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Recent LHCb results in charm spectroscopy

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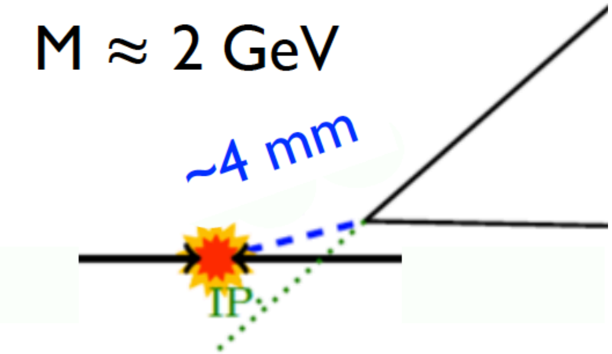
presented at ICHEP 2018 @Seoul, 07/2018

Outline

- Singly charmed baryon
  - Λ_c^* states
  - Ω_c^* states
- Doubly charmed baryon
  - Ξ_{cc}^{++} observation
  - Ξ_{cc}^{++} lifetime
  - $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
- Please refer to LHCb webpage for more results

Charm production / signature

- Large production cross-section @ 7 TeV
  - Minimum bias ~60 mb
  - Charm ~6 mb

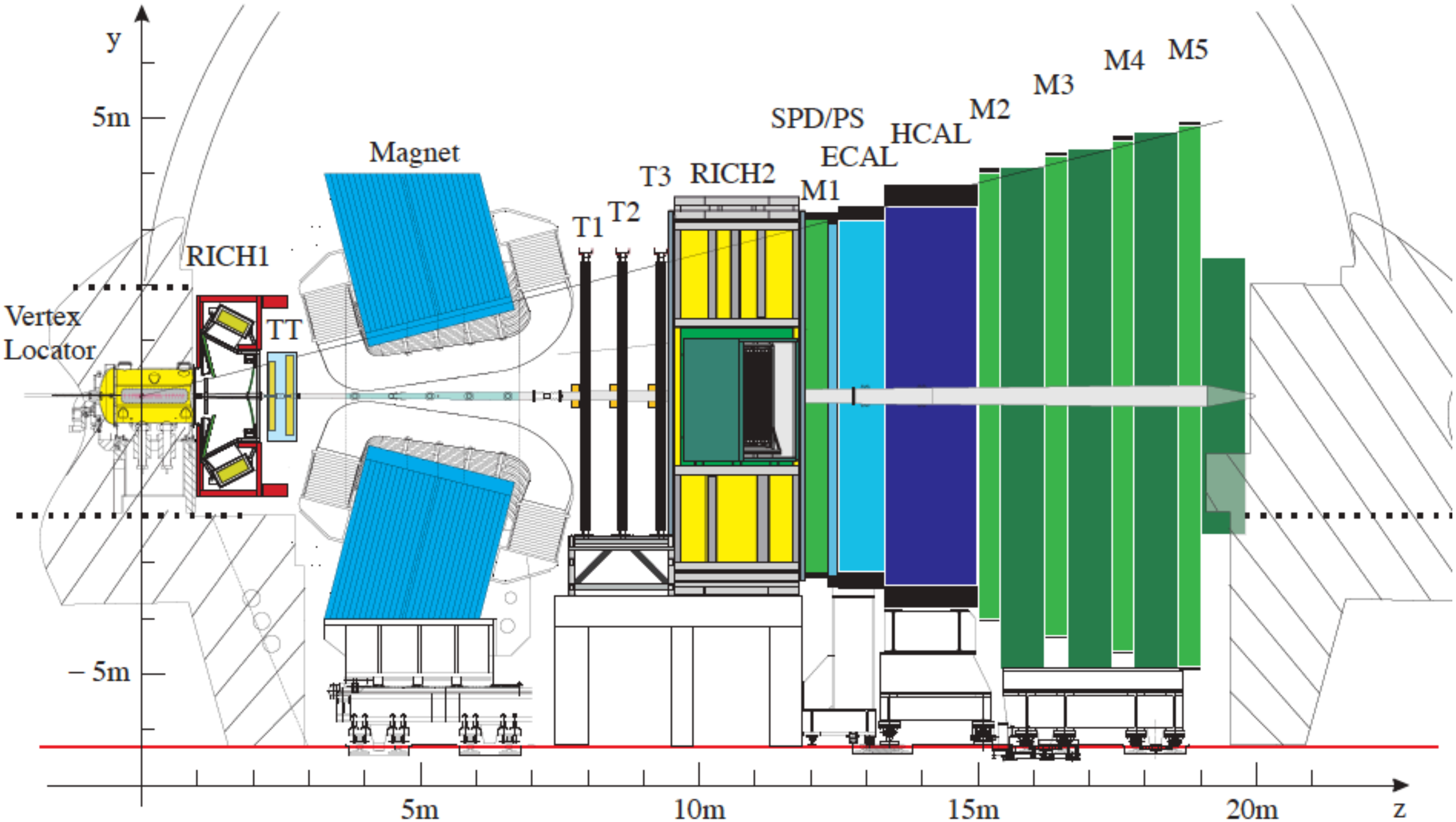


- Charm, compared to minimum bias (bkg)
  - Relatively high mass → high p_T
  - Relatively long lifetime → large IP
- Requires excellent vertexing, tracking, PID

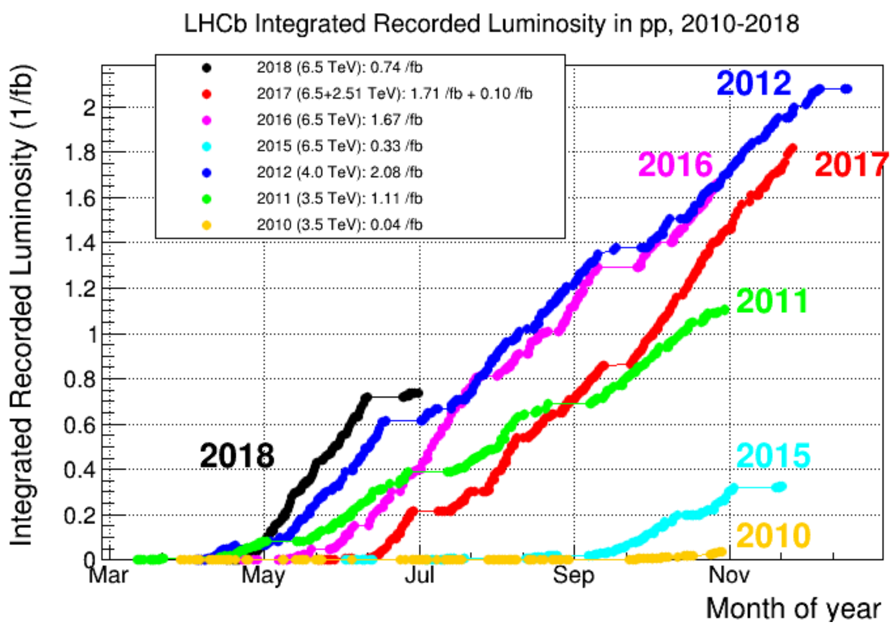
The LHCb experiment

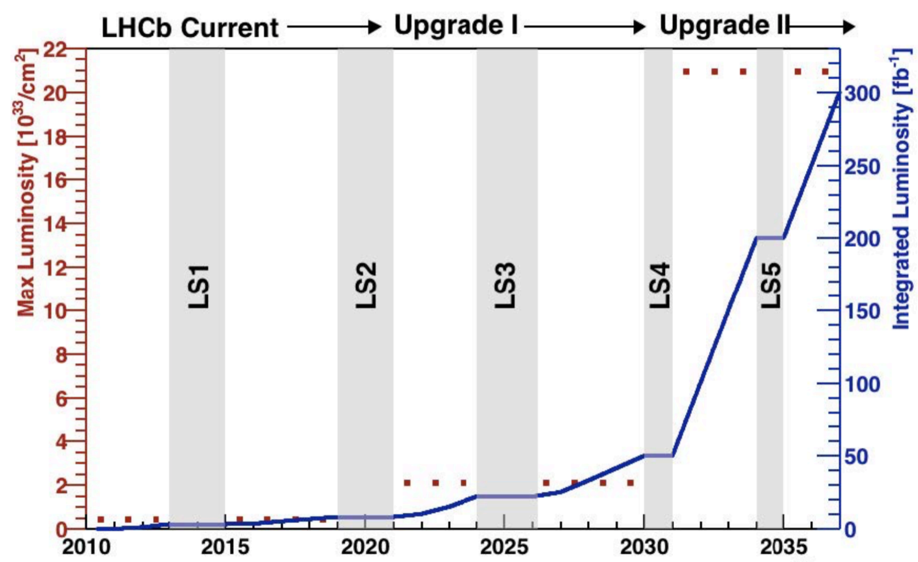
- Dedicated to precision study of *b/c*-hadrons

[JINST 3 (2008) S08005]



LHCb luminosity prospects





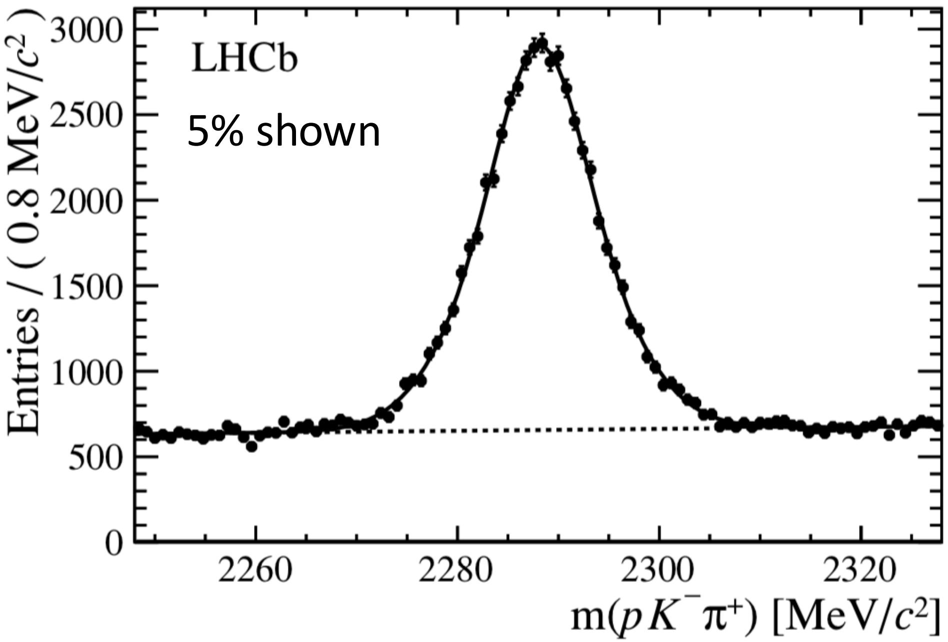
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

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

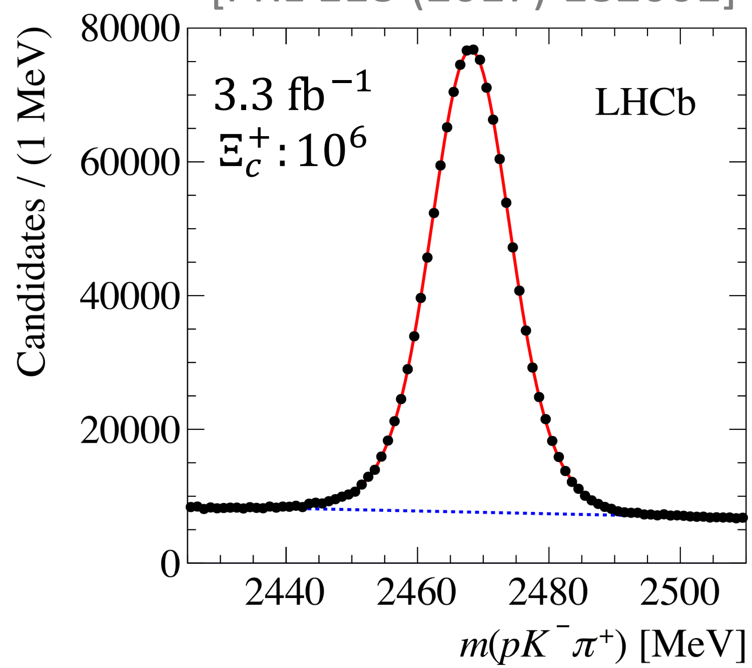
Lots of singly charmed baryons

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

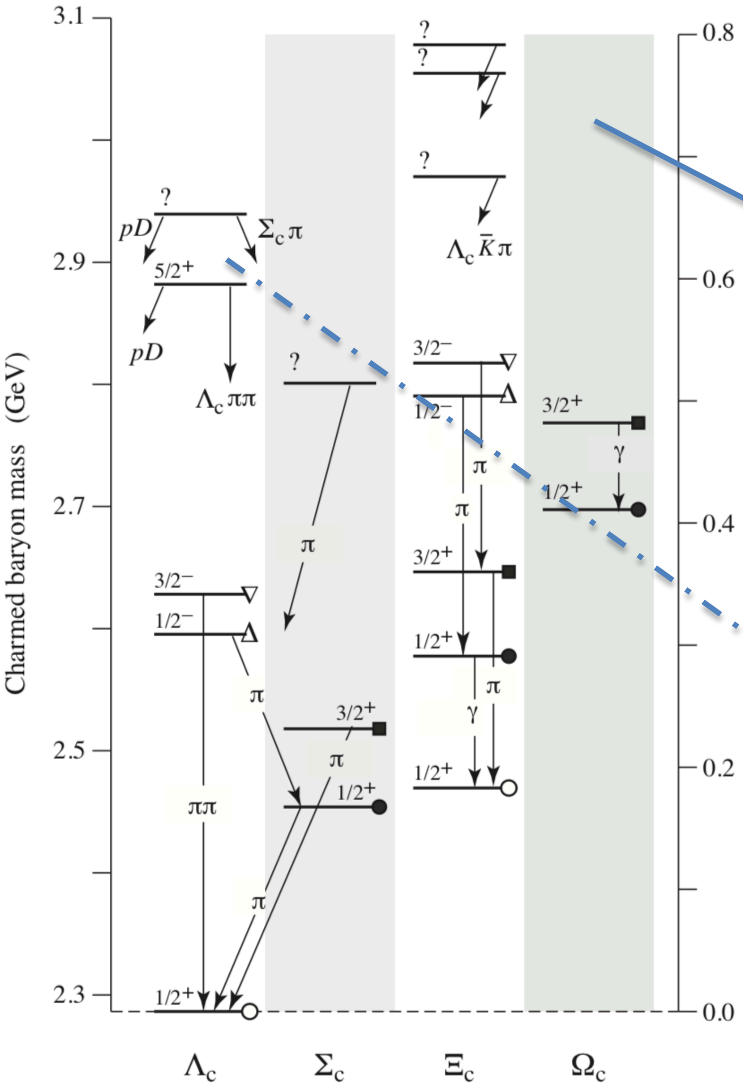
[JHEP 12 (2013) 90]

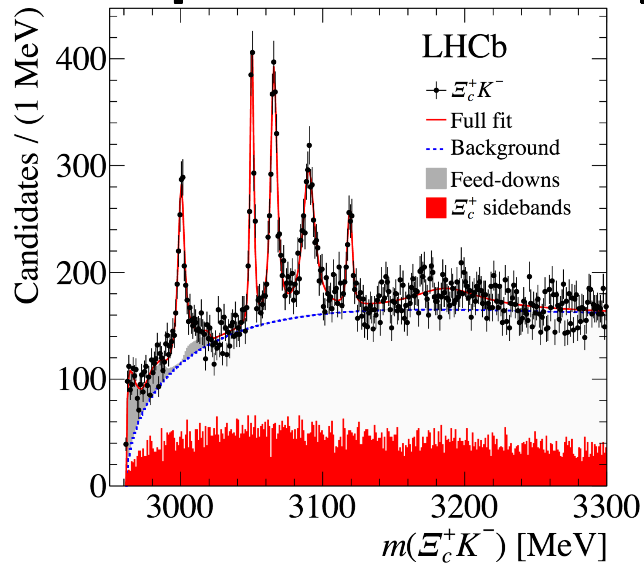


[PRL 118 (2017) 182001]

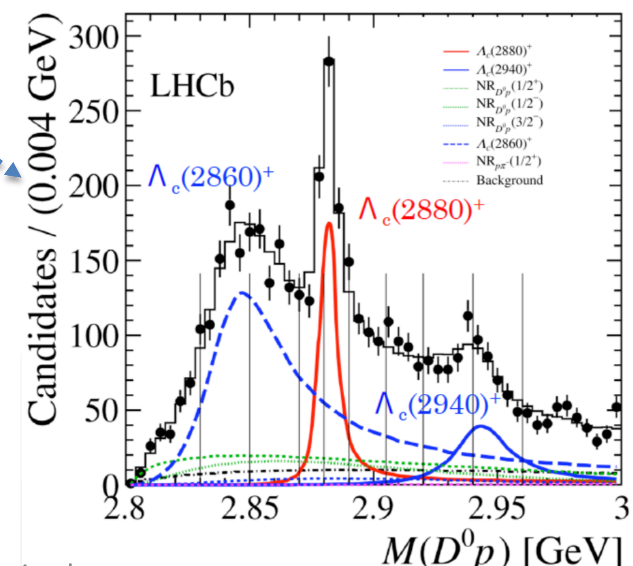


Charmed baryon spectroscopy





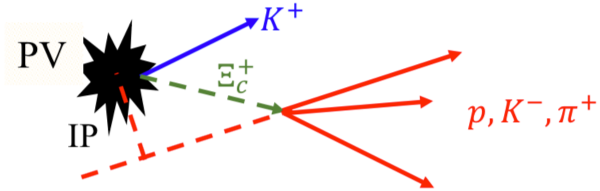
[PRL 118 (2017) 182001]



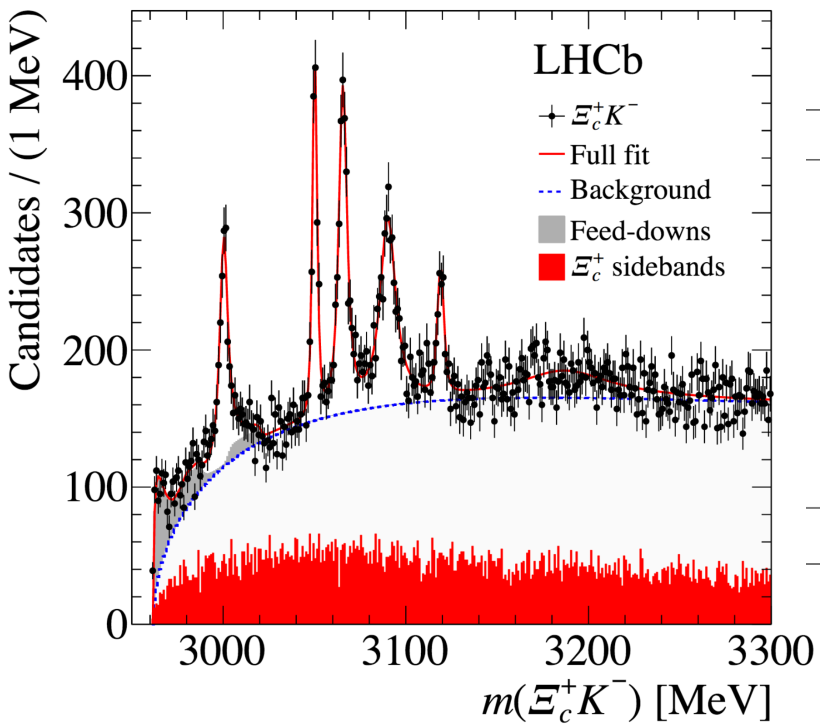
[JHEP 05 (2017) 030]

Observation of excited Ω_c states

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



[PRL 118 (2017) 182001]

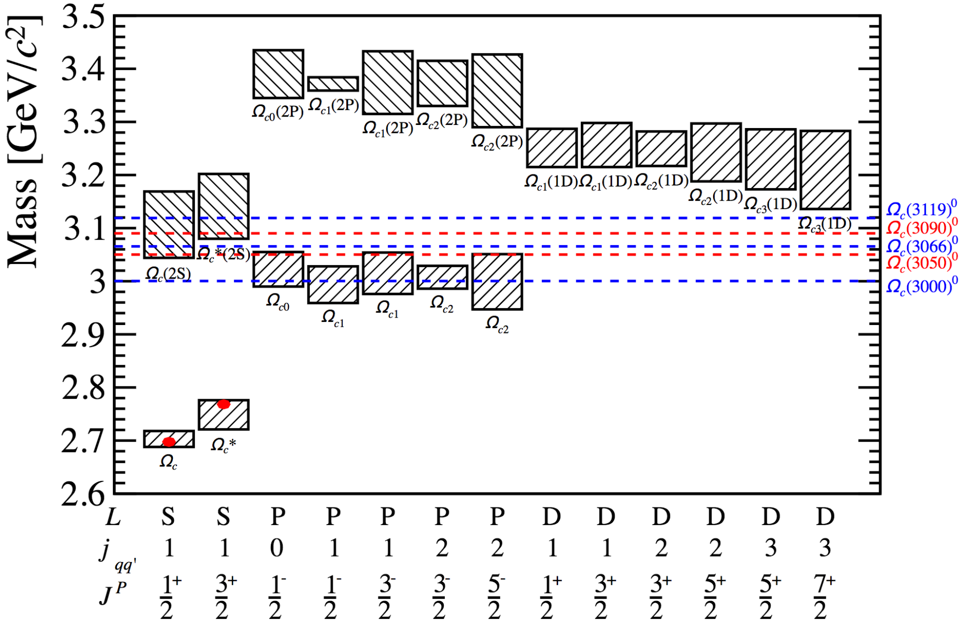


Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		< 1.2 MeV, 95% CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	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

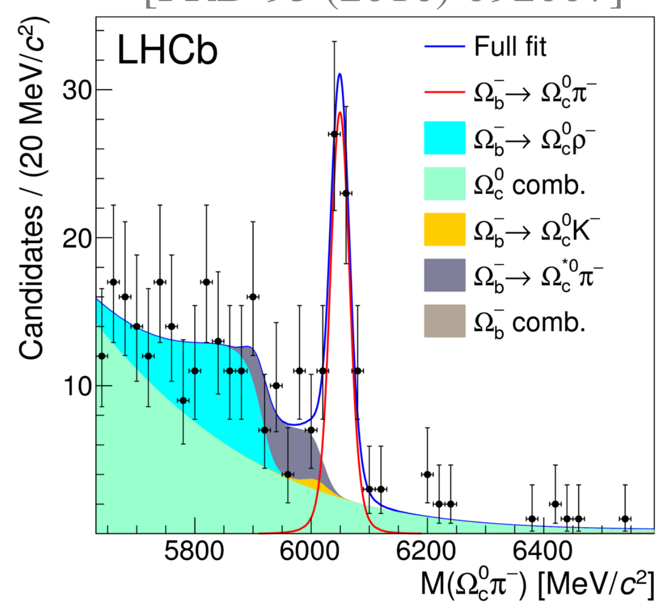
Understand these Ω_c states?

- Matching between observed peaks and predictions requires spin-parity info
  - Not easy in direct production due to unknown polarization, maybe try $\Omega_b \to \Omega_c^* \pi^-$?

[PRL 118 (2017) 182001]



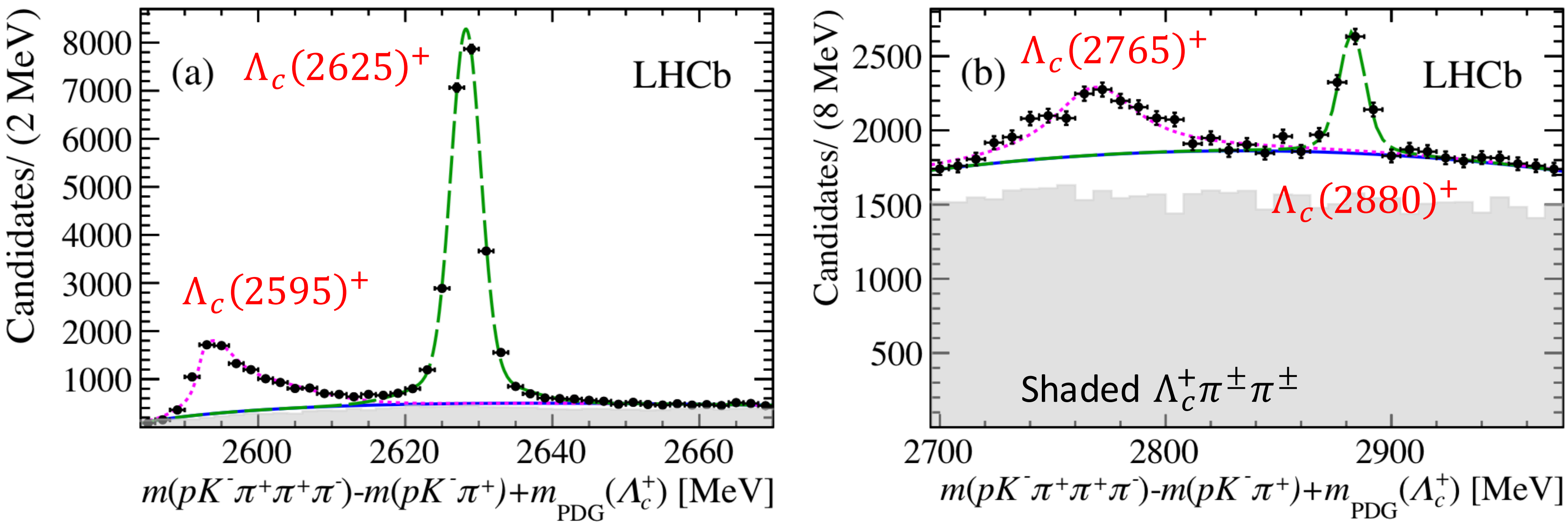
[PRD 93 (2016) 092007]



Λ_c^* states with semileptonic Λ_b^0 decay

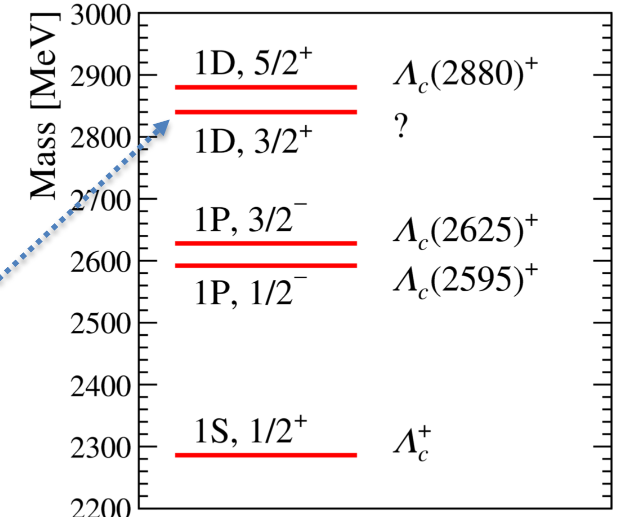
[PRD 96 (2017) 112005]

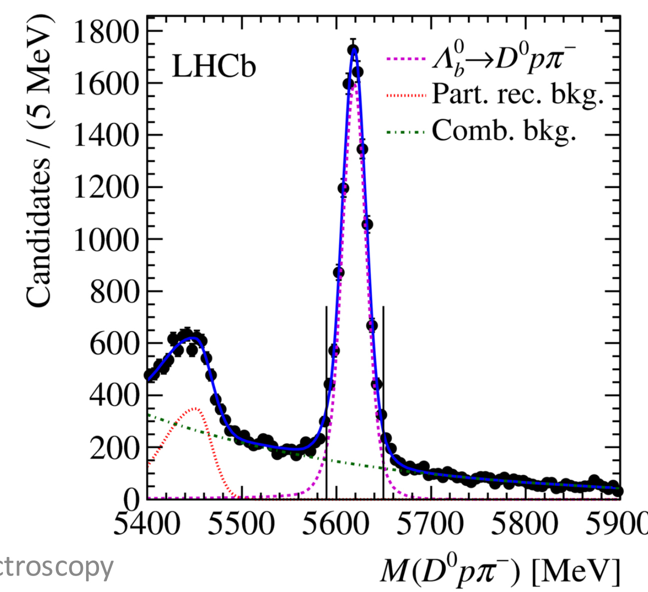
- Studied with $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\mu^-\bar{\nu}_\mu$
- New sightings from LHCb



Λ_c^* states

- The excited states are 1P & 1D doublets, small mass splitting, but one missing state, and no place for $\Lambda_c(2765)^+$
- Look for $\Lambda_b^0 \rightarrow D^0 p\pi^-$, $\Lambda_c^* \rightarrow D^0 p$





[JHEP 05 (2017) 030]

Λ_c^* states in $\Lambda_b^0 \to D^0 p \pi^-$

[JHEP 05 (2017) 030]

- Amplitude analysis (5D) of the angular distributions of the $\Lambda_b^0 \to D^0 p \pi^-$ decay
- New state at 2860 MeV, part of $J^P = 3/2^+$ (doublet)?

$\Lambda_c(2860)^+$ with $J^P = 3/2^+$ (preferred)

$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV}$

$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$

$\Lambda_c(2880)^+$ with $J^P = 3/2$ (preferred)

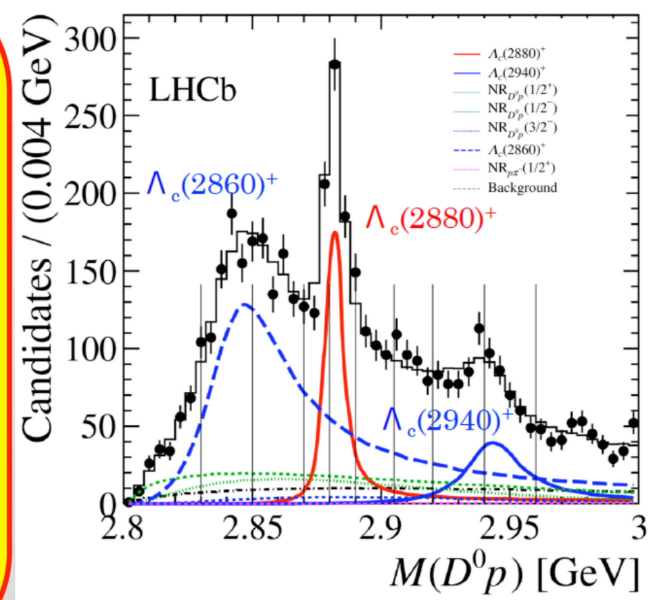
$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\ \text{MeV}$

$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\ \text{MeV}$

$\Lambda_c(2940)^+$ with $J^P = 3/2^-$ (preferred)

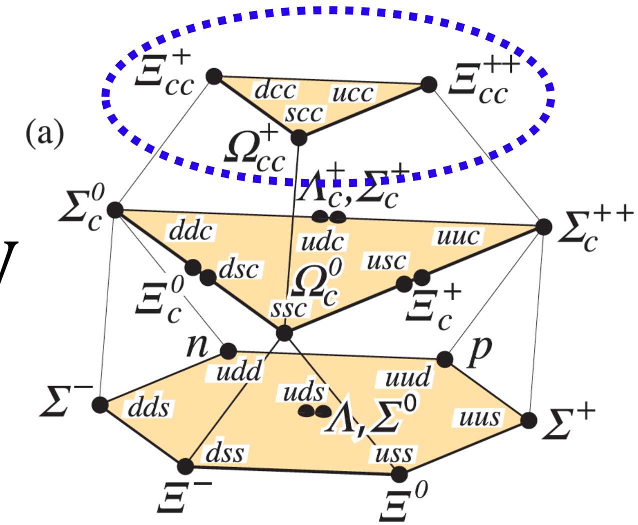
$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\ \text{MeV}$

$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\ \text{MeV}$

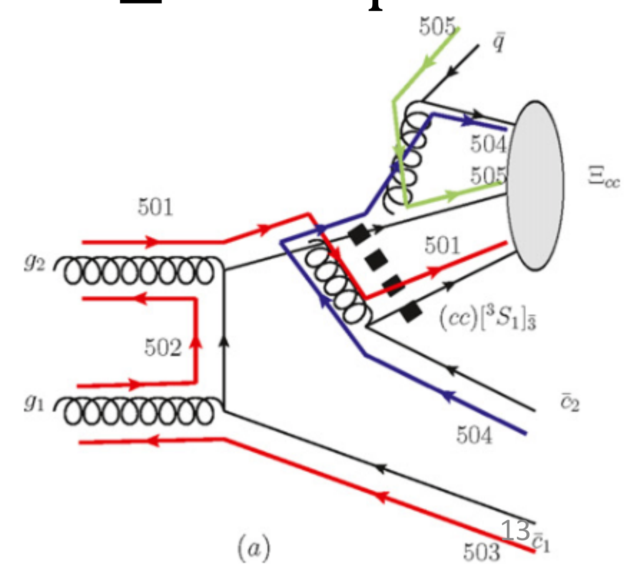


Doubly charmed baryon

- Mass
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$
    $= 3621.24 \pm 0.72$ MeV
  - $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}^{++}) + 100$ MeV

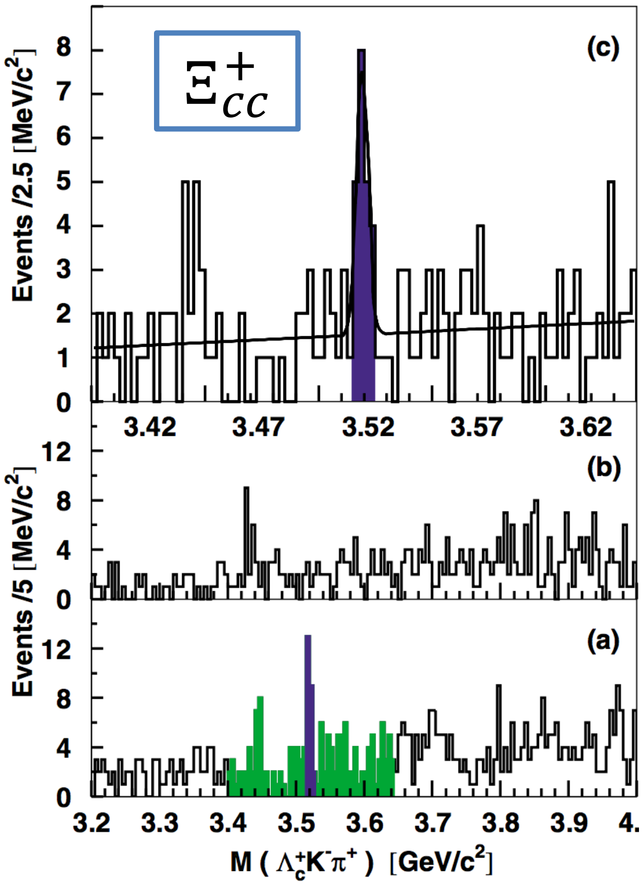


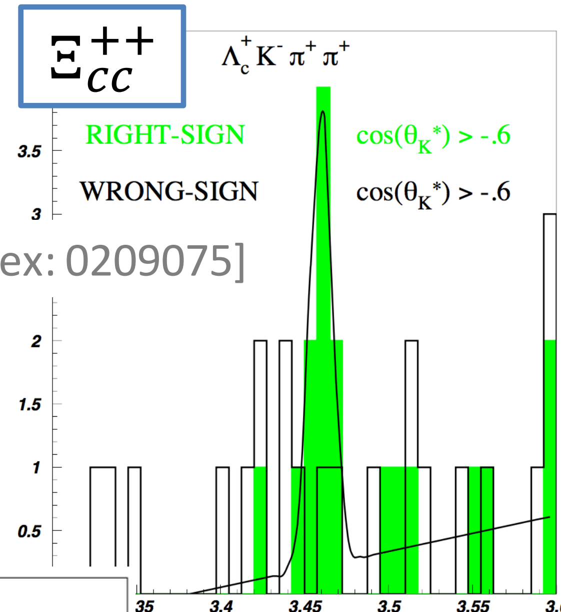
- Lifetime
  - $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027$ ps
- Production [PRD 83 (2011) 034026]
  - $\sigma(cc) = 90$ nb @ 13 TeV in LHCb
  - $f_{\text{frag}}\ u : d : s \sim 1 : 1 : 0.3$
    $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40$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



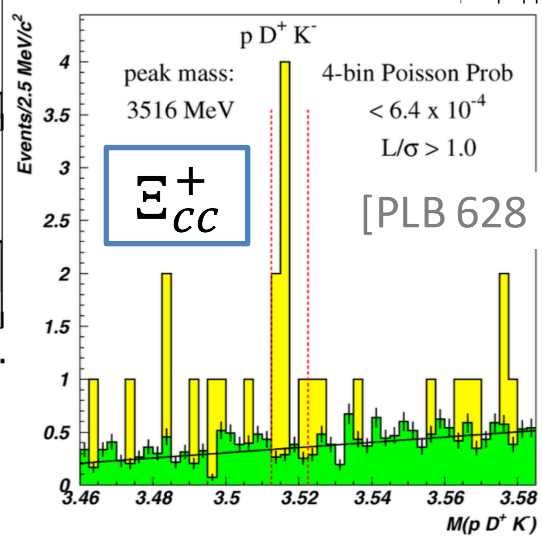
Ξ_{cc} @ SELEX

[PRL 89 (2002) 112001]





[hep-ex: 0209075]

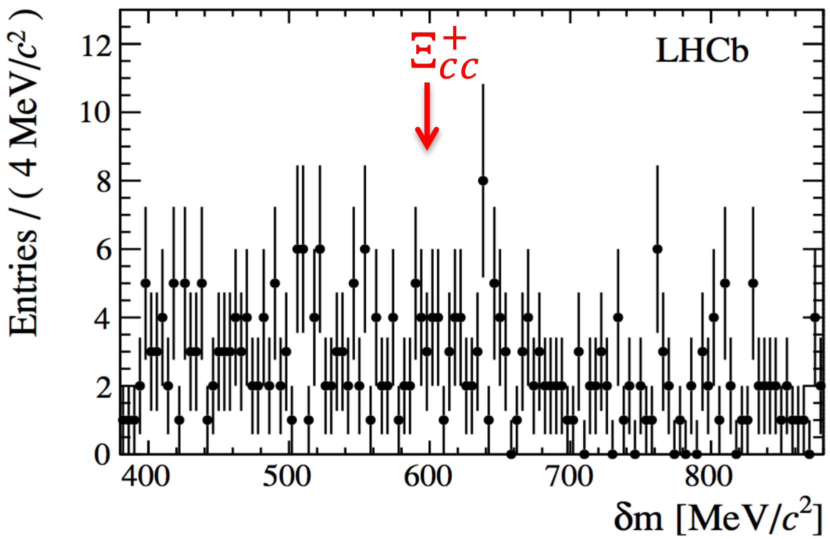


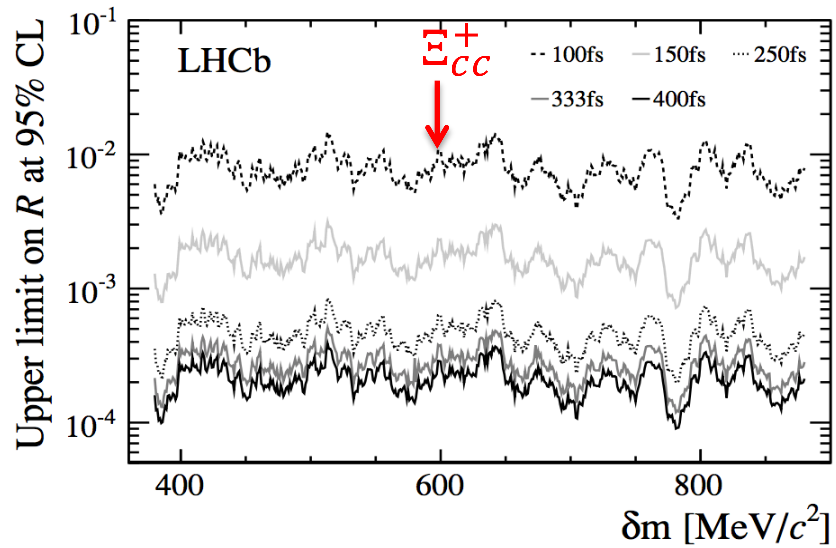
[PLB 628 (2005) 18]

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]

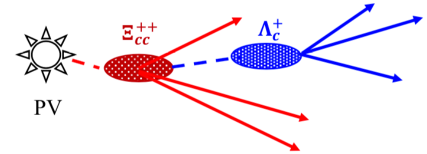


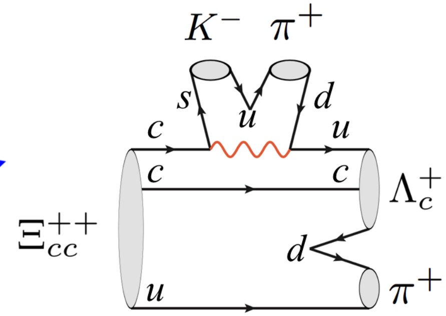


Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

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

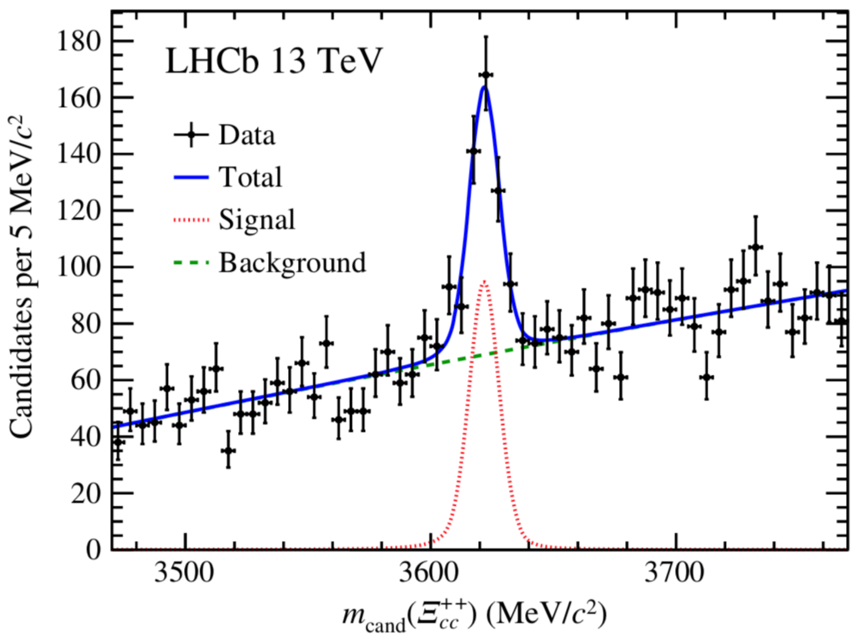
[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

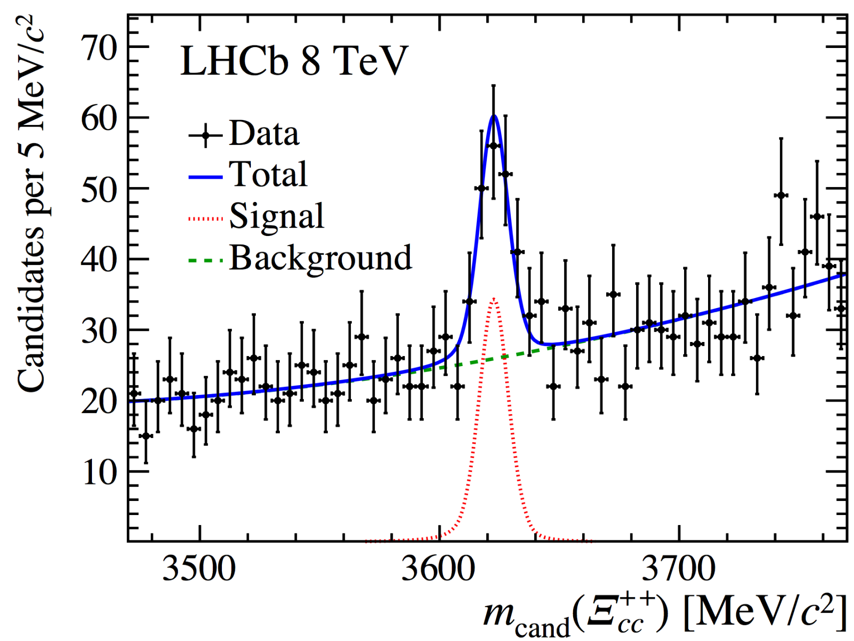




- First observation, in 2016 (>12σ) & Run-I (>7σ)

[PRL 119 (2017) 112001]





Ξ_{cc}^{++} properties

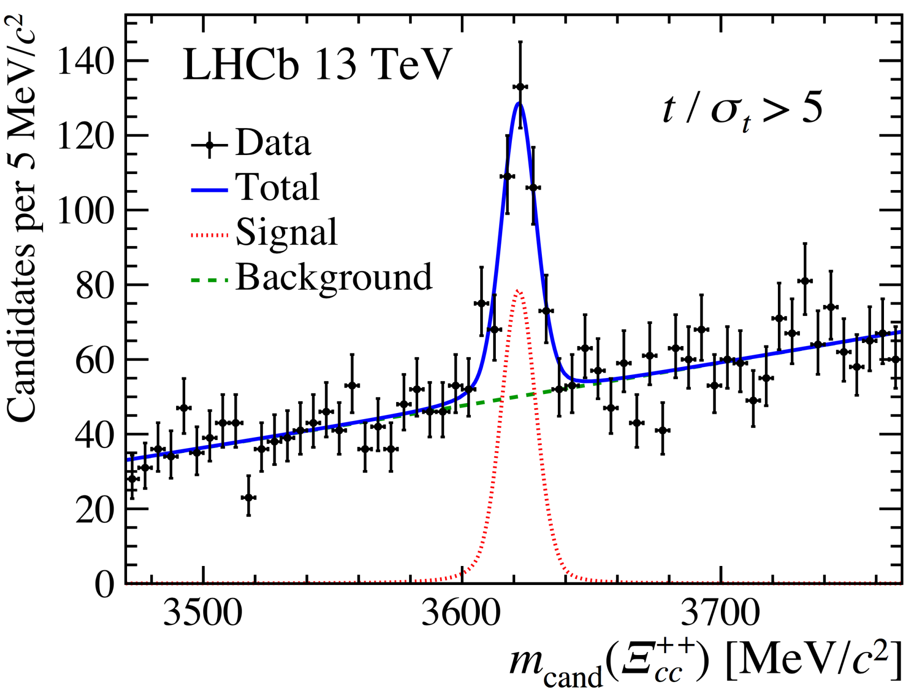
- Ξ_{cc}^{++} mass measured:
  $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$

  SELEX: m(Ξ_{cc}^{+})=3519±1 MeV

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

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

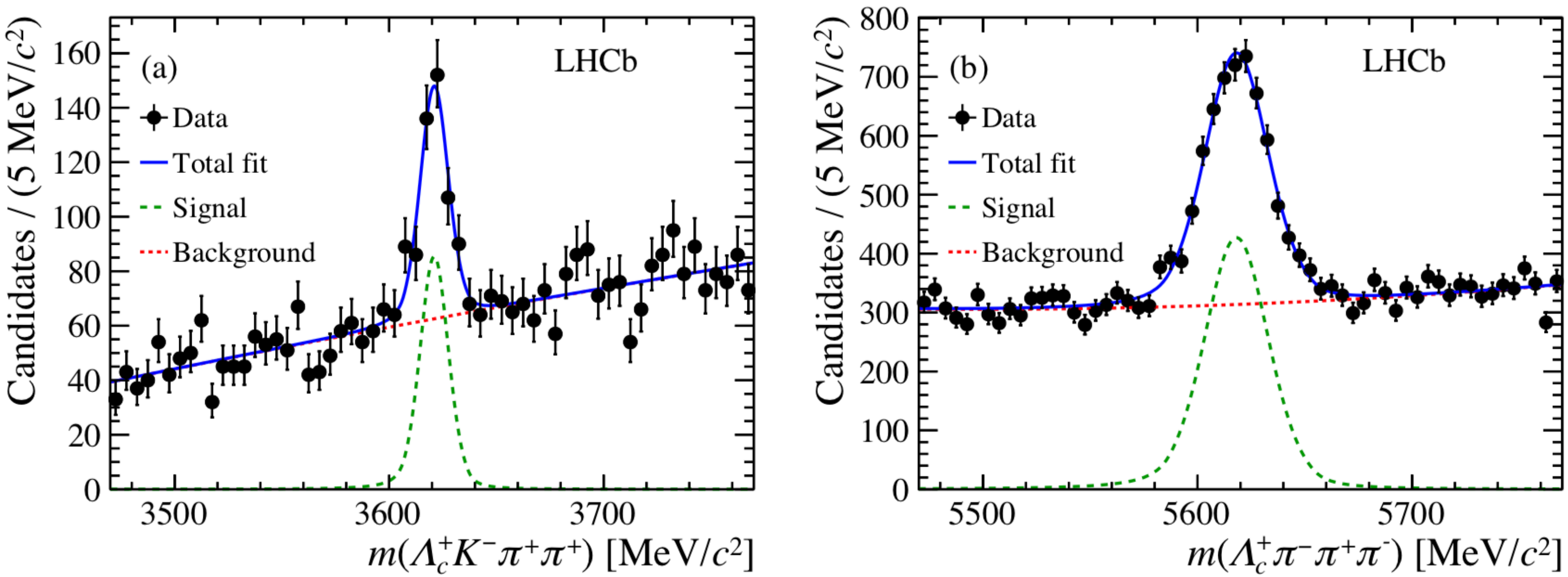
[PRL 119 (2017) 112001]



Measurement of Ξ_{cc}^{++} lifetime

- With the same 2016 data and almost the same selection as the observation
- $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ (control) selected w/ same criteria

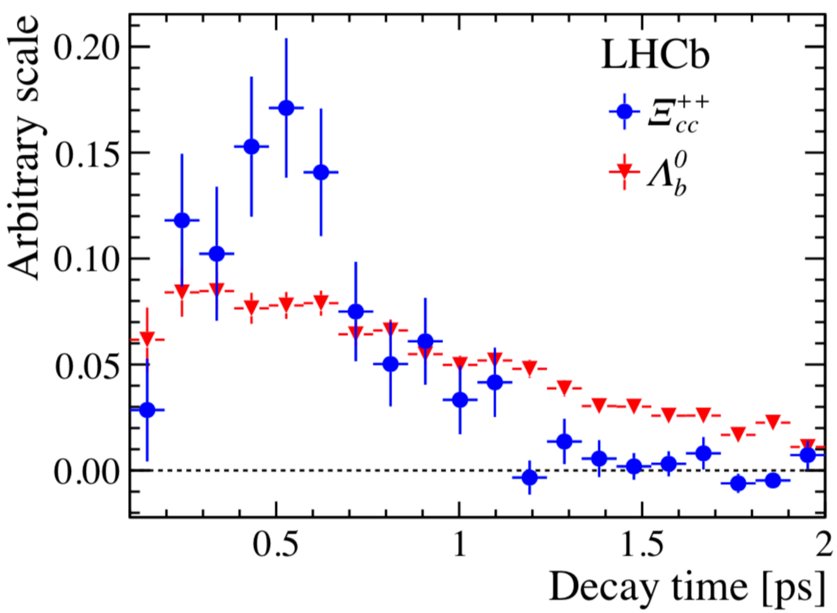
[arXiv: 1806.02744]

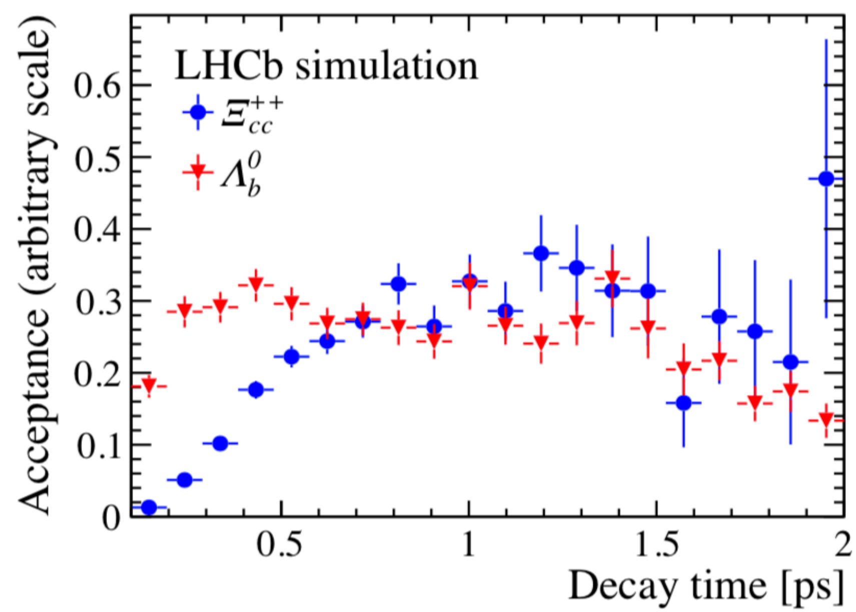


Decay time distribution/acceptance

- Measure the decay time ratio relative to Λ_b^0, w/ well known $\tau(\Lambda_b^0) = 1.470 \pm 0.010\,\mathrm{ps}$
- Decay time acceptance from simulation

[arXiv: 1806.02744]





Ξ_{cc}^{++} lifetime

[arXiv: 1806.02744]

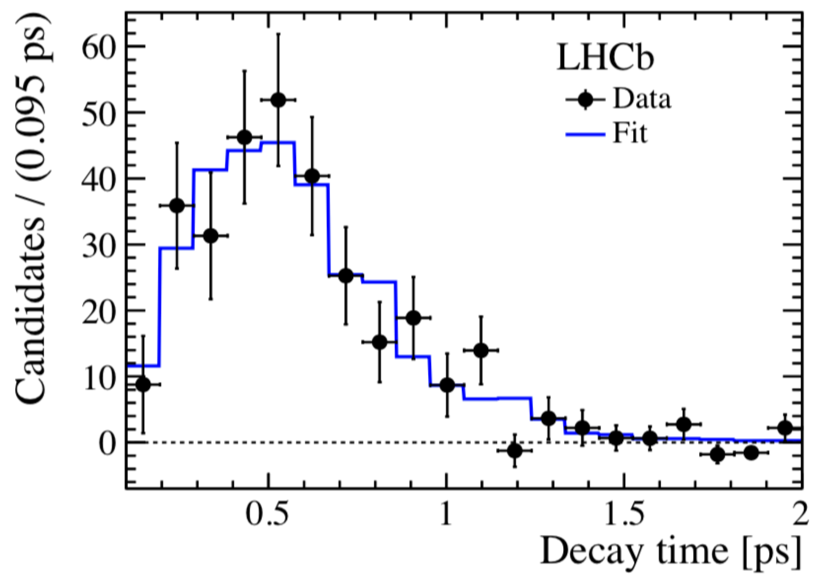
- Fitted Λ_b^0 lifetime 1.474 ± 0.077 ps, validating that simulation well-describes t acceptance
- Unbinned $t(\Xi_{cc}^{++})$ described by

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

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

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

Weakly decay nature established!



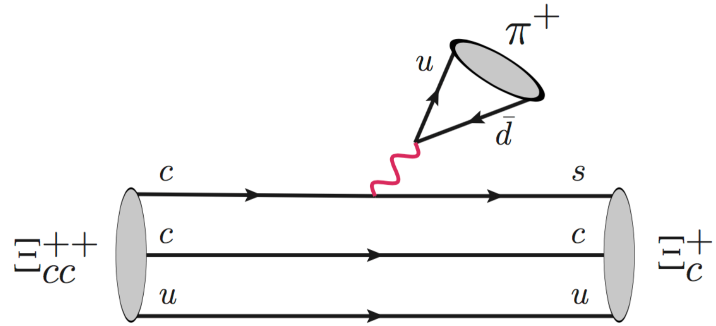
Re-discovery of Ξ_{cc}^{++}

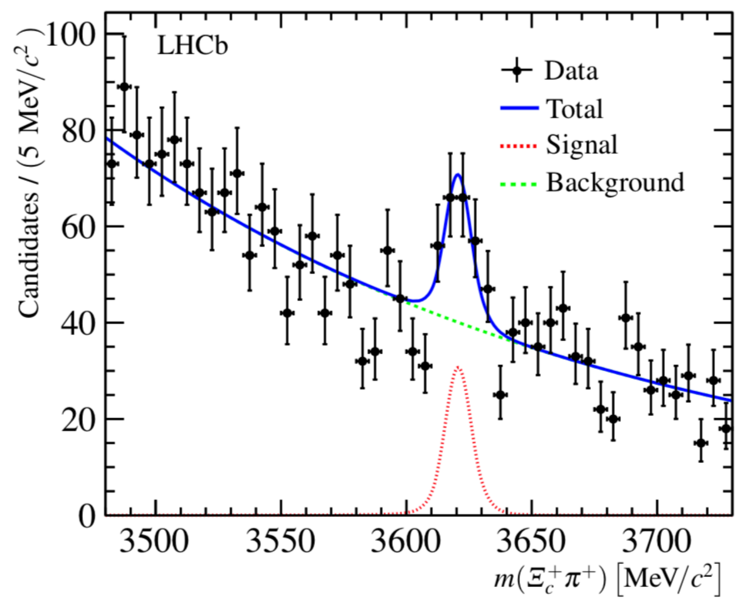
[LHCb-Paper-2018-026, in preparation]

- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ 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!

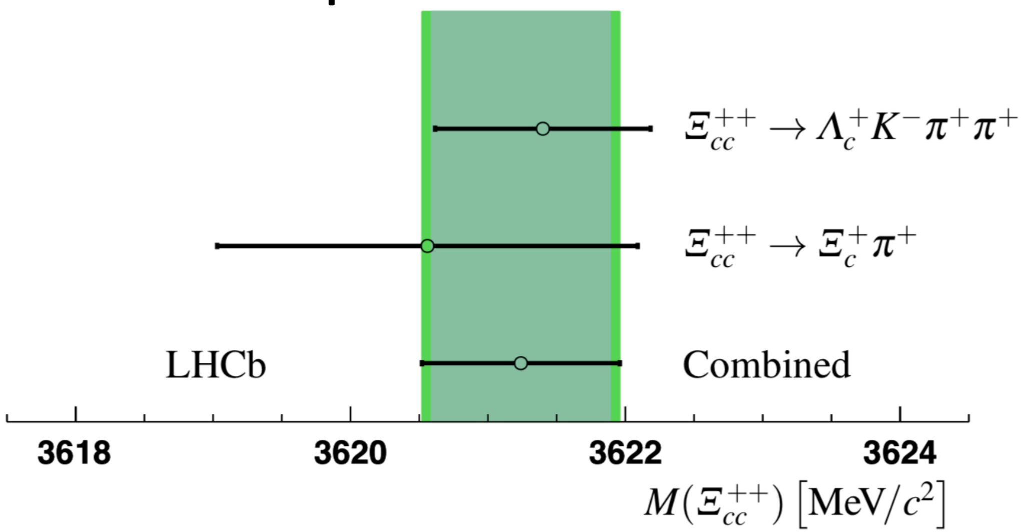




Ξ_{cc}^{++} mass and $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)$

[LHCb-Paper-2018-026, in preparation]

- $m(\Xi_{cc}^{++}) = 3620.6 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+)$
  consistent with previous measurement



- Ratio of total branching fractions

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

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

Prospects of DCB in a nutshell

- LHCb ($7.5\ \mathrm{fb}^{-1}$, 2018)
  - Ξ_{cc}^{++} properties better known, >1k signal
  - Ξ_{cc}^{+} probably observed
  - Ω_{cc}^{+} evidence?
- LHCb upgrade ($50\ \mathrm{fb}^{-1}$, 2030)
  - Ξ_{cc}^{++}, $\mathcal{O}(10\mathrm{k})$ signals, excited states, new decays, CPV study?
  - Ξ_{cc}^{+}, $\mathcal{O}(1\mathrm{k})$ signals, properties better known
  - Ω_{cc}^{+}, observation
- LHCb upgrade-II, another factor of 6

Summary

- LHCb has done world-leading works on singly and doubly charmed baryons spectroscopy
  - Ω_c^*, Λ_c^*
  - Ξ_{cc}^{++} observation, lifetime; new decay
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your suggestions are always welcome!