Measurement of the CKM angle β at *BaBar*

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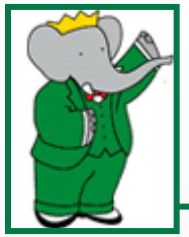
on behalf of the *BaBar* collaboration

Phenomenology Symposium – Madison – May 2007



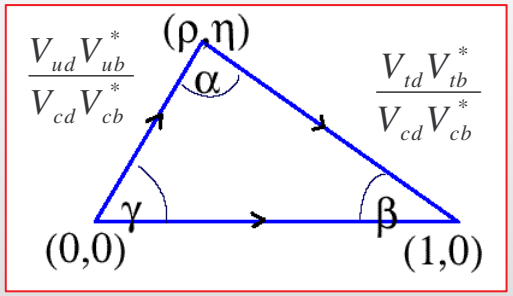
CP violation and the β angle

- CP violation in the Standard Model (SM) ⇔

CP-odd phase in the CKM matrix

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

⇔ Non-null apex of the unitarity triangle ($\eta \neq 0$)



- How to measure it? → in B^0 meson system CP violation effect in the interference between mixing and decay:

$$\Gamma(B^0(t) \to f_{CP}) \neq \Gamma(\overline{B}^0(t) \to f_{CP})$$

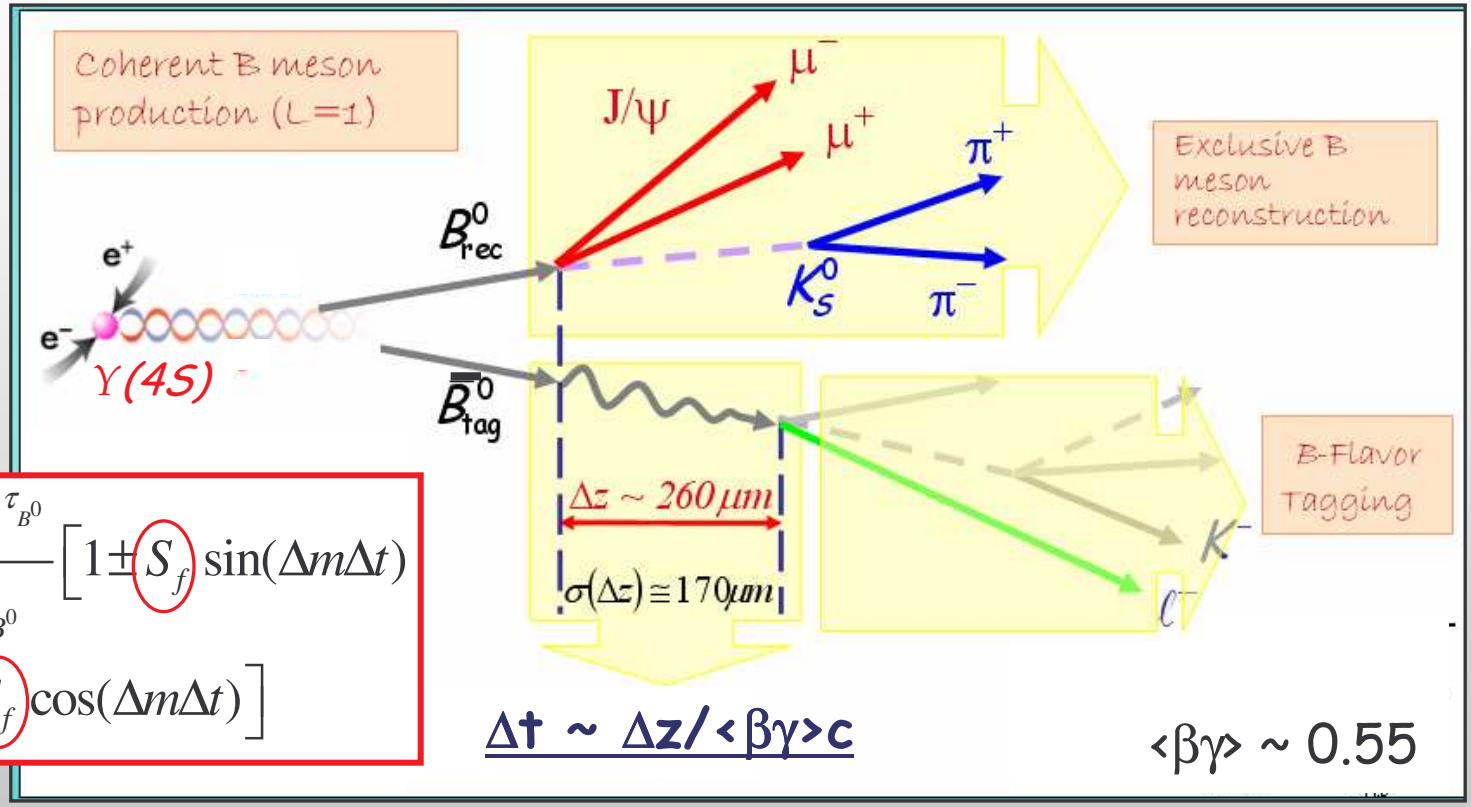
- Time-dependent asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

Difference of mass eigenstates

$$S_f = -\frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2} \qquad C_f = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad \lambda = \frac{q}{p} \cdot \frac{\overline{A}_f}{A_f}$$

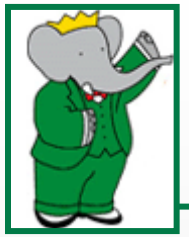
CP violation at the Υ(4S)



$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm S_f \sin(\Delta m \Delta t) \mp C_f \cos(\Delta m \Delta t)\right]$$

In all modes considered in this talk the SM expectations are:

$C_f = 0$ $\qquad$ $S_f = \pm \sin 2\beta$

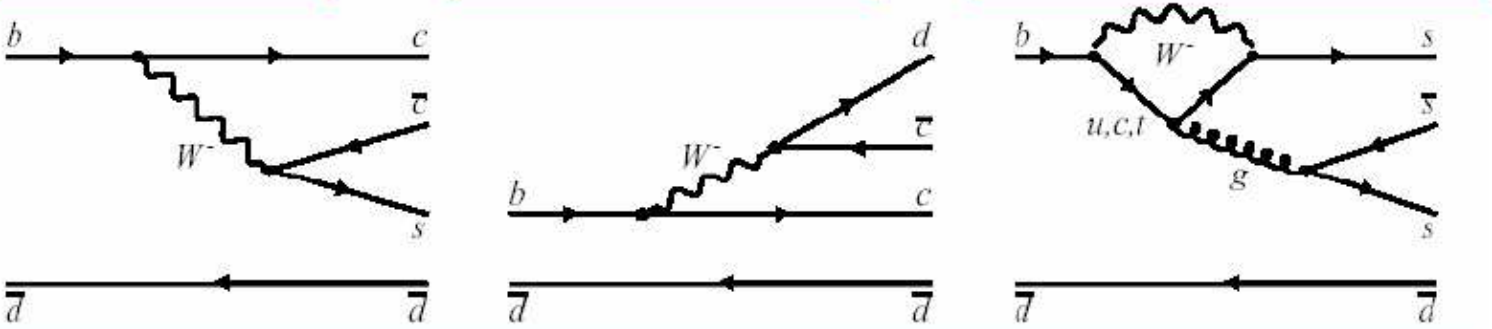


Many ways of measuring β…

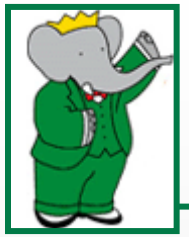
a) $b \to c\bar{c}s$ (charmonium)

b) $b \to c\bar{c}d$ charm (and charmonium)

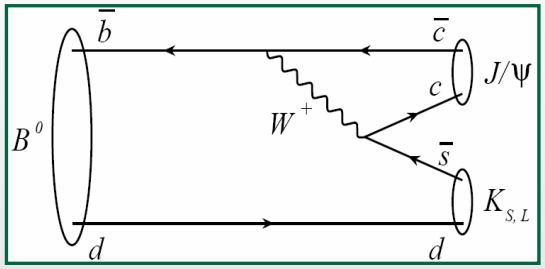
c) Penguin-dominated $b \to d\bar{d}s, b \to s\bar{s}s$



a)	b)	c)
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0,$ $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$
Large tree amplitude Low penguin pollution	Both tree and penguin amplitudes Cabibbo-suppressed: small BF's	No tree: sensitivity to New Physics particles in the loop

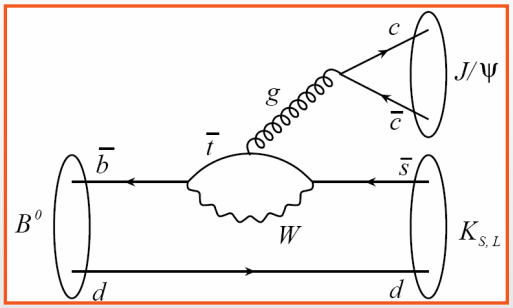


1) b → cc̄s (charmonium)



Color-suppressed tree

+



Gluonic penguin
(same weak phase)

- Experimentally clean
- BF = $O(10^{-3}) \div O(10^{-4})$
- Still "golden-plated" channels
- In the SM:

$$\mathcal{A}_{penguin} << \mathcal{A}_{tree}$$

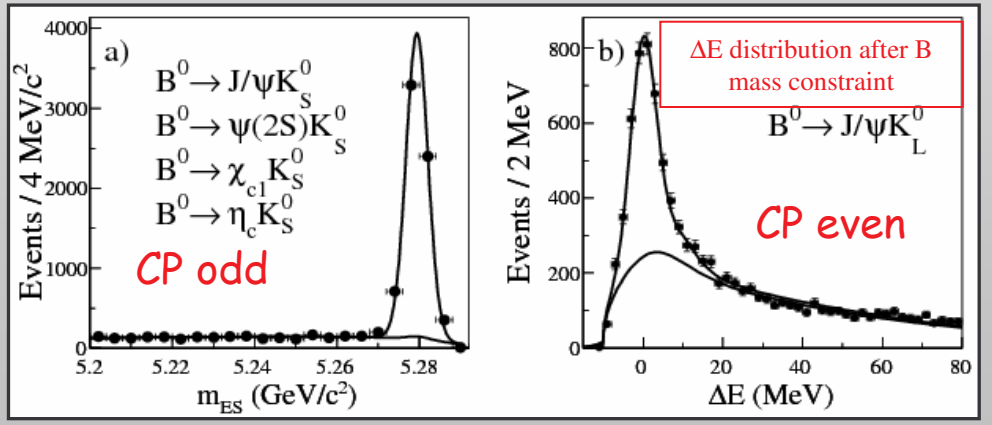
- Theoretical uncertainties on $\Delta S_f = S_f - \sin 2\beta$:
  - Factorization + non-perturbative QCD:
    - $\Delta S_{J/\psi Ks} = (-2.2 \pm 2.2) \cdot 10^{-4}$ [Boos et al., PRD 70, 036006 (2004)]
    - $\Delta S_{J/\psi Ks} = (9.3\ ^{+3.6}_{-4.6}) \cdot 10^{-4}$ [Li and Mishima, hep-ph/0610120]
  - Model-independent data-driven calculation: ΔS is constrained using measurements of the SU(3)-related process $B^0 \to J/\psi\pi^0$:

    $\Delta S_{J/\psi Ks} = (0.000 \pm 0.012)$ [Ciuchini et al., PRL 95, 221804 (2005)]
    [Ciuchini at CKM 2006]

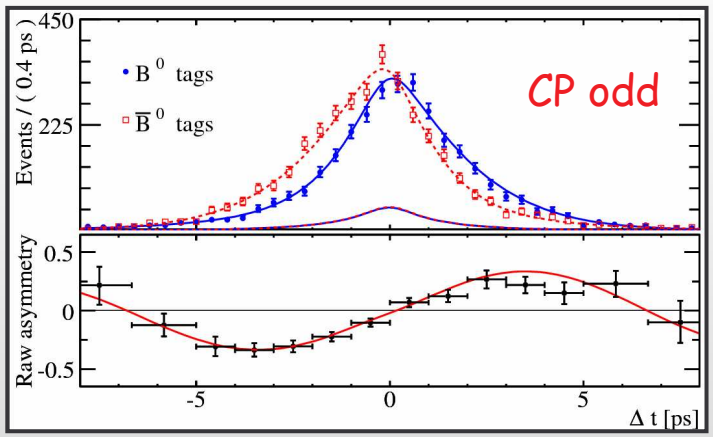
sin2β from $B^0 \to (c\bar{c})K^{(*)0}$ (I)

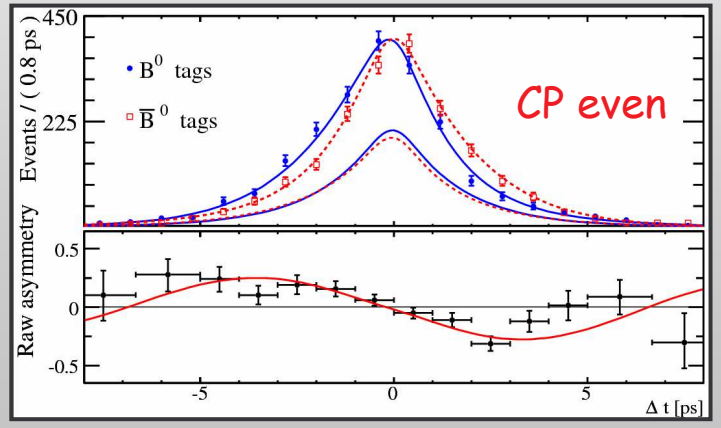
- "Reference" sin2β measurement (O(%) uncertainty)
- Improvements with respect to previous BaBar measurements:
  - Using full BaBar statistics: 383 ·10^6 $B\bar{B}$ pairs
  - Alternative Δt fit configurations added to the nominal one (all even/odd modes together):
    - Fit of sin2β and |λ| for each mode separately
    - Fit of sin2β and |λ| for $J/\psi K^0$ (K_S + K_L) and $J/\psi K_S$ only
  - Now including $J/\psi K^{*0}$ ($K_S\pi^0$) and $J/\psi K_L$ in the |λ| measurement
  - Reduction of systematic error related to backgrounds

Sample	N_{events}	Purity (%)
CP-odd	6873	92
CP-even	4730	55
J/ψ K^{*0}	1056	66



sin2β from $B^0 \to (c\bar{c})K^{(*)0}$ (II)



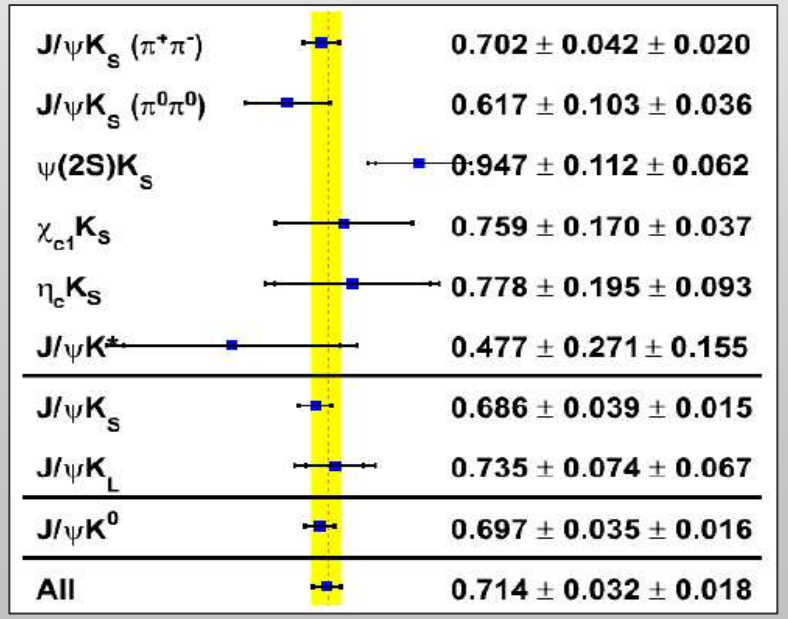


hep-ex/0703021, submitted to PRL

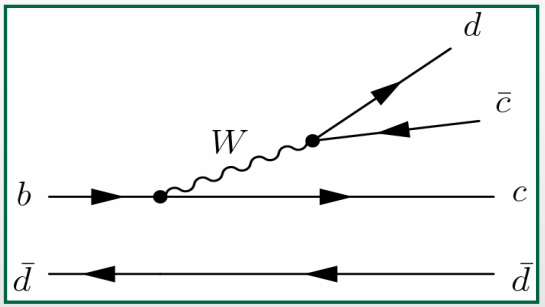
$$\sin 2\beta = 0.714 \pm 0.032(\text{stat}) \pm 0.018(\text{syst})$$
$$|\lambda| = 0.952 \pm 0.022(\text{stat}) \pm 0.017(\text{syst})$$

- ~5% total uncertainty on sin2β
- |λ| result compatible with 1 at 1.7σ

sin2β result split in sub-modes:



2) b → cc̄d transitions



Cabibbo-suppressed tree

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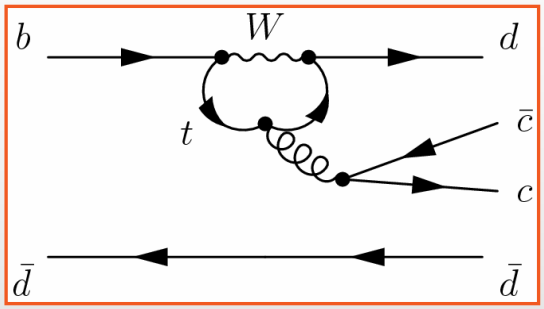


Gluonic penguin
(different weak phase)

- $BF(B^0 \to D^{(*)}D^{(*)}) = O(10^{-4})$
- Expected penguin contribution negligible: 2-10%

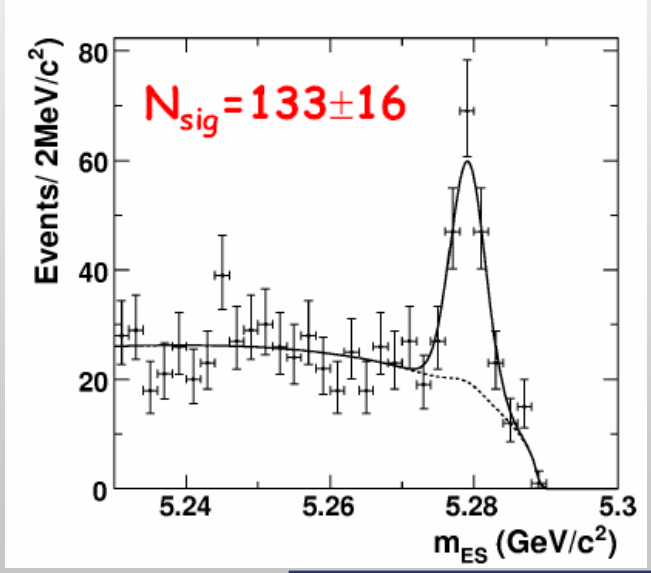
[Z.-Z. Xing, Phys. Rev. D 61, 014010 (2000)]

- β_{eff} (i.e. β angle as effectively measured in such processes) sensitive to New Physics in loops: $\beta_{eff} - \beta$ up to 0.6 in supersymmetric models

[Y. Grossman and M. Worah, Phys. Lett. B 395, 241 (1997)]

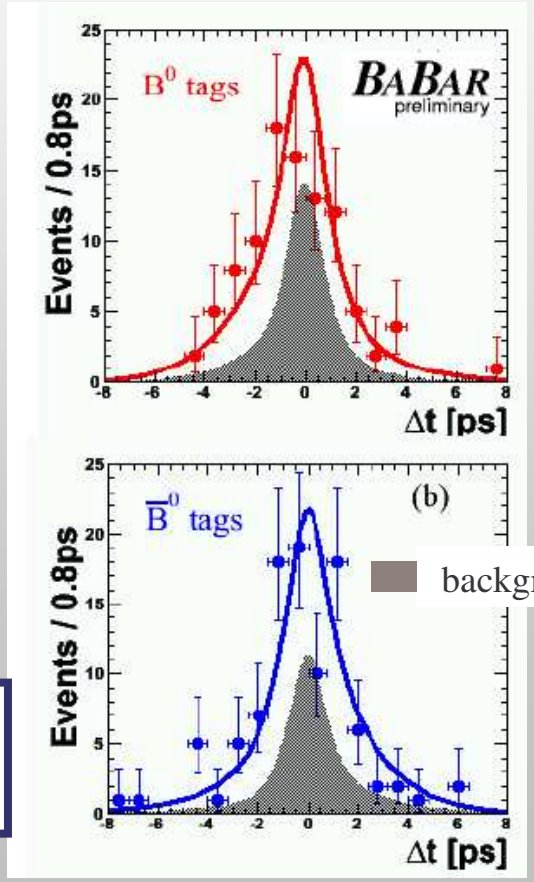
Recent results: $B^0 \to D^+D^-$

- Claim of a large CP violation measurement by Belle in $B^0 \to D^+D^-$:
  $(C_{DD}, S_{DD}) \neq (0, 0)$ at 4.1σ [hep-ex/0702031, submitted to PRL]
- BaBar does not confirm observation:

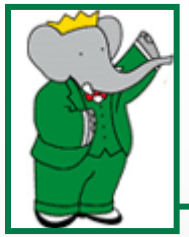


364 ·10⁶ $B\bar{B}$ pairs

D. Lange at Moriond 2007, PRELIMINARY



$$\sin 2\beta_{eff} = 0.54 \pm 0.34(\text{stat}) \pm 0.06(\text{syst})$$
$$C = 0.11 \pm 0.22(\text{stat}) \pm 0.07(\text{syst})$$



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

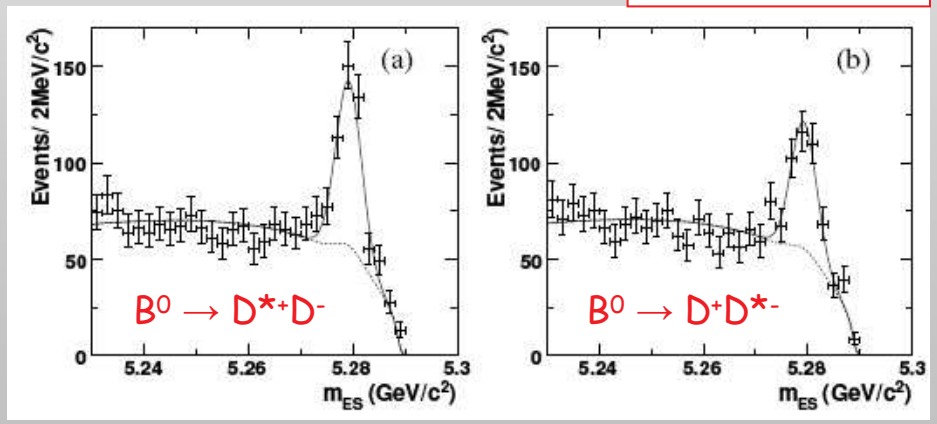
- Not a CP eigenstate: need to define C_{+-}/C_{-+} and S_{+-}/S_{-+} that depend on the strong phase difference between the two processes.
- General relation: $S_{\pm\mp} = -\sqrt{1-C^2_{\pm\mp}}\,\sin(2\beta_{eff} \pm \delta)$
- If penguin contribution is negligible: $\beta_{eff} = \beta$, $C_{+-} = -C_{-+}$
- Signal of CP violation:

$$\sin 2\beta \neq 0 \quad \Leftrightarrow \quad S_{+-} \neq -S_{-+}$$

364 ·10^6 B$\overline{\text{B}}$ pairs

D. Lange at Moriond 2007, PRELIMINARY

$$C_{+-} = 0.18 \pm 0.15(\text{stat}) \pm 0.04(\text{syst})$$
$$C_{-+} = 0.23 \pm 0.15(\text{stat}) \pm 0.04(\text{syst})$$
$$S_{+-} = -0.79 \pm 0.21(\text{stat}) \pm 0.06(\text{syst})$$
$$S_{-+} = -0.44 \pm 0.22(\text{stat}) \pm 0.06(\text{syst})$$

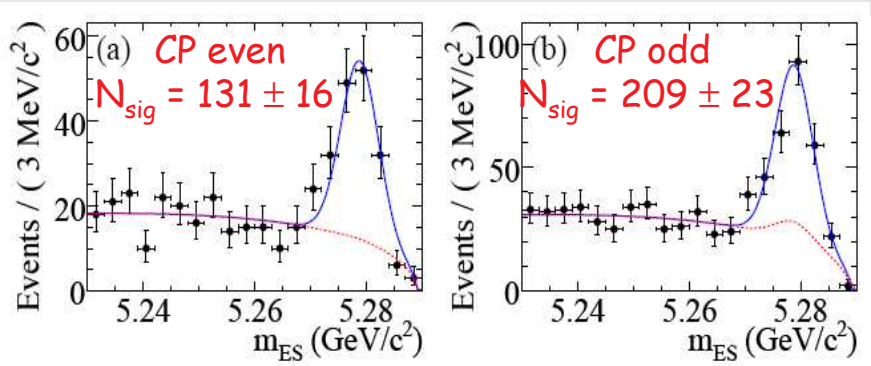


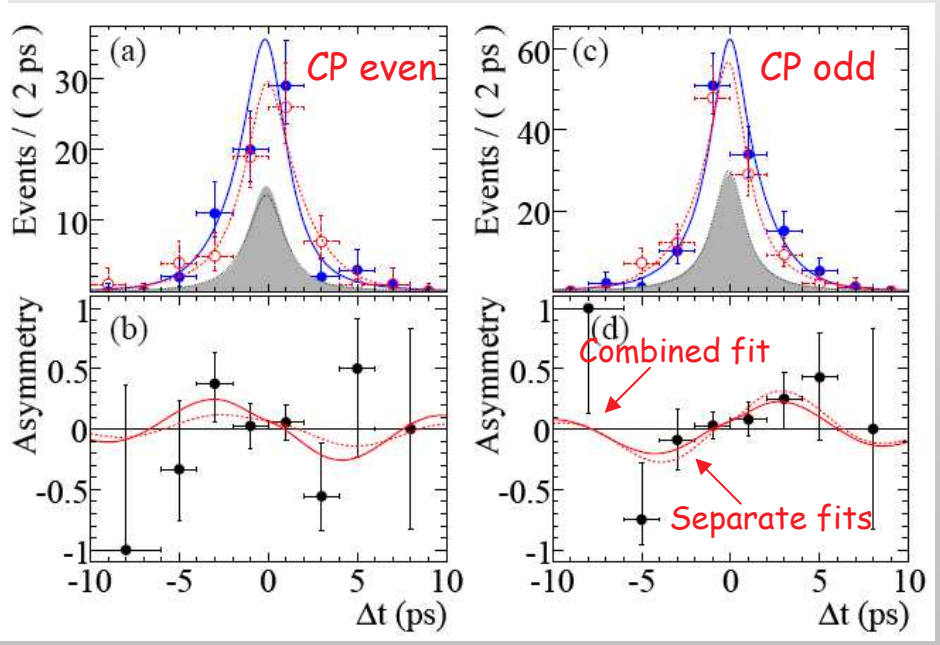
Recent results: $B^0 \to D^{(*)0}h^0$

- Used modes: $h^0 = \pi^0, \eta, \omega$ $D^0 = D^0_{CP} \to K^+K^-, K_S\pi^0, K_S\omega$
- $b \to c\bar{u}d$ transition:
  - No penguin contribution → theoretically clean
  - Very small contribution from DCS decays ($b \to u\bar{c}d$)

hep-ex/0703019, submitted to PRL

$383 \cdot 10^6$ $B\bar{B}$ pairs

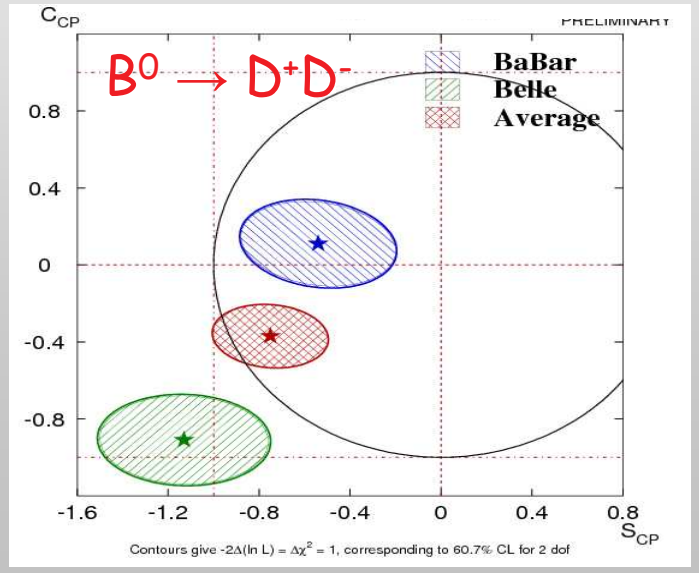




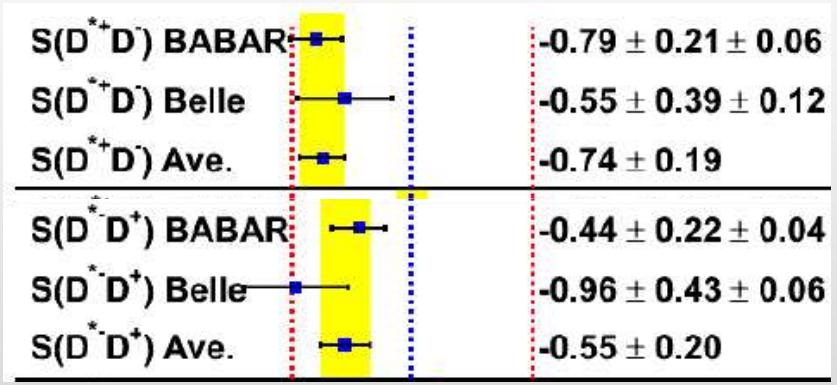
$$\sin 2\beta_{eff} = 0.56 \pm 0.23(\text{stat}) \pm 0.05(\text{syst})$$
$$C = -0.23 \pm 0.16(\text{stat}) \pm 0.04(\text{syst})$$

Summary of $b \to c\bar{c}d$ ($c\bar{u}d$)

- $B^0 \to D^+D^-$
  - No evidence of CP violation measured
  - ~3σ disagreement between BaBar and Belle results

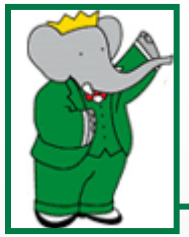


- $B^0 \to D^{*+}D^-$, D^+D^{*-}



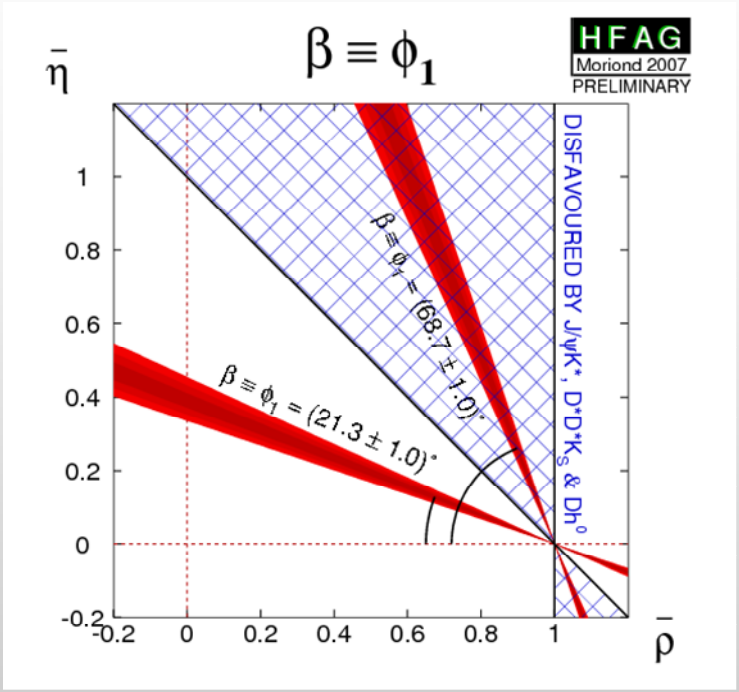
  - Hints of CPV when combining Babar and Belle results: $S_{+-} \neq -S_{-+}$ at ~ 4σ

- $B^0 \to D^{(*)0}h^0$ (first measurement)
  - Both $\sin 2\beta_{eff}$ and C consistent with SM expectations



Resolving the β ambiguity

- When extracting β from sin2β, two-fold ambiguity left in the ρ-η positive quadrant
- cos2β is measured from time-dependent analyses of J/ψK*, D^0h^0, $D^{*+}D^{*-}K_S$
- Recent BaBar results:
  - Time-dependent Dalitz analysis of $B^0 \to D^{(*)0}h^0$ ($D^0 \to K_S\pi^+\pi^-$)



$\cos2\beta > 0$ at 87% CL

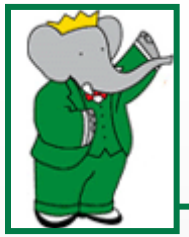
hep-ex/0607105, PRELIMINARY

  - Time-dependent Dalitz analysis of $B^0 \to D^{*+}D^{*-}K_S$:

$(J_{s2}/J_0)\cos2\beta > 0$ at 94% CL

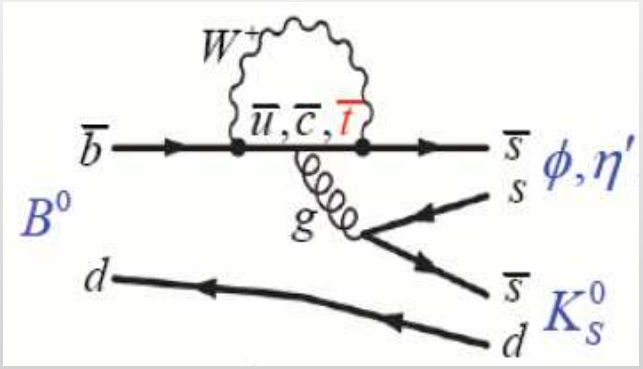
Phys. Rev. D 74, 091101 (2006)

Integrals over Dalitz phase space: positive under certain theoretical assumptions



3) β in penguins: motivations

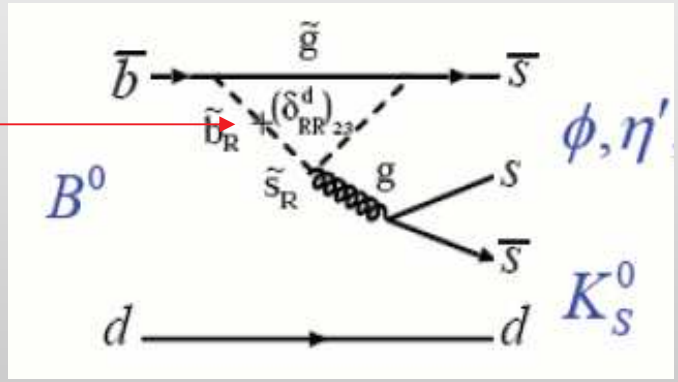
- Pure b → ss̄s transitions include a Flavor Changing Neutral Current: in the SM they must proceed through a penguin diagram
- b → dd̄s (and similar): theoretical calculation predict penguin-dominated



SM

SUSY coupling:
- mass-suppressed ($\sim 1/M^2$)
- coupling-enhanced ($\sim \alpha_S/\alpha_W$)

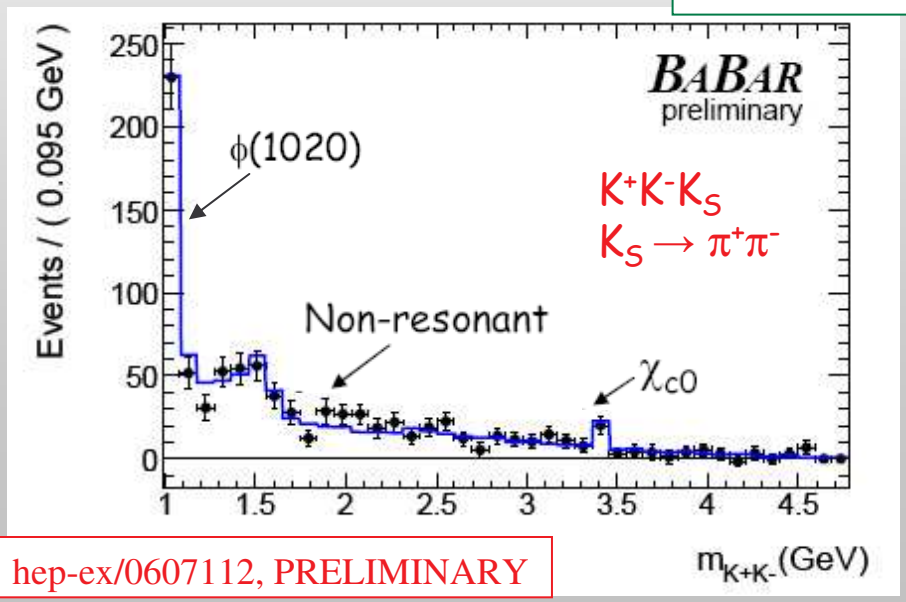
SUSY



- Quark-squark coupling adds unknown SUSY phases to the mixing phase 2β → $A_{CP}(\Delta t)$ sensitive to presence of new particles in the loop
- Caveat: interpretation of $\beta_{eff} - \beta$ not completely clean in all cases due to hadronic uncertainties

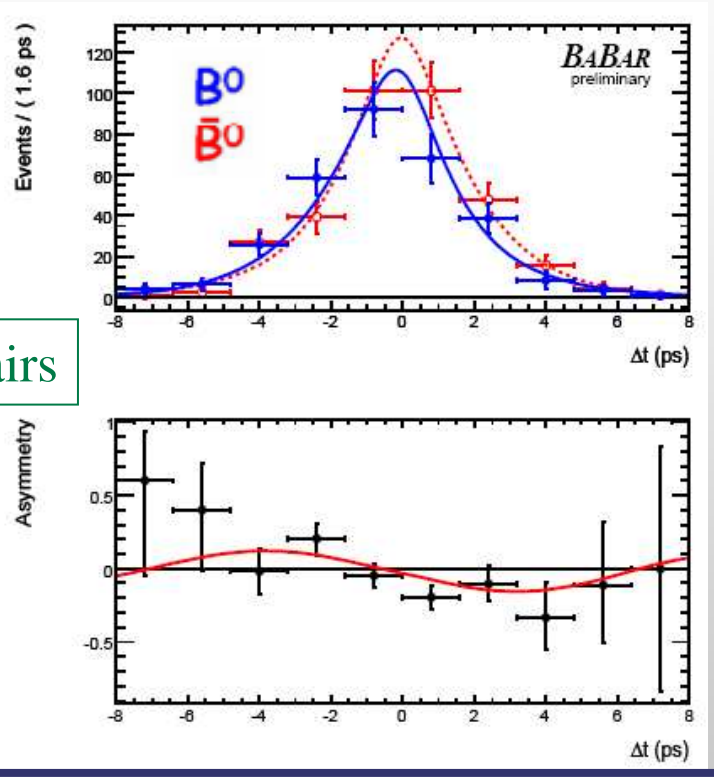
Dalitz analysis of $B^0 \to K^+K^-K^0$

- Time-dependent Dalitz analysis:
  - Taking for the first time into account interference between high and low KK mass (close to ϕ resonance) regions



hep-ex/0607112, PRELIMINARY

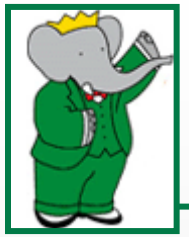
347 ·10^6 B$\bar{B}$ pairs



Combined (whole Dalitz plot):

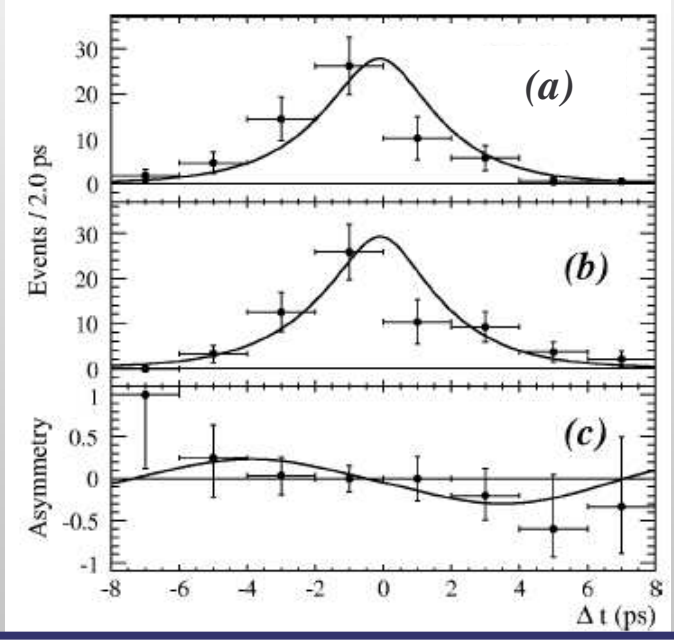
$\beta_{eff} = 0.361 \pm 0.079(\text{stat}) \pm 0.037(\text{syst})$

$C = 0.034 \pm 0.079(\text{stat}) \pm 0.025(\text{syst})$



$B^0 \to K_S K_S K_S$ and $B^0 \to \eta' K^0$

- $B^0 \to K_S K_S K_S$: hep-ex/0702046, Submitted to PRL
  - Challenging vertex reconstruction (beam-spot constraint used)

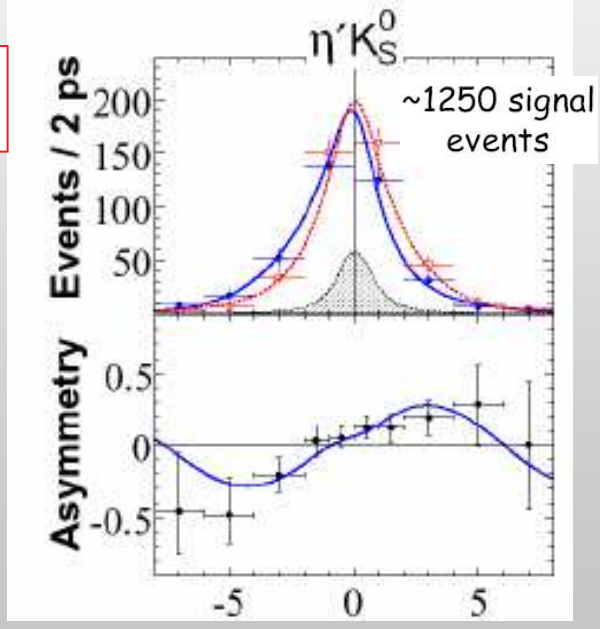


$\sin 2\beta_{eff} = 0.71 \pm 0.24(\text{stat}) \pm 0.04(\text{syst})$

$C \quad = 0.02 \pm 0.21(\text{stat}) \pm 0.05(\text{syst})$

- $B^0 \to \eta' K^0$:
  - Large BF ($\sim 6 \cdot 10^{-5}$)
  - Many η' reconstruction modes

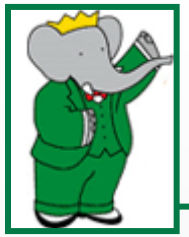
Phys.Rev.Lett. 98, 031801 (2007)



Evidence of CPV with > 5σ significance

$\sin 2\beta_{eff} = 0.58 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$

$C \quad = -0.16 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$



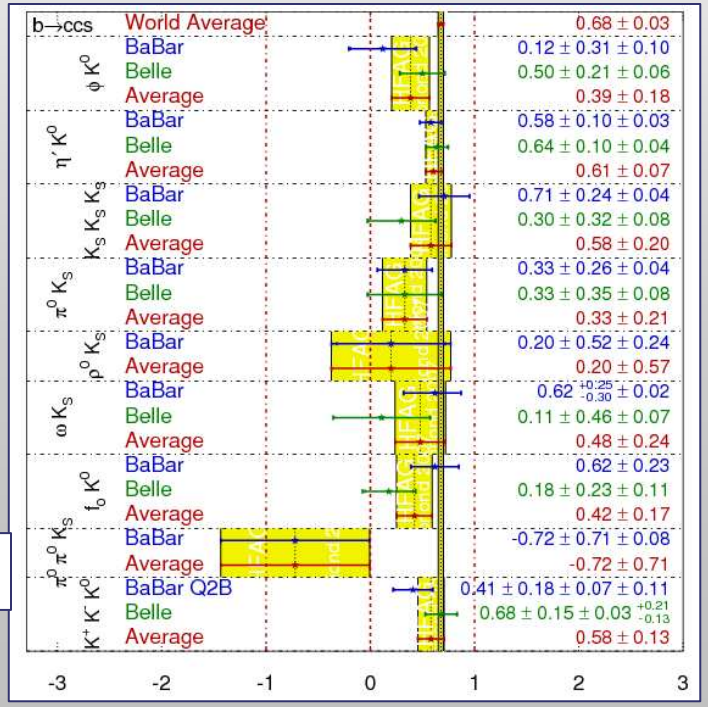
Conclusions

- Measurements of the CKM angle β have reached the O(%) precision:
  - CP violation well established in B^0-meson system
  - Main input in unitarity triangle fits

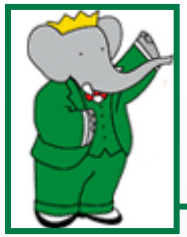
$\beta = (21.3 \pm 1.0)^o$

(World Average)

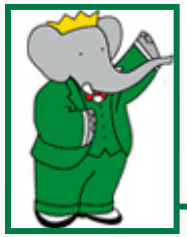
- New results from BaBar:
  - sin2β update on $B^0 \to (c\bar{c})K^{(*)0}$ with 383 million B pairs
  - β ambiguity broken by cos2β measurements
  - New results on $B \to D^{(*)}D^{(*)}$ and $B \to D^{(*)0}h^0$
    - Evidence for CPV in $B^0 \to D^{*+}D^-$
    - 3σ puzzle in $B^0 \to D^+D^-$ (BaBar-Belle)
  - Hints of difference between sin2β in trees and penguins persist ($\Delta S = \sin2\beta_{eff} - \sin2\beta < 0$) but handle averages with care …



$\sin(2\beta^{eff})$



Backup slides



Penguin averaging …

- Averaging over all s-penguin modes assumes that contributions with non-zero weak phases to the decay amplitudes can be neglected. This assumption may be significantly violated due to doubly CKM-suppressed V_{ub} penguin amplitudes, and, in some cases, doubly CKM-suppressed and color-suppressed V_{ub} tree amplitudes that contribute to the decay amplitude.
- Recent theoretical analyses indicate that it is reasonable to expect that, while the modes φK^0, $\eta' K^0$ and $K_S\, K_S\, K_S$ have theoretical uncertainties of the order of 0.05 or smaller, these can be significantly larger for the other modes (in particular for non-ss-resonance modes: $\pi^0 K_S$, $\rho^0 K_S$, ωK_S and $K^+K^-K^0$).

[Heavy Flavor Averaging Group webpage]