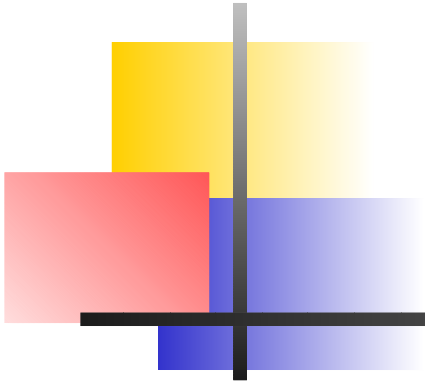

Belle実験における CKM angle ϕ_1の測定

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Introduction

- CKM matrix

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

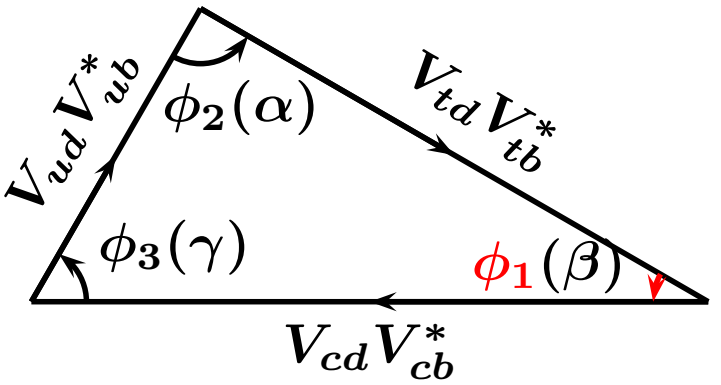
Irreducible complex phase $\Longrightarrow$ CP violation

- Unitarity Triangle
  - Unitary cond. describes triangle in complex plane.

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

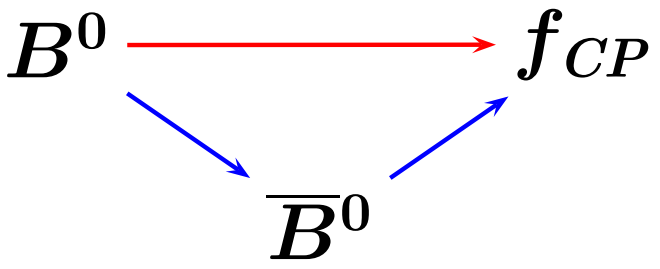
  - Measurement of UT

$\Longleftrightarrow$ Test of CKM picture



CP Violation in B^0-$\overline{B}^0$ System

- Decay into CP eigenstate
  - Interference between decays with and without mixing



  - Asymmetry in time-dependent decay rate

$$A_{CP}(t) \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = A_{f_{CP}} \cos(\Delta m_d t) + S_{f_{CP}} \sin(\Delta m_d t)$$

$$A_{f_{CP}} = \frac{|\lambda_{f_{CP}}|^2 - 1}{|\lambda_{f_{CP}}|^2 + 1} \qquad S_{f_{CP}} = \frac{2\mathrm{Im}\lambda_{f_{CP}}}{|\lambda_{f_{CP}}|^2 + 1}$$

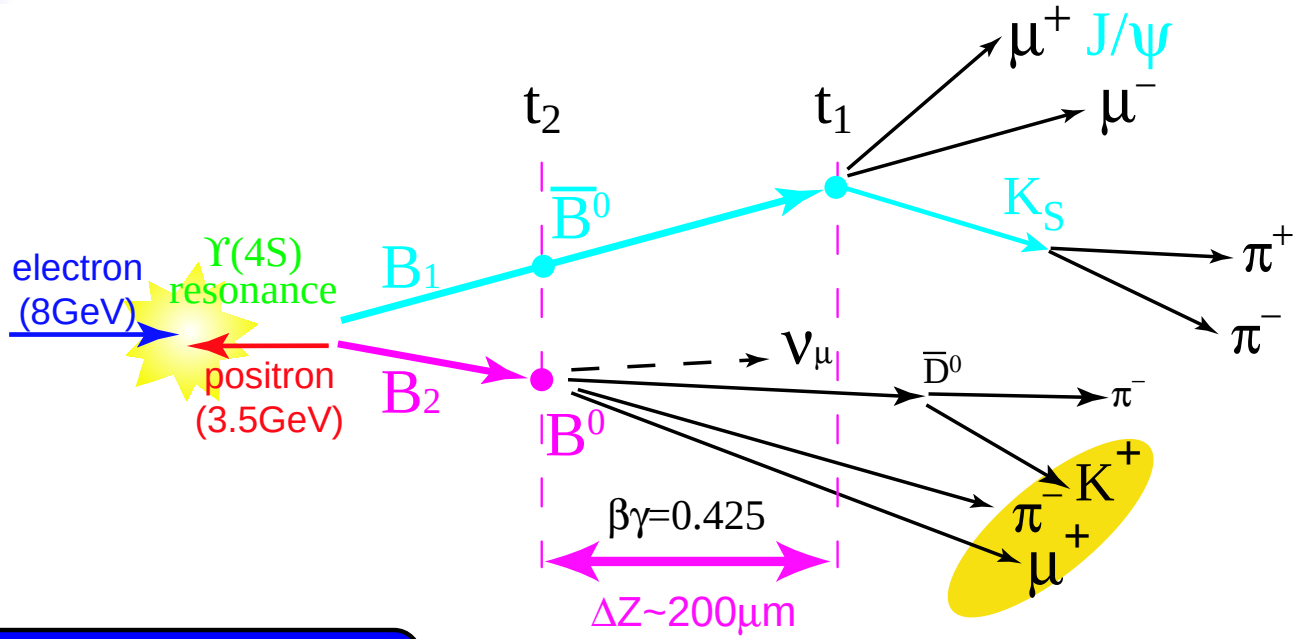
  - In the Standard Model, for $b \to c\bar{c}s$ transition,

$$A_{f_{CP}} = 0,\ S_{f_{CP}} = -\xi_{f_{CP}} \sin 2\phi_1$$

($\xi_{f_{CP}}$: CP eigenvalue of f_{CP})

$$A_{CP}(t) = -\xi_{f_{CP}} \sin 2\phi_1 \sin(\Delta m_d t)$$

Principle of Measurement



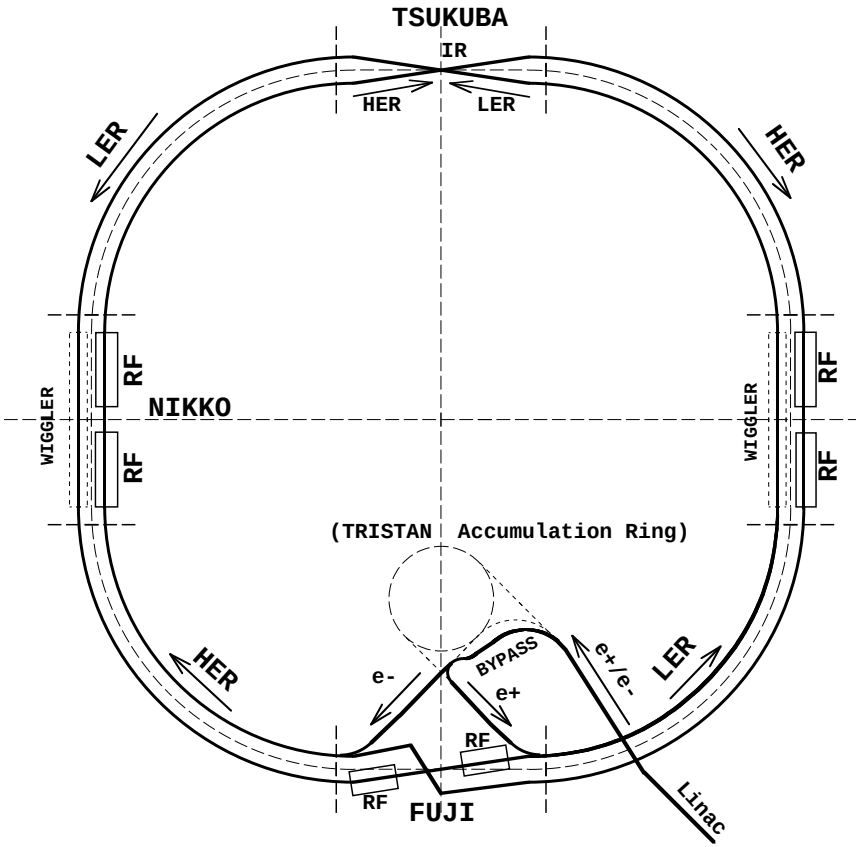
Event reconstruction (CP eigenstates)

Flavor tagging

Vertex reconstruction ($\Delta t \simeq \Delta z / \beta\gamma c$)

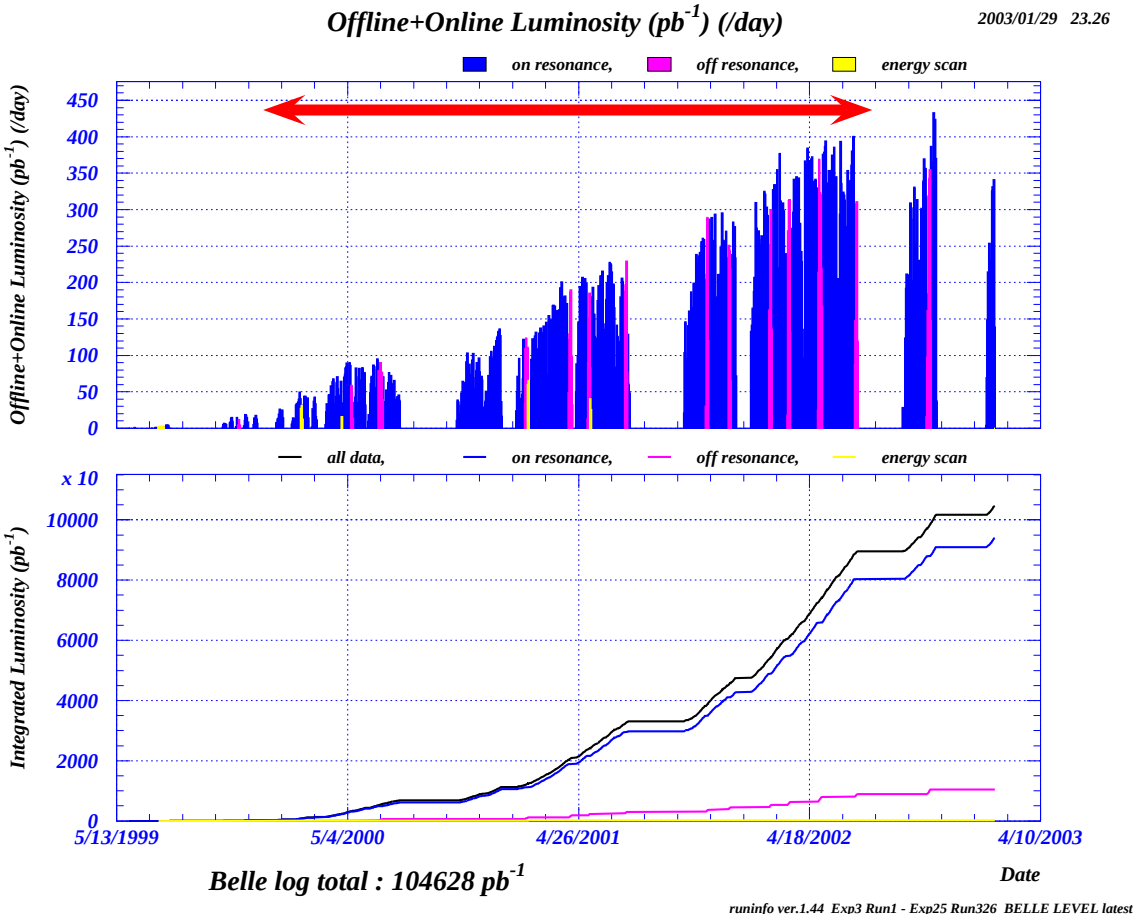
Maximum likelihood fit $\Longrightarrow \sin 2\phi_1$

KEKB Accelerator



- 8 GeV e^- (HER) + 3.5 GeV e^+ (LER)
  - $E_{\mathrm{CMS}} = 10.58$ GeV at $\Upsilon(4S)$
  - $(\beta\gamma)_\Upsilon = 0.425$
- 3 km circumference
- ± 11 mrad crossing angle

Luminosity

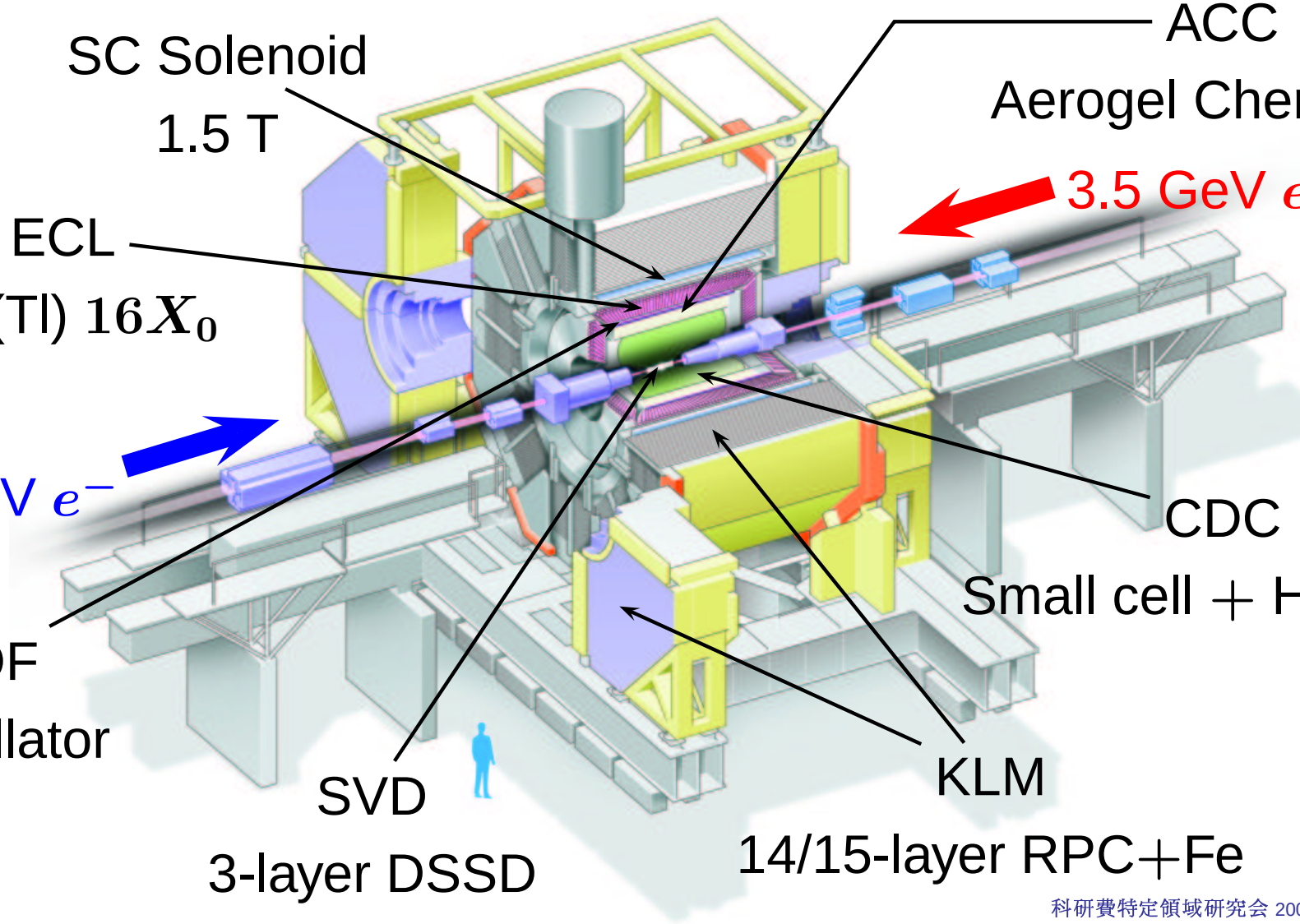


- 85×10^6 $B\overline{B}$ pairs recorded before the summer 2002.

$$L_{\mathrm{peak}} = 8.26 \times 10^{33} /\mathrm{cm}^2/\mathrm{s}$$

Int. lum. $= 89.6$ fb^{-1}
($\sim 90\%$ on $\Upsilon(4S)$
$+ \sim 10\%$ off peak)

Belle Detector



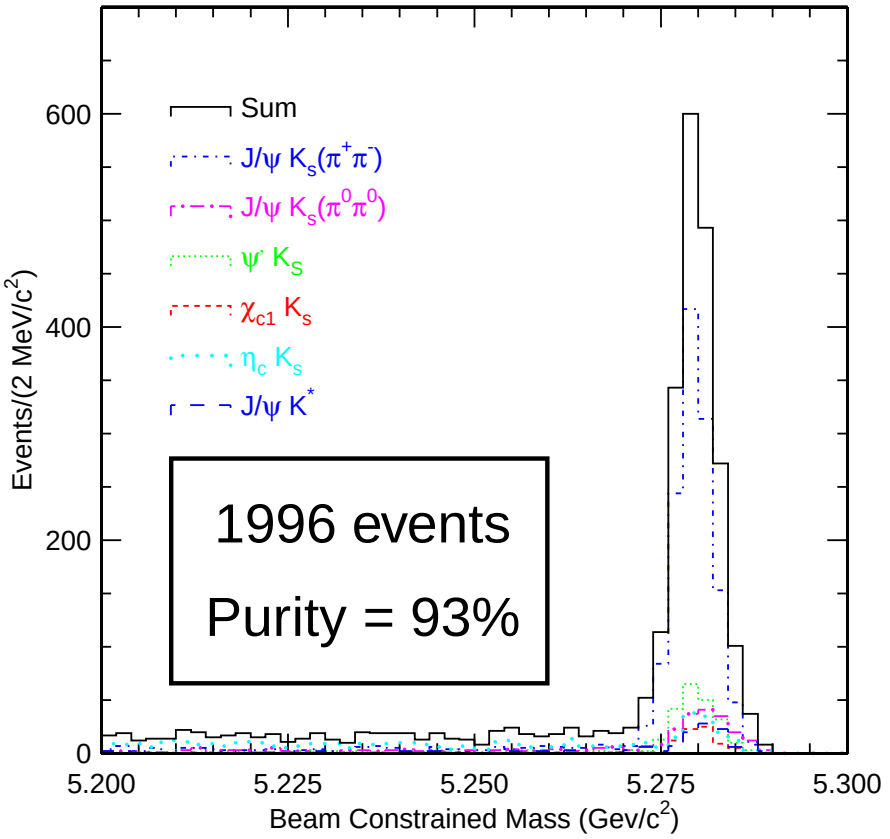
Performance of Detectors

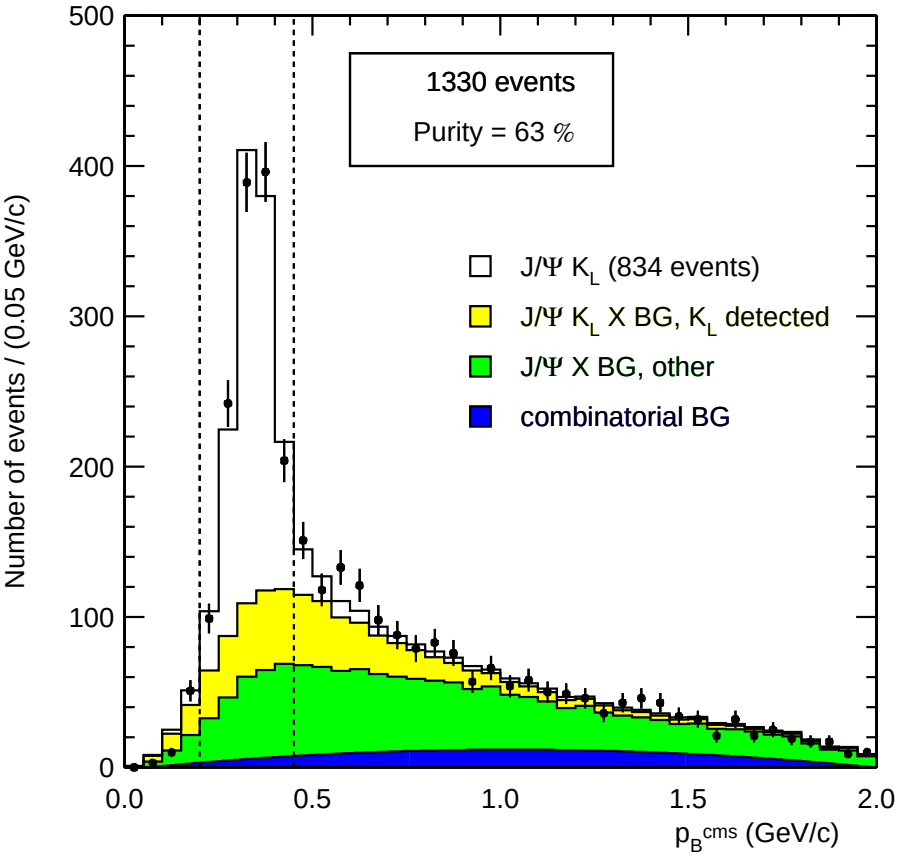
- Vertexing
  - Impact parameter resolution:
    55 μm for 1 GeV/c norm. trk.
- Tracking
  $(\sigma_{p_t}/p_t)^2 =$
  $(0.29/\beta)^2 + (0.20 p_t)^2$ (%^{2})
- EM calorimetry
  - $\sigma_E/E \sim 1.8\%$ @ $E = 1$ GeV
  - $e^{\pm}$ efficiency $> 90\%$
    ($\sim 0.3\%$ fake at $p > 1$ GeV/c)
- K/π separation
  - dE/dx ($\sigma = 6.9\%$)
  - TOF ($\sigma = 95$ ps)
  - Aerogel Cherenkov

  Efficiency $\sim 90\%$,
  Fake rate $\sim 6\%$ up to 3.5 GeV/c
- K_L and $\mu^{\pm}$ detection
  - $\mu^{\pm}$ efficiency $> 90\%$
    ($< 2\%$ fake at $p > 1$ GeV/c)

Event Reconstruction

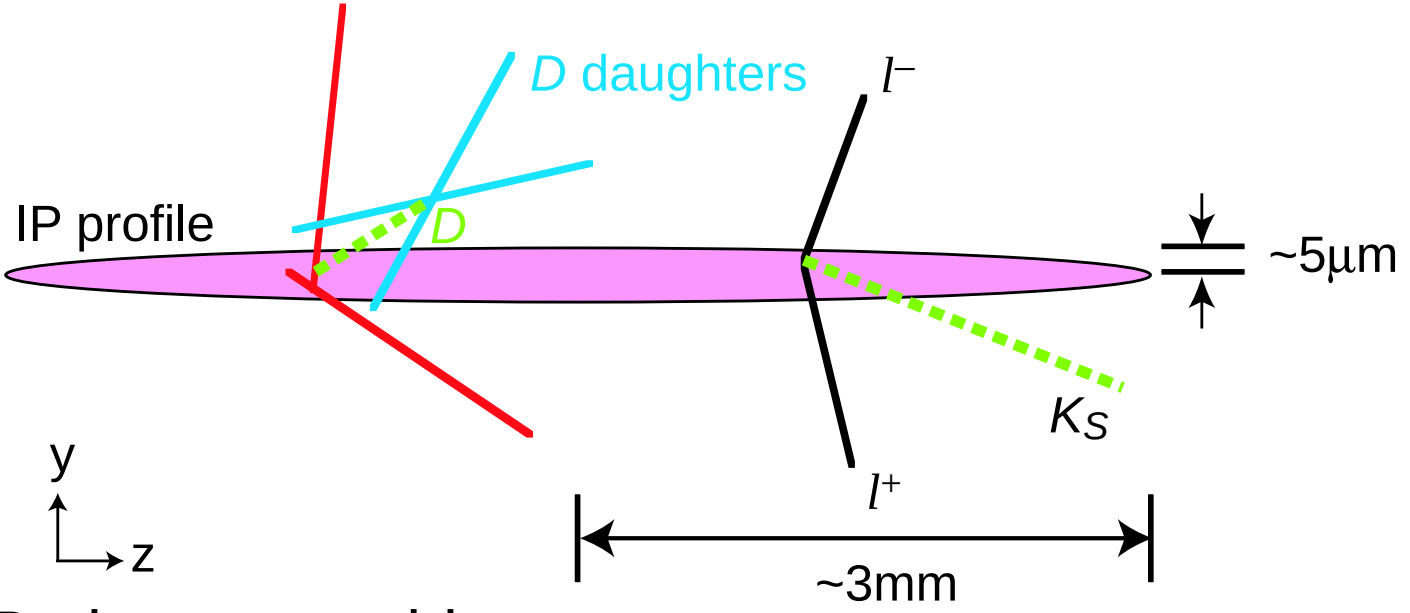
Selection based on $M_{\rm bc} \equiv \sqrt{(E^{\rm cms}_{\rm beam})^2 - (p^{\rm cms}_B)^2}$ and $\Delta E \equiv E^{\rm cms}_B - E^{\rm cms}_{\rm beam}$ (other than $J/\psi K_L$), or $p^{\rm cms}_B$ $(J/\psi K_L)$.





Vertex Reconstruction

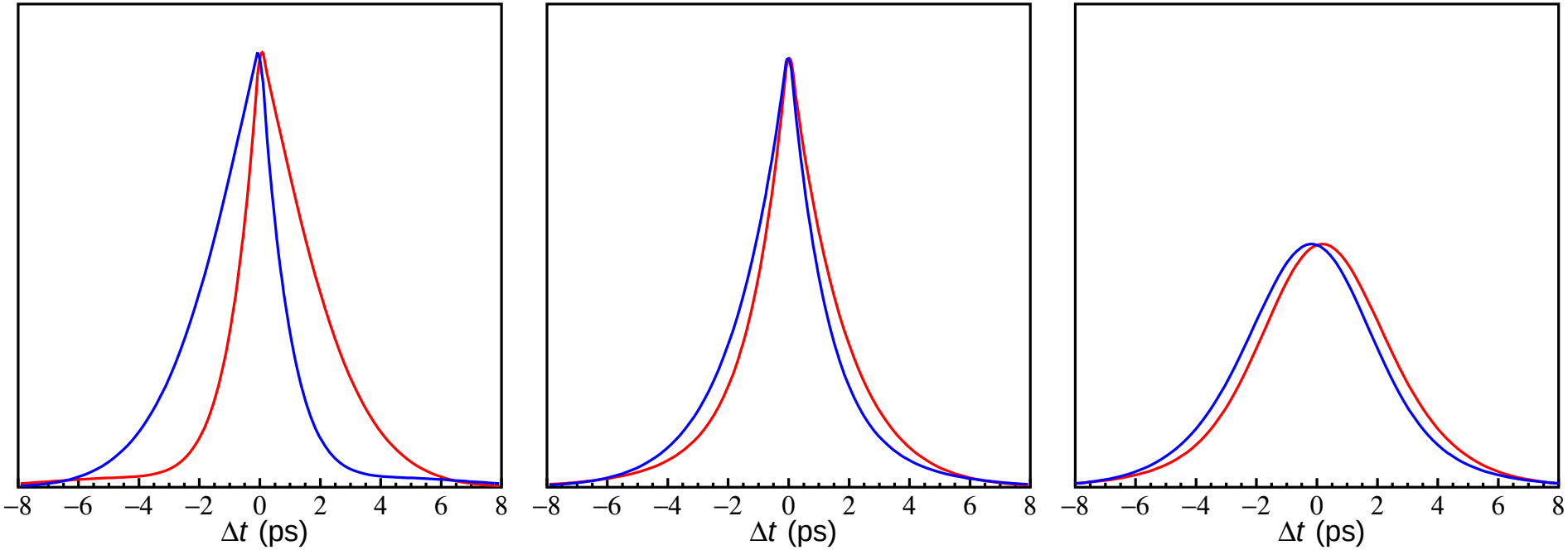
- IP(Interaction Point)-constrained vertex fit



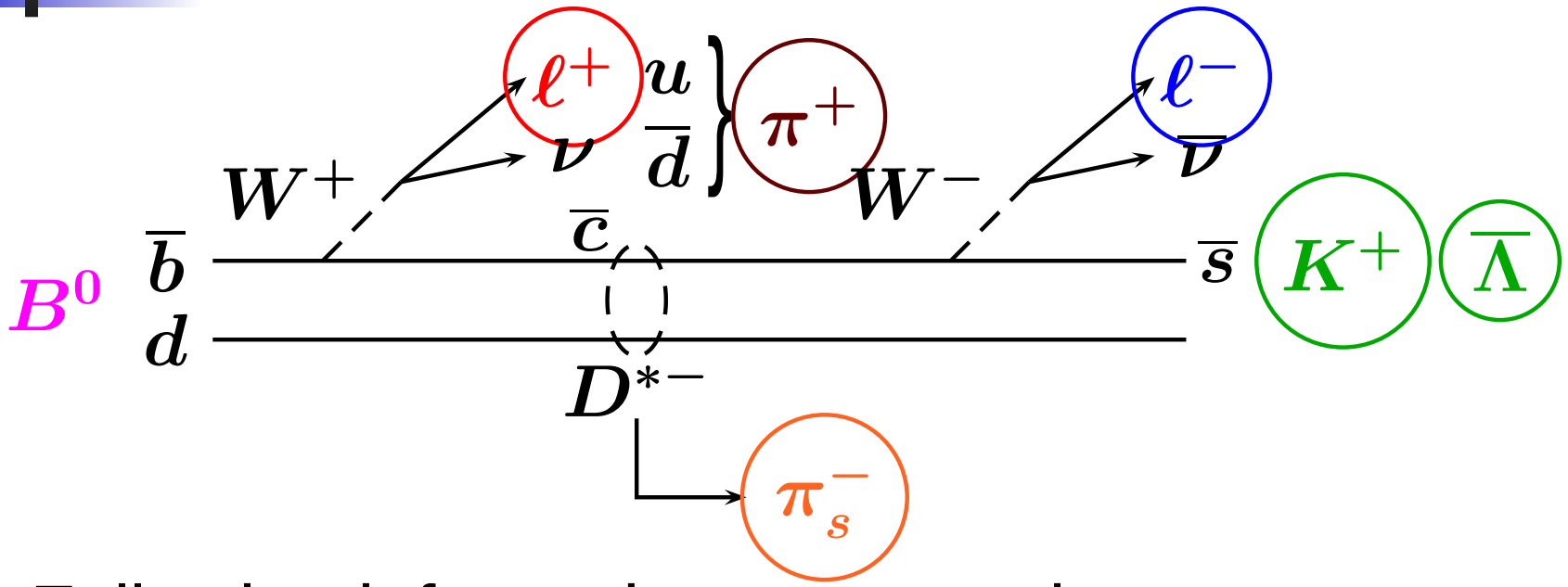
- CP-eigenstate side
  - Leptons from ψ, or primary K/π tracks from η_c
- Associated side
  - Remaining tracks except for poorly reconstructed tracks and K_S daughters

Δt Distribution

- Theoretical dist.: $\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 - q\xi_f \sin 2\phi_1 \sin(\Delta m_d \Delta t)\right]$ (flavor (± 1))
- Diluted by wrong tag: $\left[1 - q\xi_f (1-2w) \sin 2\phi_1 \sin(\Delta m_d \Delta t)\right]$
- Smeared by resolution: $P(\Delta t) = \int_{-\infty}^{+\infty} dt \mathcal{P}(t) R(\Delta t - t)$



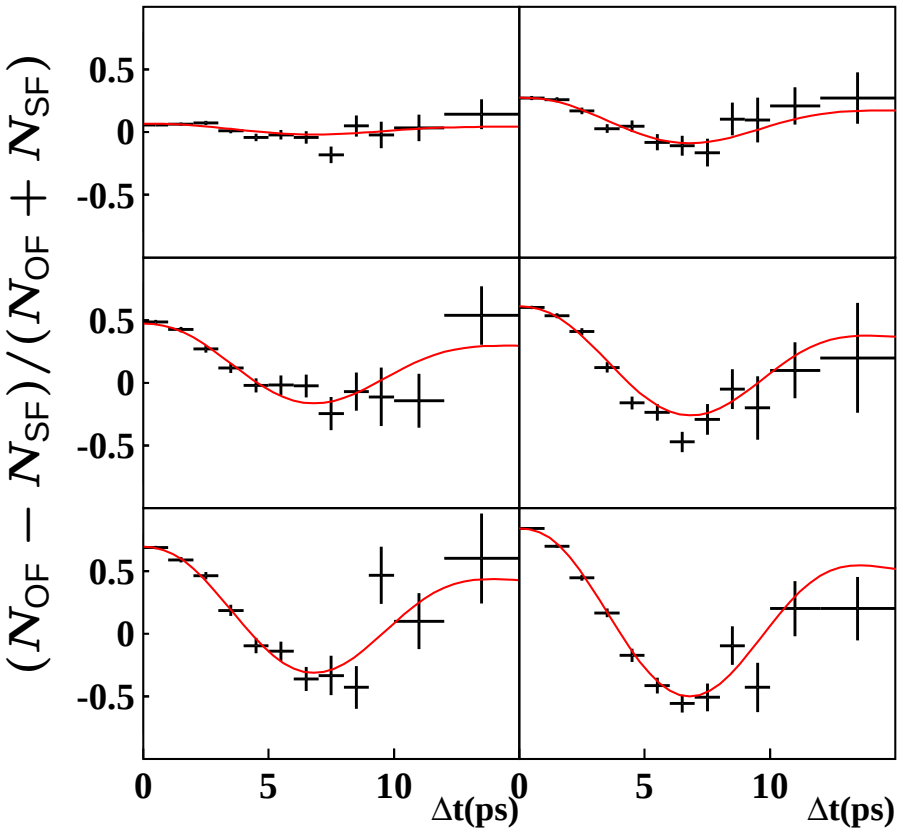
Flavor Tagging

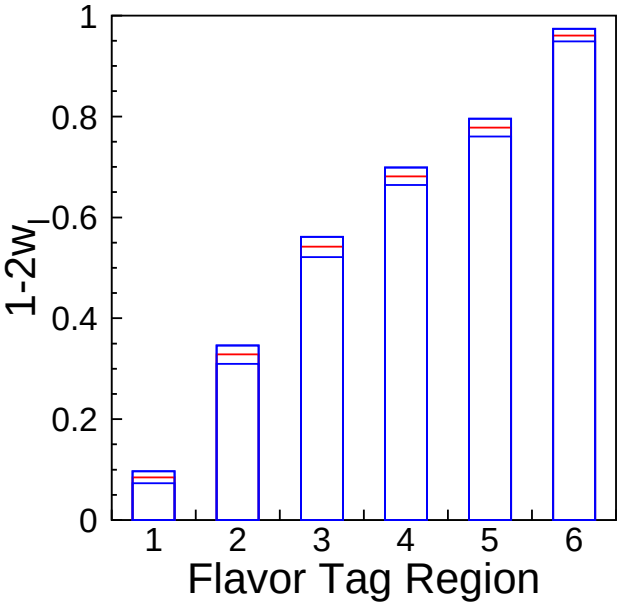


- Following informations are used:
  - High p (primary) lepton, low p (secondary) lepton
  - Strangeness (K, Λ from $b \to c \to s$ chain)
  - Fast π, slow π

Wrong Tag Fraction

- Determined from B^0-$\overline{B}^0$ mixing fit.
  - $B^0 \to D^- \pi^+$, $D^{*-} \pi^+$, $D^{*-} \rho^+$, and $D^{*-} \ell^+ \nu$



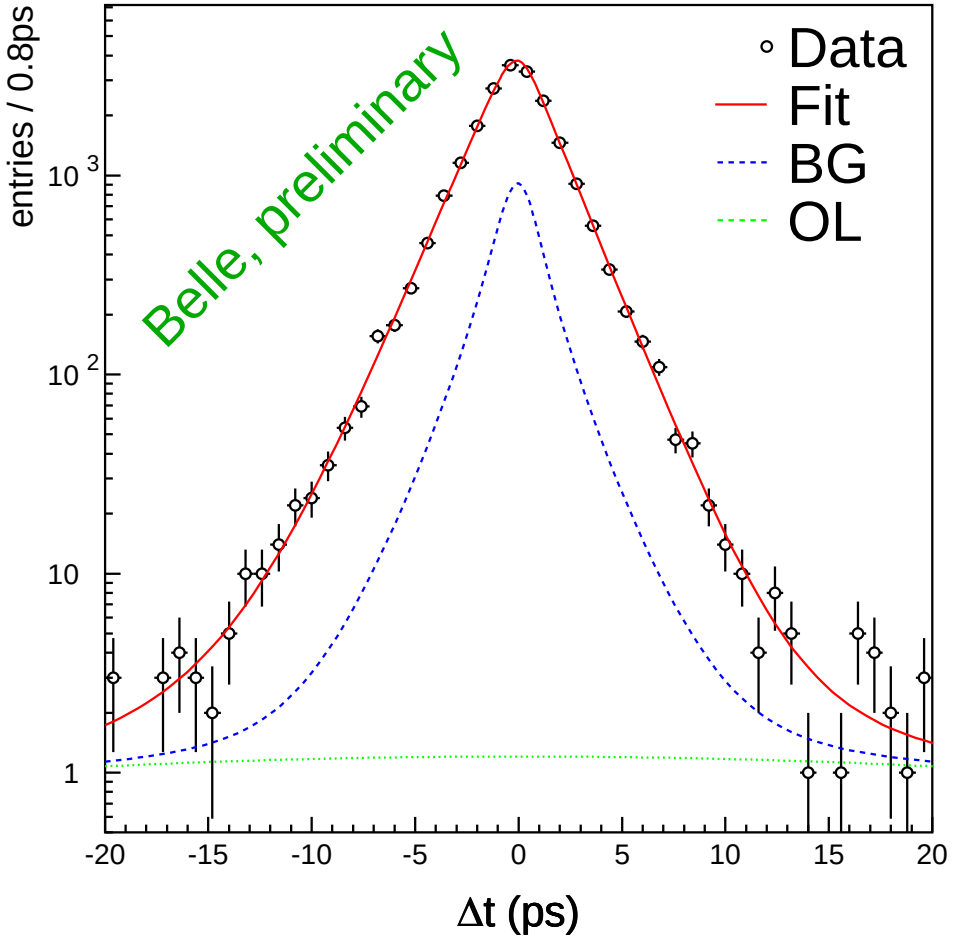


Efficiency $> 99.5\%$

$\epsilon_{\text{effective}} = 28.8 \pm 0.5\%$

Resolution

- Obtained from lifetime fit with 78 fb^{-1} data.



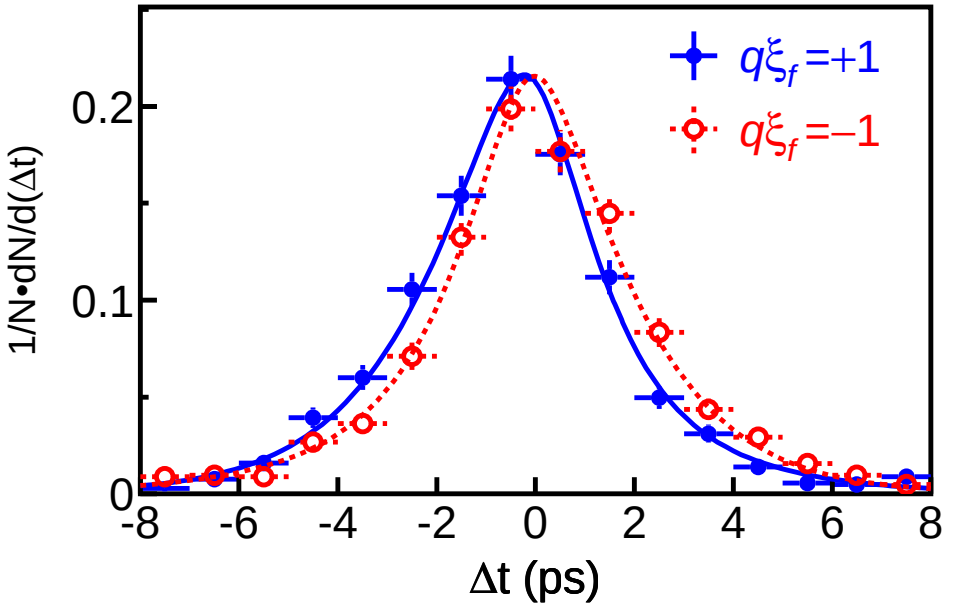
$$B^0 \to D^- \pi^+, D^{*-} \pi^+, D^{*-} \rho^+, J/\psi K_S, \text{ and } J/\psi K^{*0}$$

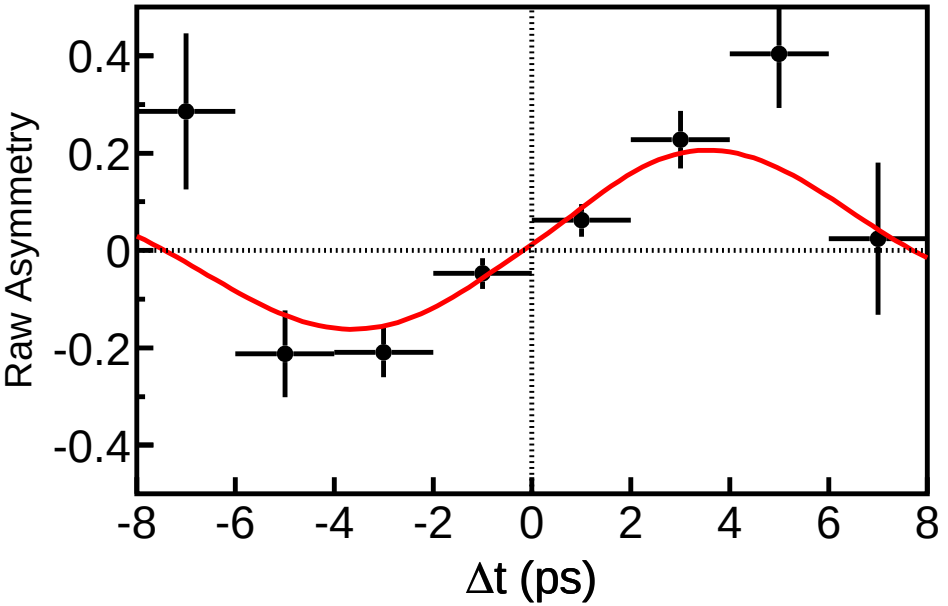
B^0 lifetime
1.551 ± 0.018(stat) ps
PDG2002:
1.542 ± 0.016 ps

Time resolution (rms)
~ 1.43 ps

Result

- Unbinned maximum likelihood fit is performed.



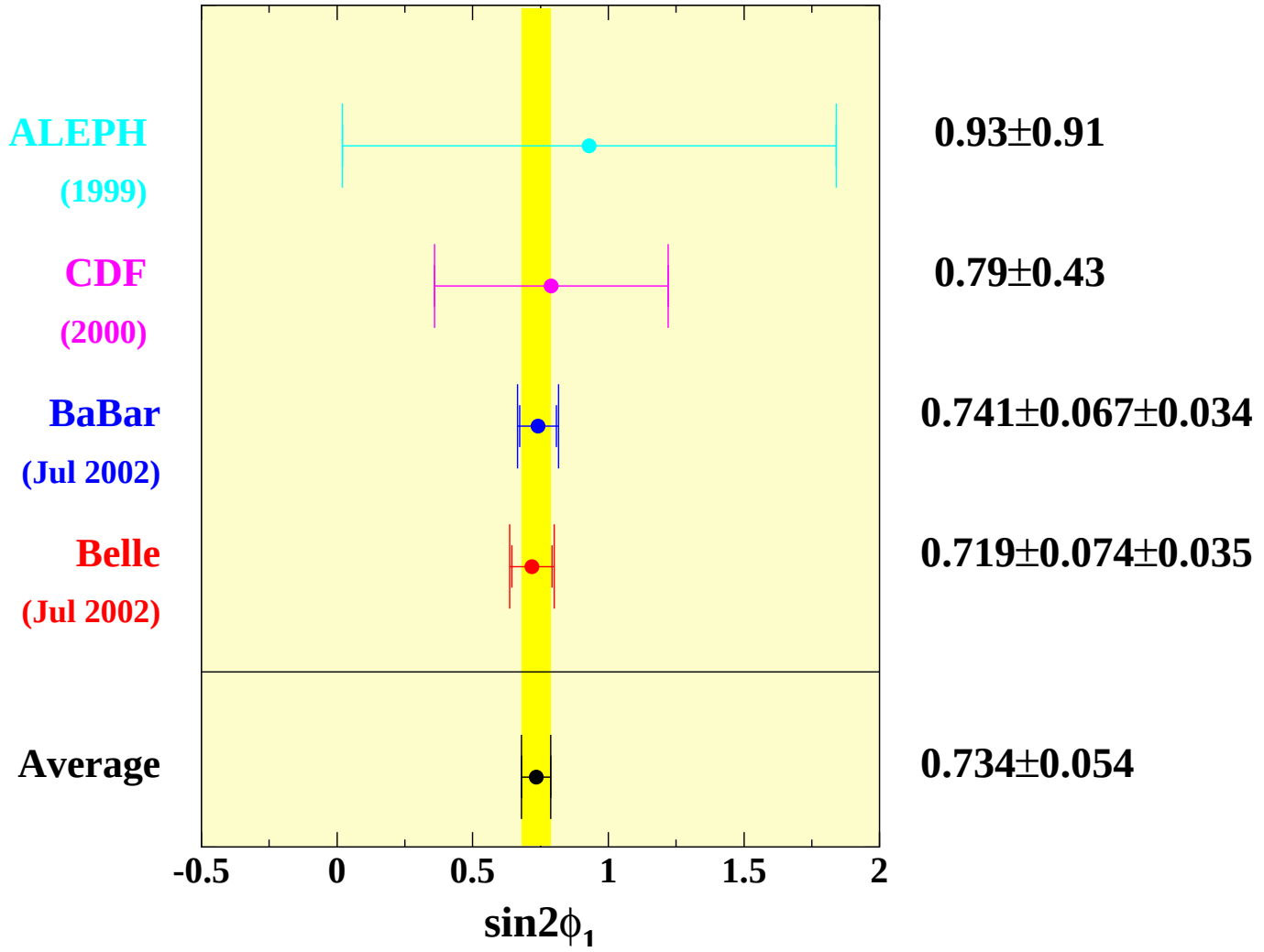


- Using 78 fb^{-1} data sample, we obtain

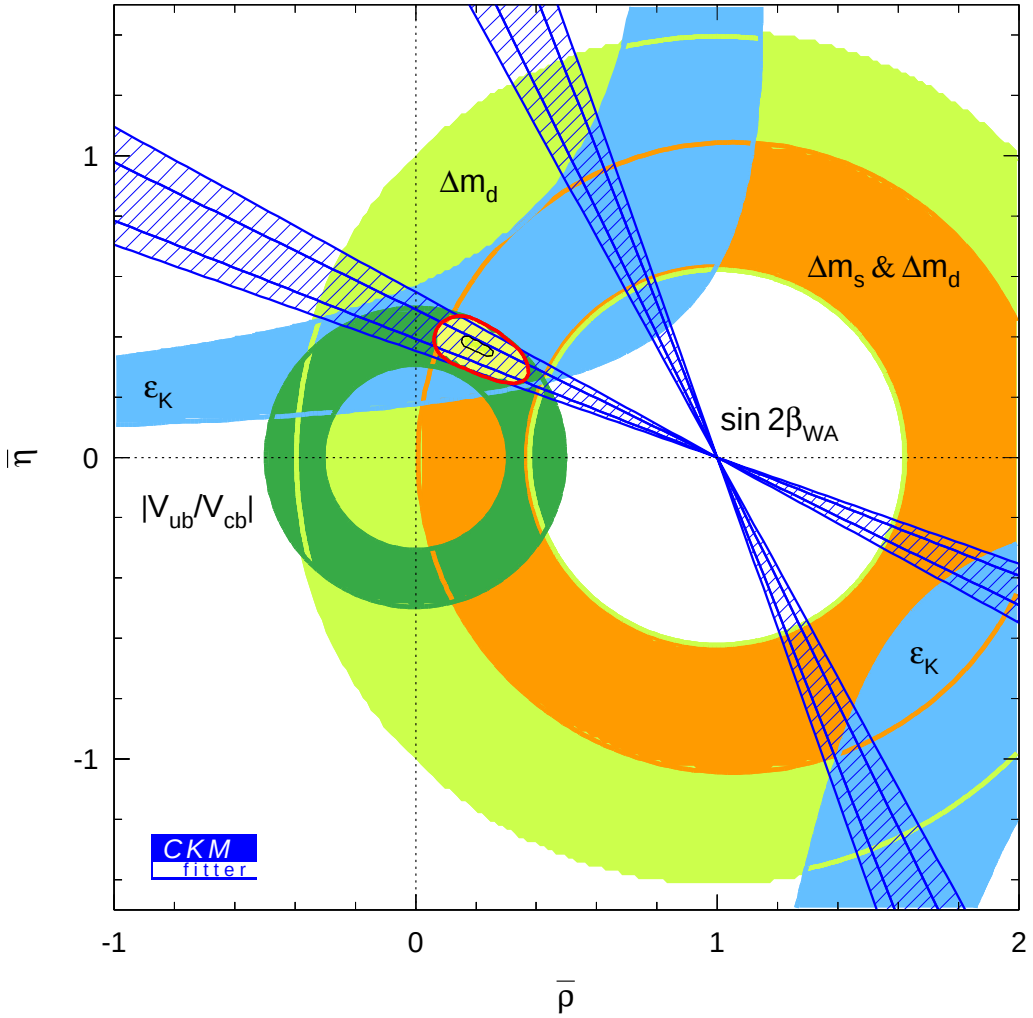
$$\sin 2\phi_1 = 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{syst})$$

- Dominant systematics: Vertexing, Flavor tagging

Comparison with Other Experiments



Constraints on $\overline{\rho}$-$\overline{\eta}$ Plane



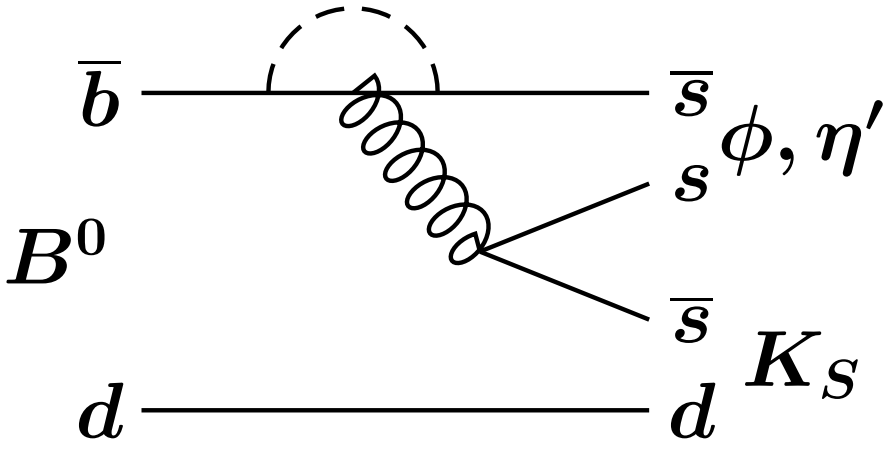
- Normalized UT

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

Vertices: $(0,0)$, $(1,0)$, $(\overline{\rho},\overline{\eta})$

- Independent measurements of angles and sides of UT are consistent.
- KM mechanism is most probably the dominant source of CP violation at EW scale.

CP Violation in $b \to s\bar{s}s$



In the Standard Model,

$$S_{s\bar{s}s} = -\xi_{f_{CP}} \sin 2\phi_1$$

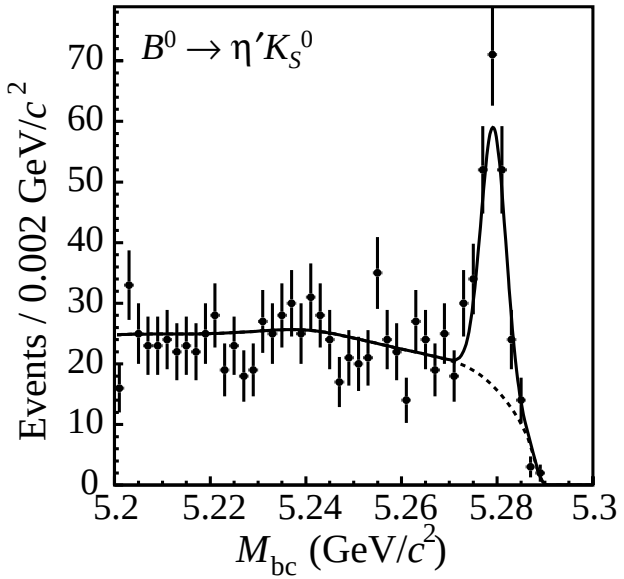
$$A_{s\bar{s}s} \simeq 0$$

- These decay modes are potentially sensitive to new CP-violating phases from physics beyond the SM.
  - A significant deviation from $b \to c\bar{c}s$ modes $\Longrightarrow$ evidence of a new physics

Reconstruction of $b \to s\bar{s}s$ modes

$B^0 \to \eta' K_S$

$(\eta' \to \pi^+\pi^-\eta, \rho\gamma)$

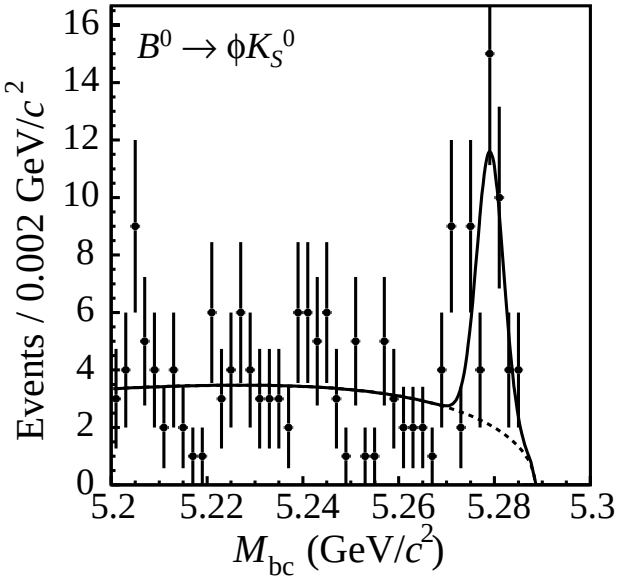


299 events

Purity $= 0.49 \pm 0.05$

$B^0 \to \phi K_S$

$(\phi \to K^+K^-)$

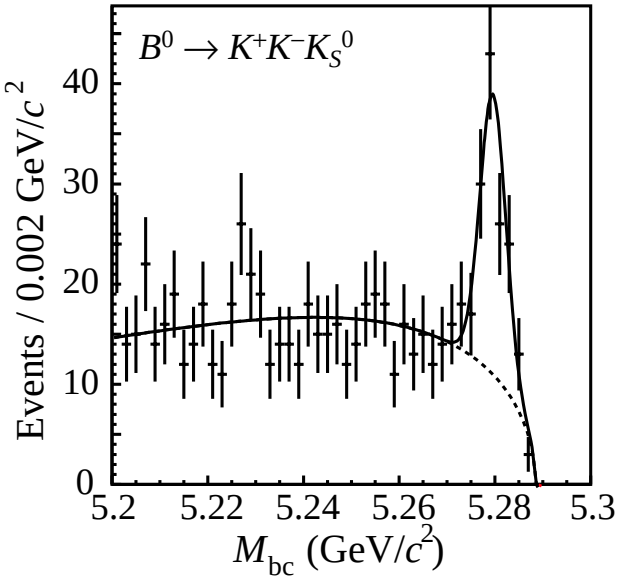


53 events

Purity $= 0.67^{+0.07}_{-0.05}$

$B^0 \to K^+K^-K_S$

$(K^+K^- \neq \phi)$

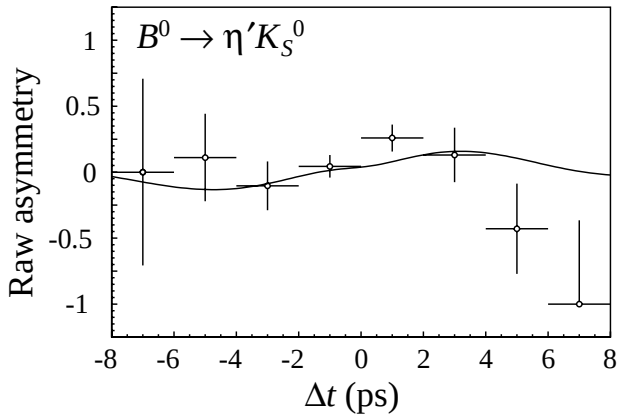


191 events

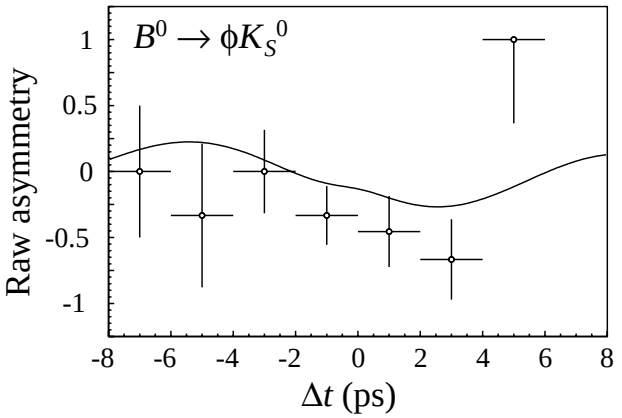
Purity $= 0.50^{+0.04}_{-0.03}$

CP Fit Result for $b \to s\bar{s}s$

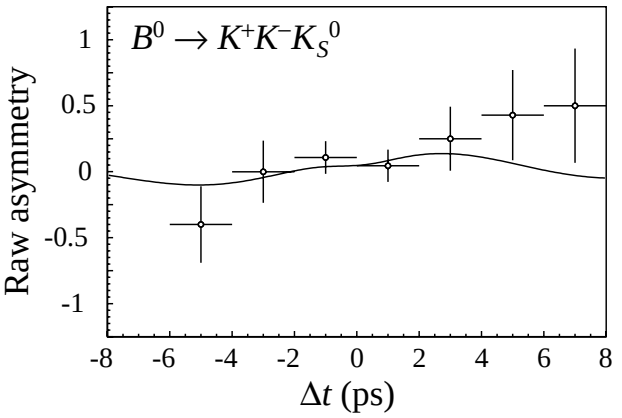
$B^0 \to \eta' K_S$ $(\xi_f = -1)$



$B^0 \to \phi K_S$ $(\xi_f = -1)$



$B^0 \to K^+K^-K_S$ $(\xi_f \simeq +1)$



$$S_{\eta' K_S} = +0.71 \pm 0.37^{+0.05}_{-0.06}$$

$$A_{\eta' K_S} = +0.26 \pm 0.22 \pm 0.03$$

$$S_{\phi K_S} = -0.73 \pm 0.64 \pm 0.22$$

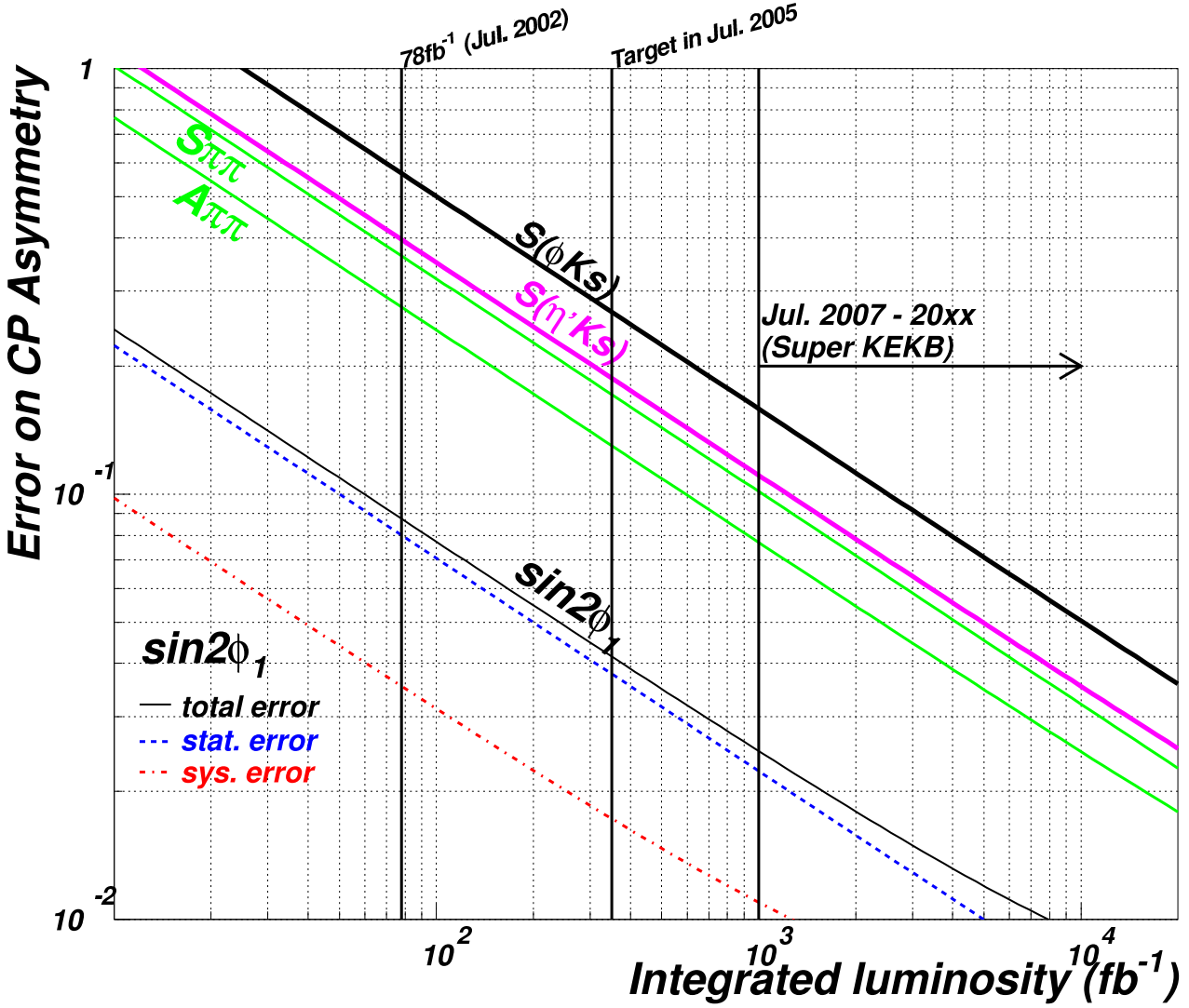
$$A_{\phi K_S} = -0.56 \pm 0.41 \pm 0.16$$

$$-S_{KKK_S} = +0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$$

$$A_{KKK_S} = -0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}$$

$$\sin 2\phi_1 = 0.719 \pm 0.074 \pm 0.035 \quad (f_{\text{even}} = 1.04 \pm 0.19 \pm 0.06)$$

Future Prospect



Summary

- CP violation parameter $\sin 2\phi_1$ is precisely measured based on 85×10^6 $B\overline{B}$ pairs using $b \to c\bar{c}s$ transitions:

$$\sin 2\phi_1 = 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{syst})$$

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- Time-dependent CP violations in $b \to s\bar{s}s$ transitions are measured.
  - 2.1σ deviation is observed for $B^0 \to \phi K_S$.
- Precise test of SM is becoming possible.
  - Unitarity Triangle, $b \to c\bar{c}s \Leftrightarrow b \to s\bar{s}s$