Charm Physics at Hadron Machines

Dominik Mitzel
CERN
on behalf of the
LHCb collaboration

9 June 2020
Charm Physics at LHC(b)*

Mixing and CPV
- Meson oscillations
- Time-integrated CPV
- Time-dependent CPV
- CPV in baryons
- ...

Production and decay properties
- Doubly charmed baryons
- Charm production [see Yanxi’s talk Wed 10:15]
- Excited charm baryons [see Roberta’s talk Wed 13:00]
- ...

Rare decays
- Flavour-changing neutral current processes
- Lepton-flavour, lepton-number violation
- ...

*only LHCb analyses discussed in this talk, for results on charm hadron production and spectroscopy (including LHCb, CMS and ALICE results) see Yanxi’s and Roberta’s talks tomorrow 10:15 and 13:00.
Why care about Charm?

Unique:
- Only bound system made of up-type quarks, complementary sensitivity to BSM couplings wrt to K and B(s) decays
- \( m_c \approx 1.3 \text{ GeV}/c^2 \) makes theoretical predictions hard, but allows for insights into QCD from a different perspective

Discovery tool:
- All processes involving quantum-loops are highly suppressed in the SM
  - Charm meson oscillation probability very low
  - CP violating effects tiny (\( \approx \mathcal{O}(10^{-3}) \))
  - Rare decays extremely rare (\( \approx \mathcal{O}(10^{-9}) \))

room for new physics to show up!
• Large production cross-sections of charm hadrons at LHCb

\[ \sigma(pp \rightarrow c\bar{c}X) \approx 2.4 \text{ mb} \]
\[ \sim 20 \times \sigma(pp \rightarrow b\bar{b}X) \]
@ \( \sqrt{s} = 13\text{ TeV} \)

• Collected 9 fb\(^{-1}\) of data at 7, 8 and 13 TeV

enormous yields available
Mixing & CPV
Charm mixing & CPV

- Measurements of mixing \((x, y)\) and CPV \((A_{CP}, |q/p|, \phi)\) parameters

\[
|D_{1,2}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle
\]

- CPV in the decay \(\left| \frac{A_f}{A_{\bar{f}}} \right| \neq 1\)

- CPV in mixing \(\left| \frac{q}{p} \right| \neq 1\)

- CPV in interference between mixing and decay

\[
\phi_f = \arg \left( \frac{q \bar{A}_f}{p A_f} \right) \approx \arg (q/p) \neq 0
\]

We are in the post-mixing & post-CPV-observation phase, but…

\[
x \neq 0 \quad \left| \frac{q}{p} \right| \neq 1 \quad \phi \neq 0
\]

No evidence of mixing induced CPV, sizeable BSM effects possible
Observation of CP violation in charm

- Measurement of decay-time integrated CP asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

- How experimentally?

  - Detection asymmetry of tagging track
  - Production asymmetry

  $$A(D^0 \to f) = A_{CP}(f) + A_{det} + A_{prod}$$

  $$= \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

- Compute the difference of measured raw asymmetries $\Delta A_{CP}$, in the limit of SU(3) symmetry

  $$A^{SM}_{CP}(K^+K^-) = - A^{SM}_{CP}(\pi^+\pi^-) \approx \mathcal{O}(10^{-4} - 10^{-3})$$

  $\Delta A_{CP} = A(K^+K^-) - A(\pi^+\pi^-)
  = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$

  $\approx \mathcal{O}(10^{-4} - 10^{-3})$

  *mainly sensitive to CPV in the decay (=direct CPV)
Observation of CP violation in charm

- Analyse full Run2 (6 fb\(^{-1}\)) data set

- Pion tagged sample
  
  \[ N(D^0 \to K^+K^-) \approx 44 \text{M} \]
  
  \[ N(D^0 \to \pi^+\pi^-) \approx 14 \text{M} \]

- Semileptonically tagged sample
  
  \[ N(D^0 \to K^+K^-) \approx 9 \text{M} \]
  
  \[ N(D^0 \to \pi^+\pi^-) \approx 3 \text{M} \]

Combination Run1 and Run2 results:

\[ \Delta A_{CP} = [-15.4 \pm 2.9]) \times 10^{-4} \]

5.3\(\sigma\) deviation from zero, first observation!

Compatible with SM! (?)

Additional measurements will help to clarify the picture, e.g. \(A_{CP}(K^+K^-), A_{CP}(\pi^+\pi^-)\),....
Time-dependent CP asymmetry in $D^0 \to h^+h^-$

- Measurement of $A_\Gamma$ in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

$$A_\Gamma(f) = \frac{\hat{\tau}(D^0 \to f) - \hat{\tau}(\bar{D}^0 \to f)}{\hat{\tau}(D^0 \to f) + \hat{\tau}(\bar{D}^0 \to f)}$$

$$\approx -x\phi_f + y(|q/p| - 1) - yA_{CP}^{\text{decay}}(f)$$

$$\sim \text{arg}(q/p), \quad <10^{-5}$$

$A_\Gamma$ probes CPV in mixing and interference of decay with and w/o mixing

- How experimentally?

$$A(t) = \frac{N(D^0(t) \to f) - N(\bar{D}^0(t) \to f)}{N(D^0(t) \to f) + N(\bar{D}^0(t) \to f)} = A_{CP}(t) + A_{det} + A_{prod}$$

$$A_{CP}(t) = A_{CP}^{\text{decay}} - \frac{t}{\tau} A_\Gamma$$

$A_{CP}(t)$ independent of $t$; $t$-dependent!
Time-dependent CP asymmetry in $D^0 \rightarrow h^+h^-$

Averaging the four samples and combining with Run1 results:

$$A_{\Gamma} = [-1.1 \pm 1.7\,(stat) \pm 0.5\,(sys)] \times 10^{-4}$$

Analysis of full (pion tagged) Run2 data still to come!
Multiple interfering amplitudes in $D^0 \rightarrow K_s\pi^+\pi^-$ decays enhance sensitivity to mixing.

Bin the Dalitz plot to avoid amplitude analysis in bins with approximately constant strong phase difference (Bin-Flip method).

Measure ratio of signal yields in bin -b and +b

$$R_b \approx r_b - \sqrt{r_b}[(1-r_b)c_b y - (1+r_b)s_b x]\Gamma t$$

Hadronic parameters $c_b, s_b$ constraint using measurements with quantum correlated $D^0\overline{D^0}$ pairs (CLEO, BESIII).

Mixing parameters from simultaneous fit to all bins, access to CPV by splitting in $D^0$ and $\overline{D^0}$.
• LHCb analysed semileptonically (1M) and pion tagged (1.3M) samples (3/fb Run1)

Mixing and CPV with $D^0 \rightarrow K_s \pi^+ \pi^-$

- Combined $D^0$ and $\bar{D}^0$ decays (measure mixing parameters)
- $D^0$ and $\bar{D}^0$ decays separated (measure mixing induced CPV)
Mixing and CPV with $D^0 \rightarrow K_S\pi^+\pi^-$

Today's most precise measurement of $x$, $|q/p|$, $\phi$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>95.5% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x \ [10^{-2}]$</td>
<td>$0.27^{+0.17}_{-0.15}$</td>
<td>$[-0.05, 0.60]$</td>
</tr>
<tr>
<td>$y \ [10^{-2}]$</td>
<td>$0.74\pm0.37$</td>
<td>$[0.00, 1.50]$</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$-0.09^{+0.22}_{-0.17}$</td>
<td>$[-0.73, 0.29]$</td>
</tr>
</tbody>
</table>

New WA results in first evidence for nonzero (positive) value of $x$

$x = [3.9^{+1.1}_{-1.2}] \times 10^{-3}$

Analysis of full Run2 data set on the way!
Search for CPV in $\Xi_c^+ \rightarrow pK^-\pi^+$

- Searches for CPV in charmed baryon largely unexplored, search for CPV using model-independent techniques in the Dalitz plot

- Analyse full Run1 (3fb$^{-1}$) data set ($\sim$0.25M $\Xi_c^+$ candidates)
  - A sample of 2M $\Lambda_c^+ \rightarrow pK^-\pi^+$ is used for validation

$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\alpha \sqrt{n_+^i + n_-^i}} \quad \alpha = \frac{n_+}{n_-} = 1.029 \pm 0.004 \quad n_+ = n(\Xi_c^+) \quad n_- = n(\Xi_c^-)$$

- If no CPV the $S_{CP}^i$ are gaussian distributed with zero mean and width of unity

$$\chi^2 = \sum (S_{CP}^i)^2$$

exclude CP conservation if

$$p < 3 \times 10^{-7} \quad (n_{dof}=n_{bins}-1)$$

- Measured p-value 32%

- Alternative (unbinned) k-nearest neighbour method gives same result

NEW

arXiv:2006.03145
Production & decay properties
Doubly Charmed baryons

- Triggered a lot of attention in the last ~3 years
- Discovery of $\Xi_{cc}^{++}$ in decays to $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^- \pi^+$ final states
- First measurement of $\Xi_{cc}^{++}$ production in pp collision
- First measurement of the lifetime $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{sys})\text{ps}$
- And now?
  - Further precision measurements of $\Xi_{cc}^{++}$ properties
  - Search for singly charged $\Xi_{cc}^+$ and $\Omega_{cc}^+$, which have not been seen at hadron colliders and b-factories
    - SELEX reported observation of the decays $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \rightarrow pD^+ K^-$ using a charged hyperon beam at $m(\Xi_{cc}^+) = [3518.7 \pm 1.7]\text{ MeV}/c^2$ ($\tau < 33$ fs @ 90CL)
Mass measurement of $\Xi_{cc}^{++}$

- Analyse Run 2 pp collision data (5.6/fb)
- $\Xi_{cc}^{++}$ candidates are reconstructed via the decay modes $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ (~600 signals)

Combined results word’s most precise value

$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23\text{(stat)} \pm 0.30\text{(syst)} \text{MeV}/c^2$$
Search for singly charged $\Xi_{cc}^+$

- Analyse full Run1 and Run2 data set (9/fb)
- Search for $\Xi_{cc}^+$ decays to final state $\Lambda_c^+K^-\pi^+$ (SELEX observation channel)
- Mass search window from $[3.4 - 3.8]$ GeV/c$^2$
- No significant signal found
- Set limits on the production ratios for different lifetime hypotheses

\[
\mathcal{R}(\Lambda^+_c) \equiv \frac{\sigma(\Xi_{cc}^+) \times B(\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+)}{\sigma(\Lambda^+_c)} \\
\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+ \times B(\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+)\times B(\Xi_{cc}^{++} \rightarrow \Lambda_c^+K^-\pi^+\pi^+)}{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \rightarrow \Lambda_c^+K^-\pi^+\pi^+)}
\]

We will extend our searches to different final states soon!
Rare decays
Rare decays

- Mainly investigation of processes involving FCNC $c \rightarrow u\ell\ell$ transitions
- Covering a very large variety of analyses
  - BF measurements
  - Angular+CP asymmetries
  - Searches for forbidden/extremely rare modes
Searches for 25 rare and forbidden decays of $D^+$ and $D_s^+$ mesons

LHCB-PAPER-2020-007-001 (in preparation)

<table>
<thead>
<tr>
<th>LFV, LNV, LNV &amp; LFV</th>
<th>FCNC</th>
<th>Resonance dominated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{(s)}^+ \rightarrow \pi^+ \mu^\pm e^\mp$</td>
<td>$D_{(s)}^+ \rightarrow \pi^\pm e^+ e^-$</td>
<td>$D_{(s)}^+ \rightarrow \pi^+ \phi(\mu^+ \mu^-)$</td>
</tr>
<tr>
<td>$D_{(s)}^+ \rightarrow K^+ \mu^\pm e^\mp$</td>
<td>$D_{(s)}^+ \rightarrow \pi^- e^+ e^+$</td>
<td>$D_{(s)}^+ \rightarrow K^+ e^+ e^-$</td>
</tr>
<tr>
<td>$D_{(s)}^+ \rightarrow K^- e^+ e^+$</td>
<td>$D_{(s)}^+ \rightarrow \pi^- e^+ e^+$</td>
<td>$D_{(s)}^+ \rightarrow K^- \mu^+ \mu^-$</td>
</tr>
<tr>
<td>$D_{(s)}^+ \rightarrow K^- \mu^+ e^+$</td>
<td>$D_{(s)}^+ \rightarrow K^- \mu^+ e^+$</td>
<td>$D_{(s)}^+ \rightarrow K^+ \phi(e^+ e^-)$</td>
</tr>
<tr>
<td>$D_{(s)}^+ \rightarrow \pi^- \mu^+ e^+$</td>
<td>$D_{(s)}^+ \rightarrow \pi^- \mu^+ e^+$</td>
<td></td>
</tr>
</tbody>
</table>

**Legend:***
- LFV, LNV, LNV & LFV
- FCNC
- Resonance dominated
- VMD
- Radiative
Search for the rare decays $D^0 \rightarrow h l^\pm l^\mp$(‘)\(\mp\)

- Non-forbidden decay modes are dominated by intermediate resonances
- BSM enhancement in regions away from resonances possible
- Forbidden modes clear null-tests of the SM

\[ \frac{d\mathcal{B}(D^+ \rightarrow \pi^+\mu^+\mu^-)}{dq^2}\text{[GeV}^2\text{]} = m^2(\mu^+\mu^-) \]
\[ \frac{d\mathcal{B}(D^+ \rightarrow \pi^+e^+\mu^-)}{dq^2}\text{[GeV}^2\text{]} = m^2(\mu^+e^-) \]

\[ |K_{9(10)}| = 0.5 \]
\[ |K_{S(P)}| = 0.05 \]
\[ |K_{T(T5)}| = 0.5 \]
\[ |K_9| = |K_{10}| = 0.5 \]
Non-forbidden decay modes are dominated by intermediate resonances

BSM enhancement in regions away from resonances possible

Forbidden modes clear null-tests of the SM
Search for the rare decays \( D^0 \rightarrow h \ell \ell \pm \ell') \)

- How experimentally?

\[
\mathcal{B}(D^+_s \rightarrow h \ell \ell) = \frac{N(D^+_s \rightarrow h \ell \ell)}{N(D^+_s \rightarrow h\phi(\rightarrow \ell \ell))} \cdot \frac{\epsilon(D^+_s \rightarrow h\phi(\rightarrow \ell \ell))}{\epsilon(D^+_s \rightarrow h \ell \ell)} \cdot \mathcal{B}(D^+_s \rightarrow h\phi(\rightarrow \ell \ell))
\]

- Resonant reference channels (Run2, 1.7fb⁻¹)

LHCb Preliminary

\( D^+_s \rightarrow \phi(e^+e^+)\pi^+ \)

\( D^+ \rightarrow \phi(e^+e^+)\pi^+ \)

LHCb Preliminary

\( D^+_s \rightarrow \phi(\mu^+\mu^+)\pi^+ \)

\( D^+ \rightarrow \phi(\mu^+\mu^+)\pi^+ \)
Search for the rare decays $D^0 \rightarrow h\ell^\pm(\ell')\mp$

- All mass spectra well described by background only hypothesis
Search for the rare decays $D^0 \to h l^\pm (l^\mp)^\mp$

- No significant signal found, upper limits on the BFs $\mathcal{B}(10^{-8} - 10^{-7})$
- Improved limits by several orders of magnitude

LHCb Preliminary

previous best limit
observed limit
expected limit
with 1$\sigma$ and 2$\sigma$
intervals

2016 limit at 90% confidence

new limit

We come close to SM expectation of resonant contributions for some modes

Analysis of full Run2 data still to come
Future prospects

Short term future:

- We are working on fully exploiting the total Run2 data set (9/fb)
  - Many of the measurements shown today are expected to be updated soon ($A_{\Gamma}$, $D^0 \rightarrow K_S \pi^+ \pi^-$, $D^0 \rightarrow h \ell^+ \ell^-$, ...)
  - Plus many updates of analyses not shown today, such as $A_{CP}(K^+K^-)$, $D^0 \rightarrow \mu^+ \mu^-$, further searches for $\Xi^{+}_{cc}$ and $\Omega^{+}_{cc}$, ...

Long(er) term future:

- Upgrade I is ongoing, plan to collect up to 50fb$^{-1}$ by ~2030
  - The vast majority of our measurements are limited by the statistical precision
- Upgrade II is in preparation, eventually plan to collect up to 300fb$^{-1}$ by ~2038
- Projections for specific modes can be found in CERN-PUB-LHCC-2018-027
Summary

- First observation of CPV, fruitful discussions about its interpretation
- First evidence of non-zero mass difference of neutral D meson eigenstates
- Upper limits on indirect CPV are shrinking towards SM prediction, still one order of magnitude room for NP

- Doubly Charmed baryon saga puzzling, still no hints for $\Xi_{cc}^+$ at LHC, precision measurements of $\Xi_{cc}^{++}$ have started
- Important results on spectroscopy and production from LHCb, CMS, ALICE not shown today [Roberta’s and Yanxi’s talks tomorrow]

- Limits on rare and forbidden decays pushed down by orders of magnitudes
- Many more results are soon to come with full Run2 data set, including CPV in rare/radiative decays and angular distributions
Supplemental
Table 6.1: Extrapolated signal yields, and statistical precision on the mixing and \(CP\)-violation parameters, from the analysis of promptly produced WS \(D^{*+} \to D^0(\to K^+\pi^-)\pi^+\) decays. Signal yields of promptly produced RS \(D^{*+} \to D^0(\to K^-\pi^+)\pi^+\) decays are typically 250 times larger.

| Sample (\(\mathcal{L}\))     | Yield \((\times 10^6)\) | \(\sigma(x^2_{K\pi})\) | \(\sigma(y_{K\pi})\) | \(\sigma(A_D)\) | \(\sigma(|q/p|)\) | \(\sigma(\phi)\) |
|-------------------------------|--------------------------|-------------------------|-----------------------|------------------|------------------|------------------|
| Run 1–2 (9fb\(^{-1}\))       | 1.8                      | \(1.5 \times 10^{-5}\)  | \(2.9 \times 10^{-4}\) | 0.51\%           | 0.12             | \(10^\circ\)     |
| Run 1–3 (23fb\(^{-1}\))      | 10                       | \(6.4 \times 10^{-6}\)  | \(1.2 \times 10^{-4}\) | 0.22\%           | 0.05             | \(4^\circ\)      |
| Run 1–4 (50fb\(^{-1}\))      | 25                       | \(3.9 \times 10^{-6}\)  | \(7.6 \times 10^{-5}\) | 0.14\%           | 0.03             | \(3^\circ\)      |
| Run 1–5 (300fb\(^{-1}\))     | 170                      | \(1.5 \times 10^{-6}\)  | \(2.9 \times 10^{-5}\) | 0.05\%           | 0.01             | \(1^\circ\)      |

Table 6.3: Extrapolated signal yields, and statistical precision on the mixing and \(CP\) violation parameters, for the analysis of the decay \(D^0 \to K_S^0\pi^+\pi^-\). Candidates tagged by semileptonic \(B\) decay (SL) and those from prompt charm meson production are shown separately.

| Sample (lumi \(\mathcal{L}\)) | Tag   | Yield | \(\sigma(x)\) | \(\sigma(y)\) | \(\sigma(|q/p|)\) | \(\sigma(\phi)\) |
|-------------------------------|-------|-------|----------------|----------------|------------------|------------------|
| Run 1–2 (9 fb\(^{-1}\))       | SL    | 10M   | 0.07\%         | 0.05\%         | 0.07             | 4.6\(^\circ\)    |
|                               | Prompt| 36M   | 0.05\%         | 0.05\%         | 0.04             | 1.8\(^\circ\)    |
| Run 1–3 (23 fb\(^{-1}\))      | SL    | 33M   | 0.036\%        | 0.030\%        | 0.036            | 2.5\(^\circ\)    |
|                               | Prompt| 200M  | 0.020\%        | 0.020\%        | 0.017            | 0.77\(^\circ\)   |
| Run 1–4 (50 fb\(^{-1}\))      | SL    | 78M   | 0.024\%        | 0.019\%        | 0.024            | 1.7\(^\circ\)    |
|                               | Prompt| 520M  | 0.012\%        | 0.013\%        | 0.011            | 0.48\(^\circ\)   |
| Run 1–5 (300 fb\(^{-1}\))     | SL    | 490M  | 0.009\%        | 0.008\%        | 0.009            | 0.69\(^\circ\)   |
|                               | Prompt| 3500M | 0.005\%        | 0.005\%        | 0.004            | 0.18\(^\circ\)   |
Table 6.5: Extrapolated signal yields and statistical precision on direct $CP$ violation observables for the promptly produced samples.

<table>
<thead>
<tr>
<th>Sample ($\mathcal{L}$)</th>
<th>Tag</th>
<th>Yield $D^0 \rightarrow K^- K^+$</th>
<th>Yield $D^0 \rightarrow \pi^- \pi^+$</th>
<th>$\sigma(\Delta A_{CP})$ [%]</th>
<th>$\sigma(A_{CP}(hh))$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1–2 (9 fb$^{-1}$)</td>
<td>Prompt</td>
<td>52M</td>
<td>17M</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Run 1–3 (23 fb$^{-1}$)</td>
<td>Prompt</td>
<td>280M</td>
<td>94M</td>
<td>0.013</td>
<td>0.03</td>
</tr>
<tr>
<td>Run 1–4 (50 fb$^{-1}$)</td>
<td>Prompt</td>
<td>1G</td>
<td>305M</td>
<td>0.007</td>
<td>0.015</td>
</tr>
<tr>
<td>Run 1–5 (300 fb$^{-1}$)</td>
<td>Prompt</td>
<td>4.9G</td>
<td>1.6G</td>
<td>0.003</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 6.4: Extrapolated signal yields, and statistical precision on indirect $CP$ violation from $A_{\Gamma}$.

<table>
<thead>
<tr>
<th>Sample ($\mathcal{L}$)</th>
<th>Tag</th>
<th>Yield $K^+ K^-$</th>
<th>$\sigma(A_{\Gamma})$ [%]</th>
<th>Yield $\pi^+ \pi^-$</th>
<th>$\sigma(A_{\Gamma})$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1–2 (9 fb$^{-1}$)</td>
<td>Prompt</td>
<td>60M</td>
<td>0.013%</td>
<td>18M</td>
<td>0.024%</td>
</tr>
<tr>
<td>Run 1–3 (23 fb$^{-1}$)</td>
<td>Prompt</td>
<td>310M</td>
<td>0.0056%</td>
<td>92M</td>
<td>0.0104%</td>
</tr>
<tr>
<td>Run 1–4 (50 fb$^{-1}$)</td>
<td>Prompt</td>
<td>793M</td>
<td>0.0035%</td>
<td>236M</td>
<td>0.0065%</td>
</tr>
<tr>
<td>Run 1–5 (300 fb$^{-1}$)</td>
<td>Prompt</td>
<td>5.3G</td>
<td>0.0014%</td>
<td>1.6G</td>
<td>0.0025%</td>
</tr>
</tbody>
</table>
Multiple interfering amplitudes in $D^0 \rightarrow K_s \pi^+ \pi^-$ decays enhance sensitivity to mixing

Bin the Dalitz plot to avoid amplitude analysis in bins with approximately constant strong phase difference (Bin-Flip method)

Measure ratio of signal yields in bin -b and +b

$$R_b \approx r_b - \sqrt{r_b} \left[ (1 - r_b) c_b y - (1 + r_b) s_b x \right] \Gamma t$$

Hadronic parameters constraint using measurements with quantum correlated $D^0 \overline{D^0}$ pairs (CLEO, BESIII)

Mixing parameters from simultaneous fit to all bins, access to CPV by splitting in $D^0$ and $\overline{D^0}$
Analyse full Run1 and Run2 data set (9(fb))

Search for $\Xi_{cc}^+$ decays to final state $\Lambda_{cc}^{+} K^- \pi^+$ (SELEX observation channel)

Mass search window from $[3.4 - 3.8] \text{GeV}/c^2$

No significant signal found

Set limits $\mathcal{O}(10^{-4} - 10^{-3})$ on the production ratios for different lifetime hypotheses

\[
\mathcal{R}(\Lambda_{cc}^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times B(\Xi_{cc}^+ \to \Lambda_{cc}^{+} K^- \pi^+)}{\sigma(\Lambda_{cc}^+)}
\]

\[
\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \to \Lambda_{cc}^{+} K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \to \Lambda_{cc}^{+} K^- \pi^+ \pi^+)}
\]

We will extend our searches to different final states soon!
Production measurement of $\Xi_{cc}^{++}$

- Analyse Run2 pp collision data set (1.7/fb) at $\sqrt{s} = 13$ TeV

$$R \equiv \frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)}$$

- Measurement in the range $4 < p_T < 15$ GeV and $2.0 < \eta < 4.5$

<table>
<thead>
<tr>
<th>$\tau_{\Xi_{cc}^{++}}$</th>
<th>$\tau_{\Xi_{cc}^{++}}$</th>
<th>$\tau_{\Xi_{cc}^{++}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.230 ps</td>
<td>0.256 ps</td>
<td>0.284 ps</td>
</tr>
<tr>
<td>$2.53 \pm 0.31 \pm 0.30$</td>
<td>$2.22 \pm 0.27 \pm 0.29$</td>
<td>$1.98 \pm 0.23 \pm 0.26$</td>
</tr>
</tbody>
</table>

First measurement of the production of doubly charmed baryons in pp collisions
Search for the rare decays $D^0 \rightarrow h \ell^\pm (\ell')\mp$

- Non-forbidden decay modes are dominated by intermediate resonances
- BSM enhancement in regions away from resonances possible
- Forbidden modes clear null-tests of the SM
Search for the rare decays $D^0 \to h l^{\pm} (\ell')$:

- No significant signal found, upper limits on the BFs $\mathcal{O}(10^{-8} - 10^{-7})$.
- Improved limits by several orders of magnitude, we come close to SM expectation of resonant contributions for some modes.