CP Violation and Rare B Decays at Belle

DESY Seminar
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Representing the Belle Collaboration

Outline

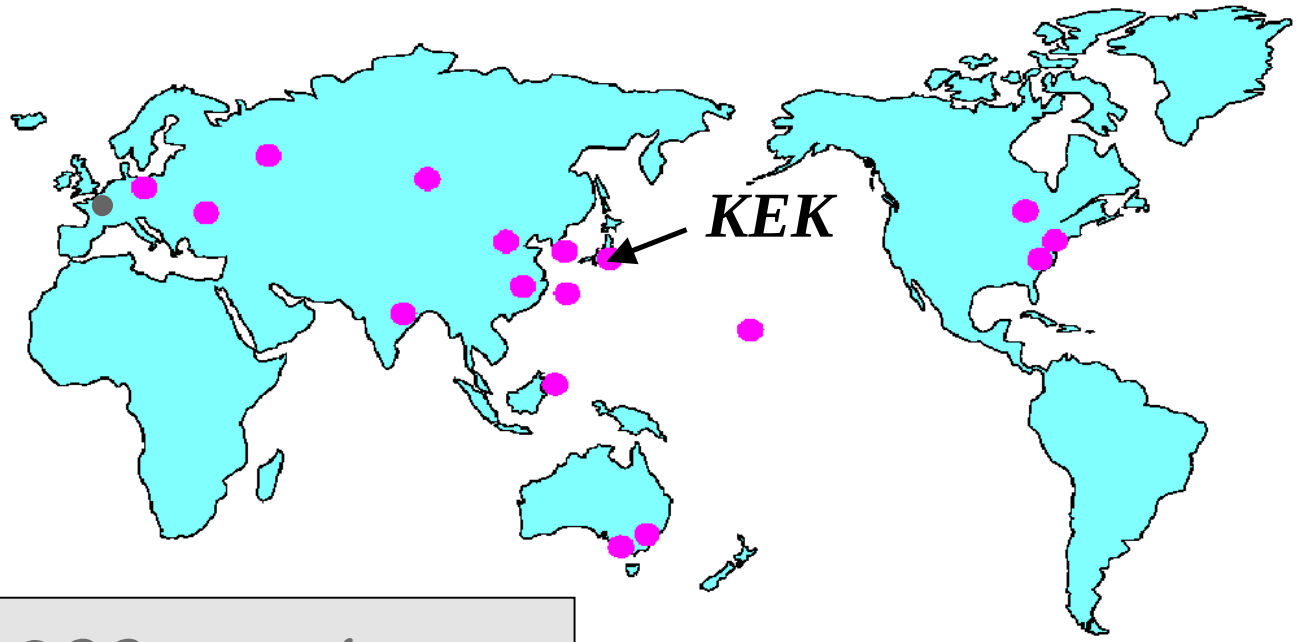
- **Introduction**
- **KEKB Accelerator and Belle Detector**
- **Observation of Large CP Violation**
- **Rare B Decays**
- **Conclusion**

Today's Main Topic

- **Introduction**
- **KEKB Accelerator and Belle Detector**
- **Observation of Large CP Violation**
- **Rare B Decays**
- **Conclusions**

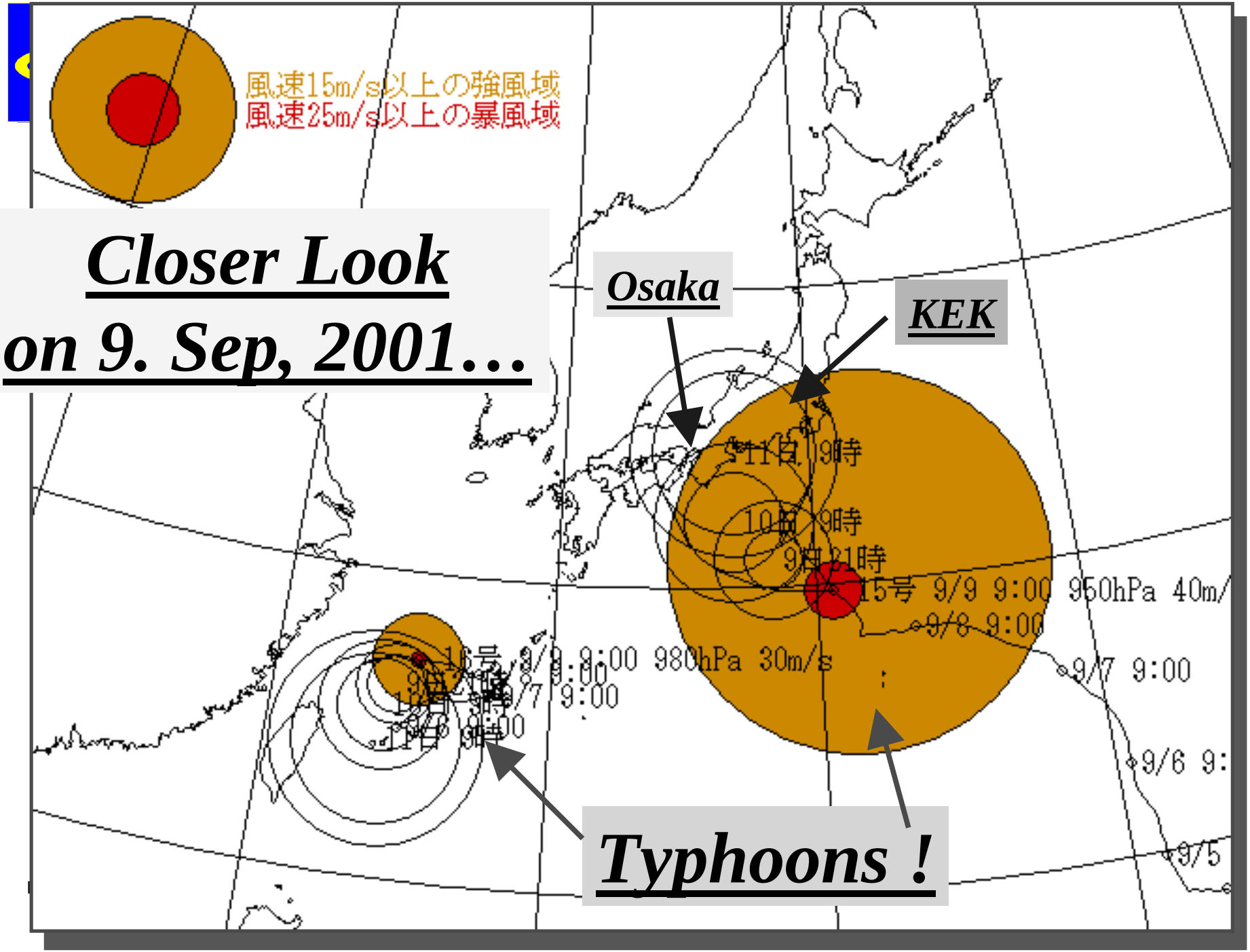
The Belle Collaboration

A World-Wide Activity Involving 50 Institutions



~300 members

→ room for additional 300 physicists available ☺

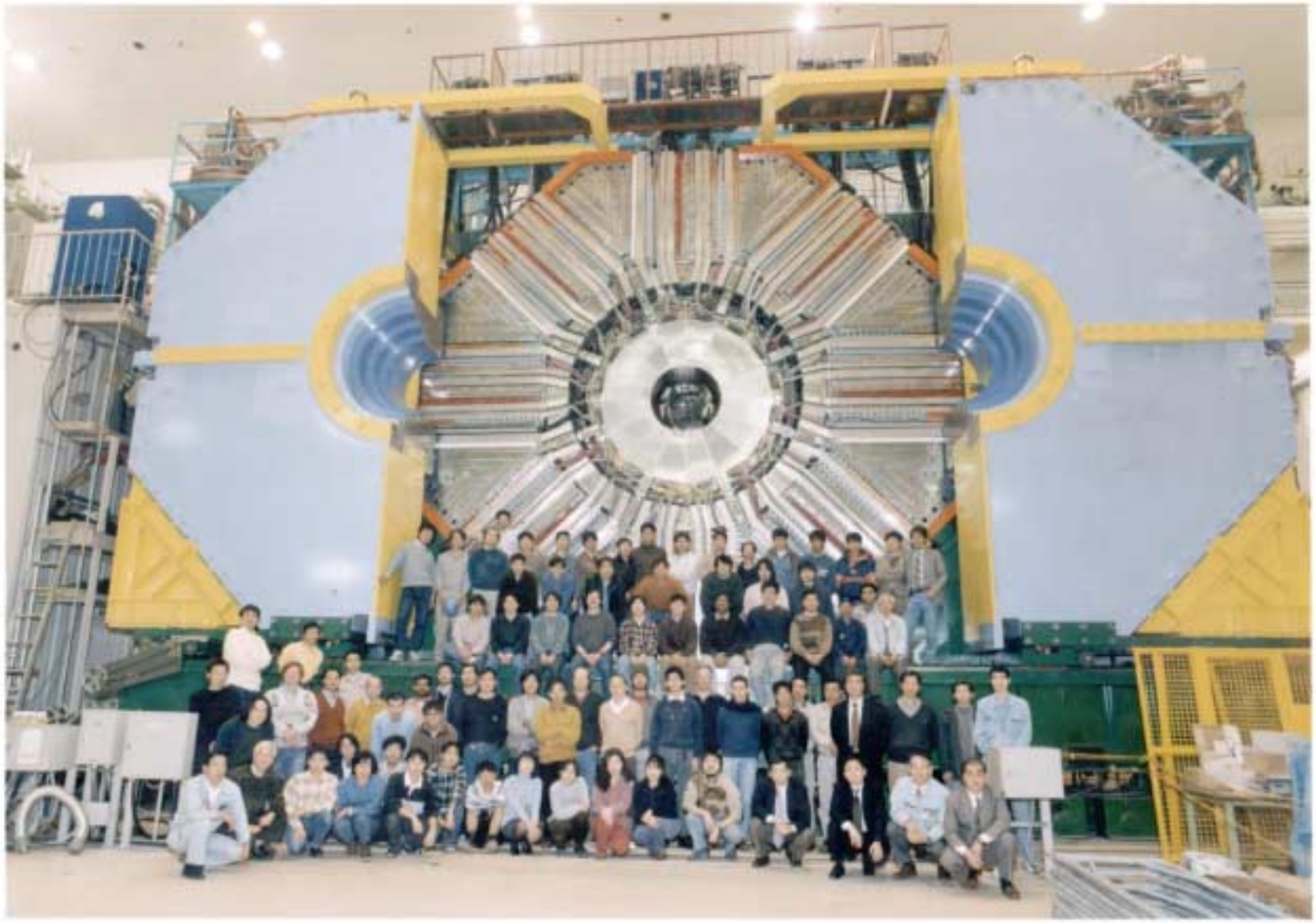

風速15m/s以上の強風域
風速25m/s以上の暴風域
Closer Look
on 9. Sep, 2001…
Osaka
KEK
9時
10日 9時
9日 21時
15号 9/9 9:00 950hPa 40m/
9/8 9:00
9/7 9:00
9/6 9:
9/5
16号 9/9 9:00 980hPa 30m/s
Typhoons !

Much closer look at KEK

KEK

KEKB Collider

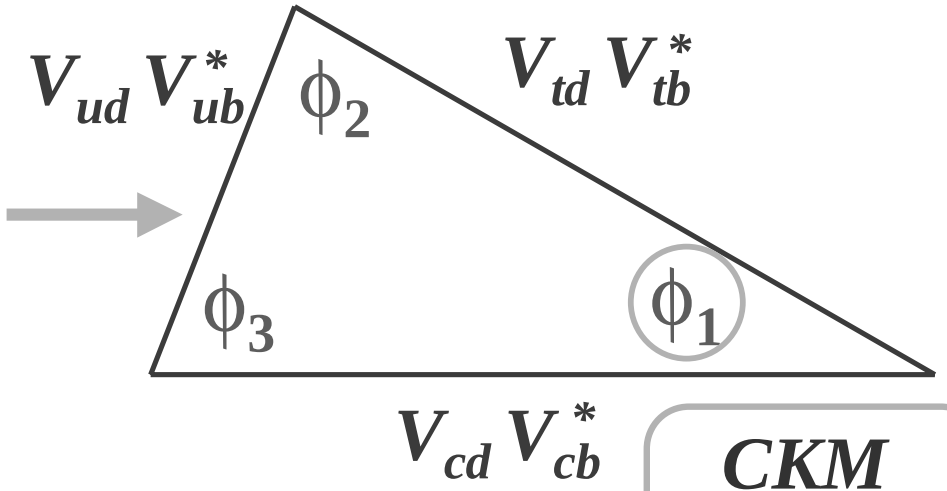
The Belle Detector



Kobayashi-Maskawa and CPV

CPV due to complex phases in CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



CKM matrix Unitarity triangle

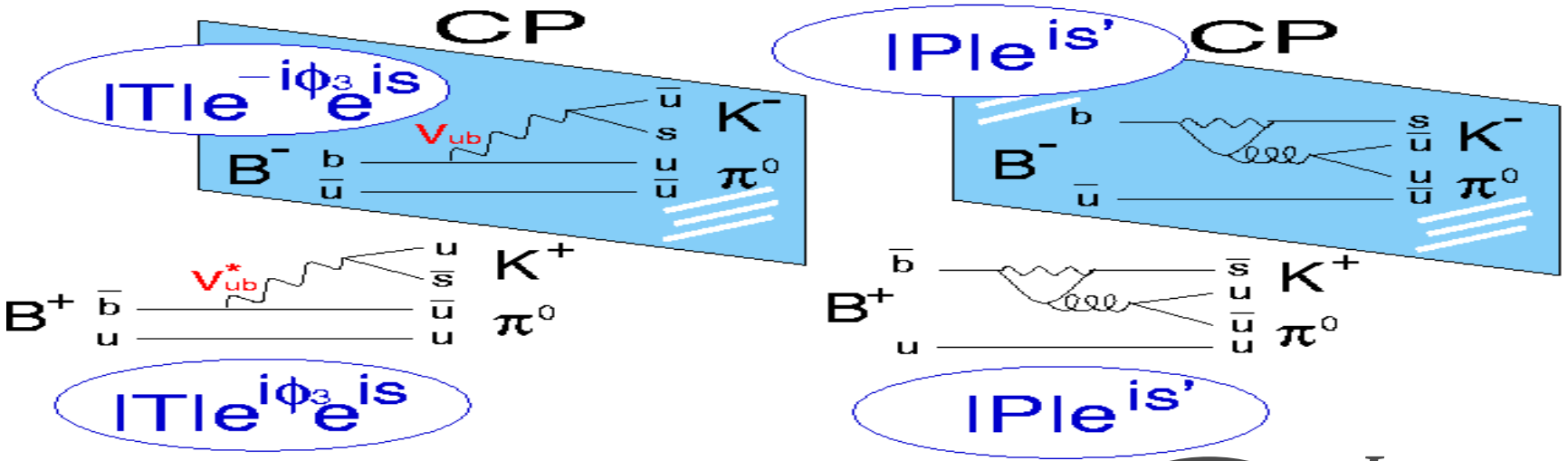
Goals of B-factory

1) **Discover / Establish CPV**
2) Precise/Redundant Measurement of CKM elements : **angles and lengths**
3) **Beyond SM**

The Rules of the CPV Game

- Find a decay mode which has two decay paths with different weak phases (i.e. one of them has Vub or Vtd).
- Two amplitudes should be similar for sizable interference.
- Two paths should have "static" phase difference.

Example : $B^+ \to K^+\pi^0$ and $B^- \to K^-\pi^0$

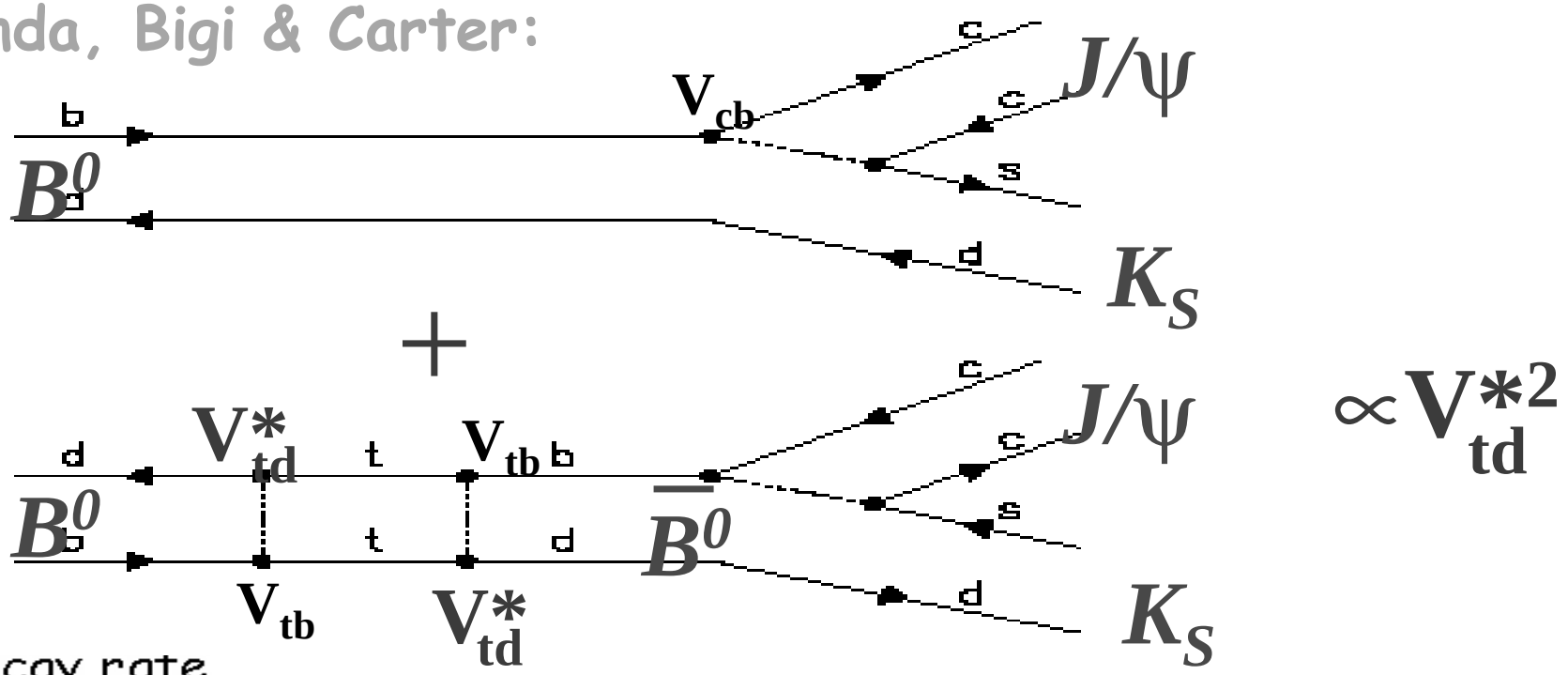


$$\Gamma(B^+ \to K^+\pi^0) - \Gamma(B^- \to K^-\pi^0) = 4|T||P|\sin(\phi_3)\sin(s'-s)$$

Large Uncertainty !

Time-dependent CP Violation

Sanda, Bigi & Carter:



Decay rate

$$\Gamma = \langle f_{CP} \mid \bar{B}^0 \rangle^2 e^{-\Gamma t} \left\{ \cos^2 \frac{\Delta m t}{2} + |\lambda|^2 \sin^2 \frac{\Delta m t}{2} + i(\lambda - \lambda^*) \frac{1}{2} \sin \Delta m t \right\}$$

$$\approx \langle f_{CP} \mid \bar{B}^0 \rangle^2 e^{-\Gamma t} \{ 1 - \xi \sin 2\phi_1 \sin \Delta m t \} \qquad |\lambda| \sim 1$$

Δm_B is the origin of "static" phase difference.
No hadronic uncertainty !

Large $B\bar{B}$ Mixing !

ARGUS (1987)

(103pb^{-1} on resonance)

$r = (N(BB)+N(\bar{B}\bar{B}))/N(B\bar{B})$

$= 0.21 \pm 0.08$

$\downarrow$

$\Delta m_{B0} = (0.472 \pm 0.017)\ ps^{-1}$

(PDG2000)

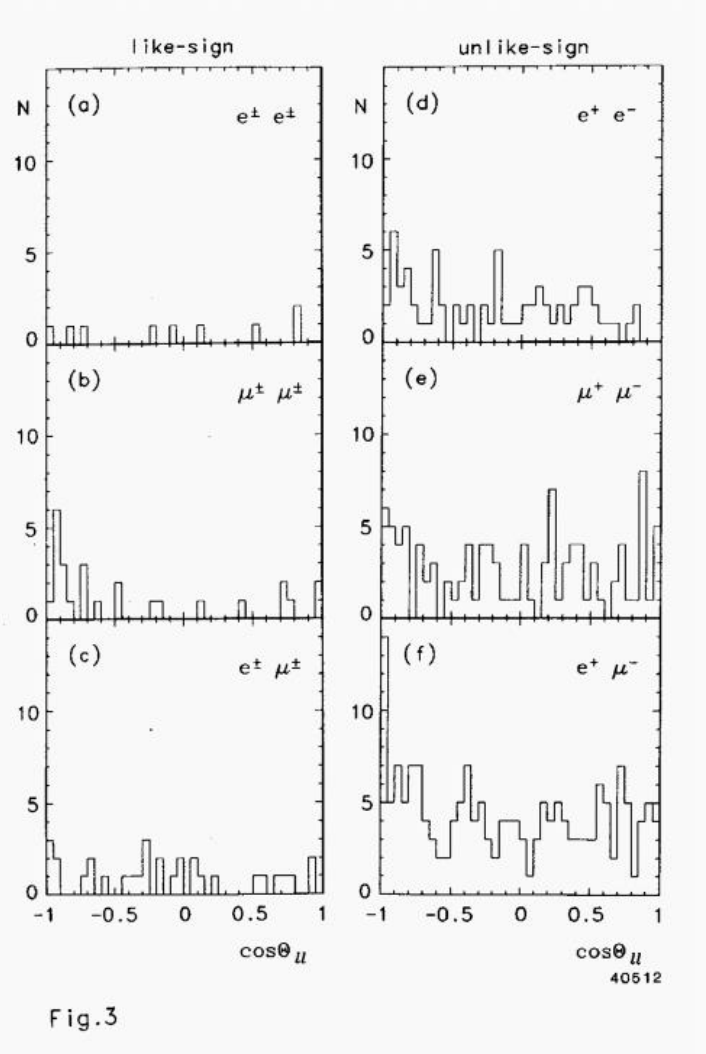


Fig.3

Appropriate $B\bar{B}$ Mixing !

$\sin\Delta mt = 1$

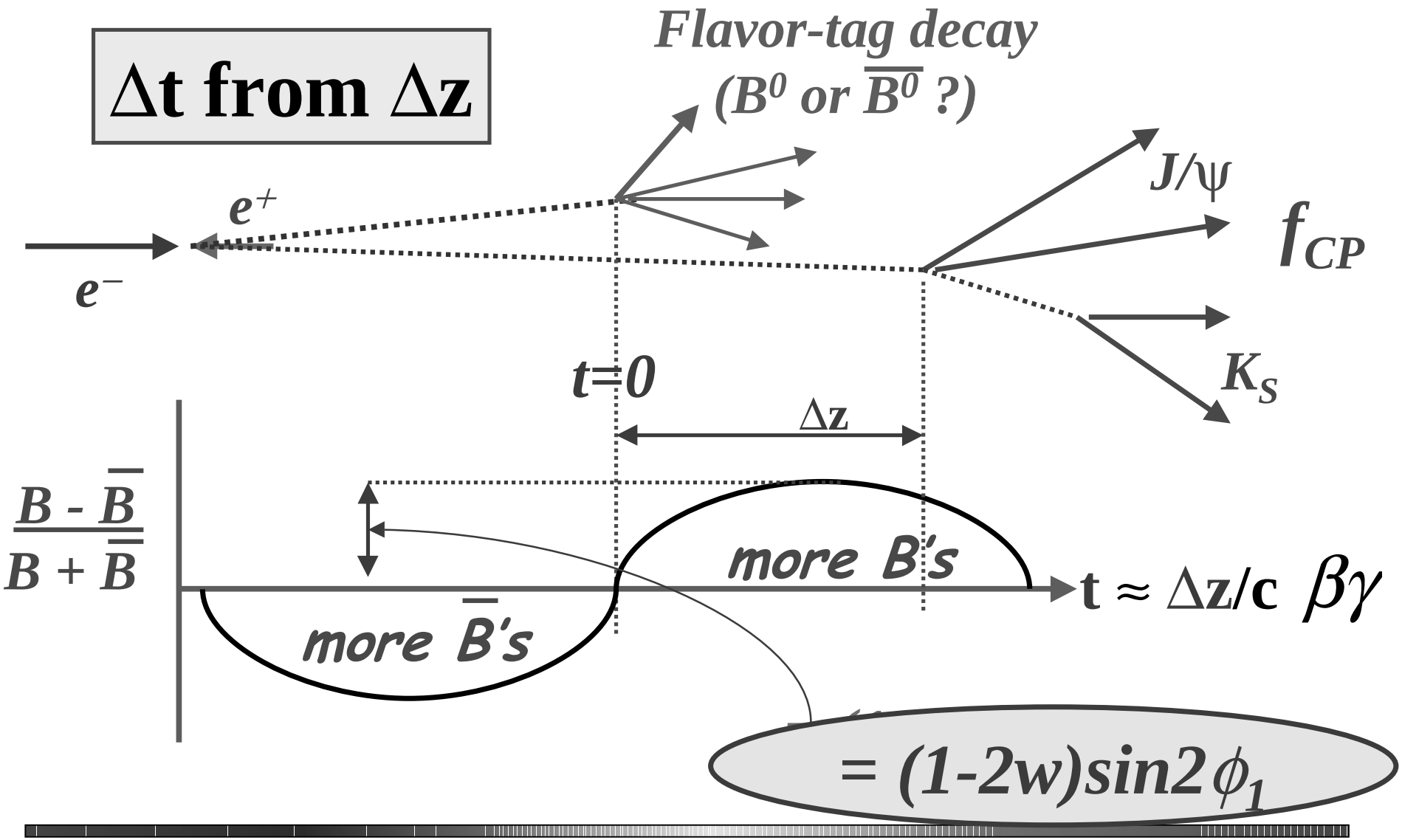
$\downarrow$

Maximal CP at 3.3 ps

B0 Lifetime = 1.55ps

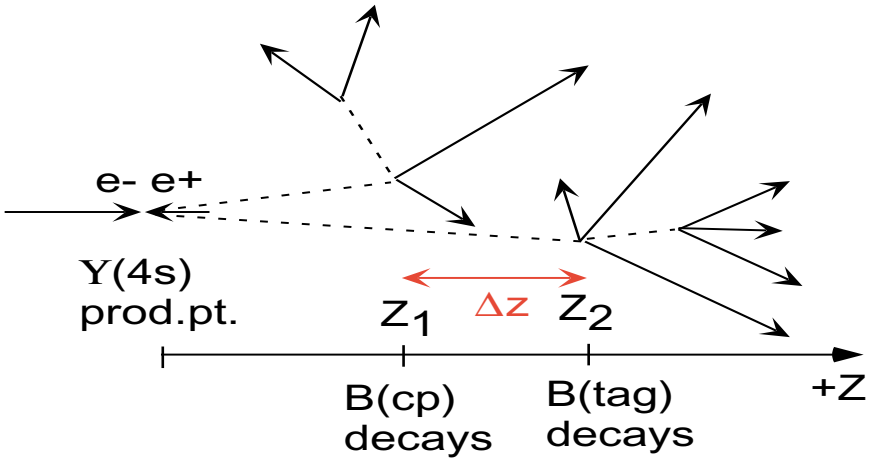
Large enough and small enough
(It is a miracle to me.)

Principle of the Measurement



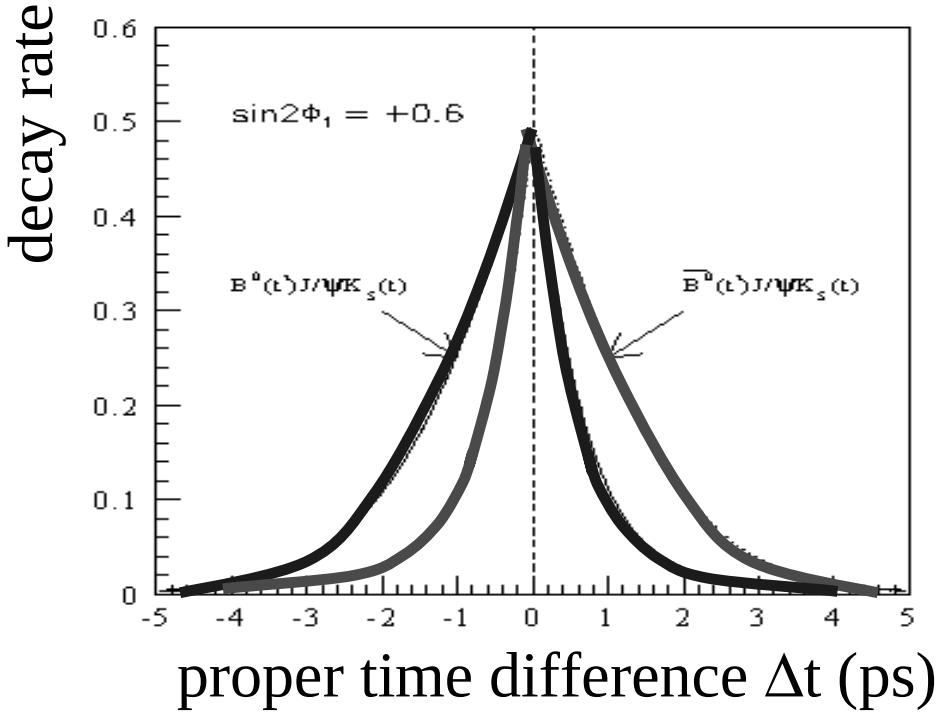
Experimental Challenges

1) Copious B pair production, efficient B reconstruction
2) Efficient and correct flavor tagging
3) Observation of time-dependent CP asymmetry in B decays to a CP eigenstate with good vertex resolution



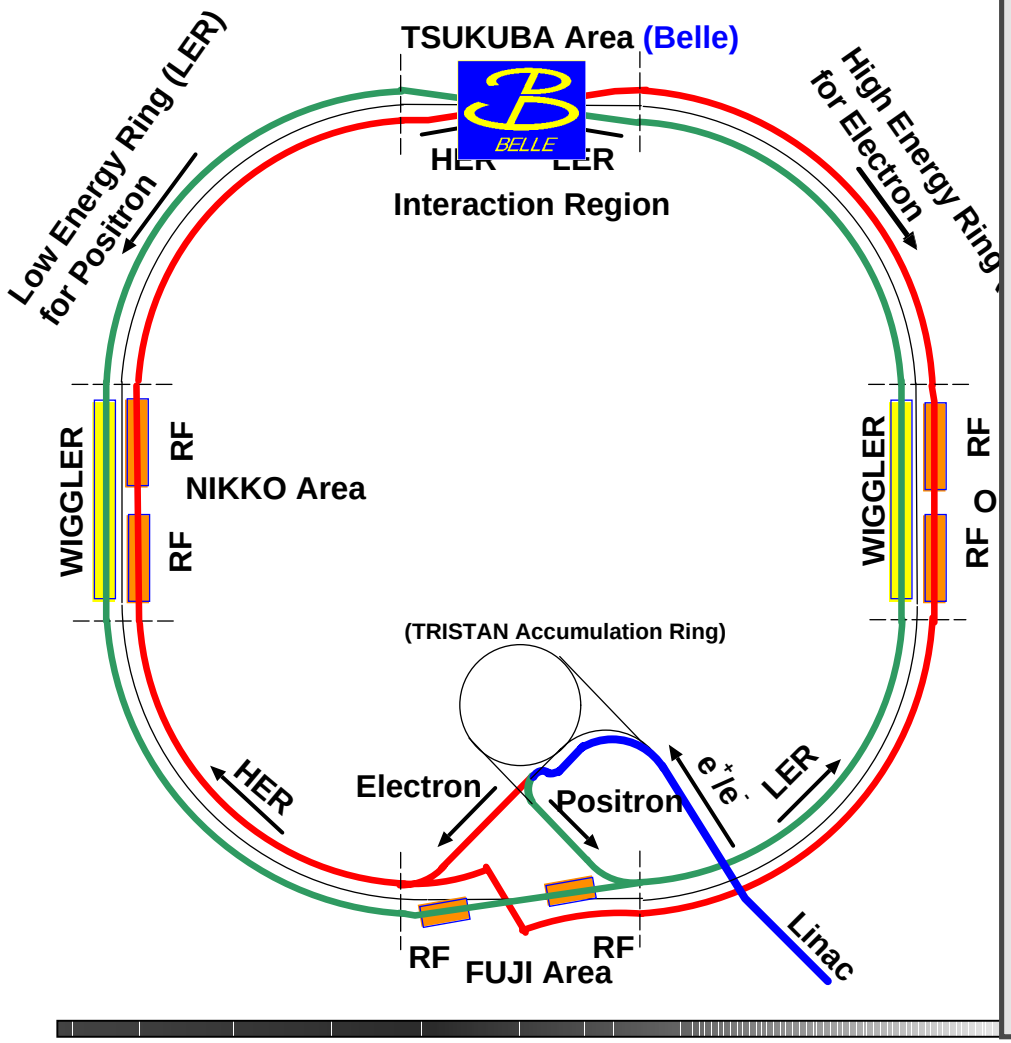
$\Delta z \approx c\beta\gamma\Delta t$

(~200μm at Belle)



- **Introduction**
- **KEKB Accelerator and Belle Detector**
- **Observation of Large CP Violation**
- **Rare B Decays**
- **Conclusions**

KEKB asymmetric e^+e^- collider

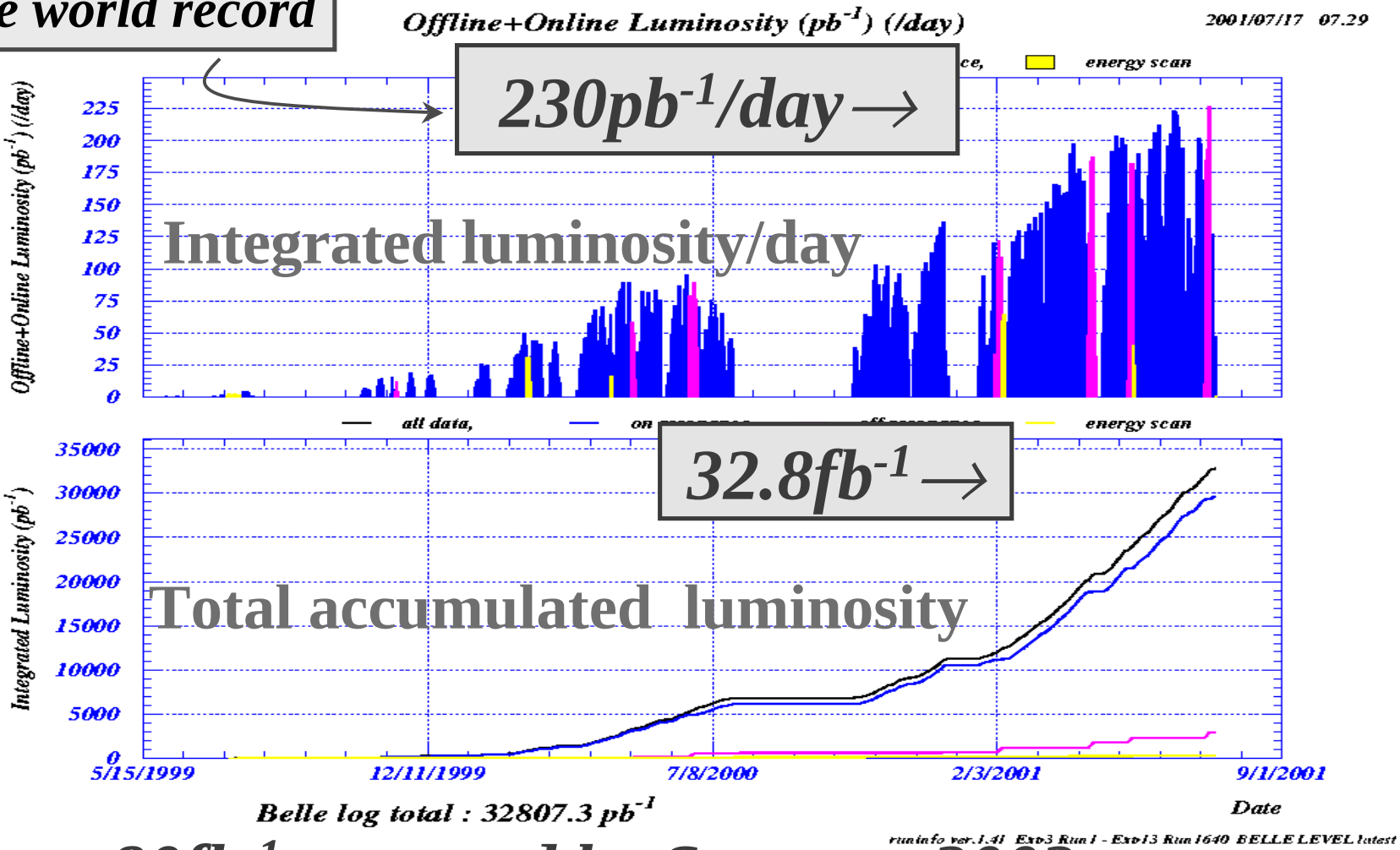


- Two separate storage rings
  - e^+ (LER) : 3.5 GeV
  - e^- (HER) : 8.0 GeV
- E_{CM} : 10.58 GeV at $\Upsilon(4S)$
- Luminosity — ***World Record***
- target: $10^{34}\ cm^{-2}s^{-1}$
- achieved: $4.5 \times 10^{33} cm^{-2}s^{-1}$
- ±11 mrad crossing angle
- Small beam sizes:

$\sigma_y \approx 3\ \mu m$; $\sigma_x \approx 100\ \mu m$

KEKB performance

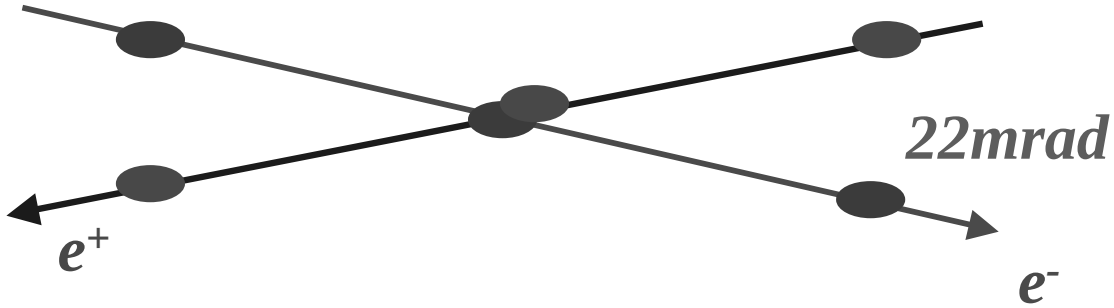
The world record



~80fb^{-1} expected by Summer 2002

KEKB's Special Features

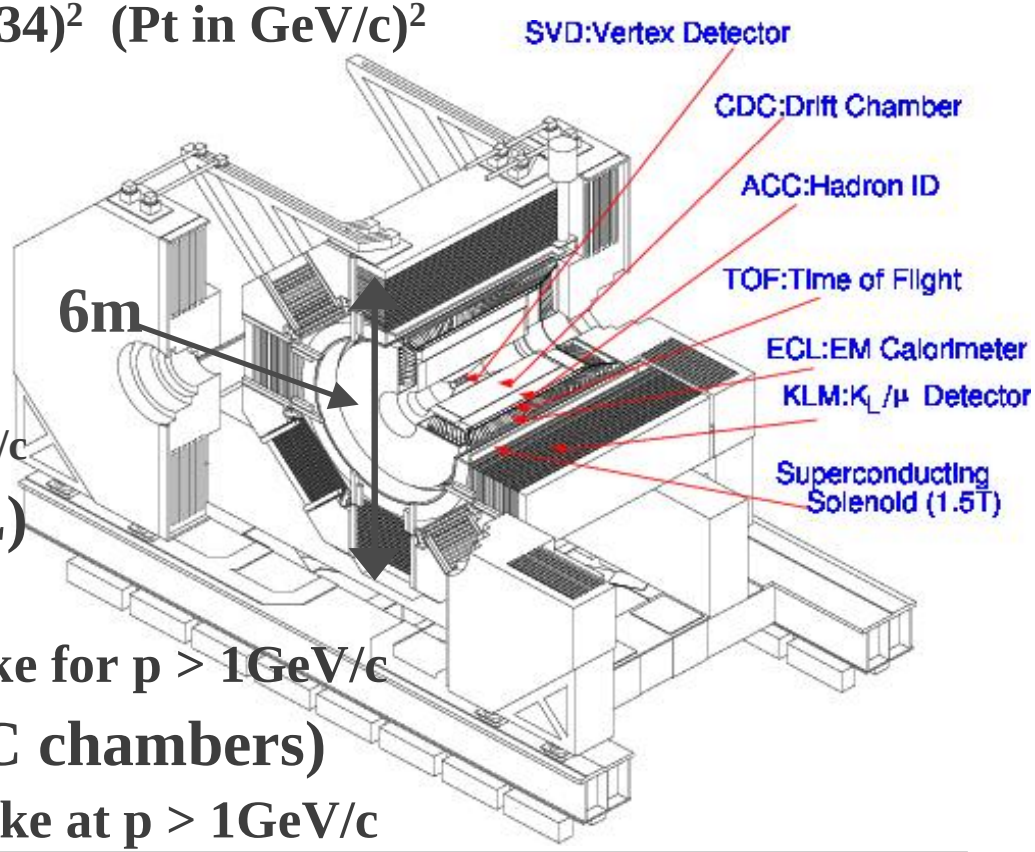
- **Small beam sizes ⇒ low beam currents**
  - **4.5×10^{33} with less than 1 Amp in each ring**
- **$\pm$ 11 mrad beam crossing angle**



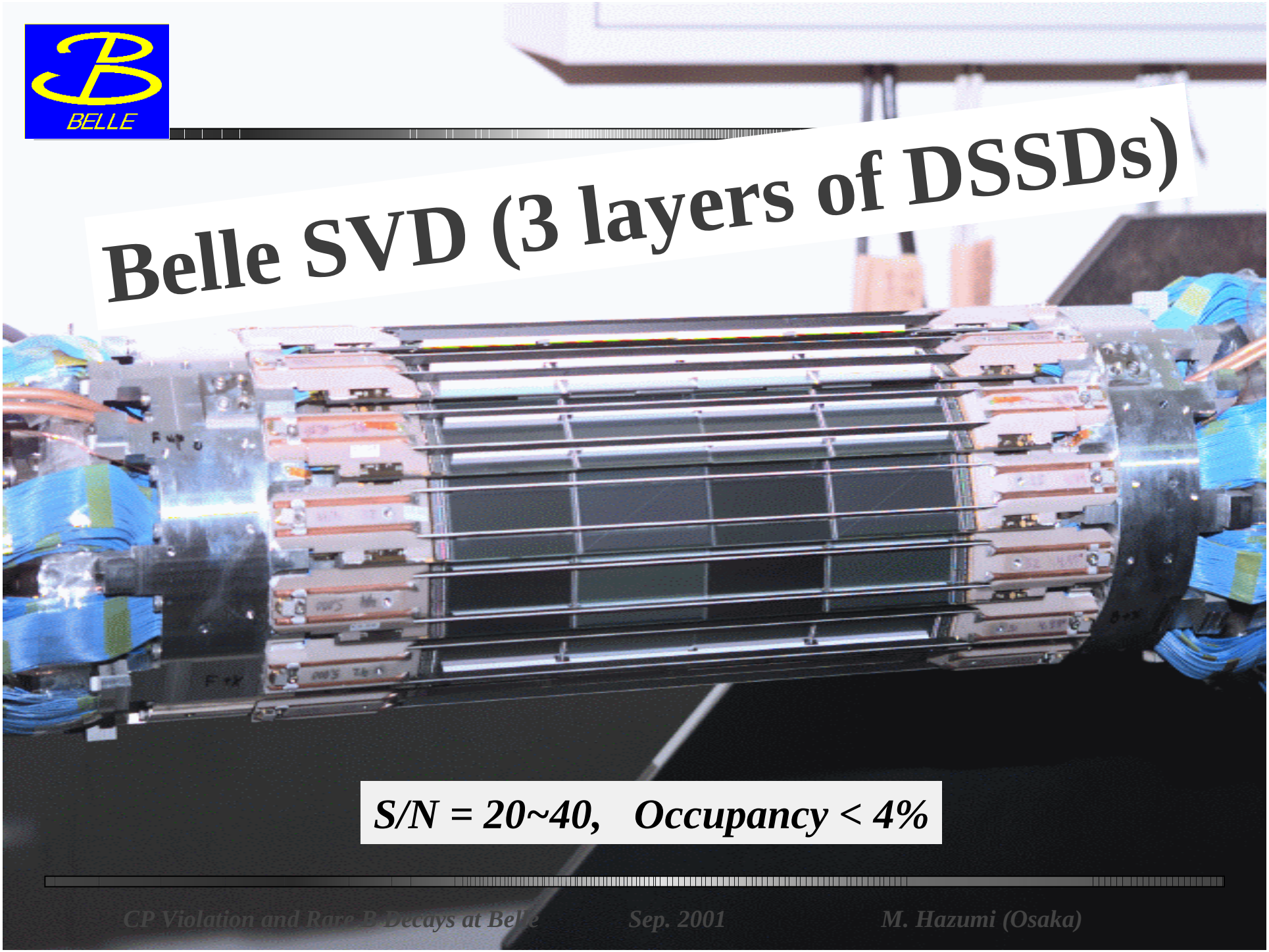
  - **No strong bending magnets near the IR**
  - **Fewer spent particles into *Belle***
  - **Synchrotron X-rays easily handled**

Belle Detector Performance

- Silicon Vertex Detector (SVD)
  - Impact parameter resolution : 55μm for p=1GeV/c at normal incidence
- Central Drift Chamber (CDC)
  - $(\sigma_{Pt}/Pt)^2 = (0.0019Pt)^2 + (0.0034)^2$ (Pt in GeV/c)^2
- K/π separation with
  - dE/dx in CDC ($\sigma_{dE/dx}$ =6.9%)
  - TOF (σ_{TOF} = 95ps)
  - Aerogel Cerenkov (ACC)
    - Efficiency = ~85%,
      Fake rate = ~10% up to 3.5GeV/c
- γ, $e^{\pm}$ with CsI crystals (ECL)
  - σ_E/E ~ 1.8% @ E=1GeV
  - $e^{\pm}$: effic. > 90% w/ ~0.3% fake for p > 1GeV/c
- K_L and $\mu^{\pm}$ with KLM (RPC chambers)
  - $\mu^{\pm}$: effic. > 90% with ~2% fake at p > 1GeV/c

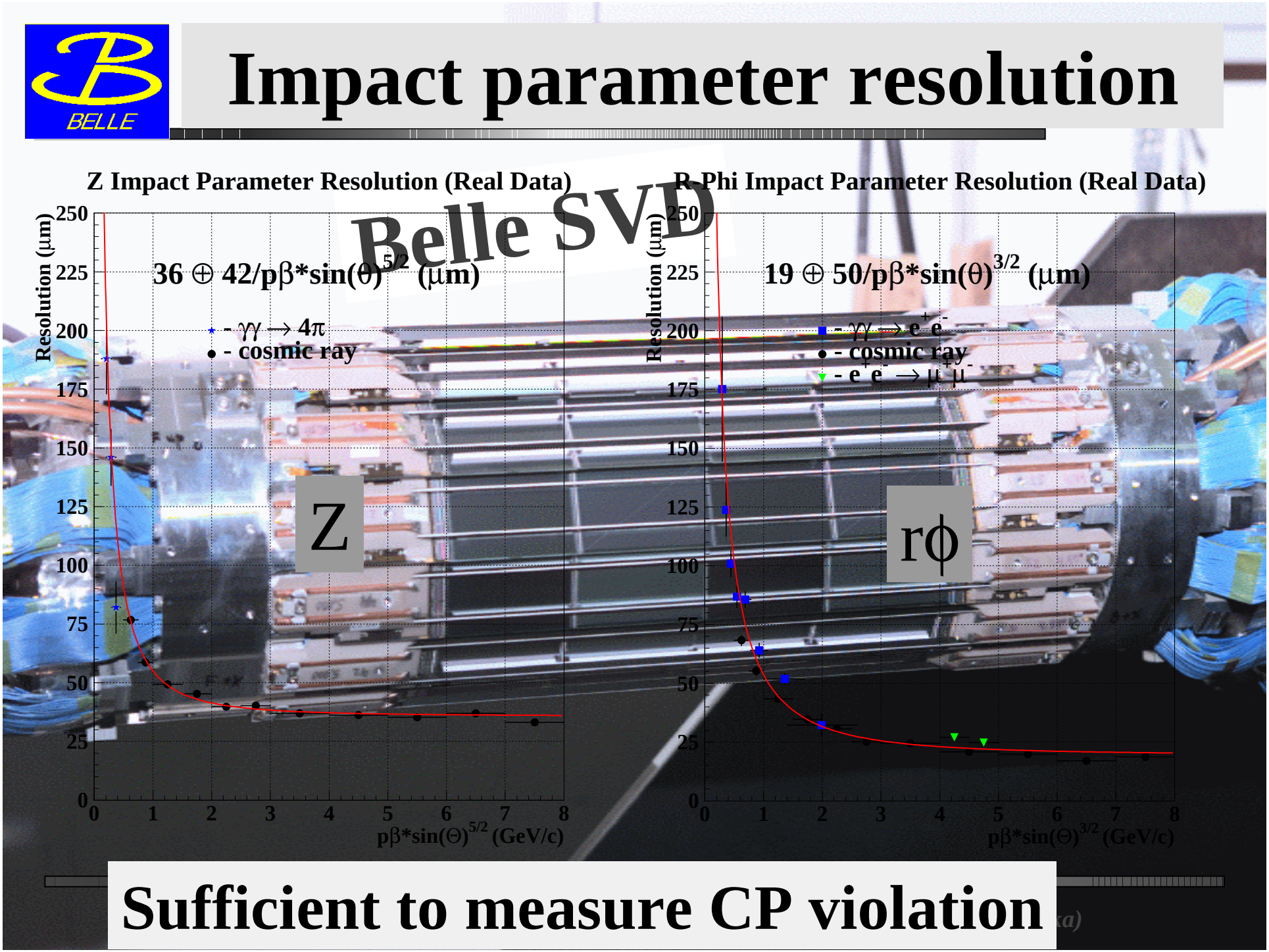


Belle SVD (3 layers of DSSDs)



S/N = 20~40, Occupancy < 4%

Impact parameter resolution



Sufficient to measure CP violation

- **Introduction**
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Summary of data samples

3 data sets were used:

Set 1: 10.5 fb^{-1} (June 1999-July 2000)

Set 2: 10.6 fb^{-1} (Oct 2000-May 2001)

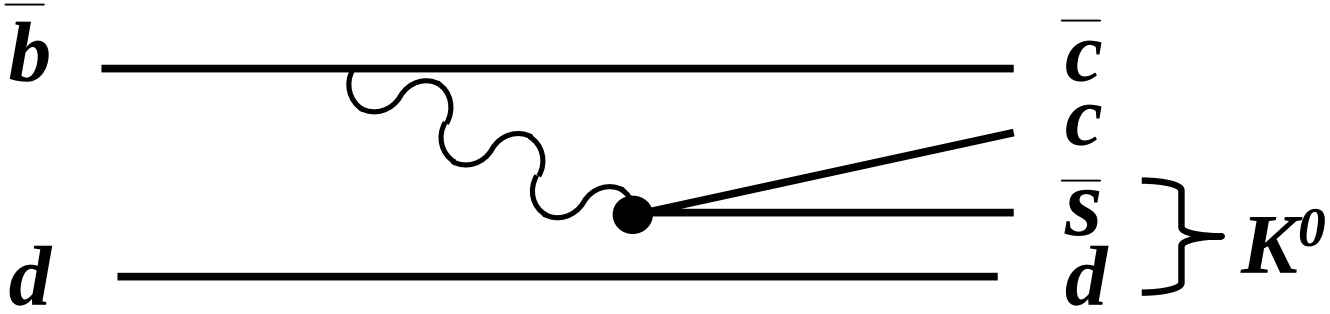
Set 3: 8.0 fb^{-1} (May 2001-July 2001)

Total: 29.1 fb^{-1} (corresponds to 31.3 million BBbar)

All data samples were analyzed and reconstructed with the same consistent procedure.

$B \rightarrow CP$ Eigenstate Decays

Use ~all low-background $c\bar{c}K^0$ modes



$B_{CP} \rightarrow J/\psi\, K_S(\rightarrow \pi^+\pi^- \,\&\, \pi^0\pi^0)$

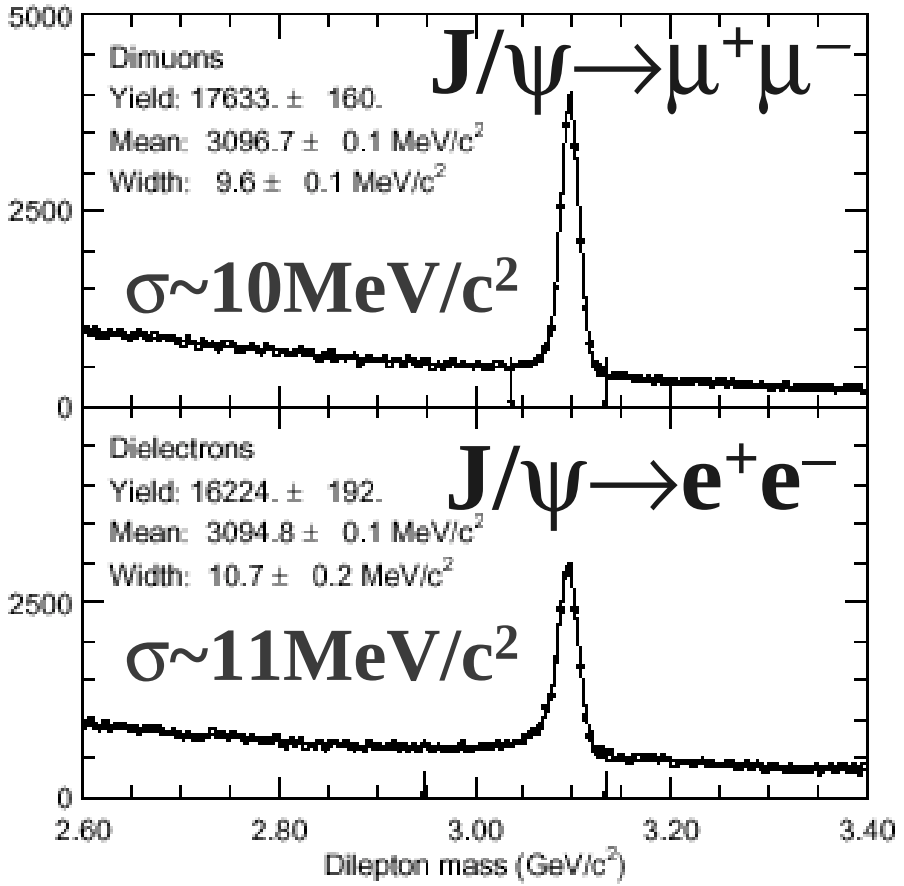
CP odd:
- $\psi(2S)(\rightarrow l^+l^- \,\&\, J/\psi\pi^+\pi^-)\, K_S$
- $\chi_{c1}(\rightarrow J/\psi\gamma)\, K_S$
- $\eta_c(\rightarrow K_S K^+\pi^-, K^+K^-\pi^0)\, K_S$

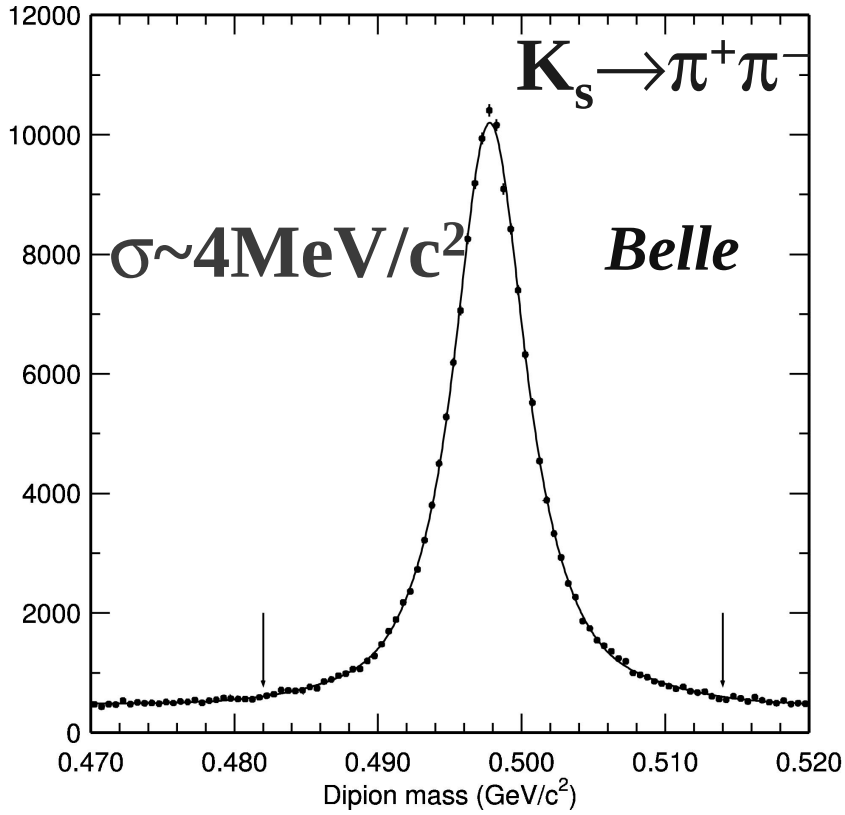
$\xi_f = -1$

CP even:
- $J/\psi\, K_L$
- $J/\psi\, K^{*0}\,(\rightarrow K_S\pi^0)$ (mostly)

$\xi_f = +1$

Golden mode: $B^0 \to J/\psi K_s(\to \pi^+\pi^-)$

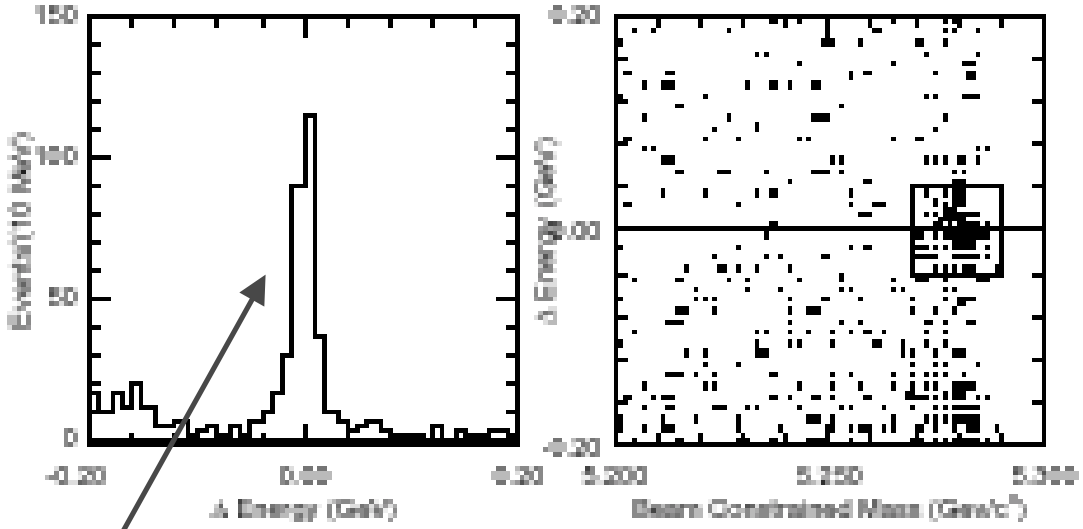




Biggest contributor to the f_{cp} event sample

$B^0 \to J/\psi\, K_S(\to\pi^+\pi^-)$ (cont'd)

457 events
~3% bkgd

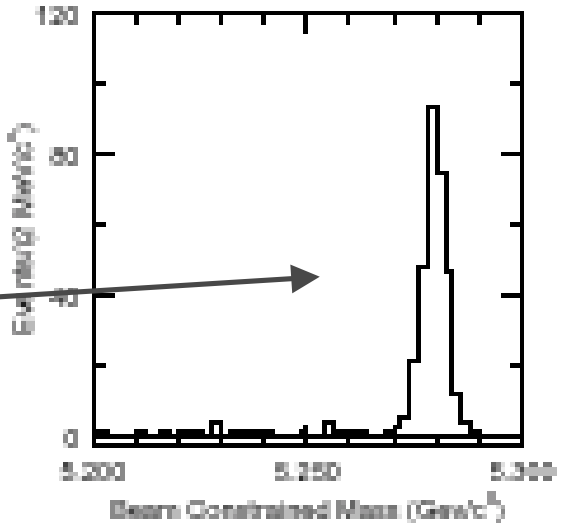


Energy difference:

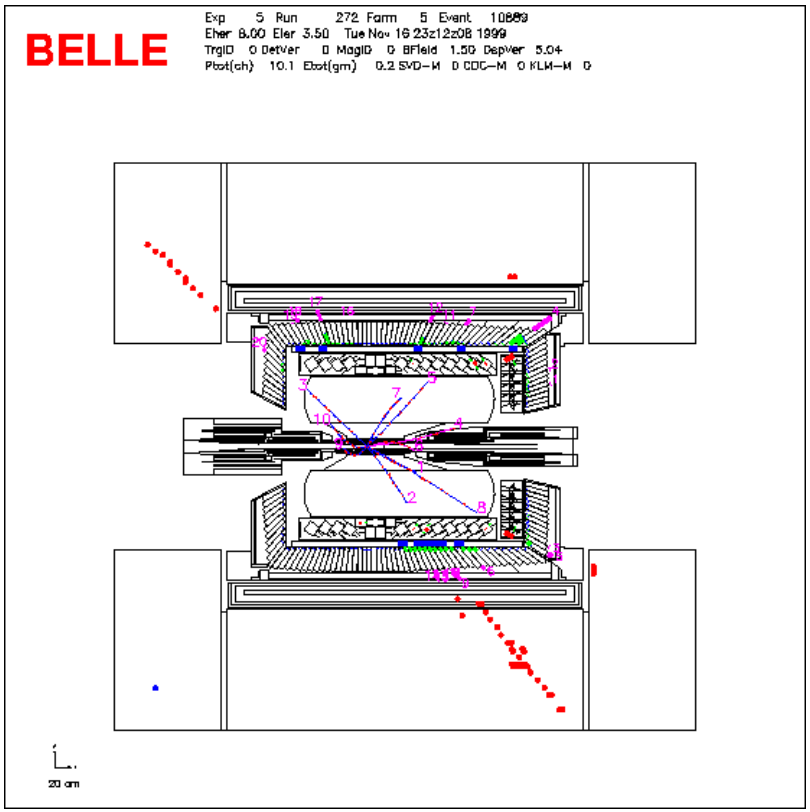
$$\Delta E \equiv E_{J/\psi} + E_{K_S} - E_{CM}/2$$

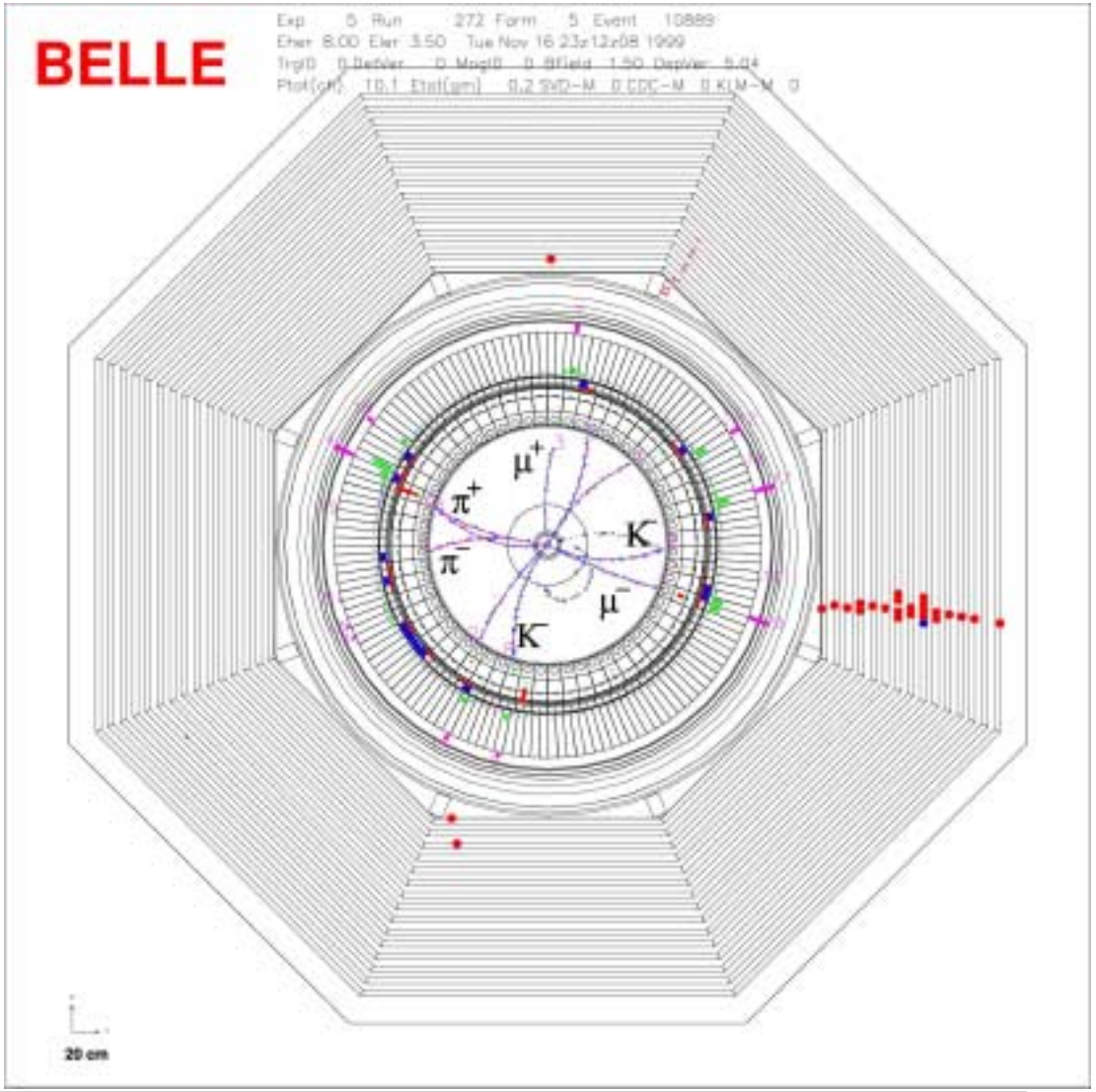
Beam-constrained mass:

$$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$



$B^0 \to J/\psi\, Ks(\to \pi^+\pi^-)$ Event Display





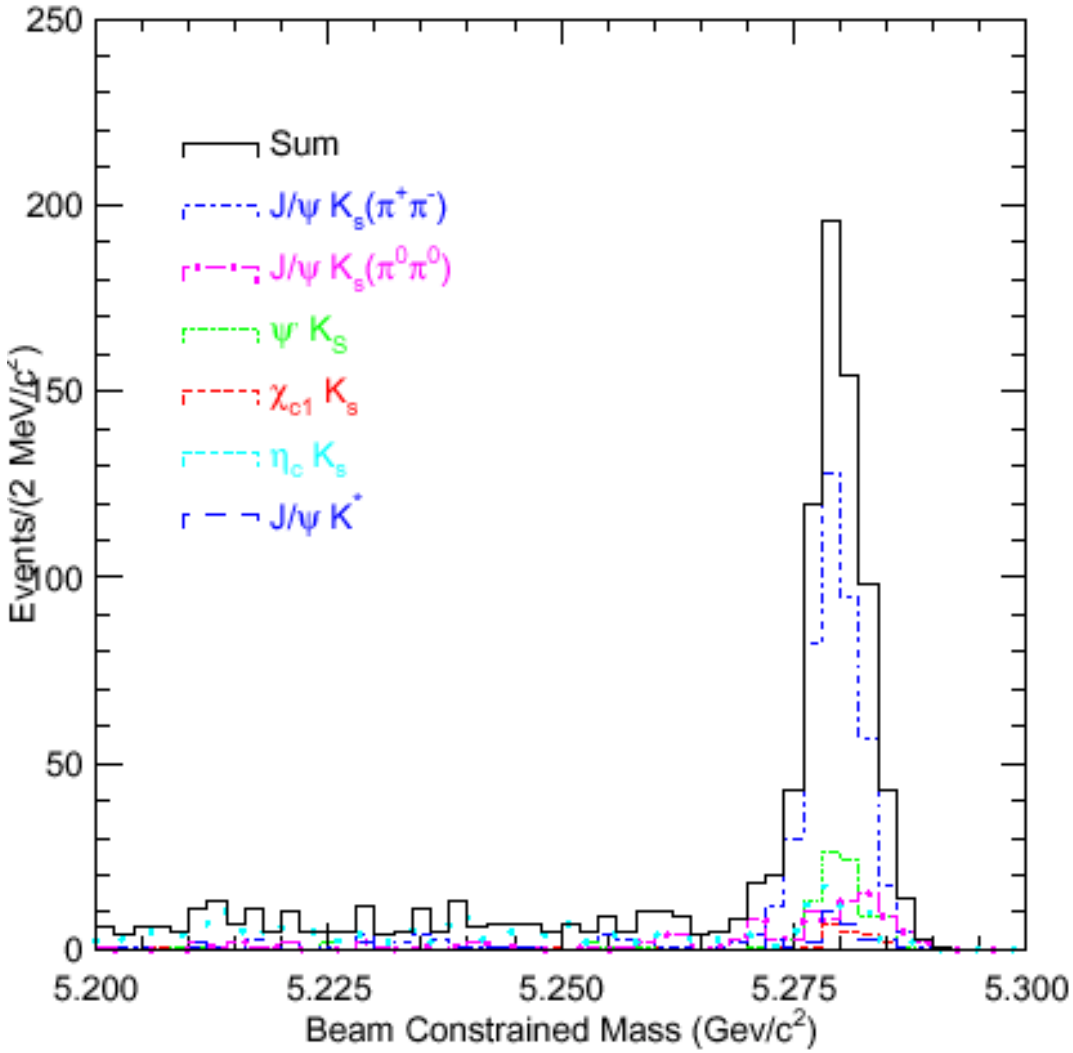
All except $J/\psi K_L$

$B^0 \to J/\psi$ Ks($\to \pi^+\pi^-$)

457 candidates
~12 background
(Purity = 97%)

$B^0 \to$ other modes

290 candidates
46 background
(Purity = 84%)



$B^0 \rightarrow J/\psi\, K_L$

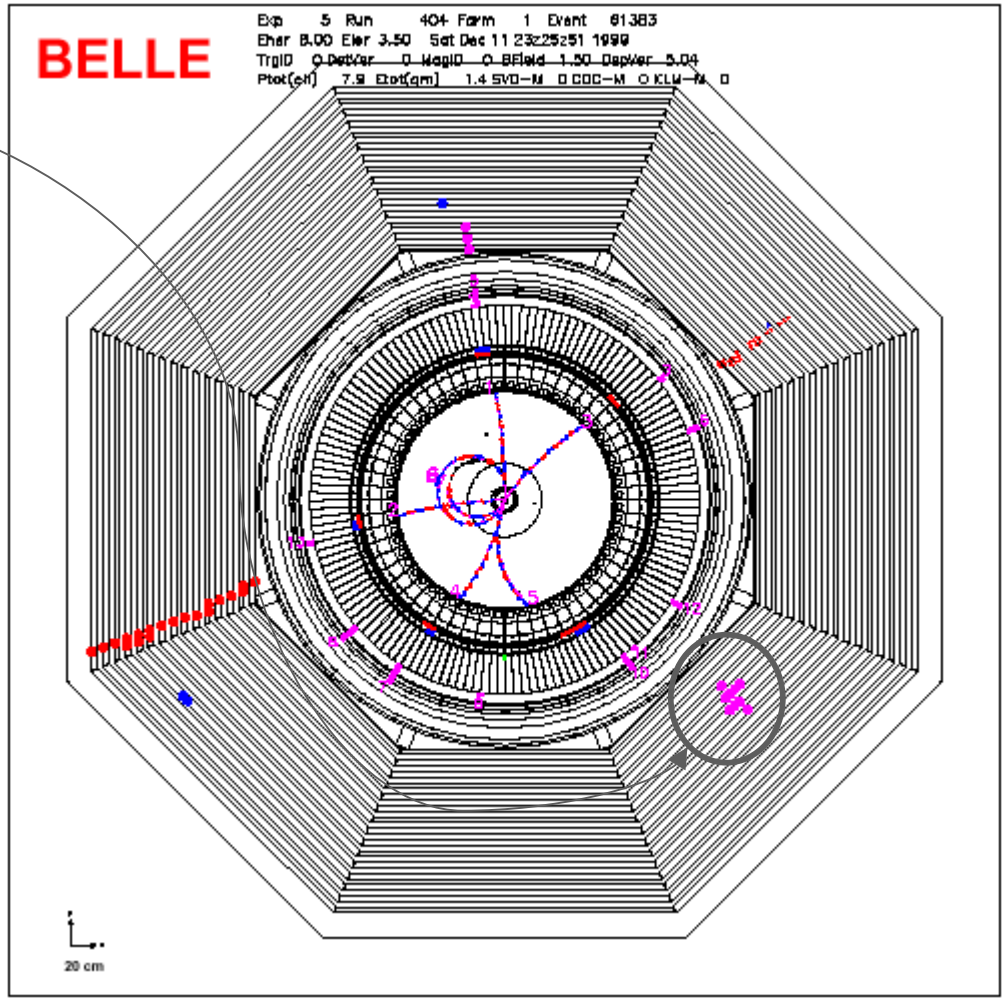
- $J/\psi \rightarrow l^+l^-$ + K_L

2) Assume $B \rightarrow J/\psi\, K_L$: compute $\vec{P}_{KL}$

3) Remove reconstructed $B \rightarrow J/\psi\, K$, $J/\psi\, K^*$, …

4) Cut on a likelihood based on kinematical and shape quantities

5) Plot $P^*_B = |\vec{P}_{J/\psi} + \vec{P}_{KL}|$

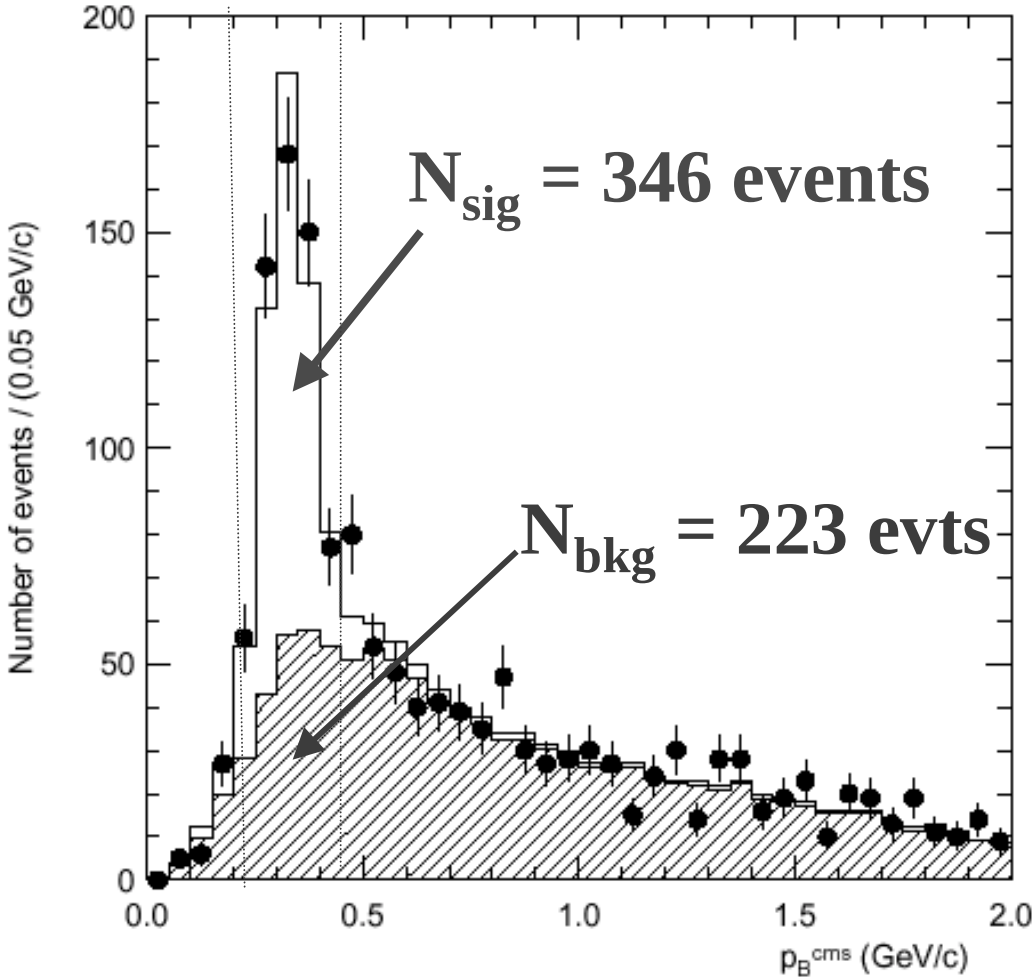


$B^0 \to J/\psi\, K_L$ signal yield

$$P_B^* = |\vec{P}^*_{J/\psi} + \vec{P}^*_{KL}|$$

$B^0 \to J/\psi\, K_L$

569 total events
346 signal
(Purity = 61%)



P_B(cms)

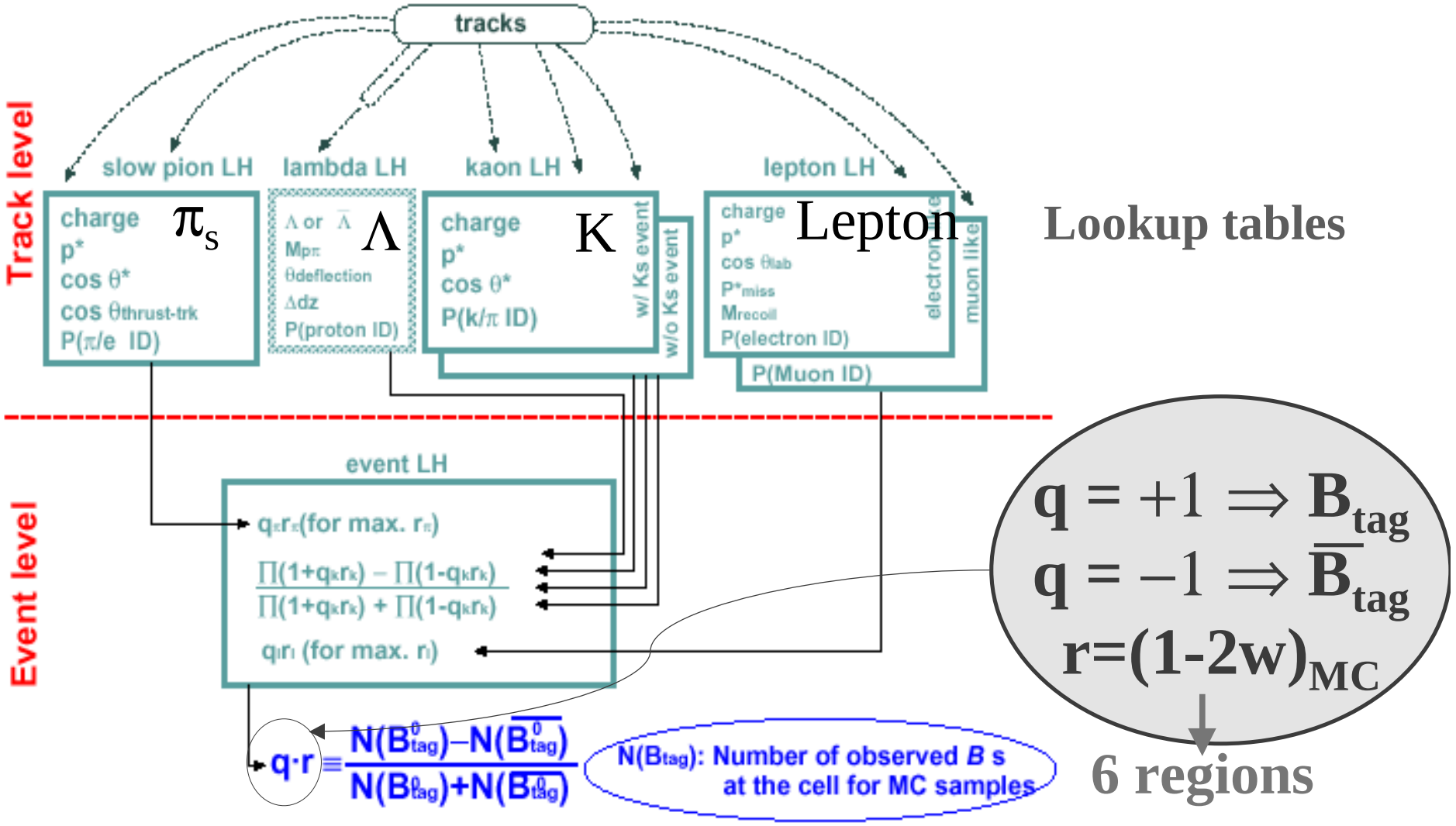
Flavor-tag the other B meson

Use *inclusive* flavor-specific properties:

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

Also include *correlations*

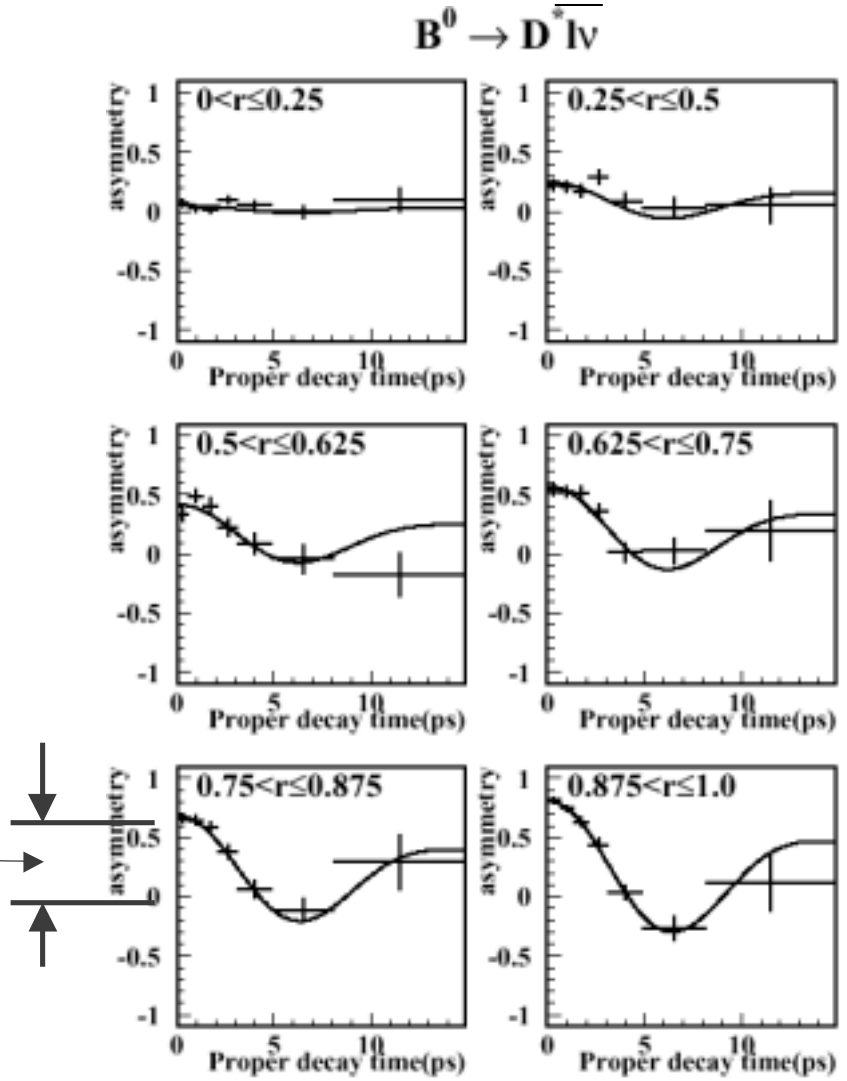
2-level Multi-dimensional Flavor Tagging



Determination of wrong tag fraction w_l

obtain w from $B \Leftrightarrow \bar{B}$ mixing amplitude:

$(1-2w_l)\cos(\Delta m_d \Delta t)$

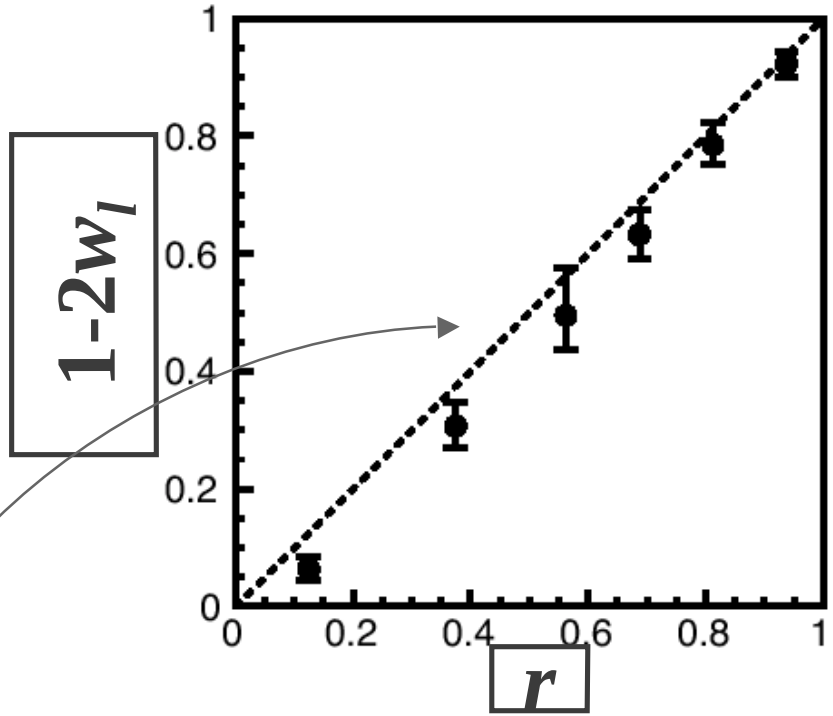


Dilution : Measured vs. Expected

- **Uses all events**
  - **Efficiency > 99%**

$$\varepsilon_{\text{effective}} = 27.0 \pm 1.2\%$$

- **Includes correlations**
- **Use MC-*r* as a classifier**
- **Use data-*w* for CP fits**



MC-determined $r \approx 1\text{-}2w$ measured from data

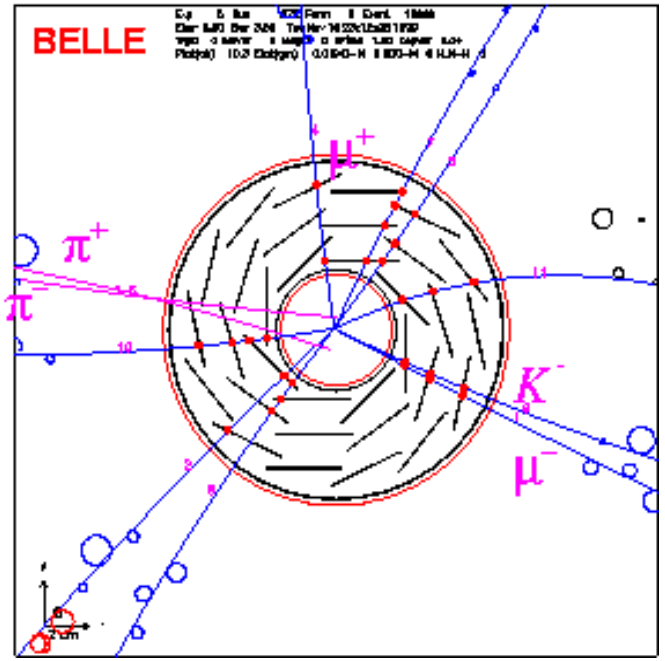
Vertex Reconstruction

- **For *CP*-side, use $J/\psi \rightarrow l^+l^-$**
  - **Reject poorly fit events.**

    $\delta z_{CP} \approx 75\ \mu m$ **(rms)**
- **For *Tag*-side**
  - **use well fit tracks**
  - **iterate: discard worst track**
  - $\delta z_{tag} \approx 140\ \mu m$ **(rms)**
- **Require $|z_{CP} - z_{tag}| < 2mm\ (\approx 10\,\tau_B)$**

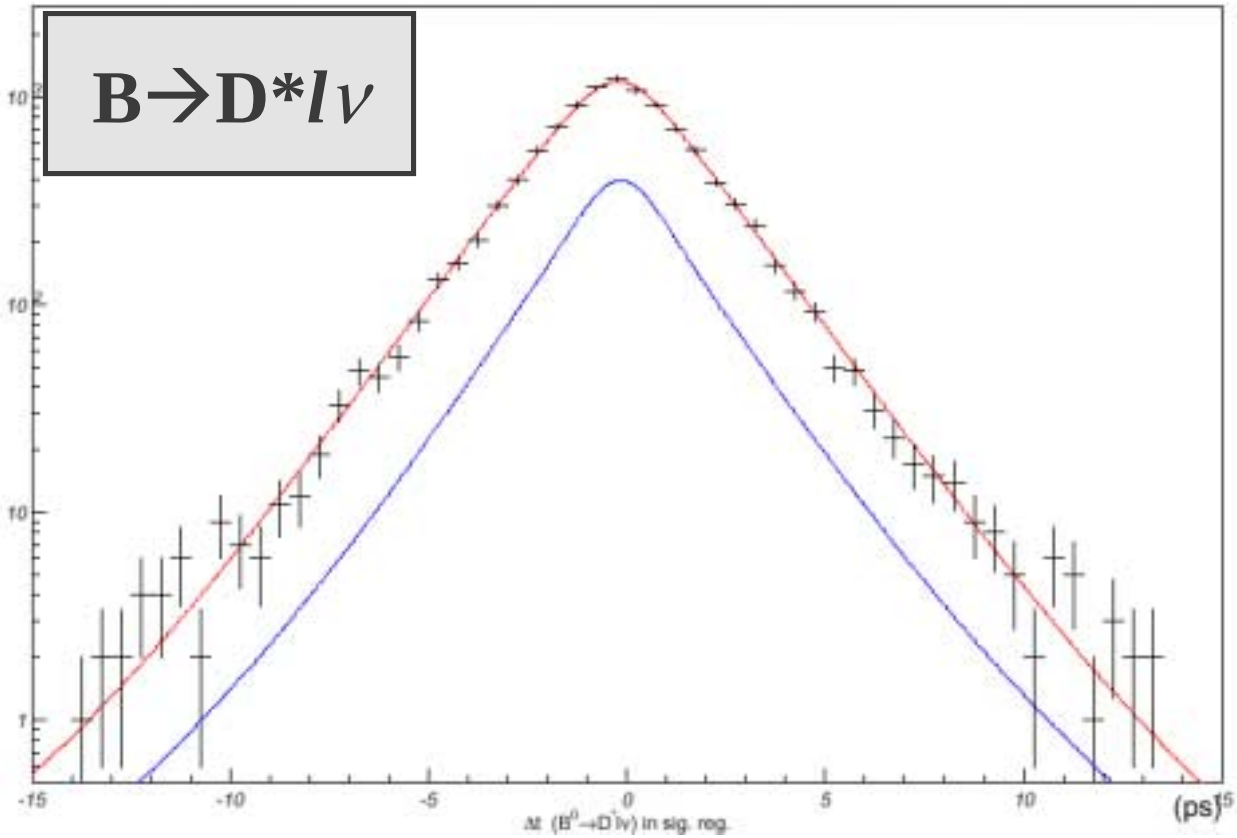
$\sigma_{\Delta t} \approx 1.5$ **ps**

- **Tails ≈ 3%; Effic. ≈ 85%**



1137 evts used in the CP fit.

Validation: B lifetimes



$\tau_{B0} = 1.55 \pm 0.02$ps $\quad\quad$ $\tau_{B+} = 1.64 \pm 0.03$ps

PDG: 1.55 ± 0.03ps $\quad\quad$ PDG: 1.65 ± 0.03ps

Summary so far

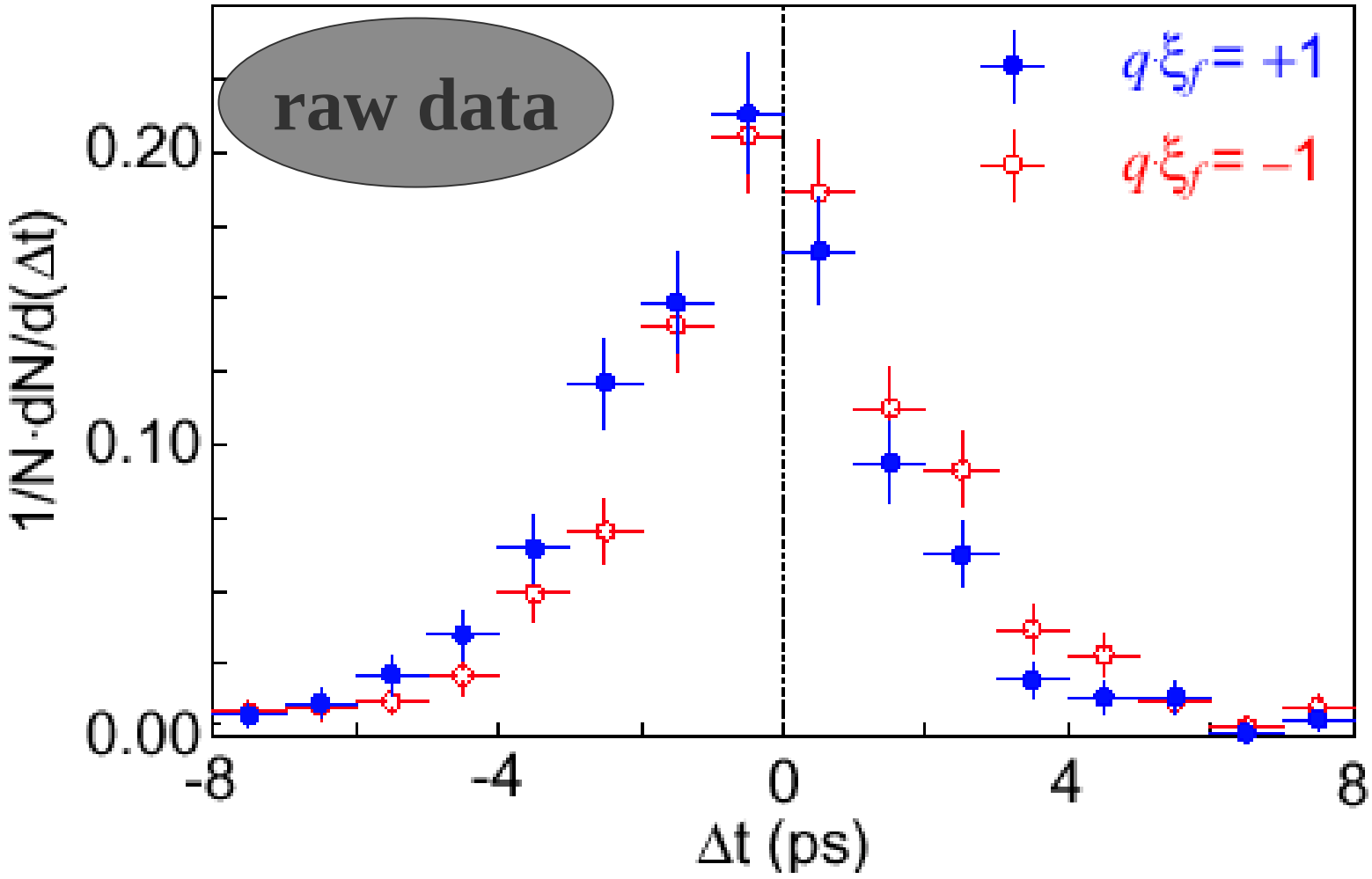
- CP eigenstates with high purity.
  - Purity ~ 90% except for $J/\psi K_L$ (~60% for $J/\psi K_L$ **)**
- Efficient flavor tagging.
  - Effective efficiency = 27.0%
- Efficient vertexing with good resolution

1137 candidate events

- B lifetime measured precisely (high stat. control sample)

Everything is ready. Now let's open the box !

Combine q, ξ_f & Δt



CP is violated in B decays

- **Large effect**
- **Apparent even in the raw data**

Event-by-event Likelihood

$$L_i = \int ((1 - f_{bk}) P_{sig}(\Delta t') \otimes R_{sig}(\Delta t - \Delta t')$$
$$+ f_{bk} P_{bk}(\Delta t') \otimes R_{bk}(\Delta t - \Delta t')) d\Delta t'$$

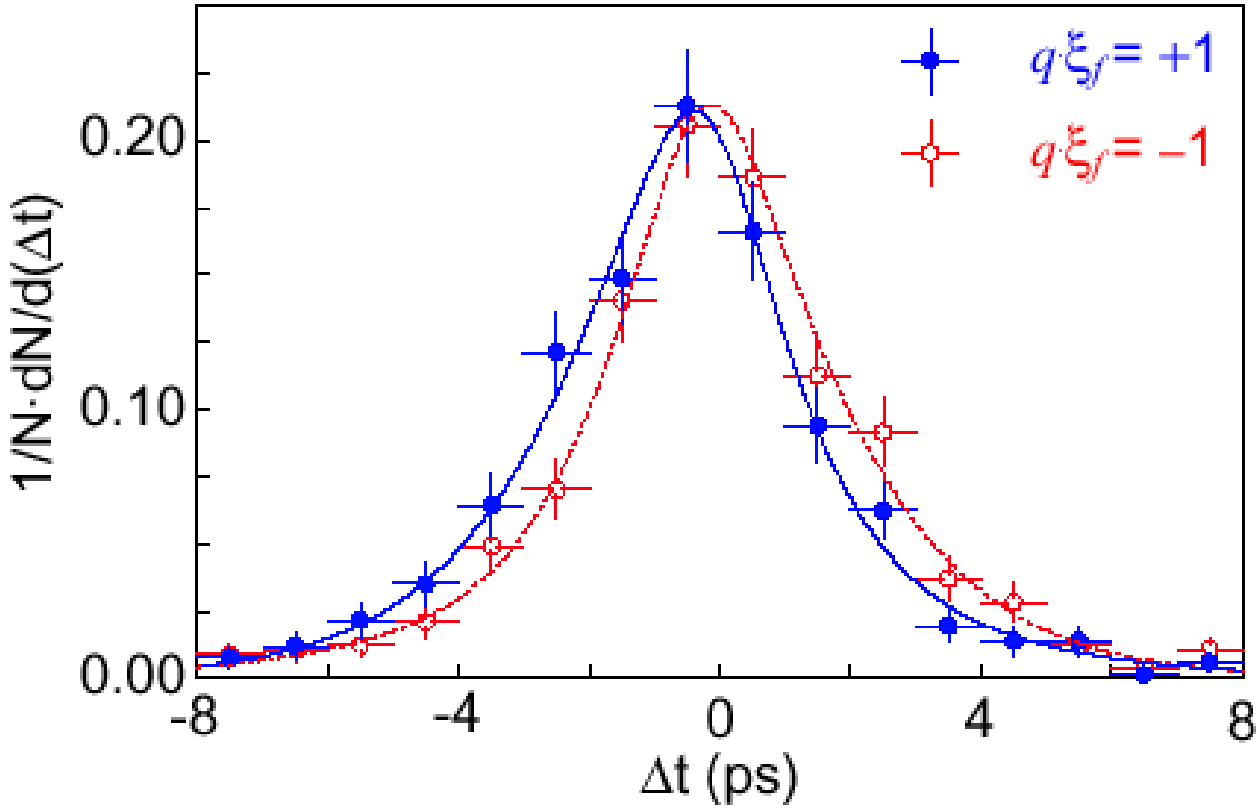
Taken from data

$$P_{sig}(\Delta t) = \frac{1}{2\tau_B} e^{-|\Delta t|/\tau_B} (1 - \xi_f q (1 - 2w)$$
$$\times \sin(2\phi_1) \sin(\Delta m_d \Delta t))$$

$$P_{bk}(\Delta t) = f_\tau e^{-|\Delta t|/\tau_{bkg}} / 2\tau_{bkg} + (1 - f_\tau)\delta(\Delta t)$$

$\sin 2\phi_1$ value that maximizes $\Pi_i L_i$

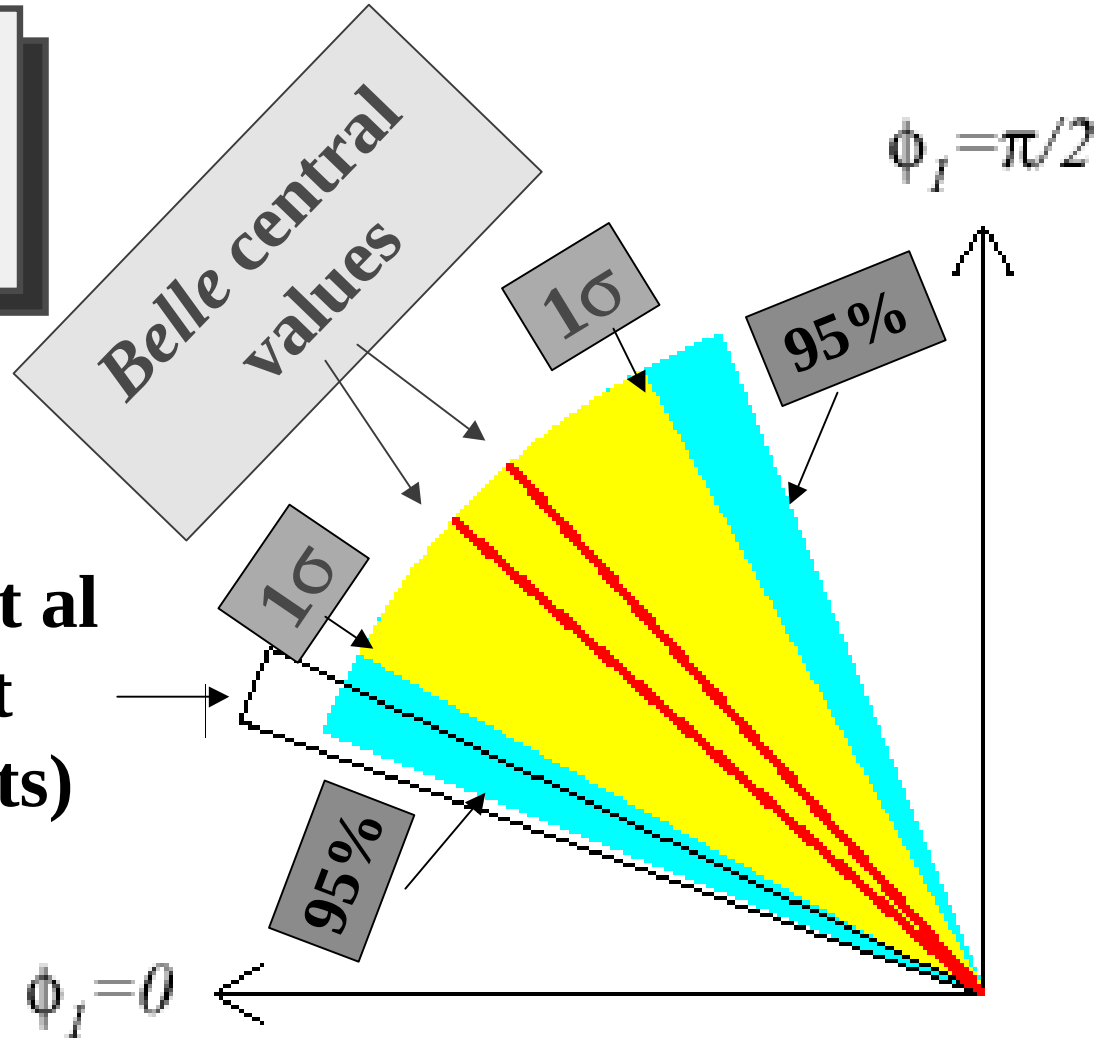
$$\sin 2\phi_1 = 0.99 \pm 0.14\ (\text{stat}) \pm 0.06(\text{sys})$$



curves from unbinned fit

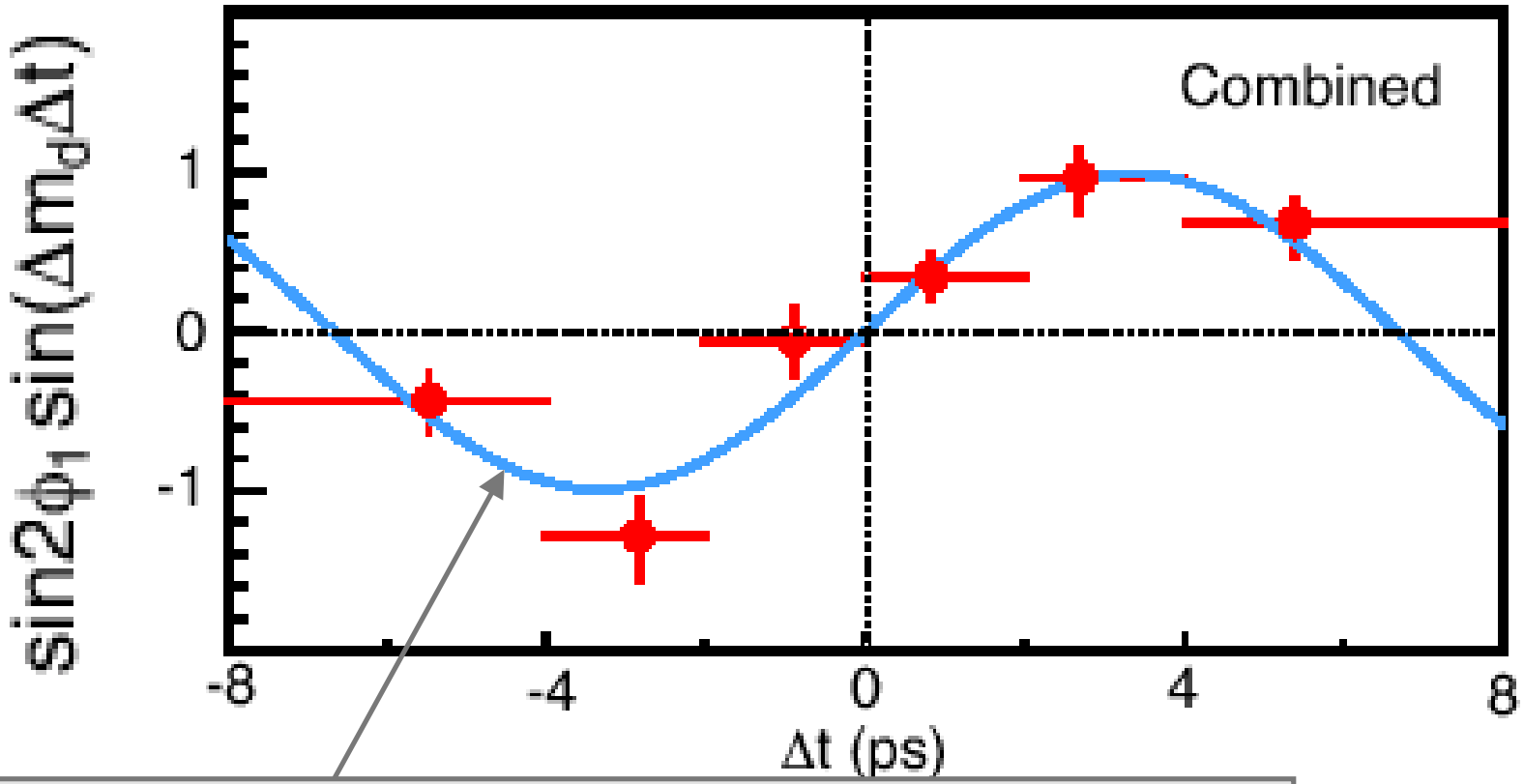
Confidence intervals

$$1 \geq \sin 2\phi_1 \geq 0.70$$
(95% C.L.)



Ciuchini et al (indirect constraints)

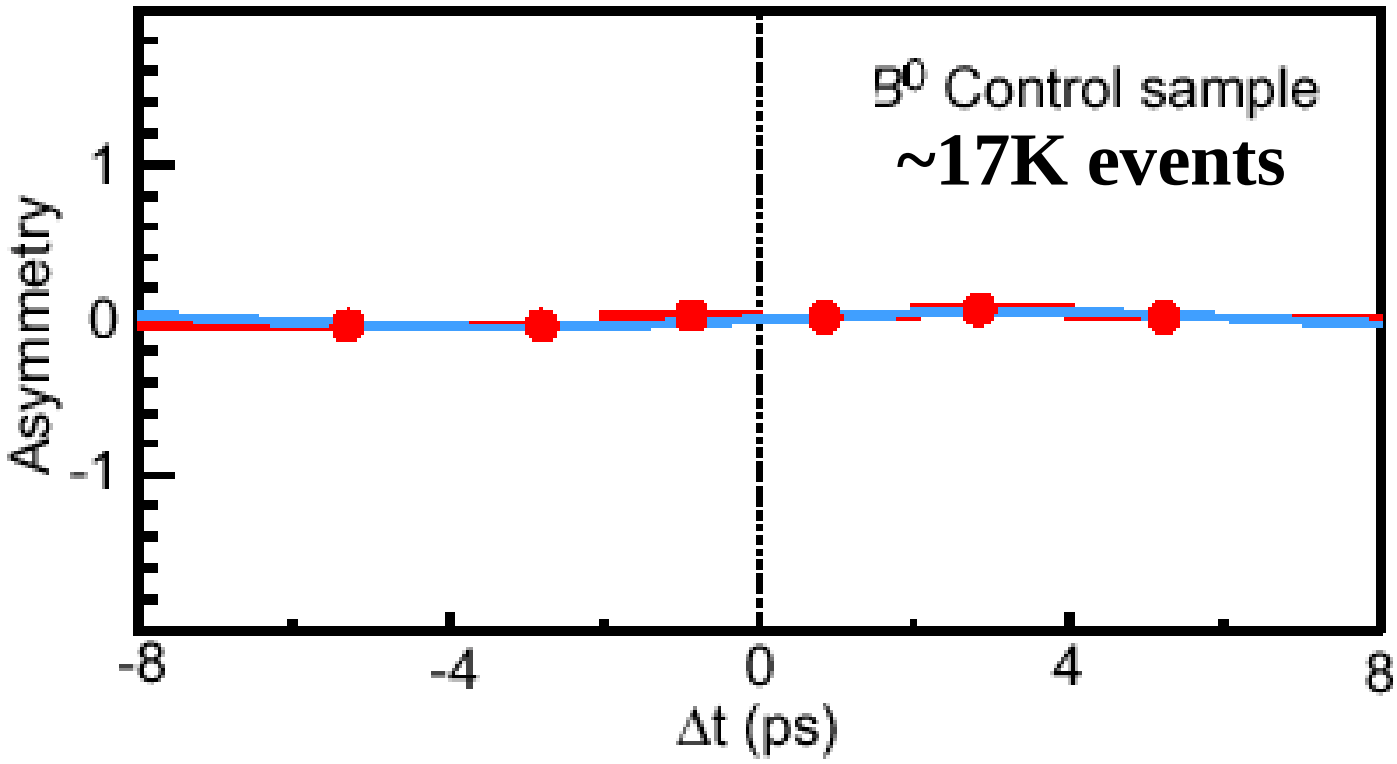
asymmetry plot: all data



Result from global fit ($\sin 2\phi_1 = 0.99$)

Control sample: $B^0 \rightarrow$ non-CP states

use: $B^0 \rightarrow D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $D^{*-}l^+\nu$, $J/\psi K^*(K^+\pi^-)$

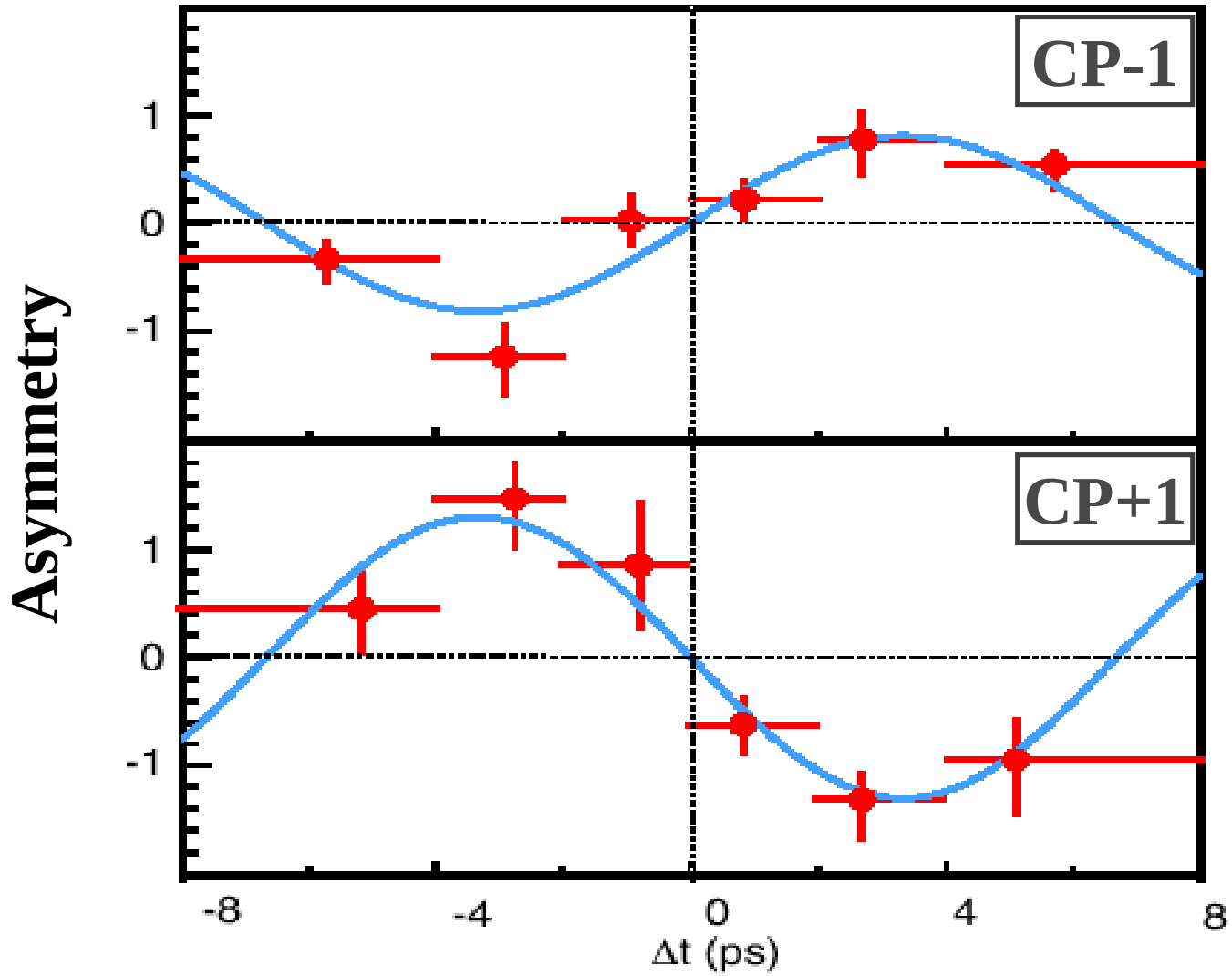


"$\sin 2\phi_1$"

0.05 ± 0.04

(statistical error only)

Compare CP –1 and CP+1



$\sin 2\phi_1$

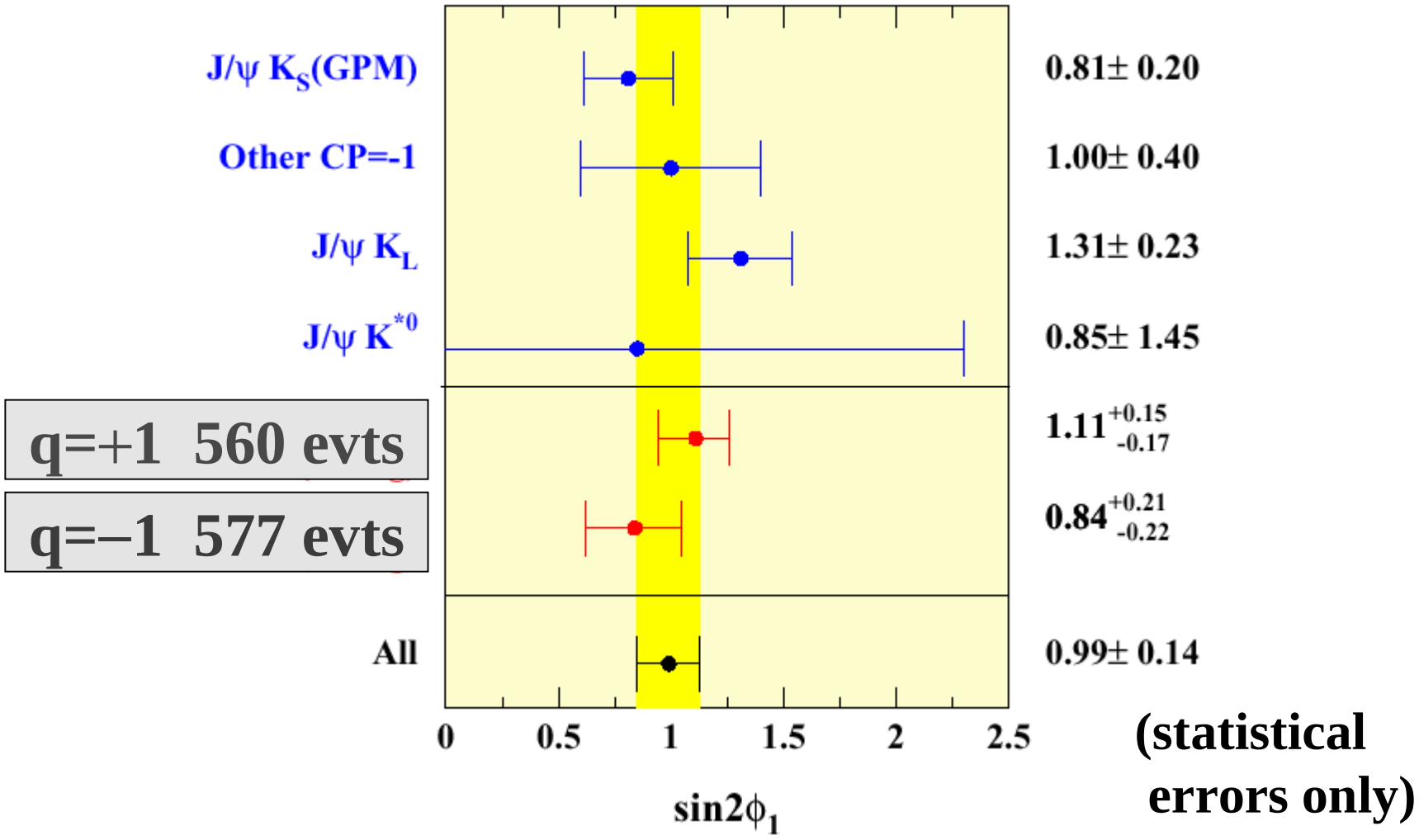
0.84±0.17

opposite!

1.31±0.23

(statistical errors only)

$sin2\phi_1$ from various subsamples



(statistical errors only)

Test of Direct CP Term

If |?| is allowed to float, (i.e. a cos(?m t) term)

$$|\lambda| = 1.03 \pm 0.09$$

$$\sin 2\phi_1 = 0.99 \pm 0.14$$

The CPV asymmetry is unchanged.

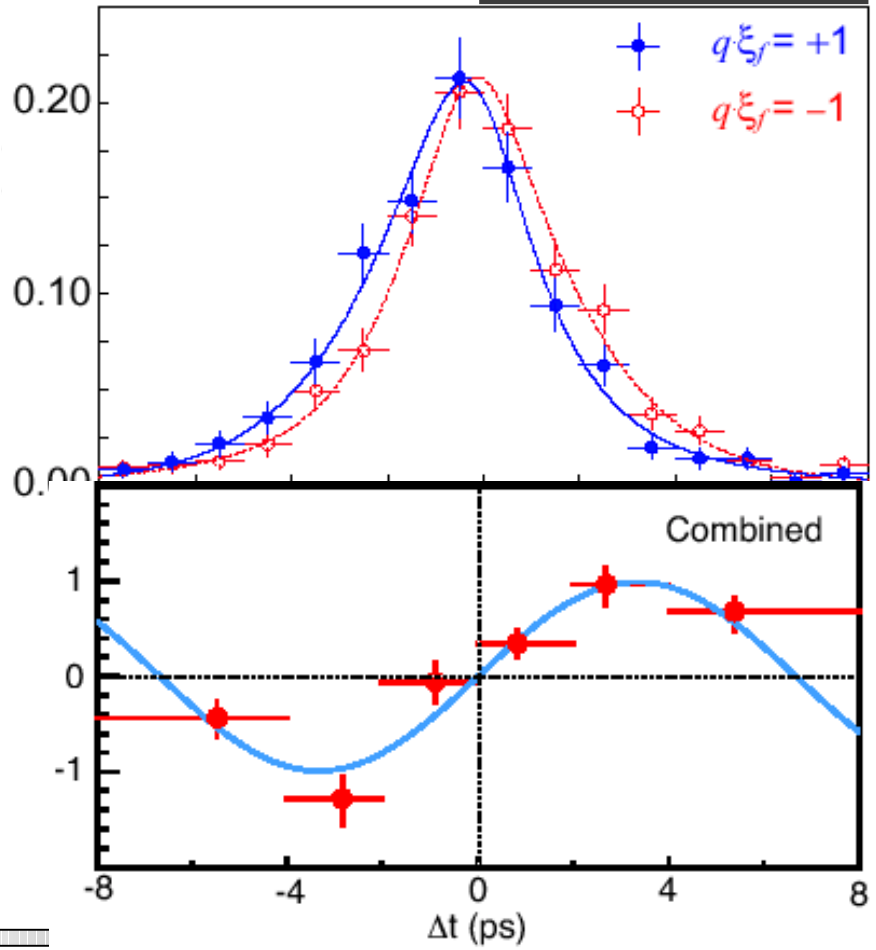
CP fit : Systematic Error

Vertex algorithm	±0.04
Flavor tagging	±0.03
Resolution function	±0.02
K_L background fraction	±0.02
Background shapes	±0.01
Δm_d and τ_{B0} errors	±0.01
Total	±0.06

Conclusions on CPV

- **CP is violated in B decay** **>6σ!!**
- **sin $2\phi_1$ is large:**

$$0.99 \pm 0.14 \pm 0.06$$



- **Introduction**
- **KEKB Accelerator and Belle Detector**
- **Observation of Large CP Violation**
- **Rare B Decays**
- **Conclusions**

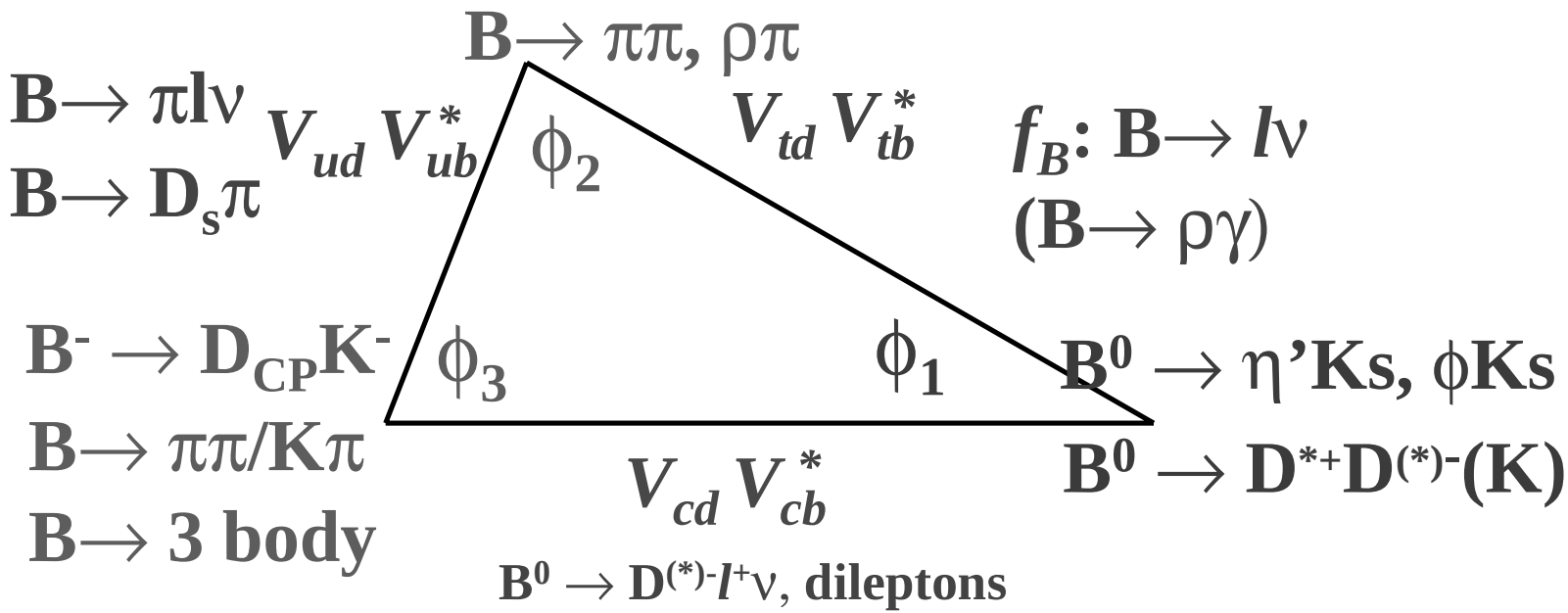
Goals of Rare B Decay Program

1) Discover / Establish "Direct" CPV

2) Precise Measurements of CKM elements :

→ ***angles*** **and** ***lengths***

3) ***Beyond SM***



EM/EW Penguin : B→ $K_x\gamma$, B→Kl^+l^-

Belle 2001 Summer Results

(2001 Lepton-Photon Conferences)

In addition to the observation of large CPV,

35 contributed papers

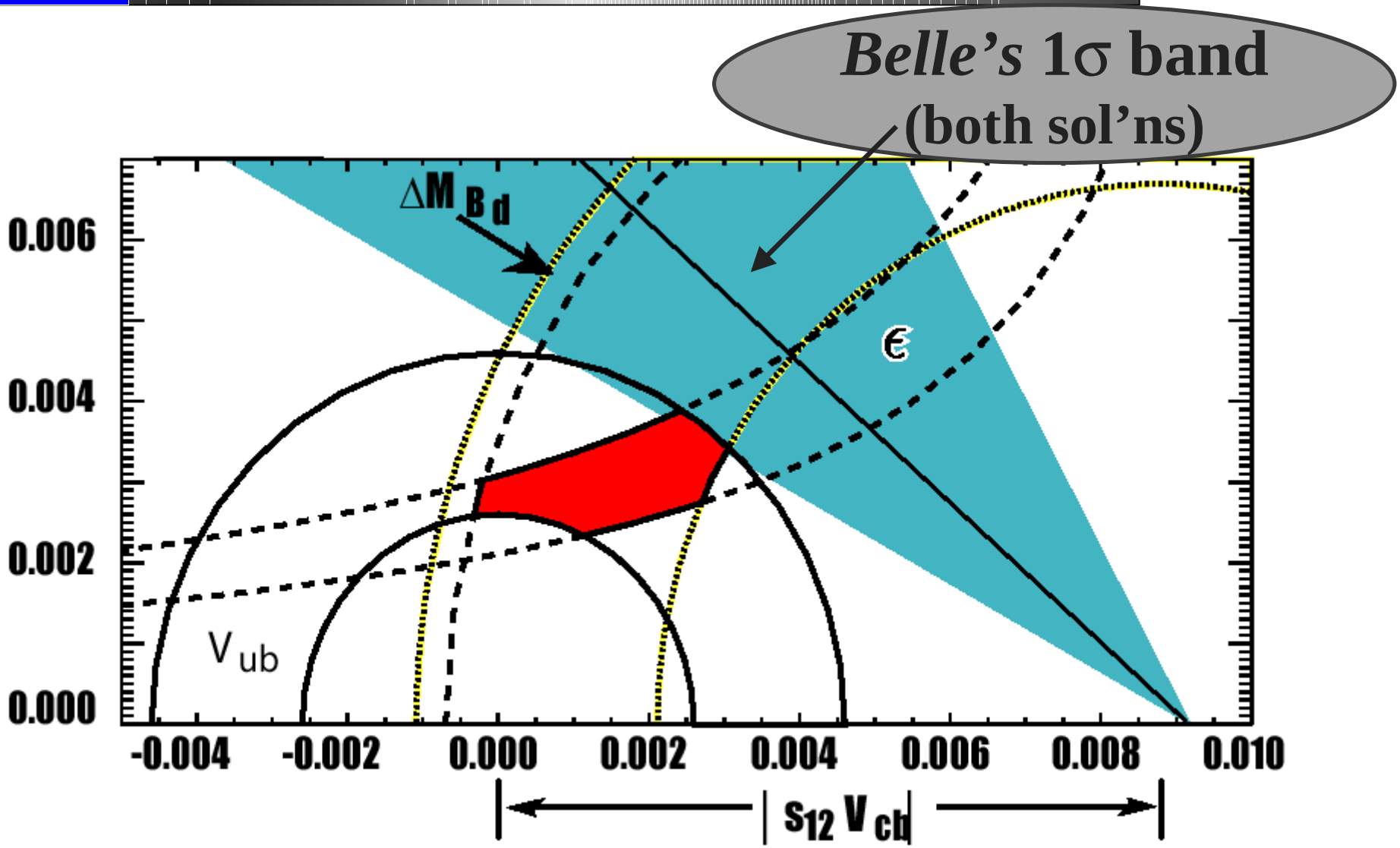
(5 charm, 3 τ, 2 two-γ physics)

[4 final results - sent to journal]

14 First Observations !

[see Web: http://belle.kek.jp/conferences/LP01-EPS
for the datails of analyses and results]

Importance of Vub Measurement



Towards $|V_{ub}|$: $B^0 \to \pi l^+ \nu$

Important to check large $\sin 2\phi_1$

update 21.3 fb^{-1}

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

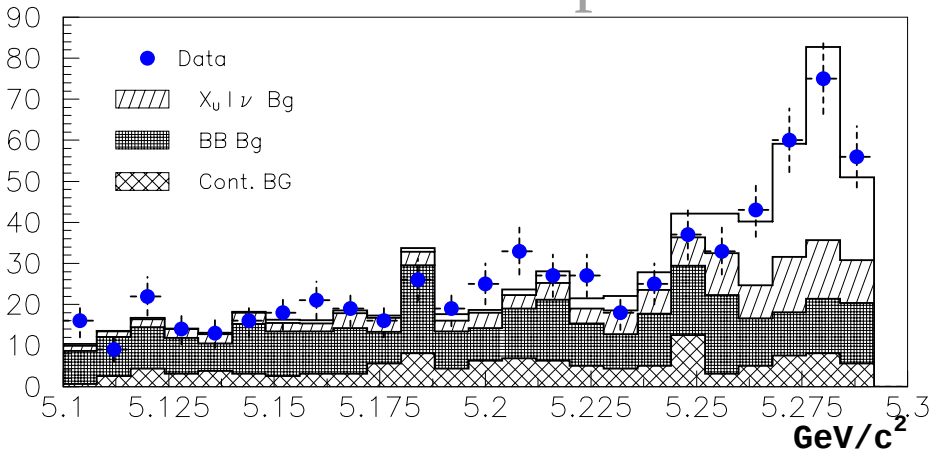
Missing mass recon.

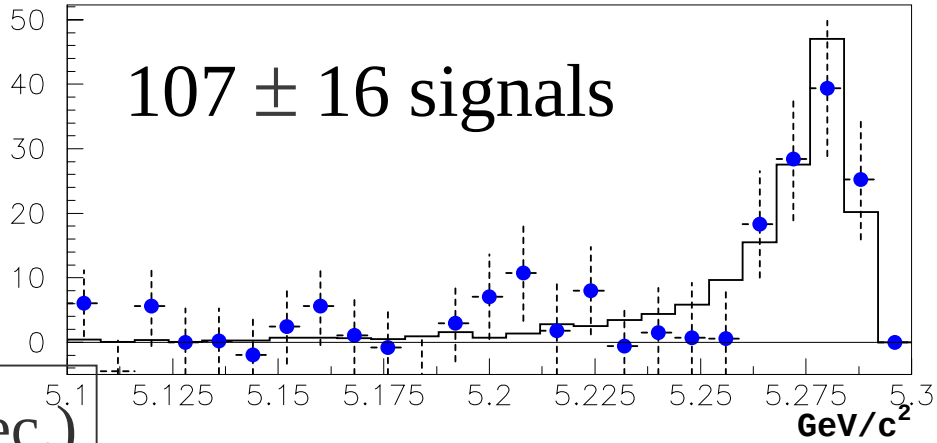
$M_{miss}^2 = E_{miss}^2 - p_{miss}^2$

< 2 GeV

$p_l > 1.2$ GeV

$p_l + p_\pi > 3.1$ GeV

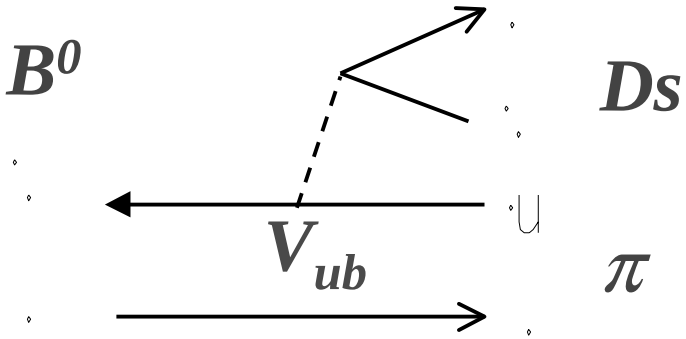




Br = $(1.28 \pm 0.2 \pm 0.26) \times 10^{-4}$

ε(trk/g rec.)

Towards $|V_{ub}|$: $B^0 \to Ds\ \pi$



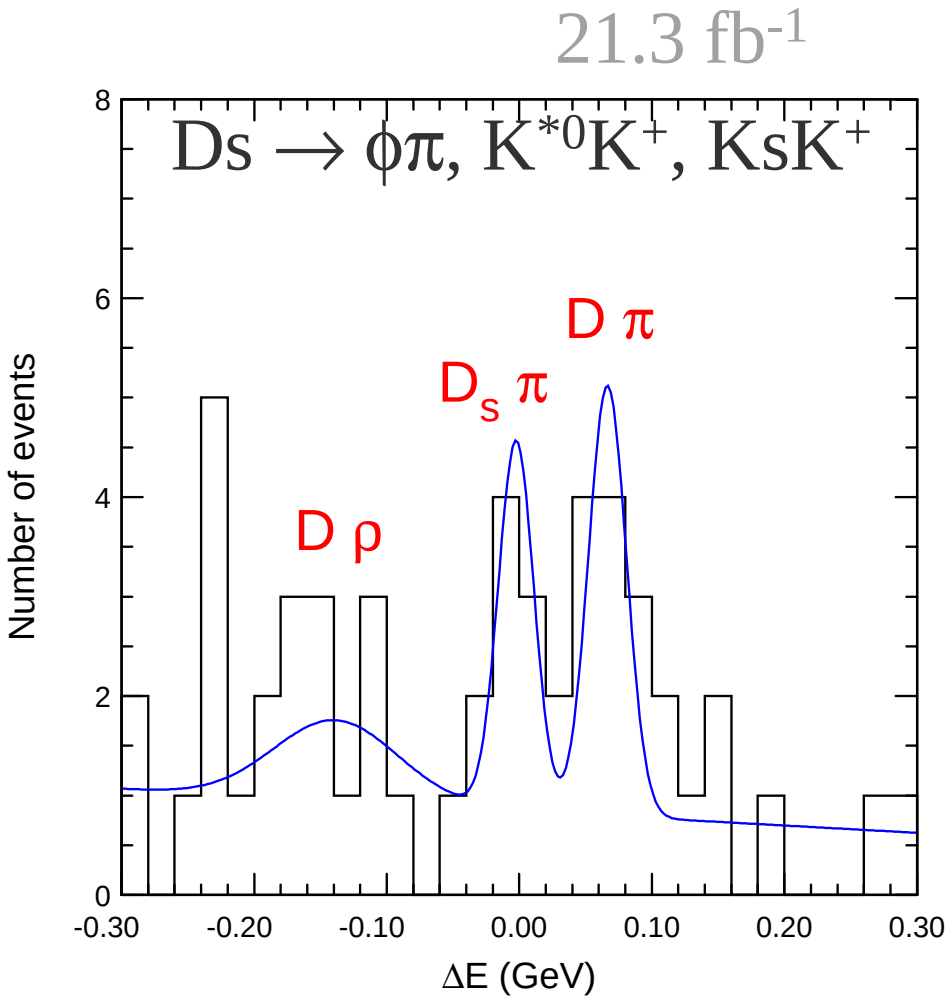
Tree dominant
(No Penguin)

6.3 ± 3 evens

Br < 1.1 x10^{-4}

(CLEO:< 2.7 x10^{-4})

About to see signal !



Towards ϕ_3 : $B^- \to D_{CP}K^-$

1) $B^- \to D^0K$ (ICHEP2000) [PRL]

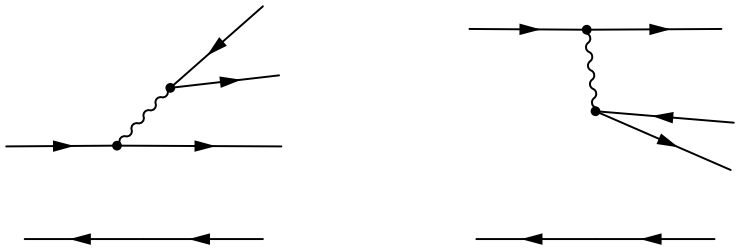
First Observation 21.3 fb^{-1}

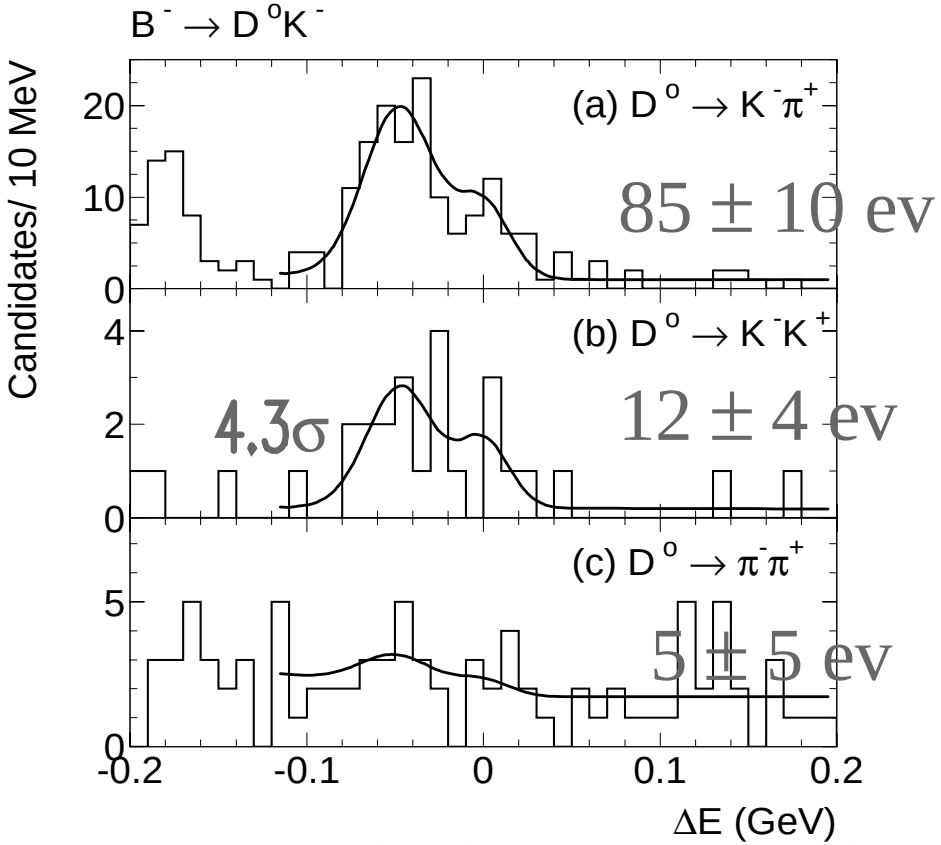
2) $B \to D_{CP}K$ decay

$D_{CP} \to K^+K^-, \pi^+\pi^-$

(Br ~ 1%)

$D_{CP} = (D^0 + \bar{D}^0)/\sqrt{2}$



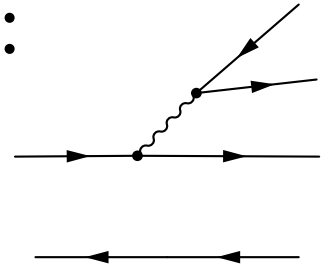


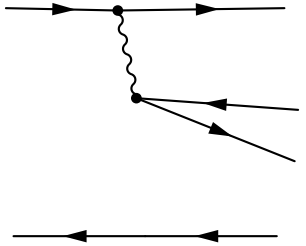
$$\frac{Br(B^- \to D_{CP}K^-) - Br(B^+ \to D_{CP}K^+)}{Br(B^- \to D_{CP}K^-) + Br(B^+ \to D_{CP}K^+)} = 0.04 \,{}^{+0.40}_{-0.35}(stat) \pm 0.15(syst)$$

$D^{(*)0}X^0$ decays : First Observation

Color suppressed modes:

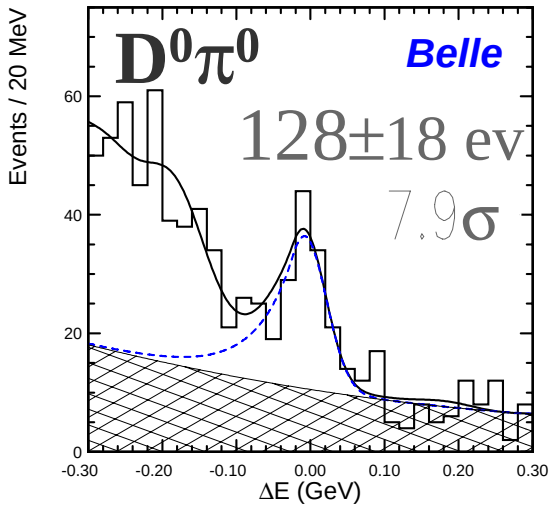
~0.1x Non-suppr. mode

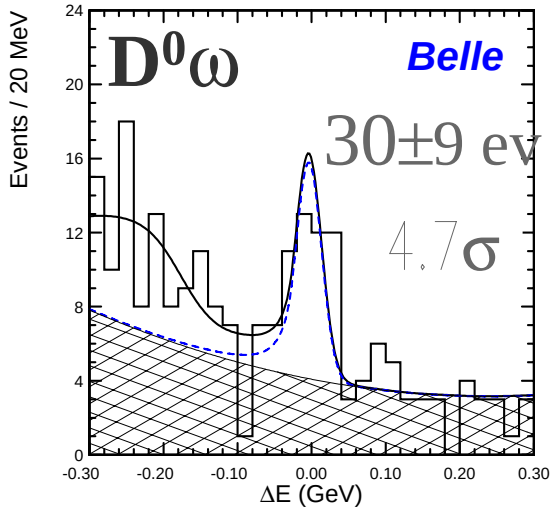


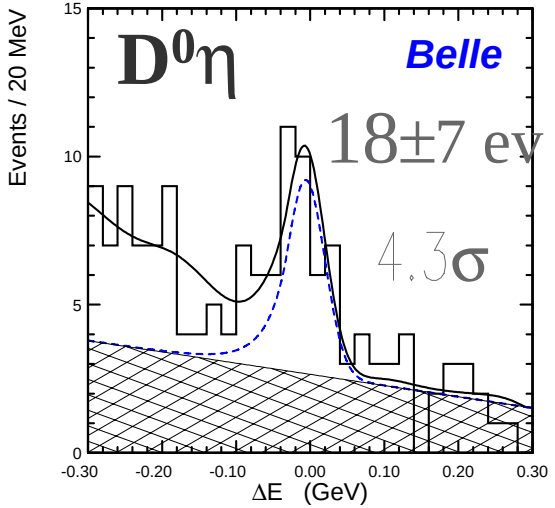


Step towards $\bar{D}^0K/DKs$

Br = 2.9 ±0.4±0.6 | 1.7 ±0.6±0.4 | 3.4 ±1.3±0.8 (x10^{-4})





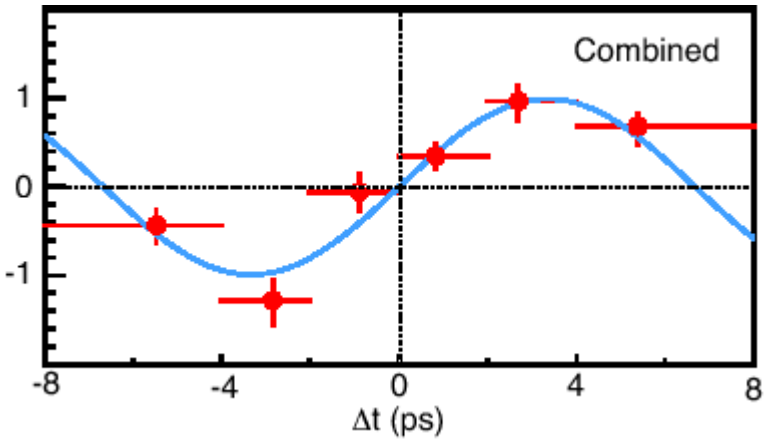


Evidence for: $D^{*0}\pi^0(3.2\sigma)$, $D^{*0}\omega(3.6\sigma)$, $D^{*0}\eta(3.8\sigma)$

Bcp events at Belle as of July 2001

- **For sin2ϕ1 analysis**

sin2ϕ1 = 0.99 ±0.14 ±0.06



	candidates	purity	int. lumi.
$J/\psi\, Ks(\to\pi^+\pi^-)$	457ev.	97%	29.1fb^{-1}
Other *(cc) Ks*	290ev.	84%	29.1fb^{-1}
$J/\psi\, K_L$	569ev.	61%	29.1fb^{-1}

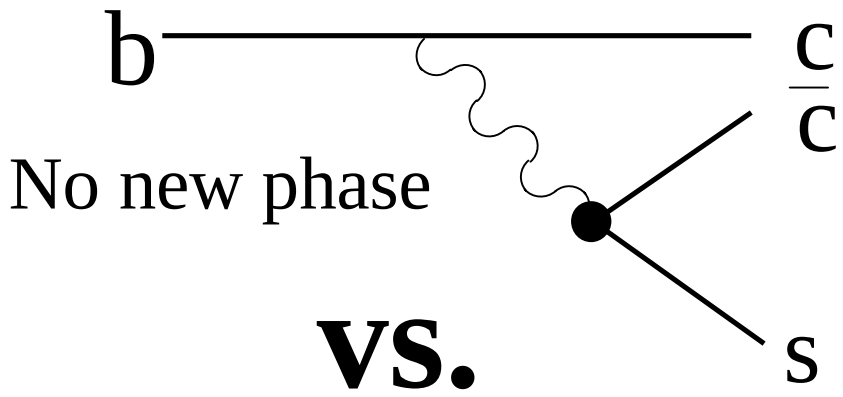
- **"Rare" decays**

$\phi\,(\to K^+K^-)\, Ks$	10ev.	80%	21.3fb^{-1}
$\eta'\, Ks$	26ev.	63%	10.4fb^{-1}
$D^*D^{(*)}$	27ev.	82%	21.3fb^{-1}
$Ks\ \pi^0$	12ev.	67%	10.4fb^{-1}

	Penguin	Tree
$b \to s\bar{s}s$		$(u\bar{u}s)$
$b \to s\bar{u}u$, $s\bar{d}d$		$u\bar{u}s$
$b \to$		$u\bar{c}d$, $c\bar{c}d$
$b \to d\bar{d}s$,		$u\bar{u}s$, $d\bar{d}s$

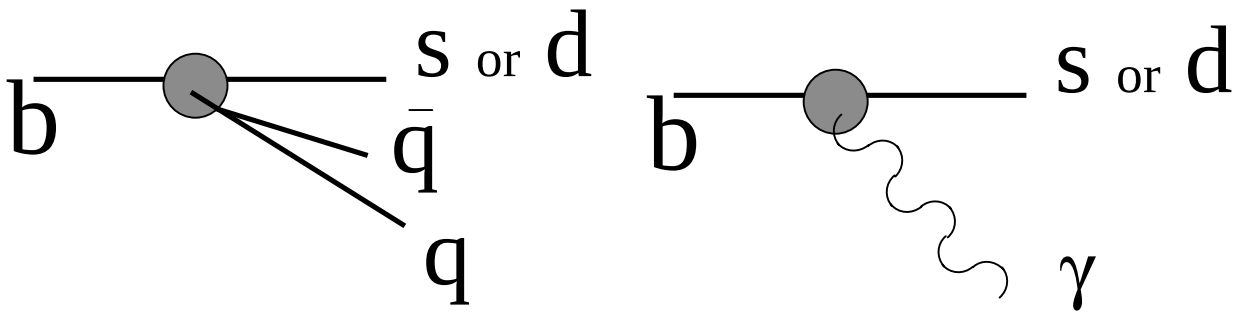
Clear Manifestation of New Physics !

Acp($J/\psi Ks$) ≠ Acp(Bcp with Penguin)

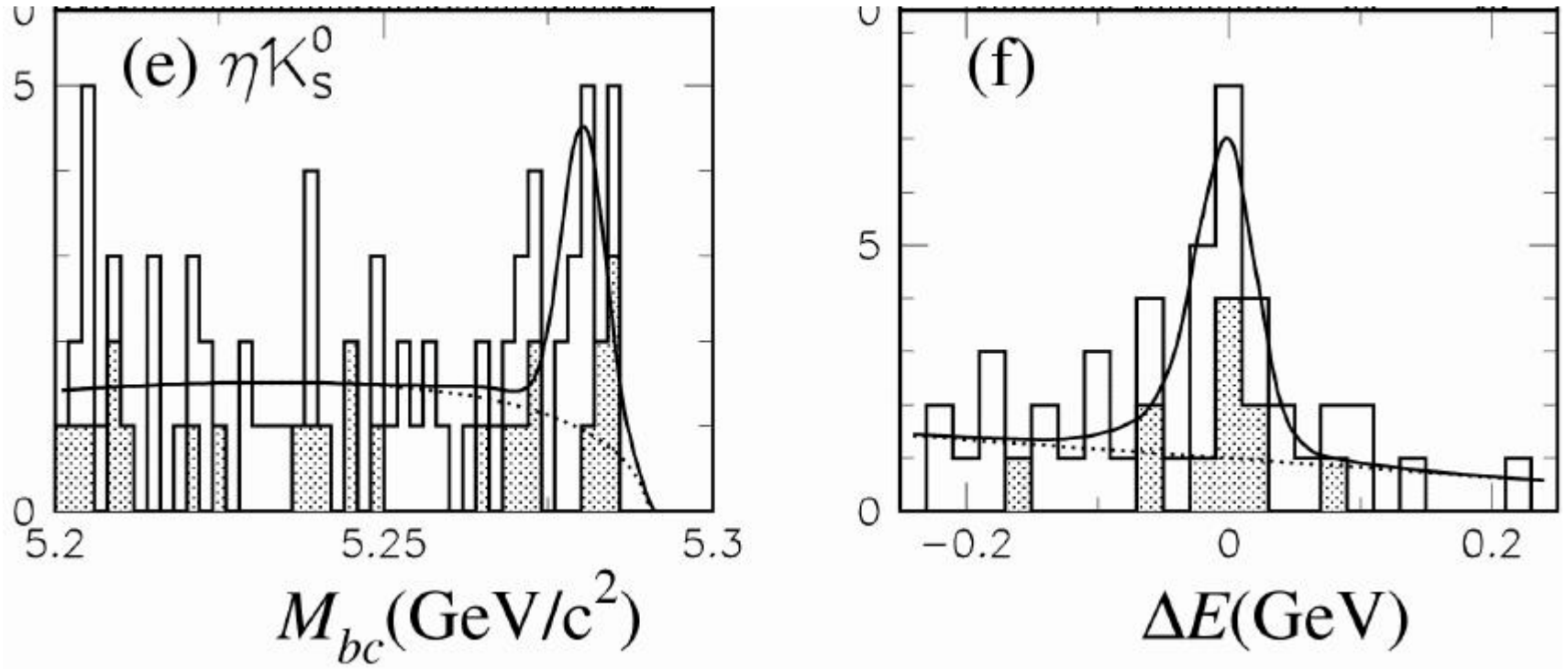


vs.

CP eigenstates (or flavor non-specific states) with any other decay diagrams, such as the following;



B0 → η' Ks (10.4fb^{-1})



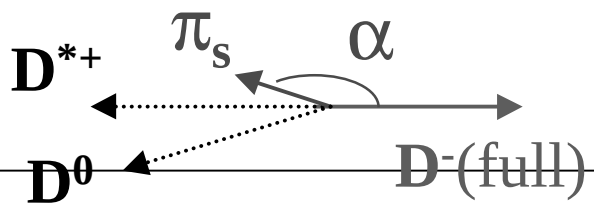
Origin of the large branching fraction is not understood yet. It may include contribution from new physics !

$B^0 \rightarrow D^{*+}D^- \Rightarrow \phi_1$

ϕ_1 measurements with other diagrams

- Partial Reconstruction Technique :

Use only slow π and ~~D^-(full)~~

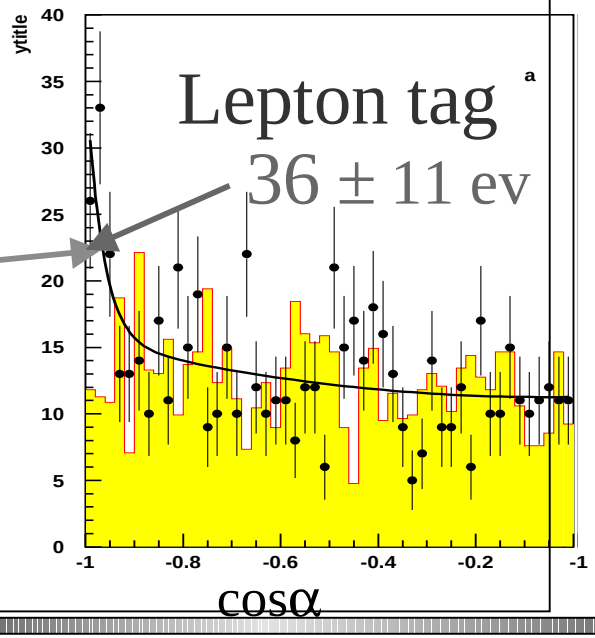


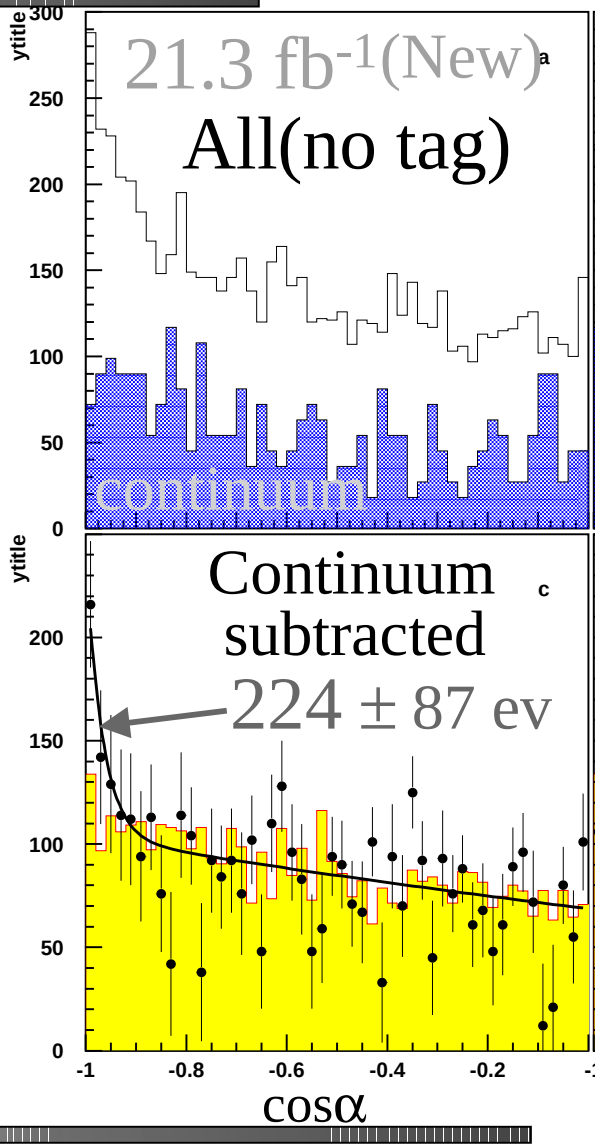
Br=1.84 ±0.46±0.68 ($\times 10^{-3}$)

To be used for CP

corresponds to ~100 ev

First Observation





$B^0 \to D^{*+}D^{(*)-} \Rightarrow \phi_1$

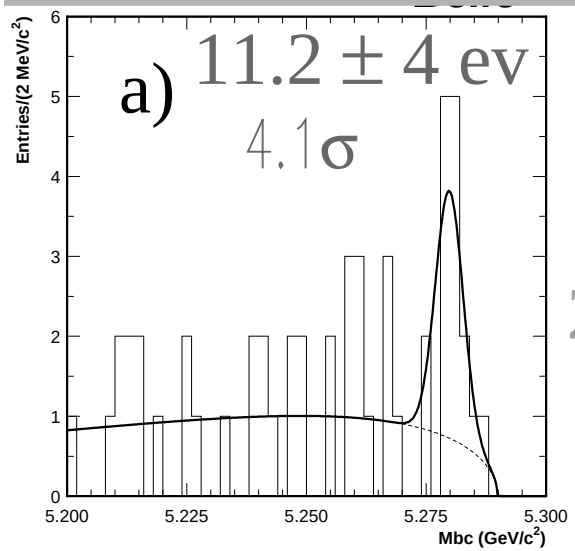
Full Reconstruction : better S/N

B0 → D*+D-

Confirm partial Recon.

Br=1.04 ±0.38±0.22 (x10^{-3})

First Observation



21.3 fb^{-1}

(New)

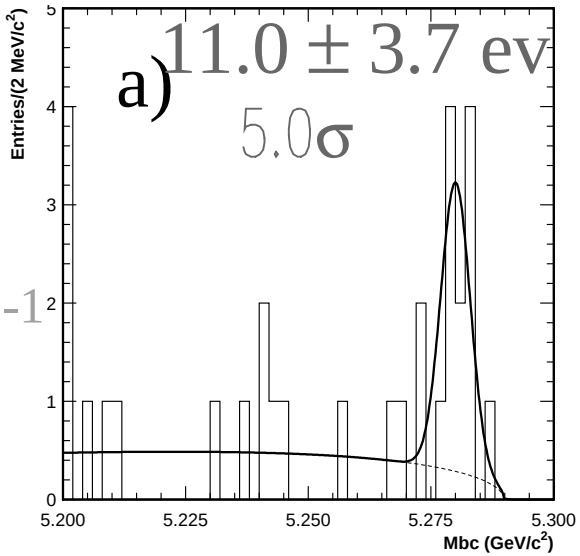
B0 → D*+D*-

$D^{*+} \to D^0 \pi^+$ only

$\Rightarrow$ add $D^{*+} \to D^+ \pi^0$ mode

Need angular anal. for ϕ_1

Br=1.21 ±0.41±0.27 (x10^{-3})



$D^0 \to$
$K^- \pi^+$
$K^- \pi^+ \pi^0$
$K^- \pi^+ \pi^+ \pi^-$

EW Penguin : $b \to s\, l^+ l^-$

Awaited mode sensitive to SUSY after $b \to s\gamma$ (consistent to SM)

Exclusive mode: $B \to K^{(*)}\, l^+ l^-$

x10^{-4}

$B \to K^* \mu^+ \mu^-$: $< 3.0\ (2.8\ ^{+2.9}_{-2.1})$

$B \to K^* e^+ e^-$: $< 5.1\ (5.5\ ^{+3.7}_{-3.0})$

$B \to K \mu^+ \mu^-$: **$0.99\ ^{+0.39\ +0.13}_{-0.32\ -0.15}$**

$B \to K e^+ e^-$: $< 1.2\ (2.6\ ^{+2.7}_{-2.0})$

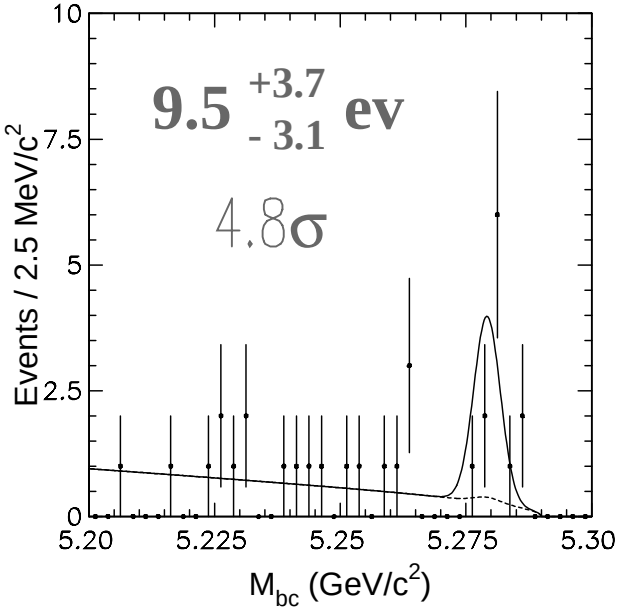
First Observation

29.1 fb^{-1}

$B \to K^+ \mu^+ \mu^-$

$B \to Ks\, \mu^+ \mu^-$

combined



Conclusions

- **Large CPV in B decays !**

$$sin2\phi_1 = 0.99 \pm 0.14 \pm 0.06$$

- **14 First Observations mainly on Rare B Decays**
- **~80fb^{-1} by Summer 2002 !**
  - **Precision measurements of sin2ϕ1**
  - **Vub, ϕ2 to constrain the Triangle**
  - **Mixing-induced CPV in penguin diagrams**
  - **Search for direct CPV**
  - **More rare decays**

Exciting new results in the near future !