RECENT BELLE RESULTS ON CP VIOLATION.

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The Belle experiment’s recent results on CP violation in B meson decays are summarized.

In the Standard Model (SM), CP violation is due to the spontaneous breaking of electroweak symmetry that results in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. In particular, the SM predicts a time-dependent CP-violating asymmetry in the rates for $B^0_\text{d}$ and $\bar{B}^0_\text{d}$ decays to a common CP eigenstate, $f_{CP}$:

$$A(t) = \frac{dN/dt(\bar{B}^0_\text{d} \to f_{CP}) - dN/dt(B^0_\text{d} \to f_{CP})}{dN/dt(\bar{B}^0_\text{d} \to f_{CP}) + dN/dt(B^0_\text{d} \to f_{CP})} = -\xi_f \sin 2\phi_i \sin \Delta m_d t,$$

where $t$ is the proper time, $dN/dt(\bar{B}^0_\text{d} \to f_{CP})$ is the decay rate for a $\bar{B}^0_\text{d}$ produced at $t = 0$ to decay to $f_{CP}$ at time $t$, $\xi_f$ is a CP-eigenvalue of $f_{CP}$, $\Delta m_d$ is the mass difference between two $B^0_\text{d}$ mass eigenstates, and $\phi_i$ is an internal angle of the CKM Unitarity Triangle. For CP eigenstate decays that proceed via a $b \to c$ tree diagram (e.g., $B^0 \to K_S J/\psi$, $\phi_i = \phi_1 \equiv \arg(-(V^*_{cb} V_{cd})/(V^*_{tb} V_{td}))$, where $V_{ij}$ ($i = u,c$ or $t$ and $j = d,s$ or $b$) are elements of the CKM quark-flavor mixing matrix. For $B^0 \to K^0 J/\psi$ decays, the theoretical uncertainty associated with the determination of $\sin 2\phi_1$ is very small, at the 0.01 level.

Belle and BaBar first established non-zero values for $\sin 2\phi_1$ in 2001. This year, using 7484 $B^0 \to K_S J/\psi$ ($\xi_f = -1$) decays and 6512 $B^0 \to K_L J/\psi$ ($\xi_f = +1$) decays in a total sample of 535M $B \bar{B}$ meson pairs, Belle has reported $\sin 2\phi_1 = +0.642 \pm 0.031\text{(stat)} \pm 0.017\text{(syst)}$. Figure (top) shows the background-subtracted $-\xi_f \Delta t$ distribution for events with a $B^0$ tag (open circles) and a $\bar{B}^0$ tag (closed circles). Figure (bottom) shows the $-\xi_f \Delta t$-dependent asymmetry.

In the absence of competing penguin processes, for CP eigenstate decays that proceed via a $b \to u$ tree diagram (e.g., $(B^0 \to \pi^+ \pi^-, \rho^+ \rho^-$ and $\pi \rho$), $\phi_i = \phi_2 \equiv \arg(-(V^*_{ub} V_{ud})/(V^*_{tb} V_{td}))$. The influence of penguins can be determined from measurements of the branching fractions and asymmetries of all isospin partner decays. Because $b \to u$ decays are suppressed (e.g. in the data sample in which Belle finds $\sim 14K B \to K^0 J/\psi$ decays, only 1464 $B^0 \to \pi^+ \pi^-$ decays are seen) and also because of complications from penguins, the precision on $\phi_2$ is reduced.

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to the Dalitz distributions for 331 $e^+D^0 \rightarrow K^0/\psi$ events with high-quality $B^0$ (open circles) and $B^0$ (closed circles) tags. (Bottom) The $-\xi_J \Delta t$-dependent asymmetry compared to that for $\phi_1$. In addition, there are discrete ambiguities associated with extracting $\phi_2$ from the measured asymmetry. For the $\pi^+\pi^-$ analysis, Belle finds a solution consistent with SM expectations of $\phi_2 = (97 \pm 11)^\circ$. Most of the ambiguous solutions are ruled out by time-dependent analyses of $B^0 \rightarrow \pi^0$ and $B^0 \rightarrow \rho\rho$.

The third angle of the Unitary Triangle, $\phi_3 \equiv \arg\left(\frac{\langle V_{ub}\bar{V}_{ud}\rangle}{\langle V_{cb}\bar{V}_{cd}\rangle}\right)$, is the most difficult to measure. Most proposed techniques involve interference between the Cabibbo-suppressed but CKM-favored $b \rightarrow c\bar{s}s$-tree-mediated $B^- \rightarrow K(\pi^+\pi^-)$ decay with the CKM-disfavored $b \rightarrow u\bar{c}s$-tree-mediated $B^- \rightarrow K^{(*)-}D^{(*)0}$ decay. Here, since the amplitude for the latter decay is suppressed relative to the former both by a CKM factor of $|V_{ub}/V_{cd}| \sim 0.38$ and a color-suppression factor estimated to be in the range $0.1 \sim 0.2$, the expected $CP$ asymmetries are expected to be small. The most promising technique uses differences in the $K_S\pi^+\pi^-$ Dalitz-plot densities between $B^+$ and $B^-$ decays to $``D^{(*)0}K^\pm$ with $``D^{(*)0} \rightarrow K_S\pi^+\pi^-$. The gist of the technique is as follows. Assuming no $CP$ asymmetry in the $D^0 \rightarrow K_S\pi^+\pi^-$ decay, the amplitude for $``D^{(*)0} \rightarrow K_S\pi^+\pi^-$ decay from $B \rightarrow KD$ decays is $M_\pm = f(m_\pm^2, m_2^2) + r e^{i(\pm \phi_3)} f(m_\pm^2, m_2^2)$, where $m_{\pm}^2 = m_{K_S\pi^\pm}$ are the two Dalitz plot variables, $f(m_\pm^2, m_2^2)$ is the amplitude for $D^0 \rightarrow K_S\pi^+\pi^-$ decay and $r$ & $\phi_3$ are the ratio and relative strong phase of the $B \rightarrow KD$ and $B \rightarrow K\bar{D}$ decay amplitudes.

In Belle, $f(m_\pm^2, m_2^2)$ is parameterized by 18 two-body decay amplitudes with strengths and relative phases determined from a fit to a large (262K event) sample of $D^+ \rightarrow \pi^+D^0(K_S\pi^+\pi^-)$ and charge conjugate decays produced via the continuum $e^+e^- \rightarrow c\bar{c}$ annihilation process. The resulting $f(m_\pm^2, m_2^2)$ is used in a fit of $|M_\pm|^2$ to the Dalitz distributions for 331 $K^\pm D$, 81 $K^\pm D^{(*)0}$ and 54 $K^{(*)\pm}D^{(*)0}$ signal events found in a data sample containing 386M $BB$ meson pairs. Values of $r, \phi_3$ for
each mode are extracted from the fit parameters. The value for $\phi_3$ in the range $0 \leq \phi_3 \leq 180^\circ$ for three combined modes is $\phi_3 = 53^\circ \pm 15^\circ$ (stat) $\pm 3^\circ$ (syst) $\pm 9^\circ$ (model).

A difficulty is the sensitivity of the measured $\phi_3$ value to $r$, which is measured to be small and only $\sim 3\sigma$ from zero. For the $K^\pm D$ mode the measured value is $r = 0.159^{+0.054}_{-0.050} \pm 0.013 \pm 0.049$.

The current experimental situation involving tree diagrams is succinctly summarized in the two plots from the UTfit group shown in Fig. 2. The plot on the left shows constraints in the $\bar{\rho} - \bar{\eta}$ plane using all measurements other than those of the Unitary Triangle angles. The plot on the right shows the constraints that derive only from measurements of $\phi_1$, $\phi_2$ and $\phi_3$. The fact that both sets of measurements pick out the same allowed region in $\rho$ and $\eta$ is striking evidence for the validity of the KM ansatz. A second striking feature that is evident from these plots is that, in spite of the limited precision of the $\phi_2$ measurement and the primitive state of the $\phi_3$ measurement, the constrains from the angle measurements are more stringent than those from all other measurements. Part of the reason for this is the theoretical cleanliness of the angle measurements.

In addition to improving the precision, especially on $\phi_2$ and $\phi_3$, which can be done with increased statistics, the next step is to measure the same angles using processes involving loop (or penguin) diagrams. Such measurements are very sensitive probes for new non-SM physics. In the SM, the loop processes are dominated by $W$ bosons and $t$-quarks, two of the SM’s most massive particles. Thus, effects of non-SM particles in the loop on $CP$-violating phases can be large even for masses of order TeV or higher, i.e. beyond the reach of the LHC. In this program, $\phi_i$ values determined from measurements of tree processes provide precise and theoretically robust benchmarks against which to compare the loop process measurements.

In the SM, measurements of mixing-induced $CP$ asymmetries with $b \to s$ pen-
guin decays to $CP$ eigenstates should give a value of $\sin 2\phi_1^{eff}$ that is equal to $\sin 2\phi_1$ to high precision. For many $b \to s$ penguin processes, such as $B^0 \to \phi K^0$, the experimental circumstances are nearly identical to those for $B^0 \to J/\psi K^0$ and, so, comparisons can be made with small systematic uncertainties. The main issue is statistics: the branching fractions for $b \to s$ decays are usually about 1% that for $J/\psi K^0$. Belle has made measurements of $\sin 2\phi_1^{eff}$ for an assortment of $b \to s$ CP eigenstate modes.\cite{6,14} The $-\xi_f \Delta t$-dependent asymmetries for the $\eta' K^0$ and $\phi K^0$ modes are shown in Figs.\cite{3} (a) and (b), respectively; $CP$-violating asymmetries are evident in both cases. For these modes, $\sin 2\phi_1^{eff}$ is found to be $+0.64 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$ ($\eta' K^0$) and $+0.50 \pm 0.21(\text{stat}) \pm 0.06(\text{syst})$ ($\phi K^0$). In both cases there is good consistency with $\sin 2\phi_1$ from $B^0 \to J/\psi K^0$. Measurements for other $b \to s$ modes indicate no dramatic deviation from the SM expectation but with poorer statistical precision. The implication is that any new physics that may be accessible at the LHC has to be carefully hidden from the quark-flavor sector.

Since SM predictions for $CP$-violating phases are free of hadronic corrections, tests of SM predictions for these angles are reliable and theoretically robust. Moreover, the experimental techniques to measure them are mature and well understood. The primary limit is statistical precision. Future measurements at LHCb and, hopefully, at one or more of the proposed high-luminosity “Super-B-factories,” will provide tests of the SM at mass scales that are well beyond the reach of the LHC.

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