Measurement of $\sin 2\beta (2\phi_1)$ at B–factories

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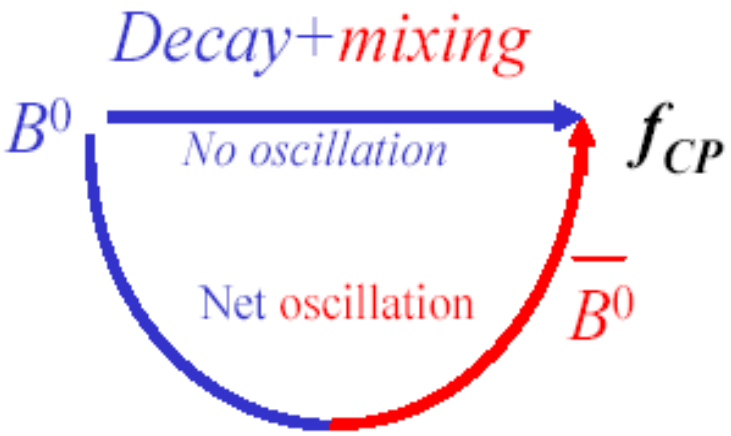
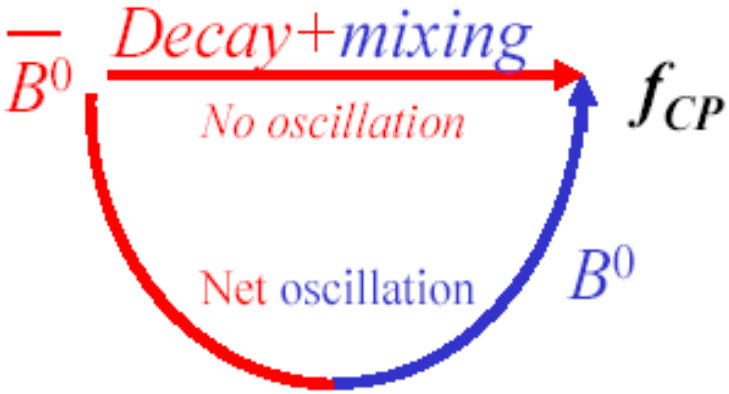
CP violation in SM

- CP violation arises from a single complex phase in the quark-mixing matrix (CKM)
- In the neutral B_d system large effect in the interference between B_d- $\overline{B}_d$ mixing and decay
- B-factories give:
  - high L_{int} (Belle 446 fb^{-1} , BaBar 244 fb^{-1})
  - high Q = $\epsilon(1-2w^2)$~30%
- Decays with single amplitude measure β:
  - b→c: $B^0 \to J/\psi K^0$, $B^0 \to D^* D^*$ "tree" mediated
  - b→s: $B^0 \to \phi K^0$, $B^0 \to K_s K_s K_s$, $B^0 \to K^+ K^- K^0$ "penguin" mediated
- New Physics effects in the loops?

$A_{CP}(t)$: ~~CP~~ "time dependent"





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

CP Asymmetry:

$$A_{f_{CP}}(t) = \frac{\Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right) - \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)}{\Gamma\left(B^0_{phys}(t) \to f_{CP}\right) + \Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right)}$$

$$A_{f_{CP}} = -C_{f_{CP}} \cos(\Delta m t) + S_{f_{CP}} \sin(\Delta m t)$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} \approx e^{-2i\beta}\,\eta_{CP}$$

Amplitude ratio

CP parameter

$$C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

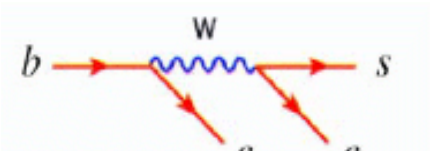
For single amplitude $= 0$

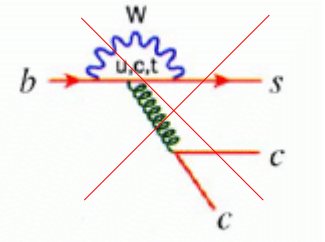
$$S_{f_{CP}} = \frac{-2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2} = -\mathrm{Im}\,\lambda_{f_{CP}}$$

$C_{f\,CP} \neq 0 \Rightarrow$ direct CPV

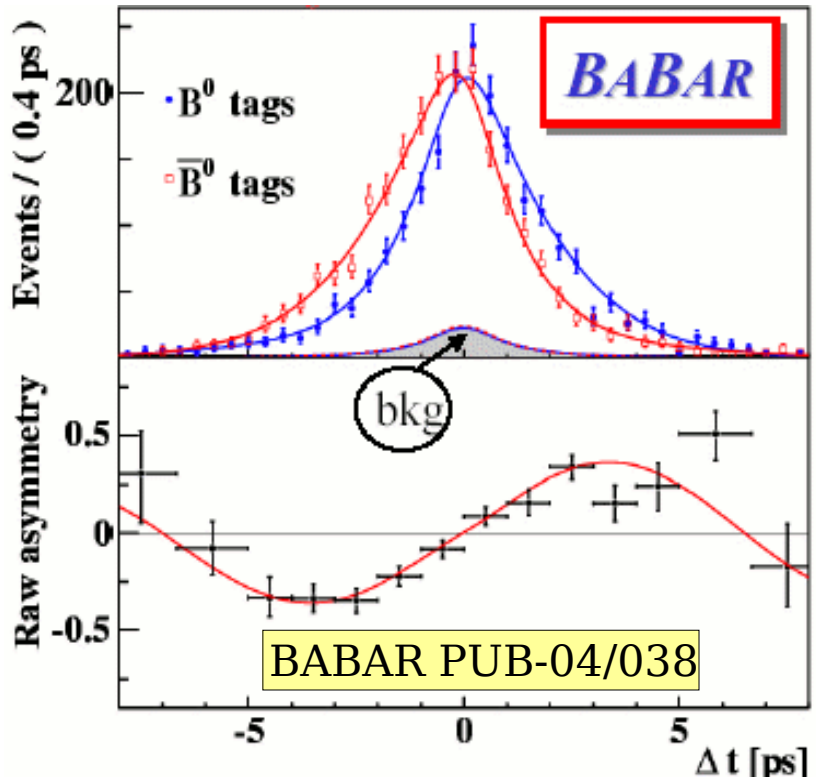
CP: $B^0 \to \bar{c}cK^0$

- Mixing phase $\Phi_M = 2\beta$
- Penguin/Tree ~ $A|\lambda|^2 \Rightarrow$ small hadronic uncertainties





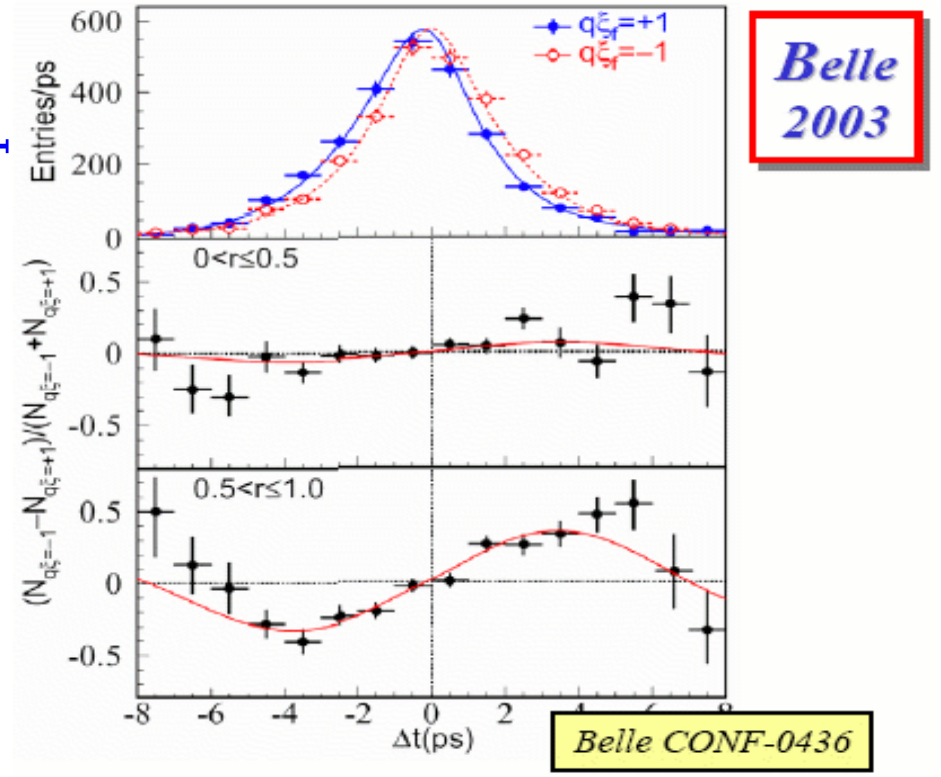
205 fb-1 or 227M $\bar{B}B$ pairs



$\sin 2\beta = +0.722 \pm 0.040 \pm 0.023$

$\lambda = |\bar{A}/A| = 0.950 \pm 0.031 \pm 0.013$

140 fb-1 or 152M $\bar{B}B$ pairs

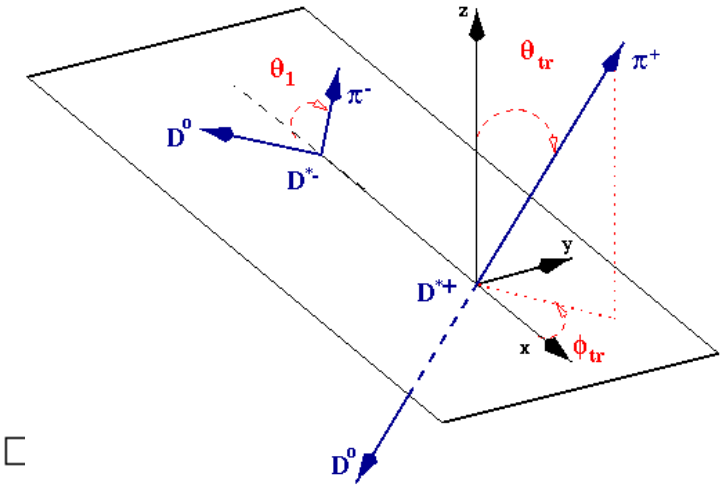


$\sin 2\beta = +0.728 \pm 0.056 \pm 0.023$

$\lambda = |\bar{A}/A| = 1.007 \pm 0.041 \pm 0.033$

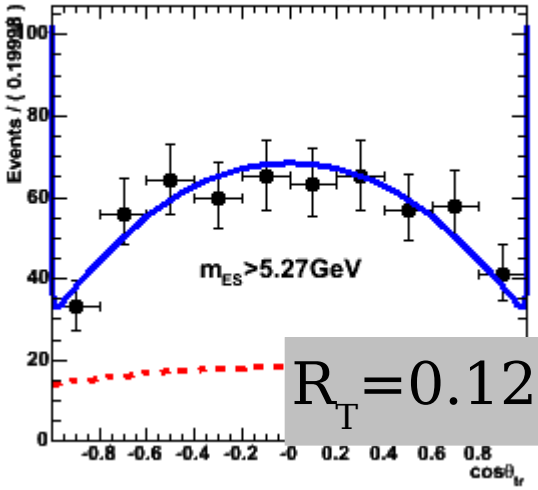
$B^0 \rightarrow D^*D^*$

- Vector-Vector decay
- CP content not known ⇒ CP-odd fraction R_T determined in time-integrated transversity analysis

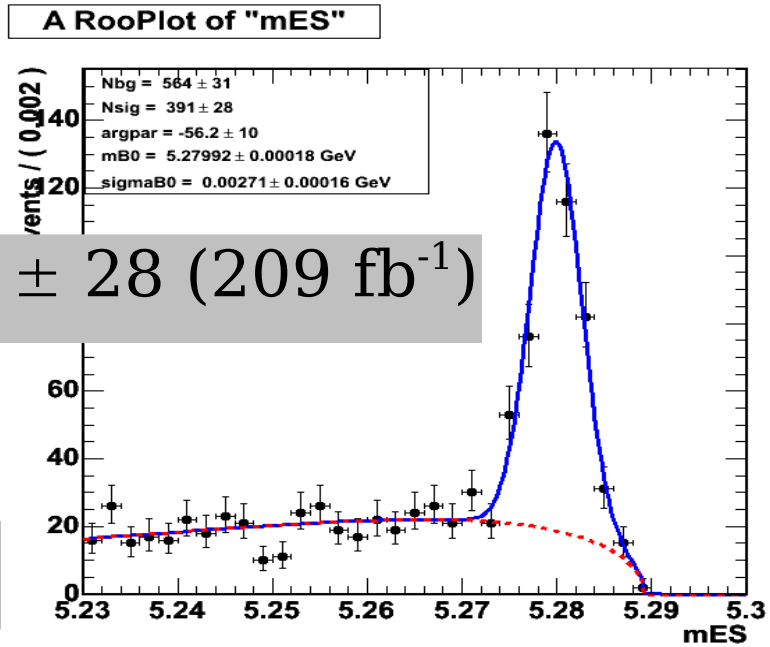


Three angles in Transversity basis: θ_1,θ_{tr}, and ϕ_{tr}

Integrate over θ1and ϕtr and taking into account the angular acceptance



$R_T = 0.125 \pm 0.044 \pm 0.007$

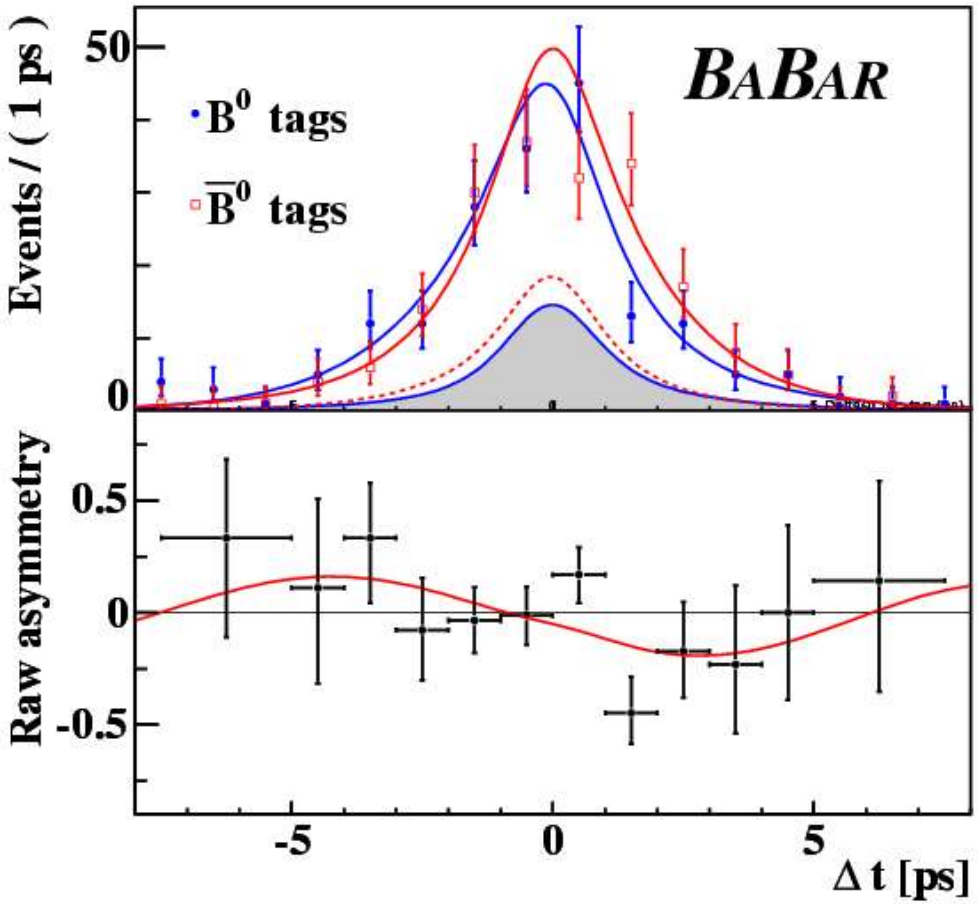


$N_{sig} = 391 \pm 28$ (209 fb^{-1})

$B^0 \to D^{*}D^{*}$: asymmetry

Peaking background:

- No significant peaking bg from generic MC studies
- Conservative estimate: 1.5%±1.5%
- Assume NO CP asymmetry of peaking background by default



R_T determines the dilution to calculate S^{even} from S^{fit}

$$C = 0.04 \pm 0.14(\text{stat}) \pm 0.02(\text{sys})$$

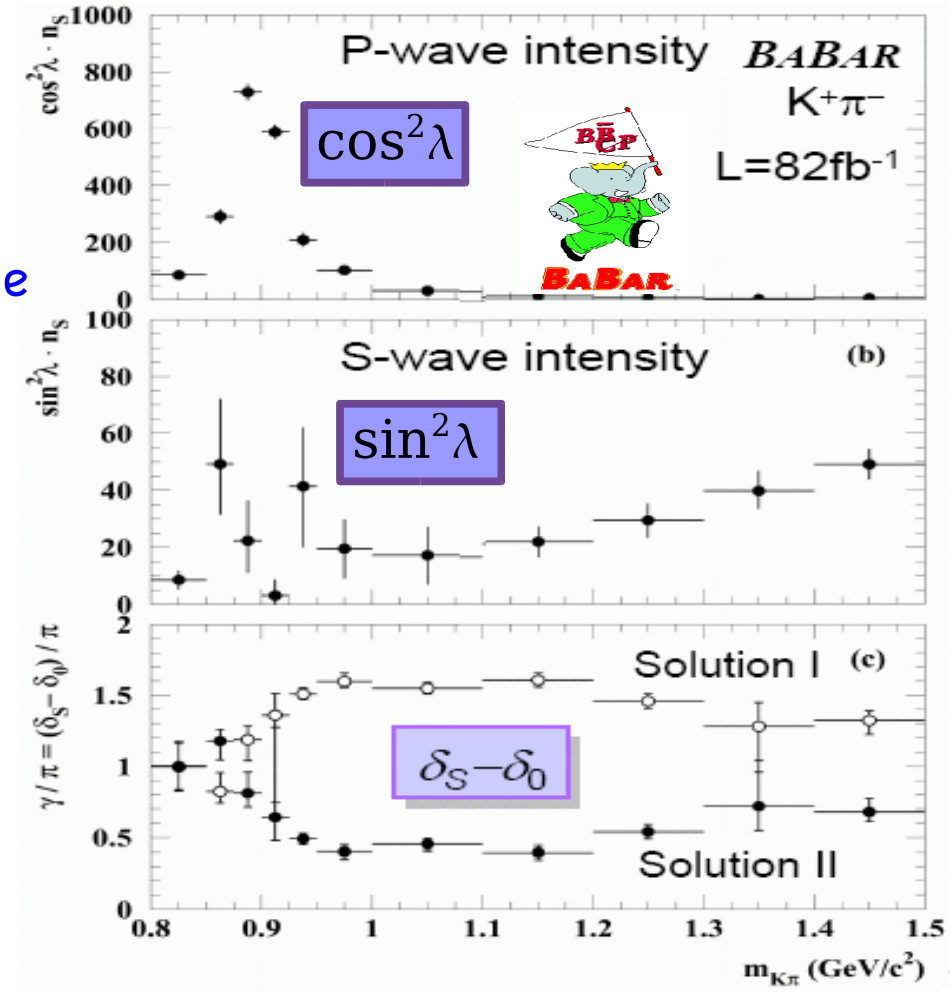
$$S^{even} = -0.65 \pm 0.26(\text{stat})^{+0.09}_{-0.07}(R_T) \pm 0.04(\text{sys})$$

$\cos 2\beta$ from $B^0 \to \bar{c}cK^{*0}$

- The 4-fold ambiguity on β from $\sin 2\beta$ can be reduced to 2-fold from $\cos 2\beta$ measurement (in SM, $\cos 2\beta > 0$)
- $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K_S \pi^0$ sensitive to $\cos 2\beta$
  - CP-even/CP-odd interference contribute to $\cos 2\beta$
  - Sign ambiguity (due to strong phase ambiguity) resolved by BaBar

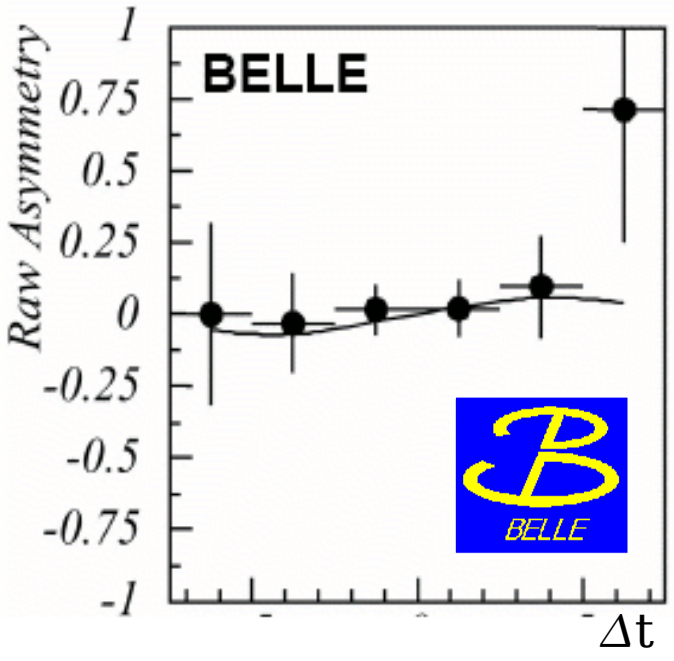
    Phys. Rev. D 71, 032005 (2005)

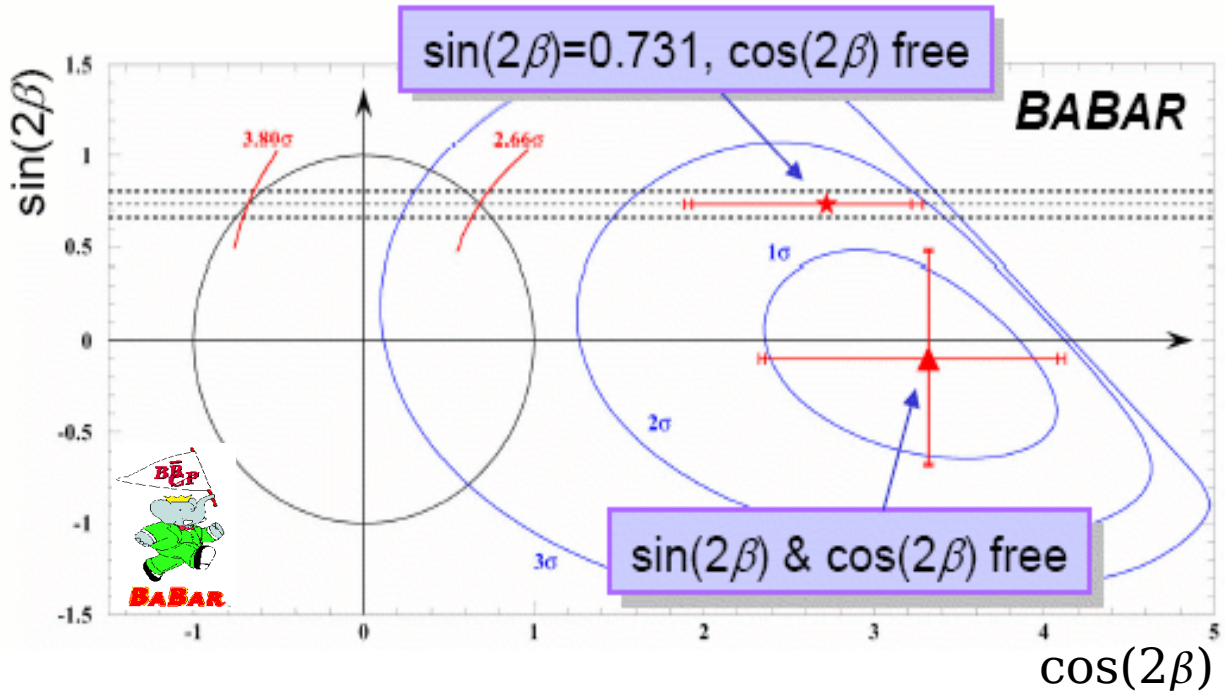
- Fit for *P* and *S* wave intensities and $\delta_S - \delta_0$ by $K\pi$ mass bin, fixing $\delta_\parallel - \delta_0$ and $\delta_\perp - \delta_0$ to
  - Solution I : (2.73, 0.18)
  - Solution II : (3.55, 2.96)
- ***Physical behaviour observed for Solution II***



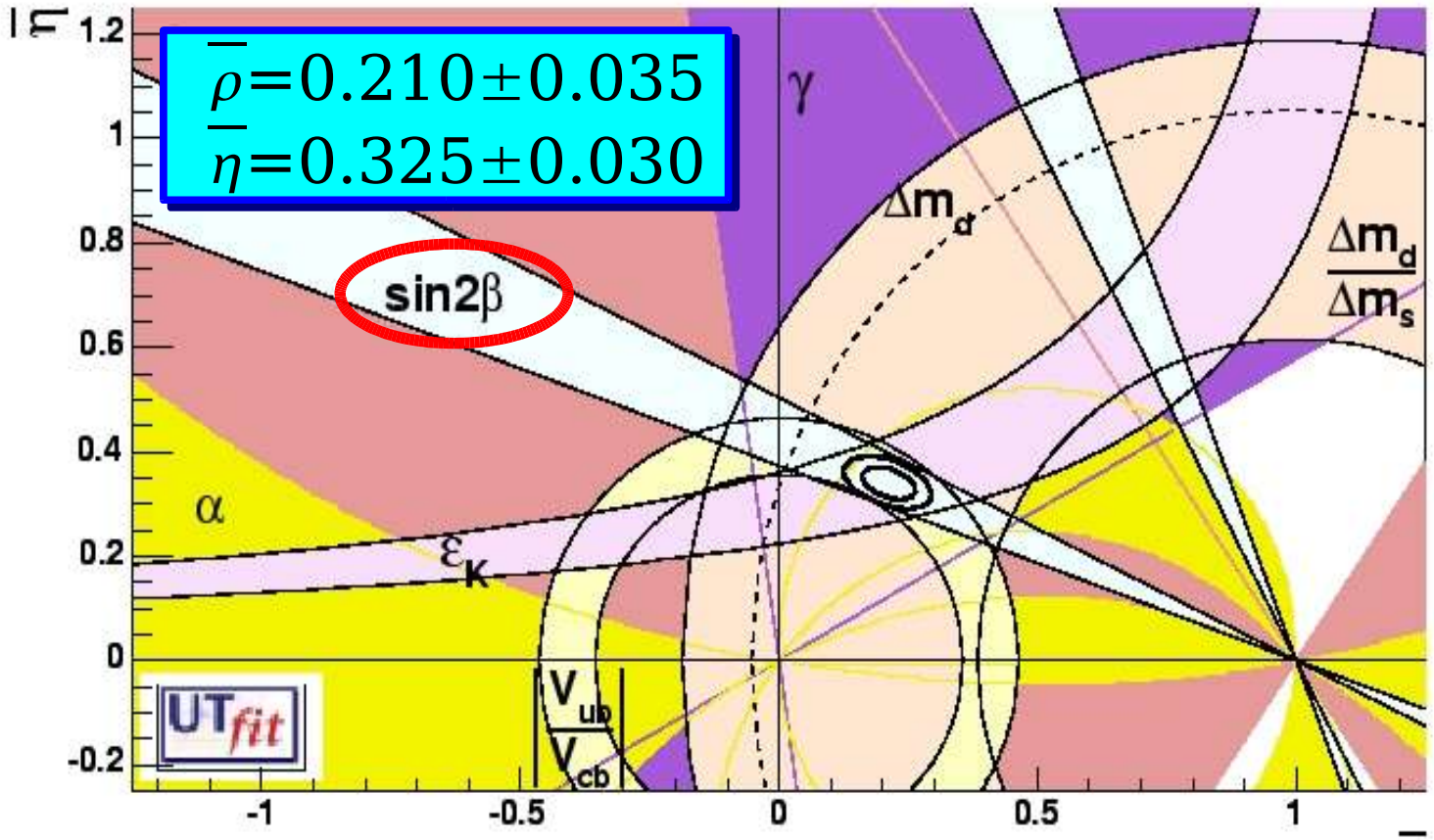
$\cos 2\beta$ from $B^0 \to \bar{c}cK^{*0}$: result

	BELLE	BABAR	AVERAGE (HFAG) *Care !*
# Events	354	104	
$\sin(2\beta/2\phi_1)$	$0.30 \pm 0.32 \pm 0.02$	$0.10 \pm 0.57 \pm 0.14$	0.21 ± 0.28 (CL=0.55, 0.6σ)
$\cos(2\beta/2\phi_1)$	$+0.31 \pm 0.91 \pm 0.11$	$+3.32^{+0.76}_{-0.96} \pm 0.27$	1.60 ± 0.67 (CL=0.026, 2.2σ)
$\sin(2\beta/2\phi_1)$	0.731 (WA)	0.731(WA)	
$\cos(2\beta/2\phi_1)$	$+0.31 \pm 0.86 \pm 0.11$	$+2.72^{+0.50}_{-0.79} \pm 0.27$	





Impact of β on CKM



$\cos2\beta < 0$ excluded by s-wave, p-wave interference in: $B0\to J\psi K^*(K_S\pi^0)$ angular analysis

- Angle measurements: CP-violating processes
- Sides measurements: CP-conserving processes
- UT fit on indirect constraints overlaid with $\sin2\beta_{WA}$

$$[\sin2\beta]_{WA}=+0.726\pm0.037_{(stat+syst)}$$

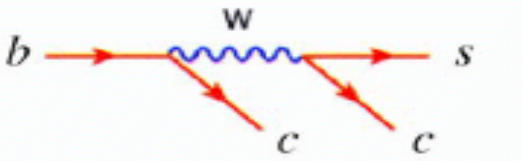
The End

?

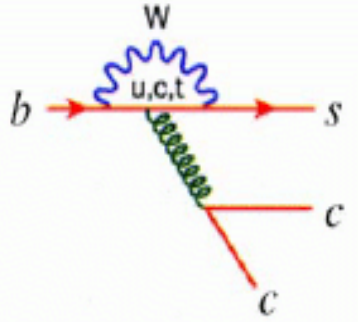
CP: why b→s?

- $B_d - \overline{B}_d$ mixing: phase $\Phi_M = 2\beta$

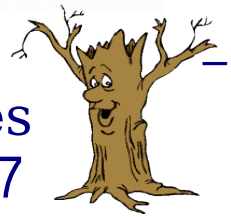
b ⇨ c



b ⇨ s



– Penguin contribution $o(\lambda^2)$
  - small hadronic uncertainties
  - measure $\sin(2\beta)=0.726\pm0.037$



– FCNC absence in SM:
  - only penguin amplitude
  - measure $\sin(2\beta)$ in SM

- New heavy particles in the loop? Look at $A_{CP}(t)$:

$\tilde{b}_A$ — — × — — $\tilde{s}_B$

A,B=Left,Right

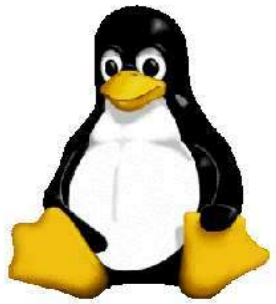
SUSY quark-squark coupling add new phases [$\mathrm{Im}(\Delta_{23})$] to ϕ_M

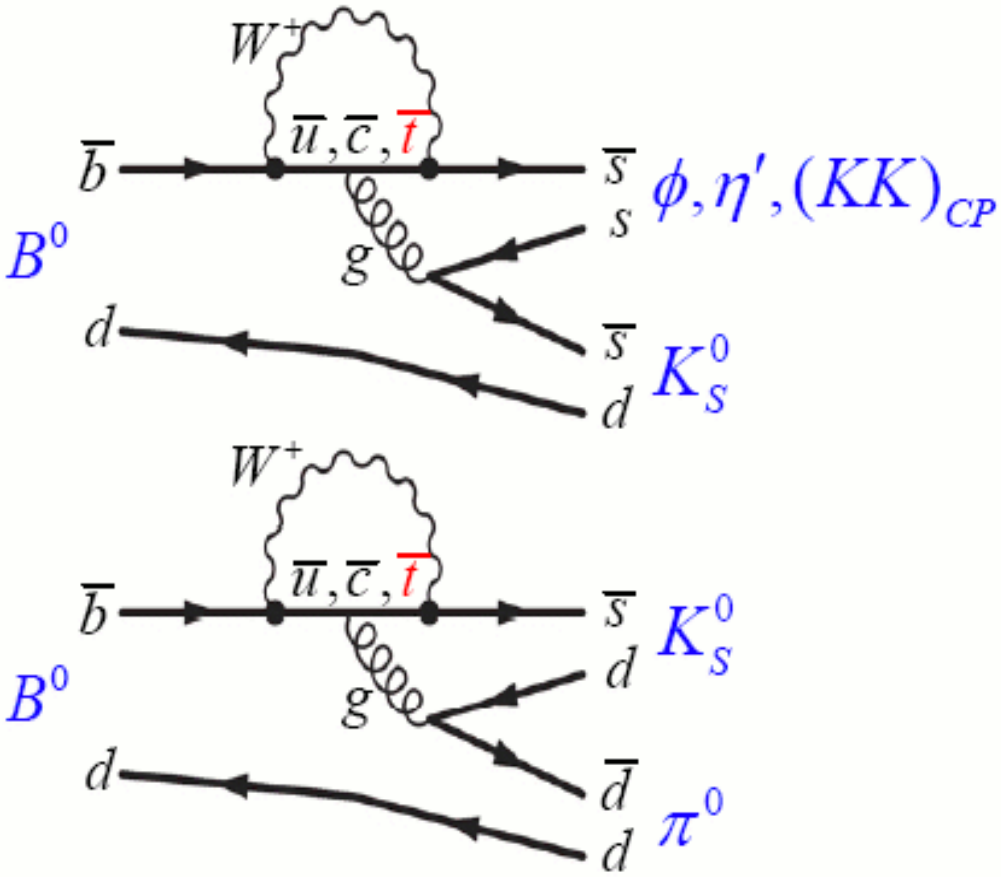
- Due to hadronic uncertainties, not all b→s decays have clean interpretation of $|\beta_{penguin} - \beta_{\bar{c}c}|$

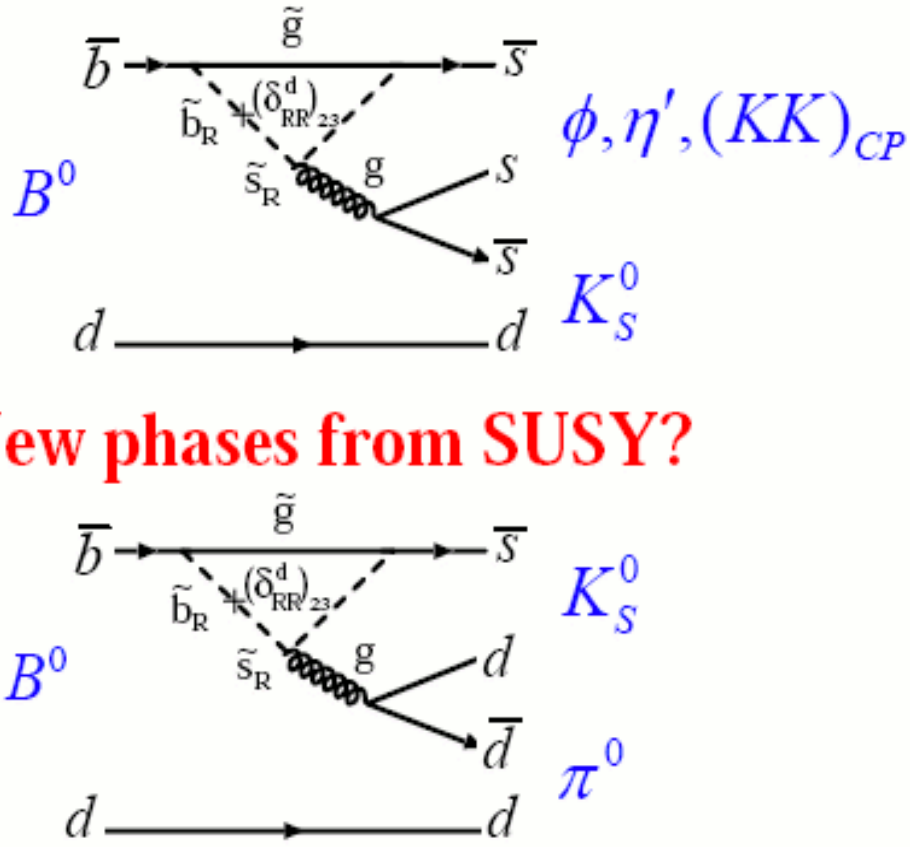
Penguin decays

In the loops SUSY contributions are:

- mass suppressed: ($\propto 1/M^2$)
- coupling enhancement ($\sim \alpha_s/\alpha_W$)



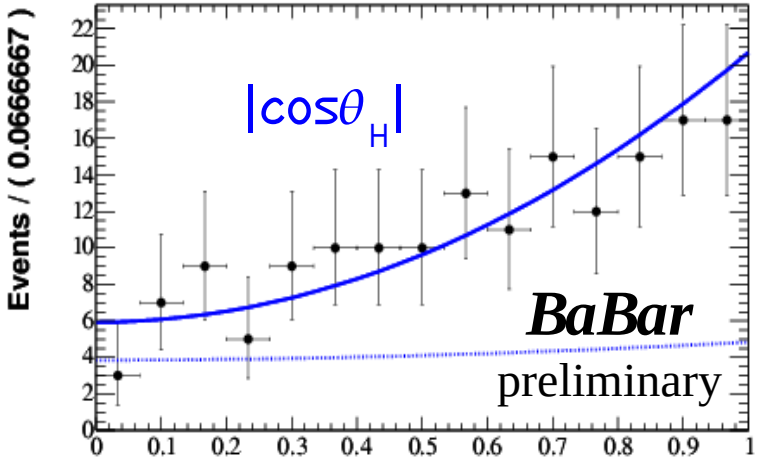


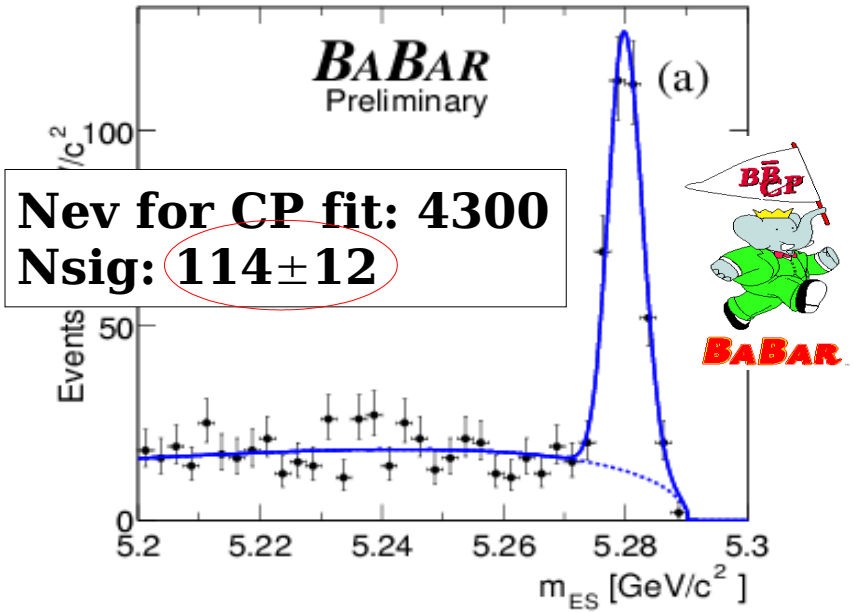


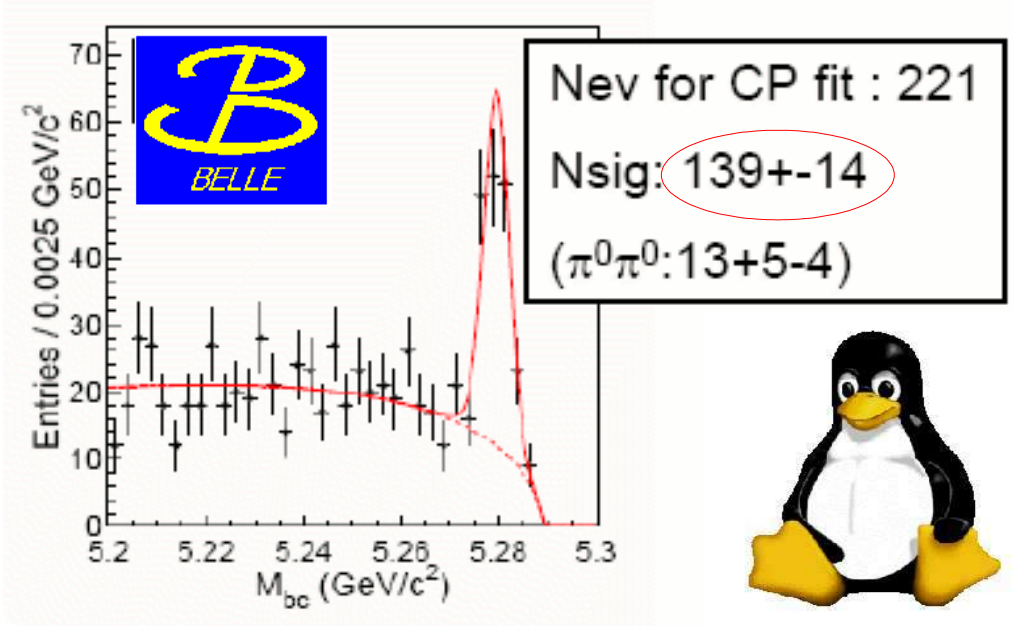
$B^0 \to \phi K_S$

The golden mode!

- The theoretically cleanest mode: pure penguin
- Reconstruction:
  - $\phi \to K^-K^+$: critical K^+ ID: Čerenkov angle
  - ϕ: $J^{CP}=1^{--}$, K^+:$J^P=0^-$ $\Rightarrow$ $|\cos\theta_H| \propto \cos^2\theta$
- ~2% peaking $\bar{B}B$ background
  (S-wave f_0K^0, ϕK^*): largest systematic source: $\Delta S=\pm 0.06$





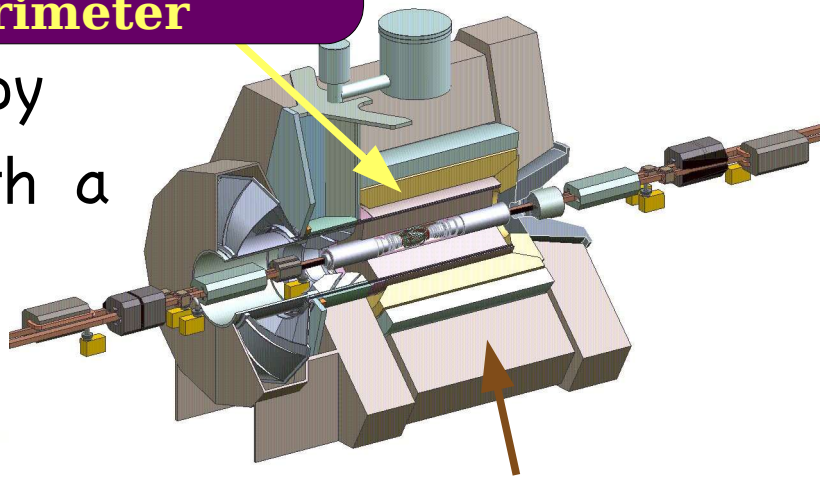


$B \to \phi K_L$

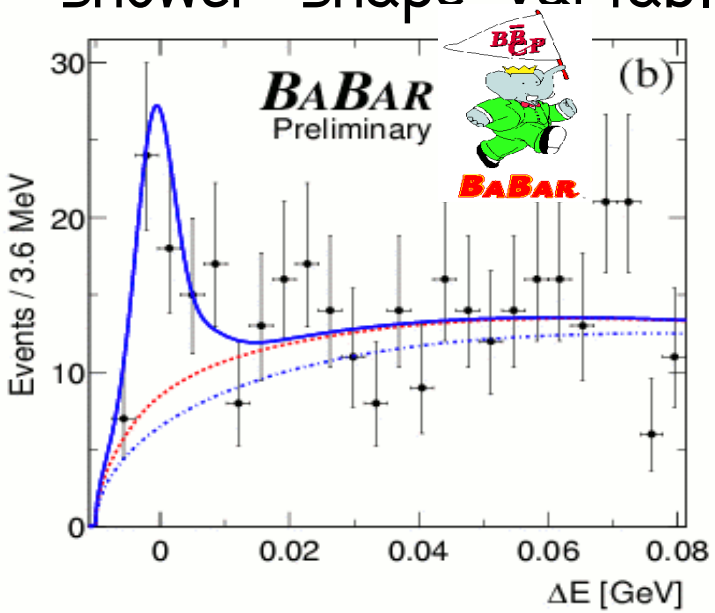
The golden mode!

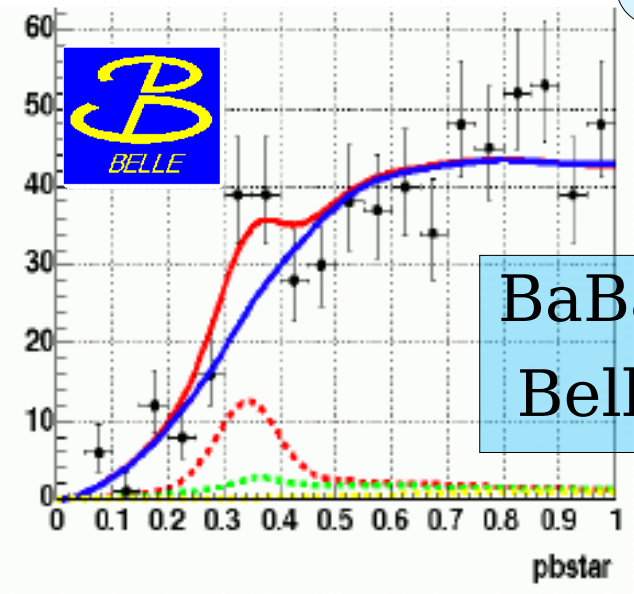
- $CP(\phi K_L) = -CP(\phi K_S)$
- K_L momentum not measured, inferred by direction in the EMC or IFR and with a B mass constraint
- m_{ES} constrained → Only ΔE (BaBar)
- Photon background rejected with shower shape variables combined in a NN

EMC = ElectroMagnetic Calorimeter



IFR = Instrumented Flux Return



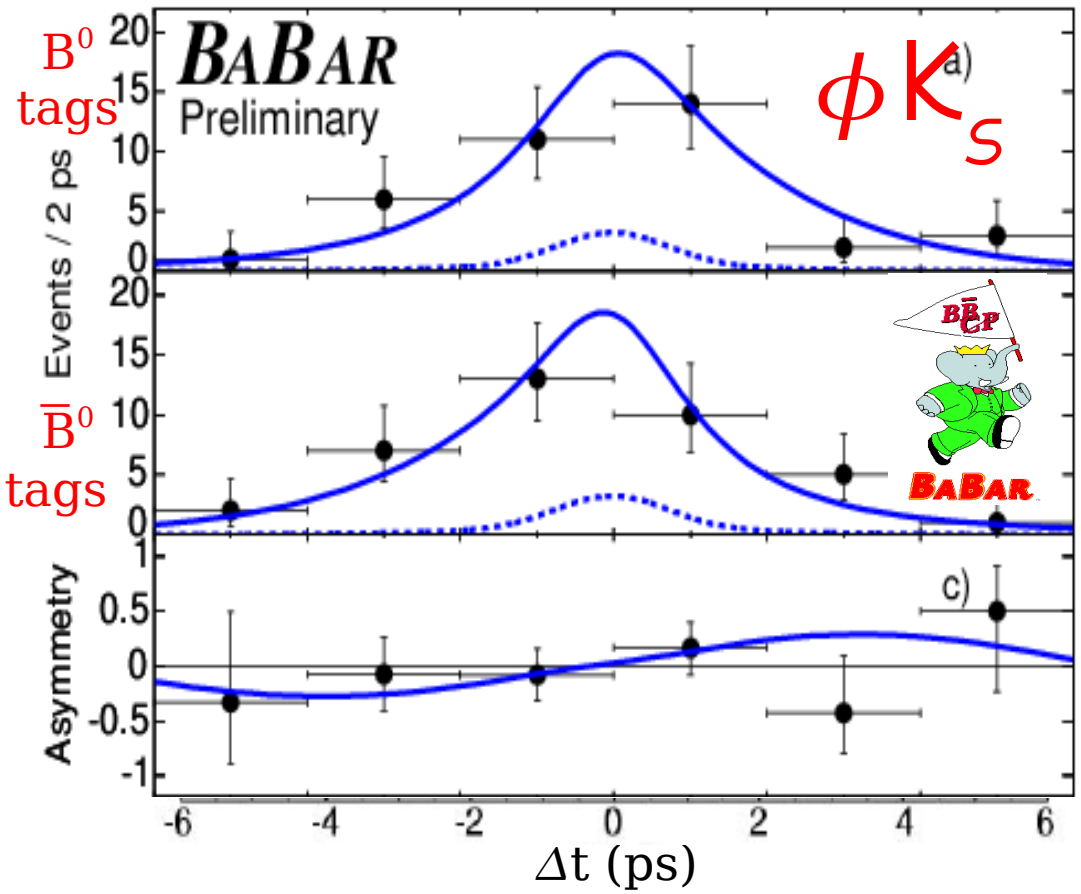


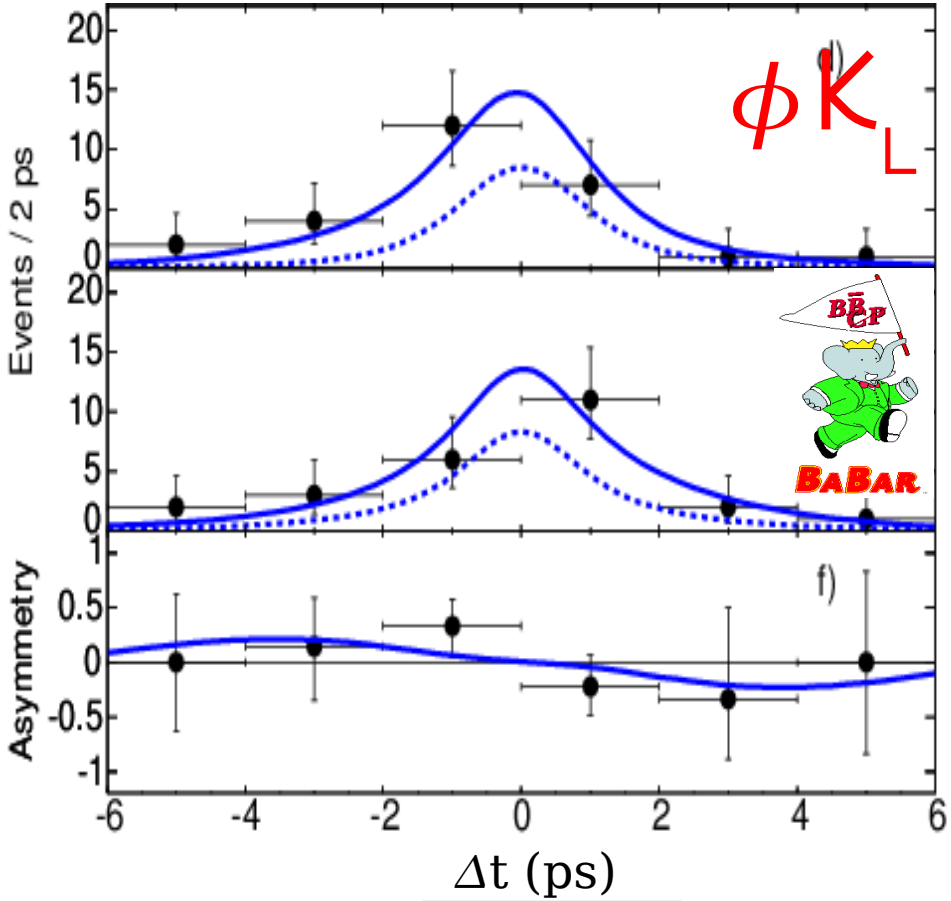
BaBar: $N_{sig} = 98 \pm 18$

Belle: $N_{sig} = 36 \pm 15$

Combined $A_{CP}(t)$ results

The golden mode!





CP=-1

CP=+1

$S = +0.50 \pm 0.25^{+0.08}_{-0.05}$

$C = 0.00 \pm 0.23 \pm 0.09$

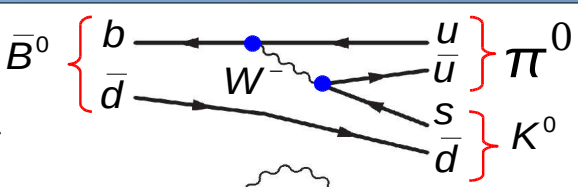
$S = +0.06 \pm 0.33 \pm 0.09$

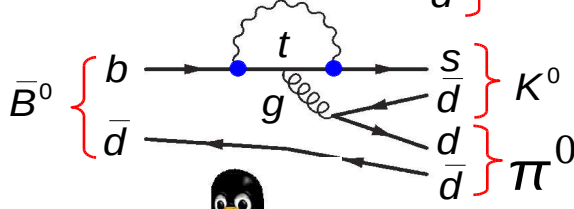
$C = 0.08 \pm 0.22 \pm 0.09$

$B^0 \to K_s \pi^0$

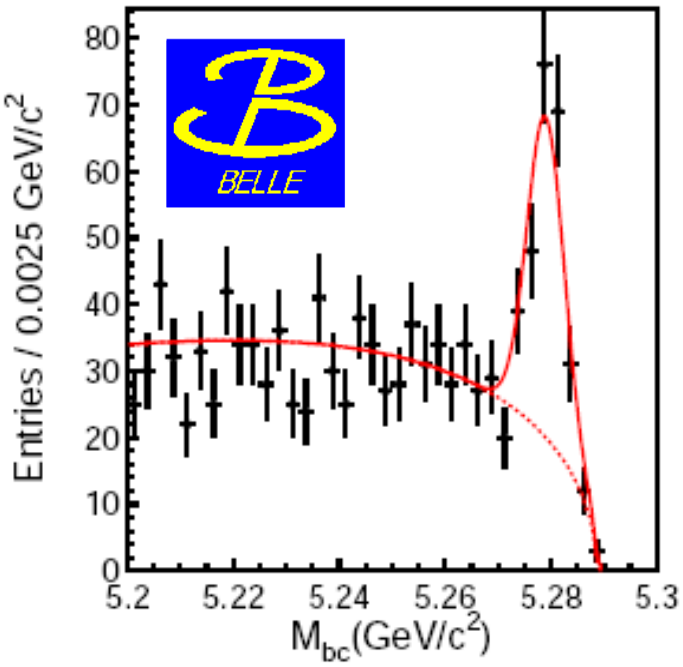
- Doubly CKM-suppressed tree amplitude
  - Penguin dominated b→sdd
  - CP-odd eigenstate
  - hadronic uncertainties quite under control (see CKM WS)

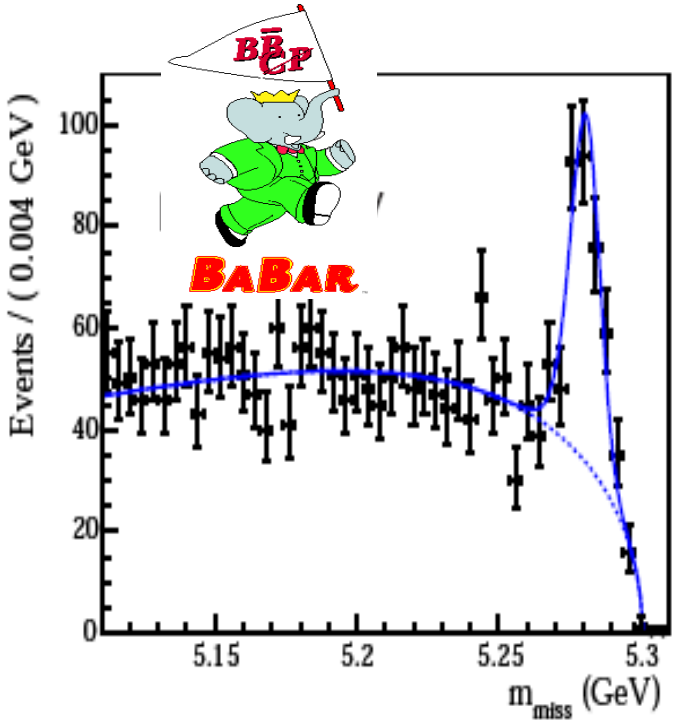
http://ckm2005.ucsd.edu/WG/WG4/tue3/WG4_charge_session1.php





- Experimental challenge: no charged track from primary vertex

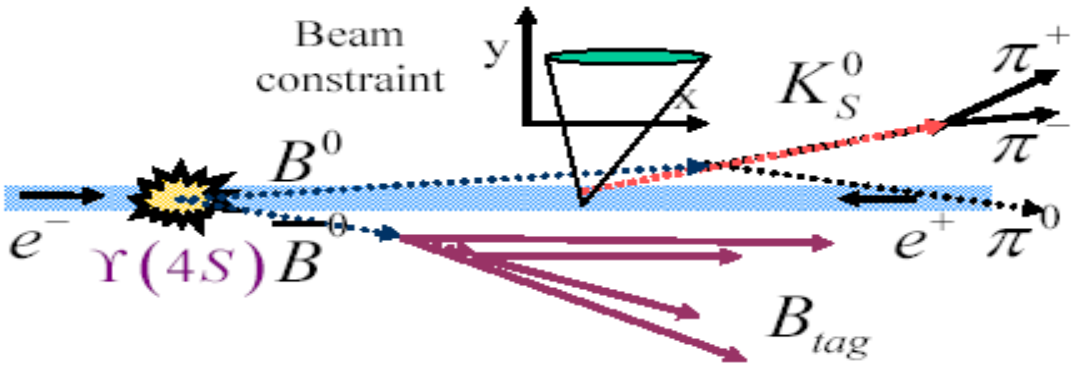


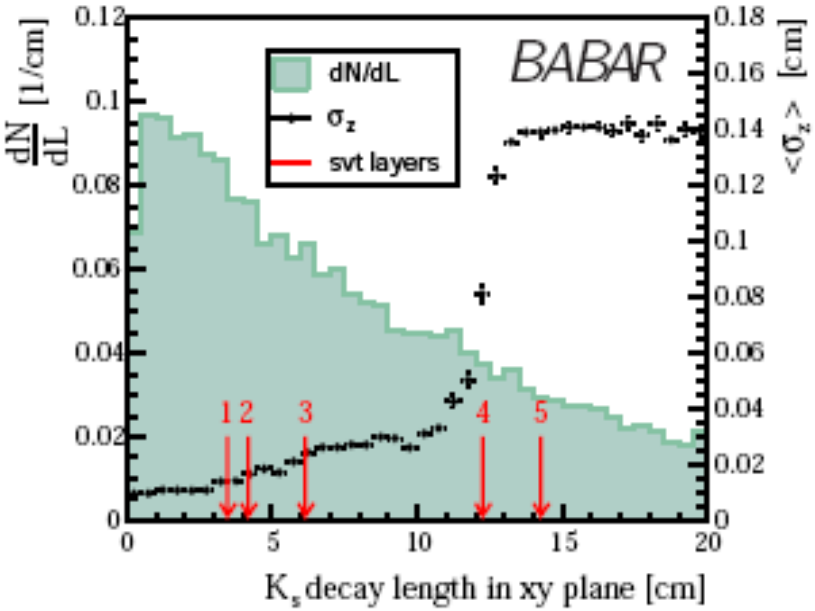


- BaBar yield: $N(K_s\pi^0)=300\pm23$
- Belle yield: $N(K_s\pi^0)=(168\pm16)+(83\pm18)$

$B^0 \to K_S \pi^0$: a new vertexing

- If K_S decays in the first layers of Si vertex detector, use K_S vertex for the B_{CP}:
  - other events used for C





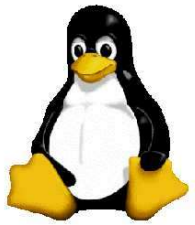
- Beam-spot constrained vertexing
- Validated on $B^0 \to J/\psi K_S$ using K_S vertex

BaBar:
$C = 0.06 \pm 0.18 \pm 0.06$
$S = 0.35^{+0.30}_{-0.33} \pm 0.04$

Belle:
$C = 0.12 \pm 0.20 \pm 0.07$
$S = 0.30 \pm 0.59 \pm 0.11$

A 3body mode: $B \to K_S K_S K_S$

- Dominantly penguin amplitude
- Defined $CP(3K_S)=+1$
  - Bose statistics ⇨ $(K_S K_S)$ even
  - Total angular momentum conservation ⇨ $CP(3K_S)=CP(K_S)$



Gerhson-Hazumi
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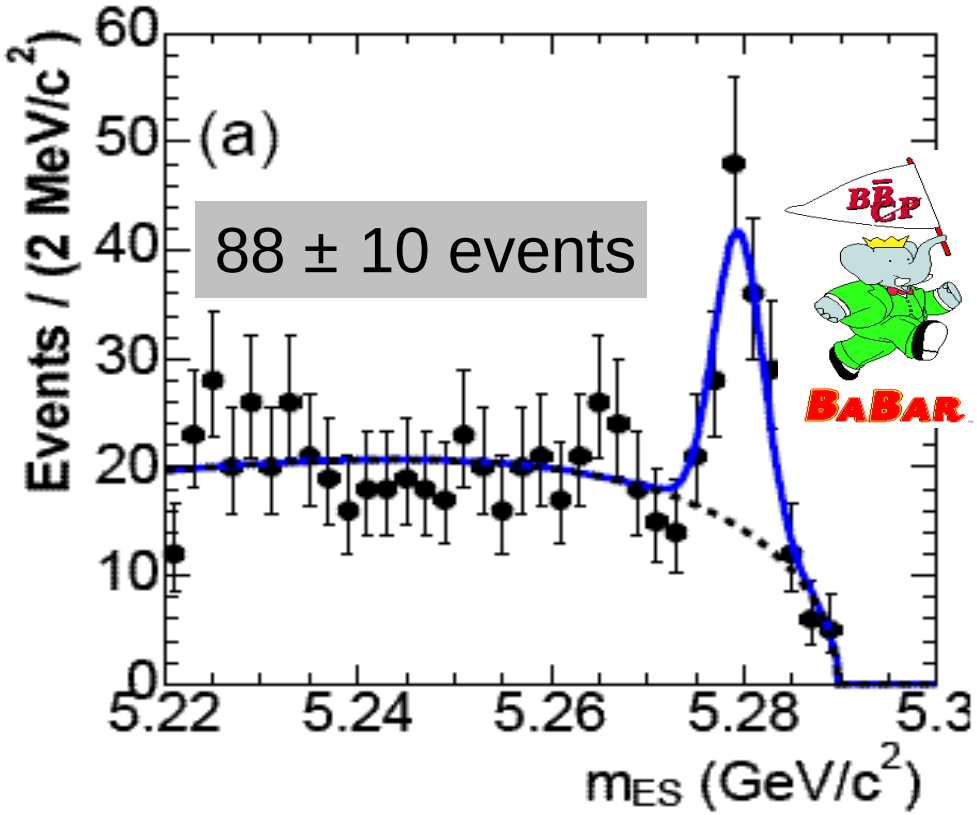
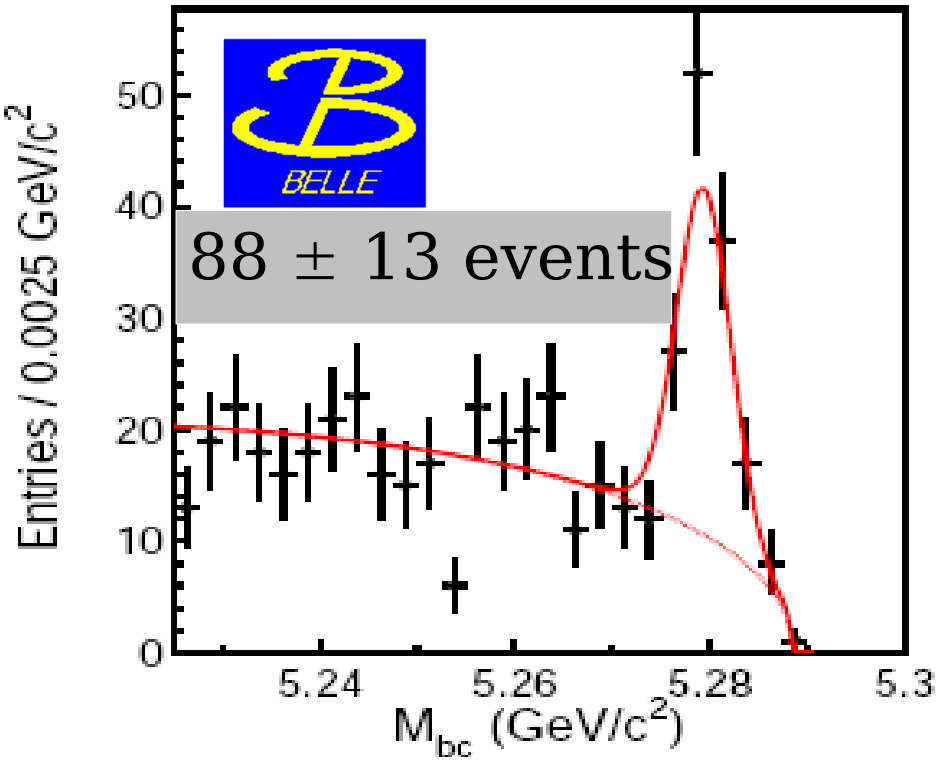
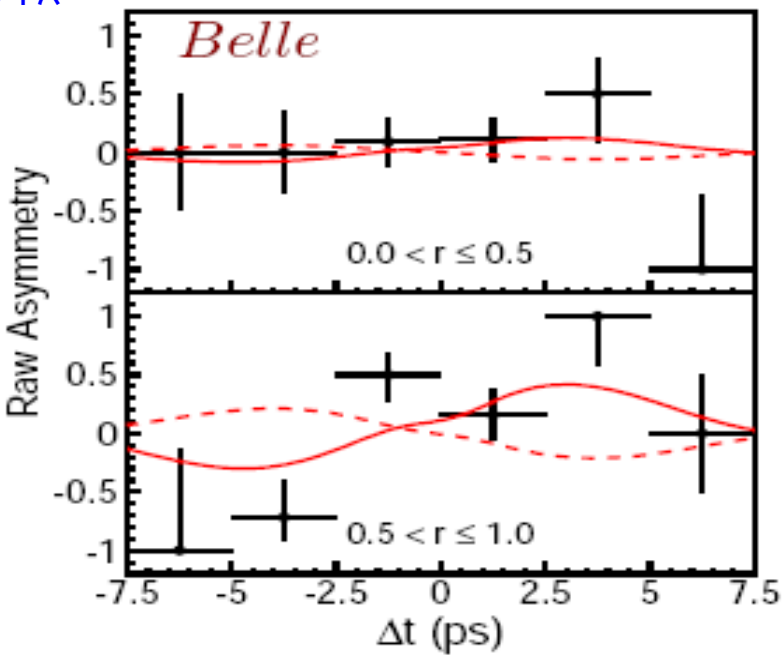
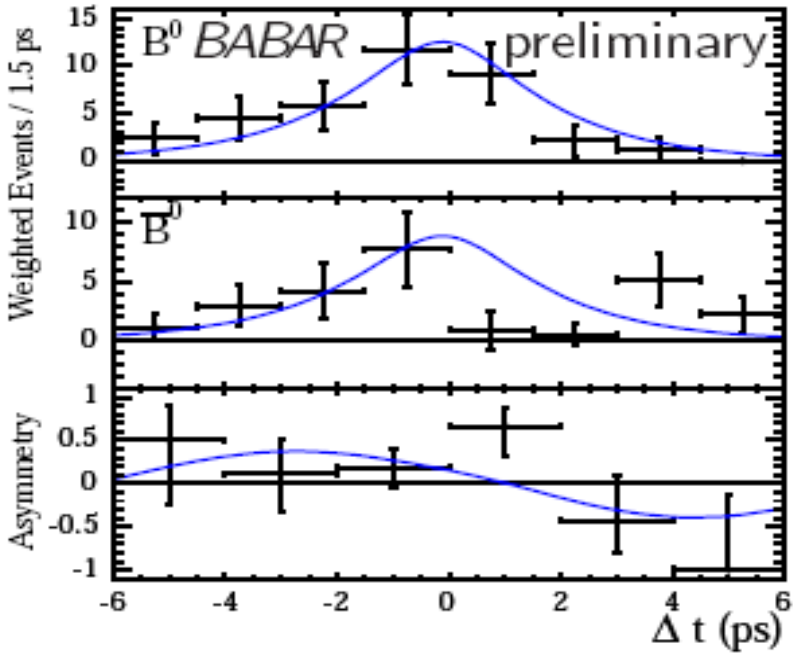




A 3body mode: $B^0 \to K_S K_S K_S$

- Again Beam Spot Constrained vertexing
- If one K_S decays outside the "good-vertexing" fiducial region, most likely 1 or 2 of the other K_S decay within (ϵ_{VTX}~100%)



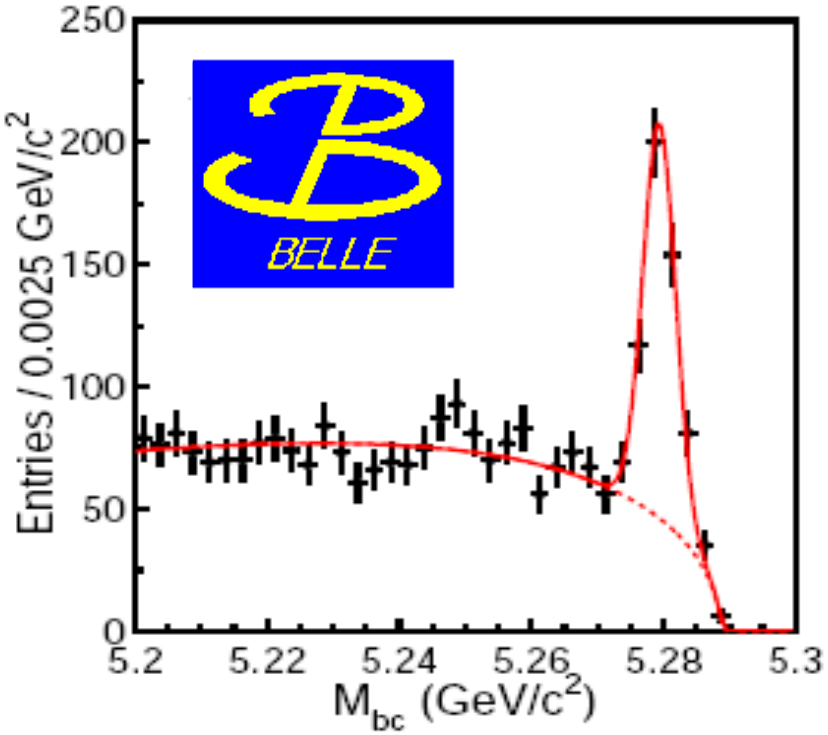


$S = +1.26 \pm 0.68 \pm 0.18$
$C = -0.54 \pm 0.34 \pm 0.08$

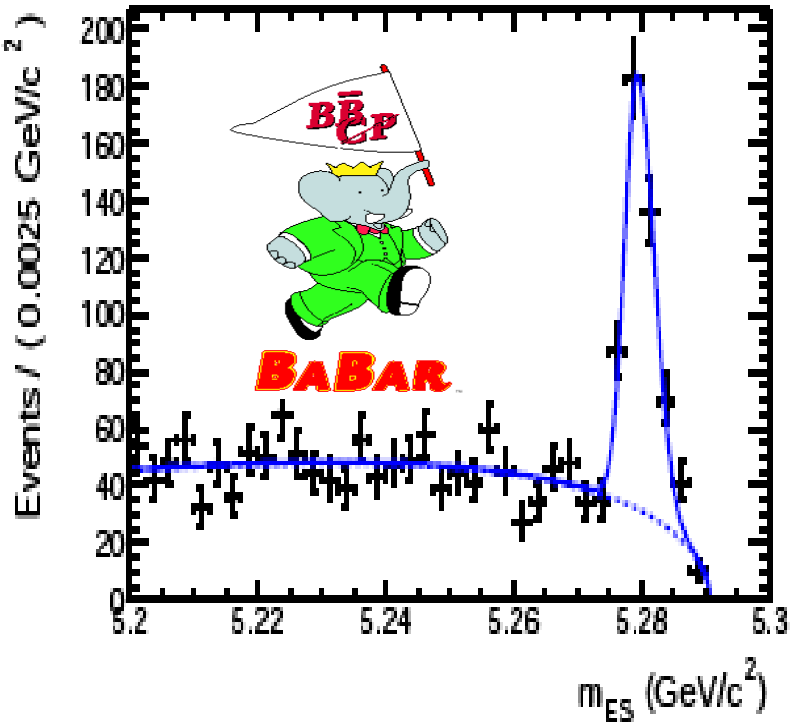
$S = -0.71^{+0.38}_{-0.32} \pm 0.04$
$C = -0.34^{+0.28}_{-0.25} \pm 0.05$

Non resonant $B^0 \to K^+K^-K_S$

- Same final state particles as $B^0 \to \phi K_S$, but higher BF
- Tighter PID (π mis-ID < 2%)
- Standard vertexing with 2 tracks



399 ± 28 events



452 ± 28 events

CP-content in $B^0 \to K^+K^-K_S$

- $b \to c$ transition vetoed: D^0, χ_{c0}, $\chi_{c2} \to K^+K^-$ and $D^+ \to K^+K_S$
- Unlike $3K_S$ case, $B^0 \to K^+K^-K_S$ *not* CP-eigenstate by symmetry
- Belle argument(*) to define the CP-content + Grossmann/Ligeti/Nir/Quinn and Gronau/Rosner: isospin analysis

$$f_{even}^{SU(2)} = 2\Gamma(B^+ \to K^+K_S^0K_S^0)/\Gamma(B^0 \to K^+K^-K^0)$$

$f^{Belle}_{even} = 0.83 \pm 0.10 \pm 0.04$ on 140 fb^{-1}

hep-ex/0504023

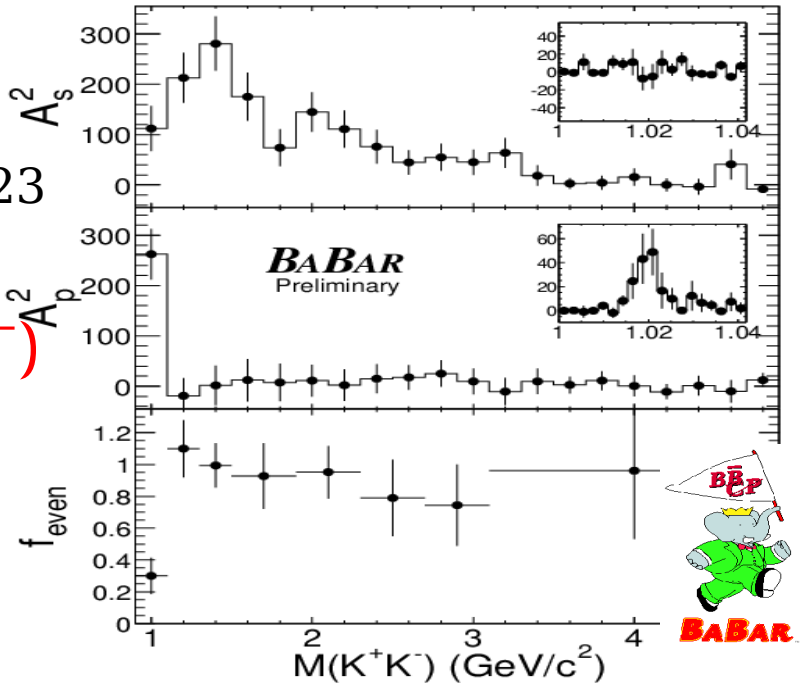
(*)[Belle coll., Phys. Rev. **D** 69 012001]

- BaBar uses angular moment analysis: use S,P wave to describe $\cos\theta_H$@m(K^+K^-)

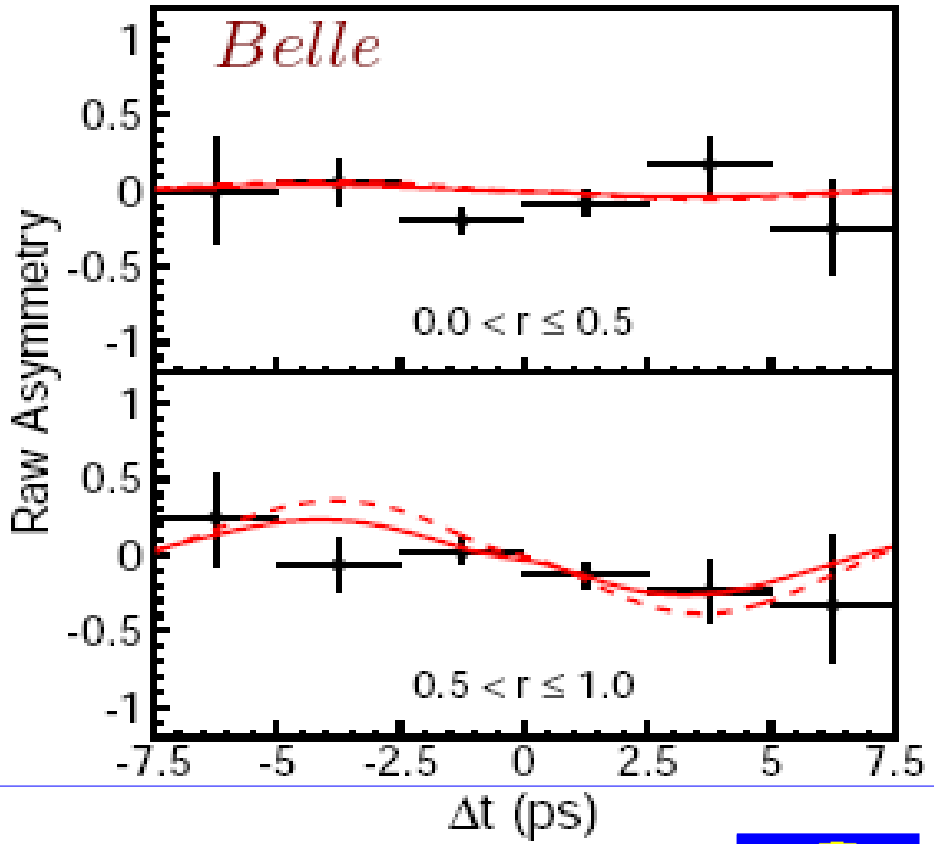
$$f_{even} = A^2_S/(A^2_S + A^2_P)$$

PRD-RC 71, 091102 (2005)

$f^{BaBar}_{even} = 0.89 \pm 0.08 \pm 0.06$



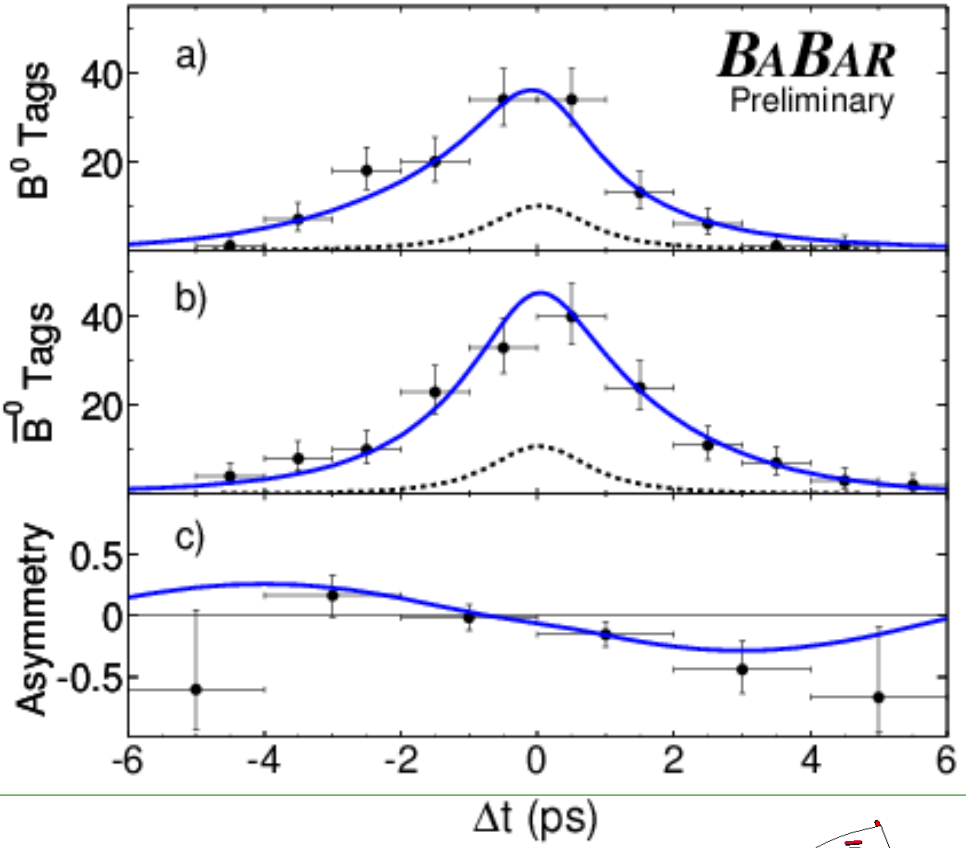
$B^0 \to K^+K^-K_s$ asymmetries



$S = -0.49 \pm 0.18 \pm 0.04$

$C = 0.08 \pm 0.12 \pm 0.07$

$\sin 2\beta_{eff} = S/(1-2f_{even}) = 0.74 \pm 0.27 \pm 0.04$ $^{+0.39}_{-0.19}$ (CP-content)



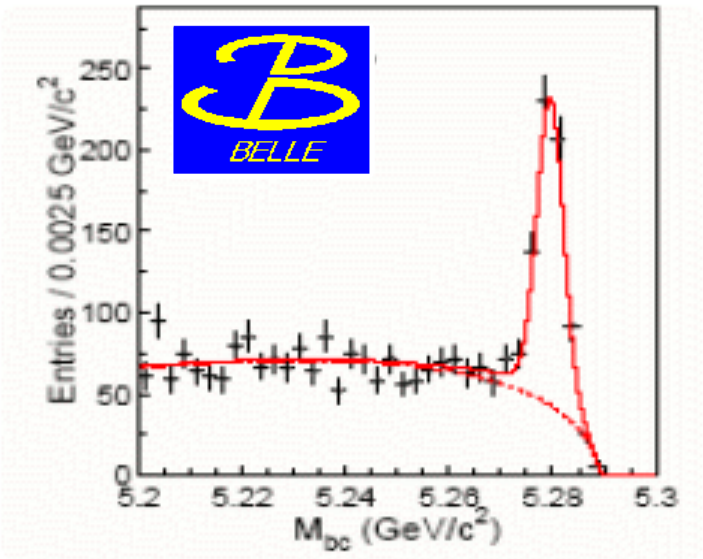
$S = -0.42 \pm 0.17 \pm 0.04$

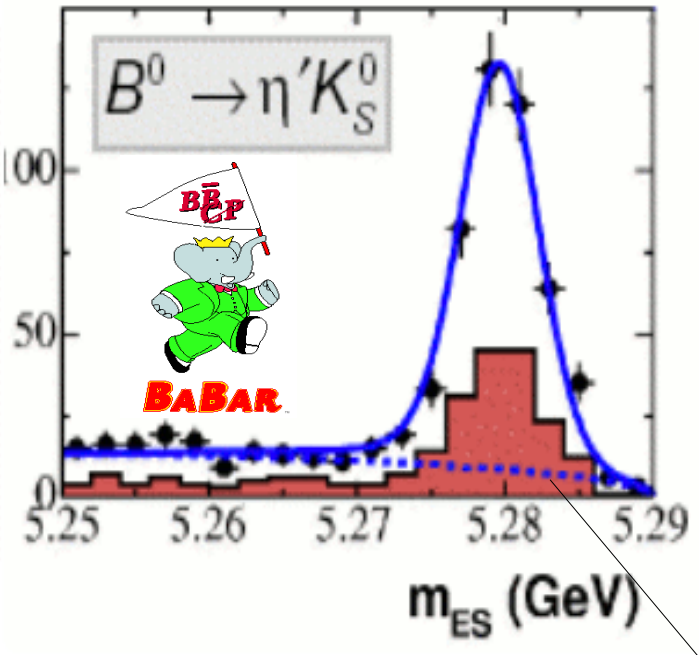
$C = 0.410 \pm 0.14 \pm 0.06$

$\sin 2\beta_{eff} = S/(1-2f_{even}) = 0.55 \pm 0.22 \pm 0.04$ ± 0.11 (CP-content)

$B^0 \to \eta' K_S$

- Many final states reconstructed:
  - $\eta' \to \eta\pi^+\pi^-$, $\rho\gamma$. $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$. $K_S \to \pi^+\pi^-$, $\pi^0\pi^0$
- High BF: $(60.6 \pm 5.6 \pm 4.6) \times 10^{-6}$





$N_{sig} = 512 \pm 27$

$N_{sig} = 804 \pm 40$

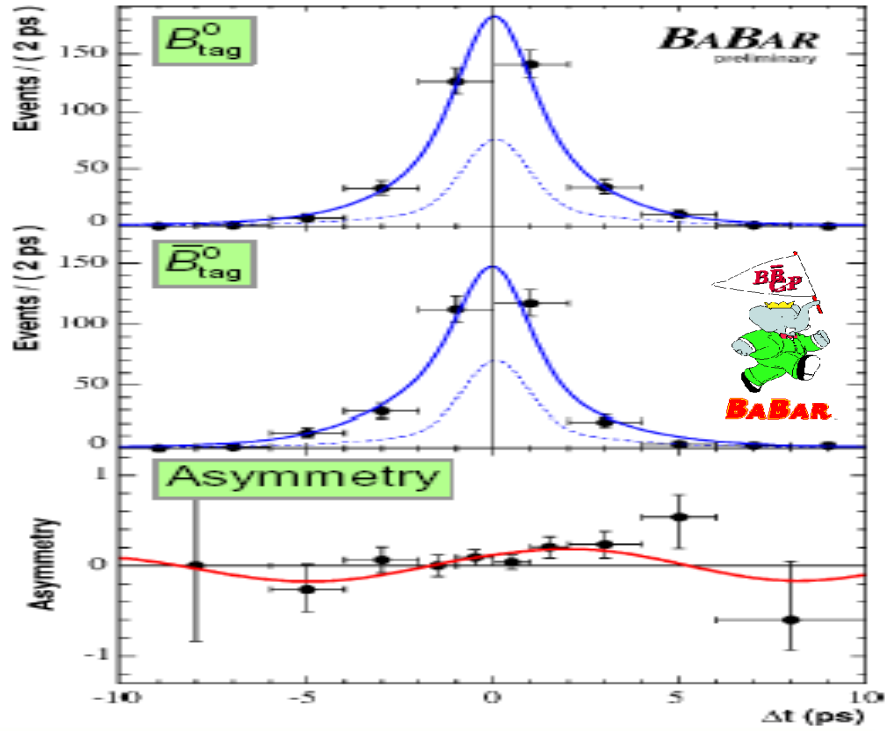
Mode	Signal yield
$\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^+\pi^-}$	188 ± 15
$\eta'_{\rho\gamma} K^0_{\pi^+\pi^-}$	430 ± 26
$\eta'_{\eta(3\pi)\pi\pi} K^0_{\pi^+\pi^-}$	54 ± 8
$\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^0\pi^0}$	44 ± 9
$\eta'_{\rho\gamma} K^0_{\pi^0\pi^0}$	94 ± 23
Combined fit	804 ± 40

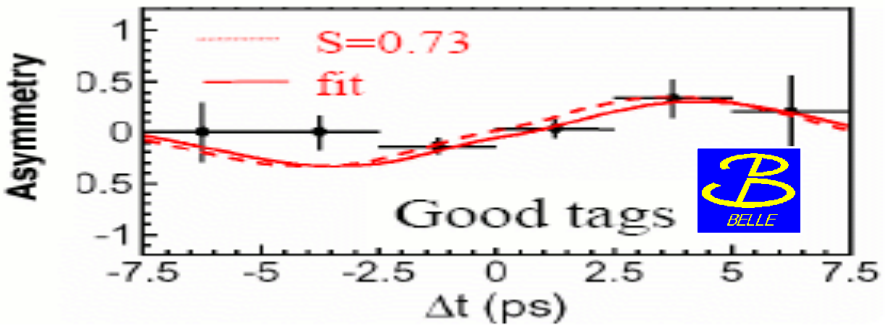
	η' mode	SVD1	SVD2
$\eta' K^0_S$	$\eta(\gamma)\pi\pi$	83^{+11}_{-10}	$69.6^{+9.9}_{-9.2}$
	$\rho\gamma$	171^{+16}_{-15}	142^{+15}_{-14}
	$\eta(3\pi)\pi\pi$	$25.9^{+5.9}_{-5.2}$	$21.7^{+5.5}_{-4.8}$

$\eta' \to \rho\gamma$ subsample

$B^0 \to \eta' K_s$: asymmetries

- Estimated $\bar{B}B$ from MC:
  - only a few % in $\eta' \to \rho\gamma$ (~3% Belle, 1-2% BaBar)



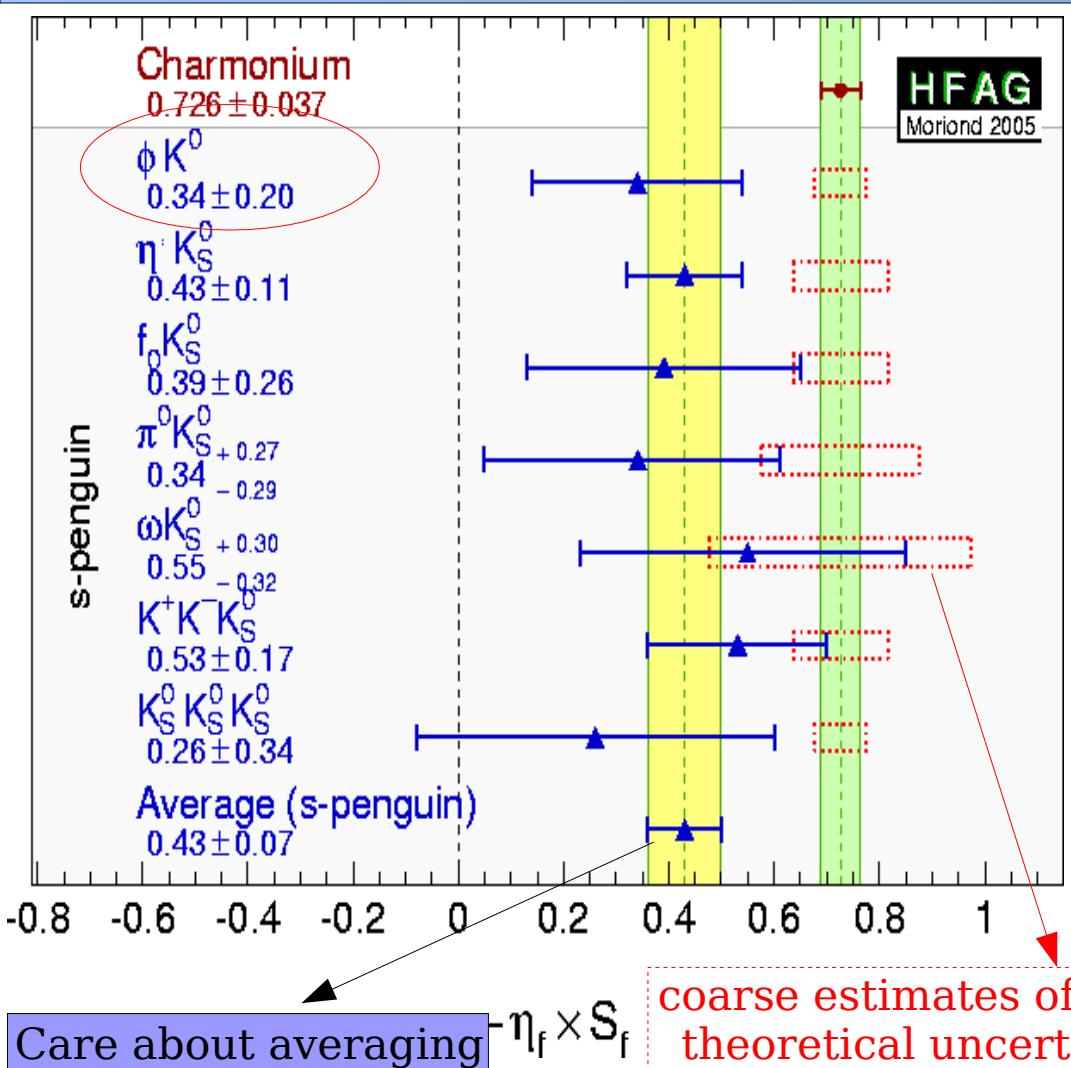


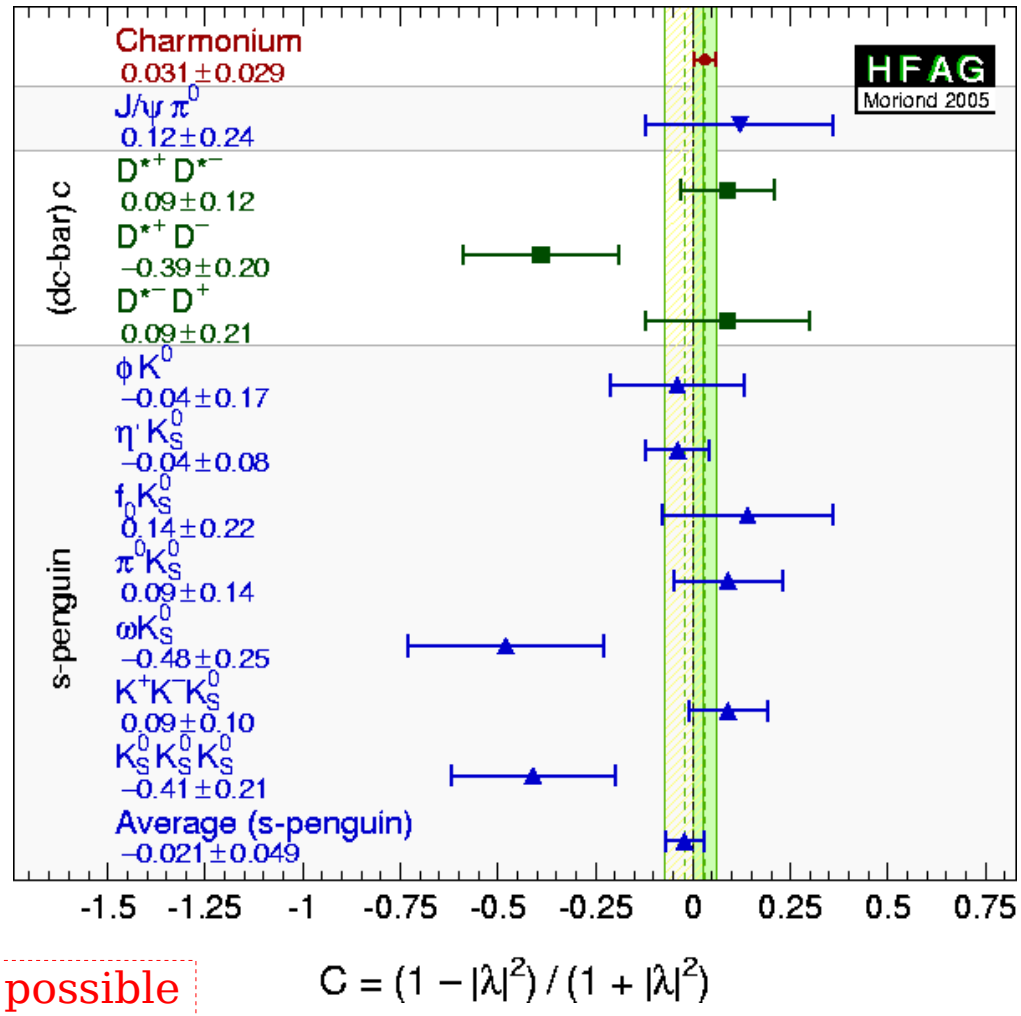
BaBar:
S=+0.30 ± 0.14 ± 0.02
C=-0.21 ± 0.10 ± 0.02

Belle:
S=+0.65 ± 0.18 ± 0.04
C=-0.19 ± 0.11 ± 0.05

- Penguin mode with lowest statistical uncertainty
- But theoretical uncertainties still under discussion...

Summary of results





Care about averaging different SM, NP, ΔS!

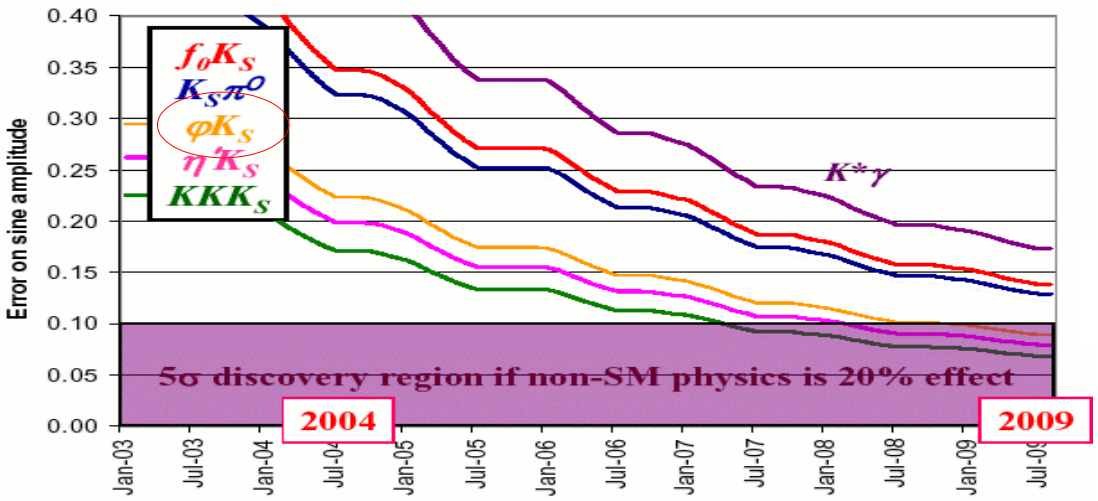
coarse estimates of possible theoretical uncertainties

- $S_{penguins} = 0.43 \pm 0.07$
- $S_{c\bar{c}} = 0.726 \pm 0.037$

- $C_{penguins} = -0.021 \pm 0.049$
- $C_{c\bar{c}} = 0.031 \pm 0.029$

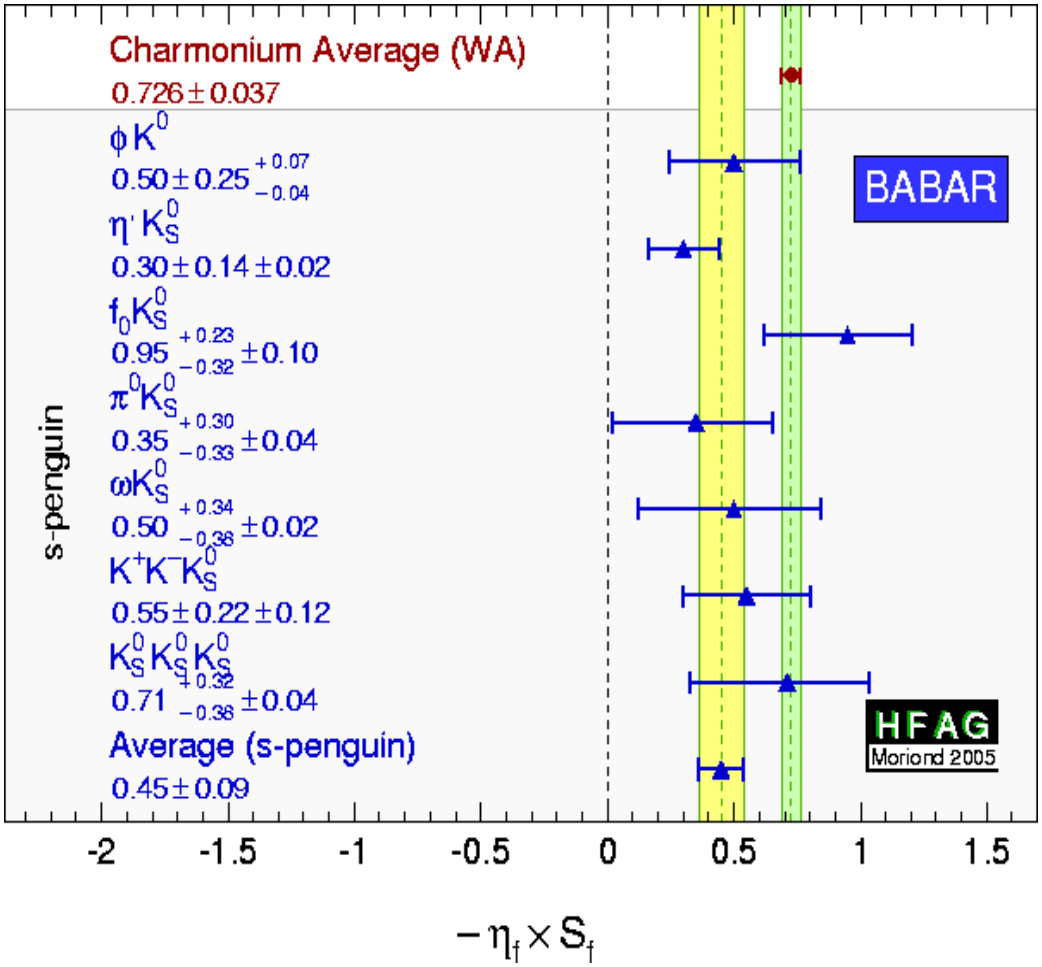
Conclusions

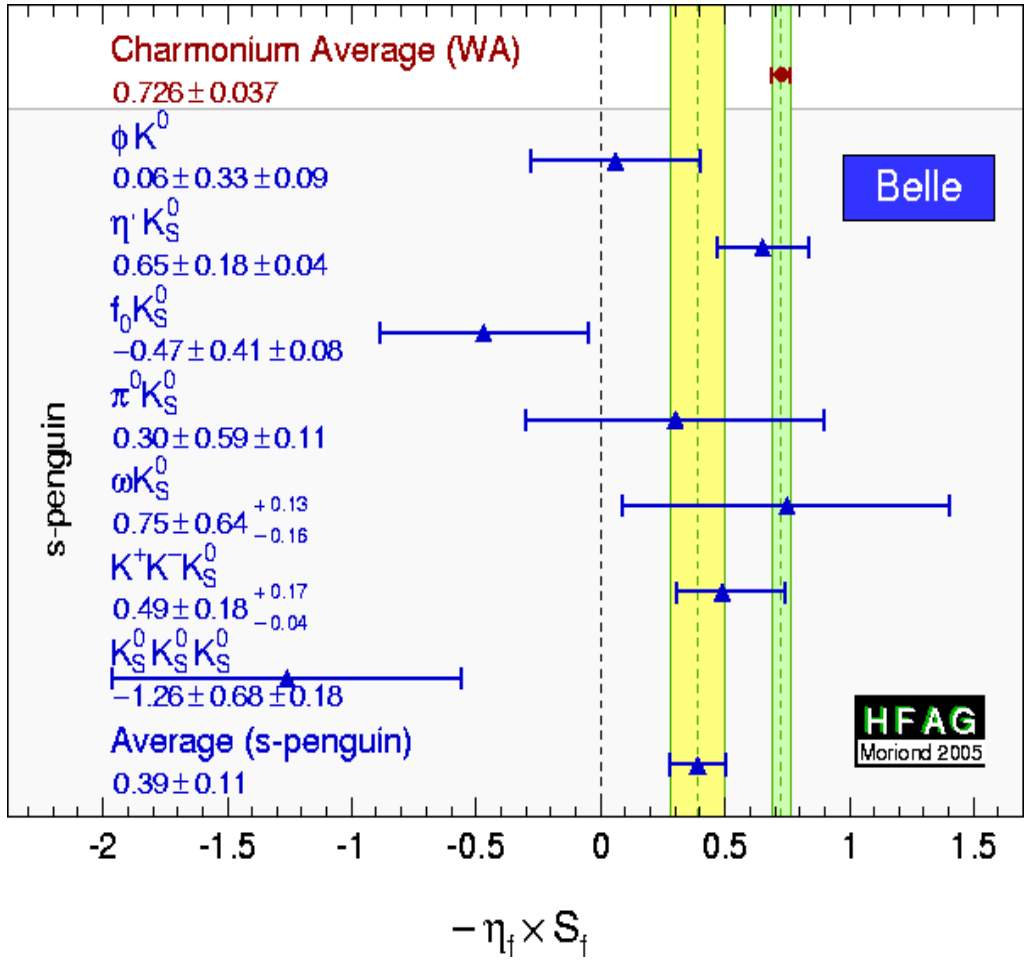
- $\sin 2\beta$ from $B^0 \to \bar{c}cK_s$ the best constraint on CKM unitarity triangle
- $\sin 2\beta$ from penguin modes probe for New Physics
- The modes with cleanest theoretically interpretation (ϕK_s, $K_sK_sK_s$) within 1σ from SM
- The two B-factories BaBar (SLAC) and Belle (KEK) show agreement in most of them (but $K_sK_sK_s$)
- $\sigma_{stat} \gg \sigma_{syst}$ today.
  The increasing integrated luminosity is necessary to show indirect New Physics effects



BACK UP

$\sin 2\beta_{eff}$: BaBar vs. Belle

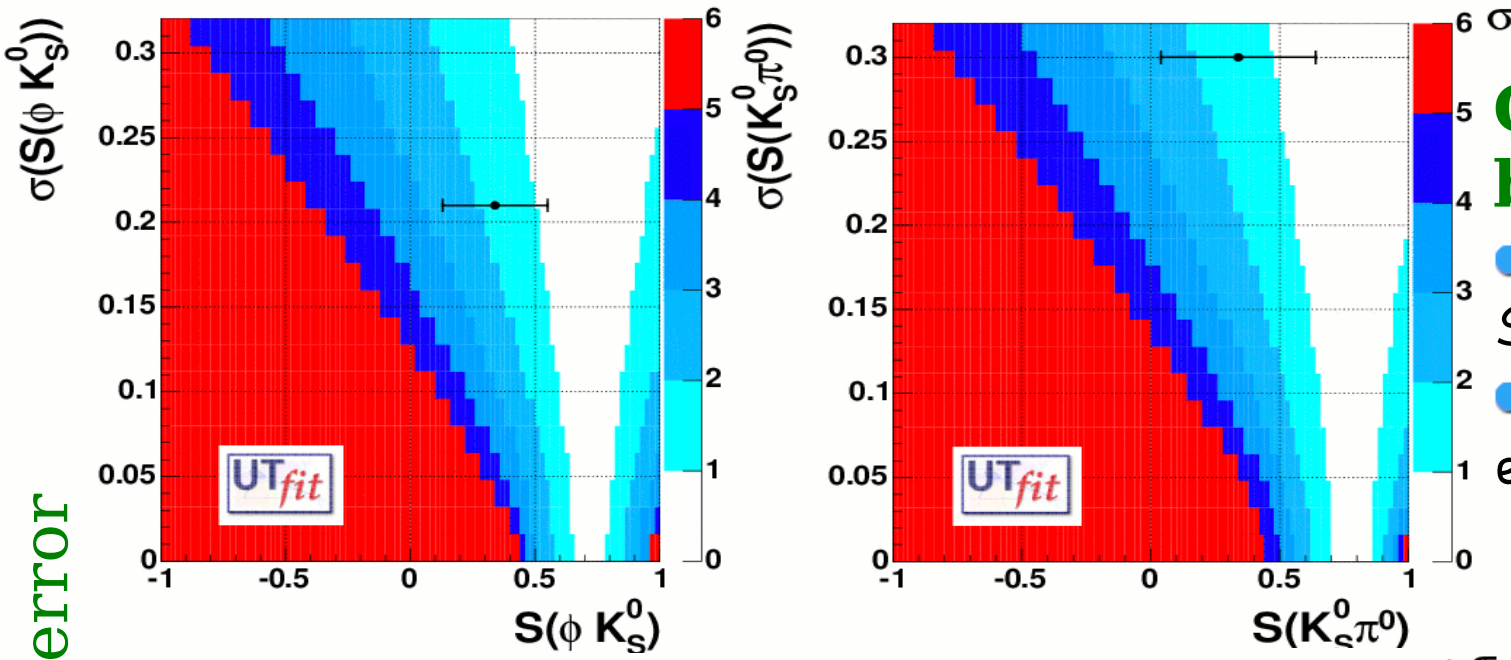


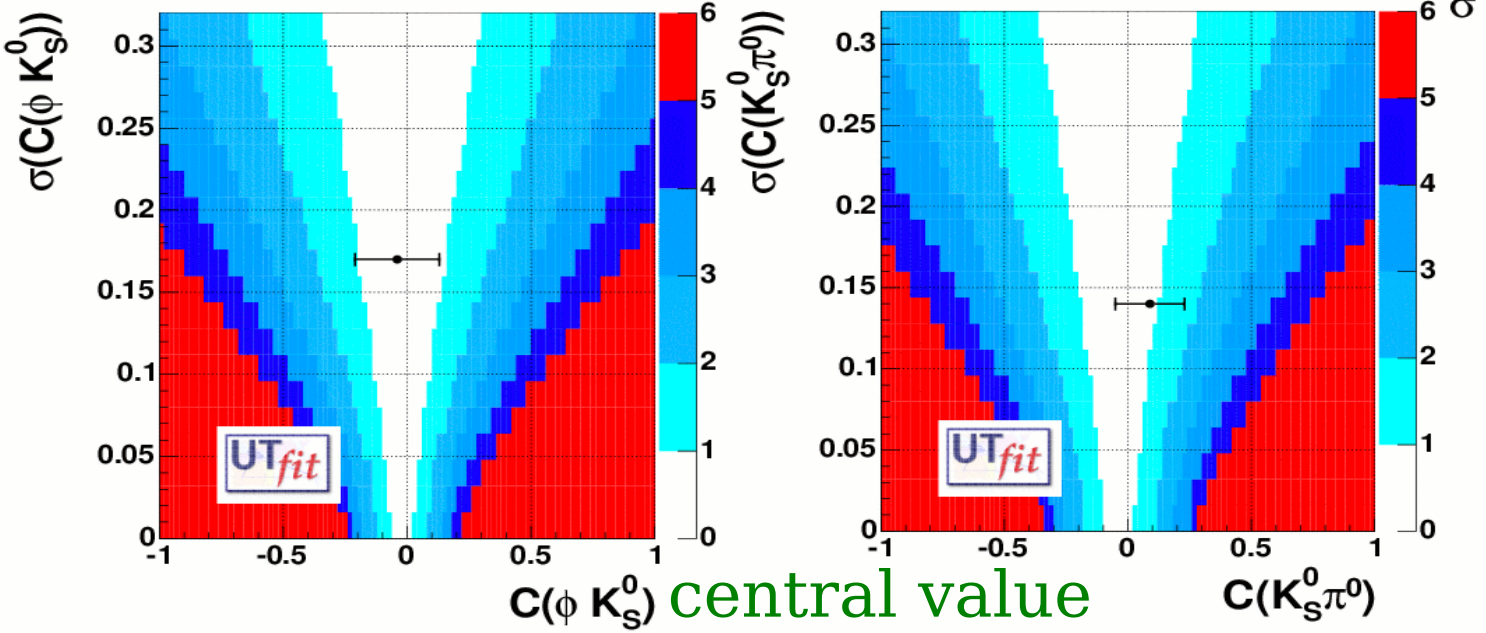


- consistent $S_{\phi K}$
- inconsistent S_{f^0K} , S_{KsKsKs}
- $\sigma(K_S\pi^0)_{BaBar} \ll \sigma(K_S\pi^0)_{Belle}$

$$S_{charmonium} = 0.726 \pm 0.037$$

Compatibility with SM





error

central value

Comparison between:

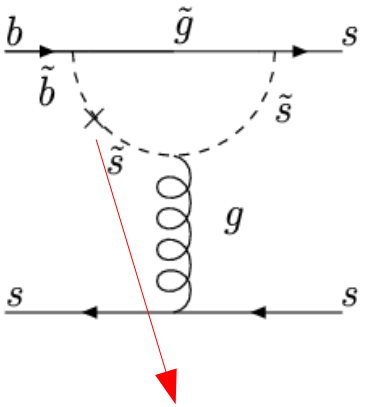
- SM prediction of S and C
- Direct experimental measure

http://www.utfit.org

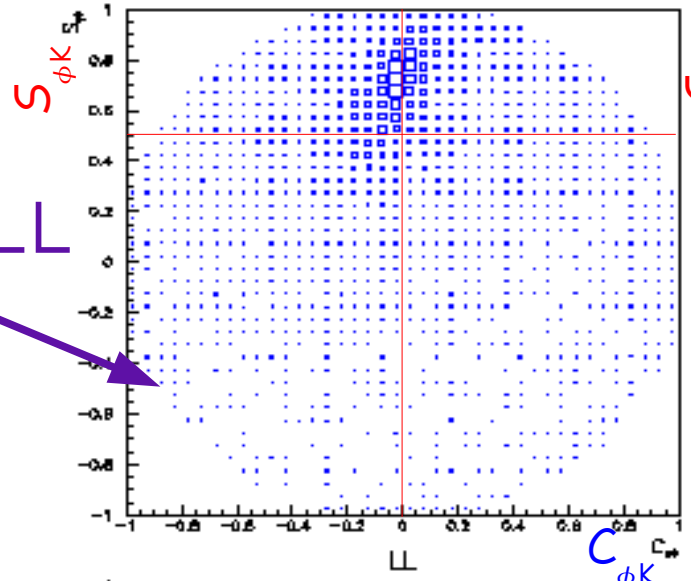
- **Results:**
  - ϕK_S and $K_S\pi^0$ @1σ from charmonium
  - Statistical uncertainty still high

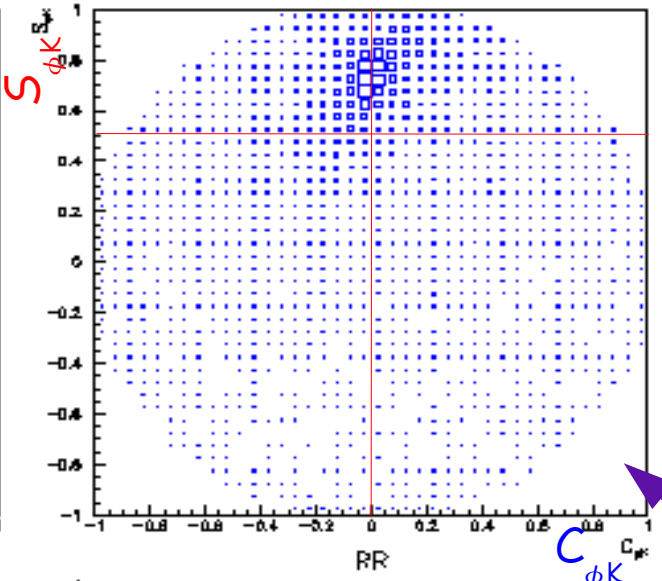
B→φK: constraints on SUSY

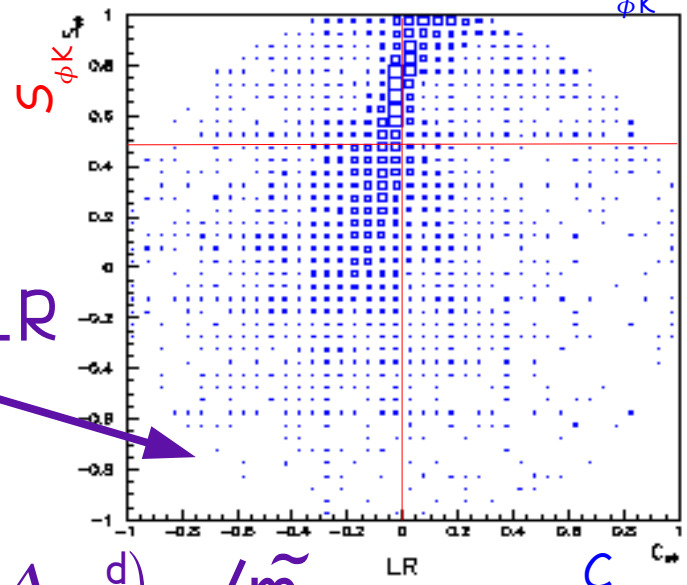
Ciuchini et al., hep-ph/0212397

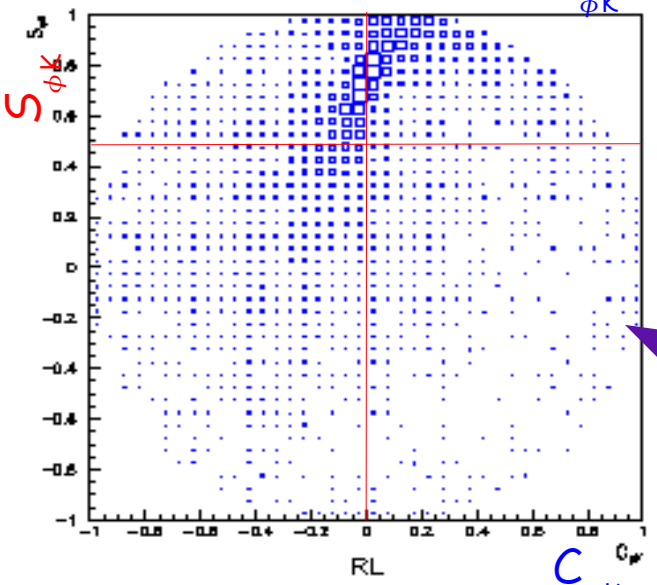


Mass insertion $(\delta_{23}^{d})_{AB}$









$(\delta_{23}^{d})_{LL}$

$(\delta_{23}^{d})_{RR}$

$(\delta_{23}^{d})_{LR}$

$(\delta_{23}^{d})_{RL}$

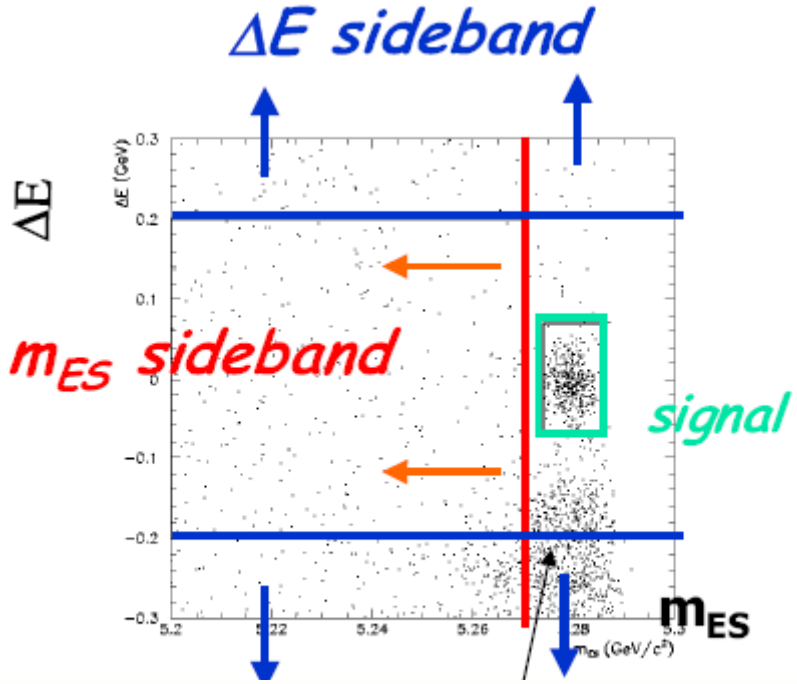
$(\delta_{23}^{d})_{LR} = (\Delta_{23}^{d})_{LR} / \tilde{m}$

B characterization

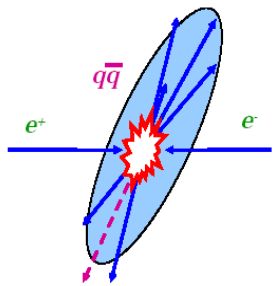
- Kinematic variables:

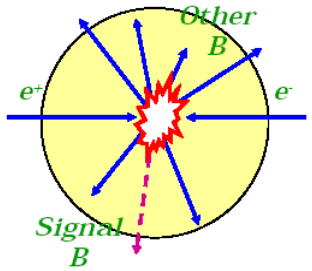
$$m_{ES} = \sqrt{(s/2 + \vec{p}_B \vec{p}_Y)^2 / E_Y^2 - \vec{p}_B^{\,2}}$$
$$\Delta E = E_B^* - \sqrt{s}/2$$

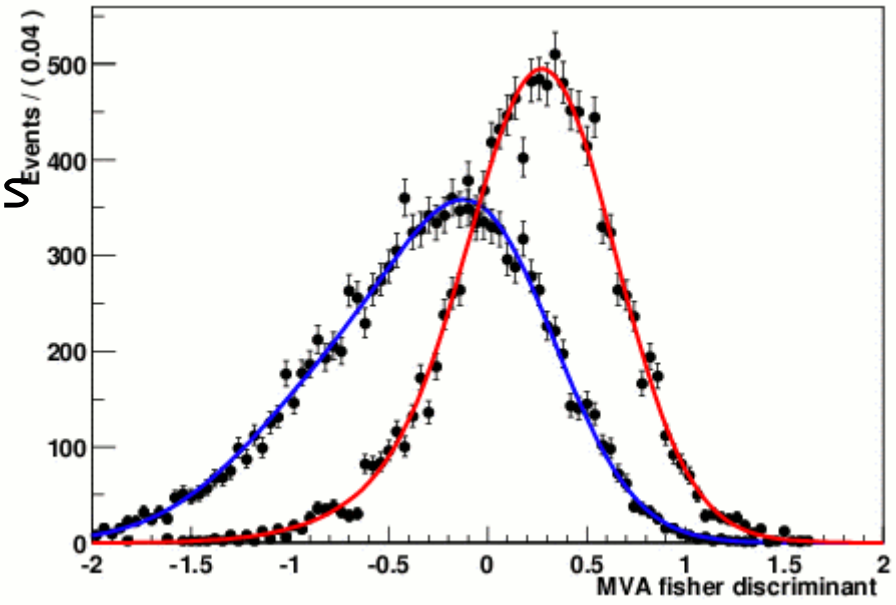
$(E_{B(Y)}, \mathbf{p}_{B(Y)})$=4 momenta of B ($\Upsilon(4S)$) in laboratory frame



- Most of background from $e^+e^- \to \bar{q}q$ (q=u,d,s,c)
  - $|\cos\theta_{SPH}|$ peak to 1 for $\bar{q}q$
  - Combination of Legendre polynomials L_2, L_0 (Fisher, Neural Net, L_2/L_0)



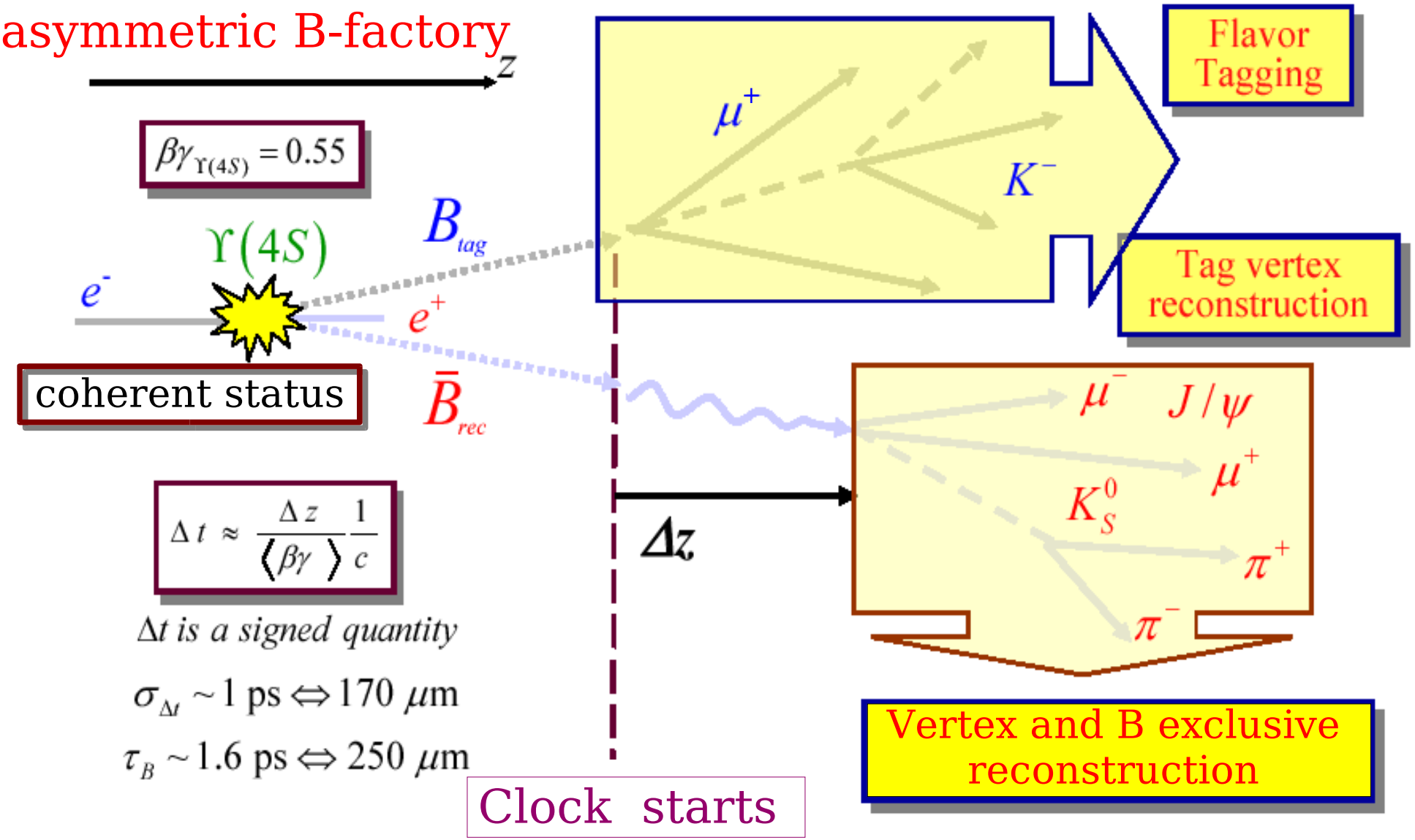




Measurement of $A_{CP}(t)$

Tagging performance: $\mathbf{Q=\epsilon(1-2w^2)=30.5\%}$

BaBar – Belle:
asymmetric B-factory



Rare processes measurement

Integrated Luminosity @ B-factories:

244 fb^{-1} + 446 fb^{-1} = 0.690 ab^{-1} !

BaBar Run5 started one month ago!