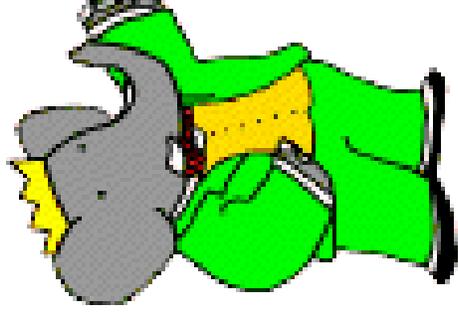


Measurement of CKM angles at BaBar and Belle

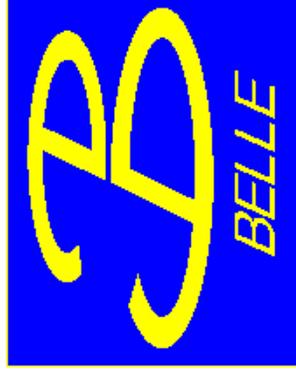
Nick Barlow

University of Manchester/

University of Cambridge



DIS 2007



Contents

- CKM matrix and Unitarity Triangle
- Time-dependant analysis at the B factories
- Measurement of β (ϕ_1)
 - $b \rightarrow c\bar{c}s$ decays ($B \rightarrow c\bar{c} K^0$)
 - $b \rightarrow c\bar{c}d$ decays (e.g. $B \rightarrow DD$)
 - $b \rightarrow s$ penguin-dominated decays (e.g. $B \rightarrow \phi K^0$)
- Measurement of α (ϕ_2)
 - $B \rightarrow \pi\pi$
 - $B \rightarrow \rho\rho$
- Measurement of γ (ϕ_3)
 - $B \rightarrow DK$
- Conclusions

CKM matrix and Unitarity Triangle

- Relationship between flavour eigenstates and weak eigenstates of quarks is described by **CKM matrix**:

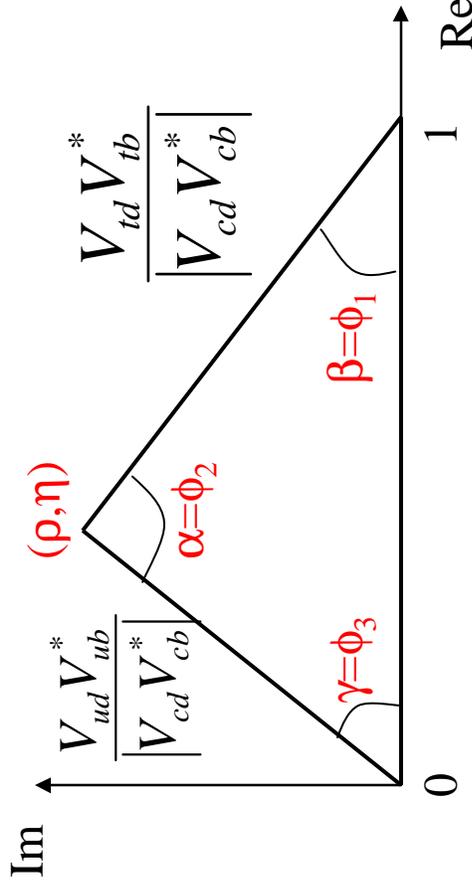
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 + \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

- Matrix is Unitary: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



Unitarity Triangle

- Area of triangle is measure of how much CP violation there is in the Standard Model

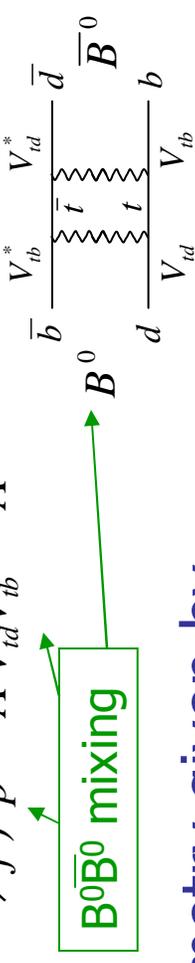


Time-dependent CP asymmetries

- Look for situations where both B^0 and \bar{B}^0 can decay to a common final state f



- Define quantity λ_f :
$$\lambda_f = \frac{A(\bar{B}^0 \rightarrow f) q}{A(B^0 \rightarrow f) p} = \frac{\bar{A} V_{td}^* V_{tb}}{A V_{td} V_{tb}^*} \approx \frac{\bar{A}}{A} e^{2i\beta}$$



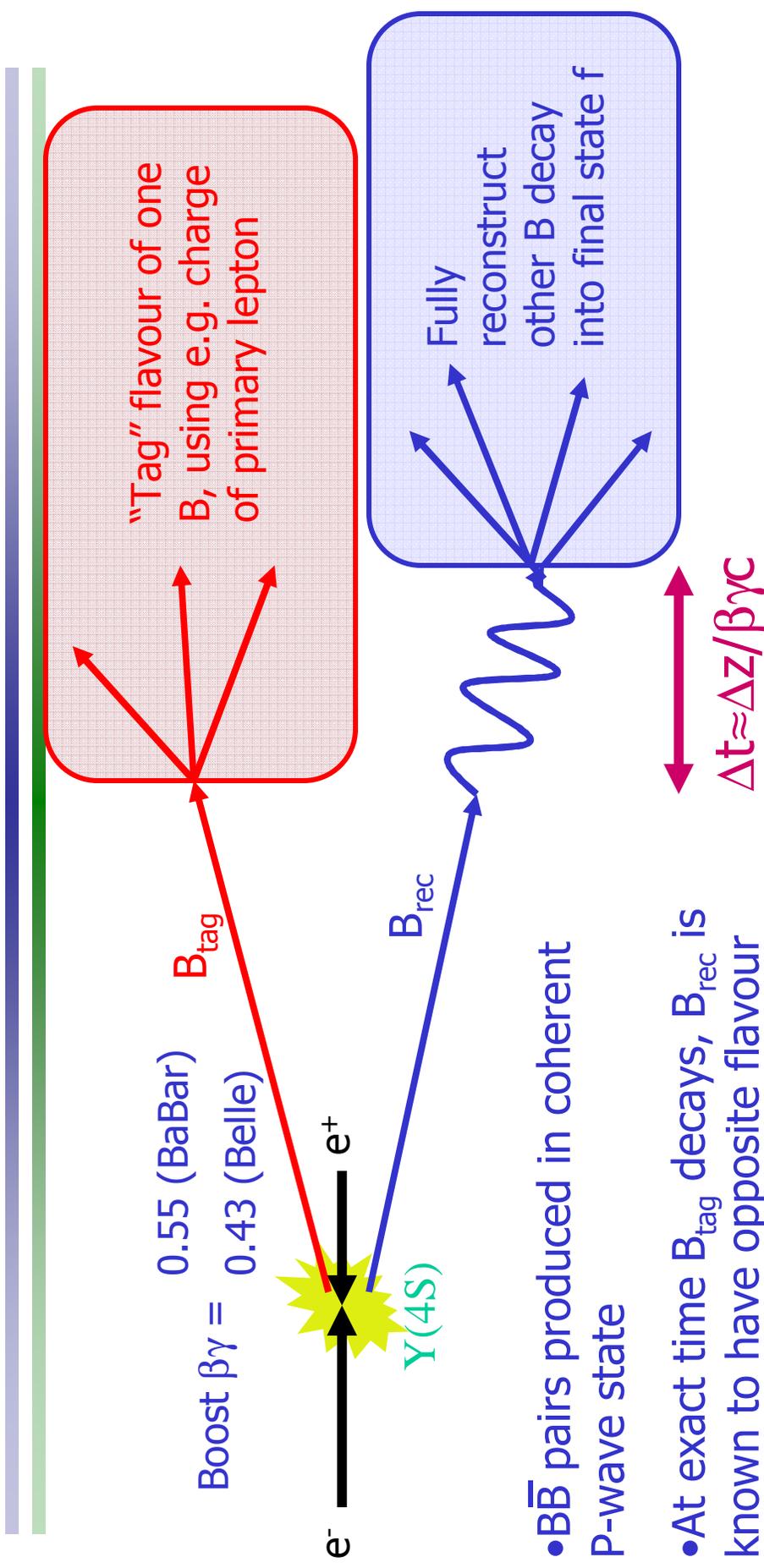
- Time-dependent CP asymmetry given by:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow f) - \Gamma(B^0(t) \rightarrow f)}{\Gamma(\bar{B}^0(t) \rightarrow f) + \Gamma(B^0(t) \rightarrow f)} = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos(\Delta m \cdot t) + \frac{2 \operatorname{Im}(\lambda_f)}{1 + |\lambda_f|^2} \sin(\Delta m \cdot t)$$

} C_{CP}
} S_{CP}

- If $|\lambda_f|=1$ (no direct CPV), $C=0$

Time-dependent analysis at B factories

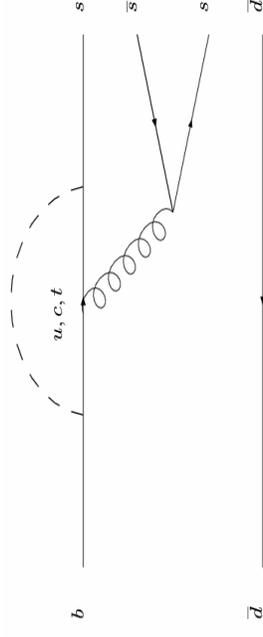
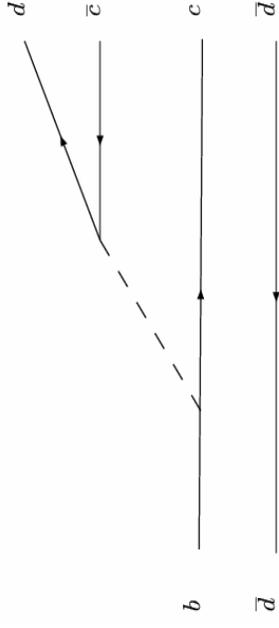
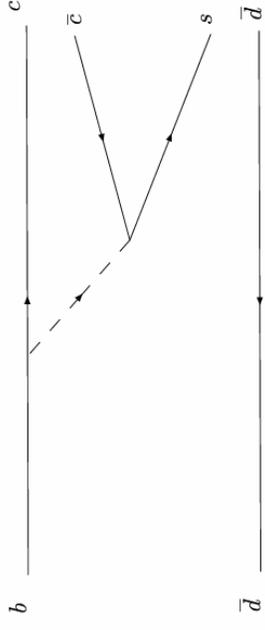


- $B\bar{B}$ pairs produced in coherent P-wave state
- At exact time B_{tag} decays, B_{rec} is known to have opposite flavour
- B_{rec} may or may not mix in the time interval Δt between the two B decays

Measuring β (ϕ_1)

$$\beta = \arg \left[- \frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}} \right]$$

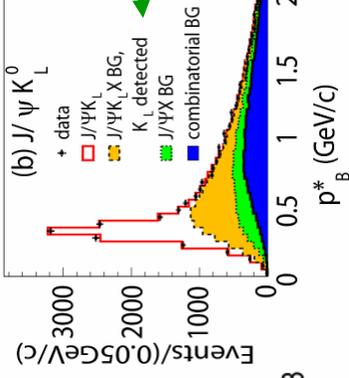
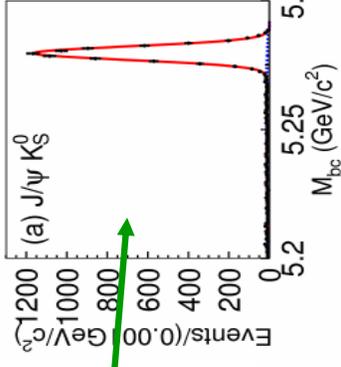
- $\sin 2\beta$ can be measured in several ways:
 - $b \rightarrow c\bar{c}s$ decays (e.g. charmonium K^0):
 - Golden channel
 - No direct CPV expected
 - Already a precision measurement
 - $b \rightarrow c\bar{c}d$ decays (e.g. $B \rightarrow DD$)
 - Both tree and penguin diagrams may contribute
 - Measure $\sin 2\beta_{\text{eff}}$, may differ from $\sin 2\beta$, depending on amount of direct CP violation.



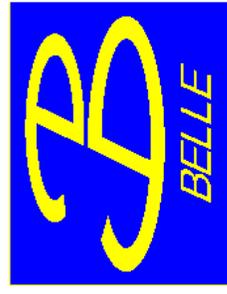
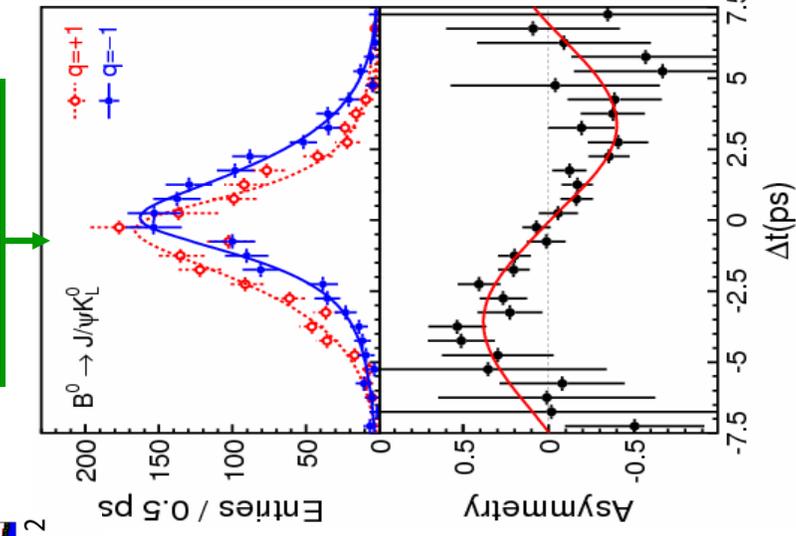
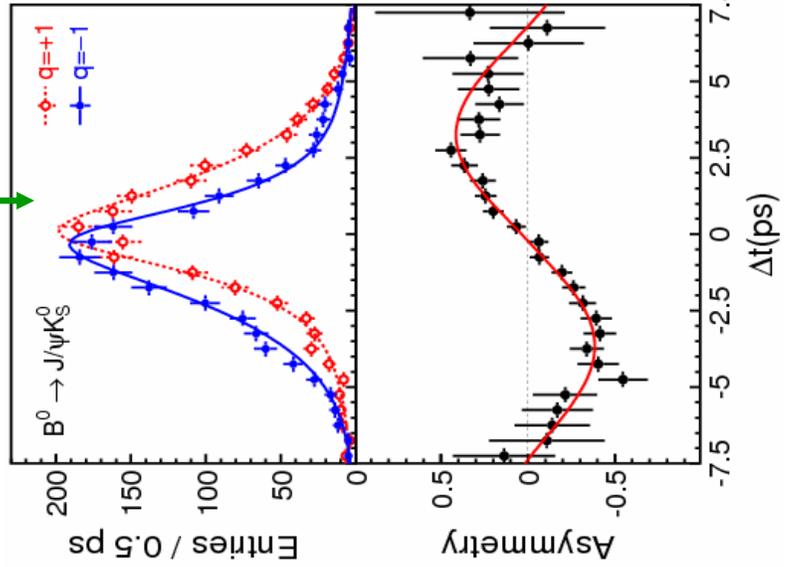
- Penguin dominated decays (e.g. ϕK^0)
 - Sensitive probe of New Physics, due to possibility of non-SM particles in loops

Belle results for $\sin 2\beta$ in $b \rightarrow c\bar{c}s$

CP=-1
7482 events
97% purity



CP=+1
6512 events
59% purity



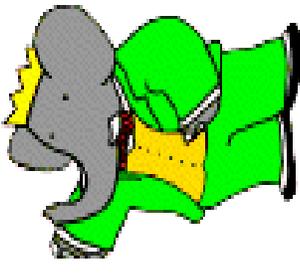
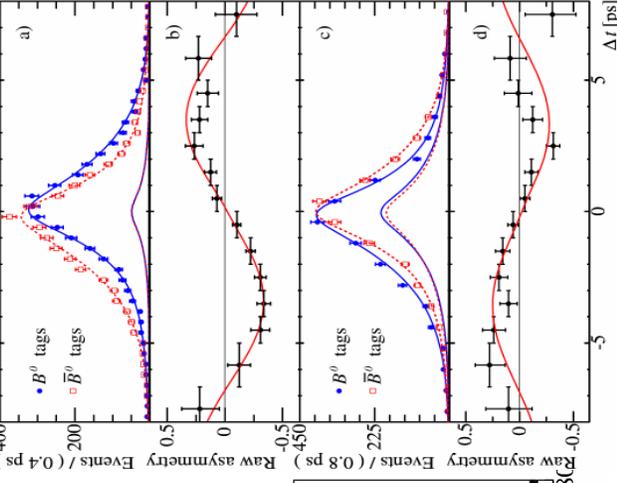
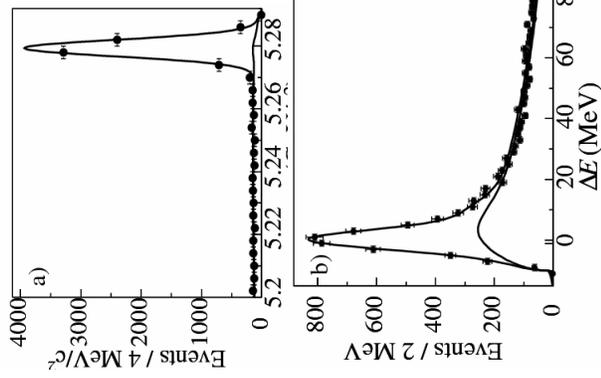
535M BB events

$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$
 $C = -0.018 \pm 0.021 \pm 0.014$

PRL 98, 031892 (2007)

BaBar results for $\sin 2\beta$ in $b \rightarrow c\bar{c}s$

- BaBar use several additional decay channels
 - CP-odd: $\psi(2S)K_S, \eta_c K_S, \chi_{c1} K_S$
 - Mixture of CP-even and CP-odd: $J/\psi K^{*0}$
 - More events per unit luminosity, but slightly lower purity



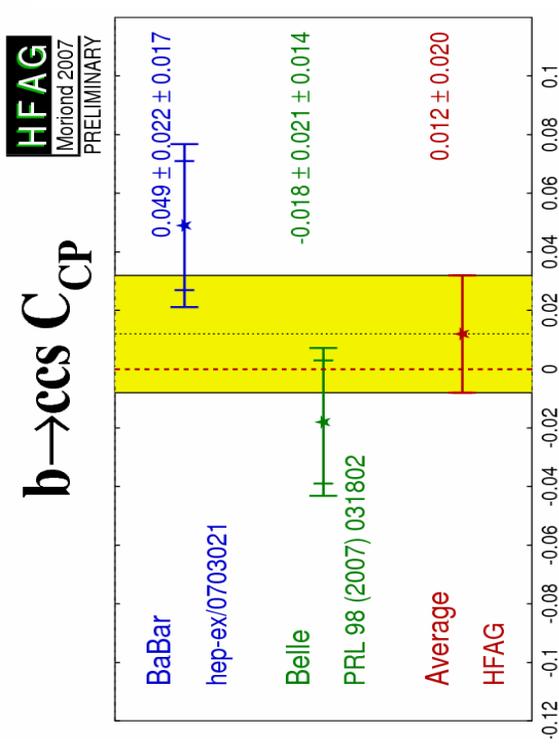
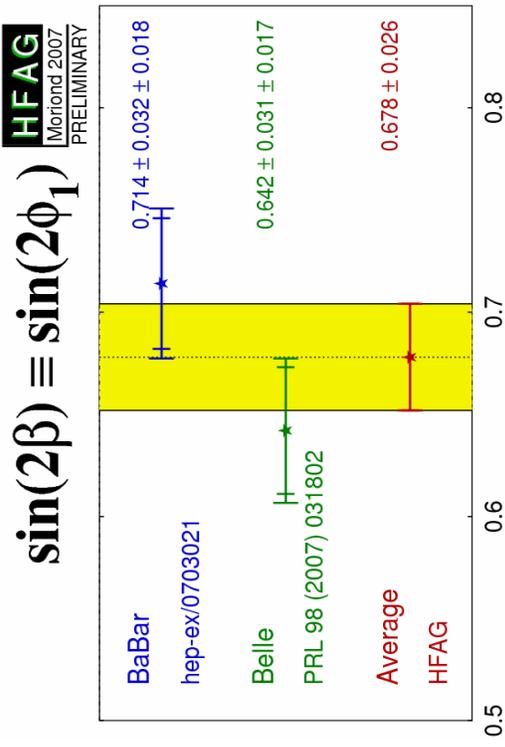
384M BB events

CP=-1
6900 events
92% purity

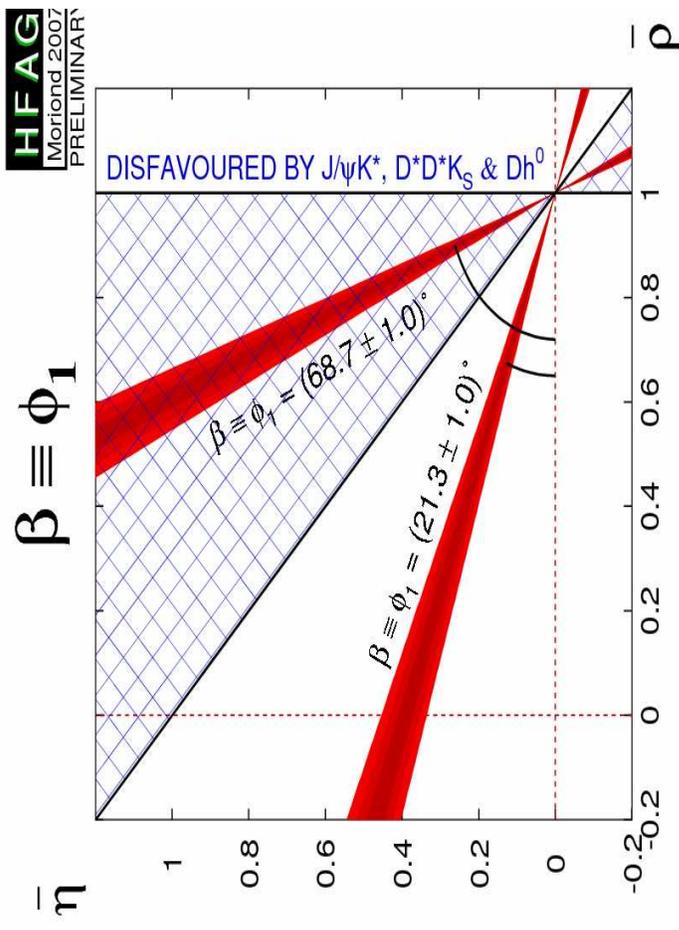
CP=+1
3700 events
55% purity

$\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$
 $C = 0.049 \pm 0.022 \pm 0.017$

Summary of β from $b \rightarrow c\bar{c}s$



- Can also reduce the four-fold ambiguity on β by measuring the sign of $\cos 2\beta$ using $B \rightarrow J/\psi K^*$ and other modes.

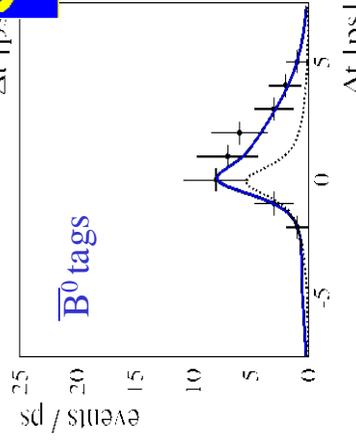
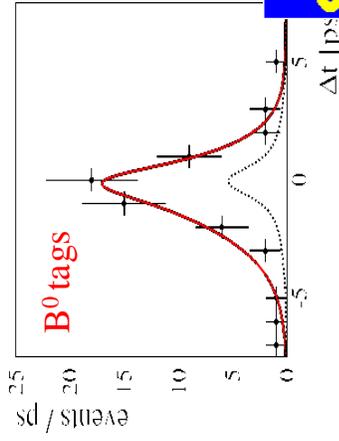


$B \rightarrow D^+ D^-$

Expect $S \sim -\sin 2\beta$, $C \sim 0$

Belle see evidence for large direct CPV

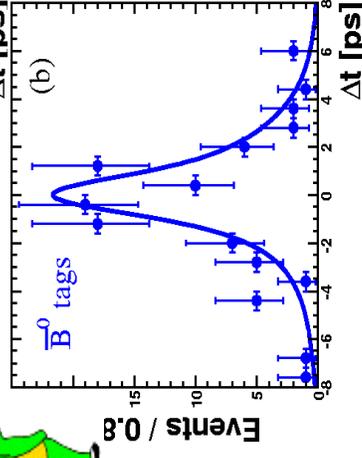
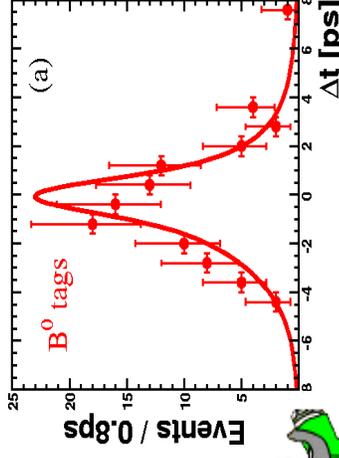
Not confirmed by BaBar.



$$S = -1.13 \pm 0.37 \pm 0.09$$

$$C = -0.91 \pm 0.23 \pm 0.06$$

hep-ex 070231, submitted to PRL



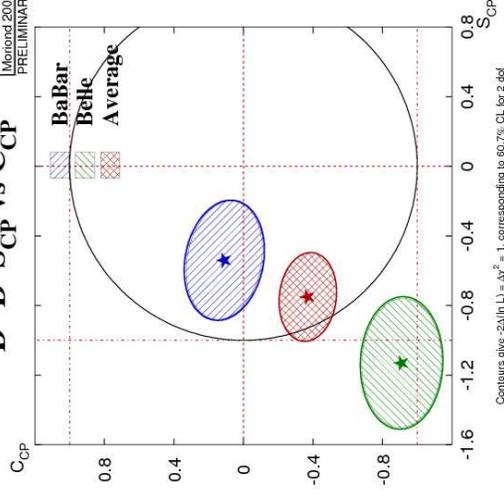
$$S = -0.54 \pm 0.34 \pm 0.06$$

$$C = 0.11 \pm 0.22 \pm 0.07$$

Presented at Moriond EW

HFAG
March 2007
PRELIMINARY

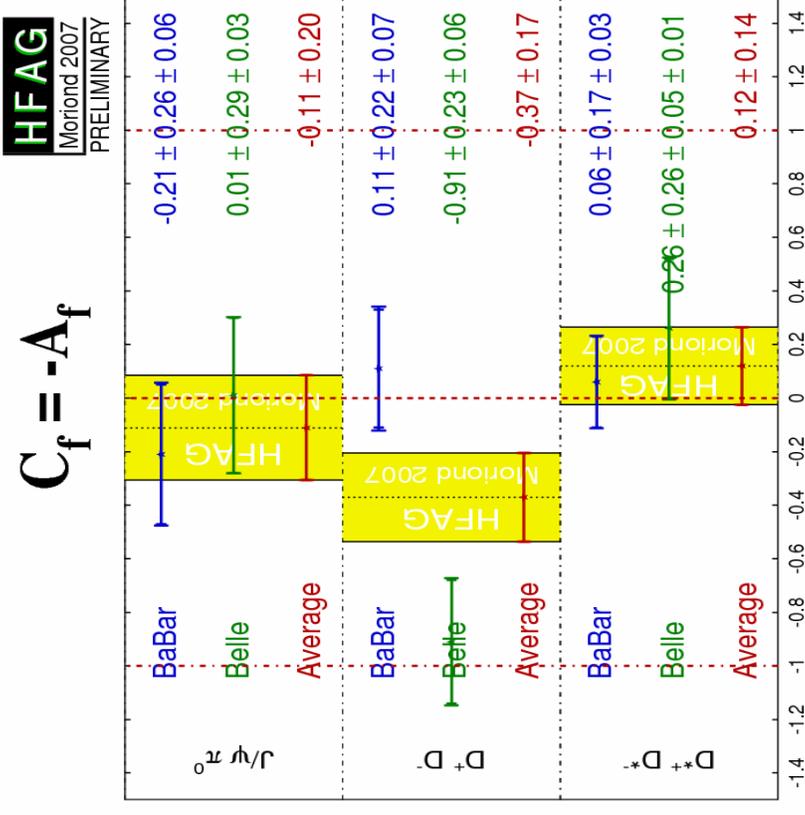
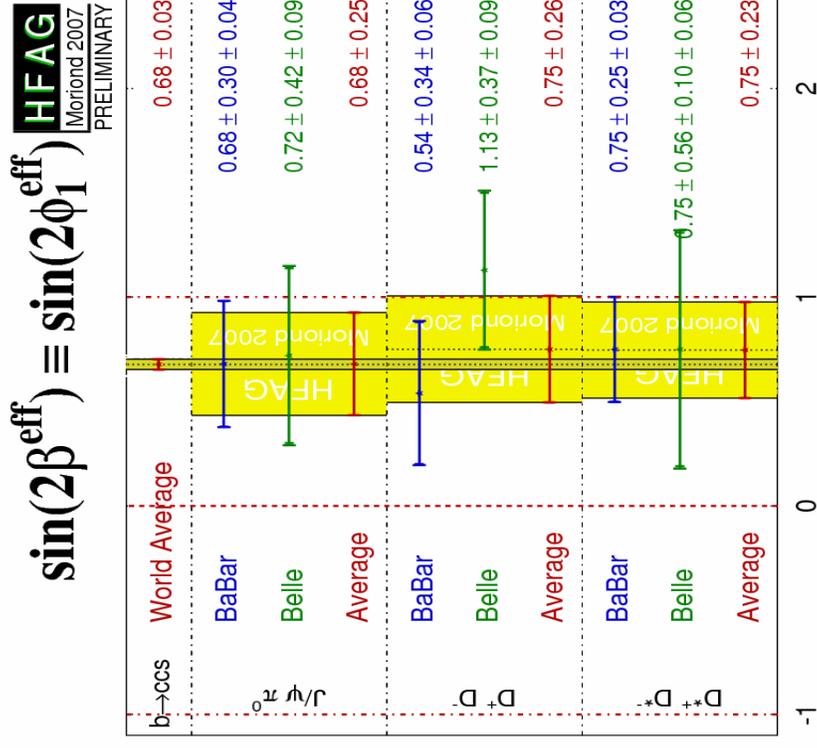
$D^+ D^- S_{CP}$ vs C_{CP}



$\sim 3\sigma$ difference between BaBar and Belle

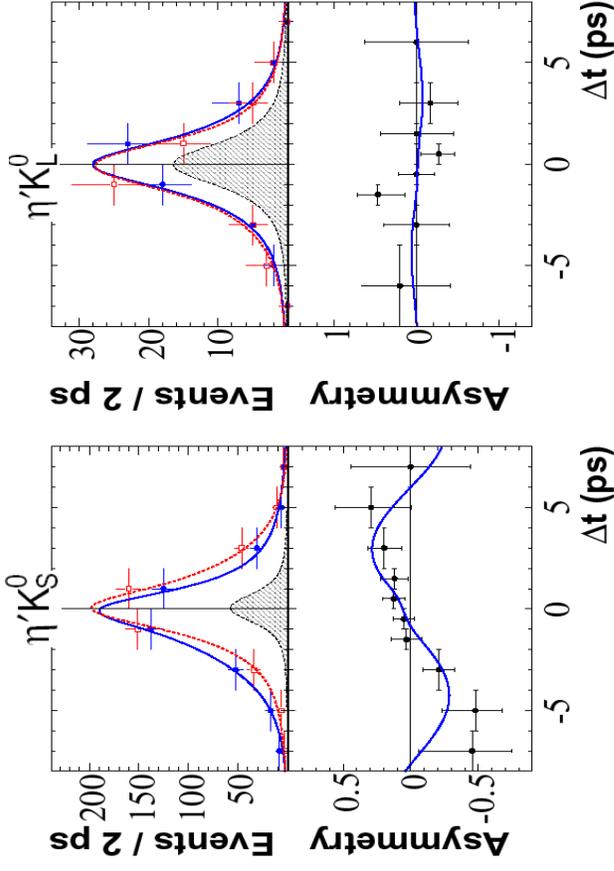
(Care must be taken when interpreting average, due to result lying in unphysical region)

Summary of β with $b \rightarrow c\bar{c}d$

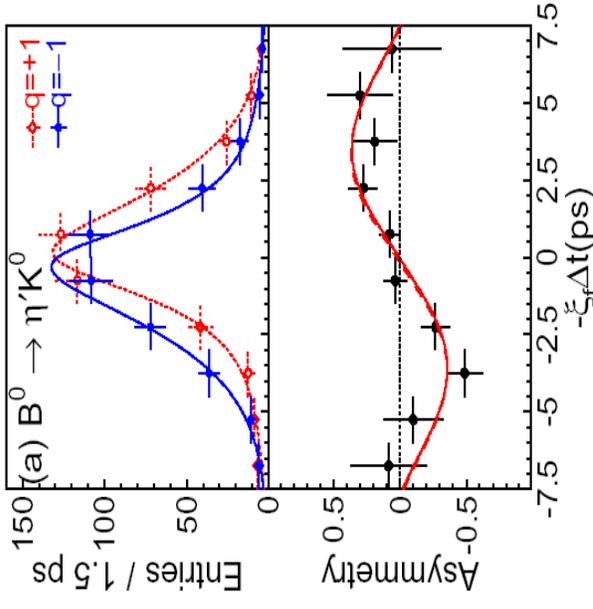


$\sin 2\beta$ in $b \rightarrow s$ penguin modes

$B \rightarrow \eta' K^0$: $> 5\sigma$ observation of CPV in charmless B decays from both BaBar and Belle



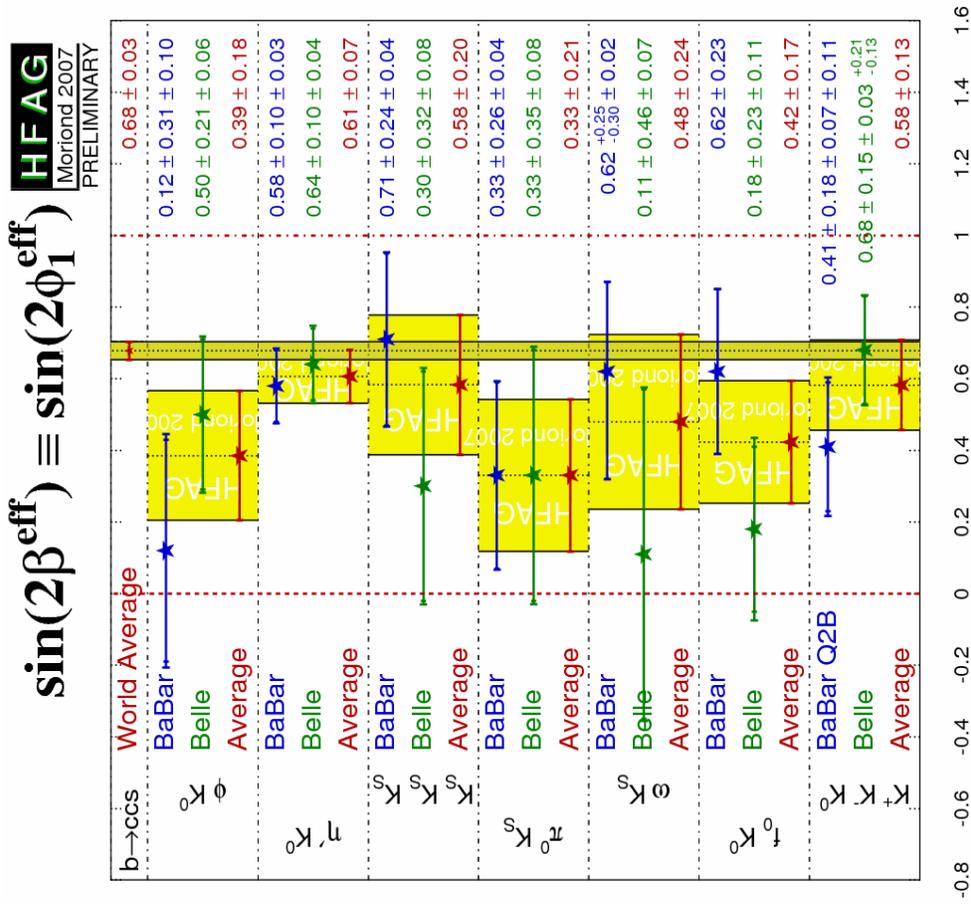
$\sin 2\beta = 0.58 \pm 0.10 \pm 0.03$
 $C = -0.16 \pm 0.07 \pm 0.03$



$\sin 2\beta = 0.64 \pm 0.10 \pm 0.04$
 $C = 0.011 \pm 0.07 \pm 0.05$

Summary of β with $b \rightarrow s$ penguins

- In general, values of $\sin 2\beta$ from penguin-dominated modes are smaller than that from $b \rightarrow ccs$
- Some theoretical uncertainties, but these tend to lead us to expect a shift in the other direction
- Shift is not yet statistically significant, but both experiments are expected to double their data samples by summer 2008



Measuring $\alpha(\phi_2)$

$$\alpha = \arg \left(- \frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right)$$

- If only tree diagrams contributed:



Tree decay

$B^0 B^0$ mixing

$$\lambda_{\pi\pi} = (q/p)(A/A) = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$S = \sin(2\alpha)$$

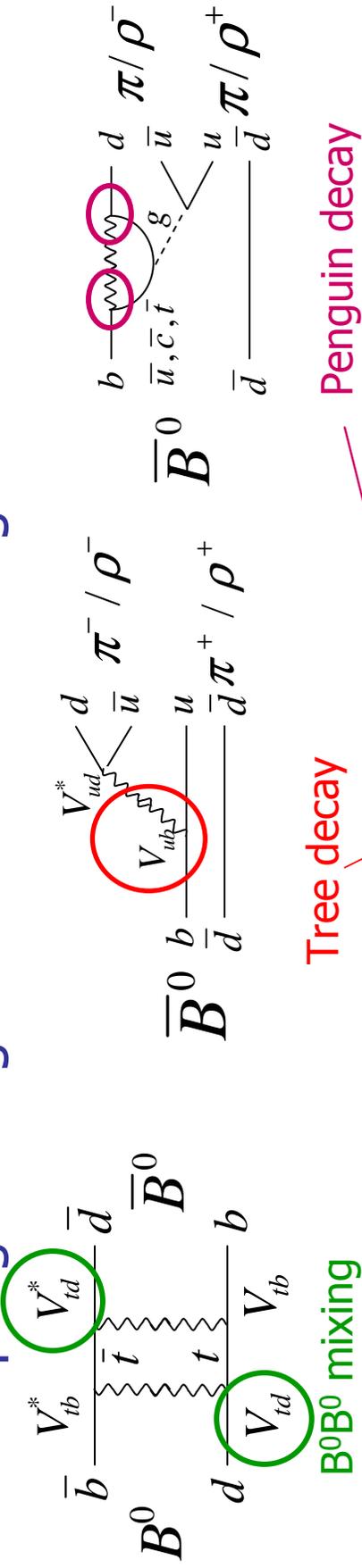
$$C = 0$$

Similar to $\sin 2\beta$ measurement in golden channel

Measuring $\alpha(\phi_2)$

$$\alpha = \arg \left(- \frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right)$$

- With penguin diagram also contributing:



Tree decay

$$\lambda_{\pi^+ \pi^-} = e^{i2\alpha} \frac{T + P e^{+i\gamma} e^{i\delta}}{T + P e^{-i\gamma} e^{i\delta}}$$

$$S = \sqrt{1 - C^2} \sin(2\alpha_{\text{eff}})$$

$$C \propto \sin \delta$$

$$\delta = |\alpha - \alpha_{\text{eff}}|$$

Can we still measure α from α_{eff} ?

Isospin analysis

- Amplitudes of different $\pi\pi$ and $\rho\rho$ decay channels are related by SU(2):

Gronau and London, PRL 65, 3381 (1990)

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

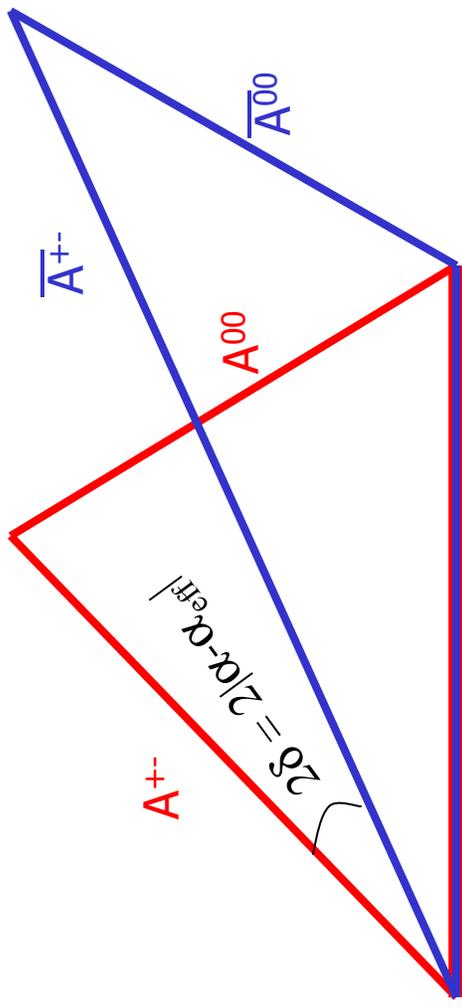
$$A^{00} = A(B^0 \rightarrow \pi^0 \pi^0) \quad \bar{A}^{00} = A(\bar{B}^0 \rightarrow \pi^0 \pi^0)$$

$$A^{0+} = A(B^+ \rightarrow \pi^0 \pi^+) \quad \bar{A}^{0-} = A(B^- \rightarrow \pi^0 \pi^-)$$

$$A^{+-} = A(B^0 \rightarrow \pi^+ \pi^-) \quad \bar{A}^{+-} = A(\bar{B}^0 \rightarrow \pi^+ \pi^-)$$

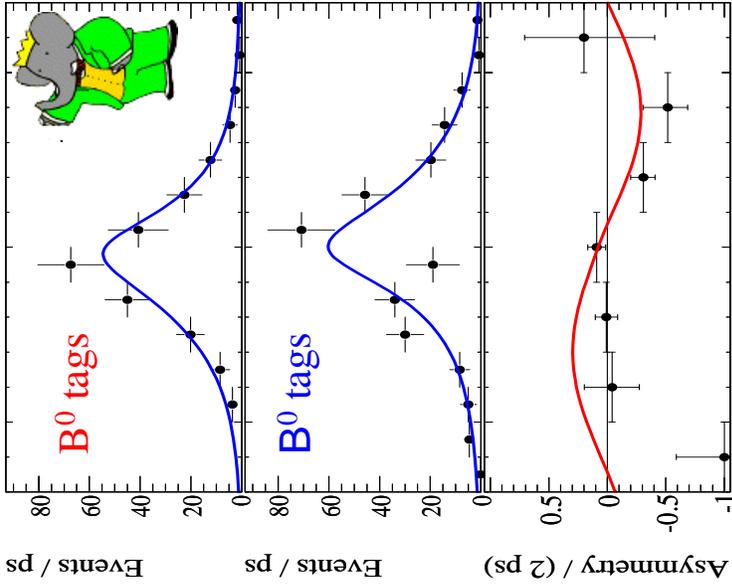
$$\frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$$

- Measure sides of triangles to get $|\alpha - \alpha_{\text{eff}}|$



$$A^{+0} = \bar{A}^{-0} \quad (\text{tree only})$$

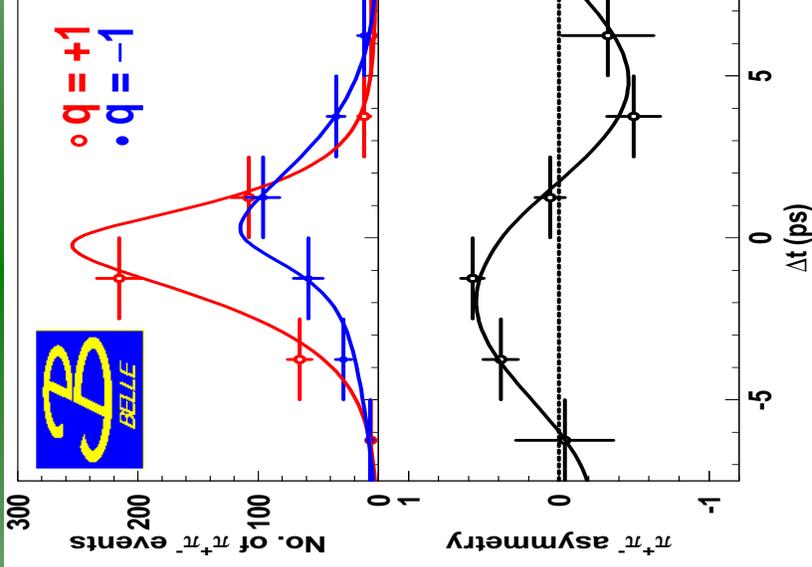
$B \rightarrow \pi^+ \pi^-$



hep-ex/0703136 347M BB pairs

$$S_{CP} = -0.60 \pm 0.11 \pm 0.03$$

$$C_{CP} = -0.21 \pm 0.09 \pm 0.02$$

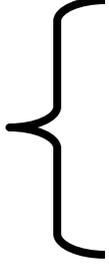


hep-ex/0608135 535M BB pairs

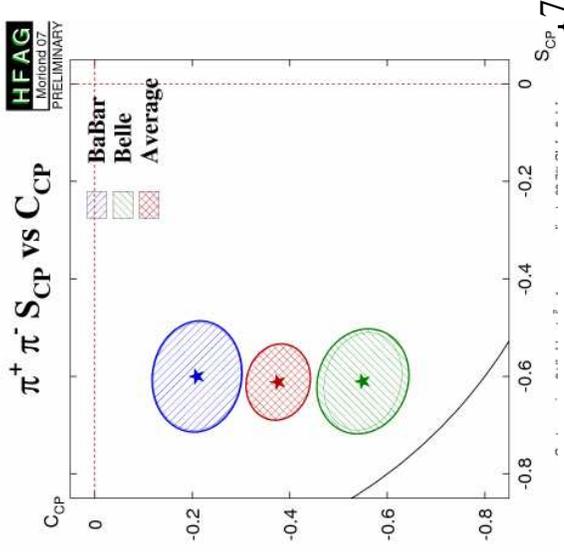
$$S_{CP} = -0.60 \pm 0.10 \pm 0.04$$

$$C_{CP} = -0.55 \pm 0.08 \pm 0.05$$

$\times 10^{-6}$ (HFAG)



$BR(B^0 \rightarrow \pi^+ \pi^-) = 5.2 \pm 0.2$	-
$BR(B^+ \rightarrow \pi^+ \pi^0) = 5.7 \pm 0.4$	$A_{CP}(B^+ \rightarrow \pi^+ \pi^0) = 0.04 \pm 0.05$
$BR(B^0 \rightarrow \pi^0 \pi^0) = 1.3 \pm 0.2$	$A_{CP}(B^0 \rightarrow \pi^0 \pi^0) = 0.36^{+0.33}_{-0.31}$



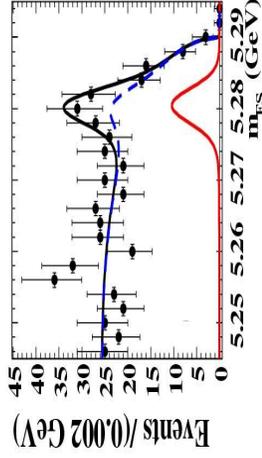
B → ρρ

- B → ρρ is a pseudoscalar → vector vector decay
 - Final state could be mixture of CP-odd and CP-even
 - However, turns out that decay is almost 100% longitudinally polarized ☺
 - Penguin fraction is smaller than in ππ
 - $|\alpha - \alpha_{\text{eff}}|$ small due to limit on $\text{BF}(B^0 \rightarrow \rho^0 \rho^0) / \text{BF}(B^+ \rightarrow \rho^+ \rho^0)$
- BUT

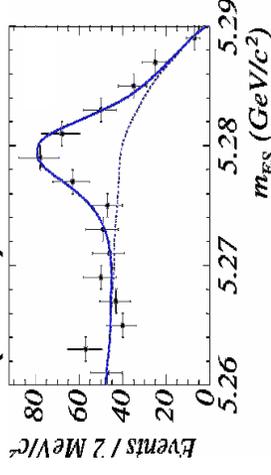
New BaBar measurements:

3.5σ evidence for B → ρ⁰ ρ⁰
 $\text{BF}(B \rightarrow \rho^0 \rho^0) = (1.07 \pm 0.33 \pm 0.19) \times 10^{-6}$

hep-ex/0612021 384M BB events



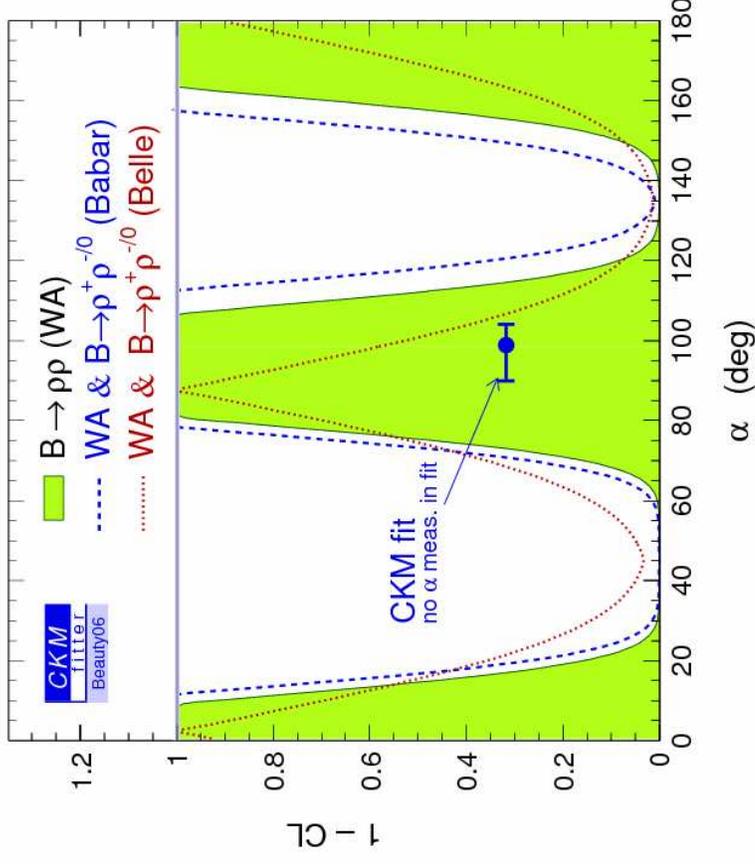
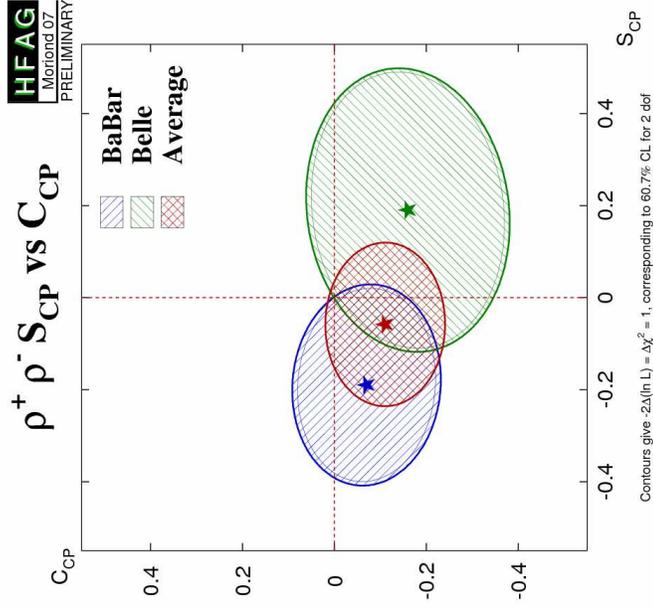
PRL 97, 261801 (2006) 232M BB events



$\text{B.F.}(B \rightarrow \rho^+ \rho^0) = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$
 (previous average was $(26 \pm 6) \times 10^{-6}$)

⇒ $|\alpha - \alpha_{\text{eff}}|$ increased from 11° to 18° (@68%CL)

$B \rightarrow \rho^+ \rho^-$



BaBar: α between 74° and 117° (68% C.L.)

hep-ex/0607098

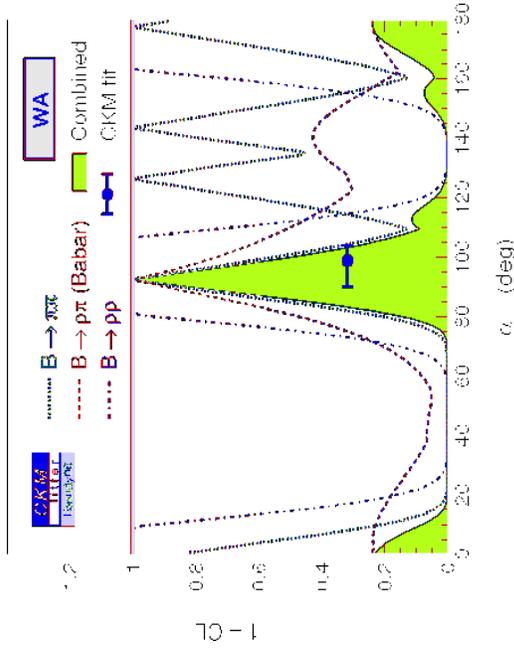
Belle: α between 59° and 117° (90% C.L.)

hep-ex/0702009

Mirror solution at $\alpha \rightarrow \alpha + \pi$ also exists

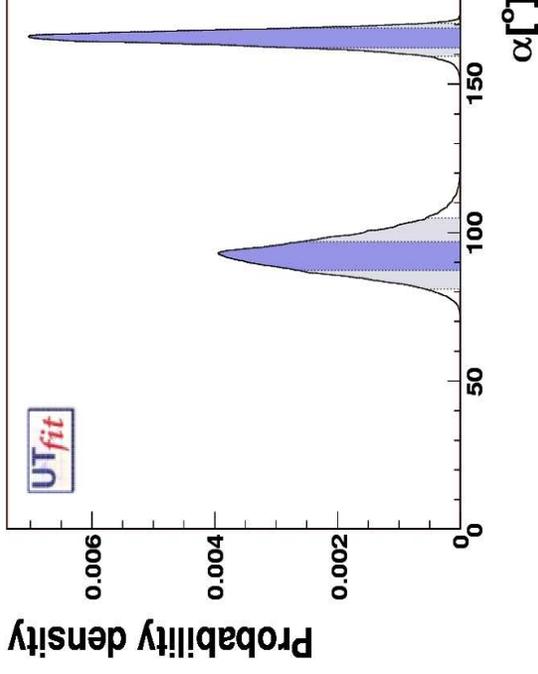
Summary of $\alpha(\phi_2)$

- Can also perform Dalitz fit on $B \rightarrow \pi^+ \pi^- \pi^0$
 - Including $B \rightarrow \rho\pi$
 - Too complicated to go into here!
- Different statistical treatments (frequentist or Bayesian) give slightly different results for α



Frequentist (CKMFitter):

$$\alpha = (93^{+11}_{-9})^\circ$$



Bayesian (UTfit):

$$\alpha = [81, 105]^\circ \text{ OR } [159, 171]^\circ \text{ (95\% C.L.)}$$

Measuring γ , Dalitz method (GGSZ)

- Decay rates Γ_{\pm} for B^{\pm} decays to $D(K_S\pi^+\pi^-)K^{\pm}$ as a function of m_{-}^2 ($\equiv m(K_S\pi^-)^2$) and m_{+}^2 ($\equiv m(K_S\pi^+)^2$) can be written:

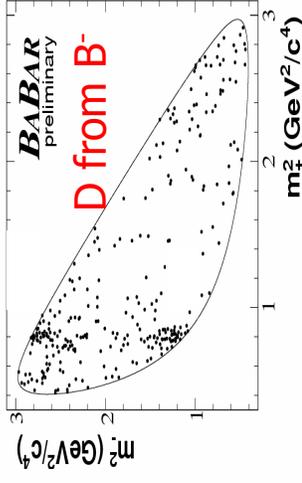
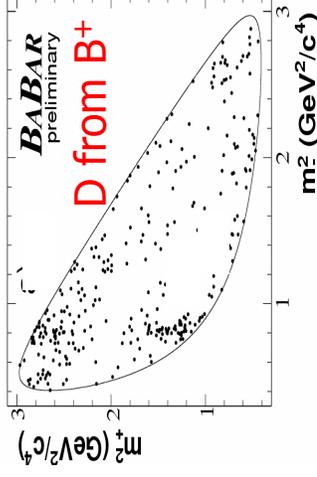
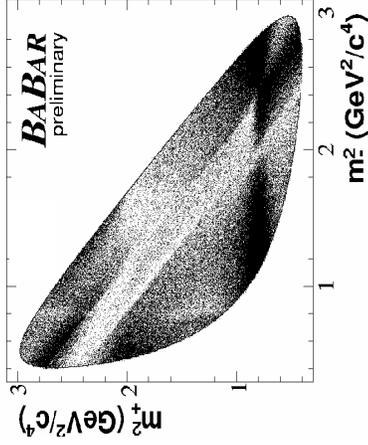
$$\Gamma_{\mp}(m_{-}^2, m_{+}^2) \propto |A_{D\mp}|^2 + r_B |A_{D\pm}|^2 + 2r_B [\cos(\delta\mp\gamma) \text{Re}(A_{D\mp} A_{D\pm}^*) + \sin(\delta\mp\gamma) \text{Im}(A_{D\mp} A_{D\pm}^*)]$$

↙ Amplitude for D^0 or \bar{D}^0 to decay to $K_S \pi^+ \pi^-$, as a function of (m_{-}^2, m_{+}^2)
↘ Strong phase

Amplitude for D^0 or \bar{D}^0 to decay to $K_S \pi^+ \pi^-$, as a function of (m_{-}^2, m_{+}^2)

Measure r_B , δ , and γ using D Dalitz plot from $B^{\pm} \rightarrow DK^{\pm}$ sample

Measure using Dalitz plot from large D^0 control sample



BaBar ($D^{(*)0}K^{\pm}$, 347M BB events)

$$\gamma = (92 \pm 42 \pm 10 \pm 13)^{\circ} \quad \text{hep-ex/0607104}$$

Belle ($D^{(*)0}K^{(*)\pm}$, 386M BB events)

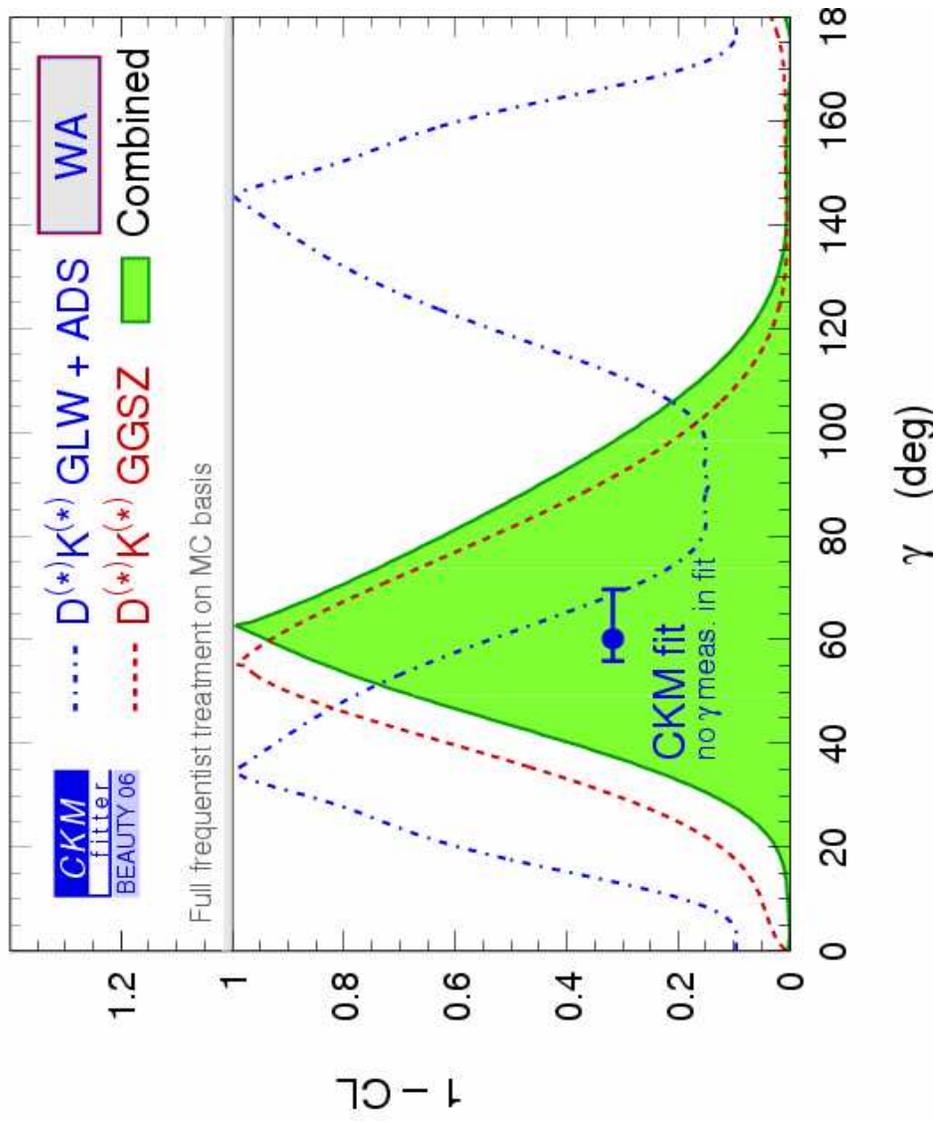
$$\gamma = (53^{+15}_{-18} \pm 3 \pm 9)^{\circ} \quad \text{PRD 73, 172009 (2006)}$$

Summary of γ (ϕ_3)

Frequentist treatment,
 combining BaBar and
 Belle results, GLW,
 ADS, GGSZ methods

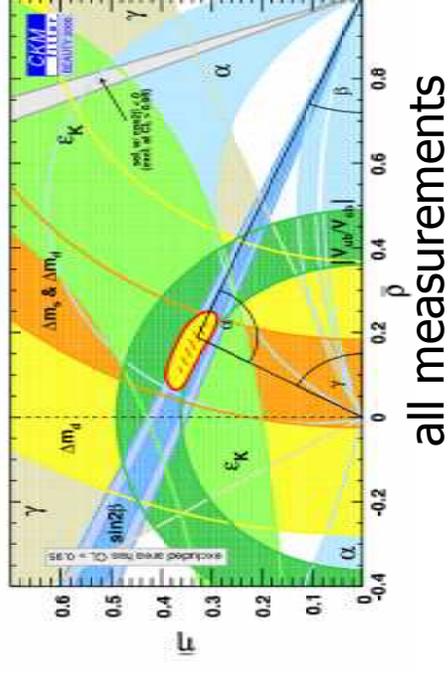
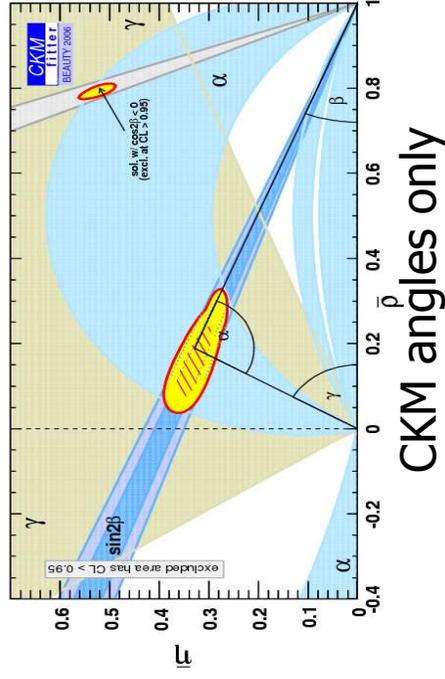
$$\gamma = (62^{+38}_{-24})^\circ$$

(CKMFitter)



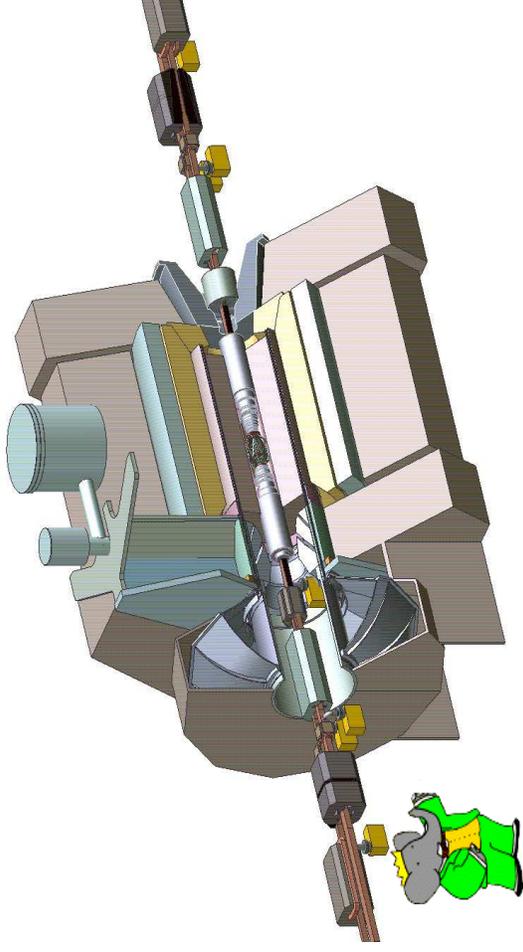
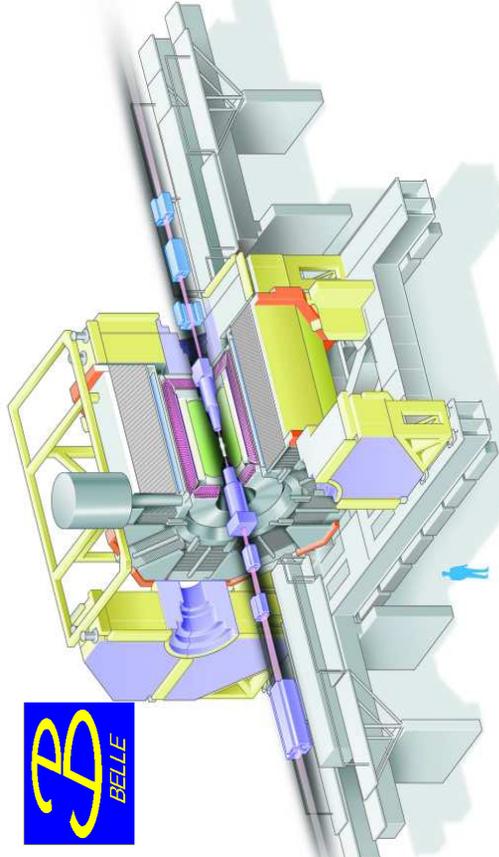
Conclusions

- $\beta(\phi_1)$: uncertainty $\sim 1^\circ$
 - Precision measurement in $B \rightarrow \text{charmonium}$ decays
 - $b \rightarrow s$ penguins are a promising place to look for new physics
- $\alpha(\phi_2)$: uncertainty $\sim 10^\circ$
 - B factories are just now getting sufficient data for branching fraction measurements of all $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ channels
- $\gamma(\phi_3)$: uncertainty $\sim 30^\circ$
 - Used to be considered beyond the reach of B factories
 - Lots of clever phenomenology work means there is potential for some useful constraint on (ρ, η) plane by the end of the B factories



Backup slides

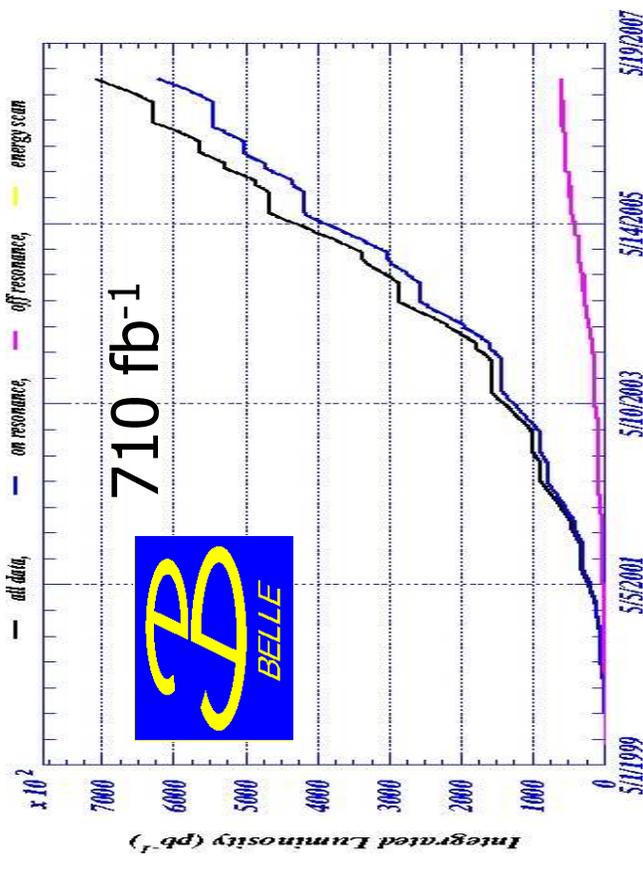
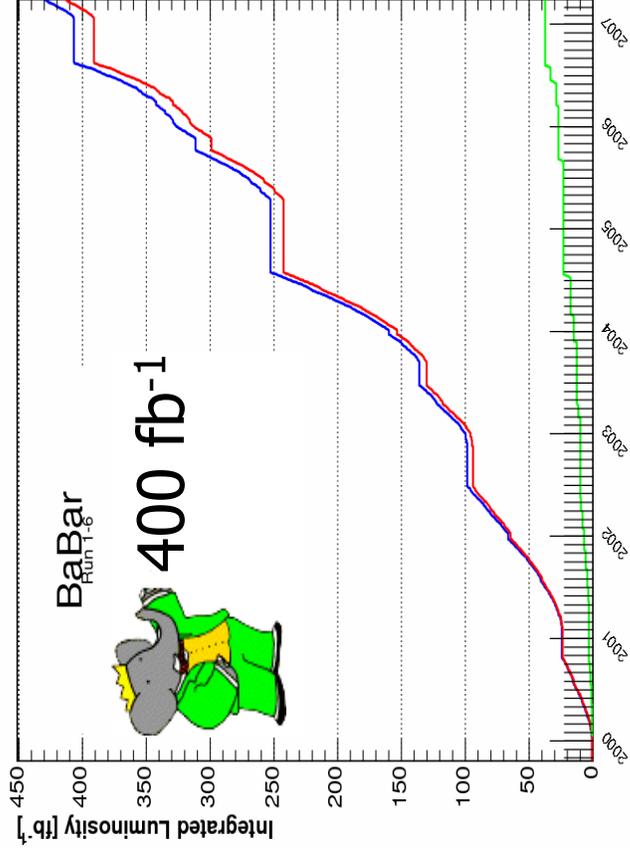
The BaBar and Belle detectors



Both detectors very similar:

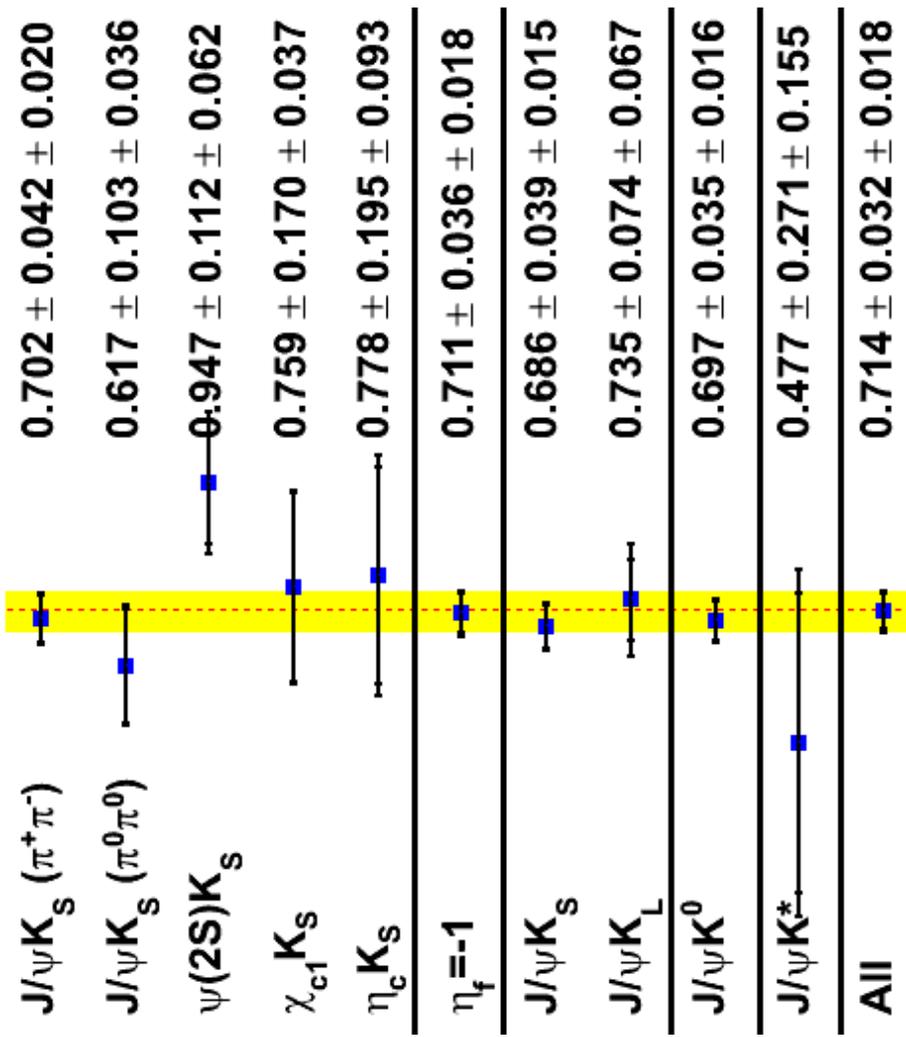
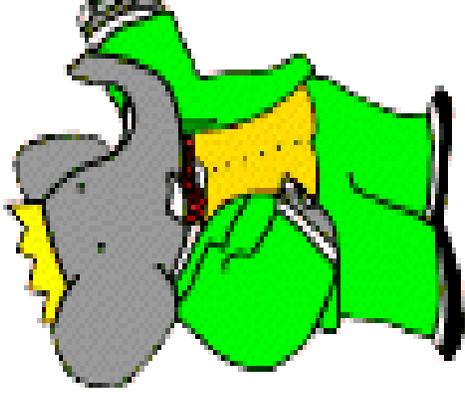
- Silicon strip detectors close to IP for good vertex resolution
- Drift chamber for charged particle tracking and momentum measurement
- Cherenkov detector for K/π identification
- Electromagnetic calorimeter for photon detection and electron ID
- Solenoid flux return instrumented with muon chambers

Integrated luminosity



- Cross-section for $Y(4S)$ production at this energy is $\sim 1.1\text{nb}$
- Therefore, total data sample is $> 10^9$ $B\bar{B}$ pairs.
- Both experiments expect to double data sample by 2008.

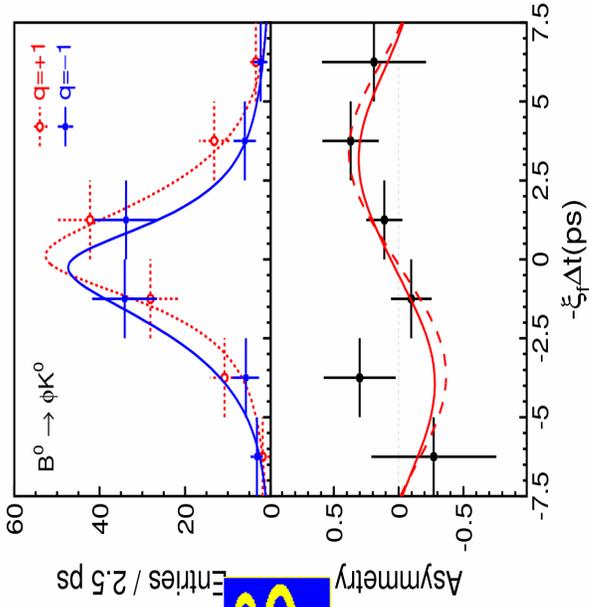
$\sin 2\beta$ with different decay channels



$\sin 2\beta$ in $b \rightarrow s$ penguin modes

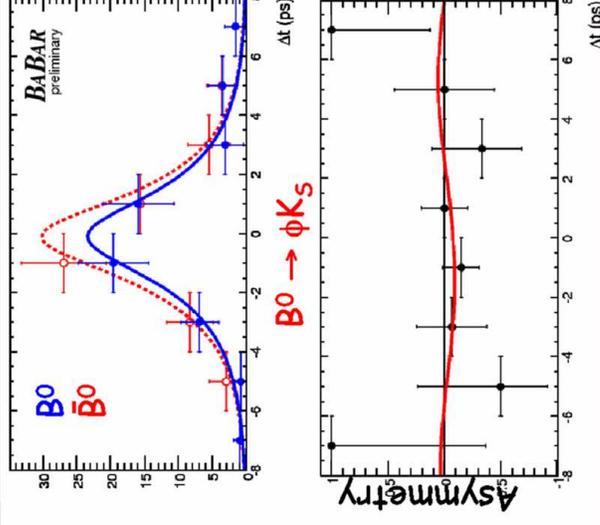
$B \rightarrow \phi K^0$: different approaches from BaBar and Belle

- BaBar perform full time-dependent Dalitz fit to $K^+K^-K^0$ system
- Belle do separate fits to ϕK^0 and $K^+K^-K^0$ non-resonant



$$\sin 2\beta = 0.50 \pm 0.21 \pm 0.06$$

$$C = -0.07 \pm 0.15 \pm 0.05$$



$$\sin 2\beta = 0.12 \pm 0.31 \pm 0.10$$

$$C = -0.18 \pm 0.20 \pm 0.10$$



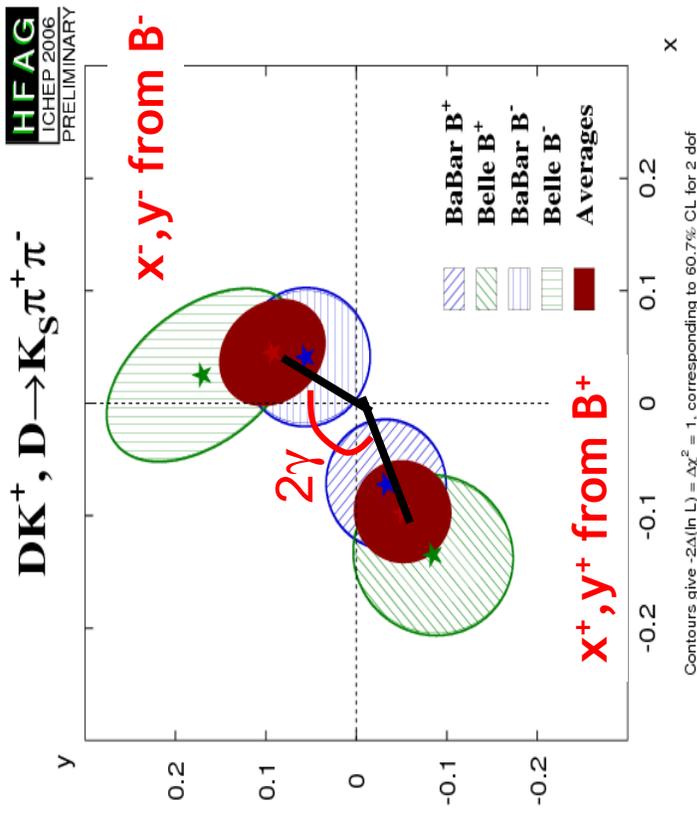
Measuring γ , Dalitz method (GGSZ)

Define Cartesian variables

$$X_{\pm} \equiv r_B \cos(\delta \pm \gamma)$$

$$Y_{\pm} \equiv r_B \sin(\delta \pm \gamma)$$

BaBar values of x, y are more precise, but constraint on γ is not as strong because they favour a smaller r_B



BaBar ($D^{(*)0}K^{\pm}$, 347M BB events)

$$\gamma = (92 \pm 42 \pm 10 \pm 13)^\circ \quad \text{hep-ex/0607104}$$

Belle ($D^{(*)0}K^{(*)\pm}$, 386M BB events)

$$\gamma = (53 \pm 3 \pm 9)^\circ \quad \text{PRD 73, 172009 (2006)}$$

BaBar: hep-ex/0607104

Belle: PRD 73, 172009 (2006)

How things have changed..

