HEAVY FLAVOUR SPECTROSCOPY

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On behalf of LHCb Collaboration

Workshop on the physics of HL-LHC, and perspectives at HE-LHC
30 October-1 November, CERN
SPECTROSCOPY AND QCD

Standard Model

Colored quarks and gluons

Long-distance effects

Nature

Color-singlet mesons and baryons

- Long-distance regime of QCD is the least understood aspect of QCD
- Many models predict states beyond the standard $qq$ and $qqq$
Spectroscopy at LHCb

Exotic candidates have been already observed? Many other? Are they really exotic states? Which kind?

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STANDARD

EXOTIC

\[ \Lambda_b^{**} \]

PRL 109 (2012) 172003

\[ X(3872) \]

PRD 92 (2015) 011102

PRL 119 (2017) 112001

\[ Z_c(4430)^+ \]

PRL 112 222002 (2014)

PRD 92 112009 (2015)

\[ \Omega_c^{**}(?) \]

PRL 118 (2017) 182001

\[ P_{c}(4450)^+ \]

PRL 115 (2015) 072001

\[ \Xi(4140) \]

PRL 118 (2015) 022003

PRD 95 (2017) 012002

Exotic candidates have been already observed? Many other? Are they really exotic states? Which kind?
Upgrade II in a Nutshell

An Upgrade II will be installed in Long Shutdown 4 of the LHC:
- It will consist of redesigned subsystems that can operate at a luminosity of $1-2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (10 x larger than Upgrade I)
- It is expected that the experiment collects data corresponding to an integrated luminosity of $> 300 \text{ fb}^{-1}$
- Extension of the experiment’s capabilities into selecting $\pi^0$, $\eta$, $\gamma$ and low-momentum tracks [CERN-LHCC-2017-003]

Rule of Thumb

“Scale present Run-1 yields by a factor ~400 for hadronic final states and ~200 for muonic final states”

- But it assumes states have been already observed in Run I...
- Educated guesses on unknown production cross-sections and branching ratios
**How to do spectroscopy?**

**Prompt Production:** (e.g. \( pp \rightarrow D_s^{**} (\rightarrow D^0 K) + X \))

- ✔️ Large cross sections
- ✗ Large combinatorial background
- ✗ Hard to disentangle broad structures
- ✗ Difficult to assess spin
- ✗ Presence of “reflections”/“feed-downs”

**Central Exclusive Production (CEP)**

- ✔️ Small background
- ✔️ \( J^{PC} = 1^- , J^{++} \)
- ✗ Limited cross sections

**b-hadron decays** (e.g. \( B_s \rightarrow D_s^{**} (\rightarrow D^0 K) \pi \))

- ✔️ Small background
- ✔️ Access to the phase of the amplitude and spin-parity
- ✗ Limited cross sections
- ✗ High spin resonances suppressed
- ✗ Presence of “shadows”
All the ground states with the charm quantum number $C = 0$ or $C = 1$ have been discovered. Three weakly decaying $C = 2$ states are expected: a $\Xi_{cc}$ isodoublet ($ccu$; $ccd$) and an $\Omega_{cc}$ isosinglet (ccs), each with $J^P = 1/2^+$. $\Xi_{cc}^{++}$ recently observed by LHCb!

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+, \quad \Lambda_c^+ \rightarrow pK^- \pi^+$$

Highly significant signal observed (>12$\sigma$) consistent with a state decaying weakly

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

- Observations of $\Xi_{cc}^+$ and $\Omega_{cc}$ expected with RUN II data or during the upcoming upgrade
- The Phase II upgrade will be useful into studying their production and excited spectra: $\Xi_{cc}^{**}$ and $\Omega_{cc}^{**}$. $\Omega_{ccc}$ is also likely to be observed
What about $\Xi_{bc}$?

- The $B_c$ meson was discovered almost two decades ago
- In LHCb, $\sim 5000 B_c \rightarrow J/\psi \pi$ in Run I

So, why have we not yet seen bcq baryons ($\Xi_{bc}$)?

- Lower production rates, guess $\sigma(X_{bc}) \sim (0.1 - 0.5) \times \sigma(B_c^+)$
- In $J/\psi$ modes, (usually) get a charm baryon: yield reduced by $BF(X_c) \times \varepsilon_{sel}(X_c)$
- Shorter lifetime ($\sim 0.15 - 0.4$ ps range, compared to $\sim 0.5$ ps for $B_c$)

$$(e.g.) \ N(\Xi_{bc}^0 \rightarrow J/\psi \Lambda_c^+ K^-; \text{Run 1}) = N(B_c^+ \rightarrow J/\psi D_s^{(*)^+}; \text{Run 1})$$

$$\times \frac{\sigma(pp \rightarrow \Xi_{bc} X)}{\sigma(pp \rightarrow B_c^+ X)} \times f_{\Xi_{bc} \rightarrow \Xi_{bc}^0}$$

$$\times \frac{Br(\Xi_{bc}^0 \rightarrow J/\psi \Lambda_c^+ K^-)}{Br(B_c^+ \rightarrow J/\psi D_s^{(*)^+})}$$

$$\times \varepsilon_{K^-}$$

$$\approx 3 \text{ candidates}$$

$N(\Xi_{bc}^0 \rightarrow J/\psi \Lambda_c^+ K^-; \text{Run 5}) \approx 6 \times 10^2$
Doubly Charmed Tetraquark: \(cc\bar{q}\bar{q}\)

- Observation of several hadronic resonances with hidden charm or beauty (so called X, Y, Z states) in the last decade at LHC and B-factories
- They barely fit into the standard quarkonium scenarios and “exotic” interpretations have been proposed

- Doubly charmed particles are a straightforward consequence
- If discovered, they would be almost full-proof states made of 4 quarks

- Observation of doubly charged states would be even more important to understand their nature: indeed in a loosely bound molecule, Coulomb repulsion would induce a fall-apart decay on very short time scales

Loosely bound molecules

[O. Esposito et al.: PRD 88 (2013) 054029]
**Doubly Charmed Tetraquark: ccq̅q̅**

- If the masses of such states are below the DD thresholds → strong decays are forbidden and weak decay pattern would be complicated
- If the masses are above the DD thresholds, pure tetraquark models predict (narrow) states with quantum numbers $J^P = 0^+, 1^+$ and $2^+$
- $0^+$ and $1^+$ states expected to be the lighter and more likely to be formed (and observed)

Natural widths as predicted by a pure tetraquark model
Doubly Charmed Tetraquark in Prompt Production

Narrow states could be easily spotted in the prompt production.

Associated production of $D^+D^+$ and $D^+D_s^+$ ($0.3 \text{ fb}^{-1}$)

$N(D^+D^+; \text{Run5}) \approx 750k$ candidates

$N(D^+D_s^+; \text{Run5}) \approx 150k$ candidates

[LHCb: JHEP 06 (2012) 141]
Doubly Charmed Tetraquark in $B_c$ Decays

- If the states are broad-ish → Search for them in $B_c$ decays where the quantum numbers can be also measured.
- The $B_c$ meson is the lightest state in the standard model that can decay to two same-flavour charmed hadrons.
- Search for tetraquark: $\mathcal{T}_s^+ (cc\bar{u}\bar{s}) \rightarrow D^0 D_s^+$

$LHCb$: PRD 87 (2013) 112012

$N = 28.9 \pm 5.6$ (3 fb$^{-1}$)

$N(B_c^+ \rightarrow D^0 \bar{D}^0 D_s^+; \text{Run5}) \sim 10^2$ candidates

Clear signature. Expected to be background free. Three pseudoscalars in the final state.
In 2015 LHCb observed two $P_c^+$ decaying to $J/\psi$ p. Are they cusps?

M. Bayar et al.: PRD 94 (2016) 074039

Observation of the $\chi_{c1}$ p decay mode will help to clarify the nature of the observed $P_c$ states.

$$N(\Lambda_b^0 \to \chi_{c1}pK^-; \text{Run5}) \simeq 9 \times 10^4$$
$$N(\Lambda_b^0 \to \chi_{c2}pK^-; \text{Run5}) \simeq 6 \times 10^4$$
MULTIPLETS OF PENTAQUARKS

As for other hadrons, multiplets of pentaquarks should exist. The two observed $P_c^+$ should be states with quark content $uudcar{c}$. We could look for strange pentaquark $P_{cs}^0 \rightarrow J/\psi \Lambda$ in $\Xi_b$ decays.

$LHCb$: PLB 772 (2017) 265

300 candidates of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ (3 fb$^{-1}$)

$N(\Xi_b^- \rightarrow J/\psi \Lambda K^-$; Run5) $\approx 6 \times 10^4$
Weak Decays of Excited $D_s$ Mesons

2003: Discovery of two narrow states decaying to $D_s(\ast)^{+}\pi^0$

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{s0}^\ast(2317) \pm$</td>
<td>$2317.7 \pm 0.6$</td>
</tr>
<tr>
<td>$D_{s1}(2460) \pm$</td>
<td>$2459.5 \pm 0.6$</td>
</tr>
</tbody>
</table>

Surprisingly narrow!

Are they ordinary $c\bar{s}$ or tetraquark/molecules states?
Predictions on the natural width vary according to the models

Weak decays not observed for any short-lived resonance.

- Best limits ($O(10^{-6})$) are measured for the $J/\psi$ meson
- If strong and/or electromagnetic processes are allowed, weak decays are suppressed by the square of the Fermi constant ($<O(10^{-10})$)

\[
\Gamma_{D_s^\ast \to \ell \nu} = \frac{G_F^2}{12\pi} |V_{cs}|^2 f_{D_s}^2 M_{D_s}^3 \left( 1 - \frac{m_\ell^2}{M_{D_s}^2} \right)^2 \left( 1 + \frac{m_\ell^2}{2M_{D_s}^2} \right) \quad [PRL 112 (2014) 212002]
\]

- Rates enhanced if the total width is suppressed as for the excited $D_s$ states
SEARCH FOR WEAK DECAYS OF EXCITED D_s MESONS AT LHCb

Assuming a production cross-section comparable to that of the D_s meson (500μb at 13 TeV), a branching fraction of $10^{-8}$ and a reconstruction efficiency of 0.1% results in an expected signal of 50 decays in a 1 fb$^{-1}$ data sample.

Where to look at?

The search for such decays in prompt production will be affected by large combinatorial background and narrow signals (i.e. small Q value) will give the best sensitivity.

$D_{s0}^*(2317)/D_{s1}(2460) \rightarrow p\bar{p}\pi$

- Outstanding particle identification performance needed to identify protons with high purity and efficiency
- Background reduction
**IMPACT OF CALORIMETER UPGRADE**

- Increased calorimeter resolution
- Reduction in background by a fast timing calorimeter information
- Increased sensitivity to low $p_T$ photon and $\pi^0$

**Measurement of $B(X(3872) \rightarrow \psi(2S) \gamma)/B(X(3872) \rightarrow J/\psi \gamma)$**

\[
\frac{BR(X(3872) \rightarrow \psi(2S)\gamma)}{BR(X(3872) \rightarrow J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29
\]

*Pure molecule scenario disfavored*

- Search for pentaquarks decaying to $\chi_{c1}p$
  where $\chi_{c1} \rightarrow J/\psi \gamma$

*See Preema Pais’s Talk on Wednesday*
Neutrals will be crucial into probing further the $X(3872)$ meson.
IMPACT OF VELO UPGRADE

Removal of RF foil
- Improved vertex resolution
- Higher signal efficiency with large background rejection
- Increased track efficiency
- Reduction in ghost rates

- Better performance into detecting low momentum tracks will contribute into studying/observing excited states decaying through dipion transitions (e.g. $B_c^* \rightarrow B_c \pi \pi$)
- Better reconstruction efficiency for multibody $B$ decays, such as $B \rightarrow \bar{D}DK$ aiming to the search for charmonium-like states
- Improved vertex resolution $\Rightarrow$ Higher efficiency into selecting short-lived particles: $B_c$, $\Xi_{cc}$, $\Omega_{cc}$, $\Xi_{bc}$, $\Omega_{ccc}$

See: Gregory Ciezarek’s talk on Wednesday
Iwan Smith’s Poster
SUMMARY

- Great interest into spectroscopy
- The observation of the two pentaquarks is the most cited LHCb paper
- The large data set collected in the HL-LHC era, together with an upgraded detector, will boost sensitivity in searches for heavy states with small production cross sections and/or small decay rates

...to be continued