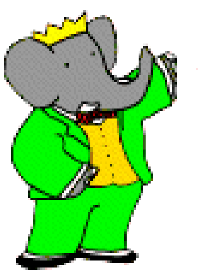
CP Violation: angle α of the Unitarity Triangle

Christos Touramanis

The University of Liverpool

BABAR Collaboration



THE UNIVERSITY *of* LIVERPOOL

Heavy Quarks and Leptons – HQL06

Munich, 18 October 2006

Outline

- Introduction
  - The experiments
  - The measurements

BABAR™ at SLAC

BELLE at KEK

- Results from the B Factories

$$B \to \pi^+\pi^- \;,\; \pi^\pm\pi^0 \;,\; \pi^0\pi^0$$

$$B \to \rho^+\rho^- \;,\; \rho^\pm\rho^0 \;,\; \rho^0\rho^0$$

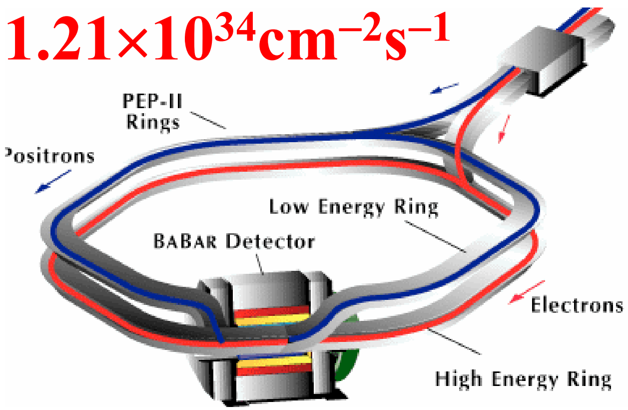
$$B \to (\rho\pi)^0$$

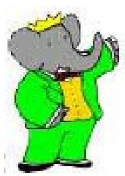
- Summary and outlook

Asymmetric-energy *B* Factories

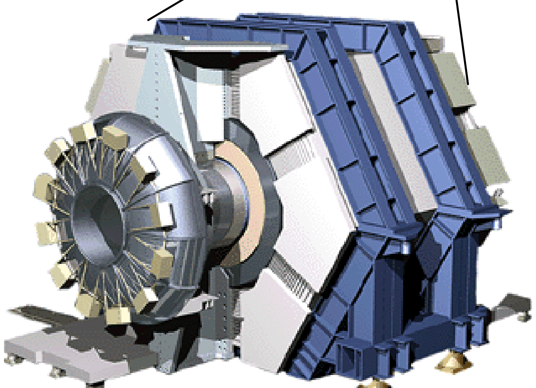
PEP-II at SLAC

9GeV (e^-) × 3.1GeV (e^+)
peak luminosity:
$1.21 \times 10^{34} cm^{-2} s^{-1}$



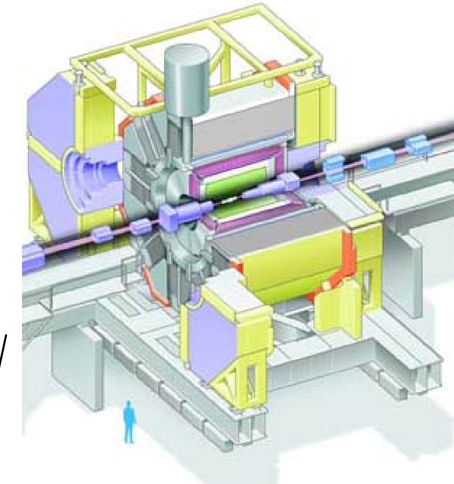


BaBar

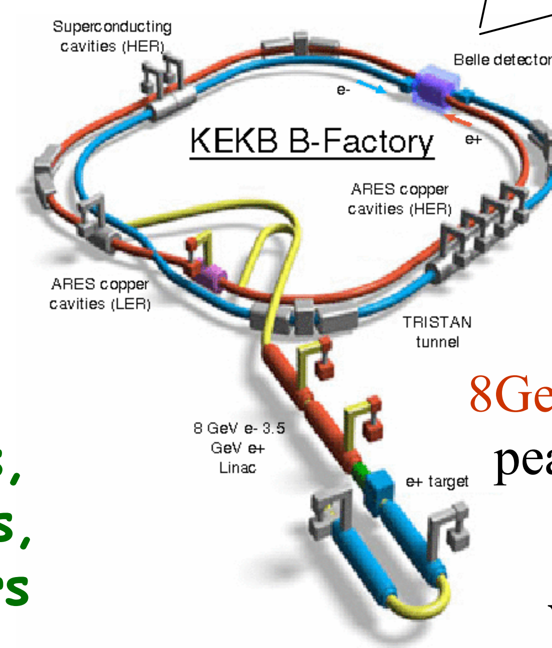


11 countries,
80 institutes,
620 members

13 countries,
57 institutes,
400 members



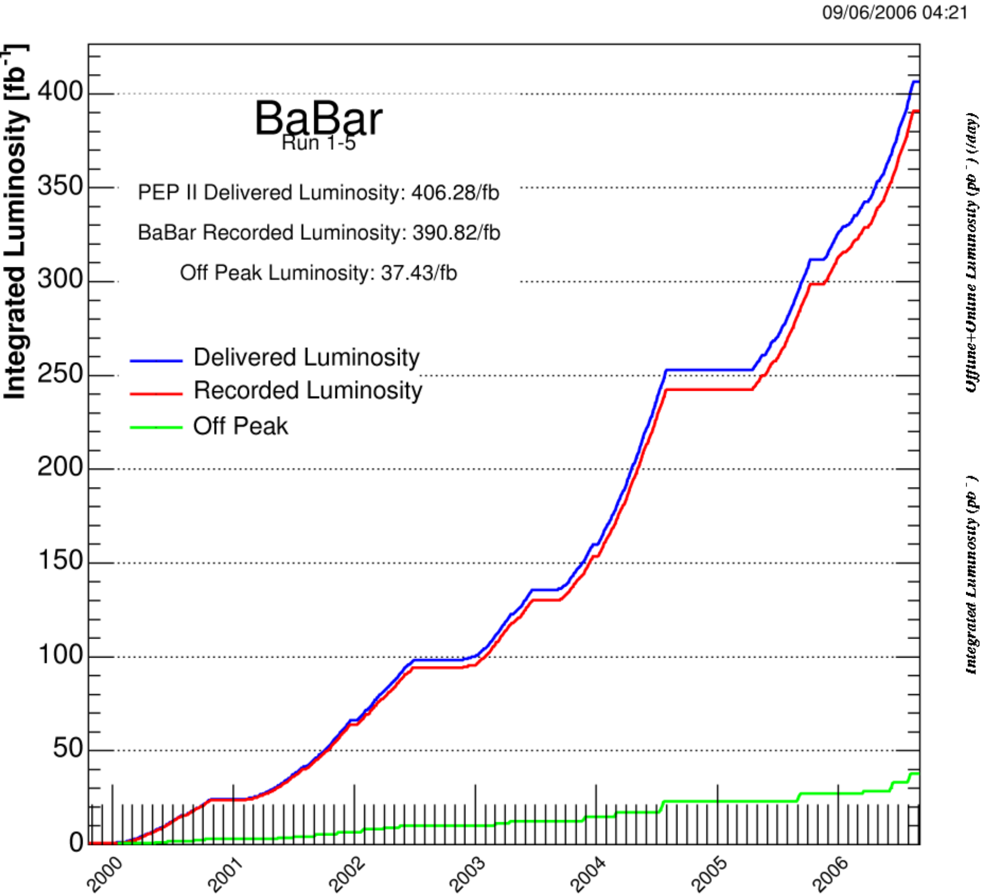
Belle

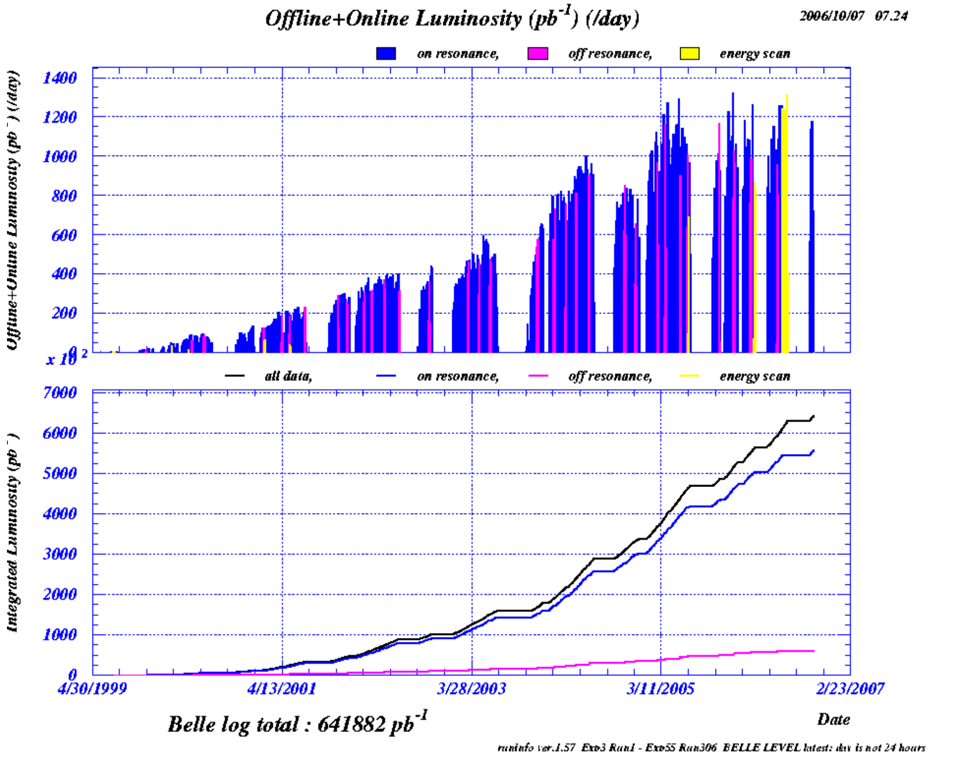


KEKB at KEK

8GeV (e^-) × 3.5GeV (e^+)
peak luminosity:
$1.65 \times 10^{34} cm^{-2} s^{-1}$
world record

B Factories reach 1000fb^{-1} !!!

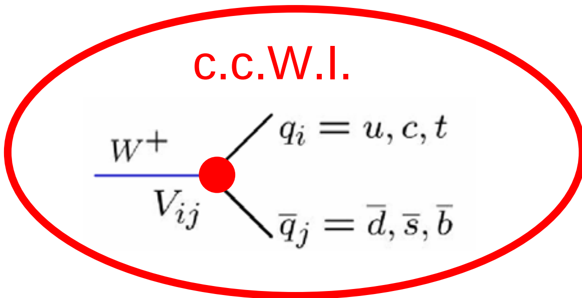




1 Billion B pairs

Both B Factories exceeding design specifications

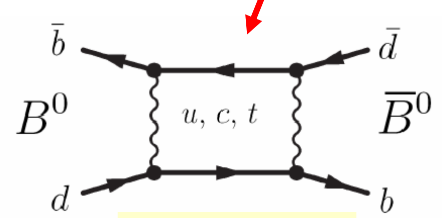
Accessing the phase of the CKM matrix



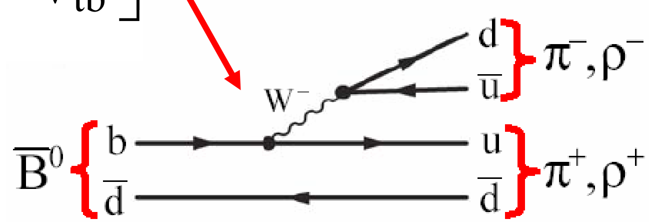
$$V_{CKM} \approx \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

(Wolfenstein parametrisation)

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



B mixing

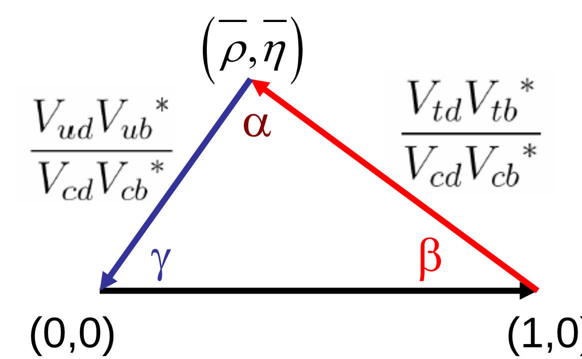


Charmless B decays

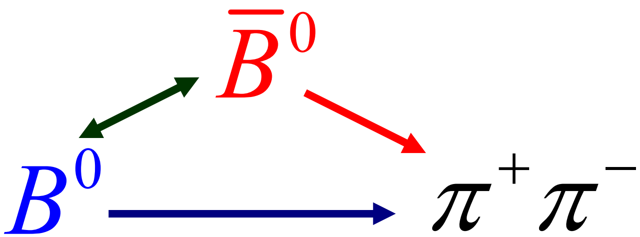
$\beta\ (\phi_1)$: phase of V_{td}

$\gamma\ (\phi_3)$: phase of V_{ub}

$\alpha\ (\phi_2) = \pi - \beta - \gamma$



Experimental method



Interference of decays with and without mixing
("double-slit" matter-antimatter experiment)

Time-dependent Decay Rates Asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = S\sin(\Delta m_{B_d} t) - C\cos(\Delta m_{B_d} t)$$

$$S = \frac{2\,\mathrm{Im}(\lambda)}{1+|\lambda|^2} \quad , \quad C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

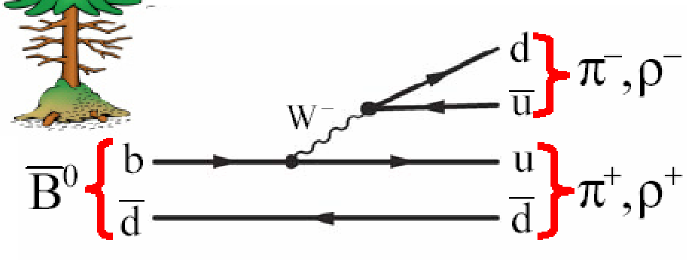
$$\lambda = \frac{q}{p}\frac{\overline{A}}{A} = e^{-2i\beta}e^{-2i\gamma} = e^{-2i\alpha}$$

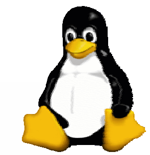
$$S = \sin(2\alpha)$$

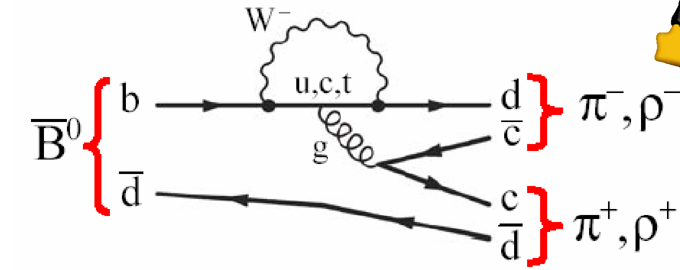
$$C = 0$$

- True in the case of tree amplitudes only
- C=0: no Direct CP violation
- Requires time-dependent measurement
    - Boost of asymmetric B Factories
    - Silicon vertex detectors
    - B flavor tagging (PID)

Trees and Penguins







$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S \sin(\Delta m_{B_d} t) - C \cos(\Delta m_{B_d} t)$$

$$\lambda = e^{i2\alpha} \frac{T + P e^{+i\gamma} e^{i\delta}}{T + P e^{-i\gamma} e^{i\delta}}$$

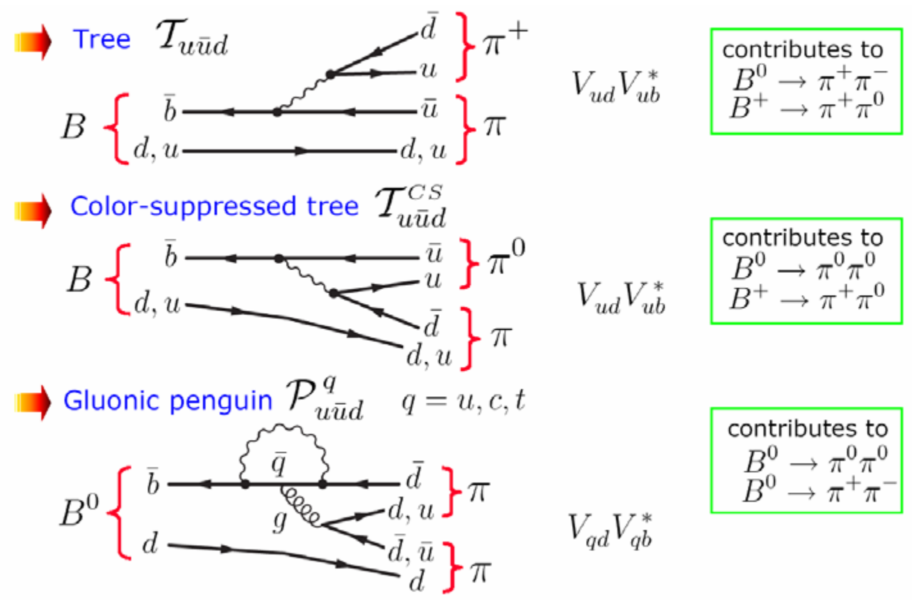
$$S = \sqrt{1 - C^2} \sin(2\alpha_{eff})$$

$$C \propto \sin\delta$$

- choice of final states: $\pi\pi$, $\rho\pi$, $\rho\rho$, $\alpha_1\pi$
- challenge: measure or limit $\Delta\alpha$

$$\Delta\alpha = |\alpha - \alpha_{eff}|$$

Controlling the Penguins



Large penguins lead to:

- sizable $\pi^0\pi^0$

And <u>may</u> give rise to:

- Direct CPV in any mode
- Large $\Delta\alpha$

Extraction of a from B→hh (h=π,ρ) requires a <u>set of</u> measurements

- Strong upper limit on h^0h^0 leads to strong limit on $\Delta\alpha$
- Otherwise $\Delta\alpha$ must be calculated from full set of measurements on all related channels

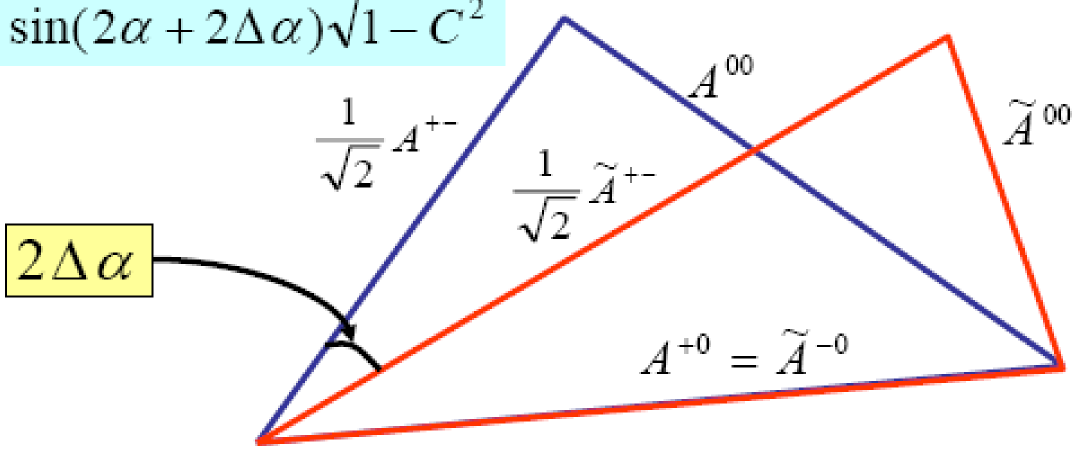
Isospin analysis

- SU(2) symmetry relating u, d quarks
- EW penguins and other SU(2)-breaking effects can be ignored at current precision levels
- Need full set of BF and A_{CP} measurements

Gronau and London, Phys. Rev. Lett. 65, 3381 (1990)

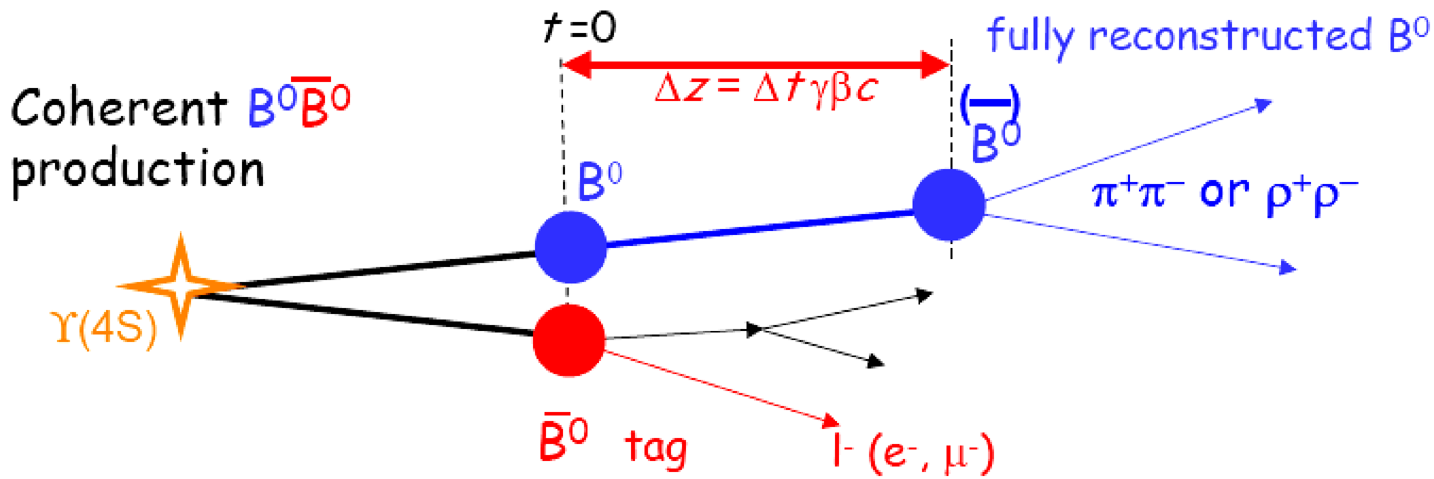
$$A^{+-} = A(B^0 \to h^+h^-)$$
$$\tilde{A}^{+-} = A(\overline{B}^0 \to h^+h^-)$$
$$A^{+0} = A(B^+ \to h^+h^0)$$
$$\tilde{A}^{-0} = A(B^- \to h^-h^0)$$
$$A^{00} = A(B^0 \to h^0h^0)$$
$$\tilde{A}^{00} = A(\overline{B}^0 \to h^0h^0)$$

$$S = \sin(2\alpha + 2\Delta\alpha)\sqrt{1-C^2}$$



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

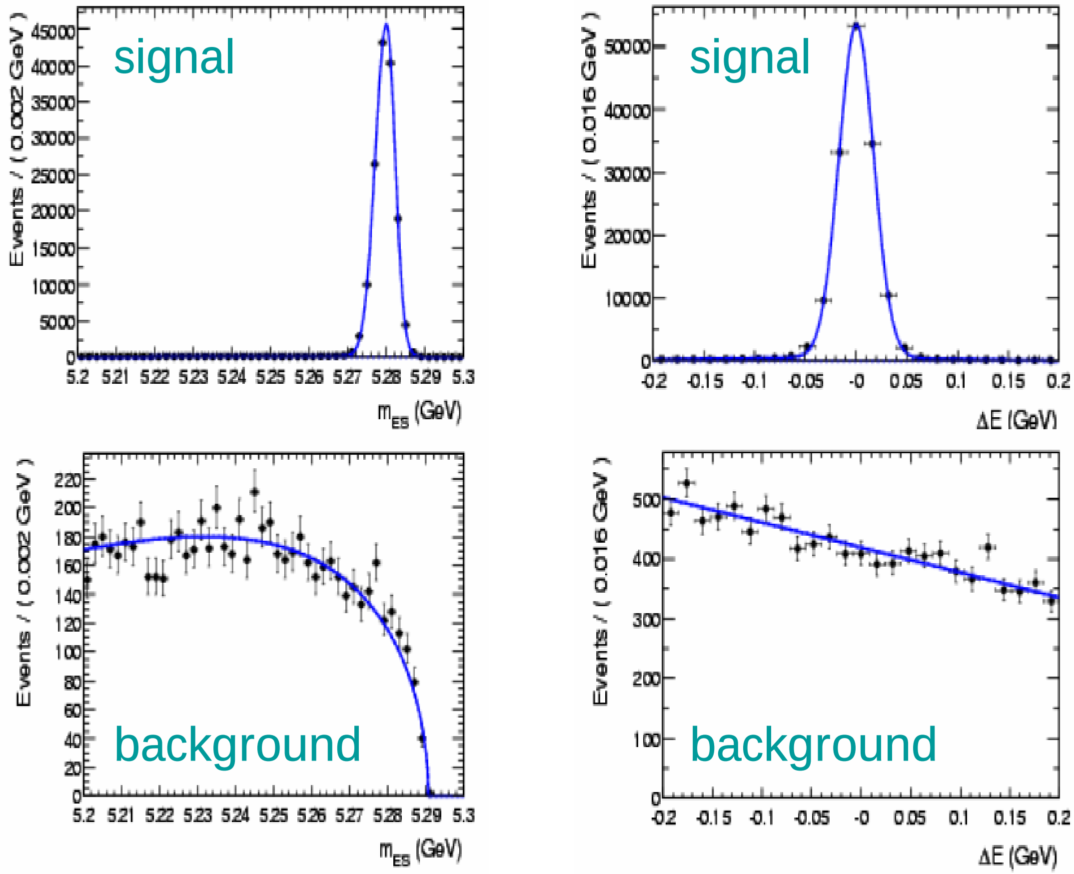
Time-dependent CP analysis



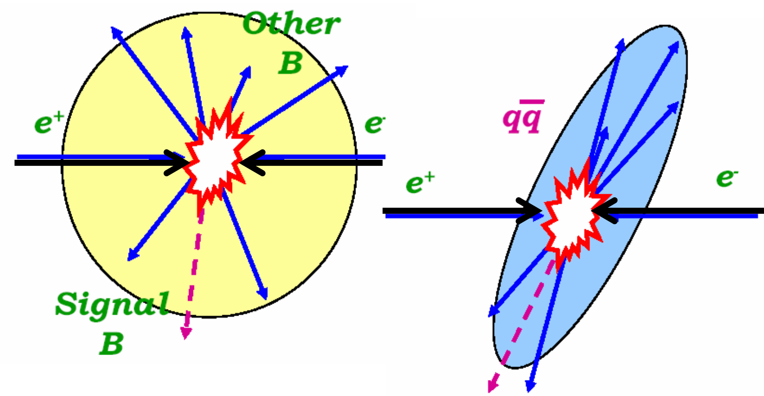
- Full reconstruction of one B decaying to CP eigenstate.
- Flavor tagging of the other B.
  - Mis-tag probability measured in B_{flav} sample.
- Measurement of Δt.
- Extraction of S and C with ML fit on signal enriched sample.
  - Signal PDFs from MC.
  - Background PDFs from MC or sidebands

Signal-background separation

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}} \qquad \Delta E = E_B^{*} - E_{beam}^{*}$$



Event Topology Variables combined in Fisher Discriminant or Neural Net



- PID info:
  - DIRC + dE/dX (BaBar)
  - Aerogel + dE/dX (Belle)

$B \to \pi\pi$

- Common wisdom (pre-2003):
  - Best system for extracting α (experimentally easiest modes)
- But penguins turned out to be large:
  - Sizable $\pi^0 \pi^0$ (BABAR and Belle)
  - Large Direct CPV (A_{CP}) in $\pi^+ \pi^-$ (Belle)

$B \to \pi^+\pi^-$

hep-ex/0607106

New Results (ICHEP)

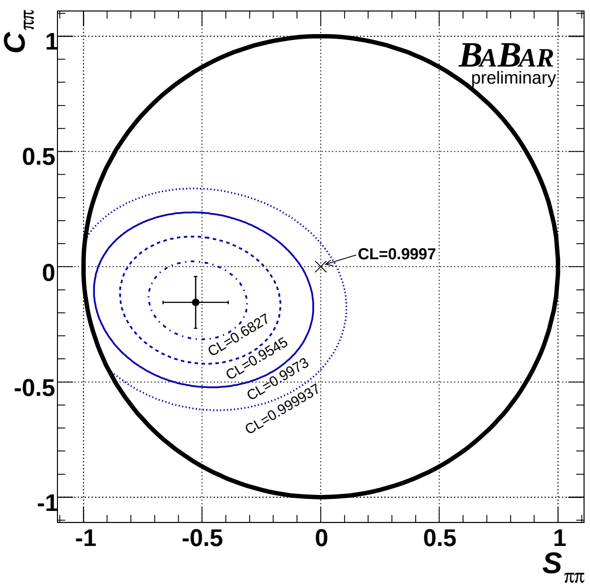
347×10^6 B pairs

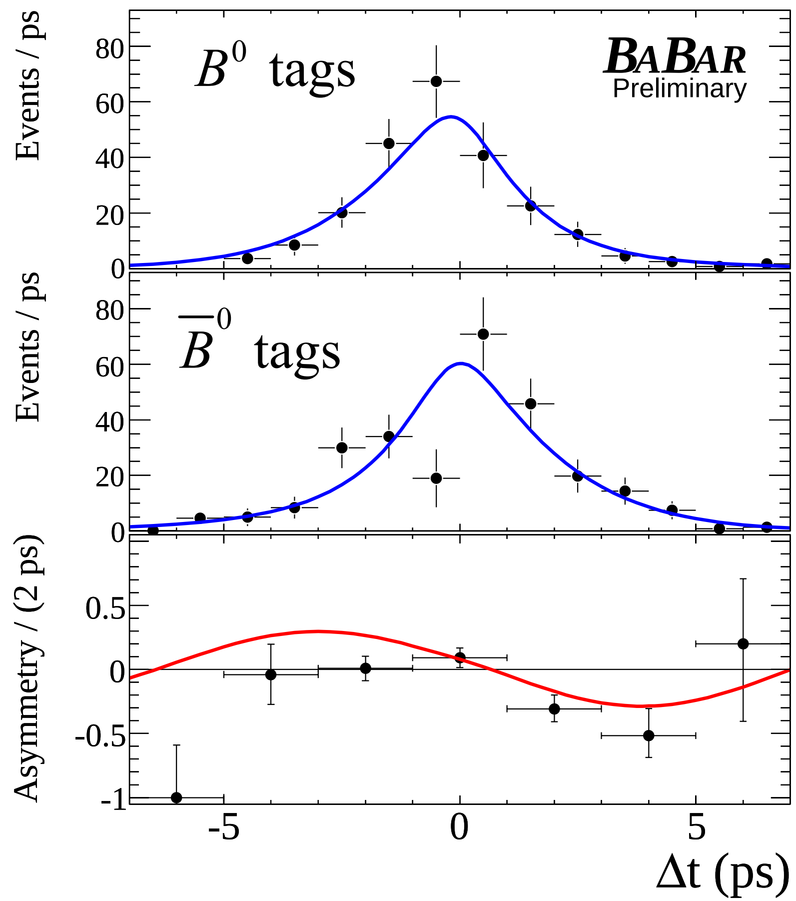
675±42 signal events

$$S_{\pi\pi} = -0.53 \pm 0.14 \pm 0.02$$

$$C_{\pi\pi} = -0.16 \pm 0.11 \pm 0.03$$

(preliminary)





(S,C) = (0,0) excluded
at a confidence level of 0.9997 (3.6 σ)

$B \to \pi^+ \pi^-$

hep-ex/0608035

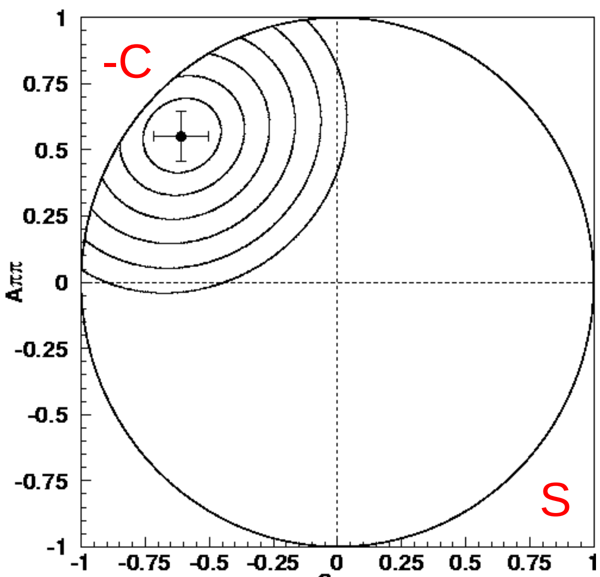
New Results (ICHEP)

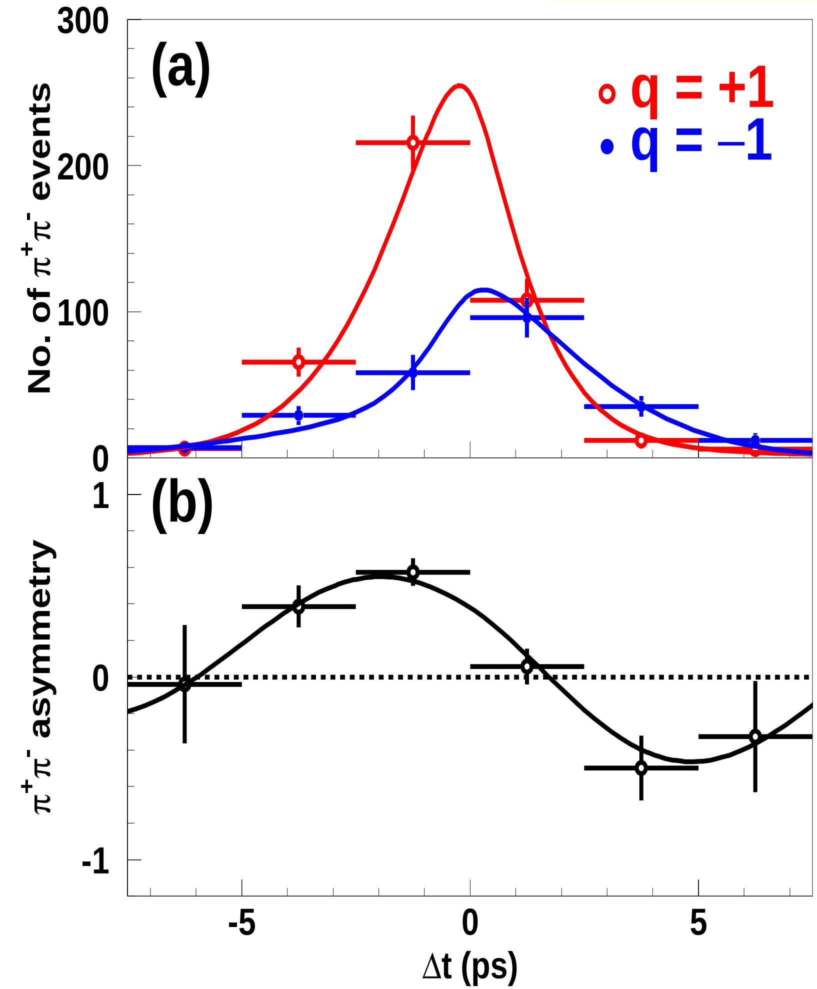
535x10^6 B pairs

1464±65 signal events

$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$$

$$C_{\pi\pi} = -0.55 \pm 0.08 \pm 0.05$$

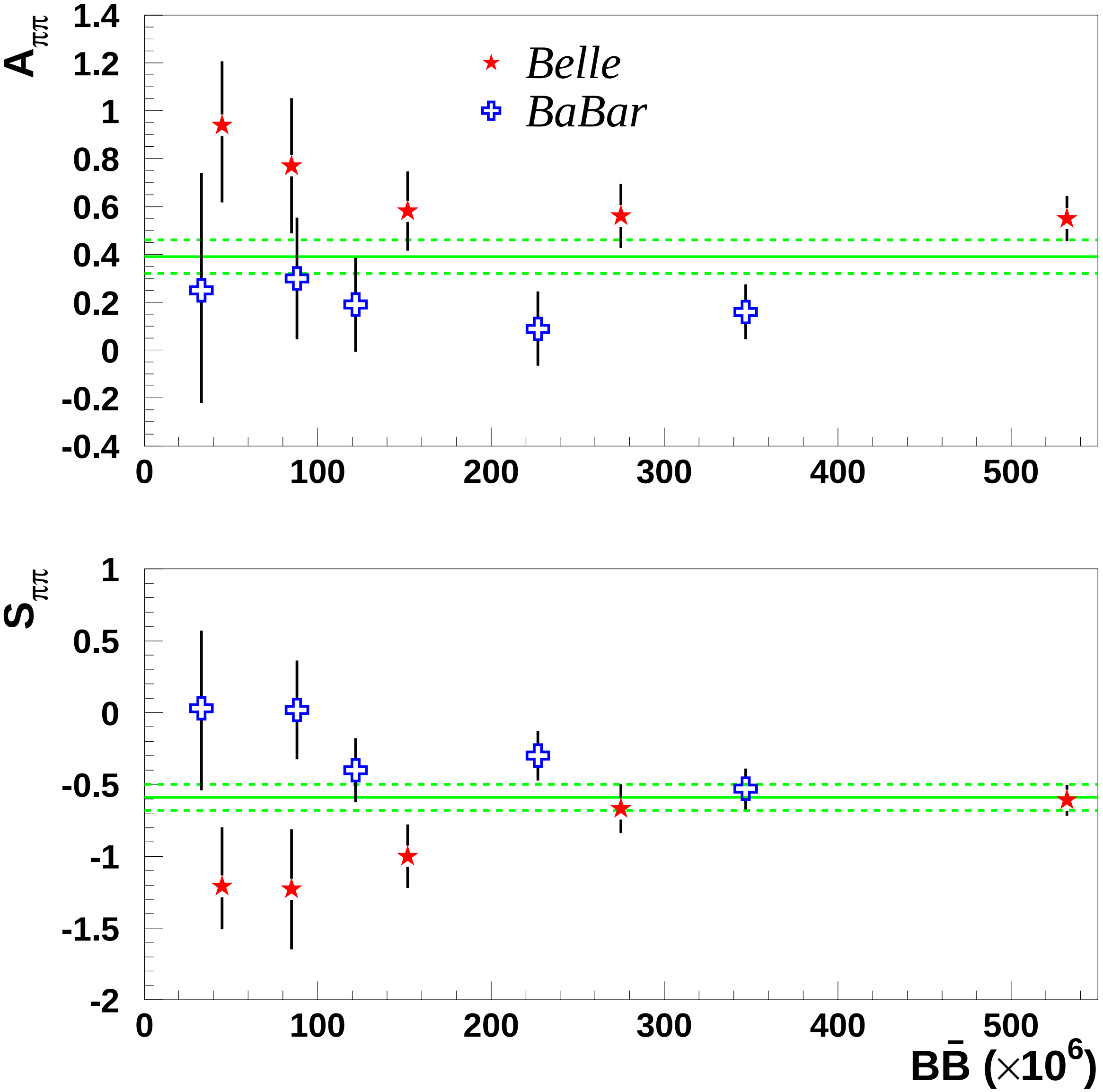




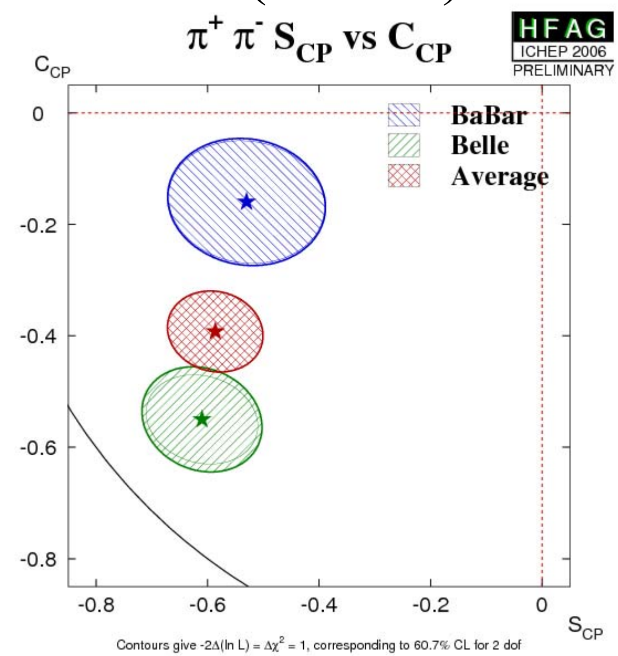
Large Direct CP Violation (5.5 σ)

Large Mixing-induced CP Violation (5.6 σ)

$B \to \pi^+\pi^-$ A long-standing issue



$(C = -\mathcal{A})$



2.3σ discrepancy

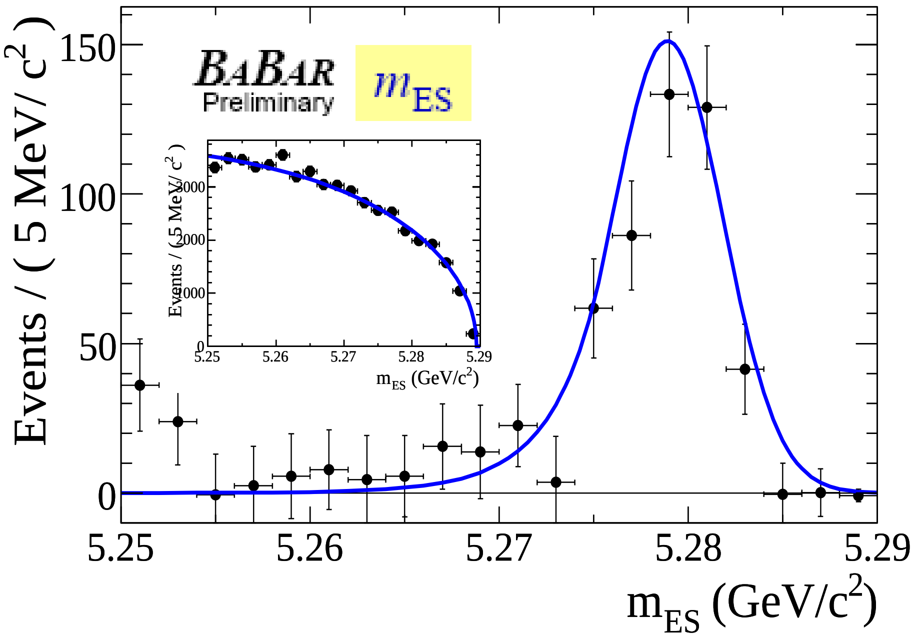
$B \to \pi^+\pi^0, \pi^0\pi^0$

New Results (ICHEP)

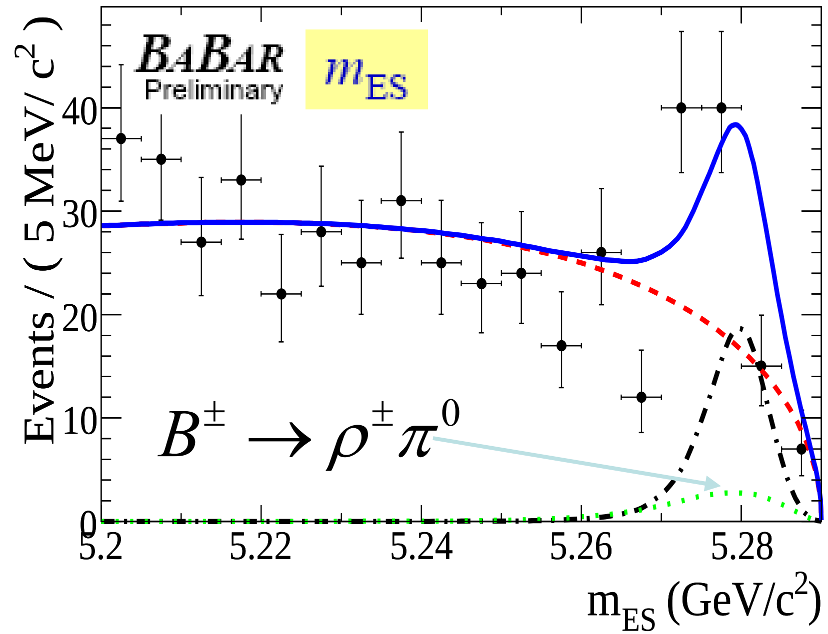
hep-ex/0607106

347×10^6 B pairs (preliminary)

$N_{\pi^\pm\pi^0} = 572 \pm 53$



$N_{\pi^0\pi^0} = 140 \pm 25$



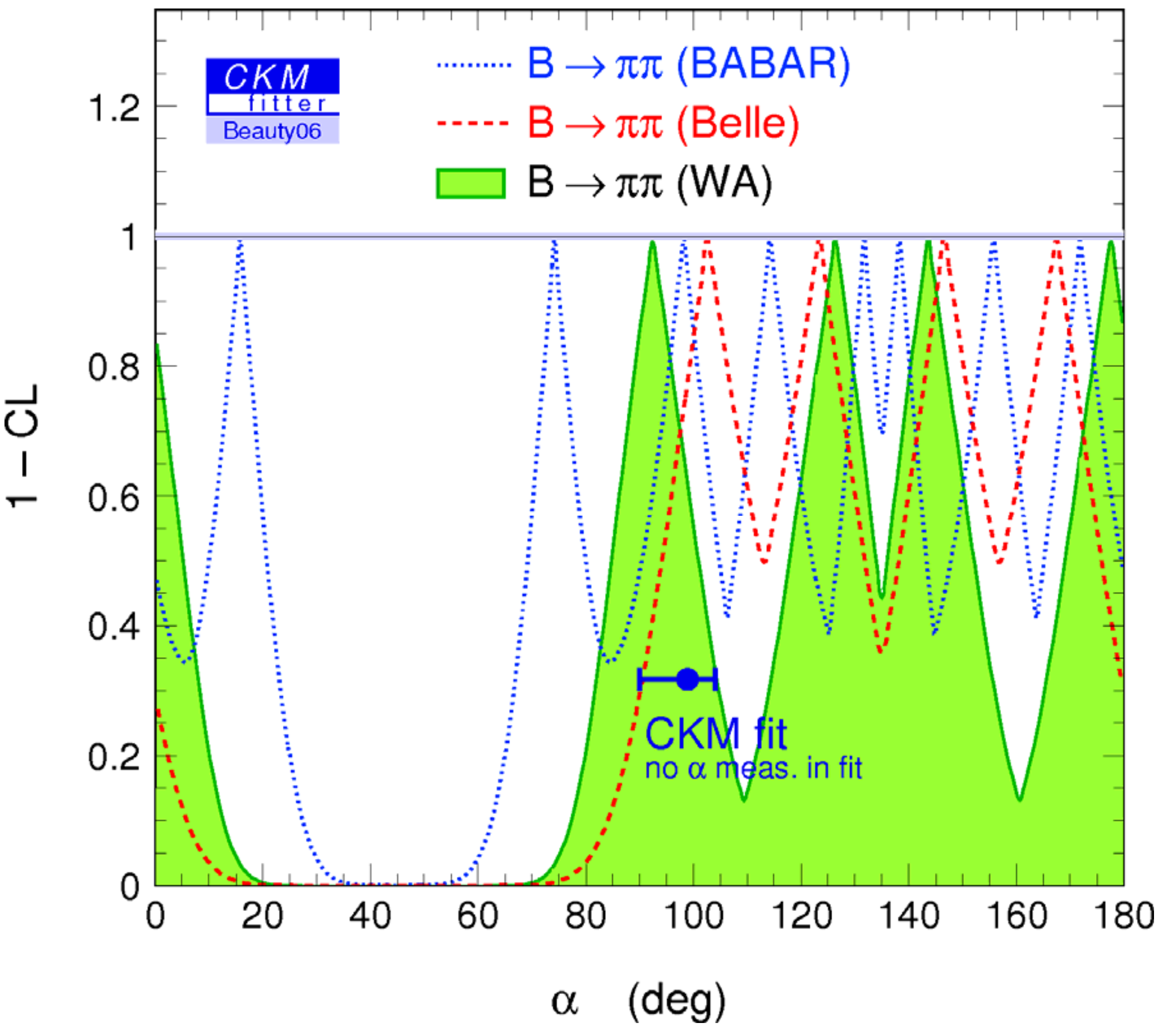
$\mathcal{B}r_{\pi^\pm\pi^0} = (5.12 \pm 0.47 \pm 0.29) \times 10^{-6}$

$\mathcal{B}r_{\pi^0\pi^0} = (1.48 \pm 0.26 \pm 0.12) \times 10^{-6}$

$A_{CP} = -0.019 \pm 0.088 \pm 0.014$

$C_{\pi^0\pi^0} = -0.33 \pm 0.36 \pm 0.08$

Summary on α from $B \to \pi\pi$



Averages

$$\left.\begin{aligned}\mathcal{B}(\pi^+\pi^0) &= (5.75 \pm 0.42)\\ \mathcal{B}(\pi^+\pi^-) &= (5.20 \pm 0.25)\\ \mathcal{B}(\pi^0\pi^0) &= (1.30 \pm 0.21)\end{aligned}\right\} \times 10^{-6}$$

$C(\pi^0\pi^0) = -0.35 \pm 0.33$

$S(\pi^+\pi^-) = -0.59 \pm 0.09$

$C(\pi^+\pi^-) = -0.39 \pm 0.07$

More data needed to:

- Resolve $\pi^+\pi^-$ issue
- Achieve meaningful constraints on α

BABAR

$|\Delta\alpha| < 41°$ (90% C.L.)

$B \to \rho\rho$

- Challenging:
  - Experimentally complicated $\rho^+\rho^- \to \pi^+\pi^0\pi^-\pi^0$
  - Angular Time Dependent analysis to extract CP content

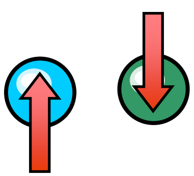
- But turned out to be most sensitive to α:
  - Small $\rho^0\,\rho^0$ (small penguin pollution)
  - Dominant longitudinal polarisation (CP-even final state)
  - No significant 3-body and 4-body components

CP in a vector-vector final state

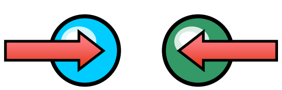
- three partial waves:
  - S (L=0, CP even)
  - P (L=1, CP odd)
  - D (L=2, CP even)

OR

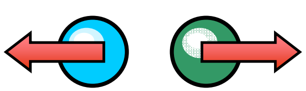
- three transversity amplitudes:



$$A_0 = -\frac{1}{\sqrt{3}} S + \sqrt{\frac{2}{3}} D \quad (CP-even\ longitudinal)$$



$$A_\parallel = \sqrt{\frac{2}{3}} S + \frac{1}{3} D \quad (CP-even\ transverse)$$

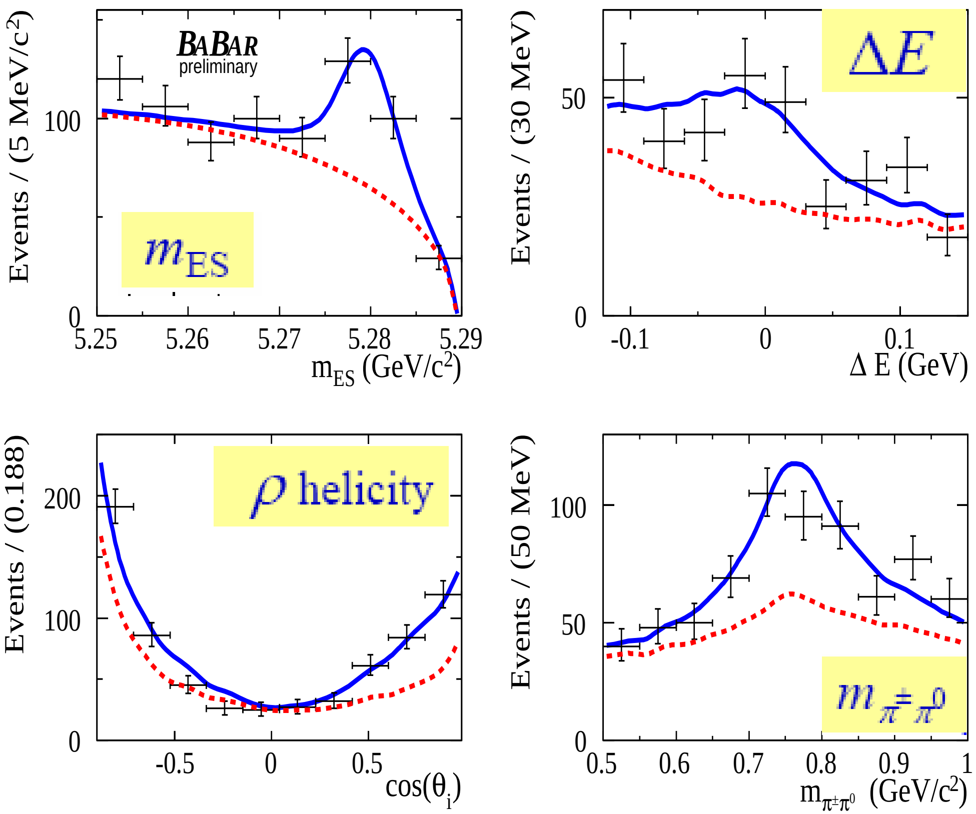


$$A_\perp = P \quad (CP-odd\ \ transverse)$$

$$B^0 \rightarrow \rho^+ \rho^-$$

hep-ex/0607098

347x10⁶ B pairs (preliminary)

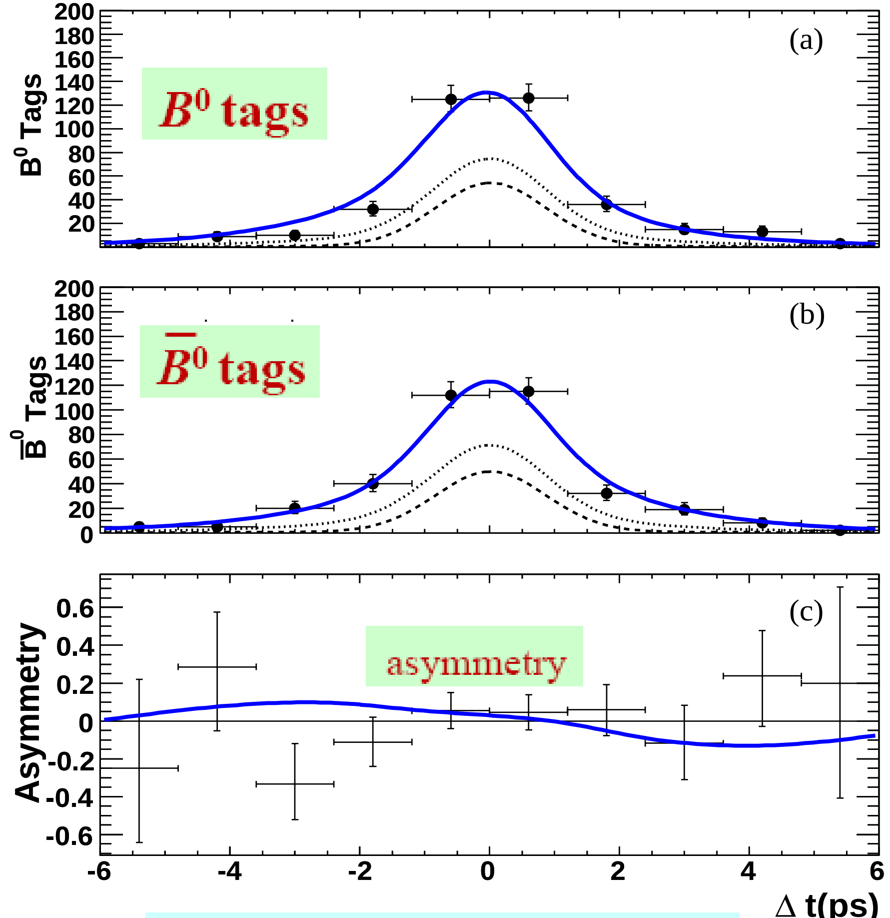


$N_{\rho^+\rho^-} = 615 \pm 57$

dominated by self-crossfeed

$\mathcal{B}r_{\rho^+\rho^-} = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$

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



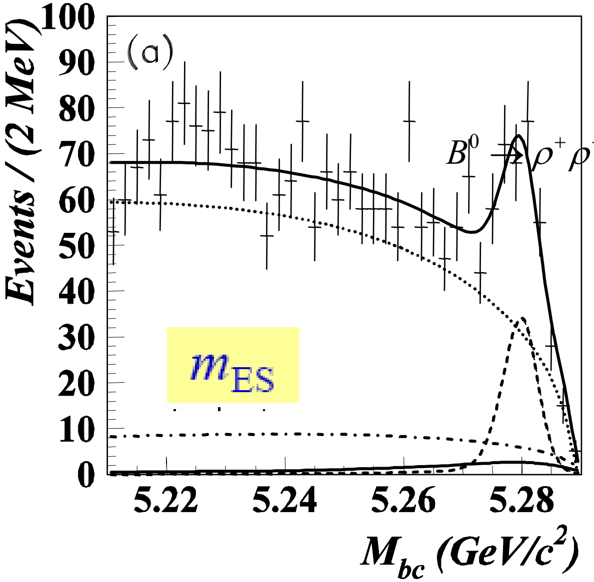
$S_{long} = -0.19 \pm 0.21^{+0.05}_{-0.07}$

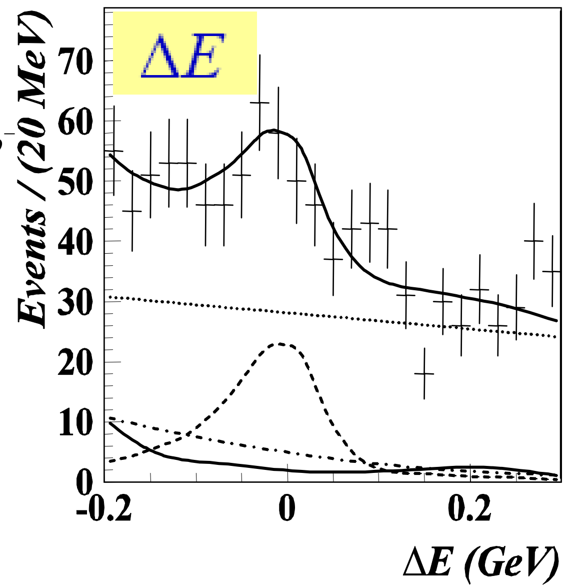
$C_{long} = -0.07 \pm 0.15 \pm 0.06$

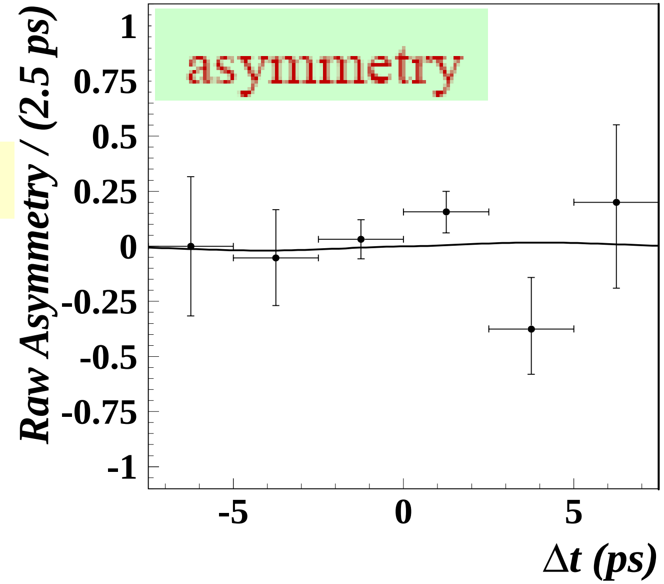
$B^0 \to \rho^+ \rho^-$

275×10^6 B pairs

PRL 96, 171801 (2006)







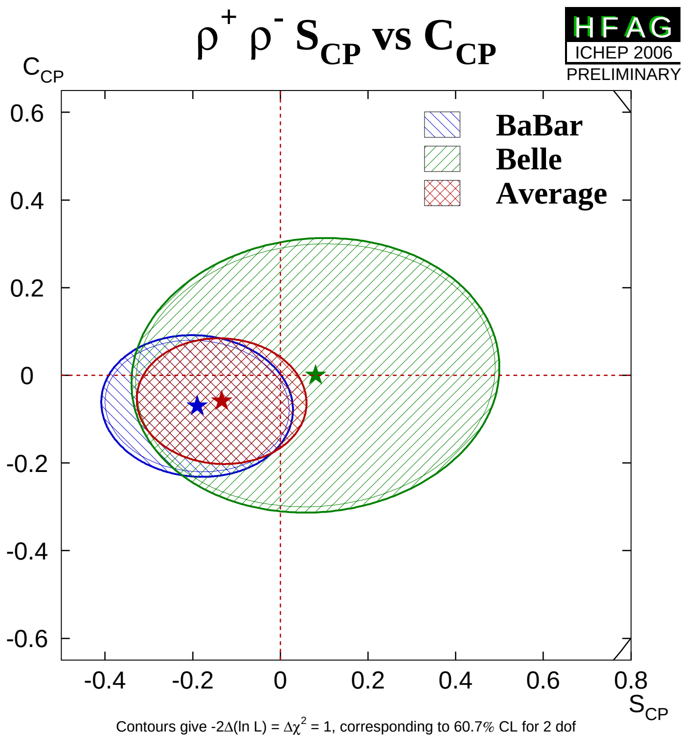
$N_{\rho\rho} = 194 \pm 32$

$$f_L = 0.941^{+0.034}_{-0.040} \pm 0.030$$

$$BR = (22.8 \pm 3.8^{+2.8}_{-2.6}) \times 10^{-6}$$

$$C_{long} = 0.00 \pm 0.30 \pm 0.09$$

$$S_{long} = 0.08 \pm 0.41 \pm 0.09$$

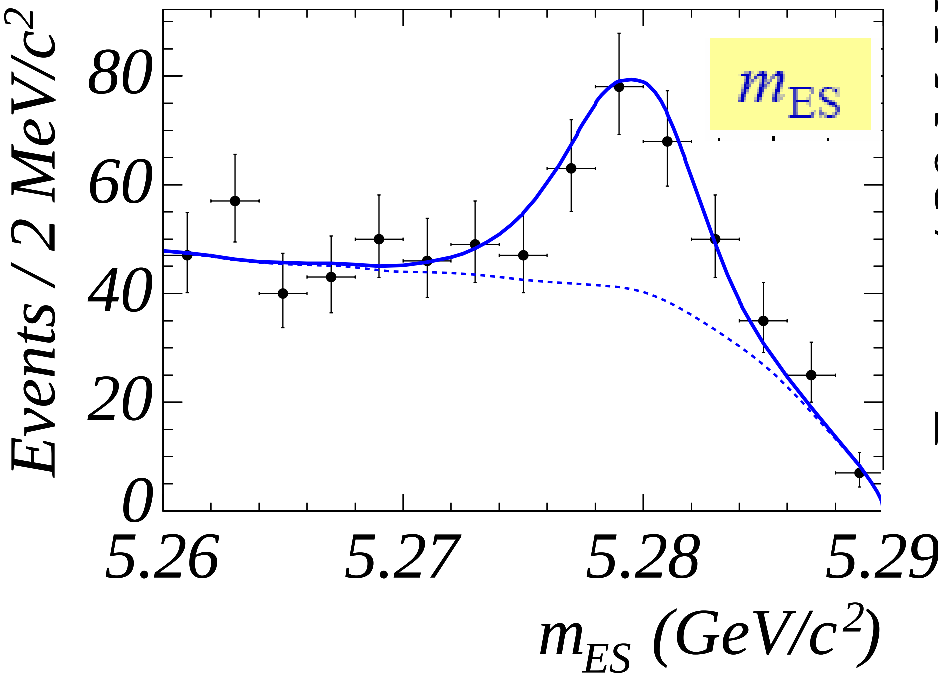


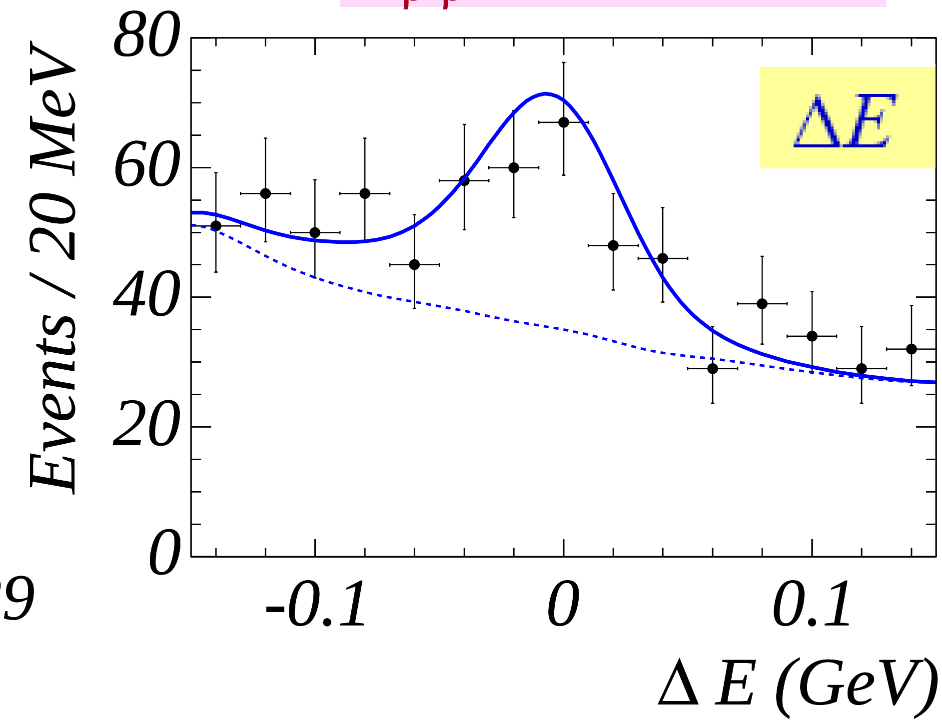
$B^{\pm} \rightarrow \rho^{\pm}\rho^{0}$

hep-ex/0607092

232×10^6 B pairs (preliminary)

$N_{\rho^+\rho^0} = 390 \pm 49$





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

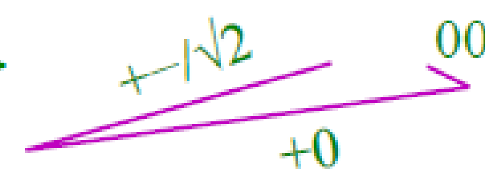
$f_L(B^{\pm} \rightarrow \rho^{\pm}\rho^{0}) = 0.905 \pm 0.042^{+0.023}_{-0.027}$

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

Phys. Rev. Lett. **91**, 221801 (2003)
Phys. Rev. Lett. **91**, 171802 (2003)

PDG 2004: $(26 \pm 6) \times 10^{-6}$
Belle: $(31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$
Previous *BaBar* : $(22.5^{+5.7}_{-5.4} \pm 5.8\ ) \times 10^{-6}$

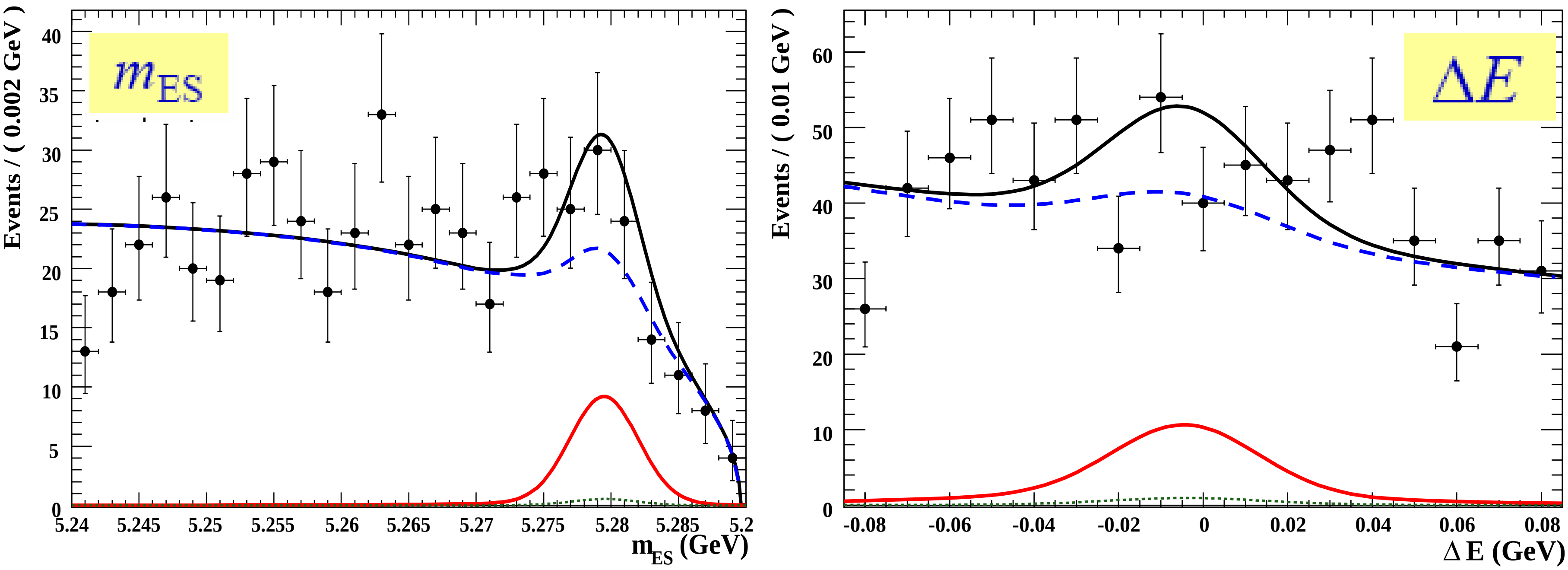
"before":



BaBar $B^0 \to \rho^0 \rho^0$

hep-ex/0607097

347x10⁶ B pairs (preliminary)



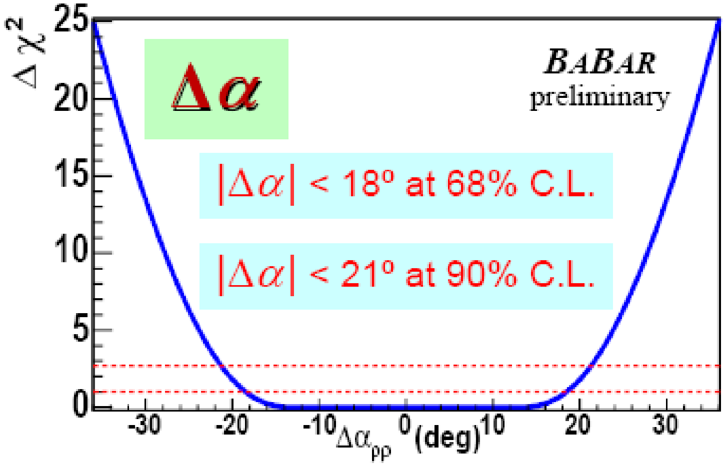
$N_{\rho^0\rho^0} = 98 \pm 32 \pm 22$

3.0 σ evidence

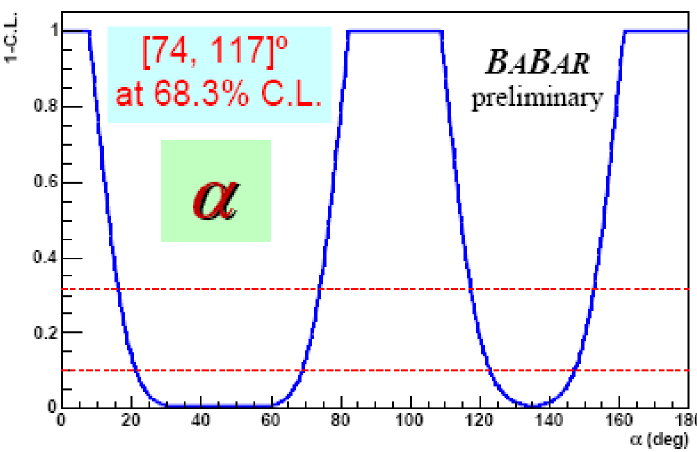
$$\mathcal{B}r_{\rho^0\rho^0} = (1.16^{+0.37}_{-0.36} \pm 0.27) \times 10^{-6}$$

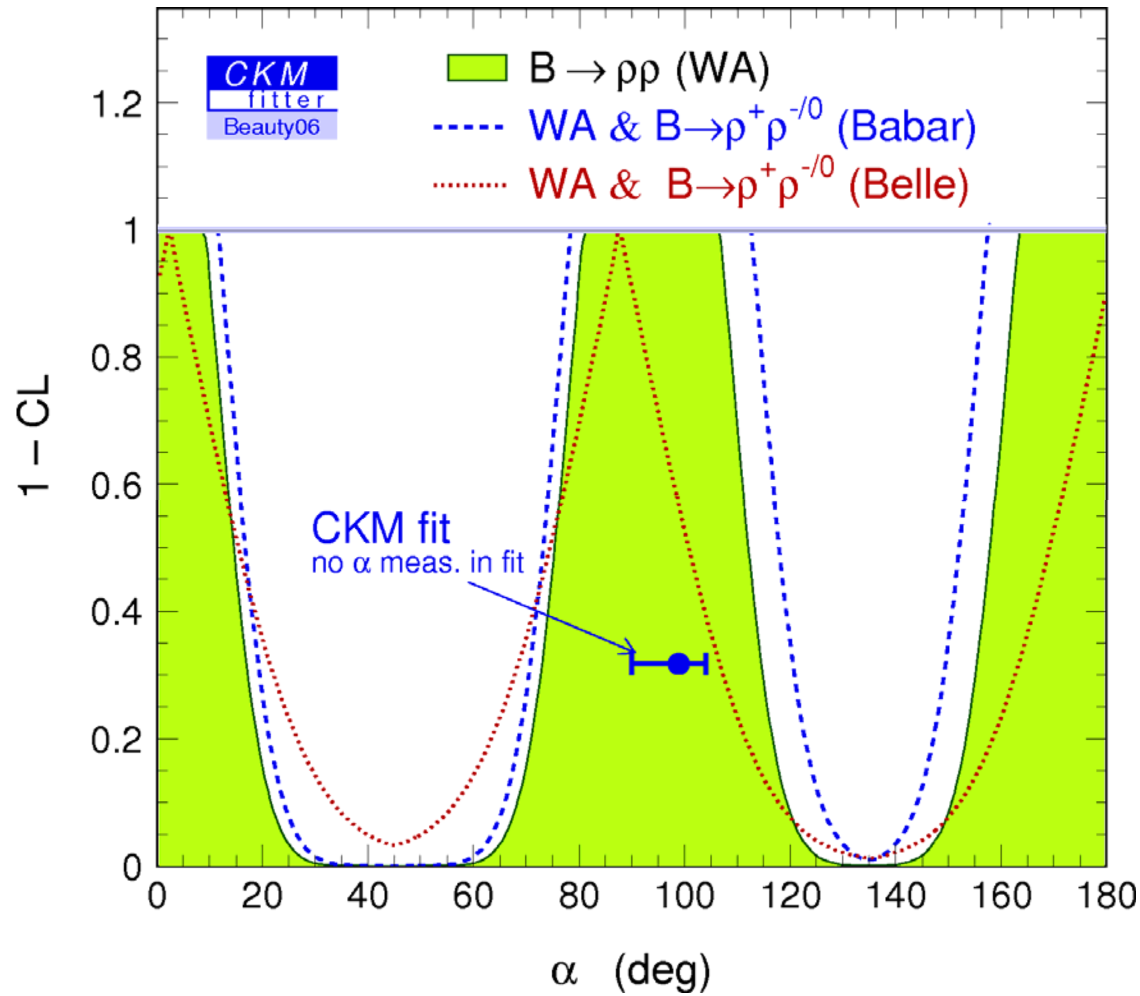
$$f_L(B^0 \to \rho^0\rho^0) = 0.86^{+0.11}_{-0.13} \pm 0.05$$

α from $B \to \rho\rho$



$$\alpha_{\rm eff} = (95.5^{+6.9}_{-6.2})^\circ$$



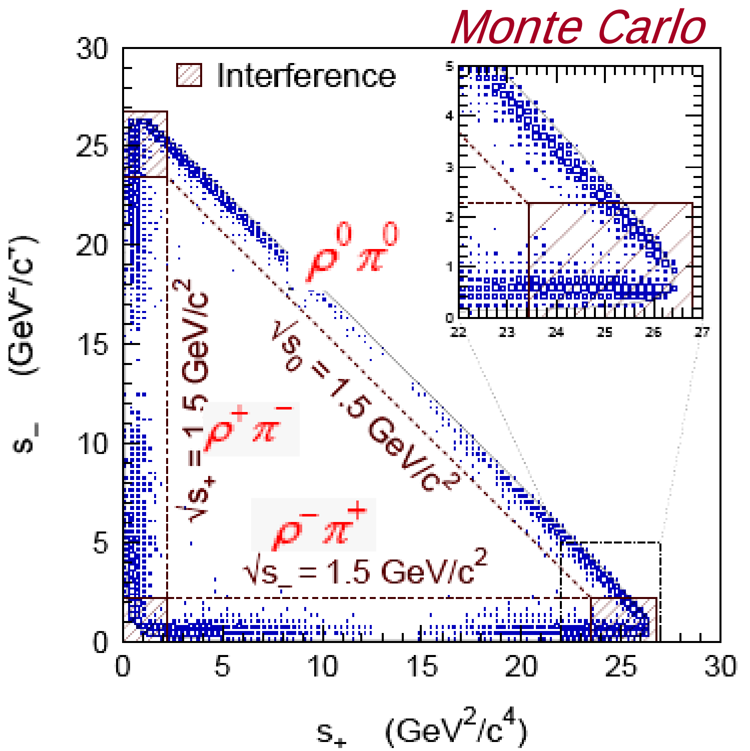


$B^0 \to (\rho\pi)^0$

$$\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix} \to \begin{pmatrix} \rho^+\pi^- \\ \rho^-\pi^+ \\ \rho^0\pi^0 \end{pmatrix} \to \pi^+\pi^-\pi^0$$

$$A(B^0 \to \pi^+\pi^-\pi^0) = f_+A(\rho^+\pi^-) + f_-A(\rho^-\pi^+) + f_0A(\rho^0\pi^0)$$
$$\tilde{A}(\overline{B}^0 \to \pi^+\pi^-\pi^0) = f_+\tilde{A}(\rho^+\pi^-) + f_-\tilde{A}(\rho^-\pi^+) + f_0\tilde{A}(\rho^0\pi^0)$$

Monte Carlo



Time-Dependent Dalitz plot analysis and Isospin symmetry assumption

$B^0 \to \rho\pi$

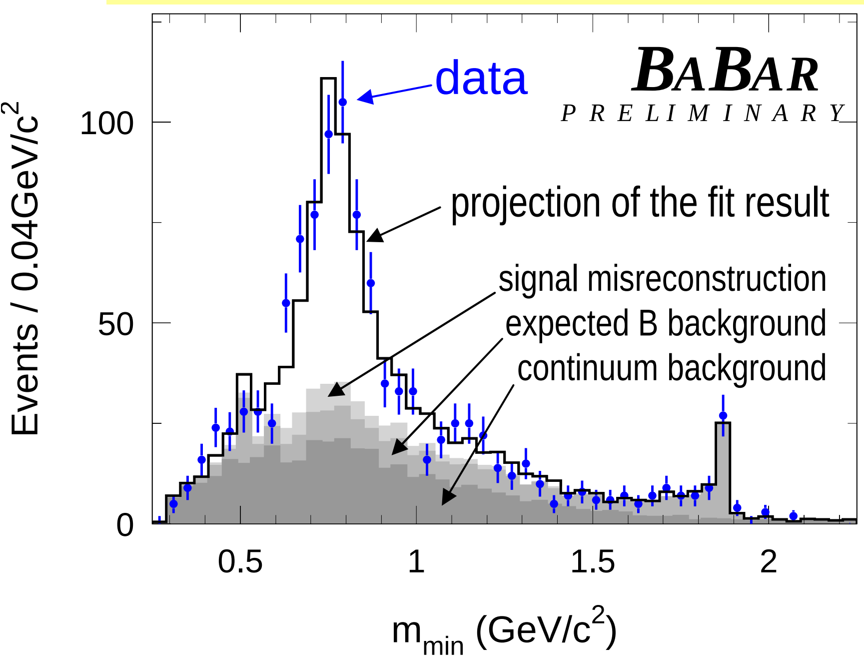
hep-ex/0608002

347x10⁶ B pairs (preliminary)

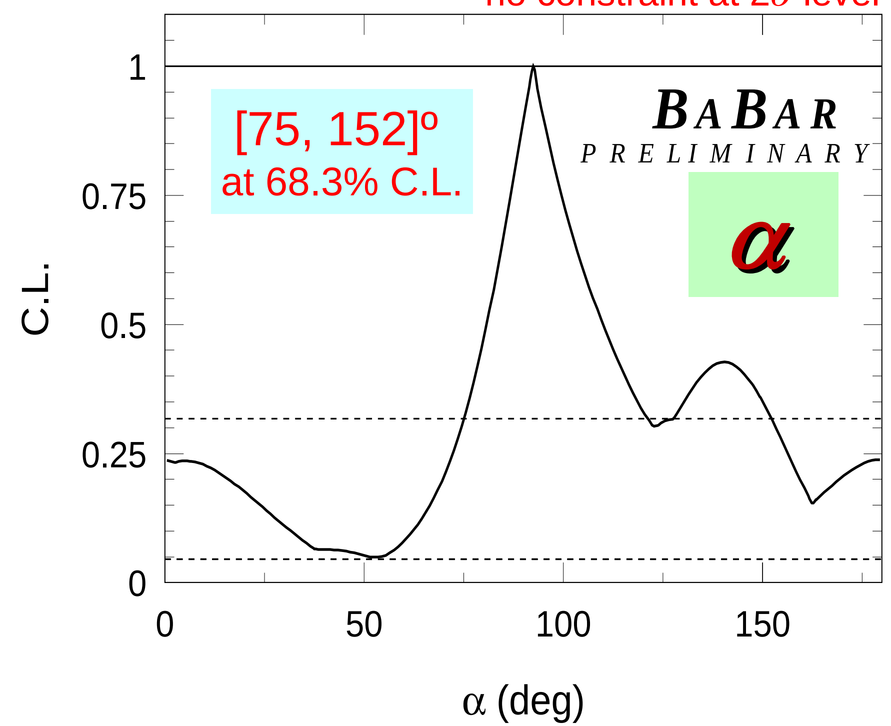
A. Snyder and H. Quinn, Phys. Rev. D, 48, 2139 (1993)

- UML fit with 27 coefficients (bilinear form factors)
- Simultaneous fit for time-dependence
- Fit includes ρ(1450) and ρ(1700)
- CP parameters extracted from subsequent fits to these coefficients

minimum of the three di-pion invariant masses



no constraint at 2σ level



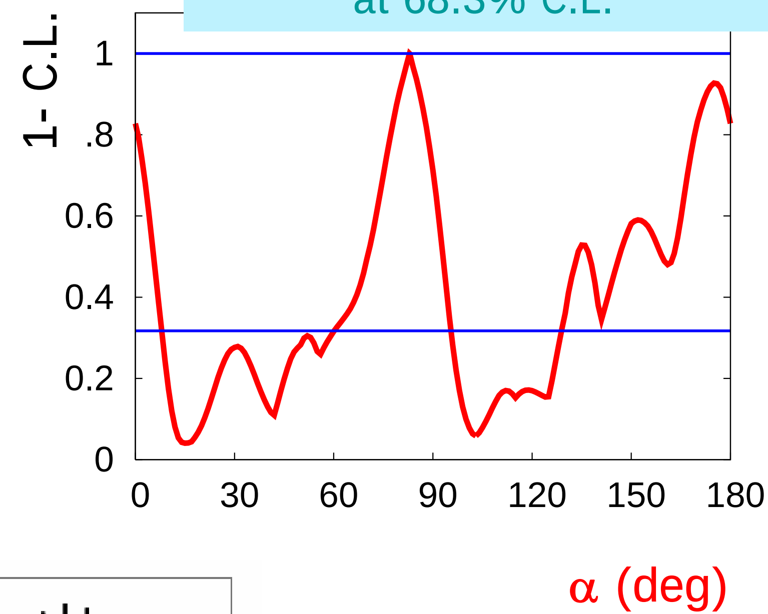
$B^0 \to \rho\pi$

449×10^6 B pairs

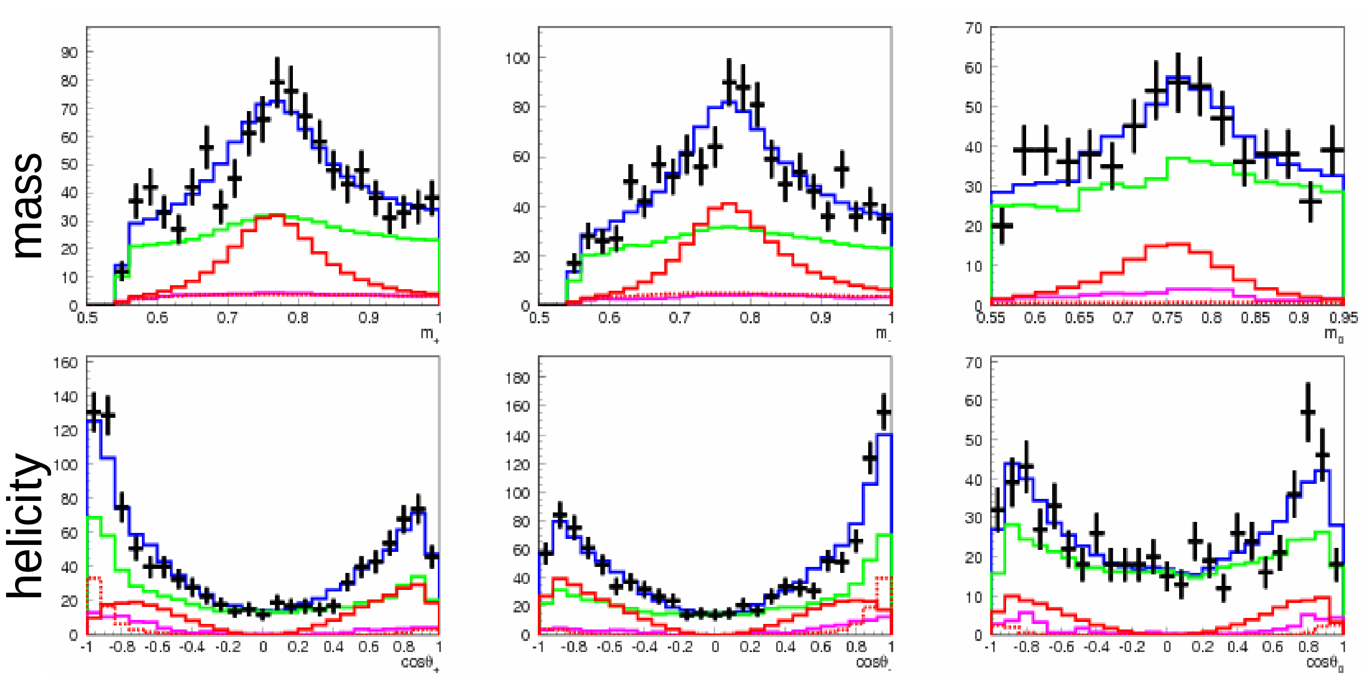
hep-ex/0609003

- Dalitz + Isospin (pentagon) analysis
- 26(Dalitz) + 5(Br($\rho^\pm\pi^\pm$), Br($\rho^+\pi^0$), Br($\rho^0\pi^+$), A($\rho^+\pi^0$), and A($\rho^0\pi^+$))

[0,8]° U [60,95]° U[129,180]° at 68.3% C.L.



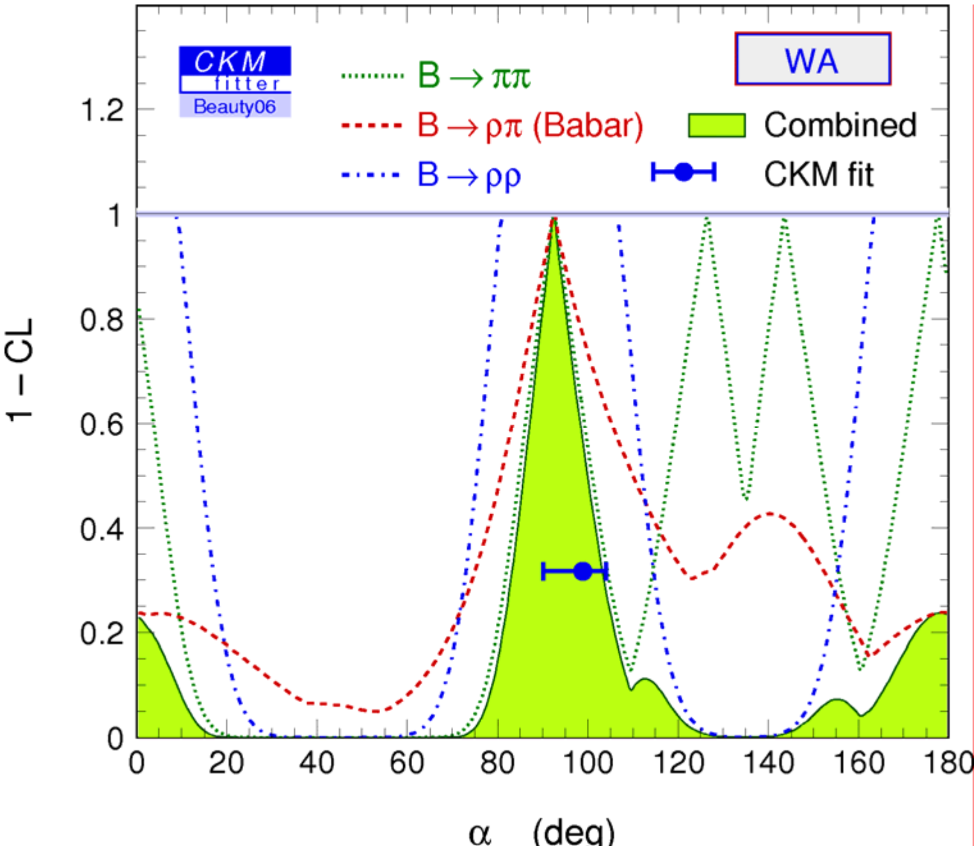
$\rho^+\pi^-$ $\rho^-\pi^+$ $\rho^0\pi^0$

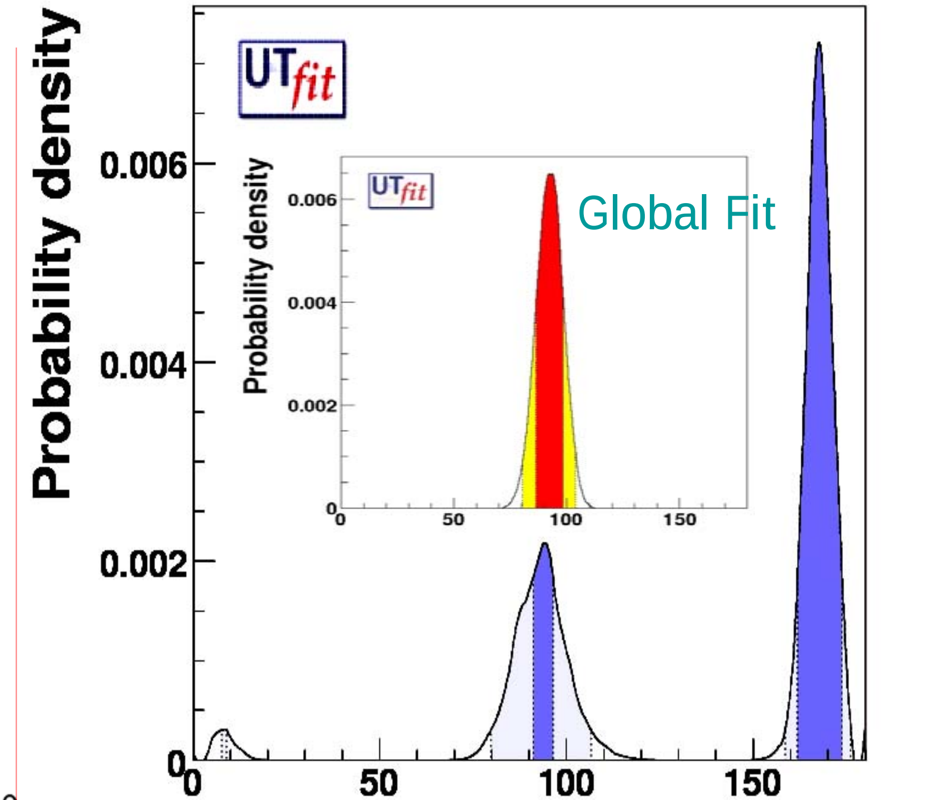


Signal
SCF
BB bkg
continuum

Putting it all together

CKMfitter http://ckmfitter.in2p3.fr/
UTfit http://utfit.dreamhosters.com/





$\alpha = 93^{+11}_{-9}$ Direct (deg)

$\alpha = 100^{+5}_{-7}$ Indirect (deg)

$\alpha = 99^{+4}_{-9}$ Global Fit (deg)

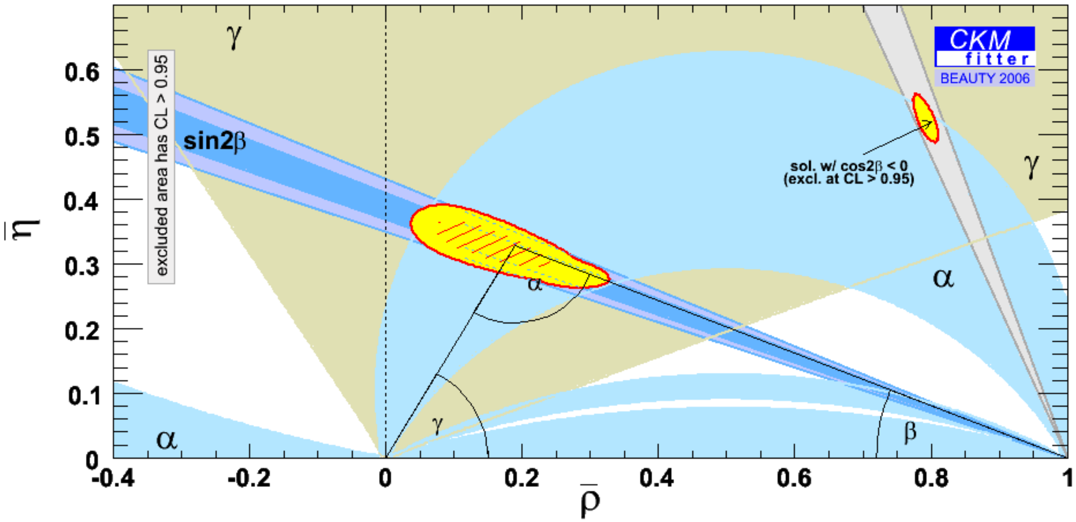
$\alpha = 92 \pm 7$ Direct (deg)

$\alpha = 93 \pm 6$ Indirect (deg)

$\alpha = 93 \pm 4$ Global Fit (deg)

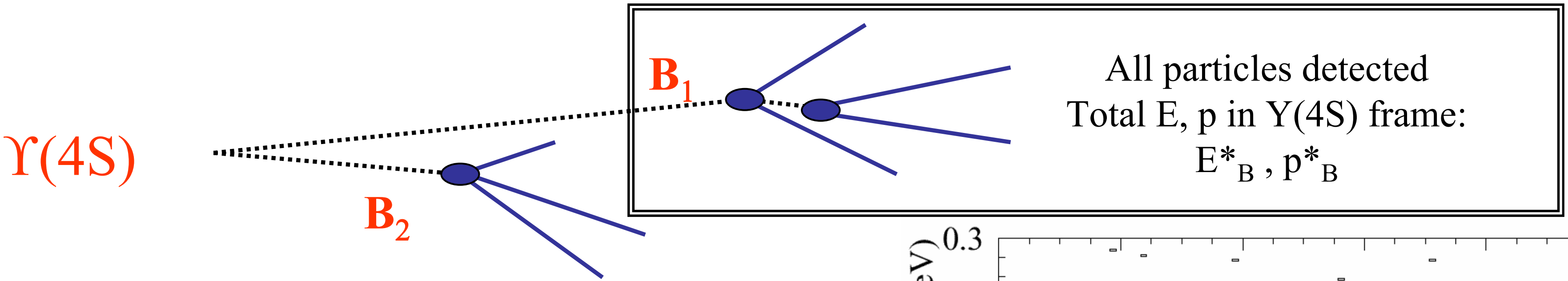
Summary and prospects

- Large data samples and elaborate analysis techniques allow direct α determination with precision of 10^0.
- Result in excellent agreement with global U.T. fit
- More data from the B Factories will clarify possible experimental discrepancies, and could provide precision around 5^0.
- LHCb and Super-B required to go beyond that



Backup material

Exclusive B reconstruction

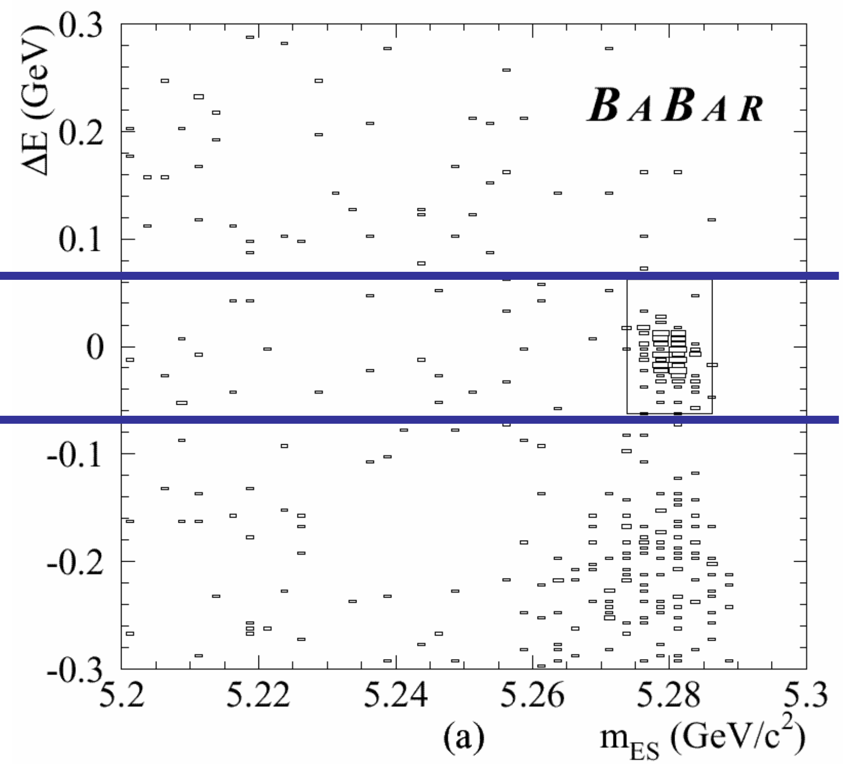


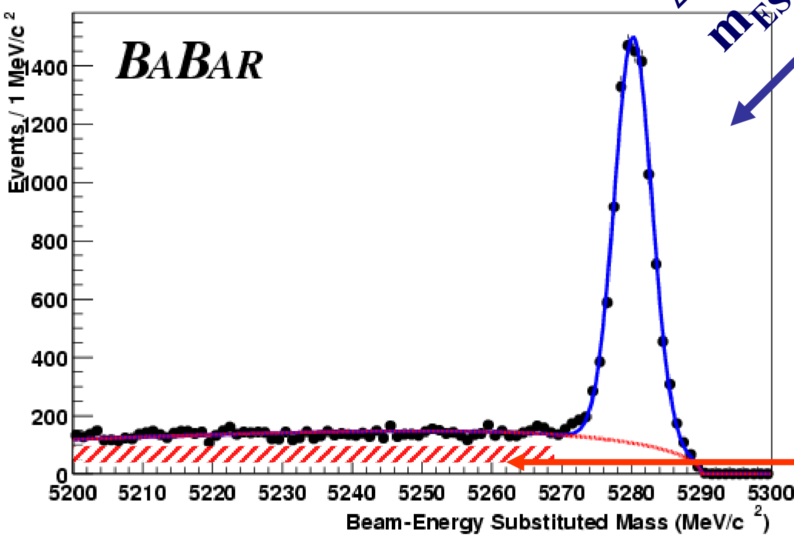
Kinematic variables:

$\Delta E = E^*_B - \sqrt{s}/2$

$m_{ES} = \sqrt{(s/4 - p^{*2}_B)}$

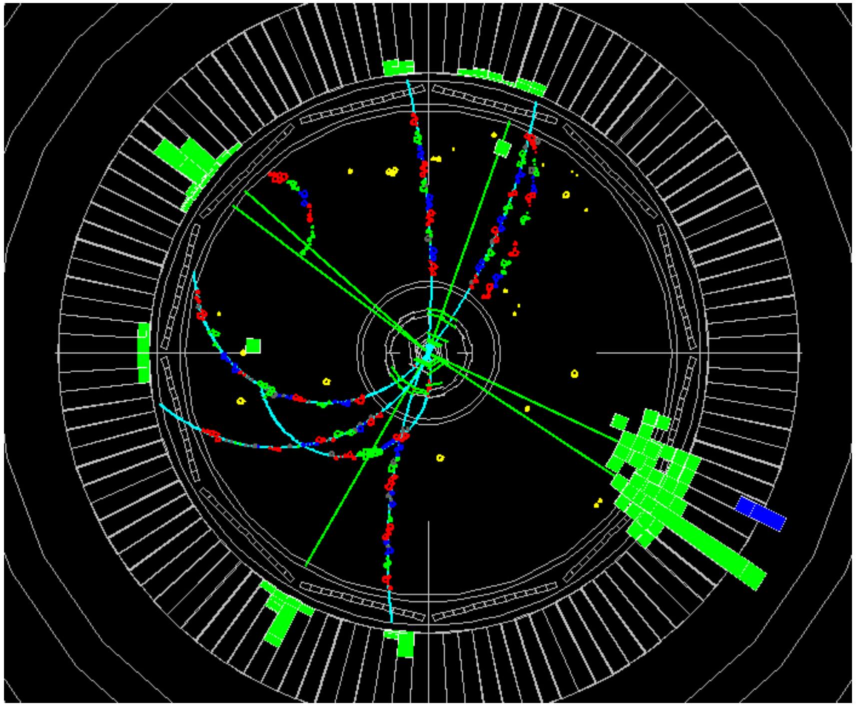
ΔE : $\sigma \sim 15$ MeV
m_{ES} : $\sigma \sim 3$MeV

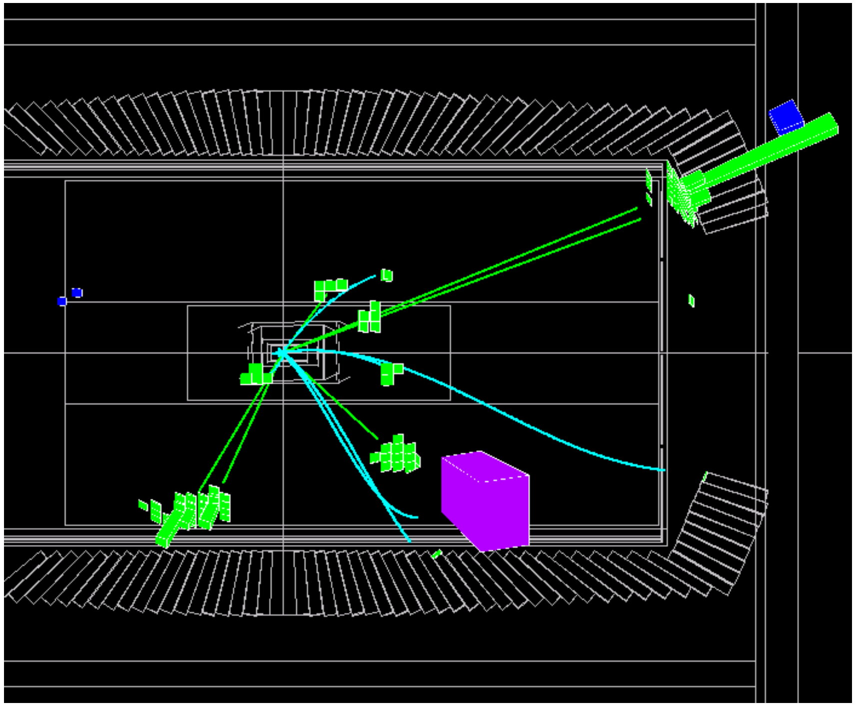




Extraction of background characteristics

A real $B^0 \rightarrow \pi^0 \pi^0$ candidate event





$B^0 \rightarrow \rho^+\rho^-$

hep-ex/0607

Conservative uncertainty on mis-reconstructed signal fraction which can be reduced.

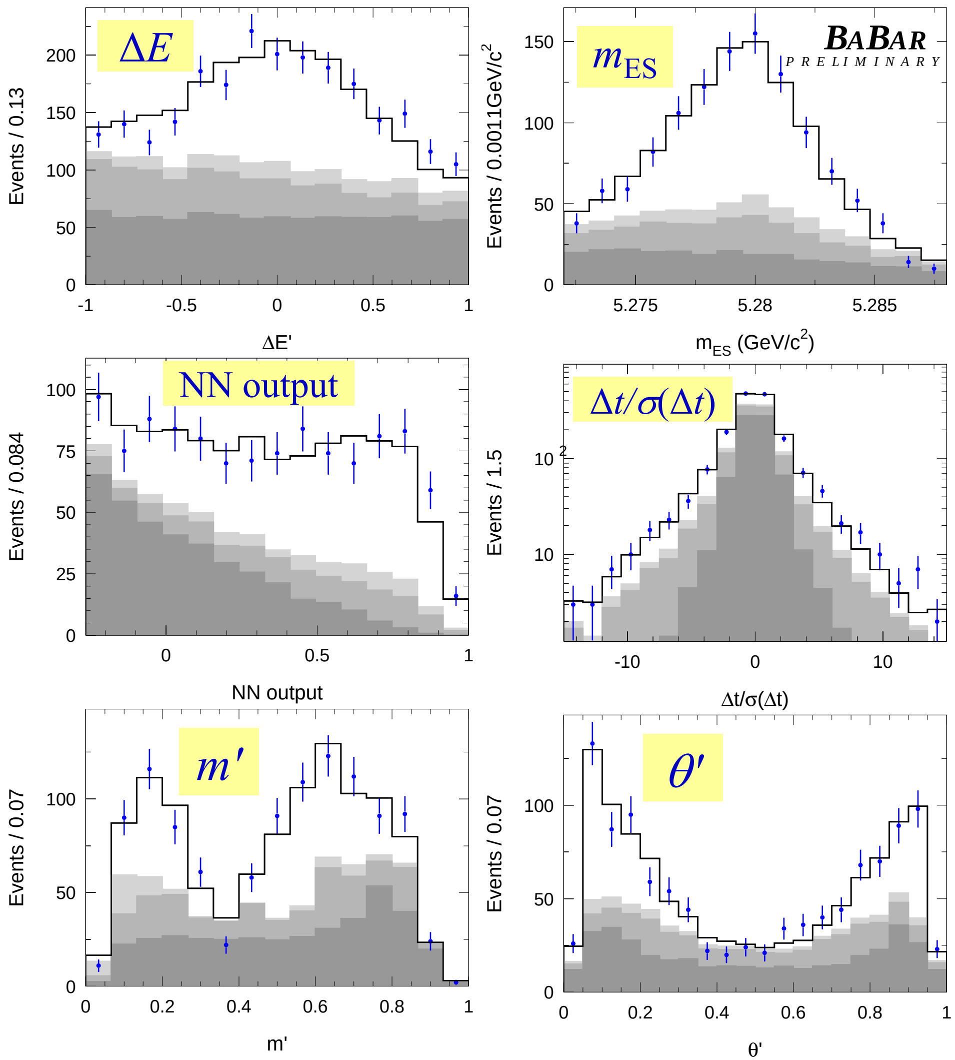
Table 4: Summary of additive systematic uncertainty contributions.

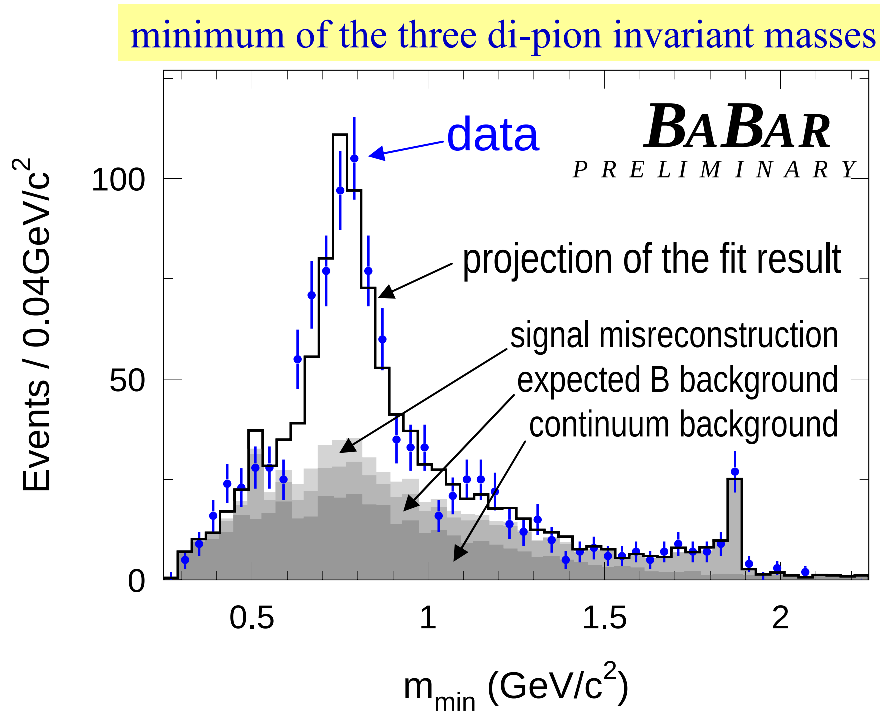
Contribution	$\sigma(N_{signal})$	$\sigma(f_L)$	$\sigma(S_{\rm long})$	$\sigma(C_{\rm long})$
PDF parameterisation	$^{+16.7}_{-30.2}$	$^{+0.0082}_{-0.0064}$	$^{+0.0149}_{-0.0425}$	$^{+0.0300}_{-0.0306}$
SCF fraction	84.0	$^{+0.0007}_{-0.0011}$	$^{+0.00235}_{-0.00355}$	$^{+0.0070}_{-0.00683}$
m_{ES} and ΔE width	22.9	0.005	0.011	0.012
B background normalisation	$^{+16.0}_{-17.2}$	$^{+0.0033}_{-0.0038}$	$^{+0.0096}_{-0.0115}$	$^{+0.0024}_{-0.0015}$
floating B backgrounds	33.6	0.004	0.033	0.006
CPV in B background	$^{+3.3}_{-2.0}$	$^{+0.0006}_{-0.0016}$	$^{+0.0059}_{-0.0214}$	$^{+0.0118}_{-0.0115}$
τ	$^{+0.1}_{-0.4}$	$^{+0.0000}_{-0.0002}$	$^{+0.0002}_{-0.0008}$	0.0007
Δm	$^{+0.0}_{-0.2}$	$^{+0.0000}_{-0.0002}$	$^{+0.0014}_{-0.0020}$	$^{+0.0018}_{-0.0012}$
tagging and dilution	$^{+2.6}_{-8.1}$	$^{+0.0029}_{-0.0021}$	$^{+0.0016}_{-0.0053}$	$^{+0.0068}_{-0.0054}$
transverse polarisation CPV	$^{+0.0}_{-8.3}$	$^{+0.0057}_{-0.0000}$	$^{+0.0125}_{-0.0152}$	$^{+0.0095}_{-0.0110}$
WT SCF CPV	$^{+0.2}_{-1.1}$	$^{+0.0000}_{-0.0003}$	$^{+0.0051}_{-0.0065}$	$^{+0.0116}_{-0.0113}$
DCSD decays	–	–	0.012	0.037
Interference	14.8	0.0036	0.023	0.022
Fit Bias	28	0.007	0.002	0.022
SVT Alignment	–	–	0.0100	0.0055
Total	$^{+97}_{-101}$	$^{+0.015}_{-0.013}$	$^{+0.05}_{-0.07}$	± 0.06

- Improvements in modelling correlations and backgrounds result in a reduced systematic uncertainty on S and C.
- Improved upper limit for $B \rightarrow a_1\rho$ also helps to reduce systematic uncertainty.

$$\mathcal{B}(B^0 \rightarrow \rho^+\rho^-) = (23.5 \pm 2.2(\text{stat}) \pm 4.1(\text{syst})) \times 1$$
$$f_L = 0.977 \pm 0.024(\text{stat})^{+0.015}_{-0.013}(\text{syst}),$$
$$S_{\rm long} = -0.19 \pm 0.21(\text{stat})^{+0.05}_{-0.07}(\text{syst}),$$
$$C_{\rm long} = -0.07 \pm 0.15(\text{stat}) \pm 0.06(\text{syst}).$$

New *BaBar* results: $B^0 \to (\rho\pi)^0$ (1)





New *BaBar* results: $B^0 \to (\rho\pi)^0$ (2)

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

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

$$\mathcal{A}_{\rho\pi} = -0.142 \pm 0.041 \pm 0.015$$

a more physically intuitive way to represent direct-*CP* quantities:

$$\mathcal{A}_{\rho\pi}^{+-} = 0.03 \pm 0.07 \pm 0.03$$

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

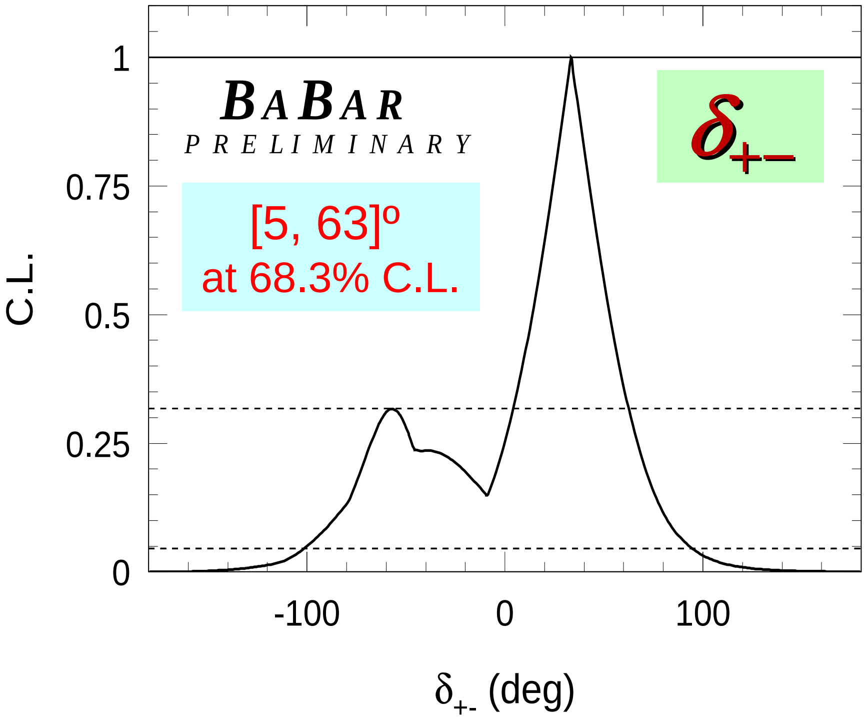
parameters from the quasi-two-body description of $B \to \rho\pi$:

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

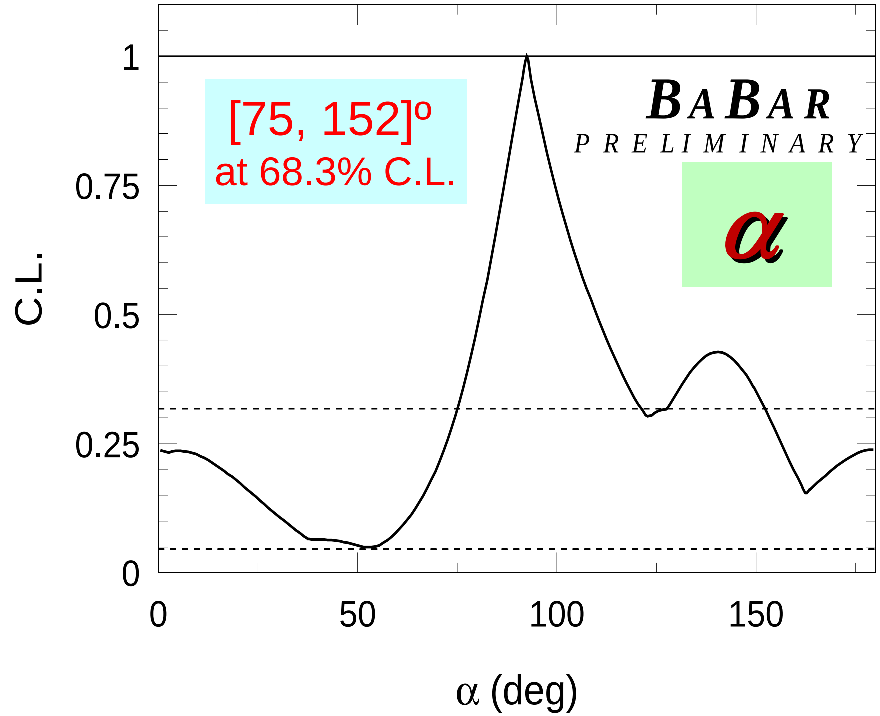
$$\Delta C_{\rho\pi} = 0.377 \pm 0.091 \pm 0.021$$

An interpretation of the new $B^0 \to (\rho\pi)^0$ results

$\delta_{+-} = \arg(A^{+*}A^{-})$: the relative phase between the amplitudes of $B^0 \to \rho^-\pi^+$ and $B^0 \to \rho^+\pi^-$



no constraint at 2σ level



The constraint on α from $B^0 \to (\rho\pi)^0$ is relatively weak – but free from ambiguities!