Pentaquarks and exotic baryonic states

Meson 2018

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On behalf of LHCb

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Pentaquarks and exotic states

- Quark model allows for states beyond the well established $q\bar{q}$ mesons and qqq baryons
- States such as $qqqq\bar{q}$ (pentaquark), $qq\bar{q}\bar{q}$ (tetraquark) postulated in Gell-Mann's and Zweig's original quark model papers (1964) *Phys.Lett. 8 (1964) 214-215, CERN-TH-412*

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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 b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

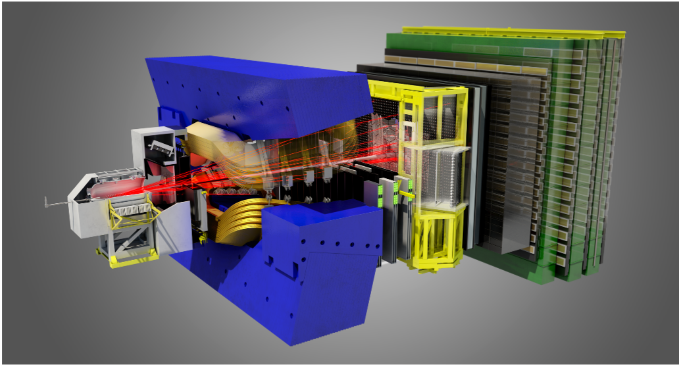
- Now refer to any hadron that does not follow $q\bar{q}/qqq$ as exotic

How to search for exotic states

- Short lived states which can appear as resonances in decays
- Effects can be seen on the Dalitz plot of invariant mass variables
- A full amplitude analysis can confirm presence as well as determine mass/width and quantum numbers (J^P) of states
- LHCb in unique postition to search for exotic contributions in decays of various b hadrons
- b hadrons in LHCb acceptance have the ratio 4:2:1 $B^0 : \Lambda_b^0 : B_s^0$

LHCb detector

A single-arm forward spectrometer specialising in decays of b hadrons



Tracking efficiency $> 96\%$

$\sigma_{IP} = 20\ \mu$m

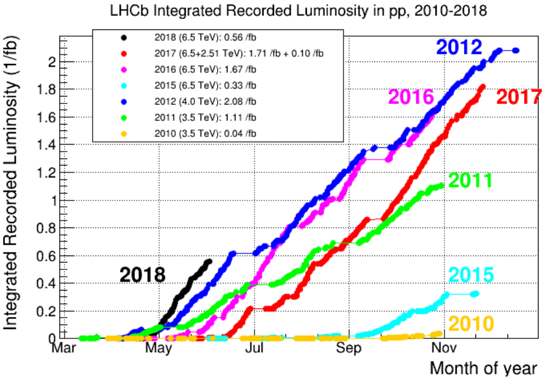
$\Delta p/p = 0.5 - 1.0\%$ for 5-100 GeV

RICH $K - \pi$ separation: $\epsilon(K \rightarrow K) \approx 95\%$, $\epsilon(\pi \rightarrow K) \approx 5\%$

Muon ID: $\epsilon(\mu \rightarrow \mu) \approx 97\%$, $\epsilon(\pi \rightarrow \mu) \approx 1 - 3\%$

Int. J. Mod. Phys. A 30 (2015) 1530022

LHCb detector



https://lbgroups.cern.ch/online/OperationsPlots/index.htm

Analyses presented today:

- Run 1 dataset - 1 fb^{-1} at $\sqrt{s} = 7$ TeV + 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- 2016 dataset - 1.7 fb^{-1} at $\sqrt{s} = 13$ TeV

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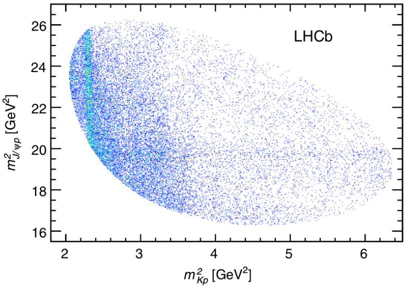
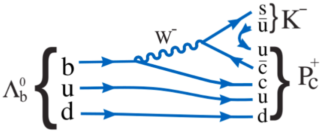
   - *Model independent evidence for J/ψ constributions to $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays* PRL 117, 082002 (2016)
   - *Evidence for exotic hadron contributions to $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decays* PRL 117, 082003 (2016)
2. Investigating the nature of observed pentaquark states
   - *Observation of the decays $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$ and $\Lambda_b^0 \rightarrow \chi_{c2} p K^-$* PRL 119, 062001 (2017)
3. Searches for further pentaquark states
   - *Observation of the $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decay* Phys. Lett. B. 772 (2017) 265-273
   - *A search for weakly decaying b-flavored pentaquarks* Phys. Rev. D 97, 032010
   - *Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$* Phys. Rev. Lett. 118, 182001

Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$

- $\Lambda_b^0 \to J/\psi p K^-$ decay first observed using 2011 in measurement of Λ_b^0 lifetime
- Dalitz plot of run 1 (3 fb^{-1}) data shows structures in
  - $m^2_{K^-p}$ due to known $\Lambda_b^0 \to \Lambda^*(\to K^- p) J/\psi$ resonances
  - $m^2_{J/\psi p}$ due to ???



PRL 115, 072001 (2015)



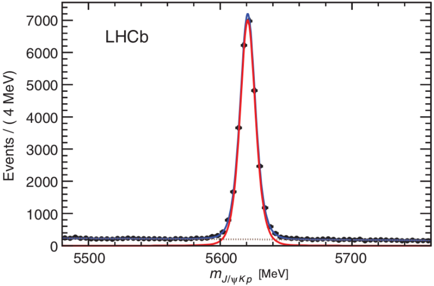
- Any resonance decaying strongly to $J/\psi p$ has minimal quark content $uudc\bar{c}$

Perform full amplitude analysis to determine nature of this structure

$\Lambda_b^0 \rightarrow J/\psi p K^-$ dataset

- Very clean 3 fb^{-1} dataset
- 26,007$\pm$ 116 signal events with 94.6% purity

- Trigger on $J/\psi \rightarrow \mu^+\mu^-$ displaced from PV
- High quality track and vertex reconstruction
- Veto $\bar{B}^0_{(s)} \rightarrow J/\psi h^- h^+$ misID background decays



PRL 115, 072001 (2015)

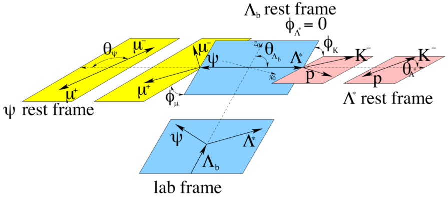
$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Consider the two interfering decay channels

$$\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to pK^- \quad \Lambda_b^0 \to P_c^+ K^-, P_c^+ \to J/\psi p$$

- Fit 6-dimensional phasespace (m_{K^-p} and 5 decay angles) using helicity formalism

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



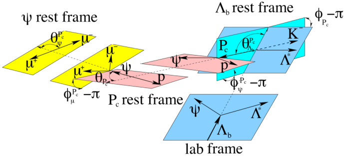
$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Consider the two interfering decay channels

$$\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to pK^- \quad \Lambda_b^0 \to P_c^+ K^-, P_c^+ \to J/\psi p$$

- Fit 6-dimensional phasespace (m_{K^-p} and 5 decay angles) using helicity formalism

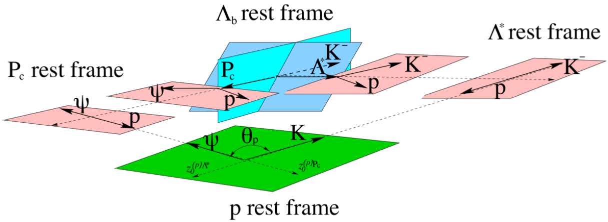
$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0 \to P_{cj} K}_{\lambda_{P_c}, 0} D^{J_{\Lambda_b^0}}_{\lambda_{\Lambda_b^0}, \lambda_{P_c}} (\phi_{P_c}, \theta^{P_c}_{\Lambda_b^0},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



$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Helicity couplings $\mathcal{H}$ expressed as LS couplings
- Number of couplings to be fit reduced by parity considerations and considering only lowest values of orbital angular momentum in decay
- Add two decay chains coherently summing over Λ_b^0 polarisations

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} |\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + D^{J_p}_{\Delta\lambda_\mu,\lambda_p}(\alpha_\mu,\theta_p,0)\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu}|^2$$



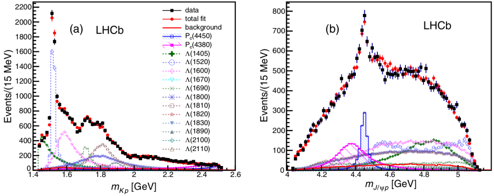
$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Fit using only (but all configurations of) the $\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to pK^-$ decay chain - *extended model* - cannot reproduce structure in seen in $m_{J/\psi p}$
- Try restricted set of well motivated Λ^* components - *reduced model* - with two P_c^+ components

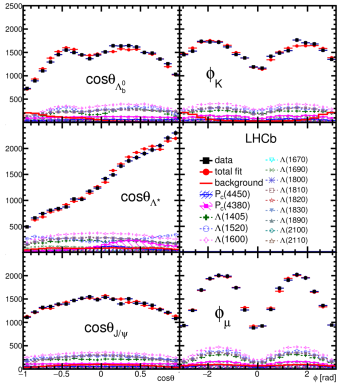
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	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
$\Lambda(2585)$	$5/2$	$\approx$2585	200	0	6

$\Lambda_b^0 \rightarrow J/\psi p K^-$ amplitude analysis

- Acceptable fits found - P_c states needed to describe structure in $m_{J/\psi p}$



	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
J^P	$3/2^-$	$5/2^+$
Fit fraction	$4.1 \pm 0.5 \pm 1.1$	$8.4 \pm 0.7 \pm 4.2$
Significance	9	12



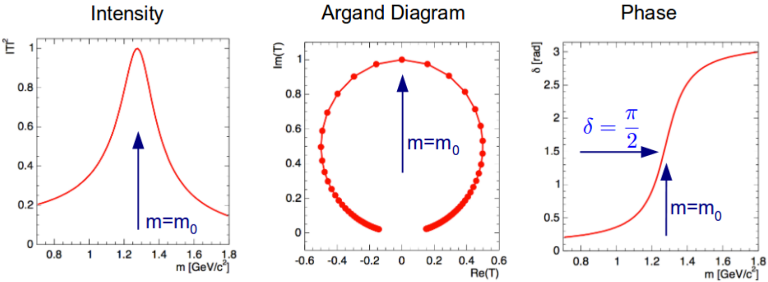
PRL 115, 072001 (2015)

- $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ also acceptable
- Central values use reduced model - systematics consider extended model

$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

Do the P_c states have the characteristics of a resonance?

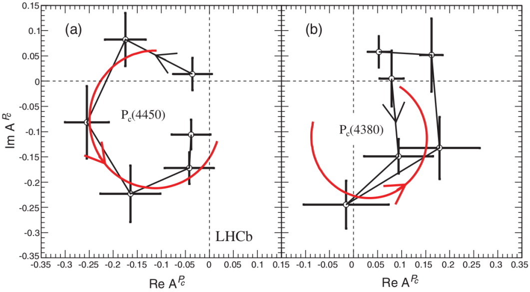
- Resonances often modelled by Breit Wigner amplitudes
- Breit Wigner amplitudes have characteristic nature in complex plane
    - Anticlockwise circular trajectory
    - Phase change of $\pi/2$ across pole mass m_0



iktp.tu-dresden.de/IKTP/Seminare/IS2012/pelizaeus.pdf

$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Represent P_c amplitude as 6 points in complex plane with $m_{J/\psi p}$ values equally spaced between $M_{P_c} - \Gamma_{P_c} < M_{P_c} < M_{P_c} + \Gamma_{P_c}$ that are to be fit
- Interpolate between fitted points



PRL 115, 072001 (2015)

- $P_c(4450)$ trajectory consistent with rapid anticlockwise motion
- $P_c(4380)$ not conclusive

$\Lambda_b^0 \to J/\psi p K^-$ model independent approach

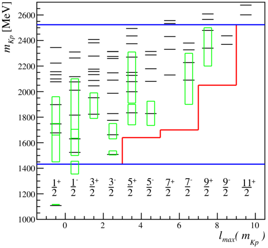
- Λ^* spectroscopy is complex - many more higher mass excitations predicted that have not been found experimentally
- Want a model-independent method that makes no assumptions about how many Λ^* states exist and minimal assumptions about spin and lineshapes
- Begin with hypothesis that data can be described by only Λ^* (incl. nonresonant and Σ excitations) resonances - H_0
- Considering $(m_{Kp}, \cos\theta_{\Lambda^*})$ plane, expand $\cos\theta_{\Lambda^*}$ angular distribution in Legendre polynomials (P_l) using m_{Kp} dependent coefficients (moments) $\langle P_l^U \rangle$ of rank l

$$\frac{dN}{d\cos(\theta_{\Lambda^*})} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

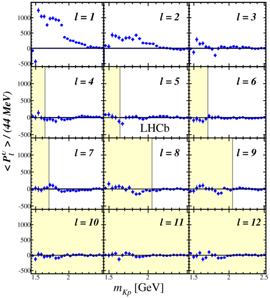
where N is efficiency-corrected and background-subtracted yield

$\Lambda_b^0 \to J/\psi p K^-$ model independent approach

- H_0 resonances cannot contribute to moments higher than $2J_{max}$ where J_{max} is highest spin of H_0 contribution at given m_{Kp} - $l_{max} = 2J_{max}$
- Exotic contributions OR rescattering effects of ordinary hadrons can give moments higher than l_{max} through a range of m_{Kp}



PRL 117, 082002 (2016)



PRL 117, 082002 (2016)

Experimentally established Λ^* states with width

Predicted states

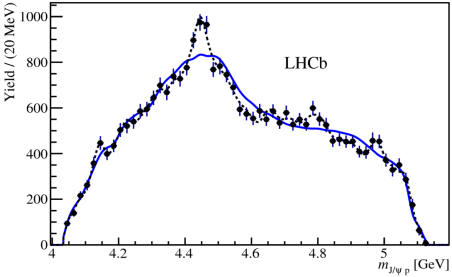
m_{Kp} mass range probed

$l_{max}(m_{Kp})$ filter

$\langle P_l^U \rangle$ as a function of m_{Kp}. Contributions to higher rank Legendre moments than l_{max}

$\Lambda_b^0 \to J/\psi p K^-$ model independent approach

- Alternative hypothesis H_1 where l_{max} is large enough to reproduce possible pentaquark structures



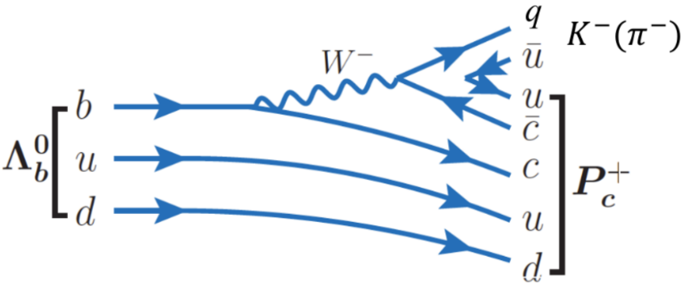
PRL 117, 082002 (2016)

H_0 hypothesis, H_1 hypothesis

- H_0 rejected at more than 9σ
- Cannot rule out that this is due to rescattering effects of ordinary hadrons

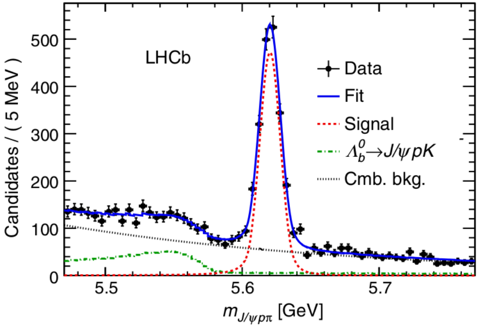
Pentaquarks in $\Lambda_b^0 \to J/\psi p\pi^-$

- Observations of $P_c(4450)$ and $P_c(4380)$ in another decay strengthens the case for genuine exotic baryonic states
- Use Cabibbo supressed analogue of $\Lambda_b^0 \to J/\psi pK^-$ decay $\Lambda_b^0 \to J/\psi p\pi^-$
- Allow for contribution of $Z_c(4200)^- \to J/\psi\pi^-$ reported by Belle Phys. Rev. D 90, 112009 (2014)



$\Lambda_b^0 \to J/\psi p \pi^-$ dataset

- Same LHCb dataset used as for the $\Lambda_b^0 \to J/\psi p K^-$ analysis
- Very similar selection applied
- 1885$\pm$ 50 signal events



PRL 117, 082003 (2016)

- $p\pi^-$ from nucleon excitations (N^*) expected to dominate amplitude
- Decay matrix elements for
  - $\Lambda_b^0 \to J/\psi N^*$, $N^* \to p\pi^-$
  - $\Lambda_b^0 \to P_c^+ \pi^-$, $P_c^+ \to J/\psi p$ identical to $\Lambda_b^0 \to J/\psi p K^-$ analysis
- Additional $\Lambda_b^0 \to Z_c^- p$, $Z_c^- \to J/\psi \pi^-$ decay chain

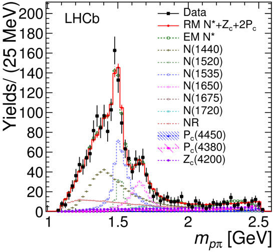
$\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis

State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

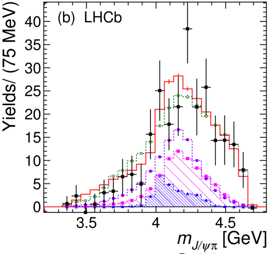
- Possibility of unknown high-mass, low spin N^* accounted for with addition of BES III claimed (but unconfirmed) $N(2300)$ and $N(2570)$ resonances Phys. Rev. Lett. 110, 022001 (2013)

$\Lambda_b^0 \to J/\psi p\pi^-$ amplitude analysis

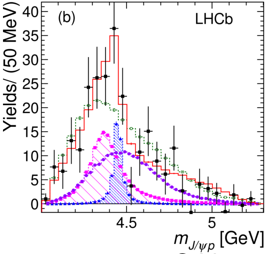
- Limited statistics - cannot perform open-ended amplitude analysis
- Search for previously observed pentaquark and $Z_c(4200)^-$ states fixing mass/width to reported values
- Fix P_c J^P assignments and $\mathcal{H}$ couplings describing $P_c^+ \to J/\psi p$ from Cabibbo favored channel
- Reduced model with pentaquark and $Z_c(4200)^-$ states favored over N^* only extended model



PRL 117, 082003 (2016)



$m_{p\pi} > 1.8$ GeV

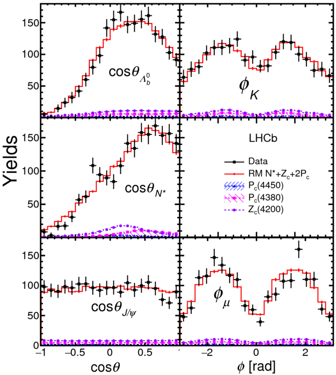


$m_{p\pi} > 1.8$ GeV

$\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis

	Fit fraction (%)
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.6}_{-1.6}$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$

- Some ambiguity between 3 exotic contributions
- Significance of two P_c and $Z_c(4200)^-$ together is 3.1σ
- Assuming a negligible $Z_c(4200)^-$ contribution the significance of two P_c states is 3.3σ



PRL 117, 082003 (2016)

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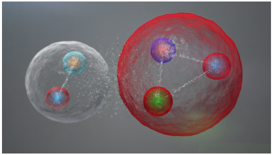
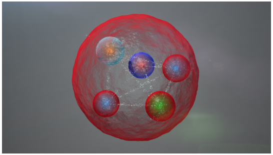
Nature of pentaquarks

Possible models describing the observed pentaquark states include



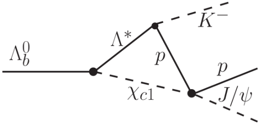
Meson-baryon molecules

Phys. Rev. Lett. 115, 122001 (2015)
Phys. Rev. Lett. 115, 172001 (2015)
Phys. Rev. D. 92, 094003 (2015)



Compact tightly-bound pentaquarks

Phys. Lett. B 749, 289 (2015)
Phys. Lett. B 749, 454 (2015)
JHEP 12(2015) 128

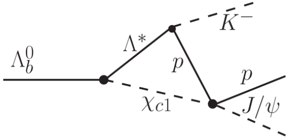


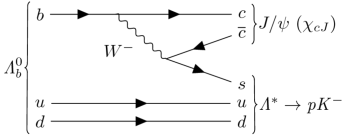
Rescattering effects

Phys. Rev. D. 92, 071502 (2015)
Phys. Lett. B 757, 231 (2016)
Phys. Lett. B 751, 59 (2015)
Eur. Phys. J. A 52, 318 (2016)

Pentaquarks in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Model independent study could not rule out that P_c states can be explained by rescattering
- $m(\chi_{c1} p) \approx m(P_c(4450))$
- Could $P_c(4450)$ be explained by $\chi_{c1} p \to J/\psi p$?





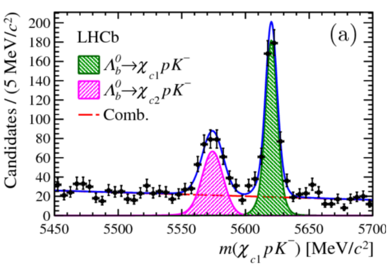
- Can be easily tested by searching for $P_c(4450) \to \chi_{c1} p$ resonance in $\Lambda_b \to \chi_{c1} p K^-$ - requires amplitude analysis

Observation of $\Lambda_b^0 \to \chi_{c1} p K^-$ and $\Lambda_b^0 \to \chi_{c2} p K^-$ decays

- Preliminary work towards amplitude analysis - branching fraction measurement - performed on run 1 dataset
  - Measure branching fractions relative to $\Lambda_b^0 \to J/\psi p K^-$
  - Reconstruct χ_{cJ} as $J/\psi\gamma$
  - Mass constraint to J/ψ and χ_{c1} separating peaks
  - No suppression of χ_{c2} relative to χ_{c1} as observed in B decays

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$



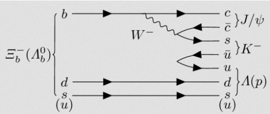
PRL 119, 062001 (2017)

With dataset from Run 2 can perform full amplitude analysis

Table of Contents

Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

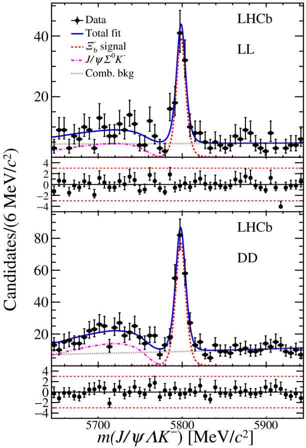
- Pentaquarks with strangeness $udsc\bar{c}$ could be observed as $J/\psi\Lambda$ state in $\Xi_b^- \to J/\psi \Lambda K^-$ decays



- First observation at LHCb using run 1 dataset

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}$$

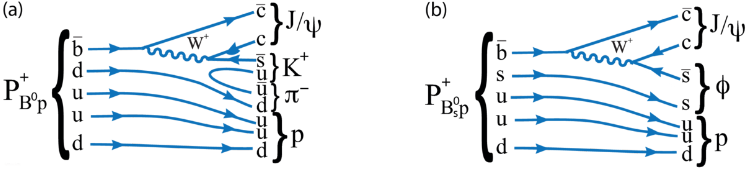
With run 2 dataset a full amplitude analysis can be performed



Phys. Lett. B. 772 (2017) 265-273

Search for b-flavored pentaquarks

- Skyrme model predicts that the heavier the constituent quarks the more tightly bound the pentaquark - more stable state *Proc. R. Soc. A 260, 127 (1961)*
- Investigate existence of pentaquark states containing a single b or $\bar{b}$ quark that then decays weakly



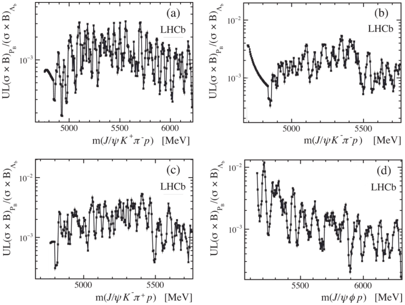
Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \rightarrow J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \rightarrow J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \rightarrow J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \rightarrow J/\psi \phi p$	5055–6305 MeV

Search for b-flavored pentaquarks

- Search windows are defined below dominant strong decay thresholds
- Scan $m_{J/\psi hhh}$ in 4 MeV steps
- No significant evidence for signal - set upper limits at 90% CL in $m_{J/\psi hhh}$

$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p)}$$

Measured by LHCb *Chin. Phys. C40,011001 (2016)*

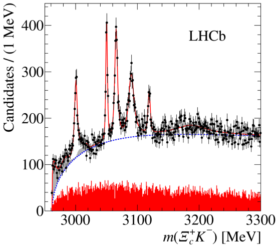


Phys. Rev. D 97, 032010

Pentaquarks contributions to Ω_c^0 states

- Observation of 5 new, narrow excited Ω_c^0 states at $\approx$ 3000 MeV with minimal quark content *ssc*

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		$<$ 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		$<$ 2.6 MeV, 95% CL



Phys. Rev. Lett. 118, 182001

- Two states have extremely narrow width compared with conventional hadrons
  - $\bar{K}\Xi_c$ and $\bar{K}\Xi_c'$ thresholds $\approx$ 3000 MeV
  - Predictions for Ω_c^0 resonances being meson-baryon molecules *Phys. Rev. D85 (2012) 114032*

...could these in fact be pentaquarks with $sscu\bar{u}$?

Conclusions

- Two charmonium pentaquarks seen by LHCb in $\Lambda_b^0 \to J/\psi p K^-$ decays
- Existence supported by model-independent approach and as contribution to $\Lambda_b^0 \to J/\psi p \pi^-$ decays
- Investigations into other possible explainations for pentaquark states ongoing
- Several channels being investigated for other pentaquark states including *b*-flavored pentaquarks and pentaquarks with strangeness
- Interpretations of 'conventional' hadrons being challenged
- Many of these channels require full run 1+2 data to perform amplitude analyses so stay tuned...