Heavy flavour spectroscopy and exotic states at LHCb

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On behalf of the LHCb Collaboration

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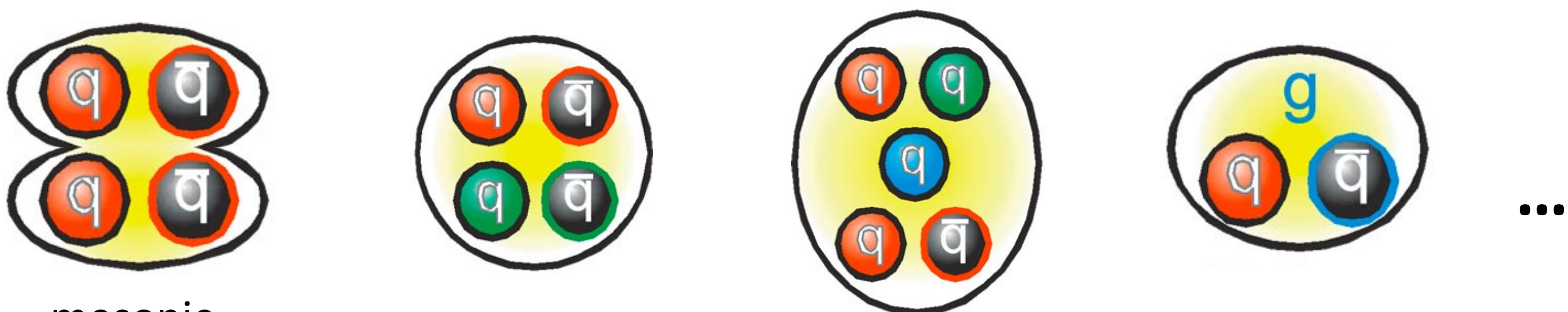
Introduction

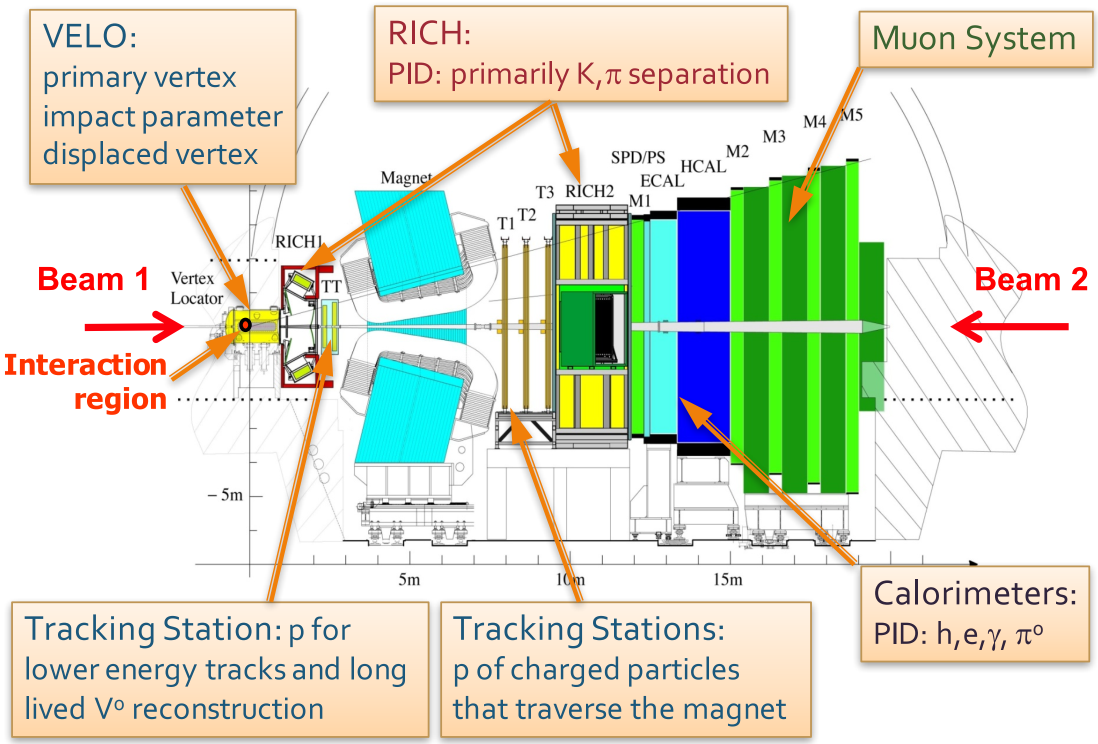
- Spectroscopy provides opportunities to study QCD predictions for models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic states are important for understanding strong force in QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



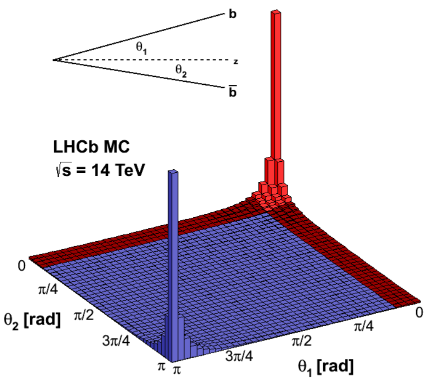
mesonic molecule ? tetraquark ? pentaquark ? hybrid ?

LHCb detector

The LHCb detector described in JINST 3 (2008) S08005



- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



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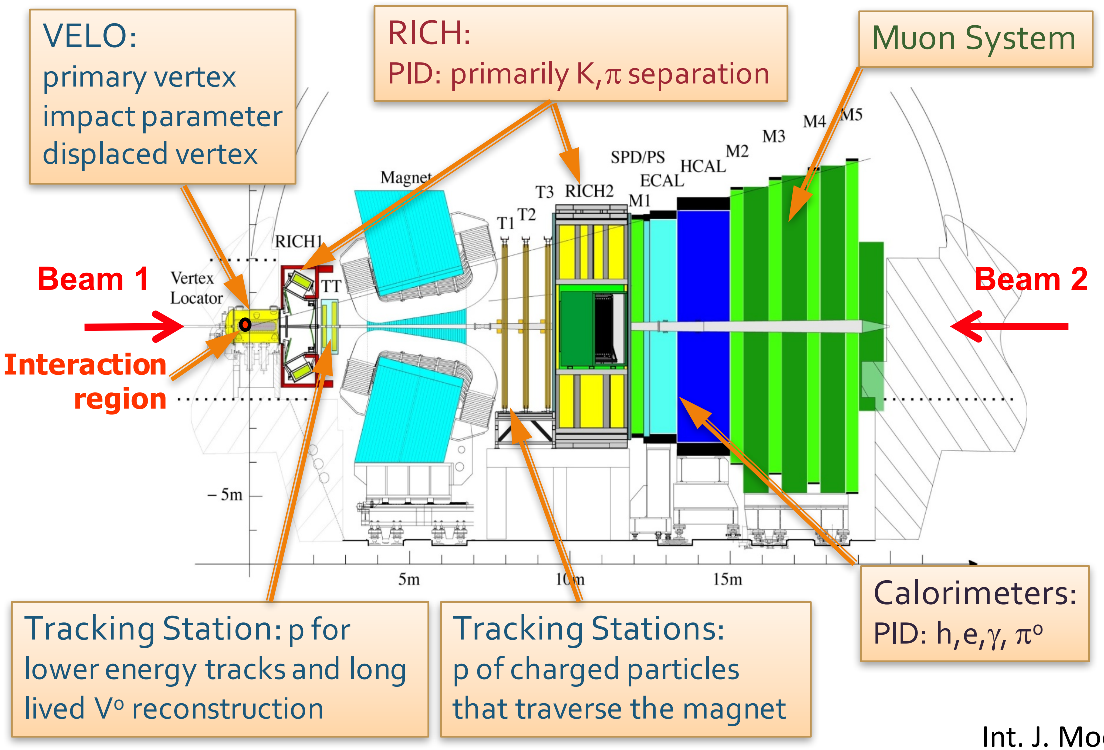

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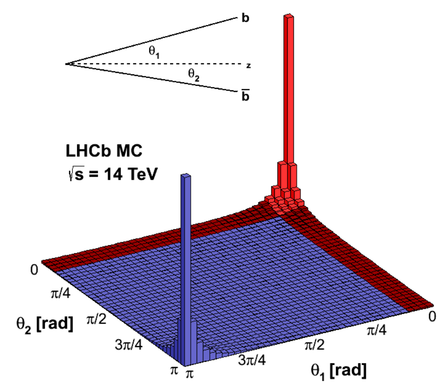
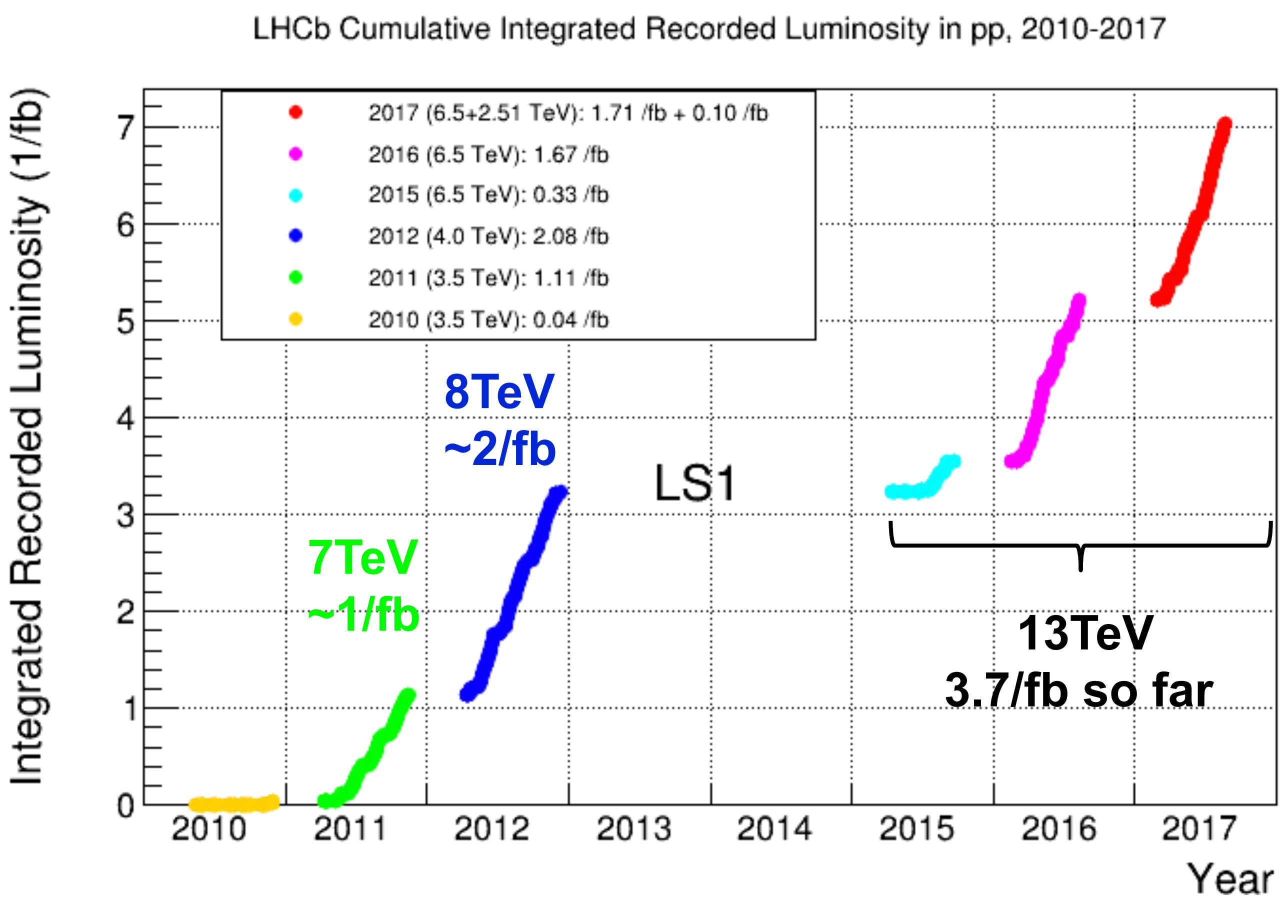


Int. J. Mod. Phys. A 30 (2015) 1530022

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \mathrm{GeV}/c)$
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrainted** $\boldsymbol{m_{J/\psi}}$**)**
RICH $K-\pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1-3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb collected luminosity

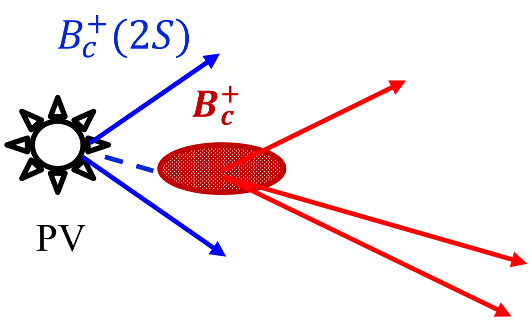


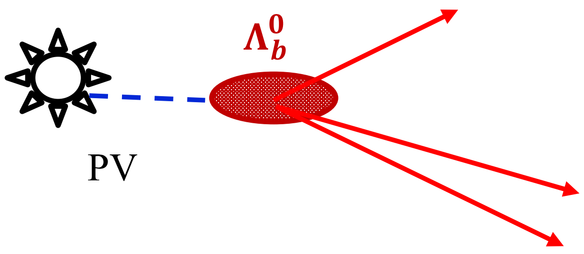
$\sigma(pp \to b\bar{b}X) \approx 300\ \mu\text{b}$ @7 TeV vs $\approx 500\ \mu\text{b}$ @13 TeV

Two methods for spectroscopy

- Direct production in *pp* collisions
- Combine a heavy flavour (HF) hadron with one or more light particles
- High statistics

- Production by a heavier particle decay, usually with amplitude analysis
- Low background
- Better determination of J^P



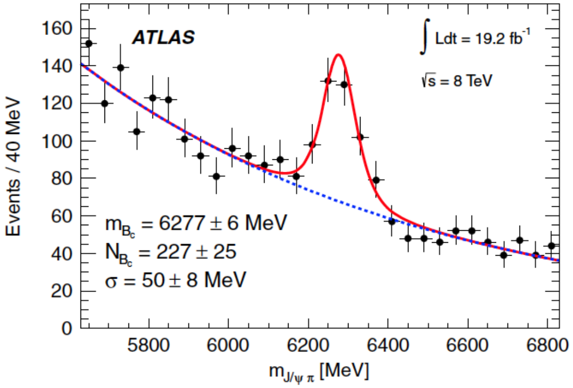


$B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-$ from ATLAS

Based on a yield of 327
$B_c^+ \to J/\psi\pi^+$ decays

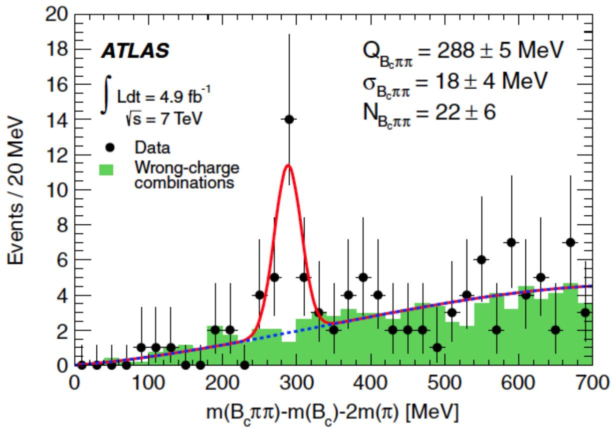
Data	Signal events
7 TeV	100 ± 23
8 TeV	227 ± 25

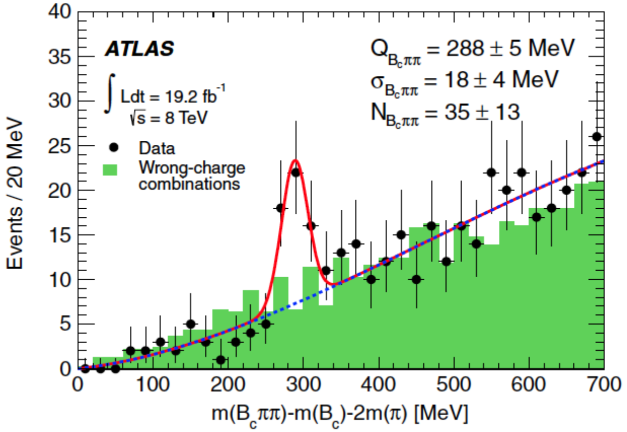
ATLAS, PRL 113 (2014) 212004



ATLAS observed a peak in $B_c^+\pi^+\pi^-$ spectrum

$m_{B_c(2S)} = 6842 \pm 4 \pm 5$ MeV **5.2σ**





$B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-$ search at LHCb

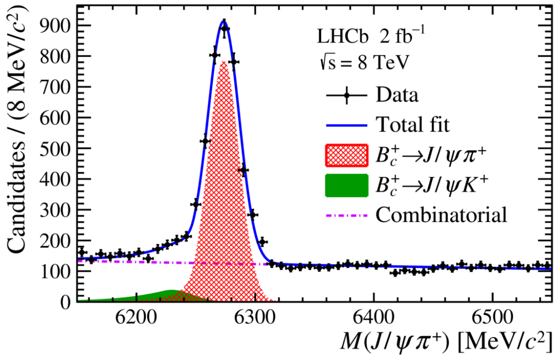
- The peak could be due to
  - $B_c^+(2S) \to B_c^+\pi^+\pi^-$ or
  - $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^-$with $B_c^{*+} \to B_c^+\gamma$ (missing)

- LHCb used ~3300 B_c^+ signals and searched for $B_c^{(*)+}(2S)$

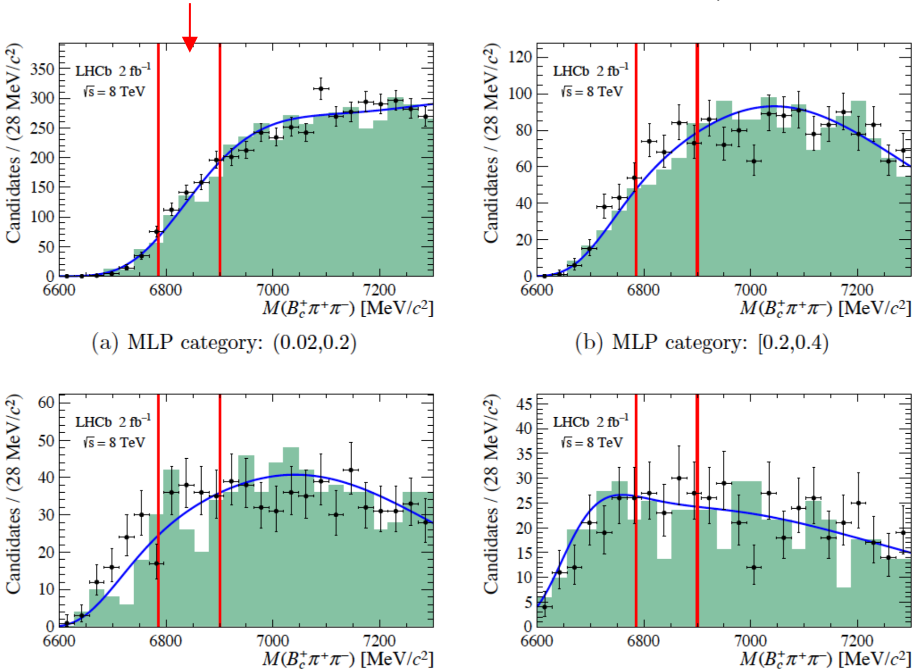
- No $B_c^{(*)+}(2S)$ signal

JHEP 01 (2018) 138

$$N_{B_c}^{\text{LHCb 8TeV}} = 3325 \pm 73$$



Signal region



(a) MLP category: (0.02,0.2) (b) MLP category: [0.2,0.4)

(c) MLP category: [0.4,0.6) (d) MLP category: [0.6,1.0]

$B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-$ search at LHCb

JHEP 01 (2018) 138

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$

	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$

Upper limit @95%CL

$\varepsilon_7, \varepsilon_8$: relative efficiencies of reconstructing $B_c^{(*)}(2S)^+$ wrt B_c^+

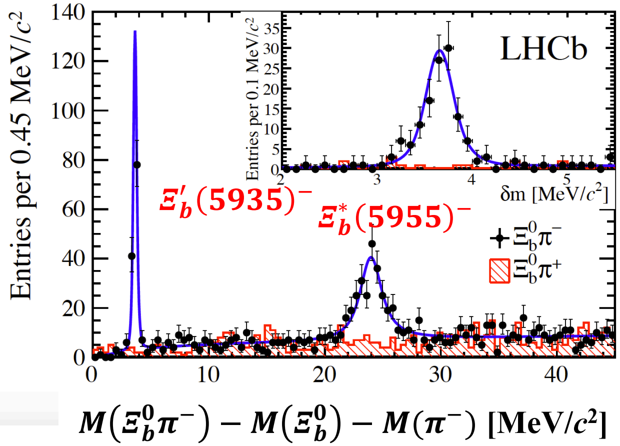
- **ATLAS did not publish $\varepsilon_7, \varepsilon_8$**
- **More studies needed to resolve the tension between ATLAS and LHCb.**

Ξ_b baryon spectroscopy

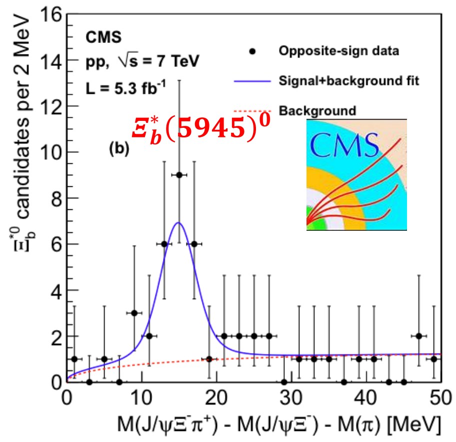
- Numbers of excited *b*-baryons have already been discovered
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \rightarrow \Xi_b^0\pi^-$
  - $\Xi_b^*(5945)^0 \rightarrow \Xi_b^-\pi^+$

State	J^P	$b(sq)$
Ξ_b	$1/2^+$	$\uparrow(\uparrow\downarrow)$
Ξ_b'	$1/2^+$	$\downarrow(\uparrow\uparrow)$
Ξ_b^*	$3/2^+$	$\uparrow(\uparrow\uparrow)$

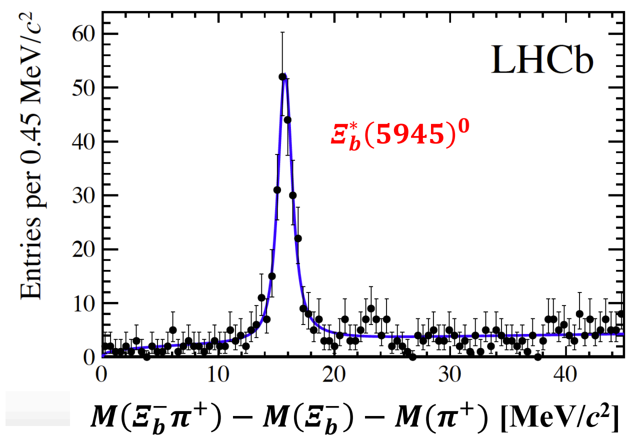
PRL 114 (2015) 062004



PRL 108, 252002 (2012)



JHEP 05 (2016) 161



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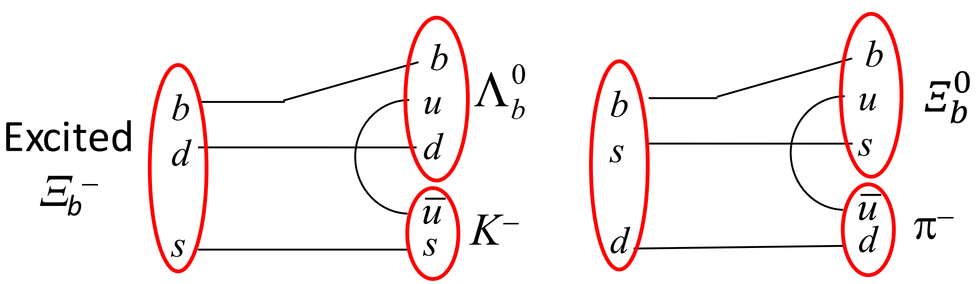
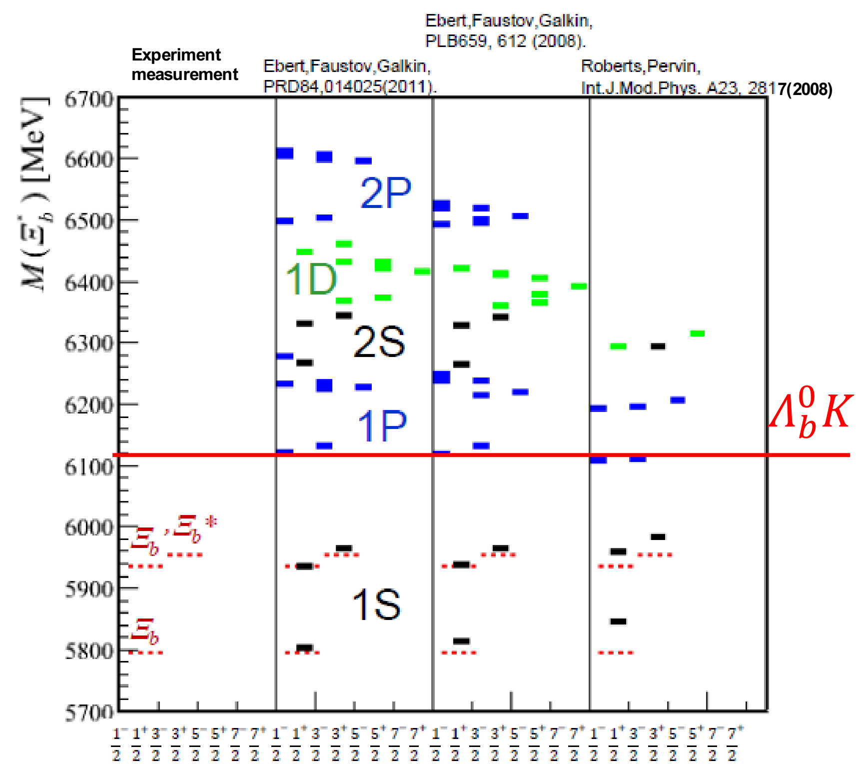
  - $\Xi_b^*(5945)^0 \to \Xi_b^-\pi^+$

- The higher excited states are expected to be above $\Lambda_b^0 K$ threshold



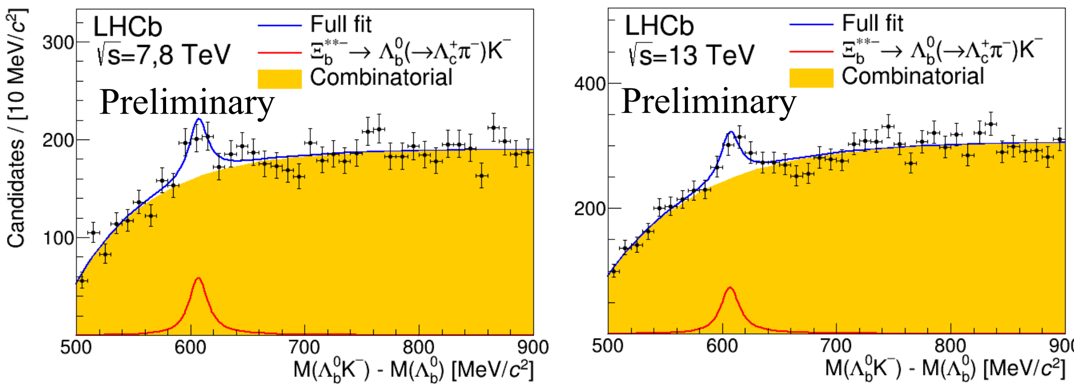


First observation of a new Ξ_b^{**-} state

new

LHCb-PAPER-2018-013, in preparation

- Hadronic $\Lambda_b^0 \to \Lambda_c^+ \pi^-$:
  - Resolution: 2 MeV
  - 7.9σ



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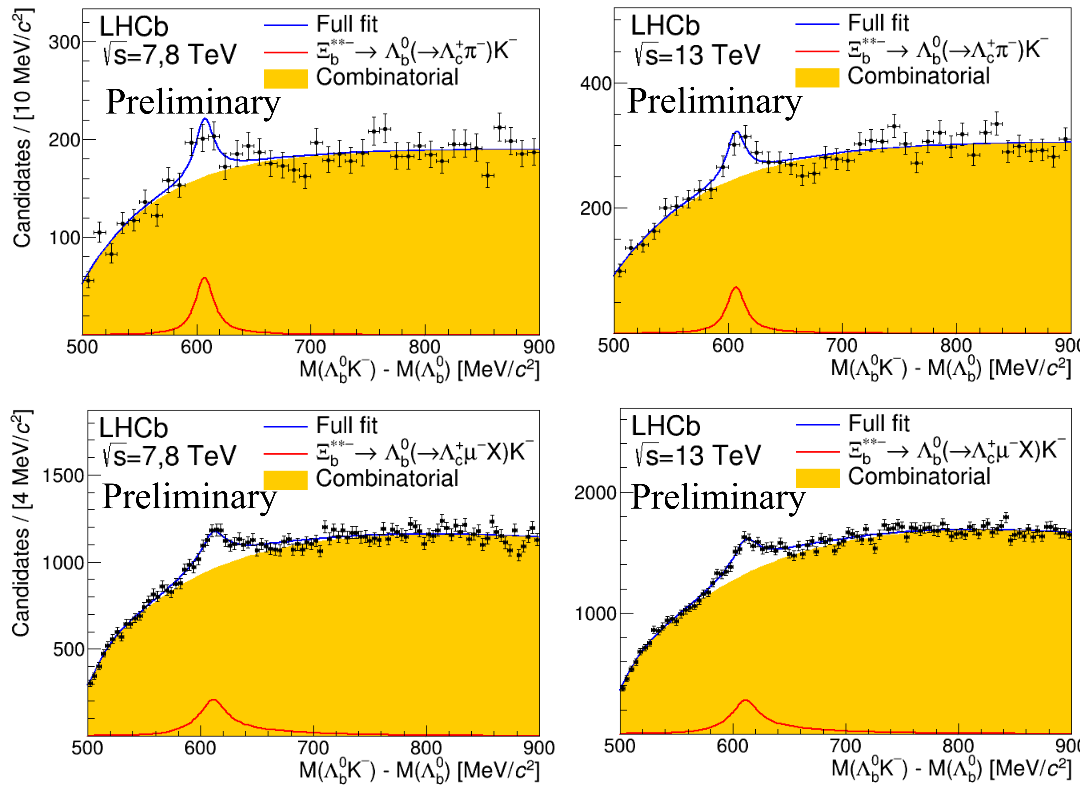
- Semileptonic (SL) $\Lambda_b^0 \to \Lambda_c^+ \mu^- X \bar{\nu}_\mu$
  - Resolution: ~18 MeV
  - Yields ~15 larger
  - 25σ



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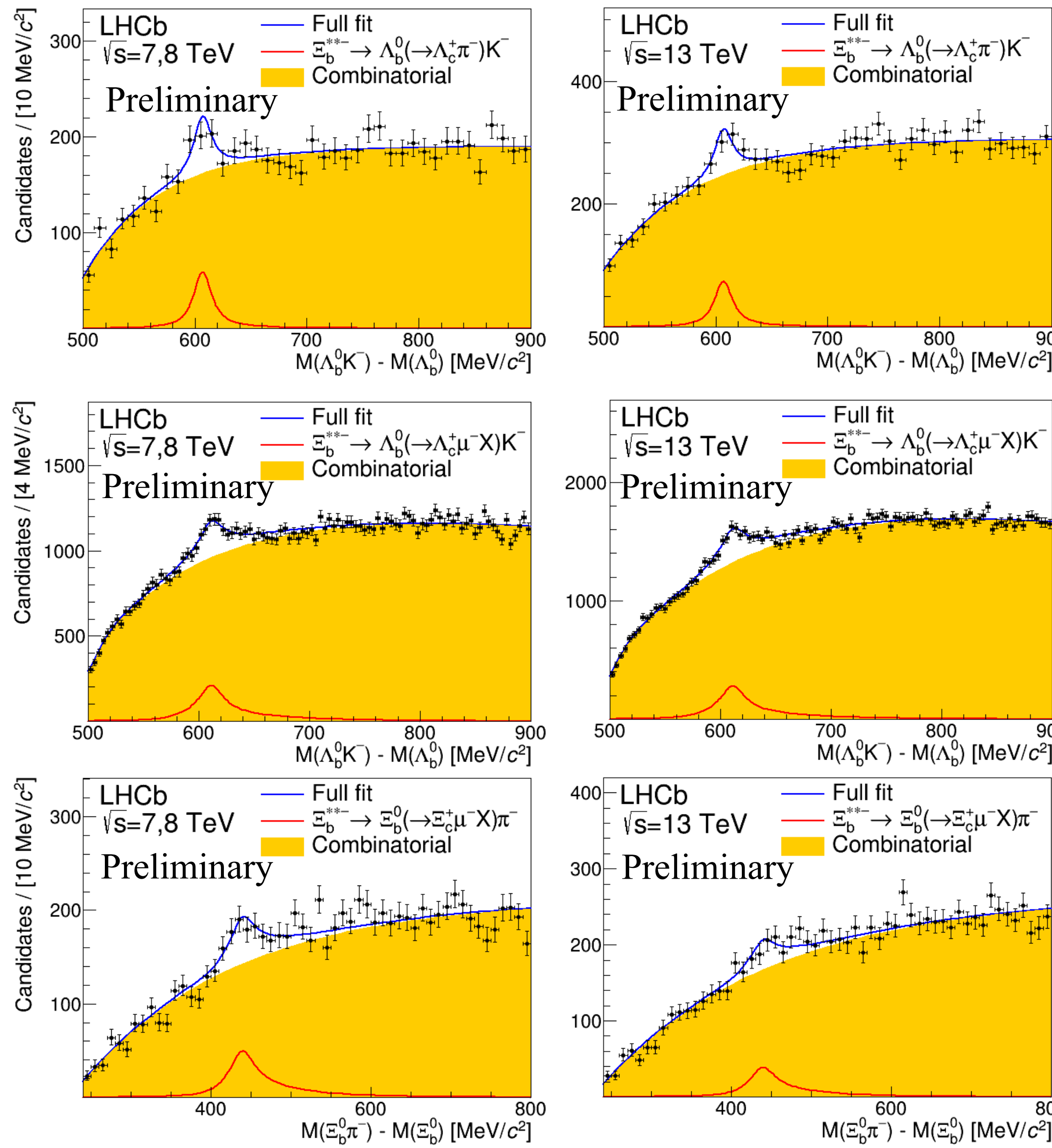
  - 25σ
- Semileptonic (SL) $\Xi_b^0 \to \Lambda_c^+ \mu^- X \bar{\nu}_\mu$
  - 9.2σ



The Ξ_b^{**-} properties (preliminary)

LHCb-PAPER-2018-013, in preparation

- With hadronic mode

$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})\,\mathrm{MeV}/c^2,$$
$$\Gamma = 18.1 \pm 5.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst})\,\mathrm{MeV}/c^2,$$
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst}) \pm 0.2(\Lambda_b^0)\,\mathrm{MeV}/c^2,$$

Mass peak position is consistent between the three decay channels

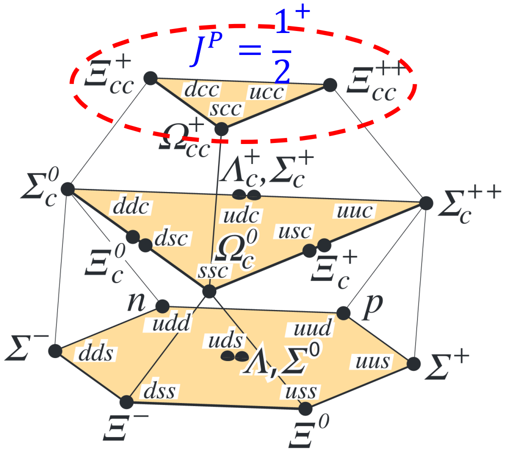
- Production ratios are measured with SL modes

Quantity	7+8 TeV	13 TeV
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Lambda_b^0})\mathcal{B}(\Xi_b^{**-} \to \Lambda_b^0 K^-)$	$(3.0 \pm 0.4 \pm 0.4) \times 10^{-3}$	$(3.4 \pm 0.4 \pm 0.4) \times 10^{-3}$
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Xi_b^0})\mathcal{B}(\Xi_b^{**-} \to \Xi_b^0 \pi^-)$	$(47 \pm 9 \pm 7) \times 10^{-3}$	$(22 \pm 6 \pm 3) \times 10^{-3}$

- The new state could be either a $\Xi_b(1P)^-$ or $\Xi_b(2S)^-$
  - To distinguish them further information needed (e.g. J^P)

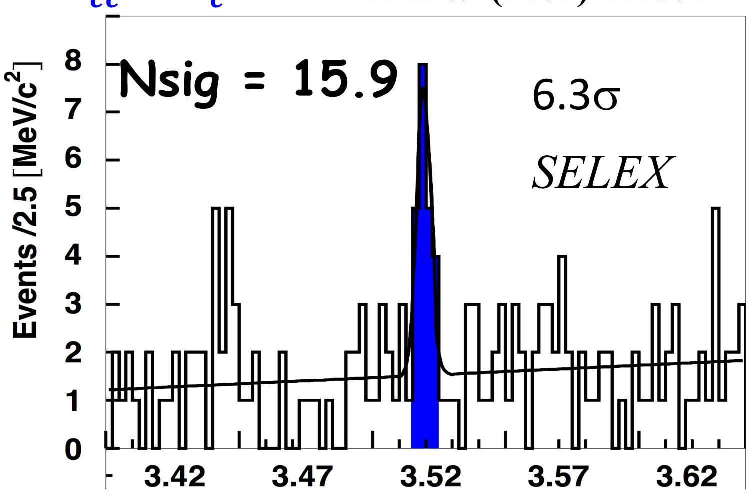
Doubly charmed baryons

- Observation of $\Xi_{cc}^{+}(ccd)$ reported by SELEX
  - Mass: 3518.7 ± 1.7 MeV
  - Unexpected short lifetime and large production

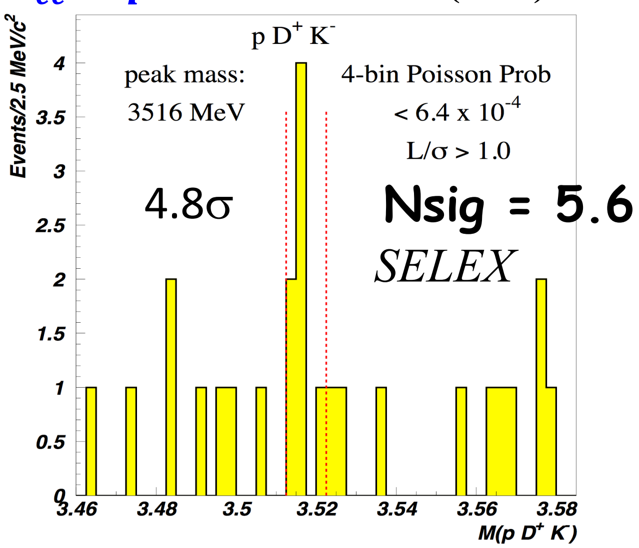


- Not confirmed by Babar [PRD 74 (2006) 011103], Belle [PRL 97(2006) 162001] nor LHCb [JHEP 12 (2013) 090]

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ PRL 89 (2002) 112001



$\Xi_{cc}^{+} \to p D^{+} \pi^{-}$ PLB 628 (2005) 18



Observation of Ξ_{cc}^{++} at LHCb

PRL 119 (2017) 112001

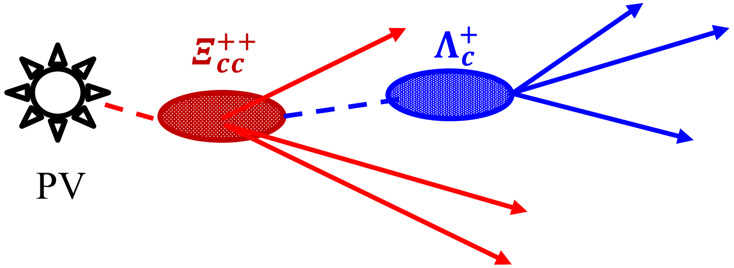
- Expected to have longer lifetime than Ξ_{cc}^{+}, higher sensitivity at LHCb
- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\mathcal{B}$ could be as large as 10%

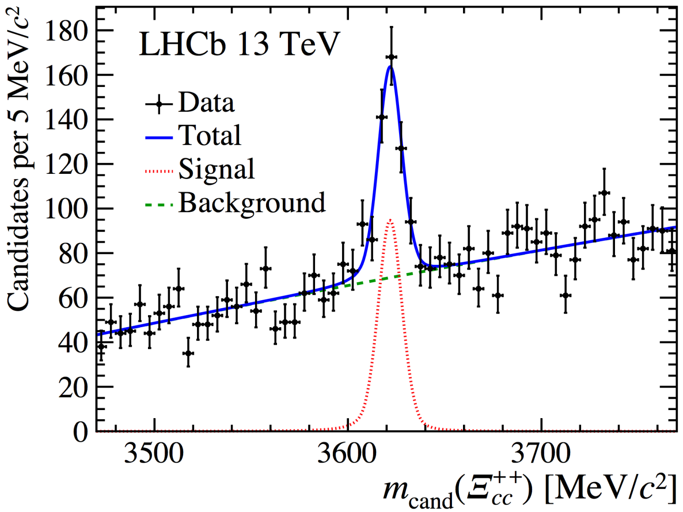
Yu et al., arXiv:1703.09086

- LHCb run II at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}
  - 313 ± 33 events, 12σ
  - 8 TeV data analyzed for cross-check, 7σ
  - Consistent with weakly decays
  - $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV

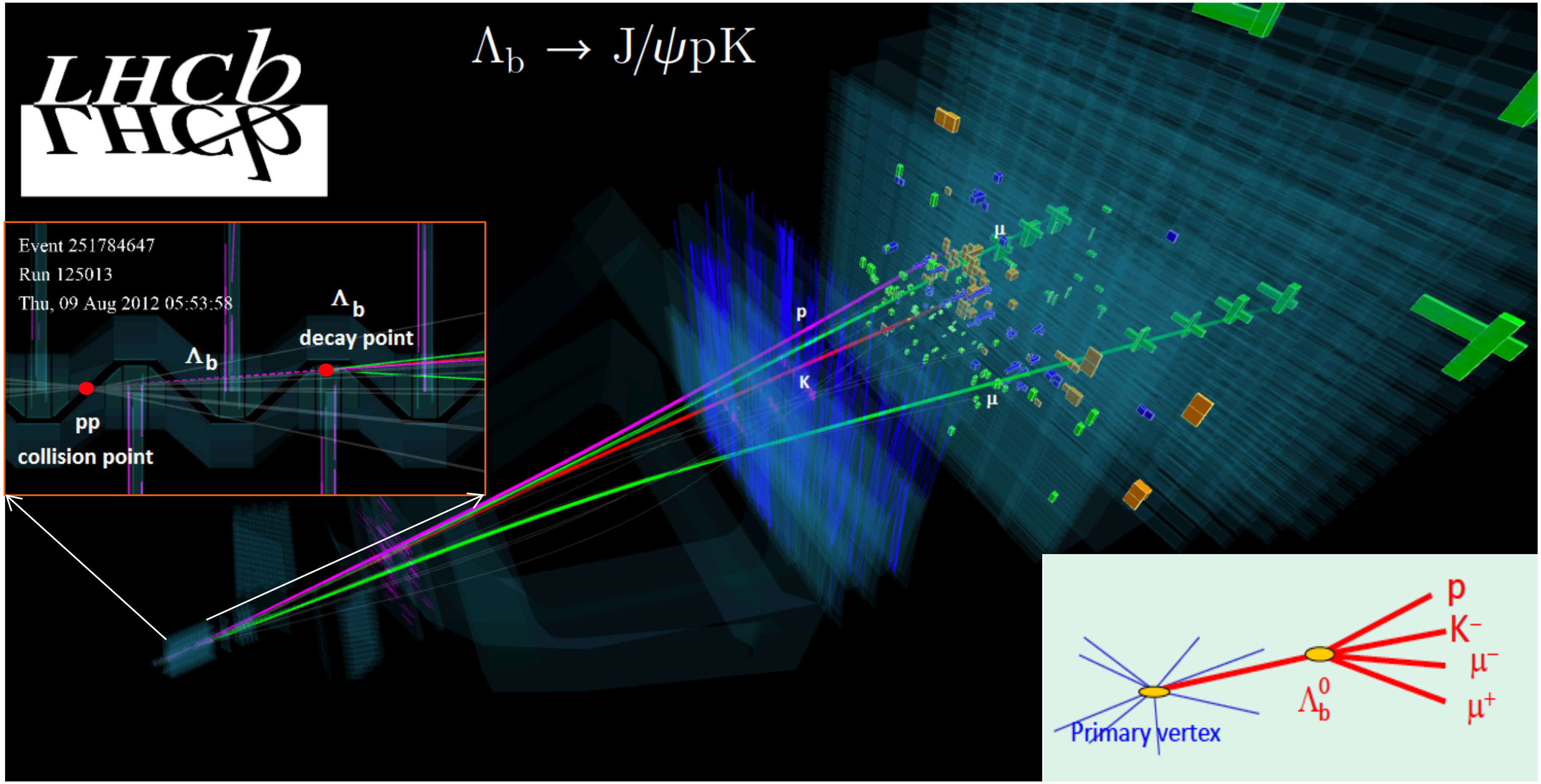
    ~ 100 MeV above SELEX Ξ_{cc}^{+} peaks

$\Xi_{cc}^{++} \to K^- \pi^+ \pi^+ \Lambda_c^+ (\to p K^- \pi^+)$





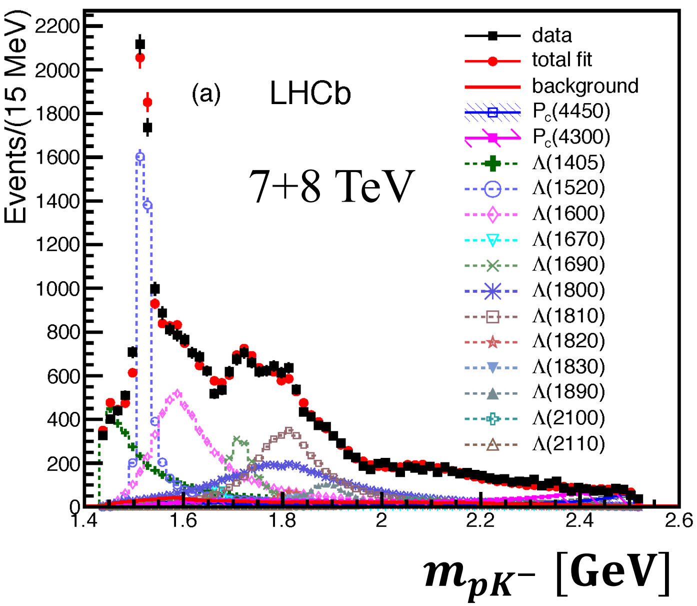
Pentaquark studies

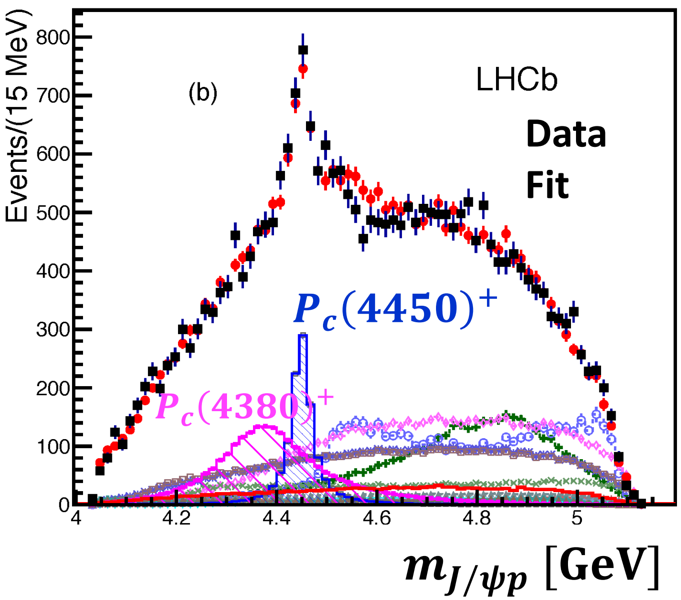


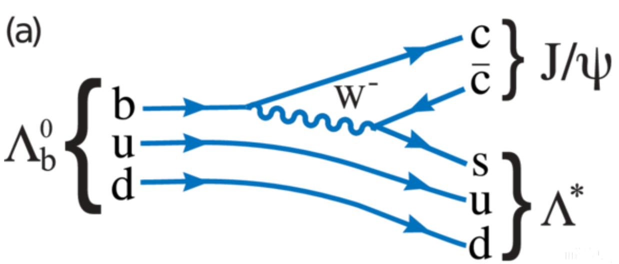
Discovery of pentaquark states

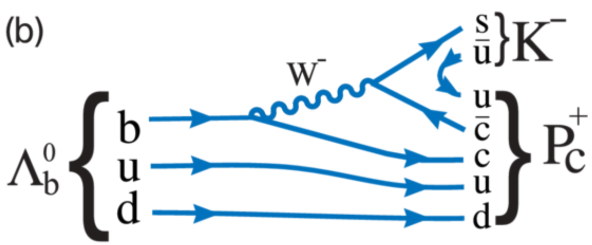
PRL 115 (2015) 072001

- Two pentaquark states observed in $\Lambda_b^0 \to J/\psi p K^-$







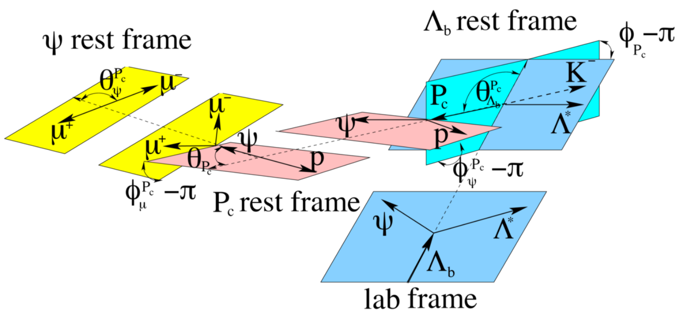


Discovery of pentaquark states

PRL 115 (2015) 072001

- Amplitude analysis reveals the properties

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



- Confirmed by a model independent analysis

PRL 117 (2016) 082002

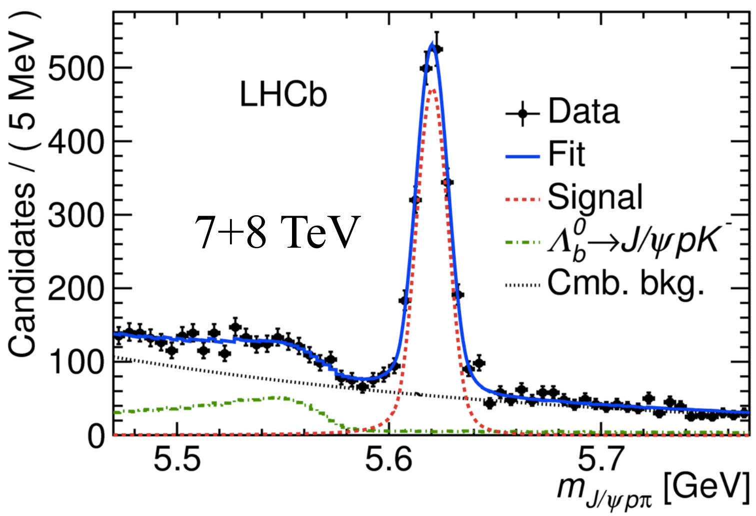
- Production & decay

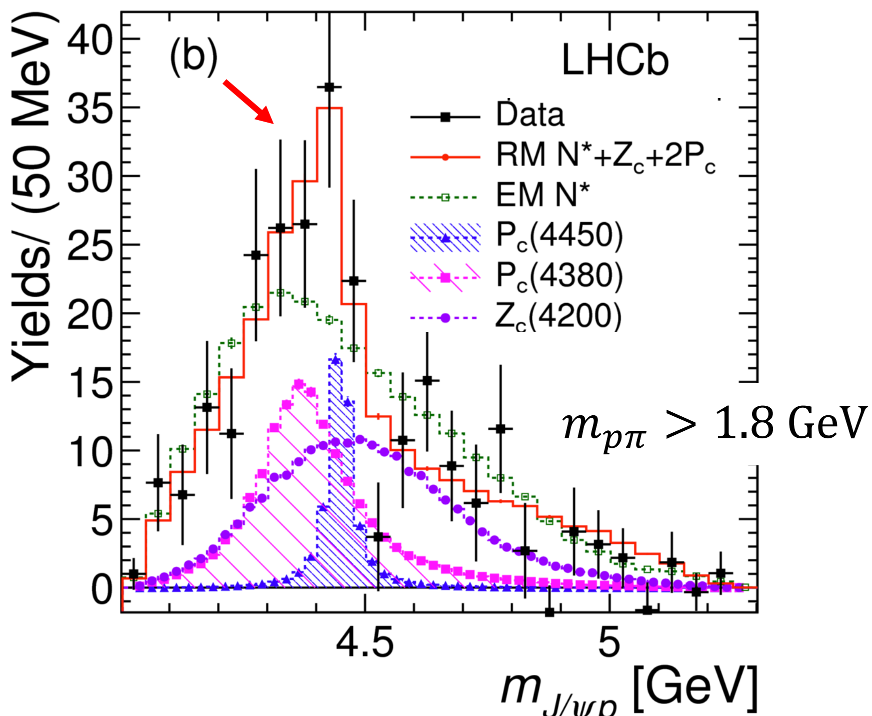
Chin. Phys. C 40 (2016) 011001

$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\,^{+\,0.46}_{-\,0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\,^{+\,0.22}_{-\,0.18}\right) \times 10^{-5}$$

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

- Cabbibo suppressed mode with less statistics
- Exotic Z_c^- contribute in $J/\psi\pi^-$
- Fit with 2 $P_c^+ + Z_c(4200)^-$ favored by 3σ compared to no exotic contributions





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

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \boxed{\chi_{c(1,2)} p} K^-$ decays
  $\Rightarrow$ Test hypothesis of kinematic rescattering effect

PRD 92 (2015) 071502

- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

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

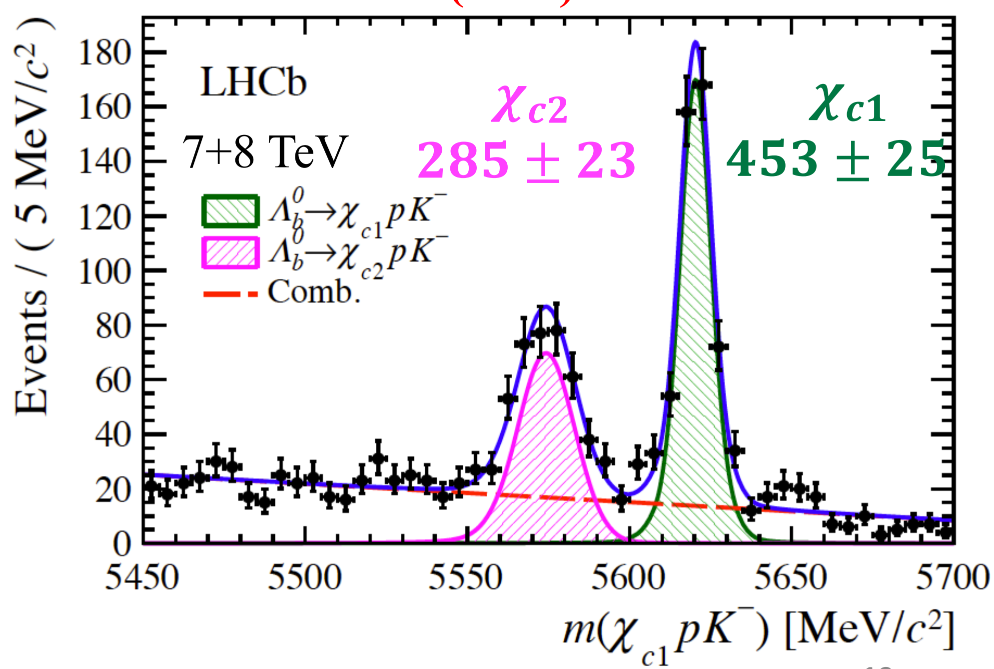
$$\mathbf{0.242 \pm 0.014 \pm 0.013 \pm 0.009}$$

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

$\mathcal{B}(\chi_{cJ})$

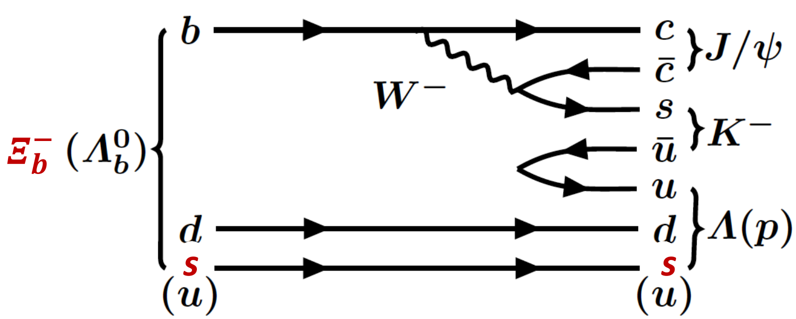
$$\mathbf{0.248 \pm 0.020 \pm 0.014 \pm 0.009}$$

PRL 119 (2017) 062001



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

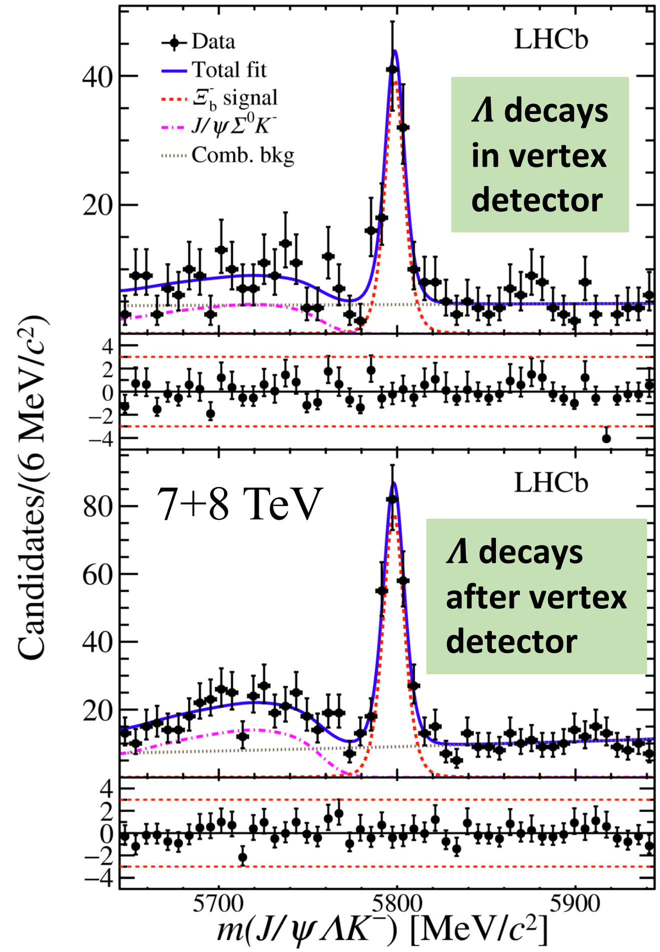
- Strange pentaquark ($uds c\bar{c}$) predicted in [PRL 105 (2010) 232001]
- Can be searched for in the Ξ_b^- decay [PRC 93 (2016) 065203]



$N_{sig} = 308 \pm 21\ (21\sigma)$

PLB 772 (2017) 265-273

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



Weakly decaying b-flavoured pentaquarks

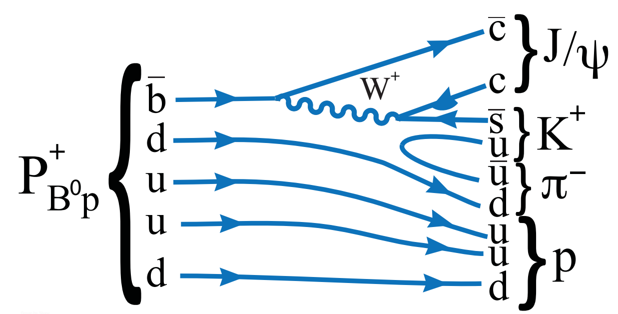
PRD 97 (2018) 032010

new

- Skyrme model: heavy quarks give tightly bound pentaquark

PLB 590(2004) 185; PLB 586(2004)337; PLB 331(1994)362

- Search for mass peaks below strong decay threshold



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

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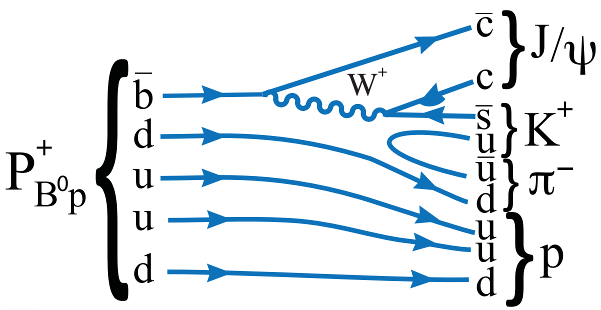


Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \to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

- Upper limit on production ratio $\sigma\cdot\mathcal{B}$ wrt $\Lambda_b^0 \to J/\psi K^- p$

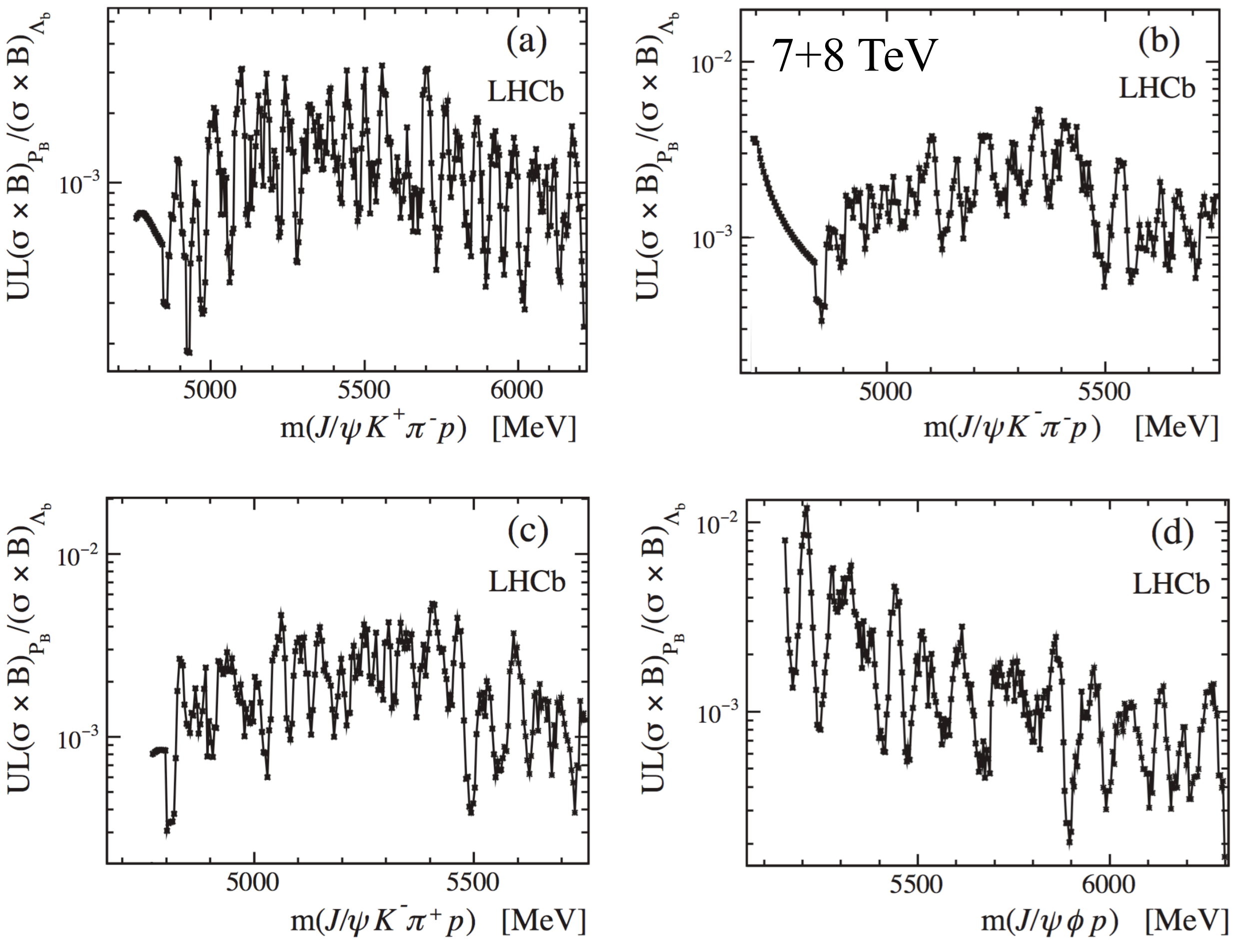
$$R = \frac{\sigma(pp\to P_B X)\cdot\mathcal{B}(P_B\to J/\psi X)}{\sigma(pp\to \Lambda_b^0 X)\cdot\mathcal{B}(\Lambda_b^0\to J/\psi K^- p)}$$

Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

new

- No evidence for signal, 90% CL limits on $R < 10^{-2} - 10^{-3}$



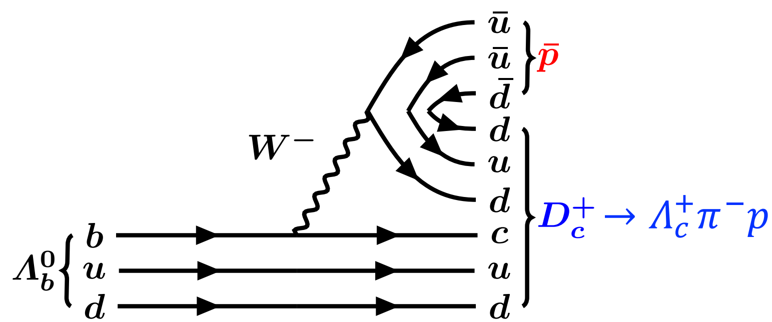
Search for dibaryon state

new

LHCb-PAPER-2018-005, in preparation

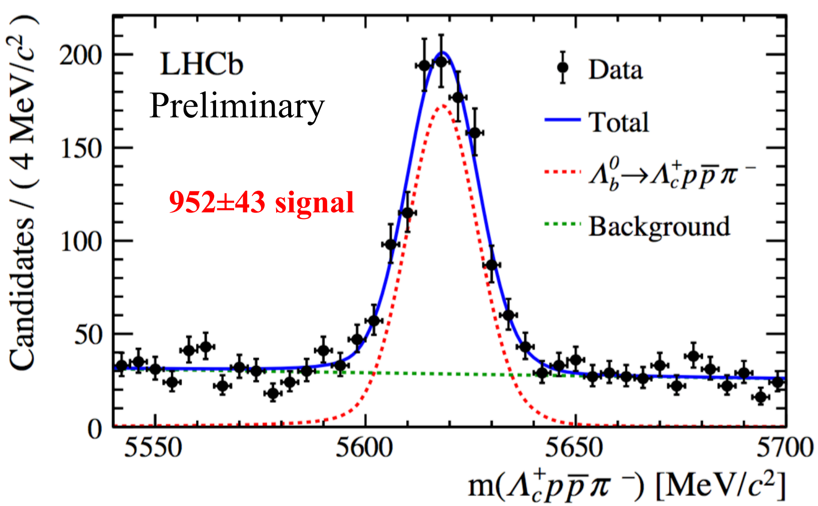
- A dibaryon state $[cd][ud][ud]$ could be produced in Λ_b^0 decays to final state $\Lambda_c^+\pi^-p\bar{p}$

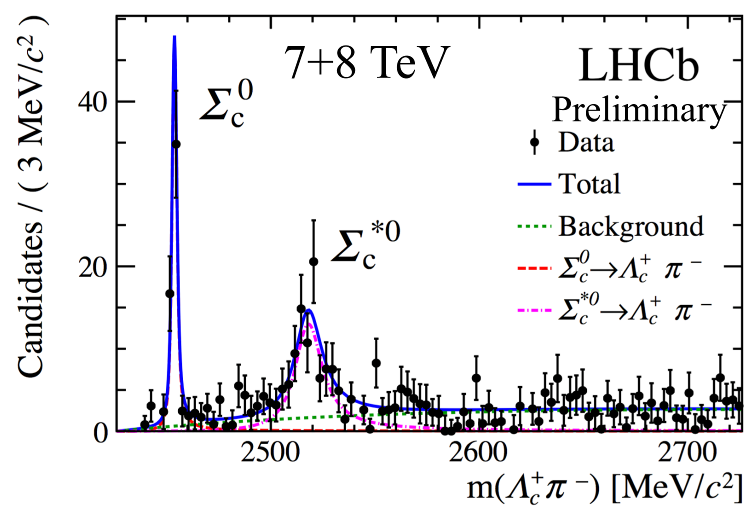
L. Maiani, et al. PLB 750 (2015) 37



- LHCb has discovered the decay $\Lambda_b^0 \to \Lambda_c^+\pi^-p\bar{p}$

Resonance contributions





Search for dibaryon state

new

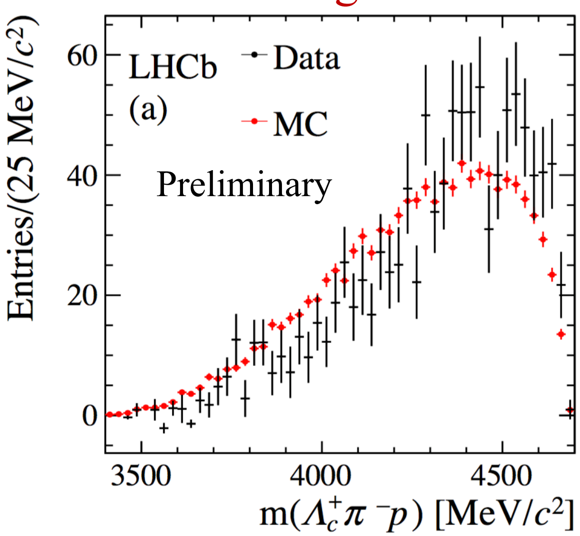
LHCb-PAPER-2018-005, in preparation

- Ratio of branching fractions (preliminary)

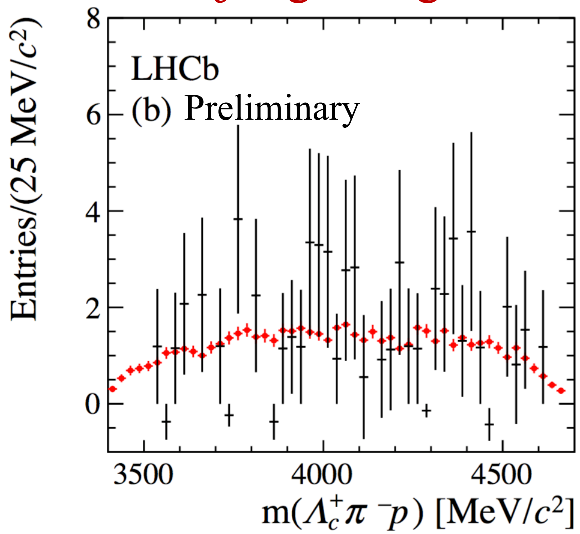
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0544 \pm 0.0023 \pm 0.0032$$

- No obvious dibaryon peak in $m(\Lambda_c^+\pi^- p)$ spectra

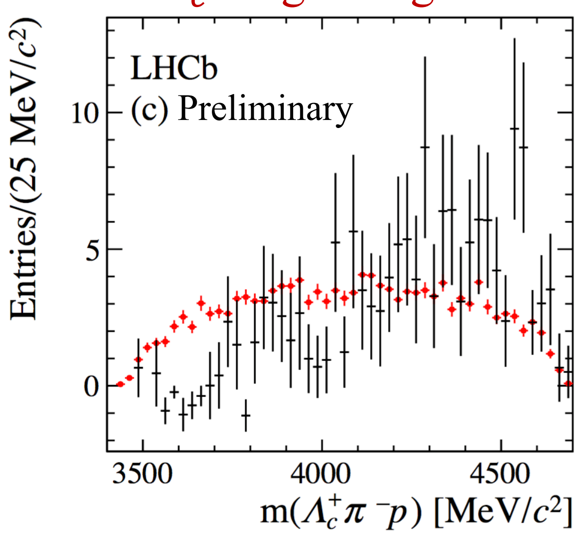
All signals



Σ_c^0 region signals



Σ_c^{*0} region signals



Summary

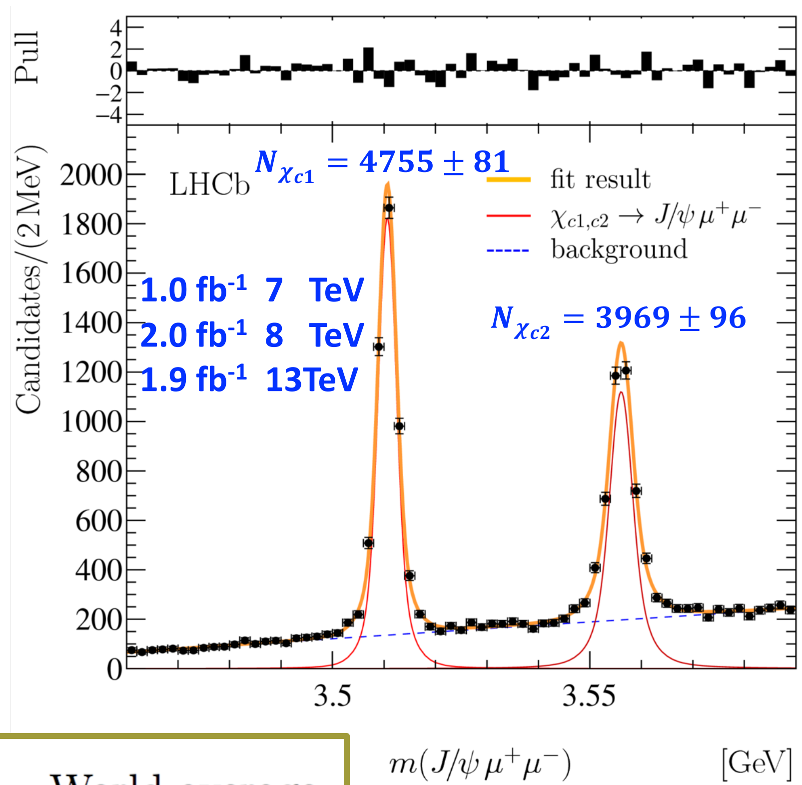
- LHCb has made important contributions to the knowledge of hadron spectroscopy
  - Observation/study of excited $B(D)$mesons & $b(c)$ baryons
  - Observation/study of exotic states
  - Discovery of doubly charmed baryons
  - …
- Stay tuned with new results from RUNI+RUNII
- Spectroscopy at the upgraded LHCb is challenging and promising

Backup

Muonic decays of χ_{c1} and χ_{c2}

PRL 119 (2017) 221801

- $c\bar{c}$ states χ_c usually studied in $\chi_c \to J/\psi\gamma$ decays
- First observation of $\chi_c \to J/\psi\mu^+\mu^-$ decays
- Much better mass resolution allows competitive mass and width measurements



Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11

Physics program at LHCb

- Not only precision measurements in b, c sectors
  - CKM and CP-violation parameters
  - Rare decays
  - Testing lepton universality
  - …
- But also a general purpose detector
  - Electroweak measurments: sin θ_W, W/Z, top quark
  - Spectroscopy, exotic hadrons
  - Soft QCD
  - Heavy ions
  - …