a and b at the *B* factories

XX Rencontres de physique de la
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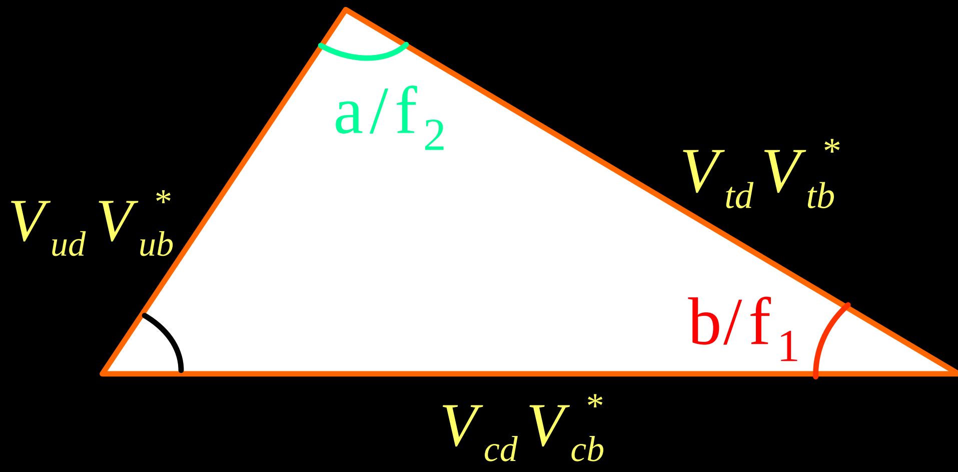
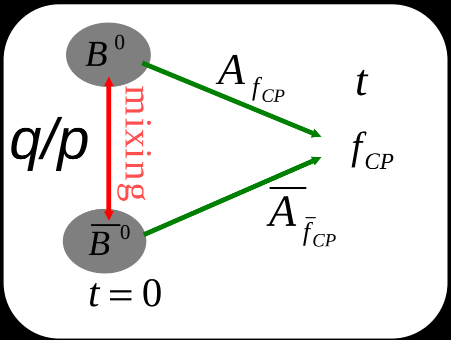


Preamble: time dependent measurements at the *B* factories



CPV can arise from interference between two paths, e.g. decay with and without mixing

Independent of phase convention ← $l_{f_{CP}} = \frac{q}{p} \cdot \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$ ← amplitude ratio

mixing

Time-dependent *CP* asymmetry:

$$A_{CP}(t) \equiv \frac{N(\overline{B}^0_{phys}(\Delta t) \to f_{CP}) - N(B^0_{phys}(\Delta t) \to f_{CP})}{N(\overline{B}^0_{phys}(\Delta t) \to f_{CP}) + N(B^0_{phys}(\Delta t) \to f_{CP})} = S_{f_{CP}} \sin(\Delta m \Delta t) - C_{f_{CP}} \cos(\Delta m \Delta t)$$

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

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

Main ingredients:

a. reconstruction of final (*CP* eigen)state

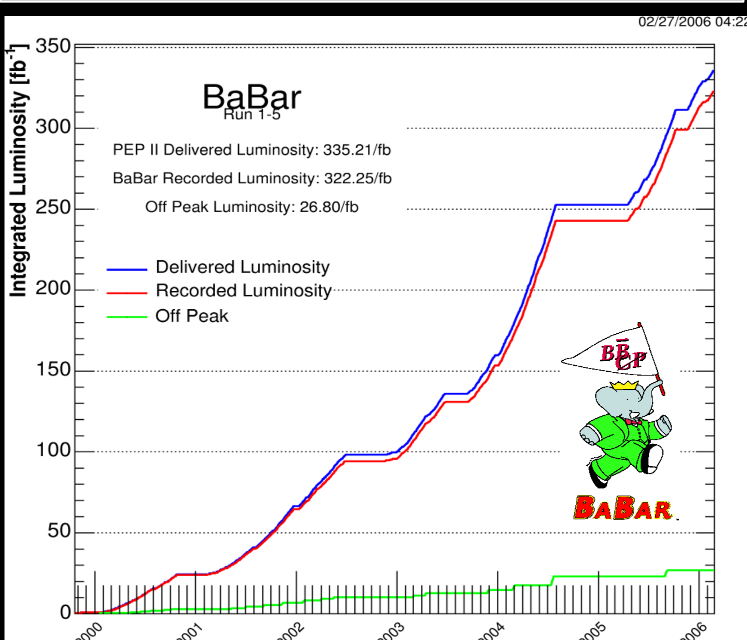
b. determination of B^0 flavour at decay time (‘tagging’)

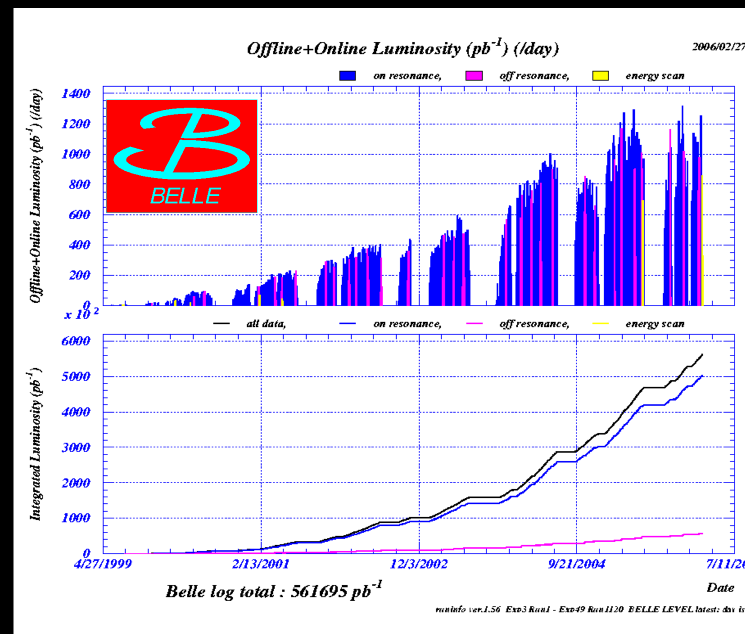
c. measurement of decay vertices ➔ $\Delta t \sim \Delta z/(cbg)$

The asymmetric *B* factories

Peak luminosity $1.00\times10^{34}\ cm^{-2}s^{-1}$
> 3 times higher than design
Integrated luminosity 320 fb^{-1}
Results in this talk based on 232M BB
C.M. boost $\beta\gamma$~0.55

Peak luminosity $1.63\times10^{34}\ cm^{-2}s^{-1}$
~1.5 times higher than design
Integrated luminosity 500 fb^{-1}
Results in this talk based on 386M BB
C.M. boost $\beta\gamma$~0.42





Memento: at the Y(4S), 1fb^{-1}~ 1.1M BB events

Basic (experimental) techniques

- Signal identified through (almost) uncorrelated kinematic variables:

$$m_{ES} \equiv \sqrt{E_{beam}^{*2} - p_B^{*2}} \quad (s_{m_{ES}} \approx s_{beam} \approx 2.7 MeV)$$

$$\Delta E \equiv E_{beam}^{*} - E_B^{*} \quad (s_{\Delta E} \approx s_{E_B^*} \approx 10 \div 50 MeV)$$

- Tagging based on charge correlation of decay products with B^0 flavour ➔ Different algorithms, similar effective efficiency

$Q = \sum e_i (1-2w_i)^2 \sim 30\%$ [$s(\sin 2b) \sim 1/\sqrt{Q}$, cf. w/ $Q \sim 3\%$ at hadron machines]

- *Δz resolution ~ 170μm, dominated by tagging vertex*
- A_{CP} determined on unbinned maximum likelihood fits
  - after cuts on selection variables (Belle)
  - on more inclusive event samples, with multivariate analysis (*BABAR*)

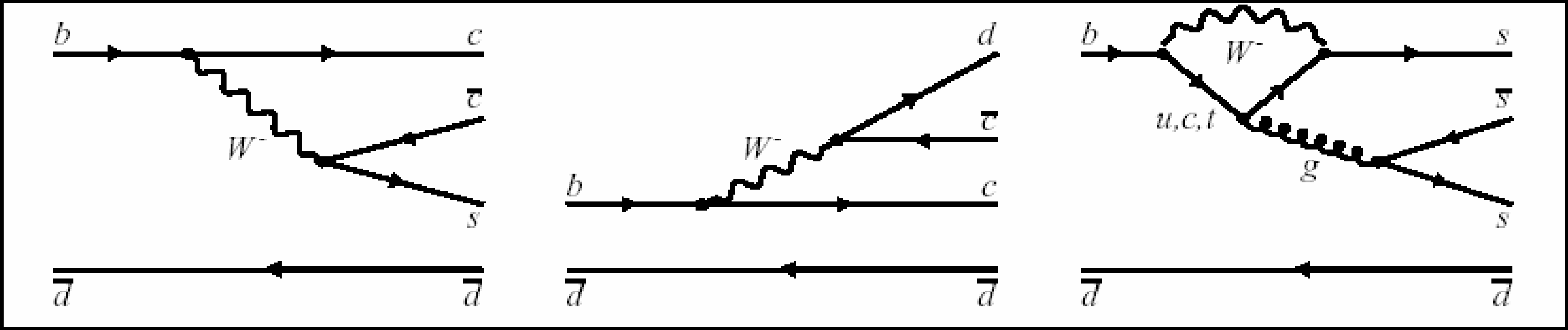
Several independent measurements of β

- Can independently measure β using three different categories of *B⁰* decays

a) $b \to c\bar{c}s$ (charmoniu m)

b) $b \to c\bar{c}d$ charm (and charmonium)

c) Penguin - dominated $b \to d\bar{d}s, b \to s\bar{s}s$

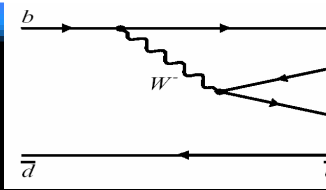


$J/yK_S^0, y(2S)K_S^0, c_{c1}K_S^0,$
$h_c K_S^0, J/yK_L^0,$
$J/yK^{*0}(K^{*0} \to K_S^0 p^0)$

$D^{*+}D^-, D^+D^-$
$J/yp^0, D^{*+}D^{*-}$

$fK^0, K^+K^-K_S^0,$
$K_S^0K_S^0K_S^0, h'K^0, K_S^0 p^0,$
$wK_S^0, f_0(980)K_S^0$

The precision frontier: sin2β from $B^0 \to$ charmonium K^0

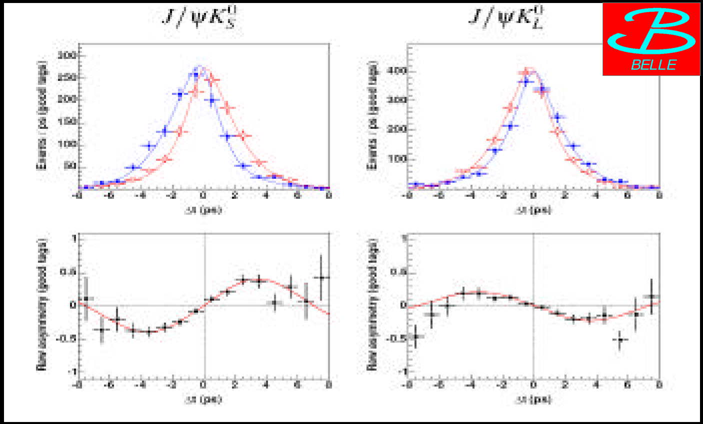


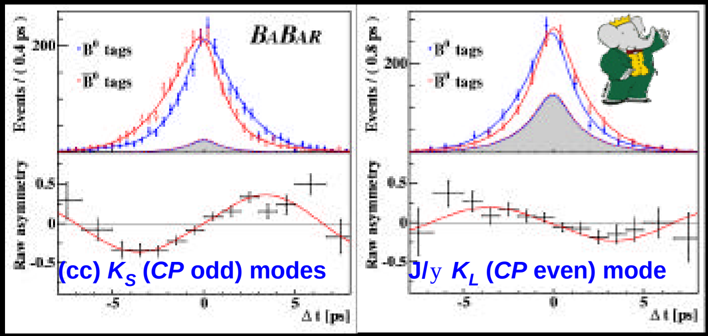
- Very clean theoretically
  - dominant penguin amplitude (suppressed by λ^2_{Cab}) has same phase as tree ➔ $C_f=0$, or $A_{CP}(\Delta t) = -\eta_f \sin 2\beta \sin(\Delta m \Delta t)$ in SM
  - confirmed by recent model-independent analyses [e.g. PRL 95 131802 (2005)] $\Delta S = 0.000 \pm 0.017$
- … and experimentally
  - large BF
  - clean signature
- Stands as a 'platinum mode'
- Latest measurements:
  - Belle [hep-ex/0507037, 386M BB]:

$$\sin 2b = 0.652 \pm 0.039 \pm 0.020$$
$$(was\ 0.728 \pm 0.056 \pm 0.023)$$

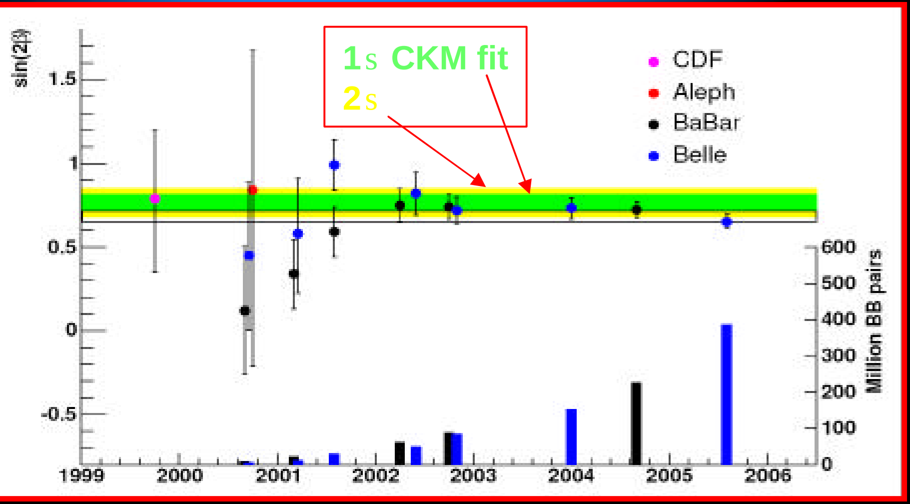
  - *BABAR* [PRL94, 161803 (2005), 227M BB]:

$$\sin 2b = 0.722 \pm 0.040 \pm 0.023$$

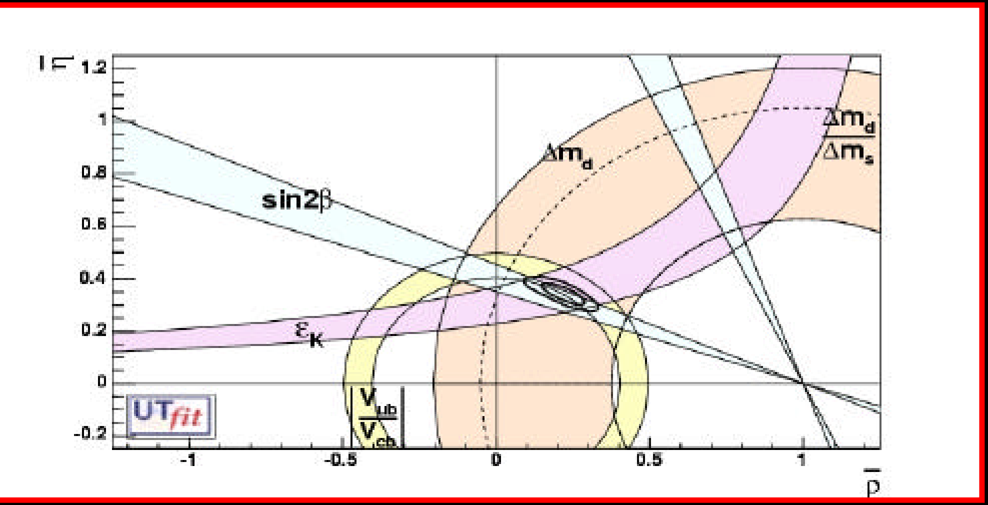




sin2β from charmonium K^0 (II)



- Experimental measurement $\sin 2\beta_{[WA]}=0.687\pm0.032$ now as precise as external constraints $\sin 2\beta_{[UTFit]}=0.793\pm0.033$ (sides) [0.734 ± 0.024 (all)]
- Improved experimental precision will directly impact UT fits



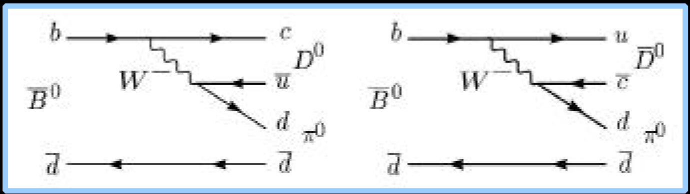
- Important reference point for constraining the UT
  - in fact, a great success of the SM!

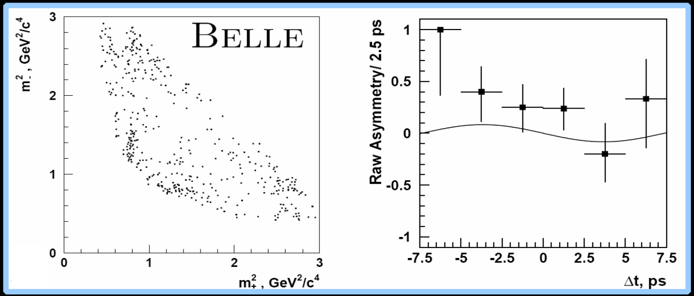
Interlude: breaking the $2\beta/\pi-2\beta$ ambiguity

$h^0=\pi^0,\eta,\omega$

Use $b\to cu\,d$ [$B^0\to D_{CP}(K_s\pi^+\pi^-)\,h^0$] decays

[A.Bondar, T.Gershon, P.Krokovny, PL **B**624 1 (2005)]





- Theoretically clean (no penguins)
- Neglect DCS $B^0\to D_{CP}h^0$ decay
- Interference of Dalitz amplitudes sensitive to $\cos 2\beta$

$$M_{B^0} = f_+\cos(\Delta m\Delta t/2) - ie^{+i2\phi_1}\eta_{h^0}(-1)^l f_-\sin(\Delta m\Delta t/2)$$
$$M_{\overline{B}^0} = f_-\cos(\Delta m\Delta t/2) - ie^{-i2\phi_1}\eta_{h^0}(-1)^l f_+\sin(\Delta m\Delta t/2)$$

$$|f_\pm| \equiv |f(m^2_{K_Sp^\pm}, m^2_{K_Sp^\mp})|^2$$

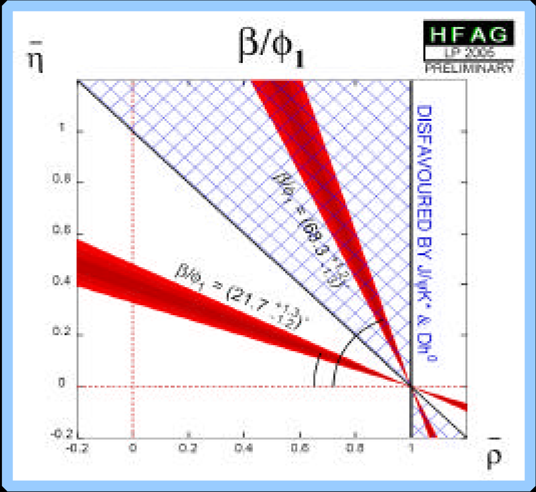
- Dalitz model fitted in D^*-tagged D^0 decays
- $\phi_1=(16\pm21\pm12)^o$
  - rules out $\phi_1=68^o$ @ 97% CL [Belle. hep-ex/0507065]

$B^0\to J/\psi K^{*0}(K^{*0}\to K_s\pi^0)$

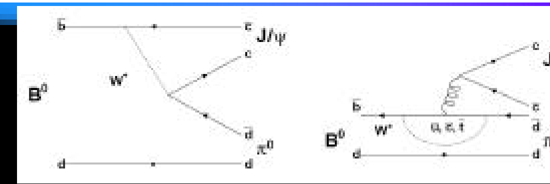
Extract $\cos 2\beta$ from interference of *CP*-even and *CP*-odd states (L=0,1,2) in time-dependent transversity analysis

- $\cos 2\beta<0$ excluded at 86% C.L.

[*BABAR*, PRD **71**, 032005 (2005)]



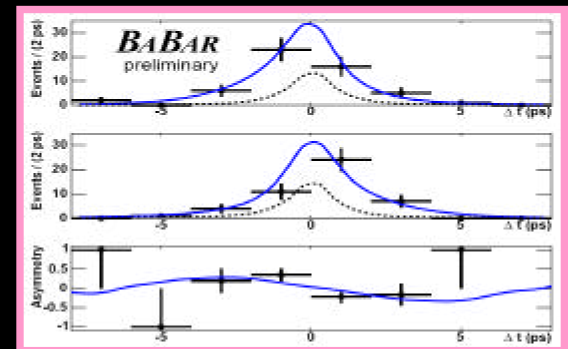
$b \to c\bar{c}d$ decays :
$B^0 \to J/yp^0, D^{(*)+}D^{(*)-}$



- Potentially <u>penguin-polluted trees</u>: $S \neq \sin 2b$, $C \neq 0$
- $J/\psi\pi^0$ [being submitted to PRD] updated meas.:

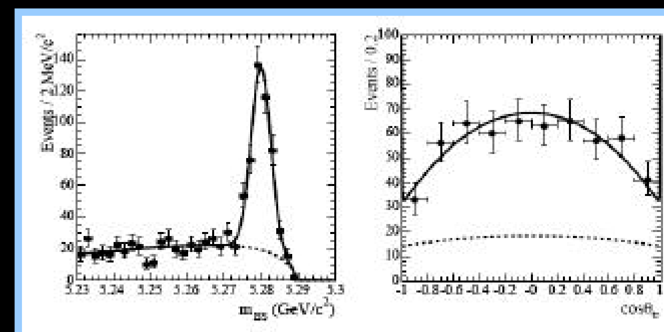
  $S_{J/\psi\pi^0}$=–0.68±0.30±0.04
  $C_{J/\psi\pi^0}$=–0.21±0.26±0.09

  NEW!



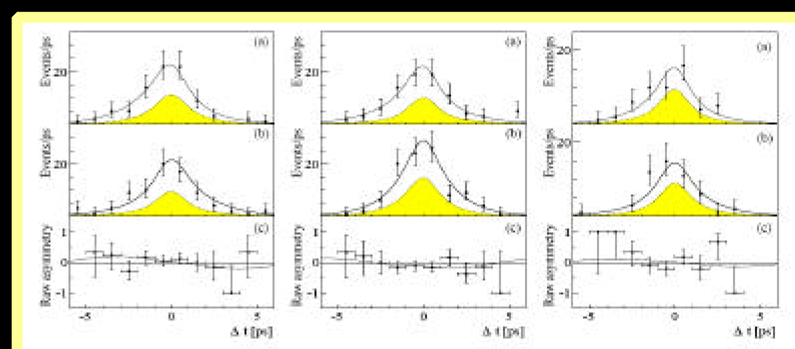
- $D^{*+}D^{*-}$: [PRL **95**, 151804 (2005)] updated meas.:

  f_{odd}=0.125±0.044±0.070
  [VV decay: both *CP*-odd and *CP*-even components.
  CP-odd fraction extracted with transversity analysis]
  S_+=–0.75±0.25±0.03
  C_+=+0.06±0.17±0.03

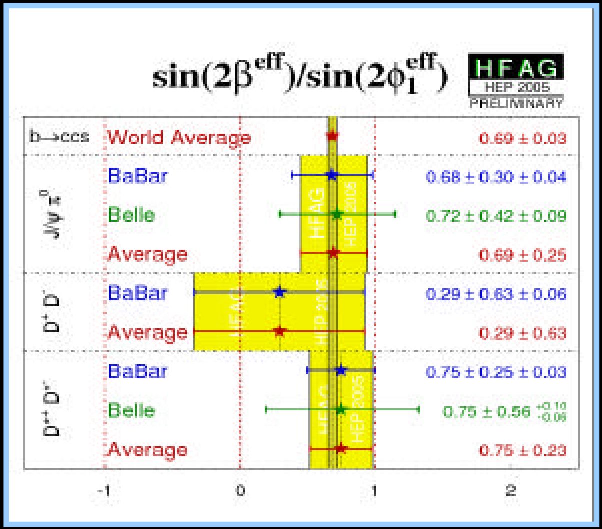


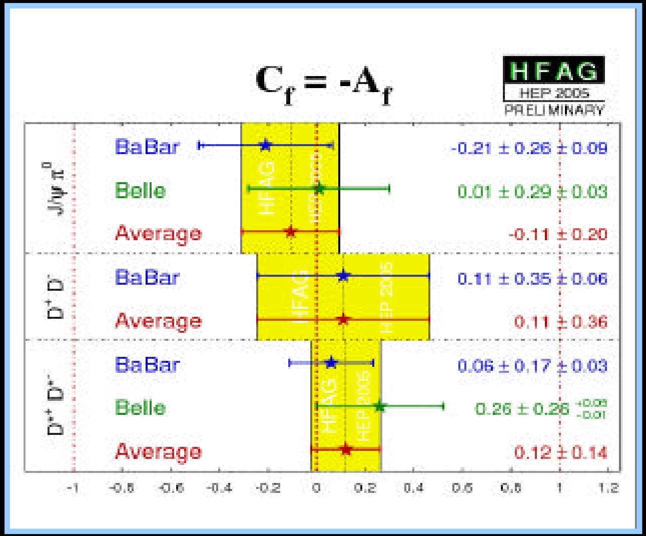
- $D^{(*)+}D^-$ [PRL **95**, 131802 (2005)]:

  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
  $C_{D^{*-}D^+}$=+0.17±0.24±0.04



$b \to c\bar{c}d$ decays : summary

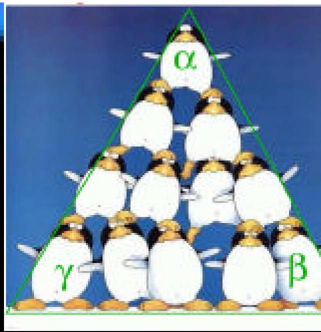




All results consistent with SM expectation of tree dominance

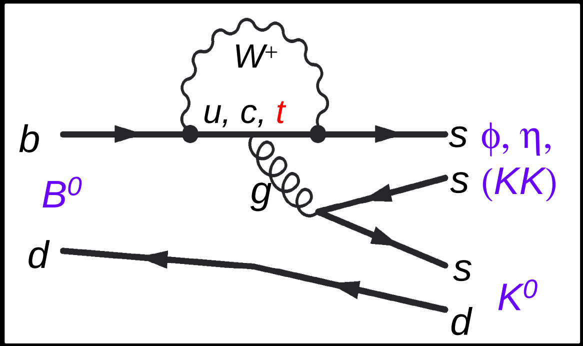
- $\Delta S_{DD}=S_{DD}-\sin 2\beta \sim 0.02-0.05$ [Z-Z. Xing, PR **D**61 014010 (2000)]
- Still below current experimental sensitivity

A path to New Physics: $b \to s$ penguins

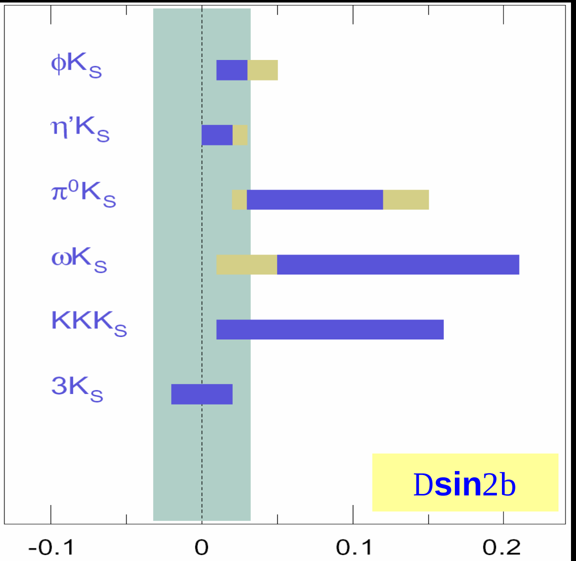


- Small effects (e.g. from propagators of heavy particles circulating in the loop) more easily detectable since Tree is missing
- CKM factors same as $J/\psi K_s$. *If single phase,* SM predicts:

$$S_{peng} = S_{charmonium} = \sin 2\beta$$
$$C_{peng} = C_{charmonium} = 0$$



- Deviations from this pattern could be sign of NP
- Theory issue:
  - more than 1 amplitude/phase are (usually) involved
  - e.g., $b \to u\bar{u}s$ CS tree (g) in channels involving non-strange neutral mesons
  - Intense theoretical work lately to calculate SM corrections to the naïve picture
    - ✓ SU(3)-based model-independent bounds
    - ✓ QCD Factorization
    - ✓ theory parameters constrained to measured BFs (expected to improve in the future)



Example from recent calculations (QCD factorization)
2-body: [Beneke; PL B620, 143 (2005)]
3-body: [Cheng,Chua,Soni; PRD72, 094003 (2005)]

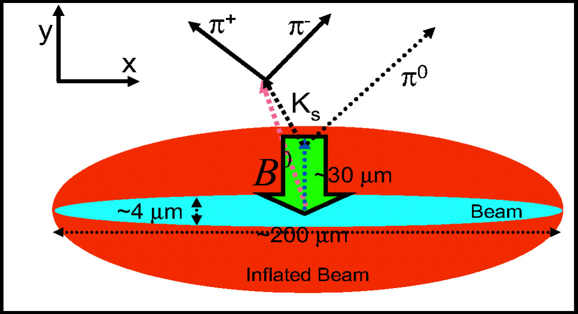
$b \to s$ penguin: experimental issues

- Small branching fractions
- Large background from $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$
  - In addition to standard ΔE and m_{ES}, use event-shape discriminating variables in M.L. fit

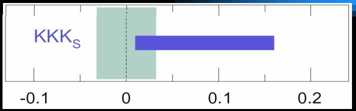
B produced (almost) at rest in ϒ(4S) frame

Decay mode	BF(*B*? f) x10[6]	Π_iBF$_i$ x10[6]
B ® $J/\psi K^0$	850.0	100.3
B ® $\eta' K^0$	63.2	16.6
B ® $K^+K^-K^0$	20.6	17.4
B ® ϕK^0	8.3	3.4
B ® ωK_S	2.4	2.1
B ® $f_0 K_S$	2.7	1.8
B ® $K_S K_S K_S$	3.1	1.4
B ® $\pi^0 K_S$	5.8	3.9
B ® $\pi^0\pi^0 K_S$	11	7.5

- No charged tracks from decay vertex for some channels
  - extrapolate back the K_s
    - ✓ require K_s to decay in the inner part of vtx detector
    - ✓ use constraint of the beam spot in the transverse plane
    - ✓ cross-check using $J/\psi K_s$



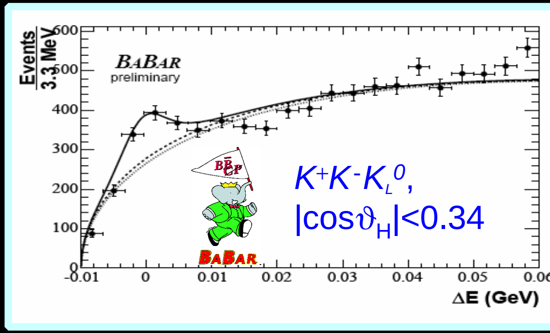
Exploring new submodes



$B^0 \to K^+K^-K_L^0$ (ϕK^0 excluded)

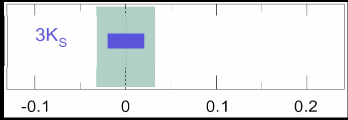
K_L^0 direction measured in EMC or IFR, energy from *B*-mass constraint

- 777±80 events in sample (452±28 in $K^+K^-K_S^0$)
- $S_{K^+K^-K^0_L}$=0.07±0.28±0.12, $C_{K^+K^-K^0_L}$=0.54±0.22±0.09
- *CP content* in $K^+K^-K^0$ sample
  - from angular momentum analysis of $K^+K^-K_S$: $f_{CP\text{-}even}$=0.89±0.08±0.06
  - consistent w/ Belle's isospin analysis [PRD69 012001 (2004)]
- $\sin 2\beta_{K^+K^-K^0}$ =0.41±0.18±0.07±0.11$_{CP}$



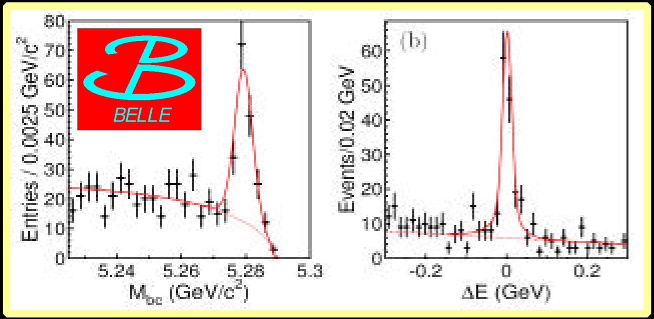
hep-ex/0507016

$B^0 \to K_sK_sK_s$



- *CP* eigenstate (η_{3K_S}=+1), |Δsin2β|<0.05
- small BF
  - add more data (Belle)
  - add $K_SK_SK_S(\pi^0\pi^0)$ (*BABAR*)

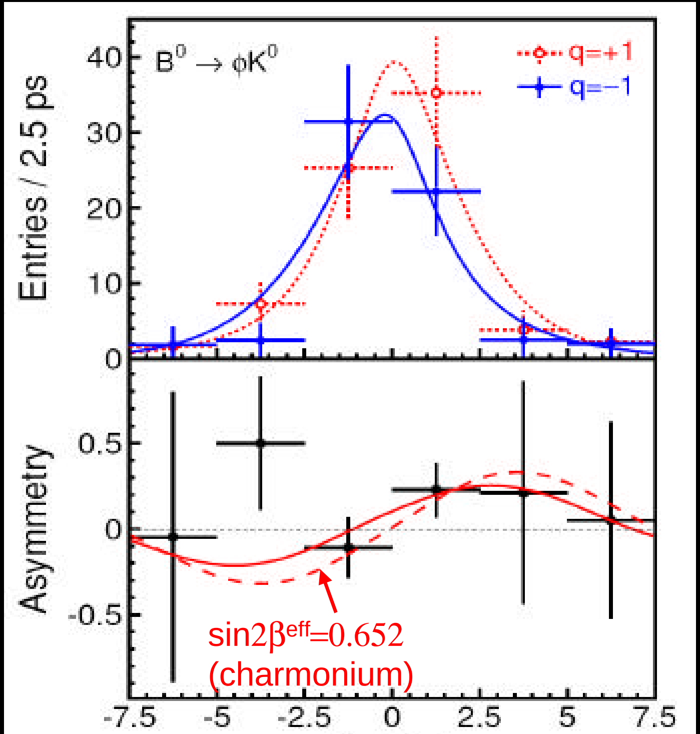
$S_{3K_S^0} = +0.63^{+0.28}_{-0.32} \pm 0.04$	*BABAR*
$S_{3K_S^0} = +0.58 \pm 0.36 \pm 0.08$	Belle



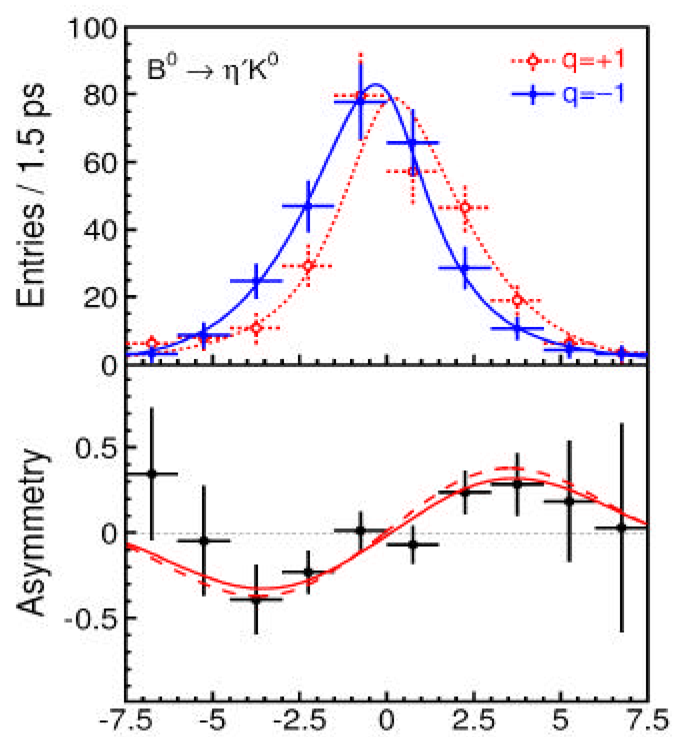
Belle results on $b \to s\bar{s}s, b \to q\bar{q}s$

BELLE

Updated results on $B^0 \to \phi K^0$, $\eta' K^0$, $f_0 K_S$, $\pi^0 K_S$, ωK_S, $K^+K^- K_S$, $K_S K_S K_S$ [hep-ex/0507037] "K^0" includes both K_S and K_L



$\sin 2\phi_1 = 0.44 \pm 0.27 \pm 0.05$

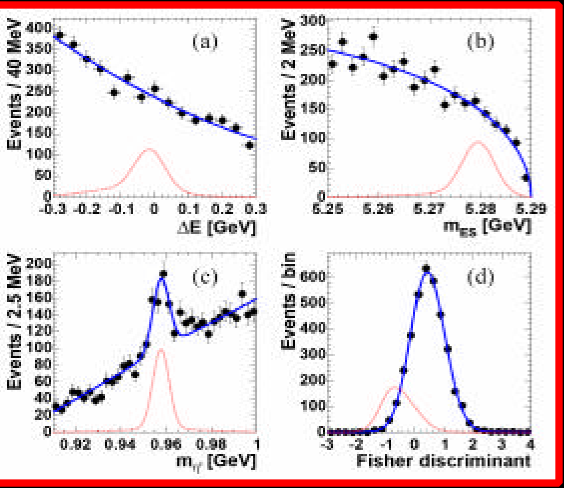


$\sin 2\phi_1 = 0.62 \pm 0.12 \pm 0.04$

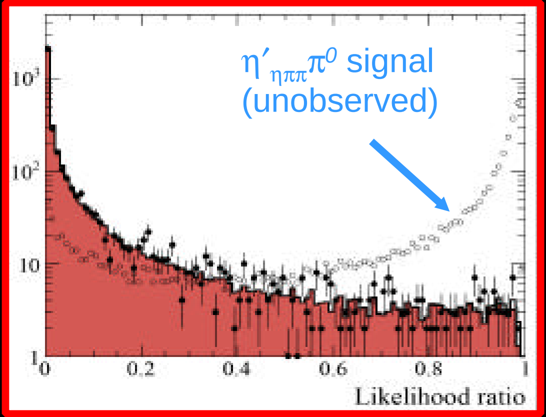
Searches for $\eta'\pi^0$, $\eta\pi^0$, $\eta'\eta$

NEW!

- Expected BF ~ $0.2 \div 2.0 \times 10^{-6}$
- Use $\eta_{\gamma\gamma}$, $\eta_{3\pi}$, $\eta'_{\eta\pi\pi}$, $\eta'_{\rho\gamma}$ modes



- Decays dominated by 'flavor-singlet' penguin and ($\eta\eta'$) color-suppressed tree.
- More precise measurements can reduce (by ~ 20%) the theoretical uncertainty of CS tree amplitude for $\eta' K^0$ decays in SU(3)-based analysis [Gronau, Rosner, Zupan PL **B596**, 107 (2004)]



Likelihood ratio
$\mathcal{L}_{sig}/[\mathcal{L}_{sig} + \sum \mathcal{L}_{bkg}]$
from m_{ES}, ΔE, $m_{\eta'}$, Fisher

$$\mathcal{B}(B^0 \to \eta'\eta) = (0.2^{+0.7}_{-0.5} \pm 0.4) \times 10^{-6} \;(< 1.7 \times 10^{-6})$$
$$\mathcal{B}(B^0 \to \eta\pi^0) = (0.6^{+0.5}_{-0.4} \pm 0.1) \times 10^{-6} \;(< 1.3 \times 10^{-6})$$
$$\mathcal{B}(B^0 \to \eta'\pi^0) = (0.8^{+0.8}_{-0.6} \pm 0.1) \times 10^{-6} \;(< 2.1 \times 10^{-6})$$

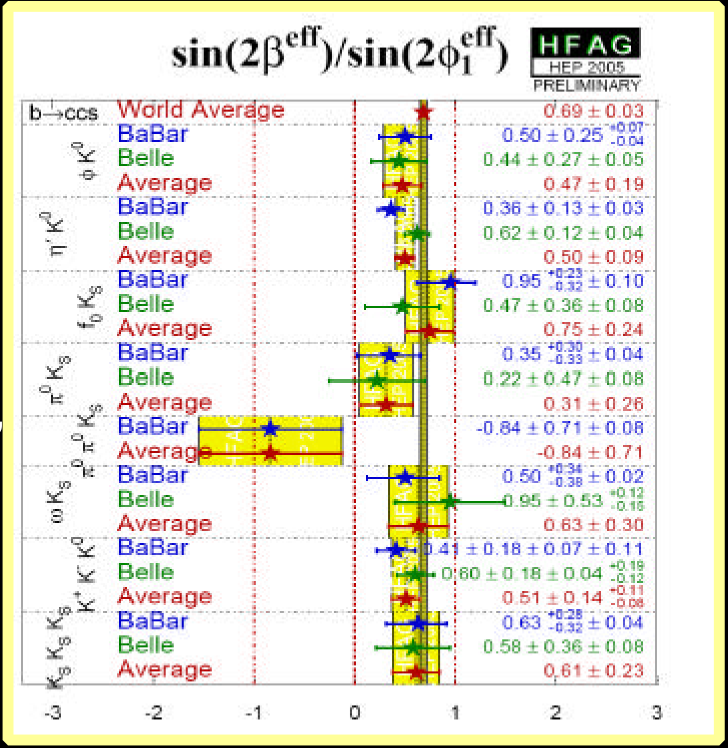
[*BABAR*, hep-ex/0603013, submitted to PRL]

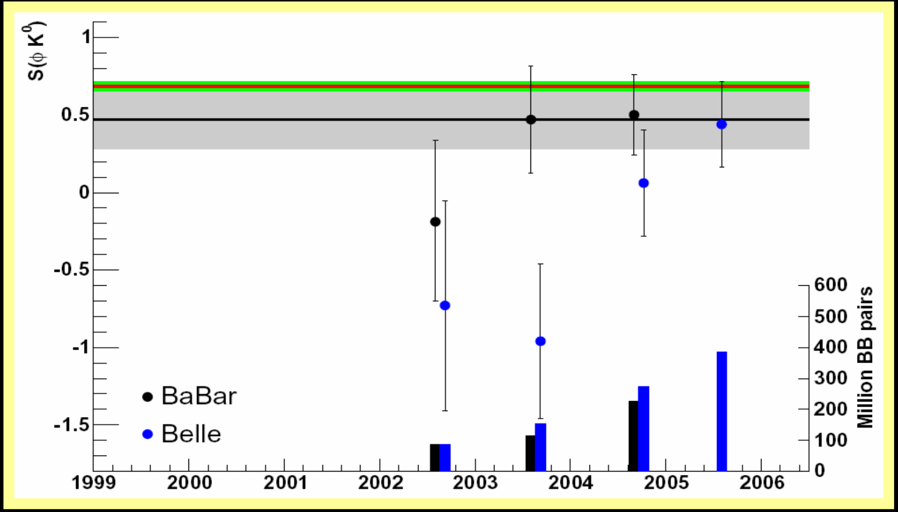
Belle [hep-ex/0603001, subm. to PRL] finds

$$BF(B^0 \rightarrow h'p^0) = [2.79^{+1.02}_{-0.96}(stat)^{+0.35}_{-0.34}(syst)] \times 10^{-6}$$

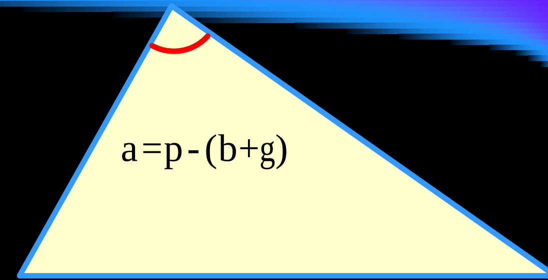
$b \rightarrow s$ penguins: current experimental status

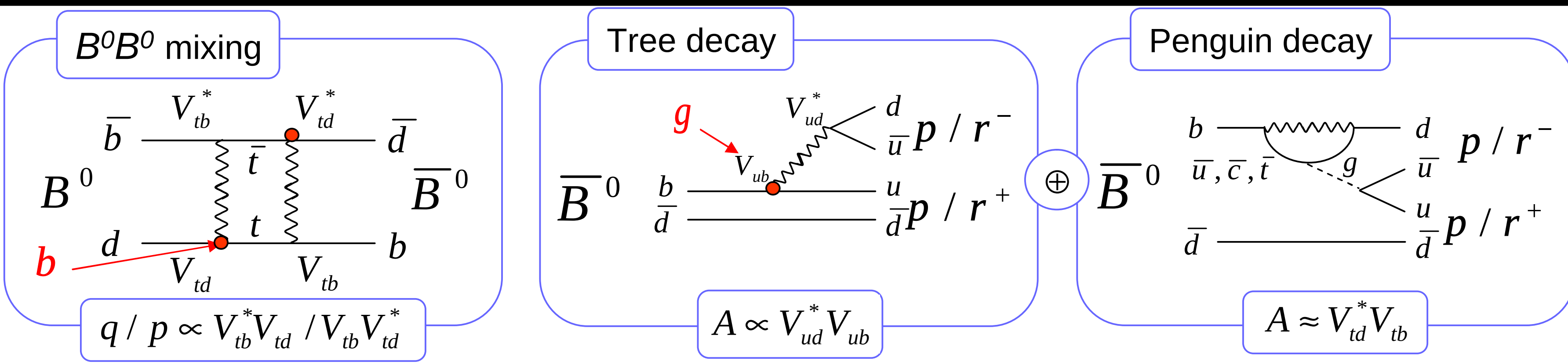
- Good agreement between *BABAR* and Belle
  - similar errors!
- Consistency among different channels
- Almost all modes within ~ 1 sigma from charmonium (but sign opposite to prediction)
  - deviations further reduced by shift of charmonium average
- Remember: due to different SM and NP corrections, AVERAGING NOT ALLOWED
- Need more statistics





Measuring α at the *B* factories





- Difficult to reliably estimate how much penguins contribute
  - BF($B^0 \to K^+\pi^-$) (~ pure penguin) indicates they cannot be neglected
  - In general $C_{hh} \neq 0$, and we measure $S_{hh} = \sqrt{1-C_{hh}}\sin(2\alpha_{eff})$

$$\lambda_{hh} \equiv \frac{q}{p}\frac{\bar{A}}{A} = -e^{2i\alpha}\frac{1-{}^{P}\!/_{T}\,e^{-i\alpha}}{1-{}^{P}\!/_{T}\,e^{i\alpha}} \equiv |\lambda|e^{-2i\alpha_{eff}}$$

a: coping with penguins

Gronau/London analysis

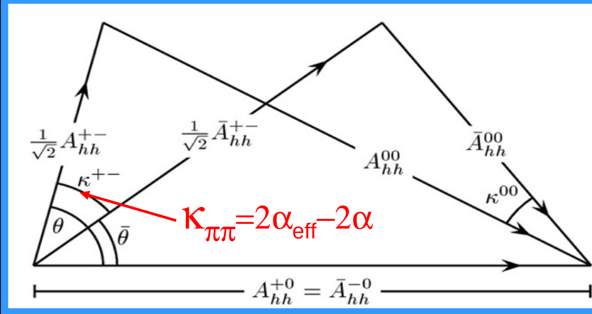
- Using isospin symmetry, $B \to hh$ amplitudes related by:

$$A(B^+ \to h^+ h^0) = 1/\sqrt{2} \cdot A(B^0 \to h^- h^+) + A(B^0 \to h^0 h^0)$$

- Neglecting EW penguins, $B^+ \to h^+ h^0$ $(\Delta I = 2)$ pure tree

➔ $A(B^+ \to h^+ h^0) = \bar{A}(B^- \to h^- h^0)$

- *B* and *B* triangles do not match, and $\alpha = \alpha_{eff} - \kappa/2$
- Need to measure 6 BFs, including $A(B^0 \to h^0 h^0)$ from *tagged* samples
- still a 8-fold ambiguity



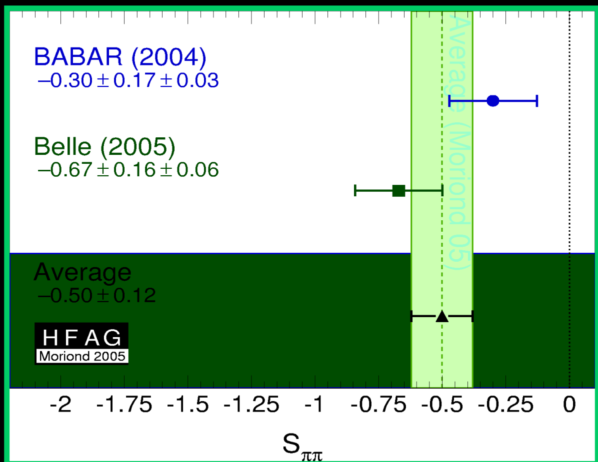
Grossman/Quinn bound:

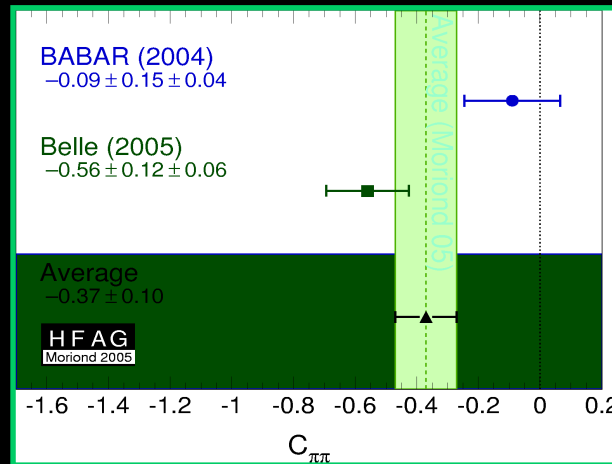
$$\sin^2(\alpha_{eff} - \alpha) \le \frac{BF(B \to h^0 h^0)}{BF(B^\pm \to h^\pm h^0)}$$

Don't need to tag B flavour

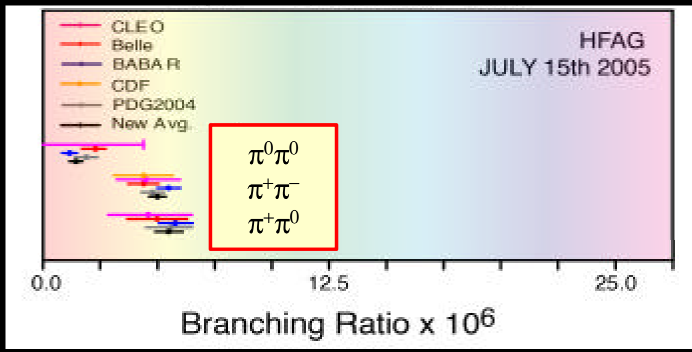
Useful if BF($B \to h^0 h^0$) is small

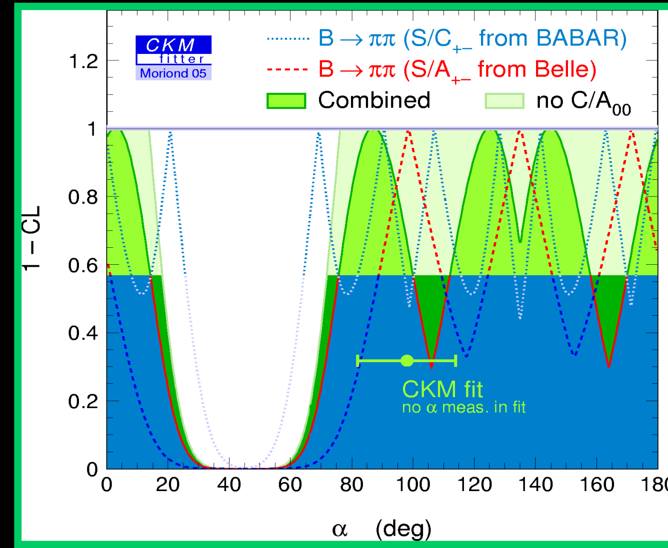
The classic mode: $\pi\pi$





Fat $\pi\pi$ triangles ➔ weak SU(2) bound





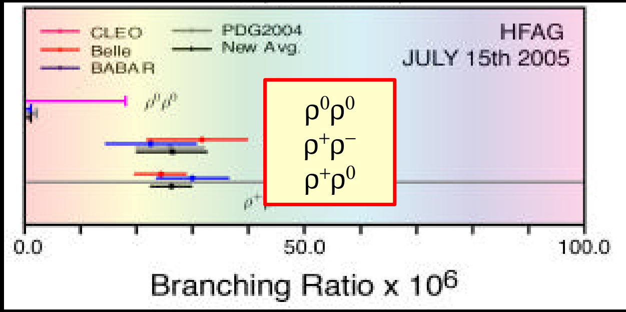
$$\sin^2(\alpha_{eff} - \alpha) \le \frac{BF(B \to \pi^0\pi^0)}{BF(B^\pm \to \pi^\pm\pi^0)}$$

$|\alpha - \alpha_{eff}| < 35^o$

SU(2) bound works for ρρ!

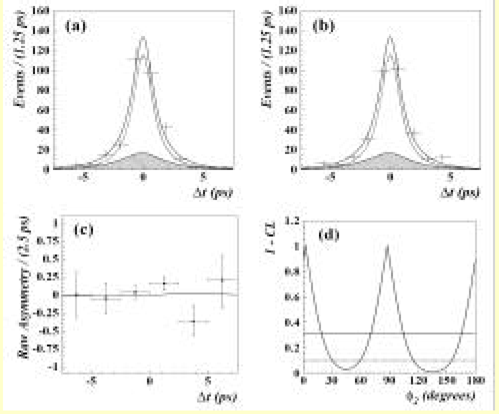
- Experimentally challenging (2 π^0s, wide ρs, VV final state)
- However:
  - ✓ BF($\rho^+\rho^-$) ~ 6 times larger than $\pi^+\pi^-$
  - ✓ almost purely *CP*-even:

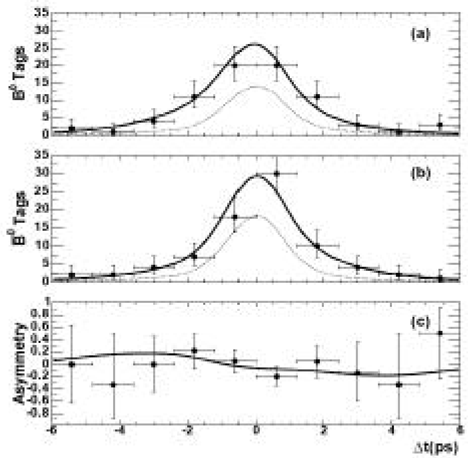
$$f_L = 0.978 \pm 0.014^{+0.021}_{-0.029} \quad (BABAR)$$
$$f_L = 0.941^{+0.034}_{-0.040} \pm 0.030 \quad (Belle)$$



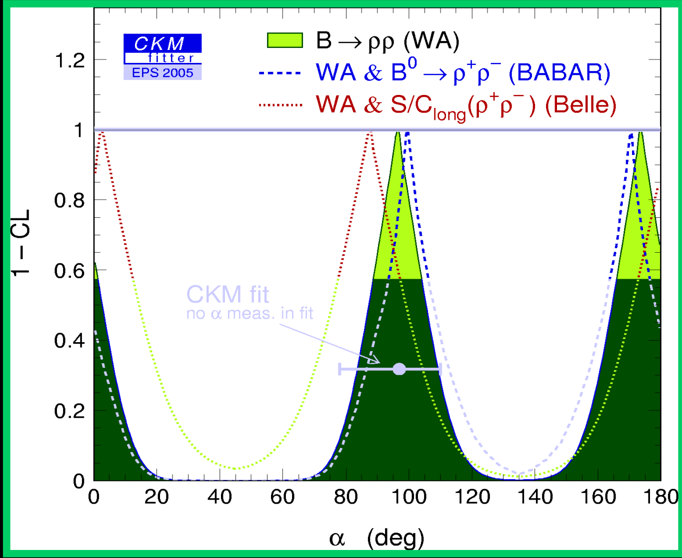
$|\alpha - \alpha_{eff}| < 11^o$ @ 68% C.L.

hep-ex/0601024 275 M BB
subm. to PRL NEW!





PRL 95 041805 (2005)

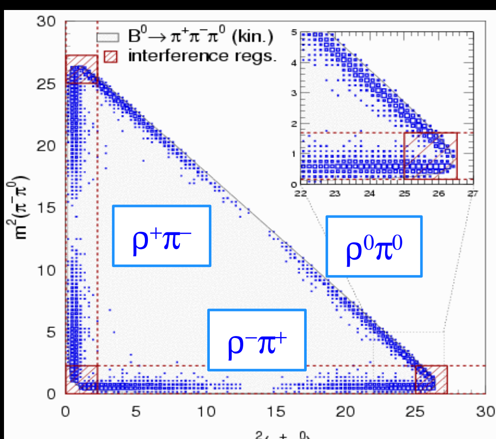


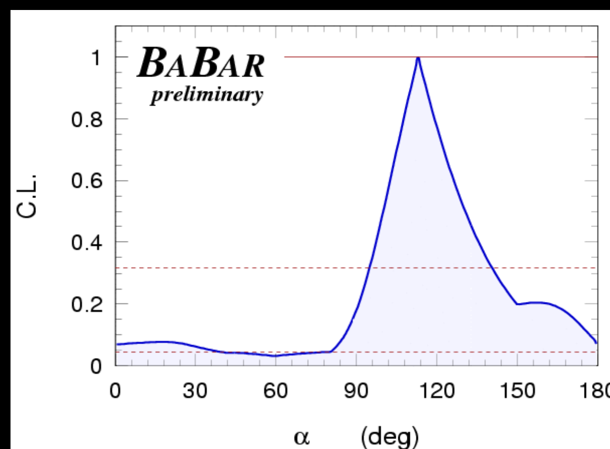
The 3rd way to α: TD Dalitz analysis of $B^0 \to \pi^+\pi^-\pi^0$

- Assume ρ dominance and use phase information across Dalitz plane to extract α

A. Snyder and H. Quinn, Phys. Rev. D, 48, 2139 (1993)

$$A(B^0 \to p^+p^-p^0) = f_+ A(r^+p^-) + f_- A(r^-p^+) + f_0 A(r^0p^0)$$
$$\overline{A}(\overline{B}^0 \to p^+p^-p^0) = f_+ \overline{A}(r^+p^-) + f_- \overline{A}(r^-p^+) + f_0 \overline{A}(r^0p^0)$$



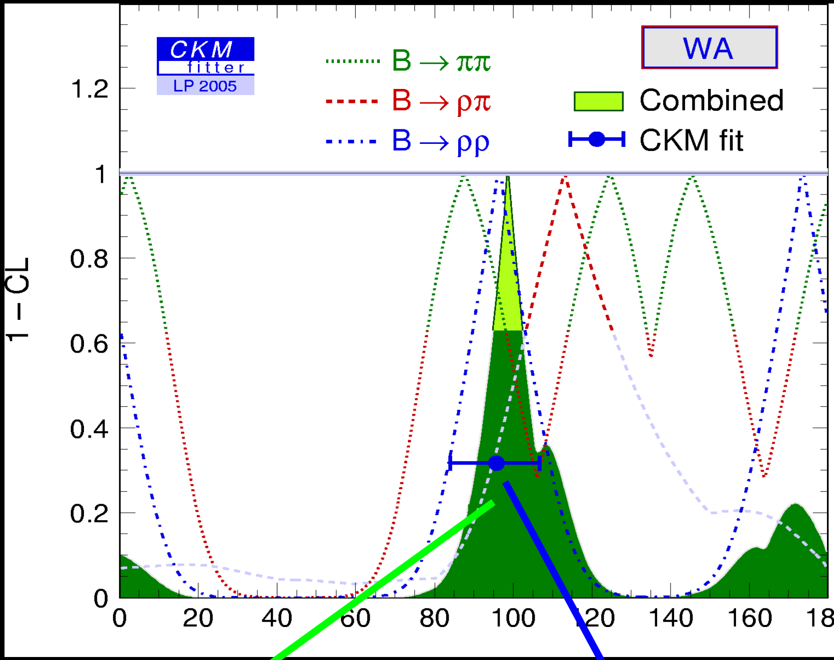


No ambiguity: only one solution:

$$a = (113^{+27}_{-17} \pm 6)^\circ$$

Putting all together:

- All three modes give consistent and complementary measurements of α
- ππ constraint weak
- ρρ most precise
- TD analysis of 3π Dalitz plot in ρπ. Weak constraint at 90% CL, but disfavors ρρ mirror solution near 170º



$$a[hh] = (99^{+12}_{-9})^{\circ}$$

$$a_{CKM} = (95^{+10}_{-13})^{\circ}$$

Summary and outlook

- *BABAR* and Belle measure sin2β in $(c\bar{c})K^0$ modes to 5% precision

$$\sin 2\beta_{\mathrm{charmonium}} = 0.687 \pm 0.032$$

- Comparison with $\sin 2\beta^{\mathrm{eff}}$ in $b \rightarrow s$ penguin modes could reveal New Physics effects
  - need to carefully evaluate SM contributions
- $\sin 2\beta^{\mathrm{eff}}$ measurements are statistically limited
  - uncertaintites scaled faster than $1/\sqrt{L}$ so far (adding new channels)
- Extraction of α depends crucially on penguin bounds ($\rho^0\rho^0/\rho^+\rho^0$)
- Theory often fed by experimental measurements
  - also improves with more data
- Expected precision vs. time: