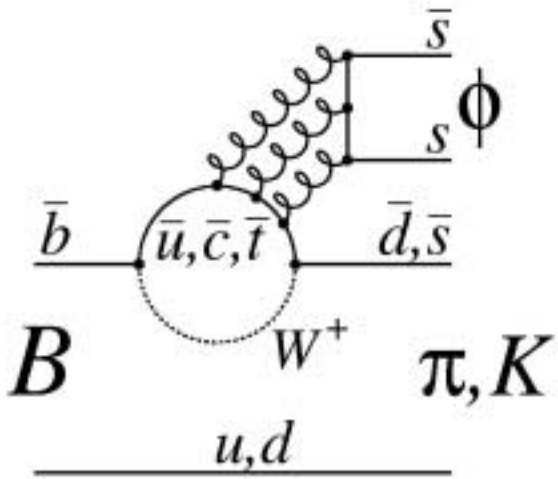
Need more data to see tree/penguin interference



Sin2β with (pure) Penguins

- pure penguin decay B → ϕK
  - dominated by top quark in loop, up quark contribution is highly suppressed



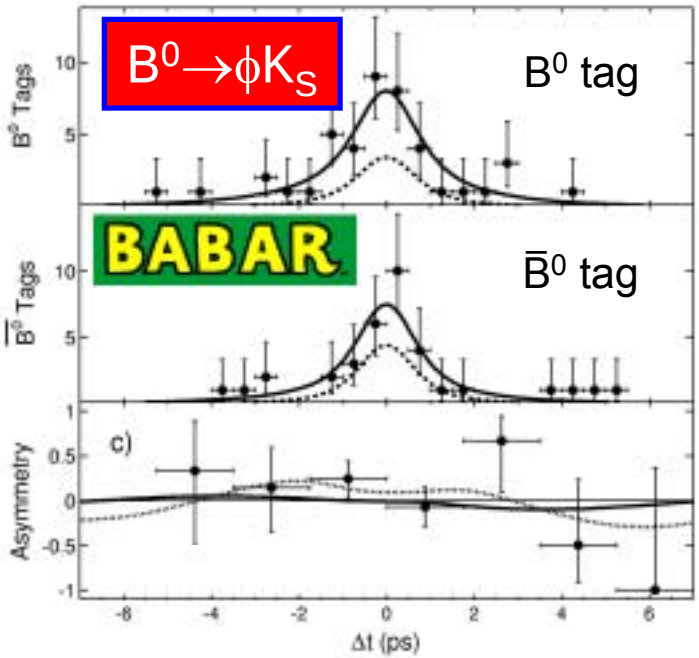


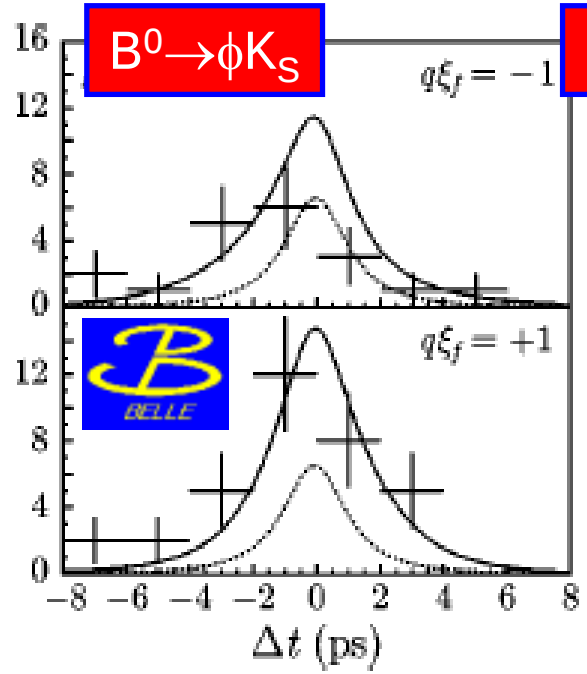
$$BR(B^+ \to \eta' K^+) = (8.8 \pm 1.1) \times 10^{-6}$$
$$BR(B^0 \to \eta' K^0) = (8.4 \pm 1.6) \times 10^{-6}$$

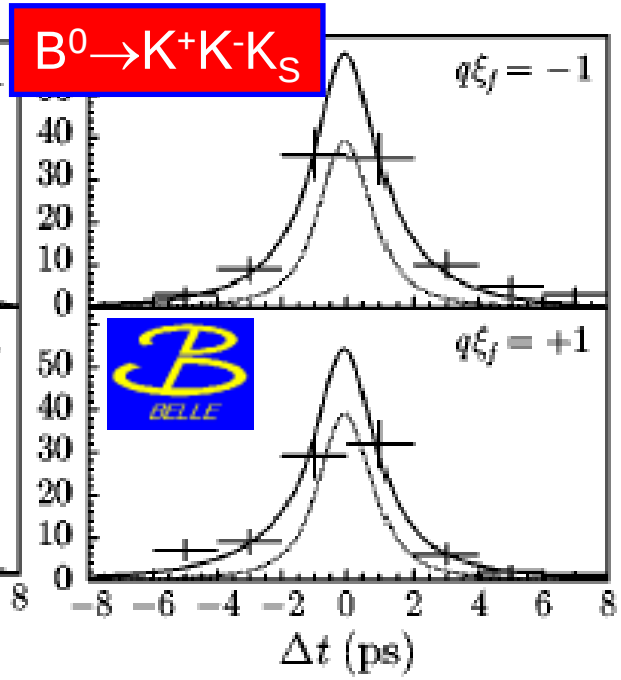
(HFAG averages)

- SM top penguin has no weak phase and expected time-dependent CP asymmetry is sin2β
- new physics may show up due to new (virtual) heavy particles replacing top quark or W in the loop

$B \to \phi K$ Results







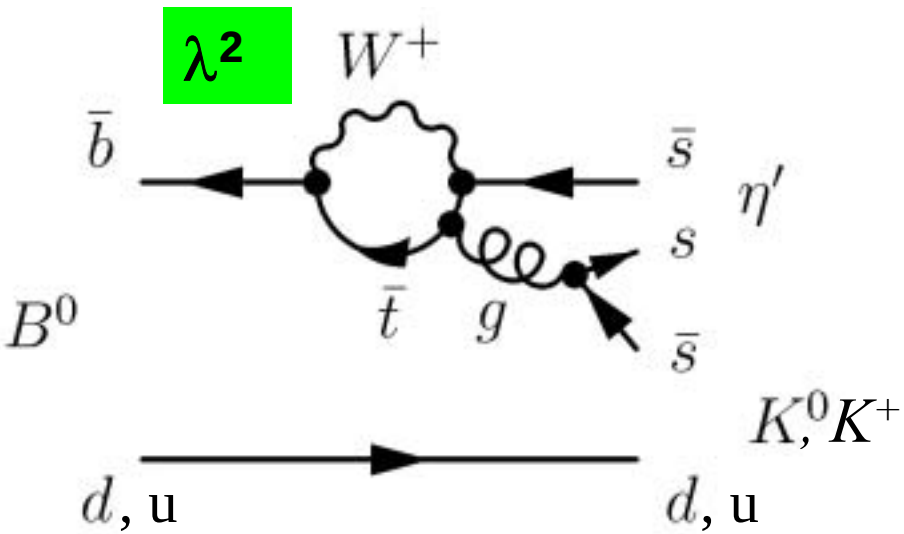
	BaBar Preliminary	Belle
ϕK_S	S = -0.18 ±0.51 ±0.06 C = -0.80 ±0.38 ±0.11	S = -0.73 ±0.64 ±0.22 C = 0.56 ±0.41 ±0.16
$K^+K^-K_S$		S = $0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$ C = $0.40 \pm 0.33 \pm 0.10^{+0.26}_{-0.00}$
ϕK^+	A = 0.04 ± 0.09 ± 0.01	A = 0.01 ± 0.12 ± 0.05

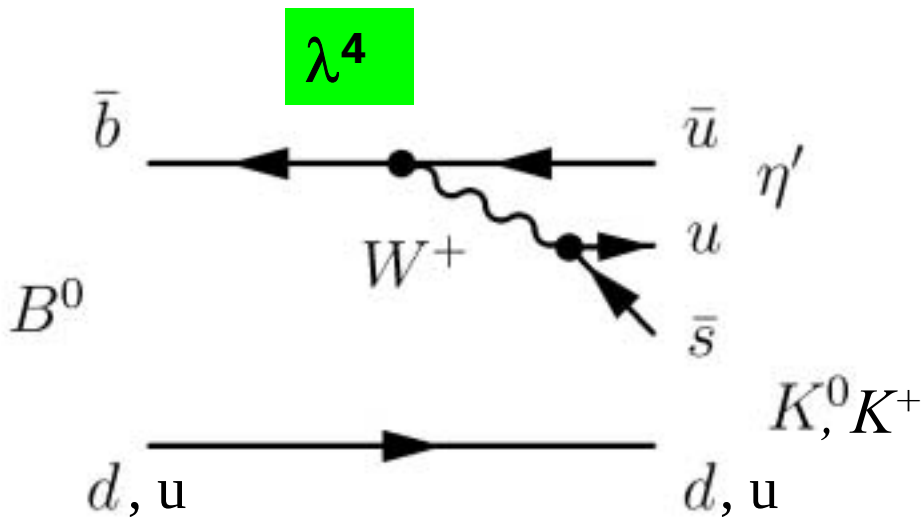
BaBar & Belle: 2σ discrepancy between S and $\sin 2\beta$ for ϕK_S

3rd error for $K^+K^-K_S$ from error in CP-odd fraction

Another penguin: B → η′K

- Gluonic top penguin dominates
  - up penguin and tree have different weak phase (γ), but are suppressed by $\lambda^2 \sim 0.04$

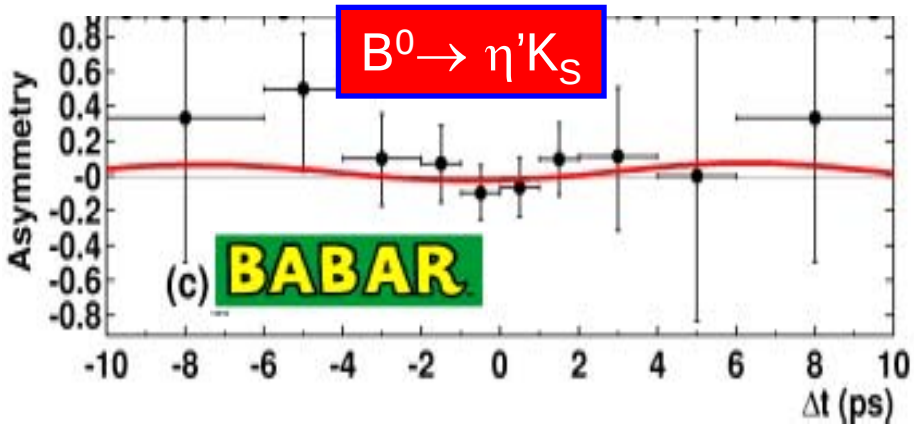


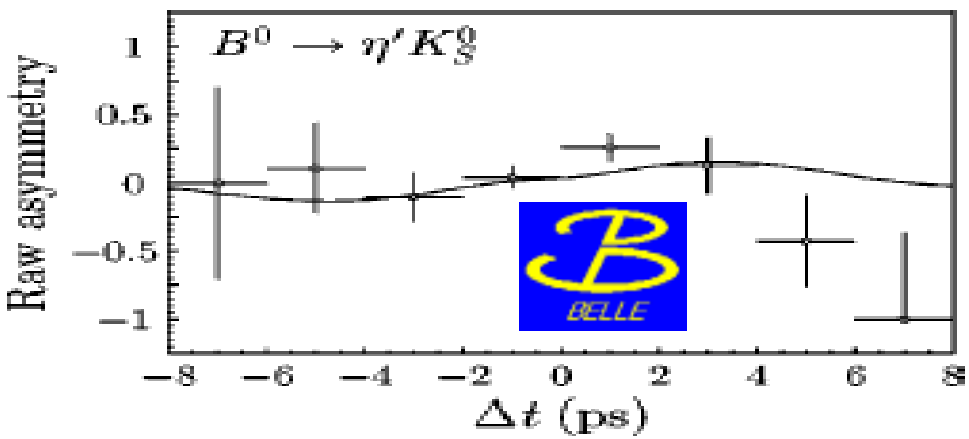


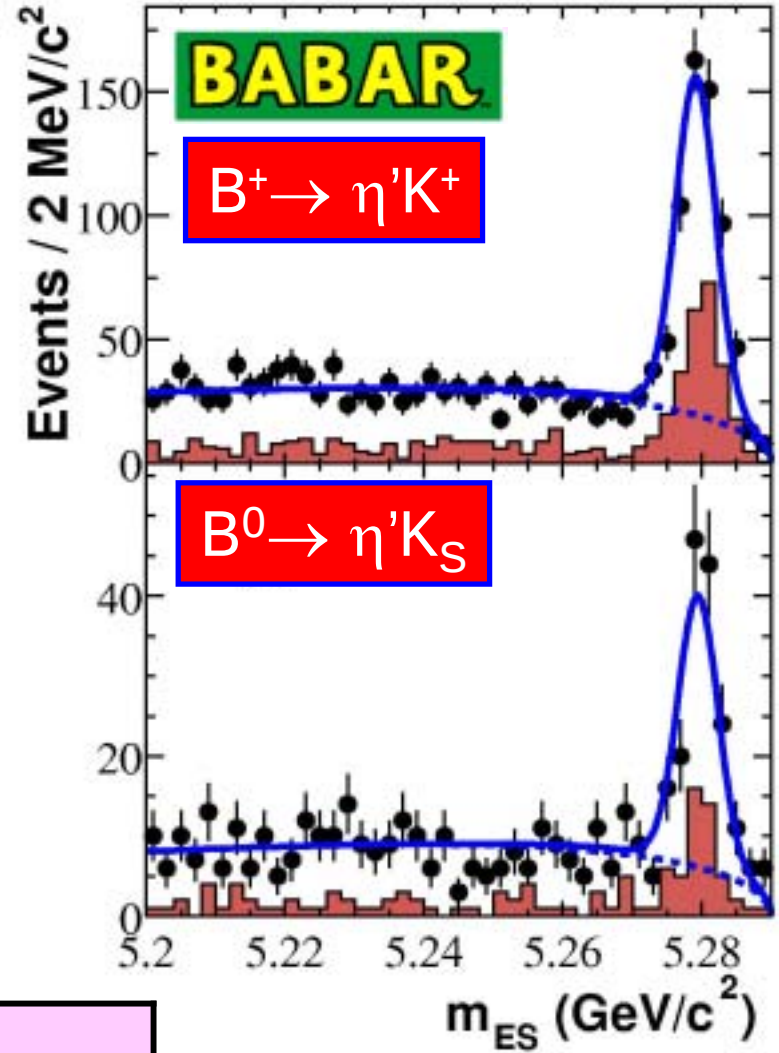
$$BR(B^+ \to \eta' K^+) = (78 \pm 5) \times 10^{-6}$$
$$BR(B^0 \to \eta' K^0) = (60.8 \pm 5.6) \times 10^{-6}$$

(HFAG averages)

$B \to \eta' K$ Results



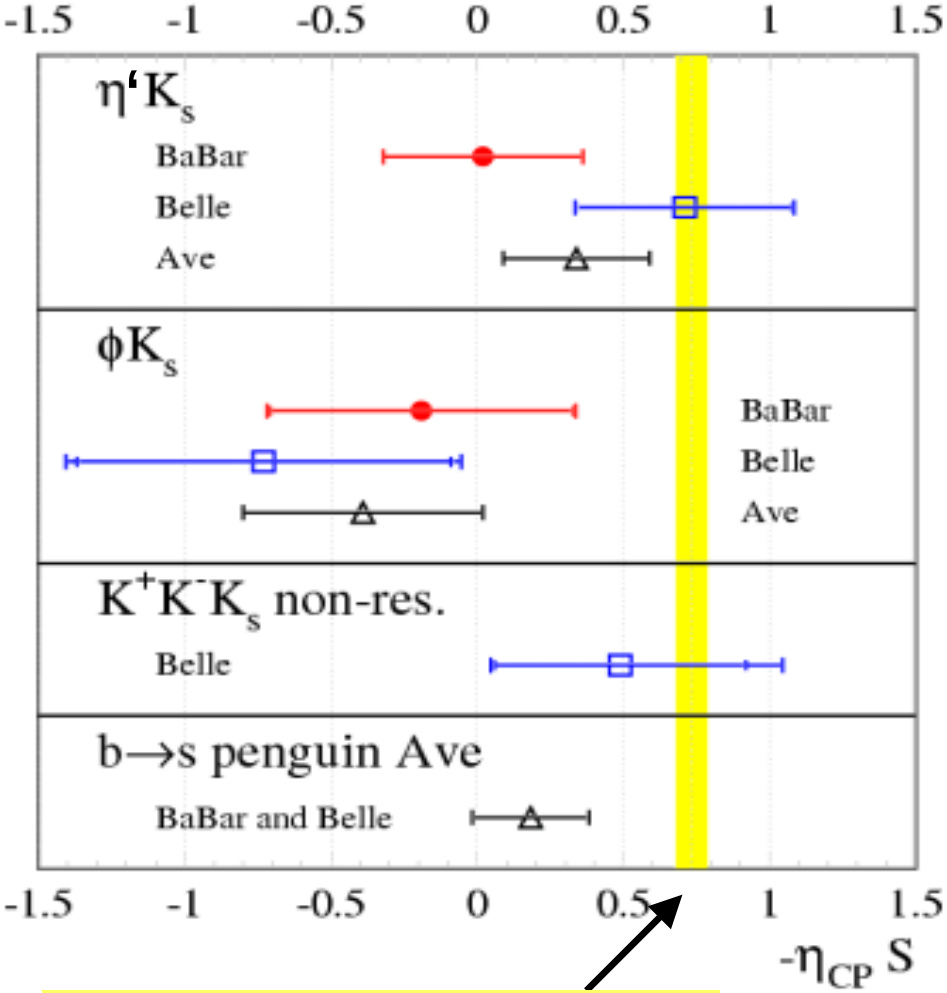




	BaBar	Belle
$\eta' K_S$	S = 0.02 ±0.34 ±0.03 C = 0.10 ±0.22 ±0.03	S = 0.71 ±0.37 ±0.06 C = -0.26 ±0.22 ±0.03
$\eta' K^+$	A = 0.04 ± 0.05 ± 0.01	A = -0.02 ± 0.07 ± 0.01

BaBar: 2σ discrepancy between S and sin2β
Belle: no discrepancy

b → s Penguin Averages



Expectation from J/ψ K_S

b → s penguin average

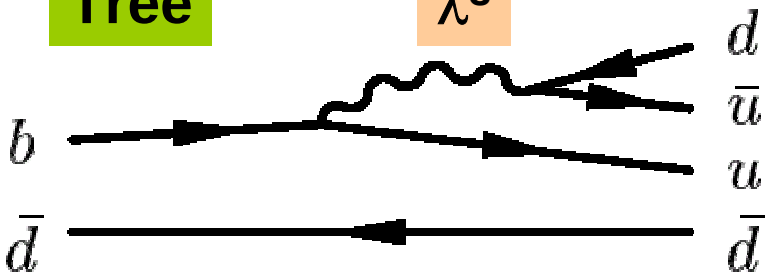
S = 0.19 ± 0.20

~ 2.6 σ smaller than charmonium modes

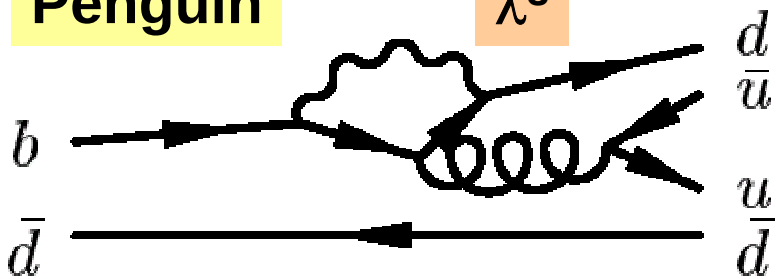
A statistical fluctuation or a hint of new physics…

α from B → $\pi^+\pi^-$

Tree λ^3



Penguin λ^3



If no penguin, expect:

$\lambda_{\pi\pi} = e^{-2i\alpha}$

$S_{\pi\pi} = \sin(2\alpha)$

$C_{\pi\pi} = 0$

Tree + Penguin:

$$\lambda_{\pi\pi} = e^{-2i\alpha}\frac{1+|P/T|e^{i(\delta+\gamma)}}{1+|P/T|e^{i(\delta-\gamma)}}$$

$$S_{\pi\pi} = \sqrt{1-C_{\pi\pi}}\sin(2\alpha_{eff})$$

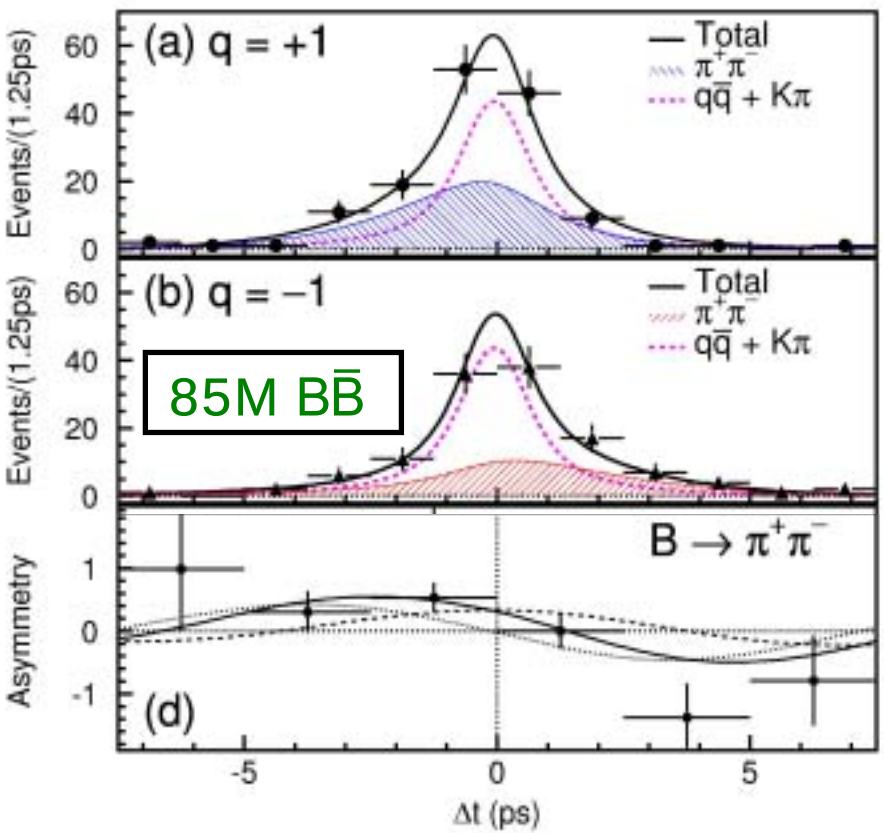
$$C_{\pi\pi} \propto \sin\delta$$

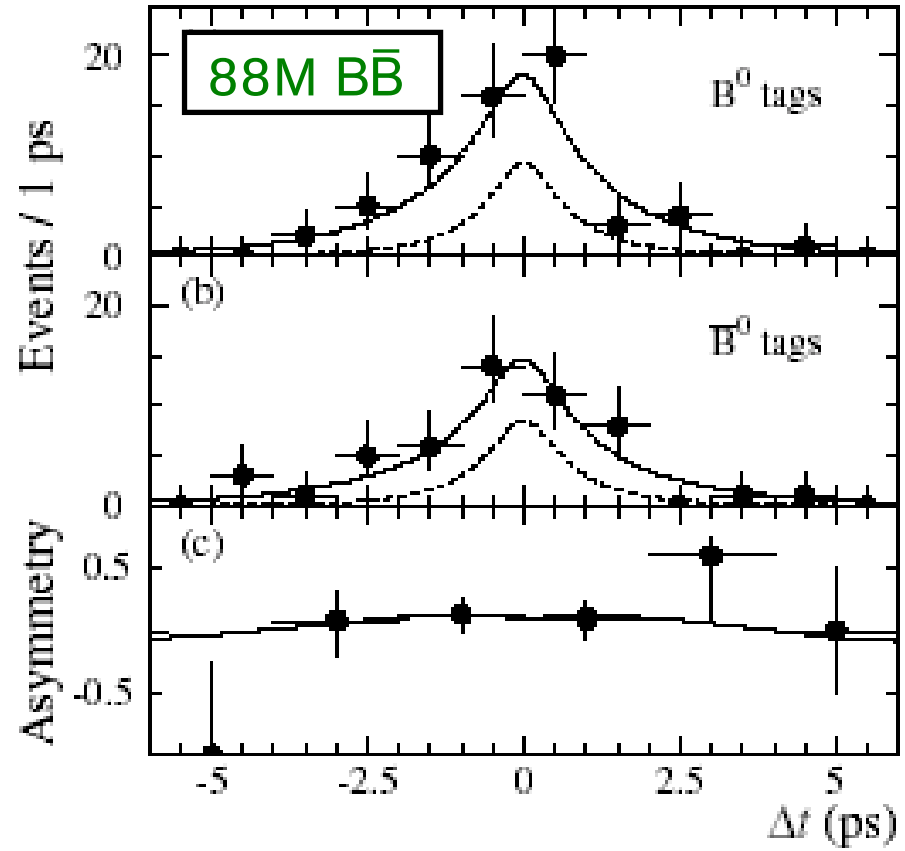
Penguin is color suppressed:
amplitude ratio P / T ~ 0.3

Time evolution q=+1 (B^0 tag), q=-1 ($\bar{B}^0$ tag)

$$\frac{d\Gamma}{d\Delta t} \propto e^{-\frac{|\Delta t|}{\tau}}[1+q(S_{\pi\pi}\sin\Delta m\Delta t - C_{\pi\pi}\cos\Delta m\Delta t]$$

B → $\pi^+\pi^-$ Results





$$S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$$
$$C_{\pi\pi} = -0.77 \pm 0.27 \pm 0.08$$

$$S_{\pi\pi} = +0.02 \pm 0.34 \pm 0.05$$
$$C_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04$$

3.4 σ evidence for CP violation

Consistent with no CP violation

B → ππ: BELLE vs. BABAR

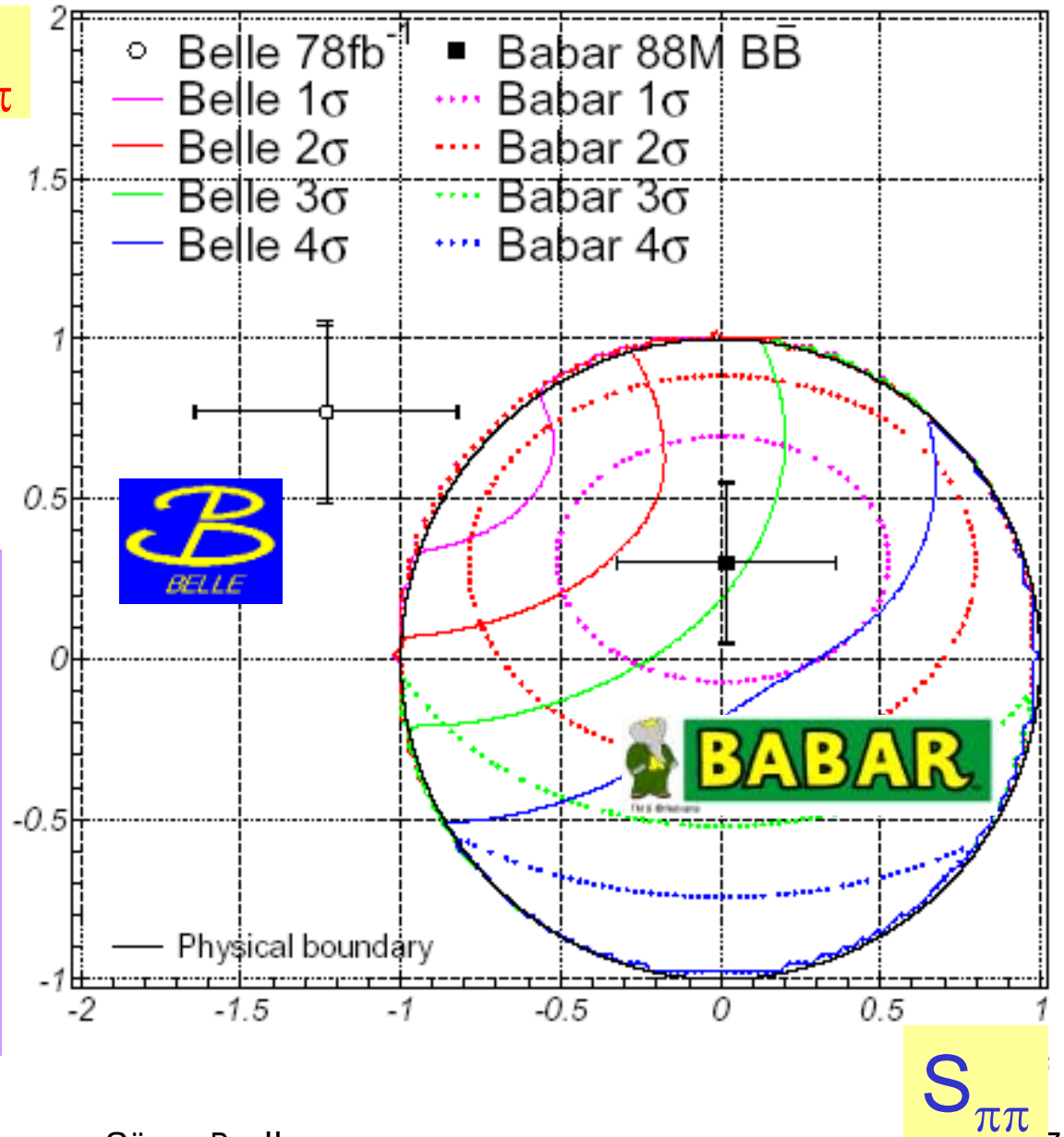
BaBar & Belle averages

$$S_{\pi\pi} = -0.47 \pm 0.26$$

$$C_{\pi\pi} = -0.49 \pm 0.19$$

~ 2.2 σ discrepancy between BaBar and Belle B → $\pi^+\pi^-$ results

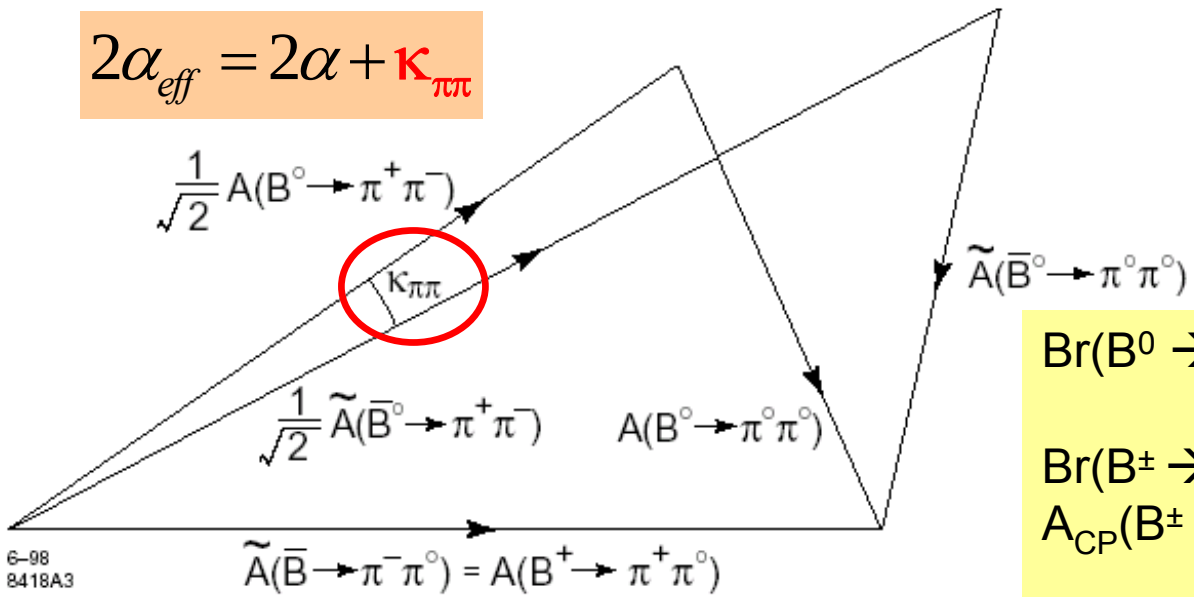
Need to resolve with more data !



How to get α from $B \rightarrow \pi^+\pi^-$?

- α can be determined with isospin analysis
  - Need $Br(B^+ \rightarrow \pi^+\pi^0)$, $Br(B^0 \rightarrow \pi^0\pi^0)$, $Br(\bar{B}^0 \rightarrow \pi^0\pi^0)$

$$2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$$



BaBar, Belle & CLEO

$Br(B^0 \rightarrow \pi^+\pi^-) = (4.8 \pm 0.5) \times 10^{-6}$

$Br(B^\pm \rightarrow \pi^\pm\pi^0) = (5.6 \pm 0.9) \times 10^{-6}$
$A_{CP}(B^\pm \rightarrow \pi^\pm\pi^0) = 0.05 \pm 0.15$

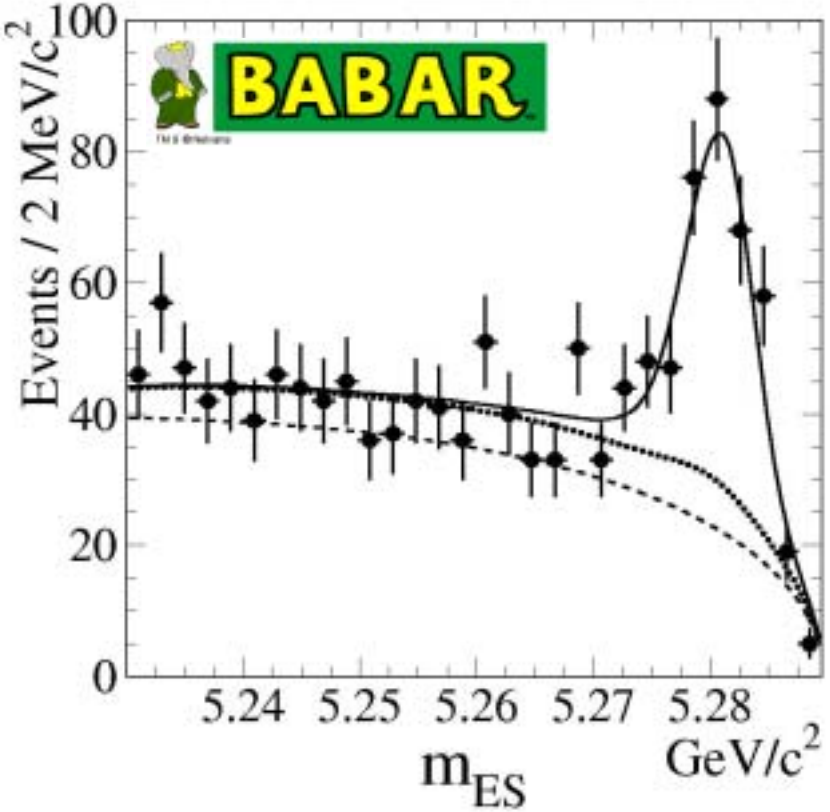
$Br(B^0 \rightarrow \pi^0\pi^0) < 3.6 \times 10^{-6}$ (90%CL)
$[Br(B^0 \rightarrow \pi^0\pi^0) = (2.0 \pm 0.7) \times 10^{-6}]$

$|\alpha_{eff} - \alpha| < 54^o$ (90% CL)

- $B^0/\bar{B}^0 \rightarrow \pi^0\pi^0$ not seen, yet
  - Need ~ 2/ab to resolve large/small $|\kappa_{\pi\pi}|$ solutions (at 95% CL level)
  - limit on α can be obtained with model input (SU(3) symmetry, QCD factorization)

$B \rightarrow \rho^+\pi^-$

- Tree and penguin amplitudes contribute
  - Same Feynman diagrams as in $B^0 \rightarrow \pi^+\pi^-$
- Not a CP eigenstate
  - Separate C and S for $\rho^+\pi^-$ and $\rho^-\pi^+$
  - $\rho^+\pi^-$ and $\rho^-\pi^+$ yield asymmetry **A**



$N(\rho\pi) = 428 \pm 34$ in 81/fb

Time-dependent rate

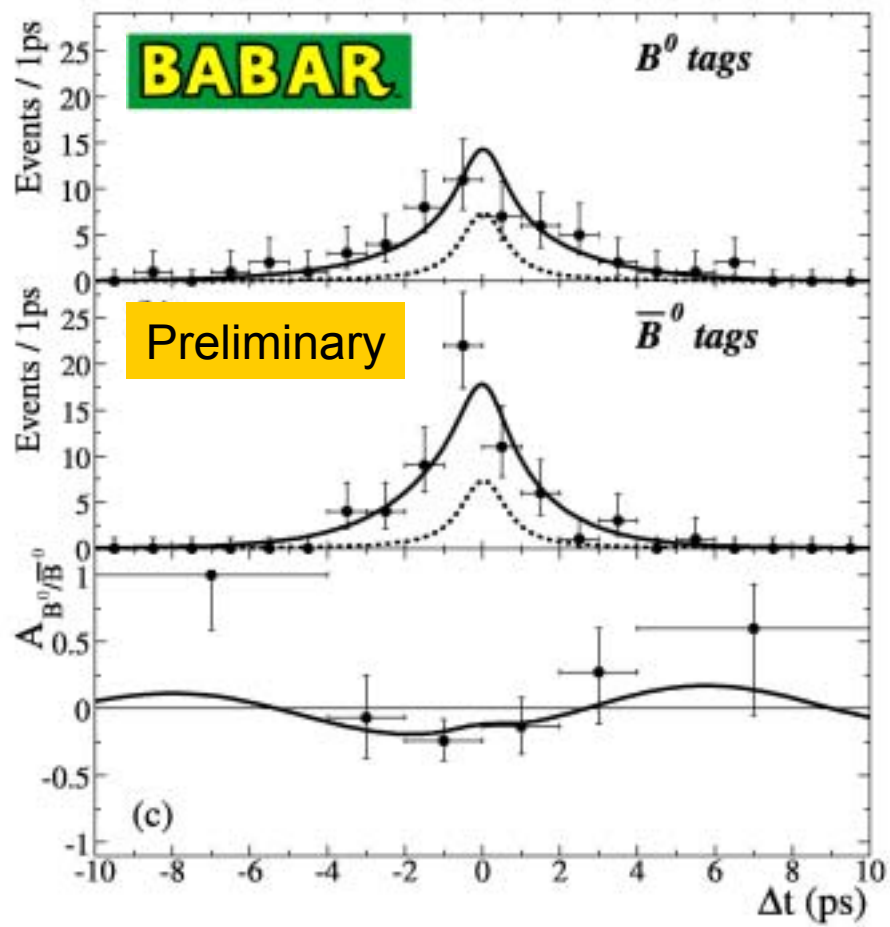
$$f_{\rho^\pm\pi^\mp}(\Delta t) = (1 \pm \mathbf{A})\left[1 + q\left\{(\boldsymbol{S} \pm \Delta S)\sin\Delta m\Delta t - (\boldsymbol{C} \pm \Delta C)\cos\Delta m\Delta t\right\}\right]$$

B → $\rho^+\pi^-$ Results (BaBar 81/fb)

$$A_{\rho\pi} = -0.18 \pm 0.08 \pm 0.03$$

$$S_{\rho\pi} = 0.19 \pm 0.24 \pm 0.03$$
$$\Delta S_{\rho\pi} = 0.15 \pm 0.25 \pm 0.03$$

$$C_{\rho\pi} = 0.36 \pm 0.18 \pm 0.04$$
$$\Delta C_{\rho\pi} = 0.28 \pm 0.18 \pm 0.04$$



The (usual) C's are

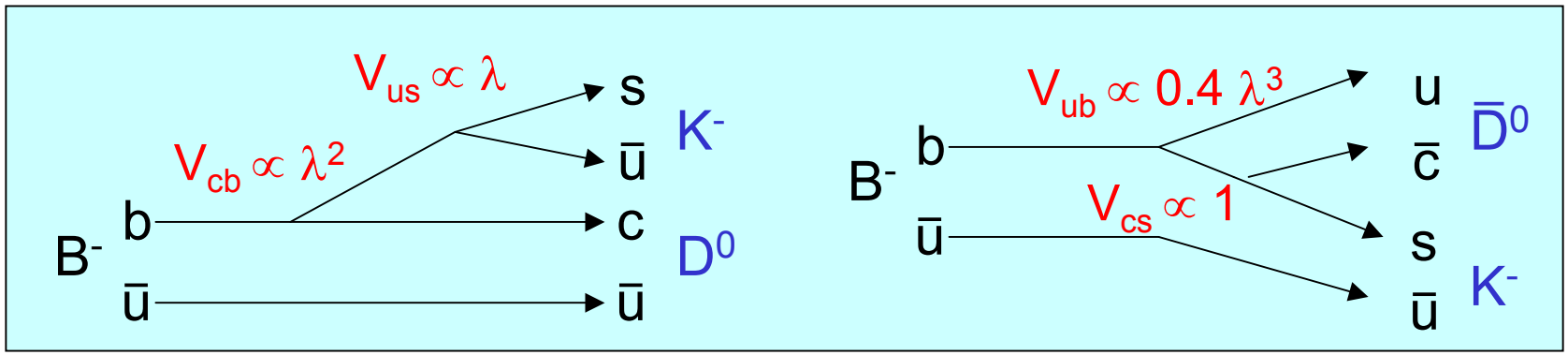
$$C(B^0 \to \rho^+\pi^-) = 0.62 \pm 0.26 \pm 0.06$$
$$C(B^0 \to \rho^-\pi^+) = 0.11 \pm 0.17 \pm 0.04$$

~ 2σ hint of direct CP violation

γ from $B^+ \rightarrow D^0K^+$

Interference of b → c tree and b → u tree

- Single charm quark ensures absence of penguin contribution
- Common final state for D^0 and $\bar{D}^0$ e.g. CP eigenstates
  - D_1 (CP-even): K^+K^-, $\pi^+\pi^-$
  - D_2 (CP-odd): $K_S\pi^0$, $K_S\omega$, $K_S\eta$, $K_S\eta'$



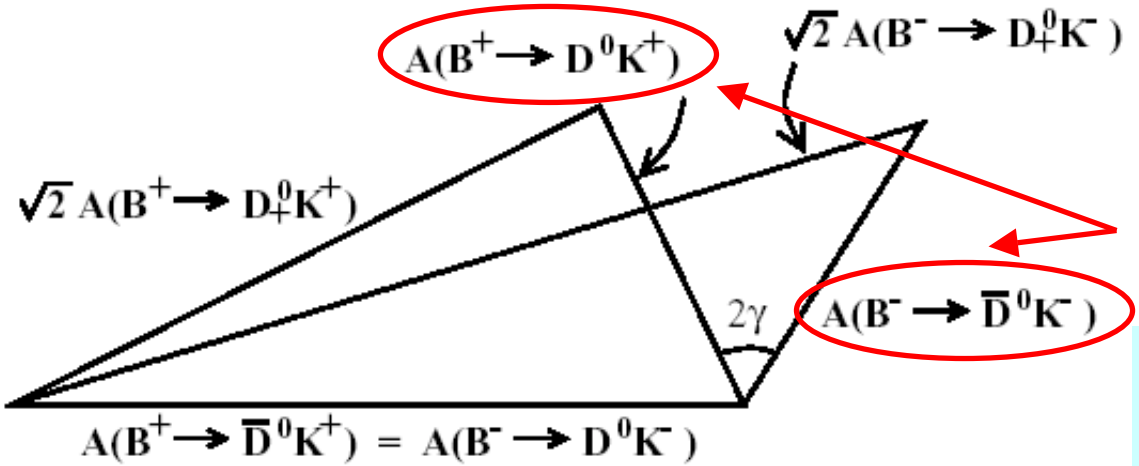
b → u transition is color-suppressed

- Expect up to ~10% CP asymmetry (depending on the relative strong phase)

$$r \equiv \frac{A(B^- \rightarrow \bar{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} = 0.1 - 0.2$$

Extract γ with $B^+ \rightarrow DK^+$

- Reconstruct D^0 in Cabibbo-favored modes and CP-modes (Cabibbo-suppressed)



Can't measure with hadronic D decays !

Rate for $B^+ \rightarrow D^0 K^+ (D^0 \rightarrow K^- pi^+)$ and $B^+ \rightarrow \bar{D}^0 K^+ (\bar{D}^0 \rightarrow K^- pi^+)$ are about the same !

- Experimental difficulties:
  - $D\pi$ final state has higher branching ratio (need good K ID)
  - All hadronic final states are common for D^0 and $\bar{D}^0$!
    - Solution: use at least 2 doubly Cabibbo-suppressed D final states instead of CP eigenstates

$B \rightarrow D_{CP}K$

Measure CP asymmetries and Cabibbo-suppression

$$A_{1,2} = \frac{Br(B^- \rightarrow D_{1,2}K^-) - Br(B^+ \rightarrow D_{1,2}K^-)}{Br(B^- \rightarrow D_{1,2}K^-) + Br(B^+ \rightarrow D_{1,2}K^-)} = \frac{\pm 2r \sin\delta \sin\gamma}{1 + r^2 \pm 2r\cos\delta\cos\gamma}$$

$$R_{1,2} = \frac{Br(D_{1,2}K^-)/Br(D_{1,2}\pi^-)}{Br(D^0K^-)/Br(D^0\pi^-)} = 1 + r^2 \pm 2r\cos\delta\cos\gamma$$

Error $O(r^2)$ for hadronic D decays (DCSD).

r can't be determined cleanly from $A_{1,2}$ and $R_{1,2}$, but

$$\frac{R_1 - R_2}{2} = 2r\cos\delta\cos\gamma$$

$$\frac{A_1 - A_2}{2} \sim 2r\sin\delta\sin\gamma \qquad O(r^2)$$

$B \rightarrow D_{CP}K$ Results

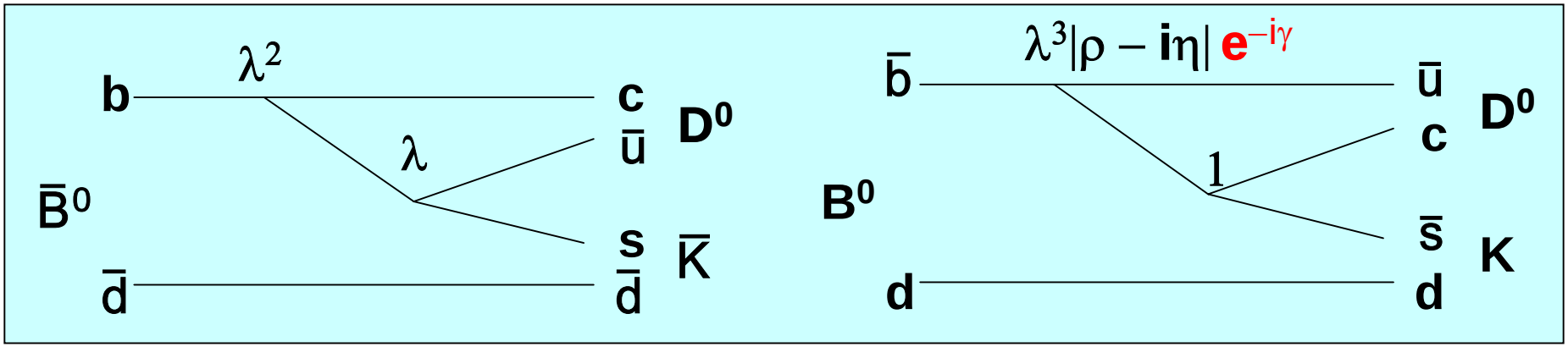
Preliminary	CP even	CP odd
BaBar (DK)	$A_1 = 0.17 \pm 0.23 \pm 0.08$ $R_1 = 1.06 \pm 0.26 \pm 0.17$	
Belle (DK)	$A_1 = 0.06 \pm 0.19 \pm 0.04$ $R_1 = 1.21 \pm 0.25 \pm 0.14$	$A_2 = -0.19 \pm 0.17 \pm 0.05$ $R_2 = 1.41 \pm 0.27 \pm 0.15$
Belle (DK*)	$A_1 = -0.02 \pm 0.33 \pm 0.07$	$A_2 = 0.19 \pm 0.50 \pm 0.04$

From DK results,

$$2r \sin\delta \sin\gamma \sim \frac{A_1 - A_2}{2} = 0.15 \pm 0.12 \qquad \left[O(r^2)\right]$$

$$2r \cos\delta \cos\gamma = \frac{R_1 - R_2}{2} = -0.14 \pm 0.19$$

γ from $B^0 \rightarrow D^{(*)0}K^{(*)0}$



- K_S modes: $D^{(*)0}K_S$
  - Time-dependent CP asymmetry sensitive to $\sin(2\beta+\gamma \pm\delta)$
  - Both amplitudes are about $O(\sim\lambda^3)$
- Self-tagging modes with K^{*0} ($\rightarrow K^+\pi^-$)
  - Ratio $r = Br(B^0 \rightarrow D^{(*)0}\bar{K}^*)/Br(B^0 \rightarrow D^{(*)0}K^*)$ sensitive to relative contribution of V_{ub} and V_{cb} diagrams
  - Expect $r \sim 0.2$

$B^0 \rightarrow D^{(*)0}K^{(*)}$ Results (Belle 78/fb)

Observe b→c transition, but not b→u transition transition, yet

$$BR(B^0 \rightarrow \overline{D}^0 K^{*0}) = (4.8 \pm 1.1 \pm 0.5) \times 10^{-5}$$ **V_{cb}**

$$BR(B^0 \rightarrow D^0 K^{*0}) < 1.8 \times 10^{-5}$$ **V_{ub}**

V_{cb} / V_{ub} (interference)

$$BR(B^0 \rightarrow (D/\overline{D}^0)K^0) = (5.0 \pm 1.3 \pm 0.6) \times 10^{-5}$$

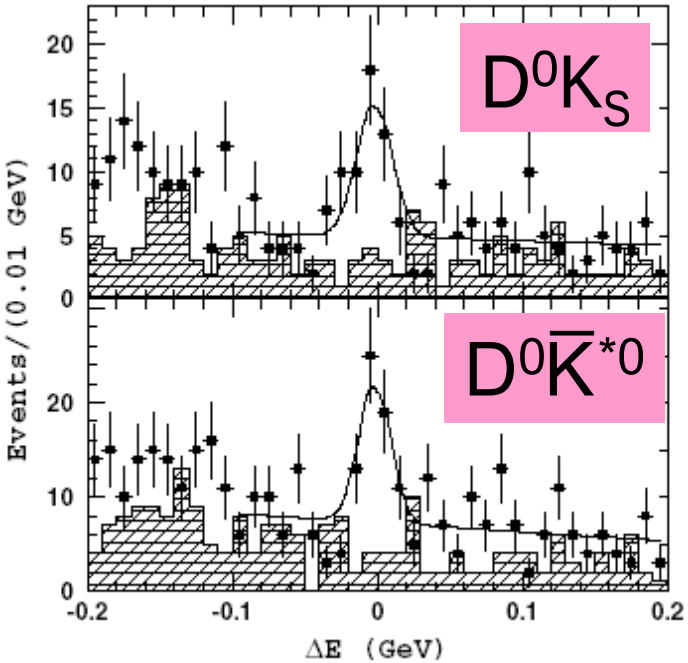
Modes with D^{*0} not observed, yet

$$BR(B^0 \rightarrow \overline{D}^{*0} K^0) < 6.6 \times 10^{-5}$$

$$BR(B^0 \rightarrow \overline{D}^{*0} K^{*0}) < 6.9 \times 10^{-5}$$ **V_{cb}**

$$BR(B^0 \rightarrow D^{*0} K^{*0}) < 4.0 \times 10^{-5}$$ **V_{ub}**

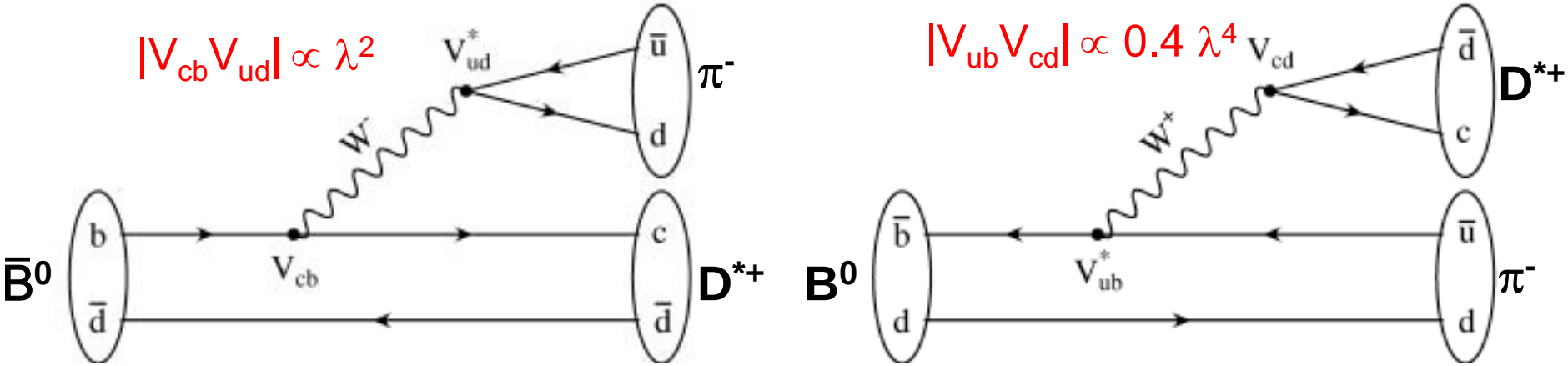
27.0 ± 7.3 'CP' events



41.0 ± 8.4 'self-tag' events

More events needed for γ measurement !

γ from $B^0 \rightarrow D^{(*)+}\pi^-$



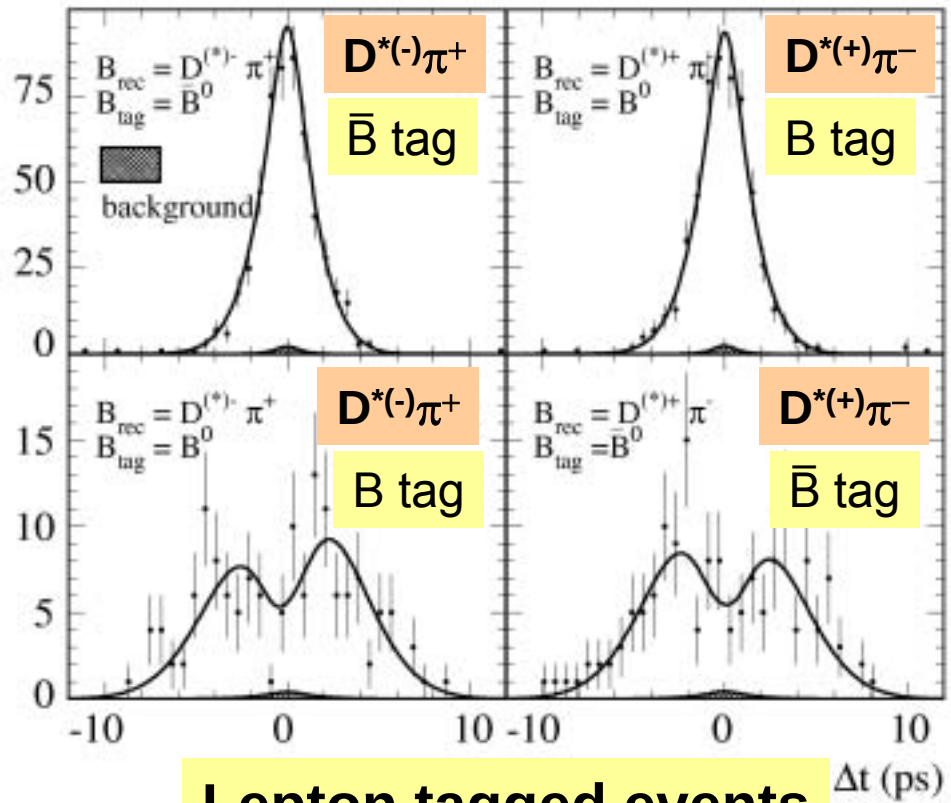
- Large branching fractions, but b → u diagram strongly suppressed
- Expect time-dependent CP asymmetry amplitude to be small ($S^{\pm} = 2r \sin(2\beta+\gamma\pm\delta)$, $|S^{\pm}| \sim 0.04$)
  - Cannot fit for $|r^{(*)}|^2 = Br(B^0 \rightarrow D^{(*)+}\pi^-)/Br(B^0 \rightarrow D^{(*)-}\pi^+)$, use BaBar measurements of $Br(\bar{B}^0 \rightarrow D_s^{(*)+}\pi^-)$ and SU(3)
    - $|r| = 0.021\ ^{+0.004}_{-0.005}$, $|r^*| = 0.017\ ^{+0.005}_{-0.007}$ [±30% error from SU(3)]
  - Tag-side b → c,u interference for non-lepton tags is same order as CP amplitude under study

γ from $B^0 \rightarrow D^{(*)+}\pi^-$ (BaBar 81/fb)

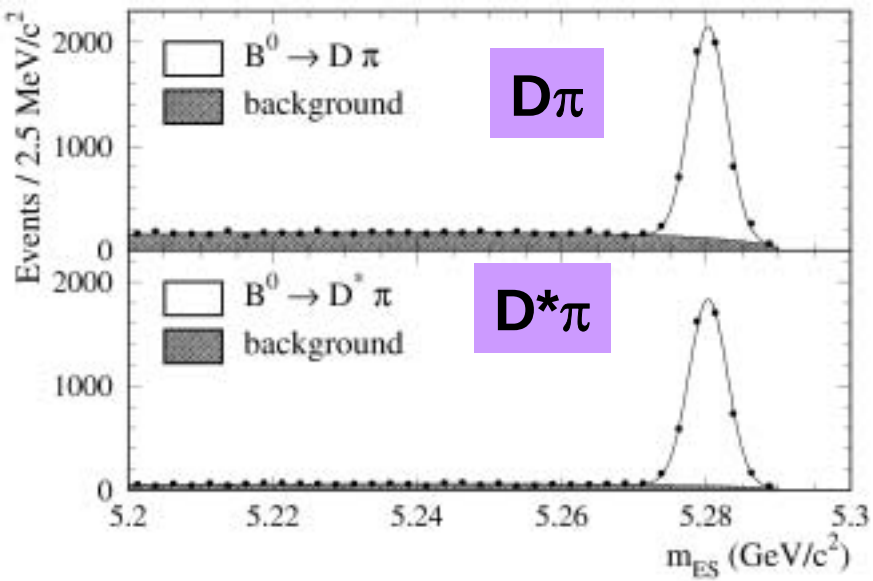
Fully reco'ed B's: **Preliminary**

5200 $D^+\pi^-$ (purity 85%)

4750 $D^{*+}\pi^-$ (purity 94%)



Lepton tagged events

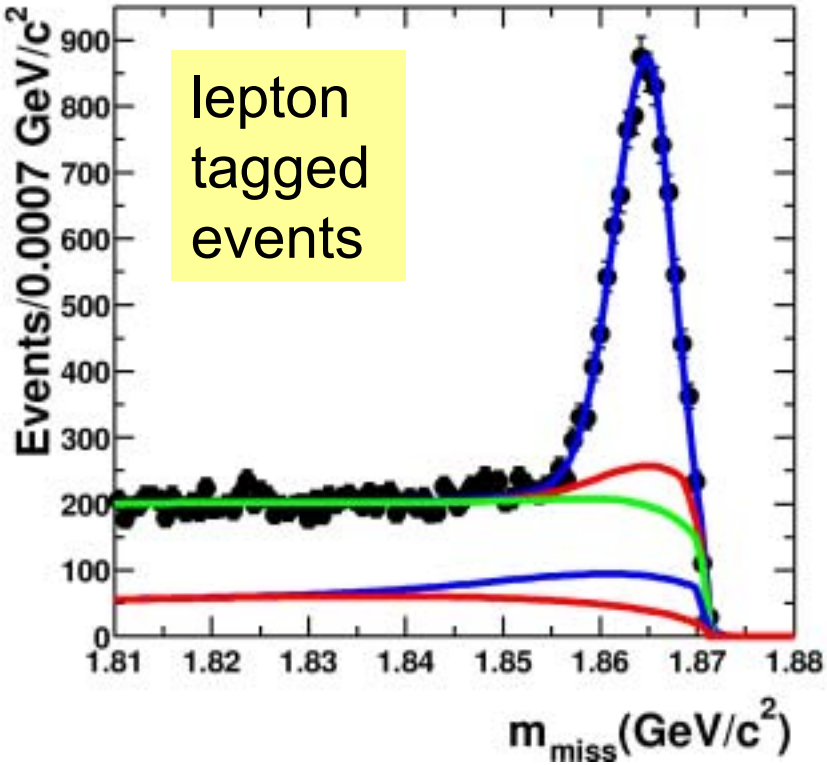


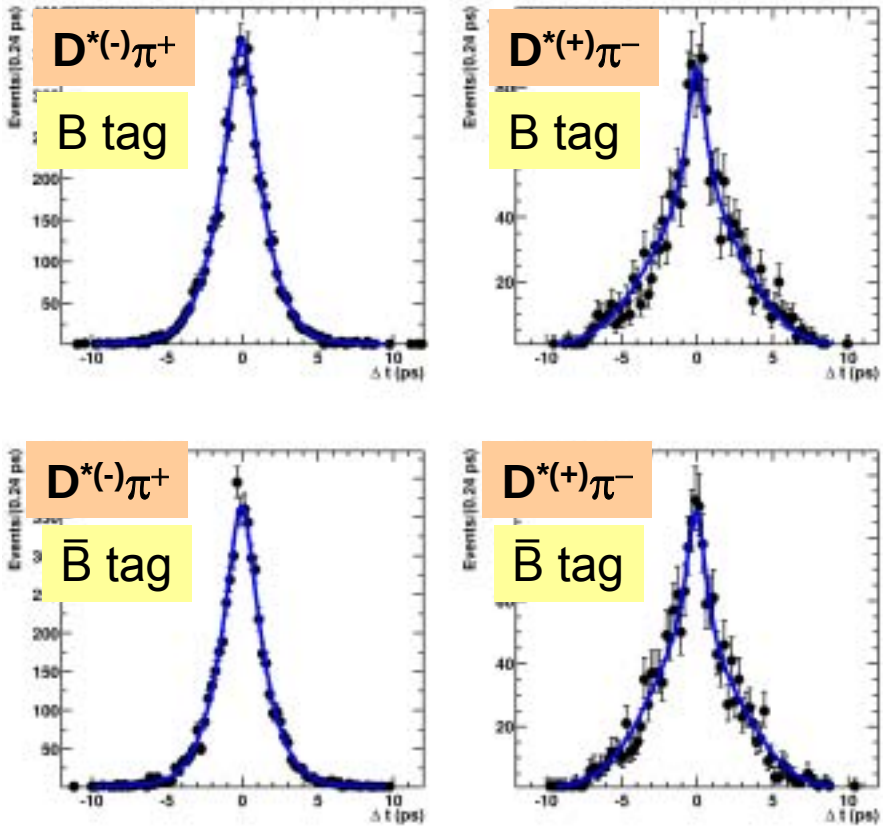
$\delta(*)$ is strong phase difference between two amplitudes for $D^{(*)+}\pi^-$

$$2|r|\ \sin(2\beta+\gamma)\cos\delta = -0.02 \pm 0.04 \pm 0.02$$
$$2|r*|\sin(2\beta+\gamma)\cos\delta* = -0.07 \pm 0.04 \pm 0.02$$
$$2|r|\ \cos(2\beta+\gamma)\sin\delta = 0.03 \pm 0.07 \pm 0.04$$
$$2|r^*|\cos(2\beta+\gamma)\sin\delta* = 0.03 \pm 0.07 \pm 0.04$$

Fit $|\sin(2\beta+\gamma)|$,$|\cos\delta(*)|$:
$|\sin(2\beta+\gamma)| > 0.69$ (68% CL)

γ from $B^0 \rightarrow D^{*+}\pi^-$ (BaBar 81/fb)





Partially reco'ed $D^{*+}\pi^-$:
$D^{*+} \rightarrow (D^0)\ \pi^+$
use lepton and kaon tags

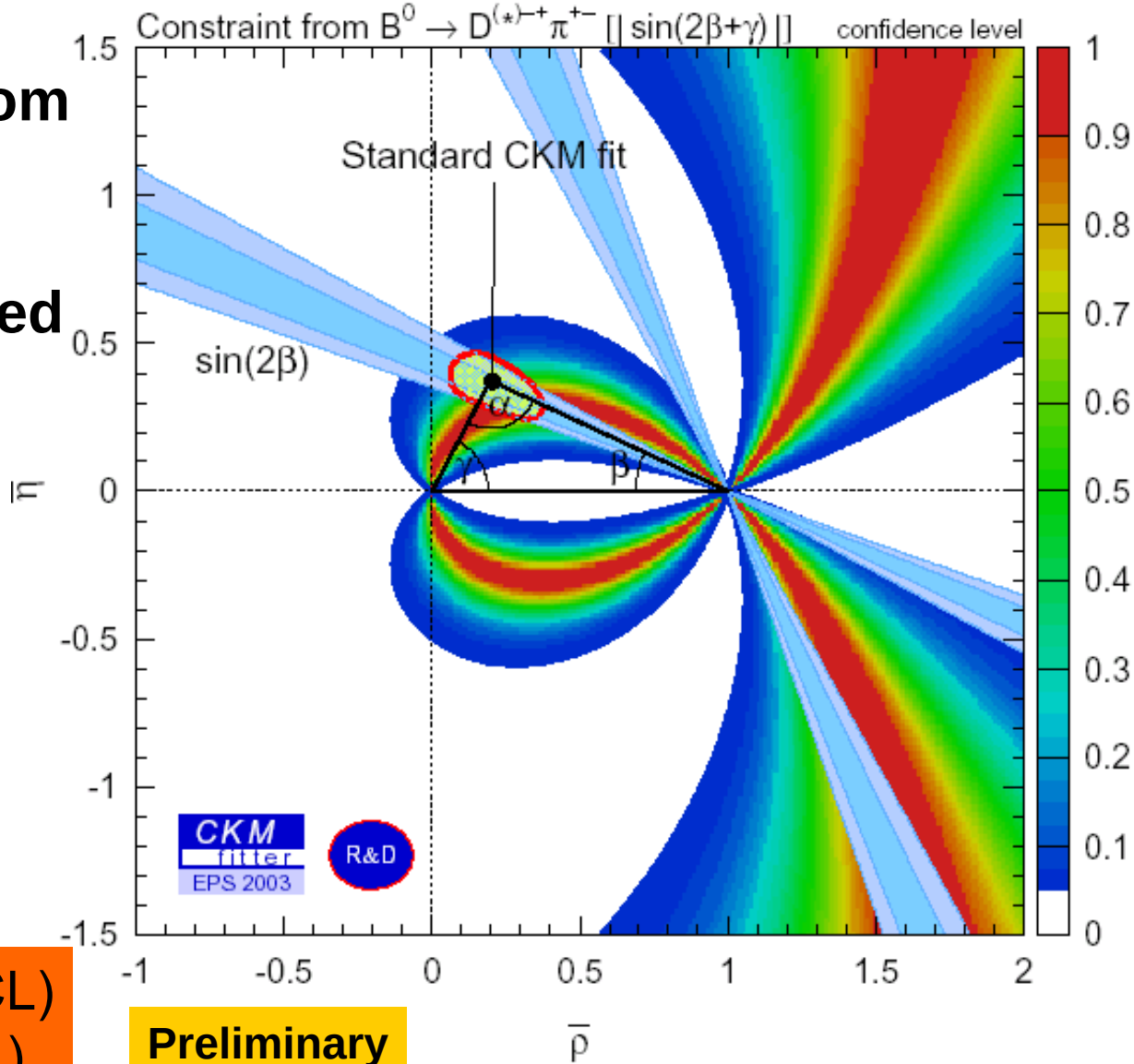
$2\,|r*|\sin(2\beta+\gamma)\cos\delta* = -0.063 \pm 0.024 \pm 0.017$
$2\,|r*|\cos(2\beta+\gamma)\sin\delta* = -0.004 \pm 0.037 \pm 0.020$

Preliminary

Fit $|\sin(2\beta+\gamma)|$, $|\cos\delta(*)|$: $|\sin(2\beta+\gamma)| > 0.75$ (90% CL)

γ from $B^0 \rightarrow D^{(*)+}\pi^-$ (BaBar 81/fb)

Combined results from fully-reconstructed $D^{(*)+}\pi^-$ samples and partially-reconstructed $D^{*+}\pi^-$ sample:



Preference for 'small β' solution in $\bar{\eta} > 0$ half-plane

$\sin(2\beta+\gamma) > 0.76$ (90% CL)
$\sin(2\beta+\gamma) > 0$ (99.5% CL)

Preliminary

Summary

- CP violation in the B system is established
  - Sin2β is > 13 σ away from zero
  - Most precise constraint on apex of Unitarity Triangle
- Consistency: tree vs. penguin for sin2β
  - 2.6 σ discrepancy; more data needed
- Measurements of α and γ have larger uncertainties (theoretical and/or experimental)
  - α / ϕ_2
    - Need to control penguins in $\pi\pi$, $\rho\pi$, etc. (need $B^0 \rightarrow \pi^0\pi^0$)
  - γ / ϕ_3
    - DK modes are theoretically clean, but need much more data
    - Dπ becomes interesting, will be limited by (theoretical) error on $|\lambda(*)|$
- Need better precision on α and γ to constrain Unitarity Triangle

Conclusions

- Standard Model CKM prediction of only one complex phase as single source of *CP* violation has not been disproved, yet

- Current experimental measurements of *CP* violation in weak interactions of quarks are unlikely to explain the *CP* asymmetry observed in the universe.

- New physics and its contribution to *CP* violation in B decays are still possible, but remain to be discovered…