Experimental studies of doubly-charmed baryons at LHCb

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for the LHCb collaboration

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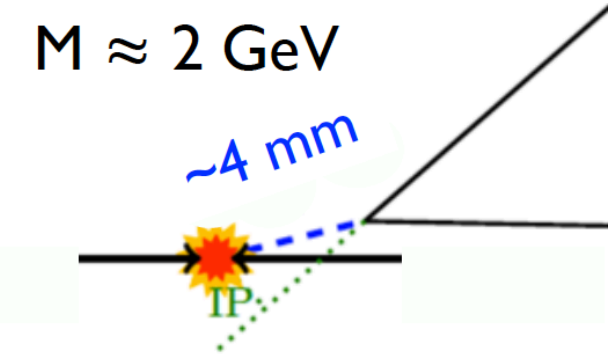
Charm production / signature

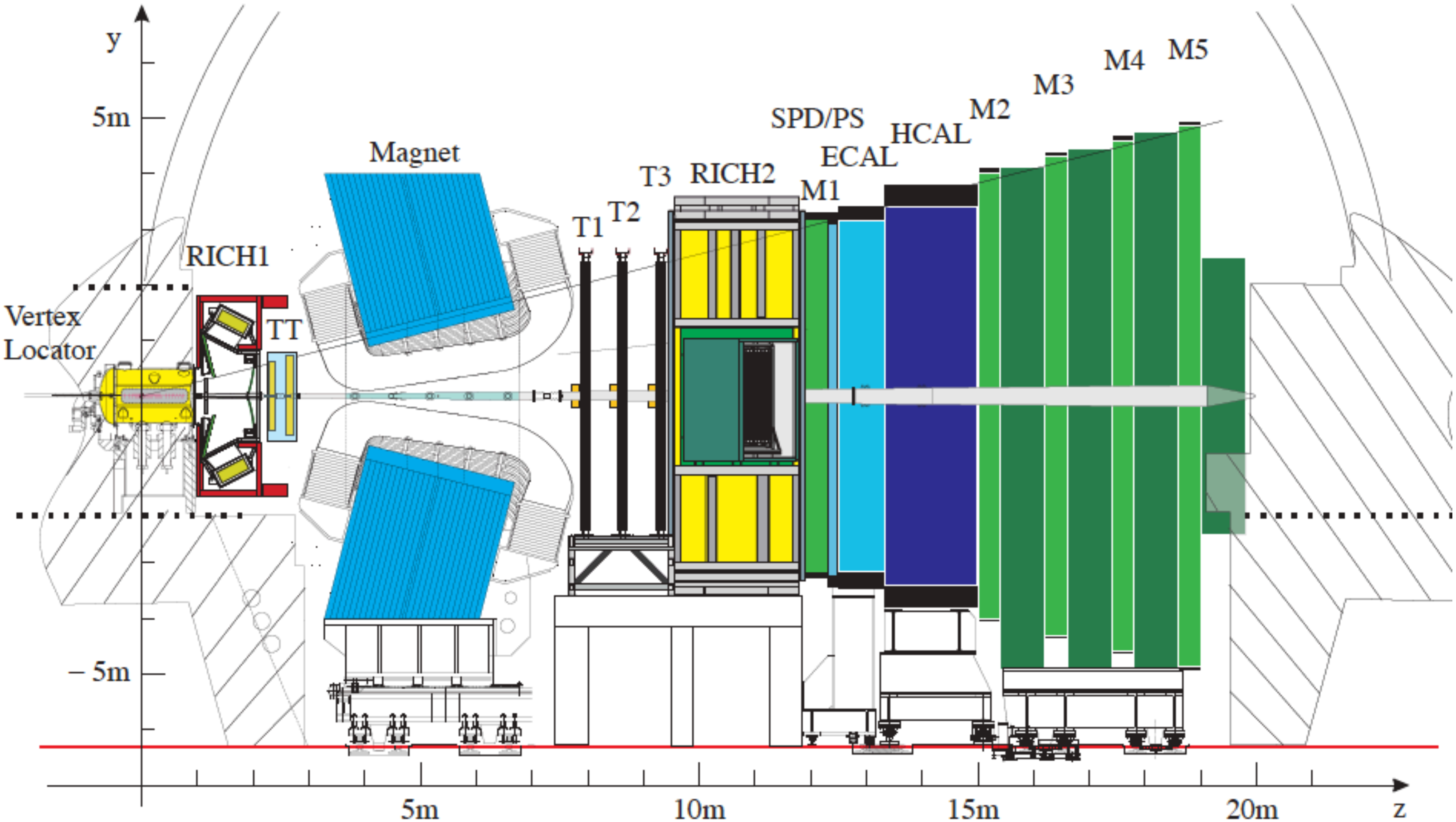
- Large production cross-section @ 7 TeV
  - Minimum bias ~60 mb
  - Charm ~6 mb



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

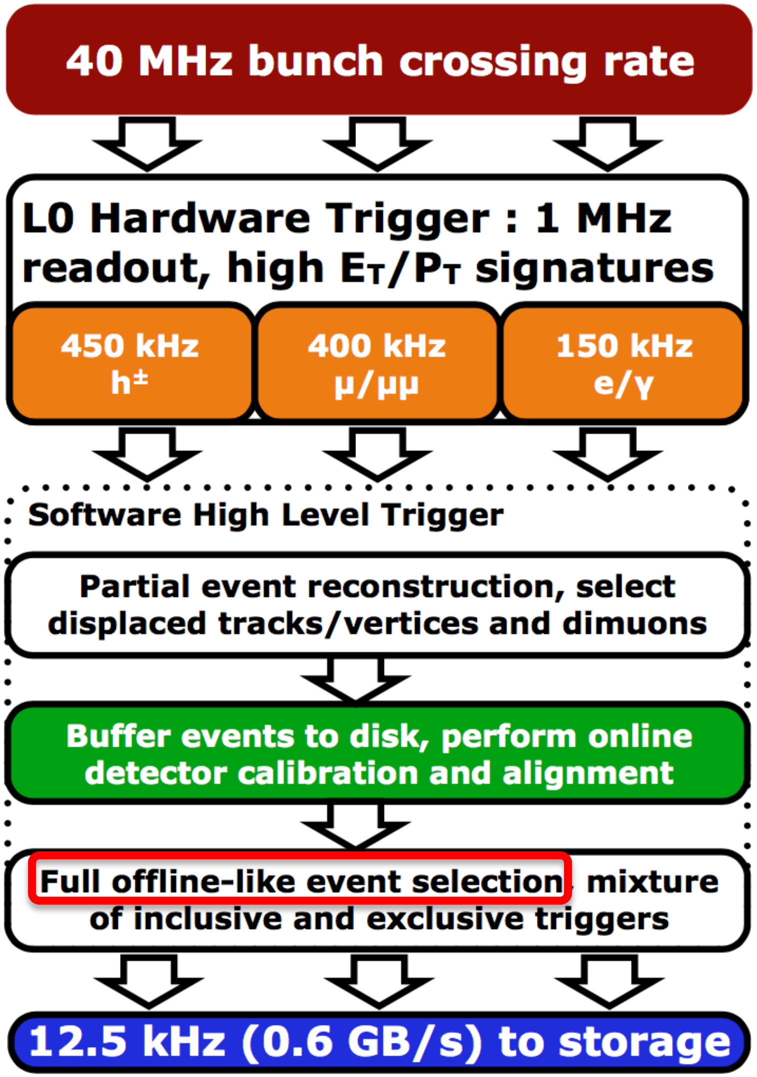
The LHCb experiment

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



[JINST 3 (2008) S08005]

The LHCb trigger (Run-II)



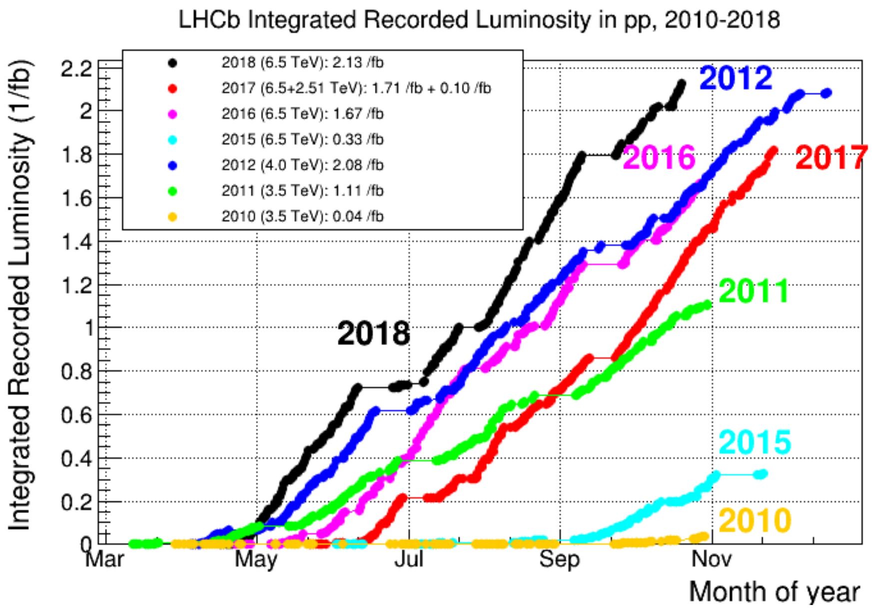
- Level-0, Hardware
  - Fully synchronous at 40 MHz
  - Selection of high p_{T} particles
    - $p_{\mathrm{T}}(\mu) >\sim 1.5$ GeV/c, $p_{\mathrm{T}}(\mu_1) \times p_{\mathrm{T}}(\mu_2) >\sim (1.5\,\mathrm{GeV}/c)^2$
    - $E_{\mathrm{T}}(h, e, \gamma) > 2.5 - 4$ GeV
- High Level Trigger (HLT), Software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

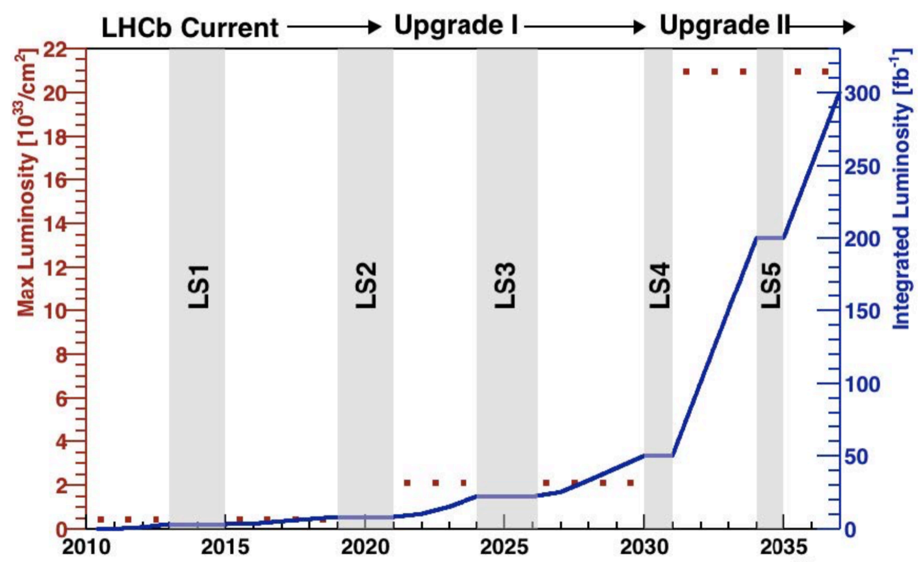
  $\sim$50 kB/event $\Rightarrow$ 0.25GB/s, $\sim$ 2 PB/year
- Offline data flow

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

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

LHCb luminosity prospects





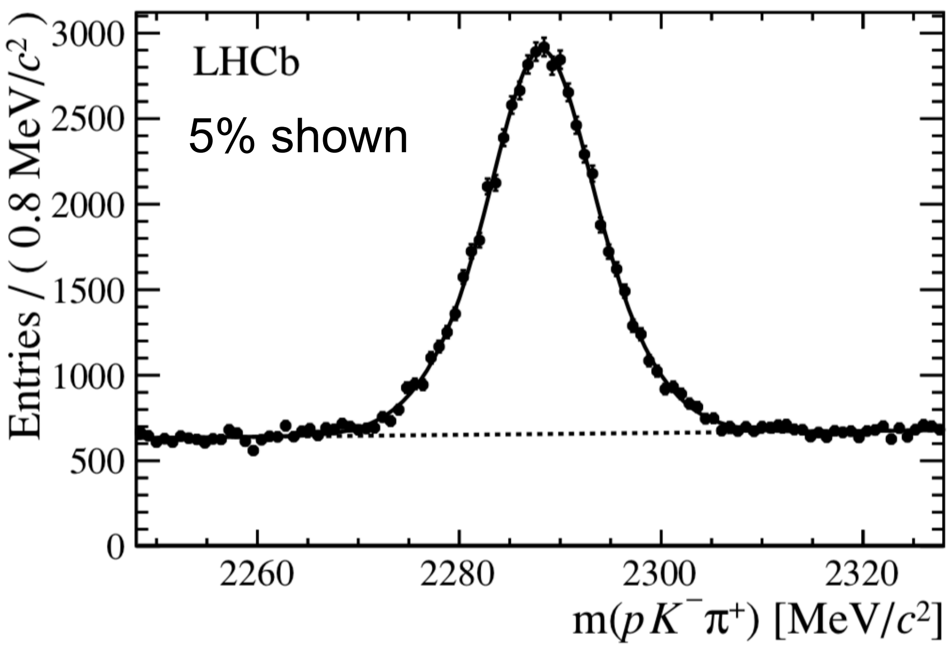
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

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

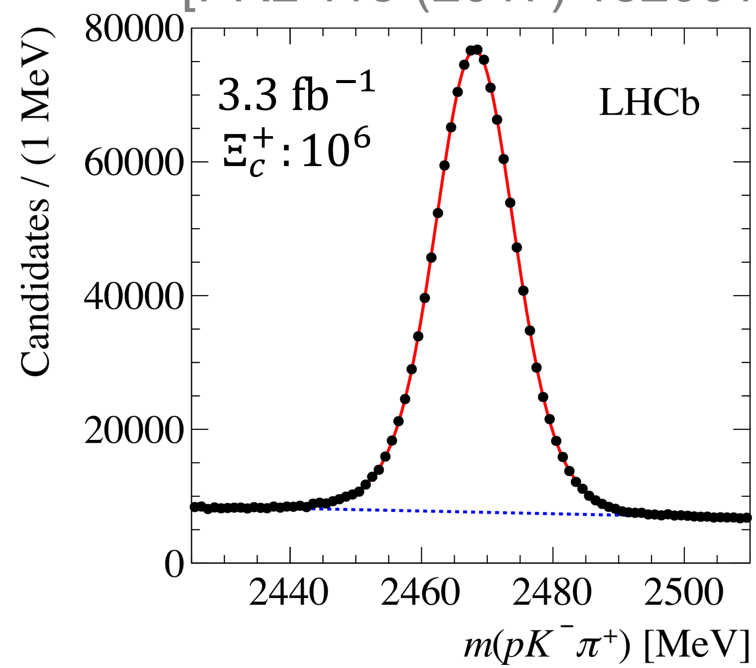
Lots of singly charmed baryons

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

[JHEP 12 (2013) 90]

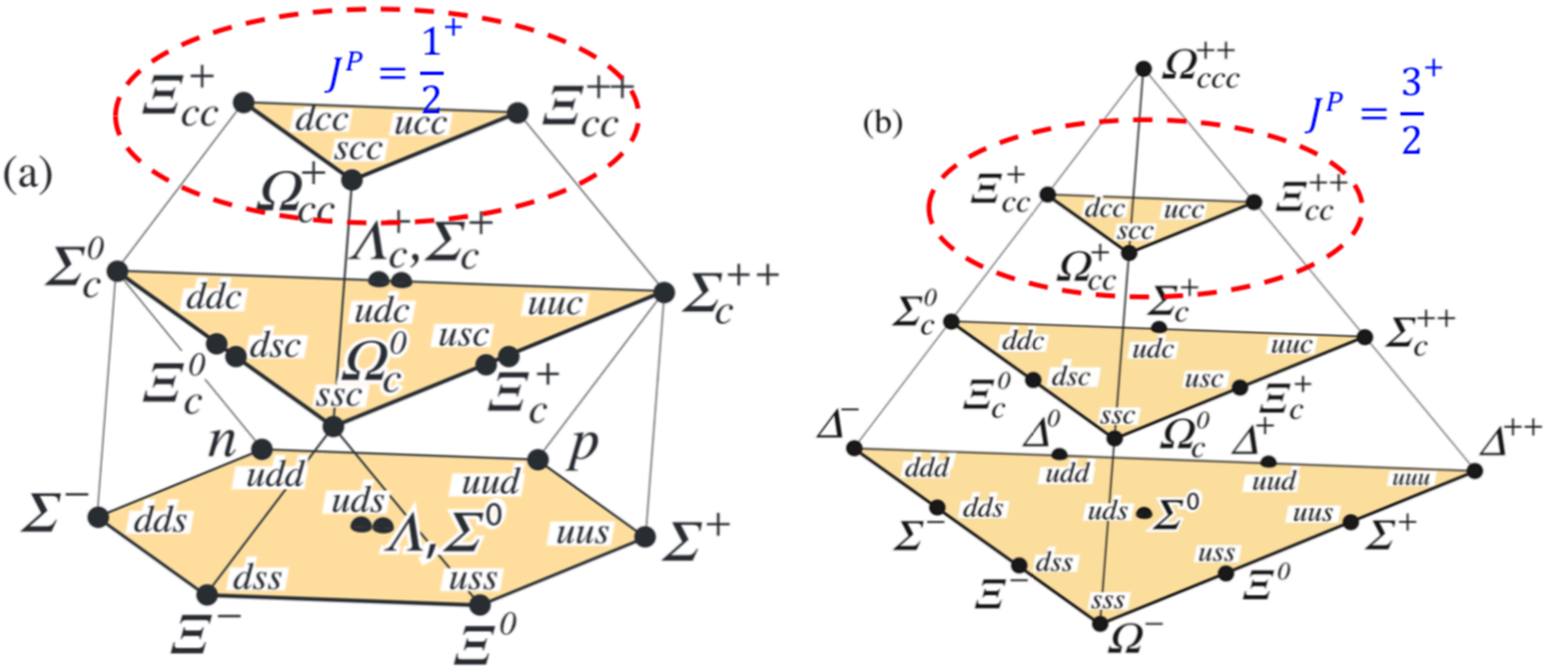


[PRL 118 (2017) 182001]



Doubly charmed baryons

- Two SU(4) 20-plets
  - $J^P = 3/2^+$ decays to $1/2^+$
  - $J^P = 1/2^+$ decays weakly



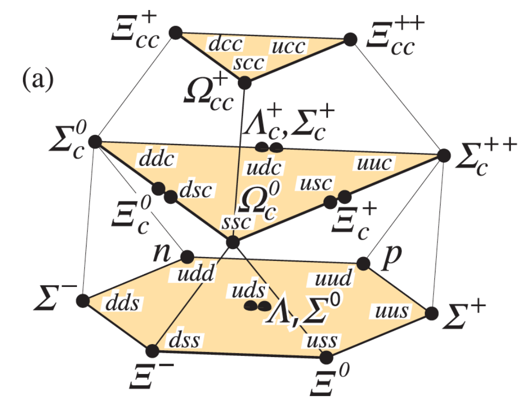
Predicted mass

- $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$~3.5-3.7 GeV

  LQCD*: 3610(23)(22) MeV

- $M(\Omega_{cc}^{+})$~3.6-3.9 GeV

  LQCD*: 3738(20)(20) MeV



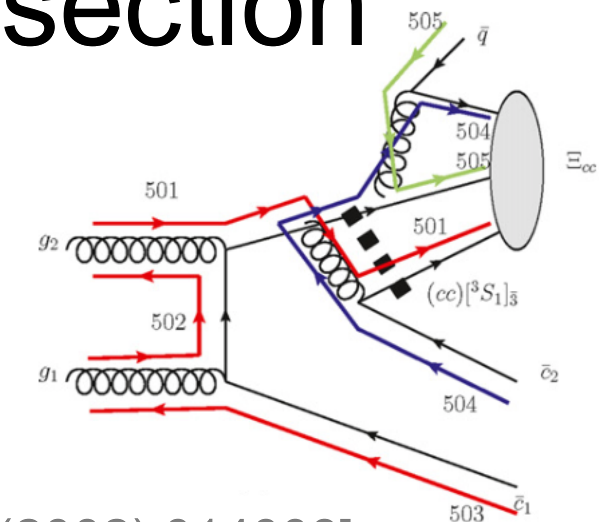
[D. Ebert *et al.*, PRD 66 (2002) 014008]

Mass in GeV

Baryon	Quark content	J^P	Present work	[11]	[10]	[9]	[6]	[28]
Ξ_{cc}	$\{cc\}q$	$1/2^+$	3.620	3.478	3.66	3.66	3.61	3.69
Ξ_{cc}^*	$\{cc\}q$	$3/2^+$	3.727	3.61	3.81	3.74	3.68	
Ω_{cc}	$\{cc\}s$	$1/2^+$	3.778	3.59	3.76	3.74	3.71	3.86
Ω_{cc}^*	$\{cc\}s$	$3/2^+$	3.872	3.69	3.89	3.82	3.76	

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

Production cross-section



- Production similar to B_c
  - Accompanying $\bar{c}\bar{c} \Longrightarrow$ Trigger
- Total cross-section [nb] for p_T>4 GeV & |y|<1.5

[J.-W. Zhang *et al.*, PRD 66 (2002) 014008]

	Ξ_{cc}		Ξ_{bc}		Ξ_{bb}	
	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV
$[^3S_1]$	38.11	69.40	16.7	28.55	0.503	1.137
$[^1S_0]$	9.362	17.05	3.72	6.315	0.100	0.226
Total	47.47	86.45	20.42	34.87	0.603	1.363

- In LHCb acceptance at 13 TeV: $\sigma(cc) = 90$ nb
- Fragmentation fraction: u:d:s~1:1:0.3
  - $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40$ nb, $\sigma(\Omega_{cc}^{+}) \sim 13$ nb

Predicted lifetime

- Large ambiguity…

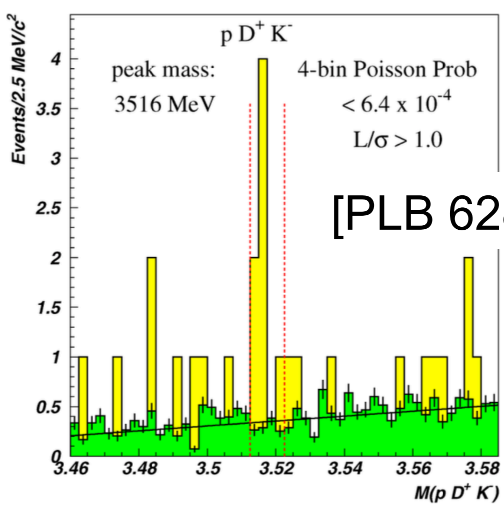
Literatures	Ξ_{cc}^{++}	Ξ_{cc}^{+}	Ω_{cc}^{+}
Karliner, Rosner, 2014	185	53	
Kiselev, Likhoded, Onishchenko, 1998	430±100	110±10	
Kiselev, Likhoded, 2002	460±50	160±50	270±60
Guberina, Melic, Stefancic, 1998	1550	220	250
Chang, Li, Li, Wang, 2007	670	250	210

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

  => Ξ_{cc}^{++} is easier to detect

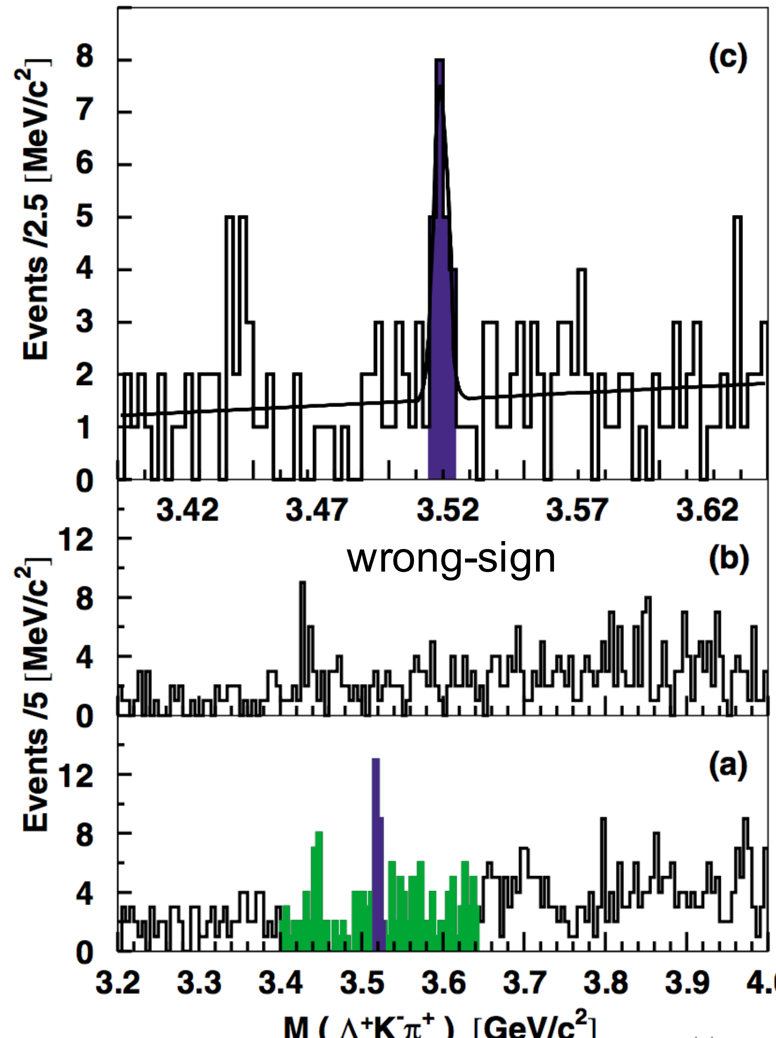
Ξ_{cc}^{+} @ SELEX

- 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]

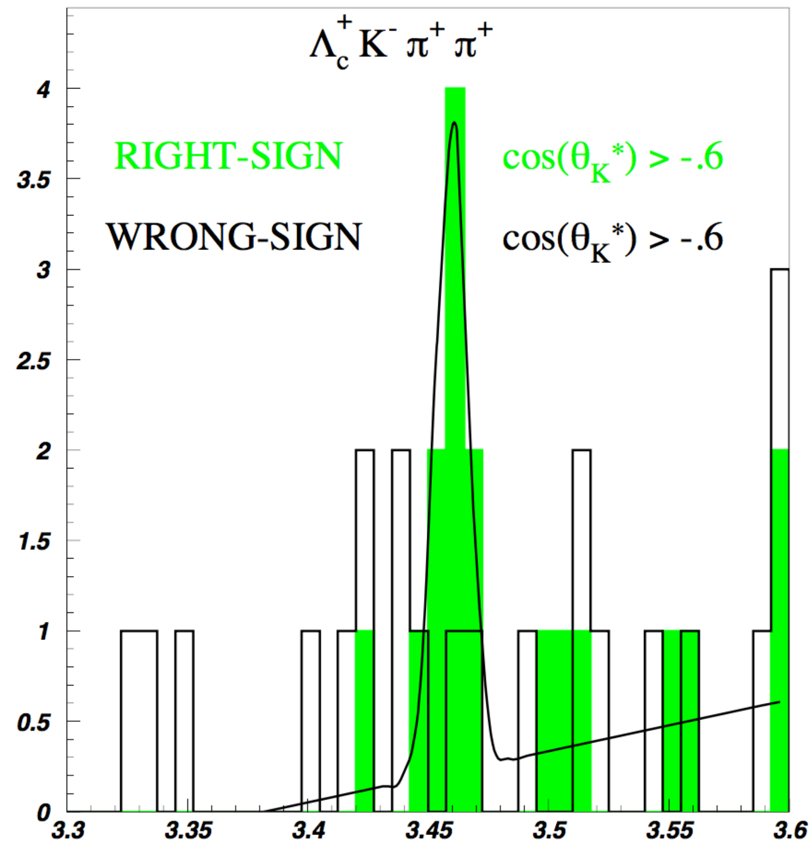
[PRL 89 (2002) 112001]



Ξ_{cc}^{++} @ SELEX

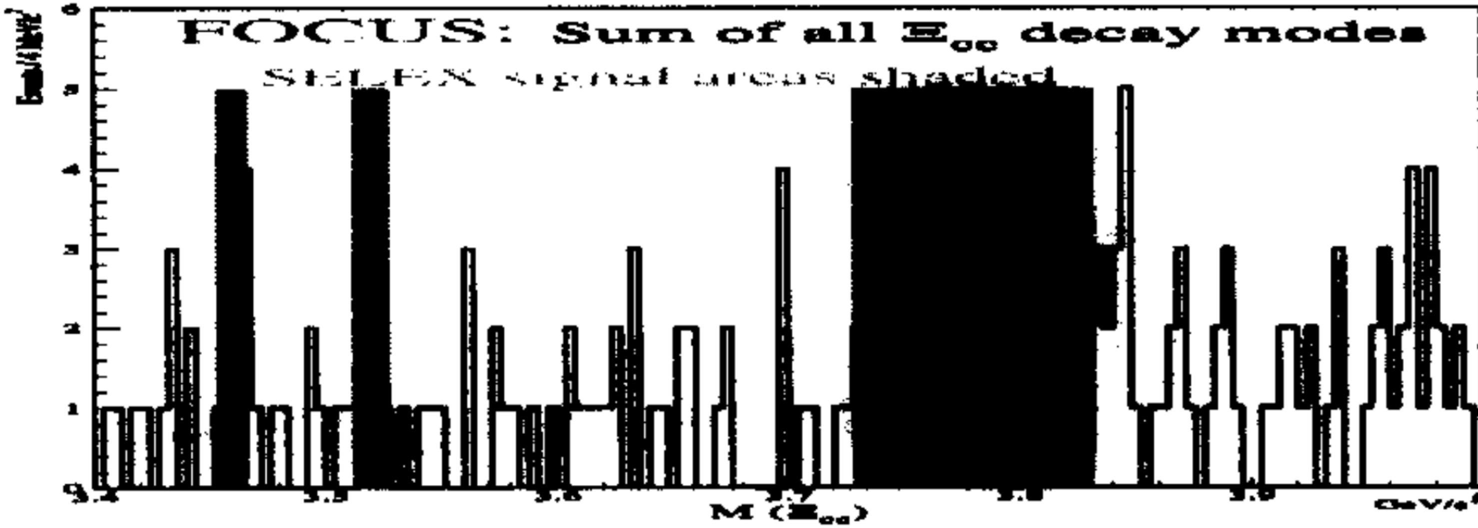
- SELEX claimed evidence of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ in ICHEP 2002 (4.4σ)
  - M: 3460 MeV
    c.f. $M(\Xi_{cc}^{+})$: 3519 MeV
    big isospin breaking?
  - τ: ~$\tau(\Xi_{cc}^{+})$

[hep-ex: 0209075]



Ξ_{cc} @ FOCUS

[NPB (Proc. Suppl.) 115 (2003) 33]



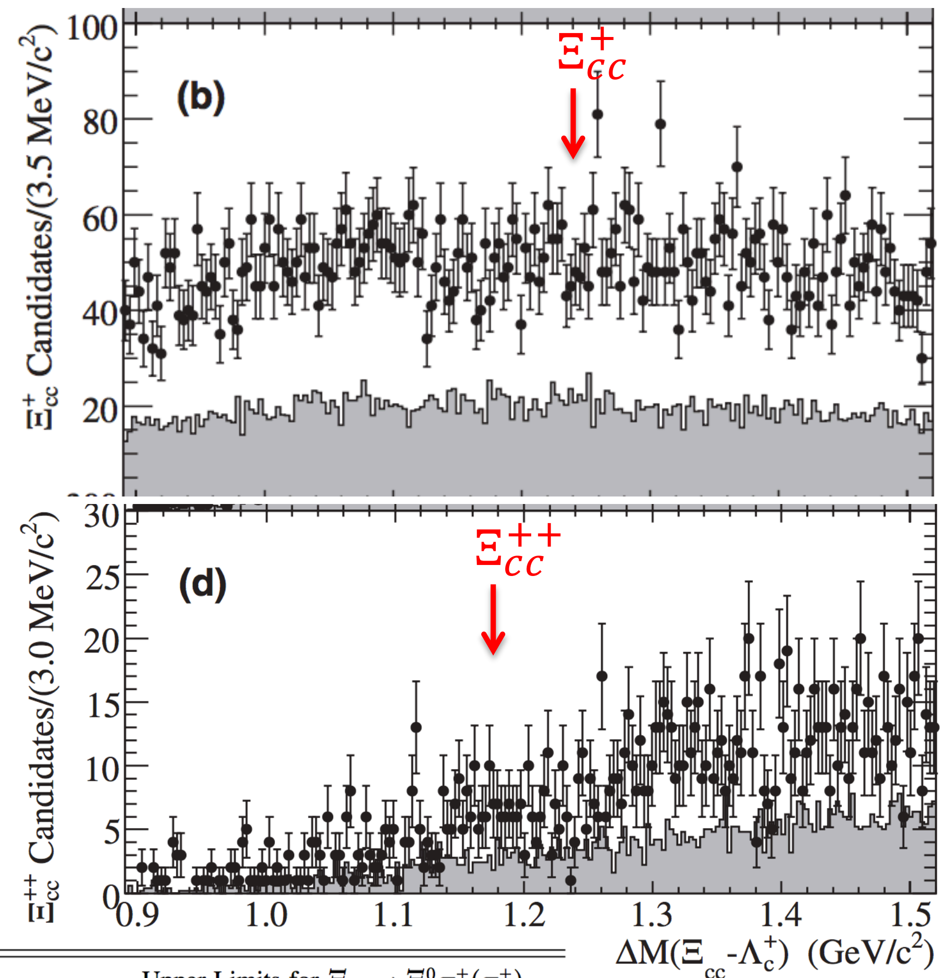
Decay mode	$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$		$\Xi_{cc}^{++} \to \Lambda_c^+ K^- 2\pi^+$	
Experiment	FOCUS	SELEX	FOCUS	SELEX
Ξ_{cc} Events	< 2.21 @ 90% CL	15.8	< 2.21 @ 90% CL	8
Reconstructed Λ_c^+	$19,444 \pm 262$	1650	$19,444 \pm 262$	1650
ϵ_r relative to Λ_c^+	5%	10%	13%	5%
Ξ_{cc}/Λ_c^+ Ratio	$\approx 0.23\%$ @ 90% CL	$\approx 9.6\%$	$\approx 0.09\%$ @ 90%	$\approx 9.7\%$
$\frac{FOCUS}{SELEX}$ Rel. $\Xi_{cc}/\Lambda_c^+ \sigma_{prod}$	> 42 @ 90% CL		> 111 @ 90%	

Ξ_{cc} @ BaBar

- Babar searched
  - $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$
  - $\Xi_{cc}^{+} \rightarrow \Xi_c^{0} \pi^{+}$
  - $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$
  - $\Xi_{cc}^{++} \rightarrow \Xi_c^{0} \pi^{+} \pi^{+}$

  No clear signal, upper limit

[PRD74 (2003) 011103]

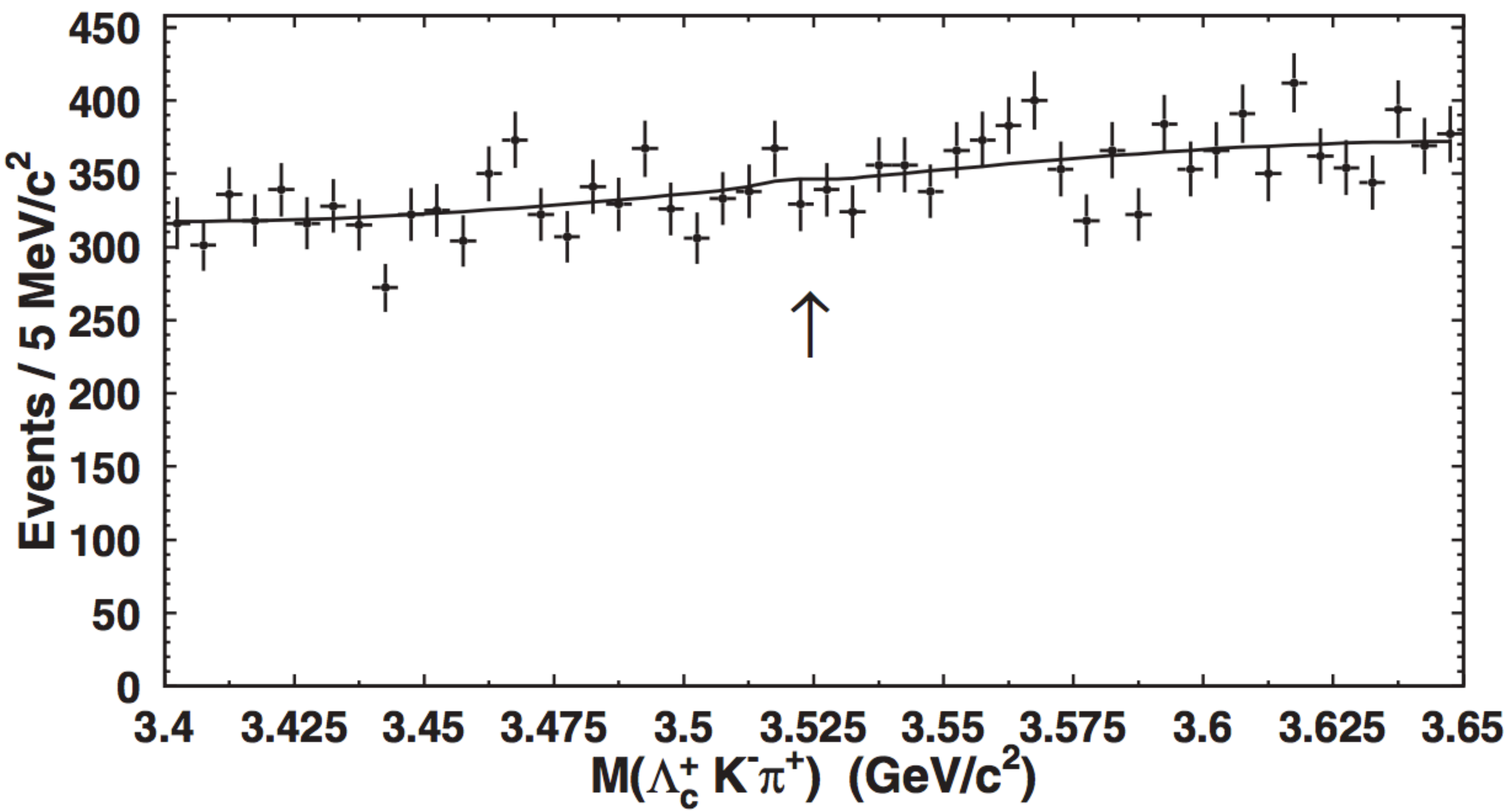


	Upper Limits for $\Xi_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+)$						Upper Limits for $\Xi_{cc} \rightarrow \Xi_c^0 \pi^+ (\pi^+)$			
	N^+	$\sigma^+ B$	$(\sigma^+/\sigma)B$	N^{++}	$\sigma^{++} B$	$(\sigma^{++}/\sigma)B$	N^+	$\sigma^+ B$	N^{++}	$\sigma^{++} B$
Wide Mass Range	328	14.5 fb	13.3×10^{-4}	199	23.9 fb	22.0×10^{-4}	58	4.3 fb	58	6.6 fb
Wide Mass Range, p^* Req.	106	4.4 fb	5.6×10^{-4}	54	5.5 fb	6.9×10^{-4}	41	3.0 fb	28	3.1 fb
SELEX Mass	169	7.5 fb	6.9×10^{-4}	91	10.9 fb	10.0×10^{-4}	26	2.0 fb	49	5.6 fb
SELEX Mass, p^* Req.	53	2.2 fb	2.7×10^{-4}	31	3.2 fb	4.0×10^{-4}	18	1.3 fb	31	3.4 fb

Ξ_{cc} @ Belle

- Belle searched $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$, no clear signal, upper limit

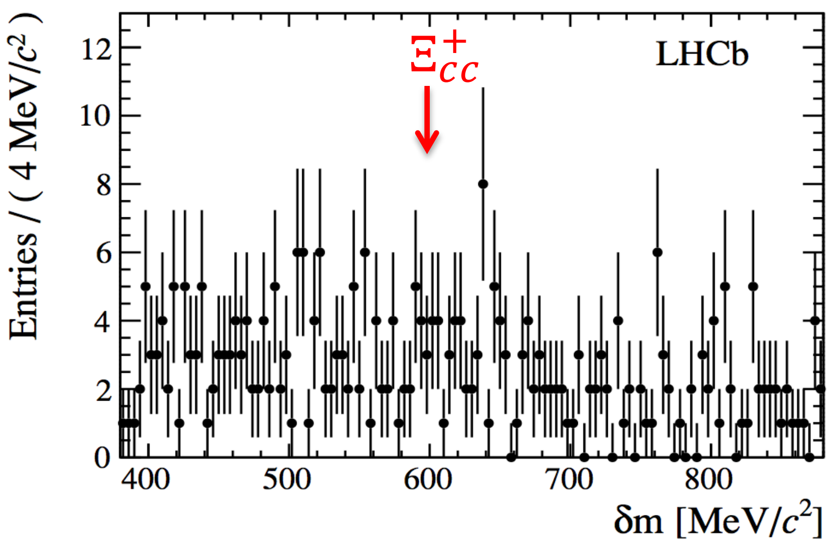
[PRL 97 (2006) 162001]

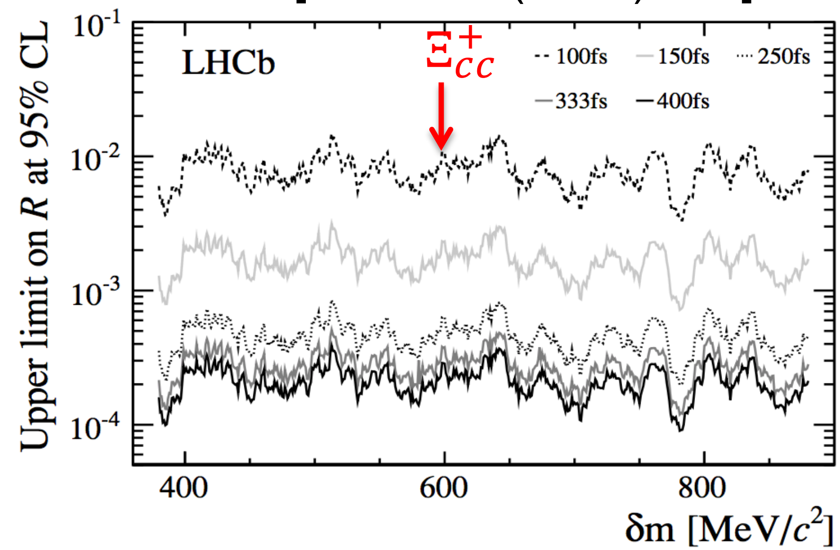


Ξ_{cc} @ LHCb

- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ searched by LHCb with 2011 data, no clear signal, upper limit

[JHEP 12 (2013) 090]

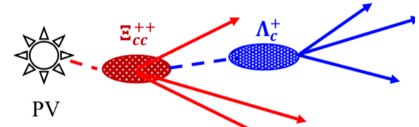


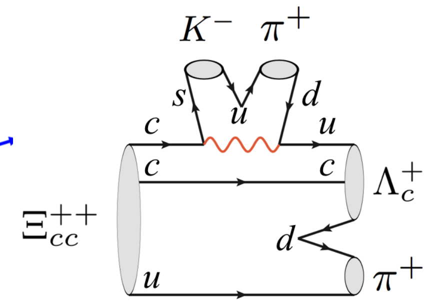


- However, LHCb already had lots of B_c events, and double-charm events…

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

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

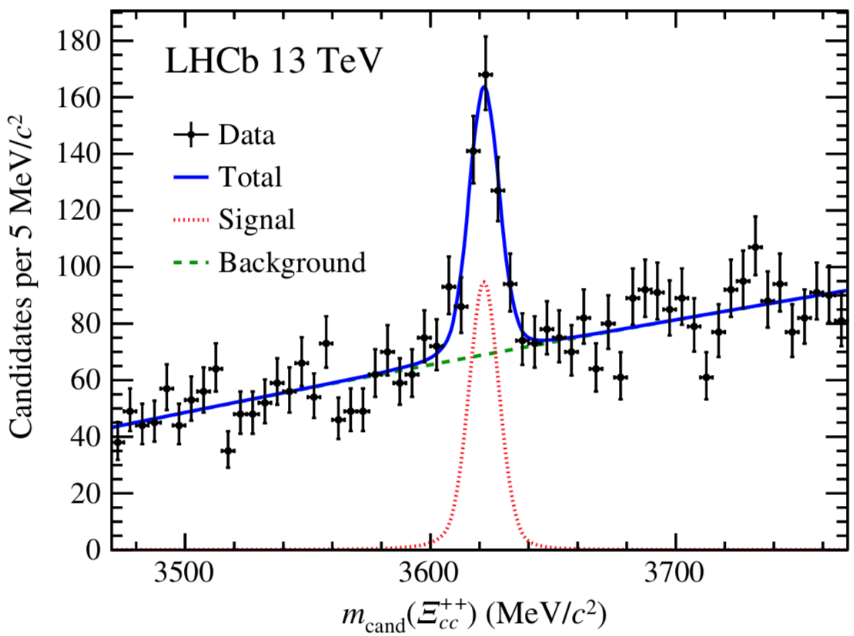


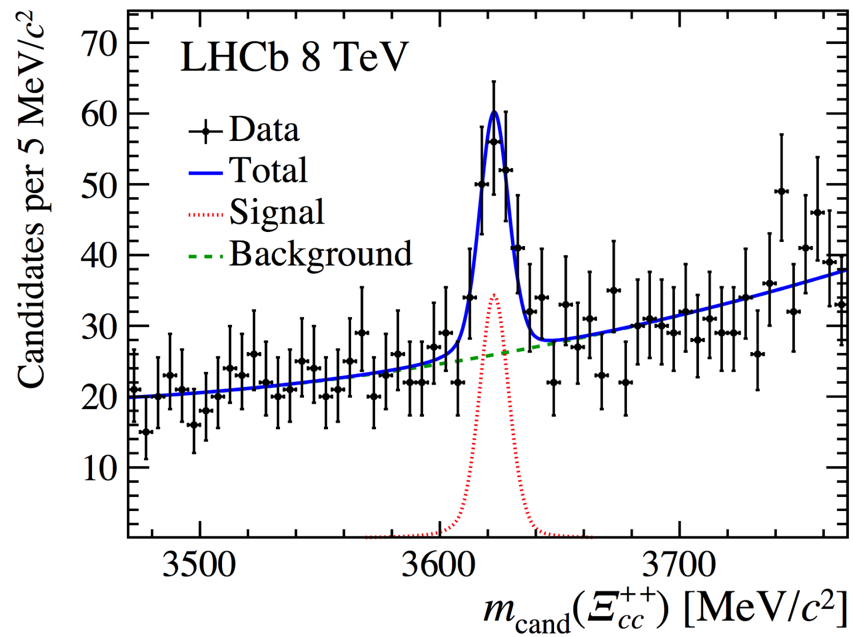


[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

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

[PRL 119 (2017) 112001]





Ξ_{cc}^{++} properties

[PRL 119 (2017) 112001]

- Ξ_{cc}^{++} mass measured:

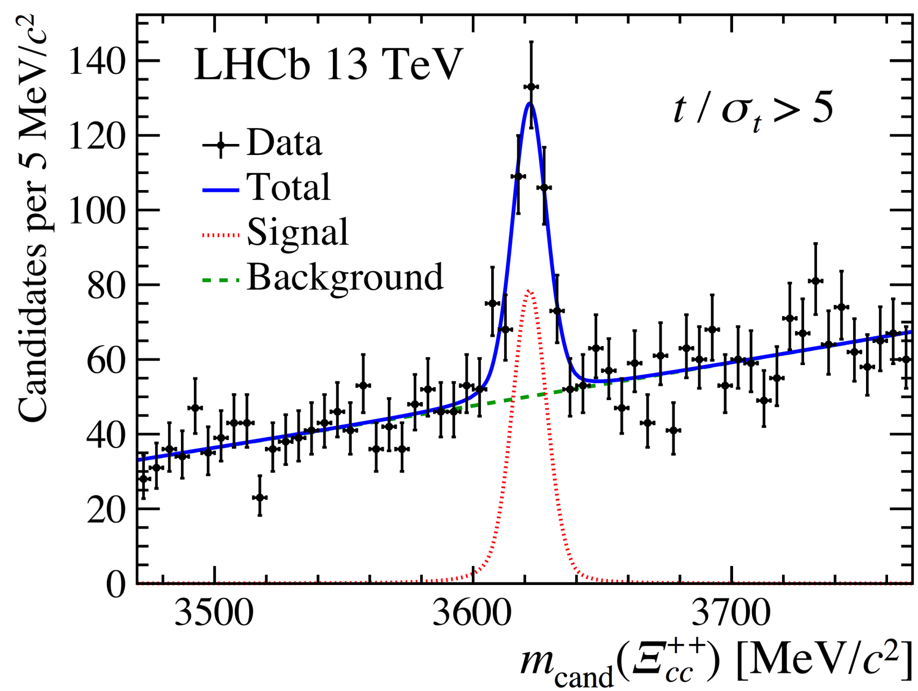
$$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

SELEX: m(Ξ_{cc}^{+})=3519±1 MeV

Isospin partner?

- Decay weakly, mass peak remains after lifetime cut

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

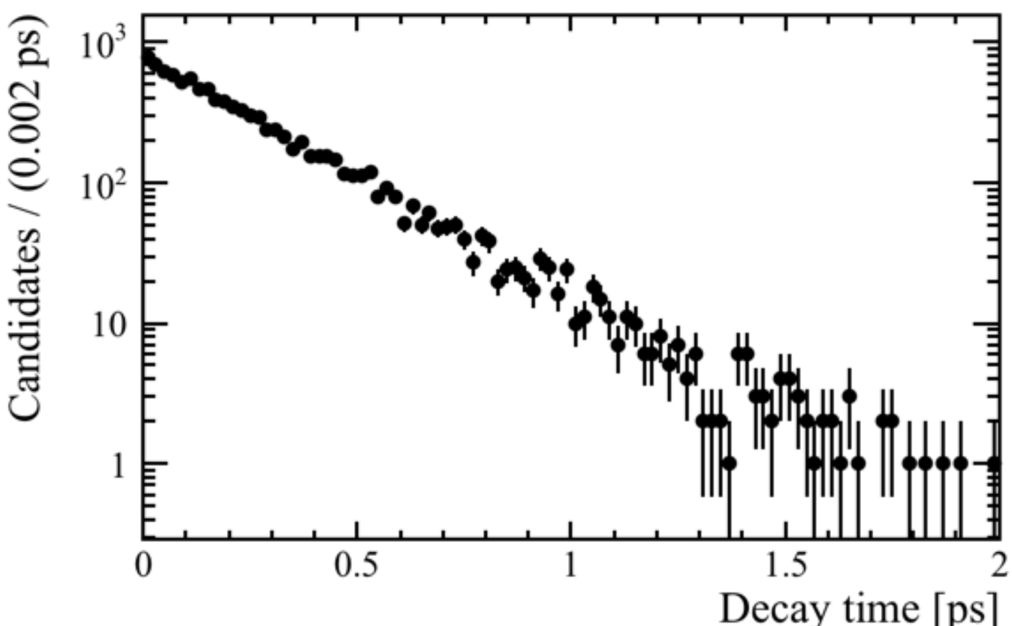


Lifetime measurement

- Half-life ($T_{1/2}$), average lifetime (τ)

$$N = N_0 2^{-\frac{t}{T_{1/2}}} = N_0 e^{-\frac{t}{\tau}}$$

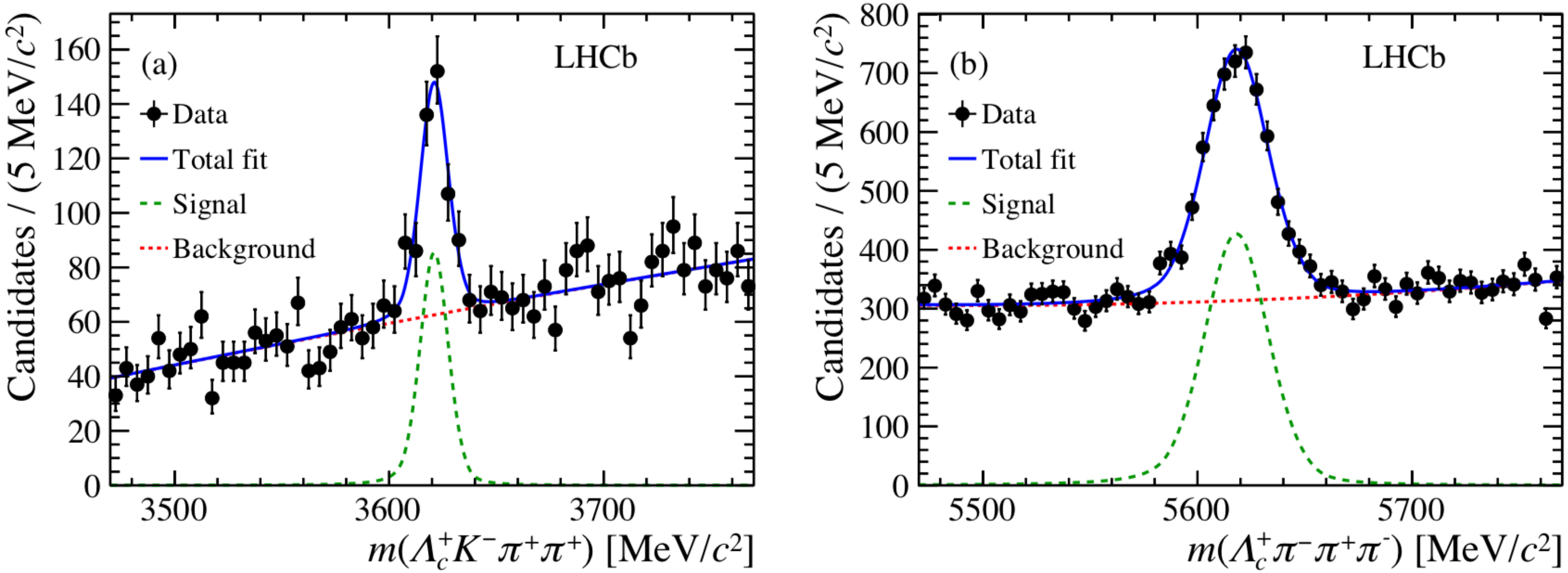
- Expected distribution with $\tau = 0.256$ ps



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

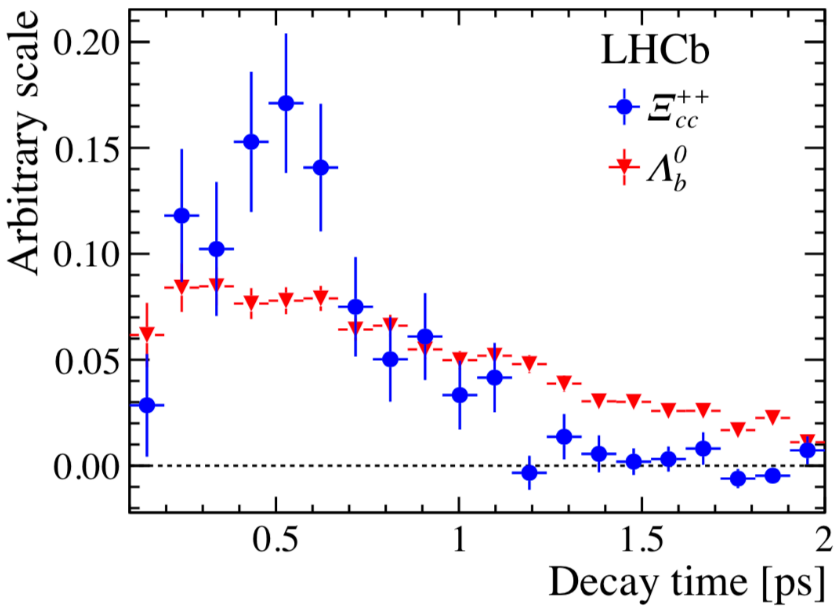
[PRL 121 (2018) 052002]

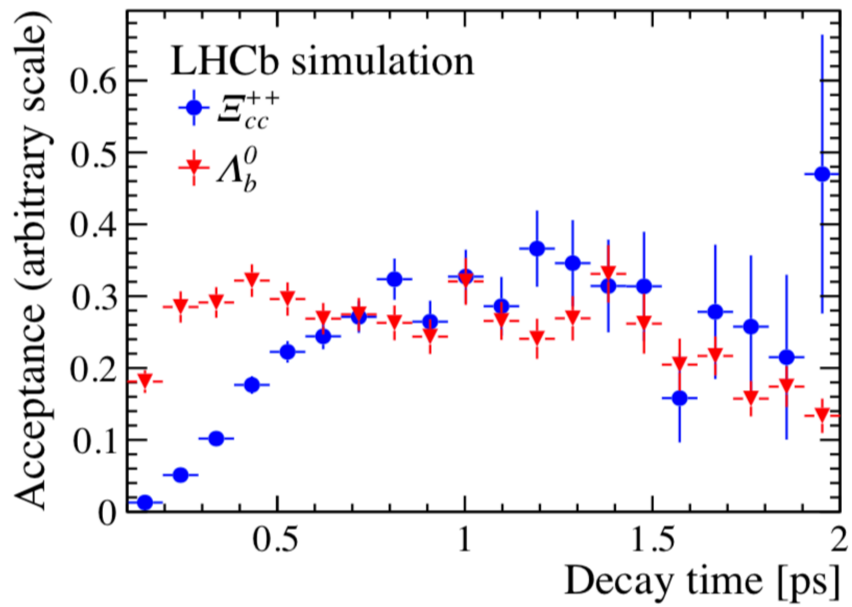


Decay time distribution/acceptance

[PRL 121 (2018) 052002]

- 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





Ξ_{cc}^{++} lifetime

[PRL 121 (2018) 052002]

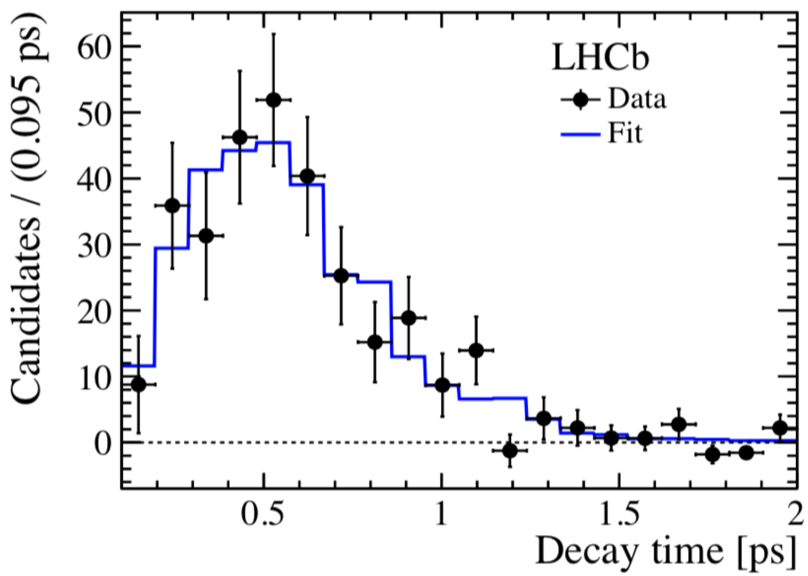
- Fitted Λ_b^0 lifetime 1.474 ± 0.077 ps, validating that simulation well-describes t acceptance
- Unbinned $t(\Xi_{cc}^{++})$ described by

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

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

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

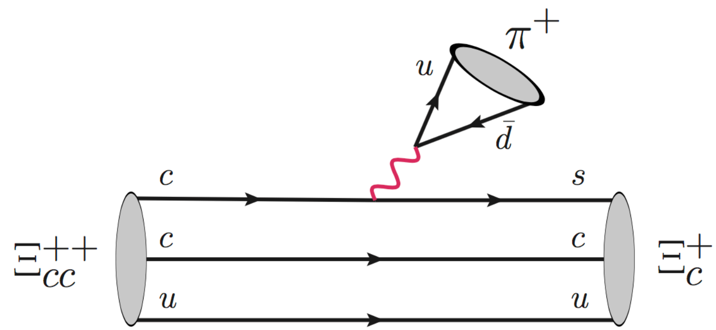
Weakly decay nature established!



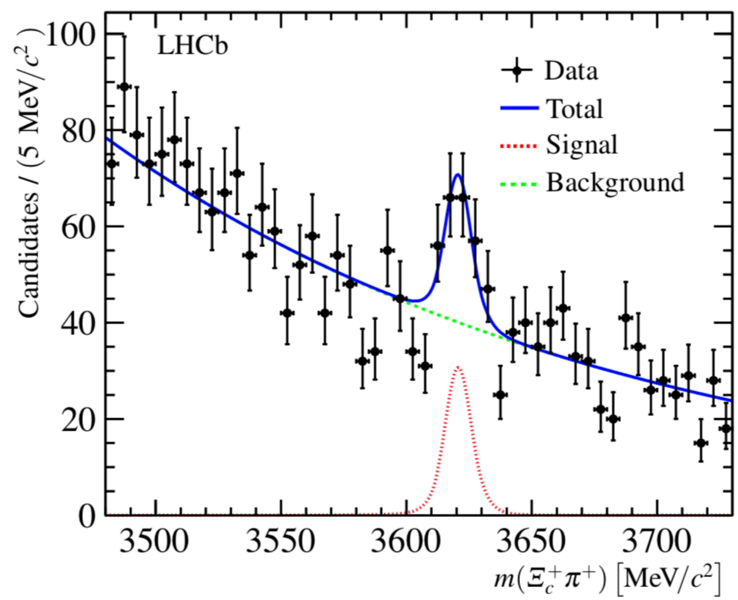
Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

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

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



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

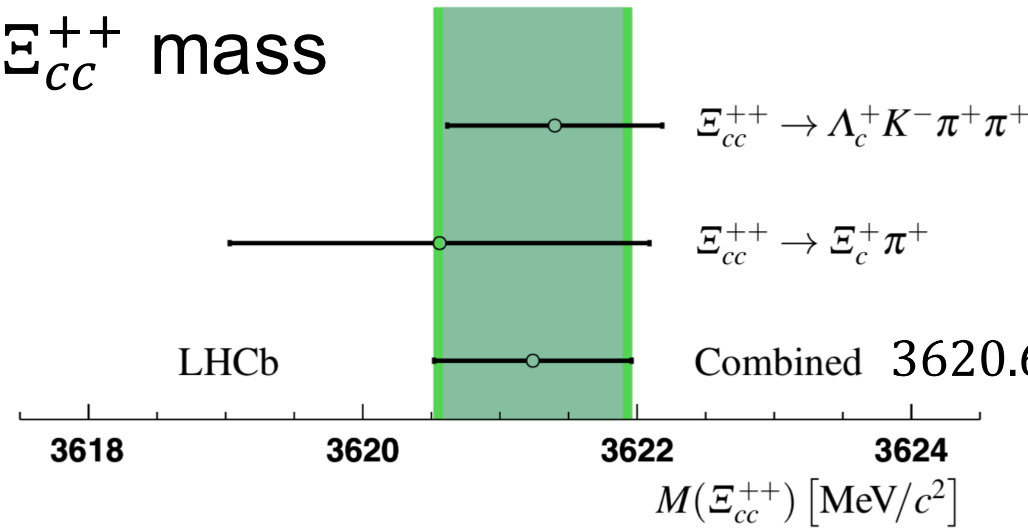


[PRL 121 (2018) 162002]

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

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

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 doubly charmed baryons
  - Ξ_{cc}^{++} observation via $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - $\tau(\Xi_{cc}^{++})$
  - $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your suggestions are always welcome!