CKM Angle α in $B \rightarrow \rho\pi$ and $B \rightarrow \rho\rho$ at BaBar

Yury Kolomensky
UC Berkeley/LBNL

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Outline

- Overview
  - Theoretical challenges
  - Experimental techniques
- New results from BaBar
  - CP asymmetries and Branching Ratios in $B \to \rho\rho$
  - CP asymmetries in $B \to \rho\pi$
- Summary and Conclusions

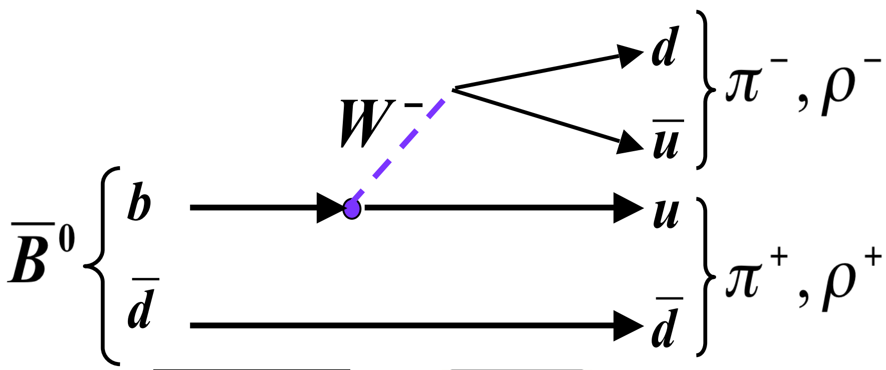
Measuring α in B→hh Decays

At ***tree level***, time-dependent asymmetry $A_{CP}(t)$ in $b \to u\bar{u}d$ transition to a *CP* eigenstate measures

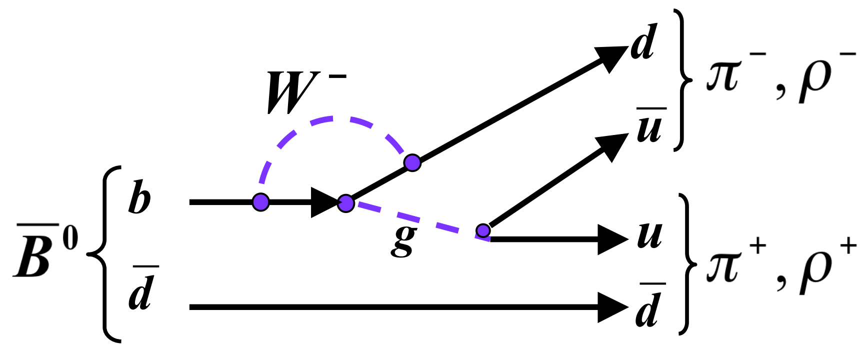
$$\arg\left[\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] = \pi - \beta - \gamma \;\equiv \alpha \quad \text{(in SM)}$$

Possible interference with ***Penguin*** amplitudes:

$$A_{CP}(t) \Rightarrow \sin(2\alpha_{\text{eff}});\; \alpha_{\text{eff}} = \alpha - \Delta\alpha;\;\; \text{direct } A_{CP} \neq 0$$



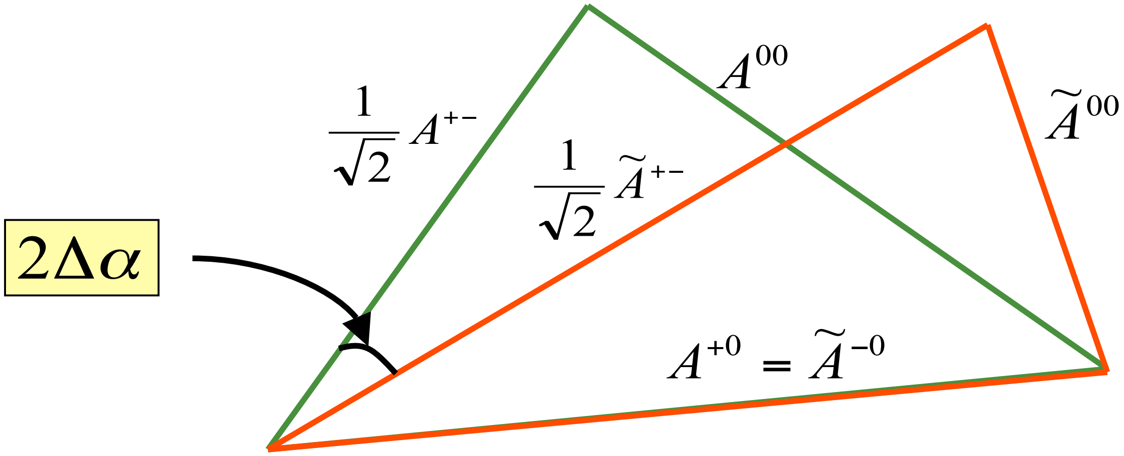
Tree



Penguin

Isospin analysis in B → ρρ, ππ

M. Gronau, D. London, Phys. Rev. Lett. ***65****, 3381 (1990)*



$$A_{hh} = e^{+i\gamma} T + e^{-i\beta} P$$

$$\tilde{A}_{hh} = e^{-i\gamma} T + e^{+i\beta} P$$

$$\begin{aligned}
A^{+-} &= A(B^0 \to \rho^+\rho^-) \\
\tilde{A}^{+-} &= A(\overline{B}^0 \to \rho^+\rho^-) \\
A^{00} &= A(B^0 \to \rho^0\rho^0) \\
\tilde{A}^{00} &= A(\overline{B}^0 \to \rho^0\rho^0) \\
A^{+0} &= A(B^+ \to \rho^+\rho^0) \\
\tilde{A}^{-0} &= A(B^- \to \rho^-\rho^0)
\end{aligned}$$

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

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

Neglecting EW penguins, ±0 is a pure tree mode: two triangles share a common side

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

- 6 unknowns, 7 observables in B→ρρ (or 5, until CP asymmetries in $\rho^0\rho^0$ are measured)
  - 4-fold ambiguity in 2Δα : either triangle can flip up or down
  - In principle, 3 sets of triangles in $B \to \rho\rho$ (one for each polarization)

See also Mark Allen's talk this afternoon

Common Themes in All Measurements

- Small Branching Fractions: $O(10^{-6}\text{–}10^{-5})$
  - Multivariate analyses to maximize sensitivity
    - Often deal with <1/100 S/B ratios
  - Typical variables
    - m_{ES}, ΔE, event topology (neural nets or Fisher): discriminate against continuum backgrounds
    - ΔE, resonance masses and helicity angles: discriminate against dominant B backgrounds
    - B vertex and tagging: for CP analyses and further background suppression
  - Main backgrounds: continuum, charm B decays, charmless crossfeeds
    - Systematic understanding of backgrounds and signal distributions crucial
    - Correlations often important !
- Vector-vector modes: angular analysis

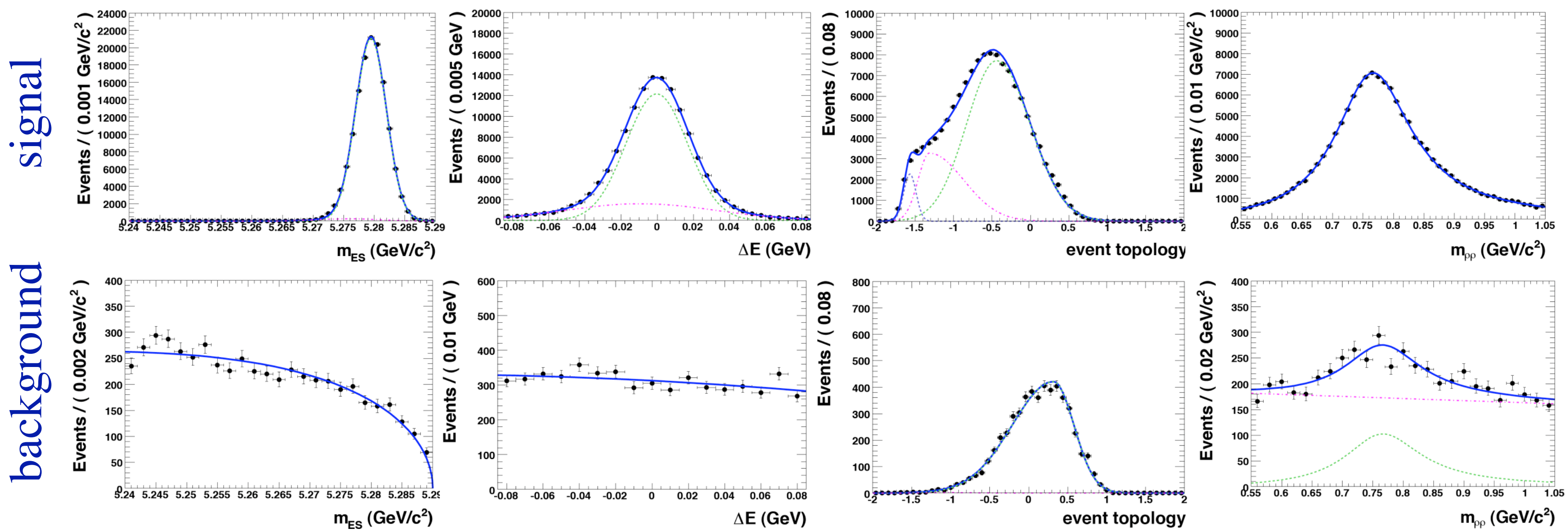
Maximum Likelihood Fits

Use (extended) ML fits to maximize sensitivity

$$L = \exp\left(-\sum_i n_i\right)\prod_{j=1}^{N}\left(\sum_i n_i f_i(\vec{x}_j;\vec{\theta})\right) \rightarrow \max$$

yield term — PDF term

- n_i : yield of each event type (fixed or free
- f_i : PDF for each event type
- x_j : variables for each event
- θ : PDF parameters (fixed or free)



- Simplest case: uncorrelated variables, PDF = product of projections
  - → Often not so simple: have to understand correlations (systematics)
- Compare parameters against data (systematics)
- ML fits are not always unbiased: test with plenty of MC

Angular Analysis in $B \to \rho\rho$

$B \to \rho\rho$ is a vector-vector state; angular analysis is required to determine CP content:

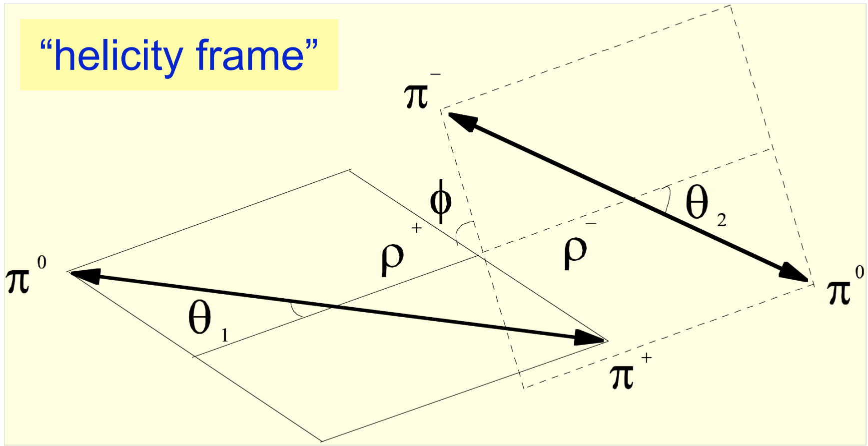
⇨ Helicity angle distributions

Longitudinal: $A_0 = -\frac{1}{\sqrt{3}}S + \sqrt{\frac{2}{3}}D$ pure $CP = +1$

Transverse: $A_{+1} = \frac{1}{\sqrt{3}}S + \frac{1}{\sqrt{6}}D + \frac{1}{\sqrt{2}}P$

Transverse: $A_{-1} = \frac{1}{\sqrt{3}}S + \frac{1}{\sqrt{6}}D - \frac{1}{\sqrt{2}}P$

transverse is not a CP eigenstate



Fortunately, the fraction f_L of the helicity-zero state in $B \to \rho\rho$ decays is very close to 1:

⇨ V-A/pQCD prediction: $f_L \approx 1\text{-}O((m_V/m_B)^2)$

$$f_L(B^0 \to \rho^+\rho^-)_{\mathrm{WA}} = 0.967^{+0.023}_{-0.028}$$

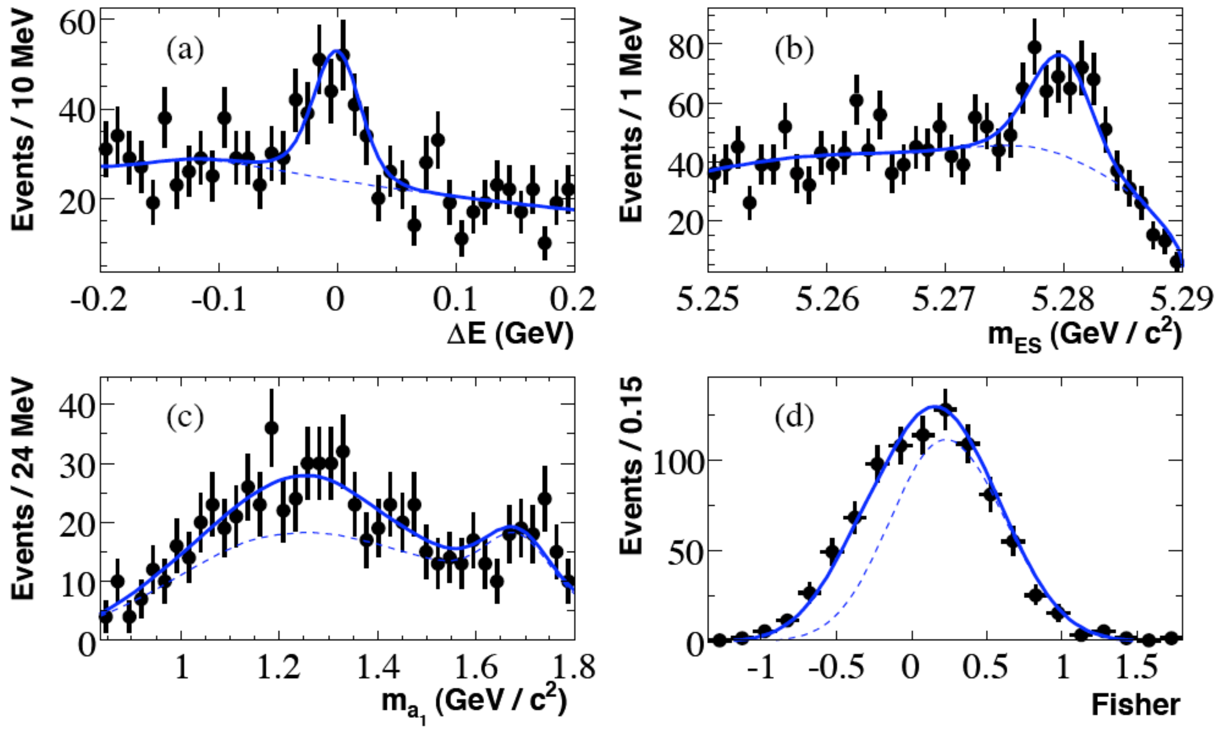
$$f_L(B^\pm \to \rho^\pm\rho^0)_{\mathrm{WA}} = 0.96 \pm 0.06$$

BaBar/Belle Average, April 2006

Don't miss Andrei Gritsan's talk tomorrow morning !

Branching Fraction Measurements: $B^0 \to a_1\pi$

⇨ One of important backgrounds in $B^0 \to \rho^0\rho^0$



Reconstruct exclusively in $a_1^{\pm} \to \pi^+\pi^-\pi^{\pm}$

Based on 218 million $B\overline{B}$ pairs: PRL **97,** 051802 (2006)

$$Br\,(B^0 \to a_1^{\pm}\pi^{\mp}) \times Br\,(a_1^{\pm} \to \rho^0(\pi^+\pi^-)\pi^{\pm}) = (16.6 \pm 1.9 \pm 1.5) \times 10^{-6}$$

(9σ significance)

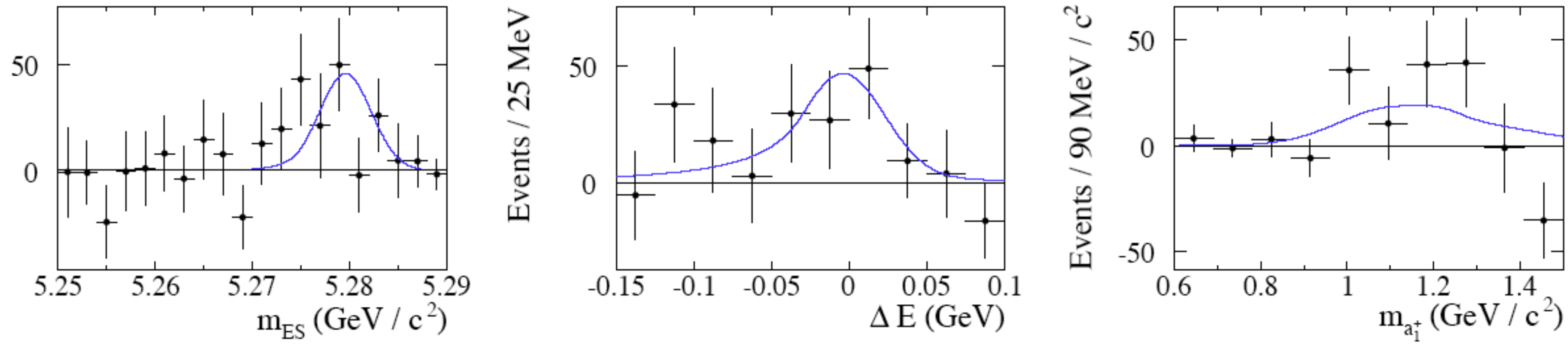
⇨ Potential for measuring α

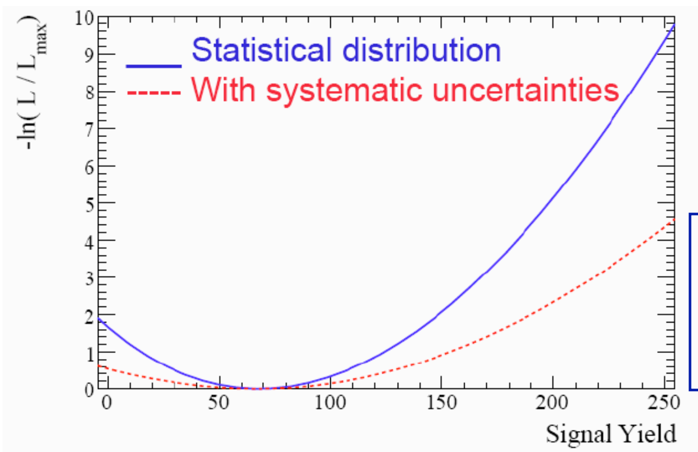
R. Aleksan et al., NP ***B361****, 141 (1991); M. Gronau and J. Zupan, PRD* ***73****, 057502 (2006).*

Branching Fraction Measurements: $B^0 \to a_1 \rho$

⇨ One of important backgrounds in $B^0 \to \rho^+\rho^-$

→ Reconstruct exclusively in $a_1^\pm \to \pi^+\pi^-\pi^\pm$





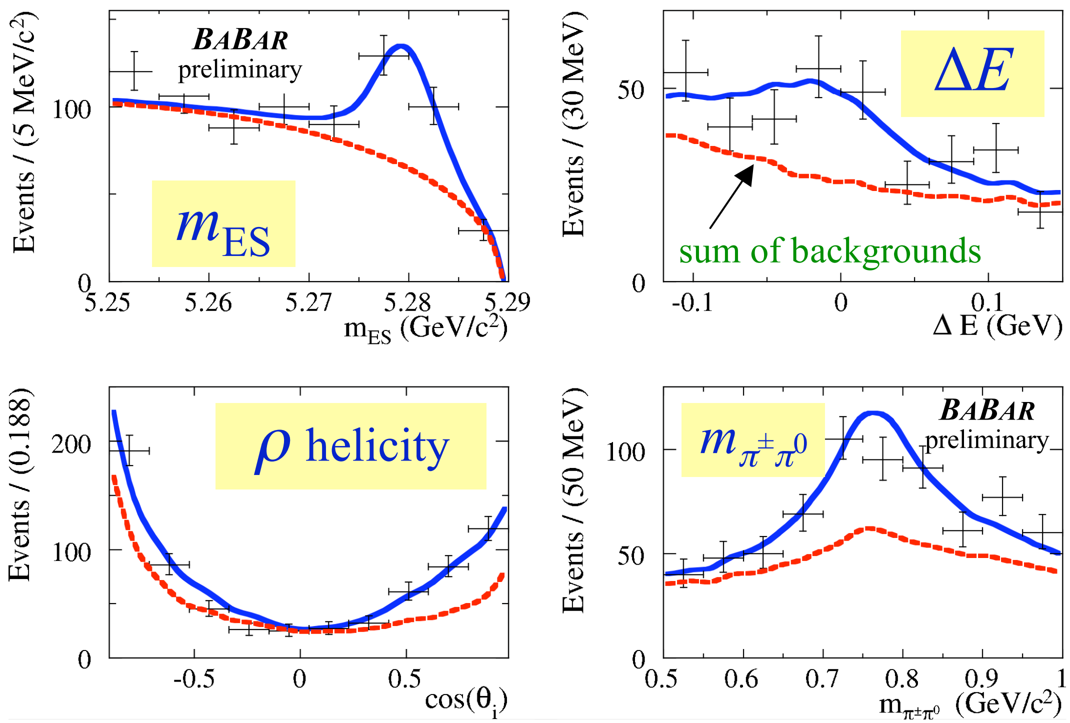
Based on 110 million $B\overline{B}$ pairs: PRD**74**, 031104 (2006)

→ 68 ± 38 events (1σ significance)

$$\boldsymbol{Br\,(B^0 \to a_1^\pm \rho^\mp) \times Br\,(a_1^\pm \to \rho^0(\pi^+\pi^-)\pi^\pm) < 30 \times 10^{-6}\ (90\%\ \mathrm{C.L.})}$$

Updated This Summer: $B^0 \rightarrow \rho^+\rho^-$

distributions for the highest-purity tagged events



hep-ex/0607098

Based on 347 million $B\bar{B}$ pairs

$$N_{\rho^+\rho^-} = 615 \pm 57$$

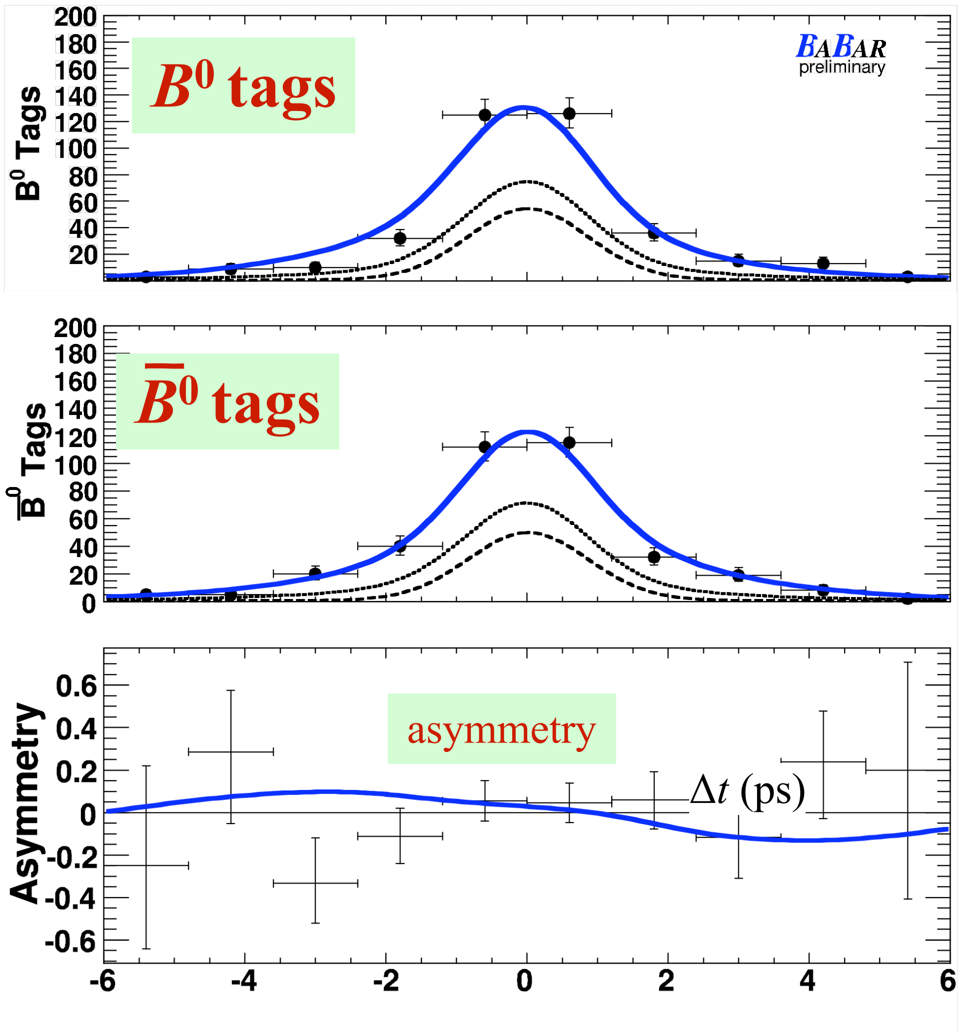
dominated by self-crossfeed

$$Br\,(B^0 \rightarrow \rho^+\rho^-) = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$$

$$f_L(B^0 \rightarrow \rho^+\rho^-) = 0.977 \pm 0.024^{+0.015}_{-0.013}$$

CP Asymmetries in $B^0 \to \rho^+\rho^-$

hep-ex/0607098

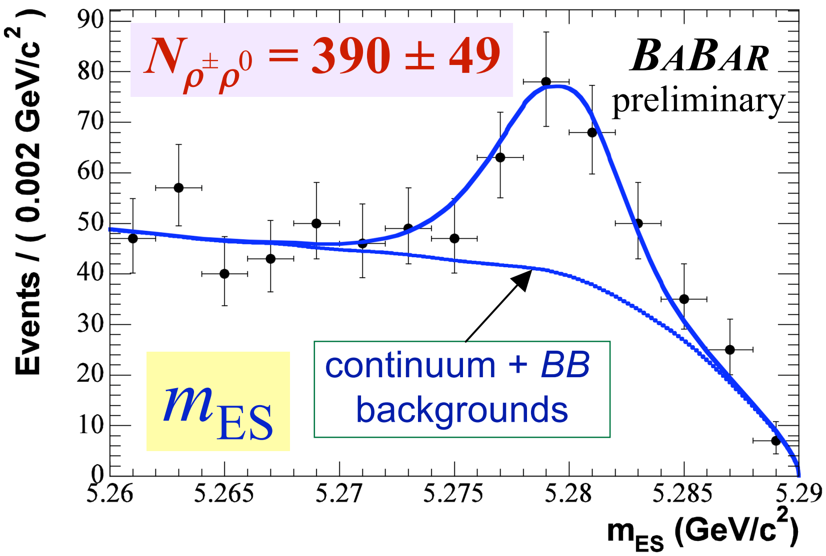


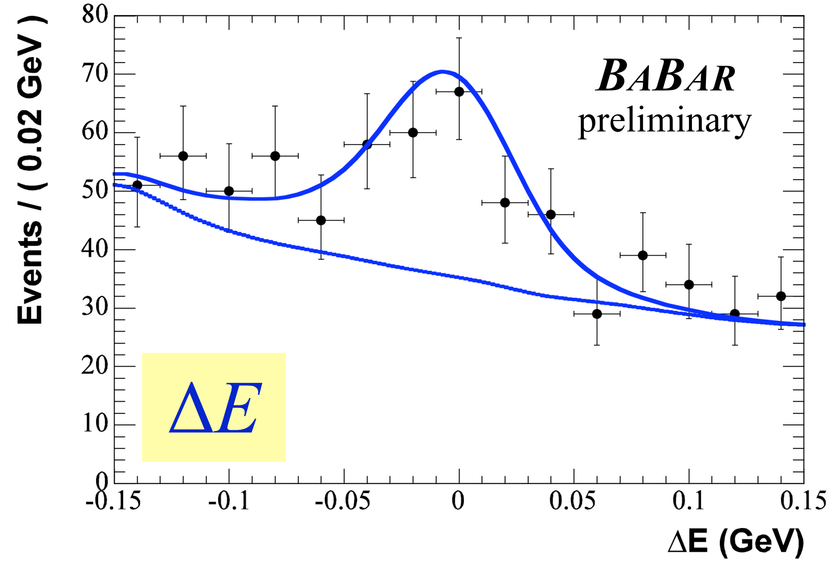
$$S_{long} = -0.19 \pm 0.21^{+0.05}_{-0.07}$$

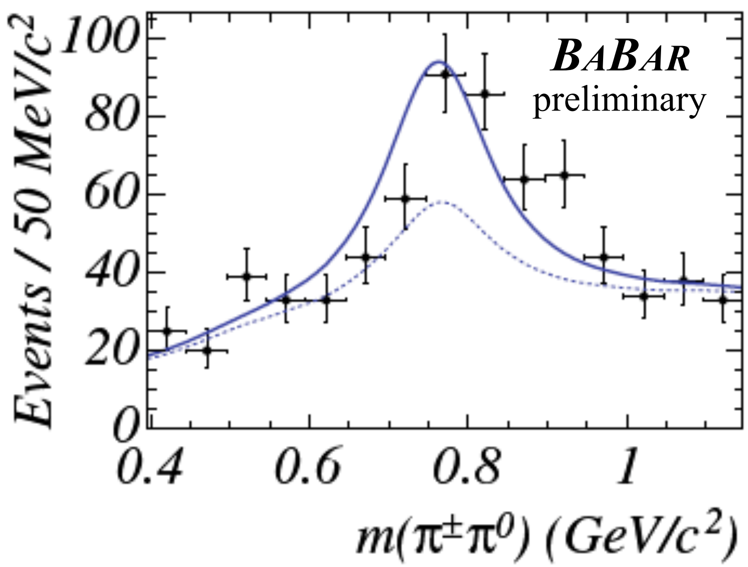
$$C_{long} = -0.07 \pm 0.15 \pm 0.06$$

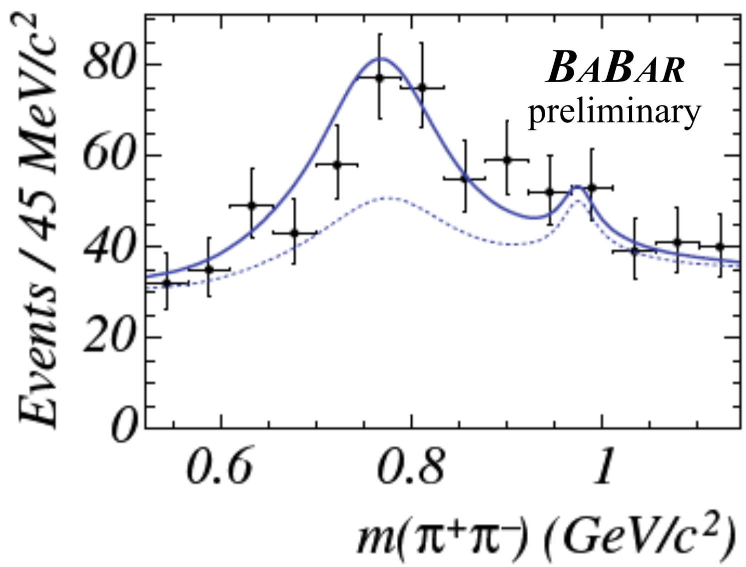
Updated This Winter: $B^{\pm} \rightarrow \rho^{\pm}\rho^{0}$

Based on 232 million $B\bar{B}$ pairs; hep-ex/0607092









$B^{\pm} \to \rho^{\pm}\rho^{0}$ Results

$$Br(B^{\pm} \to \rho^{\pm}\rho^{0}) = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$$

$$f_L(B^{\pm} \to \rho^{\pm}\rho^{0}) = 0.905 \pm 0.042^{+0.023}_{-0.027}$$

$$A_{CP} = -0.12 \pm 0.13 \pm 0.10$$

$$Br(B^{\pm} \to \rho^{\pm} f_0(980)) < 1.9 \times 10^{-6} \text{ (90\% C.L.)}$$

Largest systematic errors:
- modeling of backgrounds
- signal misreconstruction
- statistical uncertainties in signal PDF

The new measurement in $B^{\pm} \to \rho^{\pm}\rho^{0}$ allows the $\rho\rho$ isospin triangle to close

Old results:

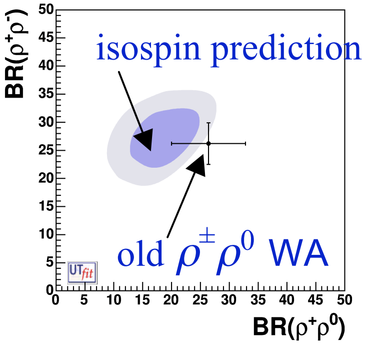
PDG 2004: $(26 \pm 6) \times 10^{-6}$

Belle: $(31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$

Phys. Rev. Lett. **91**, *221801 (2003)*

Previous *BaBar* : $(22.5^{+5.7}_{-5.4} \pm 5.8\ ) \times 10^{-6}$

Phys. Rev. Lett. **91**, *171802 (2003)*



New This Summer: $B^0 \to \rho^0\rho^0$

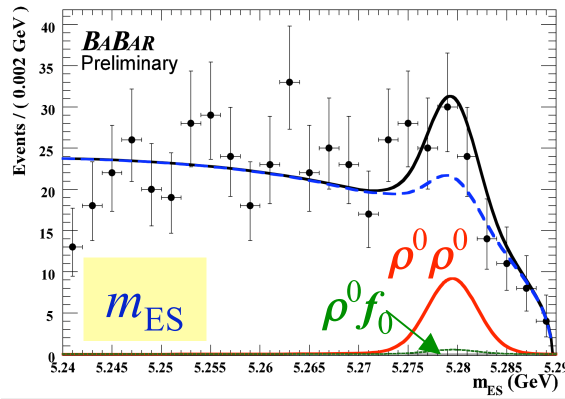
hep-ex/0607097

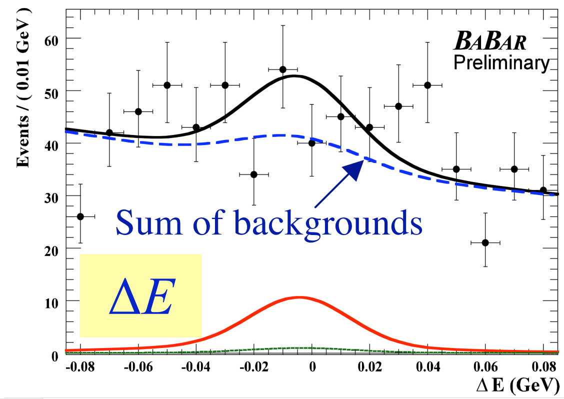
- Incremental improvements in analysis
  - Event selection, ML fit
- 8-dimensional fit
  - m_{ES}, ΔE, event topology, $m(\pi\pi)_{1,2}$, $\cos\theta_{1,2}$ (helicity angles), flavor tags
- Float 8 major components in ML fit
  - ⇨ $B^0 \to \rho^0\rho^0$: simultaneous fit for yield and polarization
  - ⇨ Signal-like modes $B^0 \to \rho^0 f_0(980)$ and $B^0 \to f_0(980) f_0(980)$
  - $B^0 \to a_1\pi$ (dominant peaking background)
  - Peaking backgrounds from open charm decays
    - ☞ E.g. $B^0 \to D\pi\ (D \to K\pi\pi)$
  - Charmless decays
    - ☞ E.g. $B \to K^{*0}\rho^0$, $\rho^{\pm}\rho^0$
  - Combinatorial background (dominated by continuum)
    - ☞ Determine shape from data, float parameter values

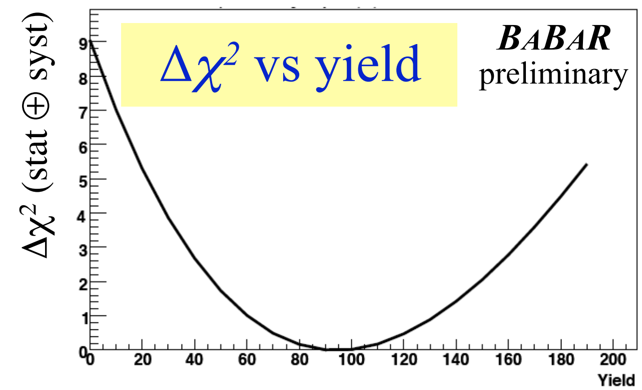
⇨ Results statistically consistent with the previous BaBar analyses

Evidence for $B^0 \to \rho^0\rho^0$

hep-ex/0607097







$$N_{\rho^0\rho^0} = 98^{+32}_{-31} \pm 22 \text{ (3.0}\sigma\text{ significance)}$$

$$Br\,(B^0 \to \rho^0\rho^0) = (1.16\,^{+0.37}_{-0.36} \pm 0.27) \times 10^{-6} \qquad f_L(B^0 \to \rho^0\rho^0) = 0.86^{+0.11}_{-0.13} \pm 0.05$$

Also measure:

$$Br\,(B^0 \to \rho^0 f_0) \times Br\,(f_0 \to \pi^+\pi^-) < 0.68 \times 10^{-6} \text{ (at 90\% C.L.)}$$

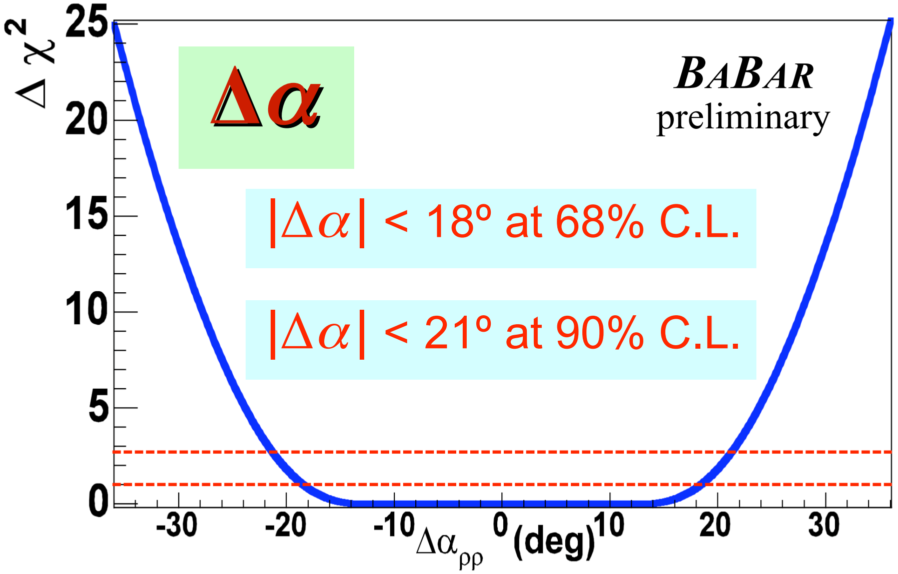
$$Br\,(B^0 \to f_0 f_0) \times Br^{\,2}(f_0 \to \pi^+\pi^-) < 0.33 \times 10^{-6} \text{ (at 90\% C.L.)}$$

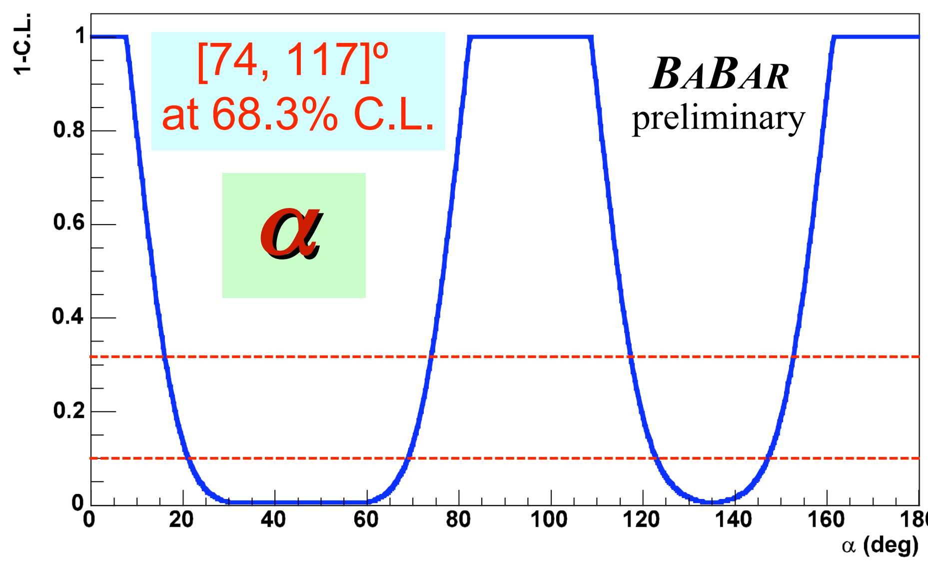
Largest systematic errors: interference with $B^0 \to a_1(1260)\pi$ and PDF parameter uncertainties

New $B \to \rho\rho$ Results: Summary

hep-ex/0607097, hep-ex/0607098

Due to increased $Br(B^0 \to \rho^0\rho^0)$, weaker constraint on α from $B \to \rho\rho$



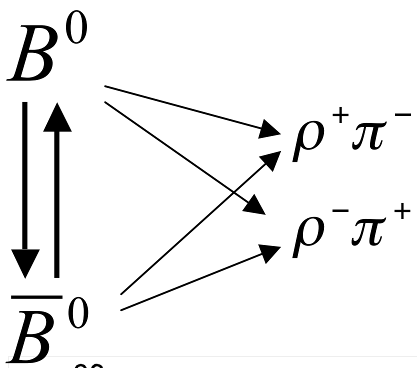


This is a *frequentist* interpretation: use only the $B \to \rho\rho$ branching fractions, polarization fractions and isospin-triangle relations in arriving at these constraints on $\Delta\alpha = \alpha - \alpha_{\text{eff}}$ and α

With more statistics, determination of both C and S in $B^0 \to \rho^0\rho^0$ will be possible, leading to an improvement in the precision of the the ρρ isospin analysis

$B^0 \to (\rho\pi)^0$: Dalitz-plot analysis

hep-ex/0608002

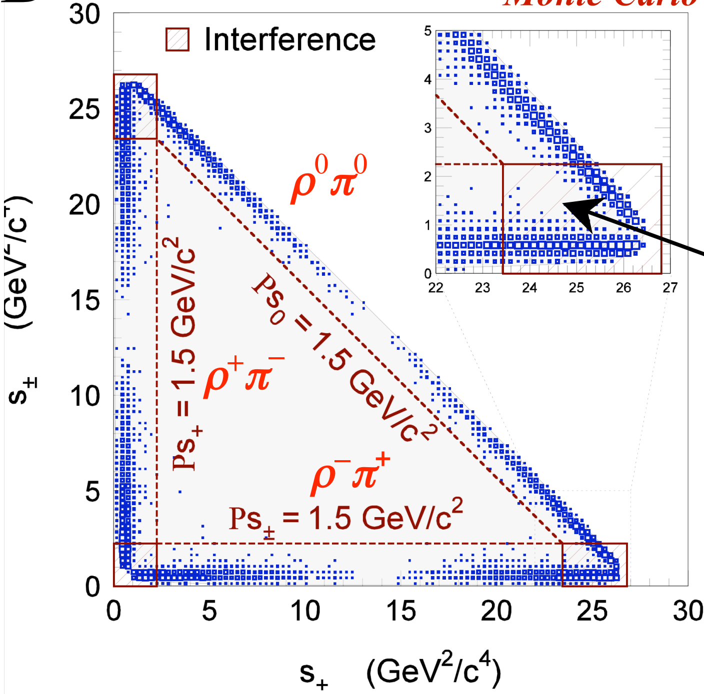


$\rho\pi$ is not a CP eigenstate

⇨ Time-dependent Dalitz-plot analysis assuming isospin symmetry: measure 26 coefficients of the bilinear form factors

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

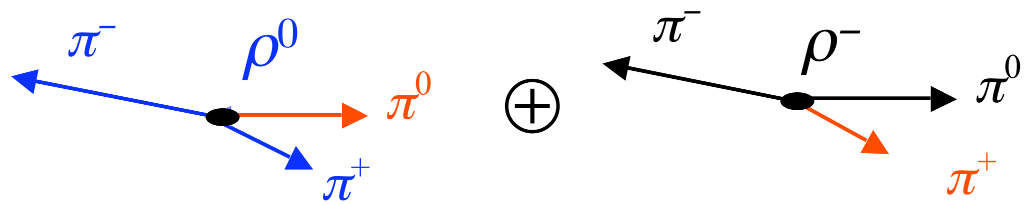
Monte Carlo



$$A(B^0 \to \pi^+\pi^-\pi^0) = f_+ A(\rho^+\pi^-) + f_- A(\rho^-\pi^+) + f_0 A(\rho^0\pi^0)$$

$$\widetilde{A}(\overline{B}^0 \to \pi^+\pi^-\pi^0) = f_+ \widetilde{A}(\rho^+\pi^-) + f_- \widetilde{A}(\rho^-\pi^+) + f_0 \widetilde{A}(\rho^0\pi^0)$$

Interference in the corners of the Dalitz plot provides information on *strong phases* between resonances

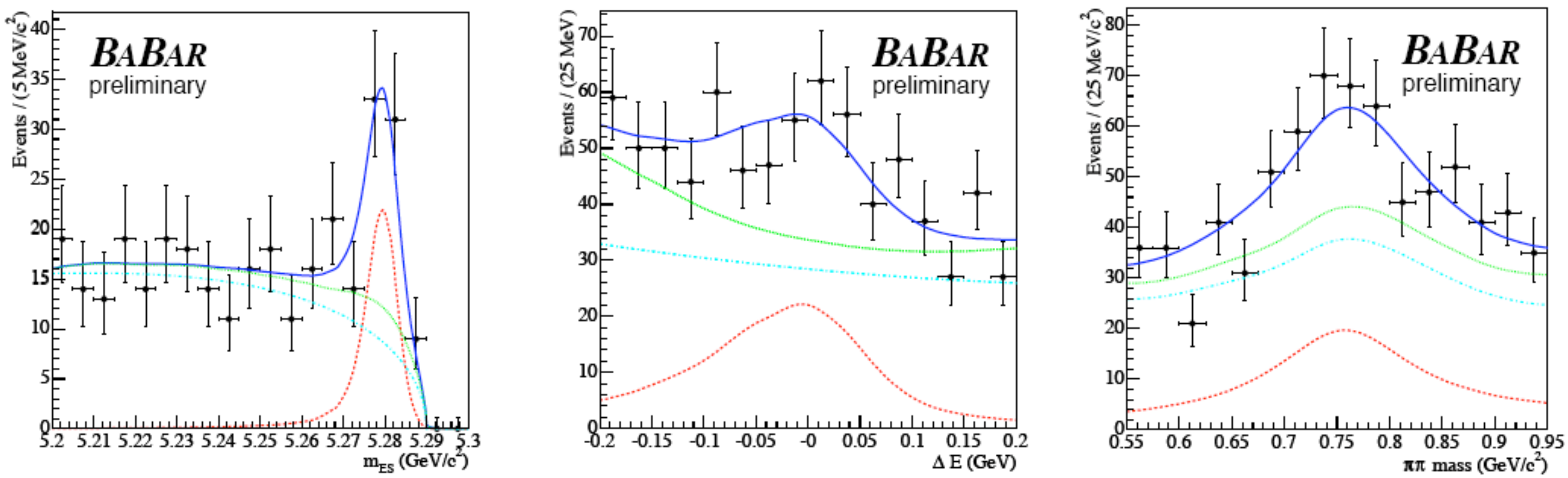


The $\rho(1450)$ and $\rho(1700)$ resonances are also included

One of the Ingredients: $B^+ \rightarrow \rho^+\pi^0$

Based on 232 million $B\bar{B}$ pairs; hep-ex/0506069

⇨ Constrain isospin relationships in $B^0 \rightarrow \rho\pi$ system

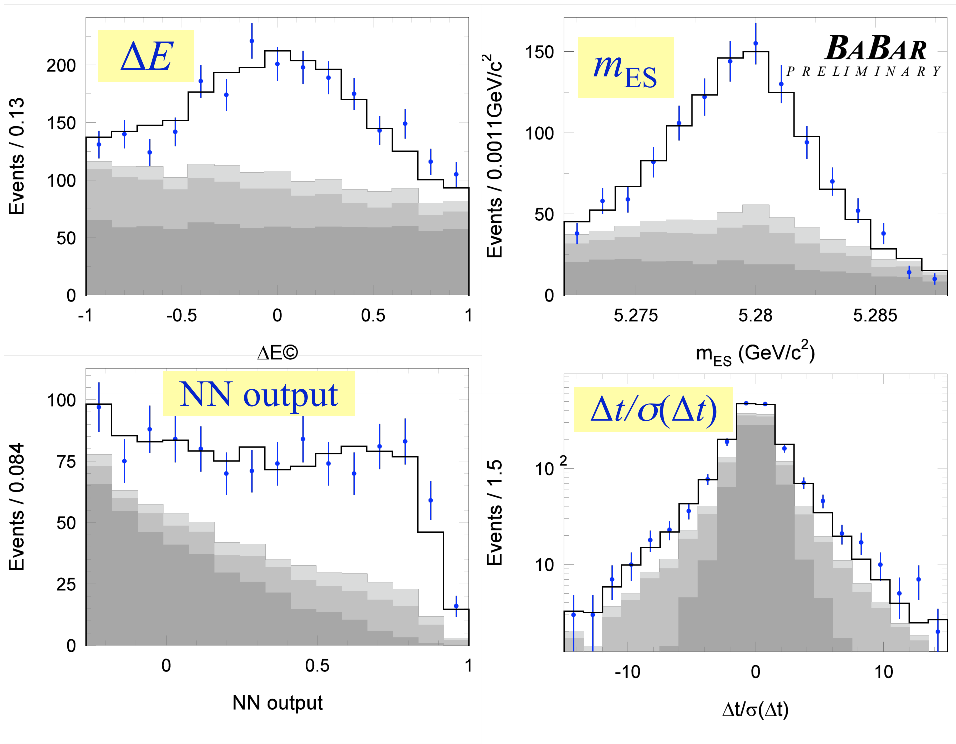


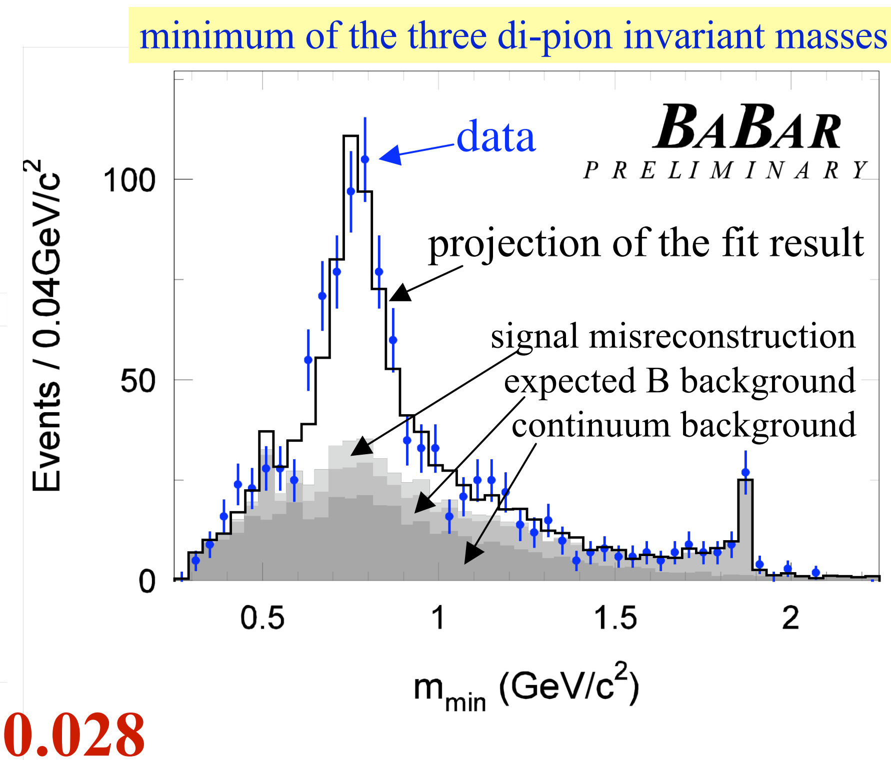
$$Br(B^{\pm} \rightarrow \rho^{\pm}\pi^0) = (10.0 \pm 1.4 \pm 0.9) \times 10^{-6}$$

$$A_{CP} = -0.01 \pm 0.13 \pm 0.02$$

New Results This Summer: $B^0 \to (\rho\pi)^0$

hep-ex/0608002





$$S_{\rho\pi} = \quad 0.01 \pm 0.12 \pm 0.028$$

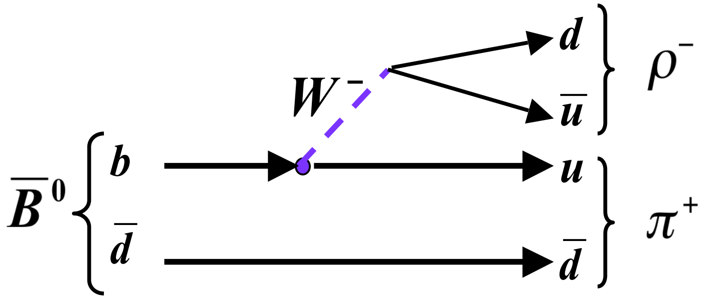
$$C_{\rho\pi} = \quad 0.154 \pm 0.090 \pm 0.037$$

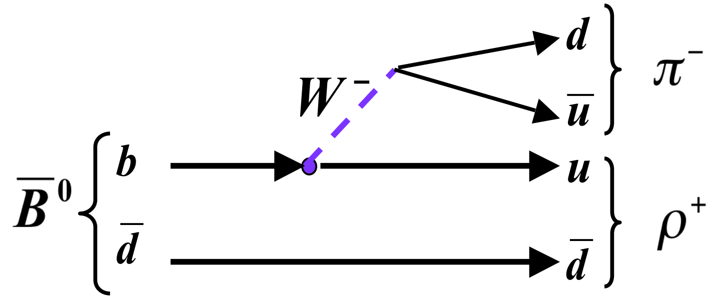
$$A_{\rho\pi} = -0.142 \pm 0.041 \pm 0.015$$

New $B^0 \to (\rho\pi)^0$ Results (cont.)

hep-ex/0608002

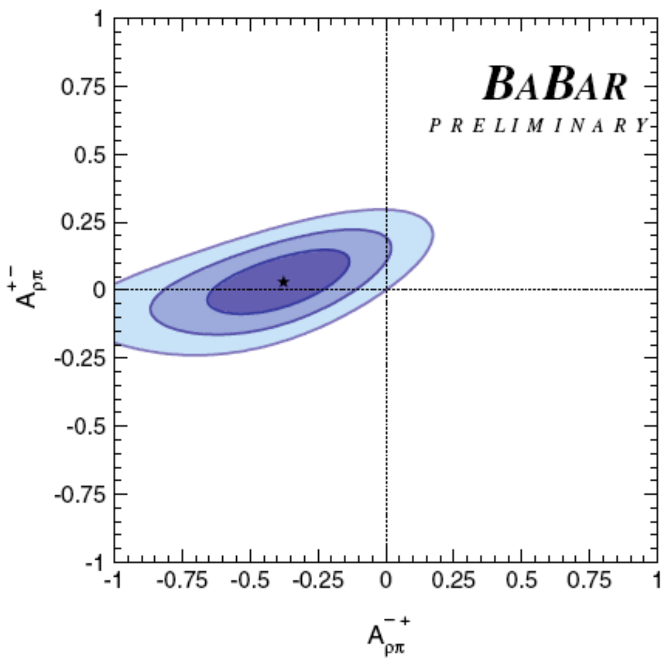
A more physical interpretation of direct-*CP* quantities:





$$A_{\rho\pi}^{+-} = 0.03 \pm 0.07 \pm 0.03$$

$$A_{\rho\pi}^{-+} = -0.38^{+0.15}_{-0.16} \pm 0.07$$



Quasi-two-body description of $B \to \rho\pi$:

$$\Delta S_{\rho\pi} = 0.06 \pm 0.13 \pm 0.029$$

$$\Delta C_{\rho\pi} = 0.377 \pm 0.091 \pm 0.021$$

Physical Interpretation

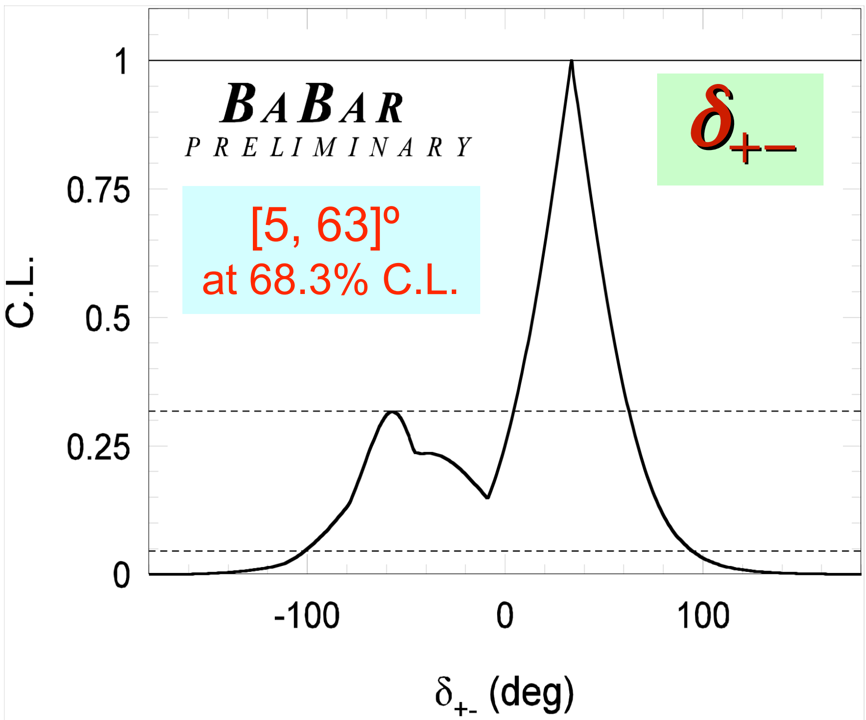
The relative phase between the amplitudes of
$B^0 \to \rho^- \pi^+$ and $B^0 \to \rho^+ \pi^-$

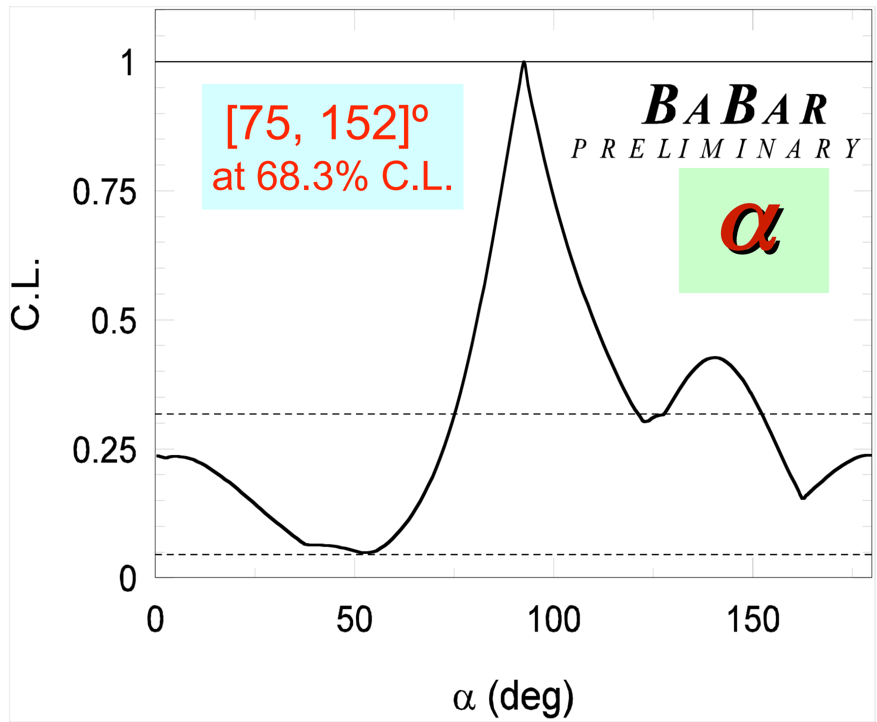
$$\delta_{+-} = \arg(A^{+*} A^-) = (34 \pm 29)^o$$

hep-ex/0608002

Constraint on α

no constraint at 2σ level

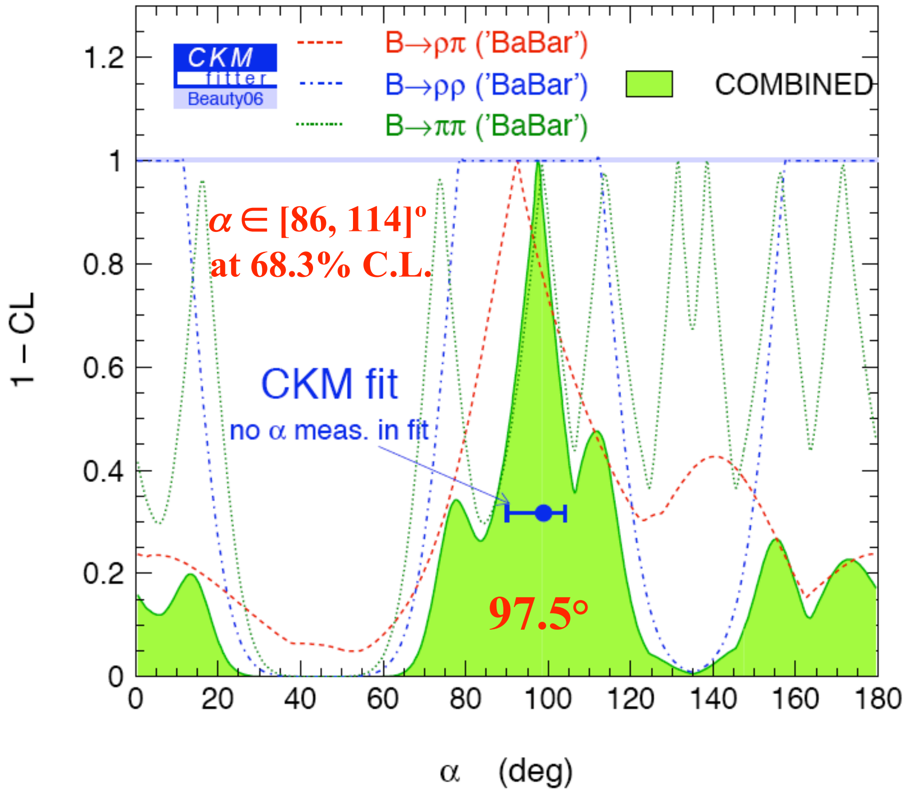


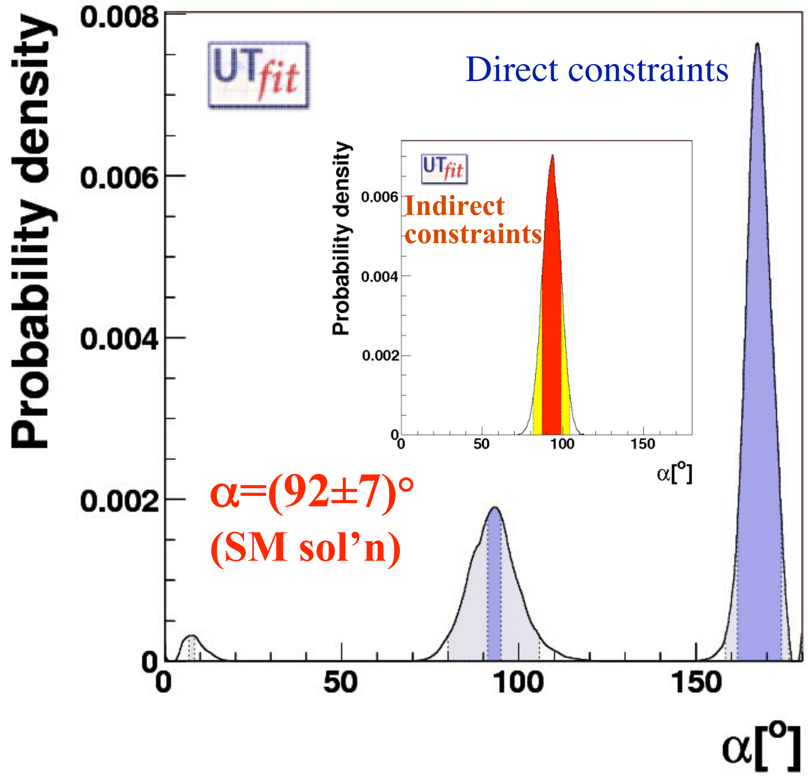


Relatively weak constraint on α from $B^0 \to (\rho\pi)^0$, but free from ambiguities!

Combined Constraints on α from BaBar

Constraints on ***α*** from ***B → ππ, ρπ, ρρ*** (Frequentist and Bayesian analyses):





CKMfitter Group (J. Charles et al.), Eur. Phys. J. C**41**, 1-131 (2005), [hep-ph/0406184], updated results and plots available at http://ckmfitter.in2p3.fr

M. Ciuchini, G. D'Agostini, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, P. Roudeau, A. Stocchi, JHEP **0107** (2001) 013 [hep-ph/0012308], updated results and plots available at http://utfit.roma1.infn.it

Summary

- New results from BaBar this year
  - First evidence for $B^0 \to \rho^0\rho^0$
  - New measurements of branching ratios and CP asymmetries in $B^\pm \to \rho^\pm\rho^0$ and $B^0 \to \rho^+\rho^-$
  - Dalitz analysis of $B^0 \to \pi^+\pi^-\pi^0$ decays
- More clarity to come with more data
  - Currently, constraints on α depend on details of theoretical and statistical treatment; these discrepancies should be clarified with more precise measurements
  - CP analysis in $B^0 \to \rho^0\rho^0$ is becoming possible: could reduce the uncertainty on α to ~10 degrees by the end of current B-factory era