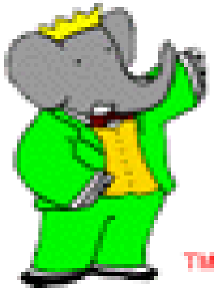
WIN`05, Delphi

June 8, 2005

Measurements of the angle α: $\rho\rho$, $\rho\pi$ (BaBar & Belle results)



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cea

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Outline

- Physics motivation
- Measurement of α in $B \rightarrow \rho\rho$.
- Measurement of α in $B \rightarrow \rho\pi$ Dalitz.
- Summary on α.

CP violation

- CP violation is explained in the Standard Model by a phase in the CKM unitary matrix.
- In the 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 $\lambda \cong 0.22$, $A \cong 0.83$

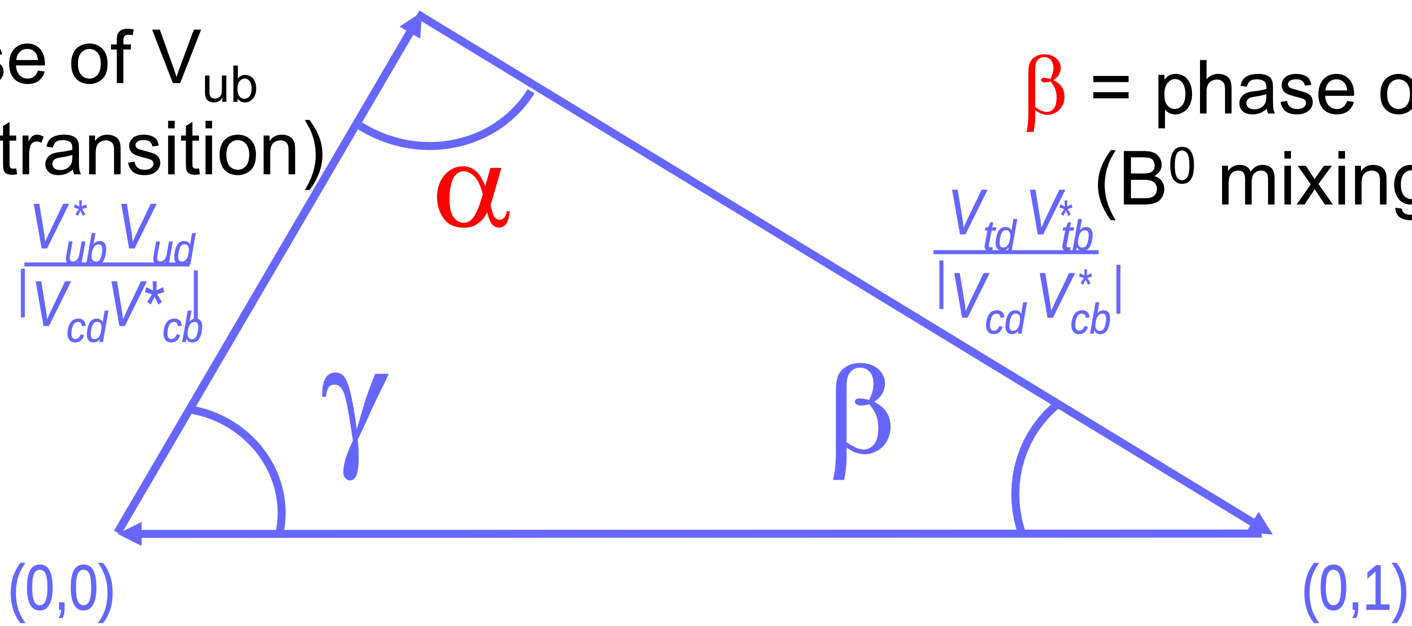
- CP violation if $\eta \neq 0$.

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 mixing)



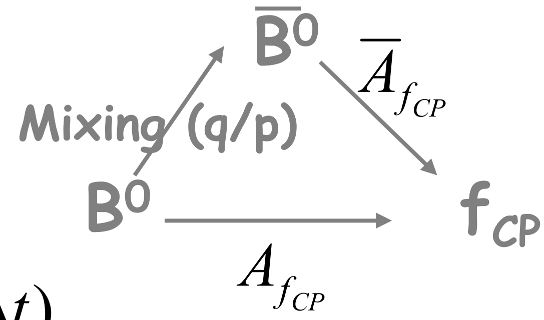
$\alpha = \pi - \beta - \gamma$ = process involving both
B^0 mixing and b→u transition

CP violation in the interference between mixing and decay

- For a CP final state f_{CP}, time-dependent asymmetry is:

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

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



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

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

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

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

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

Final State Amplitudes

from mixing

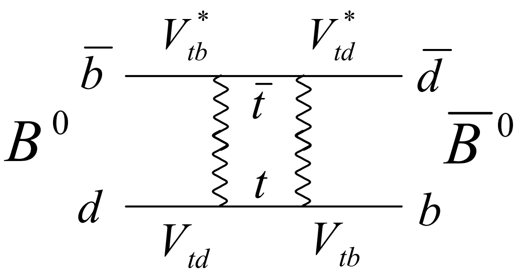
$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

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

CP violation in $B^0 \rightarrow \rho^+\rho^-$

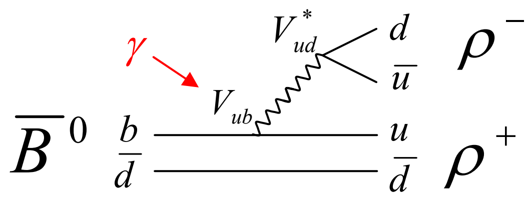
- Access to α from the interference of a $b \rightarrow u$ decay (γ) with $B^0 \overline{B}^0$ mixing (β).

$B^0 \overline{B}^0$ mixing



$q/p \propto V_{tb}^* V_{td} / V_{tb} V_{td}^*$

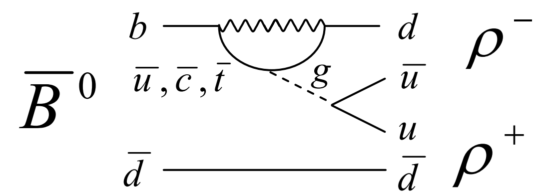
Tree decay



$A \propto V_{ud}^* V_{ub}$

$\oplus$

Penguin decay



$A \approx V_{td}^* V_{tb}$

Tree only

$$\lambda_{\rho^+\rho^-} = \frac{q}{p}\frac{\overline{A}}{A} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

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

$$C = 0$$

Tree + Penguin

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

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

$$C \propto \sin\delta$$

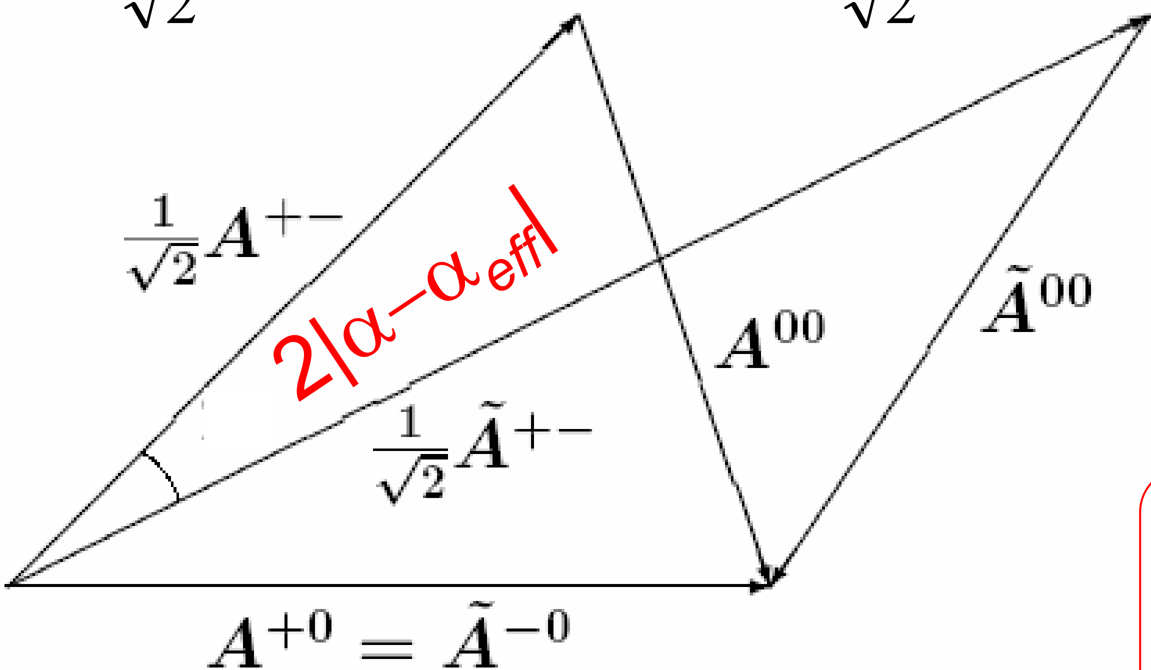
T = tree amplitude
P = penguin amplitude
δ = strong phase difference between penguin and tree

How can we obtain α from α_{eff} ?

Isospin analysis

- Use SU(2) to relate amplitudes of all ρρ modes.

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



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

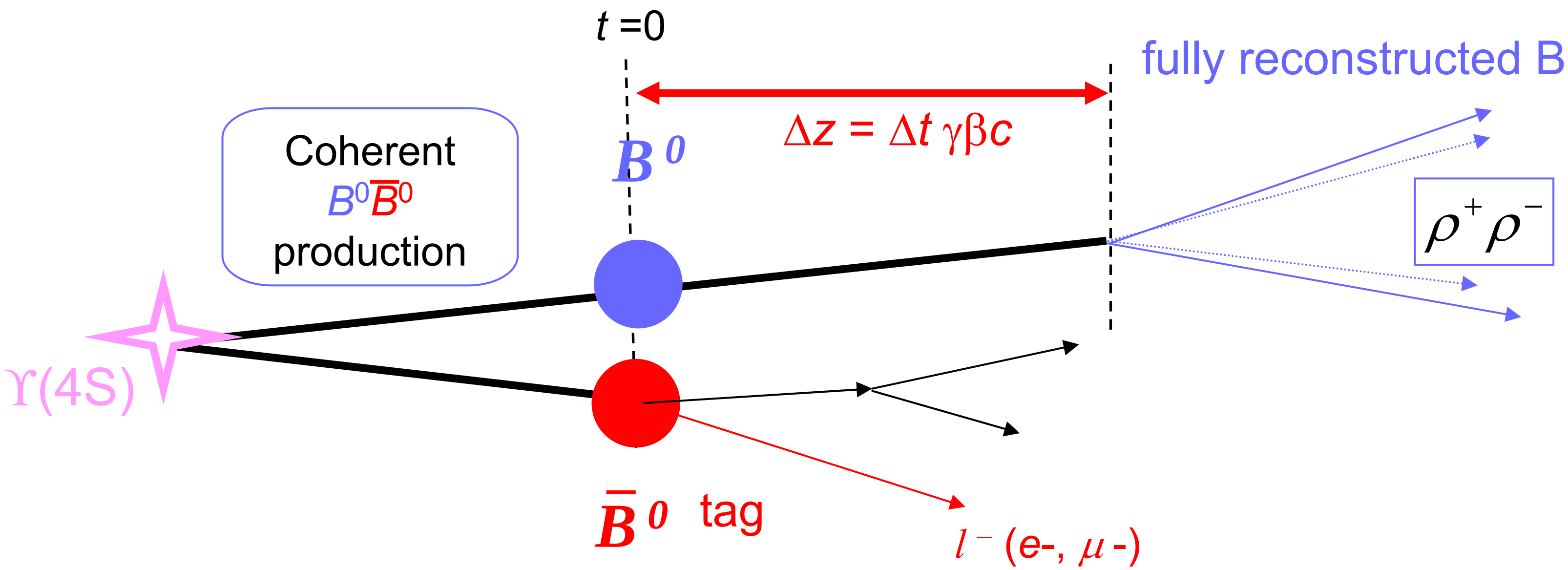
$$\mathbf{A}^{+0} = A(B^+ \to \rho^+\rho^0)$$

$$\mathbf{A}^{00} = A(B^0 \to \rho^0\rho^0)$$
$$\tilde{\mathbf{A}}^{00} = A(\overline{B}^0 \to \rho^0\rho^0)$$

Small amplitudes

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

Asymmetry measurement



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

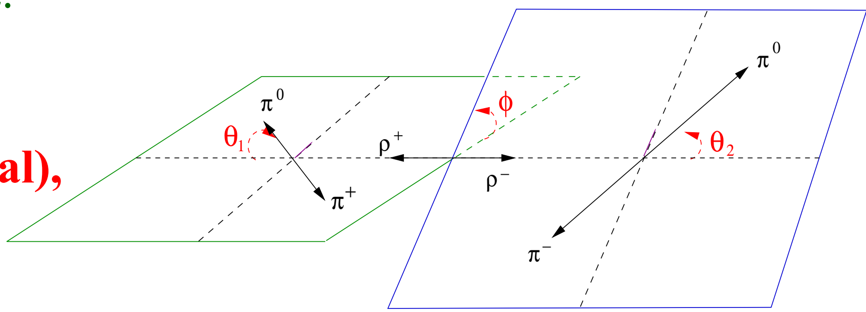
Common features of the analyses

- Kinematical signal identification with
  - Beam energy substituted mass $m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$
  - Energy difference $\Delta E = E_B^* - E_{beam}^*$
- Hadron ID (separation π/K).
- Event-shape variables combined in a neural network (NN) or Fisher discriminant to suppress jet-like continuum event.

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

$B\rightarrow\rho^+\rho^-$ not historically favored for measuring α:

- 2 π^0s in the final state.
- 3 amplitudes (VV decay): A_0 **(*CP*-even longitudinal),** $A_{\parallel}$ (*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 turned out to be the best mode:

- Large branching fraction.

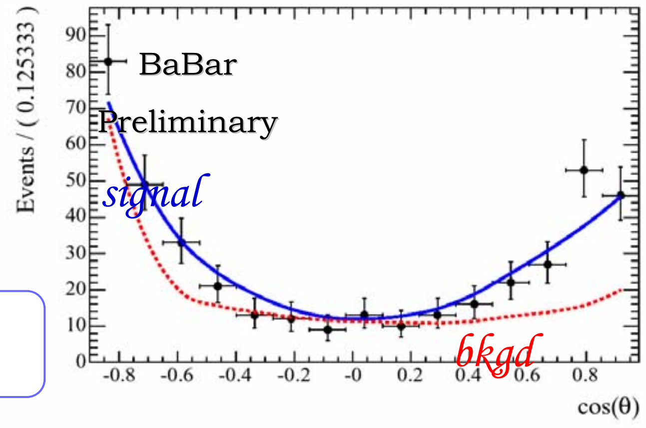
$$B(B^0 \rightarrow \rho^+\rho^-) = (30 \pm 4 \pm 5)\cdot 10^{-6} \quad (89 M_{BB})$$

BaBar, Phys.Rev.Lett 93, 231801 (2004)

- Penguin pollution much smaller than in $B\rightarrow\pi\pi$.
- ~100% longitudinally polarized! Pure *CP*-even state.

$$f_L(\rho^+\rho^-) = 0.978 \pm 0.014^{+0.021}_{-0.029}$$

232 M_{BB}



BaBar, hep-ex/050349, submitted to PRL

Details of the $B^0 \rightarrow \rho^+\rho^-$ analysis

- Unbinned extended maximum likelihood fit on a data sample of 68703 events.

232 M_{BB}

- Efficiency on signal: 7.7%.
- 8 observables: m_{ES}, ΔE, Δt, NN, $m_{\pi\pi}$ (x2), $\cos\Theta^{\pi\pi}{}_{hel}$ (x2).
- Modelisation of signal (1% of fit sample), continuum (92% of fit sample), and 38 different modes of B-background (7% of fit sample).
- Extract signal yield, longitudinal polarization fraction, cosine and sine coefficients.

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

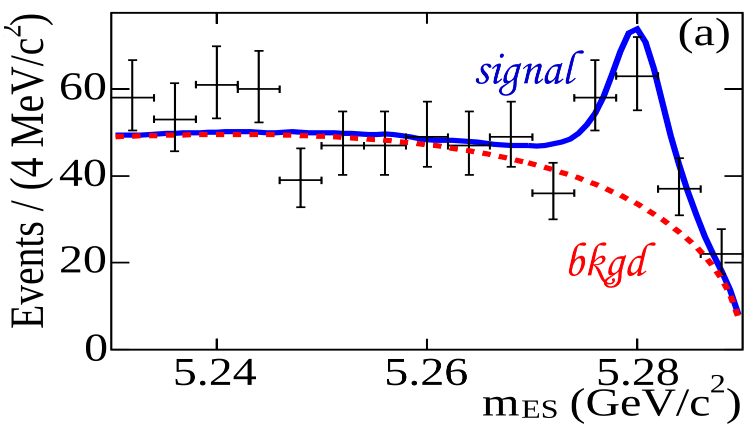
BaBar, hep-ex/0503049, submitted to PRL

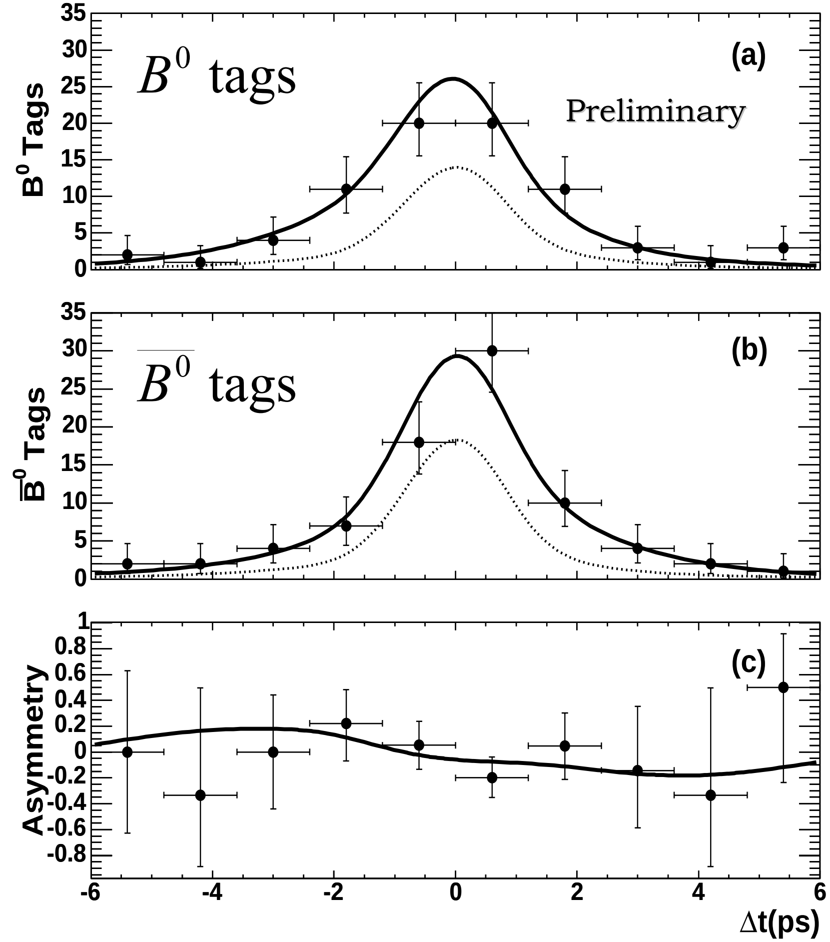
232 M_{BB}

$$N(B \to \rho^+\rho^-) = 617 \pm 52$$

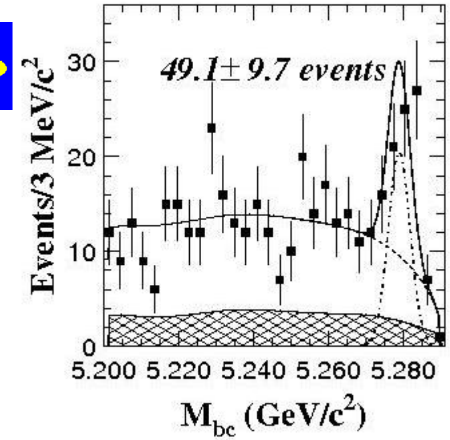
$$S_{long} = -0.33 \pm 0.24^{+0.08}_{-0.14}$$

$$C_{long} = -0.03 \pm 0.18 \pm 0.09$$





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



- For isospin analysis, need other $B \to \rho\rho$ rates.
- $B^+ \to \rho^+\rho^0$ was measured two years ago by both BaBar and Belle.

89 M_{BB}

85 M_{BB}

BaBar:

$$B(B^+ \to \rho^+\rho^0) = (22.5^{+5.7}_{-5.4} \pm 5.8)10^{-6}$$

$$f_L(\rho^+\rho^0) = 0.97^{+0.003}_{-0.007} \pm 0.04$$

Belle:

$$B(B^+ \to \rho^+\rho^0) = (31.7 \pm 7.1^{+3.8}_{-6.7})10^{-6}$$

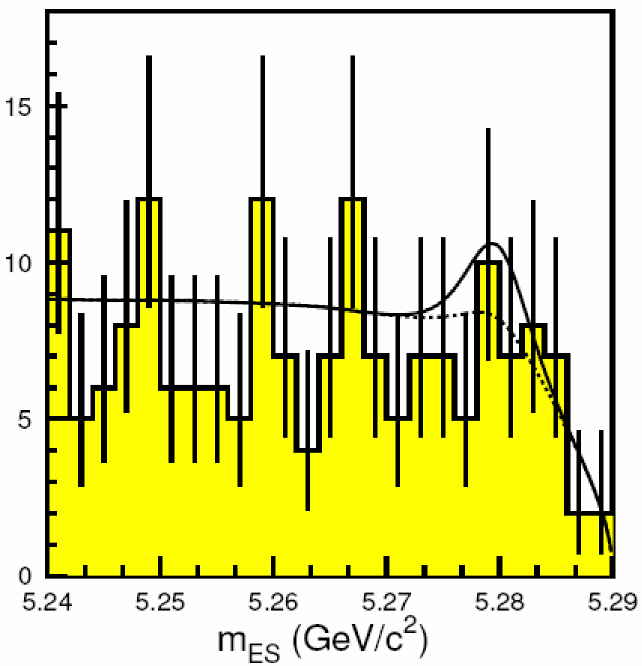
$$f_L(\rho^+\rho^0) = 0.95 \pm 0.11 \pm 0.02$$

Phys.Rev.Lett 91, 171802 (2003)

Phys.Rev.Lett 91, 221801 (2003)

World average: $B(B^+ \to \rho^+\rho^0) = (26.4 \pm 6.4)10^{-6}$ $\quad f_L(\rho^+\rho^0) = 0.96^{+0.005}_{-0.007}$

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



BaBar, Phys.Rev.Lett 94, 131801 (2005)

$(227\,\mathrm{M}_{B\overline{B}})$

$$N(B^0 \to \rho^0 \rho^0) = 33^{+22}_{-20} \pm 12$$

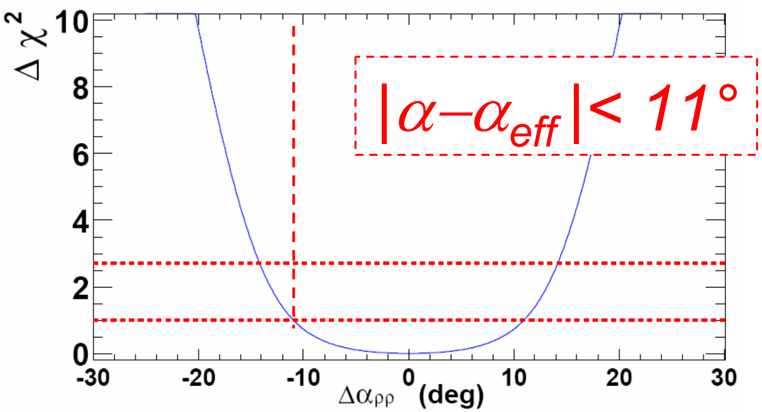
$$\text{Rec. Eff.} = 27\%$$

$$B(B^0 \to \rho^0 \rho^0) = (0.54^{+0.36}_{-0.32} \pm 0.19) \cdot 10^{-6}$$

$$< \; 1.1 \cdot 10^{-6} \quad 90\%\ \text{C.L.}$$

- Limiting factor in the isospin analysis.
- Tree is color suppressed.
- No significant signal:
  - Penguin are smalls.
- Dominant systematic comes from the potential interference from $B \to a_1^{\pm} \pi^{\pm}$ (~22%).

Isospin analysis with B→ρρ



$BF(B^0 \to \rho^+\rho^-) = (30 \pm 4 \pm 5)\times 10^{-6}$ Phys.Rev.Lett 93, 231801 (2004)

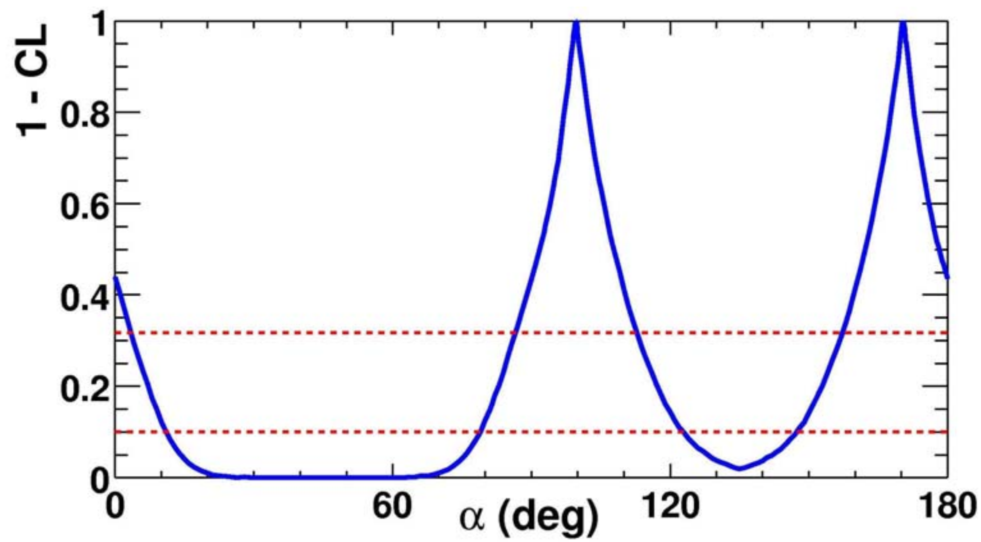
$BF(B^+ \to \rho^+\rho^0) = (26.4 \pm 6.4)\times 10^{-6}$ Phys.Rev.Lett 91, 171802 (2003) Phys.Rev.Lett 91, 221801 (2003)

$BF(B^0 \to \rho^0\rho^0) < 1.1\times 10^{-6}$ $(90\%\,CL)$ Phys.Rev.Lett 94, 131801 (2005)

Error dominated by $\rho^0\rho^0$ measurement

$\alpha = 100 \pm 13°$

$90\%\,CL$ range : [79°,123°]



BaBar, hep-ex/050349, submitted to PRL

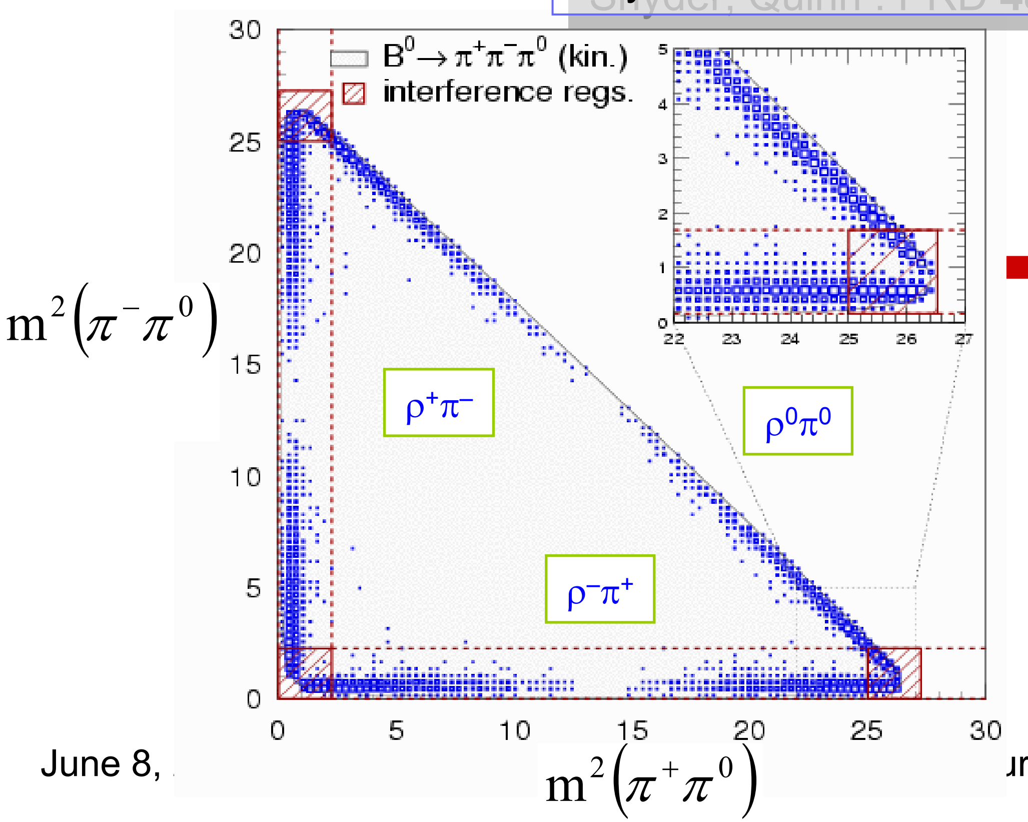
$B^0 \to (\rho\pi)^0$ analysis

- Unlike $\rho^+\rho^-$, $\rho^+\pi^-$ is not a CP eigenstate
  - Must consider 4 configurations
  - Equivalent "isospin analysis" not viable.

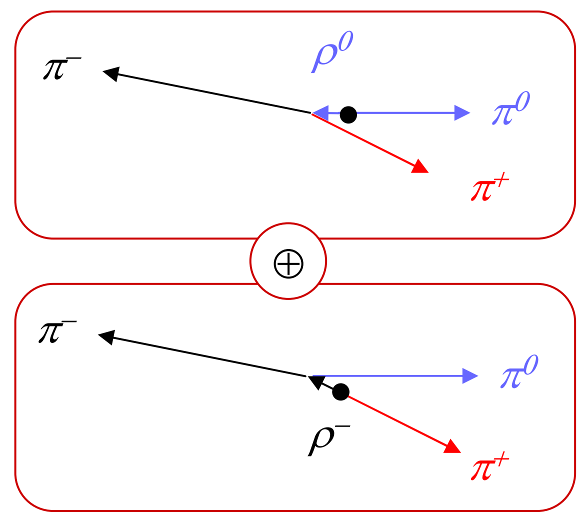
$$B^0 \to \rho^+\pi^- \quad \overline{B}^0 \to \rho^+\pi^-$$
$$\overline{B}^0 \to \rho^-\pi^+ \quad B^0 \to \rho^-\pi^+$$

- However, a full time-dependent Dalitz plot analysis can constrain α.

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



Interference at equal masses-squared gives information on strong phases between resonances



Time-dependent Dalitz analysis

- Extract α and strong phases using interferences between amplitudes of $B \to \pi^+\pi^-\pi^0$ decay.

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

$\mathcal{A}_{3\pi}^{+}$ for B^0

$\mathcal{A}_{3\pi}^{-}$ for $\overline{B}^0$

- Assuming amplitude is dominated by ρ^+,$\rho^-$and ρ^0 resonances

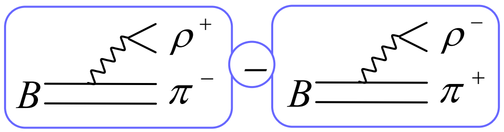
$$A_{3\pi} = f_+ A^+ + f_- A^- + f_0 A^0$$
$$\overline{A}_{3\pi} = f_+ \overline{A}^+ + f_- \overline{A}^- + f_0 \overline{A}^0$$

script $\{+,-,0\}$ refers to $\{\rho^+,\rho^-,\rho^0\}$

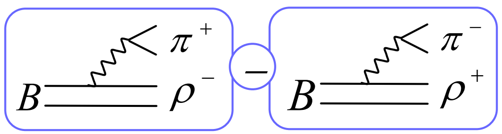
  - The "f"s are functions of the Dalitz-plot and describe the kinematics of $B \to \rho\pi$ (S→VS).
  - The "A"s are the complex amplitudes containing weak and strong phases. They are independent of the Dalitz variables.

Result with $B \to \pi^+\pi^-\pi^0$

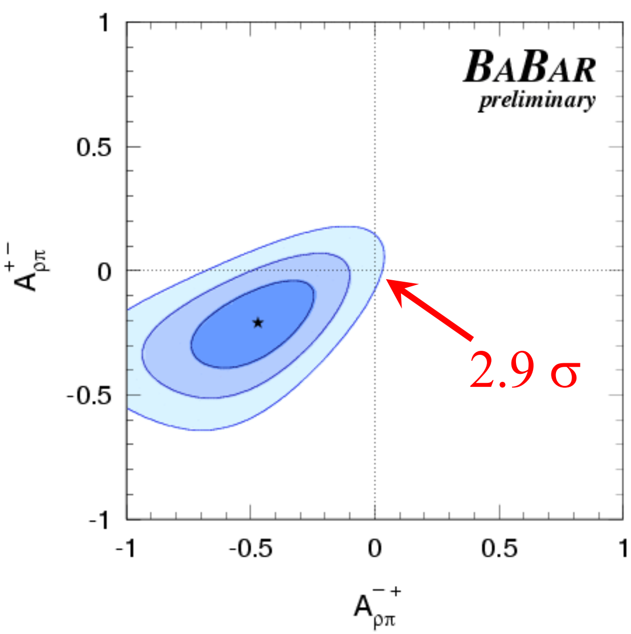
- Hint of direct *CP*-violation

$A_{\rho\pi}^{+-} \cong$ 

$= -0.21 \pm 0.11 \pm 0.04$

$A_{\rho\pi}^{-+} \cong$ 

$= -0.47^{+0.14}_{-0.15} \pm 0.06$

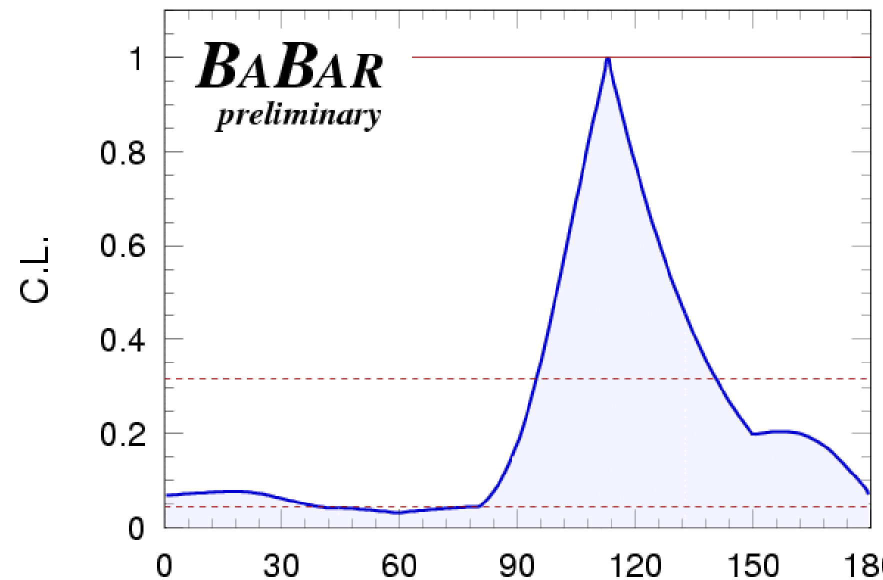


213 M_{BB}

- Likelihood scan of α using:

$$A^{\kappa} = T^{\kappa} e^{-i\alpha} + P^{\kappa}$$
$$\overline{A}^{\kappa} = T^{\overline{\kappa}} e^{+i\alpha} + P^{\overline{\kappa}}$$

$\kappa \in \{+,-,0\}$
T =tree amp.
P =penguin



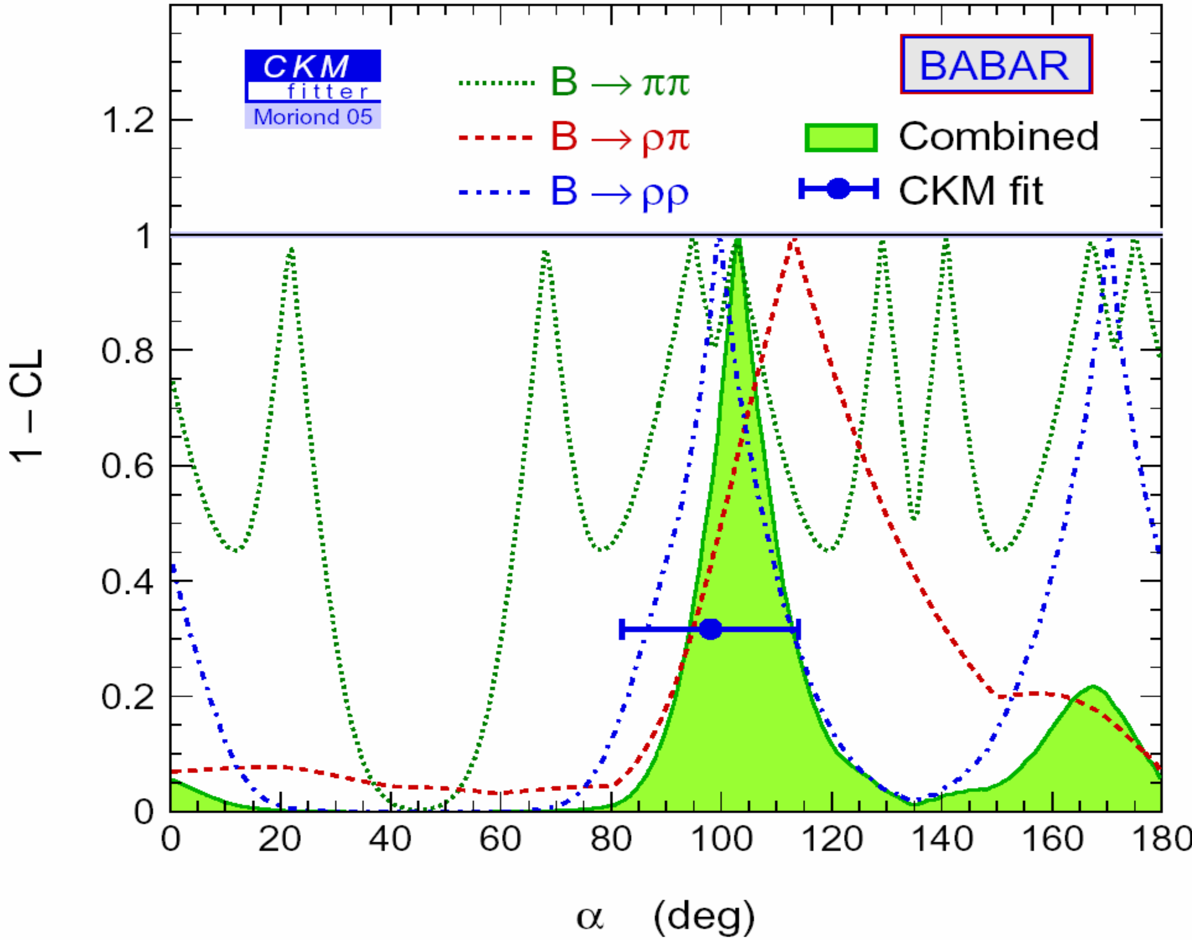
$$\alpha = \left[113^{+27}_{-17}(stat.) \pm 6(syst.)\right]^{\circ}$$

Mirror solution not shown
Weak constraint at C.L.<5%

Combined α measurement

- The best individual measurement comes from ρρ.
- Mirror solution are disfavored, thanks to ρπ.
- Good agreement with global CKM fit.
- Combined value:

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

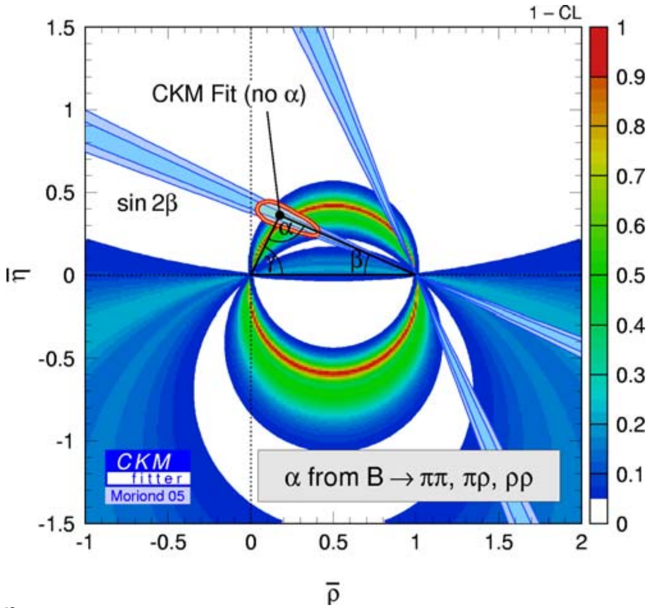


http://ckmfitter.in2p3.fr

Summary

- CP violation has entered a phase of precision measurements thanks to the B-factories.
- The angle α of the unitarity triangle has been measured with an uncertainty of ~10°.

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



- Will still improve.

http://ckmfitter.in2p3.fr