Pentaquark Candidates at LHCb

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On behalf of the LHCb Collaboration

22 August, 2017
Exotic Hadrons at ICNFP2017
In the beginning of quark model, multiquark objects were predicted - now called exotic

qqqq̄ baryons later called “pentaquarks”;
qq̅qq̅ meson called “tetraquarks”
Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond the simple quark-model picture. Could teach us a lot about QCD.

- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79), Lipkin (87)

- These would be short-lived $\sim 10^{-23}$ s “resonances” whose presence is detected by mass peaks & angular distributions showing the presence of unique $J^P$ quantum numbers
$P_c(4380)^+, P_c(4450)^+ \rightarrow J/\psi p$ in $\Lambda^0_b \rightarrow J/\psi pK^-$

Full amplitude fit and model-independent approach
Determine the $p_T$ and $\eta$ dependence of $f_{\Lambda_0^b}/f_d$


- Clear increase of $\Lambda_0^b$ at low $p_T$ and large $\eta$

The LHCb is a $\Lambda_0^b$ factory: $4:2:1 \approx B^0:\Lambda_0^b:B_s$ in LHCb acceptance
\( \Lambda_{b}^{0} \rightarrow J/\psi pK^{-} \)

- First observation of the decay with 2011 data
- Unexpected large yield, interesting structure in \( pK \) mass
- Used to measure \( \Lambda_{b}^{0} \) lifetime


Update with 2011+2012 data
Data and selection

- 2011+2012 3 fb$^{-1}$
- Reoptimized selection
  - $\bar{B}^0_s \to J/\psi K^- K^+$ & $\bar{B}^0 \to J/\psi K^- \pi^+$ misID backgrounds are vetoed
- Neural network based selection
- Large and clean $\Lambda_b^0$ signals

Neural network based selection

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

26,007±166
$\Lambda_b^0$ signals
94.6% purity

$\Lambda_b^0$ signal range

$[PRL 115, 072001 (2015)]$
“Dalitz-plot” distribution

- Dalitz-plot generally used for studying 3-body decays
- 3-body decays are often dominated by resonance processes, can be viewed by the distribution

Make a Dalitz plot.

Showed an unusual feature

[PRL 115, 072001 (2015)]
Does a 4 quark + $\bar{q}$ state exist?
Is the peak “an artifact”?

- Many checks done: this is not be the case:
  - MisID background of $B^0$ and $B_s$ are vetoed
  - $\Xi_b$ decays checked
  - Efficiency doesn’t make narrow peak
  - No peaking sideband bkg
  - Clones & ghost tracks eliminated

- Can interference between $\Lambda^*$ resonances generate a peak in the $J/\psi p$ mass spectrum?
  - A full amplitude analysis is performed using all known $\Lambda^*$ resonances

[PRL 115, 072001 (2015)]
Two interfering channels:

\[ \Lambda_b^0 \rightarrow J/\psi \Lambda^* \], 
\[ \Lambda^* \rightarrow pK^- \]

&

\[ \Lambda_b^0 \rightarrow P_c^+ K^- \], 
\[ P_c^+ \rightarrow J/\psi p \]

- Use m(K^-p) & 5 decay \( \angle \)'s as fit observables
Amplitude Analysis

• The matrix element for the $\Lambda^*$ decay is:

$$\mathcal{M}_{\Lambda_b^0, \lambda_\psi, \Delta, \mu}^{\Lambda^*} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}_{\Lambda_b^0 \rightarrow \Lambda^*_n} D_{\frac{1}{2}} \lambda_{\Lambda_b^0}, \lambda_{\Lambda^*}, \lambda_\psi (0, \theta_{\Lambda_b^0}, 0)^*$$

$$\mathcal{H}_{\Lambda^*_n \rightarrow \Lambda_b^0, \lambda_{\Lambda^*}, \lambda_\psi} D_{\frac{1}{2}} (\phi_{\Lambda^*}, \theta_{\Lambda^*}, 0)^* R_n (m_{\Lambda_b^0}) D_{\frac{1}{2}} \lambda_\psi, \Delta, \mu (\phi_\mu, \theta_\psi, 0)^*$$

• And for the $P_c$:

$$\mathcal{M}_{\Lambda_b^0, \lambda_\psi, \Delta, \mu}^{P_c} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi} \mathcal{H}_{\Lambda_b^0 \rightarrow P_c} D_{\frac{1}{2}} \lambda_{\Lambda_b^0}, \lambda_{P_c}, \lambda_\psi (0, \theta_{\Lambda_b^0}, 0)^*$$

$$\mathcal{H}_{\Lambda_b^0 \rightarrow P_c} D_{\frac{1}{2}} (\phi_{P_c}, \theta_{P_c}, 0)^* R_j (m_{P_c}) D_{\frac{1}{2}} \lambda_\psi, \Delta, \mu (\phi_\mu, \theta_\psi, 0)^*$$

• $\mathcal{H}$ are complex helicity couplings to describe decay dynamics, determined from the fit
Amplitude Analysis

• The matrix element for the $\Lambda^*$ decay is:

$$M_{\Lambda^*}^{\Lambda_0, \Lambda, \Delta \mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}_{\lambda_{\Lambda^*}, \lambda_\psi}^{\Lambda_0 \rightarrow \Lambda^*_n} D_{\lambda_{\Lambda^*}, \lambda_\psi} \frac{1}{2} (0, \theta_{\Lambda^*_0}, 0)^*$$

$$\mathcal{H}_{\lambda_{\Lambda^*}, \lambda_\psi}^{\Lambda_0 \rightarrow KP} D_{\lambda_{\Lambda^*}, \lambda_\psi}^{J_{\Lambda^*_n}} (\phi_K, \theta_{\Lambda^*}, 0)^* R_n(m_{KP}) D_{\lambda_\psi, \Delta \mu}^{1} (\phi_\mu, \theta_\psi, 0)^*$$

• And for the $P_c$:

$$M_{P_c}^{\Lambda_0, \Lambda, \Delta \mu} \equiv \sum_{j} \sum_{\lambda_{P_c}} \sum_{\lambda_{\psi}} \mathcal{H}_{\lambda_{P_c}, \lambda_{\psi}}^{\Lambda_0 \rightarrow P_c j} D_{\lambda_{\Lambda^*_0}, \lambda_{P_c}}^{1} (\phi_{P_c}, \theta_{\Lambda^*_0}, 0)^*$$

$$\mathcal{H}_{\lambda_{P_c}, \lambda_{\psi}}^{P_c j \rightarrow \psi p} D_{\lambda_{P_c}, \lambda_{\psi} - \lambda_{P_c}}^{J_{P_c j}} (\phi_{\psi}, \theta_{P_c}, 0)^* R_{j}(m_{\psi p}) D_{\lambda_\psi, \Delta \mu}^{1} (\phi_\mu, \theta_\psi, 0)^*$$

• $R(m)$ are resonance parametrizations, generally are described by Breit-Wigner, Flatté amplitude
Amplitude Analysis

• The matrix element for the $\Lambda^*$ decay is:

$$\mathcal{M}_{\Lambda_b^0, \Lambda_p, \Delta \lambda_{\mu}}^{\Lambda^*} \equiv \sum \sum \sum \mathcal{H}_{\Lambda_b^0 \to \Lambda^*_n \psi} D^{1/2}_{\Lambda_b^0, \Lambda^*_n \psi} (0, \theta_{\Lambda_b^0}, 0)^*$$

$$\mathcal{H}_{\Lambda^*_n \to K_P}^{\Lambda^*_n} J_{\Lambda^*_n}^{\Lambda^*_n} \mathcal{H}_{\Lambda^*_n \to K_P}^{\Lambda^*_n} D^{1/2}_{\Lambda^*_n \psi, \lambda_p} (\phi_K, \theta_{\Lambda^*_n}, 0)^* R_n (m_{K_P}) D^1_{\lambda_p, \Delta \lambda_{\mu}} (\phi_\mu, \theta_\psi, 0)^*$$

• And for the $P_c$:

$$\mathcal{M}_{\Lambda_b^0, \Lambda_p, \Delta \lambda_{\mu}}^{P_c} \equiv \sum \sum \sum \mathcal{H}_{\Lambda_b^0 \to P_{cj} K}^{P_{cj}} D^{1/2}_{\Lambda_b^0, \lambda_{P_c}} (\phi_{P_c}, \theta_{P_c}, 0)^* R_j (m_{P_c}) D^1_{\lambda_p, \Delta \lambda_{\mu}} (\phi_\mu, \theta_\psi, 0)^*$$

• Wigner D-matrix arguments are Euler angles corresponding to the fitted angles
Amplitude Analysis

- The matrix element for the $\Lambda^*$ decay is:

$$\mathcal{M}_{\Lambda^*}^{\Lambda_0, \lambda_p, \Delta \lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}_{\lambda_{\Lambda^*}, \lambda_\psi}^{\Lambda_0 \rightarrow \Lambda^* \psi} D_{\lambda_{\Lambda^*} \rightarrow \lambda_\psi}^{\frac{1}{2}} (0, \theta_{\Lambda_0}, 0)$$

$$\mathcal{H}_{\lambda_p, 0}^{\Lambda_n \rightarrow K P} D_{\lambda_{\Lambda^*}, \lambda_p}^{J_{\Lambda_n}} (\phi_K, \theta_{\Lambda^*}, 0) R_n (m_{K_P}) D_{\lambda_\psi, \Delta \lambda_\mu}^{\frac{1}{2}} (\phi_\mu, \theta_\psi, 0)$$

- And for the $P_c$:

$$\mathcal{M}_{P_c}^{\Lambda_0, \lambda_p, \Delta \lambda_\mu} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi} \mathcal{H}_{\lambda_{P_c}, 0}^{\Lambda_0 \rightarrow P_c, K} D_{\lambda_{\Lambda_0}, \lambda_{P_c}}^{J_{P_c}} (\phi_{P_c}, \theta_{P_c}, 0) R_j (m_{\psi_P}) D_{\lambda_\psi, \Delta \lambda_\mu}^{\frac{1}{2}} (\phi_\mu, \theta_\psi, 0)$$

- Add together coherently to model their interfering

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_0}} \sum_{\lambda_p} \sum_{\Delta \lambda_\mu} \mathcal{M}_{\lambda_0, \lambda_p, \Delta \lambda_\mu}^{\Lambda^*} + e^{i \Delta \lambda_\mu \alpha_\mu} \sum_{\lambda_{P_c}} \sum_{\lambda_p} \mathcal{M}_{\lambda_0, \lambda_p, \Delta \lambda_\mu}^{P_c}$$

Rotation angles to align helicity axes of $\mu$ & $p$ between two decay chains
### Models: extended & reduced

Consider all $\Lambda^*$ states & all allowed L values

<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$^{+1.3}_{-1.0}$</td>
<td>50.5 ± 2.0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda (1520)$</td>
<td>3/2$^-$</td>
<td>1519.5 ± 1.0</td>
<td>15.6 ± 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>
</tr>
<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>$\Lambda (2100)$</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>$-$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (2585)$</td>
<td>?</td>
<td>$\approx 2585$</td>
<td>200</td>
<td>$-$</td>
<td>6</td>
</tr>
</tbody>
</table>

Flatté BW

[PRL 115, 072001 (2015)]

# parameters 64 146
Results without $P_c$ states

- Use extended model, so all possible known $\Lambda^*$ amplitudes. $m_{Kp}$ looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra $\Lambda^*$, all $\Sigma^*$ (isospin violating process) don’t help

[Image of LHCb data plots]

[PRL 115, 072001 (2015)]
Extended model with $1 P_c$

- Try all $J^P$ up to $7/2^\pm$
- Best fit has $J^P = 5/2^\pm$. Still not a good fit

[PRL 115, 072001 (2015)]
Reduced model with 2 $P_c$'s

- Best fit has $J^P = (3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred

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**[PRL 115, 072001 (2015)]**
Angular distributions

Good fits in the angular variables

[PRL 115, 072001 (2015)]
In $m(K^-p)$ slices

$P_c$'s not appear in first interval as they outside of the Dalitz plot boundary

[PRl 115, 072001 (2015)]
$P_c^{\pm}$ decay angle distribution

- Events in $m_0 \pm \Gamma$ of $P_c(4450)$
- Asymmetric distribution from $2P_c$ is evident
- $2P_c$ overlap and interfere

CERN-THESIS-2016-086
1. $P_c$ (parity conservation in strong decays) generates forward-backward symmetric distribution.

2. Same parity states also generates symmetric distribution.

Cannot explain the data.
**JP determination**

- opposite parity states needed to explain the angle distribution
- Angular information determines: one $P_c$ is 3/2 and another is 5/2 with opposite parity

**Graph: LHCb**

- Negative interference, high $m_{Kp}$
- Positive interference, low $m_{Kp}$

**CERN-THESIS-2016-086**
### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>Fit fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>[PRL 115, 072001 (2015)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended vs. reduced</td>
<td>21</td>
<td>0.2</td>
<td>54</td>
</tr>
<tr>
<td>$\Lambda^*$ masses &amp; widths</td>
<td>7</td>
<td>0.7</td>
<td>20</td>
</tr>
<tr>
<td>Proton ID</td>
<td>2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>$10 &lt; p_p &lt; 100$ GeV</td>
<td>0</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>3</td>
<td>0.3</td>
<td>34</td>
</tr>
<tr>
<td>Separate sidebands</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>$J^P$ (3/2+, 5/2−) or (5/2+, 3/2−)</td>
<td>10</td>
<td>1.2</td>
<td>34</td>
</tr>
<tr>
<td>$d = 1.5 - 4.5$ GeV$^{-1}$</td>
<td>9</td>
<td>0.6</td>
<td>19</td>
</tr>
<tr>
<td>$L_{P_c}^{L_b}$ $A_b^0 \rightarrow P_c^+$ (low/high) $K^-$</td>
<td>6</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>$L_{P_c}^{P_c}$ $P_c^+$ (low/high) $\rightarrow J/\psi p$</td>
<td>4</td>
<td>0.4</td>
<td>31</td>
</tr>
<tr>
<td>$L_{A_b}^{A_b}$ $A_b^0 \rightarrow J/\psi \Lambda^*$</td>
<td>11</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>Efficiencies</td>
<td>1</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>Change $\Lambda(1405)$ coupling</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Overall</td>
<td>29</td>
<td>2.5</td>
<td>86</td>
</tr>
<tr>
<td>sFit/cFit cross check</td>
<td>5</td>
<td>1.0</td>
<td>11</td>
</tr>
</tbody>
</table>

For Run-II, we are working on improved $\Lambda^*$ model from coupled-channels
Fit results

- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred for low and high $P_c^+$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Significance</th>
<th>Fit fraction(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^\pm$</td>
<td>4380 ± 8 ± 29</td>
<td>205±18±86</td>
<td>9 $\sigma$</td>
<td>8.4 ± 0.7 ± 4.2</td>
</tr>
<tr>
<td>$P_c(4450)^\pm$</td>
<td>4449.8 ± 1.7 ± 2.5</td>
<td>39±5±19</td>
<td>12 $\sigma$</td>
<td>4.1 ± 0.5 ± 1.1</td>
</tr>
<tr>
<td>$\Lambda(1405)$</td>
<td></td>
<td></td>
<td></td>
<td>15 ± 1 ± 6</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td></td>
<td></td>
<td></td>
<td>19 ± 1 ± 4</td>
</tr>
</tbody>
</table>

For $P_c(4380)^+$,

$$\mathcal{B}(\Lambda_b^0 \to P_c^+K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5}$$

For $P_c(4450)^+$,

$$\mathcal{B}(\Lambda_b^0 \to P_c^+K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5}$$

Ref: $\mathcal{B}(B^0 \to Z_c(4430)^-K^+, Z_c^- \to \psi'\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$
Often a relativistic Breit-Wigner amplitude is used to model resonance.

Function has Re & Im parts.

Breit-Wigner amplitude

\[
BW(m|M_0, \Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0 \Gamma(m)}
\]

\[
\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{M_0}{m} B'_L(q, q_0, d)^2
\]

- Circular trajectory in complex plane is characteristic of resonance.
- Circle can be rotated by arbitrary phase.
- Phase change of 180° across the pole.
Argand diagrams

- Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$
- Left: too good, Right: one point $2\sigma$ away from expectation

[PRL 115, 072001 (2015)]
Model-independent confirmation

- Model-independent analysis is complimentary to the amplitude fit

<table>
<thead>
<tr>
<th>Model-independent</th>
<th>Amplitude fit</th>
</tr>
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<tbody>
<tr>
<td>No $\Lambda^*$ model needed</td>
<td>$\Lambda^*$ model needed</td>
</tr>
<tr>
<td>Can only tell if exotics present</td>
<td>Can tell the property of the exotics</td>
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</table>

PRL 117, 082002 (2016)
Rectangular Dalitz plane

\[ \Lambda_b^0 \rightarrow J/\psi pK^- \]

PRL 115, 072001 (2015)

PRL 117, 082002 (2016)
Legendre moments

\[
\frac{dN}{d \cos \theta} = \sum_{l=0}^{l_{\text{max}}} \left\langle P_l^U \right\rangle P_l(\cos \theta)
\]

\[
\left\langle P_l^U \right\rangle = \int_{-1}^{+1} \frac{dN}{d \cos \theta} P_l(\cos \theta) d \cos \theta \propto \sum_{i=1}^{n_{\text{events}}} \frac{1}{\varepsilon_i} P_l(\cos \theta_i)
\]

\(\Lambda^*\) can contribute only to low-order moments

\(\Lambda^*\)-only hypothesis called \(H_0\)

\[l_{\text{max}} = 2J_{\text{max}}\]

\(J_{\text{max}}\) is the highest spin of \(\Lambda^*\) resonance possible

Reflections of exotic hadrons can contribute to low and high order moments:

- Detecting non-zero moments above \(2J_{\text{max}}\) signals presence of exotics
Moments coefficients as function of $m_{Kp}$

From know $\Lambda^*$ resonances, quark model predictions as a guide

Much fewer known states than predicted!

Known $\Lambda^*$ states: boxes $M_0 \pm \Gamma_0$

$\Lambda^*$ mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

No $\Lambda^*$s expected here: exclude

PRL 117, 082002 (2016)
Model-independent confirmation

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PRL 117, 082002 (2016)
Cabibbo suppressed decays

$$\Lambda_b^0 \rightarrow J/\psi p\pi^-$$
\[ \Lambda_b^0 \to J/\psi p\pi^- \]

- Find the same \( P_c^+ \) in other channels is helpful to understand \( P_c^+ \) production mechanism and internal structure

- Two \( P_c^+ \) production mechanisms predicted:
  - \( b \to c \)
  - \( b \to u \) & \( c\bar{c} \) from sea quarks

\[
R_{\pi/K} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} = 0.07 \sim 0.08
\]

[Cheng, PRD 92, 096009 (2015)]

\[
R_{\pi/K} = 0.58 \pm 0.05
\]

[Hsiao, PLB 751, 572 (2015)]
$\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- $\varepsilon$ is $\sim 8\%$ of the favored $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays
- But more complex because of possible $Z_c^- \rightarrow J/\psi\pi^-$

PRL 117, 082003 (2016)
Amplitude Analysis

\[ |\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b} = \pm \frac{1}{2}} \sum_{\lambda_p = \pm \frac{1}{2}} \sum_{\Delta \lambda_\mu = \pm 1} \mathcal{M}^{N*}_{\lambda_{\Lambda_b}, \lambda_p, \Delta \lambda_\mu} + e^{i \Delta \lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c}, \lambda_p} (\theta_p) \mathcal{M}^{P_c}_{\lambda_{\Lambda_b}, \lambda_p^{P_c}, \Delta \lambda_\mu} \]

\[ + e^{i \Delta \lambda_\mu Z_c} \sum_{\lambda_p^{Z_c}} e^{i \lambda_p^{Z_c} \alpha_p^{Z_c}} d^{\frac{1}{2}}_{\lambda_p^{Z_c}, \lambda_p} (\theta_p^{Z_c}) \mathcal{M}^{Z_c}_{\lambda_{\Lambda_b}, \lambda_p^{Z_c}, \Delta \lambda_\mu} \]

Additional \( Z_c^- \) decay chain
\textbf{\(N^*\) resonance models}

<table>
<thead>
<tr>
<th>State</th>
<th>(J^P)</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>RM</th>
<th>EM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N(p\pi))</td>
<td>1/2(^-)</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>(N(1440))</td>
<td>1/2(^+)</td>
<td>1430</td>
<td>350</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(N(1520))</td>
<td>3/2(^-)</td>
<td>1515</td>
<td>115</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>(N(1535))</td>
<td>1/2(^-)</td>
<td>1535</td>
<td>150</td>
<td>4</td>
<td>4</td>
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<tr>
<td>(N(1650))</td>
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<td>1655</td>
<td>140</td>
<td>1</td>
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<tr>
<td>(N(1675))</td>
<td>5/2(^-)</td>
<td>1675</td>
<td>150</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>(N(1680))</td>
<td>5/2(^+)</td>
<td>1685</td>
<td>130</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>(N(1700))</td>
<td>3/2(^-)</td>
<td>1700</td>
<td>150</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>(N(1710))</td>
<td>1/2(^+)</td>
<td>1710</td>
<td>100</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
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<td>1720</td>
<td>250</td>
<td>3</td>
<td>5</td>
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<tr>
<td>(N(1875))</td>
<td>3/2(^-)</td>
<td>1875</td>
<td>250</td>
<td>-</td>
<td>3</td>
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<tr>
<td>(N(1900))</td>
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<tr>
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<td>2190</td>
<td>500</td>
<td>-</td>
<td>3</td>
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<tr>
<td>(N(2300))</td>
<td>1/2(^+)</td>
<td>2300</td>
<td>340</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>(N(2570))</td>
<td>5/2(^-)</td>
<td>2570</td>
<td>250</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>

Free parameters | 40 | 106

\(LS\) couplings allow for reduction of the number of free parameters by excluding high \(L\) values.

Flatté: Reduce Model for central value, Extended model for significance and syst.
Amplitude model

- Almost as many free parameters as in $\Lambda_b^0 \rightarrow J/\psi pK^-$
- Fixed $m_0$ and $\Gamma_0$ for the $N^*$ and exotic states
- $Z_c(4200)$: 10 free parameters
- Each $P_c$: 4 free parameters + 6 fixed to that from $\Lambda_b^0 \rightarrow J/\psi pK^-$
Significance of the two $P_c^+$ and $Z_c(4200)^-$ together is $3.1\sigma$.

Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p\pi^-$!
Further results

- If assume production of $Z_c(4200)^-$ is negligible, significance of two $P_c^+$ is 3.3σ
- Overall, $P_c^+$ productions are consistent between the two $\Lambda_b^0$ decays

PRL 117, 082003 (2016)

<table>
<thead>
<tr>
<th>State</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(4200)^-$</td>
<td>$7.7 \pm 2.8^{+3.4}_{-4.0}$</td>
</tr>
<tr>
<td>$P_c(4380)^+$</td>
<td>$5.1 \pm 1.5^{+2.6}_{-1.6}$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$1.6^{+0.8+0.6}_{-0.6-0.5}$</td>
</tr>
</tbody>
</table>

✗ Another prediction $R_{\pi/K} = 0.58 \pm 0.05$ is ruled out

($b \to u \& c\bar{c}$ from sea quarks)

[Cheng, PRD 92, 096009 (2015)]

[Hsiao, PLB 751, 572 (2015)]
What’s a pentaquark
Table:

<table>
<thead>
<tr>
<th>Hadronic molecules</th>
<th>Tightly-bounded states</th>
<th>Kinematic effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close to two heavy hadron thresholds</td>
<td>Predicted more than 10 $J^P$ states</td>
<td>Predicted no decay of $P_c(4450)^+ \rightarrow \chi_{c1}p$</td>
</tr>
</tbody>
</table>

Diagram:

\[
\chi_{c1}p \rightarrow J/\psi p
\]

Some explanations:

- Hadronic molecules
- Tightly-bounded states
- Kinematic effects

Karliner & Rosner, PRL 115 (2015) 122001

Maiani et al, PLB 749 (2015) 289

Guo et al, PRD 92 (2015) 071502

Close to two heavy hadron thresholds

Predicted more than 10 $J^P$ states

Predicted no decay of $P_c(4450)^+ \rightarrow \chi_{c1}p$
Rescattering

- As $m(\chi_{c1}p)=m(P_c(4450))$, $P_c(4450)$ is explained as $\chi_{c1}p \rightarrow J/\psi p$

- Can explain phase motion

- Hard to predict the size of the rescattering amplitude

- Experimental test: Could be killed if seeing $P_c(4450) \rightarrow \chi_{c1}p$ from $\Lambda_b \rightarrow \chi_{c1}pK^-$

Other channels
\[ \Lambda_b^0 \rightarrow \chi_{c(1,2)} p K^- \]

- Search for \( P_c(4450)^+ \) in \( \Lambda_b^0 \rightarrow \chi_{c1} p K^- \) decays ⇒ Test hypothesis of kinematic rescattering effect
- \( \chi_{c2} p \) can be used for higher mass and higher \( J P_c \) searches

\[
\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi p K^-)} = \frac{0.242 \pm 0.014 \pm 0.013 \pm 0.009}{0.248 \pm 0.020 \pm 0.014 \pm 0.009}
\]

\[
\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi p K^-)} = \mathcal{B}(\chi_{cJ})
\]

Next step: full amplitude analysis with more data
Strange pentaquark ($udsc\bar{c}$) predicted in
[PRL 105, 232001 (2010)]

Can be searched for in the $E_b^-$ decay
[PRC 93, 065203 (2016)]

$N_{\text{sig}} = 308 \pm 21 \ (21\sigma)$

PLB 772 (2017) 265-273

Expect $\sim$1500 signals after 2018 for amplitude analysis
Other $P_c$ channels

- **LHCb ongoing activities**
  - Hadronic: $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-$
  - $J=1/2\ P_c^+$ in $\Lambda_b^0 \rightarrow \eta_c p K^-$
  - **Direct production:** background is high in low $p_T$, other LHC experiment can do it in high $p_T$?
  - **Generic pentaquarks:** $[\bar{b}qqqq]$ and $[\bar{c}qqqq]$  

- **From non-hadron collider experiment:**
  - Photon production: $\gamma p \rightarrow J/\psi p$ could be done at JLab
  - $e^+e^-(\Upsilon) \rightarrow J/\psi p\bar{p}$

Yields: at least 1/10 smaller than ideal mode $J/\psi p$
Conclusions

- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$.  
  PRL 115, 072001 (2015)
  PRL 117, 082002 (2016)
- They are confirmed by a model-independent way
- They have spin 3/2 & 5/2 & opposite Parity
- $P_c^+$ productions are consistent between the two $\Lambda_b^0$ decays  
  PRL 117, 082003 (2016)
- Determination of their internal binding will require more study

- We are updating results with Run-II data and improved modelling
- Also more channels, stay tuned
Thanks for your attention
No convincing states 50 years after Gell-mann paper proposing \(qqqqq\) states

Prediction: \(\Theta^+ (uudd\bar{s})\) could exist with \(m \approx 1530\) MeV

In 2003, 10 experiments reported evidences of narrow peaks of \(K^0p\) or \(K^+n\), all >4 \(\sigma\)

High statistics repeats from JLab showed the original claims were fluctuation

It was merely a case of “bump hunting”

Detector performance

<table>
<thead>
<tr>
<th>Detector Performance</th>
<th>PID</th>
<th>Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertexing</strong></td>
<td><strong>PID</strong></td>
<td><strong>Tracking</strong></td>
</tr>
<tr>
<td>$B_s^0$ oscillations with $B_s^0 \rightarrow D_s\pi$</td>
<td>$K/\pi$ ID efficiency and misID rate</td>
<td>$\mu^+\mu^-$ mass spectrum</td>
</tr>
</tbody>
</table>

**Impact parameter:**
- $\sigma_{IP} = 20 \, \mu m$

**Proper time:**
- $\sigma_\tau = 45 \, fs$ for $B_s^0 \rightarrow J/\psi \phi$ or $D_s^+\pi^-$
- $\Delta p/p = 0.4 \sim 0.6\% \ (5 - 100 \, GeV/c)$

**Momentum:**
- $\sigma_m = 8 \, MeV/c^2$ for $B \rightarrow J/\psi X$ (constrained $m_{J/\psi}$)

**Mass:**
- $\epsilon(K \rightarrow K) \sim 95\%$ mis-ID $\epsilon(\pi \rightarrow K) \sim 5\%$
- $\epsilon(\mu \rightarrow \mu) \sim 97\%$ mis-ID $\epsilon(\pi \rightarrow \mu) \sim 1 - 3\%$

**RICH $K - \pi$ separation:**

**Muon ID:**

**ECAL:**
- $\Delta E/E = 1 \oplus 10\% / \sqrt{E(\text{GeV})}$
$\Lambda_{b}^{0} \rightarrow J/\psi pK^{-}$ candidate
Cross-checks

- Many done, some listed here:
- Signal found using different selections by others
- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\bar{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
- Selection varied
  - BDTG>0.5 instead of 0.9 (default)
  - $B^0$ and $B_s$ misID background modeled in the fit instead of veto
Pentaquark models

- All models must explain $J^P$ of two states not just one. They also should predict properties of other states: masses, widths, $J^P$.

- Many models: Let's start with **tightly bound quarks** ala' Jaffe
  - Two colored diquarks plus the anti-quark, L. Maiani, et. al, [arXiv:1507.04980]
  - Colored diquark + colored triquark, R. Lebed [arXiv:1507.05867]
Molecular models

- Molecular models, generally with meson exchange for binding
- Inspired by proximity of baryon-meson mass sums to $P_c$ masses

Possible decay modes

<table>
<thead>
<tr>
<th></th>
<th>$\chi_{c1}p$</th>
<th>$\Sigma_c\bar{D}$*</th>
<th>$\Lambda_c^*\bar{D}$</th>
<th>$J/\psi N^*$</th>
<th>$\Sigma_c^*\bar{D}$</th>
<th>$J/\psi N^<em>$</em></th>
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<td>×</td>
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<td>×</td>
<td>×</td>
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<td>×</td>
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</table>

[Burns arXiv:1509.02460]
Extended model with 2 $P_c$'s
Amplitude formalism \( V \)

- They are summed as:

\[
|M|^2 = \sum_{\lambda_{\mu}^0} \sum_{\lambda_\mu} \sum_{\Delta \lambda_\mu} |M_{\lambda_{\mu}^0, \lambda_\mu, \Delta \lambda_\mu}^* + e^{i \Delta \lambda_\mu \alpha_\mu} \sum_{\lambda_{\mu}^P} \frac{1}{d_{\lambda_{\mu}^P}} \alpha_{\mu} \theta \mathcal{M}_{\lambda_{\mu}^P, \lambda_{\mu}^P, \Delta \lambda_\mu}^P|^2
\]

- \( \alpha_\mu \) and \( \theta \) are rotation angles needed to align the final state helicity axes of the \( \mu \) and \( p \), as the initial helicity frames are different for the two decay chains.

- Helicity couplings \( \mathcal{H} \Rightarrow \) LS amplitudes \( B \) via:

\[
\mathcal{H}_{\lambda_B, \lambda_C}^{A \rightarrow BC} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_{A'1}}} B_{L, S} \left( \begin{array}{cc}
J_B & J_C \\
\lambda_B & -\lambda_C \\
\end{array} \right) \left( \begin{array}{cc}
S & \\
\lambda_B - \lambda_C & \\
\end{array} \right) \times \left( \begin{array}{cc}
L & S \\
0 & \lambda_B - \lambda_C \\
\end{array} \right) \left( \begin{array}{c}
J_A \\
\lambda_B - \lambda_C \\
\end{array} \right)
\]

- Convenient way to enforce parity conservation in the strong decays via: \( P_A \)
LHCb goals

- Find or establish limits on physics beyond the standard model using CP violating & rare beauty & charm decays

- Rare: \( B_{(s)} \rightarrow \mu^+\mu^- \), \( B^0 \rightarrow K^*\mu^+\mu^- \), \( B^- \rightarrow K\epsilon^+\epsilon^-/K\mu^+\mu^- \)

- CP violation: determine \( \angle \)'s: \( \gamma, \beta, \phi_s \)
  - \( \gamma \) measured with \( B^- \rightarrow D^0 K^- \) decays
  - \( \phi_s \) measured with \( B_s \rightarrow J/\psi\phi \) & \( J/\psi \pi^+\pi^- \) decays
  - All \( B \rightarrow J/\psi \pi^+\pi^- \) & \( J/\psi K^+K^- \) studied
  - In study of \( B^0 \rightarrow J/\psi K^+K^- \) [arXiv:1308.5916], \( \Lambda_b \rightarrow J/\psi K^-p \) was suggested as a potential background
Our fit explains $m(J/\psi K^-)$

- M(Kp)$<1.55$ GeV
- $1.55<M(Kp)<1.70$ GeV
- $1.70<M(Kp)<2.00$ GeV
- $2.00$ GeV$<M(Kp)$
- All M(Kp)
Significances

- To include systematic uncertainty, the extended model fits are used

- Fit improves greatly, for $1 \, P_c \, \Delta(-2\ln \mathcal{L})=14.7^2$, adding the $2^{nd} \, P_c$ improves by $11.6^2$, for adding both together $\Delta(-2\ln \mathcal{L})=18.7^2$

- Toy MCs are used to obtain significances based on $\Delta(-2\ln \mathcal{L})$

- Significances:
  - $1^{st} \, P_c \, (4450)^+ : \, 12\sigma$
  - $2^{nd} \, P_c \, (4380)^+ : \, 9 \sigma$
  - Total : $15\sigma$
Measurement of $\Lambda_b^0/B^0$ lifetime

- Long history of a puzzling discrepancy between $\Lambda_b$ and $B^0$ lifetime
- Heavy Quark Expansion (HQE) predicts similar lifetime
- With our precision measurements, this story now ends

Experiment
- LHCb (2014) Average
- LHCb 1/fb (2014) [J/$\psi$Λ]
- LHCb 3/fb (2014) [J/$\psi$K$^*$]
- LHCb 1/fb (2013) [J/$\psi$K$^*$]
- CMS (2012) [J/$\psi$Λ]
- ATLAS (2012) [J/$\psi$Λ]
- D0 (2012) [J/$\psi$Λ]
- CDF (2011) [J/$\psi$Λ]
- CDF (2010) [$\Lambda_c^+\pi^-$]
- D0 (2007) [J/$\psi$Λ]
- D0 (2007) [Semileptonic decay]
- DLPH (1999) [Semileptonic decay]
- ALEP (1998) [Semileptonic decay]
- OPAL (1998) [Semileptonic decay]
- CDF (1996) [Semileptonic decay]