

# Measurements of $\alpha$ From *BABAR*

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For The *BABAR* Collaboration

Lake Louise, 21<sup>st</sup> Feb. 2005

# Outline

- Physics motivation
- Extracting  $\alpha$  from
  - $\pi\pi$
  - $\rho\pi$
  - $\rho\rho$
- Summary

# The CKM matrix & CP violation

CKM matrix describes mixing between flavor and weak eigenstates in the Standard Model.

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

3x3 unitary matrix:  
3 real parameters,  
1 phase: only source  
of CPV in SM

Unitarity implies

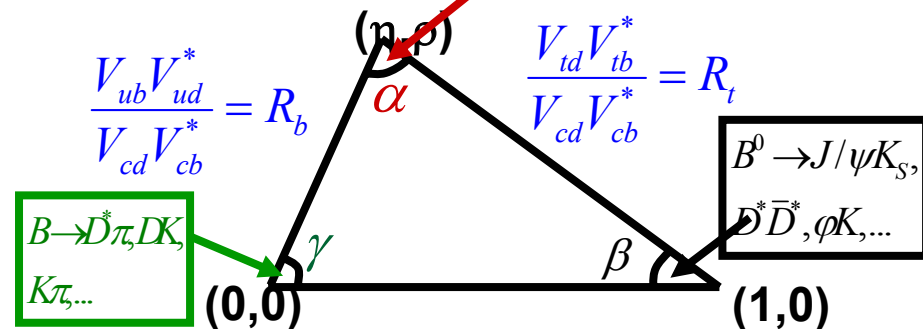
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

## Wolfenstein parameterization

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

CP violating phases

$B \rightarrow \pi\pi, \rho\pi, \rho\rho$  This talk



Area of triangle is equivalent to the amount of CP violation in SM

# Observing CP Violation at *BABAR*

Three observable effects in **B** decays to a final state **f**:

**CP violation in mixing** ( $|q/p| \neq 1$ )

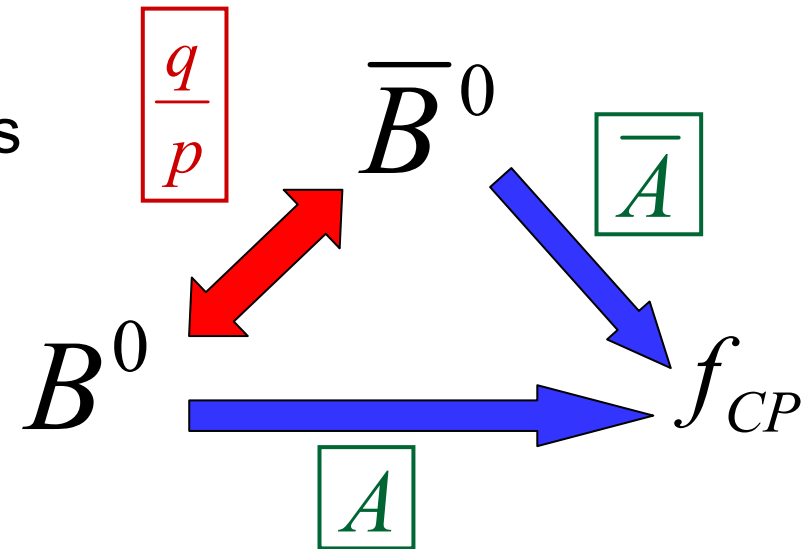
$$B^0 \rightarrow \bar{B}^0 \neq \bar{B}^0 \rightarrow B^0$$

**(direct) CP violation in decay** ( $|\bar{A}/A| \neq 1$ )

$$B^0 \rightarrow f \neq \bar{B}^0 \rightarrow \bar{f}$$

**(indirect) CP violation in the interference between mixing and decay** ( $\text{Im}\lambda_{f_{CP}} \neq 0$ )

Time dependent effect is sensitive to measure unitarity triangle angles



$$\lambda_{f_{CP}} = \frac{q}{p} \frac{\bar{A}}{A}$$

# How to measure $\alpha$

Decays sensitive to  $\alpha$

$$B^0 \rightarrow h^+ h^- \quad h = \pi, \rho$$

Time dependent CP asymmetry:

$$a_{hh}(t) = \frac{\Gamma_{B^0 \rightarrow hh} - \Gamma_{\bar{B}^0 \rightarrow hh}}{\Gamma_{B^0 \rightarrow hh} + \Gamma_{\bar{B}^0 \rightarrow hh}}$$

Can be written as:

$$= S_{hh} \sin(\Delta m_B \Delta t) - C_{hh} \cos(\Delta m_B \Delta t)$$

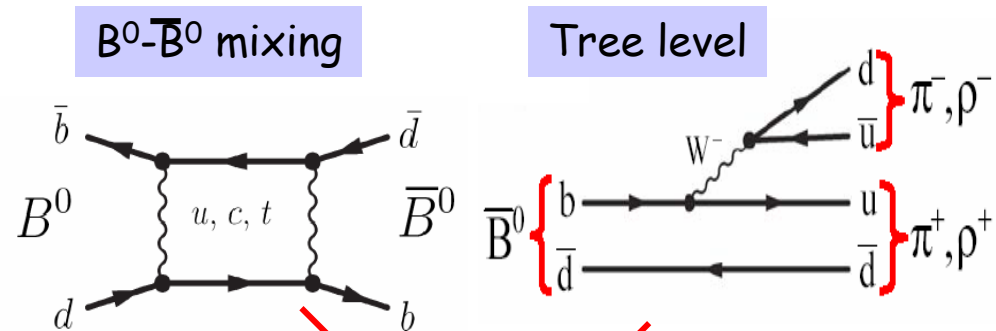
$$S \propto 2 \operatorname{Im} \lambda$$

Indirect CP

relevant to  $\alpha$

$$C \propto 1 - |\lambda|^2$$

Direct CP



$$\lambda = \frac{q}{p} \frac{\bar{A}}{A} = e^{i2\alpha}$$



$$S_{hh} = \sin 2\alpha$$

$$C_{hh} = 0$$

$$a_{hh}(t) = \sin(2\alpha) \sin(\Delta m_B \Delta t)$$

# Measuring $\alpha$ in presence of penguins

Coefficients of time-dependent CP Asymmetry in  $B^0 \rightarrow h^+h^-$  decays  
 $h = \pi, \rho$

Tree level



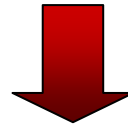
$$S_{hh} = \sin 2\alpha$$

$$C_{hh} = 0$$

But penguin diagrams are not negligible!!!

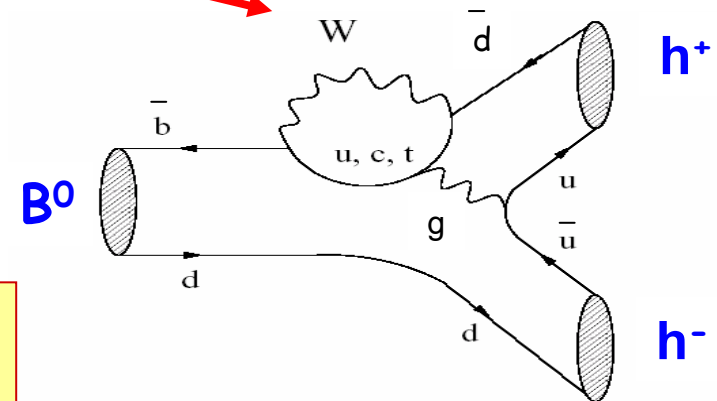
Penguin

- Carry a different phase compared to tree level
- Measure  $\alpha_{\text{eff}}$



$$S_{hh} = \sqrt{1 - C_{hh}^2} \sin 2\alpha_{\text{eff}}$$

$$C_{hh} \propto \sin \delta$$



Measure

$$\alpha_{\text{eff}} = \alpha + \delta\alpha_{\text{peng}}$$

need to bound

$$|\alpha - \alpha_{\text{eff}}|$$

Need Isospin analysis

# Measuring $\alpha$ from $B \rightarrow hh$ Isospin

Isospin relates  
different amplitudes



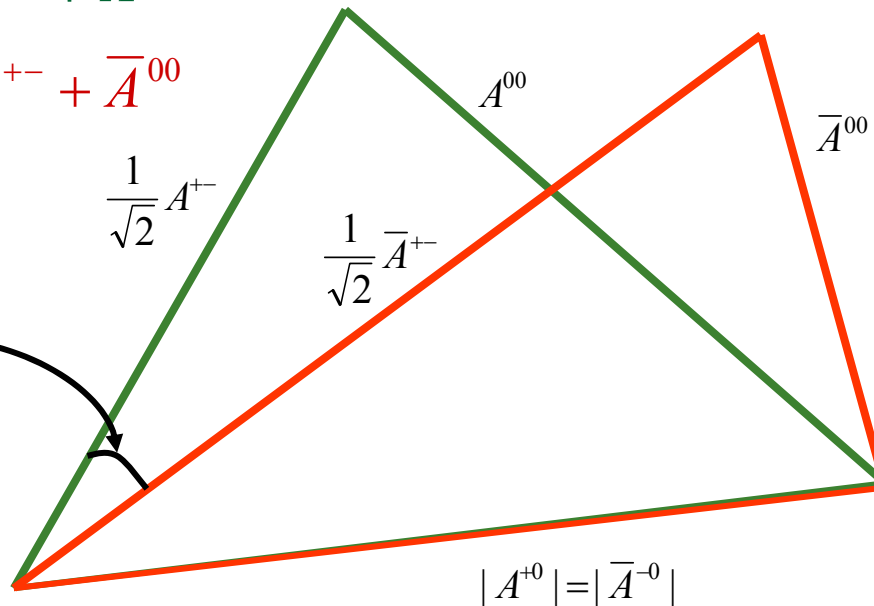
$\pi\pi/\rho\rho$  triangles

Gronau-London: PRL **65**, 3381 (1990) etc

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

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

$$2\delta\alpha_{\text{peng}}$$



Need to measure:

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

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

$$A^{00} = A(B^0 \rightarrow h^0 h^0)$$

$$\bar{A}^{00} = A(\bar{B}^0 \rightarrow h^0 h^0)$$

$$A^{+0} = A(B^+ \rightarrow h^+ h^0)$$

$$\bar{A}^{-0} = A(B^- \rightarrow h^- h^0)$$

$$h = \pi, \rho$$

small

$$A^{00} \text{ \& \ } \bar{A}^{00}$$



small

$$\delta\alpha_{\text{peng}}$$

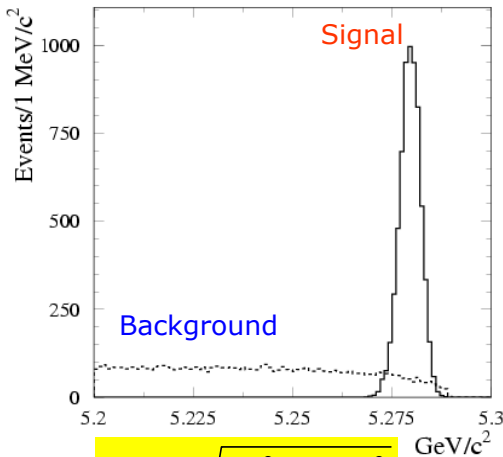
$$\sin^2(\alpha_{\text{eff}} - \alpha) < \frac{\langle \text{BF}(B^0 \rightarrow h^0 h^0) \rangle}{\text{BF}(B^+ \rightarrow h^+ h^0)} \quad \text{Grossman-Quin bound}$$

# Signal selection & background suppression

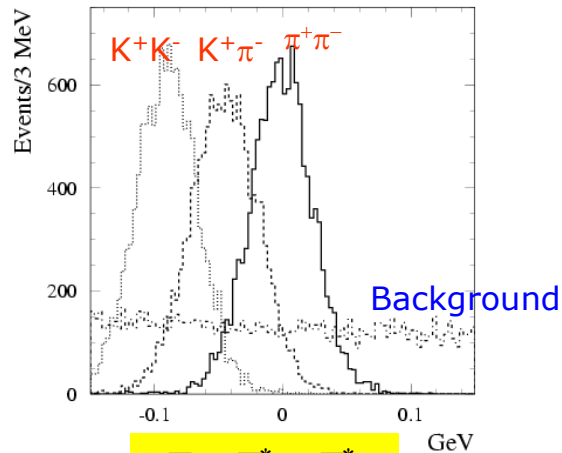
- **Signal selection**

- B candidate's mass
- B candidate's energy
- Pion/Kaon separation

From Cherenkov light detector (DIRC)  
(used in many of these analysis)



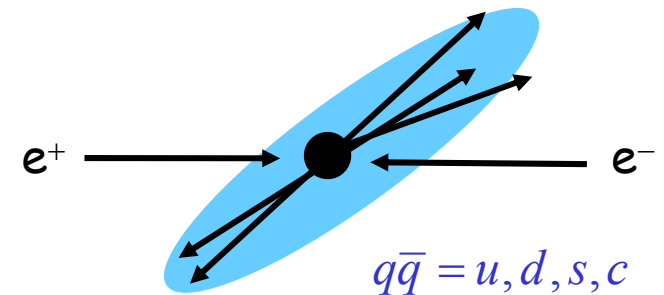
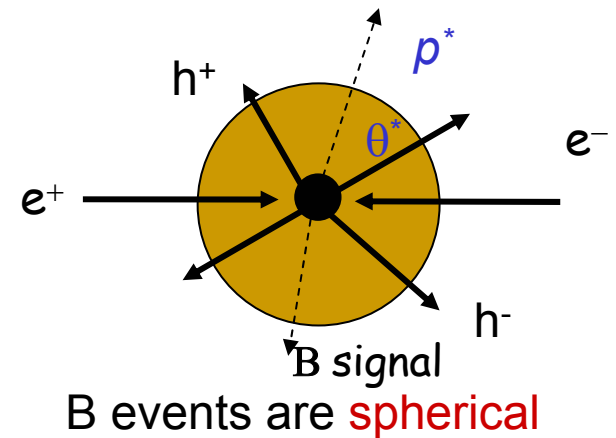
$$m_{ES} = \sqrt{E_{beam}^{*2} - P_B^{*2}}$$



$$\Delta E = E_B^* - E_{beam}^*$$

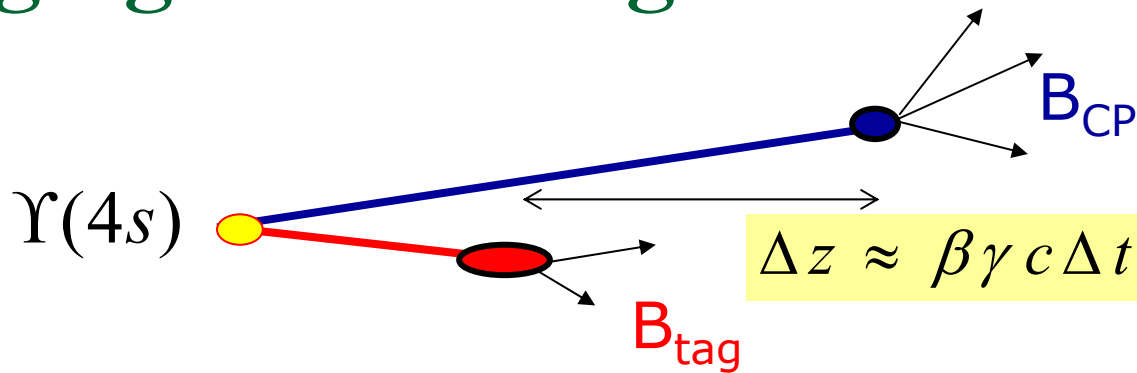
From  $\pi^+\pi^-$  Monte-Carlo

- **Event shape variables for background suppression**

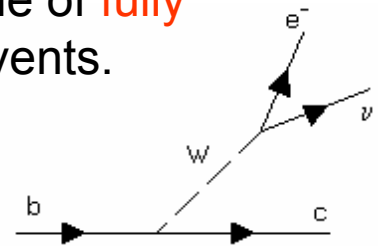


Background events from light quark have **jet-like topology**

# B tagging & vertexing



- For time-dependent analyses we must know the flavor of  $B_{CP}$  when  $B_{tag}$  decays ( $t=0$ ).
- This is done by looking at the decay products of  $B_{tag}$ . For instance, leptons and kaons.
- The "mistag" rate dilutes the measured asymmetry.
- Accurate measurement of  $\Delta t$  requires accurate measurement of the decay vertices.
- Resolution in  $\Delta t$  is dominated by the tagging side.
- Determine resolution parameters from a large sample of **fully reconstructed** B events.





hep-ex/0501071, submitted to PRL

We measure:

$$a_{\pi\pi}(t) = \frac{\Gamma_{B^0 \rightarrow \pi\pi} - \Gamma_{\bar{B}^0 \rightarrow \pi\pi}}{\Gamma_{B^0 \rightarrow \pi\pi} + \Gamma_{\bar{B}^0 \rightarrow \pi\pi}} = S \sin(\Delta m_B \Delta t) - C \cos(\Delta m_B \Delta t)$$

- Maximum likelihood fit
  - B mass
  - B energy
  - Event shape variables
  - $\theta_c$  - Cherenkov angle from DIRC
  - $\Delta t$

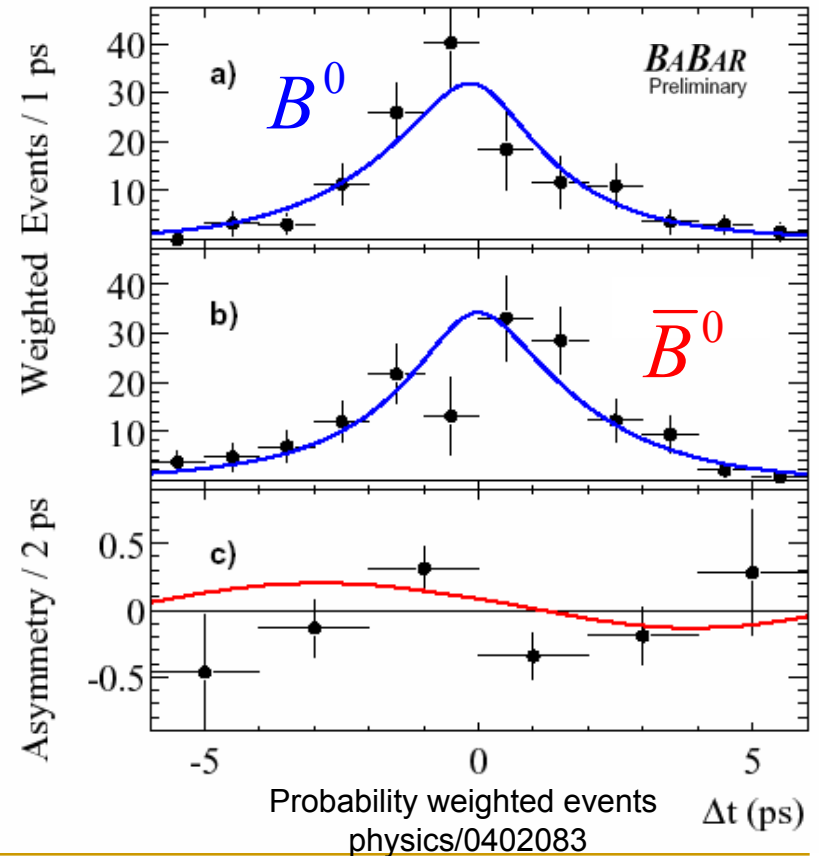
$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$

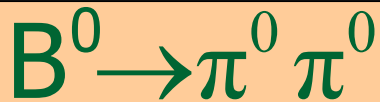
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$



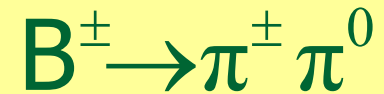
$227 \times 10^6$  B pairs

467 signal events





227 (M) B pairs  
hep-ex/0412037



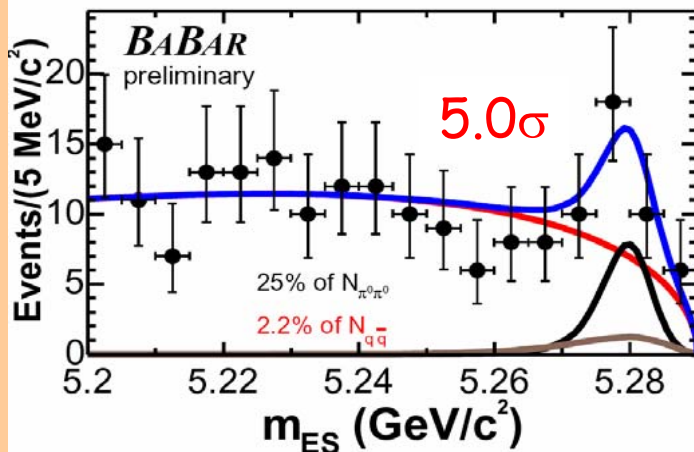
- Maximum likelihood fit
  - B mass, energy
  - Event shape variables
  - $\rho^+\pi^0$  background fixed in fit

$$\rightarrow C_{00} = \frac{N(\pi^0 \pi^0) - \bar{N}(\pi^0 \pi^0)}{N(\pi^0 \pi^0) + \bar{N}(\pi^0 \pi^0)}$$

Signal events  
 $61 \pm 17$

$$BF_{\pi^0 \pi^0} = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$

$$C_{\pi^0 \pi^0} = -0.12 \pm 0.56 \pm 0.06$$



Fit

$q\bar{q}$  bkgd

Signal

$B^\pm \rightarrow \rho^\pm \pi$

Likelihood enhanced plot

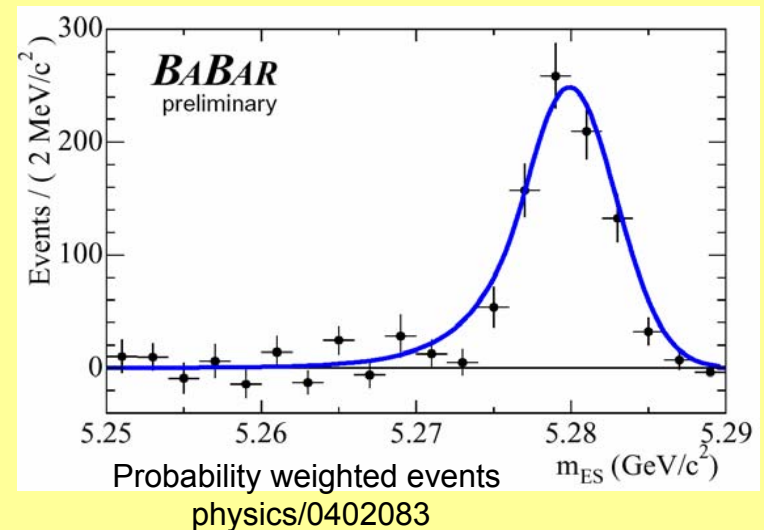
- ML fit uses  $\theta_c$  for K/ $\pi$  separation

$$\rightarrow A_{\pi^+\pi^0} = \frac{N(\pi^0 \pi^-) - N(\pi^0 \pi^+)}{N(\pi^0 \pi^-) + N(\pi^0 \pi^+)}$$

Signal events  $379 \pm 41$

$$BF_{\pi^+\pi^0} = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$$

$$A_{\pi^+\pi^0} = -0.01 \pm 0.10 \pm 0.02$$



# Constraint on $\alpha$ from $B \rightarrow \pi \pi$

Isospin analysis

Using 227 (M) B pairs

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

90% C.L.

hep-ex/0412037

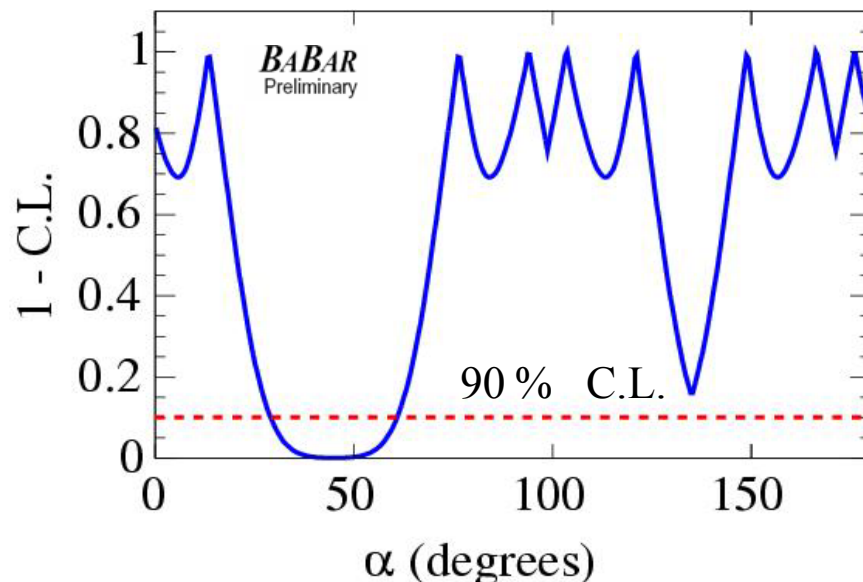
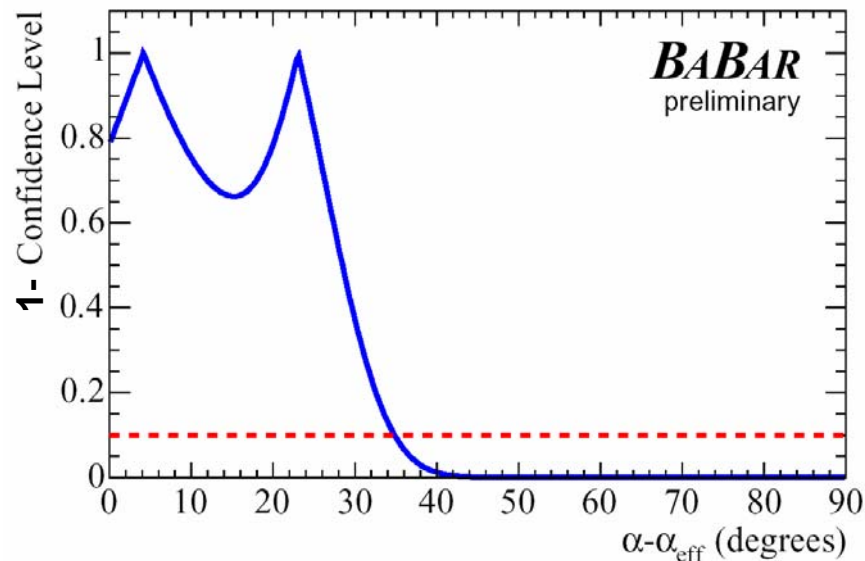
$$[29^\circ, 61^\circ] \alpha \text{ excluded}$$

90% C.L.

hep-ex/0501071



Gronau-London: PRL65, 3381 (1990)





- Vector-vector decay
  - Angular analysis needed to separate CP odd and even components

$\rho\rho$  is almost 100% longitudinally polarised  
 CP even helicity zero state dominates



Analogous to  $\pi\pi$

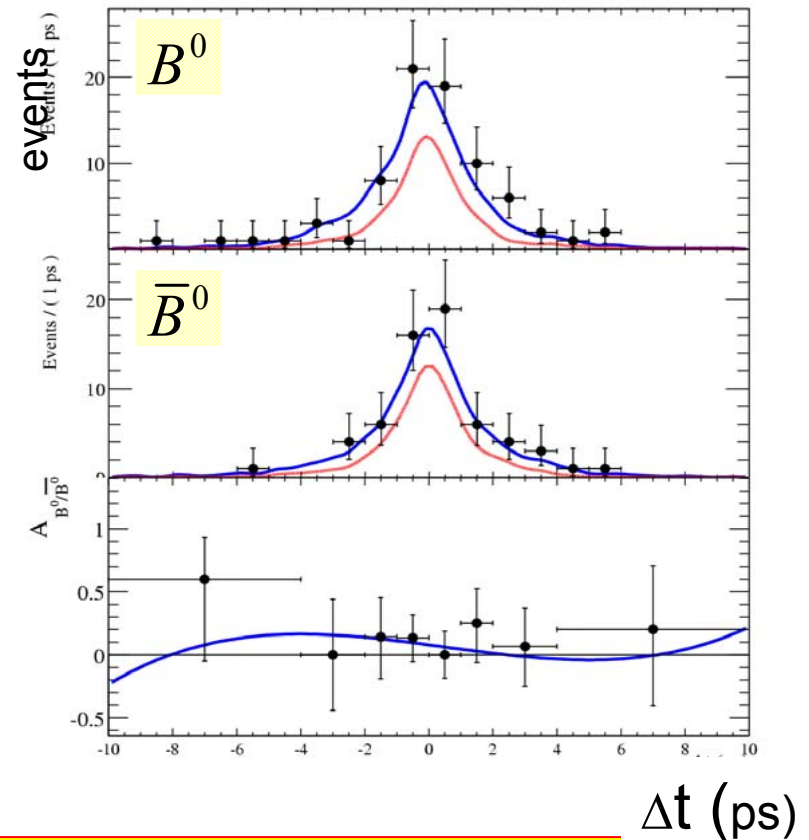
- As in  $\pi\pi$ , penguin pollution shifts  $\alpha_{\text{eff}}$

$$a_{\text{long}}(t) = S_{\text{long}} \sin(\Delta m_B \Delta t) - C_{\text{long}} \cos(\Delta m_B \Delta t)$$

- Maximum likelihood fit
  - B mass, energy
  - Event shape
  - $m(\pi^+\pi^0)$ ,  $m(\pi^-\pi^0)$
  - Helicity angles ( $\pi^0$ )

Results using 122 (M) B pairs

PRL 93, 231801 (2004)



$$S_{\text{long}} = -0.19 \pm 0.33 \pm 0.11$$

$$C_{\text{long}} = -0.23 \pm 0.24 \pm 0.14$$

$$\text{BF}(\rho^+ \rho^-) = (30 \pm 5 \pm 4) \times 10^{-6}$$

$$\Gamma_L / \Gamma = 0.99 \pm 0.03 \pm 0.04$$

# $B^0 \rightarrow \rho^0 \rho^0$

- Analogous to  $\pi^0 \pi^0$
- Maximum likelihood fit
  - B mass, energy
  - Event shape variable
  - Invariant mass of  $\rho$
  - Helicity angles

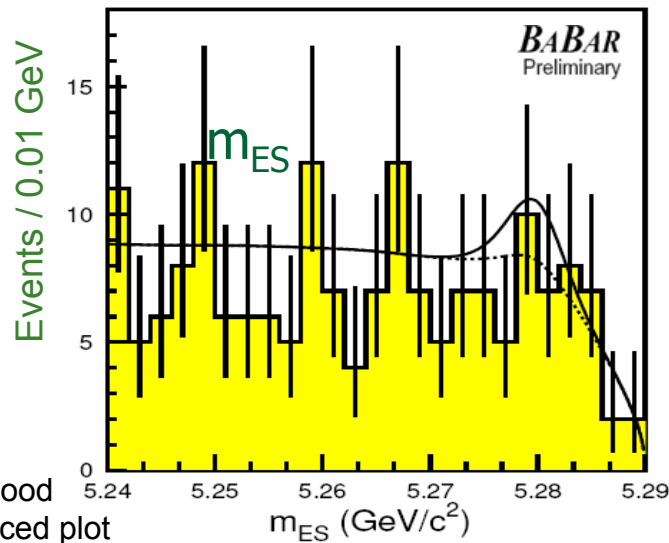
$$BF(B^0 \rightarrow \rho^0 \rho^0) < 1.1 \times 10^{-6} \quad (90\% CL)$$

$$N_{\rho^0 \rho^0} = 33^{+22}_{-20} \pm 12$$

227 (M) B pairs  
Hep-ex/0412067

$$|\alpha - \alpha_{eff}| < 11^\circ \quad 68\% \text{ C.L.}$$

Penguin contribution is smaller than in  $\pi\pi$



Likelihood enhanced plot

# $B^\pm \rightarrow \rho^\pm \rho^0$

88 (M) B pairs  
PRL 91,171802 (2003)

$$A_{cp} = -0.19 \pm 0.23 \pm 0.3$$

$$BF(\rho^\pm \rho^0) = (22.5 \pm 6 \pm 6) \times 10^{-6}$$

$$\Gamma_L / \Gamma = 0.97 \pm 0.07 \pm 0.04$$

# Constraint on $\alpha$ from $B \rightarrow \rho\rho$

- *BaBar*  $BF(\rho^+\rho^-)$ ,  $BF(\rho^0\rho^0)$  and  $S_{long}$  and  $C_{long}$
- World average  $BF(\rho^+\rho^0) = (26.4^{+6.1}_{-6.4}) \times 10^{-6}$

PRL 93, 231801 (2004)

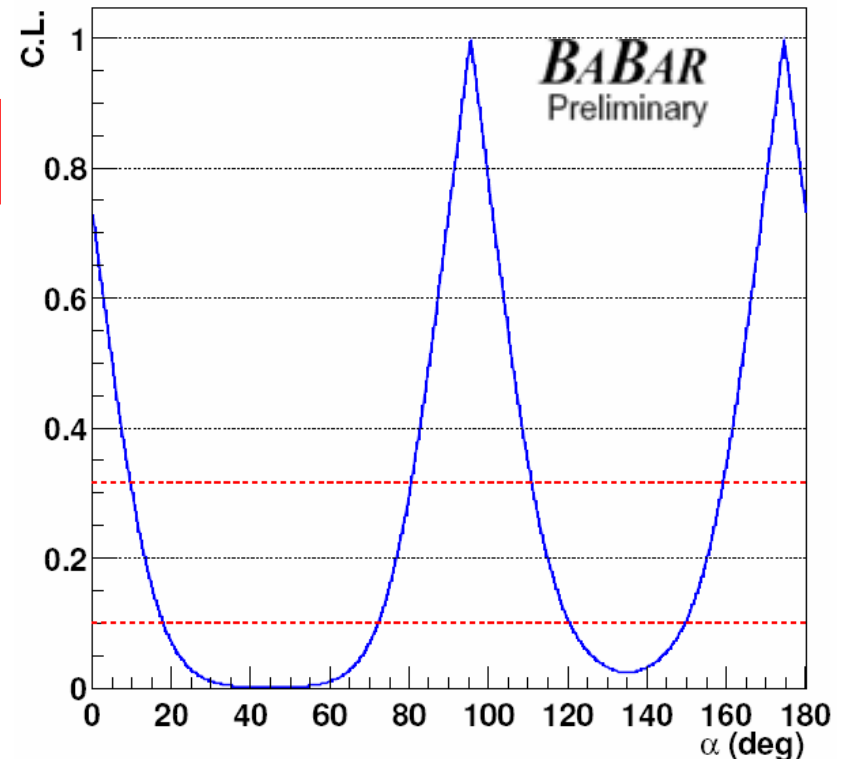
(HFAG)

$$\alpha = [96 \pm 10(stat) \pm 4(syst) \pm 11(peng)]^\circ$$

New from  $\rho^0\rho^0$  measurement

227 (M) B pairs

Full analysis using 227 (M) pairs is underway



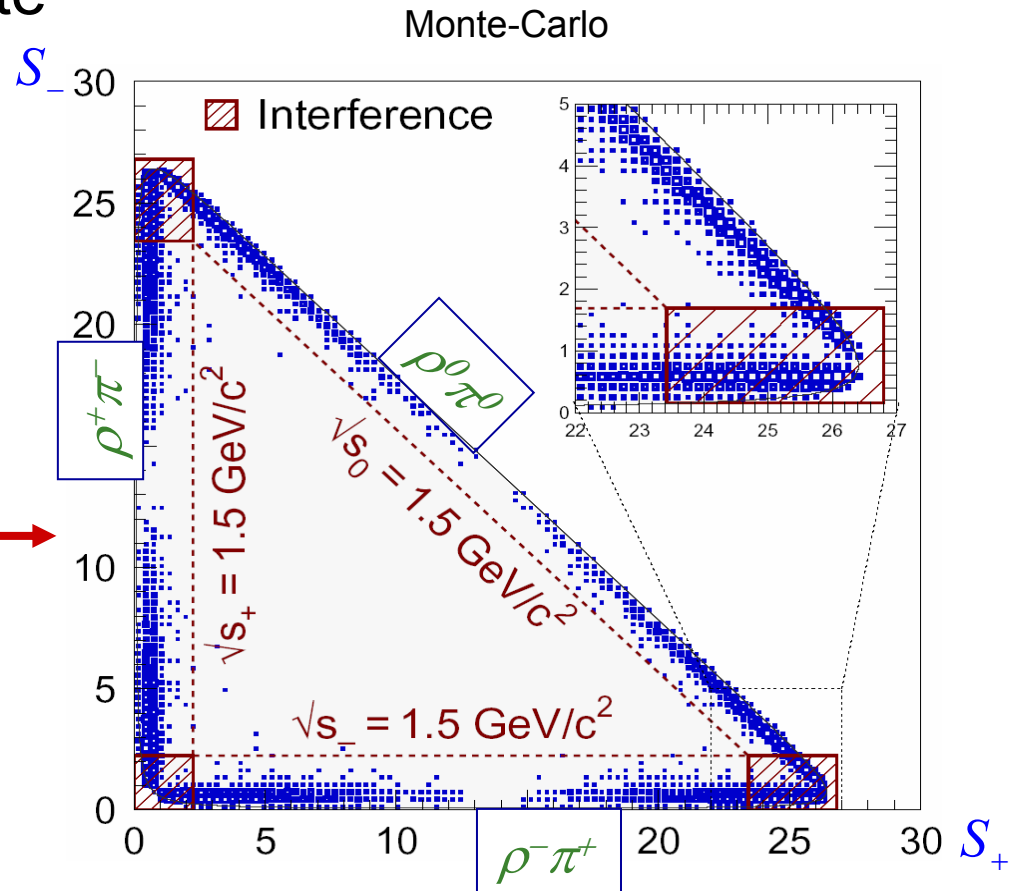
# $B^0 \rightarrow (\rho\pi)^0$

- $\rho^+\pi^-$  is not a CP eigenstate

- Final state  $\pi^+\pi^-\pi^0$   
from  $B^0 \rightarrow$

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

- Dalitz plot analysis →
  - Extract  $\alpha$  and strong phases using interference between amplitudes



# Dalitz Plot fit

Fit to the Time-dependent decay rate:

$$|\mathcal{A}_{3\pi}^{\pm}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ |\mathcal{A}_{3\pi}|^2 + |\bar{\mathcal{A}}_{3\pi}|^2 \mp \left( |\mathcal{A}_{3\pi}|^2 - |\bar{\mathcal{A}}_{3\pi}|^2 \right) \cos(\Delta m_d \Delta t) \pm 2\text{Im} \left[ \bar{\mathcal{A}}_{3\pi} \mathcal{A}_{3\pi}^* \right] \sin(\Delta m_d \Delta t) \right],$$

H. Quinn and J.Silva: PRD **62**, 054002 (2000)

Transform measured parameters into CP observables

213 (M) B pairs

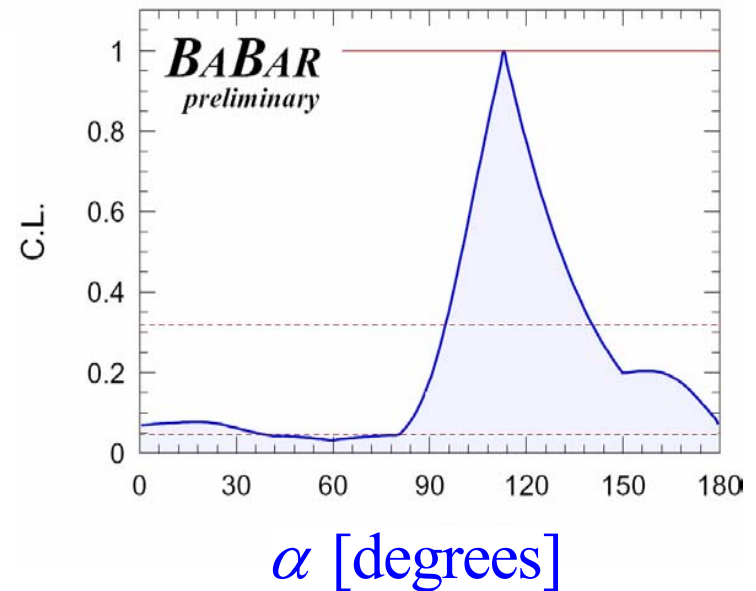
$$A_{\rho\pi} = -0.088 \pm 0.049 \pm 0.013$$

$$S_{\rho\pi} = -0.10 \pm 0.14 \pm 0.04$$

$$C_{\rho\pi} = 0.34 \pm 0.11 \pm 0.5$$

hep-ex/ 0408099

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



# Summary

Great progress towards a precision measurement of  $\alpha$

- ACP( $\Delta t$ ) from  $\rho^+\rho^-$
- First time dependent Dalitz Plot analysis in  $B \rightarrow \rho\pi$

From combined  $\pi\pi, \rho\pi, \rho\rho$



$$\alpha = 103^\circ \begin{matrix} +10^\circ \\ -11^\circ \end{matrix}$$

