Charm physics at LHCb

Alexey Dzyuba on behalf of the LHCb Collaboration

29th of August 2017, Moscow

18th Lomonosov Conference on Elementary Particle Physics
Charm quark

Important properties:
- High mass [simplify QCD calculations]

Applications of charm physics:
- Spectroscopy of charmed baryons – bridge between quarkonia spectroscopy and spectroscopy of light hadrons
Charm quark

**Important properties:**

- High mass [simplify QCD calculations]
- CP violation effects [described in Standard Model (SM) by complex phases of CKM-matrix elements] are very small for charm

**Applications of charm physics:**

- Spectroscopy of charmed baryons – bridge between quarkonia spectroscopy and spectroscopy of light hadrons
- Search for New Physics Searches for CPV in charm

<table>
<thead>
<tr>
<th>Quarks</th>
<th>mass</th>
<th>charge</th>
<th>spin</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>up</td>
<td>2.4 MeV</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>u</td>
</tr>
<tr>
<td>charm</td>
<td>1.27 GeV</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>c</td>
</tr>
<tr>
<td>top</td>
<td>171.2 GeV</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>t</td>
</tr>
<tr>
<td>down</td>
<td>4.8 MeV</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>d</td>
</tr>
<tr>
<td>strange</td>
<td>104 MeV</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>s</td>
</tr>
<tr>
<td>bottom</td>
<td>4.2 GeV</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>b</td>
</tr>
</tbody>
</table>

$\arg(V_{cd}) \sim 10^{-4}$  $\arg(V_{cs}) \sim 10^{-5}$
Charm quark

Important properties:

- High mass [simplify QCD calculations]
- CP violation effects [described in Standard Model (SM) by complex phases of CKM-matrix elements] are very small for charm
- Suppressed flavor changing neutral current (FCNC) transitions
- Mixing neutral charm meson measured, but is not-intensive (small mixing parameters $x \sim \Delta m$, $y \sim \Delta \Gamma$)

Applications of charm physics:

- Spectroscopy of charmed baryons – bridge between quarkonia spectroscopy and spectroscopy of light hadrons
- Search for New Physics (Searches for CPV in charm / rare charm decays driven by FCNC)

Quarks

- $u$: charge $\frac{2}{3}$, spin $\frac{1}{2}$, mass 2.4 MeV
- $d$: charge $\frac{-1}{3}$, spin $\frac{1}{2}$, mass 4.8 MeV
- $c$: charge $\frac{2}{3}$, spin $\frac{1}{2}$, mass 1.27 GeV
- $s$: charge $\frac{-1}{3}$, spin $\frac{1}{2}$, mass 104 MeV
- $b$: charge $\frac{-1}{3}$, spin $\frac{1}{2}$, mass 4.2 GeV
- $t$: charge $\frac{2}{3}$, spin $\frac{1}{2}$, mass 171.2 GeV

Mixing / FCNC

- $\arg(V_{cd}) \sim 10^{-4}$
- $\arg(V_{cs}) \sim 10^{-5}$
LHCb as heavy quark fabrique

\[
\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0 \ \mu b
\]

\[
\sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \ \mu b \sim 20 \times \sigma(b\bar{b})
\]
Largest charm samples in the world
Nucl.Phys.B871 (2013) 1

(at \( \sqrt{s} = 7 \) TeV)
LHCb as heavy quark fabrique

Suitable angular acceptance for heavy quark pair production in \( pp \)-collisions

\[
\sigma(\bar{b}b) = 75.3 \pm 5.4 \pm 13.0 \ \mu b
\]


\[
\sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \ \mu b \sim 20 \times \sigma(\bar{b}b)
\]

Largest charm samples in the world

Nucl.Phys.B871 (2013) 1

(at \( \sqrt{s} = 7 \) TeV)
LHCb as heavy quark fabrique

Suitable angular acceptance for heavy quark pair production in $pp$-collisions

$$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0 \, \mu b$$


$$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \, \mu b \sim 20 \times \sigma(b\bar{b})$$

Largest charm samples in the world
Nucl.Phys.B871 (2013) 1

(at $\sqrt{s} = 7$ TeV)

Exellent vertexing and tracking give access to decay time distribution / trigger for weak decays / prompt-secondary separation
LHCb as heavy quark fabrique

Suitable angular acceptance for heavy quark pair production in $pp$-collisions

\[ \sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0 \ \mu b \]


\[ \sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \ \mu b \sim 20 \times \sigma(b\bar{b}) \]

Largest charm samples in the world

Nucl.Phys.B871 (2013) 1

(at \( \sqrt{s} = 7 \text{ TeV} \))

Excellent PID allows to suppress background dramatically and explore many decay modes

\[ \epsilon_{PID}(K) \approx 95 \% \]

\[ \text{MisID } (K \to \pi) \approx 5 \% \]

Excellent vertexing and tracking give access to decay time distribution / trigger for weak decays / prompt-secondary separation

"Exellent vertexing and tracking give access to decay time distribution / trigger for weak decays / prompt-secondary separation"
LHCb as heavy quark fabrique

Nice tagging, triggering & great potential to search for rare decays with di-muons

Exellent PID allows to supress background dramatically and explore many decay modes

Suitable angular acceptance for heavy quark pair production in pp-collisions

$$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0 \, \mu b$$

$$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \, \mu b \sim 20 \times \sigma(b\bar{b})$$
(Largest charm samples in the world
Nucl.Phys.B871 (2013) 1

(at $\sqrt{s} = 7$ TeV)

More about LHCb performance:


Excellent vertexing and tracking give access to decay time distribution / trigger for weak decays / prompt-secondary separation
Luminosity and trigger

– Operated in constant instantaneous luminosity mode
Luminosity and trigger

- Operated in constant instantaneous luminosity mode
- Two stage trigger which is efficient for hadronic channels

![Graph showing integrated recorded luminosity from 2010 to 2017]

- 1 fb\(^{-1}\) in 2011 at 7 TeV
- 2 fb\(^{-1}\) in 2012 at 8 TeV
- 0.3 fb\(^{-1}\) in 2015 at 13 TeV
- 1.7 fb\(^{-1}\) in 2016 at 13 TeV
Luminosity and trigger

- Operated in constant instantaneous luminosity mode
- Two stage trigger which is efficient for hadronic channels
- Turbo stream for Run-II [Candidates reconstructed at the trigger level saved directly for offline analysis, huge accepted rates, a kind of revolution in experimental HEP]
Flavor tagging for charm

Prompt tagging

Primary vertex (PV)

$D^{**+}$

$\pi^+$

$h = \pi^\pm, K^\pm$

Higher tagging rate

Secondary (semileptonic)

$D^0$

$B$

$D^0$

$\mu^-$

More efficient triggering
Flavor tagging for charm

Prompt tagging

Primary vertex (PV)

Higher tagging rate

h = π±, K±

Secondary (semileptonic)

More efficient triggering

Mixing & CPV

Right sign (RS) \( D^{*+} / K^- \pi^+ \): 1.7M

– \( D^0 \to K\pi \) with doubly-tagged sample

– RS appears when no-mixing AND Cabibbo-favorite (CF) decay
Flavor tagging for charm

Prompt tagging

Primary vertex (PV)

$D^{*+} \rightarrow \pi^+, D^0$

$h = \pi^\pm, K^\pm$

Higher tagging rate

Secondary (semileptonic)

$D^0 \rightarrow K\pi$

$X \rightarrow \mu^- u\mu$

More efficient triggering

Mixing & CPV

Right sign (RS) $D^{*+} / K^- \pi^+$: 1.7M

Wrong sign (WS) $D^{*+} / K^+ \pi^-$: 6.7k

$D^0 \rightarrow K\pi$ with doubly-tagged sample

RS appears when no-mixing AND Cabibbo-favorite (CF) decay

WS either [mixing AND CF] OR [no-mixing and Doubly-Cabibbo suppressed decay]

Probe for all possible CPV scenarios (direct, in mixing, interference)

PR D95 (2017) 052004
Mixing & CPV

As mixing parameters ($x'$ and $y'$) are small the WS / RS ratio can be approximated as:

$$R(t)^\pm = R_D^\pm + \sqrt{R_D^\pm y'^\pm} \left( \frac{t}{\tau} \right) + \frac{(x'^\pm)^2 + (y'^\pm)^2}{4} \left( \frac{t}{\tau} \right)^2,$$

$$R_D^+ = |A_f^-/A_f|^2 \quad R_D^- = |\bar{A}_f/^\bar{A}_f|^2 \quad R_D^+ \neq R_D^- \Rightarrow \text{direct CPV}$$

$$x'^+ \neq x'^- \quad y'^+ \neq y'^- \Rightarrow \text{CPV in mixing and interference}$$
Mixing & CPV

– As mixing parameters ($x'$ and $y'$) are small the WS / RS ratio can be approximated as:

$$R(t)^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm} y'^{\pm}} \left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4} \left(\frac{t}{\tau}\right)^2,$$

$$R_D^{+} = |\mathcal{A}_f/\mathcal{A}_f|^2 \quad R_D^{-} = |\overline{\mathcal{A}_f/\mathcal{A}_f}|^2 \quad R_D^{+} \neq R_D^{-} \Rightarrow \text{direct CPV}$$

$x'^{+} \neq x'^{-}$ $y'^{+} \neq y'^{-}$ ⇒ CPV in mixing and interference

– Result of all CPV allowed fit

PR D95 (2017) 052004

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DT+Prompt</th>
<th>Prompt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D^{+}[10^{-3}]$</td>
<td>3.474 ± 0.081</td>
<td>3.545 ± 0.095</td>
</tr>
<tr>
<td>$(x'^{+})^2 [10^{-4}]$</td>
<td>0.11 ± 0.65</td>
<td>0.49 ± 0.70</td>
</tr>
<tr>
<td>$y'^{+}[10^{-3}]$</td>
<td>5.97 ± 1.25</td>
<td>5.1 ± 1.4</td>
</tr>
<tr>
<td>$R_D^{-}[10^{-3}]$</td>
<td>3.591 ± 0.081</td>
<td>3.591 ± 0.090</td>
</tr>
<tr>
<td>$(x'^{-})^2 [10^{-4}]$</td>
<td>0.61 ± 0.61</td>
<td>0.60 ± 0.68</td>
</tr>
<tr>
<td>$y'^{-}[10^{-3}]$</td>
<td>4.50 ± 1.21</td>
<td>4.5 ± 1.4</td>
</tr>
</tbody>
</table>
Mixing & CPV

– As mixing parameters \((x'\) and \(y')\) are small the \(WS / RS\) ratio can be approximated as:

\[
R(t) \pm = R_D^\pm + \sqrt{R_D^\pm} y'^\pm \left(\frac{t}{\tau}\right) + \frac{(x'^\pm)^2 + (y'^\pm)^2}{4} \left(\frac{t}{\tau}\right)^2,
\]

\[
R_D^+ = |A_f^- / A_f|^2 \quad R_D^- = |A_f^- / A_f|^2 \quad R_D^+ \neq R_D^- \Rightarrow \text{direct CPV}
\]

\[
x'^+ \neq x'^- \\
y'^+ \neq y'^- \Rightarrow \text{CPV in mixing and interference}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DT+Prompt</th>
<th>Prompt</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_D^+[10^{-3}])</td>
<td>3.474 ± 0.081</td>
<td>3.545 ± 0.095</td>
</tr>
<tr>
<td>((x'^+)^2 [10^{-4}])</td>
<td>0.11 ± 0.65</td>
<td>0.49 ± 0.70</td>
</tr>
<tr>
<td>(y'^+[10^{-3}])</td>
<td>5.97 ± 1.25</td>
<td>5.1 ± 1.4</td>
</tr>
<tr>
<td>(R_D^-[10^{-3}])</td>
<td>3.591 ± 0.081</td>
<td>3.591 ± 0.090</td>
</tr>
<tr>
<td>((x'^-)^2 [10^{-4}])</td>
<td>0.61 ± 0.61</td>
<td>0.60 ± 0.68</td>
</tr>
<tr>
<td>(y'^-[10^{-3}])</td>
<td>4.50 ± 1.21</td>
<td>4.5 ± 1.4</td>
</tr>
</tbody>
</table>

– Result of all CPV allowed fit

PR D95 (2017) 052004

– Higher signal purity and complementary decay-time coverage allow to improve precision by 10-20% when adding few percents of doubly tagged data

– No evidence for CPV in mixing / decay

2017-08-29

Lomonosov-2017
Direct CPV in charm

Measured observable:

\[ A_{\text{raw}} \equiv \frac{N(D^0 \rightarrow K^-K^+) - N(\bar{D}^0 \rightarrow K^-K^+)}{N(D^0 \rightarrow K^-K^+) + N(\bar{D}^0 \rightarrow K^-K^+)}, \]

to get access to CPV observable, it need to be corrected for production and detection asymmetries.

For example for prompt tagging:

\[ A_{CP}(D^0 \rightarrow K^-K^+) = A_{\text{raw}}(D^0 \rightarrow K^-K^+) - A_P(D^{*+}) - A_D(\pi^+_s), \]
Direct CPV in charm

Measured observable:

\[ A_{\text{raw}} = \frac{N(D^0 \rightarrow K^- K^+) - N(\bar{D}^0 \rightarrow K^- K^+)}{N(D^0 \rightarrow K^- K^+) + N(\bar{D}^0 \rightarrow K^- K^+)} \]

to get access to CPV observable, it needs to be corrected for production and detection asymmetries.

For example for prompt tagging:

\[ A_{\text{CP}}(D^0 \rightarrow K^- K^+) = A_{\text{raw}}(D^0 \rightarrow K^- K^+) - A_P(D^{*+}) - A_D(\pi^+_s), \]

Combination of the results from prompt and semileptonic tagging (per-mile precision):

\[ A_{\text{CP}}^{\text{comb}}(\pi^- \pi^+) = (0.07 \pm 0.14 \text{ (stat)} \pm 0.11 \text{ (syst)})\%, \]

\[ A_{\text{CP}}^{\text{comb}}(K^- K^+) = (0.04 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (syst)})\%. \]
Direct CPV in charm

Measured observable:

\[ A_{\text{raw}} \equiv \frac{N(D^0 \rightarrow K^- K^+) - N(\bar{D}^0 \rightarrow K^- K^+)}{N(D^0 \rightarrow K^- K^+) + N(\bar{D}^0 \rightarrow K^- K^+)} \]  

to get access to CPV observable, it need to be corrected for production and detection asymmetries.

For example for prompt tagging:

\[ A_{CP}(D^0 \rightarrow K^- K^+) = A_{\text{raw}}(D^0 \rightarrow K^- K^+) - A_{P}(D^{*+}) - A_{D}(\pi^+) \]

Combination of the results from prompt and semileptonic tagging (per-mile precision):

\[ A_{CP}^{\text{comb}}(\pi^- \pi^+) = (0.07 \pm 0.14 \text{ (stat)} \pm 0.11 \text{ (syst)})\%, \]
\[ A_{CP}^{\text{comb}}(K^- K^+) = (0.04 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (syst)})\% \]

Other decay modes are also under investigation:

\[ D^\pm(s) \rightarrow \eta'\pi^\pm \quad [\text{PLB 771 (2017) 21}] \]
\[ D^0 \rightarrow 4\pi \quad [\text{PLB 769 (2017) 345}] \]
Indirect CPV in charm sector

Time integrated CP asymmetries as well as mixing parameters are small:

\[ A_{\text{CP}}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \simeq a^f_{\text{dir}} - A_{\Gamma} \frac{t}{\tau_D} \]

- **CPV in decay close-to-zero**
- **Inverse of effective lifetime**

\[ A_{\Gamma} \equiv \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\bar{D}^0 \to f}} \]

- **CPV in mixing / interference**
  - Expected to be less than 0.005
Indirect CPV in charm sector

Time integrated CP asymmetries as well as mixing parameters are small:

\[ A_{\text{CP}}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \simeq a_{\text{dir}}^f - A_{\Gamma} \frac{t}{\tau_D} \]

- CPV in decay close-to-zero
- CPV in mixing / interference
  Expected to be less 0.005

\[ A_{\Gamma} = \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\bar{D}^0 \to f}} \]

- Prompt \( D^* \) tagging
- \( D \to K\pi \) to keep production and detection asymmetries under control

\[ A_{\Gamma} = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3} \]
Indirect CPV in charm sector

Time integrated CP asymmetries as well as mixing parameters are small:

\[ A_{CP}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \simeq a_{dir}^f - A_{\Gamma} \frac{t}{\tau_D}, \]

- CPV in decay close-to-zero
- CPV in mixing / interference Expected to be less 0.005

Inverse of effective lifetime

- Prompt \( D^* \) tagging
- \( D \to K\pi \) to keep production and detection asymmetries under control

\[ A_{\Gamma} = ( -0.13 \pm 0.28 \pm 0.10 ) \times 10^{-3} \]

Most precise CPV measurement for charm:

\[ A_{\Gamma} = ( -0.29 \pm 0.28 ) \times 10^{-3} \]

Combination with semileptonic tagged sample [JHEP 04 (2015) 043]:
Rare decays: $D^0 \rightarrow h^+ h^- \mu^+ \mu^- \; (h = \pi, K)$

Goal: Probe New Physics in $c \rightarrow u$ transitions, appears at short distances and very suppressed in SM ($< 10^{-9}$)
Rare decays: $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ ($h = \pi, K$)

**Goal:** Probe New Physics in $c \rightarrow u$ transitions, appears at short distances and very suppressed in SM ($< 10^{-9}$)

**Long range contribution** from $\rho$, $\omega$, $\phi$ due to decays into $\mu^+ \mu^-$ pair (difficult to predict leakage of events from resonance tails into search region)
Rare decays: $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ ($h = \pi$, $K$)

**Goal:** Probe New Physics in $c \rightarrow u$ transitions, appears at short distances and very suppressed in SM ($< 10^{-9}$)

**Long range contribution** from $\rho$, $\omega$, $\phi$ due to decays into $\mu^+ \mu^-$ pair (difficult to predict leakage of events from resonance tails into search region)

Short range

Long range

Non-blinded mass bins

**Candidates per 5 MeV/c^2**

Rare decays: $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ ($h = \pi, K$)

Goal: Probe New Physics in $c \rightarrow u$ transitions, appears at short distances and very suppressed in SM ($< 10^{-9}$)

Long range contribution from $\rho$, $\omega$, $\phi$ due to decays into $\mu^+ \mu^-$ pair (difficult to predict leakage of events from resonance tails into search region)

Short range

Long range

$\mathcal{B}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$,

$\mathcal{B}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$.

- The rarest charm-hadron decays ever observed!
- Branching fractions are consistent with SM expectations
Spectroscopy: five excited $\Omega_c$

– Single charmed baryons predicted from SU(3) multiplets: $3 \otimes 3 = \bar{3} \oplus 6$
– All ground states as well as excited $\Lambda_c$, $\Sigma_c$ and $\Xi_c$ states have been reported
– No exited $\Omega_c$ states were observed before LHCb
Spectroscopy: five excited $\Omega_c$

- Single charmed baryons predicted from SU(3) multiplets: $3 \otimes 3 = \bar{3} \oplus 6$
- All ground states as well as excited $\Lambda_c$, $\Sigma_c$ and $\Xi_c$ states have been reported
- No exited $\Omega_c$ states were observed before LHCb
- Many possible channels:

Ref. to theory papers in backup
Spectroscopy: five excited $\Omega_c$

- Single charmed baryons predicted from SU(3) multiplets: $3 \otimes 3 = \bar{3} \oplus 6$
- All ground states as well as excited $\Lambda_c$, $\Sigma_c$ and $\Xi_c$ states have been reported
- No exited $\Omega_c$ states were observed before LHCb
- Many possible channels:
  - $3 \text{ fb}^{-1}$ Run I + $0.3 \text{ fb}^{-1}$ Run II $pp$ collision data
  - Decay chain: $\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$, $\Xi_c^+ \rightarrow pK^- \pi^+$
  - Cabibbo suppressed, but very suitable for LHCb (high selection efficiency)
  - $\tau(\Xi_c^+) \approx 45 \text{ ps}$
  - detached from PV

Ref. to theory papers in backup
Spectroscopy: five excited $\Omega_c$

- $\Xi_c$ candidate combined with charged kaon
- Five narrow peaks for $\Xi_c^+K^-$
- No structures in $\Xi_c^+K^+$ invariant mass
Spectroscopy: five excited $\Omega_c$

- $\Xi_c$ candidate combined with charged kaon
- Five narrow peaks for $\Xi_c^+K^-$
- No structures in $\Xi_c^+K^+$ invariant mass
- Sidebands for $\Xi_c$ candidate do not produce peaking structures
Spectroscopy: five excited $\Omega_c$

- $\Xi_c$ candidate combined with charged kaon
- Five narrow peaks for $\Xi_c^+ K^-$
- No structures in $\Xi_c^+ K^+$ invariant mass
- Sidebands for $\Xi_c$ candidate do not produce peaking structures
- Feed-down contribution

$$\Omega_{c^{**0}} \rightarrow K^- \Xi_{c^+}^{'}, \Xi_{c}^{'^+} \rightarrow \gamma \Xi_{c}^{'^+}$$

missed
Spectroscopy: five excited $\Omega_c$

- $\Xi_c$ candidate combined with charged kaon
- Five narrow peaks for $\Xi_c^+K^-$
- No structures in $\Xi_c^+K^+$ invariant mass

- Sidebands for $\Xi_c$ candidate do not produce peaking structures

- Feed-down contribution

\[ \Omega_c^{**0} \rightarrow K^-\Xi_c^+, \Xi_c^+ \rightarrow \gamma \Xi_c^+ \]

- Fit quality improves when including a broad structure or multiple states around 3200 MeV
Properties of observed peaking structures:

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$\sigma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1 \pm 0.3 \pm 0.5$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1 \pm 0.3 \pm 0.5$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3 \pm 0.3 \pm 0.5$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
<td>23.9</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5 \pm 0.3 \pm 0.5$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
<td>21.1</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9 \pm 0.3 \pm 0.5$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
<td>10.4</td>
</tr>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188 \pm 5 \pm 13$</td>
<td>$60 \pm 15 \pm 11$</td>
<td>6.4</td>
</tr>
</tbody>
</table>

$N_\sigma = \sqrt{\Delta \chi^2}$

- Spectroscopy of system containing one heavy ($c$) and two intermediate mass $s$-quarks
- Spin-parity information is required to match observed peaks with theory prediction
- Options: 1) Three body decays
  2) Decays of heavier baryons

Ref. to theory papers in backup
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Two SU(3) triplets are predicted as parts of two SU(4) baryons 20-plets.

- Many predictions:
  \[ M(\Xi_{cc}^{+}) \text{ in } [3.5 - 3.7] \text{ GeV}, \]
  \[ M(\Omega_{cc}) \approx M(\Xi_{cc}) + 0.1 \text{ GeV} \]

- Few MeV difference expected between $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$

Ref. to theory papers in backup.
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Two SU(3) triplets are predicted as parts of two SU(4) baryons 20-plets

- Many predictions:
  \[ M(\Xi_{cc}^{+,++}) \text{ in } [3.5 - 3.7] \text{ GeV}, \]
  \[ M(\Omega_{cc}) \approx M(\Xi_{cc}) + 0.1 \text{ GeV} \]

- Few MeV difference expected between $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$

- Lattice QCD: \[ M(\Xi_{cc}^{++,++}) \approx 3.6 \text{ GeV}, \quad M(\Omega_{cc}) \approx 3.7 \text{ GeV} \]

- HQET: core from heavy diquark

- Lifetime expectations:
  \[ \tau(\Xi_{cc}^{++}) \in [200 - 700] \text{ fs} \]
  \[ \tau(\Xi_{cc}^{++}(ccu)) \gg \tau(\Xi_{cc}^+(ccd)) \]

Doubly heavy baryon expected to be similar to a heavy $Qq$ meson

Ref. to theory papers in backup
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Use Run-II $pp$ data $1.7 \text{ fb}^{-1}$, exclusive high efficient trigger (Turbo)
- Run-I (2012) $2 \text{ fb}^{-1}$ for cross-check
- Expected up to 10% branching fraction for decay of interest

$\Xi_{cc}^{++} \rightarrow K^- \pi^+ \pi^+ \Lambda_c^+ (\rightarrow pK^- \pi^+)$

$\tau(\Lambda_c^+) \approx 200 \text{ fs}$
$\sigma_{\tau} \approx 45 \text{ fs}$
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Use Run-II $pp$ data 1.7 fb$^{-1}$, exclusive high efficient trigger (Turbo)
- Run-I (2012) 2 fb$^{-1}$ for cross-check
- Expected up to 10% branching fraction for decay of interest

Invariant mass for:

**Right sign (RS) combination:** $\Lambda_c^+K^-\pi^+\pi^+$

**Wrong sign (WS):** $\Lambda_c^+K^-\pi^+\pi^-$

**Sidebands**

$LHCb$ 13 TeV

Candidates per 3 MeV/c$^2$
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Use Run-II $pp$ data 1.7 fb$^{-1}$, exclusive high efficient trigger (Turbo)
- Run-I (2012) 2 fb$^{-1}$ for cross-check
- Expected up to 10% branching fraction for decay of interest

Invariant mass for:

**Right sign (RS) combination:** $\Lambda_c^+ K^- \pi^+ \pi^+$

**Wrong sign (WS):** $\Lambda_c^+ K^- \pi^+ \pi^-$

**Sidebands**

LHCb 13 TeV

$\Xi_{cc}^{++} \rightarrow K^- \pi^- \pi^+ \Lambda_c^+ (\rightarrow pK^- \pi^+)$

$\tau(\Lambda_c^+) \approx 200$ fs

$\sigma_{\tau} \approx 45$ fs
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Signal yield: $313 \pm 33$ events
- Mass resolution: $6.6 \pm 0.8$ MeV
- Local significance $> 12\sigma$

\[ m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \text{(stat)} \pm 0.27 \text{(syst)} \pm 0.14(\Lambda_c^+) \text{ MeV} \]

\[ m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72 \text{(stat)} \pm 0.27 \text{(syst)} \text{ MeV} \]

- Sub-MeV precision for observation!
- Obtained value are consistent with many theoretical calculations (including LQCD)
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Signal yield: $313 \pm 33$ events
- Mass resolution: $6.6 \pm 0.8$ MeV
- Local significance $> 12\sigma$

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+) \text{ MeV}$$

$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \text{ MeV}$$

- Sub-MeV precision for observation!
- Obtained value are consistent with many theoretical calculations (including LQCD)

- Signal peak for Run-I data has $> 7\sigma$ local significance ($113 \pm 21$ events)
Spectroscopy: discovery of $\Xi_{cc}^{++}$

- Signal yield: $313 \pm 33$ events
- Mass resolution: $6.6 \pm 0.8$ MeV
- Local significance $> 12\sigma$
  
  \[
  m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\text{(stat)} \pm 0.27\text{(syst)} \pm 0.14(\Lambda_c^+) \text{ MeV}
  \]
  \[
  m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72\text{(stat)} \pm 0.27\text{(syst)} \text{ MeV}
  \]
- Sub-MeV precision for observation!
- Obtained value are consistent with many theoretical calculations (including LQCD)

- Signal peak for Run-I data has $> 7\sigma$ local significance ($113 \pm 21$ events)

- Peaking structure remains significant after requiring minimum decay time [$t > 5\sigma_t$]

- Weak force driven decay indeed.
Summary

– LHCb performs excellent
– Wide physics program in the charm sector including
  - spectroscopy studies (five new $\Omega_{c^*}$ and $\Xi_{cc}^{++}$),
  - search for New Physics in rare decays ($D \rightarrow hh\mu\mu$)
  - and in $CP$ violation ($WS / RS$, time-int. $A_{CP}$, $A_{\Gamma}$)
– A lot of new results and many analyses (Run-I & II)
  in the stack

– Thank you!
Backup
Mass $\Xi_{cc}$


Theory references for $\Omega_c^*$


Theory references for $\Omega_c^*$


