Measurement of the CKM angle α (or ϕ_2)

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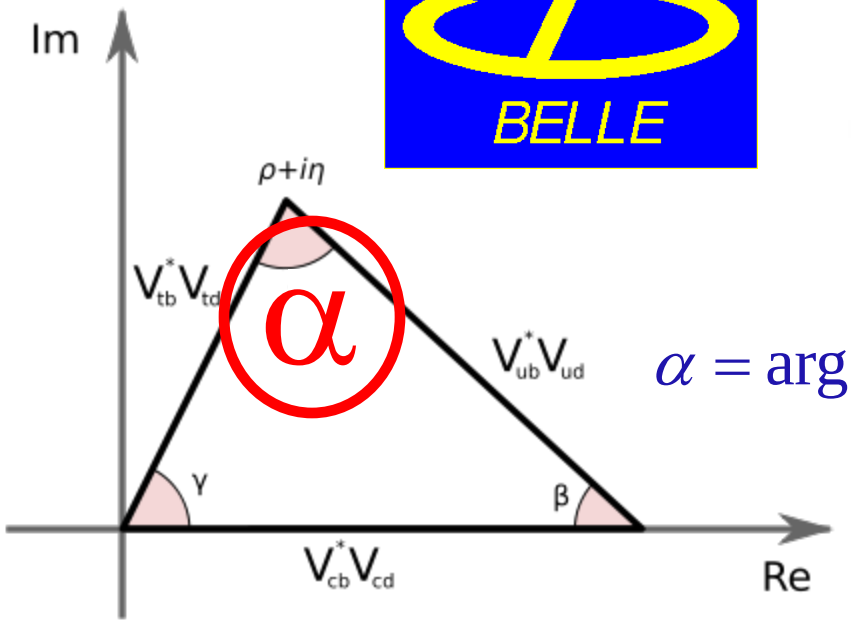


$$\alpha = \arg\left(-\frac{V_{td}(V_{tb})^*}{V_{ud}(V_{ub})^*} \right)$$

Outline

b → uūd processes:

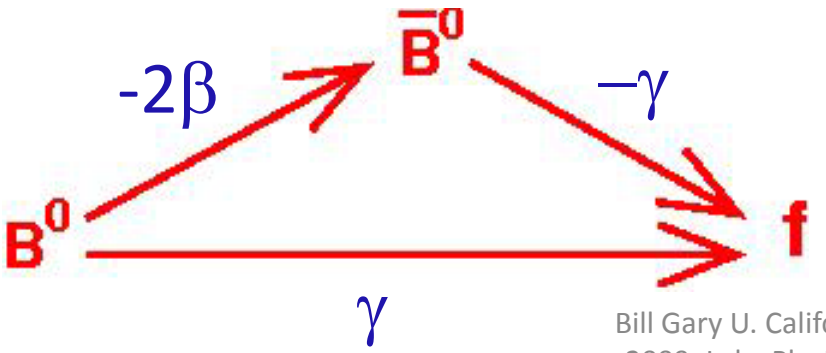
B → ππ [2π]

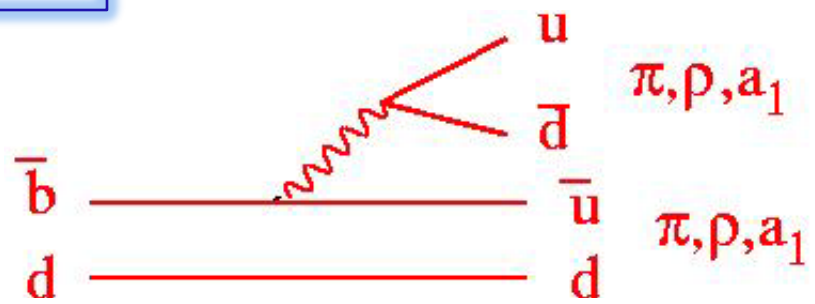
B → ρρ [4π]

B → ρπ [3π]

B → $a_1(1260)\pi$ [4π]

[→ all-π final states]





CKM phase $V_{ub} \sim e^{-i\gamma}$ in tree amplitude

Mixing-induced CP asymmetry:
Interference between direct B^0 decay and decay after B^0-$\bar{B}^0$ mixing ~ -(2β+2γ) ~ 2α
[α+β+γ=π]

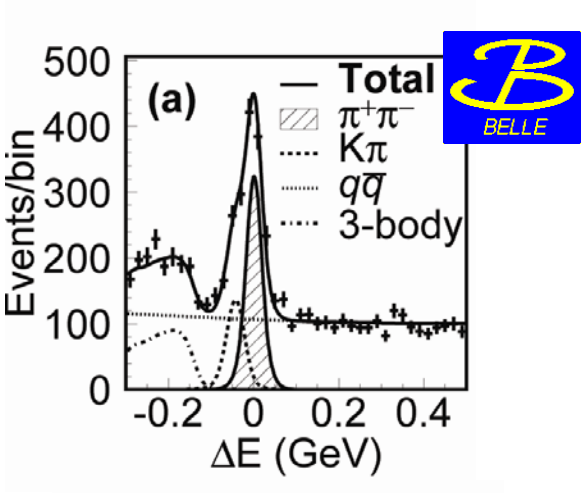
π identification & event selection

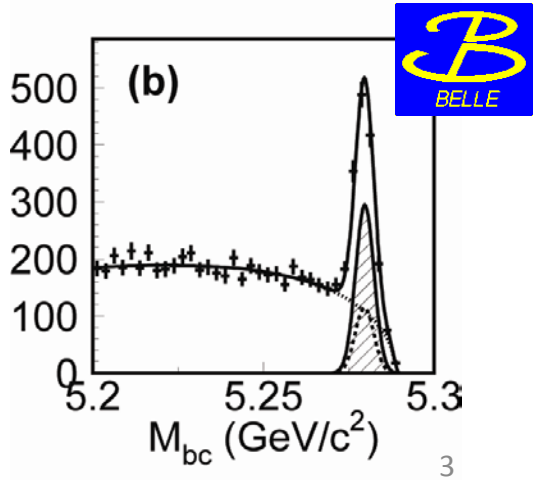
- $\pi^{\pm}$: Cherenkov detectors; dE/dx from tracking chambers

  [detection efficiency ≥ 95%; mis-ID ≈ 10%]

- $\pi^0 \to \gamma\gamma$ [some use of $\gamma \to$ e+e-, merged $\gamma\gamma$]

  [efficiency ≈ 50%, purity ~ 70%]





Key variables for B reconstruction:

- Energy difference $\Delta E = (E_B)^* - (E_{beam})^*$ (peaks at zero)
- Beam energy-constrained (-substituted) mass $m_{bc} = m_{ES} = \sqrt{(E_{beam})^* - (p_B)^*}$ (peaks at m_B)

Time-dependent CP asymmetries in $B^0(\overline{B}^0) \to f_{CP}$ (= $\pi^+\pi^-$, $\rho^+\rho^-$, $\rho^0\rho^0$)

$$a_{CP}(t) = \frac{\Gamma[B^0(t) \to f_{CP}] - \Gamma[\overline{B}^0(t) \to f_{CP}]}{\text{"} \qquad + \qquad \text{"}}$$

$$= S \sin \Delta m t - C \cos \Delta m t$$

$$S = -\frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2} \qquad C = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad \lambda = e^{-2i\beta}\frac{\overline{A}}{A}$$

$$A = \langle f_{CP} | H | B^0 \rangle$$

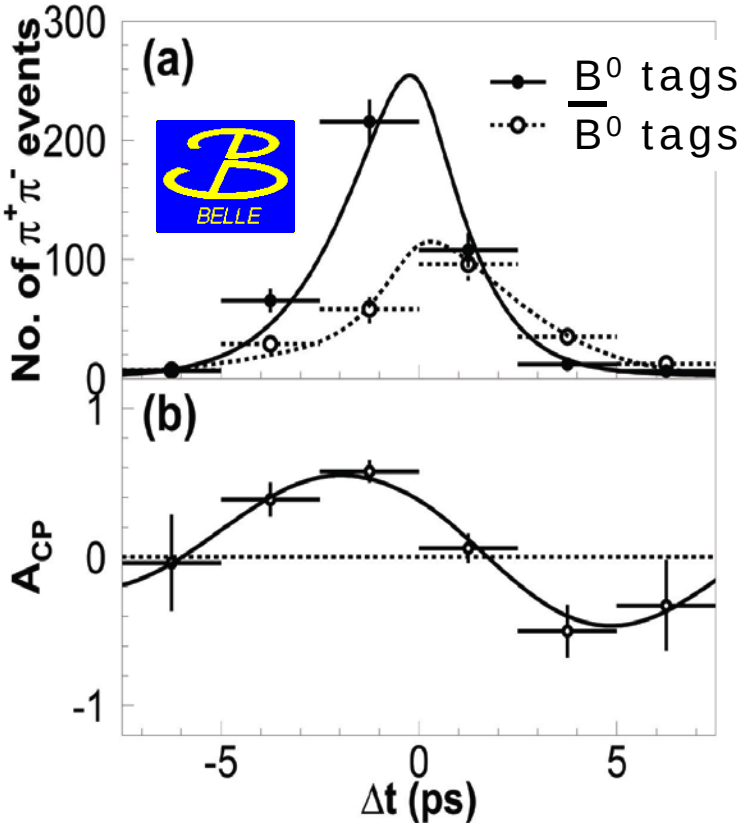
$$\overline{A} = \langle f_{CP} | H | \overline{B}^0 \rangle$$

If one amplitude (tree) dominates, $|A| = |\overline{A}|$ and $\overline{A}/A = e^{-2i\gamma}$

$$\to \quad |\lambda| = 1 \qquad C = 0 \qquad S = \sin 2\alpha$$

C ≠0 implies $|A| \neq |\overline{A}|$, i.e., more than one amplitude (penguins)

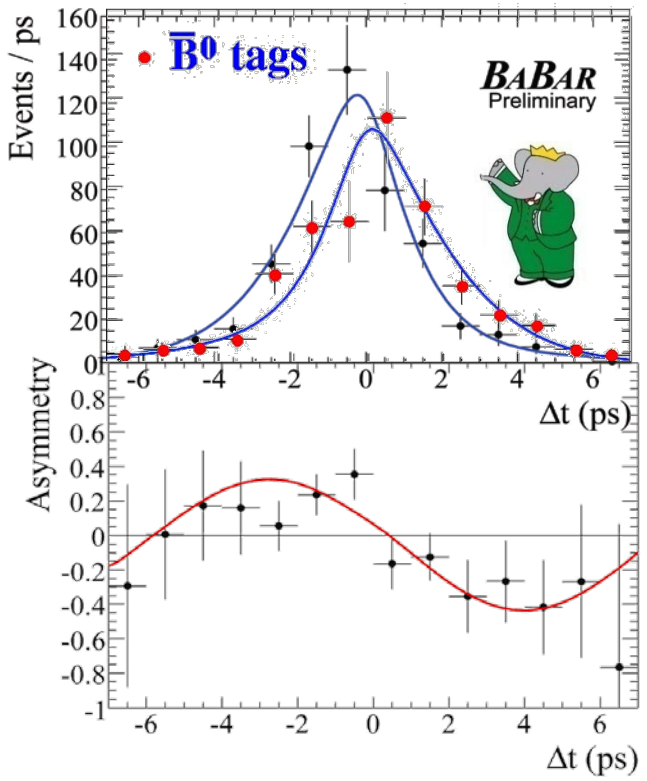
$a_{cp}(t)$ in $B \rightarrow \pi^+\pi^-$



[PRL 98 (2007) 211801, 535x10^6 events]

S = -0.61±0.10±0.04

C = -0.55±0.08±0.05

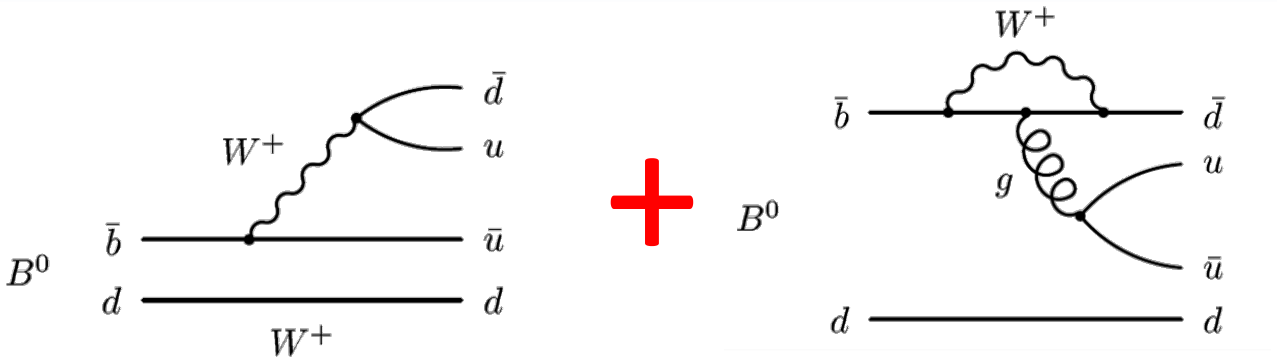


[arXiv:0807.4226 (2008), 467x10^6 events (the final event sample)]

S = -0.68±0.10±0.03

C = -0.25±0.08±0.02

$C_{\pi^+\pi^-} \neq 0 \rightarrow$ more than 1 amplitude



$$a_{CP}(t) = S \sin \Delta m t - C \cos \Delta m t$$ as before

but now a_{CP} determines an <u>effective</u> angle α_{eff}, defined by

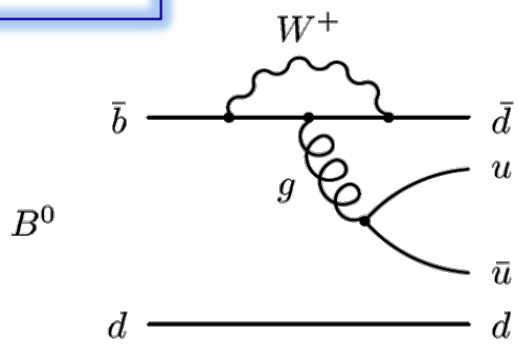
$$S \equiv \sqrt{1-C^2} \sin 2\alpha_{eff}$$

<u>Gronau & London</u> (GL) [PRL 65 (1990)3381]: use isospin symmetry to disentangle the contributions of tree and penguin amplitudes, measure $\delta\alpha = \alpha - \alpha_{eff}$

Isospin analysis

- $B^+ \to \pi^+\pi^0$: Isospin I=1,2 (I_3=1)
- Penguin: I=0,1
- I=1 forbidden by BE statistics

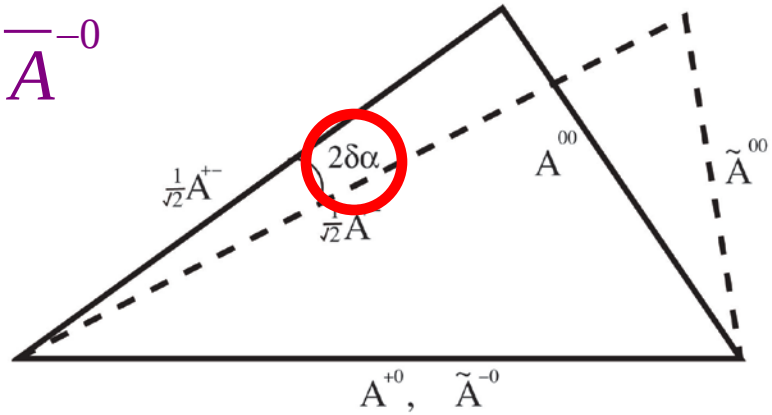
  → $B^+ \to \pi^+\pi^0$ pure tree



Three B → ππ charge states (+0, +-, 00) → triangles

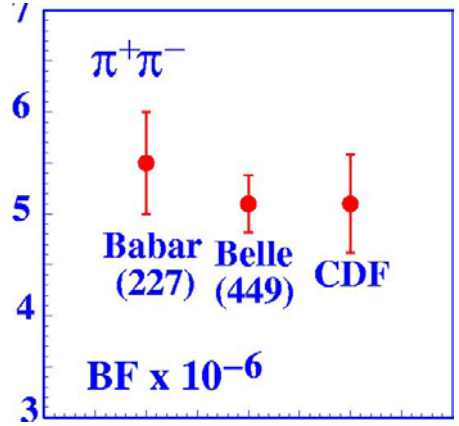
$$(1)\quad A^{+0} = \frac{A^{+-}}{\sqrt{2}} + A^{00} \qquad A^{+0} = \overline{A}^{-0}$$

$$(2)\quad \overline{A}^{-0} = \frac{\overline{A}^{+-}}{\sqrt{2}} + \overline{A}^{00}$$

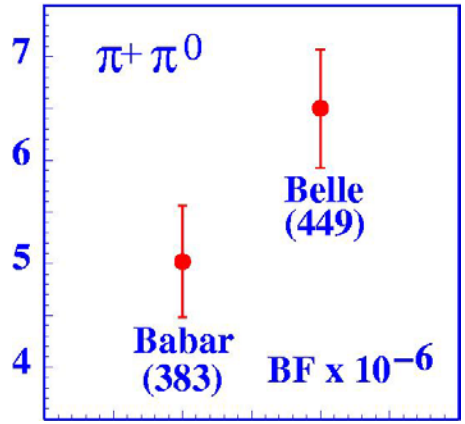


→ 8-fold discrete ambiguity : (4 relative orientations of 2 triangles) x (2 solutions to $\alpha_{eff} \sim \sin^{-1} S$) [$\alpha_{eff}$ or 90^o-α_{eff}]

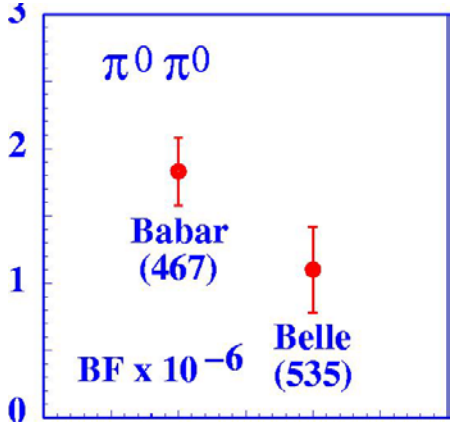
B → ππ: branching fractions and A_{CP}'s



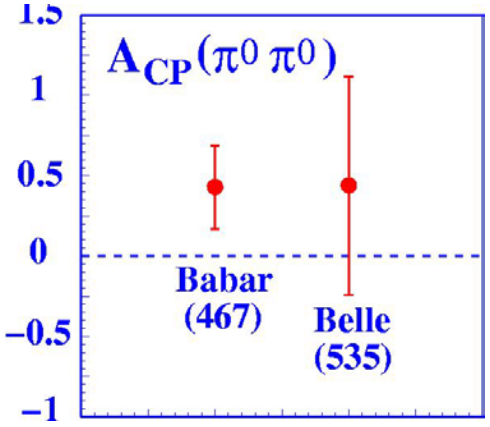
Babar PRD75(2007)012008
Belle PRL99(2007)121601
CDF hep-ex/0612018 (2007)



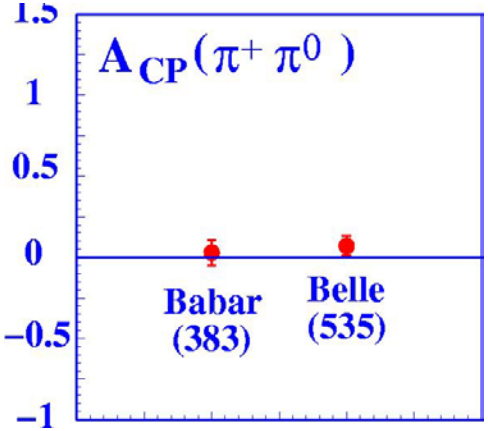
Babar PRD76(2007)091102
Belle PRL99(2007)121601



Babar arXiv:0807.4226 (2008)
Belle hep-ex/0610065 (2006)



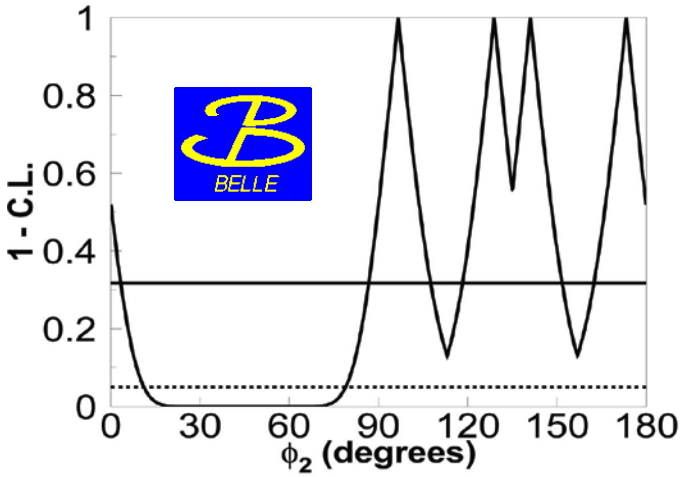
Babar arXiv:0807.4226 (2008)
Belle hep-ex/0610065 (2006)

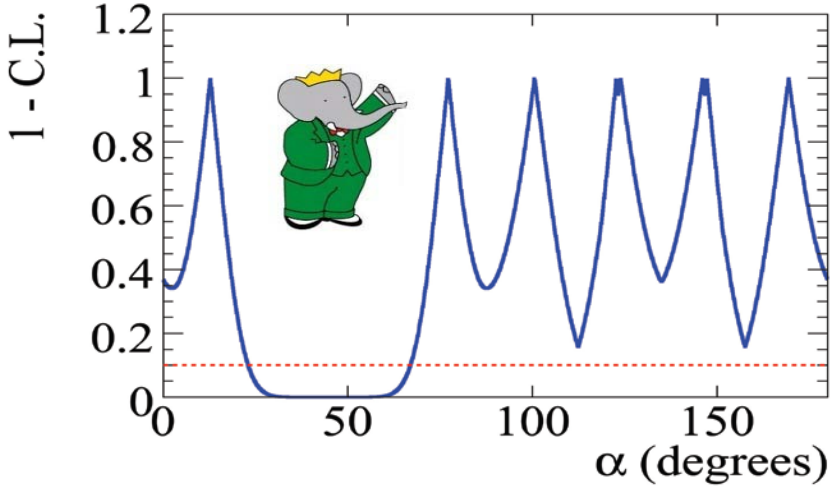


Babar PRD76(2007)091102
Belle Nature 452(2008)332

- $BF(\pi^0\pi^0)/BF(\pi^+\pi^-)\approx 30\pm 4\%$
  → large penguin contribution (tree color-suppressed in $\pi^0\pi^0$)
- $A_{CP}(\pi^+\pi^0)\approx 0$
  → EW penguins small (negligible)

α from B → $\pi\pi$: Babar and Belle





- 6 inputs: 3 BF's, S, C, A_{CP} for $\pi^0\pi^0$
- α scan; find minimum χ^2 in fit of isospin triangle to the measurements, convert to C.L. (frequentist)
- Multiple solutions from discrete ambiguities

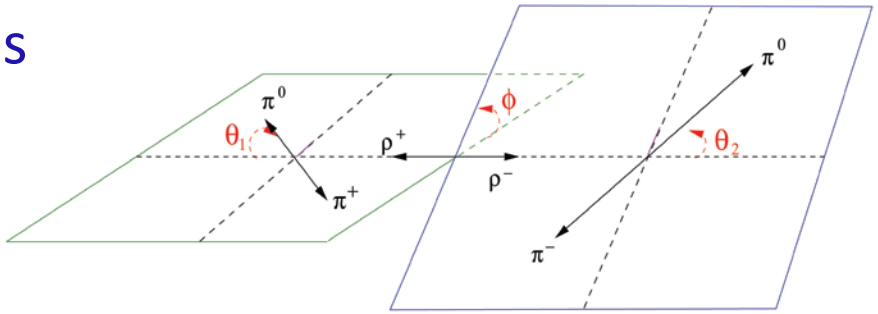
Belle: $11 < \alpha < 79^o$ excluded at 95% C.L.

Babar: $23 < \alpha < 67^o$ excluded at 90% C.L.

$B \to \rho^+\rho^-$

- Spin $0 \to 1 + 1$; $L = 0,1,2$; $CP = (-1)^L$
- Helicity basis: Superposition of 3 polarization amplitudes:
  - → 1 longitudinal (helicity=0); L=0,2 CP = +1
  - → 2 transverse (helicity=±1); L=0,1,2 CP=mixed
- Separate polarization states with an angular analysis

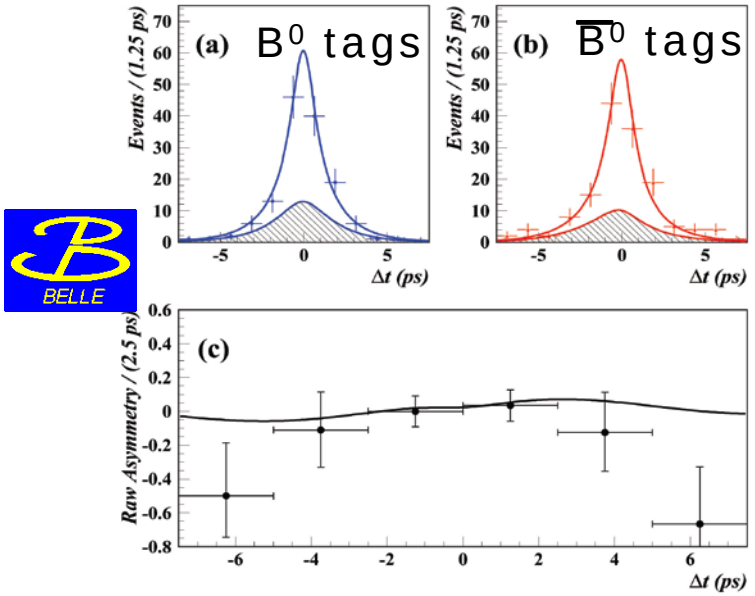
Helicity angles $\theta_{1,2}$:



Integrate over ϕ: $$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_1 d\cos\theta_2} = \frac{9}{16}[4 f_L \cos^2\theta_1 \cos^2\theta_2 + (1 - f_L)\sin^2\theta_1 \sin^2\theta_2]$$

- Simultaneously determine longitudinal polarization fraction f_L
- Apply $a_{CP}(t)$&GL isospin analysis to the longitudinal amplitudes

$a_{cp}(t)$ in $B \rightarrow \rho^+\rho^-$

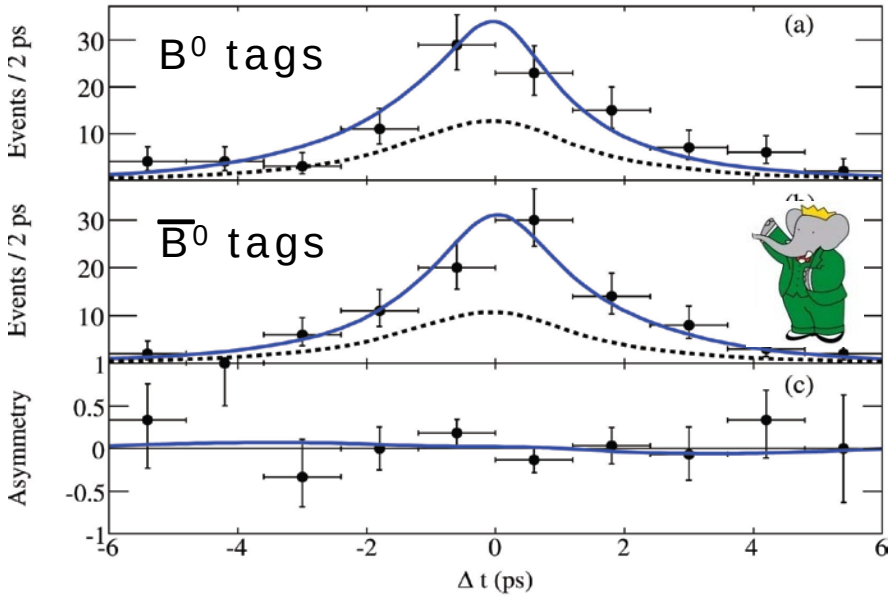


[PRD 76 (2007) 011104, 535x10^6 events]

Assume f_L=1.0

S = 0.19±0.30±0.08

C = -0.16±0.21±0.08



[PRD76(2007)052007, 384x10^6 events]

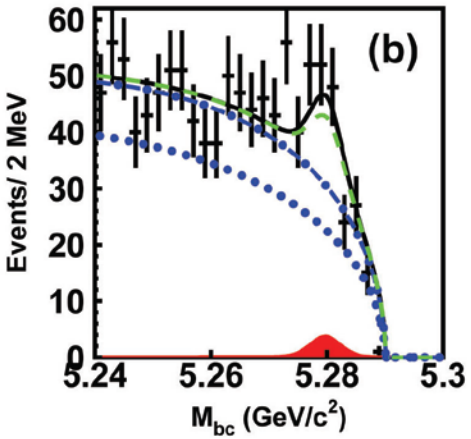
$f_L = 0.992 \pm 0.024^{+0.026}_{-0.013}$

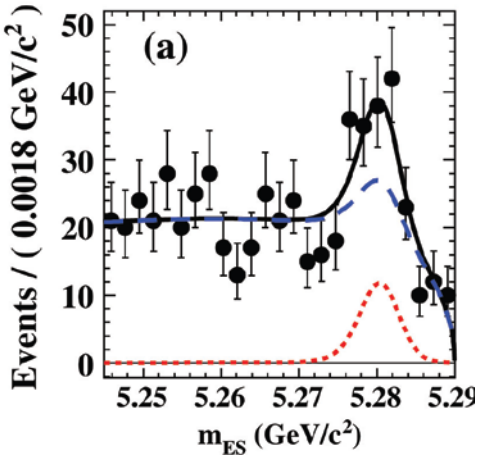
$S_{Long} = -0.17 \pm 0.20 \pm 0.06$

$C_{Long} = -0.01 \pm 0.15 \pm 0.06$

$C_{\rho+\rho-} \approx 0 \rightarrow$ <u>small</u> penguin contribution $\rightarrow$ $\alpha_{eff} \approx \alpha$ (≈ 0 or 90^o)

$a_{cp}(t)$ in $B \rightarrow \rho^0\rho^0$





[PRD 78 (2008) 111102, 657x10^6 events]

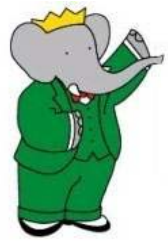
[PRD78(2008)071104, 465x10^6 events]

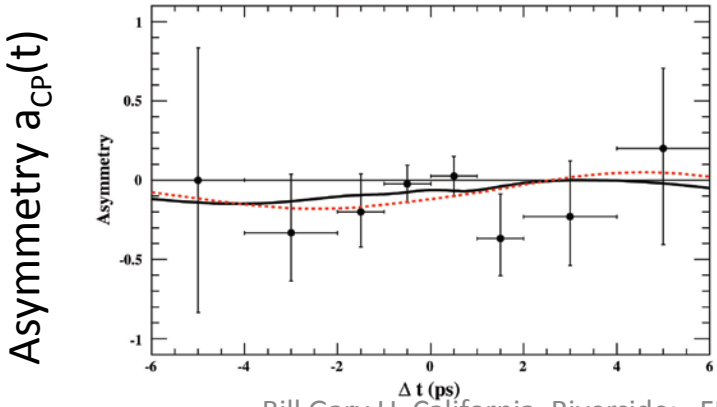
BF($B \rightarrow \rho^0\rho^0$)=$(0.4\pm0.4^{+0.2}_{-0.3})\times10^{-6}$

1 σ significance [signal eff. = 9.2%]

BF=$(0.92\pm0.32\pm0.14)\times10^{-6}$

3.1 σ significance [signal eff.=23.3%]





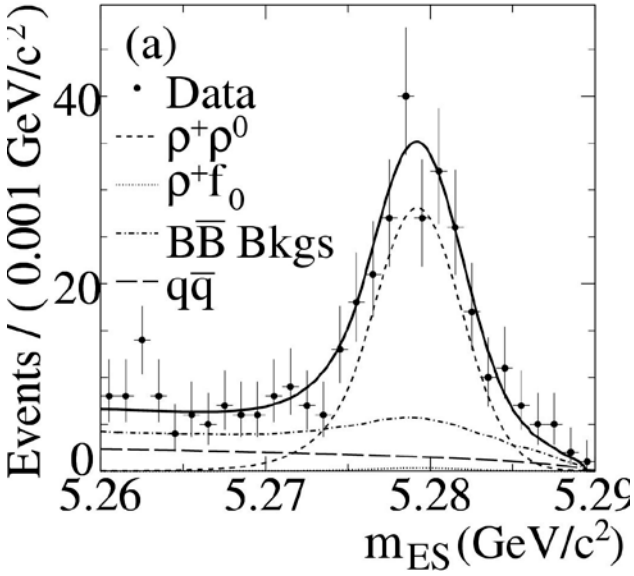
$f_L = 0.75^{+0.11}_{-0.14}\pm0.05$

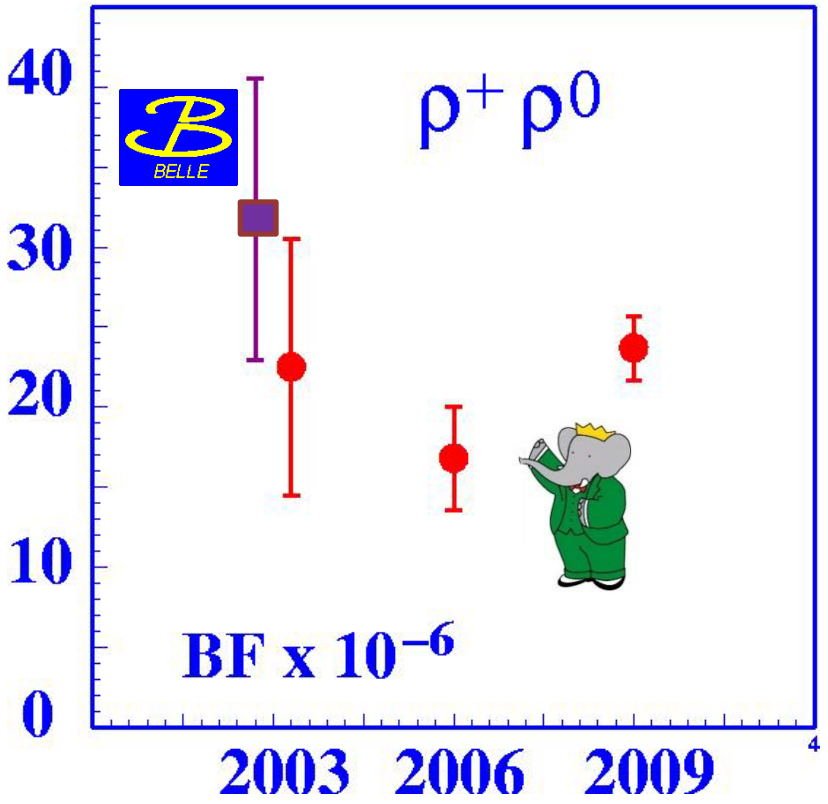
$S_{Long} = 0.3\pm0.7\pm0.2$

$C_{Long} = 0.2\pm0.8\pm0.3$

New $B^+ \to \rho^+\rho^0$ study

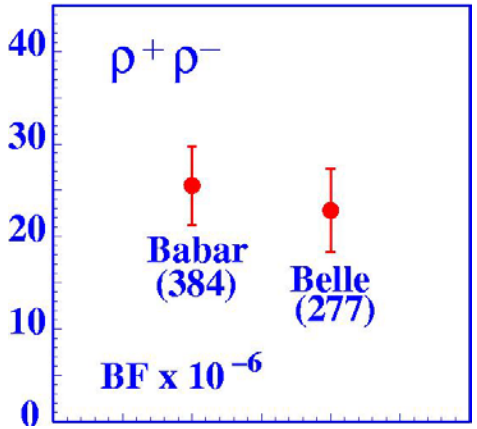
Babar PRL102 (2009) 141802



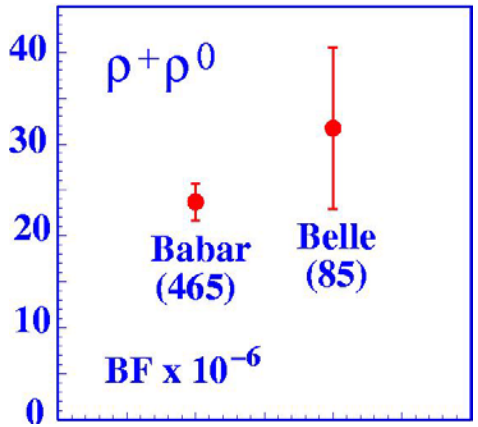


- $f_L = 0.950 \pm 0.015 \pm 0.006$
- Improved methods (3D PDFs) to account for correlations in the main (continuum & combinatoric BB) backgrounds

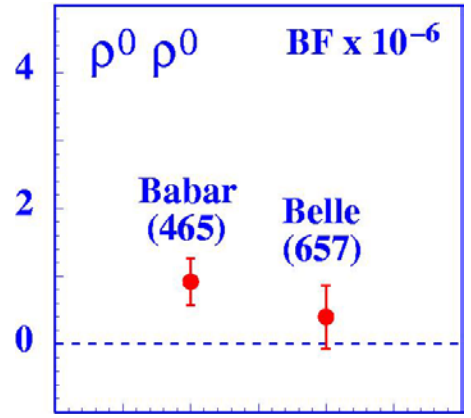
B → ρρ: branching fractions and A_{CP}'s



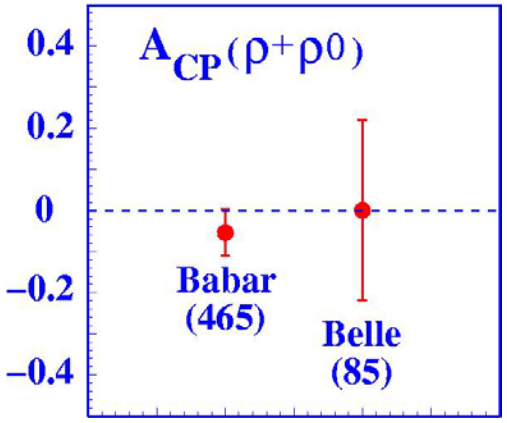
Babar PRD76(2007)052007
Belle PRL96(2006)171801

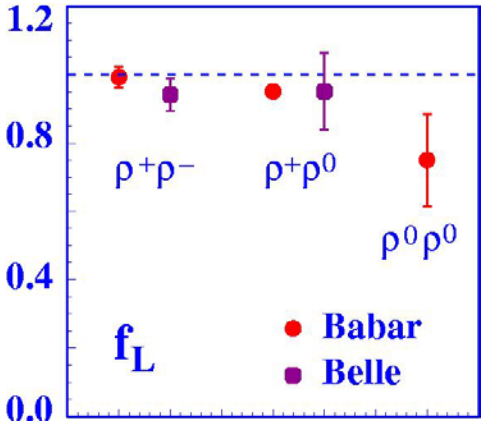


Babar PRL102(2009)141802
Belle PRL91(2003)221801



Babar PRD78(2008)071104
Belle PRD78(2008)111102

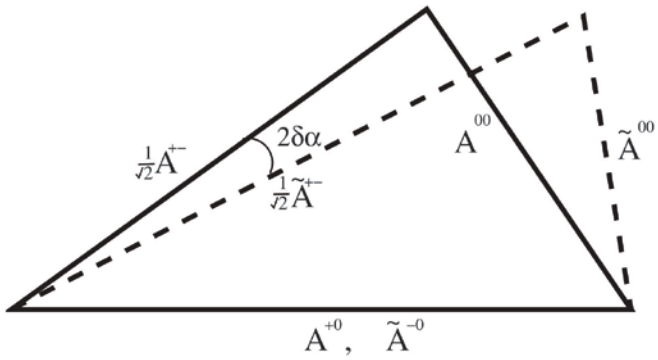




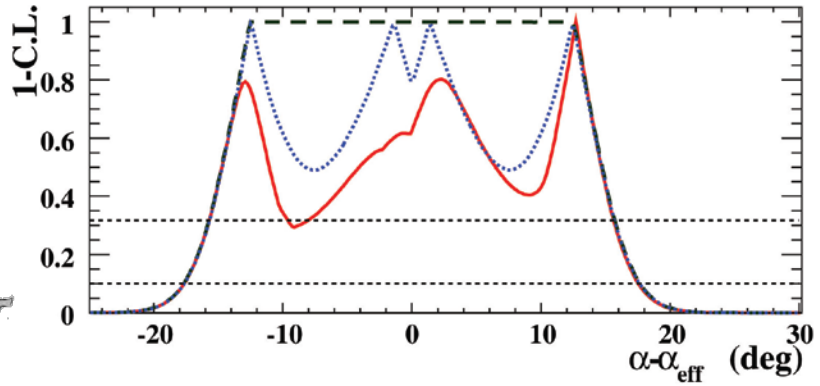
Babar PRL102(2009)141802
Belle PRL91(2003)221801

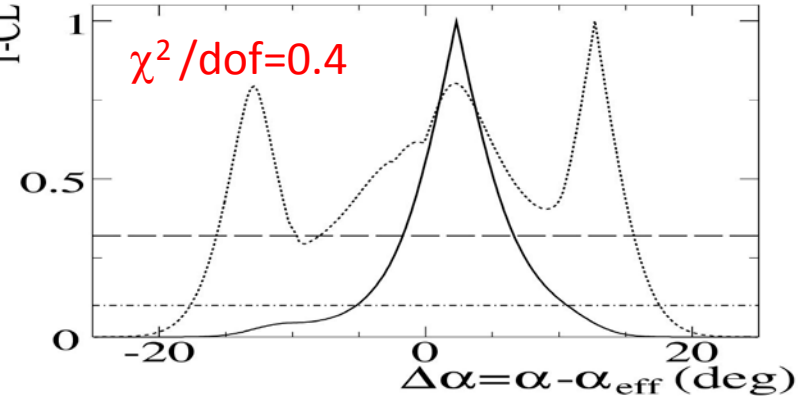
- BF($\rho^0\rho^0$)/BF($\rho^+\rho^-$)≈3.6±1.5%
  → small penguin contribution
- $A_{CP}(\rho^+\rho^0)$≈0
  → contribution of EW penguins small (negligible)

Isospin analysis: $B \to (\rho\rho)_{Long}$



- 10 inputs: 3 BF's, 3 f_L's, 2 S's & 2 A's
- Perform α scan, minimize χ^2
- Impact of S^{00} and C^{00}:
  [Babar PRD78(2008)071104]
  – – – without S^{00} or C^{00}
  ..... without S^{00}
- Impact of BF($B^+ \to \rho^+\rho^0$):
  [Babar PRL102 (2009) 141802]
  ..... with 2006 result
  —— with 2009 result

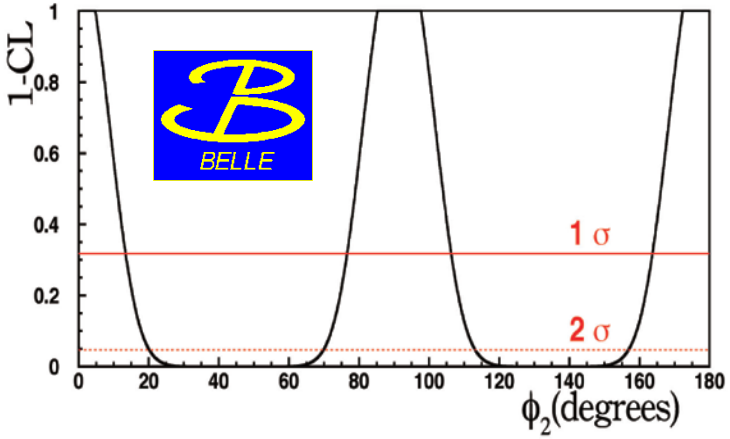




Belle $\rho^0\rho^0$: $\alpha=(91.7\pm14.9)^o$

[PRD 78 (2008) 111102]

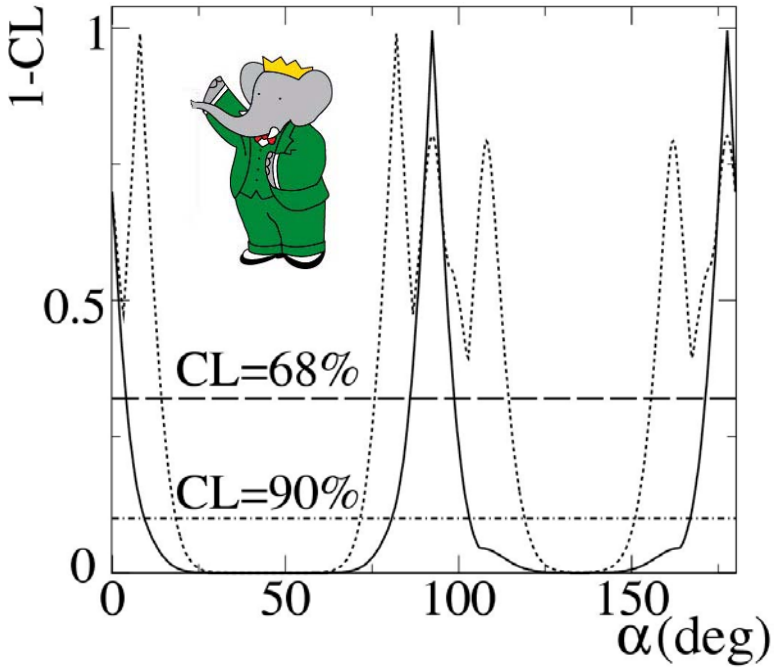
- 657×10^6 events
- Old (2006) result for $\rho^+\rho^0$



Babar $\rho^+\rho^0$: $\alpha=(92.4^{+6.0}_{-6.5})^o$

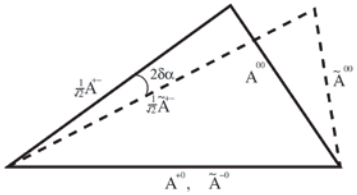
[PRL102 (2009) 141802]

- 465×10^6 events, $\rho^0\rho^0$ & $\rho^+\rho^0$
  384×10^6 events, $\rho^+\rho^-$
- Includes new S, C, f_L from $\rho^0\rho^0$



Discrete ambiguities (except for π-α) reduced by larger $\rho^+\rho^0$ BF

→ flattens the isospin triangle



$B \to \rho\pi$

- Not a CP eigenstate
- Need to simultaneously consider $B^0(\overline{B}^0) \to \rho^+\pi^-$ and $\rho^-\pi^+$
- Two methods proposed to eliminate penguin contributions:

1. Isospin analysis: [Lipkin et al., PRD44(1991)1454, Gronau, PLB265(1991)389]

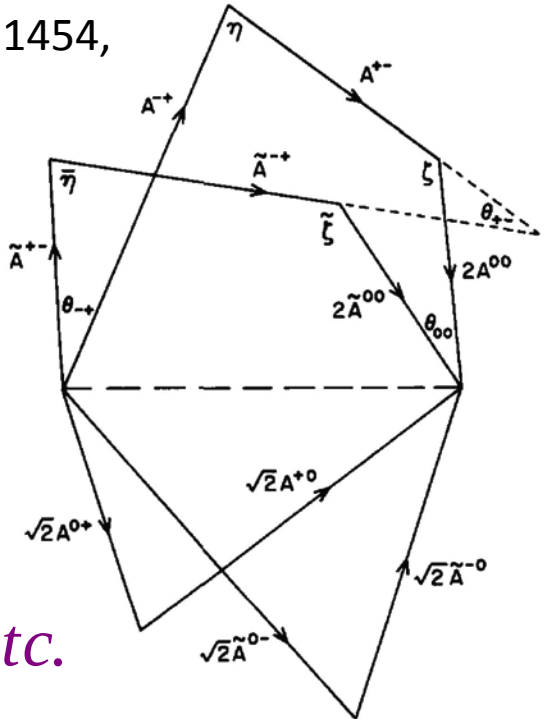
   → Extend isospin $\pi\pi/\rho\rho$ isospin method

   → 5 charge states:

   $B^+ \to \rho^+\pi^0, \rho^0\pi^+$ + c.c.

   $B^0 \to \rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0$ + c.c.

   → isospin pentagons



$$A^{-+} + A^{+-} + 2A^{00} = \sqrt{2}(A^{0+} + A^{+0}), \ etc.$$

Precision expected to be small

2. Time-dependent Dalitz plot analysis of the 3 $(\rho\pi)^0$ modes [Snyder & Quinn, PRD48(1993)2139; Quinn & Silva, PRD62(2000)054002]

→ Determine relative phases & moduli of six decay amplitudes

$$A^+(\overline{A}^+) = A[B^0(\overline{B}^0) \to \rho^+\pi^-]$$

$$A^-(\overline{A}^-) = A[B^0(\overline{B}^0) \to \rho^-\pi^+]$$

$$A^0(\overline{A}^0) = A[B^0(\overline{B}^0) \to \rho^0\pi^0]$$

through interference in the $B^0(\overline{B}^0) \to \pi^+\pi^-\pi^0$ Dalitz plot

$$A^k = T^k e^{-i\alpha} + P^k; \quad (q/p)\,\overline{A}^k = T^{\overline{k}} e^{+i\alpha} + P^{\overline{k}}; \quad k = +,-,0 = \rho \text{ charge}$$

→ $$e^{2i\alpha} = \frac{\overline{A}^+ + \overline{A}^- + 2\overline{A}^0}{A^+ + A^- + 2A^0}$$

- Assumes isospin symmetry
- No discrete ambiguities

B → ρπ: time-dependent Dalitz analysis

$$A_{3\pi}(s) \equiv A[B^0 \to \pi^+\pi^-\pi^0] = \sum_{k=+,-,0} f_k(s)\, A^k \quad ; \qquad s = m^2_{\pi^+\pi^0}, m^2_{\pi^-\pi^0}$$

$$\overline{A}_{3\pi}(s) \equiv A[\overline{B}^0 \to \pi^+\pi^-\pi^0] = \sum_{k=+,-,0} f_k(s)\, \overline{A}^k \qquad A^k = A[B^0 \to \rho^k\pi^-]$$

- ρ lineshape: $f_k(s) = [F_{\rho(770)}(s) + a_1 e^{i\phi_1} F_{\rho(1450)}(s) + a_2 e^{i\phi_2} F_{\rho(1700)}(s)]_k$
- F_ρ = Breit-Wigner functions (Gounaris-Sakurai form)
- a_1, ϕ_1, a_2, ϕ_2 → determined in a fit

Time-dependent decay rate $B \to (\pi\pi\pi)^0$

$$\frac{d\Gamma^{\pm}(s)}{dt} \propto \left(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2\right) \mp \left(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2\right)\cos\Delta m\, t$$

$$\pm\ 2\,\mathrm{Im}\left(\frac{q}{p}\overline{A}_{3\pi}A^*_{3\pi}\right)\sin\Delta m\, t \qquad \begin{pmatrix} + = B^0\ tags \\ - = \overline{B}^0\ tags \end{pmatrix}$$

B → ρπ: time-dependent Dalitz, cont.

$\frac{d\Gamma^{\pm}(s)}{dt}$ depends on 27 real-valued coefficients: $U \;\&\; I$

$$U_k^{\pm} = \left|A^k\right|^2 \pm \left|\overline{A}^k\right|^2 \quad ; \quad k = +,-,0$$

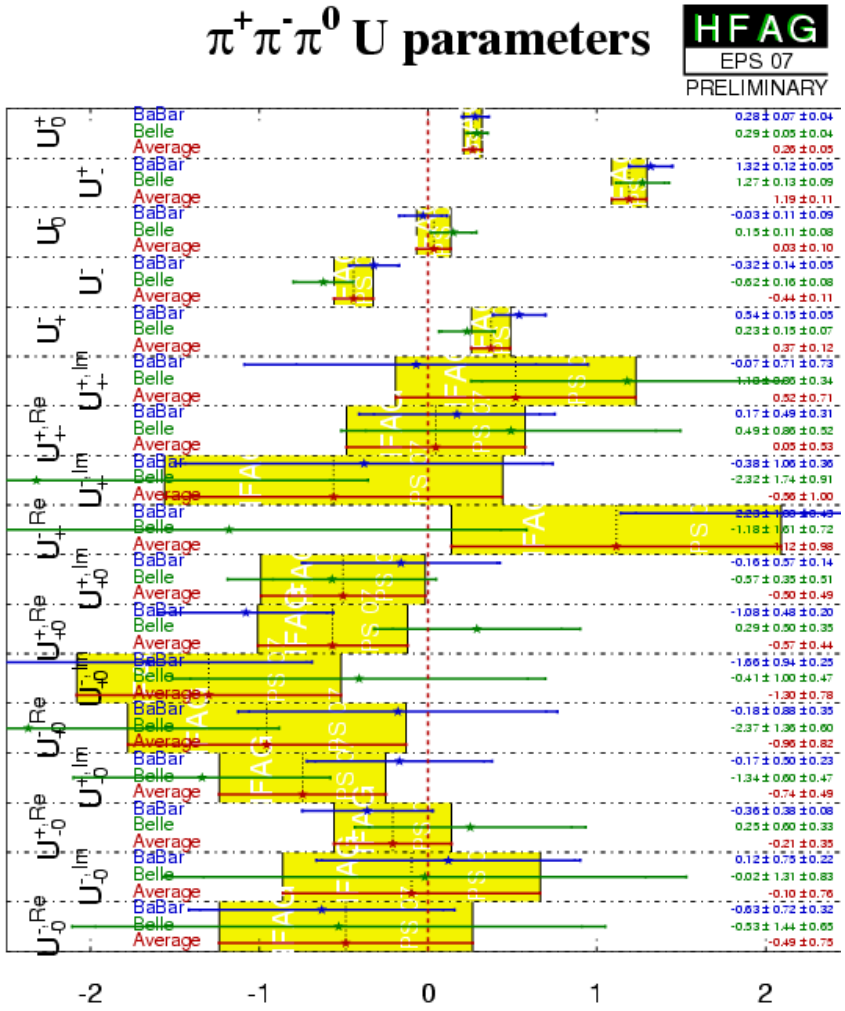
$$I_k = \mathrm{Im}\ \overline{A}^k A^{k*}, \quad etc.$$

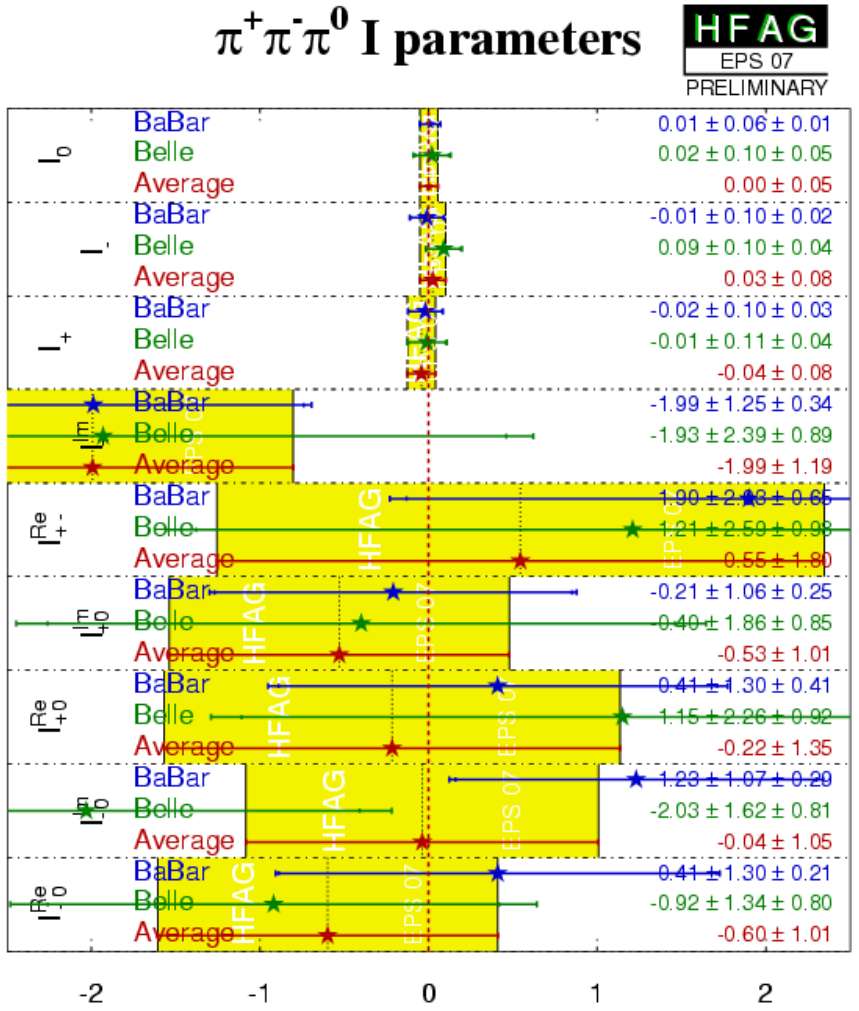
The $U \;\&\; I$ specify the phases and modulii of the A^k and $\overline{A}^k$, and thus α

U_+^+ ~ BF($B^0 \to \rho^+\pi^-$) + BF($\overline{B}^0 \to \rho^+\pi^-$) [total BF's] $A^k = A[B^0 \to \rho^k\pi^-]$

- Set $U_+^+ = 1$ (fixes overall normalization)
- Fit $\frac{d\Gamma^{\pm}(s)}{dt}$ to the time-sliced Dalitz plot with 26 free $U \;\&\; I$ coefficients (+ other parameters)

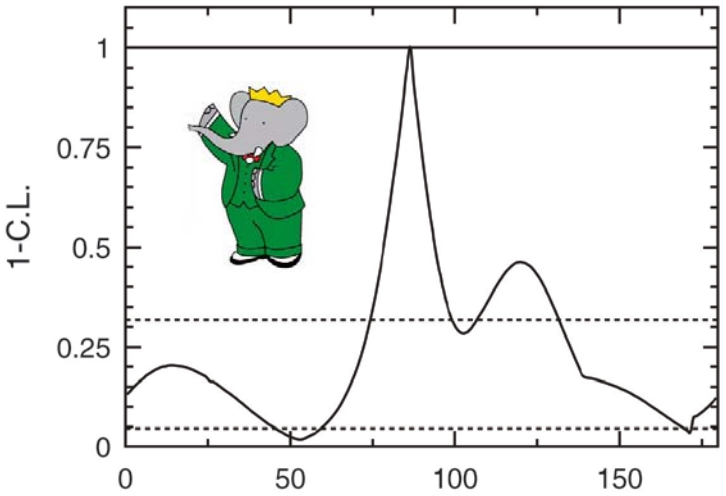
U & I: consistent results between Babar and Belle





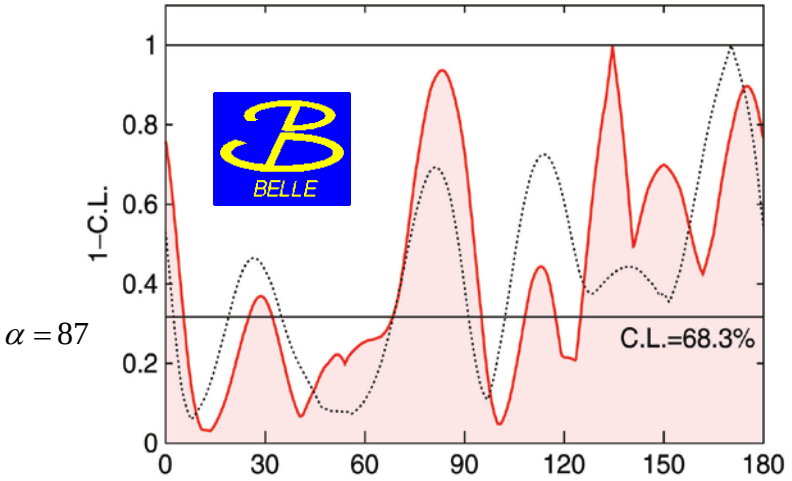
B → ρπ: α scans

PRD76 (2007) 012004; 375x10^6 events;
2067±86 $B^0 \to \pi^+\pi^-\pi^0$ events



$\alpha = (87^{+45}_{-13})^o$ at 68% C.L.

PRL98 (2007) 221602; 449x10^6 events;
971±42 $B^0 \to \pi^+\pi^-\pi^0$ events



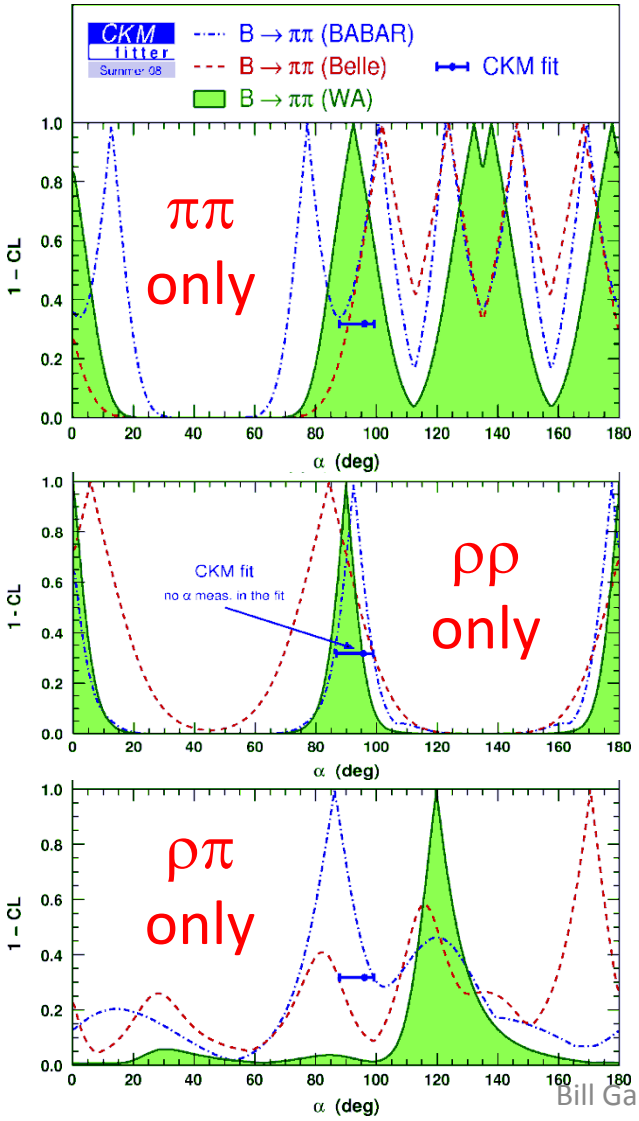
$68^o < \alpha < 95^o$ at 68% C.L.

Belle: Dotted → Dalitz analysis only

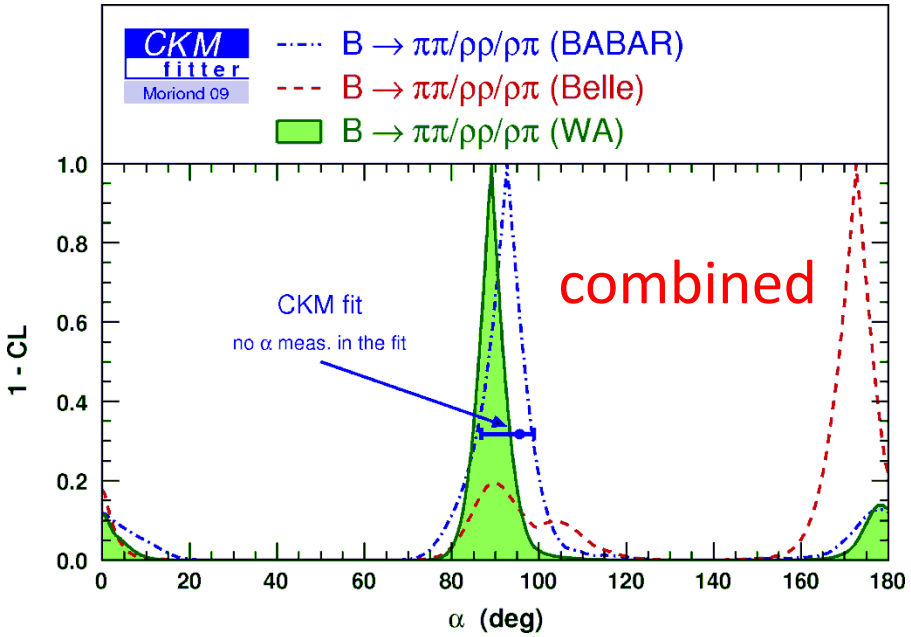
Solid → include $B^+ \to (\rho\pi)^+$ modes [pentagon relations]

Babar: ρπ results help resolve the discrete ambiguity from B→ρρ at $\alpha \approx 0^o/180^o$

Combined ππ, ρρ, ρπ results



CKMfitter group, ckmfitter.in2p3.fr
(frequentist construction of C.L.)

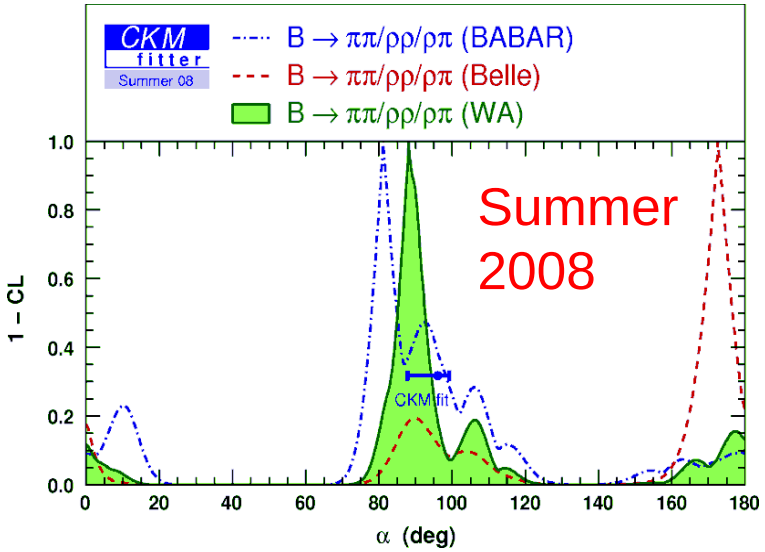


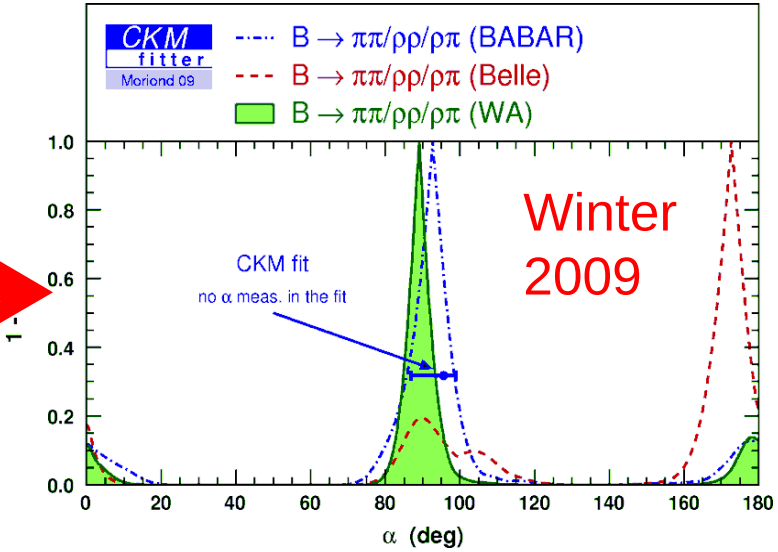
$\alpha = 89.0 \pm 4.3^{o}$ (4.8% precision)

CKM fit: indirect SM constraint on α:

$|V_{us}|$, $|V_{ud}|$, $|V_{ub}|$, $|V_{cb}|$, CPV in K^0, $B_{(s)}$-$B_{(s)}$ mixing

Improvement since Summer 2008





$\alpha = (88.2^{+6.1}_{-4.8})^{o}$ (6.2% precision)

$(89.0 \pm 4.3)^{o}$ (4.8% precision)

2σ limits: 4 allowed regions

0^{+7}_{-0} 88^{+24}_{-11} $114.4^{+1.2}_{-1.2}$ $176.9^{+3.1}_{-13.9}$

Only 3, with much tighter bounds

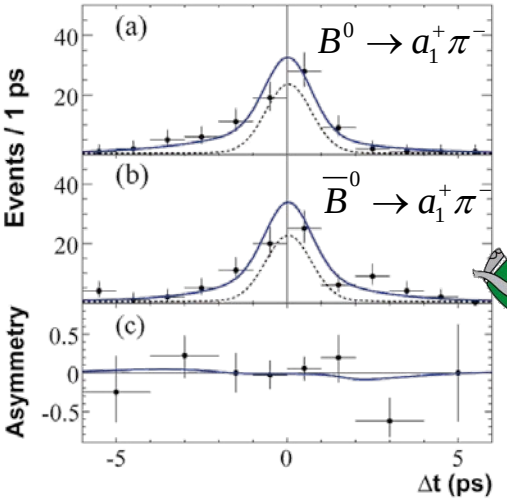
0^{+5}_{-0} $89.0^{+9.1}_{-8.3}$ $178.3^{+1.7}_{-5.6}$

$B \to a_1(1260)\pi$ with $a_1^+ \to \pi^+\pi^+\pi^-$

→ Quasi-two-body approach [Gronau & Zupan, PRD73(2006) 057502]

→ $\alpha_{eff} = (78.6 \pm 7.3)^o$ [4-fold ambiguity]

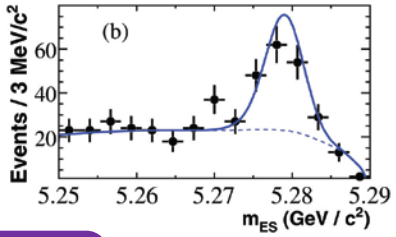
[PRL98(2007)181803, 384x10^6 BB]



→ SU(3)-flavor to constrain penguin:

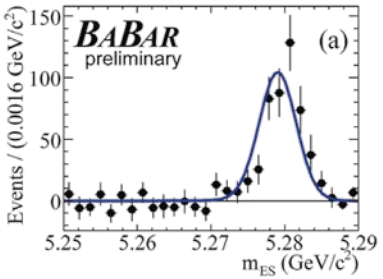
- $B \to a_1 K$ [PRL100 (2008)051803, 383x10^6 events]

$B^+ \to a_1 K^0$



- $B \to K_{1A}(1270)\pi$ [arXiv:0807.4760 (2008) , 454x10^6 BB]

$B^0 \to K_1(1270)\pi^-$
$+ K_1(1400)\pi^-$;
$[K_1 \to K\pi\pi]$



$B^0 \to K_1\pi^-$

$B \to K_1\pi$ being finalized; unofficial naïve expectation is

$\delta\alpha = |\alpha - \alpha_{eff}| \leq 16^o$

Summary and Conclusions

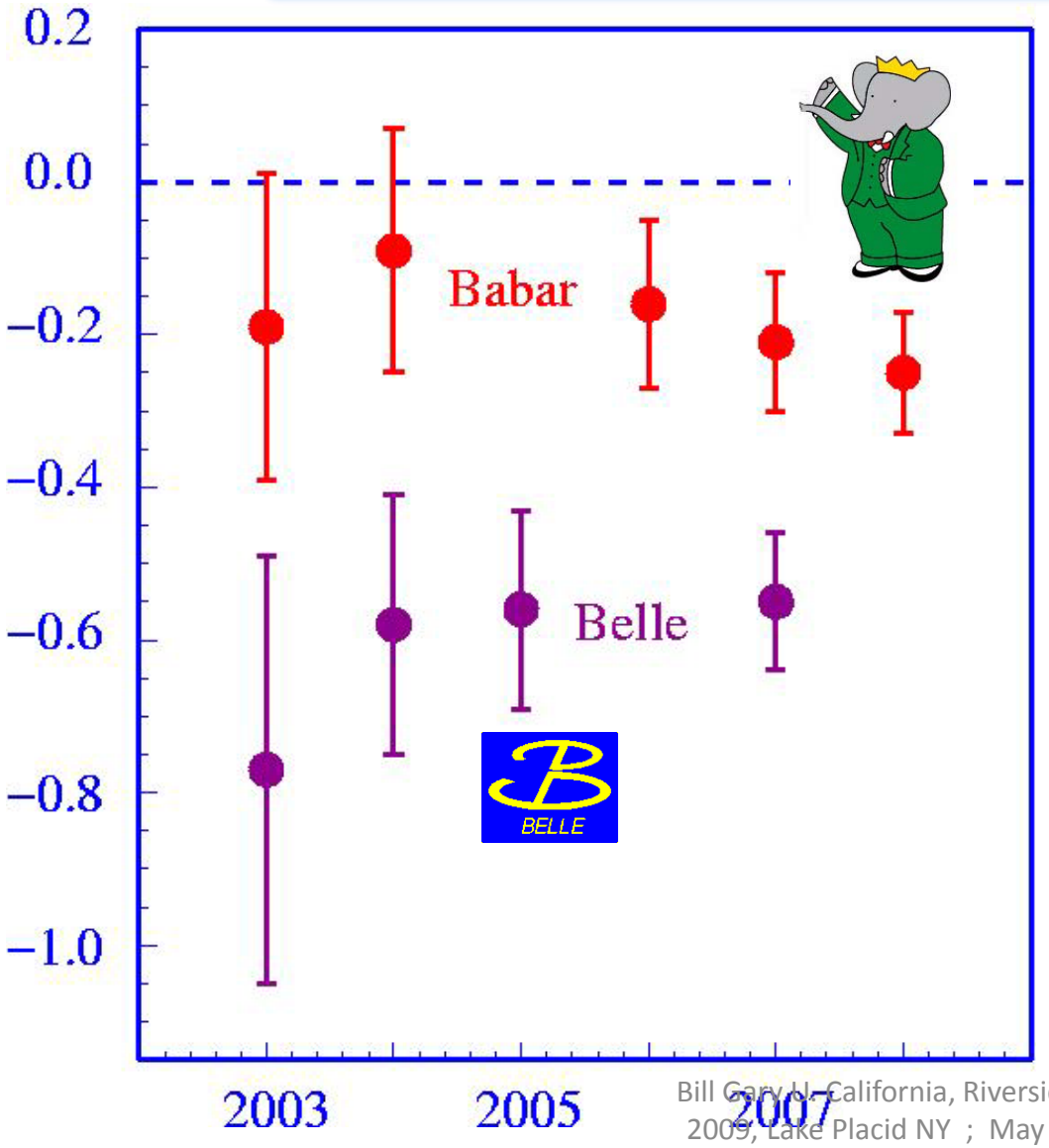
- α/ϕ_2 precision has improved considerably since summer 2008
  - new $\rho^0\rho^0$ results from Belle and Babar
  - new $\rho^+\rho^0$ results from Babar
- The $B\to\rho\pi$ Dalitz analysis important to resolve the discrete ambiguities from $\rho\rho$ at $(\alpha/\phi_2) \approx 0,180^o$
- α/ϕ_2 now known to better than 5% precision

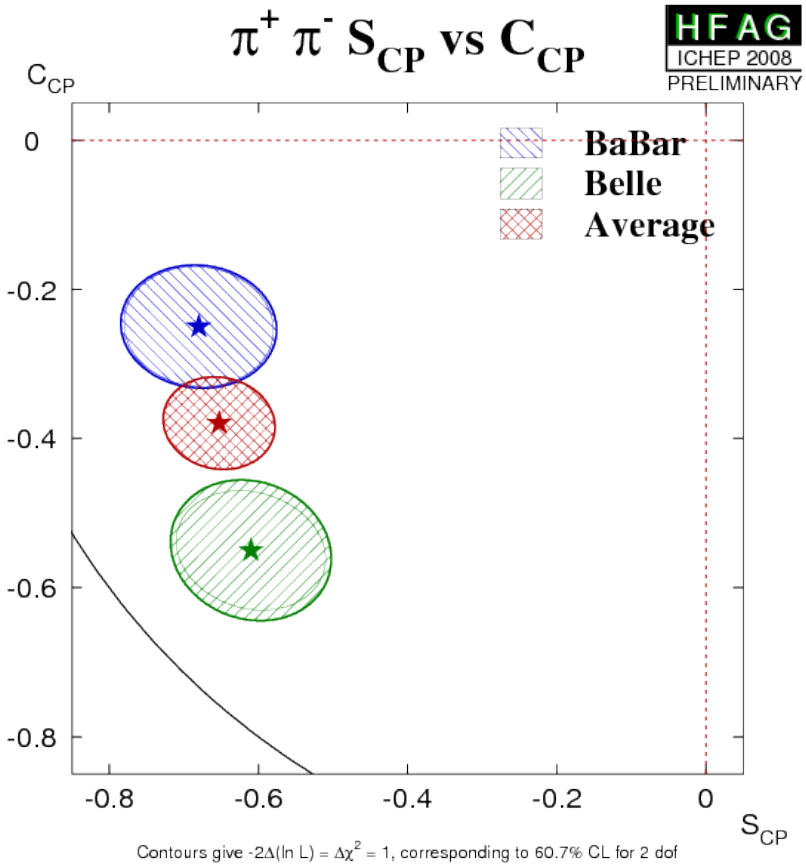
  $\alpha/\phi_2 = 89.0 \pm 4.3^o$ (CKMfitter), $= 92 \pm 7^o$ (UTfit)

  [the new $\rho^+\rho^0$ results not yet included in Utfit]
- Independent constraint from $B\to a_1\pi$ expected soon
- Babar results either final or nearly so
- Room for Belle to improve ϕ_2 with updated $\rho^+\rho^0$ BF, possibly $\rho\pi$ Dalitz results with a lot more data

BACKUP

$C_{\pi^+\pi^-}$: Babar versus Belle



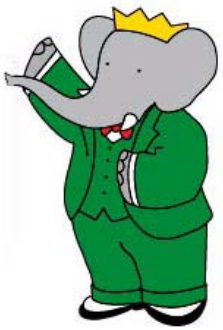


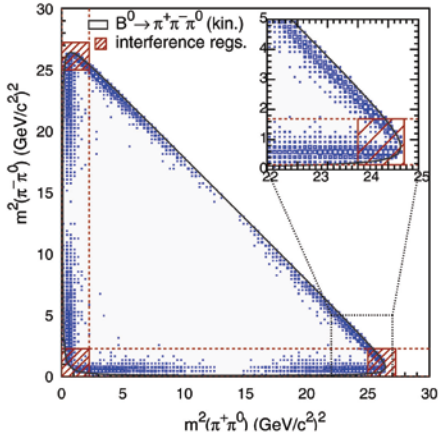
1.9 σ discrepancy

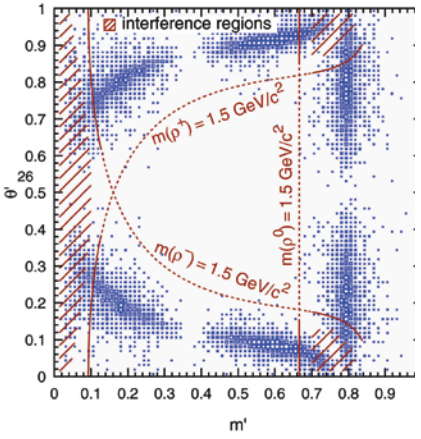
CL = 0.055 (HFAG)

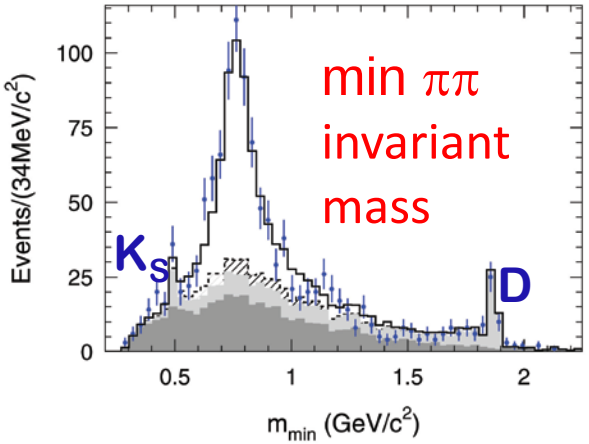
B → ρπ: time-dependent Dalitz

Babar, PRD76 (2007) 012004; 375x10^6 events; 2067±86 $B^0 \to \pi^+\pi^-\pi^0$ events



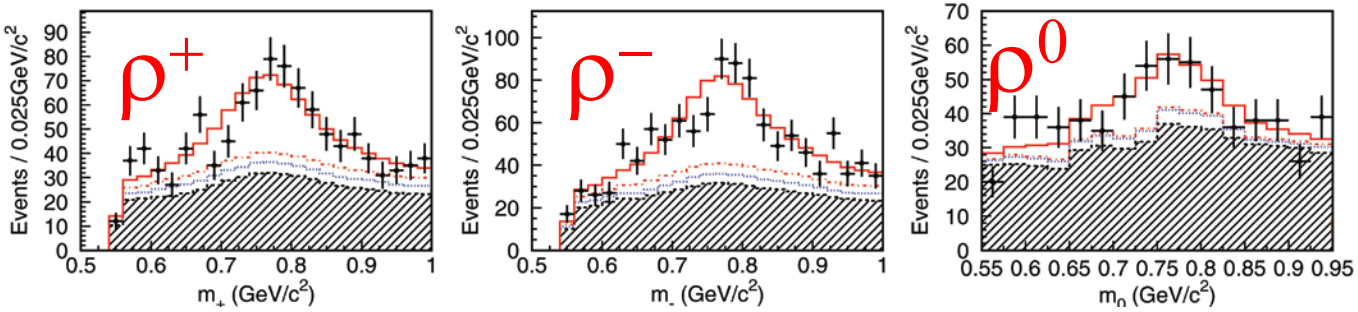




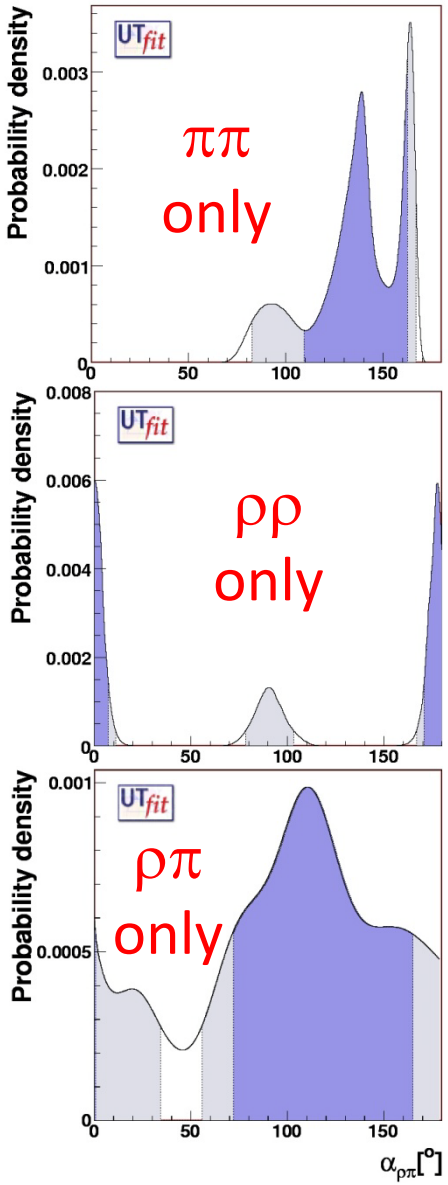


$\pi^+\pi^-\pi^0$-Dalitz plot, signal MC

Belle, PRL98 (2007) 221602; 449x10^6 events; 971±42 $B^0 \to \pi^+\pi^-\pi^0$ events



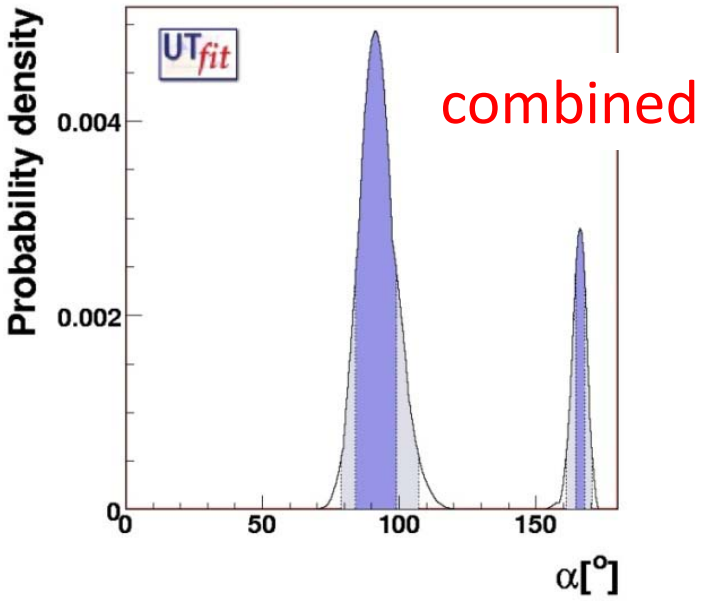
Combined ππ, ρρ, ρπ results, UTfit



Require penguin contributions finite & physical:
→ suppresses
α at 0 and 180°

Does not yet include 2009 Babar $\rho^+\rho^0$ update

UTfit group, www.utfit.org
(Bayesian construction of prob.)



α = (92 ± 7)° OR (166 ± 2)°
(7.6% precision for SM result)