Charm meson decays at Belle II

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The hunt for New Physics
Historical contributions by “B factories”

- B factories, Belle @ KEKB and BaBar @ PEPII, played crucial roles in advancing knowledge
  - Large samples of B mesons, charm, tau, and low-multiplicity events
  - Discovery of CPV in the B system (2008 Nobel Prize)
  - Published more than 1200 papers, still publishing more than 13 years after shutdown

- Belle II @ SuperKEKB represent significant improvements
  - Expected to record 50 ab⁻¹, two orders of magnitude more than BaBar and 50 times that of Belle

Per ab⁻¹ (events × 10⁹): 1.1 B̅B, 1.3 c̅c, 2.1 q̅q, 0.9 τ⁺τ⁻

Also a charm factory!
The Belle II Experiment
The high-luminosity super B factory

$u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, \ell^+\ell^- \leftrightarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow \B^{(*)}\B^{(*)}$
Precise charm lifetime measurements
Leveraging the excellent detector performance

- Belle II can make precision, absolute lifetime measurements
  - Large samples of exclusive charm decays without lifetime-biasing triggers and selections
  - Precise calibration of final state particle momenta
  - Excellent vertex detector alignment
  - Very good vertex resolution, small beam size
  - World-leading measurements for $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, confirmation of $\Omega_c^0$

\[ t = \frac{m_D}{p} \left( \vec{d} \cdot \hat{p} \right) \]
Charm physics at a (super) B factory

a flavor of the possible avenues of exploration

- Two possible production mechanisms
  - One or more charmed hadrons produced in B meson decays
  - Two charmed hadrons produced from continuum, along with fragmentation particles

- Typically only reconstruct the signal channel
- Also provides access to charmed baryons
- No entanglement between two charmed hadrons, inaccessible strong phases

- Exploit charmed flavor tagging: using $D^{*+} \rightarrow D^0 \pi^+$ or with information from rest-of-event*
  - High precision SM (e.g. lifetimes), branching ratios, searches for rare or forbidden decays
  - Can also use B decays or reconstruct fragmentation system to make absolute measurements
Searching for New Physics in charm decays

Three paths for discovery

- Processes **allowed** in the Standard Model at **tree level**
  - SM rates and uncertainties are known
  - e.g. CKM triangle relations

- Processes **suppressed** in the Standard Model at **tree level**
  - New physics may contribute at a detectible level beyond the SM prediction
  - e.g. penguin decays, D-mixing, etc.

- Processes **forbidden** in the Standard Model to **all orders**
  - Any evidence may indicate new physics
  - Sometimes complicated by SM backgrounds
CP violation in charm

Unitarity triangle involving charm quarks is “squashed”

- CPV in the Standard Model originates from the complex phase of the CKM matrix
  - Unitarity conditions visualized as triangles
  - Charm CPV difficult to predict → strong role for experiment

- Direct CPV in charm established in 2019 (PRL.122.211803)
  \[ \Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}^{\text{wgt}}(D^0 \to \pi^+\pi^-) = (-0.154 \pm 0.029)\% \]
  - Observed value consistent with SM, at the upper end of the expectation

- Fundamental importance to continue CPV searches in charm
  - Understand origin and further constrain SM
  - Increase number and precision of measurements and observables

\[ \frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}} \propto \mathcal{O}(\lambda^4) \]
\[ \frac{V_{ub}^* V_{cd}}{V_{us}^* V_{cs}} \propto 1 + \mathcal{O}(\lambda^4) \]

where \( A_{CP}^f = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} \propto \sin(\phi)\sin(\delta) \)
CPV in T-odd observables
Another handle to search for CP violation

- Assuming CPT, T-odd observables are also sensitive to CP violation: \( a_{CP}^{T-odd} \propto \sin(\phi)\cos(\delta) \)
  - Need four or more final state particles, e.g. \( D^+ \rightarrow K^+K_S^0h^+h^- \)
  - Determine triple products \( C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} + \vec{p}_h) \)
  - Construct asymmetries for particles and antiparticles

\[
A_T = \frac{\Gamma_+(C_T > 0) - \Gamma_+(C_T < 0)}{\Gamma_+(C_T > 0) + \Gamma_+(C_T < 0)}
\]
\[
\bar{A}_T = \frac{\Gamma_-(\bar{C}_T > 0) - \Gamma_-(\bar{C}_T < 0)}{\Gamma_-(\bar{C}_T > 0) + \Gamma_-(\bar{C}_T < 0)}
\]

- Remove effects from final state interactions with difference

\[
a_{CP}^{T-odd} = \frac{1}{2}(A_T - \bar{A}_T)
\]
T-odd asymmetry in $D_{(s)}^{+} \rightarrow K^{+}K_{S}^{0}h^{+}h^{-}$

Most precise measurements

- Suppress backgrounds, taking advantage of precise $D$ decay length
- Separate candidates by $C_{T}/\bar{C}_{T}$ and parameterize signal yields
  
  \[ N_{1} = \frac{N(D_{(s)}^{+})}{2} + A_{T} \]
  \[ N_{3} = \frac{N(D_{(s)}^{+})}{2} + A_{T} - 2 \cdot a_{CP}^{T-odd} \]
  \[ N_{2} = \frac{N(D_{(s)}^{+})}{2} - A_{T} \]
  \[ N_{3} = \frac{N(D_{(s)}^{+})}{2} - A_{T} - 2 \cdot a_{CP}^{T-odd} \]

- Simultaneous fit to extract observables
  
  \[ a_{CP}^{T-odd}(D^{+} \rightarrow K^{+}K_{S}^{0}\pi^{+}\pi^{-}) = (0.34 \pm 0.87 \pm 0.32) \% \]
  \[ a_{CP}^{T-odd}(D_{s}^{+} \rightarrow K^{+}K_{S}^{0}\pi^{+}\pi^{-}) = (-0.46 \pm 0.63 \pm 0.38) \% \]
  \[ a_{CP}^{T-odd}(D^{+} \rightarrow K^{+}K^{-}K_{S}^{0}\pi^{+}) = (-3.34 \pm 2.66 \pm 0.35) \% \]

- Bonus! First measurement of SCS decay $D_{s}^{+} \rightarrow K^{+}K^{-}K_{S}^{0}\pi^{+}$: $B = (1.29 \pm 0.14 \pm 0.04 \pm 0.11) \times 10^{-4}$
T-odd asymmetry in $D^{+}_{(s)} \rightarrow Kh\pi^{+}\pi^{0}$

First measurements

- No evidence of (global) CPV
  - Precision <1% (statistical) for most modes with systematic uncertainty $O(1\%)$

- Also check in regions of phase space corresponding to dominant resonances (with different strong phases)
  - Vector resonances: $\phi, \rho^{+,0}, \bar{K}^{*0}, K^{*+}$
  - No evidence for local CPV

\[ a_{\text{CP}}^{T-\text{odd}}(D^{+} \rightarrow K^{-}K^{+}\pi^{+}\pi^{0}) = (+2.6 \pm 6.6 \pm 1.3) \times 10^{-3} \]
\[ a_{\text{CP}}^{T-\text{odd}}(D^{+} \rightarrow K^{+}\pi^{-}\pi^{+}\pi^{0}) = (-1.3 \pm 4.2 \pm 0.1) \times 10^{-2} \]
\[ a_{\text{CP}}^{T-\text{odd}}(D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}\pi^{0}) = (+0.2 \pm 1.5 \pm 0.8) \times 10^{-3} \]
\[ a_{\text{CP}}^{T-\text{odd}}(D^{+} \rightarrow K^{+}\pi^{-}\pi^{+}\pi^{0}) = (-1.1 \pm 2.2 \pm 0.1) \times 10^{-2} \]
\[ a_{\text{CP}}^{T-\text{odd}}(D^{+} \rightarrow K^{-}K^{+}\pi^{+}\pi^{0}) = (+2.2 \pm 3.3 \pm 4.3) \times 10^{-3} \]
Charm flavor tagger (CFT)

Novel method to identify production flavor of neutral charmed mesons

- CFT exploits correlation between the flavor of a reconstructed neutral $D$ meson and the electric charges of the rest of the event

- Tagging decision $(q)$ chosen to be $+1$ (-1) for $D^0$ ($\bar{D}^0$), dilution factor $(r)$ close to one for perfect prediction, zero for random guess
- Effective tagging efficiency $\epsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07(\text{stat}) \pm 0.51(\text{syst}))\%$, independent of decay mode
- Approximately doubles effective size of many CPV, mixing measurements
- Basic principles can be used at other experiments
Search for neutral $D \to p\ell$

Forbidden in the Standard Model

- Observed matter-antimatter asymmetry requires Baryon Number Violation (BNV)
  - Nucleon BNV allowed in some BSM theories with $\Delta(B - L) = 0$
    - (B = baryon number, L = lepton number)
  - Interest also for meson decays (allowed in e.g. GUT, leptoquark models)

- Search for BNV in $D \to p\ell$, in which B and L are separated violated with $\Delta(B - L) = 0$
  - Separately investigate $D^0$ and $\bar{D}^0$ with $\ell = e, \mu$
  - Reference channel: $D^0 \to K^-\pi^+$

- No signal observed: set upper limits of $(5 - 8) \times 10^{-7}$ at 90% CL
  - Most stringent measurements for $e$ channels
  - First measurements for $\mu$ channels
Search for $D^0 \rightarrow hh' e^+ e^-$

Suppressed in the SM

- Flavor Changing Neutral Current $c \rightarrow u \ell^+ \ell^-$ suppressed in SM; probe for new physics
  - SM long-distance contributions dominate near resonances
  - BSM contributions may be comparable far from resonances

- Search for signal in $q^2 = m^2(e^+ e^-)$
  - near resonances (BR measurement)
  - and far from resonances (sensitive to NP)

$D^0 \rightarrow K\pi\pi$ as reference

Search for $D^0 \rightarrow hh'e^+e^-$

Suppressed in the SM

- Measured BR for $D^0 \rightarrow K\pi e^+e^-$ in the $\rho/\omega$ region $(39.6 \pm 4.5 \pm 2.9) \times 10^{-7}$
  - Compatible with BaBar $(40 \pm 5 \pm 2 \pm 1) \times 10^{-7}$
  - No signal in other regions and channels
    - Upper limits set at $(2 - 8) \times 10^{-7}$; most stringent to date
    - Significantly improved limits with respect to BESIII and BaBar (but at different $q^2$ regions)

PRL 122.081802 (2019)
Mesons get all the attention…

- No neutrinoless, semileptonic FCNC decays of charmed baryons yet observed
  - Hamiltonian helicity structure through W-exchange diagrams makes theory more complicated than for mesons
  - Any observed signal would allow LFU tests with $\ell = e, \mu$

- No signal observed
  - Upper limits set at $9.9 \times 10^{-5}$ (e channel) and $6.5 \times 10^{-5}$ (\(\mu\) channel)
  - Compatible with SM: $2.35 \times 10^{-6}$ (e channel) and $2.25 \times 10^{-6}$ (\(\mu\) channel)

First search for $\Xi_c^0 \rightarrow \Xi^0 \ell^+ \ell^-$

PRD.109.052003 (2024)
Study of $\Xi_c^0 \rightarrow \Xi^0 h^0$
Combined Belle and Belle II datasets

- Theoretical approaches differ on how to deal with non-factorizable amplitudes from W-exchange and internal W-emission
  - Measurement of BRs will help clarify theoretical picture

$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^0\pi^0) = (6.9 \pm 0.3 \pm 0.5 \pm 1.5) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^0\eta) = (1.6 \pm 0.2 \pm 0.2 \pm 0.4) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^0\eta') = (1.2 \pm 0.3 \pm 0.1 \pm 0.3) \times 10^{-3}$

- First measurements for all three BRs
  - Rule out some theoretical models, favoring those based on SU(3)$_F$-breaking

arXiv:2406.04642
*similar for Belle data
Study of $\Xi_c^0 \to \Xi^0 h^0$

Combined Belle and Belle II datasets

- Also measure the asymmetry parameter $\alpha$, related to P-violation (can also be compared with theoretical expectations)

$$\frac{dN}{d\cos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0) \alpha(\Xi^0 \to \Lambda\pi^0) \cos\theta_{\Xi^0}$$

$$\alpha(\Xi^0 \to \Lambda\pi^0) = -0.349 \pm 0.009$$

\[\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15\text{(stat)} \pm 0.23\text{(syst)}\]

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
<th>$B(\Xi^0 \to \Xi^0\pi^0)$</th>
<th>$B(\Xi^0 \to \Xi^0\eta)$</th>
<th>$B(\Xi^0 \to \Xi^0\eta')$</th>
<th>$\alpha(\Xi^0 \to \Xi^0\eta')$</th>
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</thead>
<tbody>
<tr>
<td>Körner, Krämer [5]</td>
<td>Quark</td>
<td>0.5</td>
<td>3.2</td>
<td>11.6</td>
<td>0.92</td>
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<tr>
<td>Ivanov et al. [6]</td>
<td>Quark</td>
<td>0.5</td>
<td>3.7</td>
<td>4.1</td>
<td>0.94</td>
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<tr>
<td>Xu, Kamal [7]</td>
<td>Pole</td>
<td>7.7</td>
<td>-</td>
<td>-</td>
<td>0.92</td>
</tr>
<tr>
<td>Cheng, Tseng [8]</td>
<td>Pole</td>
<td>3.8</td>
<td>-</td>
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<td>-0.78</td>
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<tr>
<td>Ženczykowski [9]</td>
<td>Pole</td>
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<td>Zou et al. [10]</td>
<td>Pole</td>
<td>18.2</td>
<td>26.7</td>
<td>-</td>
<td>-0.77</td>
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<tr>
<td>Sharma, Verma [11]</td>
<td>CA</td>
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<td>Cheng, Tseng [8]</td>
<td>CA</td>
<td>17.1</td>
<td>-</td>
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<td>0.54</td>
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<tr>
<td>Geng et al. [12]</td>
<td>SU(3)$_F$</td>
<td>4.3$^{+0.9}_{-1.0}$</td>
<td>1.7$^{+1.0}_{-1.7}$</td>
<td>8.6$^{+1.0}_{-0.3}$</td>
<td>-</td>
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<tr>
<td>Geng et al. [13]</td>
<td>SU(3)$_F$</td>
<td>7.6$^{+1.0}_{-1.2}$</td>
<td>10.3$^{+2.0}_{-2.3}$</td>
<td>9.1$^{+4.1}_{-2.9}$</td>
<td>-1.00$^{+0.07}_{-0.00}$</td>
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<tr>
<td>Zhao et al. [14]</td>
<td>SU(3)$_F$</td>
<td>4.7$^{+0.9}_{-1.0}$</td>
<td>8.3$^{+2.3}_{-2.3}$</td>
<td>7.2$^{+1.9}_{-1.9}$</td>
<td>-</td>
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<td>Huang et al. [15]</td>
<td>SU(3)$_F$</td>
<td>2.56$^{+0.93}_{-1.0}$</td>
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<td>-0.23$^{+0.60}_{-0.60}$</td>
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<tr>
<td>Hsiao et al. [16]</td>
<td>SU(3)$_F$</td>
<td>6.0$^{+1.2}_{-1.3}$</td>
<td>4.2$^{+1.6}_{-1.6}$</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Hsiao et al. [16]</td>
<td>SU(3)$_F$-breaking</td>
<td>3.6$^{+1.2}_{-1.5}$</td>
<td>7.3$^{+3.2}_{-3.2}$</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Zhong et al. [17]</td>
<td>SU(3)$_F$</td>
<td>1.13$^{+0.39}_{-0.40}$</td>
<td>1.56$^{+1.92}_{-1.7}$</td>
<td>0.683$^{+3.272}_{-2.286}$</td>
<td>0.50$^{+0.37}_{-0.35}$</td>
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<tr>
<td>Zhong et al. [17]</td>
<td>SU(3)$_F$-breaking</td>
<td>7.74$^{+2.52}_{-2.52}$</td>
<td>2.43$^{+2.70}_{-2.90}$</td>
<td>1.63$^{+5.14}_{-5.14}$</td>
<td>-0.29$^{+0.20}_{-0.17}$</td>
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<tr>
<td>Xing et al. [18]</td>
<td>SU(3)$_F$</td>
<td>1.30$^{+0.51}_{-0.51}$</td>
<td>-</td>
<td>-</td>
<td>-0.28$^{+0.18}_{-0.18}$</td>
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<tr>
<td>Geng et al. [19]</td>
<td>SU(3)$_F$</td>
<td>7.10$^{+0.41}_{-0.41}$</td>
<td>2.94$^{+0.97}_{-0.97}$</td>
<td>5.66$^{+0.93}_{-0.93}$</td>
<td>-0.49$^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>Zhong et al. [20]</td>
<td>Diagrammatic-SU(3)$_F$</td>
<td>7.45$^{+0.64}_{-0.64}$</td>
<td>2.87$^{+0.66}_{-0.66}$</td>
<td>5.31$^{+1.33}_{-1.33}$</td>
<td>-0.51$^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>Zhong et al. [20]</td>
<td>Irreducible-SU(3)$_F$</td>
<td>7.72$^{+0.65}_{-0.65}$</td>
<td>2.28$^{+0.53}_{-0.53}$</td>
<td>5.66$^{+1.62}_{-1.62}$</td>
<td>-0.51$^{+0.09}_{-0.09}$</td>
</tr>
</tbody>
</table>
Conclusions

- Belle continues to produce important measurements more than 10 years after data taking
  - CPV searches using T-odd observables in D decays
  - Rare searches for $D \rightarrow p\ell$ and $\Xi_c^0 \rightarrow \Xi^0 \ell^+\ell^-$
  - Study of FCNC $D^0 \rightarrow hh'\ell^+\ell^-$
  - Charmed baryon measurements in $\Xi_c^0 \rightarrow \Xi^0 \ell^+\ell^-$ and $\Xi_c^0 \rightarrow \Xi^0 h^0$

- The physics program of Belle II has outstanding potential for charm physics
  - Upgraded SuperKEKB accelerator, improved Belle II detector, refined analysis techniques
  - Significant room to improve basic knowledge of baryons decays
  - With higher statistics samples, more and better precision results are on the way