Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b \rightarrow J/\psi pK^- \rightarrow$ decays

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On behalf of the LHCb Collaboration
Tetra- and Penta-quarks conceived at the birth of Quark Model

A Schematic Model of Baryons and Mesons

M. Gell-Mann
California Institute of Technology, Pasadena, California

Received 4 January 1964

... A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon if we assign to the triplet the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^3$, $d^3$, and $s^3$ of the triplet as "quarks" $\bar{q}$ and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q q)$, etc., while mesons are made out of $(q \bar{q})$, $(q q q)$, etc. It is assuming that the lowest baryon configuration $(q q q)$ gives just the representations 1, 8, and 10 that have been observed, while

- Searches for such states made out of the light quarks $(u, d, s)$ are ~50 years old, but no undisputed experimental evidence have been found for them
Two waves of past pentaquark claims (with s)

Baryons

$Z^*$s, $Z_0(1780)$, $Z_0(1865)$, $Z_1(1900)$

$S=1$ $I=0$ EXOTIC STATES ($Z_0$)

Last mention of baryonic $Z^*$s PDG 1992

Found/debunked by looking for "bumps" in mass spectra

Last mention of 2nd pentaquark wave: PDG 2006

In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only $u,d$, and $s$ quarks, Diakonov et al.

To summarize, with the exception described in the previous 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.
“XYZ” States

- Several charmonium and bottomonium-like states have been observed by several different experiments.
- These states do not fit into the conventional quark model and are candidates for tetraquarks.
- Example: The Z(4430) is a $c\bar{c}d\bar{u}$ candidate first seen by Belle in 2007 and confirmed in 2014 by LHCb.

- Despite the history of pentaquarks, the discovery of strong tetraquark candidates makes their existence appear more plausible!
The LHCb detector


- Forward arm spectrometer designed for precision CP violation measurements and decays of bottom and charm hadrons.
- Rapidity coverage $2.0 < \gamma < 4.5$
- Excellent particle identification:
  - Muons: $\varepsilon \sim 97\%$ for $1 - 3\% \pi \rightarrow \mu$ misidentification
  - Kaons: $\varepsilon \sim 95\%$ for $5\% \pi \rightarrow K$ misidentification
- Very good vertex resolution: $\sigma = 20\mu m$ impact parameter resolution
- Momentum resolution $\Delta p/p = 0.5\%$ at 20GeV to 0.8\% at 100 GeV
$\Lambda_b^0 \to J/\psi \ p K^-$ Selection

- The data sample consists of the full LHCb Run 1 data set of 3fb$^{-1}$
- Candidates have a $(\mu^+ \mu^-) K p$ vertex, with the $(\mu^+ \mu^-)$ pair consistent with a $J/\psi$

- Standard selection to ensure good track and vertex quality, as well as cuts on particle identification, $p_T$ cuts, and separation from the primary vertex.
- Reflections from $B^0$ and $B_s$ are vetoed.
- Final background suppression is done with a multivariate analyzer (boosted decision tree).
The decay first observed by LHCb and used to measure \( \Lambda_b^0 \) lifetime

\[ \Lambda_b^0 \rightarrow J/\psi \ p \ K^- \text{ At LHCb} \]

- The sideband distributions are flat → no major reflections from the other b-hadrons after the selection
- The background is only 5.4% in the signal region!

26,007\( \pm \)166 \( \Lambda_b^0 \) candidates

- The decay first observed by LHCb and used to measure \( \Lambda_b^0 \) lifetime

\[ \text{PRL 111, 102003 (2013)} \]
An unexpected structure in $m_{J/\psi p}$

$\Lambda(1520)$ and other $\Lambda^*$'s $\rightarrow p K^-$

Unexpected narrow peak in $m_{J/\psi p}$!
Necessary Checks

- Many checks done to ensure it is not an “artifact” of selection:
  - Efficiency across Dalitz plane is smooth, wouldn’t create peaking structures.
  - The same $P_c^+$ structure found using very different selections by different LHCb teams
  - Split data shows consistency: 2011/2012, magnet up/down, $\Lambda_b/\bar{\Lambda}_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
  - Exclude $\Xi_b$ or other high mass decays as a possible source
  - Veto $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$ decays
  - Suppress fake tracks: the peak is not an experimental artifact.
Amplitude Analysis of $\Lambda_b^0 \rightarrow J/\psi pK^-$, $J/\psi \rightarrow \mu^+\mu^-$

• Could it be a reflection of interfering $\Lambda^*$'s $\rightarrow p K^-$?
  – Full amplitude analysis absolutely necessary!

• Analyze all dimensions of the decay kinematics for
  $\Lambda_b^0 \rightarrow J/\psi pK^-$, $J/\psi \rightarrow \mu^+\mu^-$:
  – to maximize sensitivity to the decay dynamics
  – to avoid biases due to averaging over some dimensions in presence of non-uniform detector efficiency

• Our PDF used in the fit is:

  $$\mathcal{P}_{\text{sig}}(m_{Kp}, \Omega | \omega) = \frac{1}{I(\omega)} |\mathcal{M}(m_{Kp}, \Omega | \omega)|^2 \Phi(m_{Kp}) \epsilon(m_{Kp}, \Omega)$$

- Fitted parameters (helicity couplings, $M_0, \Gamma_0$)

- Matrix element describing decay
- Phase space factor
- Selection efficiency
- Normalization integral
Background modeling

The remaining background can be handled in two ways. In the fit we minimize:

\[-2 \ln \mathcal{L}(\omega) = -2s_W \sum_i W_i \ln \mathcal{P}(m_{Kp}, \Omega_i | \omega)\]

\[s_W \equiv \frac{\sum_i W_i}{\sum_i W_i^2}\]

“sFit”

- \(W_i\) are sWeights (arXiv:0402083v3) based on the fit to \(m_{J/\psi pK}\) distribution
- Negative weights correspond to background events, and are used to subtract the background in the likelihood.
- The data in the extended \(m_{J/\psi pK}\) range including the sidebands is passed to the amplitude fit
The remaining background can be handled in two ways. In the fit we minimize:

$$
-2 \ln \mathcal{L}(\omega) = -2 s_W \sum_i W_i \ln \mathcal{P}(m_{K_p i}, \Omega_i | \omega)
$$

$$
s_W \equiv \sum_i W_i / \sum_i W_i^2
$$

"cFit" (default method)

- $W_i = 1$; no event weights. Sideband data used to construct 6D model of the background which is added to the signal PDF:

$$
\mathcal{P}(m_{K_p}, \Omega | \omega) = (1 - \beta) \mathcal{P}_{\text{sig}}(m_{K_p}, \Omega | \omega) + \beta \mathcal{P}_{\text{bkg}}(m_{K_p}, \Omega)
$$

$\beta = 5.4\%$ background fraction

- Data only in the $\Lambda_b^0$ signal range passed to the amplitude fit.
- Fitters using cFit and sFit were coded completely independently and used to cross-check each other.
Helicity Formalism

- The matrix element for these decays is written using the helicity formalism.

- Each sequential decay $A \to BC$ of a spin $J_A$ resonance adds a term:

\[
\mathcal{H}_{\lambda_B,\lambda_C}^{A \to BC} \ D_{\lambda_A,\lambda_B-\lambda_C}^{J_A} (\phi_B,\theta_A,0) * R_A(m_{BC})
\]

- $R_A(m_{BC})$ is the resonance parametrization used if $A$ has a non-negligible natural width.

- The three arguments of Wigner’s D-matrix are Euler angles describing the rotation from helicity frame of $A$ to helicity frame of $B$. 
\( \Lambda^* \) Matrix Element

\[ \Lambda_b \text{ rest frame} \]

\[ \phi_\Lambda = 0 \]

\[ \Lambda^* \text{ rest frame} \]

\[ \phi_K \]

\[ \theta^\prime \]

\[ m \rightarrow \Lambda^* J/\psi \text{ with } \Lambda^* \rightarrow Kp \text{ and } J/\psi \rightarrow \mu\mu \]

4-6 independent complex helicity couplings per \( \Lambda_{n}^* \) resonance

6 independent data variables:
1 mass, 5 angles

\[ M^{\Lambda^*}_{\lambda_{\Lambda_0}, \lambda_p, \Delta \lambda_{\mu}} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_{\psi}} \mathcal{H}^{\Lambda_0 \rightarrow \Lambda^*_n \psi}_{\lambda_{\Lambda_b}, \lambda_{\psi}} D_{\lambda_{\Lambda_0}, \lambda_{\Lambda^*} - \lambda_{\psi}}^{1/2} (0, \theta_{\Lambda_{b}}, 0)^* \]

\[ \mathcal{H}^{\Lambda_{n}^* \rightarrow Kp}_{\lambda_{\Lambda^*_n}, \lambda_{p}} D_{\lambda_{\Lambda^*_n}, \lambda_{\psi}}^{J_{\Lambda^*_n}} R_n (m_{KP}) D_{\lambda_{\psi}, \Delta \lambda_{\mu}}^{1} (\phi_{\mu}, \theta_{\psi}, 0)^* \]

\[ R_X (m) = B_{L_X}^\prime (p, p_0, d) \left( \frac{p}{M_{\Lambda_0}} \right)^{L_{X \Lambda_0}} \text{ BW}(m | M_{0X}, \Gamma_{0X}) B_{L_X}^\prime (q, q_0, d) \left( \frac{q}{M_{0X}} \right)^{L_X} \]

\[ \text{ BW}(m | M_{0X}, \Gamma_{0X}) = \frac{1}{M_{0X}^2 - m^2 - iM_{0X}\Gamma(m)} \]

Blatt-Weisskopf functions

Breit-Wigner
**Λ* resonance model**

- Large number of possibly contributing resonances, each contributing $4\text{-}6$ complex amplitudes.
- $\Sigma^* \rightarrow pK^-$ contributions would have $\Delta I = 1$ and are excluded, based off expectation that they’re suppressed in analogy with $\Delta I = 1/2$ rule in kaon decays.

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># amplitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda (1405)$</td>
<td>$1/2^-$</td>
<td>$1405.1^{+1.3}_{-1.0}$</td>
<td>$50.5 \pm 2.0$</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>6</td>
</tr>
<tr>
<td>$\Lambda (1600)$</td>
<td>$1/2^+$</td>
<td>$1600$</td>
<td>$150$</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda (1670)$</td>
<td>$1/2^-$</td>
<td>$1670$</td>
<td>$35$</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda (1690)$</td>
<td>$3/2^-$</td>
<td>$1690$</td>
<td>$60$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (1800)$</td>
<td>$1/2^-$</td>
<td>$1800$</td>
<td>$300$</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda (1810)$</td>
<td>$1/2^+$</td>
<td>$1810$</td>
<td>$150$</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda (1820)$</td>
<td>$5/2^+$</td>
<td>$1820$</td>
<td>$80$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (1830)$</td>
<td>$5/2^-$</td>
<td>$1830$</td>
<td>$95$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (1890)$</td>
<td>$3/2^+$</td>
<td>$1890$</td>
<td>$100$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (2100)$</td>
<td>$7/2^-$</td>
<td>$2100$</td>
<td>$200$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (2110)$</td>
<td>$5/2^+$</td>
<td>$2110$</td>
<td>$200$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (2350)$</td>
<td>$9/2^+$</td>
<td>$2350$</td>
<td>$150$</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda (2585)$</td>
<td>$5/2^-$</td>
<td>$\approx 2585$</td>
<td>$200$</td>
<td>6</td>
</tr>
</tbody>
</table>
\( \Lambda^* \) resonance model

- We use two models in our fits to study the dependence on \( \Lambda^* \) model.
- “Extended model” includes all states, all possible amplitudes

<table>
<thead>
<tr>
<th>State</th>
<th>( J^P )</th>
<th>( M_0 ) (MeV)</th>
<th>( \Gamma_0 ) (MeV)</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>4</td>
</tr>
<tr>
<td>( \Lambda(1520) )</td>
<td>3/2(^-)</td>
<td>( 1519.5 \pm 1.0 )</td>
<td>15.6 ± 1.0</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1600) )</td>
<td>1/2(^+)</td>
<td>1600</td>
<td>150</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1670) )</td>
<td>1/2(^-)</td>
<td>1670</td>
<td>35</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1690) )</td>
<td>3/2(^-)</td>
<td>1690</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1800) )</td>
<td>1/2(^-)</td>
<td>1800</td>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1810) )</td>
<td>1/2(^+)</td>
<td>1810</td>
<td>150</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1820) )</td>
<td>5/2(^+)</td>
<td>1820</td>
<td>80</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1830) )</td>
<td>5/2(^-)</td>
<td>1830</td>
<td>95</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1890) )</td>
<td>3/2(^+)</td>
<td>1890</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2100) )</td>
<td>7/2(^-)</td>
<td>2100</td>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2110) )</td>
<td>5/2(^+)</td>
<td>2110</td>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2350) )</td>
<td>9/2(^+)</td>
<td>2350</td>
<td>150</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2585) )</td>
<td>5/2(^-)?</td>
<td>( \approx 2585 )</td>
<td>200</td>
<td>6</td>
</tr>
</tbody>
</table>

Total fit parameters: 146
**Λ⁺ resonance model**

- Helicity couplings are rewritten in terms of LS couplings:

\[
\mathcal{H}_{\Lambda_B \Lambda_C}^{A \to BC} = \sum_{L} \sum_{S} \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \left( \begin{array}{c|c} J_B & J_C \\ \lambda_B & -\lambda_C \end{array} \right) \times \left( \begin{array}{c|c} S & \lambda_A \\ \lambda_B & -\lambda_C \end{array} \right)
\]

- Reduced model excludes high-mass, high-spin states and also places limitations on L

<table>
<thead>
<tr>
<th>State</th>
<th>J^P</th>
<th>M₀ (MeV)</th>
<th>Γ₀ (MeV)</th>
<th># Reduced</th>
<th># Extended</th>
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<tr>
<td>Λ(1405)</td>
<td>1/2⁻</td>
<td>1405.1 ± 1.3</td>
<td>50.5 ± 2.0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Λ(1520)</td>
<td>3/2⁻</td>
<td>1519.5 ± 1.0</td>
<td>15.6 ± 1.0</td>
<td>5</td>
<td>6</td>
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<tr>
<td>Λ(1600)</td>
<td>1/2⁺</td>
<td>1600</td>
<td>150</td>
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<tr>
<td>Λ(1670)</td>
<td>1/2⁻</td>
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<tr>
<td>Λ(1690)</td>
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<td>1690</td>
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<tr>
<td>Λ(1800)</td>
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<tr>
<td>Λ(1810)</td>
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<td>150</td>
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<tr>
<td>Λ(1820)</td>
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<td>80</td>
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<td>Λ(1830)</td>
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<td>95</td>
<td>1</td>
<td>6</td>
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<tr>
<td>Λ(1890)</td>
<td>3/2⁺</td>
<td>1890</td>
<td>100</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Λ(2100)</td>
<td>7/2⁻</td>
<td>2100</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Λ(2110)</td>
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<td>2110</td>
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<tr>
<td>Λ(2350)</td>
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<tr>
<td>Λ(2585)</td>
<td>5/2⁻</td>
<td>≈2585</td>
<td>200</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

Total fit parameters: 64, 146
So is it just a reflection?

• Can interfering $\Lambda^*$ resonances reproduce the peaking structure seen in $m_{J/\psi p}$?
• We use the extended model to answer this, with the philosophy being that we should throw everything we can at it before introducing pentaquark states.
Fit with $\Lambda^* \rightarrow pK^-$ contributions only

- $m_{Kp}$ looks fine, but $m_{J/\psi p}$ looks terrible
- Addition of non-resonant terms, $\Sigma^*$'s or extra $\Lambda^*$'s doesn't help.
- There is no ability to describe the peaking structure with conventional resonances!
$P_c^+$ Matrix Element

Completely describes the decay $\Lambda_b \to P_c K$ with $P_c \to J/\psi p$ and $J/\psi \to \mu\mu$

One more angle than in $\Lambda^*$ decay: $P_c^+$ production angles must be defined relative to the $\Lambda_b$ reference frame established for $\Lambda_b \to J/\psi \Lambda^*$ decay

3-4 independent complex helicity couplings per $P_{c,j}^+$ resonance depending on its $J^P$

$$M^{P_c}_{\lambda_{\Lambda_b}^0, \lambda_p^{P_c}, \Delta \lambda_{P_c}^{P_c}} = \sum_j \sum_{\lambda_{P_c}^{P_c}} \sum_{\lambda_{\psi}^{P_c}} \mathcal{H}^{P_{c,j} \to \psi p}_{\lambda_{\psi}^{P_c}, \lambda_p^{P_c}} \mathcal{D}^{1/2}_{\lambda_{\Lambda_b}^0, \lambda_{P_c}^{P_c}} (\phi_{P_c}, \theta_{P_c}, 0)^*$$

$$\mathcal{H}^{P_{c,j} \to \psi p}_{\lambda_{\psi}^{P_c}, \lambda_p^{P_c}} = J_{P_{c,j}} \mathcal{D}^{1}_{\lambda_{\psi}^{P_c}, \lambda_p^{P_c}} (\phi_{\psi}, \theta_{P_c}, 0)^* R_{P_{c,j}} (m_{\psi p})$$

$1$ mass ($m_{J/\psi p}$), $6$ angles all derivable from the $\Lambda^*$ decay variables

$\Lambda_b \to J/\psi \Lambda^*$ decay

Breit-Wigner

Blatt-Weisskopf functions
\( \Lambda^* \) Plus \( P_c^+ \) Matrix Element

- To add the two matrix elements together we need two additional angles to align the muon and proton helicity frames between the \( \Lambda^* \) and \( P_c \) decay chains.
  - This is necessary to describe \( \Lambda^* \) plus \( P_c^+ \) interferences properly

With \( \theta_p \), \( \alpha_\mu \) the full matrix element is written as

\[
|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda^*_0}} \sum_{\lambda_p} \sum_{\Delta \lambda_\mu} \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda^*_0}, \lambda_p, \Delta \lambda_\mu} + e^{i \Delta \lambda_\mu \alpha_\mu} \sum_{\lambda_{P_c}} \frac{1}{d_{\lambda_{P_c}, \lambda_p}(\theta_p)} |\mathcal{M}|^2_{\lambda_{\Lambda^*_0}, \lambda_{P_c}, \Delta \lambda_\mu}
\]
Fit with $\Lambda^*$'s and one $P_c^+ \rightarrow J/\psi p$ state

- Try all $J^P$ of $P_c^+$ up to $7/2^\pm$
- Best fit has $J^P = 5/2^\pm$. Still not a good fit
Fit with $\Lambda^*$’s and two $P_c^{+}\rightarrow J/\psi p$ states

- With two $P_c$ resonances we are able to describe the peaking structure!
- Obtain good fits even with the reduced $\Lambda^*$ model
- Best fit has $J^P (P_c(4380), P_c(4450))=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ are preferred

PRL 115, 072001 (2015)
Fit with $\Lambda^*$'s and two $P_c^+ \rightarrow J/\psi p$ states

- Need for the 2$^{nd}$ broad $P_c^+$ state becomes visually apparent in the region where the $\Lambda^* \rightarrow pK^-$ background is the smallest
Angular distributions

All data

P_c enriched region

- Good description of the data in all 6 dimensions!

PRL 115, 07201 (2015)
No need for exotic $J/\psi K^-$ contributions

- $J/\psi K^-$ system is well described by the $\Lambda^{*}$ and $P_c^+$ reflections.

\[ m_{Kp} < 1.55 \text{ GeV} \]
\[ 1.55 < m_{Kp} < 1.70 \text{ GeV} \]
\[ 1.70 < m_{Kp} < 2.00 \text{ GeV} \]
\[ m_{Kp} > 2.00 \text{ GeV} \]

\[ P_c \]

\[ P_{c1}(4450) \]
\[ P_{c2}(4380) \]
\[ \Lambda(1405) \]
\[ \Lambda(1520) \]
\[ \Lambda(1600) \]
\[ \Lambda(1610) \]
\[ \Lambda(1670) \]
\[ \Lambda(1690) \]
\[ \Lambda(1800) \]
\[ \Lambda(1810) \]
\[ \Lambda(1820) \]
\[ \Lambda(1830) \]
\[ \Lambda(1890) \]

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PRL 115, 07201 (2015)
Data preference for opposite parity $P_c^+$ states

- Two opposite parity states necessary to generate the interference pattern

- Positive interference between the $P_c$ states
- Negative interference between the $P_c$ states

Events/(20 MeV) vs. $m_{Kp}$

LHCb

PRL 115, 07201 (2015)
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>Fit fractions (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Extended vs. reduced</td>
<td>21</td>
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<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>$L_{Pc}^c \Lambda_b^0 \rightarrow P_c^+ (low/ high) K^-$</td>
<td>6</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>$L_{Pc}^c P_c^+ (low/ high) \rightarrow J/\psi p$</td>
<td>4</td>
<td>0.4</td>
<td>31</td>
</tr>
<tr>
<td>$L_{\Lambda^<em>}^c \Lambda_b^0 \rightarrow J/\psi \Lambda^</em>$</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>

- **Uncertainties in the $\Lambda^*$ model dominate**
- **Quantum number assignment and resonance parametrization are also sizeable.**
Results

- Parameters of the $P_c^+$ states (and F.F. of well isolated $\Lambda^*$’s )

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$205 \pm 18 \pm 86$</td>
<td>$8.4 \pm 0.7 \pm 4.2$</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>$4.1 \pm 0.5 \pm 1.1$</td>
</tr>
<tr>
<td>$\Lambda(1405)$</td>
<td>$15 \pm 1 \pm 6$</td>
<td></td>
<td>$15 \pm 1 \pm 6$</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$19 \pm 1 \pm 4$</td>
<td></td>
<td>$19 \pm 1 \pm 4$</td>
</tr>
</tbody>
</table>

- With the $\mathcal{B}(\Lambda_b^0 \to J/\psi \ p \ K^-)$ measurement (arXiv:1509.00292) we can also calculate the branching fractions:

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = \begin{cases} 
(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5} & \text{for } P_c(4380)^+ \\
(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5} & \text{for } P_c(4450)^+ 
\end{cases}$$
Significances

- Significances assessed using the extended model.
- This includes the dominant systematic uncertainties, coming from difference between extended and reduced Λ* model results.
- Fit quality improves greatly, and simulations of pseudoexperiments are used to turn the $\Delta(-2\ln \mathcal{L})$ values to significances.

<table>
<thead>
<tr>
<th>State</th>
<th>$\Delta(-2\ln \mathcal{L})$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \rightarrow 1 P_c$</td>
<td>$14.7^2$</td>
<td>$12\sigma$</td>
</tr>
<tr>
<td>$1 \rightarrow 2 P_c$</td>
<td>$11.6^2$</td>
<td>$9\sigma$</td>
</tr>
<tr>
<td>$0 \rightarrow 2 P_c$</td>
<td>$18.7^2$</td>
<td>$15\sigma$</td>
</tr>
</tbody>
</table>

- Each of the states is overwhelmingly significant.
Resonance Phase Motion

- Relativistic Breit-Wigner function is used to model resonances

\[ BW(m|M_0, \Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0 \Gamma(m)} \quad \text{,} \quad \Gamma(m) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2L+1} \frac{M_0}{m} B_L'(q, q_0, d)^2 \]

- The complex function \( BW(m|M_0, \Gamma_0) \) displayed in an Argand diagram exhibits a circular trajectory.
Resonance Phase Motion

- The Breit-Wigner shape for individual $P_c$’s is replaced with 6 independent amplitudes in $M_0 \pm \Gamma_0$
- $P_c(4450)$: shows resonance behavior: a rapid counterclockwise change of phase across the pole mass
- $P_c(4380)$: does show large phase change, but is not conclusive.

[Graph showing fitted values in an Argand diagram with points labeled $P_c(4450)$ and $P_c(4380)$]
Interpretations of the states

- Already ~50 citations on the arXiv, with a variety of models being proposed.
- Most common models employ molecular binding or additional hadron building blocks of diquarks or triquarks.
- Additional explanations have been offered in terms of kinematical effects. However these cannot explain two states.
Where else to look for these pentaquarks?

- There are many ideas on where to look. None will be as ideal as the clean \( J/\psi \) signature plus two charged tracks forming a secondary vertex. This was a good channel to accidentally find this in.

- They can be looked for in decays to other charmonium states: \( \eta p, \chi_c p \)

- Or to open charm pairs: \( \Lambda_c \bar{D}, \Lambda_c \bar{D}^*, \Sigma \bar{D} \)

- Would be very interesting to see them from different sources:
  - Direct production: However there is a difficulty from huge number of protons coming from primary vertices
  - It’s been proposed to look for these states in \( \gamma p \to J/\psi p \)
    (arXiv:1508.00339, 1508.00888, and 1508.01496)
And for other pentaquarks?

- Discovery of further states is crucial for shedding light on internal bindings and the nature of these states.
- Should look for more $c\bar{c}uud$ resonances: with different charge, spin-parity, isospin
- Huge number of possibilities. One could look for them decaying to many combinations of a baryon + meson.
- Given the trend of finding exotic hadron candidates with heavy quark content, finding them in decays of $\Lambda_b$’s or other $b$-baryons is an attractive possibility.
- A systematic search should be done, as we also learn from non-observations.
Conclusions

• Two pentaquark candidates decaying to J/ψp have been observed with overwhelming significance in a state of the art amplitude analysis. Both are absolutely needed to obtain a good description of the data.

• The nature of the states is unknown. For elucidation, more sensitive studies as well as searches for other pentaquark candidates will be absolutely necessary.

• Towards this effort we continue to fully utilize the Run 1 data, and have increased statistics on the way. LHCb expects 8 fb\(^{-1}\) in Run 2 (-2018) followed by the detector/luminosity upgrade which will bring ~50 fb\(^{-1}\) by 2028.

• We look forward to more input from theory and other experiments.
BACKUP SLIDES
Table 3: Fit fractions of the different components from cFit and sFit for the default \( (3/2^-, \ 5/2^+) \) model. Uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Fit fraction (%) cFit</th>
<th>Fit fraction (%) sFit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_c(4380)^+ )</td>
<td>8.42 ± 0.68</td>
<td>7.96 ± 0.67</td>
</tr>
<tr>
<td>( P_c(4450)^+ )</td>
<td>4.09 ± 0.48</td>
<td>4.10 ± 0.45</td>
</tr>
<tr>
<td>( \Lambda(1405) )</td>
<td>14.64 ± 0.72</td>
<td>14.19 ± 0.67</td>
</tr>
<tr>
<td>( \Lambda(1520) )</td>
<td>18.93 ± 0.52</td>
<td>19.06 ± 0.47</td>
</tr>
<tr>
<td>( \Lambda(1600) )</td>
<td>23.50 ± 1.48</td>
<td>24.42 ± 1.36</td>
</tr>
<tr>
<td>( \Lambda(1670) )</td>
<td>1.47 ± 0.49</td>
<td>1.53 ± 0.50</td>
</tr>
<tr>
<td>( \Lambda(1690) )</td>
<td>8.66 ± 0.90</td>
<td>8.60 ± 0.85</td>
</tr>
<tr>
<td>( \Lambda(1800) )</td>
<td>18.21 ± 2.27</td>
<td>16.97 ± 2.20</td>
</tr>
<tr>
<td>( \Lambda(1810) )</td>
<td>17.88 ± 2.11</td>
<td>17.29 ± 1.85</td>
</tr>
<tr>
<td>( \Lambda(1820) )</td>
<td>2.32 ± 0.69</td>
<td>2.32 ± 0.65</td>
</tr>
<tr>
<td>( \Lambda(1830) )</td>
<td>1.76 ± 0.58</td>
<td>2.00 ± 0.53</td>
</tr>
<tr>
<td>( \Lambda(1890) )</td>
<td>3.96 ± 0.43</td>
<td>3.97 ± 0.38</td>
</tr>
<tr>
<td>( \Lambda(2100) )</td>
<td>1.65 ± 0.29</td>
<td>1.94 ± 0.28</td>
</tr>
<tr>
<td>( \Lambda(2110) )</td>
<td>1.62 ± 0.32</td>
<td>1.44 ± 0.28</td>
</tr>
</tbody>
</table>
Extended Model with Two $P_c$ Resonances

(a) LHCb

(b) LHCb

$m_{Kp}$ [GeV]

$m_{J/ψp}$ [GeV]