New measurement of CP-violating parameters in $B \to \rho^+\rho^-$ Decays at Belle

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JPS/DPF, Hawaii 2006

New Belle results on $B^0 \to \rho^+ \rho^-$ (492 fb^{-1})

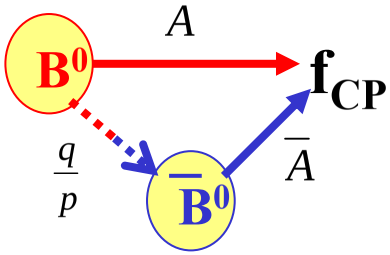
- **Time depemdent CP asymmetry**

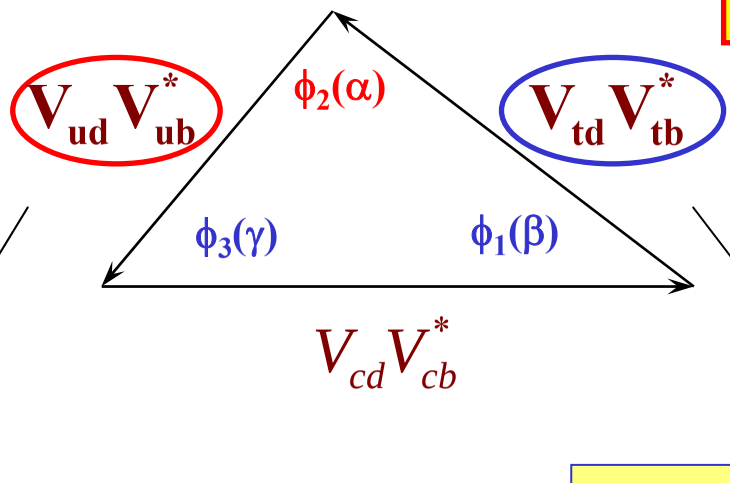
ϕ_2 constraint from an Isospin analysis

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

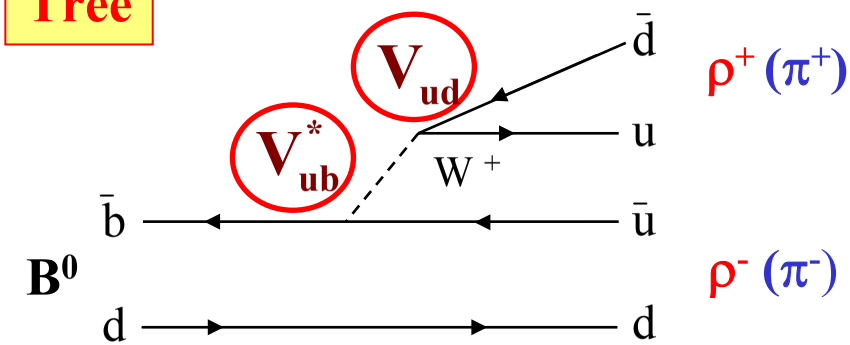
$$\phi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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

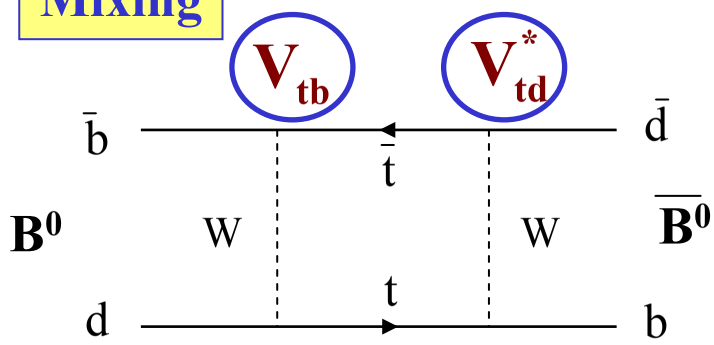




Tree

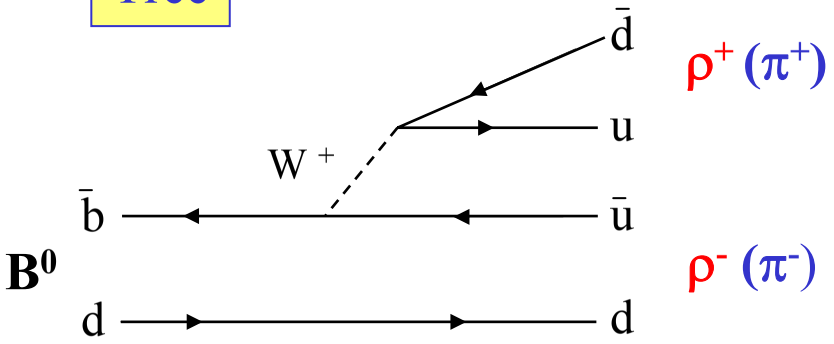


Mixing

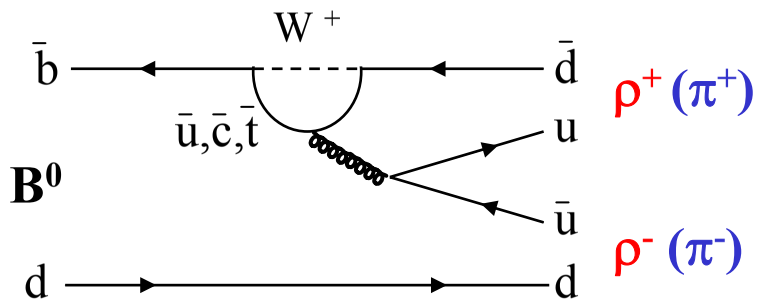


CP Violation in $B^0 \to \rho^+ \rho^-$ decays

Tree



Penguin



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

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 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

$B^0 \to \rho^+ \rho^-$ ⟸ New Belle results

- Extract ϕ_2 using an isospin analysis (similar to $\pi^+ \pi^-$ analysis)
- The penguin contribution can also be bound using flavor SU(3) relations

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

Advantages:

- 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]***

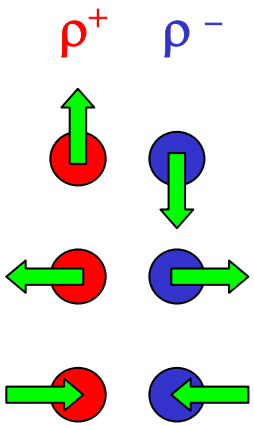
- relatively large measured branching fraction for $b \to u$ process

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

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

Complications:

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



longitudinal polarization

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

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

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

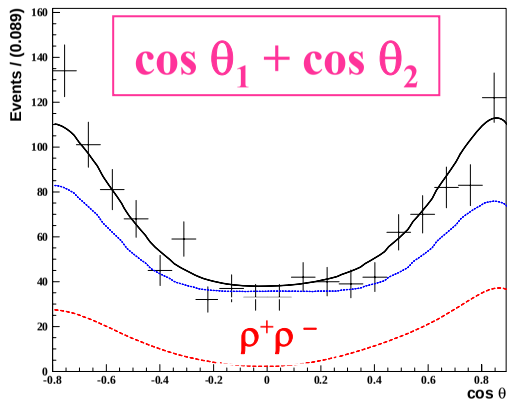
Fortunately, longitudinal polarization dominates

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

Belle



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

Complications (cont'd):

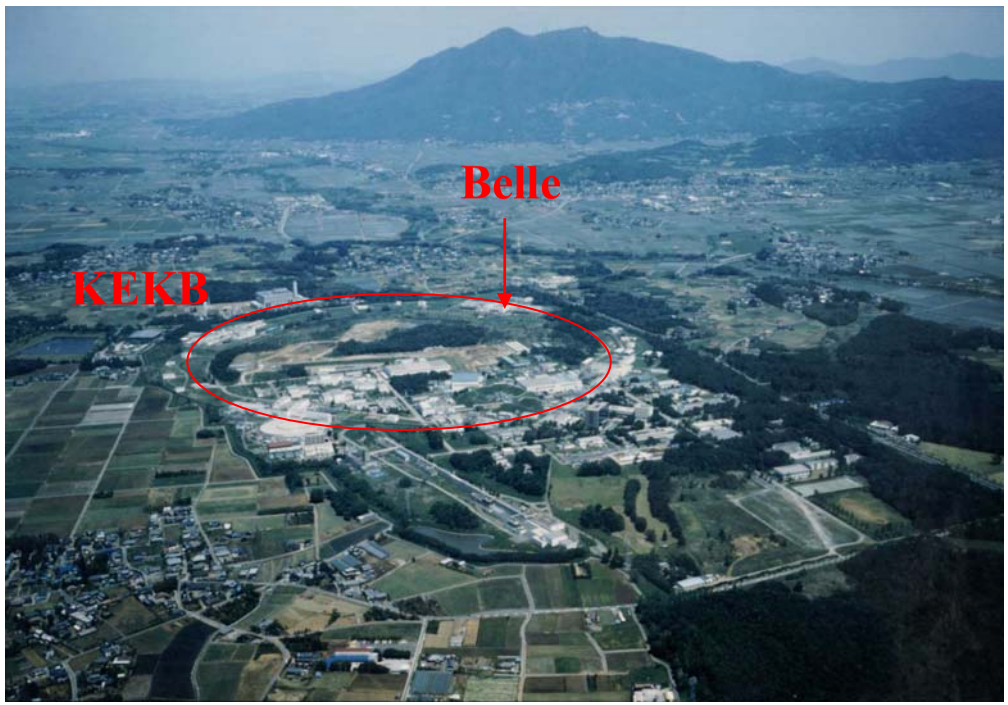
- **'Dirty' final state $\rho^+\rho^- \rightarrow \pi^+\pi^0\ \pi^-\pi^0$; $\Gamma(\rho) = 150$ MeV**
  large backgrounds
- **I = 1 contribution due to finite width of ρ**
  [A.F.Falk, Z.Ligeti, Y. Nir, H.Quinn PRD69, 011502, 2004]
- **Contribution from EW penguin**

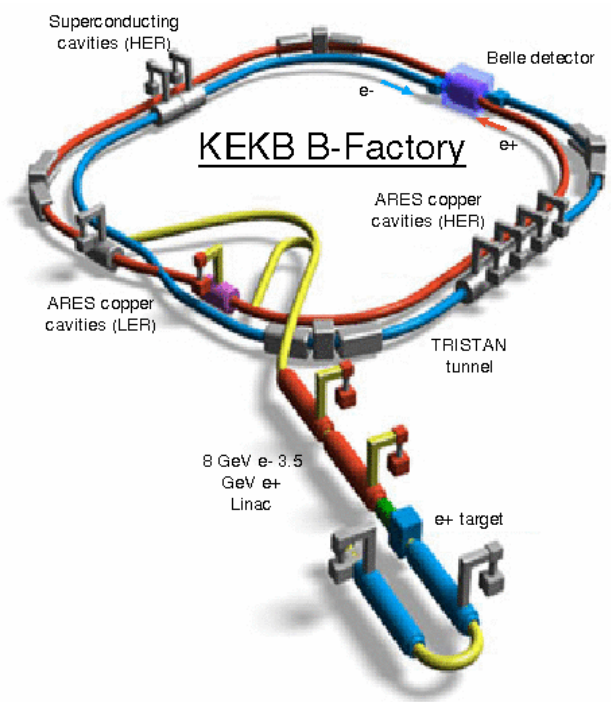
KEKB B-Factory

KEKB

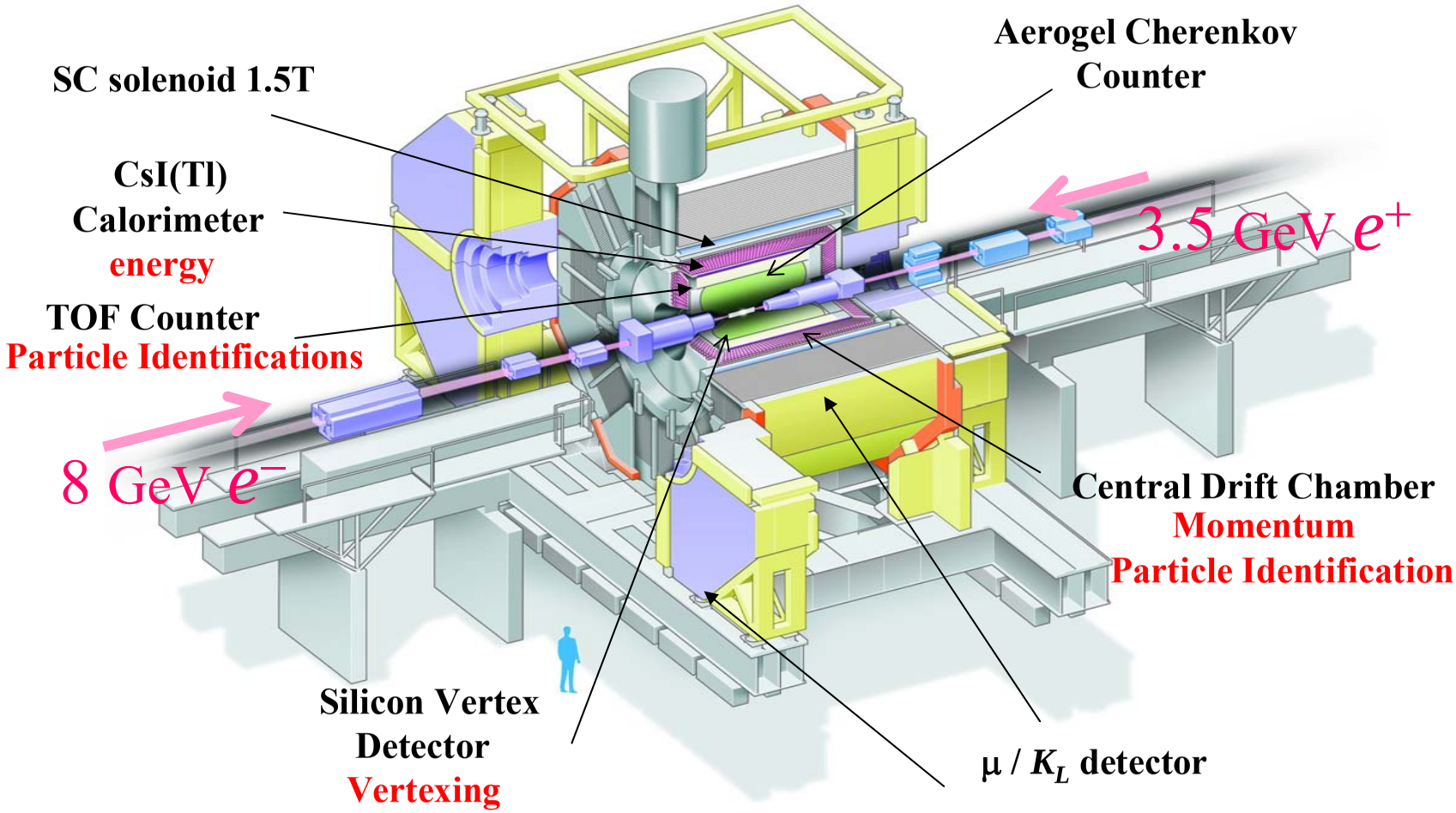
- Asymmetric Energy e^+e^- B-factory
- 8 GeV e^- + 3.5 GeV e^+
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ $\sqrt{s} = 10.58$ GeV

Integrated Luminosity ~650 fb^{-1}
L_{peak} ~1.6 10^{34} (> 1M $B\bar{B}$ pairs/day)

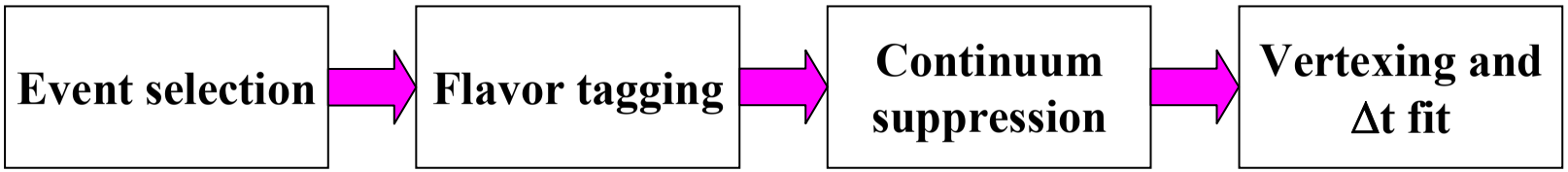




Belle Detector



Analysis overview



1) Event selection

- $\pi^+ \pi^0$ $\pi^- \pi^0$ combinations
- eID < 0.9
- KID < 0.4
- $0.118 < m(\gamma\gamma) < 0.150$ GeV/c²
- $p(\pi^0) > 0.35$ GeV/c
- $0.62 < m(\pi^\pm \pi^0) < 0.92$ GeV/c²
- $-0.8 < \cos(\theta_{hel}) < 0.98$

Beam constrained mass

$$M_{bc} \equiv \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

Energy difference

$$\Delta E = E^*_B - E^*_{beam}$$

2) Flavor tagging

Lepton ($b \to l^- X$)
$K^\pm$ ($b \to c \to s$)
Λ ($b \to c \to s$)

low-energy $\pi^\pm$ (D^*)
high-energy tracks
($D^- \pi^+$ etc)

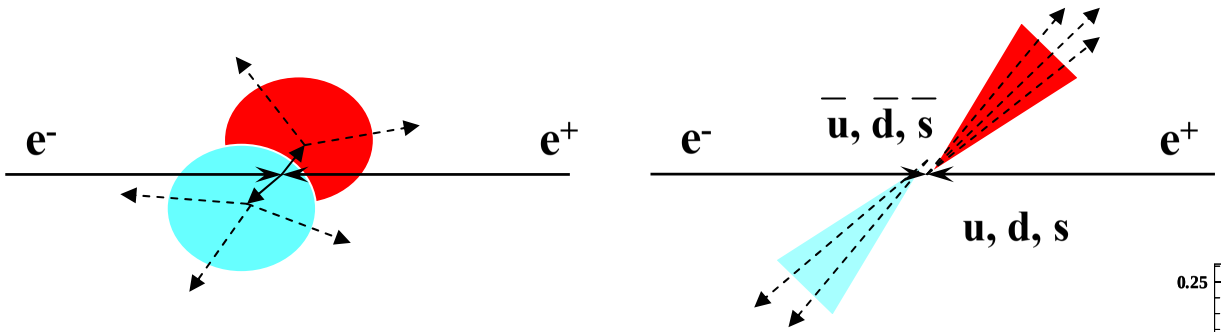
Output:

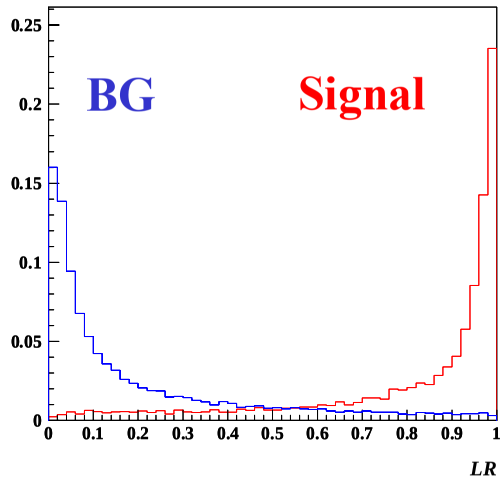
q = +1/-1 (tag side B^0/ $\bar{B}^0$)
0 < r < 1 'quality' of tag

Analysis overview (cont'd)

3) Continuum suppression

Use kinematics and topology to separate spherical B decays from jet-like qq events





- **Fisher dicsriminant based on FoxWolfram moments**
- **B flight direction ($\cos\theta_B$)**

Form the likelihood ratio

$$LR \equiv \frac{L_{B\bar{B}}}{(L_{B\bar{B}} + L_{q\bar{q}})}$$

Use LR PDF in the fit functions

4) Vertexing and Δt fit

- **Reconstruct CP-side and tag-side vertices**
- **Fit Δt(Δz) distributions for *CP*-violating parameters A and S**

Analysis overview (cont'd)

Analysis consists of two main steps:

1) Determine event yields using a 3-D M_{bc} - ΔE – LR extended unbinned ML fit

- B^0 candidate selection: $5.23 < M_{bc} < 5.29$, $-0.2 < \Delta E < 0.26$
- Components in the fit

  - signal, SCF, $\rho\pi\pi$ non-resonant Fix the shapes of PDFs from Monte Carlo simulation. Correct M_{bc}-ΔE shapes using $B \rightarrow D^0 \rho^-$ control sample

  - $b \rightarrow c$ background PDFs are taken from MC simulation

  - continuum background LR PDFs are taken from off-resonance data, parameters for M_{bc} and ΔE PDFs are floated in the fit. Account for ΔE – LR correlations

  - $b \rightarrow u$ ($a_1\rho$, $a_1\pi$, $\rho\pi$, $K^*\rho$, etc.)

- Data sample is divided into 6 bins with different tag qualities *qr* (the shapes of most PDFs depend on *qr*)

M_{bc} - ΔE - LR fit results

535 Million BB pairs

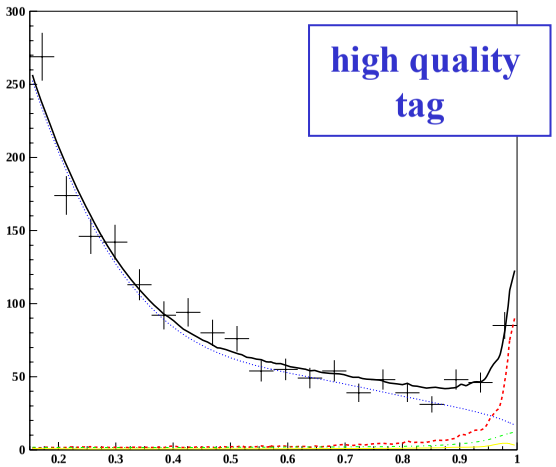
Fit results:

N_{evt} in the fit = 176843

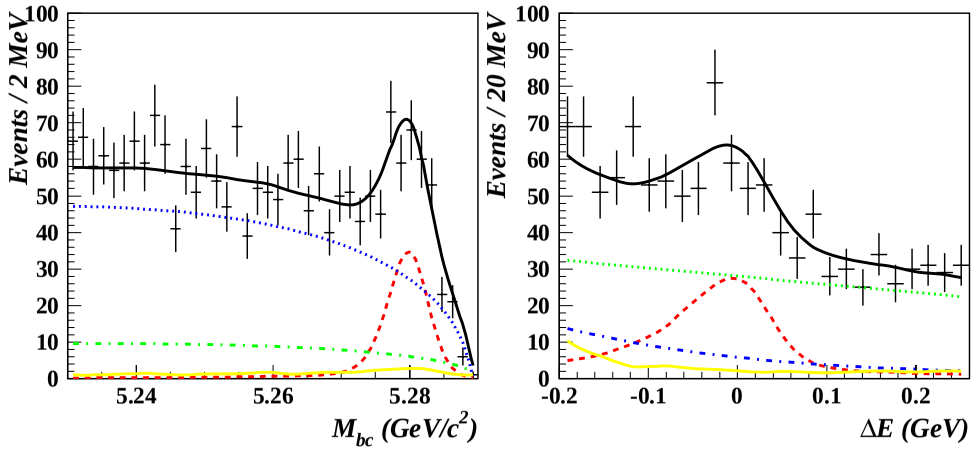
$N_{\rho\rho+\rho\pi\pi} = 567$

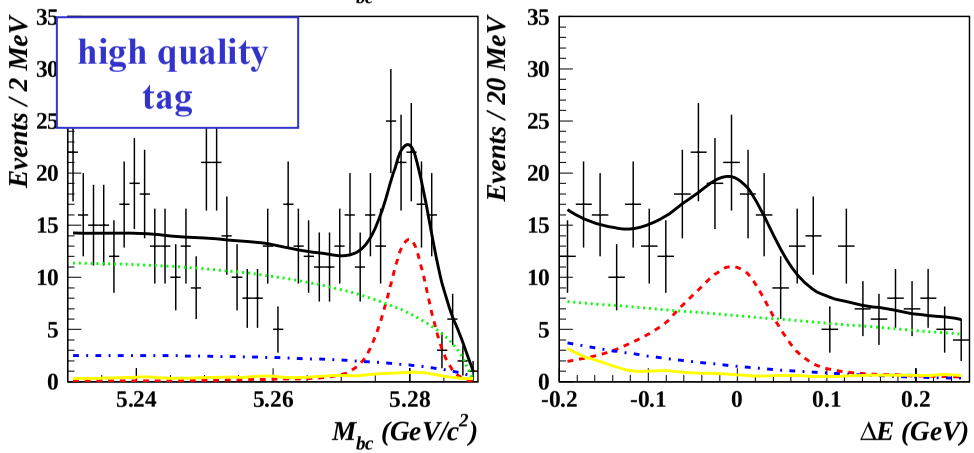
Fit projections:

$5.273 < M_{bc}$; $-0.1 < \Delta E < 0.06$



LR > (0.96, 0.94, 0.92, 0.9, 0.82, 0.58) in six tag bins





CP fit results

535 Million BB pairs

Signal true PDF

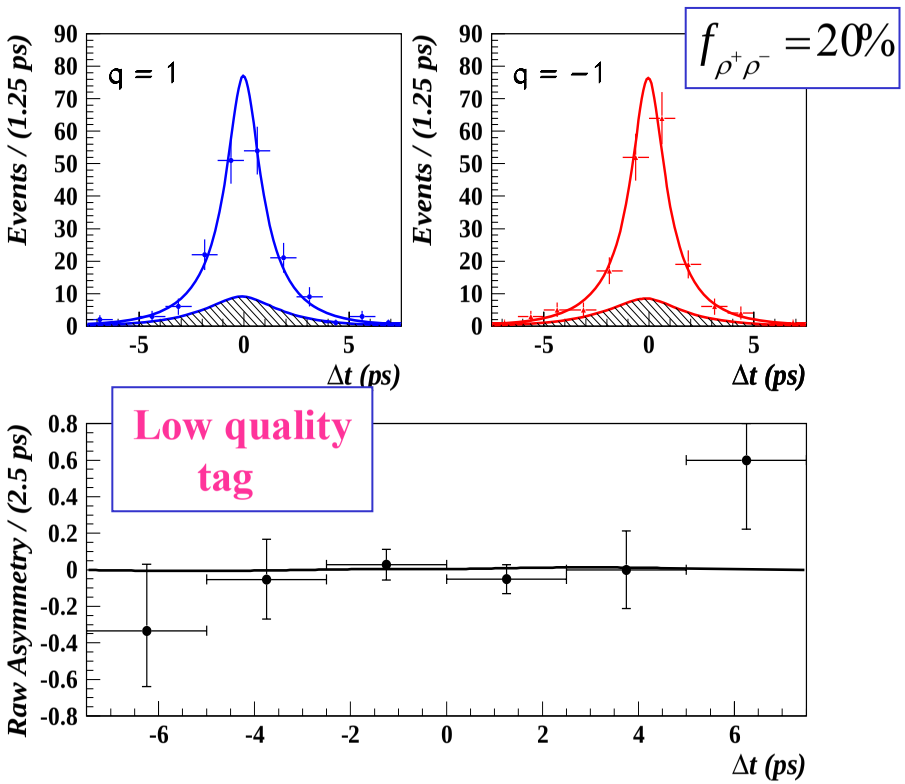
$$P^{long}_{q=\pm1} = \frac{e^{-|\Delta t|/\tau_B}}{4\tau}\{1+q(A_{\rho\rho}\cos(\Delta m\Delta t)+S_{\rho\rho}\cos(\Delta m\Delta t)\}$$

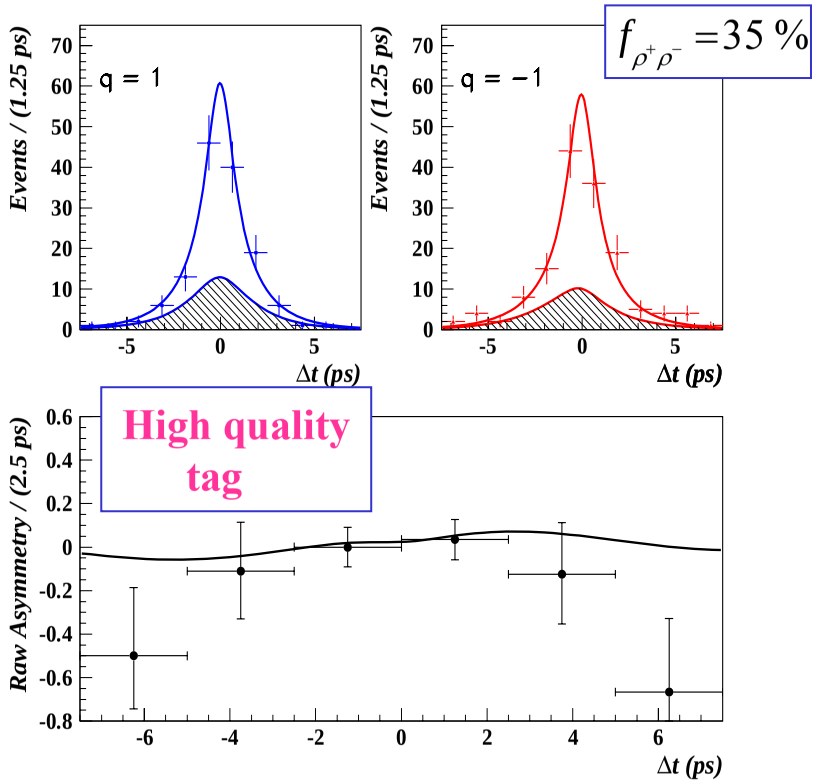
fit for two parameters $A_{\rho\rho}$, $S_{\rho\rho}$

Preliminary

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

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





Systematic errors

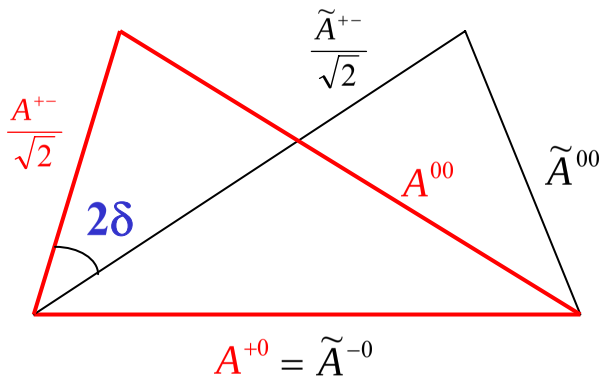
Type	$\delta\mathcal{A}$ $(\times 10^{-2})$		$\delta\mathcal{S}$ $(\times 10^{-2})$	
	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$
Wrong tag fractions	0.5	0.5	0.8	0.8
Parameters Δm, τ_{B^0}	0.2	0.3	0.6	0.7
Resolution function	1.4	1.5	1.0	1.7
Background Δt distributions	0.5	0.5	1.0	1.1
Component fractions	1.5	1.9	3.9	3.7
$\rho\pi\pi$ nonresonant fractions	1.2	1.0	1.5	1.2
SCF fraction, Δt PDF	0.2	0.2	0.1	0.1
Continuum LR PDF	0.8	0.7	1.2	1.3
Vertexing	2.1	2.1	1.0	1.3
Possible fitting bias	0.2	0.0	0.1	0.0
Background asymmetry	1.1	0.0	0.0	0.4
$b \to u$ asymmetry	2.4	2.9	2.4	3.2
Transversely-polarized components, $f_\perp$, $f_{\|\|}$	3.8	2.8	4.6	2.7
Tag-side interference	3.7	3.7	0.1	0.1
Total	6.9	6.5	7.1	6.4

[PRD68, 034010, 2003]

Constraint on ϕ_2

- **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: $\frac{A^{+-}}{\sqrt{2}} + A^{00} = A^{0+}$, $\quad \frac{\bar{A}^{+-}}{\sqrt{2}} + \bar{A}^{00} = \bar{A}^{0+}$ $\quad \tilde{A}^{ij} = e^{2i\phi_3}$



A^{+-} $(\bar{A}^{+-})$	B^0 $(\bar{B}^0)$ $\rightarrow$ $\rho^+\rho^-$
A^{00} $(\bar{A}^{00})$	B^0 $(\bar{B}^0)$ $\rightarrow$ $\rho^0\rho^0$
A^{+0} $(\bar{A}^{-0})$	B^+ (B^-) $\rightarrow$ $\rho^+\rho^0$ $(\rho^-\rho^0)$

- **Calculate confidence level applying R-fit method**

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

Constraint on ϕ_2 (cont'd)

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

(Old 26.6 ± 0.6)	$B(\rho^+\rho^0)$	=	$(18.2 \pm 3.0)\cdot 10^{-6}$
	$f_L(\rho^+\rho^0)$	=	$0.912^{+0.044}_{-0.045}$
(Old 26 ± 6)	$B(\rho^+\rho^-)$	=	$(23.1^{+3.2}_{-3.3})\cdot 10^{-6}$
	$f_L(\rho^+\rho^-)$	=	0.968 ± 0.023
(Old <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.

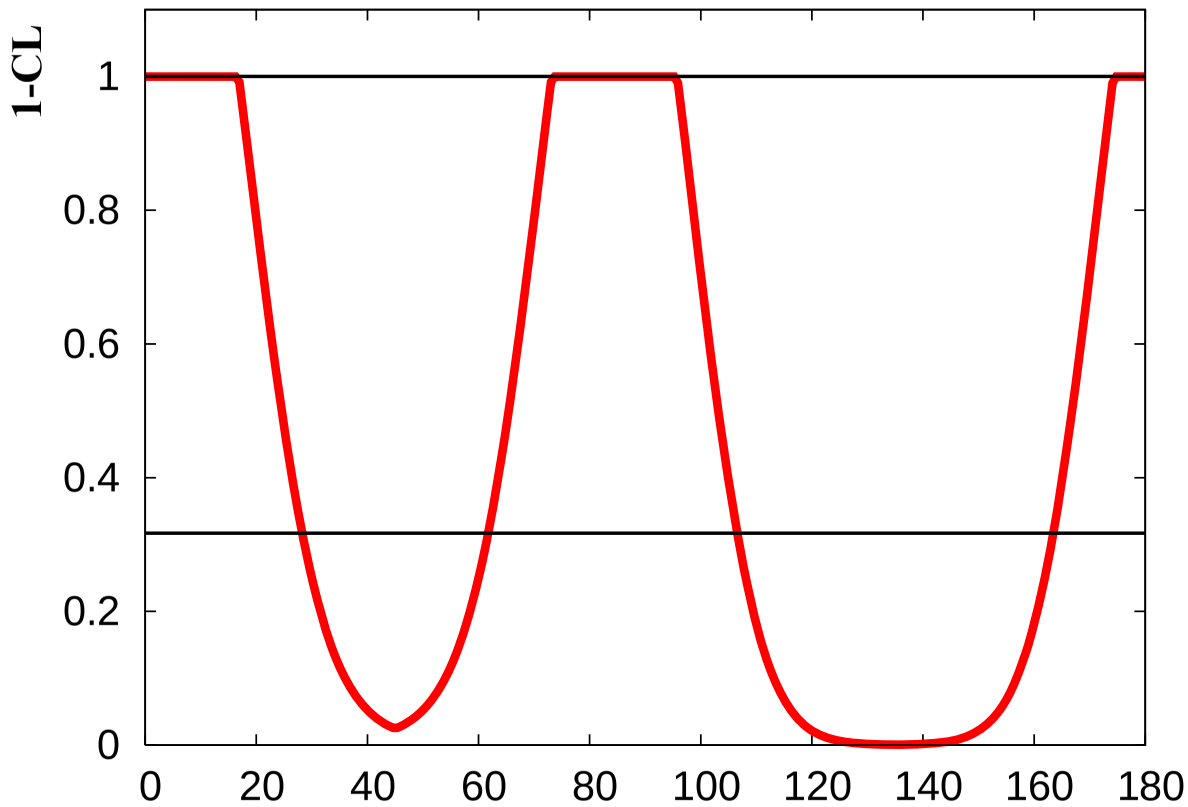
The isospin triangle is 'closed' with new measurements of $Br(\rho^+\rho^-)$, $Br(\rho^+\rho^0)$, $Br(\rho^0\rho^0)$,

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



$54 < \phi_2 < 113^\circ$

at 90% CL

$62 < \phi_2 < 107^\circ$

at 68% CL

The error is dominated by

$$|\phi_2^{eff} - \phi_2|$$

Summary

Measurement of CP asymmetries

$$A_{\rho\rho} = 0.16 \pm 0.21(stat) \pm 0.07(syst)$$
$$S_{\rho\rho} = 0.19 \pm 0.30(stat) \pm 0.07(syst)$$

from an isospin analysis we obtain

$54 < \phi_2 < 113^\circ$ **at 90% CL**

$62 < \phi_2 < 107^\circ$ **at 68% CL**