Recent results from Belle

- (No) Introduction
- KEKB accelerator and Belle detector
- Observation of CP violation in B system

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Oct. 9th, 2001

Siena2001

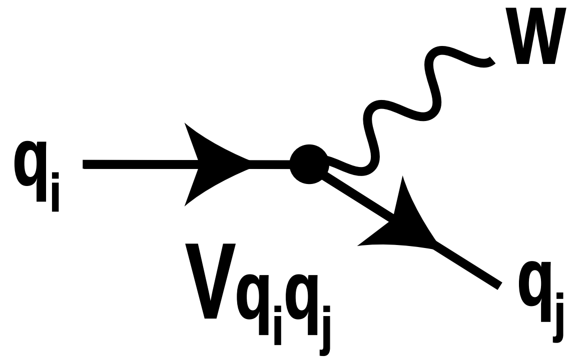
Physics Motivation of Belle

- Observe CP violation in B meson system
- Try to establish the mechanism of the CP violation
  - In particular, we must know whether the measurements (of the CP violation) are consistent with the description given by the CKM matrix of weak interactions in the standard model
  - Otherwise we need to find the new CP violating interaction

CKM Matrix

- The Cabibbo-Kobayashi-Maskawa quark mixing matrix
  - A unitary matrix which relates the mass eigenstates to eigenstates of weak force
  - The strength of the weak interaction is proportional to $V_{q_i q_j}$
  - Wolfenstein parameterization is the most popular approximation, writing in terms of the powers of λ;sine of Cabibbo angle

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



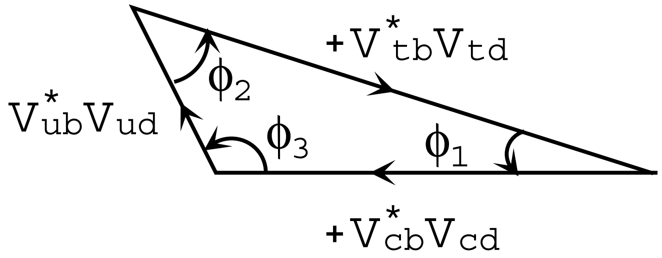
$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The Unitarity Triangle

- Unitarity ($U^\dagger U=1$) of the CKM matrix applied to the first and third columns yields:

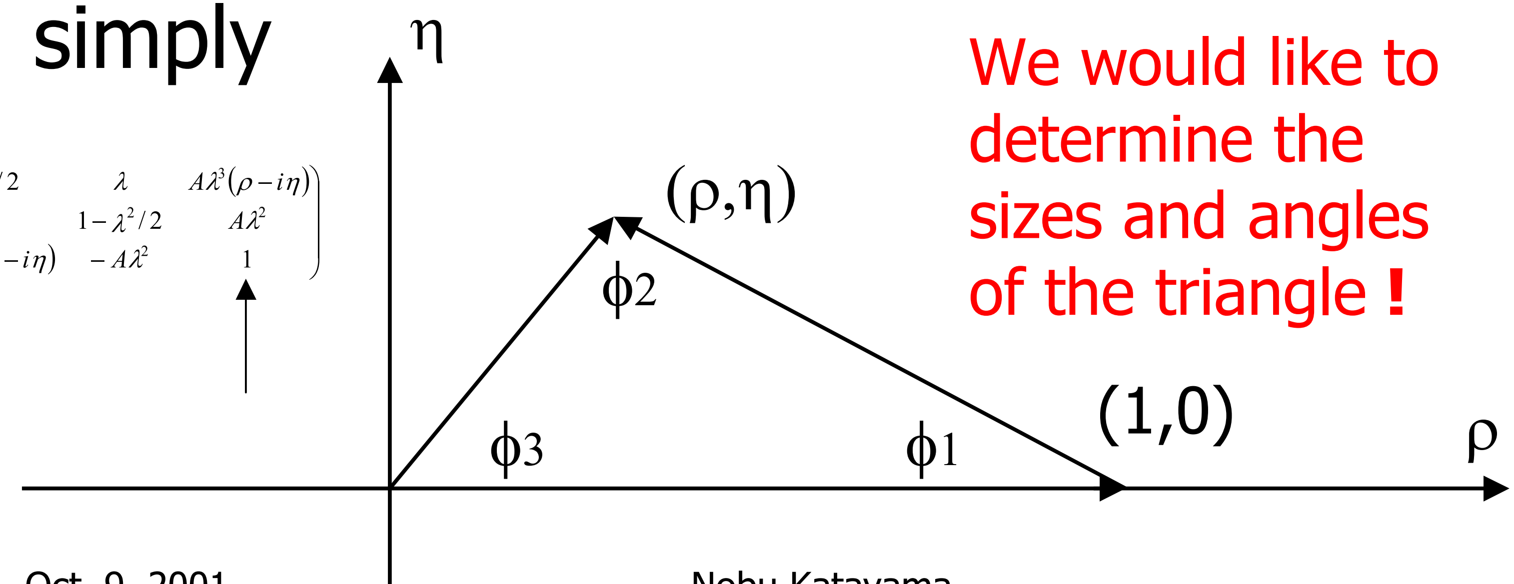
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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



- In the Wolfenstein parameterization, it is simply

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



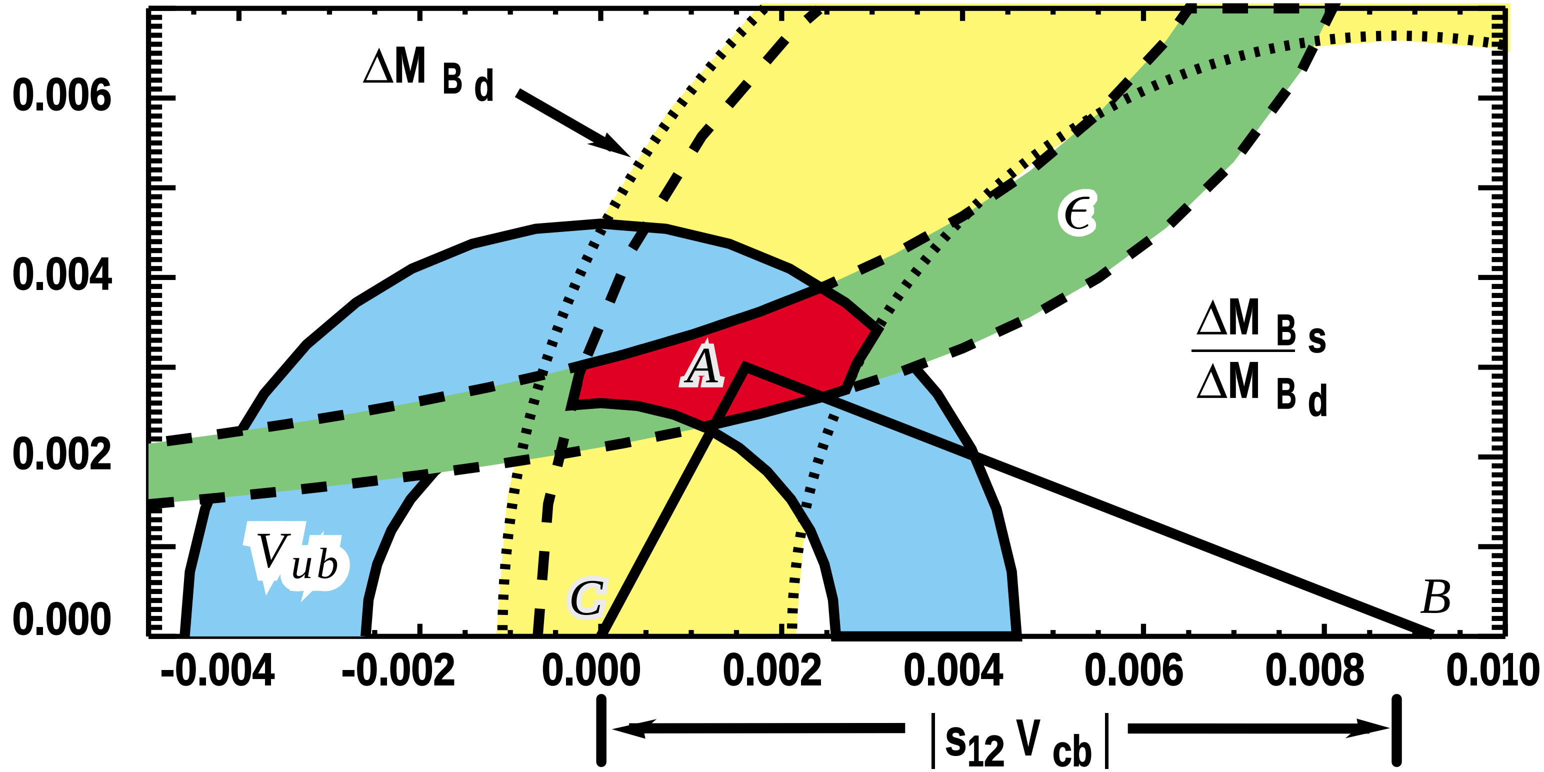
We would like to determine the sizes and angles of the triangle !

CP Violation in the Standard Model

- In the standard model, CP-violating processes/amplitudes involve the phase in the CKM matrix (Kobayashi-Maskawa)
  - A 3x3 unitary matrix has one non-trivial phase
- For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry and sin(2ϕ) (Bigi, Sanda, Carter)
  - For example, asymmetry in the golden mode, $B_d^o\left(\overline{B_d^o}\right) \rightarrow J/\psi K_S$ determines $\sin(2\phi_1)$

Unitarity Triangle 2001

- Other measurements (ε, b→u, etc.) constrain the triangle in other ways
- The CKM matrix given in PDG2001



How to measure sin($2\phi_1$) at Belle

1. Reconstruct one B meson decay into the CP eigenstates
2. Tag the flavor of the other B decay
3. Measure the signed time difference Δt
   - The asymmetry A(Δt) will distribute as

$$A(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} \propto \xi_{CP} \sin 2\phi_1 \sin \Delta m_d \Delta t$$

Asymmetric e^+e^- collider

$\Downarrow\Downarrow\Downarrow\Downarrow$

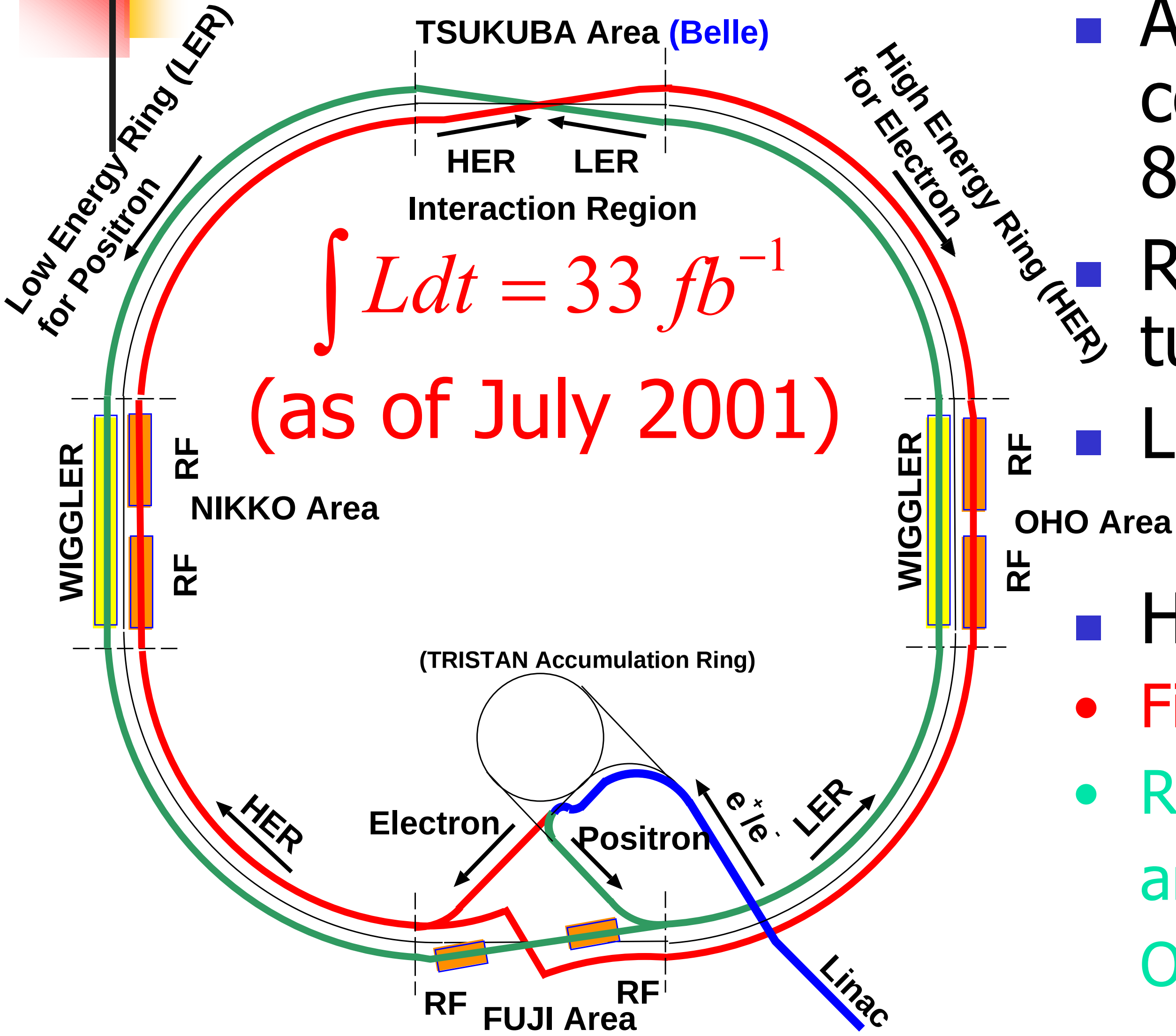
B mesons are moving

KEK

- High Energy Accelerator Research Organization
- KEKB and Belle
- ATLAS/LHC
- K2K
- JHF
- ...

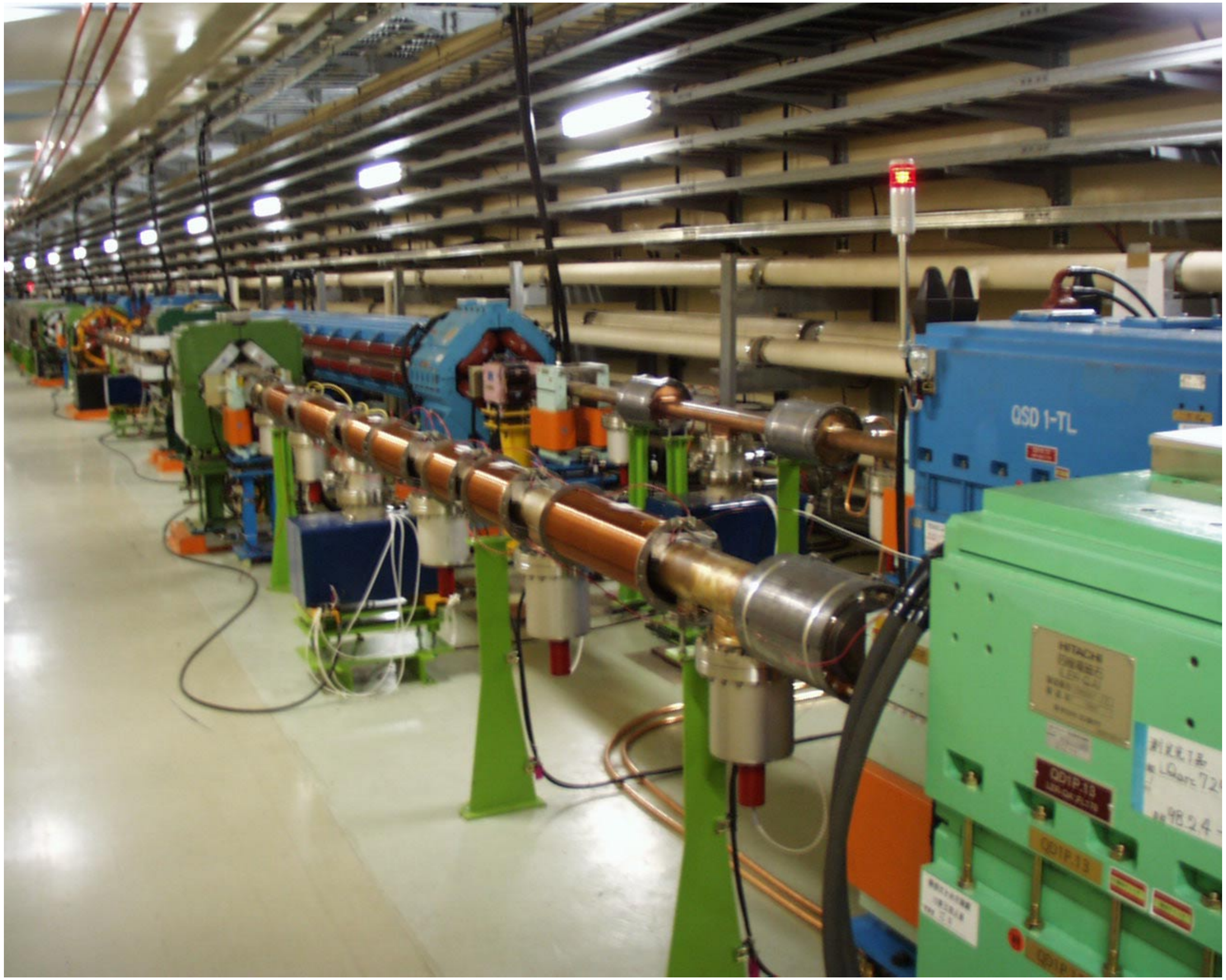
Mount Tsukuba

KEKB accelerator system

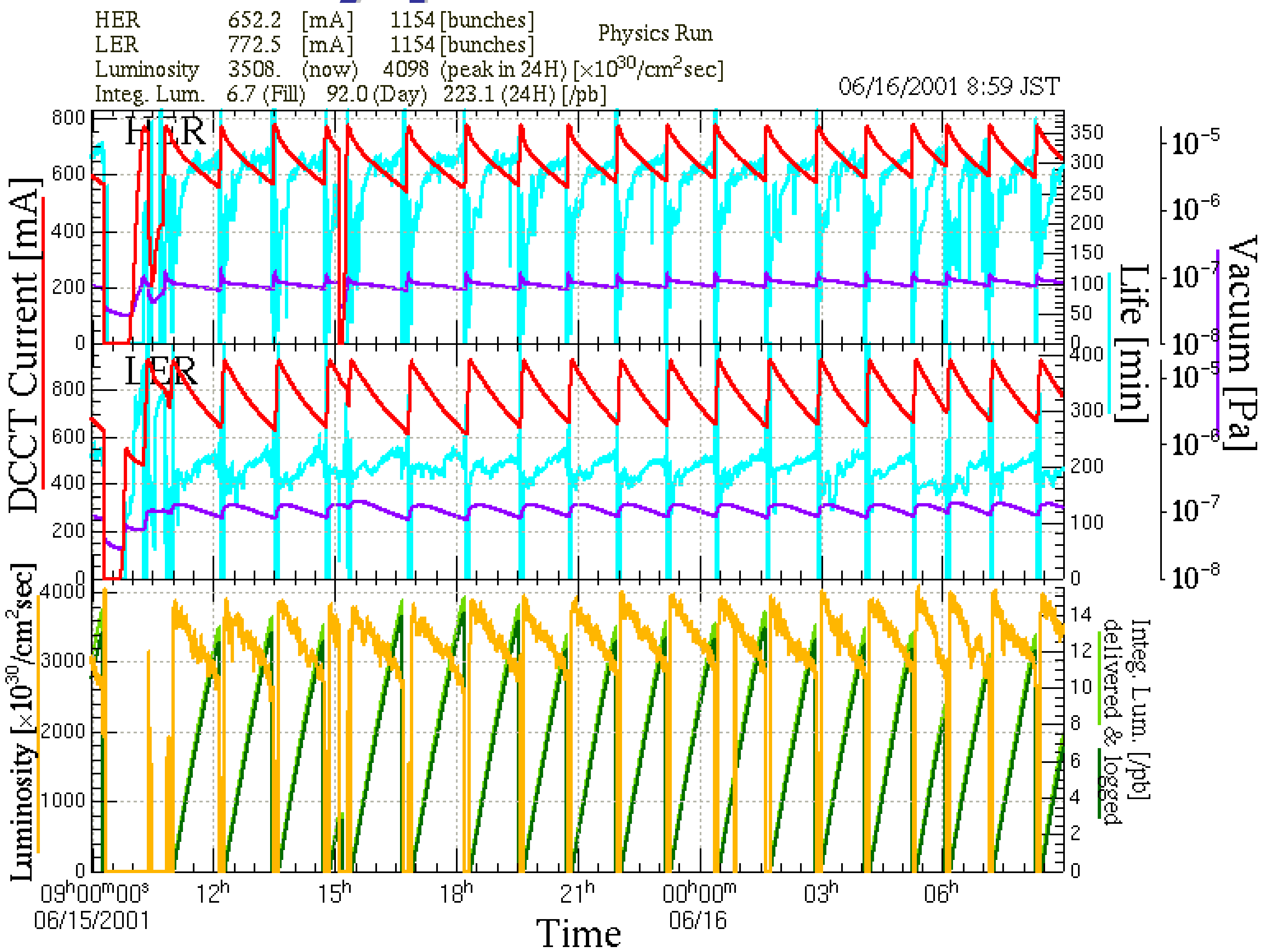


- Asymmetric e^+e^- collider (3.5GeV vs 8.0GeV)
- Reuse TRISTAN tunnel
- $L_{goal}=10^{34}\ cm^{-2}s^{-1}$
- History
  - First collision:1999/5
  - Runs used for this analysis
    Oct. 1999–July 2001

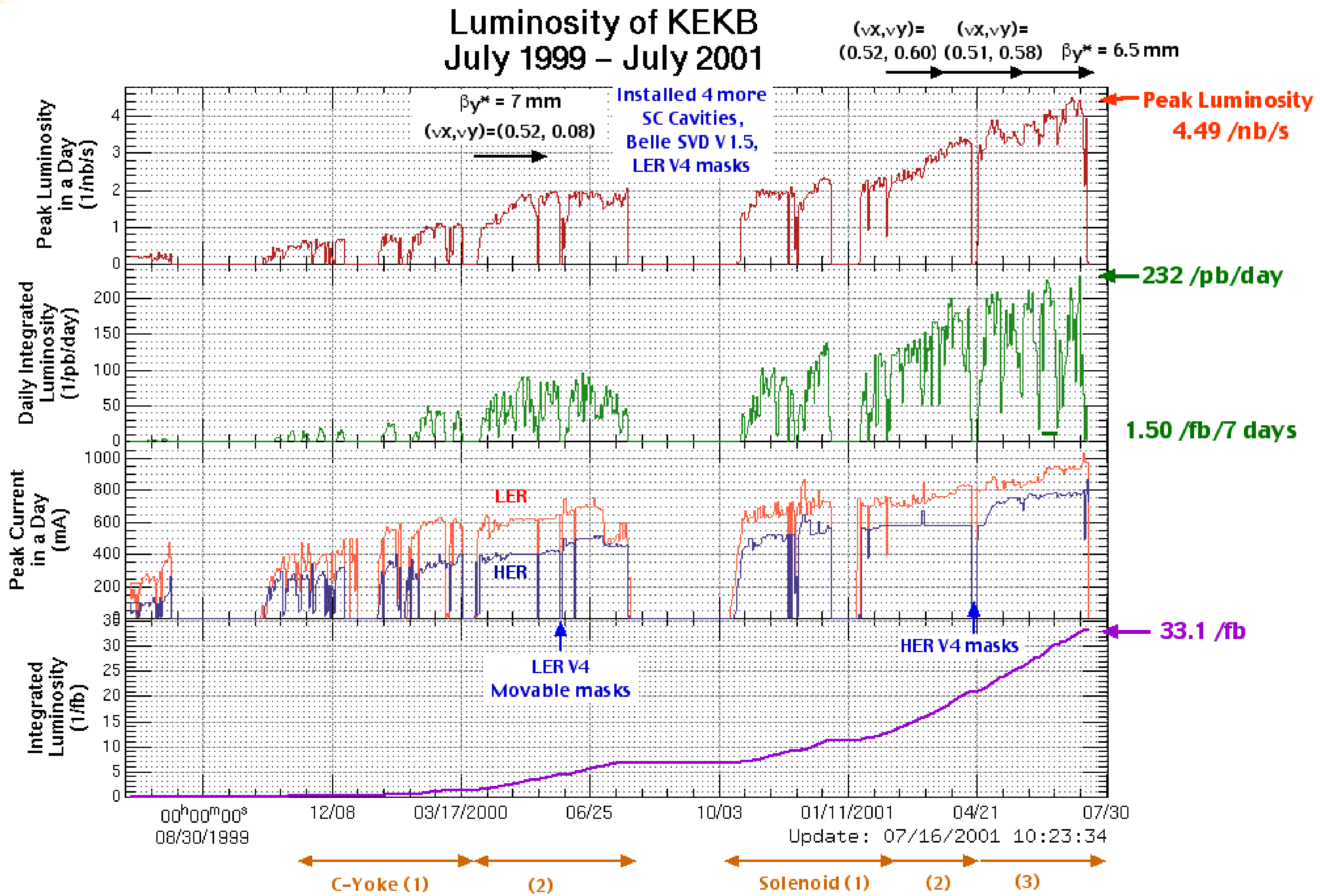
KEKB accelerator



One day performance

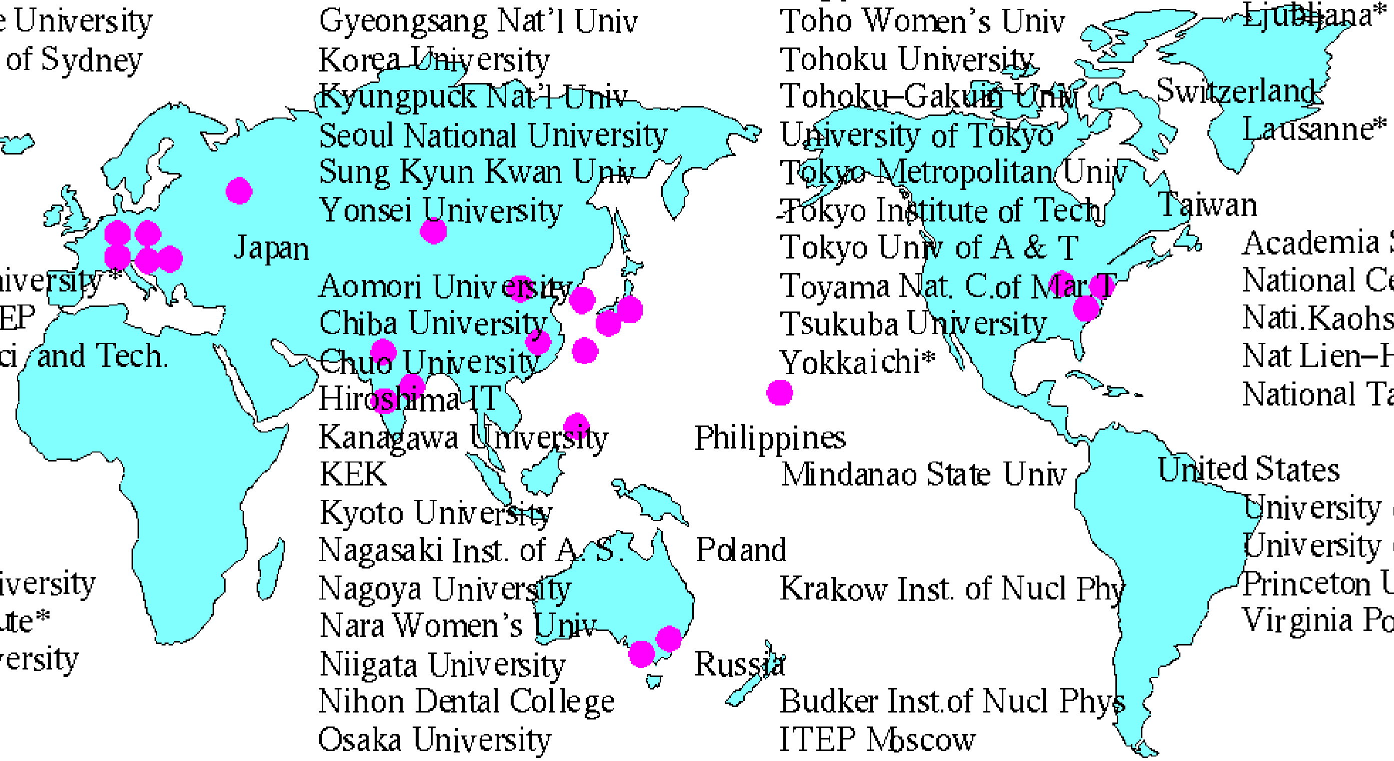


KEKB performance



The Belle Collaboration

World-Wide Activity Involving 50 Institutions



Australia
- Melbourne University
- University of Sydney

Austria
- Vienna*

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- Beijing University*
- Inst. for HEP
- Univ. of Sci. and Tech.

Germany
- Frankfurt*

India
- Panjab University
- Tata Institute*
- Utkal University

Korea
- Gyeongsang Nat'l Univ
- Korea University
- Kyungpuck Nat'l Univ
- Seoul National University
- Sung Kyun Kwan Univ
- Yonsei University

Japan
- Aomori University
- Chiba University
- Chuo University
- Hiroshima IT
- Kanagawa University
- KEK
- Kyoto University
- Nagasaki Inst. of A. S.
- Nagoya University
- Nara Women's Univ
- Niigata University
- Nihon Dental College
- Osaka University
- Osaka City University
- Saga University
- Sugiyama Women's Univ
- Toho Women's Univ
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- National Taiwan Univ

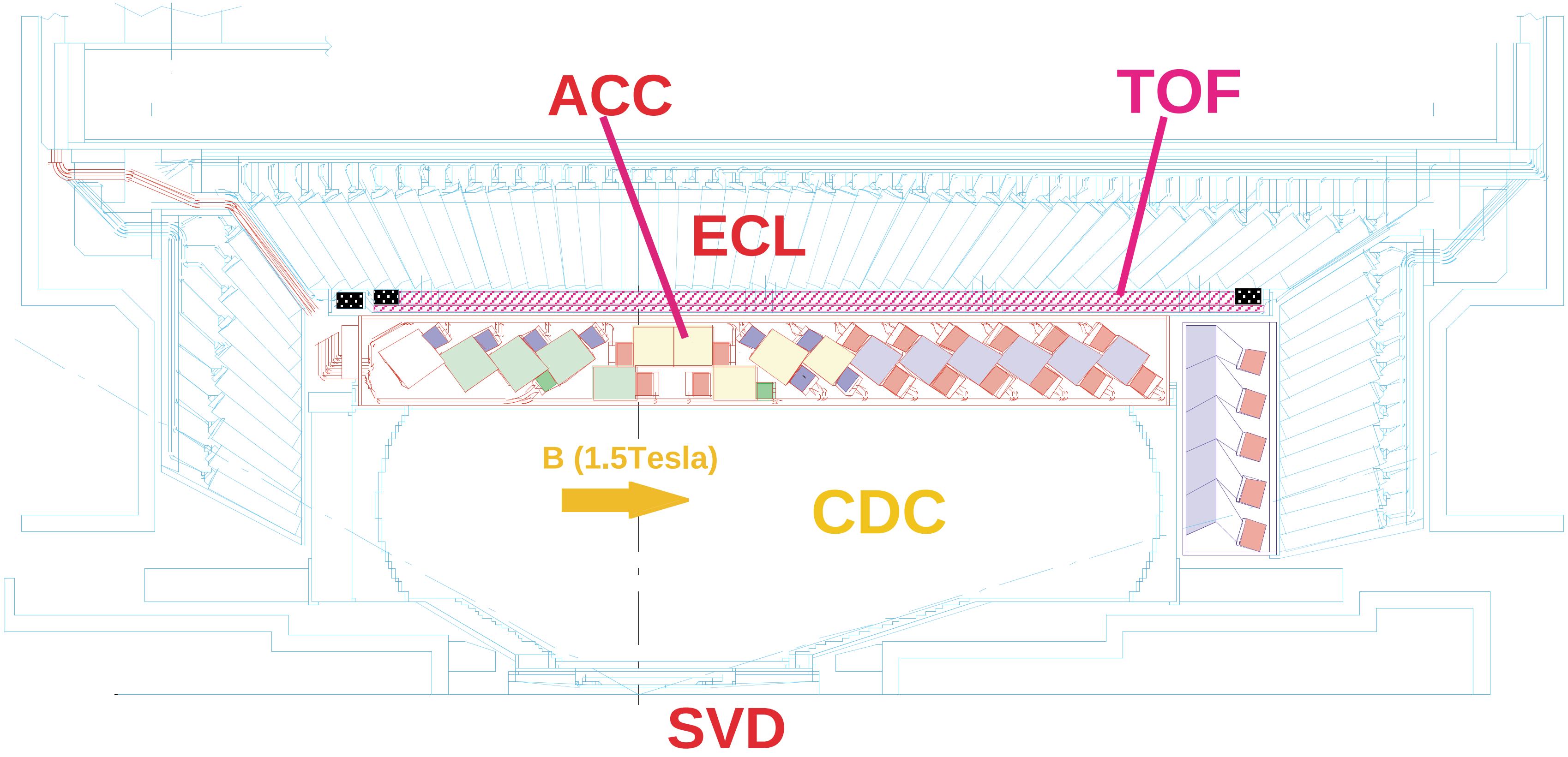
United States
- University of Cincinnatti
- University of Hawaii
- Princeton University
- Virginia Polytechnic

~250 authors

Belle detector

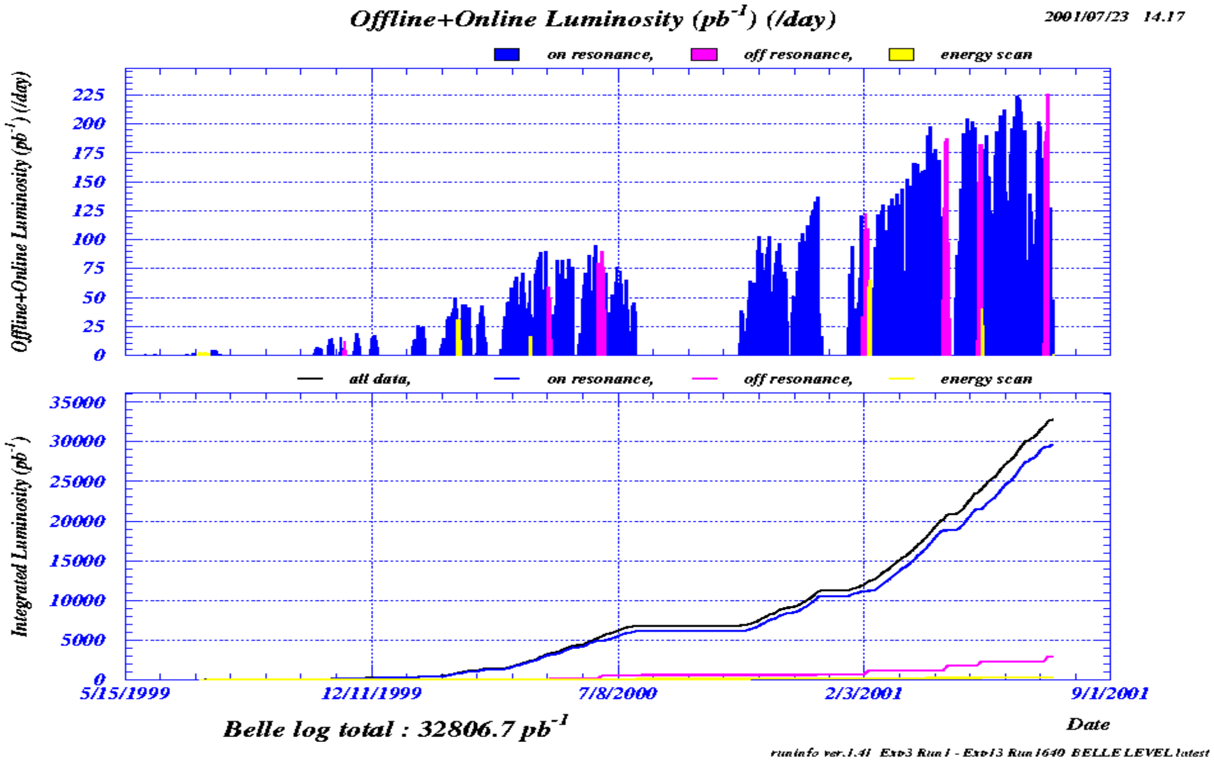
Belle detector

- SVD:3lyr silicon detector
- CDC:50 lyr drift chamber
- ACC:Aerogel Cherenkov counter
- TOF:4cm Scint. Counter
- ECL:16 rad. len. CsI
- KLM:14lyr RPC



Dataset

- In this analysis we used a data sample of 29.1 fb^{-1} taken from Oct. 1999 to July 2001



How to measure sin($2\phi_1$) at Belle

1. Reconstruct one B meson decay into the CP eigenstates
2. Tag the flavor of the other B decay
3. Measure the signed time difference
   - The asymmetry A(Δt) will distribute as

Asymmetric collision
⇓⇓⇓
B meson is moving

$$A(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} \propto \xi_{CP} \sin 2\phi_1 \sin \Delta m_d \Delta t$$

- Experimental concerns
  - Resolution function
  - Wrong tagging fraction
  - Backgrounds

Must understand these very well

$\sin 2\phi_1$ analysis procedure

1. Reconstruct CP eigenstates

↓ Background function: f_{BG}

2. Tag flavor of the other B

↓ Wrong tag fraction: w

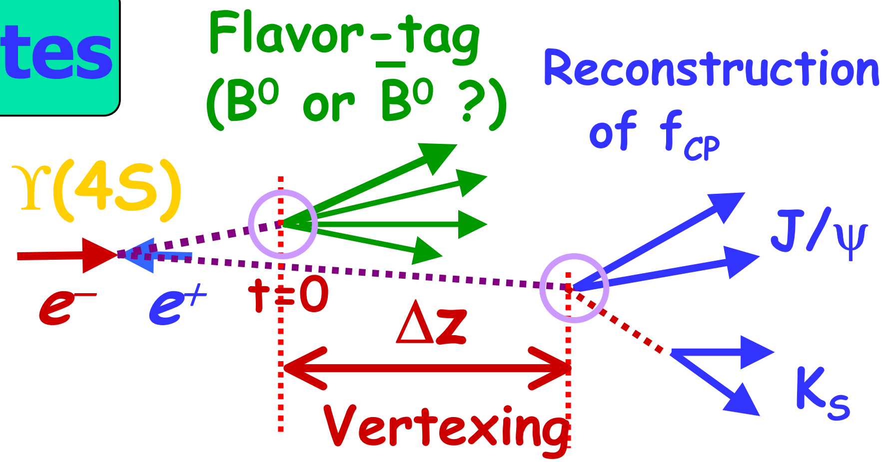
3. Measure decay-time difference

↓ Resolution function: R_{res}

4. Maximum Likelihood fit

↓

$\sin 2\phi_1$



$$A^{CP}(t) \equiv \frac{\Gamma(\overline{B_d^0}(t) \to f_{CP}) - \Gamma(B_d^0(t) \to f_{CP})}{\Gamma(\overline{B_d^0}(t) \to f_{CP}) + \Gamma(B_d^0(t) \to f_{CP})}$$

$$= -\xi_f \sin 2\phi_1 \sin \Delta m_B t$$

Reconstruction of B to f_{cp}

Use low background $cc\bar{K}^o$ modes

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

} $\xi_f = -1$ CP odd

- $J/\psi\ K_L$

} $\xi_f = +1$ CP even

- $J/\psi\ K^{*0}\ (\to K_S\pi^0)$ (81% $\xi_f = +1$)

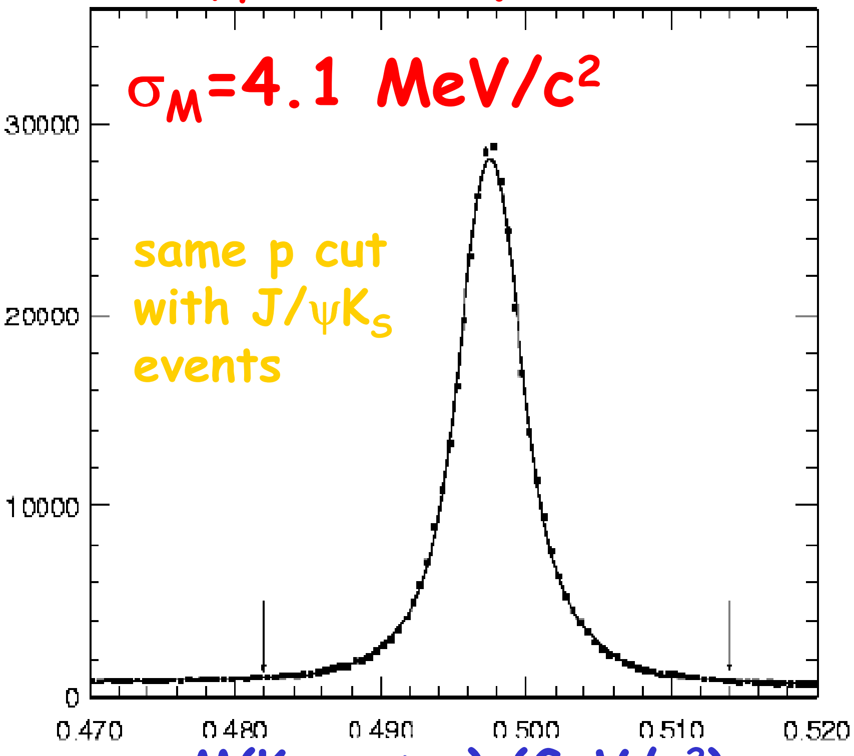
[full angular analysis]

Reconstruction of K_S

$K_S \to \pi^+ + \pi^-$

- CDC($\sigma_{r\phi}$~100μm)
- SVD($\sigma_{r\phi}$~30μm)

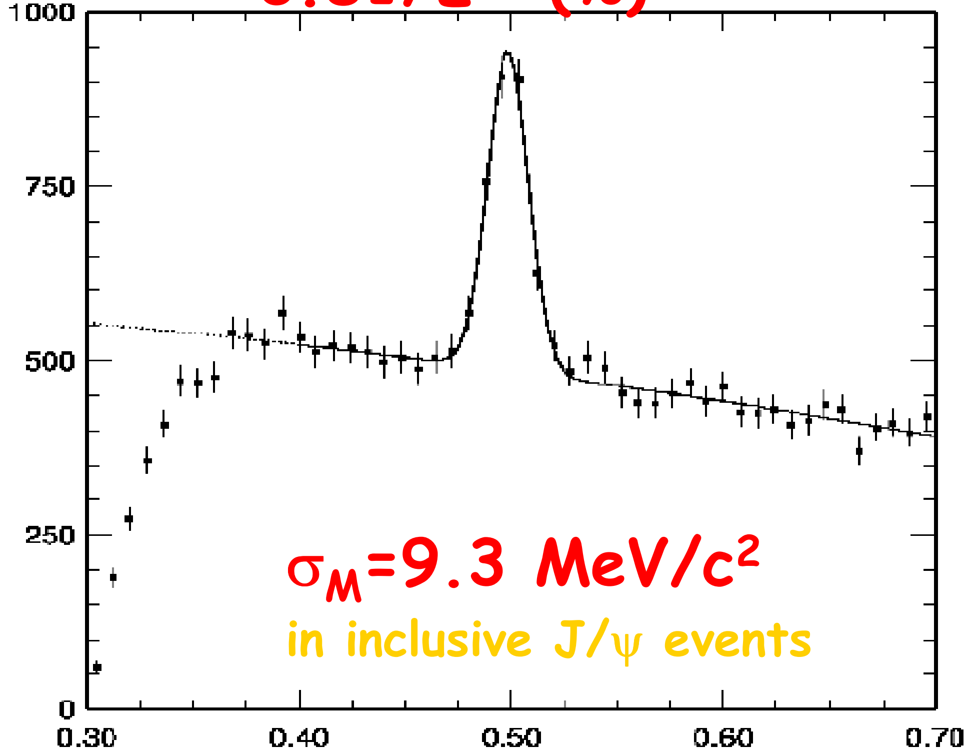
$\sigma_{p_t} = 0.19 p_t \oplus 0.34/\beta$ %



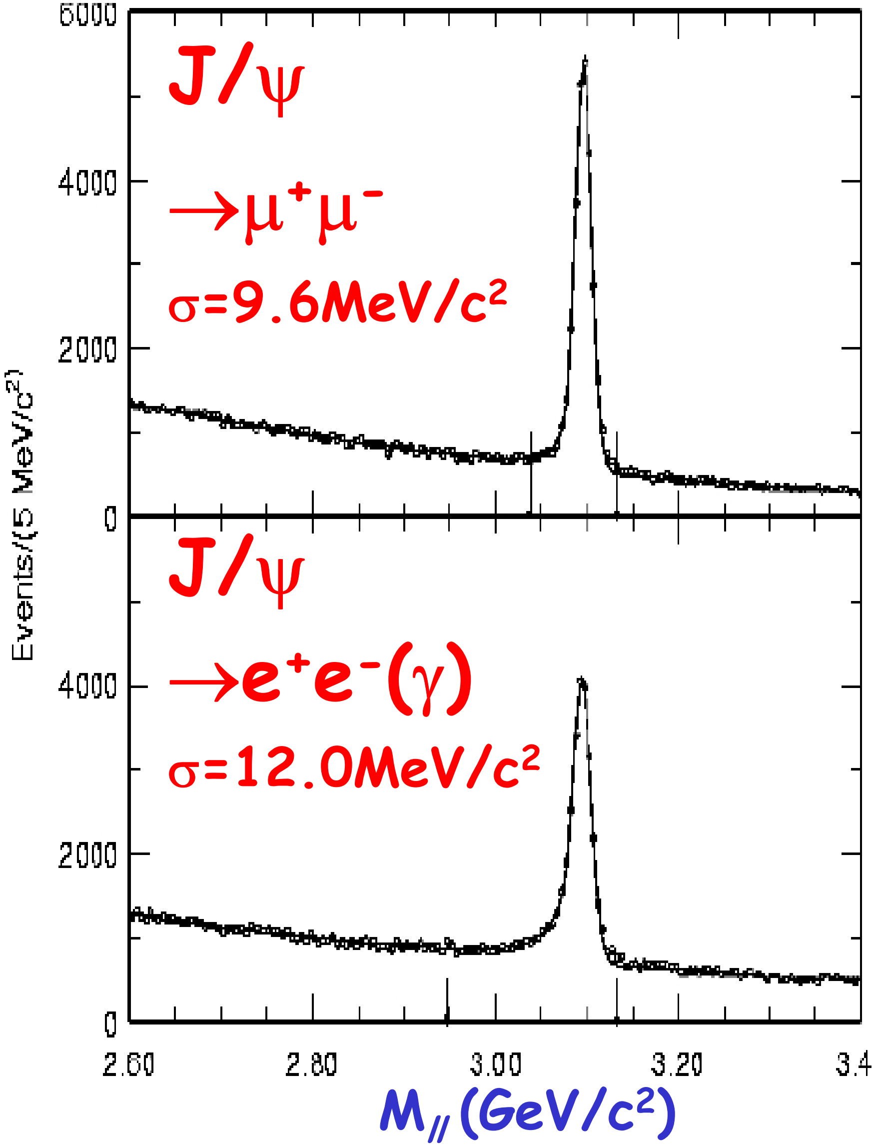
$K_S \to \pi^0 + \pi^0$

- Electromagnetic Calorimeter

$\sigma_E/E = 1.34 \oplus 0.066/E \oplus 0.81/E^{1/4}$(%)

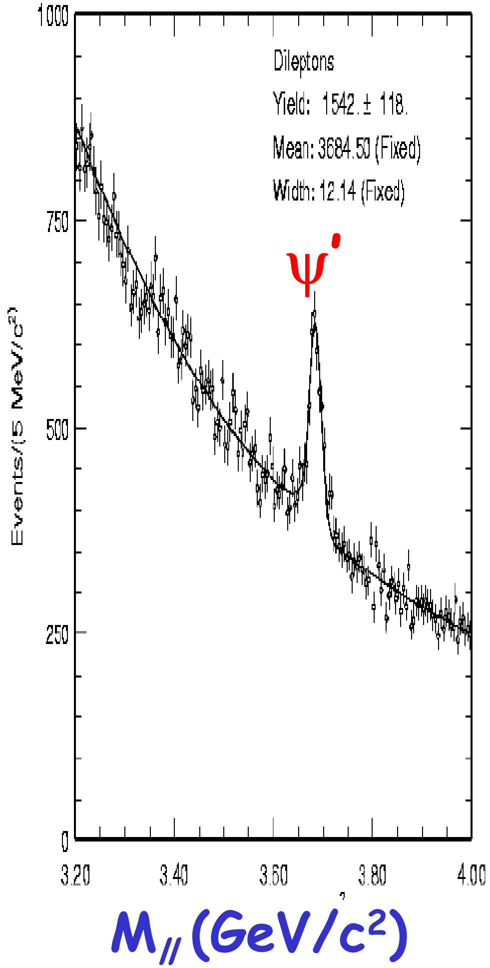


Reconstruction: $J/\psi, \psi', \chi_{c1}$ (χ_{c2})



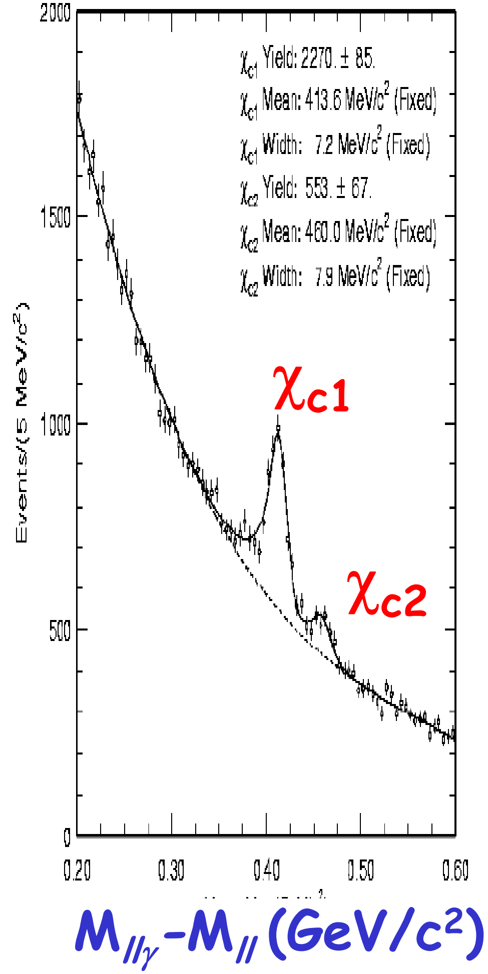
$\psi' \to \mu^+\mu^-, e^+e^-$

$\sigma = 12.1$ MeV/c^2



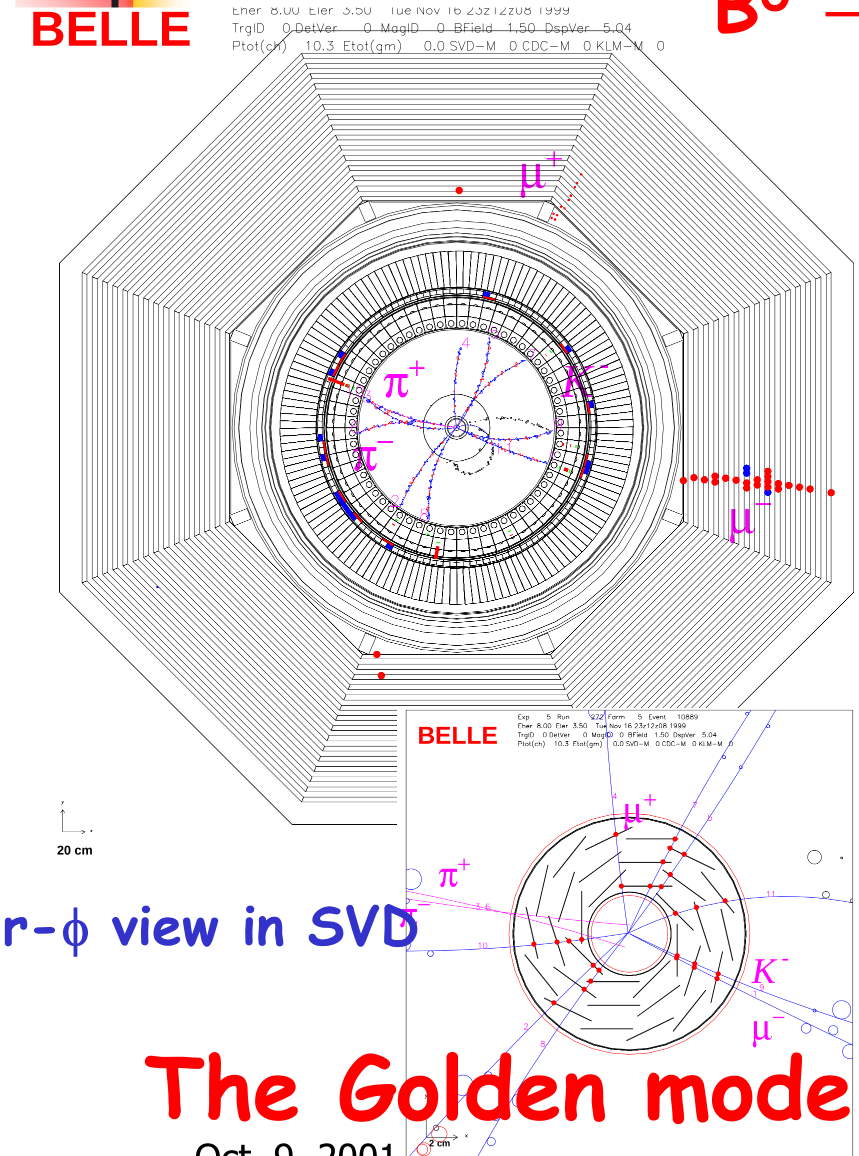
$\chi_{c1}, \chi_{c2} \to J/\psi + \gamma$

$\sigma = 7.0$ MeV/c^2

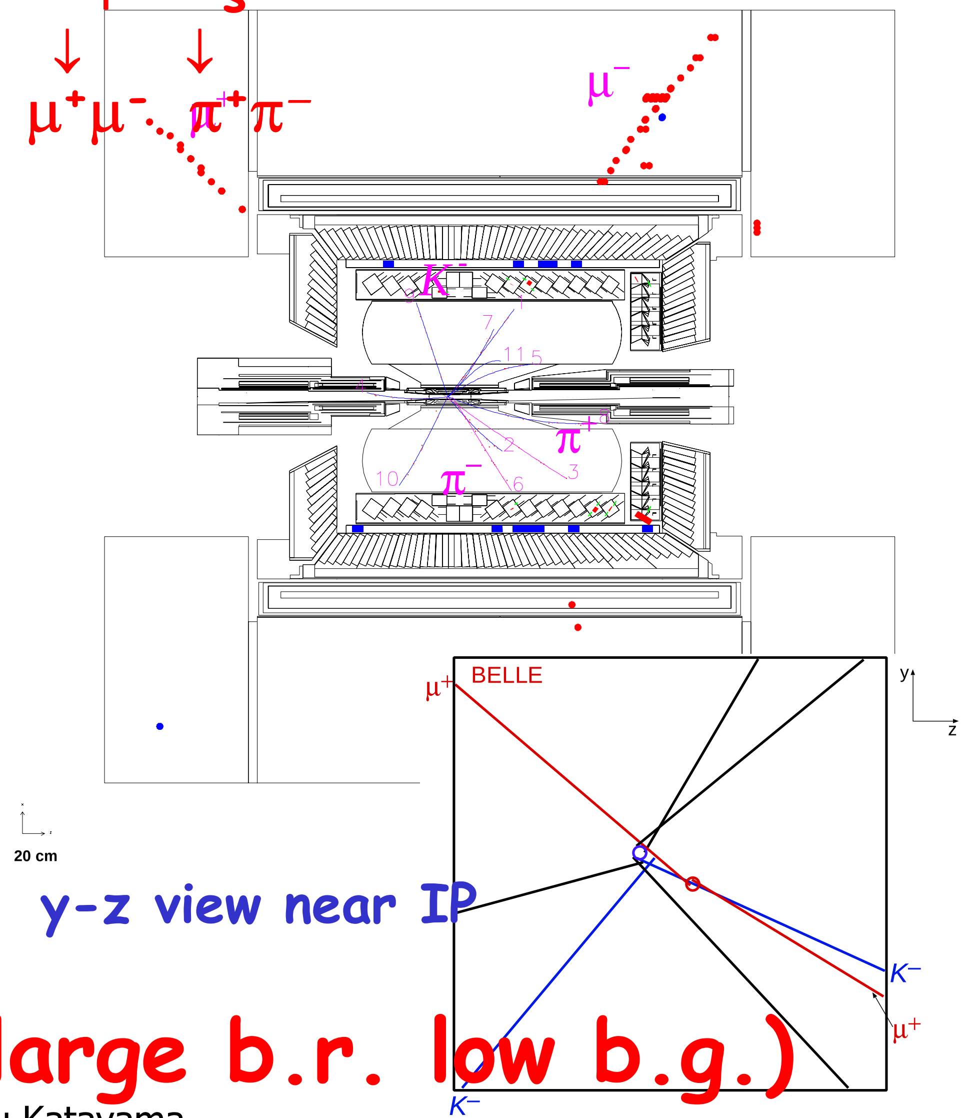


An example of $J/\psi\ (l^+l^-)+K_s(\pi^+\pi^-)$

$B^0 \rightarrow J/\psi + K_s$, $J/\psi \rightarrow \mu^+\mu^-$, $K_s \rightarrow \pi^+\pi^-$



r-φ view in SVD



y-z view near IP

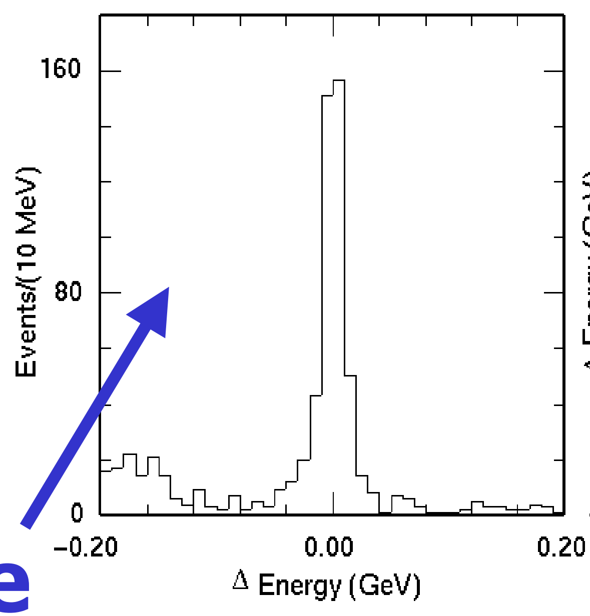
The Golden mode (large b.r. low b.g.)

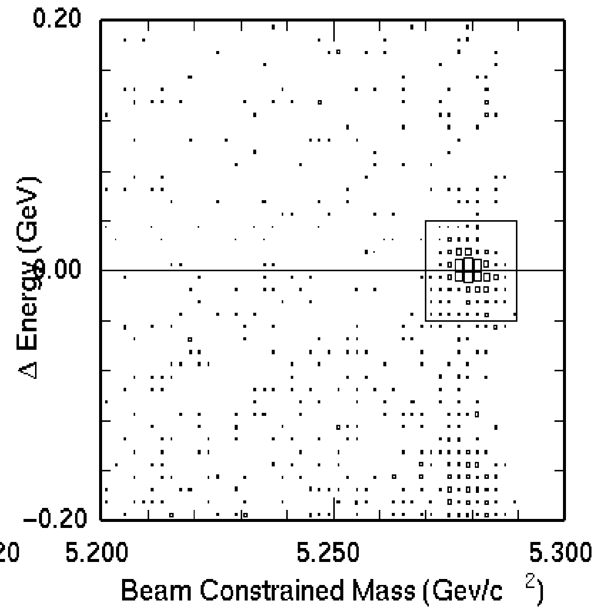
The $J/\psi+K_s(\pi^+\pi^-)$ event sample

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

457 events

~3% background

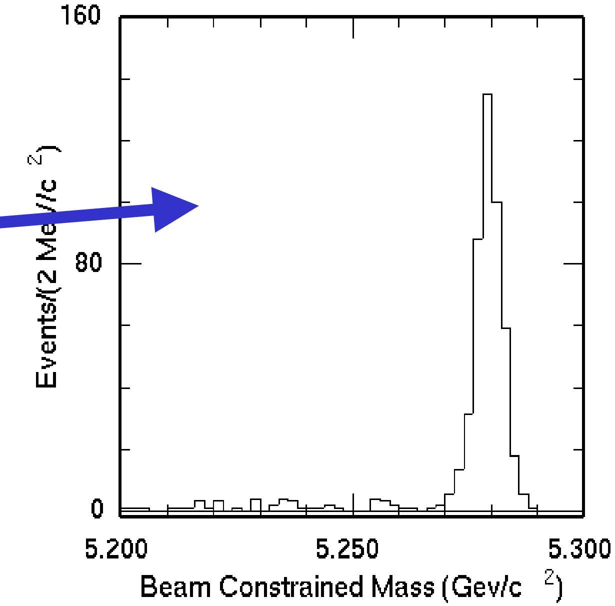




Energy difference

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

Beam constrained mass



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

Summing up all modes but $J/\psi K_L$

All modes except for $J/\psi K_L$

Signal(+BG) 747

Background~59

(purity:92%)

$B^0 \rightarrow J/\psi\ K_S(\rightarrow \pi^+\pi^-)$

Signal(+BG) 457

Background~12

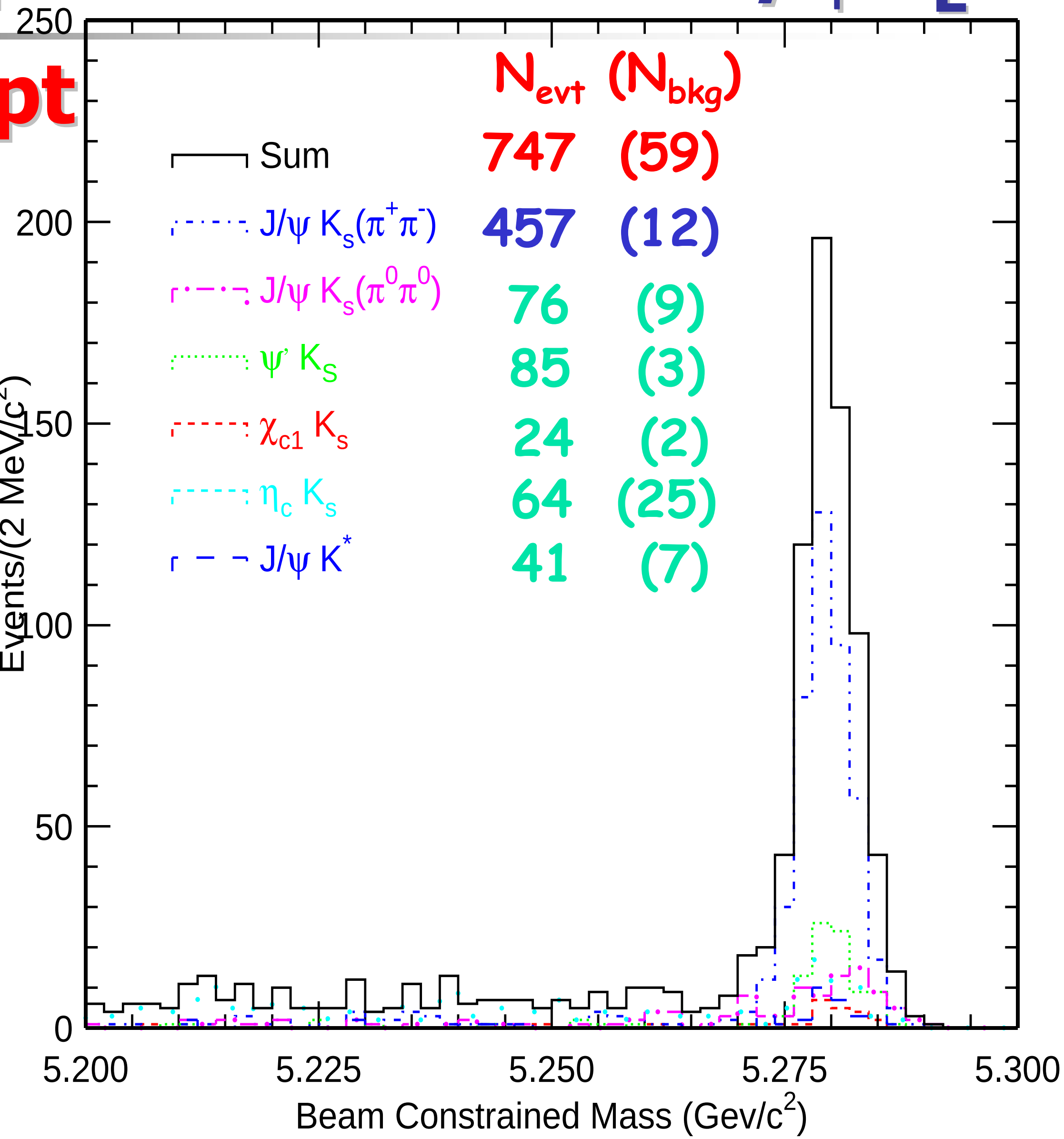
(purity:97%)

Other modes

Signal(+BG) 290

Background~46

(purity:84%)



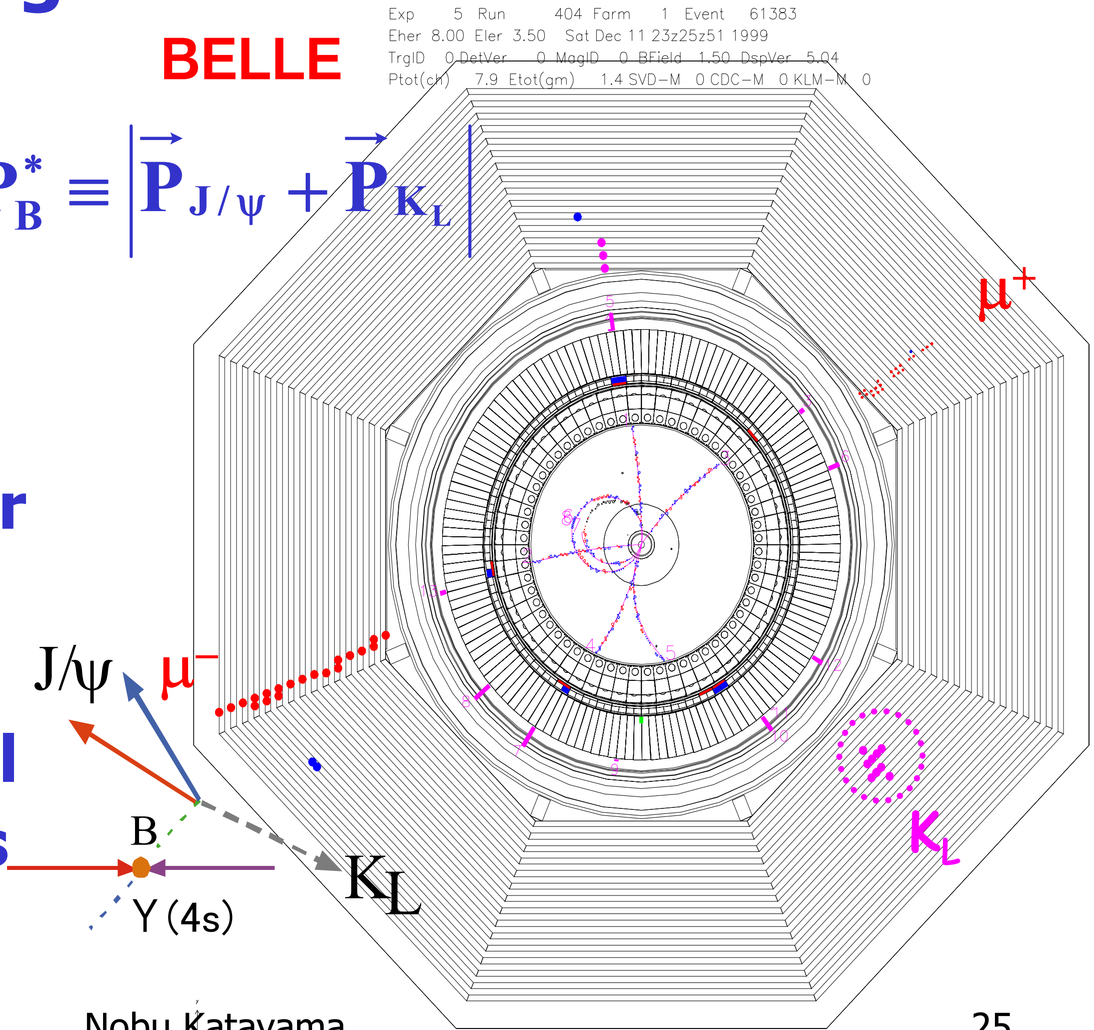
$B^0 \rightarrow J/\psi\ K_L$ event selection

K_L : Get the direction of hadronic shower using ECL and KLM

Selection procedure

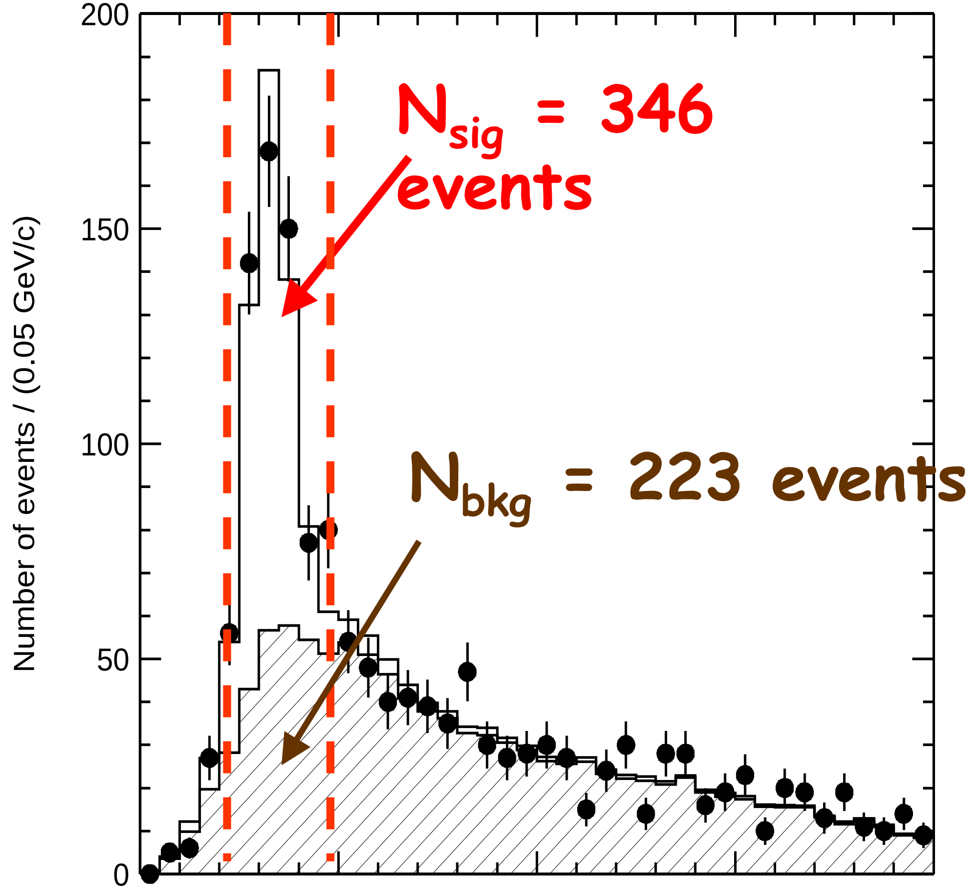
$$P_B^* \equiv \left| \vec{P}_{J/\psi} + \vec{P}_{K_L} \right|$$

1. Find $J/\psi \rightarrow l^+ l^-$
2. Assume $B^0 \rightarrow J/\psi\ K_L$ and calculate the K_L direction
3. Find ECL/KLM cluster within 45° cone
4. Cut on a likelihood based on kinematical and shape quantities
5. Calculate P_B^*



P_B^* distribution in $B^0 \to J/\psi\, K_L$

P_B^*:If $B^0 \to J/\psi\, K_L$, peaks at around ~340 MeV/c



$$P_B^* \equiv \left| \vec{P}_{J/\psi} + \vec{P}_{K_L} \right|$$

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

Signal(+BG) 569

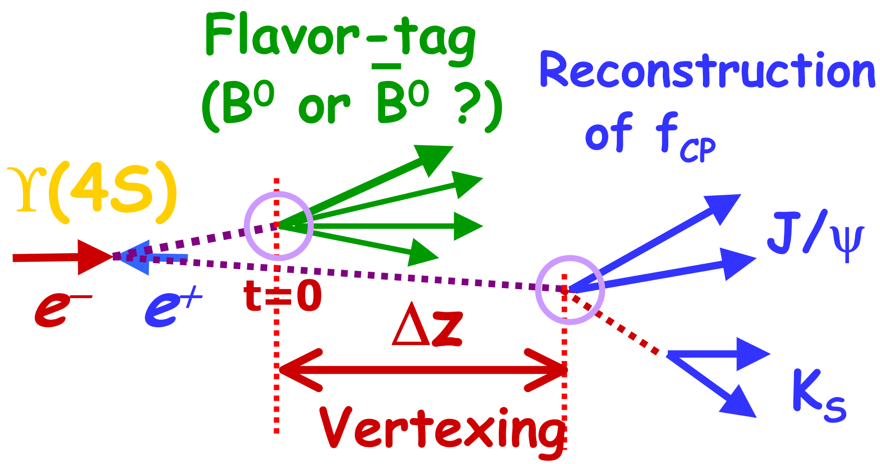
Background~223

(purity:61%)

Total of 1316 events (incl.BG) in all CP=±1 modes

Tag flavor of the other B

Would like to know the flavor of the B meson which decayed into the CP eigenstate



We can flavor tag the other B meson

- Lepton from B, D
- Kaon from $b \to c \to s$
- Slow pion from D*
- Fast pion from B

Combine into a two layered likelihood function

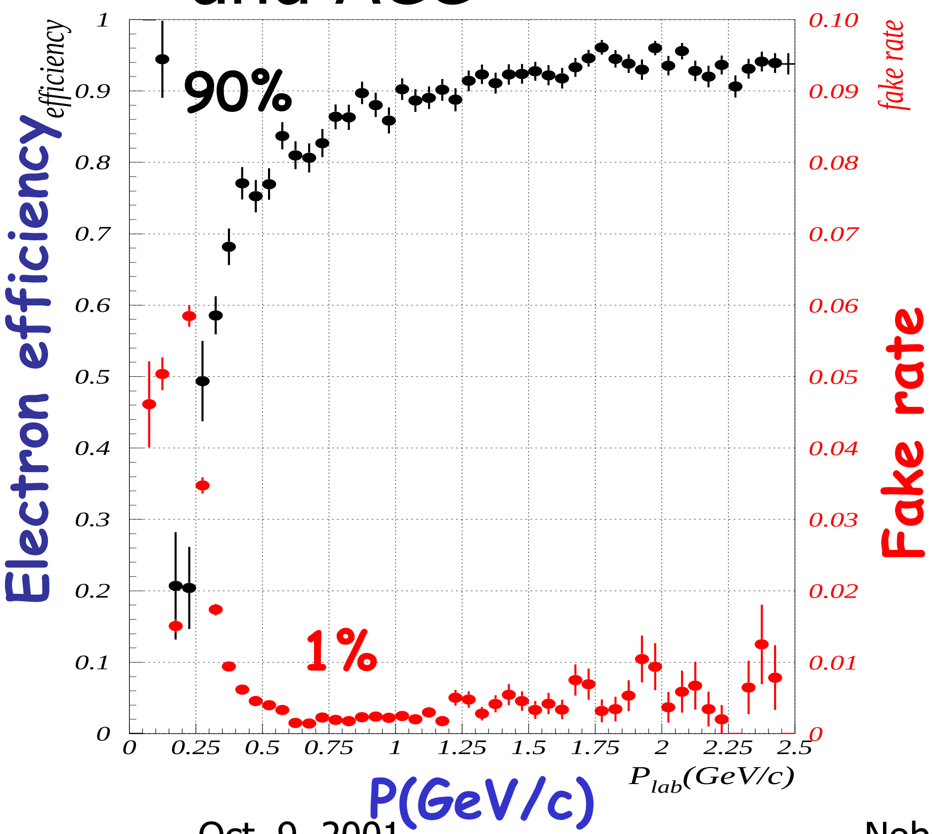
$b \to c\, l^- \nu$, $c \to s\, l^+ \nu$

$B^0 \to D^{(*)-} \pi^+$, $D^{(*)-} \rho^+$, etc.

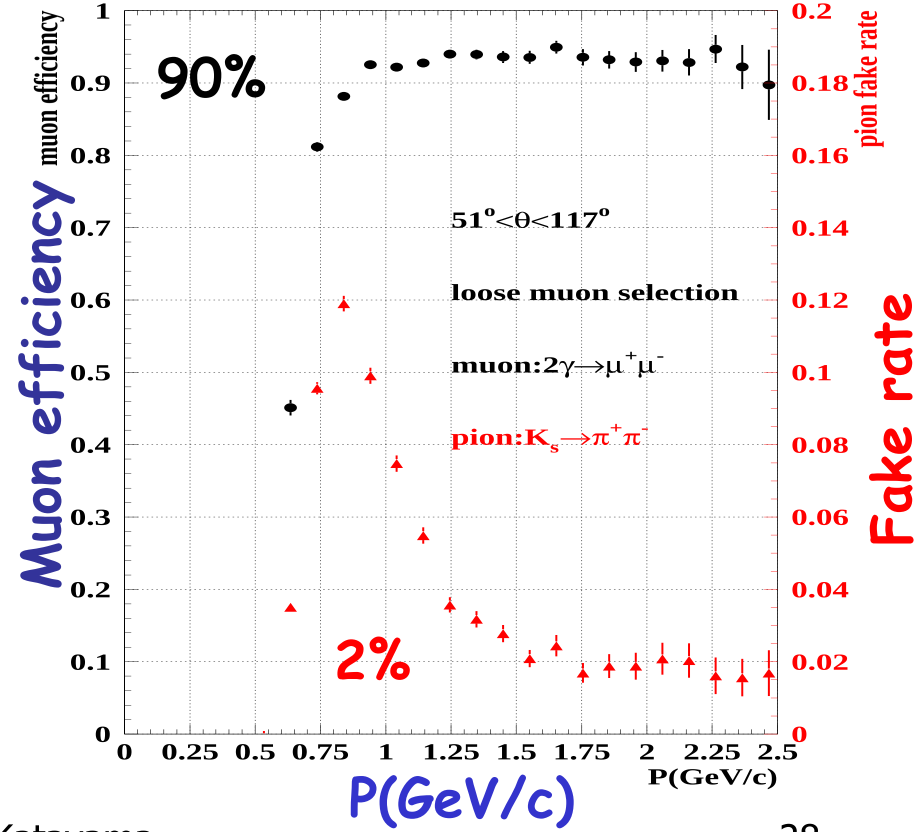
$D^{(*)-} \to K^+ X$, $D^0 \pi^-$; $\rho^+ \to \pi^+ \pi^0$

Lepton identification

- Electron ID by E/p, CsI shower shape, dE/dx, track matching, TOF and ACC

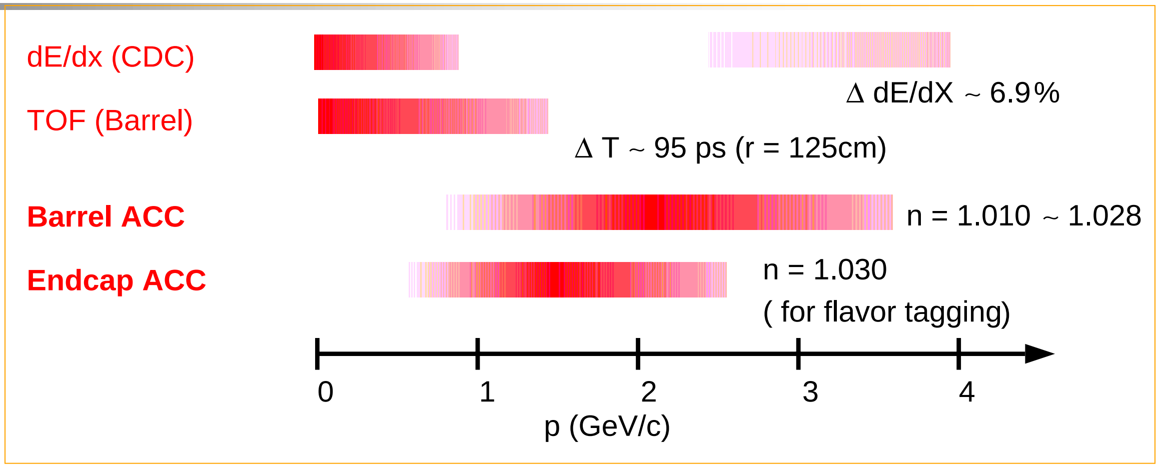


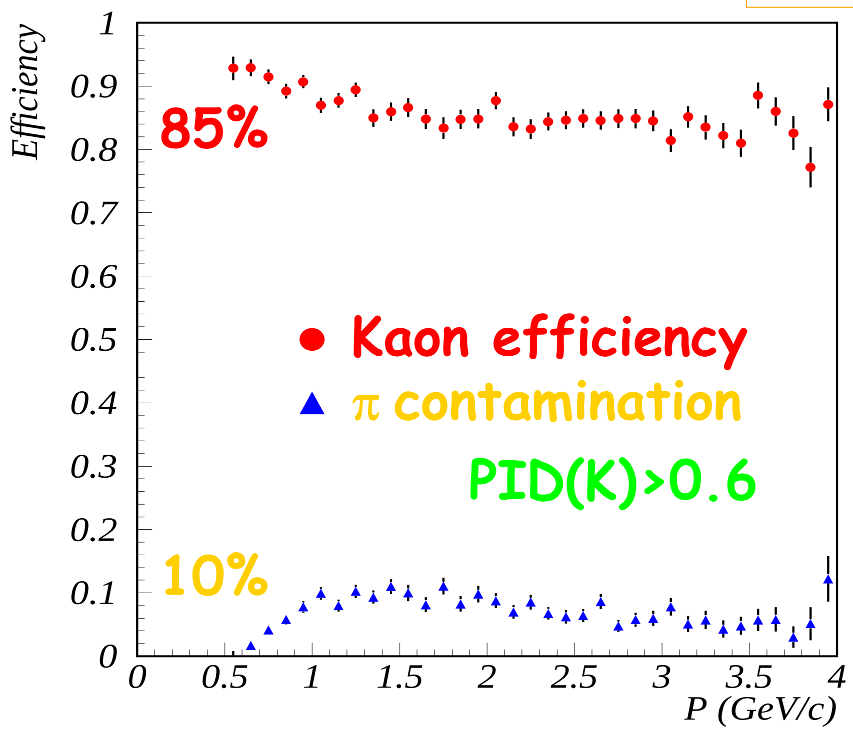
- Muon ID: by KLM
  - 14 layers of glass resistive plate chambers (RPC) in iron yoke

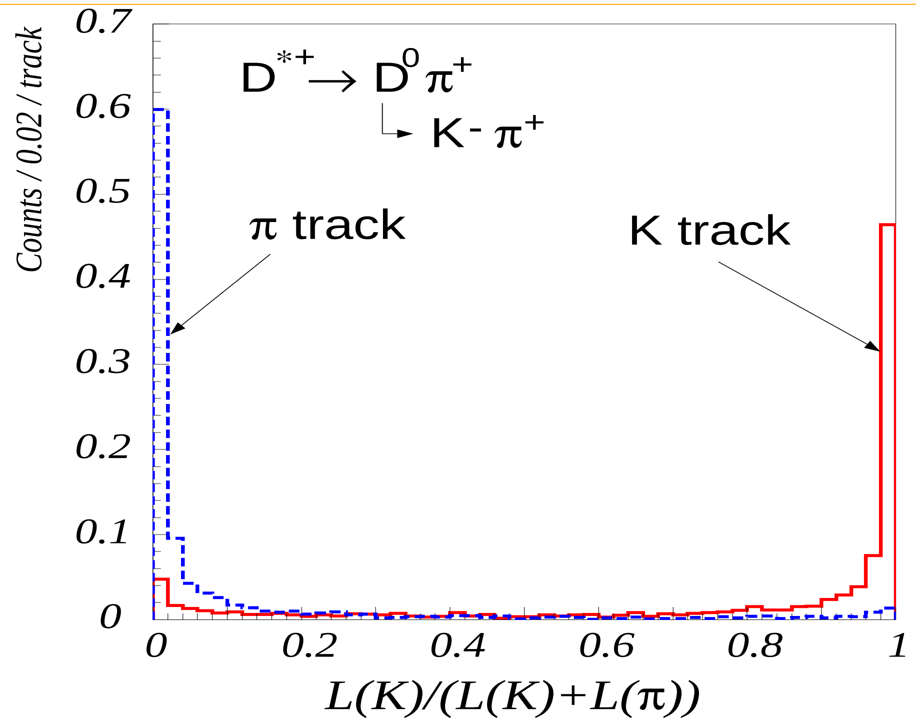


Kaon identification

- **We measure efficiency, fake rate using D*s**







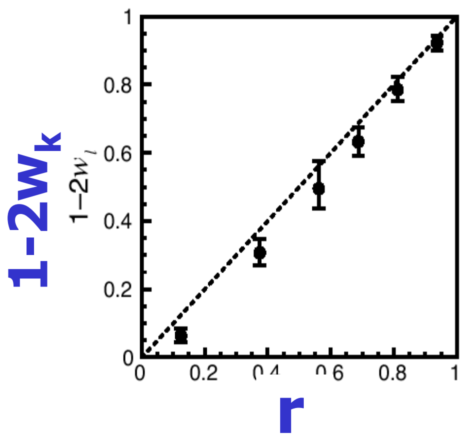
Wrong tagging fraction: w_k

- Get w_k from $B\bar{B}$ mixing amplitude using $B \to D^* l \nu$ events

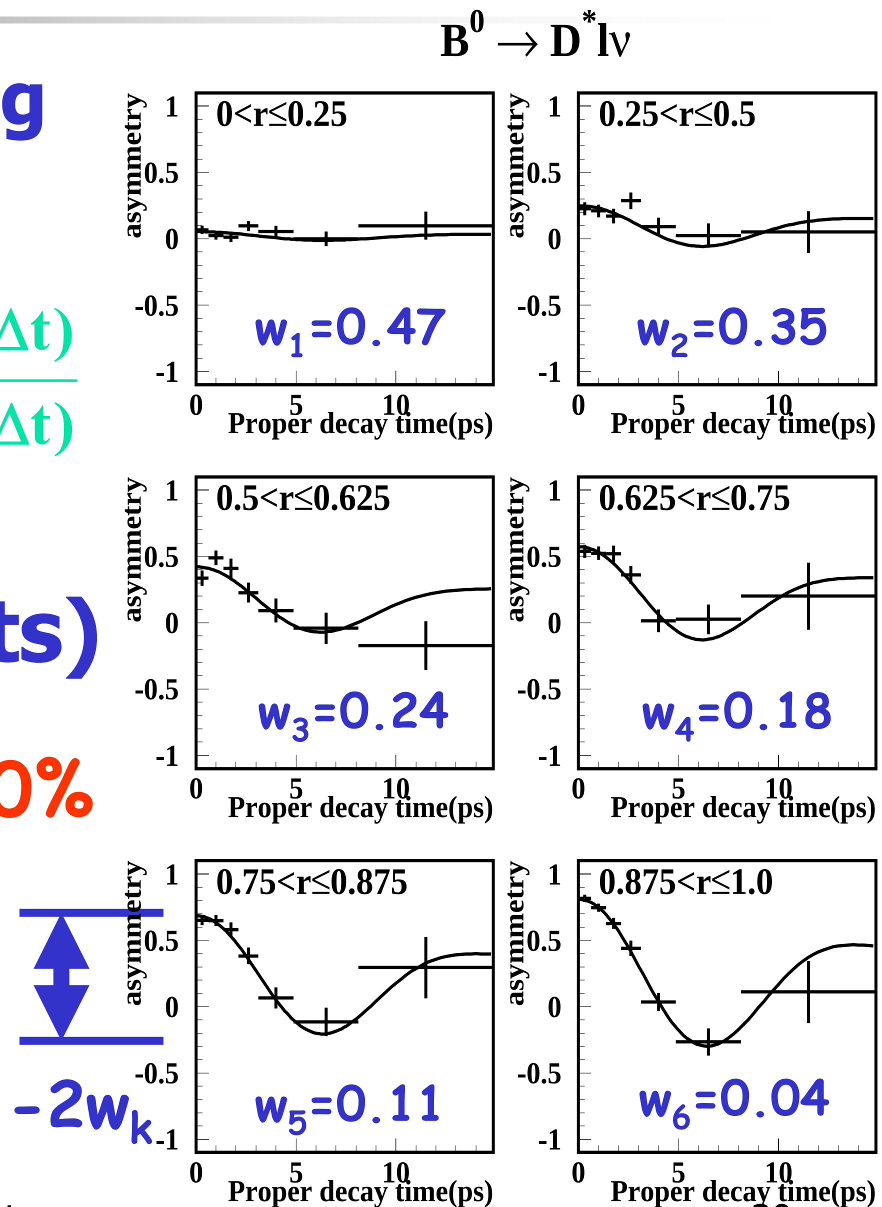
$$A(\Delta t) \equiv \frac{P_{Opposite-Flavor}(\Delta t) - P_{Same-Flavor}(\Delta t)}{P_{Opposite-Flavor}(\Delta t) + P_{Same-Flavor}(\Delta t)}$$

$$\approx (1-2w)\cos(\Delta m_B \Delta t)$$

(r:to categorize events)



Efficiency~100%
Effective efficiency is 27.0±1.2%



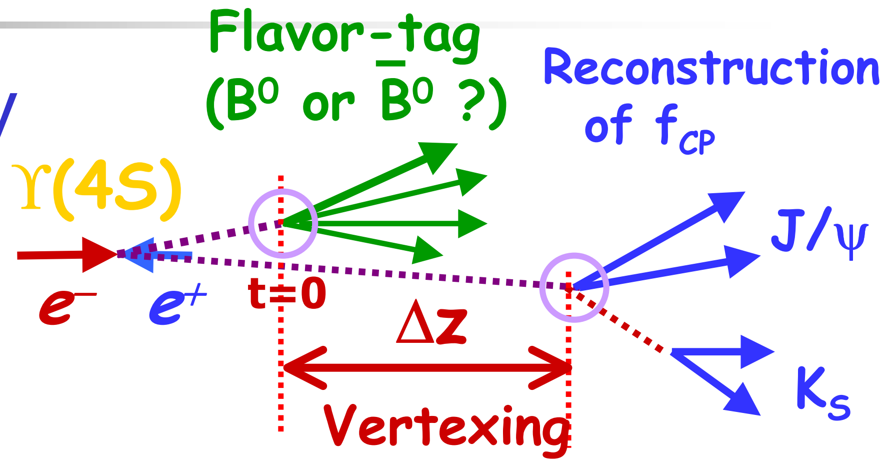
Measure decay time difference

$\Delta t = \Delta z / \beta\gamma c$ is measured by

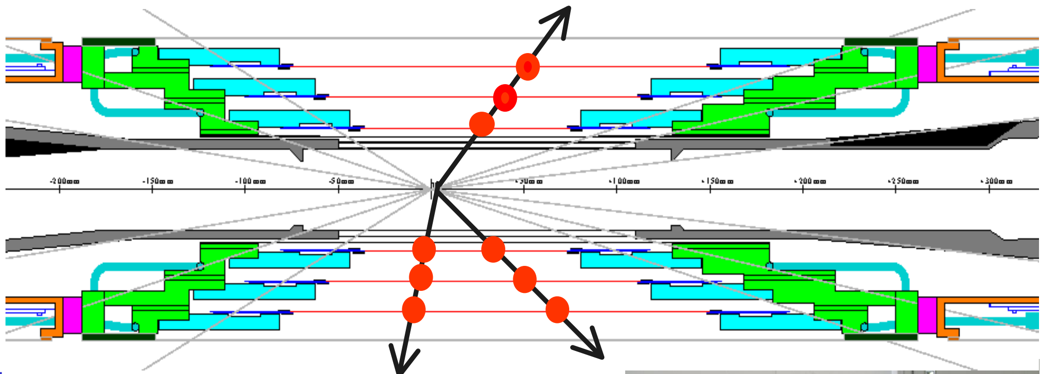
SVD : 3 layers of Double Sided Silicon Detectors (DSSD)

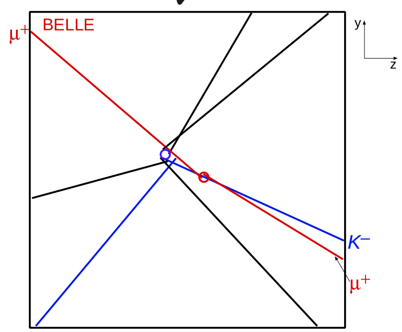
$\sigma_{rf} = 19 \oplus 50/p\beta\sin^{3/2}\theta$ (μm)

$\sigma_{z} = 36 \oplus 42/p\beta\sin^{5/2}\theta$ (μm)

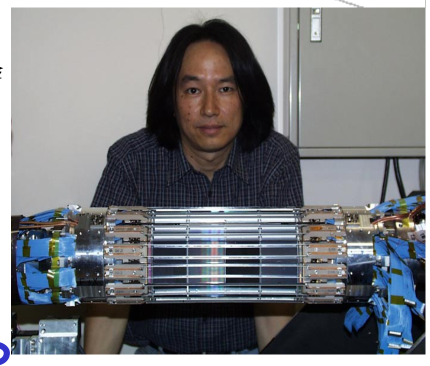


- For CP-side, use $J/\psi \to l^+l^-$
  - $\sigma z_{CP} \approx 75\ \mu$m
  - $\varepsilon \approx 92\%$
- For Tag-side,
  - use tracks other than those in CP side
  - iterate: discard worst track
  - $\sigma z_{tag} \approx 140\mu m \Leftarrow$ Charm effect
  - $\varepsilon \approx 91\%$
- Require $|z_{CP} - z_{tag}| < 2$mm ($\gg 10\tau_B$)





y-z view near IP



Resolution function $R(\Delta t-\Delta t')$

Measured Δt: smeared by detector resolution & charm lifetimes

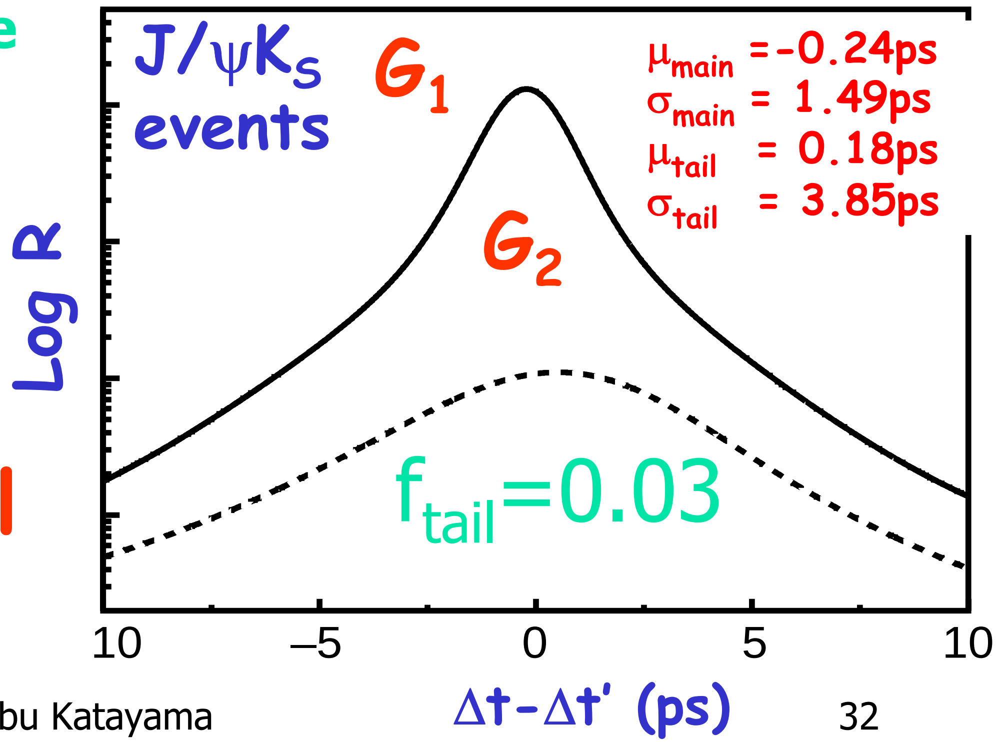
Resolution function: a sum of two Gaussians

$$R(\Delta t-\Delta t')=(1-f_{tail})\times G_1(\Delta t-\Delta t';\mu_{main},\sigma_{main})+f_{tail}\times G_2(\Delta t-\Delta t';\mu_{tail},\sigma_{tail})$$

SVD vertex resolution
Charmed meson lifetime

Poorly reconstructed tracks

- σ/μ :
  Calculated event by event from vertex fit errors
- Average Δt error: 1.5ps



After vertexing, total of 1137 events left

Validation for R: B lifetimes

B lifetimes are measured using the same R

τ_{B^0} = 1.55 ± 0.02ps

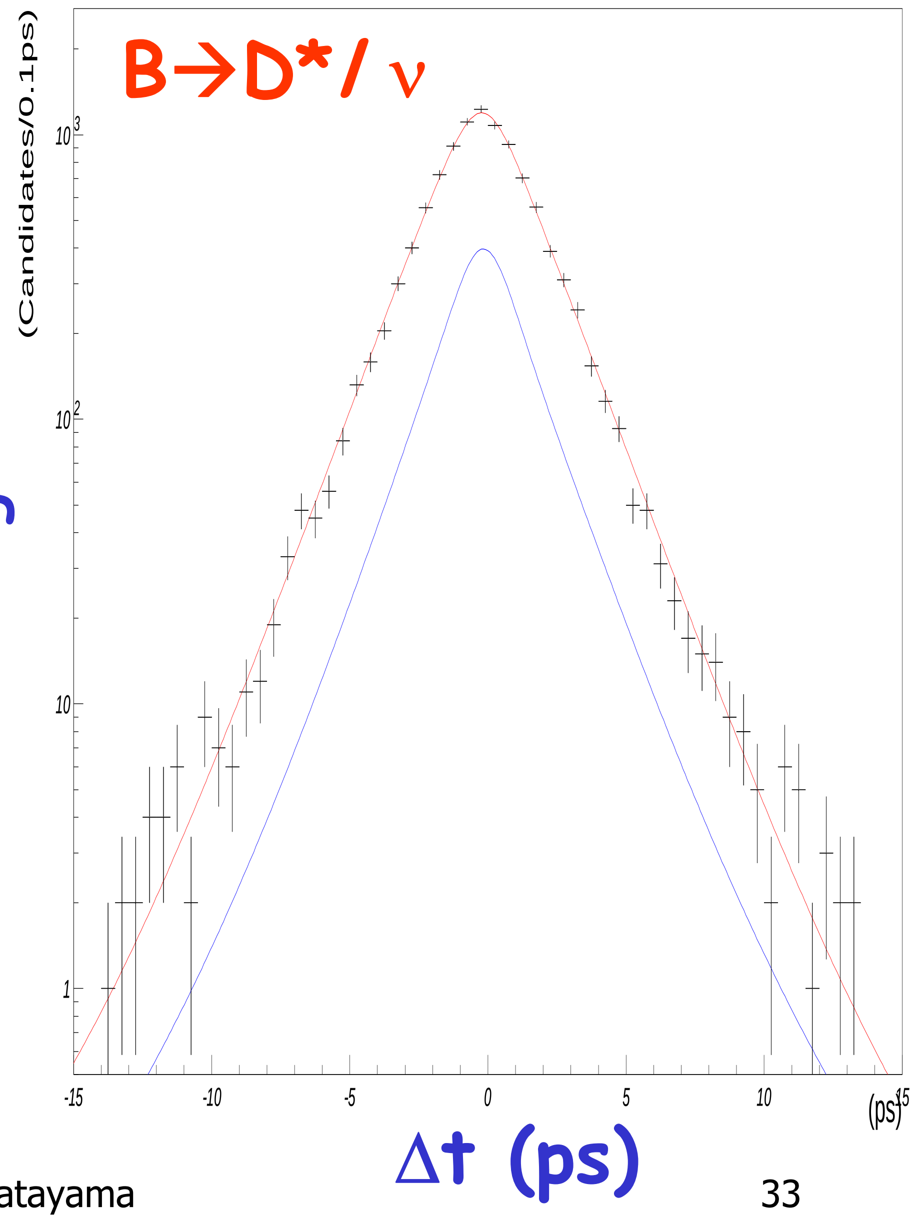
(PDG: 1.55 ± 0.03ps)

τ_{B^+} = 1.64 ± 0.03ps

(PDG: 1.65 ± 0.03ps)

Agree very well with the world averages

Very small error



Maximum likelihood fit for $\sin 2\phi_1$

Estimate $\sin 2\phi_1$ using event by event likelihood f.

$$L_{event} = \int ((1 - f_{BG})PDF_{sig} + f_{BG} PDF_{BG}) \times R(\Delta t - \Delta t')d\Delta t'$$

f_{BG} : background function, R : resolution function

PDF : Probability density function

$$PDF_{sig} = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B}\left(1 - \xi_f q(1 - 2w)\sin 2\phi_1 \sin \Delta m_B \Delta t\right)$$

$$PDF_{BG} = f_\tau \frac{e^{-|\Delta t|/\tau_{BG}}}{2\tau_{BG}} + (1 - f_\tau)\delta(\Delta t)$$

ξ_f : ± 1 for CP= ± 1

q : tagged flavor

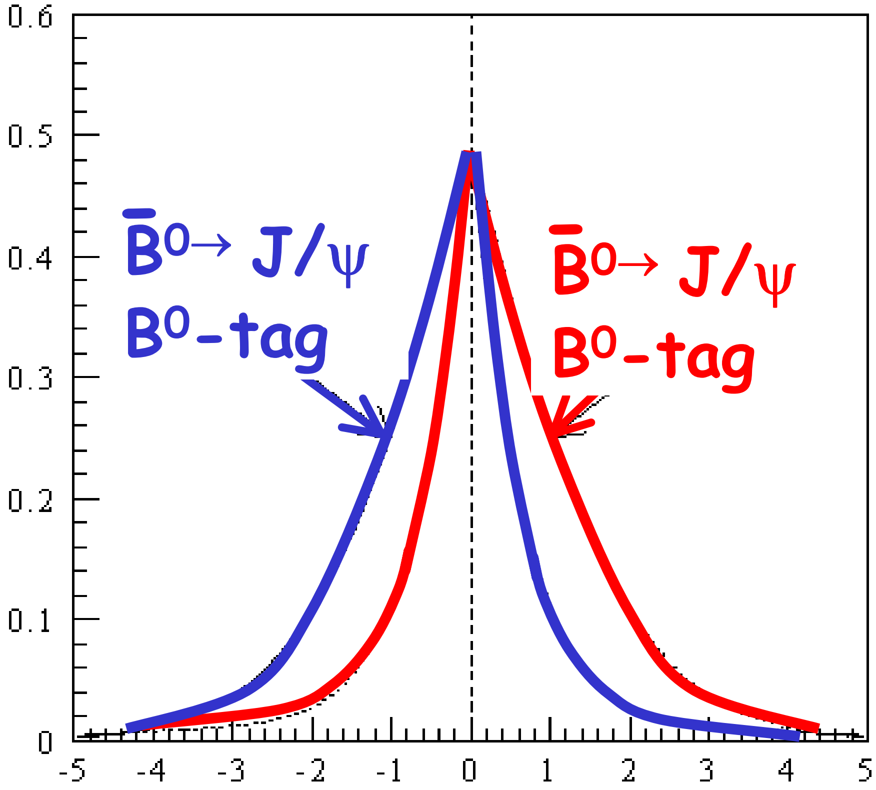
W : wrong tag fraction

Δm_B, τ_B : from PDG

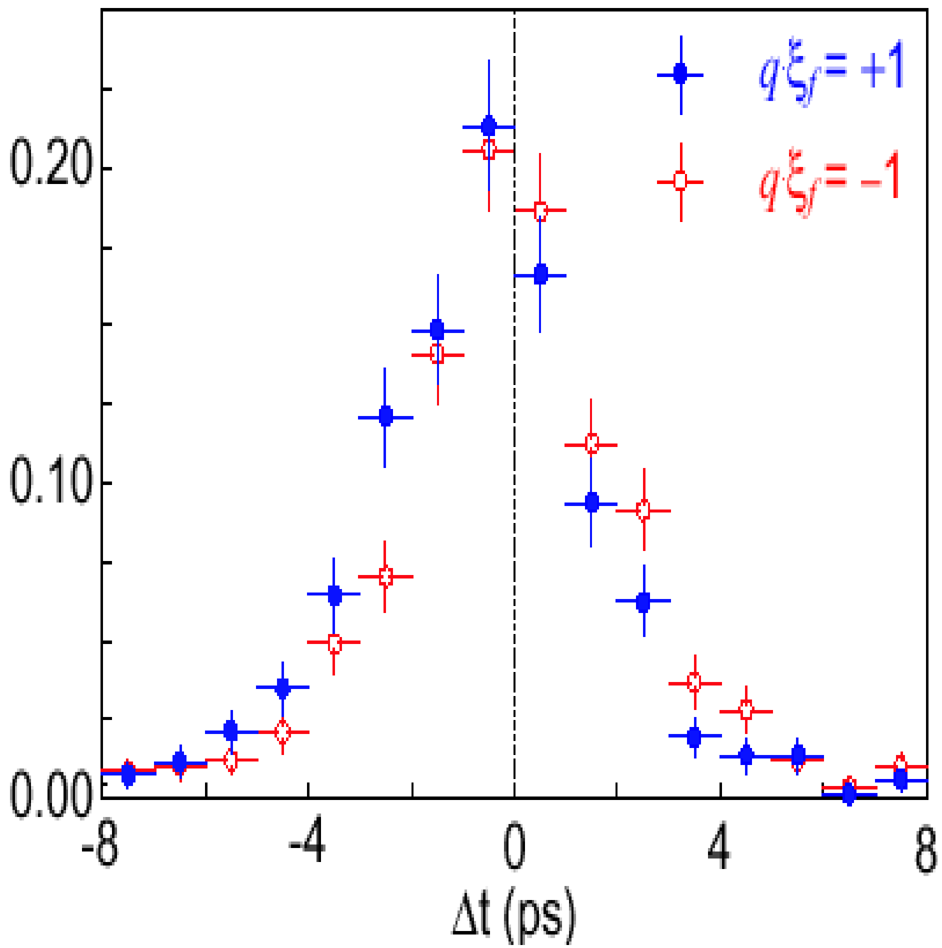
τ_{BG}, f_τ : MC and side band data

$\sin 2\phi_1$ is the only free parameter in the fit

What we want to observe



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

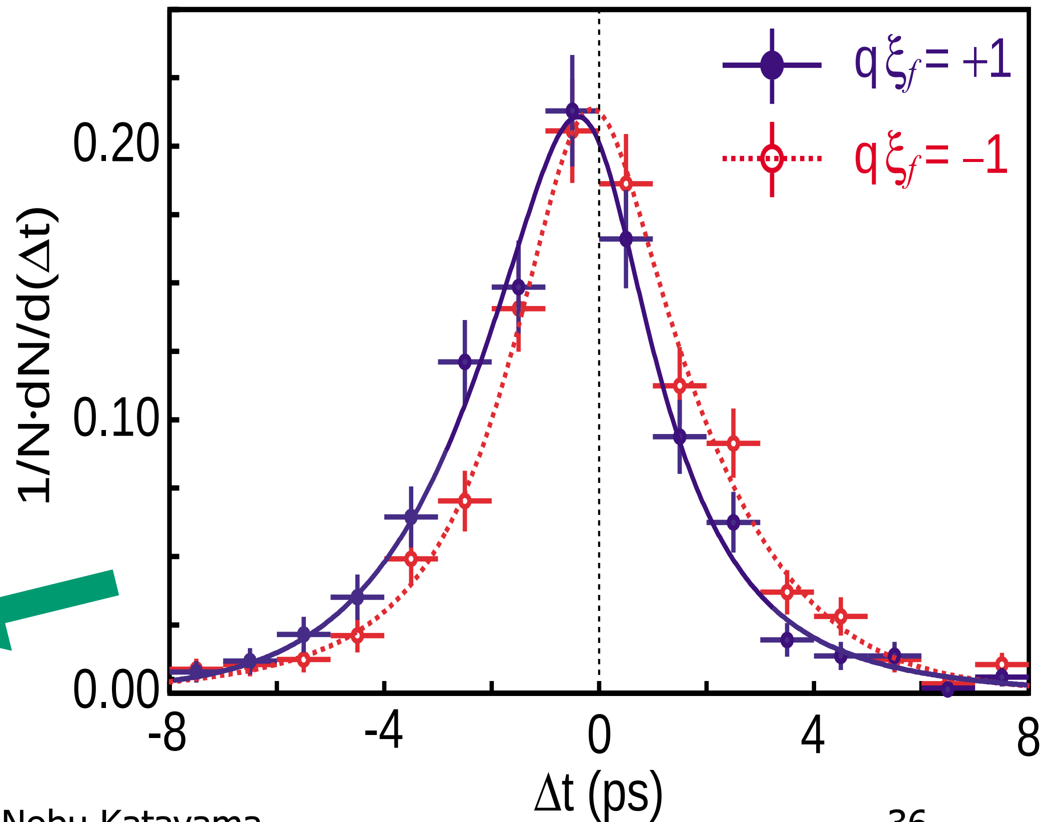


Result of the fit: $\sin2\phi_1$

Maximizing log*L* sum, we obtained

$$\sin2\phi_1 = 0.99 \pm 0.14(stat) \pm 0.06(sys)$$

We observed CP violation in B meson system



- **Curves are from the result of unbinned fit**
- **$q\xi_{f+}$ +1 and −1 are shown separately**

Δt binned asymmetry plots

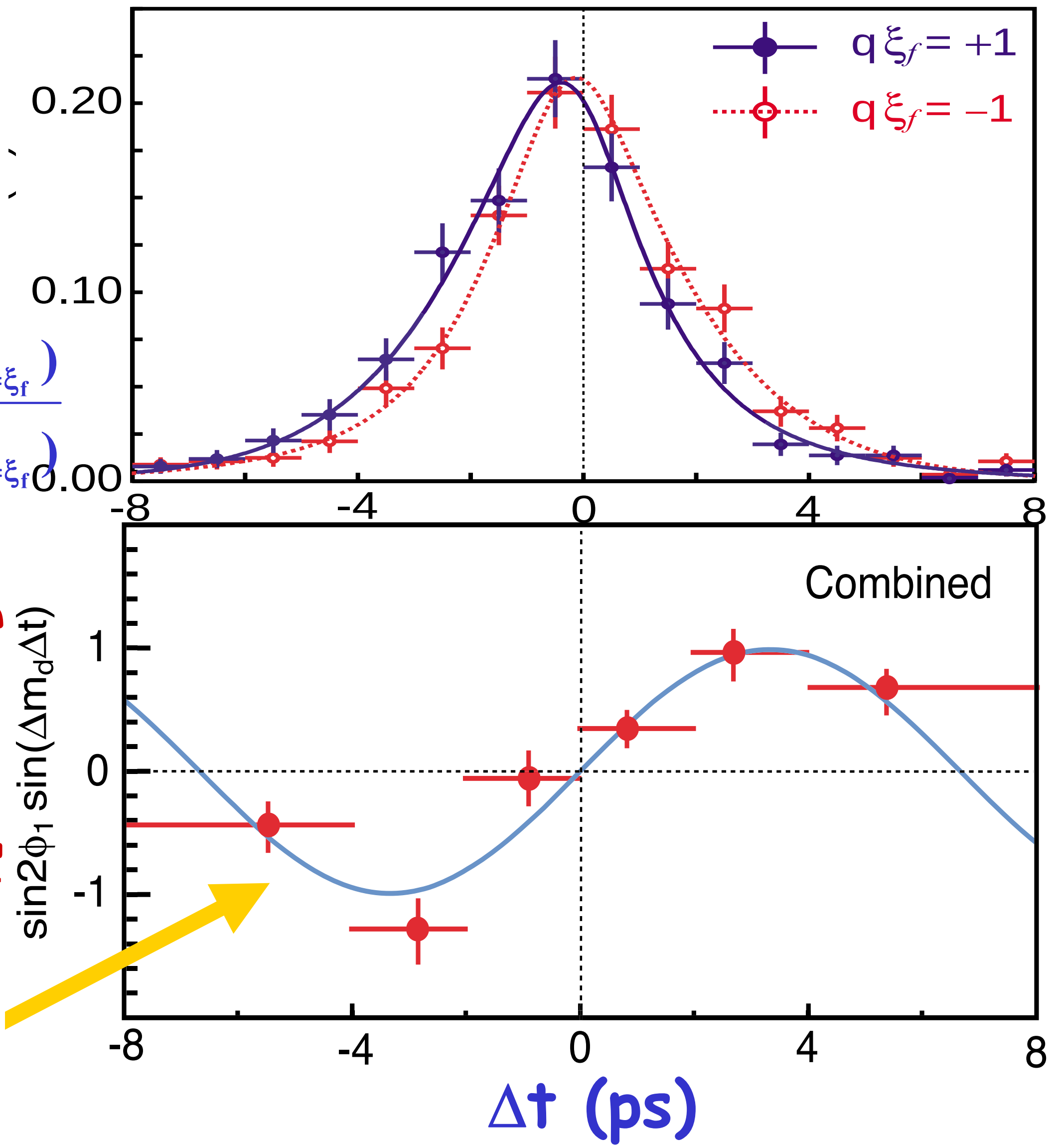
Δt dependent (binned) asymmetry

$$\equiv \frac{\Gamma(\overline{B^0_d}(\Delta t) \to f_{CP=\xi_f}) - \Gamma(B^0_d(\Delta t) \to f_{CP=\xi_f})}{\Gamma(\overline{B^0_d}(\Delta t) \to f_{CP=\xi_f}) + \Gamma(B^0_d(\Delta t) \to f_{CP=\xi_f})}$$

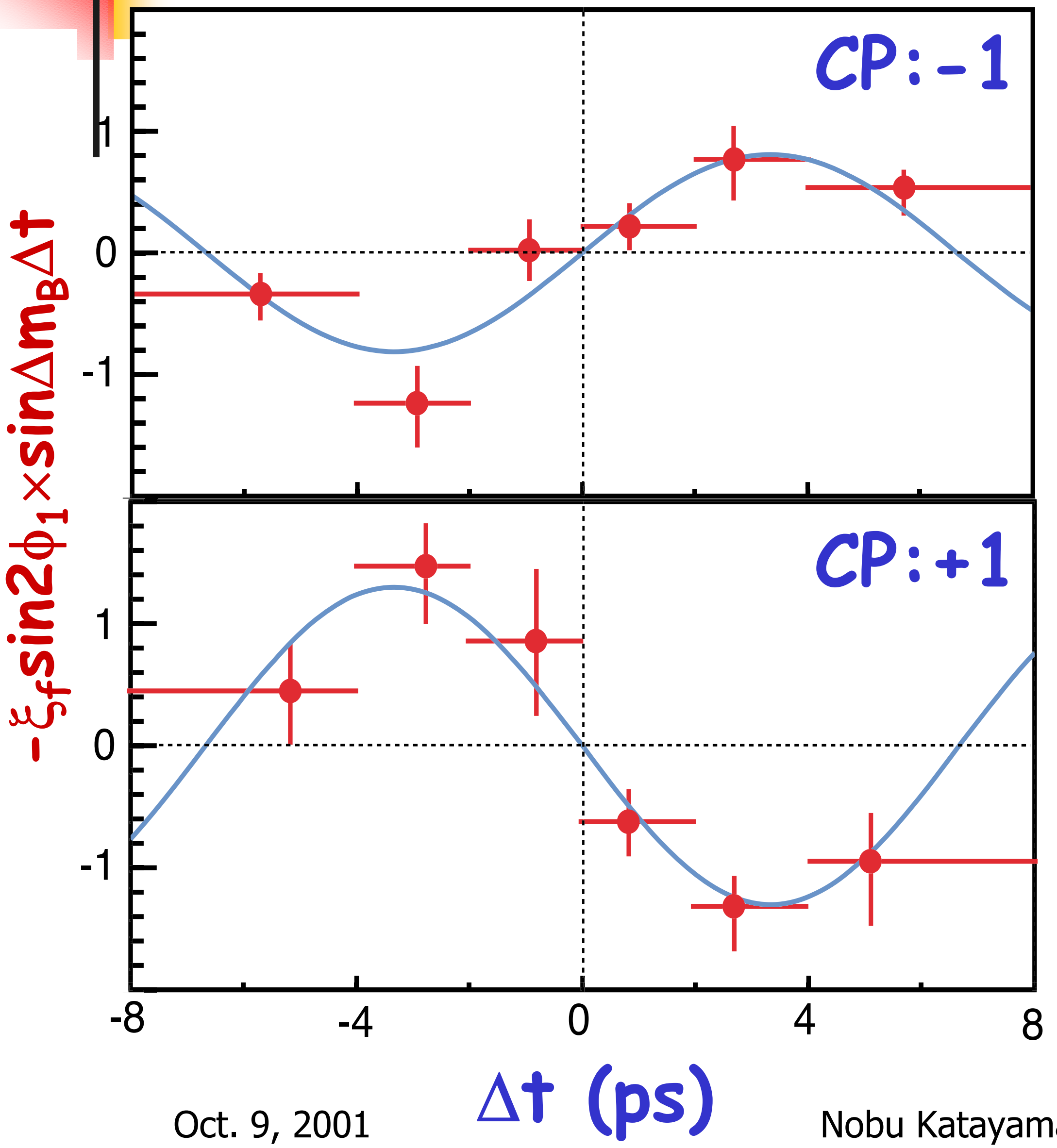
$$= -\xi_f \sin 2\phi_1 \times \sin \Delta m_B \Delta t$$

Δt dependence as expected from the max. likelihood fit

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



CP=−1/CP=+1 fitted separately



0.84 ± 0.17
Statistical error

⇑

$\sin 2\phi_1$

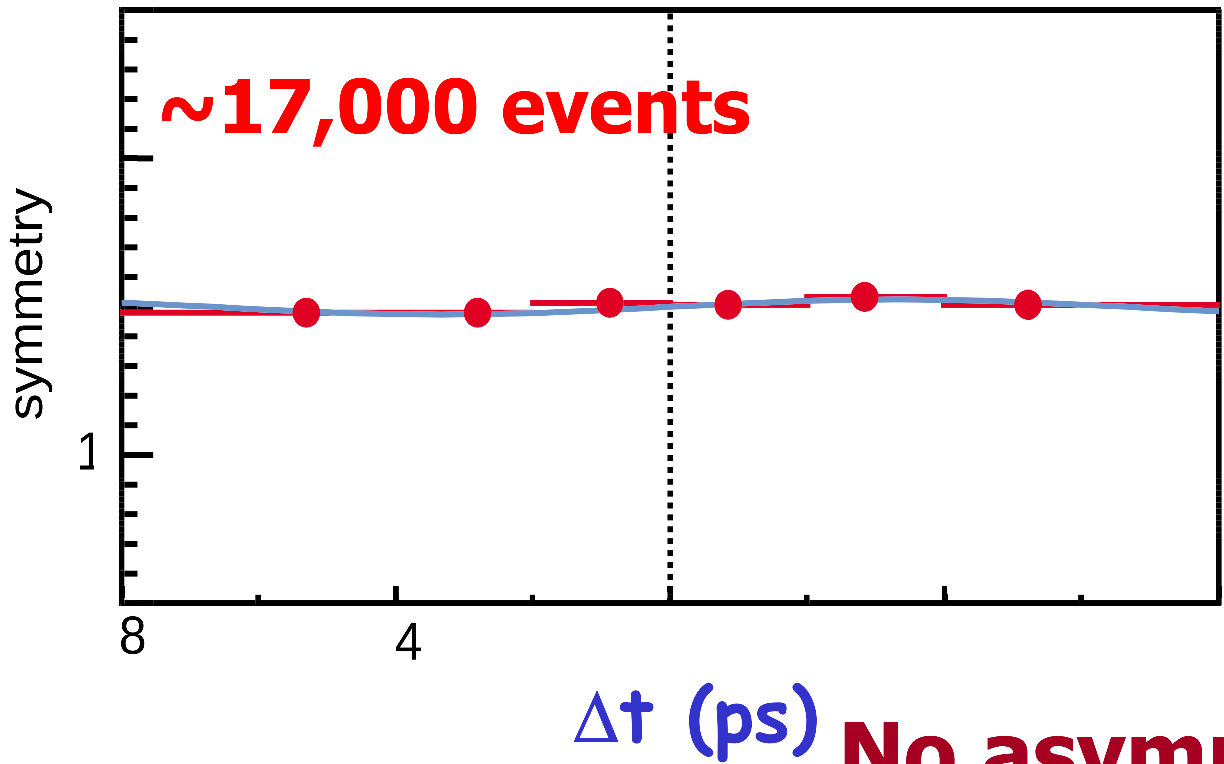
⇓

1.31 ± 0.23
Statistical error

Distribute oppositely
Agrees within errors

Control sample: non-CP modes

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



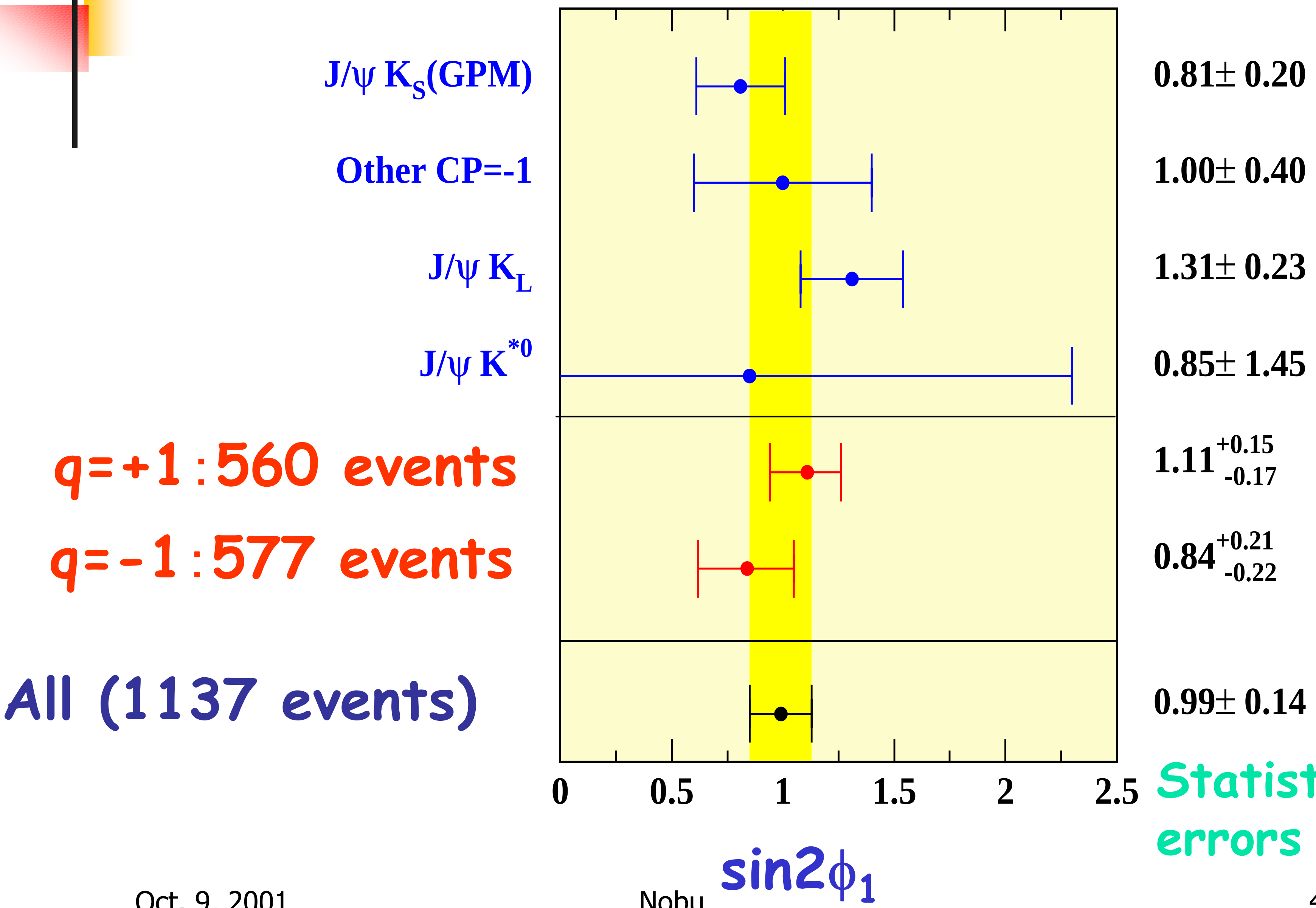
"$\sin 2\phi_1$"

$= 0.05 \pm 0.04$

Statistical error only

No asymmetry observed

$\sin 2\phi_1$ from various subsamples



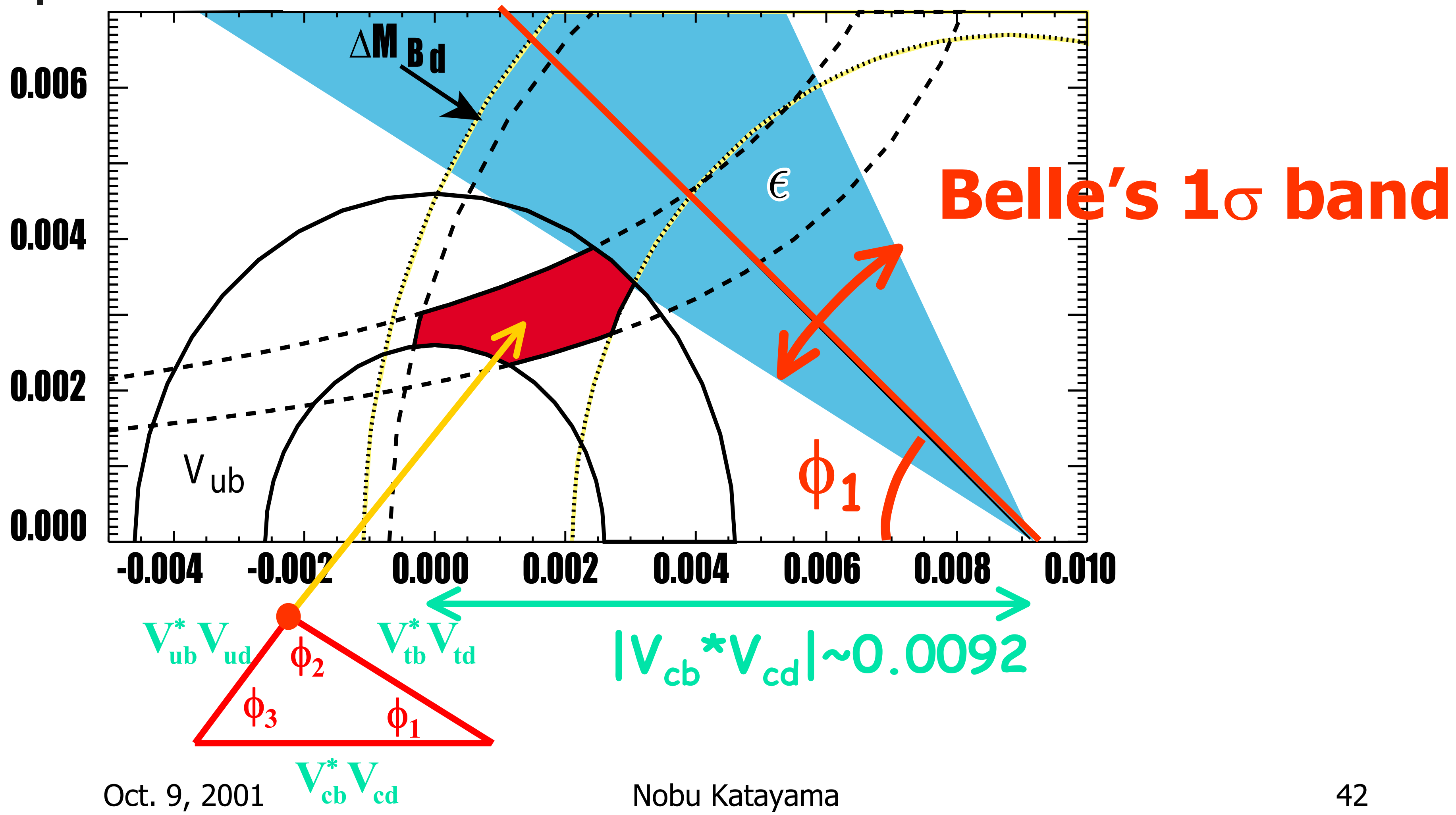
Statistical errors only

Systematic errors

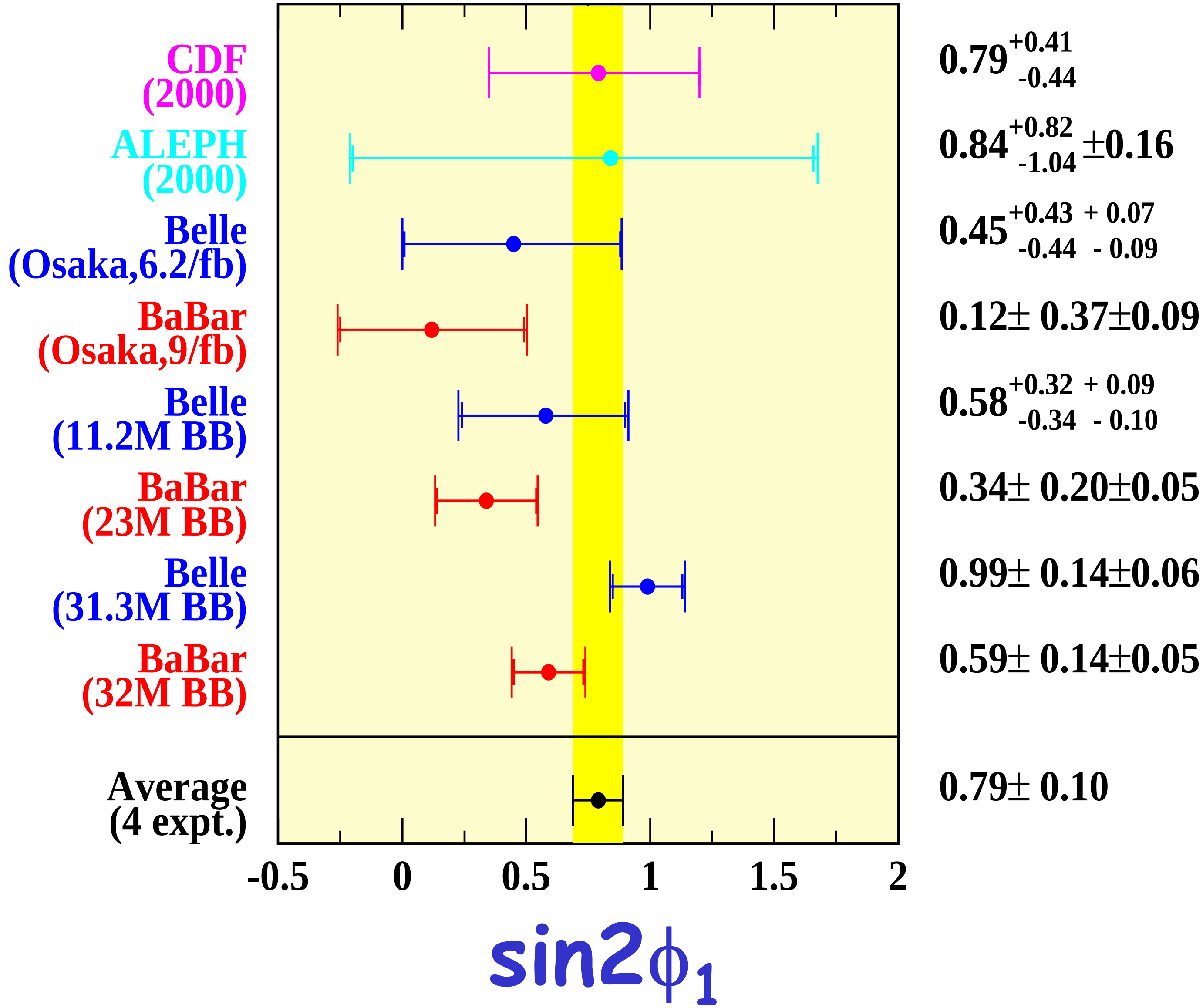
Vertexing algorithm	± 0.04
Flavor tagging	± 0.03
Resolution function	± 0.02
K_L background fraction	± 0.02
Background shapes	± 0.01
Δm_d and τ_{B0} errors	± 0.01
Total	± 0.06

Belle in the unitarity triangle

Unitarity triangle in PDG2001



Compare with other experiments



Prospects

Is Triangle triangle?

$$\left\{\begin{array}{l} V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \\ \phi_1 + \phi_2 + \phi_3 = \pi \end{array}\right.$$

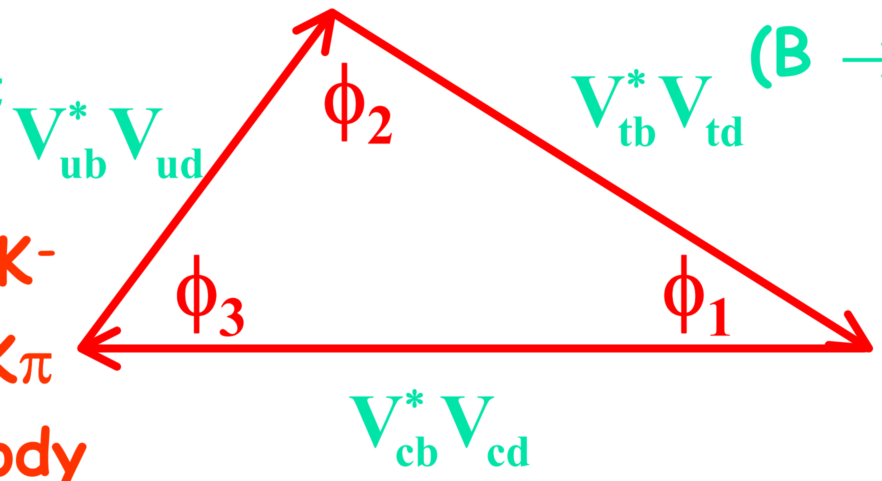
$B \to \pi l \nu$

$B \to D_S \pi$

$B \to \pi\pi,\ \rho\pi$

f_B: $B \to l \nu$

$(B \to \rho\gamma)$



$B^- \to D_{CP} K^-$

$B \to \pi\pi / K\pi$

$B \to 3$ body

$B^0 \to (c\bar{c}) K^{(*)0}$

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

$B^0 \to \eta' K_S,\ \phi K_S$

$B^0 \to D^{(*)-} l^+ \nu$

If
$$\left.\begin{array}{l} V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} \neq 0 \\ \phi_1 + \phi_2 + \phi_3 \neq \pi \\ \phi_i(A) \neq \phi_i(B) \end{array}\right\}$$
New Physics!

Summary and conclusions

- KEKB accelerator has achieved
  $4.5\times10^{33}\ cm^{-2}s^{-1}$
- Belle has analyzed 31×10^{6} BB events and observed CP violation in the neutral B meson system

$$\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06$$

$(>6\sigma$ or $>99.999\%!)$

- KEKB/Belle plans to accumulate 300 fb^{-1} in 5 years and 3,000 fb^{-1} in 10 years and contribute to the physics of the flavor sector