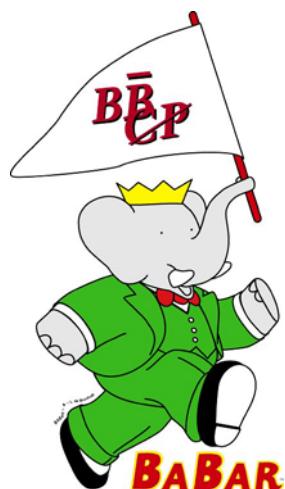


# Searching for New Physics at the B factories: Measurements of $\sin 2\beta$ at BaBar

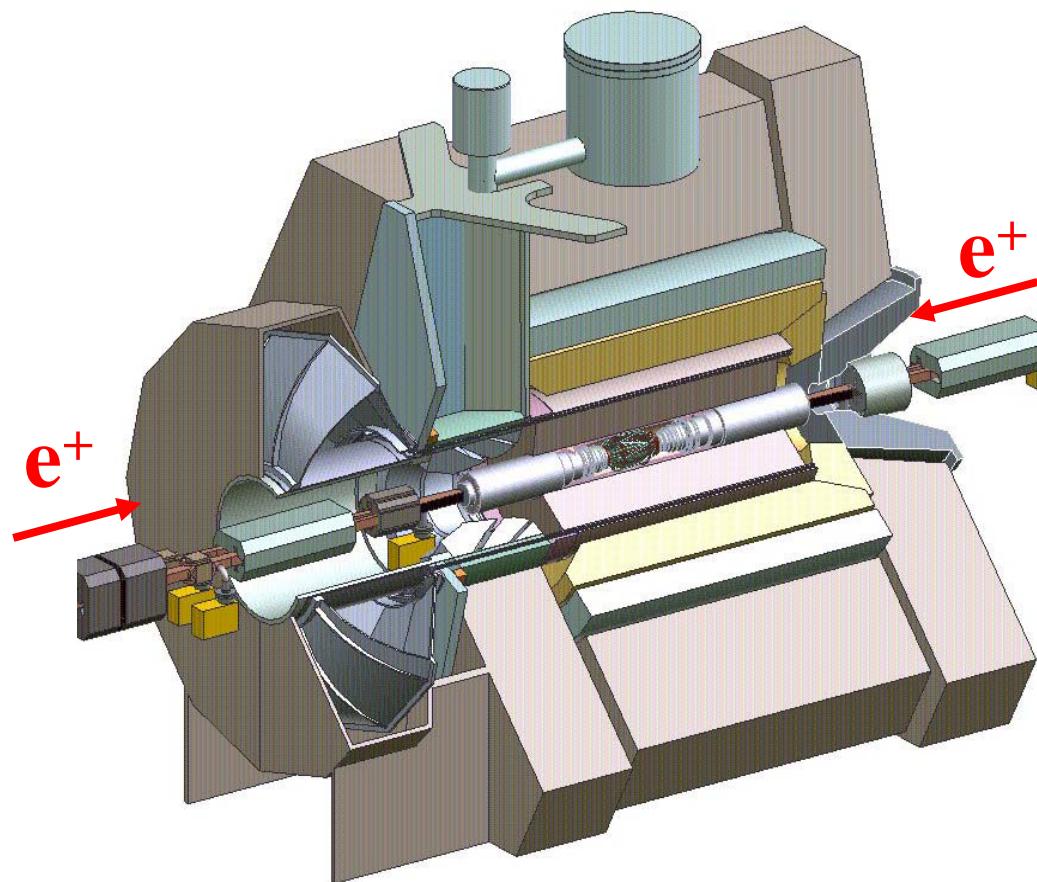


Gabriella Sciolla  
Massachusetts Institute of Technology

Representing the BaBar Collaboration

Beauty 2005 - Assisi, June 20-24, 2005

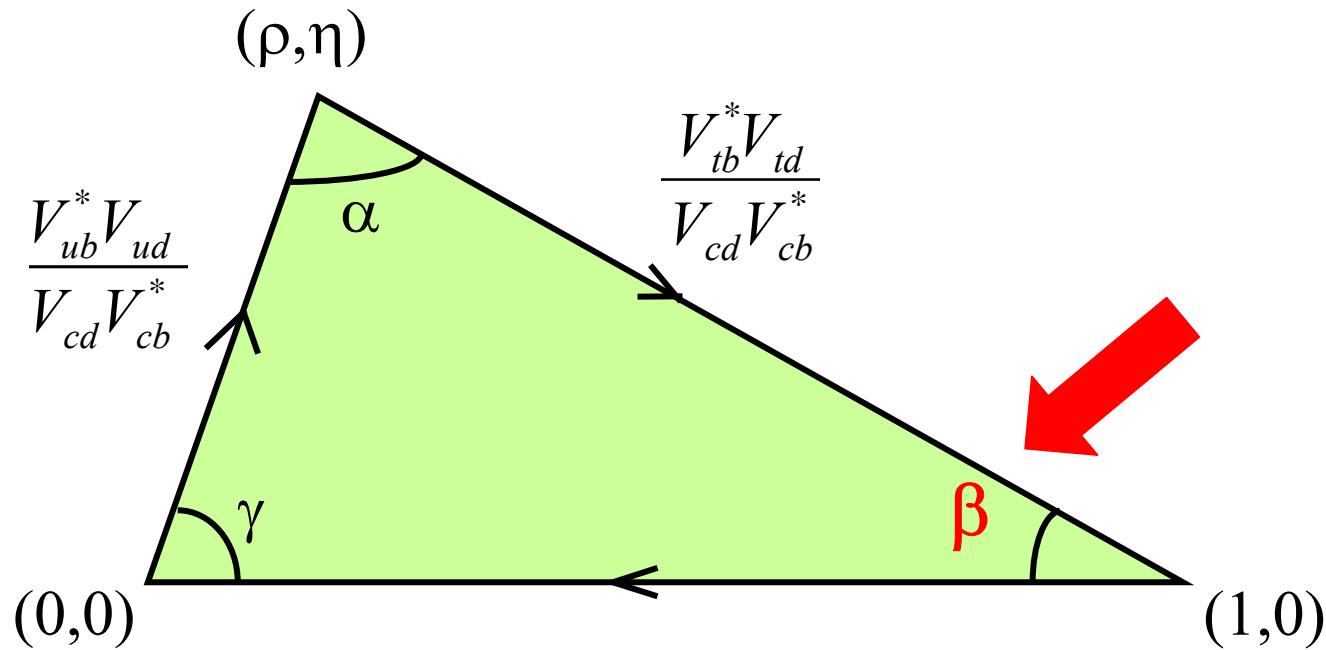
# BaBar and PEP-II



- BaBar detector
  - $4\pi$  collider detector
- PEP-II asymmetric B factory
  - 9.0 GeV  $e^-$  beam
  - 3.1 GeV  $e^+$  beam
- Peak luminosity
  - $9.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Integrated luminosity
  - Delivered:  $>268 \text{ fb}^{-1}$

Most results in this talk are based on 227 M  $B\bar{B}$  events

# The Beauty of the Unitarity Triangle



Two ways of looking for New Physics:

- Compare measurement of sides and angles
- Measure angles in channels with different sensitivity to New Physics

# The three roads to $\beta$

## ■ Charmonium modes:

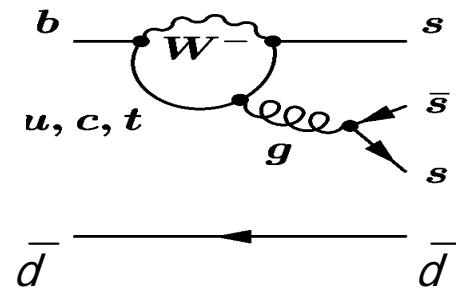
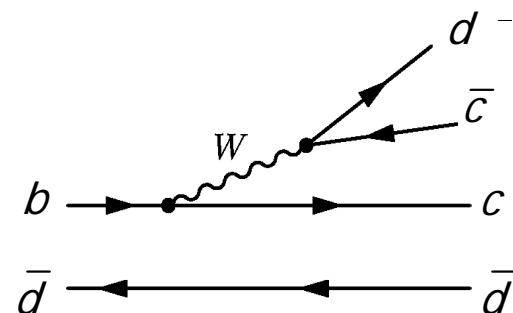
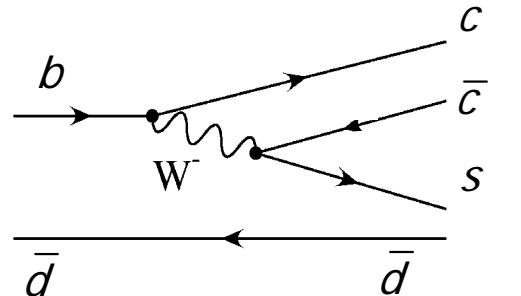
- $J/\psi K_S, \psi(2S)K_S, \chi_{c1}K_S, \eta_c K_S$
- $J/\psi K_L$
- $J/\psi K^{*0} (K^{*0} \rightarrow K_S \pi^0)$

## ■ Open-charm modes:

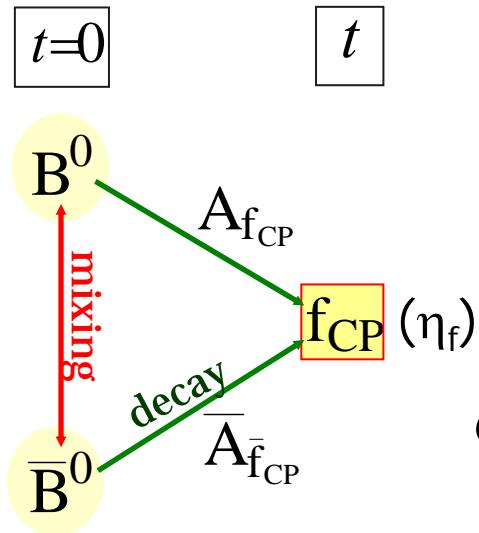
- $D^{*+} D^{*-}, D^{*+} D^-, D^+ D^-$

## ■ Penguin-dominated modes:

- $\phi K^0, K^+ K^- K_S, K_S K_S K_S$
- $\eta' K_S$
- $K_S \pi^0, \omega K_S, f_0(980) K_S$



# CP violation in interference between mixing and decays



$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \rightarrow f_{CP}) - N(B^0(t) \rightarrow f_{CP})}{N(\bar{B}^0(t) \rightarrow f_{CP}) + N(B^0(t) \rightarrow f_{CP})}$$

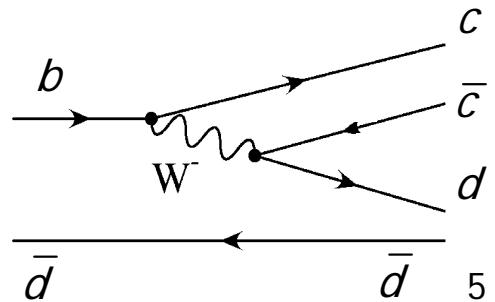
$$= S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \quad S_f = \frac{2 \operatorname{Im} \lambda_f}{1 + |\lambda_f|^2} \quad \lambda_f = \frac{q}{p} \cdot \frac{\bar{A}_f}{A_f}$$

- When only one diagram contributes to the final state:
- Example:  $B^0 \rightarrow J/\Psi K_S$ :

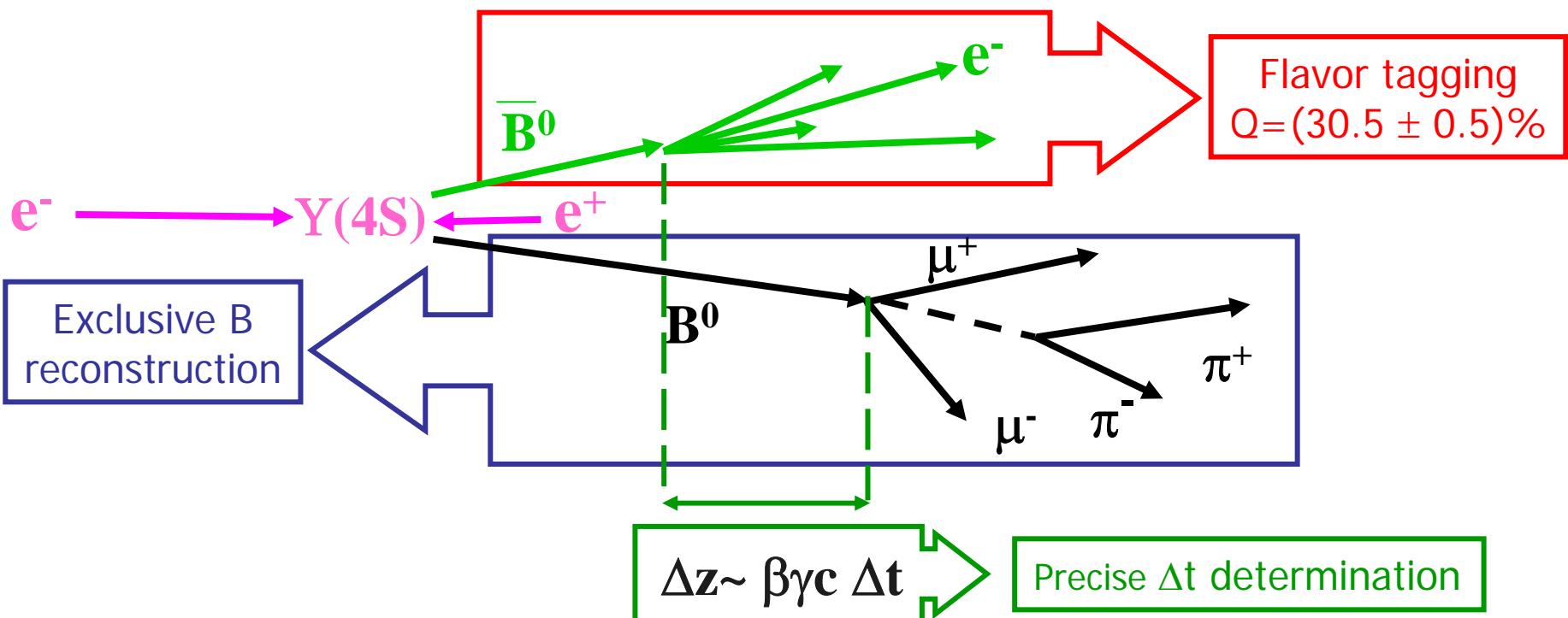
$$\lambda = \eta_f \left( \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right)_{B_{mix}^0} \left( \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \right)_{decay} \left( \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \right)_{K_{mix}^0} = -e^{-i 2\beta}$$

$$A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m t)$$



# How to measure the CP asymmetry

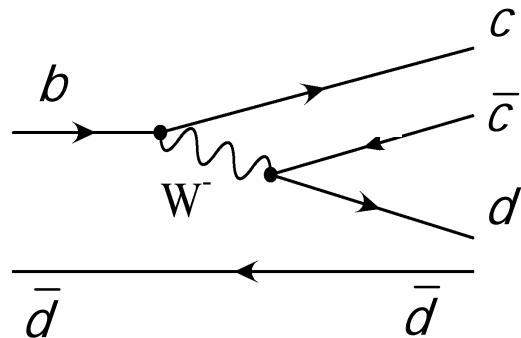
$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \rightarrow f_{CP}) - N(B^0(t) \rightarrow f_{CP})}{N(\bar{B}^0(t) \rightarrow f_{CP}) + N(B^0(t) \rightarrow f_{CP})}$$



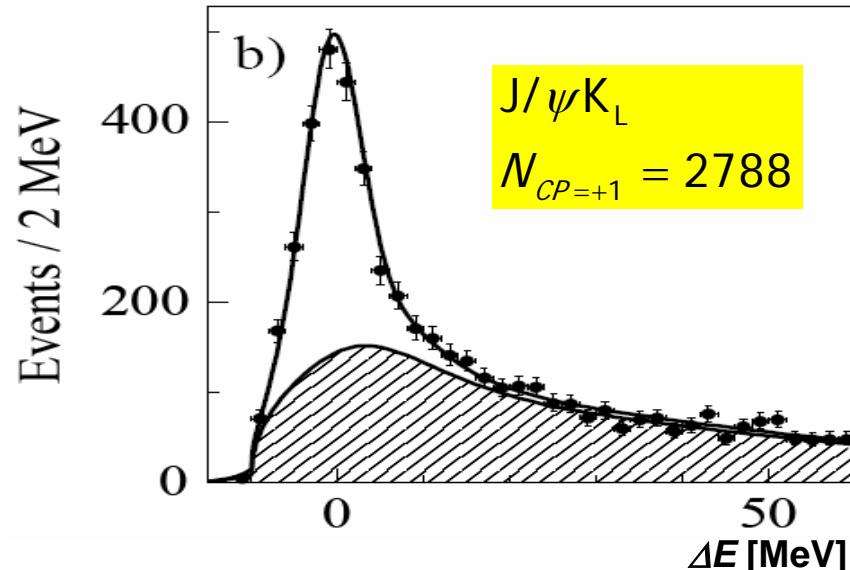
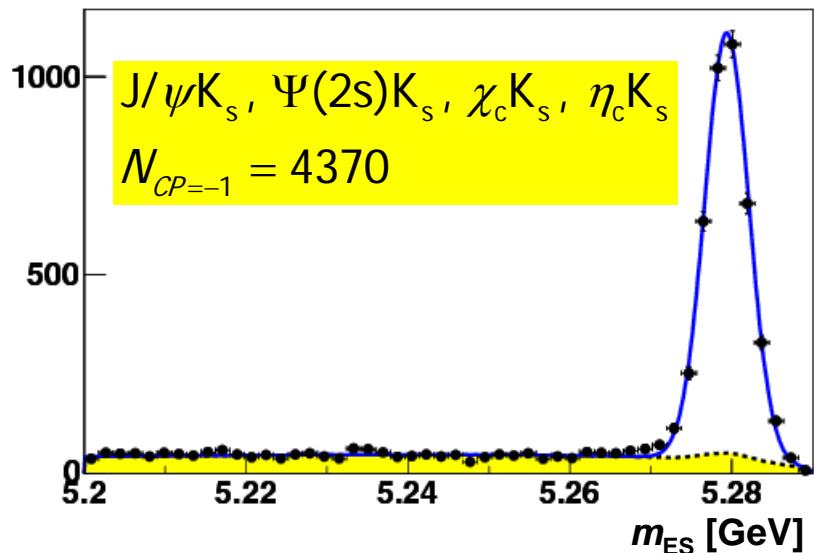
The golden mode for  $\sin 2\beta$ :

$B^0 \rightarrow \text{charmonium } K^0$

- Theoretically clean
- Experimentally clean
- Relatively large BF ( $\sim 10^{-4}$ )



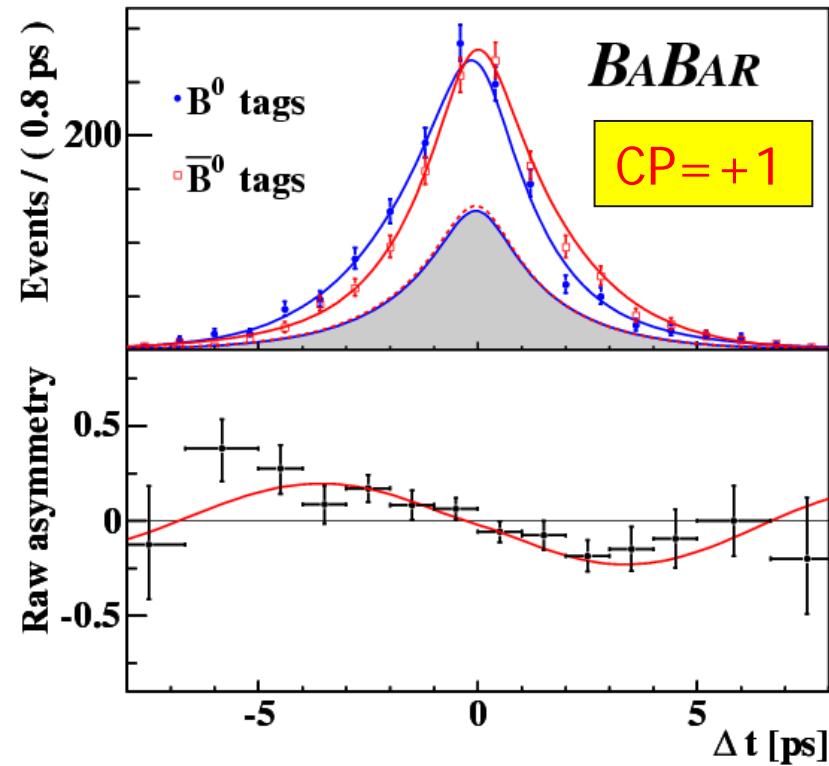
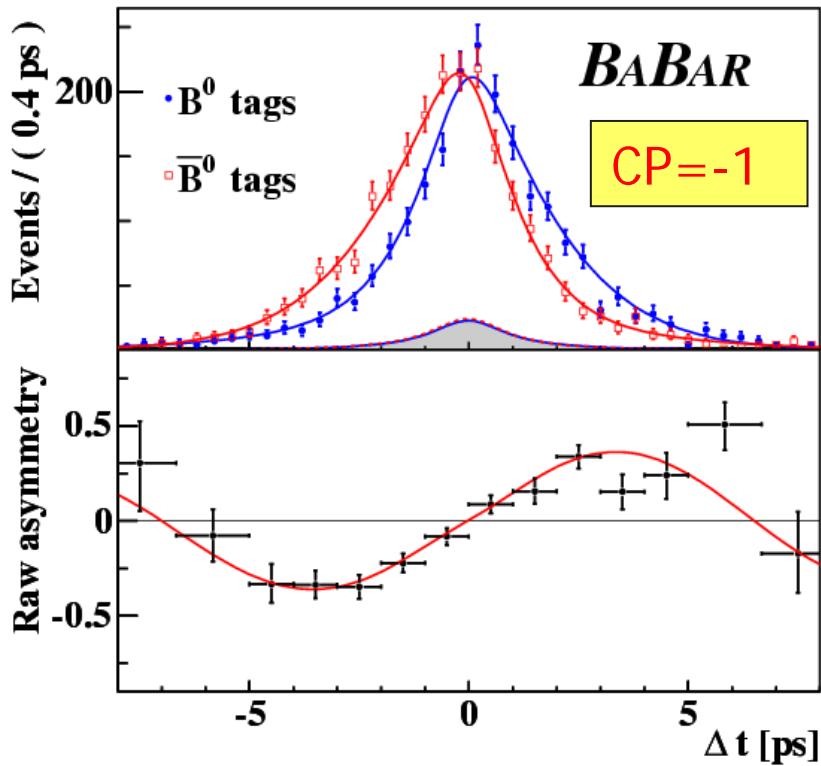
CP sample:



The golden mode for  $\sin 2\beta$ :

# CP fit in $B \rightarrow$ charmonium $K^0$

Unbinned maximum likelihood fit to  $\Delta t$  distribution

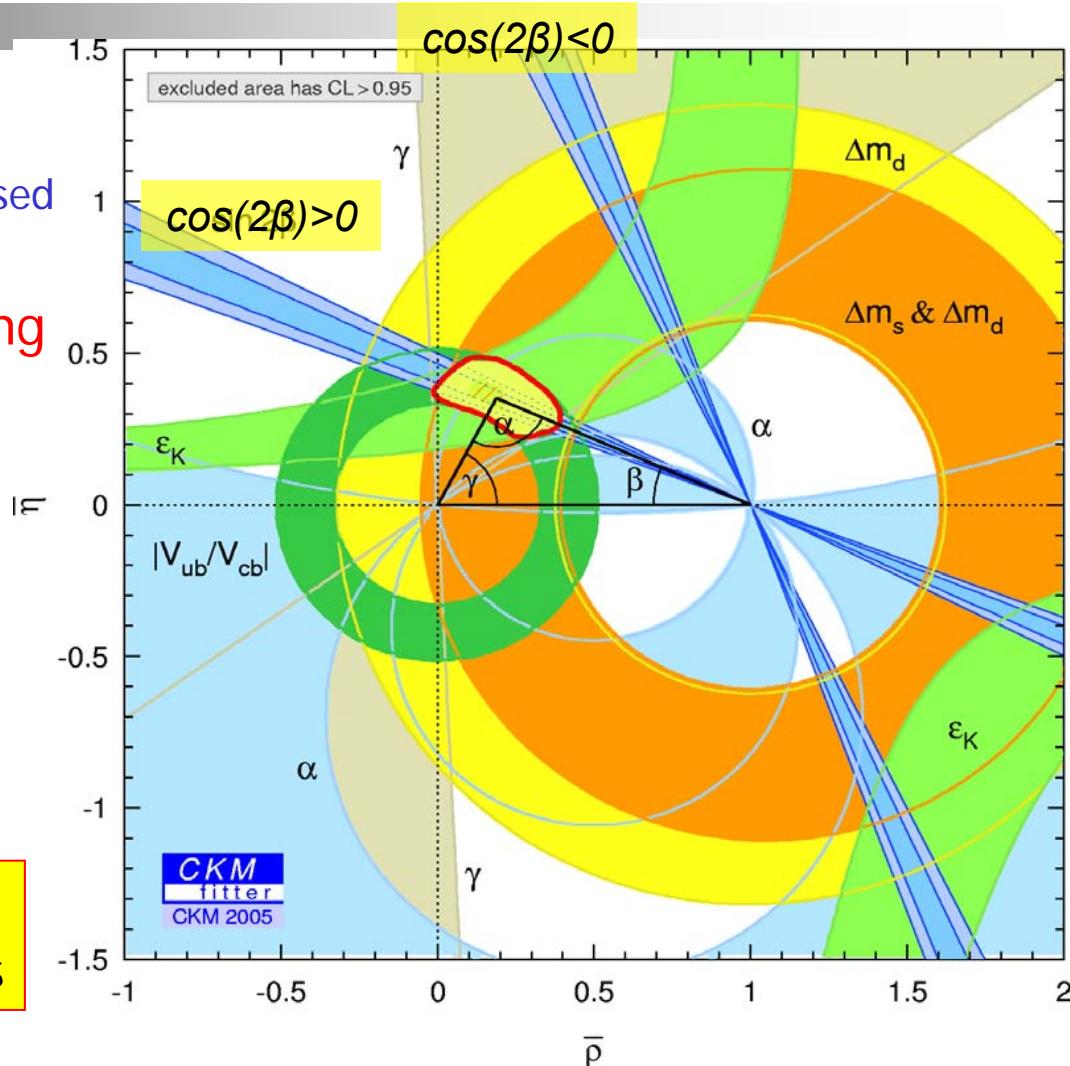


$$\sin(2\beta) = 0.722 \pm 0.040_{\text{stat}} \pm 0.023_{\text{syst}}$$

# SM test in $B^0 \rightarrow$ charmonium $K^0$

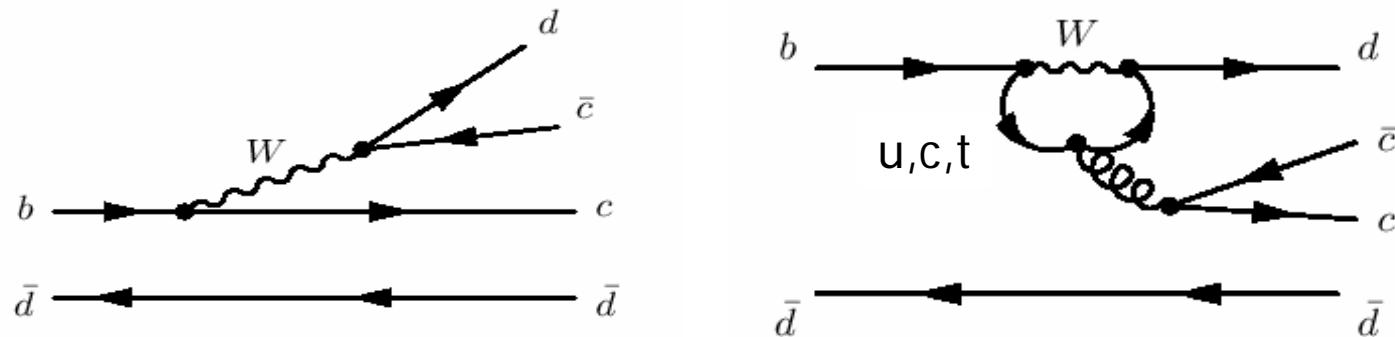
- Compare sides and angles
  - Both BaBar and Belle results used
- Ambiguity resolved measuring  $\text{sign}(\cos 2\beta)$  in  $B^0 \rightarrow J/\Psi K^*$ 
  - $\cos(2\beta) = -0.68$  excluded at 86.6%CL [PRD 71 (2005)032005]
- Excellent agreement with constraints from the sides
  - Another SM triumph?

SM test #2:  
Compare  $\beta$  in various channels



The  $b \rightarrow c\bar{c}d$  trees:

$B^0 \rightarrow \text{open charm}$



- Tree measures  $\sin 2\beta$  from  $b \rightarrow c\bar{c}d$  transitions
- Penguin expected to be small in SM (< few %)

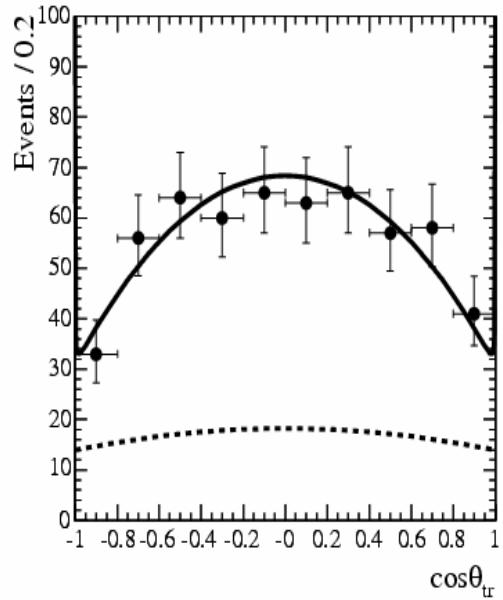
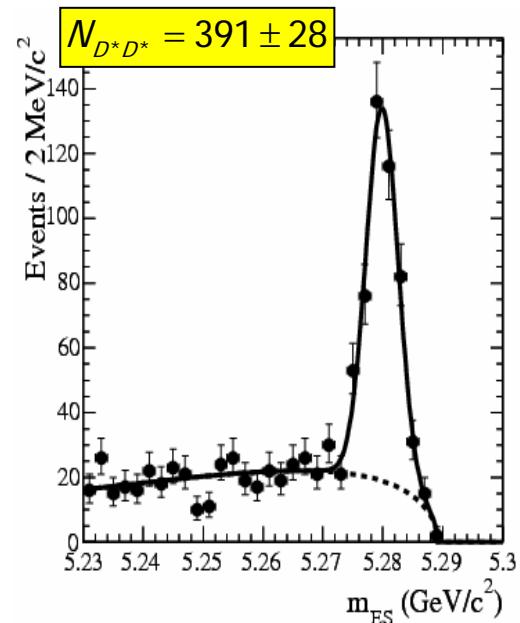
New Physics could have large effects

- $D^*D^*$ : as large as  $\Delta\beta = 0.6$  [Grossman and Worah, 1997]

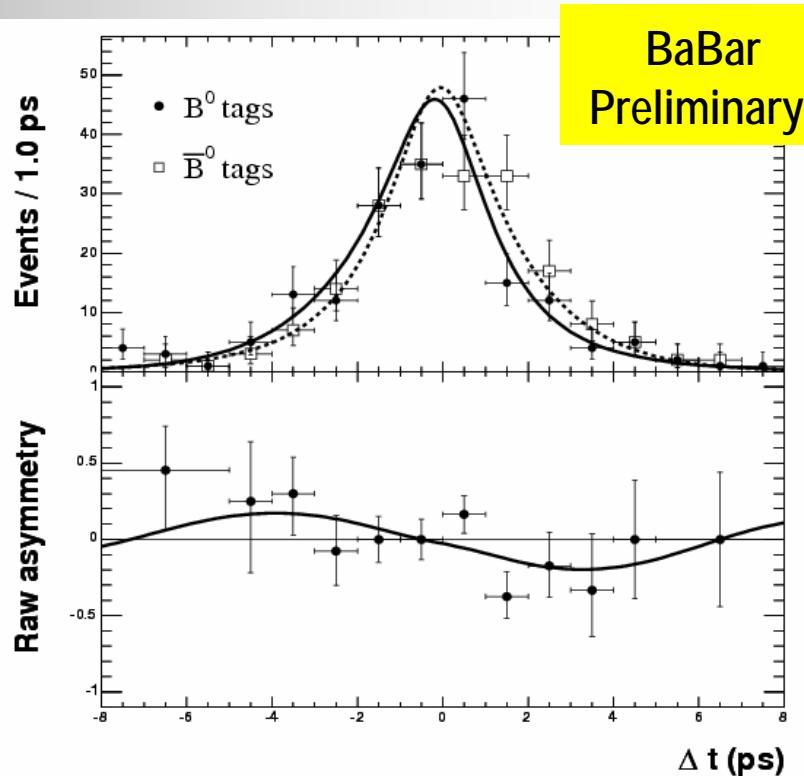
The open charm trees:

Recent update:  $B^0 \rightarrow D^* + D^{*-}$

- Vector-vector final state:
  - CP-even and CP-odd admixture
- Transversity analysis measures  $f_{CP\text{-even}}$



$$f_{CP+} = (87.5 \pm 4.4 \pm 0.7)\%$$



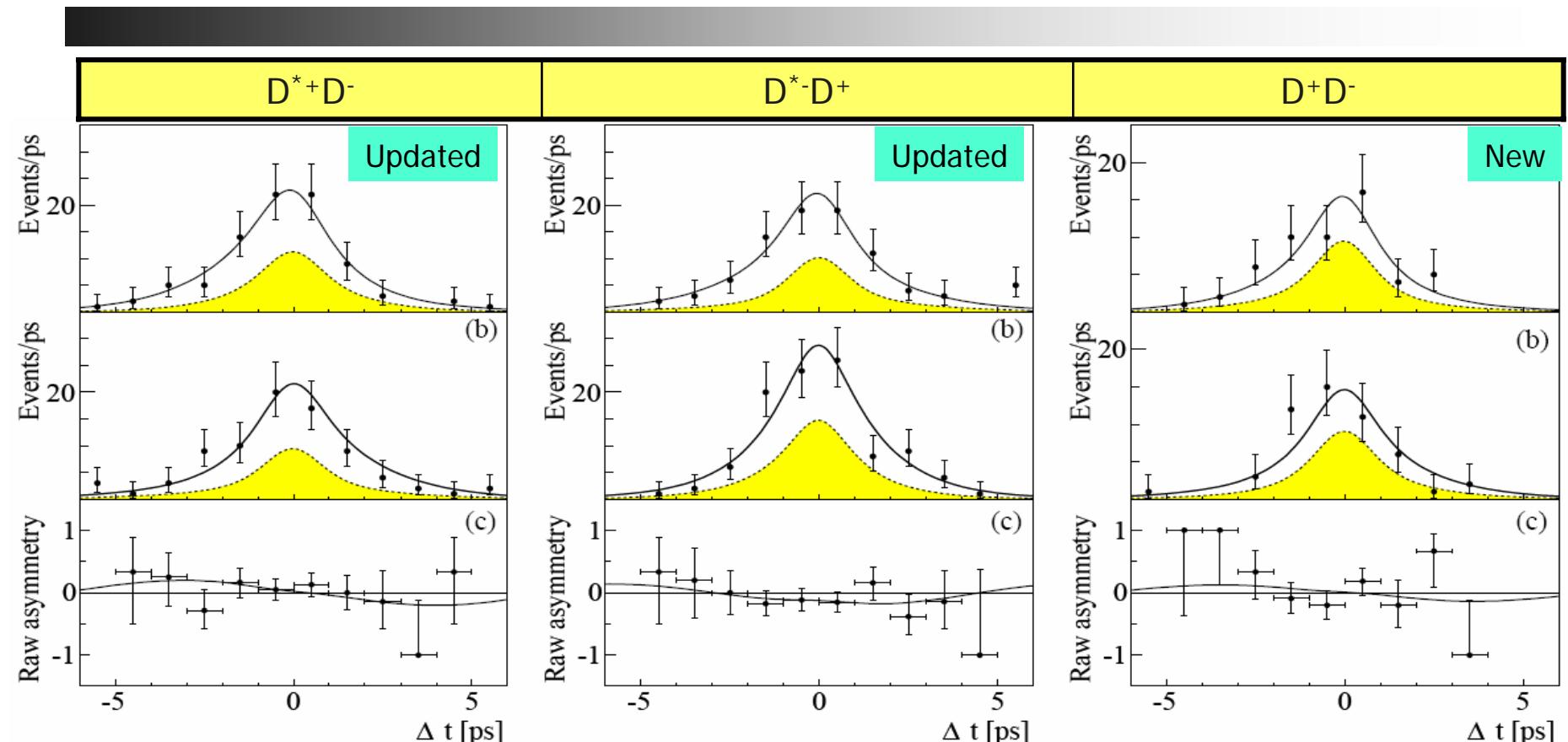
$$C_{CP+} = +0.06 \pm 0.17 \pm 0.03$$

$$-S_{CP+} = 0.75 \pm 0.25 \pm 0.03$$

In good agreement with SM

# The open charm trees:

$$B^0 \rightarrow D^{(*)\pm} D^\mp$$

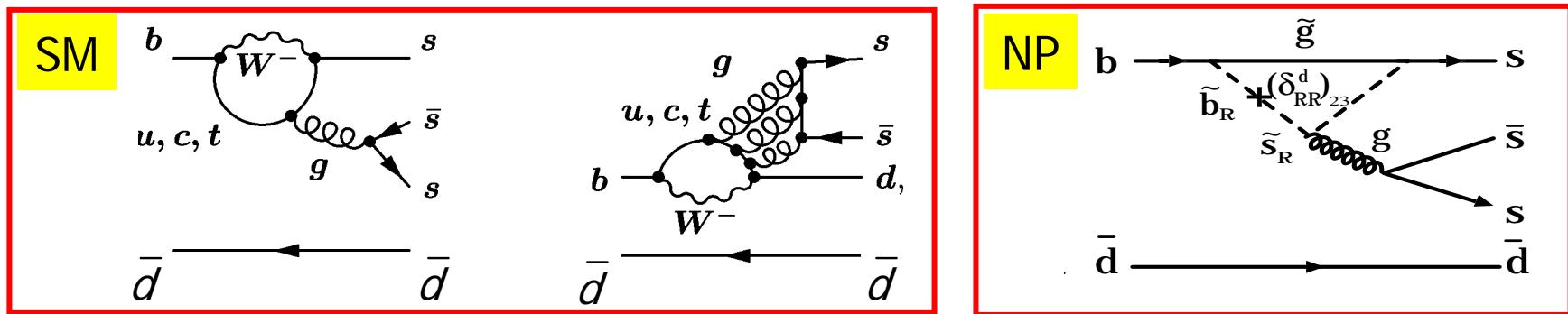


-S	$0.54 \pm 0.35 \pm 0.07$	$0.29 \pm 0.33 \pm 0.07$	$0.29 \pm 0.63 \pm 0.06$
C	$0.09 \pm 0.25 \pm 0.06$	$0.17 \pm 0.24 \pm 0.04$	$0.11 \pm 0.35 \pm 0.06$

# The key to New Physics: The Penguin Modes

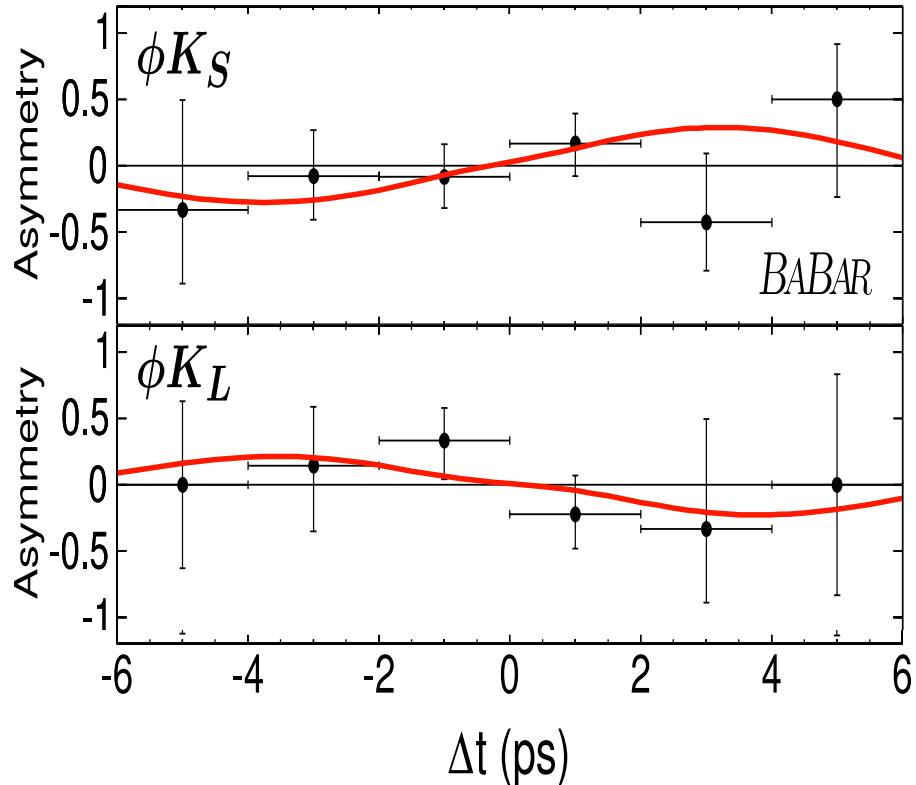
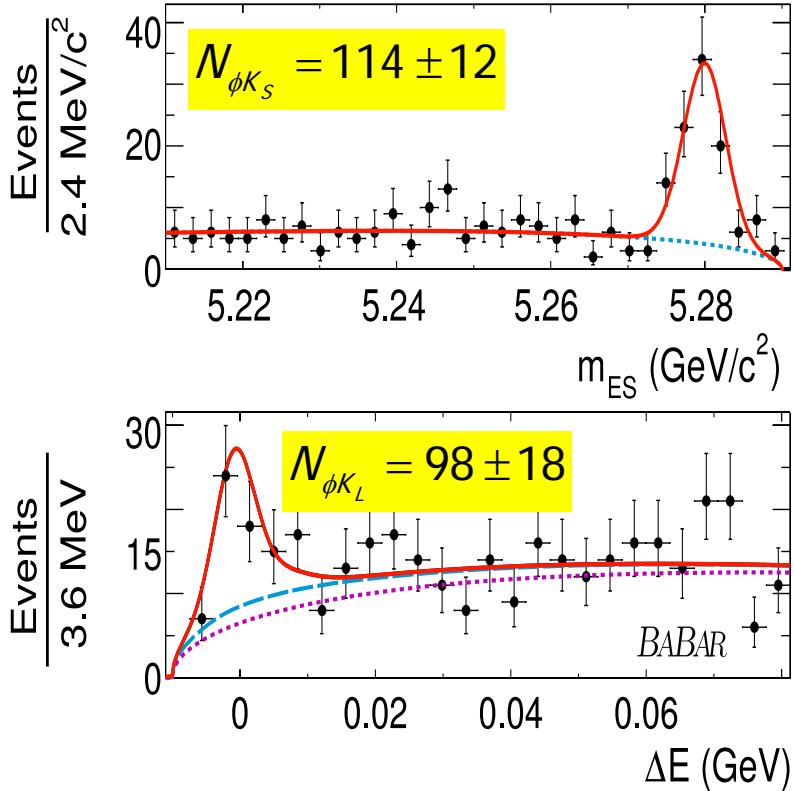
Decays dominated by gluonic penguin diagrams

- The typical example:  $B^0 \rightarrow \phi K_S$



- No tree level contributions
- In SM, top quark dominates the loop:  $C \sim 0$ ;  $S \sim \sin 2\beta$
- Impact of New Physics could be significant
  - New particles could participate in the loop  $\rightarrow$  new CPV phases
- Low branching fractions
  - Measure  $A_{CP}$  in as many  $b \rightarrow s \bar{q} \bar{q}$  penguins as possible!
    - $\varphi K^0, K^+ K^- K_S, \eta' K_S, K_S \pi^0, K_S K_S K_S, \omega K_S, f_0(980) K_S$

# The golden penguin: $B^0 \rightarrow \phi K^0$



Combined  $\phi K_S$  and  $\phi K_L$  fit:

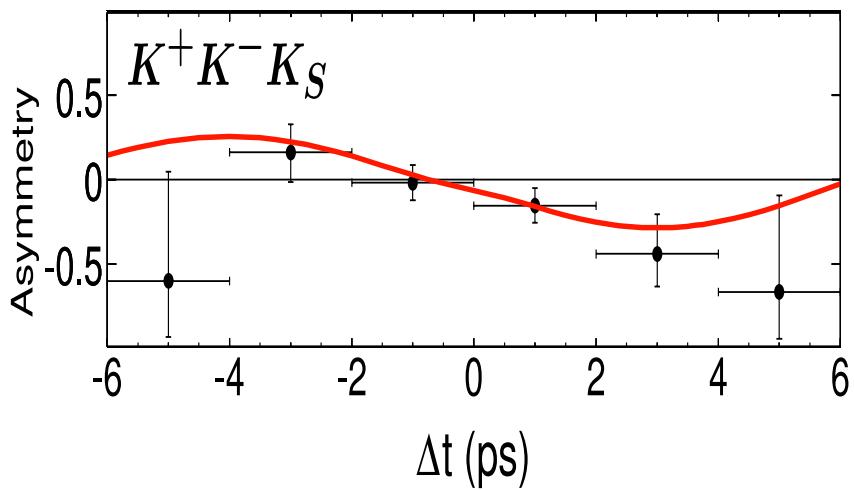
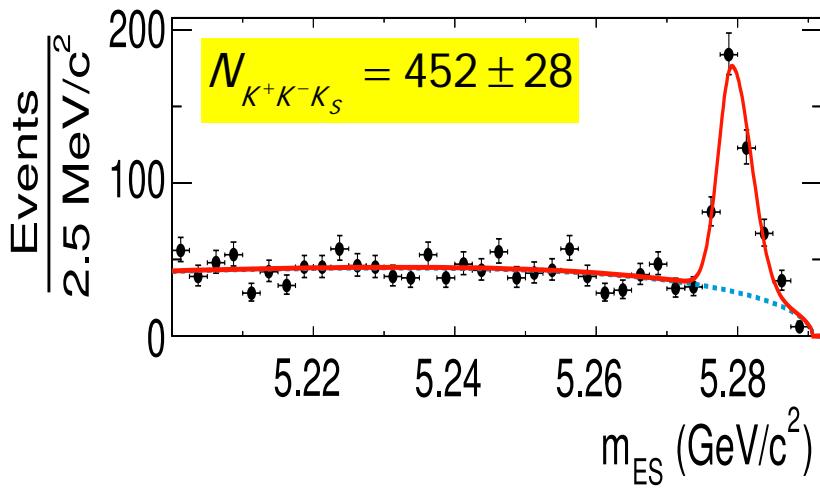
$$S_{\phi K^0} = +0.50 \pm 0.25 {}^{+0.07}_{-0.04}$$

$$C_{\phi K^0} = 0.00 \pm 0.23 \pm 0.05$$

# Related channel: $B^0 \rightarrow K^+ K^- K_S$

- For non resonant  $B^0 \rightarrow K^+ K^- K_S$  decays,  $\eta_{CP} = 2 f_{even} - 1$
- $f_{even}$  measured from angular moment analysis of the  $K^+ K^-$  system

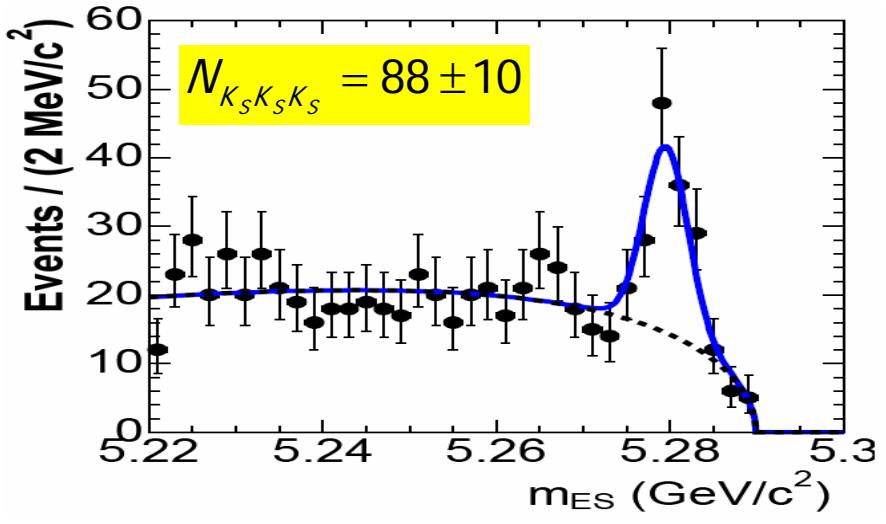
$$f_{even} = \frac{A_s^2}{A_s^2 + A_p^2} = 0.89 \pm 0.08 \pm 0.06$$



$$\sin 2\beta_{K^+ K^- K^0}^{eff} = +0.55 \pm 0.22_{stat} \pm 0.04_{syst} \pm 0.11_{CP}$$

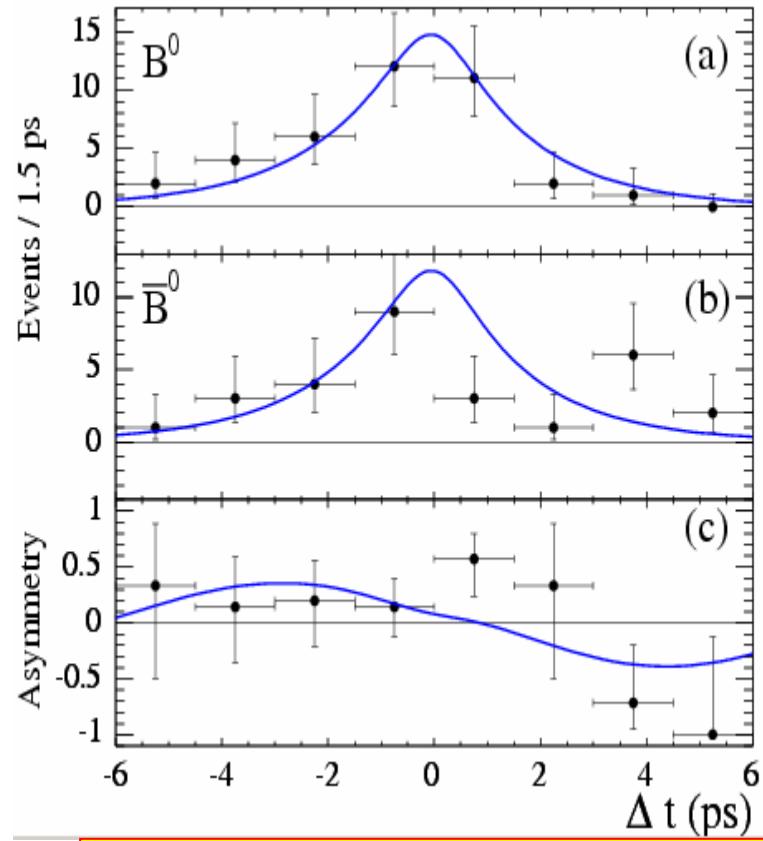
# A new golden penguin: $B^0 \rightarrow K_S K_S K_S$

- Theoretically clean
  - Penguin dominated CP=+1 eigenstate
  
- Experimentally challenging
  - B decay vertex uses  $K_S$  pseudo-particles and beam spot constraint



G. Sciolla – M.I.T.

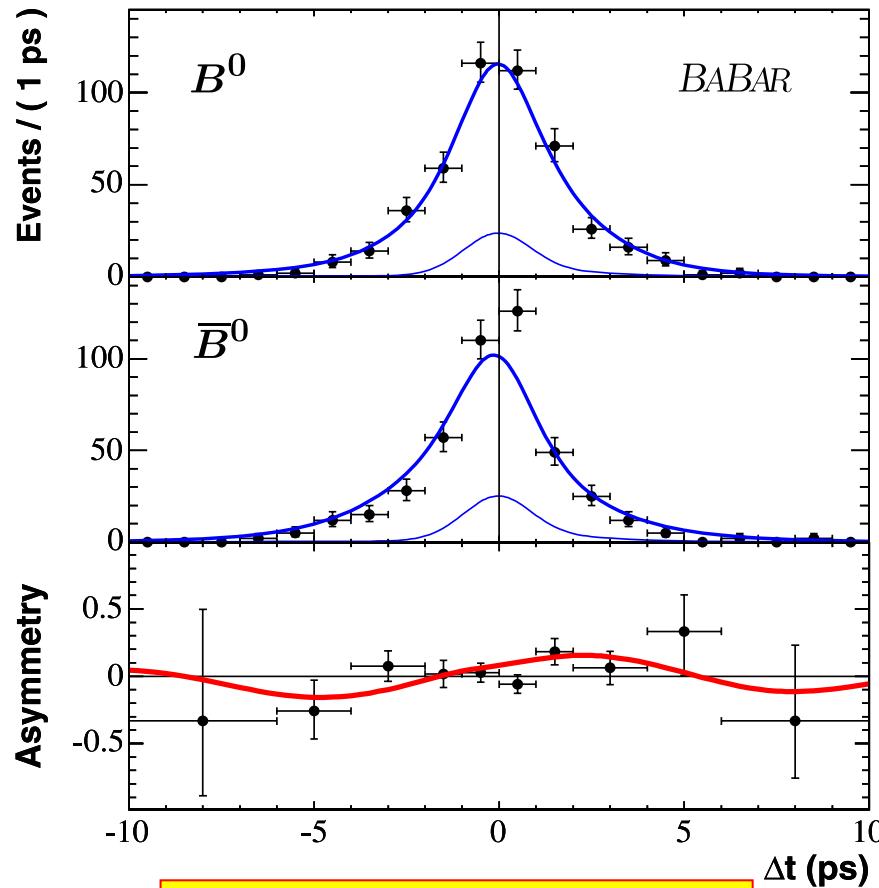
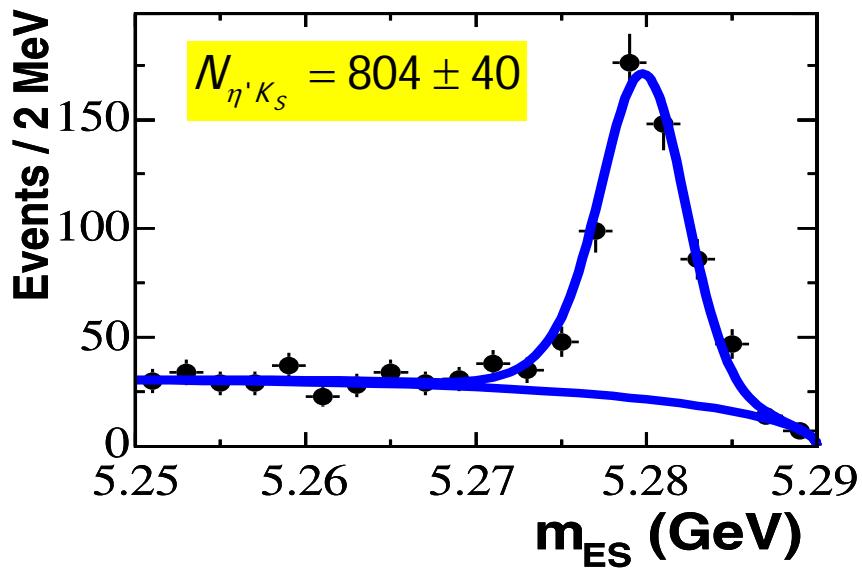
Measurements of  $\sin(2\beta)$



$-S_{K_S K_S K_S} = +0.71^{+0.32}_{-0.38} \pm 0.04$ 
 $C_{K_S K_S K_S} = -0.34^{+0.28}_{-0.35} \pm 0.05$

# The silver penguin: $B^0 \rightarrow \eta' K_S$

- Relative large BF  $\sim 6 \times 10^{-5}$
- Theoretically less clean than  $\phi K_S$ 
  - Tree diagram possible  
... but Cabibbo and color suppressed...
  - $|\Delta S| = |S_{\Psi K} - S_{\text{Penguin}}| \sim 0.01_{\text{QCDFact}} \rightarrow 0.1_{\text{SU(3)}}$



$$S_{\eta' K_S} = 0.30 \pm 0.14 \pm 0.02$$

$$C_{\eta' K_S} = -0.21 \pm 0.10 \pm 0.02$$

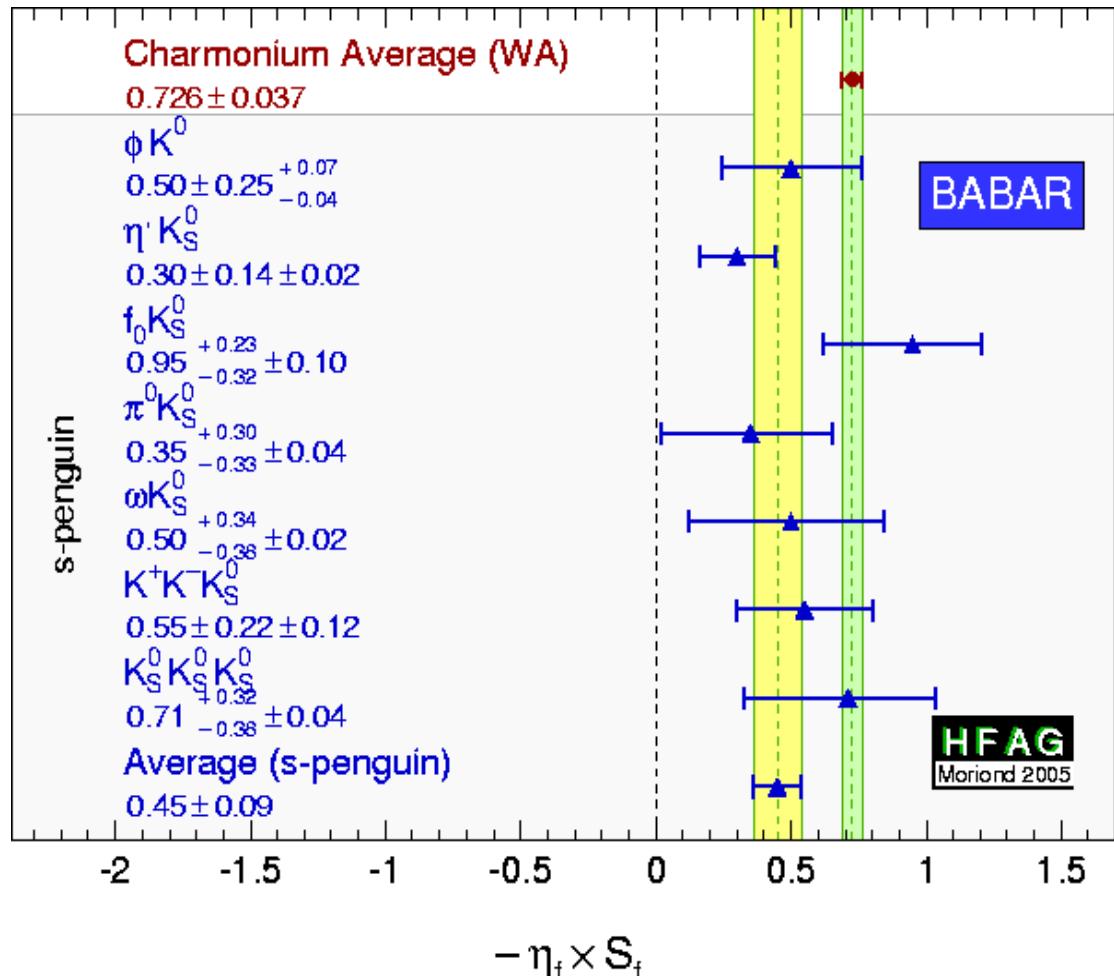
# The challenging penguins:

$B^0 \rightarrow \pi^0 K_S, f_0 K_S, \omega K_S$

- $B^0 \rightarrow \pi^0 K_S$ :
  - dominated by  $b \rightarrow s d \bar{d}$
  - $b \rightarrow s u \bar{u}$  tree contribution are non negligible ( $\Delta S \sim 0.1 - 0.2$ )
  - Experimental challenge:  $B_{CP}$  decay vertex reconstruction ( $\sigma_{\Delta t} \sim 1\text{ps}$ )
- $B^0 \rightarrow f_0 K_S$ :
  - In SM dominated by  $b \rightarrow s s \bar{s} \bar{s}$
- $B^0 \rightarrow \omega K_S$ :
  - In SM dominated by  $b \rightarrow s d \bar{d} \bar{d}$
  - But tree can be relatively large

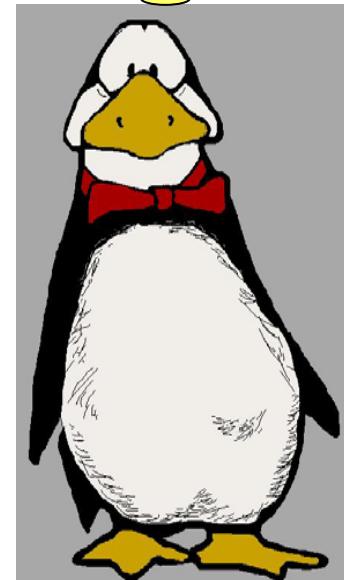
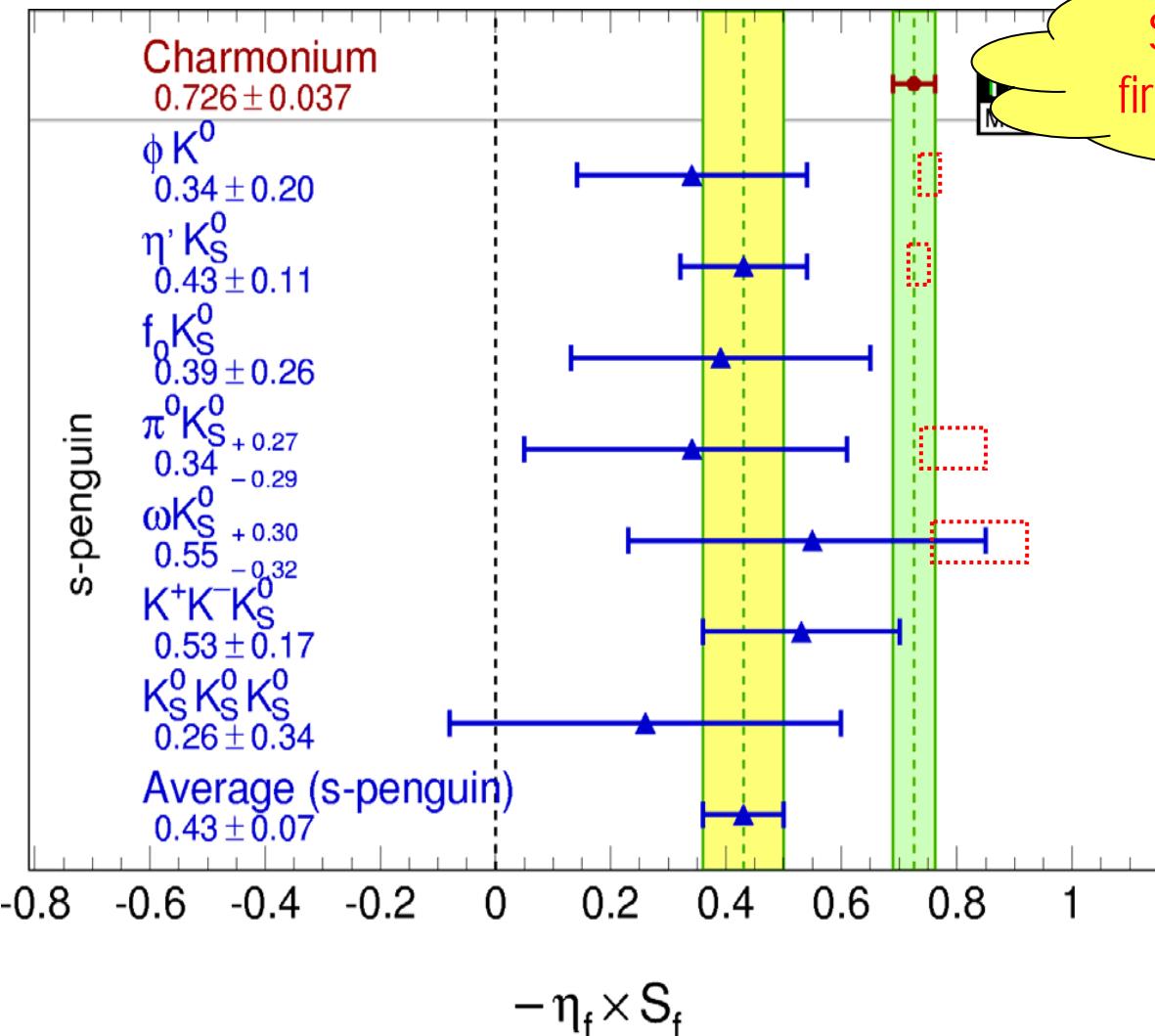
	$B^0 \rightarrow \pi^0 K_S$	$B^0 \rightarrow f_0 K_S$	$B^0 \rightarrow \omega K_S$
$-\eta_f S$	$0.35^{+0.30}_{-0.33} \pm 0.04$	$+0.95^{+0.23}_{-0.32} \pm 0.10$	$+0.50^{+0.34}_{-0.38} \pm 0.02$
C	$0.06 \pm 0.18 \pm 0.03$	$-0.24 \pm 0.31 \pm 0.15$	$-0.56^{+0.29}_{-0.27} \pm 0.03$

# "sin2β" in penguins: BaBar only



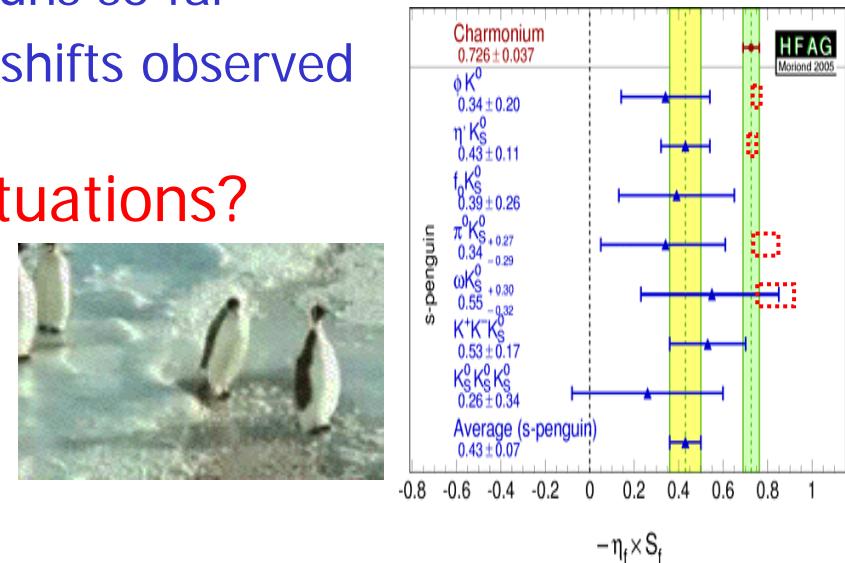
- Although each measurement is compatible with  $J/\Psi K_S$ , a trend is visible
  - $\eta' K_S$  has the most significant shift (~ $2.9\sigma$  if theory uncertainties neglected)
- ... but statistical errors are still large...

# “sin $2\beta$ ” in penguins: BaBar + Belle



# Summary and Conclusion

- Precision measurements of  $\sin 2\beta$  in many different channels are a powerful probe for New Physics
  - $B^0 \rightarrow$  charmonium  $K^0$ : our calibration point ( $\sigma_{\sin 2\beta} \sim 0.04$ )
  - $B^0 \rightarrow$  open charm: no smoking guns so far
  - $B^0 \rightarrow$  penguin modes: intriguing shifts observed
- New Physics or statistical fluctuations?
  - Time and data will tell...
- Goals for BaBar luminosity
  - Summer 2006:  $500 \text{ fb}^{-1}$
  - Summer 2008:  $1 \text{ ab}^{-1}$



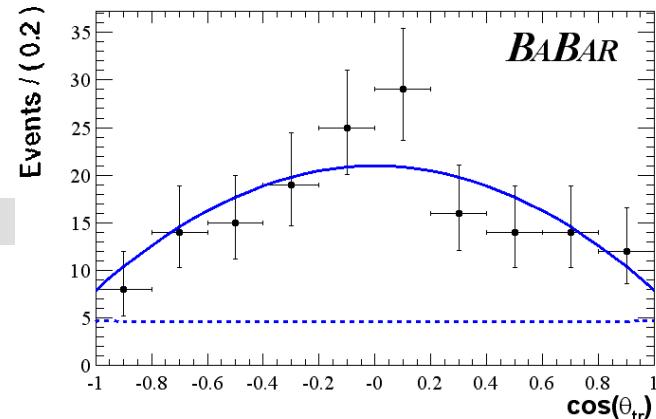
# Backup slides -----

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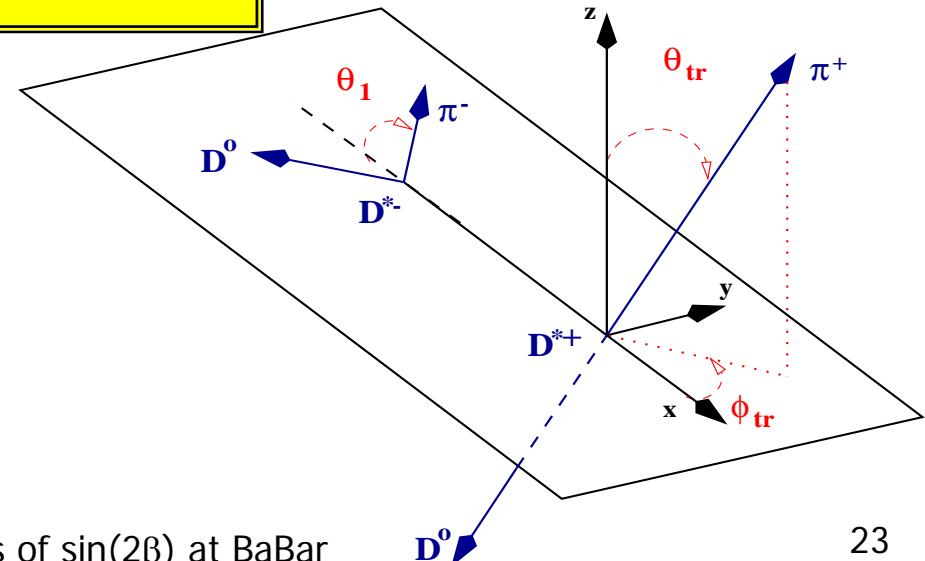
# Transversity analysis

- $D^*+D^*$ - is not a CP eigenstate
  - sum of  $L=0, 2$  (CP even) and  $L=1$  (CP odd)
- CP odd fraction  $R_\perp$  determined by transversity analysis



$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{tr}} = \frac{3}{4} (1 - R_\perp) \sin^2 \theta_{tr} + \frac{3}{2} R_\perp \cos^2 \theta_{tr}$$

$$R_\perp = \frac{|A_\perp|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$



# D<sup>\*</sup>D analysis

## SM expectations

- D+D-

- $C = 0$
- $S = -\sin 2\beta$

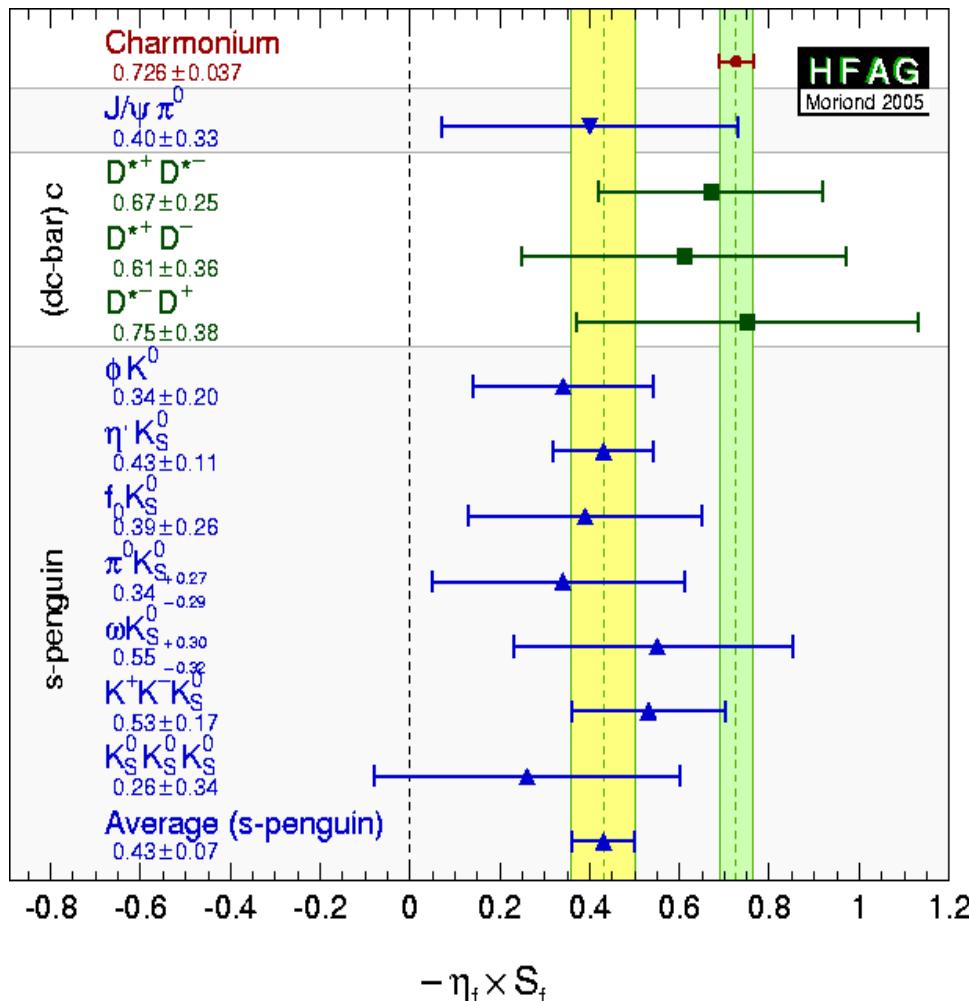
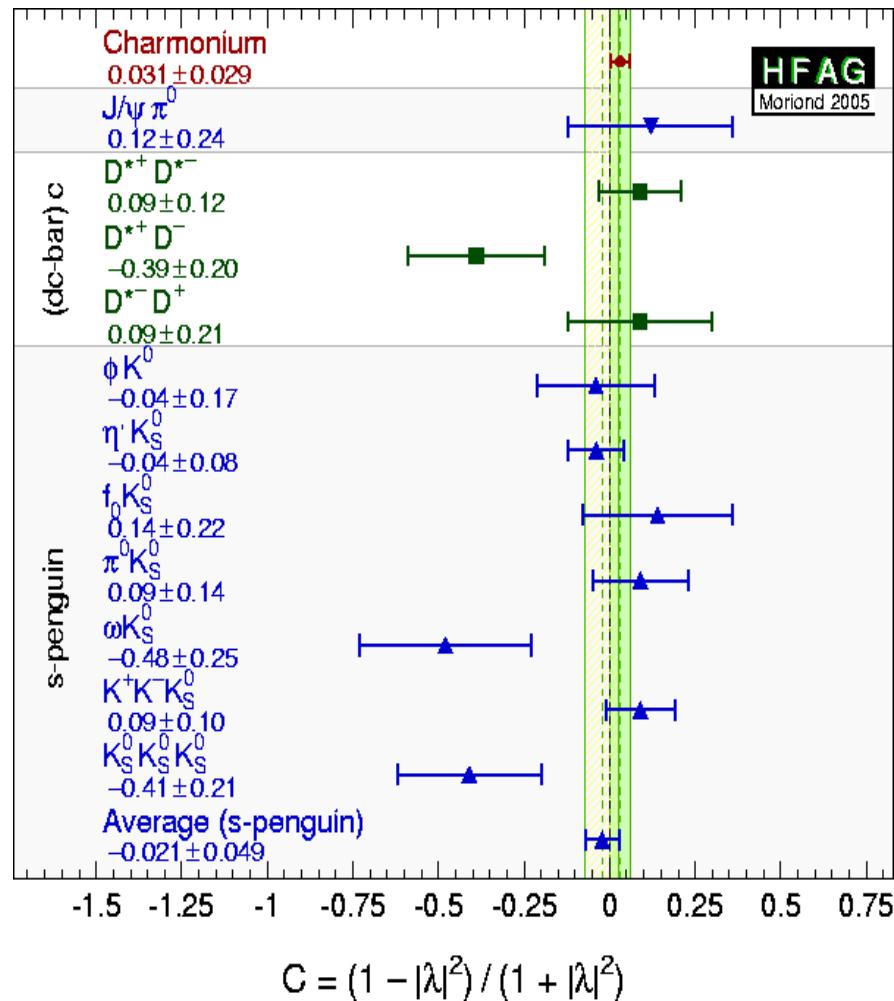
- D<sup>\*</sup>D

- $C_{D^*+D^-} = -C_{D^*-D^+}$
- $S_{D^*+D^-} = -X \sin(2\beta + \delta)$  and  $S_{D^*-D^+} = -X \sin(2\beta - \delta)$

with:

- $X = \sqrt{1 - C_{D^*-D^+}^2}$
- $\delta$ =difference of strong phases for  $B^0 \rightarrow D^{*+}D^-$  and  $B^0 \rightarrow D^{*-}D^+$

# cos and sin fits in penguin modes

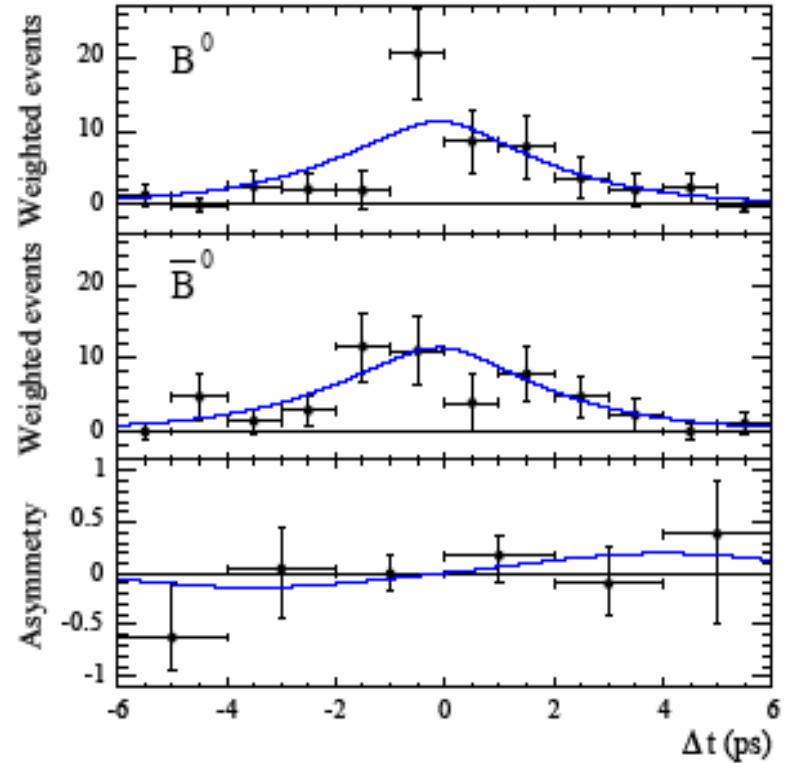


# The challenging penguins: $B^0 \rightarrow \pi^0 K_S$

- In SM these decays are dominated by  $b \rightarrow s d \bar{d}$ 
  - $b \rightarrow s u \bar{u}$  tree contribution are non negligible
    - $\Delta S \sim 0.1$  in model dependent QCD calculations
    - $\Delta S \sim 0.2$  in SU(3)
- Experimentally challenging
  - $B_{CP}$  decay vtx from  $K_S$  and beam spot
  - $K_S$  tracks with  $> 3$  SVT:  $\sigma_{\Delta t} \sim 1\text{ps}$
- $N_{\text{sig}} = 300 \pm 23$
- Unbinned max likelihood fit:

$$S_{K_S \pi^0} = +0.35^{+0.30}_{-0.33} \pm 0.04$$

$$C_{K_S \pi^0} = +0.06 \pm 0.18 \pm 0.03$$

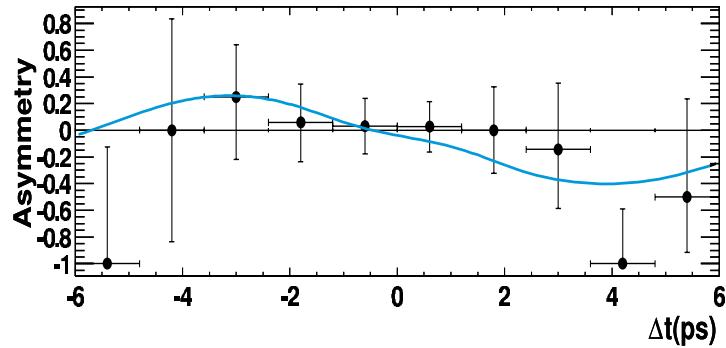
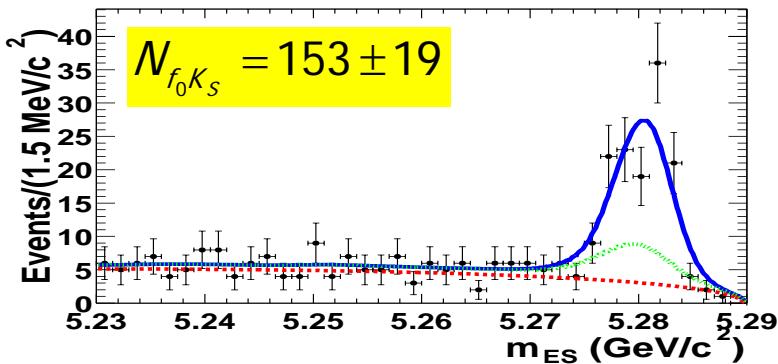


Two more penguins:

$B^0 \rightarrow f_0 K_S$  and  $B^0 \rightarrow \omega K_S$

$B^0 \rightarrow f_0 K_S$  dominated by  $b \rightarrow s\bar{s}$

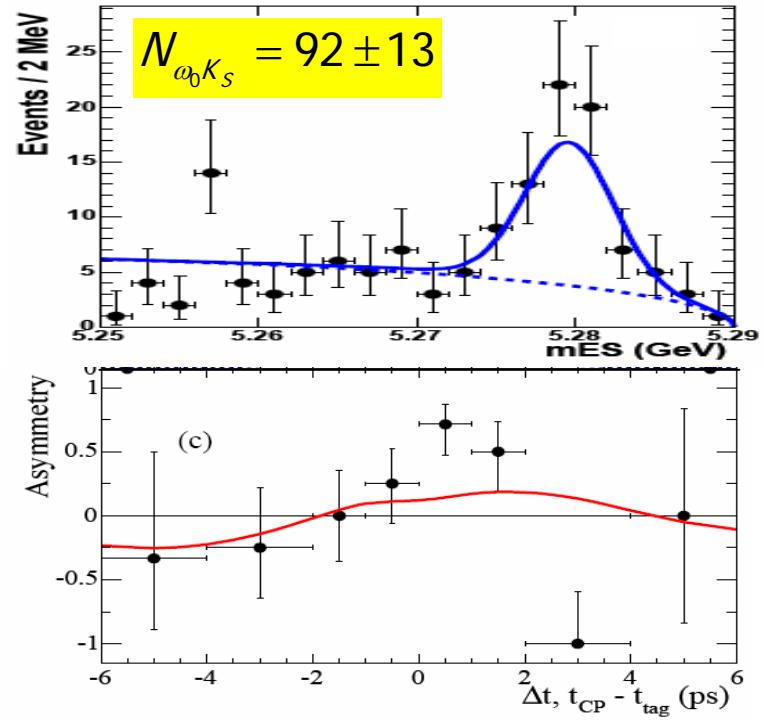
$$f_0(980) = \cos \varphi_s s\bar{s} + \sin \varphi_s \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}, \quad \varphi_s = -48^\circ \pm 6^\circ$$



$$-\eta_{CP} \times S_{f_0 K_S} = +0.95^{+0.23}_{-0.32} \pm 0.10$$

$B^0 \rightarrow \omega K_S$ : dominated by  $b \rightarrow sdd$

Tree contamination can be relatively large

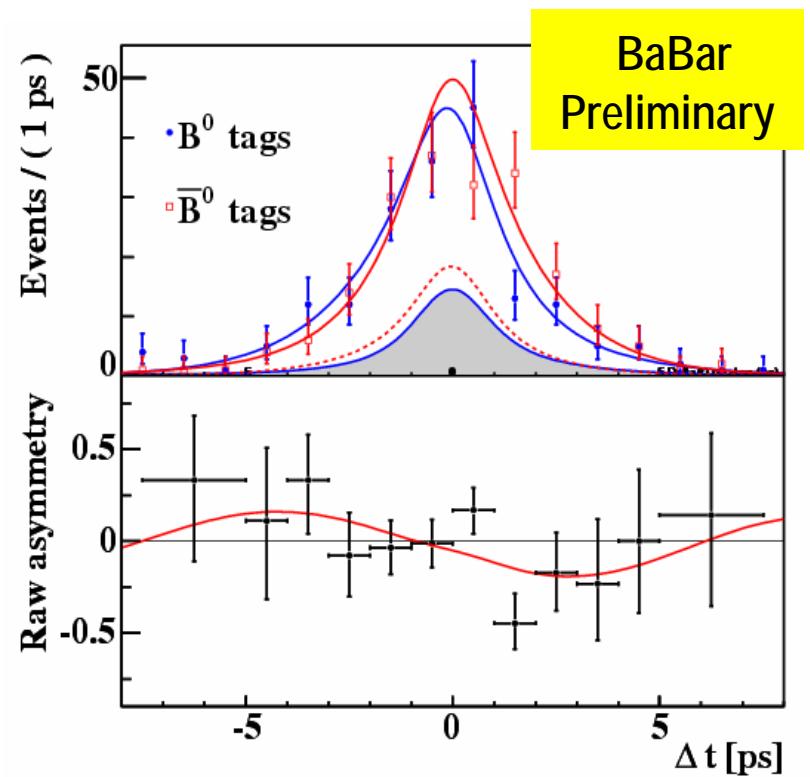
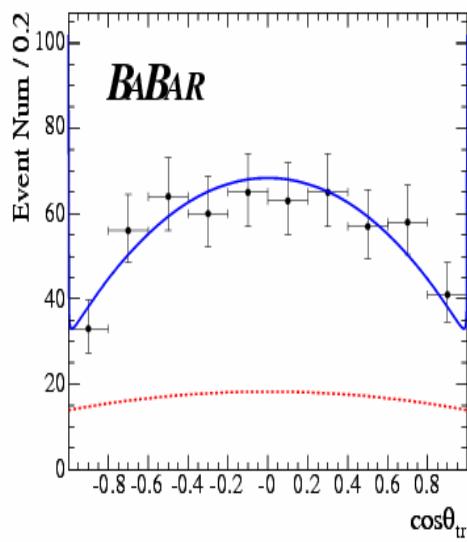
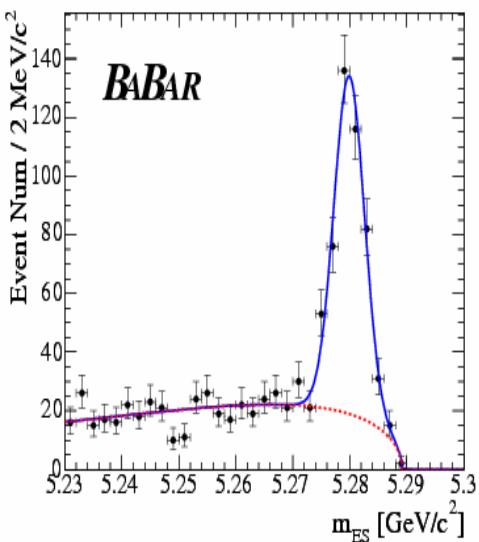


$$-\eta_{CP} \times S_{\omega K_S} = +0.50^{+0.34}_{-0.38} \pm 0.02$$

## The Other Trees:

Recent update:  $B \rightarrow D^*+D^{*-}$

- Vector-vector final state:
  - CP-even and CP-odd admixture
- Transversity analysis measures  $f_{\text{odd}}$ 
  - $f_{\text{odd}} = (12.5 \pm 4.4 \pm 0.7)\%$



$$C_{CP+} = +0.04 \pm 0.14 \pm 0.02$$

$$-S_{CP+} = 0.65 \pm 0.26 {}^{+0.09}_{-0.07} \pm 0.04$$

→ Good agreement with SM

# Penguins vs tree

