PENTAQUARKS AT LHCb

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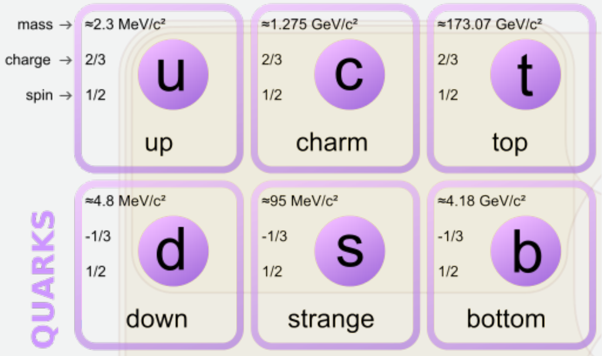
290E Presentation

Quarks & The Quark Model

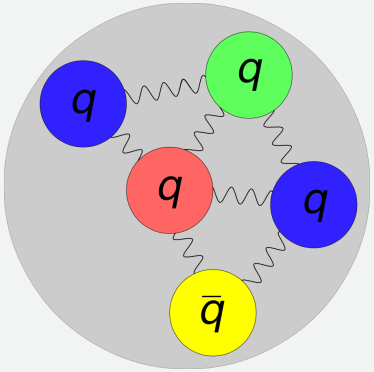
- Quark model is a classification scheme for hadrons in terms of their valence quarks
- Quark model was independently proposed by Gell-Mann and Zweig in 1964
- QCD is the theory of strong interactions which describes the interactions between quarks and gluons
- The Simple Quark Model
  - Mesons $q\bar{q}$
  - Baryons qqq

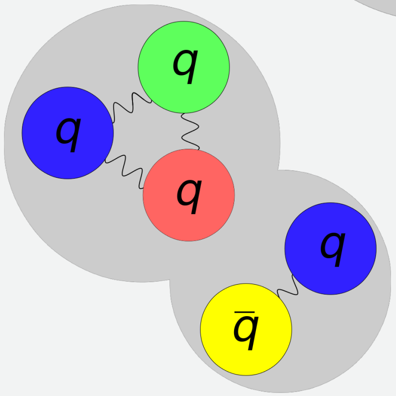


- While not predicted by the simple quark model, QCD does not rule out the existence of exotic hadrons, such as pentaquarks

Pentaquarks

- Wide variety possible
- Baryon number 1 → Baryon
- Binding mechanism not clear
  - 5 tightly bound quarks (original vision)
  - ”meson-baryon molecule”
- Color-neutral state:
  - q one color
  - q second color
  - qq third color
  - $\bar{q}$ counteract surplus color
    - Examples show one green, one red, two blue and one anti-blue (yellow)





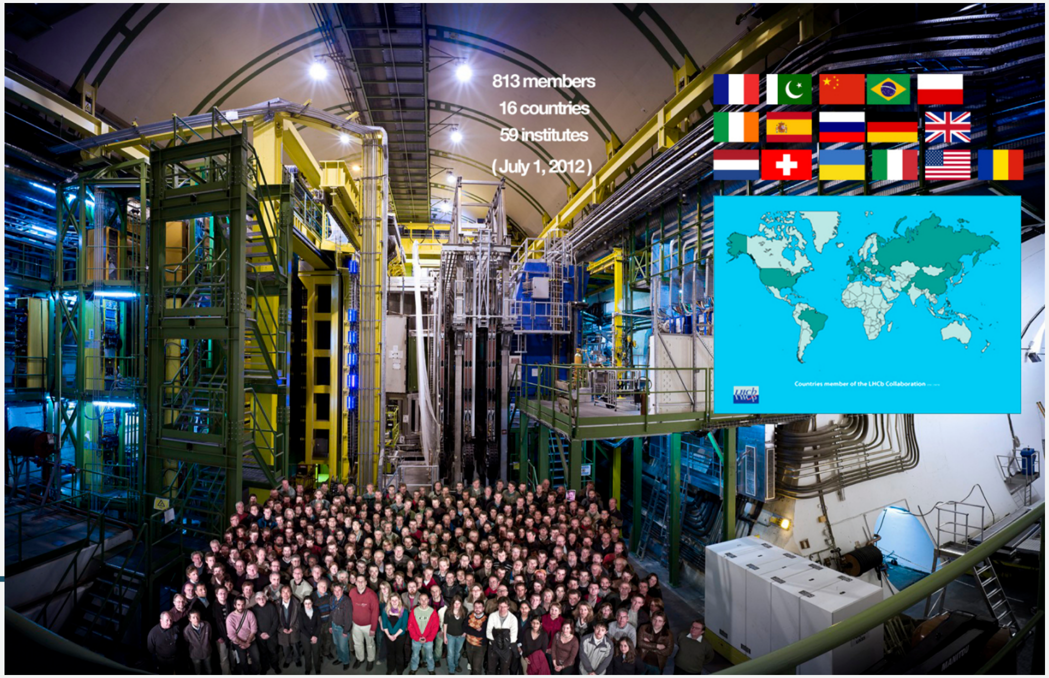
Discover of pentaquarks by LHCb was described as “something that we stumbled upon”

Previous pentaquark "discoveries"

- Many classes of pentaquark are hard to identify experimentally
  - If the flavor of the antiquark matches the flavor of any of the other four quarks, it will cancel out and will resemble a three-quark hadron.
    - Look for particles where the antiquark did not cancel.
- Several claims of pentaquark discoveries:
  - LEPS in 2003 reported the Θ^{+} $(uudd\bar{s})$, mass 1540 MeV/c² (4.6 σ)
    - Numerous other experiments looked for Θ^{+} but found nothing.
    - BELLE, CLAS, DIANA and SAPHIR claimed to have detected the Θ^{+}, but all four experiments had nearly the same conditions.
  - Two other pentaquark states were reported with low statistical significance $\Phi^{--}(ddss\bar{u})$ and $\Theta_c^{-}(uudd\bar{c})$. Both were found to be statistical effects rather than true resonances.
  - In 2008, PDG nullified the discoveries:
    - "There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist… The whole story—the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery"—is a curious episode in the history of science."
  - Despite this, 2009 LEPS results continues to show the resonance with 5.1 σ.

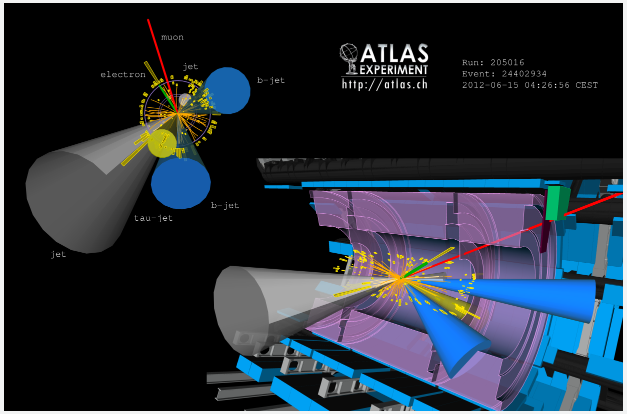
LHCb Collaboration

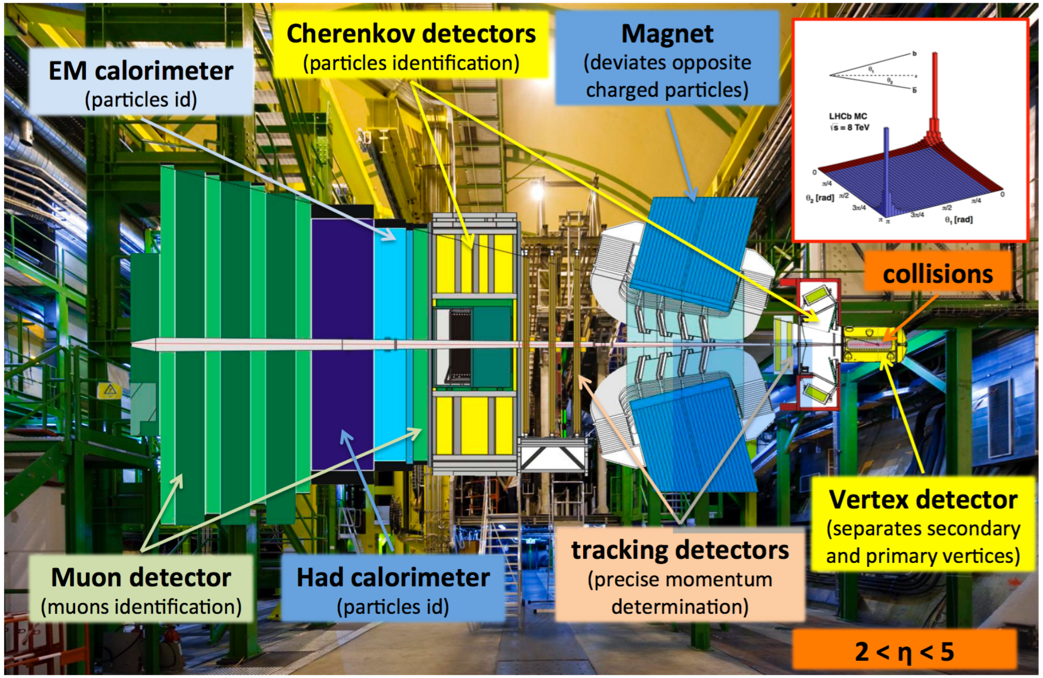
- A specialized b-physics experiment that is measuring the parameters of CP violation in the interactions of b-hadrons (heavy particles containing a bottom quark).
  - Heavy flavor, electroweak, and QCD physics
- Six key measurements have been identified involving B mesons.
- ~800 members from 69 institutes in 16 countries



LHCb Detector

- Single-arm forward spectrometer
  - b- and anti b- hadrons are predominantly produced in the same forward and backward cone.
- Subsystems:
  - VELO
  - RICH-1
  - Tracker Turicensis
  - Dipole Magnet
  - Outer Tracker
  - Inner Tracker
  - RICH-2
  - EM Calorimeter
  - Hadronic Calorimeter
  - Muon Detector





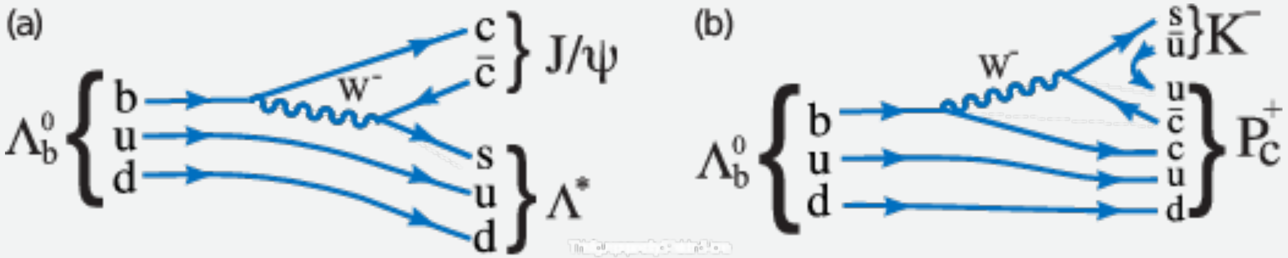
Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration[1]

Link to Paper

Introduction

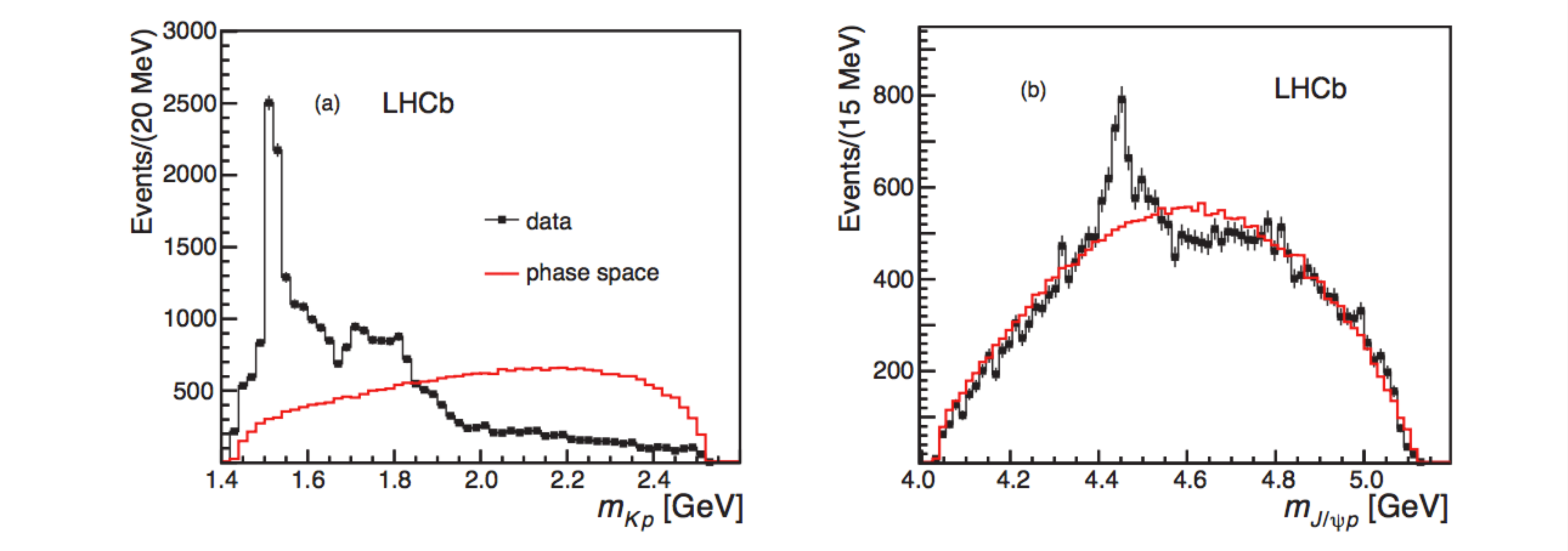
- Large yields of $\Lambda_b^0 \to J/\psi\ K^- p$ decays are available at LHCb.
  - Dominant decay chain $\Lambda_b^0 \to J/\psi\, \Lambda^*$, $\Lambda^* \to K^- p$
  - Also have contributions through the decay $\Lambda_b^0 \to P_c^+ K^-$, $P_c^+ \to J/\psi\, p$
    - P_c^+ is proposed charmonium-pentaquark baryon



- Data corresponding to 1 fb^{-1} of integrated luminosity at 7 TeV and 2 fb^{-1} at 8 TeV.
- Events are triggered by a $J/\psi \to \mu^+\mu^-$ decay.

Invariant Mass Distributions

- Invariant mass of (a) $K^- p$ and (b) $J/\psi\, p$ combinations from $\Lambda_b^0 \to J/\psi\ K^- p$ decays
  - The peak in (b) is the proposed pentaquark resonance.
  - Perform full amplitude analysis, allowing for interference effects between both decay sequences to determine if structure seen in (b) are resonant in nature and not due to reflections generated by the Λ^* states.



$\Lambda_b^0 \to J/\psi\ \Lambda^*\ ,\ \Lambda^* \to K^- p$

$\Lambda_b^0 \to P_c^+ K^-\ , P_c^+ \to J/\psi\, p$

Analysis Method

- In order to perform a full amplitude analysis, allowing for interference effects between both decay sequences:
  - Helicity[1] formalism in which each sequential decay $A \to BC$ contributes to the amplitude a term:

$$\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C}\ D^{J_A}_{\lambda_A,\lambda_B-\lambda_C}(\phi_B,\theta_A,0)^* R_A(m_{BC}) = \mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C}\ e^{i\lambda_A\phi_B}\ d^{J_A}_{\lambda_A,\lambda_B-\lambda_C}(\theta_A) R_A(m_{BC})$$

Complex helicity-coupling amplitudes

Wigner's D-matrix

Complex function describing invariant mass of B & C if A has a non-negligible natural width

θ_A : polar angle of B in the rest frame of A, also known as the "helicity angle of A"
ϕ_B : azimuthal angle of B in the rest frame of A

- After more manipulation involving expressing the helicity coupling in terms of LS coupling, each term in the decay must be multiplied together and then summed up coherently over the helicity states of intermediate particles and incoherently over the helicity states of the initial and final-state particles.
- When dealing with a subsequent decay of the daughter, $B \to DE$, four-vectors of all particles must be first Lorentz boosted to the rest frame of B.

[1] Helicity is defined as the projection of the spin of the particle onto the direction of its momentum

Analysis Method: Λ^* decay chain

- Denoting J/ψ as ψ, the matrix element for the $\Lambda_b^0 \to J/\psi\ \Lambda^*$ decay sequence is:

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

Sum over *n* due to many different Λ^* resonances.

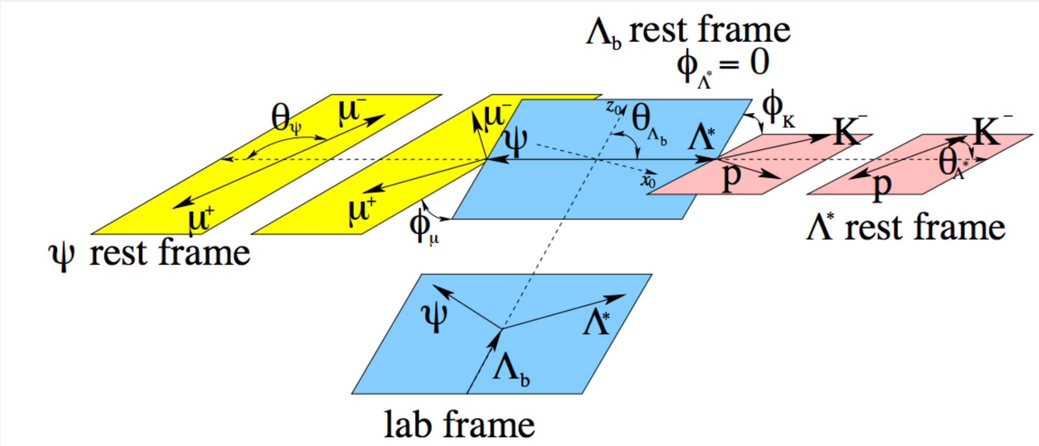


Figure 16: Definition of the decay angles in the Λ^* decay chain.

$\Lambda_b^0 \to J/\psi\ \Lambda^*$, $\Lambda^* \to K^- p$

Analysis Method: P_c^+ decay chain

- The matrix element for the P_c^+ decay gain:

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

$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_{P_{cj}}(m_{\psi p})\ D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*,$$

Sum over j allows for more than one P_c^+ resonance.

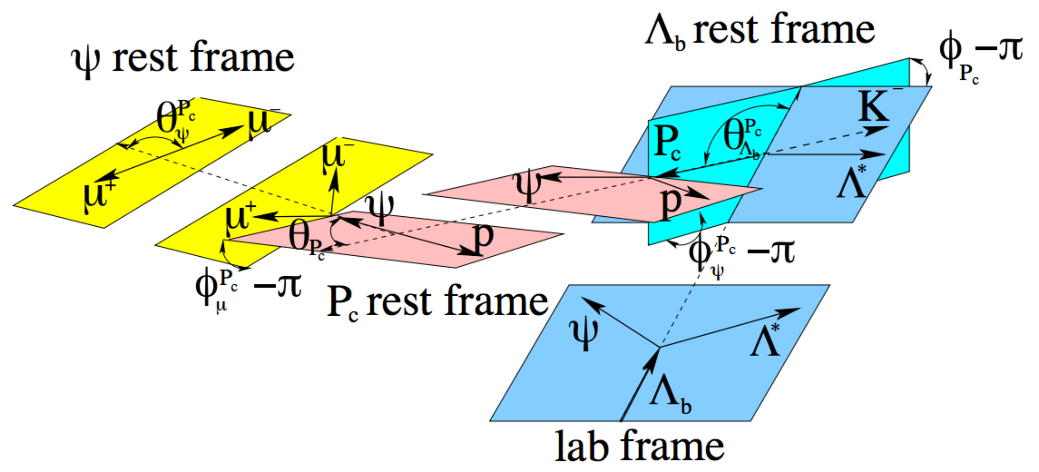


Figure 17: Definition of the decay angles in the P_c^+ decay chain.

$\Lambda_b^0 \to P_c^+ K^-$, $P_c^+ \to J/\psi\, p$

Analysis Method: Matrix Element

- Before the matrix elements for the two decay sequences can be added coherently, the proton and muon helicity states in the Λ^* decay chain must be expressed in the basis of helicities in the P_c^+ decay chain.

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

- Interferences between various $\Lambda^*{}_n$ and $P_c^+{}_j$ resonances vanish in the integrated rates unless the resonances belong to the same decay chain and have the same quantum numbers.
- The matrix element is a 6-dimensional function and depends on fit parameters which represent independent helicity or *LS* couplings and the masses and widths of the resonances.
- Two different fit algorithms (cFit & sFit) we used independently.
  - cFit has a background parameterization while sFit does not. Both fits provided consistent results and only cFit plots are shown here.

Fit: Extended Model

- Before fitting the data with the pentaquark contribution, the data was fit with a model that can describe the mass and angular distributions including only Λ^* resonances, allowing all possible know states (*** or **** in PDG) and decay amplitudes.
  - This "extended" model has 146 free parameters from the helicity couplings alone.
  - The masses and widths of the Λ^* states are fixed to their PDG values.

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6

Fit Results: Extended Model

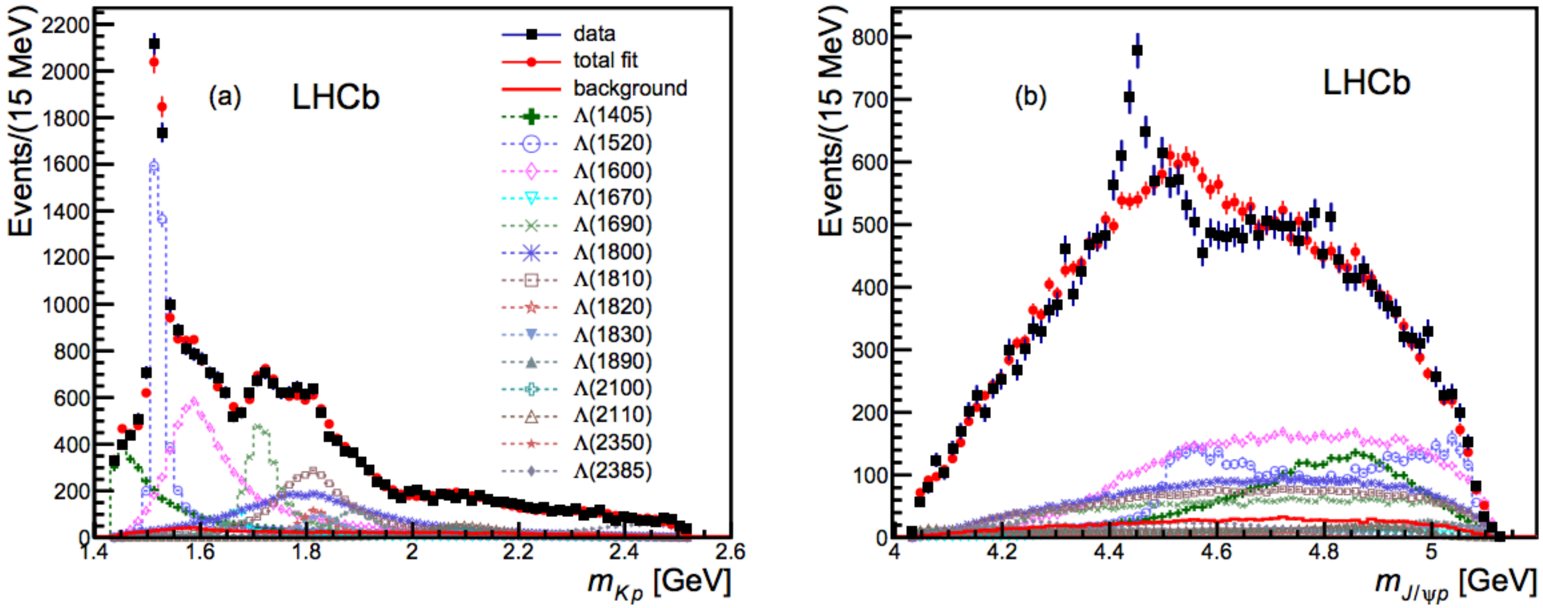


Figure 6: Results for (a) m_{Kp} and (b) $m_{J/\psi p}$ for the extended Λ^* model fit without P_c^+ states. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The error bars on the points showing the fit results are due to simulation statistics.

The m_{Kp} distribution is fitted reasonably well, but the peaking structure in $m_{J/\psi p}$ is not reproduced.

Fit: Reduced Model

- The parameters of the P_c^+ states are determined using a more restrictive model of the K^-p states that only includes the resonances that are well motivated.
  - Referred to as the "reduced" model
  - Has 64 free parameters to describe the Λ^* decays.
  - Different combinations of P_c^+ resonances add an additional 20 free parameters.

Fit Results: Reduced Model

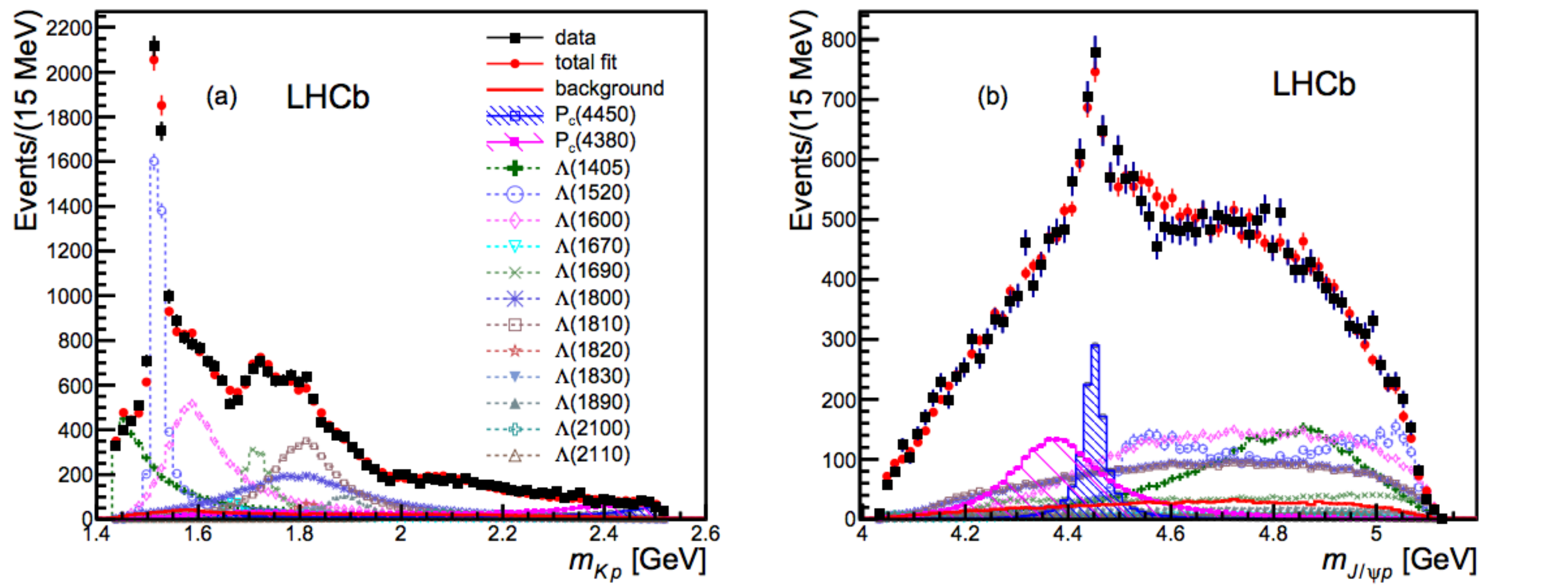


Figure 3: Fit projections for (a) m_{Kp} and (b) $m_{J/\psi p}$ for the reduced Λ^* model with two P_c^+ states

The best fit combination finds two P_c^+ states (statistical errors only):

	Mass [MeV]	J^P	Width [MeV]	Significance
$P_c^+(4380)$	4380 ± 8	$3/2^-$	205 ± 18	9σ
$P_c^+(4450)$	4449.8 ± 1.7	$5/2^+$	39 ± 5	12σ

The combined significance of two P_c^+ states is 15 σ

Fit Results: Angular Distributions

- Angular distributions are reasonably well reproduced.
- These angular distributions refer to the angles defined on slides 11 and 12.

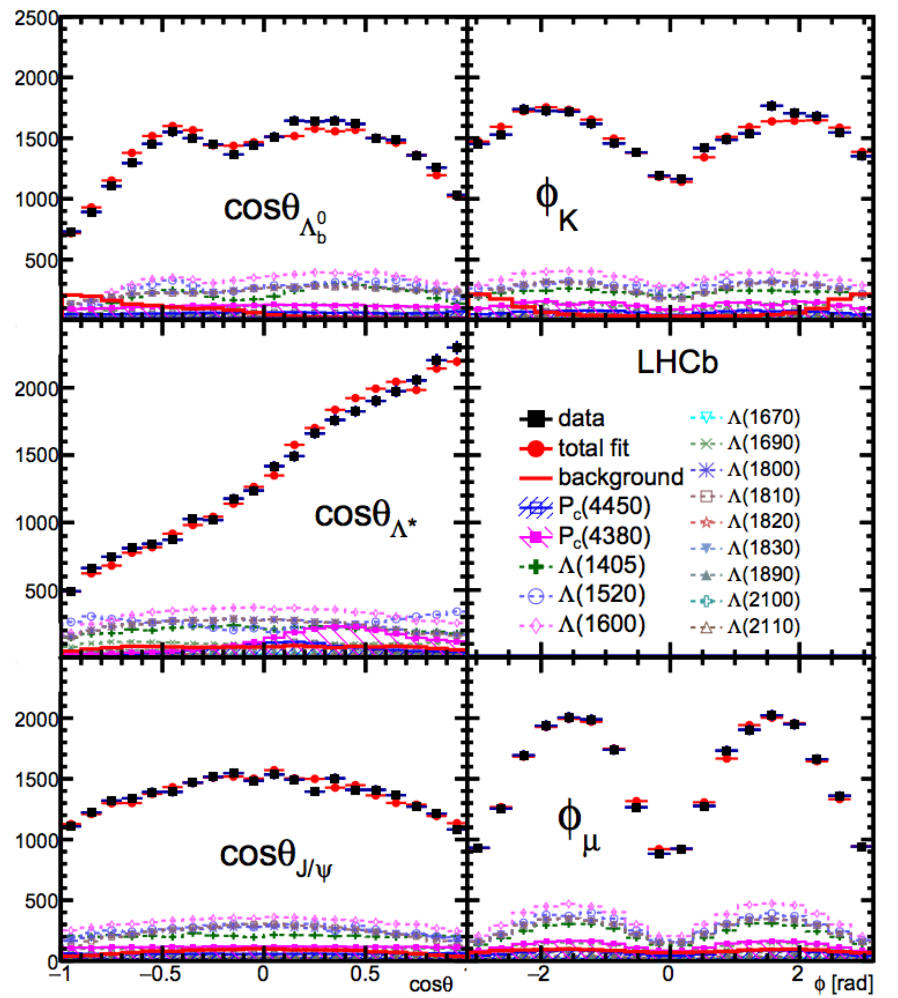


Figure 7: Various decay angular distributions for the fit with two P_c^+ states. The data are shown as (black) squares, while the (red) circles show the results of the fit. Each fit component is also shown. The angles are defined in the text.

Confirmation Tests

- A number of tests were conducted to confirm the results, including:
  - Comparing data recorded in 2011/2012 with the LHCb dipole magnet polarity in up/down configurations
  - Λ_b^0 produced with low/high values of pT
  - Adding two high mass Λ^* resonances of freely varied mass and width to the extended model fit.
  - The fitters were tested on simulated pseudoexperiments and no biases were found.
  - Selection requirements were varied.
  - Vetoes of $\bar{B}^0$ *and* $\bar{B}_s^0$ are removed and explicit models of those backgrounds added to the fit
  - Etc.
- All gave consistent results.

Conclusion

- These structures cannot be accounted for by reflections from $J/\psi\ \Lambda^*$ resonances or other known sources.
- Interpreted as resonance states they must have minimal quark content of $\mathrm{uudc}\bar{c}$ and therefore would be called charmonium-pentaquark states.

	Mass $\pm$ stat $\pm$ sys [MeV]	J^P	Width $\pm$ stat $\pm$ sys [MeV]	Significance
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$3/2^-$	$205 \pm 18 \pm 86$	9σ
$P_c^+(4450)$	$4449.8 \pm 1.7 \pm 2.5$	$5/2^+$	$39 \pm 5 \pm 19$	12σ

- The higher mass state has a fit fraction of $(4.1 \pm 0.5 \pm 1.1)\%$ and the lower mass state of $(8.4 \pm 0.7 \pm 4.2)\%$ of the total $\Lambda_b^0 \to J/\psi\ K^- p$ sample.