Exotic Hadrons at the LHC
on behalf of LHCb, CMS and ATLAS collaborations

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Outline

- Current landscape of hadron spectroscopy at the LHC
- Recap on exotic hadrons
- Recent results from the LHC experiments
68 new hadrons at the LHC

Patrick Koppenburg

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23 new exotic hadrons at the LHC
The nature of exotic hadrons

Tightly bound (compact) states

Molecular states

Other states

Glueball

Hybrid

Soeren Lange / CERN graphics
Recent results from the LHC experiments

- Observation of $T_{c\bar{s}0}^a(2900)^0$ and $T_{c\bar{s}0}^a(2900)^{++}$ tetraquark states [LHCb-PAPER-2022-027]
- Observation of near-threshold enhancement ($X(3960)$ state) [arXiv:2210.15153]
- Observation of $T_{\psi s1}^\theta(4000)^0$ tetraquark state [LHCb-PAPER-2022-040]
- Evidence of $T_{cc\bar{c}\bar{c}}$ tetraquark state [ATLAS-CONF-2022-040]
- Evidence of $T_{cc\bar{c}\bar{c}}$ tetraquark state [CMS-PAS-BPH-21-003]
- Evidence of $\chi_{c1}(3872)$ tetraquark state [arXiv:2102.13048]
- Observation of $P_{\psi s}^\Lambda(4338)^0$ pentaquark state [arXiv:2210.10346]
Open-charm tetraquarks: $T_{c\bar{s}0}(2900)^0$ and $T_{c\bar{s}0}(2900)^{++}$

Amplitude analysis of $B^0 \to \bar{D}^0 D^+_s \pi^-$ and $B^+ \to D^- D^+_s \pi^+$ decays

- Speculations as to nature of the states [arXiv:2204.02649]
- Predictions for doubly charged open-charm tetraquark and its neutral partner arose from these observations
- Thin horizontal band is visible in Dalitz plots for both channels
- Quark content: $[c\bar{s}u\bar{d}]$ and $[c\bar{s}\bar{u}d]$
- $T_{c\bar{s}0}(2900)^{++}$ is the first doubly charged tetraquark observed
- Unbinned maximum likelihood fit is performed
  - Parameters are shared between the two channels
  - Amplitude constructed using helicity formalism
  - Baseline fit: only $D^{**}$ resonances allowed
  - Signal fit: $D^+_s \pi^-$ or $D^+_s \pi^+$ resonance added
  - Fit performed implying isospin symmetry

[LHCb-PAPER-2022-026]
[LHCb-PAPER-2022-027]
Open-charm tetraquarks: $T_{c\bar{s}0}^a(2900)^0$ and $T_{c\bar{s}0}^a(2900)^{++}$ LHCb

- Baseline fit (upper row) fails to describe $m(D_s^+\pi^0)$ and $m(D_s^+\pi^-)$ spectra well
- Data is well described by introducing $J^P = 0^+$ $T_{c\bar{s}0}^a(2900)$ states
- Significance: $> 9\sigma$
- $J^P = 0^+$ favored over other spin-parity assignments by $7.5\sigma$
- Mass and width:
  
  $M = 2.908 \pm 0.011 \pm 0.020$ GeV
  
  $\Gamma = 0.136 \pm 0.023 \pm 0.011$ GeV

Open questions:

$\rightsquigarrow T_{c\bar{s}0}^a(2900)$ inner structure

$\rightsquigarrow$ Molecular / Compact?

[LHCb-PAPER-2022-026]
[LHCb-PAPER-2022-027]
Hidden-charm hidden-strangeness tetraquark: \( X(3960) \) LHCb

First observation of the \( B^+ \to D^+_s D^-_s K^+ \) decay

- Near threshold structure in \( D^+_s D^-_s \) observed
- Quark content: \( [c \bar{c} s \bar{s}] \)
- Fit with \( J^P = 0^{++} \) state \( X(3960) \) described the data well (Flatte, BW)
- \( X_0(4140) \) describes the dip at 4.14 GeV through interference - could be a new \( J^P = 0^{++} \) resonance or a \( J/\psi \phi \) coupled channel effect
- There is no obvious candidate within conventional charmonium multiplets for \( X(3960) \) or \( \chi c_0(3930) \) assignment

\[
M = 3.956 \pm 0.005 \pm 0.010 \text{ GeV} \\
\Gamma = 0.043 \pm 0.013 \pm 0.008 \text{ GeV}
\]
Hidden-charm with strangeness tetraquark: $T_{\psi s1}^{\theta}(4000)^0$

Evidence of a $J/\psi K_S^0$ structure in $B^0 \rightarrow J/\psi \phi K_S^0$ decays at LHCb

- Amplitude analysis with simultaneous fits to $B^+ \rightarrow J/\psi \phi K^+$ and $B^0 \rightarrow J/\psi \phi K_S^0$ is performed
- Structure in $J/\psi K_S^0$ established with 4$\sigma$ significance
- This new state should be an isospin partner of $T_{\psi s1}^{\theta}(4000)^+$, observed in $B^+ \rightarrow J/\psi \phi K^+$ decays
- Default fit model involves nine $K^*$, seven $X$ states, two $T_{\psi s1}^{\theta}$ and one $J/\psi \phi$ non-resonant component
- Quark content: $[c\bar{c}u\bar{s}]$
- Compact [arXiv:2103.08331]

$$M = 3.991^{+0.0117+0.0085}_{-0.0104-0.0167} \text{ GeV}$$

$$\Gamma = 0.1048^{+0.0293+0.0171}_{-0.0253-0.0233} \text{ GeV}$$

[LHCb-PAPER-2022-040]
Tetraquarks: $\chi_{c1}(3872)$

Evidence for $\chi_{c1}(3872)$ in PbPb collisions and studies of its prompt production at $\sqrt{s_{NN}} = 5.02$ TeV

- $\chi_{c1}(3872)$ has a long history: Belle, electron-positron, hadron colliders, CDF, LHCb
- Analysis in PbPb collisions can help to understand the nature of this state
- $\chi_{c1}(3872)$ reconstructed in its decay to $J/\psi\pi^+\pi^-$
- CMS uses two different datasets - inclusive and B-enriched. Excess visible in both.
- Ratio of yields of the prompt $\chi_{c1}(3872)$ to $\Psi(2S)$ is found to be $\rho^{PbPb} = 1.08 \pm 0.49 \pm 0.52$
- Significance of inclusive $\chi_{c1}(3872)$ signal is 4.2 $\sigma$
- Ideas of the nature of this state: conventional charmonium, $D^*(2010)^0-D^0$ molecule, tetraquark or admixture of different states

[arXiv:2102.13048]
Fully charm tetraquark: $T_{cc\bar{c}\bar{c}}$

Observation of an excess of di-charmonium events in the four-muon final state with the ATLAS detector

- First observed by LHCb in 2020 [SCIENCE BULLETIN 65 (2020) 1983]
- Confirmed by CMS and ATLAS with latest results
- Few thresholds opening up - rescattering effect not ruled out [DOI:2020.08.32]
- Channels $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi J/\psi \rightarrow 4\mu$ and $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\psi(2S) \rightarrow 4\mu$ are studied.
- A significant excess of events is observed in $di\cdotJ/\psi$ channel.
- In $J/\psi\psi(2S)$ channel, the significance of the signal is established at 4.6$\sigma$

[ATLAS-CONF-2022-040]
Fully charm tetraquark: \( T_{cc\bar{c}\bar{c}} \)

Observation of new structures in the \( J/\psi J/\psi \) mass spectrum in pp collisions at \( \sqrt{s} = 13 \) TeV

- Unbinned maximum likelihood fit is performed using signal models reported by LHCb and those chosen by CMS

- Three structures are identified in \( J/\psi J/\psi \) spectrum. \( X(6600) \), \( X(6900) \) and \( X(7300) \).

- Significance for \( X(6600) \) and \( X(6900) \) exceeds 5\( \sigma \). \( X(7300) \) is established at 4.1\( \sigma \) local significance.

- \( X(6900) \) previously reported by LHCb is confirmed

- These states could be from a family of P-wave radial excitations

[CMS-PAS-BPH-21-003]
First pentaquark with strangeness

Study of the $B^+ \rightarrow J/\psi\bar{\Lambda}p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV

- Limited sample studied $\sim 450$ events
- A deviation from phase space hypothesis was noticed
- This is a good channel for exotic hadron searches
- Focusing on narrow pentaquark states in $\Lambda J/\psi$ and $\Lambda p$
- Molecular pentaquarks predicted close to $\Sigma_c D^*0$ and $\Xi_c D^*0$ thresholds

[arXiv:2207.07581]

[arXiv:1907.05461]
First pentaquark with strangeness: $P_{\psi s}^{\Lambda}(4338)^0$

Observation of a $J/\psi \Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \rightarrow J/\psi \Lambda \bar{p}$ decays

- First pentaquark candidate with strangeness observed
- $P_{\psi s}^{\Lambda}(4338)^0$ state observed close to $\Xi_c^+ D^-$ threshold (indicated by a dashed line) - could be an indication of a hadronic molecule
- $J^P = 1/2^-$ preferred
- Statistical significance $> 15\sigma$
- A study has been performed to see if the state could be outside of the phase space - the cutoff would be a lot sharper

\[
M = 4.338 \pm 0.0007 \pm 0.0004 \text{ GeV}
\]

\[
\Gamma = 0.007 \pm 0.0012 \pm 0.0013 \text{ GeV}
\]

[arXiv:2210.10346]
Summary and prospects

• Hadron spectroscopy at LHC allows to explore rich landscape of exotic hadron states
• Experimental results will allow to investigate QCD and hadron structure further
• With the start of Run3 of the LHC it will be possible to dive even deeper into hadron spectroscopy
• Triggering on hadrons in LHCb will allow studies of open-flavor states
• There are still many unanswered questions about the nature and production mechanisms of exotic hadrons
• Research in this area is very active and rewarding
End of talk

Thank You for your attention
Exotic hadrons in the quark model

We can dispense entirely with the basic baryon \( b \) if we assign to the triplet \( t \) the following properties: spin \( \frac{1}{2} \), \( z = -\frac{1}{3} \), and baryon number \( \frac{1}{3} \). We then refer to the members \( u^3 \), \( d^{-\frac{1}{3}} \), and \( s^{-\frac{2}{3}} \) of the triplet as "quarks". The members of the anti-triplet as anti-quarks \( \bar{q} \). Baryons can now be constructed from quarks by using the combinations \( (q_q q) \), \( (q_q q_q q) \), etc., while mesons are made out of \( (q_q q) \), \( (q_q q_q q) \), etc.

Murray Gell-Mann

Multiquark hadrons other than conventional meson and baryon states (containing 2 and 3 quarks respectively) are considered to be Exotic Hadrons.

In general, we would expect that baryons are built not only from the product of three aces, \( AAA \), but also from \( \overline{AAAA} \), \( \overline{AAAAAA} \), etc., where \( \overline{A} \) denotes an anti-ace. Similarly, mesons could be formed from \( \overline{A} \), \( \overline{AAA} \) etc. For the low mass mesons and baryons we will assume the simplest possibilities, \( \overline{AA} \) and \( AAA \), that is, "deuces and treys".

George Zweig
Modern hadron naming scheme

- Current naming scheme is not sufficient to unambiguously index exotic hadrons.
- There is no clear solution of how to name some of the states (and how to indicate their quantum numbers). (eg. \(cs\bar{u}\bar{d}\) or \(J/\psi\Sigma\) states)
- With the future prospects of more multi-quark states being discovered, a new naming scheme has to be introduced.
- Proposal of [Exotic hadron naming convention]

<table>
<thead>
<tr>
<th>Minimal quark content</th>
<th>Current name</th>
<th>(I^G), (J^{PC})</th>
<th>Proposed name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c\bar{c})</td>
<td>(\chi_{c1}(3872))</td>
<td>(I^G = 0^+, J^{PC} = 1^{++})</td>
<td>(\chi_{c1}(3872))</td>
</tr>
<tr>
<td>(c\bar{c}ud)</td>
<td>(Z_c(3900)^+)</td>
<td>(I^G = 1^+, J^P = 1^+)</td>
<td>(T_b(3900)^+)</td>
</tr>
<tr>
<td>(c\bar{c}d)</td>
<td>(Z_c(4100)^+)</td>
<td>(I^G = 1^-)</td>
<td>(T_b(4100)^+)</td>
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<tr>
<td>(c\bar{c}u\bar{d})</td>
<td>(Z_c(4430)^+)</td>
<td>(I^G = 1^+, J^P = 1^+)</td>
<td>(T_b(4430)^+)</td>
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<tr>
<td>(cc\bar{u}\bar{s})</td>
<td>(Z_{cs}(4000)^+)</td>
<td>(I = \frac{1}{2}, J^P = 1^+)</td>
<td>(T_{cs}(4000)^+)</td>
</tr>
<tr>
<td>(cc\bar{u}\bar{s})</td>
<td>(Z_{cs}(4220)^+)</td>
<td>(I = \frac{1}{2}, J^P = 1^+)</td>
<td>(T_{cs}(4220)^+)</td>
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<tr>
<td>(cc\bar{c})</td>
<td>(X_{c0}(6900))</td>
<td>(I^G = 0^+, J^{PC} = 0^++)</td>
<td>(T_{c0}(6900))</td>
</tr>
<tr>
<td>(cs\bar{u}\bar{d})</td>
<td>(X_{c0}(2900))</td>
<td>(J^P = 0^+)</td>
<td>(T_{c0}(2900)^0)</td>
</tr>
<tr>
<td>(cs\bar{u}\bar{d})</td>
<td>(X_{c1}(2900))</td>
<td>(J^P = 1^-)</td>
<td>(T_{c1}(2900)^0)</td>
</tr>
<tr>
<td>(cc\bar{c}\bar{d})</td>
<td>(T_{cc}(3875)^+)</td>
<td>(I^G = 1^+, J^P = 1^+)</td>
<td>(T_{cc}(3875)^+)</td>
</tr>
<tr>
<td>(bb\bar{u}\bar{d})</td>
<td>(Z_b(10610)^+)</td>
<td>(I^G = 1^+, J^P = 1^+)</td>
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<tr>
<td>(cc\bar{u}\bar{u})</td>
<td>(P_{c}(4312)^+)</td>
<td>(I = \frac{1}{2})</td>
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<td>(P_{c}(4459)^0)</td>
<td>(I = 0)</td>
<td>(P_{c}^A(4459)^0)</td>
</tr>
</tbody>
</table>

Work in Progress: Hadron naming tool

A. Morris [https://hadron-names.web.cern.ch/]