Exotic hadrons - what we thought we knew, what we think we know and what we can learn

Bohr lunch seminar
N. Skidmore

University of Manchester
What are exotic states?

The quark model allows for colour-neutral states beyond the well established \( q \bar{q} \) mesons and \( qqq \) baryons

- States such as \( qqqq\bar{q} \) (pentaquark), \( qq\bar{q}\bar{q} \) (tetraquark) are postulated in Gell-Mann’s and Zweig’s original quark model papers (1964) Phys.Lett. 8 (1964) 214-215, CERN-TH-412

We now refer to any hadron that does not follow \( q\bar{q}/qqq \) as exotic
What are exotic states?

We keep finding exotic candidates... especially in charm...

\[
Z^+(4430) \text{ charged, hidden-charmonium tetraquark } (c\bar{c}ud) \text{ at Belle in } \nonumber
\]
\[
B^0 \rightarrow \psi(2S)\pi^+K^- \text{ decays}
\]

\[
X(4274), X(4500)
\]

Four neutral X state tetraquarks in \( J/\psi \phi \)

at LHCb - minimal quark content \( cs\bar{c}\bar{s} \)

(no \( u/d \) light quark)  

PRL118, 022003(2017)

PRL100, 142001(2008)
What are exotic states?

We keep finding exotic candidates... especially in charm...

$Z_b$ bottomonium tetraquarks with $b\bar{b}ud$ decaying to upsilon resonances at Belle

$P_c$ state pentaquarks in $J/\psi p$ with minimal quark content $c\bar{c}uud$ at LHCb
1. What are exotic states?
2. How to search for exotic states
3. Brief history of exotic states
4. Pentaquarks - false starts
5. The LHCb pentaquarks
6. Model interpretations
7. How to determine the nature of the pentaquarks?
8. LHCb tetraquark discoveries in 2020
9. LHCb exotic prospects in Run 3
Enhancements in mass distributions or on the Dalitz plot

Short lived exotic states appear as resonances in decays

- Exotic resonances can be seen as enhancements in mass distributions or on the Dalitz plot

Breit Wigner PDF models decay of an isolated resonance in complex plane (derived from the propagator of an unstable particle)

Characteristic nature in complex plane

- Anticlockwise circular trajectory
- Phase change of $\pi/2$ across $m_0$

Pros: Easy measurement of mass/width of states - Breit Wigner model (incl. interference for states with same $J^P$)

Cons: Only works for narrow states. Fake 'bumps'
A full amplitude analysis

Exotic resonances interfere with known, conventional resonances creating complex phasespace distributions.

\[ X \rightarrow K^- \pi^+ \pi^- \text{ with } X \rightarrow K^{*0} (\rightarrow K^- \pi^+) \pi^- \text{ and } X \rightarrow f_0 (\rightarrow \pi^+ \pi^-) K^- \]

- **Pros**: Can determine mass/width and quantum numbers \( (J^P) \) of states
- **Cons**: Model dependent - requires the most assumptions about other states and is the most complex of procedures
Model independent approaches

Exotic resonances in a moments analysis contribute at orders greater than that achieved by conventional states

- Model independent approaches evaluate the null-hypothesis that only conventional states are needed to describe the data

Evidence for non-conventional states in

- **Pros:** Model independent - only require knowledge of the spins of conventional states
- **Cons:** Can only tell you that 'something' beyond the conventional state interpretation is required. Could be a kinematic effects
How do we know if a state is exotic?

It is difficult to claim something is definitely exotic.

A state is definitely exotic if quantum numbers are not allowed for $q\bar{q}'$ or $qq'q''$

- Most exotic states do not fulfill this condition.
- Requires amplitude analysis.

Normally we have the situation where

- Mass/width do not fit into predicted spectra - must know the predicted spectra well.
- Production/decay products incompatible with conventional hadrons.

Allows for possibility to be rescattering effects, experimental artifact...
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The hadron multiplets

Have been able to classify light hadrons well using the multiplet system

\( J^P = 0^- \) pseudoscalar meson multiplet

\( J^P = 1^- \) vector meson multiplet

\( J^P = \frac{1}{2}^+ \) baryon multiplet

\( J^P = \frac{3}{2}^+ \) baryon multiplet
The hadron multiplets

Even with the addition of Charm...

\[ J^P = 0^- \] pseudoscalar meson multiplet

\[ J^P = 1^- \] vector meson multiplet

\[ J^P = \frac{1}{2}^+ \] baryon multiplet

\[ J^P = \frac{3}{2}^+ \] baryon multiplet
The situation now...

Over 20 states in charm sector alone that do not fit into conventional hadron model

The quark model is over 50 years old, only in 2003 was the first exotic discovered

Why did it take so long to find exotic states?
- Light sector (<2.4 GeV) is crowded
- and the states are broad and so must be determined through complex partial wave analysis

Discoveries of heavy quark exotic candidates
arXiv:1610.04528
The importance of Charmonium

Why were exotics first discovered in the charm system?

The conventional states are well separated and narrow

- Decays of conventional $c\bar{c}$ states with masses below open charm threshold $m_{D\bar{D}}$ are OZI suppressed - states are narrow and well separated

Above the open charm threshold OZI allowed processes dominate - wider resonances but still significantly narrower than light quark states

OZI-suppressed - there is some time when all energy/momentum is carried by gluons - can cut through only gluon lines leaving initial state particles on left and final state particles on right
The importance of Charmonium

We know the predicted spectrum of conventional states well

- Charm is the lightest ‘heavy’ quark - $m_c \gg \Lambda_{QCD}$ - can determine charmonium spectrum with simple non-relativistic quantum-mechanical treatment

\[ V^{c\bar{c}}(r) = -\frac{k\alpha_s}{r} + br \]

- Using $V^{c\bar{c}}(r)$ with SE can predict entire $c\bar{c}$ spectrum below open charm threshold and some states above
The importance of Charmonium

- States well separated
- Remarkable agreement between theory and experiment particularly below open charm threshold
\( \chi_{c1}(3872) \) the first exotic

\( \chi_{c1}(3872) \) first observed in 2003 by Belle when studying \( B^+ \to K^+(\pi^+\pi^- J/\psi) \) decays

- Resonance in \( J/\psi \pi\pi \) spectrum seen as enhancement in mass distribution
- Mass measured as \( 3871.8 \pm 0.7 \pm 0.4 \) MeV (very close to \( D^0 \bar{D}^{0*} \) ) threshold *
- Favoured quantum numbers \( J^{PC} = 1^{++} \), later confirmed by LHCb (PRL 110, 222001(2013))

Could \( \chi_{c1}(3872) \) just be excited charmonium state?

* New \( \chi_{c1}(3872) \) lineshape studies from LHCb looking to determine molecular nature of \( \chi_{c1}(3872) \)) PRD 102 092005 (2020), JHEP 08 (2020) 123
No :) 

- Nearest $J^{PC} = 1^{++}$ conventional undiscovered charmonium state is $\chi_{c1}(2P)$
- Width is very small ($< 2.3$ MeV) - would expect larger widths for charmonium states above open charm threshold
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From 1976 PDG: *Three quarks cannot produce $S = 1$ baryon resonances and this has probably been the primary motivation for the great amount of experimental effort that has gone into $S = 1$ baryon physics during the last several years.*

Any resonance with $S = 1$ must be manifestly exotic, e.g. a pentaquark with quark content $qqqq\bar{s}$

Claims of exotic contributions in kaon-nucleon scattering experiments, in 1970s, $Z_0(1780), Z_0(1865), Z_1(1900)$ but none significant

- PDG entry for $Z_0(1780)$
- $K^+N$ scattering data from Bugg (1968), Cool(1970)
Skepticism about results in kaon-nucleon scattering where many other broad resonances exist and no significant confirmation followed...

1986 PDG

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,¹ and more recently by Kelly² and by Oades.³ Two new partial-wave analyses⁴ have appeared since our 1984 edition. Both claim that the $P_{13}$ and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

1992 PDG

Z BARYONS
($S = +1$)

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,¹ and has also been reviewed by Kelly² and by Oades.³ New partial-wave analyses⁴,⁵ appeared in 1984 and 1985, and both claimed that the $P_{13}$ and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The skepticism about baryons not made of three quarks and the lack of any experimental activity in this area make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,⁶ and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$. 
In 1997 the existence of a low-mass pentaquark was predicted with the quark content \( uuudd\bar{s} \), \( m = 1.53 \) GeV and \( \Gamma < 15 \) MeV.

In 2003 a narrow peak in the \( nK^+ \) distribution of \( \gamma n \rightarrow nK^+K^- \) data was observed at \( 1.54 \pm 0.01 \) GeV at \( 4.6\sigma \) \( \Theta^+(1540) \).

The \( \gamma n \rightarrow K^+K^-n \) reaction on \(^{12}\)C has been studied by measuring both \( K^+ \) and \( K^- \) at forward angles. A sharp baryon resonance peak was observed at \( 1.54 \pm 0.01 \) GeV/c\(^2\) with a width smaller than 25 MeV/c\(^2\) and a Gaussian significance of \( 4.6\sigma \). The strangeness quantum number (\( S \)) of the baryon resonance is +1. It can be interpreted as a molecular meson-baryon resonance or alternatively as an exotic five-quark state (\( uuudd\bar{s} \)) that decays into a \( K^+ \) and a neutron. The resonance is consistent with the lowest member of an antidecuplet of baryons predicted by the chiral soliton model.
Nine other experiments in the next year claimed to observe the $\Theta^+(1540)$ with $> 4\sigma$ significance. PDG gave 3 star status to $\Theta^+(1540)$

PDG gives 3-star status to $\Theta^+(1540)$

Despite the statistical significance of the $\Theta^+(1540)$ some problems were uncovered...
Cuts were found to inadvertently to enhance signal

Pentaquarks - false starts

Re-analysis of 70’s bubble chamber data where no cuts have been applied do not show a peak

\[ K^+ N \rightarrow KN\pi \] reactions in Hydrogen and Deuterium bubble chambers. Bland et al. (1969), Hirata et al. (1971) and Berthon et al. (1973)

PDG 2005 reviews - goes into history
Pentaquarks - false starts

Mass peak positions varied between experiments far more than expected for a very narrow state and experiments with far greater statistics failed to even see the $\Theta^+(1540)$

Mass of the $\Theta^+(1540)$ reported by various experiments  


Claims of (non-)observations of $\Theta^+(1540)$ over time  

"symmetrymagazine.org"
Pentaquarks - false starts

PDG rescinded $\Theta^+(1540)$ 3-star status

\[ \Theta(1540)^+ \]

2006 PDG $I(J^P) = 0(?)$ Status: *

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006 by G. Trilling (LBNL).

In paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the $\Theta^+$; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the $\Theta^+$; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the $\Theta^+$, in particular, do not exist, appears compelling.

And this is how it remained...
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LHCb detector

Specialises in decays of $b$ and $c$ hadrons. Uniquely positioned to search for exotic contributions in decays of various $b$ hadrons.

Run 1 dataset - 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV + 2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV
Run 2 dataset - 5.9 fb$^{-1}$ at $\sqrt{s} = 13$ TeV
Total $\approx 9$ fb$^{-1}$
Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi \, pK^-$

LHCb first observed the $\Lambda_b^0 \rightarrow J/\psi \, pK^-$ decay in 2011 when performing a measurement of the $\Lambda_b^0$ lifetime.

- Dalitz plot shows structures in:
  - $m_{K^-p}^2$ due to well-known $\Lambda_b^0 \rightarrow \Lambda^* (\rightarrow K^- \, p)J/\psi$ resonances
  - $m_{J/\psi p}^2$ due to ???

Here a resonance decaying strongly to $J/\psi \, p$ has minimal quark content $uudc\bar{c}$

Full Run 1+2 dataset PRL 122, 222001 (2019)
Pentaquarks in $\Lambda^0_b \rightarrow J/\psi pK^-$

Full run 1 amplitude analysis confirmed exotic contributions decaying to $J/\psi p$ in $\Lambda^0_b \rightarrow J/\psi pK^-$

$P_c(4380)^+$ (broad state), $P_c(4450)^+$

Exotic contributions near 4450 MeV supported by model independent analysis at more than $9\sigma$

(PRL117.082002 (2016))

A nine-fold increase in statistics with the Run 2 data showed a structure at 4312 MeV and resolved $P_c(4450)^+$ into 2 narrower structures
Pentaquarks in $\Lambda^0_b \rightarrow J/\psi\, pK^-$

New structures narrow
- Cannot be reflections/interference from conventional hadrons in $K^-p$ system
- Can fit $J/\psi\, p$ invariant mass distribution with BW amplitudes (allow for various interference combinations)

\[ \rightarrow P_c(4312)^+, P_c(4440)^+, P_c(4457)^+ \]
- Cannot comment on broad $P_c(4380)^+$ seen in 2015 result
- No determination on quantum numbers
- Amplitude analysis ongoing - need even more comprehensive knowledge of $\Lambda^* \rightarrow pK^-$ spectrum due to increased statistics

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># Reduced</th>
<th># Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>$1/2^-$</td>
<td>$1405.1^{+3.7}_{-1.0}$</td>
<td>$50.5 \pm 2.0$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>$1519.5 \pm 1.0$</td>
<td>$15.6 \pm 1.0$</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>$1/2^+$</td>
<td>$1600$</td>
<td>$150$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>$1/2^-$</td>
<td>$1670$</td>
<td>$35$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1690)$</td>
<td>$3/2^-$</td>
<td>$1690$</td>
<td>$60$</td>
<td>5</td>
<td>6</td>
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<tr>
<td>$\Lambda(1800)$</td>
<td>$1/2^-$</td>
<td>$1800$</td>
<td>$300$</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1810)$</td>
<td>$1/2^+$</td>
<td>$1810$</td>
<td>$150$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1820)$</td>
<td>$5/2^+$</td>
<td>$1820$</td>
<td>$80$</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1830)$</td>
<td>$5/2^-$</td>
<td>$1830$</td>
<td>$95$</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1890)$</td>
<td>$3/2^+$</td>
<td>$1890$</td>
<td>$100$</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2010)$</td>
<td>$7/2^-$</td>
<td>$2100$</td>
<td>$200$</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2110)$</td>
<td>$5/2^+$</td>
<td>$2110$</td>
<td>$200$</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2350)$</td>
<td>$9/2^+$</td>
<td>$2350$</td>
<td>$150$</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>$?$</td>
<td>$\approx 2585$</td>
<td>$200$</td>
<td>0</td>
<td>6</td>
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Significant uncertainties on parameters

N. Skidmore (University of Manchester)
LHCb has used three methods to conclude there are contributions other than conventional resonances to the decay $\Lambda_b^0 \rightarrow J/\psi pK^-$...

How have these structures been interpreted...
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Re-scattering effects

Re-scattering effects - triangle diagrams?

- $P_c(4457)^+$ peaks at $\Lambda_c^+(2595)\bar{D}^0$ threshold - $D_{s1}(2860)$ excited strange hadron suitable candidate to be exchanged in triangle
- Purely kinematical effect - $P_c$ not a resonant state
- Some investigations into this in LHCb 2019 paper
Molecular Model

Molecular Model - bound state of baryon and meson?

Narrow width and proximity of 3 pentaquark states $P_c(4312)^+, P_c(4440)^+$ and $P_c(4457)^+$ to $\Sigma_c^+ D^0(\ast)$ baryon-meson thresholds (but crucially below) motivates molecular model with small binding energies.

- Molecular models [1] predict multiplet of states eg. HQSS molecular model predicts 7 bound states, 3 of which correspond to the observed $P_c$
- JPAC analysis of $P_c(4312)^+$ lineshape "we find evidence for the attractive effect of the $\Sigma_c^+ D^0$ channel, which is not strong enough, however, to form a bound state." PRL 123, 092001 (2019)

\[
\begin{array}{c|c|c}
 P_c(4312) & P_c(4440) & P_c(4457) \\
\hline
 \Sigma_c^+ D^0 & \Sigma_c^+ D^*0 & \Sigma_c^+ \bar{D}^*0 \\
1/2^- & 1/2^- & 3/2^- \\
\end{array}
\]

Molecular + HQSS model. arxiv:1904.01296
Tightly bound system

Bound system of quarks and/or di-quarks? $P_c = \bar{c} \cdot (cu) \cdot (ud)$ or $P_c = q^4 \bar{q}$

Doubly-heavy tri-quark + light di-quark = colour singlet pentaquark

For example, compact diquark model [2] predicts following for LHCb pentaquarks

<table>
<thead>
<tr>
<th>$P_c(4312)^+$</th>
<th>$P_c(4440)^+$</th>
<th>$P_c(4457)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{c}[cu]<em>{s=1}[ud]</em>{s=0}; L_P = 0$</td>
<td>$\bar{c}[cu]<em>{s=1}[ud]</em>{s=0}; L_P = 1$</td>
<td>$\bar{c}[cu]<em>{s=1}[ud]</em>{s=0}; L_P = 1$</td>
</tr>
<tr>
<td>3/2$^-$</td>
<td>3/2$^+$</td>
<td>5/2$^+$</td>
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</table>

Note $J^P$ of $P_c(4312)^+$ disagrees with all molecular models!
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How to determine the nature of the pentaquarks?

How can we determine the nature of the observed $P_c^+$ states

1. Determine quantum numbers
   - Require full amplitude analysis (ongoing)
2. Production
   - How else are these states produced other than from decays of $\Lambda_b^0$
3. Decays to other final states
   - The $P_c^+$ states have only been observed in one decay channel
4. Search for other members of the multiplet
   - If $qqqq\bar{q}$ states exist there must be full multiplets to discover
Production

Look for the $P_c^+$ states in other production mechanisms

JLAB has searched for known $P_c^+$ states in $J/\psi$ photoproduction \cite{PRL123_072001}.

- Observation of the $P_c^+$ states here would exclude the $P_c$ being a result of kinematical effects such as triangle singularities

Absence of signal leads to (90% CL)

- $P_c(4312) \rightarrow J/\psi p < 4.6\%$
- $P_c(4440) \rightarrow J/\psi p < 2.3\%$
- $P_c(4457) \rightarrow J/\psi p < 3.8\%$

(which some models [3]/[4] do predict)

- Where does the width come from?
- $P_c^+$’s must preferentially decay to other channels “Need a consistent picture in $A^0_b$ decays”
Decays to other final states

Many models make firm predictions for $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$ and $P_c(4380)^+$ couplings to different final states.

$\Lambda_b^0 \rightarrow \Lambda_c^+ D^0 K^-$

Molecular models [3] predict large decay widths in this channel for $P_c(4440)^+$ and $P_c(4457)^+$.

Some molecular models [5] forbid $P_c(4312)^+$

Tightly bound model [6] predicts $P_c(4380)^+$ decays dominantly to $\Lambda_c^+ D^0$

$\Lambda_b^0 \rightarrow \Lambda_c^+ D^0 K^-$

Molecular models [3] predict that $\Lambda_c^+ D^{*0}$ is dominant channel for $P_c(4440)^+$ and $P_c(4457)^+$ and overwhelms width of $P_c(4312)^+$ [4]

Tightly bound models [6] also predict dominant $P_c(4312)^+$ channel is $\Lambda_c^+ D^{*0}$

Experimentally challenging - missing $\pi^0$ and $\gamma$ 4-momenta from $D^{*0}$
Decays to other final states

\[ \Lambda_0^b \rightarrow \Sigma_c^{++}(\ast) D^- K^- \]

Lineshape predictions for \( \chi_{c1}(3872) \)

![Lineshape predictions](image)

- Molecular models predict [1] large coupling of \( P_c(4312)^+ \) to \( \Sigma_c^{++} D^- \)
- Evident as enhancement at \( \Sigma_c^{++} D^- \) threshold (similar to \( \chi_{c1}(3872) \) in \( D^0 \bar{D}^0(\ast) \))

All 3 ongoing at LHCb!

- Tightly bound models predict [6] \( I = 3/2 \) multiplet with significant decay rates to \( \Sigma_c^{++}(\ast) D^- \)
- \( I = 3/2 \) multiplet inaccessible in \( J/\psi p \) and \( \Lambda_c^+ \bar{D}^0(\ast) \) due to Isospin
Search for other members of the multiplet

Search for neutral, strange counterparts of $P_C^+$ with $udsc\bar{c}$

Search in $\Xi_b^- \rightarrow J/\psi \Lambda K^-$
- Structures in $\Lambda K^-$ due to $\Xi^{*-}\!$ (dss) resonances
- Structures in $J/\psi \Lambda$ due to $P^0_{cs}$?

Amplitude analysis gives $>3\sigma$ evidence for $P^0_{cs}$ like structure, $P_{cs}(4459)^0$ (no $J^P$ determination)

Search for other members of the multiplet

S=2 pentaquark states?

- Observation of 5 new, narrow excited $\Omega_c^0$ (ssc) states
- Two states have extremely narrow width compared with conventional hadrons

Pentaquarks with beauty?

- Investigate existence of pentaquark states containing a single $b$ or $\bar{b}$ quark (that decays weakly)
- Skyrme model predicts that the heavier the constituent quarks the more tightly bound the pentaquark - more stable state *P.R.S. A* 260, 127 (1961)
- Search in $m_{J/\psi hhh}$

- No significant evidence for signal - set upper limits at 90% CL in $m_{J/\psi hhh}$ *JHEP* 10 (2018) 086

Non-observations are just as valuable in determining nature of pentaquarks

Close to $\bar{K}\Xi'_c$ thresholds - meson-baryon molecules with ssc$u\bar{u}$?

Neutral isospin partners \((c\bar{c}udd)\) of \(P_c\)?

- Necessity for tightly bound models
- Obvious \(P_c \rightarrow J/\psi n\) is not reconstructible at LHCb
- LHCb searching in \(\Lambda_b^0 \rightarrow \Lambda_c^+ D^- K^{*-0}\) channel for neutral \(P_c\) state

Whole program of decay channels searching for known \(P_c^+\) states and potential \(P_c^+\) partners with Run 1+2 LHCb dataset...

They are challenging
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LHCb tetraquark discoveries in 2020

Amplitude analysis of $B^+ \rightarrow D^+ D^- K^+$

- Conventional contributions expected in $D^+ D^-$ system

![Graph](image)

PRD 102 112003 (2020)

- Contributions seen in $D^- K^+$ ($\bar{c}d\bar{s}u$) - 1st observation of exotic hadrons with open flavour
- Supported by model-independent study PRL 125 242001 (2020)

Structure in $J/\psi$-pairs

- All known hadrons contained at most 2 heavy quarks - models predict existence of states with four heavy quarks
- Perform 1D fit to $J/\psi$-pair invariant mass

![Graph](image)


- $>5\sigma$ evidence for $T_{c\bar{c}c\bar{c}}$ tetraquark

Amazing list of hadrons discovered at the LHC
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A look to run 3 and beyond

L0 hardware trigger removal particularly benefits selection efficiency of $P_c$ modes
A look to run 3 and beyond

New data-taking model (online + offline) required to manage the factor 30 increase in data-rate

Data model

- **Online**
  - Default Turbo model
  - To tape

- **Offline**
  - Data to tape at 10GB/s
  - Data to disk at 3.5GB/s

**Sprucing model**
- HLT2
- Tesla
- Sprucing
- Analysis production
- Validation/monitoring

**Persistency**
- To disk

**Streaming**
A look to run 3 and beyond

Study $\chi_{c1}(3872)$ lineshape with simultaneous fit to multiple channels

$P_c$ observation channel - high sensitivity amplitude analysis ($J^P$)

Search for hidden-charm pentaquark with strangeness decaying to $J/\psi \Lambda$. Already $> 3\sigma$ observation

Modes like $\Lambda_b^0 \rightarrow \Sigma_c^{++}(\ast)D^-K^-$ need run 3+4 stats for meaningful conclusions
Conclusions

Experimental and theoretical developments moving quickly

LHCb working on full run 1 and run 2 dataset where statistics are such that more amplitude analyses are possible

Excellent long term prospects for exotic searches at LHCb

Always look in the charm sector first...
References I


