Sin(2β) measurement with b→c transitions in BaBar

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On behalf of BaBar Collaboration

Outline

- Introduction
  - Motivations
  - CPV measurements at B-factories
- charmoniumK^0
- $J/\Psi\pi^0$
- $D^{(*)+}D^{(*)-}$
- Results
- Conclusions

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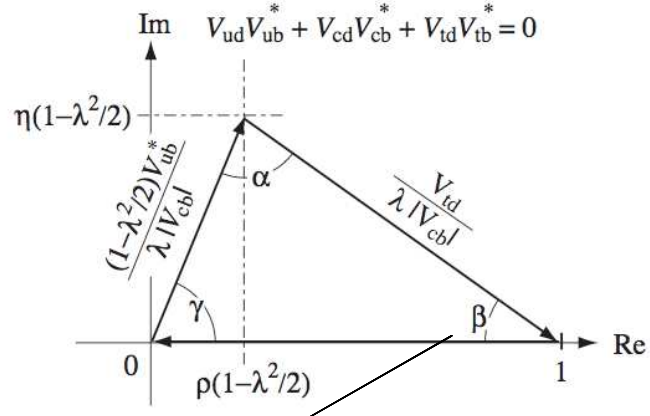
I will focus on these two analyses

Motivations

- *CPV* has been observed first in neutral Kaon system and then in B mesons.
- It can be explained in SM via quark mixing matrix (CKM)
  - *complex phase changes sign under CP application*

$$\begin{array}{c} \\ u \\ c \\ t \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$



$$\beta(\phi_1) \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

Time evolution of the B^0 meson

The time-dependent rate for B^0 (f_+) or $\overline{B}^0$ (f_-) decays to a final state f is:

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

$\Delta t \equiv$ decay time

where

$$S_f = \frac{2\eta_f \operatorname{Im}\lambda_f}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad |B_{L/H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

a_{CP} is the time-evolution asymmetry:

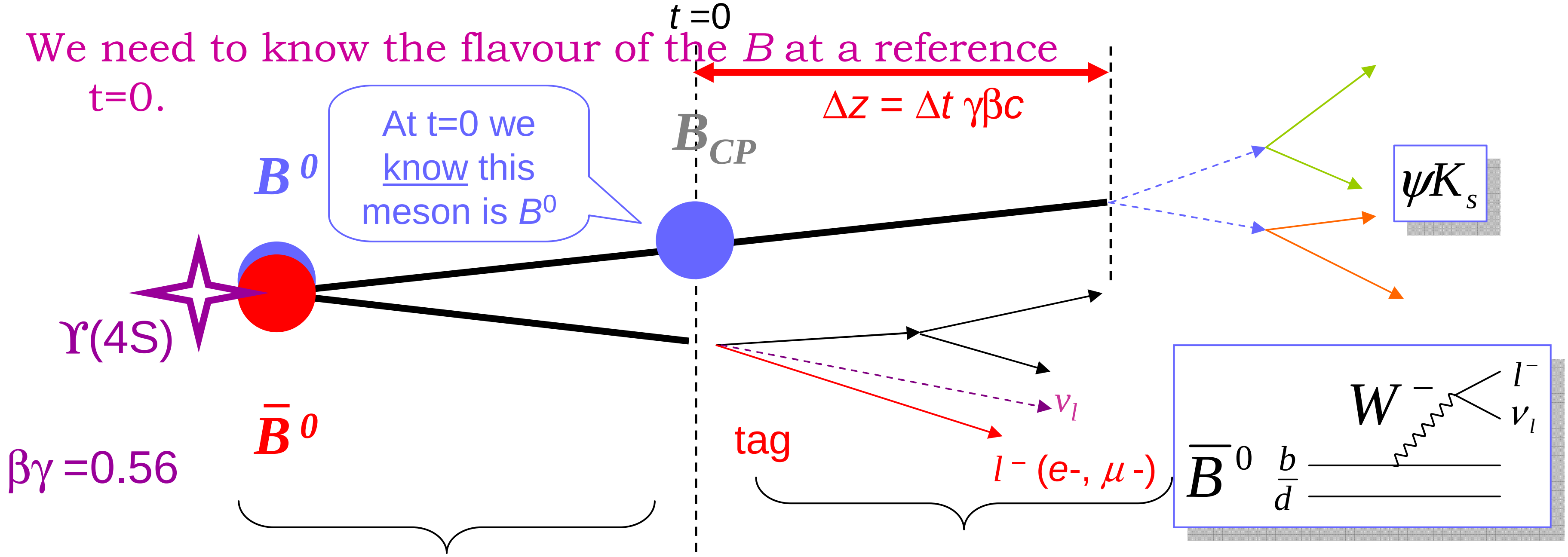
$$a_{CP}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$

If f is a CP eigenstate, f_{CP}, we have CP violation if $\lambda_f \neq \pm 1$:

- $|q/p| \neq 1$ (CP violation in mixing, negligible in SM)
- $|\overline{A}_f/A_f| \neq 1$ (direct CP violation, small in $b \to c\bar{c}s$)
- **$\operatorname{Im}(\lambda_f) \neq 0$ (interference between mixing and decay)**

CPV measurements 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 $\bar{B}^0$

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 :
$l^- = \bar{B}^0 \qquad l^+ = B^0$.
(Kaon and pion tags also used)

Δt picoseconds later, the B^0 (or perhaps it is now a $\bar{B}^0$) decays.

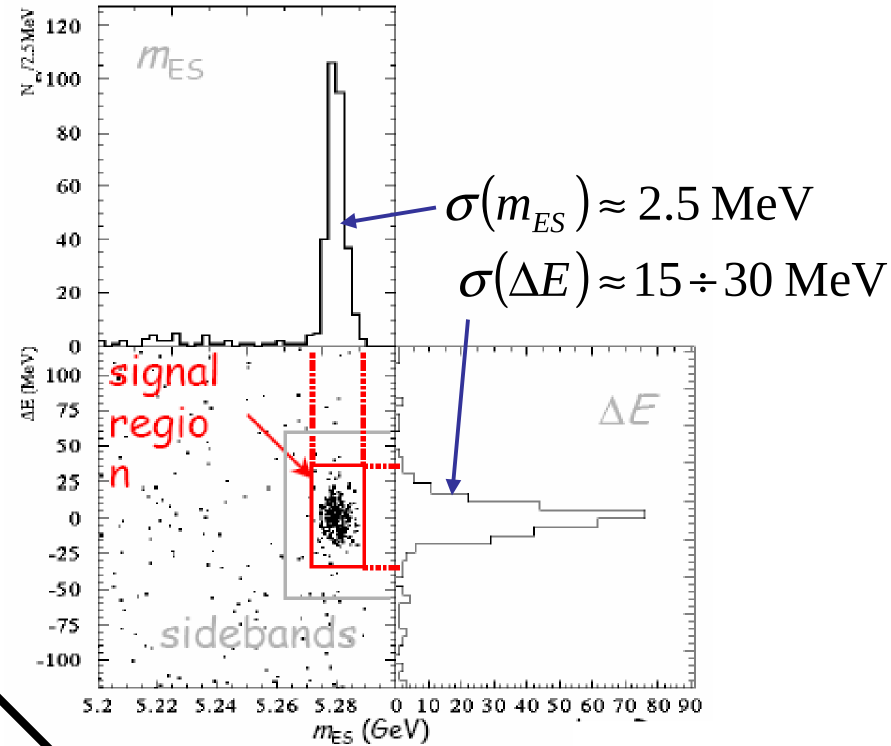
Exclusive B decay reconstruction

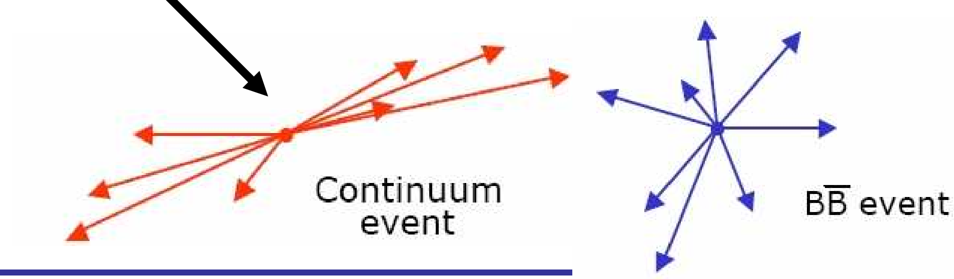
- **Likelihood fits with discriminating variables:**
  - **Kinematics:**

$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

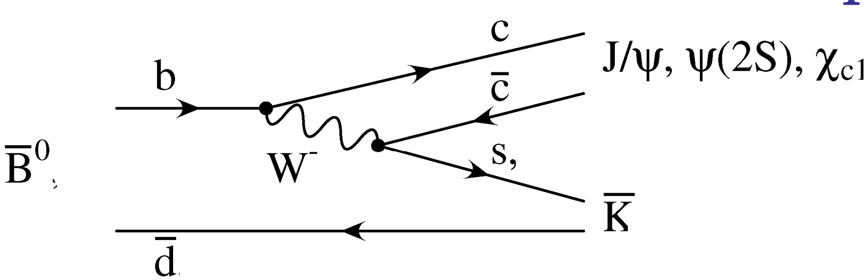
  - **Particle ID: π, K, e, μ, …**
  - **Event shape variables, to separate the continuum bkgd (use "off-resonance" data as control sample!!!)**
- **Efficiency**
  - **Typically ε ≈ 15÷40%**
- **Purity**
  - **Up to 97% (for $J/\psi K_S$)**

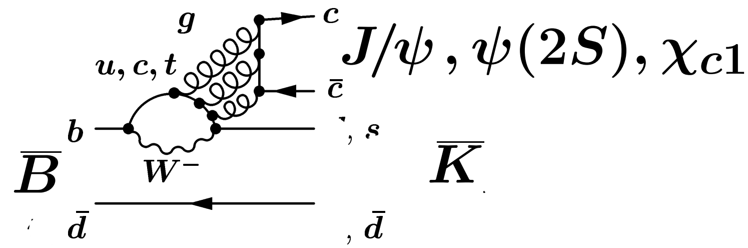




Charmonium K^0 modes

"Golden" modes: tree diagrams dominate; the *t*-quark penguin has the same weak phase as the tree, so the measured SM quantity is $\sin 2\beta$





$$\lambda(B_d \to J/\psi K^0_S) = -\left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{V^*_{cs}V_{cb}}{V_{cs}V^*_{cb}}\right)\left(\frac{V^*_{cd}V_{cs}}{V_{cd}V^*_{cs}}\right) \rightarrow \operatorname{Im}\lambda(B_d \to J/\psi K^0_S) = \sin 2\beta$$

SM prediction: $C_f=0 \rightarrow A_{CP}(\Delta t) = S_f \sin(\Delta m \Delta t)$

Experimentally very clean!
Many accessible decay modes with (relatively) large BFs

→

$B \rightarrow J/\psi K^0 \sim 8.5\times10^{-4}$
$B \rightarrow \psi(2S) K^0 \sim 6.2\times10^{-4}$
$B \rightarrow \chi_{c1} K^0 \sim 4\times10^{-4}$
$B \rightarrow \eta_c K^0 \sim 1.2\times10^{-3}$

Charmonium K^0: details (I)

- B_{CP} sample
- $B \rightarrow J/\psi K^0$
  - $J/\psi \rightarrow e\,e,\ \mu\,\mu$
  - $K_s^0 \rightarrow \pi\,\pi$
  - K_L^0 : cluster
- $B \rightarrow \psi(2S) K^0$
  - $\psi(2S) \rightarrow e\,e,\ \mu\,\mu,\ J/\psi\,\gamma$
- $B \rightarrow x_{c1} K^0$
  - $x_{c1} \rightarrow J/\psi\,\gamma$
- $B \rightarrow \eta_c K^0$
  - $\eta_c \rightarrow K^0 K^+ \pi^-$

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

For tagging performance and resolution studies

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

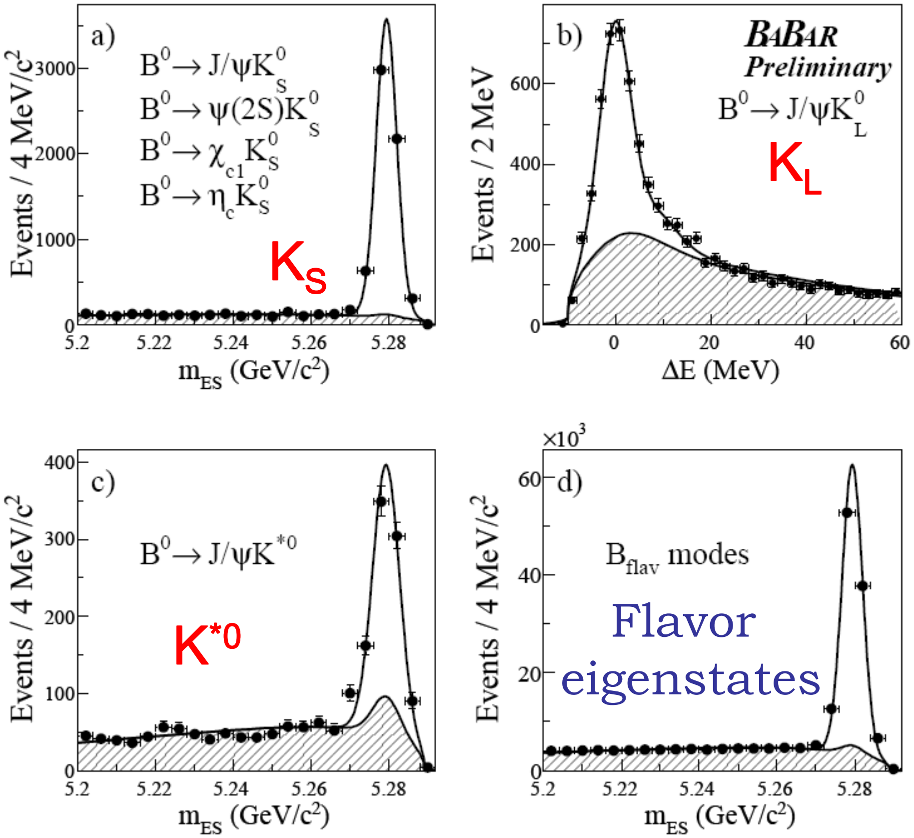
Control sample

Charmonium K^0: details (II)

Using ~ 315 fb^{-1} @ $\Upsilon(4S)$

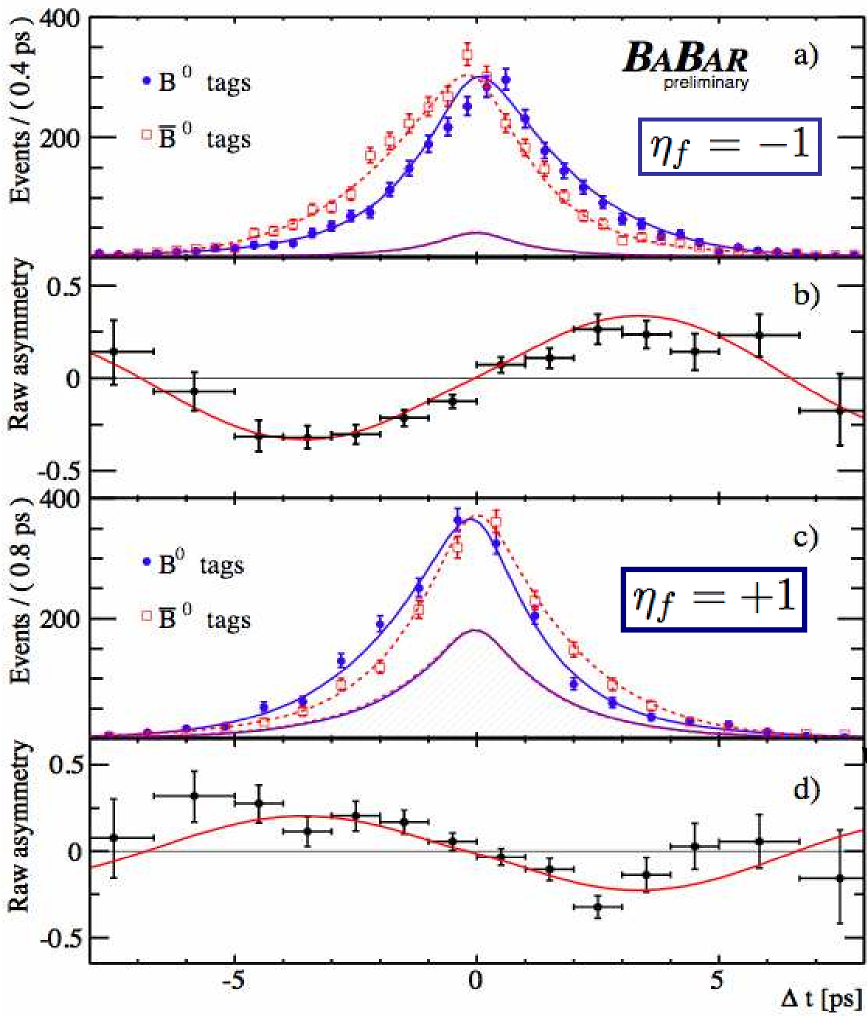
Presented @ ICHEP 06

Reference: hep-ex/0607107



Sample	N_{tag}	$P(\%)$	$\sin 2\beta$
Full CP sample	11496	76	0.710 ± 0.034
$J/\psi K^0_S, \psi(2S) K^0_S, \chi_{c1} K^0_S, \eta_c K^0_S$	6028	92	0.713 ± 0.038
$J/\psi K^0_L$	4323	55	0.716 ± 0.080
$J/\psi K^{*0} (K^{*0} \to K^0_S \pi^0)$	965	68	0.526 ± 0.284
1999-2002 data	3084	79	0.755 ± 0.067
2003-2004 data	4850	77	0.724 ± 0.052
2005-2006 data	3562	74	0.663 ± 0.062
$J/\psi K^0_S$, $\psi(2S) K^0_S$, $\chi_{c1} K^0_S$, $\eta_c K^0_S$ only ($\eta_f = -1$)			
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	4076	96	0.715 ± 0.044
$J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$)	988	88	0.581 ± 0.105
$\psi(2S) K^0_S$ ($K^0_S \to \pi^+\pi^-$)	622	83	0.892 ± 0.120
$\chi_{c1} K^0_S$	279	89	0.709 ± 0.174
$\eta_c K^0_S$	243	75	0.717 ± 0.229
Lepton category	703	97	0.754 ± 0.068
Kaon I category	900	93	0.713 ± 0.066
Kaon II category	1437	91	0.711 ± 0.075
Kaon-Pion category	1107	89	0.635 ± 0.117
Pion category	1238	91	0.587 ± 0.175
Other category	823	89	0.454 ± 0.469
B_{flav} sample	112878	83	0.016 ± 0.011
B^+ sample	27775	93	0.008 ± 0.017

Charmonium K^0: results



Raw CP asymmetry

$$A_{CP}(\Delta t) \equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$

$$\propto -(1-2\omega)\eta_f \sin 2\beta \sin(\Delta m_d \Delta t)$$

Mistag dilution

Final state CP eigenvalue

We determine sin2β with a simultaneous ML fit to the Δt distribution of the tagged B_{CP} and B_{flav} samples

$$\sin 2\beta = 0.710 \pm 0.034(\text{stat}) \pm 0.019(\text{syst})$$

$$|\lambda| = 0.932 \pm 0.026(\text{stat}) \pm 0.017(\text{syst})$$

Charmonium K^0 systematics

Source	$\sigma(\sin 2\beta)$	$\sigma(\lvert\lambda\rvert)$
CP backgrounds	0.007	0.002
Δt resolution function	0.008	0.002
$J/\psi K_L^0$ backgrounds	0.007	N/A
Mistag fraction differences	0.009	0.007
Beam spot	0.008	0.004
Δm_d, τ_B, $\Delta\Gamma_d/\Gamma_d$, $\lvert\lambda\rvert$	0.003	0.001
Tag-side interference	0.002	0.014
MC statistics	0.003	0.005
Total systematic error	0.019	0.017

2006

2004

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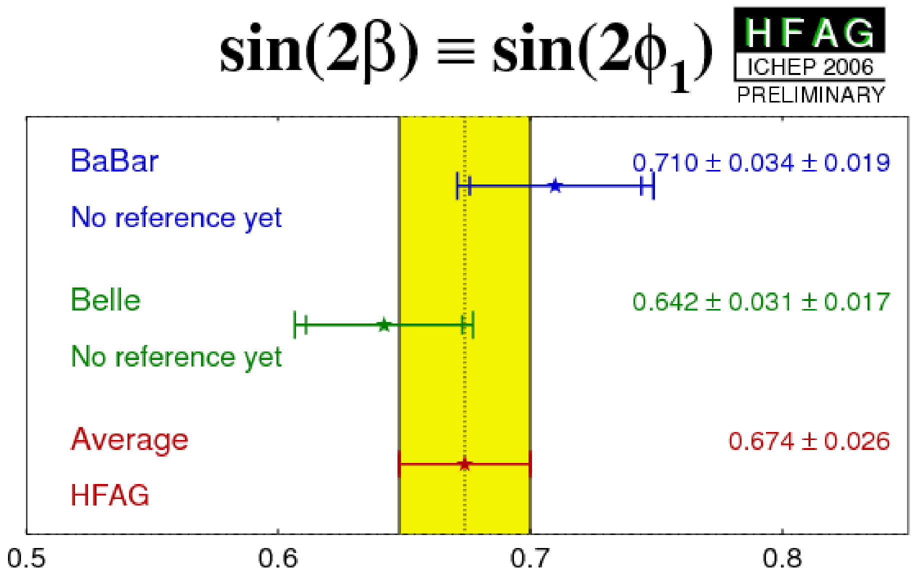
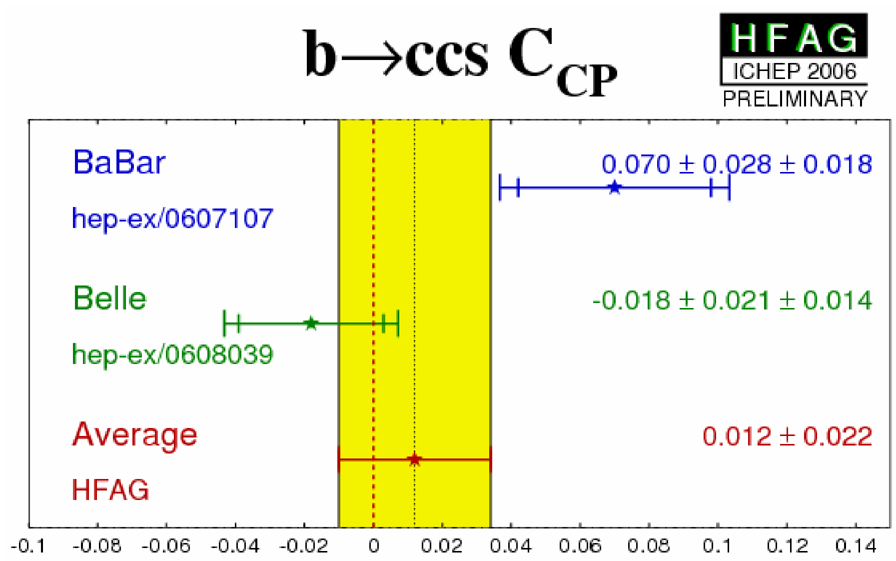
Δt resolution function	0.011	0.003
$J/\psi K_L^0$ backgrounds	0.011	N/A
Mistag fraction differences	0.007	0.001
Beam spot	0.007	0.001
Δm_d, τ_B, $\Delta\Gamma/\Gamma$, $\lvert\lambda\rvert$	0.005	0.001
Tag-side interference	0.003	0.012
MC statistics	0.003	0.003
Total systematic error	0.023	0.013

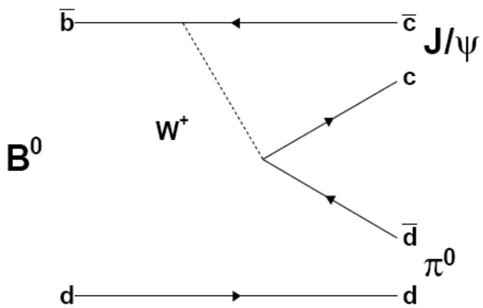
Improved CP background descriptions

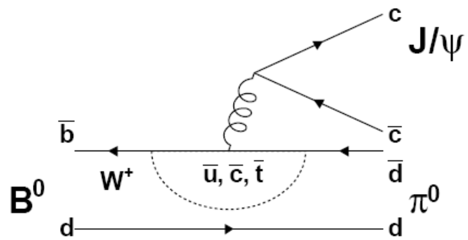
Charmonium K^0 : world average





$J/\psi\pi^0$ and Sin(2β)





Tree amplitude:

$$\lambda\left(B \to J/\psi\pi^0\right) = \left(\frac{V_{tb}^* V_{td}}{V_{td}^* V_{tb}}\right)\left(\frac{V_{cd}^* V_{cb}}{V_{cb}^* V_{cd}}\right)$$

$$\mathrm{Im}\,\lambda\left(B \to J/\psi\pi^0\right) = \sin 2\beta$$

- Potential penguin pollution
  - b→d penguin amplitude has different weak & strong phases with respect to tree.

$$z = \frac{V_{td}^* V_{tb}}{V_{cd}^* V_{cb}}$$

$$r = \frac{P}{T} = |r| e^{i\delta}$$

$$R = z\, r$$

Adding penguins

$$A(f) = V_{cd} V_{cb}^* T + V_{td} V_{tb}^* P$$

$$\bar{A}(f) = V_{cd}^* V_{cb} T + V_{td}^* V_{tb} P$$

δ≡relative strong phase between P and T.

$$C_f = \frac{-2|R| \sin\beta \sin\delta}{1 + |R|^2 - 2|R| \cos\beta \cos\delta} \qquad S_f = \eta_f \frac{\sin 2\beta - 2|R| \sin\beta \cos\delta}{1 + |R|^2 - 2|R| \cos\beta \cos\delta}$$

For small $|R|$

$$C_f \cong -2|R| \sin\beta \sin\delta \qquad S_f \cong \eta_f \;\left(\sin 2\beta + 2|R| \sin\beta \cos 2\beta \cos\delta\right)$$

$J/\psi\pi^0$: details

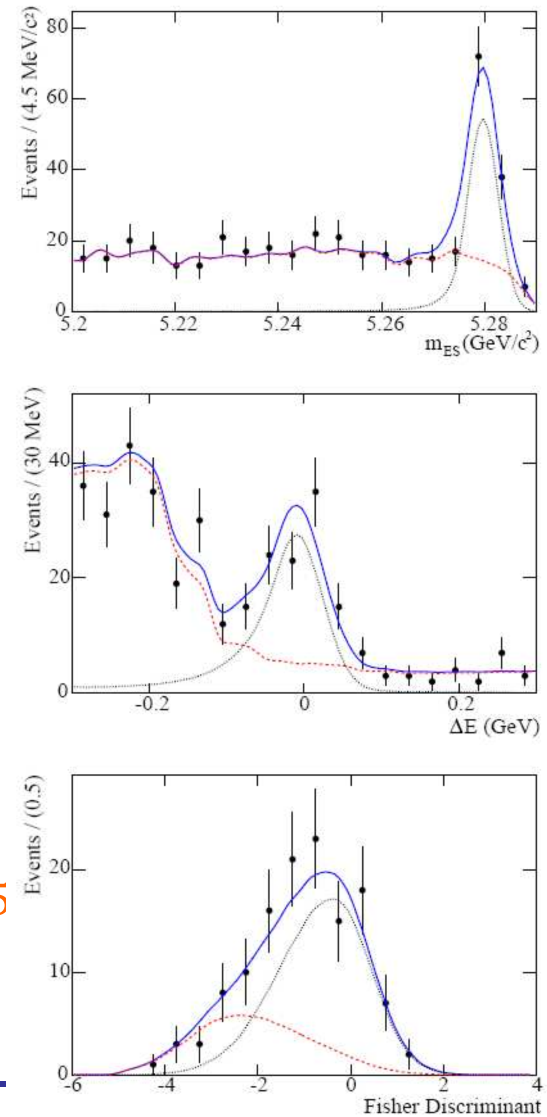
- $B \to J/\psi\pi^0$
  - $J/\psi \to e\, e,\ \mu\, \mu$
  - $\pi^0 \to \gamma\, \gamma$

- Data (points)
- Total PDF
- Signal PDF
- Background PDF

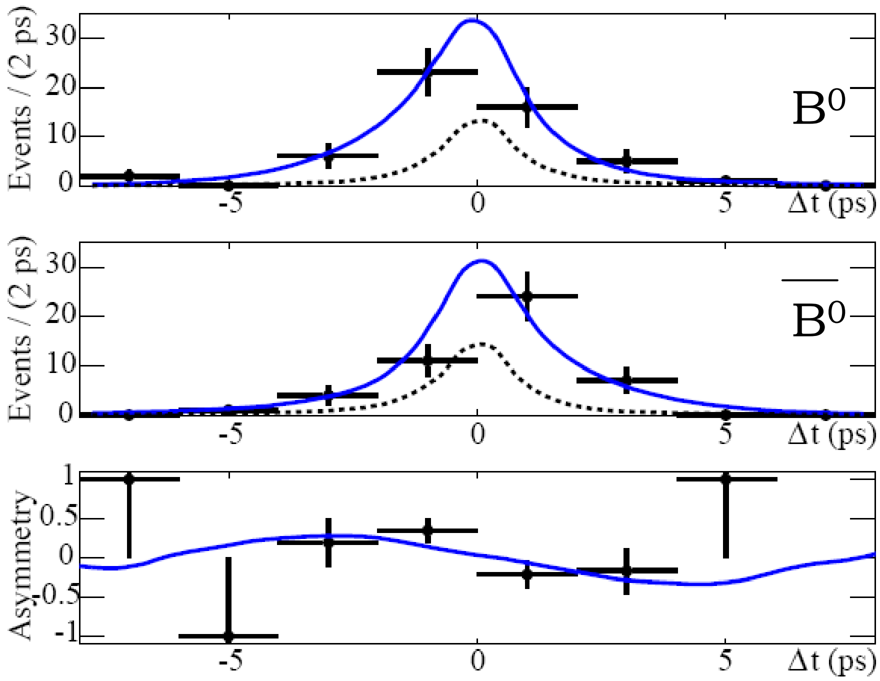
Using 210.6 fb^{-1}:
1318 on-peak events
(signal efficiency is 22.0%)

$BR(B \to J/\psi\pi^0) = (1.94 \pm 0.22 \pm 0.17) \times 10^{-5}$

Reference: hep-ex/0603012, Phys.Rev. D74 (2006) 011101



$J/\psi\pi^0$: results



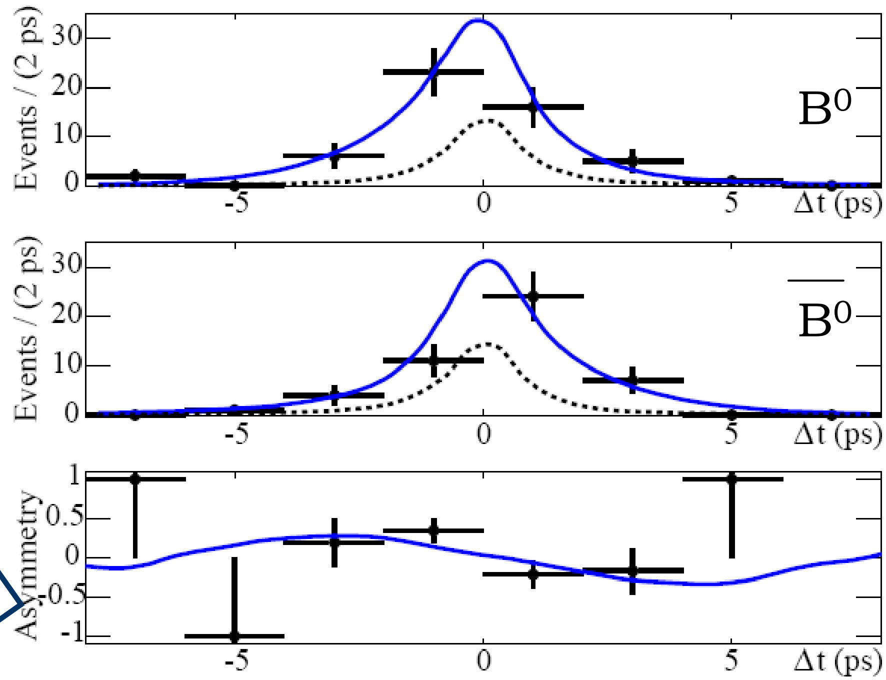
$B^0 \rightarrow J/\psi\pi^0$ updated(*) measurement

S = -0.68 ±0.30 ±0.04

C = -0.21 ±0.26 ±0.09

(*)consistent with previous results

$J/\psi\pi^0$: results



Consistent with a SM tree-dominated amplitude

$B^0 \rightarrow J/\psi\pi^0$ updated(*) measurement

S = -0.68 ±0.30 ±0.04

C = -0.21 ±0.26 ±0.09

(*)consistent with previous results

$J/\psi K^0$ and penguin contribution

- Using $B^0 \rightarrow J/\psi\pi^0$ results we can extract estimate on penguin contribution to $B^0 \rightarrow J/\psi K^0$

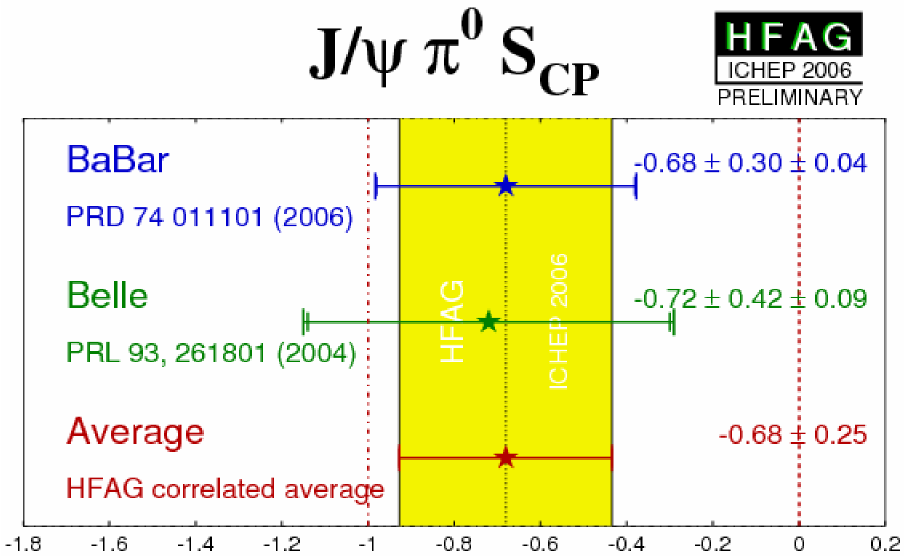
- $\Delta S = S(J/\psi K^0) - \sin 2\beta = 0.000 \pm 0.012$
  - [-0.025,0.024] @ 95% probability

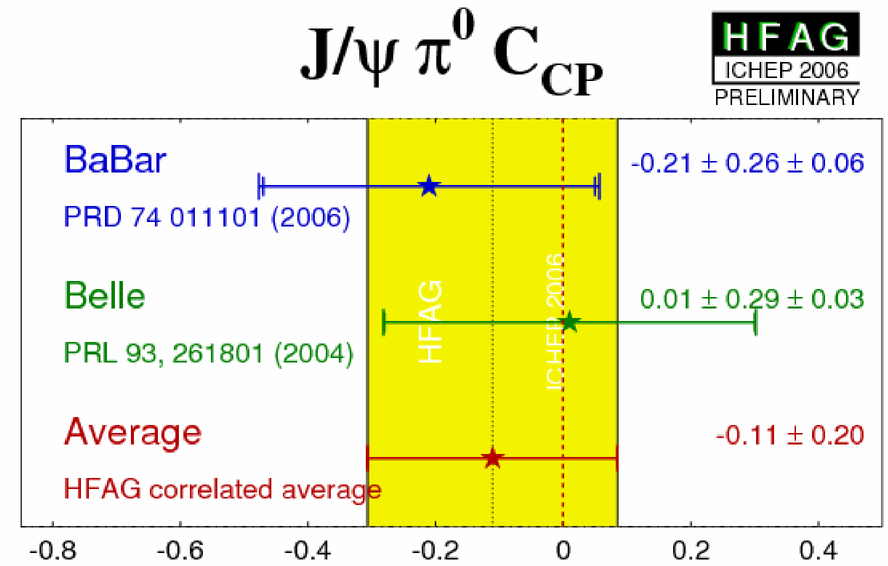
M. Ciuchini, M. Pierini and L.Silvestrini, PRL **95,** 221804 (2005)

$J/\psi\pi^0$: systematics

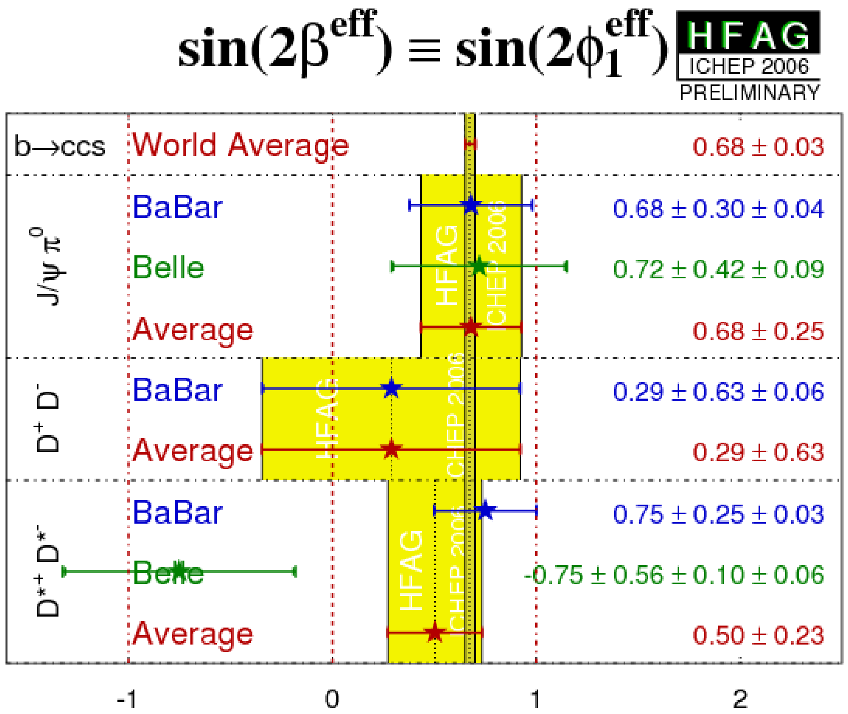
Contribution	Signal yield	S	C
PDF parameterization	$^{+3.21}_{-2.88}$	± 0.013	± 0.012
SVT mis-alignment	–	± 0.002	± 0.002
Boost and z-scale	$^{+0.08}_{-0.16}$	± 0.004	± 0.001
Beam spot position	–	± 0.007	± 0.002
Fit bias	± 3.00	± 0.026	± 0.016
Inclusive B background yields	± 3.52	± 0.003	± 0.020
m_{ES}-ΔE correlations	± 2.92	± 0.020	± 0.002
CP content of B background	$^{+0.13}_{-0.11}$	± 0.012	± 0.049
CP background lifetime	± 0.67	± 0.010	± 0.010
Tagging efficiency asymmetry	± 0.02	± 0.000	± 0.020
Tag-side interference	–	± 0.004	± 0.014
Fisher data/MC comparison	± 0.70	± 0.004	± 0.004
Total	$^{+6.42}_{-6.26}$	± 0.040	± 0.063

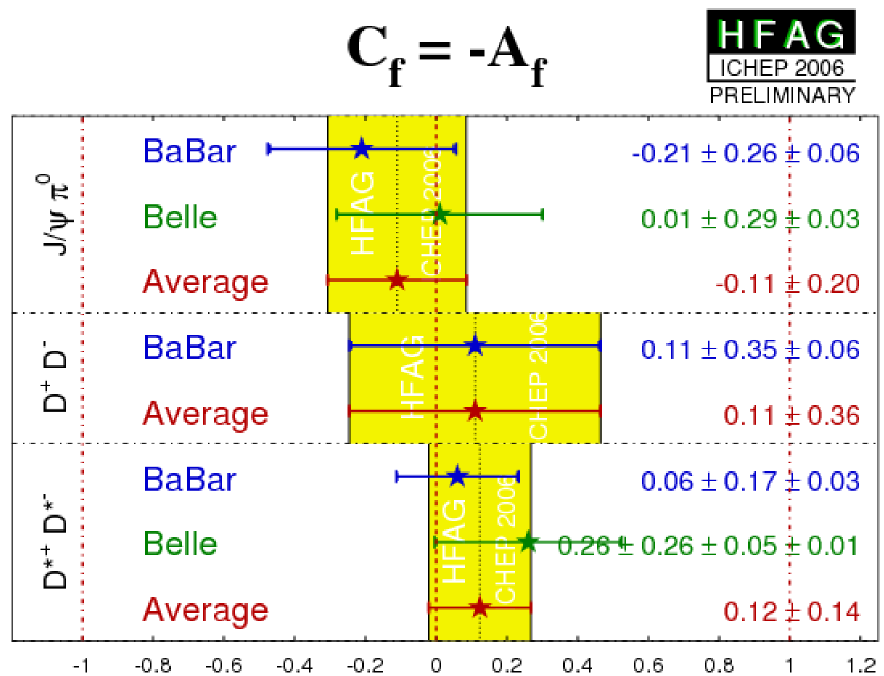
$J/\psi\pi^0$: world average





Sin2β from b→c: world average





Conclusions

- *BABAR* measures sin2β in charmoniumK^0 modes to 5% precision

  $\sin 2\beta_{ccK0} = 0.710 \pm 0.034 \pm 0.019$

- $J/\Psi\pi^0$ could give info on penguin pollution but results indicate that amplitude is tree-dominated

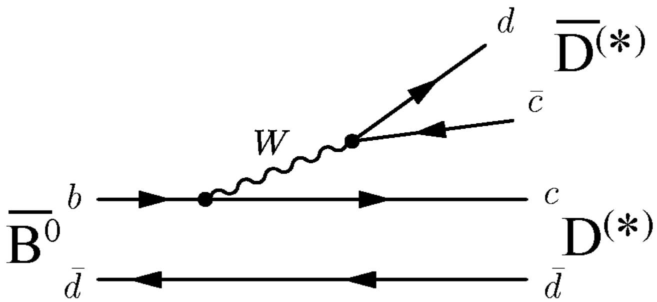
  $S = -0.68 \pm 0.30 \pm 0.04$

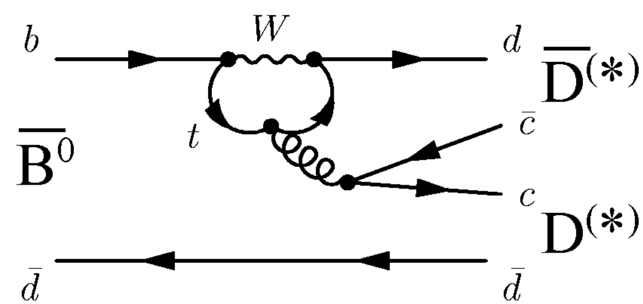
- Both measurements are still limited by statistics

Backup slides

$D^{(*)+}\ D^{(*)-}$ and Sin(2β)

$D^{(*)}D^{(*)}$ modes: the tree diagram still dominates (but is Cabibbo-suppressed); the penguin is comparatively larger and has a different weak phase – *contamination*





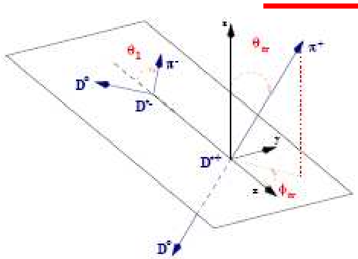
$$S \neq \sin 2\beta,\ C \neq 0$$

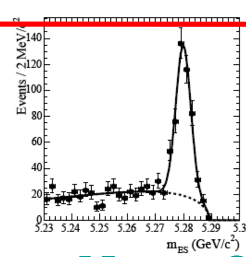
$D^{(*)+}\,D^{(*)-}$: details (I)

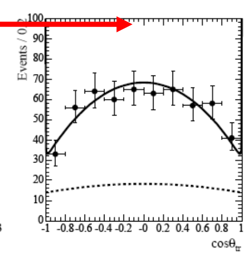
- $210.5\ fb^{-1}$ of On Peak data
- 2 analysis:
  1. $D^{(*)+}\,D^{-}$ PRL 95, 151804 (2005)
  2. $D^{*+}\,D^{*-}$ PRL 95, 131802 (2005)
- $D^{*+} \rightarrow D^{0}\pi^{+}$, $D^{+}\pi^{0}$
- $D^{0} \rightarrow K\pi$, $K\pi\pi^{0}$, $K\,\pi\pi\pi$, $K_{s}\pi\pi$
- $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$, $K_{s}\pi^{+}$, $K^{+}K^{-}\pi^{+}$ (only $D^{*+}\,D^{*-}$)

$D^{(*)+} D^{(*)-}$: details (II)

- $D^{*+} D^{*-}$
  - VV decay: both CP-odd and CP-even fraction are present
  - Angular analysis is required
  - Result: f_{odd} = 0.125±0.044±0.070

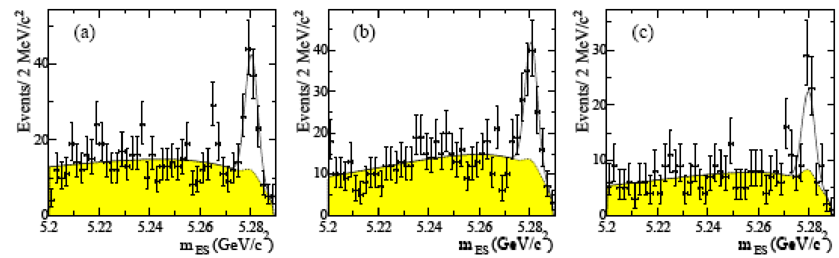






N_{sig} = 391 ± 28

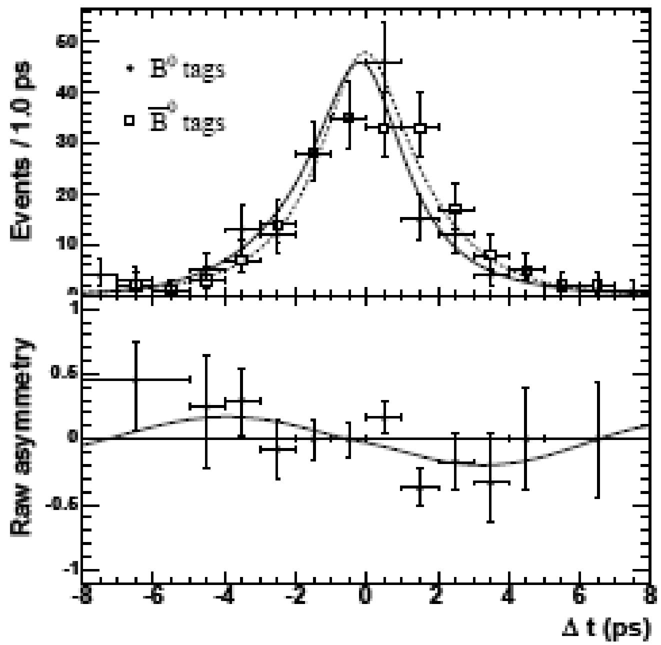
- $D^{*+}D^{-}$, $D^{*-}D^{+}$, $D^{+}D^{-}$



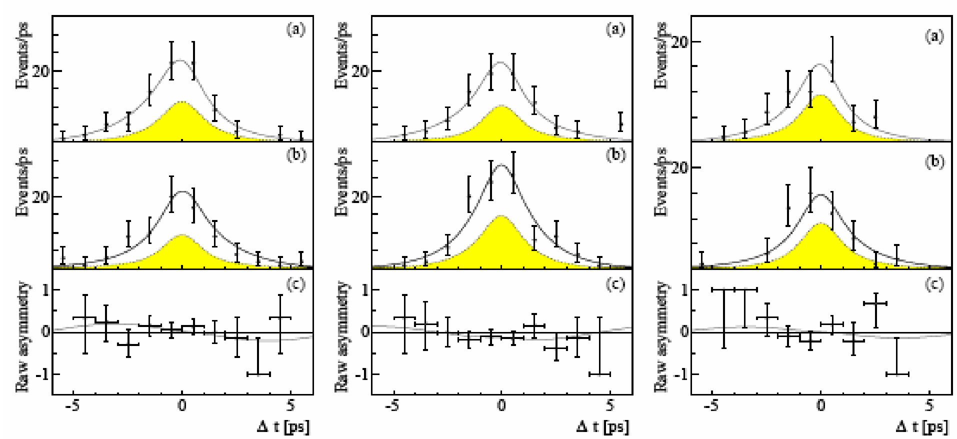
Sample	N_{cand}	N_{sig}	purity
$\overset{(-)}{B}{}^0 \to D^{*-}D^{+}$	993	126 ± 16	0.49 ± 0.03
$\overset{(-)}{B}{}^0 \to D^{*+}D^{-}$	1038	145 ± 16	0.49 ± 0.03
$\overset{(-)}{B}{}^0 \to D^{+}D^{-}$	538	54 ± 11	0.37 ± 0.06

$D^{(*)+}$ $D^{(*)-}$: results

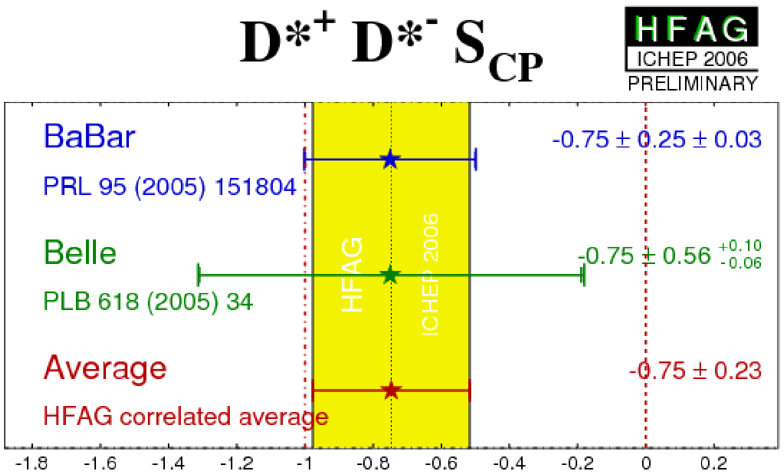
- $D^{*+}D^{*-}$
  - S_{+}=-0.75±0.25±0.03
  - C_{+}=+0.06±0.17±0.03

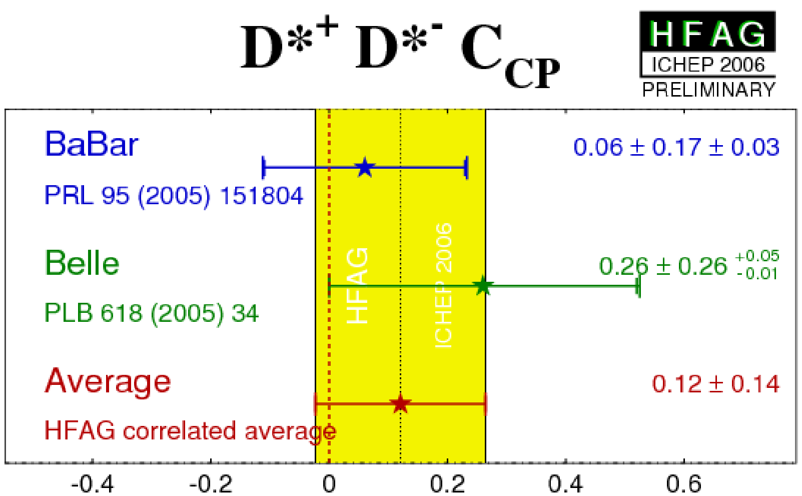


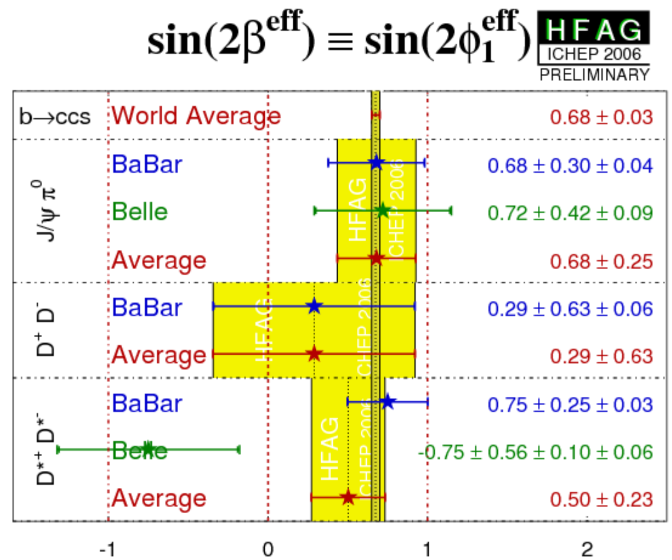
- $D^{*+}D^{-}$, $D^{*-}D^{+}$, $D^{+}D^{-}$
  - S_{DD}=-0.29±0.63±0.06
  - C_{DD}=+0.11±0.35±0.06
  - $S_{D^{*+}D^{-}}$=-0.54±0.35±0.07
  - $C_{D^{*+}D^{-}}$=+0.09±0.25±0.06
  - $S_{D^{*-}D^{+}}$=-0.29±0.33±0.07

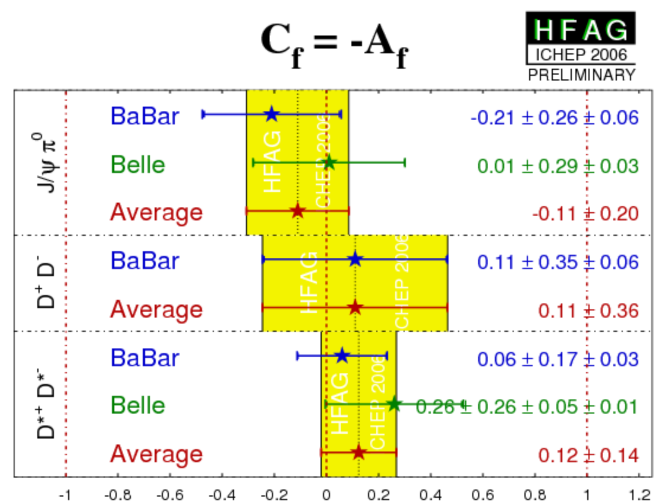


$D^{(*)+} D^{(*)-}$: world average









$D^{(*)+} D^{(*)-}$: systematics

- $D^{*+}D^{-}$
  - The systematic uncertainties on S_f and C_f are separately evaluated for each of the decay modes. The dominant systematic uncertainty is the precision to which we are able to ascertain, using a Monte Carlo simulation, that the measurement method is unbiased (giving systematic uncertainties in the range 0.03-0.06). Other important uncertainties are due to the amount of peaking background and its potential CP asymmetry (0.01-0.02); assumptions on the Δt resolution function (0.01-0.03)

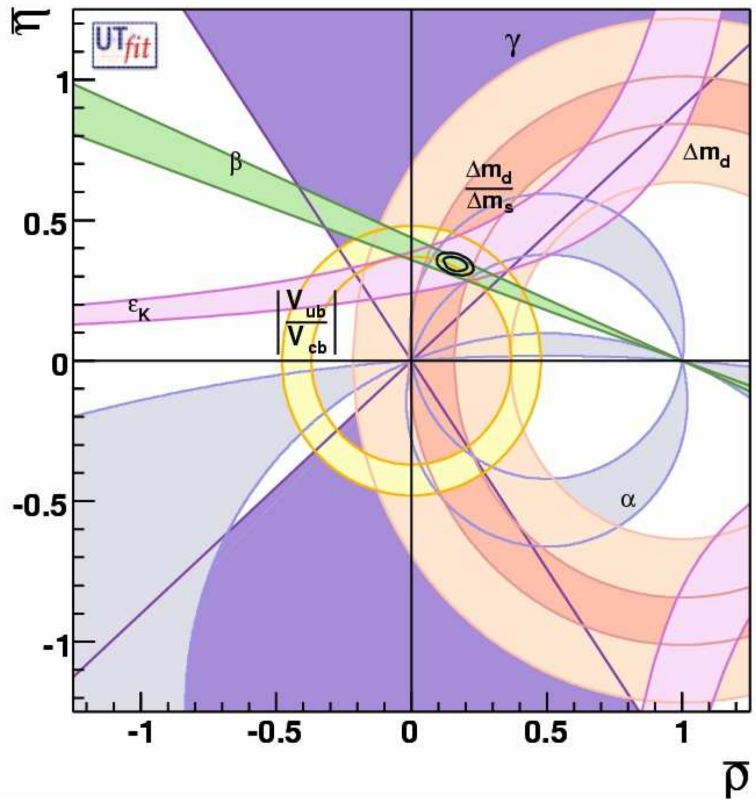
- $D^{*+}D^{*-}$
  - The systematic uncertainties on C_+ and S_+ arise from the amount of possible backgrounds that tend to peak under the signal and their CP asymmetry, the assumed parameterization of the t resolution function,

Sin(2β) : world average

PREDICTIONS:

sin 2β = 0.764 ± 0.039 (from UT sides)
sin 2β = 0.755 ± 0.040 (from UT sides + εK)
sin 2β = 0.701 ± 0.022 (all constraints)

MEASUREMENT:
sin 2β = 0.675 ± 0.026 (from b → ccs)



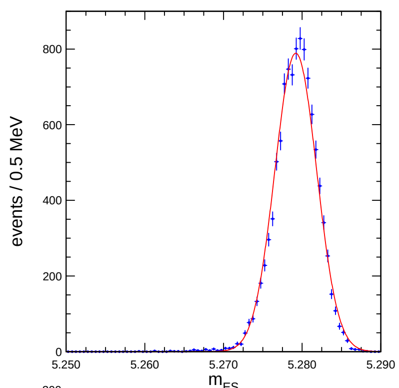
Resolutions

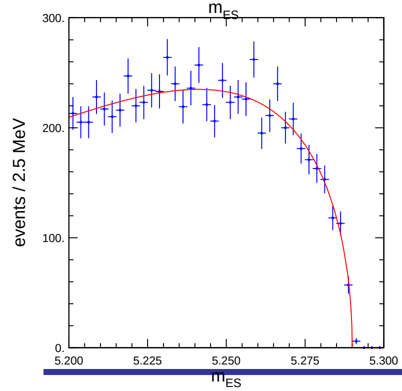
Variables that reflect energy and momentum conservation: peaking for fully reconstructed B decays, smooth for combinatorial background

$$m_{ES} \equiv \sqrt{E^2_{\text{CM beam}} - p^2_{\text{CM } B}} = m_B$$

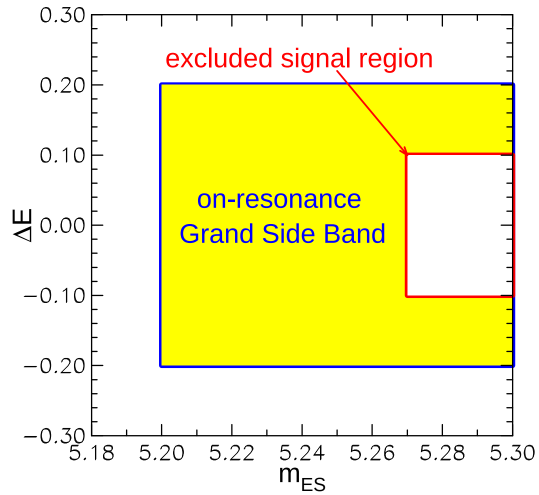
$$\Delta E \equiv E_{\text{CM } B} - E_{\text{CM beam}} = 0$$

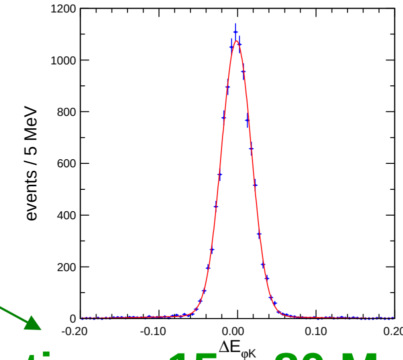
resolution ~ 2.5 – 3.0 MeV



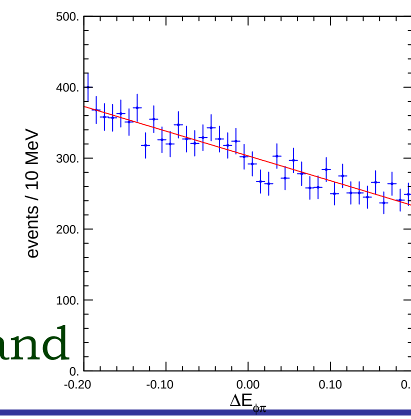


depending on presence of neutrals in the final state





resolution ~ 15 – 80 MeV



continuum background in the Grand Side Band

Tagging: efficiency and effects

The figure of merit for tagging is the
effective tagging efficiency $Q \equiv \Sigma_i\, \varepsilon_i(1 - 2w_i)^2 = (30.4 \pm 0.3)\%$

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.67 ± 0.08	3.0 ± 0.3	-0.2 ± 0.6	7.67 ± 0.13
Kaon I	10.96 ± 0.09	5.3 ± 0.4	-0.6 ± 0.7	8.74 ± 0.16
Kaon II	17.21 ± 0.11	15.5 ± 0.4	-0.4 ± 0.7	8.21 ± 0.19
Kaon-Pion	13.77 ± 0.10	23.5 ± 0.5	-2.4 ± 0.8	3.87 ± 0.14
Pion	14.38 ± 0.10	33.0 ± 0.5	5.2 ± 0.8	1.67 ± 0.10
Other	9.61 ± 0.08	41.9 ± 0.6	4.6 ± 0.9	0.25 ± 0.04
All	74.60 ± 0.12			30.4 ± 0.3

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{(1 \mp \Delta\omega) \pm (1-2\omega) \times \left[\frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2}\sin(\Delta m_d \Delta t) - \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d \Delta t)\right]\right\}$$

$J/\psi\pi^0$: penguin contribution

- M. Ciuchini, M. Pierini and L. Silvestrini, PRL **95,** 221804 (2005)

$$A(B^0 \to J/\psi\pi^0) = V_{cb}^* V_{cd}(E_2 - P_2) + \underline{V_{ub}^* V_{ud}(P_2^{GIM} - P_2)}$$

- Potential effect on S and C
- $|P_2^{GIM} - P_2| = 0.27 \pm 0.27$