Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

Bernardo Adeva*, on behalf of the LHCb collaboration

* University of Santiago de Compostela, Spain

New Frontiers in Physics ICNFP2015, Kolymbari, Greece, 23-30 August 2015

1. Pentaquark observation

Large yields of $\Lambda_b^0 \to J/\psi K^- p$ decays at LHCb

In addition to known states $\Lambda^* \to K^- p$, structures in $J/\psi p$ mass are found

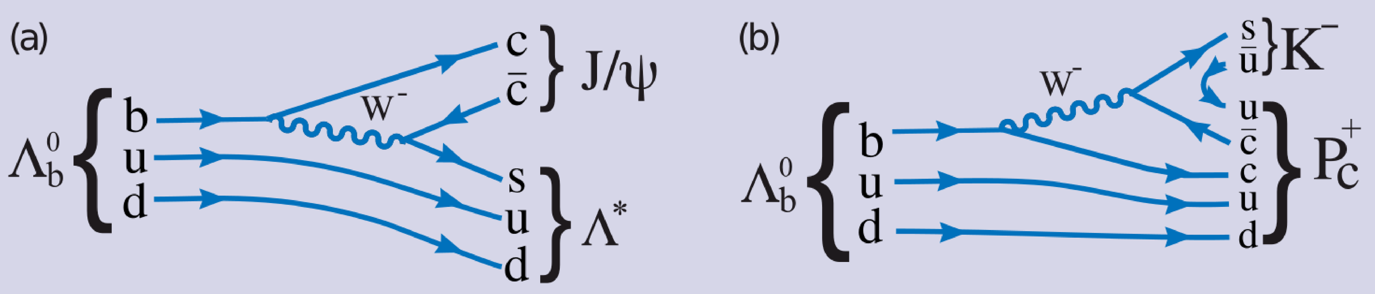
Minimal quark content : $c\bar{c}uud$, charmonium-pentaquarks P_c^+

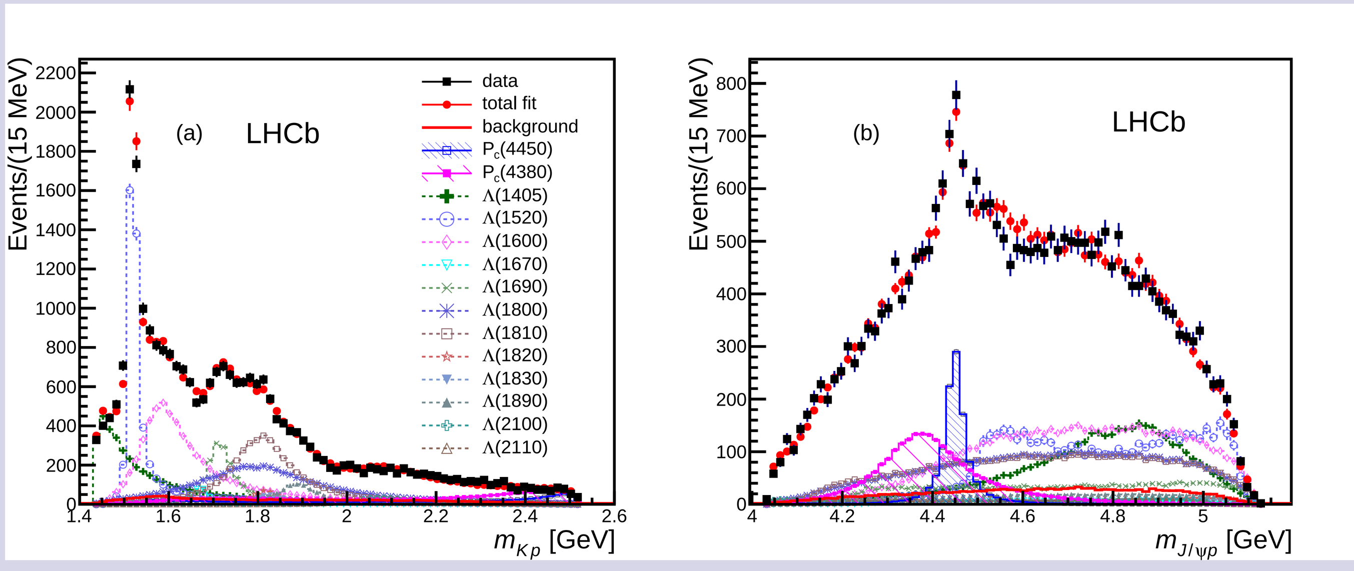
Two P_c^+ states are found, with mass and width:

$M_1 = 4380 \pm 8 \pm 29$ MeV $\Gamma_1 = 205 \pm 18 \pm 86$ MeV, and

$M_2 = 4449.8 \pm 1.7 \pm 2.5$ MeV $\Gamma_2 = 39 \pm 5 \pm 19$ MeV

Feynman diagrams for $\Lambda^* \to J/\psi \Lambda^*$ and $\Lambda^* \to P_c^+ K^-$

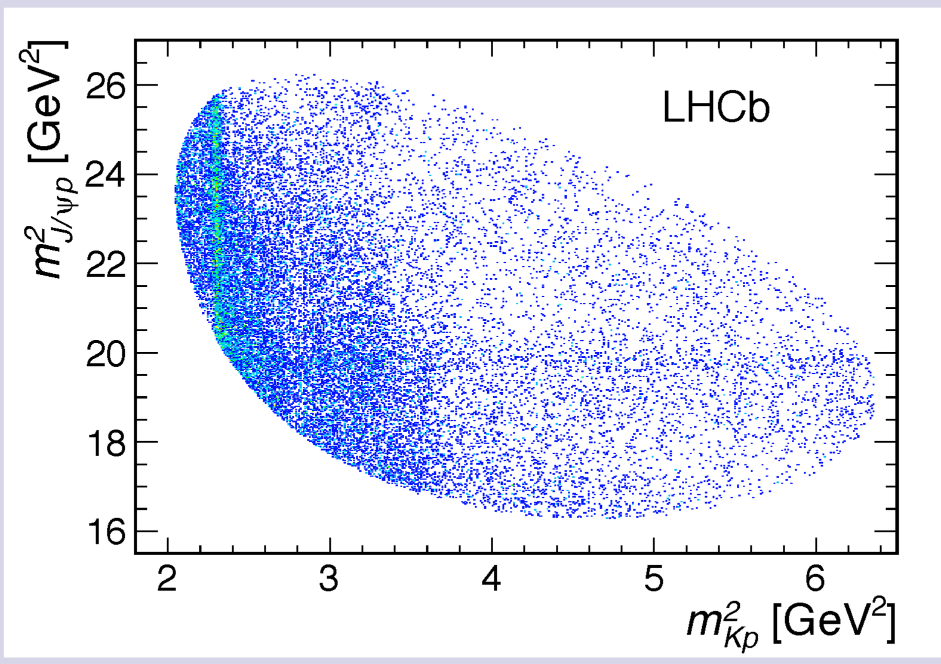


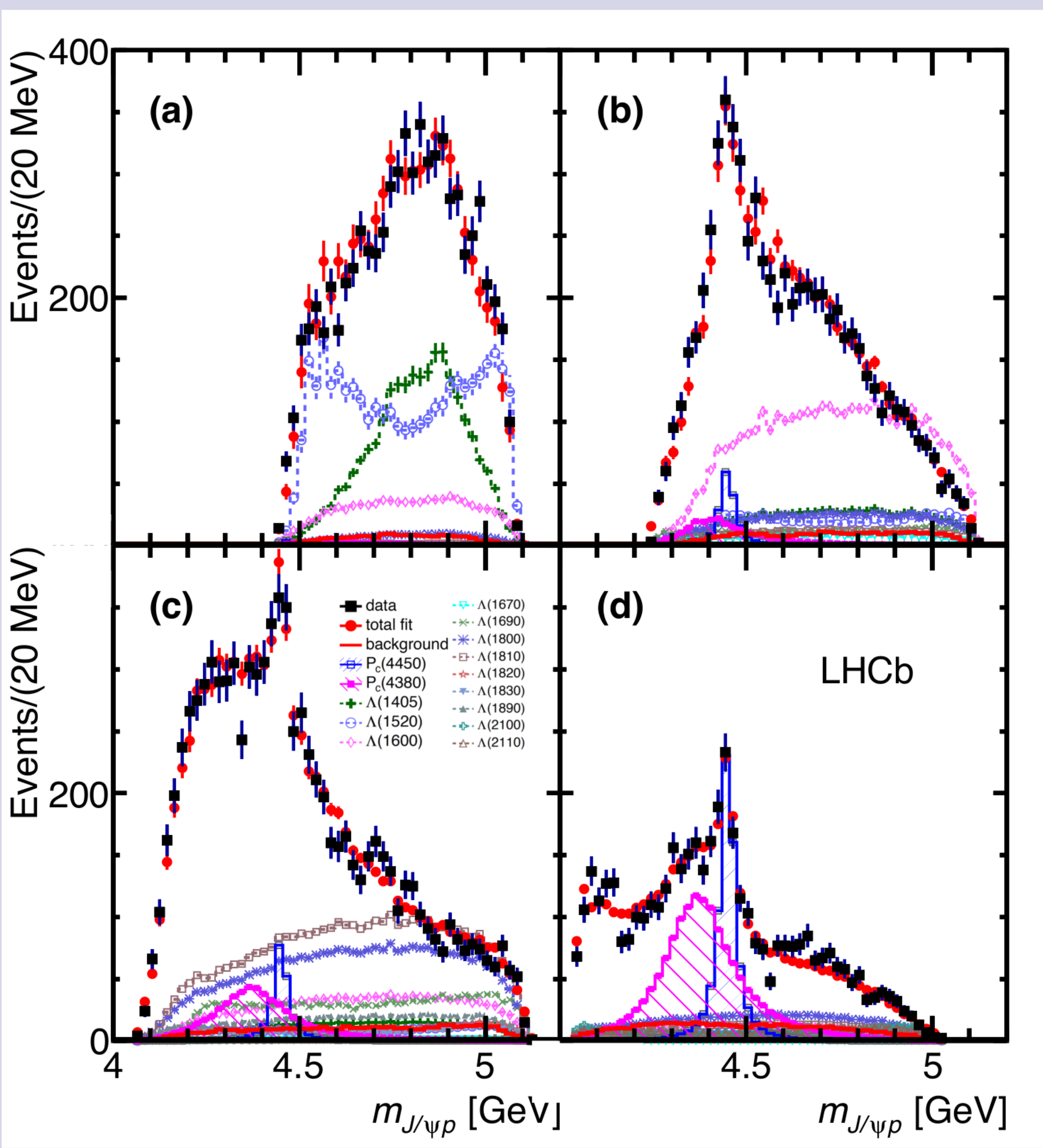


Fit projections for (a) m_{Kp} and (b) $m_{J/\psi p}$ for a reduced Λ^* model with two P_c^+ states. The data are shown as solid (black) squares, while the solid (red) points show the results of the fit. The solid (red) histogram shows the background distribution. The blue (open) squares with the shaded histogram represent the $P_c(4450)^+$ state, and the shaded histogram topped with (purple) filled squares represents the $P_c(4380)^+$ state. Each Λ^* component is also shown. Error bars on the points showing the fit results are due to simulation statistics.

3. Analysis as function of the Kp mass

Invariant mass squared of K^-p versus $J/\psi p$ candidates within ± 15MeV of the Λ_b^0 mass. 26007 ± 166 signal candidates are selected after BDTG output, with 5.4% background. A distinct vertical band is observed in the K^-p invariant mass near 2.3 GeV^2 corresponding to the $\Lambda(1520)$ resonance. There is also a distinct horizontal band near 19.5 GeV^2.





$m_{J/\psi p}$ in intervals of m_{Kp} for the fit with two P_c^+ states: (a) $m_{Kp} < 1.55$GeV, (b) $1.55 < m_{Kp} < 1.70$GeV, (c) $1.70 < m_{Kp} < 2.00$GeV, and (d) $m_{Kp} > 2.00$GeV. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The blue and purple histograms show the two P_c^+ states. Other components are also indicated.

References

[1] R. Aaij et al., "Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays ", Phys. Rev. Lett. 115, 072001 (2015), published August 12, 2015.

[2] S. Stone, on behalf of the LHCb Collaboration, EPS-HEP2015, 22 July 2015, Vienna.

2. Model for angular and mass analysis

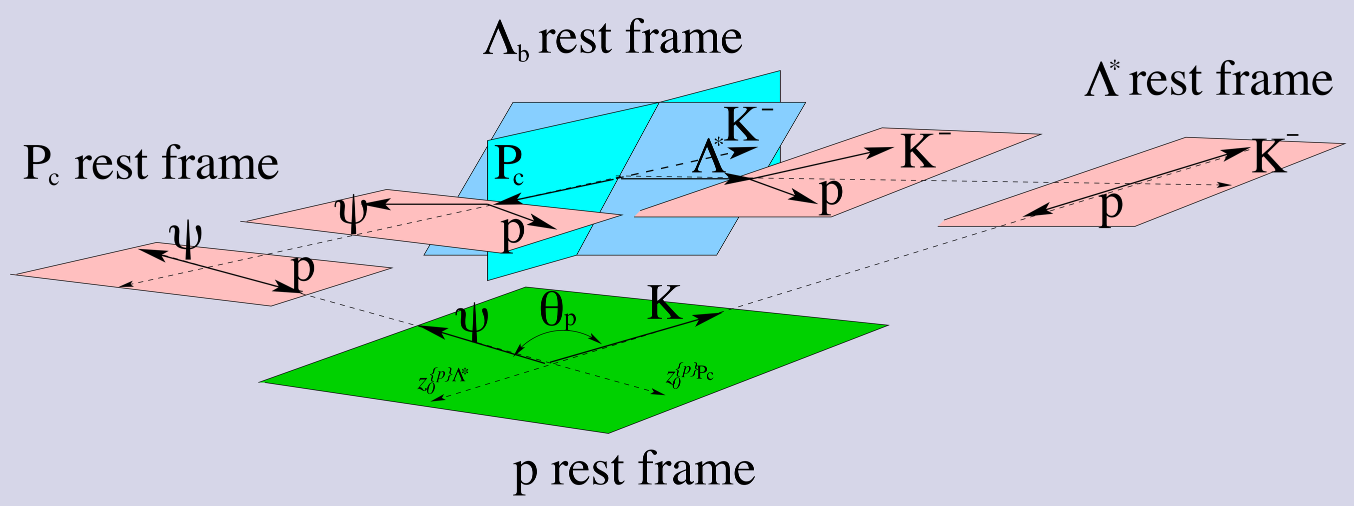
Helicity formalism in sequential decays:

- $\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C}$ are complex helicity-coupling amplitudes
- Wigner's D-matrices depend on Euler angles describing rotation from A helicity frame to B helicity frame
- $R_A(m_{BC})$ is a complex Breit-Wigner like mass propagator
- j sum allows for two P_c^+ resonances (ratio of respective magnitudes determined from data)
- 6 independent dimension of $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)pK^-$ decay angles: $\Omega = (\theta_{\Lambda_b^0}, \theta_{\Lambda^*}, \phi_K, \theta_\psi, \phi_\mu)$

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_{\Lambda_n^*}(m_{Kp}) D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_b^0,\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\lambda_b^0},0)^* \mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_{P_{c_j}}(m_{\psi p}) D^1_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

To describe interference between Λ^* and P_c^+ amplitudes, proton and muon helicity states must be rotated by angles (θ_p, α_μ) from the Λ^* decay frame to the P_c^+ decay frame:



leading to the expression

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

where $\Delta\lambda_\mu = \pm 1$ accounts for both muon spin-aligned orientations.

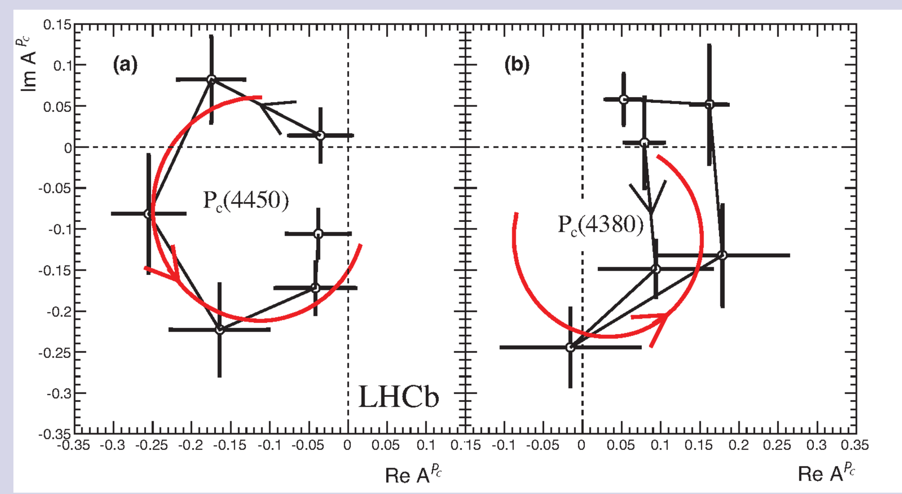
Parity conservation in Λ_b^0 production at the LHC (in absence of polarized beams) prevents Λ_b^0 longitudinal polarization, so $\lambda_{\Lambda_b^0} = +1$ and $\lambda_{\Lambda_b^0} = -1$ are equally likely. Also parity is conserved in the strong chain decays, which restricts the number of observables.

4. Phase behaviour

Unitary Breit-Wigner amplitude $R_{P_c}(m)$ for a resonance (M_{0X}, Γ_{0X}) of size $d \sim 0.6$ fm decaying into system of orbital angular momentum L_X

$$\frac{1}{M_{0X}^2 - m^2 - iM_{0X}\Gamma(m)} \quad \Gamma(m) = \Gamma(m \mid M_{0X}, \Gamma_{0X}, L_X, d)$$

Causality requires the phase to rotate counter-clockwise across the maximum magnitude. This is observed for the $P_c(4450)^+$ state in the range $\pm\Gamma_0 = 39MeV$. The wider state also shows large phase variation, but values sensitive to details of Λ^* model, the study is not conclusive



Fitted values of the real and imaginary parts of the amplitudes for the $(3/2^-, 5/2^+)$ baseline fit for the $P_c(4450)^+$ state, each divided into six $m(J/\psi p)$ bins of equal width in $(-\Gamma_0, +\Gamma_0)$. The points are connected in increasing order.

5. Quantum number assignments

$-2ln\mathcal{L}(\vec{\omega})$ is minimized where $\vec{\omega}$ are the fit parameters (helicity amplitudes or LS couplings and resonance parameters)

Best fit: two P_c^+ states $J^P = (\frac{3}{2}^-, \frac{5}{2}^+)$ for (Low,High) mass

- adding $(\frac{5}{2})^+$ P_c^+ alone reduces $-2ln\mathcal{L}$ by $(14.7)^2$ units
- adding a second $(\frac{3}{2})^-$ P_c^+ further reduces $-2ln\mathcal{L}$ by $(11.6)^2$ units
- combined reduction of $-2ln\mathcal{L}$ by both states together $(18.7)^2$ units
- significance reduced by $\sim 20\%$ when p-values are obtained from pseudoexperiments: 9σ (lower P_c^+) and 12σ (higher P_c^+), and 15σ (combined)

Significance of the quantum numbers:

a) $-2ln\mathcal{L}$ is increased by ~ 1 unit for $J^P = (\frac{3}{2}^+, \frac{5}{2}^-)$

b) $-2ln\mathcal{L}$ is increased by $\sim (2.3)^2$ units for $J^P = (\frac{5}{2}^+, \frac{3}{2}^-)$

c) all other choices (in particular $J = \frac{1}{2}$ for either) are disfavoured by $\sim 5^2$ units