Pentaquarks

Lorenzo Capriotti
on behalf of the LHCb Collaboration
with results from the Belle Collaboration

FPCP, Victoria BC
07/05/2019

Quarkonia spectroscopy

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The excitation spectrum of a $[Q\overline{Q}]$ state is well described by a semi-relativistic phenomenological potential (effective Cornell potential)

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma r + \delta(1/r^2)$$

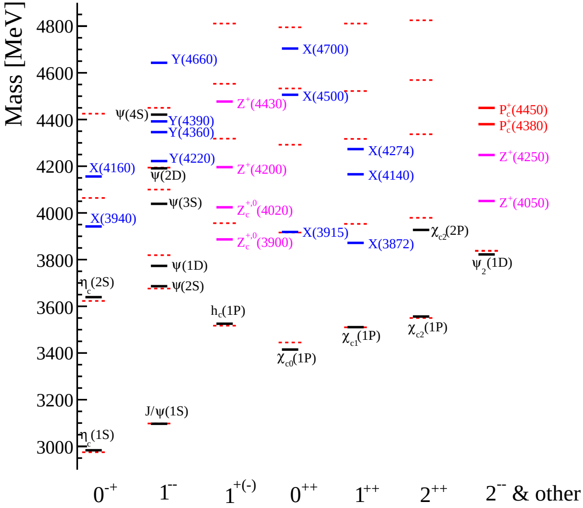
- A short-distance **colour potential**
- A long-distance **confinement** term
- **Spin-spin** and **spin-orbit** corrections

Developed in the 70's, particularly accurate to describe and predict the spectrum of $[c\bar{c}]$ and $[b\bar{b}]$ states.

[Phys. Rev. D 21, 203 (1980)]

Charmonium spectrum

In the last 15 years a large number of states have been discovered which contain a $c\bar{c}$ pair but do not fit in the expected spectrum



Adapted from [Rev. Mod. Phys. 90, 15003 (2018)]

Exotic candidates

All the unpredicted states are labelled as **exotic** states.

- They must contain a $c\bar{c}$ pair as they all decay into a final state with a charmonium
- They do not present the same properties expected from a pure $c\bar{c}$ state

As an example, look at X(3872):

- The first exotic state ever observed (Belle, 2003)
- Extremely narrow to be above the open charm threshold
- Radiative decay rates do not match prediction for a $c\bar{c}$ state
- Decays into two different final states with different isospin (maximal violation)

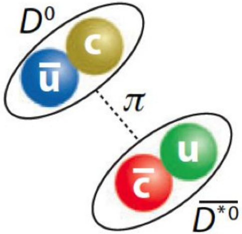
Furthermore, the Z states are charged and this implies a minimal quark content of $[c\bar{c}d\bar{u}]$

Models for multiquark states

Several models have been proposed to describe the exotic states.
Main interpretations:

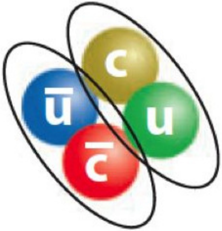
Mesonic (baryonic) molecule

- Low binding energy, narrow states
- Only S-wave, few states predicted
- Independently decaying components



Compact multiquark

- Tightly bound states
- Large widths in principle
- Many states expected



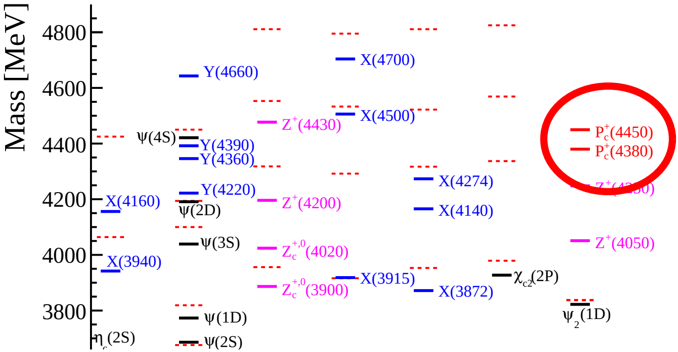
Other models are in principle allowed, as well as mixture of different models

Pentaquarks

The charmonium spectrum is the ideal place to look for unexpected states

- Large mass difference between states wrt light $[q\bar{q}]$ states
- Clean environment
- Wide range of detailed studies (better than bottomonium spectrum)

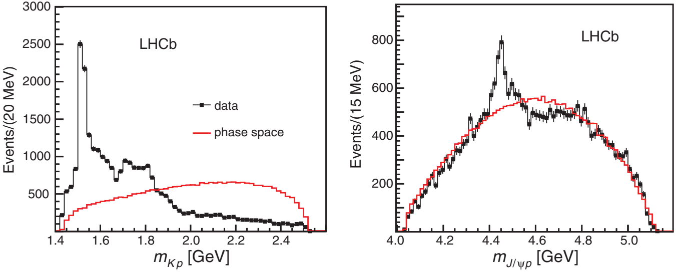
This presentation will focus on measurements and searches for states with 5 constituent quarks $[qqqq\bar{q}]$, in particular $[qqqc\bar{c}]$



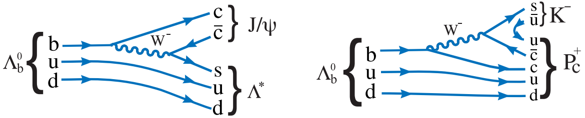
OBSERVATION OF PENTAQUARKS IN $\Lambda_b^0 \to J/\psi K^- p$ DECAYS (RUN 1)

Analysis of $\Lambda_b^0 \to J/\psi K^- p$ decays

Structures are visible, over a non-resonant distribution, in the $m_{J/\psi p}$ spectrum from $\Lambda_b^0 \to J/\psi K^- p$ decays using the full LHCb Run 1 statistics ($3\ \mathrm{fb}^{-1}$)



The resonant contributions are expected to be dominated by $\Lambda^* \to K^- p$ decays, need to check if structures in $m_{J/\psi p}$ are reflections in Dalitz plot



[Phys. Rev. Lett. 115, 072001 (2015)]

Analysis strategy

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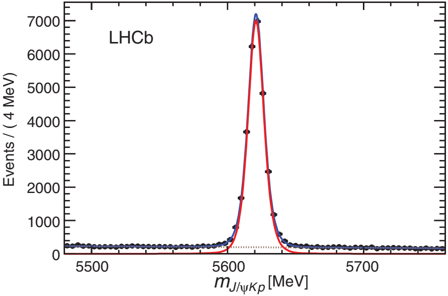
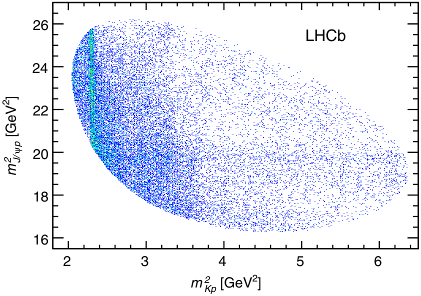
- 14 well established $\Lambda^* \to pK^-$ resonances to take into account
- 5 decay angles + m_{Kp} (6D fit)
- Helicity formalism
- Background-subtracted data

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

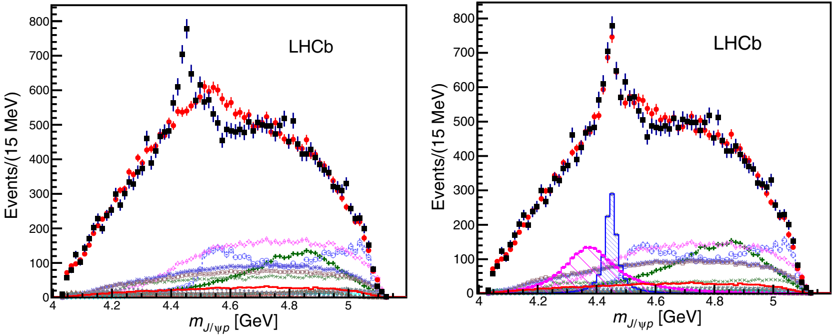




[Phys. Rev. Lett. 115, 072001 (2015)]

Fit projections and results

To have an acceptable fit two new P_c^+ states need to be included



- Black points: data
- Red points: amplitude fit
- $P_c(4380)^+$, $J^P = 3/2^-$, $\Gamma = 205 \pm 18$ MeV, significance 9σ
- $P_c(4450)^+$, $J^P = 5/2^+$, $\Gamma = 39 \pm 5$ MeV, significance 12σ

[Phys. Rev. Lett. 115, 072001 (2015)]

Model-independent confirmation

To confirm the previous result, the analysis is repeated using a different, model-independent approach.

- Minimal assumptions on the excited Λ^* spin and shapes
- Can include also nonresonant $K^- p$ and Σ^* contributions

The strategy is to describe the 2D plane (m_{Kp},$\cos\theta_{\Lambda^*}$) expanding the helicity angle θ_{Λ^*} in Legendre polynomials:

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

where

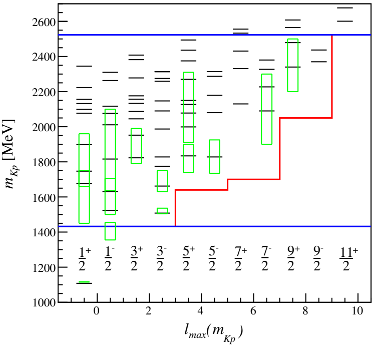
$$\left\langle P_l^U \right\rangle = \int_{-l}^{+l} d\cos\theta_{\Lambda^*} P_l(\cos\theta_{\Lambda^*}) dN/d(\cos\theta_{\Lambda^*})$$

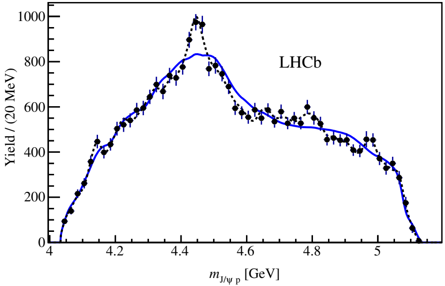
and it is extracted from the m_{Kp} distribution in data.
If no exotic contribution is present and the structures in $m_{J/\psi p}$ are due to reflections, then this expansion will be enough to describe the $m_{J/\psi p}$ spectrum

[Phys. Rev. Lett. 117, 082002 (2016)]

Model-independent confirmation

In practise, the Legendre moments include all contributions in $K^{-}p$ with spin $2J_{max}$ or less, depending on the given m_{Kp} range, up to $J_{max} = 9/2$.





By looking at $m_{J/\psi p}$ it is clear that the distribution cannot be explained using only reflections.
The discrepancy is more than 9σ.

[Phys. Rev. Lett. 117, 082002 (2016)]

EXOTIC RESONANCES AND RESCATTERING EFFECTS

Rescattering effects

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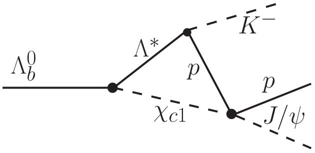
The narrow structure at 4450 MeV/c^2 observed by LHCb happens to be located exactly at the $\chi_{c1}p$ mass threshold. This can be a signal of a kinematic enhancement due to rescattering effects.

- All intermediate particles must be on shell to have a threshold enhancement
- The Λ^* mass must lie within a kinematically allowed mass range
- One happens to exist: $\Lambda(1890)$



$\Longrightarrow$ An observation of $P_c(4450)^+$ decaying in the $\chi_{c1}p$ final state (and not $\chi_{c0,c2}p$) would confirm the exotic nature of the resonance

$\Longrightarrow$ An observation of $P_c(4450)^+ \to J/\psi p$ from $\Lambda_b^0 \to J/\psi p \pi^-$ decays would be harder to accommodate in this picture (dominated by N^*)

[Phys. Rev. D 92, 071502 (2015)], [Phys. Rev. D 93, 094001 (2016)]

Search for $P_c^+ \to \chi_{c1} p$

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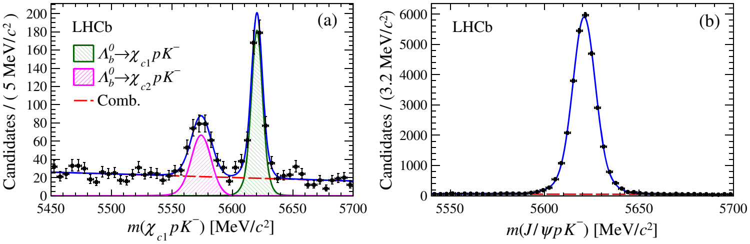
First observation of the decays $\Lambda_b^0 \to \chi_{c1} p K^-$ and $\Lambda_b^0 \to \chi_{c2} p K^-$

- First investigation, with limited statistics (3 fb^{-1}, full LHCb Run 1)
- $\text{N}(\Lambda_b^0 \to \chi_{c1} p K^-) = 453 \pm 25$
- Not enough to analyse the $\chi_{c1} p$ mass spectrum, will be updated with Run 2 data
- First measurement of the branching fractions relative to $\Lambda_b^0 \to J/\psi p K^-$
- $\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$
- $\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$

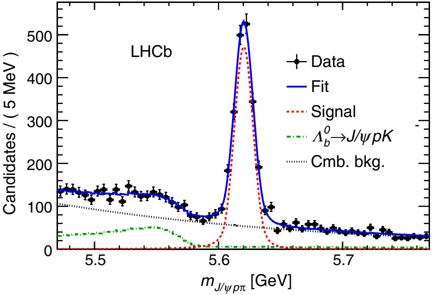


[Phys. Rev. Lett. 119, 062001 (2017)]

Analysis of the $\Lambda_b^0 \to J/\psi p\pi^-$ channel

- Data: 3 fb^{-1}, full LHCb Run 1
- Thanks to the $\Delta I = 1/2$ rule the Λ^* contributions are suppressed
- 14 well established $N^* \to p\pi^-$ resonances to take into account
- 5 decay angles + m_{Kp}
- Helicity formalism
- Background-subtracted data

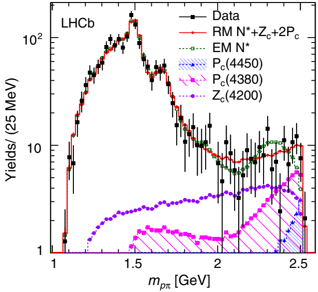
State	J^P	Mass (MeV)	Width (MeV)	RM	EM
$NR\ p\pi$	$1/2^-$	...	...	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	...	3
$N(1700)$	$3/2^-$	1700	150	...	3
$N(1710)$	$1/2^+$	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

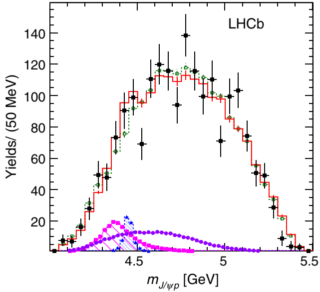


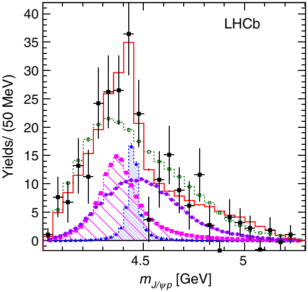
[Phys. Rev. Lett. 117, 082003 (2016)]

Fit projections and results

- Adding $P_c(4380)^+$, $P_c(4450)^+$ and a $Z_c(4200)^- \to J/\psi\pi^-$ contribution significantly improves the fit
- P_c^+ production rates as expected from previous observation (including Cabibbo suppression)
- Combined significance: 3.1σ





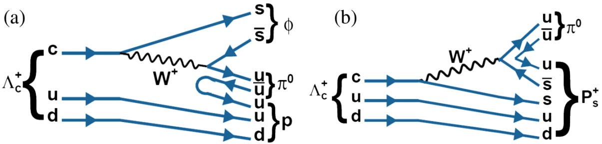


[Phys. Rev. Lett. 117, 082003 (2016)]

RECENT SEARCHES FOR STRANGE AND BEAUTY PENTAQUARKS

Search for s-flavoured pentaquarks

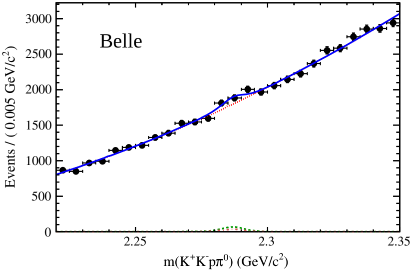
- Strange-flavour analogue of the P_c^+ discovery channel: $\Lambda_c^+ \to \phi p \pi^0$
- This channel has never been studied before
- Dataset: 915 fb^{-1} at $\Upsilon(4S)$ and $\Upsilon(5S)$ collected by the Belle experiment
- P_s^+ can be observed as peak in the ϕp mass spectrum if the same production mechanism holds, and if $m_{P_s^+} < m_{\Lambda_c^+} - m_{\pi^0}$

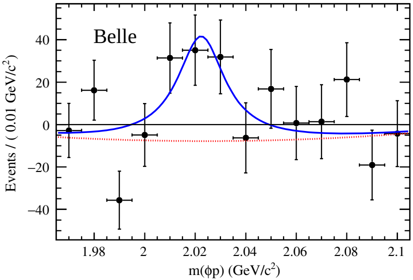


[Phys. Rev. D 96, 051102 (2017)]

Search for s-flavoured pentaquarks

No signal is observed in a mass window of 20 MeV/c^2 around the ϕ peak, upper limits at 90%CL are set on the branching fraction product, normalised using $\Lambda_c^+ \to pK^-\pi^+$ decays





$$\mathcal{B}(\Lambda_c^+ \to P_s^+\pi^0) \times \mathcal{B}(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$$

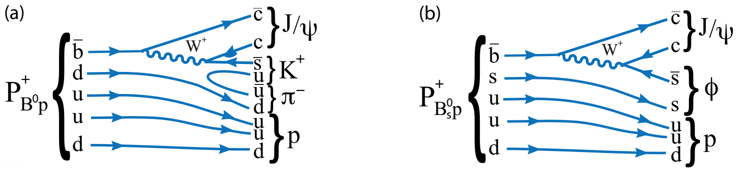
(as a reference)

$$\mathcal{B}(\Lambda_b^0 \to P_c(4450)^+K^-) \times \mathcal{B}(P_c(4450)^+ \to J/\psi p) = (1.3 \pm 0.4) \times 10^{-5}$$

[Phys. Rev. D 96, 051102 (2017)]

Search for b-flavoured pentaquarks

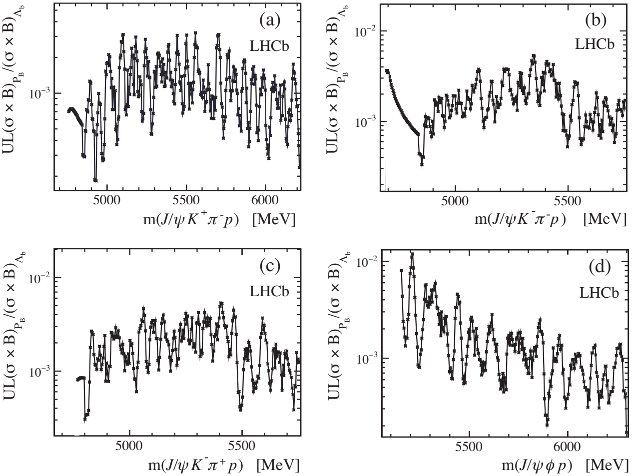
- According to the Skyrme model, the heavier the constituent quarks are, the more tightly bound the state is
- No searches for b-flavoured pentaquarks have ever been published
- Full LHCb Run 1 integrated luminosity (3 fb^{-1})
- Four different states considered:
  - $P^+_{B^0 p} \to J/\psi K^+ p \pi^-$
  - $P^+_{\Lambda^0_b \pi^+} \to J/\psi K^+ p \pi^+$
  - $P^-_{\Lambda^0_b \pi^-} \to J/\psi K^+ p \pi^-$
  - $P^+_{B^0_s p} \to J/\psi \phi p$
- Mass ranges chosen to be below the strong decay threshold



[RSPA 260, 1300 (1961)], [Phys. Rev. D 97, 032010 (2018)]

Search for b-flavoured pentaquarks

No signal is observed, upper limits at 90%CL are set on the production cross sections times the BR, normalised using $\Lambda_b^0 \to J/\psi K^- p$ decays

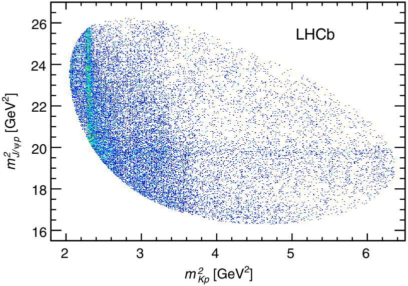


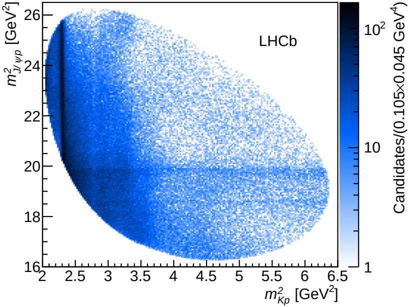
[Phys. Rev. D 97, 032010 (2018)]

OBSERVATION OF PENTAQUARKS IN $\Lambda_b^0 \to J/\psi K^- p$ DECAYS (RUN 1 + RUN 2)

Update with full Run 1 and Run 2 statistics

- Latest LHCb result on pentaquark searches: update of 2015 analysis
- Integrated luminosity 9 fb^{-1}, better data selection, increase in production cross-section (13 TeV instead of 7 and 8 TeV)
- 9 times more statistics $\Longrightarrow$ improved resolution on mass spectra

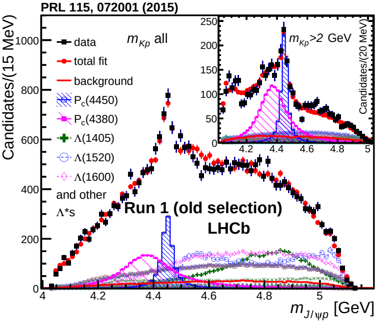


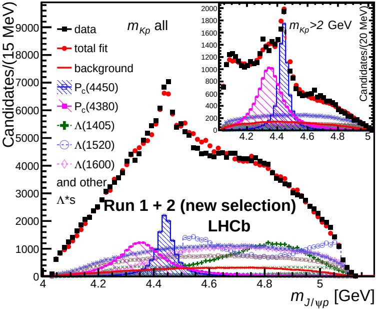


[arXiv:1904.03947]

Consistency check

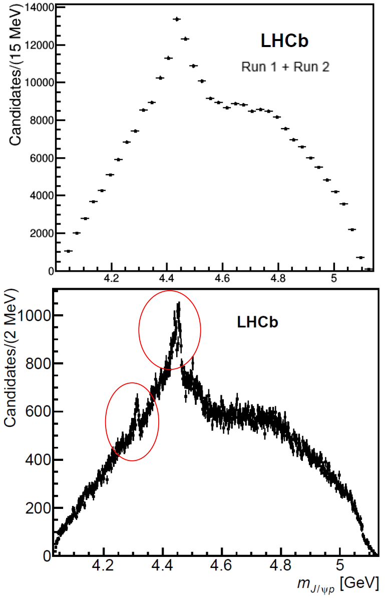
First check: using the new dataset, the new selection and the same amplitude model we get compatible results





[arXiv:1904.03947]

New features

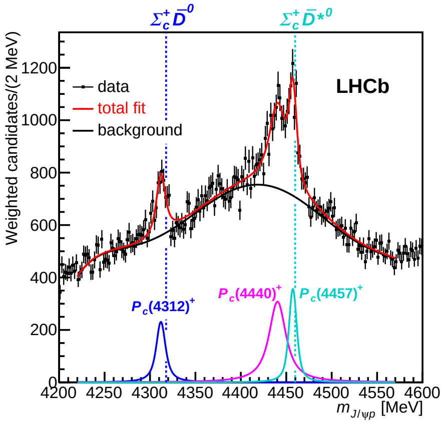


[arXiv:1904.03947]

- Increase in mass resolution (≈2.5 MeV)
- New narrow structure at 4.3 GeV, $P_c(4450)^+$ is resolved into two peaks
- Amplitude fit computationally challenging, currently work in progress
- Very narrow states, cannot be artificial reflections
- Cut at $m_{Kp} > 1.9$ GeV to suppress the dominant $\Lambda^* \to pK^+$ contributions
- 1-dimensional fit using different composition of Λ^* reflections to model the background
- This analysis is not sensitive to broad $J/\psi p$ contribution, like $P_c(4380)^+$

Fit to the $J/\psi p$ invariant mass

- The masses of the narrow peaks are just below the $\Sigma_c^+ \overline{D}^{(*)0}$ masses
- Although the compact pentaquark model is not ruled out, these features favour the molecular interpretation
- Need to measure quantum numbers and find isospin partners in order to have a definitive answer



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

[arXiv:1904.03947]

CONCLUSIONS

Conclusions

- Exotic spectroscopy is an extremely rich and productive field
- Several observations and searches for pentaquark states in the last 4 years
- Quite a recent discovery - this is just the beginning of a new era in both discovery of new states and understanding of QCD binding mechanisms
- We still do not know what the real nature of these new states is
- The LHCb Run 2 update measurement is the strongest evidence so far towards a molecular interpretation of the P_c^+ states
- Amplitude analysis is challenging, but ongoing
- LHCb clearly dominates the scene for now, waiting for Belle II to join

BACKUP