Belle 実験における CKM angle ϕ_2 の測定

Nakadaira Takeshi

nakadair@hep.phys.s.u-tokyo.ac.jp

Univ. of Tokyo

Outline

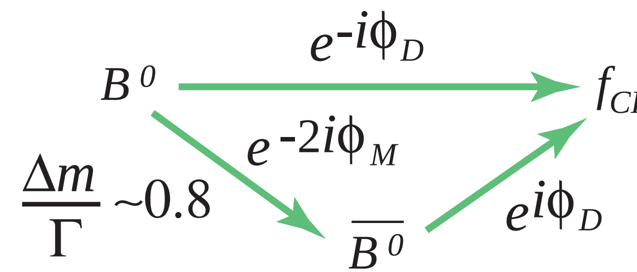
1. Introduction
   - CP violation in $B^0 \to \pi^+\pi^-$ decay.
2. Analysis procedure
   - Event and time reconstruction
   - Determination of CP-violation parameters $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$
   - Cross checks
3. Result
   - CP-violation parameters $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$
   - Constraint on the CKM angle ϕ_2
4. Conclusion

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

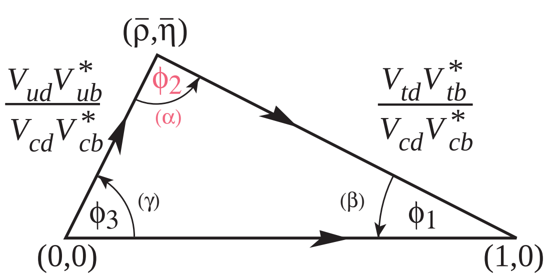
- Time-dependent decay ratio asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma(\overline{B}^0 \to \pi^+\pi^-;t) - \Gamma(B^0 \to \pi^+\pi^-;t)}{\Gamma(\overline{B}^0 \to \pi^+\pi^-;t) + \Gamma(B^0 \to \pi^+\pi^-;t)}$$

$$= A_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)$$



$$\lambda_f \equiv e^{-2i\phi_M} \frac{A(\overline{B}^0 \to \pi^+\pi^-)}{A(B^0 \to \pi^+\pi^-)}, \; A_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1}, \; S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{|\lambda_f|^2 + 1}$$

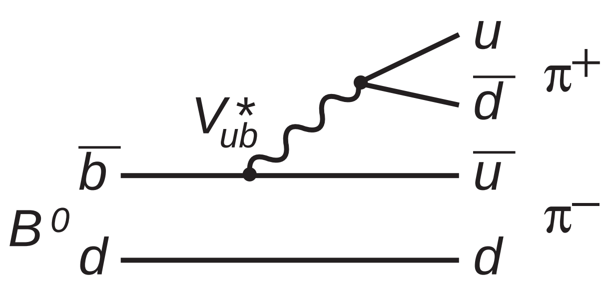


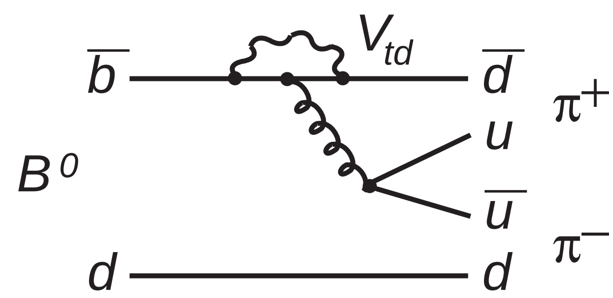
Standard model predictions

	$b \to c\bar{c}s$	$b \to u\bar{u}d$
example	$B^0 \to J/\psi K_S$	$B^0 \to \pi^+\pi^-$
A_f	0	0 (Tree level)
S_f	$\sin 2\phi_1$	$\sin 2\phi_2$ (Tree level)

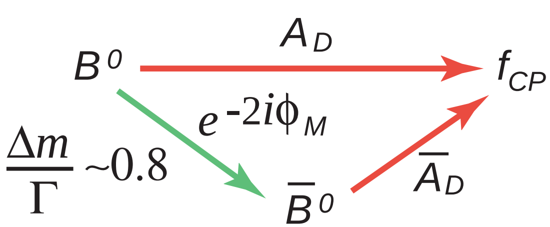
Penguin pollution

- In $B^0 \to \pi^+\pi^-$, Penguin contribution is not negligible.

$A(B^0 \to f_{CP}) =$ 

$+$ 

tree ($\ni \phi_3$) penguin ($\ni \phi_1$)



- $|\lambda_f| \neq 1$
  $\cdots \mathcal{S}_{\pi\pi} \neq \sin 2\phi_2, \mathcal{A}_{\pi\pi} \neq 0$
  (Penguin Pollution)

- $\mathcal{A}_{\pi\pi} \neq 0$
  $\Longrightarrow \Gamma(\overline{B}^0 \to \pi^+\pi^-) \neq \Gamma(B^0 \to \pi^+\pi^-)$
  $\ldots$ Direct CP violation

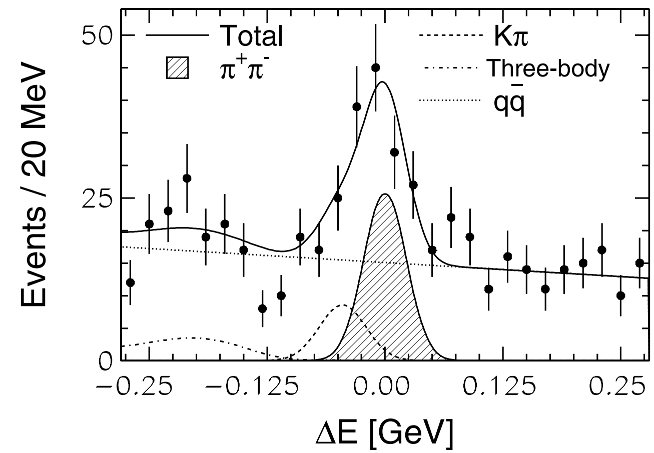
Previous measurements at Belle

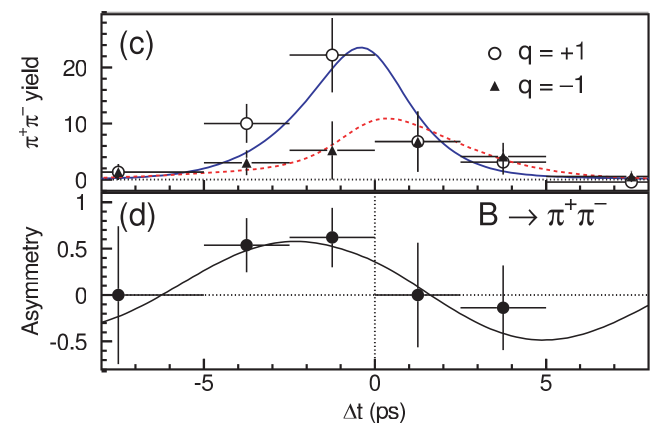
- "Study of CP-violating Asymmetries in $B^0 \to \pi^+\pi^-$ Decays" Phys. Rev. Lett. **89**, 0.71801 (2002)
  - 45M $B\overline{B}$ (42 fb^{-1}) $\cdots$ 162 candidates

    $$\mathcal{S}_{\pi\pi} = -1.21^{+0.38}_{-0.27}(\mathrm{stat})^{+0.13}_{-0.16}(\mathrm{syst})$$

    $$\mathcal{A}_{\pi\pi} = +0.94^{+0.25}_{-0.31}(\mathrm{stat}) \pm 0.09(\mathrm{syst})$$

  - Results indicated large CPV.





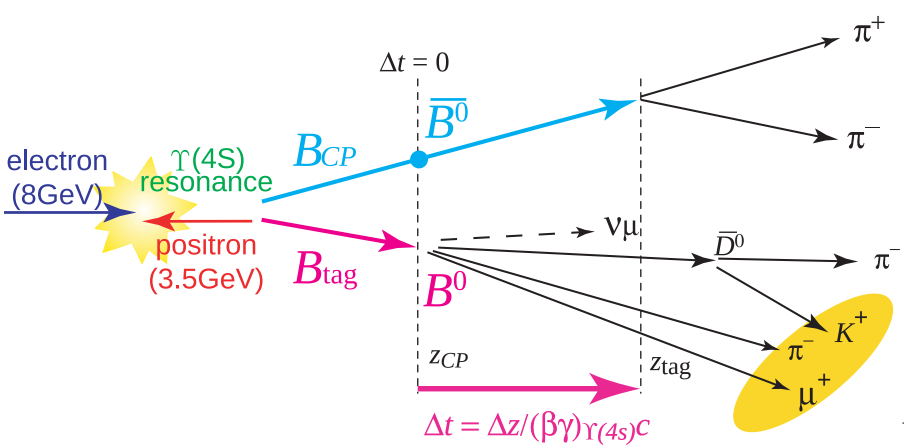
- Change in the new analysis.
  - More data
  - Improvements to the analysis
    - Better tracking algorithm
    - More sophisticated Δt resolution function
    - Inclusion of additional signal candidates by optimizing event selection

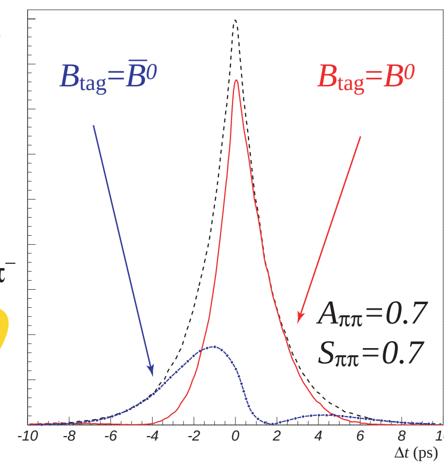
Experimental Method

Data set: 85×10^6 $B\overline{B}$ events (78fb^{-1})

1. Reconstruction of B_{CP} with tracks identified as pion.
   Small BR.($(4.4 \pm 0.9) \times 10^{-6}$ cf. 4.4×10^{-4} for $B^0 \to J/\psi K_S$)
   Large BG w.r.t $B \to c\bar{c}K_S$: K/π separation is important.
2. Determination of $B_{\rm tag}$ flavor
3. Measurement of Δt

$\longleftarrow$ Adopt the same method used in ϕ_1 measurement.





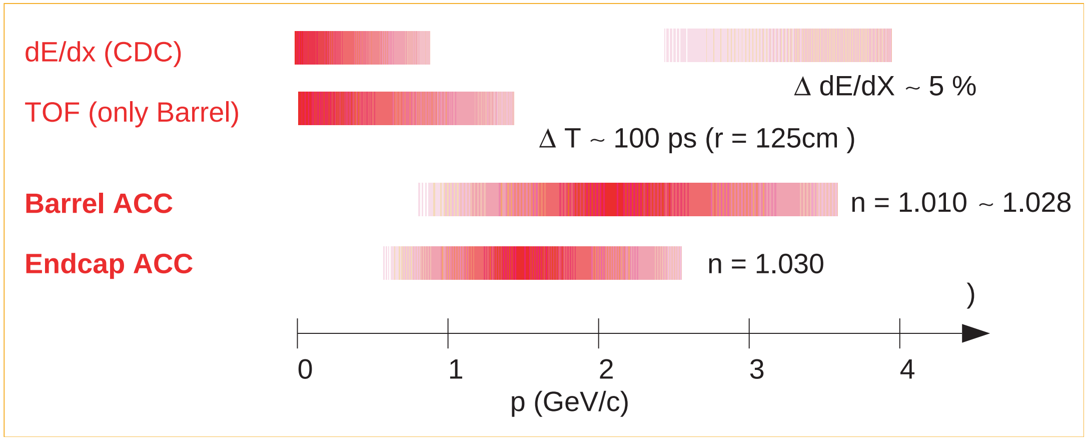
$$q = \begin{cases} +1 & B_{\rm tag} = B^0 \\ -1 & B_{\rm tag} = \overline{B}^0 \end{cases}$$

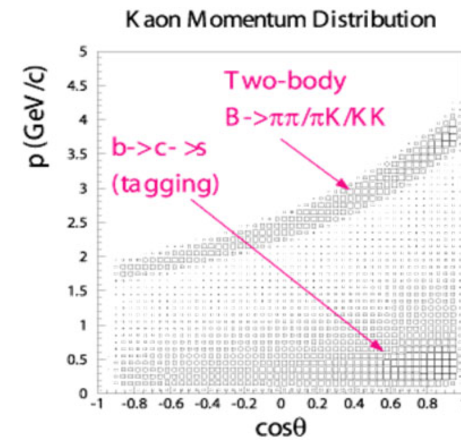
$\mathcal{A}_{\pi\pi} \neq 0$
$\longrightarrow$ Yield Asym.

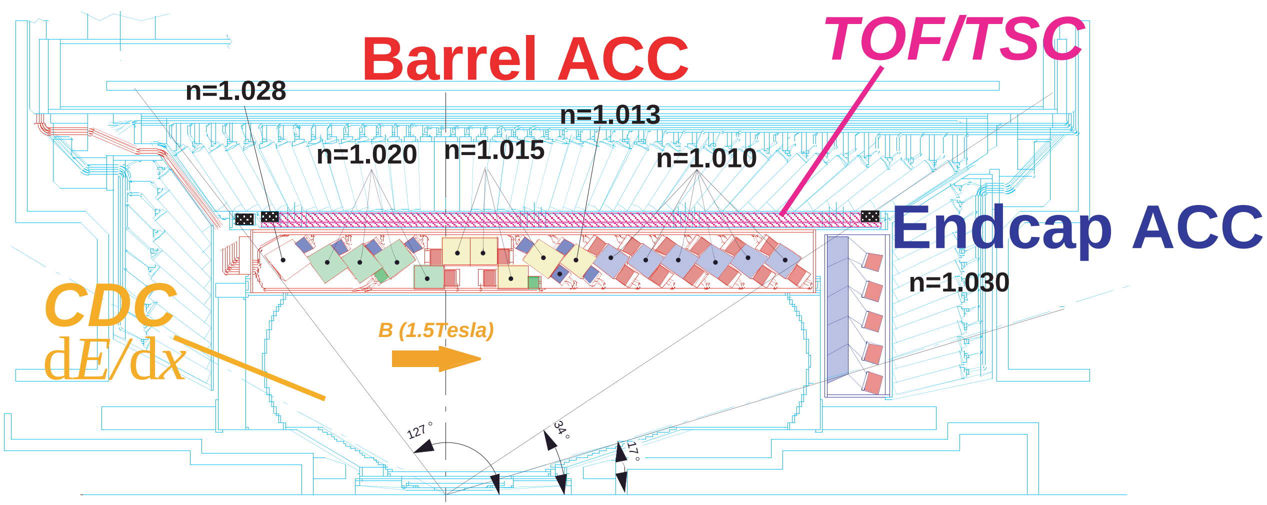
$\mathcal{S}_{\pi\pi} \neq 0$
$\longrightarrow$ Shape Asym.

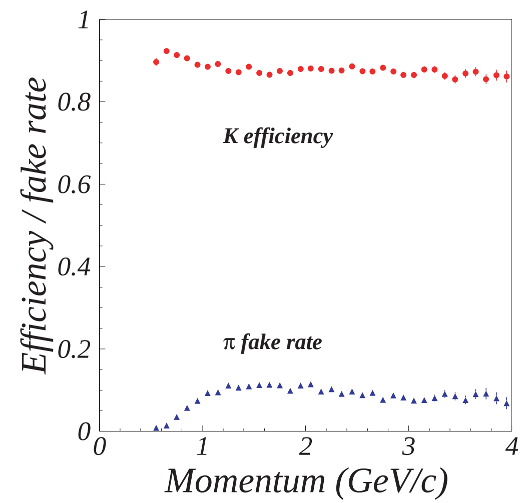
$$f(\Delta t; q, \mathcal{A}_{\pi\pi}, \mathcal{S}_{\pi\pi})$$
$$= \frac{1}{4\tau_{B^0}} \exp\left(-\frac{|\Delta t|}{\tau_{B^0}}\right) \{1 + q\left[\mathcal{A}_{\pi\pi}\cos(\Delta m_d \Delta t) + \mathcal{S}_{\pi\pi}\sin(\Delta m_d \Delta t)\right]\}$$

K/π separation

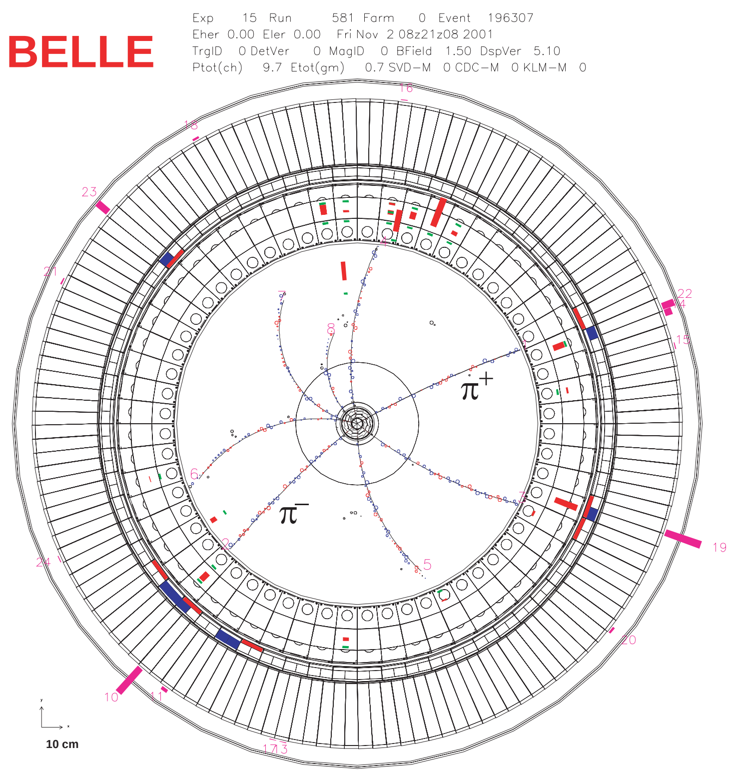


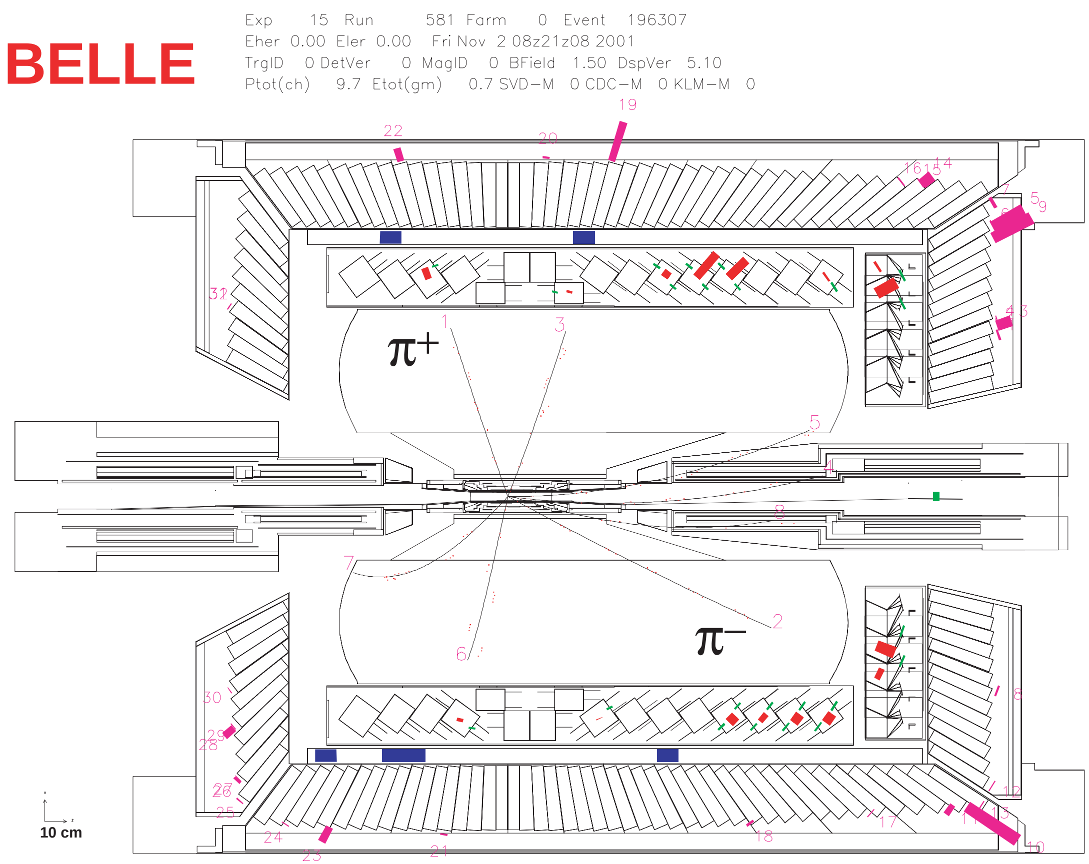






$B^0 \to \pi^+\pi^-$ Sample

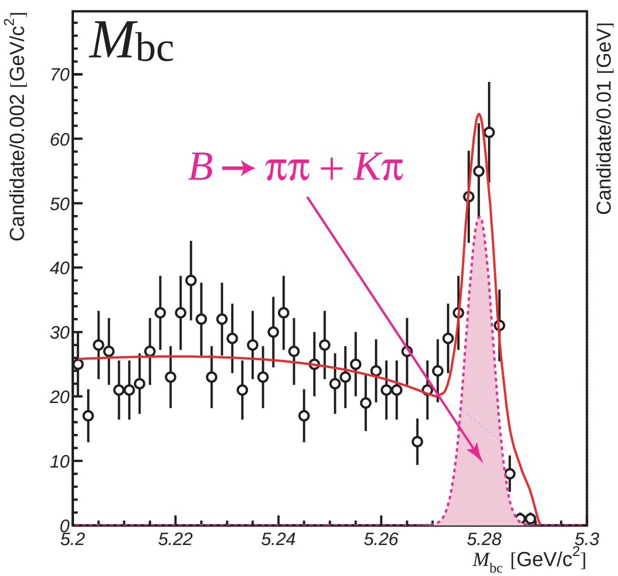


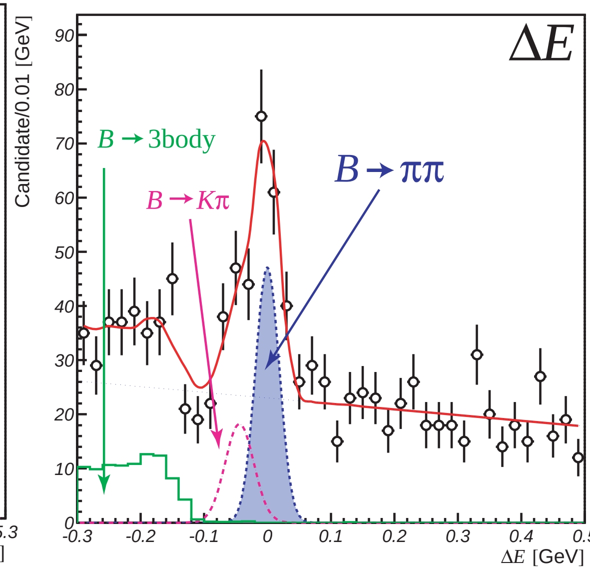


$B^0 \to \pi^+\pi^-$ reconstruction

- $B^0 \to \pi^+\pi^-$ is reconstructed with two kinematical variables.
  - Beam-energy constrained mass($M_{\rm bc}$)

    $$M_{\rm bc} = \sqrt{(E^{\rm cms}_{\rm beam})^2 - (\boldsymbol{p}^{\rm cms}_B)^2}$$
  - Energy difference (ΔE) $\Delta E = E^{\rm cms}_B - E^{\rm cms}_{\rm beam}$



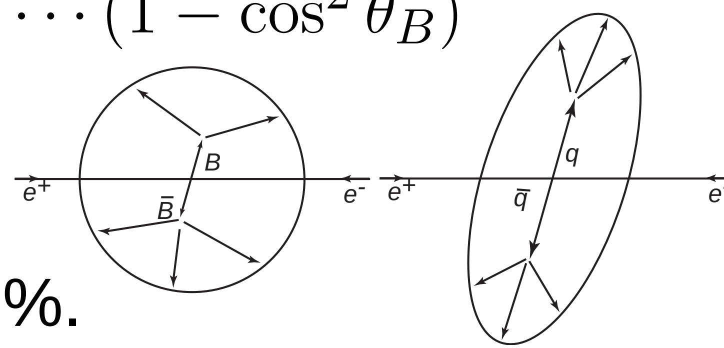


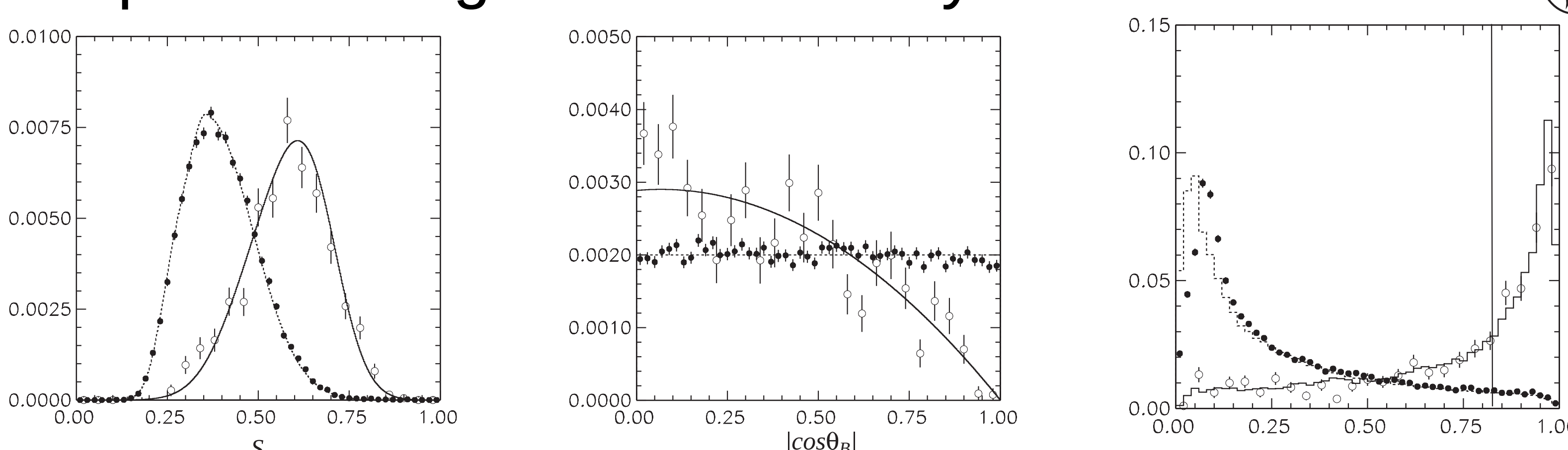
Background

- $B^0 \to K^+\pi^-$ ($\Delta E = -45{\rm MeV}$)
- Continuum event suppression is applied. $\to$next slide

Continuum Suppression

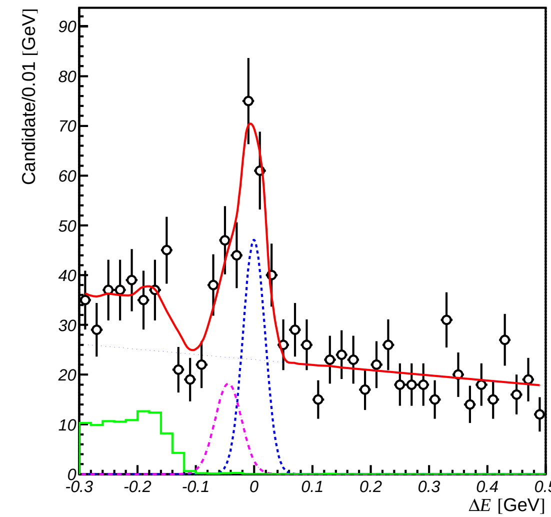
- Continuum Background: $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$
  - Jet-like event phase $\leftrightarrow B\overline{B}$ event: spherical
  - Likelihood Ratio of Event shape: $\mathcal{LR} = \frac{L_{B\overline{B}}}{L_{B\overline{B}} + L_{q\bar{q}}}$
    - Improved Fox-Wolfram moment
    - Flight Direction of B : flat $\leftrightarrow B\overline{B} \cdots (1 - \cos^2\theta_B)$
- Requirement of $\mathcal{LR} > 0.825$
  - Reject 95% of Continuum BG.
  - Keep 53% of signal $\to$ Efficiency 31%.

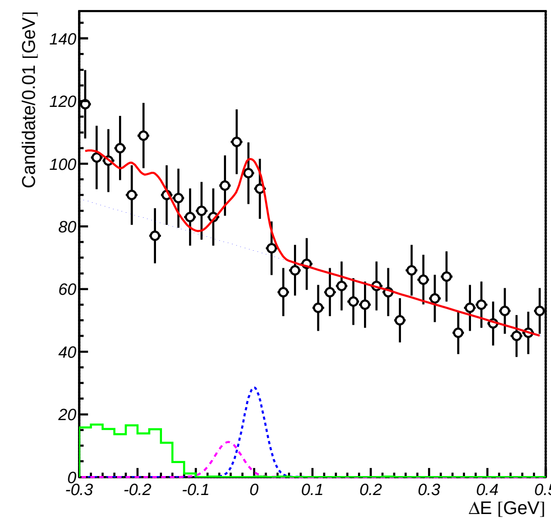




signal yield

- Signal region: $5.271 < M_{\rm bc} < 5.278 \mathrm{GeV}/c^2$, $|\Delta E| < 0.057 \mathrm{GeV}$
- Signal yields is extracted from ΔE distribution of $\mathcal{LR} > 0.825$ region.
  - $B^0 \to \pi^+\pi^- \cdots 106^{+16}_{-15}$
  - $B^0 \to K^+\pi^- \cdots 41^{+10}_{-9}$
  - Continuum $\cdots 128^{+5}_{-6}$
- Part of $\mathcal{LR} \leq 0.825$ region is used in CP analysis.
  - $B^0 \to \pi^+\pi^- \cdots 57 \pm 8$
  - $B^0 \to K^+\pi^- \cdots 22^{+6}_{-5}$
  - Continuum $\cdots 406 \pm 17$





Determination of $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$

- Un-binned Maximum Likelihood Fit: 2 Free parameters
  - Probability Density Function $\cdots$ 4 components

$$
\begin{aligned}
P(\Delta t, q; \mathcal{A}_{\pi\pi}, \mathcal{S}_{\pi\pi}) = (1 - f_{\rm ol})\{[f_{\pi\pi} P_{\pi\pi}(\Delta t, q; \mathcal{A}_{\pi\pi}, \mathcal{S}_{\pi\pi}) &\Leftarrow \text{signal} \\
+ f_{K\pi} P_{K\pi}(\Delta t)] \otimes R_{\rm sig}(\Delta t) &\Leftarrow B^0 \to K^+\pi^- \\
+ f_{q\bar{q}} P_{q\bar{q}}(\Delta t)\} &\Leftarrow \text{Continuum} \\
+ f_{\rm ol} P_{\rm ol}(\Delta t) &\Leftarrow \text{Outlier}
\end{aligned}
$$

- $P_{K\pi}(\Delta t)$: Assume no CP asymmetry($\mathcal{A}_{K\pi} = 0$).
- $f_{\pi\pi}$, $f_{K\pi}$, $f_{q\bar{q}}$: Event-by-event Signal/Background probability
  $\leftarrow$ Function of $(\Delta E, M_{\rm bc})$.
- $P_{q\bar{q}}(\Delta t)$: Continuum $\leftarrow$ Modeled by $(\Delta E, M_{\rm bc})$ sideband
- Δt resolution, Outlier: same as ϕ_1 measurement.

Check

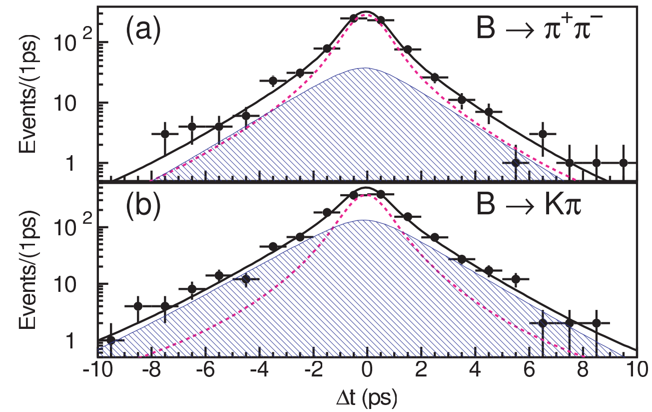
- B^0 Lifetime measurement

  $\tau_{B^0} = 1.42^{+0.14}_{-0.12}$ ps : $B^0 \to \pi^+\pi^-$

  $\tau_{B^0} = 1.46 \pm 0.08$ ps : $B^0 \to K^+\pi^-$

  PDG2002(1.542 ± 0.016 ps)

  $\Rightarrow \Delta t$ measurement & Resolution is OK.

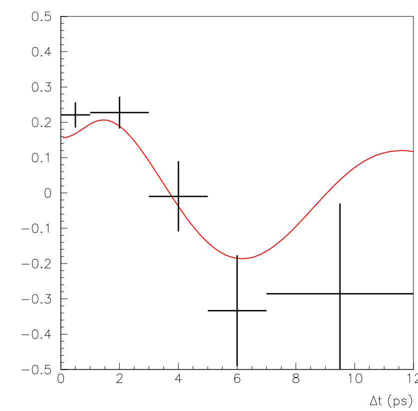


- B^0-$\overline{B}^0$ mixing measurement using $B^0 \to K^+\pi^-$ sample.

  $\Delta m_d = 0.55^{+0.05}_{-0.07}\ \hbar\ \mathrm{ps}^{-1}$: $B^0 \to K^+\pi^-$

  PDG2002($0.489 \pm 0.008\ \hbar\ \mathrm{ps}^{-1}$)

  $\Rightarrow$ Flavor tagging is also OK.



Check (cont'd)

- bias test using non-CP sample

  "$\mathcal{A}_{\pi\pi}$"$= -0.015 \pm 0.022$

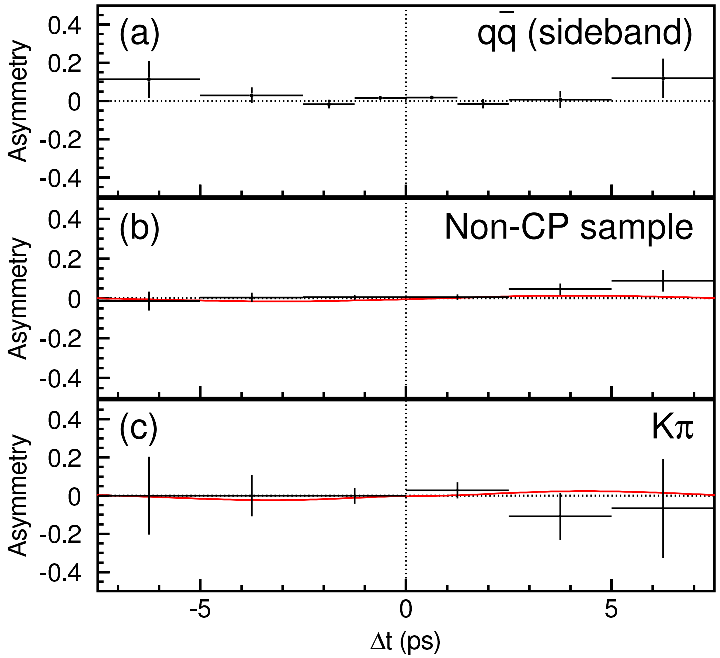
  "$\mathcal{S}_{\pi\pi}$"$= -0.045 \pm 0.033$,

- $B^0 \to K^+\pi^-$ sample has no asymmetry.

  $\mathcal{A}_{K\pi} = +0.08 \pm 0.16$

  $S_{K\pi} = -0.03 \pm 0.11$,

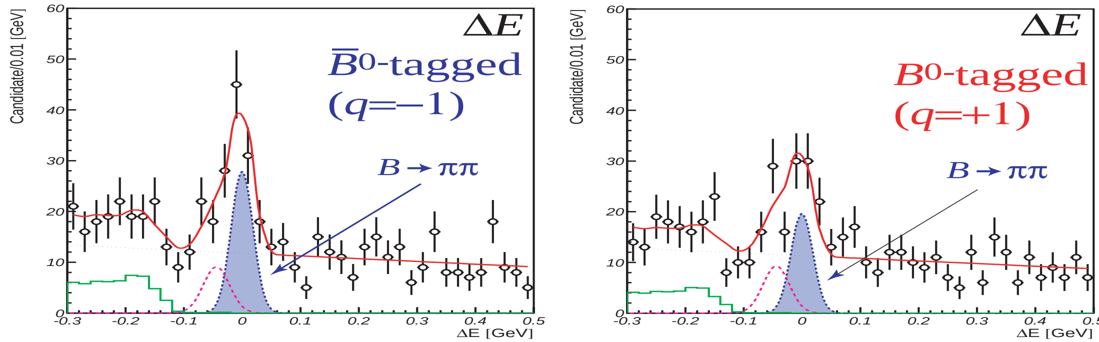
- Continuum BG (mass sideband) has no asymmetry.

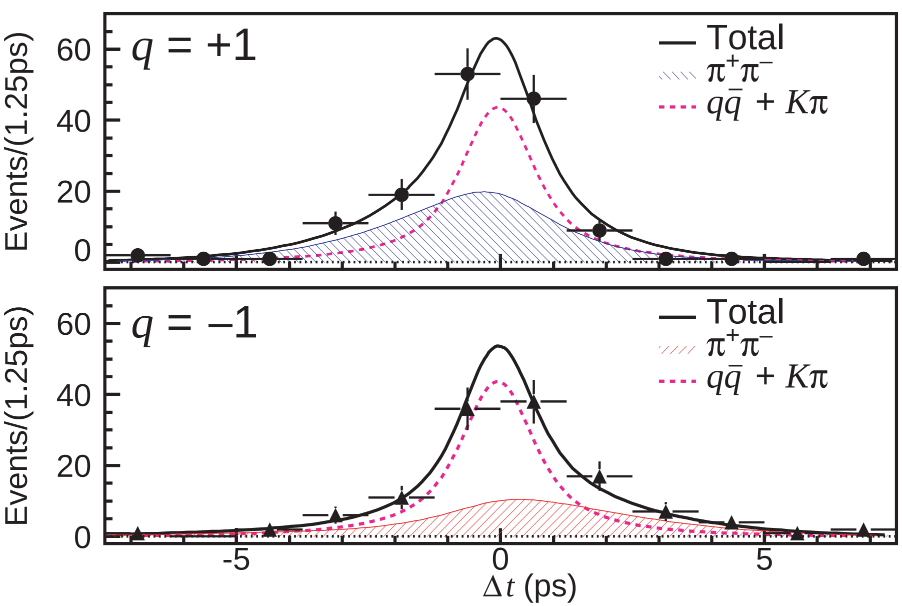


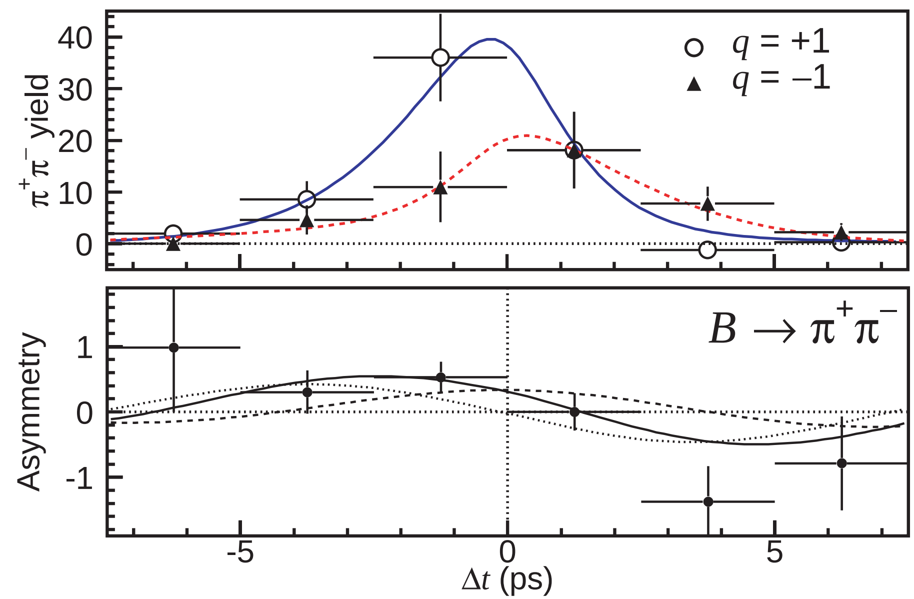
Fit result

- 760 Candidates $\cdots$ 391 B^0-tagged & 369 $\overline{B}^0$-tagged
- 163^{+24}_{-23} signal events

$$\mathcal{A}_{\pi\pi} = +0.77 \pm 0.27(\text{stat})$$
$$\mathcal{S}_{\pi\pi} = -1.23 \pm 0.41(\text{stat})$$





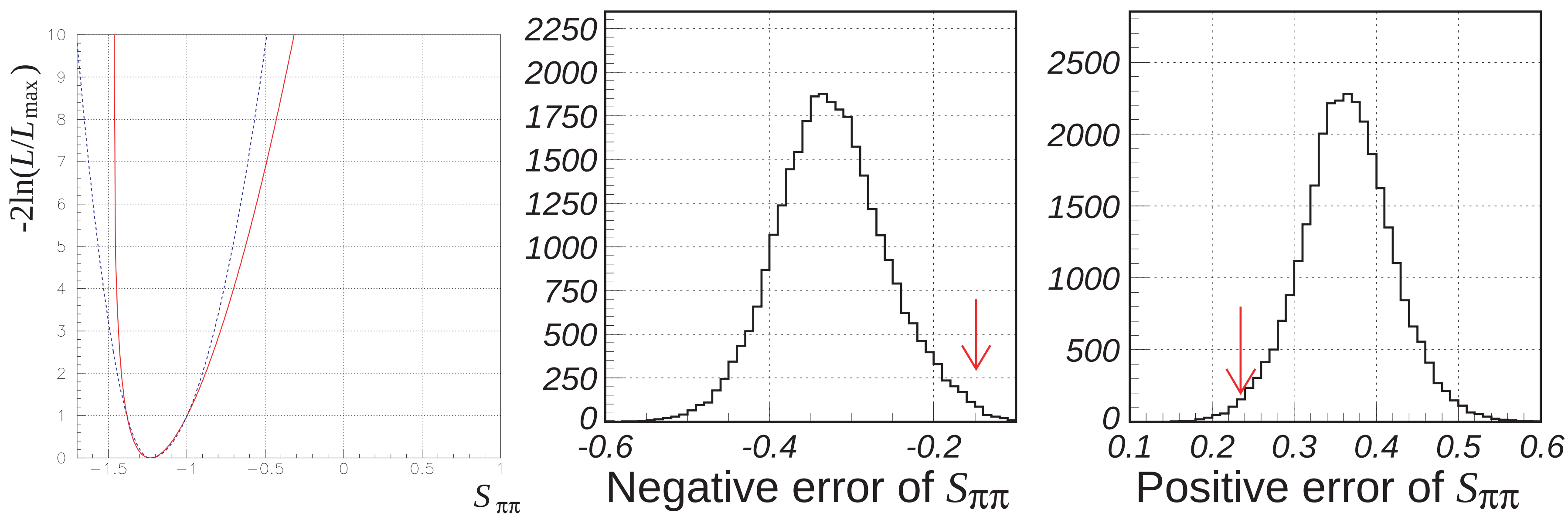


Statistical errors

- Likelihood curves are not parabolic.

$\leftarrow$ Central values are outside the physical boundary.$(\mathcal{A}_{\pi\pi}{}^2 + \mathcal{S}_{\pi\pi}{}^2 \leq 1)$

$\Longrightarrow$ We use most probable errors from pseudo-experiments.



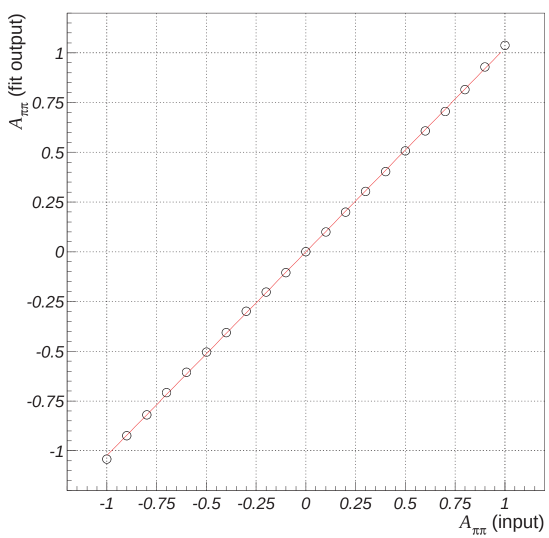
Check with pseudo-experiments

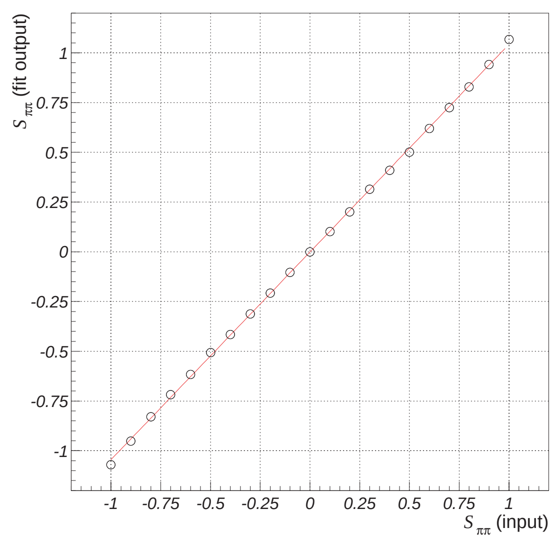
- How often are we outside the physical boundary?

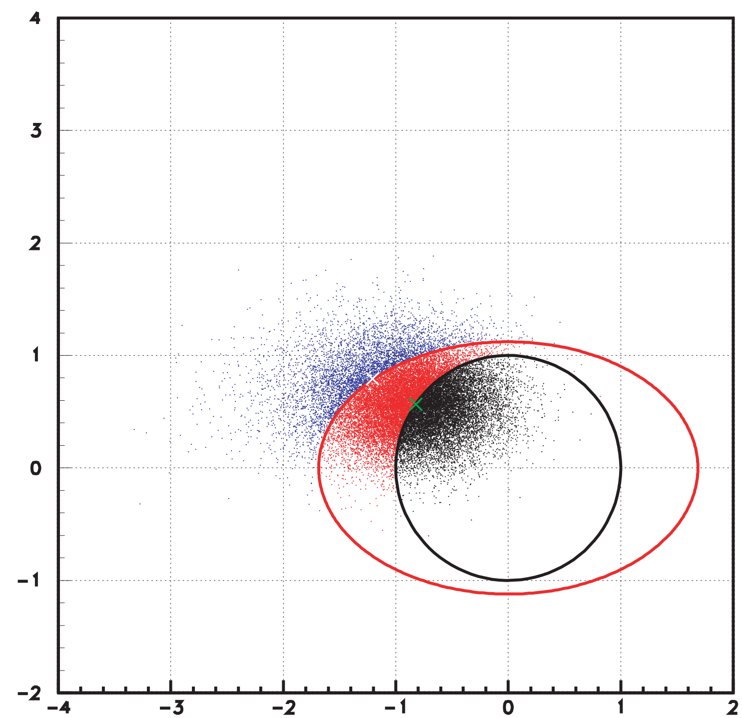
If if true values are at the boundary,

- Prob. out side the boundary$=$60.1%.
- Prob. that we have a fluctuation equal to or lager than the fit to data$=$16.6%

- linearity test







$A_{\pi\pi}$ vs $S_{\pi\pi}$ (input $A_{\pi\pi}$=0.569, $S_{\pi\pi}$=−0.822)

There are no significant bias.

Systematics uncertainty

	$\mathcal{A}_{\pi\pi}$		$\mathcal{S}_{\pi\pi}$	
Source	positive error	negative error	positive error	negative error
Background fraction	$+0.058$	-0.048	$+0.044$	-0.055
Vertex reconstruction	$+0.044$	-0.054	$+0.037$	-0.012
Fit bias	$+0.016$	-0.021	$+0.052$	-0.020
Wrong tag fraction	$+0.026$	-0.021	$+0.015$	-0.016
Physics parameters	$+0.021$	-0.014	$+0.022$	-0.022
Resolution function	$+0.019$	-0.020	$+0.010$	-0.013
Background shape	$+0.003$	-0.015	$+0.007$	-0.002
Total	$+0.084$	-0.083	$+0.083$	-0.067

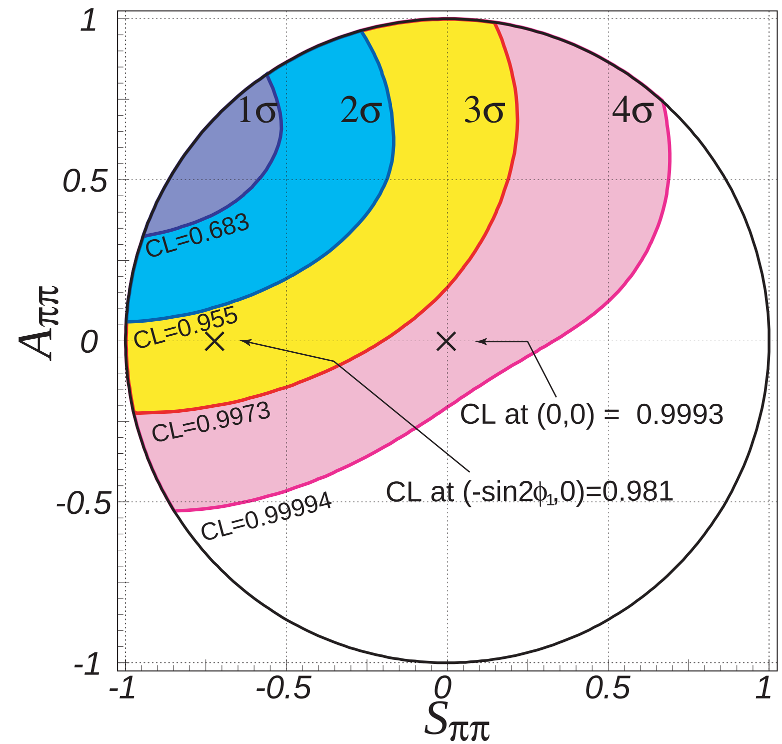
$$\mathcal{A}_{\pi\pi} = +0.77 \pm 0.27(\mathrm{stat}) \pm 0.08(\mathrm{syst})$$

$$\mathcal{S}_{\pi\pi} = -1.23 \pm 0.41(\mathrm{stat}) \,{}^{+\,0.08}_{-\,0.07}(\mathrm{syst})$$

Statistical Significance

Confidence region ... Feldman & Cousins method

- CP conserving hypothesis, $(\mathcal{S}_{\pi\pi}, \mathcal{A}_{\pi\pi}) = (0, 0)$ is excluded with CL=99.93%.
  $\Longrightarrow$ 3.4σ significance for CPV
- 2.2σ significance for Direct CPV



Constraint on CKM angle ϕ_2

- Convert confidence region in $(\mathcal{A}_{\pi\pi}, \mathcal{S}_{\pi\pi})$ space to (ϕ_2, δ) space. (M. Gronau *et al.* Phys. Rev. **D65** 093012 (2002))

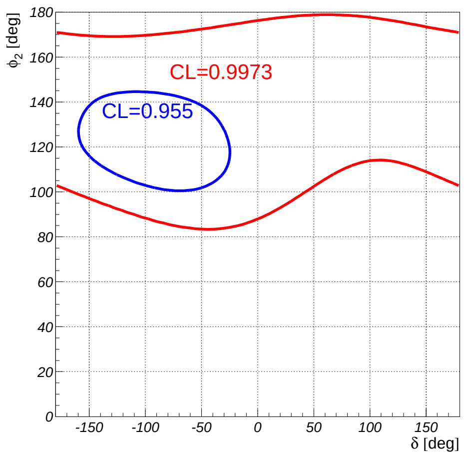
$$\mathcal{A}_{\pi\pi} = \frac{2|P/T|\sin(\phi_1+\phi_2)\sin\delta}{\mathcal{R}_{\pi\pi}}$$

$$\mathcal{S}_{\pi\pi} = \frac{\sin 2\phi_2 + 2|P/T|\sin(\phi_1-\phi_2)\cos\delta - |P/T|^2\sin 2\phi_1}{\mathcal{R}_{\pi\pi}}$$

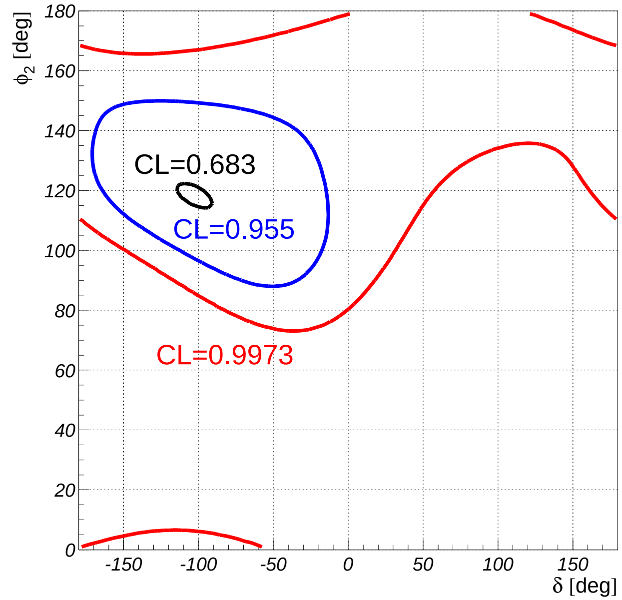
$$\mathcal{R}_{\pi\pi} = 1 - 2|P/T|\cos\delta\cos(\phi_1+\phi_2) + |P/T|^2$$

  - $\delta \cdots$ Strong phase difference between tree and penguin diagrams.
  - $|P/T| \cdots$ Ratio of the amplitude of penguin to tree. $\Longrightarrow |P/T| \sim 0.3$ (Large theoretical uncertainty.)
  - $\phi_1 = 23.5\,^{+2.4}_{-2.2}$ [deg] $\cdots$ Belle and *BABAR*

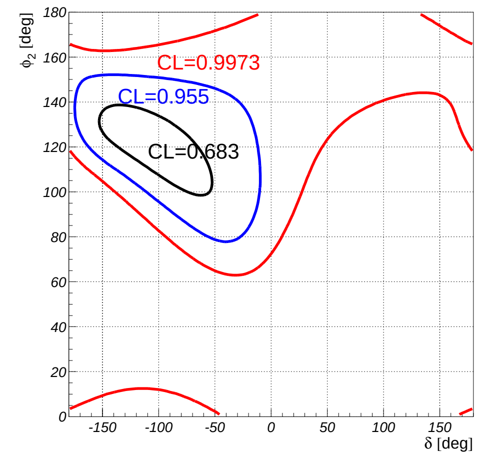
Constraint on CKM angle ϕ_2(cont'd)



$\phi_1 = 23.5^\circ$
$|P/T| = 0.15$



$\phi_1 = 23.5^\circ, |P/T| = 0.30$



$\phi_1 = 23.5^\circ$
$|P/T| = 0.45$

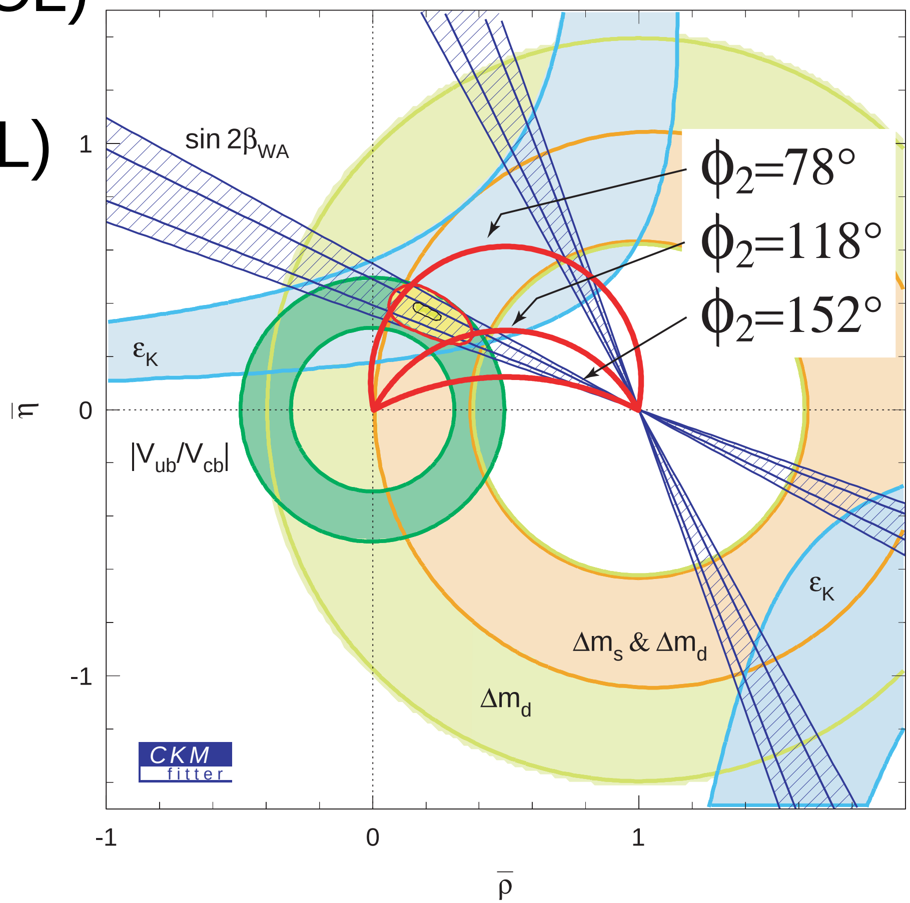
- $78^\circ \leq \phi_2 \leq 152^\circ$ (95.5% CL) for $|P/T| = 0.15 \sim 0.45$

Constraint on Unitarity Triangle

- ϕ_2 constraint from the other experiments.
  (CKM fitter group, 2002)
  $-0.743 \leq \sin 2\phi_2 \leq 0.094$(≥32%CL)
  $\Longrightarrow 93^\circ \leq \phi_2 \leq 114^\circ$
  $-0.892 \leq \sin 2\phi_2 \leq 0.397$(≥5%CL)
  $\Longrightarrow 78.3^\circ \leq \phi_2 \leq 121.6^\circ$

- Belle $B^0 \to \pi^+\pi^-$ (78fb^{-1})
  $78^\circ \leq \phi_2 \leq 152^\circ$ (95.5% CL)
  for $|P/T| = 0.15 \sim 0.45$

- Belle's ϕ_2 are consistent with the other experiments.



Comparison with other experiments

- *BABAR* 88×10^6 $B\overline{B}$ pairs
(B. Aubert *et al*. Phys. Rev. Lett. **89**, 281802 (2002))

$$\mathcal{C}_{\pi\pi} = -0.30 \pm 0.25(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$

$$\mathcal{S}_{\pi\pi} = +0.02 \pm 0.34(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

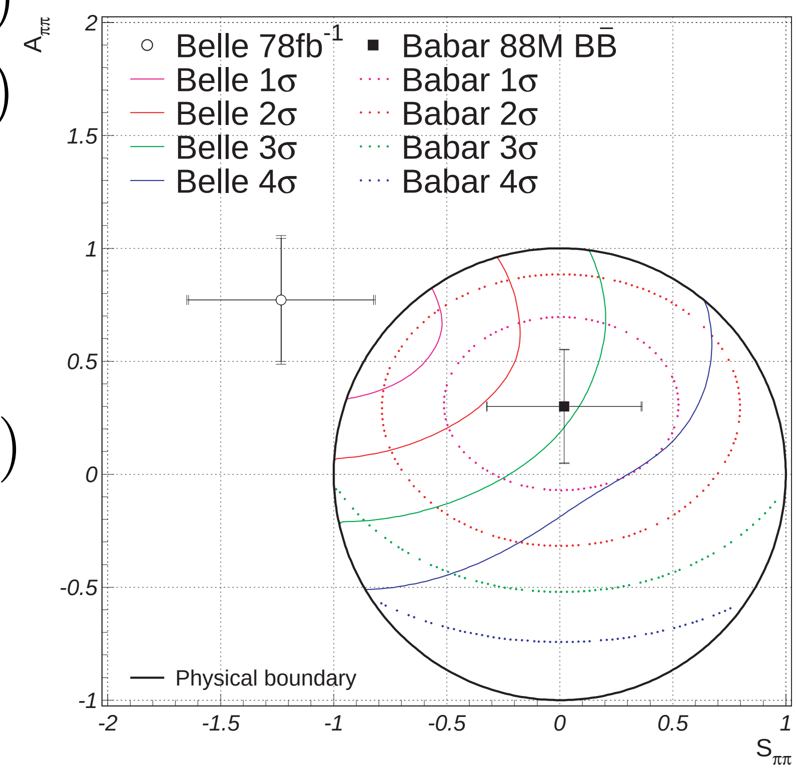
$$(\mathcal{C}_{\pi\pi} = -\mathcal{A}_{\pi\pi})$$

- Belle 78 fb^{-1}

$$\mathcal{A}_{\pi\pi} = +0.77 \pm 0.27(\mathrm{stat}) \pm 0.08(\mathrm{syst})$$

$$\mathcal{S}_{\pi\pi} = -1.23 \pm 0.41(\mathrm{stat}) \,^{+0.08}_{-0.07}(\mathrm{syst})$$

- The difference is below 3σ level
$\cdots$ within the statistical fluctuation.



Feldman & Cousins confidence interval

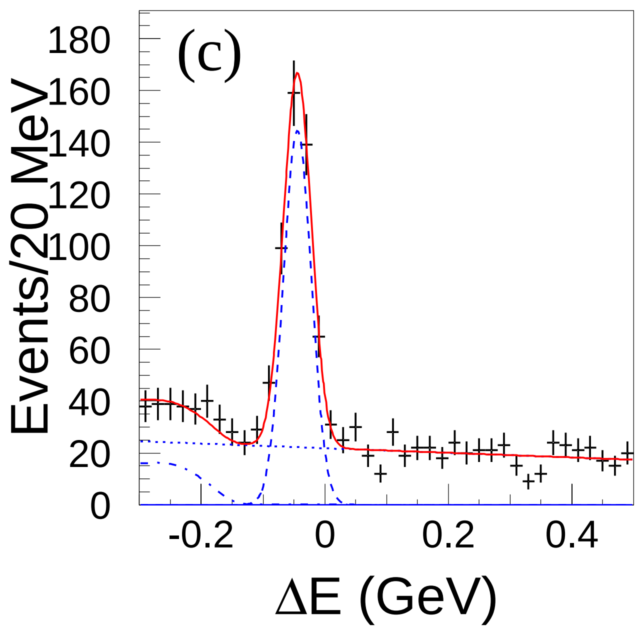
Conclusion

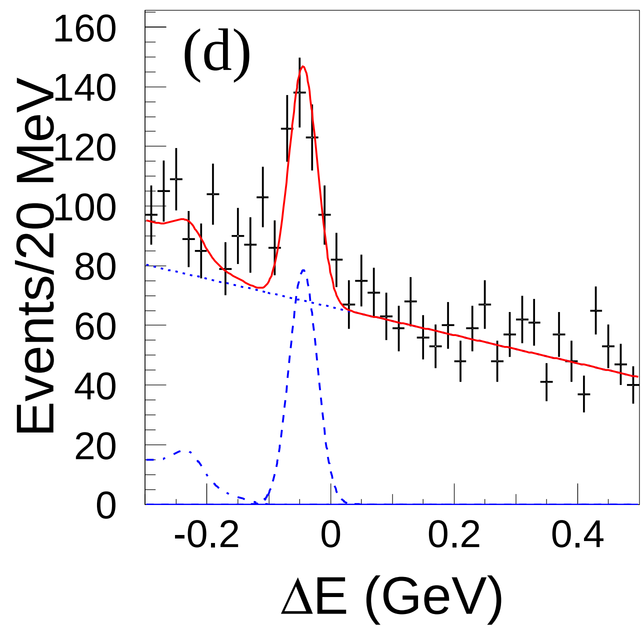
- Evidence for CP violation in $B^0 \to \pi^+\pi^-$
  CP conservation ruled out at the 99.93% CL (3.4σ)
  $\Longrightarrow$ Paper is submitted to Phys. Rev. D (hep-ex/0301032)
  - Large $\mathcal{A}_{\pi\pi}$ value indicates direct CP violation.
    More Belle data will come ($\times$ 5 by 2005) for confirmation.
- First constraints (within the SM) on the CKM angle ϕ_2
  $78^\circ \leq \phi_2 \leq 152^\circ$ (95.5%CL) for $0.15 < |P/T| < 0.45$ and
  $\phi_1 = 23.5^\circ$
  Consistent with indirect constraints on the unitarity triangle from other experiments.
  Additional support for Kobayashi-Maskawa mechanism.

$B^0 \to K^+\pi^-$ control sample

- Positively-identified kaons
  (reversed particle ID requirements w.r.t $B^0 \to \pi^+\pi^-$ selection)

$\mathcal{LR} > 0.825$ $\mathcal{LR}_{\rm min} \le \mathcal{LR} \le 0.825$





- Total $B^0 \to K^+\pi^-$ yield: 610 events