New Results from Belle
TCPV in $B^0 \to \pi^+\pi^-$ Decays

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For the Belle Collaboration

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Aspen Winter 2005

Time dependent CP-violating parameters in $B^0 \to \pi^+\pi^-$ decays

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

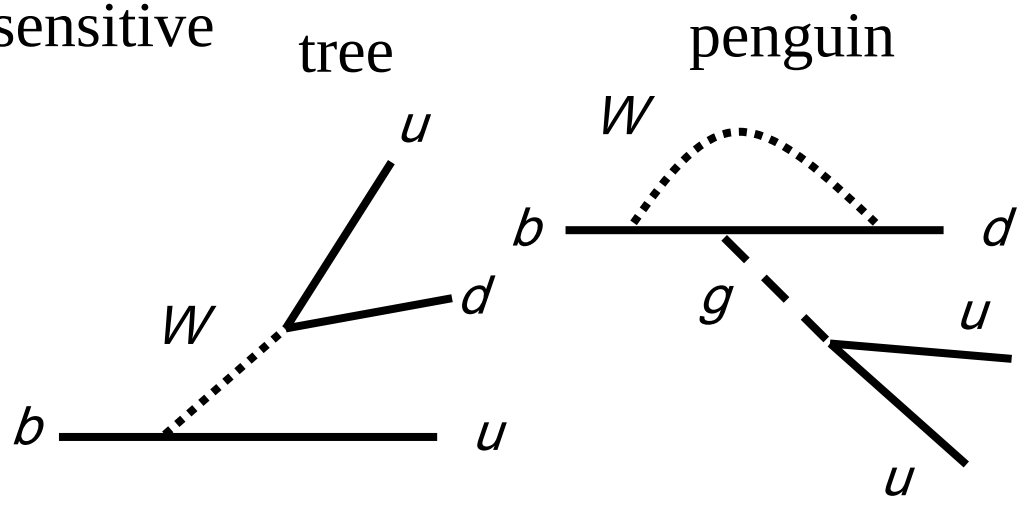
$S_{\pi\pi}$: $B^0\overline{B}^0$ mixing induced CPV

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

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

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

θ can be determined with isospin relations



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

Previous experimental situation

Belle 152 M $B\bar{B}$

with 372±32 $B^0 \to \pi^+\pi^-$ events

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

PRL 93, 021601 (2004)

BABAR 227M $B\bar{B}$

with 467±33 $B^0 \to \pi^+\pi^-$ events

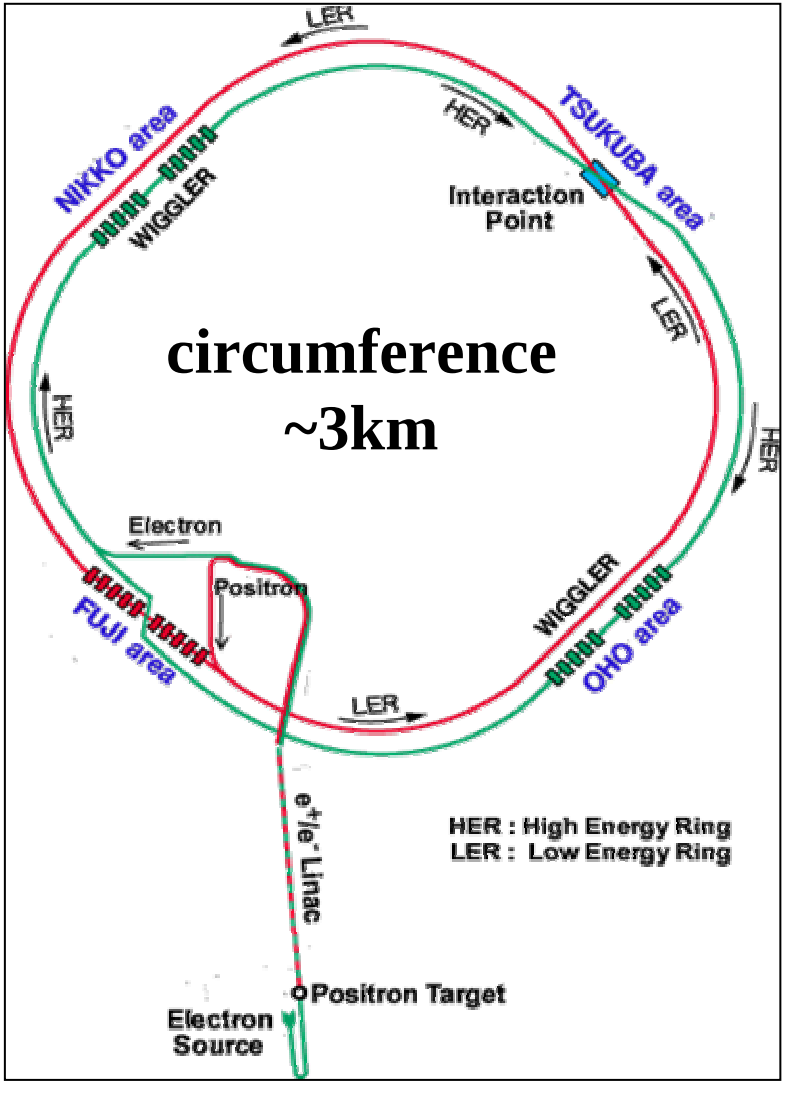
$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$A_{\pi\pi} = +0.09 \pm 0.15 \pm 0.04$$

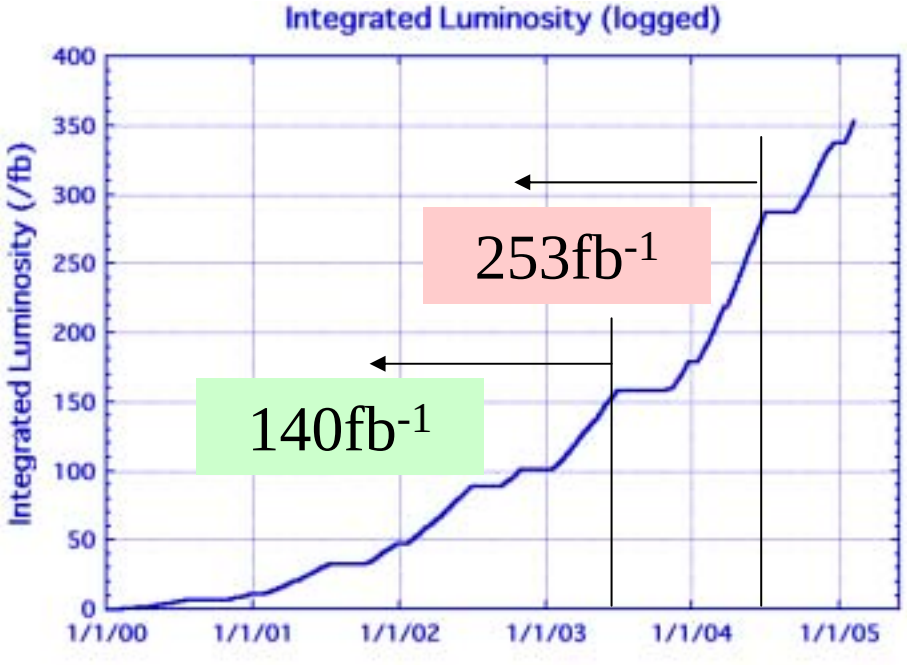
hep-ex/0501071

CPV with 5.2σ,
3.2σ evidence for DCPV

3.2σ difference

KEKB accelerator



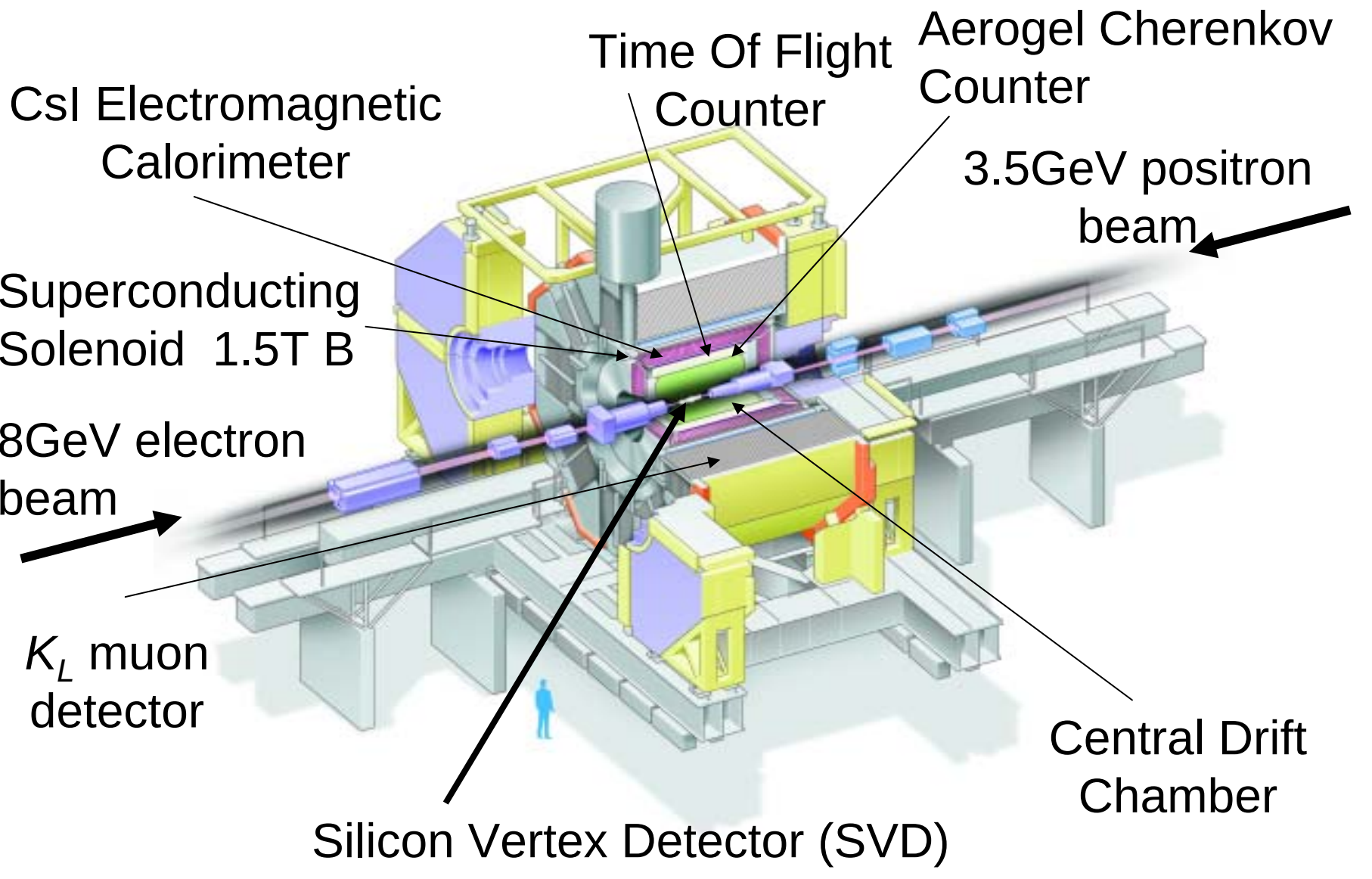


The e^- (8GeV) e^+ (3.5GeV) beams are collided at the central position of the Belle detector.

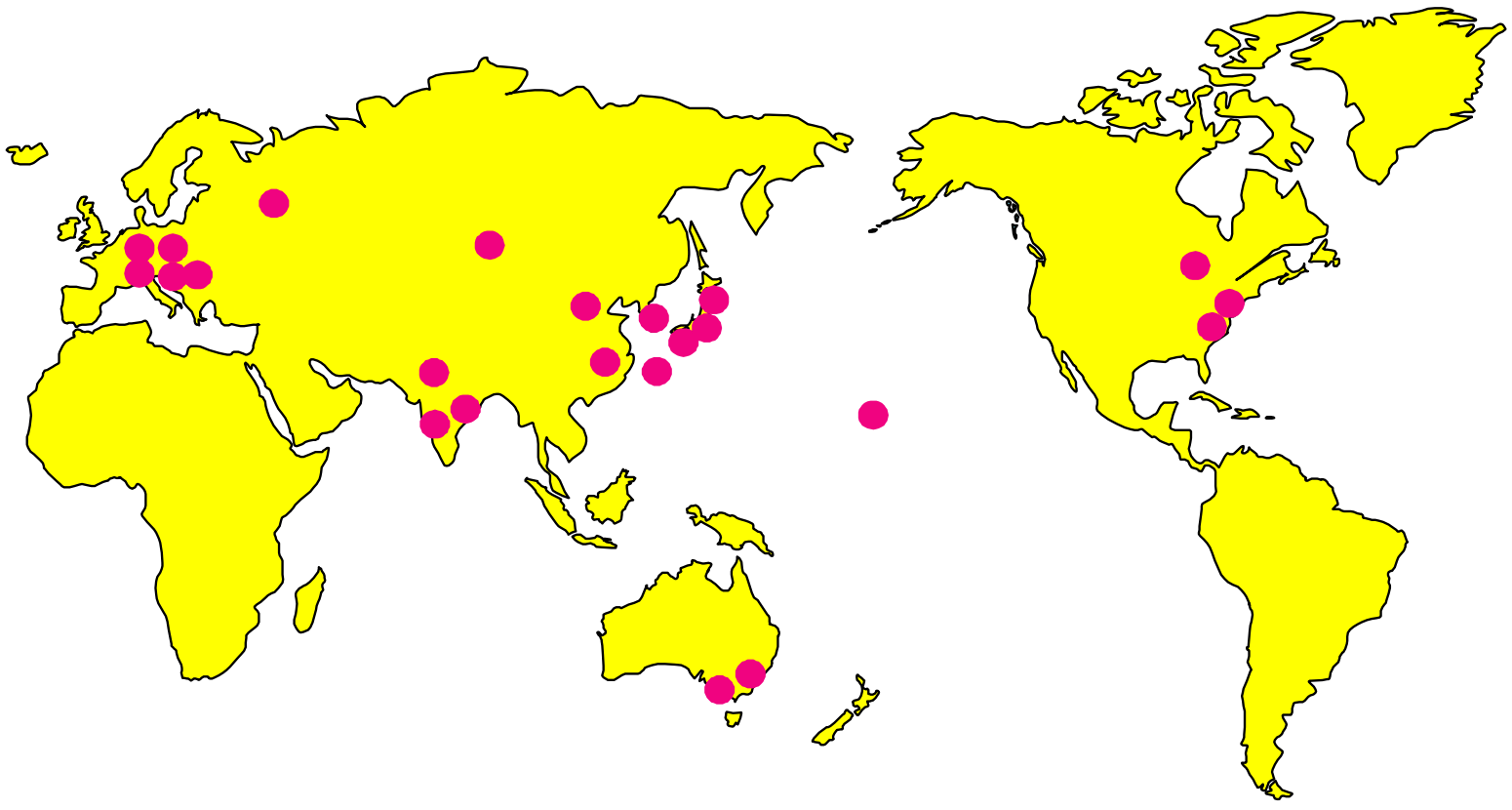
L_{max} = 1.51 × 10^{34} /cm^2/s

Feb. 15th, 2005

The Belle Detector



Belle Collaboration



~400 people, 59 institutions

from many nations

New Belle measurement with 275M $B\bar{B}$ pairs

- additional data
  - 152 → 275 M $B\bar{B}$ pairs
  - the inner tracker and interaction region was replaced in the summer 2003
    - 3-layer SVD (152 M $B\bar{B}$) to 4-layer SVD with small-cell drift chamber (123 M $B\bar{B}$).
- Analysis procedure is basically same as before

Event Selection

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

Pion Identification using aerogel and dE/dx

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

Kinematical Selection

$$5.271 < M_{bc} < 5.287 GeV/c^2$$
$$|\Delta E| < 0.064 GeV$$
corresponding ±3σ

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

Flavor Tagging

q: flavor charge

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

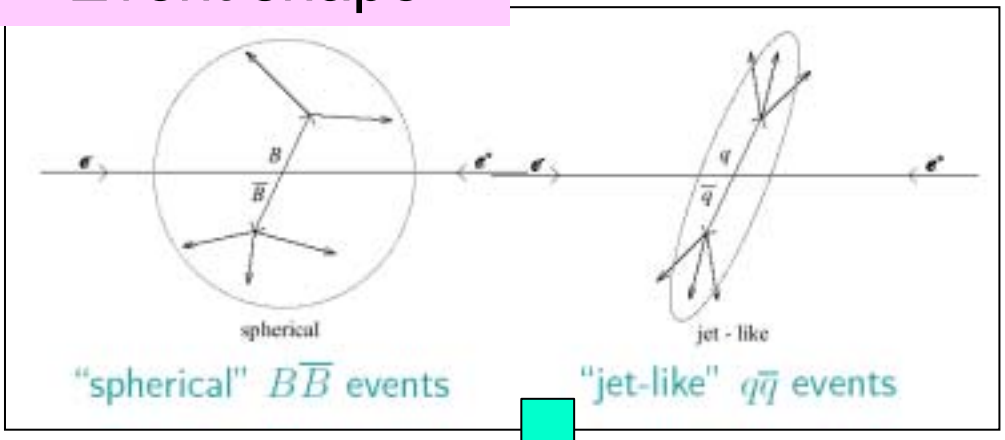
r: dilution factor
0<r≤1

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

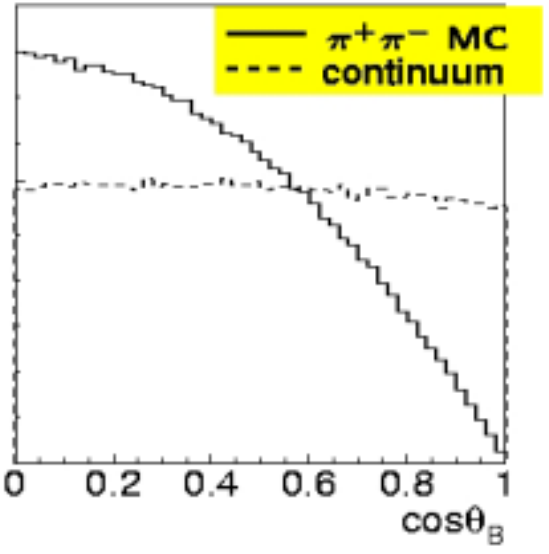
Event Selection (continuum suppression)

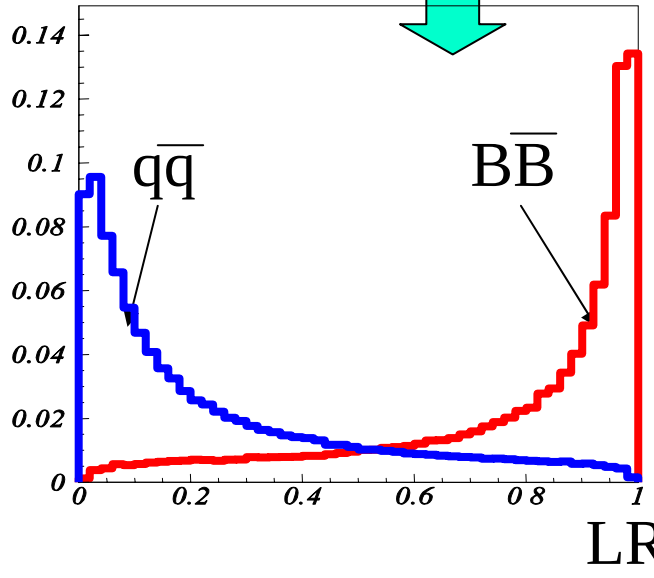
$$e^+e^- \to q\bar{q}, (q = u, d, s, c)$$

Event shape



B flight direction



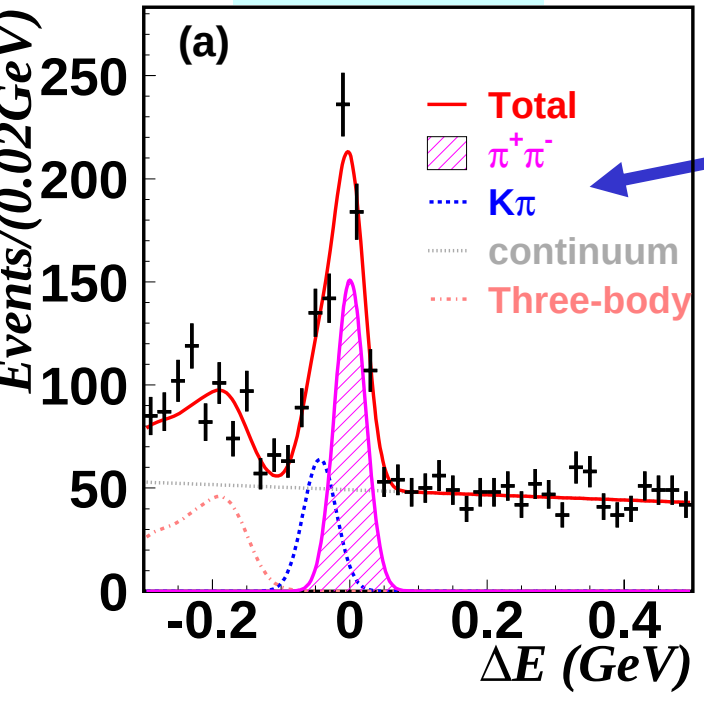


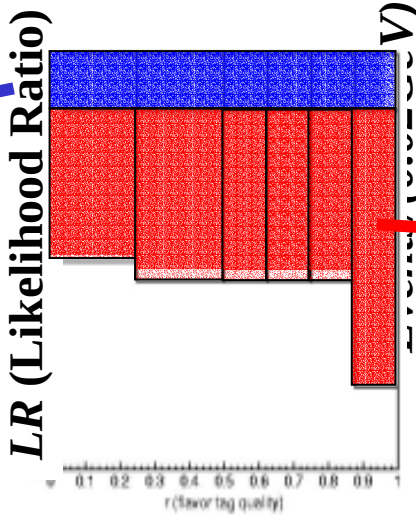
$$LR = \frac{\mathcal{L}_{B\bar{B}}}{\mathcal{L}_{B\bar{B}} + \mathcal{L}_{q\bar{q}}}$$

(Likelihood Ratio)

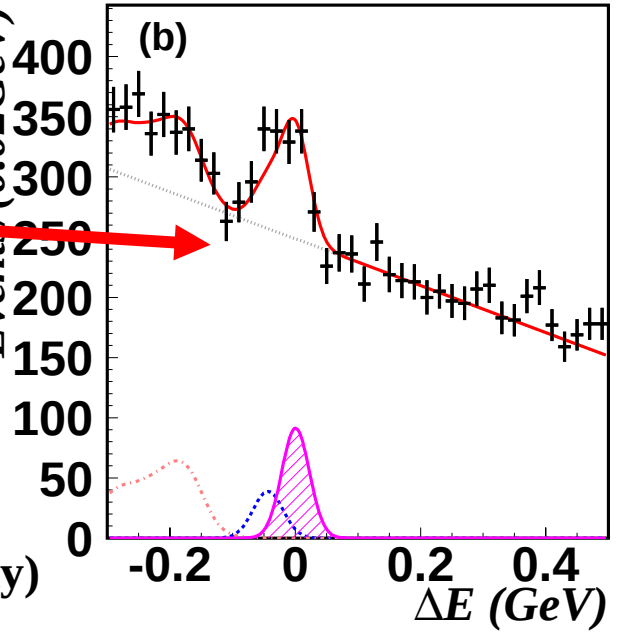
$B^0 \to \pi^+\pi^-$ signals

(LR>0.86)



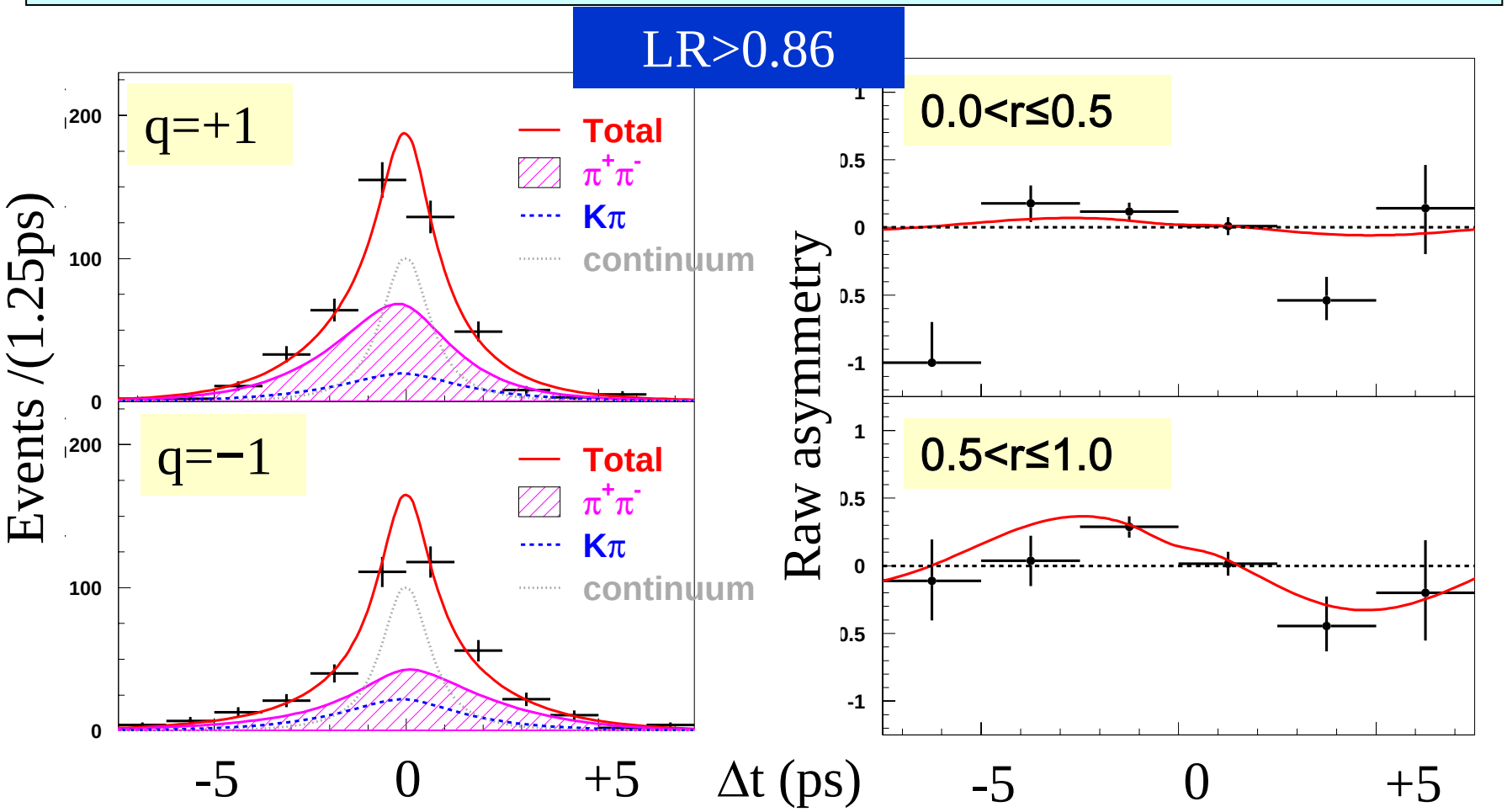


(LR<0.86)



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

Unbinned CP fit results

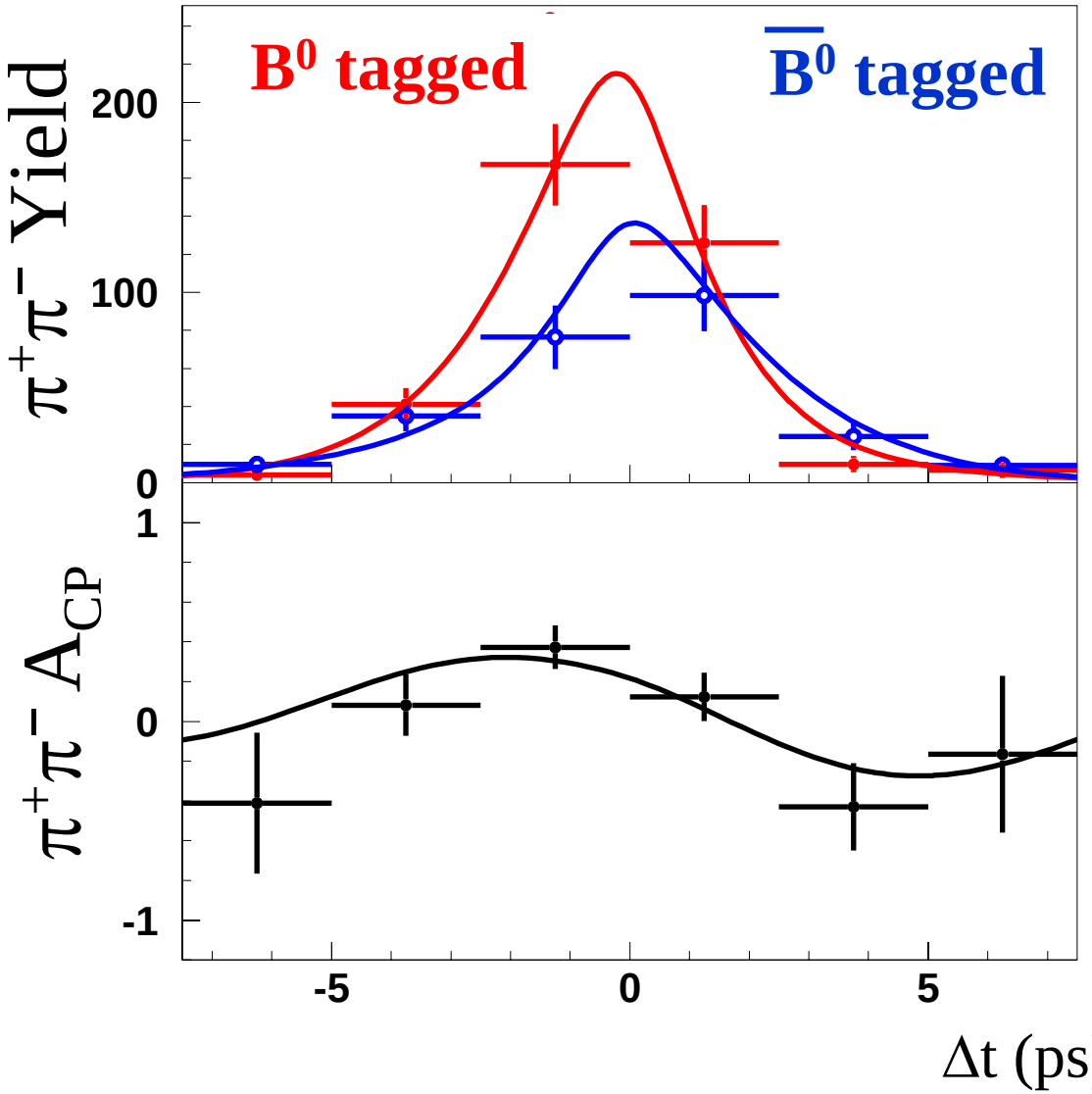


$$A_{\pi\pi} = +0.56 \pm 0.12 \pm 0.06$$

$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$$

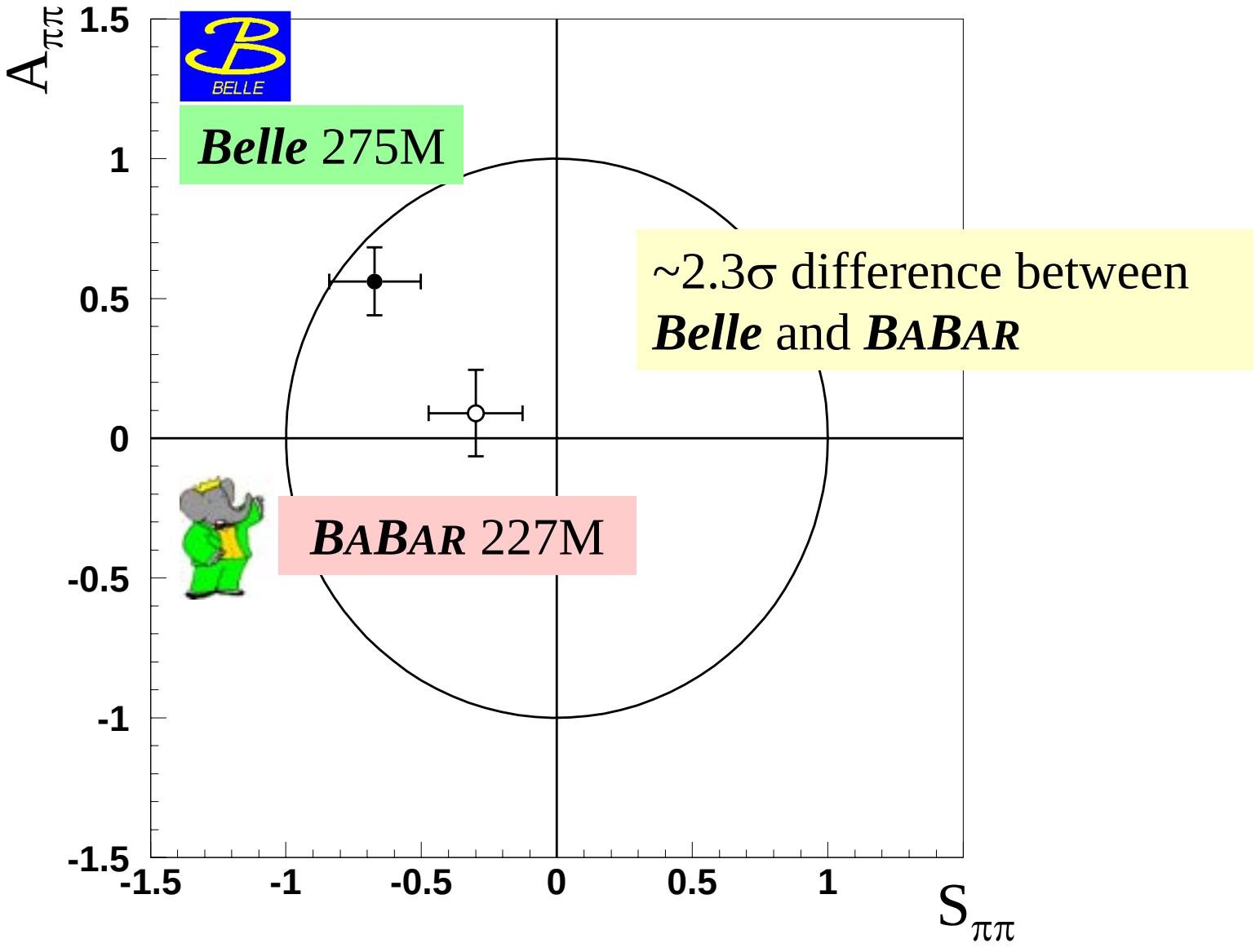
1st error statistical,
2nd systematic

Background subtracted fit projection for all events

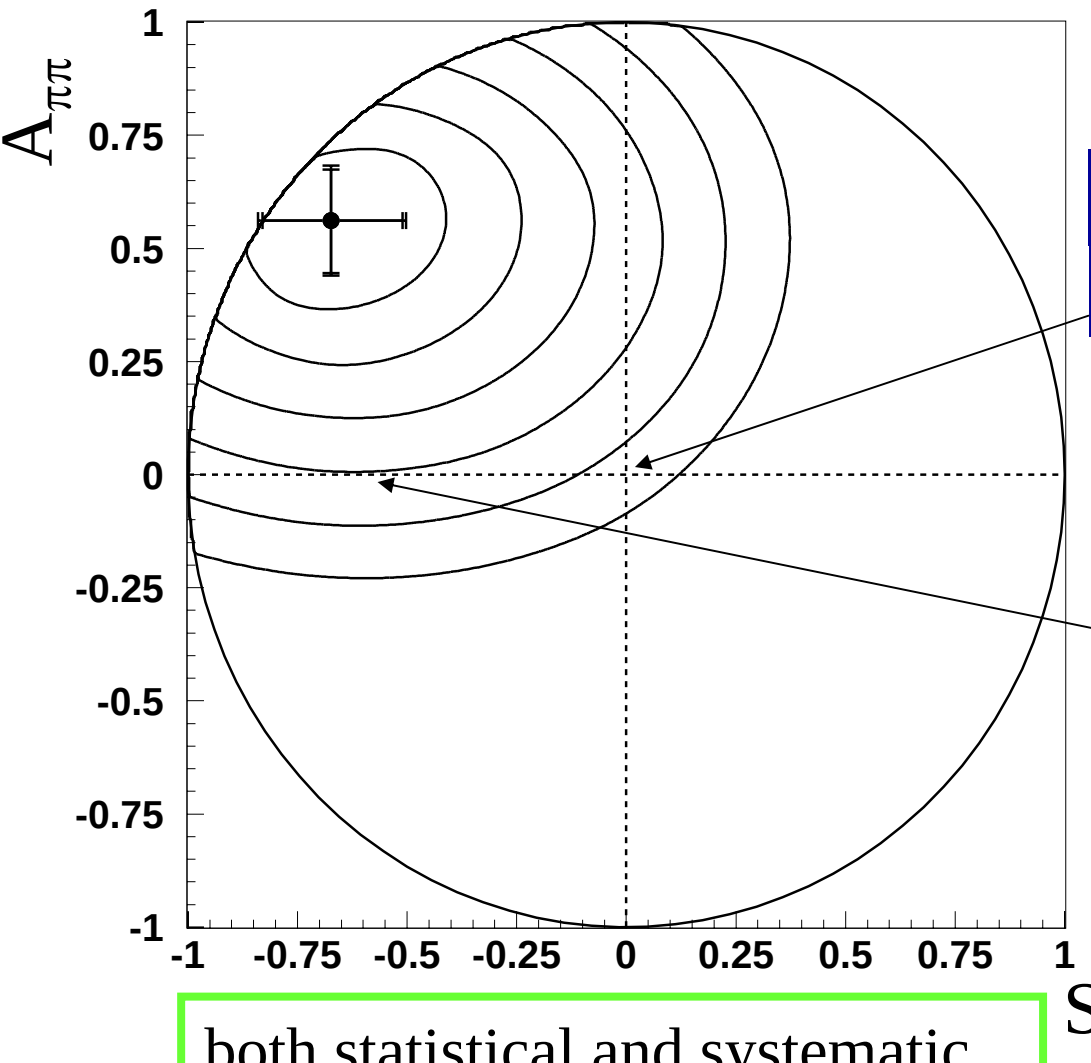


ΔE-Mbc 2D fits to individual time intervals

New experimental situation



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.

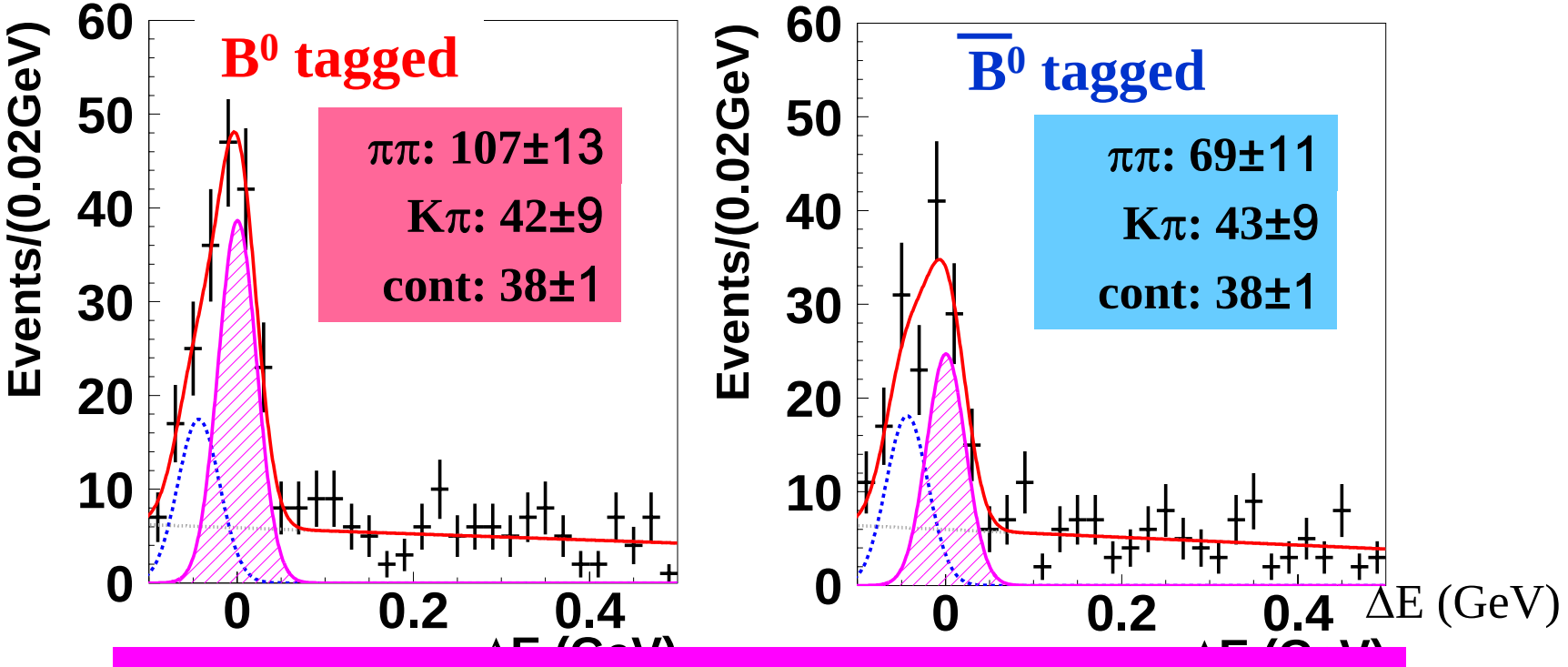
C.L. = Confidence Level

Consistency checks with Time-integrated fits

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

consistent with time-dependent fit

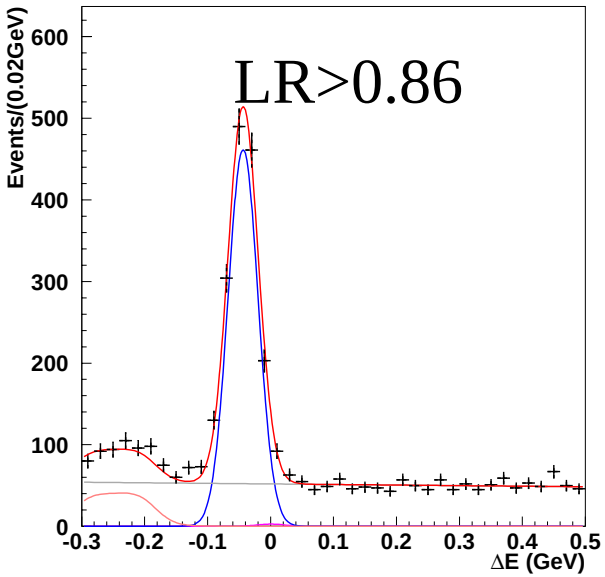
LR>0.86 & 0.5<r≤1.0



Direct CP Violation is evident!

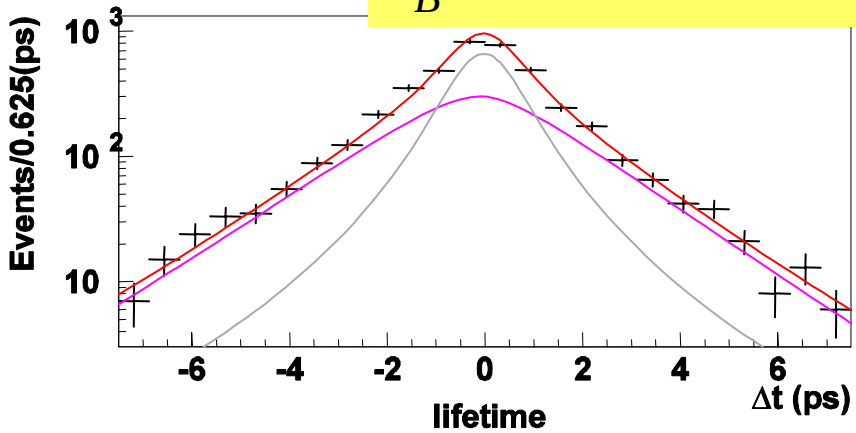
Validity check with $B^0 \to K^+\pi^-$

We extract $B^0 \to K^+\pi^-$ events

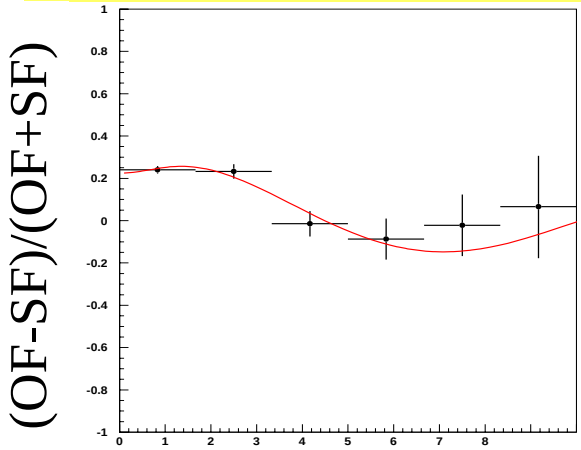


in total 4,293 (including 2,207 $K^+\pi^-$) events

Lifetime fit $\tau_{B^0} = 1.51 \pm 0.04$ ps



$\Delta m = 0.46 \pm 0.03$ ps^{-1}



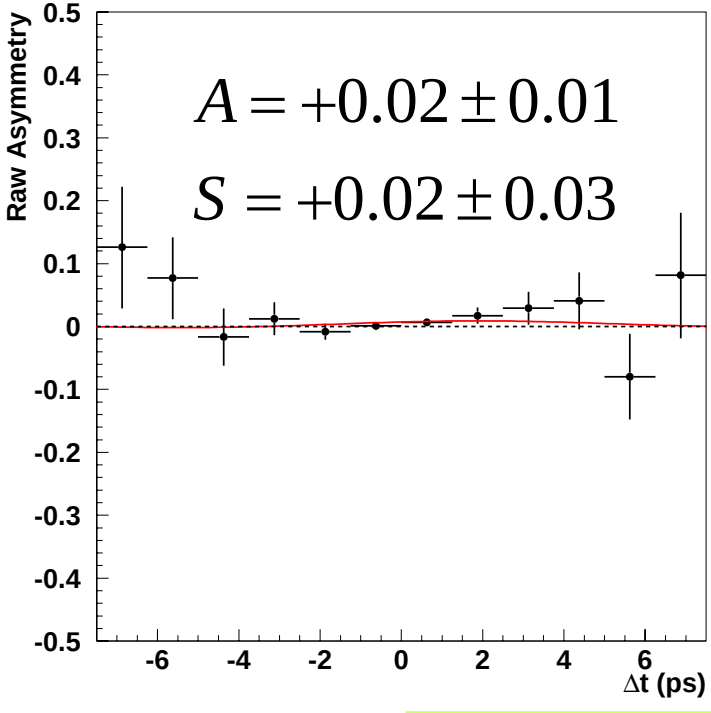
good control sample because of the similar topology to $B^0 \to \pi^+\pi^-$

consistent with the WA values

Background asymmetry

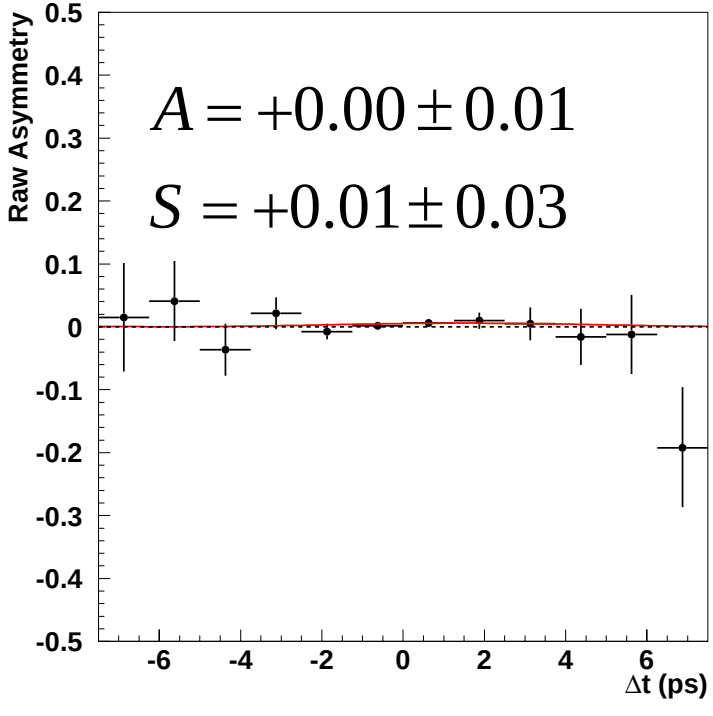
ππ sideband

B0:42467, B0b:42090



Kπ sideband

B0:43577, B0b:43308



No background asymmetry

possible background asymmetries are included in the systematic error

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 Dt 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 :direct CP violation

The results support the expectation from SU(3) symmetry that

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

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

$A_{CP}(K^+\pi^-) = -0.109 \pm 0.019$ HFAG summer 2004

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

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

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

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

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

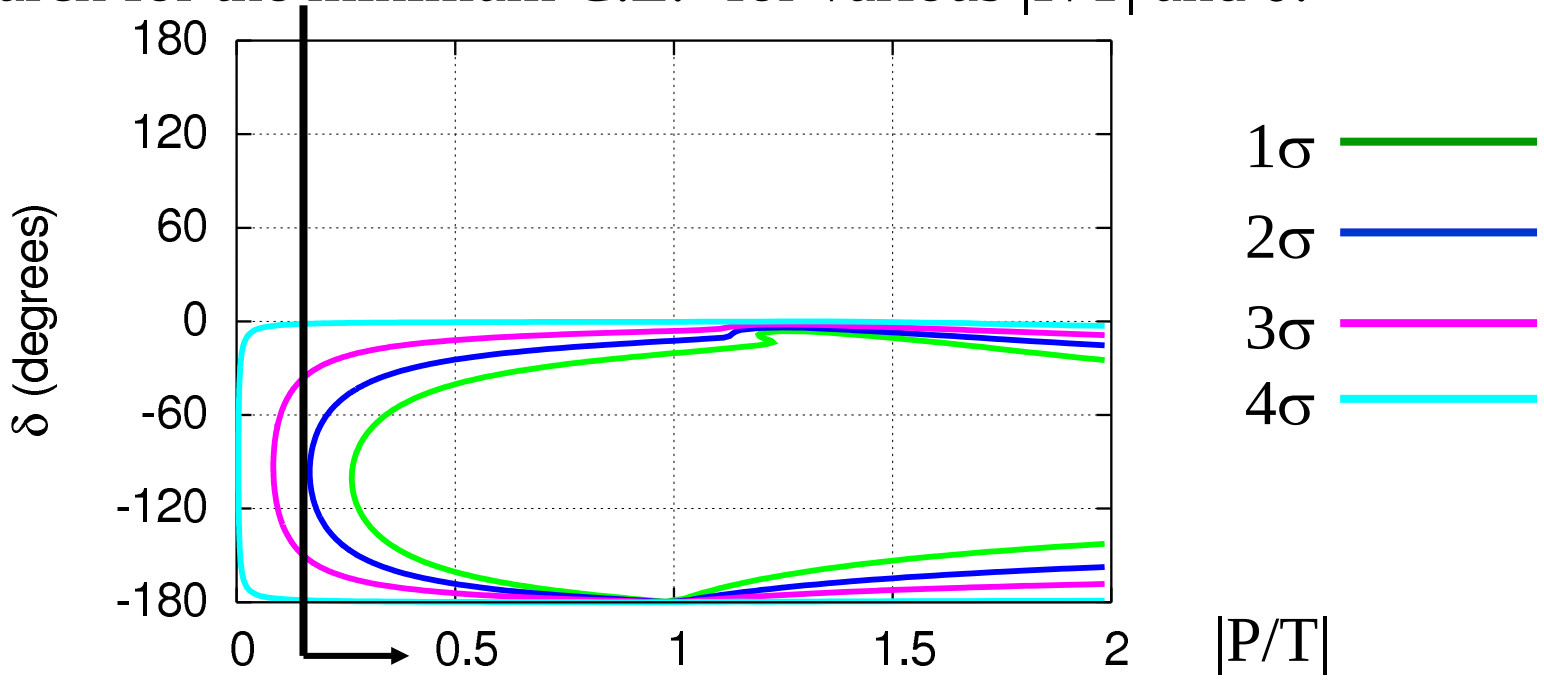
$$\delta \equiv \delta_P - \delta_T$$

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)
$\sin 2\phi_1$	0.726±0.037 (HFAG 2004)

Interpretation: |P/T| and δ

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



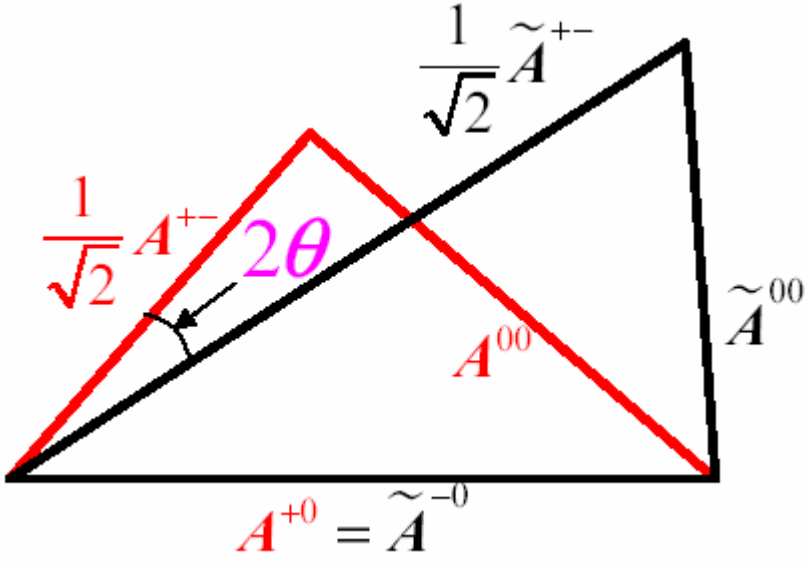
model-independent 95.4% confidence interval

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

Exclude $\delta > 0$ and $|P/T| = 0$ with 4σ significance

Interpretation: ϕ_2 constraint using isospin

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



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

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

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

The cleanest method to extract ϕ_2

We use the HFAG summer 2004 values for the branching ratios of $B^0 \to \pi^+\pi^-$, $\pi^0\pi^0$, $B^+ \to \pi^+\pi^0$ and direct CP asymmetry of $B^0 \to \pi^0\pi^0$.

We use the statistical treatment of
J. Charles *et al.*, hep-ph/0406184

$B^0 \to \pi^0\pi^0$ branching ratio and asymmetry

Belle measurement with 275M $B\bar{B}$ pairs

$$Br(\pi^0\pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$$
$$A_{CP}(\pi^0\pi^0) = +0.44^{+0.53}_{-0.52} \pm 0.17$$

hep-ex/0408101
submitted to PRL

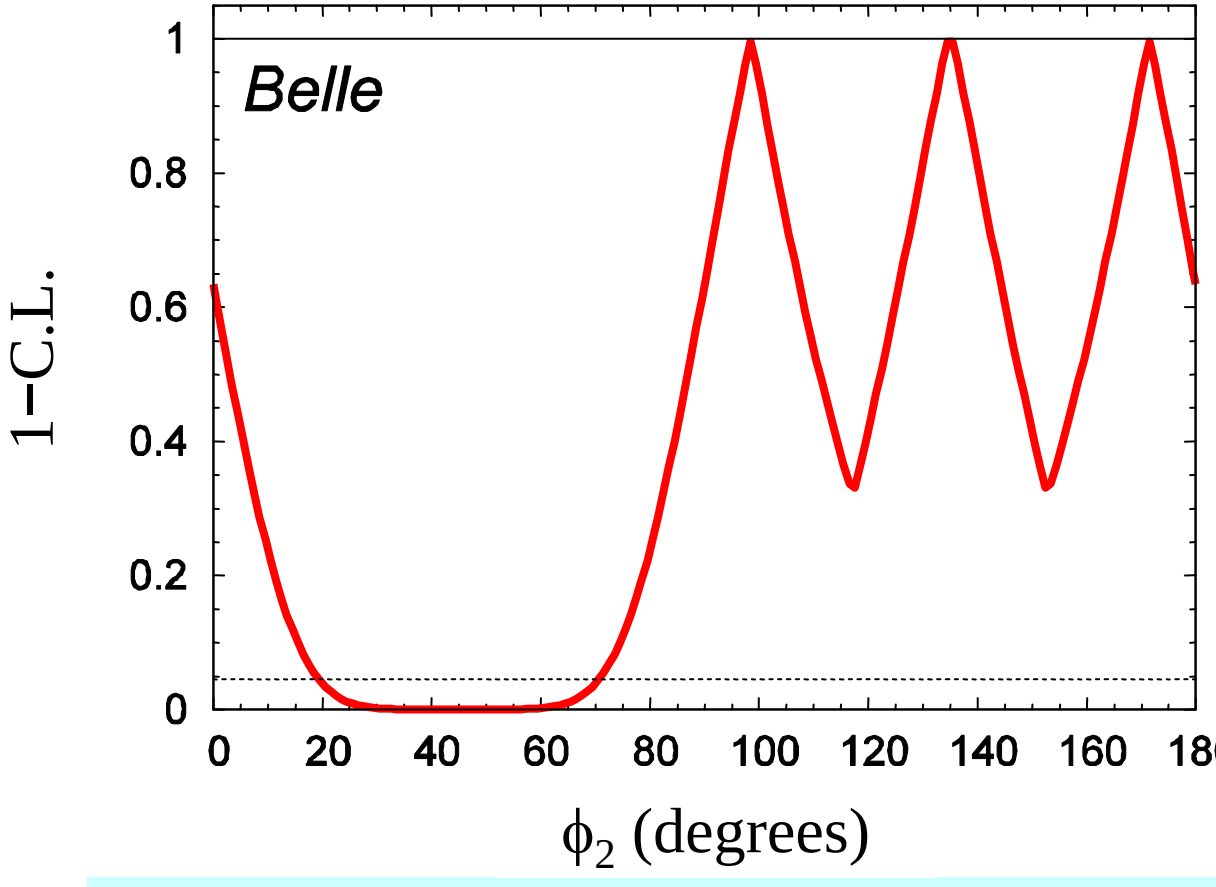
BABAR measurement with 227M $B\bar{B}$ pairs

$$Br(\pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$
$$A_{CP}(\pi^0\pi^0) = +0.12 \pm 0.56 \pm 0.06$$

hep-ex/0412037
submitted to PRL

First $A_{CP}(B^0 \to \pi^0\pi^0)$ measurements in the summer 2004.

Interpretation : ϕ_2 constraint with isospin



using HFAG summer 2004

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

95.4% confidence interval

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

Summary of new Belle $B^0 \to \pi^+\pi^-$ CP results

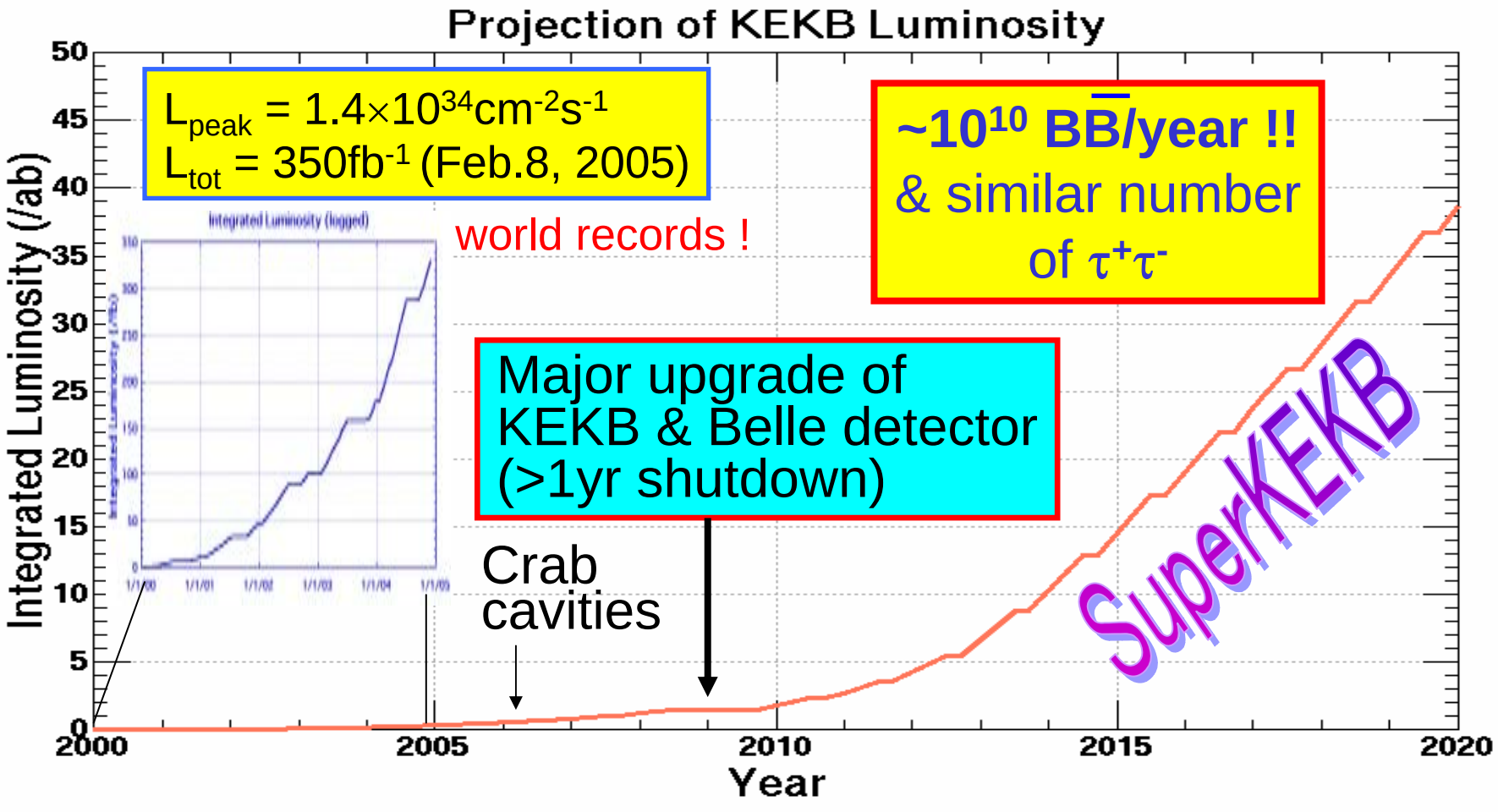
- The fit yields

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

1st error statistical, 2nd systematic

- Large direct CP violation with 4.0σ significance is observed
- The results confirm the previous Belle results.
- Isospin analysis gives $0^\circ < \phi_2 < 19^\circ \;\&\; 71^\circ < \phi_2 < 180^\circ$ at 95.4% C.L.

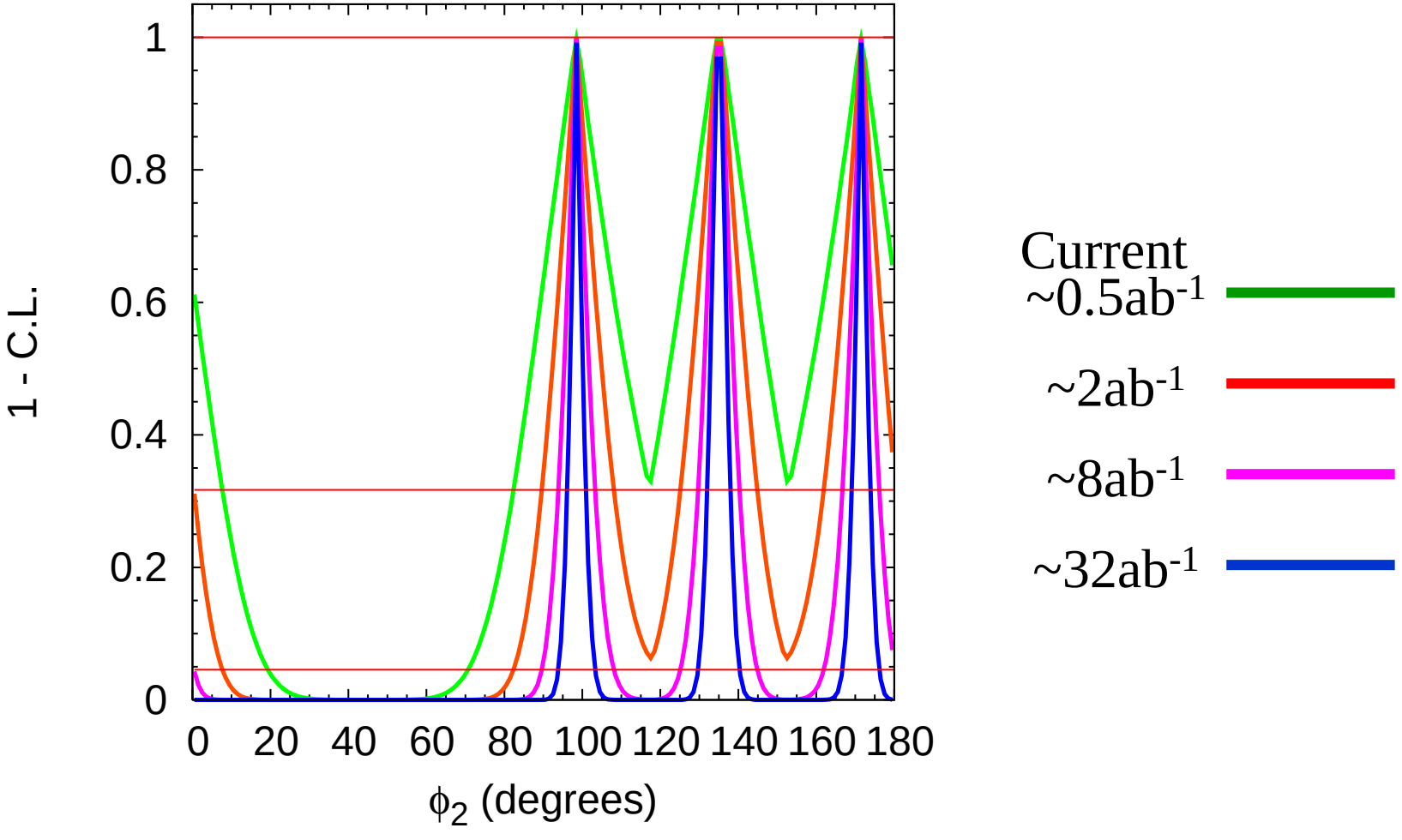
Future prospect



L_{peak} (cm^{-2}s^{-1})	1.4x10^{34}	5x10^{34}	5x10^{35}
L_{int}	330 fb^{-1}	~1 ab^{-1}	~10 ab^{-1}

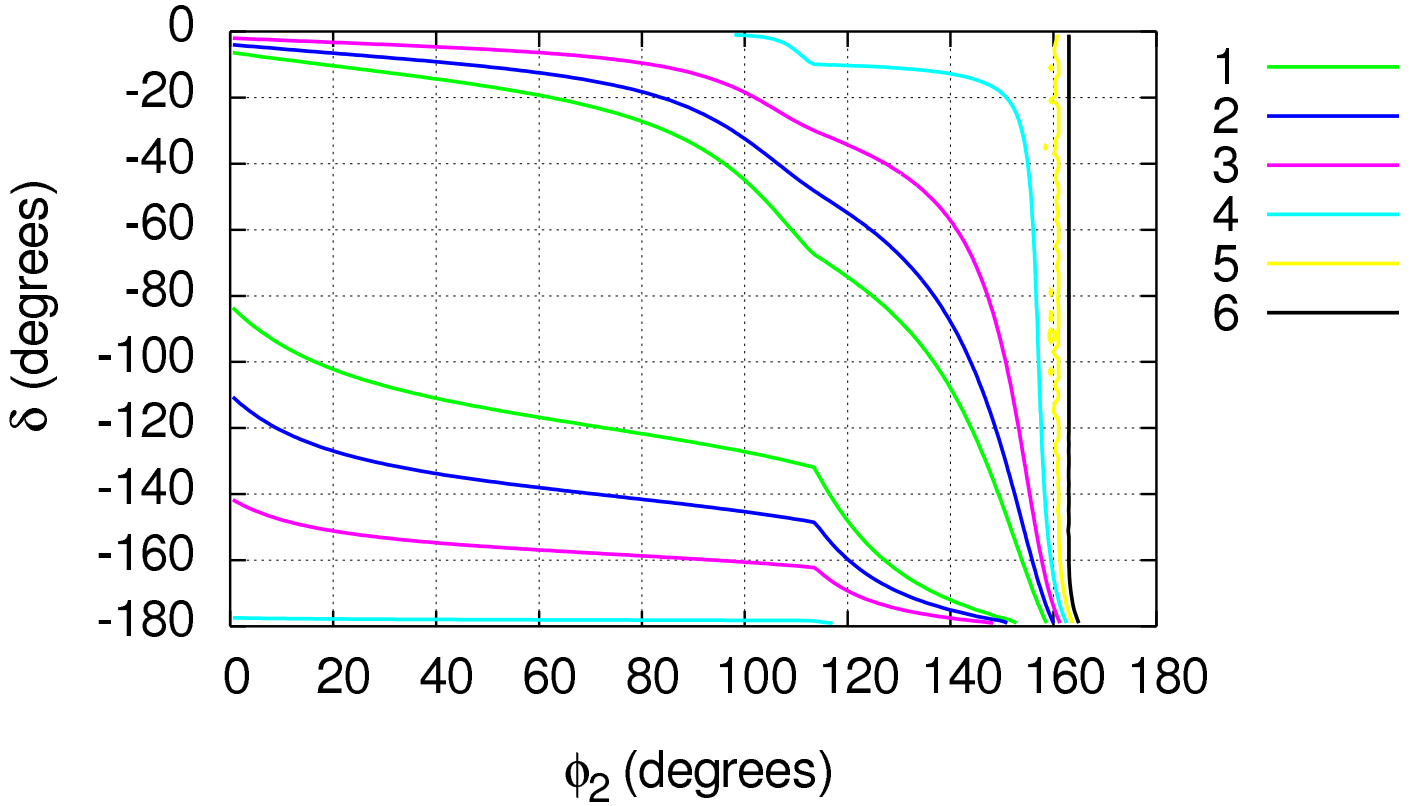
Future prospect

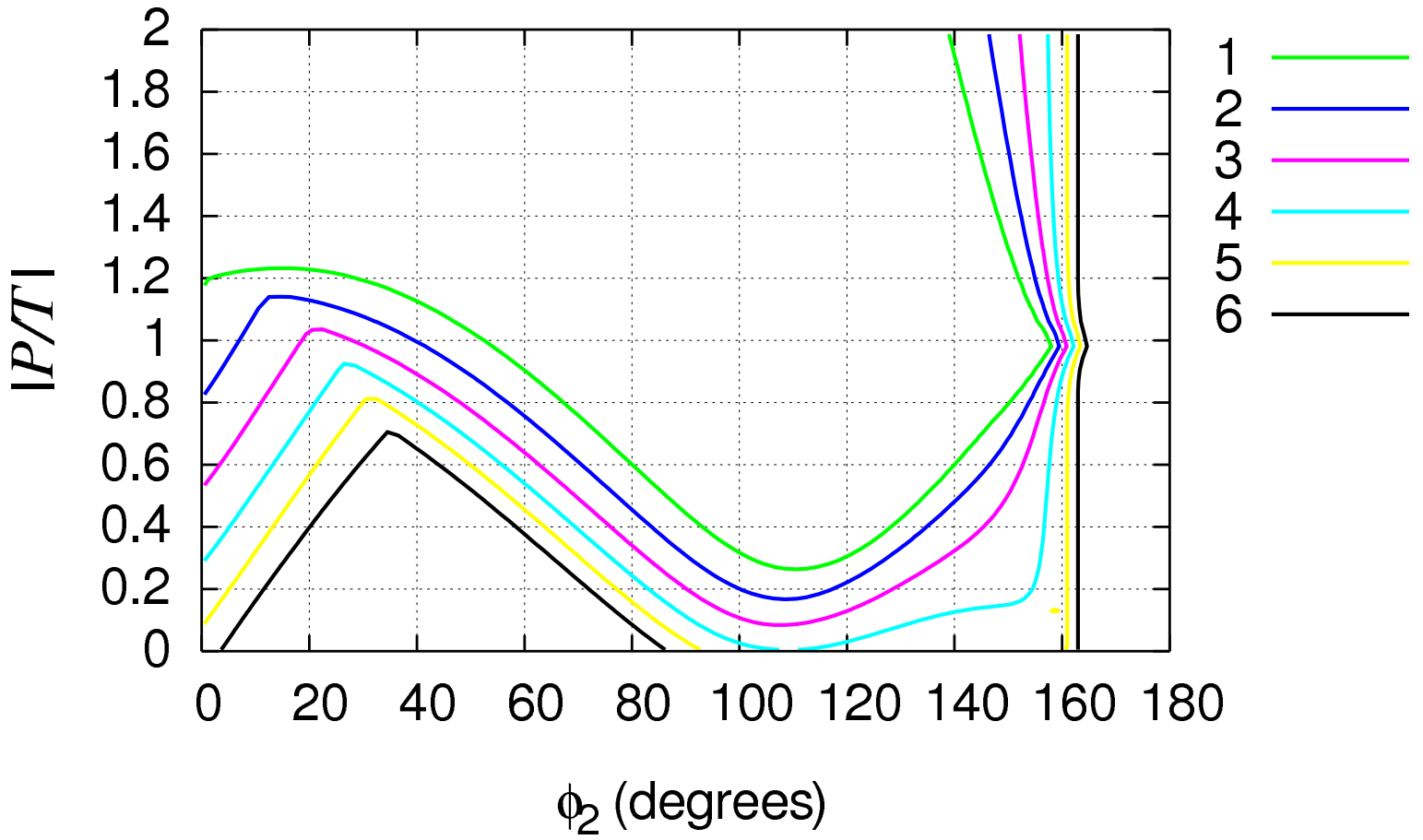
assuming the current measured values

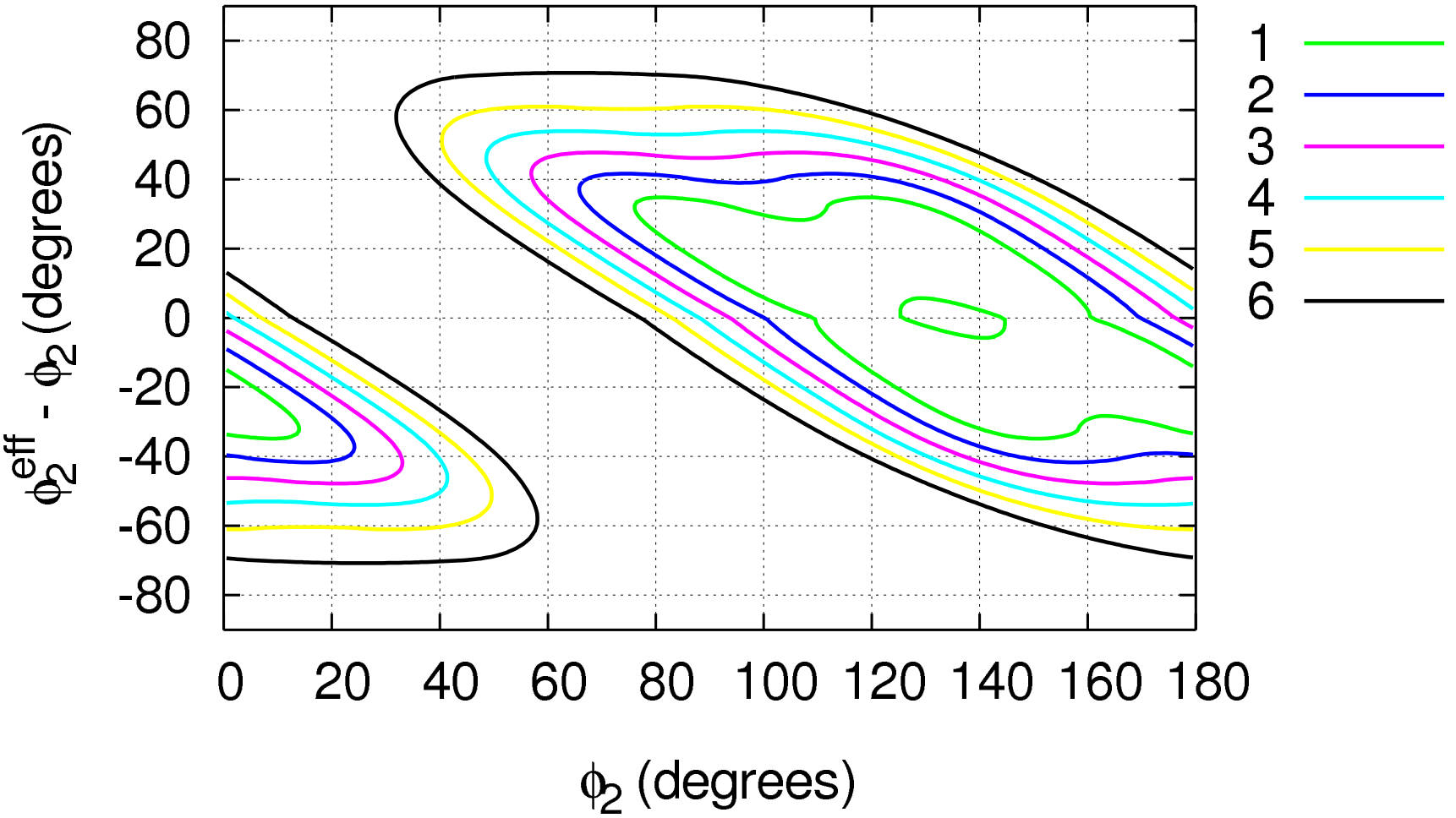


Super-B factories can pin down the ϕ_2 value.

backup slides


0
-20
-40
-60
-80
-100
-120
-140
-160
-180
δ (degrees)
0
20
40
60
80
100
120
140
160
180
ϕ2 (degrees)
1
2
3
4
5
6


|P/T|
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
180
ϕ_2 (degrees)
1
2
3
4
5
6


80
60
40
20
0
-20
-40
-60
-80
0
20
40
60
80
100
120
140
160
180
$\phi_2^{eff} - \phi_2$ (degrees)
ϕ_2 (degrees)
1
2
3
4
5
6

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

Probability Density Functions (PDFs) for the CP fit

a likelihood function

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

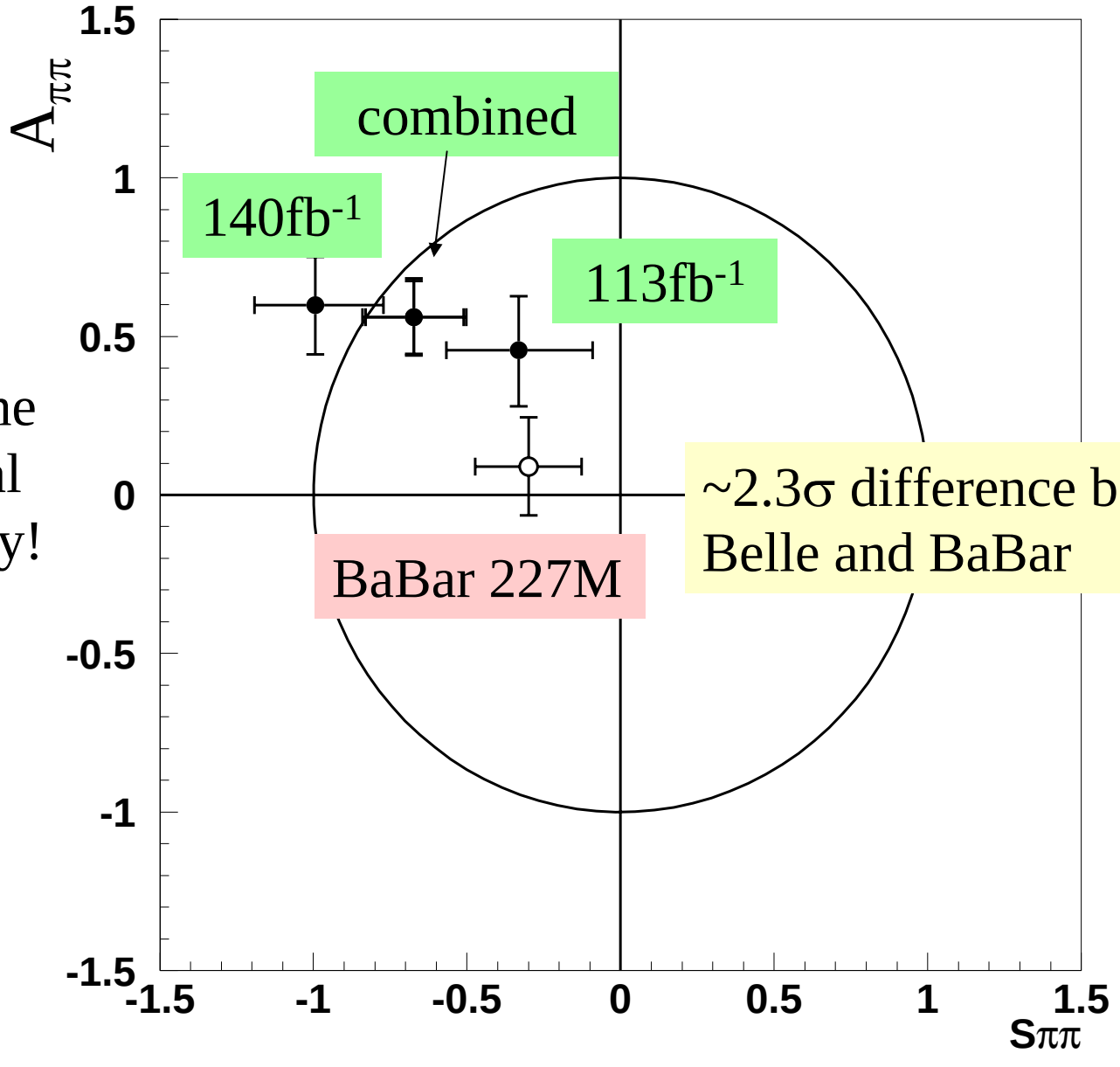
$$f_{\pi\pi} + f_{K\pi} + f_{q\bar{q}} = 1$$

$f_{\pi\pi}, f_{K\pi}, f_{q\bar{q}}$ 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 $S_{\pi\pi}$

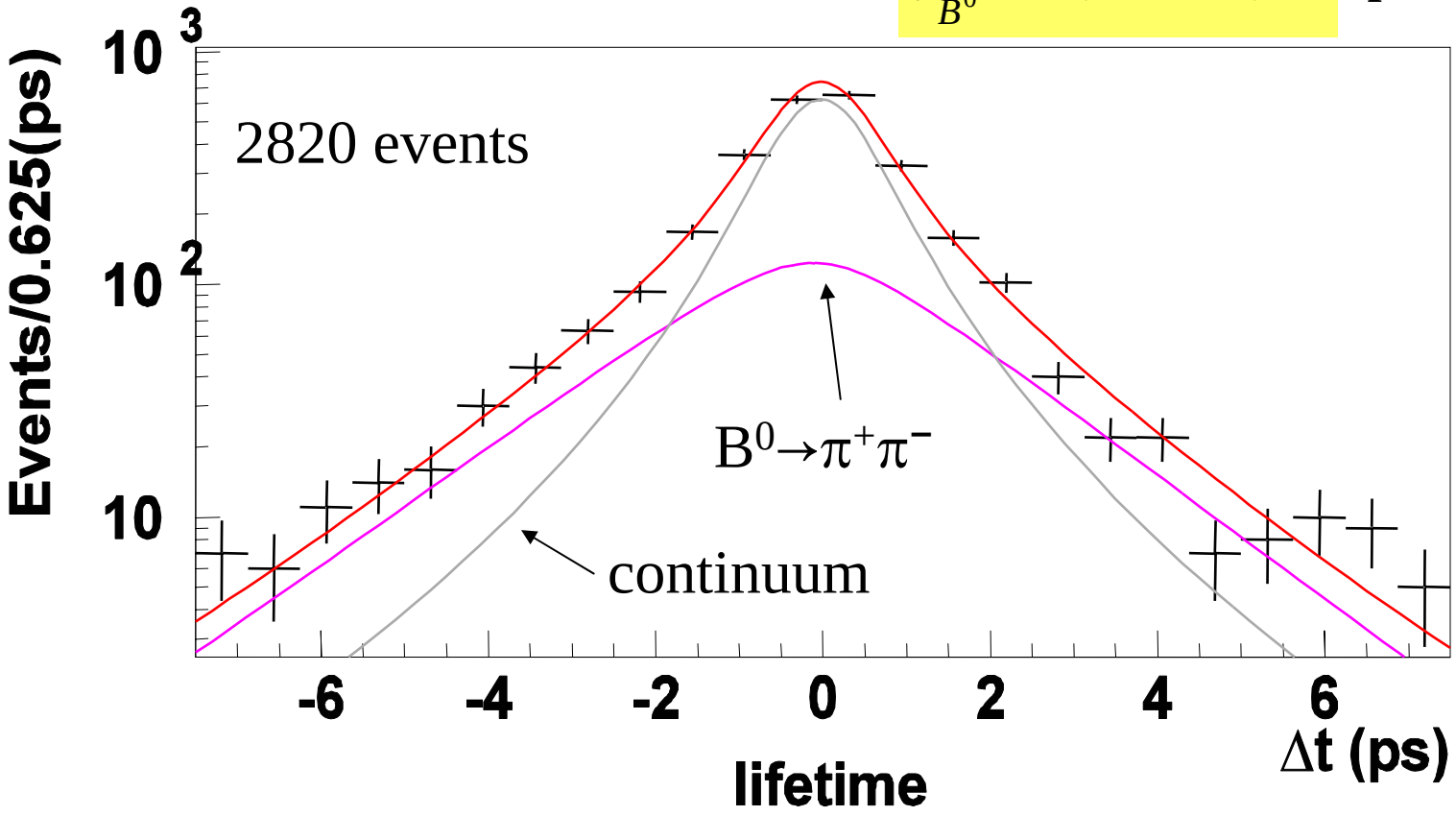
New experimental situation



Validity check (lifetime fit with $B^0 \to \pi^+\pi^-$)

Lifetime fit

$\tau_{B^0} = 1.50 \pm 0.07$ ps

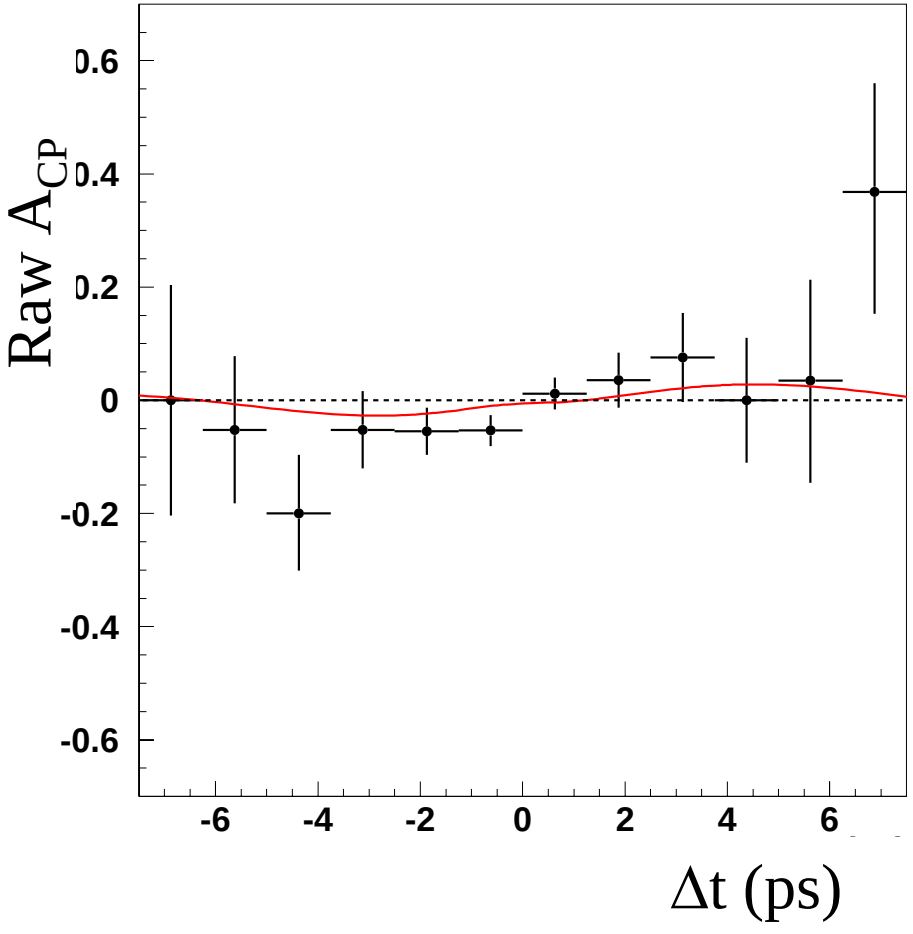


good agreement with the World Average (W.A.) Value

$\tau_{B^0} = 1.536 \pm 0.014$ ps PDG2004

Validity check with $B^0 \to K^+\pi^-$

CP fit results



total 4293 events

B0: 2106,

B0b: 2187

$A_{K\pi} = -0.06 \pm 0.06$

consistent with the WA value

$S_{K\pi} = +0.09 \pm 0.08$

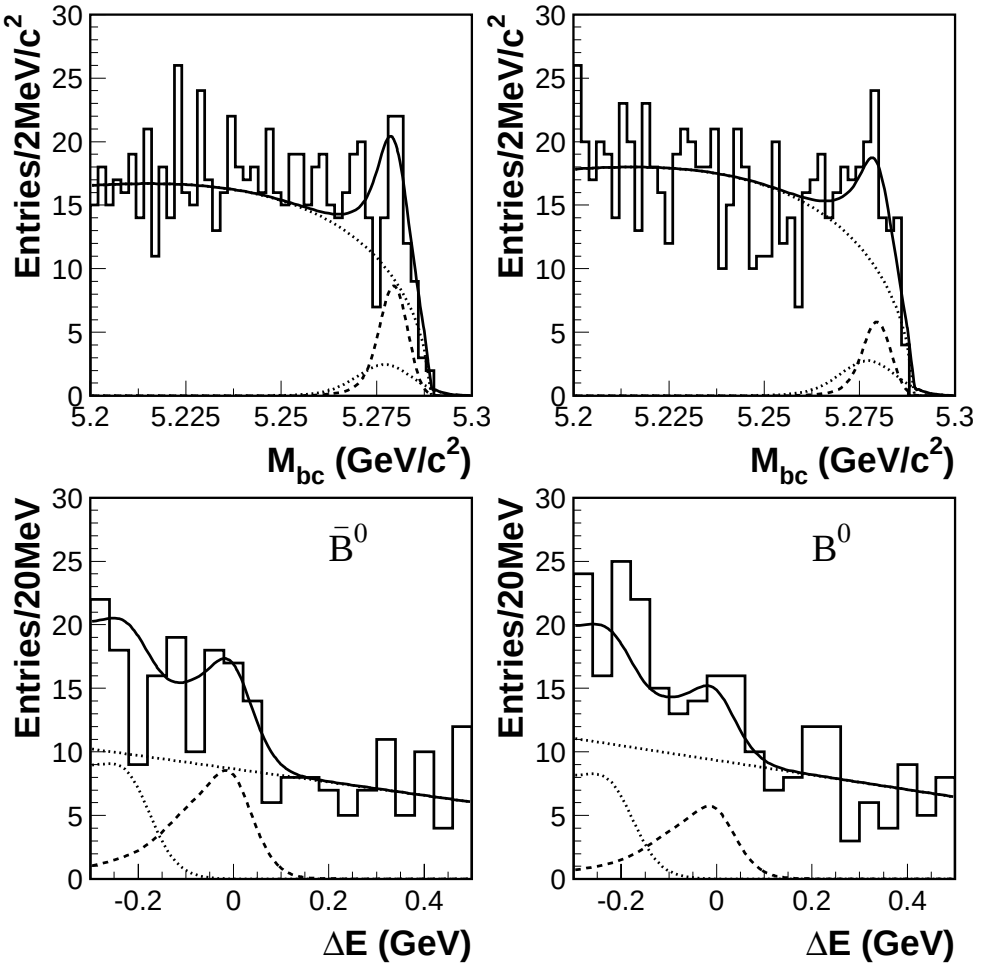
in agreement with null asymmetry

Belle measurement with 275M BB pairs

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

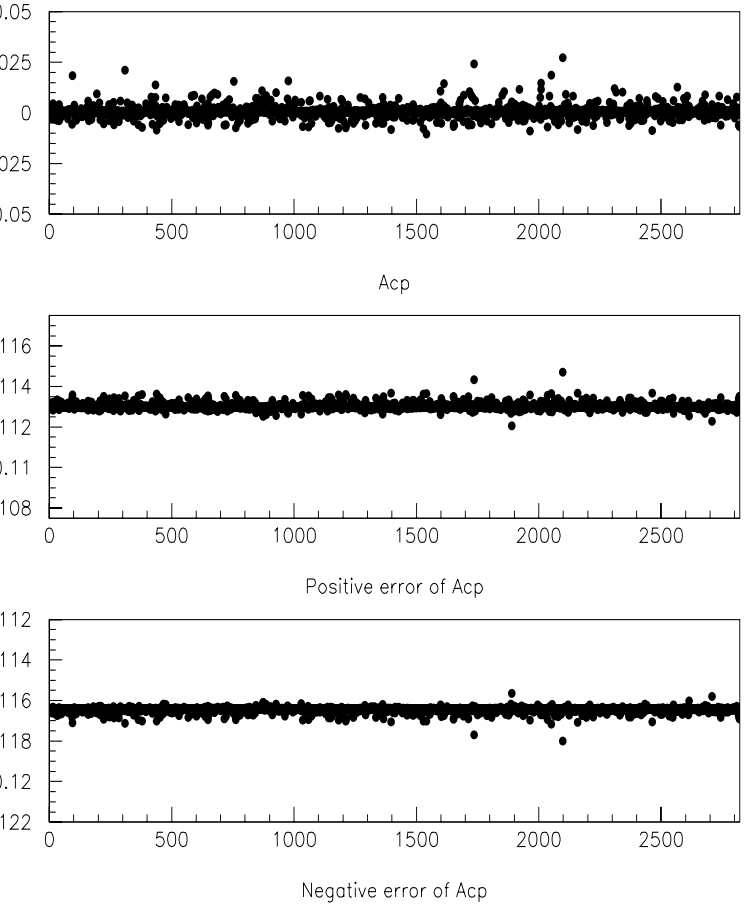
$$A_{CP}(\pi^0\pi^0) = +0.44^{+0.53}_{-0.52} \pm 0.17$$

hep-ex/0408101
submitted PRL

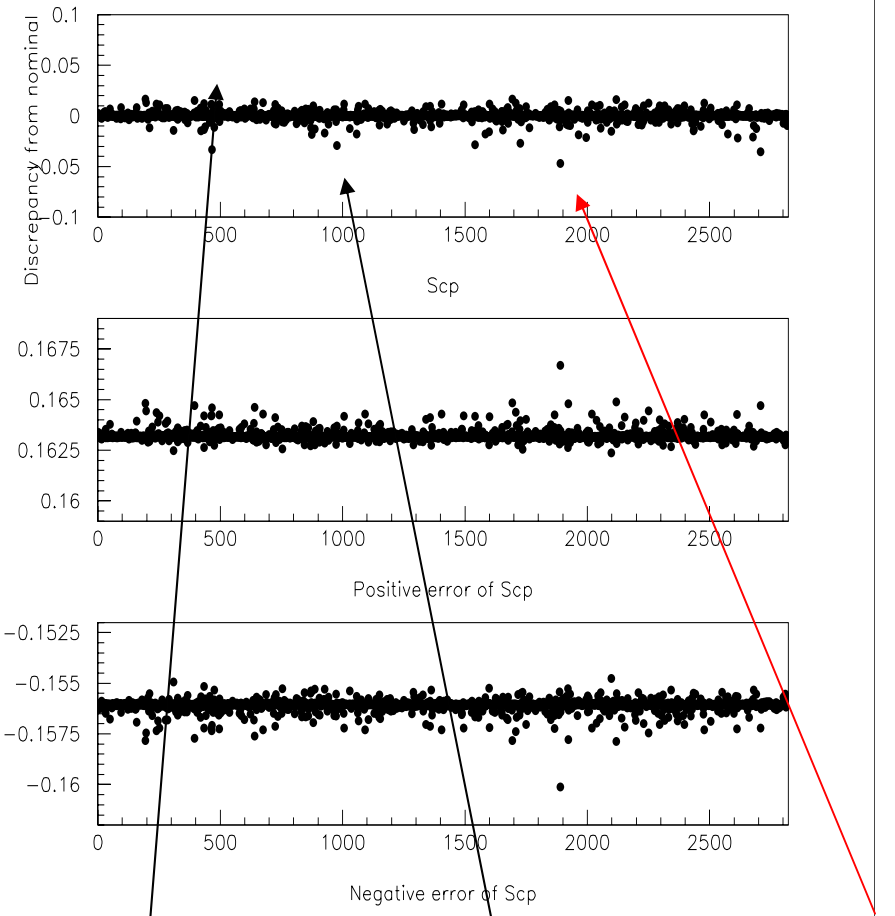


Validity check: single event sensitivity

Acp



Scp



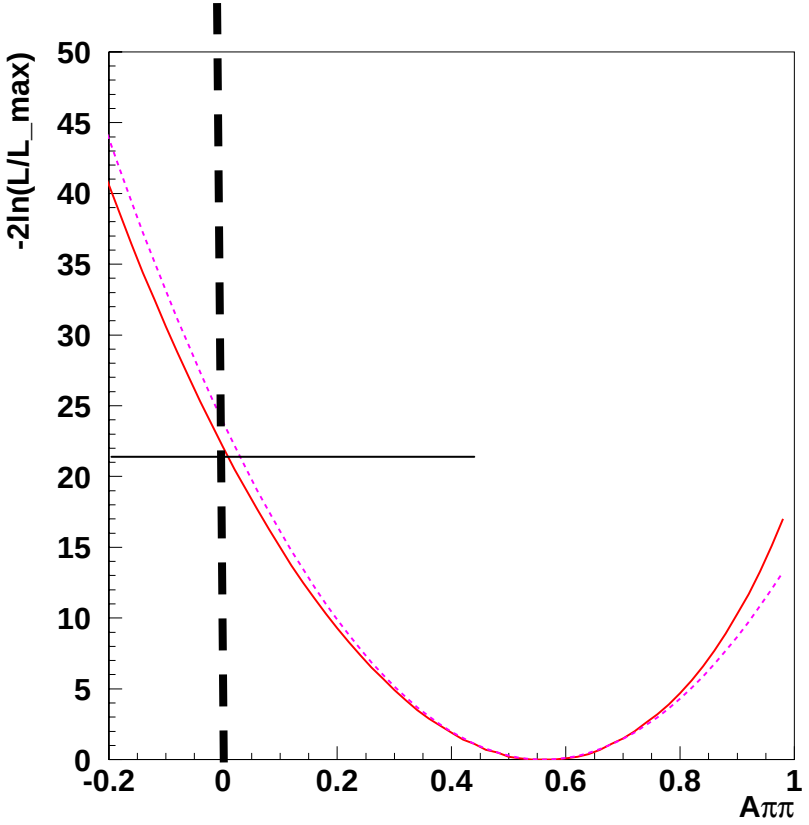
at most -0.04 in Sππ

1st

2nd

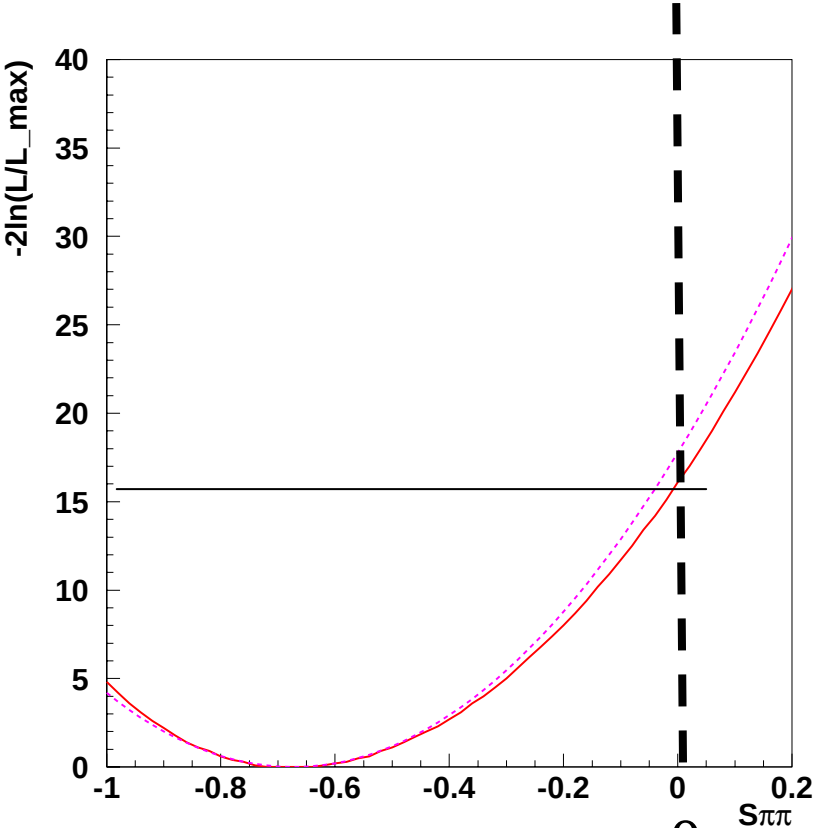
3rd (New!)

-2ln(L/L_max)



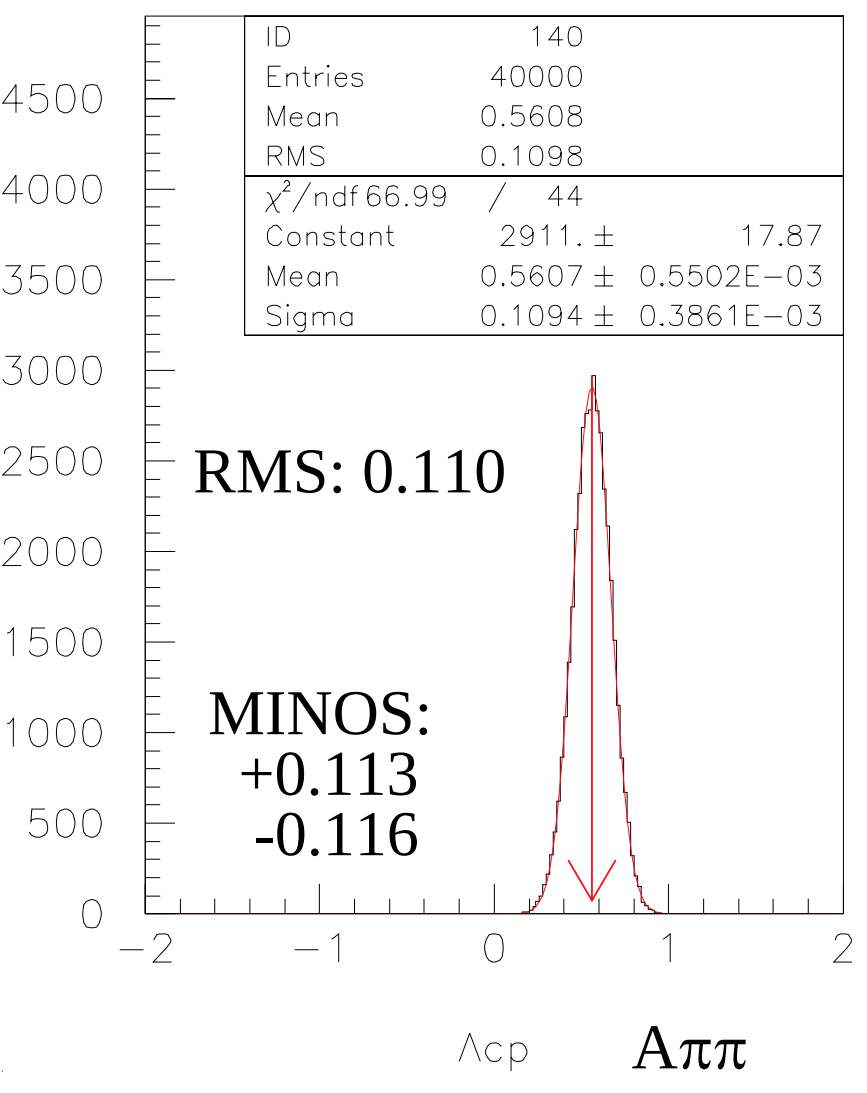
0

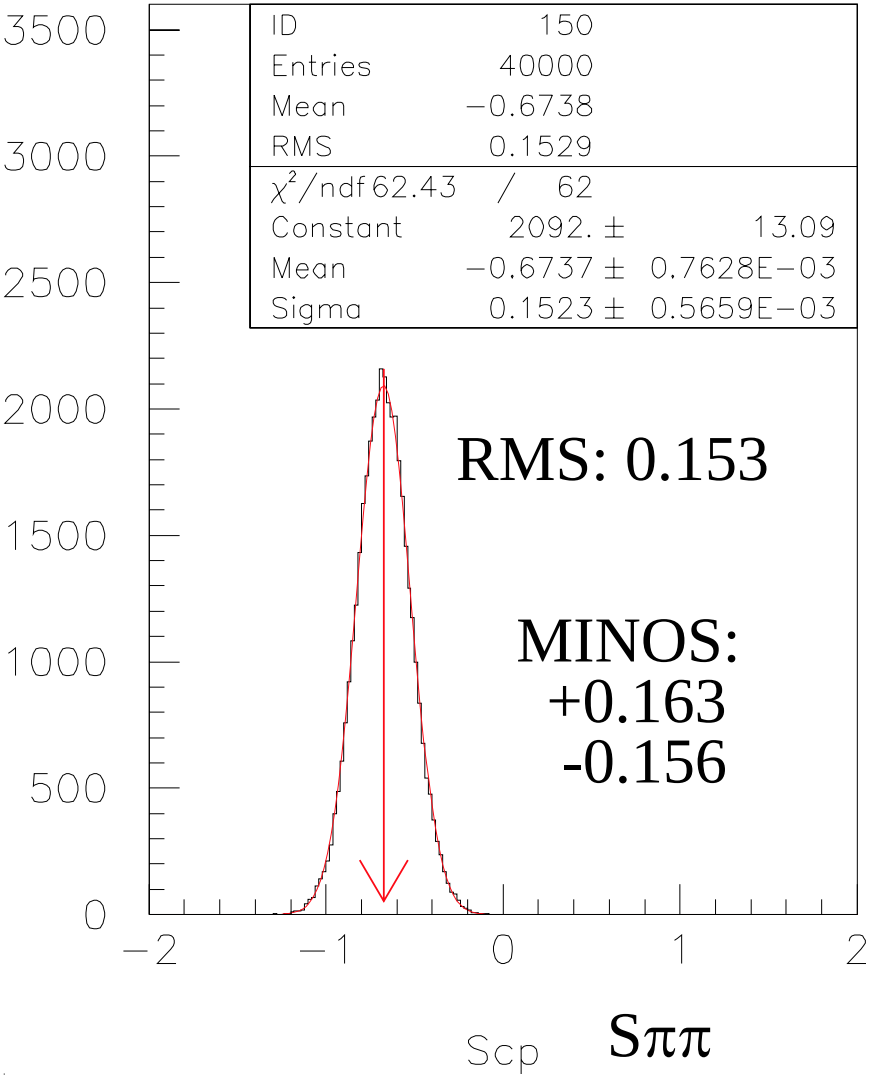
Aππ



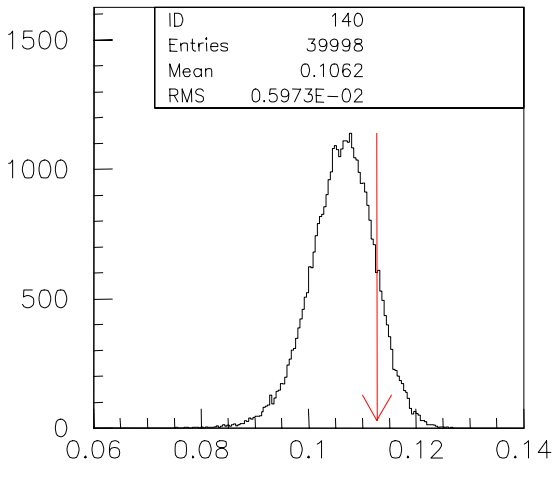
0

Sππ

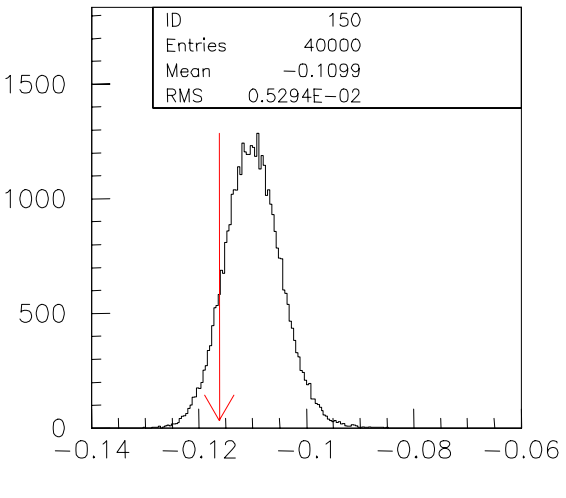

ID 140
Entries 40000
Mean 0.5608
RMS 0.1098
χ²/ndf 66.99 / 44
Constant 2911. ± 17.87
Mean 0.5607 ± 0.5502E−03
Sigma 0.1094 ± 0.3861E−03
RMS: 0.110
MINOS:
+0.113
-0.116
Acp
Aππ


ID 150
Entries 40000
Mean −0.6738
RMS 0.1529
χ²/ndf 62.43 / 62
Constant 2092. ± 13.09
Mean −0.6737 ± 0.7628E−03
Sigma 0.1523 ± 0.5659E−03
RMS: 0.153
MINOS:
+0.163
-0.156
Scp
Sππ

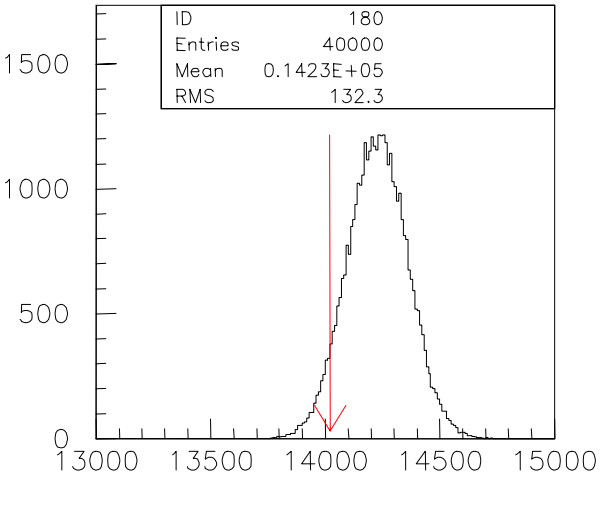
Pos. error Aππ

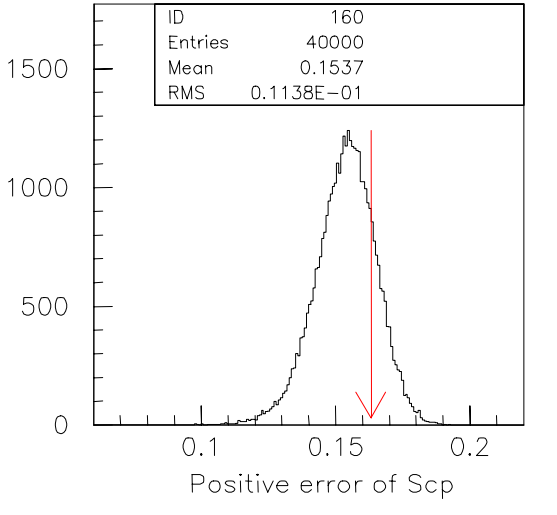


Neg. error Aππ

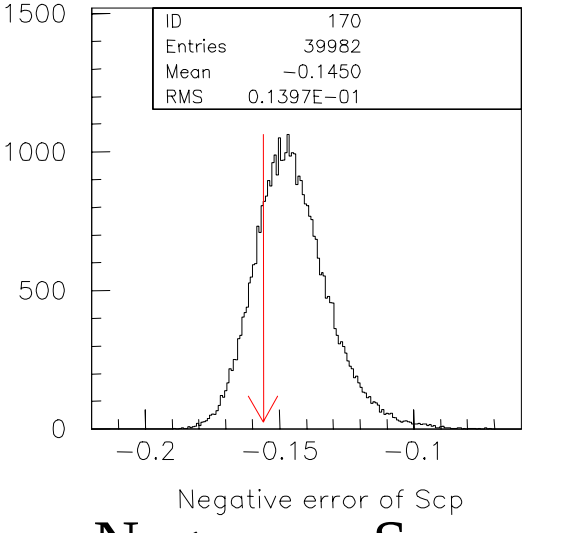


FCN

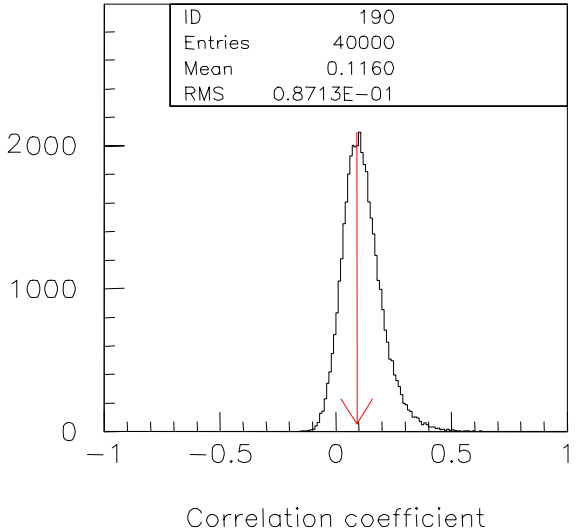




Pos. error Sππ



Neg. error Sππ



correlation coeff.