中国科学院大学

University of Chinese Academy of Sciences

Recent results on heavy baryon spectroscopy at LHCb

Jibo He (何吉波), UCAS (中国科学院大学)

第五届强子谱与强子结构研讨会

(Jan 23-25, 2021)

Outline

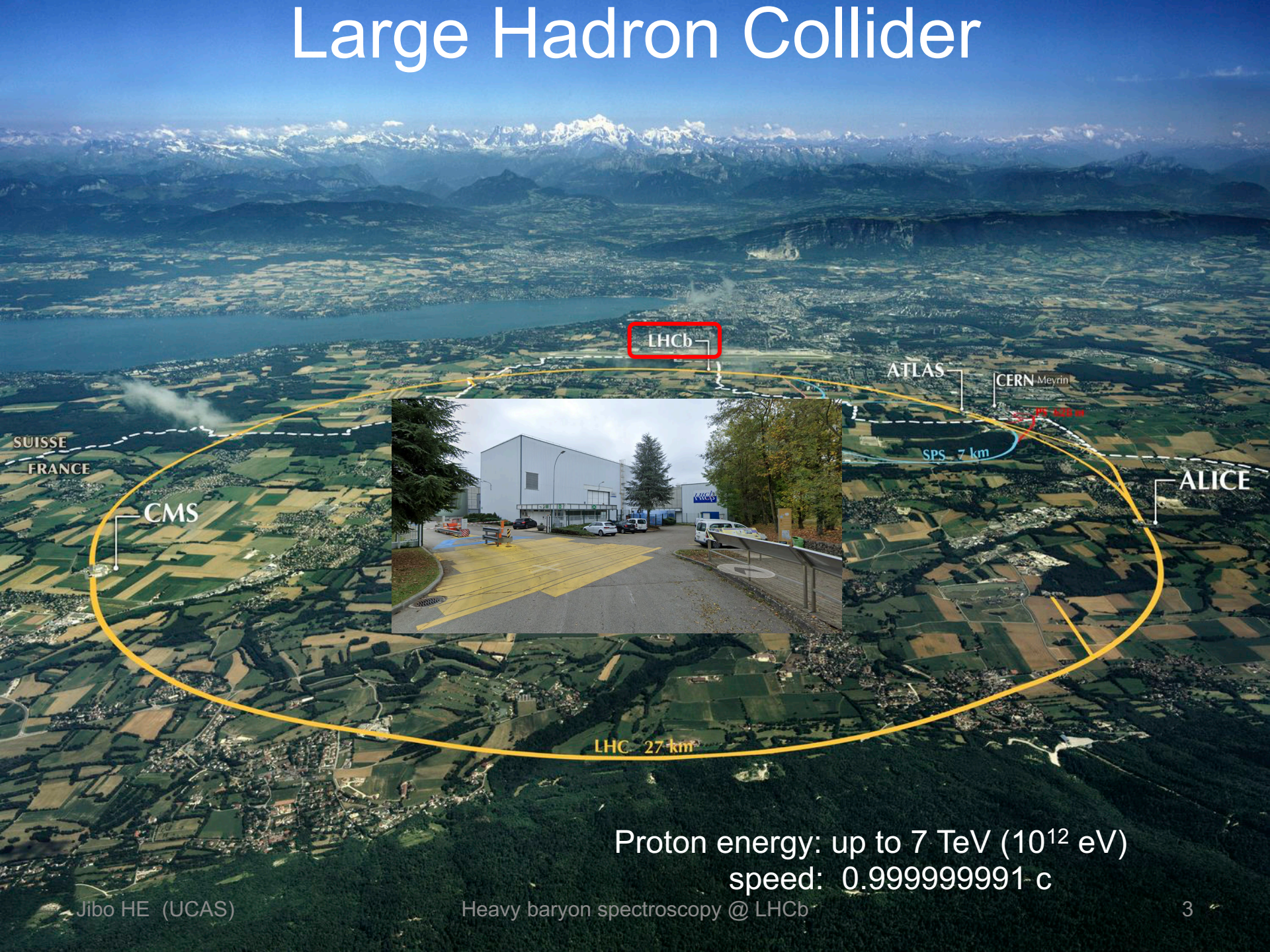
- Introduction
- Charmed baryon
- Doubly heavy baryon
- Beauty baryon
- Summary

Please see Liming's talk on Exotic hadrons at LHCb

More results can be found here:

https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

Large Hadron Collider



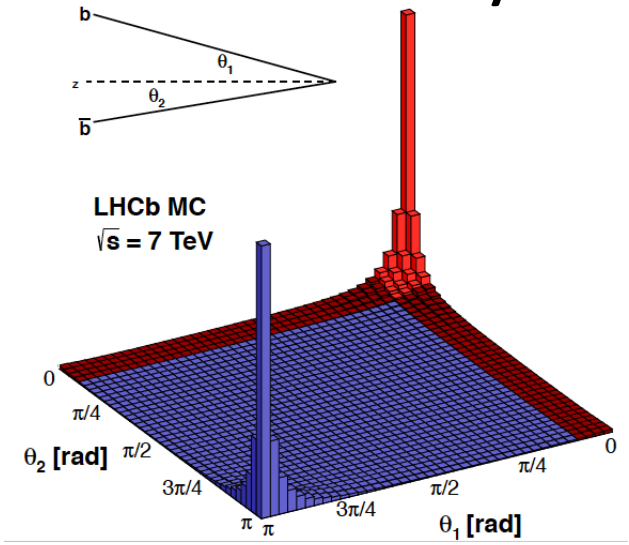
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

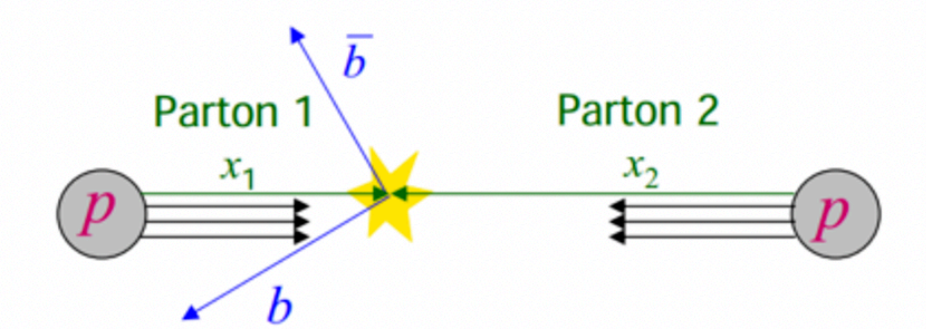
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb **c.f. 1nb @$\Upsilon(4S)$**

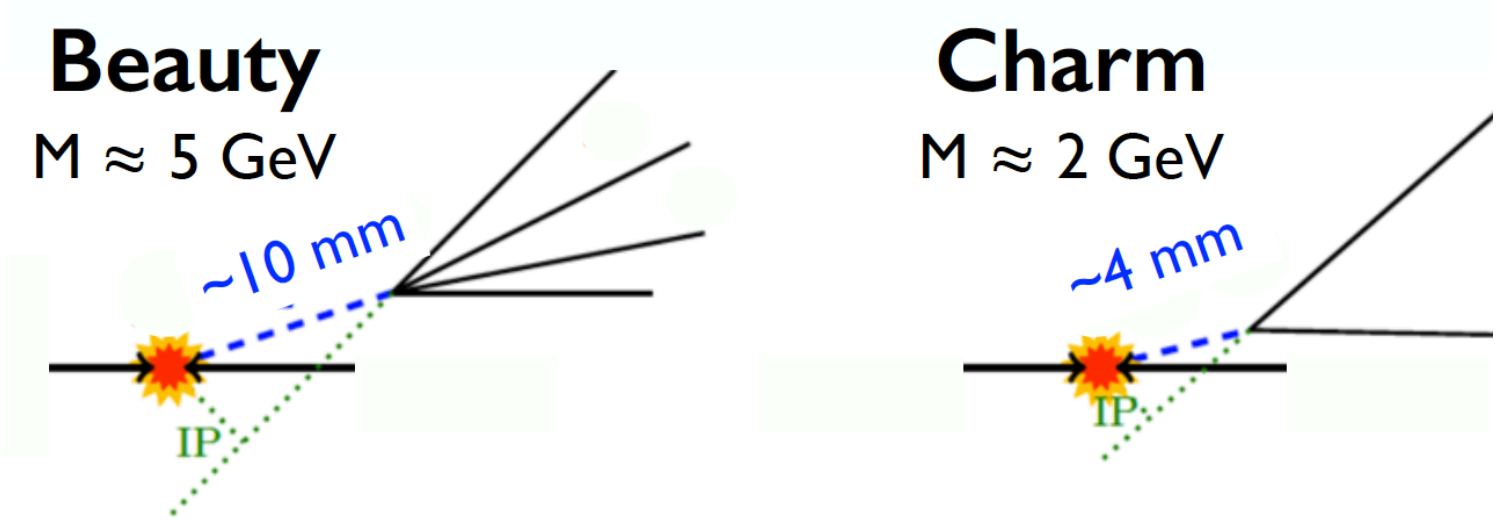
} Flavor factory!

- Predominantly in forward/backward cones



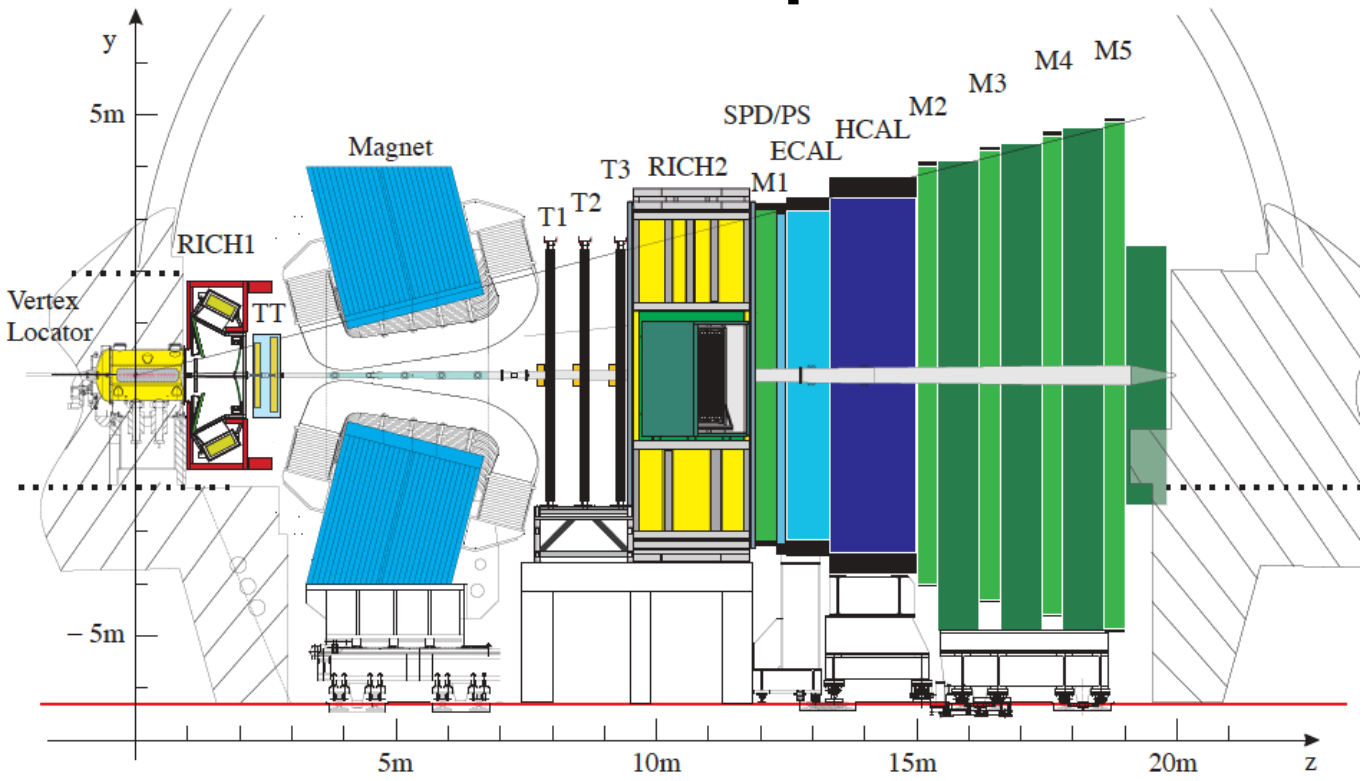


Beauty/charm signature



- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

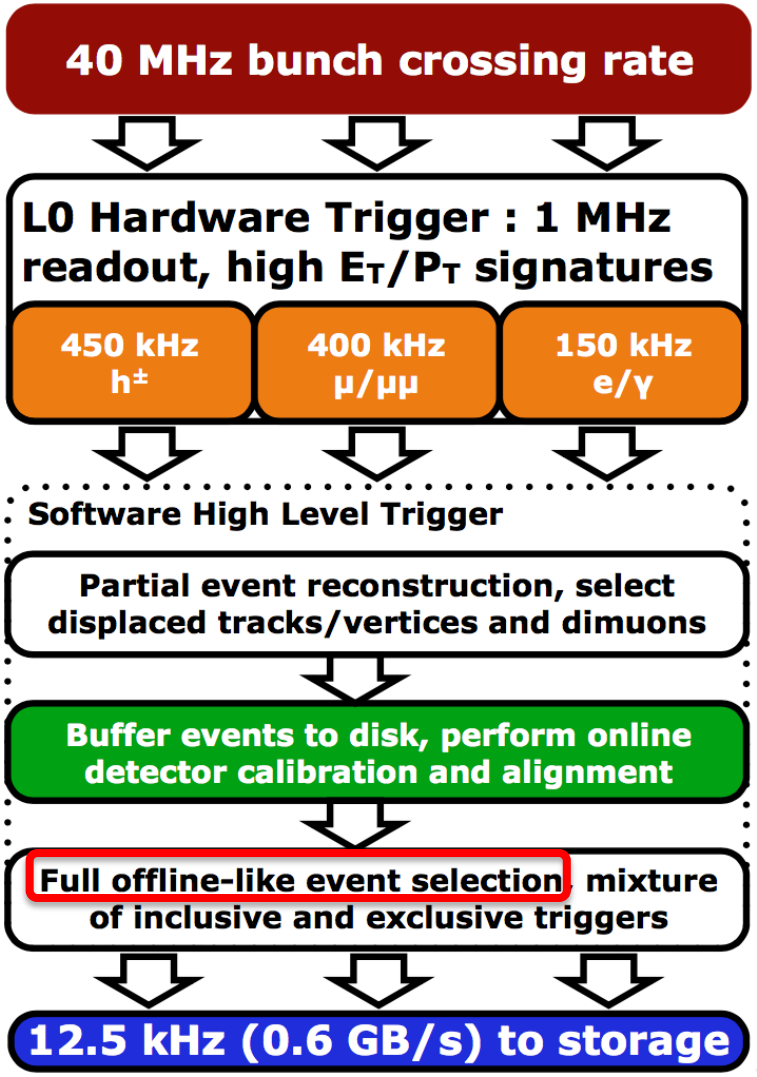
The LHCb experiment



[JINST 3 (2008) S08005]

Vertex Locator	$\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (Run-II)



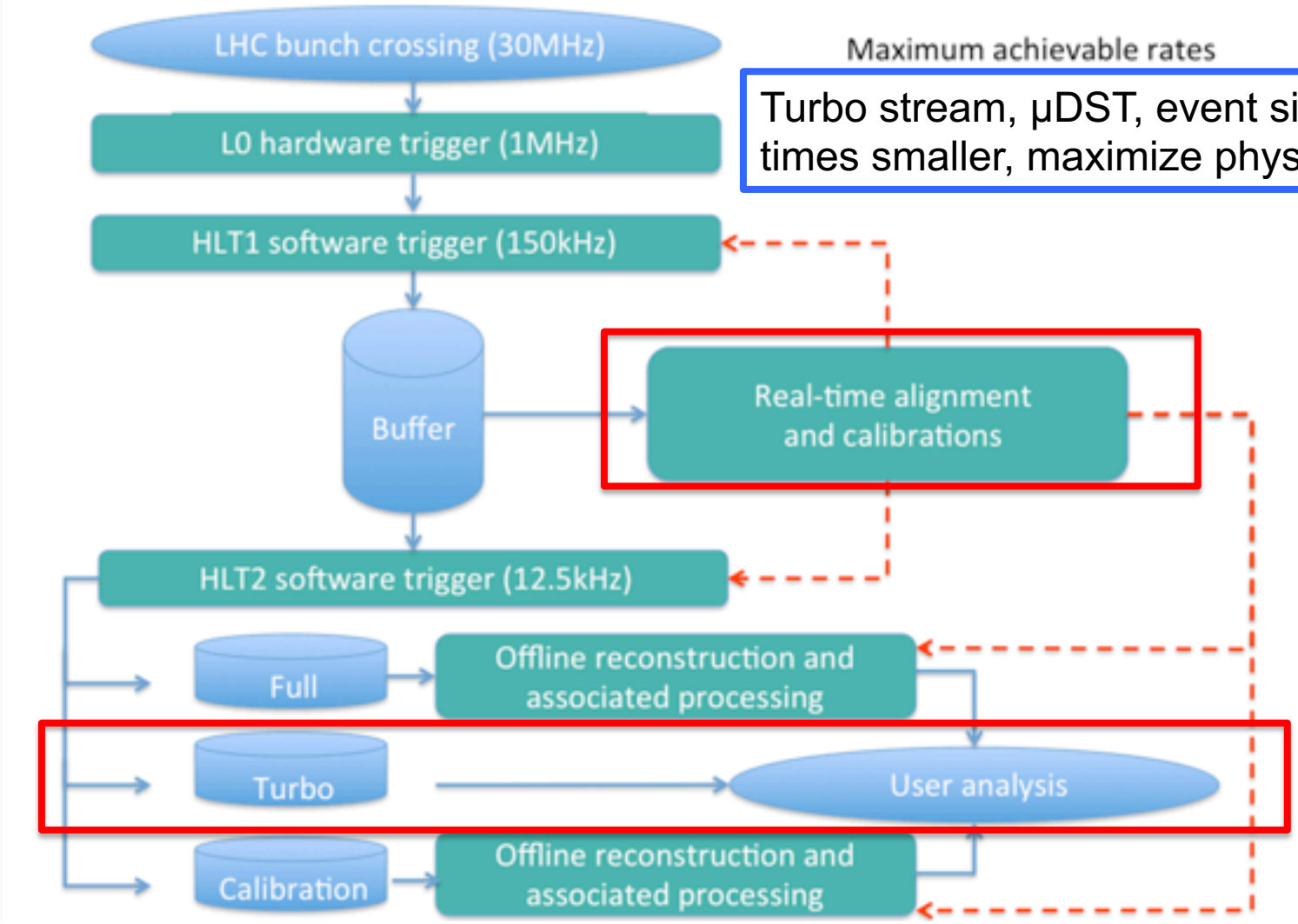
- Level-0, Hardware
  - Fully synchronous at 40 MHz
  - Selection of high p_{T} particles
    - ★ $p_{\mathrm{T}}(\mu) >\sim 1.5$ GeV/c,
      $p_{\mathrm{T}}(\mu_1) \times p_{\mathrm{T}}(\mu_2) >\sim (1.5\,\mathrm{GeV}/c)^2$
    - ★ $E_{\mathrm{T}}(h, e, \gamma) > 2.5 - 4$ GeV
- High Level Trigger (HLT), Software
  - Stage 1, tracking info, IP cuts
  - Stage 2, full reconstruction + selections

  $\sim$50 kB/event $\Rightarrow$ 0.25GB/s, $\sim$ 2 PB/year
- Offline data flow

  Raw data $\xrightarrow{\text{Rec}}$ Stripping $\xrightarrow{10\%}$ (μ)DST

  Stripping, also as HLT3, Pre-selections of all decay channels under study

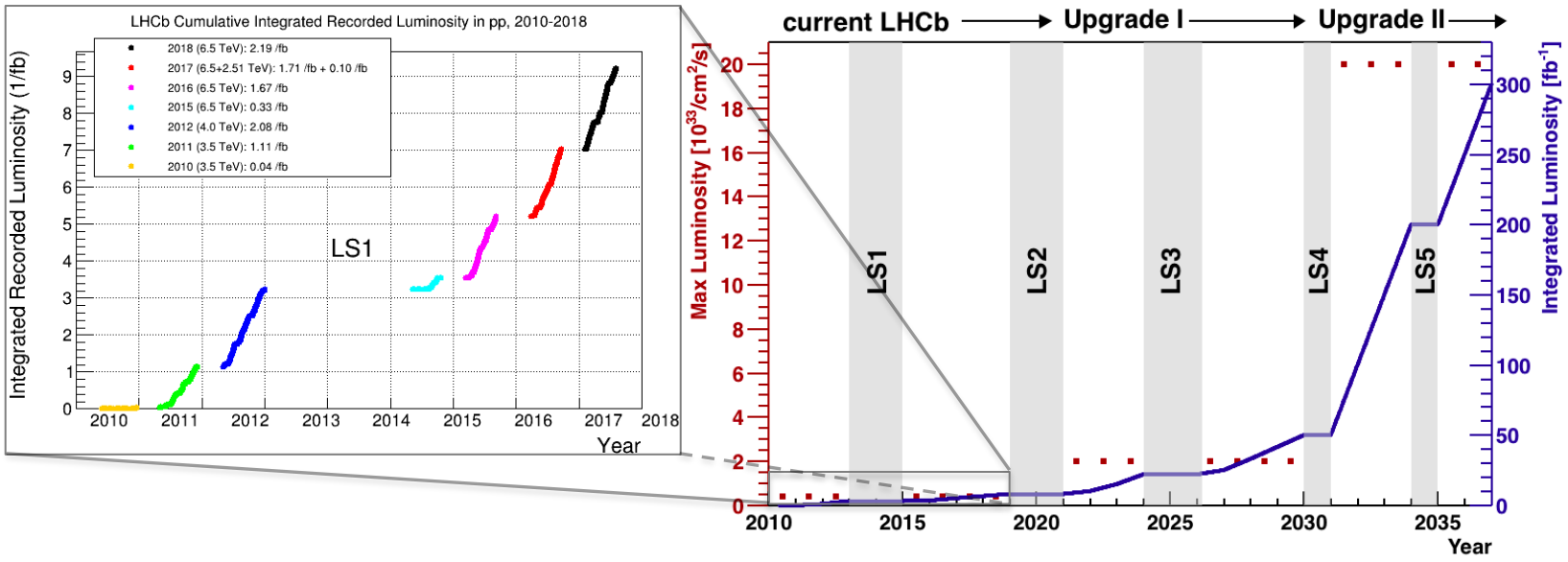
The turbo stream



Maximum achievable rates

Turbo stream, μDST, event size 10 times smaller, maximize physics output!

LHCb luminosity prospects

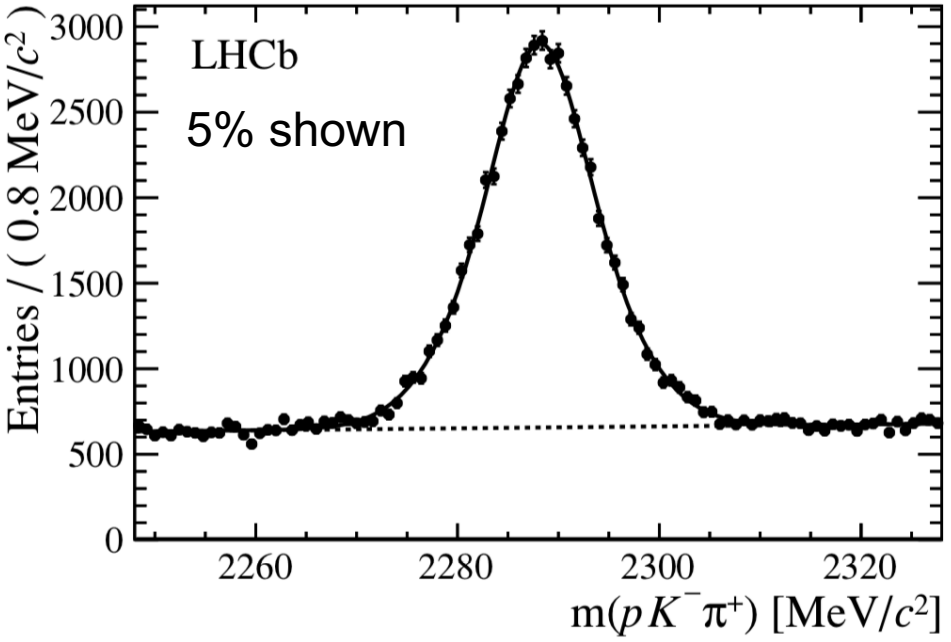


LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

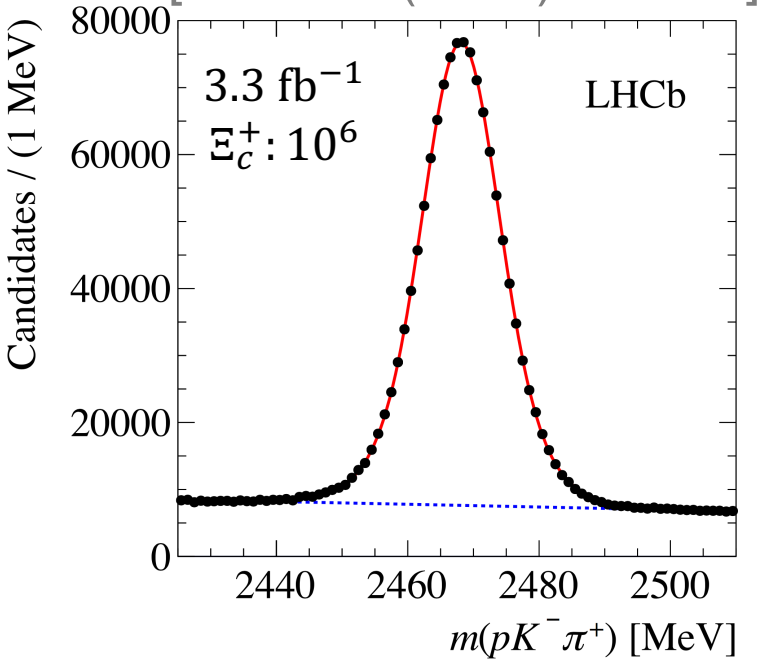
Lots of singly charmed baryons

- $\Lambda_c^+ \to pK^-\pi^+$: ~ 1×10^6 per fb^{-1} @ 7 TeV
- $\Xi_c^+ \to pK^-\pi^+$: ~ 3×10^5 per fb^{-1} @ 7 TeV

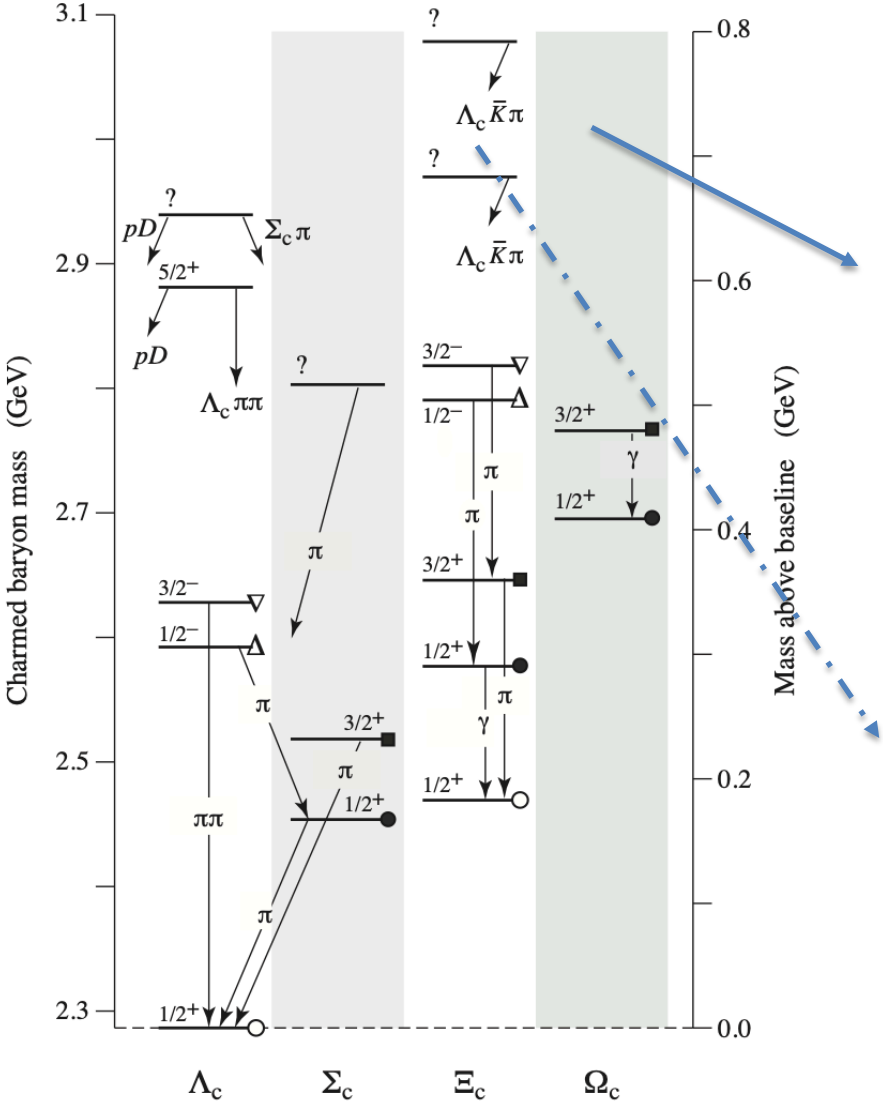
[JHEP 12 (2013) 90]

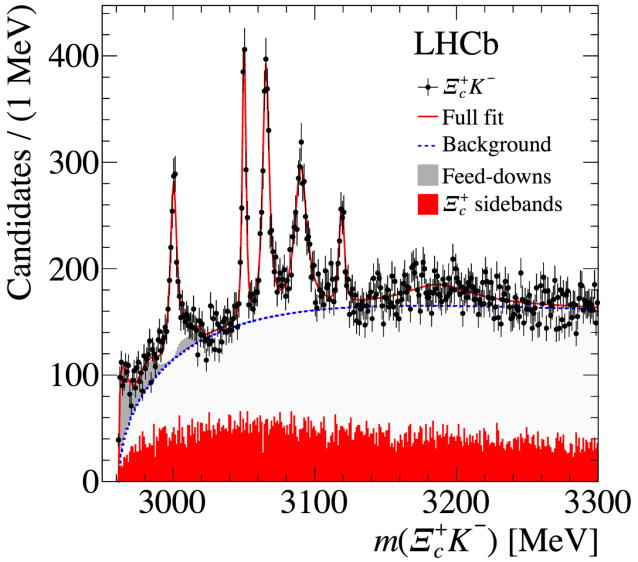


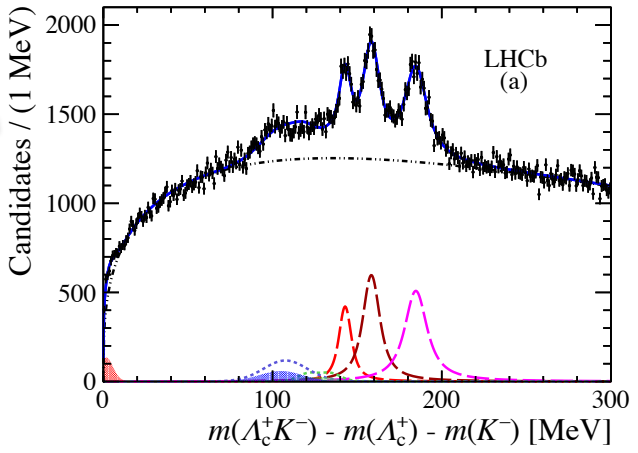
[PRL 118 (2017) 182001]



Charmed baryon spectroscopy





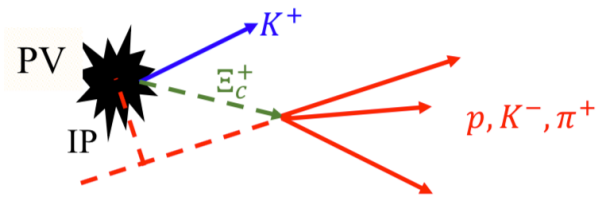


[PRL 118 (2017) 182001]

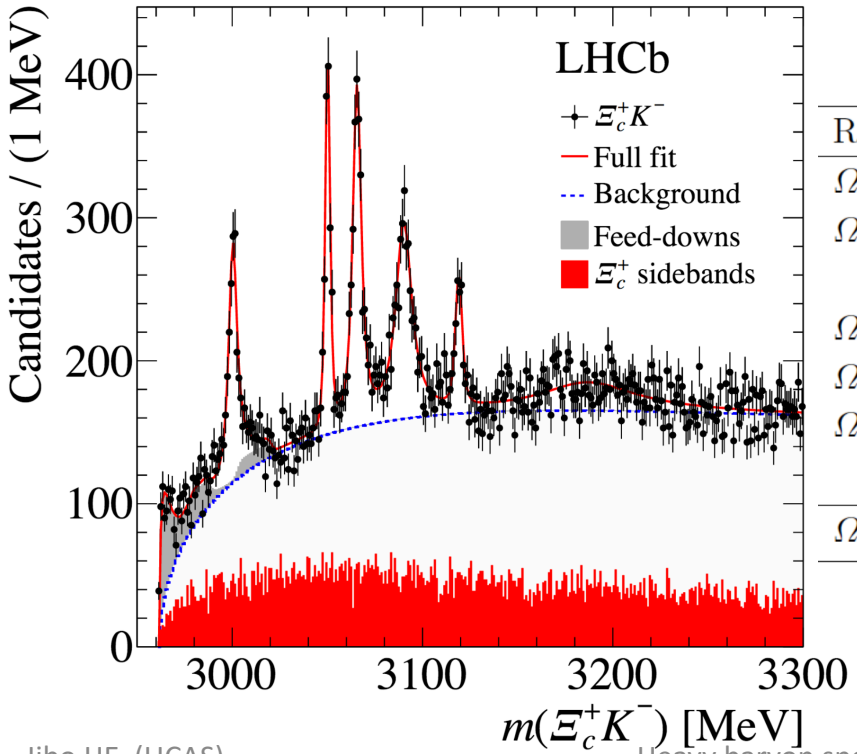
[PRL 124 (2020) 222001]

Observation of excited Ω_c^0 states

- With $\Xi_c^+ K^-, \Xi_c^+ \to pK^-\pi^+$
- 5 narrow states + evidence of a broader one



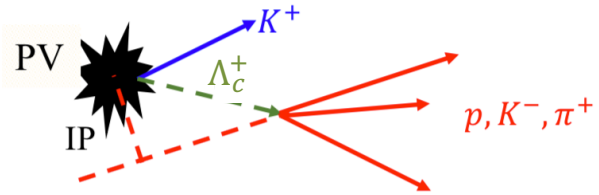
[PRL 118 (2017) 182001]

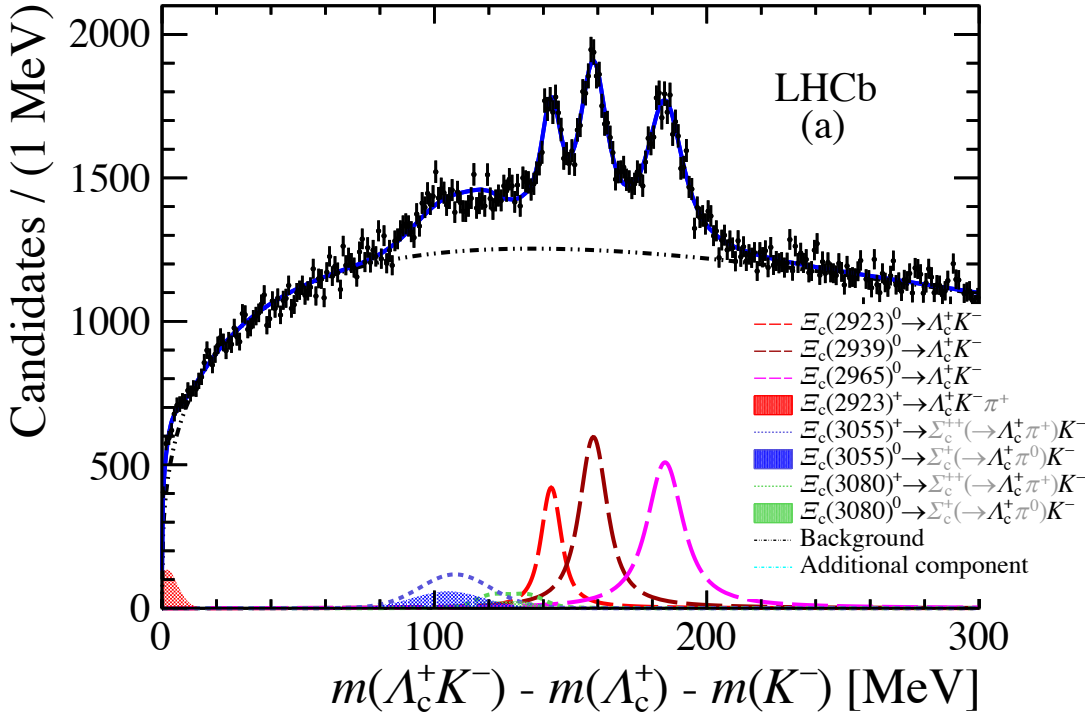


Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		< 1.2 MeV, 95% CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	10.4
		< 2.6 MeV, 95% CL	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	6.4

Observation of excited Ξ_c^0 states

- Three excited Ξ_c^0 states





Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

[PRL 124 (2020) 222001]

Observation of excited Ξ_c^0 states

- Gell-Mann-Okubo formula for baryons

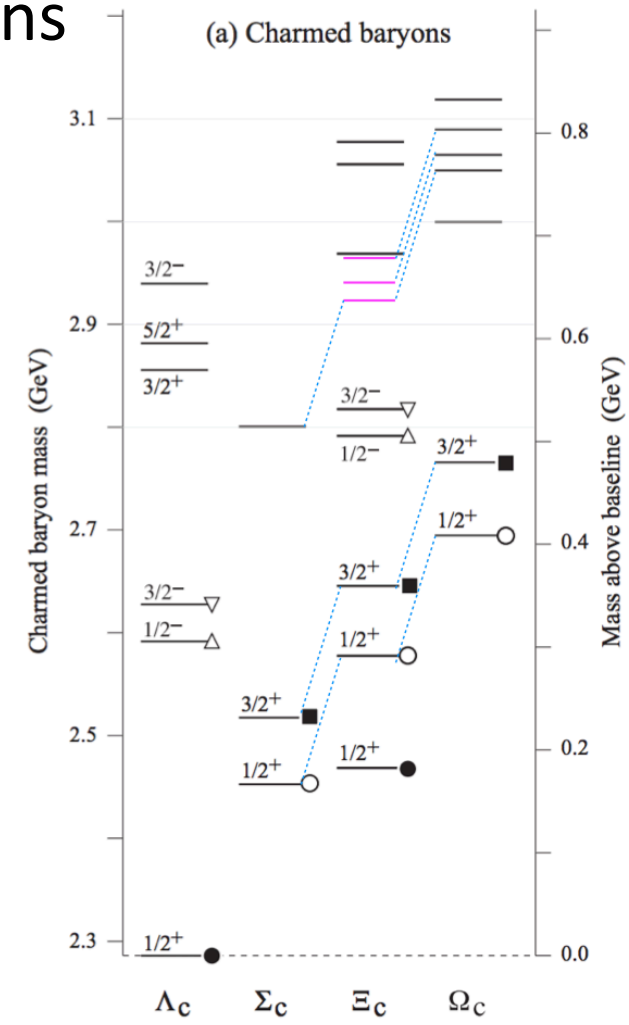
$$m(\Omega_c^{**}) - m(\Xi_c^{**}) = m(\Xi_c^{**}) - m(\Sigma_c^{**})$$

- We have

$$m[\Omega_c(2770)^0] - m[\Xi_c(2645)^0]$$
$$\simeq m[\Xi_c(2645)^0] - m[\Sigma_c(2520)^0] \simeq 125 \text{ MeV}.$$

it also holds for

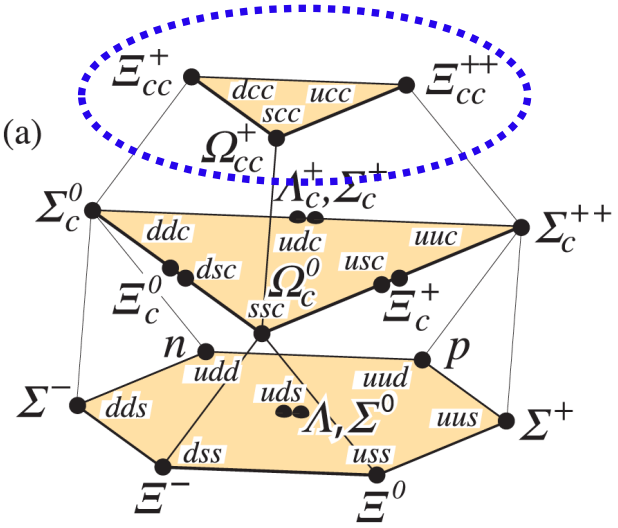
$$m[\Omega_c(3050)^0] - m[\Xi_c(2923)^0]$$
$$\simeq m[\Xi_c(2923)^0] - m[\Sigma_c(2800)^0] \simeq 125 \text{ MeV},$$
$$m[\Omega_c(3065)^0] - m[\Xi_c(2939)^0] \simeq 125 \text{ MeV},$$
$$m[\Omega_c(3090)^0] - m[\Xi_c(2965)^0] \simeq 125 \text{ MeV}.$$

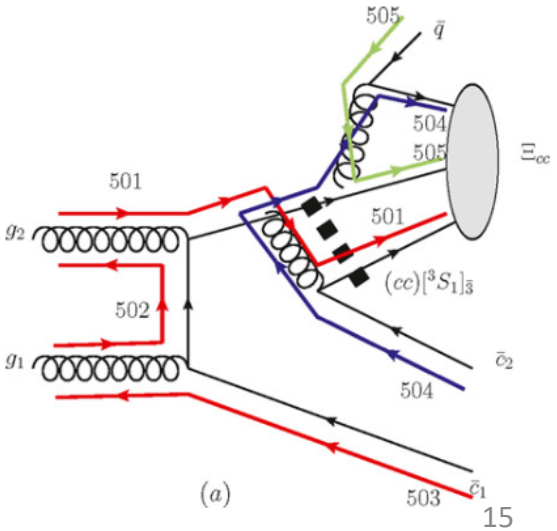


[PRL 124 (2020) 222001]

Doubly charmed baryon

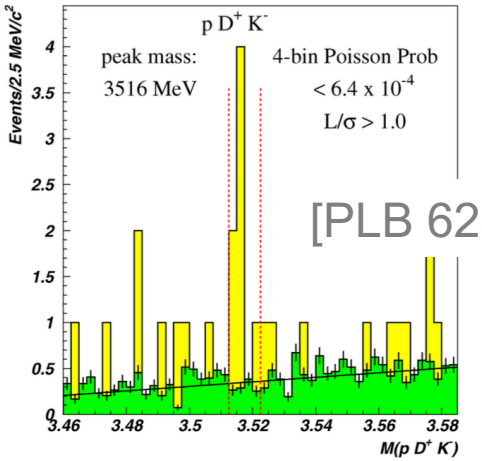
- Mass
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$
    $= 3621.55 \pm 0.38$ MeV
  - $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}^{++}) + 100$ MeV
- Lifetime
  - $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027$ ps
- Production [PRD 83 (2011) 034026]
  - $\sigma(cc) = 90$ nb @ 13 TeV in LHCb
  - $f_{\rm frag}\ u:d:s \sim 1:1:0.3$
    $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40$ nb
    $\sigma(\Omega_{cc}^{+}) \sim 13$ nb





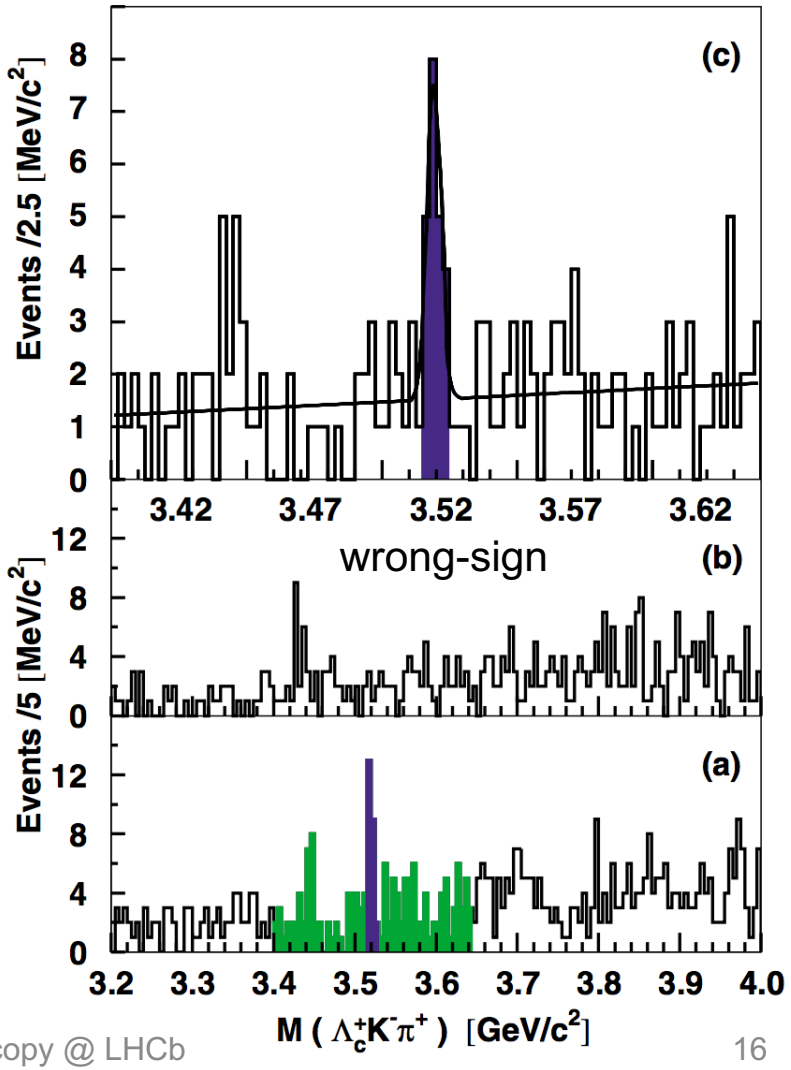
Ξ_{cc}^{+} @ SELEX

- SELEX claimed
  $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (6.3σ)
  - M: 3519±1 MeV
  - τ:<33 fs @90%CL
  - σ_{prod}: 20% Λ_c^{+} from Ξ_{cc}^{+}
- Also $\Xi_{cc}^{+} \to p D^{+} K^{-}$



[PLB 628 (2005)18]

[PRL 89 (2002) 112001]



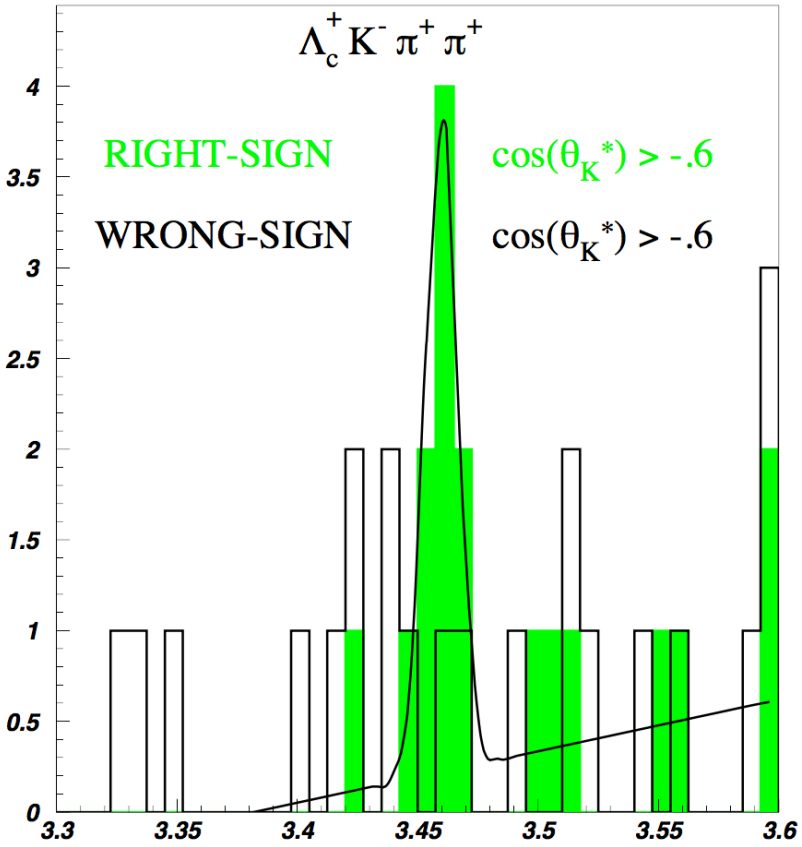
Ξ_{cc}^{++} @ SELEX

- SELEX claimed evidence of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ in ICHEP 2002 (4.4σ)
  - M: 3460 MeV

    c.f. $M(\Xi_{cc}^+)$: 3519 MeV

    big isospin breaking?
  - τ: ~$\tau(\Xi_{cc}^+)$

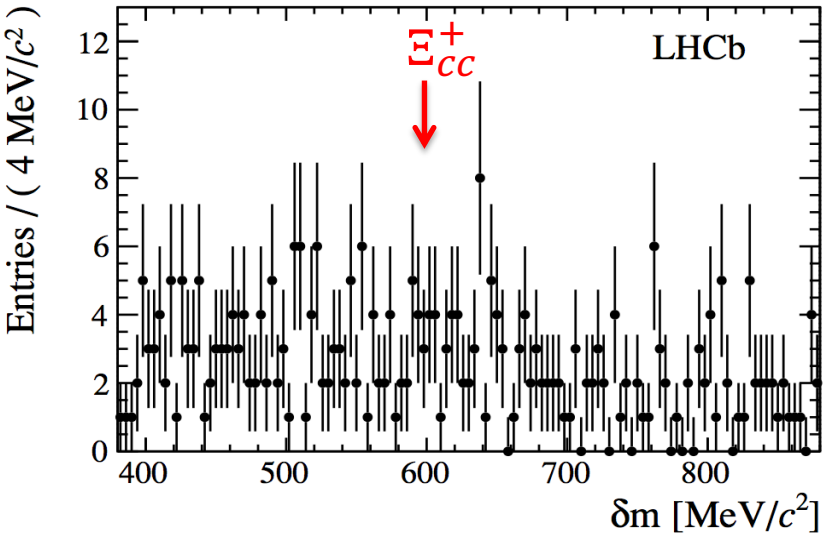
[hep-ex: 0209075]

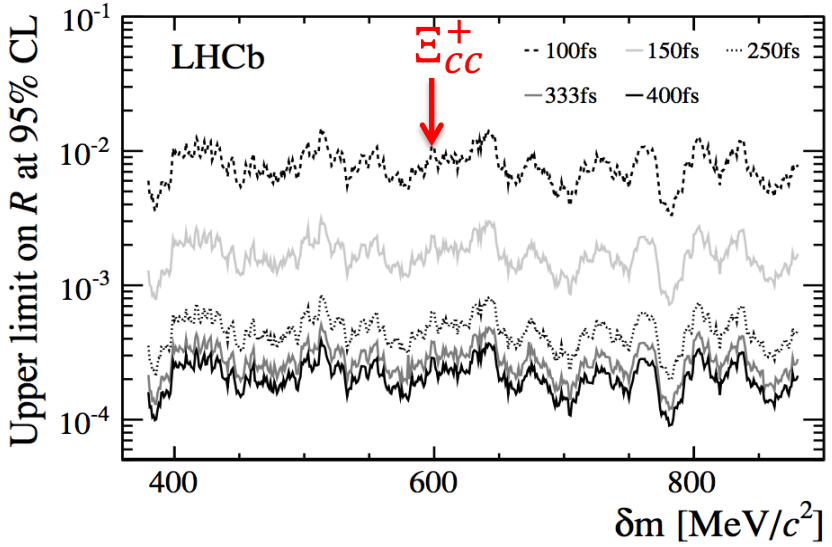


Ξ_{cc} @ LHCb & others

- 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]



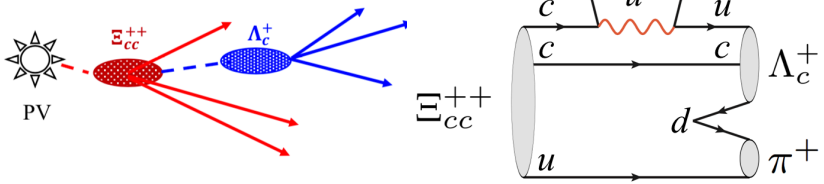


- However, LHCb already had lots of B_c^{+} events, and double-charm events…

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

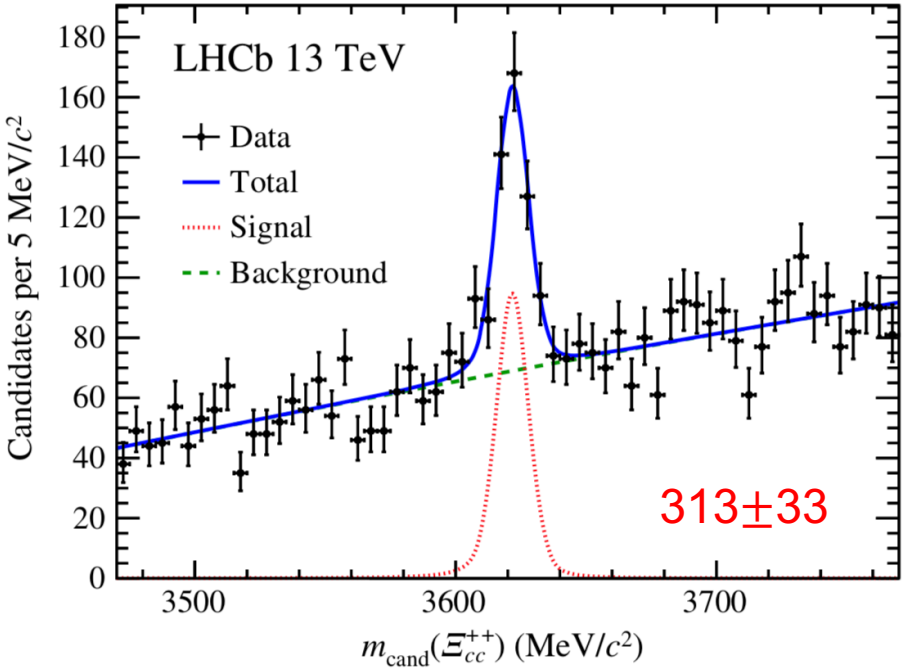
- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel

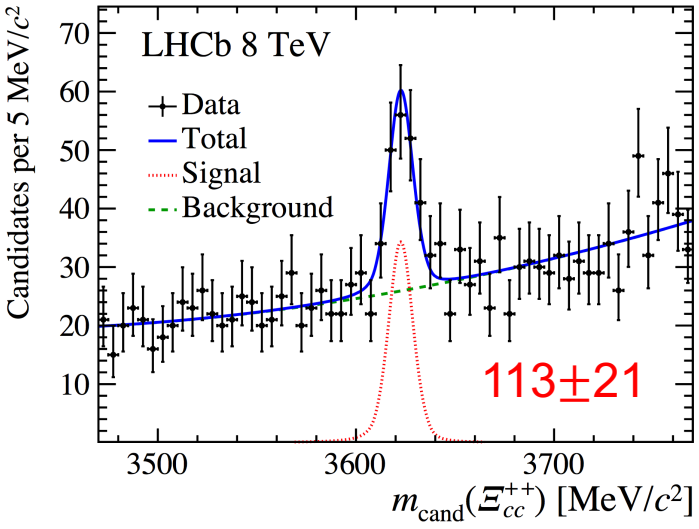
[F.-S. Yu *et al.*, CPC 42 (2018) 051001]



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

[PRL 119 (2017) 112001]





Ξ_{cc}^{++} properties

- Ξ_{cc}^{++} mass measured:

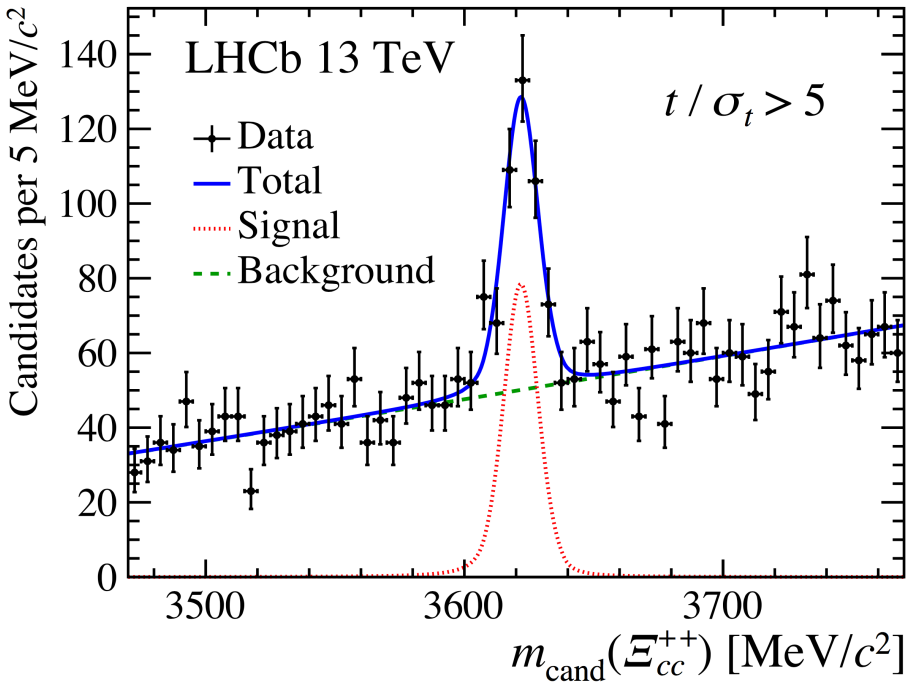
$$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

SELEX: m(Ξ_{cc}^{+})=3519±1 MeV

Isospin partner?

- Decay weakly, mass peak remains after lifetime cut

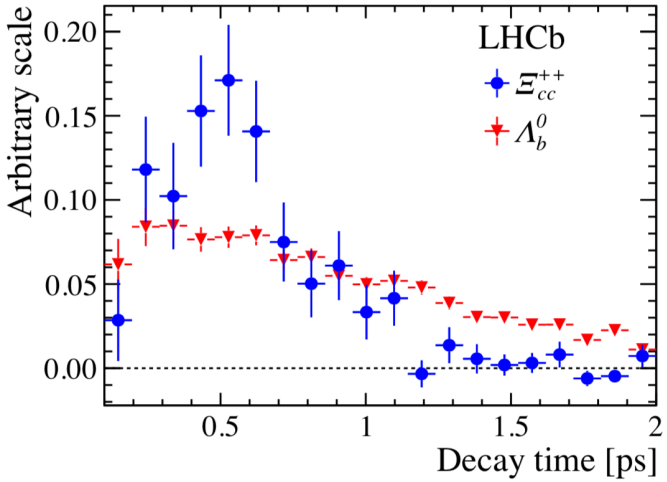
$\Longrightarrow$Measurement of $\tau(\Xi_{cc}^{++})$ needed

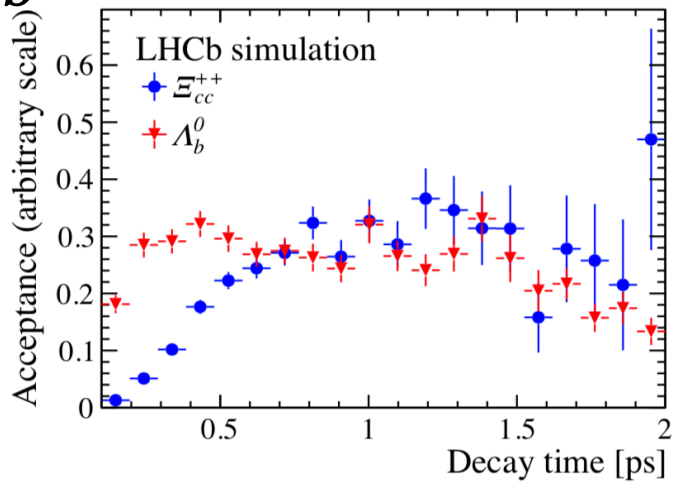


[PRL 119 (2017) 112001]

Ξ_{cc}^{++} lifetime

- Measured relative to Λ_b^0

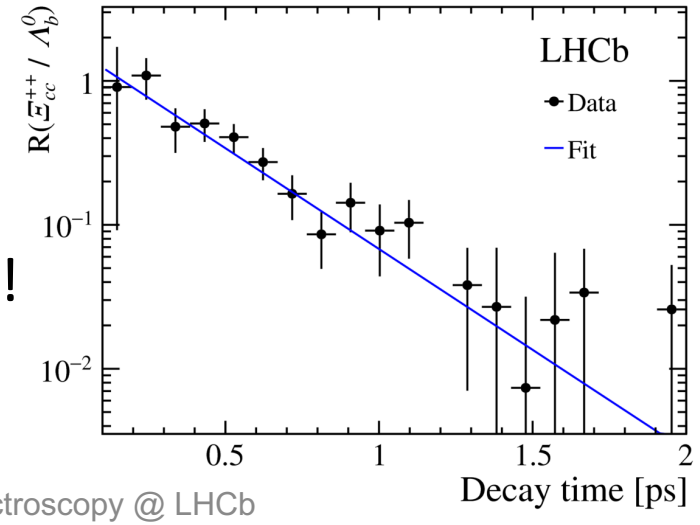




- $\tau(\Xi_{cc}^{++})$

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

Weakly decay nature established!

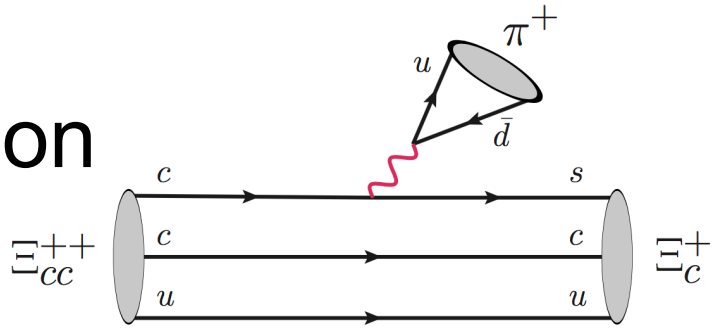


[PRL 121 (2018) 052002]

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

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

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

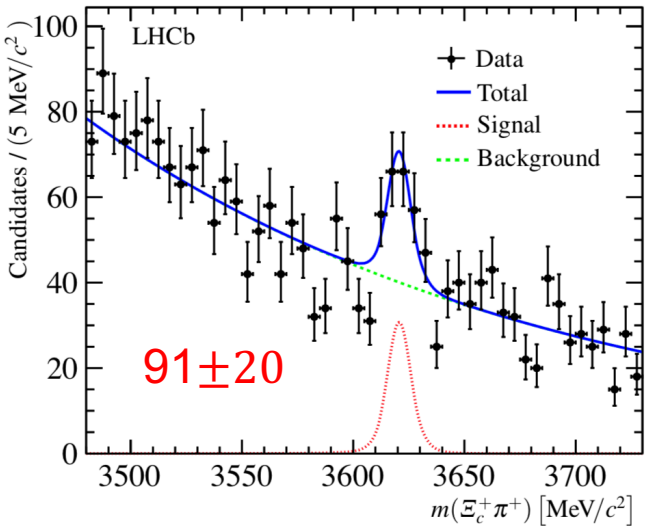


- Searched w/ 2016 data
- Ratio of total BR:

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \cdot \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009 \pm 0.003$$

  at the lower end of prediction

- 5.9σ, re-discovery!

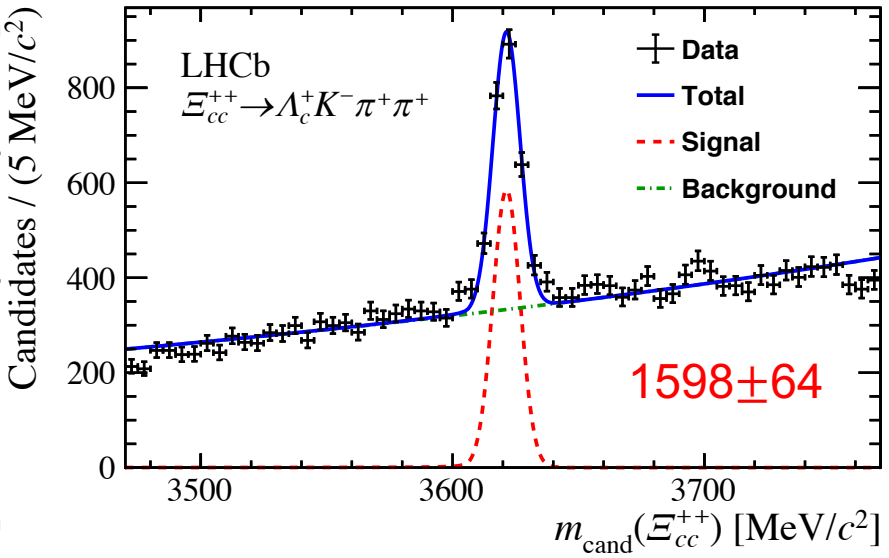


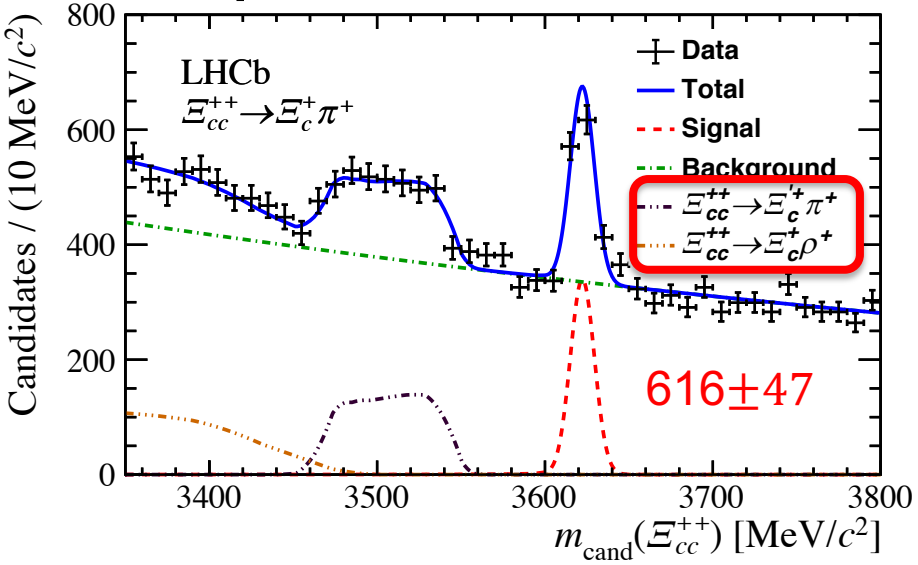
[PRL 121 (2018) 162002]

Precision measurement of $m(\Xi_{cc}^{++})$

- UROP, as preparation to search for excited states, event-selection re-optimised

[JHEP 02 (2020) 049]





$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30\ \text{MeV}/c^2$$

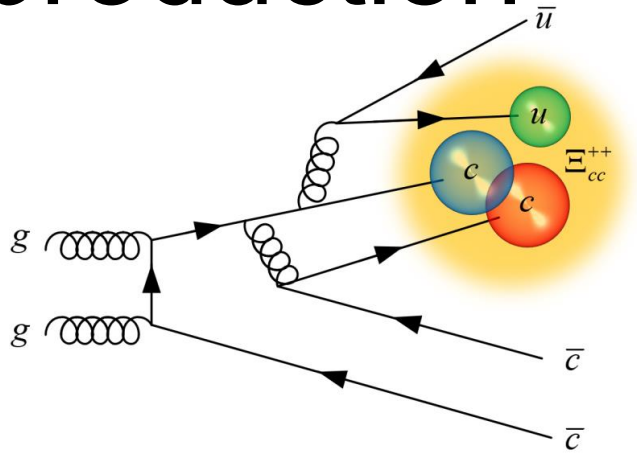
c.f., $3620.6 \pm 0.65 \pm 0.31\ \text{MeV}/c^2$

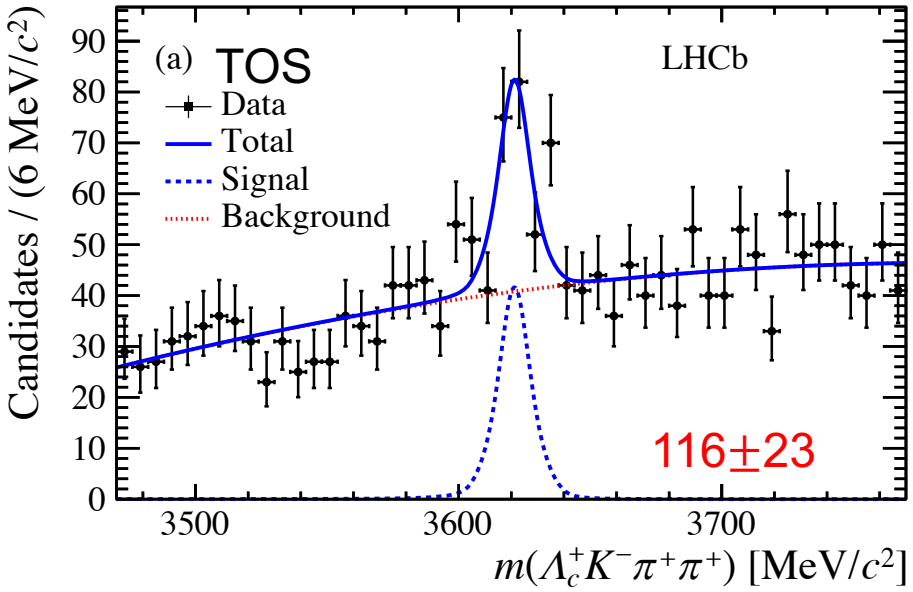
- Lattice QCD: $3610 \pm 23 \pm 22\ \text{MeV}/c^2$

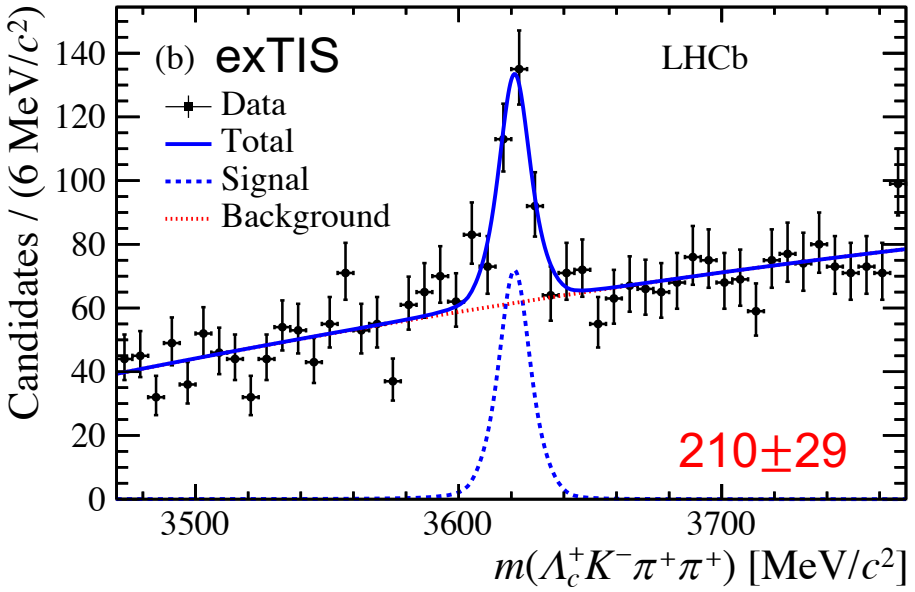
[Z. S. Brown *et al.*, PRD 90 (2014) 094507]

Measurement of Ξ_{cc}^{++} production

- Measured w/ 2016 data
- Accompanying $\bar{c}\bar{c}$ dominates in trigger, lots of work on validating efficiency

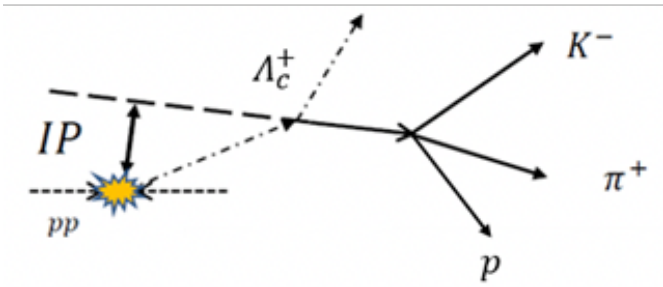


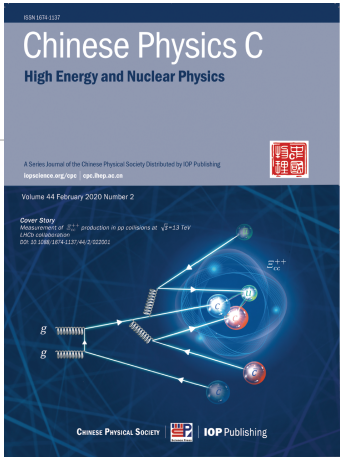




Measurement of Ξ_{cc}^{++} production

- Relative to Λ_c^+, in
  $4 < p_{\mathrm{T}} < 15$ GeV,
  2<y<4.5

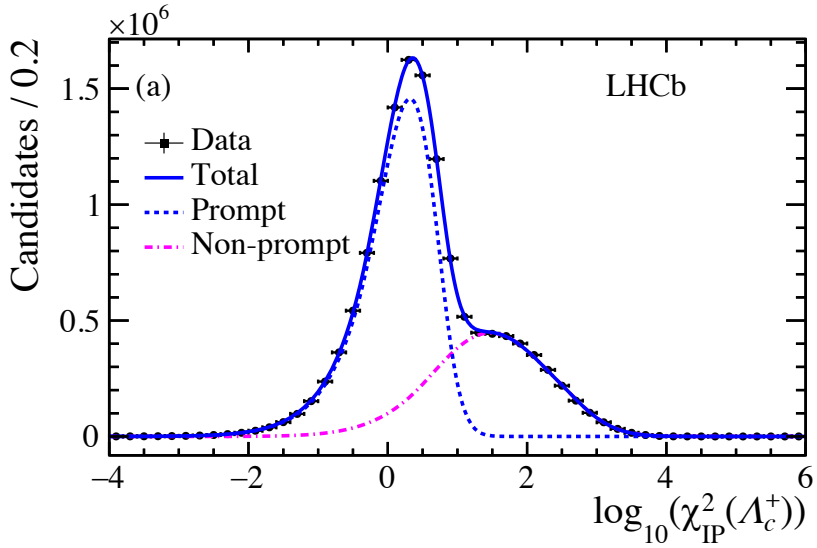




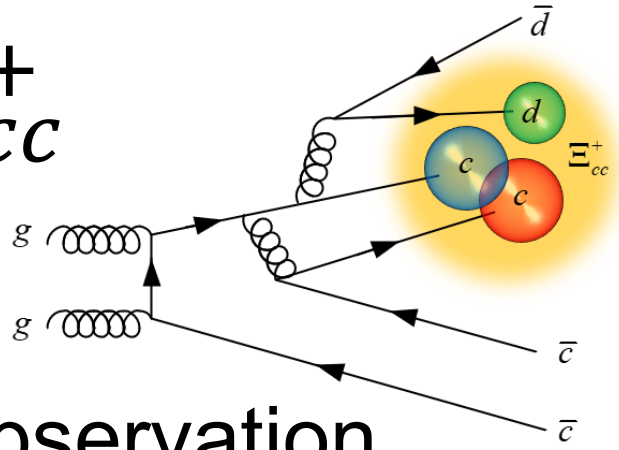
$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) = (2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$$

[CPC 44 (2020) 022001]

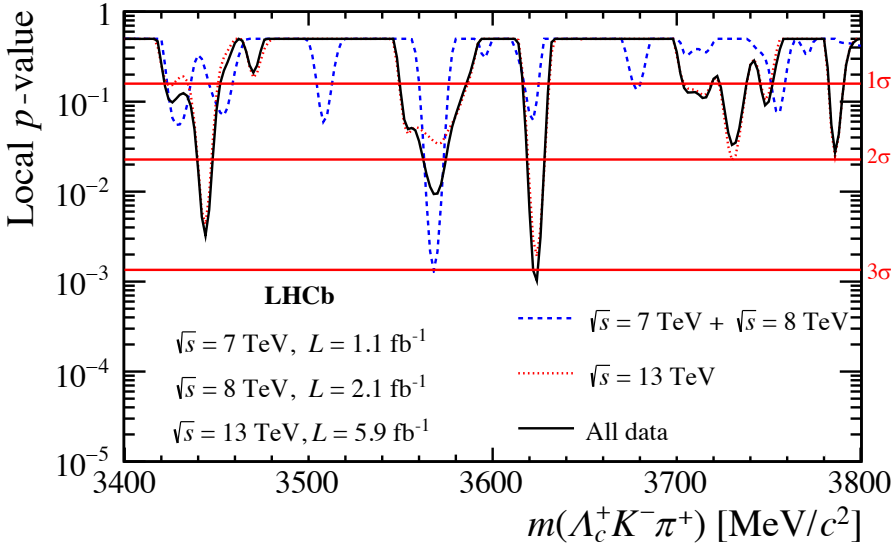
SELEX, 20% Λ_c^+ from Ξ_{cc}^+

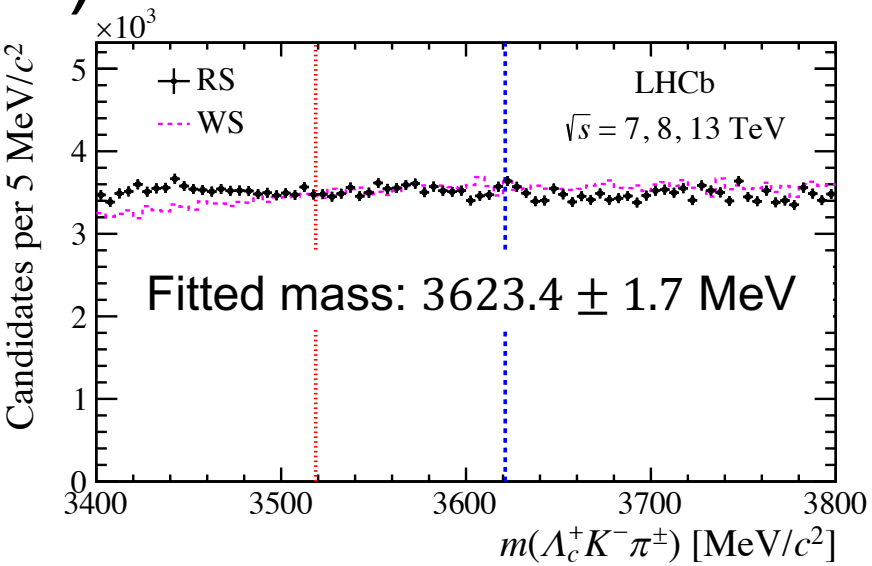


Search for Ξ_{cc}^{+}



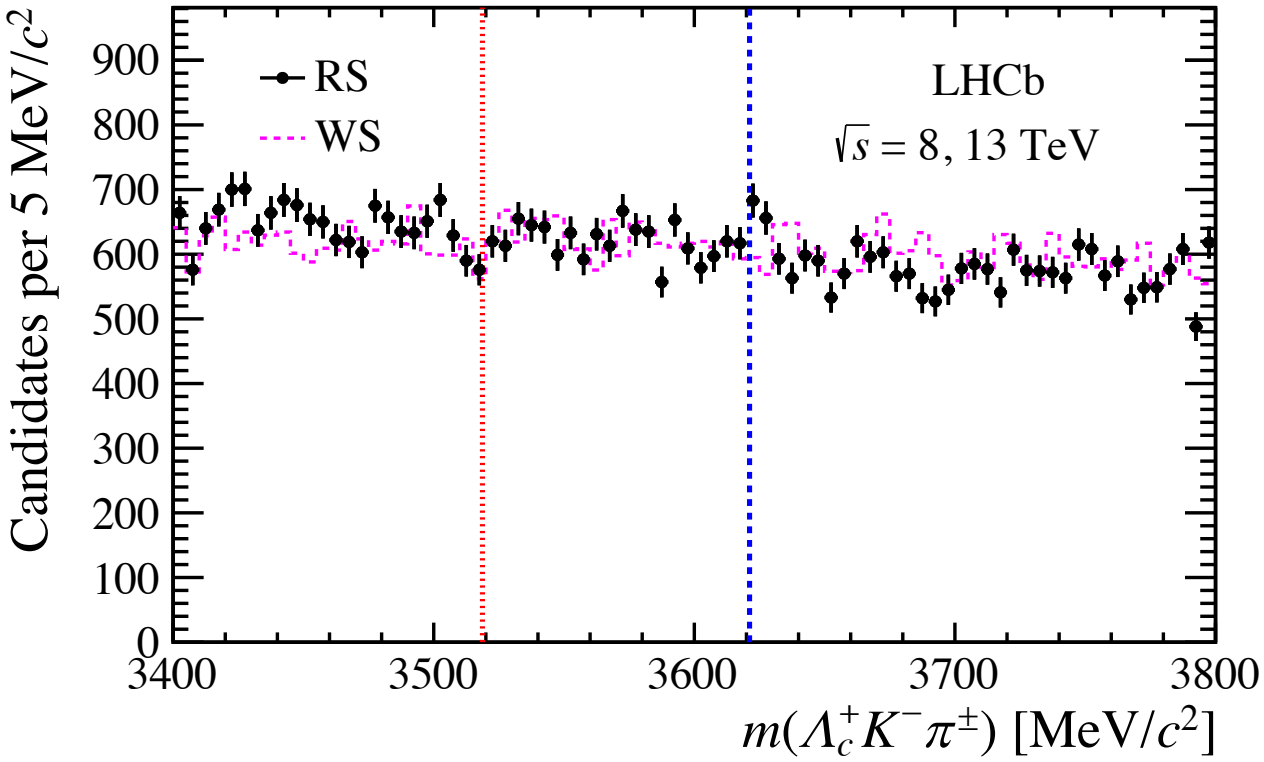
- Blinded analysis
- $\tau(\Xi_{cc}^{+})$: (0 fs, 80 fs) × (non)observation
- Evidence around Ξ_{cc}^{++}, with local (global) significance 3.1σ (1.7σ)





Unblinded Ξ_{cc}^{+} mass distribution

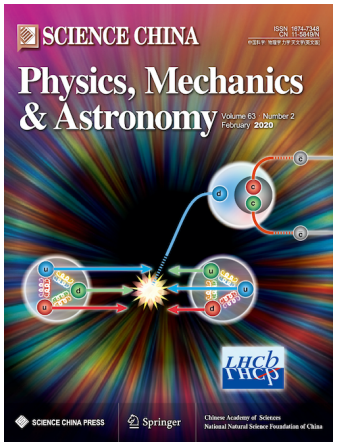
- Swtiching to event-selection designed for setting upper limit



[SCPMA 63 (2020) 221062]

Upper limits on Ξ_{cc}^{+} production

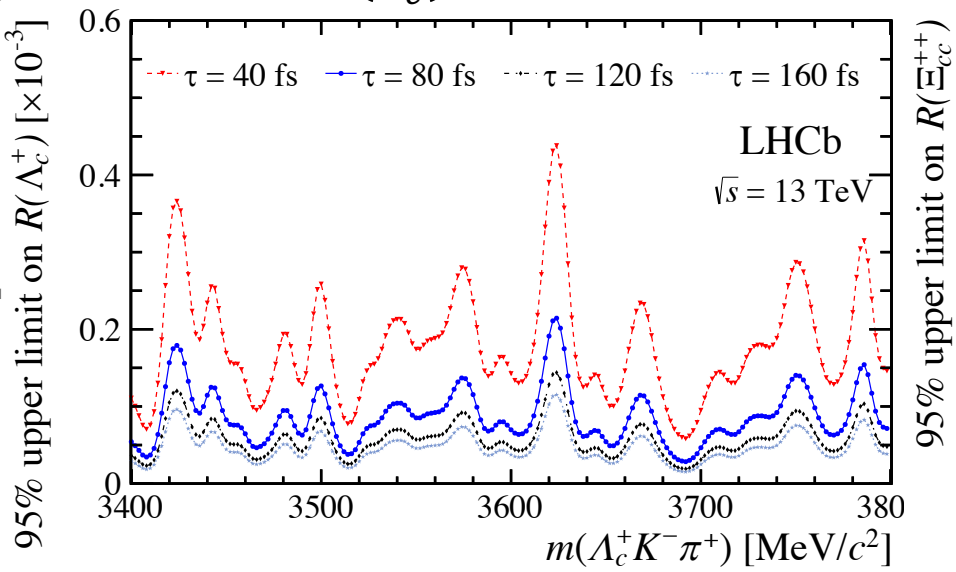
- UL relateive to Λ_c^+ and Ξ_{cc}^{++} in the fiducial region
  $4 < p_{\mathrm{T}} < 15$ GeV, 2<y<4.5

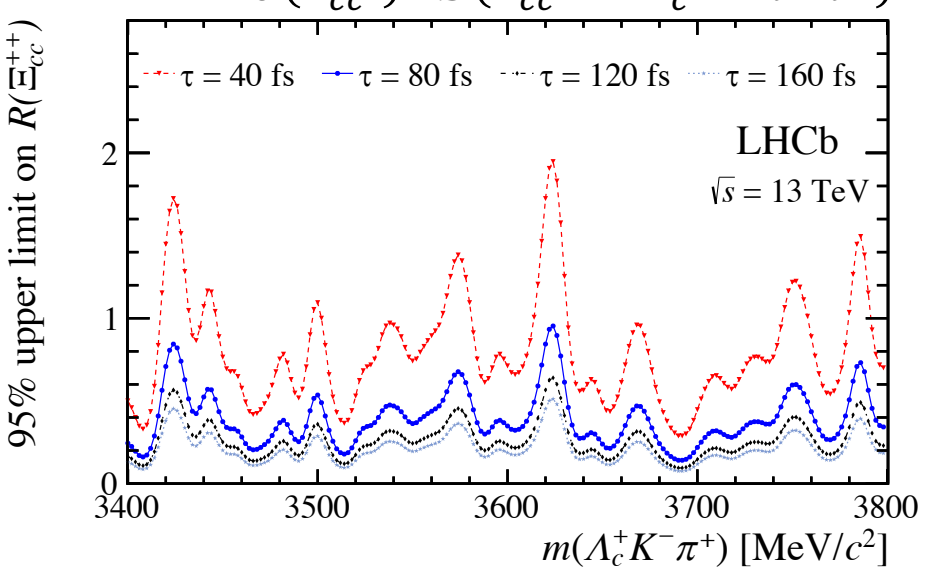


[SCPMA 63 (2020) 221062]

$$R(\Lambda_c^+) = \frac{\sigma(\Xi_{cc}^+)}{\sigma(\Lambda_c^+)}\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+)$$

$$R(\Xi_{cc}^{++}) = \frac{\sigma(\Xi_{cc}^+)\cdot\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+)}{\sigma(\Xi_{cc}^{++})\cdot\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)}$$





Doubly heavy baryon

- Mass
  - $M(\Xi_{bc}^+) \approx M(\Xi_{bc}^0)$: 6.7-7.2 GeV
  - $M(\Omega_{bc}^0) \approx M(\Xi_{bc}^+) + 100\ \mathrm{MeV}$
- Lifetime
  - $\tau(\Xi_{bc}^+) \approx \tau(\Xi_{bc}^0) \approx \tau(\Omega_{bc}^0)$: 100-500 fs
- Production [PRD 83 (2011) 034026]
  - $\sigma(bc) = 35\ \mathrm{nb}$ @ 13 TeV in LHCb, c.f. $\sigma(cc) = 90\ \mathrm{nb}$
  - $f_{\mathrm{frag}}\ u:d:s \sim 1:1:0.3$

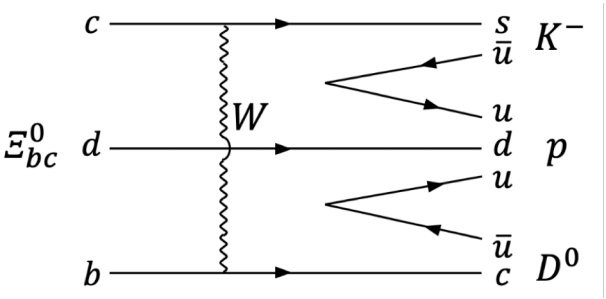
    $\sigma(\Xi_{bc}^+) = \sigma(\Xi_{bc}^0) \sim 15\ \mathrm{nb}$

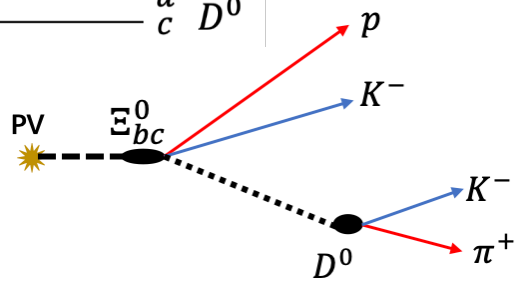
    $\sigma(\Omega_{bc}^0) \sim 5\ \mathrm{nb}$

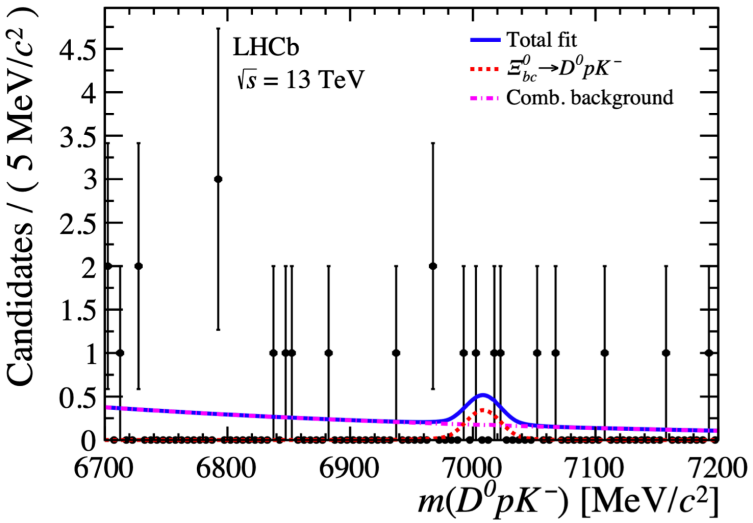
First search for Ξ_{bc}^0

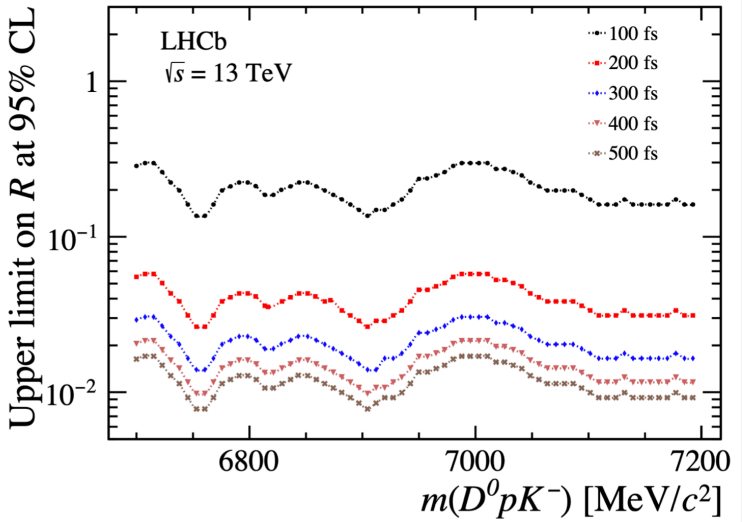
- $\Xi_{bc}^0 \to D^0 p K^-$
- No obvious signal, UL as function of m/τ on

$$R = \frac{\sigma(\Xi_{bc}^0) \cdot \mathcal{B}(\Xi_{bc}^0 \to D^0 p K^-)}{\sigma(\Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to D^0 p K^-)}$$



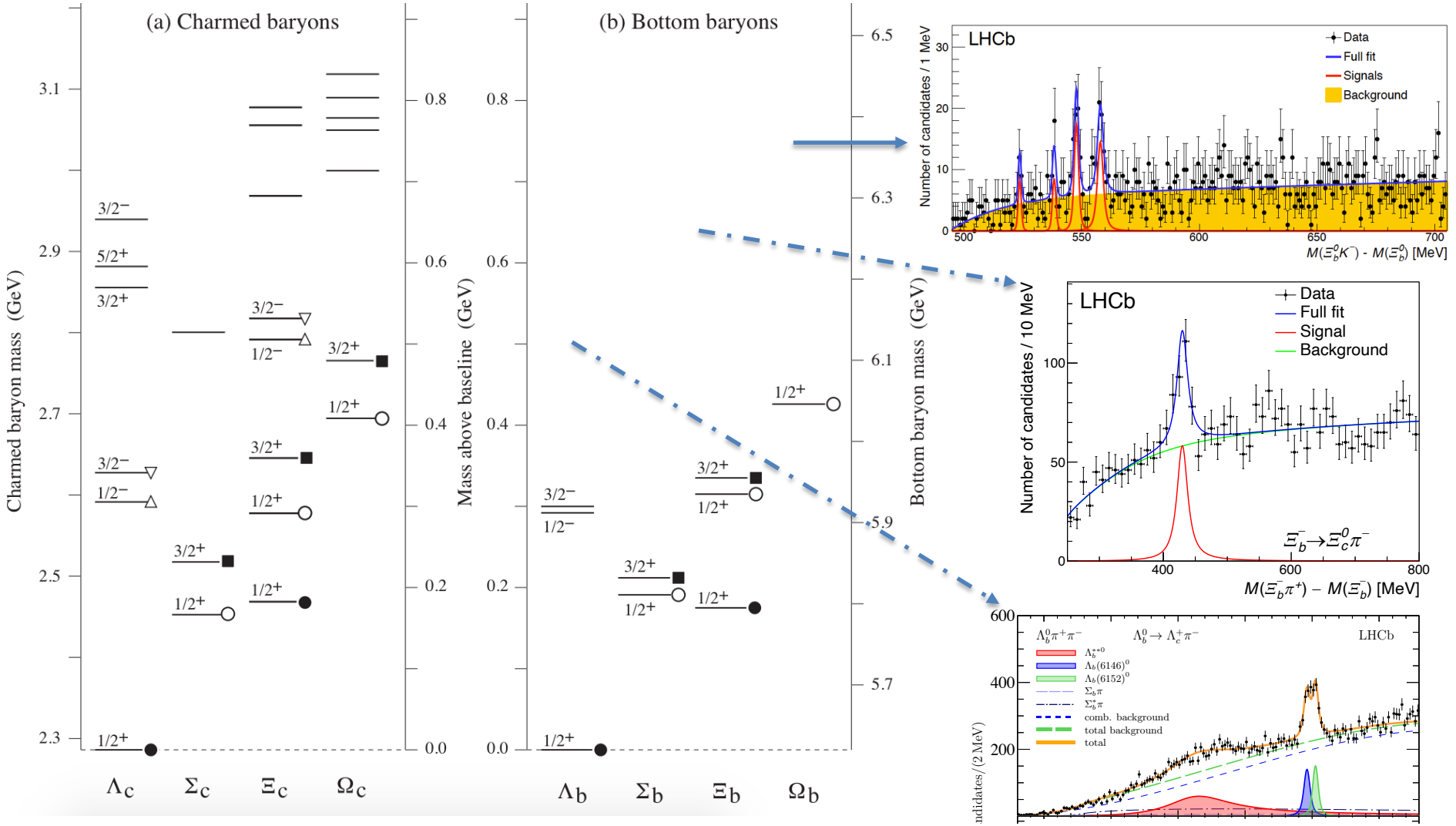






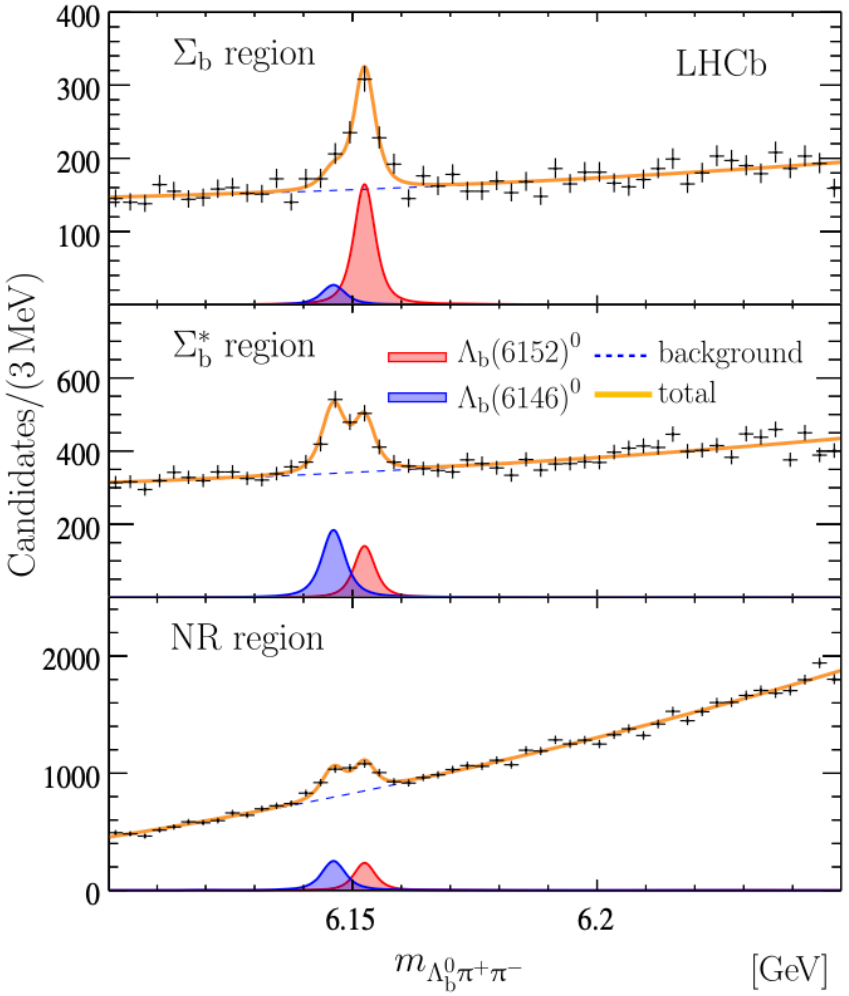
[JHEP 11 (2020) 095]

Beauty baryon



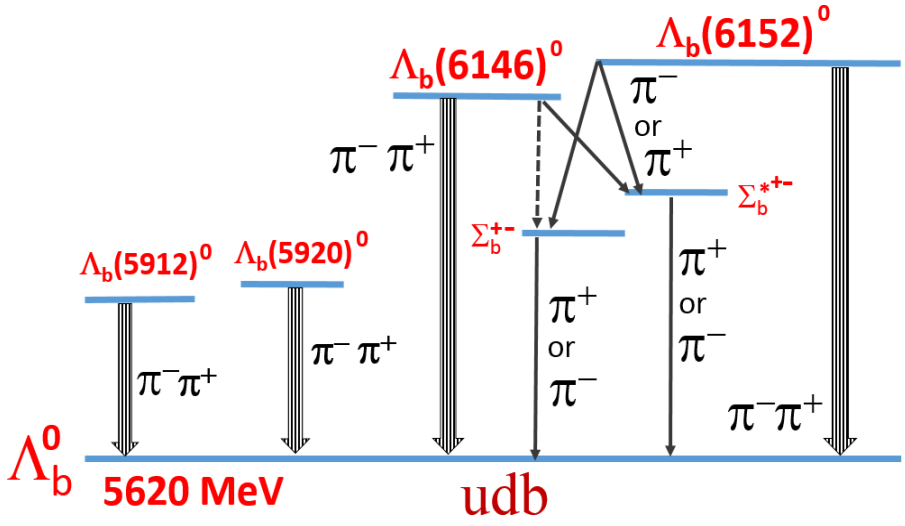
Excited Λ_b/Σ_b states

[PRL 123 (2019) 152001]



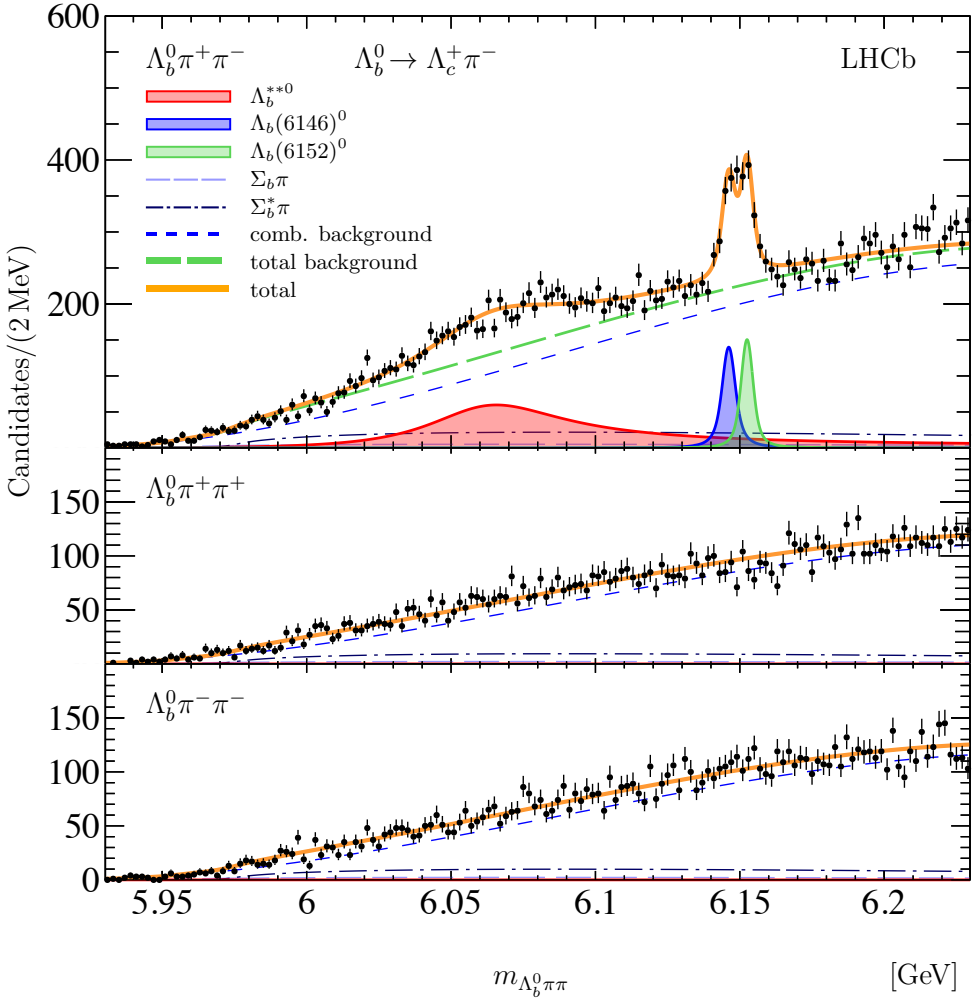
$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3 \text{ MeV},$$

1D Λ_b^0 or neutral Σ_b?



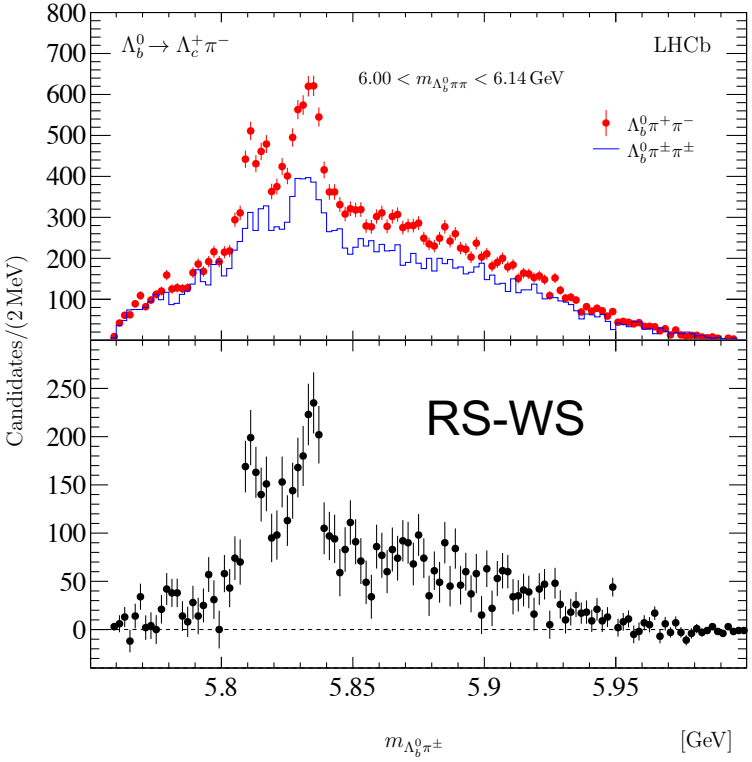
Excited Λ_b/Σ_b states

[JHEP 06 (2020) 136]



$$m = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\text{MeV},$$
$$\Gamma = 72 \pm 11 \pm 2\,\text{MeV},$$

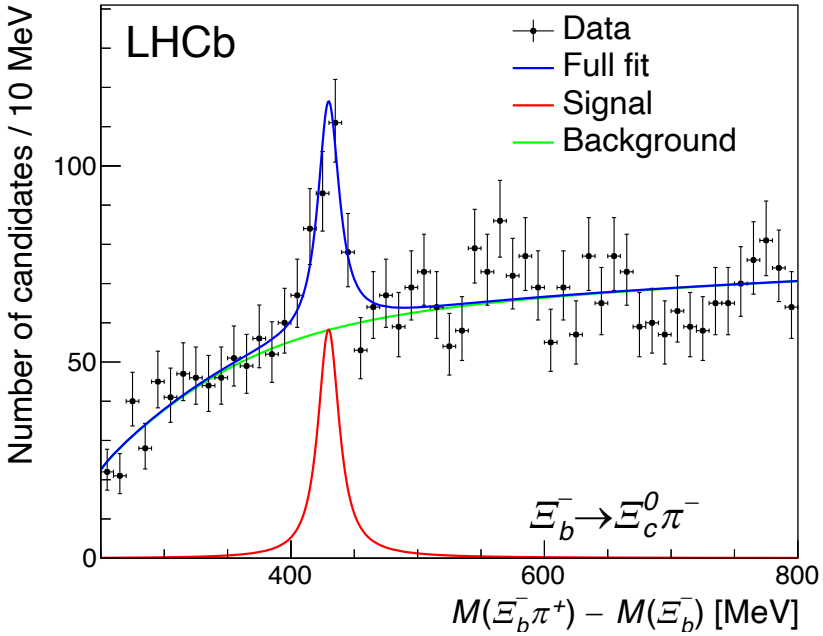
Consistent with 2S Λ_b^0

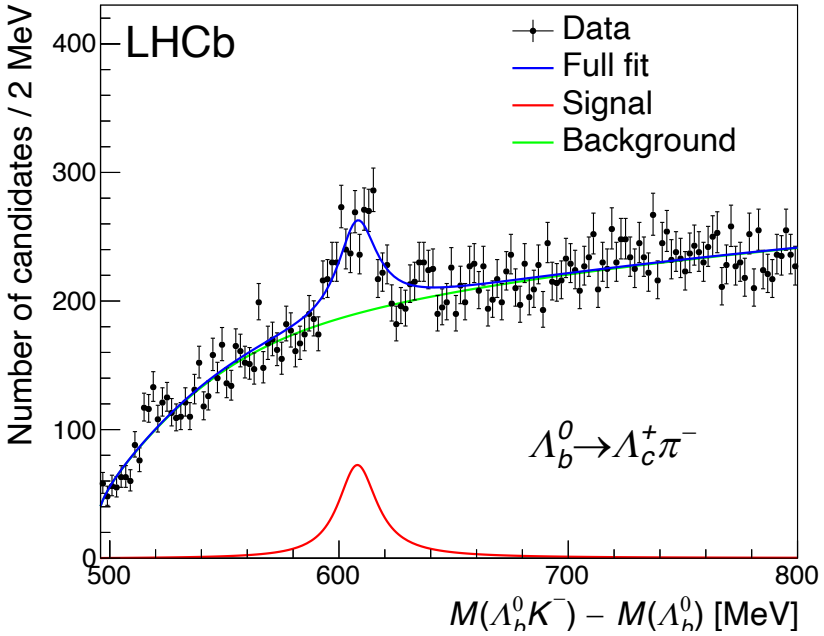


Excited Ξ_b states

- Netural $\Xi_b(6227)$ with $\Xi_b^- \pi^+, \Xi_b^- \to \Xi_c^0 \pi^-$

[PRD 103 (2021) 012004]





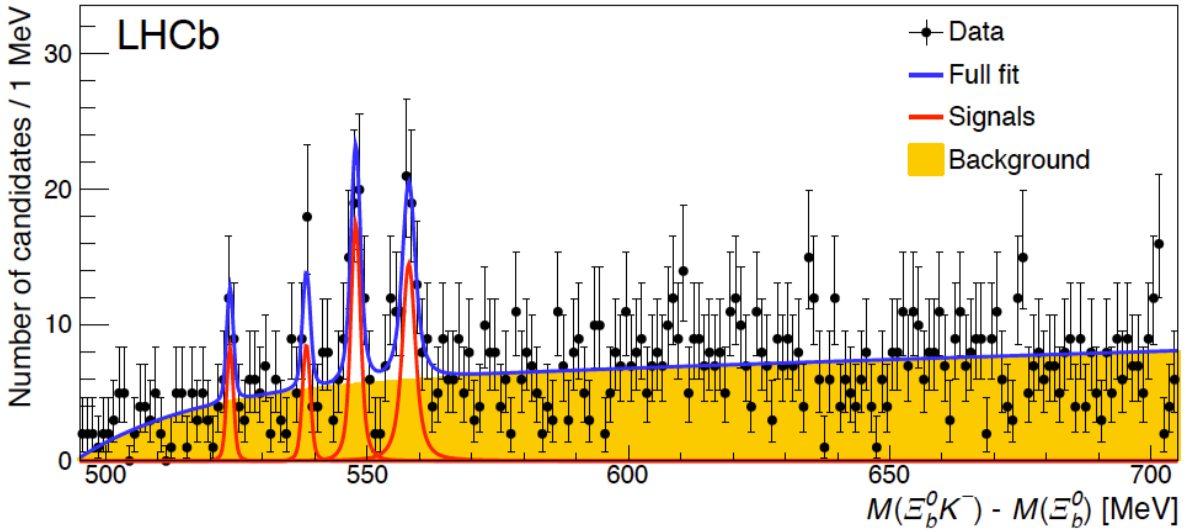
$$\delta m_\pi^{\text{peak}} = 429.8\,^{+1.4}_{-1.5} \pm 0.3\,\text{MeV}, \qquad \delta m_K^{\text{peak}} = 608.3 \pm 0.8 \pm 0.4\,\text{MeV},$$

$$m(\Xi_b(6227)^0) = 6227.1\,^{+1.4}_{-1.5} \pm 0.5\,\text{MeV}, \qquad m(\Xi_b(6227)^-) = 6227.9 \pm 0.8 \pm 0.5\,\text{MeV},$$

$$\Gamma(\Xi_b(6227)^0) = 18.6\,^{+5.0}_{-4.1} \pm 1.4\,\text{MeV}, \qquad \Gamma(\Xi_b(6227)^-) = 19.9 \pm 2.1 \pm 1.5\,\text{MeV},$$

Excited Ω_b states

- Four states decaying to $\Xi_b^0 K^-, \Xi_b^0 \to \Xi_c^+ \pi^-$

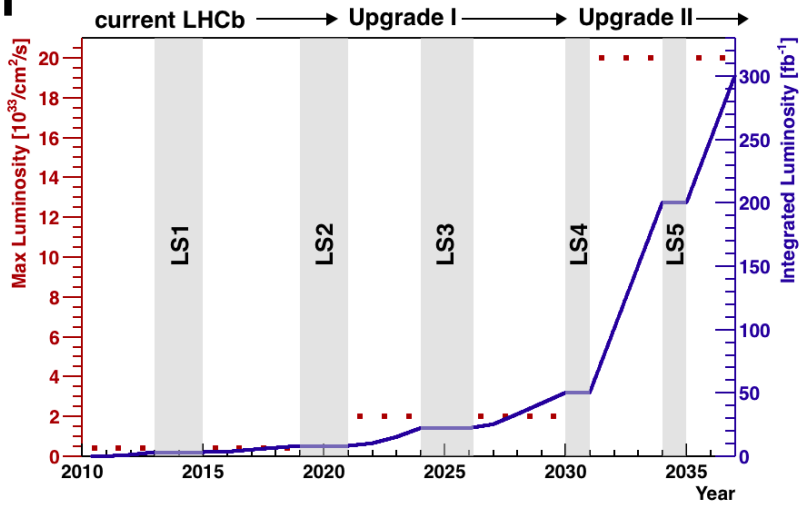


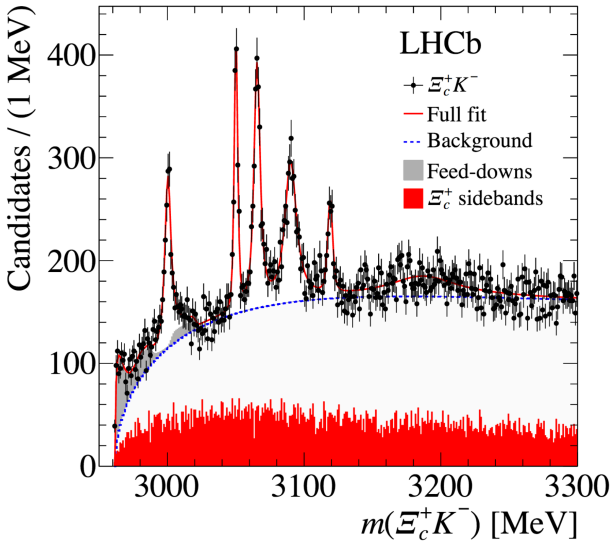
[PRL 124 (2020) 082002]

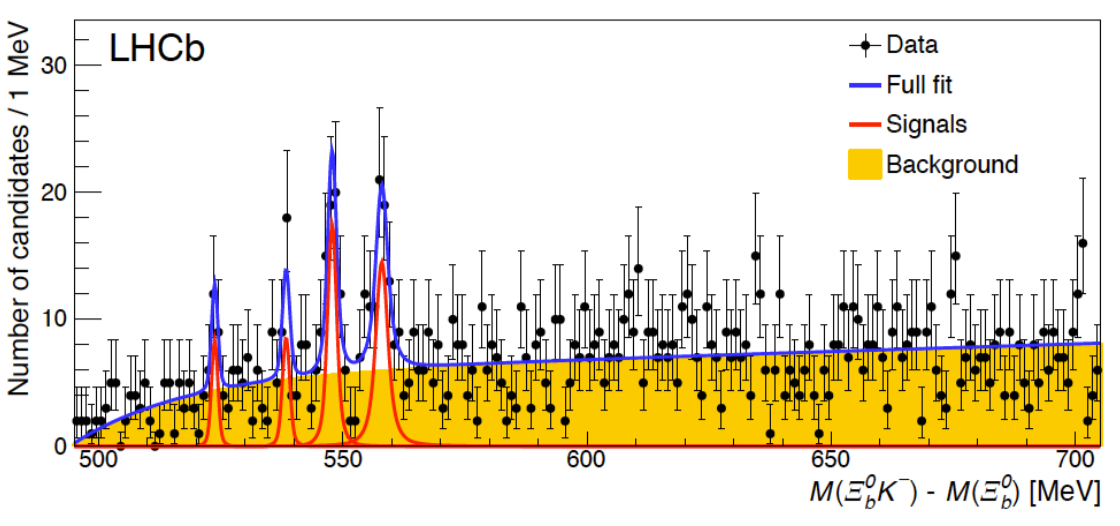
State	Mass [MeV]	Width [MeV] (90% UL)	Nsig	Local significance	Global significance
$\Omega_b(6316)^-$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	<2.8	15^{+6}_{-5}	3.6	2.1
$\Omega_b(6330)^-$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	<3.1	18^{+6}_{-5}	3.7	2.6
$\Omega_b(6340)^-$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	<1.5	47^{+11}_{-10}	**7.2**	**6.7**
$\Omega_b(6350)^-$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	<2.8 $1.4^{+1.0}_{-0.8} \pm 0.1$	57^{+14}_{-13}	**7.0**	**6.2**

Prospects

- Beauty/charmed baryon
- Doubly heavy baryon
  - $\Xi_{cc}^{++} \Longrightarrow \Xi_{cc}^{+} \Longrightarrow \Omega_{cc}^{+}$, excited states
  - $\Xi_{bc}^{+/0}$, Ω_{bc}^{0}

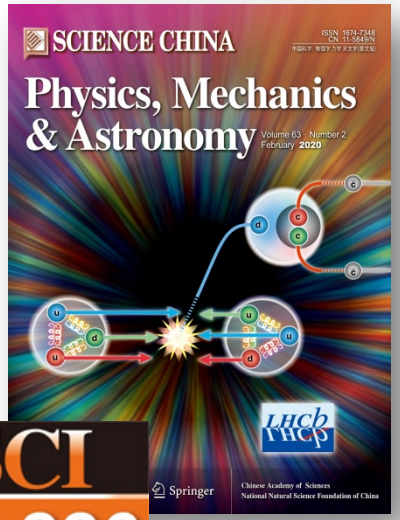






Summary

- LHCb has done world-leading works on charmed & beauty baryon spectroscopy
  - Charmed baryon, e.g., excited Ω_c/Ξ_c states
  - Doubly heavy hadrons, e.g., Ξ_{cc}^{++}
  - Beauty baryon, e.g., excited Ω_b/Ξ_b states
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your suggestions are always welcome



SCI 4.226 IMPACT FACTOR | Q1

Science China Physics, Mechanics & Astronomy

- **Editor's Focus:** aim at PRL quality, fast channel
- Full-text HTML and timely publication (online immediately)
- Highlighted at EurekAlert and other public media

Editor's Focus

Scan the QR code Get the news

Scientia Sinica Physica, Mechanica & Astronomica

- Since 1950, in Chinese
- Indexed in Scopus, ESCI, etc.
- Special topic is encouraged, published over 50 special topics

Supervised by 中国科学院 CHINESE ACADEMY OF SCIENCES | Sponsored by 中国科学院 CHINESE ACADEMY OF SCIENCES, 国家自然科学基金委员会 National Natural Science Foundation of China | Published by 《中国科学》杂志社 SCIENCE CHINA PRESS, Springer