Charm physics at Belle and Belle II
Mirco Dorigo (for the Belle and Belle II collaborations)
CP violation in charm

- **Highly suppressed in the standard model.** Discovery tool for new physics.

- **Observed in** $D^0 \rightarrow (K^+K^-, \pi^+\pi^-)$ **decays** [PRL 122, 211803 (2019)], value in the standard model ballpark. Need better control of QCD to get its origin.

- **Expand the search:** look for CPV in radiative decays, test isospin sum-rules and SU(3) related modes…

- Huge program of measurements, where Belle/Belle II role with neutrals is crucial
Today results from Belle

- **Belle**, steady and fruitful production of new results continues, although data-taking finished >10 years ago:

  arXiv:2106.04286, submitted to JHEP
  JHEP 06(2021)160,
  Phys. Rev. D 103, 112002 (2021),
  Phys. Rev. D 103, 111101 (2021),
  Phys. Rev. D 103, 072004 (2021),
  Phys. Rev. D 103, 072002 (2020),
  ... ... ...

  CPV and BR for
  \[ D^0 \rightarrow (K^+K^-\eta, \pi^+\pi^-\eta, \phi\eta) \]

  CPV and BR for
  \[ D_{s}^+ \rightarrow (K^+\eta, K^+\pi^0, \pi^+\eta, \pi^+\pi^0) \]
Today results from *Belle* and *Belle II*

- **Belle II**, getting ready for mixing and decay-time-dependent CPV analyses

- **Belle**, steady and fruitful production of new results continues, although data-taking finished >10 years ago:

  * arXiv:2106.04286, submitted to JHEP
  * Phys. Rev. D 103, 112005 (2021)
  * JHEP 06(2021)160,
  * Phys. Rev. D 103, 112002 (2021),
  * Phys. Rev. D 103, 111101 (2021),
  * Phys. Rev. D 103, 072004 (2021),
  * Phys. Rev. D 103, 072003 (2020),
  * Phys. Rev. D 103, 072002 (2020),
  … … …

Precise measurement of \( D^0 \) and \( D^+ \) lifetimes

*Brand new, exclusive for EPS!*

**CPV and BR for**
\[ D^0 \rightarrow (K+K-\eta, \pi^+\pi^-\eta, \phi\eta) \]

**CPV and BR for**
\[ D_s^+ \rightarrow (K^+\eta, K^+\pi^0, \pi^+\eta, \pi^+\pi^0) \]
- Operated in asymmetric-energy $e^+e^-$ collisions provided by KEKB
- Good performances on momentum/vertex resolution and particle identification.
- In about 10 years, accumulated a sample of $\sim 1 \text{ ab}^{-1}$
**CPV and BR for $D_{s}^+ \rightarrow (K+\eta, K+\pi^0, \pi^+\eta, \pi^+\pi^0)$**

- Reconstruct both $D_{s}^{*} \rightarrow D_s \gamma$ tagged and untagged $D_{s}^+$ decays from 921 fb$^{-1}$ of data.

- Measure $CP$ asymmetries and branching fractions (relative to $D_{s}^+ \rightarrow [\phi \rightarrow K^+K^-]\pi^+$).

- Suppress background with neural-net classifiers exploiting signal kinematic and topology.

- Measures raw asymmetries from fitted signal yields, and correct for $K^+$ and $\pi^+$ efficiency asymmetries.

[Phys. Rev. D 103, 112005 (2021)]
CPV and BR for $D_{s}^+ \rightarrow (K^+\eta, K^+\pi^0, \pi^+\eta, \pi^+\pi^0)$

- Obtain world’s best results for both BR and CP asymmetries.
- No evidence of $D_{s}^+ \rightarrow \pi^+\pi^0$, set an upper limit on its BR.
- No evidence of CP violation in these decays.

[Phys. Rev. D 103, 112005 (2021)]

\[
\begin{align*}
\mathcal{B}(D_{s}^+ \rightarrow K^+\pi^0) &= (0.735 \pm 0.052 \pm 0.030 \pm 0.026) \times 10^{-3} \\
\mathcal{B}(D_{s}^+ \rightarrow K^+\eta) &= (1.75 \pm 0.05 \pm 0.05 \pm 0.06) \times 10^{-3} \\
\mathcal{B}(D_{s}^+ \rightarrow \pi^+\pi^0) &= (0.037 \pm 0.055 \pm 0.021 \pm 0.001) \times 10^{-3} \\
\mathcal{B}(D_{s}^+ \rightarrow \pi^+\eta) &= (19.00 \pm 0.10 \pm 0.59 \pm 0.68) \times 10^{-3},
\end{align*}
\]

Uncertainties: stat, syst, and from BR($D_{s}^+ \rightarrow [\phi \rightarrow K^+K^-]\pi^+$)

\[
\mathcal{B}(D_{s}^+ \rightarrow \pi^+\pi^0) < 1.2 \times 10^{-4} \quad (90\% \ C.L.)
\]

\[
\begin{align*}
A_{CP}(D_{s}^+ \rightarrow K^+\pi^0) &= 0.064 \pm 0.044 \pm 0.011 \\
A_{CP}(D_{s}^+ \rightarrow K^+\eta) &= 0.021 \pm 0.021 \pm 0.004 \\
A_{CP}(D_{s}^+ \rightarrow \pi^+\eta) &= 0.002 \pm 0.003 \pm 0.003.
\end{align*}
\]
**CPV and BR for**

\( D^0 \to (K^+K^-\eta, \pi^+\pi^-\eta, \phi\eta) \)

- \( D^*-tagged \) decays from 980 fb\(^{-1} \) of data.

- Measure \( CP \) asymmetries and branching fractions (relative to \( D^0 \to K^-\pi^+\eta \)).

- Fit the \( Q \)-values distributions and correct the signal yields in bins of the Dalitz plot.

- Measure \( A_{\text{raw}} = A_{CP} + A_{FB} + A_{\pi\text{soft}} \)

What we want

\( \gamma-Z \) interference, odd in \( \cos\theta^* \)

Cancel with weights for \( \pi_{\text{soft}}(\rho_T, \cos\theta) \)

[arXiv:2106.04286]
CPV and BR for $D^0 \rightarrow (K^+K^-\eta, \pi^+\pi^-\eta, \phi\eta)$

- First search for CPV in $D^0 \rightarrow (\pi^+\pi^-\eta, \phi\eta)$. No evidence of asymmetries found.

$$A_{CP}(D^0 \rightarrow \pi^+\pi^-\eta) = [0.9 \pm 1.2 \text{ (stat)} \pm 0.4 \text{ (syst)}] \%,$$
$$A_{CP}(D^0 \rightarrow K^+K^-\eta) = [-1.4 \pm 3.3 \text{ (stat)} \pm 1.0 \text{ (syst)}] \%,$$
$$A_{CP}(D^0 \rightarrow \phi\eta) = [-1.9 \pm 4.4 \text{ (stat)} \pm 0.6 \text{ (syst)}] \%.$$ 

- First observation of the color-suppressed decay $D^0 \rightarrow \phi\eta$. Improved determination of the branching fractions of $D^0 \rightarrow (K^+K^-\eta, \pi^+\pi^-\eta)$

arXiv:2106.04286 submitted to JHEP

$$\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\eta) = [1.22 \pm 0.02 \text{ (stat)} \pm 0.02 \text{ (syst)} \pm 0.03 (\mathcal{B}_{\text{ref}})] \times 10^{-3},$$
$$\mathcal{B}(D^0 \rightarrow K^+K^-\eta) = [1.80^{+0.07}_{-0.06} \text{ (stat)} \pm 0.04 \text{ (syst)} \pm 0.05 (\mathcal{B}_{\text{ref}})] \times 10^{-4},$$
$$\mathcal{B}(D^0 \rightarrow \phi\eta) = [1.84 \pm 0.09 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.05 (\mathcal{B}_{\text{ref}})] \times 10^{-4},$$
Belle II

- 2nd generation B-factory detector, aiming at collecting 50x Belle dataset

- SuperKEKB: nano-beams scheme with aggressive vertical focusing, holds world luminosity record of $\sim3.1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

- Data-taking started in 2019. Currently $\sim210$ fb$^{-1}$ of data on disk.

- Much improved vertexing w.r.t. Belle: first silicon layer (pixel) at only 1.4 cm from the interaction region.
- High-precision measurement of $D$ lifetimes proves excellent vertexing performance and in-depth understanding of systematic effects for time-dependent CPV/mixing analyses.

- World’s best $D$ lifetimes from FOCUS: sub-1% precision dominated by systematic uncertainty. No update since then (~20 years).

- Early Belle II dataset already competitive. Controlling systematics is crucial.

G. Casarosa, ICHEP 2020 (Belle II with 9 fb$^{-1}$)
At a glance

- Select high-purity samples of $D^*$-tagged $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays. Avoid any cut that biases the decay time.

- Get the decay-time (and its uncertainty) from the displacement between the decay vertex and the interaction region (and the $D$ momentum).

- Fit the distribution of the decay time with accurate modelling of the resolution

- Check, check and check… any systematic bias associated to the measurement

At a glance

\[
\langle d_{D^0} \rangle \sim 200 \, \mu m \\
\langle d_{D^+} \rangle \sim 500 \, \mu m
\]
Signal decays

- High-purity samples, selected to limit background-related systematic uncertainty.

$$\sim 171K \ D^*+ \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$$

$$\sim 59k \ D^*+ \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\pi^0$$
Lifetime fit

- Fit to unbinned \((t,\sigma_t)\) distribution

- Background neglected for \(D^0 \to K^-\pi^+\), while it is modelled using data sidebands for \(D^+ \to K^-\pi^+\pi^+\)

- Resolution function (2 gaussian for \(D^0\), gaussian for \(D^+\)) determined directly in data. Width of \(~60-70\) fs.
Uncertainty budget

- Most critical contribution from misalignment of the vertex detector, as it affects the scale of the flight length. Periodic calibration with control data measures misaligned sensors with few μm accuracy.

- For $D^+$ dominant systematic from background modelling.

- Both contributions can improve.

- Validation with independent sample of $D^{*+} \rightarrow D^0(\rightarrow K^{-}π^{+}π^{−}π^{+})π^{+}$. Different decay topology, larger (~1%) background contamination than $D^0 \rightarrow K^{-}π^{+}$. Measure $D^0$ lifetime with 1.2 fs precision (stat-only) in agreement with $D^0 \rightarrow K^{-}π^{+}$ result.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D^0 \rightarrow K^{-}π^{+}$</td>
</tr>
<tr>
<td>Statistical</td>
<td>1.1</td>
</tr>
<tr>
<td>Resolution model</td>
<td>0.16</td>
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<tr>
<td>Backgrounds</td>
<td>0.24</td>
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<tr>
<td>Detector alignment</td>
<td>0.72</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.19</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.8</td>
</tr>
</tbody>
</table>
(Preliminary) Results

\[ \tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs} \]

\[ \tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs} \]

More precise than, and consistent with, the respective world-average values (410.1±1.5 fs and 1040±7 fs).

Few-per-mille accuracy establishes excellent performance of our detector!

Determine also lifetimes ratio considering correlations between uncertainties:

\[ \tau(D^+)/\tau(D^0) = 2.510 \pm 0.015 \]
Conclusion and prospect

- **Belle** continues to harvest new results on charm to improve CPV and BR measurements.

- **Belle II** in great shape: established excellent vertexing performance with world’s best D lifetimes measurement.

- Have already >200 fb$^{-1}$ of data on disk currently being analysed. New results soon to come!
\[ D_{s}^{+} \rightarrow (K^{+}\eta, K^{+}\pi^{0}, \pi^{+}\eta, \pi^{+}\pi^{0}): \text{systematic errors} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>( \mathcal{B}(K^{+}\pi^{0}) )</th>
<th>( \mathcal{B}(K^{+}\eta\gamma) )</th>
<th>( \mathcal{B}(K^{+}\eta_{3\pi}) )</th>
<th>( \mathcal{B}(\pi^{+}\pi^{0}) )</th>
<th>( \mathcal{B}(\pi^{+}\eta\gamma) )</th>
<th>( \mathcal{B}(\pi^{+}\eta_{3\pi}) )</th>
<th>( \mathcal{B}(\phi \pi^{+}) )</th>
</tr>
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<tbody>
<tr>
<td>Tracking</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Particle identification</td>
<td>1.8</td>
<td>1.8</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>4.0</td>
</tr>
<tr>
<td>( \pi^{0}/\eta \rightarrow \gamma\gamma )</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>( O_{NN} ) requirement</td>
<td>1.1</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>( D_{s}^{++} ) fraction in ( \varepsilon )</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
<td>Fitting</td>
<td>2.2</td>
<td>2.6</td>
<td>2.4</td>
<td>56.2</td>
<td>1.5</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{B}(\eta \rightarrow \gamma\gamma) )</td>
<td>–</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td>0.5</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{B}(\eta \rightarrow \pi^{+}\pi^{-}\pi^{0}) )</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
</tr>
<tr>
<td>Overall uncertainty</td>
<td>4.1</td>
<td>4.4</td>
<td>4.4</td>
<td>56.3</td>
<td>3.9</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

**CP asymmetries**

<table>
<thead>
<tr>
<th>Source</th>
<th>( K^{+}\pi^{0} )</th>
<th>( K^{+}\eta\gamma )</th>
<th>( K^{+}\eta_{3\pi} )</th>
<th>( \pi^{+}\eta\gamma )</th>
<th>( \pi^{+}\eta_{3\pi} )</th>
<th>( \phi \pi^{+} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting</td>
<td>0.0056</td>
<td>0.0035</td>
<td>0.0020</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0002</td>
</tr>
<tr>
<td>( D^{+} \rightarrow \pi^{+}(\pi^{0}/\eta) ) background</td>
<td>0.0062</td>
<td>0.0022</td>
<td>0.0031</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( \cos\theta^{CM}<em>{B</em>{s}} ) binning</td>
<td>0.0068</td>
<td>0.0028</td>
<td>0.0068</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( A_{CP} ) in ( D^{+}_{s} \rightarrow \phi \pi^{+} )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.0027</td>
<td>0.0027</td>
<td>–</td>
</tr>
<tr>
<td>Overall uncertainty</td>
<td>0.0108</td>
<td>0.0050</td>
<td>0.0077</td>
<td>0.0027</td>
<td>0.0027</td>
<td>0.0002</td>
</tr>
</tbody>
</table>
$D^0 \rightarrow (K^+K^-\eta, \pi^+\pi^-\eta, \phi\eta)$: systematic errors

<table>
<thead>
<tr>
<th>Systematic sources</th>
<th>$\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\eta)$</th>
<th>$\mathcal{B}(D^0 \rightarrow K^+K^-\eta)$</th>
<th>$\mathcal{B}(D^0 \rightarrow (\phi\rightarrow K^+K^-)\eta)$</th>
</tr>
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<tbody>
<tr>
<td>PID efficiency correction</td>
<td>1.8%</td>
<td>1.9%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Signal PDF</td>
<td>0.3%</td>
<td>0.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Background PDF</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Mass resolution calibration</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Yield correction with efficiency map</td>
<td>0.3%</td>
<td>0.7%</td>
<td>–</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.3%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$K^0_S$ veto</td>
<td>0.1%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Interference in $M_{KK}$</td>
<td>–</td>
<td>–</td>
<td>2.5%</td>
</tr>
<tr>
<td>Total syst. error</td>
<td>1.9%</td>
<td>2.1%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\sigma_{ACP}(D^0 \rightarrow \pi^+\pi^-\eta)$</th>
<th>$\sigma_{ACP}(D^0 \rightarrow K^+K^-\eta)$</th>
<th>$\sigma_{ACP}(D^0 \rightarrow \phi\eta)$</th>
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</thead>
<tbody>
<tr>
<td>Signal and bkg</td>
<td>0.004</td>
<td>0.010</td>
<td>0.006</td>
</tr>
<tr>
<td>$\cos \theta^*$ binning</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>$A_\ell(\pi_s)$ map</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Total syst. error</td>
<td>0.005</td>
<td>0.011</td>
<td>0.006</td>
</tr>
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