Observation of Large CP Violation in the Neutral B Meson System

Presentation for PHY7357 final exam
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- Background:
- In 1973, Kobayashi and Maskawa(KM) proposed quark mixing matrix when only u, d and s quarks were know
- c, b and t quarks were discovered subsequently
- CP violation in the neutral K meson was observed
- In 1981, Sanda, Bigi and Carter pointed out that KM model predicted large CP violation in certain decays of B mesons
- Discovery of $B^0\overline{B^0}$ mixing in 1987

- CP violating asymmetry in the time-dependent rates for intial B^0 and $\overline{B^0}$ decays to a common CP eigenstate, f_{CP}

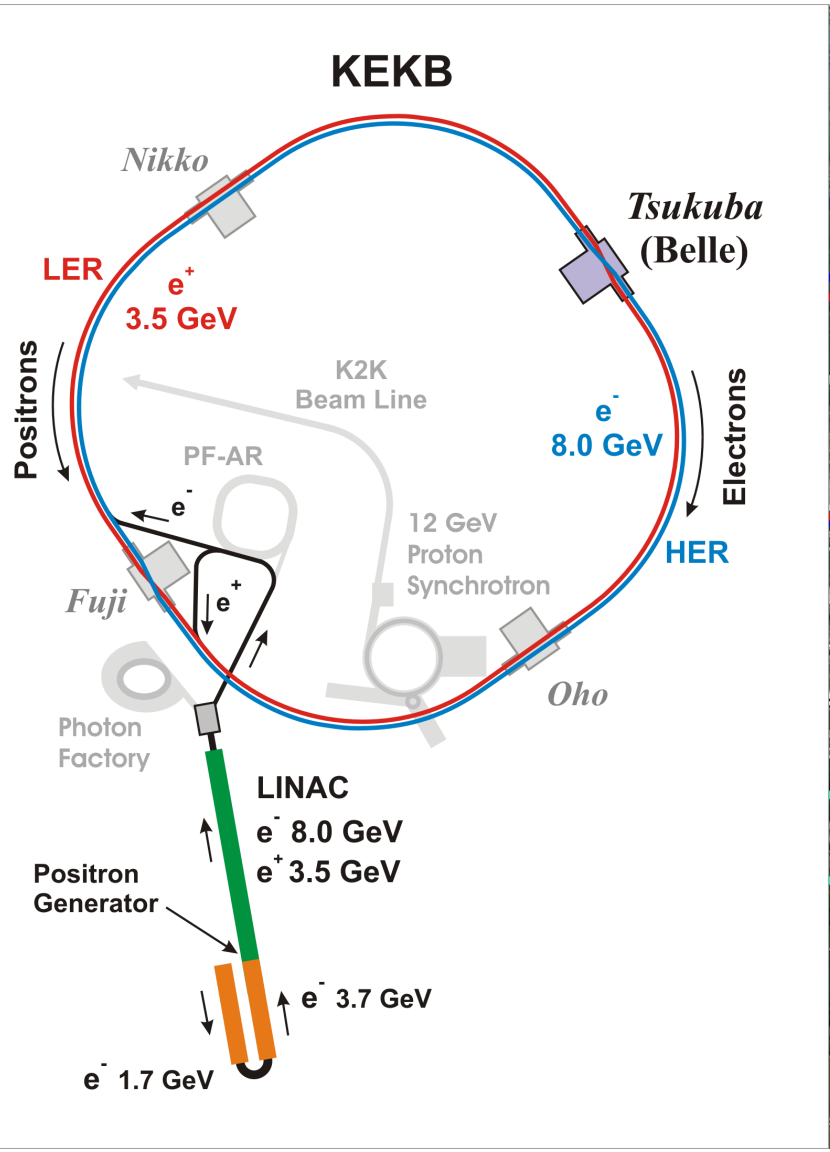
$$A(t) = \frac{\Gamma\left(\overline{B^0} \to f_{CP}\right) - \Gamma(B^0 \to f_{CP})}{\Gamma\left(\overline{B^0} \to f_{CP}\right) + \Gamma(B^0 \to f_{CP})} = -\xi_f sin2\phi_1 sin\Delta m_d t$$

$\Gamma\left(\overline{B^0}(B^0) \to f_{CP}\right)$: the decay rate for $\overline{B^0}(B^0)$ to f_{CP} at a proper time t after production

ξ_f: CP-eigenvalue of f_{CP}

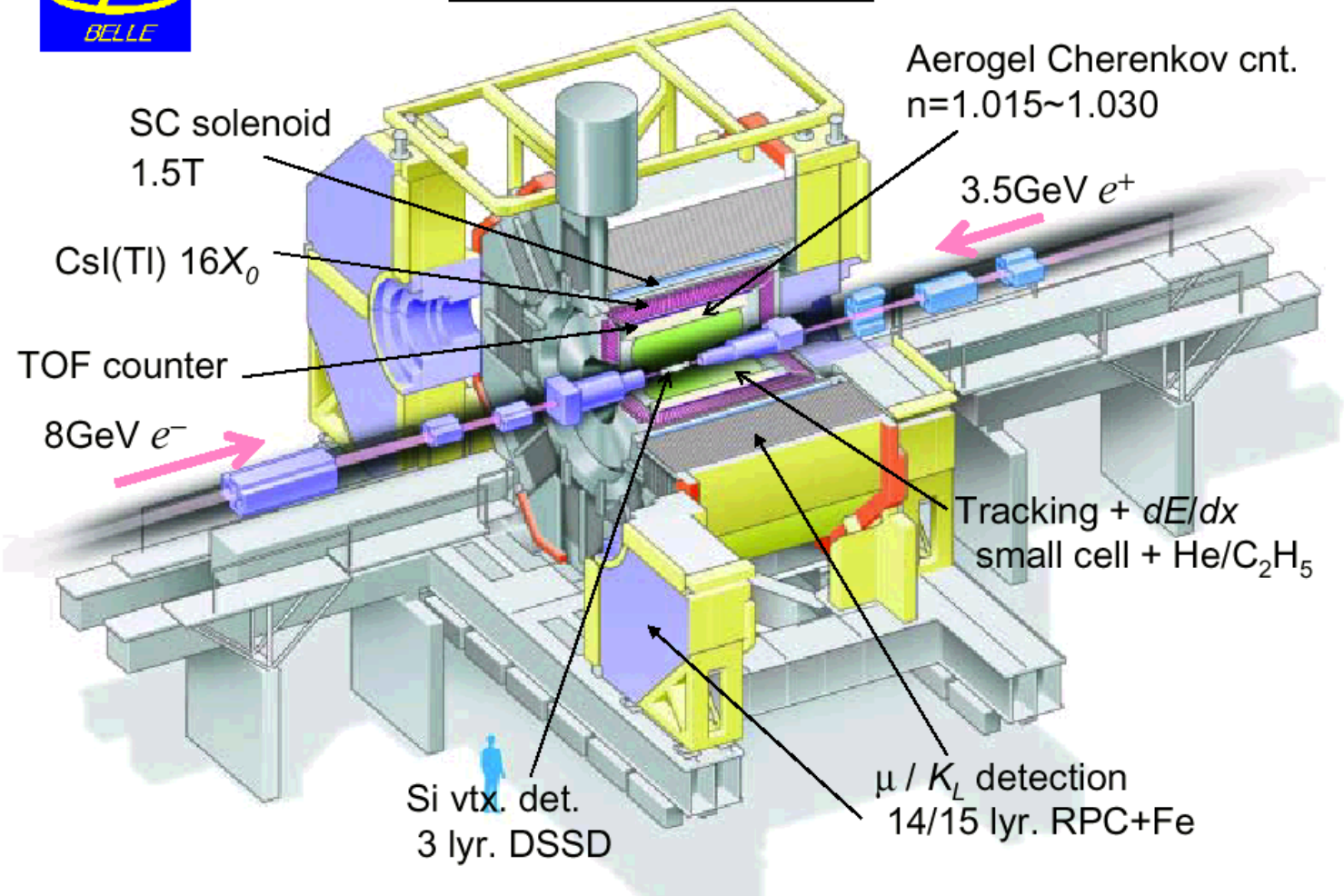
Δm_d: mass difference between the two B^0 mass eigenstates

ϕ_1: internal angle, defined as $\phi_1 = \pi - \arg(\frac{-V_{tb}^* V_{tb}}{-V_{cb}^* V_{cd}})$


KEKB
Nikko
Tsukuba
(Belle)
LER
e+
3.5 GeV
Positrons
K2K
Beam Line
e-
8.0 GeV
Electrons
PF-AR
e-
12 GeV
Proton
Synchrotron
HER
Fuji
e+
Oho
Photon
Factory
LINAC
e- 8.0 GeV
e+ 3.5 GeV
Positron
Generator
e- 3.7 GeV
e- 1.7 GeV


LINAC

Belle Detector



- KEKB accelerator: the world's highest luminosity machine
  - 8 GeV e-, 3.5 GeV e+, $E_{cms} = 10.58, \quad \Upsilon(4S) \rightarrow B\bar{B}$
  - Lorentz boost $\beta\gamma \sim 0.425$
  - Luminosity $\mathcal{L} \sim 2.11\times10^{34} cm^{-2}s^{-1}$
  - Integrated luminosity $\sim 710\ fb^{-1}$ (771 million $B\bar{B}$ pairs)

- Belle Detector:
  - SVD : three-layer silicon vertex detector
  - CDC : 50-layer central drift chamber
  - ACC : aerogel threshold Cerenkov counters
  - TOF : time-of-flight scintillation counters
  - ECL : CsI(Tl) crystals
  - KLM : KL mesons and to identify muons

- Flavor tagging
  - one of the B mesons decays at time t_{tag} to a final state, f_{tag}
  - the accompanying B mesons decays to f_{CP}, at t_{CP}
  - proper time: $\Delta t = t_{CP} - t_{tag}$, CP violation appears in $\mathrm{A}(\Delta t)$
  - Δt is determined from the displacement in z between the f_{CP} and f_{tag} decay vertices: $\Delta t = \frac{z_{CP} - z_{tag}}{\beta\gamma c} = \frac{\Delta z}{\beta\gamma c}$

- Measurement
  - reconstruction of $B^0 \rightarrow f_{CP}$ decay
  - determination of the b-flavor of B meson
  - measurement of Δt
  - fit of Δt distribution with a likelihood method

- reconstruction of $B^0 \to f_{CP}$ decay
  - $\xi_f = -1$ for J/ψ K_s, ψ(2S)K_s , $\chi_{c1}K_s$, $\eta_c K_s$
  - $\xi_f = +1$ for J/ψ K_L
  - specially, for $B^0 \to$ J/ψ K^{*0}, $K^{*0} \to K_s\, \pi^0$, the final state is mixture of even and odd CP depending on the relative orbital angular momentum of the J/ψ and K^{*0}. A fit to angular distribution of all J/ψ K^* shows the final state is primarily $\xi_f = +1$, with the fraction of $\xi_f = -1$ is 0.19±0.04(stat)±0.04(syst)

J/ψ and ψ(2S) and reconstructed via their decays into l^+l^- ($l = \mu, e$)
ψ(2S) is also reconstructed via J/ψ $\pi^+\pi^-$, χ_{c1} via J/ψγ
η_c is reconstructed in $K^+K^-\pi^0$ and $K_sK^-\pi^+$ modes

Different selection algorithm is applied in each decay channel based on the study of MC simulation

- Identification of B mesons ($\xi_f = -1$)
  - identify B decays using the energy difference $\Delta E = E_B^{cms} - E_{beam}^{cms}$, and beam energy constrained mass $M_{bc} = \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$

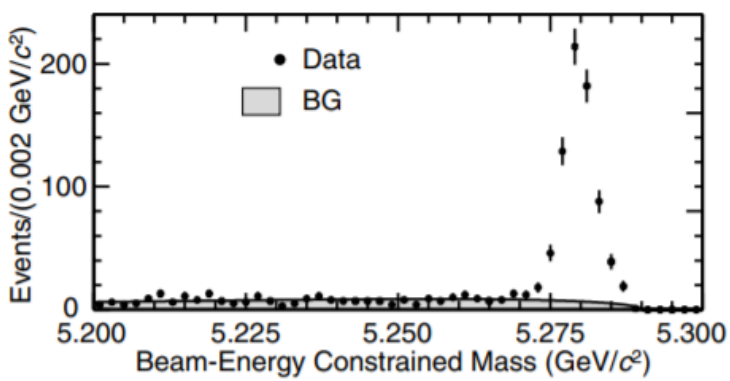


FIG. 1. The beam-energy constrained mass distribution for all decay modes combined other than $J/\psi K_L$. The shaded area is the estimated background. The signal region is the range 5.27−5.29 GeV/c^2.

TABLE I. The numbers of observed events (N_{ev}) and the estimated background (N_{bkgd}) in the signal region for each f_{CP} mode.

Mode	N_{ev}	N_{bkgd}
$J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$	457	11.9
$J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$	76	9.4
$\psi(2S)(\ell^+\ell^-)K_S(\pi^+\pi^-)$	39	1.2
$\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$	46	2.1
$\chi_{c1}(J/\psi\gamma)K_S(\pi^+\pi^-)$	24	2.4
$\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$	23	11.3
$\eta_c(K_SK^-\pi^+)K_S(\pi^+\pi^-)$	41	13.6
$J/\psi K^{*0}(K_S\pi^0)$	41	6.7
Subtotal	747	58.6
$J/\psi(\ell^+\ell^-)K_L$	569	223

$m_B = 5279.63 \pm 0.15$ MeV

- Identification of B mesons ($\xi_f = +1$)
  - $B^0 \rightarrow$ J/ψ K_L, signal purity is about 61%

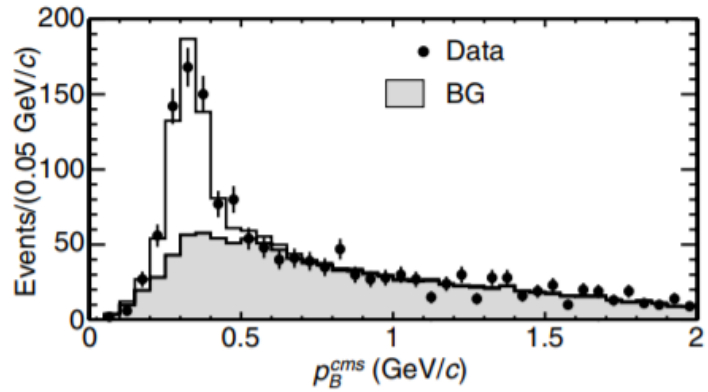


FIG. 2. The $p_B^{\rm cms}$ distribution for $B^0 \rightarrow J/\psi K_L$ candidates with the results of the fit. The solid line is the signal plus background; the shaded area is background only. The signal region for KLM (ECL-only) clusters is $0.2 \leq p_B^{\rm cms} \leq 0.45(0.40)$ GeV/c.

- Identification of b flavor
  - Leptons, charged pions, and kaons that are not associated with a reconstructed CP eigenstate decay
  - well measured tracks:
    - high momentum leptons from $b \to cl^-\bar{\nu}$
    - low momentum leptons from $c \to sl^+\bar{\nu}$
    - charged kaons and lambdas from $b \to c \to s$
    - high momentum pions from decays of $B^0 \to D^{(*)-}(\pi^+, \rho^+, a_1^+, etc)$
    - low momentum pions from $D^{(*)-} \to \overline{D^0}\pi^-$

MC sample data is use to determine a category-dependent variable that indicates the b flavor.

q, discrete, +1 when B^0- like, -1 when $\overline{B^0}$- like

r, event-by-event flavor-tagging dilution factor, ranges from r=0 (no flavor discrimination) to r=1(unambiguous flavor assignment)

- CP violation
  - after vertexing we find 560 events with q = +1 flavor tags and 577 events with q = −1
  - observed Dt distributions for the $q\xi_f = +1$(solid points) and $q\xi_f = -1$(open points) event samples

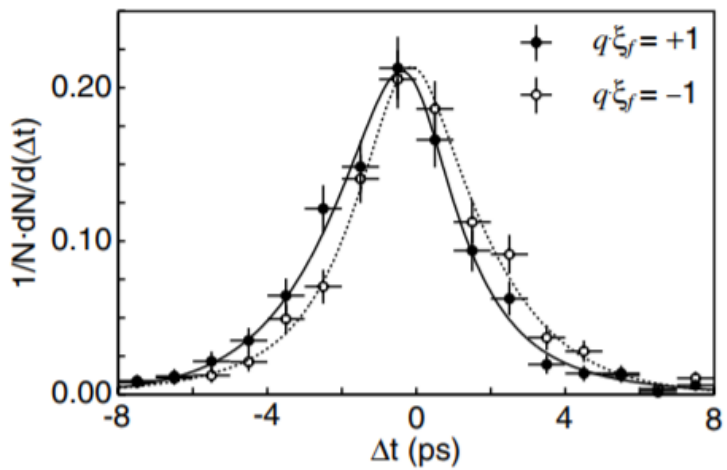


FIG. 3. Δt distributions for the events with $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points). The results of the global fit (with $\sin 2\phi_1 = 0.99$) are shown as solid and dashed curves, respectively.

- Determination of $sin2\phi_1$
  - performing an unbinned maximum-likelihood fit of a CP violating probability density function (pdf) to the observed Δt distributions

$$\mathcal{P}_{\rm sig}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - \xi_f q(1 - 2w_l) \times \sin 2\phi_1 \sin(\Delta m_d \Delta t)\},$$

$$\mathcal{P}_{\rm bkg}(\Delta t) = f_\tau e^{-|\Delta t|/\tau_{\rm bkg}}/2\tau_{\rm bkg} + (1 - f_\tau)\delta(\Delta t)$$

For all modes other than J/ψ K_L, use events in background-dominant regions of ΔE vs M_{bc} to study the background and shows that it is negligibly small. For J/ψ K_L, main background is B→ J/ψX where some final states are CP eigenstates. Using MC simulation to determine the fraction of events with definite CP component in each component.

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

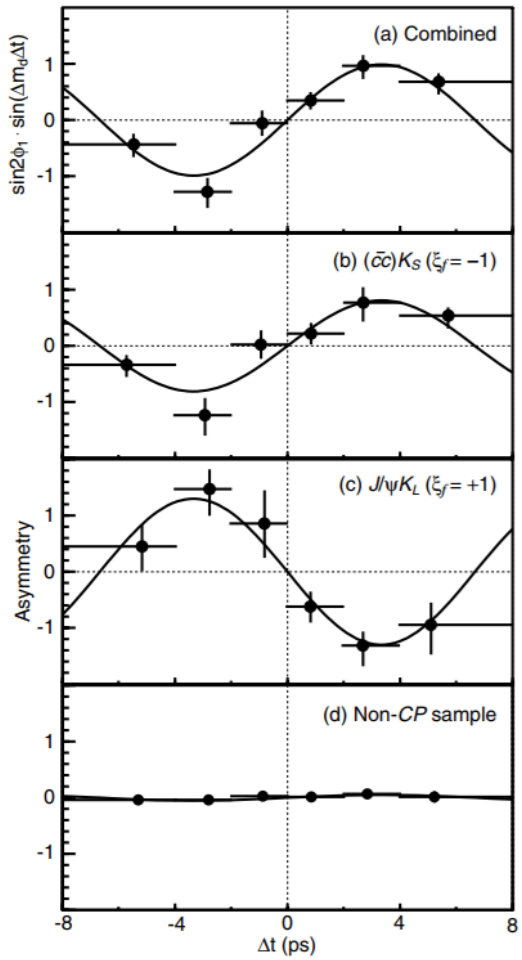


FIG. 4. (a) The asymmetry obtained from separate fits to each Δt bin for the full data sample; the curve is the result of the global fit. The corresponding plots for the (b) $(c\bar{c})K_S$ ($\xi_f = -1$), (c) $J/\psi K_L$ ($\xi_f = +1$), and (d) B^0 control samples are also shown. The curves are the results of the fit applied separately to the individual data samples.

- (a)asymmetries for the combined data sample that are obtained by applying the fit to the events in each Δt bin separately
- (b)corresponding asymmetry for $(c\bar{c})K_s(\xi_f = -1)$
- (c) corresponding asymmetry for J/ψ $K_L(\xi_f = +1)$
- (d) non-CP eigenstates

- Conclusion
  - there exists large CP violation in the neutral B meson system
  - a zero value for sin $sin2\phi_1$ is ruled out at a level greater than 6σ
  - result is consistent with the higher range of values allowed by the constraints of the KM model as well as with previous measurement

- Reference:
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