Spectroscopy studies at LHCb

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for the LHCb collaboration

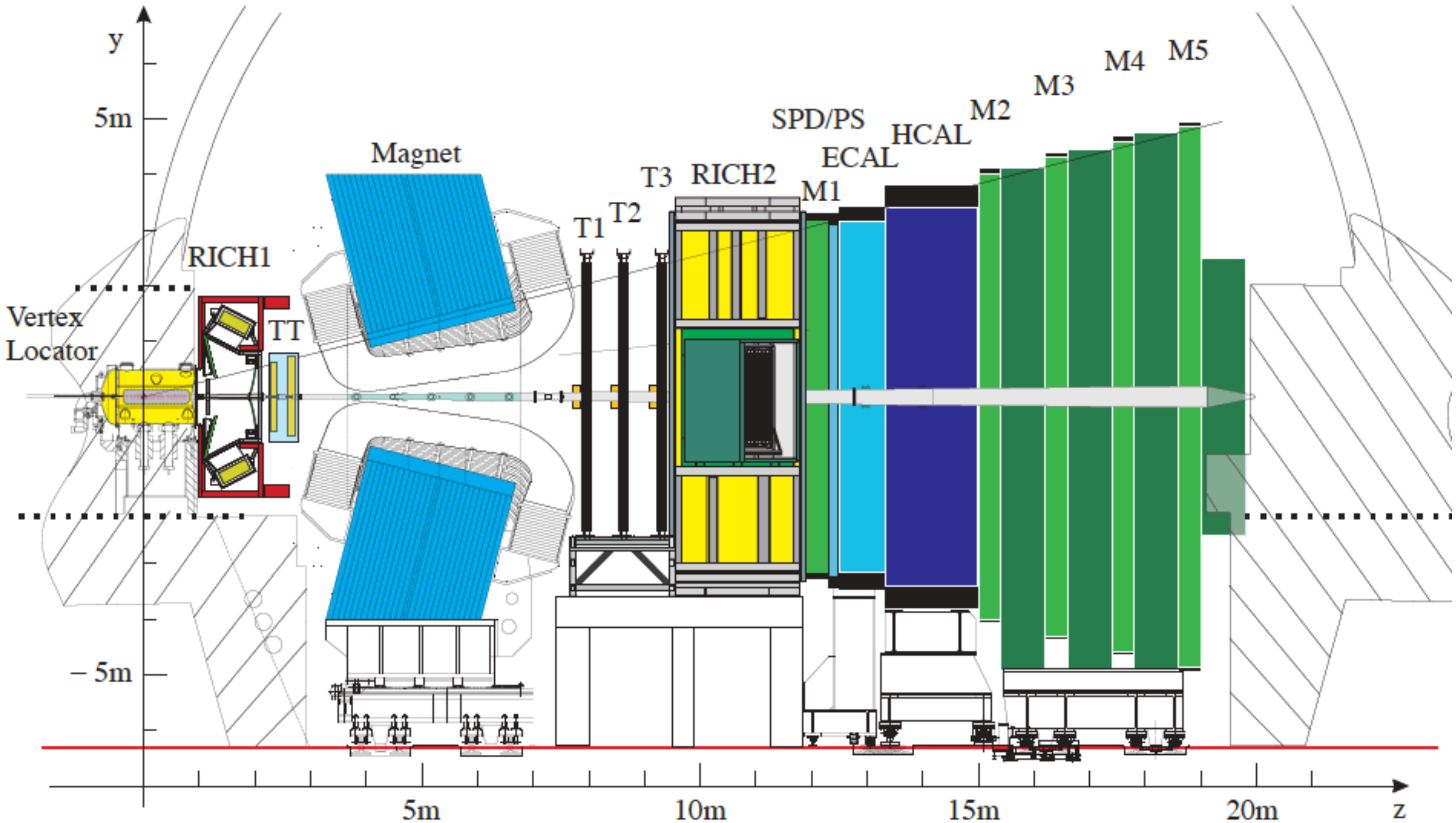
presented at HFCPV-2018 @Zhengzhou, 10/2018

The LHCb experiment

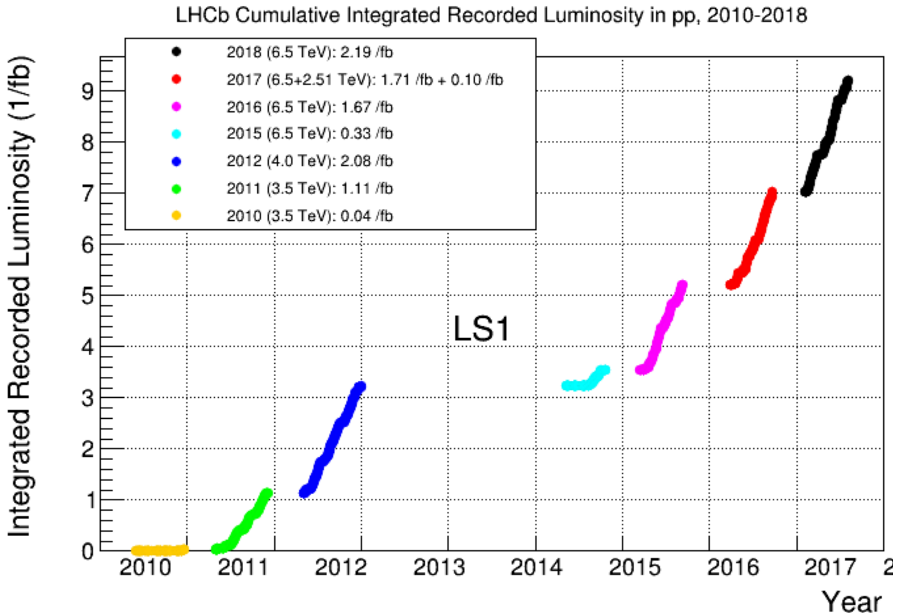
[JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022]

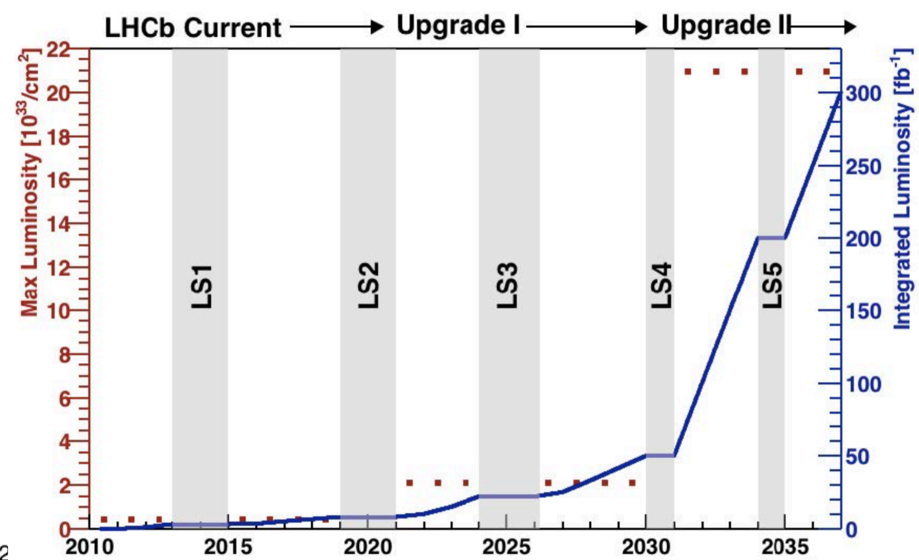
- Excellent vertexing, tracking & PID

⟹Ideal experiment to study spectroscopy



LHCb luminosity prospects





LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

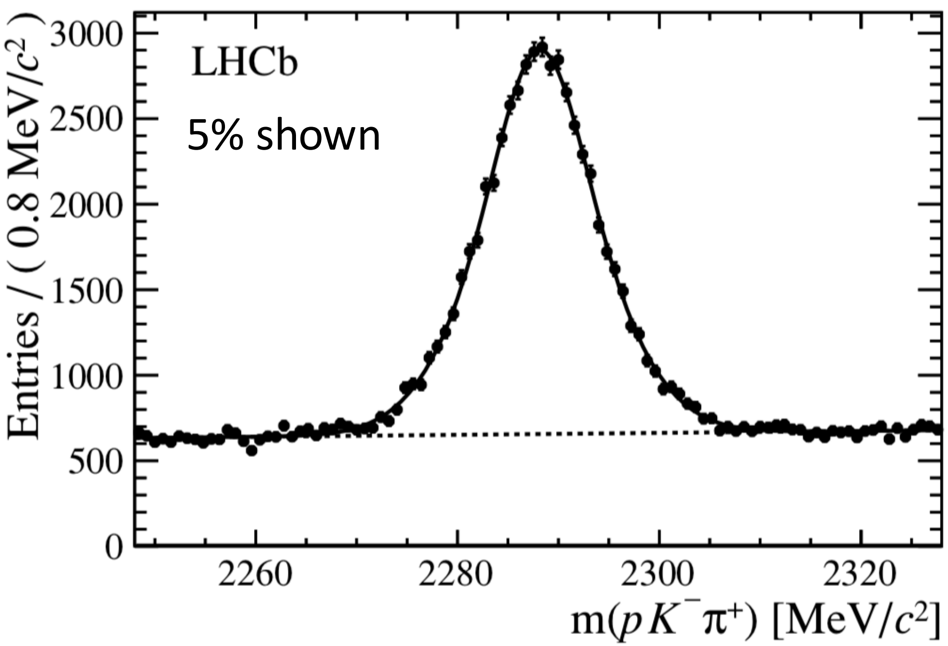
Phase-1 Upgrade!! **Phase-1b Upgrade!?** **Phase-2 Upgrade??**

See Z. Yang's talk

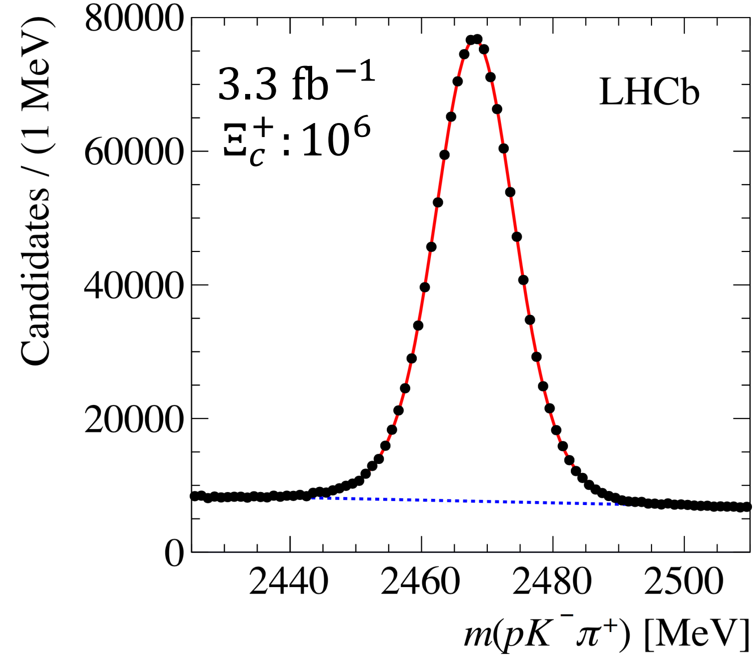
Lots of singly charmed baryons

- $\Lambda_c^+ \to pK^-\pi^+$: $\sim 1\times10^6$ per fb^{-1} @ 7 TeV
- $\Xi_c^+ \to pK^-\pi^+$: $\sim 3\times10^5$ per fb^{-1} @ 7 TeV

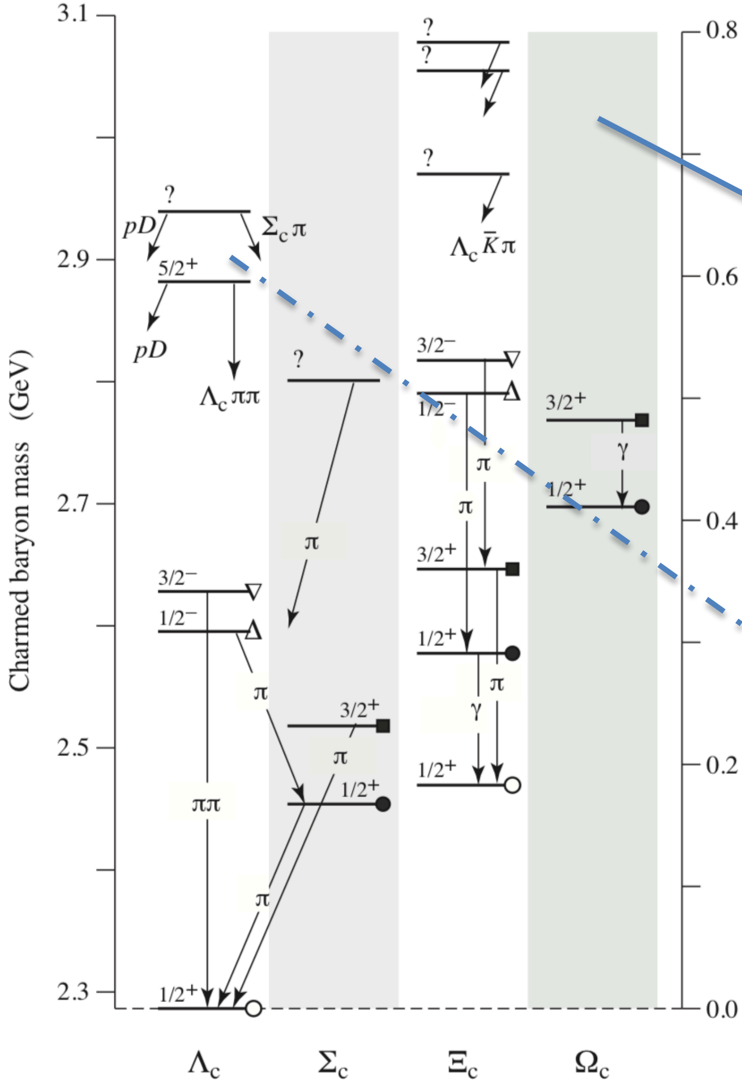
[JHEP 12 (2013) 090]

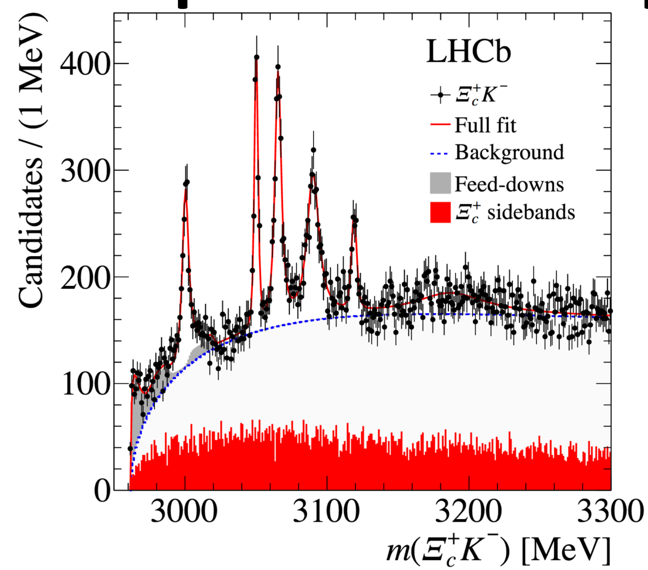


[PRL 118 (2017) 182001]

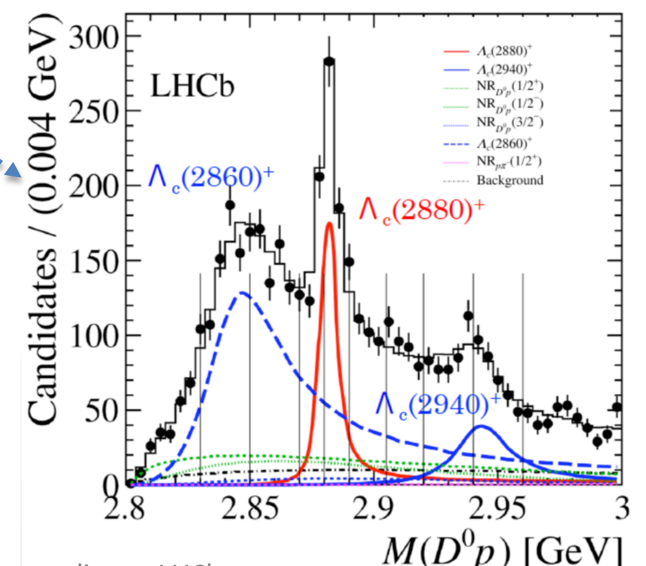


Charmed baryon spectroscopy





[PRL 118 (2017) 182001]



[JHEP 05 (2017) 030]

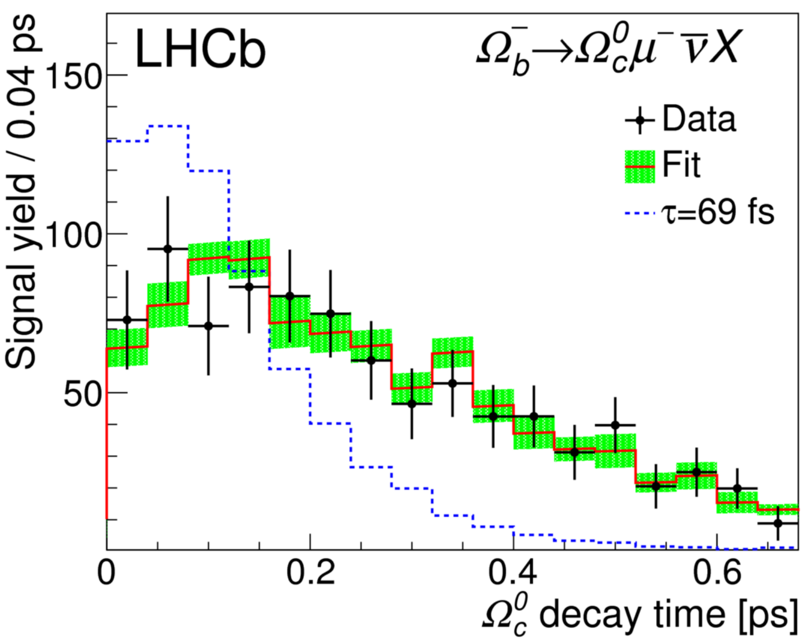
Measurement of Ω_c^0 lifetime

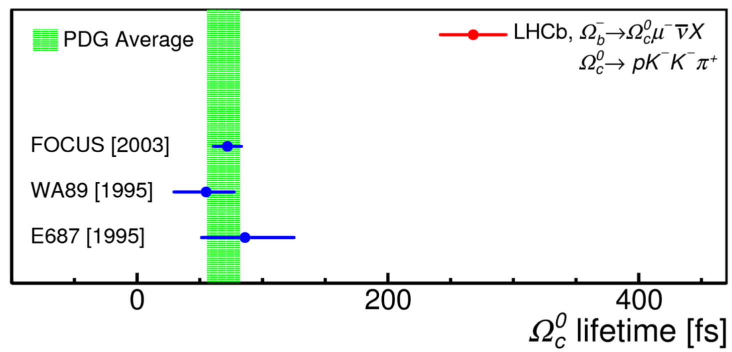
- With $\Omega_b^- \to {\color{red}\Omega_c^0}\mu^-\bar{\nu}_\mu X, \Omega_c^0 \to pK^-K^-\pi^+$, related to D^+

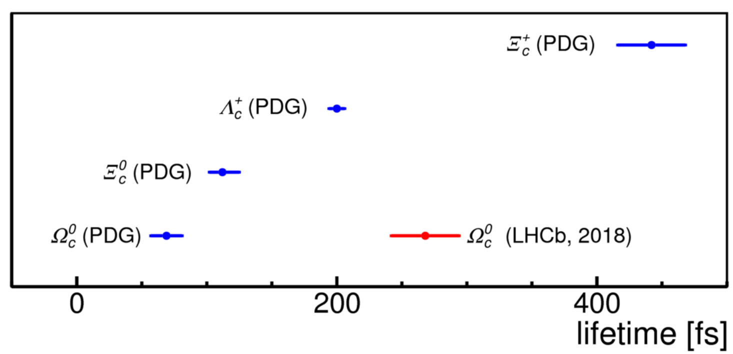
See H.-Y. Cheng's talk

- $\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2$ fs

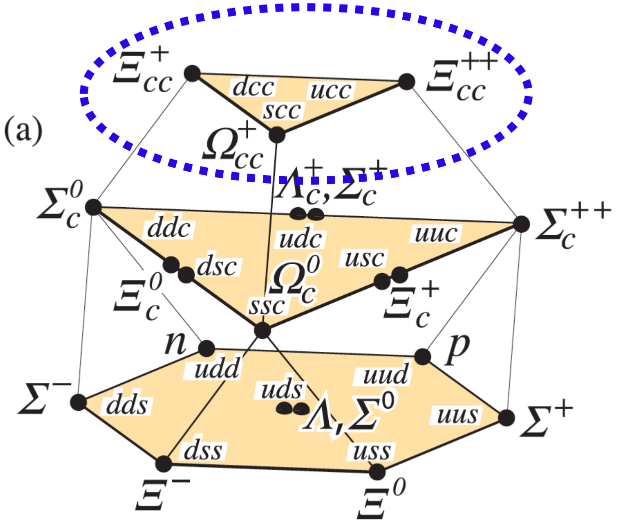
[PRL 121 (2018) 092003]



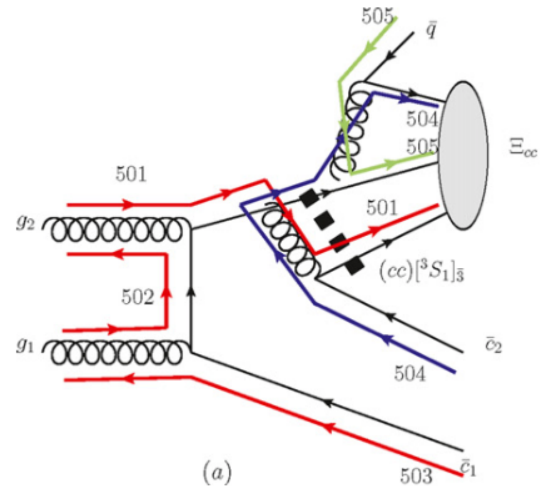




Doubly charmed baryon

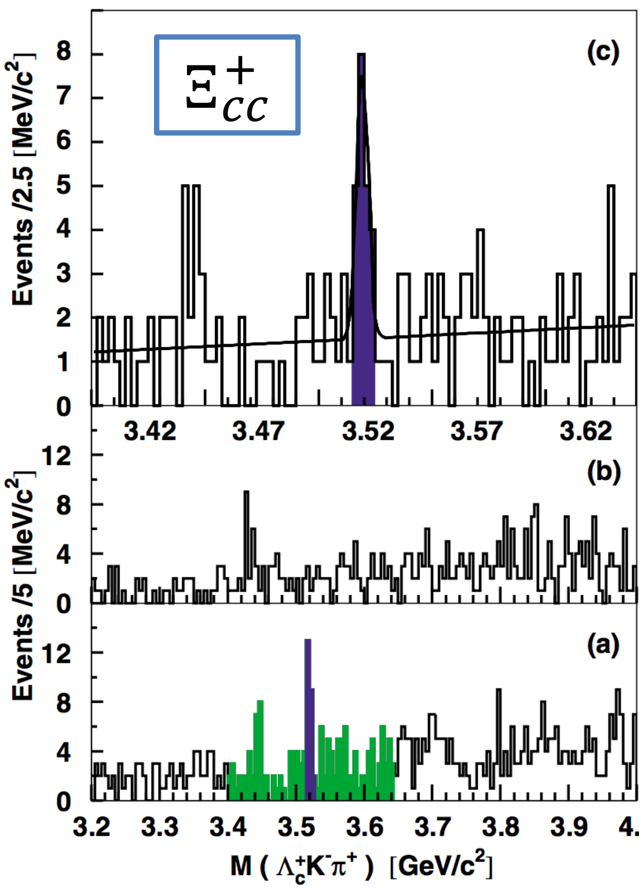


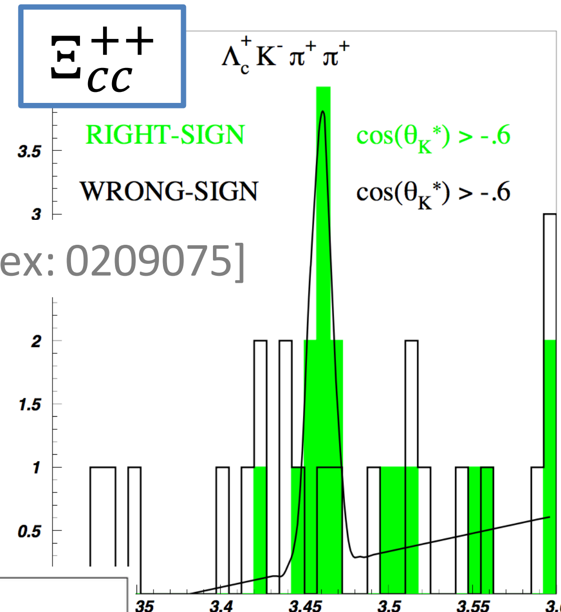
- Mass
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$
    $= 3621.24 \pm 0.72$ MeV
  - $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}^{++}) + 100$ MeV
- Lifetime
  - $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027$ ps
- Production [PRD 83 (2011) 034026]
  - $\sigma(cc) = 90$ nb @ 13 TeV in LHCb
  - $f_{\text{frag}}\ u{:}\,d{:}\,s \sim 1{:}\,1{:}\,0.3$
    $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40$ nb
    $\sigma(\Omega_{cc}^{+}) \sim 13$ nb



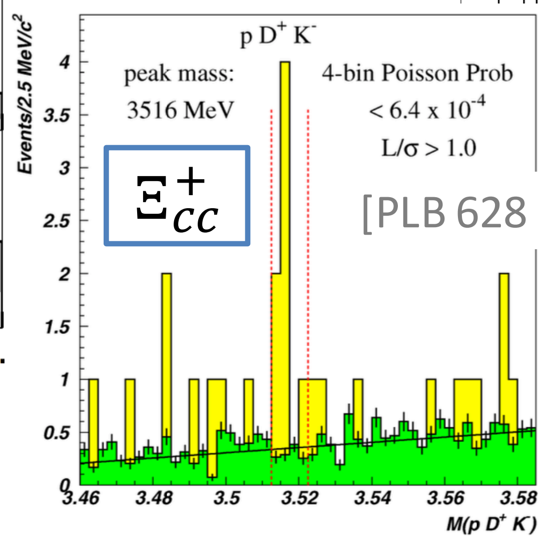
Ξ_{cc} @ SELEX

[PRL 89 (2002) 112001]





[hep-ex: 0209075]

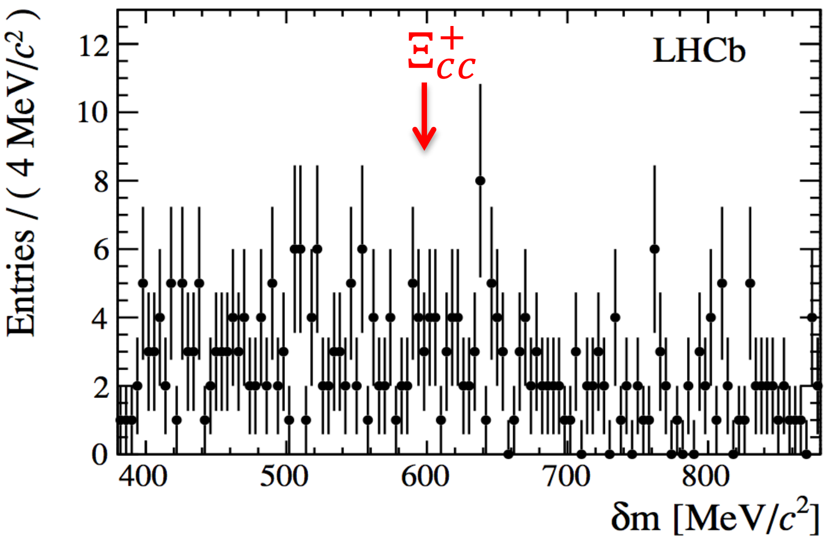


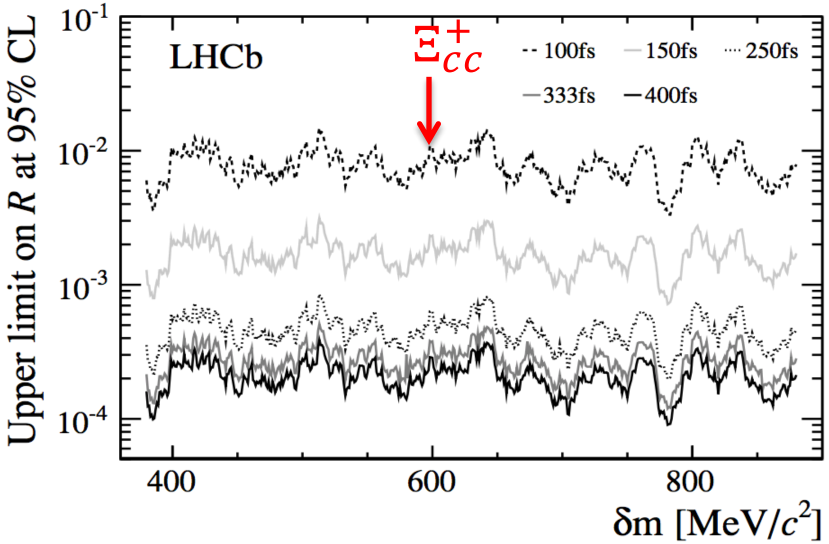
[PLB 628 (2005) 18]

Ξ_{cc} @ LHCb & others

- SELEX results not confirmed by FOCUS, Babar, Belle & LHCb
- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ searched by LHCb w/ 2011 data

[JHEP 12 (2013) 090]

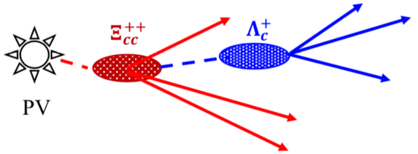


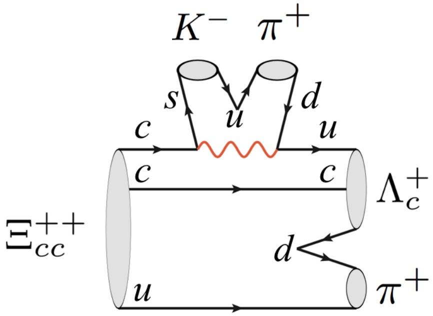


Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel

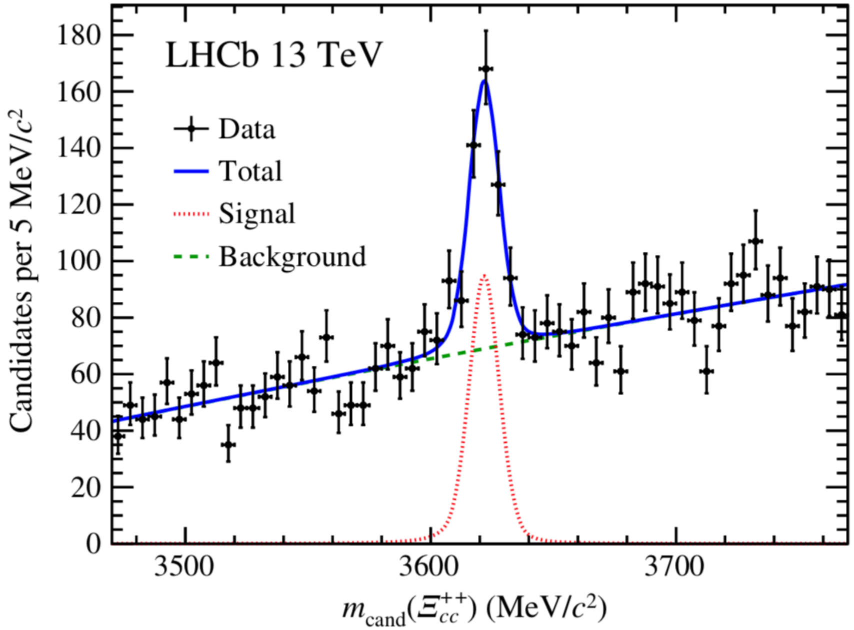
[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

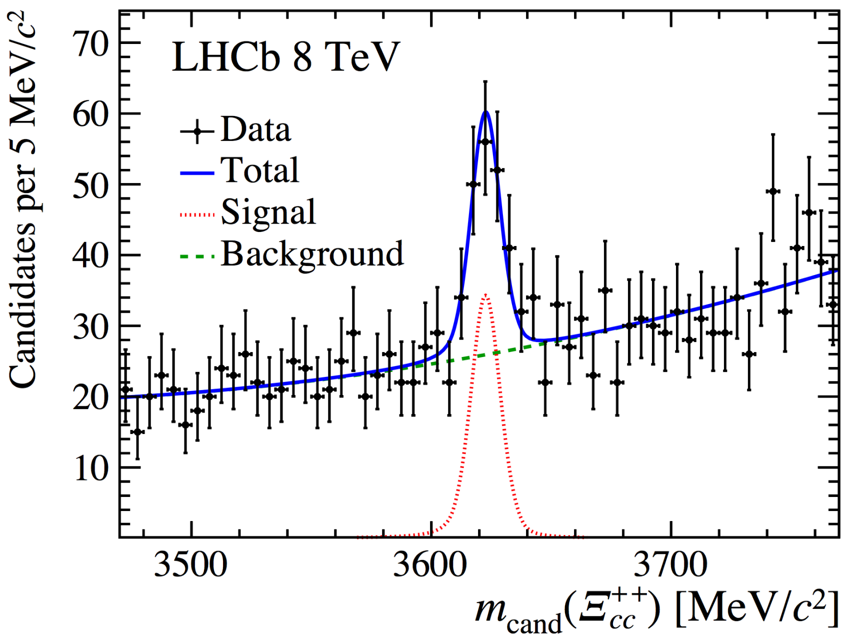




- First observation, in 2016 (>12σ) & Run-I (>7σ)

[PRL 119 (2017) 112001]





Ξ_{cc}^{++} properties

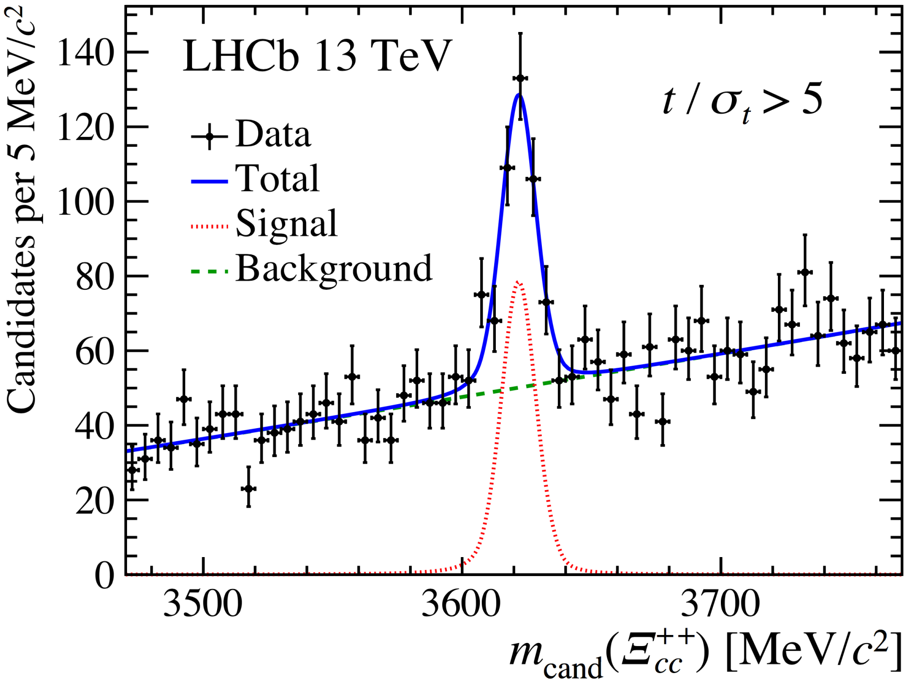
[PRL 119 (2017) 112001]

- Ξ_{cc}^{++} mass measured:
  $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$

  SELEX: m(Ξ_{cc}^{+})=3519±1 MeV

  Isospin partner?
- Decay weakly, mass peak remains after lifetime cut

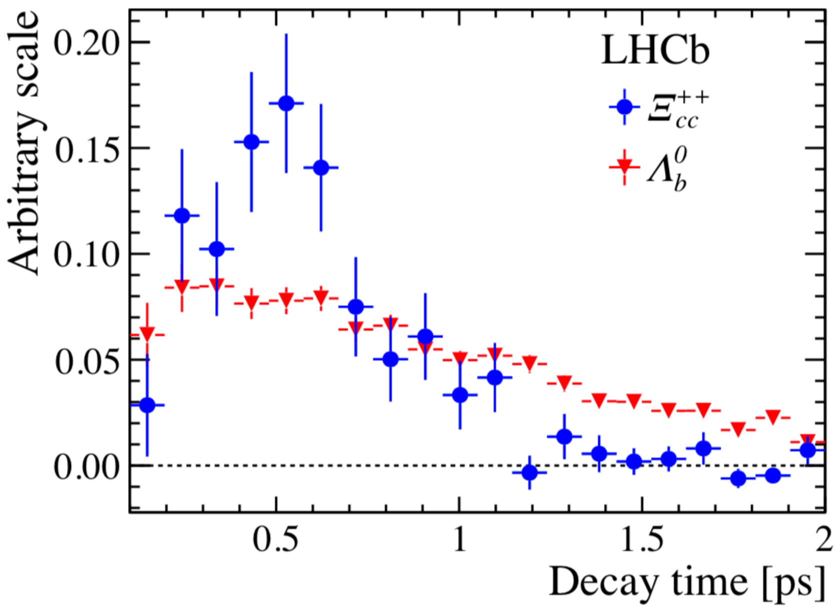
$\Longrightarrow$Measurement of $\tau(\Xi_{cc}^{++})$ needed

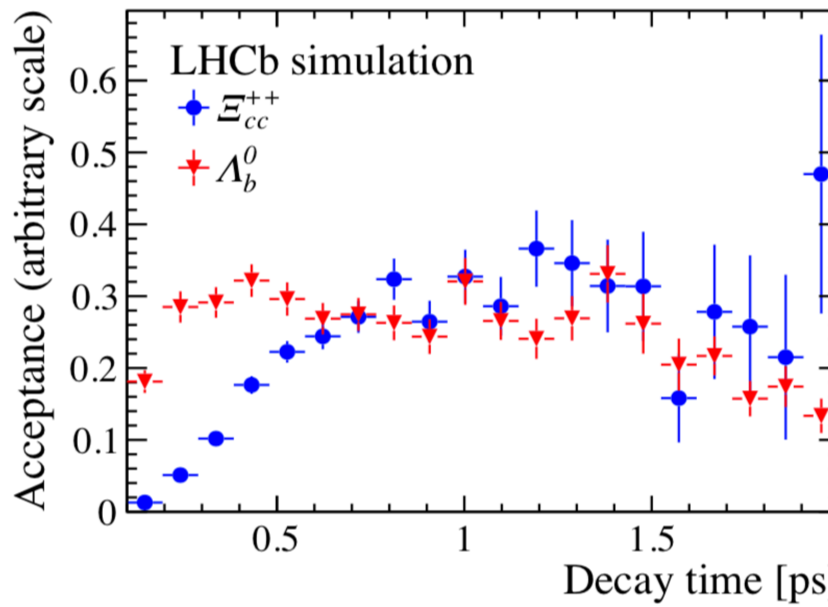


Measurement of Ξ_{cc}^{++} lifetime

[PRL 121 (2018) 052002]

- Take decay time ratio relative to $\Lambda_b^0 \to \Lambda_c^+ 3\pi$, w/ well known $\tau(\Lambda_b^0) = 1.470 \pm 0.010$ ps
- Decay time acceptance from simulation





Ξ_{cc}^{++} lifetime

[PRL 121 (2018) 052002]

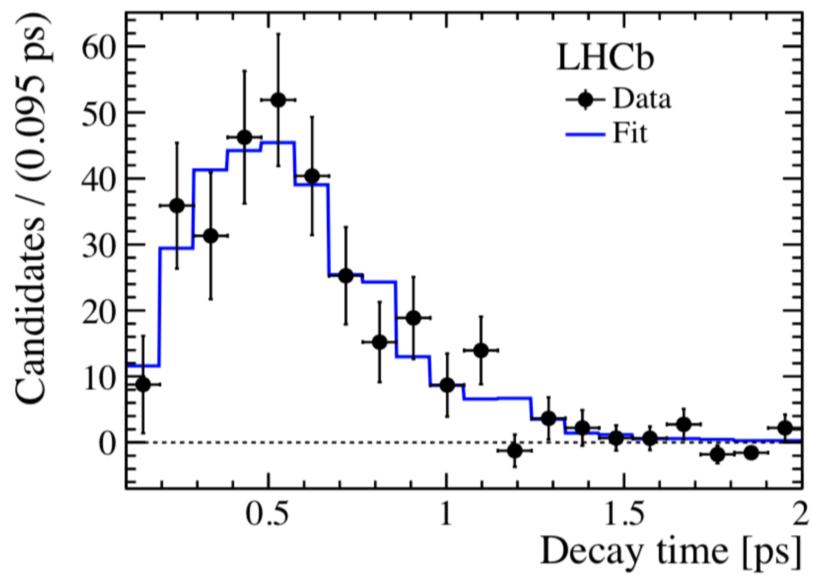
- Fitted Λ_b^0 lifetime 1.474 ± 0.077 ps, validating that simulation well-describes t acceptance
- Unbinned $t(\Xi_{cc}^{++})$ described by

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

- $\tau(\Xi_{cc}^{++})$

$= 0.256^{+0.024}_{-0.022} \pm 0.014$ ps

Weakly decay nature established!

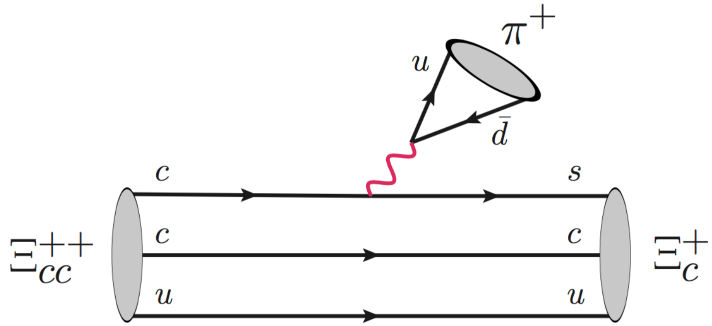


Re-discovery of Ξ_{cc}^{++}

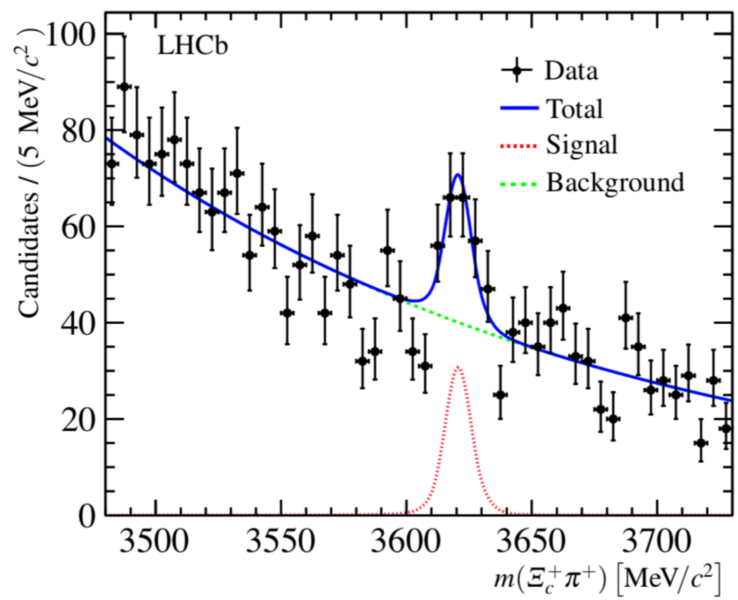
[PRL 121 (2018) 162002]

- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ expected to have large BR

  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]



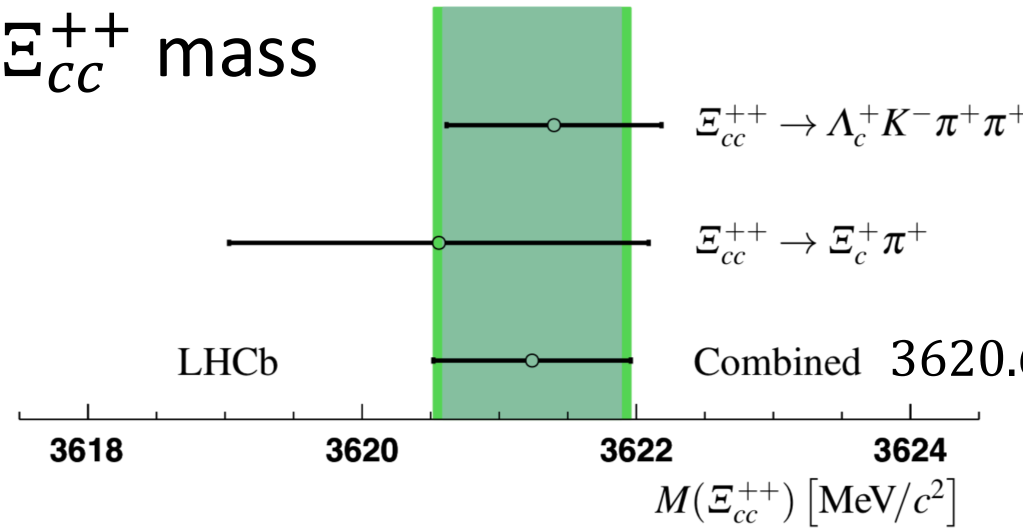
- Searched with 2016 data, following similar selection strategy to $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- 91 ± 20 signals seen, 5.9σ, re-discovery!



Ξ_{cc}^{++} mass and $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)$

[PRL 121 (2018) 162002]

- Ξ_{cc}^{++} mass



$3620.6 \pm 0.65 \pm 0.31\ \mathrm{MeV}/c^2$

consistent with predictions, e.g., by lattice QCD

$3610 \pm 23 \pm 22\ \mathrm{MeV}/c^2$ [Z. S. Brown *et al.*, PRD 90 (2014) 094507]

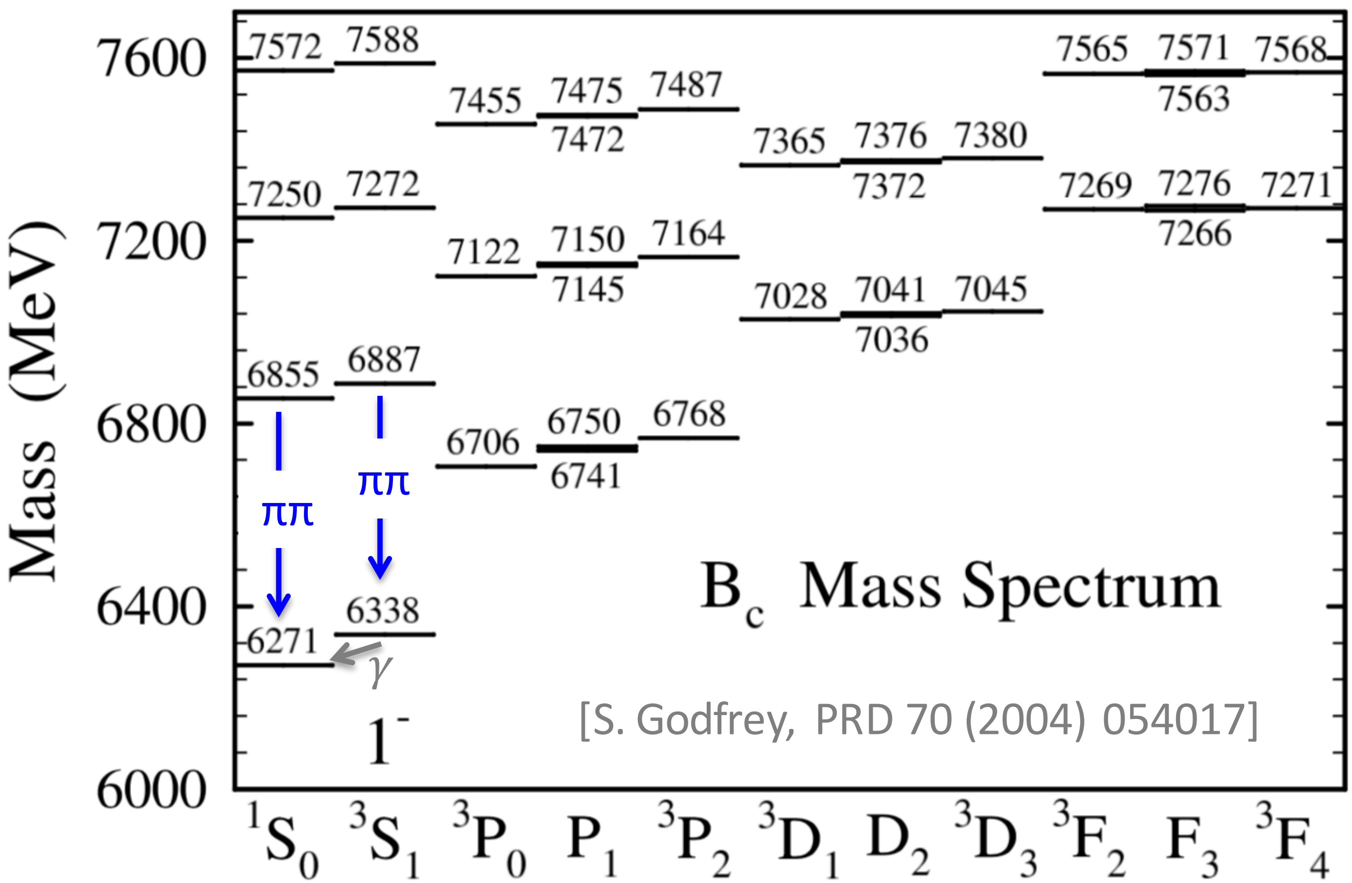
- Ratio of total branching fractions

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)} = 0.035 \pm 0.009\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst})$$

at the lower end of prediction [F.-S. Yu *et al.*, CPC 42 (2018) 051001]

B_c spectrum

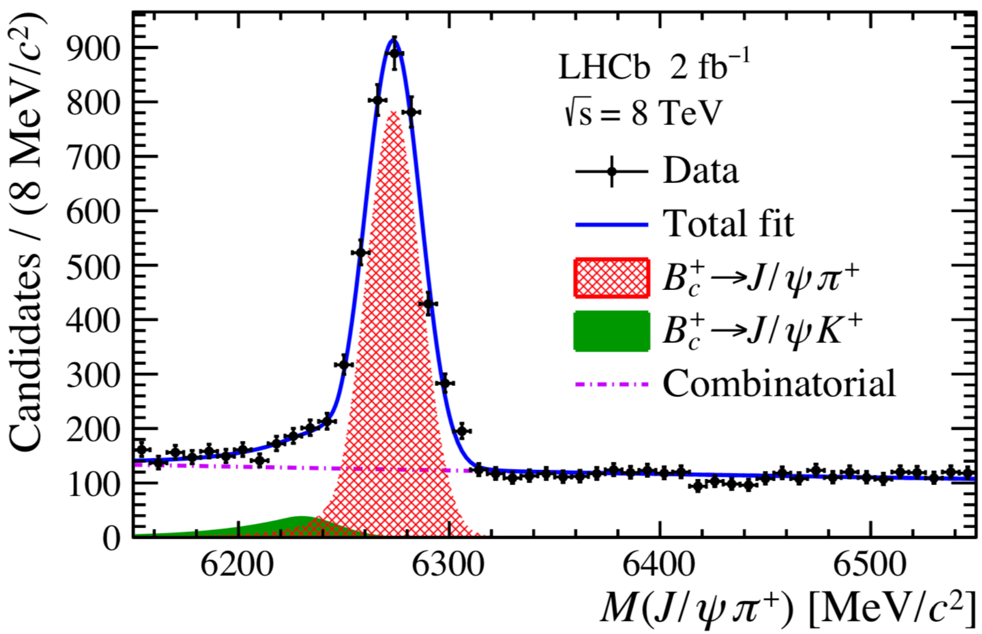
- B_c, doubly heavy meson, rich spectrum

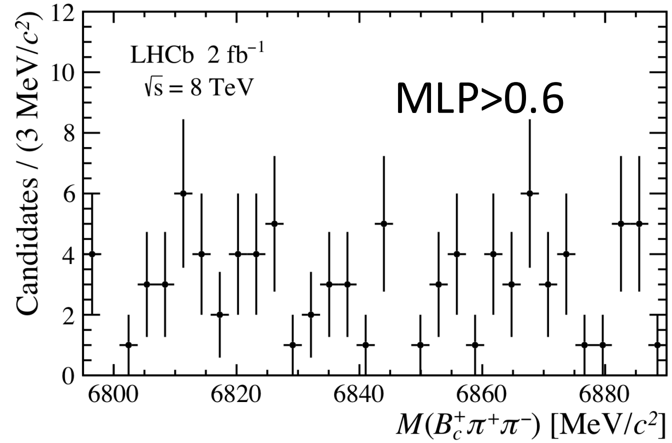


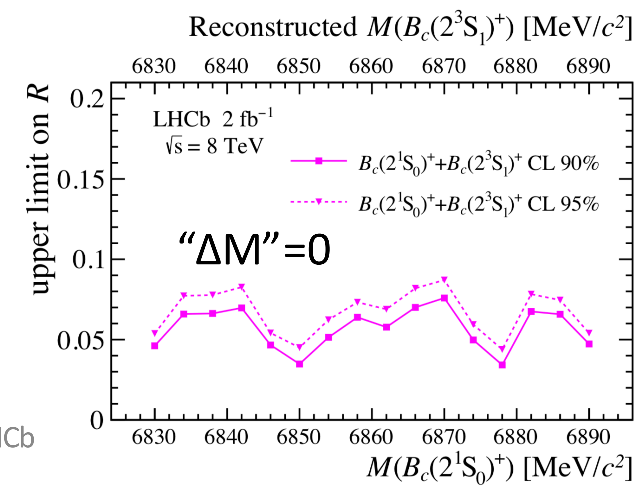
Search for $B_c(2S)$ by LHCb

- LHCb has the largest (low p_T) B_c^+ sample, not-yet confirming ATLAS observation
- Setting upper limits

[JHEP 01 (2018) 138]

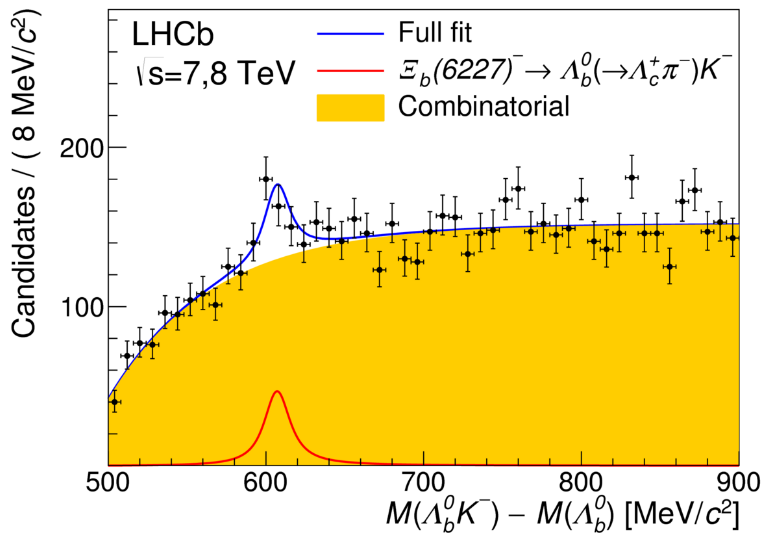


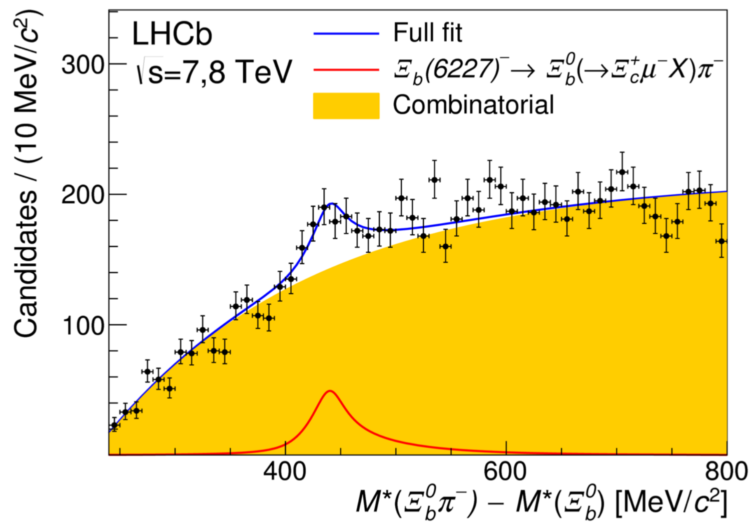


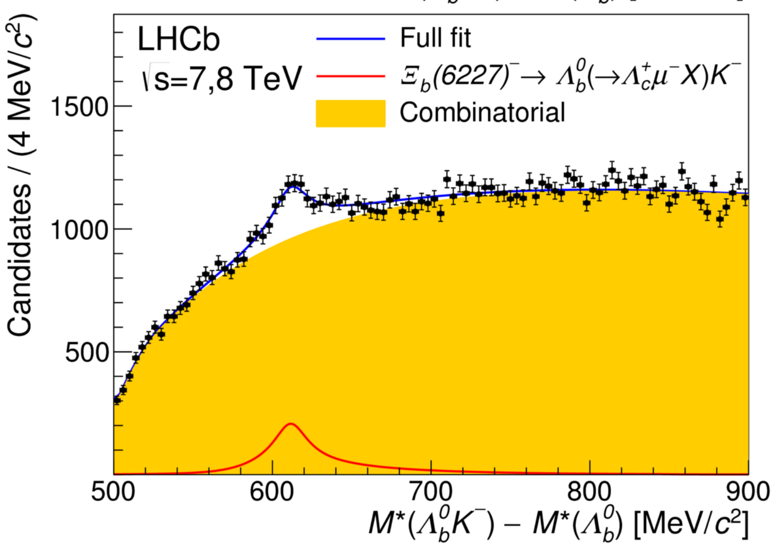


Observation of $\Xi_b(6227)^- \to \Lambda_b^0 K^-, \Xi_b^0 \pi^+$

[PRL 121 (2018) 072002]







Mass/width measured w/ hadronic channel:

$m = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2(\Lambda_b^0)$ MeV

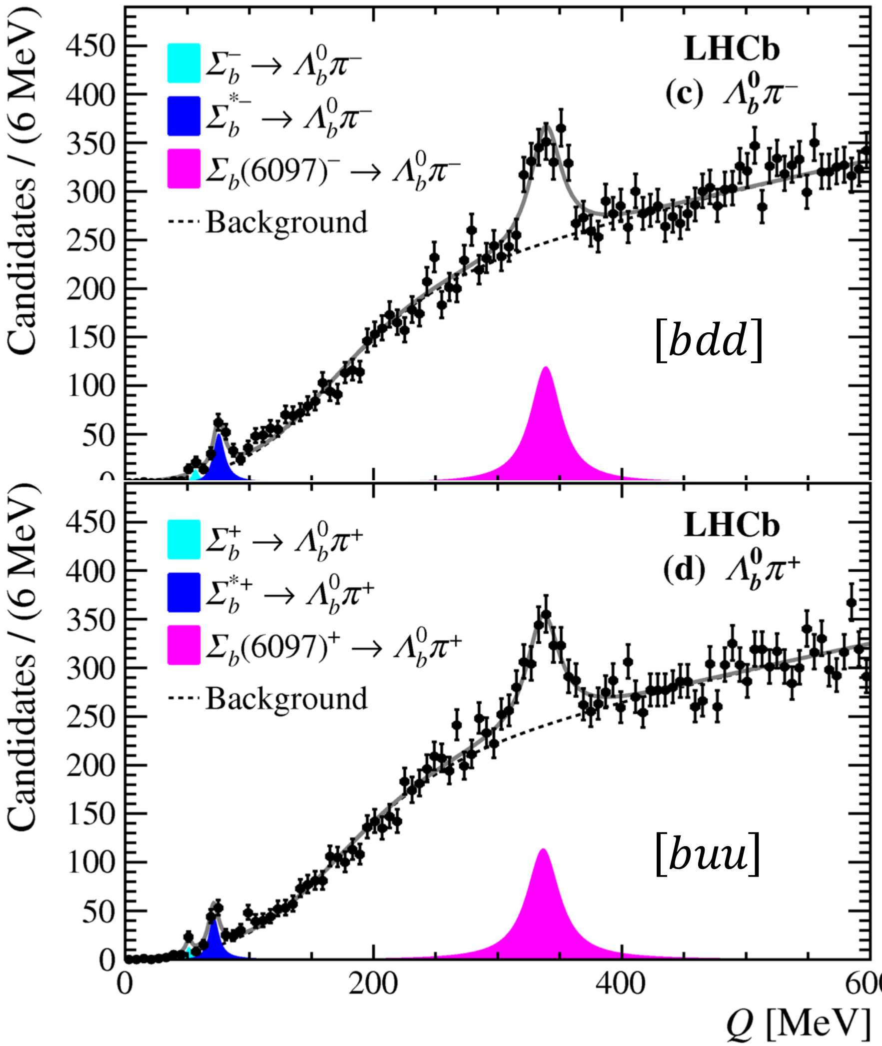
$\Gamma = 18.1 \pm 5.4 \pm 1.8$ MeV

Relative production wrt $\Lambda_b^0(\Xi_b^0)$

Quantity $[10^{-3}]$	$7,8$ TeV	13 TeV
$R(\Lambda_b^0 K^-)$	$3.0 \pm 0.3 \pm 0.4$	$3.4 \pm 0.3 \pm 0.4$
$R(\Xi_b \pi^-)$	$47 \pm 10 \pm 7$	$22 \pm 6 \pm 3$

Observation of $\Sigma_b(6097)^{\pm} \to \Lambda_b^0 \pi^{\pm}$

[arXiv:1809.07752]

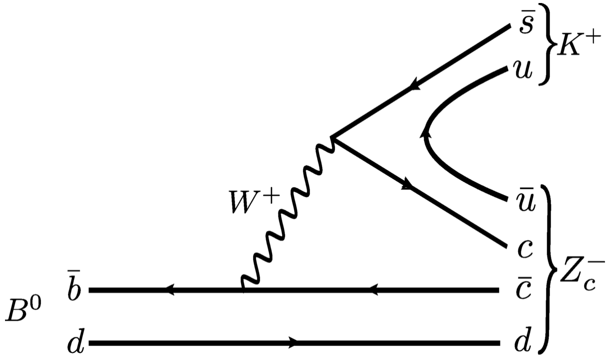


Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$
$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$
$m(\Sigma_b^{*-}) - m(\Sigma_b^-)$	$19.09 \pm 0.22 \pm 0.02$
$m(\Sigma_b^{*+}) - m(\Sigma_b^+)$	$19.73 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b(6097)^{\pm})$	$-2.2 \pm 2.4 \pm 0.3$
$\Delta(\Sigma_b^{\pm})$	$-5.09 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b^{*\pm})$	$-4.45 \pm 0.22 \pm 0.01$

$1P$ excitation or molecular states?

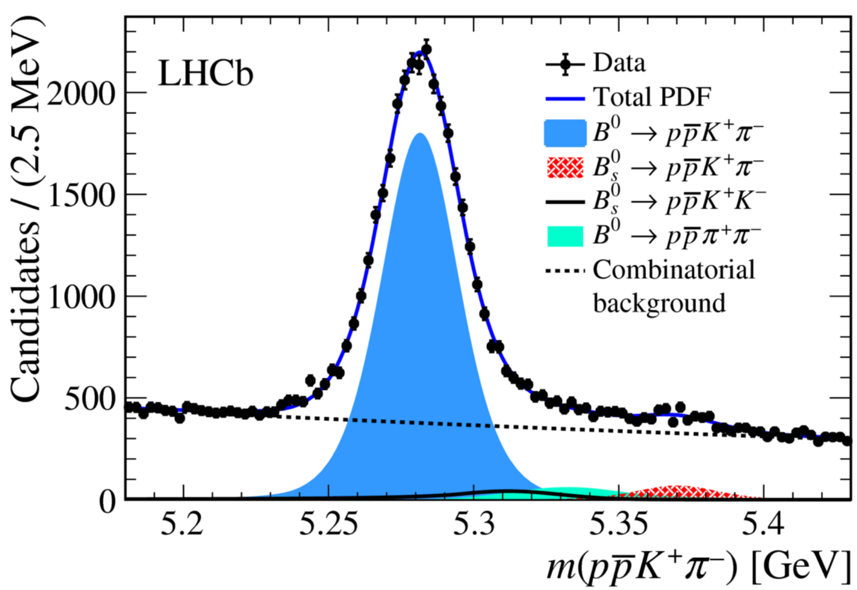
Evidence of $\eta_c\pi^-$ resonance

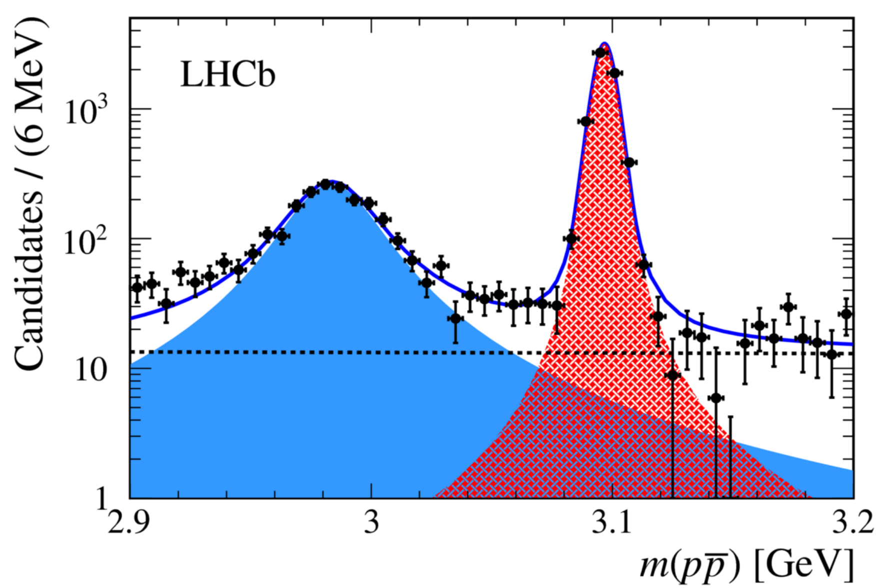
- $\eta_c\pi^-$ access J^P other than 1^+
  - $0^+, 1^-, 2^+$
- $B^0 \to \eta_c K^+\pi^-$ signal



$$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$$

[arXiv:1809.07416]

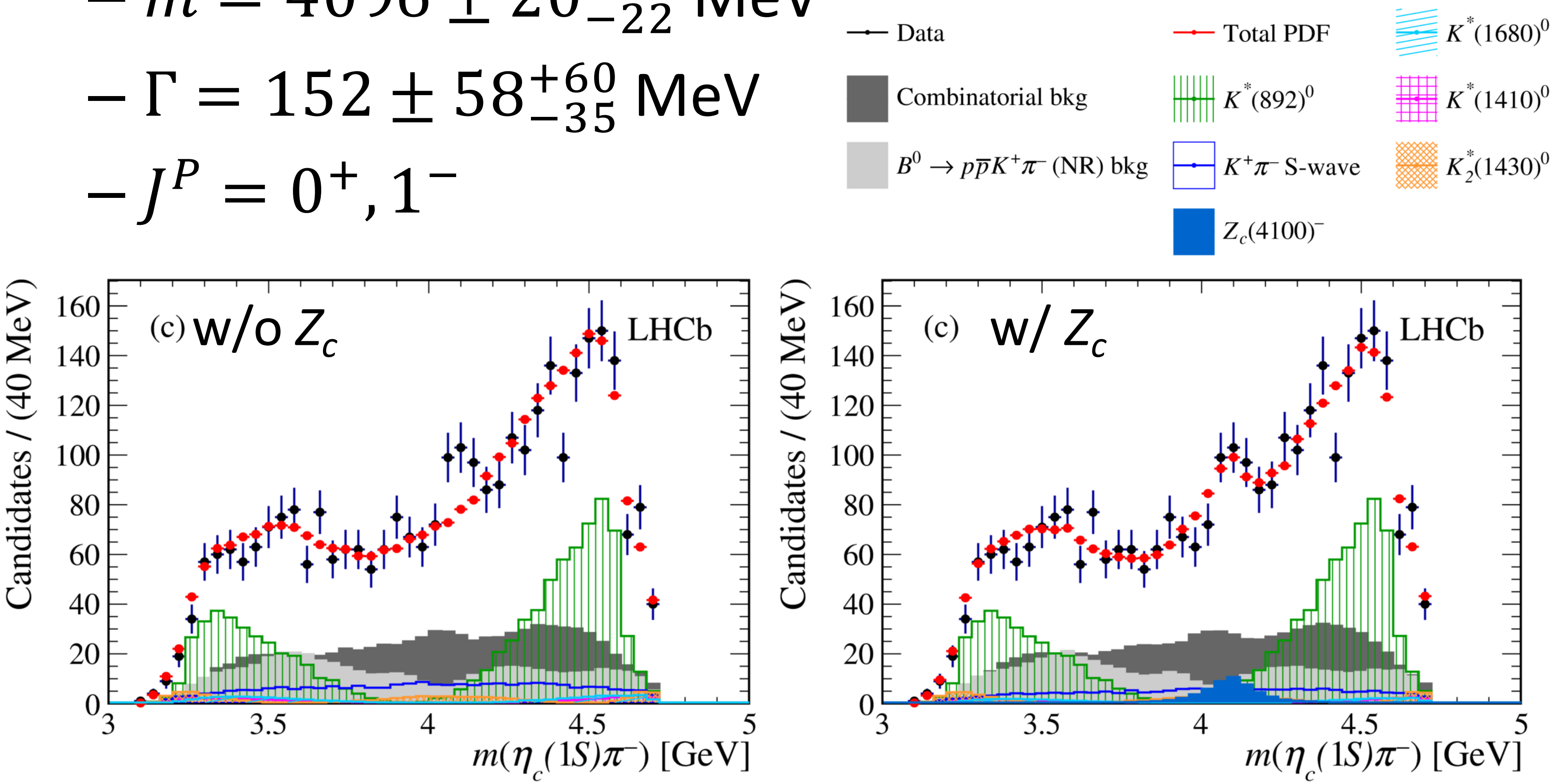




Evidence of $\eta_c\pi^-$ resonance (cont.)

- Z_c needed to describe data (significance>3σ)
  - $m = 4096 \pm 20^{+18}_{-22}$ MeV
  - $\Gamma = 152 \pm 58^{+60}_{-35}$ MeV
  - $J^P = 0^+, 1^-$

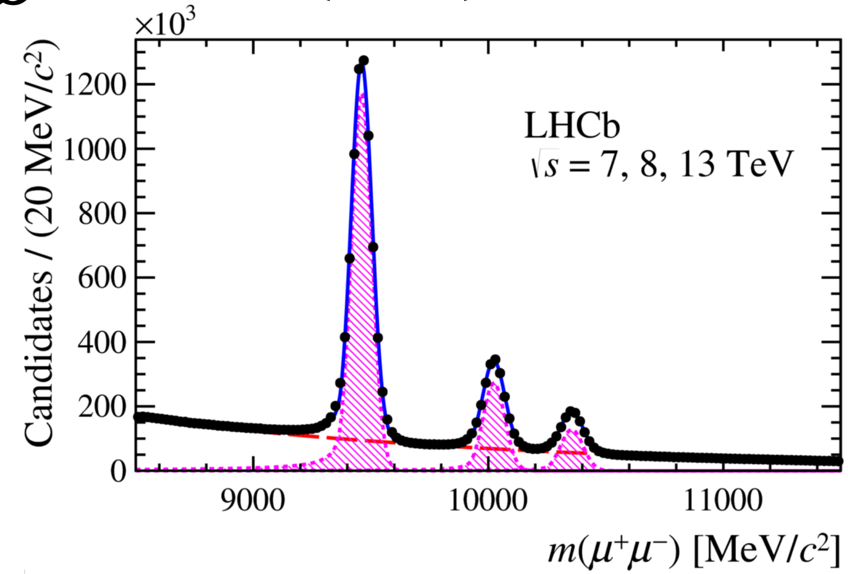
[arXiv:1809.07416]

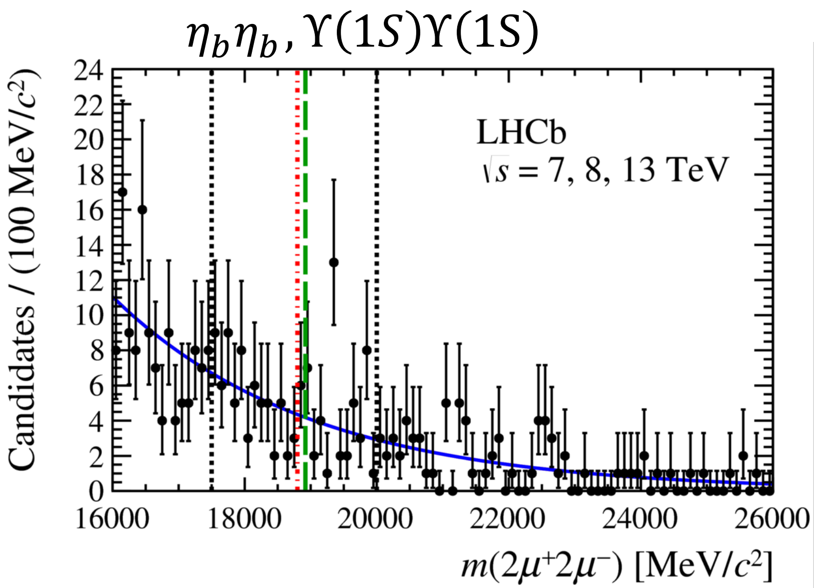


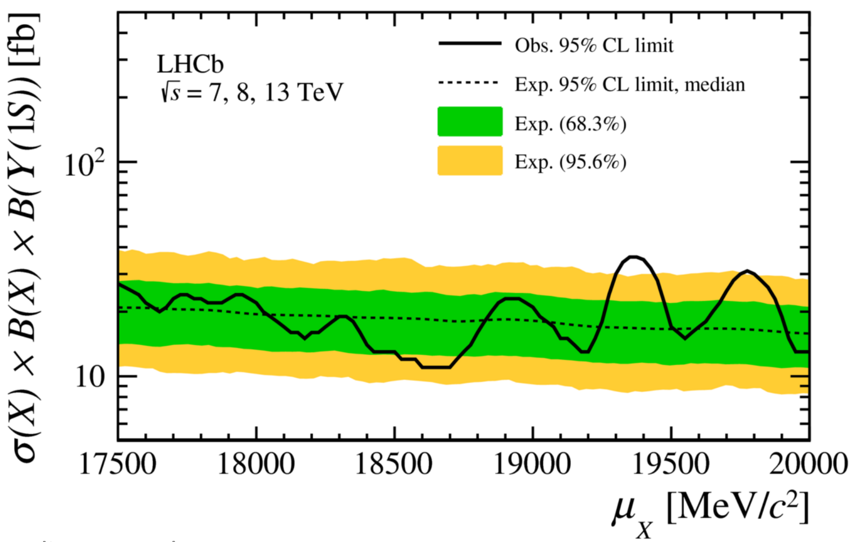
Search for $X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$

- Searched w/ 6.3 fb^{-1} data taken 2011-17
- No obvious signal, upper limit

[JHEP 10 (2018) 086]







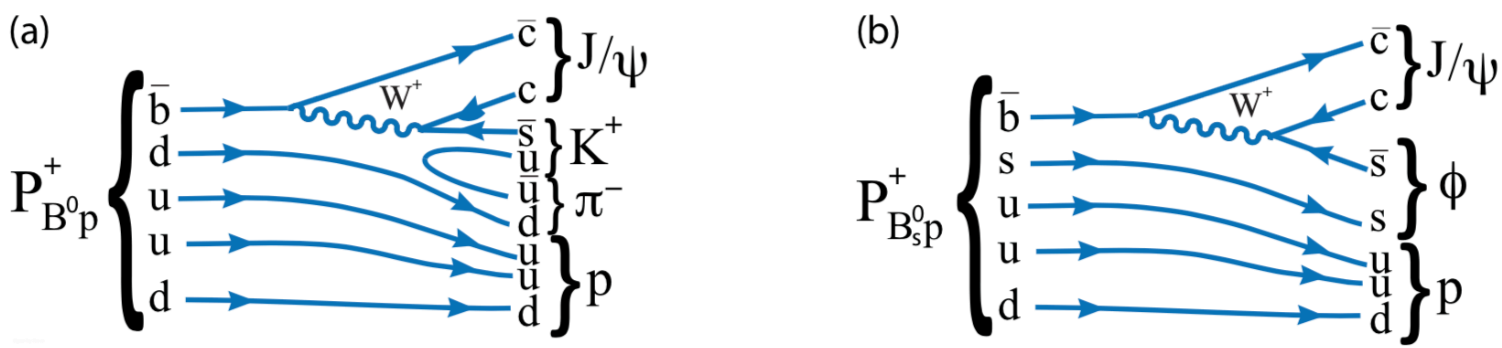
Search for *b*-flavored pentaquarks

- Skyrme model: the heavier the constituent quarks, the more tightly bound the state

[T.H.R. Skyrme, Proc. Roy. Soc. Lond. A 260 (1961) 127] & other refs. in paper

[PRD 97 (2018) 032010]

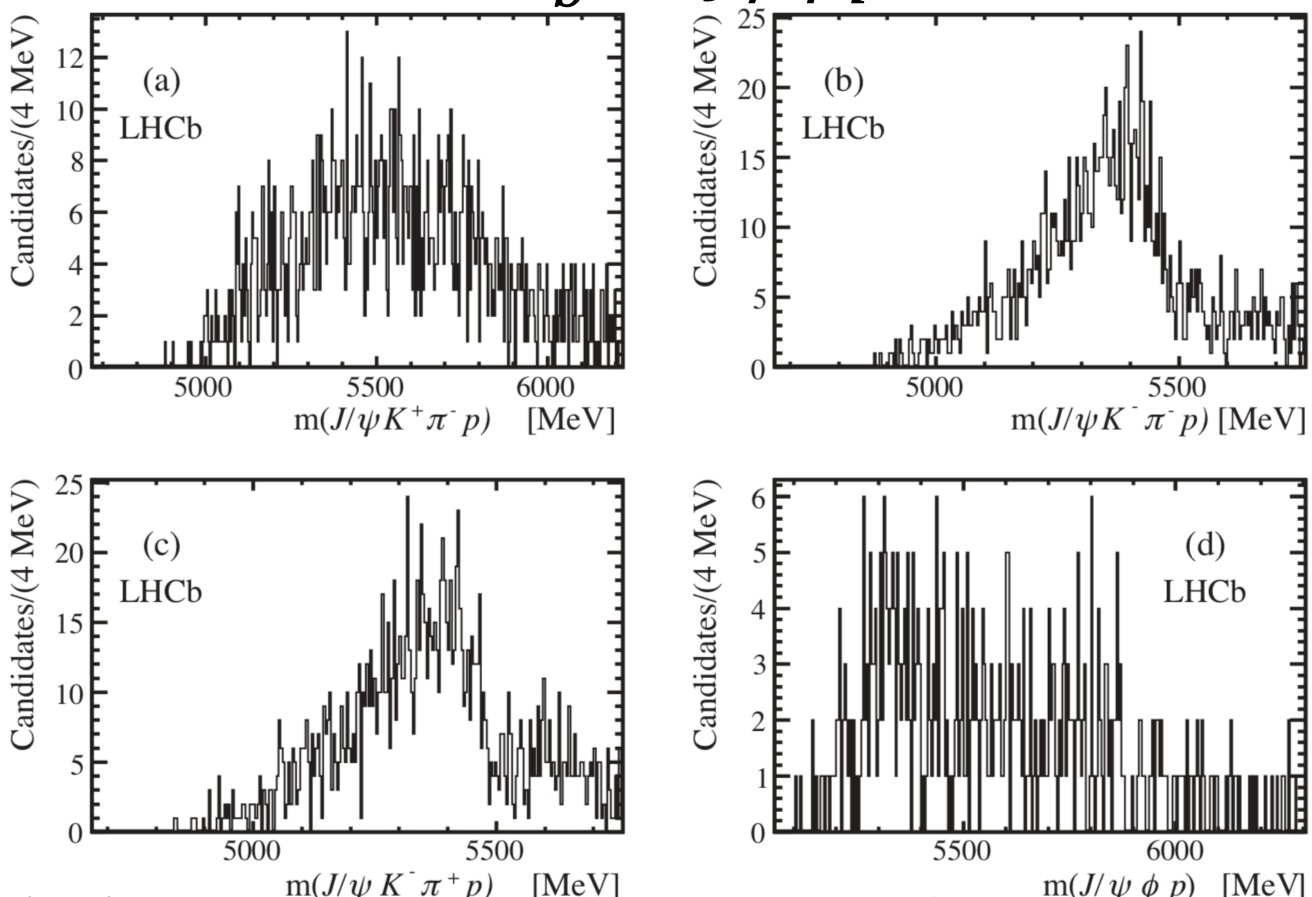
Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi\, K^+\pi^-p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda_b^0\pi^-} \to J/\psi\, K^-\pi^-p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda_b^0\pi^+} \to J/\psi\, K^-\pi^+p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B_s^0p} \to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



Search for b-flavored pentaquarks

- No clear signal, upper limits on production ratio $\sigma \cdot \mathcal{B}$ wrt $\Lambda_b^0 \to J/\psi p K^-$, ~$10^{-3}$

[PRD 97 (2018) 032010]



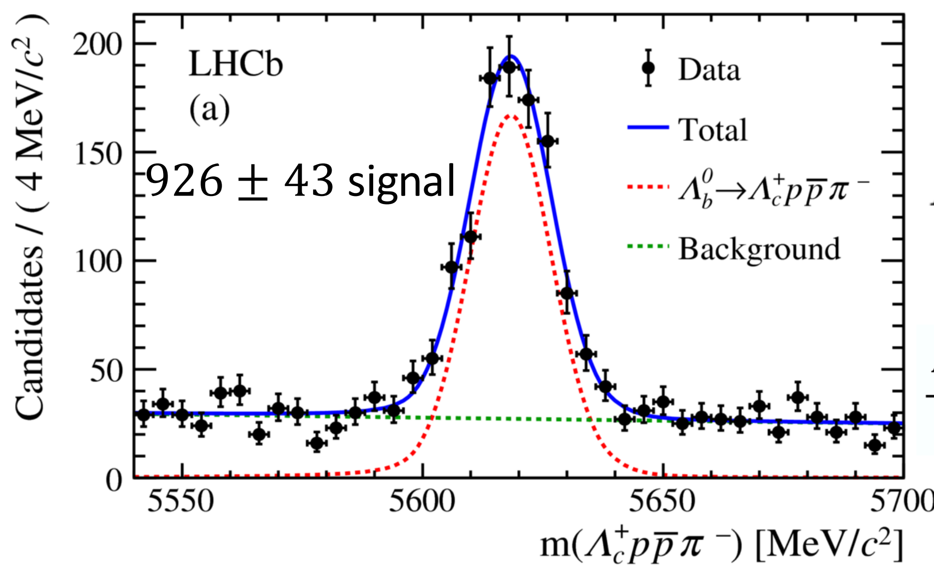
Search for dibaryon state

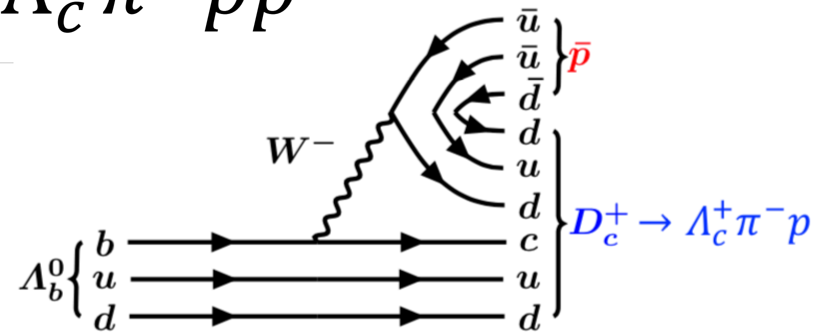
- Dibaryon state $[cd][ud][ud]$ could be present in $\Lambda_b^0 \to \Lambda_c^+\pi^- p\bar{p}$, $\mathcal{D}_c^+ \to p\mathcal{P}_c(\bar{u}[cd][ud]), p\Sigma_c^0$

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

- First observation of $\Lambda_b^0 \to \Lambda_c^+\pi^- p\bar{p}$

[PLB 184 (2018) 101]





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

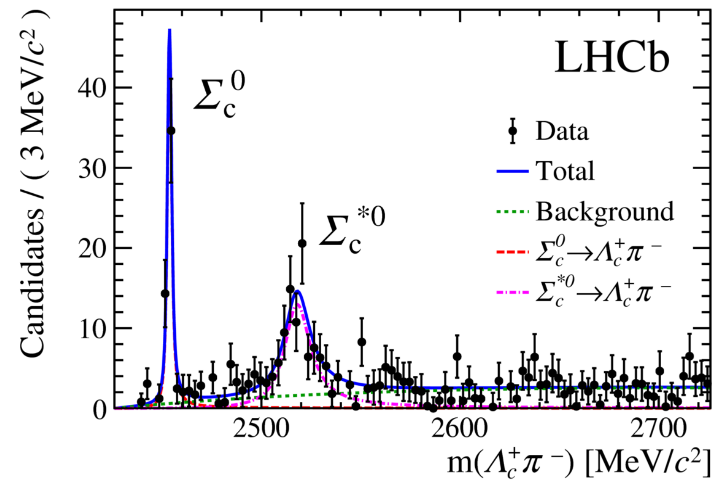
Search for dibaryon state (cont.)

- Resonance contribution

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^0 p\overline{p}) \times \mathcal{B}(\Sigma_c^0 \to \Lambda_c^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\overline{p}\pi^-)} = 0.089 \pm 0.015 \pm 0.006,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*0} p\overline{p}) \times \mathcal{B}(\Sigma_c^{*0} \to \Lambda_c^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\overline{p}\pi^-)} = 0.119 \pm 0.020 \pm 0.014.$$

- No sign of dibaryon yet



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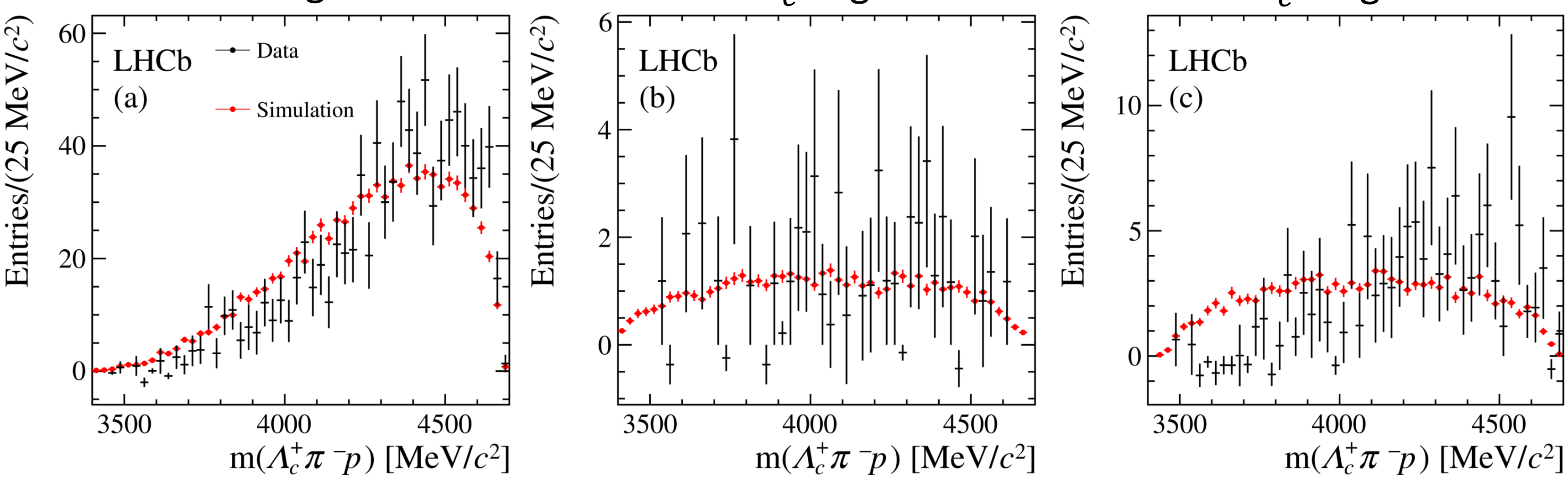
Full region | Σ_c^0 region | Σ_c^{*0} region



Summary

- Lots of studies on spectroscopy at LHCb
  - Conventional spectroscopy
    - Ω_c^*, Λ_c^*; Ω_c^0 lifetime
    - Ξ_{cc}^{++} observation, lifetime; new decay
    - $B_c(2S)$ search
    - $\Xi_b(6227)^-, \Sigma_b(6097)^\pm$ observation
  - Exotic states
    - $Z_c(4100)^-$ evidence
    - $X_{b\bar{b}b\bar{b}}$, *b*-flavored pentaquark, dibaryon search
- More results to come, stay tuned!
- Your suggestions are always welcome!