New results on exotic baryon resonances at LHCb

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On behalf of LHCb Collaboration

10th International Workshop on $e^+e^-$ collisions from Phi to Psi
(USTC, Hefei, China)
These multiquark states would be short-lived \( \sim 10^{-23} \) s "resonances" whose presences are detected by mass peaks & angular distributions showing the unique \( J^P \) quantum numbers.
Curious history of pentaquark $\Theta^+$ search


- No convincing states 50 years after Gell-mann paper proposing $qqqqq\bar{q}$ states
- Prediction: $\Theta^+ (uudd\bar{s})$ could exist with $m \approx 1530$ MeV
- In 2003, 10 experiments reported seeing 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”
Tetraquark

- Experimental evidence started to appear only recently
- $Z(4430)^+$ (Belle, LHCb)
  - Both analyses performed full amplitude fits

- $Z_c(3900)^+$ and its families (BESIII)
- $Z_b(10610)^+$ and $Z_b(10650)^+$ (Belle)
- These give support to the possibility of pentaquark states
LHCb detector at LHC

- Advantages over $e^+e^-$ B-factories:
  - ~1000x larger b production rate
  - produce b-baryons at the same time as B-mesons
  - long visible lifetime of b-hadrons (no backgrounds from the other b-hadron)

- Advantages over GPDs:
  - RICH detectors for $\pi/K/p$ discrimination (smaller backgrounds)
  - Small event size allows large trigger bandwidth (up to 5 kHz in Run I); all devoted to flavor physics
The decay first observed by LHCb and used to measure $\Lambda_b^0$ lifetime:

- LHCb-PAPER-2013-032 (PRL 111, 102003)

The background is only 5.4% in the signal region!

26,007±166 $\Lambda_b^0$ candidates

LHCb $\Lambda_b^0 \to J/\psi \ p \ K^-$
\( \Lambda_b^0 \rightarrow J/\psi pK^- \): unexpected structure in \( m_{J/\psi p} \)

- Unexpected, narrow peak in \( m_{J/\psi p} \)
- Many checks done to ensure it is not an “artifact” of selection:
  - Veto \( B_s \rightarrow J/\psi K^- K^+ \) & \( B^0 \rightarrow J/\psi K^- \pi^+ \) after changing \( p \) to \( K \), or \( K \) to \( \pi \)
  - Clone and ghost tracks carefully eliminated
  - Exclude \( \Xi_b \) decays as a possible source
- Could it be a reflection of interfering \( \Lambda^* \)'s \( \rightarrow p K^- \)?
  - Proper amplitude analysis absolutely necessary!
Amplitude Analysis Formalism

- Helicity formalism
  - Allows for the conventional $\Lambda^* \rightarrow pK$ resonances to interfere with pentaquark states $P_c^+ \rightarrow J/\psi p$
  - Use $m(K^-p)$ & 5 decay angles as fit parameters.

\[ |\mathcal{M}|^2 = \sum_{\lambda_{A_b}^0} \sum_{\lambda_p} \sum_{\Delta \lambda_\mu} \left| \mathcal{M}_{\lambda_{A_b}^0, \lambda_p, \Delta \lambda_\mu}^{\Lambda^*} + e^{i \Delta \lambda_\mu \alpha_{\mu}} \sum_{\lambda_{P_c}} \frac{1}{2} \frac{d}{\chi_{P_c, \lambda_p}^{P_c}}(\theta_p) \mathcal{M}_{\lambda_{A_b}^0, \lambda_{P_c}^{P_c}, \Delta \lambda_\mu}^{P_c} \right|^2 \]

$\Lambda^*$ Decay Chain

$P_c^+$ Decay Chain
### Λ* resonance model

\[ \mathcal{H}_{\Lambda \to BC}^{L} = \sum_{L} \sum_{S} \sqrt{\frac{2L+1}{2J_{A}+1}} B_{L,S} \left( \begin{array}{c} J_{B} \cr \lambda_{B} \cr J_{C} \cr -\lambda_{C} \end{array} \right) \left( \begin{array}{c} S \cr \lambda_{B} - \lambda_{C} \end{array} \right) \times \left( \begin{array}{c} L \cr 0 \cr S \cr \lambda_{B} - \lambda_{C} \end{array} \right) \]

In Λ* decay:

\[ P_{A} = P_{B} P_{C}^{-} (-1)^{L} \]

<table>
<thead>
<tr>
<th>State</th>
<th>J^P</th>
<th>M_0 (MeV)</th>
<th>Γ_0 (MeV)</th>
<th># Reduced</th>
<th># Extended</th>
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<tbody>
<tr>
<td>Λ(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>
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<tr>
<td>Λ(1520)</td>
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<td>1519.5 ± 1.0</td>
<td>15.6 ± 1.0</td>
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<tr>
<td>Λ(1600)</td>
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<td>150</td>
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<tr>
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<tr>
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<td>Λ(2100)</td>
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<td>Λ(2110)</td>
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<tr>
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<td>6</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>

No high-J^P high-mass states

All states, all L

# of fit parameters: 64 146
Extended model fits with only $\Lambda^*$

- Fails to reproduce the $M(J/\psi p)$ peaking structures!
- Other possibilities we have studied:
  - All $\Sigma^{*0}$ (I=1), isospin violating decay
  - Two new $\Lambda^*$ with free $m&Gamma$
  - 4 non-resonant $\Lambda^*$ with $J^P = 1/2^\pm$ and $3/2^\pm$
- Still fail to describe the data
Extended model fits with 1 $P_c^+$

- Try all $J^P$ up to $7/2^\pm$. All don’t give good fit
2 $P_c^+$ fit in reduced model

- Best fit has $J^P= (3/2^- \text{ (low)}, 5/2^+(\text{high}))$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred
$M(J/\psi p)$ in $M(Kp)$ Slices

(a) $m_{Kp} < 1.55$ GeV
(b) $1.55 < m_{Kp} < 1.70$ GeV
(c) $1.70 < m_{Kp} < 2.00$ GeV
(d) $2.00$ GeV $< m_{Kp}$

Events/(20 MeV)

- data
- total fit
- background
- $\Lambda(1405)$
- $\Lambda(1520)$
- $\Lambda(1600)$
- $\Lambda(1670)$
- $\Lambda(1690)$
- $\Lambda(1800)$
- $\Lambda(1810)$
- $\Lambda(1820)$
- $\Lambda(1830)$
- $\Lambda(1890)$
- $\Lambda(2100)$
- $\Lambda(2110)$

Second $P_c$ now obvious!
Angular distributions

All data

P_c enriched region ($m_{Kp}>2$ GeV)

• Good description of the data in all 6 dimensions!
Data preference for opposite parity $P_c^+$ states

- Positive interference between the $P_c$ states
  - (display before efficiency)

- Negative interference between the $P_c$ states
  - (display after efficiency)

- This interference pattern only for states with opposite parity

Events/(20 MeV)

$\textit{m_{Kp}} < 1.55 \text{ GeV}$

$1.55 < \textit{m_{Kp}} < 1.70 \text{ GeV}$

$1.70 < \textit{m_{Kp}} < 2.00 \text{ GeV}$

$2.00 \text{ GeV} < \textit{m_{Kp}}$

$\textit{m_{J/\psi p}}$ [GeV]

$\textit{m_{J/\psi p}}$ [GeV]

Combined $P_c$

$P_c(4450)$

$P_c(4380)$

LHCb
Significances and results

- Significance include systematic uncertainty
- Fit improves greatly, for 1 \( P_c^+ \) \( \Delta(-2\ln L)=216=14.7^2 \), adding the 2nd \( P_c^+ \) improves by 135=11.6^2
- Toy MCs used to obtain significances based on \( \Delta(-2\ln L) \)

<table>
<thead>
<tr>
<th></th>
<th>( P_c(4380)^+ )</th>
<th>( P_c(4450)^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>9( \sigma )</td>
<td>12( \sigma )</td>
</tr>
<tr>
<td>Mass (MeV)</td>
<td>4380 ± 8 ± 29</td>
<td>4449.8 ± 1.7 ± 2.5</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>205 ± 18 ± 86</td>
<td>39 ± 5 ± 19</td>
</tr>
<tr>
<td>Fit fraction(%)</td>
<td>8.4 ± 0.7 ± 4.2</td>
<td>4.1 ± 0.5 ± 1.1</td>
</tr>
<tr>
<td>( \mathcal{B}(\Lambda_b^0 \to P_c^+K^-; P_c^+ \to J/\psi p) )</td>
<td>( (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5} )</td>
<td>( (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5} )</td>
</tr>
</tbody>
</table>

Branching ratio results are submitted to Chin. Phys. C (arXiv:1509.00292)
Ref: \( \mathcal{B}(B^0 \to Z^-(4430)K^+; Z^- \to J/\psi\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5} \)
Cross-checks

- Two independently coded fitters using different background subtractions (sFit & cFit)

- Split data show consistency 2011/2012, magnet up/down, $\Lambda^0_b/\bar{\Lambda}^0_b$, two $\Lambda^0_b$ $p_T$ bins

- Selection varied
  - BDTG>0.5 instead of 0.9 (default)
  - B^0 and B_s reflections modelled in the fit instead of veto
Breit-Wigner amplitude

- Often a relativistic Breit-Wigner function is used to model resonance
- \( q \) is daughter momentum in the resonance rest frame

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

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

Blatt-Weisskopf function for orbital angular momentum \((L)\) barrier factors

- 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

$P_c^+$ amplitudes for 6 $m_{J/ψp}$ bins between $+\Gamma$ & $-\Gamma$ around the resonance mass

- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive
Different types of tetra- and penta-quarks
• Crucial for understanding QCD & points to other states.

Maiani, Polosa & Riquer [arXiv:1507.04980]

Summarized by Burns [arXiv:1509.02460]

+ kinematic effects
Conclusions

• LHCb has found two pentaquark candidates decaying to $J/\psi p$ with overwhelming significance in a state of the art amplitude analysis: they will not go away!
• The preferred $J^P$ are of opposite parity, with one state having $J=3/2$ and the other $5/2$
• Both the $P_c^+$ and $Z_{(c)}^+$ states contain $c\bar{c}$, strong binding due to this?
• Determination their internal binding mechanism will require more study
• We look forward to establishing the structure of many other states or other decay modes
Backup
sFit

- **Signal PDF**

  \[
  \mathcal{P}_{\text{sig}}(m_{K^p}, \Omega | \vec{\omega}) = \frac{1}{I(\vec{\omega})} |\mathcal{M}(m_{K^p}, \Omega | \vec{\omega})|^2 \Phi(m_{K^p}) \epsilon(m_{K^p}, \Omega)
  \]

  - $\vec{\omega}$: fitting parameters
  - $\Phi$: phase-space = $pq$
  - $\epsilon$: efficiency

- **sFit minimizes**

  \[
  -2 \ln \mathcal{L}(\vec{\omega}) = -2s_W \sum_i W_i \ln \mathcal{P}_{\text{sig}}(m_{K^p i}, \Omega_i | \vec{\omega})
  \]

  \[
  = -2s_W \sum_i W_i \ln |\mathcal{M}(m_{K^p i}, \Omega_i | \vec{\omega})|^2 + 2s_W \ln I(\vec{\omega}) \sum_i W_i
  \]

  \[
  - 2s_W \sum_i W_i \ln[\Phi(m_{K^p i}) \epsilon(m_{K^p i}, \Omega_i)].
  \]

  - $W_i$ is $s$ Weighs from $m(J/\psi K^p)$ fits
  - $s_W = \Sigma_i W_i / \Sigma_i W_i^2$ constant factor to correct uncertainty

- **Normalization calculated using simulated PHSP MC ($\Phi \epsilon$ included)**

- $w^{MC}$ discuss later

- Constant (invariant of $\vec{\omega}$), is dropped
- No need to know $\Phi \epsilon$ parameterization
cFit

- cFit uses events in $\pm 2\sigma$ window ($\sigma=7.52\text{MeV}$)
- Total PDF $\mathcal{P}(m_{Kp}, \Omega|\bar{\omega}) = (1 - \beta)\mathcal{P}_{\text{sig}}(m_{Kp}, \Omega|\bar{\omega}) + \beta \mathcal{P}_{\text{bkg}}(m_{Kp}, \Omega)$
- Background is described by sidebands $5\sigma$-$13.5\sigma$
- cFit minimizes

$$-\ln \mathcal{L}(\bar{\omega}) = \sum_i \ln \left[ |\mathcal{M}(m_{Kp i}, \Omega_i|\bar{\omega})|^2 + \frac{\beta I(\bar{\omega})}{(1-\beta)I_{\text{bkg}}} \frac{\mathcal{P}^u_{\text{bkg}}(m_{Kp i}, \Omega_i)}{\Phi(m_{Kp i})\epsilon(m_{Kp i}, \Omega_i)} \right]$$

$$+ N \ln I(\bar{\omega}) + \text{constant},$$

Background fraction $\beta=5.4\%$

Signal efficiency parameterization becomes part of background parameterization, effects only a tiny part of total PDF because of small $\beta$
cFit efficiency and background parameterizations

- Both use similar ways

\[ \epsilon(m_{Kp}, \Omega) = \epsilon_1(m_{Kp}, \cos \theta_\Lambda) \cdot \epsilon_2(\cos \theta_{\Lambda_0} | m_{Kp}) \cdot \epsilon_3(\cos \theta_{J/\psi} | m_{Kp}) \cdot \epsilon_4(\phi_K | m_{Kp}) \cdot \epsilon_5(\phi_\mu | m_{Kp}) \]

\[ \frac{P^{u}_{bkg}(m_{Kp}, \Omega)}{\Phi(m_{Kp})} = P_{bkg_1}(m_{Kp}, \cos \theta_\Lambda) \cdot P_{bkg_2}(\cos \theta_{\Lambda_0} | m_{Kp}) \]

\[ \cdot P_{bkg_3}(\cos \theta_{J/\psi} | m_{Kp}) \cdot P_{bkg_4}(\phi_K | m_{Kp}) \cdot P_{bkg_5}(\phi_\mu | m_{Kp}). \]
Amplitude Analysis Formalism II

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

\[
\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda^0}, \lambda_{\Lambda^*}, \Delta \lambda_{\mu}} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_{\psi}} \mathcal{H}^{\Lambda^0 \rightarrow \Lambda^* \psi}_{\lambda_{\Lambda^0}, \lambda_{\Lambda^*}} D^{\frac{1}{2}}_{\lambda_{\Lambda^0}, \lambda_{\Lambda^*} - \lambda_{\psi}} (0, \theta_{\Lambda^0}, 0) \nonumber
\]

\[
\mathcal{H}^{\Lambda^* \rightarrow K \psi}_{\lambda_{\Lambda^*}, \lambda_{\psi}} D^{J_{\Lambda^*}}_{\lambda_{\Lambda^*}, \lambda_{\psi}} (\phi_K, \theta_{\Lambda^*}, 0) R_n (m_{K\psi}) D^{\frac{1}{4}}_{\lambda_{\psi}, \Delta \lambda_{\mu}} (\phi_\mu, \theta_\psi, 0) \nonumber
\]

- And for the $P_C$:

\[
\mathcal{M}^{P_C}_{\lambda_{\Lambda^0}, \lambda_{P_C}, \Delta \lambda_{\mu}^{P_C}} \equiv \sum_j \sum_{\lambda_{P_C}} \sum_{\lambda_{\psi}^{P_C}} \mathcal{H}^{\Lambda^0 \rightarrow P_{Cj} K}_{\lambda_{\Lambda^0}, \lambda_{P_C}} D^{\frac{1}{2}}_{\lambda_{\Lambda^0}, \lambda_{P_C}} (\phi_{P_C}, \theta_{P_C}, 0) \nonumber
\]

\[
\mathcal{H}^{P_{Cj} \rightarrow \psi \psi}_{\lambda_{\psi}, \lambda_{P_C}} D^{J_{P_{Cj}}}_{\lambda_{\psi}, \lambda_{P_C} - \lambda_{P_C}} (\phi_{\psi}, \theta_{P_C}, 0) R_j (m_{\psi \psi}) D^{\frac{1}{4}}_{\lambda_{\psi}, \Delta \lambda_{\mu}^{P_C}} (\phi_{\psi}, \theta_{\psi}, 0) \nonumber
\]
• The matrix element for the $\Lambda^*$ decay is:

$$
\mathcal{M}_{\Lambda^*}^{A*} = \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_{\psi}} \mathcal{H}_{\lambda_{\Lambda^*}^0, \lambda_{\psi}} \mathcal{D}_{\lambda_{\Lambda^*}^0, \lambda_{\Lambda^*}^0 - \lambda_{\psi}} (0, \theta_{\Lambda^0}, 0)^* 
\mathcal{H}_{\lambda_{\Lambda^*}^0, \lambda_{\Lambda^*}^0} \mathcal{D}_{\lambda_{\Lambda^*}^0} (\phi_K, \theta_{\Lambda^*}, 0)^* R_n(m_{K^0}) \mathcal{D}_{\lambda_{\psi}, \Delta \lambda_{\mu}} (\phi_{\mu}, \theta_{\psi}, 0)^* 
$$

• And for the $P_c$:

$$
\mathcal{M}_{P_c}^{P_c} = \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_{\psi}} \mathcal{H}_{\lambda_{P_c}^0, \lambda_{\psi}} \mathcal{D}_{\lambda_{P_c}^0} (\phi_{P_c}, \theta_{P_c}, 0)^* 
\mathcal{H}_{\lambda_{P_c}^0, \lambda_{P_c}} \mathcal{D}_{\lambda_{P_c}^0, \lambda_{P_c}^0 - \lambda_{P_c}} (\phi_{\psi}, \theta_{P_c}, 0)^* R_j(m_{\psi^0}) \mathcal{D}_{\lambda_{\psi}, \Delta \lambda_{\mu}} (\phi_{\mu}, \theta_{\psi}, 0)^* 
$$

• $R(m)$ are resonance parametrizations, generally are described by Breit-Wigner amplitude
• The matrix element for the $\Lambda^*$ decay is:

\[
\mathcal{M}_{\Lambda^*_0, \Lambda_0^*, \Delta \mu} = \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}_{\Lambda^*_0 \to \Lambda_n^*} D_{\lambda_{\Lambda_0^*}, \lambda_\psi} \left( 0, \theta_{\Lambda_0^*}, 0 \right)^* \]

$$\mathcal{H}_{\Lambda_n^* \to K_P} D_{\lambda_{\Lambda_n^*}, \lambda_\psi} \left( \phi_K, \theta_{\Lambda_n^*}, 0 \right)^* R_n \left( m_{K_P} \right) D_{\lambda_\psi, \Delta \mu} \left( \phi_\mu, \theta_\psi, 0 \right)^*$$

• And for the $P_c$:

\[
\mathcal{M}_{P_c, \Lambda_0^*, \Delta \mu} = \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi} \mathcal{H}_{\Lambda^*_0 \to P_{cj}} D_{\lambda_{\Lambda_0^*}, \lambda_{P_c}} \left( \phi_{P_c}, \theta_{P_c}, 0 \right)^* \]

$$\mathcal{H}_{P_{cj} \to \psi} D_{\lambda_{P_c}, \lambda_\psi} \left( \phi_\psi, \theta_{P_c}, 0 \right)^* R_j \left( m_{\psi} \right) D_{\lambda_\psi, \Delta \mu} \left( \phi_\mu, \theta_\psi, 0 \right)^*$$

• $\mathcal{H}$ are complex helicity couplings determined from the fit.
Amplitude Analysis Formalism II

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

$$M_{\Lambda^*}^{\Lambda_0^*, \lambda_p, \Delta \lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}_{\Lambda_b^{0} \rightarrow \Lambda_{\Lambda^*}^{0}, \lambda_\psi}^{\Lambda_0^*, \lambda_\psi} D^{1/2}_{\Lambda_\psi, \lambda_{\Lambda^*}^{0}, \lambda_{\Lambda^*}^{0} - \lambda_\psi} (0, \theta_{\Lambda_0^*}, 0)^*$$

- And for the $P_c$:

$$M_{P_c}^{\Lambda_0^*, \lambda_p^{P_c}, \Delta \lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi} \mathcal{H}_{\Lambda_b^{0} \rightarrow P_{cj} K}^{\Lambda_0^*, \lambda_\psi} D^{1/2}_{\lambda_{\Lambda_b^{0}}, \lambda_{P_c}, \lambda_{P_c}} (\phi_{P_c}, \theta_{P_c}, 0)^*$$

- Wigner D-matrix arguments are Euler angles corresponding to the fitted angles.
• They are added together as:

\[ |M|^2 = \sum_{\lambda_{A_0}} \sum_{\lambda_p} \sum_{\Delta \lambda_{\mu}} |M_{\lambda_{A_0}, \lambda_p, \Delta \lambda_{\mu}}^{A*} + e^{i \Delta \lambda_{\mu}} \alpha_{\mu} \sum_{\lambda_p^C} d^{\frac{1}{2}}_{\lambda_p^C, \lambda_p} (\theta_{\lambda_p}) M_{\lambda_{A_0}, \lambda_p^C, \Delta \lambda_{\mu}}^{P_c} |^2 \]

• \( \alpha_{\mu} \) and \( \theta_{\lambda_p} \) are rotation angles to align the final state helicity axes of the \( \mu \) and \( p \), as helicity frames used are different for the two decay chains.

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

\[ \mathcal{H}_{\lambda_B, \lambda_C}^{A \rightarrow BC} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \begin{pmatrix} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{pmatrix} \begin{pmatrix} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C \end{pmatrix} \]

– Convenient way to enforce parity conservation in the strong decays via: \( P_A = P_B P_C (-1)^L \)
Impact parameter: \( \sigma_{IP} = 20 \ \mu m \)
Proper time: \( \sigma_{\tau} = 45 \ \text{fs} \) for \( B_s^0 \to J/\psi \phi \) or \( D_s^+ \pi^- \)
Momentum: \( \Delta p/p = 0.4 \sim 0.6\% \) (5 - 100 GeV/c)
Mass: \( \sigma_m = 8 \ \text{MeV}/c^2 \) for \( B \to J/\psi X \) (constrained \( m_{J/\psi} \))
RICH \( K - \pi \) separation: \( \epsilon(K \to K) \sim 95\% \) \( \text{mis-ID} \) \( \epsilon(\pi \to K) \sim 5\% \)
Muon ID: \( \epsilon(\mu \to \mu) \sim 97\% \) \( \text{mis-ID} \) \( \epsilon(\pi \to \mu) \sim 1 - 3\% \)
ECAL: \( \Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})} \)
Extended model fits with 2 $P_c^+$

- Leads to a good fit
- The second broad $P_c^+$ is visible in other projections (shown later)
- It also modifies the narrow $P_c^+$’s decay angular distribution via interference to match with the data distribution
## 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>
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<tr>
<td>Extended vs. reduced</td>
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<td>0.2</td>
<td>54</td>
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<tr>
<td>(\Lambda^*) masses &amp; widths</td>
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<td>0.7</td>
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<td>(10 &lt; p_p &lt; 100) GeV</td>
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<td>1</td>
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<td>0.3</td>
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<td>(J^P) ((3/2^+, 5/2^-)) or ((5/2^+, 3/2^-))</td>
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<td>(d = 1.5 - 4.5) GeV(^{-1})</td>
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<td>(L_{P_c}^0) (\Lambda_b^0 \to P_c^+) (low/high) (K^-)</td>
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<td>Change (\Lambda(1405)) coupling</td>
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<td>29</td>
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<tr>
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\(\Lambda^*\) modelling contributes the largest
### 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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<tbody>
<tr>
<td></td>
<td>low</td>
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<tr>
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<td>54</td>
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<td>$\Lambda^*$ masses &amp; widths</td>
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<tr>
<td>Separate sidebands</td>
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<td>5</td>
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<tr>
<td>$J^P$ (3/2$^+$, 5/2$^-$) or (5/2$^+$, 3/2$^-$)</td>
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<tr>
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<td>0.6</td>
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<td>$L_{P_c}^0 \Lambda_b^0 \rightarrow P_c^+ \ (low/high) K^-$</td>
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<tr>
<td>Change $\Lambda(1405)$ coupling</td>
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<td>0</td>
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<tr>
<td>Overall</td>
<td>29</td>
<td>2.5</td>
<td>86</td>
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<tr>
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Alternate $J^P$ fits give sizeable uncertainty
Systematic Uncertainties

<table>
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<tr>
<th>Source</th>
<th>$M_0$ (MeV)</th>
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<td>54</td>
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<td>$\Lambda^*$ masses &amp; widths</td>
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<td>Nonresonant</td>
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<tr>
<td>Separate sidebands</td>
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<tr>
<td>$J^P (3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$</td>
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<td>$d = 1.5 - 4.5$ GeV$^{-1}$</td>
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<tr>
<td>sFit/cFit cross check</td>
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Varying choices in mass depend function also give sizeable uncertainty
## 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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</table>

sFit/cFit give consistent results
**J/ψ K System**

- **J/ψ K system** is well described by the Λ* and $P_c$ reflections.
LHCb detector at LHC

- **Advantages over e^+e^- B-factories:**
  - ~1000x larger b production rate
  - **produce b-baryons at the same time as B-mesons**
  - long visible lifetime of b-hadrons (no backgrounds from the other b-hadron)

- **Advantages over GPDs:**
  - RICH detectors for \( \pi/K/p \) discrimination (smaller backgrounds)
  - Small event size allows large trigger bandwidth (up to 5 kHz in Run I); all devoted to flavor physics
Different types of tetra- and penta-quarks

“plain”

diquark model

triquark model

hydro-charmonium model

molecular model

baryon model
Prejudices against pentaquark

• No convincing states 50 years after Gell-mann paper proposing $qqqqq$ states

• Previous “observations” of several pentaquark states have been refuted

• These included
  – $\Theta^+ \rightarrow K^0 p, K^+ n$, mass=1.54 GeV, $\Gamma \sim 10$ MeV
  – Resonance in $D^*^- p$ at 3.10 GeV, $\Gamma = 12$ MeV
  – $\Xi^- \rightarrow \Xi^- \pi^-$, mass=1.862 GeV, $\Gamma < 18$ MeV

• Generally they were found/debunked by looking for “bumps” in mass spectra circa 2004