Latest results from LHCb on hadron spectroscopy

Pei-Rong Li

(University of Chinese Academy of Sciences)

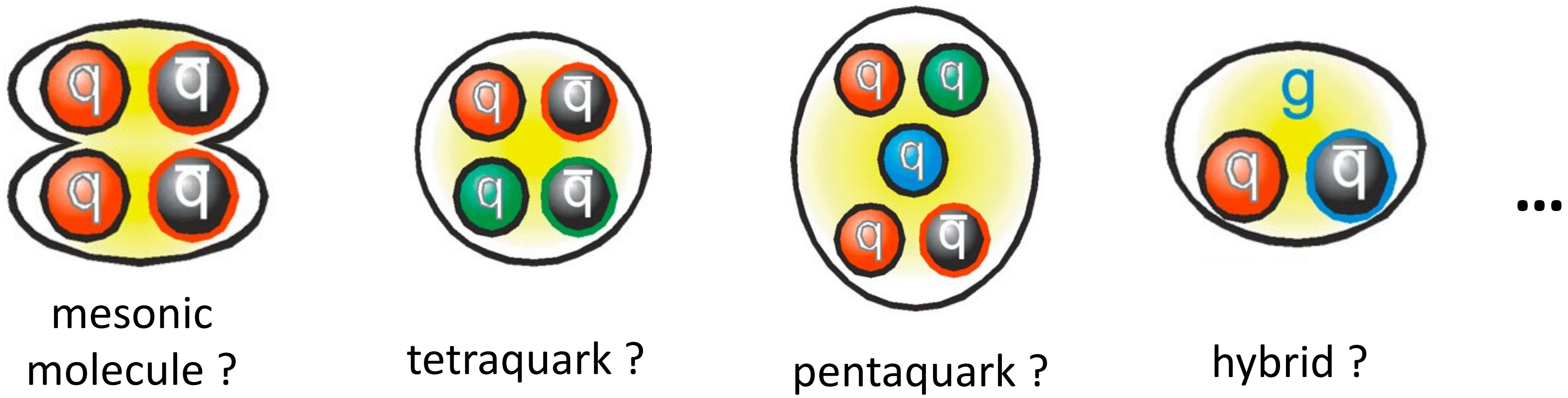
On behalf of the LHCb Collaboration

The 10th Workshop on Hadron physics in China and Opportunities Worldwide

(26-30 July, 2018, Weihai, China)

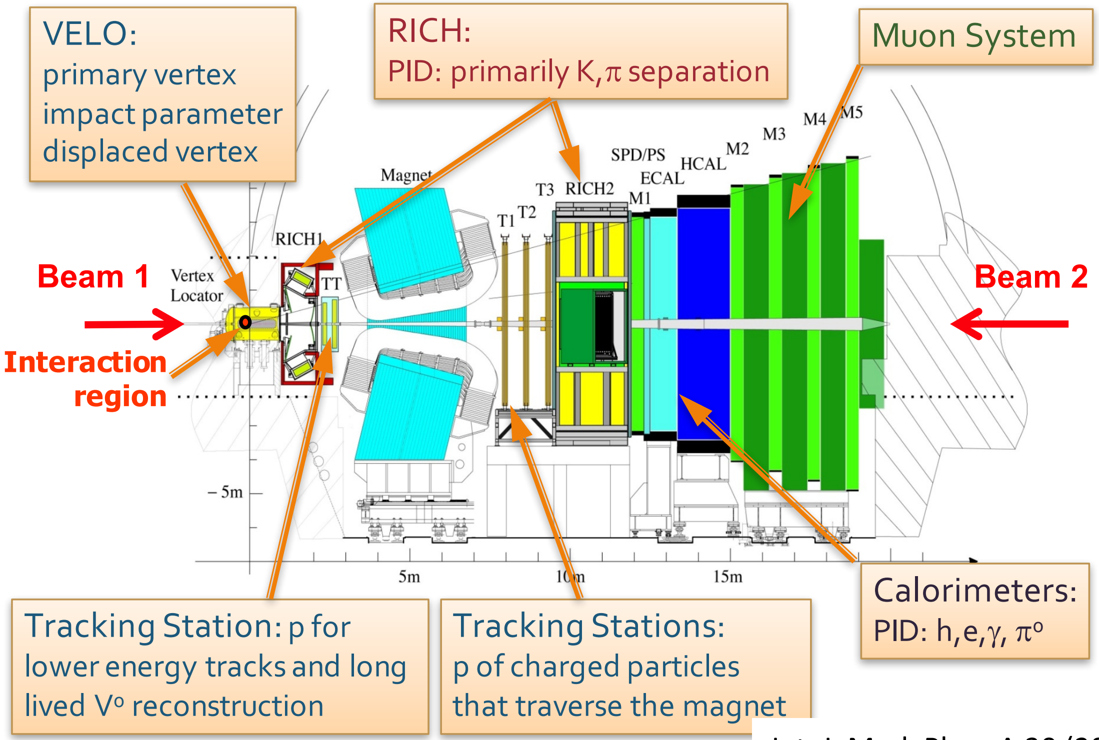
Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



LHCb detector and performance

The LHCb detector described in JINST 3 (2008) S08005

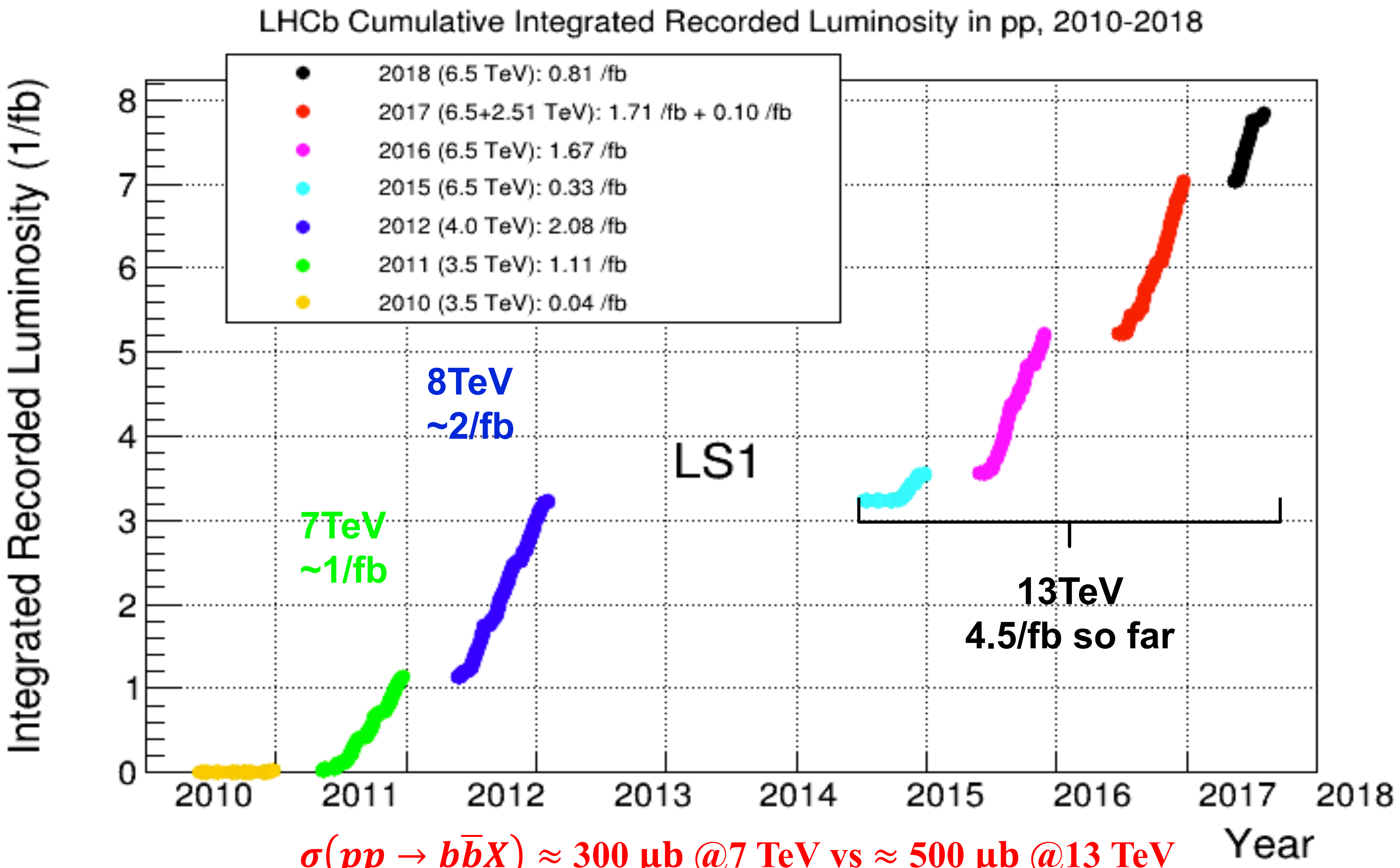


Int. J. Mod. Phys. A 30 (2015) 1530022

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** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{m_{J/\psi}}$**)**
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:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

- Single arm spectrometer designed for high-precision measurement oif flavor physics
- Highly powerful particle identification for p,K,π
- Very good momentum resolution
- Excellent primary and secondary vertex reconstruction.

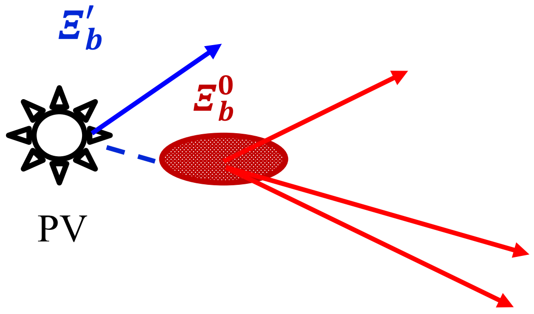
LHCb data taking

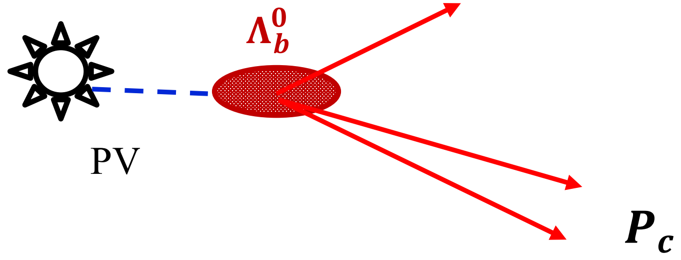


$\sigma(pp \to b\bar{b}X) \approx 300\ \mu\text{b}$ @7 TeV vs $\approx 500\ \mu\text{b}$ @13 TeV

Two methods for spectroscopy

- Direct production in pp collisions
  - Combine a heavy flavor hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P
- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited states and limited J





Outline

- Standard heavy flavor spectroscopy
  - Observation of a new Ξ_b^{**-} state
  - Lifetime measurement of Ω_c^0 baryon
  - Doubly charmed baryon Ξ_{cc}^{++}(new decay channel, life time)

- Exotic hadrons
  - Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$
  - Weakly decaying *b*-flavored pentaquarks
  - Search for dibaryon states in $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ decays
  - Search for a beautiful otetraquark in the $\Upsilon(1S)\ \mu^+\mu^-$ invariant mass spectrum.

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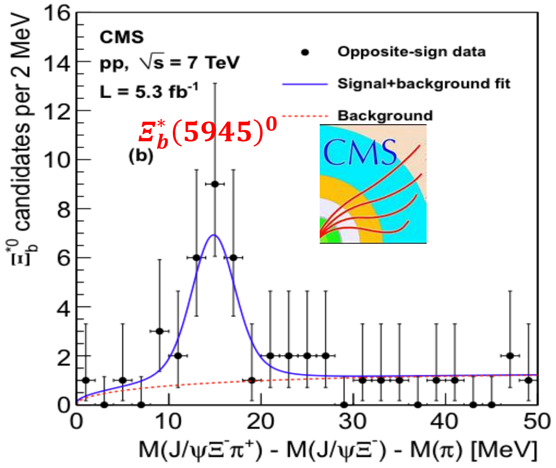
Ξ_b baryon spectroscopy

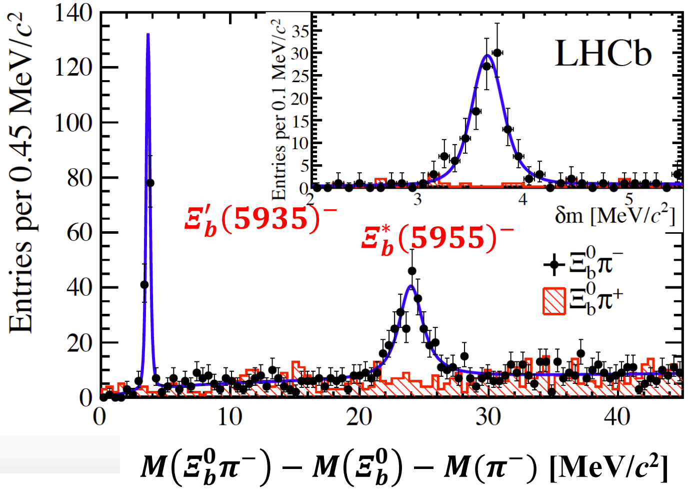
- b-baryon is less studied before LHC
- Experiments at LHC are continuing to contribute to Ξ_b baryons studies
  - $\Xi_b^*(5945)^0 \to \Xi_b^- \pi^+$ [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - ${\Xi_b'}^0$ not yet observed

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

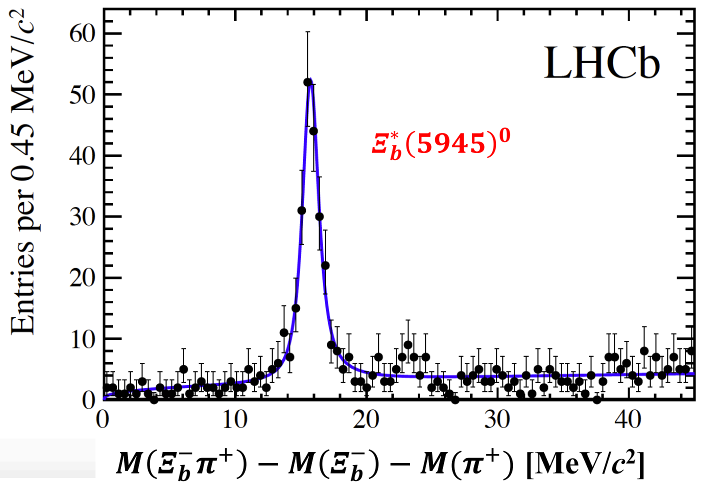
PRL 108, 252002 (2012)



PRL 114 (2015) 062004



JHEP 05 (2016) 161



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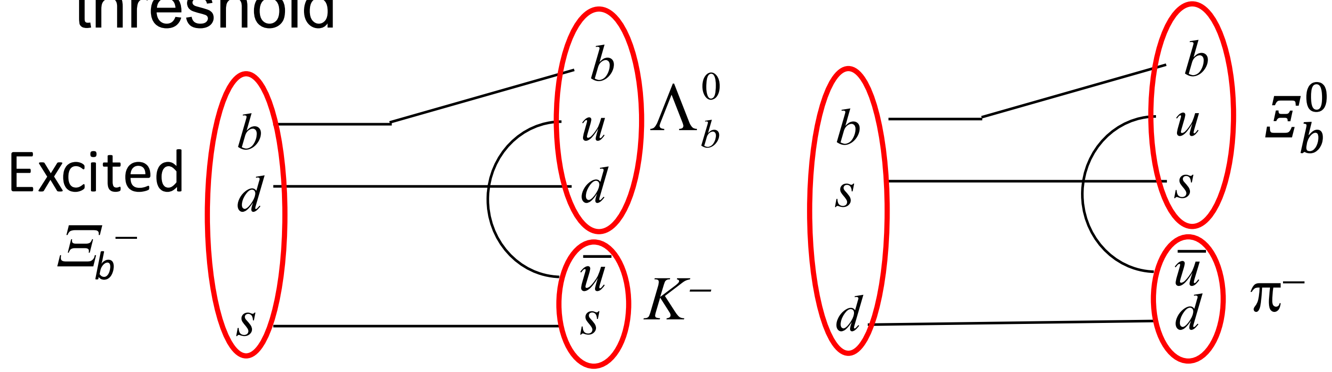
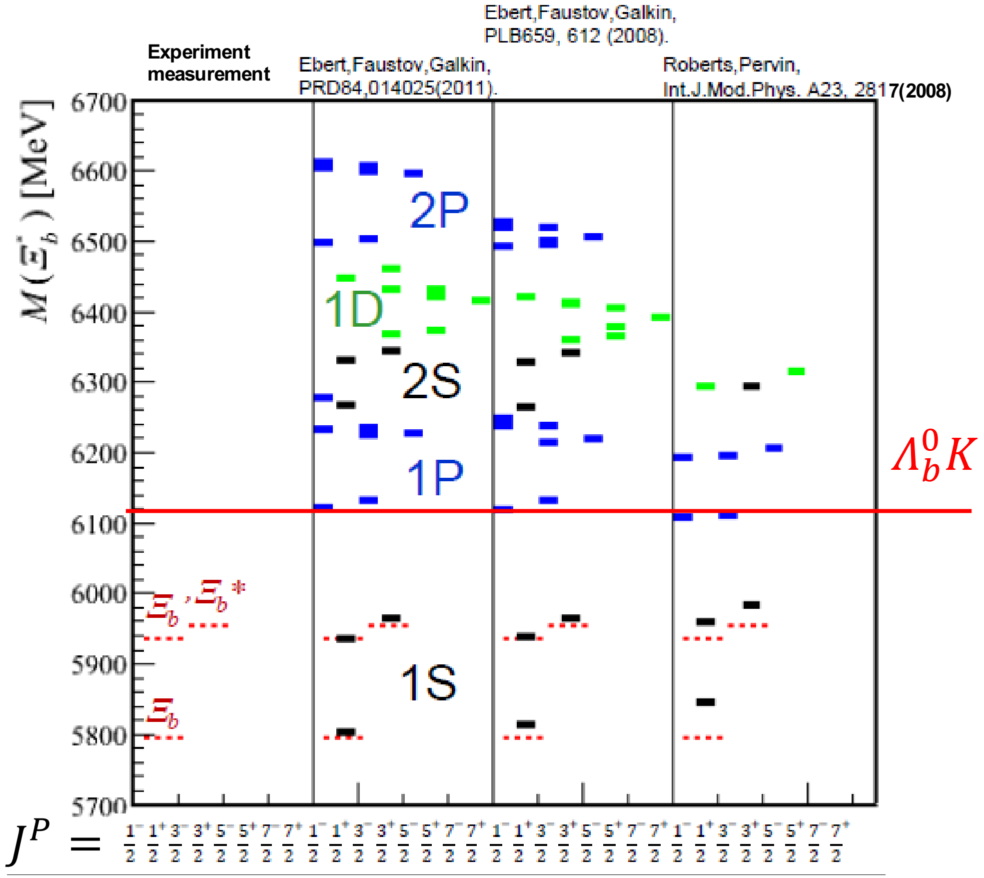
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - $\Xi_b'^0$ not yet observed
- More higher excited states are expected to be above $\Lambda_b^0 K$ threshold

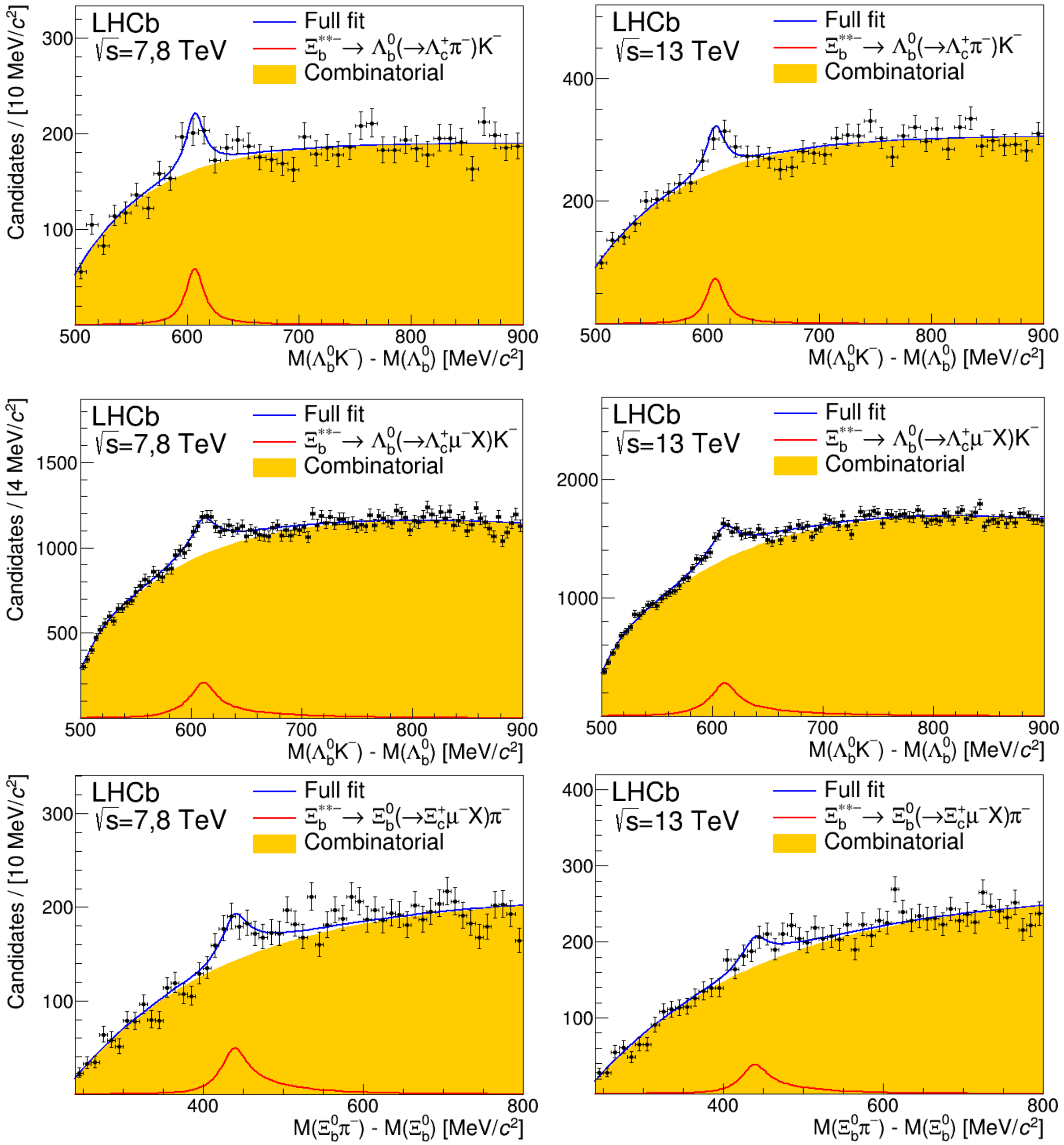


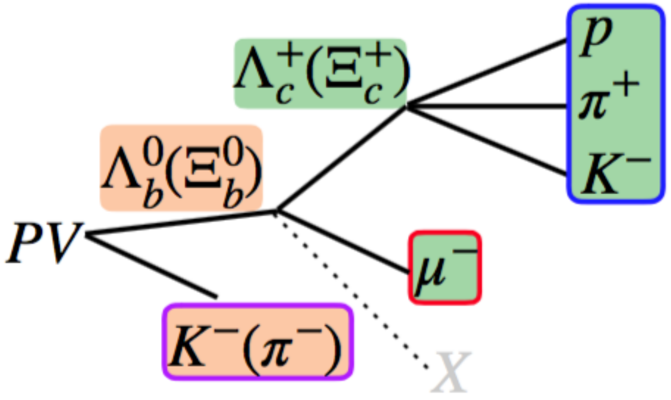


Observation of a new Ξ_b^{**-} state (Run I +Run II)

arXiv:1805.09418, submitted to PRL

- Hadronic $\Lambda_b^0 \to \Lambda_c^+ \pi^-$:
  - Yields:~400
  - Resolution: 2 MeV
  - 7.9σ
- Semi-leptonic (SL) $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$
  - Resolution: ~18 MeV
  - Yields ~15 larger
  - 25σ
- Semi-leptonic (SL) $\Xi_b^0 \to \Xi_c^+ \mu^- X$
  - Yields: ~600
  - 9.2σ





- The missing momentum estimated assuming a massless particle balancing momentum transverse to the $\Lambda_b^0(\Xi_b^0)$ direction.
- The total invariant mass is constrained to the known $\Lambda_b^0(\Xi_b^0)$ mass.

The Ξ_b^{**-} properties

arXiv:1805.09418, submitted to PRL

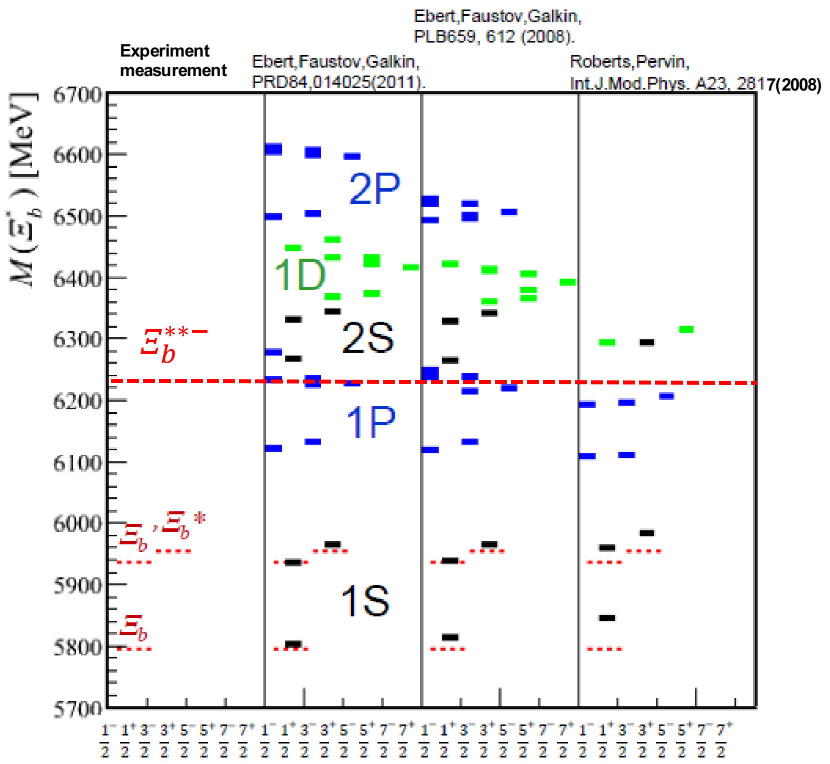
- Hadronic mode for mass measurement

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

Mass peak positions are consistent between the three decay channels

- Production measured with SL modes

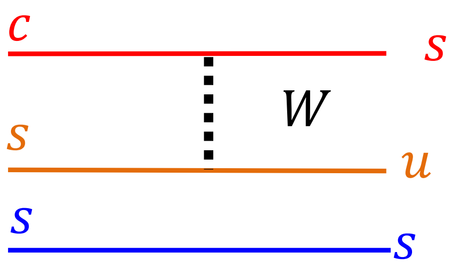
Quantity	7+8 TeV	13 TeV
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Lambda_b^0})\mathcal{B}(\Xi_b^{**-} \to \Lambda_b^0 K^-)$	$(3.0\pm0.4\pm0.4)\times10^{-3}$	$(3.4\pm0.4\pm0.4)\times10^{-3}$
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Xi_b^0})\mathcal{B}(\Xi_b^{**-} \to \Xi_b^0 \pi^-)$	$(47\pm9\pm7)\times10^{-3}$	$(22\pm6\pm3)\times10^{-3}$

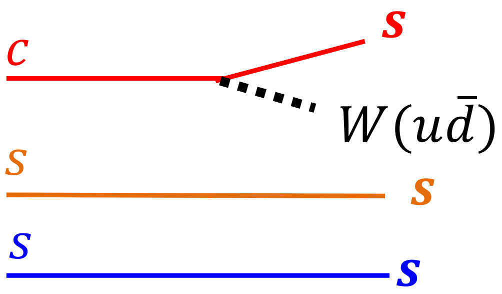


- Dominating systematic uncertainty: background model
- The new state can be either $\Xi_b(1P)^-$ or $\Xi_b(2S)^-$
- To distinguish them further information needed (e.g. J^P, $\mathcal{B}$)

Measurement of the lifetime of Ω_c^0

- Test theoretical approaches, e.g. Heavy Quark Expansion (HQET)
  - Higher order effects are important: expansion in powers of $1/m_Q$
  - *c*-hadrons: sizable high-order corrections
  - *c*-baryon decays: *W*-exchange and Pauli interference [Nucl. Phys. B**248** (1984) 261] larger than in *c*-meson decays





- *c*-baryon lifetimes are not well measured, in particular for Ω_c^0 uncertainty up to 17%

- Test the popular lifetime hierarchy in charmed baryons.

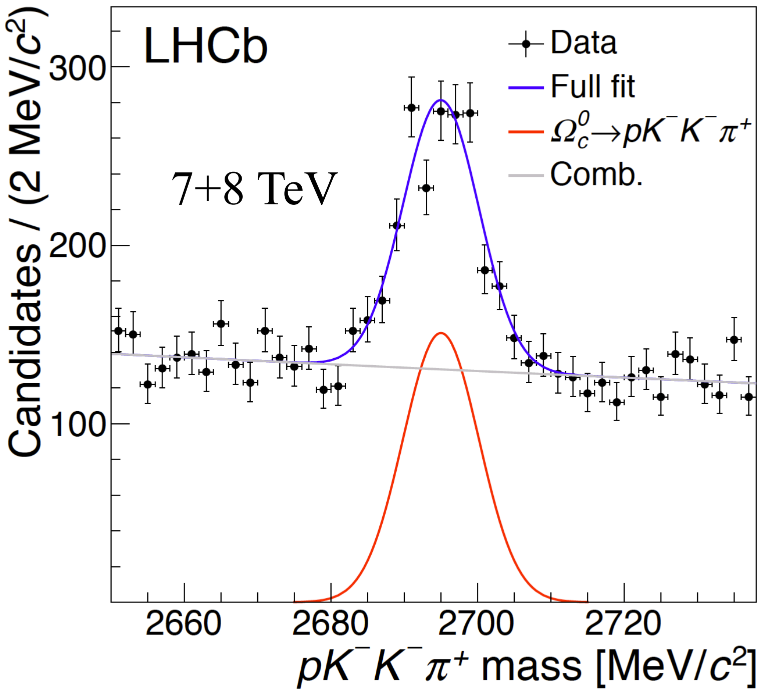
$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$

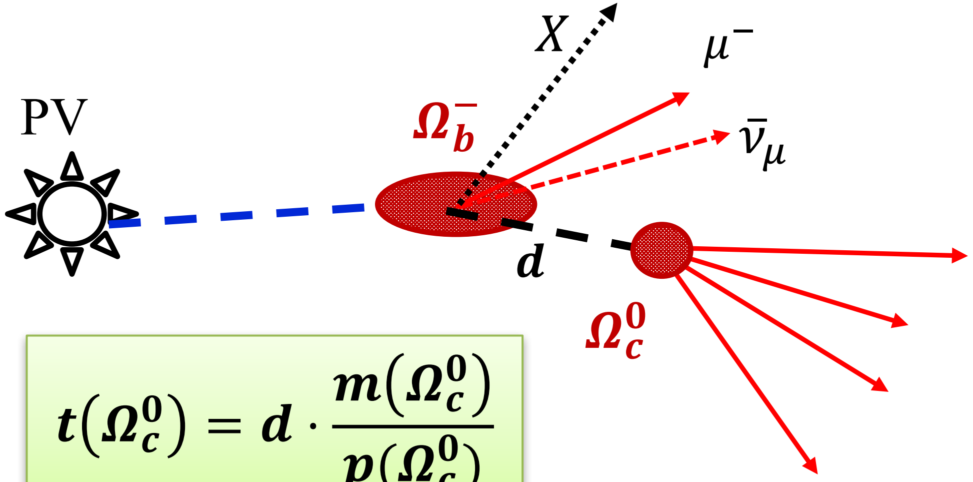
Front. Phys. (Beijing) 10 (2015) 101406
Riv. Nuovo Cim. 26N7 (2003) 1
Proceedings, 3rd Workshop, Marbella, Spain, June 1-6, 1993, 1991
Phys. Rev. D56 (1997) 2783
Phys. Rept. 289 (1997) 1
Sov. J. Nucl. Phys. 41 (1985) 120

Signal and control channels

arXiv:1807.02024, submitted to PRL

- Use $b \to c$ semileptonic decays to avoid bias from trigger and offline selections
  - Muon trigger
  - Tracks well separated from PV
- Signal: $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$
- Control: $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$





$$t(\Omega_c^0) = d \cdot \frac{m(\Omega_c^0)}{p(\Omega_c^0)}$$

Yields:

$\Omega_c^0\mu^-$: 978 ± 60

(~10 times larger than any previous sample used for τ)

$D^+\mu^-$: $(809 \pm 1)\times 10^3$

(used only 10% of LHCb Run-I data)

Lifetime fits

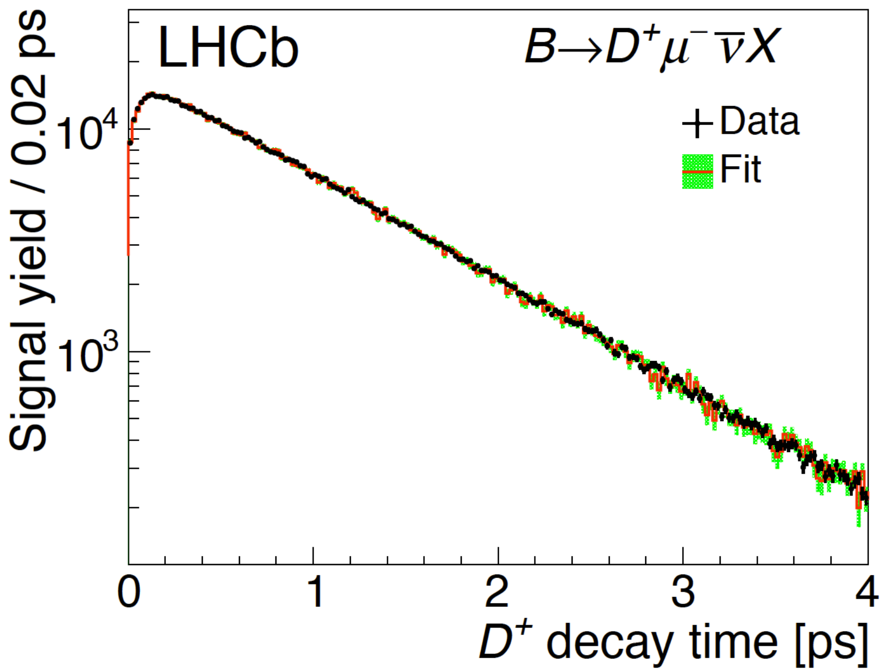
arXiv:1807.02024, submitted to PRL

- Fit background-subtracted distribution obtained with sPlot technique
- Signal PDF: Nucl.Instrum.Meth.A555(2005)356

$$S(t_{\rm rec}) = f(t_{\rm rec}) \exp\left(-\frac{t_{\rm rec}}{\tau_{\rm fit}} + \frac{t_{\rm rec}}{\tau_{\rm sim}}\right) \beta(t_{\rm rec})$$

Binned Template from simulation
✓ **Corresponding to efficiency**

Correction for small efficiency different between data and MC
✓ **Obtained from D^+ and used for Ω_c^0**



If without $\beta(t_{\rm rec})$ correction, about 1.2σ below the PDG value

- Check fit procedure with D^+ events
  Consistent with the PDG value: 1040 ± 7 fs

Ω_c^0 lifetime result

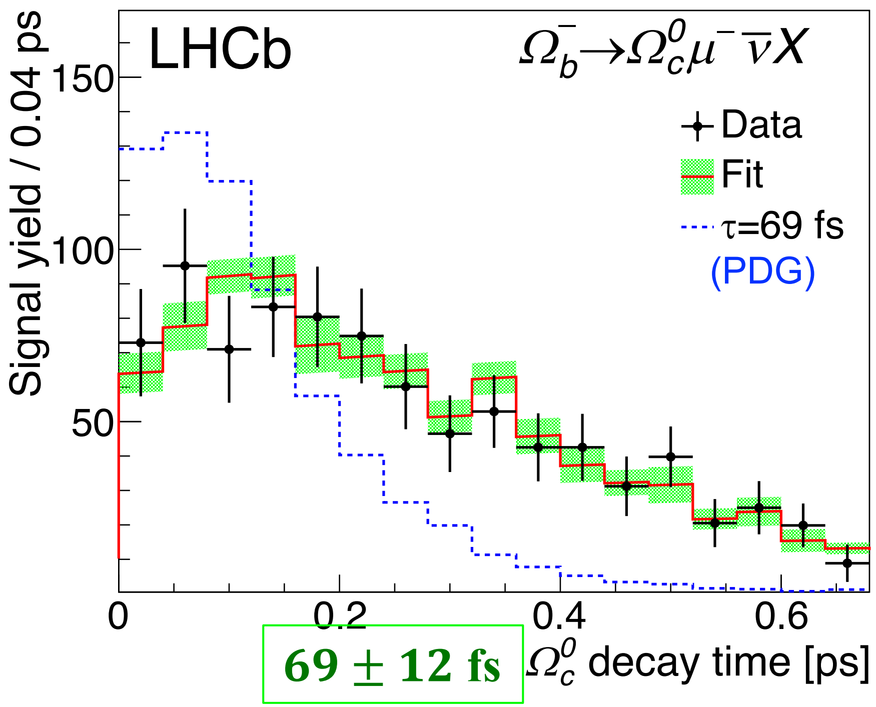
arXiv:1807.02024, submitted to PRL

- Simultaneous fit to signal and control samples

$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

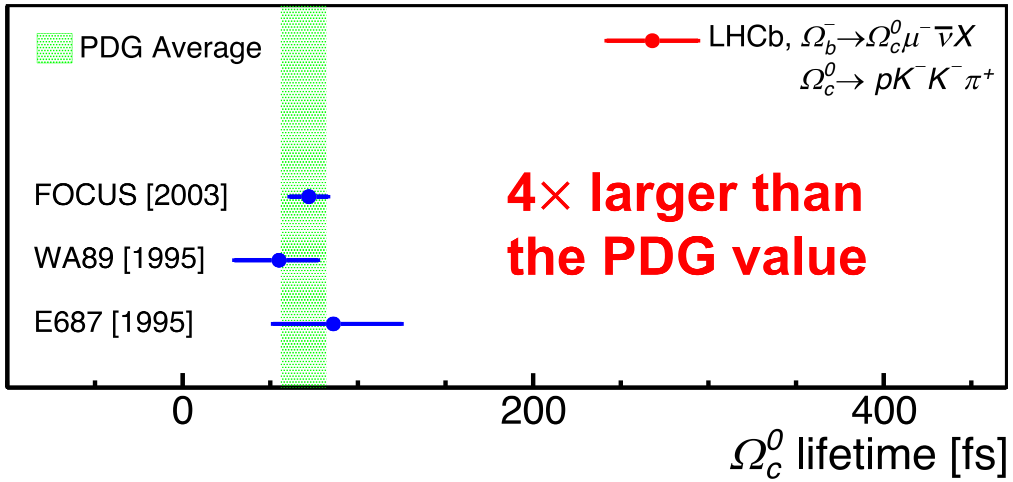
$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2\,(\tau_{D^+})\ \mathrm{fs}$$

$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$



69 ± 12 fs

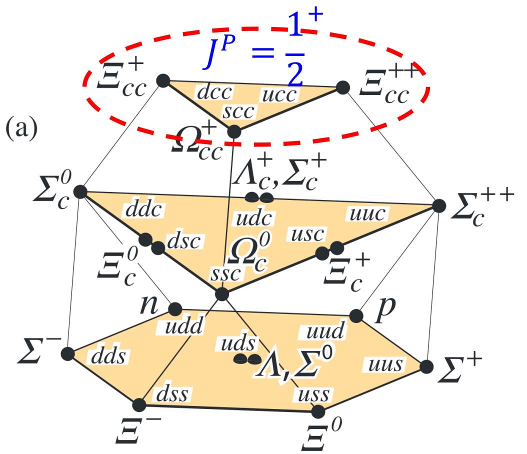
- Many cross-checks
  - 13 TeV 2016 data
  - An additional $D^0 \to K3\pi$ lifetime measurement

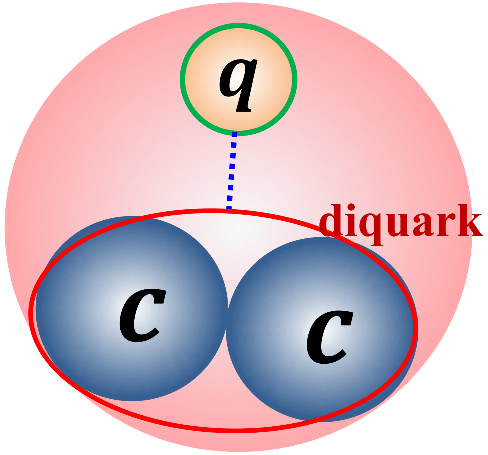


- Most theoretical predictions expect Ω_c^0 lifetime to be short.(Larger constructive Pauli-interference)
- ***Need more theoretical investigation!***

Doubly charmed baryons: motivation

- Relatively unexplored area, no observations nor evidence untill 2002
- Mass and decay width to test QCD motivated models
- Baryons with two heavy quarks probe the QCD potential in a different way than baryons with a single heavy quark [hep-ph/9811212]
  - HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson $\bar{Q}q$
  - Such diquark can be naturally extend to $\bar{Q}\bar{q}\bar{q} = cc\bar{q}\bar{q}$ exotic system

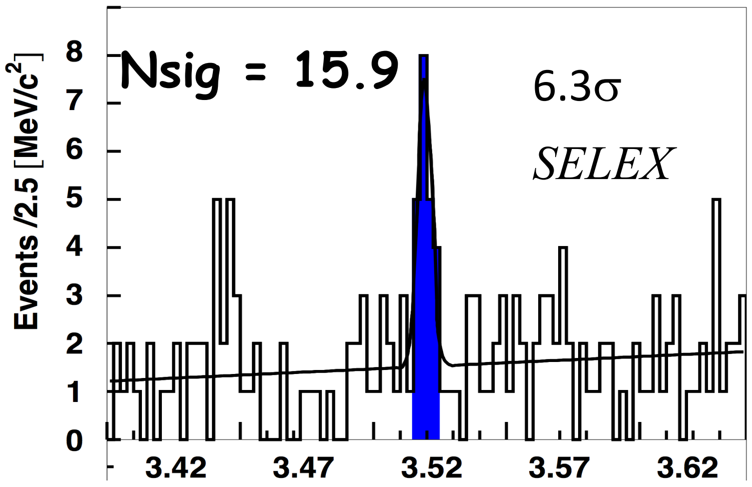




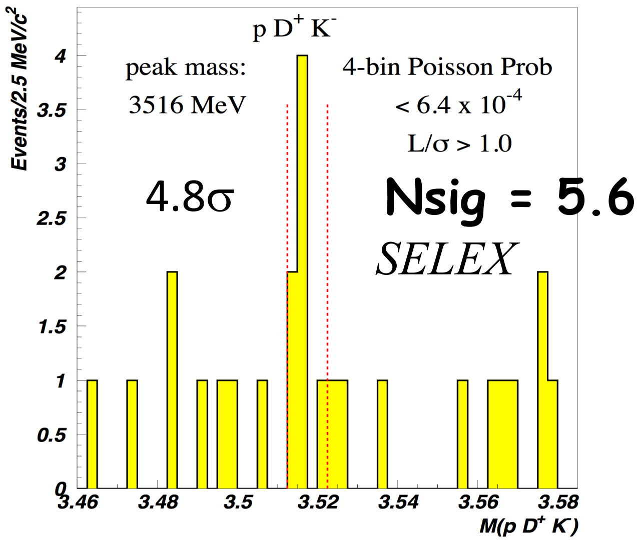
SELEX results on Ξ_{cc}^{+}

- Observation of $\Xi_{cc}^{+}(ccd)$ reported by SELEX
  - Mass: 3518.7 ± 1.7 MeV
  - Short lifetime: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but not zero
  - Large production: $R = \frac{\sigma(\Xi_{cc}^{+}) \times BF(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} \sim 20\%$
- 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

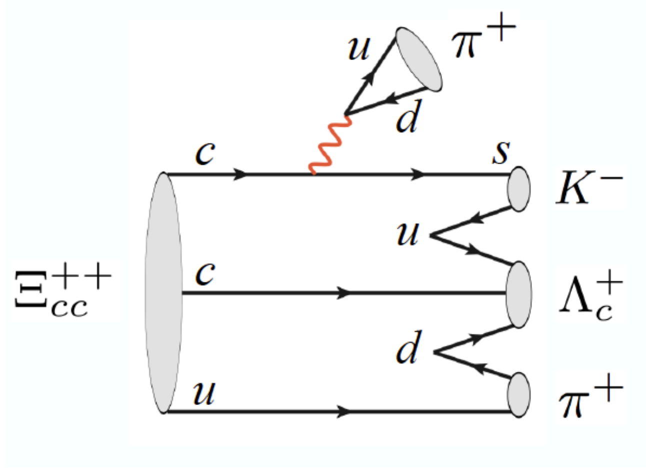


$\Xi_{cc}^{+} \to p D^{+} \pi^{-}$ PLB 628 (2005) 18



Observation of Ξ_{cc}^{++} at LHCb

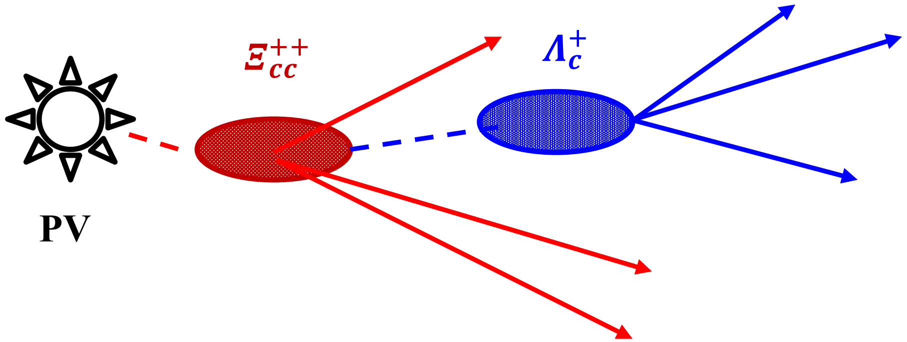
PRL 119 (2017) 112001

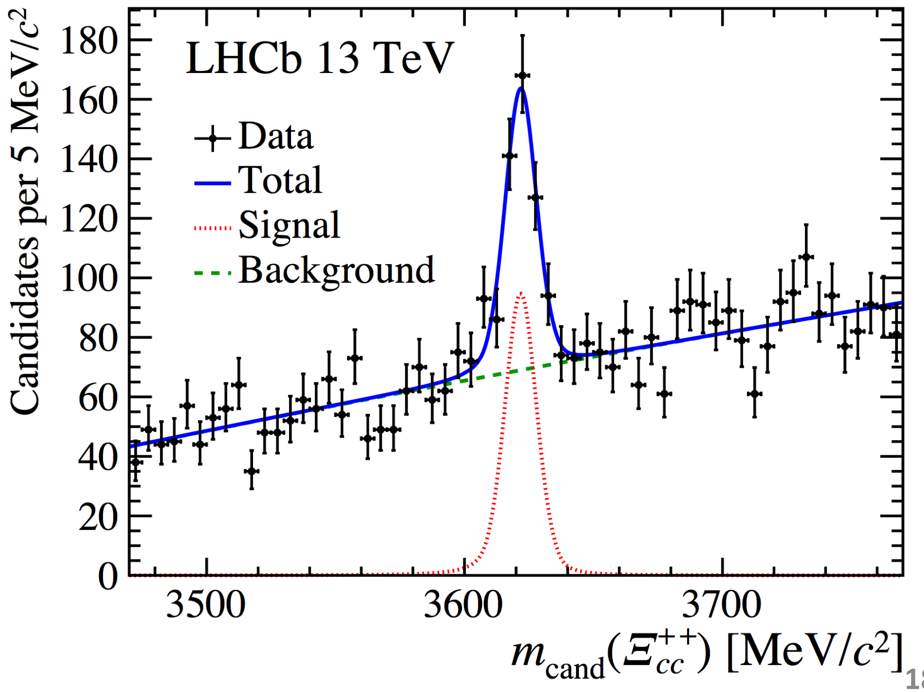


- Expected to have longer lifetime than Ξ_{cc}^{+}, higher sensitivity at LHCb
- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\mathcal{B}$ could be as large as 10% [Yu et al., arXiv:1703.09086, Chinese Phys. C **42** (2018) 051001]
- LHCb 2016 data at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}
  - 313 ± 33 signals, 12σ
  - 8 TeV data analyzed for cross-check, 7σ

$$\boldsymbol{m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+)\ \mathrm{MeV}/c^2}$$

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

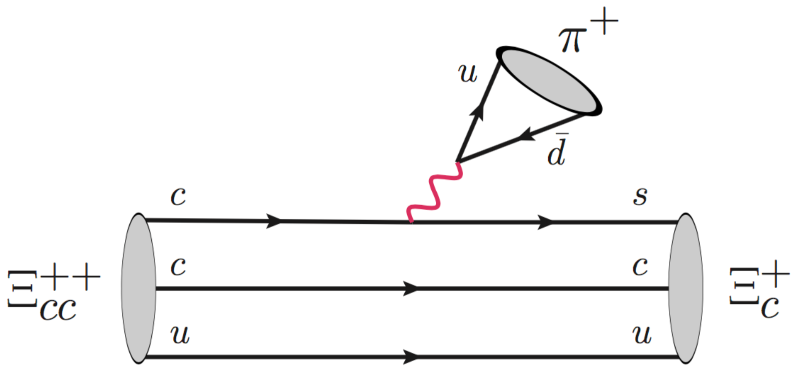




Observation of new decay mode $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

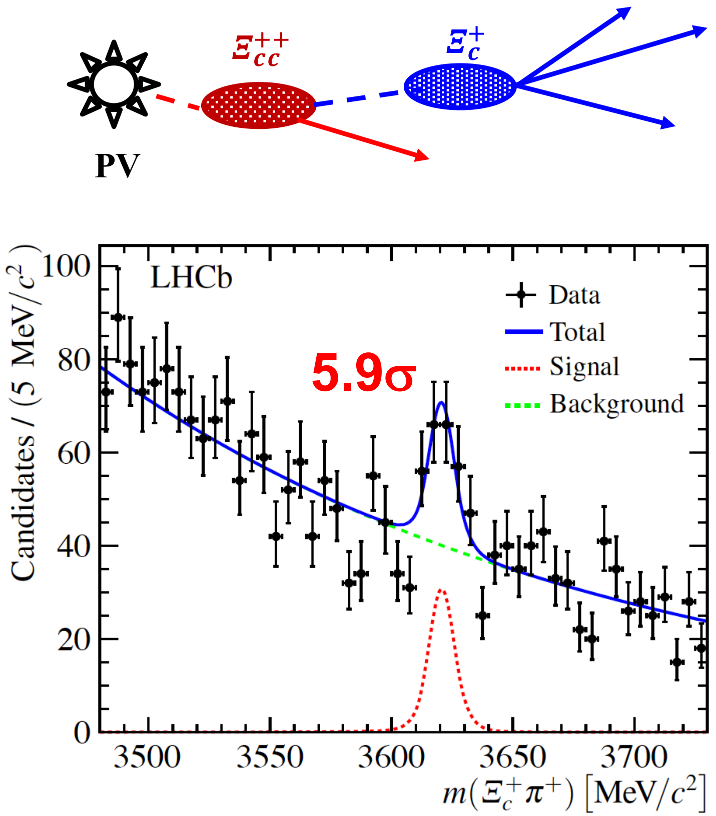
arXiv:1807.01919, submitted to PRL

- Yu et al. also suggest to seach for $\Xi_c^+(\to pK^+\pi^-)\pi^+$ at LHCb
- LHCb 2016 data, ~1.7 fb^{-1}
- Control mode:
  $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- Similar selections and triggers for signal and control modes
  - Good PID, high p_T
  - TMVA technique



Signal mode

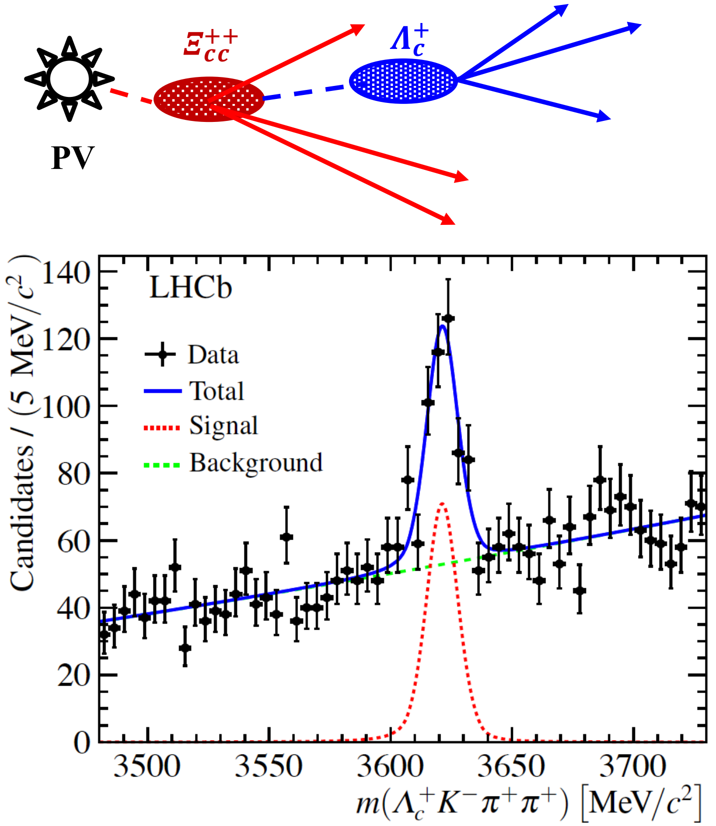
$\Xi_{cc}^{++} \to \pi^+ \Xi_c^+(\to pK^-\pi^+)$



$N_{\mathrm{sig}} = 91 \pm 20$

Control mode

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



$N_{\mathrm{con}} = 298 \pm 35$

Observation of new decay mode $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

arXiv:1807.01919, submitted to PRL

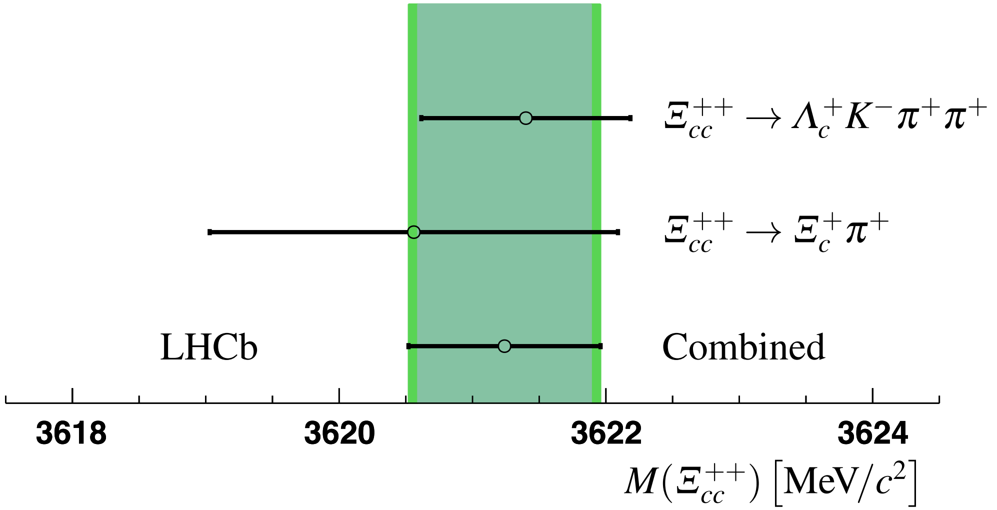
- Consistent mass measurements

$$3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+)\ \mathrm{MeV}/c^2$$

$$3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+)\ \mathrm{MeV}/c^2$$

$$3621.24 \pm 0.65 \pm 0.31\ \mathrm{MeV}/c^2$$

Confirm previous LHCb observation of Ξ_{cc}^{++}



- Mass discrepancy with the SELEX measurement(Δm=103MeV), too large to be isospin partners PRD 78 073013 PLB 698 2251-255 PRD 96 033004

- Ratio of branching fractions

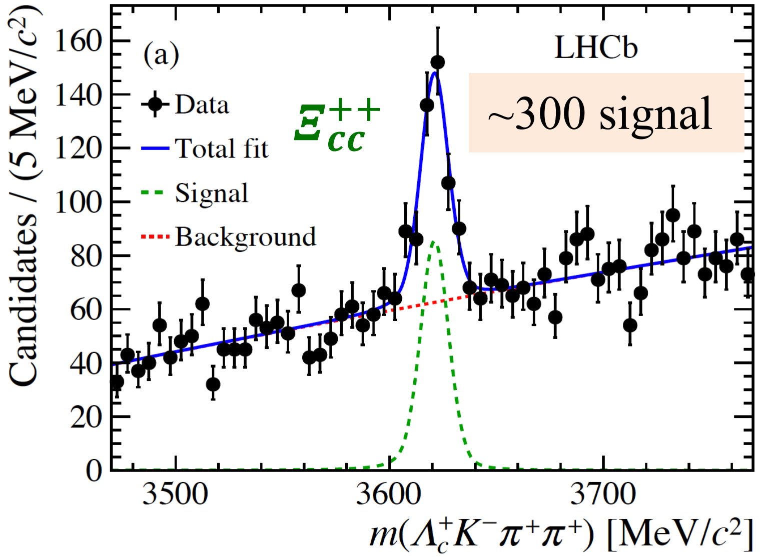
$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+; \Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+; \Lambda_c^+ \to pK^-\pi^+)} = (3.5 \pm 0.9 \pm 0.3)\times 10^{-2}$$

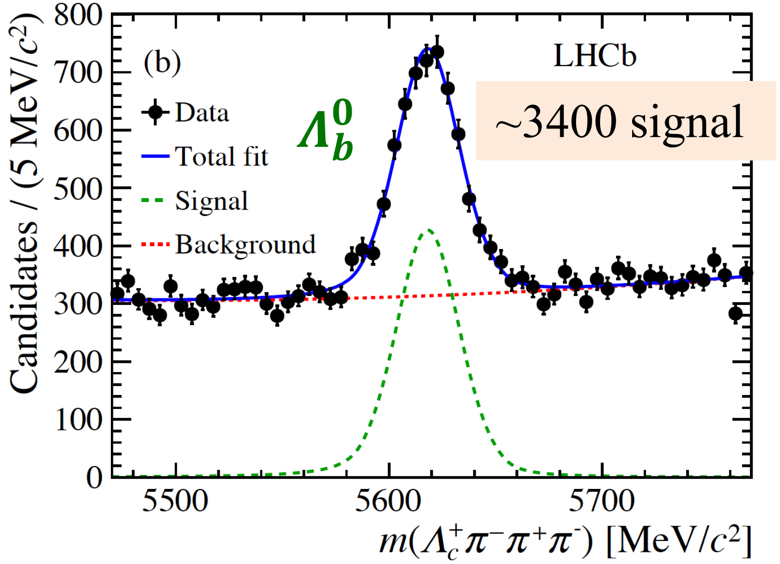
Consistent with prediction [Yu et al., arXiv:1703.09086, Chinese Phys. C **42** (2018) 051001]

First measurement of Ξ_{cc}^{++} lifetime

arXiv:1806.02744, accepted by PRL

- A lifetime measurement is critical
  - Test whether it is weakly decaying J = ½ ground state
  - Necessary ingredient for theoretical prediction of $\mathcal{B}$
  - Important information for experimental exploration of other doubly-heavy baryons
  - Test various predictions of QCD models





- Analysis strategy
  - Same data sample, event selection as previous Ξ_{cc}^{++} observation
    - **Specific trigger requirement to simplify trigger efficiency determination**
  - Relative measurement to $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$ decays

First measurement of Ξ_{cc}^{++} lifetime

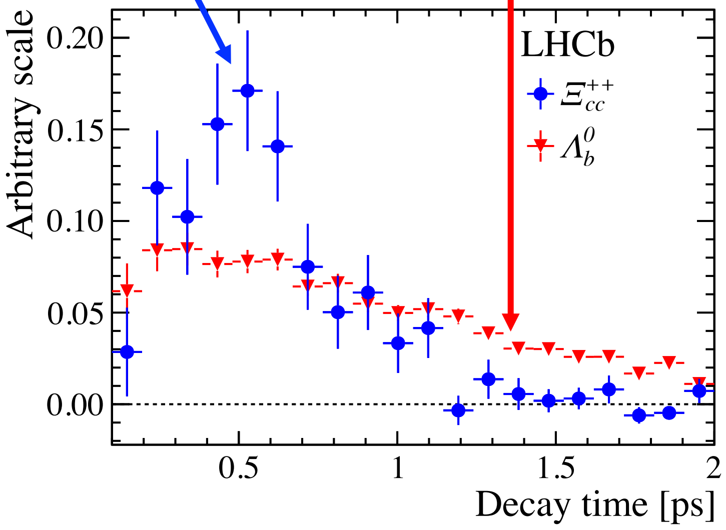
- Decay-time acceptance obtained from simulation

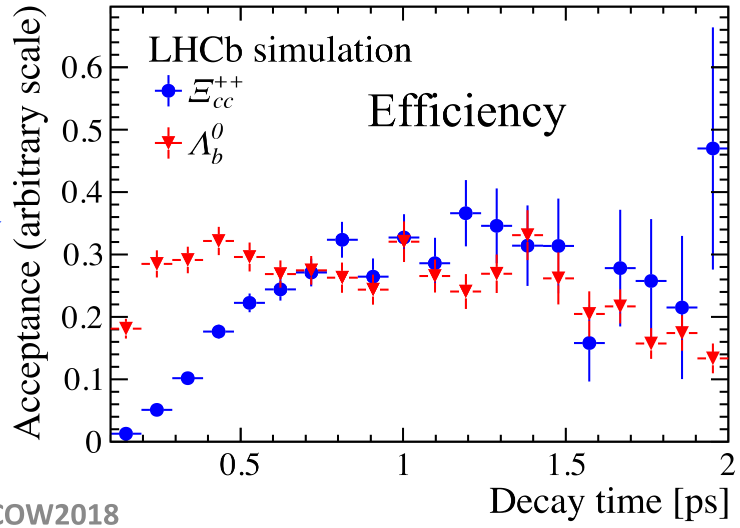
- Unbinned maximum likelihood fit to determine life time of Ξ_{cc}^{++}

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$

$\tau_{\Lambda_b^0} = 1.470 \pm 0.010$ ps (PDG)

Free parameter



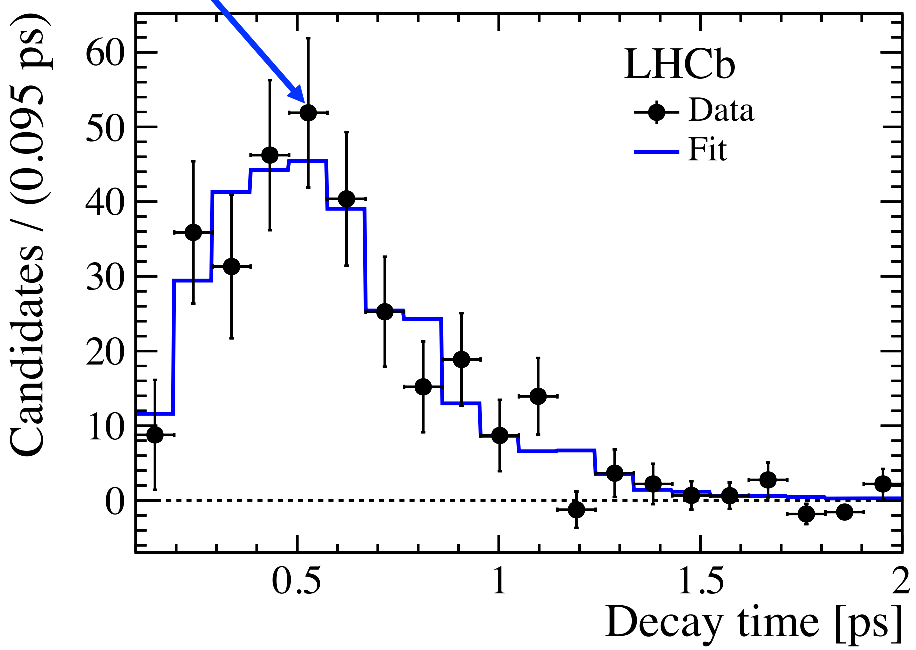


First measurement of Ξ_{cc}^{++} lifetime

arXiv:1806.02744, accepted by PRL

- Unbinned maximum likelihood fit to background-subtracted Ξ_{cc}^{++} decay time distribution

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



$$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14 \text{ fs}$$

- ✓ Fit procedure is verified by toys
- ✓ Robust result against many checks

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014

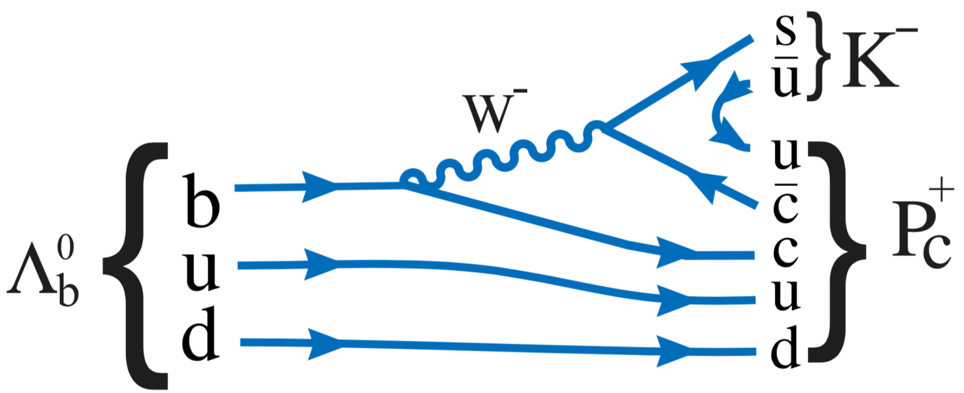
Outline

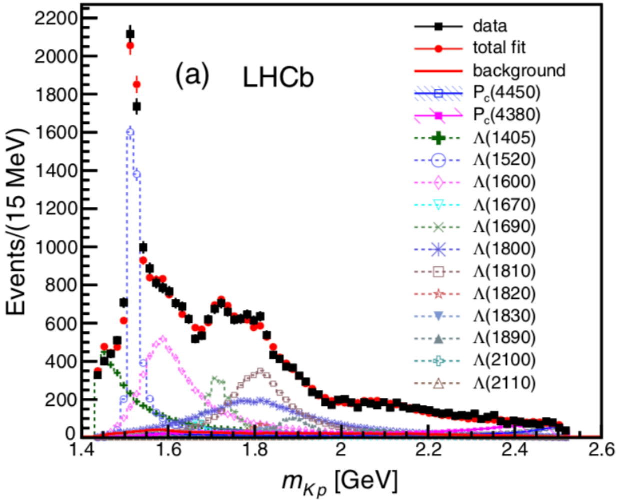
- Standard heavy flavor spectroscopy
  - Observation of a new Ξ_b^{**-} state
  - Lifetime measurement of Ω_c^0 baryon
  - Doubly charmed baryon Ξ_{cc}^{++}(new decay channel, life time)

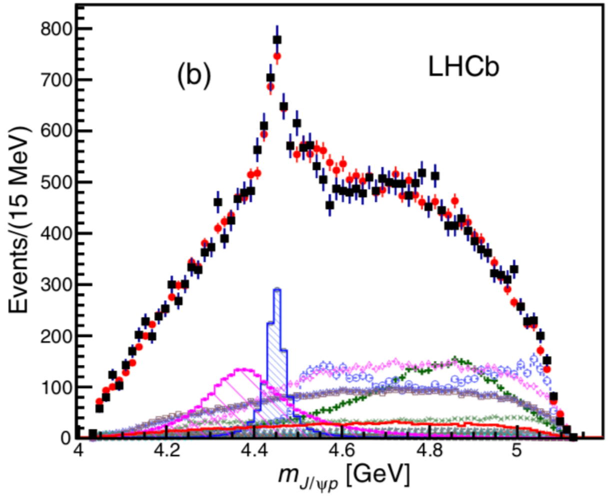
- Exotic hadrons
  - Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$
  - Weakly decaying *b*-flavored pentaquarks
  - Search for dibaryon states in $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ decays
  - Search for a beautiful otetraquark in the $\Upsilon(1S)\ \mu^+\mu^-$ invariant mass spectrum.

Observation of two pentaquark states

- LHCb has observed two resonances consistent with pentaquark states
- Amplitude analysis and model-independent confirmation
- This opened a new window of search for heavy flavor exotic states







- The nature of P_c are still unclear
- More study and search are needed

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

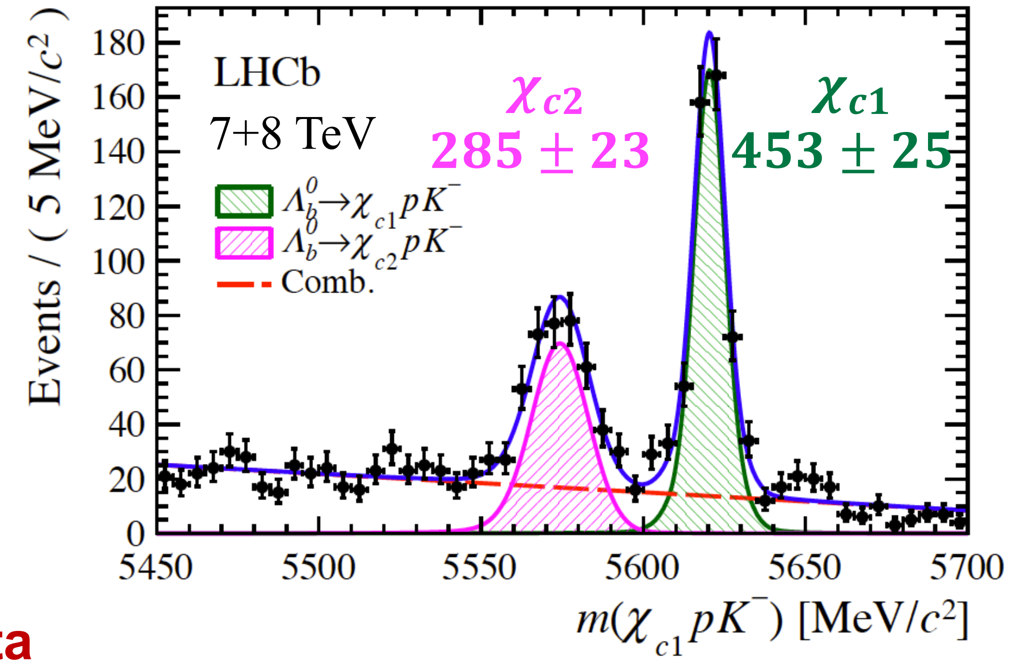
- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays
  $\Rightarrow$Test hypothesis of kinematic rescattering effect (If observed signal on $\chi_{c(1,2)} p$ channel => $P_c(4450)^+$ is not kinematical effect) **PRD 92 (2015) 071502**

- 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

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

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

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



Next step: full amplitude analysis with more data

PRL 119 (2017) 062001

Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

- Skyrme model: heavy quarks give tightly bound pentaquark [decay width of P_b(~6MeV)<< P_c(~40, 200MeV)]

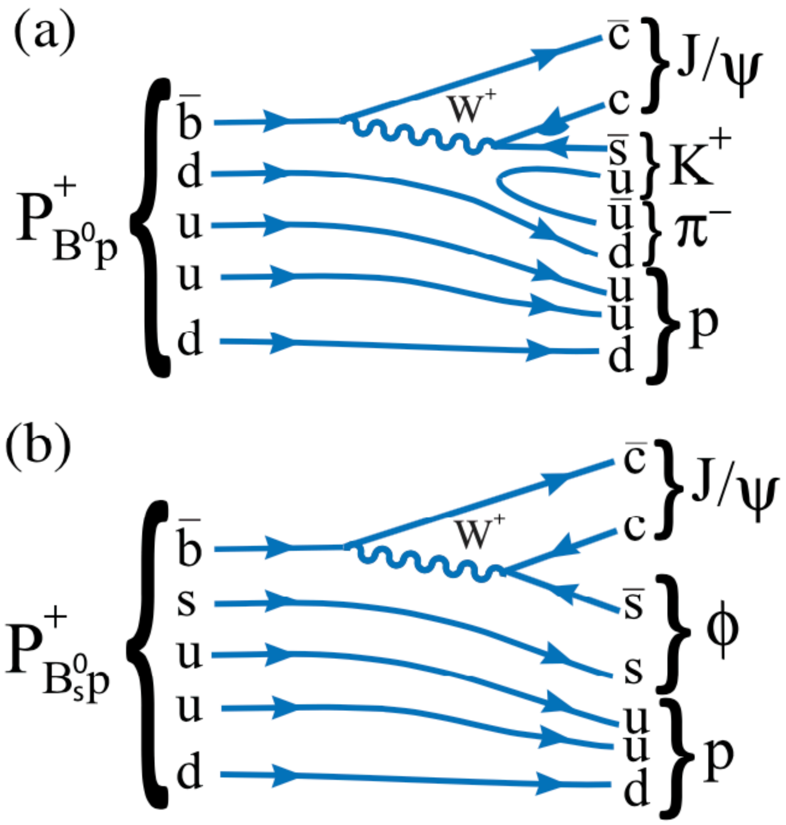
  PLB 590(2004) 185; PLB 586(2004)337; PLB 331(1994)362

- Search for mass peaks below strong decay threshold

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi K^+\pi^- p$	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

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

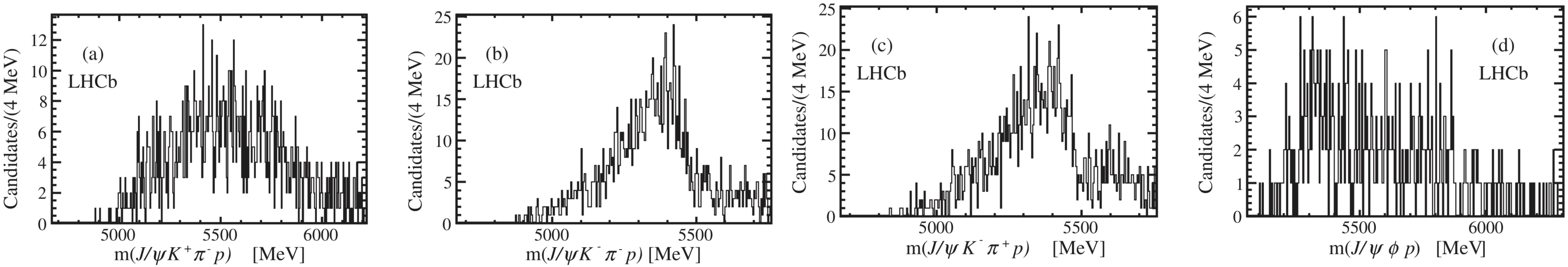
$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p)}$$



Weakly decaying *b*-flavored pentaquarks

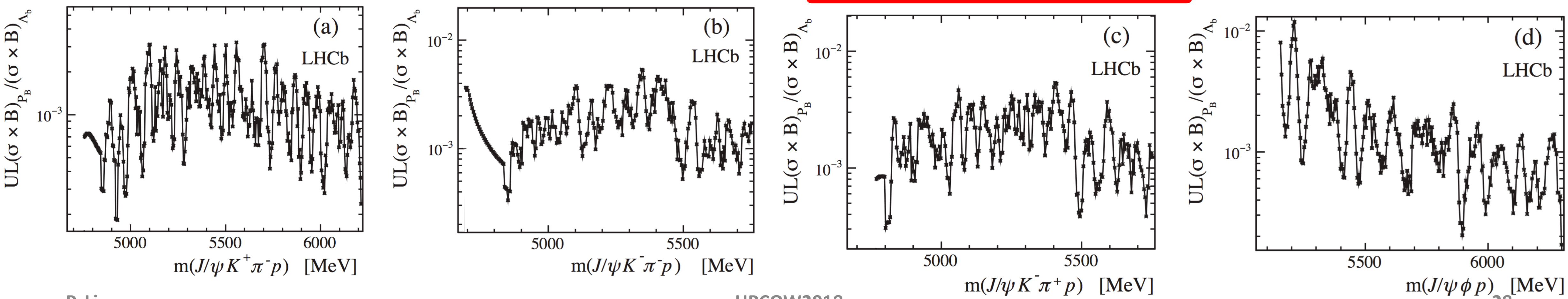
PRD 97 (2018) 032010

- **No significant excess** of signal over the expected background is observed



- UL of R with 90% confidence level $< 10^{-2} - 10^{-3}$

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

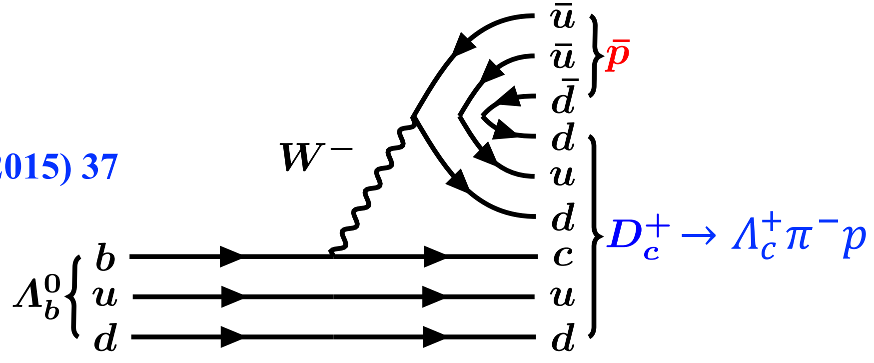


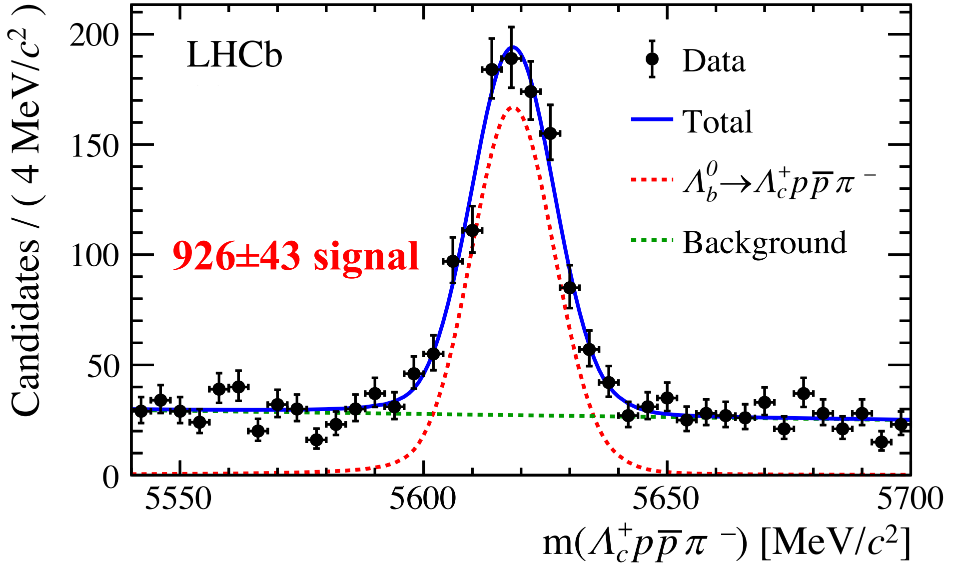
Search for dibaryon state in $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ decay

- A dibaryon state $\boldsymbol{D_c^+}$ $[cd][ud][ud]$ could be produced in Λ_b^0 decays to final state $\Lambda_b^0 \to \bar{p}D_c^+(\Lambda_c^+ p\pi^-)$
- $D_c^+ \to p\Sigma_c^0(\Lambda_c^+\pi^-)$ or $pP_c(\Lambda_c^+\pi^-)$
- LHCb has observed the decay $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ using Run I data

LHCb-PAPER-2018-005
arXiv:1804.09617 submitted to PLB

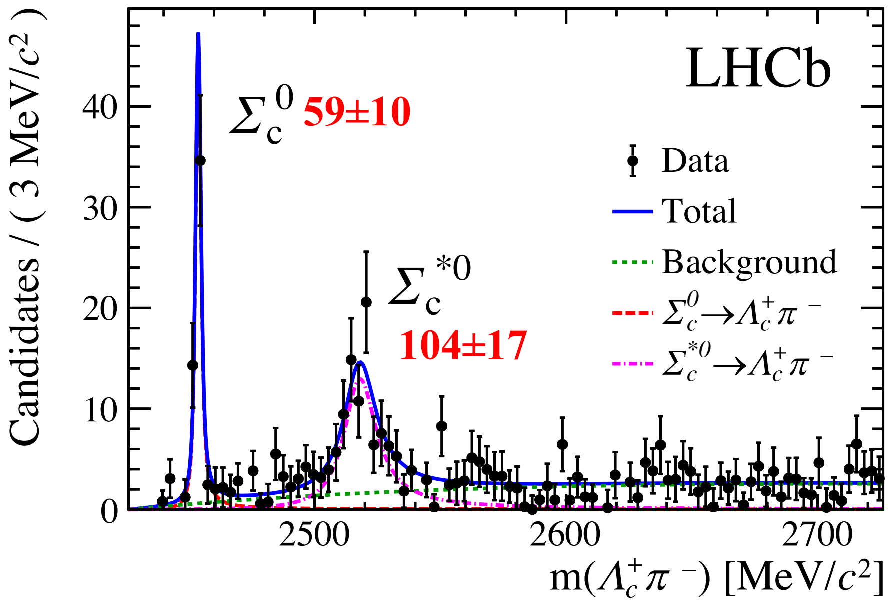
L. Maiani, et al. PLB 750 (2015) 37





7+8 TeV

Resonance contributions



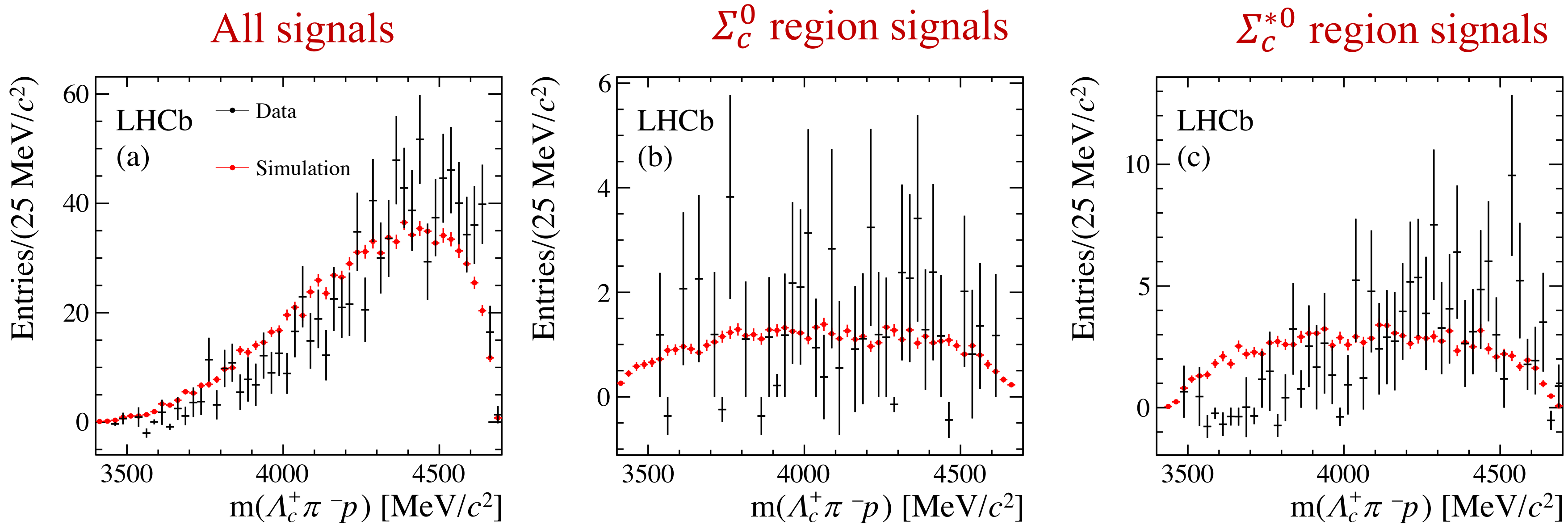
Search for dibaryon state in $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ decay

LHCb-PAPER-2018-005
arXiv:1804.09617 submitted to PLB

- Ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

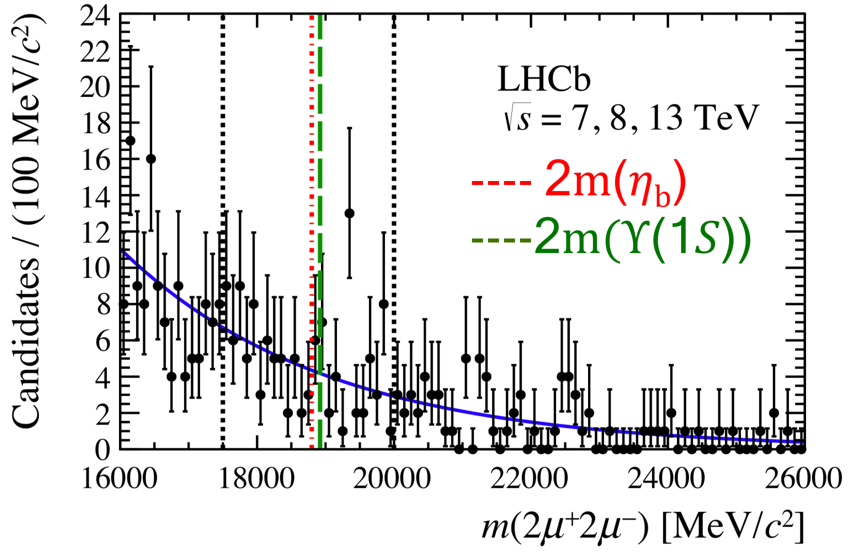
- No obvious dibaryon peak in $m(\Lambda_c^+ \pi^- p)$ spectra



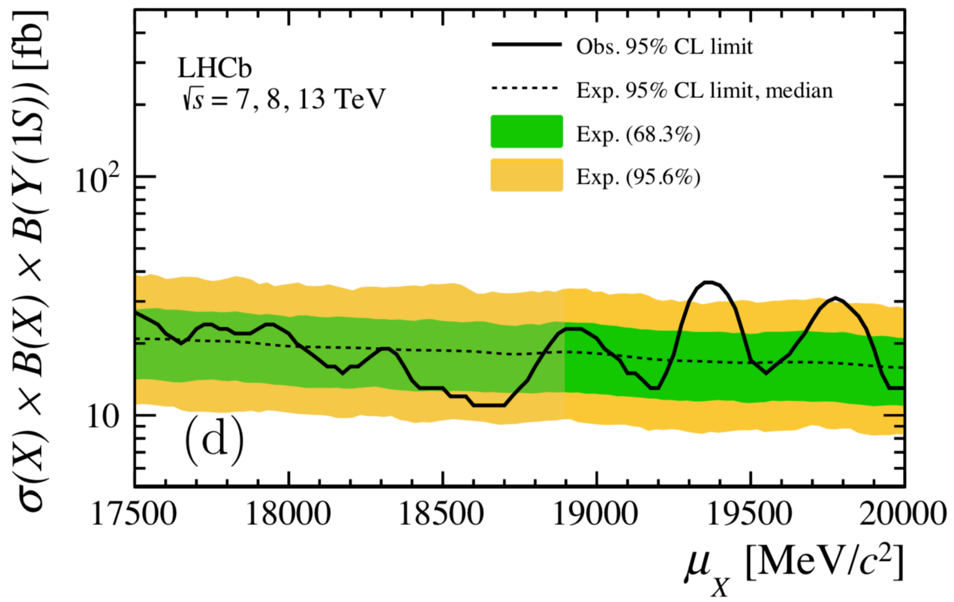
Search for beautiful tetraquarks

- Search for predicted tetraquark state $X_{b\bar{b}b\bar{b}}$ 【PRD86,034004, PLB773 247,PRD95 034011, EPJC77 432】
- It should have mass around 18.4-18.8GeV, below 2m(η_b) threshold, meaning that it can decay to $\Upsilon\mu^+\mu^-$
- Search with $X_{b\bar{b}b\bar{b}}$→(Υ(1S)→$\mu^+\mu^-$) $\mu^+\mu^-$
- Using Run I +RunII dataset, $\mathcal{L}\sim 6.3$ fb^{-1}
  - LHCb's first result using 2017 data!

LHCb-PAPER-2018-027
arXiv:1806.09707 submitted to JHEP

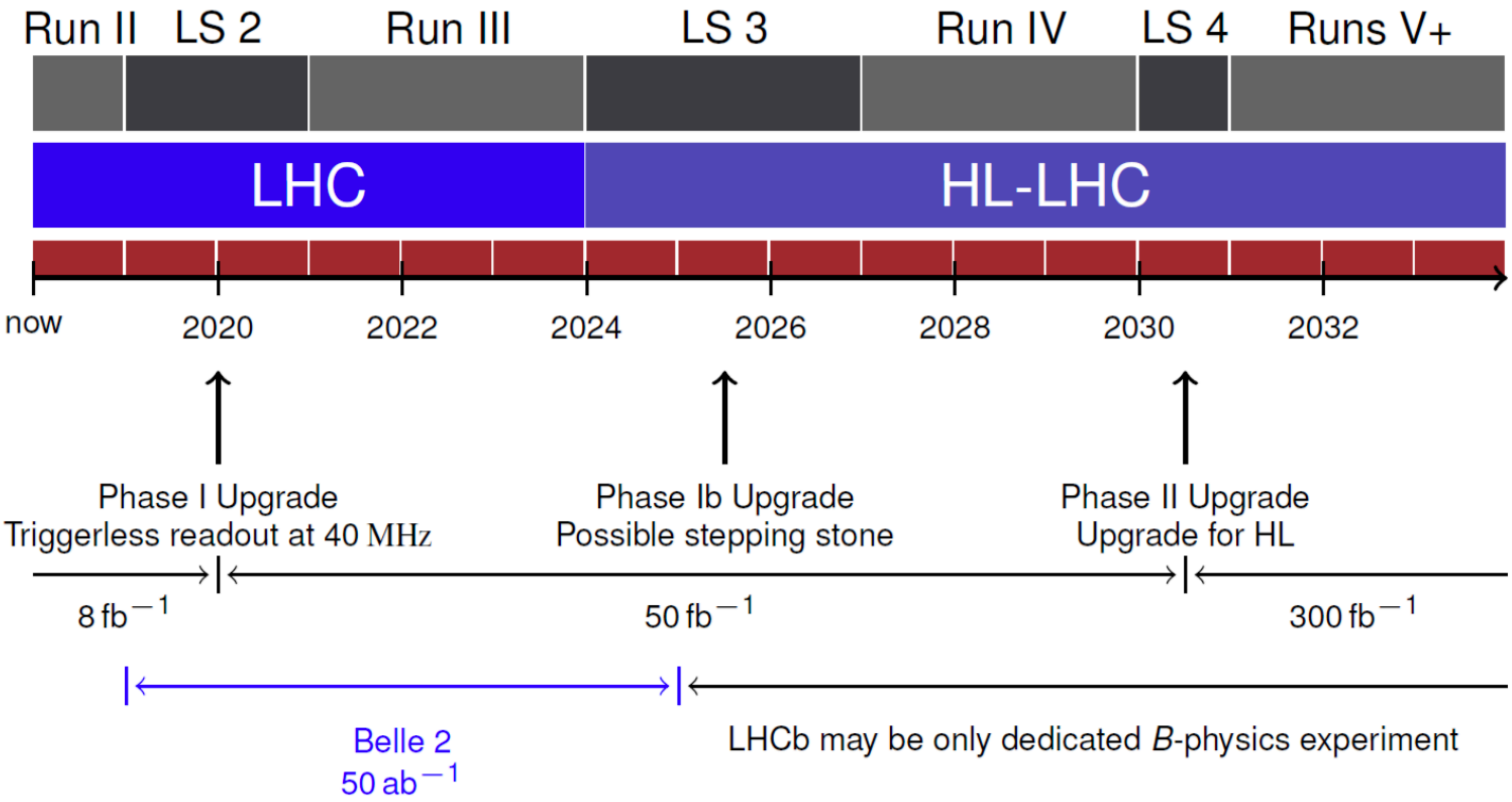


No significant peaking structure.



Upper limits of cross-section×branching fractions

LHCb upgrade(RUNIII)



Summary

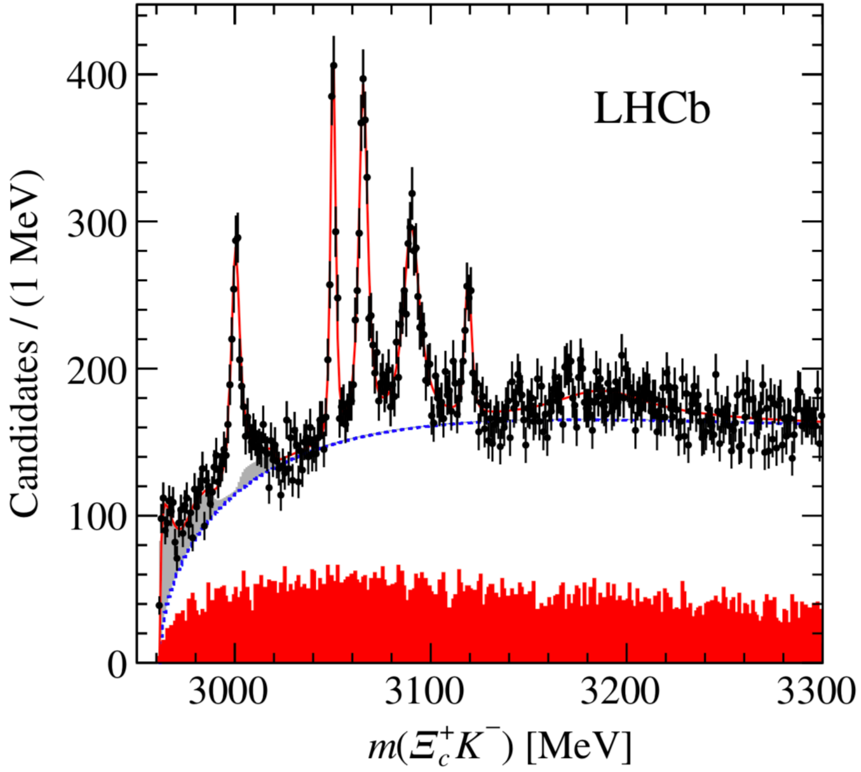
- LHCb has been making important contributions to the knowledge of hadron spectroscopy
- Exotic resonances have been observed but we still cannot describe univocally their nature
- Spectroscopy at the upgraded LHCb (RUNIII) is challenging and promising
- More new results from LHCb are stay tuning.

Backup

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: $\sin\theta_W$, W/Z, top quark
  - Spectroscopy, exotic hadrons
  - Soft QCD
  - Heavy ions
  - …

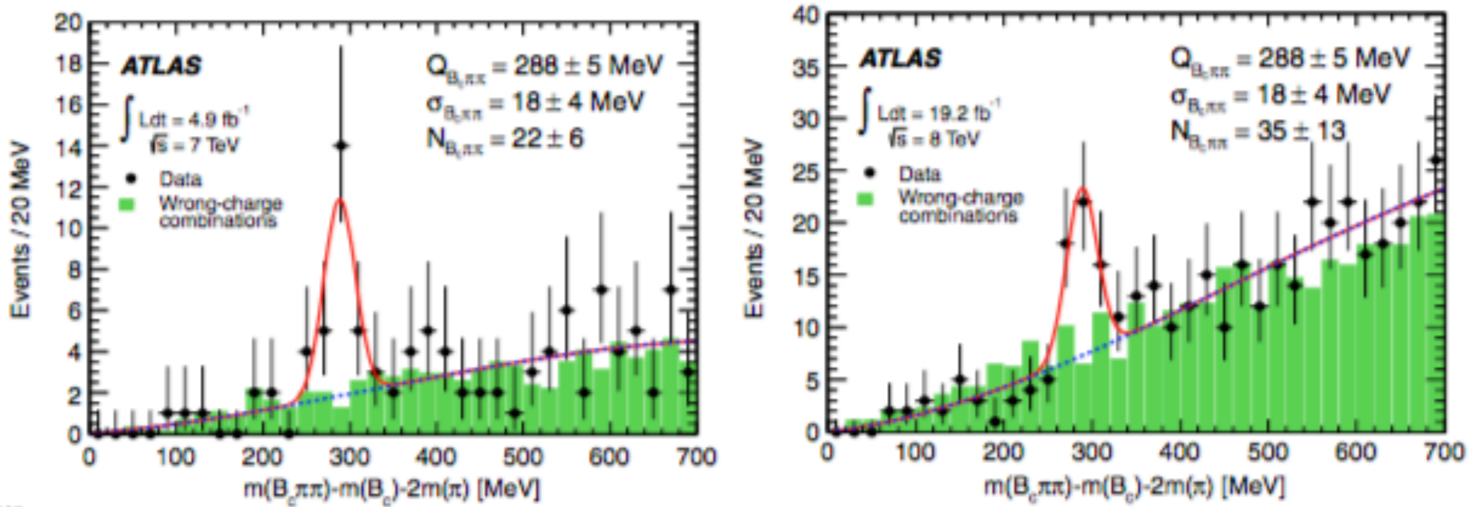
Five narrow Ω_c^0 states



Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	

Search for excited B_c^+ states

- Excited B_c^+ state observed by ATLAS, with mass $6842 \pm 4 \pm 5$ MeV$/c^2$
- Most probable interpretation:
  $B_c(2^3S_1)^+ \rightarrow (B_c(1^3S_1)^+ \rightarrow B_c(1^1S_0)^+\gamma)\pi^+\pi^-$
  $B_c^*(2S)^+ \rightarrow (B_c^{*+} \rightarrow B_c^+ \gamma)\pi^+\pi^-$
  Possibly, a non-resolved second peak:
  $B_c(2S)^+ \rightarrow B_c^+\pi^+\pi^-$

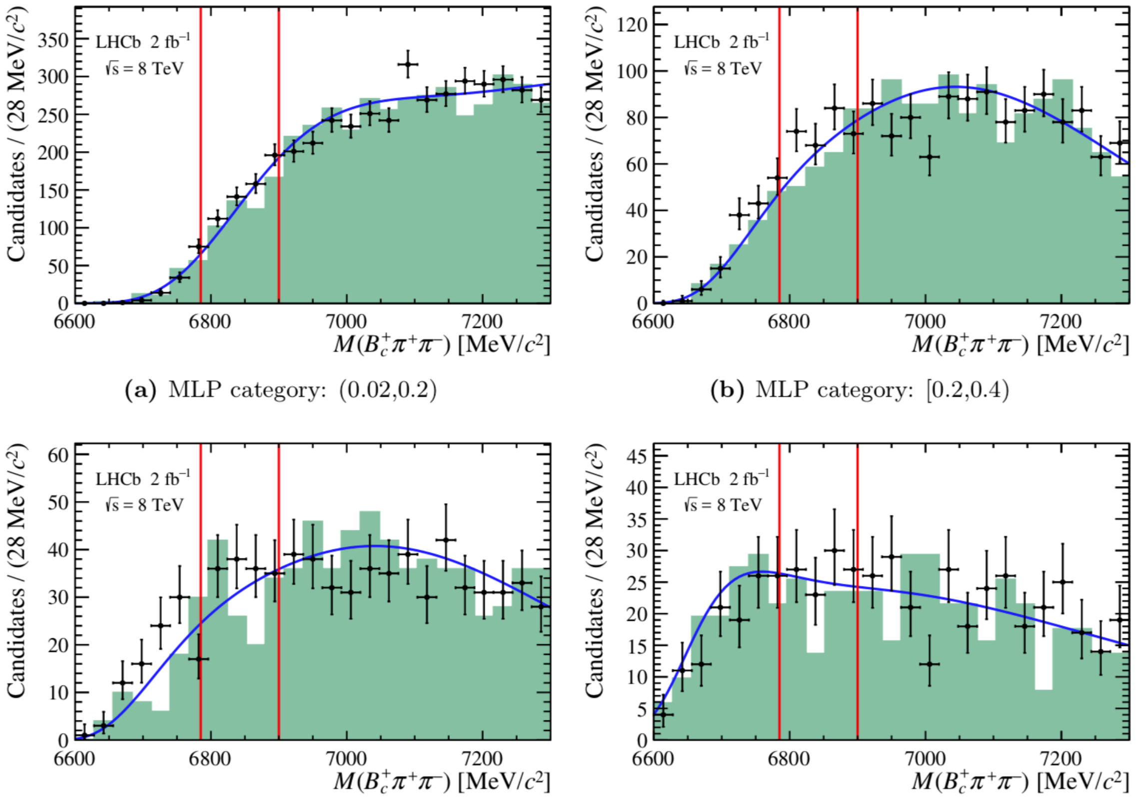


In LHCb:

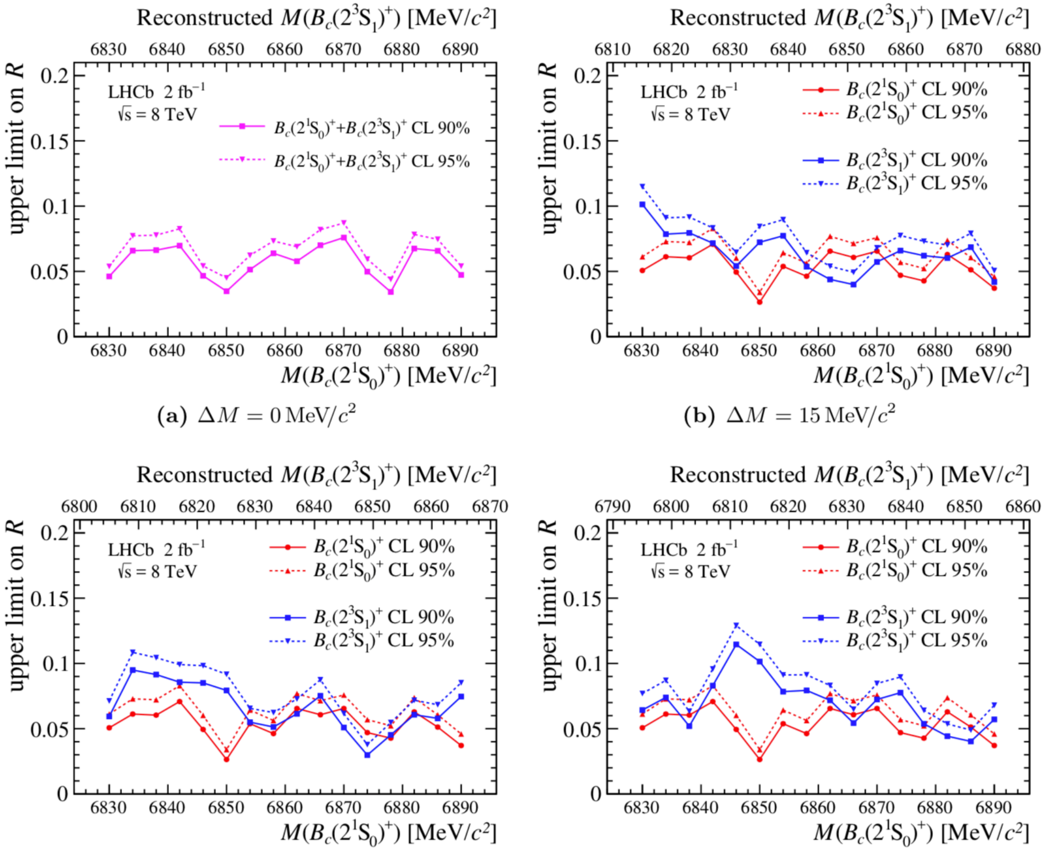
- Search for $B_c(2S)^+$ in the mass window [6830,6890] MeV$/c^2$
- Search for $B_c^*(2S)^+$ in the mass window [6795,6890] MeV$/c^2$

Search for excited B_c^+ states

No signal is observed for either state, and upper limits at 90% CL are set on the production cross sections times the BRs, normalised to the B_c^+ production cross section



(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]



(a) $\Delta M = 0\,\text{MeV}/c^2$
(b) $\Delta M = 15\,\text{MeV}/c^2$
(c) $\Delta M = 25\,\text{MeV}/c^2$
(d) $\Delta M = 35\,\text{MeV}/c^2$