Measurement of the CKM angle β at BaBar

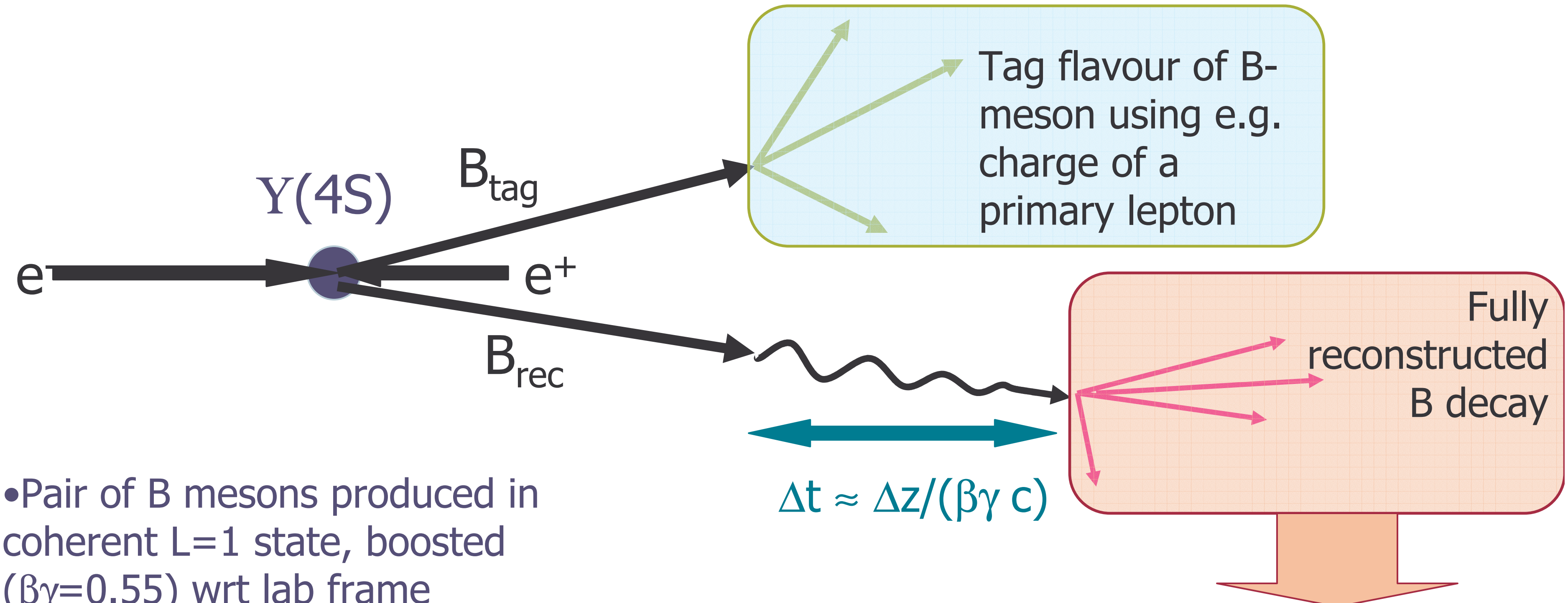
Nick Barlow
(University of Manchester)

5th Rencontres du Vietnam
August 2004

Contents

- Measuring time-dependent CP asymmetries
- Measurement of sin2β in $b \to c\bar{c}s$ transitions
  - $B \to$ charmonium K_S, $B \to$ charmonium K_L
- Determination of the sign of cos2β
  - $B \to J/\psi K^*$
- Measurement of sin2β in penguin dominated decays
  - $B \to \phi K_S$, $B \to f_0(980) K_S$, $B \to K^+ K^- K_S$, $B \to K_S \pi^0$
- Summary and conclusions

Measuring time-dependent asymmetry



- Pair of B mesons produced in coherent L=1 state, boosted ($\beta\gamma$=0.55) wrt lab frame
- At exact time that B_{tag} decays, B_{rec} is known to have opposite flavour
- B_{rec} may mix during the time Δt between the two B decays

Use 2 nearly uncorrelated variables to help distinguish signal from background:

$$m_{ES} = [(s/2 + \mathbf{p}_i.\mathbf{p}_B)^2/E_i - \mathbf{p}_B{}^2]^{1/2}$$
$$\Delta E = (E_iE_B - \mathbf{p}_i.\mathbf{p}_B - s/2)/\sqrt{s}$$

Measuring time-dependent asymmetry

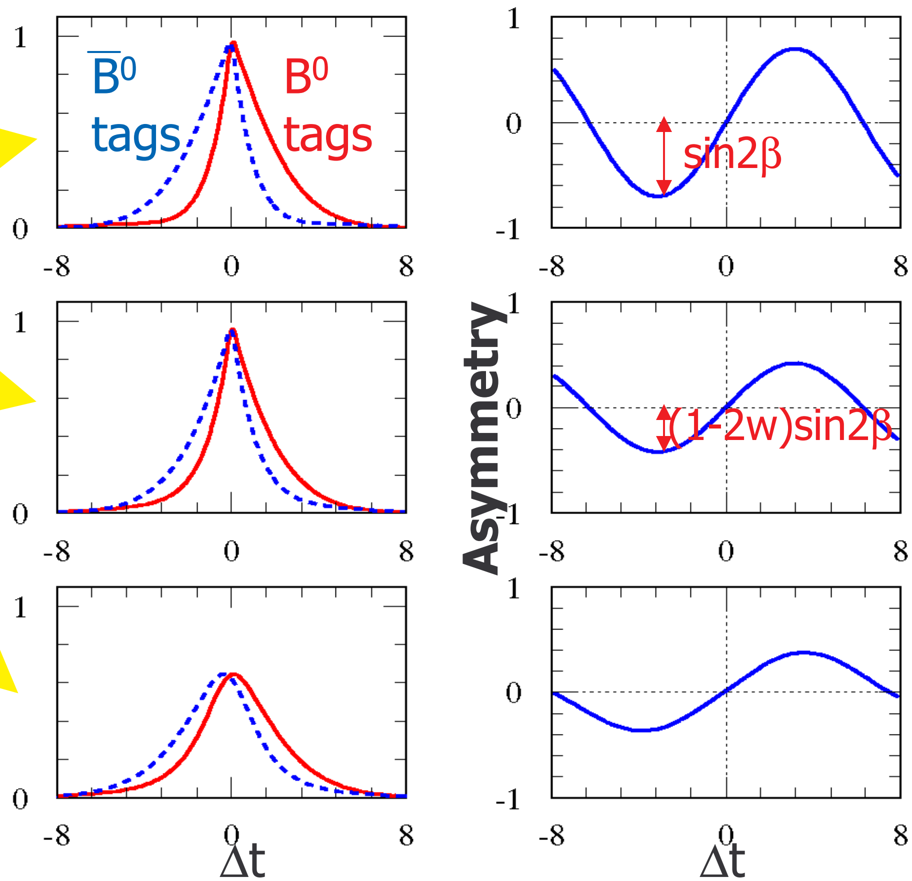
$$a_{f_{CP}}(t) = \frac{\Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right) - \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right) + \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)} = -C_{f_{CP}} \cos(\Delta m\, t) + S_{f_{CP}} \sin(\Delta m\, t)$$

e.g. For $B \to J/\psi K_S$ $C=0$, $S=\sin 2\beta$

Perfect Δt resolution, perfect tagging

Perfect Δt resolution, wrong tag fraction w

Realistic Δt resolution, wrong tag fraction w



- Measure mistag fraction and Δt resolution function by fitting large sample of reconstructed B mesons of known flavour.

sin2β in b→cc̄s modes

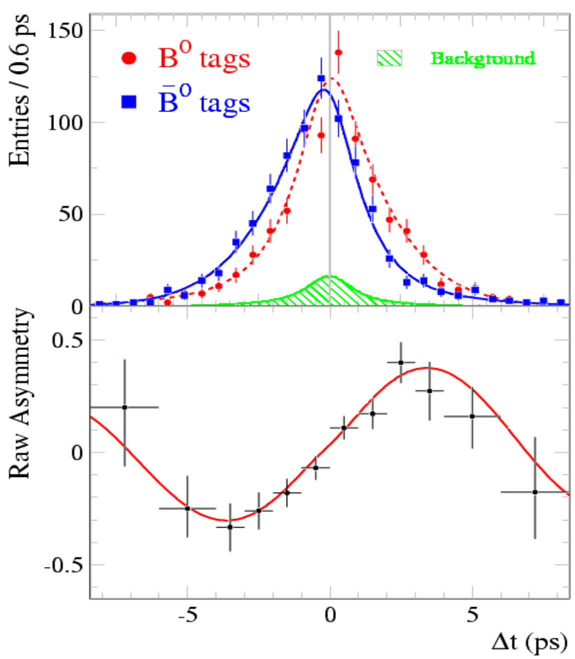
- sin2β already well measured in b→cc̄s channels by BaBar and Belle
- Small theoretical uncertainty – tree and first order penguin contributions have same phase

BaBar: 80.8 fb^{-1}:

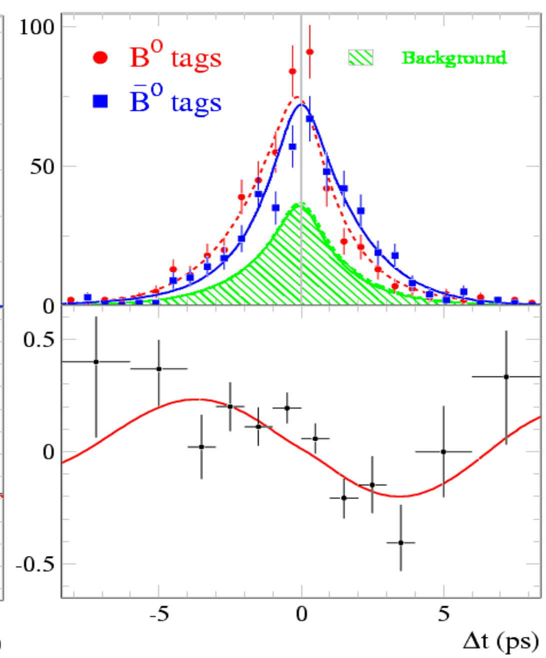
$\sin 2\beta = 0.741 \pm 0.067 \pm 0.033$

PRL 89, 201802 (2002)

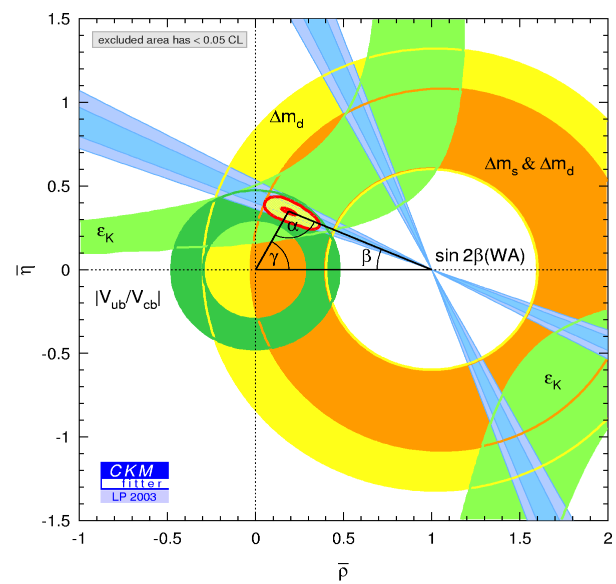
K_S modes: η_{CP}=-1



K_L modes: η_{CP}=+1



WA: sin2β=0.736±0.049



Still 4-fold ambiguity in value of β

$\cos 2\beta$ with $B \rightarrow J/\psi K^*$

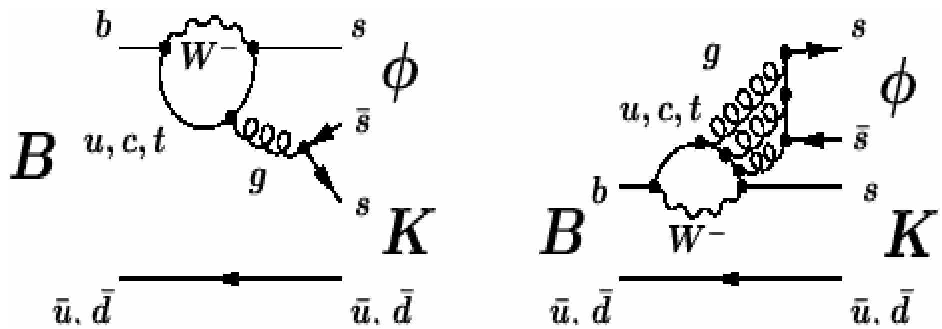
- pseudoscalar→vector vector decay – contains both CP-odd and CP-even components
- Interference between CP-odd and CP-even components gives rise to $\cos 2\beta$ term in time-dependent angular distributions

$$a(t) = P\cos\Delta mt + \sin\Delta mt\left(S\sin 2\beta + C\cos 2\beta\right)$$

- Can measure angular amplitudes to $\cos 2\beta$ up to a twofold ambiguity
- Use $K\pi$ S-wave state in $K^*(892)$ region to resolve this ambiguity by fitting for relative strong phase in bins of $m(K\pi)$
- If $\sin 2\beta = 0.736$, expect $\cos 2\beta = \pm 0.68$
- Using "toy MC" technique, find the positive solution is more probable ⇒ rule out $\cos 2\beta < 0$ at 89% CL

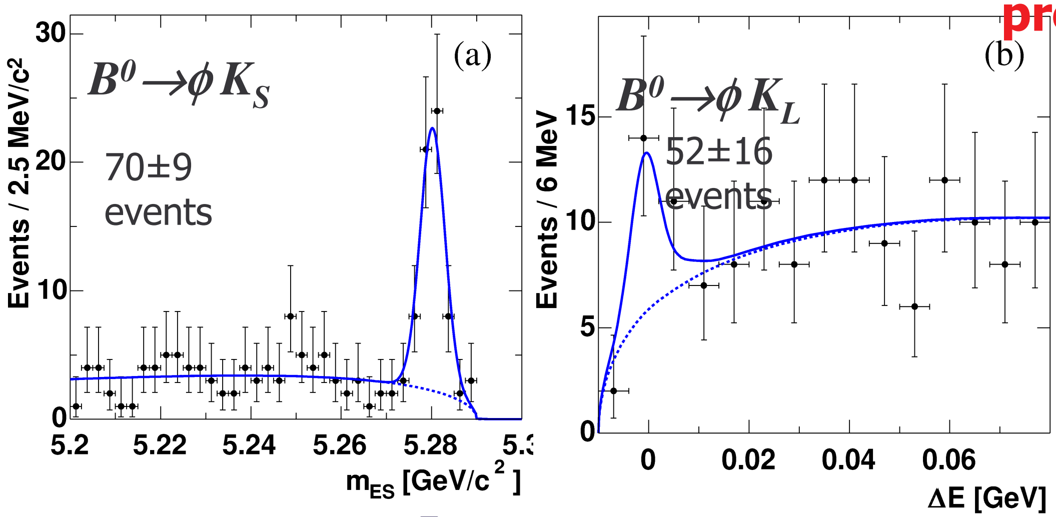
sin2β from penguin-dominated modes

- In pure b→s penguins (e.g. B→ϕK⁰), measured value of sin2β should be the same as for b→cc̄s

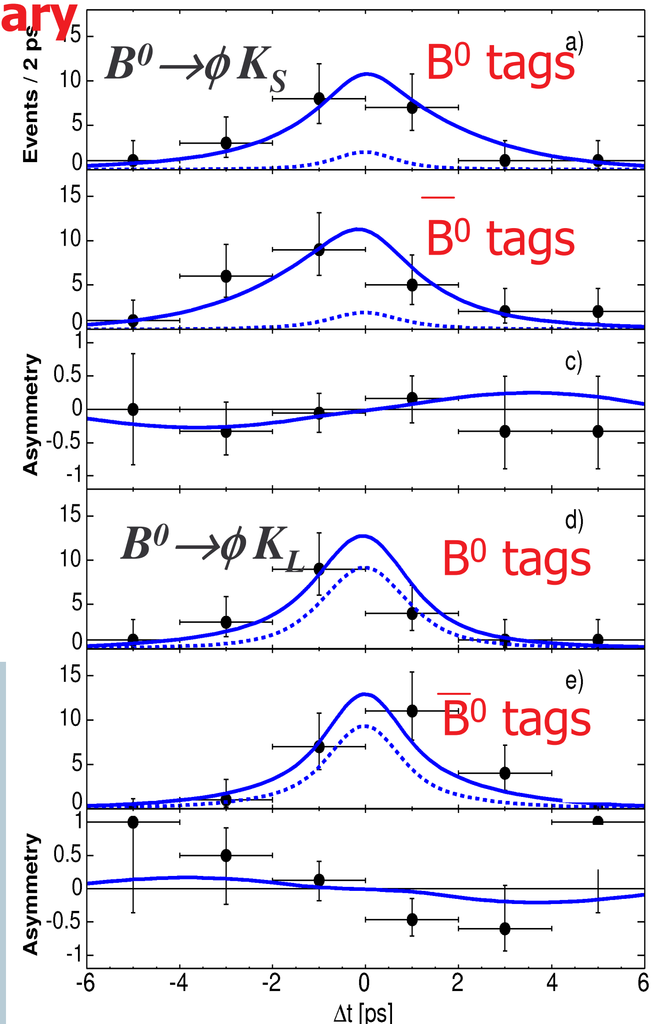


- Sensitive probe for New Physics: additional loop diagrams can contain heavy non-SM particles and new CP violating phases

B→ϕK_S and B→ϕK_L



preliminary



- In SM, pure b→ s$\bar{s}$s penguin, expect
- $S_{\phi Ks}$ = +sin2β, $S_{\phi KL}$ = -sin2β

BaBar: 113fb^{-1}

$S_{\phi K0}$ = 0.47±0.34 $^{+0.08}_{-0.06}$

$C_{\phi K0}$ = 0.10±0.33±0.10

hep-ex/0403026

Using 140fb^{-1}, Belle measure

$S_{\phi Ks}$ = -0.96±0.50±0.10

$C_{\phi Ks}$ = 0.15±0.29±0.07

⇒2.3σ disagreement!

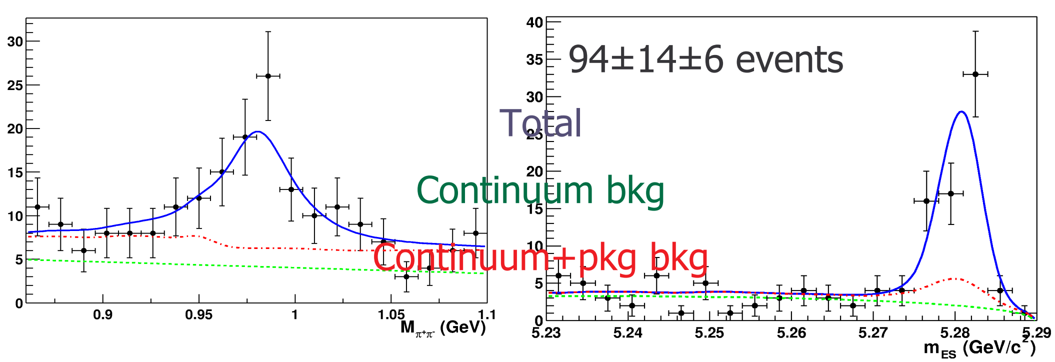
$B \to f_0(980) K_S$

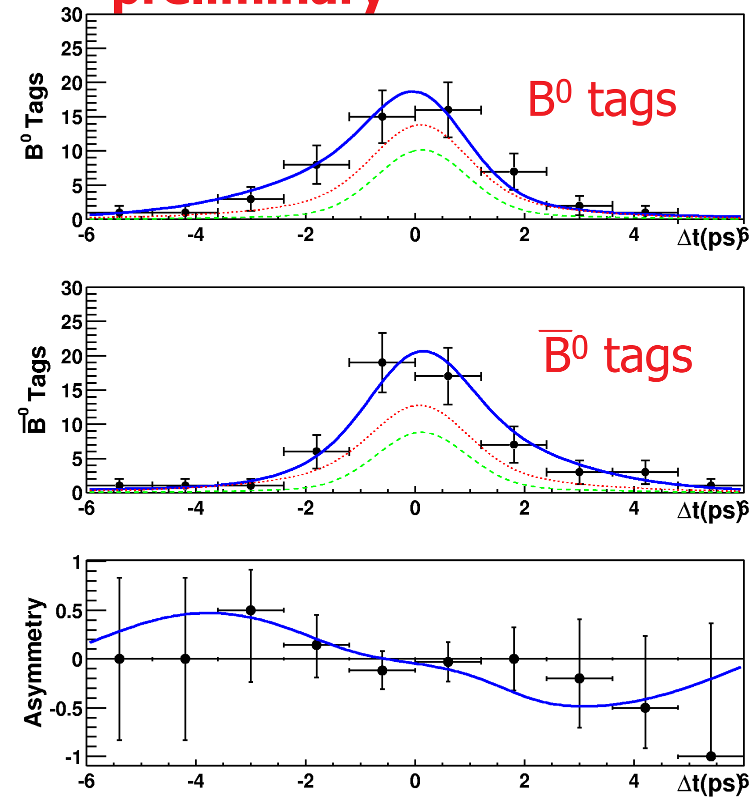
$B^0 \to f_0(980)\, K_S$

$f_0(980) \to \pi^+\pi^-$; $K_S \to \pi^+\pi^-$

- Dominated by $b \to s\bar{s}s$ penguin
- Decay to $\pi\pi$ preferred due to phase space
- "Quasi-two-body" approach – cut on Dalitz plot to reduce contamination from ρ and $f_0(1370)$
- Expect $S_{f0Ks} \approx -\sin 2\beta$

BaBar: 113fb^{-1}





$S_{f0Ks} = -1.62\ ^{+0.56}_{-0.51} \pm 0.10$

$C_{f0Ks} = 0.27 \pm 0.36 \pm 0.12$

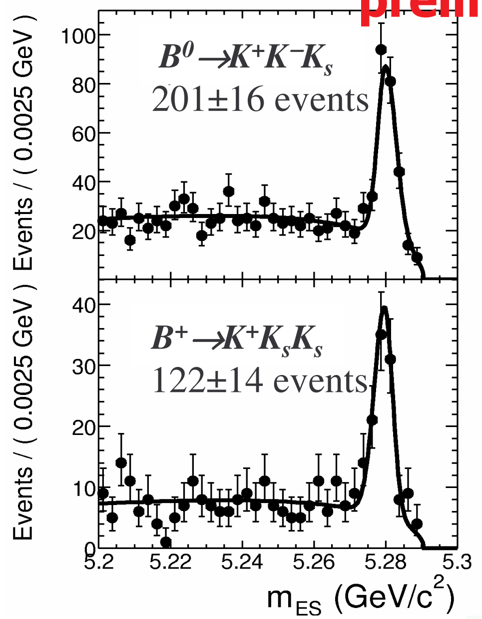
$B \rightarrow K^+K^-K_S$ (excluding ϕK_S)

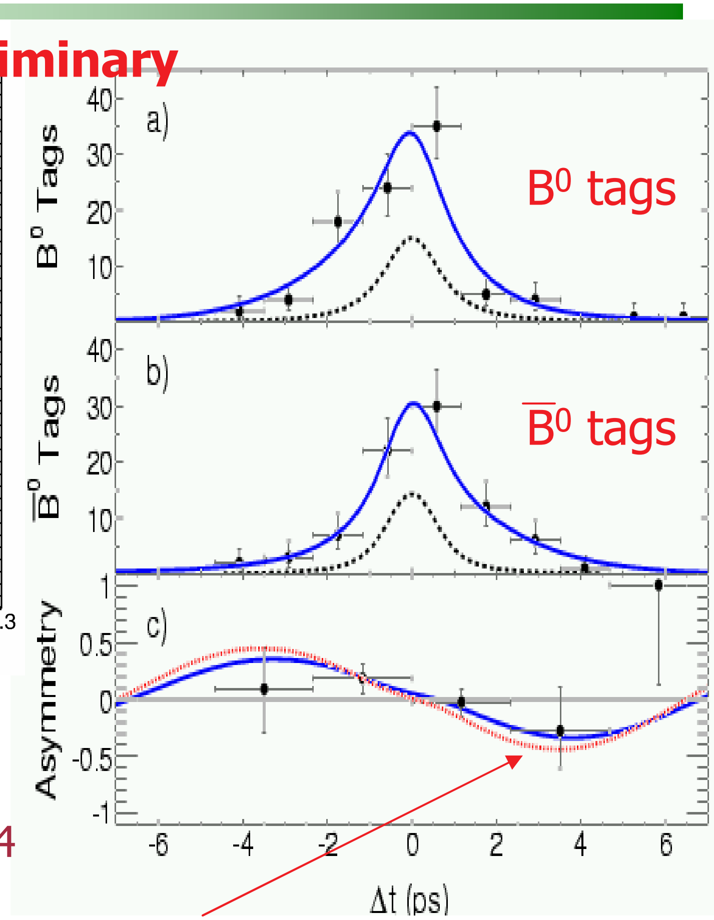
- Use charged and neutral B decays to determine CP-even fraction using isospin symmetry

$$f_{even} = \frac{2\Gamma(B^+ \rightarrow K^+K_S^0K_S^0)}{\Gamma(B^0 \rightarrow K^+K^-K^0)}$$

$=0.98\pm0.15\pm0.04$

- Expect $S \approx -\sin 2\beta$





BaBar: 113fb^{-1}

SM, $f_{even} = 1.0$

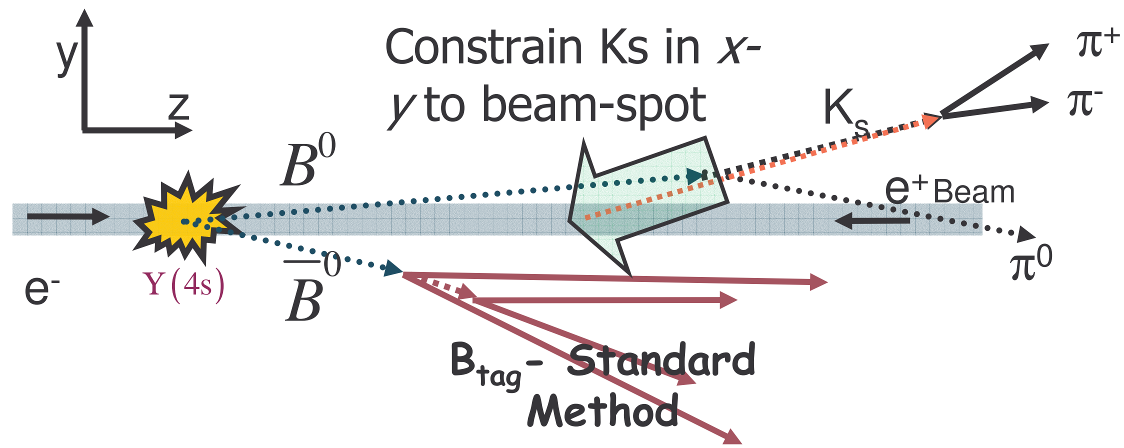
$S_{K+K-Ks} = -0.56\pm0.25\,^{+0.04}_{-0.17}$

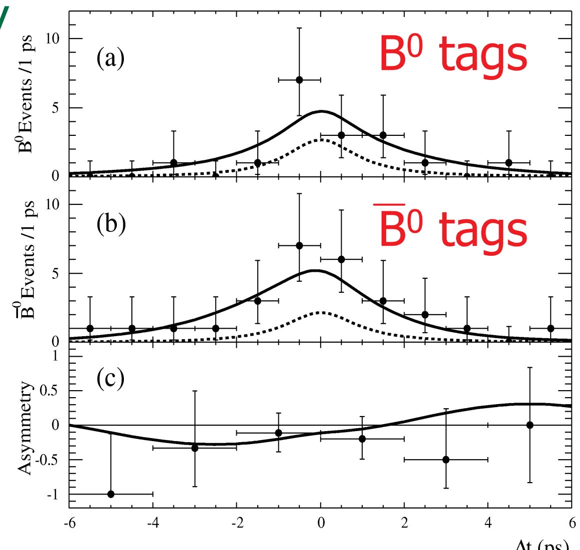
$C_{K+K-Ks} = -0.10\pm0.19\pm0.09$

hep-ex/0406005

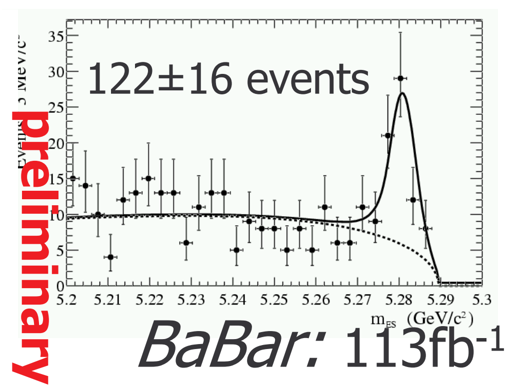
$B^0 \rightarrow K_S \pi^0$

- Experimentally challenging – no charged decay products originating from B decay point
- Use fact that transverse motion of B is small compared to motion in z-direction
- Use intersection of Ks trajectory and beamspot in x-y plane
- Non-zero tree contribution could lead to O(0.1) deviation in measured sin2β value
- Expect $S \approx +\sin 2\beta$





hep-ex/0403001

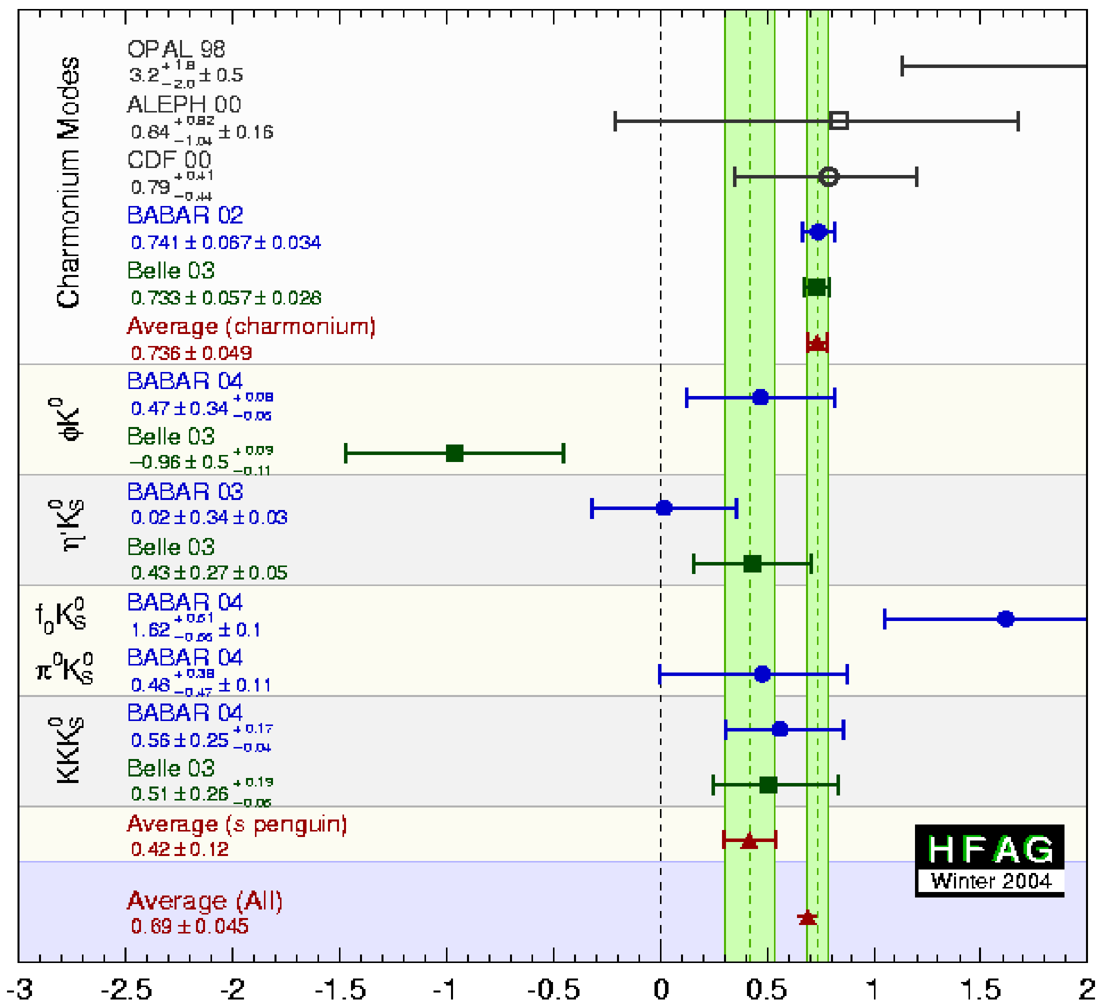


BaBar: 113fb^{-1}

$S_{K_S\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.11$

$C_{K_S\pi^0} = 0.40 \pm 0.28 \pm 0.10$

Summary of sin2β values



- Most results are reasonably consistent with SM, with the exception of Belle ϕK_S
- BaBar-only average for $b \to s$ penguins is 0.63±0.18

Conclusions

- $\sin 2\beta$ in $b \to c\bar{c}s$ decays already a precision measurement
- Statistics are now large enough that penguin dominated modes are starting to give interesting results
  - 2.3σ discrepancy between BaBar and Belle in $B \to \phi K^0$
  - Situation will be clarified with more data
- First ambiguity-free measurement of sign of $\cos 2\beta$
- The Standard Model can accommodate all *BaBar* results so far on the angle β
- Further updates on several channels with $205 fb^{-1}$ data coming this summer!

Backup slides

CP violation in the Standard Model

Quark mixing is described by the CKM matrix

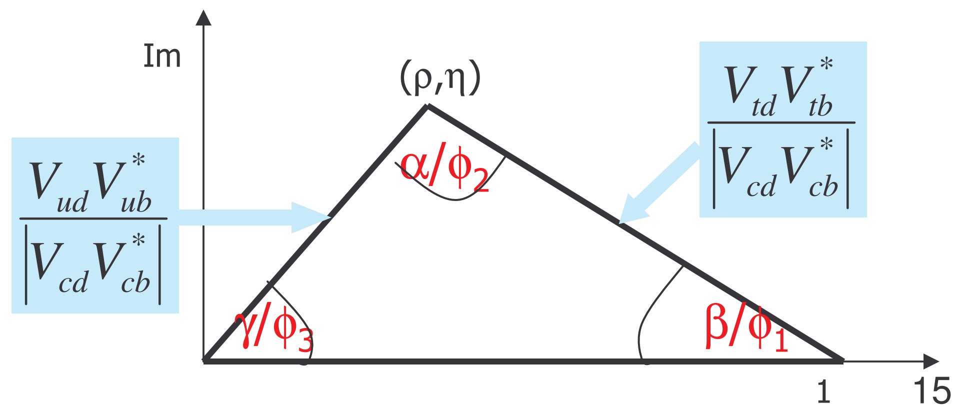
Wolfenstein parametrization

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Complex phase → CP violation

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

Matrix is unitary – can be represented by triangle on complex plane

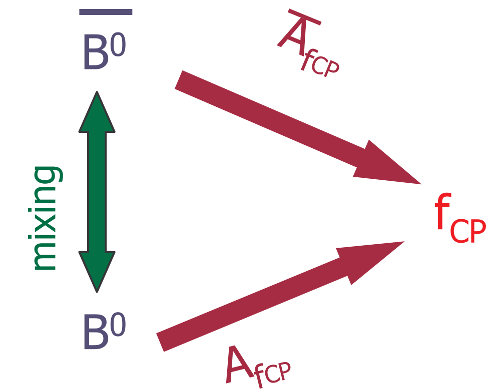


CP violation in the neutral B system

Mass eigenstates:

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

Flavour eigenstates



- Consider time-dependent asymmetry in decays to a final CP eigenstate f_{Cp}:

$$a_{f_{CP}}(t) = \frac{\Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right) - \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right) + \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)} = -C_{f_{CP}} \cos(\Delta m t) + S_{f_{CP}} \sin(\Delta m t)$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}, \quad S_{f_{CP}} = \frac{2 \mathrm{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}, \quad \lambda_{f_{CP}} = \frac{q}{p} \frac{\overline{A}}{A}$$

Im(λ)≠0→CPV in interference between mixing and decay

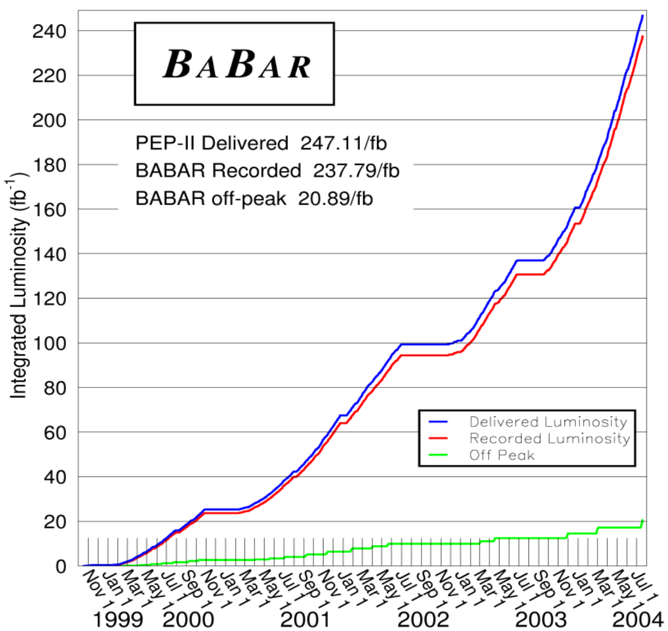
|q/p|≠1→CPV in mixing

|Ā/A|≠1→CPV in decay

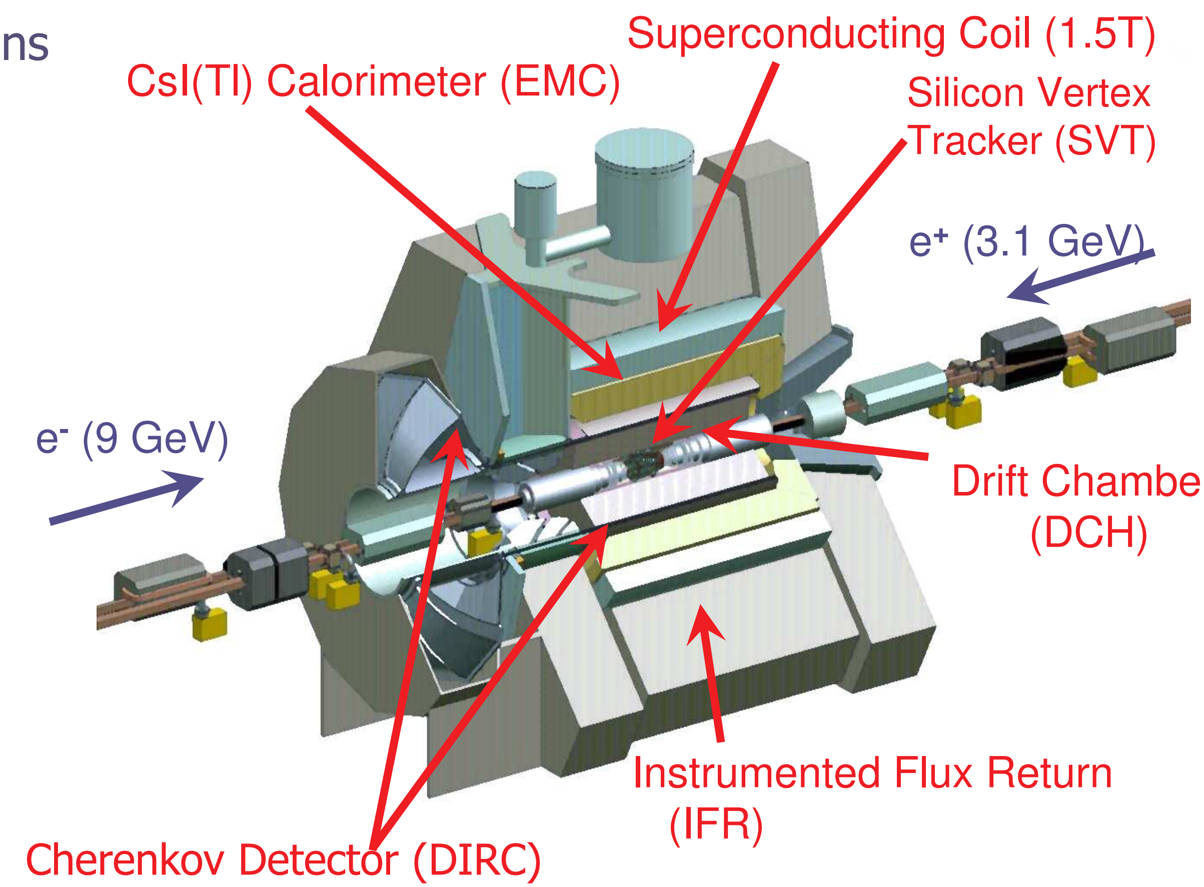
e.g. for $B \to J/\psi\ K_S$: C=0, S=sin2β

PEP-II and BaBar

- Located at SLAC, California
- PEP-II collides 9GeV electrons and 3.1 GeV positrons



Record peak luminosity = $9.2*10^{33}$ $cm^{-2}s^{-1}$



cos2β with B→J/ψ K*

- B→J/ψ K* is a scalar→vector vector decay, contains both CP-odd and CP-even components
- cos2β appears in interference between CP-even and CP-odd components in the observables of time-dependent angular distributions

$$a(t) = P\cos\Delta mt + \sin\Delta mt\left(S\sin 2\beta + C\cos 2\beta\right)$$

where P, S, C depend on the angular decay amplitudes:

$$A_i = \left|A_i\right| e^{i\delta_i};\ i = 0, \parallel, \perp$$

and the strong phases:

$$S \propto \cos\left(\delta_{\parallel} - \delta_0\right)$$
$$C \propto \cos\left(\delta_{\perp} - \delta_{\parallel}\right) \text{ and } \cos\left(\delta_{\perp} - \delta_0\right)$$
$$P \propto \sin\left(\delta_{\perp} - \delta_{\parallel}\right) \text{ and } \sin\left(\delta_{\perp} - \delta_0\right)$$

- Use neutral and charged B→J/ψK* decays to measure strong phases up to twofold ambiguity

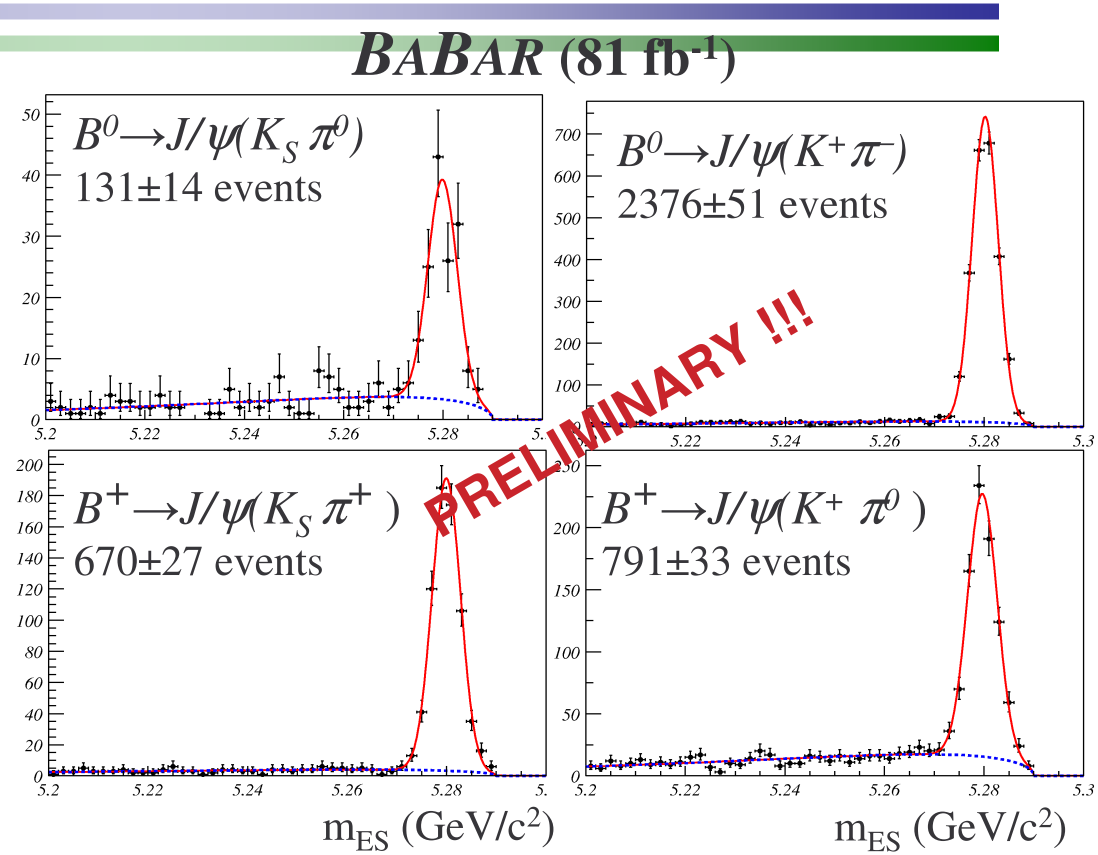
$$\left\{\left(\delta_{\parallel} - \delta_0\right), \left(\delta_{\perp} - \delta_0\right)\right\} \Leftrightarrow \left\{-\left(\delta_{\parallel} - \delta_0\right), \pi - \left(\delta_{\perp} - \delta_0\right)\right\}$$

Measurement of amplitudes

Perform angular analysis of:

- $B^0 \to J/\psi\ K^{*0}(K^+\pi^-)$
- $B^+ \to J/\psi\ K^{*+}(K_S\pi^+)$
- $B^+ \to J/\psi\ K^{*+}(K^+\pi^0)$

+c.c.



	value	stat.	syst.
$\|A_0\|^2$ =	0.566	± 0.012	± 0.005
$\|A_{\|\|}\|^2$ =	0.204	± 0.015	± 0.005
$\|A_\perp\|^2$ =	0.230	± 0.015	± 0.004

Solution 1

$\delta_{||} - \delta_0 = 2.729 \pm 0.101 \pm 0.052$

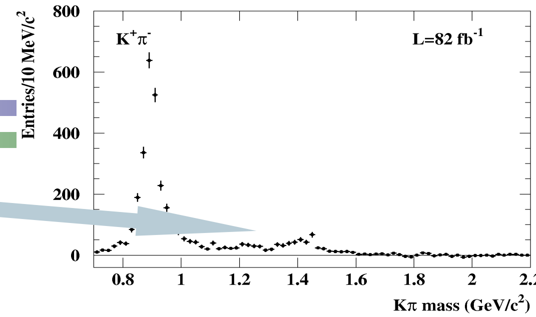
$\delta_\perp - \delta_0 = 0.184 \pm 0.070 \pm 0.046$

Solution 2

$\delta_{||} - \delta_0 = 3.554 \pm 0.101 \pm 0.052$

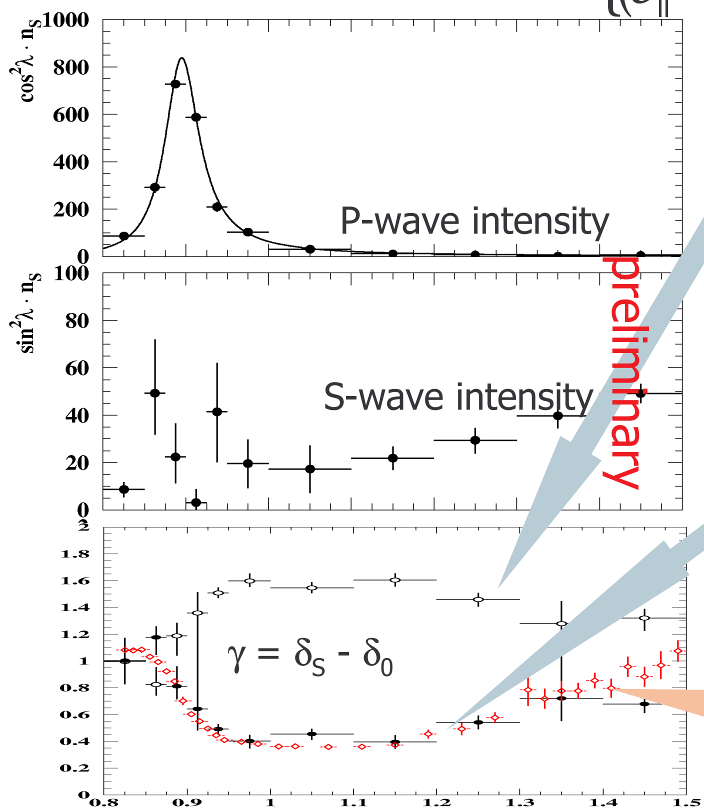
$\delta_\perp - \delta_0 = 2.958 \pm 0.070 \pm 0.046$

Resolving the strong phase ambiguity



- Broad $K\pi$ S-wave is known to lie in $K^*(892)$ region
- Introduce new amplitude and new relative phase $\gamma=(\delta_S-\delta_0)$:
  - Ambiguity becomes:

$$\{(\delta_\parallel-\delta_0),\ (\delta_\perp-\delta_0),\gamma\} \quad \{-(\delta_\parallel-\delta_0),\ \pi-(\delta_\perp-\delta_0),-\gamma\}$$



- Strong phase rotates counter-clockwise with increasing invariant mass
- In K^* region, S-wave phase rotates slowly, P-wave rotates quickly, therefore γ rotates clockwise
- Fit in bins of $M(K\pi)$ P- and S- wave intensities, and γ, fixing to the two possible solutions in turn
- Physical behaviour observed for solution 2
- Also agrees well with LASS data for $Kp\to K\pi(n)$ scattering..

Determining sign of cos2β

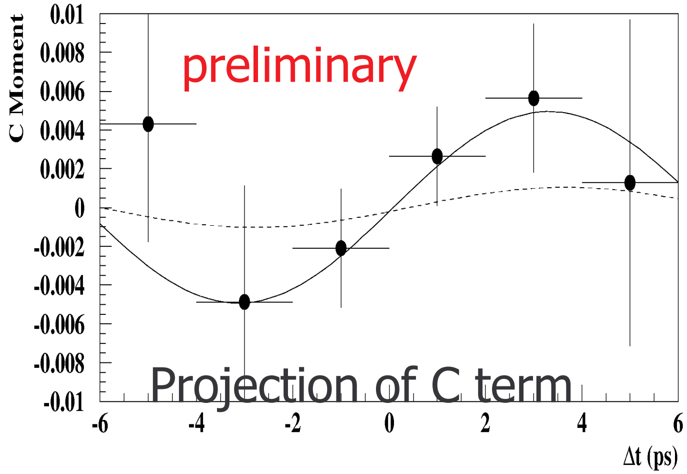
Perform time-dependent fit to $B^0 \to J/\psi K^{*0}(K_S \pi^0)$ sample:

•With sin2β floating:

$$\cos 2\beta = +3.32^{+0.76}_{-0.96} \pm 0.27$$
$$\sin 2\beta = -0.10 \pm 0.57$$

•With sin2β fixed to 0.731:

$$\cos 2\beta = +2.72^{+0.50}_{-0.79} \pm 0.27$$



•If sin2β and cos2β come from the same angle, expect cos2β = ±0.68

•Generate toy MC using both solutions:

- •Find probability for solution -0.68 is (8.1±3.1)%
- •Therefore cos2β>0 at 89% CL

cos2β contour plot