Measurement of φ_2/α (Belle and BaBar)

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Introduction

CP violation in

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

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

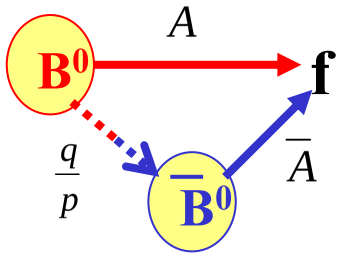
$B^0 \rightarrow \pi^+ \pi^- \pi^0$

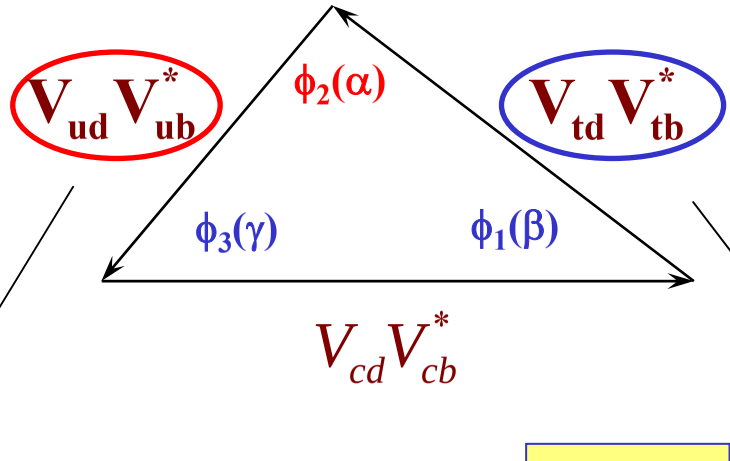
$B^0 \rightarrow a_1^+ \pi^-$

ϕ_2/α constraint from an isospin analysis

Mixing induced CP violation

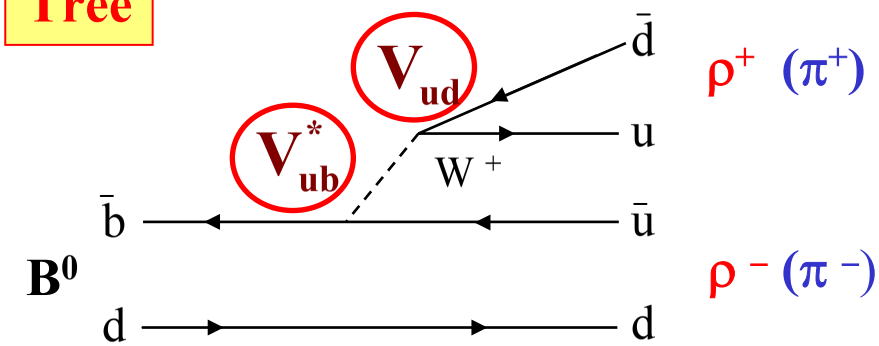
Belle ϕ_2
BaBar α



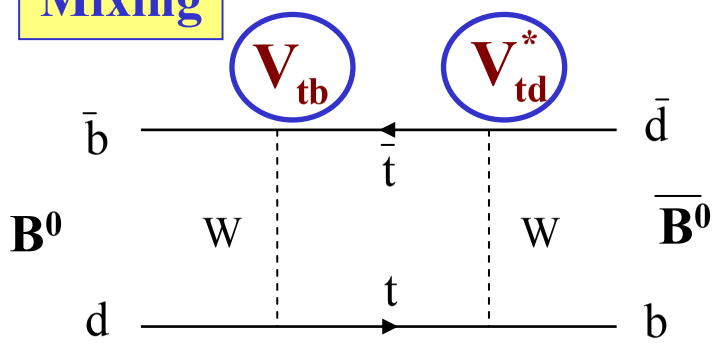


$$\phi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

Tree

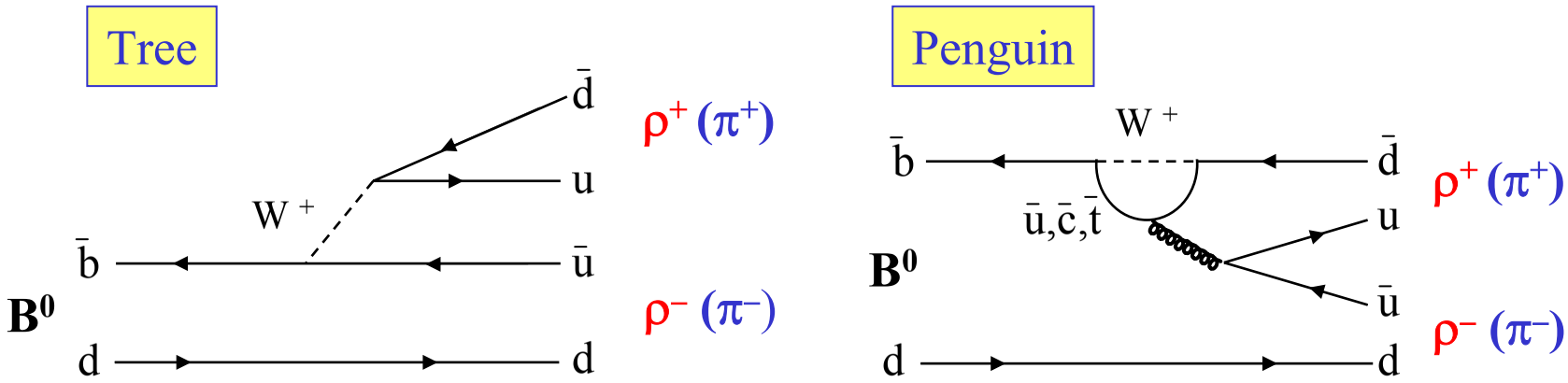


Mixing



$$A_{CP} = S \sin(\Delta m \Delta t)$$
$$S = \sin 2\phi_2$$

Mixing induced CP violation (cont'd)



$$\frac{N(\bar{B}^0 \to f) - N(B^0 \to f)}{N(\bar{B}^0 \to f) + N(B^0 \to f)} = A_{\rho\rho}\cos(\Delta m \Delta t) + S_{\rho\rho}\sin(\Delta m \Delta t)$$

Direct CPV **Mixing induced CPV**

Tree only

$A_{\rho\rho} = 0$

$S_{\rho\rho} = \sin(2\phi_2)$

Tree + Penguin

$A_{\rho\rho} \sim \sin(\delta)$ **direct CP violation**

$S_{\rho\rho} = \sqrt{1 - A_{\rho\rho}^2}\,\sin(2\phi_{eff})$ ➡ **two main approaches to extract ϕ_2**

ϕ_2/α measurement

Main decays used for the extraction of ϕ_2 (α)

$B^0 \to \pi^+ \pi^-$	relatively clean signal, large penguin contribution
$B^0 \to \rho^+ \rho^-$	relatively small penguin, reconstruction challenge
$B^0 \to \rho^\pm \pi^\mp$	not a CP eigenstate, time-dependent Dalitz analysis
$B^0 \to a^\pm \pi^\mp$	not a CP eigenstate (first measurement of $\sin(2\varphi_2^{eff})$)

- Extract ϕ_2 using an Isospin analysis
  - 'model independent' approach

- The penguin contribution can also be bound using flavor SU(3) relations

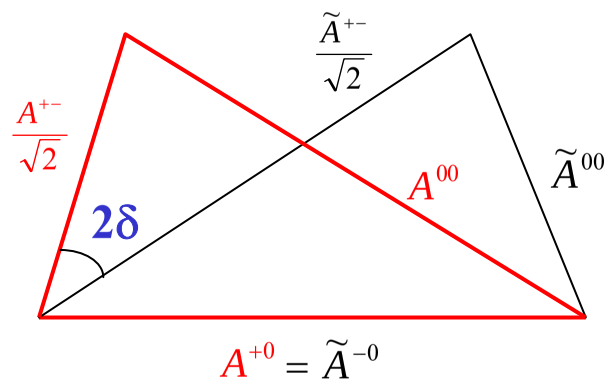
Measurement of α/φ_2 using $B \to \pi\pi$ and $B \to \rho\rho$ decays

Isospin analysis in B → ππ (ρρ)

- **Measure $A_{\pi\pi}$ and $S_{\pi\pi}$:** $S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}}\,\sin(2\phi_2^{eff})$ $\quad \phi_2^{eff} = \phi_2 + \delta$

- **Use isospin relations** ***[M.Gronau and D.London, Phys.Rev.Letter. 65, 1990]***

Two amplitude triangles: $\dfrac{A^{+-}}{\sqrt{2}} + A^{00} = A^{0+}, \qquad \dfrac{\overline{A}^{+-}}{\sqrt{2}} + \overline{A}^{00} = \overline{A}^{0+}$



$$\widetilde{A} = e^{2i\phi_3}\,\overline{A}$$

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

Isospin analysis in B → ππ (ρρ) (cont'd)

ππ: **6 unknowns, and 6 observables:**

Br's, $A_{\pi\pi}$, $S_{\pi\pi}$, $A(\pi^0\pi^0)$ (not yet measured $S(\pi^0\pi^0)$)

ρρ: **6 unknowns, and 5 observables:**

Br's, $A_{\rho\rho}$, $S_{\rho\rho}$ (+ 2, not yet measured CP asymmetries in $\rho^0\rho^0$)

Generally, Isospin analysis allows to extract ϕ_2 /α with 8-fold ambiguity

- **Follow statistical method (R-fit, CKMfitter group)**

[J.Charles et. Al. Eur.Phys.J.C41:1-131, 2005]

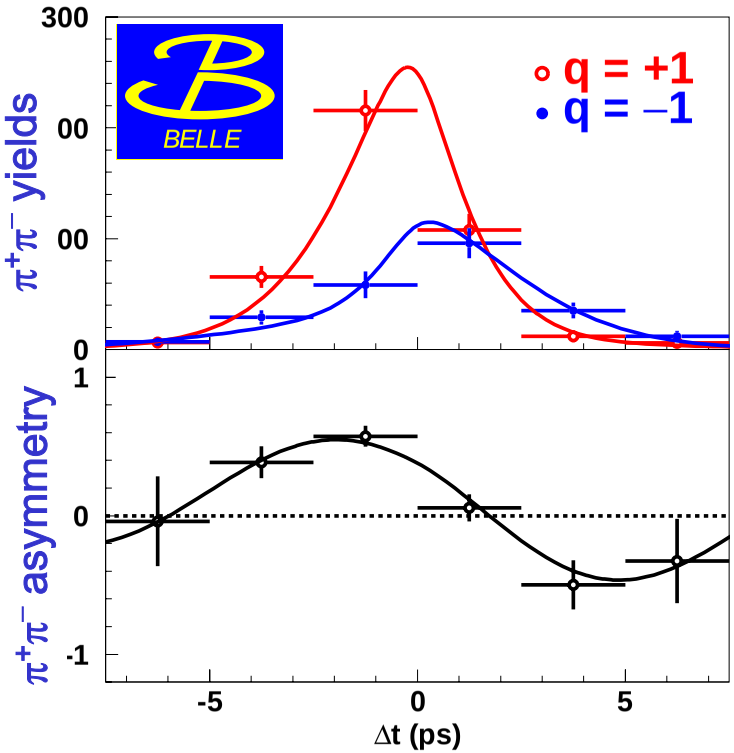
Caveats

- **neglect EW penguin**
- **ignore interference with $\rho\pi\pi$, $\pi^+\pi^0\pi^-\pi^0$, $a_1\pi$**
- **ignore possible I = 1 contribution**

(all believed to be small)

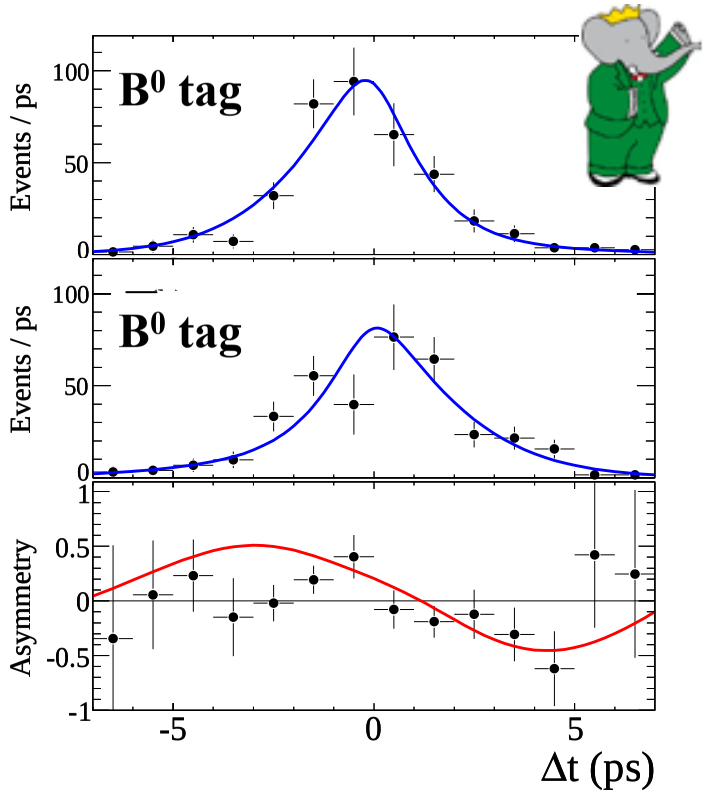
$B^0 \to \pi^+ \pi^-$: CP asymmetry

535 Million BB pairs, *hep-ex/0608035*



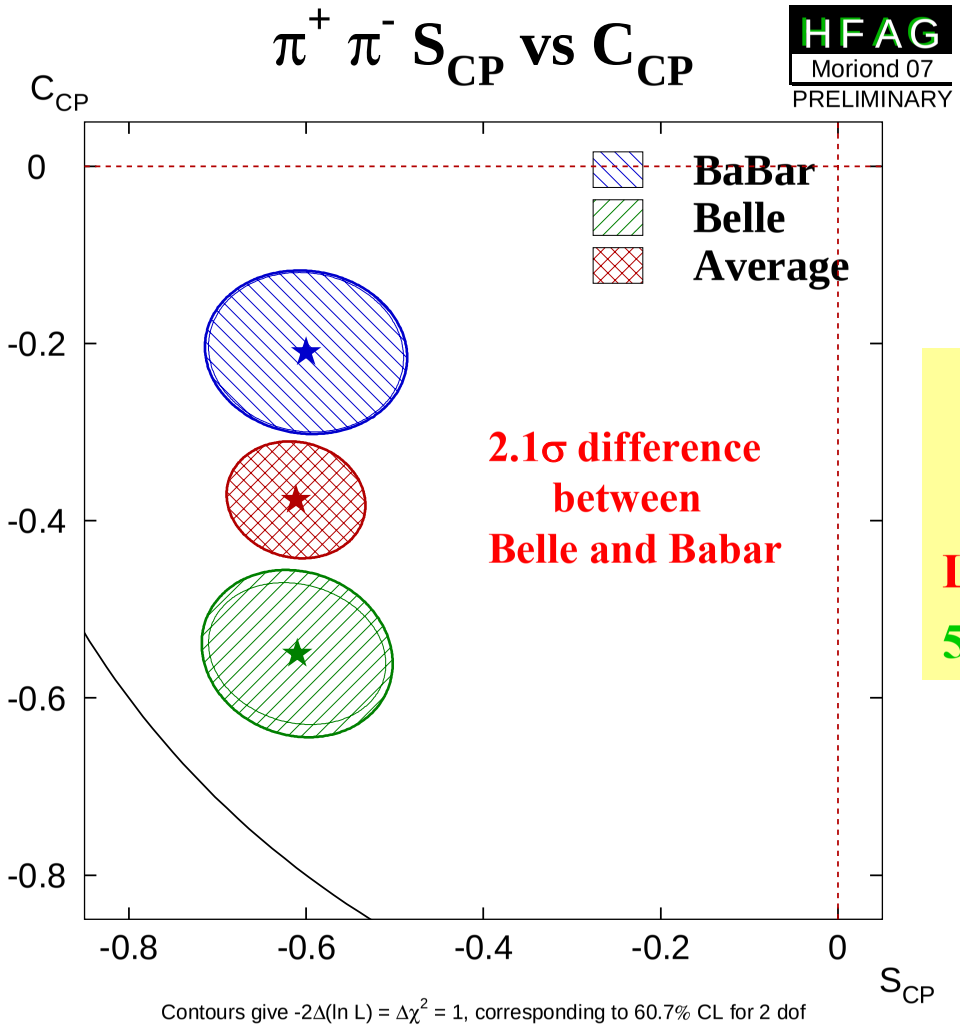
$$A_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$$
$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$$

383 Million BB pairs, *hep-ex/0703016*



$$C_{\pi\pi}(-A_{\pi\pi}) = -0.21 \pm 0.09 \pm 0.02$$
$$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03$$

$B^0 \to \pi^+ \pi^-$: CPV significance



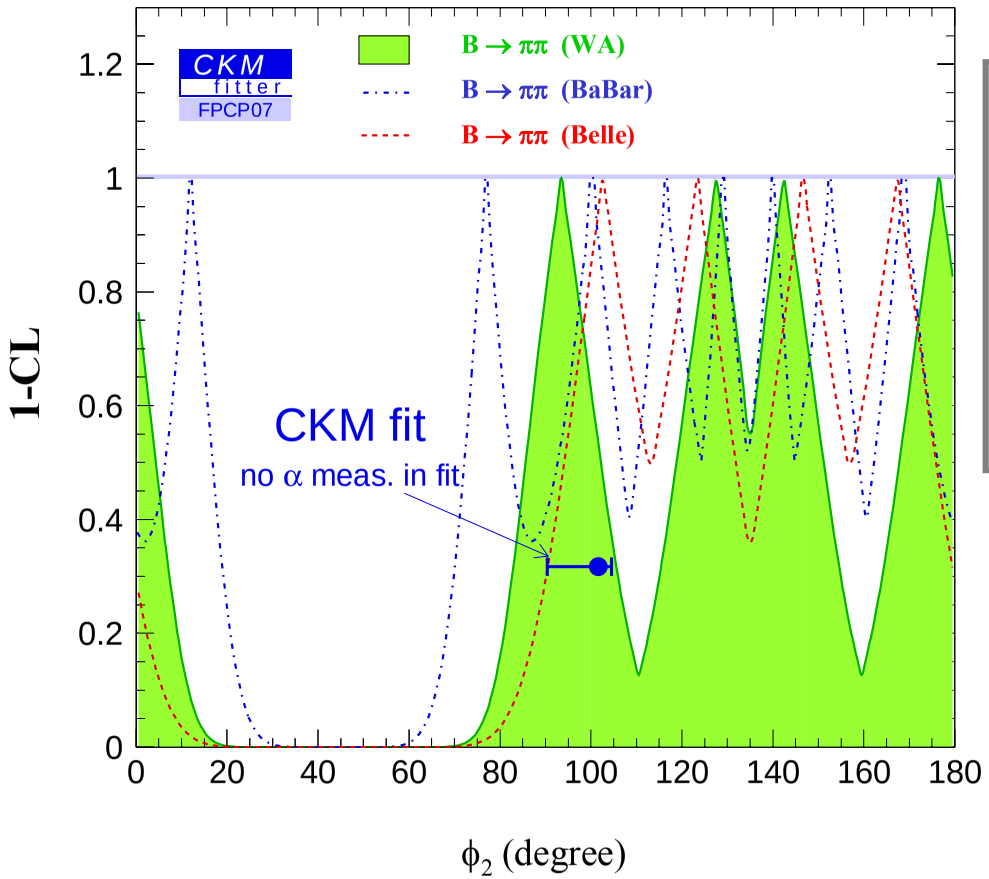
Large Direct CP violation

5.5 σ Belle

Large mixing-induced CP violation

5.6 σ Belle **5.1 σ BaBar**

$B^0 \to \pi^+ \pi^-$: Constraint on ϕ_2/α using Isospin analysis



$$\varphi_2 = 93.5^{+12.1}_{-10.0}$$

Br $(\pi^+\pi^0)$	=	(5.75 ± 0.42)	$\times 10^{-6}$
Br $(\pi^+\pi^-)$	=	(5.20 ± 0.25)	
Br $(\pi^0\pi^0)$	=	(1.30 ± 0.21)	
A $(\pi^0\pi^0)$	=	$+0.35 \pm 0.33$	
S $(\pi^+\pi^-)$	=	-0.61 ± 0.08	
A $(\pi^+\pi^-)$	=	$+0.38 \pm 0.07$	

- Merged solutions
- No stringent constraint with $\pi\pi$ alone
  - other measurements needed: $\rho\pi$, $\rho\rho$, $a_1\pi$

CP analysis in $B \to \rho^+\rho^-$ decays

Advantages of $\rho^+\rho^-$:

- **small penguin contribution due to relatively small**

$$Br(B^0 \to \rho^0\rho^0) = (1.07 \pm 0.33 \pm 0.19) \times 10^{-6}$$ *[BaBar, hep-ex/0612021]*

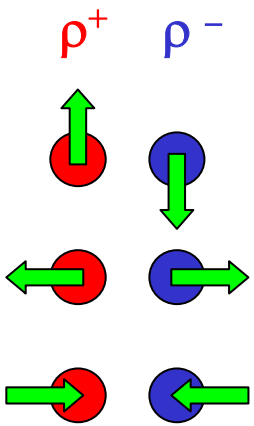
- **relatively large measured branching fraction for b → u process**

$$\frac{\mathrm{Br}(B^0 \to \rho^+\rho^-)}{\mathrm{Br}(B^0 \to \pi^+\pi^-)} \sim 4.4$$

CP analysis in B → ρ+ρ⁻ decays (cont'd)

Complications:

- $\rho^+\rho^-$ is a VV state ⟹ 3 helicity states (three helicity amplitudes should be considered)



longitudinal polarization

$$A_0 = H_0 \quad (+1 \text{ CP even})$$

$$A_{\parallel} = \frac{H_+ + H_-}{\sqrt{2}} \quad (+1 \text{ CP even})$$

$$A_{\perp} = \frac{H_+ - H_-}{\sqrt{2}} \quad (-1 \text{ CP odd})$$

Longitudinal polarization dominates

$f_L = 0.977 \pm 0.024^{+0.015}_{-0.013}$ **BaBar:** ***hep-ex/0607098***

$f_L = 0.941^{+0.034}_{-0.040} \pm 0.030$ **Belle:** ***PRL96, 171801 2006***

PDG

$f_L = 0.967^{+0.022}_{-0.027}$

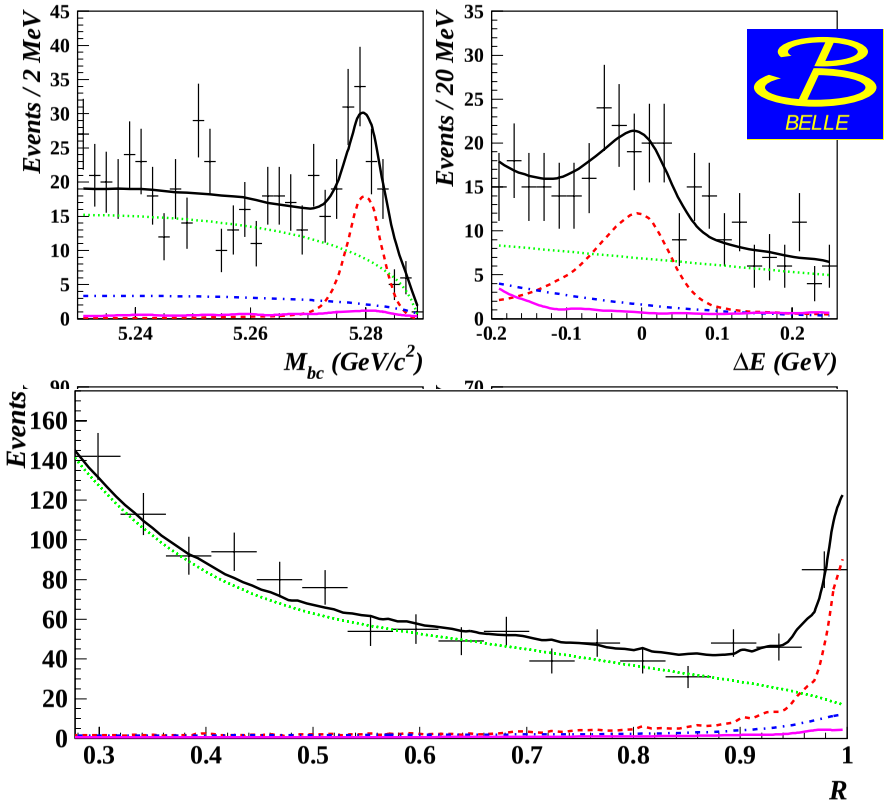
CP analysis in B $\rightarrow \rho^+\rho^-$ decays (cont'd)

Complications (cont'd):

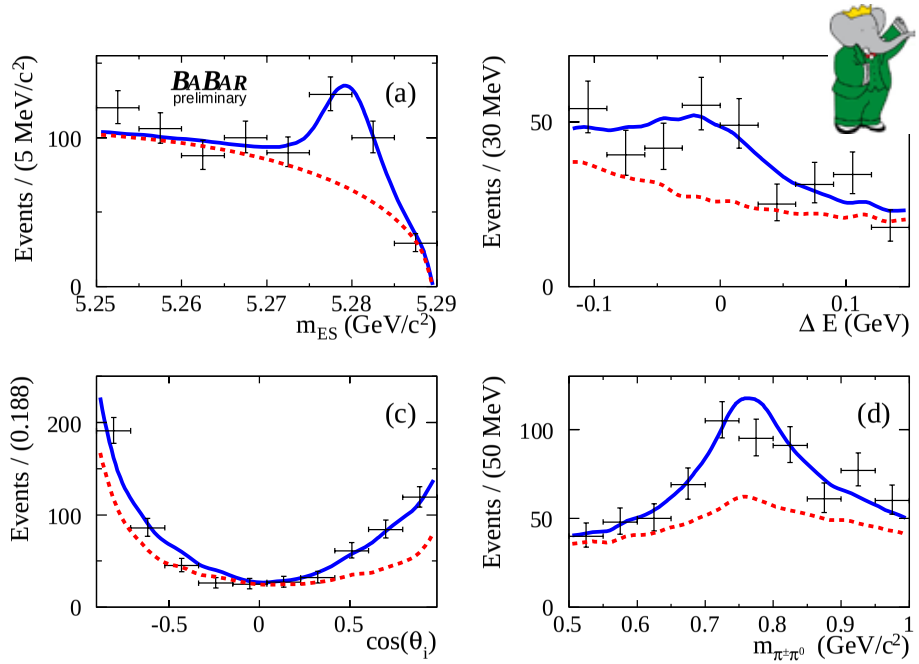
- **'Dirty' final state $\rho^+\rho^- \rightarrow \pi^+\pi^0\ \pi^-\pi^0$; $\Gamma(\rho) = 150$ MeV large backgrounds**
- **I = 1 contribution due to finite width of ρ**
  [A.F.Falk, Z.Ligeti, Y. Nir, H.Quinn PRD69, 011502, 2004]
- **Possible interference between signal and 4-π non-resonant components**

$B^0 \to \rho^+\rho^-$: Fit results

535 Million BB pairs, *hep-ex/0702009*



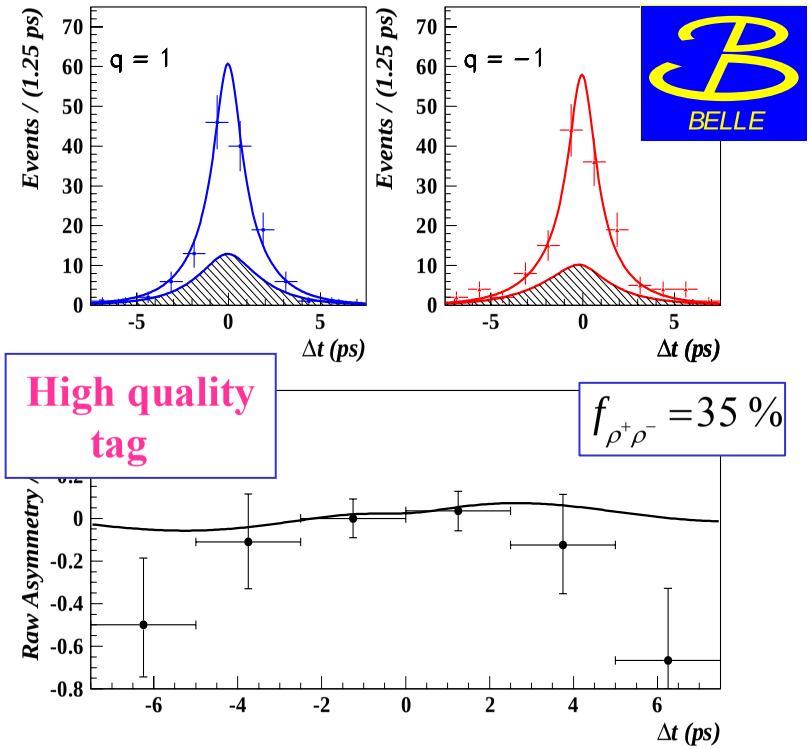
347 Million BB pairs, *hep-ex/0607098*



$$Br(B^0 \to \rho^+\rho^-) = (23.5 \pm 2.2(stat) \pm 4.1(syst)) \times 10^{-6}$$

$B^0 \to \rho^+\rho^-$: CPV fit results

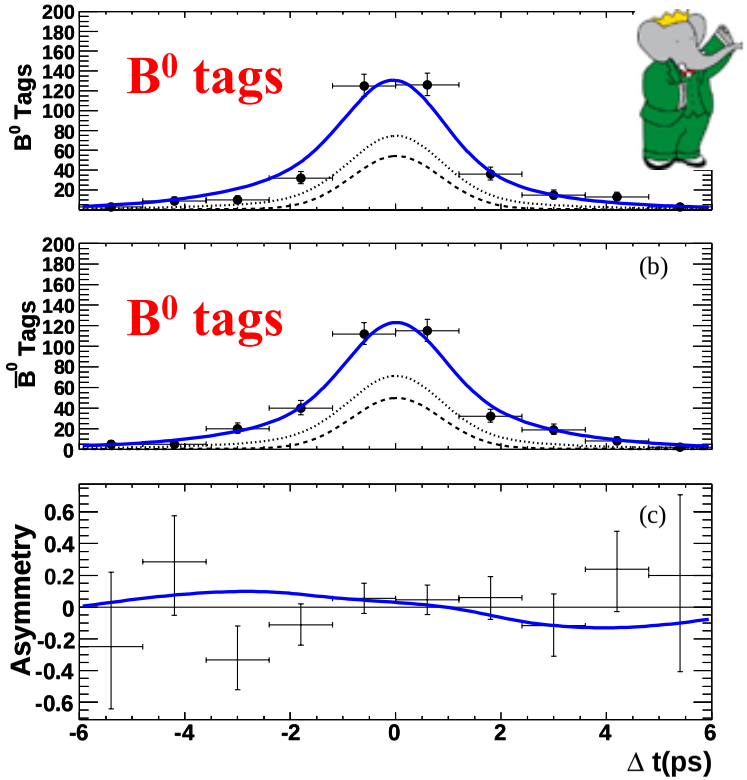
535 Million BB pairs, *hep-ex/0702009*



$$A_{\rho\rho} = 0.16 \pm 0.21(stat) \pm 0.07(syst)$$

$$S_{\rho\rho} = 0.19^{+0.29}_{-0.30}(stat)^{+0.07}_{-0.06}(syst)$$

347 Million BB pairs, *hep-ex/0607098*



$$C_{\rho\rho} = -0.07 \pm 0.15(stat) \pm 0.06(syst)$$

$$S_{\rho\rho} = -0.19 \pm 0.21(stat)^{+0.05}_{-0.07}(syst)$$

Measurements in $B^{\pm} \to \rho^{\pm} \rho^{0}$ decays

232 Million BB pairs *hep-ex/0607092*

Extract signal yield, polarization and charge asymmetry using an extended unbinned (7-dimensional) ML fit to m_{ES}, ΔE, $m(\pi\pi)^{+0}$, $\cos\theta_{+0}$, x_N

Simultaneous fit for the yield, polarization, and charge asymmetry

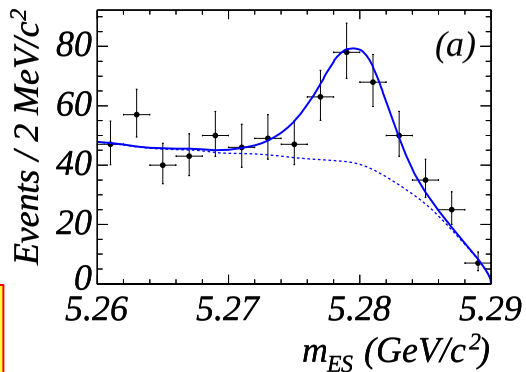
$$N_{\rho^+\rho^0} = 390 \pm 49$$

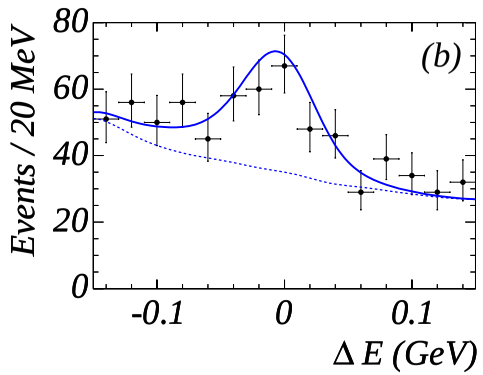
$$Br = (16.8 \pm 2.2(stat) \pm 2.3(syst)) \times 10^{-6}$$

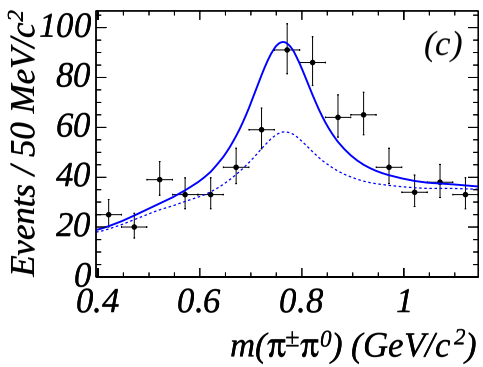
$$f_L = 0.905 \pm 0.042^{+0.023}_{-0.027}$$

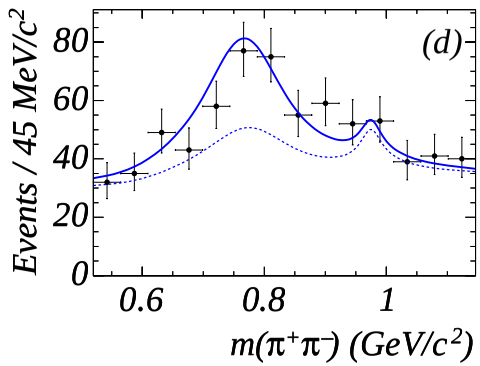
Belle (85 Million BB pairs):

$$Br = (31.7 \pm 7.1(stat)^{+3.8}_{-6.7}) \times 10^{-6}$$







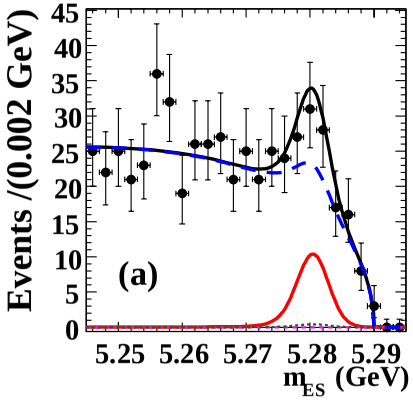


Evidence for $B \to \rho^0\rho^0$

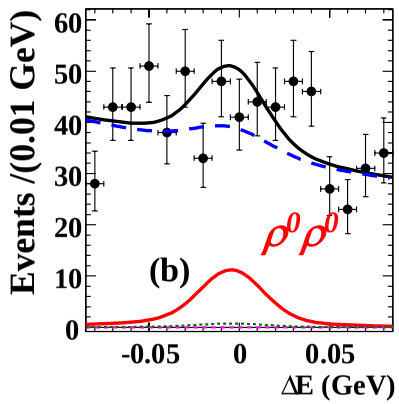
384 Million BB pairs

hep-ex/0612021
submitted to PRL

m_{ES}



ΔE



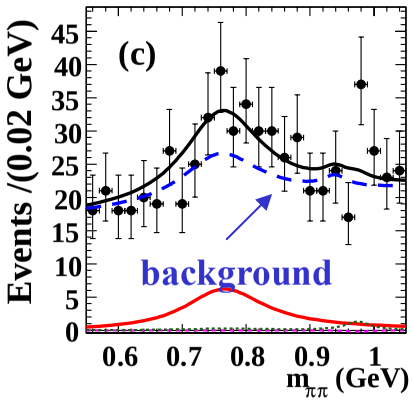
$N_{\rho^0\rho^0} = 100 \pm 32 \pm 17(syst)$

Assume no non-resonant component:

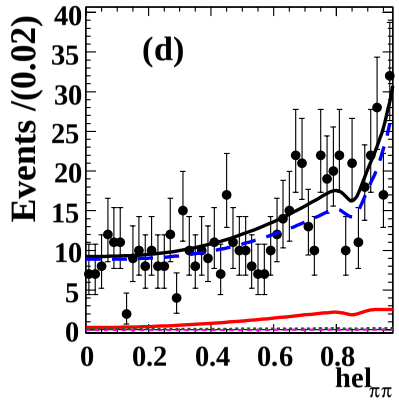
$f(\rho^o\pi\pi) = 0$

$f(\pi\pi\pi\pi) = 0$

$m_{\pi\pi}$



$\cos\theta$



$Br(B^0 \to \rho^0\rho^0) = (1.07 \pm 0.33(stat) \pm 0.19(syst)) \times 10^{-6}$

$f_L = 0.87 \pm 13(stat) \pm 0.04(syst)$

Results statistically consistent with previous BaBar measurements, *PRL 94, 131801 (2005)*
Br < 1.1 10^{-6} at 90% CL

$B \to \rho\rho$: Constraint on ϕ_2/α

Branching fractions and polarization fractions used in the isospin analysis (HFAG, 2007)

OLD

$(26 \pm 6)\ 10^{-6}$

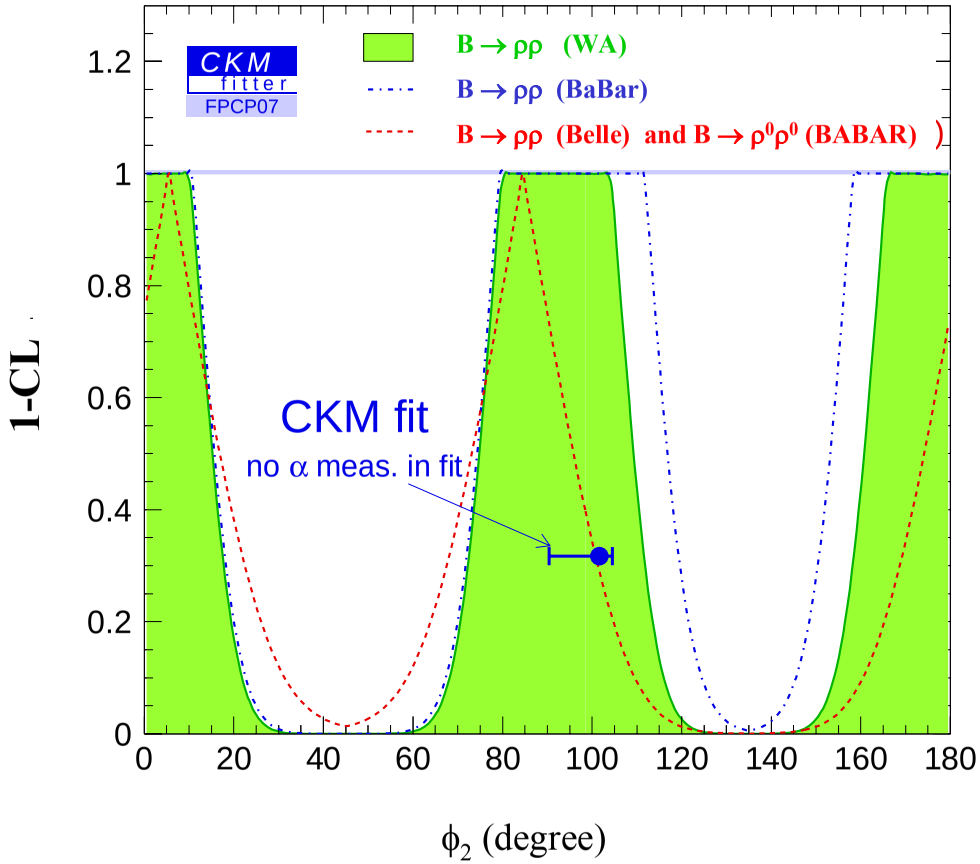
$(25 \pm 4)\ 10^{-6}$

$>1.1\ 10^{-6}$

$B(\rho^+\rho^0)$	=	$(18.2 \pm 3.0) \cdot 10^{-6}$
$f_L(\rho^+\rho^0)$	=	$0.912^{+0.044}_{-0.045}$
$B(\rho^+\rho^-)$	=	$(23.1^{+3.2}_{-3.3}) \cdot 10^{-6}$
$f_L(\rho^+\rho^-)$	=	0.968 ± 0.023
$B(\rho^0\rho^0)$	=	$(1.07 \pm 0.38) \cdot 10^{-6}$
$f_L(\rho^0\rho^0)$	=	0.87 ± 0.14
$A(\rho^0\rho^0)$	=	N.A.

The isospin triangles are 'closed' with the new measurements of $Br(\rho^+\rho^-)$, $Br(\rho^+\rho^0)$, $Br(\rho^0\rho^0)$

$B \to \rho\rho$: Constraint on ϕ_2/α (cont'd)

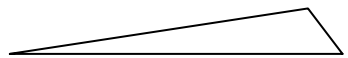


$72.5 < \phi_2 < 111.5^\circ$ **(92.0 ± 19.5)°**

$A_{\rho^0\rho^0}$ $(S_{\rho^0\rho^0})$ **is not measured. We have**
6 unknowns and 5 measurements.

- **leads to flat-top regions on 1-CL plot**
- **the plateau width depends on $Br(\rho^0\rho^0)$**

If $Br(\rho^0\rho^0) \to 0$, Isospin triangles squashes



Squashed Isospin triangles at Belle due to large $Br(B^\pm \to \rho^\pm \rho^0) = 31.7$

- **no 'plateau', 2-fold ambiguity**

Constraint on ϕ_2/α (cont'd)

- **The penguin contribution can also be bound using flavor SU(3) relations**

[M.Beneke, M.Gronau, J.Rohrer, M.Spranger Phys.Lett B638,2006, hep-ph/0604005]

[M.Gronau, O.F.Hernandez,D.London,J.L.Rosner, Phys.Rev.D50,4529 ,1994]

Measurement of α/φ_2 using $B^0 \to \pi^+ \pi^- \pi^0$ decays

CP violation in $B^0 \to \pi^+ \pi^- \pi^0$ decays

φ_2 can be constrained using a time-dependent Dalitz analysis

A.E.Snyder and H.R.Quinn Phys.Rev. D48 2139, 1993

- **Time dependent Dalitz plot decay width**

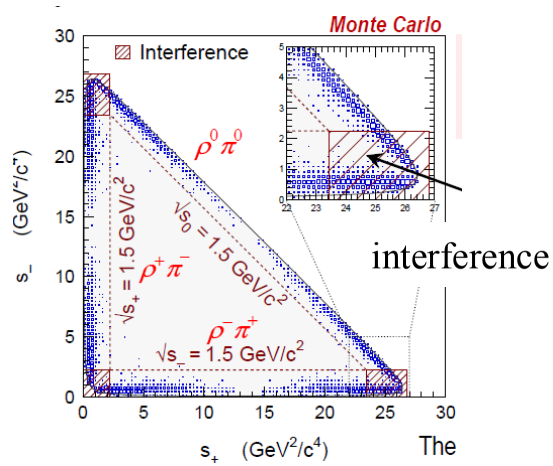
$$|A(\Delta t; S_+, S_-)|^2 = e^{-\Gamma|\Delta t|}\{(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2) - q_{tag}[(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2)\cos(\Delta m \Delta t) - 2\,\mathrm{Im}[\frac{q}{p} A^*_{3\pi}\overline{A}_{3\pi}]\sin(\Delta m \Delta t)]\}$$

- **Dalitz plot amplitude**

$$A_{3\pi}(s_+, s_-) = f_+(s_+, s_-)A^+ + f_-(s_+, s_-)A^- + f_0(s_+, s_-)A^0$$

$$f_k(s_+, s_-) = T^k_{J=1} F^k(s_k)$$

$$F^k(s) = BW_{\rho(770)} + \beta_k BW_{\rho(1450)} + \gamma_k BW_{\rho(1700)}$$



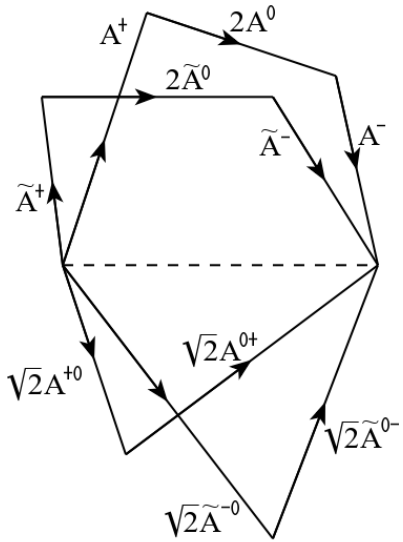
Obtain 26 parameters from the fit

CP violation in $B^0 \to \pi^+ \pi^- \pi^0$ decays

- **Isospin relations**

$$e^{+2i\phi_2} = \frac{\overline{A}^+ + \overline{A}^- + 2\overline{A}^0}{A^+ + A^- + 2A^0}$$

H.J. Lipkin et. Al. Phys.Rev.D 44,1991
M.Gronau, Phys. Lett. B265, 1991



- **Use branching fractions for $\rho^+\pi^-$, $\rho^+\pi^0$, $\rho^0\pi^+$ and flavor asymmetries for $\rho^+\pi^0$, $\rho^0\pi^+$**

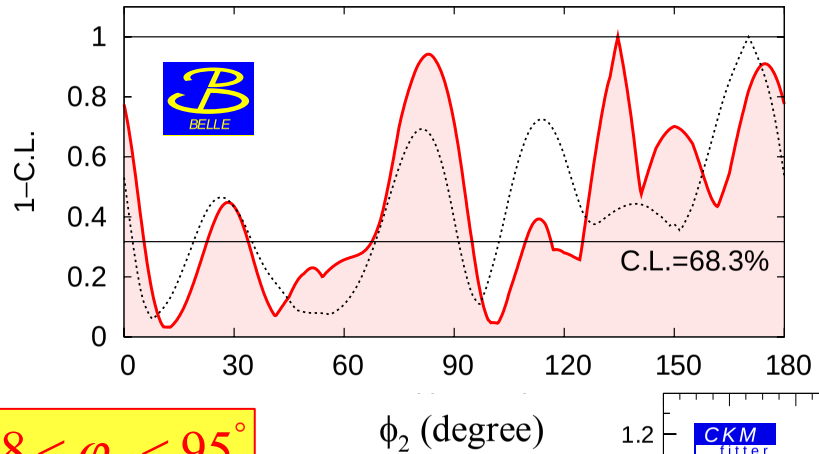
Consistency with previous measurements

Measure $B^0 \to \rho^0\pi^0$ CP-violation parameters and decay fraction

$$\frac{Br(B^0 \to \rho^0\pi^0)}{Br(B^0 \to \rho^\pm\pi^\mp)} = 0.133 \pm 0.022 \pm 0.023$$ **Belle** $0.130^{+0.049}_{0.046}$ **(Belle previous measurement)**

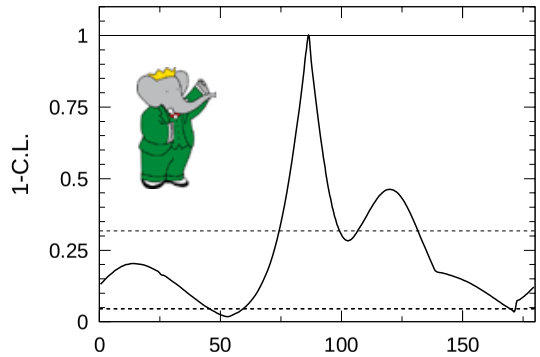
$B^0 \to \pi^+ \pi^- \pi^0$: Constrain on ϕ_2/α

449 Million BB pairs, *hep-ex/0701015*



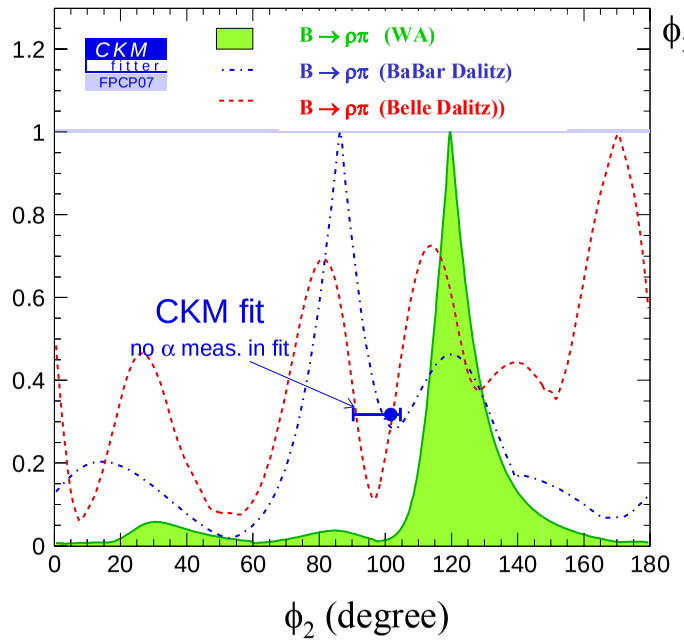
$68 < \varphi_2 < 95^\circ$

375 Million BB pairs, *hep-ex/0703008*



$\varphi_2 = [87^{+45}_{-13}]^\circ$

Preliminary



Measurement of α/φ_2 using $B^0 \to a_1^{+-} \pi^{-+}$ decays

CP Violation in $B^0 \to a_1^+\pi^-$ decays

$B^0 \to a_1^{+-}\pi^{-+}$ is not a CP-eigenstate (four flavor-charge configurations must be considered)

Decay rate distribution

$$P(a_1^{\pm}\pi^{\mp}) = (1 \pm A_{CP}^{a_1\pi})\frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left\{1 - q(C_{a_1\pi} \pm \Delta C_{a_1\pi})\cos(\Delta m\Delta t) + q(S_{a_1\pi} \pm \Delta S_{a_1\pi})\sin(\Delta m\Delta t)\right\}$$

q = 1 $\bar{B}^0$ tag
q = -1 B^0 tag

$$A_{CP}^{a_1\pi} = \frac{N(a_1^+\pi^-) - N(a_1^-\pi^+)}{N(a_1^+\pi^-) + N(a_1^-\pi^+)}$$

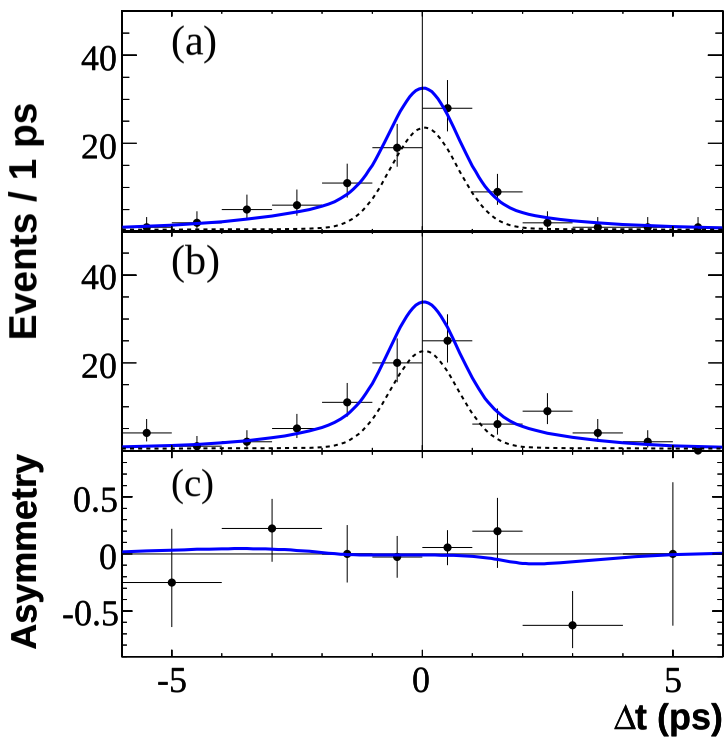
time and flavor integrated asymmetry

$C_{\rho\pi}$: direct CP violation
$S_{\rho\pi}$: CP violation arising from mixing
$\Delta C_{\rho\pi}$: difference between ($W \to \rho$) and (spectator $\to \rho$) rates
$\Delta S_{\rho\pi}$: difference between ($W \to \rho$) and (spectator $\to \rho$) strong phase

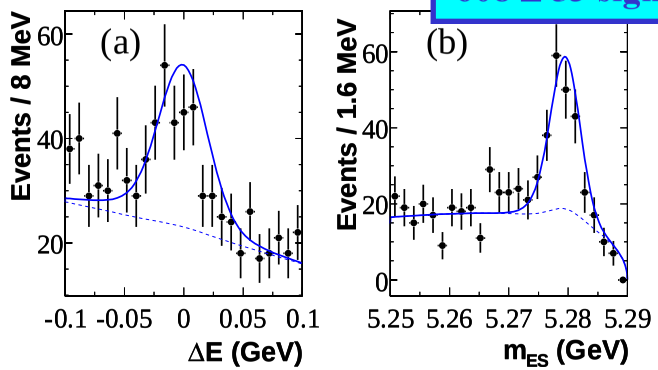
direct CP violation $\to$ C and $A_{CP} \neq 0$
Indirect CP violation $\to$ $S \neq 0$

$B^0 \to a_1^+ \pi^-$ fit results

384 Million BB pairs, *hep-ex/0612050*



608 ± 53 signal events



Fit results:

$A_{CP} = -0.07 \pm 0.07 \pm 0.02$

$S = +0.37 \pm 0.21 \pm 0.07$

$C = -0.10 \pm 0.15 \pm 0.09$

$\Delta S = -0.14 \pm 0.21 \pm 0.06$

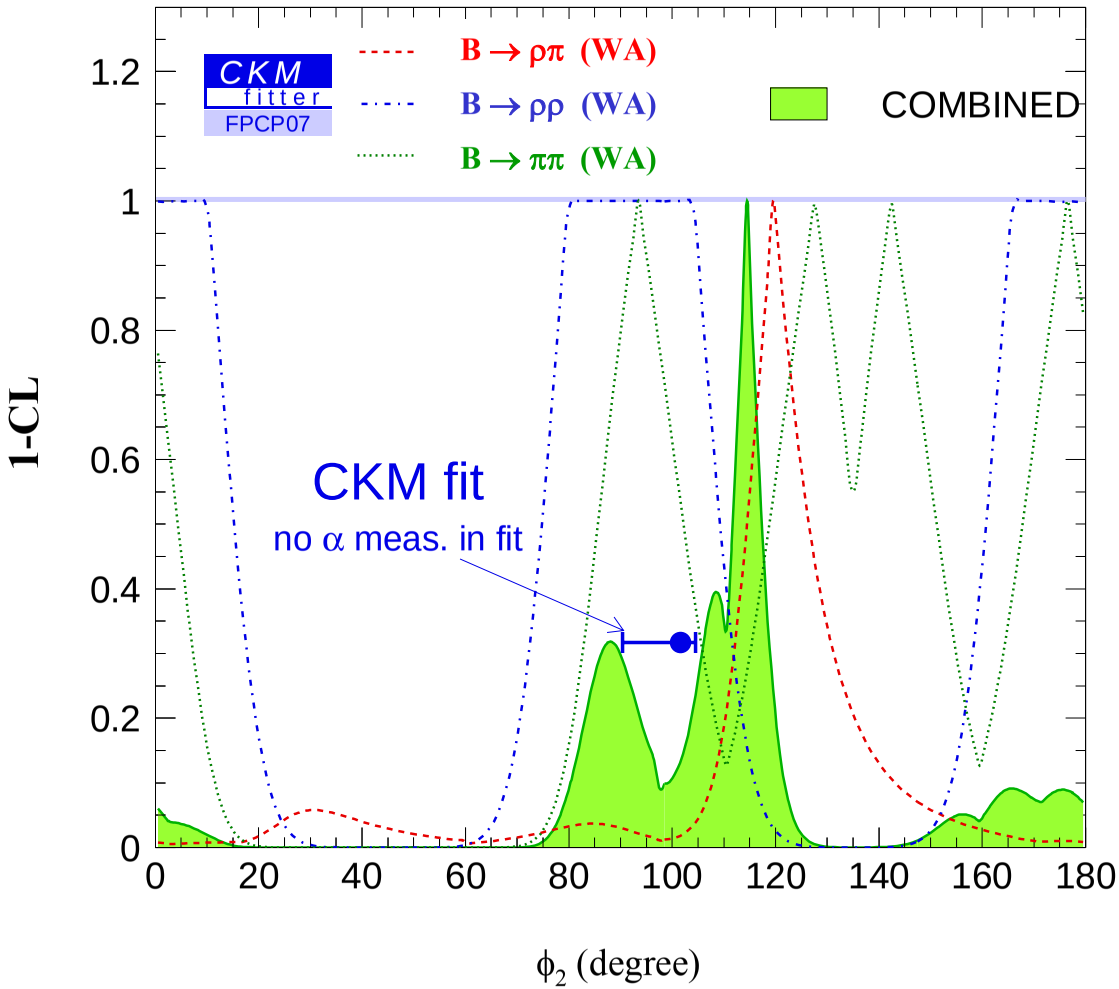
$\Delta C = +0.26 \pm 0.15 \pm 0.07$

$\varphi_2^{eff} = (78.6 \pm 7.3)^\circ$

Flavor SU(3) can be used to constrain φ_2 (applying SU(3) to a_1K and $K_1\pi$ decays , where K_1 is an admixture of $K_1(1270)$ and $K_1(1400)$) *Gronau, Zupan, PRD 73 (2006) 057502*

Preliminary

Constraint on ϕ_2/α



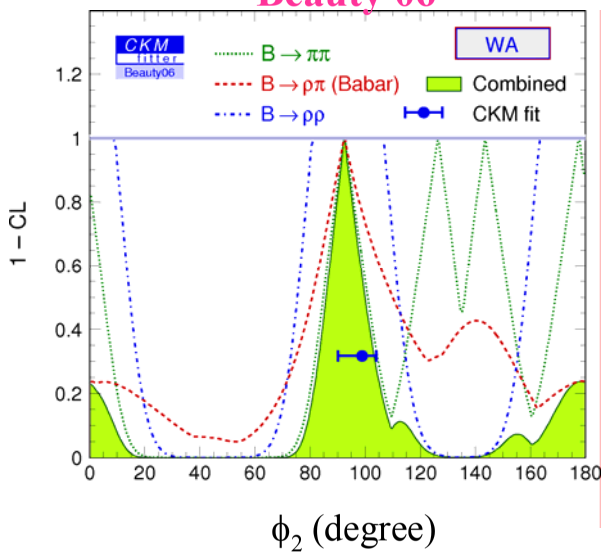
1σ interval

$(\varphi_2 = 114.5^{+4.4}_{-8.3})^\circ$

2σ interval

$(\varphi_2 = 114.5^{+9.2}_{-36.5})^\circ$

Beauty 06



$(93.5^{+10.8}_{-9.6})^\circ$

Summary

Several new results during this /last years:

- **Measurements of CP asymmetries (Belle and BaBar)**
  - $B^0 \rightarrow \pi^+\pi^-$
  - $B^0 \rightarrow \pi^+\pi^-\pi^0$ **time-dependent Dalitz analysis**
  - $B^0 \rightarrow \rho^+\rho^-$
- **Updated branching fraction for**
  $B \rightarrow \rho^+\rho^-$ **and** $B \rightarrow \rho^+\rho^0$ **decays (BaBar)**
- **First evidence for** $B \rightarrow \rho^0\rho^0$ **decays at BaBar**

From an isospin analysis φ_2/α is constrained as (CKMfitter)

$$(\varphi_2 = 114.5^{+4.4}_{-8.3})^\circ$$

New measurements are awaited to improve our knowledge on φ_2/α

(Belle first results on Br($B \rightarrow \rho^0\rho^0$) will appear soon)

Backup slides

$B^{\pm} \to \rho^{\pm} \rho^{0}$ results

	232 Million BB pairs	85 Million BB pairs	HFAG
Br (10^{-6})	$16.8 \pm 2.2 \pm 2.3$	$31.7 \pm 7.1^{+3.8}_{-6.7}$	18.2 ± 3.0
f_L	$0.905 \pm 0.042^{+0.023}_{-0.027}$	$0.948 \pm 0.106 \pm 0.021$	$0.912^{+0.044}_{-0.045}$
A_{CP}	$-0.12 \pm 0.13 \pm 0.10$	$0.00 \pm 0.22 \pm 0.03$	-0.08 ± 0.13

Previous *BaBar* measurement:

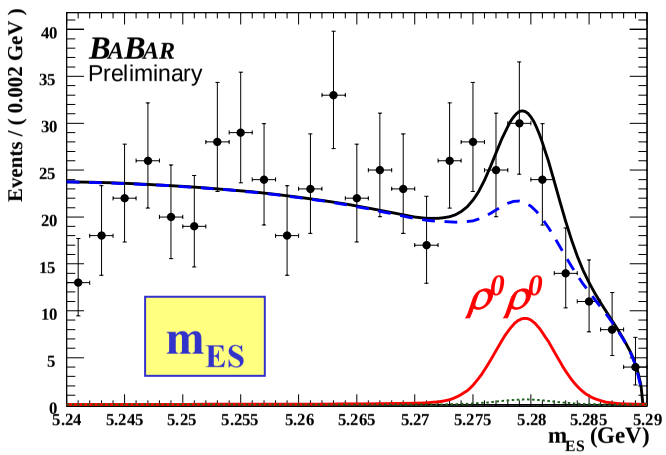
$$Br = (22.5^{+5.7}_{-5.4} \pm 5.8) \times 10^{-6}$$

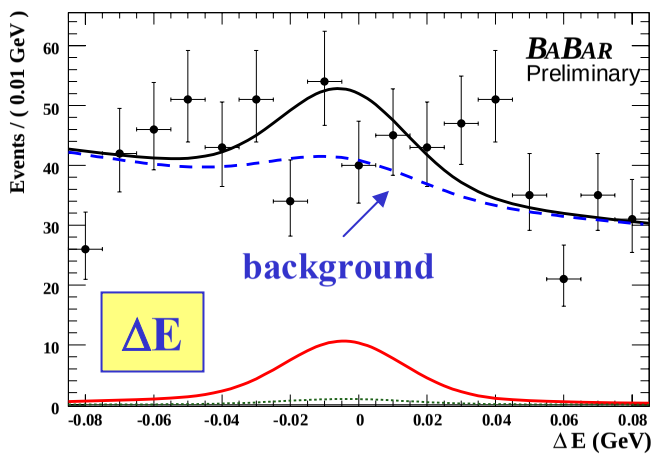
$$f_L = 0.97^{+0.03}_{-0.07} \pm 0.04$$

$$A_{CP} = -0.19 \pm 0.23 \pm 0.03$$

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

Evidence for $B \to \rho^0\rho^0$ (cont'd)





hep-ex/0607097

$$N_{\rho^0\rho^0} = 98^{+32}_{-31} \pm 22(syst)$$

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

$$f_L = 0.86^{+0.11}_{-0.13} \pm 0.05(syst)$$

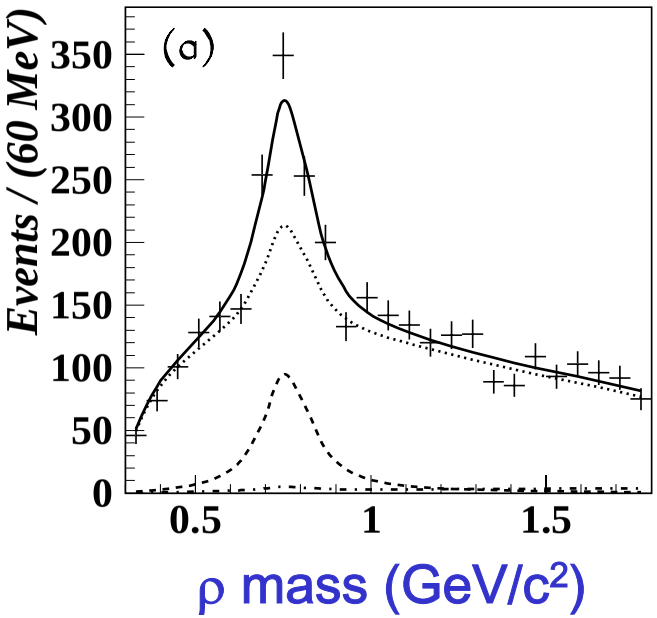
Sourses of dominant systematic errors:

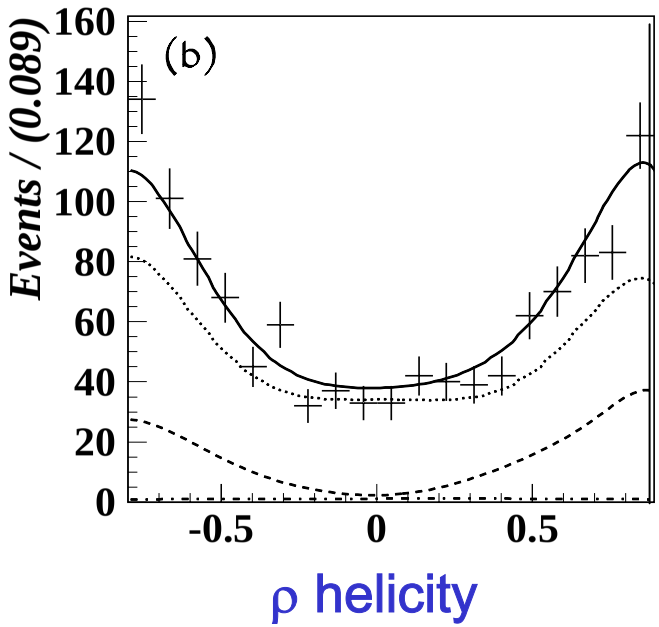
PDF shapes, interference with $B^0 \to a_1\pi$, fit bias

Results statistically consistent with previous BaBar measurements, *PRL 94, 131801 (2005)*

Br < 1.1 10^{-6} at 90% CL

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





275 Million BB pairs

PRL 96, 171801 (2006)

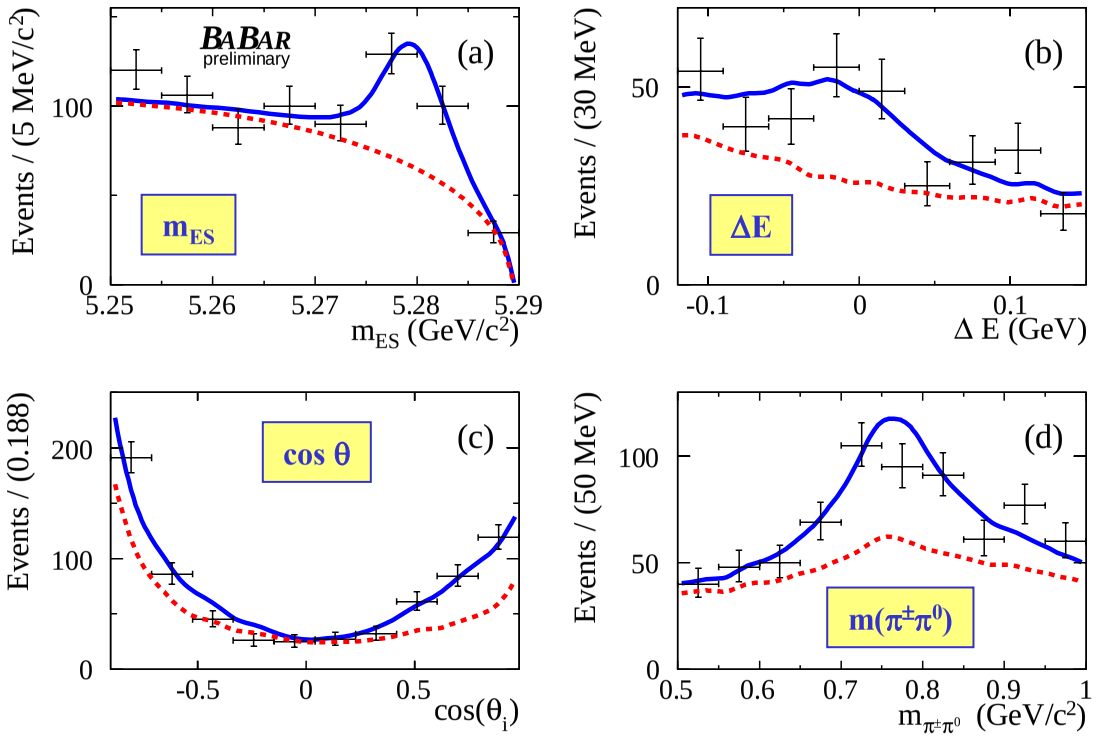
$$\tilde{f}_{\rho\pi\pi} = \frac{f_{\rho\pi\pi}}{f_{\rho\pi\pi} + f_{\rho\rho}} = 6.3 \pm 6.7\%$$

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

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

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

high-purity events



347 Million BB pairs

Updated this summer
hep-ex/0607092

Simultaneous fit for the yield, polarization, and *CP* parameters C and S

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

$$\mathbf{Br = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}}$$

$$\mathbf{f_L = 0.977 \pm 0.024\ ^{+0.015}_{-0.013}}$$

Previous BaBar:

$Br = 30.0 \pm 4 \pm 5$
(PRL 95,041805, 2005)

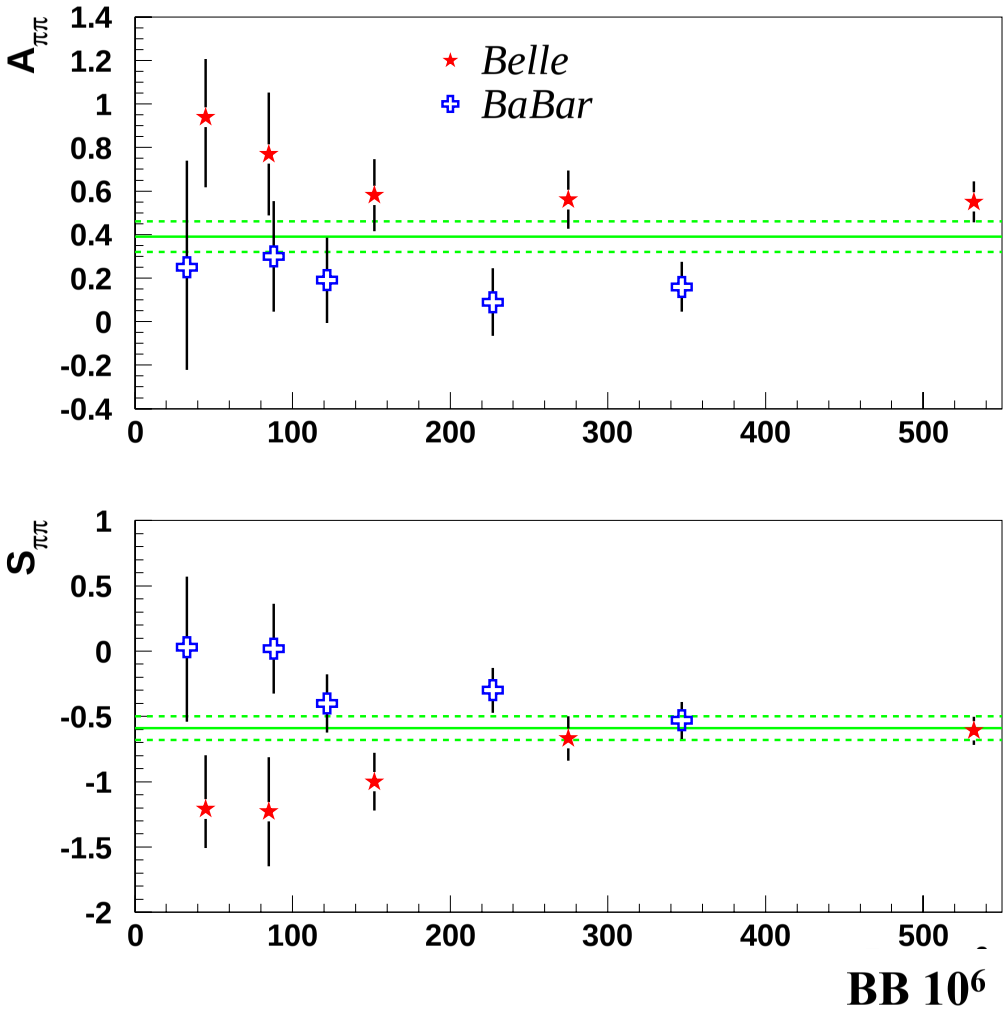
$f_L = 0.978 \pm 0.014^{+0.021}_{-0.029}$
(PRL 95,041805, 2005)

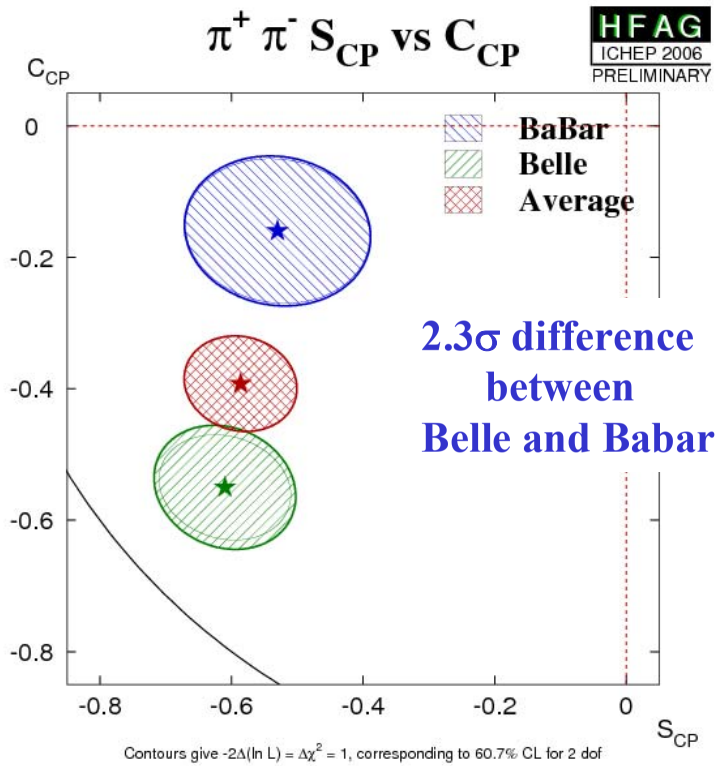
Previous Belle:
(PRL 96,171801, 2006)

$Br = 22.8 \pm 3.8^{+2.3}_{-2.6}$

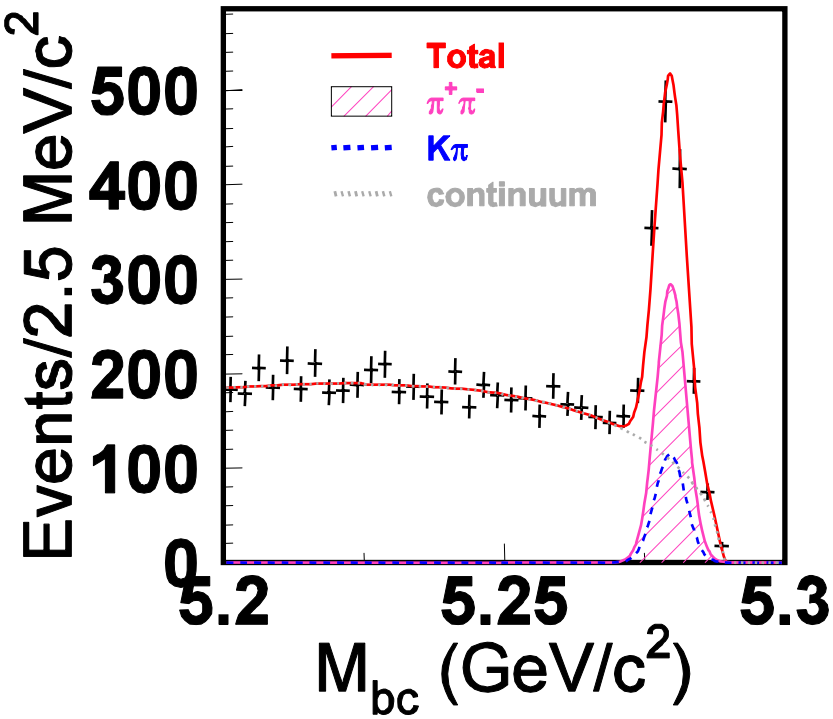
$f_L = 0.941^{+0.034}_{-0.040} \pm 0.030$

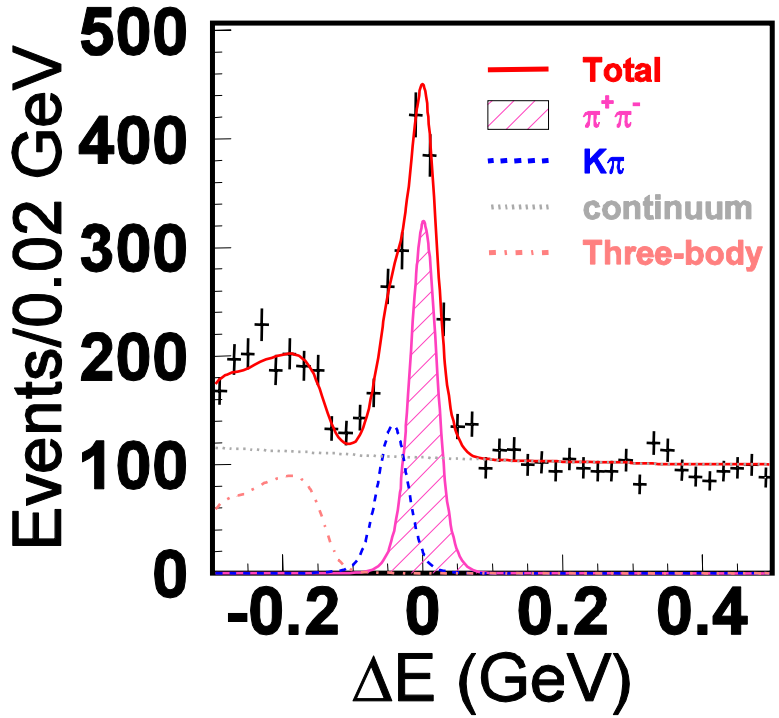
$B^0 \to \pi^+ \pi^-$: History of measurements





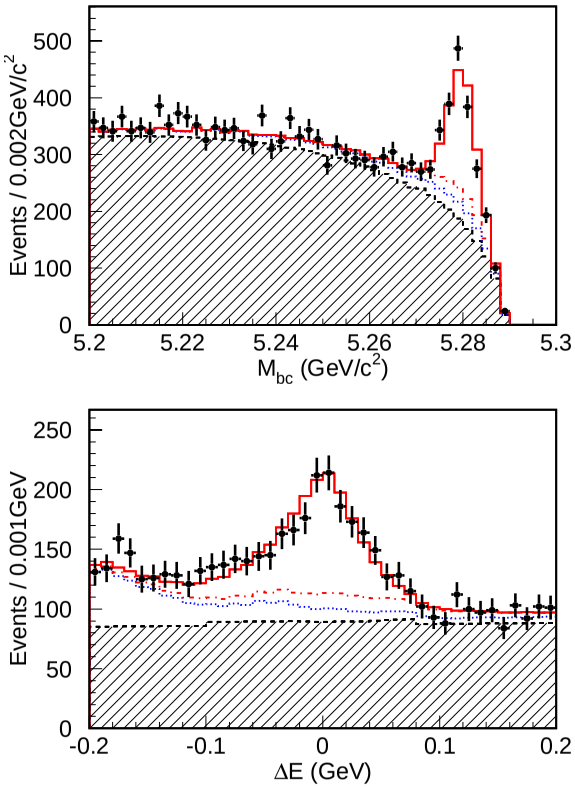
$B^0 \to \pi^+ \pi^-$: Signal yield





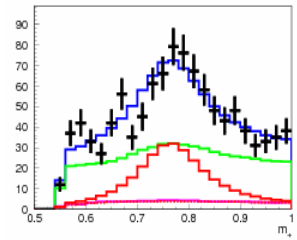
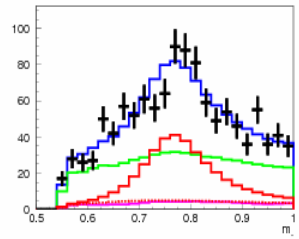
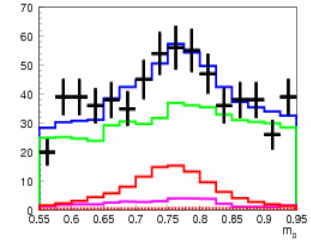
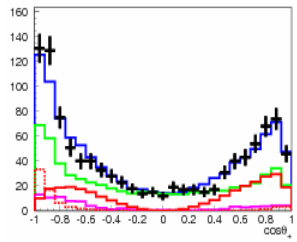
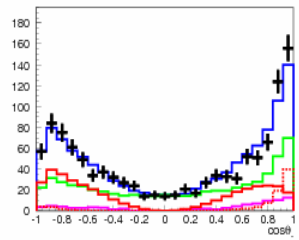
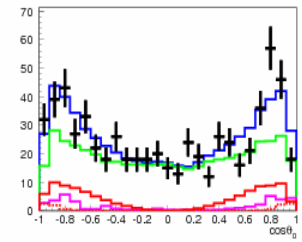
1464 $\pm$ 65 signal events

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



449 Million BB pairs

hep-ex/0609003

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

Mbc - ΔE and Dalitz simultaneous fit

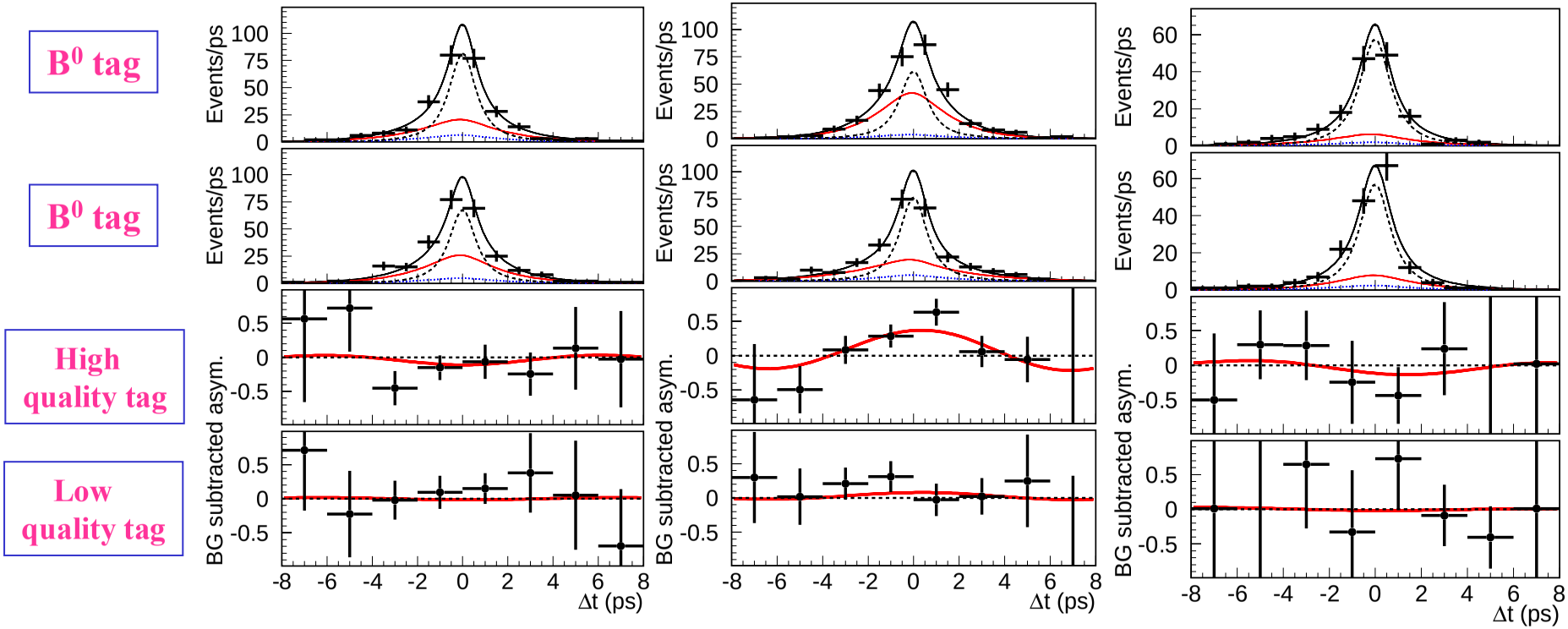
987 ± 42 signal events

$B^0 \to \pi^+ \pi^- \pi^0$: CP fit results

hep-ex/0609003

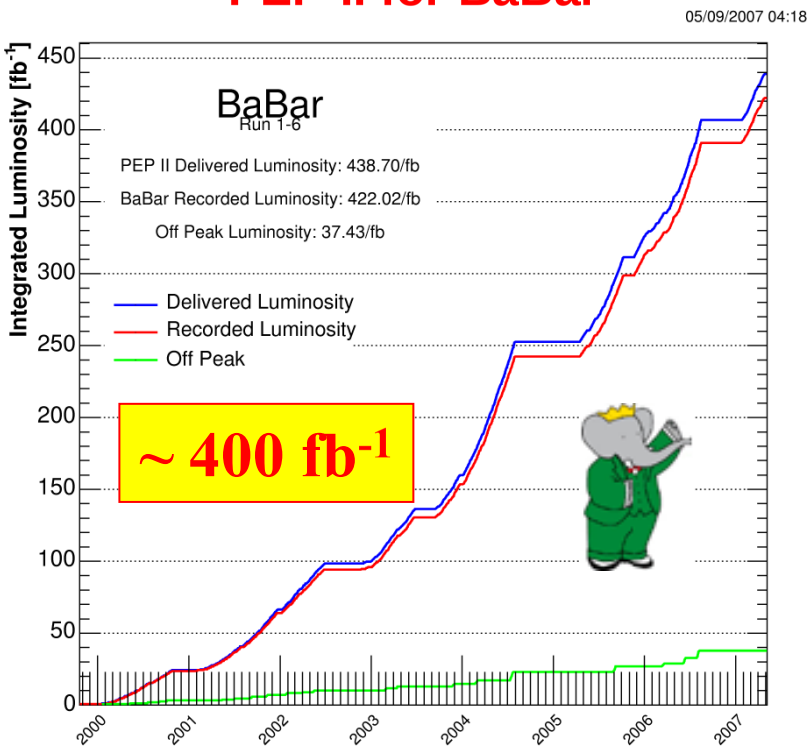
Preliminary

449 Million BB pairs

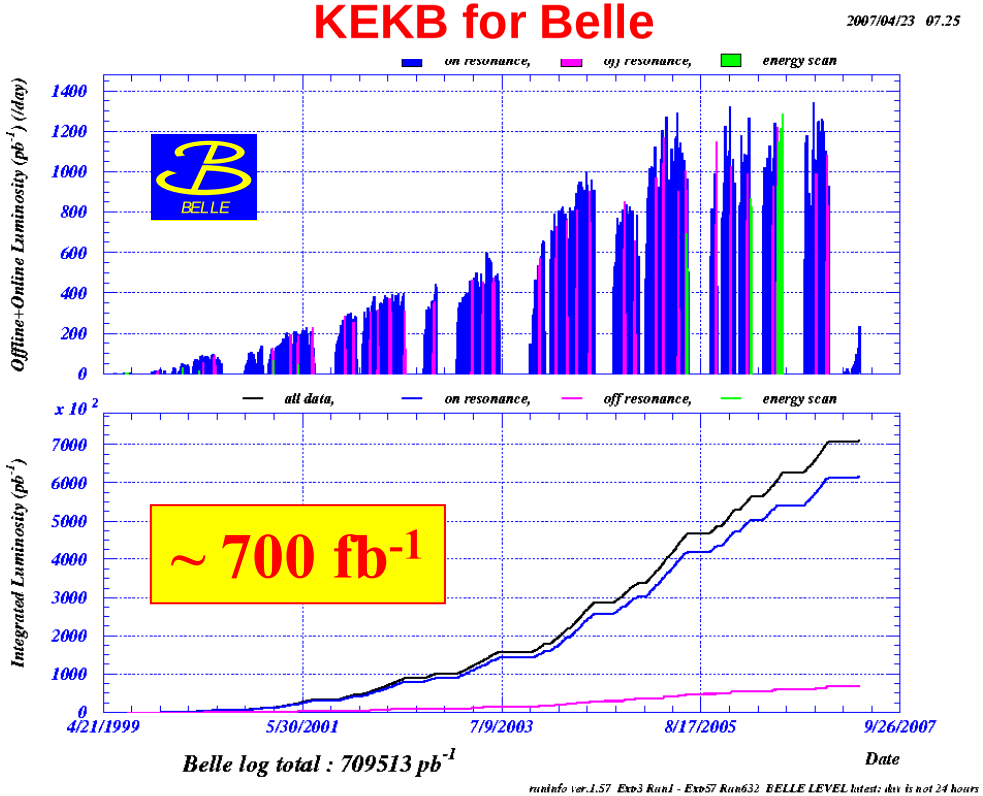


B-factories: PEP-II and KEKB

PEP-II for BaBar



KEKB for Belle



Belle and BaBar accumulated > 1 ab^{-1}
(more than one billion BB pairs !)