XYZ States at LHCb

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1. LHCb spectrometer - a tool for heavy hadron spectroscopy
2. Standard vs exotic heavy hadron states

3a. Pentaquarks in $\Lambda_b \rightarrow J/\psi \ p \ K$ decay: $P_c(4380)$ and $P_c(4450)$
3b. Search for $P_c$ states in $\Lambda_b \rightarrow J/\psi \ p \ \pi$ decay
3c. Search for $P_c$ states in $\Lambda_b^0 \rightarrow \chi_{c(1,2)} \ p \ K^-$ decays
3d. Observation of $\Xi_b^- \rightarrow J/\psi \Lambda \ K^-$ Decay
3e. Search for $b$-flavoured pentaquarks

4a. The puzzling states $X \rightarrow J/\psi \ \phi$
4b. Tetraquark $X(5568)$ ?

5. Charged Exotic State $Z(4430)^-$
LHCb Detector
Weight: 5,600 tonnes
Height: 10 m
Length: 20 m

Precise tracking system:
ε(trk) ≈ 96 %
Momentum resolution:
\[ \frac{\Delta p}{p} = 0.5 \% \quad p = 20 \text{ GeV} \]
\[ 0.8 \% \quad p = 100 \text{ GeV} \]

Electromagnetic and hadronic calorimeters
ECAL: \[ \frac{\Delta E}{E} = \frac{10}{E \text{[GeV]}}, 10 \% \]

Muon system:
ε(μ → μ) ≈ 97 %
ε(π → μ) ≈ (1-3) %

Trigger:
Highly flexible, currently have “offline quality”

Dipole magnet:
Bending power: 4 Tm

The first hadron-collider experiment that is dedicated to heavy flavour (HF) physics

The geometry of forward spectrometer

RICH:
Separation of K, p from π:
ε(K → K) ≈ 95 %
ε(π → K) ≈ 5 %
ε(p → p) ≈ 95 %
ε(π → p) ≈ 5 %

Vertex Detector:
Impact parameter resolution:
\[ \sigma_{IP} = 20 \mu m \]
Decay time resolution:
heavy hadrons: ≈50 fs

Precise trackingsystem:
ε(trk) ≈ 96 %
Momentum resolution:
\[ \frac{\Delta p}{p} = 0.5 \% \quad p = 20 \text{ GeV} \]
\[ 0.8 \% \quad p = 100 \text{ GeV} \]

Spectrometer:
very good mass resolution \( \sigma(m_{B \rightarrow hh}) \approx 22 \text{ MeV} \)
Pros and Cons of Heavy Flavour Spectroscopy with LHCb

- **General advantages (pp interaction):**
  - High production cross-sections for HF (at the LHC are $10^3$ larger than at the $e^+e^-$ B factories)
  - Simultaneous accumulation of huge $B_d$, $B_s$, $B_c$ and $b$-baryons data samples
  - The decay vertices are well separated from the production point (high boost of the b- and c-hadrons)

- **LHCb specific advantages** (single arm forward spectrometer: $0.8^\circ < \Theta < 15.4^\circ$):
  - LHCb captures a HF production cross-section, comparable to that of ATLAS and CMS (high-$p_T$ range) in MUCH SMALLER SOLID ANGLE $\Rightarrow$ smaller number of electronic channels $\Rightarrow$ smaller event size $\Rightarrow$ larger trigger bandwidth to store
  - LHCb – forward detector ($p >> p_T$): efficient muon identification for lower $P_T$ values
  - Space to accommodate excellent RICH detectors (flavour tagging, background suppression)

- **General drawbacks:**
  - The instantaneous luminosity is limited ($4 \times 10^{32}$ cm$^{-2}$s$^{-1}$)
  - The efficiencies of $\gamma$, $\pi^0$ and $\eta$ reconstruction are much lower to compare with the $e^+e^-$
All results presented here correspond to Run 1 data: 3 fb$^{-1}$
4 x $10^{12}$ b-hadrons produced

Run 2 vs Run 1:
- more abundant production of b-hadrons
- improvements in trigger and selection efficiencies
Standard vs Exotic States

- **Standard states:**
  - Area: 312,679 km² (6th in EU, 8th in Europe)
  - Population: 38,425,000 (6th in EU, 8th in Europe)
  - Male/female: 0.94
  - Natural increase: -0.7‰ (per 1000)
  - GDP: 475 G$ (rank: 23rd)
  - GDP per capita: 12,361 $ (rank: 44th)

As from: http://stat.gov.pl
http://data.worldbank.org

- **Exotic states:**
  - **Pentaquark**
    - diquark-diquark-antiquark
  - **H-dibaryon**
    - diquark-diquark-diquark
  - **Tetraquark**
    - diquark-diantiquark

Molecule
Hybrid
Glueball
Exotic states (with heavy quarks)

- About 30 heavy, potentially exotic states observed (since 2003)
- Most of them are charmonium (cc) or bottomonium (bb) like

- Quantum numbers:

  - Unconventional charges may occur (e.g. baryon with $S=1$ or meson with electric charge $+2$)

  - Tools:
    - angular distributions, Dalitz and Argand plots, amplitude analysis, model independent approach...

- Taxonomy (general, not universally accepted, guidelines):

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>P</td>
<td>pentaquarks</td>
</tr>
<tr>
<td>X</td>
<td>Neutral-charge resonances (most of them observed in B decays), positive parity</td>
</tr>
<tr>
<td>Y</td>
<td>States produced in the Initial State Radiation (ISR) processes, negative parity</td>
</tr>
<tr>
<td>Z</td>
<td>Charmonium-like, charged states (and its isospin partners)</td>
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</tbody>
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Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p K^-$ Decays

- Pentaquarks stay with us from the onset of the quark model...
- Intense experimental searches (rumour about the $\Theta^+(1540)$ state...)

LHCb (2015, Run 1 data, 3fb$^{-1}$):

- Study of the decay $\Lambda_b \rightarrow [J/\psi p] K^-$
- Huge, very clean sample of $\Lambda_b$s: 26 007+166 signal events, background fraction: 5.4%

- Surprising structure in $m(J/\psi p)$

- Phys. Lett. 8 (1964) 214-215

- Pentaquarks in $\Lambda_b^0$ states at LHCb

- Intense experimental searches (rumour about the $\Theta^+(1540)$ state...)

- Anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q q \bar{q})$, etc., while mesons are made out of $(q \bar{q})$, $(q q q \bar{q})$, etc. It is assuming that the lowest

- PRL 115 (2015) 072001

- Standard contribution:
  - $\Lambda_b^0 \rightarrow J/\psi \mu^+ \mu^-$
  - $J/\psi \rightarrow \mu^+ \mu^-$
  - $\Lambda^+ \rightarrow K^- p$

- Exotic contribution:
  - $P_c^+ \rightarrow J/\psi p$
  - $P_c^+ -$ the minimal valence quark content: uudc$c$
Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p K^-$ Decays

- discovery of two hidden-charm pentaquark-like states $P_c(4380)^+$ and $P_c(4450)^+$

- The full 6D amplitude analysis using the helicity formalism and Breit-Wigner (BW) amplitudes
  - observables: resonance mass, three helicity angles, two angles between decay planes;
  - takes into account 14 well-defined $\Lambda^*$ states and interference between both decay sequences

- The satisfactory description only after including two additional BW amplitudes of $P_c$ states:

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<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$205 \pm 18 \pm 86$</td>
<td>$3/2^- (3/2^+)$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$4449.8 \pm 1.7 \pm 2.5$</td>
<td>$39 \pm 5 \pm 19$</td>
<td>$5/2^+ (3/2^-)$</td>
</tr>
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</table>
Argand Diagrams  (for 3/2⁻ and 5/2⁺ hypothesis)

Data points in the six equidistant bins of $m(J/\psi p)$ in the range from $(-\Gamma)$ to $(+\Gamma)$

$P_c(4450)^+$:  
Consistent with resonant behaviour  
(rapid counter-clockwise change of the phase around the maximum)

$P_c(4380)^+$: needs more statistics

The amplitude method is powerful but

👎 - requires the $\Lambda^*$ model (spectroscopy of these states is complicated)

👍 - can provide the detailed info about new states (mass, width, $J^{PC}$...
**Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p K^-$ Decays**

- **LHCb: fortification of the $P_c$ states observation:** Model independent approach
  - No need for the $\Lambda^*$ model; can only indicate the presence of exotic states
  - 2D analysis in terms of $\langle m(Kp), \cos \theta_{\Lambda^*} \rangle$ ($\theta_{\Lambda^*}$ - helicity angle of the K-p system)
  - The $\cos \theta_{\Lambda^*}$ ang. Distribution is expanded in Legendre polynomials (in bins of $m(Kp)$):
    
    $\frac{dN}{d\cos \theta_{\Lambda^*}} = \sum_{l=0}^{l_{\text{max}}} \langle P_l^{\perp} \rangle P_l(\cos \theta_{\Lambda^*})$

    - $\Lambda^*$ resonances can contribute only to low order moments up to $l_{\text{max}} = 2J_{\text{max}}$
    - $J_{\text{max}}$ – the highest spin of any Kp contribution at the given $m_{kp}$ bin

- \(< P_l^{\perp} >\) - Legendre moments: contain all the information of the angular structure of the system as well as the spin of $\Lambda^*$ resonances

- The [Kp] mass and angular distributions are projected as reflection into the $J/\psi p$ system

- 9σ discrepancy with data, assuming only $\Lambda^*$ contributions (H0 hypothesis)

- The discrepancy concentrated in the region of mass corresponding to the $P_c$ states (best seen on the $m(J/\psi p)$ distribution)
Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ Decays

- The Cabibbo suppressed mode \[ \frac{B(\Lambda_b \rightarrow J/\psi p \pi^-)}{B(\Lambda_b \rightarrow J/\psi K^-)} = 0.0824 \pm 0.0024 \pm 0.0012 \]
- 1885+50 $\Lambda_b$ candidates
  Run 1 data, 3fb$^{-1}$

- The background fraction is higher by a factor of three
  - Four contributions - three of them exotic - considered:
    - $N^* \rightarrow p\pi^-$
    - $P_c(4380)^+ \rightarrow J/\psi p$
    - $P_c(4450)^+ \rightarrow J/\psi p$
    - $Z_c(4200)^- \rightarrow J/\psi \pi^-$

  (The masses and widths of $N^*$ and $P_c$ states are fixed; $Z_c(4200)^-$ parameters set free)

  - The data favour the existence of exotic contributions
  - 3.1σ significance if both types of exotic resonances are included: $P_c(4380)^+ & P_c(4450)^+ & Z_c(4200)^-$
  - 3.3σ for the $P_c$s, assuming that the $Z_c(4200)^-$ contribution is negligible: $P_c(4380)^+ & P_c(4450)^+$

  Reported by Belle in $(J/\psi \pi)$ (2014)

  $$M = 4196^{+31}_{-29}^{+17}_{-13} \text{ MeV}$$
  $$\Gamma = 370 \pm 70^{+70}_{-132} \text{ MeV}$$
  $$J^P = 1^+$$

  $PRL 117 (2016) 082003$
The First Observation of $\Lambda_b^0 \rightarrow \chi_{c(1,2)} p K^-$

Motivation:

1. Test the kinematic rescattering effect (KRE) hypothesis
   - The mass of $P_c(4450)$ is very close to the $[\chi_{c1}p]$ threshold
     \[ m_{P_c(4450)}^+ - m_{\chi_{c1}} - m_p = (0.9 \pm 0.3) \text{ MeV} \]
   - If $P_c(4450)^+$ is due to KRE \( \Rightarrow \) should NOT be observed as a narrow enhancement near the $[\chi_{c1}p]$ threshold in the $\Lambda_b \rightarrow \chi_{c1}pK^-$ mode

2. Test the factorisation approach: the decay with $\chi_{c2}$ is expected to be suppressed w.r.t. that with $\chi_{c1}$

LHCb: both $\Lambda_b \rightarrow \chi_{c1}pK^-$ and $\Lambda_b \rightarrow \chi_{c2}pK^-$ observed for the first time

Ad 1. distributions of $m(\chi_{c1}p)$ and $m(pK)$ studied – more statistics needed for the amplitude analysis
Run 1 & 2: \( >1000 \chi_{c1} \) candidates

Ad 2. $\frac{\mathcal{B}(\Lambda_b \rightarrow \chi_{c2}pK^-)}{\mathcal{B}(\Lambda_b \rightarrow \chi_{c1}pK^-)} = 1.02 \pm 0.11$ - no $\chi_{c2}$ suppression,

\[ \frac{\mathcal{B}(B^0 \rightarrow \chi_{c2}K^{*0})}{\mathcal{B}(B^0 \rightarrow \chi_{c1}K^{*0})} = 0.17 \pm 0.05 \]

T.Lesiak
XYZ states at LHCb
WPCF18
25 May 2018
Motivation: search for possible (udsc\bar{c}) states, decaying to (J/\psi \Lambda) pair

LHCb: the first observation of the \( \Xi_b^- \rightarrow J/\psi \Lambda K^- \) decay

Results:

\[
\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{B(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}
\]

\[
m(\Xi_b^-) - m(\Lambda_b^0) = (177.08 \pm 0.47 \pm 0.16) \text{ MeV}
\]

The amplitude analysis, in search for (udsc\bar{c}) states, feasible with the full data sample of Run 2
The (uudc̅) states observed (decaying strongly)

The Skyrme model:
- expectation of b-flavoured pentaquarks $P_b(bqqqq/\bar{b}qqqq)$, that decay via the weak interaction and are
  - tightly bound (Skyrme model: the binding grows with the mass of the constituent quarks)
  - narrow ($\Gamma \approx 6$ MeV, to compare with (40-200) MeV for $P_c$s)

**LHCb:** the search for four types of $P_b$ states

<table>
<thead>
<tr>
<th>Mode</th>
<th>Quark content</th>
<th>Decay mode</th>
<th>Search window</th>
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<tbody>
<tr>
<td>I</td>
<td>$\bar{b}duud$</td>
<td>$P_{B^0p}^+ \rightarrow J/\psi K^+ \pi^- p$</td>
<td>4668–6220 MeV</td>
</tr>
<tr>
<td>II</td>
<td>$b\bar{u}udd$</td>
<td>$P_{L^0\pi^-}^- \rightarrow J/\psi K^- \pi^- p$</td>
<td>4668–5760 MeV</td>
</tr>
<tr>
<td>III</td>
<td>$\bar{b}d\bar{u}ud$</td>
<td>$P_{L^0\pi^+}^+ \rightarrow J/\psi K^- \pi^+ p$</td>
<td>4668–5760 MeV</td>
</tr>
<tr>
<td>IV</td>
<td>$\bar{b}suud$</td>
<td>$P_{B^0p}^+ \rightarrow J/\psi \phi p$</td>
<td>5055–6305 MeV</td>
</tr>
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below the threshold for strong decays
Search for b-flavoured Pentaquarks

- No signal observed

- Upper limits on the $P_b$ production ratio w.r.t. $\Lambda_b^- \rightarrow J/\psi K^- p$

$$R = \frac{\sigma(pp \rightarrow P_b X) \cdot B(P_b \rightarrow J/\psi X)}{\sigma(pp \rightarrow \Lambda_b^0 X) \cdot B(\Lambda_b \rightarrow J/\psi pK^-)}$$

- The limits (90% CL) on $R$ are at the level $10^{-2} - 10^{-3}$
The Puzzling States X → J/ψΦ

- Reminder: the X(3872) revolution
- The most studied exotic state
  - LHCb: J^P_C = 1++
  - X is most probably a mixture of χ_{c1}(2P) and of DD* molecule

- The X(4140) - evidence for a narrow near threshold structure in B⁺ → (J/ψ φ) K⁺ decays: CDF, D0, CMS
- The X(4274) – the second relatively narrow [J/ψ φ] state – evidence from CDF and CMS
- Negative results from other experiments (B-factories)
**LHCb: the first amplitude analysis of $B^+ \rightarrow [J/\psi \phi] K^+$ decays**

- 4289±151 candidates; nearly background free

- 6D phase space composed of $m(\phi K)$, helicity angles and $\Delta \phi$ angles

- The amplitude analysis aimed to resolve $K^* \rightarrow K \phi$ from the potential $X \rightarrow J/\psi \phi$ resonances

- The model with excited $K^*$s ($\rightarrow K\phi$) does not describe the data

- Good description upon inclusion of four broad exotic resonances

- The $X(4140)$ width is substantially larger than previously determined (average of other meas.: 15.7±6.3 MeV)

- $X(4140)$ and $X(4274)$ – $J^{PC}$ incompatible with cusps and molecular bound states - possible interpretation as tetraquarks $c\bar{c}s\bar{s}$ (no light valence quarks) or $\chi_{c1}(3P)$

- $X(4500)$ and $X(4700)$ – $D_s^{(*)+} D_s^{(*)-}$ state or $\chi_{c1}(4P), \chi_{c1}(5P)$

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**Reflections from $K^*$ states**

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<tbody>
<tr>
<td>$X(4140)$</td>
<td>8.4</td>
<td>$4146.5 \pm 4.5^{+4.6}_{-2.8}$</td>
<td>$83 \pm 21^{+21}_{-14}$</td>
<td>$1^{++}$</td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>6.0</td>
<td>$4273.3 \pm 8.3^{+17.2}_{-3.6}$</td>
<td>$56 \pm 11^{+8}_{-8}$</td>
<td>$1^{++}$</td>
</tr>
<tr>
<td>$X(4500)$</td>
<td>6.1</td>
<td>$4506 \pm 11^{+12}_{-15}$</td>
<td>$92 \pm 21^{+21}_{-20}$</td>
<td>$0^{++}$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td>5.6</td>
<td>$4704 \pm 10^{+14}_{-24}$</td>
<td>$120 \pm 31^{+33}_{-20}$</td>
<td>$0^{++}$</td>
</tr>
</tbody>
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**Data and fits**

- Run 1 3 fb$^{-1}$

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**References**

- PRL 118 (2017) 02203
- PR D95 (2017) 012002
Controversy About the Tetraquark X(5568)

- **D0 (2016):** reports a narrow structure X(5568) in the $B_s^0 \pi^+$ spectrum
  \[
  \vec{X}(5568) \rightarrow B_s^0 \pi^+ \\
  B_s^0 \rightarrow J/\psi \phi
  \]
  \[
  \rho_X = \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow B_s^0 \pi^+)}{\sigma(pp \rightarrow B_s^0 + \text{anything})} = (8.6 \pm 1.9 \pm 1.4) \%
  \]
  (5.1 $\sigma$)

  A system (tetraquark or molecule) containing valence (anti)quarks with four different flavours (b,s,d,u)?

- **LHCb (2016):** 20x more $D_s$ than D0 collab.
  - lack of observation of any X(5568)-like signal

- **Not seen by CDF (27 Dec. 2017):**

- **Seen again by D0 (29 Dec. 2017):**
  \[
  \vec{X}(5568) \rightarrow B_s^0 \pi^+ \\
  B_s^0 \rightarrow \mu^+ D_s^\pm X, D_s^\pm \rightarrow \psi \pi^\pm
  \]

\[
\rho_X < 2 \% \quad (95 \% C.L.)
\]

- Similar negative result from CMS:
  - CMS-PAS-BPH-16-002 (2016)

\[
m = 5566.9^{+3.2+0.6}_{-3.1-1.2} \text{ MeV} \quad (6.7 \sigma)
\]

\[
\Gamma = 18.6^{+7.9+3.5}_{-6.1-3.8} \text{ MeV}
\]
Charged Exotic State $Z(4430)^-$

- **Belle (2008):** evidence for $Z(4430)^-$ in $\psi'\pi$ mass distribution ($B^0 \rightarrow \psi'(2S)\pi^- K^+$ decays)
- **LHCb (2014):** tenfold increase in signal yield (25176+174 decays); Run 3fb$^{-1}$

4D amplitude analysis:

$Z(4430)^-$

- $m(Z(4430)^-) = 4475 \pm 7^{+15}_{-25}$ MeV
- $\Gamma(Z(4430)^-) = 172 \pm 13^{+37}_{-34}$ MeV

$J^P = 1^+$ assignment established relative to:

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>0$^-$</th>
<th>1$^-$</th>
<th>2$^+$</th>
<th>2$^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>sign. $</td>
<td>\sigma</td>
<td>$</td>
<td>9.7</td>
<td>15.8</td>
</tr>
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</table>

Positive parity $\rightarrow$ hypothesis of threshold effect $\bar{D}^*(2007)D_1(2420)$ and $\bar{D}^*(2007)D_2^*(2460)$ ruled out

Model independent approach:

- The $K\pi$ angular distributions are extracted from data with Legendre polynomial moments and projected as reflection of the $m(\psi'\pi)$ spectrum
- The $K\pi$ reflections with $J(K^*) \leq 2$ excluded (>8σ)

- The most plausible interpretation of $Z(4430)$: a tetraquark; the minimal quark content $c\bar{c}d\bar{u}$
Conclusions

➢ The renaissance of heavy flavour spectroscopy in recent 15 years:

• Observation of numerous new states: many of them exotic-like

• A vivid field of research with strong liaisons between theory and experiment

➢ LHCb has recently provided valuable contributions to heavy flavour spectroscopy of exotic states:

  ▪ Observation of hidden-charm pentaquarks $P_c$; searches for $b$-flavoured states $P_b$
  ▪ Observation of candidates for tetraquark $c\bar{c}s\bar{s}$ states in the $J/\psi\phi$ final state
  ▪ Non-confirmation of a tetraquark $X(5568)$
  ▪ Confirmation and extensive studies of $Z(4430)^-$ in $\psi'\pi$ mass distribution

➢ More precise spectroscopic measurements from the LHCb experiment and, hopefully, some discoveries should follow with the analysis of Run 2 data

➢ LHC and LHCb upgrade: 50 $fb^{-1}$ of integrated luminosity expected by 2030....