Colors of QCD: Hadron spectroscopy and exotic states at LHCb

Mikhail Mikhasenko
on behalf of LHCb Collaboration

CERN, Switzerland

June 5th, 2019
Perspective of QCD – large white space with little colorful objects

Proton $\sim 1$ fm
Perspective of QCD – large white space with little colorful objects

\[ \sim 1 \text{ fm} \]

proton
Perspective of QCD – large white space with little colorful objects

simple hadrons (baryons, mesons)

proton

neutron

hardonic molecules (atoms)

deuteron

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Search for the new type of matter

How to search for color physics with colorless environment?

LHCb

Modification of a plot from [INT. J. MOD. PHYS. A 30, 1530022]
Several stories to tell
Run-II data, just-released results

1. Double heavy
2. Pentaquarks
3. Near-threshold $D\bar{D}$ spectroscopy
Excitation of the double-heavy double-flavor meson $B_c$
Double-flavor meson $B_c$ and its excitations

**$B_c$ spectroscopy**
- (CDF1998) first observation of $B_c$
- (ATLAS2014) first observation of excited $B_c(2S)$
- (CMS2019) resolving two radial-excited states, $(\uparrow\downarrow)^*$ and $(\uparrow\uparrow)^*$
- (LHCb2019) confirmation of two states

- Clean $B_c$ sample, $3785 \pm 73$ ev.
- Large combinatorial background
Double-flavor meson $B_c$ and its excitations

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Pentaquark states $P_c$

Hadronic molecules

\[
\bar{D}^0 \quad \leftrightarrow \quad \Sigma_c^+
\]
Almost-stable hadrons

Lifetime measurements of $\Lambda_b^0$ and $B^0$

- Identification of displaced vertex

$$\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-$$

$$B^0 \rightarrow \pi K^-\mu^+\mu^-$$

- Similar decay chains

$$B^0 \rightarrow b\bar{u}W^+\bar{s}\bar{v}$$

$$\Lambda_b^0 \rightarrow u\bar{u}W^+\bar{s}\bar{v}$$

Yield / (0.3 ps)

$Y(t) \sim e^{-t/\tau}$

$\tau_{\Lambda_b^0}/\tau_B = 0.974 \pm 0.006 \pm 0.004$

$\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010$ ps
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$\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010$ ps,
Observation of $P_c(4450)$ and $P_c(4380)$,

\[ P_c(4450) \sim P_c(4380) \]

Amplitude analysis of 2015

Helicity formalism, isobar model, 6-dim. analysis.

$A_{uu}^{\Lambda_b}$

$\Lambda_b, \Lambda \rightarrow J/\psi, \mu$

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$\Lambda_b, \Lambda \rightarrow J/\psi, \mu$

$\Rightarrow$ first ever observation of 5-quark states $[uudc\bar{c}]$.
Adding more data with Run-II (2017,2018)

PRL 115, 072001 (2015)

LHCb data total fit background

P_c(4450) P_c(4380) P_c(1405) Λ(1520) Λ(1600) Λ’s

Gain in statistics × 9 = 246k events

Luminosity: 3 fb⁻¹ ⊕ 6 fb⁻¹,

Cross section × 2:
7 TeV → 13 TeV,

Selection efficiency × 2.

Amplitude Analysis

same AA gives consistent results, but unacceptable quality.

▶ Narrow peaks in J/ψ p

▶ Lineshape of Λ.

New features

Peak at 4.312 GeV becomes significant
Peak at 4.457 GeV got resolved in two!

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Hadrons at LHCb

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Adding more data with Run-II (2017, 2018)

Gain in statistics \( \times 9 \)

- Luminosity: \( 3 \text{ fb}^{-1} \oplus 6 \text{ fb}^{-1} \),
- Cross section \( \times 2 \):
  - 7 TeV \( \rightarrow \) 13 TeV,
- Selection efficiency \( \times 2 \).

Amplitude Analysis

- same AA gives consistent results,
- but unacceptable quality.
  - Narrow peaks in \( J/\psi p \)
  - Lineshape of \( \Lambda \).

\( \sqrt{s} > 2 \text{ GeV} \)
Adding more data with Run-II (2017, 2018)

Gain in statistics $\times 9$

- 26$k$ events $\Rightarrow$ 246$k$ events
  - Luminosity: $3 \text{ fb}^{-1} \oplus 6 \text{ fb}^{-1}$,
  - Cross section $\times 2$:
    - 7 TeV $\rightarrow$ 13 TeV,
  - Selection efficiency $\times 2$.

Amplitude Analysis

- same AA gives consistent results,
- but unacceptable quality.
  - Narrow peaks in $J/\psi p$
  - Lineshape of $\Lambda$.

New features

- Peak at 4.312 GeV becomes significant
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Extracting resonance properties

[arXiv:1904.03947]

1-dim. fit and extensive systematic studies:

- Three different projection methods
- Several background parametrization
- Interference effects
- Procedure is validated using 6-dim. MC

Mass and width of the peaks

<table>
<thead>
<tr>
<th>State</th>
<th>M [ MeV ]</th>
<th>Γ [ MeV ]</th>
<th>(95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>$4311.9 \pm 0.7^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
<td>&lt; 27</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>$4440.3 \pm 1.3^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
<td>&lt; 49</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>$4457.3 \pm 0.6^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>$P_c(4380)^+$</td>
<td>inconclusive with 1-dim. analysis</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Hadrons at LHCb

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Plausible interpretation of $P_c$ states

hadronic molecule

tightly-bound pentaquark

Many theoretical predictions of $P_c$ binding published before 2015 (see backup).

Ampl.-Ana. is needed to check $J^P$.

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Hadrons at LHCb

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Plausible interpretation of $P_c$ states

$\Sigma_c \overline{D}$ hadronic molecules

- Narrow width
  - Problematic in tightly-bound picture
  - Problematic in the rescattering picture
- Number of states (HQSS):
  \[
  \begin{align*}
  \Sigma_c^+ \overline{D}^0 &\rightarrow 1/2^+ \otimes 0^- \quad S\text{-wave} \quad J^P : 1/2^- \\
  \Sigma_c^+ \overline{D}^{*0} &\rightarrow 1/2^+ \otimes 1^- \quad S\text{-wave} \quad J^P : 1/2^- \oplus 3/2^- \\
  \Sigma_c^{*+} \overline{D}^{*0} &\rightarrow 3/2^+ \otimes 1^- \quad S\text{-wave} \quad J^P : 1/2^- \oplus 3/2^- \oplus 5/2^-
  \end{align*}
\]

Many theoretical predictions of $\Sigma_c D$ binding published before 2015 (see backup).

Ampl.-Ana. is needed to check $J^P$.

Look forward for Run-III
New narrow charmonium state $X(3842)$
$D\bar{D}$ spectrum with $9\text{ fb}^{-1}$ (Run-I+Run-II)

[arXiv:1903.12240]

- displaced vertices
- $80 - 90\%$ purity
$D\bar{D}$ spectrum with 9 fb$^{-1}$ (Run-I+Run-II) [arXiv:1903.12240]

- displaced vertices
- 80 – 90 % purity

Candidates/(5 MeV /c$^2$)$^2$

\[ m_{K^+\pi^-} \Rightarrow D^0 \bar{D}^0 \not\pi(\not\gamma) \]

$\chi_c(3872) \rightarrow D^0 \bar{D}^0 \not\pi(\not\gamma)$

$\psi(3770)$

$\psi(3842)$

$\chi_c(3930)$

$M_{\chi_c} \approx 3.879 \text{ GeV}$

$J^P = 3^-$

New state is consistent with $D_3^3$ ($\psi_3$), $J^P = 3^-$.
$D\bar{D}$ spectrum with 9 fb$^{-1}$ (Run-I+Run-II) [arXiv:1903.12240]

- displaced vertices
- 80 – 90% purity

New state is consistent with $1^3 D_3 (\psi_3(1D)), J^{PC} = 3^{--}.$
Conclusion

Exciting news on the color physics from LHCb:

- Confirmation of the $B_c(2S)$ and $B_c^*(2S)$ states,
- Groundbreaking update on pentaquarks,
- Amazing $D\bar{D}$ spectrum with new charmonium state, $\psi_3(3842)$.
Conclusion

Exciting news on the color physics from LHCb:

- Confirmation of the $B_c(2S)$ and $B_c^*(2S)$ states,
- Groundbreaking update on pentaquarks,
- Amazing $D\bar{D}$ spectrum with new charmonium state, $\psi_3(3842)$.

Not shown:

- new decay channel of $\Xi_{cc}$, $\Xi_{cc} \to \pi^+\Xi_c$
- first observation of the $\Lambda_b \to \Lambda\gamma$
- Observation of $B_{(s)}^0 \to J/\psi p\bar{p}$
- Observation of $\Xi_c \to \phi p$
- Many more, see complete list [here].
Thank you for the attention

backup slides follow...
Impact of new measurements on charmonium

Great interest in community

- $\psi_3(3842)$ is just seen on lattice, [arXiv:1905.03506v1]
$B_c$ spectrum in relativistic quark model

[St. Godfrey PRD 70 054017 (2004)]
$P_c$ interpretations

- $\Sigma_c D$ binding (published before 2015)
  - Z.-C. Yang et al., Chin. Phys. C36 (2012) 6

- Dynamically generated (see references in arXiv:1904.03947)

- Heavy-quark-spin-symmetry (HQSS) consequences
  - Ming-Zhu Liu et al., arXiv:1903.11560
  - C.W. Xiao et al., arXiv:1904.01296

- $P_c(4312)$ pole position and molecular binding,

- Tightly-bound pentaquark models (see references in arXiv:1904.03947)
Rescattering interpretation

Triangle singularity [see Appendix of arXiv:1904.03947]

- There are many thresholds around $P_c$ peaks
  - $\Lambda_c \bar{D}^0$, $\Sigma_c \bar{D}^0$, $\chi_c N^*$ with different exchanges as suggested in [Guo et al.(PRD92 (2015) 071502), U.-G. Meißner et al. (PLB751 (2015) 59), X.-H. Liu et al. (PLB757 (2016) 231), MM (arXiv:1507.06552)]
  
- An appropriate Triangle Singularity can be found for all peaks
  
- BUT, as soon as width of exchange particle is taken into account

$\Rightarrow$ no acceptable description in rescattering picture have been found
Investigation on molecular picture


Scattering-length approximation

$$T_{ij}^{-1} = m_{ij} - ik_i \delta_{ij},$$

$$k_i = \sqrt{s - s_i}$$

Two channels: $\Sigma_c^+ \bar{D}^0$ and $J/\psi p$.

Intensity

$$I(s) = \rho(s)(|T_{11}(s)p(s)|^2 + b(s)),$$

- $p(s)$ and $b(s)$ are the first order polynomials.
- $\rho(s)$ is a phase-space factor.

Consistent with the virtual state.