Measurements of the angle φ_2 / α at B factories

BELLE

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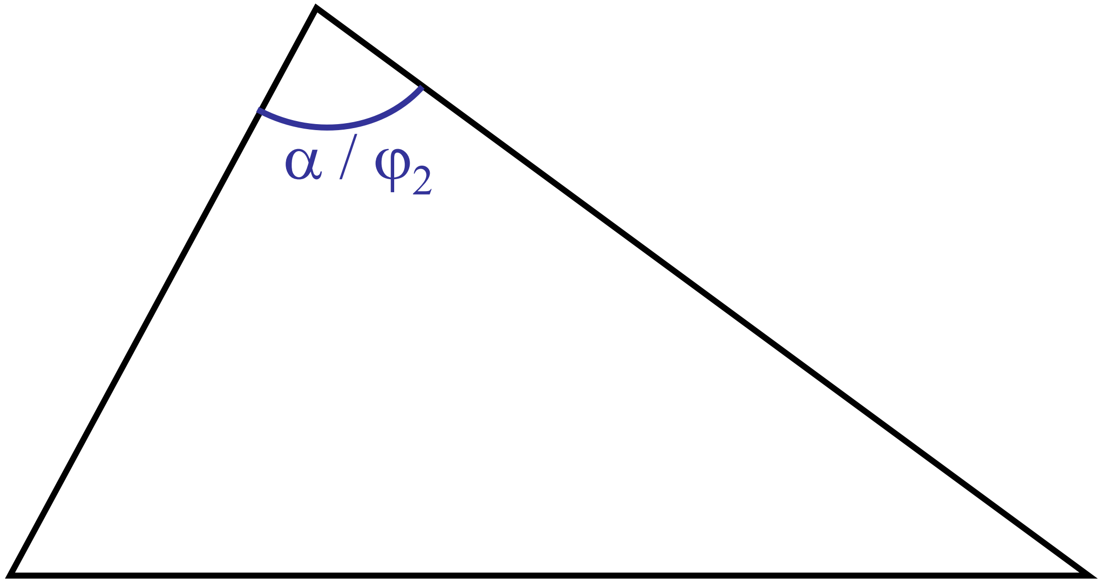
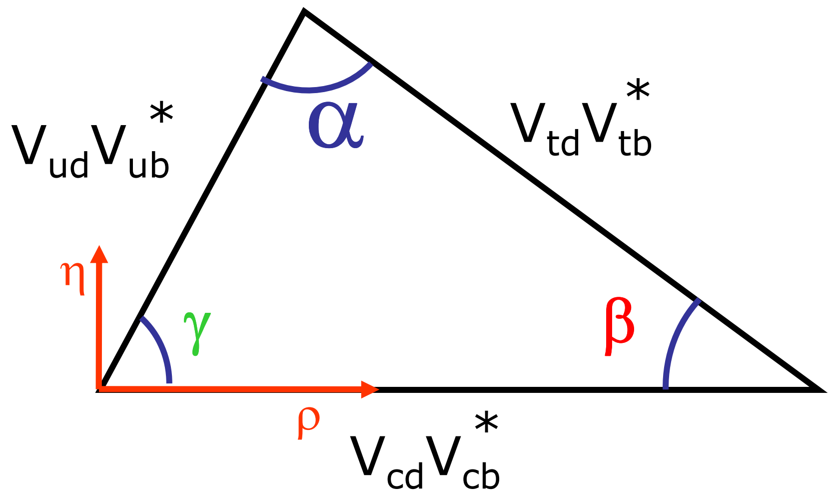
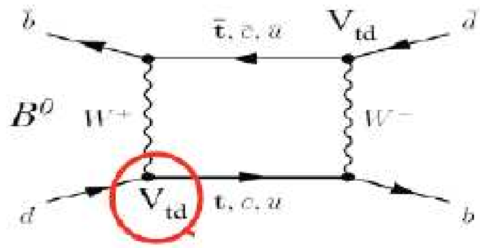
Outline

- Introduction
- $\pi\ \pi$ modes
- $\rho\ \rho$ modes
- $\rho\ \pi$ modes
- $a_1\ \pi$ modes
- Conclusion



Introduction

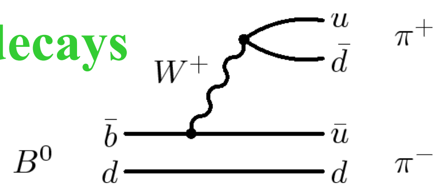




B mixing

$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right]$$

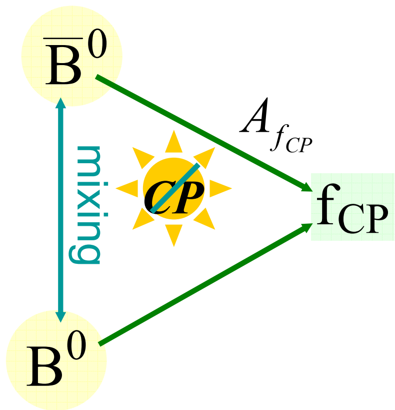
b→u decays



- The angle α can be measured from CP violating asymmetries in the interference of mixing and decays in b→u decays of the neutral B mesons.
- Dependence on -2β -2γ → 2α

CP violation in the interference between decay and mixing

For B decaying to f_{CP} (CP eigenstate) .



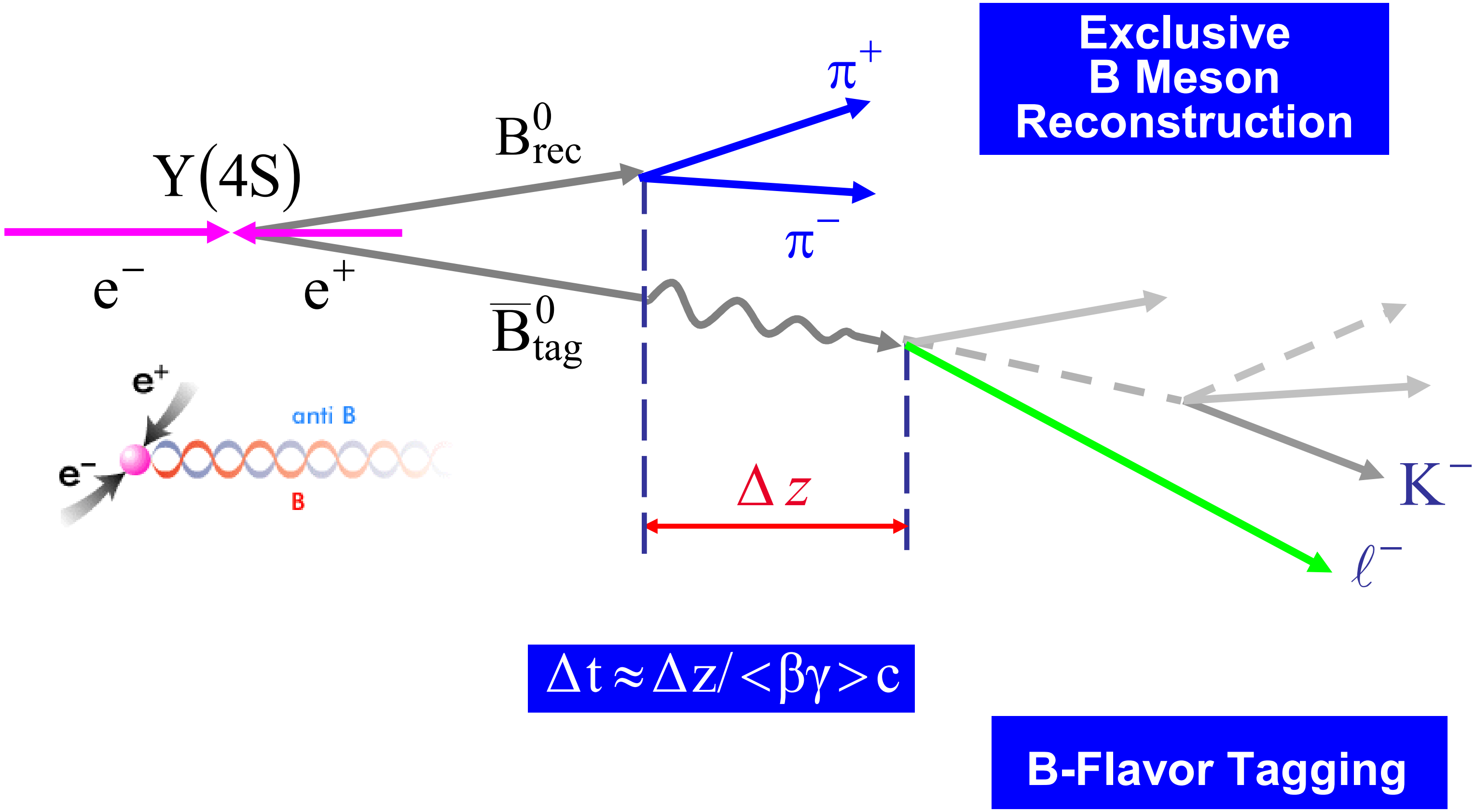
$$\mathcal{A}_f(\Delta t) \equiv \frac{\Gamma_{\overline{B}^0\to f}(\Delta t) - \Gamma_{B^0\to f}(\Delta t)}{\Gamma_{\overline{B}^0\to f}(\Delta t) + \Gamma_{B^0\to f}(\Delta t)}$$

$$= S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t)$$

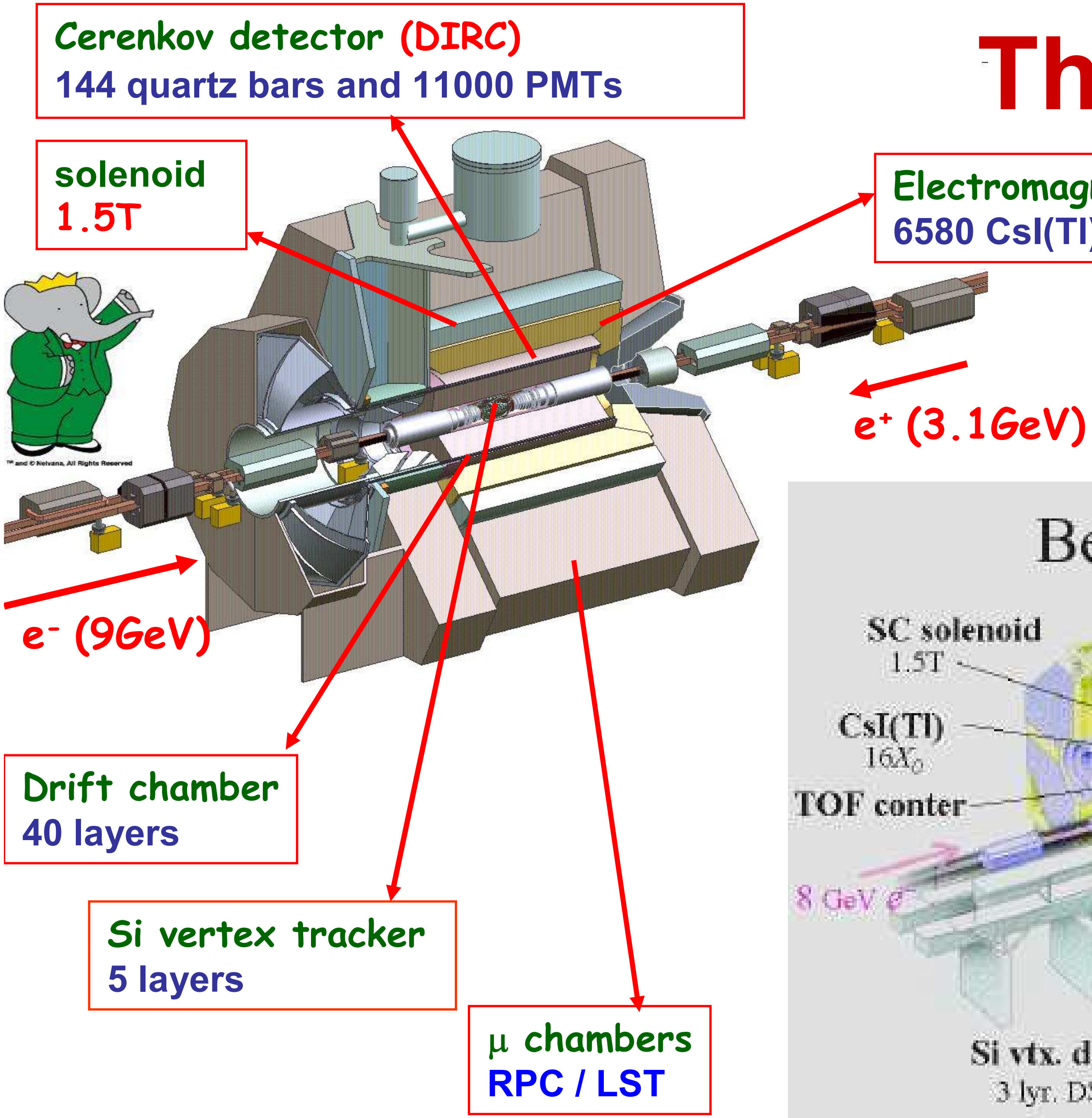
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \qquad S_f \equiv \frac{2\,\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2} \qquad C_f \equiv -A_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

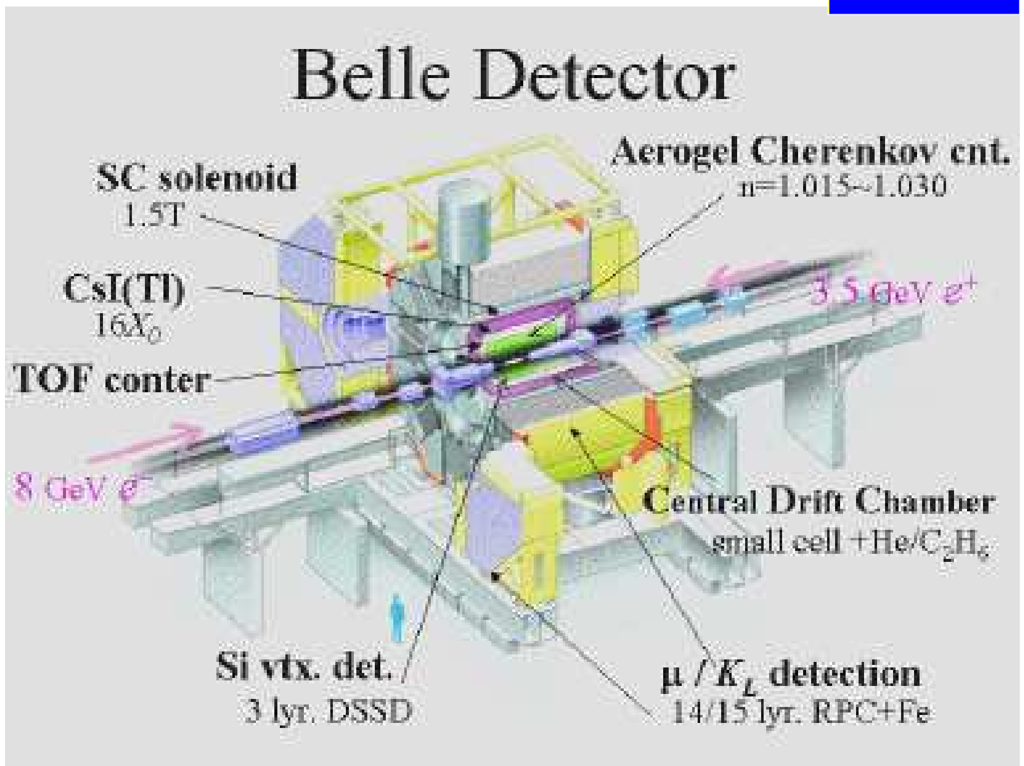
$\frac{q}{p}$: $e^{-2i\beta}$

CP asymmetry measurement



The detectors

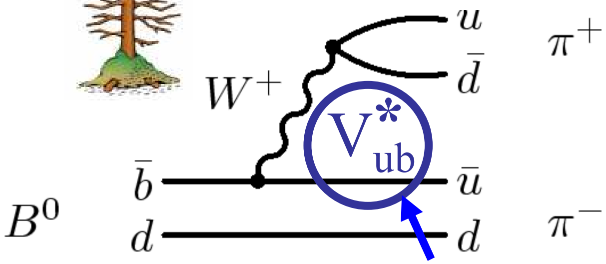




α and penguin pollution

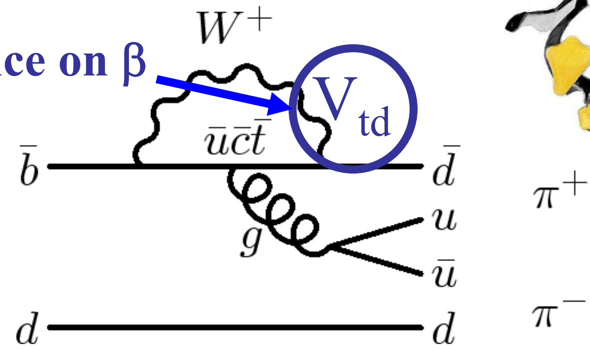
$$A(B^0/\overline{B}^0) = S \sin\Delta m_d \Delta t - C \cos\Delta m_d \Delta t$$

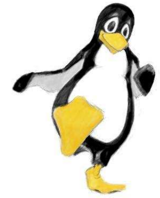
Tree Diagram



|P/T| ~ 30-60% in $\pi^+\pi^-$

Penguin Diagram





For single phase from CKM matrix

$C = 0$, $S = \sin(-2(\gamma+\beta)) = \sin 2\alpha$

- α extracted directly from S.

With additional weak phases

$C \neq 0$, $S = \sqrt{1 - C^2} \sin 2\alpha_{eff}$

- More information needed to constraint α.

SU(2) Symmetry: Isospin analysis

Similar approaches for B → ρρ and B → ππ:

M. Gronau, D. London, PRL, 65, 3381 (1990)

- Two isospin relations (one for (B^0,B^+), one for (B^0,B^-))

$$A(B^+ \to h^+ h^0) = 1/\sqrt{2} \cdot A(B^0 \to h^- h^+) + A(B^0 \to h^0 h^0)$$

- Neglecting EW penguins, $B^+ \to h^+ h^0$ (I=2) is pure tree diagram

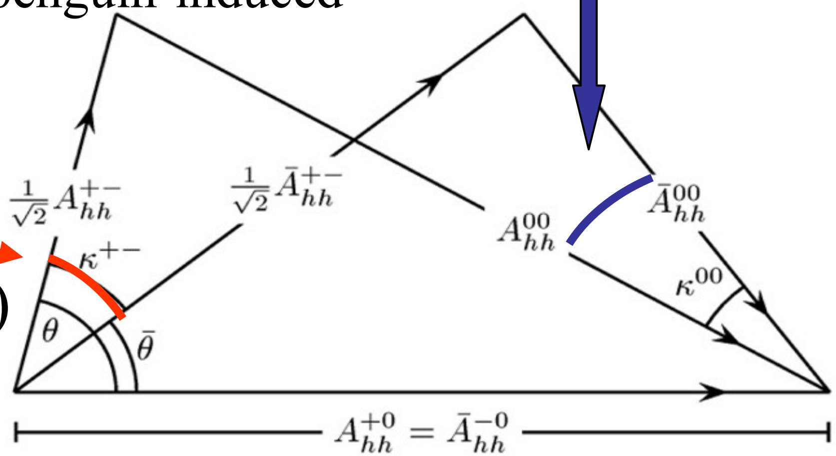
$$A(B^+ \to h^+ h^0) = \overline{A}(B^- \to h^- h^0)$$

For $B^0 \to \rho^0 \rho^0$, S^{00} measurement ⇒ constraint on this angle

- Representation with a triangle with a common side.
- Triangle relations allow determination of penguin-induced shift in α.

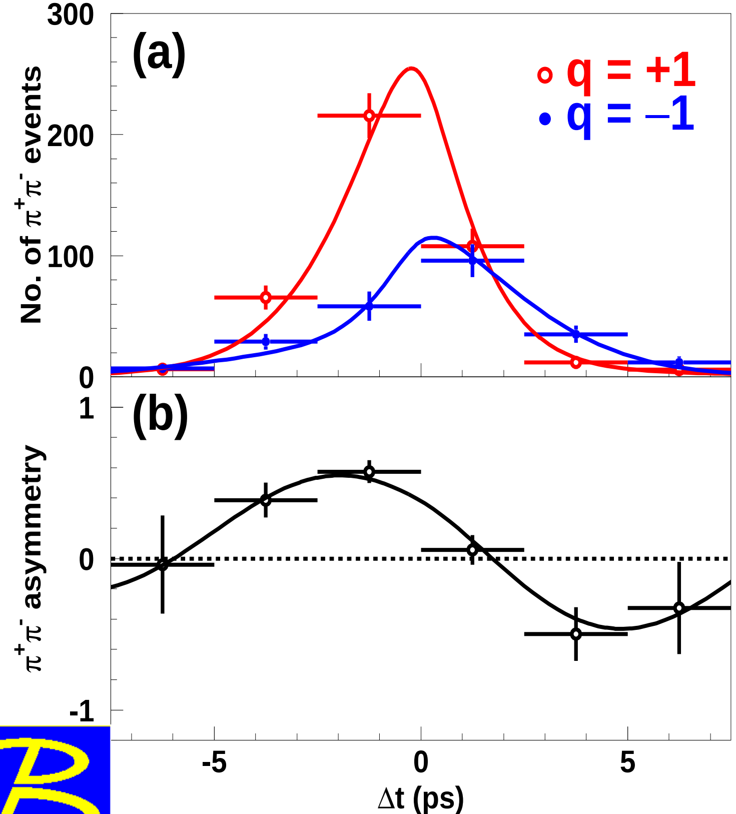
$$\kappa^{+-} = 2(\alpha_{eff} - \alpha)$$

- Four-fold ambiguities in $\kappa^{+-} = \pm(\theta \pm \overline{\theta})$
- In addition to two-fold ambiguities in 2α



CP asymmetries in $B^0 \to \pi^+\pi^-$

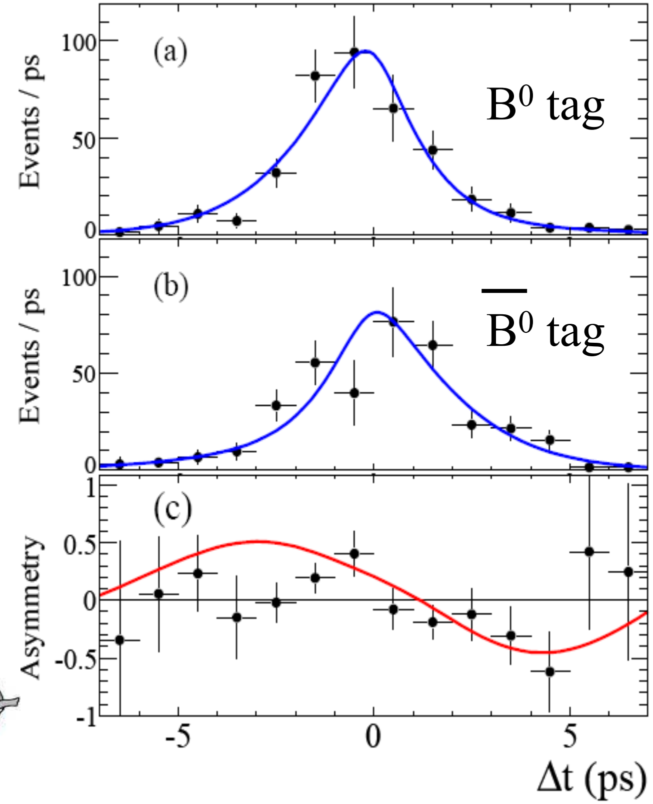
535M BB *PRL 98, 211801 (2007)*

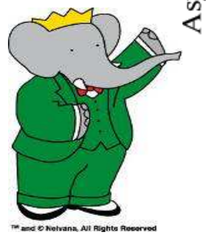


1464 ± 65 signal events

$$S_{+-} = -0.61 \pm 0.10 \pm 0.04 \ (5.3\sigma)$$
$$C_{+-} = -0.55 \pm 0.08 \pm 0.05 \ (5.5\sigma)$$

383M BB *PRL 99, 021603 (2007)*

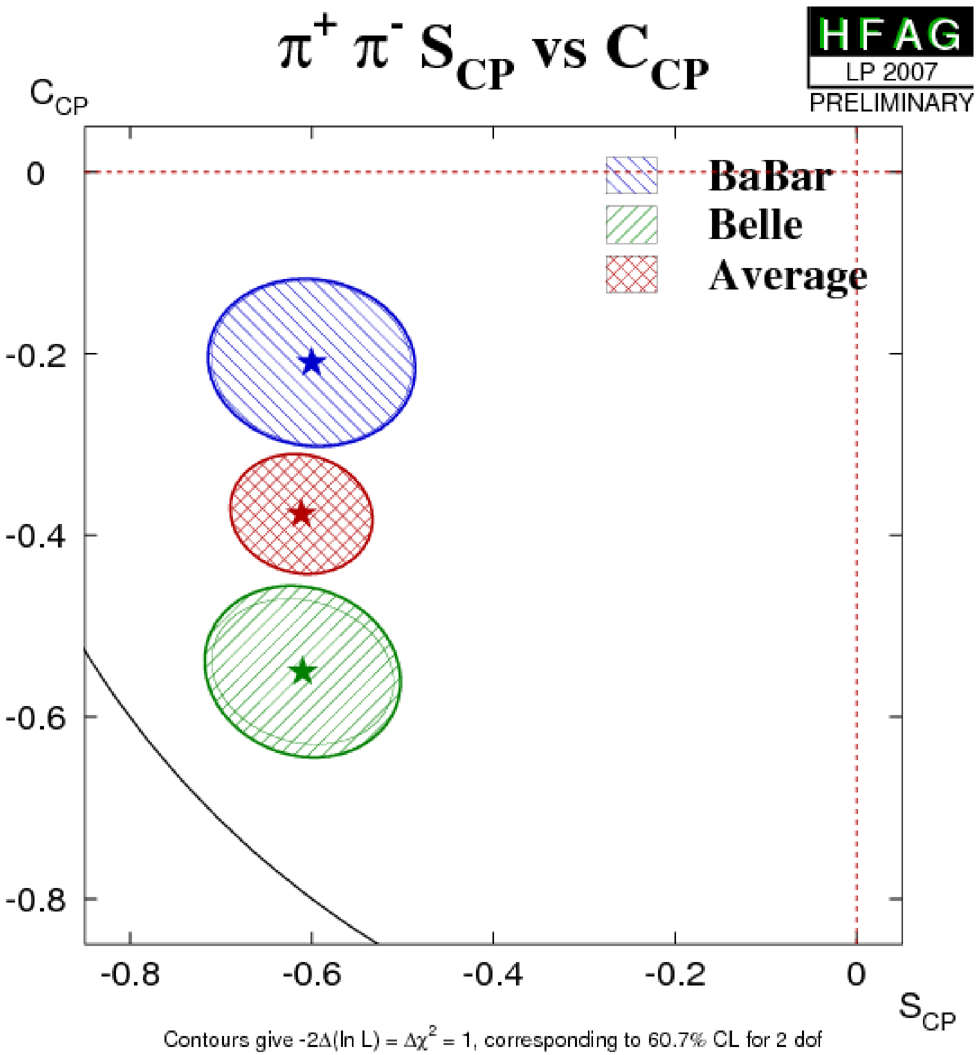




1139 ± 49 signal events

$$S_{+-} = -0.60 \pm 0.11 \pm 0.03 \ (5.1\sigma)$$
$$C_{+-} = -0.21 \pm 0.09 \pm 0.02 \ (2.2\sigma)$$

CP asymmetries in $B^0 \to \pi^+\pi^-$



- Large direct CP violation seen by Belle.
  - 2.1 σ difference between BaBar and Belle.
- CP violation in the interference between mixing and decay seen by both experiments.

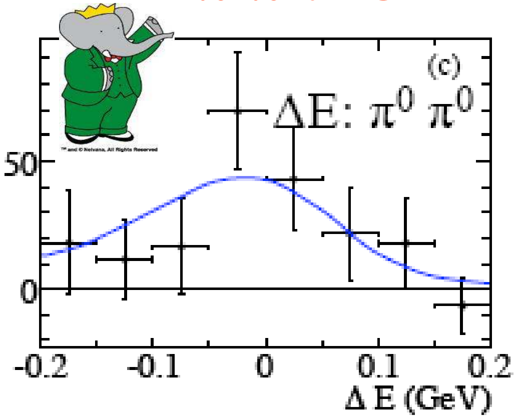
- World average:

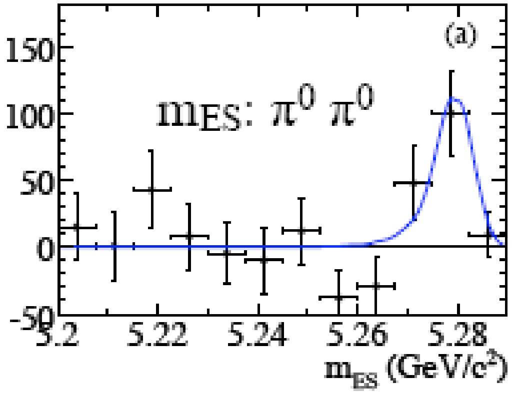
$$S_{+-} = -0.61 \pm 0.08$$
$$C_{+-} = -0.38 \pm 0.07$$

BF in B→ ππ modes

$B^0 \to \pi^0\pi^0$: 154 ± 26 signal events

383M BB





- "Large" BR for $B^0 \to \pi^0\pi^0$ (tree diagram is color suppressed).
- Large fraction of penguin contamination.

- World averages:

$$\mathrm{BF}(B^0 \to \pi^+\pi^-) = (5.2 \pm 0.2)\times 10^{-6}$$
$$\mathrm{BF}(B^0 \to \pi^0\pi^0) = (1.3 \pm 0.2)\times 10^{-6}$$
$$C_{00} = -0.48 \pm 0.32$$
$$\mathrm{BF}(B^+ \to \pi^\pm\pi^0) = (5.6 \pm 0.4)\times 10^{-6}$$
$$A^{CP}_{\pm 0} = 0.06 \pm 0.05$$

BaBar: PRD 75, 012008 (2007)	*227M BB*
PRD 76, 091102 (2007)	*383M BB*
Belle: PRL 99, 121601(2007)	*449M BB*

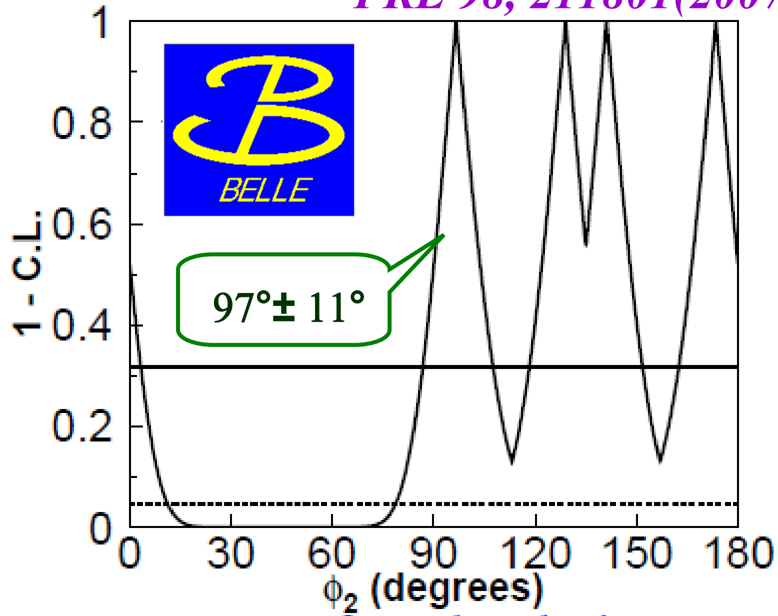
Isospin analysis in B→ ππ

- Isospin analysis using BF for $\pi^+\pi^-$, $\pi^+\pi^0$ and $\pi^0\pi^0$, and CP parameters C_{+-}, S_{+-}, and C_{00}.

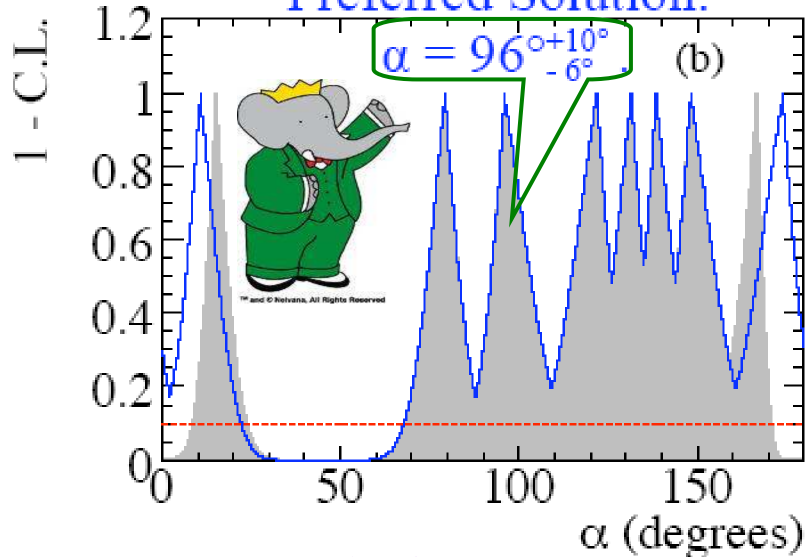
- 6 observables, 6 unknown.

- Ambiguities.
- $11° < \alpha < 79°$ excluded at 95% C.L (Belle).
- $25° < \alpha < 66°$ excluded at 90% C.L (BaBar).
- SU(3) constraint on penguin amplitude

PRL 98, 211801(2007)



Preferred Solution:

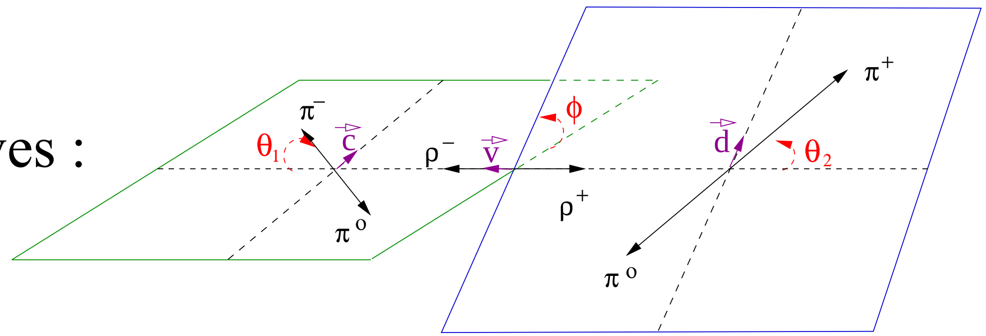


PRD 76, 091102 (2007)

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

Analysis more difficult:

- 2 π^0 in the final state.
- Wide ρ resonances.
- V-V decay: L=0,1,2 partial waves :
  - Longitudinal: CP-even state.
  - Transverse: Mixed CP states.
- **Analysis based on ρ polarization**.



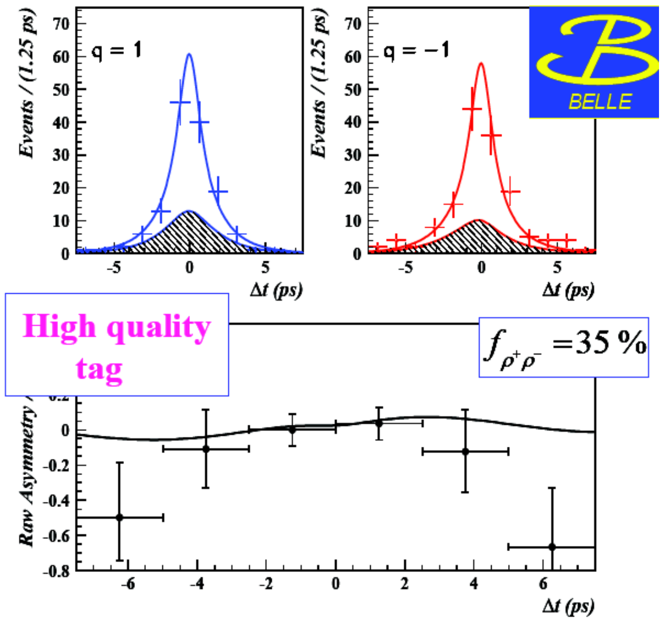
Helicity Frame

Eventually a very efficient mode:

- BF~ **5 times larger** than for B→ ππ.
- Penguin pollution smaller than in ππ.
- ρ are ~100% longitudinally polarized.
- **Almost a pure CP-even state!**

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

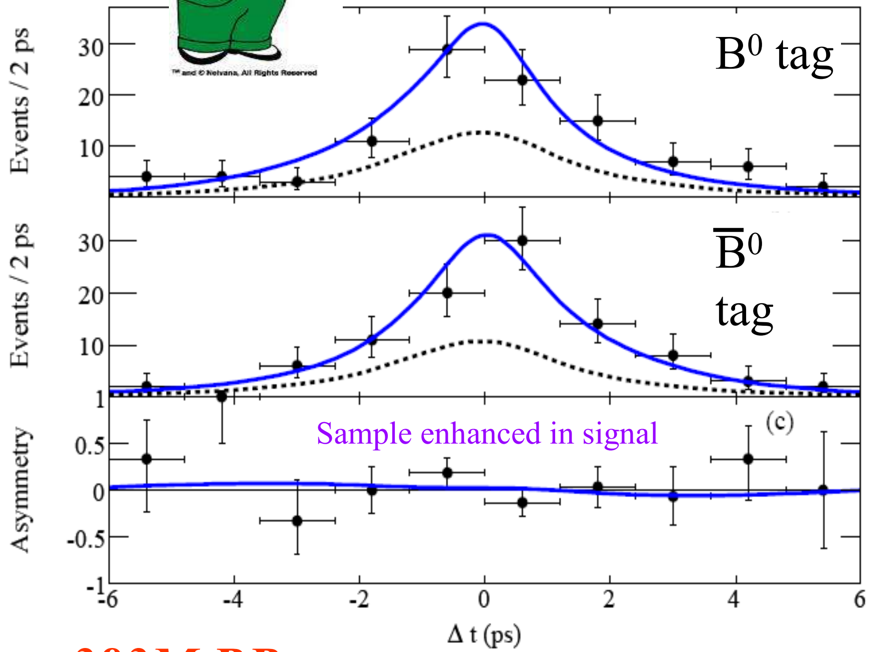
PRL 96, 171801 (2006)
PRD 76, 011104 (2007)



535M BB (CP part)

$$BF(B^0 \to \rho^+\rho^-) = (22.8 \pm 3.8^{+2.3}_{-2.6}) \times 10^{-6}$$
$$f_L^{+-} = 0.941^{+0.034}_{-0.040} \pm 0.30$$
$$C_L^{+-} = -0.16 \pm 0.21 \pm 0.08$$
$$S_L^{+-} = 0.19 \pm 0.30 \pm 0.08$$

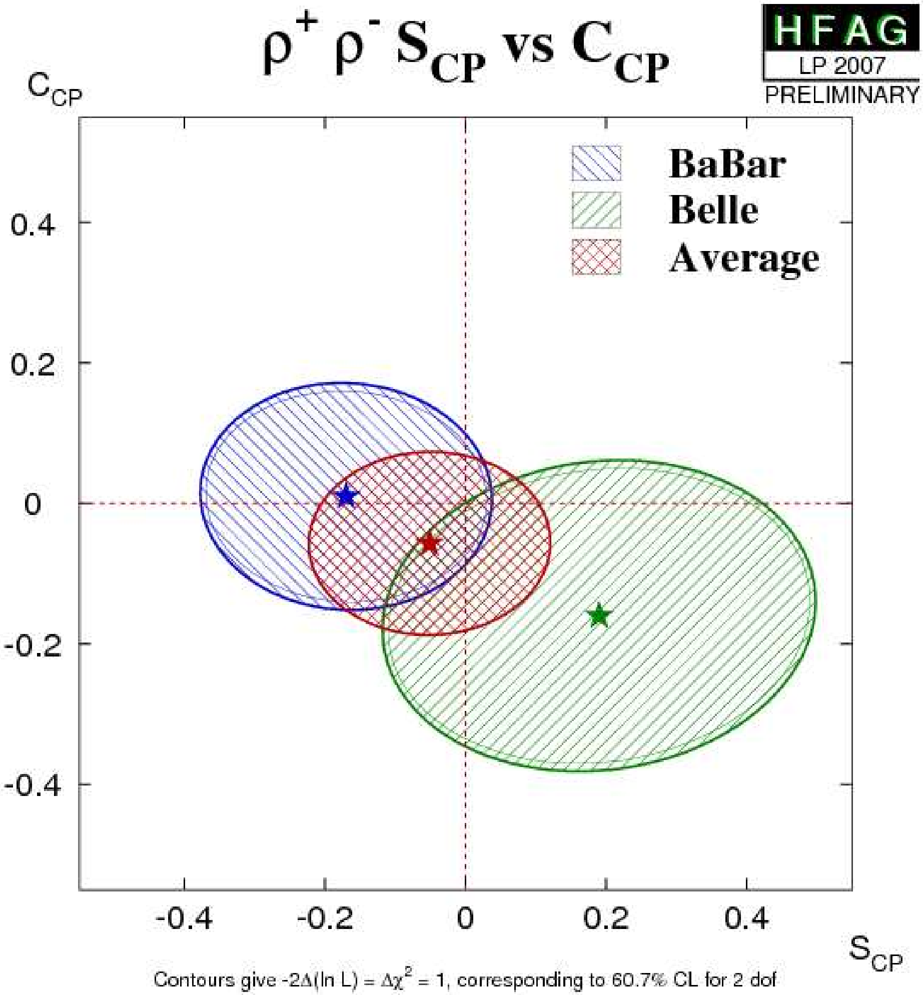
PRD 76, 052007 (2007)



383M BB **729 ± 60 signal events**

$$BF(\rho^+\rho^-) = (25.5 \pm 2.1^{+3.6}_{-3.9}) \times 10^{-6}$$
$$f_L^{+-} = 0.992 \pm 0.024^{+0.026}_{-0.013}$$
$$C_L^{+-} = 0.01 \pm 0.15 \pm 0.06$$
$$S_L^{+-} = -0.17 \pm 0.20^{+0.05}_{-0.06}$$

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



- Good agreement between BaBar and Belle.

- World average:

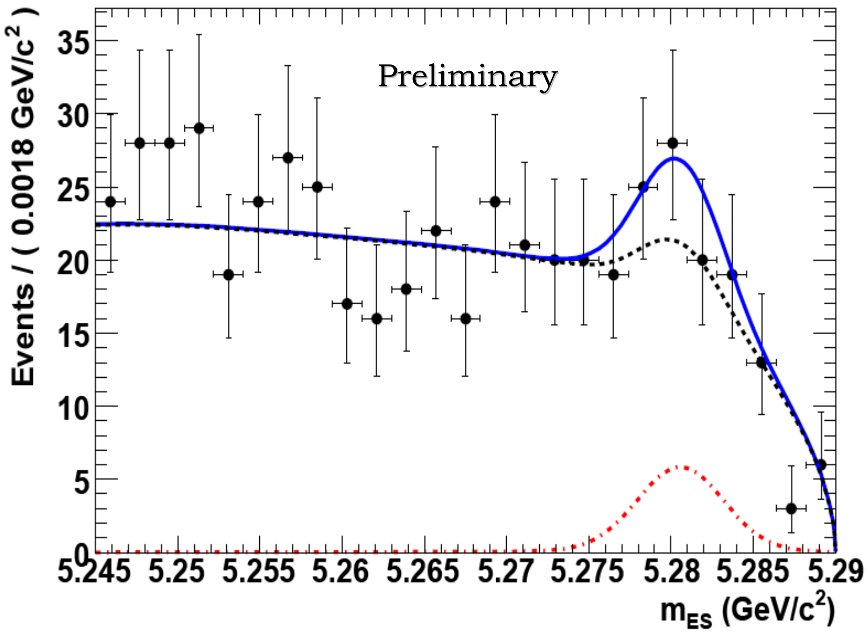
$$S_{+-} = -0.05 \pm 0.17$$
$$C_{+-} = -0.06 \pm 0.13$$

- For isospin analysis, need also BF for $B^+ \to \rho^+ \rho^0$:

$$\mathrm{BF}(B^+ \to \rho^+ \rho^0) = (18.2 \pm 3.0) \times 10^{-6}$$
$$f_L^{+0} = 0.912 \pm 0.045$$

Babar: PRL 97, 261601 (2006) ***232M BB***
Belle: PRD 67, 032003 (2003) ***85M BB***

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



First measurements of time-dependent CP asymmetries in $B^0 \to \rho^0 \rho^0$:

- Small BF for $B^0 \to \rho^0 \rho^0$
- In contrast to $\pi^0\pi^0$, decay vertex can be reconstructed ($\rho^0 \to \pi^+\pi^-$).
- Time-dependent analysis feasible.
- Measurement of C_L^{00} and S_L^{00}

427M BB

85 ± 28 ± 17 signal events
3.6σ (syst. included)

Preliminary
arXiv: 0708.1630

$$BF(\rho^0\rho^0) = (0.84 \pm 0.29 \pm 0.17) \times 10^{-6}$$

$$f_L^{00} = 0.70 \pm 0.14 \pm 0.05$$

$$C_L^{00} = 0.4 \pm 0.9 \pm 0.2$$

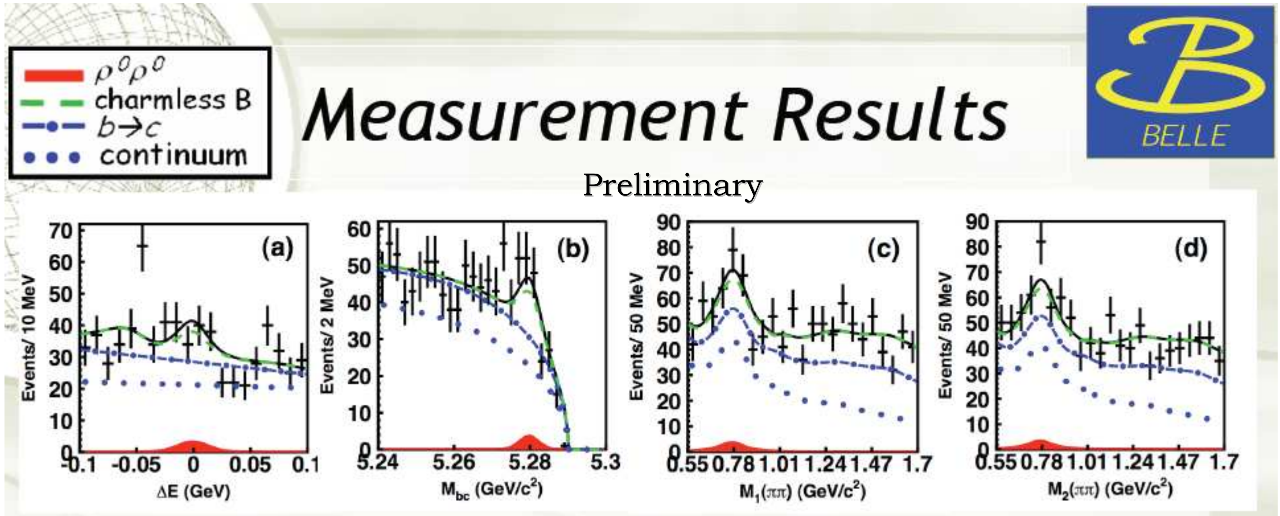
$$S_L^{00} = 0.5 \pm 0.9 \pm 0.2$$

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

657M BB

New result from Belle:

- BF ($B^0 \to \rho^0\rho^0$) < 1.0 10^{-6} @ 90% C.L.
- **Not inconsistent with BaBar result.**
- Non resonant 4π and $\rho\pi\pi$ decays.
- Watch for further measurements.



Mode	Yield	Eff.(%)	Σ	BF ($\times 10^{-6}$)	UL ($\times 10^{-6}$)
$\rho^0\rho^0$	$24.5^{+23.6+9.7}_{-22.1-9.9}$	9.16	1.0	$0.4 \pm 0.4 \pm 0.2$	<1.0 (assume f_L=1)
$\rho^0\pi\pi$	$161.2^{+61.2+26.0}_{-59.4-28.5}$	2.90	1.3	$5.9^{+3.5+2.7}_{-3.4-2.8}$	<11.9
4π	$112.5^{+67.4+51.5}_{-65.6-53.7}$	1.98	2.5	$12.4^{+4.7+2.0}_{-4.6-2.2}$	<19.0
$\rho^0 f_0$	$-11.8^{+14.5+4.9}_{-12.9-3.6}$	5.10	0.0	0.0	<0.6
$f_0 f_0$	$-7.7^{+4.7+3.0}_{-3.5-2.9}$	2.75	0.0	0.0	<0.4
$f_0\pi\pi$	$6.3^{+37.0+18.0}_{-34.7-18.1}$	1.55	0.0	$0.6^{+3.6}_{-3.4} \pm 1.8$	<7.3

Isospin analysis in B→ρρ

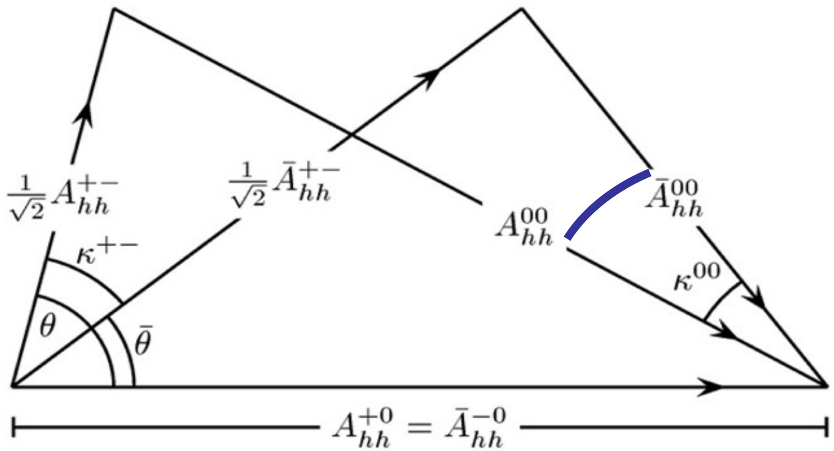
- ➢If we take $B^0 \to \rho^0\rho^0$ time-dependent analysis from Babar, can perform a full isospin analysis.

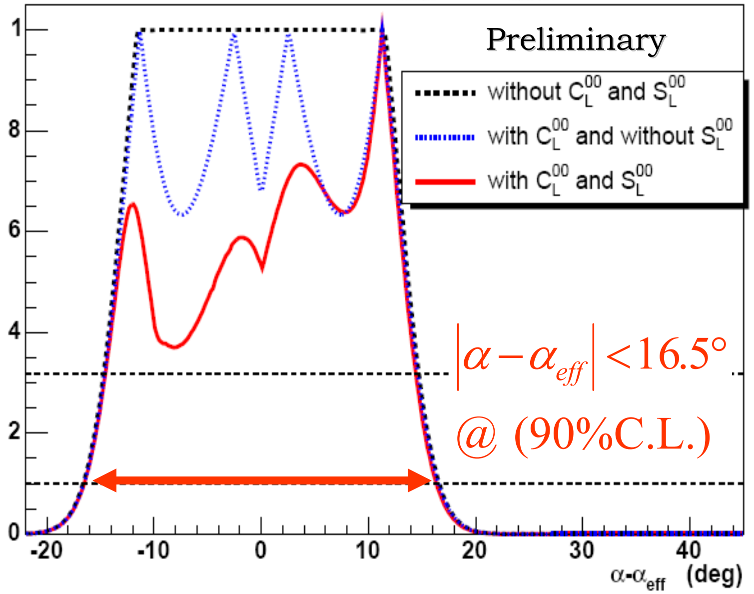
- ➢Isospin analysis without C_L^{00} and S_L^{00} : plateau in $\Delta\alpha$
- ➢Measurement of C_L^{00}: see four ambiguities
- ➢ Measurement of C_L^{00} and S_L^{00}

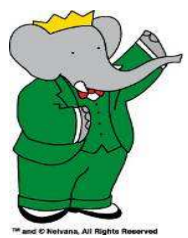
⇒Overconstrained isospin relations

⇒Favor one solution

Preliminary
arXiv: 0708.1630







SU(3) approach in B→ρρ

Beneke et al., Phys.Lett.B 638, 68 (2006)

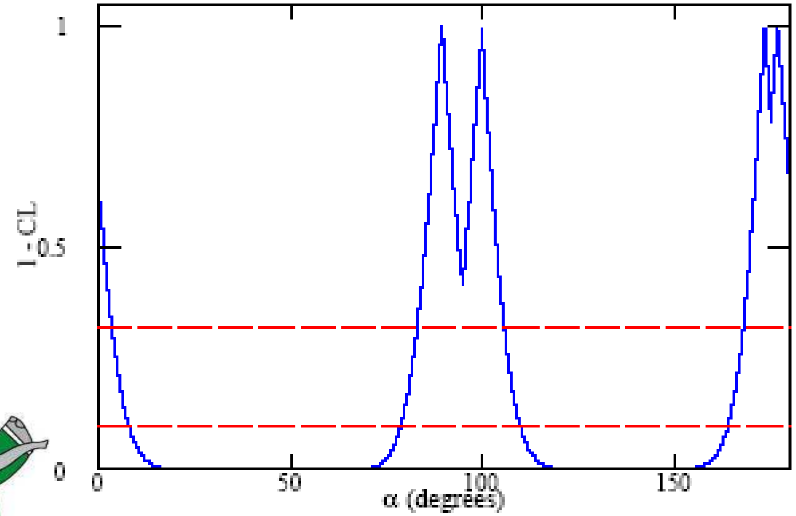
Constrain the penguin contribution in $B^0 \to \rho^+ \rho^-$ using flavor SU(3) symmetry:

- Experimental constraints from $B^+ \to K^{*0} \rho^+$ assuming penguins in the two modes are related.
- Three unknowns: α, r = |P/T| et δ.
  - $A(\rho^+\rho^-) = Te^{i\gamma} + Pe^{i\delta}$
- The method gives a good constaint: $83.3 < \alpha < 105.8°$ at 68% CL.
- SU(3) breaking effects taken into account.

$$\mathrm{BF}(B^+ \to \rho^+ K^{*0}) = (9.2 \pm 1.5) \times 10^{-6}$$
$$f_L = 0.48 \pm 0.08$$

Babar: PRL 97, 201801 (2006) 232M BB

Belle: PRL 95, 141801 (2005) 275M BB



PRD 76, 052007 (2007)

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

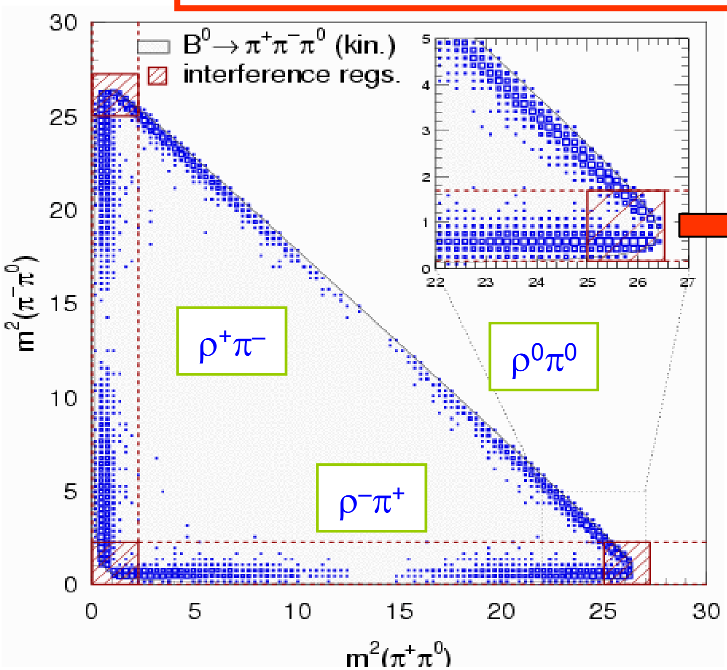
- Dominant decay $B^0 \to \rho^+\pi^-$ is not **a CP eigenstate**
- Two-body Isospin analysis not viable: 5 amplitudes need to be considered

$B^0 \to \rho^+\pi^-/\rho^-\pi^+/\rho^0\pi^0$ and $B^+ \to \rho^+\pi^0/\rho^0\pi^+$ Isospin Triangle $\Rightarrow$ Isospin Pentagon.

- Better approach: **Time-dependent Dalitz analysis** assuming Isospin symmetry:

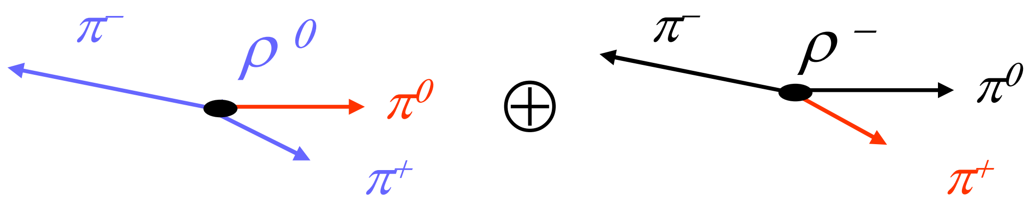
$$A(B^0 \to \pi^+\pi^-\pi^0) = f_+ A(\rho^+\pi^-) + f_- A(\rho^-\pi^+) + f_0 A(\rho^0\pi^0)$$
$$\overline{A}(\overline{B}^0 \to \pi^+\pi^-\pi^0) = f_+ \overline{A}(\rho^+\pi^-) + f_- \overline{A}(\rho^-\pi^+) + f_0 \overline{A}(\rho^0\pi^0)$$

f_k lineshape



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

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

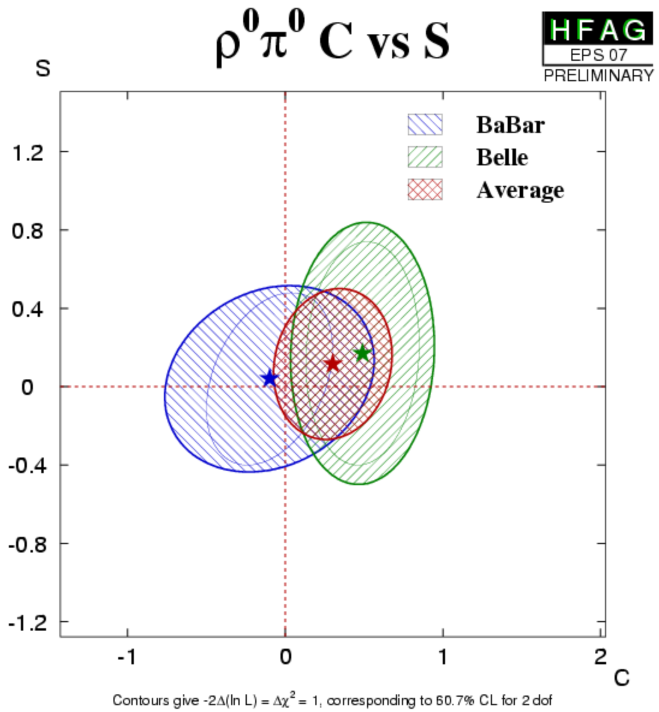


Dalitz analysis of $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$

PRD 76, 012004 (2007) *375M BB*

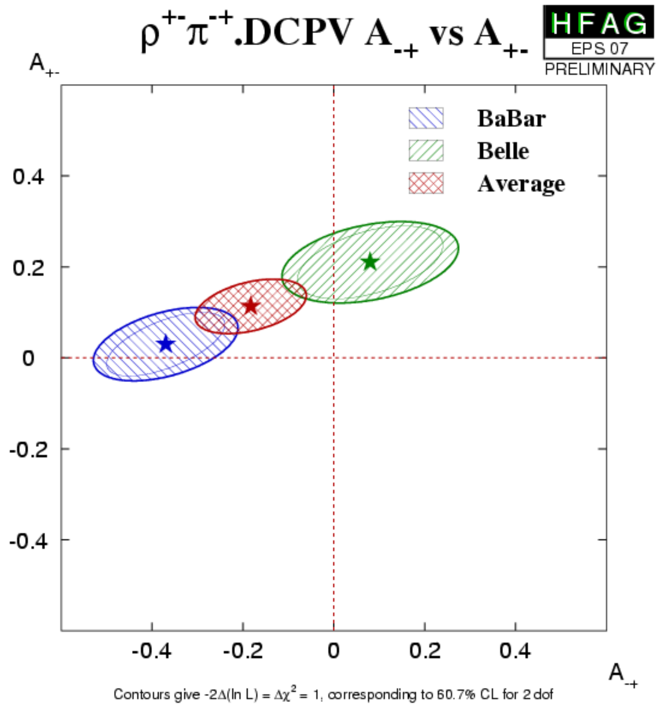
PRD 77, 072001 (2008) *449M BB*

➢World average:



$$A^{+-} = -0.13 \pm 0.04$$
$$C^{+-} = 0.01 \pm 0.07$$
$$S^{+-} = 0.01 \pm 0.09$$
$$\Delta C^{+-} = 0.37 \pm 0.08$$
$$\Delta S^{+-} = -0.04 \pm 0.10$$

$$C^{00} = 0.30 \pm 0.38$$
$$S^{00} = 0.12 \pm 0.38$$

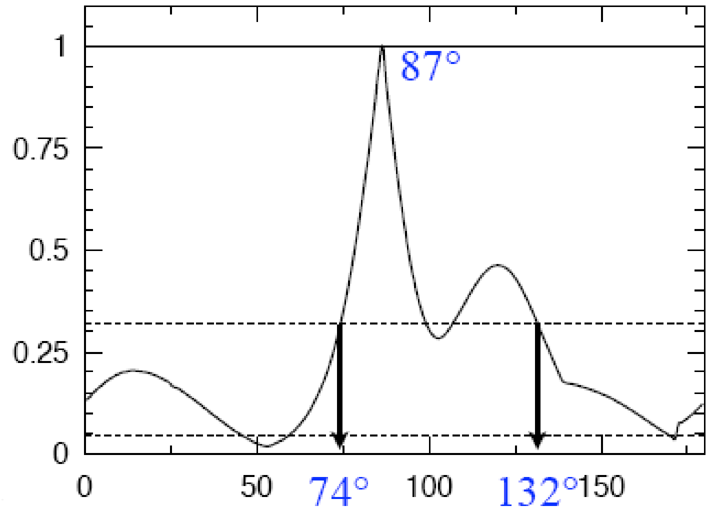


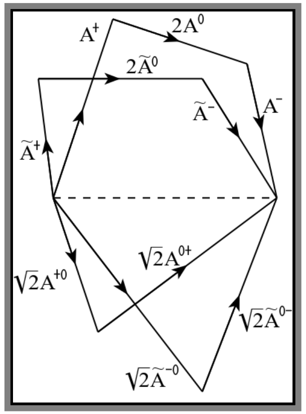
Dalitz analysis of $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$

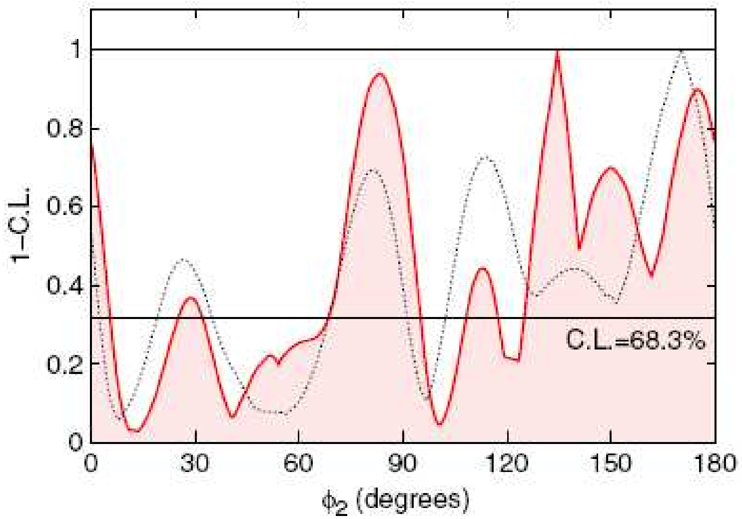
2067 ± 86 signal events

$74 < \alpha < 132°$ at 68% CL

PRD 76, 012004 (2007)



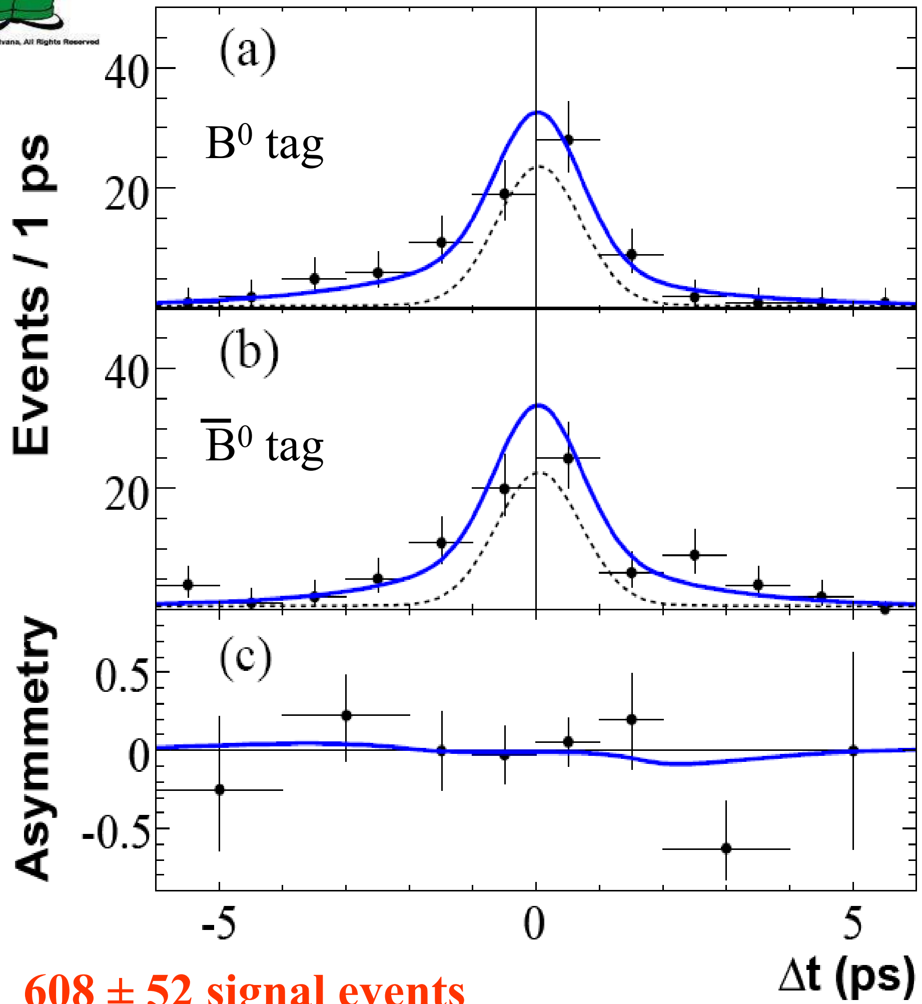




$68 < \alpha < 95°$ at 68% CL

PRD 77, 072001 (2008)

$B^0 \to a_1\pi$



- $B \to a_1\pi$ decay: same quark diagram as $B\to\pi\pi/\rho\rho/\rho\pi$
- High branching fraction:

BR = $(33.2 \pm 3.8 \pm 3.2)\ 10^{-6}$

PRL 97, 051802 (2006)

BR = $(29.8 \pm 3.2 \pm 4.26)\ 10^{-6}$

hep-ex 0706.3279

- similar to $B\to\rho\pi$
  - Not a CP eigenstate
  - Quasi-2 body approach

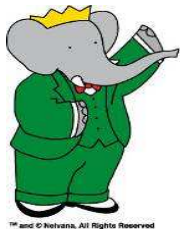
608 ± 52 signal events

PRL 98, 181803 (2007)

$$\alpha_{eff}^{a_1\pi} = 78.6° \pm 7.3°$$

$$A^{+-} = -0.07 \pm 0.07 \pm 0.02$$
$$C^{+-} = -0.10 \pm 0.15 \pm 0.09$$
$$S^{+-} = 0.37 \pm 0.21 \pm 0.07$$
$$\Delta C^{+-} = 0.26 \pm 0.15 \pm 0.07$$
$$\Delta S^{+-} = -0.14 \pm 0.21 \pm 0.06$$

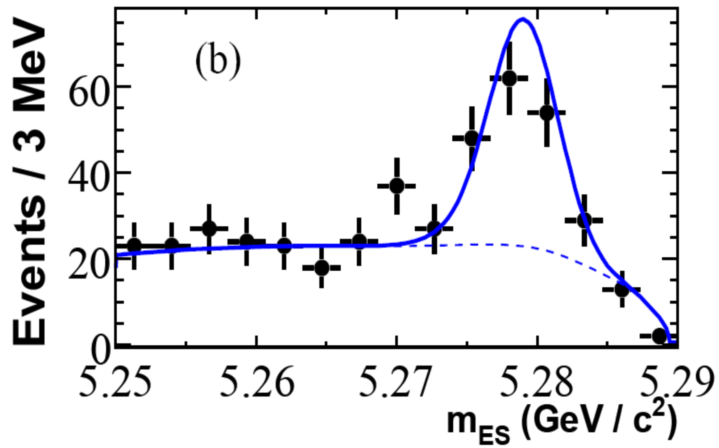
SU(3) symmetry : $B \rightarrow a_1\pi$ / $K_1\pi$ / a_1K



Set an upper bound on $\alpha - \alpha_{eff}$ or extract true α value.

241 ± 32
$B \rightarrow a_1 K_S^0$

383M BB



- Use SU(3) symmetry ($\pi \leftrightarrow K$ and $a_1 \leftrightarrow K_1$) to extract information from $B \rightarrow K_1\pi$ and $B \rightarrow a_1K$ decays.

Gronau and Zupan, PRD 73, 057502 (2006)

- $B \rightarrow a_1K$ modes have been measured.

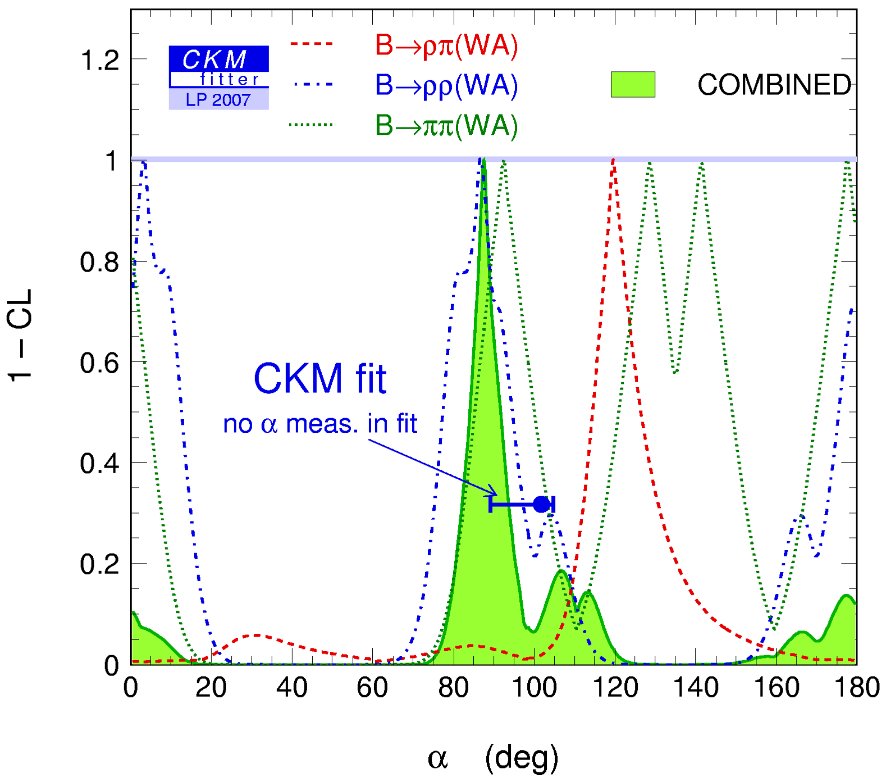
$\mathrm{BF}(B^0 \rightarrow a_1^- K^+) = (16.3 \pm 2.9 \pm 2.3) \times 10^{-6}$

$\mathrm{BF}(B^+ \rightarrow a_1^+ K^0) = (34.9 \pm 5.0 \pm 4.4) \times 10^{-6}$

- $B \rightarrow K_1\pi$ modes are being measured.
  - K_1 is a mixture of $K_1(1270)$ and $K_1(1400)$
- First bounds on $\alpha - \alpha_{eff}$ are coming.

PRL 100, 051803 (2008)

Summary on α



$$\alpha = 87.5^{\circ}{}^{+6.2^{\circ}}_{-5.3^{\circ}}$$

- The decay modes B→ ππ/ ρπ/ ρρ give consistent and complementary measurements of α.
- ρπ(Dalitz): disfavors mirror solution.
- ρρ: efficient mode, improved with the measurement of C_{00} and S_{00} (to be confirmed).
- New result from B →a_1π is coming.
- The combined average is in good agreement with global CKM fits.