Belle Results on *CP* Violation

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For Belle Collaboration

Les Rencontres de Physique
de la Vallée d'Aoste
La Thuile, Mar. 6 2002

Outline:

Introduction (KEKB and Belle)

$\sin 2\phi_1$ measurement

- Event reconstruction
- Vertex reconstruction
- Flavor tagging
- Fitting

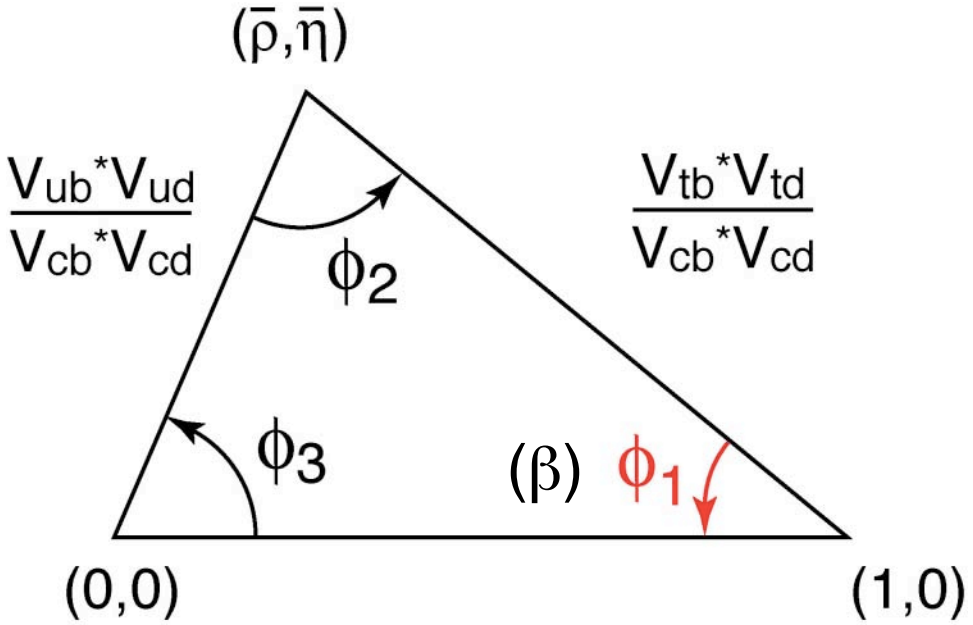
Results and prospects

Goal: Test of KM Model

CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

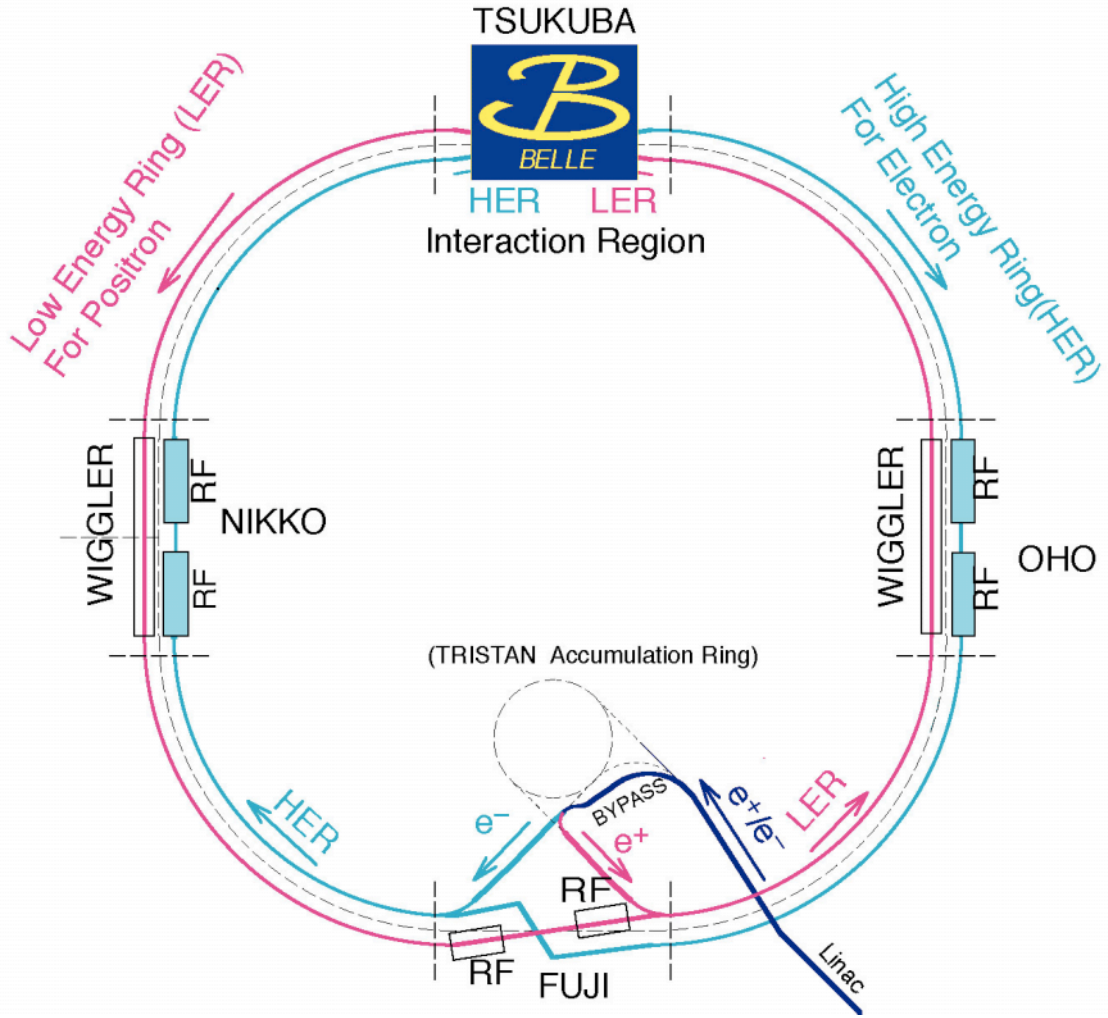
Wolfenstein parametrization



KEKB Collider

Asymmetric e^+e^- collider.

- Two separate rings
  8.0GeV e^- (HER)
  3.5GeV e^+ (LER) [$\beta\gamma$=0.425]
- E_{CM}: 10.58GeV (at Υ(4S))
- Design Luminosity: 10^{34} $cm^{-2}s^{-1}$.
- Beam size: $\sigma_y \approx 3\mu m$
  $\sigma_x \approx 100\mu m$
- ±11mrad crossing angle

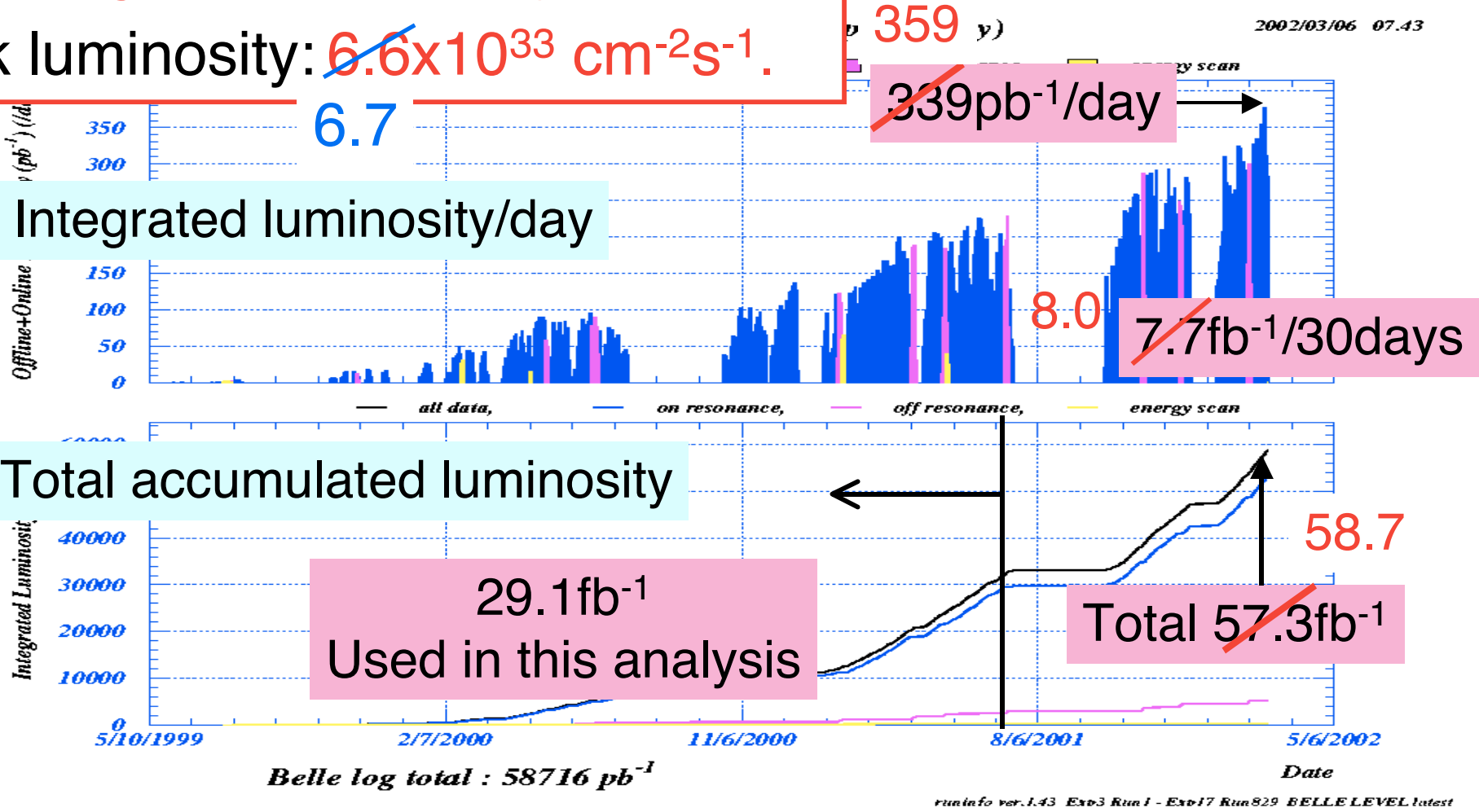


KEKB Performance

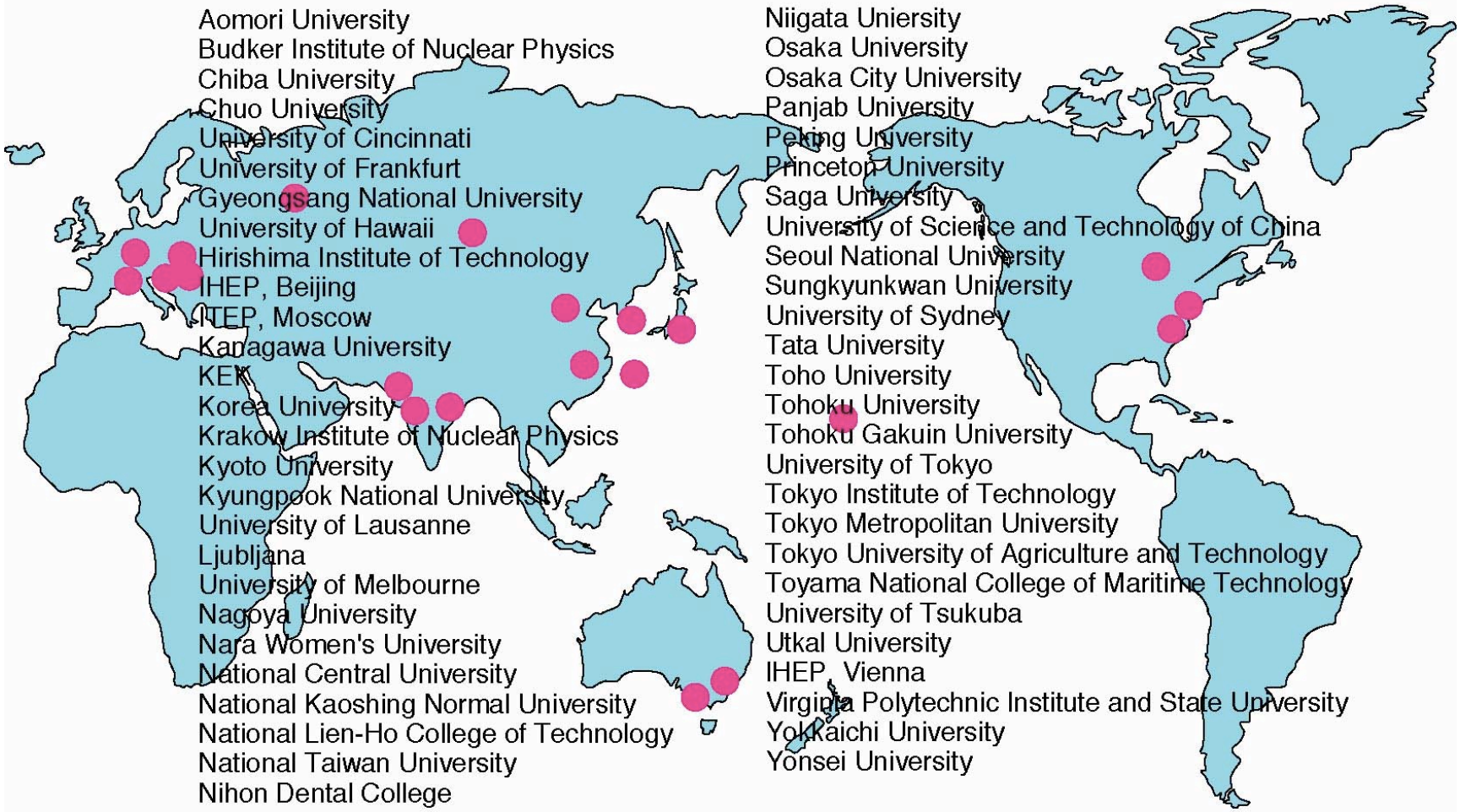
World Highest Luminosity Machine.

Peak luminosity: ~~6.6~~6.7x10^{33} cm^{-2}s^{-1}.

still improving!



BELLE Collaboration



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Krakow Institute of Nuclear Physics
Kyoto University
Kyungpook National University
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National Central University
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University of Tsukuba
Utkal University
IHEP, Vienna
Virginia Polytechnic Institute and State University
Yokkaichi University
Yonsei University

World-wide collaboration of ~50 institutions, ~300 people

Belle Detector

Silicon Vertex Detector (**SVD**)

- σ~55μm for 1GeV/c@90°

Central Drift Chamber (CDC)

- σ_p/p~0.35%@1GeV/c
- $\sigma_{dE/dx}$~7%

Aerogel Cerenkov Counter (ACC)

- n=1.01-1.03

Time of Flight counter (TOF)

- σ_{TOF}~95ps

K/π 3.5 GeV/c

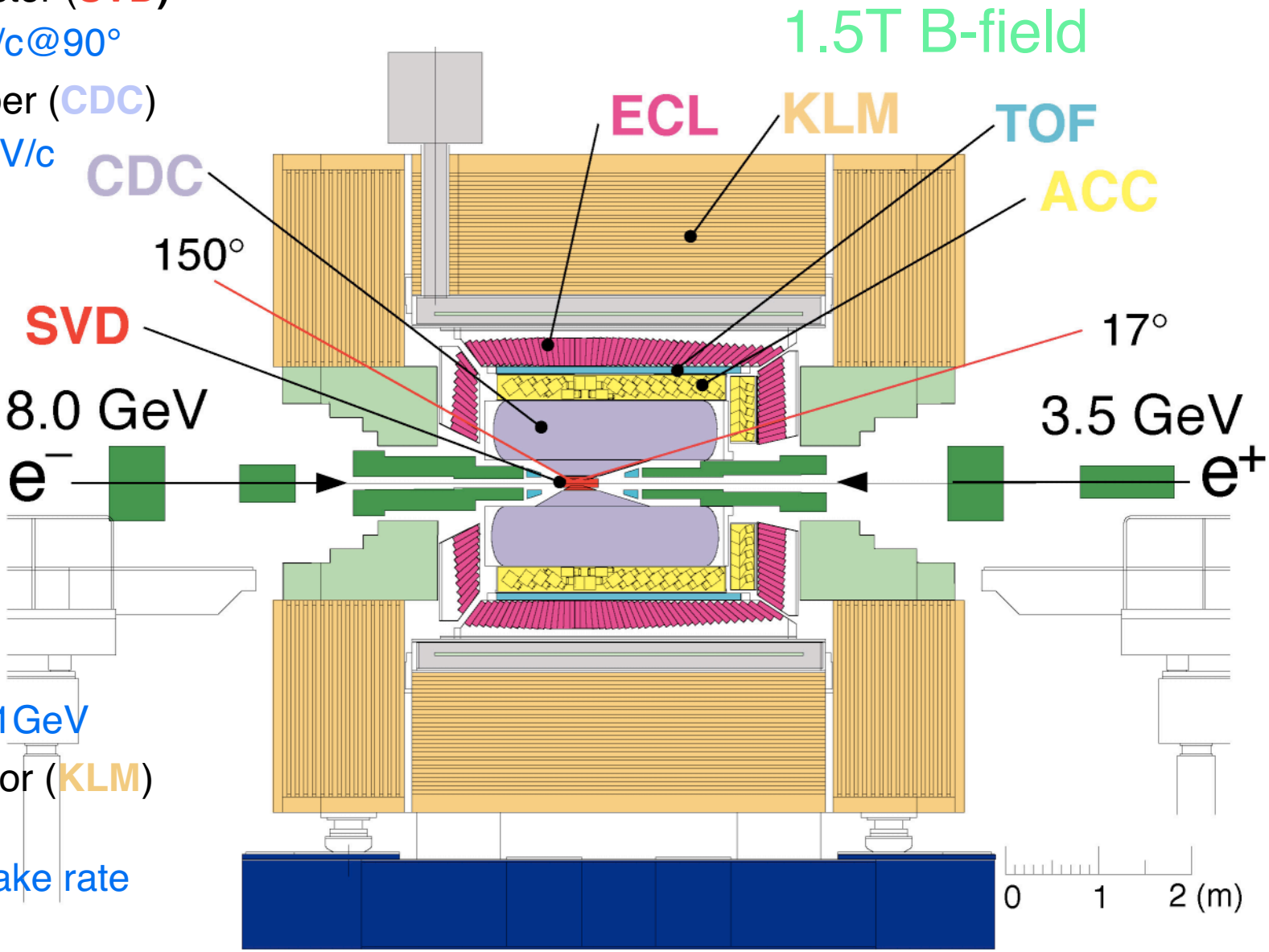
Electromagnetic Calorimeter (ECL)

- CsI: σ_E/E_γ~1.8%@1GeV

K_L and Muon detector (KLM)

- RPC 14layers:

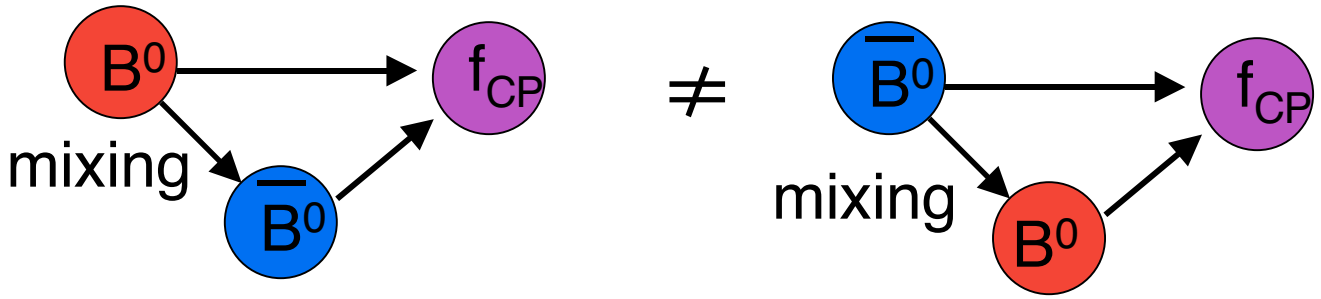
μ eff. >90%; ~2% fake rate



M.Yokoyama (U. Tokyo)

Time-dependent CP Asymmetry in $B^0 \to (c\bar{c})K^0$

Mixing-induced CP violation.



$$A(\Delta t) \equiv \frac{\Gamma(\bar{B}^0 \to J/\psi K^0) - \Gamma(B^0 \to J/\psi K^0)}{\Gamma(\bar{B}^0 \to J/\psi K^0) + \Gamma(B^0 \to J/\psi K^0)} = -\xi_f \sin 2\phi_1 \sin(\Delta m \Delta t)$$

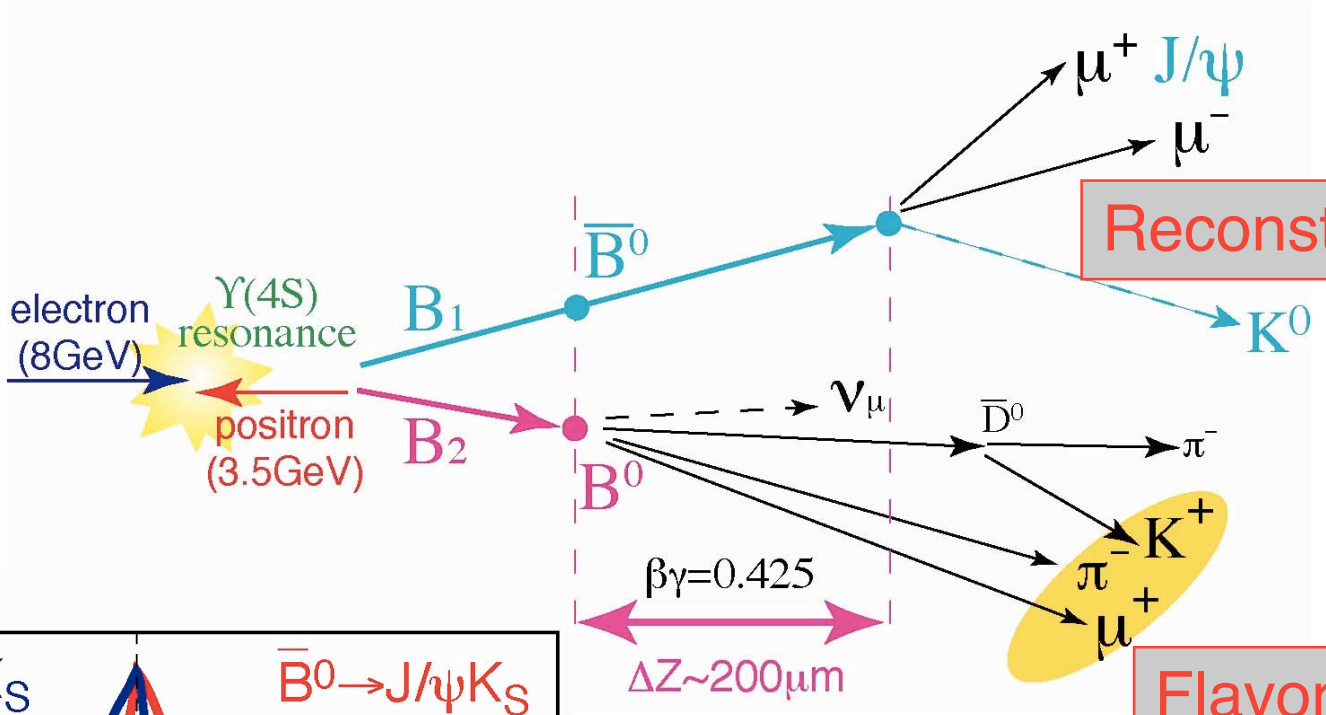
ξ_f: CP eigenvalue — $+1$ ($c\bar{c}K_L$), -1 ($c\bar{c}K_S$)

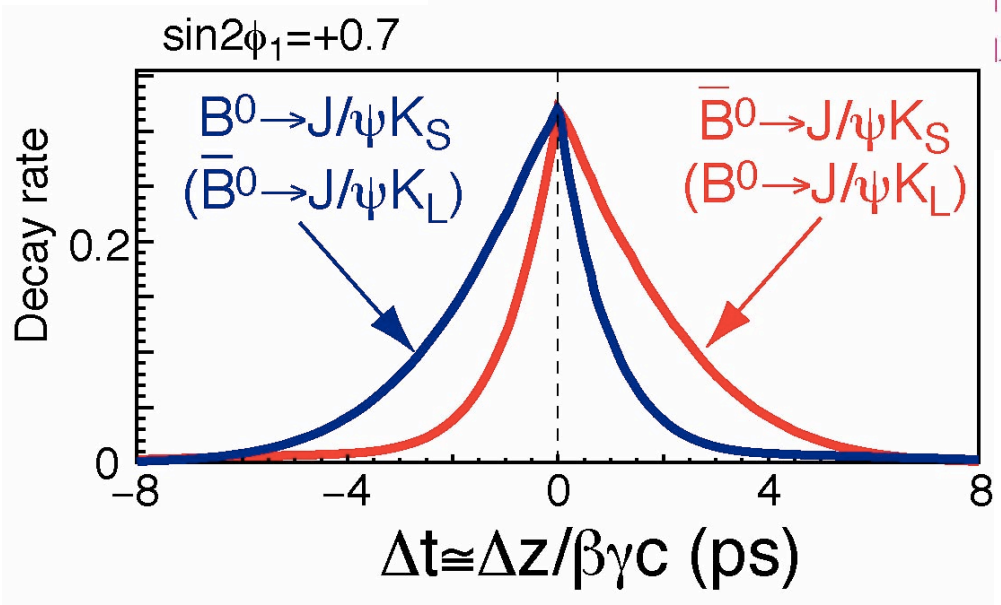
$c\bar{c}\,K^0$: Theoretically & Experimentally clean

- $\approx$single weak phase
- signal of J/ψ ($\to l^+l^-$)

"Golden" mode for CPV measurement.

Measurement Principle





CP Eigenstates Reconstruction

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

$B_{CP} \rightarrow$

$J/\psi\ Ks(\rightarrow \pi^+\pi^- \ \&\ \pi^0\pi^0)$
$\psi(2S)(\rightarrow l^+l^- \ \&\ J/\psi\pi^+\pi^-)\ Ks$
$\chi_{c1}(\rightarrow J/\psi\gamma)\ Ks$
$\eta_c(\rightarrow K^+K^-\pi^0 \ \&\ KsK^+\pi^-)\ Ks$

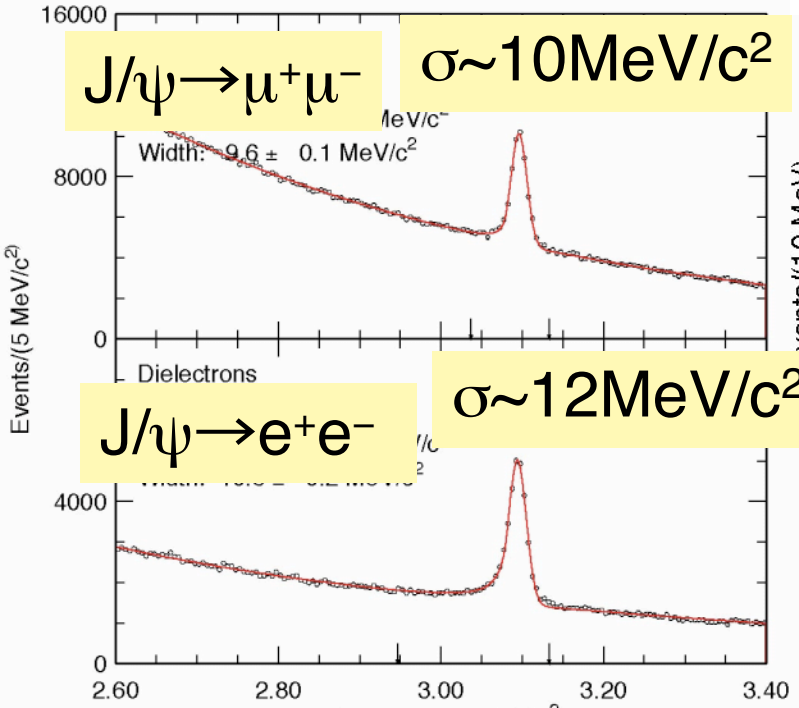
$\xi_f = -1$

$J/\psi\ K_L$
$J/\psi\ K^{*0}\ (\rightarrow K_S\pi^0)$

$\xi_f = +1$
$(81\%\ \xi_f = +1)$
[full angular analysis]

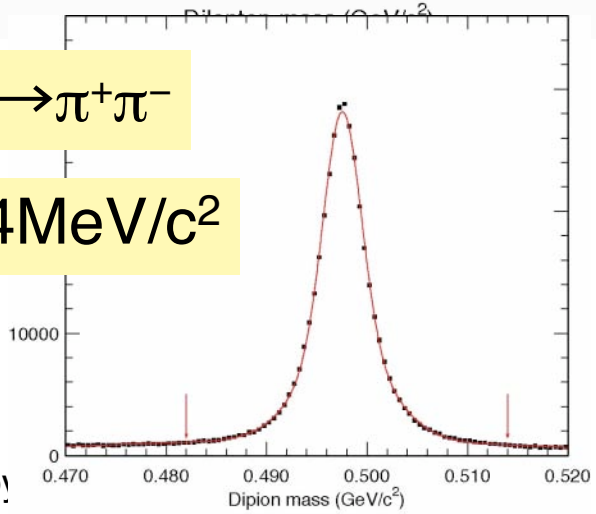
Reconstruction: J/ψ K_S

$J/\psi \to \mu^+\mu^-$ $\sigma \sim 10 MeV/c^2$

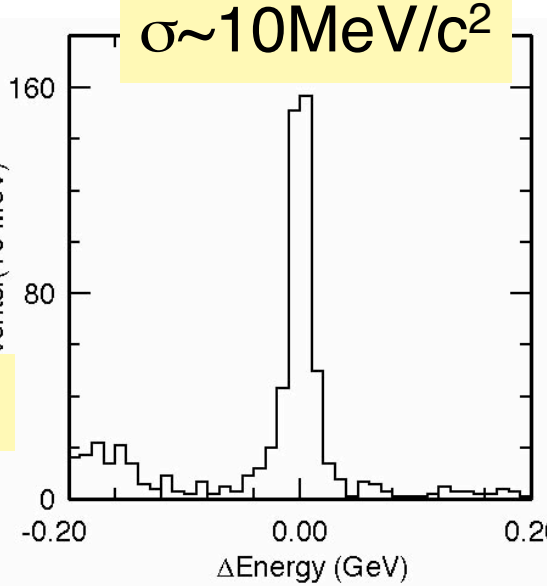


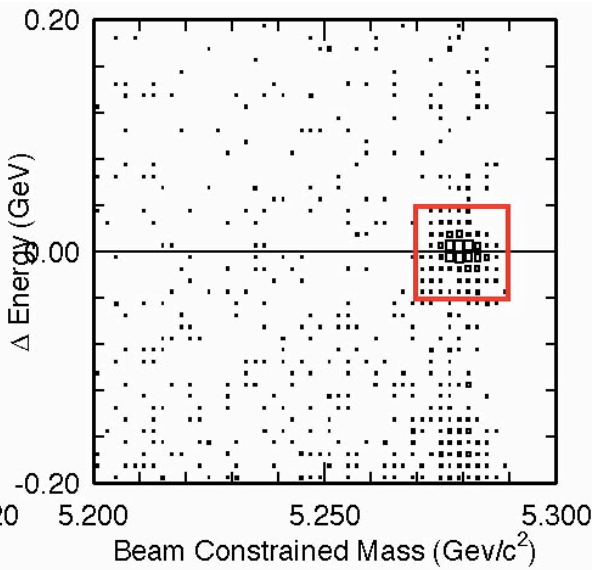
$J/\psi \to e^+e^-$ $\sigma \sim 12 MeV/c^2$

$K_S \to \pi^+\pi^-$ $\sigma \sim 4 MeV/c^2$



$\sigma \sim 10 MeV/c^2$

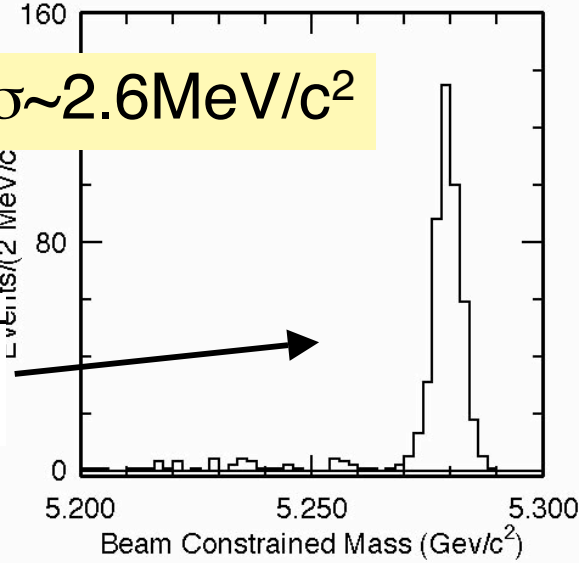




$\Delta E = E_B^* - E_{beam}^*$

$M_{bc} = \sqrt{(E_{beam}^*)^2 - (p_B^*)^2}$

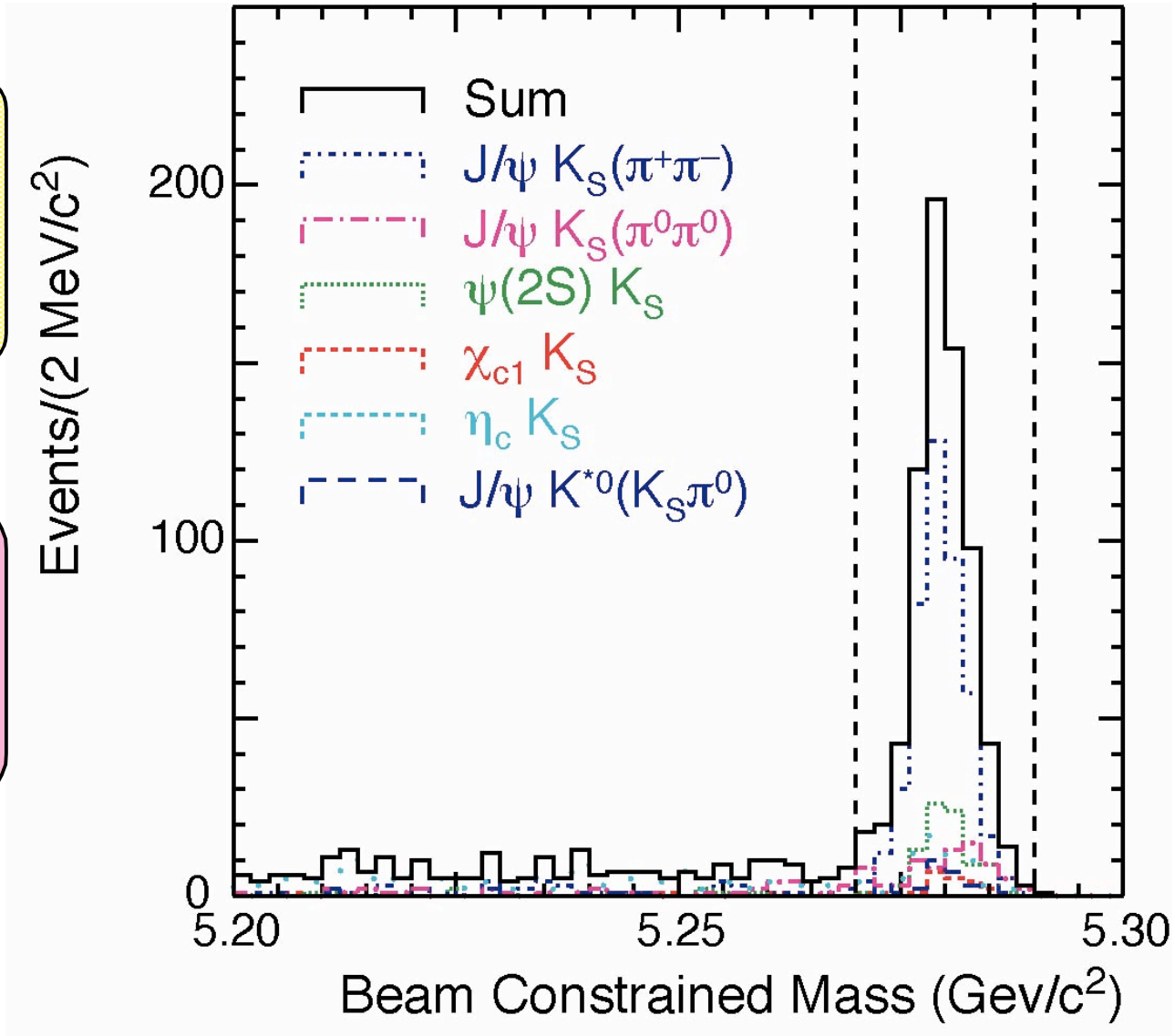
$\sigma \sim 2.6 MeV/c^2$



Charmonium+$K_S(K^{*0})$ modes

$J/\psi\ K_S(\pi^+\pi^-)$
457 candidates
purity=97%

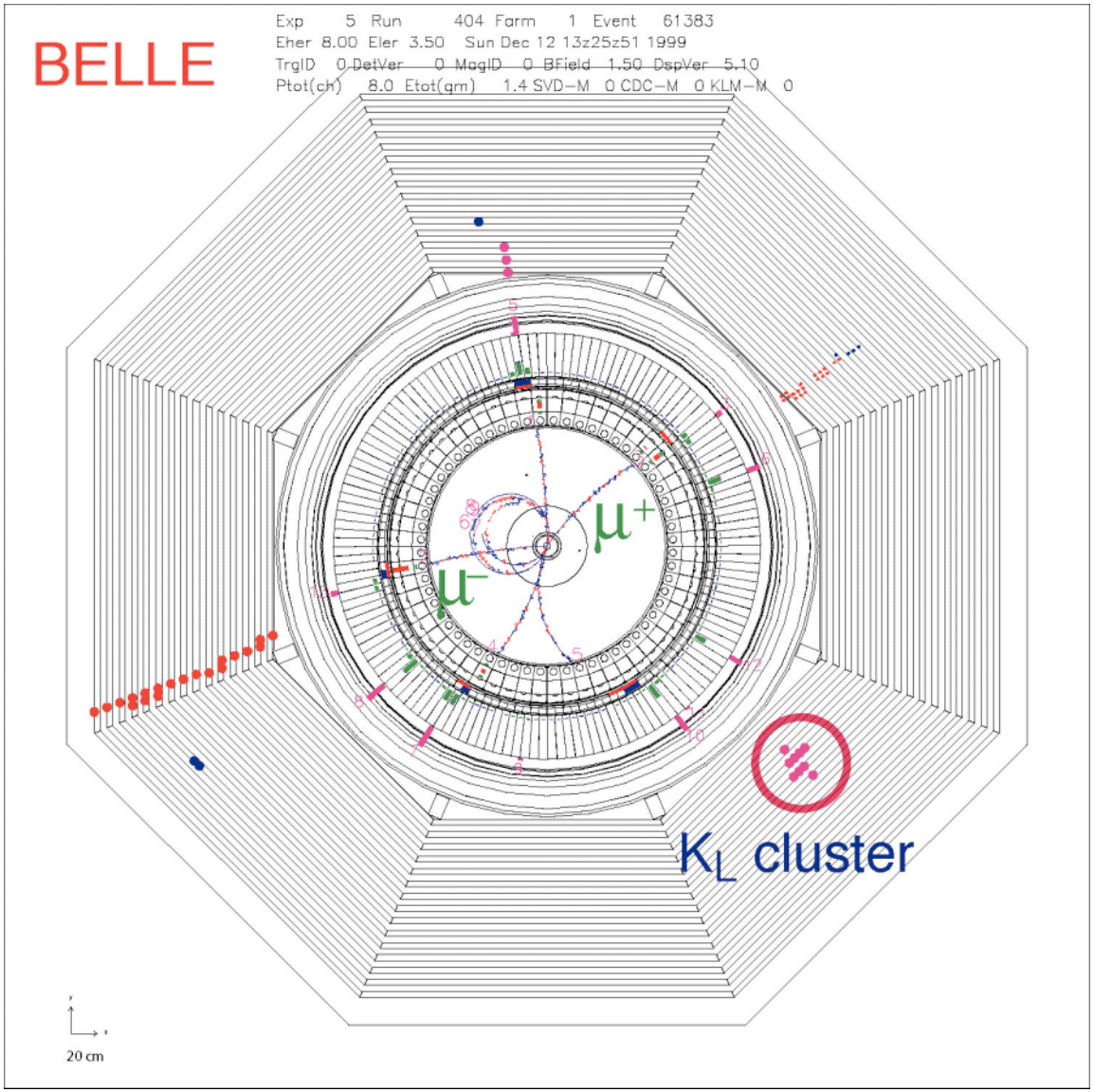
other modes
290 candidates
purity=84%



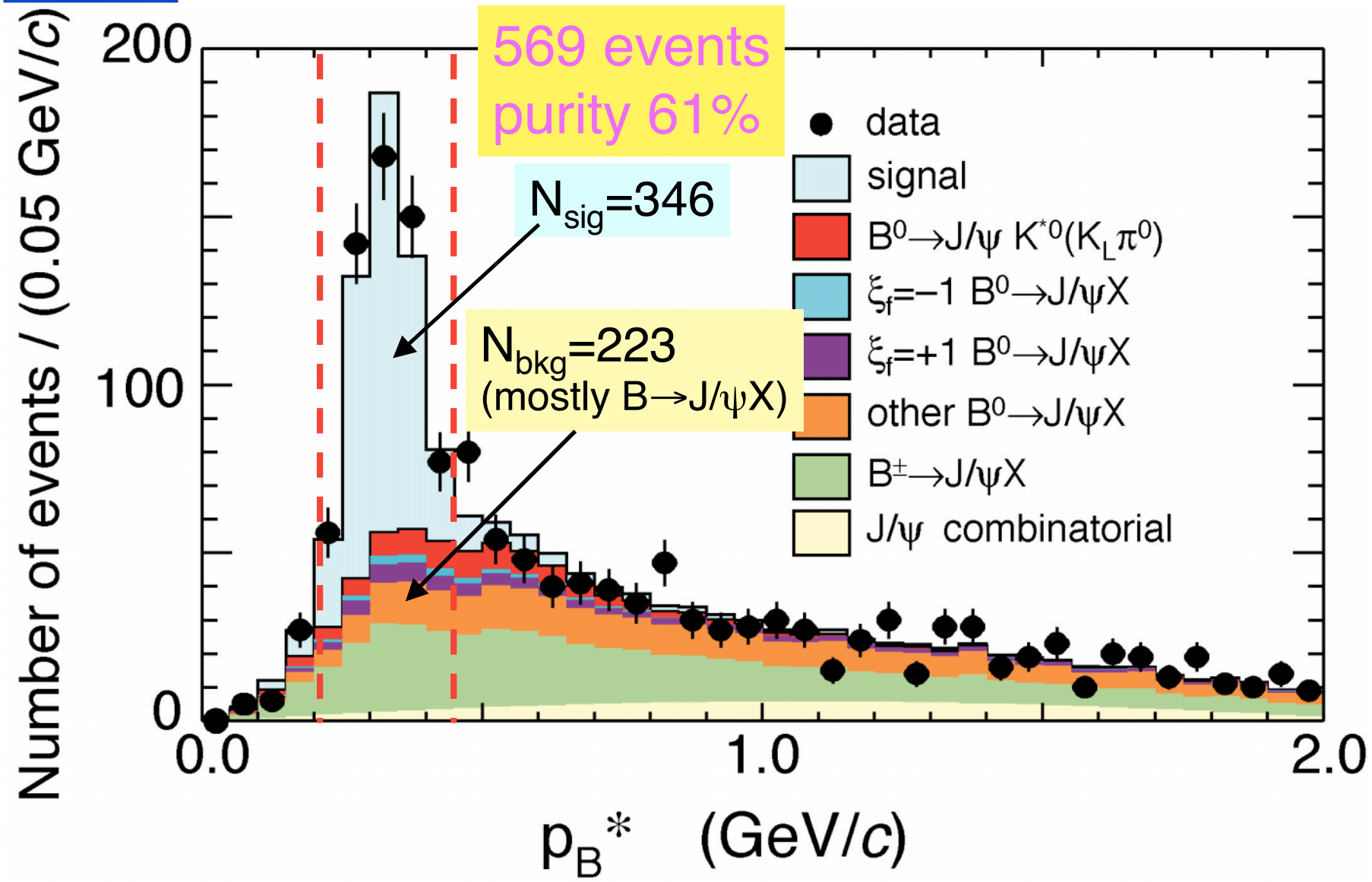
Reconstruction: J/ψ K_L

Only direction for K_L..

1. Reconstruct J/ψ (→ l^+l^-).
2. Search for K_L candidate in KLM and/or ECL.
3. Compute K_L energy assuming B→J/ψ K_L.
4. Cut on a likelihood based on kinematical/event shape variables.
   - Major background : other B→J/ψ X decays.
     - Separated using p_B^* (B momentum in CMS).



$J/\psi\ K_L$: Real Data



Vertex Reconstruction

CP-side: Leptons from J/ψ

Constraint to B decay point profile.

$\delta(z_{CP})$~75μm (rms)

Tagging-side: [charm effect]

Secondary tracks, poor tracks are rejected.

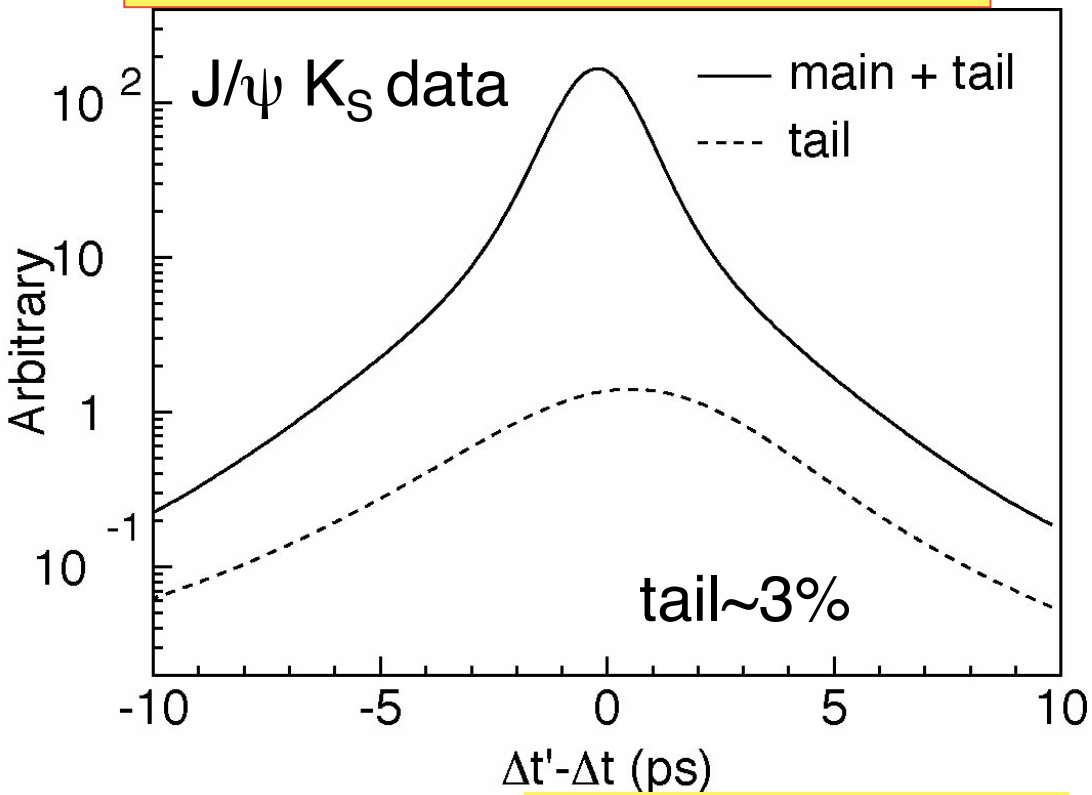
Iteration (discard worst track)

$\delta(z_{tag})$~140μm (rms)

Require $|\Delta z|<2$mm ($\approx 10\tau_B$).

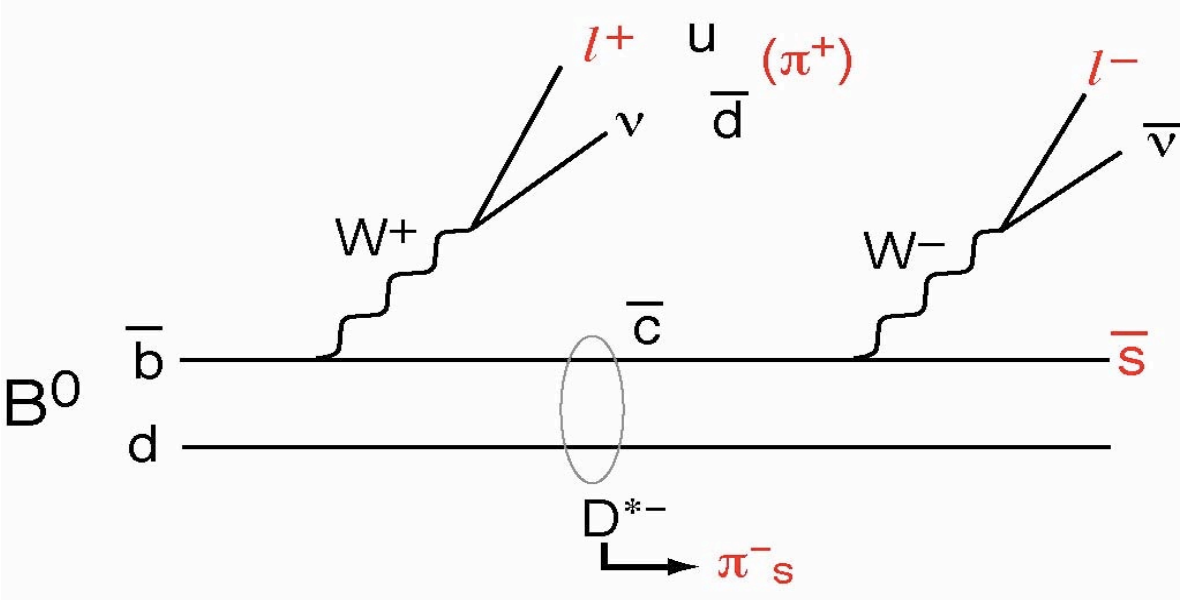
Efficiency: ~88%

Resolution function based on event-by-event vertex error



typical $\sigma_{\Delta t}$=1.49ps

Flavor Tagging



§ high-p l^+(primary), med-p l^- (secondary)

§ strangeness: K^+,Λ ($b \to c \to s$)

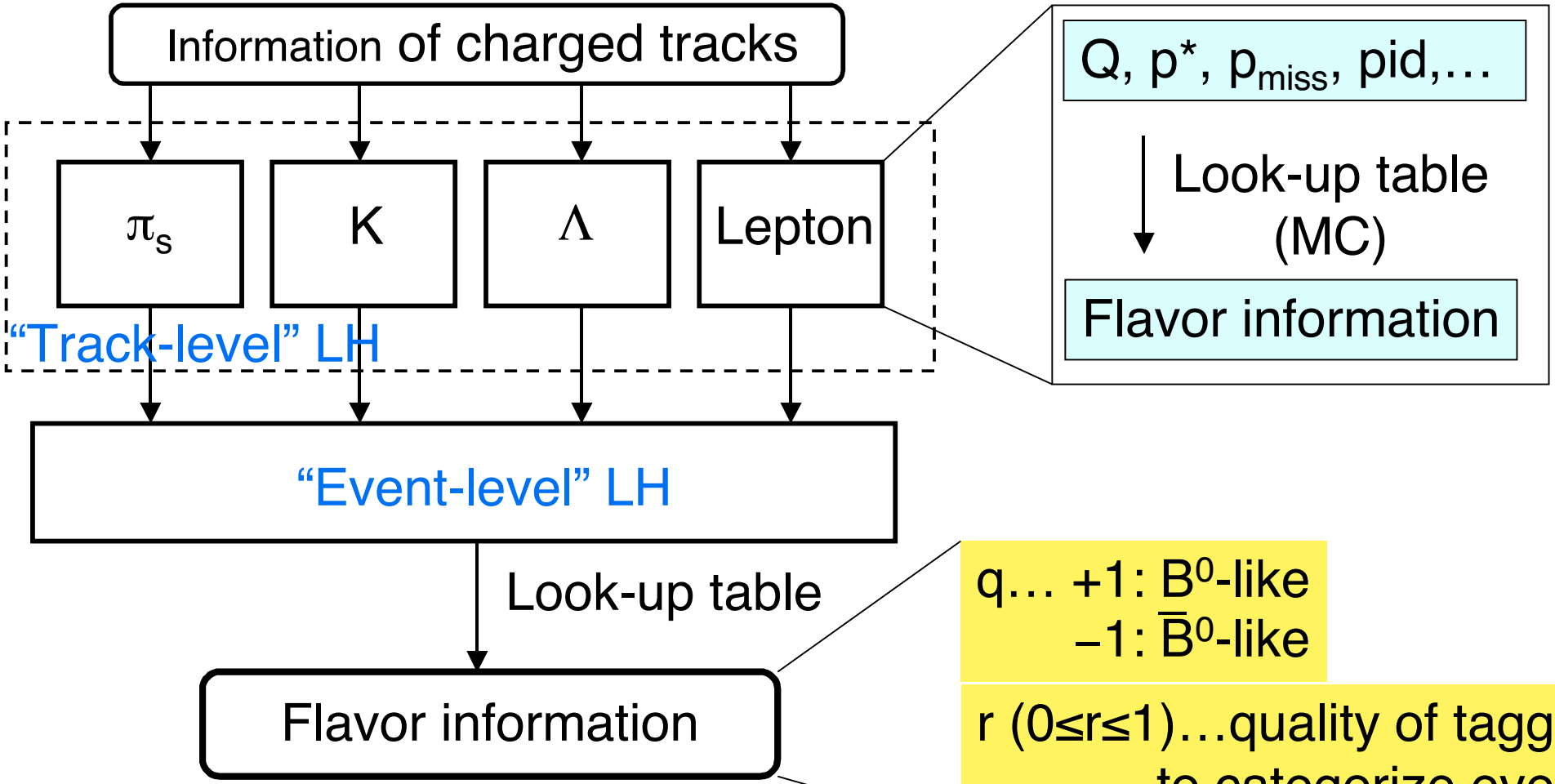
§ slow π^- ($B^0 \to D^{*-}X$, $D^{*-} \to D^0\pi^-$)

§ high-p π^+ ($B^0 \to D^-\pi^+$)

Use *inclusive* flavor-specific properties and their correlations.

Flavor Tagging Method

2-stage multi-dimensional likelihood



q… +1: B^0-like
−1: $\bar{B}^0$-like

r (0≤r≤1)…quality of tagging to categorize events

(six r-intervals=six categories)

Wrong-tagging Probability

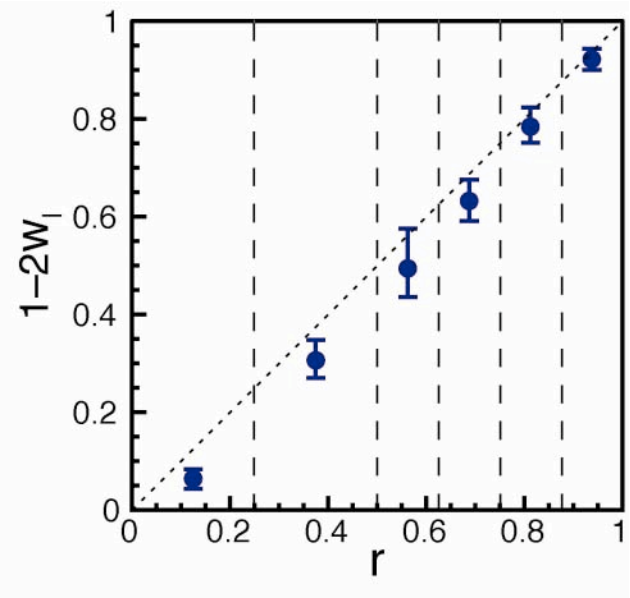
Flavor-specific decays+tagging

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

$$\text{Asym} = \frac{OF - SF}{OF + SF}$$

Efficiency ε: >99.5%

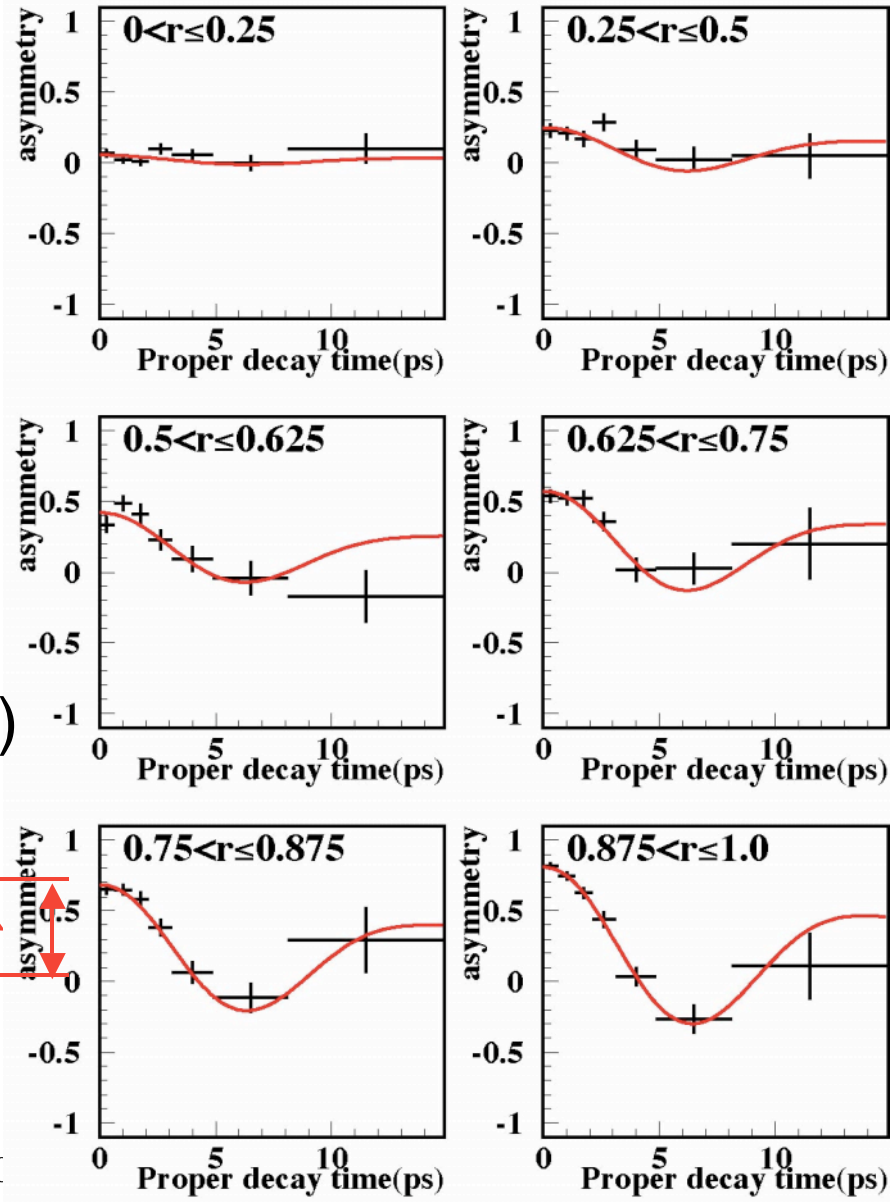
$\varepsilon_{effective} = 27.0 \pm 1.2\%$



Mixing amplitude:

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

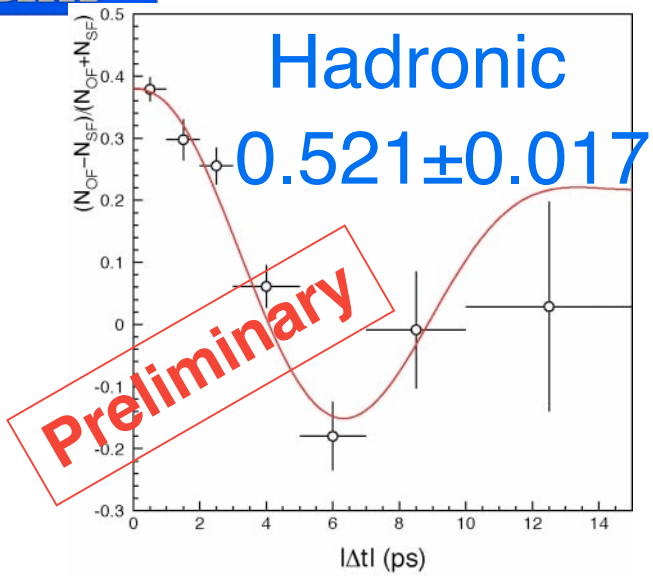
$[=(1-w_l)A+w_l(-A)]$



Δm_d Measurements

Hadronic

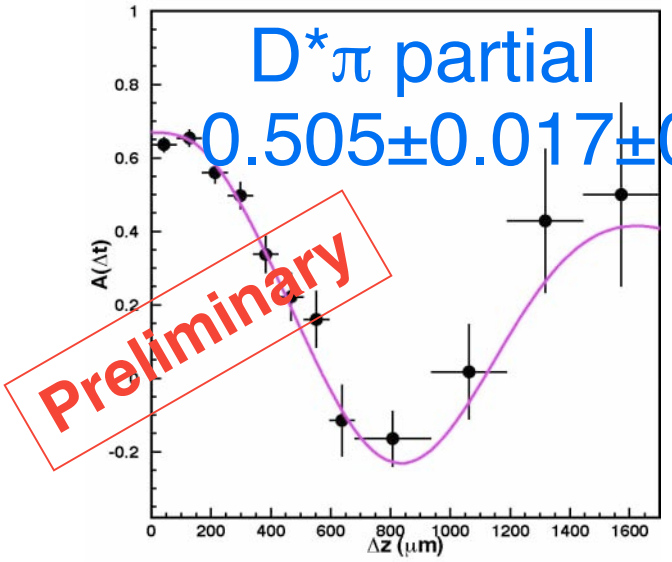
$0.521 \pm 0.017^{+0.011}_{-0.014}$



29.1fb^{-1}

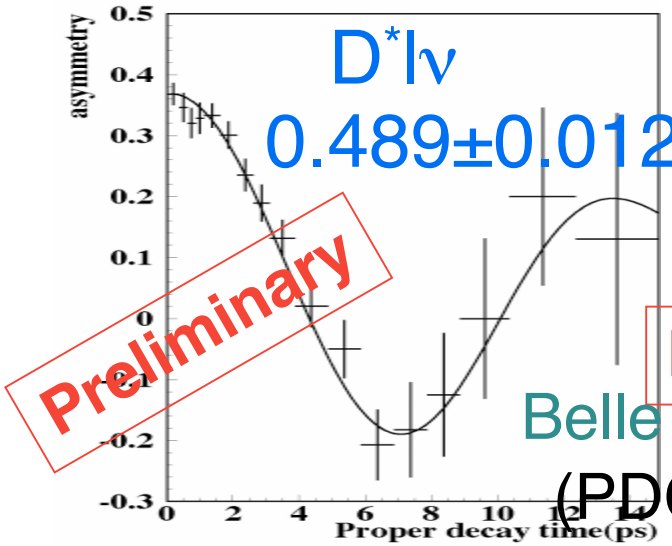
D*π partial

$0.505 \pm 0.017 \pm 0.020$



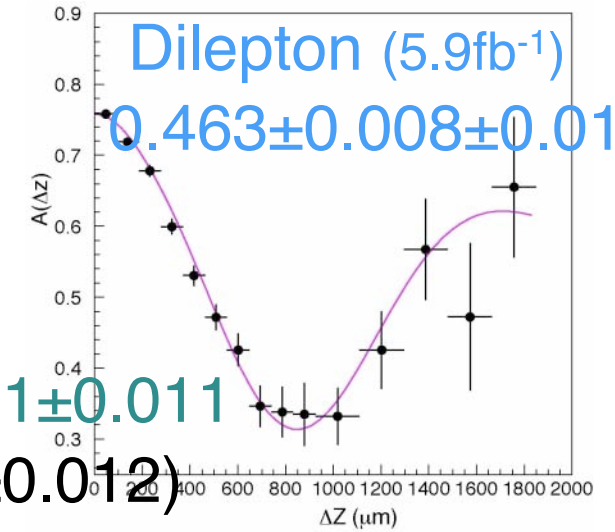
D*lν

$0.489 \pm 0.012^{+0.011}_{-0.014}$



Dilepton (5.9fb^{-1})

$0.463 \pm 0.008 \pm 0.016$



Preliminary

Belle 4 modes: 0.491 ± 0.011

(PDG2001: 0.479 ± 0.012)

Unbinned Maximum Likelihood Fit

Probability Density Function (PDF)

$$L_i = \int (1 - f_{bkg}) P_{sig}(\Delta t') R(\Delta t - \Delta t') d\Delta t' + f_{bkg} P_{bkg}$$

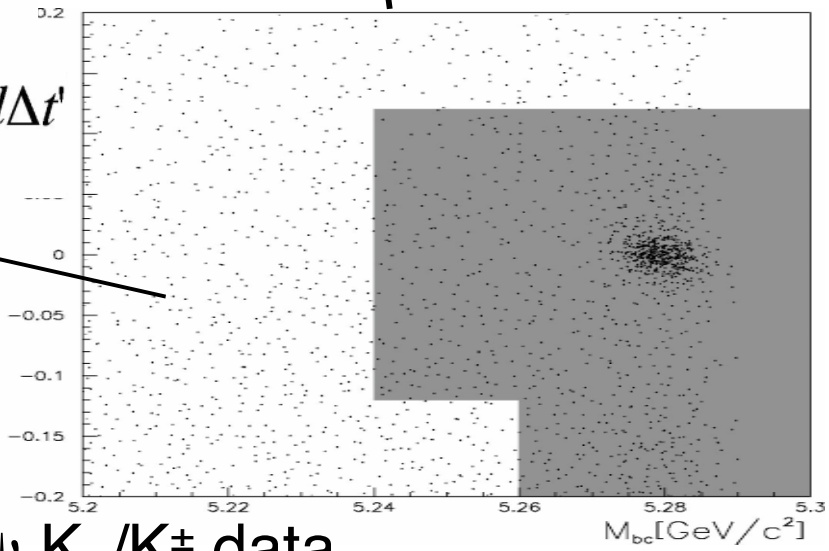
R: resolution function

bkg probability
(ΔE, M_{bc}) 2D-fit

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

$$P_{bkg} = \int [f_\tau \frac{e^{-|\Delta t'|/\tau_{bkg}}}{2\tau_{bkg}} + (1 - f_\tau)\delta(\Delta t')] R_{bkg}(\Delta t - \Delta t') d\Delta t'$$

sideband

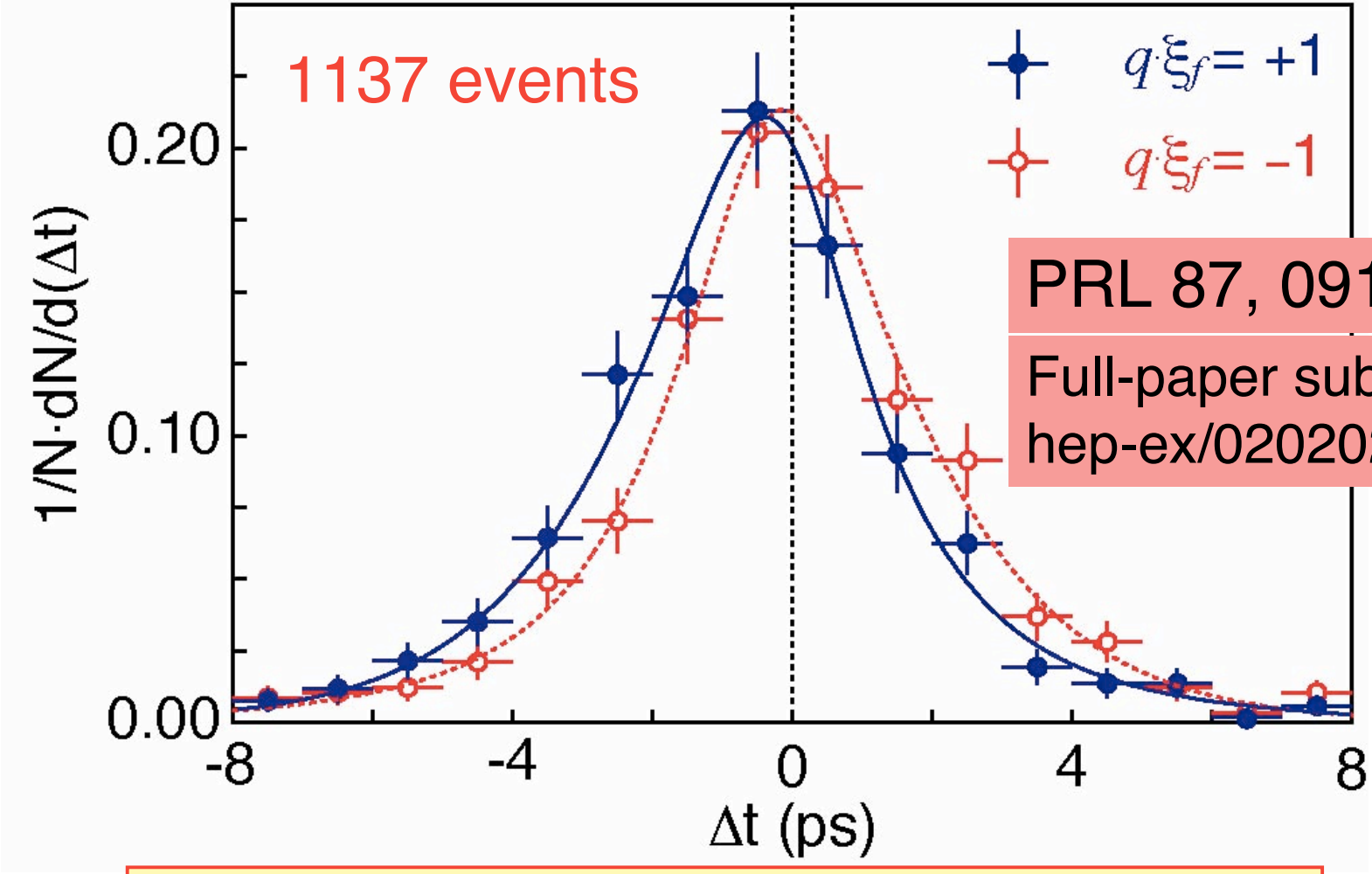


Free parameter: sin2ϕ_1 only

J/ψ K_S/$K^\pm$ data

M_{bc}

Fit Result

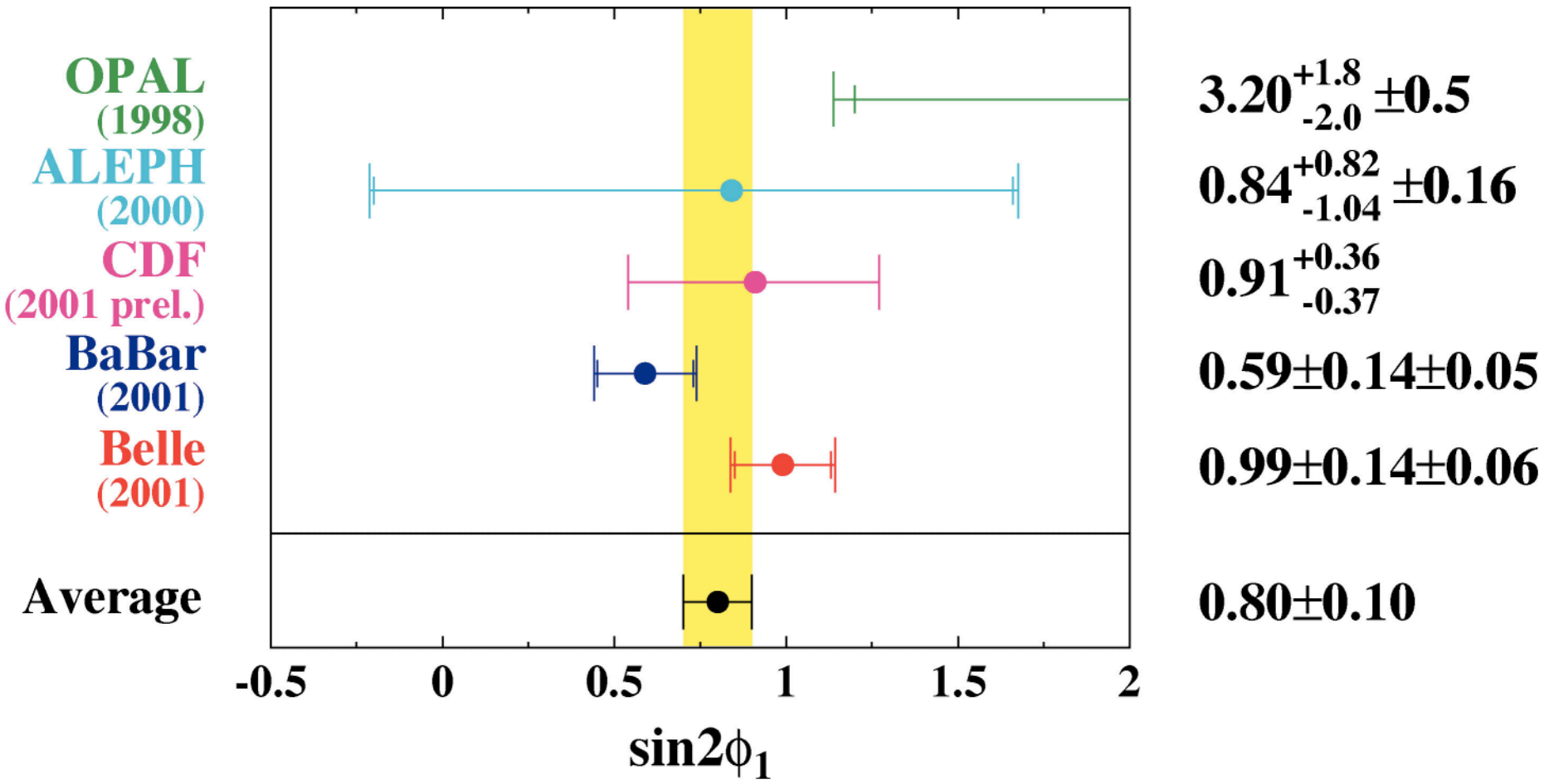


PRL 87, 091802 (2001)

Full-paper submitted to PRD
hep-ex/0202027

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

Comparison to Other Measurements



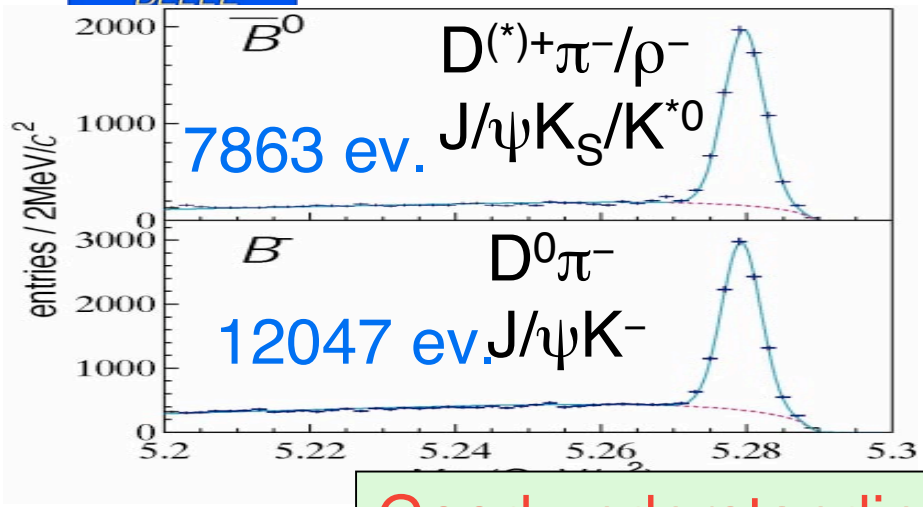
(indirect constraint: 0.70±0.10)

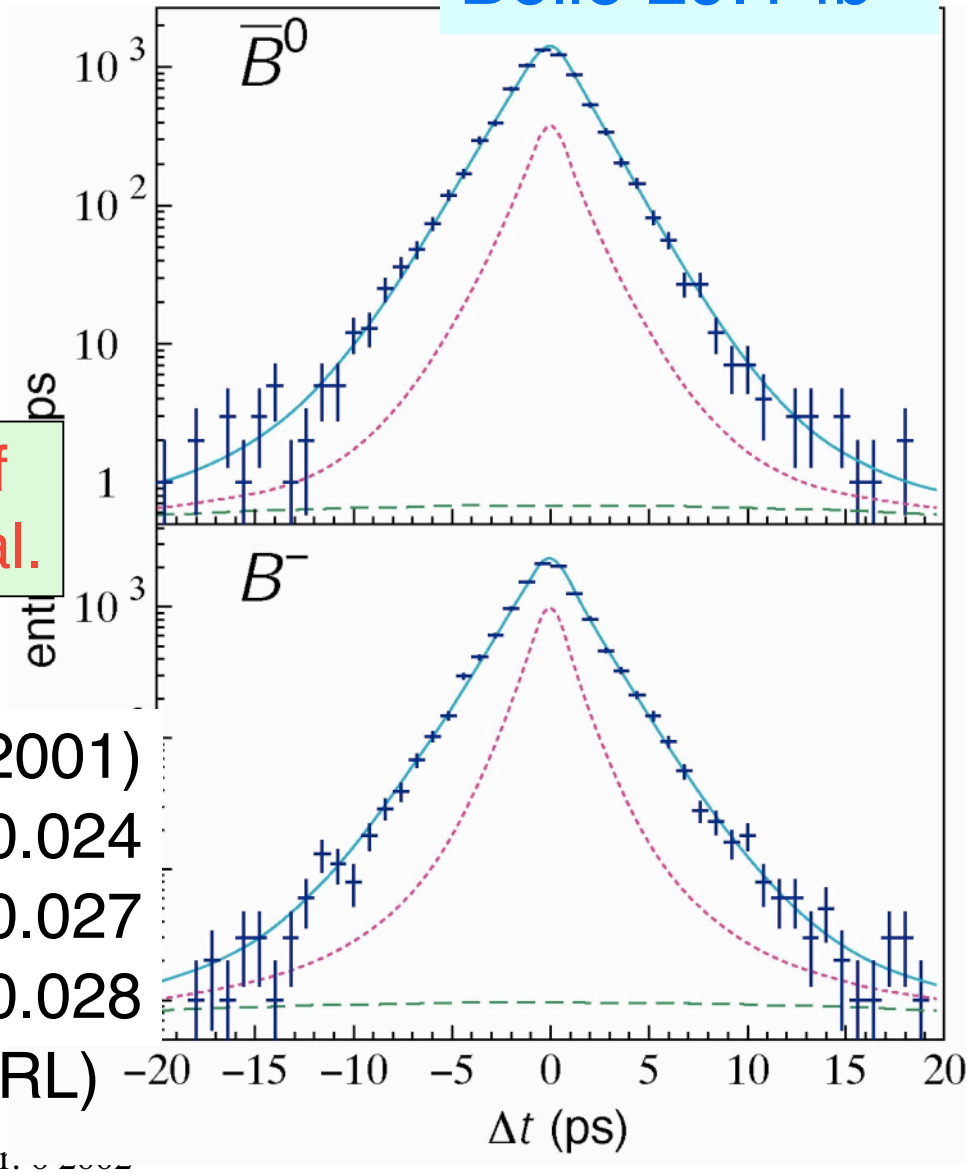
Systematic Error Estimation

Source	Error
Vertexing algorithm	0.04
Flavor tagging	0.03
K_L background	0.02
Resolution function	0.02
Background shape	0.01
Lifetime&mixing	0.01
Total	0.06

B Lifetime with Hadronic Decays

Belle 29.1 fb^{-1}





$\sigma_{\Delta t} \approx \tau_B$

Good understanding of vtx&resolution is crucial.

$pdf(\Delta t)=P_{sig} \otimes R_{sig}+P_{BG}+P_{OL}$

$R_{sig}=R_{det} \otimes R_{NP} \otimes R_{kin}$

	(PDG2001)
τ_{B0}: 1.554±0.030±0.019 ps	1.540±0.024
$\tau_{B\pm}$: 1.695±0.026±0.015 ps	1.655±0.027
$\tau_{B\pm}/\tau_{B0}$: 1.091±0.023±0.014	1.074±0.028

(hep-ex/0202009, submitted to PRL)

Summary and Prospects

KEKB/Belle operations are going very well.

$\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06$ ($>6\sigma$) ($29.1\,fb^{-1}$)

Established *CP* violation in B meson system.

Lifetime/Δm_d measurements with $29\,fb^{-1}$

τ_{B0}: 1.554±0.030±0.019 ps

$\tau_{B\pm}$: 1.695±0.026±0.015 ps

$\tau_{B\pm}/\tau_{B0}$: 1.091±0.023±0.014

submitted to PRL

$\Delta m_d = 0.521 \pm 0.017^{+0.011}_{-0.014}$ ps^{-1} (Hadronic)

$\Delta m_d = 0.489 \pm 0.012^{+0.011}_{-0.014}$ ps^{-1} ($D^* l\nu$)

$\Delta m_d = 0.505 \pm 0.017 \pm 0.020$ ps^{-1} ($D^*\pi$ partial)

Preliminary

~most precise measurements.

Precise knowledge of vertex/resolution/flavor-tagging.

Step towards precise $\sin 2\phi_1$ measurement

Other time dep. *CP* measurements also coming soon!