Charm mixing and $CP$ violation at BESIII

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Outline

• BESIII
• The data samples and double-tagging
• Recent results
  • Direct $CP$ violation
  • Strong phases
• Outlook

$e^+e^-$ collisions at BEPCII between $\sqrt{s} = 2.0 - 4.7$ GeV
BESIII detector - NIM A 614, 345 (2010)
### BESIII charm data sets

#### Dominant processes of interest

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Dominant processes of interest</th>
<th>Integrated luminosity (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.773</td>
<td>$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0/D^+D^-$</td>
<td>2.93</td>
</tr>
<tr>
<td>4.178-4.226</td>
<td>$e^+e^- \rightarrow D_s^+D_s^{<em>-}$, $D_s^{</em>-} \rightarrow D_s^-\gamma$</td>
<td>6.32</td>
</tr>
<tr>
<td>4.60-4.70</td>
<td>$e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$</td>
<td>4.48</td>
</tr>
</tbody>
</table>

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*Image of a graph showing various processes and data sets.*

**PDG 2021**

**CKM 2021 - WG7**
The “single vs. double-tag” techniques

- Threshold production means that no other particles are produced along with the $DD$, $DD^*$ and $\Lambda\Lambda$ pairs
- Full event reconstruction “double tag” possible

✓ Advantages
  1. absolute branching fractions
  2. full kinematic constraint to reconstruct $\nu$ or neutron/$K_L^0$, and
  3. low backgrounds (i.e. good for amplitude analyses)

✗ Disadvantages
  1. reduced reconstruction efficiency but still O(10%) c.f. FEI at Belle II
  2. time-integrated measurements only
Single tag samples

$$M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_D|^2}$$

Phys. Rev. D 89 (2014) 051104(R)

1.7 million


2.8 million
Direct CP violation at BESIII

- Direct CP violation observed at $10^{-3}$ level in $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-
- Sample of millions of flavour tagged events used [LHCb, PRL 122 (2019) 211803]
- In comparison 9300 flavour tagged $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ reconstructed from the BESIII $\psi(3770)$ sample - JHEP 05 (2021) 164
- Not competitive unless there is a very big surprise in a specific decay
- Surprises happen e.g. doubly Cabibbo suppressed branching fraction for $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ [PRL 125 (2020) 14180]
  \[ B(D^+ \rightarrow K^+\pi^+\pi^-\pi^0) = (6.28 \pm 0.52) \times \tan^4 \theta_C \times B(D^+ \rightarrow K^-\pi^+\pi^+\pi^0) \]
- $A_{CP} = -0.04 \pm 0.06 \text{ (stat)} \pm 0.01 \text{ (syst)}$
- PRL 124 (2020) 241803: 14 branching fractions of 3- and 4-body D decays with an $\eta$
  • No significant $A_{CP}$ observed - measured with 0.01 to 0.05 precision
So where does BESIII contribute?

The major result in charm physics this year is the determination of the mass difference ($\Delta m$) between the $D^0$ eigenstates

- LHCb PRL 127 (2020) 111801

Measurement is decay-time ($t$) dependent in bins of the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ phase-space


No direct CP

Ratio of $D^0$ (+) or $\bar{D}^0$ (−) events between $b$ and $-b$ in $j$-th $t$ bin

\[
R_{bj}^\pm \approx \frac{r_b + \frac{\langle t \rangle}{4} \text{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t \rangle}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b \langle t \rangle} \text{Re}[X_b^x(z_{CP} \pm \Delta z)]}{1 + \frac{\langle t \rangle}{4} \text{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle t \rangle}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b \langle t \rangle} \text{Re}[X_b^x(z_{CP} \pm \Delta z)]}
\]

$z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y+i\pi)$

\[
[D_{i,2}] = p[D^0] \pm q[\bar{D}^0], x = (m_1 - m_2)/2\Gamma, y = (\Gamma_1 - \Gamma_2)/2\Gamma
\]

$X_b$ is the amplitude-weighted strong-phase difference between bins $b$ and $-b$ – external input from BESIII
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Measurement of the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ phase-

- Independent of resolution, efficiency and amplitude modelling

What we actually measure

$\mathcal{c}_i = c_b \equiv \text{Re}[X_b] = \text{amplitude-weighted cosine}$

$\mathcal{s}_i = s_b \equiv \text{Im}[X_b] = \text{amplitude-weighted sine}$

Ratio of $D^0$ (+) or $\bar{D}^0$ (–) events between $b$ and $-b$ in j-th $t$ bin

$$R_{bj}^\pm \approx \frac{r_b + r_b \frac{\langle \hat{f}^i \rangle}{4} \text{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle \hat{f}^i \rangle}{4} |z_{CP} + \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \text{Re}[X_b^* (z_{CP} + \Delta z)]}{1 + \frac{\langle \hat{f}^i \rangle}{4} \text{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle \hat{f}^i \rangle}{4} |z_{CP} + \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \text{Re}[X_b (z_{CP} + \Delta z)]}$$

$z_{CP} \pm \Delta z \equiv -(q / p)^{\pm 1} \left( y + i x \right)$

$\left[ D_{t,2} \right] = p |D^0\rangle \pm q |\bar{D}^0\rangle$, $x = (m_1 - m_2) / 2 \Gamma$, $y = (\Gamma_1 - \Gamma_2) / 2 \Gamma$}

$X_b$ is the amplitude-weighted strong-phase difference between bins $b$ and $-b$ – external input from BESIII
Quantum correlated measurements

At the $\psi (3770)$ neutral $D$ pairs produced in quantum-entangled state:

\[ e^+ e^- \rightarrow \psi'' \rightarrow \frac{1}{\sqrt{2}} \left[ D^0 \bar{D}^0 - \bar{D}^0 D^0 \right] \]

\[ e^+ e^- \rightarrow \psi'' \rightarrow \frac{1}{\sqrt{2}} \left[ D_{CP=}-D_{CP=} - D_{CP+} D_{CP-} \right] \]

where $D_{CP\pm} = \frac{1}{\sqrt{2}} \left[ D^0 \pm \bar{D}^0 \right]$

Reconstruct one $D \rightarrow K_s \pi \pi$ and the other in a $CP$ eigenstate such as KK, $K_s \pi^0$ then CP of the other is fixed

$CP \pm$ tagged yield in bin $i$ $\propto K_i + K_{-i} \pm 2c_i \sqrt{K_i K_{-i}}$

Also tag with $K_s \pi \pi$ tag

Yield in bin $i$ tagged by bin $j$ $\propto K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j} \left( c_i c_j + s_i s_j \right)$

fractional $D^0$ yield in each bin
Yields

2.93 fb\(^{-1}\) of data compared with 0.82 fb\(^{-1}\) for CLEO – PRD 82 (2010) 112006

New final states: CP even \(\pi^+\pi^-\pi^0\) and \(K_S^0(\pi^0\pi^0)\pi^+\pi^-\)
where one \(\pi^0\) is not reconstructed
Results

Three different binning schemes – some for $\gamma$ measurements – see Xinyu Shan WG5

Use equal strong-phase binning - $\pi/4$ intervals

Fit binned quantum-correlated yields to extract $c_i$ and $s_i$

\[
\begin{array}{cc}
  c_i & s_i \\
  1 & 0.708 \pm 0.020 \pm 0.009 \\
  2 & 0.671 \pm 0.035 \pm 0.016 \\
  3 & 0.001 \pm 0.047 \pm 0.019 \\
  4 & -0.602 \pm 0.053 \pm 0.017 \\
  5 & -0.965 \pm 0.019 \pm 0.013 \\
  6 & -0.554 \pm 0.062 \pm 0.024 \\
  7 & 0.046 \pm 0.057 \pm 0.023 \\
  8 & 0.403 \pm 0.036 \pm 0.017
\end{array}
\]

Statistically dominated

PRL 124 (2020) 241802
PRD 101 (2020) 112002
1. Ignoring asymmetric bin-to-bin migration
   • can be mitigated by unfolding in the future

2. To leverage $D \to K_L \pi \pi$ we have to make assumptions related to the model and the size CF to DCS interference induced difference between $D \to K_L \pi \pi$ and $D \to K_S \pi \pi$
   • implemented a constraint hence appears in statistical uncertainty
   • potentially learn more from studying the $D \to K_L \pi \pi$ amplitude model
   • more weight to $D \to K_S \pi \pi$

3. Better understanding with more data
LHCb mixing and CP violation results

Systematic uncertainty related to $c_i$ and $s_i$ on these measurements are between 50% and 25% of the statistical uncertainty – will be limiting with LHCb upgrade data samples.
Other BESIII measurements I

Other self-conjugate decays can be used in the same way for mixing as $D \to K_S \pi \pi$ and indirect CPV:

- $D \to K_S KK$ [PRD 102 (2020) 052008], $D \to K_S \pi \pi \pi^0$, $D \to 4\pi$ and $D \to 2K2\pi$ [in preparation]

**Wrong-sign mixing measurements**

In $D \to K\pi$ the measurements are $x' = x \cos \delta_{K\pi}$ and $y' = y \sin \delta_{K\pi}$ where

$$A_{DCS} / A_{CF} = (-)r_D \exp(-i\delta_{K\pi})$$

BESIII measured $\cos \delta_{K\pi} = 1.02 \pm 0.13$ [PLB 734 (2014) 227] with eight CP tags

Many more tags in use now, including $D \to K_S \pi \pi$ that allows $\sin \delta_{K\pi}$ thus $\delta_{K\pi}$ [in preparation]

Power of better $\delta_{K\pi}$ knowledge shown in recent preprint [LHCb, arXiv:2110.02350] where $y$ precision improved by 50% using $\delta_{K\pi}$ information from $B$ decay
Other BESIII measurements II

$D \to K\pi\pi^0 (14.4\%)$ and $D \to K3\pi (8.2\%)$ have larger branching fractions compared to $D \to K\pi (3.9\%)$

So despite the more difficult reconstruction and interpretation power to learn more about mixing

- $K\pi\pi^0$ [BaBar, PRL 103 (2009) 211801]
- $K3\pi$ [LHCb, PRL 116 (2016) 241801] – CLEO-c inputs

Improved measurements of the relevant parameters

$$R_s e^{-i\phi_D^S} = \frac{\int A_S^*(x) A_S(x) dx}{A_s A_{\bar{S}}}$$

$$A_S^2 = \int |A_S(x)|^2 dx,$$

coherence factor
0 (a lot of interference)
1 (quasi two-body)

JHEP 05 (2021) 164 with $S=K3\pi$ (integrated and binned) and $S=K\pi\pi^0$ (integrated) – ready to use in new measurements
Conclusion and looking forward

Model-independent strong-phase parameters measured by BESIII essential for the improved determination of mixing and indirect CP violation parameters

Unique samples of threshold $D$, $D_s$ and $A$ decays can be searched for direct CP surprises, particularly in multibody modes with neutrals


- 20 fb$^{-1}$ at $\psi(3770)$ – run underway prior to BEPC upgrade in 2023

Improving $c_i$ and $s_i$ for charm mixing and indirect CP violation one of the primary motivators

Questions to the community

- binnings driven by $\gamma$ measurements but would alternatives help charm measurements?
- are there modes we should be looking more closely at?