Measurement of β in B decays to charm and charmoniun at *BaBar*

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On behalf of the *BaBar* Collaboration

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Overview

- Introduction
- CP violation at B-factories
- $\beta(\phi_1)$ measurements
  - Sin(2β) measurements
    - charmonium K
    - D^0h^0, $D^0 \rightarrow$CP-eigenstate
    - $D^{(*)+}D^-$
  - Cos(2β) measurements
- Conclusions

Introduction

CP Violation and β angle

CP-odd phase

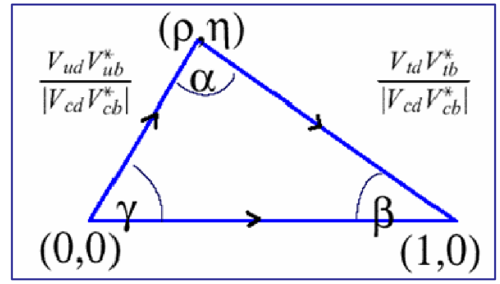
in CKM matrix

Non null apex of the Unitarity Triangle (UT)

CP violation (CPV) in Standard Model (SM) ⇔

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

⇔



- CPV in neutral B mesons can be tested via their decay to CP-eigenstates
- A B^0 that mixes into a $\overline{B}^0$ "gains" a 2β phase

Δm ≡ mixing frequency

- The interference between mixing and decay produces the CP asymmetry

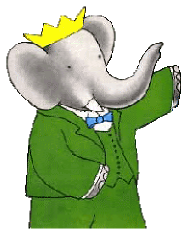
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} = \boldsymbol{S}_f \sin(\Delta m t) - \boldsymbol{C}_f \cos(\Delta m t)$$

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

In SM with one diagram only:

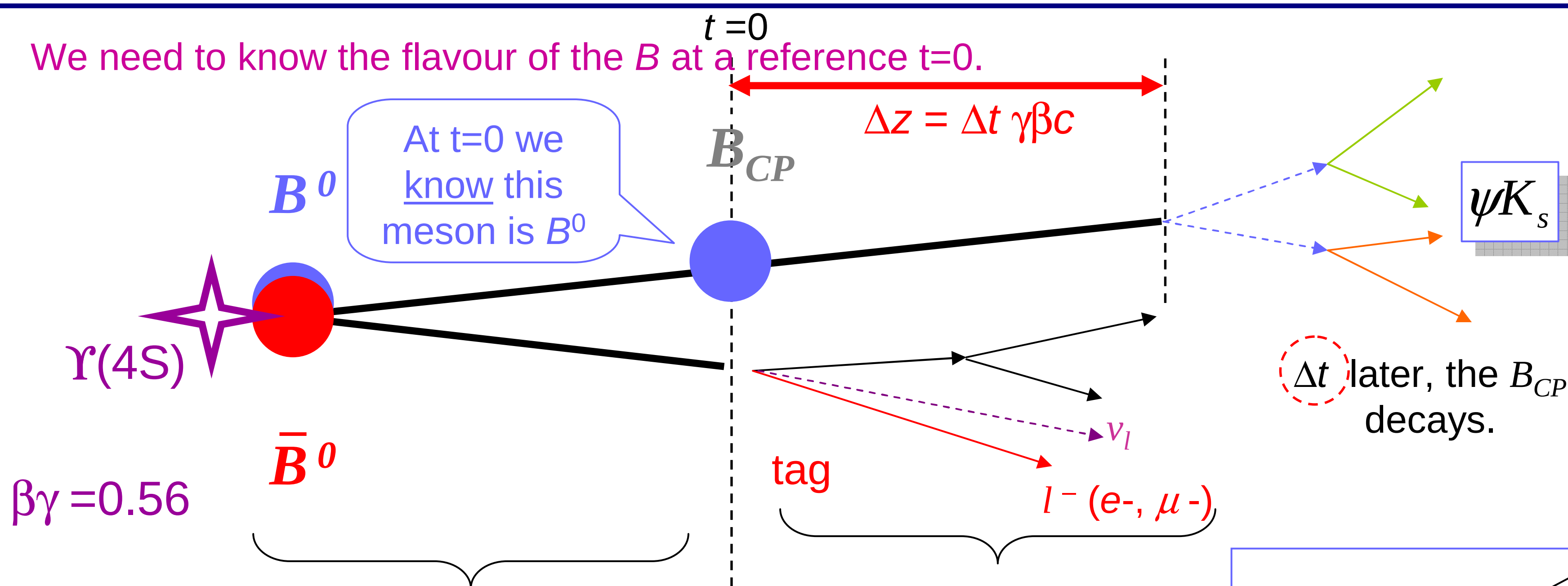
$q/p = e^{-2i\beta}$

PEP-II B-factory and *BaBar* experiment



CPV at B-factories

We need to know the flavour of the *B* at a reference t=0.

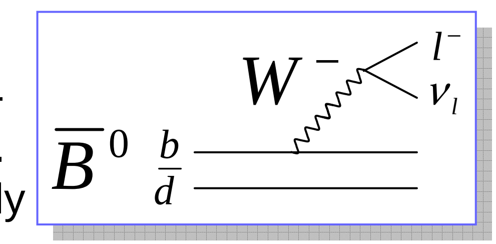


The two mesons oscillate coherently : at any given time, if one is a B^0 the other is necessarily a $\overline{B}^0$

In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson :

$l^- = \overline{B}^0 \qquad l^+ = B^0.$

(Kaon and pion tags also used)



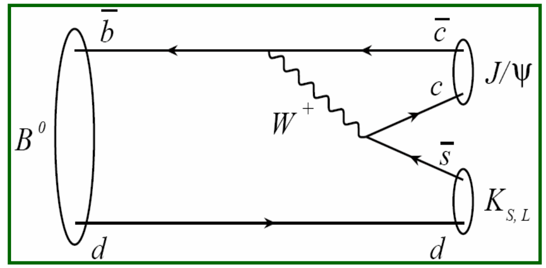
BABAR

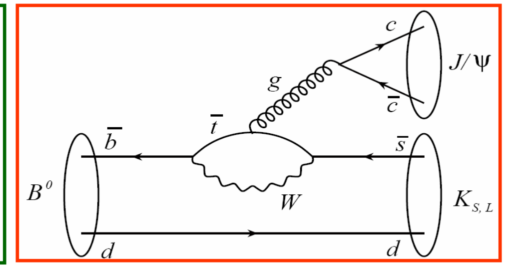
Sin(2β) measurements

Charmonium K^0 : introduction

- Golden modes:
  1. Small SM uncertainties: tree and penguin diagrams have same weak phase

Model-independent data-driven calculation, using SU(3)-related process $B^0 \to J/\psi\pi^0$





  - $\Delta S_{J/\psi Ks}$ = (0.000 ± 0.012) [Ciuchini et al., PRL 95, 221804 (2005)]
  - $\Delta S_{J/\psi Ks}$ = $(9.3\ ^{+3.6}_{-4.6})\cdot 10^{-4}$ [Li and Mishima, hep-ph/0610120]

Factorization + NPQCD

  2. Relatively large Branching Fractions

$B \to J/\psi K^0 \sim 8.5\text{x}10^{-4}$
$B \to \psi(2S) K^0 \sim 6.2\text{x}10^{-4}$
$B \to \chi_{c1} K^0 \sim 4\text{x}10^{-4}$
$B \to \eta_c K^0 \sim 1.2\text{x}10^{-3}$

  3. Clear experimental signature

$$B^0 \to J/\psi\, K_S,\ J/\psi \to \ell^+\ell^-,\ K_S \to \pi^+\pi^-$$

Charmonium K^0: samples

B_{CP} sample

- $B \to J/\psi K^0$
  - $J/\psi \to e\, e,\ \mu\, \mu$
  - $K_S^0 \to \pi\, \pi$
  - K_L^0 : cluster
- $B \to \psi(2S) K_S^0$
  - $\psi(2S) \to e\, e,\ \mu\, \mu,\ J/\psi\, \gamma$
- $B \to \chi_{c1} K_S^0$
  - $\chi_{c1} \to J/\psi\, \gamma$
- $B \to \eta_c K_S^0$
  - $\eta_c \to K^0 K^+ \pi^-$
- $B \to J/\psi K^{*0}$
  - $K^{*0} \to K_S^0\, \pi^0$

B_{flav} sample

- $B \to D^{*-}\, \pi^+$
- $B \to D^{*-}\, \rho^+$
- $B \to D^{*-}\, a_1^+$
- $B \to D^-\, \pi^+$
- $B \to J/\psi K^{*0} (K^{*0} \to K^+\, \pi^-)$

For tagging performance and resolution studies

B^- sample

- $B^- \to D^0\, \pi^-$
- $B^- \to D^{*0}\, \pi^-$
- $B^- \to J/\psi K^-$
- $B^- \to \psi(2S) K^-$
- $B^- \to \chi_{c1} K^-$
- $B^- \to J/\psi K^{*-} (K^{*-} \to K^-\, \pi^0)$

Control sample;

null expected asymmetry

Charmonium K^0: results

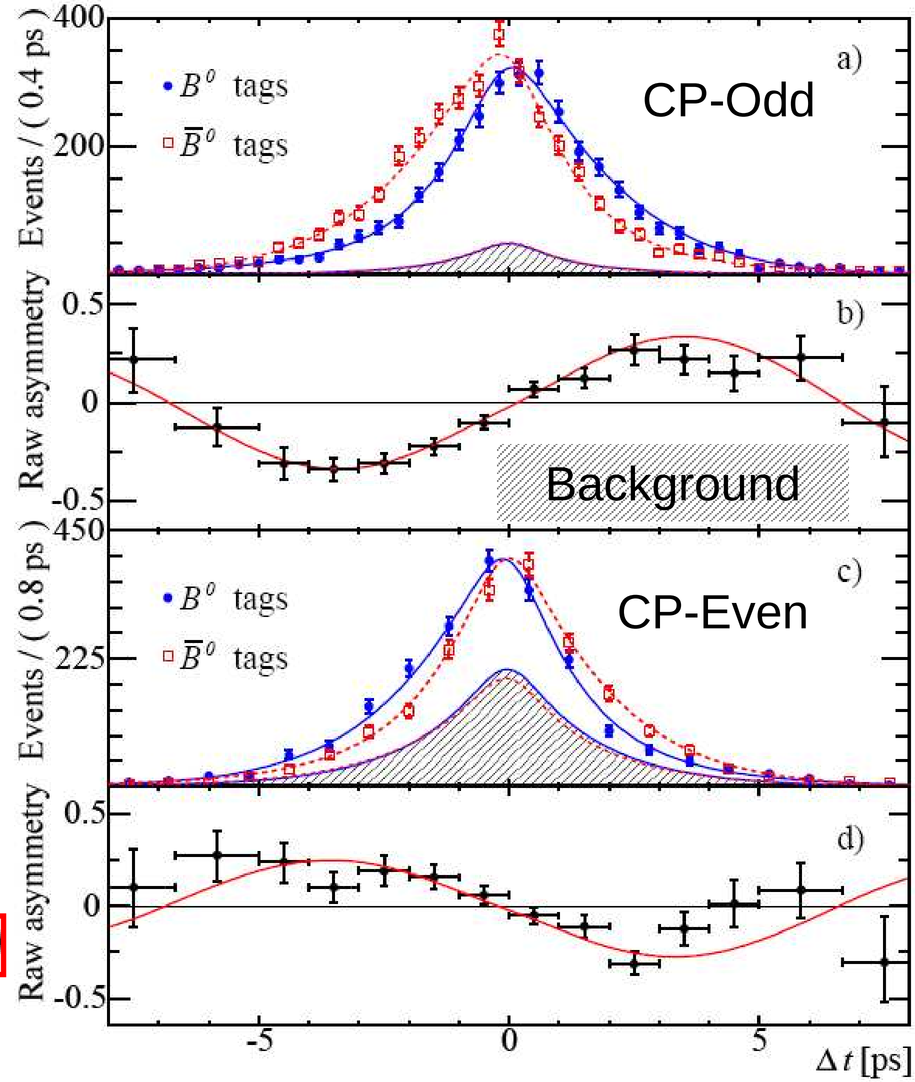
hep-ex/0703021, submitted to PRL

384 M $B\bar{B}$ pairs

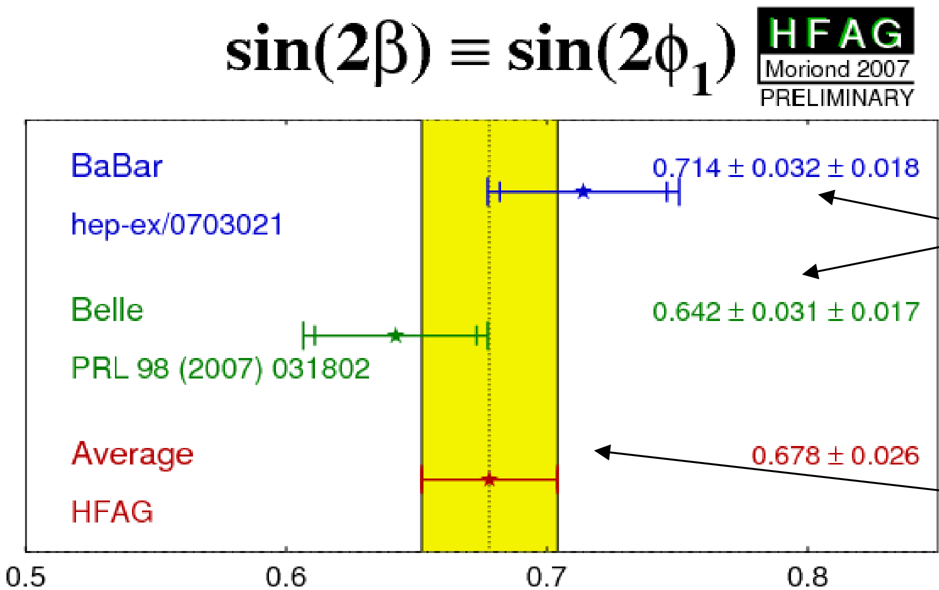
Mode	$\sin 2\beta$
$J/\psi K_S\ (\pi^+\pi^-)$	$0.702 \pm 0.042 \pm 0.020$
$J/\psi K_S\ (\pi^0\pi^0)$	$0.617 \pm 0.103 \pm 0.036$
$\psi(2S) K_S$	$0.947 \pm 0.112 \pm 0.062$
$\chi_{c1} K_S$	$0.759 \pm 0.170 \pm 0.037$
$\eta_c K_S$	$0.778 \pm 0.195 \pm 0.093$
$J/\psi K^*$	$0.477 \pm 0.271 \pm 0.155$
$J/\psi K_S$	$0.686 \pm 0.039 \pm 0.015$
$J/\psi K_L$	$0.735 \pm 0.074 \pm 0.067$
$J/\psi K^0$	$0.697 \pm 0.035 \pm 0.016$
All	$0.714 \pm 0.032 \pm 0.018$

$$\sin 2\beta = 0.714 \pm 0.032\,(\text{stat}) \pm 0.018\,(\text{syst})$$

$$|\lambda| = 0.952 \pm 0.022\,(\text{stat}) \pm 0.017\,(\text{syst})$$

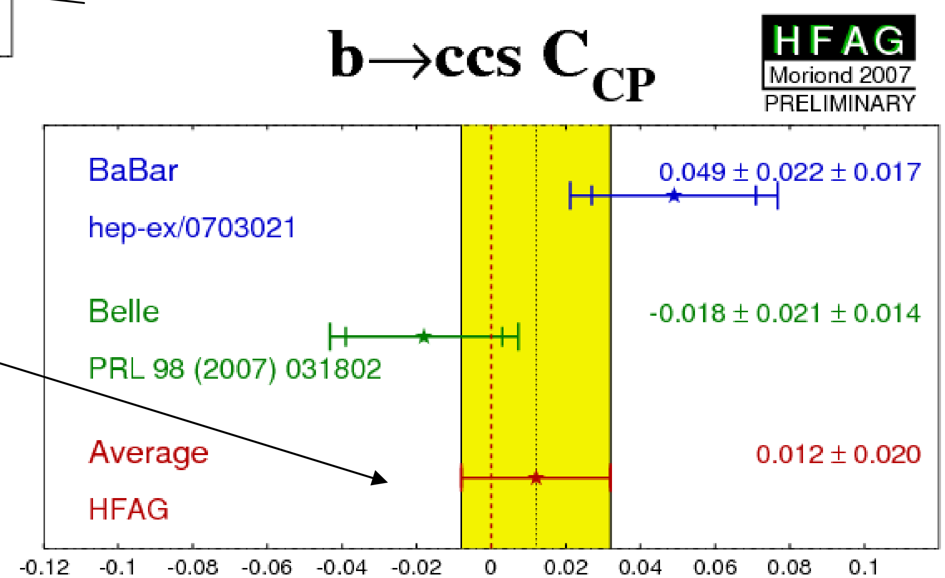


Charmonium K^0: comparison



It has become a precision measurement: O(4%)

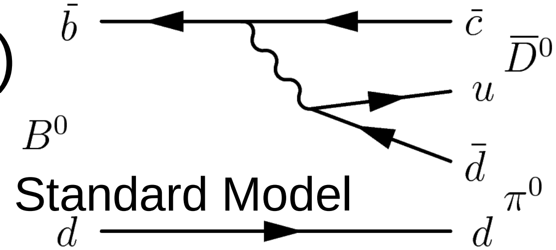
Good world agreement



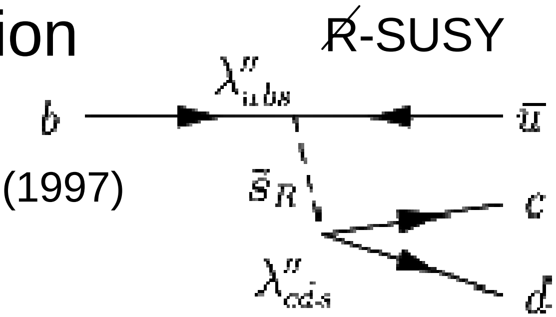
Consistent with Standard Model expectations

$B^0 \to D^{(*)0}h^0$, $D^0 \to CP$

- $B^0 \to D^{(*)0}h^0$ are color suppressed $b \to c\bar{u}d$ transitions
  - h^0 is a light meson (such as π^0, η or ω)



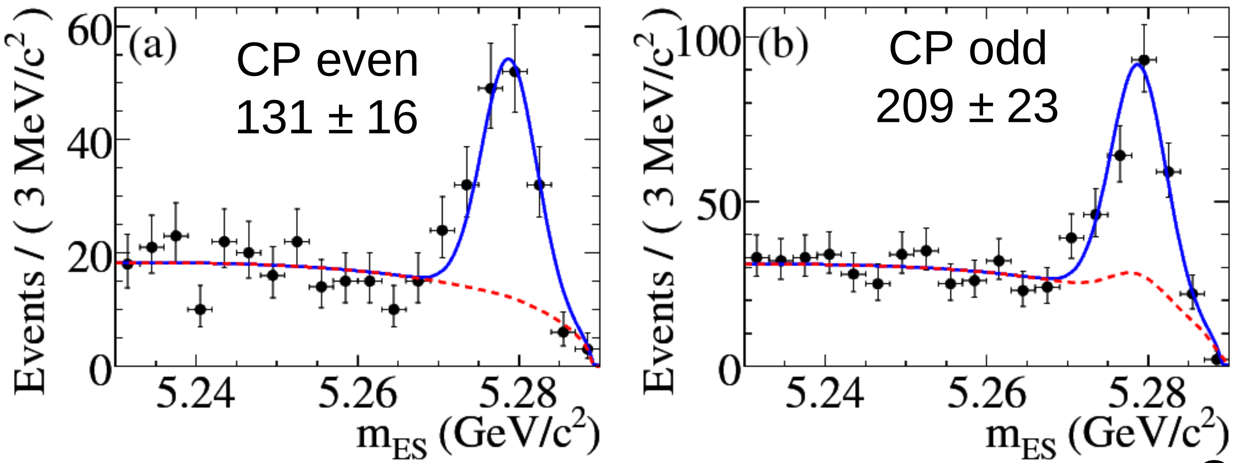
1. No penguin contribution
2. Small SM uncertainty (DCS process $b \to u\bar{c}d$)
3. Potential large New Physics contribution



– $\Delta\beta = (\beta_{eff} - \beta) < 0.5$
  - Y. Grossman and M. Worah, Phys. Lett. B 395, 241 (1997)

- We can measure $\sin(2\beta)$ by reconstructing D^0 in a CP-eigenstate
  - $D^0 \to KK$, $D^0 \to K_s\pi^0$, $D^0 \to K_s\omega$

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



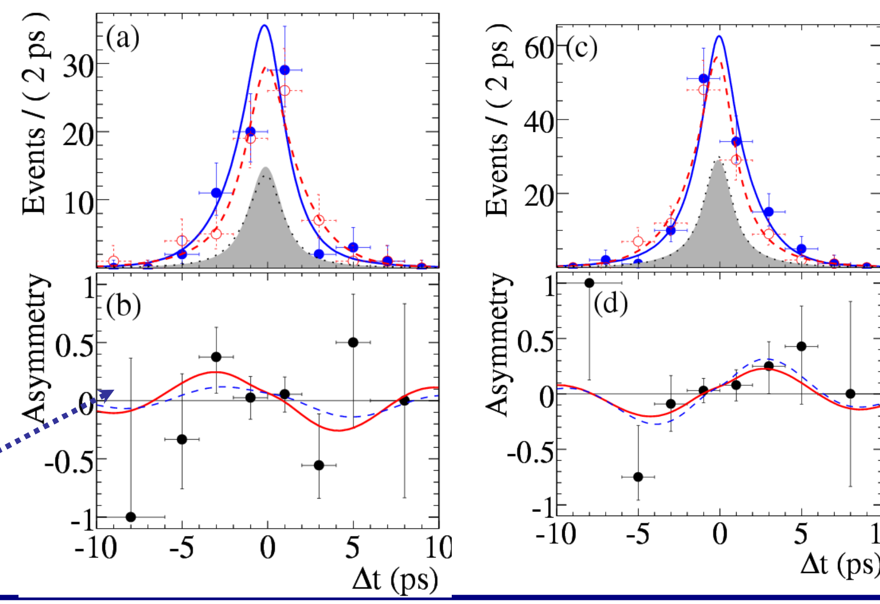
383 M $B\bar{B}$ pairs

hep-ex/0703019
accepted by PRL

Background

CP even

CP odd



$$\sin 2\beta_{\rm eff} = +0.56 \pm 0.23 \pm 0.05$$
$$C = -0.23 \pm 0.16 \pm 0.04$$

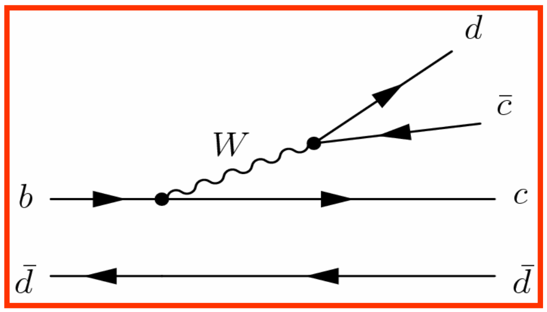
First measurement of
sin2β in these modes!

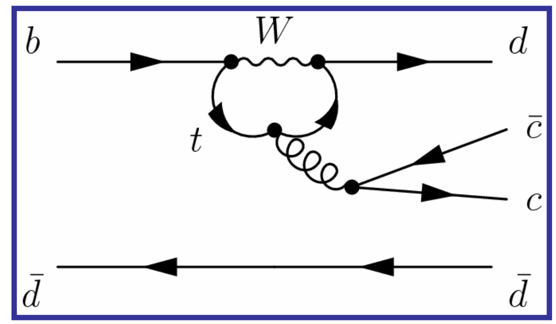
2.3σ from CP conservation.
Consistent with SM expectations

separate
fit

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

- Competition between tree and penguin diagrams





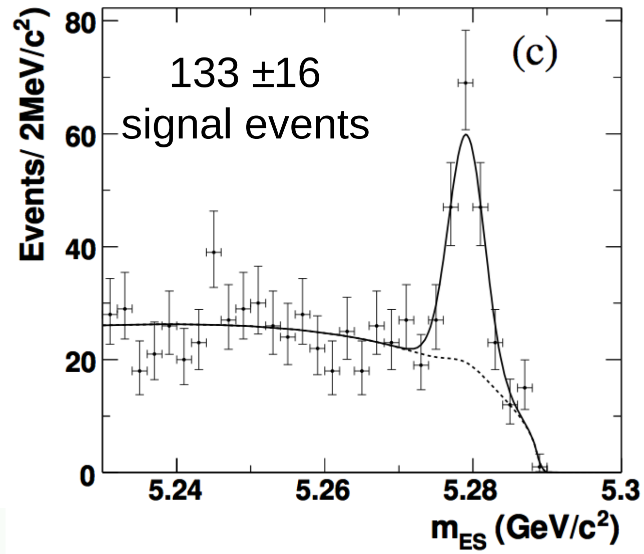
- Expected small penguin contribution: 2-10%
  – Z.-Z. Xing, Phys. Rev. D 61, 014010 (2000)
- β_{eff} is sensitive to New Physics in loops
  – $\Delta\beta = (\beta_{eff} - \beta)$ up to 0.6 in some SUSY models
    - Y. Grossman and M. Worah, Phys. Lett. B 395, 241 (1997)

$B^0 \rightarrow D^- D^+$: *BaBar* results

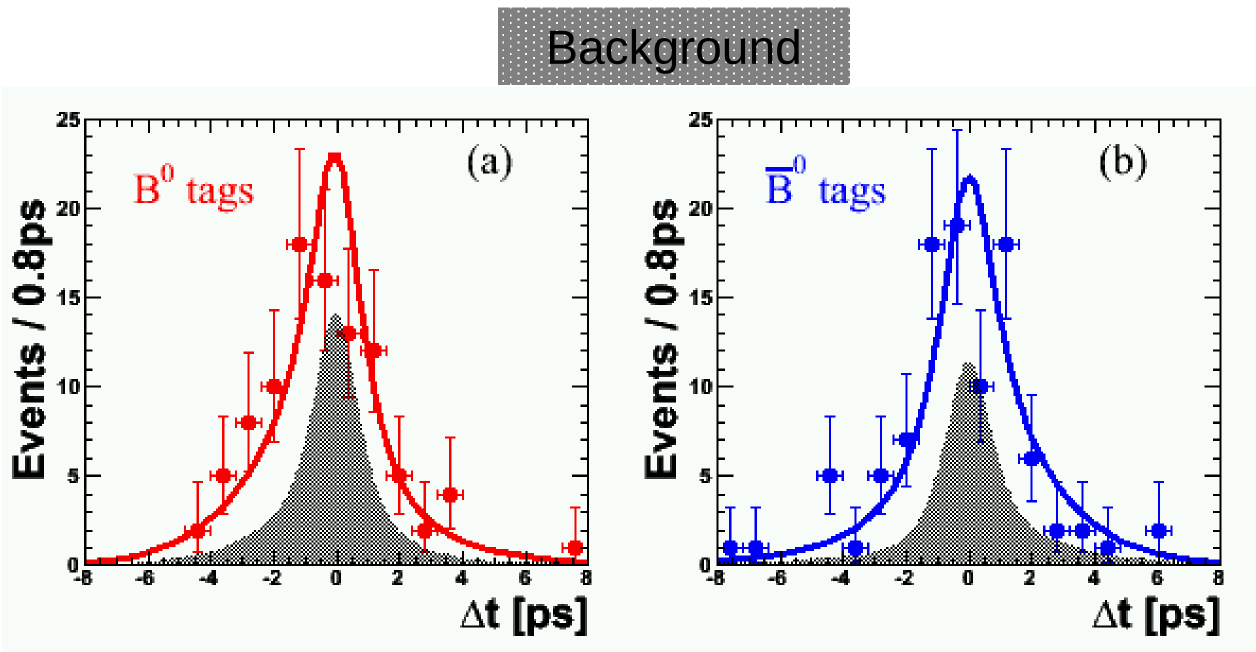
arXiv.org:0705.1190, submitted to PRL

$$S = -0.54 \pm 0.34 \pm 0.06$$
$$C = +0.11 \pm 0.22 \pm 0.07$$

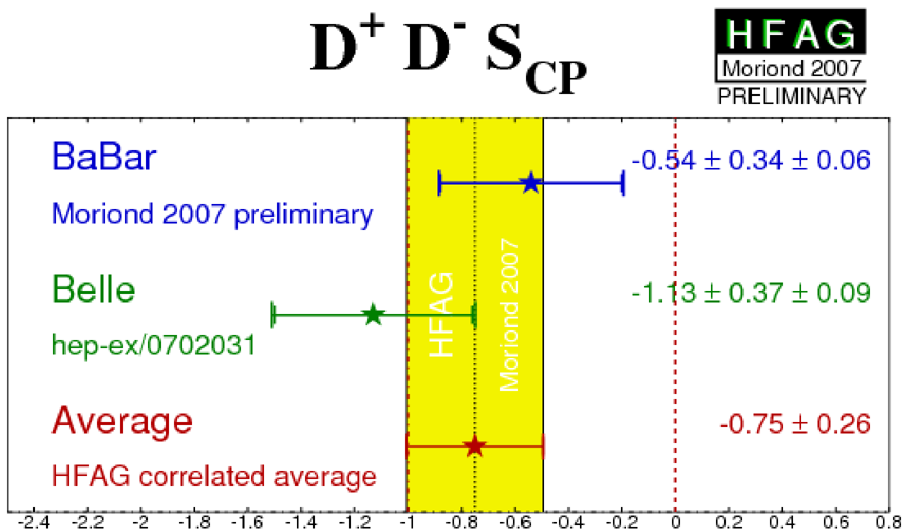
384 M $B\bar{B}$ pairs

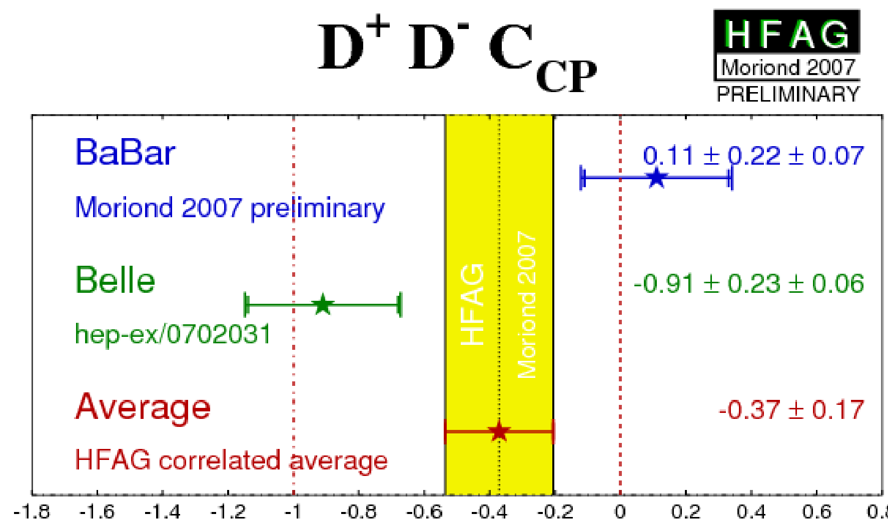


Consistent with SM expectations



$B^0 \rightarrow D^- D^+$: comparison





- Belle claimed direct CP violation at 3.2 σ
  - $(C_{DD}, S_{DD}) \neq (0, 0)$ at 4.1σ (hep-ex/0702031, submitted to PRL)

$535 \times 10^6 B\bar{B}$

$$\begin{cases} \mathcal{S} = -1.13 \pm 0.37 \pm 0.09 \\ \mathcal{A} = +0.91 \pm 0.23 \pm 0.06 \ (= -C) \end{cases}$$

$$S = -0.54 \pm 0.34 \pm 0.06$$
$$C = +0.11 \pm 0.22 \pm 0.07$$

between the two: χ^2/dof =12/2 (CL=0.003, 3σ)

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

- It is not a CP-eigenstate
  - We define a time integrated CP-asymmetry:

$$\mathcal{A}_{D^{*\pm}D^{\mp}} = \frac{N_{D^{*+}D^-} - N_{D^{*-}D^+}}{N_{D^{*+}D^-} + N_{D^{*-}D^+}}$$

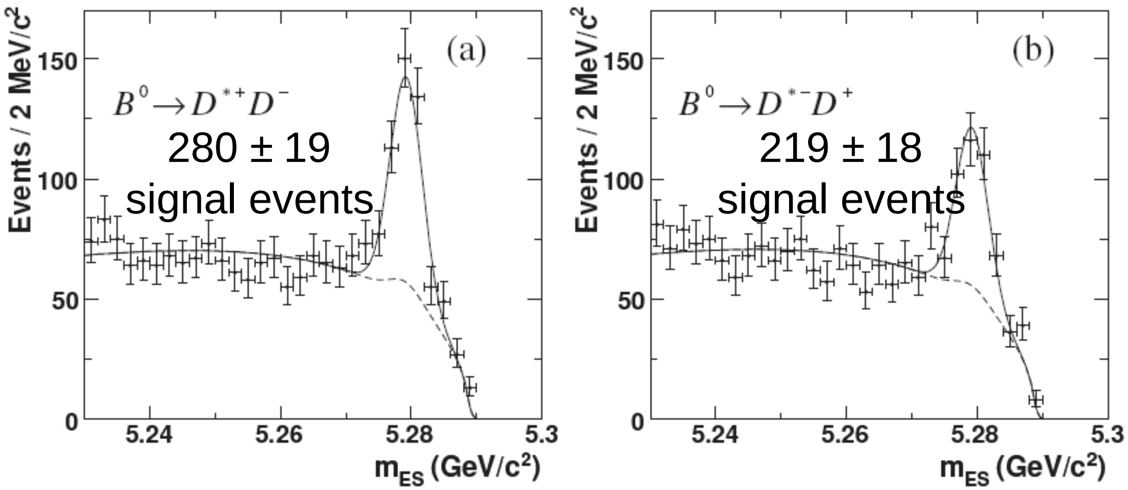
- However, we can extract information for $\sin(2\beta_{eff})$:

$$S_{D^{*\pm}D^{\mp}} = -\sqrt{1 - C^2_{D^{*\pm}D^{\mp}}}\,\sin(2\beta_{\rm eff} \pm \delta)$$

Strong-phase difference

- If penguin contribution is zero: $C_{-+} = -C_{+-}$ & $\beta_{eff} = \beta$
- If there's no CP violation: $S_{-+} = -S_{+-} \Leftrightarrow \sin(2\beta) = 0$

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



384 M BB pairs

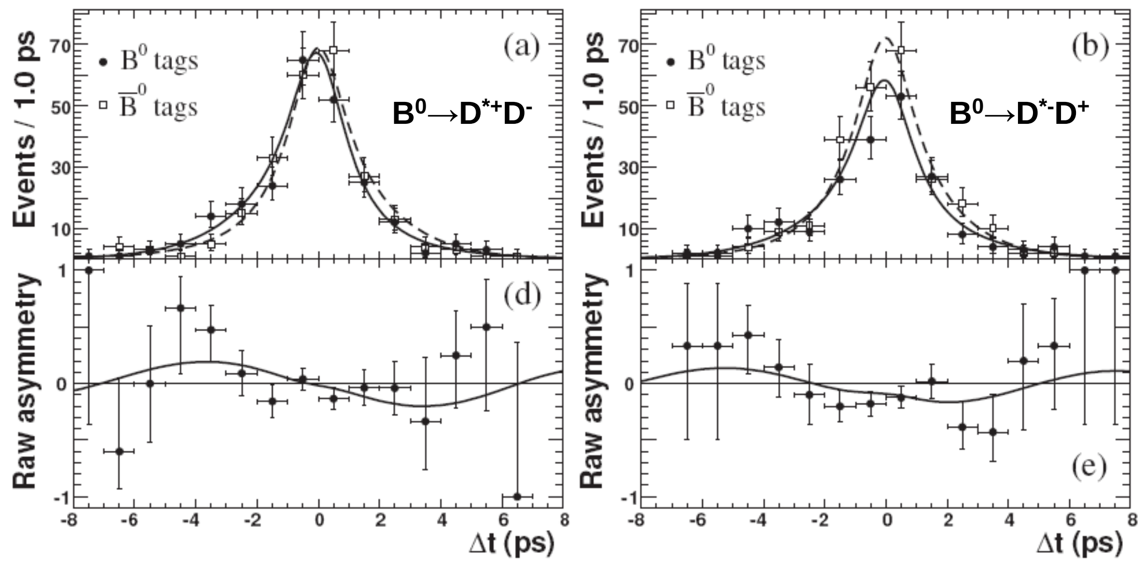
arXiv.org:0705.1190,

submitted to PRL

Evidence of CP violation

$$\mathcal{A}_{D^{*\pm}D^{\mp}} = 0.12 \pm 0.06 \pm 0.02$$
$$C_{D^{*+}D^{-}} = 0.18 \pm 0.15 \pm 0.04$$
$$S_{D^{*+}D^{-}} = -0.79 \pm 0.21 \pm 0.06$$
$$C_{D^{*-}D^{+}} = 0.23 \pm 0.15 \pm 0.04$$
$$S_{D^{*-}D^{+}} = -0.44 \pm 0.22 \pm 0.06$$

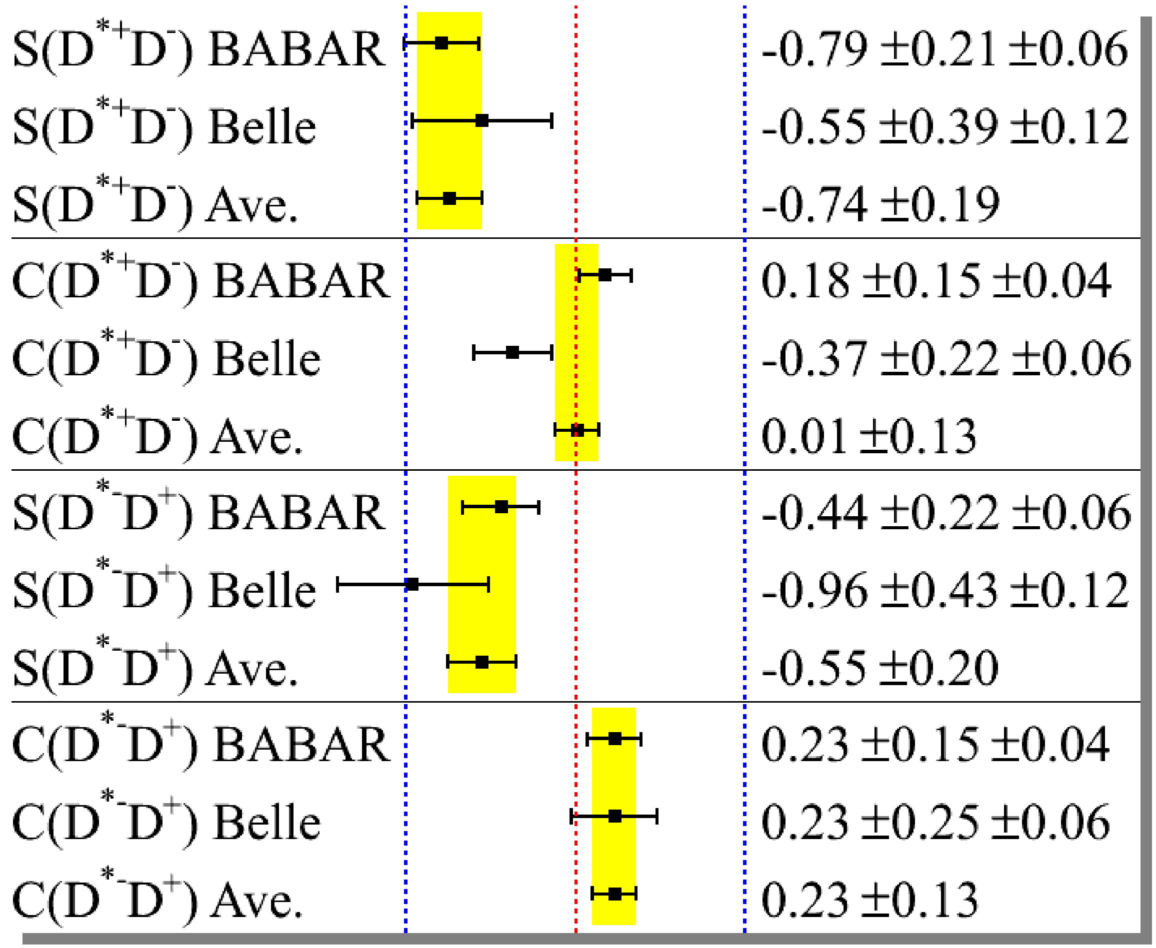
$\sin(2\beta)\cos\delta \neq 0$ @ 4σ



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

Good agreement

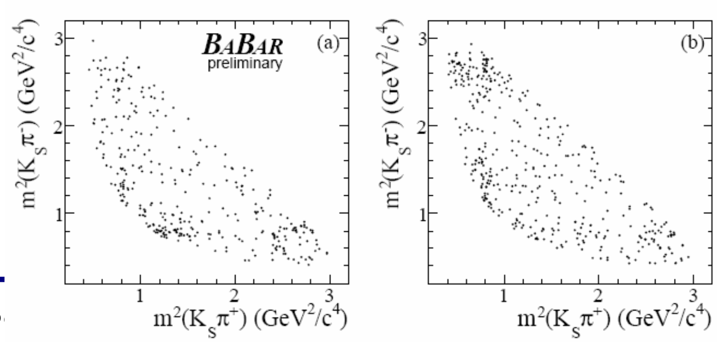
$152 \times 10^6 B\bar{B}$
[PRL 93, 201802 (2004)]



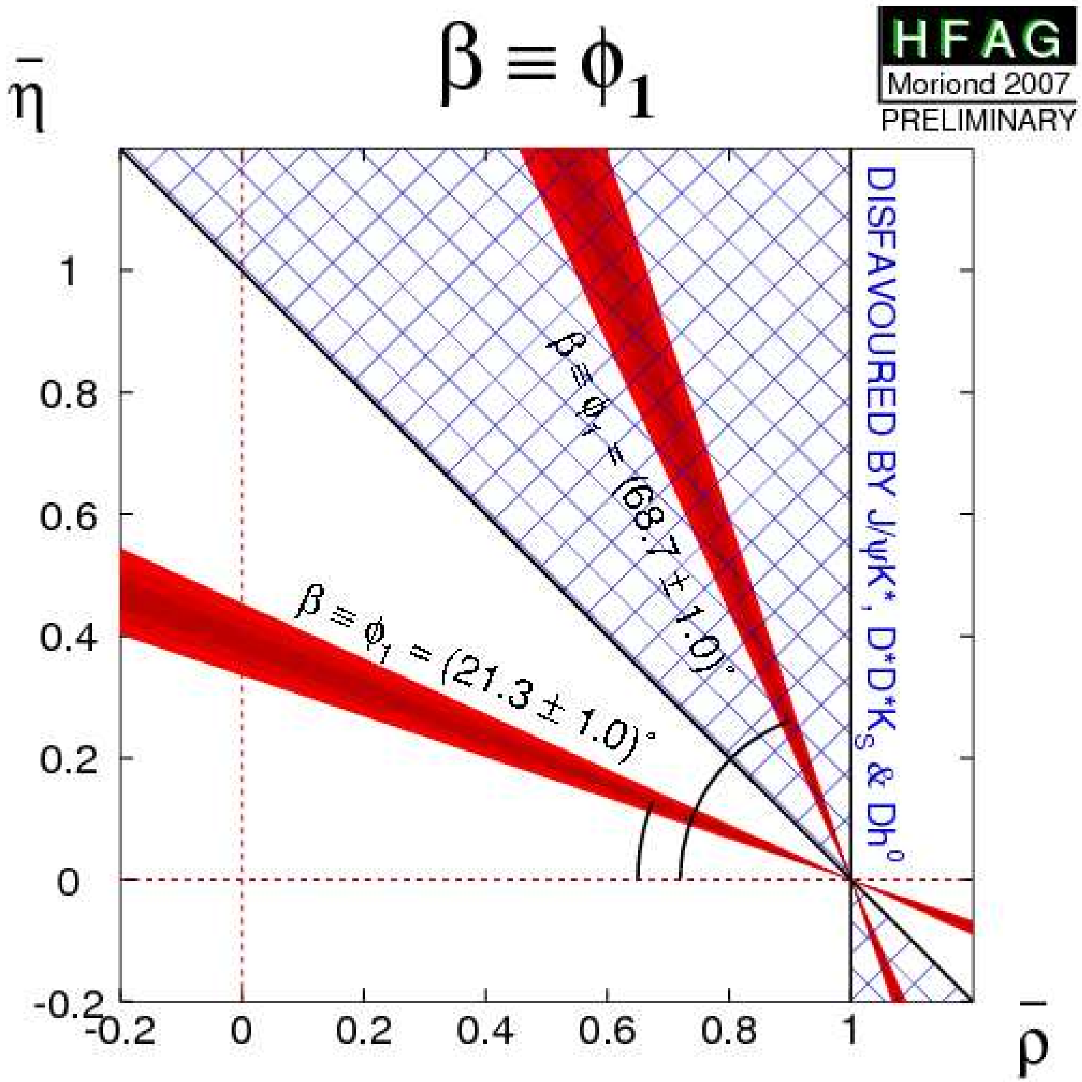
Cos(2β) measurements

Resolve ambiguity in β (I)

- Sin2β has 4-fold ambiguity in β, reduced using the sign of cos2β.
- Negative cos2β is ruled out by:
  - $B^0 \to J/\psi\, K\pi$: Interference between CP even and odd; resolve strong phase using Kπ S- and P-wave.
    - BABAR [PRD 71, 032005 (2005)]
  - $B^0 \to D^0[K_S\pi^+\pi^-]\, h^0$: Time-dependent Dalitz analysis
    - BABAR [hep-ex/0607105] 87% CL.
  - $B^0 \to D^*D^*K_S$: Time-dependent Dalitz analysis
    - BABAR [PRD 74, 091101 (2006)] 94% CL.



Resolve ambiguity in β (II)



Conclusions

Conclusions

- $\beta(\phi_1)$ measurement has reached the 4% precision level
- Many different decays have been used
- A very large quantity of data has been analyzed
- *BaBar* has been giving (and will continue to give) an important contribution to probe flavor sector of Standard Model

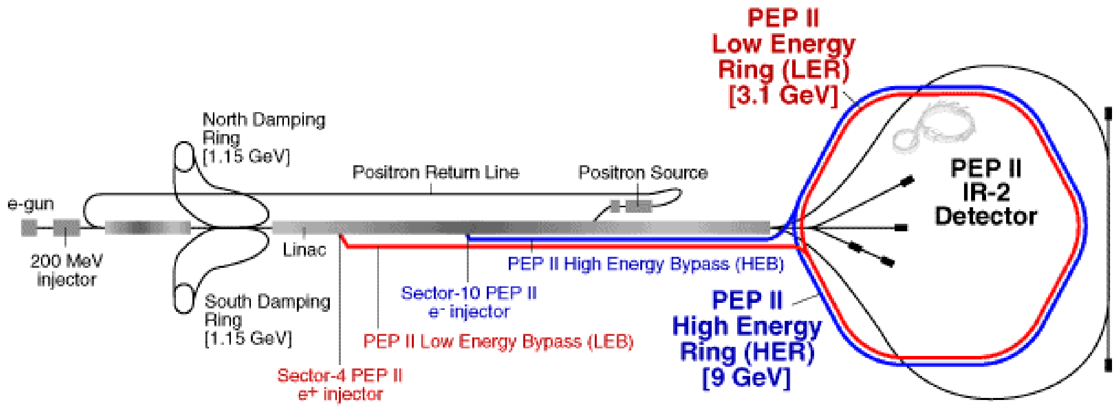
$$\beta = (21.3 \pm 1.0)^{o}$$

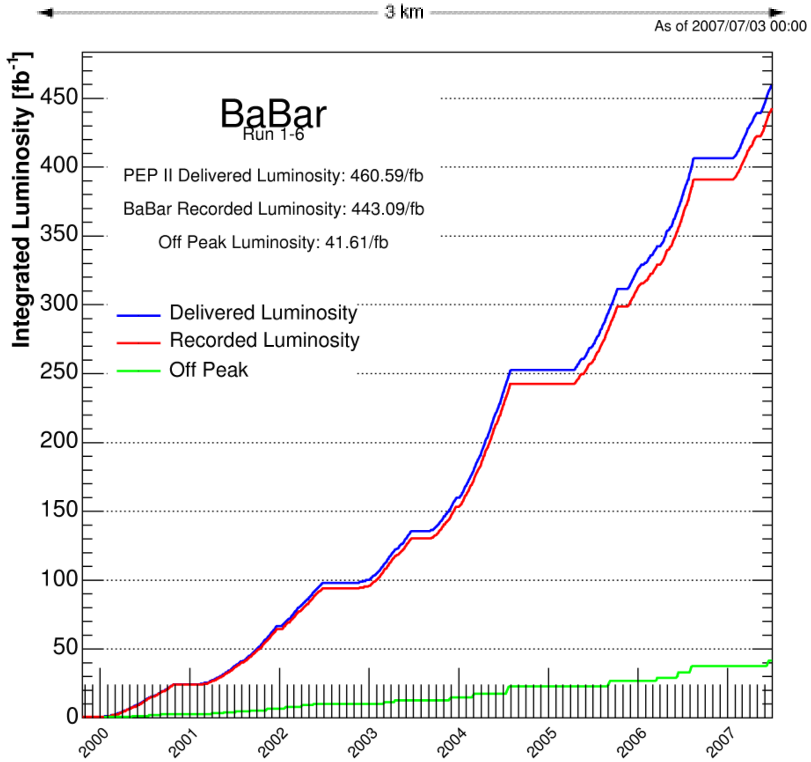
(World Average)

That’s it!

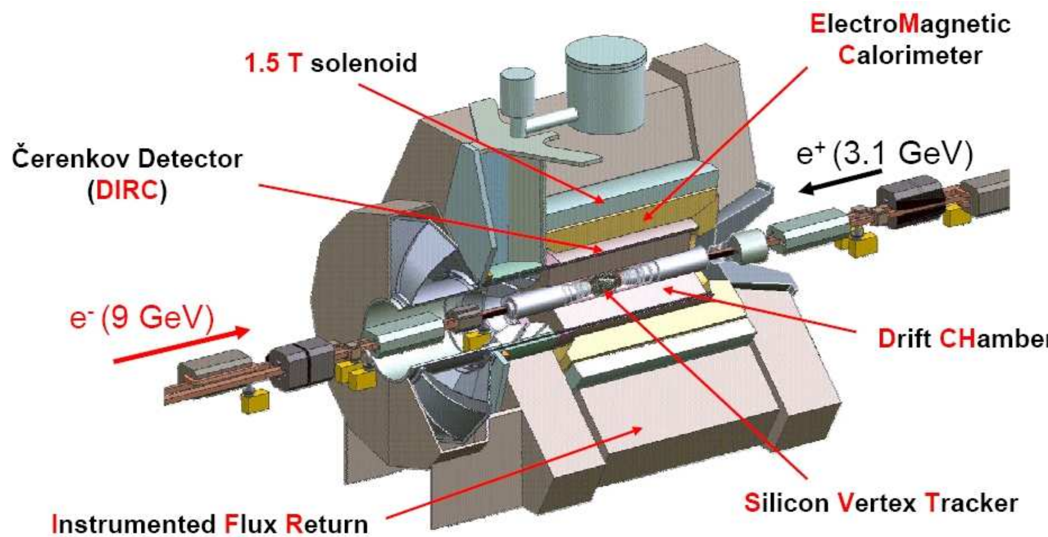
Backup slides

A successful B-factory!

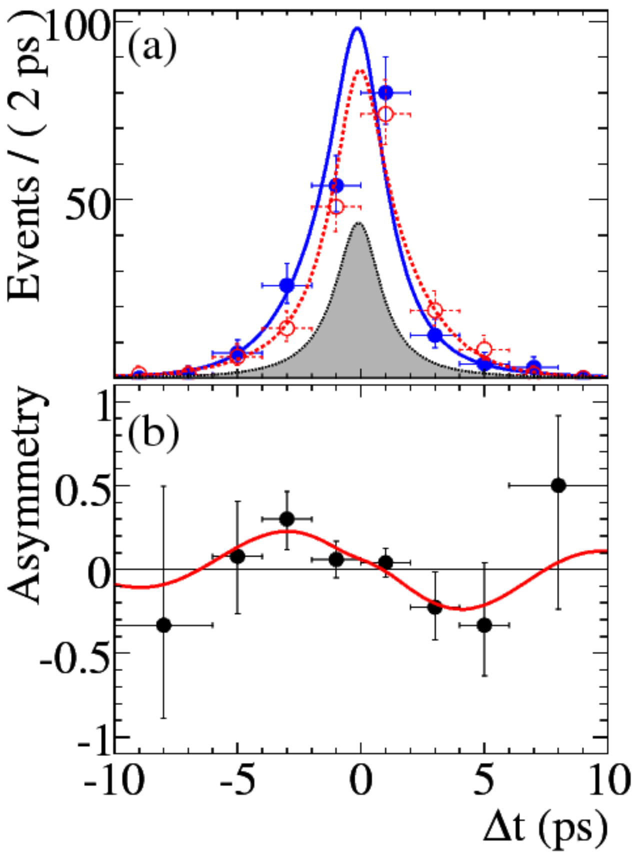




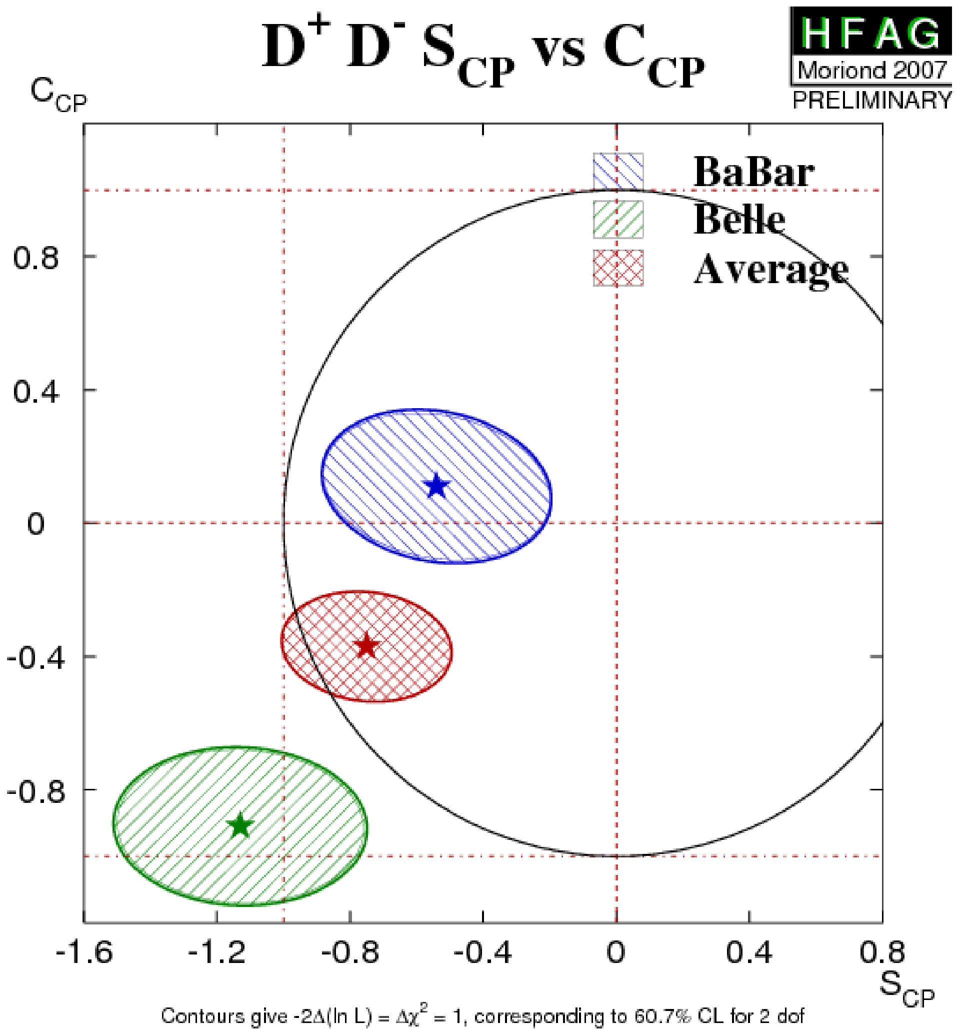
More than 400 millions BB pairs!



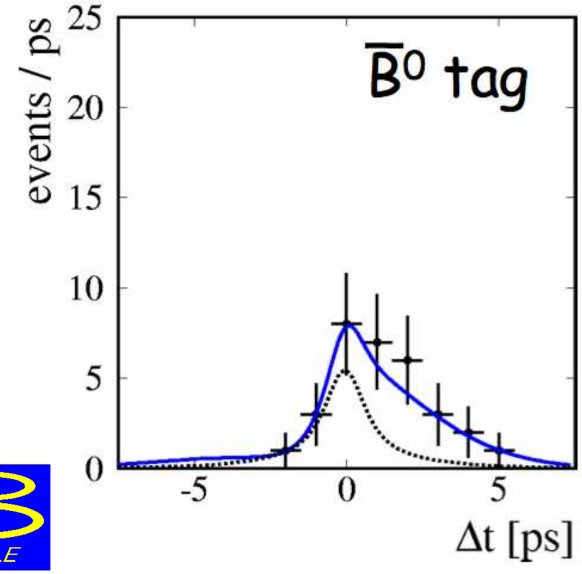
$B^0 \to D^{(*)0}h^0$, $D^0 \to CP$: merged

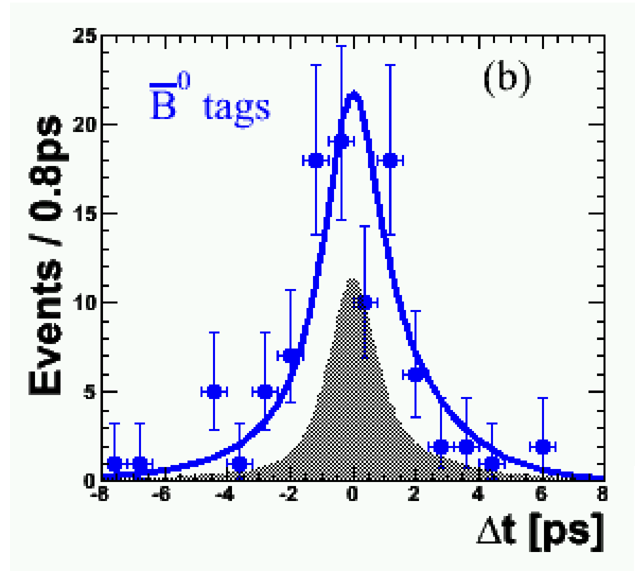


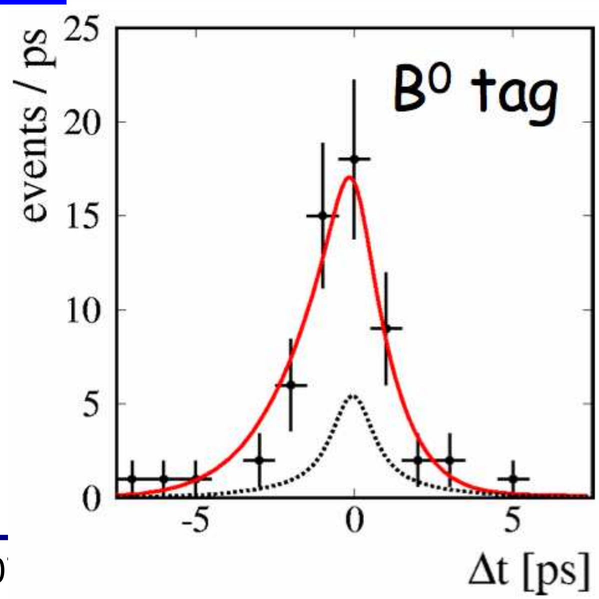
$B^0 \rightarrow D^- D^+$: further comparison

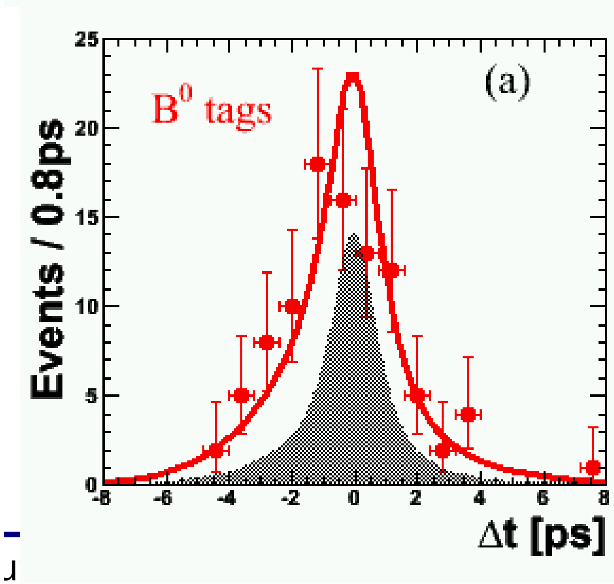


$B^0 \rightarrow D^- D^+$: Δt distributions





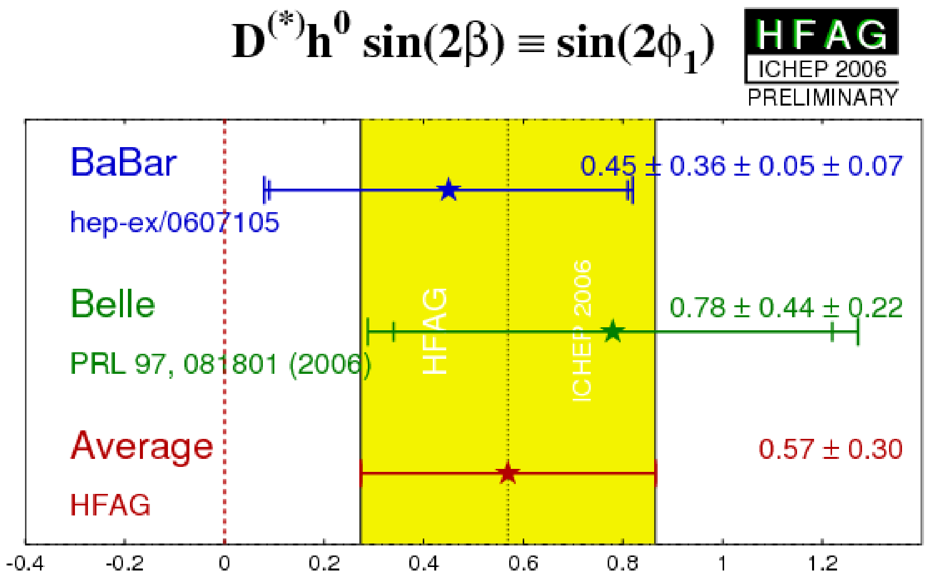


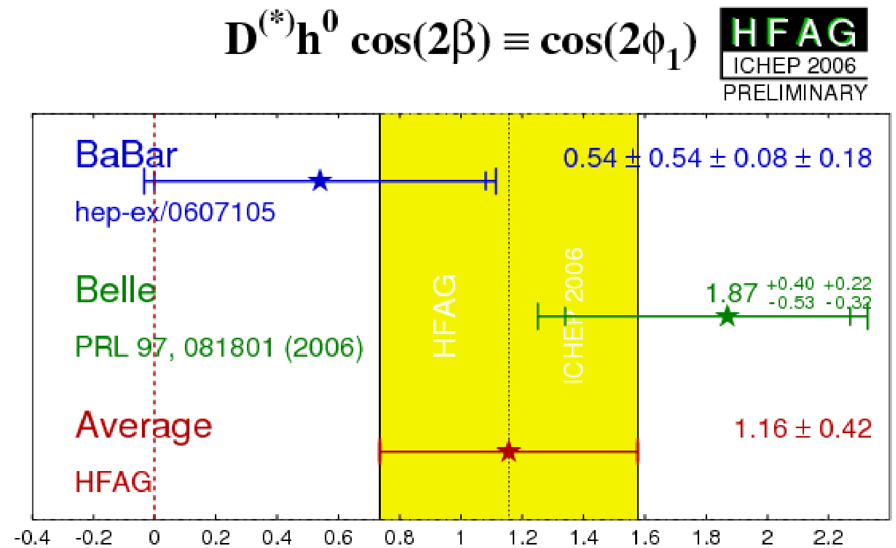


$B^0 \to D^{(*)-} D^+$: systematics

Source	$C_{D^{*+}D^-}$	$S_{D^{*+}D^-}$	$C_{D^{*-}D^+}$	$S_{D^{*-}D^+}$	$C_{D^+D^-}$	$S_{D^+D^-}$
Peaking backgrounds	0.026	0.041	0.027	0.031	0.044	0.042
Δt resolution parameterization	0.011	0.021	0.013	0.012	0.015	0.020
Mistag fraction differences	0.014	0.011	0.016	0.012	0.023	0.013
Beam-spot position	0.004	0.006	0.007	0.036	0.005	0.002
Δm_d, τ_B	0.002	0.003	0.003	0.004	0.001	0.004
MC statistics	0.011	0.015	0.011	0.015	0.036	0.023
Tag-side interference and others	0.016	0.025	0.017	0.020	0.020	0.013
Total	0.037	0.056	0.040	0.056	0.066	0.055

$B^0 \to D^{(*)0}h^0$, $D^0 \to K_s\pi\pi$ comp.





- Belle determine the sign of cos(2β) to be positive at 98.3% confidence level
- Babar determine the sign of cos(2β) to be positive at 87% confidence level

World average