CP Violation in $B^0 \rightarrow \pi^+\pi^-$ from Belle

Hirokazu Ishino
Tokyo Institute of Technology
For the Belle Collaboration

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Hawaii

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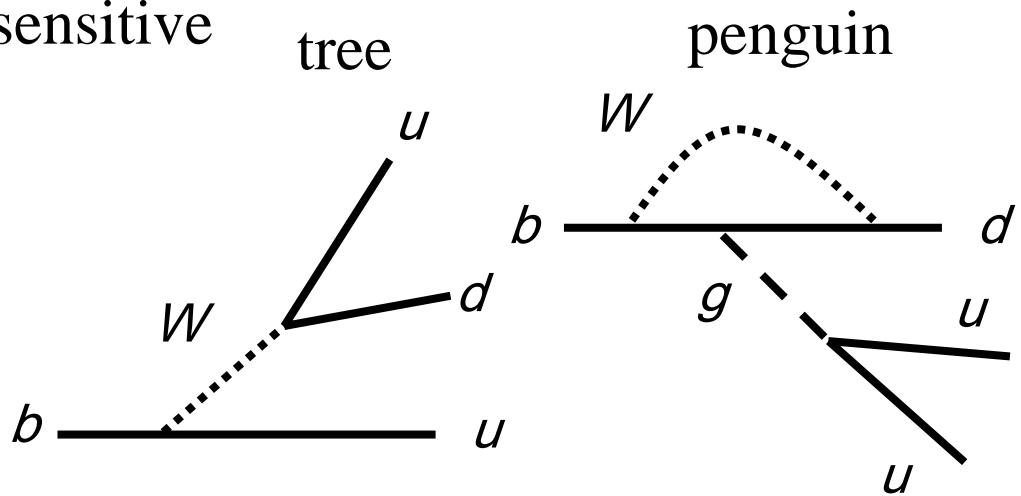
$S_{\pi\pi}$: $B^0\overline{B}^0$ mixing induced CPV

$A_{\pi\pi}$: 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

tree   penguin

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

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

- Previous publication: PRL 95 101801 (2005)
  - with 275M BB, 666±43 signal events
  - $A_{\pi\pi}$=+0.56±0.12±0.06
  - $S_{\pi\pi}$=−0.67±0.16±0.06
  - 4σ evidence for Direct CP Violation

- New measurement with 535 M BB
  - Particle ID information in the PDF newly introduced.
    - for better discrimination of the $B^0 \to K\pi$ contamination
  - 5dim. PDF for the time-dependent fit
    - ΔE, M_{bc}, PID of pos. and neg. tracks and Δt
  - the results are preliminary

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

Kinematical Selection

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

corresponding $\pm 3\sigma$
for the signal box

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

Flavor Tagging

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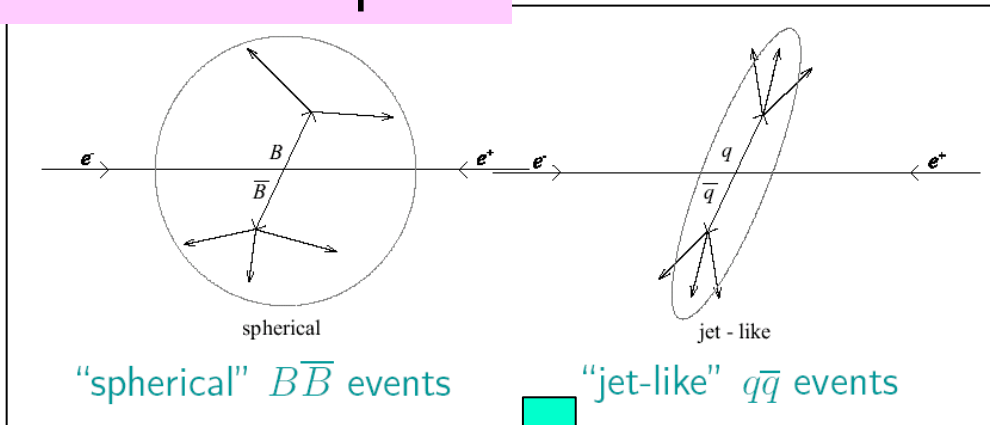
q=+1 tagged as a B^0,
q=−1 tagged as a $\overline{B}^0$

r: dilution factor
$0 < r \leq 1$

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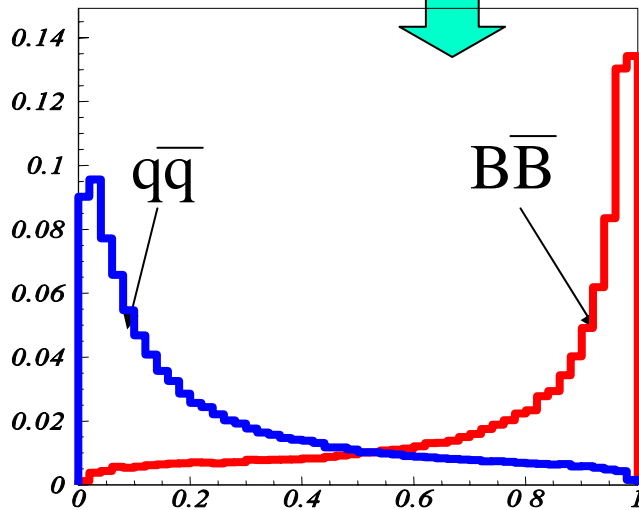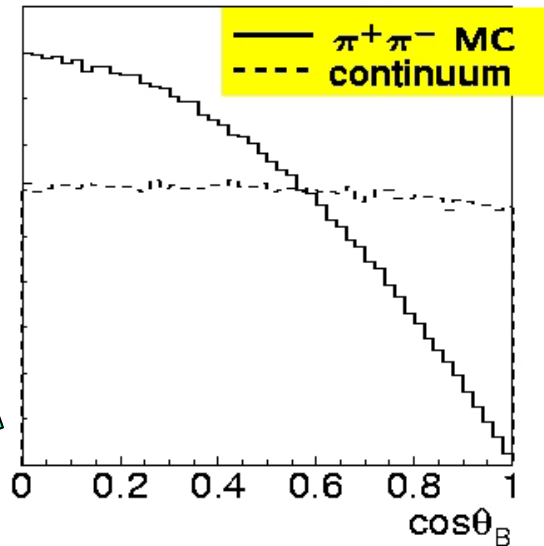r=1 unambiguous flavor assignment

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

Event shape

"spherical" $B\overline{B}$ events   "jet-like" $q\bar{q}$ events

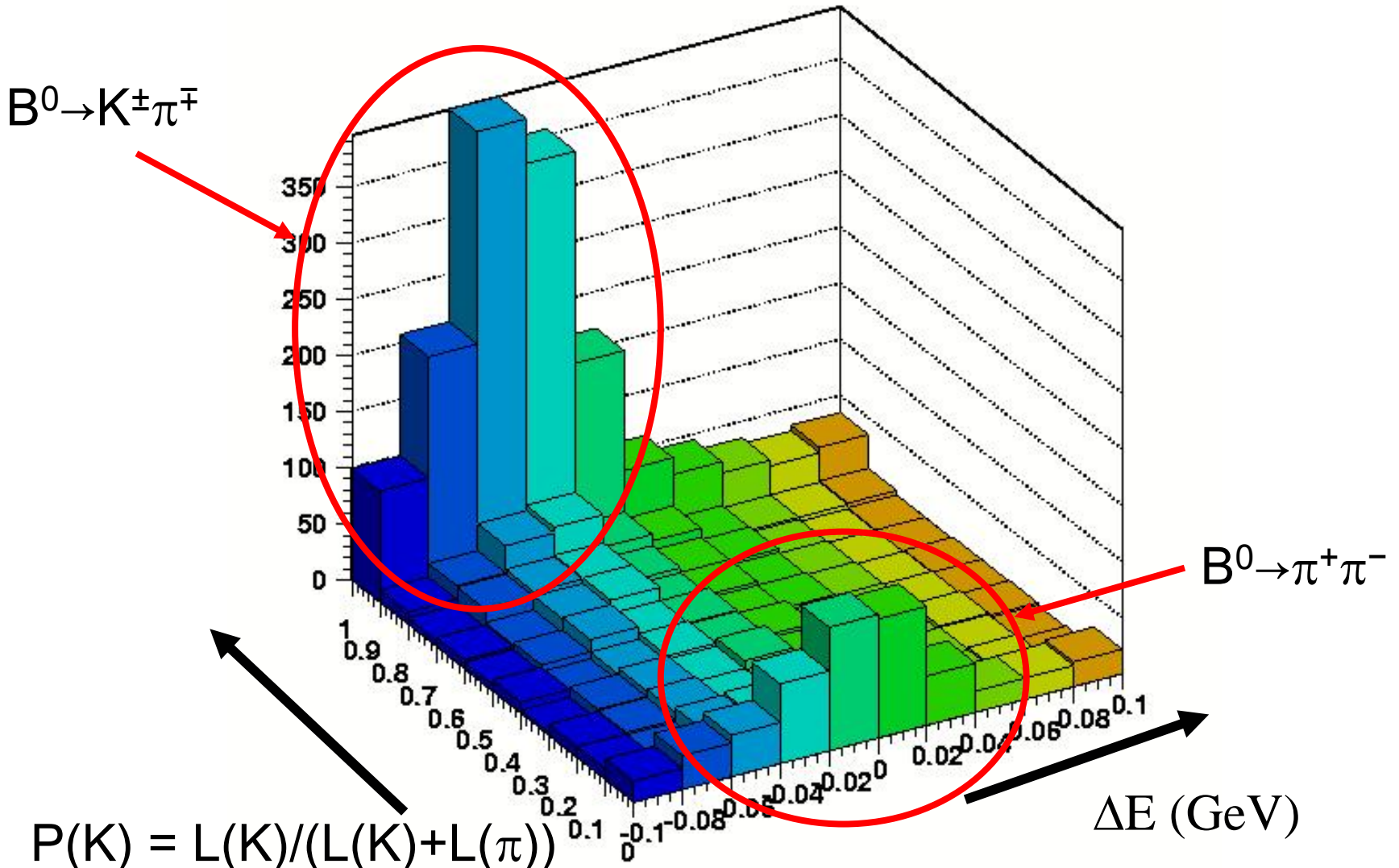## B flight direction

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

(Likelihood Ratio)
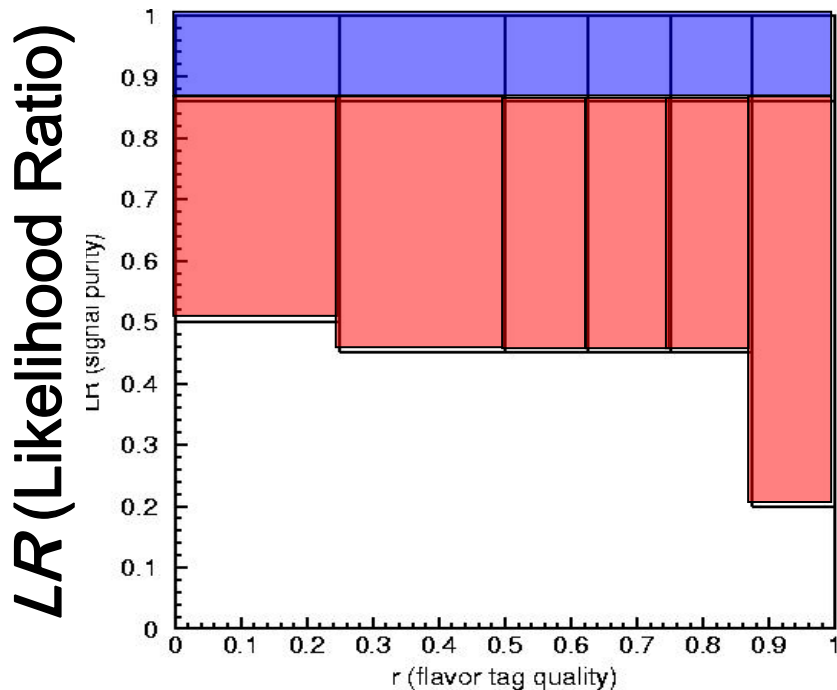
B⁰→π⁺π⁻ decay

$B^0 \to K^\pm \pi^\mp$

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

$P(K) = L(K)/(L(K)+L(\pi))$
PID likelihood ratio

ΔE (GeV)

12 distinct bins in LR vs r

LR (Likelihood Ratio)

r (flavor tag quality)

An unbinned extended maximum likelihood fit for the signal yield estimation

$$L = \exp(-\sum_{k,\ell} n_k^{\ell}) \prod_i \sum_{k,\ell} [n_k^{\ell} P_k^{(\ell)}(\Delta E, M_{bc}, x_+, x_-)]$$
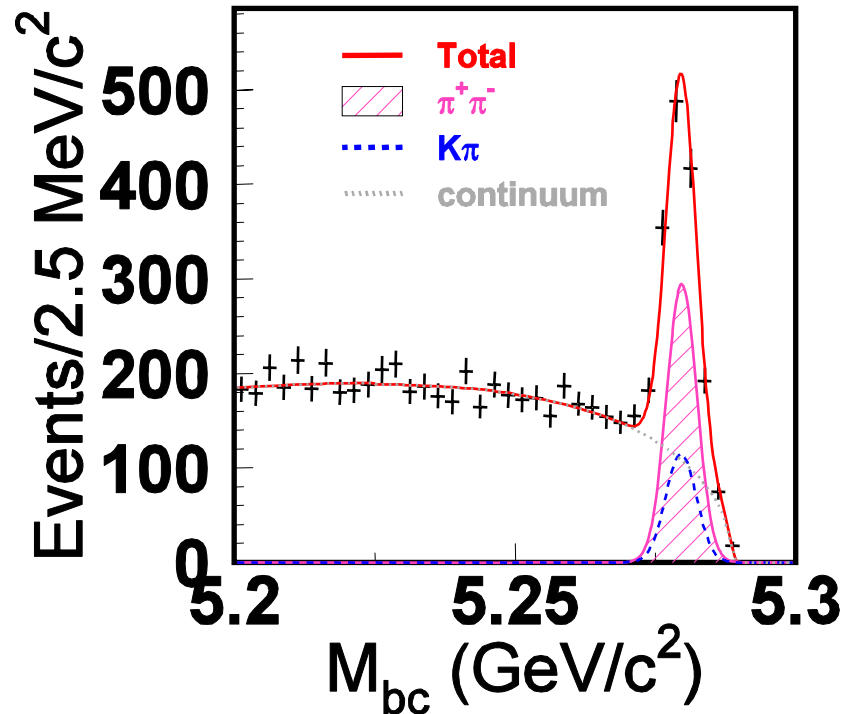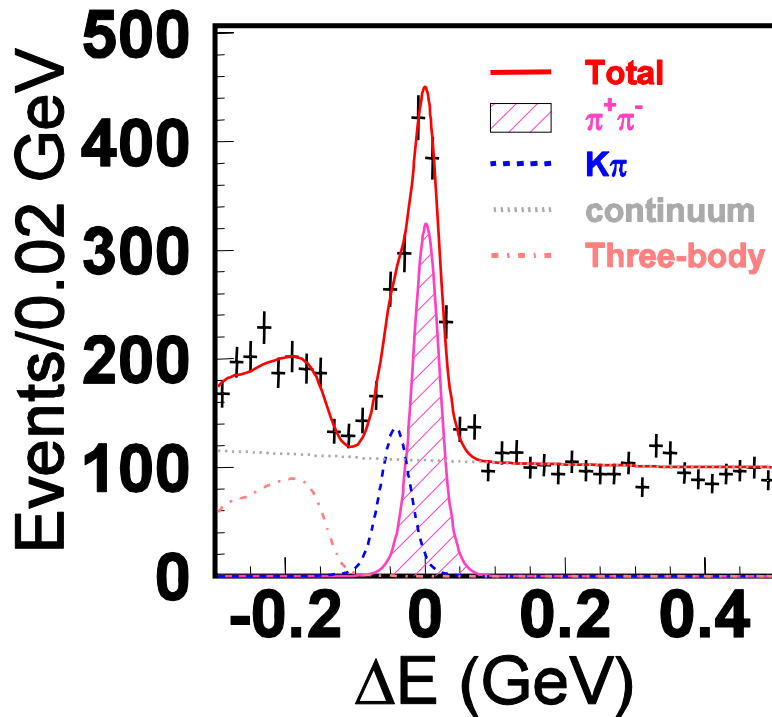
k=$\pi\pi$, Kπ, continuum and three-body decays

ℓ=1,12; the LR-r bin

n_k^{ℓ} = the yield of type k in bin ℓ

$P_k^{(\ell)}$ = the PDF as a function of ΔE, M_{bc}, and PID of pos. and neg. charged track x_+, x_-

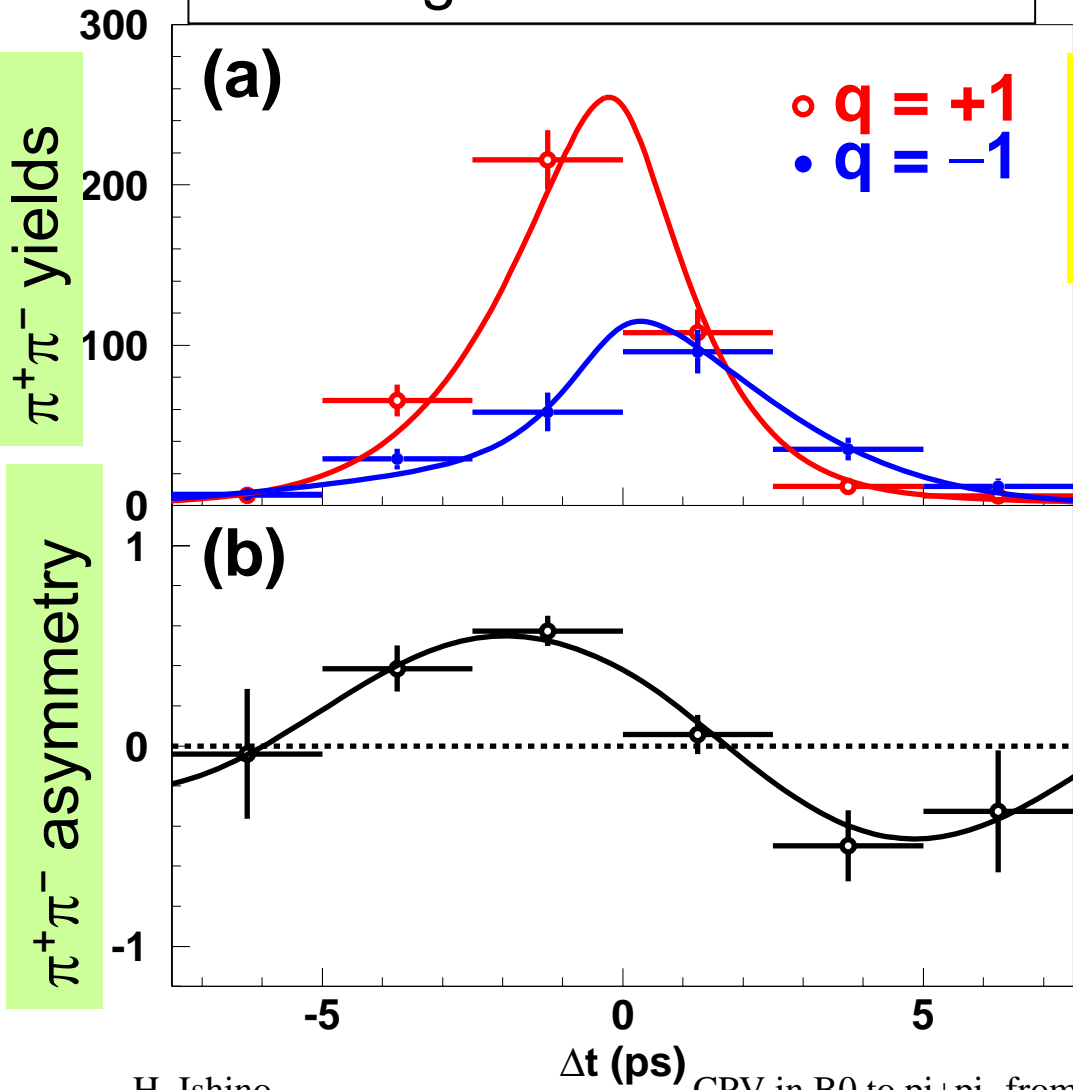# $B^0 \to \pi^+\pi^-$ decay (time-integrated fit)

projection to the area with P(K)<0.4 ($\pi^+\pi^-$ enhanced)

1464±65 signal events

B⁰→π⁺π⁻ decay (CP asymmetry)

$$A_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$$

$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$$

first error: stat., second: syst.

$$\rho = +0.15$$

Large violation in both mixing-induced and Direct CP symmetries

$B^0 \to \pi^+ \pi^-$ systematic error

	$S_{\pi\pi}$	$A_{\pi\pi}$
vertex reconstruction	$\pm$ 0.03	$\pm$ 0.01
event fraction	$\pm$ 0.01	$\pm$ 0.04
tag side interference	$\pm$ 0.01	$\pm$ 0.02
wrong tag fraction	$\pm$ 0.01	$\pm$ 0.01
physics parameters	< 0.01	< 0.01
resolution function	$\pm$ 0.02	$\pm$ 0.02
background Δt shape	< 0.01	< 0.01
fit bias	$\pm$ 0.01	$\pm$ 0.01

$B^0 \to \pi^+ \pi^-$ decay (CPV significance)

confidence level contour
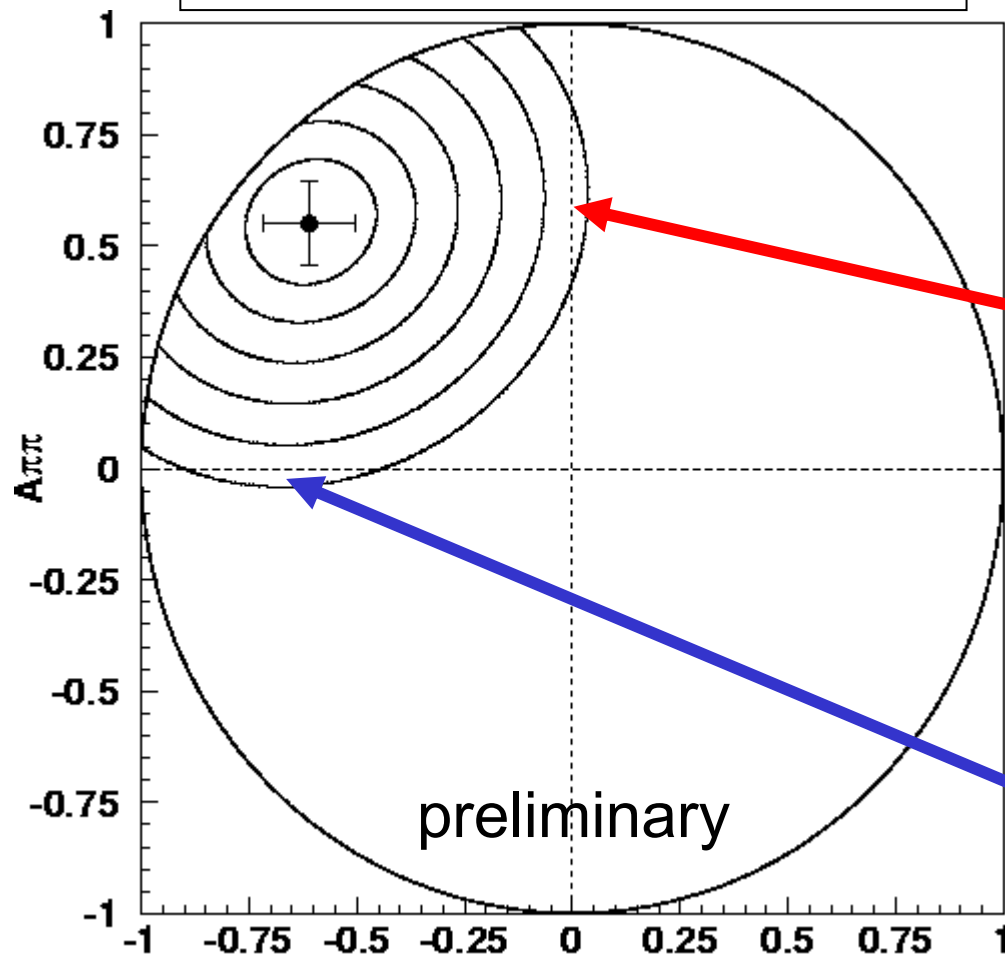
1−CL = 1.6×10^{-8}
for $A_{\pi\pi}$ = +0.62, $S_{\pi\pi}$=0
corresponds to 5.6σ

Observation of mixing-induced CP Violation

1−CL = 2.8×10^{-8}
for $A_{\pi\pi}$ = 0, $S_{\pi\pi}$=−0.67
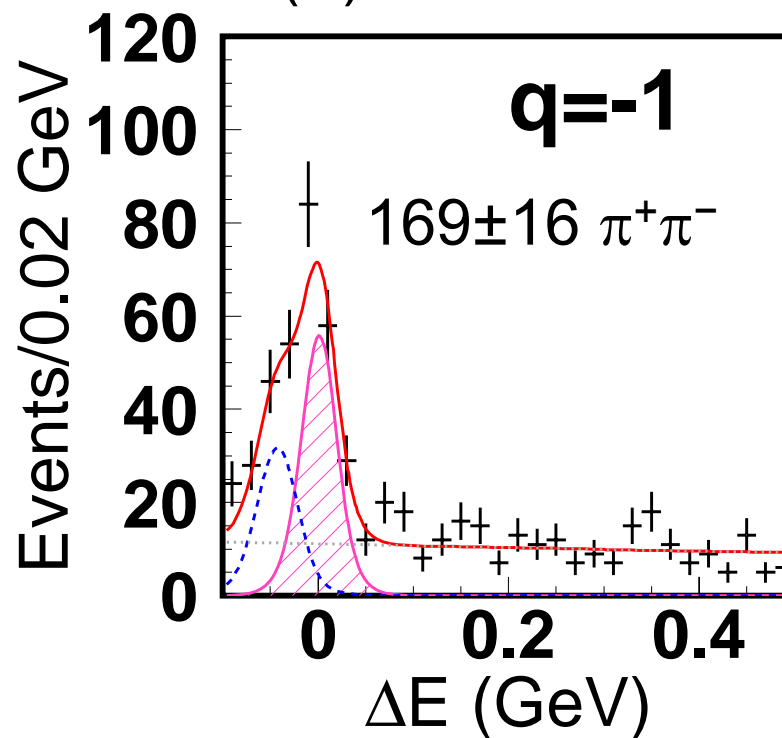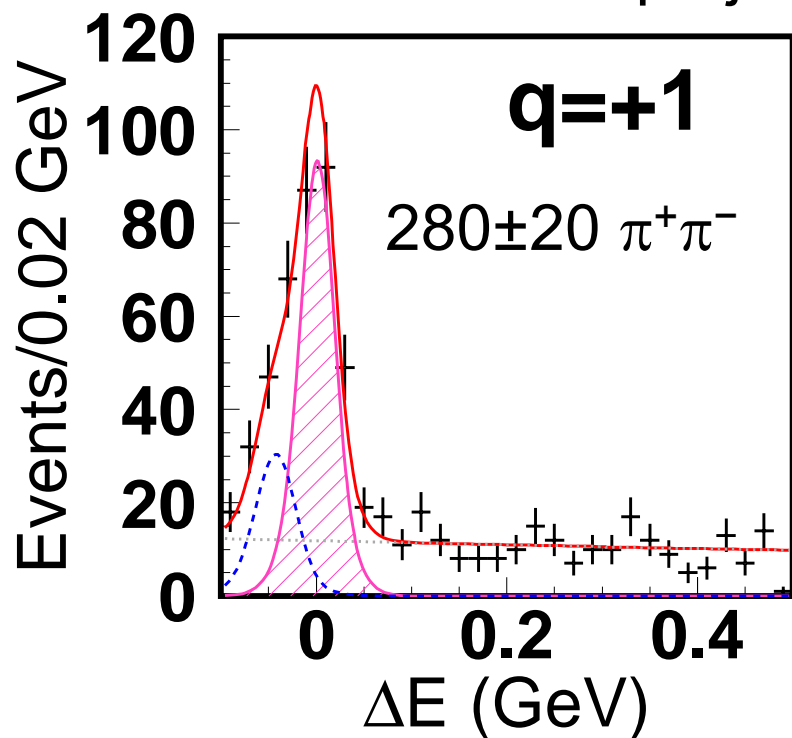corresponds to 5.5σ

Observation of Direct CP Violation

preliminary

both statistical and systematic errors are taken into account

B⁰→π⁺π⁻ decay validity check

time-integrated fit $A_{\pi\pi} = +0.56 \pm 0.10$

ΔE projection onto P(K)<0.4

P(K)<0.4 & good tag

B⁰→π⁺π⁻ decay validity check

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

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

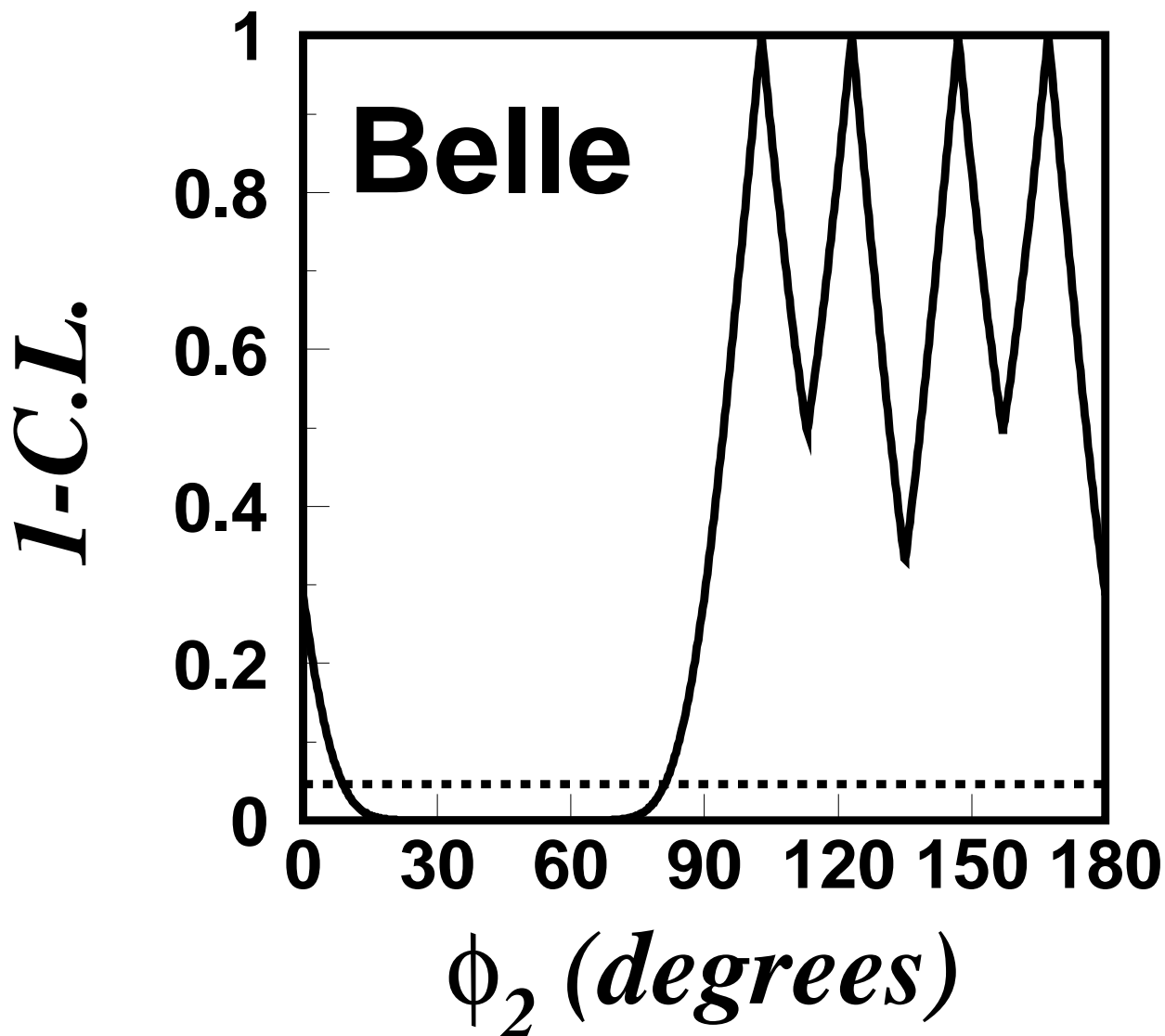$$\widetilde{A}^{ij} = e^{2\phi_3}\overline{A}^{ij}$$

The cleanest method to extract ϕ_2

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

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

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

H. Ishino

14
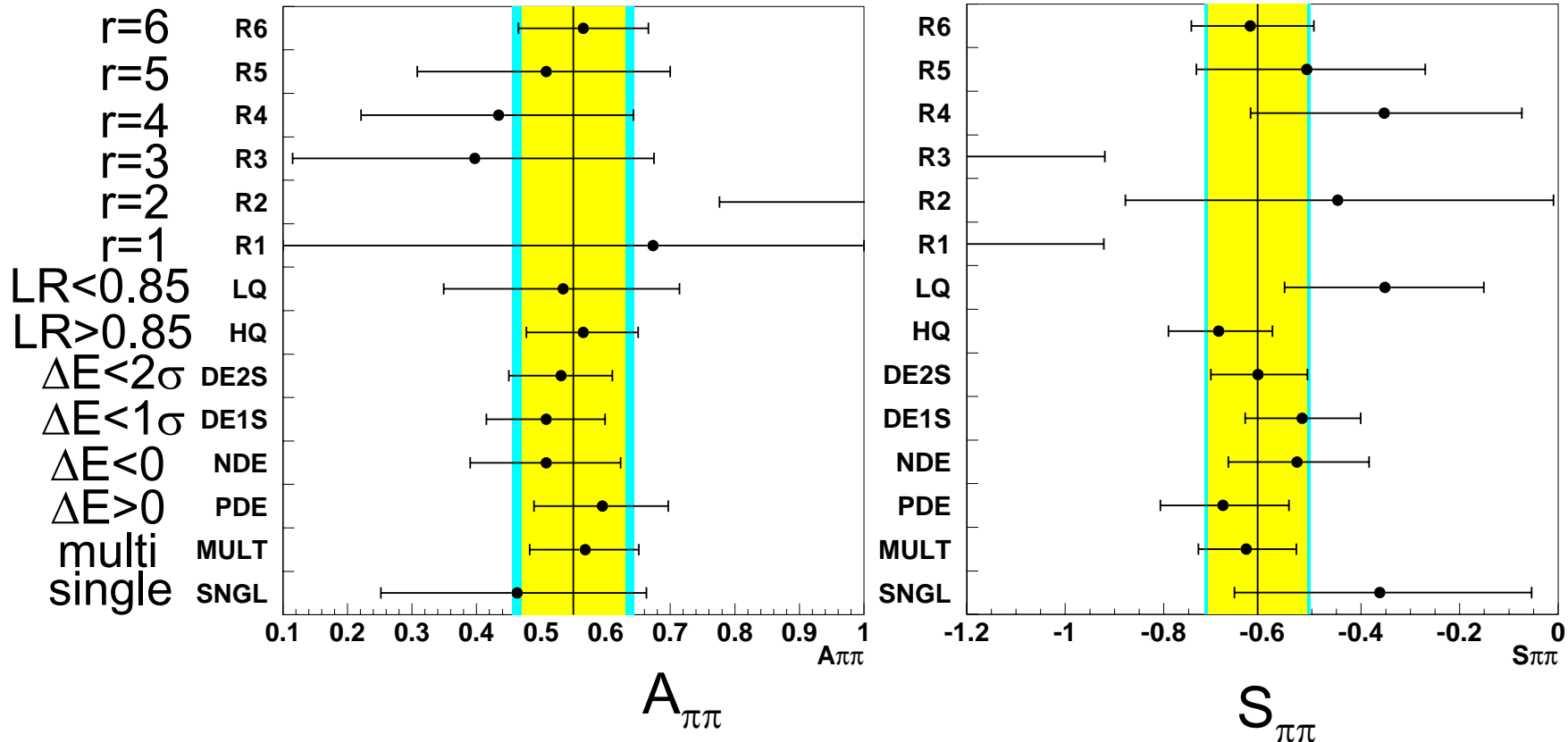
Interpretation: ϕ_2 constraint using isospin

Belle

1-$C.L.$ vs ϕ_2 (degrees)

Excluding

$$9° < \phi_2 < 81°$$

@95.4% C.L.

Branching ratios and $B^0 \to \pi^0\pi^0$ A_{CP}

hep-ex/0609015
hep-ex/0610065

Conclusion
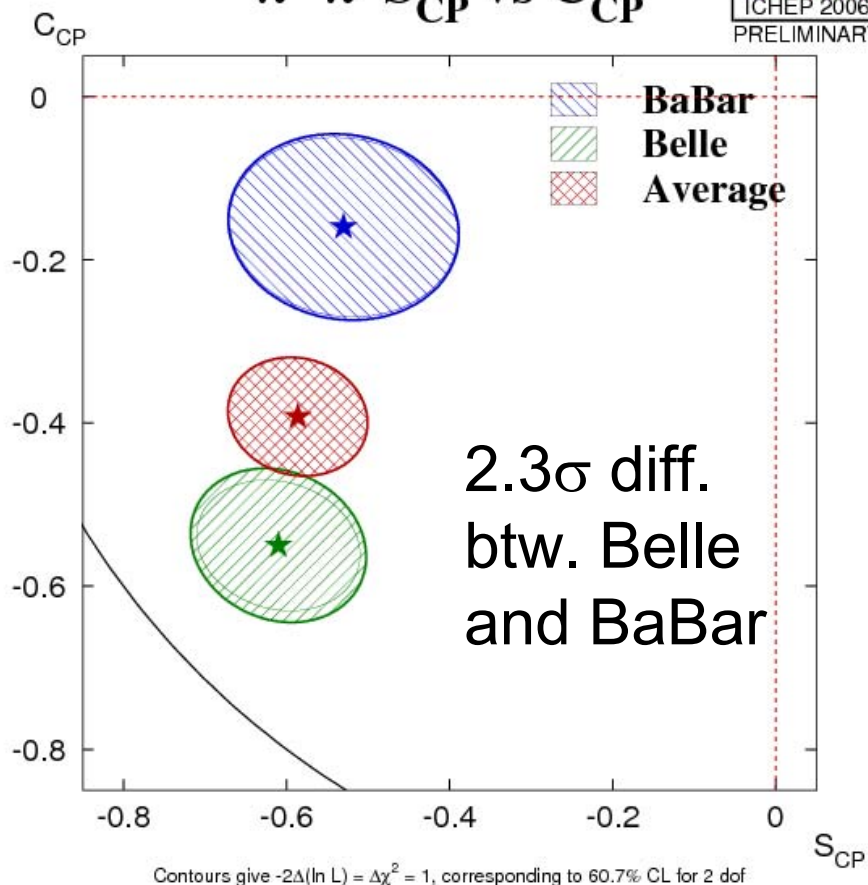
- Belle measures CPV parameters in $B^0 \to \pi^+\pi^-$ decays with 535MBB
  - $A_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$,   preliminary
    $S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$
    - Observation of both Direct and mixing-induced CP Violation with a significance $\sim 5.5\sigma$
- hep-ex/0608035
- The results confirm the previous Belle measurements.

backup slides
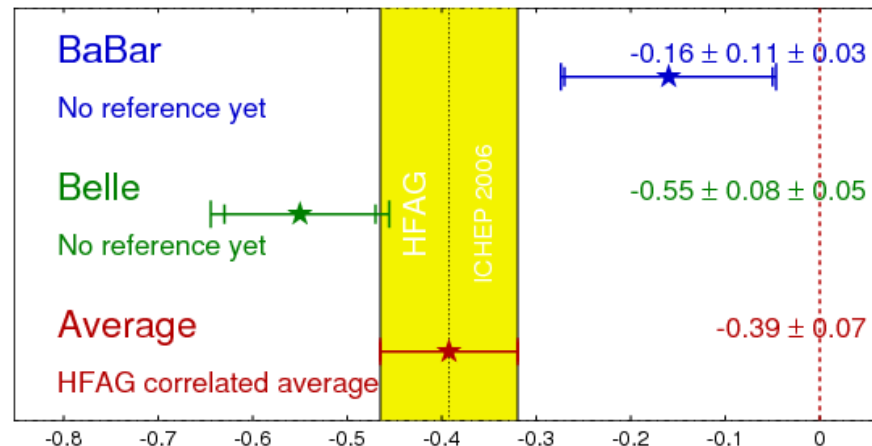
$B^0 \rightarrow \pi^+\pi^-$ decay
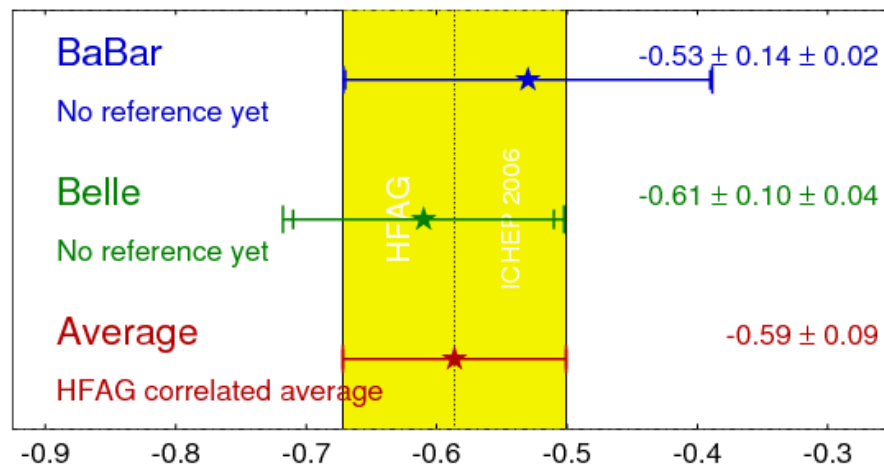
C = −A

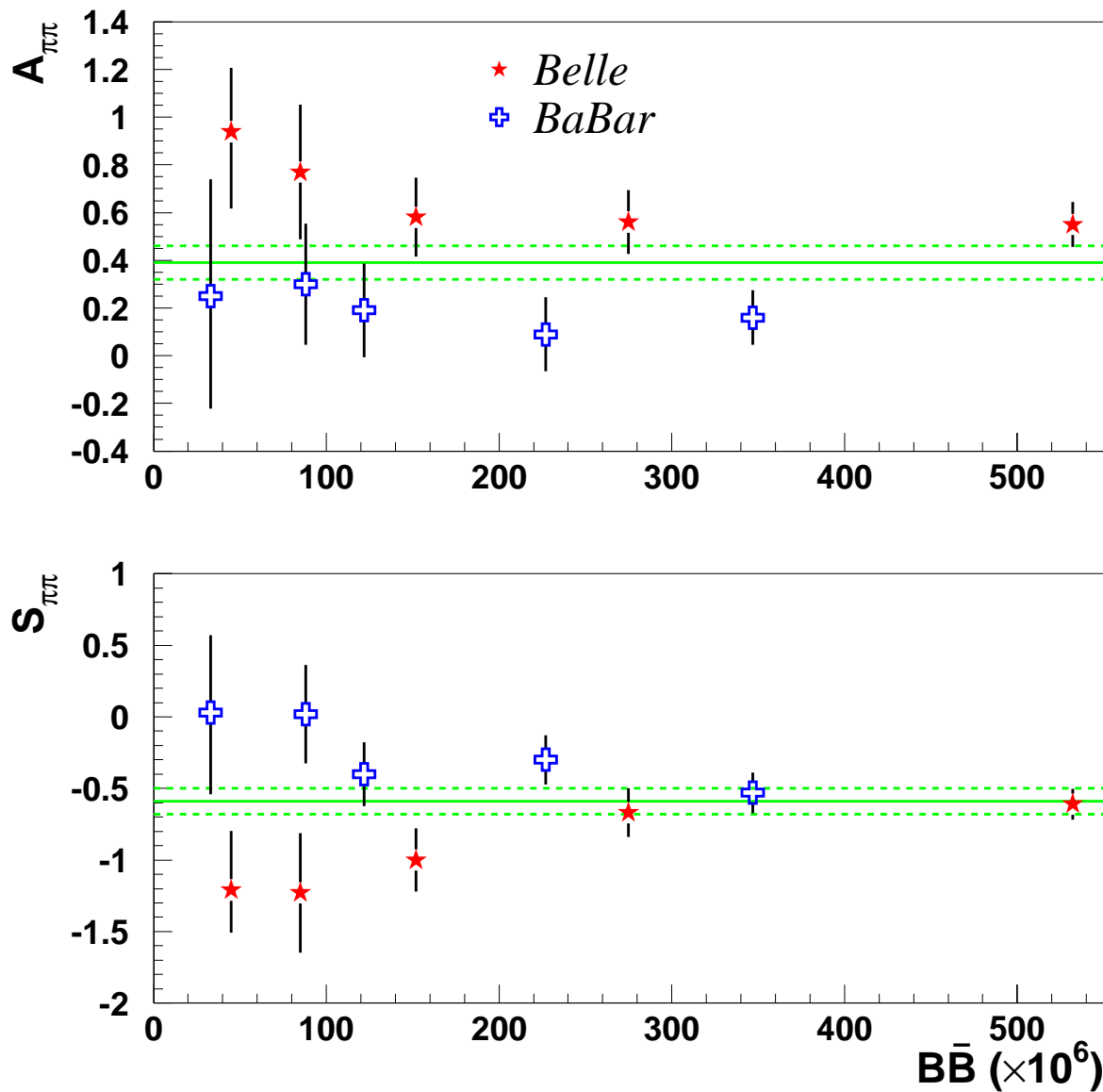$\pi^+ \pi^- S_{CP}$ vs C_{CP}

HFAG ICHEP 2006 PRELIMINARY

- BaBar
- Belle
- Average

Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

2.3σ diff. btw. Belle and BaBar

$\pi^+ \pi^- C_{CP}$

HFAG ICHEP 2006 PRELIMINARY

BaBar	$-0.16 \pm 0.11 \pm 0.03$
No reference yet	
Belle	$-0.55 \pm 0.08 \pm 0.05$
No reference yet	
Average	-0.39 ± 0.07
HFAG correlated average	

$\pi^+ \pi^- S_{CP}$

HFAG ICHEP 2006 PRELIMINARY

BaBar	$-0.53 \pm 0.14 \pm 0.02$
No reference yet	
Belle	$-0.61 \pm 0.10 \pm 0.04$
No reference yet	
Average	-0.59 ± 0.09
HFAG correlated average	

History of $B^0 \to \pi^+ \pi^-$ decay

ϕ_2 constraints from $B^0 \to \pi^+\pi^-$ decay
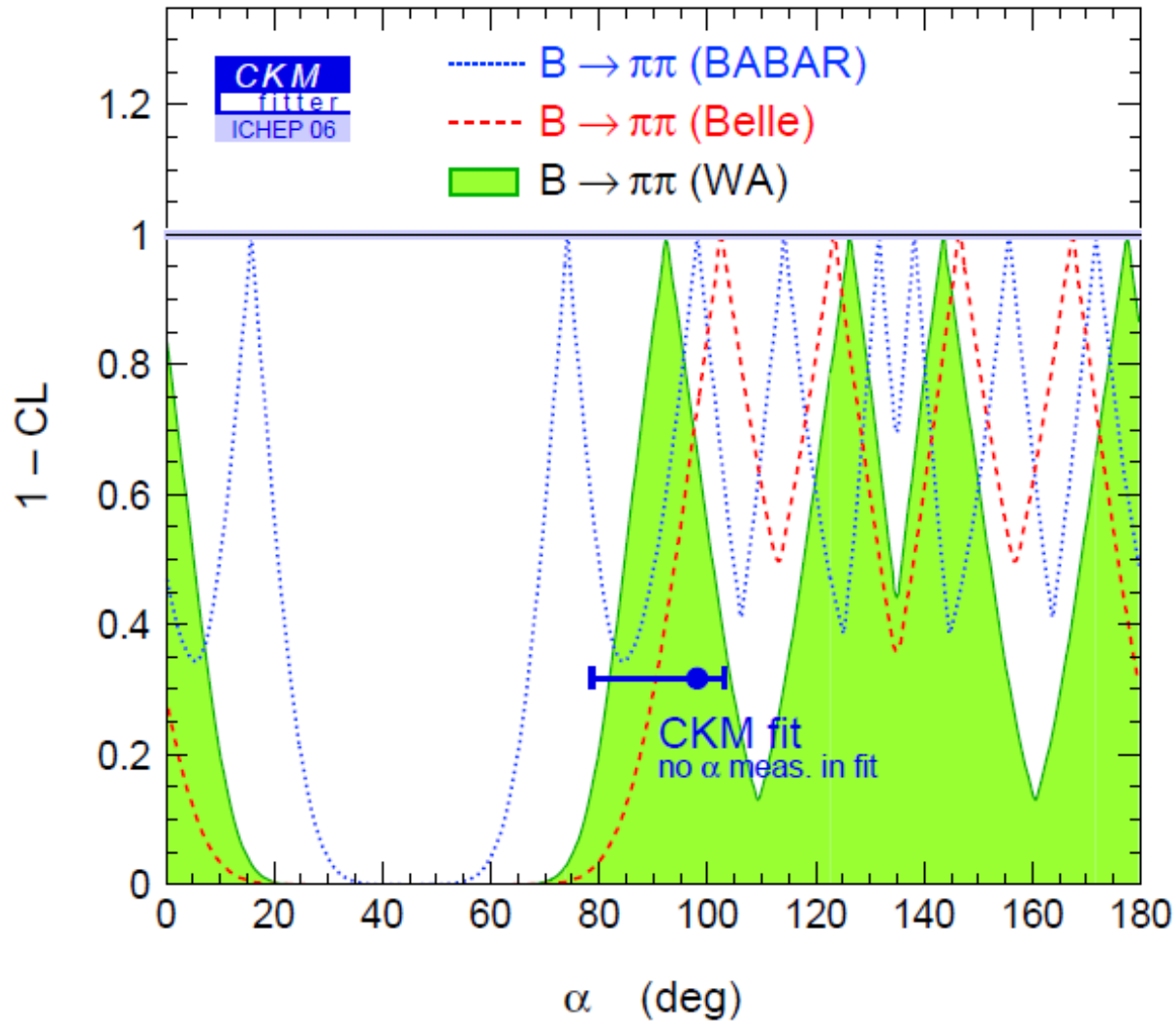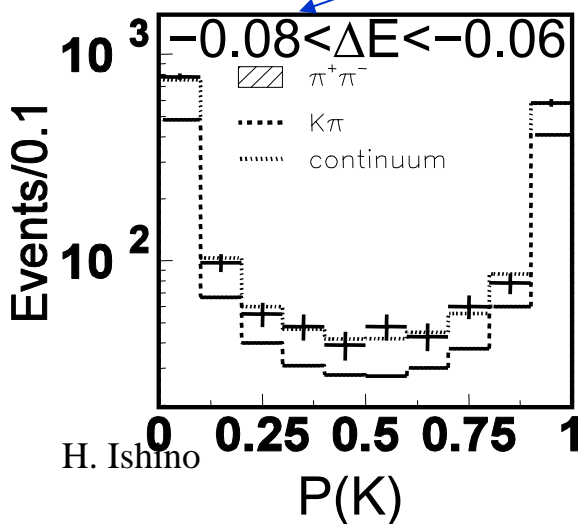
B⁰→π⁺π⁻ decay (time-integrated fit)

LR>0.85 & P(K)<0.4

1464±65 signal events

H. Ishino   CPV in B0 to pi+   ...le
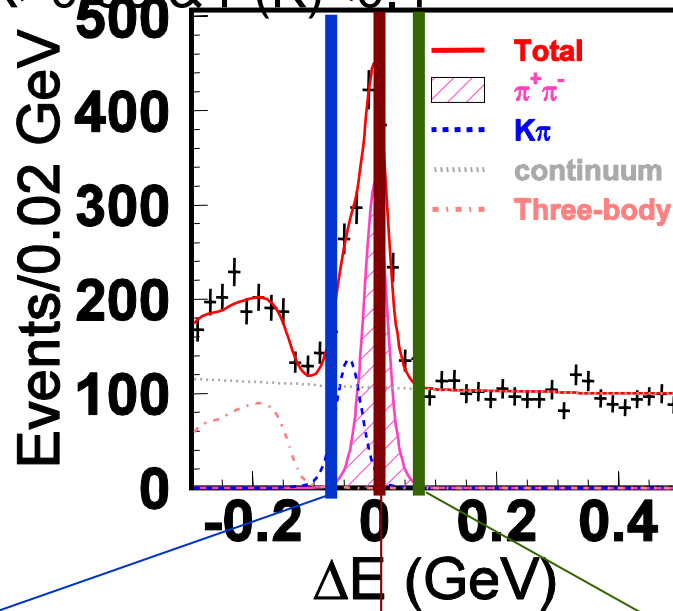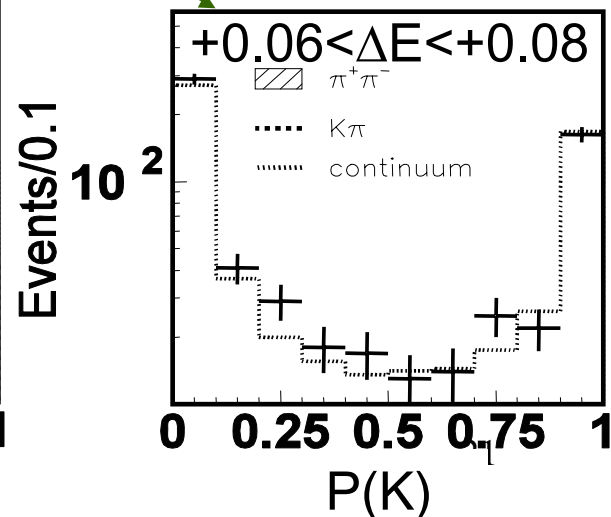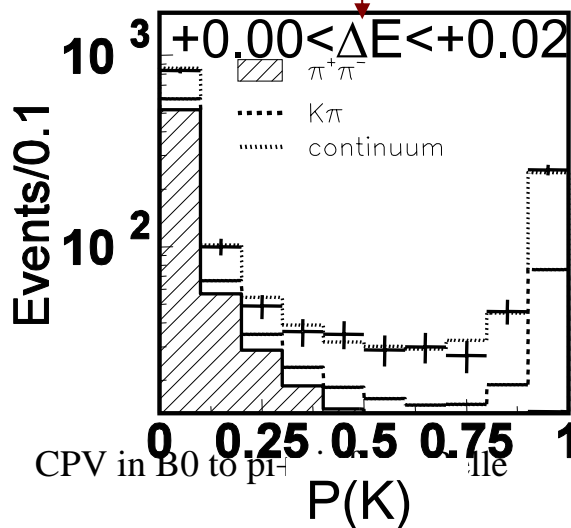
Interpretation :direct CP violation

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

$$A_{CP}(K^+\pi^-) \sim -\frac{1}{3} A_{CP}(\pi^+\pi^-)$$
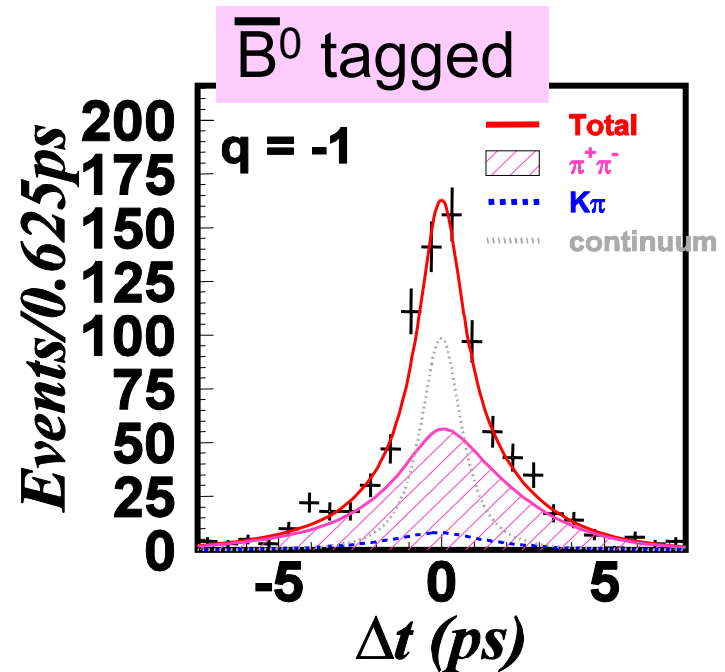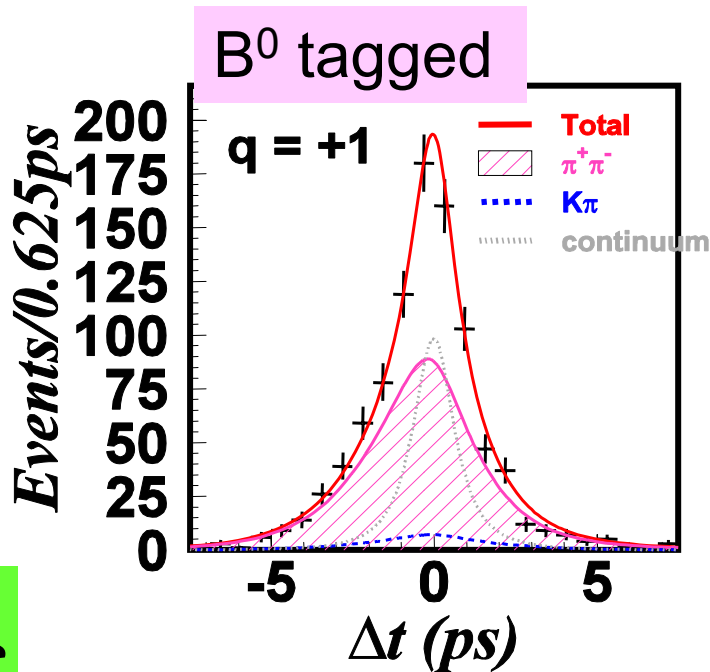
M. Gronau and J.L. Rosner, PLB 595, 339 (2004)

$$A_{CP}(K^+\pi^-) = -0.115 \pm 0.018 \qquad \text{HFAG summer 2004}$$

$$-\frac{1}{3} A_{CP}(\pi^+\pi^-) = -0.18 \pm 0.03 \qquad \text{our measurement}$$

$B^0 \to \pi^+\pi^-$ decay (time-dependent fit)