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 known
  • 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 initial $B^0$ and $\bar{B}^0$ decays to a common CP eigenstate, $f_{CP}$

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

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

$\xi_f$: CP-eigenvalue of $f_{CP}$

$\Delta m_d$: mass difference between the two $B^0$ mass eigenstates

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

- SC solenoid 1.5T
- CsI(Tl) 16X₀
- TOF counter
- 8GeV e⁻
- 3.5GeV e⁺
- Aerogel Cherenkov counter n=1.015~1.030
- Tracking + dE/dx small cell + He/C₂H₆
- Si vtx. det. 3 lyr. DSSD
- μ/Κ detection 14/15 lyr. RPC+Fe
• KEKB accelerator: the world's highest luminosity machine
  • 8 GeV e-, 3.5 GeV e+, $E_{ cms} = 10.58$, $\Upsilon(4S) \rightarrow B\bar{B}$
  • Lorentz boost $\beta\gamma \sim 0.425$
  • Luminosity $\mathcal{L} \sim 2.11 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  • Integrated luminosity $\sim 710 \text{ fb}^{-1}$ (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 $A(\Delta t)$
  • $\Delta t$ 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 $\Delta t$
  • fit of $\Delta t$ distribution with a likelihood method
- reconstruction of $B^0 \rightarrow f_{CP}$ decay
  - $\xi_f = -1$ for $J/\psi K_S, \psi(2S) K_S, \chi_{c1} K_S, \eta_c K_S$
  - $\xi_f = +1$ for $J/\psi K_L$
  - specially, for $B^0 \rightarrow J/\psi K^{*0}, K^{*0} \rightarrow K_S \pi^0$, the final state is mixture of even and odd CP depending on the relative orbital angular momentum of the $J/\psi$ and $K^{*0}$. A fit to angular distribution of all $J/\psi K^*$ shows the final state is primarily $\xi_f = +1$, with the fraction of $\xi_f = -1$ is $0.19 \pm 0.04 \text{(stat)} \pm 0.04 \text{(syst)}$

$J/\psi$ and $\psi(2S)$ and reconstructed via their decays into $l^+ l^- (l = \mu, e)$
$\psi(2S)$ is also reconstructed via $J/\psi \pi^+ \pi^-$, $\chi_{c1}$ via $J/\psi \gamma$
$\eta_c$ is reconstructed in $K^+ K^- \pi^0$ and $K_S K^- \pi^+$ 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 $\Delta E = E_{B}^{\text{cms}} - E_{\text{beam}}^{\text{ cms}}$, and beam energy constrained mass $M_{bc} = \sqrt{\left(E_{\text{beam}}^{\text{ cms}}\right)^2 - \left(p_{B}^{\text{ cms}}\right)^2}$

$M_{bc} = 5279.63 \pm 0.15 \text{ MeV}$
• Identification of B mesons ($\xi_f = +1$)
  • $B^0 \rightarrow J/\psi K_L$, signal purity is about 61%
• 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 \(b \to c l^- \nu\)
    • low momentum leptons from \(c \to s l^+ \overline{\nu}\)
    • 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 \(D^{(*)-} \to D^0 \pi^-\)

MC sample data is used 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 $D_t$ distributions for the $q_{\xi_f} = +1$(solid points) and $q_{\xi_f} = -1$(open points) event samples
• Determination of $sin2\phi_1$
  • performing an unbinned maximum-likelihood fit of a CP violating probability density function (pdf) to the observed $\Delta t$ distributions

\[
P_{\text{sig}}(\Delta t, q, w_l, \xi_f) = e^{-|\Delta t|/\tau_{B0}} \left\{ 1 - \xi_f q(1 - 2w_l) \times sin2\phi_1 \sin(\Delta m_d \Delta t) \right\},
\]

\[
P_{\text{bkg}}(\Delta t) = f_\tau e^{-|\Delta t|/\tau_{bkg}}/2\tau_{bkg} + (1 - f_\tau) \delta(\Delta t)
\]

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

\[sin2\phi_1 = 0.99 \pm 0.14(stat) \pm 0.06(syst)\]
- (a) asymmetries for the combined data sample that are obtained by applying the fit to the events in each $\Delta t$ bin separately
- (b) corresponding asymmetry for $(c\bar{c})K_S(\xi_f = -1)$
- (c) corresponding asymmetry for $J/\psi K_L(\xi_f = +1)$
- (d) non-CP eigenstates
• Conclusion

• there exists large CP violation in the neutral B meson system

• a zero value for $\sin sin 2\phi_1$ 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:
  • K. Abe et al. Phys. Rev. Lett. 87, 091802
  • M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973)
  • Belle Collaboration, A. Abashian, Phys. Rev. Lett. 86, 2509