Measurements of $\sin 2\beta$ in B decays

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- Time evolution of B^0 decays
- Connection with standard model
- “Golden mode” charmonium decays
- Interpretation of measurements in rare decays
- Open charm modes
- Penguin decays
- Summary

Quark weak couplings in the standard model

Wolfenstein parameterization of the CKM matrix V:

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

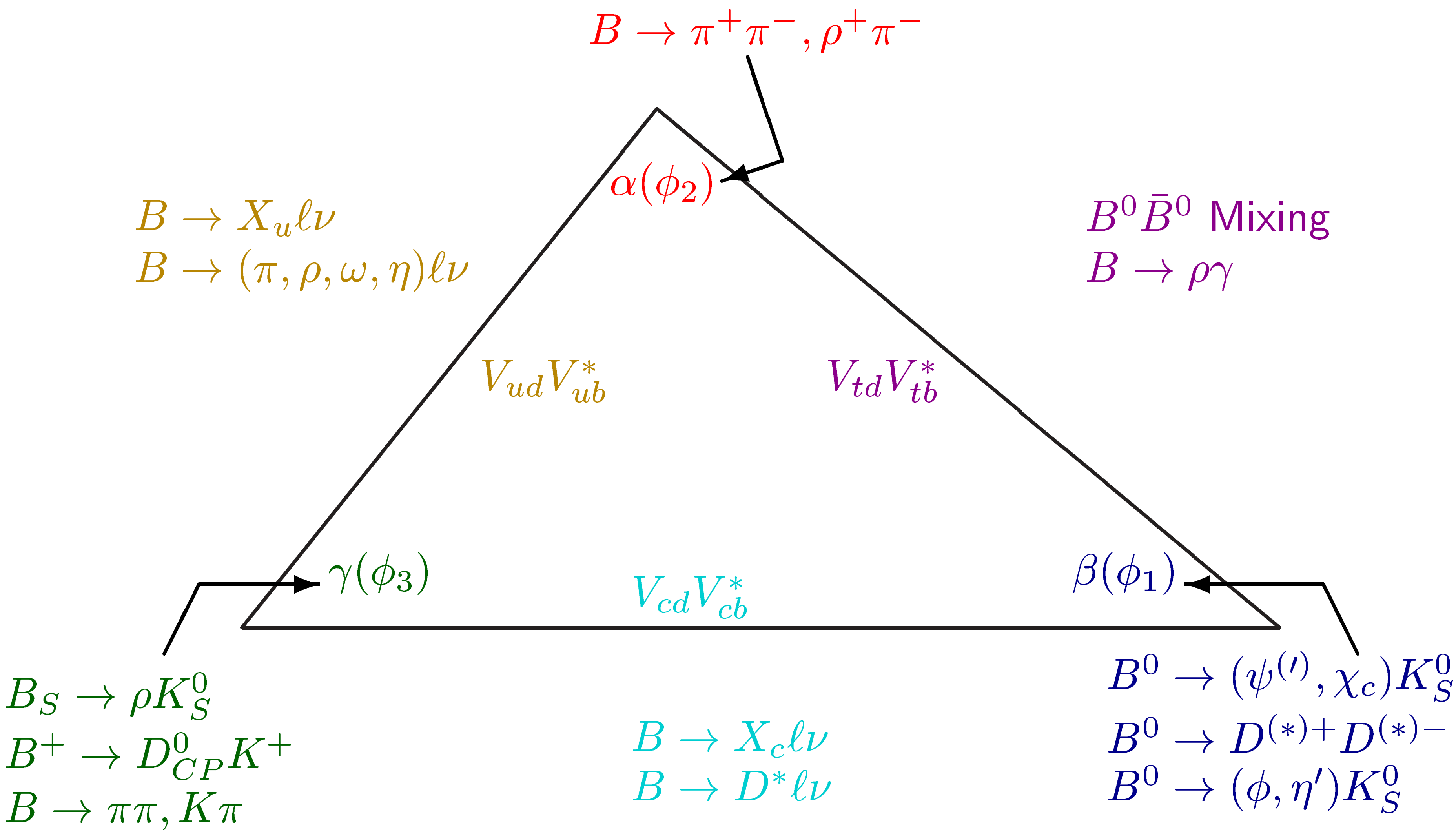
$$\begin{aligned} \lambda &\simeq \sin\theta_c \simeq 0.22 \\ A &\sim 1 \end{aligned}$$

The irreducible phase generates CP non conservation:

$$(CP)^{-1} HCP = H^* \neq H$$

Unitarity triangle

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



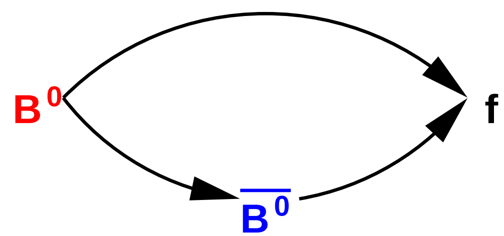
Time evolution and CP violation

- The decay amplitude for $B^0 \to f$ is

$$\boxed{\langle f|H|B^0{}_{\text{phys}}(t)\rangle = e^{-imt}e^{-\Gamma t/2}\left[A_f \cos\tfrac{1}{2}\Delta m t + i\tfrac{q}{p}\overline{A}_f \sin\tfrac{1}{2}\Delta m t\right]}$$

$$A_f \equiv \langle f|H|B^0\rangle, \quad \overline{A}_f \equiv \langle f|H|\overline{B}^0\rangle \qquad |B^0{}_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

- CP violation appears through the Interference between mixing ($\frac{q}{p}$) and decay ($\frac{\overline{A}_f}{A_f}$)

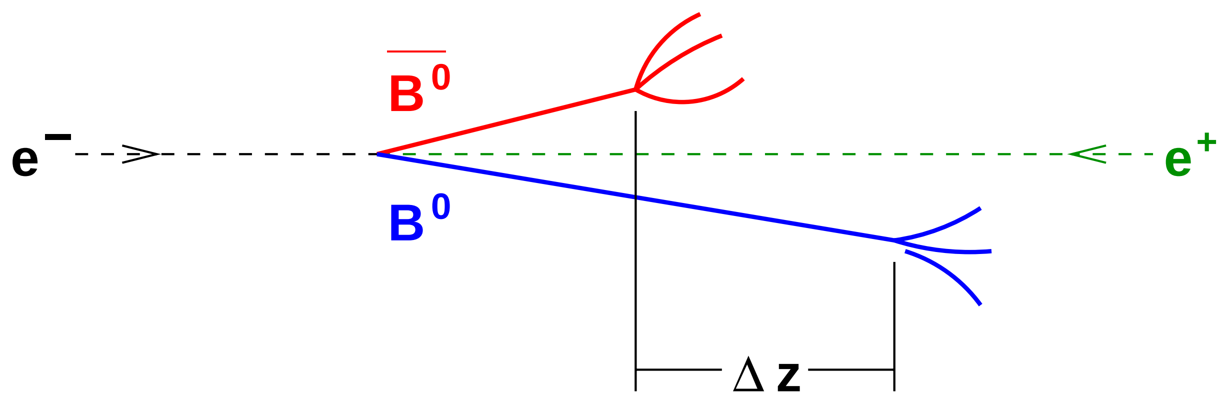


B meson pairs from boosted $\Upsilon(4S)$

In $\Upsilon(4S)$ decay $B^0\overline{B}^0$ pair created in a $C = -1$ eigenstate

These oscillate coherently between B^0 and $\overline{B}^0$ until one decays

(Einstein-Podolsky-Rosen effect)



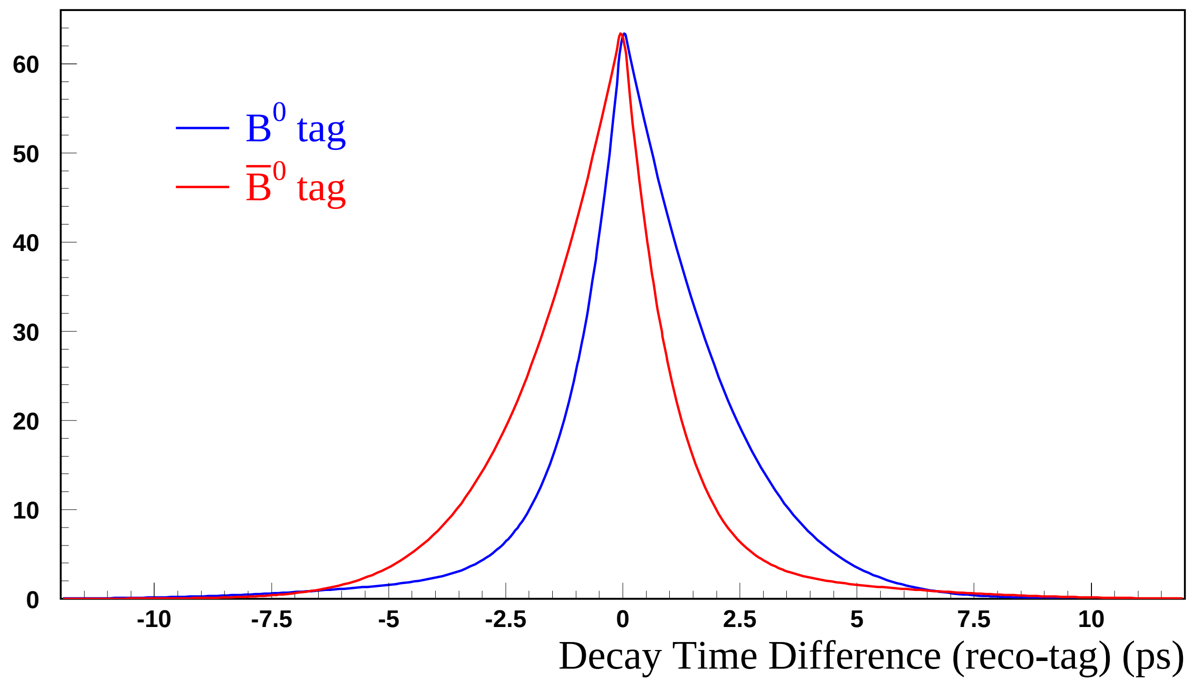
$\Delta z \simeq \beta\gamma c \Delta t$

$\beta\gamma = 0.56$ (PEP-II), 0.425 (KEKB)

Measurement of time evolution: Δt

Start the Δt clock on the decay of one B to a flavor eigenstate ("tag")
Stop it on the decay of the other B to CP eigenstate f

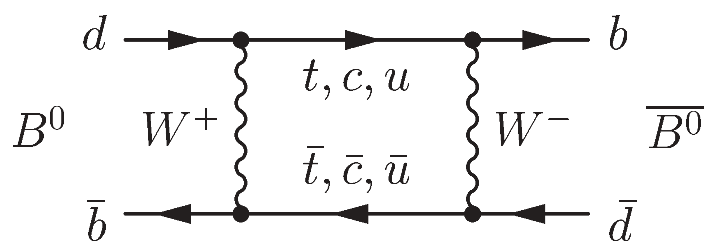
$$\frac{d\Gamma(\Delta t)}{d\Delta t} \propto e^{-|\Delta t|/\tau}\left(1 \pm \mathcal{I}m\lambda_f \sin\Delta m \Delta t\right), \quad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}, \quad (|\lambda_f| = 1)$$



The $B\overline{B}$ mixing factor

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad |B^0{}_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

Parton level calculation is reliable (short-distance dominated) for heavy mesons

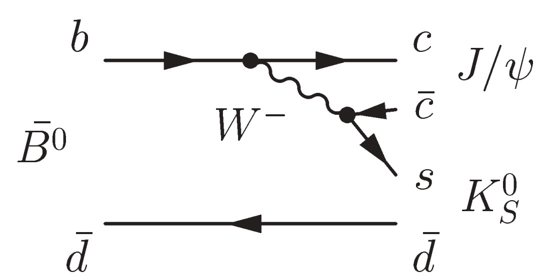


Massive t quark dominates (frustrated GIM mechanism); in Wolfenstein phase convention

$$\frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{-2i\beta}, \quad \Rightarrow \lambda_f = e^{-2i\beta}\frac{\overline{A}_f}{A_f}$$

$\sin 2\beta$ from charmonium $K^{0(*)}$ modes

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$



$$\frac{\overline{A}_f}{A_f} = \eta_f \left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)\left(\frac{V_{cs}^*V_{cb}}{V_{cs}V_{cb}^*}\right)\left(\frac{V_{cd}^*V_{cs}}{V_{cd}V_{cs}^*}\right) = \eta_f \qquad \text{(or } \xi_f\text{)}$$

$\eta_f = \pm 1$ for a CP even/odd final state f; for this example, $\eta_f = -1$

$$\lambda_f = \eta_f e^{-2i\beta}, \qquad \mathcal{I}m\lambda_f = -\eta_f \sin 2\beta$$

Reconstruction of B candidates at the $\Upsilon(4S)$

- $\Upsilon(4S) \to (B^0\bar{B}^0,\, B^+B^-)$ nearly at rest ($p_B^* \simeq 325$ MeV/c)
- $m_B \simeq 5.3$ GeV/c^2 $= m_{\text{recoil}}$

  $\Rightarrow$

  $$\boxed{E_B^* = E_{\text{beam}}^*, \quad \text{i.e.,} \quad \Delta E \equiv E_B^* - E_{\text{beam}}^* = 0}$$

  and

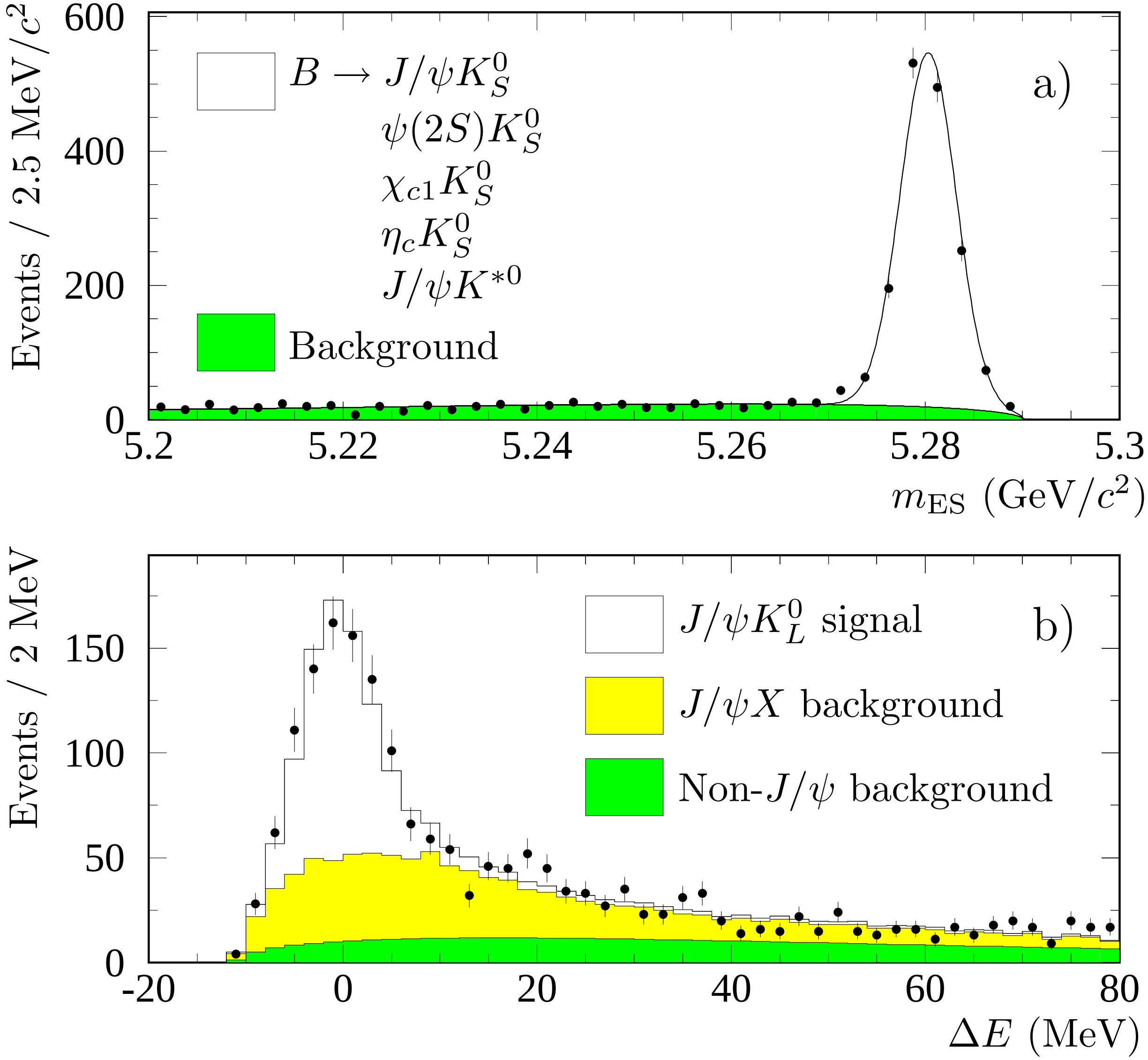
  $$\boxed{m_{ES} \equiv \sqrt{E_{\text{beam}}^{*2} - |\mathbf{p}_i^*|^2} = m_B}$$

  Typical resolution m_{ES} : 3 MeV/c^2, ΔE : 15 – 50 MeV

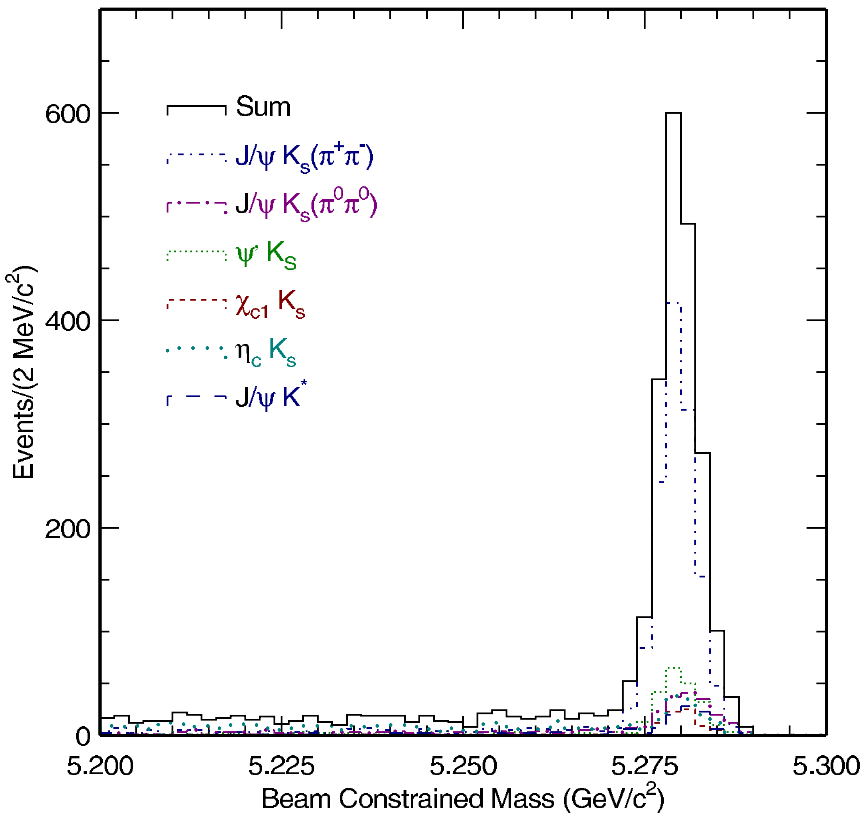
- For two-body
  - ◇ daughter $E^* \simeq 2.6$ GeV
  - ◇ daughters nearly back-to-back

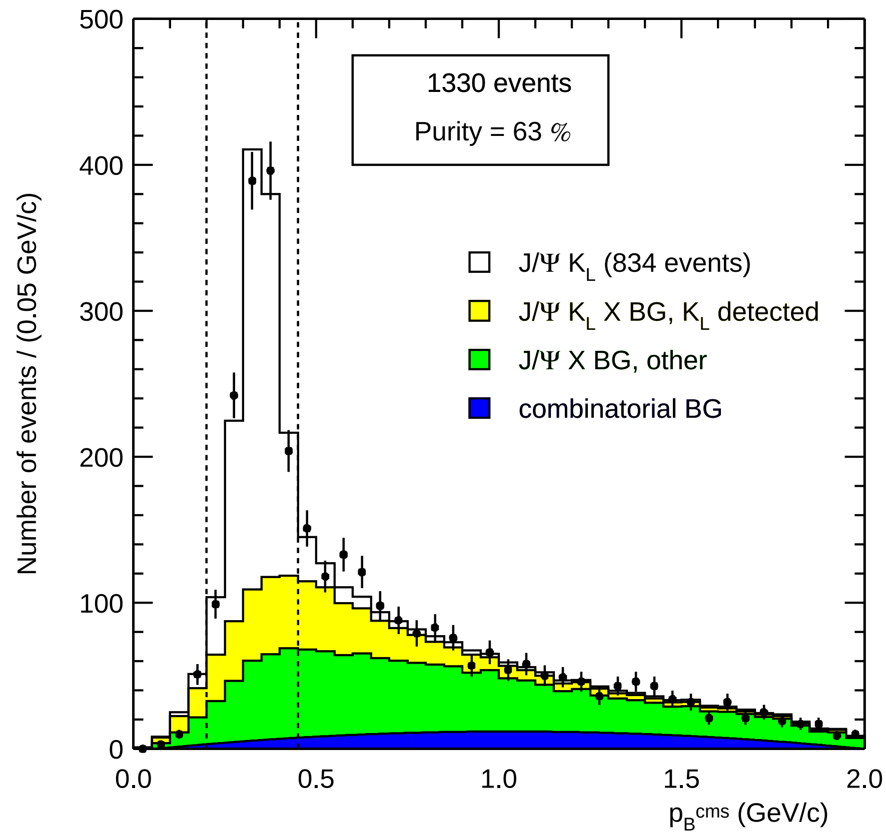
B_{CP} candidates

Tagged events
(88×10^6 $B\overline{B}$)



B_{CP} candidates





Tagged events (85×10^6 produced $B\overline{B}$ pairs)

Flavor of the tag B

The other B is not fully reconstructed, but we need to know whether it's B^0 or $\overline{B}^0$.

Tagging signatures:

$$B^0 \to \ell^+,\ \overline{B}^0 \to \ell^-$$

$$B^0 \to K^+,\ \overline{B}^0 \to K^-$$

Inclusive flavor signatures

etc.

Efficiency ϵ, mistag rate w measured with reconstructed flavor eigenstate decays.

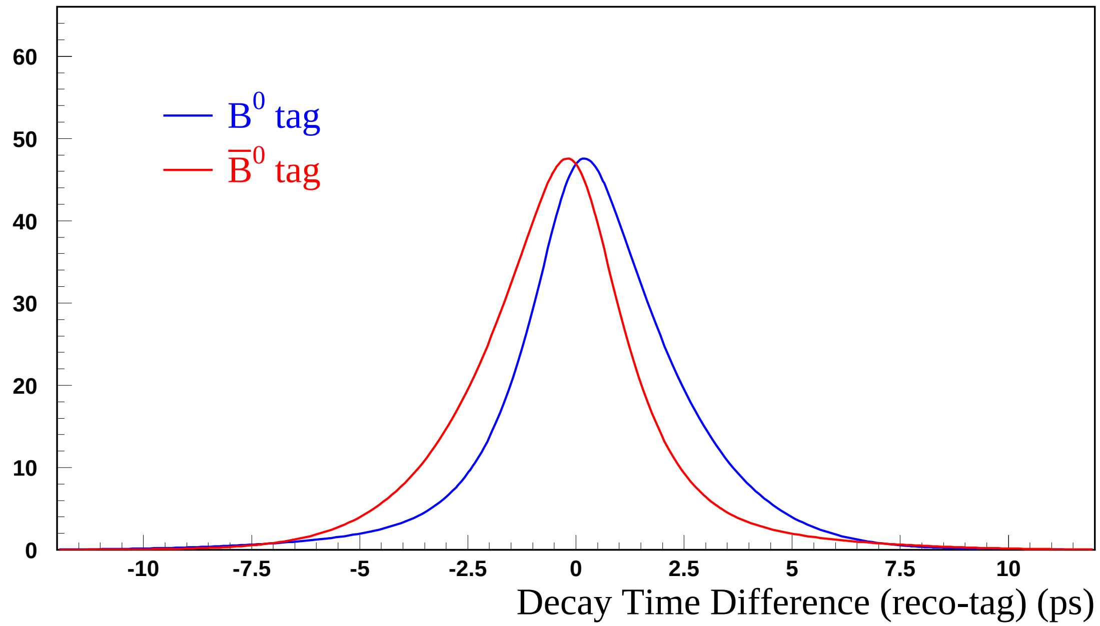
The effective efficiency is

$$Q = \langle \epsilon (1-2w)^2 \rangle = (28.1 \pm 0.7)\% \text{ (BABAR)},\ (28.8 \pm 0.6)\% \text{ (Belle)}$$

Decay rate with resolution and realistic tagging

$$\frac{1}{\Gamma}\frac{d\Gamma(\Delta t)}{d\Delta t} = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left(1 \pm (1-2w)\mathcal{I}m\lambda_f \sin \Delta m \Delta t\right) \otimes \mathcal{R}$$

Vertex resolution (largest contribution from tag side) $\simeq 180\ \mu\mathrm{m}$, or ~ 1.25 ps



Time development fit for B_{CP} BABAR

CP Odd modes, with asymmetry, above

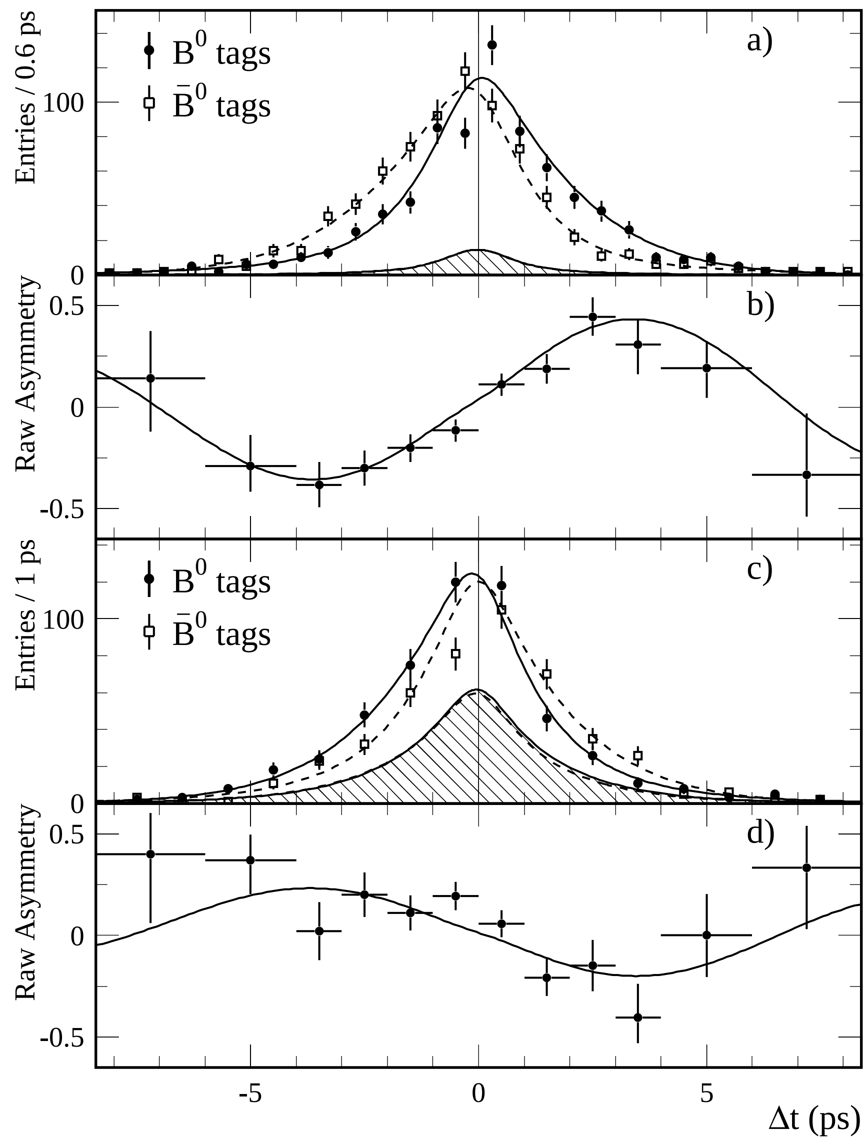
CP Even K_L^0 mode below

34 parameter likelihood fit

$$\sin 2\beta = 0.741 \pm 0.067 \pm 0.034$$

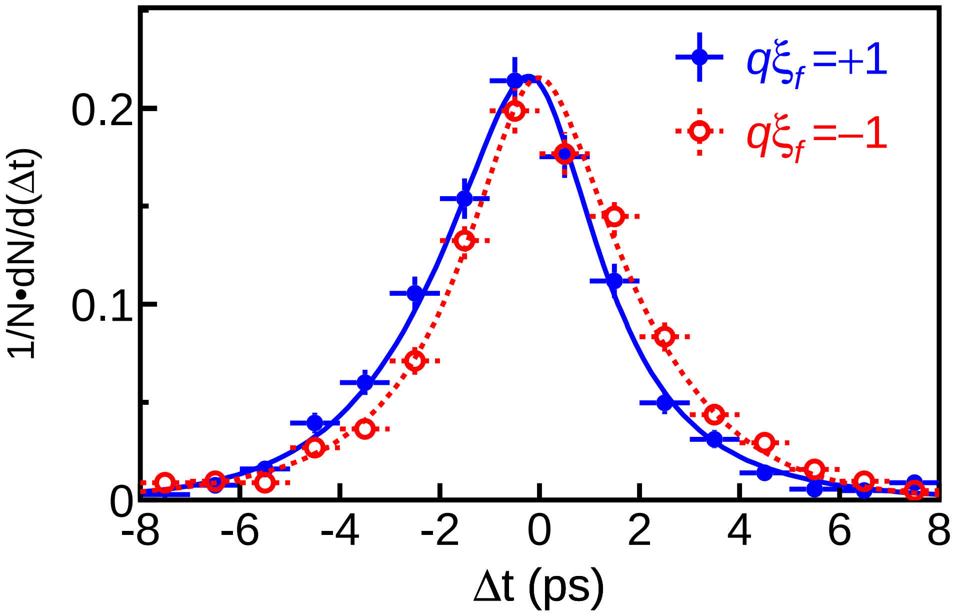
2641 tagged events, 78% purity

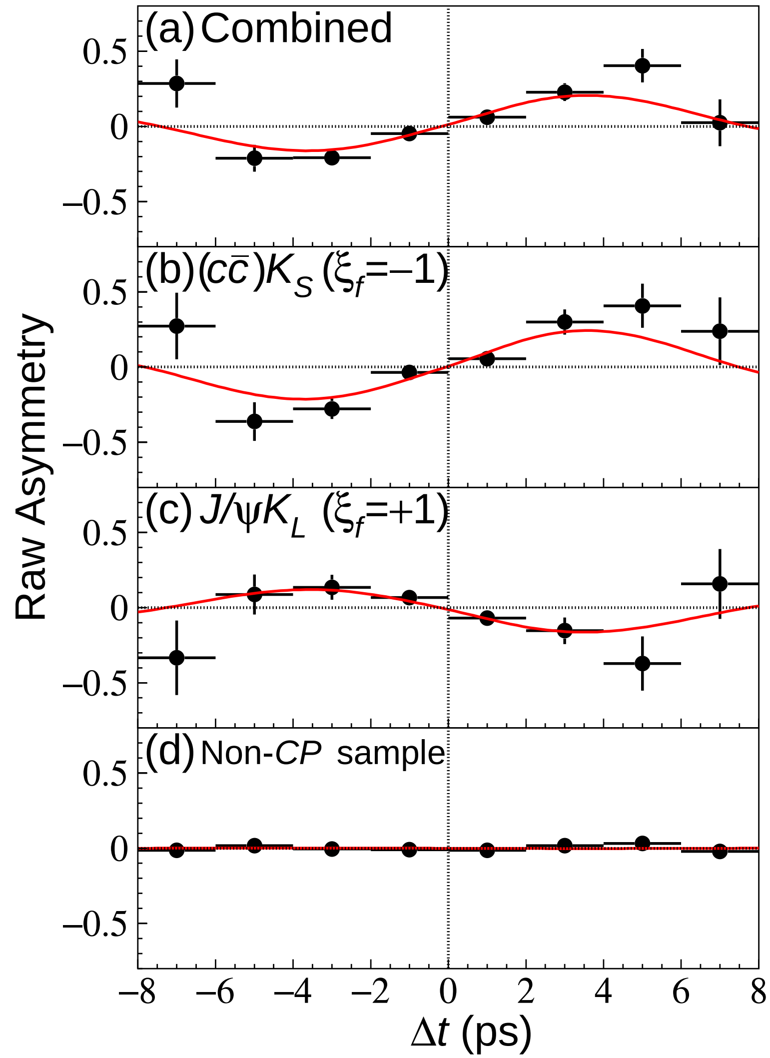
(88×10^6 $B\overline{B}$ pairs)



Time development fit for B_{CP}

$q =$ tag sign, $B^0 = +$



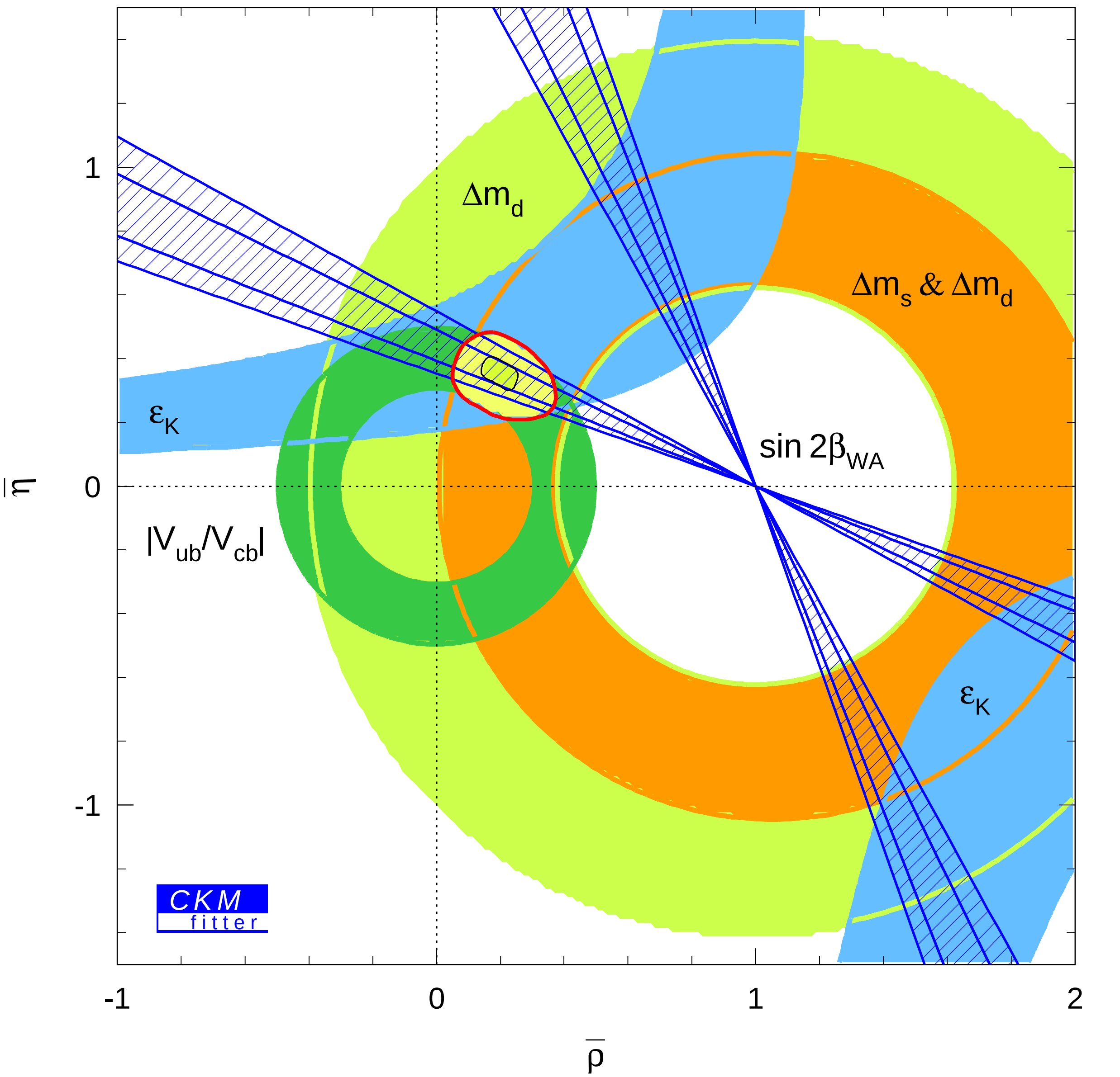


$$\sin 2\beta = 0.719 \pm 0.074 \pm 0.035$$

2958 tagged events, 81% purity

(85×10^6 $B\overline{B}$ pairs)

Unitarity triangle and CP measurements



Further Investigations

- Rarer $\mathcal{O}(\lambda^3)$ B decays
  - ◇ $b \to c\bar{c}d$ (Cabibbo-suppressed; charmonium π^0, open charm pair)
  - ◇ $b \to s\bar{q}q$ (gluonic penguin; ϕK^0_S, $\eta' K^0_S$)
- Sensitive to new physics
  - ◇ Smaller amplitudes may reveal NP through interference terms
  - ◇ Virtual particles (e.g., SUSY) in penguin loops
- These experiments are harder
  - ◇ Lower rates, higher backgrounds
  - ◇ tree, (multi-) penguin amplitudes complicate interpretation
  - ◇ Uncertainties from short-distance effects

For these decays we remove the assumption $|\lambda_f| = 1$,

Cast the decay time dependence in terms of

sine-like (S_f) and cosine-like (C_f) coefficients.

For final CP eigenstate f

(defining $\Delta w = w(B^0) - w(\overline{B}^0)$, still assuminng $\Gamma_H - \Gamma_L = 0$)

$$\boxed{\frac{d\Gamma(\Delta t)}{d\Delta t} \propto \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta w \pm (1 - 2\langle w \rangle)\,(S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t))]}$$

where

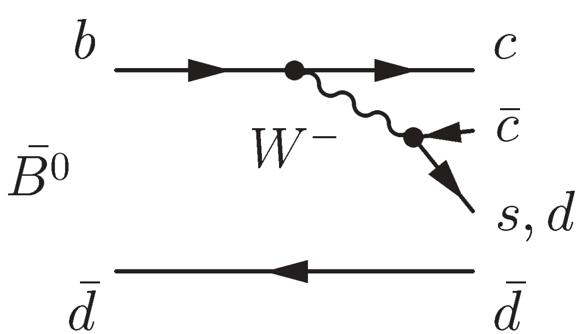
$$\boxed{S_f = \frac{2\mathcal{I}m\lambda_f}{1+|\lambda_f|^2} \;\; (= \sin 2\beta \text{ for } B^0 \to \psi K_S^0)}$$

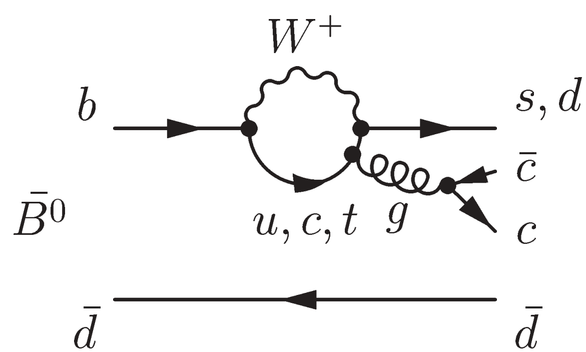
and

$$\boxed{-\mathcal{A}_f = C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \;\; (= 0 \text{ for } B^0 \to \psi K_S^0)}$$

$b \to c\bar{c}d$ decays

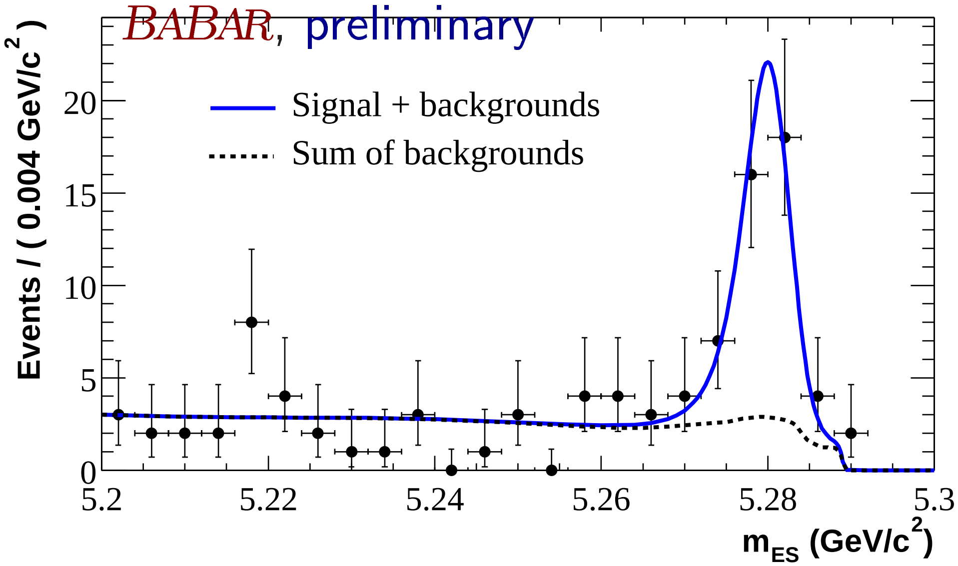
- In $b \to c\bar{c}(s,d)$ the color-suppressed tree competes with penguins having in the loop:
  - ◇ $c - t$ (same CP phase as the tree)
  - ◇ $u - t$ (different CP phase)





- For $b \to c\bar{c}s$ (e.g., $J/\psi K^0_S$), (u,t) penguin/tree $= \mathcal{O}(\lambda^4/\lambda^2)$
- For (also Cabibbo-suppressed) $B \to c\bar{c}d$ (e.g., $J/\psi\pi^0$), both are $\mathcal{O}(\lambda^3)$
- The P/T ratio becomes a major theoretical systematic for interpretation of $b \to c\bar{c}d$ decays.

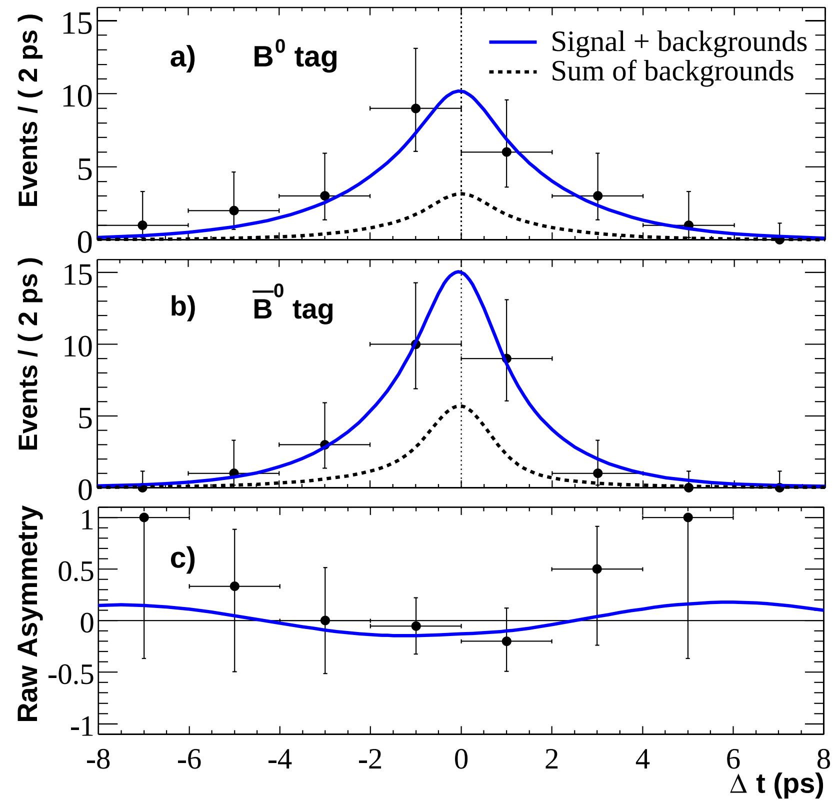
$\sin 2\beta$ from $B^0 \to J/\psi\pi^0$



$$S_{J/\psi\pi^0} = 0.05 \pm 0.49 \pm 0.16$$
$$C_{J/\psi\pi^0} = 0.38 \pm 0.41 \pm 0.09$$

(40 ± 7 signal events, 88×10^6 $B\overline{B}$ pairs)

BABAR



BELLE preliminary

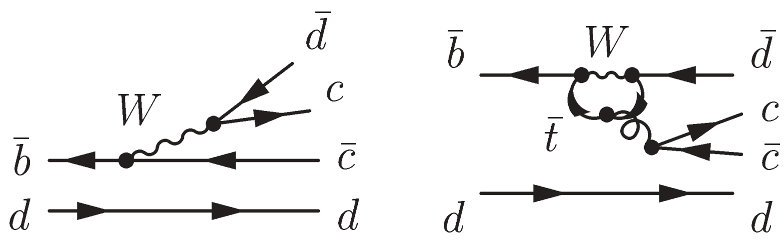
$$S_{J/\psi\pi^0} = 0.93 \pm 0.49 \pm 0.11^{+0.27}_{-0.03}$$
$$-C_{J/\psi\pi^0} = \mathcal{A} = -0.25 \pm 0.39 \pm 0.06$$

(57 total events, 86% purity, 85×10^6 $B\overline{B}$)

Both measurements consistent with $S_{J/\psi\pi^0} = \sin 2\beta$, $C_{J/\psi\pi^0} = 0$, within large errors.

$B^0 \to D^{*\pm} D^{\mp}$

The penguin with t or u brings in a second weak phase, ...

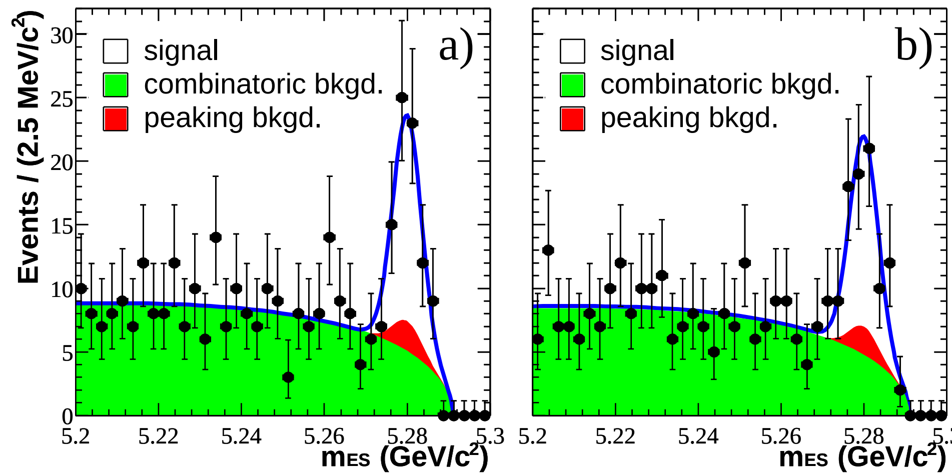


... expected to be small ($\Delta\beta \sim 0.1$).

These are not CP eigenstates, but are accessible from B^0 and $\overline{B}^0$.

BABAR, preliminary

$D^{*-}D^{+}$ $D^{*+}D^{-}$



$D^{*\pm} \to \pi^{\pm} D^0$, (4 D^0 modes)

$D^+ \to K\pi\pi, K^0_S\pi$

$\sin 2\beta$ from $B^0 \to D^{*\pm} D^{\mp}$

BABAR (preliminary, 113 ± 13 signal events, 88×10^6 $B\overline{B}$ pairs)

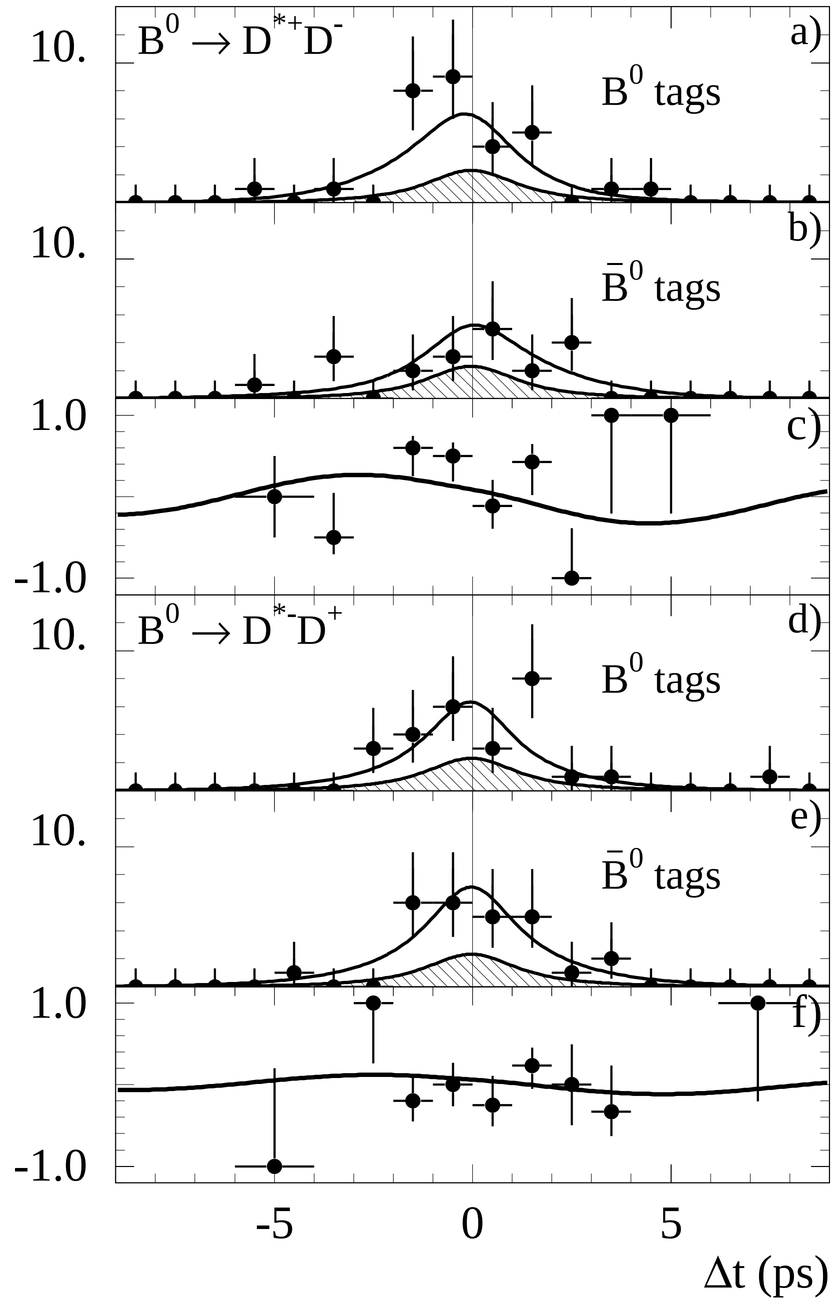
With notation S_{+-} for $D^{*+} D^{-}$, etc.,

$$S_{-+} = -0.24 \pm 0.69 \pm 0.12$$
$$C_{-+} = -0.22 \pm 0.37 \pm 0.10$$
$$S_{+-} = -0.82 \pm 0.75 \pm 0.14$$
$$C_{+-} = -0.47 \pm 0.40 \pm 0.12$$

If equal amplitudes for $D^{*-}D^{+}$, $D^{*+}D^{-}$, expect $C_{-+} = C_{+-} = 0$

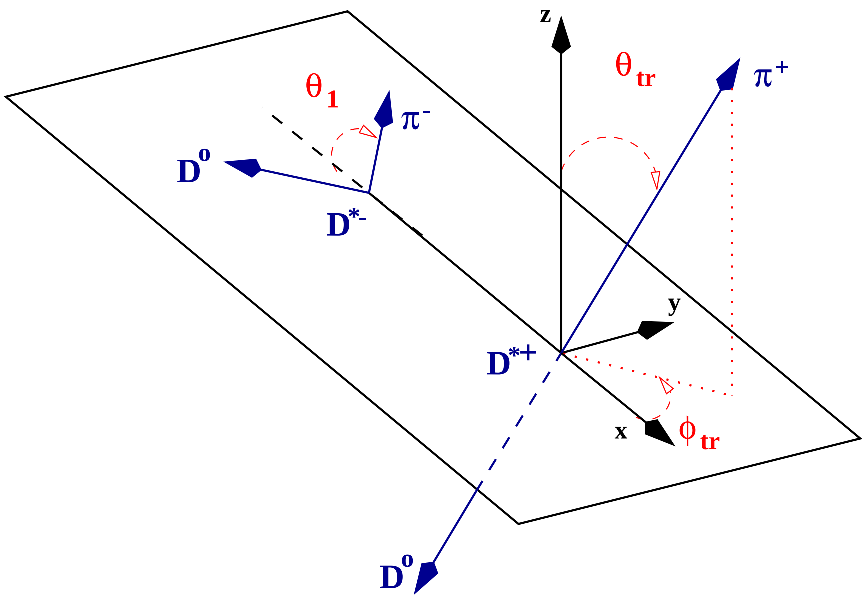
and if penguins negligible,

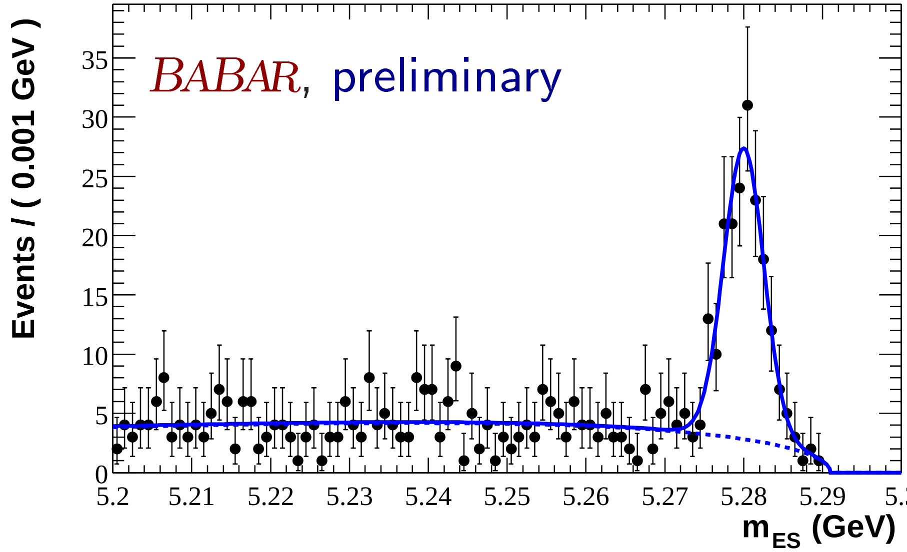
$S_{-+} = S_{+-} = -\sin 2\beta = -0.7$



$B^0 \to D^{*\pm} D^{*\mp}$

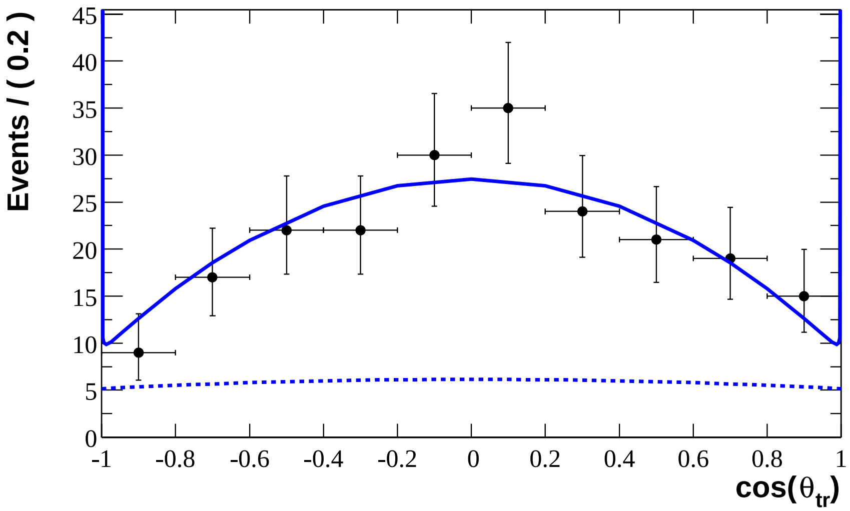
Vector-vector decay, with S, P, D-wave contributions.





$D^{*\pm} \to D^0\pi^\pm, D^\pm\pi^0$
(excl. $B^0 \to D^+D^-\pi^0\pi^0$)

Fit to θ_{tr} yields CP-odd component $R_\perp$



$R_\perp = 0.063 \pm 0.055 \pm 0.009 \quad \Rightarrow \sim 94\%$ CP even

$\sin2\beta$ from $B^0 \to D^{*\pm}D^{*\mp}$

BABAR, preliminary

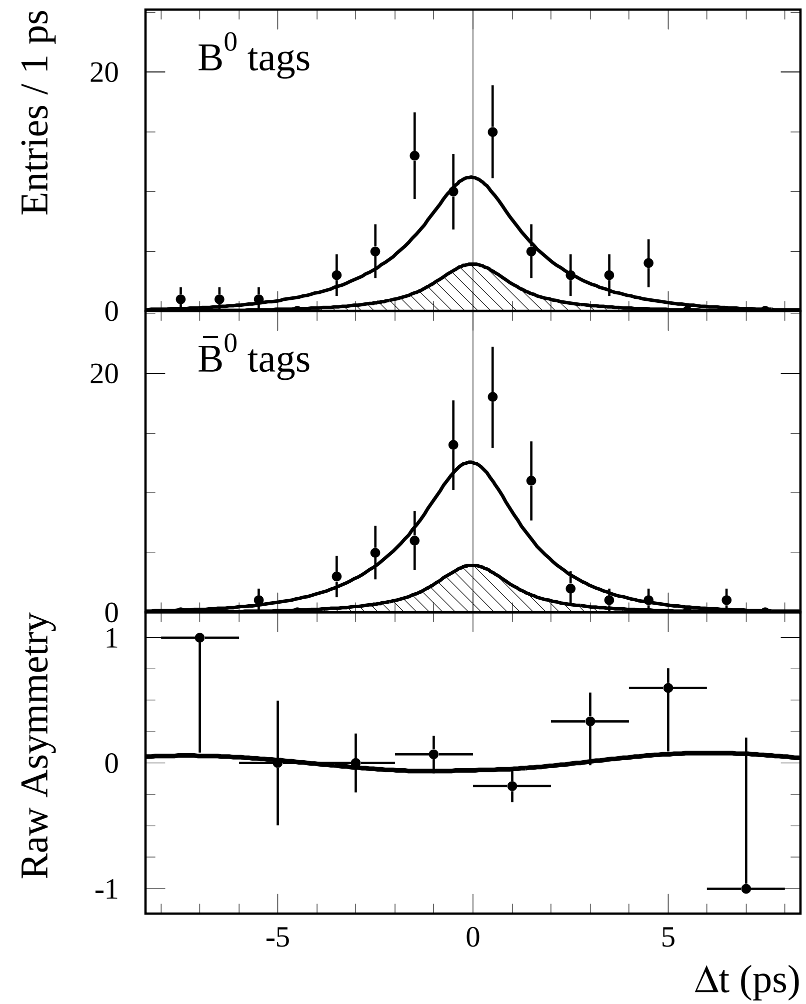
New, updated from ICHEP02

156 ± 14 signal events (before tagging),

73% purity, 88×10^6 $B\overline{B}$ pairs

Defining λ_{f_+} for CP-even component

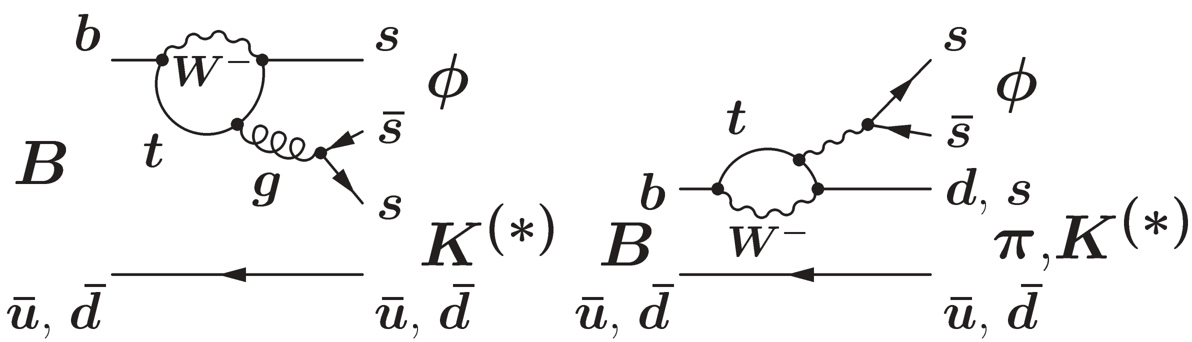
$$\begin{aligned} \mathrm{Im}\lambda_{f_+} &= 0.05 \pm 0.29 \pm 0.10 \\ \left|\lambda_{f_+}\right| &= 0.75 \pm 0.19 \pm 0.02 \end{aligned}$$



Compare with tree-level expectation $\left|\lambda_{f_+}\right| = 1,\ \mathrm{Im}\lambda_{f_+} = -\sin2\beta$

$B \to \phi K^0_S$

Pure $b \to s\bar{s}s$ transition; Gluonic penguins dominate:



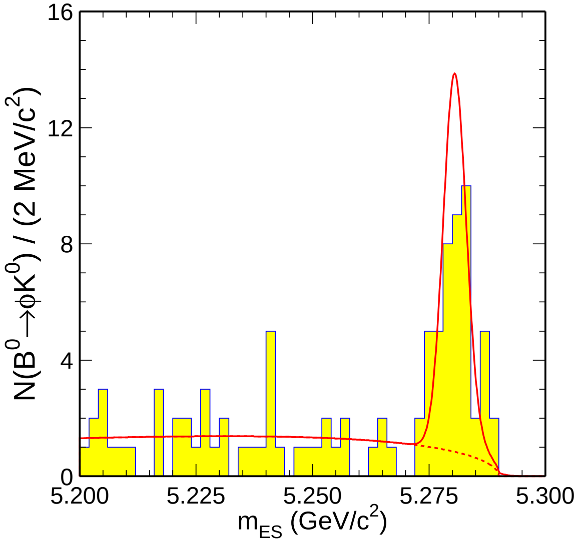
No tree, and like $b \to c\bar{c}s$, u-loop with different weak phase is suppressed by $\mathcal{O}(\lambda^2)$ (but here there is no penguin suppression), $\Rightarrow$

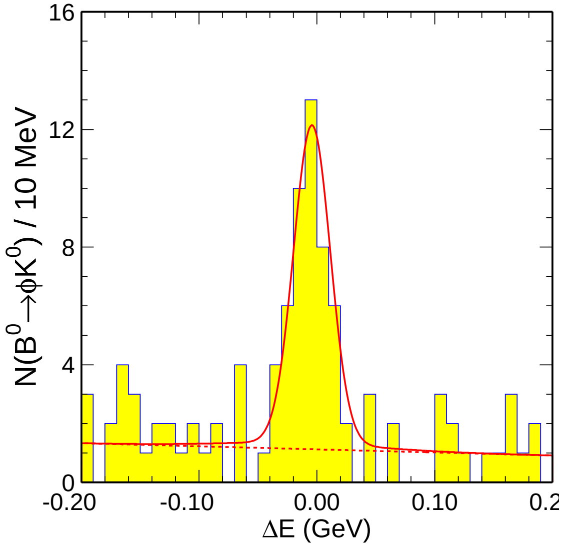
Deviation of $S_{\phi K^0_S}$ from $\sin 2\beta \Rightarrow$ new physics

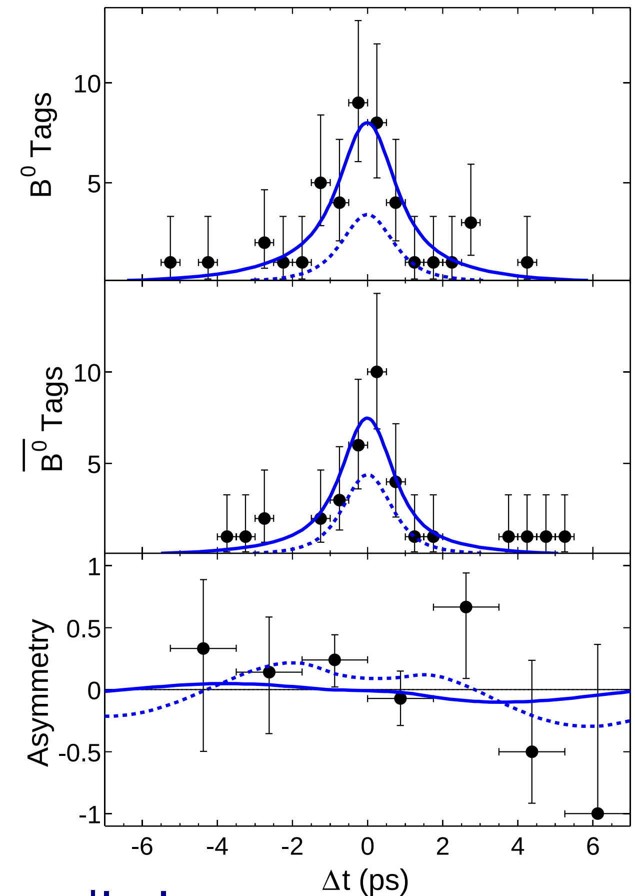
The naive estimate can eventually be replaced by bounds from $SU(3)$ relations to channels not yet measured.

(see Grossman, Ligeti, Nir, Quinn, hep-ph/0303171)

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







51 signal events (31 tagged), 87×10^6 $B\overline{B}$ pairs

preliminary

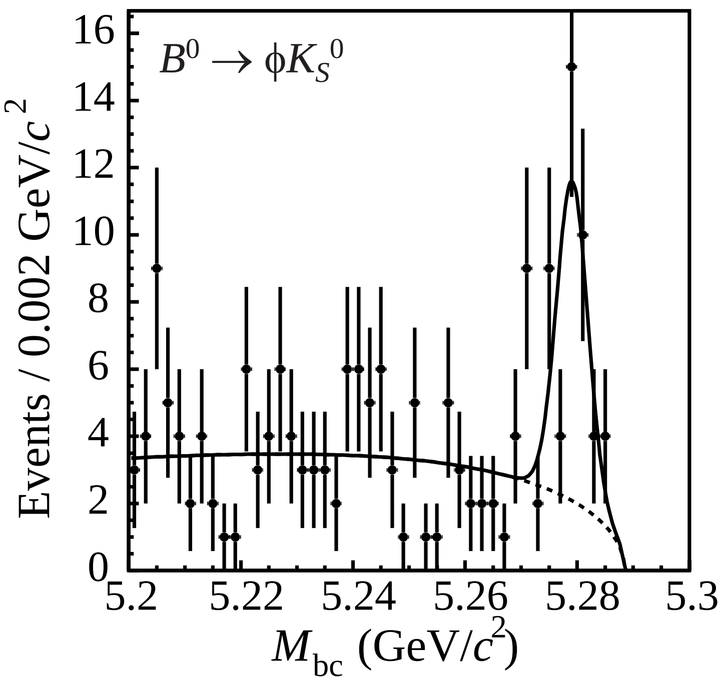
$$S_{\phi K^0_S} = -0.18 \pm 0.51 \pm 0.07$$

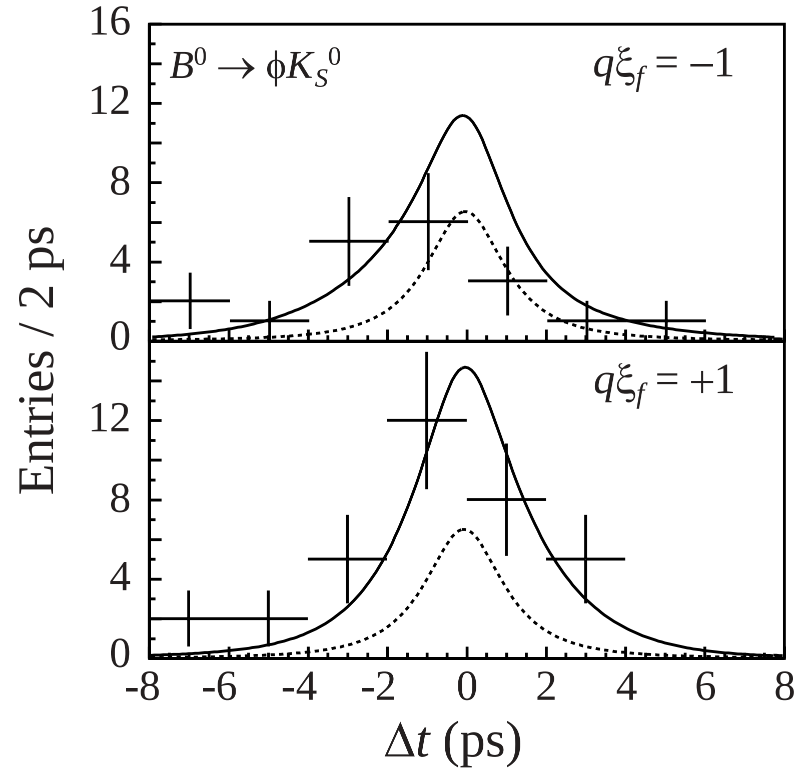
$$C_{\phi K^0_S} = -0.80 \pm 0.38 \pm 0.12$$

fix $C_{\phi K^0_S} = 0$, $S_{\phi K^0_S} = -0.26 \pm 0.51$ (stat)

($\sim$ null result, though consistent within errors with $S_{\phi K^0_S} = \sin 2\beta = 0.7$)

$\sin 2\phi_1$ from $B^0 \to \phi K^0_s$

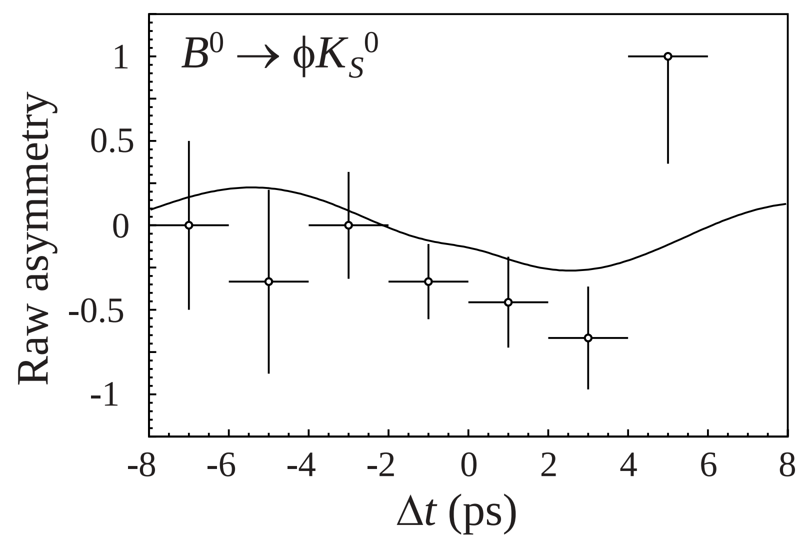




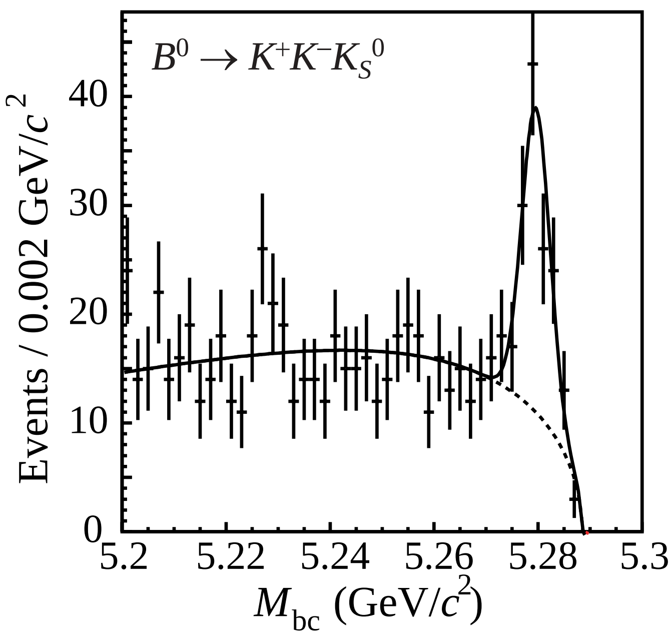
53 total events, purity 67%, 78×10^6 $B\overline{B}$

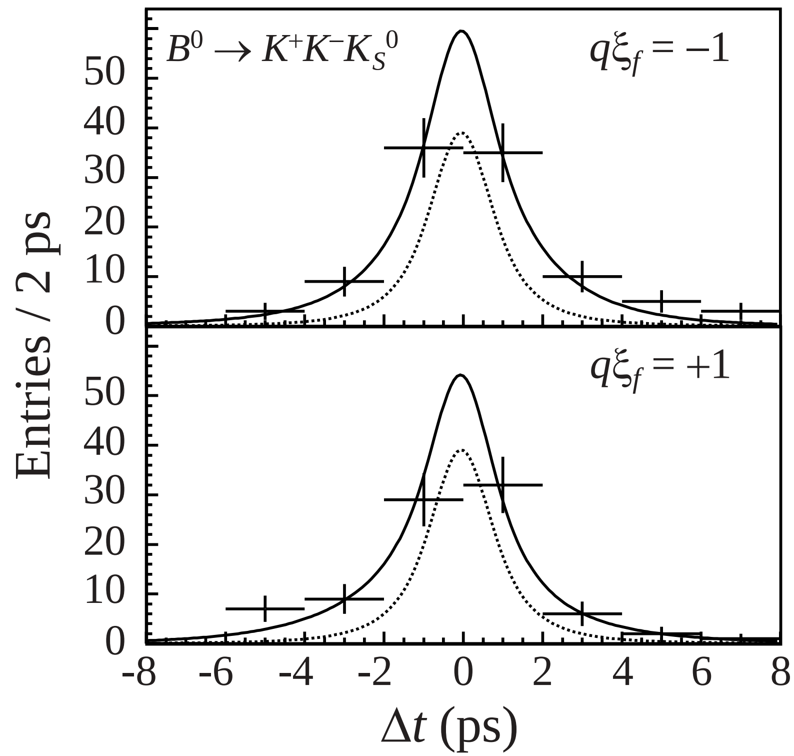
$$\sin 2\beta = S_{\phi K^0_S} = -0.73 \pm 0.64 \pm 0.22$$

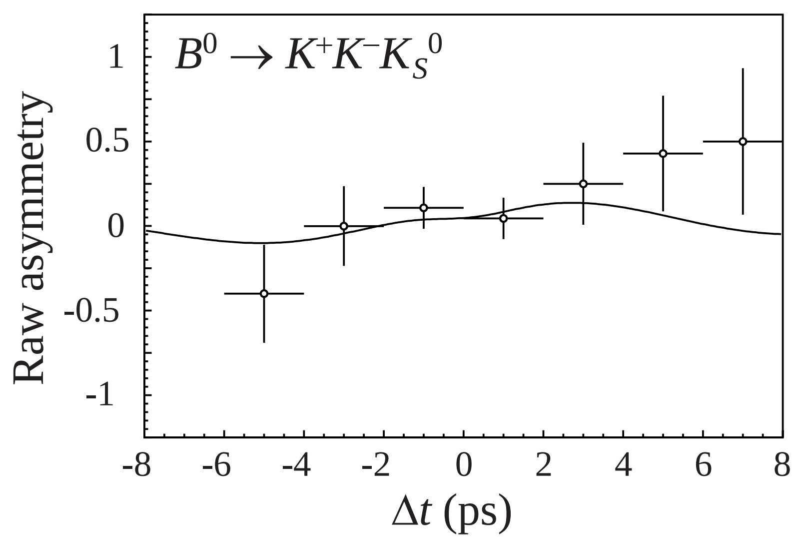
$$\mathcal{A}_{\phi K^0_S} = -C_{\phi K^0_S} = -0.56 \pm 0.41 \pm 0.16$$



$B^0 \to K^+K^-K^0_S$







191 total events, purity 50%, 78×10^6 $B\overline{B}$

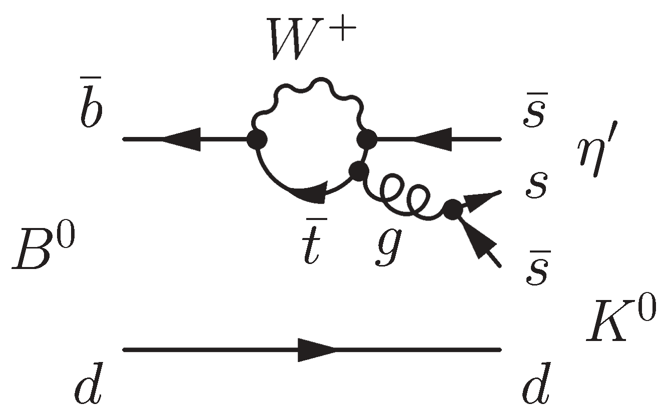
Dalitz analysis $\Rightarrow \xi_f = +1$ (97%)

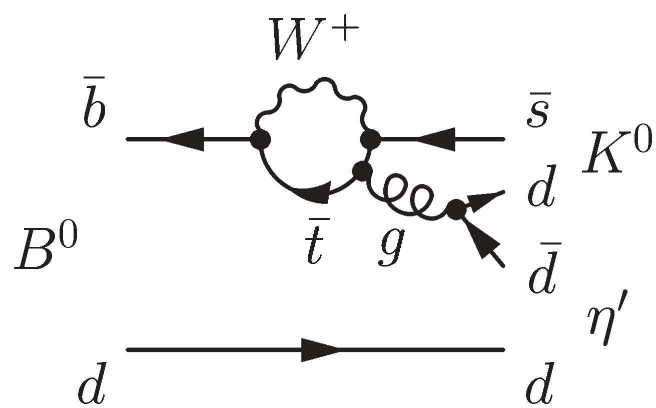
$$\sin 2\beta = -\xi_f S = 0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$$

$$\mathcal{A} = -C = -0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}$$

$B^0 \to \eta' K^0_S$

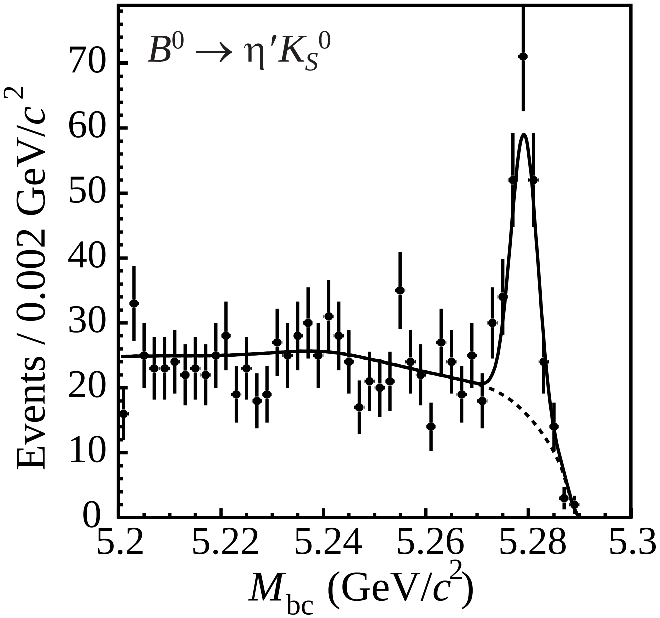
Again, gluonic penguins dominate:

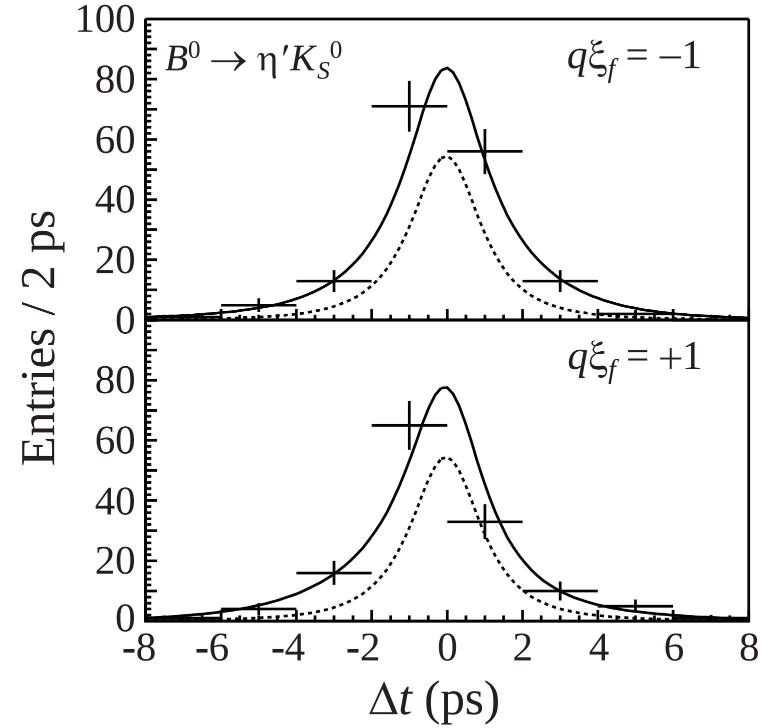




Decay rate not well understood; a $b \to u$ color-suppressed tree would bring in phase of V_{ub}, but with $\mathcal{O}(\lambda^2)$ suppression.

$B^0 \to \eta' K^0_S$

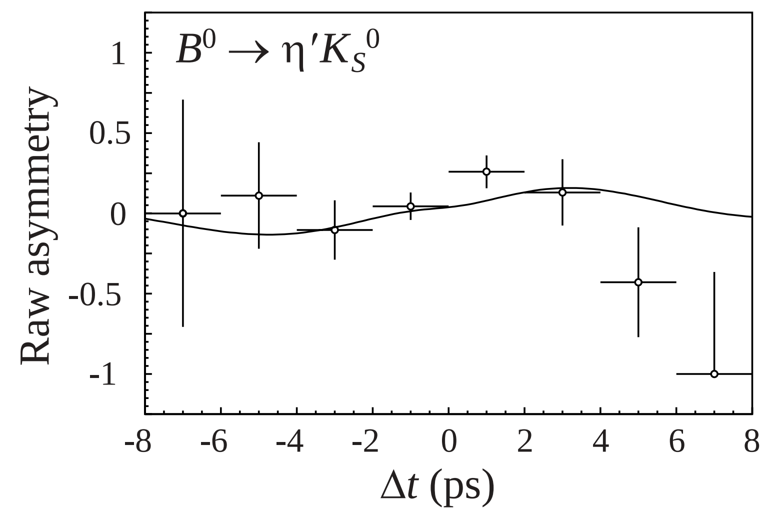




299 total events, purity 49%, 78×10^6 $B\overline{B}$

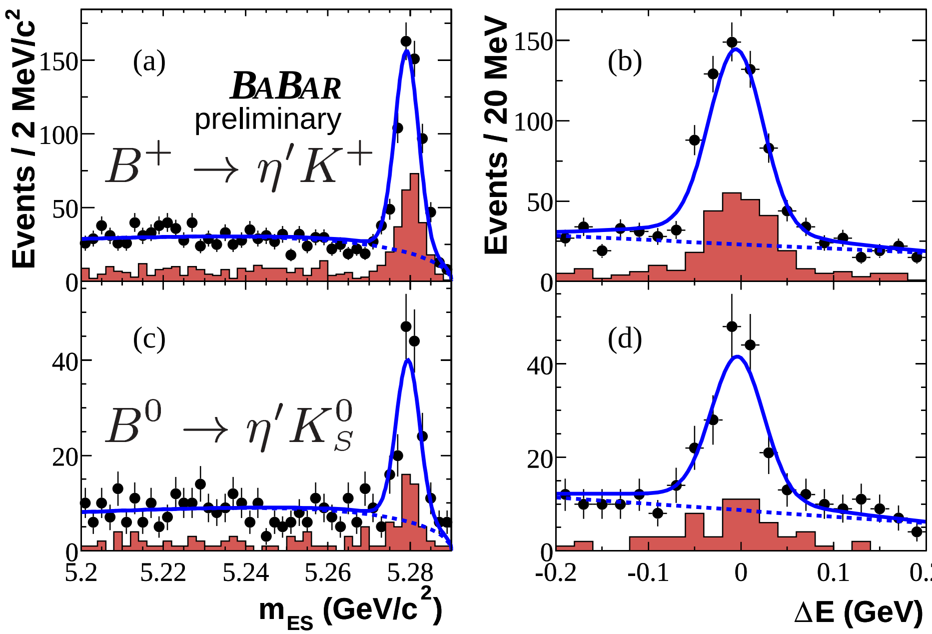
$$\sin\phi_1 = S_{\eta' K^0_S} = +0.71 \pm 0.37^{+0.05}_{-0.06}$$

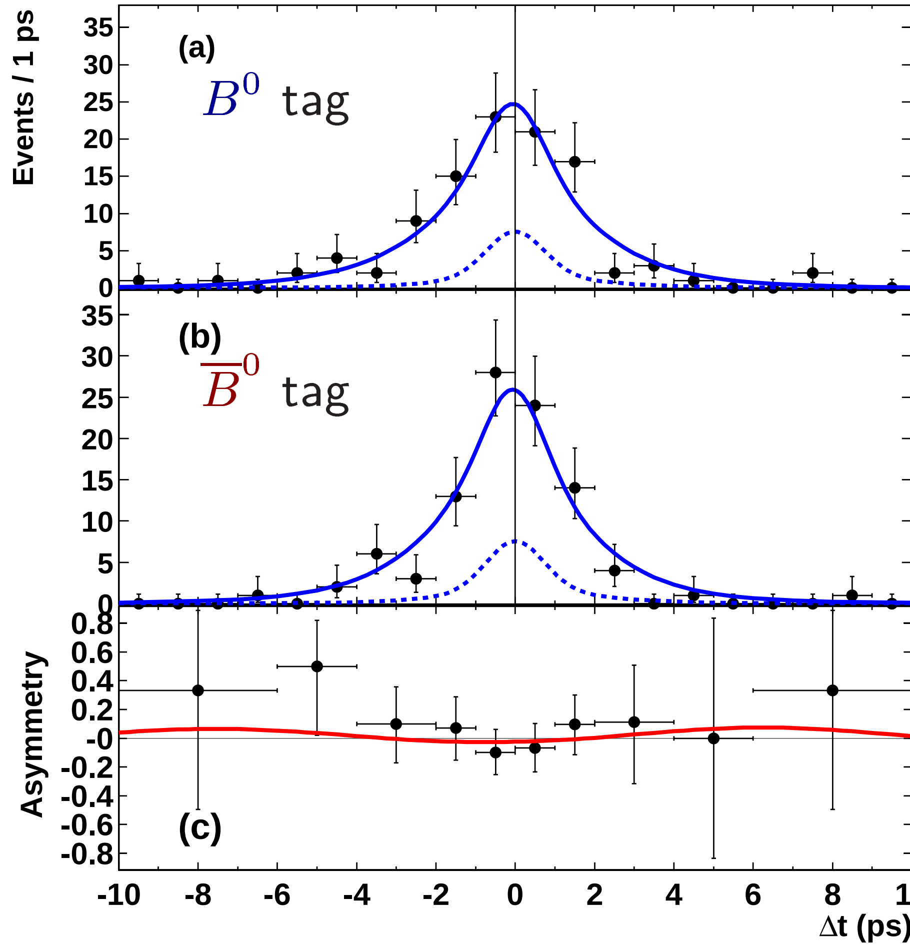
$$\mathcal{A} = -C_{\eta' K^0_S} = +0.26 \pm 0.22 \pm 0.03$$



(Consistent with charmonium result)

$\sin 2\beta$ from $B^0 \to \eta' K^0_s$





$\eta' \to \eta\pi\pi$ (shaded), $\rho\gamma$

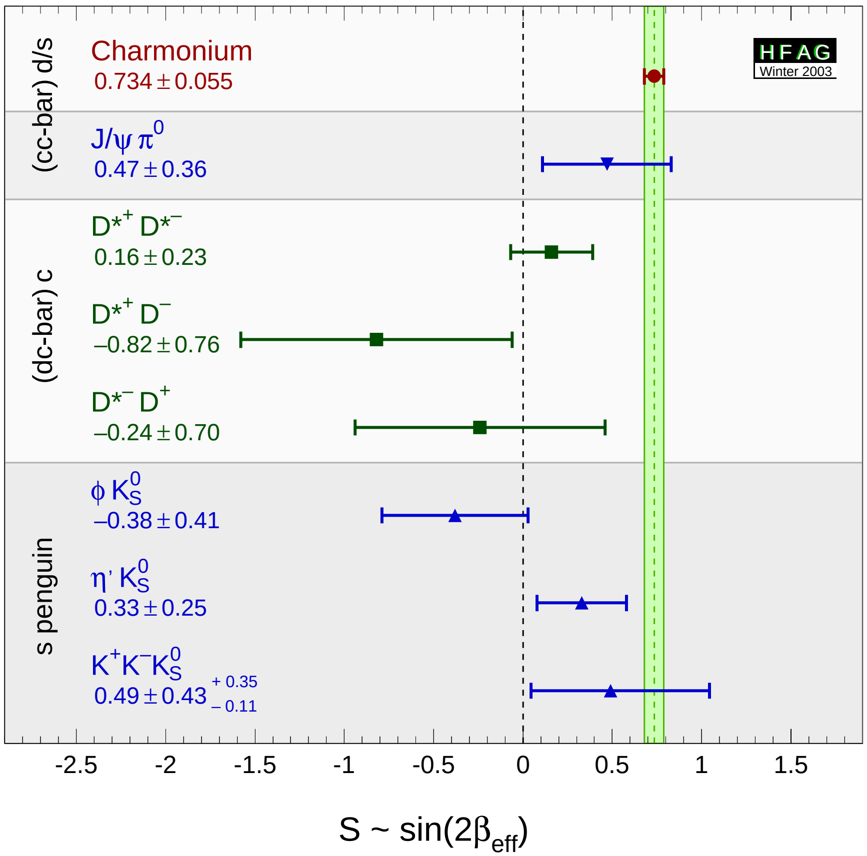
109.2 tagged signal events, purity 70%

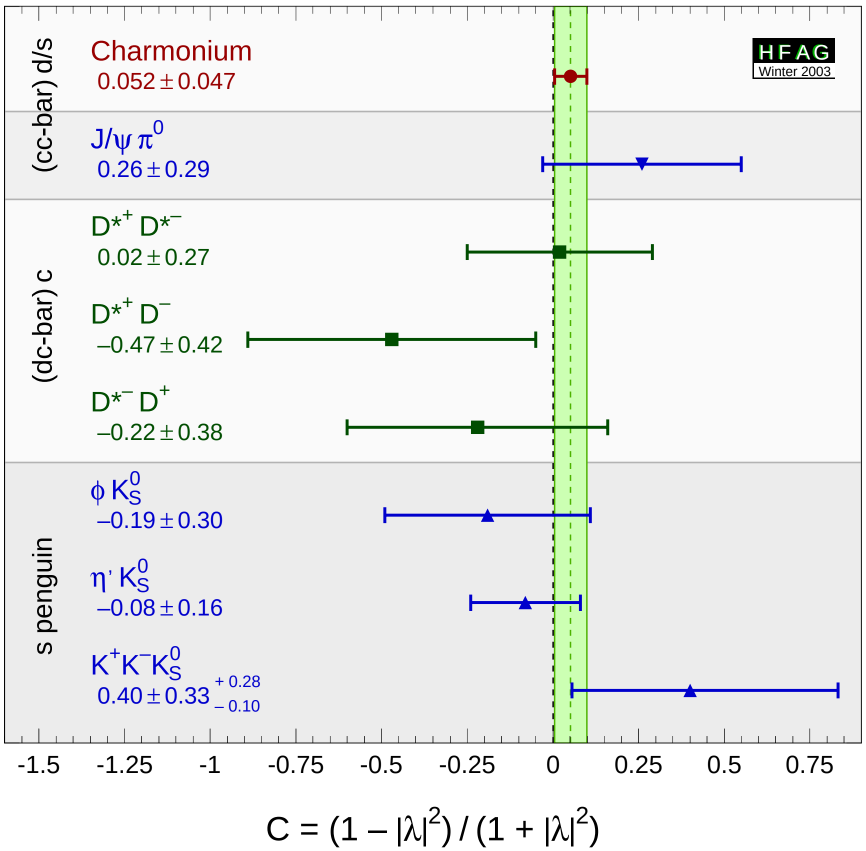
89×10^6 $B\overline{B}$ pairs

$$\sin 2\beta = S_{\eta' K^0_S} = 0.02 \pm 0.34 \pm 0.03, \quad C_{\eta' K^0_S} = 0.10 \pm 0.22 \pm 0.03$$

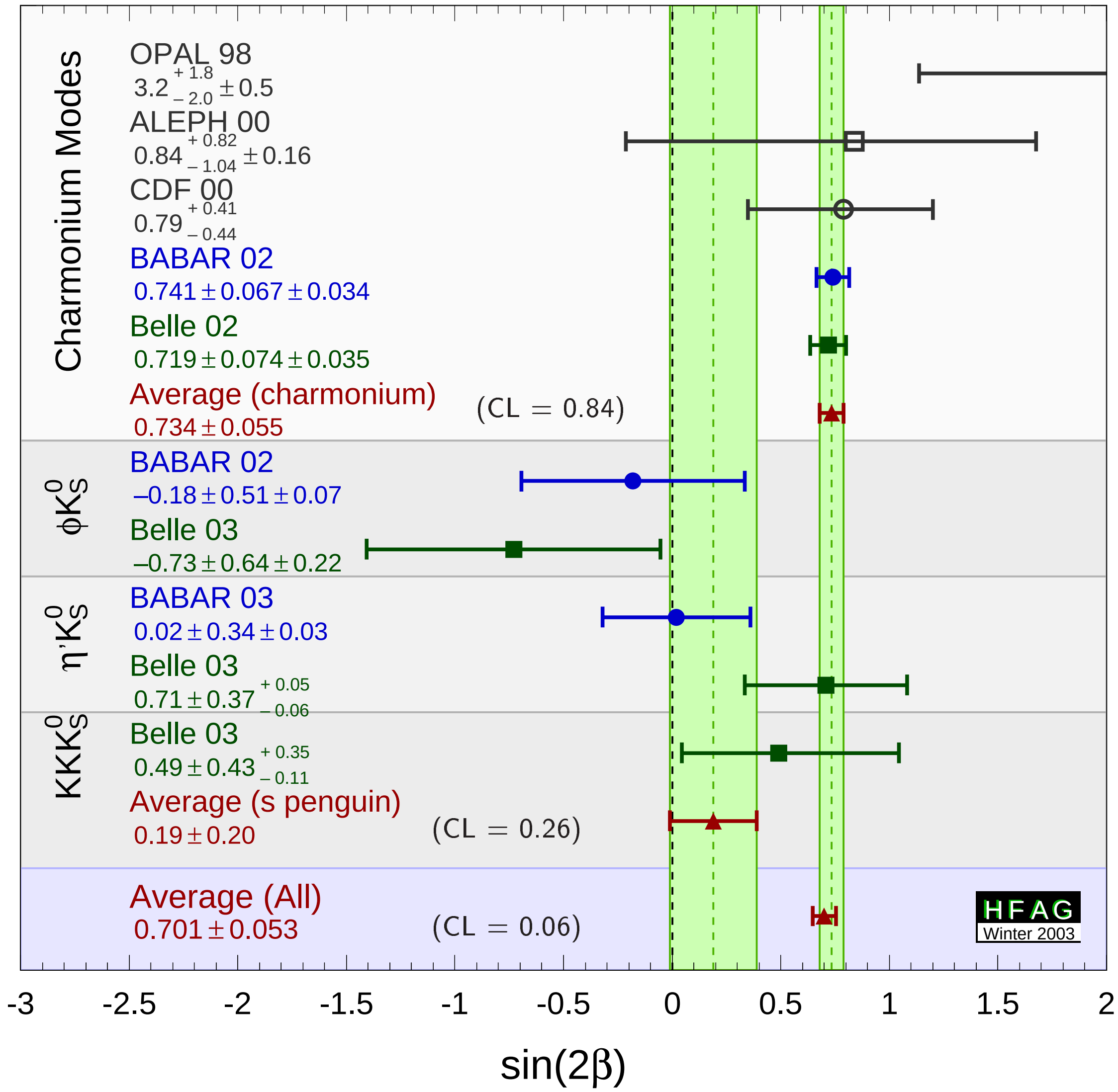
(Null result, though consistent within errors with $\sin 2\beta = 0.7$)

World average measurements of S, C





Measurements of $\sin 2\beta$



Future confirmation of the separation of the two bands would challenge the standard model.

Theoretical as well as experimental improvements needed.

Conclusions

- CP non conservation is well established in B^0 decays
- The effect is large in the interference between mixing and decay
- The effect is well accommodated in the standard CKM model
- Just beginning to explore further
  - ◇ Anything new happening where S.M. effects are suppressed?
  - ◇ Hint of inconsistencies in β from $\mathcal{O}(\lambda^3)$ decays
- Several channels now measured, needing only more data for definitive results