States in QCD: Pentaquarks, Tetraquarks and other hadrons

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on behalf of the LHCb Collaboration

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Standard Model at the LHC 2018

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Modelling QCD bound states works better and better

QCD predictions based on both

- Effective models
- Computation on the lattice

is reaching great reliability for both mesons and baryons:

- predictions from different toolkits agree with each other
- and agree with the experiments.
Predictions on the $\Xi_{cc}^{++}$ baryon

- Doubly Heavy Baryons (baryon with two heavy quarks) is a mostly unexplored region, modeled without support from the observation in a very different regime!

For the $\Xi_{cc}^{++}$ baryon:


Predictions stringent enough to question the observation of the isospin partner for which SELEX recorded a $5\sigma$-significant peak

with lifetime < 33 fs @90% C.L.
Discovery of the $\Xi_{cc}^{++}$ baryon

Dataset: 2016 data (Lumi: 1.7 fb$^{-1}$)

LHCb 13 TeV

$\Xi_{cc}^{++} \rightarrow \Lambda_c^- K^+ \pi^+ \pi^+ \downarrow p K \pi^+$

Candidates per 5 MeV/c$^2$

$m_{\text{cand}(\Xi_{cc}^{++})}$ (MeV/c$^2$)

Signal yield: 313 ± 33
Local significance: 12 $\sigma$

Mass measurement:

$$m_{\Xi_{cc}^{++}} = 3621.40 \pm 0.70(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+) \text{ MeV}/c^2$$

Very different from the SELEX candidate for $\Xi_{cc}^+$:

$$m_{\text{LHCb}}(\Xi_{cc}^{++}) - m_{\text{SELEX}}(\Xi_{cc}^+) = \mathcal{O}(100 \, \text{MeV}/c^2)$$

$\Xi_{cc}$ flight distance significance inconsistent with an em/strong decay!
Many states still lack of unambiguous interpretation

The study of the heavy flavours, of raising interest since the start of the B-factories in 2000`s, has opened new scenarios for hadron spectroscopy, indentifying unambiguously exotic states not fitting the meson (q̅q) and baryon (qqq) pictures.

charmonium-like only!
Tetraquark interpretations

The interpretation of exotic states as dynamic effects due to the opening of a threshold (cusp) is not favoured by the observation of a very resonant-like phase movement for example in the Z(4430) analysis, but still alive.
**Hadron machines opened to new spectroscopies**

**Excited $\Omega_c$ states**
Incredibly narrow (possibly exotics?)

PRL 118, 182001 (2017)

*prompt production*

**Excited $B_c$ states**
PRL 113 (21) 212004
(not confirmed by LHCb, JHEP (2018) 2018 138)

*prompt production*

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**Discovery of the pentaquark**
First exotic baryon

PRL 115 (2015) 072001

*production from $\Lambda_b$ decay*
Open-flavoured exotic states: X(5568)

In 2016, the D0 Collaboration reports the evidence of the first open-flavoured exotic state composed of four different flavours (buds) and decaying as

\[ X(5568) \rightarrow B_s \pi^+ \]

Value measured for mass and width:

\[ m = 5567.8 \pm 2.9 \text{ (stat)}^{+0.9}_{-1.9} \text{ (syst)} \text{ MeV/c}^2 \]

\[ \Gamma = 21.9 \pm 6.4 \text{ (stat)}^{+5.0}_{-2.5} \text{ (syst)} \text{ MeV/c}^2 \]

Statistical significance: 4.8 \( \sigma \)
No sign of $X(5568)$ at the LHC

No sign at CDF either

Further evidence at D0 using SL decays of $B_s$
Theoretical perspectives

Even if there were hints that the X(5568) poorly fits other resonances, the theoretical framework is definitely not as mature as for conventional hadrons, and much less predictive.

The nature of the binding of the exotic hadrons is still debated. Consequently predictions on new states (and interpretation of reported bumps) is not reliable.

Open heavy flavour exotics is the new frontier
Search for open-flavour pentaquarks at LHCb [NEW]

Search for long-lived pentaquarks, flying in the detector with a lifetime of the same order as for other $b$-hadrons.

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<tr>
<td>I</td>
<td>$bduud$</td>
<td>$P_{B^{0}}^{+} \rightarrow J/\psi K^{+} \pi^{-} p$</td>
<td>4668–6220 MeV</td>
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<td>IV</td>
<td>$\bar{b}suud$</td>
<td>$P_{B_{s}^{0}}^{+} \rightarrow J/\psi \phi p$</td>
<td>5055–6305 MeV</td>
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Nothing is observed,
Production measurements as probe of exotic hadrons

Production measurements disfavour the pure molecular interpretation of the $X(3872)$: the $p_T$ distribution presents a much harder component than other molecules.

But, the interpretation as a superposition of a molecular and $\chi_{c1}^{(2P)}$ state is still open.

The $X(3872)$ would be produced in high-energy $pp$ collisions through its $\chi_{c1}^{(2P)}$ component.

If this is the case, the relative production of $X(3872)$ and $\chi_{c1}^{(1P)}$ should be independent of the momentum.

Production measurements are relevant to establish the nature of exotic hadrons.
Production measurement of the $\chi_c$ states

Prompt production of $\chi_c$ is challenging to measure because of the overlap of the peaks and to the important background level.

The observation of the high-efficiency high-purity $\chi_{c1,c2} \rightarrow J/\psi \mu \mu$ final state will allow improved production measurements, especially at low $p_T$. 

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April 11
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Dalitz decay $\chi_{cJ} \rightarrow J/\psi \mu^+ \mu$

The very low Q-value of the decay and the absence of Bremsstrahlung of the soft muons allow extraordinary resolution.

$$m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09 \text{ MeV},$$

$$m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11 \text{ MeV},$$

$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03 \text{ MeV},$$

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20 \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ MeV}.$$
Perspectives for the future upgrades
Spectroscopy with the upgraded LHCb

LHCb is going through an upgrade phase which will allow higher integrated luminosity by processing with the software trigger all events at the bunch-crossing energy of 40 MHz.

**Teasers:** hadron identification will be available at the trigger level: great increase of trigger efficiency on prompt decays to purely hadronic final states including of low $p_T$ particles.

**Challenges:** a new computing approach to data-analysis is needed to move as much as possible to exclusive selections.
Full exploitation of the $b$ decays to multi-open charm

- Direct searches of long-lived, heavy-flavoured exotic states
  - higher production cross-section than Belle-2
  - higher efficiency on hadron-only final states than the current LHCb version

- Exotics with hidden beauty
  - Multiquark in the beauty sector, above the $B \bar{B}$ threshold might be difficult to produce at B-factories and escape direct searches in the hadronic environment.
  - Searches through clean, but highly suppressed decay modes ($\gamma\mu\mu$) might be the way to go

- Full exploitation of $b$ decays to multi-open charm final states
  - e.g. $B^0_s \rightarrow D_s^0 D^0 K [\pi ...]$
  - Can explore states unaccessible at B-factories
  - Much higher statistics than the current LHCb will enable full amplitude analyses
Conclusion

Heavy flavour spectroscopy is not stamp collection.

There is a lot we can learn on QCD studying the exotic states, for which a coherent picture concerning:

- their **masses** and **width**
- their **production**
- their **decay modes**

requires inputs from several experiments.

LHCb will certainly play a key role on the subject in the coming years

- analysing the collected data in Run-1 and Run-2,
- through its upgrade to increase the integrated luminosity by a factor five
- proposing a future Phase-II upgrade [CERN-LHCC-2017-003]

Exciting times ahead.
Backup slides
Further LHCb upgrades

The LHCb Collaboration has recently submitted a LoI to the LHCC for a Phase-II upgrade (starting operations in LHC Run 5).

Such an upgrade would allow to collect up to 300 fb$^{-1}$ of data preserving good hadron identification and vertex resolution capabilities.

This would allow, among many other things, the exploitation of $B_c^-$ decays to three charm hadrons to investigate doubly-charmed final tetraquarks.

This would be particularly interesting for the case of the $T_s^{++}$ ($cc\bar{s}\bar{d}$) because a doubly charged state wouldn’t be a molecular one [PRD 88, 054029 (2013)].
Upper limit on b-flavoured pentaquarks