Observation of pentaquarks at the LHCb experiment

20/06/2022

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Outlines

- History of pentaquarks
- Pentaquarks @ LHCb
  - First observation
  - Validations
  - Latest result with enlarged sample size
- Conclusions

Quark Model and pentaquark

Pentaquark discussed in 1964 when Gell-Mann and Zweig proposed the Quark Model

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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ 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**.

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf

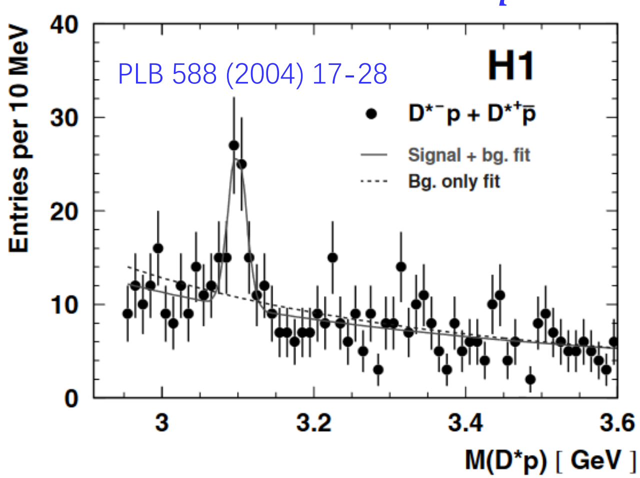
Phys.Lett.8 (1964) 214-215

Summarized in Eur.Phys.J.H 37 (2012) 1-31

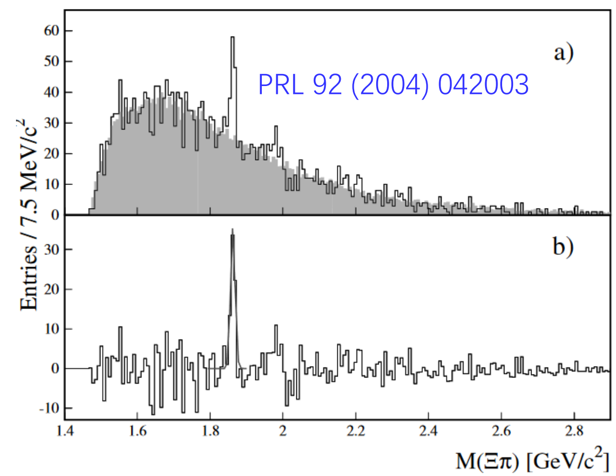
Previous "observations"

- In the 50 years after the proposal of $q\bar{q}qqq$, several "observation" of pentaquarks made but later refuted

$udud\bar{c} \rightarrow D^{*-}p$



$\Xi^{--} \rightarrow \Xi^{-}\pi^{-}$



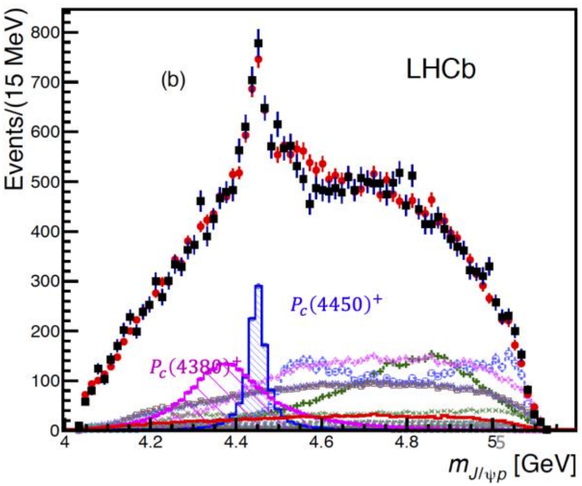
experiments did not confirm these claims [6]. In the last mention of the best known candidate from that period, $\Theta(1540)^{+}$, the 2006 Particle Data Group listing [7] included a statement: "The conclusion that pentaquarks in general, and that Θ^{+}, in particular, do not exist, appears compelling." which well reflected the prevailing mood in the particle physics community until a study

not seen by companion experiments or further studies with larger sample size

Today's menus

Observation @ 2015

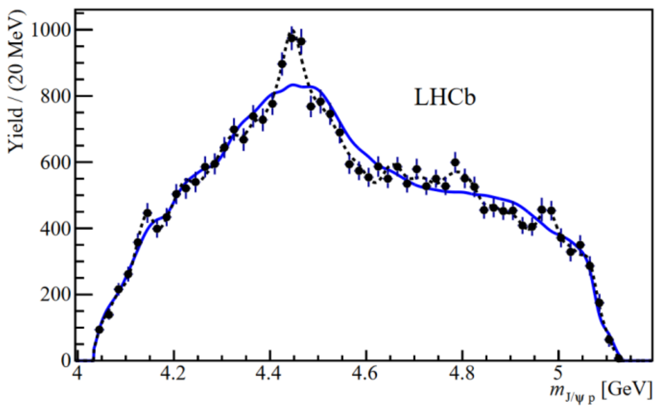
PRL 115(2015)072001



Follow-up cross checks @ 2016

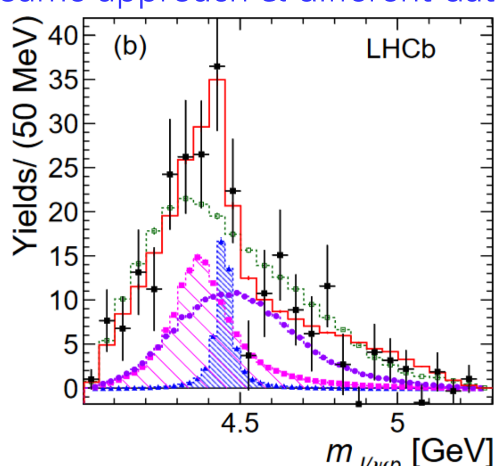
PRL 117(2016)082002

Same dataset & different approach



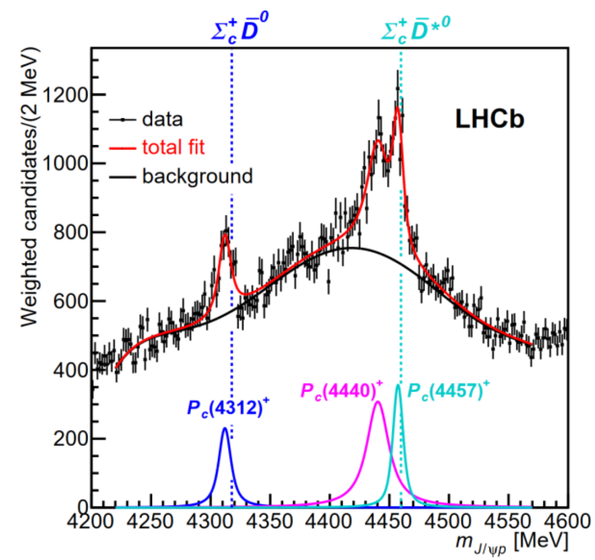
PRL 117(2016)082003

Same approach & different dataset



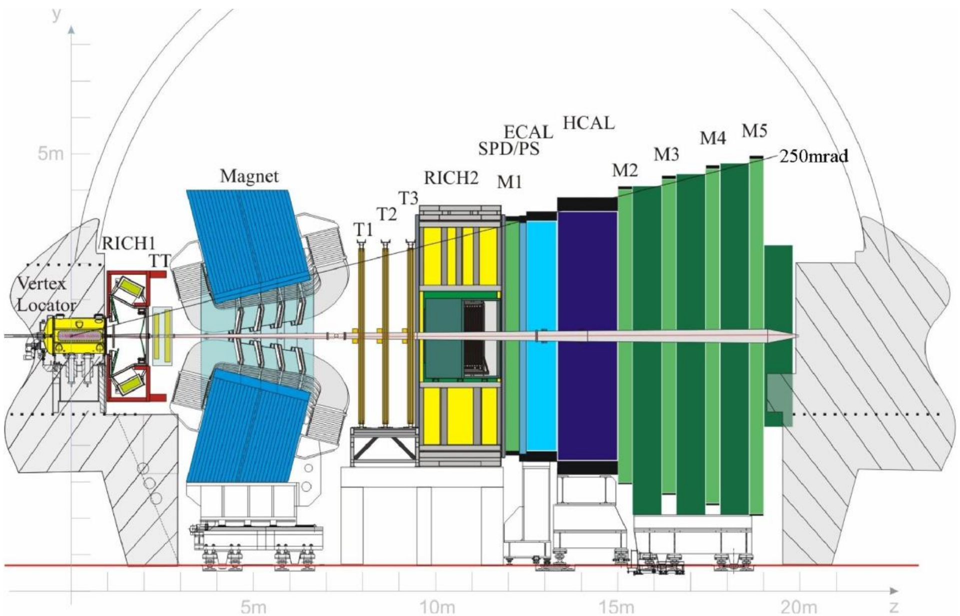
New analysis with X10 statistic @ 2019

PRL 122 (2019) 222001



The LHCb detector

- Optimized for heavy-flavor studies @ LHC
  - Single-arm and forward spectrometer, $\eta \in (2, 5)$



JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

- Powerful particle identification

$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$

- Good momentum resolution

$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \text{GeV}/c)$
$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)

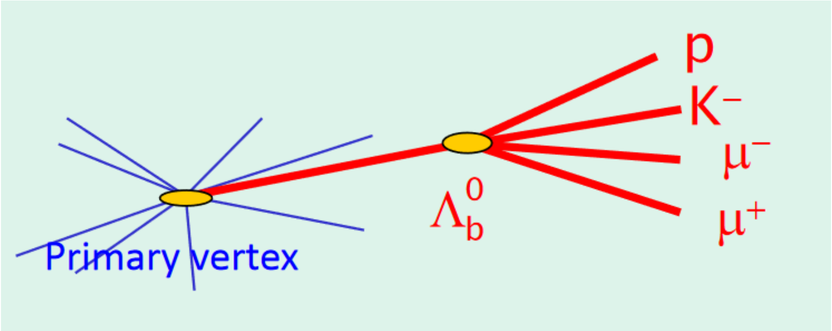
- Precise vertex resolution

$\sigma_{\text{IP}} = 20\mu\text{m}$ to select long-lived beauty & charm candidates

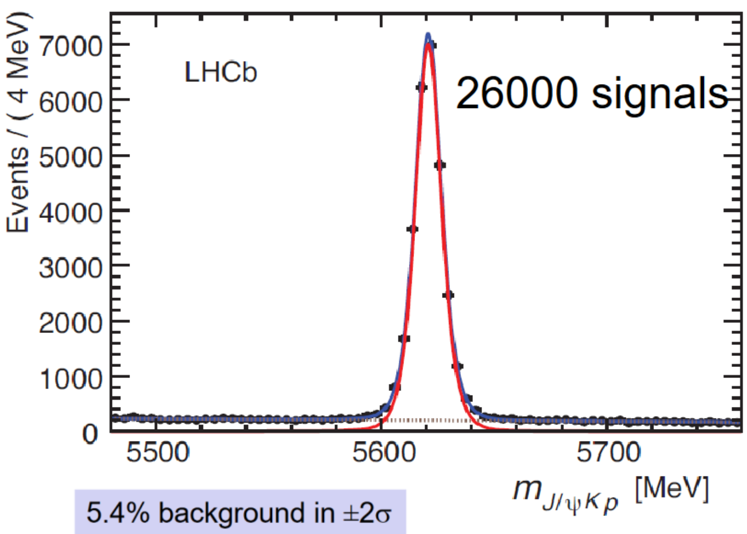
Data sample of $\Lambda_b^0 \to J/\psi p K^-$ decay

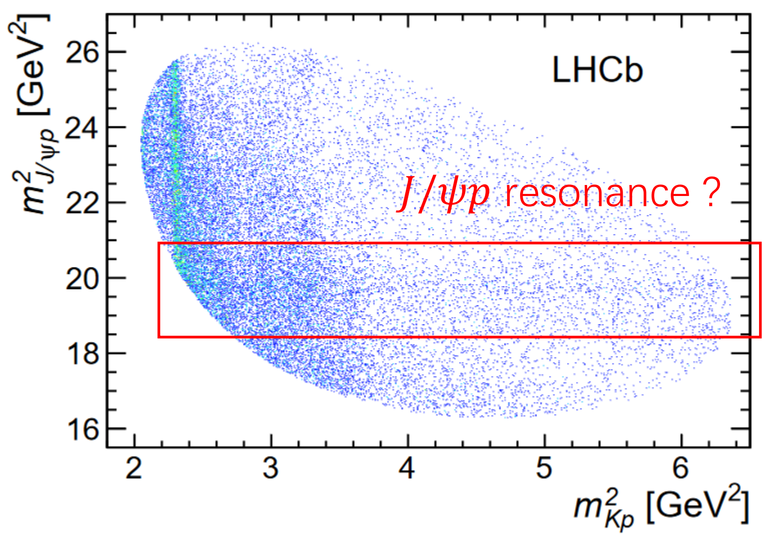
- $\Lambda_b^0 \to J/\psi p K^-$ was observed by LHCb and used for Λ_b^0 lifetime measurement

PRL 111 (2013) 102003

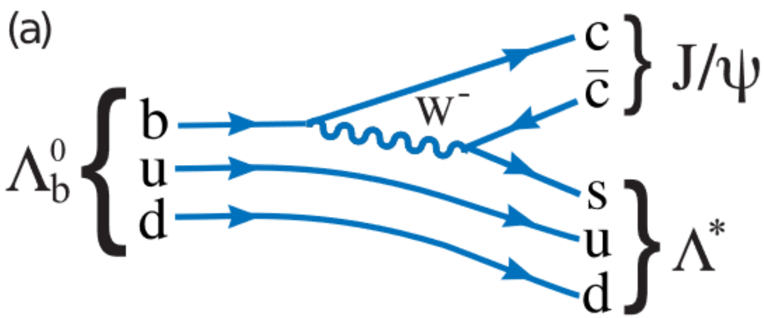


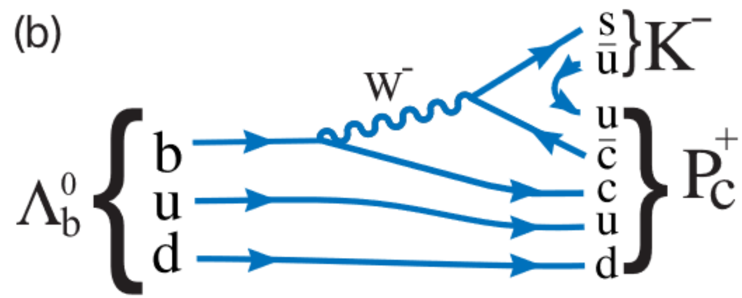
- LHCb Run1 pp collision data, $L \sim 3\ \mathrm{fb}^{-1}$, $J/\psi \to \mu^+\mu^-$
- Loose preselection + further MVA-based selection





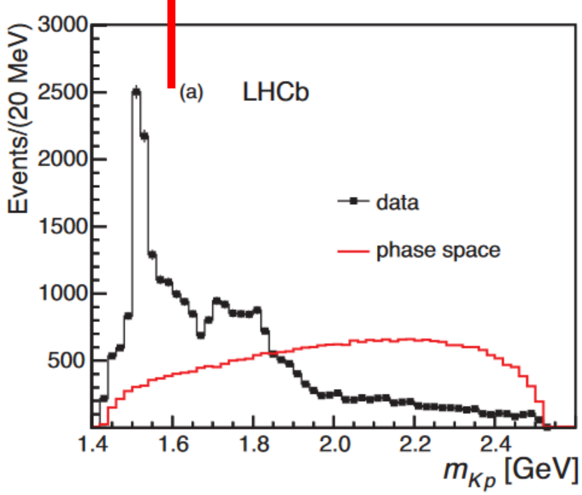
Intermediate states in $\Lambda_b^0 \to J/\psi p K^-$

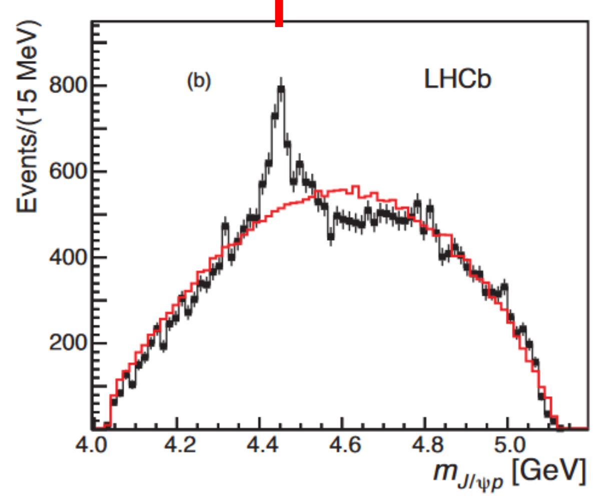




Known contributions

This state exist, or reflections from Λ^* ?

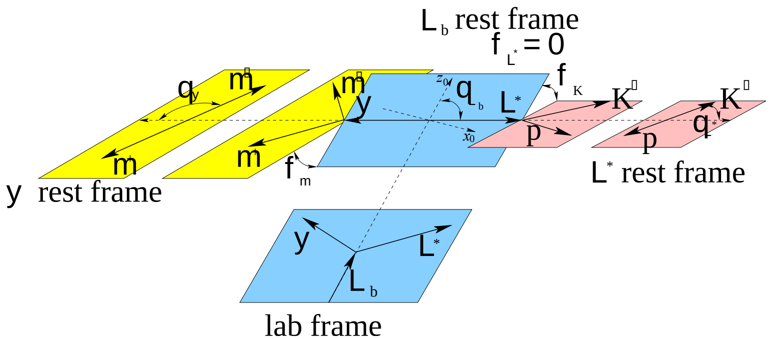




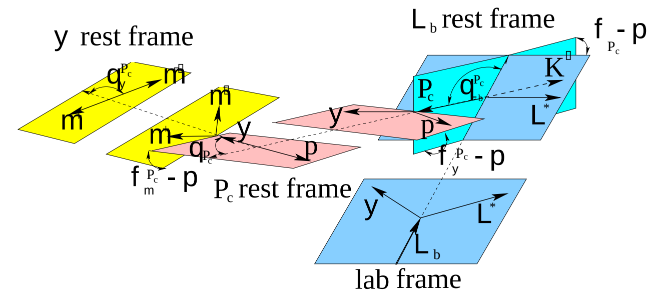
Need a technique to describe pentaquark contributions in data & reflections from Λ^* spontaneously involved

Full amplitude analysis

- Λ^* decay chain (reference chain):
  - $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda^*(\to pK)$



- P_c^+ decay chain:
  - $\Lambda_b^0 \to P_c^+(\to J/\psi(\to \mu^+\mu^-)p)K$



For single decay chain:

Mass term

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

Wigner-D functions + constant couplings for angular terms

Two chains combined to get total amplitude:

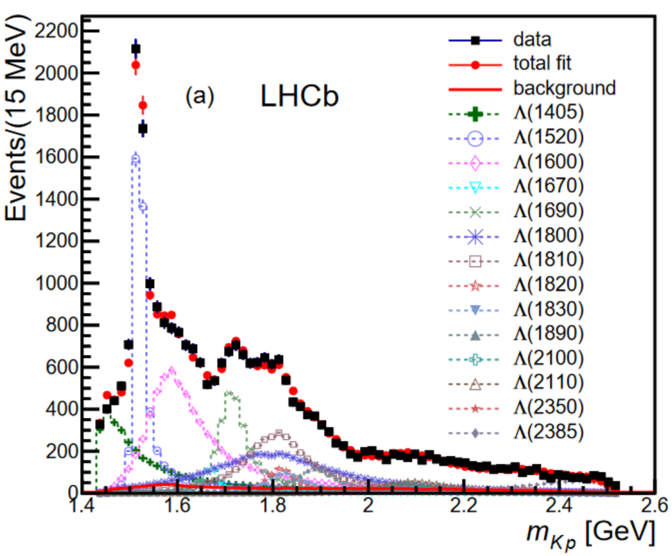
Final state alignment

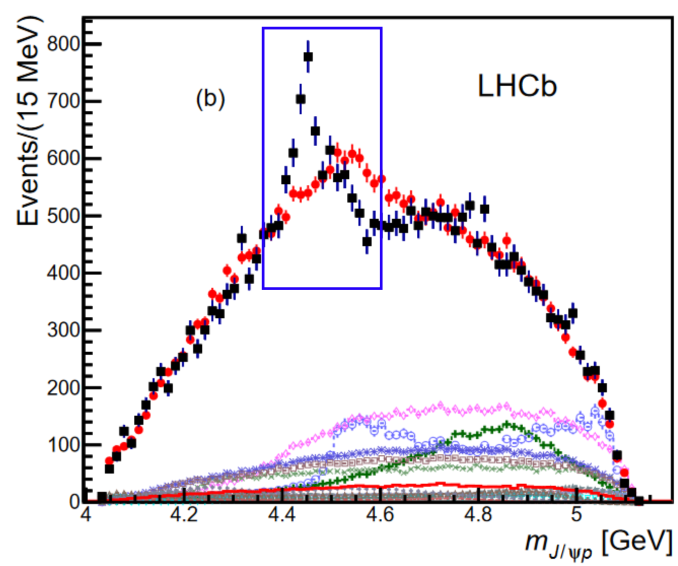
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}=\pm\frac{1}{2}} \sum_{\lambda_p=\pm\frac{1}{2}} \sum_{\Delta\lambda_\mu=\pm 1} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\,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

Λ^* resonances

- Λ^* – only model cannot well describe data
- Still fails even when
  - Consider Σ^* resonance (isospin violating)
  - Add unobserved Λ^*
  - Add non-resonant pK^-

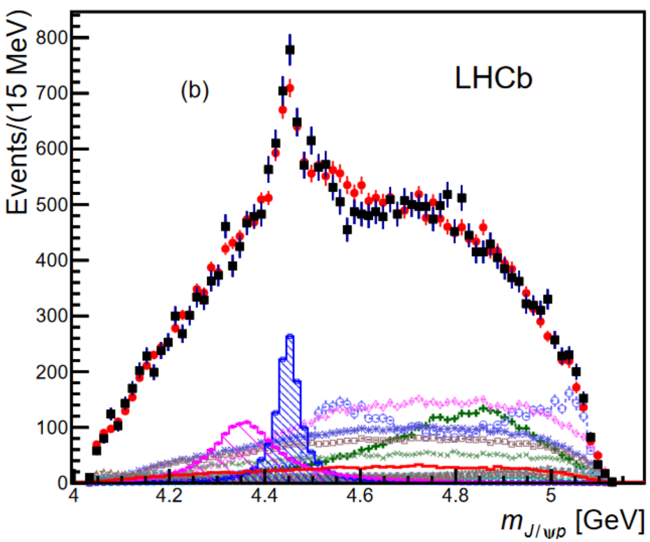
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800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





Fit with pentaquark (P_c)

Much better description in $m(J/\psi p)$ spectrum when **two pentaquarks** involved

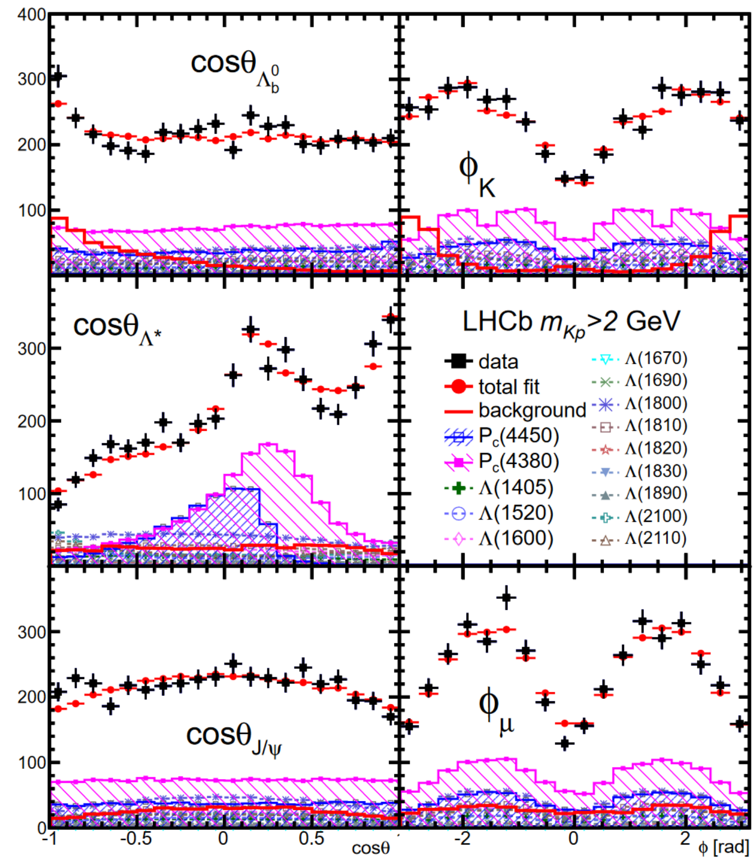


Resonance	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	4380±8±29	205±18±86	8.4±0.7±4.2
$P_c(4450)^+$	4449.8±1.7±2.5	39±5±19	4.1±0.5±1.1

Significances:

- 1st $P_c(4450)^+$: 12σ
- 2st $P_c(4380)^+$: 9 σ

Angular spectra also well modeled



Major syst. uncertainties: Λ^* model, parameterization of P_c mass shapes

Observation of intermediate states consistent with pentaquarks ($c\bar{c}uud$)

Previous "observations"

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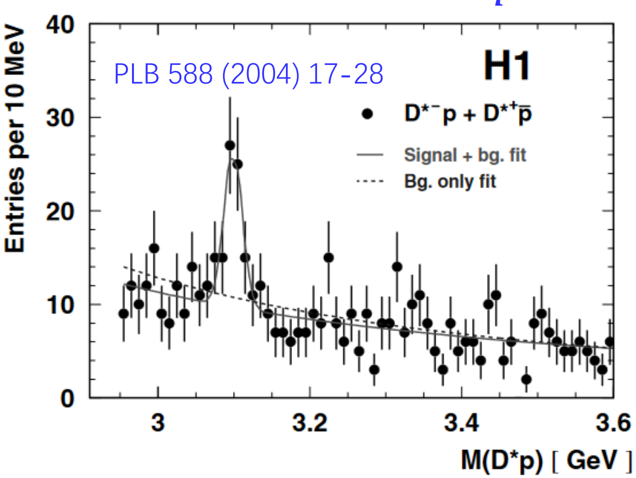

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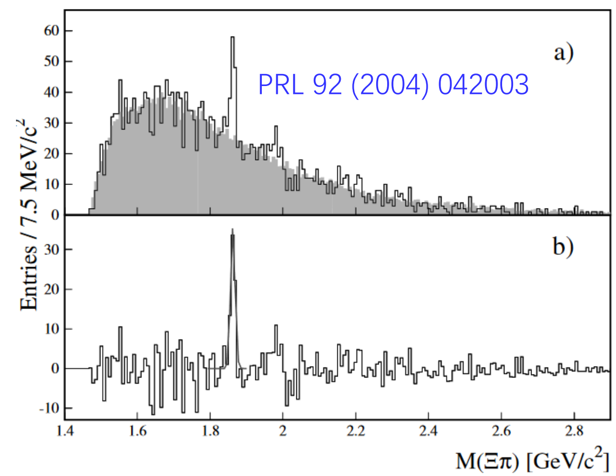
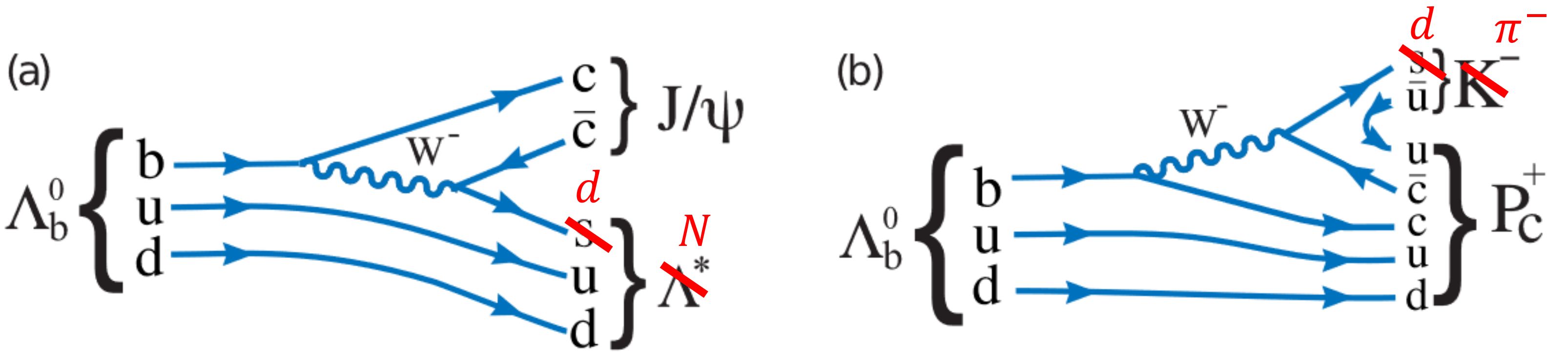


experiments did not confirm these claims [6]. In the last mention of the best known candidate from that period, $\Theta(1540)^{+}$, the 2006 Particle Data Group listing [7] included a statement: "The conclusion that pentaquarks in general, and that Θ^{+}, in particular, do not exist, appears compelling." which well reflected the prevailing mood in the particle physics community until a study

not seen by companion experiments or further studies with larger sample size

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

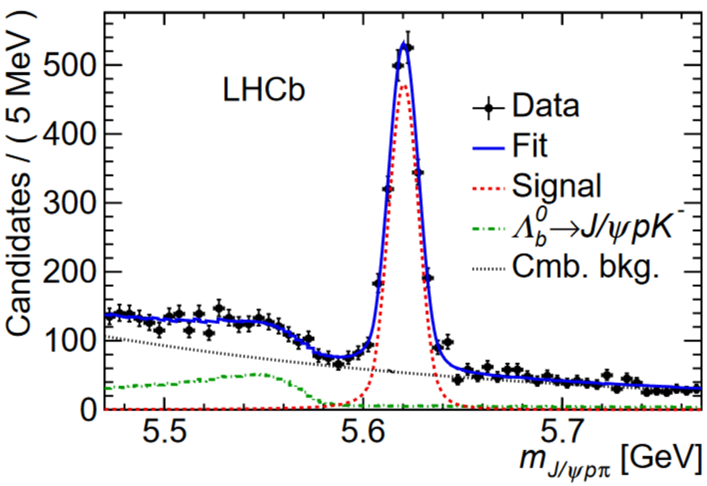
- $\Lambda_b^0 \to J/\psi p \pi^-$
  - Expect similar intermediate states as $\Lambda_b^0 \to J/\psi p K^-$
  - **Cabibbo-suppressed**, stat. X ~0.1

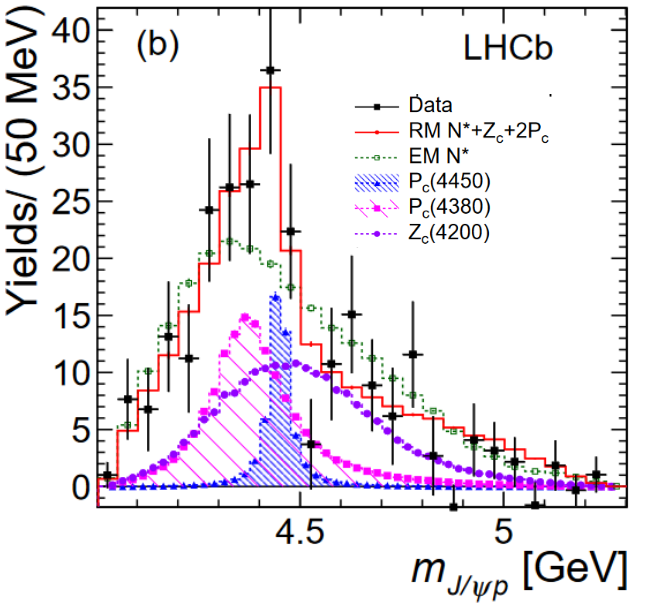


- P_c states found in $\Lambda_b^0 \to J/\psi p K^-$ should also contribute to $\Lambda_b^0 \to J/\psi p \pi^-$

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

- Amplitude analysis on $\Lambda_b^0 \to J/\psi p\pi^-$, following similar strategy as $\Lambda_b^0 \to J/\psi pK^-$ study





- Joint significance of $P_c(4380) + P_c(4450)$ larger than 3σ
- Mass & width parameters consistent with results from $\Lambda_\mathrm{b}^0 \to J/\psi pK^-$ study

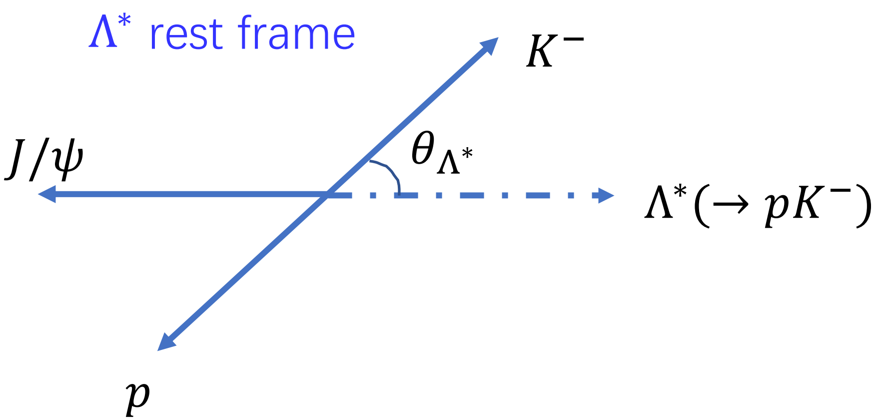
Model-independent P_c search in $\Lambda_b^0 \to J/\psi p K^-$

- Model dependence in amplitude analysis
  - Selection of states to be involved in the fit model
  - Line-shape functions of the intermediate states
  - …

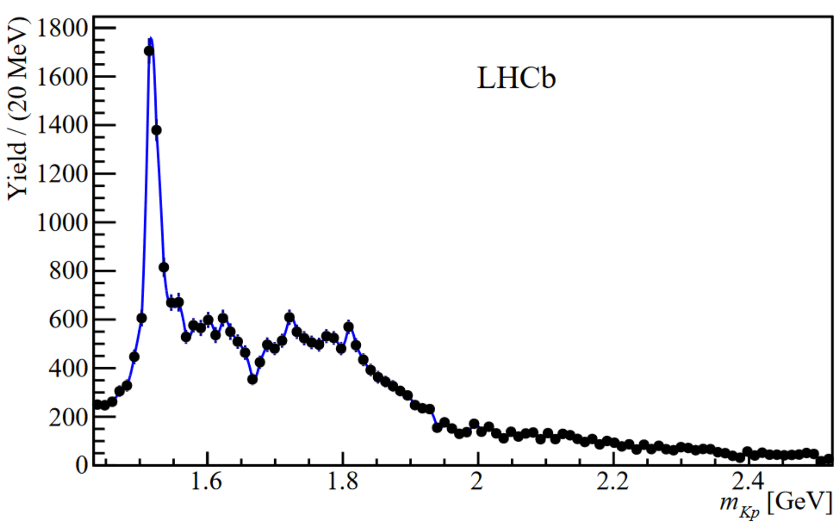
$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} = \sum_n R_{\Lambda_n^*}(m_{Kp}) \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p} \sum_{\lambda_\psi} e^{i\lambda_\psi\phi_\mu}\ d^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)$$
$$\times \sum_{\lambda_{\Lambda^*}} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda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

- The angular sector are more model-independent
  - angular-momentum conservation, very basic
- **An angular moments analysis for a model-independent confirmation of P_c states**

The moments analysis



A fixed $m(pK^-)$ and θ_{Λ^*} lead to a fixed $m(J/\psi p)$



Split the dataset into different $m(pK^-)$ slices. For each subset, if we know θ_{Λ^*} distribution, we can get the contribution to the $m(J/\psi p)$ spectrum

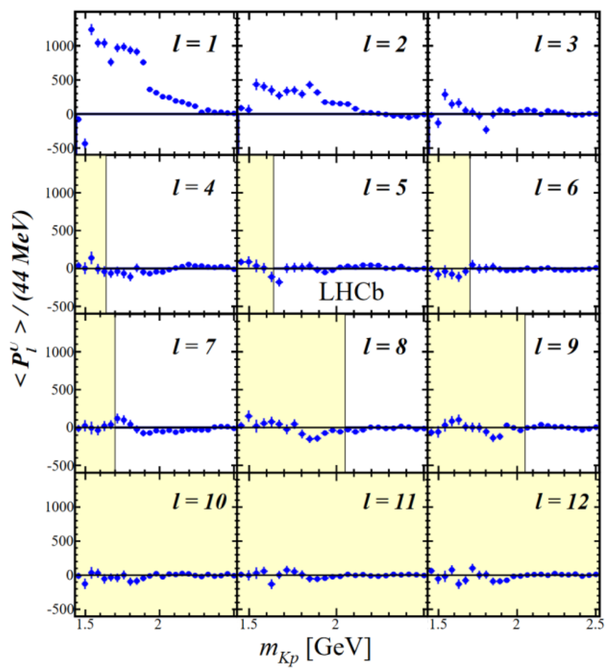
Features of angular spectrum → mass spectrum

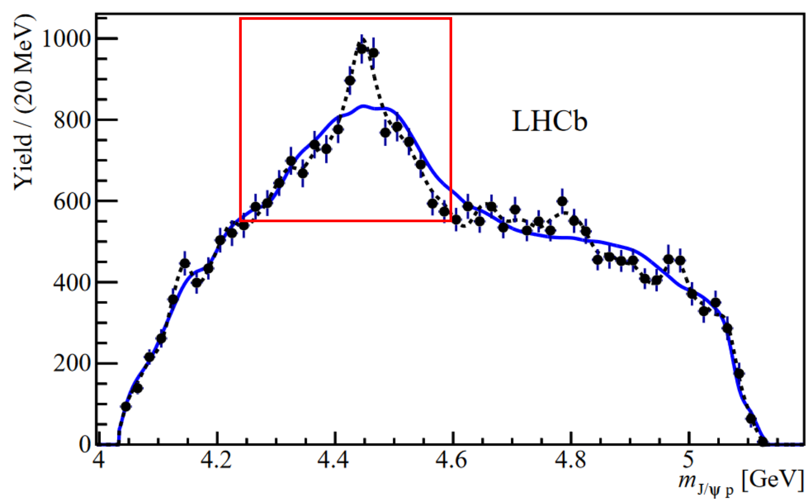
The moments analysis

- If consider only Λ^* chain

$$dN/d\cos\theta_{\Lambda^*} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*}), \qquad l_{max} = 2J_{\Lambda^*,max}$$

- Use $\cos\theta_{\Lambda^*}$ distribution in data to obtain all $< P_l^U >$, assign a reasonable $J_{\Lambda^*,max}$, remove higher order terms



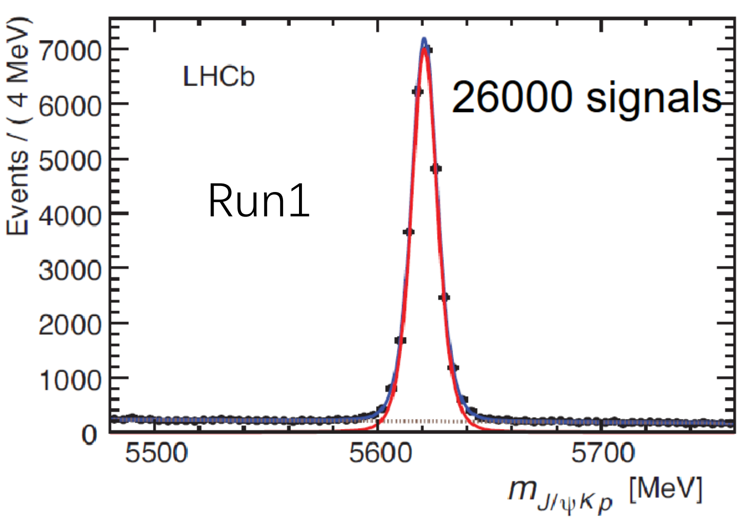


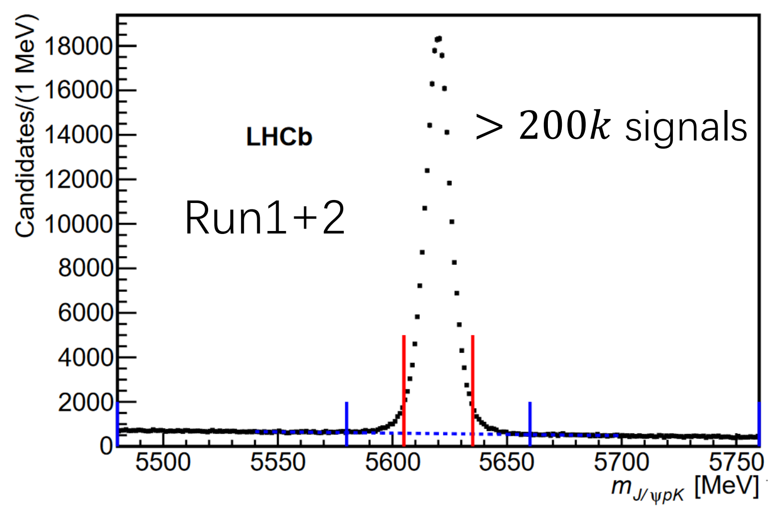
Significant misdescription.

Λ^* – only model cannot well describe data.

$\Lambda_b^0 \to J/\psi p K^-$ re-study using X10 data

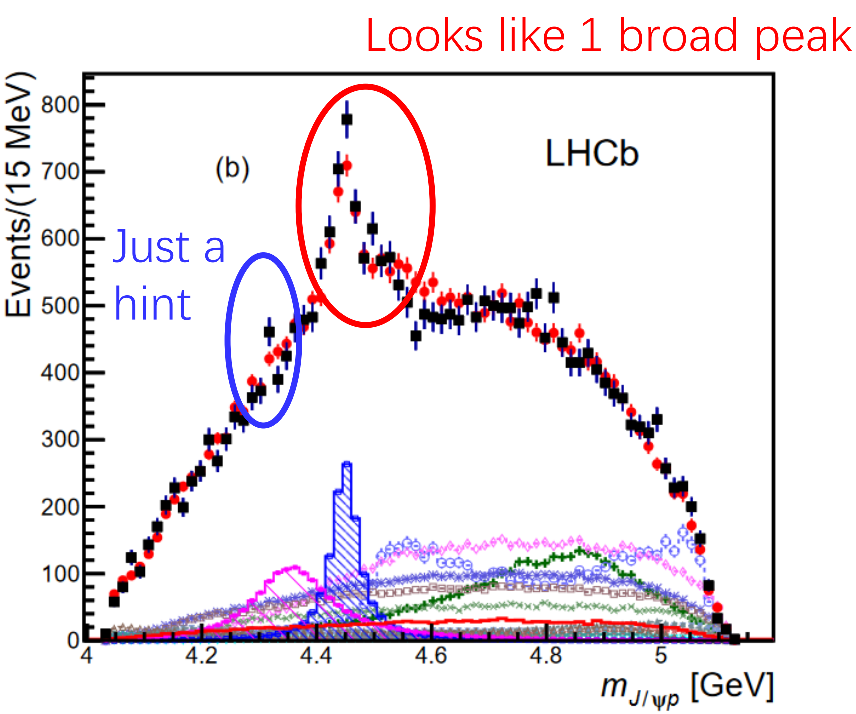
- First pentaquark observation @ LHCb is based on Run1 data, $L \sim 3\ \mathrm{fb}^{-1}$ @ 7,8 TeV
- More data available in 2019 after Run2 operation
  - $L \sim 6\ \mathrm{fb}^{-1}, \sqrt{s} = 13\ \mathrm{TeV}$ (× 4 b-production than Run1)
- Updated event selection:
  - Use particle-identification info as input of MVA training
  - Efficiency X 2 at the same BKG level



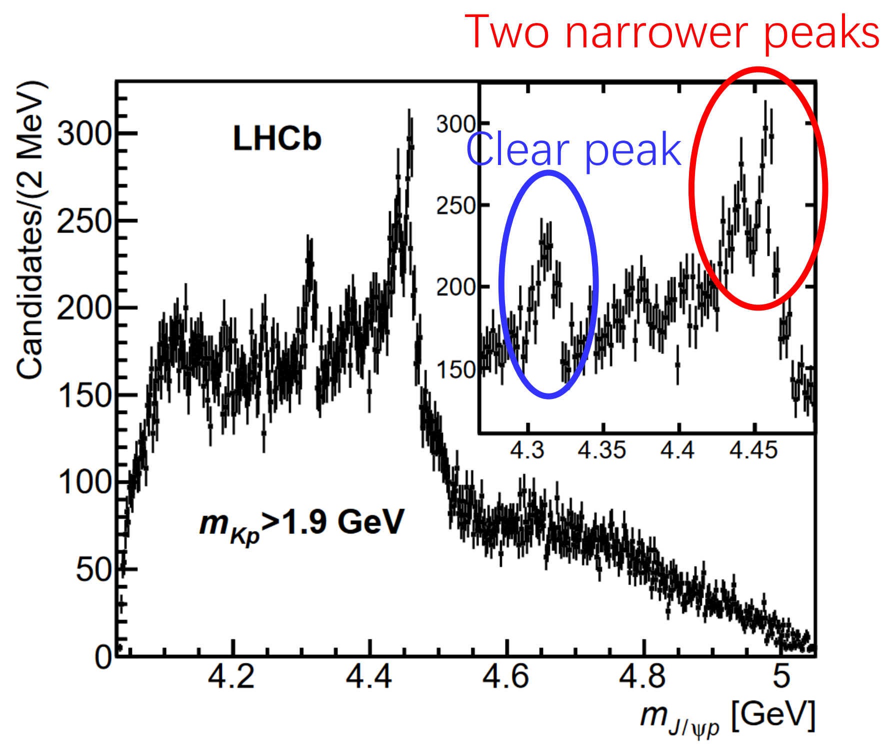


Finer structures in $m(J/\psi p)$ spectrum

Run1



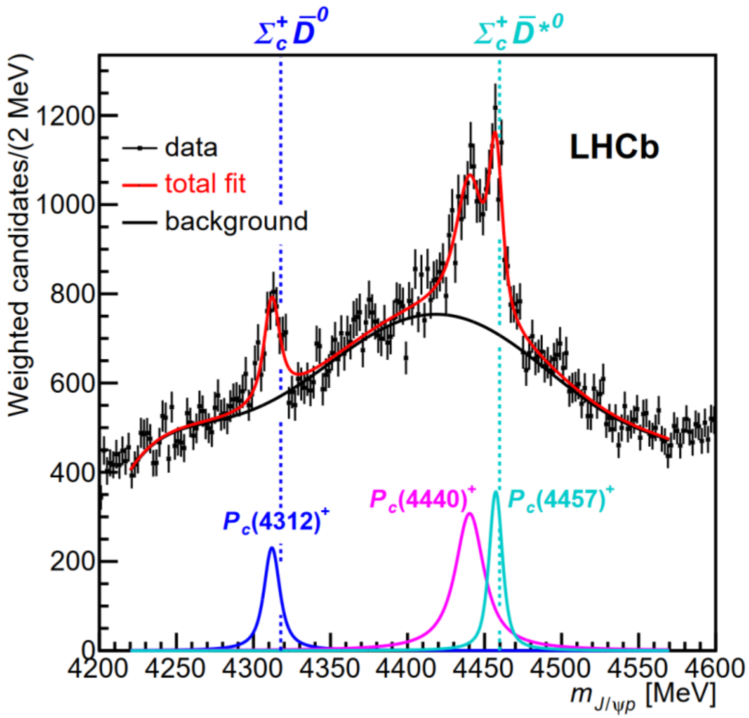
Run1+2



Properties of the new pentaquarks

- A 1D mass fit to subtract properties of peaking signals

- $m(pK^-)$-dependent weight assigned to subtract Λ^* contribution
- Breit-Wigner for P_c shapes
- High-order polynomial for flat background



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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Significance of $P_c(4312)^+$: 7.3 σ

Significance of $P_c(4440)^+$, $P_c(4457)^+$ two-peak structure: 5.4σ

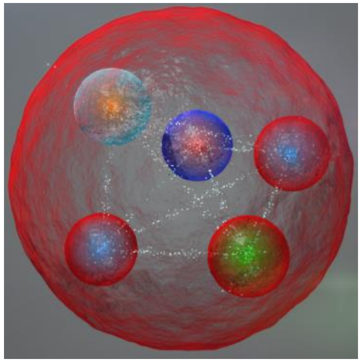
Conclusion

- Intermediate states consistent with pentaquarks observed by LHCb in 2015, using the $\Lambda_b^0 \to J/\psi p K^-$ decay
- Evidence of the same states seen in $\Lambda_b^0 \to J/\psi p \pi^-$ in 2016
- Model-independent studies prove the existence of exotic structures in $\Lambda_b^0 \to J/\psi p K^-$ process in 2016
- With LHCb Run2 data available, peaking structures in the $J/\psi p$ mass spectrum are further investigated. Three new P_c states announced in 2019

Open questions

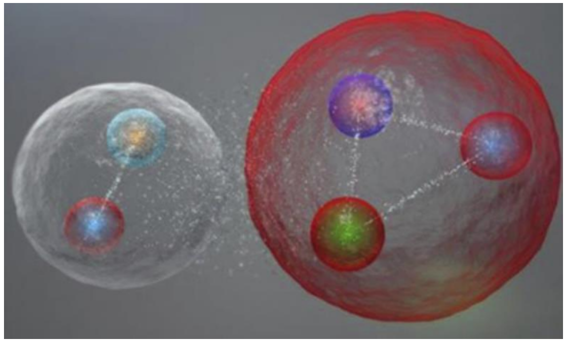
Pentaquarks observed in experiment, but the nature still unclear

Compact ?



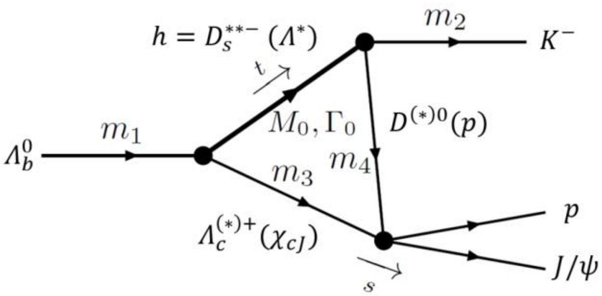
JHEP12(2015)128, PLB749(2015)289–291, PLB793(2019)365-371, PRD95(2017)5…

Hadronic molecule ?



PRL115(2015)122001, PLB753(2016)547–551, PRC85(2012)044002…

Near-threshold kinematic effects ?



PRD92(2015)071502(R)…

What we can do in experiment ?

- Spin-parity measurement

	Compact	Molecule	Triangle
$P_c(4312)^+$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$
$P_c(4440)^+$	$\frac{3}{2}^+$	$\frac{1}{2}^-$ $(\frac{3}{2}^-)$	$\frac{1}{2}^+$
$P_c(4457)^+$	$\frac{5}{2}^+$	$\frac{3}{2}^-$ $(\frac{1}{2}^-)$	$\frac{1}{2}^+$

- Search for new pentaquarks

Amplitude analysis would be a powerful tool for these targets !

Compact model

PLB793(2019)365-371

J^P	Mass(MeV)
$1/2^-$	3830 ± 34
	4150 ± 29
$1/2^+$	4030 ± 39
	4351 ± 35
	4430 ± 35
$3/2^+$	4040 ± 39
	4361 ± 35

Molecule

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J^P	Width(MeV)	Mass(MeV)
$\frac{3}{2}^-$	$8.3 - 9.2$	$4376.1 - 4377.0$
$\frac{1}{2}^-$	$25.7 - 26.5$	$4500.2 - 4501.0$
$\frac{3}{2}^-$	$15.9 - 16.1$	$4510.6 - 4510.8$
$\frac{5}{2}^-$	$3.2 - 3.5$	$4523.3 - 4523.6$

Thank you for your attention !

Any questions or comments ?