Recent results on hot topics from DHEP Seminar February 2, 2012

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Menu card

- Charm mixing in $D \to K\pi$ decays
- Mixing and CPV in $D \to K_S^0 \pi^+\pi^-$
- Looking for CPV in $D^0 \to \pi^0\pi^0$
- Lepton $A_{FB}$ in $B \to X_S\ell^+\ell^-$ decays
- BF and $A_{CP}$ in $B^0 \to \eta'K^*(892)^0$
- Amplitude analysis of $B \to J/\psi K\pi$

Fifth Workshop on Theory, Phenomenology and Experiments in Flavour Physics - Capri 2014

23-25 May 2014 Villa Oriandi, Anacapri, Capri
Island, Italy
Europe/Rome timezone
Experiment and dataset

- Multitasking magnetic spectrometer that operated at KEKB asymmetric-energy $e^+e^-$ collider in Japan
- Recorded the data at various $\Upsilon(nS)$ resonances till June 2010
D^0 \bar{D}^0$ mixing in $D \to K\pi$ decays

- Measure the time-dependent ratio of the $D^0 \to K^+\pi^-$ (wrong-sign) to $D^0 \to K^-\pi^+$ (right-sign) decay rates

- Tag RS and WS decays through the decay chain $D^{*+} \to D^0 (K^\mp \pi^\pm)\pi^+_s$ by comparing charge of the pion from the $D$ decay with that from the $D^*$ decay

"Wrong-sign" $D^{*+} \to D^0\pi^+$, $D^0 \to K^+\pi^-$

interference: mixing, double Cabibbo-suppression (DCS)

$$R(\tilde{t}/\tau) = \frac{\Gamma_{WS}(\tilde{t}/\tau)}{\Gamma_{RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2$$

Mixing

$$\begin{align*}
x &\equiv \frac{\Delta m}{\Gamma} \\
x' &\equiv x \cos \delta + y \sin \delta \\
y &\equiv \frac{\Delta \Gamma}{2\Gamma} \\
y' &\equiv y \cos \delta - x \sin \delta
\end{align*}$$

$\delta = \text{relative phase}$

DCS

$$R_D \equiv \frac{\Delta \Gamma(\text{DCS})}{\Delta \Gamma(\text{CF})}$$

- Take the resolution effect into account in the measurement of mean decay time of the tagged D’s
Event yields in RS and WS decays

N_{RS} = 2,980,710 \pm 1885

N_{WS} = 11,478 \pm 177

- Signal: A sum of a Gaussian and a Johnson distribution of common mean

- Background: An empirical threshold function \((x - m_\pi)^\alpha e^{-\beta(x-m_\pi)}\)

Biometrika 36, 149 (1949)
Observation of $D^0$-$\bar{D}^0$ mixing

No mixing hypothesis is ruled out at the 5.1 standard deviation ($\sigma$) level

Constitutes the first observation of $D^0$-$\bar{D}^0$ mixing in $e^+e^-$ collisions
CP violation in charm decays

- Provides an interesting test bed for new physics as the standard model (SM) predicts a very small asymmetry, owing to
  - Large GIM/CKM suppression
  - Lack of a large hierarchy in the down-type quark masses

- Typical SM value of the order of $10^{-3}$ most promising candidates to study are singly Cabibbo-suppressed (SCS) decays

- While talking about a percentage effect, we need a good control on the SM predictions, something that is in general lacking in this sector due to long-distance effects

An example of “short vs. long”

Further, with $D^0$-$\bar{D}^0$ mixing being firmly established, what about CP violation (CPV) in the mixing or due to interference between mixing and decay?
Current expectation for direct CP violation

\[ A_f^{\Gamma} \equiv \frac{\tau(D^0 \to f) - \tau(D^0 \to \bar{f})}{\tau(D^0 \to f) + \tau(D^0 \to \bar{f})} \approx -a_{CP}^{\text{ind}} \]

\[ A_{CP}^{f} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(D^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(D^0 \to \bar{f})} \]

\[ \Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \left(1 + y \cos \phi \frac{\langle t \rangle}{\tau}\right) \Delta a_{CP}^{\text{dir}} + \left(\frac{\langle \Delta(t) \rangle}{\tau}\right) a_{CP}^{\text{ind}} \]

\( x \equiv \Delta m / \Gamma, \ y \equiv \Delta \Gamma / \Gamma \) and \( \phi \equiv \arg(q / p) \), where \( \Delta m \) and \( \Delta \Gamma \) are the mass and width difference between two D mass eigenstates, \( \Gamma \) is their average width and \( (p, q) \) are the two complex coefficients that relate mass to flavor eigenstates.

\[ a_{CP}^{\text{ind}} = (+0.015 \pm 0.052)\% \]

\[ \Delta a_{CP}^{\text{dir}} = (-0.333 \pm 0.120)\% \]

➢ No CPV (0,0) point:
\[ \Delta \chi^2 = 7.8, \ CL = 2\% \]
(excluded at 2σ)
Study of mixing and CPV in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Determine $D^0-\bar{D}^0$ mixing and CPV effects by studying the time-dependent decay rate of self-conjugated $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays

- Expressing $A_f$ ($\bar{A}_f$), amplitude of the $D^0$ ($\bar{D}^0$) decay into $f \equiv K_S^0 \pi^+ \pi^-$, as a function of the Dalitz plot variables ($m_{K_S^0 \pi^+}^2, m_{K_S^0 \pi^-}^2$), the corresponding time-dependent decay rates are:

$$|\mathcal{M}(f, t)|^2 = \frac{e^{-\Gamma t}}{2} \left\{ (|A_f|^2 + \frac{p}{q}|A_{\bar{f}}|^2) \cosh(\Gamma y t) 
+ (|A_f|^2 - \frac{p}{q}|A_{\bar{f}}|^2 \cos(\Gamma x t) 
+ 2\Re \left( \frac{p}{q} A_f A_{\bar{f}}^{*} \right) \sinh(\Gamma y t) - 2\Im \left( \frac{p}{q} A_f A_{\bar{f}}^{*} \right) \sin(\Gamma x t) \right\}$$

$$|\overline{\mathcal{M}}(f, t)|^2 = \frac{e^{-\Gamma t}}{2} \left\{ (|A_f|^2 + \frac{q}{p}|A_{\bar{f}}|^2) \cosh(\Gamma y t) 
+ (|A_f|^2 - \frac{q}{p}|A_{\bar{f}}|^2 \cos(\Gamma x t) 
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- $\Gamma$ is the mean decay width of the two mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- $x$ and $y$ are the $D^0-\bar{D}^0$ mixing parameters, defined earlier
- $p$ and $q$ are complex coefficients that satisfy $|p|^2 + |q|^2 = 1$ in case of no CP violation, whereas possible CPV can lead to $q/p \neq 1$
Mixing and CPV results from \( D^0 \rightarrow K_S^0 \pi^+ \pi^- \)

- Time-dependent fit to the Dalitz plot (shown below together with one of its projections)

\[ \chi^2/\text{ndf} = 1.207 \]

\[ 976 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Fit type</th>
<th>Parameter</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>No CPV</td>
<td>( x(%) )</td>
<td>0.56 ± 0.19(^{+0.03}<em>{-0.09}) (^{+0.06}</em>{-0.09})</td>
</tr>
<tr>
<td></td>
<td>( y(%) )</td>
<td>0.30 ± 0.15(^{+0.04}<em>{-0.05}) (^{+0.03}</em>{-0.06})</td>
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</tr>
</tbody>
</table>

\[ |q/p| = 0.90\(^{+0.16}_{-0.15}\) \(^{+0.05}_{-0.04}\) \(^{+0.06}_{-0.05}\) \] \[ \text{arg}(q/p)(\circ) = -6 \pm 11 \pm 3^{+3}_{-4} \]

- 2.5\( \sigma \) away from the no-mixing hypothesis
- No evidence for indirect CP violation

Lifetime of \( D^0 \) = 410.3 ± 0.4 fs

Assume no direct CP violation \( \Rightarrow A_f = \overline{A}_f \) for the \( K_S^0 \pi^+ \pi^- \) mode

Why worry about CPV in $D^0 \rightarrow \pi^0\pi^0$?

- Large CP asymmetries expected in the decay for new physics scenarios having large penguin contributions as well as large chromomagnetic dipole operators

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Large penguins</th>
<th>Large c.d.o.</th>
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<tbody>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>3.96 (4.40)</td>
<td>5.18 (3.70)</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0\pi^0$</td>
<td>0.93 (1.01)</td>
<td>8.63 (6.19)</td>
</tr>
<tr>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- Large penguin contribution is predicted for $D^0 \rightarrow \pi^0\pi^0$

- Some NP models e.g., triplet model, predict a sizeable CP asymmetry in $D^0 \rightarrow \pi^0\pi^0$

- Need a precise measurement that can be only done at the $e^+e^-$ flavor factories
How do we measure CPV in $D^0 \rightarrow \pi^0 \pi^0$?

- Charge of the accompanying “slow” pion in the decay process $D^{*+} \rightarrow D^0 \pi^+_s$ determines flavor of the neutral charm meson (whether a $D^0$ or a $\bar{D}^0$)

- Measure

\[
A_{\text{rec}} = \frac{N_{D^{*+} \rightarrow D^0 \pi^+_s} - N_{D^{*-} \rightarrow \bar{D}^0 \pi^-_s}}{N_{D^{*+} \rightarrow D^0 \pi^+_s} + N_{D^{*-} \rightarrow \bar{D}^0 \pi^-_s}}
\]

in $D^0 \rightarrow \pi^0 \pi^0$ and $D^0 \rightarrow K_s^0 \pi^0$ (control) decay modes

- Has three contributions: a) underlying $A_{CP}$, b) forward-backward asymmetry ($A_{FB}$), and c) detection asymmetry between $\pi^+_s$ and $\pi^-_s$ ($A_{\pi_s^\epsilon}$)

- $A_{\pi_s^\epsilon}$ is determined subtracting $A_{\text{rec}}$ of the “untagged” $D^0 \rightarrow K^- \pi^+$ decay from that of the “tagged” $D^{*+} \rightarrow D^0 \pi^+_s$; $D^0 \rightarrow K^- \pi^+$ decay


$N(\pi^0 \pi^0) = 34k$

$N(K_s^0 \pi^0) = 467k$

966 fb$^{-1}$
CPV results for $D^0 \to \pi^0 \pi^0$ and $K^0_S \pi^0$

- $A_{FB}$ is an odd function of $\cos \theta^*$, $\theta^*$ being the $D^*$ polar angle in the center of mass frame: 
  $$A_{FB} = \frac{1}{2} [A_{\text{rec}}^\text{cor}(\cos \theta^*) - A_{\text{rec}}^\text{cor}(-\cos \theta^*)]$$

- $A_{CP}$ is independent of kinematics: 
  $$A_{CP} = \frac{1}{2} [A_{\text{rec}}^\text{cor}(\cos \theta^*) + A_{\text{rec}}^\text{cor}(-\cos \theta^*)],$$
  where $A_{\text{rec}}^\text{cor}$ is already corrected for $A_{\text{fs}}^\pi [O(0.1\%)]$

- Measured CP asymmetry is an order-of-magnitude improvement over the previous result of CLEO
  - Measured CP asymmetry $A_{CP}(D^0 \to \pi^0 \pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$

- $A_{CP}(D^0 \to K^0_S \pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$ supersedes our earlier result

- Dashed blue curves represent leading-order predictions for $A_{FB}(e^+ e^- \to c\bar{c})$

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Lepton forward-backward asymmetry in $B \to X_S \ell^+ \ell^-$

$$A_{FB} \equiv \frac{\Gamma(b \to s \ell^+ \ell^-; \cos \theta > 0) - \Gamma(b \to s \ell^+ \ell^-; \cos \theta < 0)}{\Gamma(b \to s \ell^+ \ell^-; \cos \theta > 0) + \Gamma(b \to s \ell^+ \ell^-; \cos \theta < 0)}$$

Contributions from electroweak loop and $W^+W^-$ box diagrams

$$\frac{dA_{FB}}{dq^2} = -3 \Gamma_0 m_b^3 (1 - s)^2 s C_{10} \text{Re}(C_9 + \frac{2}{s} C_7)$$

- $C_7$, $C_9$ and $C_{10}$ are the Wilson coefficients representing electromagnetic loop, electroweak vector and axial-vector contributions, respectively

- $\Gamma_0 = \frac{G_F^2 \alpha^2}{48\pi^3} |V_{tb}V_{ts}^*|^2$ and $s = q^2 / m_b^2$ with $q^2 = m_{\ell^+\ell^-}^2$

Previously measured by Belle in exclusive decays viz., $B \to K(\ast) \ell^+ \ell^-$

Inclusive $A_{FB}$ has a comparatively smaller theory uncertainty
Semi-inclusive reconstruction of $B \to X_S \ell^+ \ell^-$

- 18 exclusive hadronic final states with $X_S = \{K\}\{n\pi\}$, $K = K^{\pm}, K_S^0$ and $n = 1 \ldots 4$, where at most one pion can be neutral, and two leptons ($\ell = e, \mu$)
- In case of $B^0 (\bar{B}^0)$ decays, only self-tagging modes with a $K^+ (K^-)$ are used
- Event reconstruction using two kinematic variables: $M_{bc}$ and $\Delta E$
- Background suppression based on a neural network and veto the $J/\psi$ and $\psi(2S)$ regions

- To reduce cross-feed from the modes not used in $A_{FB}$ measurement (total 8), we remove them once the best candidate selection is done

- Plots on right are for (a) $X_S e^+ e^-$; $\cos \theta > 0$, (b) $X_S e^+ e^-$; $\cos \theta < 0$, (c) $X_S \mu^+ \mu^-$; $\cos \theta > 0$ and (d) $X_S \mu^+ \mu^-$; $\cos \theta < 0$
Results on $A_{FB}: B \rightarrow X_S \ell^+ \ell^-$

- Low $q^2$: 1.8σ away from the SM expectation
- High $q^2$: consistent with the SM and $A_{FB} < 0$ is excluded at the 2.3σ level
BF and $A_{CP}$ measurement in $B^0 \rightarrow \eta'K^*(892)^0$

- Dominant contribution from the $b \rightarrow s$ loop transition
- Possible new physics can appear in the loop

- Previous Belle analysis based on $535 \times 10^6 B\bar{B}$ pairs put a 90% confidence-level upper limit
  \[ B[B^0 \rightarrow \eta'K^*(892)^0] < 2.6 \times 10^{-6} \]
  [PRD 75, 092002 (2007)]

- BABAR claimed a signal at the 4σ level and reported
  \[ B[B^0 \rightarrow \eta'K^*(892)^0] = [3.1^{+0.9}_{-0.8}(\text{stat.}) \pm 0.30(\text{syst.})] \times 10^{-6} \]
  [PRD 82, 011502 (2010)]

- On the theory front, the branching fraction is predicted to be in the range of $(1.2-6.3) \times 10^{-6}$
  [PRD 75, 054003 (2007)]
  [NPB 675, 333 (2003)]
  [PRD 78, 034011 (2008)]
  [PRD 69, 34001 (2004)]
BF and $A_{CP}$ results for $B^0 \rightarrow \eta' K^*(892)^0$

- Reconstructed from $\eta' \rightarrow \eta \pi^+ \pi^-$, $\eta \rightarrow \gamma \gamma$ and $K^*(892) \rightarrow K^+ \pi^-$
- 4D extended maximum likelihood fit comprising $M_{bc}$, $\Delta E$, $C_{NB}'$ (continuum suppression variable), and $\cos \theta_H$ (cosine of the $K^*$ helicity angle)

- We measure

$$B(\overline{B}^0 \rightarrow \eta'K^*(892)) = [2.6^{+0.7}_{-0.6}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}$$

- Constitutes the first observation of the decay (5$\sigma$ significance)

- $A_{CP}$ is obtained by splitting the obtained yields according to the flavor of the decaying $B$ meson

$$A_{CP} = -0.22 \pm 0.29(\text{stat}) \pm 0.03(\text{syst})$$
Amplitude analysis of $B \to J/\psi K\pi$

- Look for possible exotic, charmonium-like resonances in the $J/\psi\pi$ system
- 4D amplitude analysis comprising $(M_{K\pi}^2, M_{J/\psi\pi}^2, \cos \theta, \phi)$, where $\theta$ is the $J/\psi$ helicity angle and $\phi$ is the angle between the two planes containing $J/\psi(\ell^+\ell^-)$ and $(K\pi)$ systems in the $B$ rest frame
- Resonances: 10 $K^*$ resonances and the $Z_c(4430)^+$ state for the $J/\psi\pi$ system; additional $Z_c^+$ states are used for a cross-check
- Tried out five spin-parity hypotheses: $0^-, 1^+, 1^-, 2^+, 2^-$ for the $Z_c^+(J^P = 0^+$ is forbidden due to parity conservation)

![Graphs showing projections of the invariant mass including a new $Z_c^+$ state along with the $Z_c(4430)$](image)

- Preliminary

- Projections of the $J/\psi\pi$ invariant mass including a new $Z_c^+$ state along with the $Z_c(4430)$
- Red dashed lines with the $Z_c(4430)$ only

711 fb$^{-1}$
Observation of a new state in $B \to J/\psi K\pi$

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>0$^-$</th>
<th>1$^-$</th>
<th>1$^+$</th>
<th>2$^-$</th>
<th>2$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV/c$^2$</td>
<td>4220 ± 14</td>
<td>4315 ± 40</td>
<td>4196 ± 27</td>
<td>4209 ± 14</td>
<td>4203 ± 24</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>71 ± 20</td>
<td>220 ± 80</td>
<td>370 ± 61</td>
<td>64 ± 18</td>
<td>121 ± 53</td>
</tr>
<tr>
<td>Significance</td>
<td>3.3$\sigma$</td>
<td>2.3$\sigma$</td>
<td>8.2$\sigma$</td>
<td>3.9$\sigma$</td>
<td>1.9$\sigma$</td>
</tr>
</tbody>
</table>

- A new $Z_c^+(4200)^+$ state $[Z_c(4200)^+]$ with $J^P = 1^+$ is found with 7.2$\sigma$ significance
  \[ M = 4196^{+31+17}_{-29-6} \text{ MeV}/c^2, \ \Gamma = 370^{+70+70}_{-70-85} \text{ MeV} \]
- Other $J^P$ hypotheses are excluded: $0^-(6.7\sigma), 1^-(7.7\sigma), 2^-(5.2\sigma), 2^+(7.6\sigma)$
- Evidence for the $Z_c(4430)^+$ at the 4.0$\sigma$ significance level

\[
\begin{align*}
\mathcal{B}(\bar{B}^0 \to J/\psi K^-\pi^+) &= (1.15 \pm 0.01 \pm 0.05) \times 10^{-3} \\
\mathcal{B}(\bar{B}^0 \to J/\psi K^*(892)) &= (1.19 \pm 0.01 \pm 0.08) \times 10^{-3} \\
\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) &= (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6} \\
\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) &= (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5} \\
\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} &\sim 10
\end{align*}
\]

Preliminary
Summary and outlook

- Though close to five years have passed away since the last data taking, Belle continues to produce high-quality results.

- A small sample of those are presented here, based on the full data statistics:
  - First observation of $D^0$-$\bar{D}^0$ mixing using $D \to K\pi$ decays in $e^+e^-$ collisions.
  - $2.5\sigma$ indication for $D^0$-$\bar{D}^0$ mixing and no sign of CPV in $D \to K_S^0\pi^+\pi^-$.
  - An order-of-magnitude improvement over the previous result for $A_{CP}$ in the $D \to \pi^0\pi^0$ decay.
  - $1.8\sigma$ discrepancy with respect to the SM prediction for the lepton forward-backward asymmetry at low $q^2$ in inclusive $B \to X_s \ell^+\ell^-$ decays.
  - First observation of the $b \to s$ penguin decay $B \to \eta'K^*(892)^0$.
  - Observation of another charged charmonium-like state in $B \to J/\psi K\pi$.

- The unique explorations at the intensity frontier will continue with the start of Belle II:
  - Refer to yesterday’s talk by P. Urquijo.