中国科学院大学
University of Chinese Academy of Sciences

LHCb

Experimental studies of doubly-charmed baryons at LHCb

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Large Hadron Collider

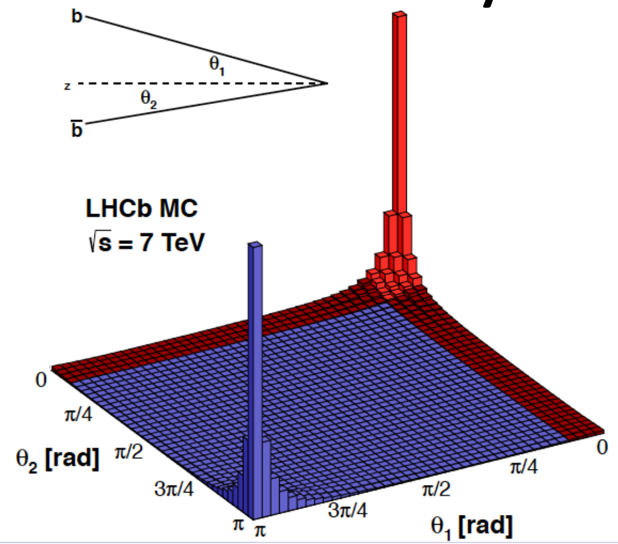
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

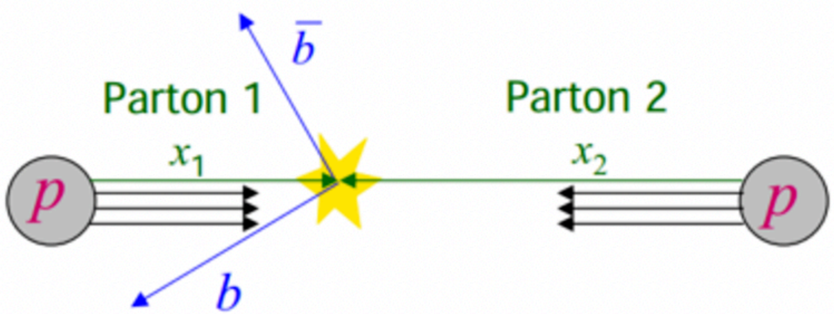
Beauty/charm production

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

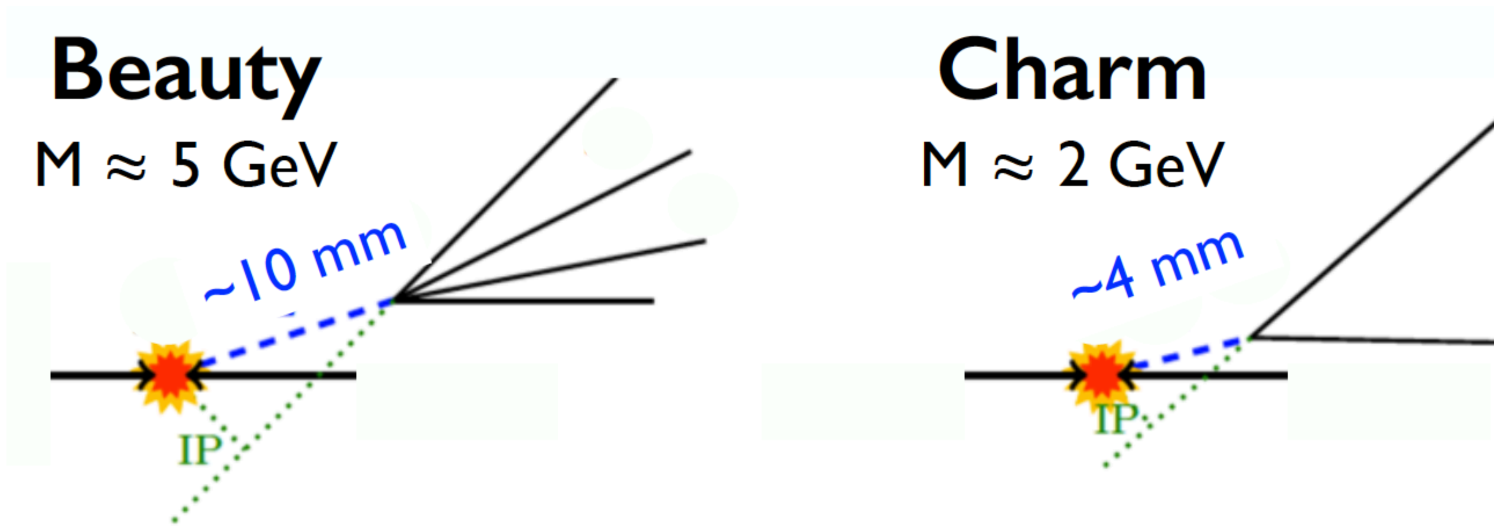
Flavor factory!

- Predominantly in forward/backward cones





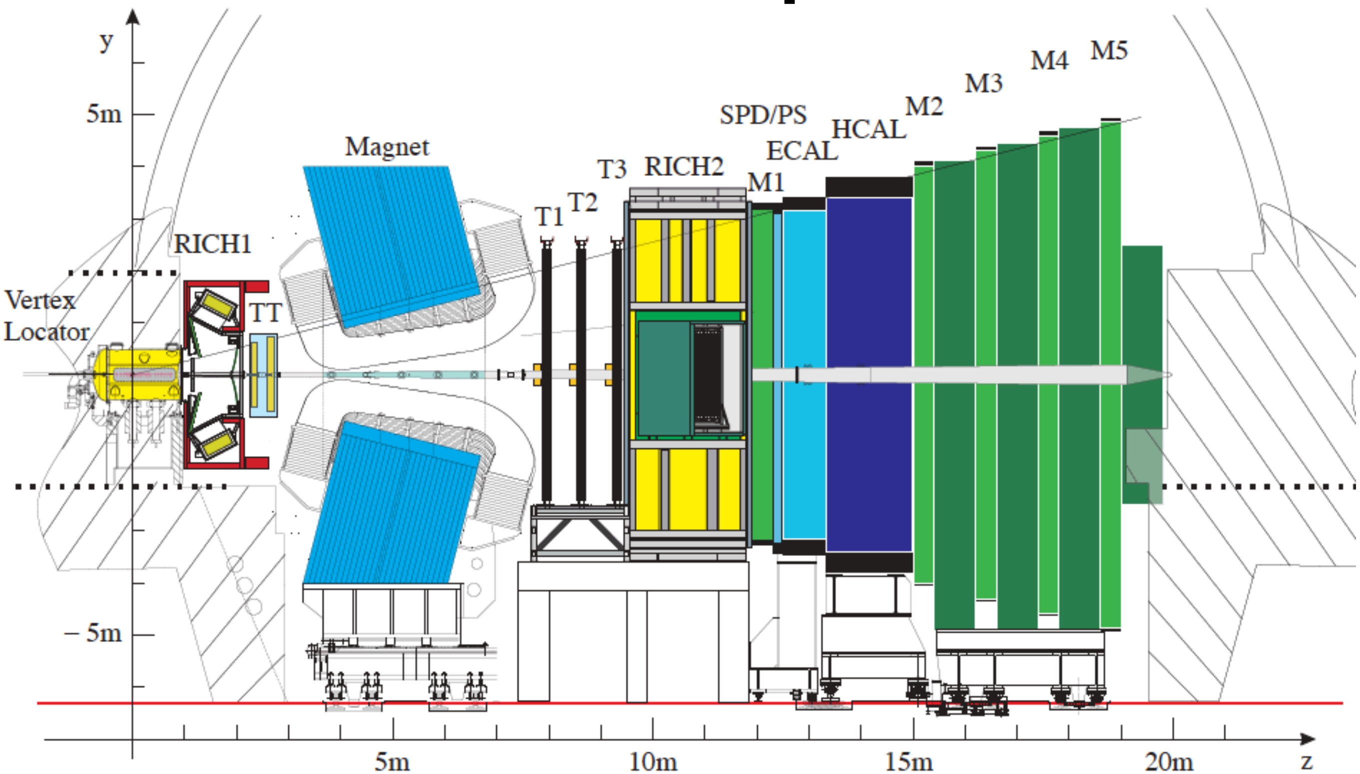
Beauty/charm signature



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

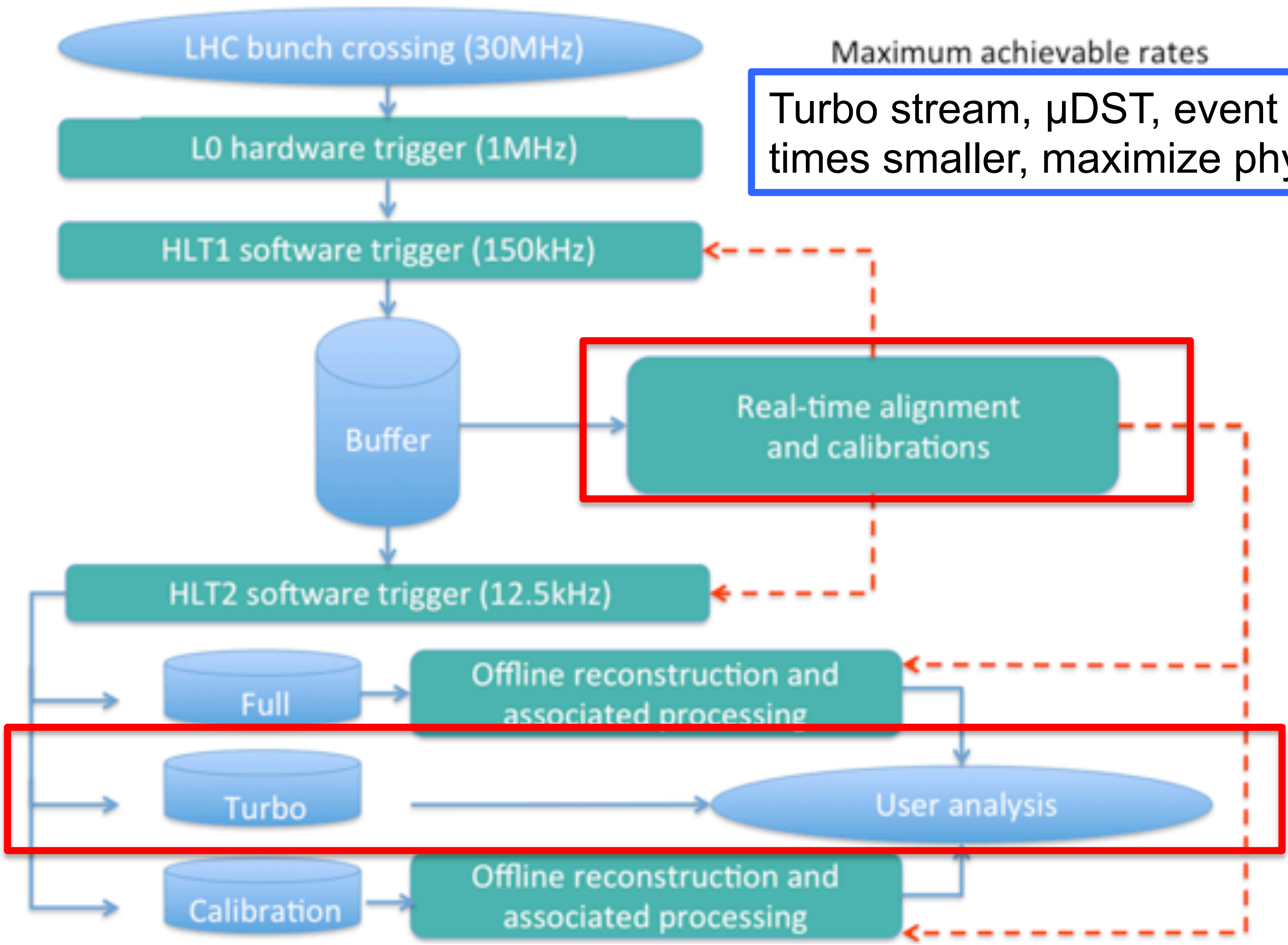
The LHCb experiment

[JINST 3 (2008) S08005]



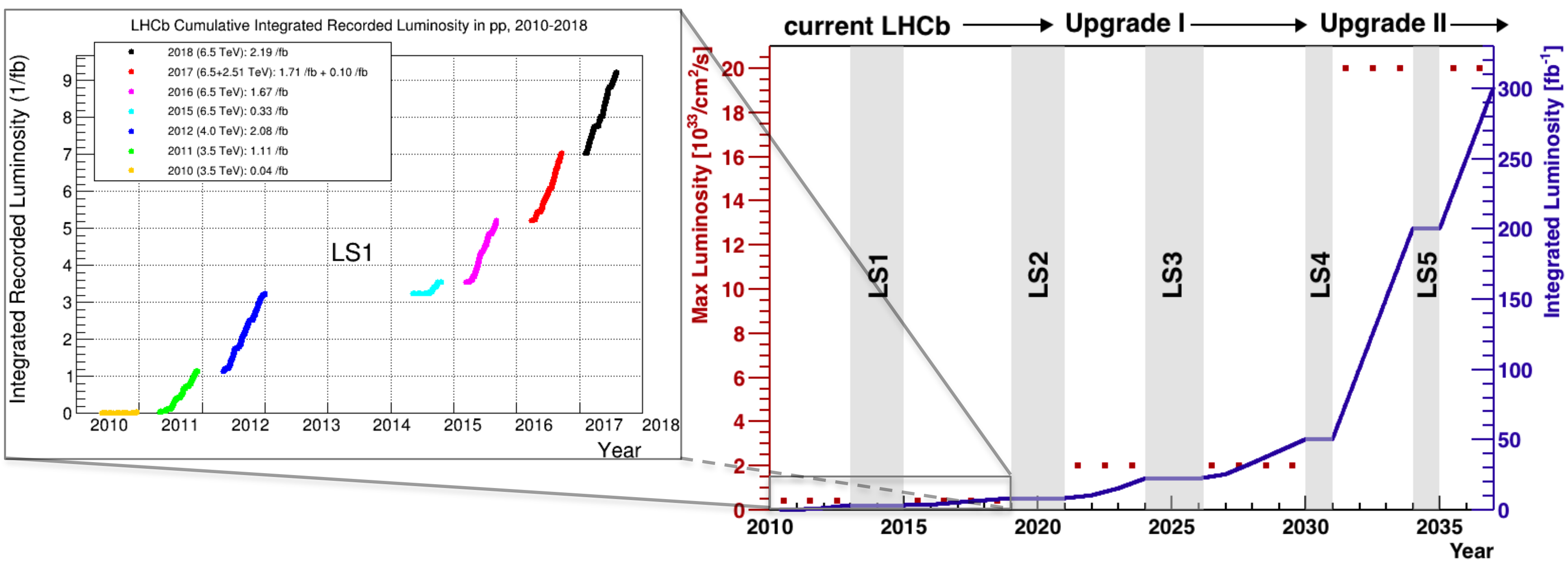
Vertex Locator	$\sigma_{\rm PV,x/y} \sim 10\ \mu$m, $\sigma_{\rm PV,z} \sim 60\ \mu$m
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate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

LHCb data flow



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

LHCb luminosity prospects



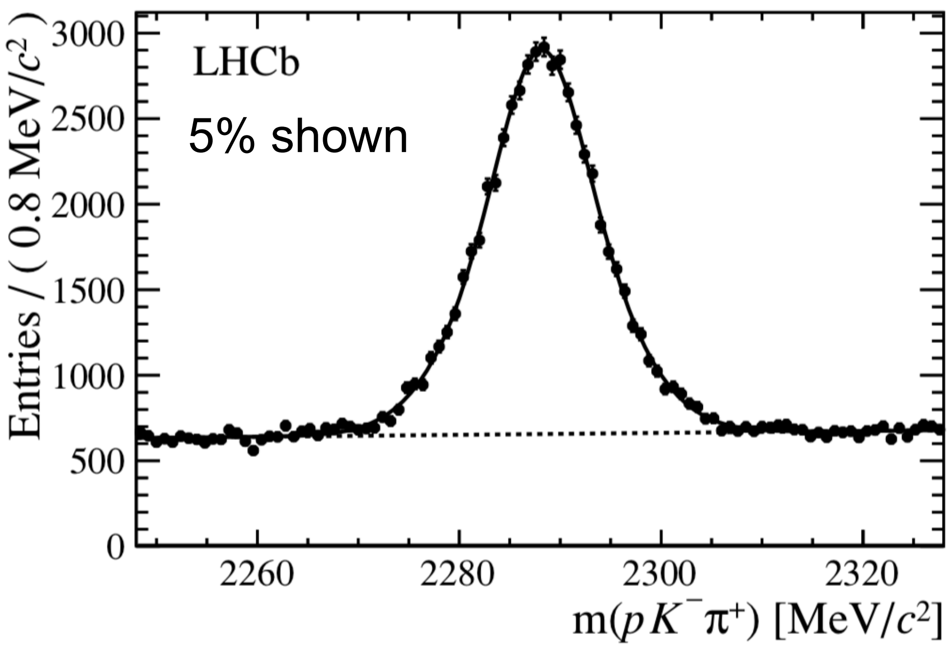
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

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

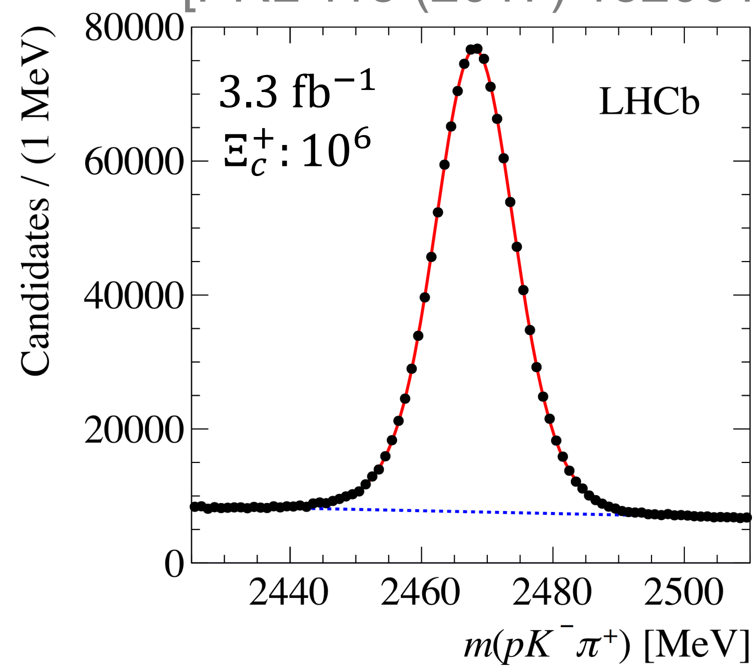
Lots of singly charmed baryons

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

[JHEP 12 (2013) 90]

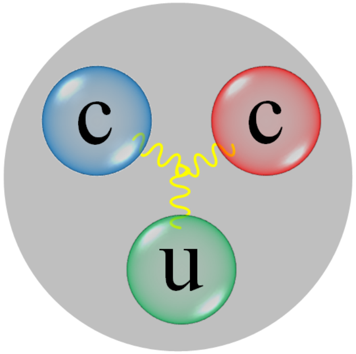


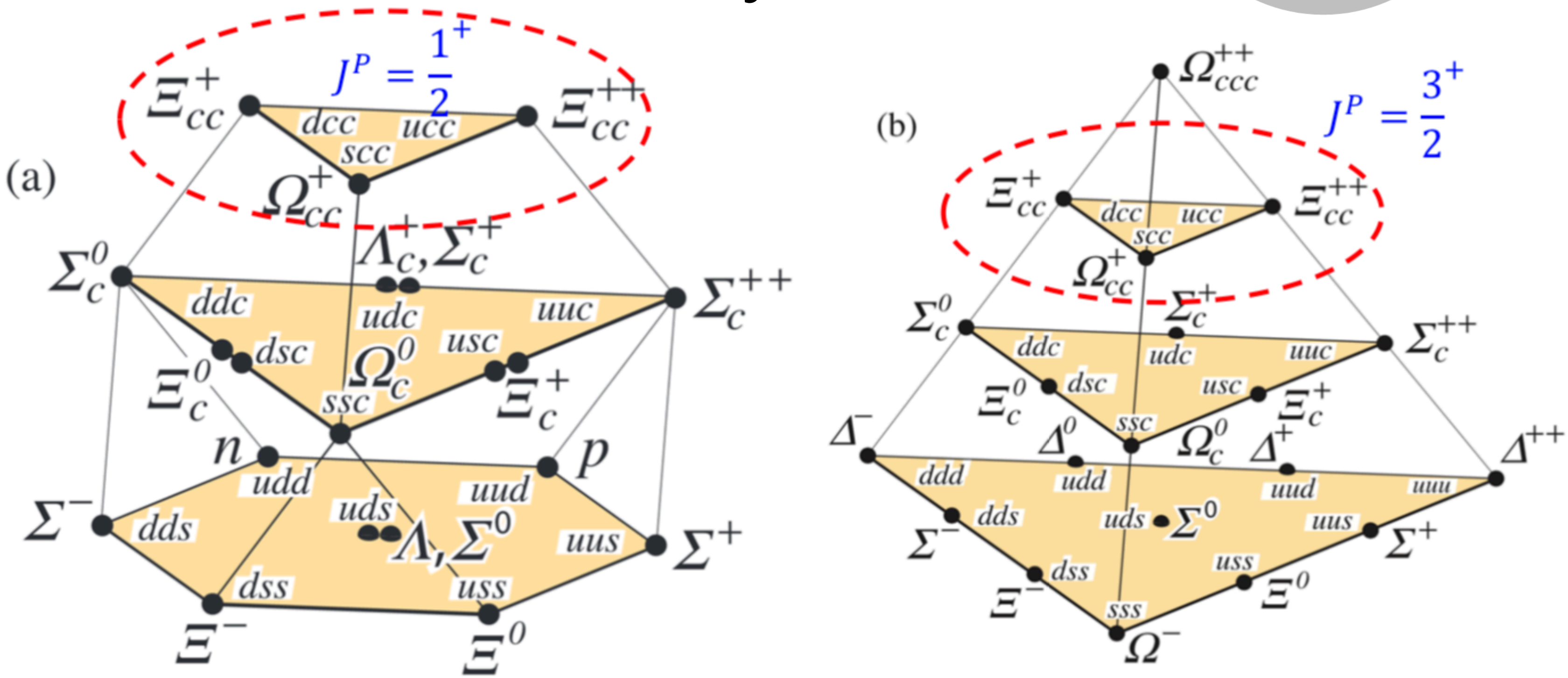
[PRL 118 (2017) 182001]



Doubly charmed baryons

- Particles formed by (*u, d, s, c*)
- Unique system for testing Quantum ChromoDynamics





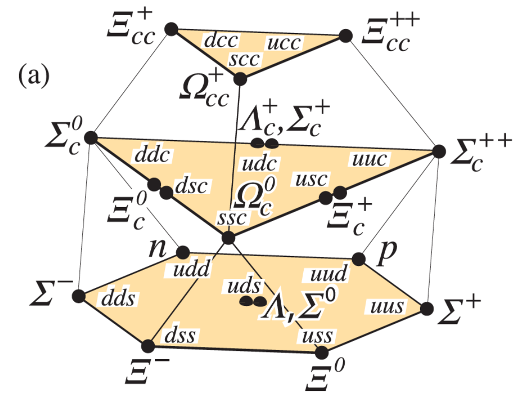
Predicted mass

- $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$~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]

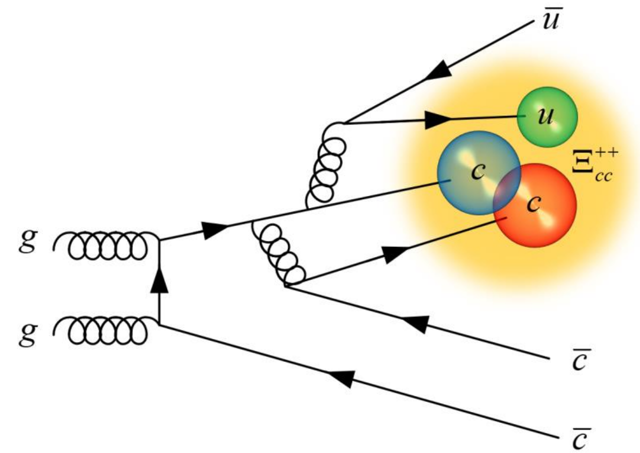
Mass in GeV

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} $\sqrt{S} = 7.0$ TeV	Ξ_{cc} $\sqrt{S} = 14.0$ TeV	Ξ_{bc} $\sqrt{S} = 7.0$ TeV	Ξ_{bc} $\sqrt{S} = 14.0$ TeV	Ξ_{bb} $\sqrt{S} = 7.0$ TeV	Ξ_{bb} $\sqrt{S} = 14.0$ 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: $\sigma(cc) = 90\ \text{nb}$
- Fragmentation fraction: u:d:s~1:1:0.3
  - $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40\ \text{nb},\ \sigma(\Omega_{cc}^{+}) \sim 13\ \text{nb}$

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

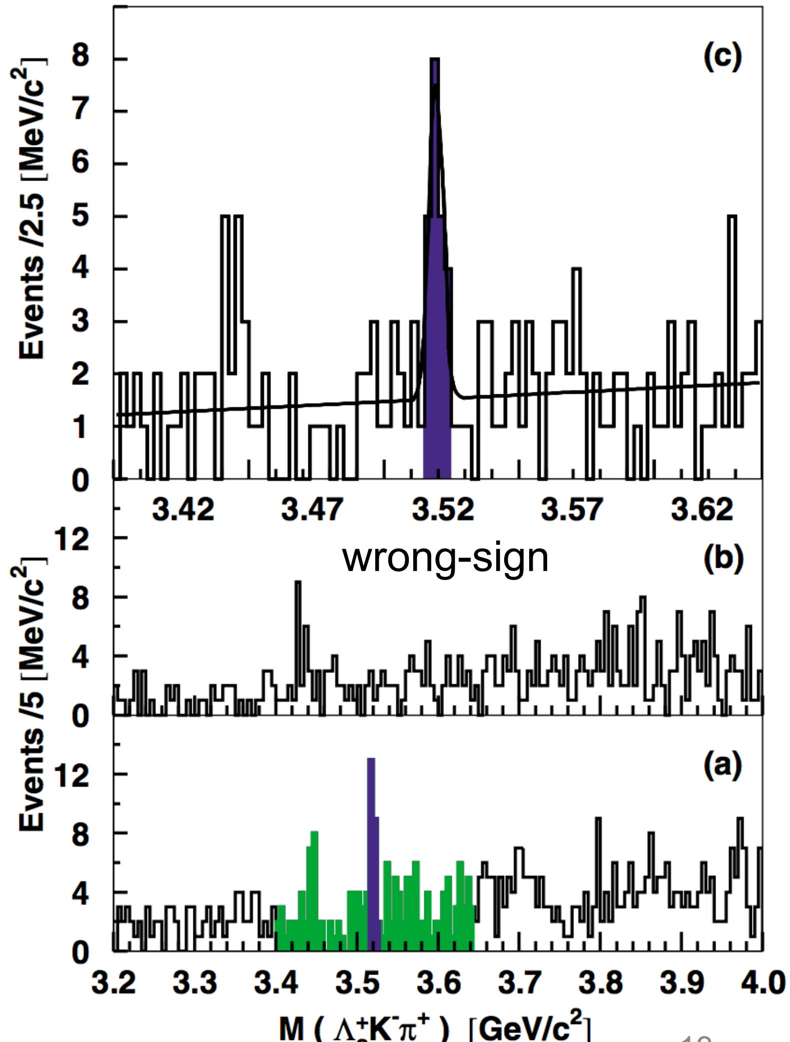
- $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+}) \approx \tau(\Omega_{cc}^{+})$

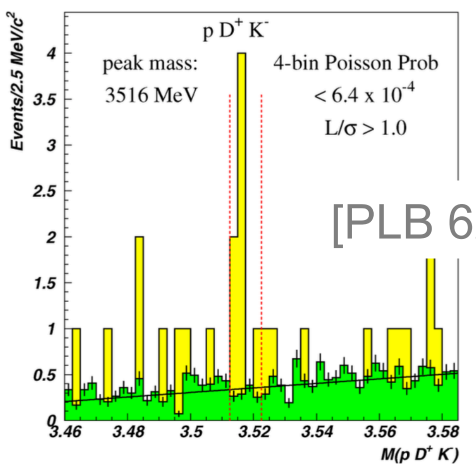
=> Ξ_{cc}^{++} is easier to detect

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 $\Xi_{cc}^{+} \to p D^{+} K^{-}$

[PRL 89 (2002) 112001]

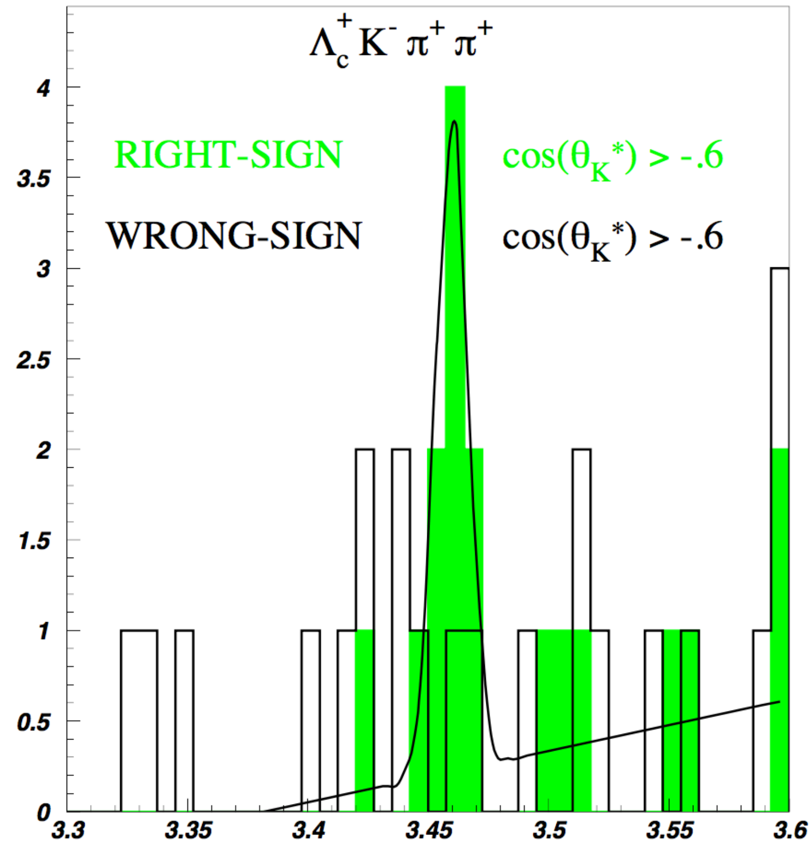




[PLB 628 (2005)18]

Ξ_{cc}^{++} @ SELEX

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

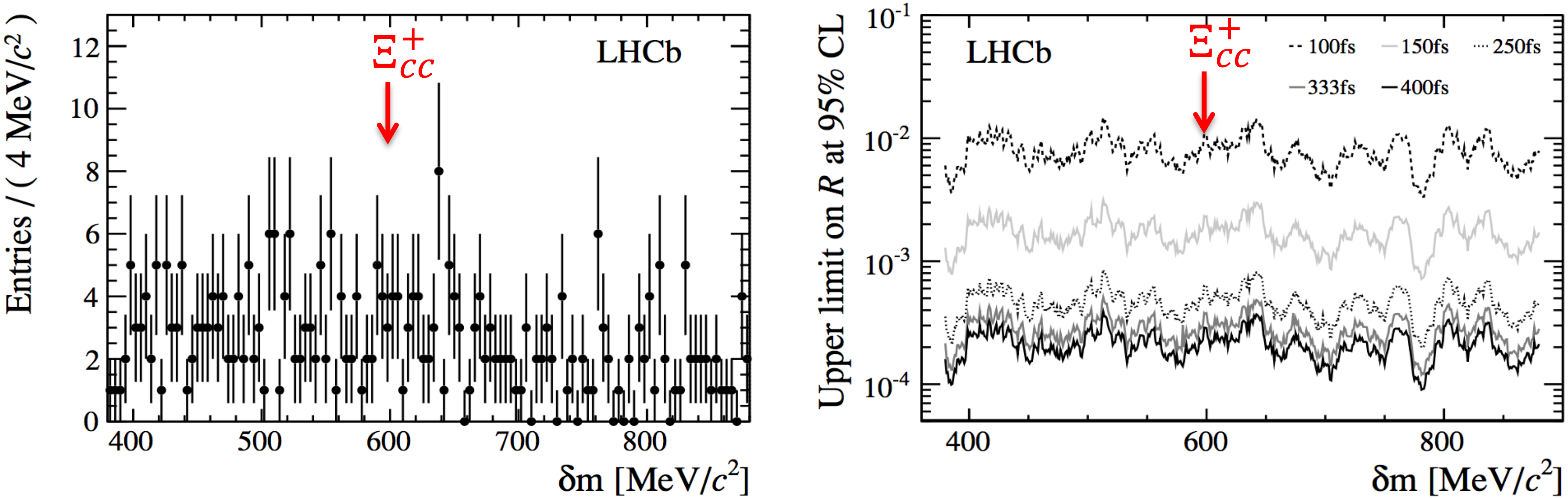


[hep-ex: 0209075]

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]

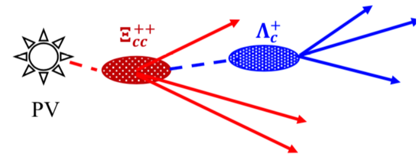


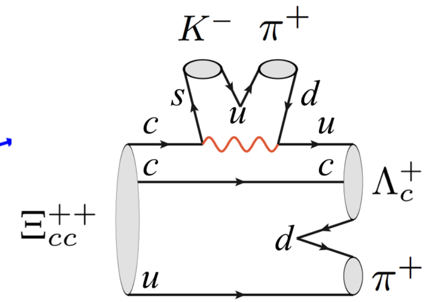
- However, LHCb already had lots of B_c^{+} events, and double-charm events…

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

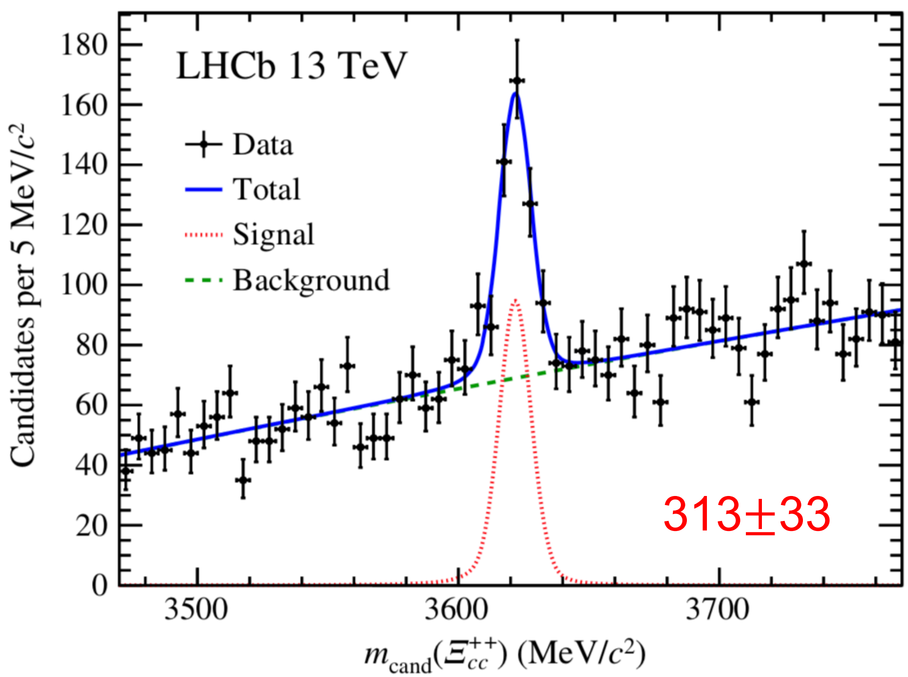
[PRL 119 (2017) 112001]

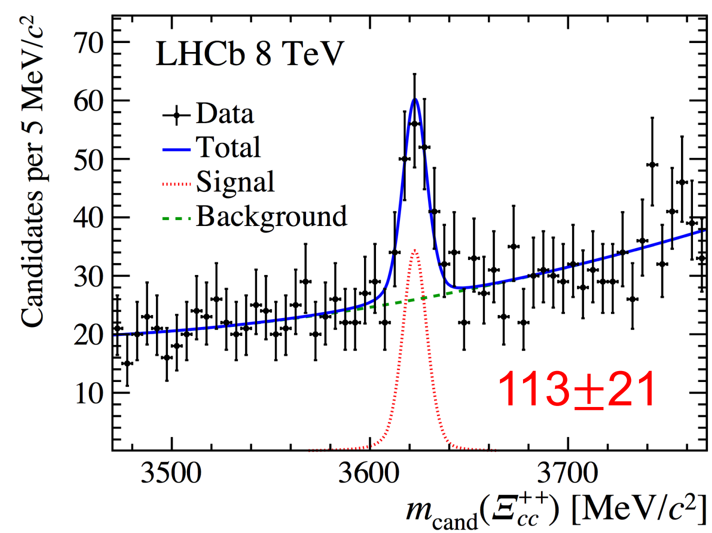
- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel
  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]





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





Ξ_{cc}^{++} properties

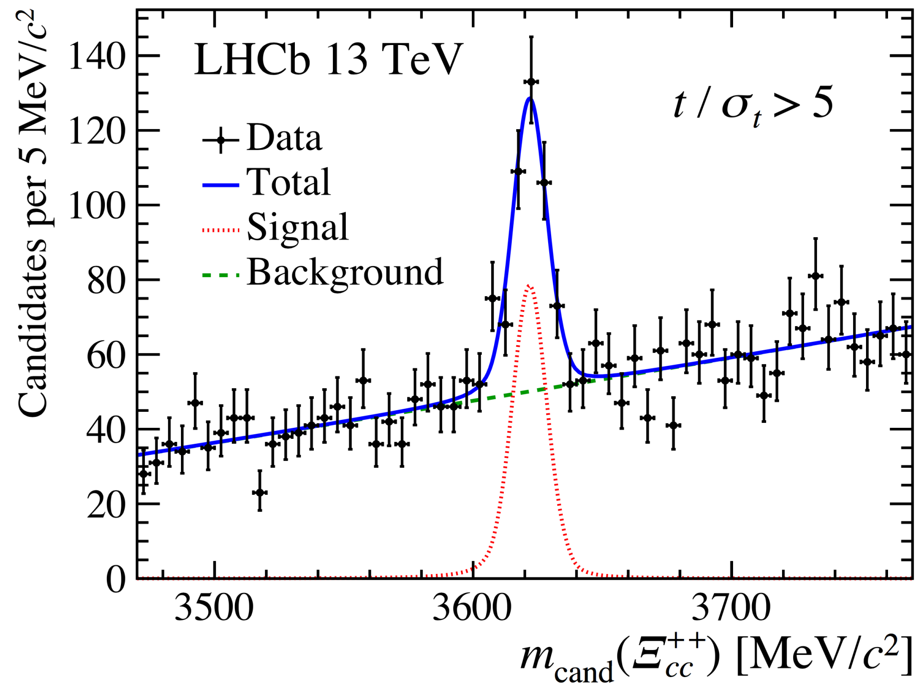
[PRL 119 (2017) 112001]

- 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

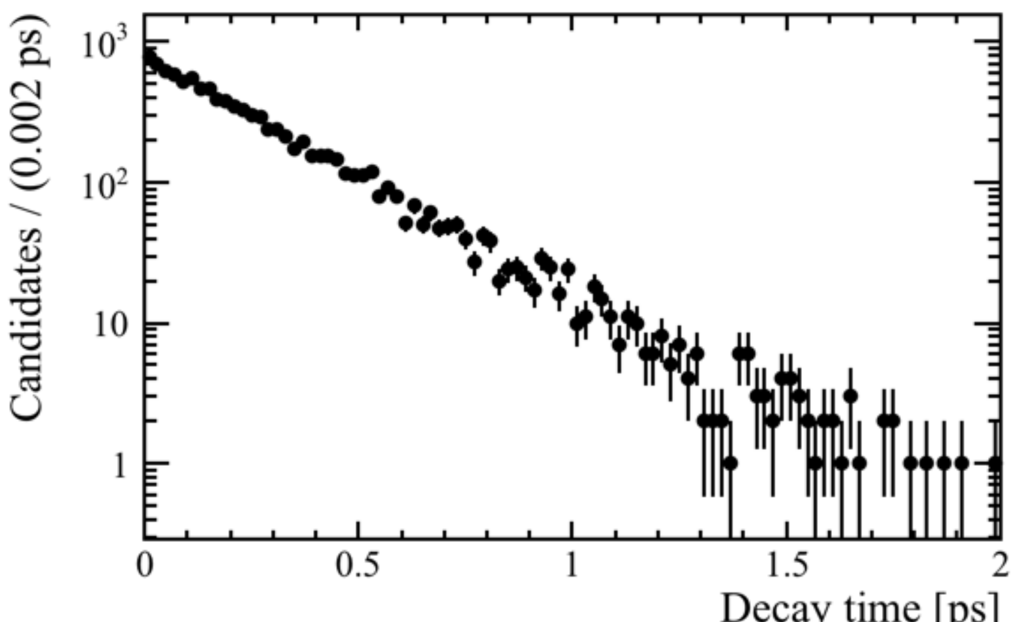


Lifetime measurement

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

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

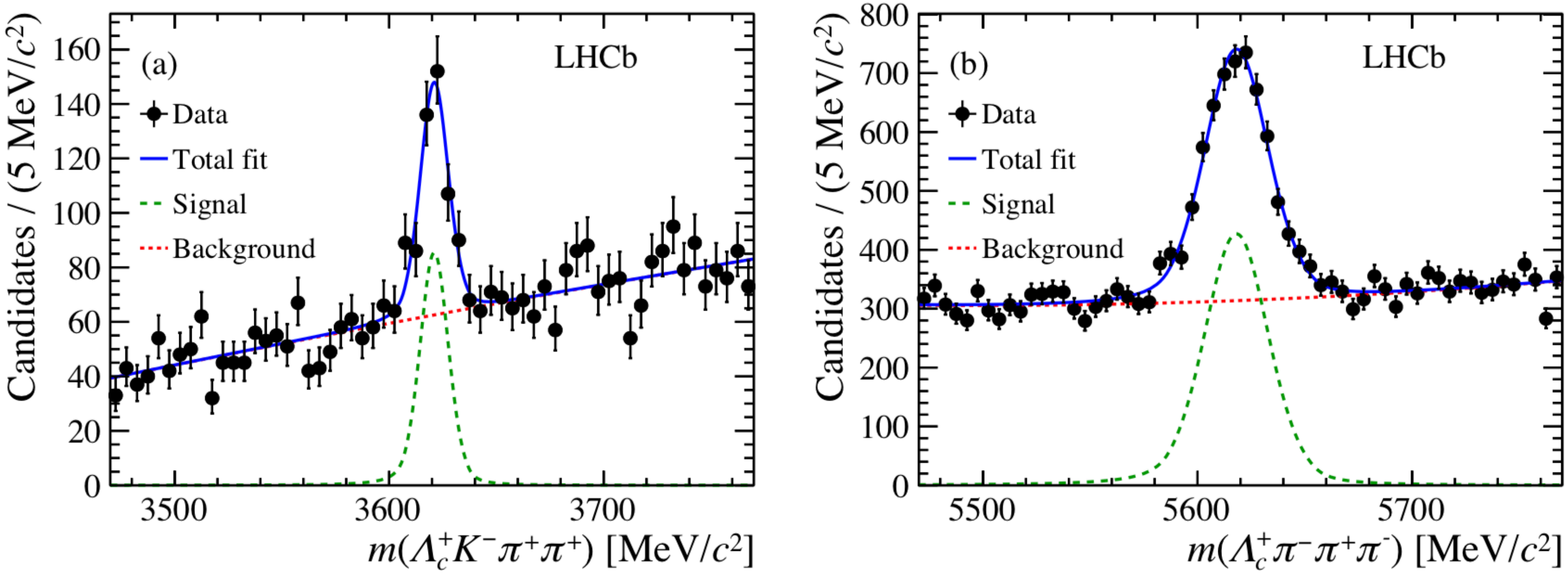
- Expected distribution with $\tau = 0.256$ ps



Measurement of Ξ_{cc}^{++} lifetime

[PRL 121 (2018) 052002]

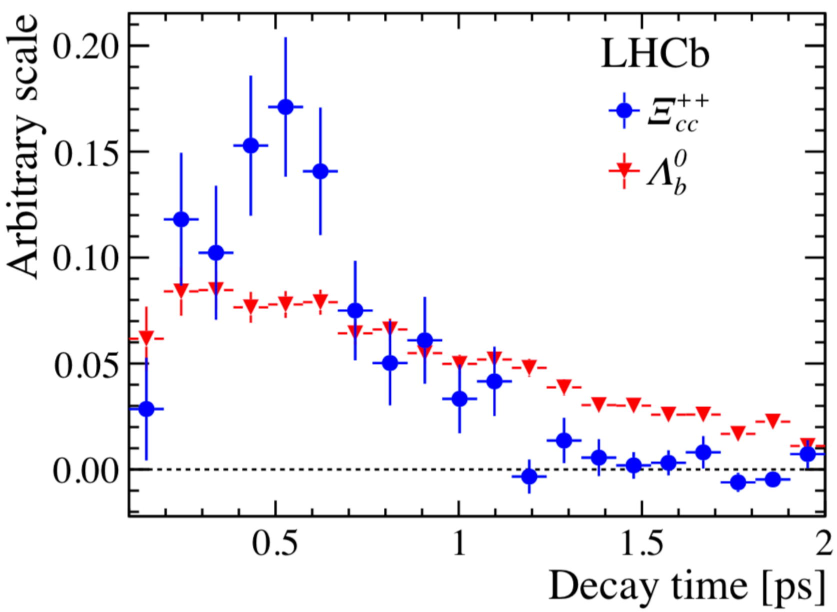
- With the same 2016 data and almost the same selection as the observation
- $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ (control) selected w/ same criteria

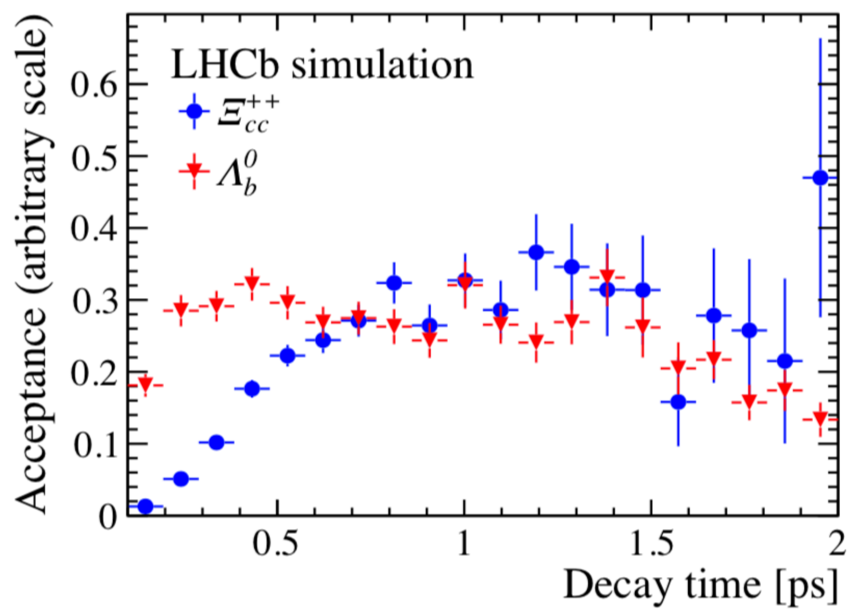


Decay time distribution/acceptance

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

[PRL 121 (2018) 052002]





Ξ_{cc}^{++} lifetime

[PRL 121 (2018) 052002]

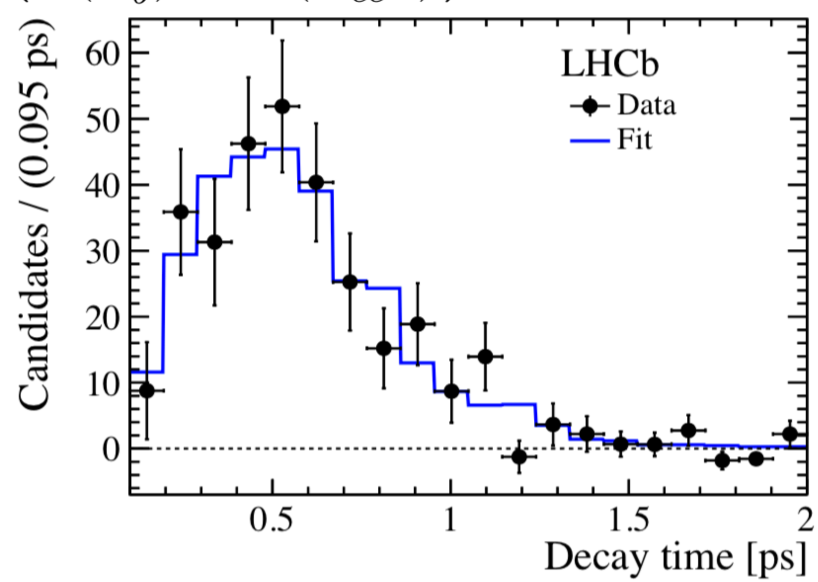
- Fitted Λ_b^0 lifetime 1.474 ± 0.077 ps, validating that simulation well-describes *t* acceptance
- Unbinned $t(\Xi_{cc}^{++})$ described by

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

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

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

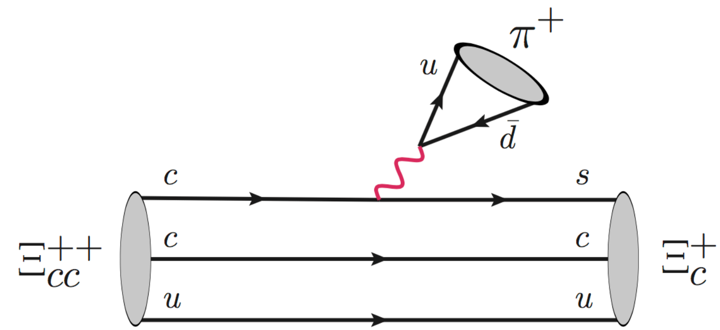
Weakly decay nature established!



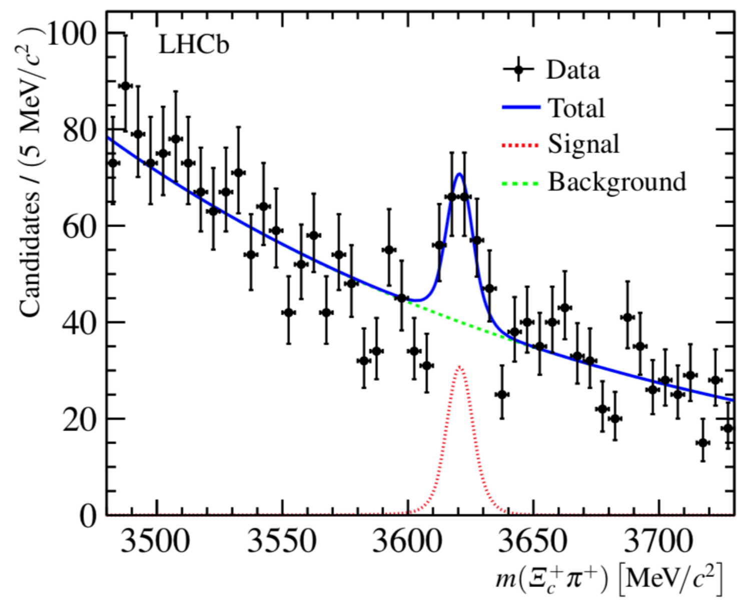
Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

[PRL 121 (2018) 162002]

- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ expected to have large branching fraction
  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]



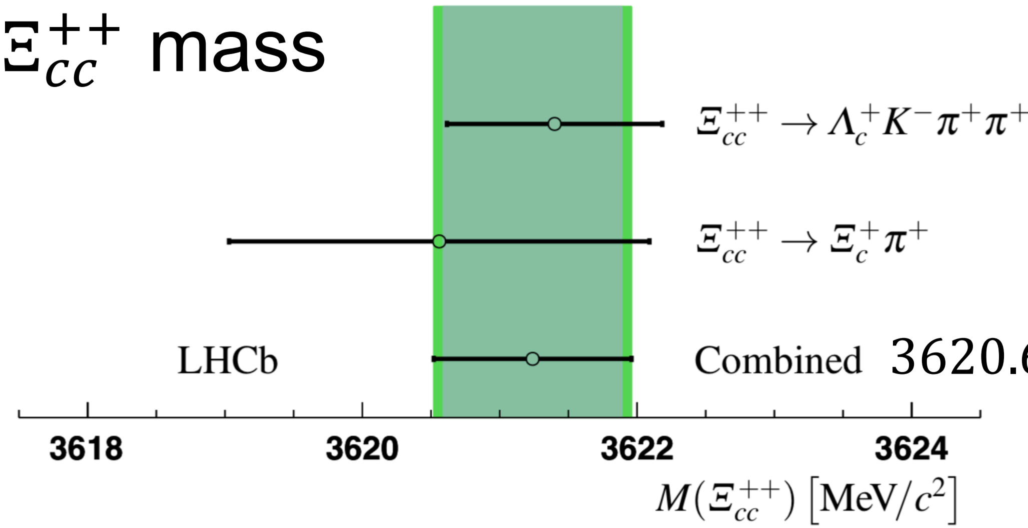
- Searched with 2016 data, following similar selection strategy to $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- 91 ± 20 signals seen, 5.9σ, re-discovery!



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

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

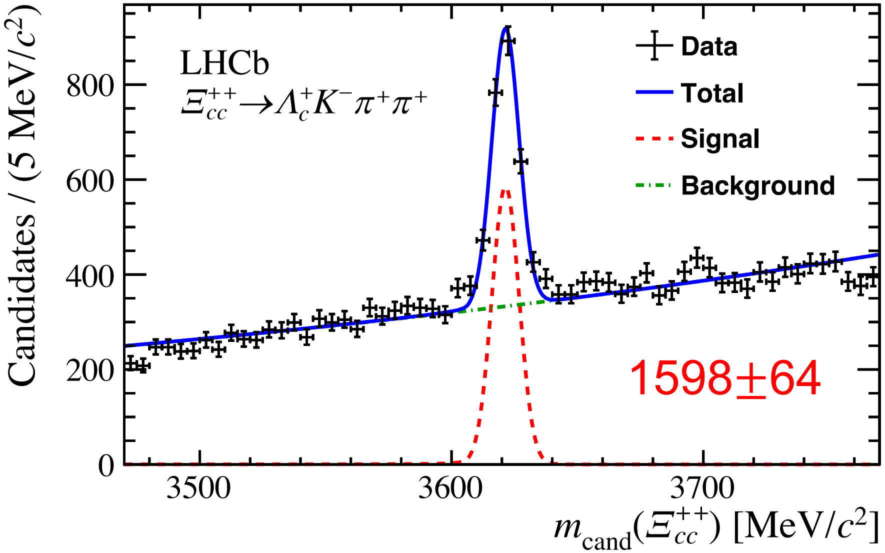
at the lower end of prediction

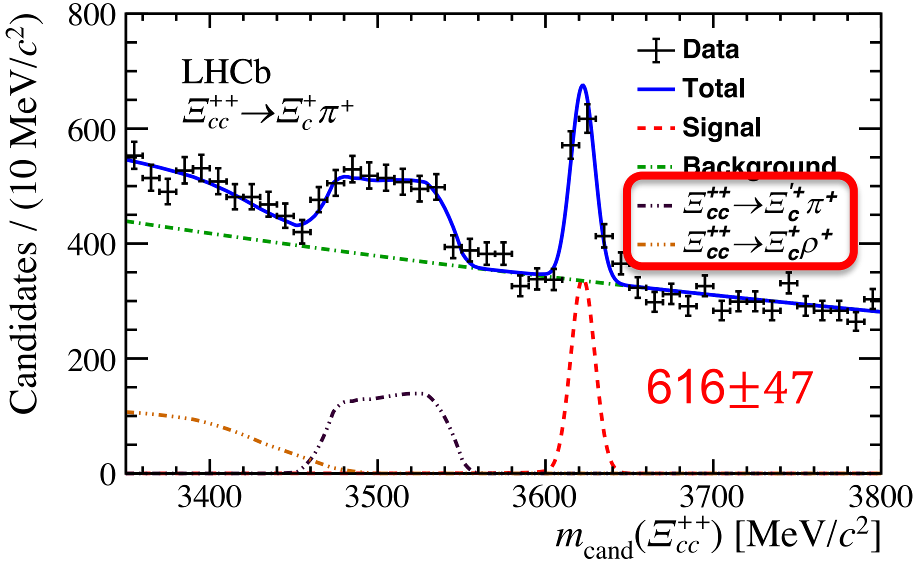
[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

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

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

[JHEP 02 (2020) 049]



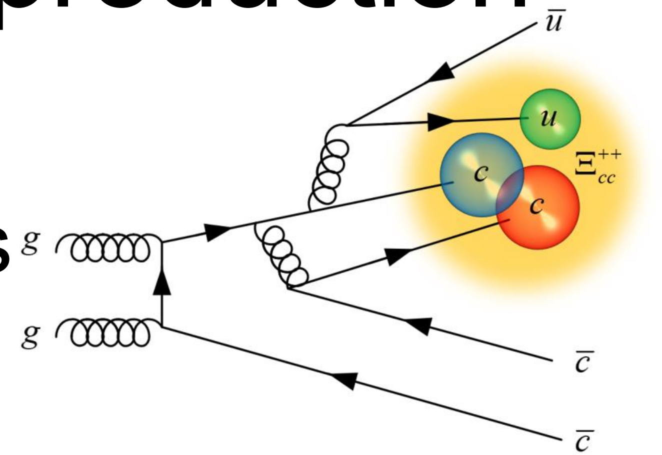


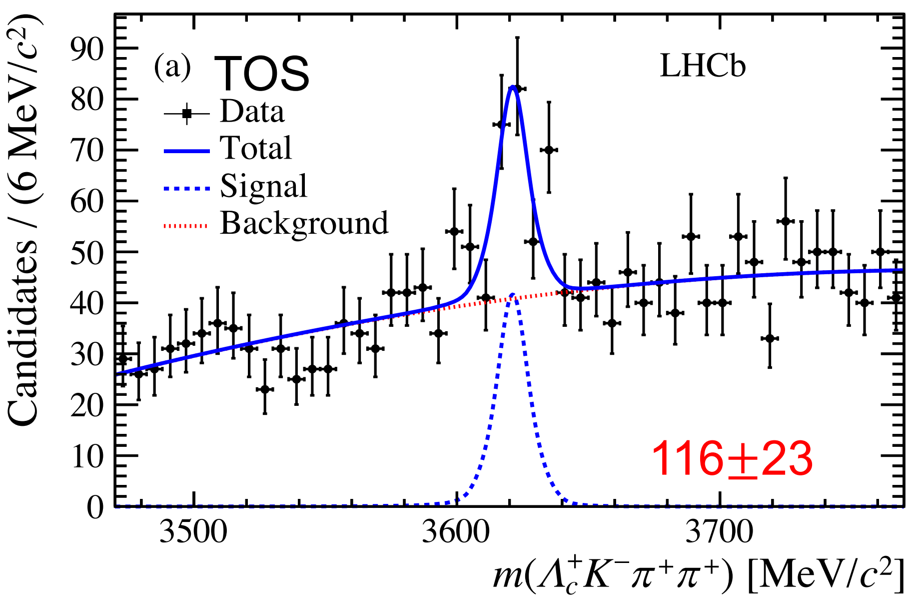
$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30\ \mathrm{MeV}/c^2$$

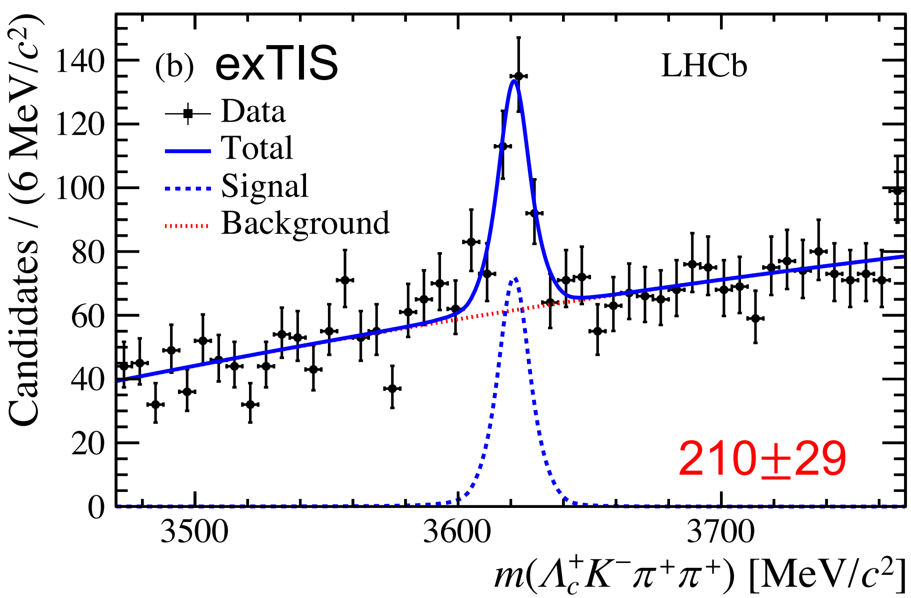
c.f., $3620.6 \pm 0.65 \pm 0.31\ \mathrm{MeV}/c^2$

Measurement of Ξ_{cc}^{++} production

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

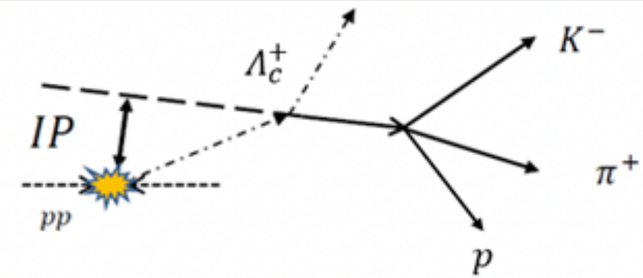


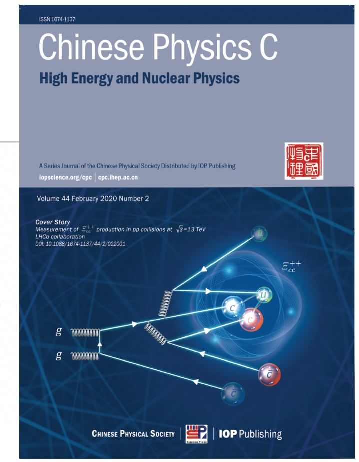




Measurement of Ξ_{cc}^{++} production

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

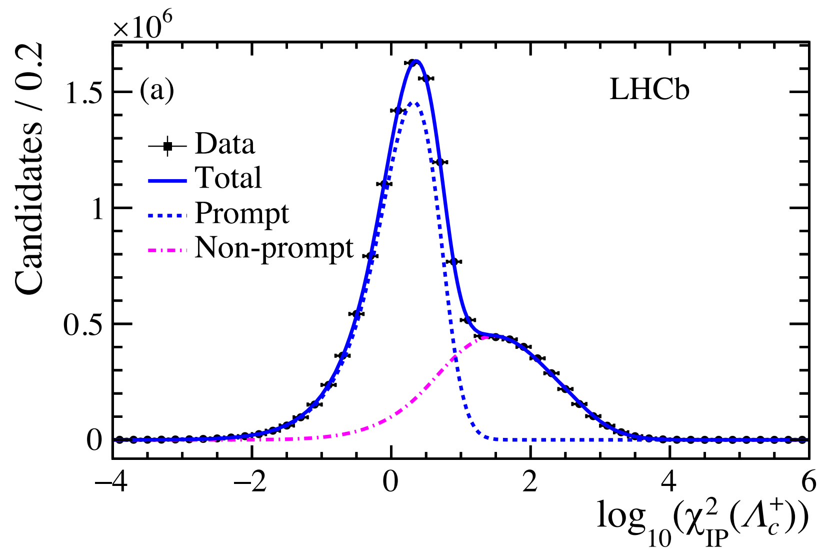




$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\mathcal{B}(\Lambda_c^+ K^-\pi^+\pi^+)$$
$$= (2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$$

[CPC 44 (2020) 022001]

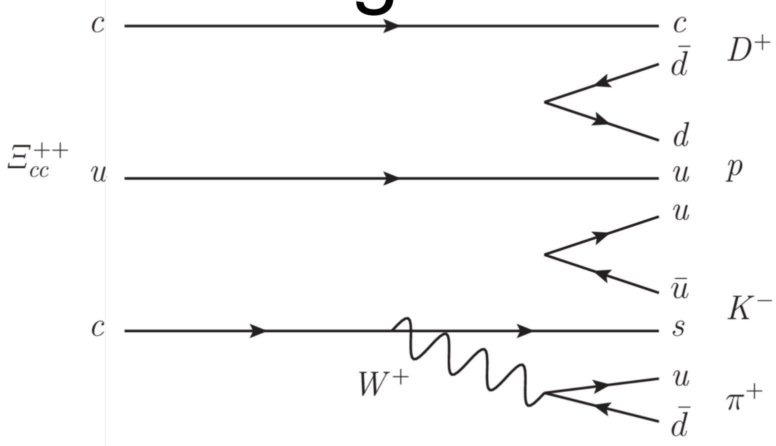
SELEX, 20% Λ_c^+ from Ξ_{cc}^+

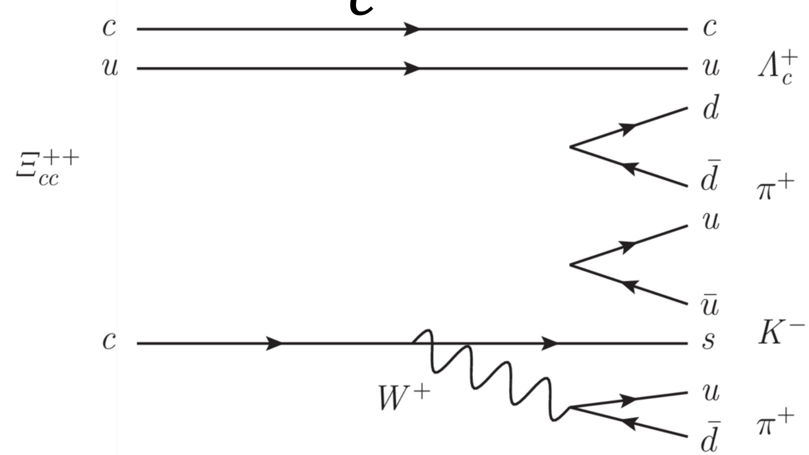


Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$

[JHEP 10 (2019) 124]

- Branching fraction similar to $\Lambda_c^+ K^- \pi^+ \pi^+$?

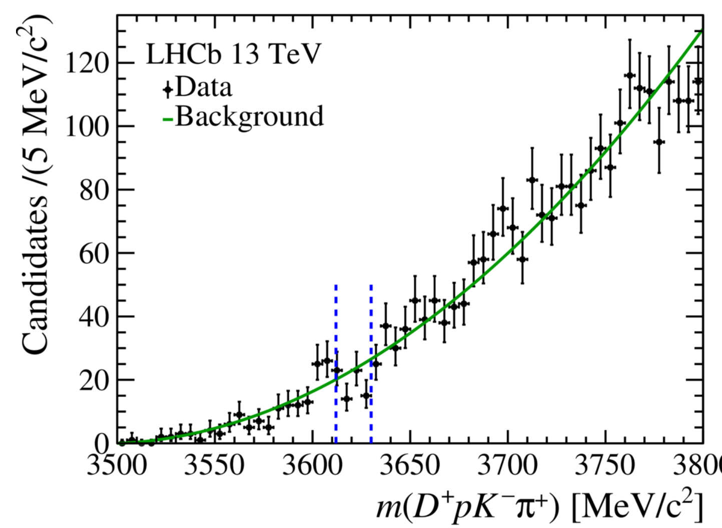




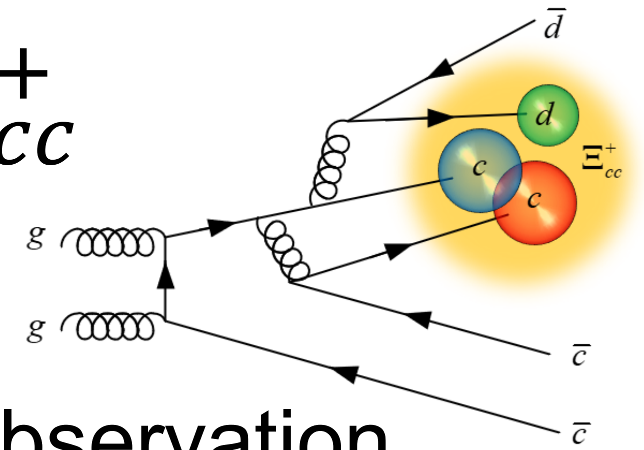
- No signal in 2016 data

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

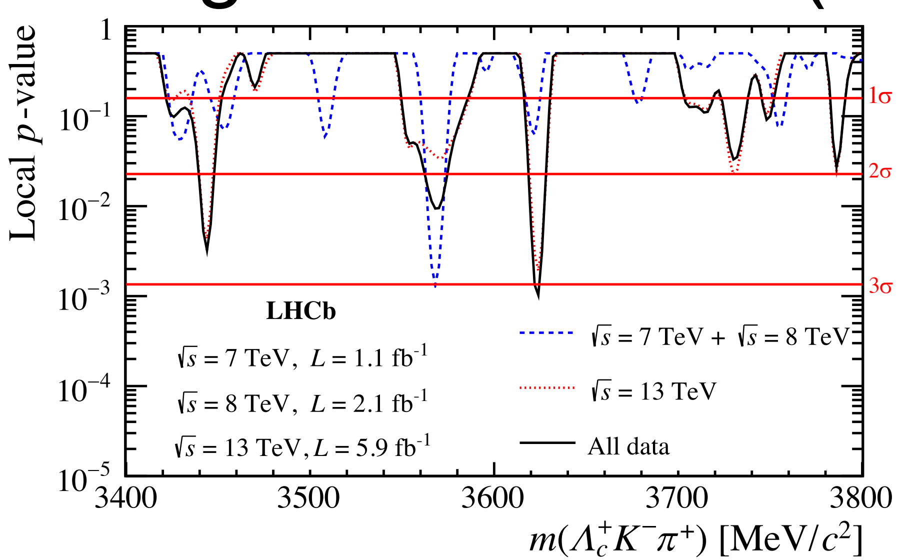
$< 1.5\,(1.9) \times 10^{-2}$ @ 90% (95%) CL

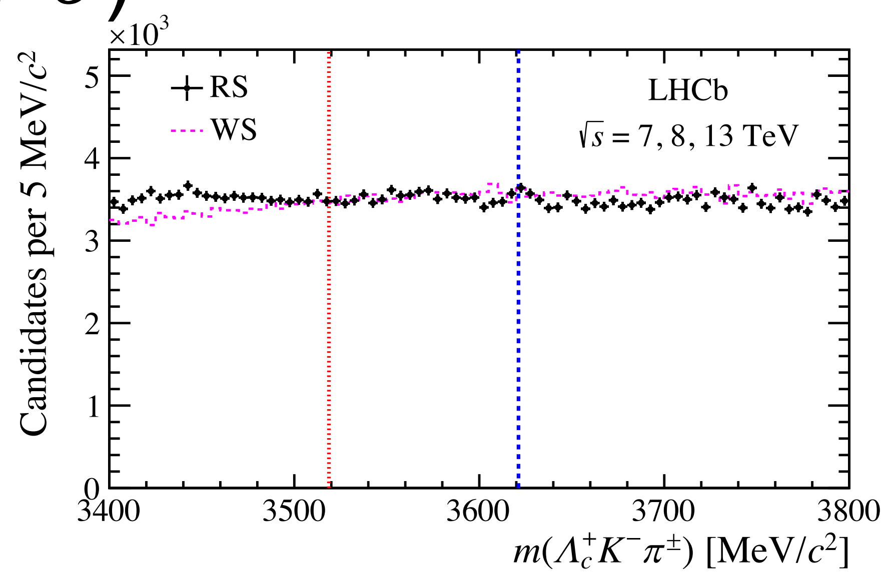


Search for Ξ_{cc}^{+}



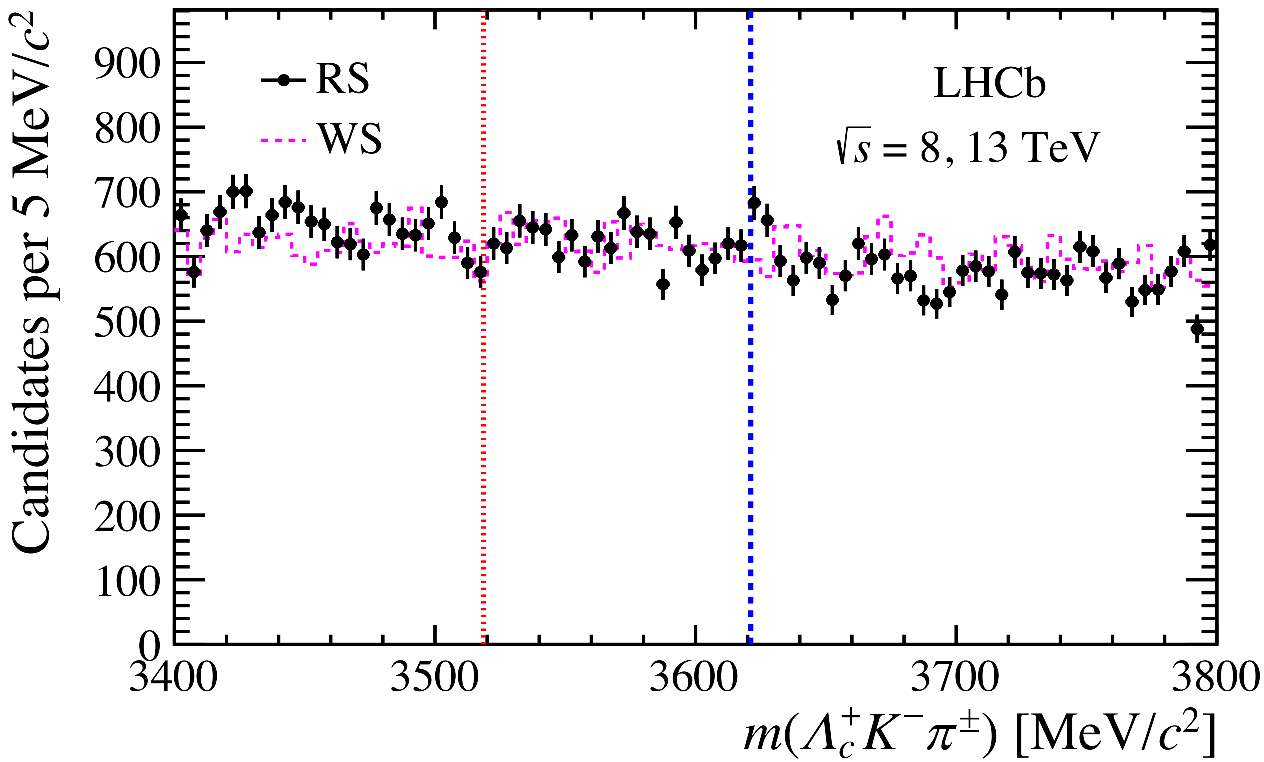
- Blinded analysis
- $\tau(\Xi_{cc}^{+})$: (0 fs, 80 fs) × (non)observation
- Evidence around Ξ_{cc}^{++}, with local (global) significance 3.1σ (1.7 σ)





Unblinded Ξ_{cc}^{+} mass distribution

- Swtiching to event-selection designed for setting upper limit

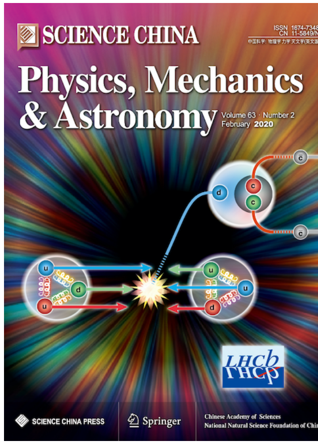


[SCPMA 63 (2020) 221062]

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



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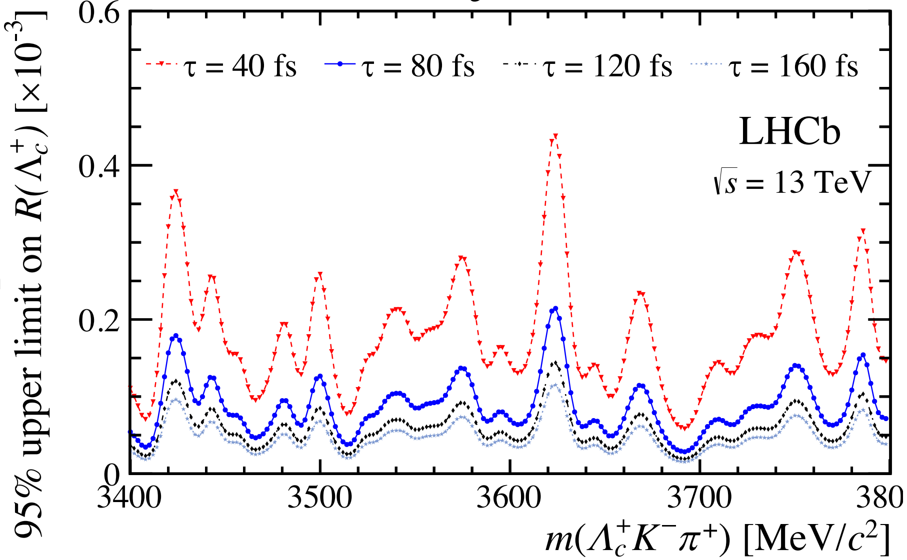
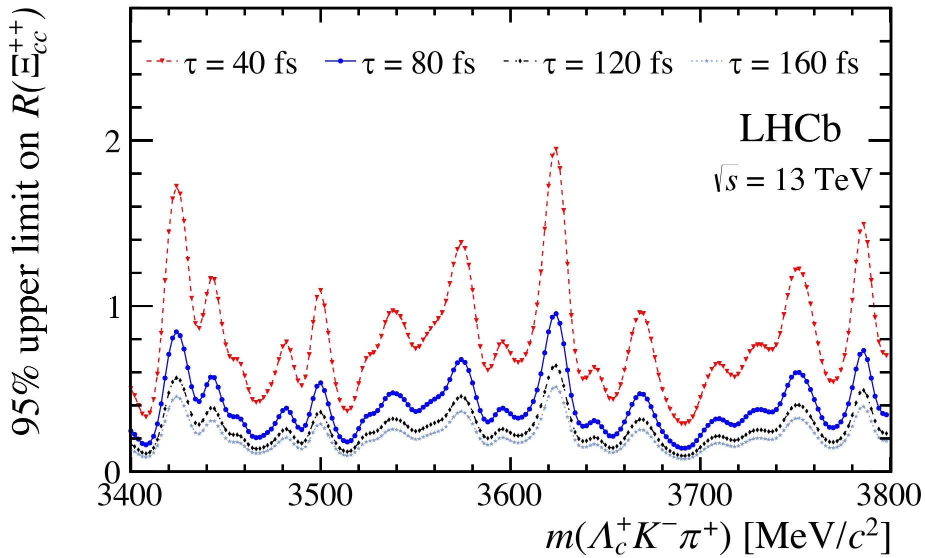
$$R(\Lambda_c^+) = \frac{\sigma(\Xi_{cc}^{+})}{\sigma(\Lambda_c^+)}\mathcal{B}(\Lambda_c^+ K^- \pi^+)$$

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





Prospects of DCB in a nutshell

- LHCb ($9\ \mathrm{fb}^{-1}$, 2018)
  - Ξ_{cc}^{++} more decay modes observed
  - Ξ_{cc}^{+} search w/ more decay modes
  - 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 $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, mass, lifetime, production, decay: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
  - Ξ_{cc}^{+} appearing on the horizon
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Continuous & strong supports from Chinese theorists greatly appreciated