Hadron spectroscopy and hadron-hadron interactions

Paolo Gandini
INFN - Sezione di Milano

On behalf of the LHCb collaboration + results from CMS, ATLAS and ALICE
Outline

• This talk was originally assigned to Liupan An (LHCb), but unfortunately she was not able to attend
• This is the outline of the talk → as usual the shopping list is too long → I will cover only a small subset
• Hope to make justice to the good work by all the experiments in this rich field!

**LHCb**

• Observation of new charmonium(-like) states in $B^+ \rightarrow D^{*+}D^{*-}K^+$ decays
  PRELIMINARY: PAPER-2023-047 about to be submitted to arXiv

• Observation of exotic $J/\psi \phi$ resonances in CEP collisions
  PRELIMINARY: PAPER-2023-043 in preparation

• Search for $P_c$ in open charm modes
  arXiv: 2404.07131 submitted to PRD

**CMS**

• $\Xi_b \rightarrow \Psi(2S) \Xi$ & $\Xi_b^* \rightarrow \Xi_b \pi$
  Accepted for publication in Phys. Rev. D

• $f_0(980)$ hadron in proton-lead collisions and evidence for its quark-antiquark composition
  Submitted to Nature Physics

**ALICE**

• Observation of abnormal suppression of $f_0(980)$ production in p-Pb collisions at $\sqrt{s} = 5.02$ TeV
  https://alice-publications.web.cern.ch/node/10258

• Exploring the strong interaction of three-body systems at the LHC
  https://alice-publications.web.cern.ch/node/9595
  arXiv:2308.16120
Parallel sessions

More results and detailed presentations can be found in today’s parallel session
Dedicated talks for each experiment + interesting theoretical insights

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<td>Paolo Gandini</td>
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<td>The Pentaquark Spectrum from Fermi Statistics</td>
<td>Antonio Polosa</td>
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Introduction: QCD

- **QCD dilemma**: understanding the non-perturbative property of QCD at low-energy scale
- **Hadron spectroscopy**: a main tool to probe QCD at low-energy regime
- **Heavy quarks bring advances both experimentally and theoretically**
New hadrons at LHC

- Spectroscopy is a super-active field at LHC and all the experiments are contributing!
- So far 72 hadrons have been discovered at the LHC, of which 64 by LHCb
- The list is growing... All sectors represented
New hadrons at LHC

- In 2024, no new hadrons yet!
- But summer conferences have just started...
- And Run3 data taking is in full steam...

LHCb collaboration, P. Koppenburg, *List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates*. 

patrick.koppenburg@cern.ch 2023-08-16
New hadrons at LHC

SPOILER ALERT
3 new states

75 new hadrons at the LHC

Patrick Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.
Selected results by LHCb
Observation of new charmonium(-like) states in $B^+ \rightarrow D^{*\pm} D^{\mp} K^+$

$B^+ \rightarrow D^{*+} D^- K^+$  \hspace{1cm}  $B^+ \rightarrow D^{*-} D^+ K^+$

- A simultaneous amplitude fit performed to two channels
- Include contributions from resonances decaying to $D^+ D^-\text{ and } D^{*+} D^- \text{ (states linked by C parity)}$
- Determine the C parity of any new states

Preliminary PAPER-2023-047 to be submitted to arXiv
Observation of new charmonium(-like) states in $B^+ \rightarrow D^{*\pm}D^{\mp}K^+$

Figure 3: Difference between the $M(D^*D)$ distributions of the two channels ($B^+ \rightarrow D^{*+}D^-K^+$ and $B^+ \rightarrow D^{*-}D^+K^+$). Only interference between states with the same $J^P$ but different $C$-parities, and reflections from $T_{3S0,1}(2900)^0$ resonances, have significant contributions. The reference fit where $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$ are not included is shown as green dashed line.
Observation of new charmonium(-like) states in $B^+ \rightarrow D^{*\pm} D^{\mp} K^+$

• Four charmonium(-like) states are observed: at least 3 are new
• Existence of 2 tetraquark resonances in $D^-K^+$ confirmed (different channel, already observed $B^+ \rightarrow D^+D^-K^+$)

$\eta_c(3945)$, $h_c(4000)$, $\chi_c1(4010)$ and $h_c(4300)$ $J^{PC}$ equal to 0$^{--}$, 1$^{+-}$, 1$^{++}$ and 1$^{+-}$

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<td>$T_{oo}(2900)^0$ mass (MeV)</td>
<td>2914 ± 11 ± 15</td>
<td>2866 ± 7</td>
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<td>$T_{oo}(2900)^0$ width (MeV)</td>
<td>128 ± 22 ± 23</td>
<td>57 ± 13</td>
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<tr>
<td>$T_{oo}(2900)^0$ mass (MeV)</td>
<td>2887 ± 8 ± 6</td>
<td>2904 ± 5</td>
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<tr>
<td>$T_{oo}(2900)^0$ width (MeV)</td>
<td>92 ± 16 ± 16</td>
<td>110 ± 12</td>
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<tr>
<td>$B(B^+ \rightarrow T_{oo}(2900)^0 D^{(*)+})$</td>
<td>$(4.5^{+0.9}<em>{-0.8}^{+1.0}</em>{-1.0} \pm 0.4) \times 10^{-5}$</td>
<td>$(1.2 \pm 0.5) \times 10^{-5}$</td>
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<tr>
<td>$B(B^+ \rightarrow T_{oo}(2900)^0 D^{(*)+})$</td>
<td>$(3.8^{+0.7}<em>{-0.6}^{+1.0}</em>{-1.0} \pm 0.3) \times 10^{-5}$</td>
<td>$(6.7 \pm 2.3) \times 10^{-5}$</td>
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<tr>
<td>$B(B^+ \rightarrow T_{oo}(2900)^0 D^{(*)+})$</td>
<td>$1.17 \pm 0.31 \pm 0.48$</td>
<td>$0.18 \pm 0.05$</td>
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Observation of exotic $J/\psi \Phi$ resonances in CEP

- Central Exclusive Production can be done at LHCb → What do we look for?
- $pp \rightarrow p + X + p$ (rapidity gaps and protons intact)
- Colourless objects in QCD, Very low PT objects, Clean experimental environment
- Rich Physics: Photon-Pomeron, Double-Pomeron, Photoproduction, Glueballs, Exotica

- Experimentally clean even @LHC
- Spin-parity option narrowed down
- Much smaller rate
Observation of exotic J/ψΦ resonances in CEP

Tracks = 4

Tracks > 4

Preliminary

Preliminary

N = 989
purity = (93.0 ± 0.5)%
Observation of exotic $J/\psi\Phi$ resonances in CEP

Mass & width measurement  
slightly higher mass of $X(4500)$

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<th>Parameter (MeV)</th>
<th>This Letter</th>
<th>Ref. [12]</th>
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<td>$M_{\chi_{c1}(4274)}$</td>
<td>4298 ± 6 ± 9</td>
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<td>$\Gamma_{\chi_{c1}(4274)}$</td>
<td>92 ± 22 ± 57</td>
<td>53 ± 5 ± 5</td>
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<td>$M_{\chi_{c0}(4500)}$</td>
<td>4512.5 ± 6.2 ± 3.0</td>
<td>4474 ± 3 ± 3</td>
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<td>$\Gamma_{\chi_{c0}(4500)}$</td>
<td>65.2 ± 20 ± 32</td>
<td>77 ± 6 ± 10</td>
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</table>

Cross-section measurement

- $\sigma_{\chi_{c1}(4140)} \times B_{\text{eff}}^{\chi_{c1}(4140)} = (0.85^{+0.16}_{-0.16} ± 0.30) \text{ pb}$,
- $\sigma_{\chi_{c1}(4274)} \times B_{\text{eff}}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} ± 0.18) \text{ pb}$,
- $\sigma_{\chi_{c0}(4500)} \times B_{\text{eff}}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} ± 0.07) \text{ pb}$,
- $\sigma_{\chi_{c1}(4685) + \chi_{c0}(4700)} \times B_{\text{eff}}^{\chi_{c1}(4685) + \chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} ± 0.06) \text{ pb}$,
- $\sigma_{NR} \times B_{\text{eff}}^{NR} = (0.46^{+0.25}_{-0.19} ± 0.21) \text{ pb}$,
Search for Pc in open charm modes

- Inclusive search performed using 5.7 fb\(^{-1}\) data from 2016-2018
- Reconstruction of several different modes & combinations:
  - $\Lambda_c^+ \rightarrow pK^−\pi^+, D^- \rightarrow K^+\pi^-\pi^−, D^0 \rightarrow K\pi$
  - $\Sigma_c^{++(0)} \rightarrow \Lambda_c^+\pi^+(-), D^{(*-)} \rightarrow D^{(-0)}\pi^−$

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<tr>
<th>Hadron 1</th>
<th>Hadron 2</th>
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<th>$Y$</th>
<th>C</th>
<th>Limit Set</th>
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10 modes too statistically limited to set up upper limits
Search for $P_c$ in open charm modes

- Every combination investigated (complete list in the paper)
- No significant signal found
- Upper Limits set for all combinations

$$R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \rightarrow \frac{\sigma(P_c) \times B(P_c \rightarrow \Lambda_c^+ D(\pi)) \times B(D)}{\sigma(\Lambda_c^+)}$$

<table>
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<th>Decay Mode</th>
<th>Width (MeV/$c^2$)</th>
<th>Significance ($\sigma$) Local</th>
<th>Significance ($\sigma$) Corrected</th>
<th>Q-value (MeV/$c^2$)</th>
<th>Signal Yield</th>
<th>UL ($\times 10^{-3}$) 90% CL</th>
<th>95% CL</th>
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<td>$\Lambda_c^+ \pi^+ D^-$</td>
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<td>245</td>
<td>115.0 ± 28.5</td>
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<td>3.40</td>
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</table>

- Pseudo-experiments indicate average number of channels fluctuate above $3\sigma$ is $7 \pm 5$, so we conclude the results are consistent with background-only
- Known $P_c$ states tested and yields all agree with zero

$P_c(4312)^+ M = 4311.9 \text{ MeV}, \Gamma = 10 \text{ MeV}$
$P_c(4440)^+ M = 4440 \text{ MeV}, \Gamma = 21 \text{ MeV}$
$P_c(4457)^+ M = 4457.3 \text{ MeV}, \Gamma = 6.4 \text{ MeV}$

$ccuud$

$M \sim 4520.69 \text{ MeV}$
Selected results by

CMS
\[ \Xi_b \rightarrow \Psi(2S)\Xi \text{ and } \Xi_b^* \rightarrow \Xi_b \pi \]

- Integrated luminosity of 140 fb\(^{-1}\)
- Muon final states and different final states (different topologies)
- Several measurements in one paper (BFs, Production and competitive mass measure)

Thus, we can conclude that about a third of the \(\Xi_b^-\) baryons are produced from \(\Xi_b^*\) decays
f_0(980) hadron in p-Pb collisions

• f_0(980) hadron discovered half a century ago, but...
• Its quark content has not been settled:
  • Ordinary meson q\bar{q} ?
  • Tetraquark q\bar{q}q\bar{q} ?
  • Exotic state ?
  • Kaon-Antikaon K\bar{K} molecule ?
  • Glue q\bar{q}g hybrid ?

• Strong evidence that f_0(980) is an ordinary meson
• Inferred from scaling of elliptic anisotropies (v_2)
  with the number of constituent quarks (n_q)
• Empirically established using conventional hadrons
  in relativistic heavy ion collisions
• Other hypothesis on exotic nature ruled out

The argument of the function, KE_T/n_q, is related to the kinetic energy per constituent quark.
Selected results by ALICE
Suppression of $f_0(980)$ production in p-Pb collisions

- Similar study to CMS
- Nuclear modification factor $Q_{p\text{Pb}}$ of $f_0(980)$ measured in various multiplicity ranges
- A lot of interesting results:
  - $f_0(980)$ nuclear modification factor is lower than unity: suppression
  - For $p_T<4\text{GeV}$
    - Lower than charged hadrons
    - Difference increases with multiplicity
    - Suppression of the $f_0(980)/\pi$ and $f_0(980)/K^*(892)^0$ depends on $p_T$
- The results on the particle yield ratios may help to understand the nature of the internal structure of $f_0(980)$ particle
- No enhancement at intermediate $p_T$ hints at 2-quark vs 4-quark structure

$Q_{p\text{Pb}} = \frac{d^2N^{p\text{Pb}}_{f_0(980)}}{\langle T_{p\text{Pb}} \rangle d^2\sigma_{f_0(980)}^{p\text{Pb}}/dp_Tdy}$

Nuclear modification factor adapted to p-Pb collisions

Clear suppression of $f_0$ nuclear modification factor production suggests impact of final state scattering and meson like structure
Strong interaction of 3-body systems at the LHC

- Measure the correlation functions of 3-body systems with femtoscopic techniques

Proton-deuteron correlations
Distance comparable to the proton radius

$p - p - p/\bar{p}$ and $p - p - \Lambda$

Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data
(Av18+UIX full)

published results from Run 2
**Strong interaction of 3-body systems at the LHC**

- Measure the correlation functions of 3-body systems with femtoscopy techniques

Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data

(Av18+UIX full)

- First result for Run3
- Preliminaries results from RUN3
- Improvement in term of uncertainties
- Message is confirmed
Conclusions

- LHC is a wonderful playground for hadrons physics!
- Unprecedented & probably unique opportunity for these type of studies
- Upgrade era started: higher statistics + access to states with lower production rates
- Summer conferences are just starting → plenty of new results expected!

Image courtesy of CERN
Backup Slides