CP Violation in $J/\psi K_L^0$ Decay at Belle

1. CP violation in B decay
2. KEKB and Belle
3. $J/\psi K_L^0$
   - Event selection
   - Vertexing
   - Flavour tagging
4. Results from other modes/experiments
5. Summary and Outlook

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The CKM Triangle

Unitary CKM matrix governs weak decay of quarks

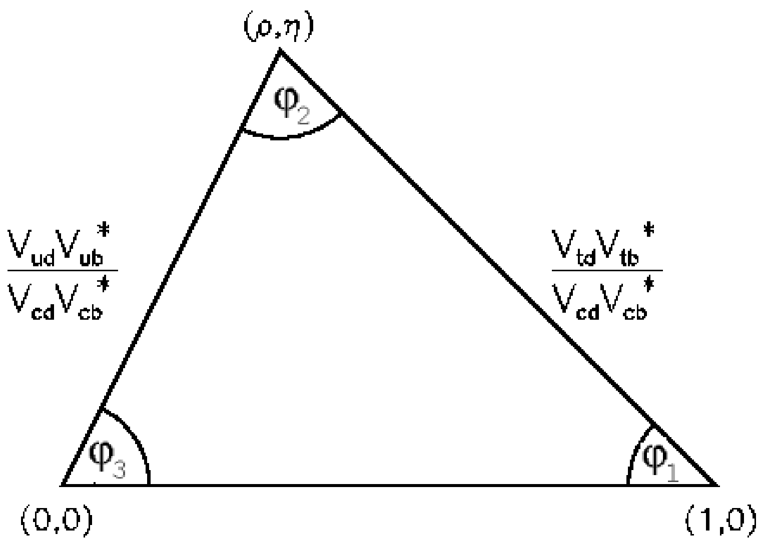
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation:

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

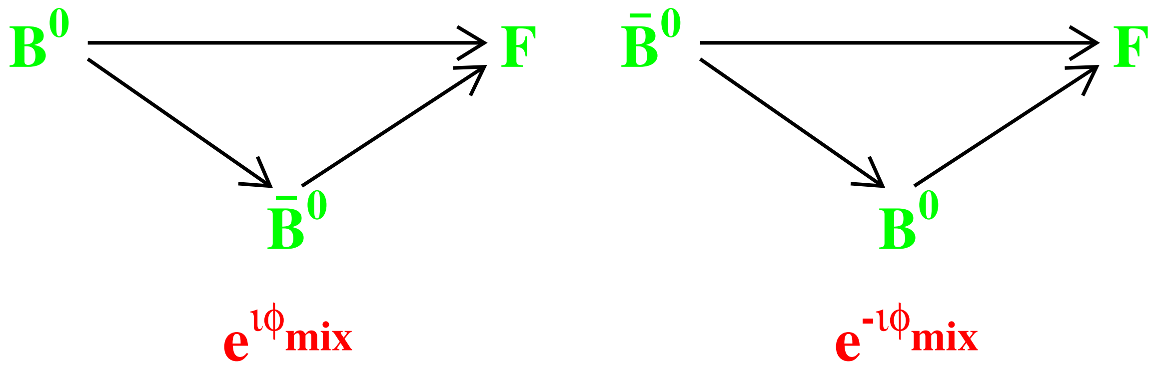
Unitarity $\to V^\dagger V = 1$ gives:

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



$$\phi_2 = \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \phi_1 = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \phi_3 = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Indirect CP Asymmetry

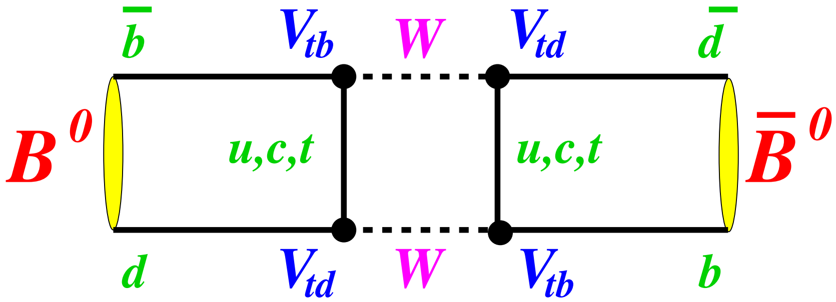


- Results in:

$$\frac{dN}{dt}(B^0 \to J/\psi K_L^0) \sim 1 + \sin\ 2\phi_1\ \sin\ \Delta m t$$

$$\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_L^0) \sim 1 - \sin\ 2\phi_1\ \sin\ \Delta m t$$

- CP phase easily seen in CKM matrix element V_{td}



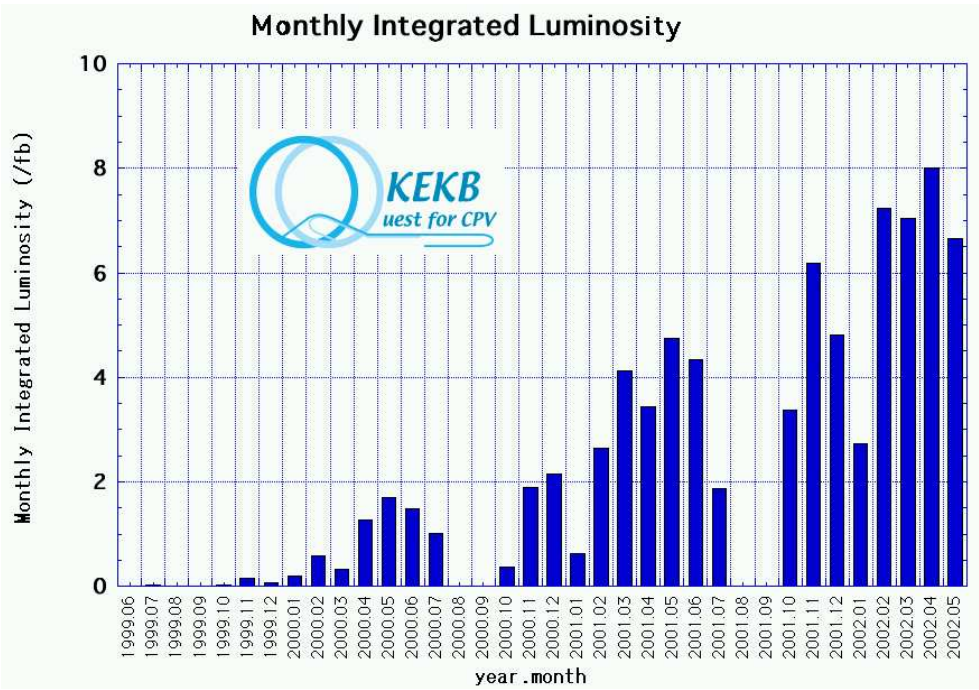
- B^0 and $\bar{B}^0$ produced at equal rates develop asymmetry:

$$\begin{aligned} A_{CP}(t) &= \frac{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_L^0) - \frac{dN}{dt}(B^0 \to J/\psi K_L^0)}{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_L^0) + \frac{dN}{dt}(B^0 \to J/\psi K_L^0)} \\ &= \text{- } \sin\ 2\phi_1\ \sin\ \Delta m t \end{aligned}$$

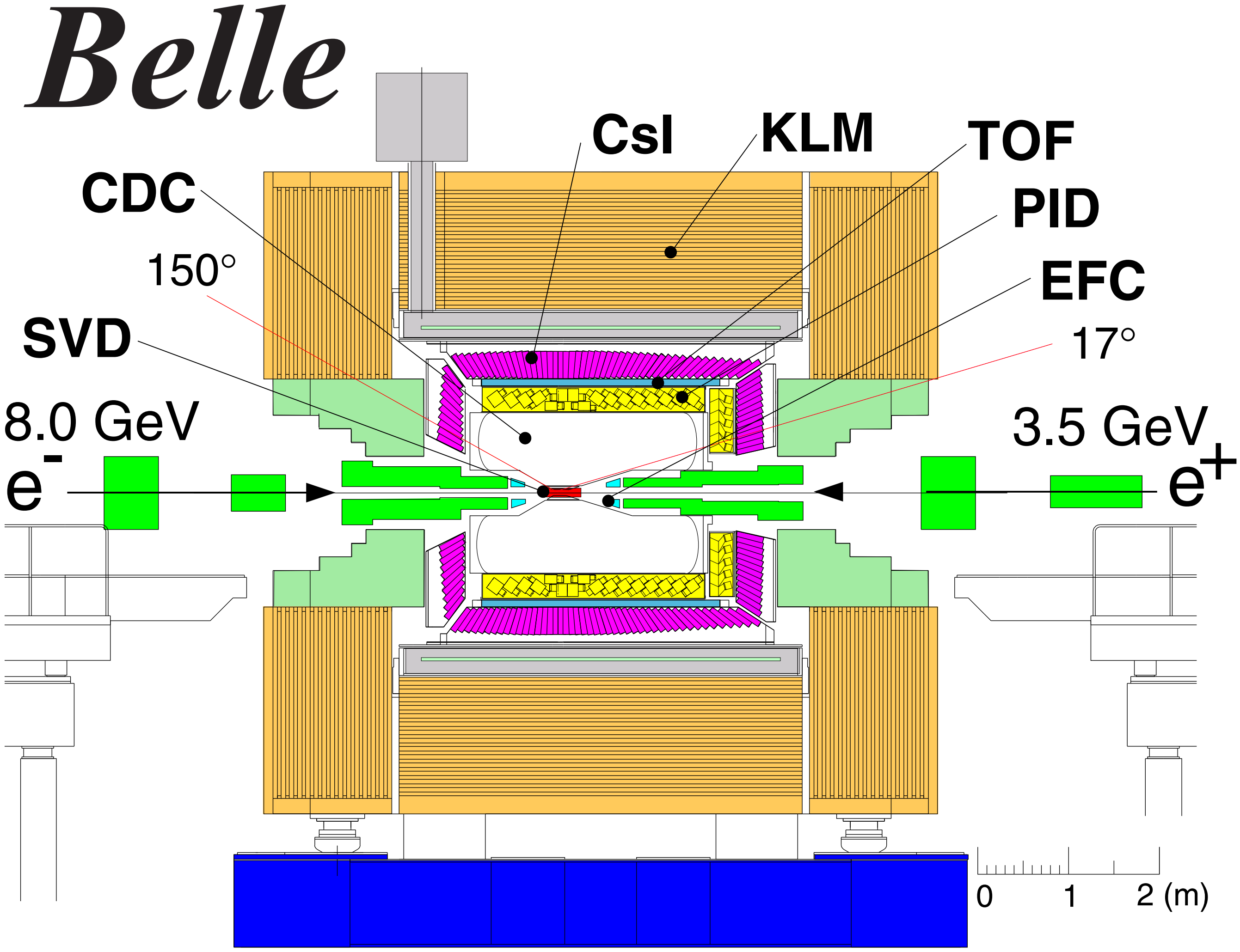
The KEK-B Collider

- 8.0 GeV electrons and 3.5 GeV positrons
  - $\sqrt{s} = 10.6$ GeV and $\beta\gamma = 0.425$
- 11 mrad crossing angle $\rightarrow$ reduces backgrounds

$\mathcal{L}$	KEK-B	PEP-II
Peak ($\times 10^{33}$)	7.4	4.6
Record Day (pb^{-1})	394	303
Record Month (fb^{-1})	8.8	6.6
Total (fb^{-1})	82	89



The BELLE Detector



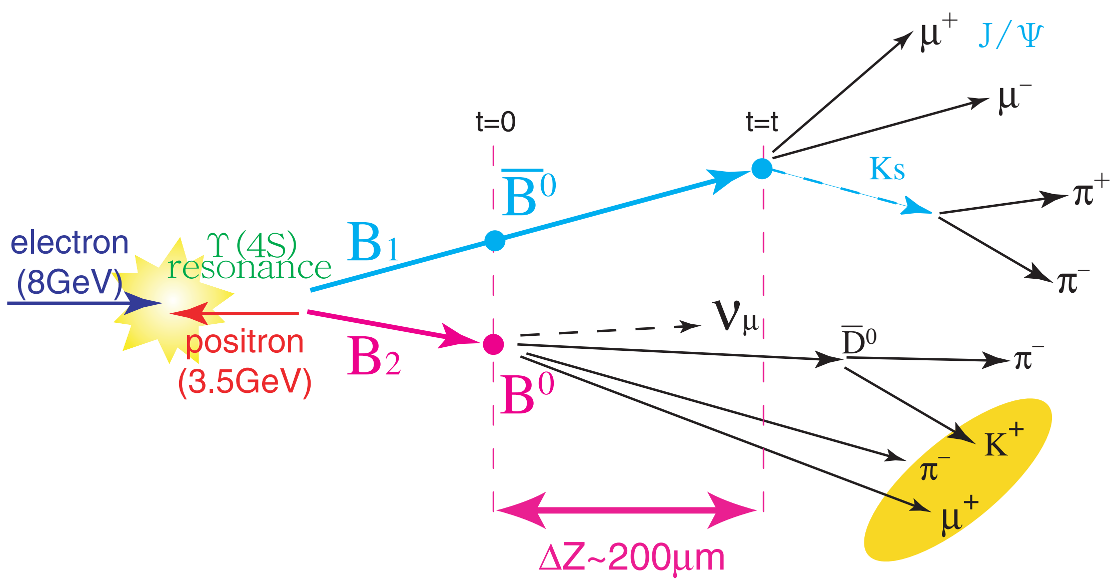
CP Violation Analysis Roadmap

1. Select $B^0 \to$ CP-eigenstate candidates ($J/\psi K^0_L$)

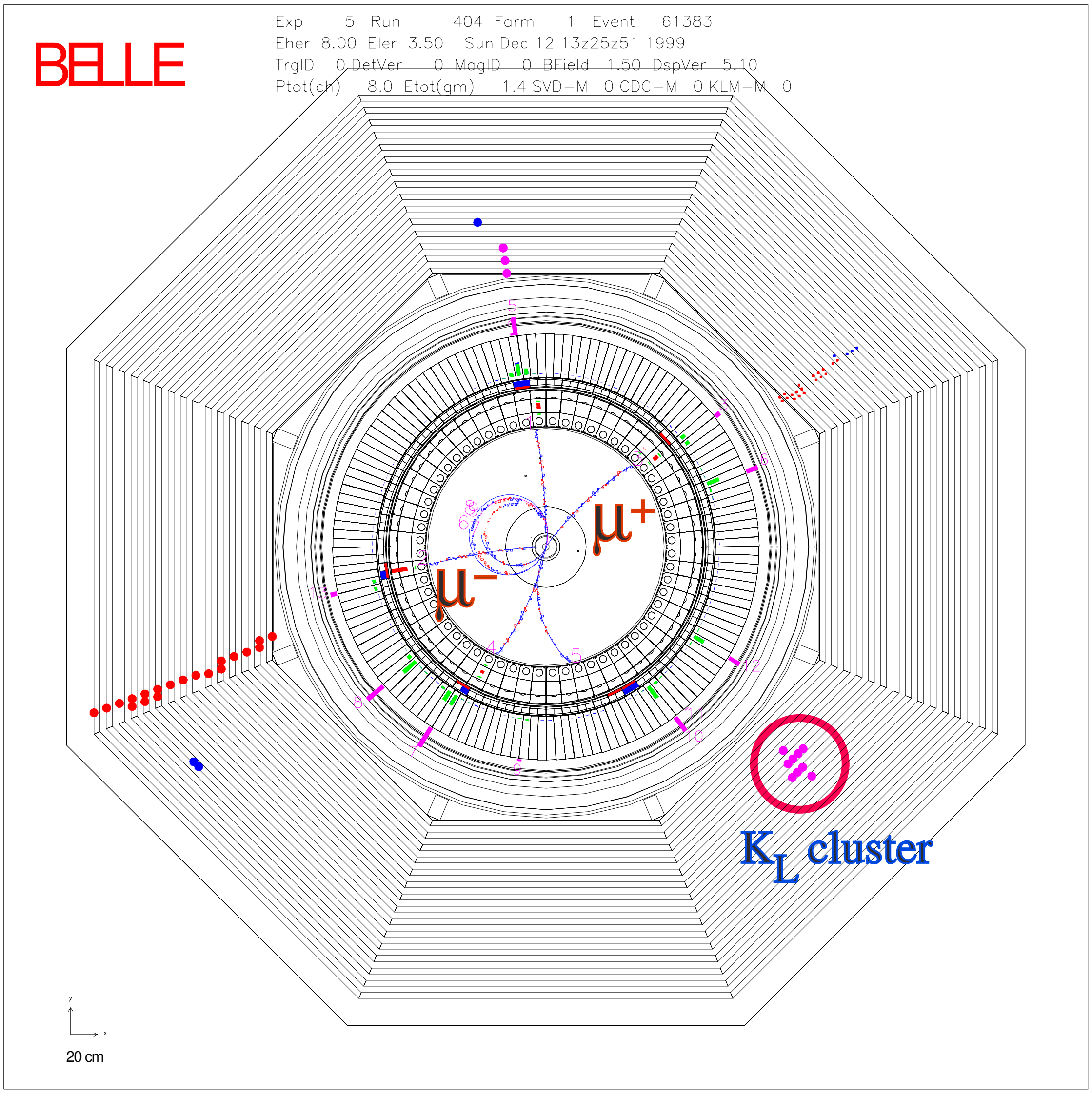
2. Find decay vertex and measure decay separation (Δt)

3. Tag flavour of "other B"

4. Fit time dependent flavour asymmetry



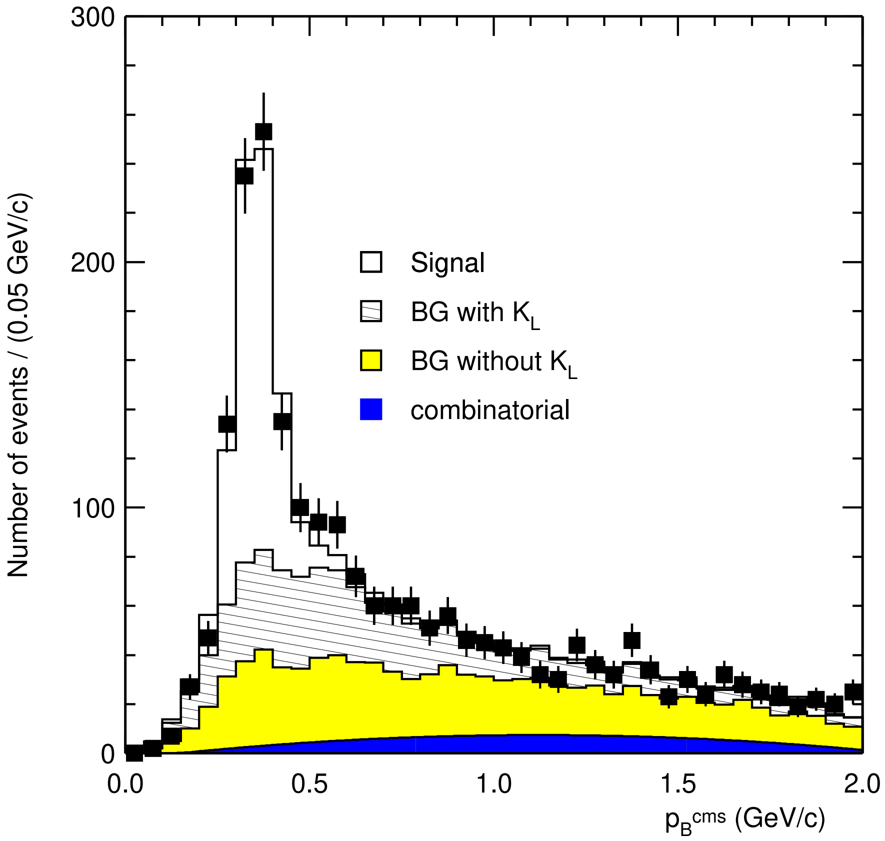
A $J/\psi K_L^0$ Candidate



- Muons leave continuous tracks in KL/muon detector
- K_L^0 leave a hadronic shower (cluster of hits)
- Only measure K_L^0 direction, not its energy/momentum

Identifying K_L^0 Candidates

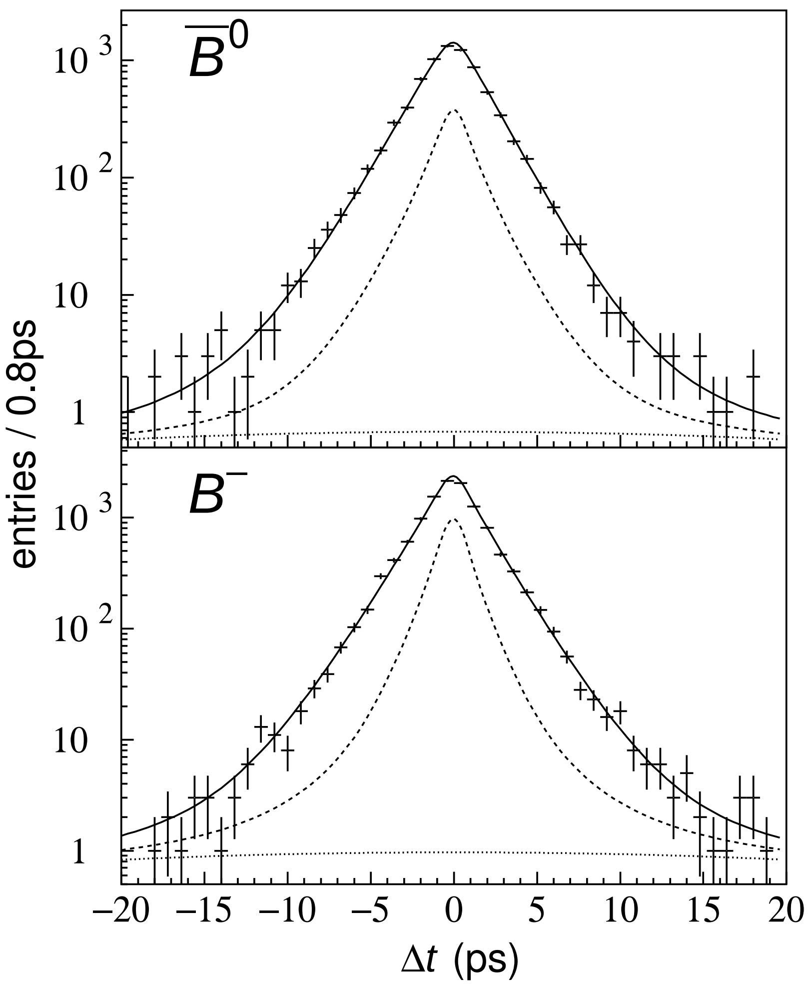
- Constrain K_L^0 momentum to give B mass. Know:
  - $\vec{p}_B^{\,*} = \vec{p}_{J/\psi}^{\,*} + \vec{p}_{K_L^0}^{\,*}$
  - $E_{J/\psi}^* + E_{K_L^0}^* = m_B$
  - Given $\hat{p}_{K_L^0}$ this gives a unique $|\vec{p}_{K_L^0}^{\,*}|$
- Look for signal (peak near 330 MeV/c^2) in p_B^* distribution



- Veto all other $J/\psi X$ candidates found
- B decay backgrounds (hatched with K_L^0, yellow without K_L^0)
- Select 767 events ($200 \leq p_B^* \leq 450$ MeV/c) with 60% purity

Find the Decay Vertices

- Measure the separation in decay vertex
  - Subtle since detector resolution ≈ B flight distance
- Parametrise resolution function carefully
  - CP side has 75μm resolution
  - Tagging side has 140μm resolution
- Resolutions well understood beyond 10 B lifetimes

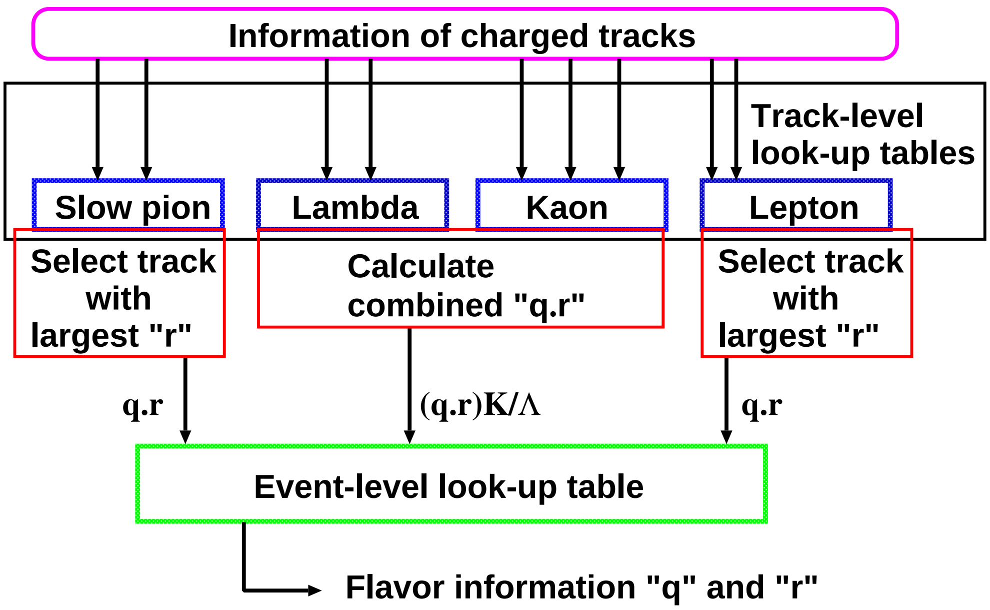


$$\frac{\tau_{B^-}}{\tau_{\bar{B}^0}} = 1.09 \pm 0.03$$

(PRL 88, 171801 (2002))

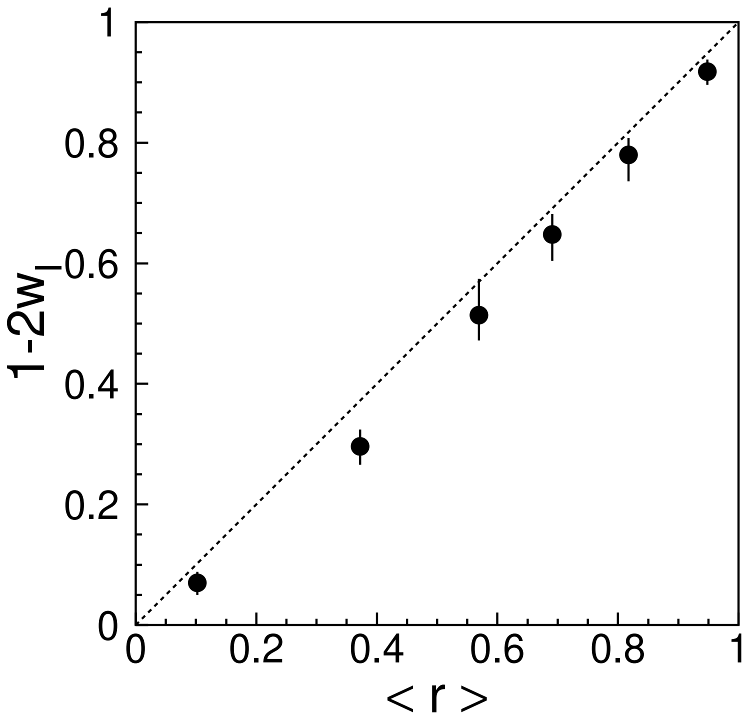
Flavour Tagging Method

- $B^0 \to J/\psi K_L^0$ is a flavour eigenstate
- Must tag "other" B using a combination of:
  - high p_t leptons ($b \to cl\nu$: l^-)
  - lower p_t leptons ($b \to c \to sl\nu$:l^+)
  - Kaons ($b \to c \to sX$: K^-)
  - low momentum pions ($B \to D^* \to D\pi$:π^-)
  - and other information
- Combine this information with look-up tables based on MC



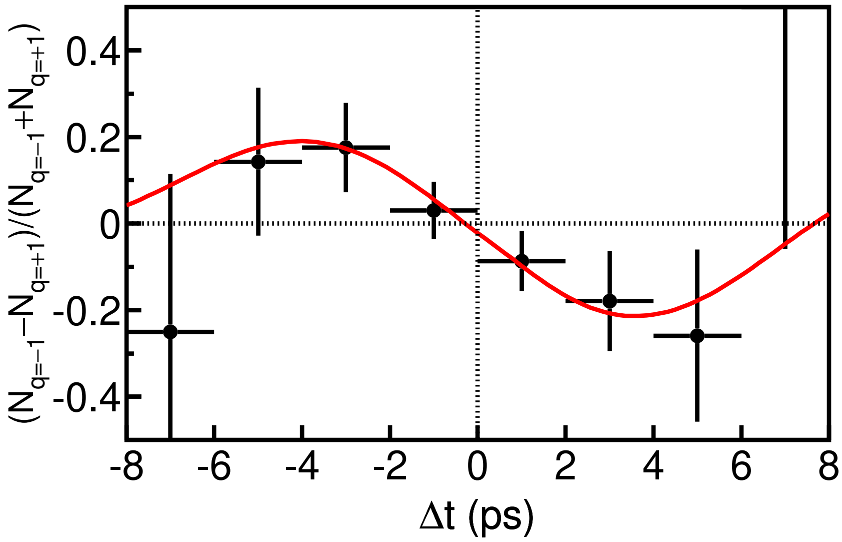
Flavour Tagging Calibration

- Calibrate effectiveness on control data samples
- Measure $B^0\bar{B}^0$ mixing in six intervals of r
- Wrong tag fractions (w_l) as a function of r from data



- No tagging bias observed
- Effectively tag 27.0 ± 1.2 % of B^0 decays

CP Asymmetry from $J/\psi K_L^0$

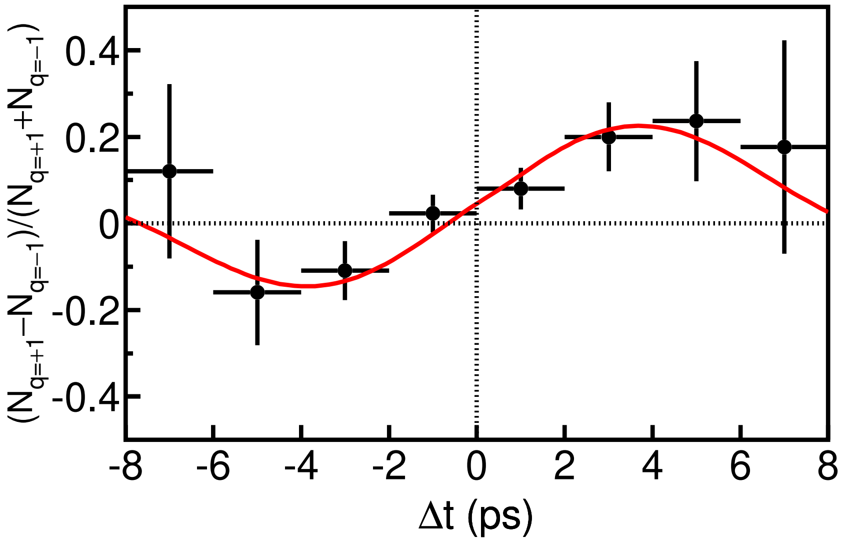


$$\sin 2\phi_1 = 1.14 \pm 0.23(stat.) \pm 0.09(sys.)$$

Uncertainty Source	Value
Background	0.08
Vertexing	0.03
Flavour Tagging	0.02
Vertex Resolution	0.02
$\delta m_d,\ \tau_B$	0.01
Total	0.09

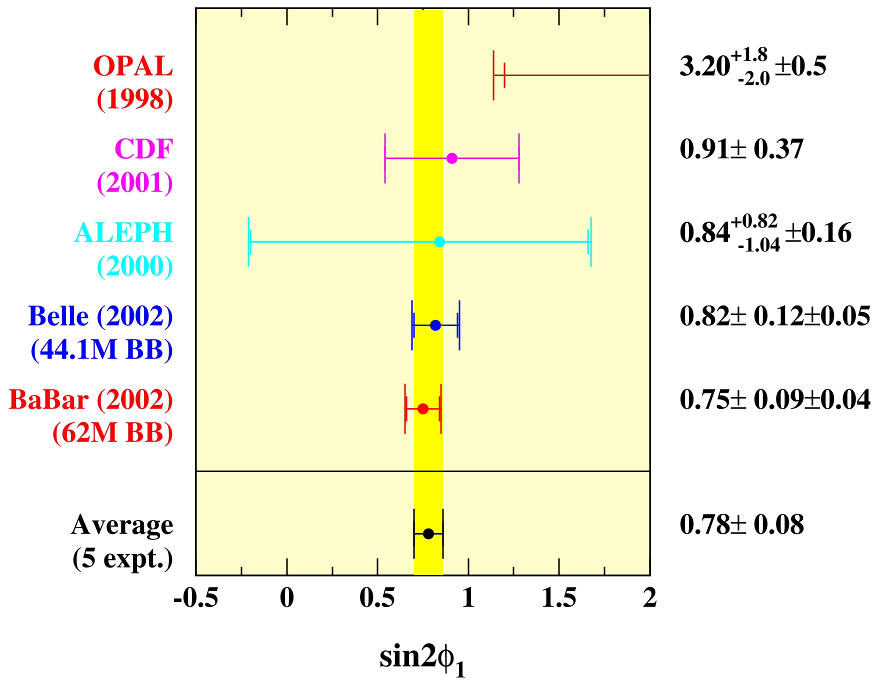
Other Measurements of $\sin 2\phi_1$

BELLE result from all modes (dominated by $J/\psi K_S^0$)



$$\sin 2\phi_1 = 0.82 \pm 0.12(stat.) \pm 0.05(sys.)$$

Comparison to other experiments



Summary and Outlook

- e^+e^- environment allows selection of clean $J/\psi K_L^0$ sample
- $\sin 2\phi_1 = 1.14 \pm 0.23(stat.) \pm 0.09(sys.)$ from K_L^0 mode alone
- Other modes clearly have opposite CP
- Combining all modes BELLE gets
  - $\sin 2\phi_1 = 0.82 \pm 0.12(stat.) \pm 0.05(sys.)$
- Attention now shifting to
  - ϕ_2 and $\pi^+\pi^-$ asymmetry
  - rare modes where "new physics" may distort ϕ_1

- Twice as much data available this summer