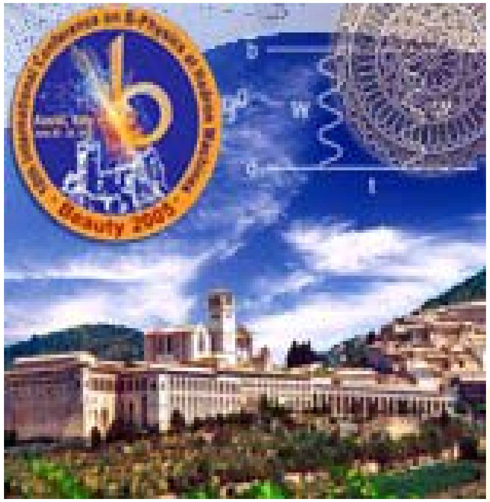


Beauty`05, Assisi
June 20, 2005

Measurements of the angle α (ϕ_2) at BABAR

Sandrine Emery

dapnia SPP
cea
saclay

Outline

- Physics motivation
- How to extract α
- *BABAR* analysis of the decays:
  - $B \rightarrow \pi\pi$
  - $B \rightarrow \rho\rho$
  - $B \rightarrow \pi\pi\pi$ Dalitz
- Summary on α

CP violation

In Standard Model: due to complex CKM unitary matrix

Wolfenstein parameterization:

$$V_{CKM} = \begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

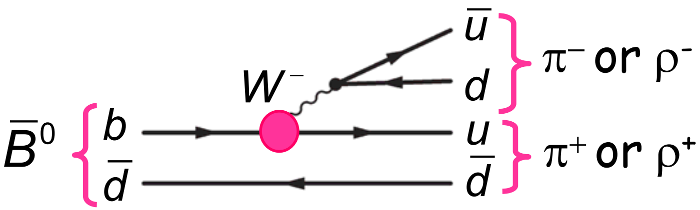
with $\lambda \cong 0.22$, $A \cong 0.83$

CP violation if $\eta \neq 0$.

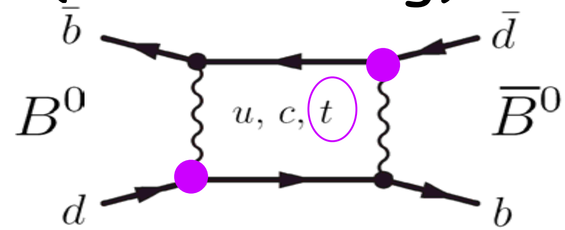
The unitarity triangle

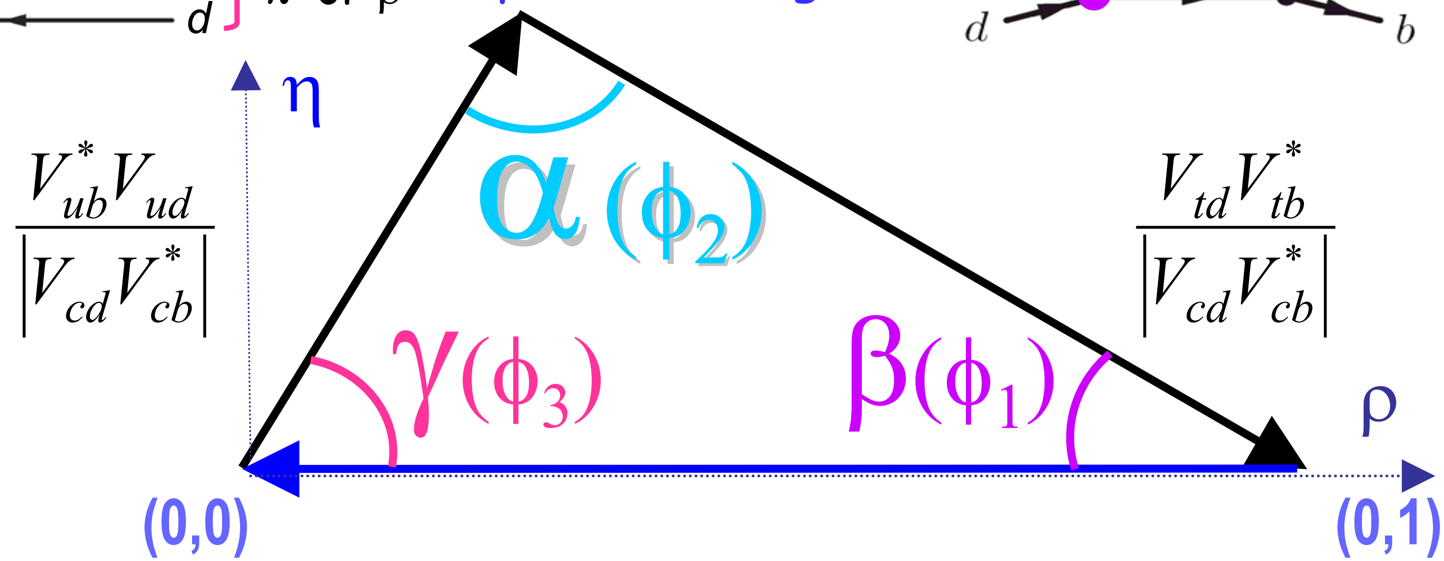
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

γ = phase of V_{ub}
(b→u transition)



β = phase of V_{td}
(B^0-$\bar{B}^0$ mixing)





$\alpha = \pi-\beta-\gamma \Rightarrow$ **process involving both B^0 mixing and b→u transition**

CP violation in the interference between mixing and decay

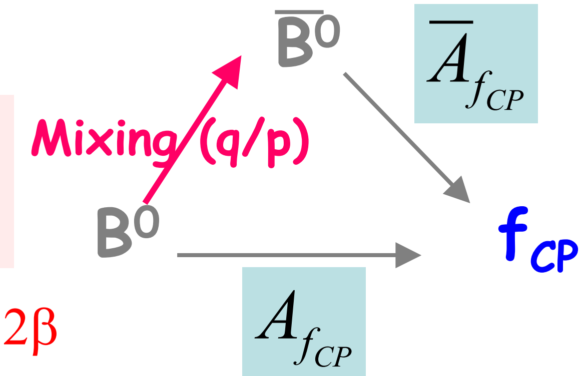
B^0 mixing

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

$$\left|\frac{q}{p}\right| \cong 1$$

phase 2β



CP final state like $\pi^+\pi^-$ or $\rho^+\rho^-$

Time-dependent CP asymmetry

$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

$$= S_{f_{CP}} \sin(\Delta m_d \Delta t) - C_{f_{CP}} \cos(\Delta m_d \Delta t)$$

$$\lambda_{f_{CP}} = \frac{q}{p} \times \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$S \neq 0$: Indirect *CP* violation

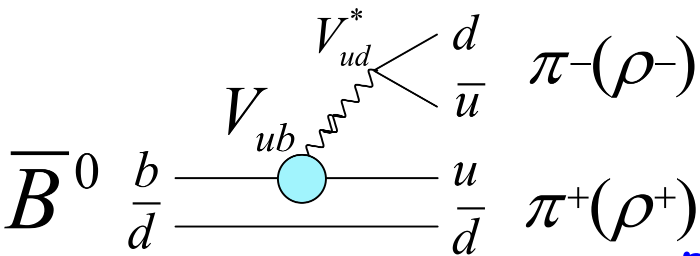
$$S_{f_{CP}} = \frac{2\,\Im(\lambda_{f_{CP}})}{1 + |\lambda|^2_{f_{CP}}}$$

$C \neq 0$: Direct *CP* violation

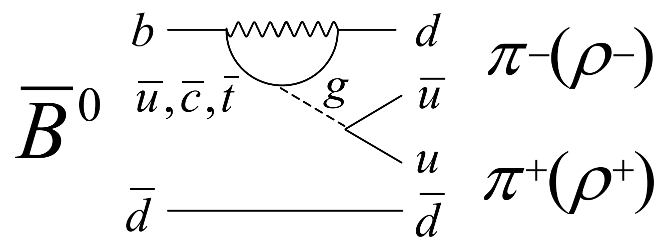
$$C_{f_{CP}} = \frac{1 - |\lambda|^2_{f_{CP}}}{1 + |\lambda|^2_{f_{CP}}}$$

Case of $B^0 \to \pi^+\pi^-$ or $B^0 \to \rho^+\rho^-$

Tree decay **Penguin decay** pollution



$\oplus$



phase γ

$$Amplitude\ T \propto V_{ud}^* V_{ub}\ (\propto A\lambda^3 \times e^{i\gamma})$$

$$Amplitude\ P \propto V_{td}^* V_{tb} (\propto A\lambda^3)$$

δ = strong phase difference between penguin and tree

Tree only

$$\lambda_{\pi^+\pi^-(\rho^+\rho^-)} = \frac{q}{p} \times \frac{\overline{T}}{T} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$S = \sin(2\alpha)$$
$$C = 0$$

Tree + Penguin

$$\lambda_{\pi^+\pi^-(\rho^+\rho^-)} = e^{i2\alpha} \times \frac{|T| + |P| e^{+i\gamma} e^{i\delta}}{|T| + |P| e^{-i\gamma} e^{i\delta}}$$

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

α effective only

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

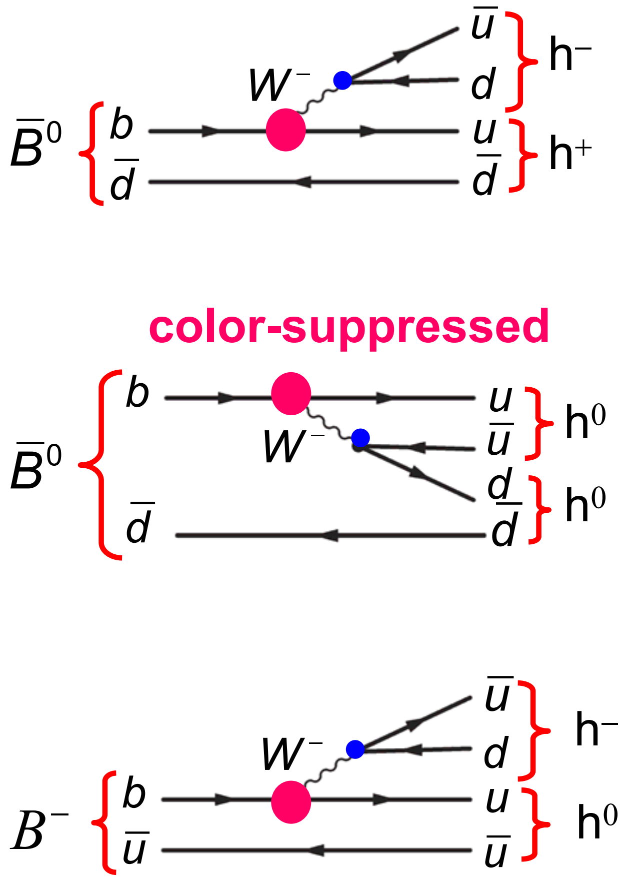
$$\overline{B}^0 \to h^0 h^0$$

small

$$B^- \to h^- h^0$$

$$h = \pi \ or \ \rho$$

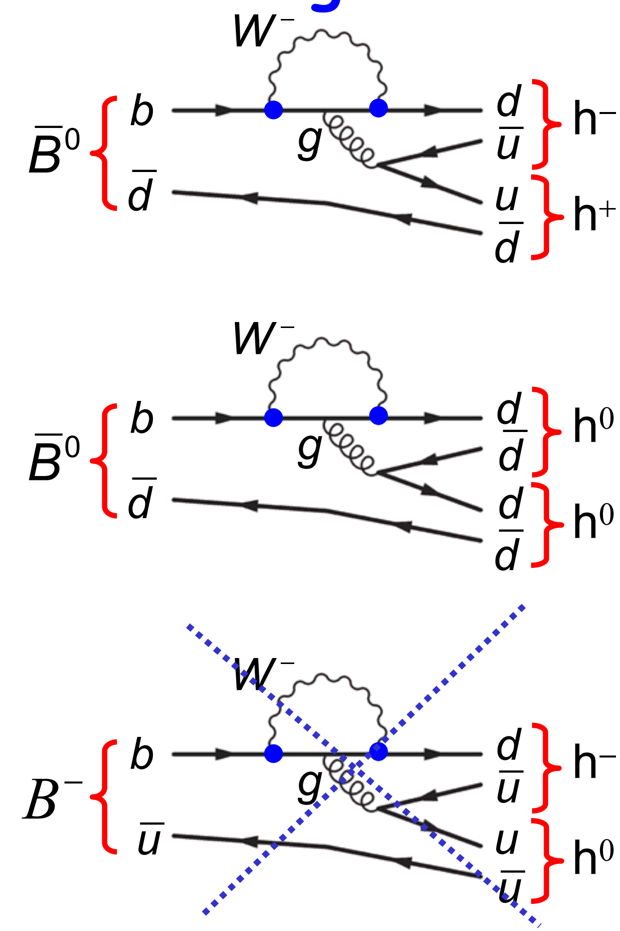
Tree



V_{ub}

Phase γ

Penguin



Isospin=2 final state for $B^+ \to \pi^+\pi^0$

Forbidden for penguins

Almost true for $B^+ \to \rho^+\rho^0$

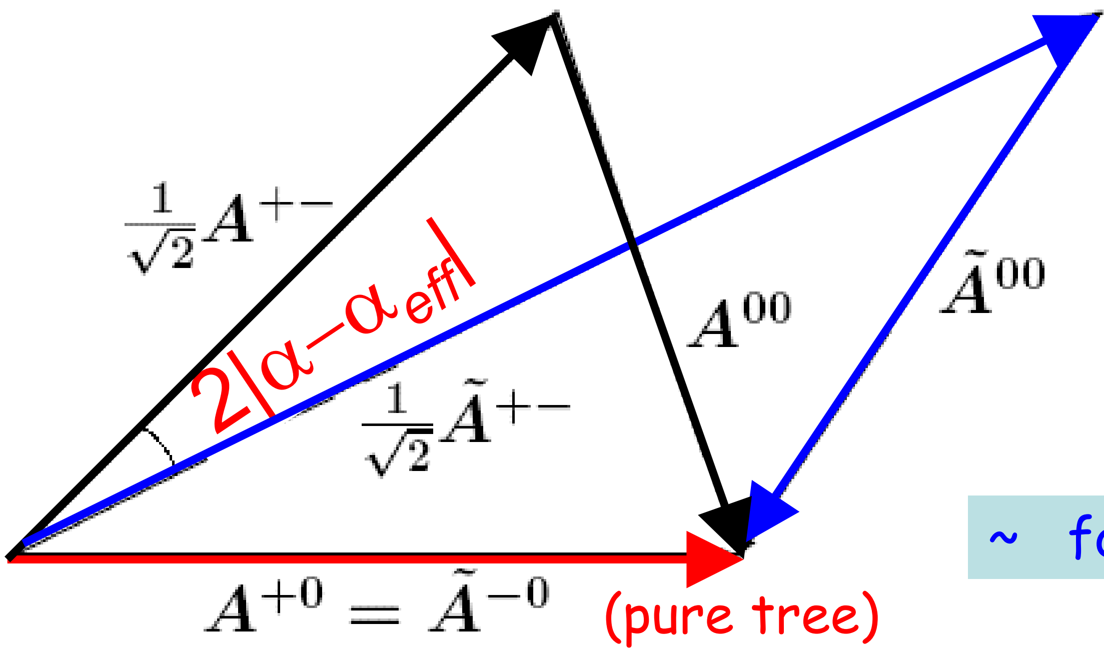
Falk, Ligeti, Nir, Quinn

hep-ph/0310242

Isospin analysis

Use SU(2) (u and d quarks) to relate amplitudes of all $\pi\pi$ ($\rho\rho$) modes.

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



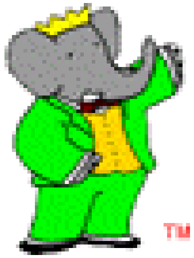
$h\,h=\pi\pi,\rho\rho$

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

~ for charge conjugate reaction

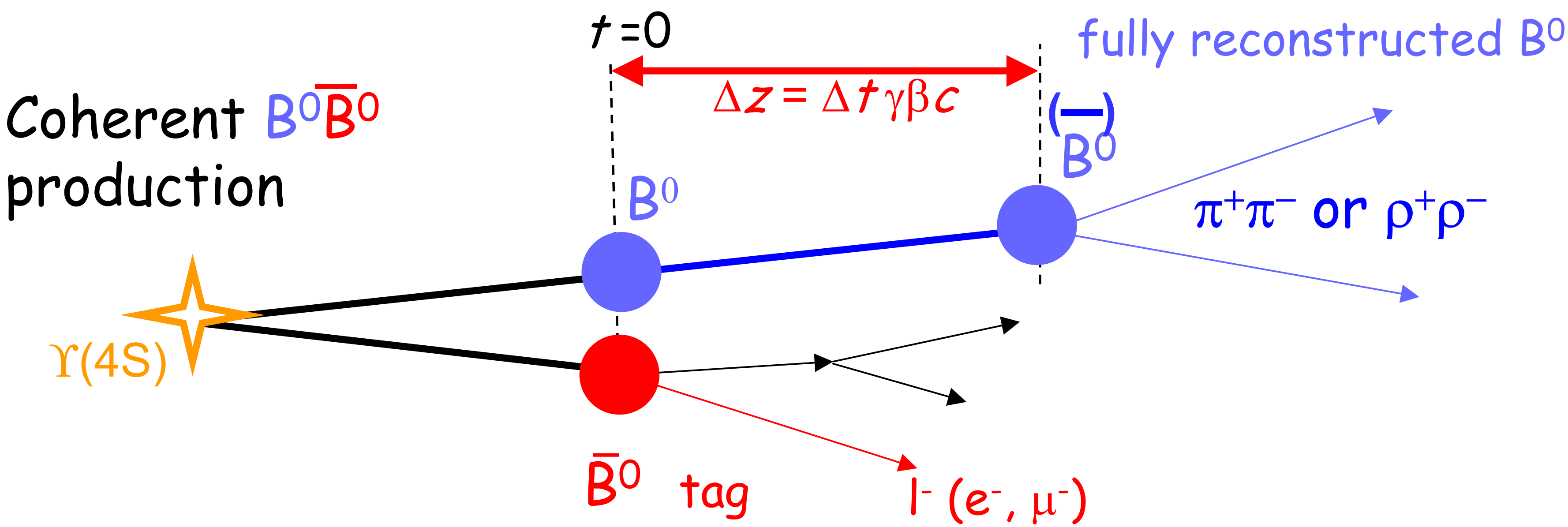
Gronau, London : PRL**65**, 3381 (1990)

EW penguins neglected



Measurements of α at BABAR

CP Asymmetry Measurement



- Exclusive B^0 meson reconstruction.
- Time measurement: $\Delta z \approx 250\ \mu m$, $\sigma_{\Delta z} \approx 170\ \mu m$.
- B-flavor tagging: $Q = \Sigma\, \varepsilon(1-2\omega)^2 \approx 30\%$.

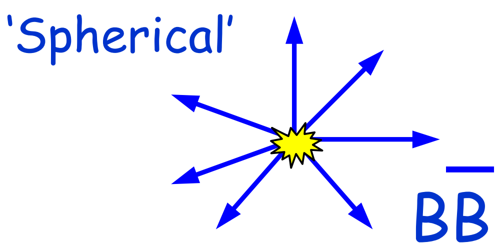
  with ε efficiency and ω mistag rate.

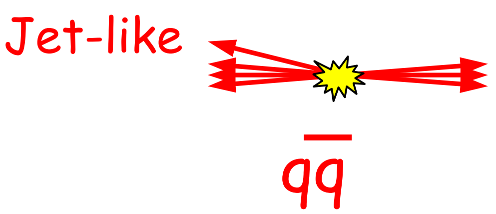
Signal Selection

- **Hadron ID** $\Rightarrow$ separation π/K

- **Kinematical identification** with
  - Beam energy substituted mass $$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$
  - Energy difference $$\Delta E = E_B^* - E_{beam}^*$$

- **Event-shape variables** combined in a neural network or Fisher discriminant to suppress jet-like continuum events





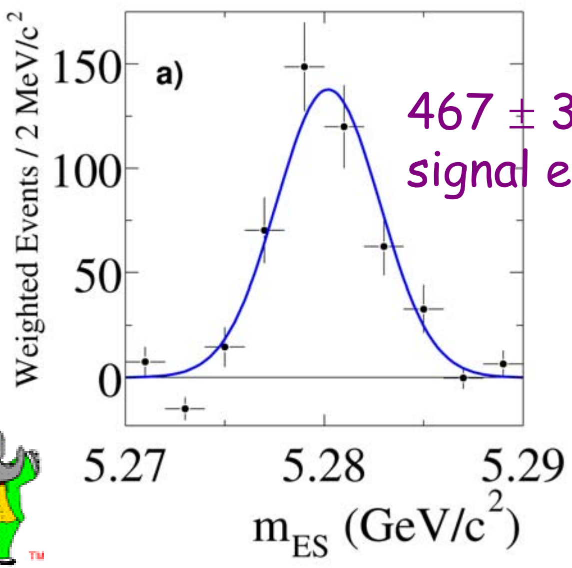
Results of the $B^0 \rightarrow \pi^+\pi^-$ analysis

227×10^6 BB

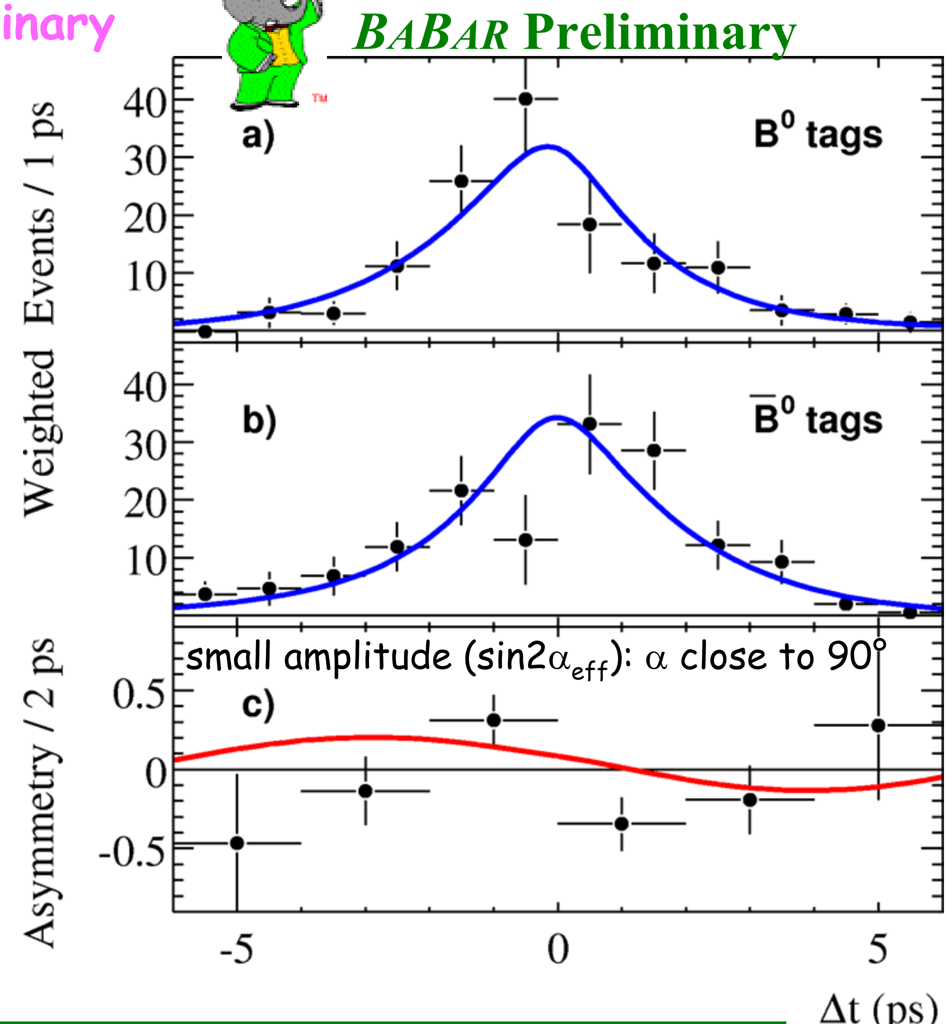
hep-ex/0501071, submitted to PRL Preliminary

$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$

Consistent with no direct CPV



467 ± 33
signal evts



small amplitude ($\sin 2\alpha_{eff}$): α close to 90°

PRL 89 281820 (2002) 88×10^6 BB

$BR = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$

Old result

sPlots (event-weighting technique)
M. Pivk, F. Le Diberder *physics/0402083*

$B^0 \to \pi^0\pi^0$

227×10^6 BB

PRL **94**, 181802 (2005)

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

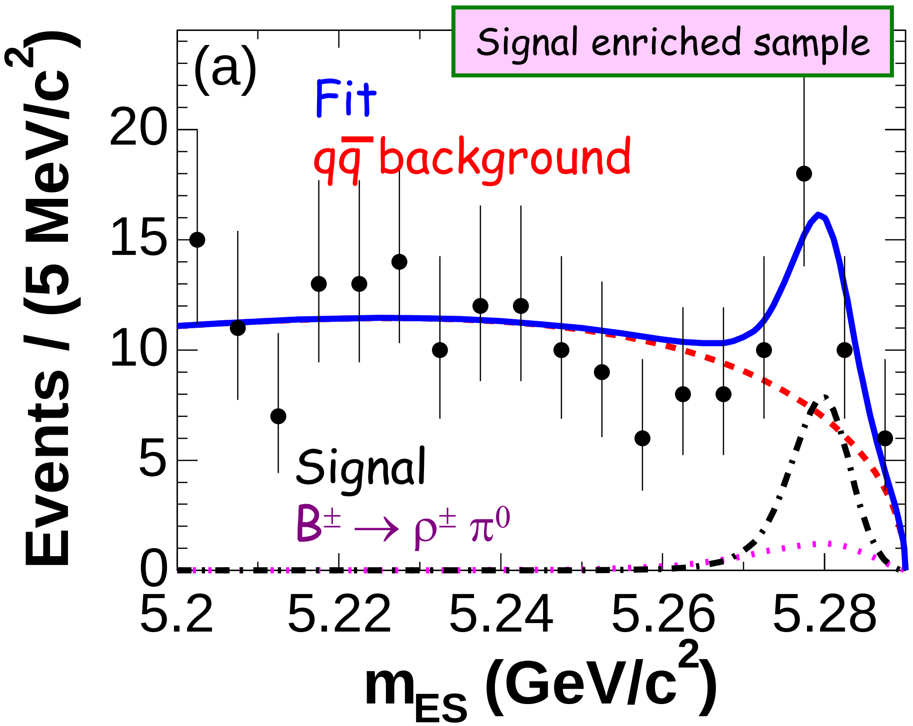
$BR = (1.17 \pm 0.32 \pm 0.10)\times 10^{-6}$
$C_{00} = -0.12 \pm 0.56 \pm 0.06$

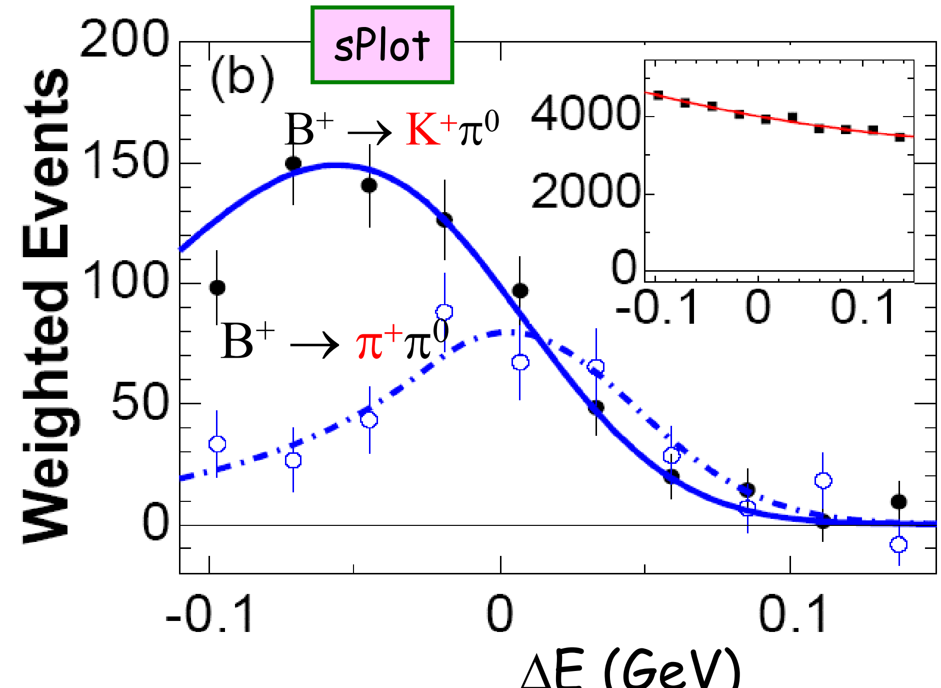
$BR = (5.8 \pm 0.6 \pm 0.4)\times 10^{-6}$
$A_{\pm 0} = -0.01 \pm 0.10 \pm 0.02$

C_{00} and A_{+0} : time-integrated charge asymmetries

$61 \pm 17 \pm 5$ signal events
5.0σ significance

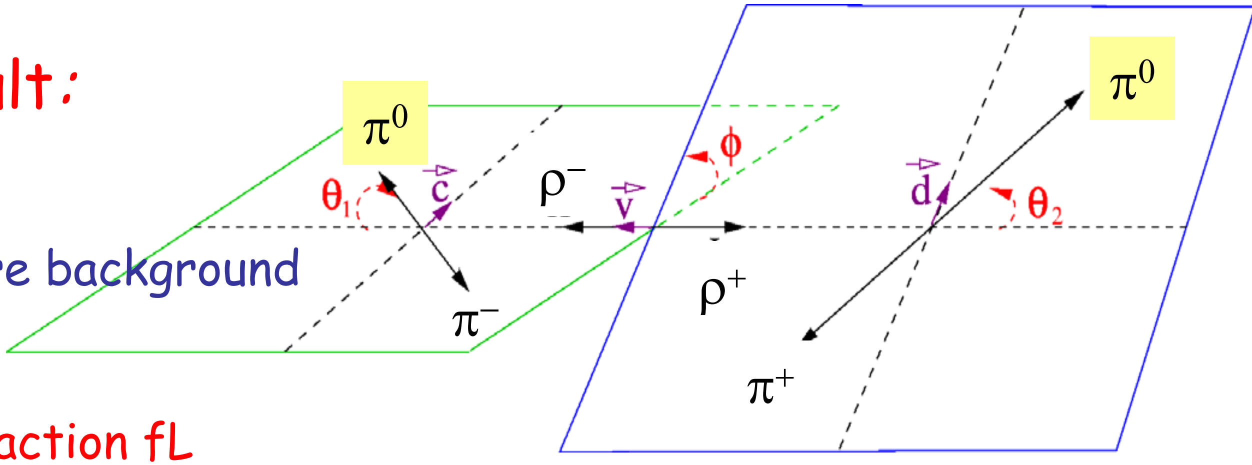
379 ± 41 signal events





Result of Isospin analysis shown later

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



Analysis more difficult:

- 2 π^0s in the final state
- Wide ρ resonances $\Rightarrow$ more background
- 3 amplitudes (VV decay):

A_0 (CP-even longitudinal), fraction fL

$A_{||}$ (CP-even transverse), $A_\perp$ (CP-odd transverse).

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left\{\frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2 + f_L\cos^2\theta_1\cos^2\theta_2\right\}$$

But eventually the best mode:

- Branching fraction ~ 6 times larger than for $B\to\pi\pi$
- Penguin pollution much smaller than in $B\to\pi\pi$ *(see later)*
- Almost 100% longitudinally polarized! Pure CP-even state.

$B^0 \to \rho^+\rho^-$ analysis (2)

232×10^6 BB

- Unbinned extended maximum likelihood fit on a data sample of 68703 events.
- Signal Efficiency: 7.7%.
- 8 observables:
  - m_{ES}, ΔE, Δt, NN (like $B^0 \to \pi\pi$ analysis)
  - $m(\rho \to \pi\pi)$ (x2), $\cos\theta(\rho \to \pi\pi)_{hel}$ (x2)
- Model signal (1% of sample), continuum (92%), and 38 different modes of B-background (7%).
- Extract signal yield, longitudinal polarization fraction, cosine and sine coefficients.

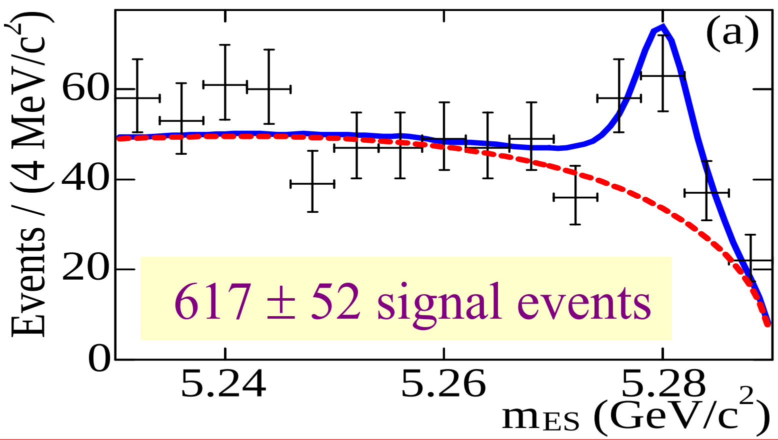
$A_{CP}(t)$ in $B^0 \to \rho^+\rho^-$ decays

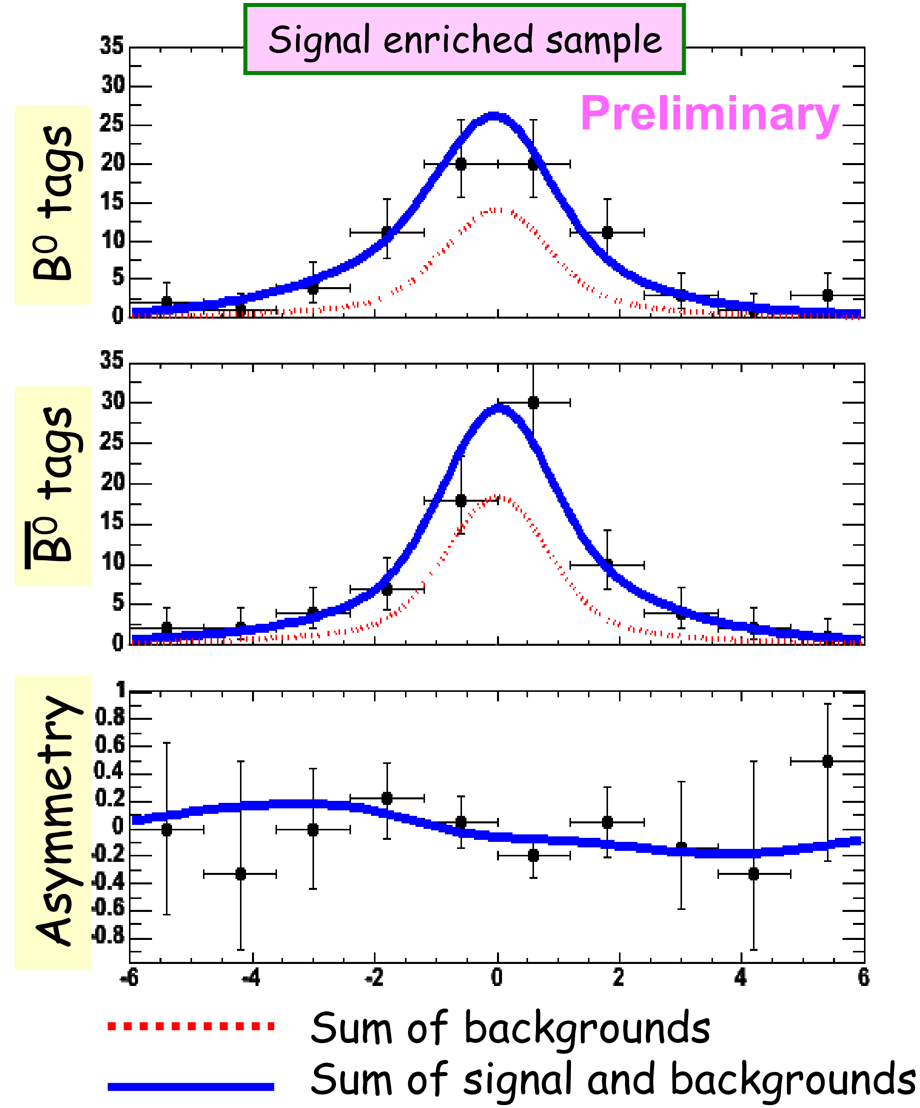
hep-ex/0503049
submitted to PRL

232×10^6 BB

Preliminary

$$f_L = 0.978 \pm 0.014 \,^{+0.021}_{-0.029}$$
$$S_L = -0.33 \pm 0.24 \,^{+0.08}_{-0.14}$$
$$C_L = -0.03 \pm 0.18 \pm 0.09$$





Consistent with previous measurement

PRL 93 231801 (2004)

89×10^6 BB

$BR = (30 \pm 4 \pm 5) \times 10^{-6}$

$B^0 \to \rho^0\rho^0$ and $\rho^+\rho^0$ analyses

PRL **94**, 131801 (2005) 227×10^6 BB

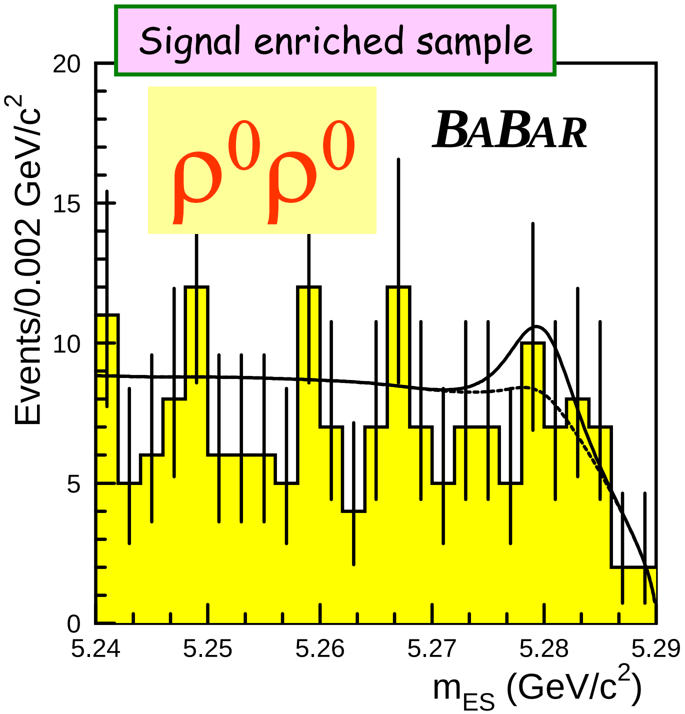
$BR(B^0 \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ @90% C.L.

$33^{+22}_{-20} \pm 12$ signal events

No significant signal, Penguins small in $\rho\rho$!

$f_L = 1$ assumed: most conservative limit on BR

Dominant systematic: potential interference from $B \to a_1^{\pm}\pi^{\pm}$ (~22%).



No update yet for $\rho^+\rho^0$: old world average for isospin analysis

85×10^6 BB

PRL **91**, 221801 (2003)

89×10^6 BB

PRL **91**, 171802 (2003)

$$\mathrm{WA}: \; B(B^+ \to \rho^+\rho^0) = (26.4 \pm 6.4)10^{-6} \qquad f_L(\rho^+\rho^0) = 0.96^{+0.05}_{-0.07}$$

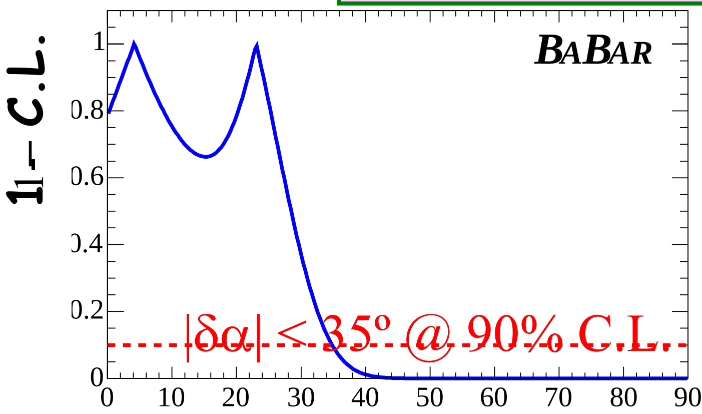
Constraining α with $B \to \pi\pi, \rho\rho$

$\delta\alpha = \alpha - \alpha_{eff}$ using isospin

Constrain α

$B \to \pi\pi$

PRL **94**, 181802 (2005)

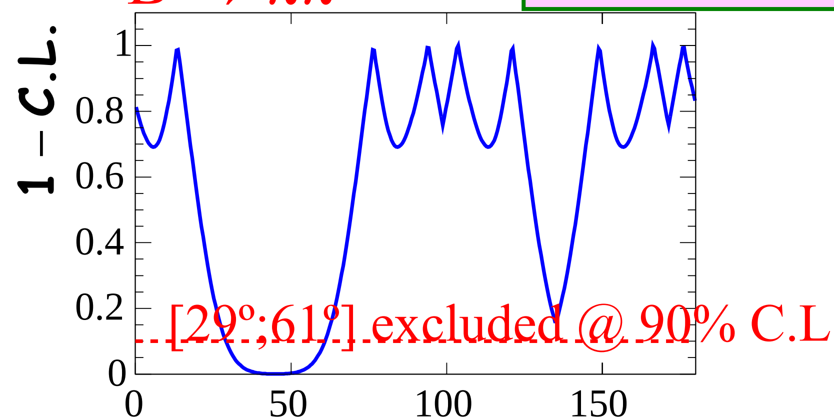


$\delta\alpha = \alpha - \alpha_{eff}$ (°)

Preliminary

$B \to \pi\pi$

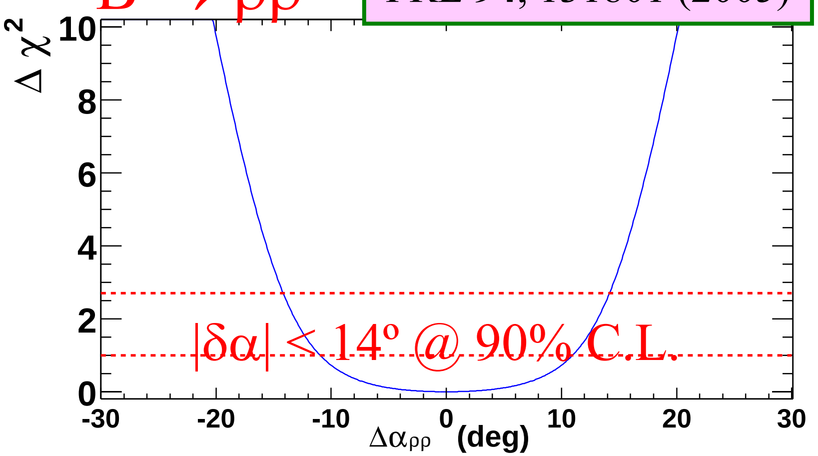
hep-ex/0501071
submitted to PRL



α (°)

$B \to \rho\rho$

PRL **94**, 131801 (2005)



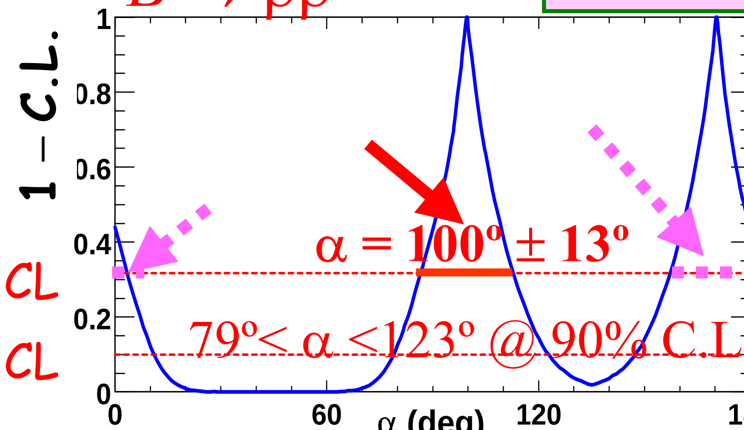
68% CL

90% CL

Preliminary

$B \to \rho\rho$

hep-ex/0503049
submitted to PRL



Mirror solution $\alpha \sim 165°$

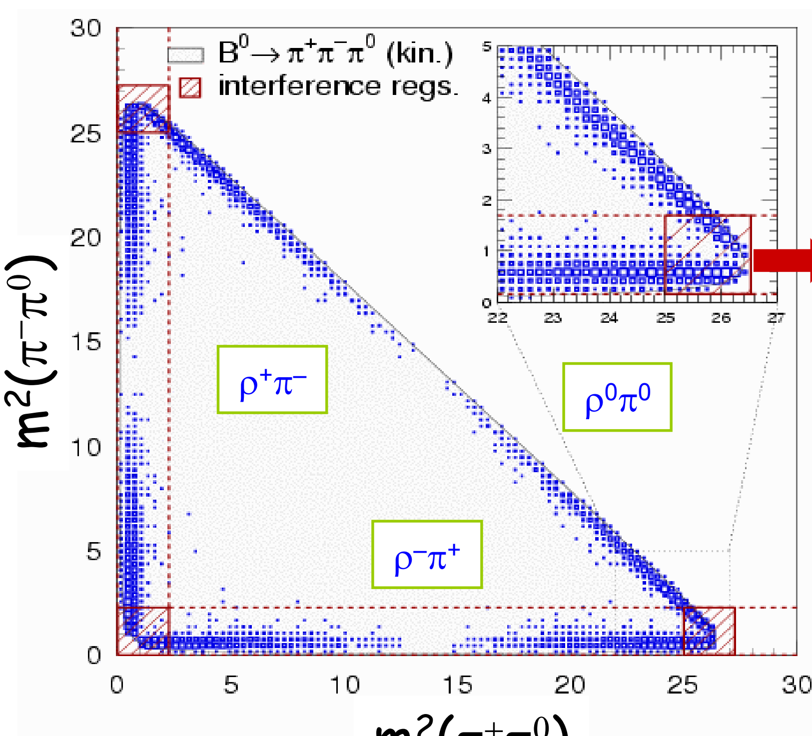
Dalitz analysis of $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$

- Dominant decay $B^0 \to \rho^+\pi^-$: not a CP eigenstate
- Isospin analysis not viable, too many amplitudes to consider

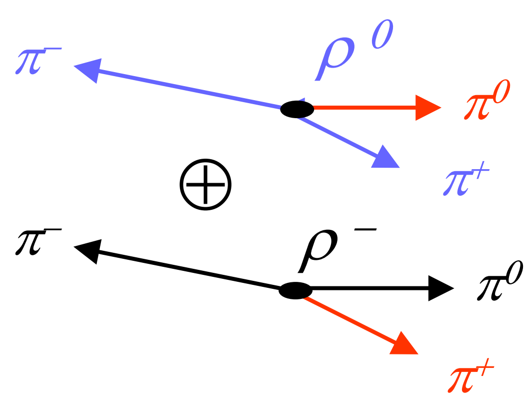
$B^0 \to \rho^+\pi^-$, $B^0 \to \rho^-\pi^+$, $B^0 \to \rho^0\pi^0$, $B^+ \to \rho^+\pi^0$, $B^+ \to \rho^0\pi^+$ and charge conjugates

- Better approach: Time-dependent Dalitz analysis
  - Simultaneous fit of α and T, P amplitudes
  - α constrained with no ambiguity (not like in $\sin(2\alpha)$ measurement)

Snyder-Quinn, PRD **48**, 2139 (1993)



Amplitude $A(B \to 3\pi)$ dominated by ρ^+, ρ^- and ρ^0 resonances



$B^0 \to \pi^+\pi^-\pi^0$ results

213×10^6 BB

$$A(B^0 \to \rho^\kappa \pi^\lambda) = A^{\kappa\lambda} = T^{\kappa\lambda} e^{-i\alpha} + P^{\kappa\lambda}$$
$$A(\overline{B}^0 \to \rho^\kappa \pi^\lambda) = \overline{A}^{\kappa\lambda} = T^{\kappa\lambda} e^{+i\alpha} + P^{\kappa\lambda}$$

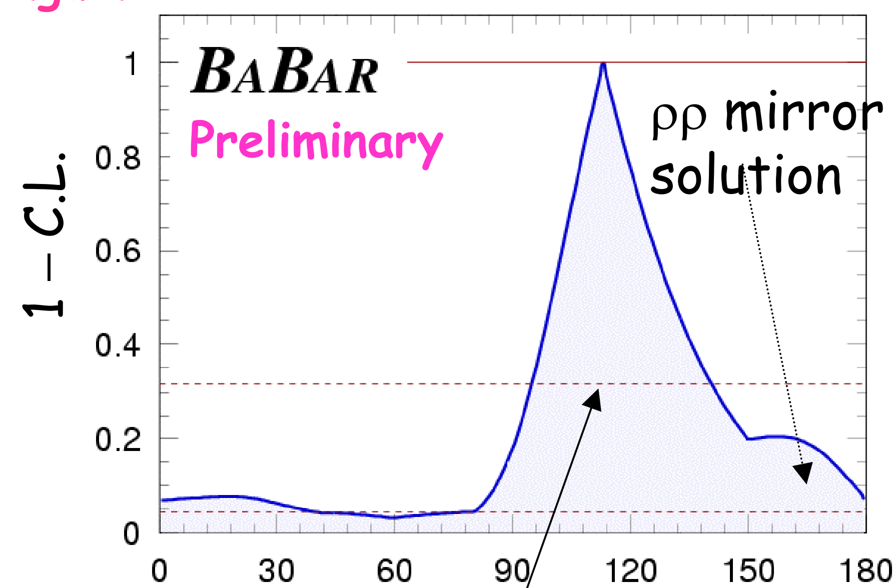
κ,λ {+,0,−}
T tree
P penguin

$A(\overset{(-)}{B}{}^0 \to 3\pi)$: functions of the $\overset{(-)}{A}{}^{\kappa\lambda}$ and well-known kinematics functions of the Dalitz variables $m^2(\pi^+\pi^0)$ and $m^2(\pi^+\pi^0)$

$A(\overset{(-)}{B}{}^0 \to 3\pi)$ Time-dependent analysis:
Disentangles:
- One constant term
- One $\sin(\Delta mt)$ term
- One $\cos(\Delta mt)$ term

Providing enough contraints on α and tree and penguin amplitudes

Likelihood scan of α:



$$\alpha = \left[113^{+27}_{-17}(stat.) \pm 6(syst.)\right]^\circ$$

Weaker constraint than ρρ but ρρ mirror solutions disfavored

Summary on α

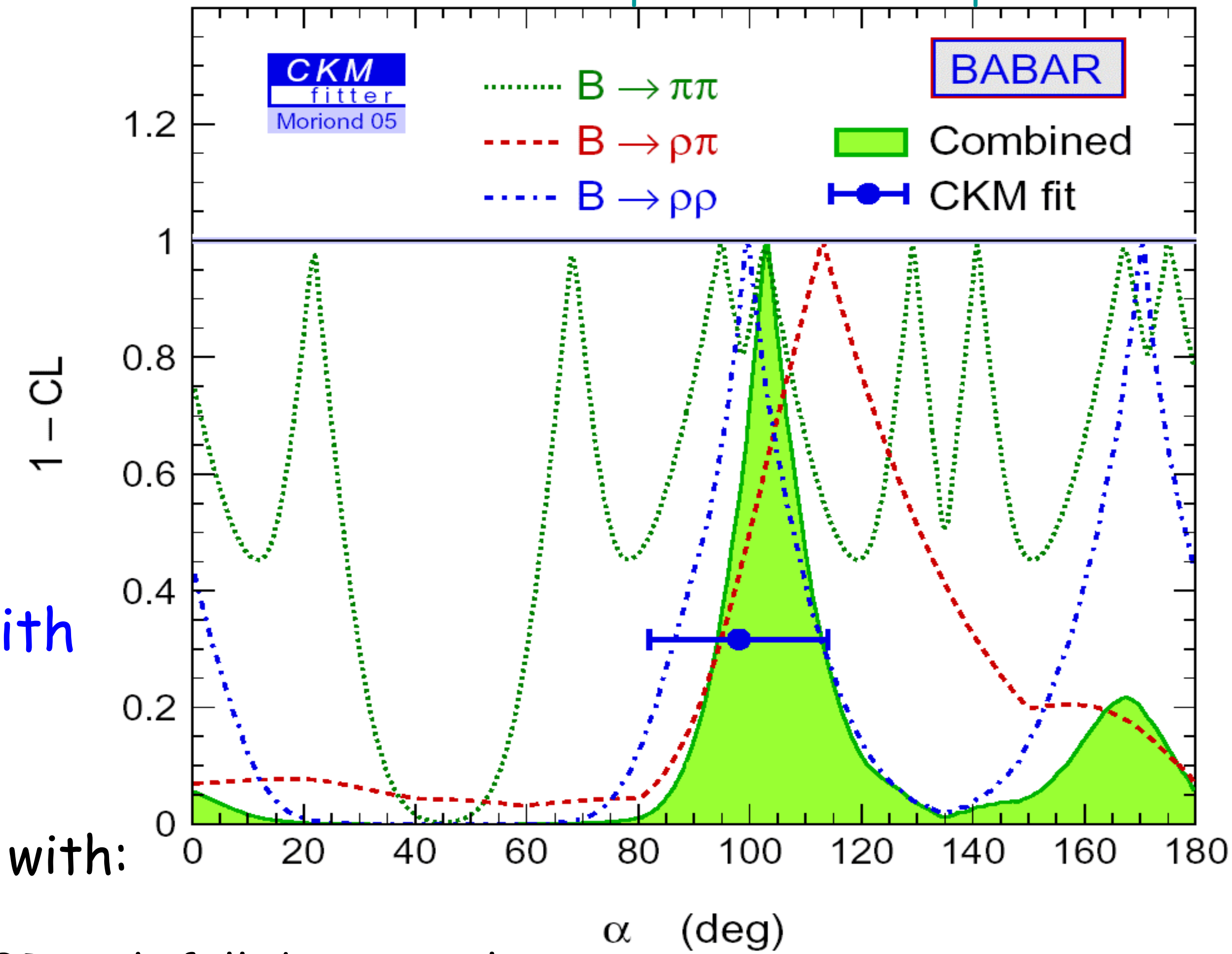
Preliminary

http://ckmfitter.in2p3.fr

- ρρ: best single measurement
- ρπ: disfavors ρρ mirror solutions
- Combined value:

$$\boxed{\alpha = (103^{+10}_{-\ 9})^\circ}$$

- Good agreement with global CKM fit



Accuracy will improve with:
More data
Update of $\rho^+\rho^0$ and $\rho^+\rho^-$ BR with full data sample