Measurement of CKM angle ϕ_2/α from Belle

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for the Belle collaboration

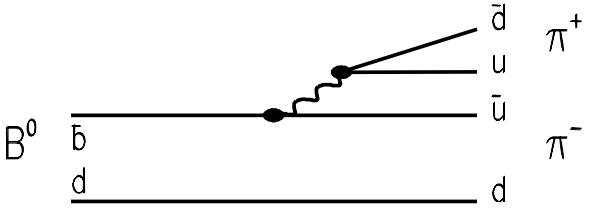
Beauty2005, June 20-24, Assisi, Italy

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

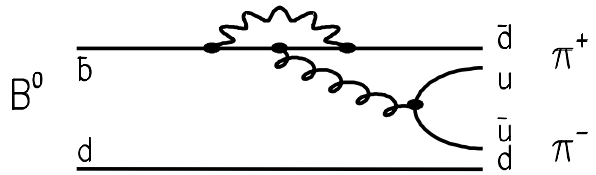
$S_{\pi\pi}$: B^0B^0 mixing induced CPV

$$A_{CP} = \frac{\Gamma(\overline{B^0}(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B^0}(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = S_{\pi\pi} \sin(\Delta m_d \Delta t) + A_{\pi\pi} \cos(\Delta m_d \Delta t)$$

$A_{\pi\pi}$: direct CPV



Tree



Penguin

In $B^0 \to \pi^+\pi^-$ decays, $S_{\pi\pi}$ is sensitive to ϕ_2 (α):

$$S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}^2}\, \sin 2(\phi_2 + \theta)$$

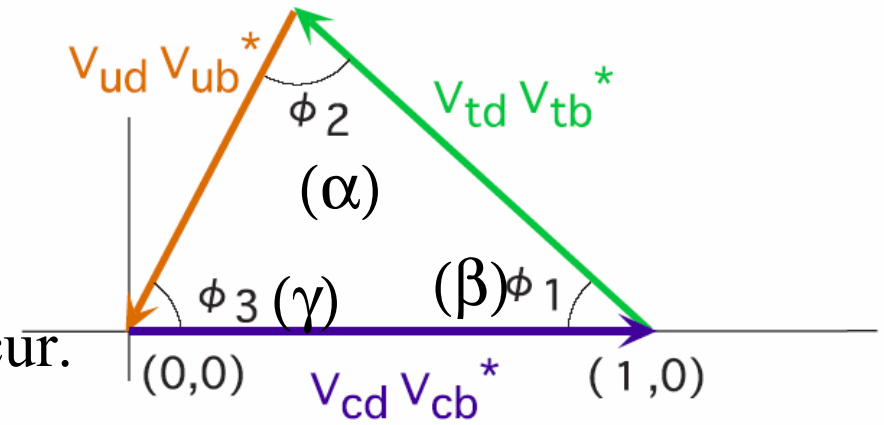
ϕ_{eff} = =

θ can be determined with isospin relations

Direct CP violation $A_{\pi\pi} \neq 0$ may occur.

Note; $\phi_2 = \alpha$

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



CP asymmetry measurement

b→uud transition, sensitive to ϕ_2

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

Less penguin ambiguity
But challenging
experimentally…..

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

275M BB events(253/fb)

Result updated on Moriond EW 2005

Previous result PRL 93, 021601 (2004)

152 M $B\bar{B}$ with 372 ± 32 $B^0 \to \pi^+\pi^-$ events

$$S_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07$$
$$A_{\pi\pi} = +0.58 \pm 0.15 \pm 0.07$$

CPV with 5.2σ,
3.2σ evidence for DCPV

Analysis flow

1) $B^0 \to \pi^+\pi^-$ selection

Pion Identification using aerogel and dE/dx

$$\varepsilon(\pi) \cong 90\% \quad p(K \to \pi) \cong 11\%$$

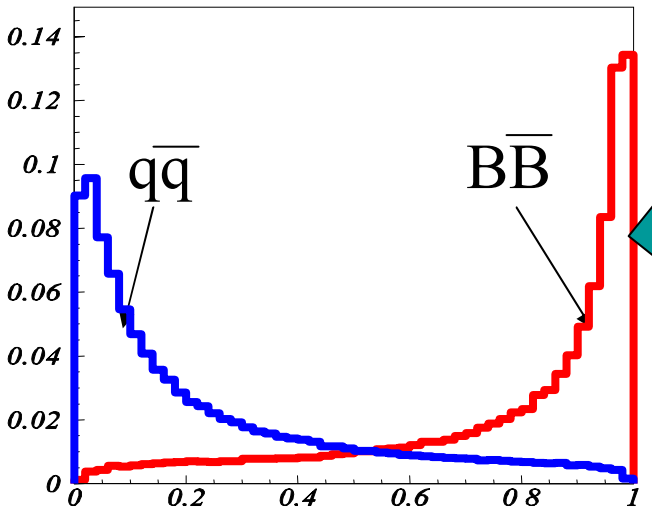
Kinematical Selection

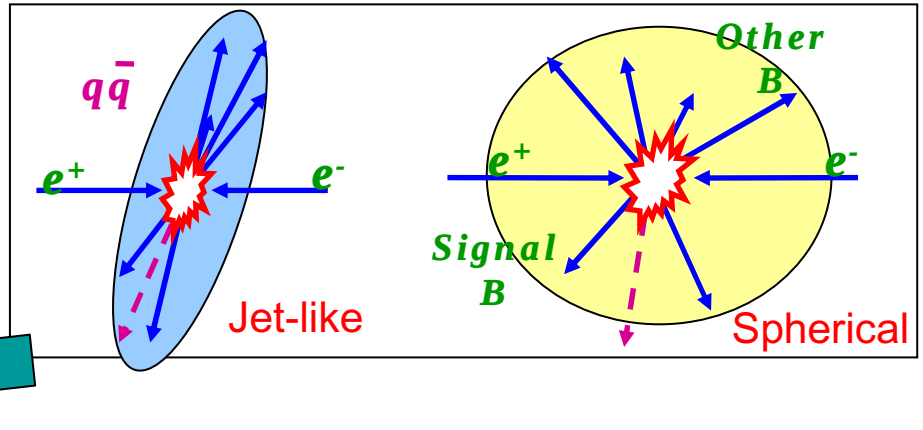
$$\Delta E = E_B^{CMS} - E_{beam}^{CMS} \qquad M_{bc} = \sqrt{(E_{beam}^{CMS})^2 - (p_B^{CMS})^2}$$

2) Continuum suppression

$e^+e^- \to q\bar{q}, (q = u, d, s, c)$

$$LR = \frac{\mathcal{L}_{B\bar{B}}}{\mathcal{L}_{B\bar{B}} + \mathcal{L}_{q\bar{q}}}$$





Fisher discriminant from Fox-Wolfram moments and B flight direction with beam axis

Analysis flow (cont)

3)Flavor Tagging

q: flavor charge

q=+1 tagged as a B^0,
q=−1 tagged as a $\overline{B}^0$

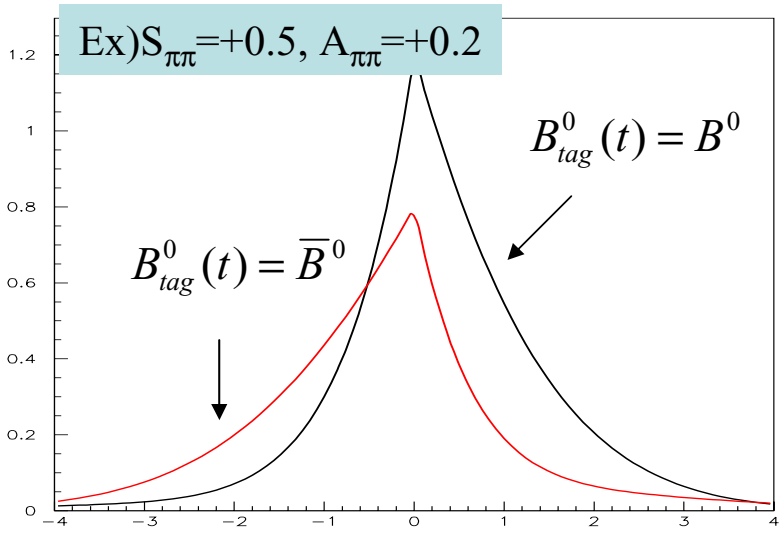
r: flavor tag quality
$0<r\leq 1$

r=0 no flavor discrimination,
r=1 unambiguous flavor assignment

Same as $\phi_1(\beta)$ measurement

4)Vertex reconstruction

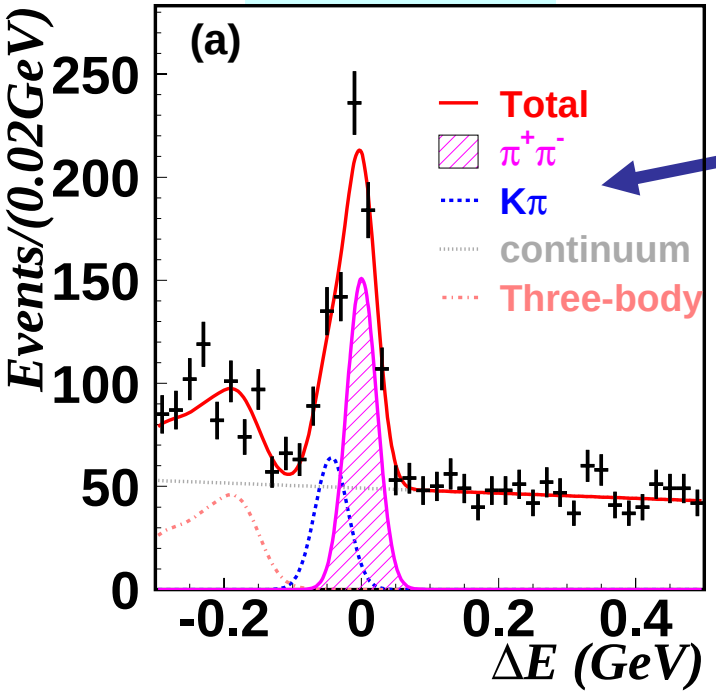
To get Δt information, recon. Both B vertices

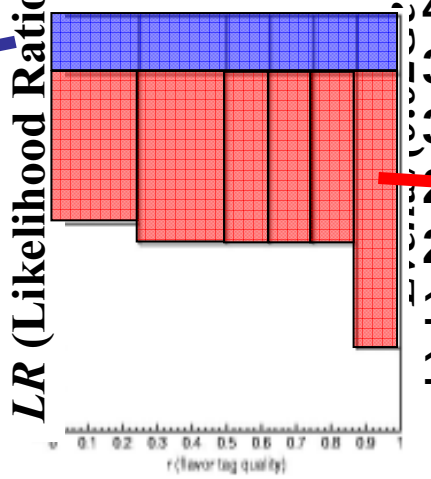


5)Fit CP asymmetry!

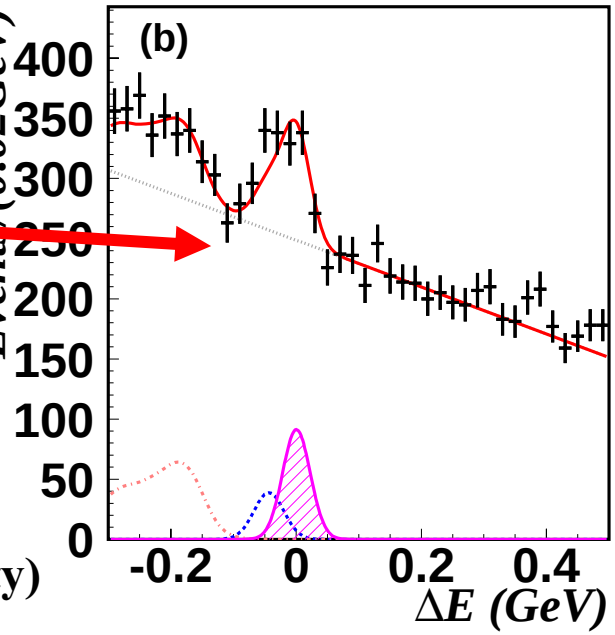
$B^0 \to \pi^+\pi^-$ signals

(LR>0.86)





(LR<0.86)



$$5.271 < M_{bc} < 5.287 GeV/c^2 \qquad |\Delta E| < 0.064 GeV$$

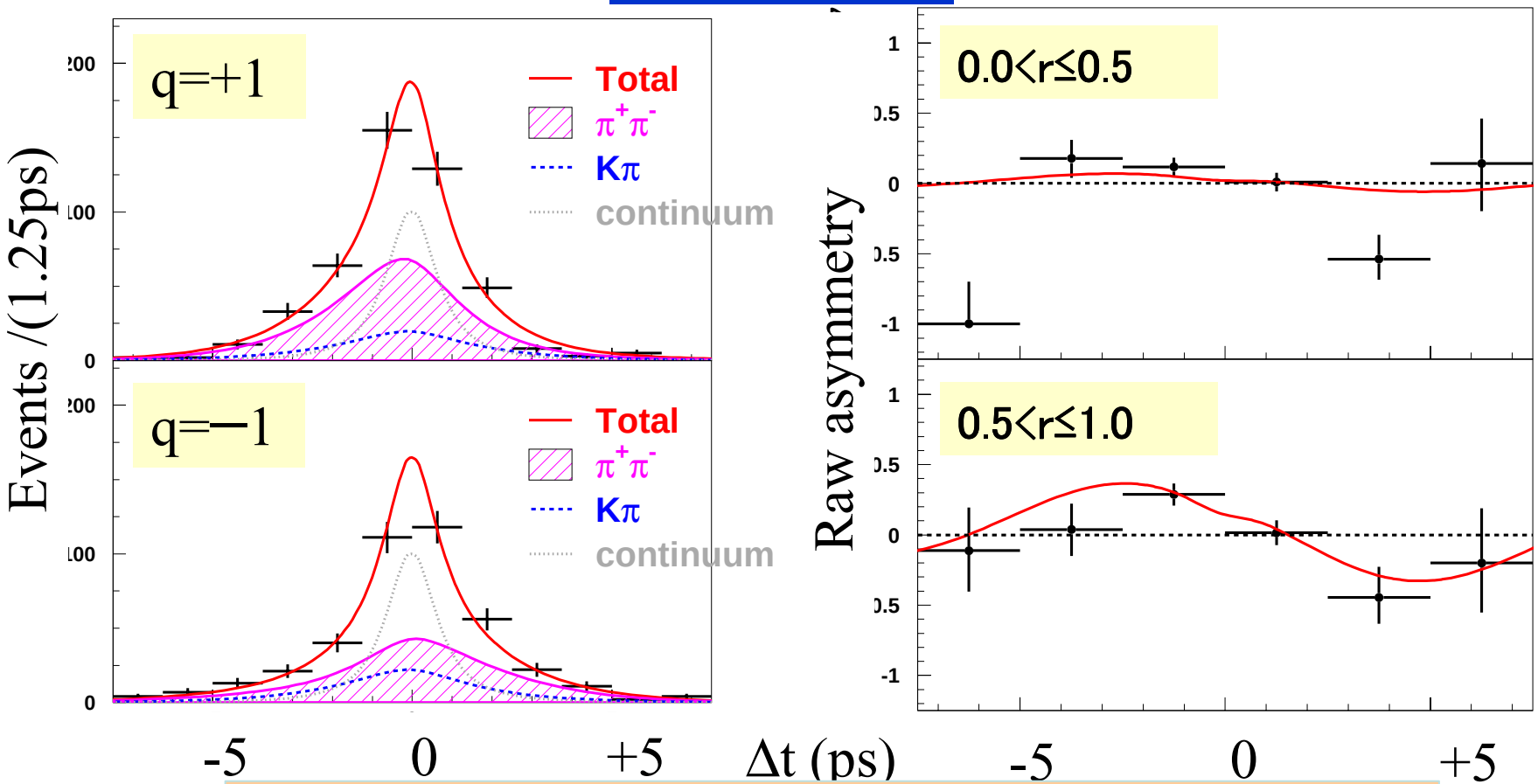
(corresponding $\pm 3\sigma$)

2,820 candidates containing **(666 ± 43)** $\pi^+\pi^-$ signal events

Obtained by an unbinned 2 D maximum likelihood fitting to ΔE-M_{bc}

Δt distribution and raw asymmetry

LR>0.86

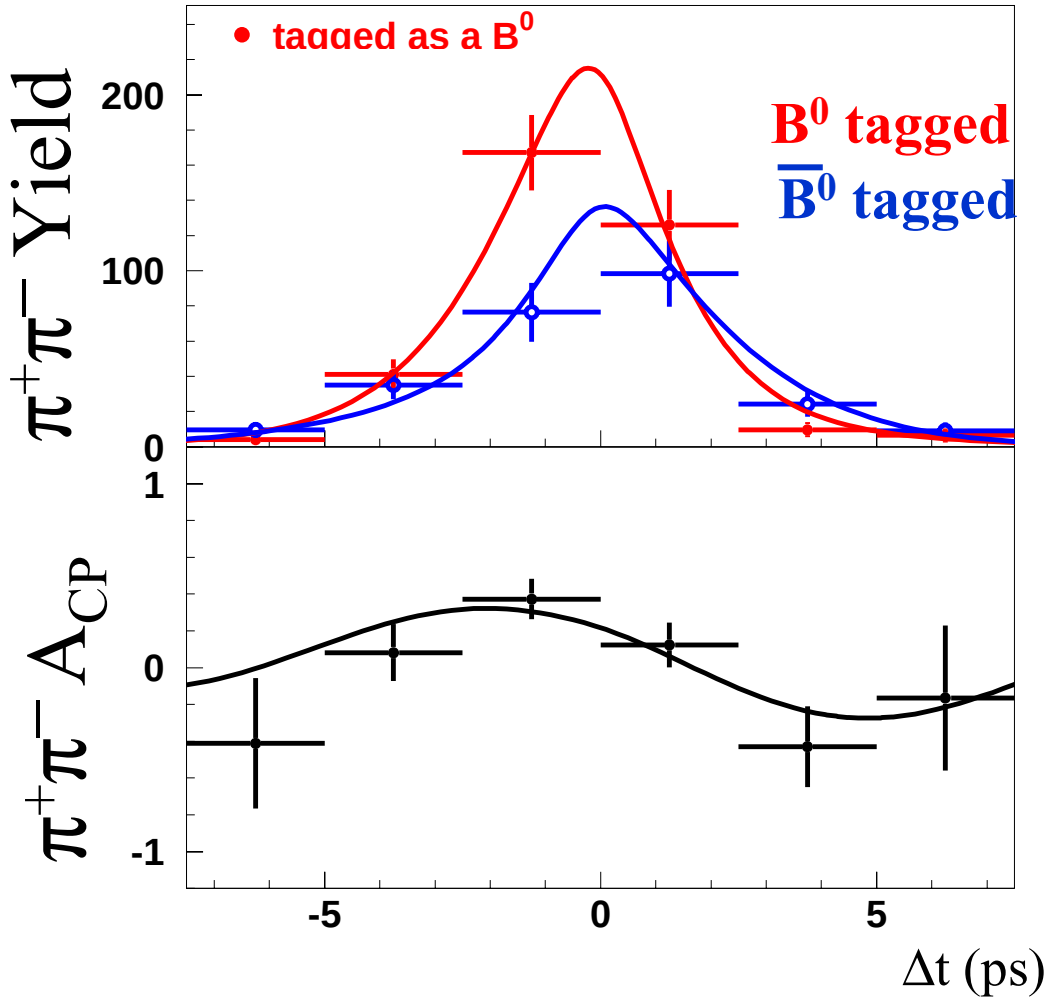


$$A_{\pi\pi} = +0.56 \pm 0.12\,(\text{stat}) \pm 0.06\,(\text{syst})$$

$$S_{\pi\pi} = -0.67 \pm 0.16\,(\text{stat}) \pm 0.06\,(\text{syst})$$

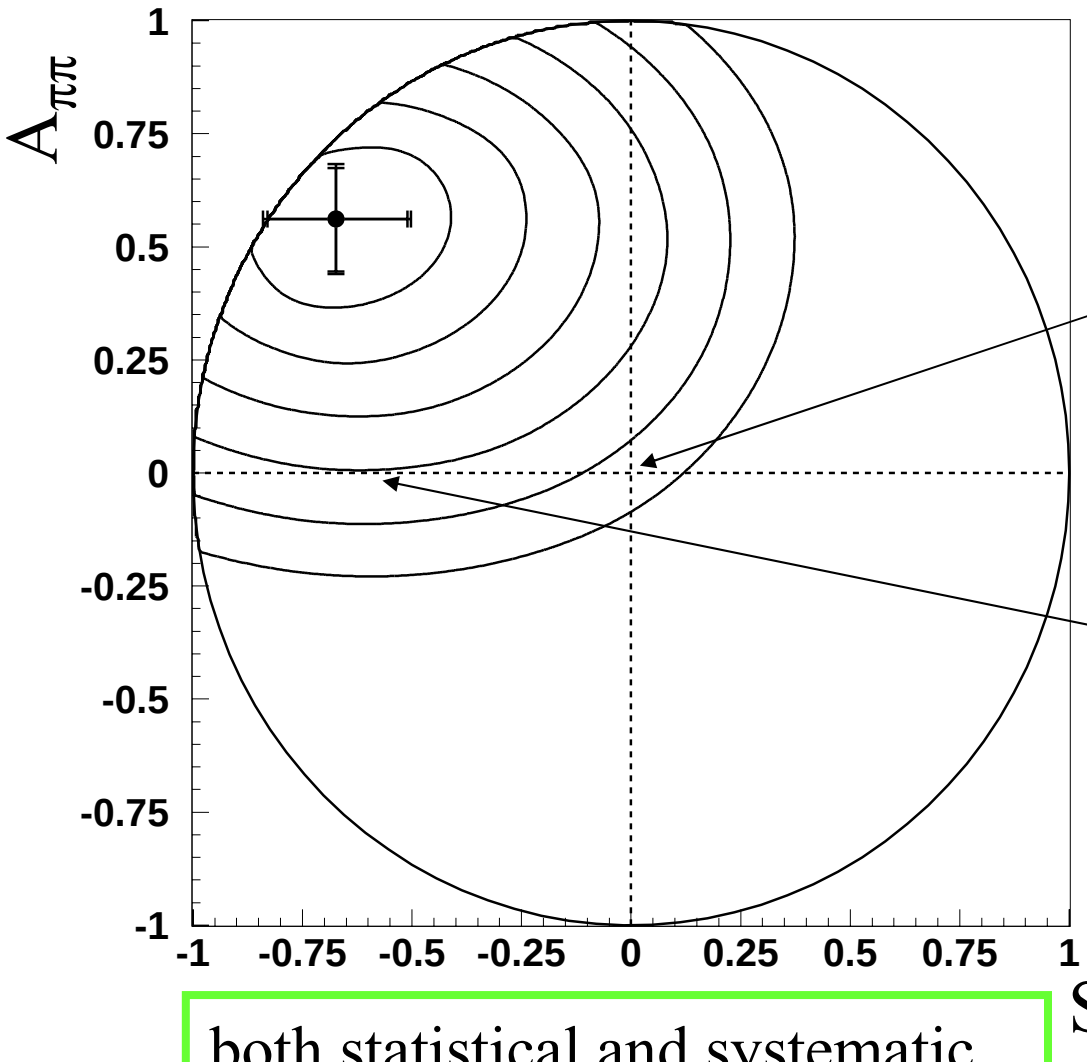
Unbinned CP Fit Result

Background subtracted fit projection for all events



Points: ΔE-Mbc 2D fits to individual time intervals

Significance calculation with Feldman–Cousins method



Large CP Violation,

(A,S)=(0,0)
1-C.L.=5.62×10^{-8}, 5.4σ

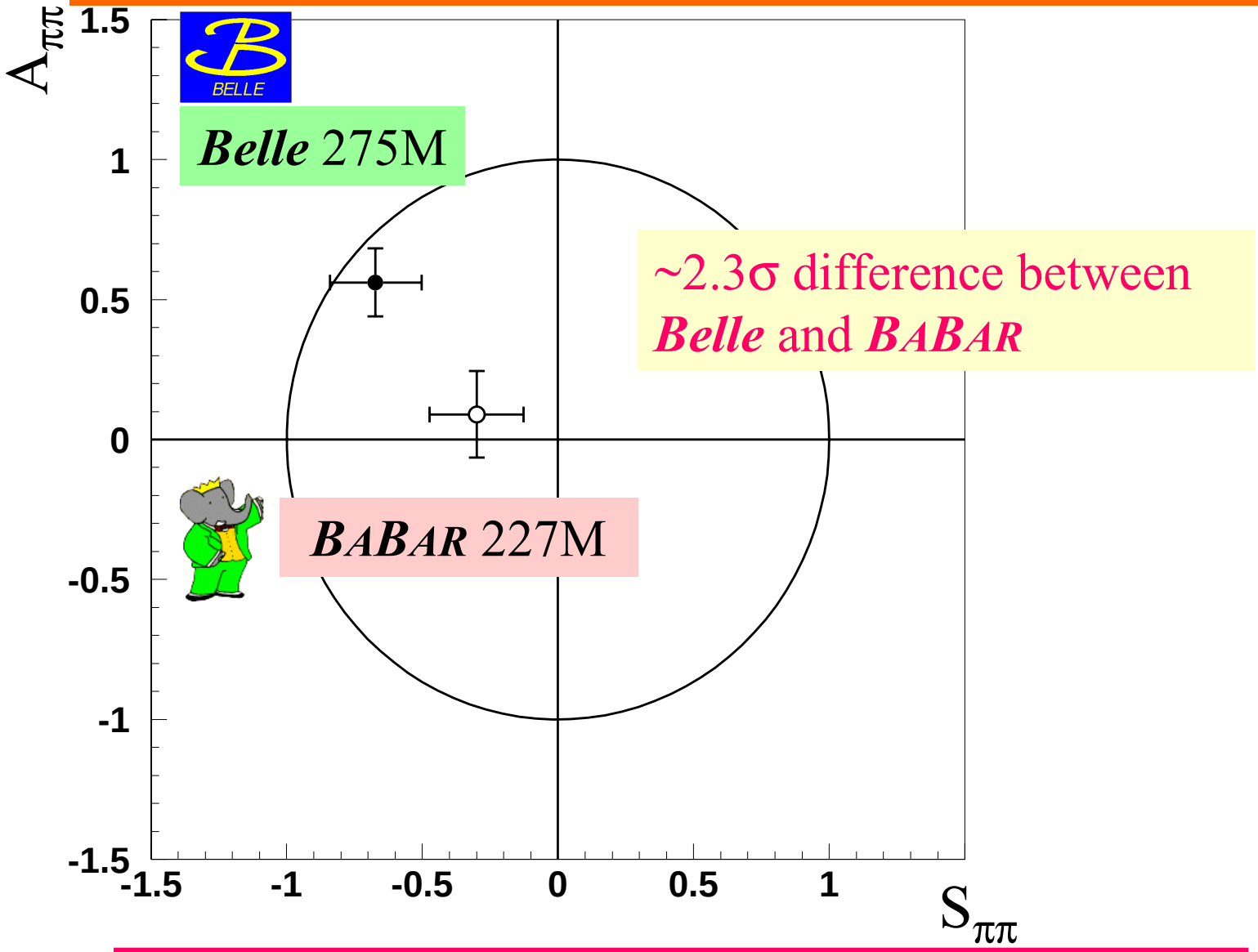
(A,S)=(0,−0.62)
1-C.L.=5.13×10^{-5}, 4.0σ

Large Direct CP violation, confirmation of the previous Belle results

both statistical and systematic errors are taken into account.

C.L. = Confidence Level

Experimental situation



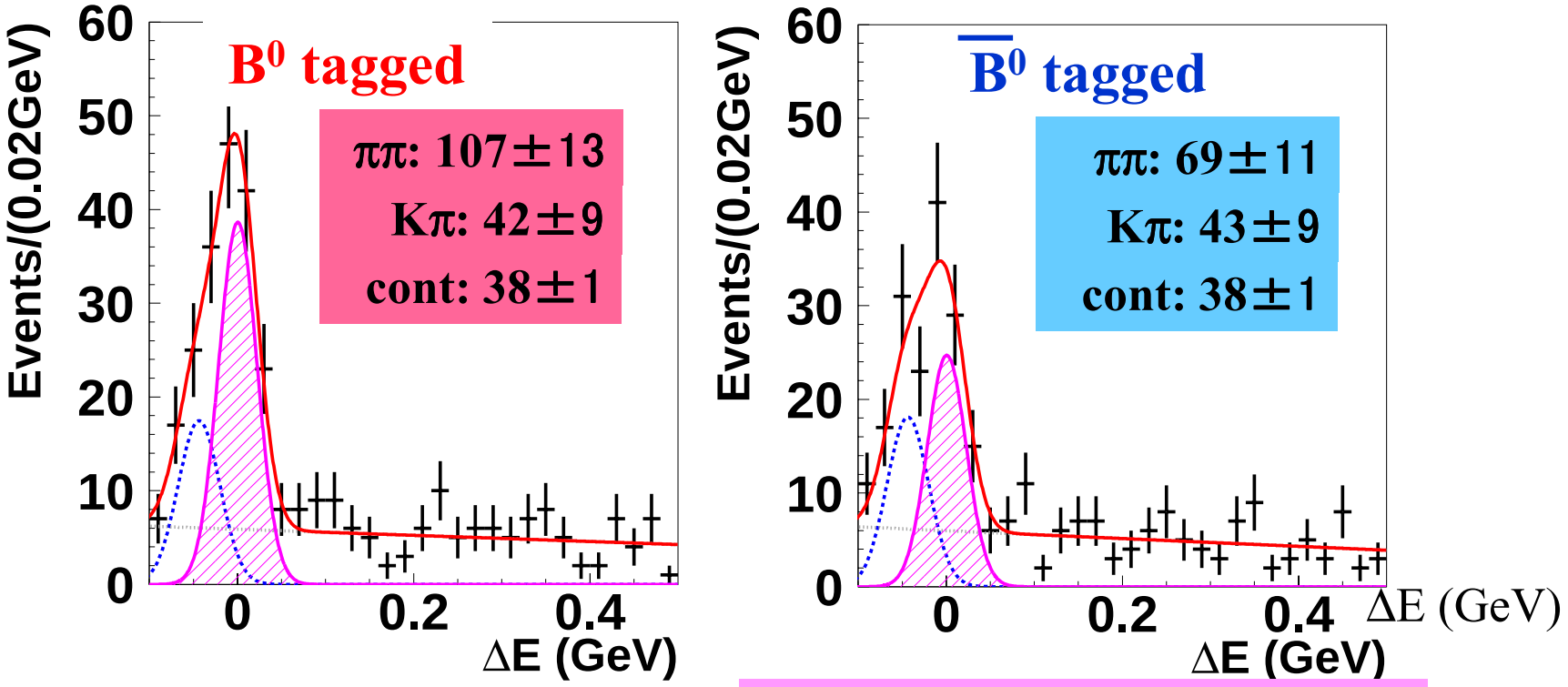
Our result: Large Direct CP Violation is apparent

Consistency checks with Time-integrated fits

$A_{\pi\pi} = +0.52 \pm 0.14$

consistent with time-dependent fit

LR>0.86 & 0.5<r≤1.0 (high likelihood and high tag quality region)



Expectation from SU(3) symmetry

$$A_{CP}(K^+\pi^-) = -\frac{1}{3} A_{CP}(\pi^+\pi^-)$$

M.Gronau, J.L.Rosner,PLB 595,339(2004)

$$-\frac{1}{3} A_{CP}(\pi^+\pi^-) = -0.19 \pm 0.04$$

$$A_{CP}(K^+\pi^-) = -0.109 \pm 0.019$$

HFAG Summer 2004

Interpretation: |P/T| and δ

$$A(B^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{i\phi_3} + |P|e^{i\delta_P}),$$
$$A(\overline{B}^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{-i\phi_3} + |P|e^{i\delta_P}),$$

convention taken from
M.Gronau and J.L.Rosner
Phys. Rev. D65, 093012 (2002)

$$\lambda_{\pi\pi} = e^{i2\phi_2}\frac{1+|P/T|e^{i(\delta+\phi_3)}}{1+|P/T|e^{i(\delta-\phi_3)}}$$

4 parameters

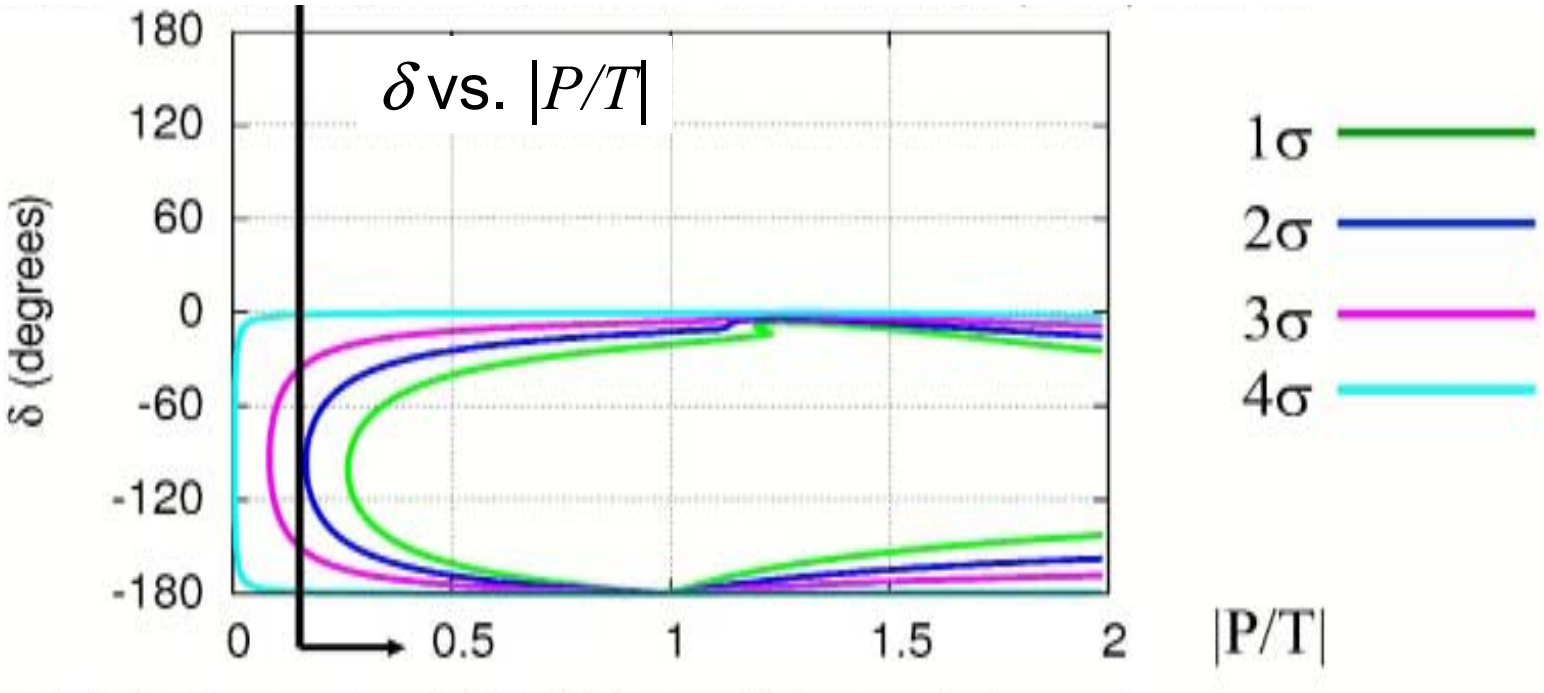
$$S_{\pi\pi} = [\sin 2\phi_2 + 2|P/T|\sin(\phi_1 - \phi_2)\cos\delta - |P/T|^2 \sin 2\phi_1]/R_{\pi\pi},$$
$$A_{\pi\pi} = -[2|P/T|\sin(\phi_1+\phi_2)\sin\delta]/R_{\pi\pi},$$
$$R_{\pi\pi} = 1 - 2|P/T|\cos(\phi_1+\phi_2)\cos\delta + |P/T|^2$$

$\delta \equiv \delta_P - \delta_T$
Strong phase difference

$\|P/T\|$	Theory ~0.15~0.45 M.Gronau and J.L.Rosner PRD 65, 013004 (2002), YY.Keum, H.-N.Li and A.I.Sanda PRD 63, 054008 (2001)
$\sin 2\phi_1$	0.736 ± 0.049 (HFAG Summer2003)

Interpretation: |P/T| and δ

We scan ϕ_2 with a constraint of $0^\circ < \phi_1 + \phi_2 < 180^\circ, \quad \phi_1 = (23.5 \pm 1.6)^\circ$
to search for the minumim C.L. for various |P/T| and δ



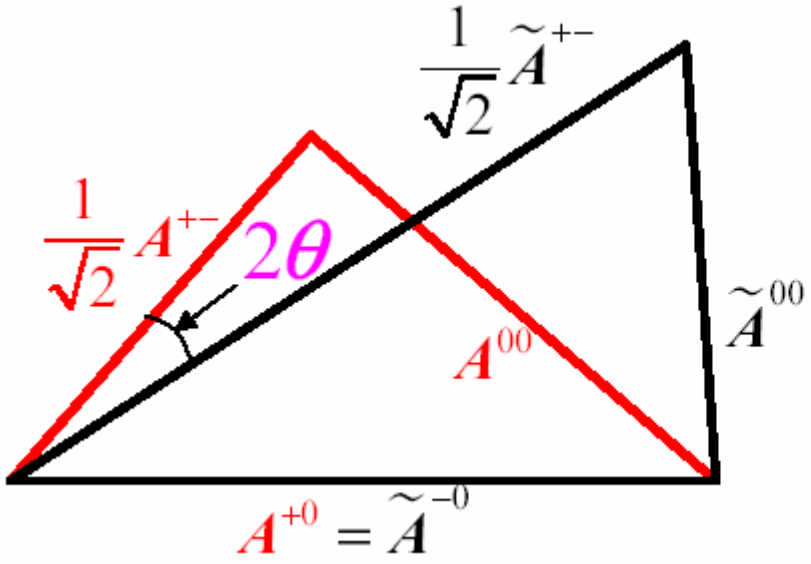
Results support Large penguin magnitude and negative strong phase

Model-independent 95.4% confidence interval

$$|P/T| > 0.17 \ , \quad -180^\circ < \delta < -4^\circ$$

Interpretation: ϕ_2 constraint using isospin

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



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

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

The cleanest method to extract ϕ_2

$$S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}^2}\,\sin 2(\phi_2 + \theta)$$

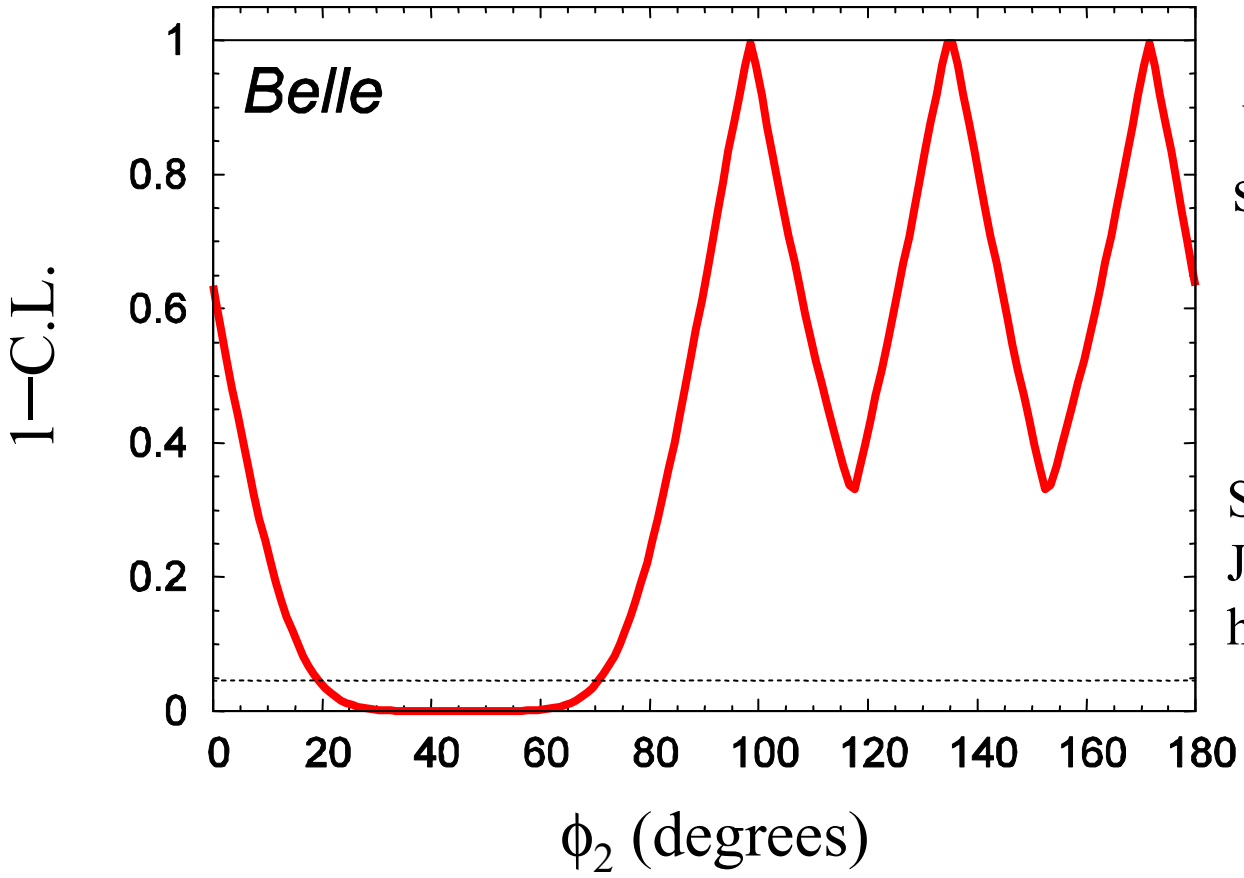
$$Br(\pi^0\pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$$

$$A_{CP}(\pi^0\pi^0) = +0.44^{+0.53}_{-0.52} \pm 0.17$$

Use summer 2004 values

hep-ex/0412037, appear to PRL

Interpretation : ϕ_2 constraint using isospin



using HFAG
summer 2004

Statistical treatment
J. Charles *et al.*,
hep-ph/0406184

95.4% confidence interval

$0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$

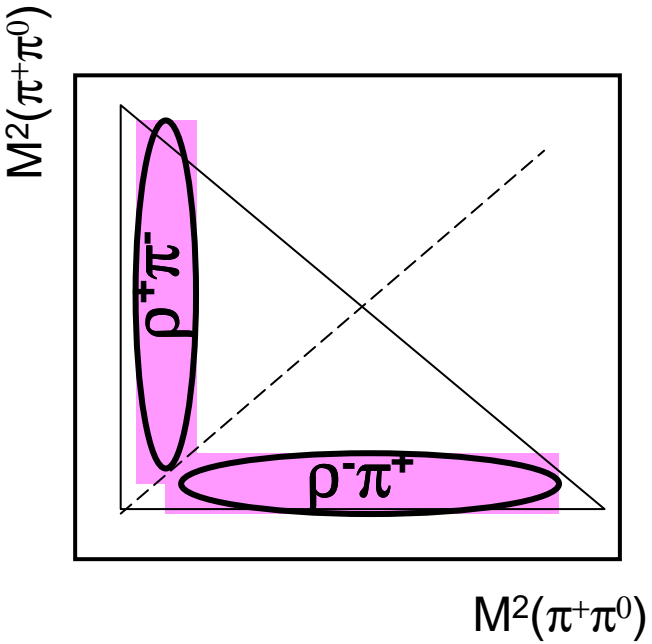
$B^0 \to (\rho\pi)^0$ CP analysis (brief result)

Full Dalitz analysis not done yet.

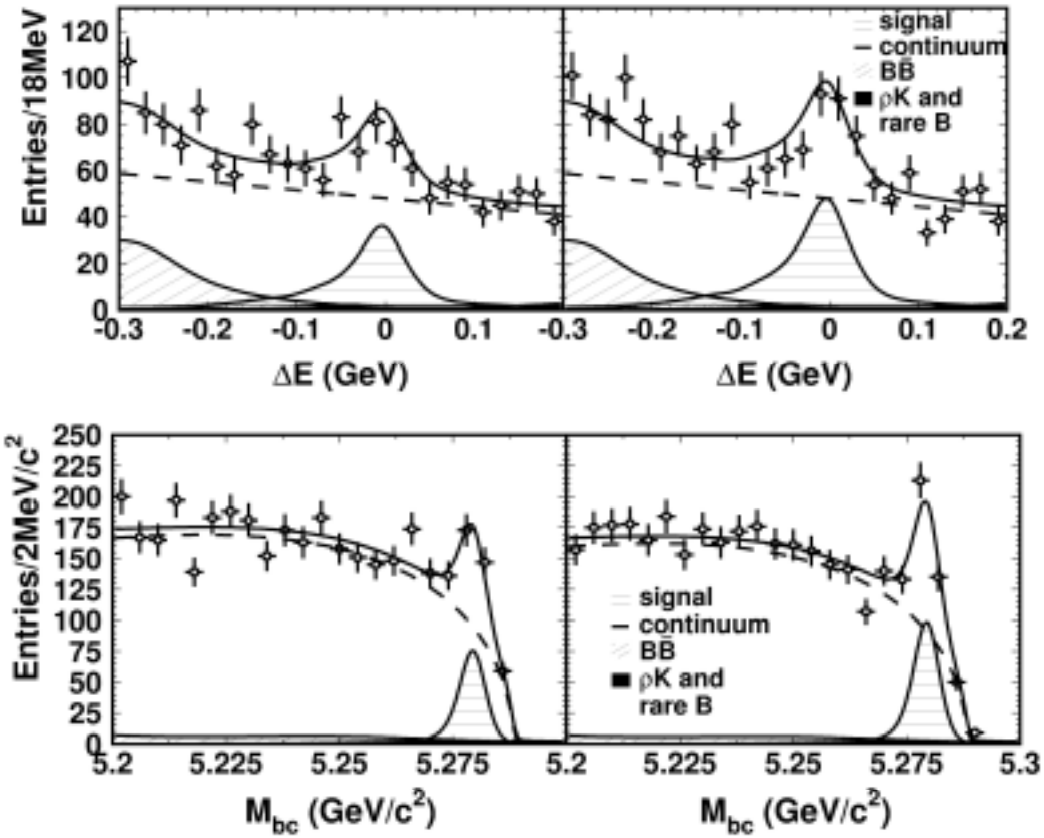
Result on Summer 2004

Use signals with applying cuts on the interference regions

$$P_q^{\rho^\pm\pi^\mp}(\Delta t) = (1 \pm A_{CP}^{\rho\pi}) \frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}} \{1 + q[(S_{\rho\pi} \pm \Delta S_{\rho\pi})\sin(\Delta m_d t) - (C_{\rho\pi} \pm \Delta C_{\rho\pi})\cos(\Delta m_d t)]\}$$



$B^0 \to \rho^+\pi^-$ $B^0 \to \rho^-\pi^+$ **152M BB**



$B^0 \to (\rho\pi)^0$ CP analysis (brief result)

$$A_{CP} = -0.16 \pm 0.10 \pm 0.02$$

$$S_{\rho\pi} = -0.28 \pm 0.23^{+0.10}_{-0.08}$$

$$C_{\rho\pi} = 0.25 \pm 0.17^{+0.02}_{-0.06}$$

$$\Delta S_{\rho\pi} = -0.30 \pm 0.24 \pm 0.09$$

$$\Delta C_{\rho\pi} = 0.38 \pm 0.18^{+0.02}_{-0.04}$$

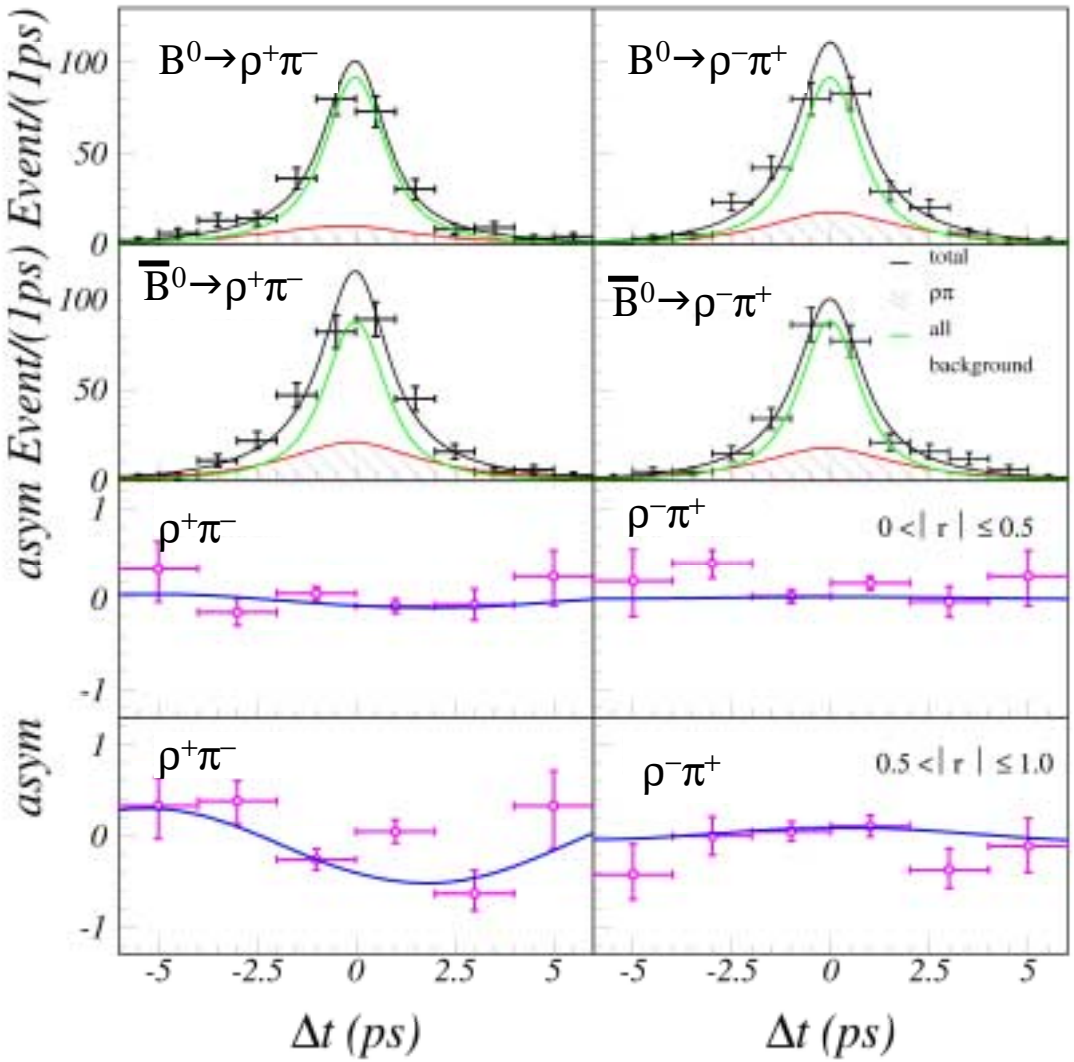
From SU(3) constraint
M.Gronau&J.Zupan:PRD70,074031(2004)

$$\phi_2 = (102 \pm 13 \pm 15)^\circ$$

PRL 94, 121801 (2005)

152M $B\bar{B}$

349 $\rho\pi$ **7 $K\pi$** **903 $q\bar{q}$**



Summary of Belle ϕ_2 measurement results

- **$B^0 \to \pi^+\pi^-$ CP analysis with 275M BB**

$$A_{\pi\pi} = +0.56 \pm 0.12(stat) \pm 0.06(syst)$$
$$S_{\pi\pi} = -0.67 \pm 0.16(stat) \pm 0.06(syst)$$

[hep-ex/0502035] accepted and appear to PRL soon

- Large direct CP violation with 4.0σ significance is observed
- The results confirm the previous Belle results.
- Isospin analysis gives at 95.4% C.L.

$$0^\circ < \phi_2 < 19^\circ, \quad 71^\circ < \phi_2 < 180^\circ$$

- The result is consistent with UT fit value,

$$\phi_2 = 180^\circ - \phi_1 - \phi_3 = (89 \pm 23)^\circ$$

See you at LP05

Backup slides

Systematic errors

	$S_{\pi\pi}$	$A_{\pi\pi}$
wrong tag	±0.01	±0.01
physics param.	<0.01	±0.01
resolution func.	±0.04	±0.01
bkg Δt shape	<0.01	<0.01
event fraction	±0.02	±0.04
fit bias	±0.01	±0.01
vertexing	±0.04	+0.03 −0.01
tag side interfere	±0.01	+0.02 −0.04
total	±0.06	±0.06

including uncertainties in the b.k.g and Final State Radiation

O. Long, M. Baak, R.N. Cahn, and D. Kirkby, PRD 68, 034010 (2003)

Interpretation of direct CP violation

$$A_{CP}(K^+\pi^-) = -\frac{1}{3} A_{CP}(\pi^+\pi^-)$$

M.Gronau, J.L.Rosner,
PLB 595,339(2004)

$$A_{CP}(K^+\pi^-) = -0.109 \pm 0.019$$

HFAG 2004 summer

Consistent

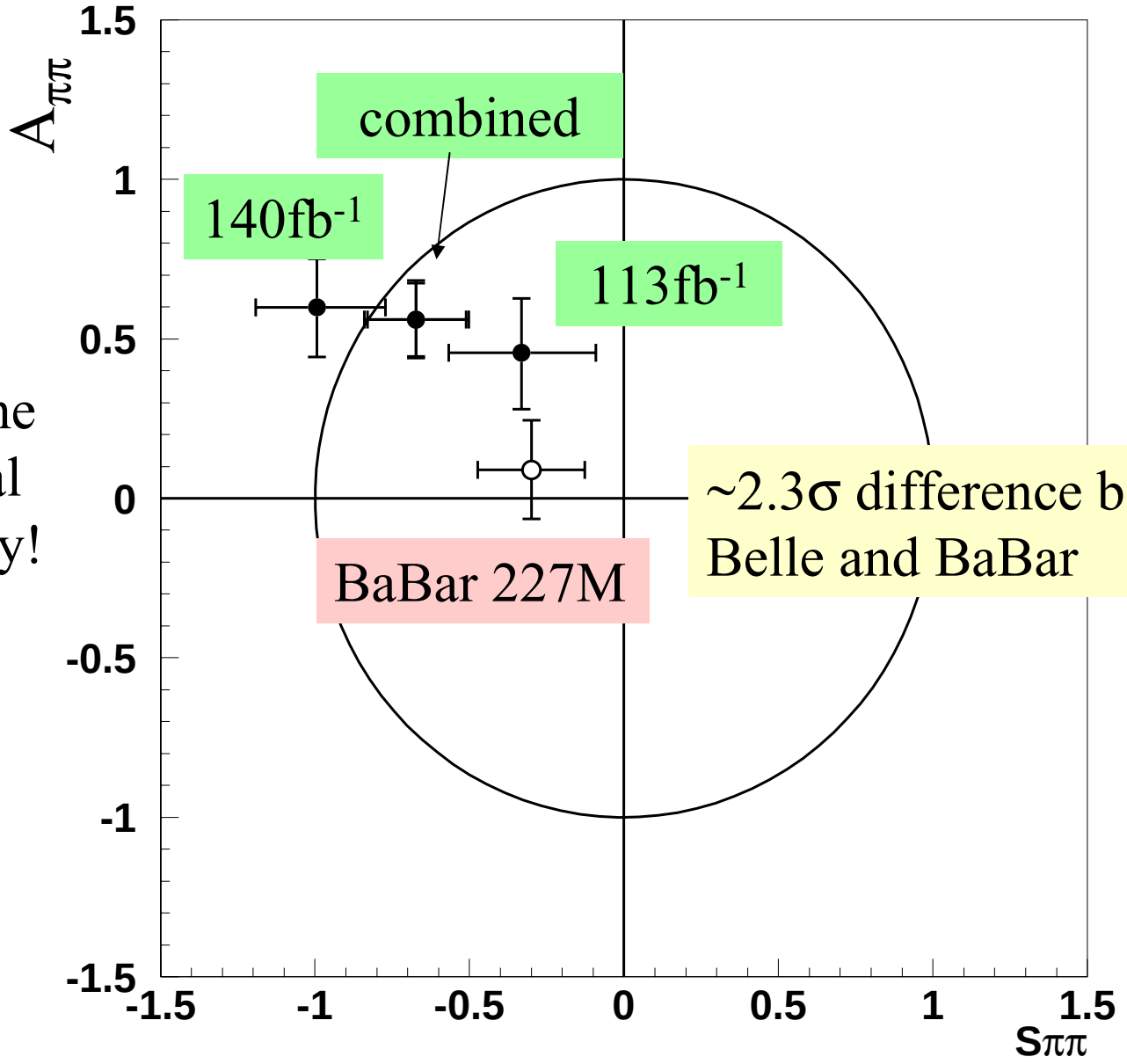
$$A_{CP}(K^+\pi^-) = -0.133 \pm 0.030 \pm 0.009$$ **Babar**

$$A_{CP}(K^+\pi^-) = -0.101 \pm 0.025 \pm 0.005$$ **Belle**

PRL 93, 191802(2004)

$$-\frac{1}{3} A_{CP}(\pi^+\pi^-) = -0.19 \pm 0.04$$

New experimental situation

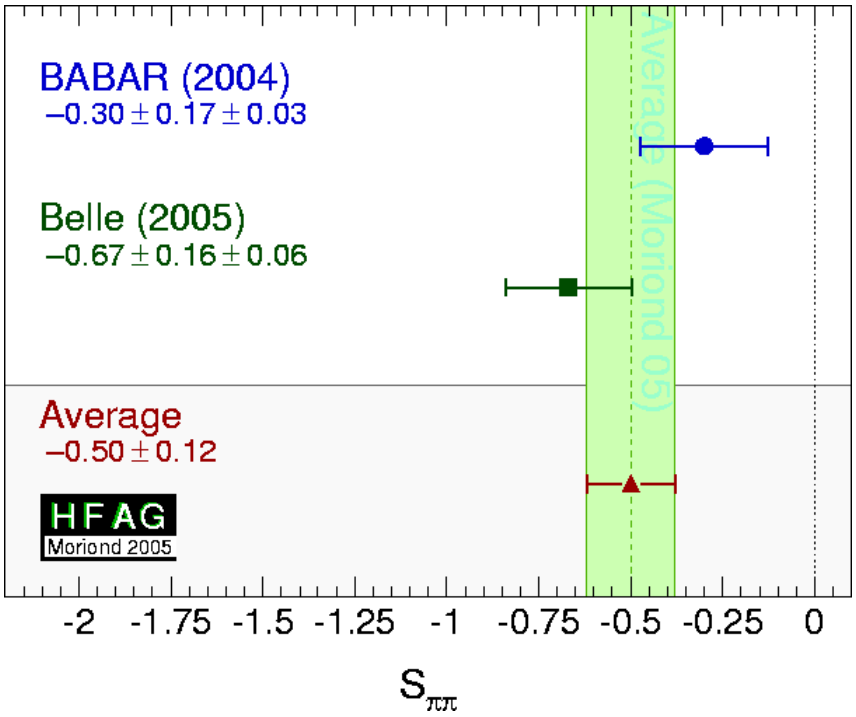


inside the physical boundary!

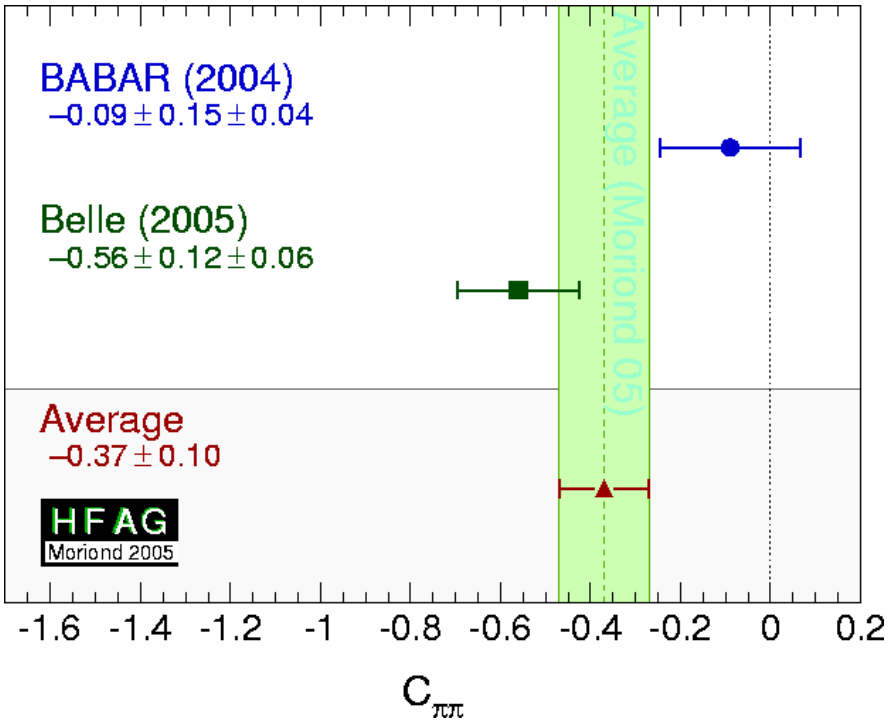
~2.3σ difference between Belle and BaBar

New experimental situation

$S_{\pi\pi}$



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



HFAG Moriond 2005

Probability Density Functions (PDFs) for the CP fit

a likelihood function

$$L = (1 - f_{ol}) \int d\Delta t' \{ (f_{\pi\pi} p_{\pi\pi} + f_{K\pi} p_{K\pi}) R_{sig}(\Delta t - \Delta t') + f_{q\bar{q}} p_{q\bar{q}} R_{q\bar{q}}(\Delta t - \Delta t') \} + f_{ol} p_{ol}(\Delta t)$$

$$f_{\pi\pi} + f_{K\pi} + f_{q\bar{q}} = 1$$

$f_{\pi\pi}, f_{K\pi}, f_{q\bar{q}}$ are event fractions as functions of ΔE and M_{bc}

$L_{tot} = \prod L(\Delta t_i, q_i)$ is maximized.

two free parameters: $A_{\pi\pi}$ and $S_{\pi\pi}$

Probability Density Functions (PDFs) for the CP fit

For $\pi^+\pi^-$

$$p_{\pi\pi}(\Delta t, q; A_{\pi\pi}, S_{\pi\pi}) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q(1-2w)[A_{\pi\pi}\cos\Delta m\Delta t + S_{\pi\pi}\sin\Delta m\Delta t]\}$$

wrong tag fraction obtained from data

For $K^+\pi^-$

$$p_{K\pi}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q(1-2w)A_{K\pi}^{eff}\cos(\Delta m\Delta t)\}$$

$$A_{K\pi}^{eff} = \frac{A_\varepsilon + A_{K\pi}}{1 + A_\varepsilon A_{K\pi}} \qquad A_\varepsilon = \frac{p(K^- \to \pi^-)\varepsilon_{\pi^+} - p(K^+ \to \pi^+)\varepsilon_{\pi^-}}{p(K^- \to \pi^-)\varepsilon_{\pi^+} + p(K^+ \to \pi^+)\varepsilon_{\pi^-}}$$

$$A_{K\pi} = -0.109 \pm 0.019 \text{ HFAG2004}$$

For $q\bar{q}$

$$p_{q\bar{q}}(\Delta t, q) = \frac{1 + q\delta_{q\bar{q}}}{2}\{f_\tau \frac{e^{-|\Delta t|/\tau_{q\bar{q}}}}{2\tau_{q\bar{q}}} + (1 - f_\tau)\delta(\Delta t)\}$$

backup

$\delta_{q\bar{q}}$ is set to 0 in default