CP violation in $B \to \pi\pi, \rho\pi$

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Outline

- *CP* asymmetries in $B^0 \to \pi^+\pi^-$ decay
  - *CP* violating parameters : **Sππ** and **Aππ(= – Cππ)**

    ↑ *Belle* ↑ *BaBar*

    - ***Belle*** : ***hep-ex/0301032 (*** to be appeared in ***PRD***)
    - ***BaBar*** : ***Phys. Rev. Lett. 281802***
  - Bound on **Penguin Pollution** from **isospin relation** ($B \to \pi^+\pi^-$, $\pi^-\pi^0$, and $\pi^0\pi^0$ decays)
- *CP* asymmetries in $B^0 \to \rho\pi$ decay ($\pi^+\pi^-\pi^0$)
  - **Quasi-two-body** analysis
    - ***BaBar :*** update at ***Recontres de Moriond 2003***

Introduction

Introduction

Quark mixing is described by the 3x3 Cabibbo-Kobayashi-Maskawa (CKM) matrix. (Wolfenstein parametrization)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

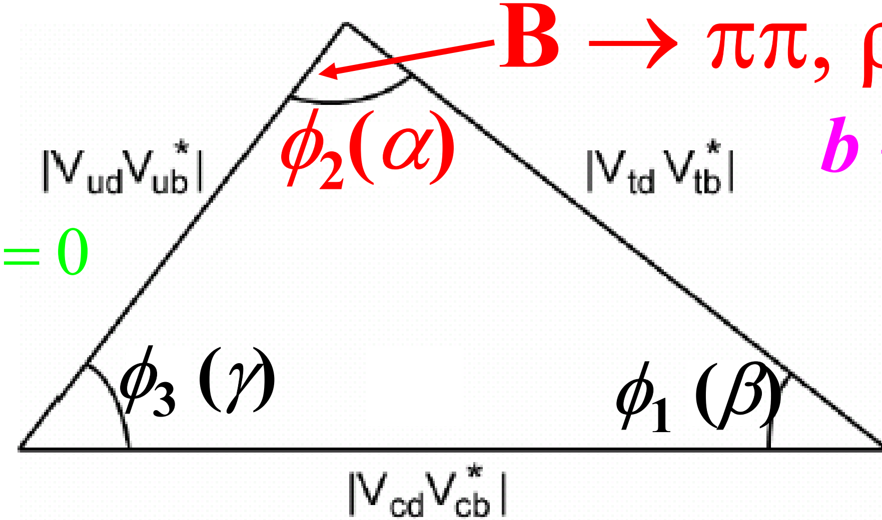
One irreducible **complex phase** derives *CP* violation .

$B \rightarrow \pi\pi, \rho\pi$

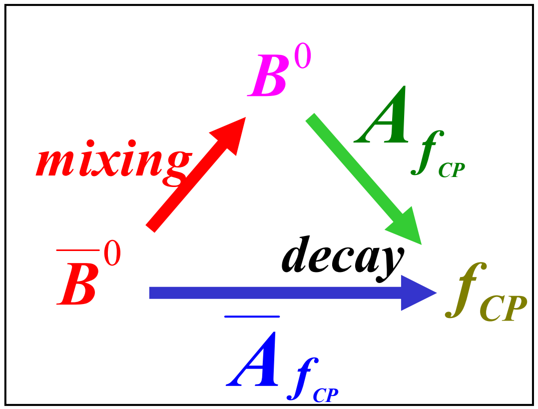
$b \rightarrow u\bar{u}d$

Unitarity triangle

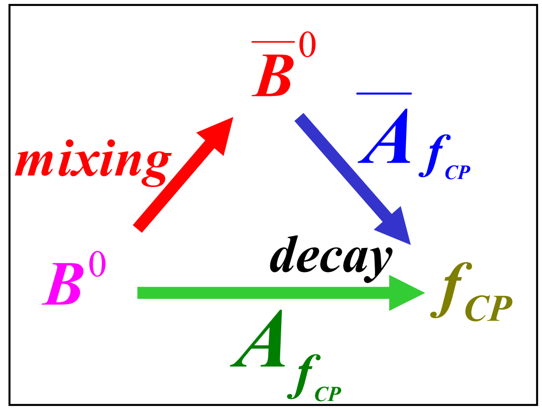
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



CP violation in mixing and decay



$\neq$



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

CP **violation in neutral** ***B*** **meson results from the interference between decays with and without mixing.**

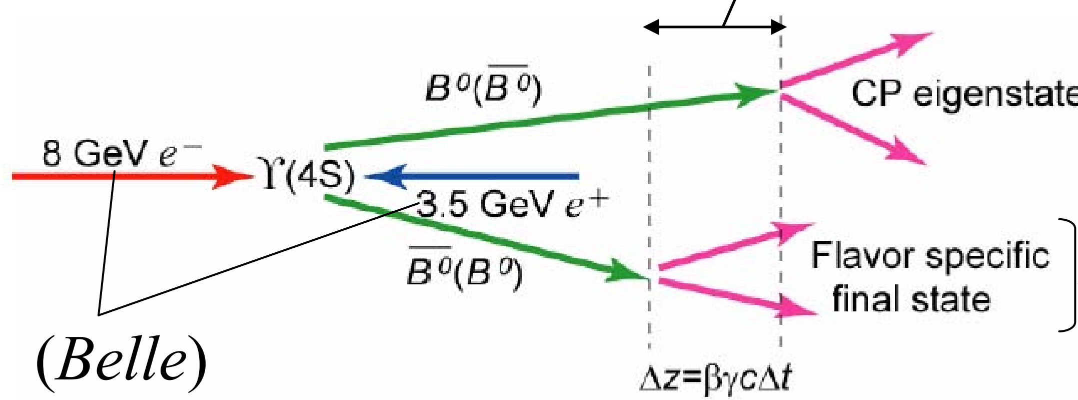
Time evolution in $B^0 \to \pi^+\pi^-$

$$P^q_{\pi\pi}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q \cdot \{S_{\pi\pi}\sin(\Delta m_d \Delta t) + A_{\pi\pi}\cos(\Delta m_d \Delta t)\}]$$

q= {+1 for B^0 tag; −1 for $\overline{B}^0$ tag}

$\Delta t = \Delta z/(\beta\gamma c)$

$$S_{\pi\pi} = \frac{2\,\mathrm{Im}\,\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}, \quad A_{\pi\pi} = \frac{|\lambda_{\pi\pi}|^2 - 1}{|\lambda_{\pi\pi}|^2 + 1} = -C_{\pi\pi}$$

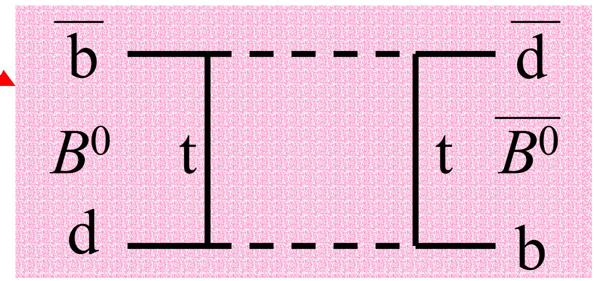


(*Belle*)

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

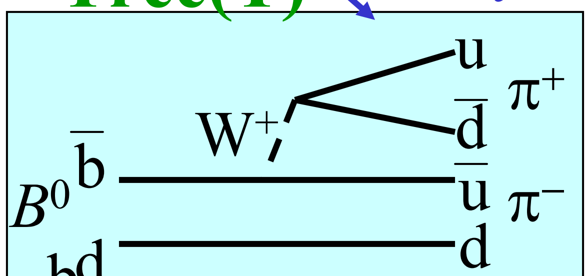
mixing

$$\lambda_{\pi\pi} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}$$

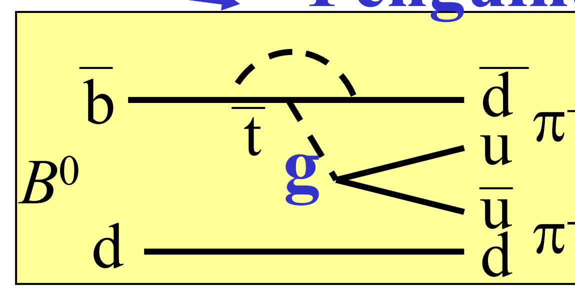


decay

Tree(T)



Penguin(P)



Tree only

$$\lambda_{\pi\pi} = e^{2i\phi_2}$$

$$A_{\pi\pi} = 0$$

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

Tree + Penguin

$$\lambda_{\pi\pi} = e^{2i\phi_2} \frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}, \qquad (\phi_2 = \alpha)$$

$A_{\pi\pi} \propto \sin(\delta) \rightarrow$ ***direct CP violation***, $\quad (A_{\pi\pi} = -C_{\pi\pi})$

$S_{\pi\pi} = \sqrt{1-C_{\pi\pi}^2}\sin(2\phi_{2eff}) \rightarrow$ ***related to*** ϕ_2 ***thru. isospin analysis***

Analysis Procedure

Data sample

Event Selection → Flavor tagging → Continuum suppression → Vertex and Δt

$\pi^+\pi^-$, $\rho\pi(\pi^+\pi^-\pi^0)$: charmless B decays

BR ~ 10^{-5}-10^{-6} : rare decays

world average (10^{-6})

$$BR(\pi^+\pi^-) = 4.8 \pm 0.5$$

$$BR(\rho^+\pi^-) = 25.4 \pm 4.2$$

$$BR(\rho^0\pi^0) < 5.3$$

(HFAG table)

⇨ Need a lot of data

Data sample

$\pi^+\pi^-$

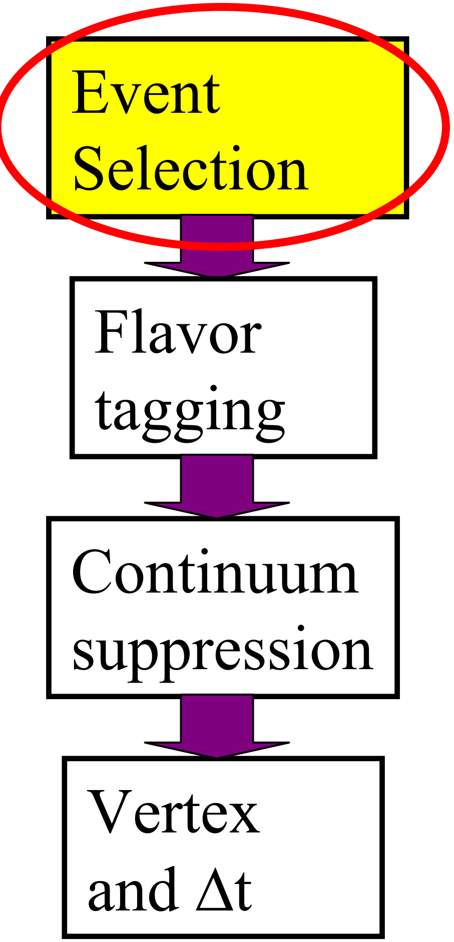
Belle ***85*** million $B\bar{B}$ pairs

BaBar ***88*** million $B\bar{B}$ pairs

$\rho\pi$

BaBar ***89*** million $B\bar{B}$ pairs

Kinematics: Reconstruction of *CP* side



Beam – constrained mass

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

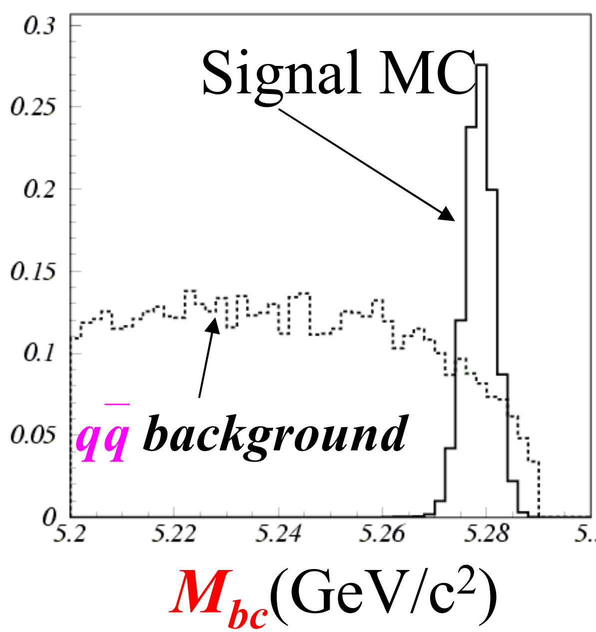
Energy difference

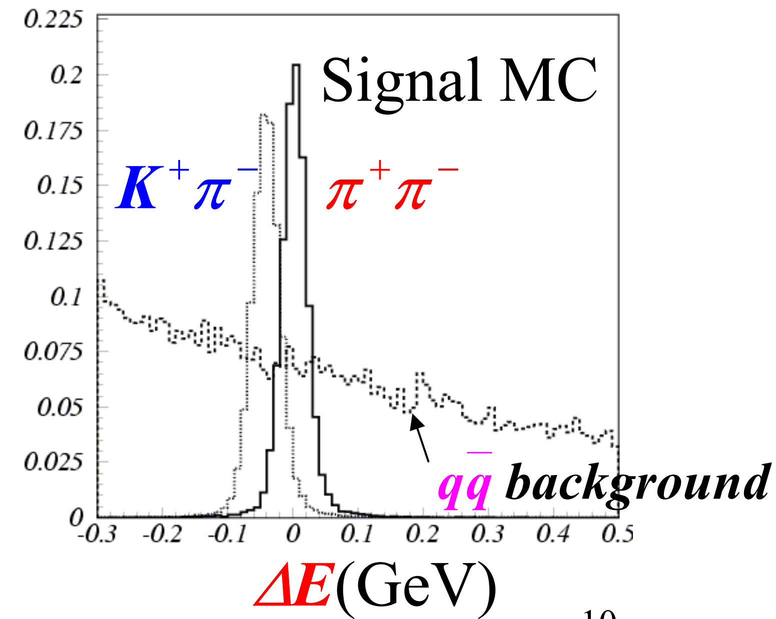
$$\Delta E \equiv E^{*}_{B} - E^{*}_{beam}$$

E^{*}_{beam} : *cms beam energy*

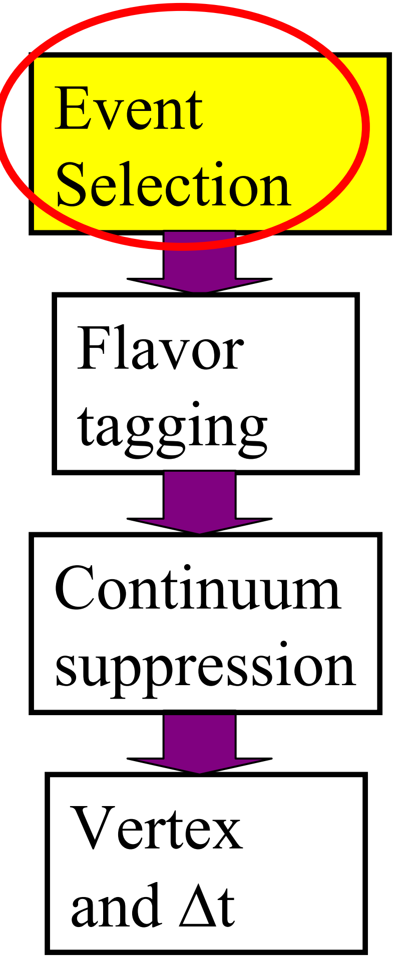
E^{*}_{B} : *cms energy of B candidate*

p^{*}_{B} : *cms momentum of B candidate*





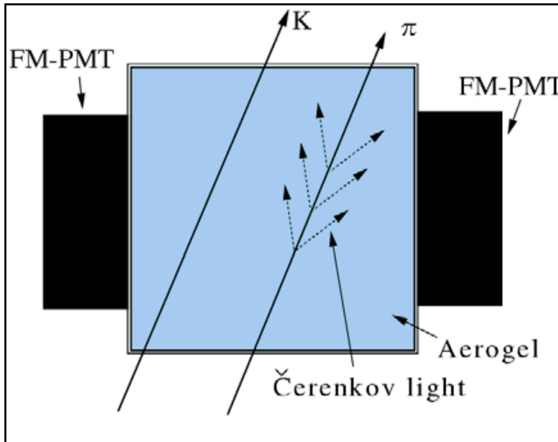
Good K/π separation



Belle

ACC(Aerogel Cherenkov Counter) Threshold type

+ CDC dE/dx



Schematic view of the ACC.

For the tracks in the momentum range that covers the $B^0 \to \pi^+\pi^-$ signal,

π effciency = 91%

10.3% of kaons are misidentified as pions.

10.0 ±0.2% from K^-

10.6 ±0.2% from K^+

The effect of asymmetry of this misidentification is negligible for the measurement of Aππ and Sππ.

Good K/π separation

Event Selection

Flavor tagging

Continuum suppression

Vertex and Δt

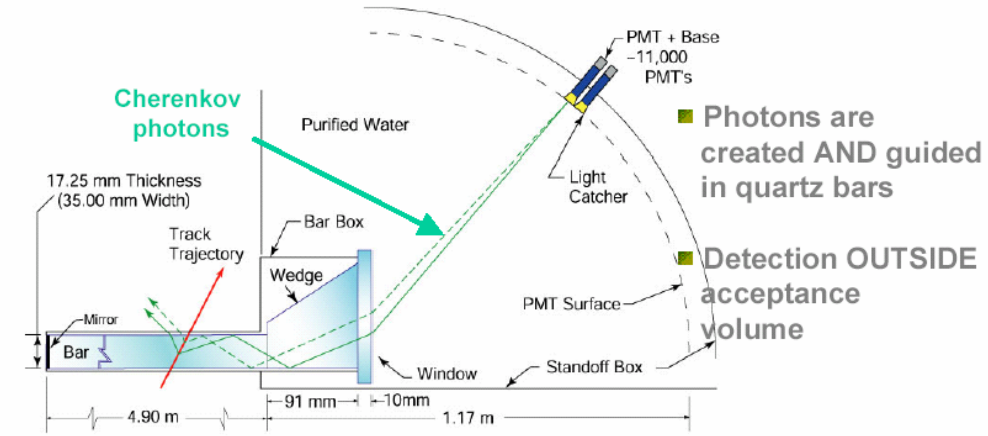
BaBar

DIRC

(Detector of Internally Reflected Cherenkov light)

π/*K* separation

$$\begin{cases} 8\sigma_{\theta_c} \ \textit{at}\ 2\,GeV/c \\ 2.5\sigma_{\theta_c} \ \textit{at}\ 4\,GeV/c \end{cases}$$



Cherenkov angle (θ_C^+, θ_C^-):
is used separately as PDF for maximum likelihood fit.

θ_C^+, θ_C^- : Cherenkov angle for positively and negatively charged tracks

Flavor tagging

- Event Selection
- **Flavor tagging**
- Continuum suppression
- Vertex and Δt

Use flavor specific properties and correlations

Identify B^0/ $\overline{B^0}$ by the charges of the inclusive decay products.

- Inclusive leptons:
  - high p l^- — $b \to c\, l^- \nu$
  - intermed. p l^+ — $\hookrightarrow s\, l^+ \nu$
- Inclusive hadrons:
  - high p π^+ — $B^0 \to D^{(*)-} \pi^+,\ D^{(*)-} \rho^+$, etc.
  - intermed. p K^+ — $\hookrightarrow K^+ X$, $\hookrightarrow \pi^+ \pi^0$
  - low p π^- — $\hookrightarrow \overline{D}^0 \pi^-$

Continuum background

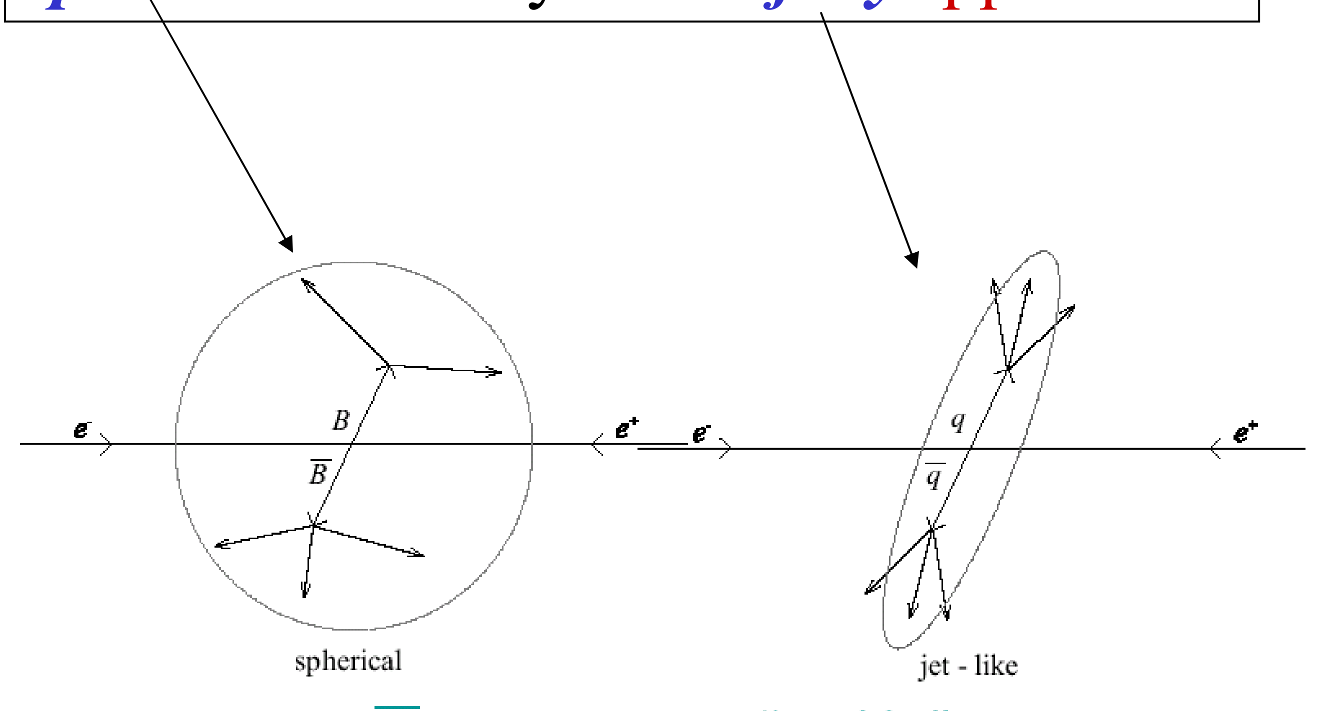
Event Selection

Flavor tagging

Continuum suppression

Vertex and Δt

use ***kinematics*** and ***topology*** to separate ***spherical*** *B* decays from ***jetty*** $q\bar{q}$ events



Continuum suppression

$B^0 \rightarrow \pi^+\pi^-$ for the case of ***Belle***

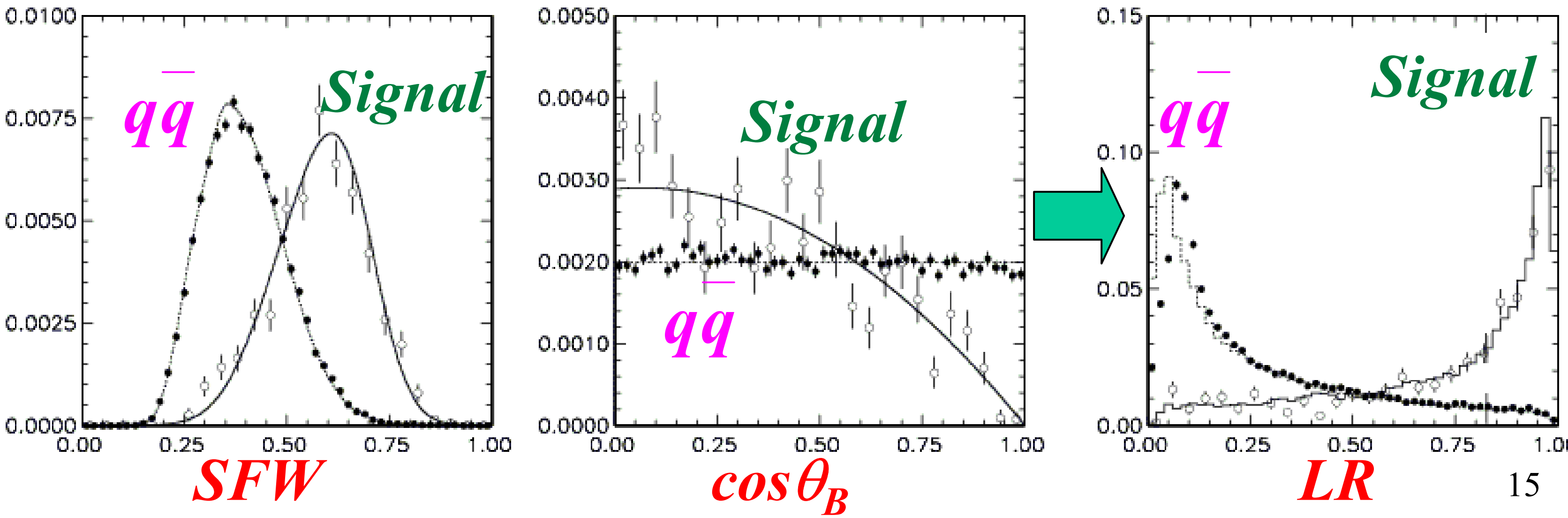
Cut on a likelihood ratio (***LR***) that combines

an event topology variable (***SFW***) and

B flight direction ($\cos\theta_B$)

SFW: *Super Fox Wolfram*

Fisher discriminant using modified Fox-Wolfram moments



Vertex reconstruction

Event Selection

Flavor tagging

Continuum suppression

Vertex and Δt

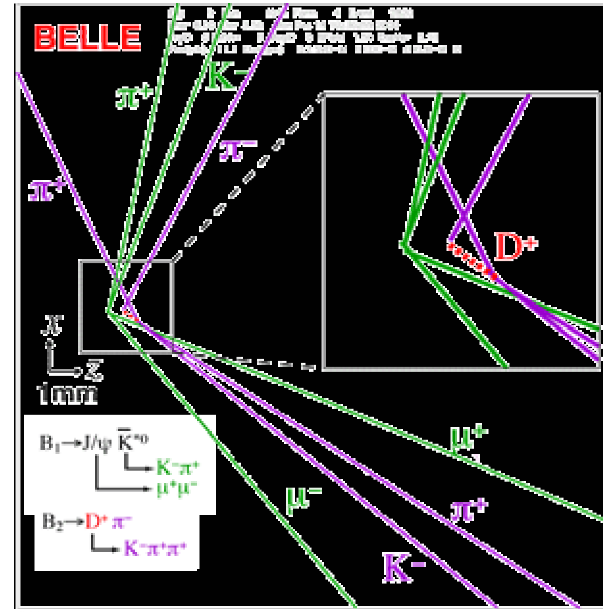
Example vertices

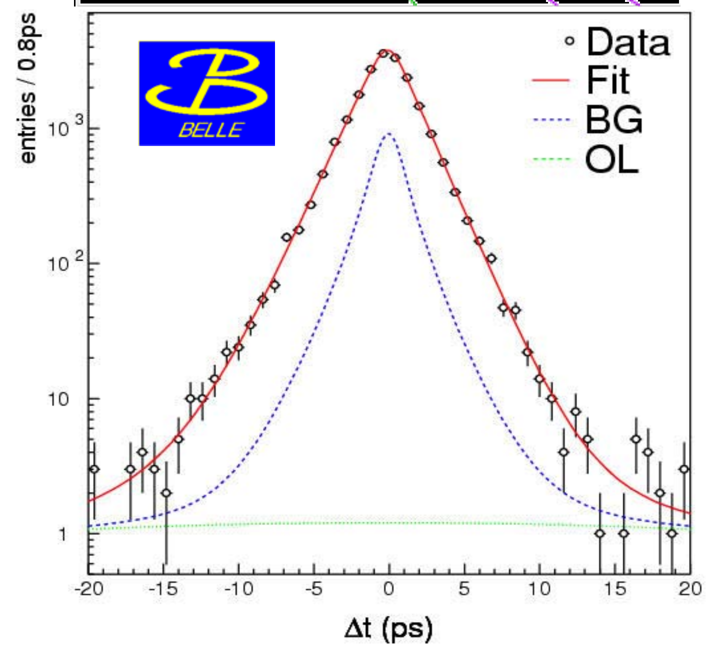
- **The same algorithm as that used for $\sin 2\phi_1$ meas.**
- **Resolution mostly determined by the tag-side vtx.**

B^0 lifetime of control sample
1.551±0.018(stat) ps

(PDG02: 1.542±0.016 ps)

Time resolution (rms) 1.43ps

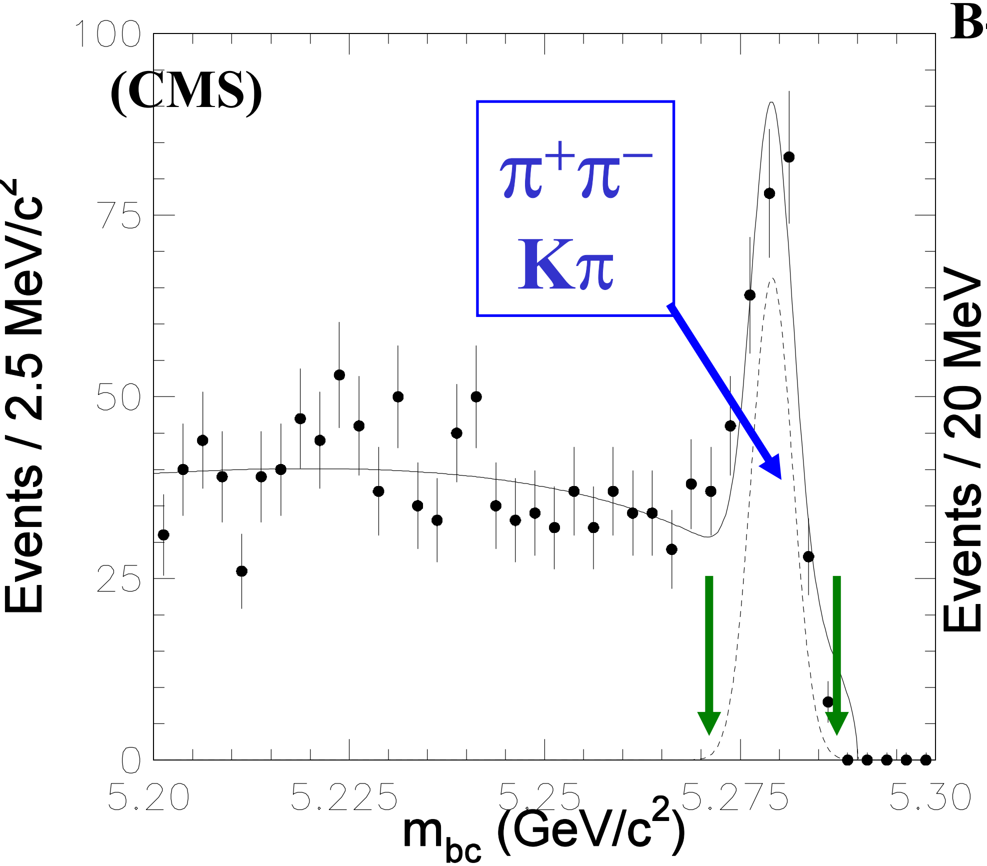




CP asymmetries in $B^0 \to \pi^+\pi^-$

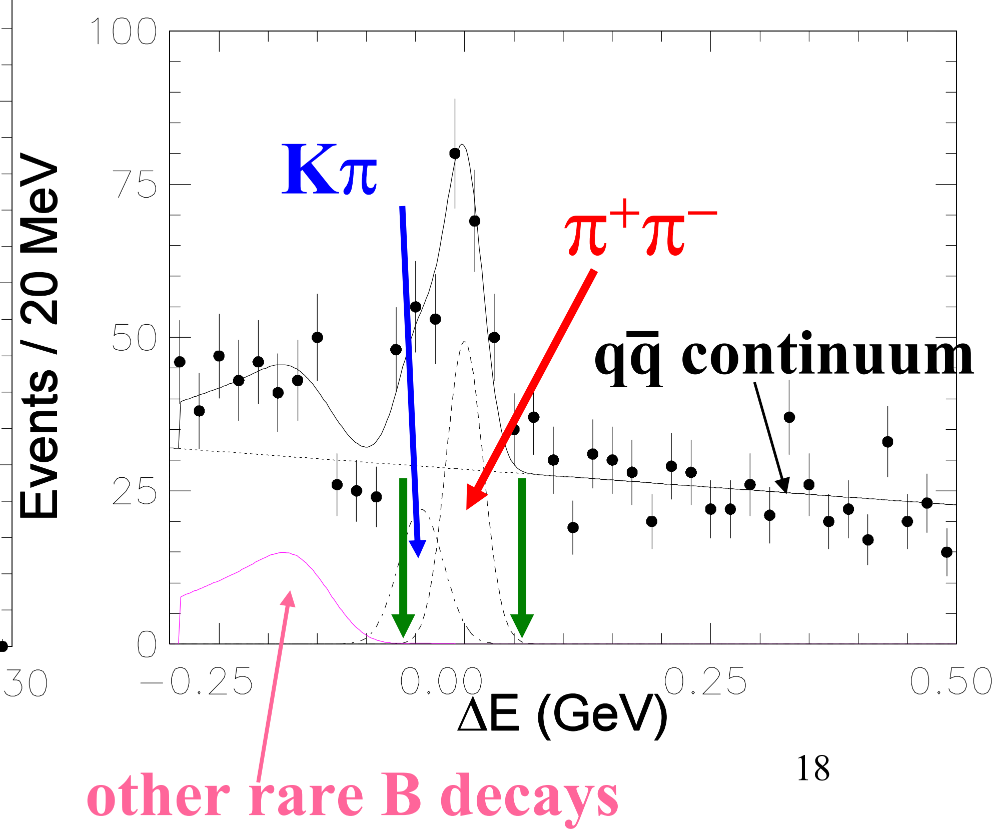
Event reconstruction (*Belle*)

Beam-constrained mass (M_{bc})
(in ΔE signal region)



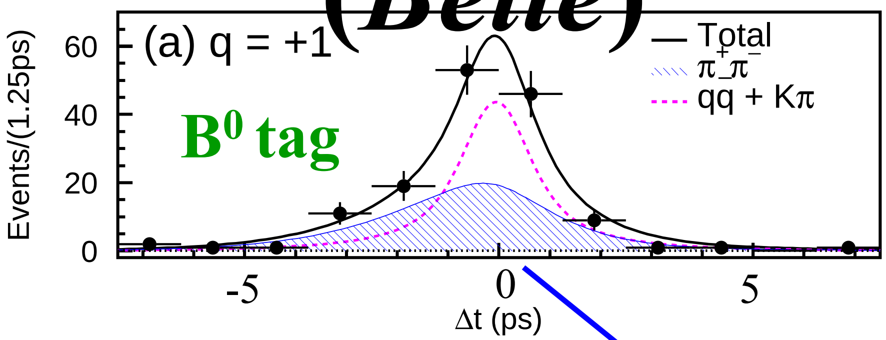
energy difference (ΔE)
(in M_{bc} signal region)

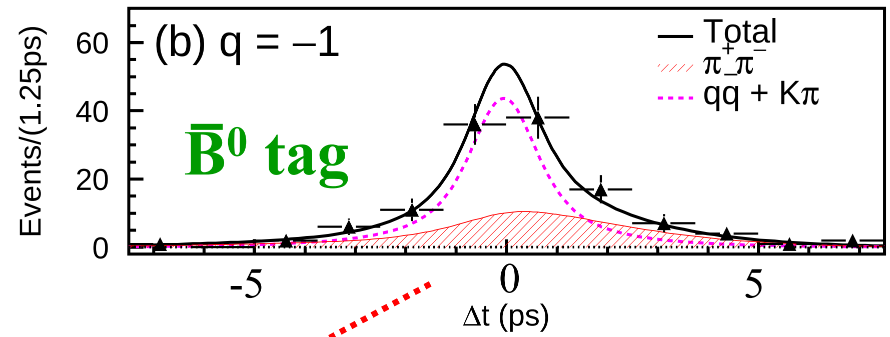
B-candidate energy – beam energy

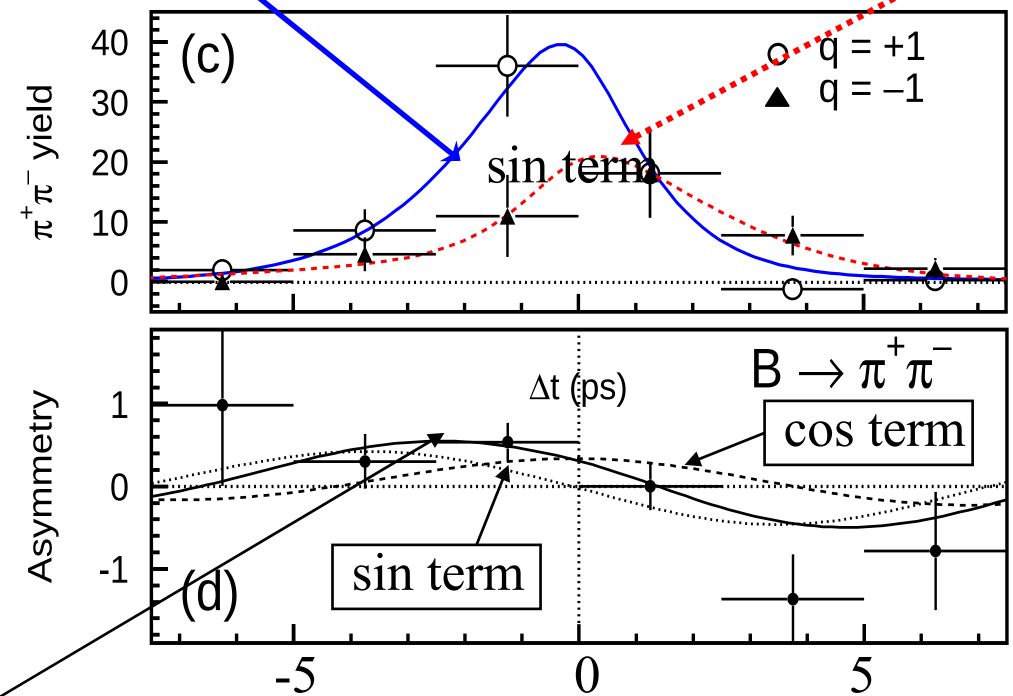


Fit results (Belle)

Large *CP* Violation is seen !







***LR*>0.825**

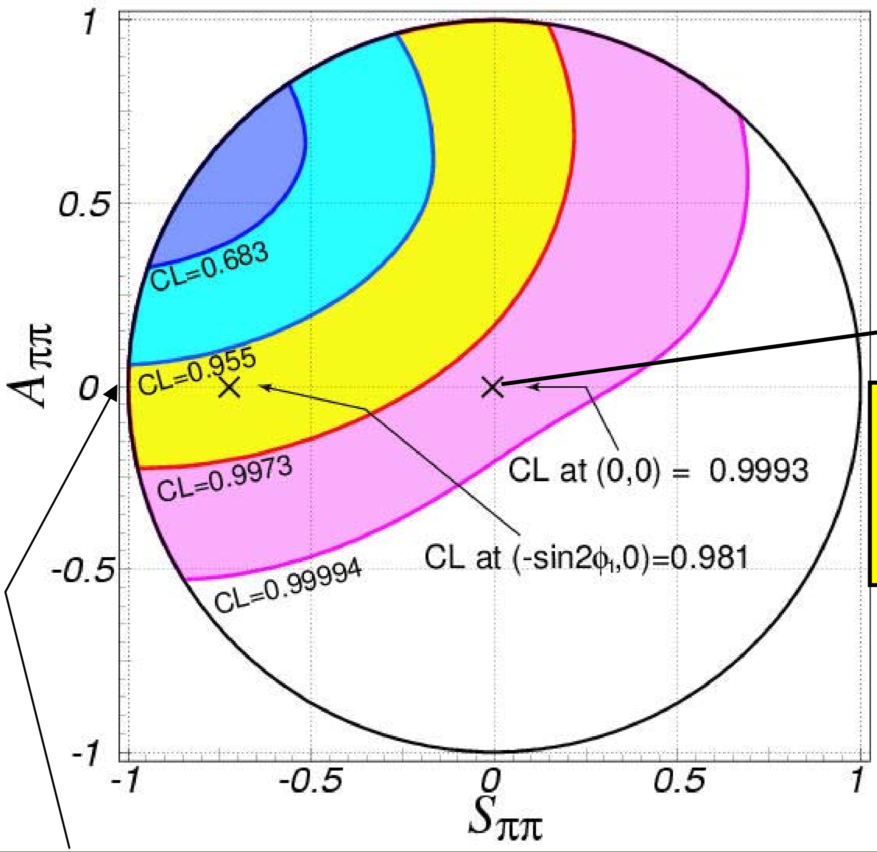
hep-ex/0301032 accepted for Phys. Rev. D

$$A_{\pi\pi} = +0.77 \pm 0.27(\textit{stat}) \pm 0.08(\textit{syst}) = -C_{\pi\pi}$$

$$S_{\pi\pi} = -1.23 \pm 0.41(\textit{stat})^{+0.08}_{-0.07}(\textit{syst})$$

Confidence Regions (*Belle*)

Feldman-Cousins frequentist approach



CL for CP conservation **3.4σ**

1) Evidence for *CP* violation in $B^0 \to \pi^+\pi^-$

2) "Indication" of direct CP Violation ($A_{\pi\pi}>0$)

Constraints on the CKM angle $\phi_2(\alpha)$

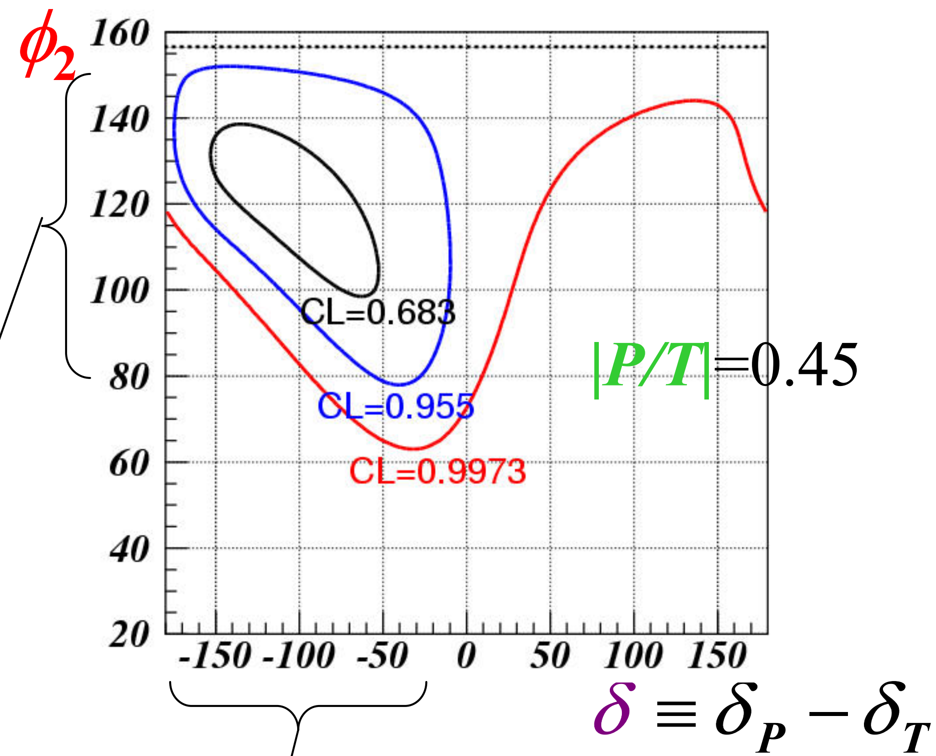
$$S_{\pi\pi} = [\sin 2\phi_2 + 2|P/T|\sin(\phi_1 - \phi_2)\cos\delta - |P/T|^2 \sin 2\phi_1]/R_{\pi\pi},$$

$$A_{\pi\pi} = -[2|P/T|\sin(\phi_1 + \phi_2)\sin\delta]/R_{\pi\pi},$$

$$R_{\pi\pi} = 1 - 2|P/T|\cos(\phi_1 + \phi_2)\cos\delta + |P/T|^2$$

$\|P/T\|$	**0.15-0.45 (representative)** Theory ~0.3
ϕ_1	**23.5deg (=β)** **(Belle & BaBar combined)**
ϕ_2	**(=α)**
δ	**strong phase difference**

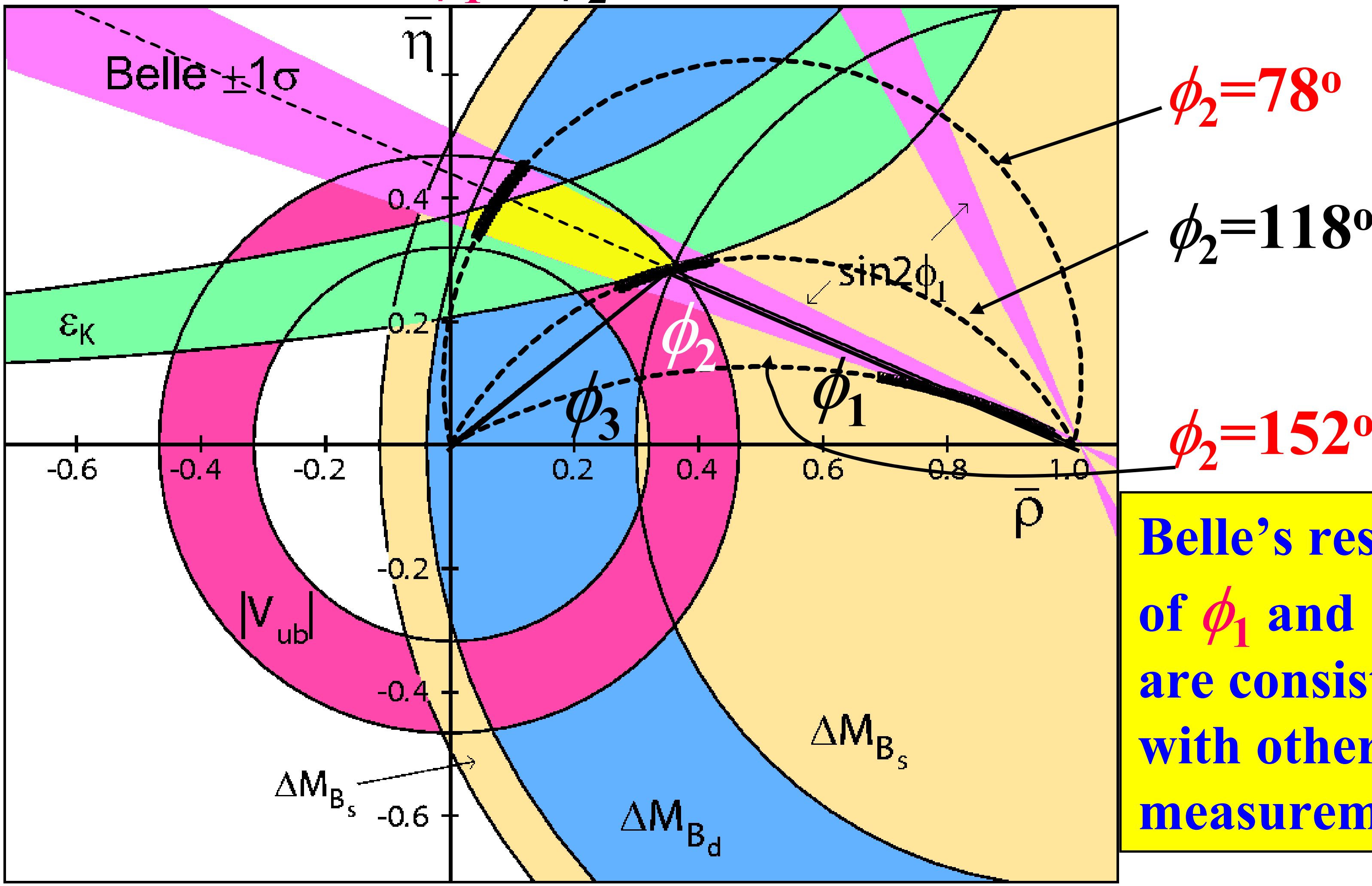
$78^o < \phi_2 < 152^o$ (95.5%C.L.)



δ<0 favored

Constraint on ρ-η

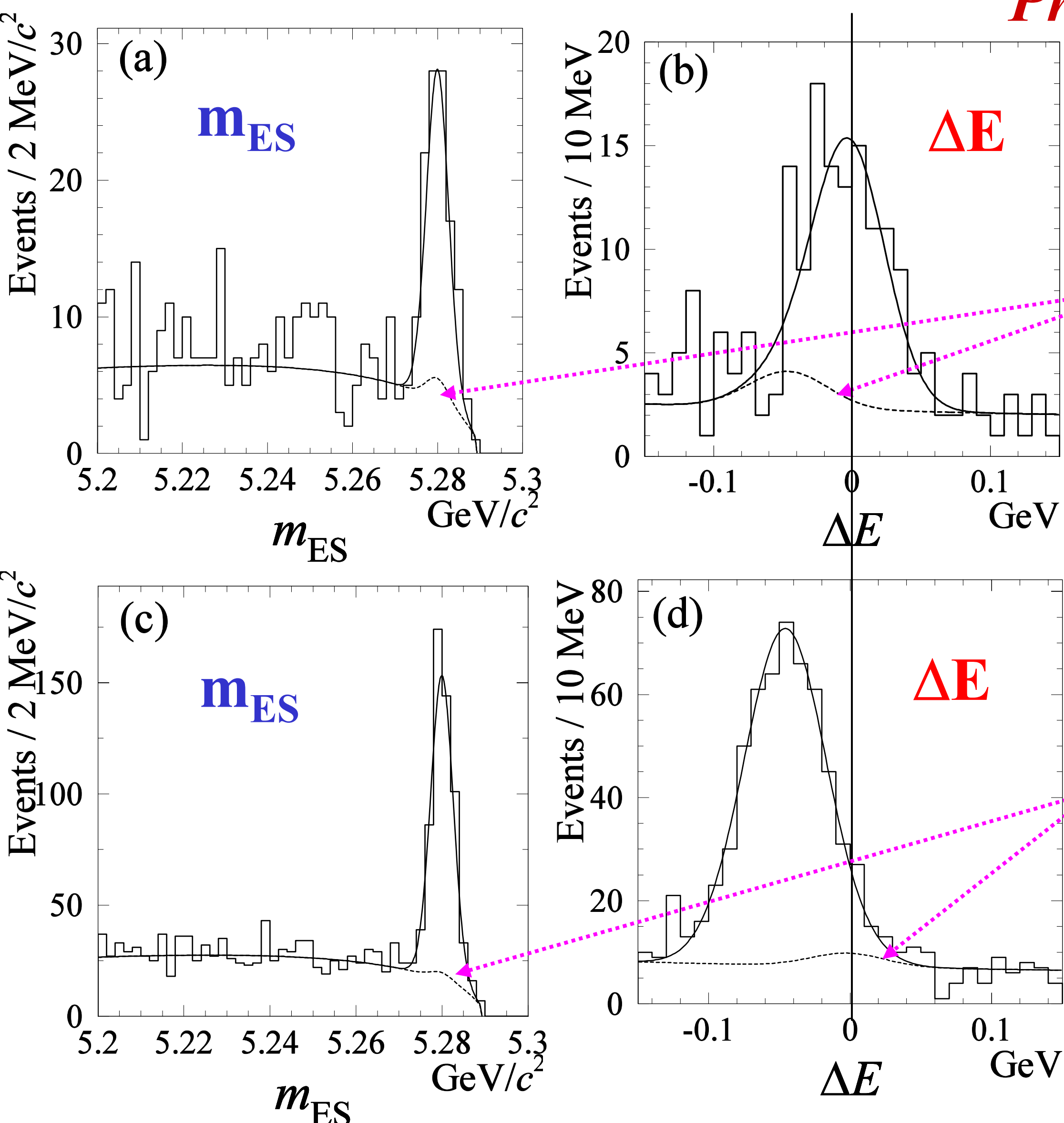
PDG2002 + (Belle ϕ_1 & ϕ_2)



Belle's results of ϕ_1 and ϕ_2 are consistent with other measurements.

m_{ES} and ΔE (*BaBar*)

Phys Rev Lett 89, 281802 (2002)



$\pi\pi$-enhanced events

$q\bar{q}$ + $K\pi$ ***background***

$K\pi$-enhanced events

$q\bar{q}$ + $\pi\pi$ ***background***

CP asymmetry result (***BaBar***)

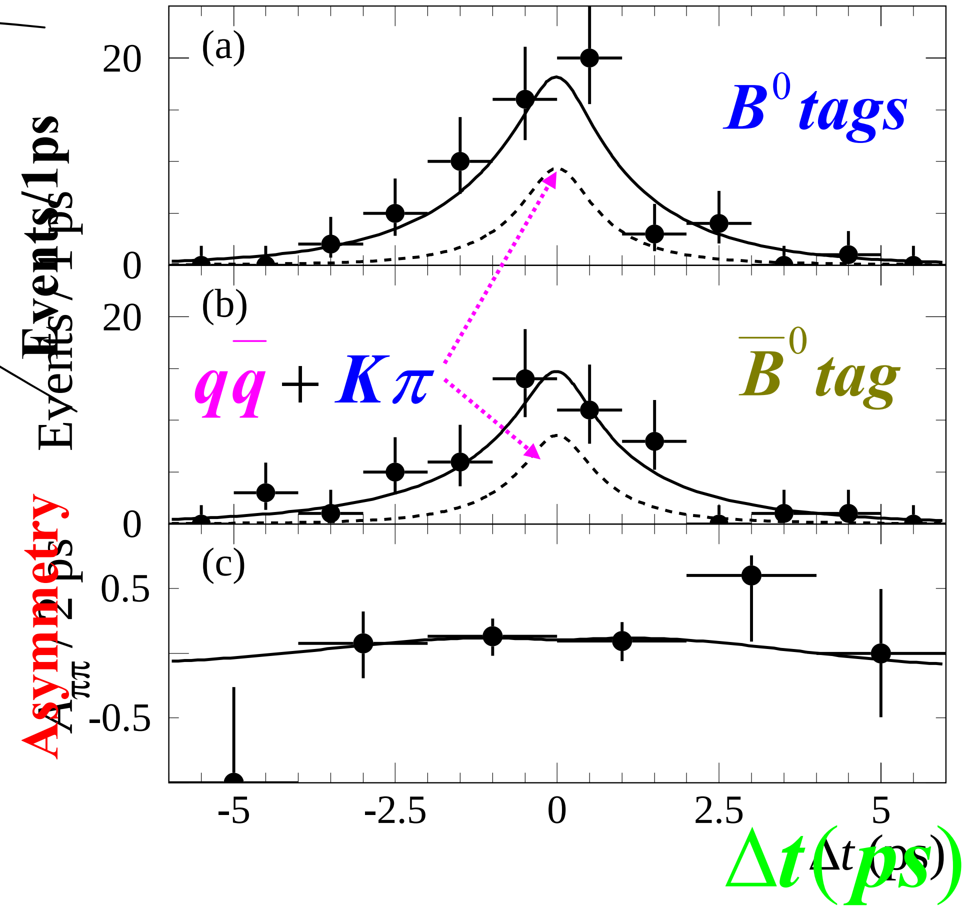
Phys Rev Lett 89, 281802 (2002)

Projection in signal ππ-enhanced events

$$Asym(\Delta t) = \frac{N(B^0_{tag}) - N(\overline{B}^0_{tag})}{N(B^0_{tag}) + N(\overline{B}^0_{tag})}$$

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

$$(C_{\pi\pi} = -A_{\pi\pi})$$

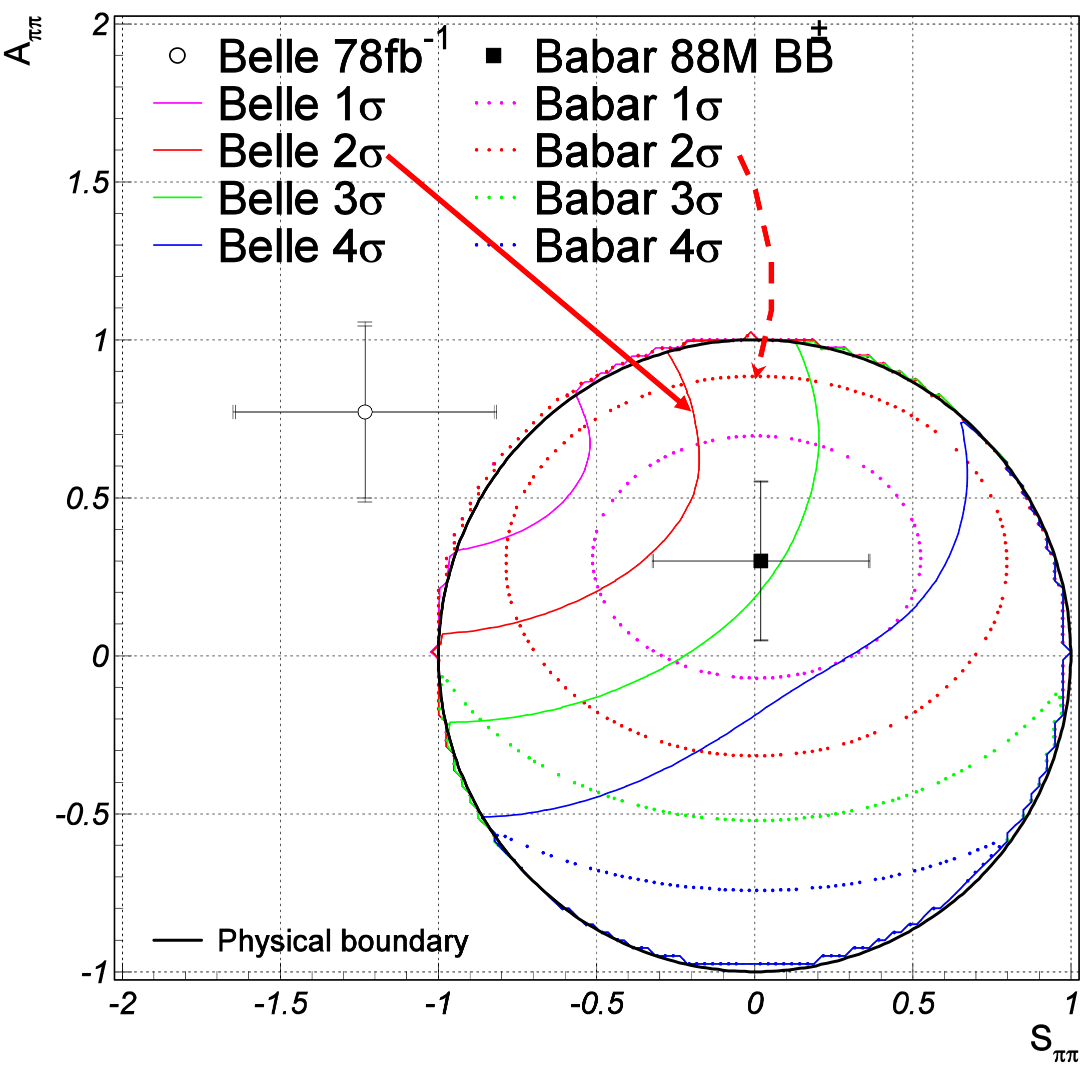


$$S_{\pi\pi} = 0.02 \pm 0.34 \pm 0.05$$

$$C_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04$$

$(A_{\pi\pi} = +0.30)$

Fit results (*Belle&BaBar*)

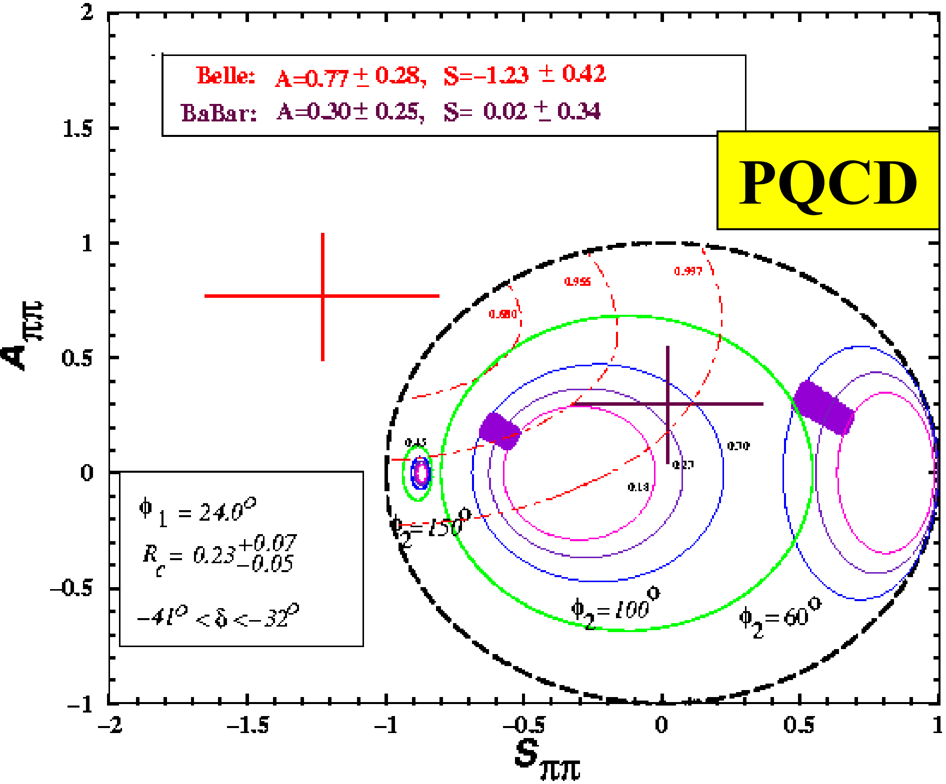


Feldman & Cousins confidence interval

The difference is at 2.2σ level.

It's early to say conclusively for the difference.

Comparison with predictions



R_c ***lines*** = 0.18(***pink***), 0.23(***purple***), 0.30(***blue***), 0.45(***green***).

Purple regions : PQCD favored Region for each ϕ_2 (60^o, 100^o, 150^o)

Aππ	Belle	BaBar	PQCD	QCDF
	hep-ex/0301032	PRL,281802 (2002)	PRD67,054009 (2003)	NPB606,245 (2001)
(%)	$77 \pm 27 \pm 8$	$30 \pm 25 \pm 4$	$16 \sim 30$	-6 ± 12

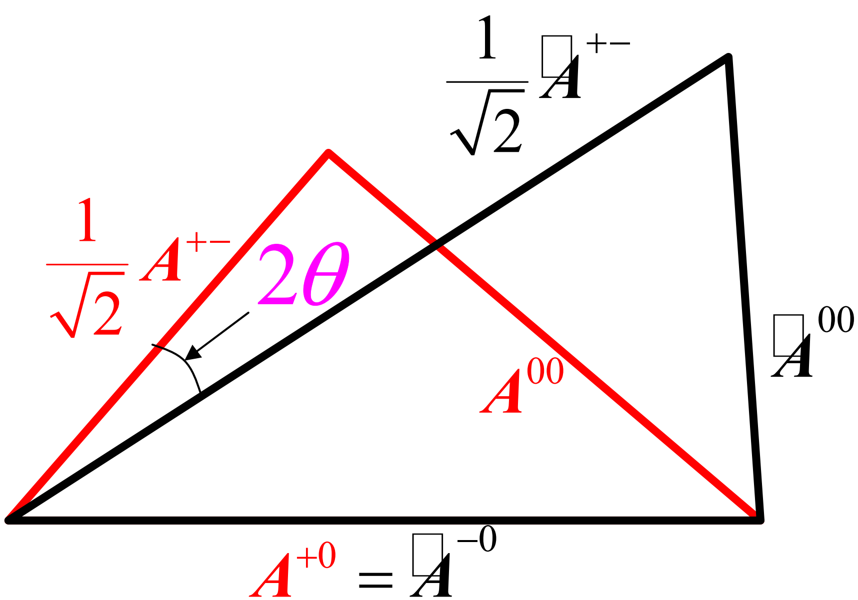
A bound on $\theta = |\phi_{2\text{eff}} - \phi_2|$ with an upper limit on $\pi^0\pi^0$

$\boldsymbol{BRs}$: $\pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$ (limit)

$\boldsymbol{CP\ asymmetries}$: $A_{\pi\pi}, S_{\pi\pi} \left(= \sqrt{1 - A_{\pi\pi}^2}\,\sin 2(\phi_2 + \theta)\right)$

$(\phi_2 = -\alpha,\ A_{\pi\pi} = -C_{\pi\pi})$

can constrain on ϕ_2 using **isospin relation**.



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

$$\tilde{A}^{ij} = e^{2\phi_3}\overline{A}^{ij}$$

A bound on $\theta = |\phi_{2eff} - \phi_2|$

- Gronau/London/Sinha/Sinha bound (*PL B514, 315 (2001)*)

$$\cos 2\theta \geq \frac{\left(\frac{1}{2} B^{+-} + B^{+0} - B^{00}\right)^2 - B^{+-}B^{+0}}{B^{+-}B^{+0}\sqrt{1 - A_{\pi\pi}^2}}$$

Average branching ratios

for $\pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$

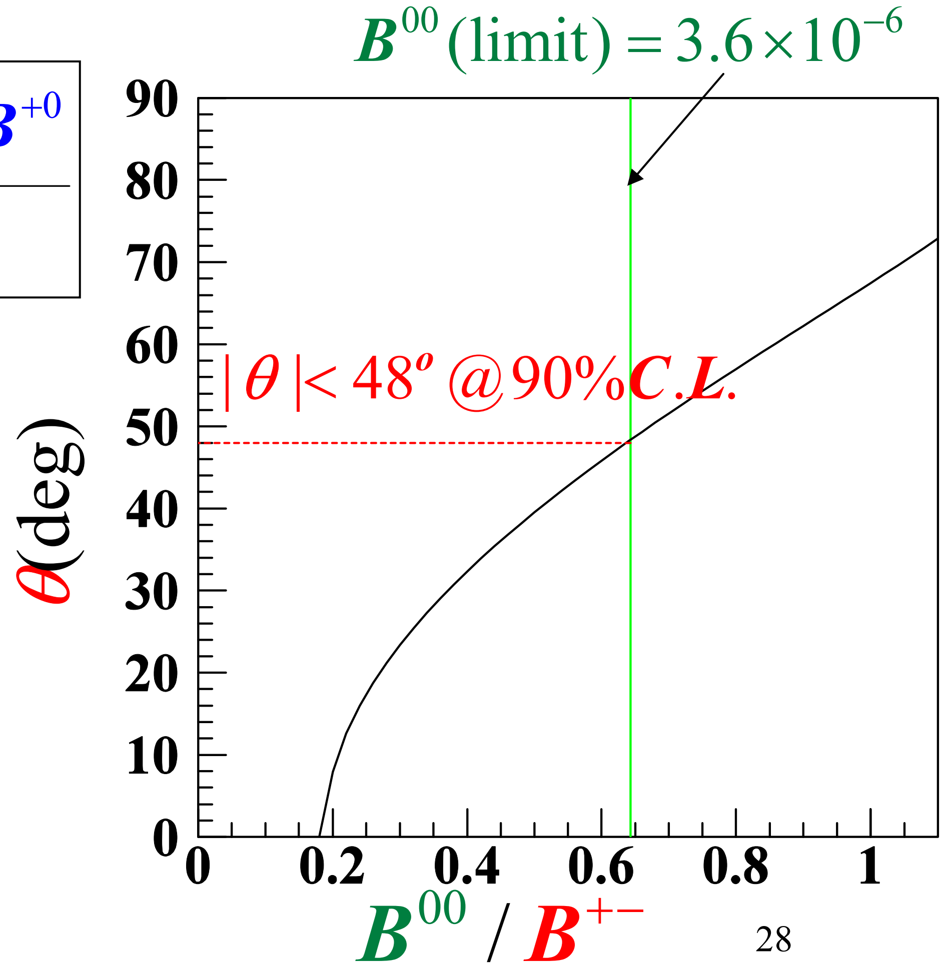
$B^{+-} = (4.8 \pm 0.5) \times 10^{-6}$,

$B^{+0} = (5.6 \pm 0.9) \times 10^{-6}$,

$B^{00} =< 3.6 \times 10^{-6}$,

$A_{\pi\pi} = 0.48 \pm 0.19.$

HFAV table



CP asymmetries in $B^0 \to \rho\pi$

CP-Violating Asymmetries in $B^0 \to \rho^+\pi^-, \rho^+K^-$

- Principle: measure α directly, even with penguins using full Dalitz-plot analysis
  - difficulty
    - Combinatorics and lower efficiency in **three-body** topology with π^0
    - Large backgrounds from misreconstructed signal events and other B decays

  → Need large statistics to extract α cleanly

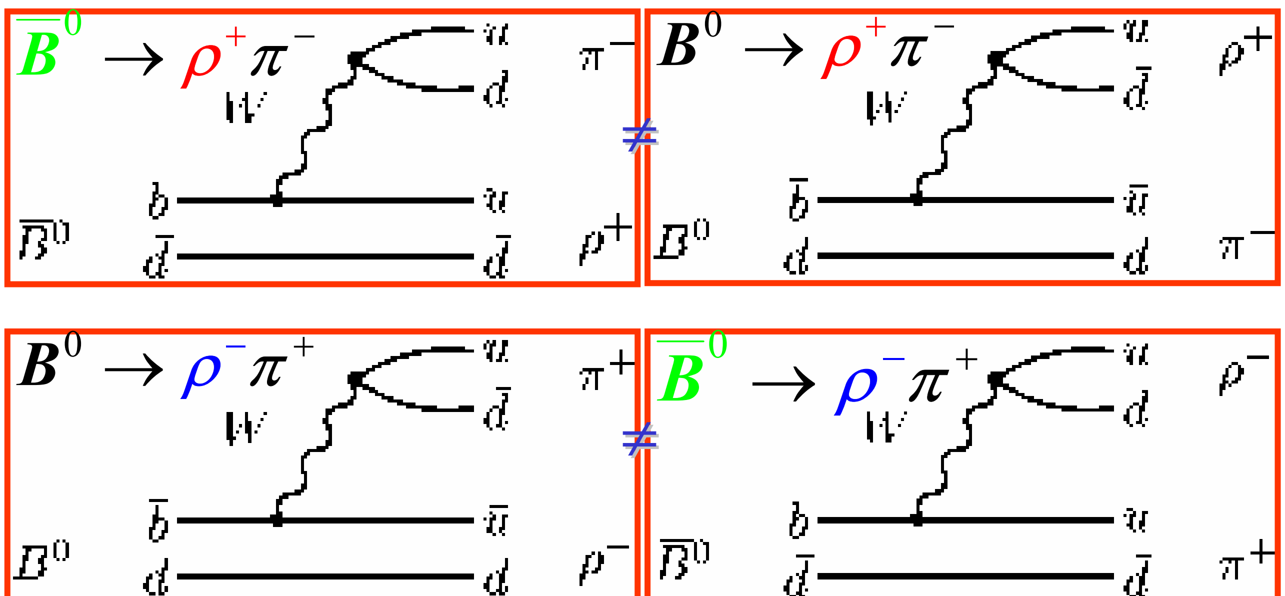
- "**quasi-two-body**" analysis:
  - Select the ρ-dominated region of the $\pi^+\pi^-\pi^0$ / $K^+\pi^-\pi^0$ Dalitz plane (Rejected when $0.4 < \boldsymbol{m}(\pi^+\pi^0), \boldsymbol{m}(\pi^-\pi^0) < 1.3\boldsymbol{GeV}/\boldsymbol{c}^2$.)
  - Suppression of $q\bar{q}$ backgrounds
  - Simultaneous fit for $\rho^+\pi^-$ and ρ^+K^-

CP Violation Study in $B^0 \to \rho\,\pi$ decay

Final state $\pi^+\pi^-\pi^0$: **not a CP eigenstate**

Basically there are four tree amplitudes:

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



$B^0 \to \rho\,\pi$ Time-dependence

Decay rate distribution

(± for ρ charge)

$$f^{\rho^\pm h^\mp}_{B^0\,\mathrm{tag}}(\Delta t) = (1 \pm A^{\rho h}_{CP})\frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 + \left((S_{\rho h} \pm \Delta S_{\rho h})\sin(\Delta m_d \Delta t) - (C_{\rho h} \pm \Delta C_{\rho h})\cos(\Delta m_d \Delta t)\right)\right]$$

$$f^{\rho^\pm h^\mp}_{\bar{B}^0\,\mathrm{tag}}(\Delta t) = (1 \pm A^{\rho h}_{CP})\frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 - \left((S_{\rho h} \pm \Delta S_{\rho h})\sin(\Delta m_d \Delta t) - (C_{\rho h} \pm \Delta C_{\rho h})\cos(\Delta m_d \Delta t)\right)\right]$$

Fit parameters

$\overset{(-)}{B}{}^0 \to \rho^+\pi^-$: $\lambda_{\rho^+\pi^-}$

$\overset{(-)}{B}{}^0 \to \rho^-\pi^+$: $\lambda_{\rho^-\pi^+}$

→ λ_{CP}, λ_{tag}

→

- $\mathcal{A}_{\rho\pi}$ — Global charge asymmetry
- $C_{\rho\pi}$ — Direct CP-violating
- $S_{\rho\pi}$ — Mixing/decay interference CP-violating
- $\Delta S_{\rho\pi}$, $\Delta C_{\rho\pi}$ — Dilution parameter; Linked to $B^0 \to \rho^-\pi^+$ vs $\bar{B}^0 \to \rho^-\pi^+$

Time-integrated asymmetry:

$$A_{CP}^{\rho h} = \frac{N(\rho^+ h^-) - N(\rho^- h^+)}{N(\rho^+ h^-) + N(\rho^- h^+)}$$

Time evolution includes:

$$(S_{\rho h} + Q\Delta S_{\rho h})\sin(\Delta m_d \Delta t)$$

$$(C_{\rho h} + Q\Delta C_{\rho h})\cos(\Delta m_d \Delta t)$$

Q is the ρ charge

direct CP violation → A_{CP} and C ≠ 0

indirect CP violation → S ≠ 0

ΔC and ΔS are insensitive to CP violation

ρK is self-tagging:

$$C_{\rho K} = 0,\ \Delta C_{\rho K} = -1,\ S_{\rho K} = 0,\ \Delta S_{\rho K} = 0$$

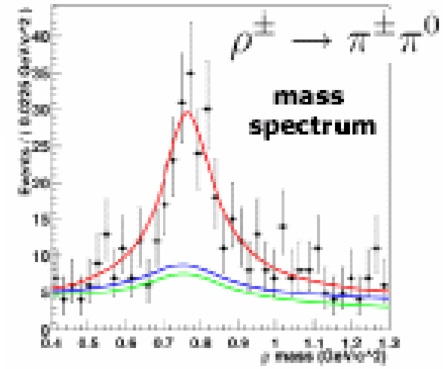
Fit for:

$$A_{CP}^{\rho\pi},\ A_{CP}^{\rho K},\ C_{\rho\pi},\ \Delta C_{\rho\pi},\ S_{\rho\pi},\ \Delta S_{\rho\pi}$$

$B^0 \to \rho\pi / \rho K$ (*BaBar*)

Yields and Charge Asymmetries

The results with 89 million BB pairs @2003 **Moriond** EW



Preliminary

BR of ρπ and ρK

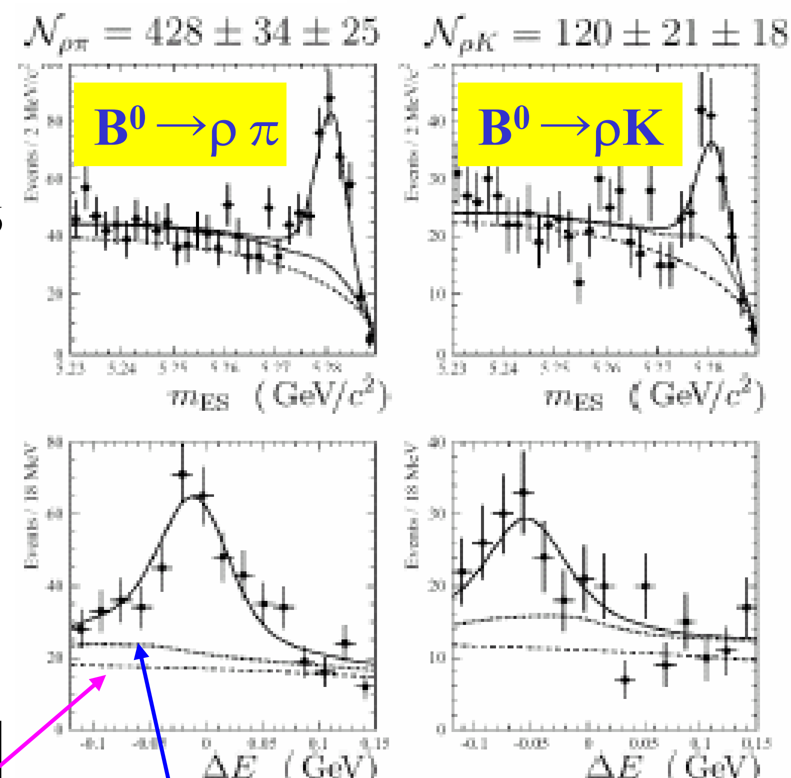
$$\boldsymbol{B}(\boldsymbol{B} \to \rho^{\pm}\pi^{\mp}) = (22.6 \pm 1.8 \pm 2.2) \times 10^{-6}$$

$$\boldsymbol{B}(\boldsymbol{B} \to \rho^{\pm}\boldsymbol{K}^{\mp}) = (7.3^{+1.3}_{-1.2} \pm 1.3) \times 10^{-6}$$

Charge asymmetry of ρπ and ρK

$$A_{\rho K} = +0.28 \pm 0.17 \pm 0.08$$

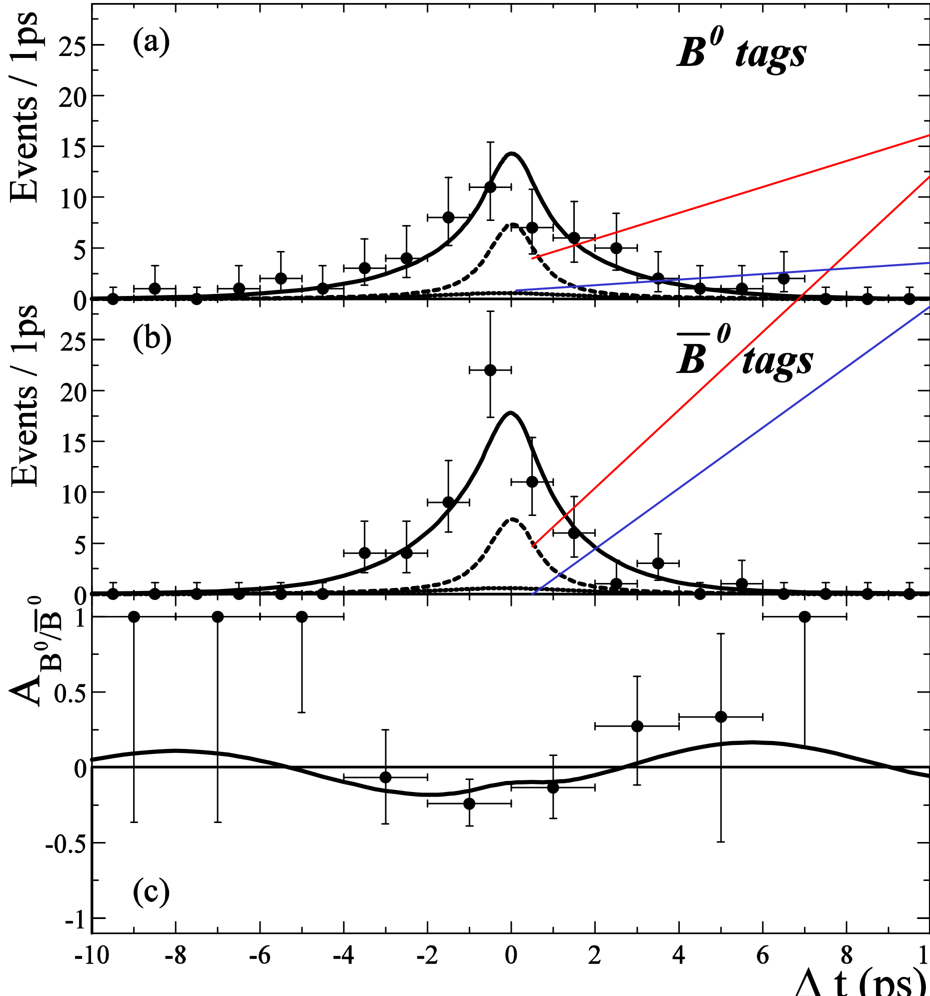
$$A_{\rho\pi} = -0.18 \pm 0.08 \pm 0.03$$



$q\bar{q}$

$q\bar{q} + B - related$

$B^0 \to \rho\pi/\rho K$ (*BaBar*) : Δt distributions



B+continuum background

B-related background

2σ (or more) from zero

$$\mathcal{A}_{\rho\pi} = -0.18 \pm 0.08 \pm 0.03$$
$$C_{\rho\pi} = +0.36 \pm 0.18 \pm 0.04$$
$$S_{\rho\pi} = +0.19 \pm 0.24 \pm 0.03$$
$$\Delta C_{\rho\pi} = +0.28 \pm 0.19 \pm 0.04$$
$$\Delta S_{\rho\pi} = +0.15 \pm 0.25 \pm 0.03$$

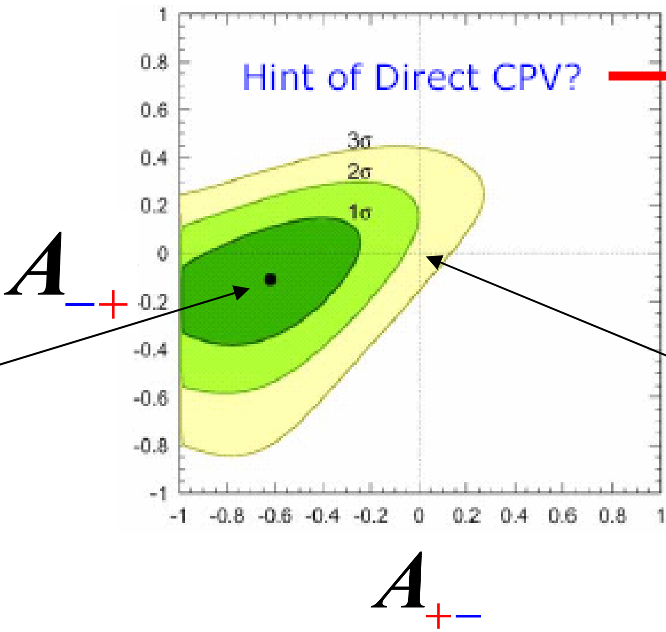
Direct CP violation in $B^0 \to \rho\pi$

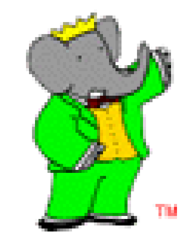
$$A_{+-} \equiv \frac{N(\overline{B}^0_{\rho\pi} \to \rho^+\pi^-) - N(B^0_{\rho\pi} \to \rho^-\pi^+)}{N(\overline{B}^0_{\rho\pi} \to \rho^+\pi^-) + N(B^0_{\rho\pi} \to \rho^-\pi^+)} = \frac{A_{CP}^{\rho\pi} - C_{\rho\pi} - A_{CP}^{\rho\pi} \cdot \Delta C_{\rho\pi}}{1 - \Delta C_{\rho\pi} - A_{CP}^{\rho\pi} \cdot C_{\rho\pi}}$$

$$A_{-+} \equiv \frac{N(\overline{B}^0_{\rho\pi} \to \rho^-\pi^+) - N(B^0_{\rho\pi} \to \rho^+\pi^-)}{N(\overline{B}^0_{\rho\pi} \to \rho^-\pi^+) + N(B^0_{\rho\pi} \to \rho^+\pi^-)} = \frac{A_{CP}^{\rho\pi} + C_{\rho\pi} + A_{CP}^{\rho\pi} \cdot \Delta C_{\rho\pi}}{1 + \Delta C_{\rho\pi} + A_{CP}^{\rho\pi} \cdot C_{\rho\pi}}$$

$$A_{+-} = -0.62^{+0.24}_{-0.28} \pm 0.06$$

$$A_{-+} = -0.11^{+0.16}_{-0.17} \pm 0.04$$





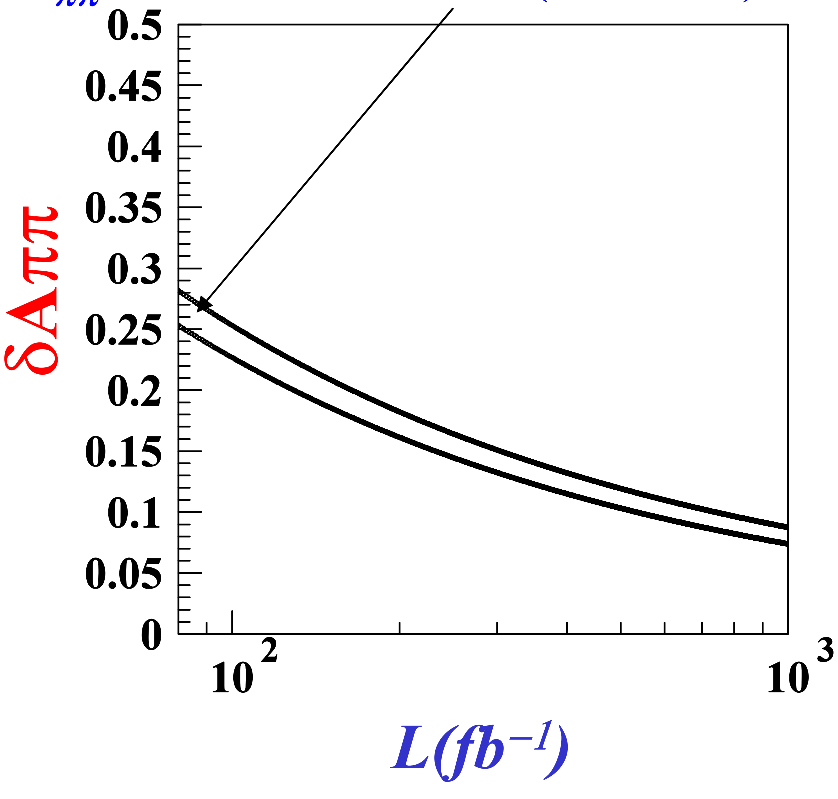
Comparison with predictions

BaBar:	QCDF:	w/ Charming Penguin(CP):
$A_{\rho\pi}$ = -0.18 ± 0.08 ± 0.03 $C_{\rho\pi}$ = +0.36 ± 0.15 ± 0.04 $\Delta C_{\rho\pi}$ = +0.28 ± 0.19 ± 0.04	$A_{\rho\pi}$ = -0.015 $C_{\rho\pi}$ = 0.019 $\Delta C_{\rho\pi}$ = 0.250	$S_{\rho\pi}$ = -0.015 $C_{\rho\pi}$ = 0.092 = 0.228
	Phys. Rev. D67,094019, 2003	

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

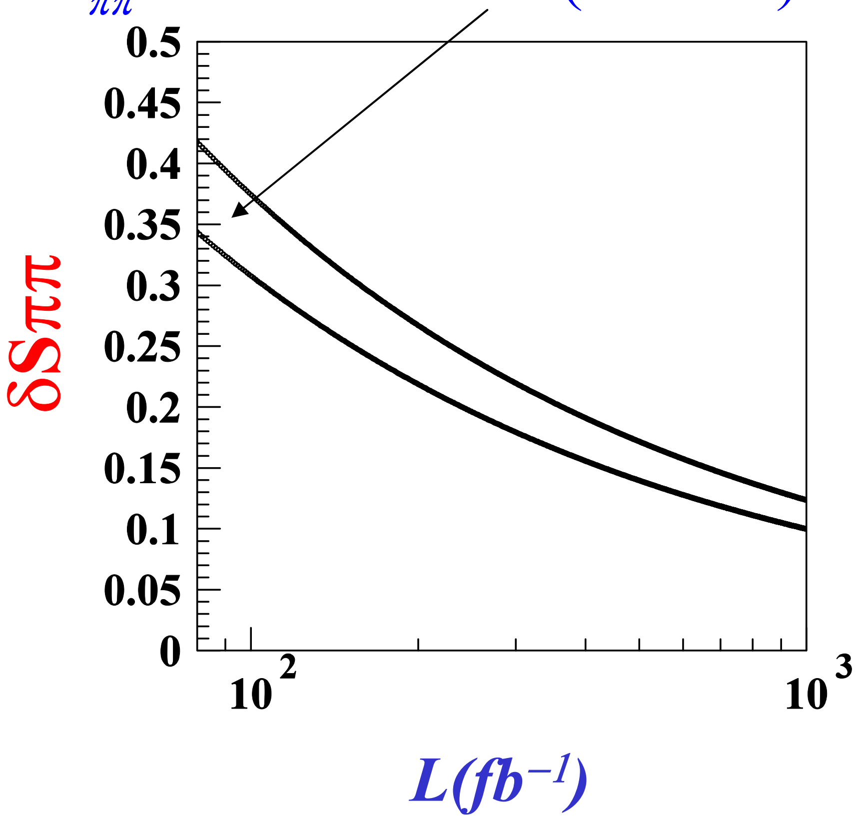
$A_{\pi\pi} = +0.77 \pm 0.28$ (***Belle***)

$A_{\pi\pi} = +0.30 \pm 0.25$ (***BaBar***)

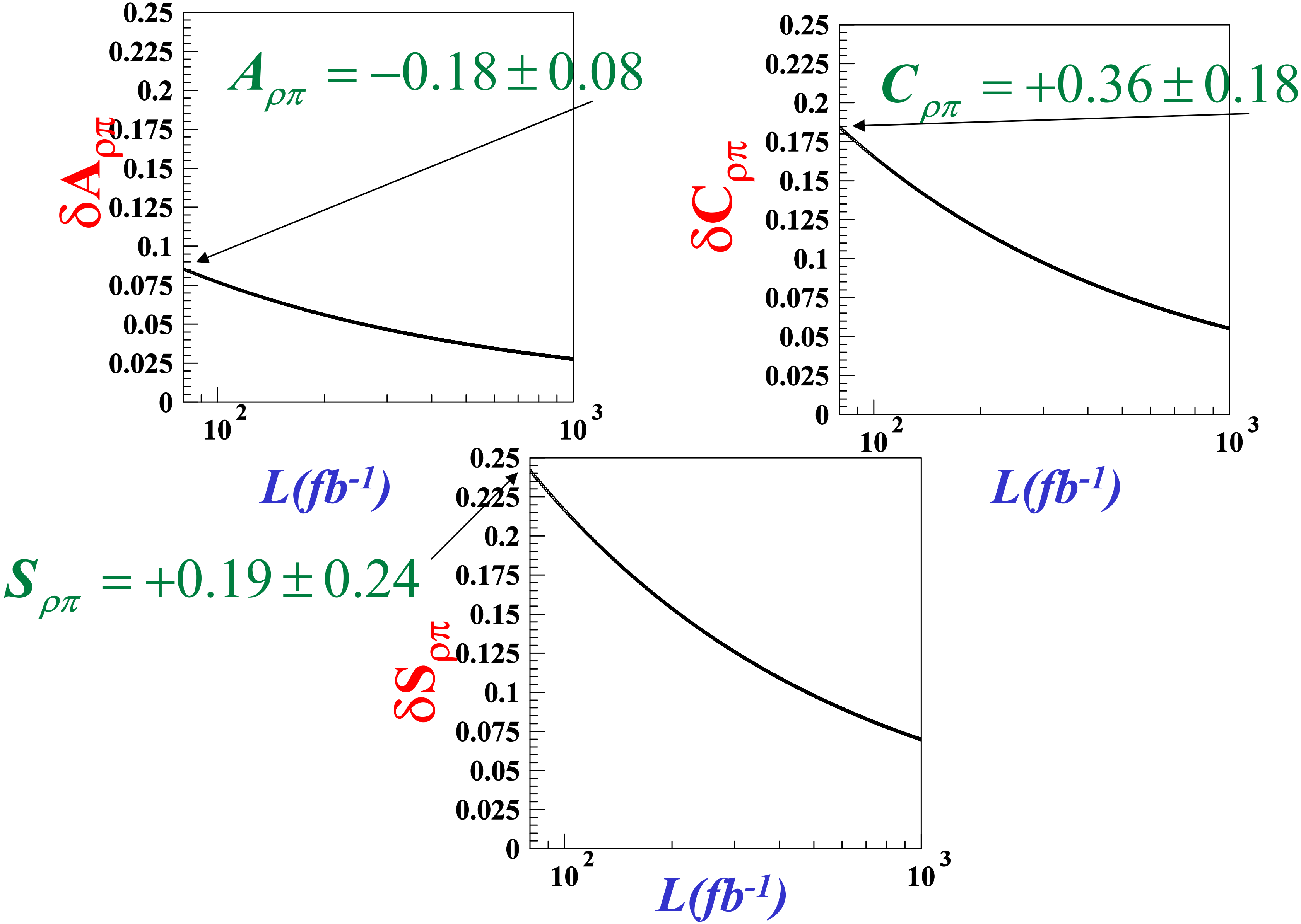


$S_{\pi\pi} = -1.23 \pm 0.42$ (***Belle***)

$S_{\pi\pi} = +0.02 \pm 0.34$ (***BaBar***)



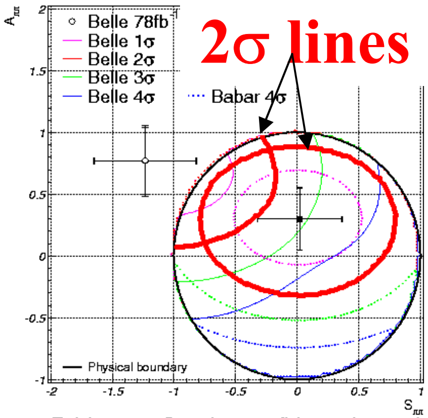
Prospect ($B^0 \rightarrow \rho\pi$)



Summary

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

	$C_{\pi\pi} (= -A_{\pi\pi})$	$S_{\pi\pi}$
Belle	$-0.77 \pm 0.27 \pm 0.08$	$-1.23 \pm 0.41^{+0.08}_{-0.07}$
BaBar	$-0.30 \pm 0.25 \pm 0.04$	$+0.02 \pm 0.34 \pm 0.05$

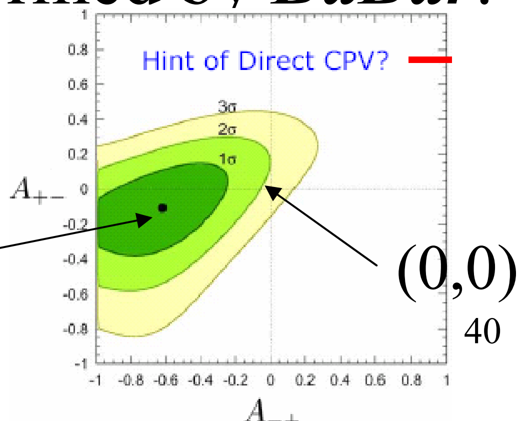


Feldman & Cousins confidence interval

  - Still early to say conclusively for the difference.

- **Measurement of CP asymmetries in $B^0 \to \rho\pi$**
  - Quasi-two-body analysis was performed by ***BaBar***.
  - Hint of Direct CPV ?

$$A_{-+} = -0.62^{+0.24}_{-0.28} \pm 0.06$$
$$A_{+-} = -0.11^{+0.16}_{-0.17} \pm 0.04$$



end