Update of *CP* Violation Study in $B^0 \rightarrow \pi^+\pi^-$ decay

KEK seminar
Jan 23, 2003
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for
the Belle Collaboration

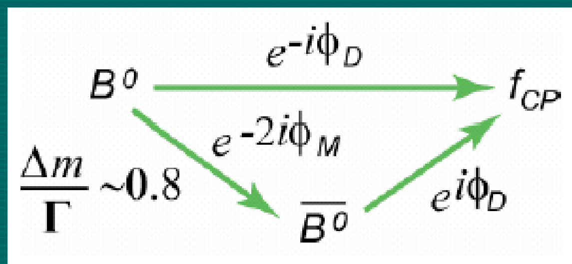
Outline

1. Introduction
2. Experimental Apparatus (**KEKB** & **Belle**)
3. Analysis procedure
   - Event and time reconstruction for $\mathbf{B^0 \to \pi^+\pi^-}$ events
   - Time-dependent analyses
4. Results
   - *CP*-asymmetry parameters $\mathbf{A}_{\pi\pi}$ and $\mathbf{S}_{\pi\pi}$
   - Constraints on the CKM angle ϕ_2
5. Conclusion

Brandnew result !
Paper is ready for submission to Phys. Rev. D !

1. Introduction

CP violation in $B^0\overline{B}^0$ system



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

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

$$A_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1}$$

$$S_f = \frac{2Im(\lambda_f)}{|\lambda_f|^2 + 1}$$

$$\lambda_f \equiv e^{-2i\phi_M} \frac{A(\overline{B} \to \overline{f})}{A(B \to f)}$$

Standard model predictions

	$b \to c\bar{c}s$	$b \to c\bar{c}d$	$b \to s\bar{s}s$	$b \to u\bar{u}d$
example	$J/\psi K_S$	$J/\psi \pi^0$	ϕK_S	$\pi^+\pi^-$
A_f	0	0	small	$\neq 0$
S_f	$\sin 2\phi_1$	$\sin 2\phi_1$	$\sin 2\phi_1$	"$\sin 2\phi_2$"

Note: $A_f \neq 0 \Rightarrow \Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f}) \Rightarrow$ direct CP violation.

The ϕ_i's and CKM matrix

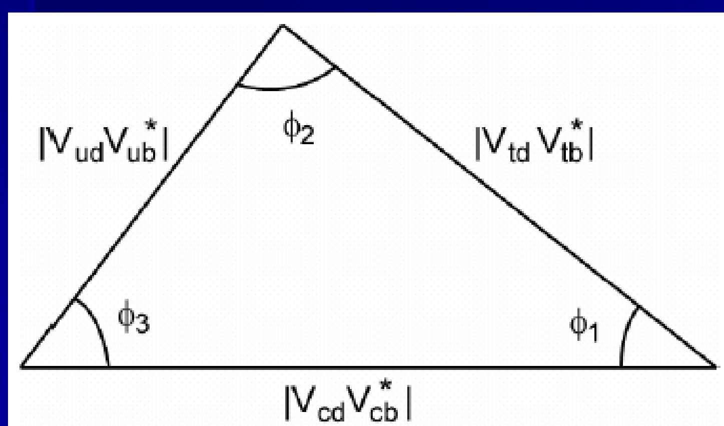
CKM quark mixing matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity

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

Unitarity triangle



$$\phi_1 \equiv \pi - \arg\left(\frac{-V_{tb}^*V_{td}}{-V_{cb}^*V_{cd}}\right)$$

$$\phi_2 \equiv \arg\left(\frac{V_{tb}^*V_{td}}{-V_{ub}^*V_{ud}}\right)$$

Time-dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ -- the best way to access the CKM angle ϕ_2

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

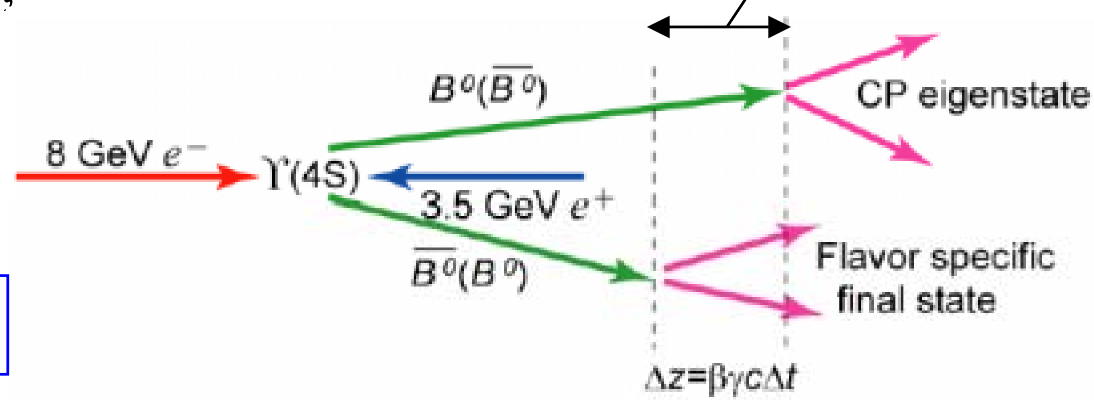
$$q = \begin{cases} +1 \text{ for } B^0 \text{ tag} \\ -1 \text{ for } \overline{B}^0 \text{ tag} \end{cases}$$

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

$$\lambda \equiv e^{-2i\phi_M}\frac{A(\overline{B} \to \overline{f})}{A(B \to f)}$$

direct CP asymmetry

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

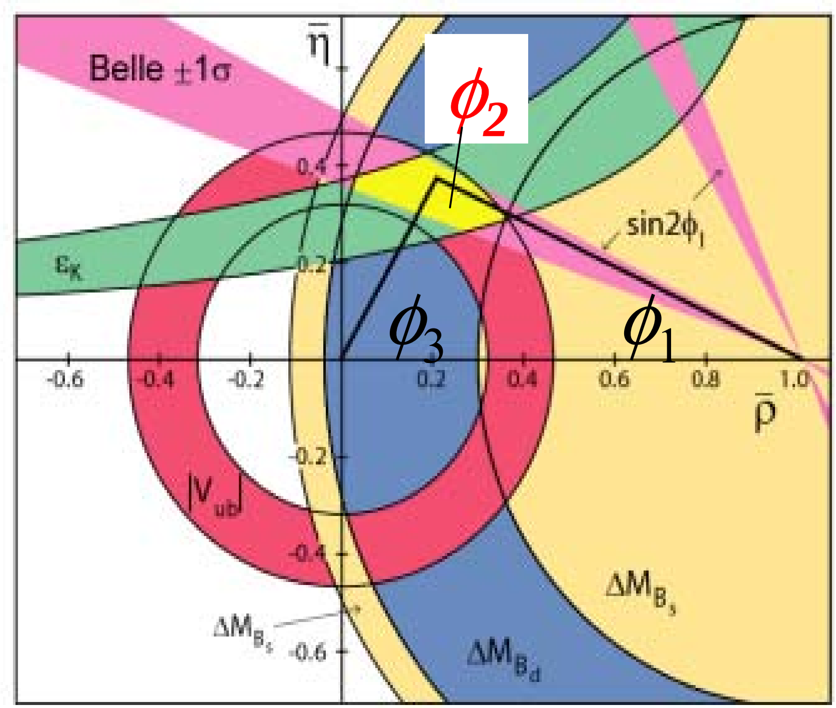


$$A_{\pi\pi} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \qquad S_{\pi\pi} = \frac{2\,Im\lambda}{|\lambda|^2 + 1},$$

$$\lambda \equiv e^{-2i\phi_M} \frac{A(\overline{B} \to \overline{f})}{A(B \to f)}$$

$$\boxed{\mathbf{A}_{\pi\pi} = 0, \;\; \mathbf{S}_{\pi\pi} = \sin 2\phi_2}$$

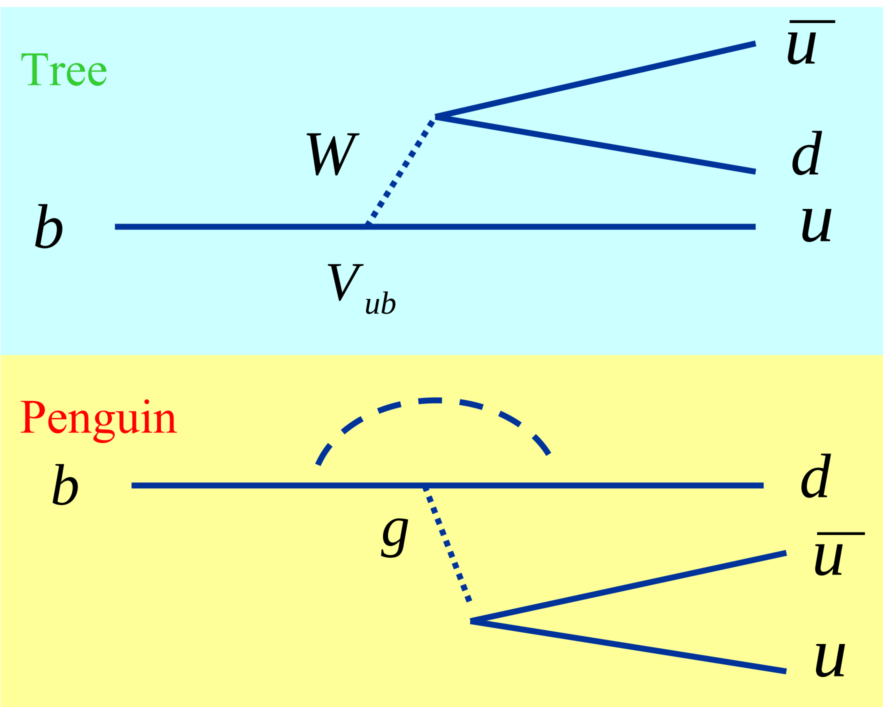
if “penguin” is negligible



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

Penguin diagram is not negligible at all.

|P/T| ~ 0.3 (theoretical preference)



Nasty "pollution" for precise ϕ_2 measurements

Wonderful "contribution" for the first observation of direct *CP* violation in *B*-meson decays !

Previous results at Belle

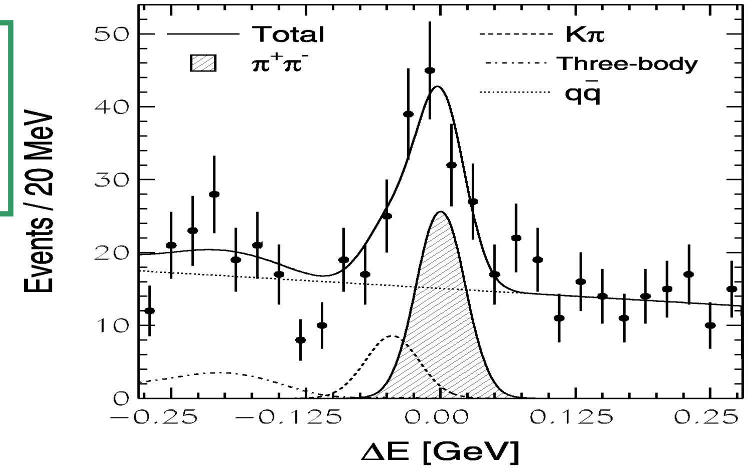
"Study of CP-Violating Asymmetries in $B^0 \to \pi^+\pi^-$ Decays"

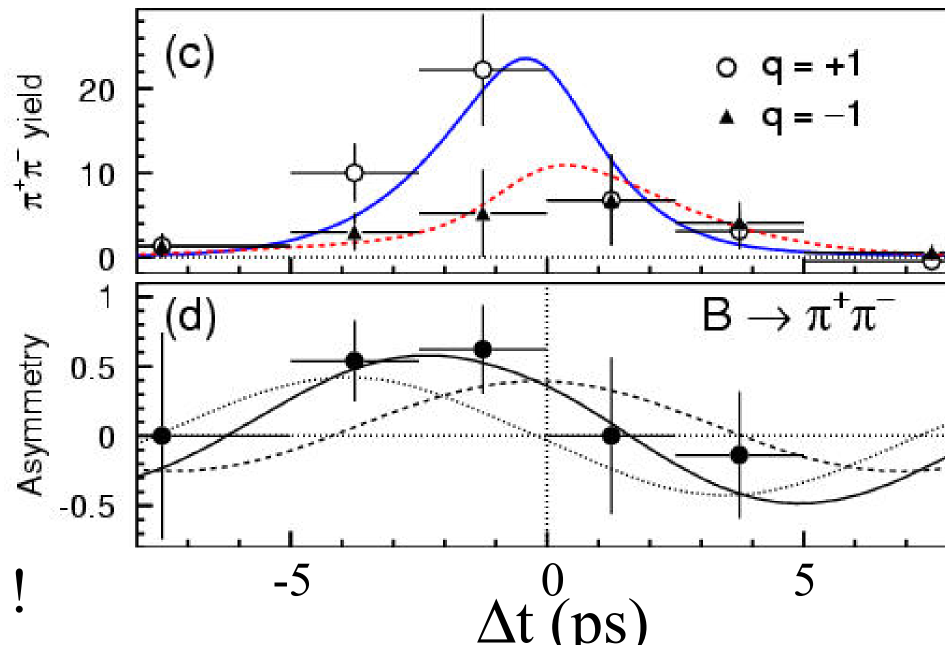
PRL **89**, 071801 (2002)

- 45 million B-meson pairs ($42\mathrm{fb}^{-1}$)
- 162 $B^0 \to \pi^+\pi^-$ candidates

$$S_{\pi\pi} = -1.21\ {}^{+0.38}_{-0.27}\,(\text{stat.})\ {}^{+0.16}_{-0.13}\,(\text{syst.})$$

$$A_{\pi\pi} = +0.94\ {}^{+0.25}_{-0.31} \pm 0.09$$





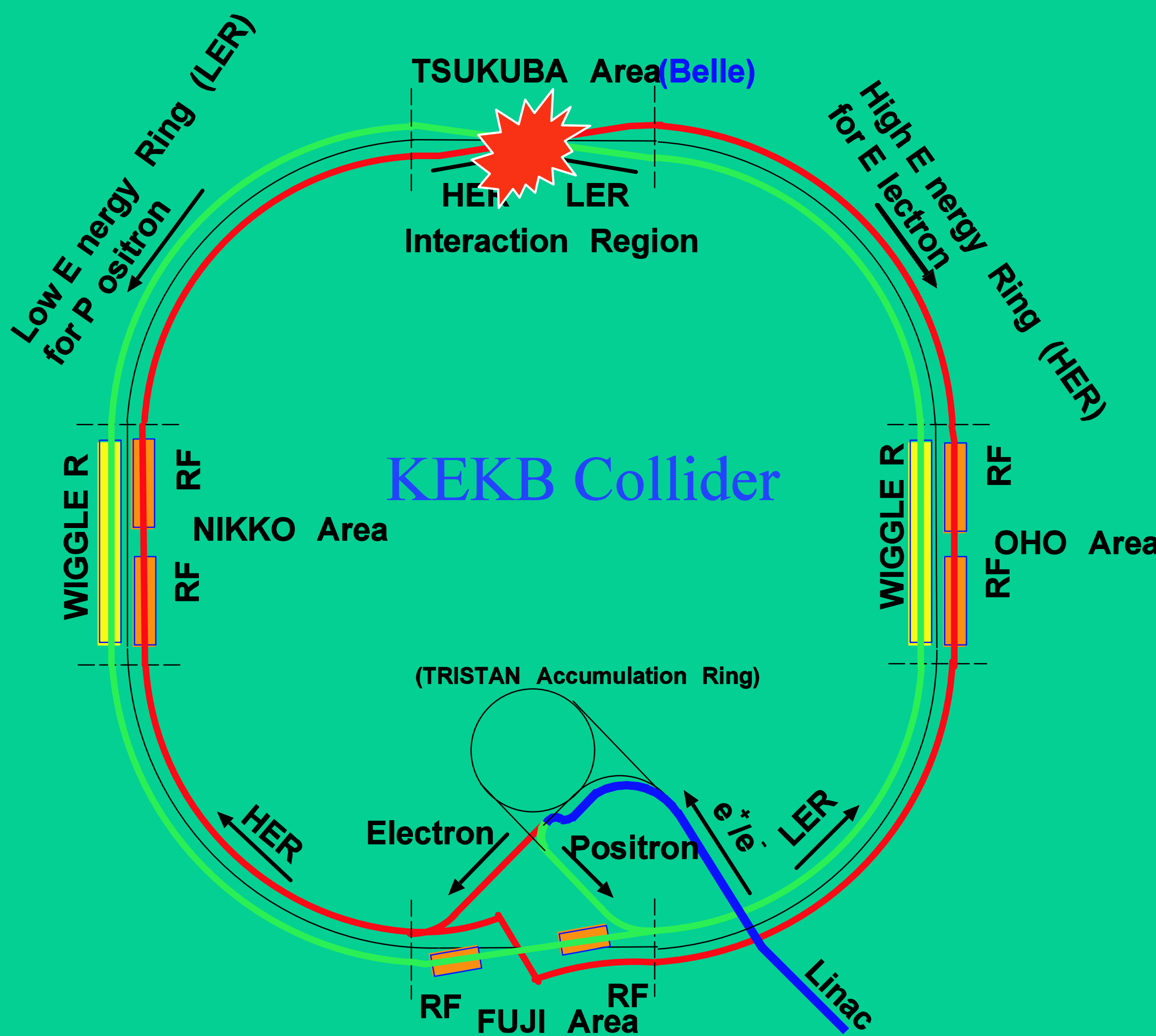
Results indicated large *CP* asymmetries. → More data needed !

Changes in the new analysis

- More data ! [85×10^6 B pairs (78 fb^{-1})]
- Improvements to the analysis
  - **Better track reconstruction algorithm**
  - **More sophisticated Δt resolution function**
  - **Inclusion of additional signal candidates by optimizing event selection**
- Thorough frequentist statistical analyses using Monte Carlo (MC) pseudo-experiments

2. Experimental apparatus KEKB & Belle

KEKB Collider

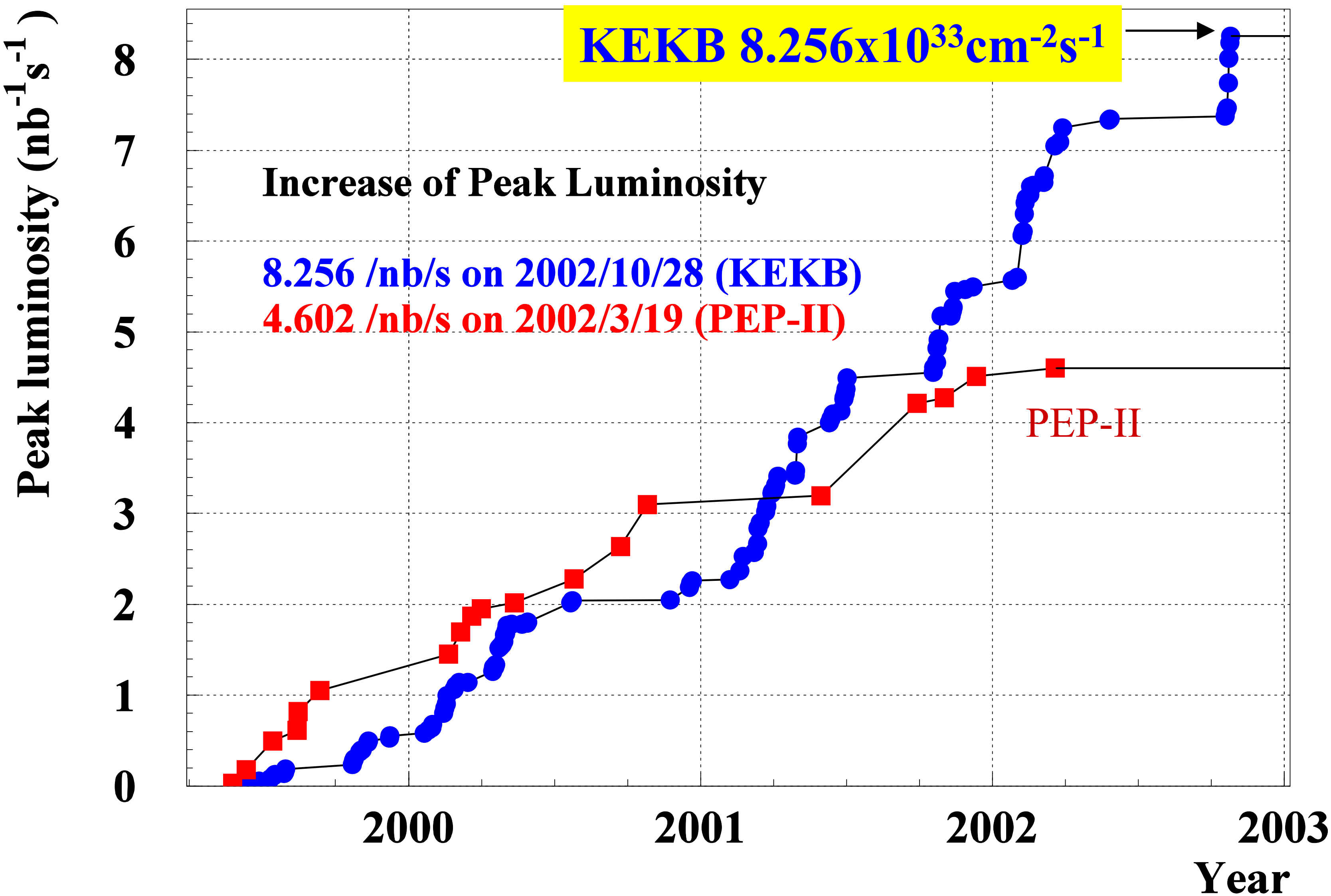


8 GeV e^- + 3.5 GeV e^+
$W_{CM}=m(Y(4s))$

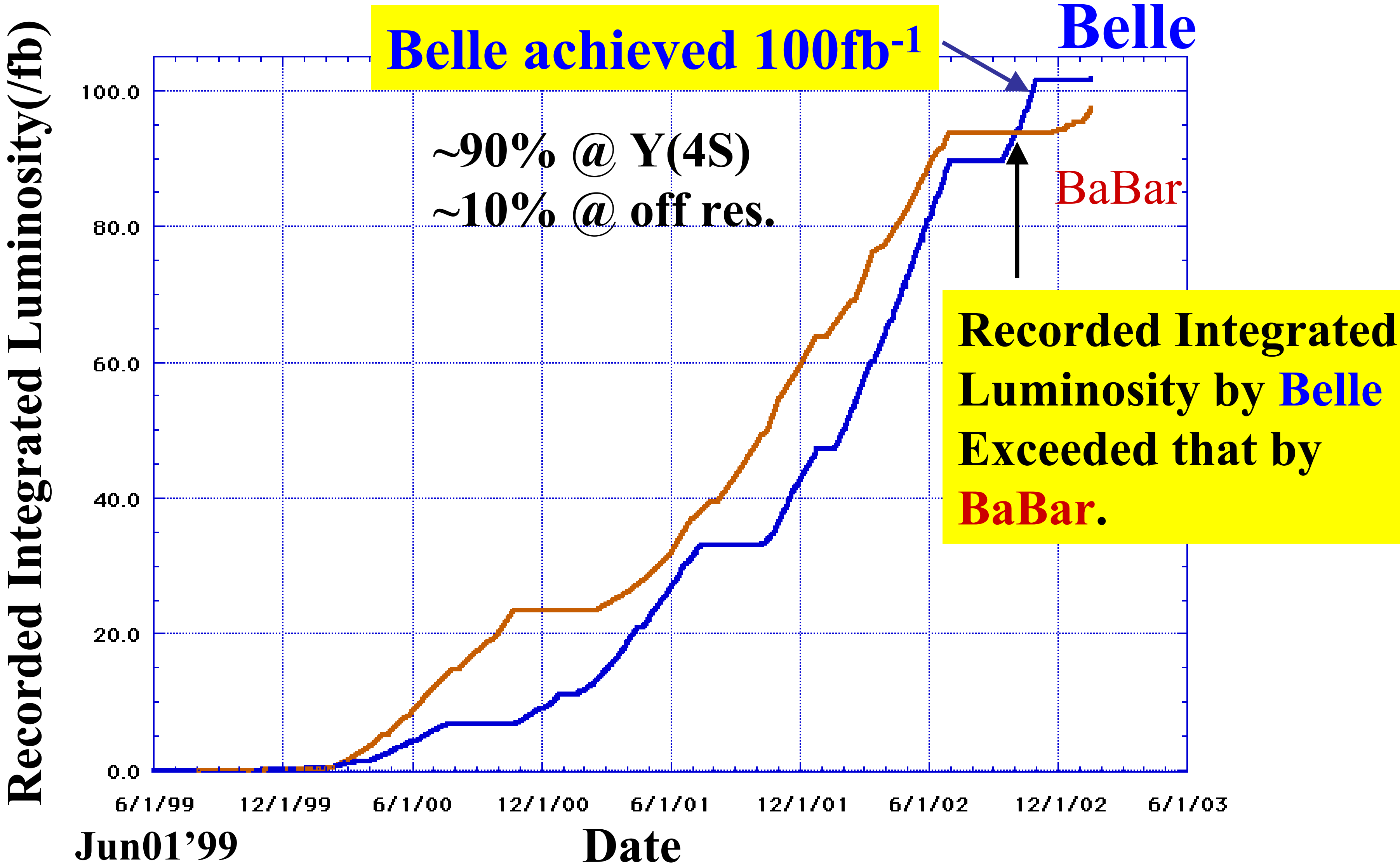
3 km circumference

± 11 mrad crossing angle

Peak Luminosity



Recorded Integrated Luminosity



Belle Collaboration

Aomori U.
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U. of Melbourne
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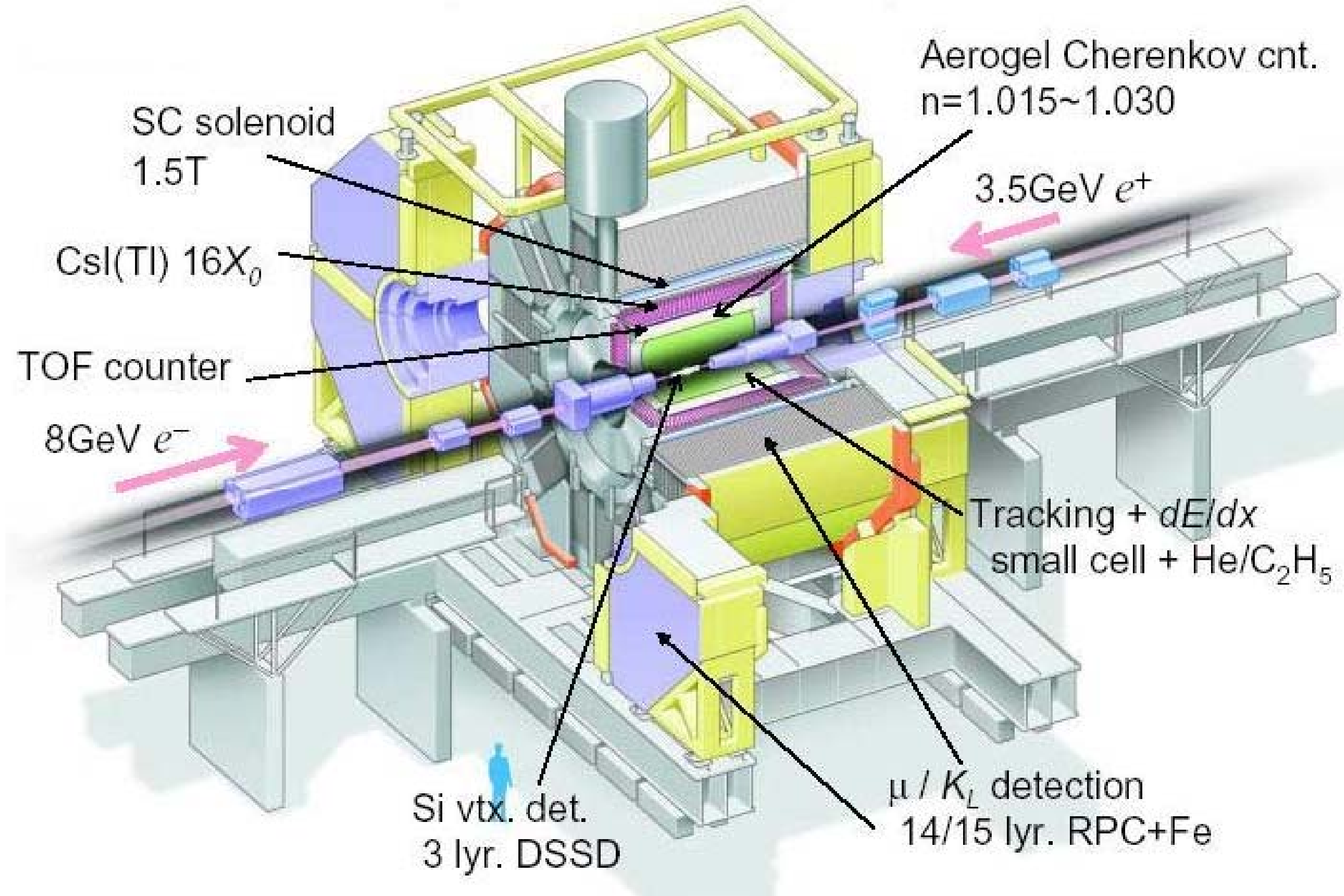
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of A and T.
Toyama Nat'l College
U. of Tsukuba
Utkal U.
IHEP, Vienna
VPI
Yokkaichi U.
Yonsei U.

Belle Detector



Detector performance

- **Vertex measurement**

  Impact parameter resolution

  = 55μm for 1GeV/c normal track

  → 100μm vertex resolution in z

- **Tracking system**

  $(\sigma_{pt}/p_t)^2 = (0.19p_t)^2+(0.30)^2\ (\%^2)$

- **EctroMagnetic calorimetry**

  photon : $\sigma_E/E \sim 1.8\%$ **at** $E\gamma \sim 3GeV$

  electron : $e^{\pm}$ **efficiency > 90%**

  ~0.3% fake at p>1GeV/c

Detector performance

- **K/π separation**
  - CDC dE/dx (σ=6.9%)
  - TOF (σ=95ps)
  - Aerogel Cerenkov counter

  Kaon efficiency~84%, mis-id($\pi \rightarrow K$)~5%

  Pion efficiency~91%, mis-id($K \rightarrow \pi$)~10%

- **K_L and μ detection**

  μ efficiency > 90%

  <2% fake at p>1GeV/c

Analyzed data

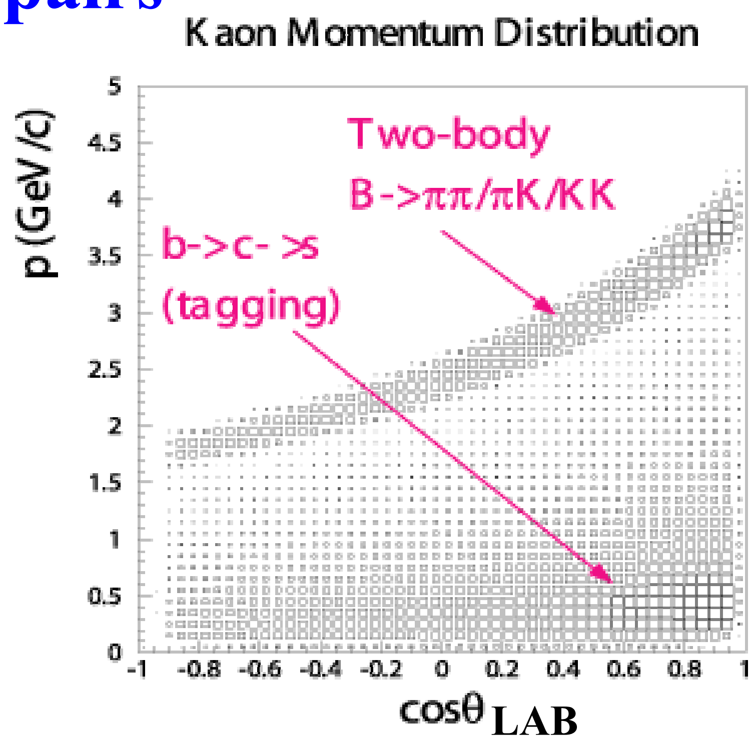
85 million $B\bar{B}$ events ($78fb^{-1}$)
at the **Y(4S)** resonance
recorded by the **Belle**
before the summer 2002
are used in this analysis.

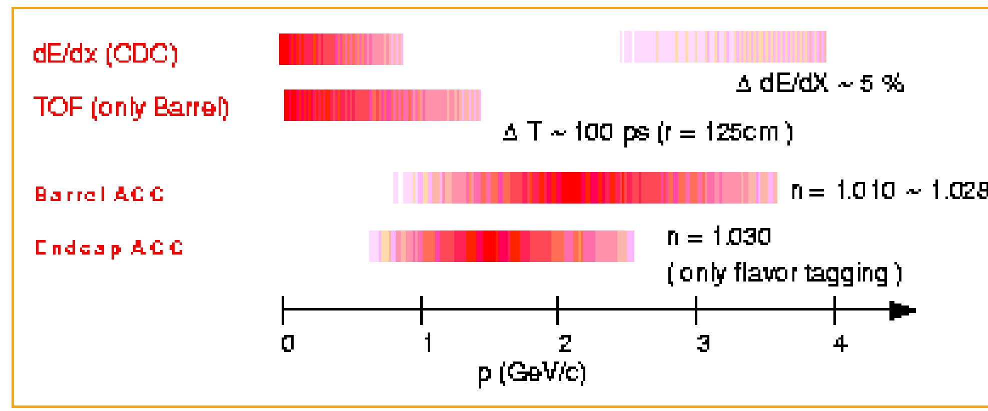
3. Analysis procedure

Event and time reconstruction (1)

Flow: $B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

- **Select oppositely charged track pairs**
- **Need** π/K separation





for $\pi^+\pi^-$,
π eff. = 0.91
K fake rate = 0.10

Event reconstruction

Flow: $B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

Kinematics

Beam-constrained mass

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

3σ requirements (σ = resolution)

signal region

$$\underbrace{5.271 < M_{bc} < 5.287\ GeV/c^2}$$

Energy difference

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

$$|\Delta E| < 0.057\ GeV$$

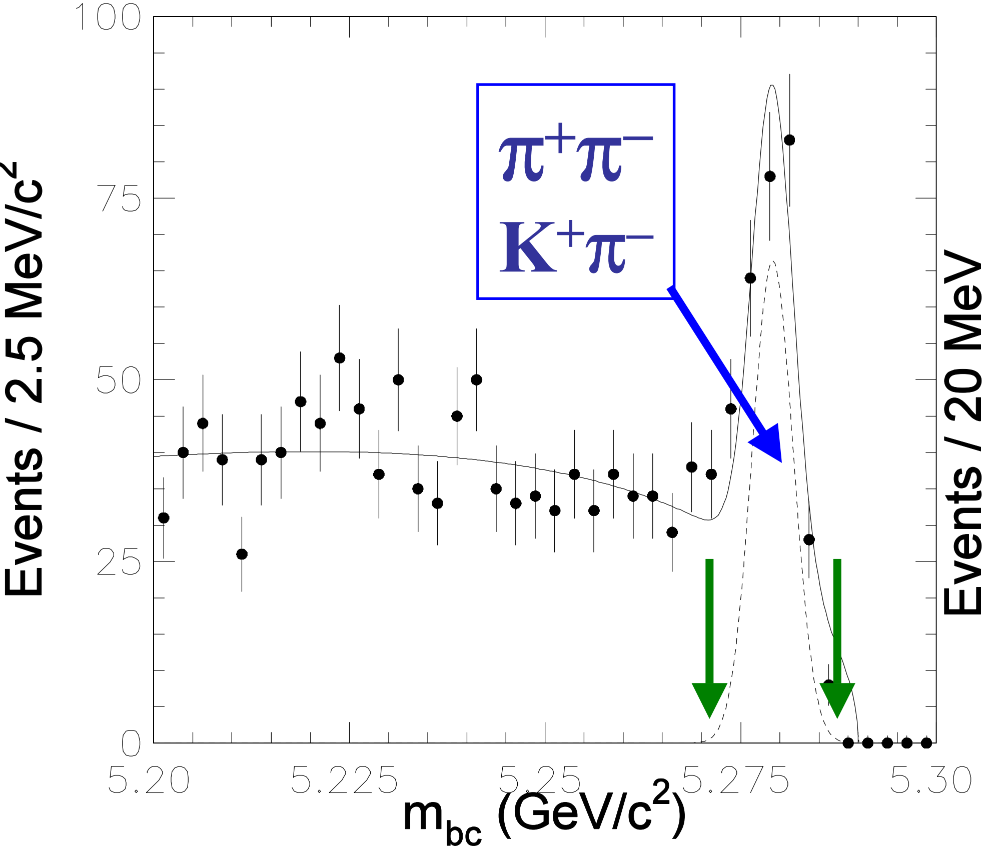
E^*_{beam} : *cms beam energy*

E^*_B : *cms energy of B candidate*

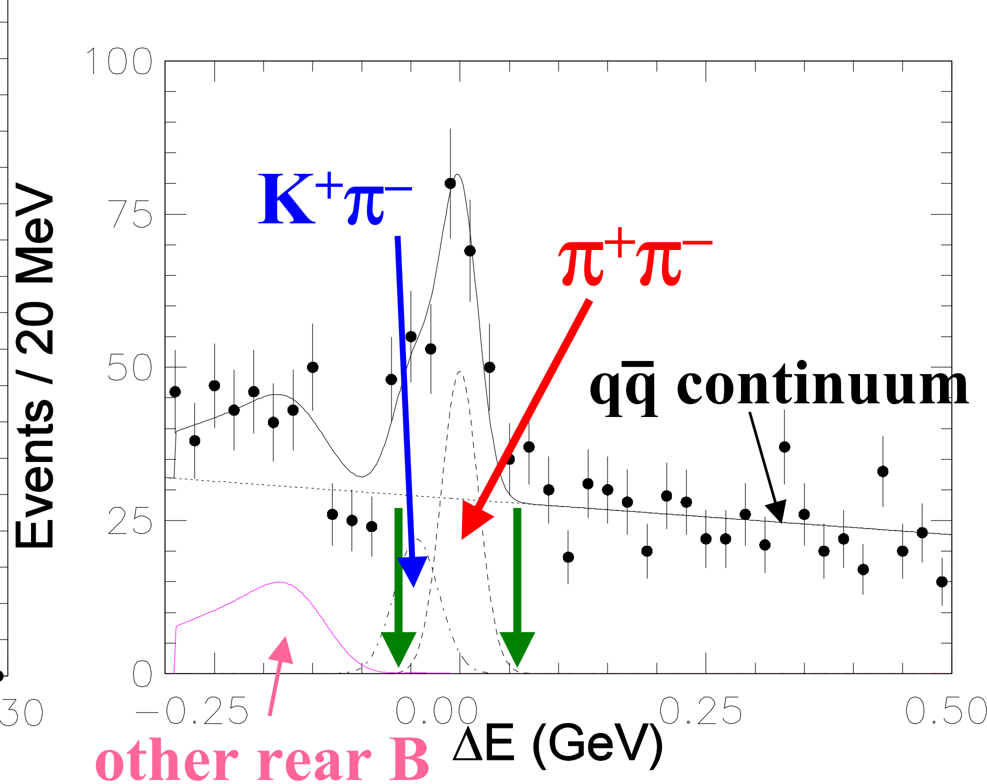
p^*_B : *cms momentum of B candidate*

Event reconstruction

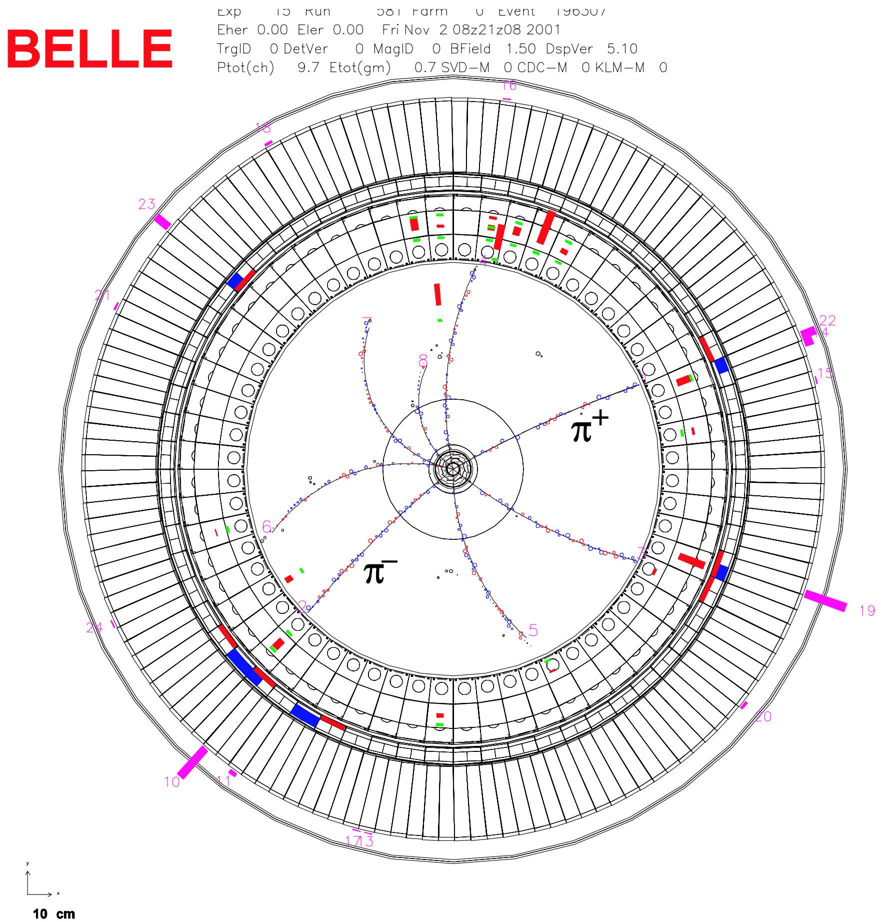
Beam-constrained mass (M_{bc})

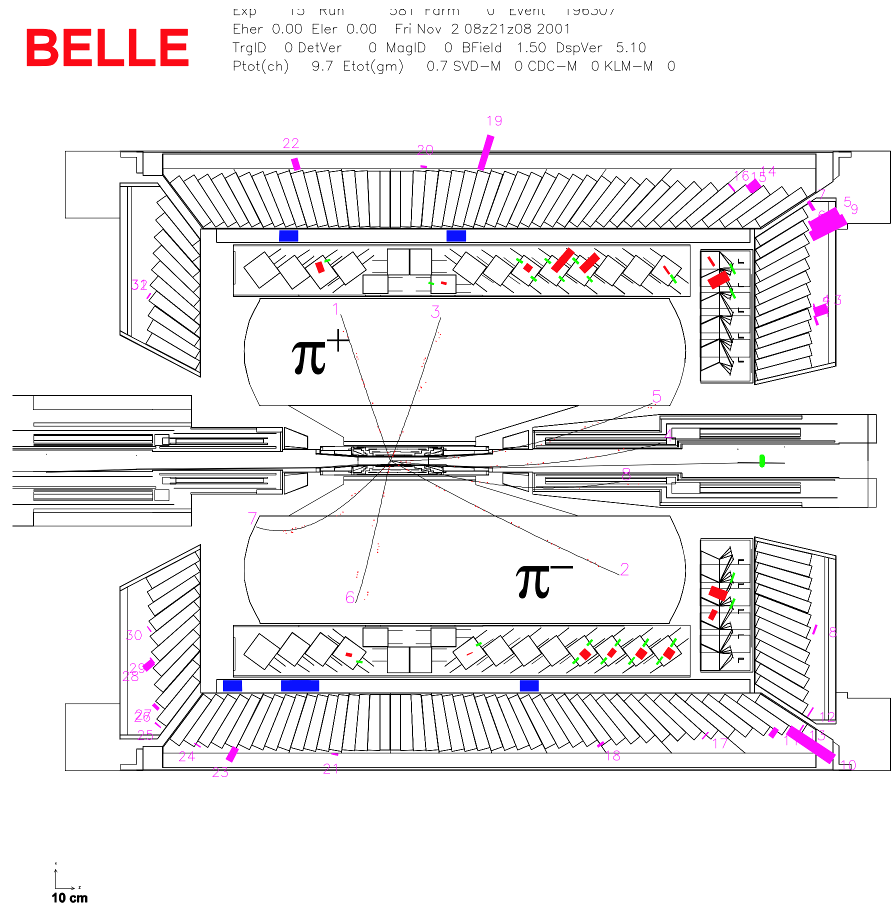


energy difference (ΔE)



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





Event and time reconstruction (2)

Flow

$B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

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

Use flavor specific properties and correlations

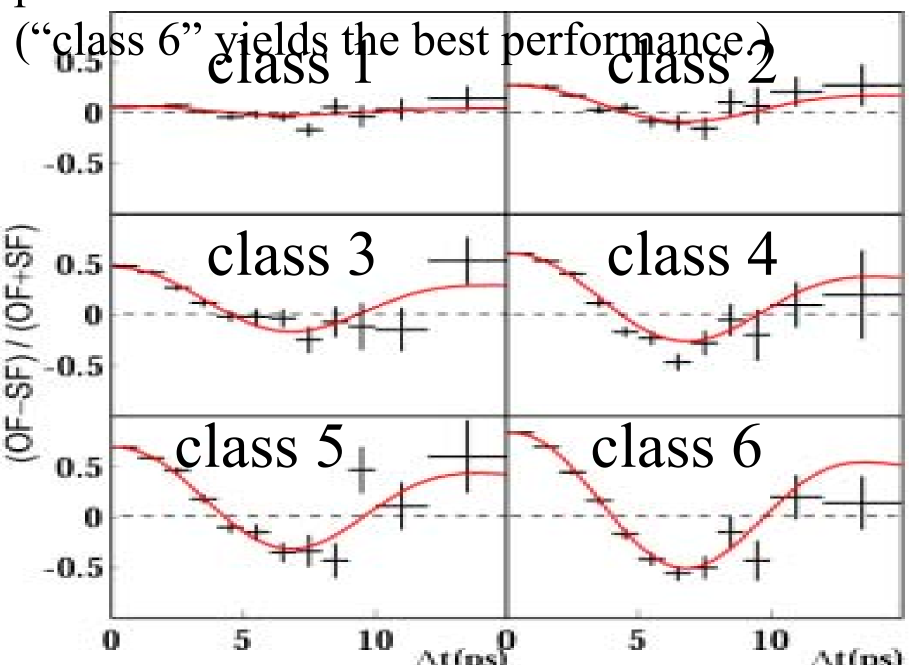
- Inclusive leptons:
  - high p l^- $b \to c\, l^- \nu$
  - intermed. p l^+ $\hookrightarrow s\, l^+ \nu$
- Inclusive hadrons:
  - high p π^+ $B^0 \to D^{(*)-} \pi^+$, $D^{(*)-} \rho^+$, etc.
  - intermed. p K^+ $\hookrightarrow K^+ X$, $\hookrightarrow \pi^+ \pi^0$
  - low p π^- $\hookrightarrow \overline{D}^0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

Event and time reconstruction (2)

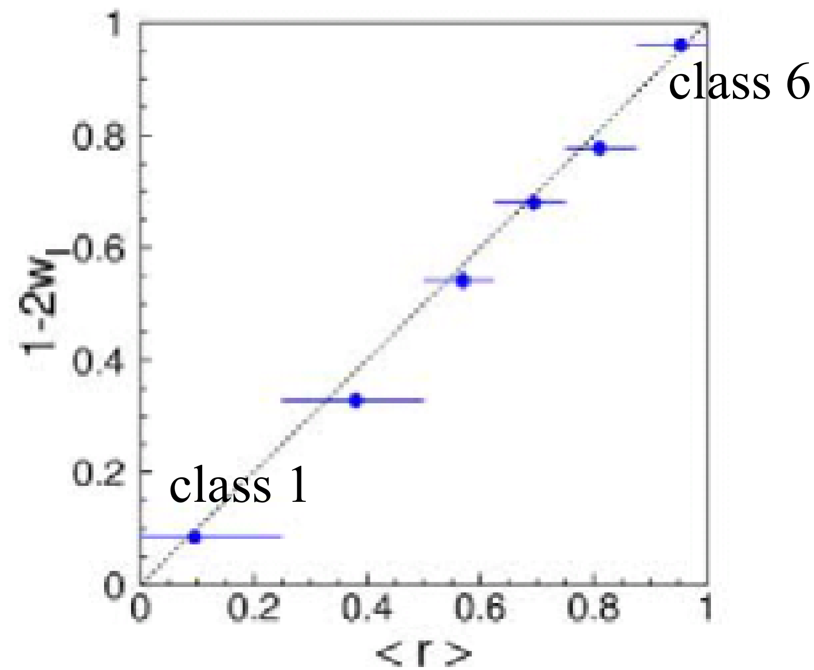
Flow: $B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

Classify events based on expected dilution

$B\overline{B}$-mixing fit → flavor tag performance
("class 6" yields the best performance.)



w= wrong tag fraction

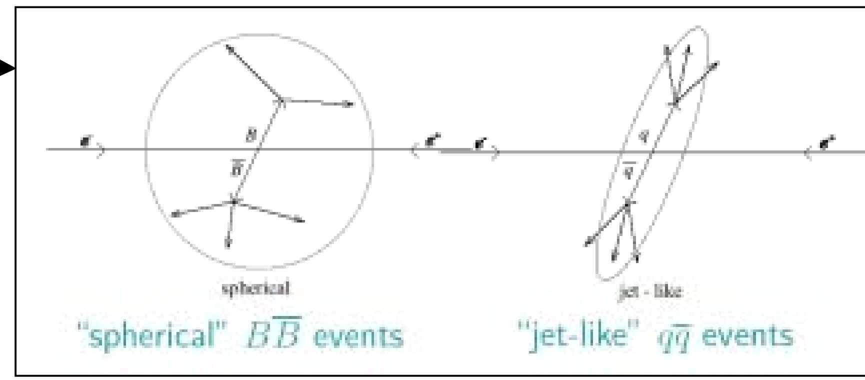


Event and time reconstruction (3)

<u>Flow</u>

$B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

- $e^+e^- \to q\bar{q}$ (q=u,d,s,c) continuum background suppression
  - **Event topology**
    - Modified Fox-Wolfram moments
    - Fisher discriminants
  - Angular distribution
    - B flight direction
- Combined into a single **L**ikelihood **R**atio



$$\boxed{LR = \frac{L_S}{L_S + L_{q\bar{q}}}}$$

Event and time reconstruction (3)

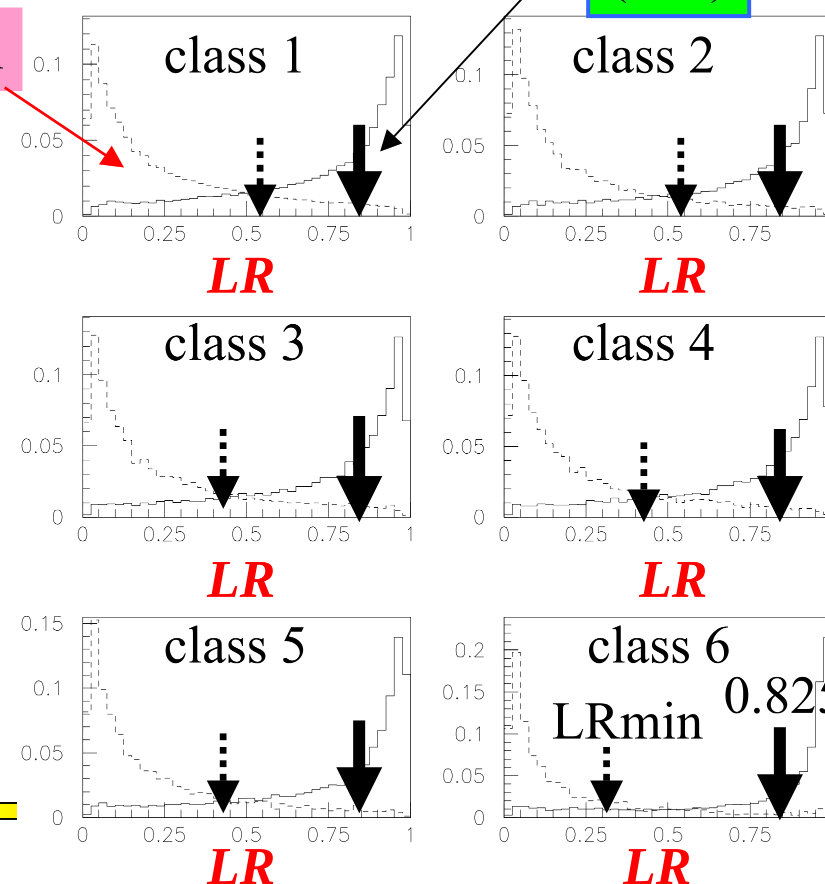
Flow: $B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

- $e^+e^- \to q\bar{q}$ (q=u,d,s,c) continuum background suppression
- Combined into a single likelihood ratio

$$\boxed{LR = \frac{L_S}{L_S + L_{q\bar{q}}}}$$

continuum

$\pi^+\pi^-$ (MC)



- Select 2 regions for each flavor tag class
  - LR > 0.825
  - LRmin < LR ≤ 0.825

(LRmin : class-dep.)

Event and time reconstruction (4)

Flow

$B^0 \to \pi^+\pi^-$ Selection → Flavor tagging → Continuum suppression → Vertex and Δt

Vertex reconstruction

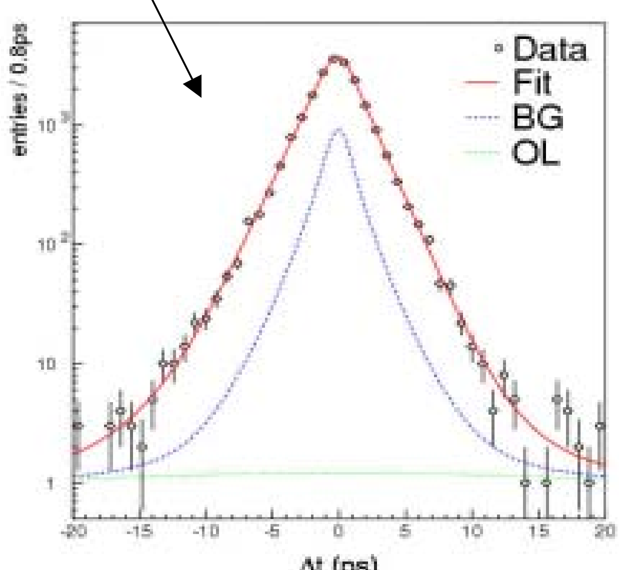
- The same algorithm as that used for $\sin 2\phi_1$ meas.
- Resolution mostly determined by the tag-side vtx.
- B lifetime demonstration with 85 million B pairs

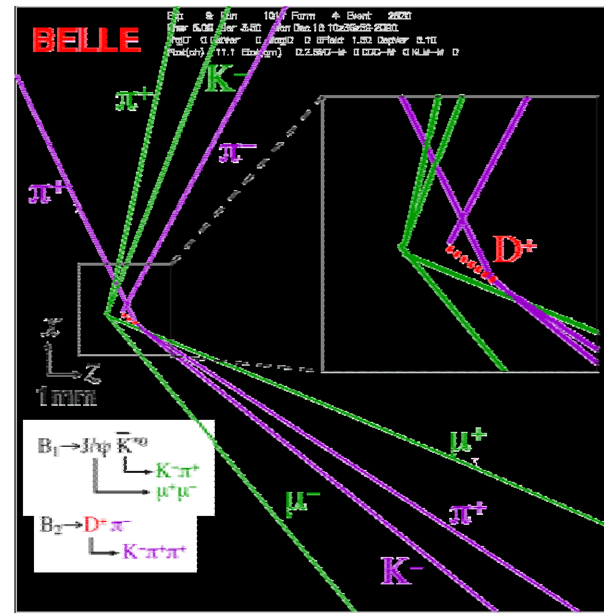
$B^0 \to D^+\pi^-$, $D^{*+}\pi^-$, $D^{*+}\rho^-$, $J/\psi K_S$ and $J/\psi K^{*0}$

B^0 lifetime
1.551±0.018(stat) ps

(PGD02: 1.542±0.016 ps)

Time resolution (rms)
1.43ps

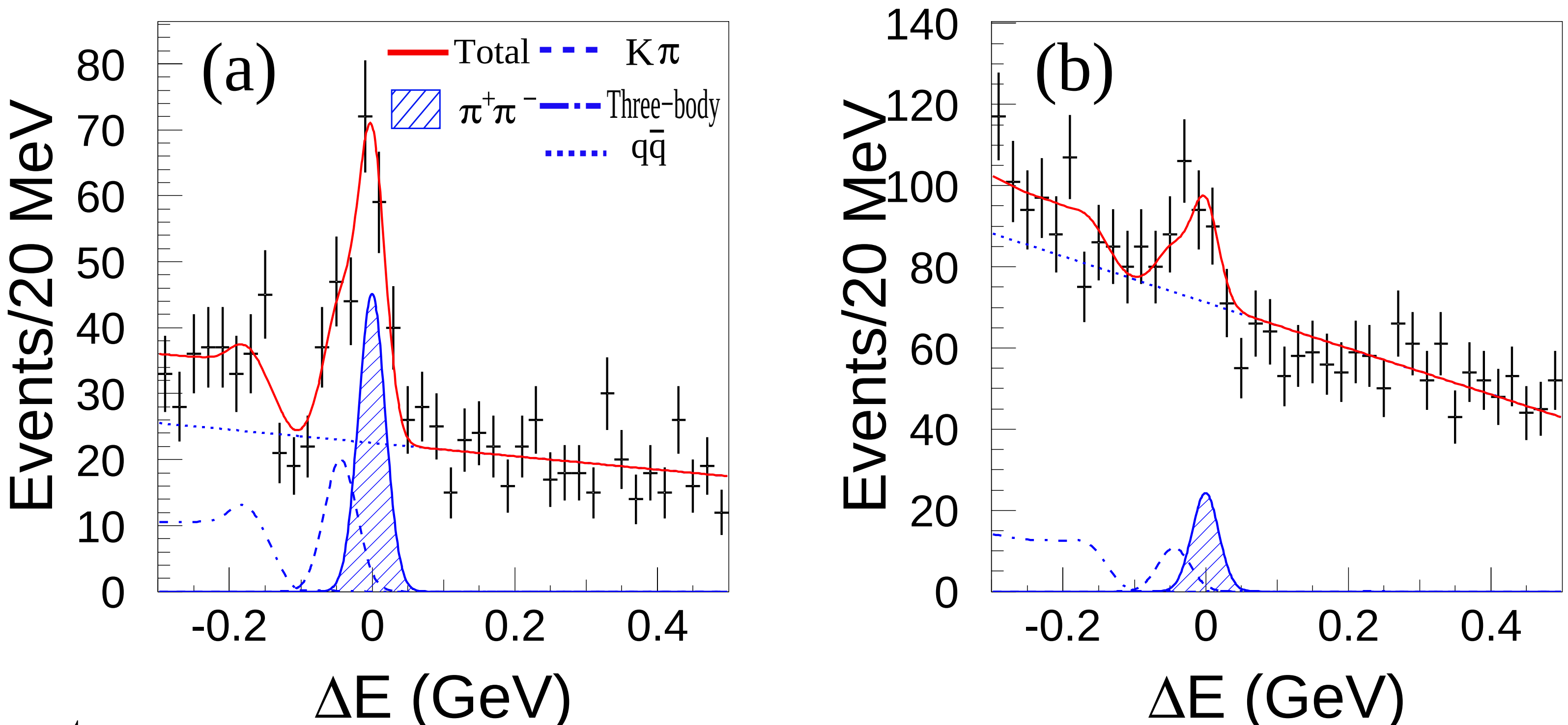




Example vertices

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

LR > 0.825 | LRmin < LR ≤ 0.825



Flavor tag.
Vertexing
|ΔE|<0.57GeV

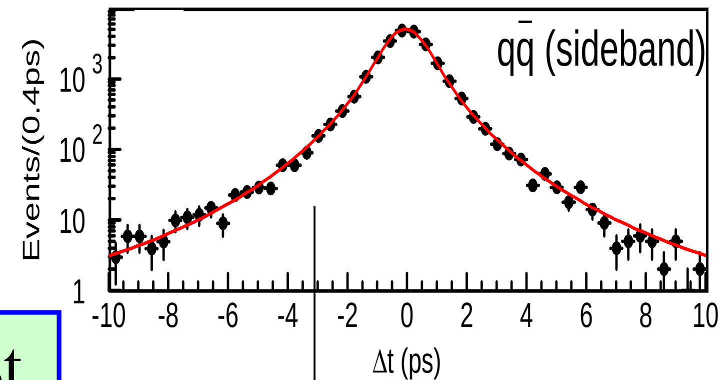
	LR > 0.825		LRmin < LR ≤ 0.825	
$\pi^+\pi^-$	106	+	57	= **163**
$K\pi$	41		22	
qq	128		406	
total	275	+	485	= **760**

Time-dependent analyses

Unbinned maximum-likelihood fit

2 free parameters ($A_{\pi\pi}$, $S_{\pi\pi}$) in the final fit

ΔE-M_{bc} dist.

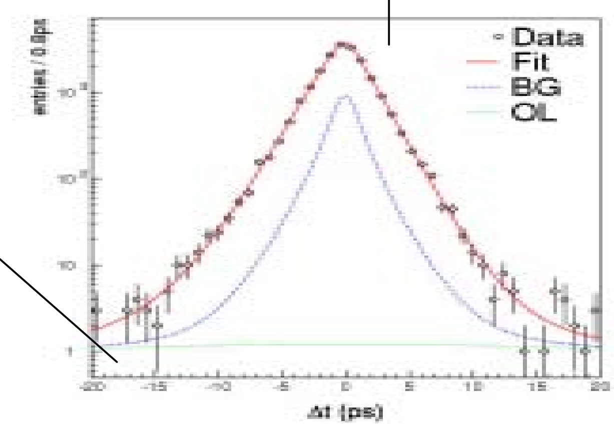


$$L = \Pi_i P_i$$

$$P_i = (1 - f_{ol}) \int_{-\infty}^{+\infty} \{ (f^m_{\pi\pi} P^q_{\pi\pi} + f^m_{K\pi} P_{K\pi}) \cdot R_{sig} + f^m_{q\bar{q}} \underbrace{P_{q\bar{q}} \cdot R_{q\bar{q}}} \} d\Delta t'$$

$$+ f_{ol} \cdot P_{ol}(\Delta t_i)$$

(single Gaussian outlier)



$B^0 \to D^+\pi^-$, $D^{*+}\pi^-$, $D^{*+}\rho^-$, $J/\psi K_S$ and $J/\psi K^{*0}$

Lifetime fit

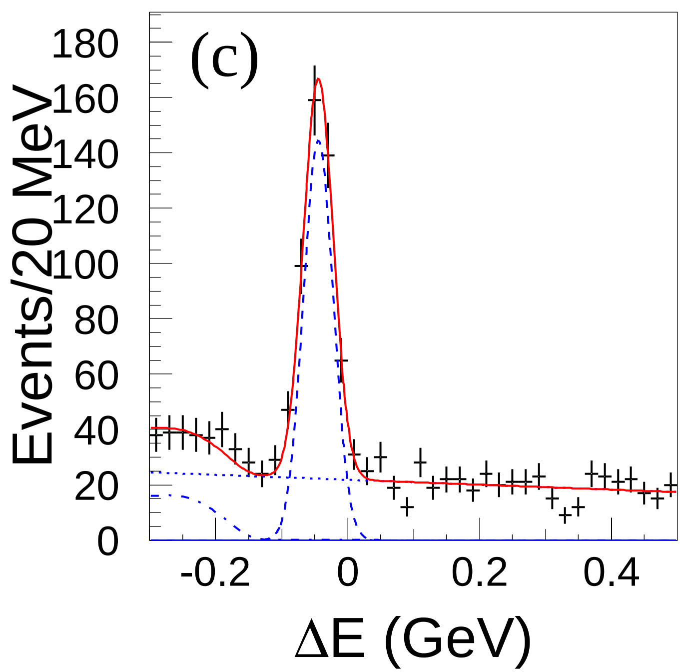
- Now we are able to obtain $A_{\pi\pi}$ and $S_{\pi\pi}$.

- But let's go through several crosschecks before opening the box.
  - Lifetime measurement
    - $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$
  - Δt asymmetry
    - Sideband ($q\overline{q}$), Non-CP sample, $B^0 \to K^+\pi^-$
  - MC pseduo-experiments

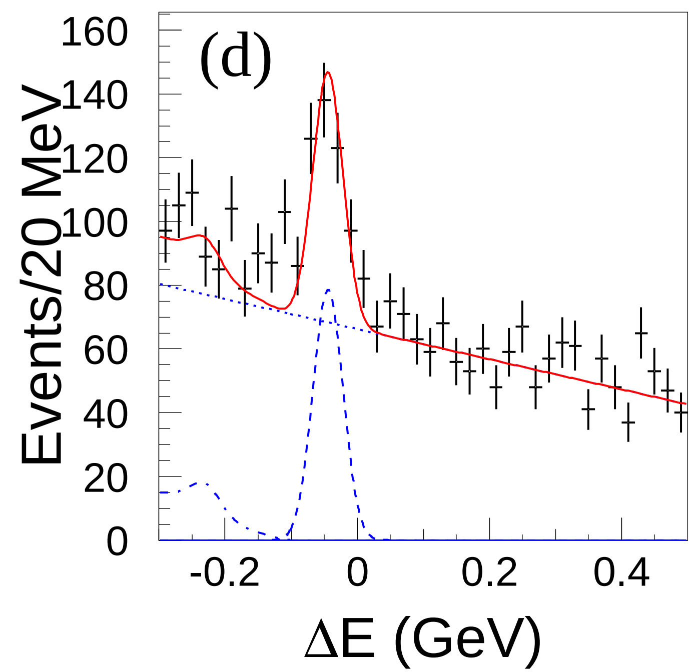
$B^0 \to K^+\pi^-$ control sample

Positively-identified kaons (opposite use of PID)

LR > 0.825

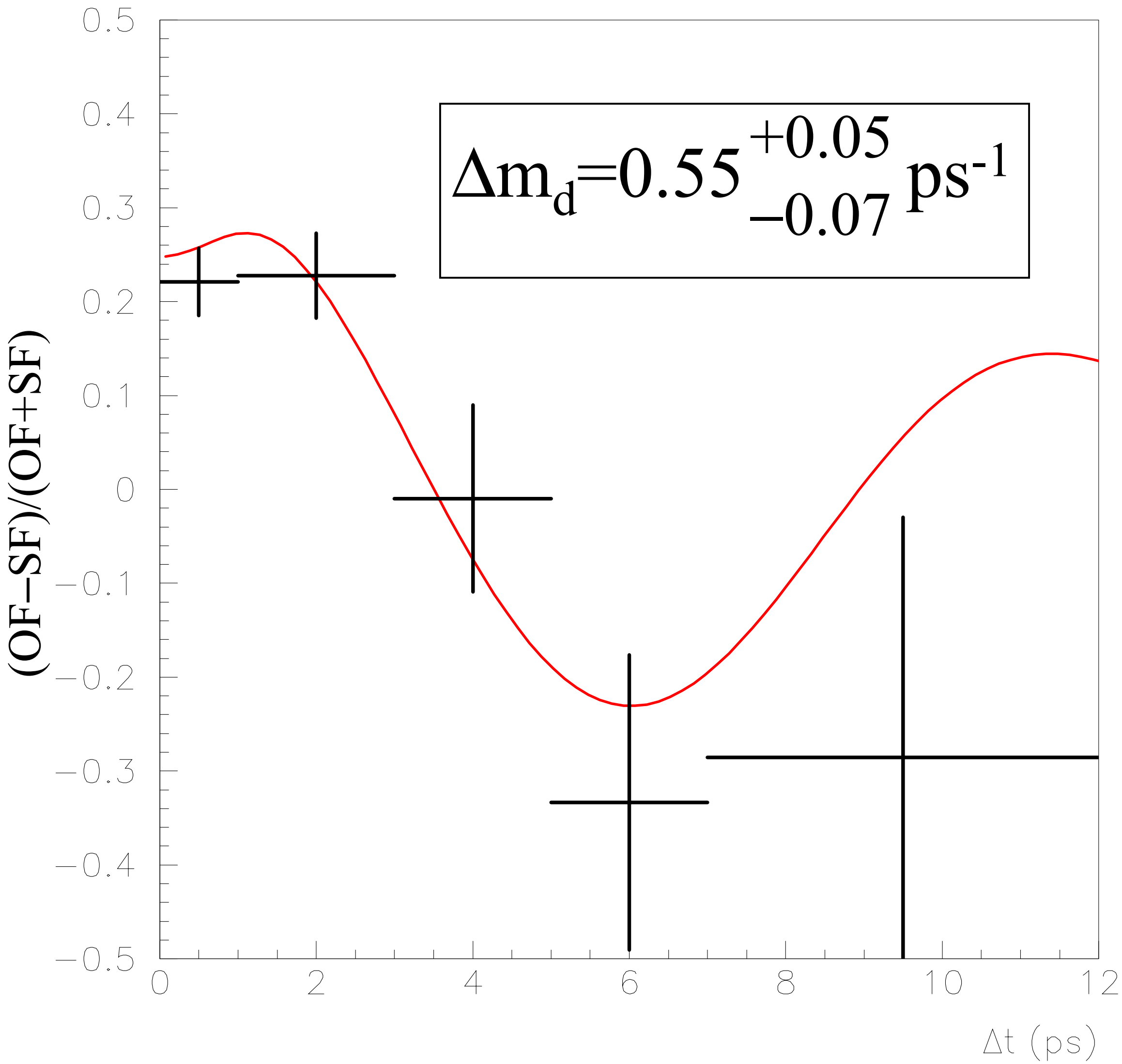


LRmin < LR ≤ 0.825



1371 candidates

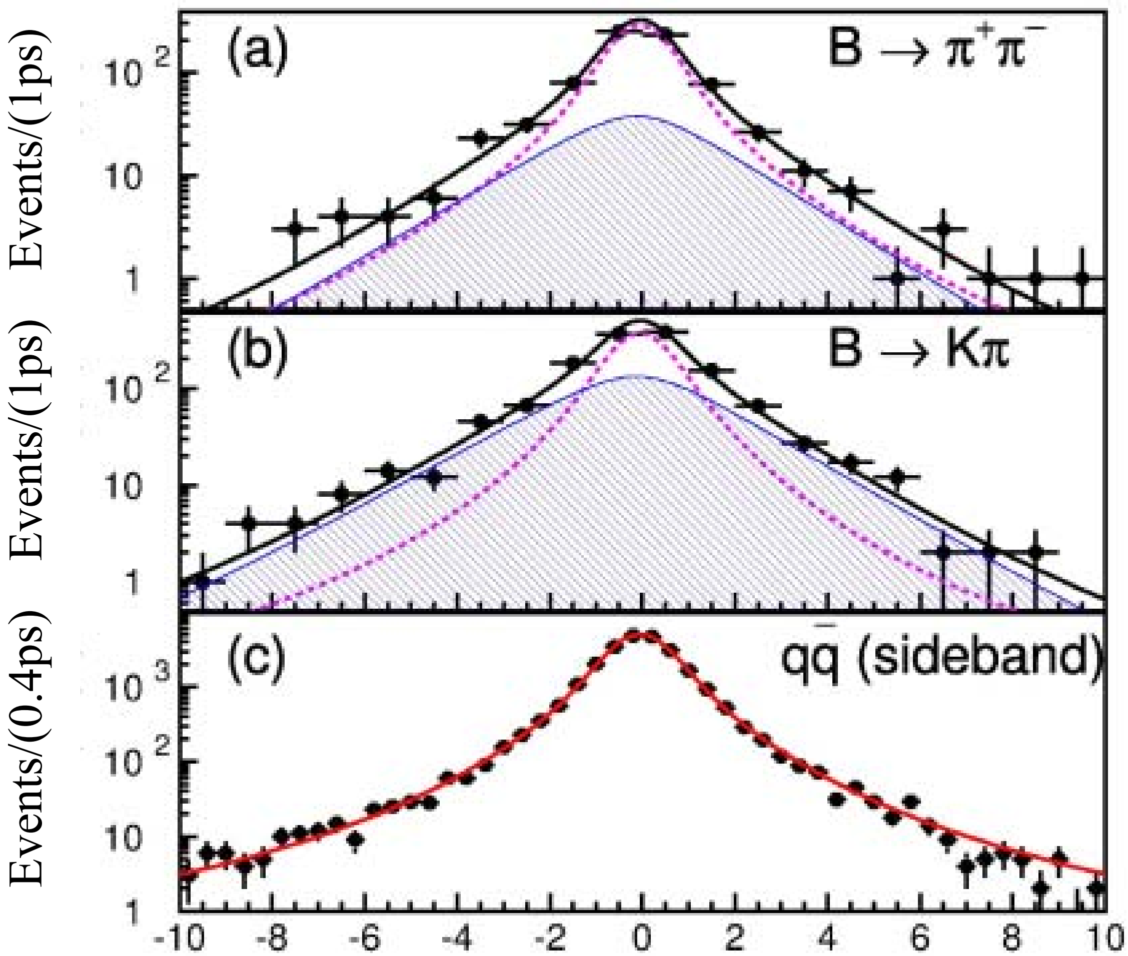
Mixing fit using $B^0 \to K^+\pi^-$: OK !



Consistent with the world average $(0.489\pm0.008)\ ps^{-1}$ PDG2002

Lifetime measurements: also good !

world average (PDG2002)
(1.542 ± 0.016) ps



$\pi\pi$: $\tau_B = (1.42 \pm 0.14)$ ps

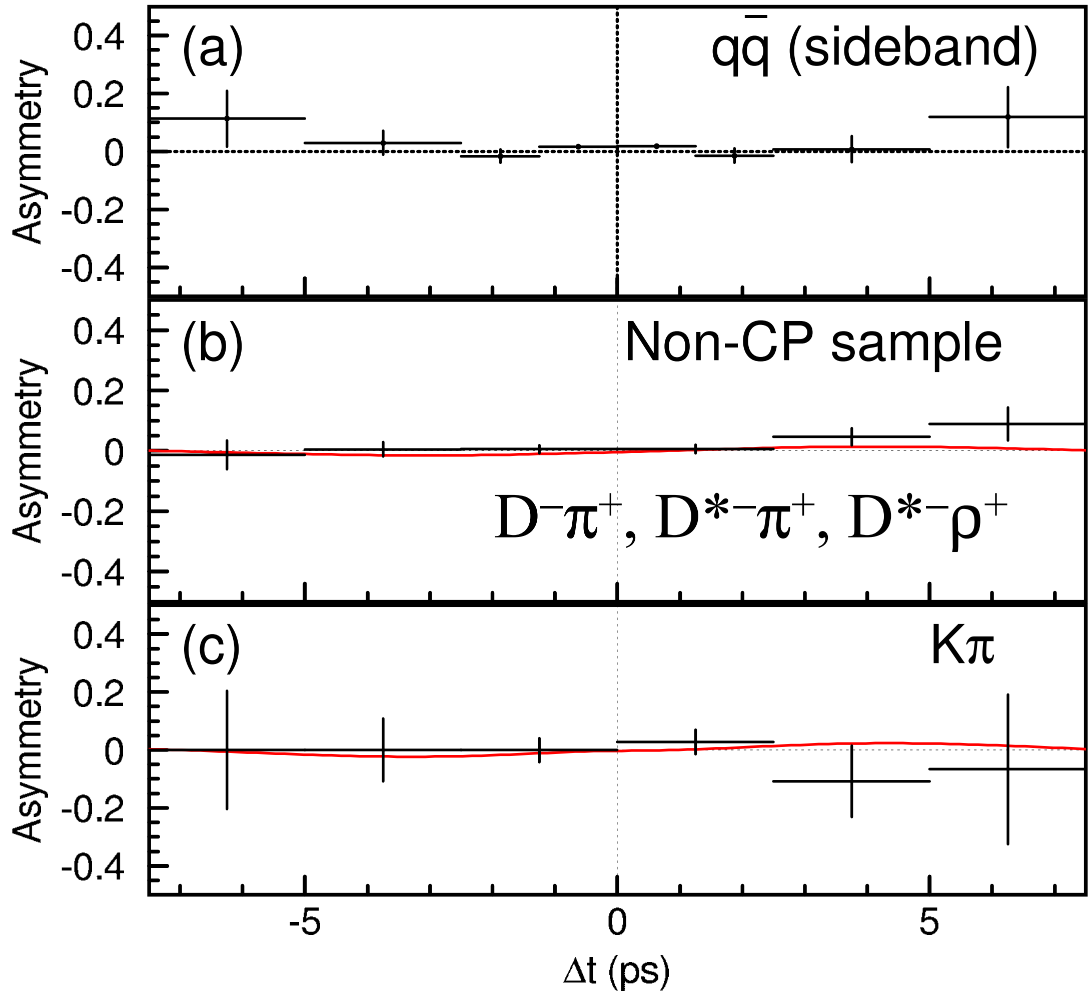
$K\pi$: $\tau_B = (1.46 \pm 0.08)$ ps

BG shape fit

Δt(ps)

$\to$ background treatment is correct !

Null asymmetry tests: OK !



Null asymmetry

$A = -0.015 \pm 0.022$

$S = \quad 0.045 \pm 0.033$

$S_{K\pi} = \quad 0.08 \pm 0.16$

$A_{K\pi} = -0.03 \pm 0.11$

(consistent with counting analysis)

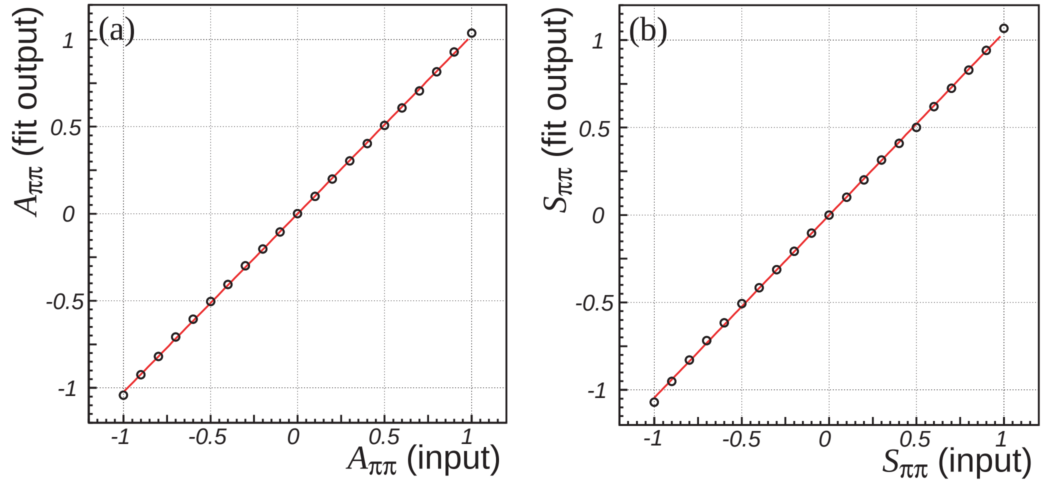
$A_{K\pi} = -0.07 \pm 0.06$

$\left\{ \begin{array}{l} B^0 \to K^+\pi^- \\ \bar{B}^0 \to K^-\pi^+ \end{array} \right.$

MC pseudo-experiments

Generate events according to the PDF used for the fit →

Good linearity over the entire range←



- Feldman-Cousins approach for **Aππ** and **Sππ** confidence regions
  ← MC pseudo-experiments to determine acceptance regions.
- We quote the **rms** values of the $A_{\pi\pi}$ and $S_{\pi\pi}$ distributions in the MC pseudo-experiments as the **standard errors** of $A_{\pi\pi}$ and $S_{\pi\pi}$.

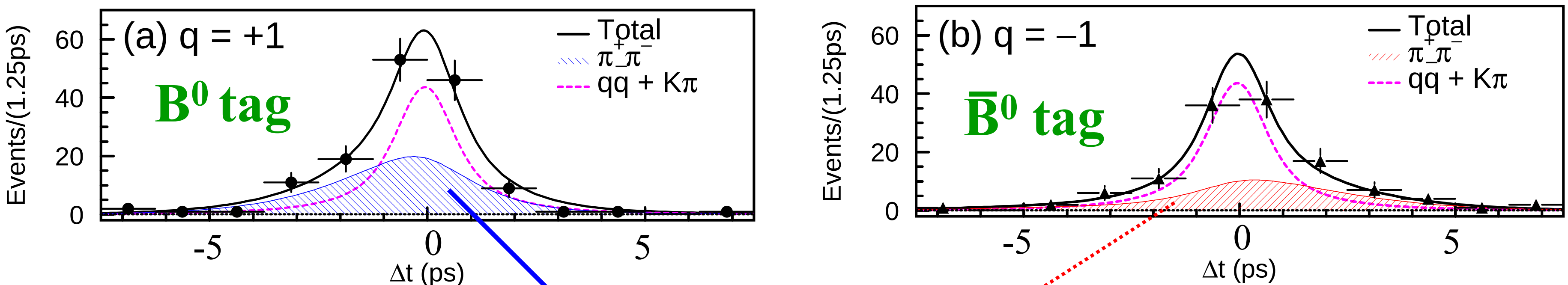
Aππ error: ±0.27
Sππ error: ±0.41

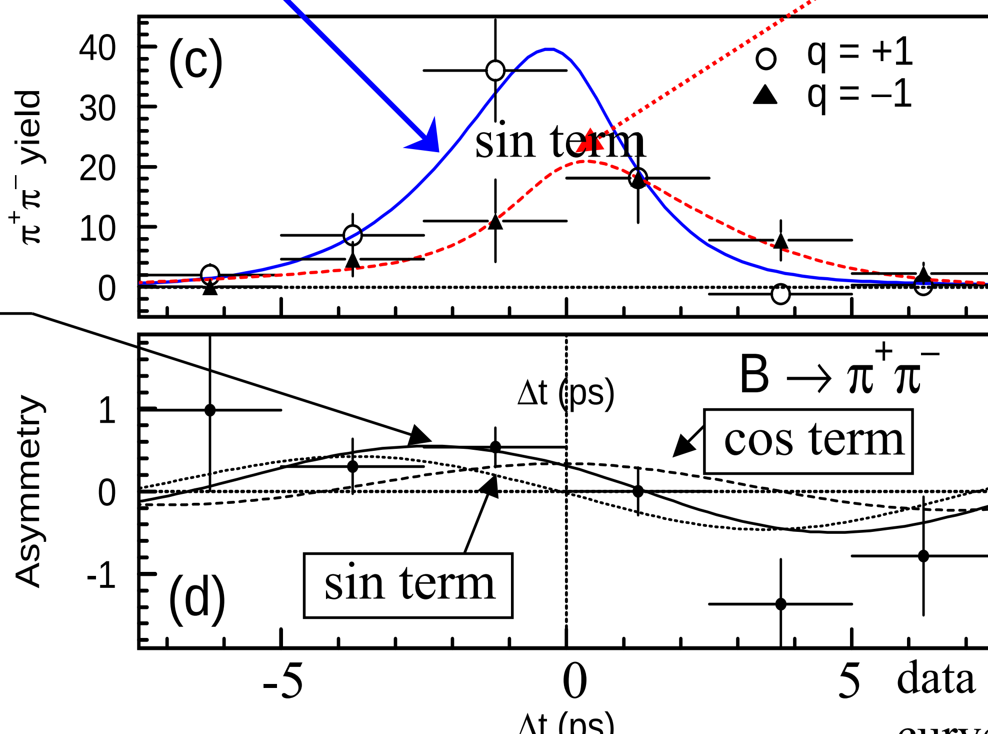
} larger than errors defined by log-likelihood curves in this measurement

- PDF is based on data (control samples, sideband) → MC pseudo-experiments are free from possible systematics in Geant-based MC.

3. Results

Fit results





Fit results

$A_{\pi\pi}$ = +0.77

$S_{\pi\pi}$ = −1.23

After background subtraction

Asymmetry with background subtracted

data points with LR > 0.825

curves from combined fit result

Large *CP* Violation is seen !

Fit results

$$A_{\pi\pi} = +0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst})$$
$$S_{\pi\pi} = -1.23 \pm 0.41(\text{stat})\ {}^{+0.08}_{-0.07}\ (\text{syst})$$

Consistent with previous results

Fit result:**outside the physical region** ($A_{\pi\pi}^2 + S_{\pi\pi}^2 \leq 1$)

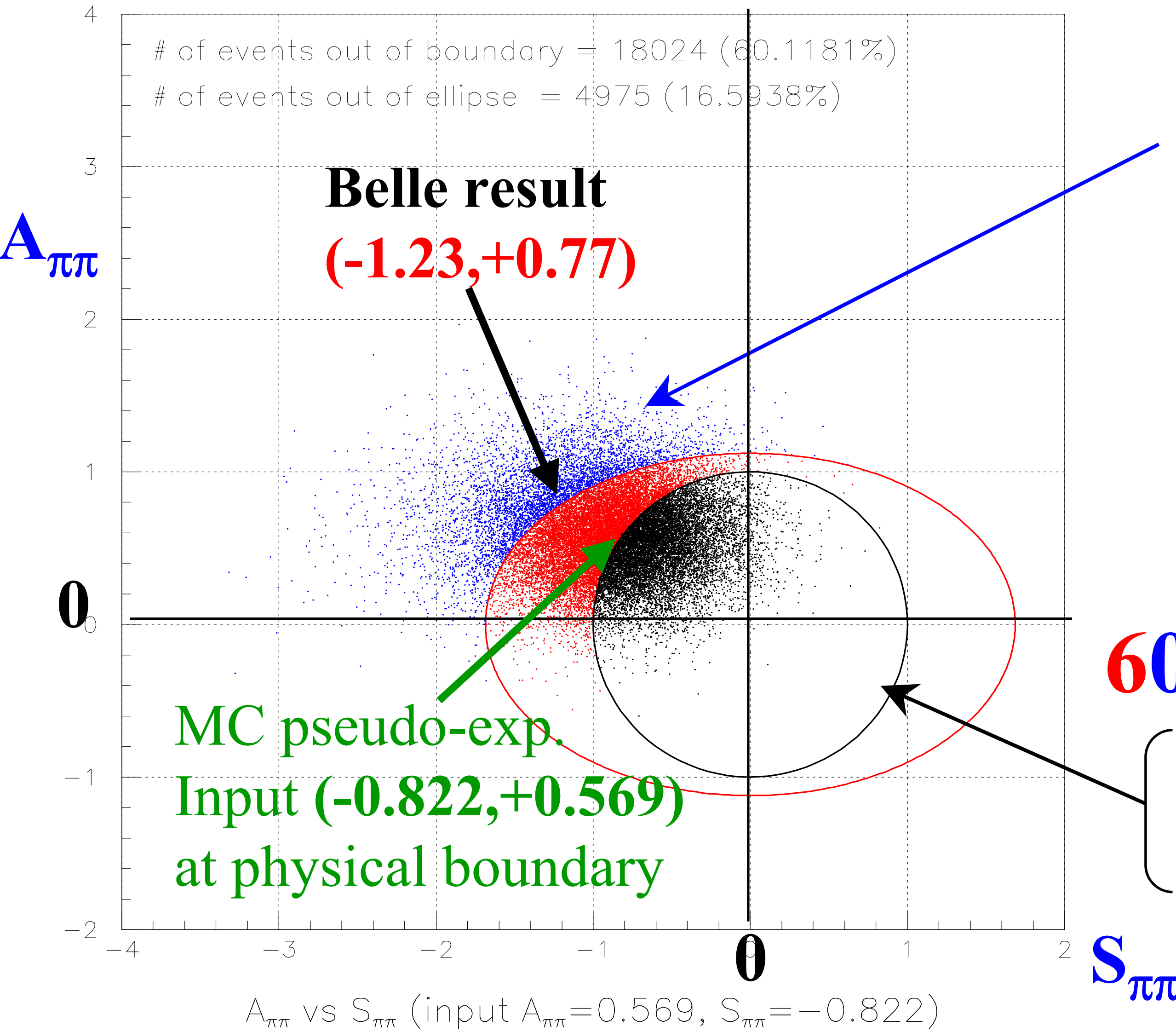
Indication of large CP-violating parameters

Then check

how often we are outside physical region and

significance next .

How often are we outside the physical region ?



Probability that we have fluctuation equal to or larger than the fit to data (input values at the physical boundary)

16.6% (blue)

60% outside $\begin{pmatrix}\text{blue}\\+\\\text{red}\end{pmatrix}$

$\left(\begin{array}{c}\text{Physical region}\\ A_{\pi\pi}^2 + S_{\pi\pi}^2 \leq 1\end{array}\right)$

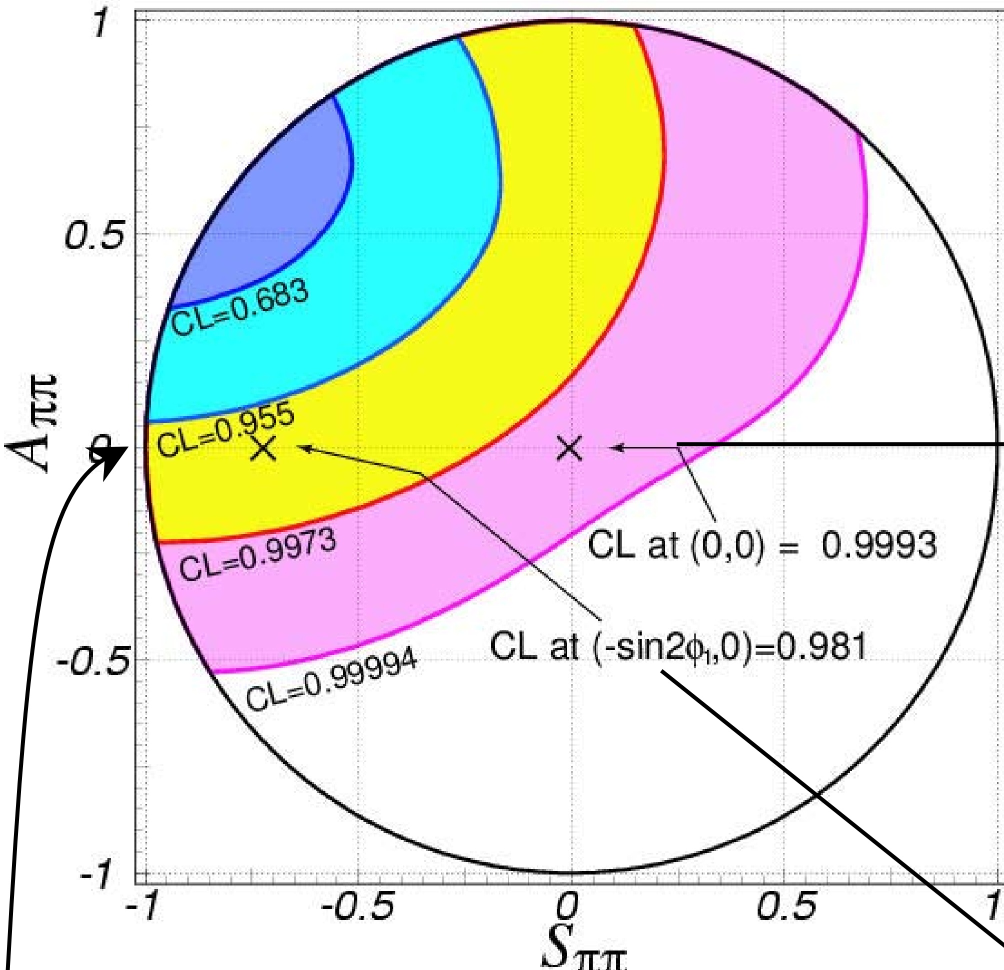
Systematic uncertainties

source	$A_{\pi\pi}$		$S_{\pi\pi}$	
	+error	–error	+error	–error
Background fractions	+0.058	–0.048	+0.044	–0.055
Vertexing	+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
τ_B, Δm_d, $A_{K\pi}$	+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	**+0.08**	**–0.08**	**+0.08**	**–0.07**

Systematic error << Statistical error

* Actual estimations were done before seeing the fit result, as we adopted a blind analysis technique.

Confidence Regions; Evidence for *CP* Violation



- Feldman-Cousins frequentist approach.
- Acceptance regions obtained from MC pseudo-experiments.
- Systematic errors also included.
- Confidence Level (CL) at each point is calculated.

CL for CP conservation **3.4σ**

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

3) **CPV from $\bar{B}$-B mixing only (“superweak” scenarios):**
e.g. Bigi (2002),
Brhlik-Everett-Kane-King-Lebedev (2000)
2.3σ

2) “Indication” of direct CP Violation ($A_{\pi\pi}$>0);
“observation” requires more statistics.

Constraints on the CKM angle ϕ_2

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

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

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

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

4 parameters

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

$$\boxed{\delta} \equiv \delta_P - \delta_T$$

Strong phase difference

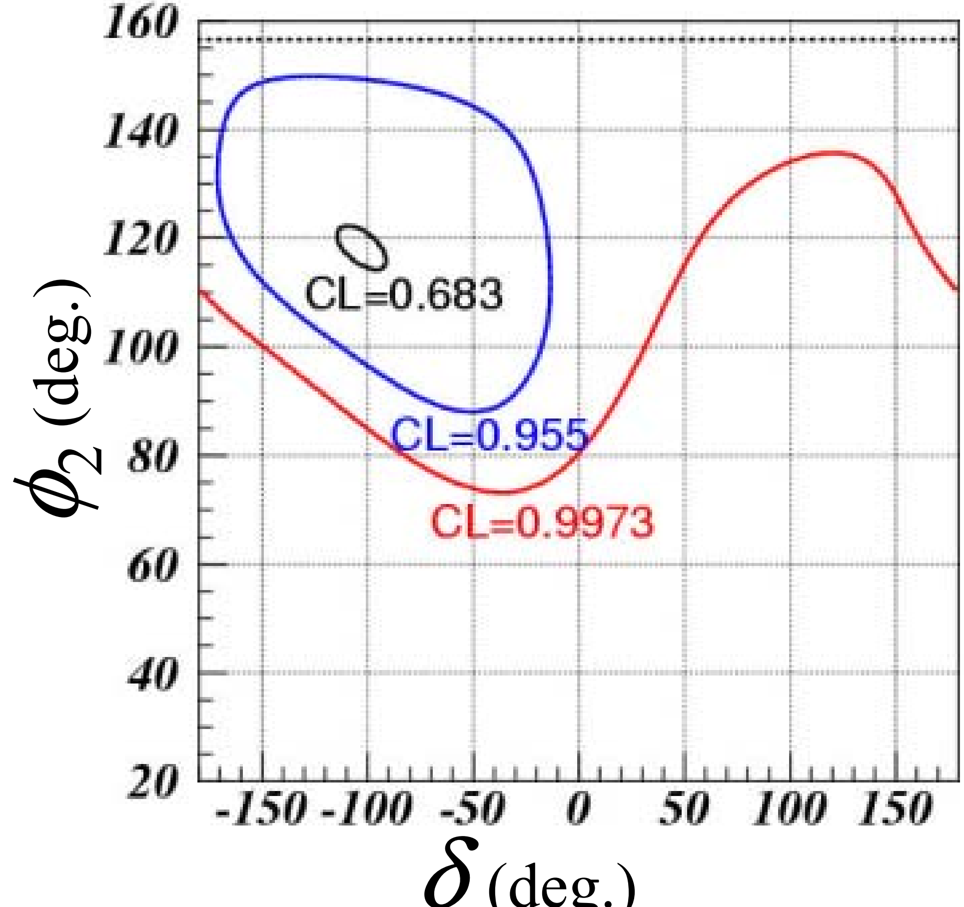
|P/T|	0.15-0.45 (representative)	Theory ~0.3
ϕ_1	21.3 - 25.9deg	(Belle & BaBar combined)

Constraint on ϕ_2

- Confidence region for $S_{\pi\pi}$ and $A_{\pi\pi}$
- Input values for ϕ_1 and |P/T|
  - ϕ_1=23.5°(sin2ϕ_1=0.73)
  - |P/T| = 0.3

- ϕ_2 constraint w/o isospin analysis !
- both $A_{\pi\pi}$ and $S_{\pi\pi}$ large
- less restrictive on δ
- $\delta < 0$ favored
  - no constraint at 3σ

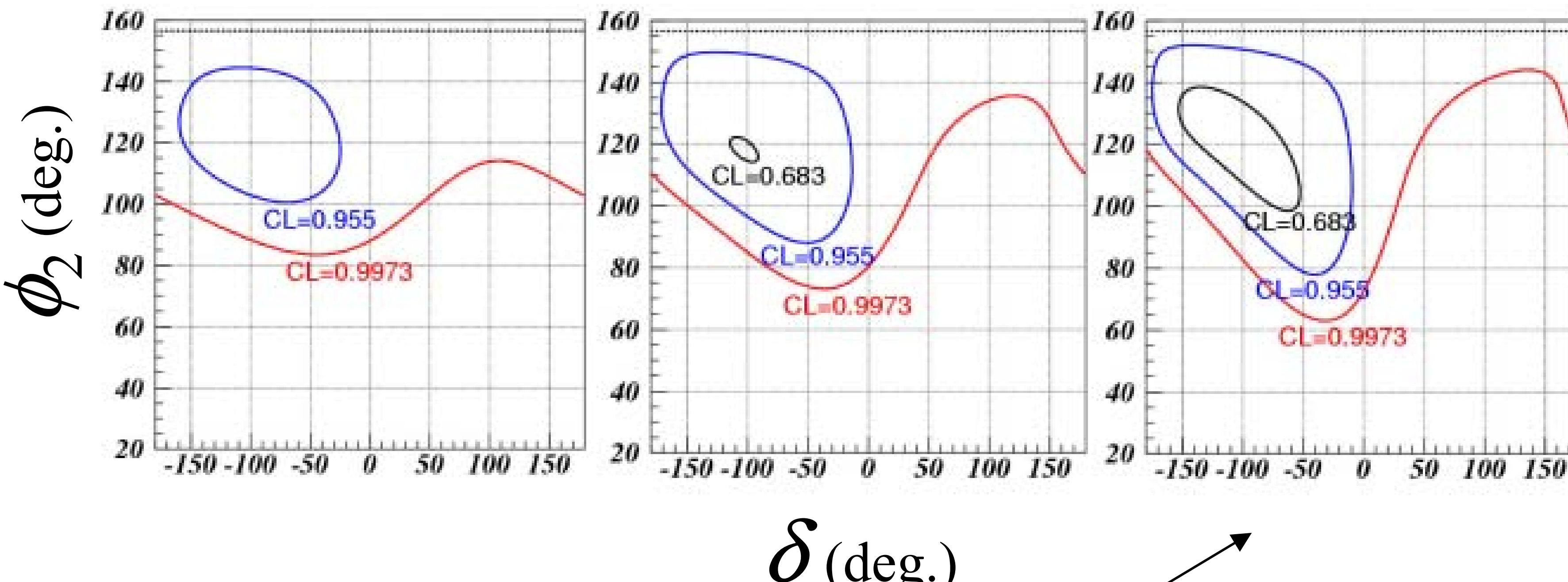
allowed regions



Constraint on ϕ_2

|P/T| dependence ($\phi_1 = 23.5°$)

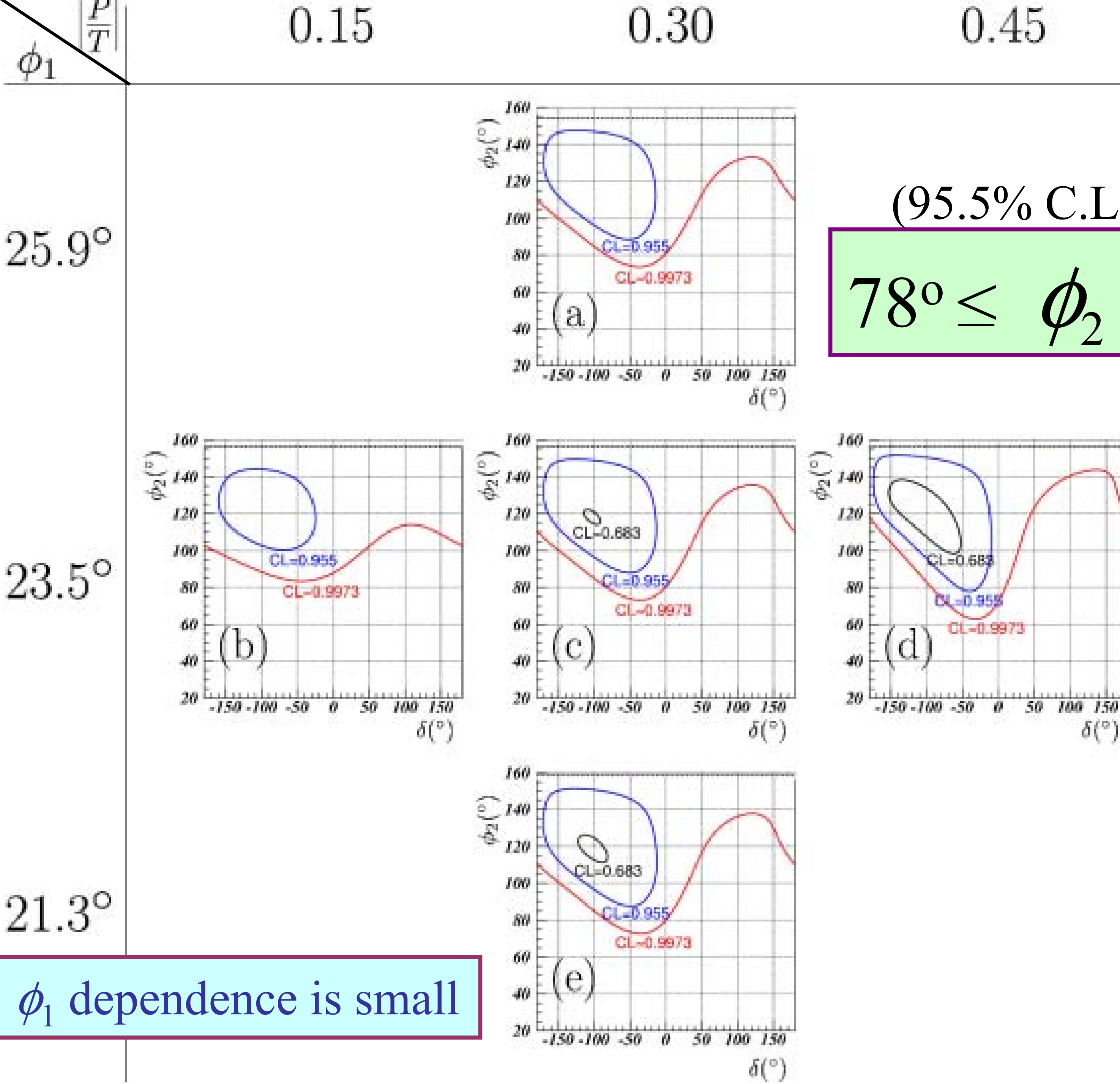
|P/T| = 0.15 |P/T| = 0.30 |P/T| = 0.45



Larger |P/T| favored

(95.5% C.L.)

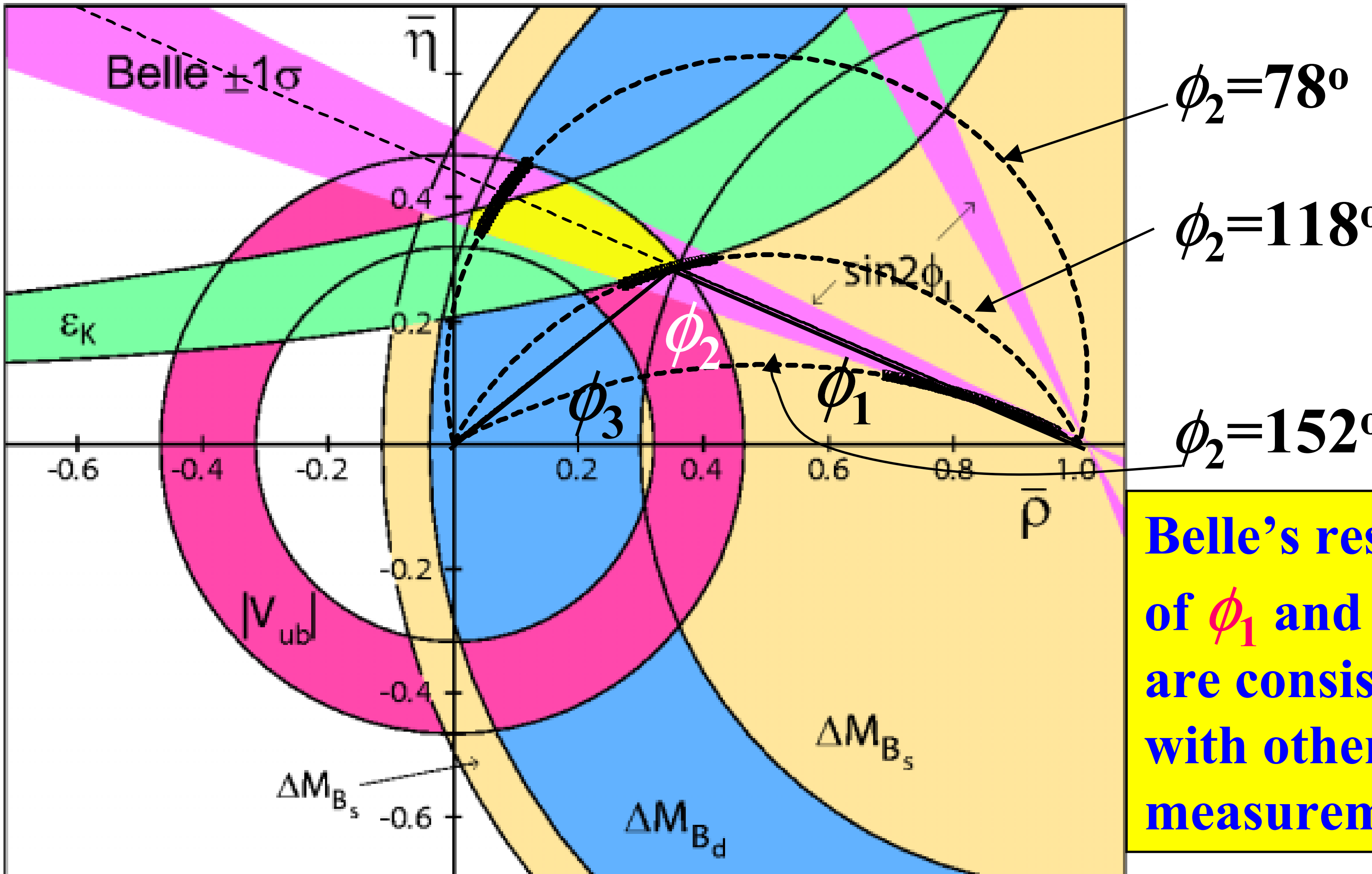
$$78^{o} \leq \phi_2 \leq 152^{o}$$



ϕ_1 dependence is small

Constraint on ρ-η

PDG2002 + (Belle ϕ_1 & ϕ_2)



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

4. Conclusion

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

CP conservation ruled out at the 99.93% CL (3.4σ)

- Large $A_{\pi\pi}$ value indicates direct CP violation. More Belle data will come (x 5 by ~2005) for confirmation.

First constraints (within the SM) on the CKM angle $\phi 2$!

$$78^o \le \phi_2 \le 152^o \quad (95.5\%\ \mathrm{CL})$$

[for $0.15 < |P/T| < 0.45$ and $\phi_1 = 23.5^o (\sin 2\phi_1 = 0.73)$]

Consistent with indirect constraints on the unitarity triangle from other measurements.

The best is yet to come.