Measurement of φ_2/α using $B \to \rho\rho$ Decays at Belle and BaBar

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CKM 06, Nagoya 2006

Introduction (CP violation in $B^0 \to \rho^+ \rho^-$ decays)
Measurements in

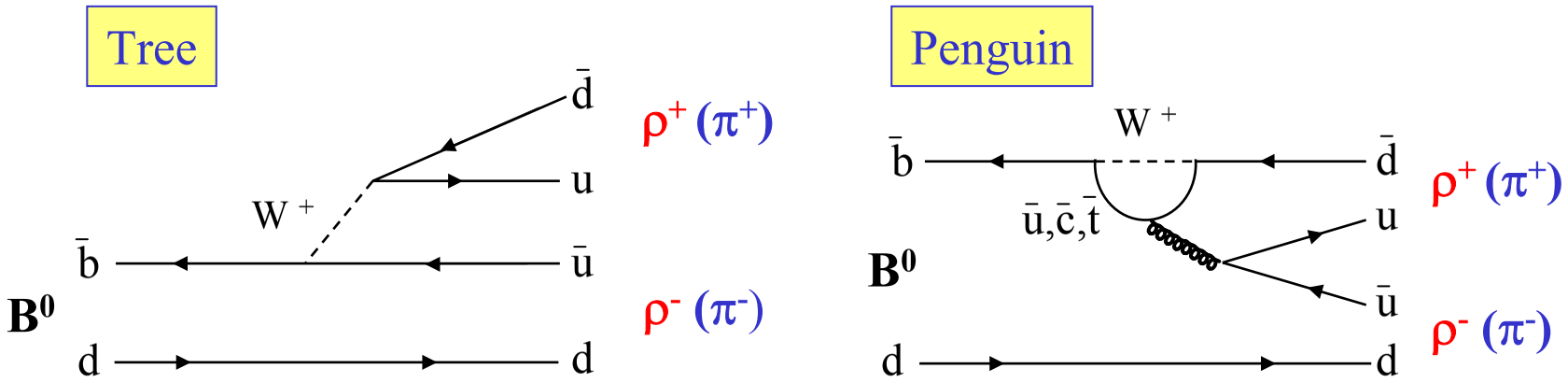
$B^0 \to \rho^+ \rho^-$

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

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

ϕ_2 constraint from an Isospin analysis

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



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

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**

$S_{\rho\rho} = \sqrt{1 - A_{\rho\rho}^2}\sin(2\phi_{eff})$ ➡ **determine ϕ_2 using isospin analysis**

ϕ_2/α measurement

Three main decays used for the extraction of ϕ_2 (α)

$B^0 \to \pi^+ \pi^-$ relatively clean signal, large penguin contribution

$B^0 \to \rho^\pm \pi^\mp$ not a CP eigenstate, time-dependent Dalitz analysis

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

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

- small penguin contribution due to relatively small

$$Br(B^0 \to \rho^0\rho^0) = (1.16^{+0.37}_{-0.36} \pm 0.27) \times 10^{-6}$$ *[Babar, hep-ex/0607097]*

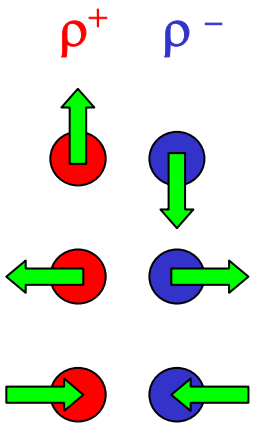
- relatively large measured branching fraction for $b \to u$ process

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

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

Complications:

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



longitudinal polarization

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

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

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

Fortunately, 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***

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

CP analysis in B → $\rho^+\rho^-$ 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]
- **Contribution from EW penguin**

Constraint on ϕ_2/α

- Extract ϕ_2 using an Isospin analysis (similar to $\pi^+\pi^-$ analysis)
  - 'model independent' approach

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

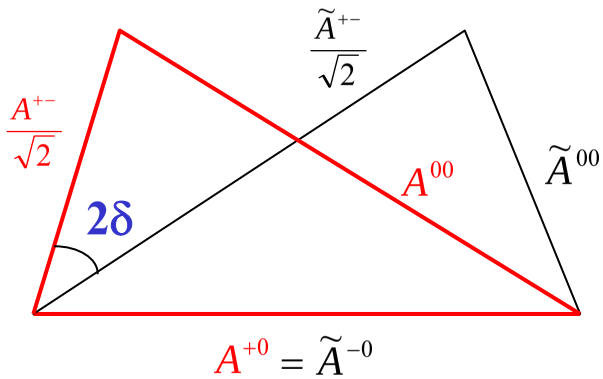
[M.Beneke, M.Gronau, J.Rohrer, M.Spranger hep-ph/0604005]

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

Isospin analysis in B → ρρ (ππ)

- **Measure $A_{\rho\rho}$ and $S_{\rho\rho}$:** $S_{\pi\pi} = \sqrt{1-A_{\pi\pi}}\sin(2\phi_2^{eff})$ $\quad \phi_2^{eff} = \phi_2 + \delta$
- **Use isospin relations** ***[M.Gronau and D.London, Phys.Rev.Letter. 65, 1990]***

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



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

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

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

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

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

$\widetilde{A}^{-0} = A(B^- \to \rho^-\rho^0)$

6 unknowns, and 5 observables:

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

- **Calculate confidence level applying R-fit method (see next talks)**

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

Common features of $B \to \rho\rho$ measurements

- small branching fractions: $10^{-6} - 10^{-5}$
- Large background S/B ~ O(1%)
- All types of background contribute: continuum, $b \to c$ and $b \to u$ continuum is a dominant background. Use Fisher or neural nets (BaBar) to discriminate
- Multiple *B* candidates in the same event. Best candidates selection based on best π^0 mass and best χ^2 of the vertex fit. Events with misreconstructed pions, SCF. Use separate PDFs.
- Several variables used to separate signal from backgrounds: m_{bc}, ΔE , $m_{\pi\pi}$, cos θ, event topology, flavor, Δt

Analysis strategy

BaBar

- **Determine signal yield, polarization, CP parameters simultaneously using a multidimensional fit.**
- **Loose cuts on kinematical variables → more signal events in the fit.**
- **Use PDFs for 'all' variables to discriminate against background**
  - **PDF shapes, correlations among variables (sometimes fits exhibit small bias)**

Belle

- **Relatively stringent cuts on kinematical variables.**
- **Separate fits for event yields, polarization, and CP parameters.**
  - **larger statistical errors**

M_{bc} - ΔE - LR fit results

NEW Belle results *(preliminary)*

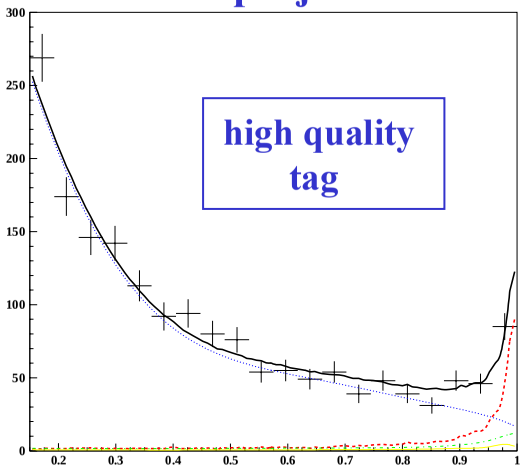
535 Million BB pairs

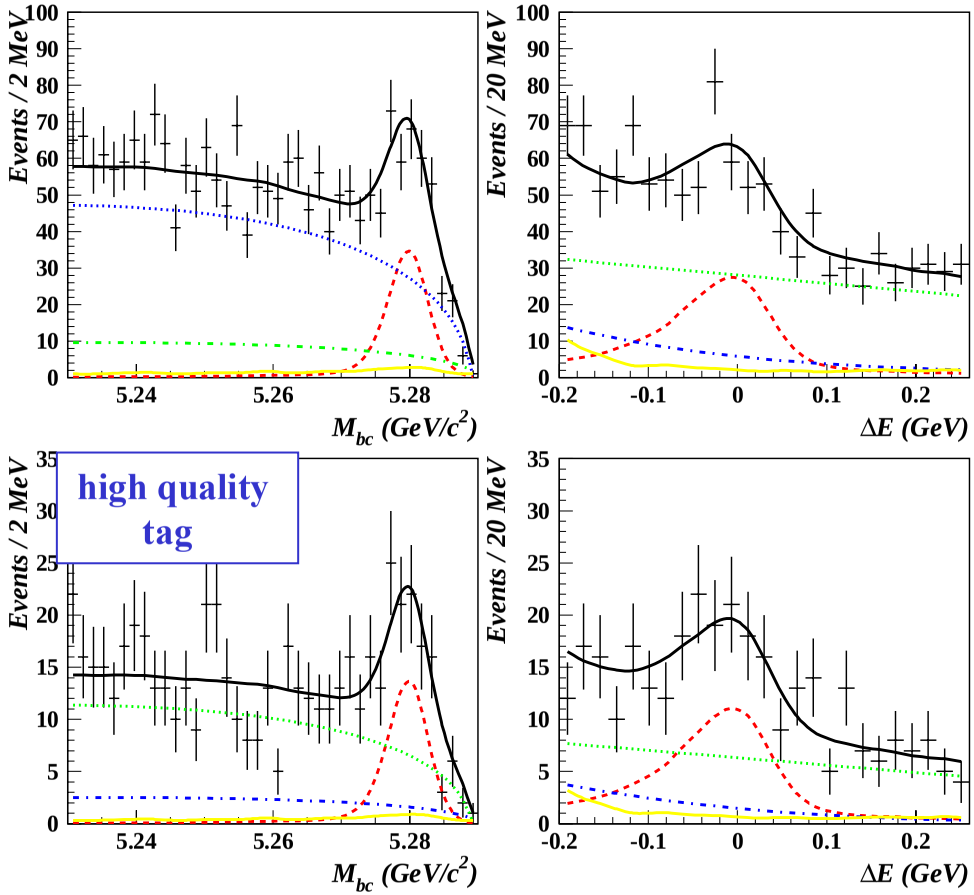
Fit results:

N_{evt} in the fit = 176843

$N_{\rho\rho+\rho\pi\pi} = 567$

***LR* fit projection**





CP fit results

535 Million BB pairs

Signal true PDF

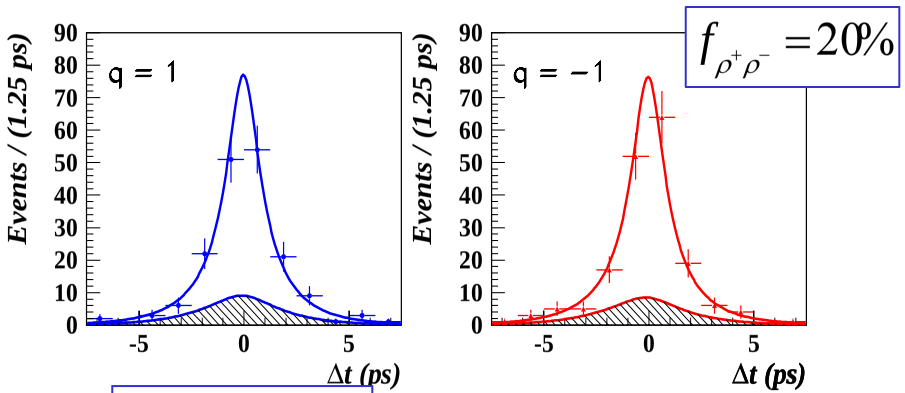
$$P^{long}_{q=\pm1} = \frac{e^{-|\Delta t|/\tau_B}}{4\tau}\{1 + q(A_{\rho\rho}\cos(\Delta m \Delta t) + S_{\rho\rho}\sin(\Delta m \Delta t)\}$$

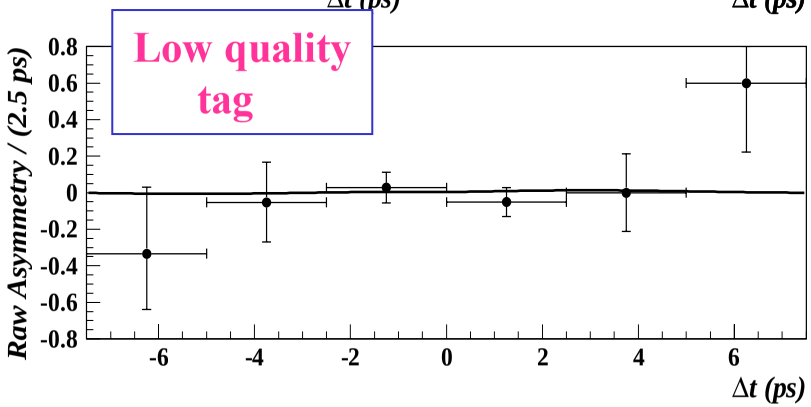
fit for two parameters $A_{\rho\rho}$, $S_{\rho\rho}$

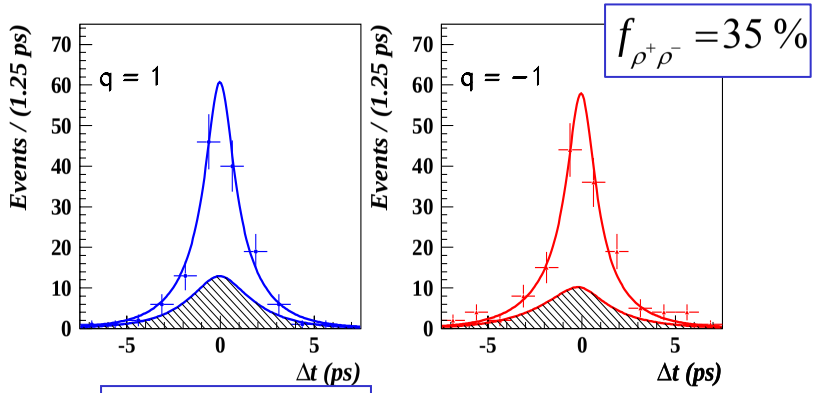
Preliminary

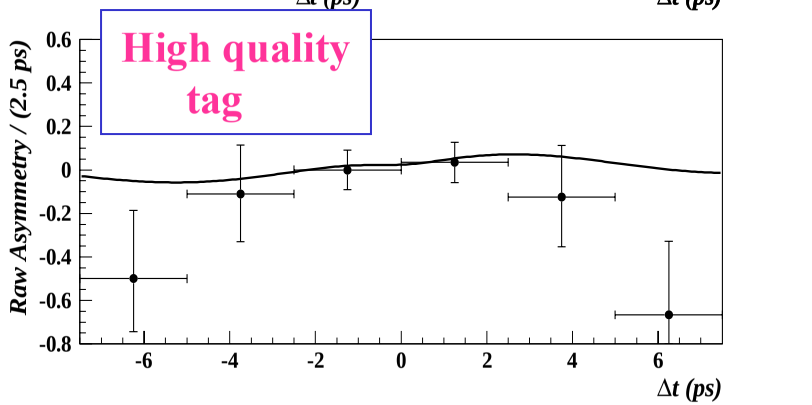
$$A_{\rho\rho} = 0.16 \pm 0.21(stat) \pm 0.07(syst)$$

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



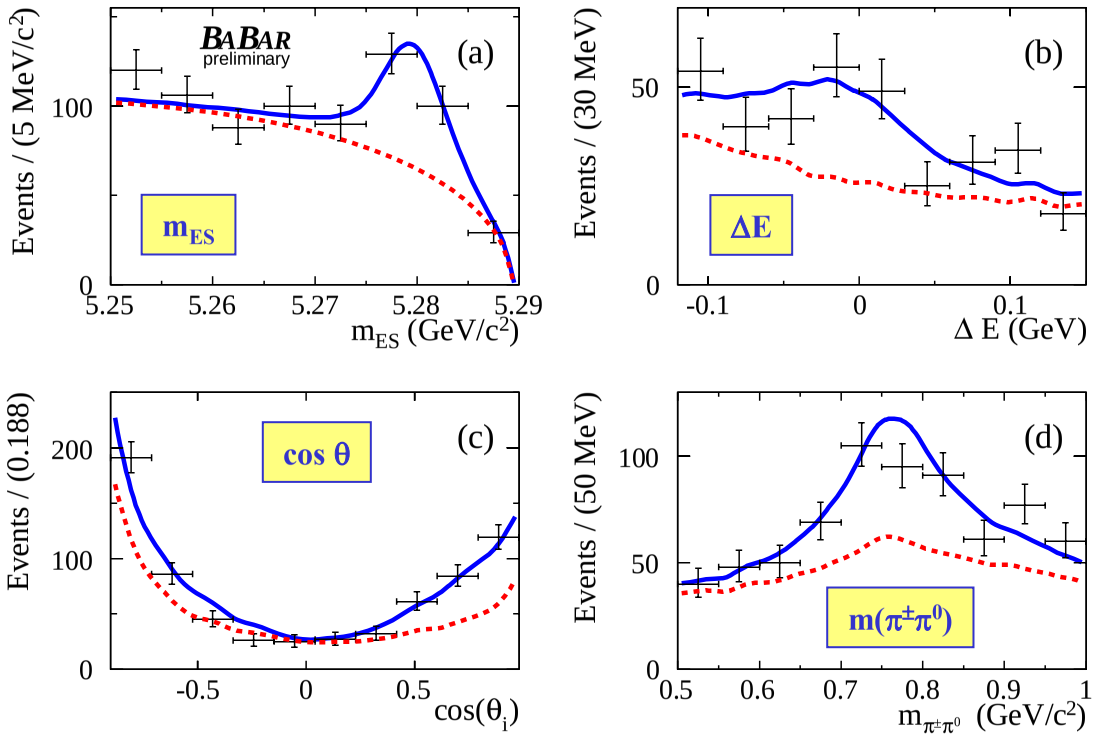






$B^0 \to \rho^+\rho^-$ fit results

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

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

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)*

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

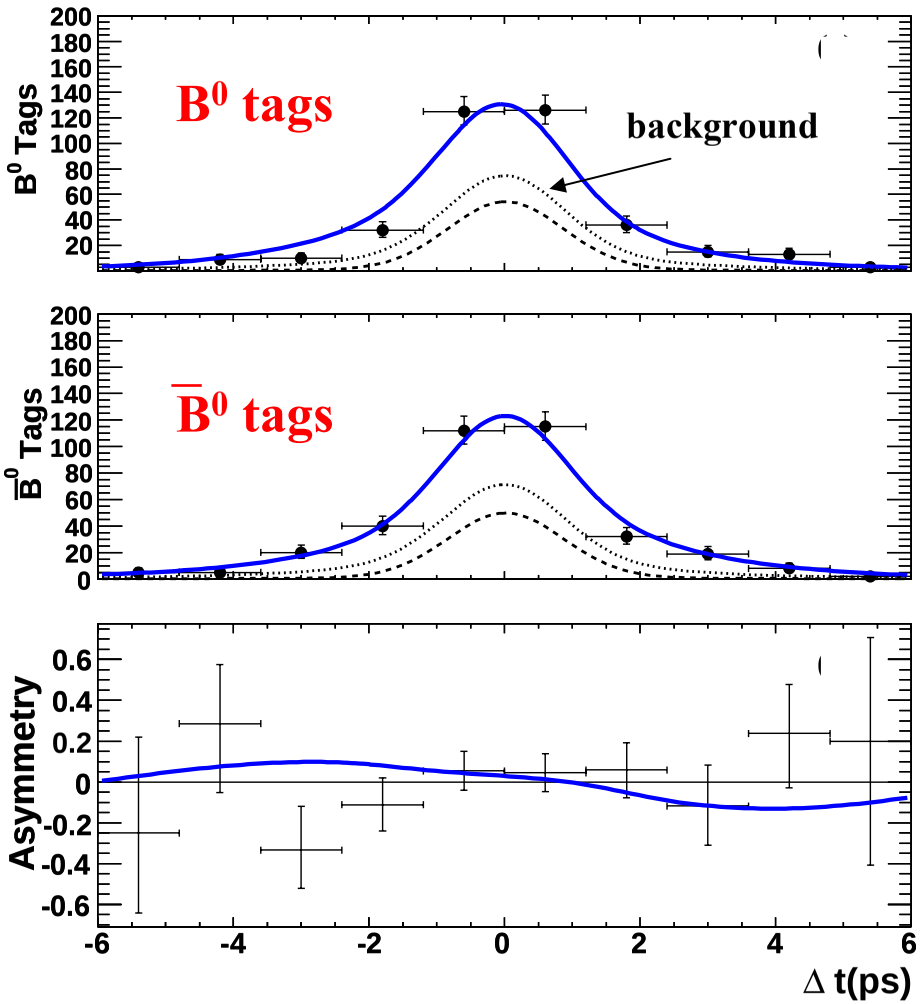
$$\mathbf{f_L = 0.977 \pm 0.024^{+0.015}_{-0.013}}$$

Previous Belle: *(PRL 96,171801, 2006)*

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

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

CP Asymmetries



hep-ex/0607092

Signal true PDF

$$P^{long}_{q=\pm1} = \frac{e^{-|\Delta t|/\tau_B}}{4\tau}\{1 + q(S_{\rho\rho}\sin(\Delta m\Delta t) - C_{\rho\rho}\cos(\Delta m\Delta t)\}$$

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

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

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

NEW measurements last summer, ***hep-ex/0607092***

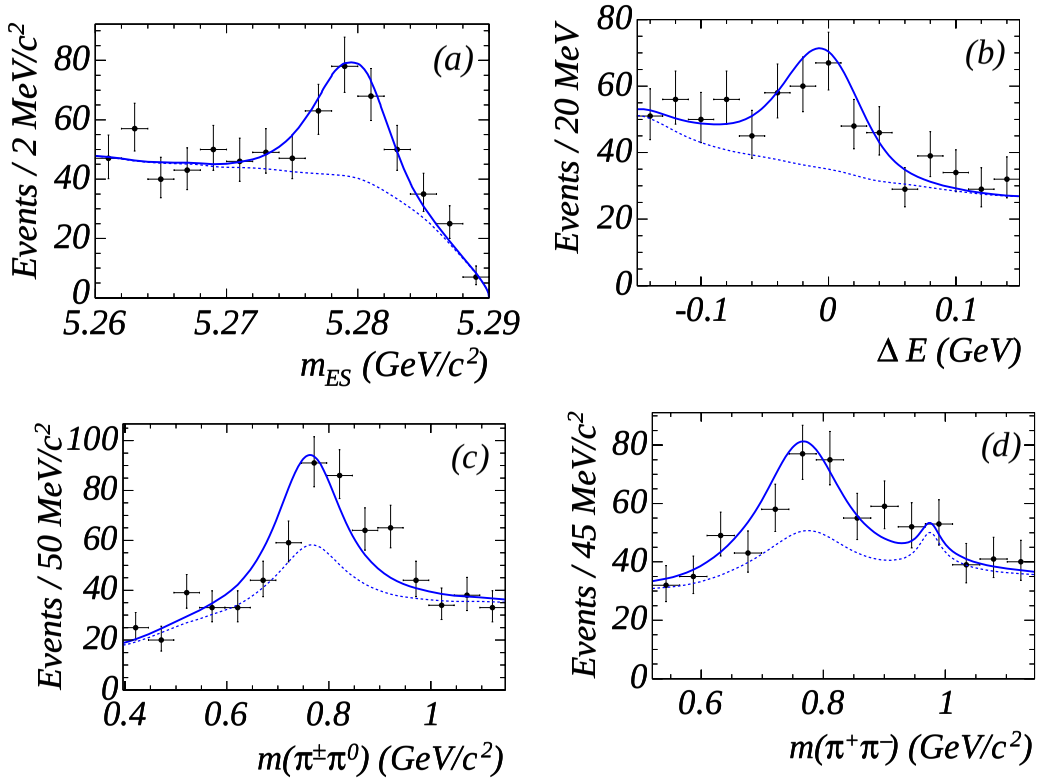
232 Million BB pairs

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

$N_{total} = 74293$

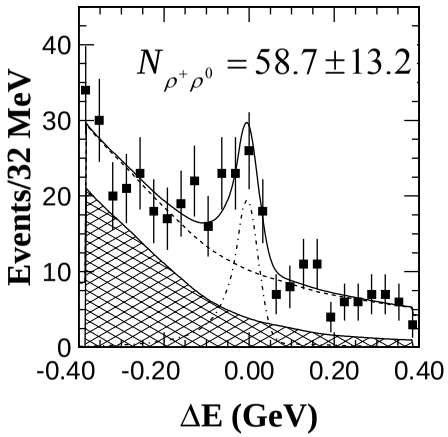
$N_{\rho^+\rho^0} = 390 \pm 49$



Measurements in $B^{\pm} \to \rho^{\pm} \rho^{0}$ decays (cont'd)

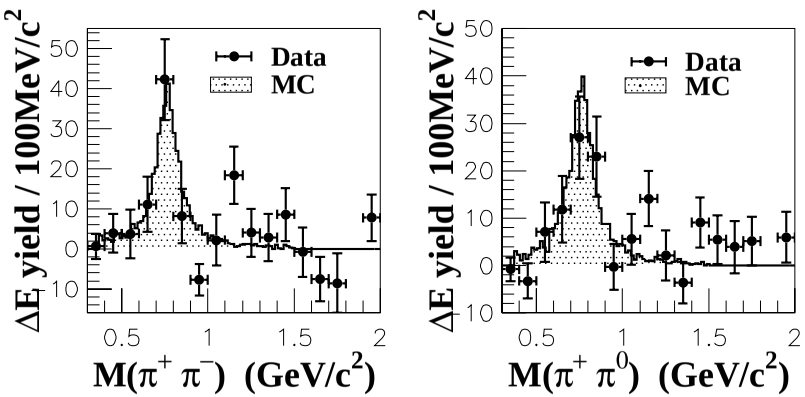
Belle results (old), *PRL 91, 221801 (2003)*

85 Million BB pairs

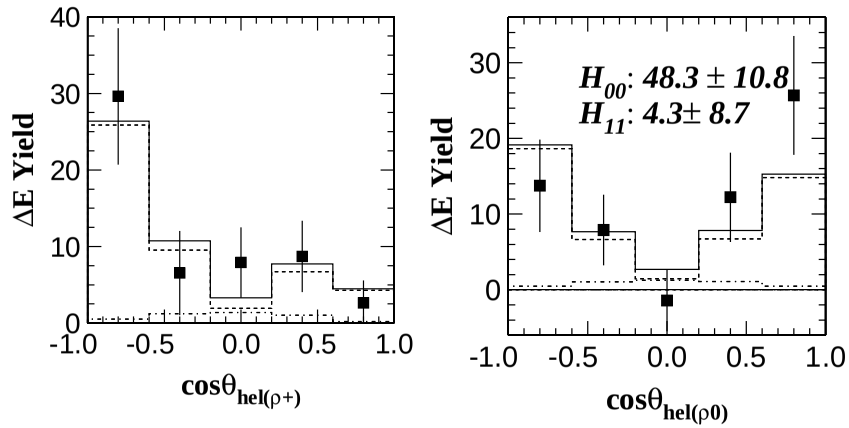


- **Determine signal yield from a fit to ΔE distribution**
- **Obtain polarization from a simultaneous fit to background subtracted cos θ_+ cos θ_0 distributions**
- **Determine charge asymmetry from separate fits to ΔE distributions of $B^+ \to \rho^+\rho^0$ and $B^- \to \rho^- \rho^0$ candidates**

Background subtracted $m(\pi^+\pi^-)$ and $m(\pi^-\pi^0)$



Background subtracted cos θ_{+-} cos θ_0



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

348 Million BB pairs

hep-ex/0607097

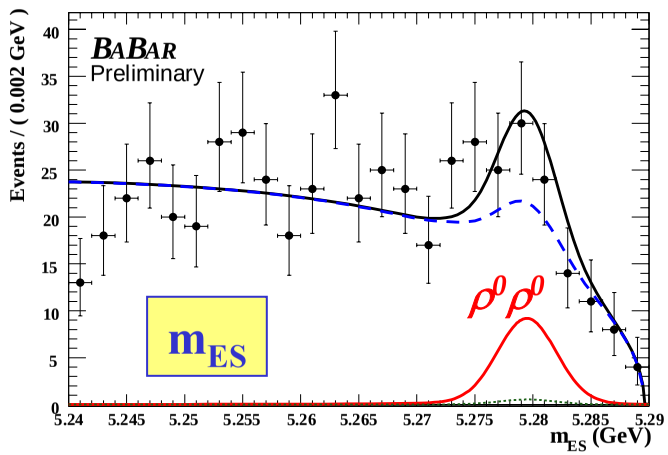
Use an unbinned extended ML fit to extract signal yield and polarization

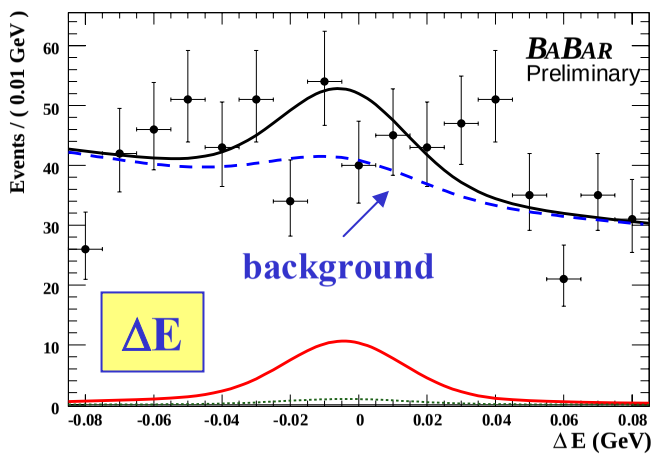
- **8 dimensional fit: m_{ES}, ΔE, $m(\pi\pi)_{1,2}$, $\cos\theta_{1,2}$, event topology, flavor tags**
- **total number of events in the fit 65180, $N(\rho^0\rho^0) = 98^{+32}_{-31}$**

Main components in the fit

- **signal, $\varepsilon = 24.2\%$**
- **continuum background (use neural network and tagging information)**
  - ⇨ **float parameter values**
- **$b \to c$ background**
- **$b \to u$ background**
  - **similar topology: $B^0 \to a_1\pi$ (dominant peaking background), $\rho^0 f_0$, $f_0 f_0$**
  - **other modes: $\rho\, ^0K^{*0}$, $\rho\, ^+\rho^0$, $\rho\pi$, $\rho^+\rho^-$, remaining**
  - ⇨ **float normalization**

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)*

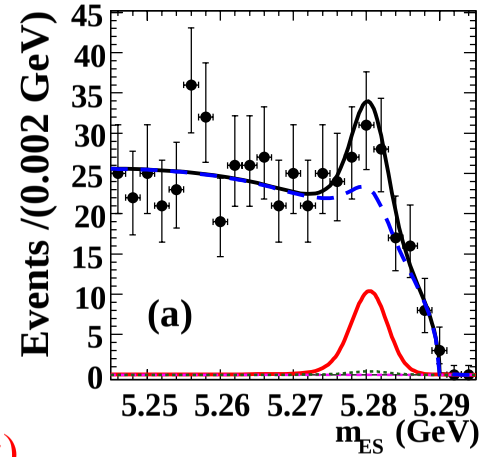
Br < 1.1 10^{-6} at 90% CL

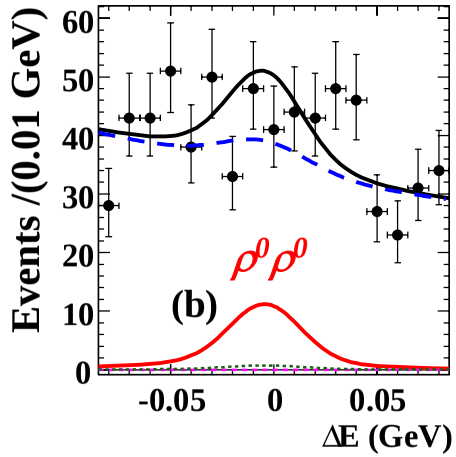
$B \to \rho^0\rho^0$ - last minute results!

384 Million BB pairs

hep-ex/0612021 (12/11/2006) submitted to PRL

m_{ES}

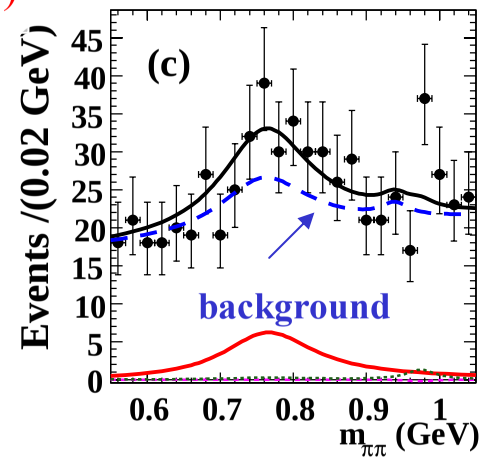


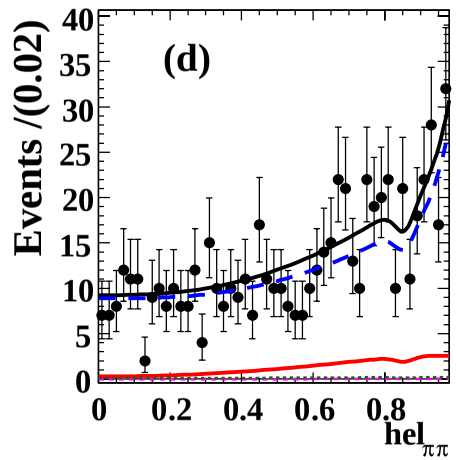


ΔE

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

$m_{\pi\pi}$





cos θ

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

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

Constraint on ϕ_2/α

Branching fractions and polarization fractions used in the calculations
(HFAG, Aug. 2006)

OLD

$(26 \pm 6)\ 10^{-6}$	$B(\rho^+\rho^0)$	$= (18.2 \pm 3.0) \cdot 10^{-6}$
	$f_L(\rho^+\rho^0)$	$= 0.912^{+0.044}_{-0.045}$
$(25 \pm 4)\ 10^{-6}$	$B(\rho^+\rho^-)$	$= (23.1^{+3.2}_{-3.3}) \cdot 10^{-6}$
	$f_L(\rho^+\rho^-)$	$= 0.968 \pm 0.023$
$>1.1\ 10^{-6}$	$B(\rho^0\rho^0)$	$= (1.16 \pm 0.46) \cdot 10^{-6}$
	$f_L(\rho^0\rho^0)$	$= 0.86^{+0.12}_{-0.14}$
	$A(\rho^0\rho^0)$	$=$ N.A.

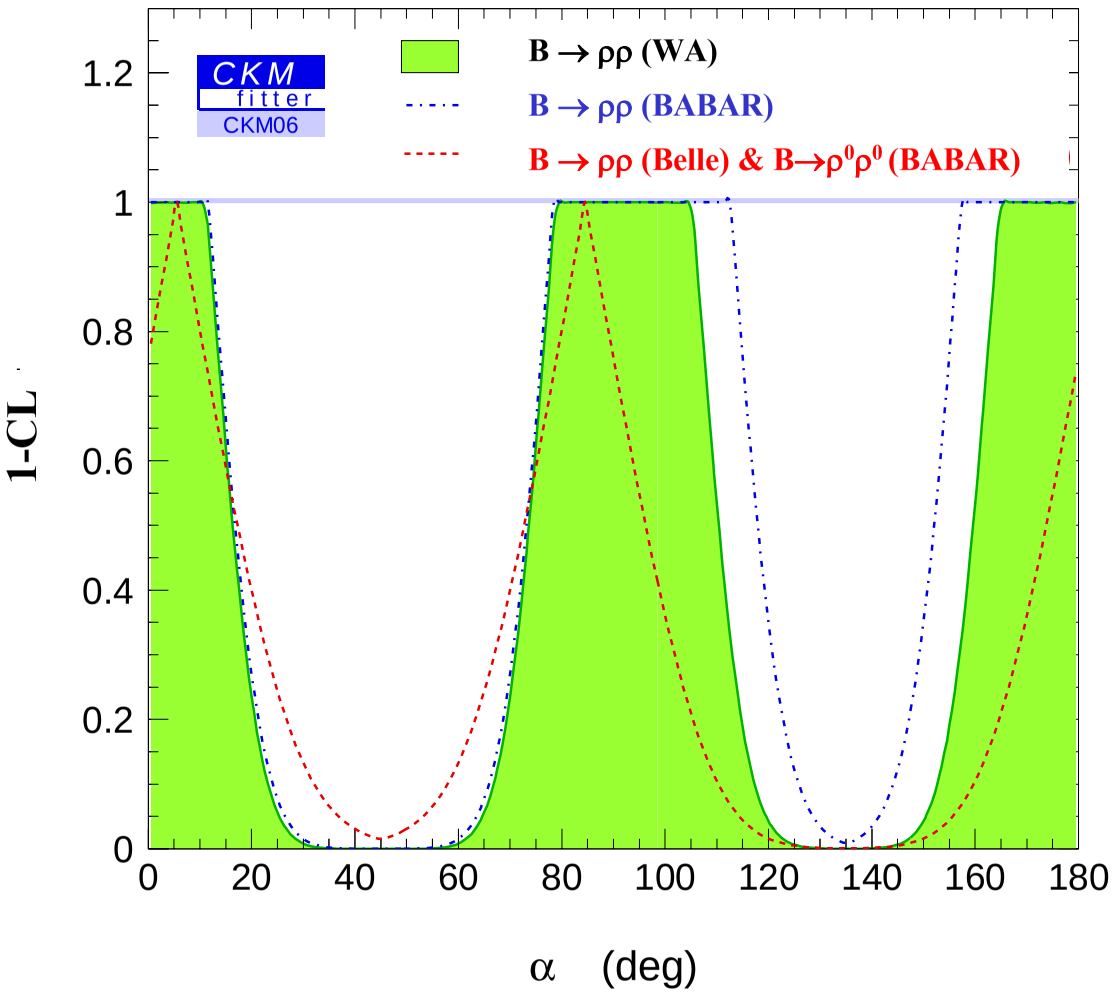
The isospin triangle is 'closed' with new measurements of $Br(\rho^+\rho^-)$, $Br(\rho^+\rho^0)$, $Br(\rho^0\rho^0)$,

Caveats

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

(all believed to be small)

Constraint on ϕ_2/α (cont'd)

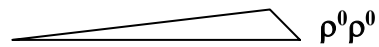


Generally, Isospin analysis allows to extract ϕ_2/α with 8-fold ambiguity

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

- leads to plateau 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

$71 < \phi_2/\alpha < 113^\circ$ $(92 \pm 21)^\circ$

at 68% CL

Summary

Several new results during this year:

- Measurement of CP asymmetries in $B \to \rho^+\rho^-$ at Belle
- Measurement of branching fractions, polarization fractions, and CP asymmetries in $B \to \rho^+\rho^-$ and $B \to \rho^+\rho^0$ decays at BaBar
- First evidence for $B \to \rho^0\rho^0$ decays at BaBar

From an Isospin analysis φ_2/α is constrained as

$$71 < \phi_2 / \alpha < 113^\circ$$ at 68% CL

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

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

Backup slides

Summary of systematic errors

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

	BB pairs 10^6	Value	BB pairs 10^6	Value
Br	347	4.1	274	+2.3-2.6
f_L	347	+0.015-0.013	274	0.03
A(C)	347	0.06	535	0.07
S	347	+0.05-0.07	535	+0.07- 0.06

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

	BB pairs 10^6	Value	BB pairs 10^6	Value
Br	232	0.23	85	+3.8-6.7
f_L	232	+0.023-0.027	85	0.021
A_{CP}	232	0.10	85	0.03

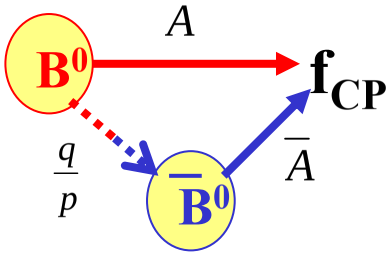
$B^0 \to \rho^0\rho^0$

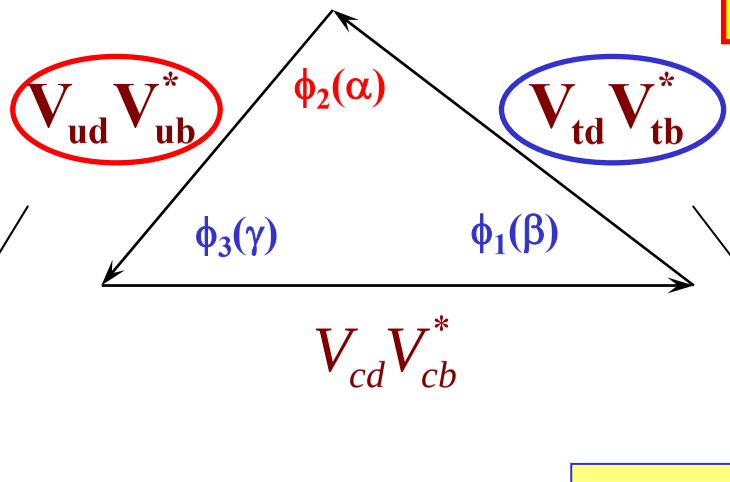
	BB pairs 10^6	Value
Br	348	0.27

Mixing induced CP violation (sin $2\phi_2/\alpha$)

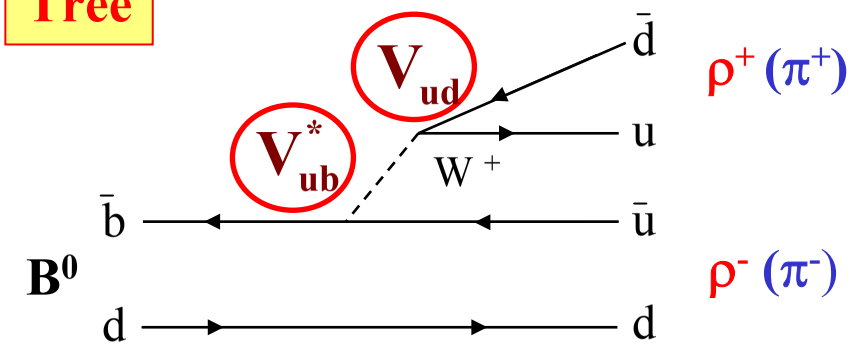
$$\phi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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





Tree



Mixing