

# Observation of the doubly charmed baryon $\Xi_{cc}^+$ with the upgraded LHCb detector

Jibo HE (何吉波), UCAS (中国科学院大学)

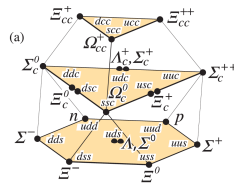
April 20, 2026

# Introduction

- Doubly charmed baryons, unique system for testing QCD
- Properties not-well known before systematic studies by LHCb
  - as shown in the 1<sup>st</sup> HAPOF talk [29/05/2020]

## Predicted mass

- $M(\Xi_{cc}^+) \approx M(\Xi_{cc}^{++}) \sim 3.5-3.7$  GeV  
LQCD\*: 3610(23)(22) MeV
- $M(\Omega_{cc}^+) \sim 3.6-3.9$  GeV  
LQCD\*: 3738(20)(20) MeV



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

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

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

## Predicted lifetime

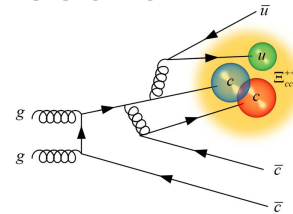
- Large ambiguity...

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

- $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^+) \approx \tau(\Omega_{cc}^+)$   
 $\Rightarrow \Xi_{cc}^{++}$  is easier to detect

## Production cross-section

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



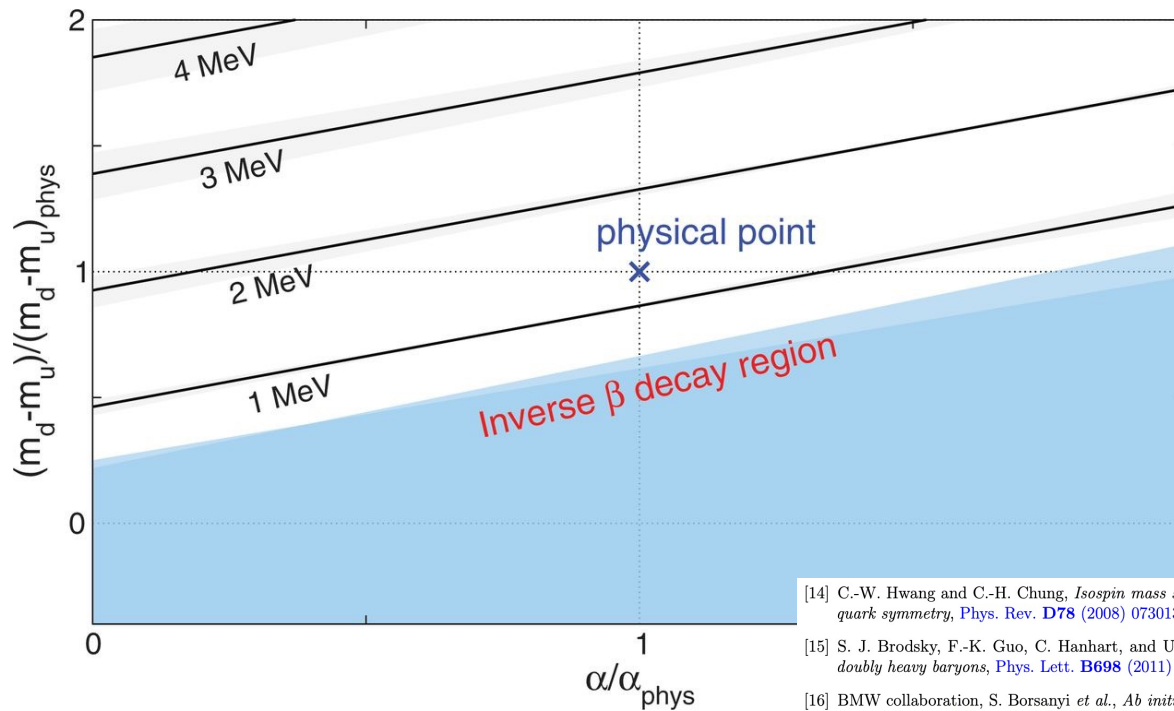
[J.-W. Zhang *et al.*, PRD 66 (2002) 014008]

	$\sqrt{s} = 7.0$ 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:  $u:d:s \sim 1:1:0.3$ 
  - $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^+) \sim 40$  nb,  $\sigma(\Omega_{cc}^+) \sim 13$  nb

# Why $\Xi_{cc}^+$ still interesting after observing $\Xi_{cc}^{++}$ ?

- $\Xi_{cc}^+$  ( $ccd$ ), isospin partner to  $\Xi_{cc}^{++}$  ( $ccu$ ), like neutron to proton
- $m(\Xi_{cc}^+) < m(\Xi_{cc}^{++})$ , **QED wins the competition with QCD!**



	Mass splitting [MeV]	QCD [MeV]	QED [MeV]
$\Delta N = n - p$	1.51(16)(23)	2.52(17)(24)	-1.00(07)(14)
$\Delta \Sigma = \Sigma^- - \Sigma^+$	8.09(16)(11)	8.09(16)(11)	0
$\Delta \Xi = \Xi^- - \Xi^0$	6.66(11)(09)	5.53(17)(17)	1.14(16)(09)
$\Delta D = D^{\pm} - D^0$	4.68(10)(13)	2.54(08)(10)	2.14(11)(07)
$\Delta \Xi_{cc} = \Xi_{cc}^{++} - \Xi_{cc}^+$	2.16(11)(17)	-2.53(11)(06)	4.69(10)(17)
$\Delta_{CG} = \Delta N - \Delta \Sigma + \Delta \Xi$	0.00(11)(06)	-0.00(13)(05)	0.00(06)(02)

- [14] C.-W. Hwang and C.-H. Chung, *Isospin mass splittings of heavy baryons in heavy quark symmetry*, *Phys. Rev. D* **78** (2008) 073013, [arXiv:0804.4044](https://arxiv.org/abs/0804.4044).
- [15] S. J. Brodsky, F.-K. Guo, C. Hanhart, and U.-G. Meißner, *Isospin splittings of doubly heavy baryons*, *Phys. Lett. B* **698** (2011) 251, [arXiv:1101.1983](https://arxiv.org/abs/1101.1983).
- [16] BMW collaboration, S. Borsanyi *et al.*, *Ab initio calculation of the neutron-proton mass difference*, *Science* **347** (2015) 1452, [arXiv:1406.4088](https://arxiv.org/abs/1406.4088).
- [17] K.-W. Wei, B. Chen, and X.-H. Guo, *Masses of doubly and triply charmed baryons*, *Phys. Rev. D* **92** (2015) 076008, [arXiv:1503.05184](https://arxiv.org/abs/1503.05184).
- [18] M. Karliner and J. L. Rosner, *Isospin splittings in baryons with two heavy quarks*, *Phys. Rev. D* **96** (2017) 033004, [arXiv:1706.06961](https://arxiv.org/abs/1706.06961).

# Large Hadron Collider



SUISSE  
FRANCE

LHCb

ATLAS

CERN Meyrin

SPS 7 km

PS 6.28 km

ALICE

CMS

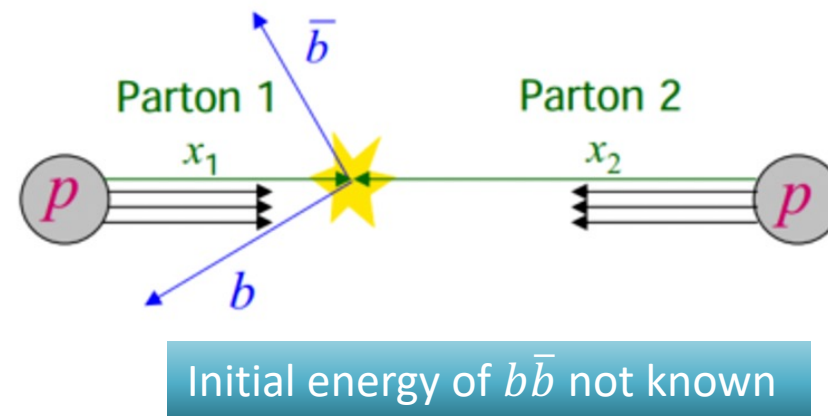
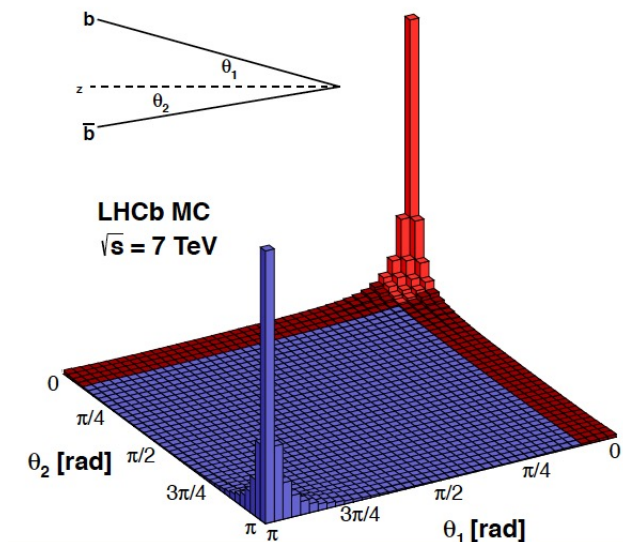
Proton energy: up to 7 TeV ( $10^{12}$  eV)  
speed: 0.999999991 c

LHC 27 km

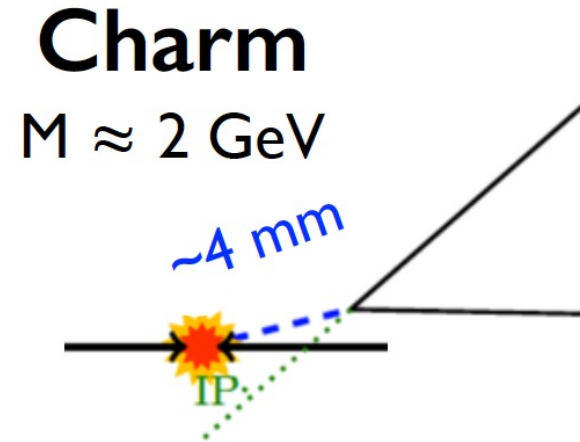
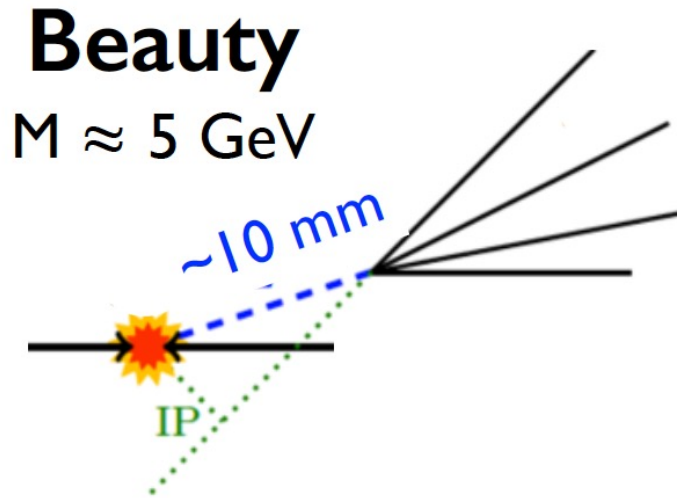
# Beauty/charm production

- Large production cross-section @ 7 TeV
    - Minibias  $\sim 60$  mb
    - Charm  $\sim 6$  mb
    - Beauty  $\sim 0.3$  mb c.f. 1nb @ $\Upsilon(4S)$
- } **Flavour factory!**
- Predominantly in forward/backward cones

All  $b$ -hadrons:  
 $B^+, B^0, B_S^0, \Lambda_b^0, B_c^+, \dots$

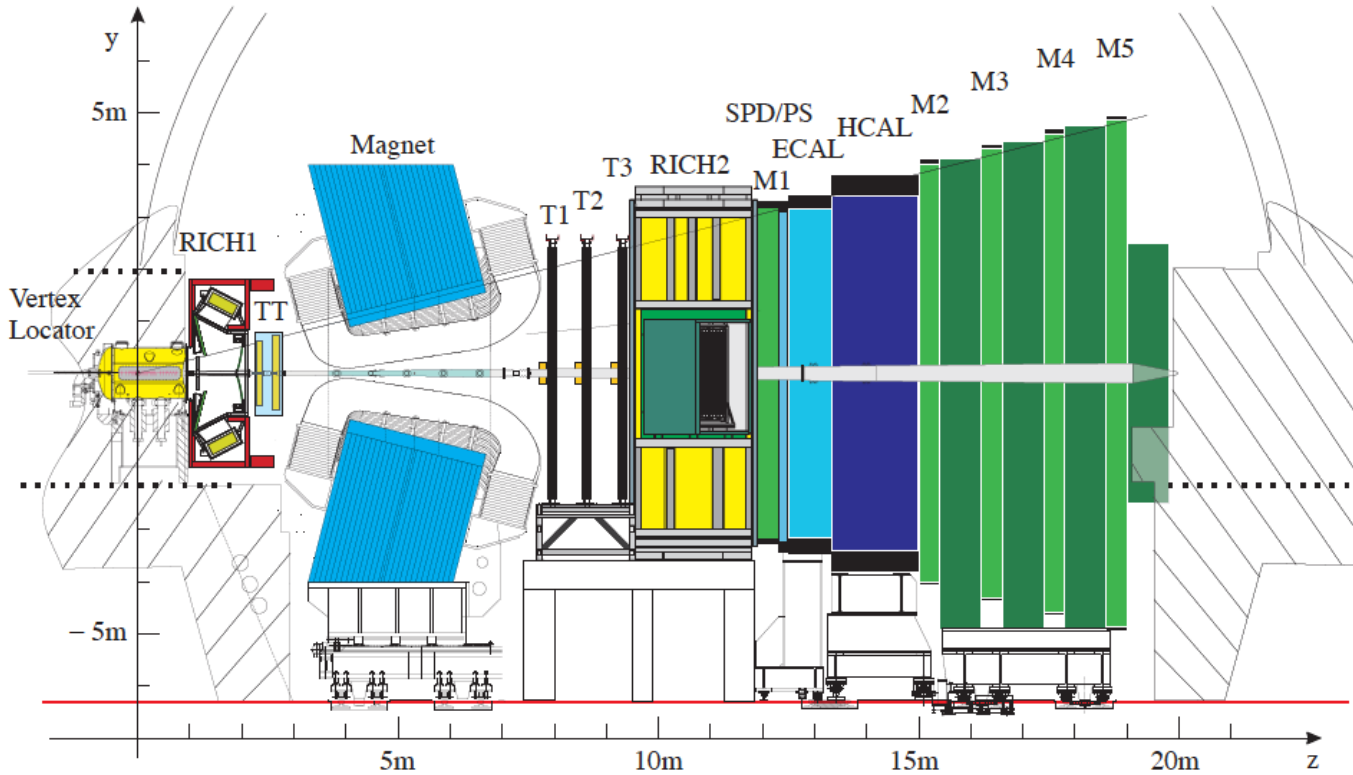


# Beauty/charm signature



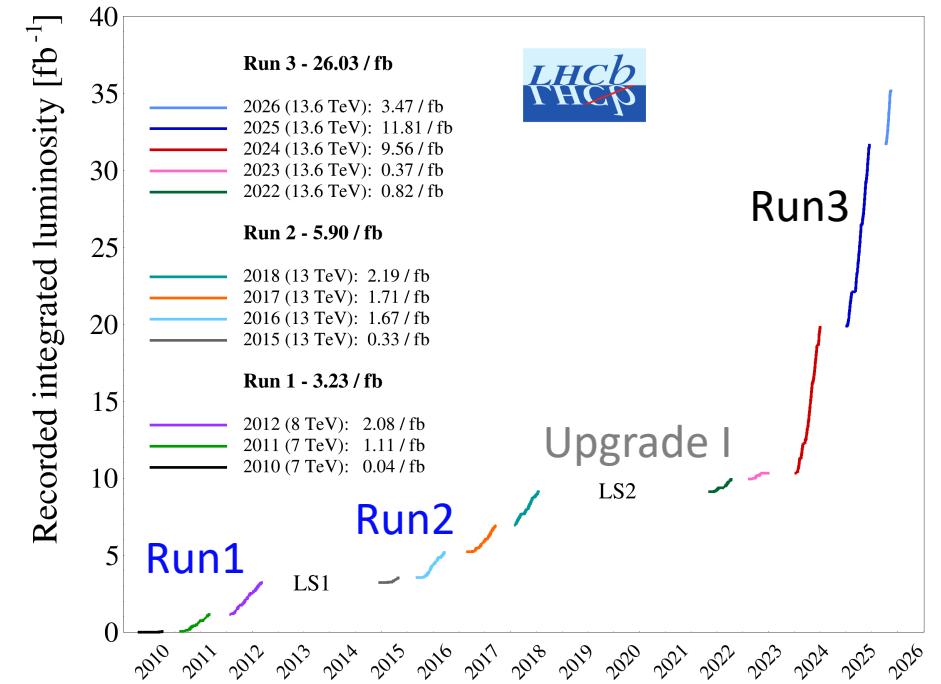
- Compared to minimum bias (background)
  - Relatively high mass  $\rightarrow$  high *transverse momentum*
  - Relatively long lifetime  $\rightarrow$  large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

# The LHCb experiment



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

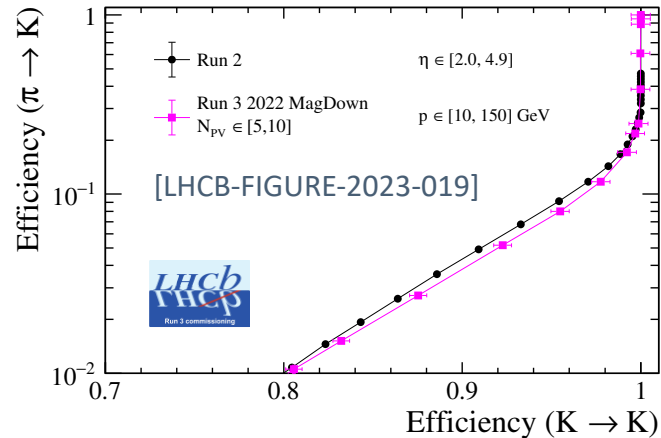
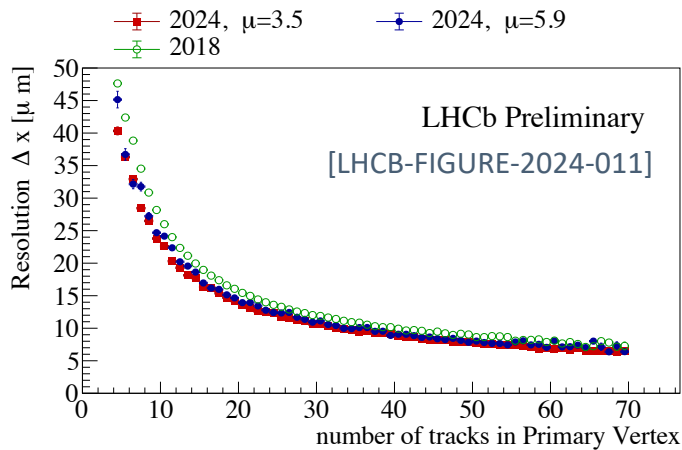
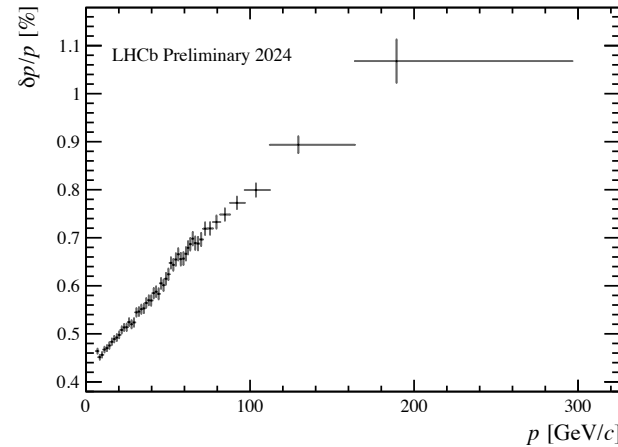
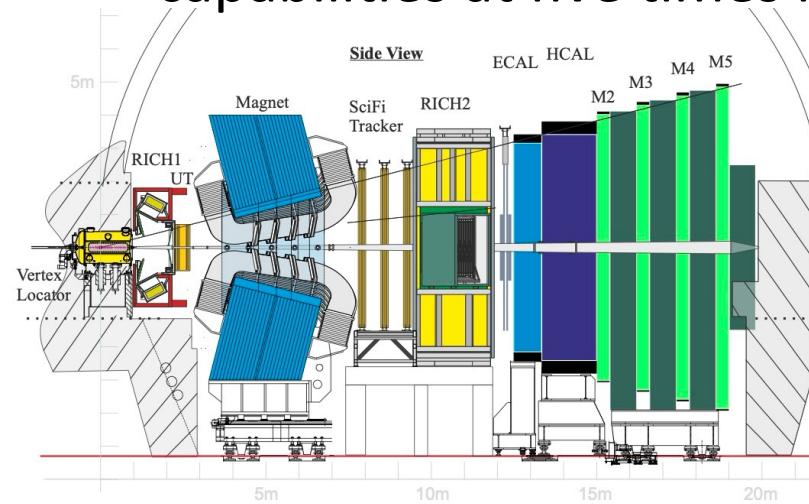
Total recorded luminosity –  $pp$  – 35.2 fb<sup>-1</sup>



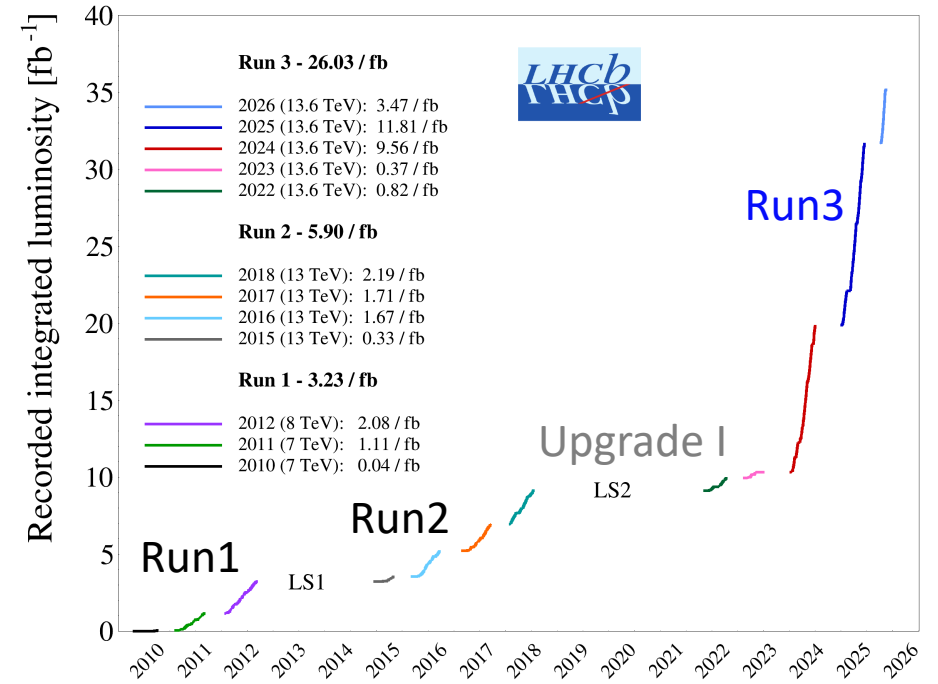
- **Run1-2 (2010-2018)**
  - Luminosity:  $\sim 9 \text{ fb}^{-1}$
  - Yields, complementary to ATLAS/CMS
    - Muon modes: Down to zero  $p_T$
    - Hadronic modes: **Unique**

# The LHCb Upgrade

- Detector mostly renewed to achieve enhanced capabilities at five times higher luminosity

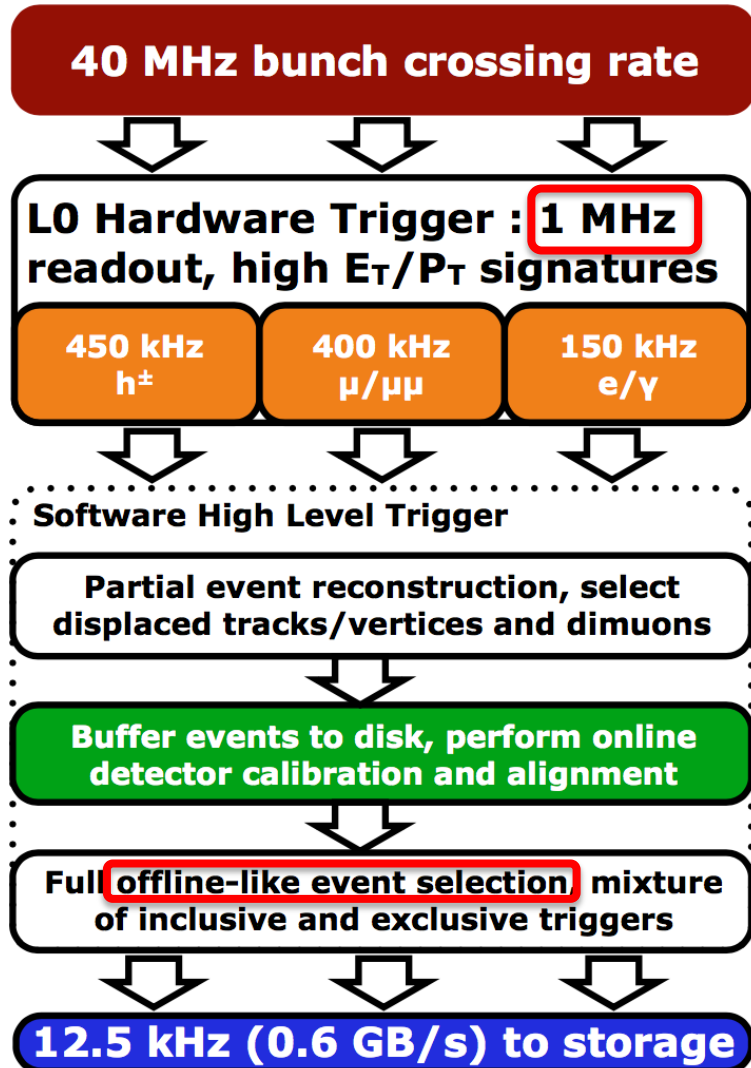


Total recorded luminosity –  $pp$  – 35.2  $\text{fb}^{-1}$



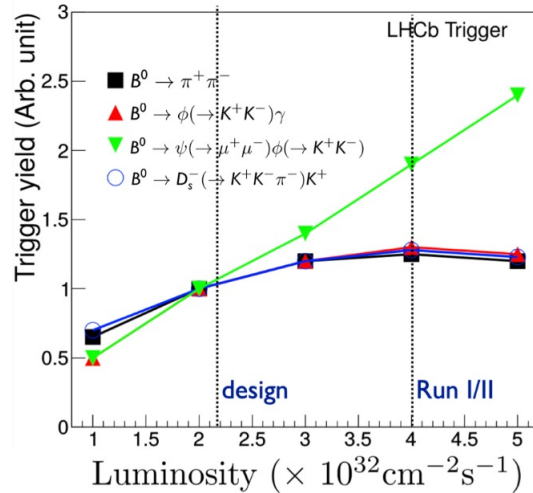
- Run3 (2024-2026)
  - Luminosity:  $\sim 27 \text{fb}^{-1}$
  - Yields, compared to Run 1+2
    - Muon modes  $\sim 3.5$
    - Hadronic modes  $\sim 7$  (higher trigger eff.)

# The LHCb trigger (2018)

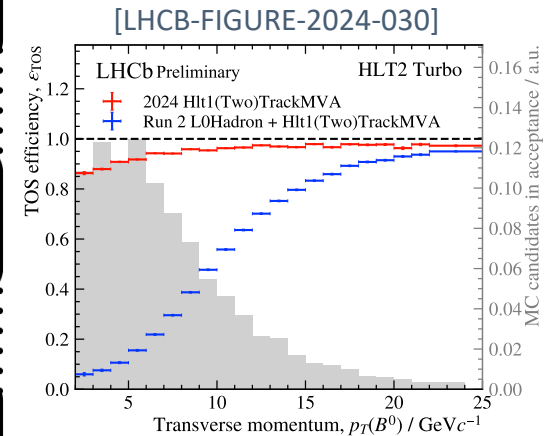
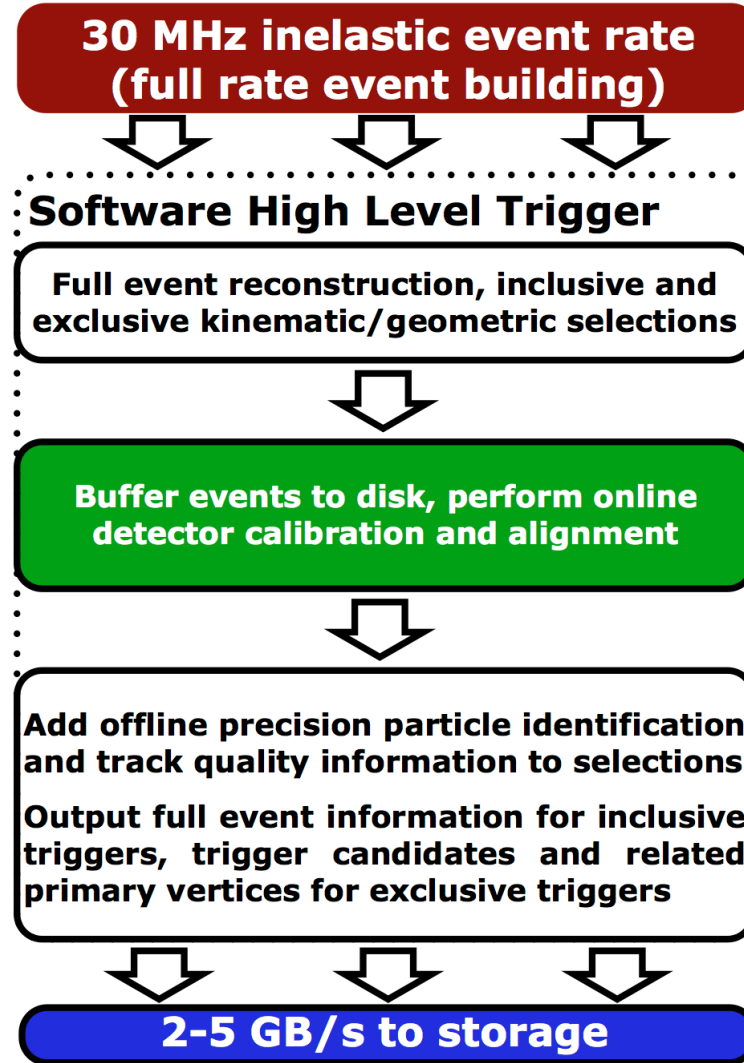
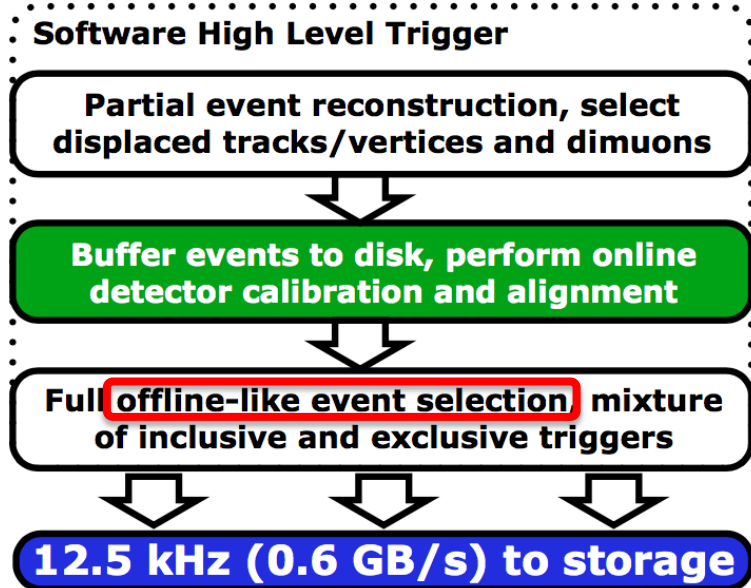


- L0, Hardware
  - $p_T(\mu_1) \times p_T(\mu_2) > (1.5 \text{ GeV})^2$
  - $p_T(\mu) > 1.8 \text{ GeV}$
  - $E_T(e) > 2.4 \text{ GeV}$
  - $E_T(\gamma) > 3.0 \text{ GeV}$
  - $E_T(h) > 3.7 \text{ GeV}$
- High Level Trigger
  - Stage1,  $p_T$ , IP
  - Stage2, full selection

# The LHCb trigger (Run3)

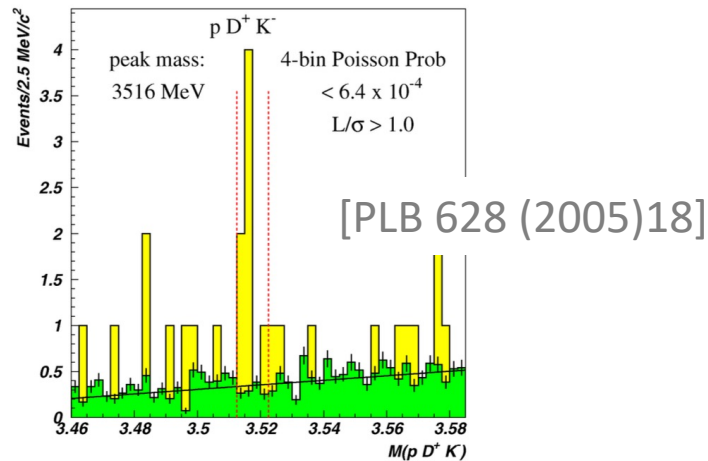


L0 removed

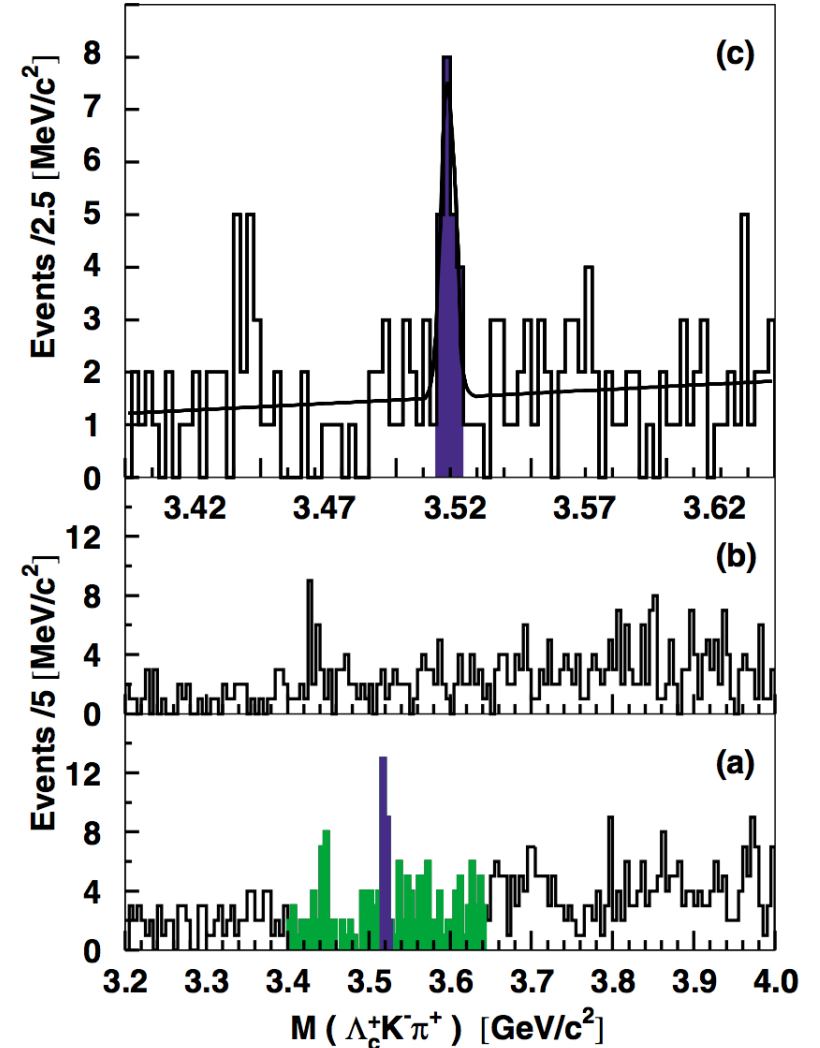


# $\Xi_{cc}^+$ @ SELEX

- SELEX claimed  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  ( $6.3\sigma$ )
  - M:  $3519 \pm 1$  MeV
  - $\tau$ :  $< 33$  fs @90%CL
  - $\sigma_{\text{prod}}$ : 20%  $\Lambda_c^+$  from  $\Xi_{cc}^+$
- Also  $\Xi_{cc}^+ \rightarrow p D^+ K^-$

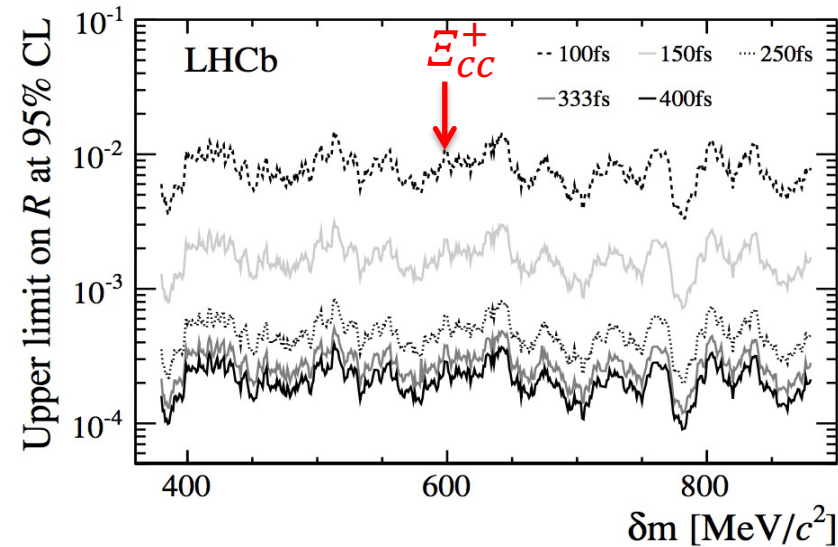
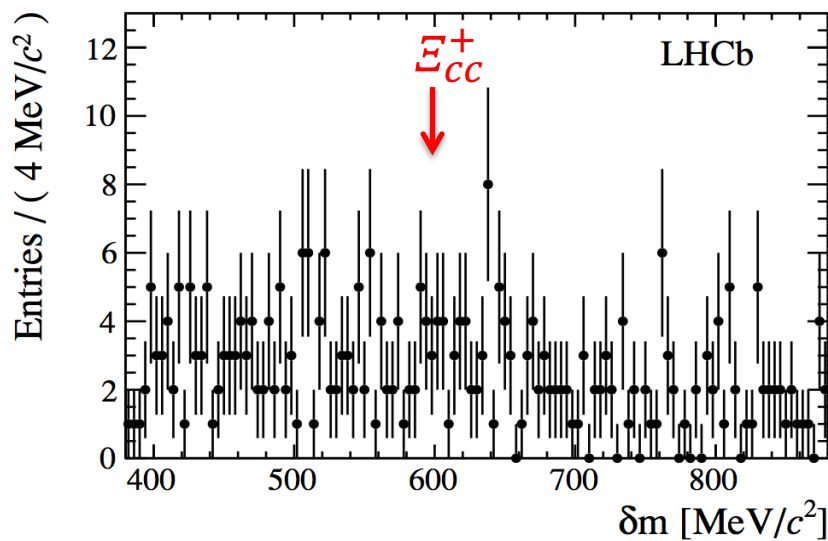


[PRL 89 (2002) 112001]



# $\Xi_{cc}$ @ LHCb & others

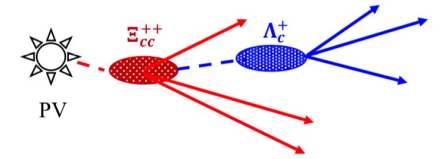
- SELEX results not confirmed by FOCUS, Babar, Belle & LHCb
- $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  searched by LHCb w/ 2011 data



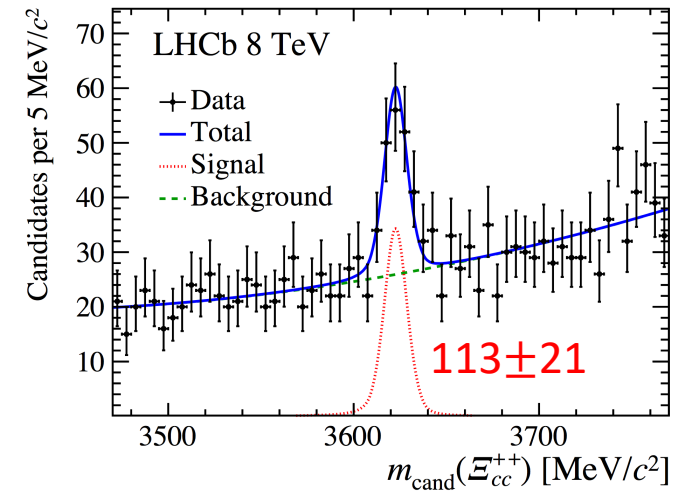
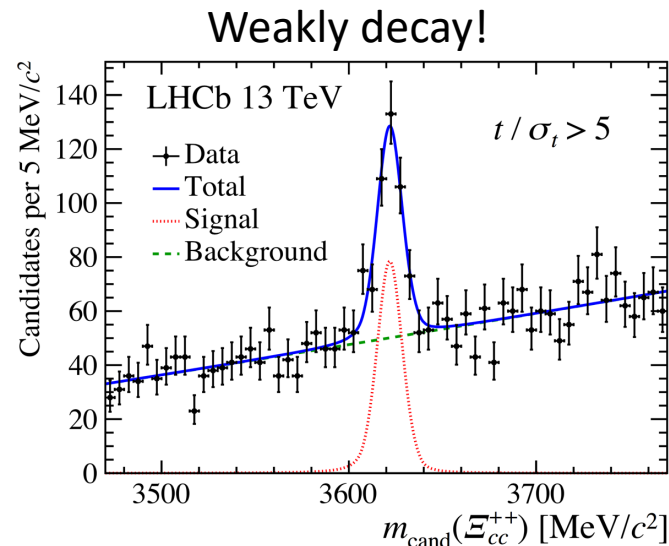
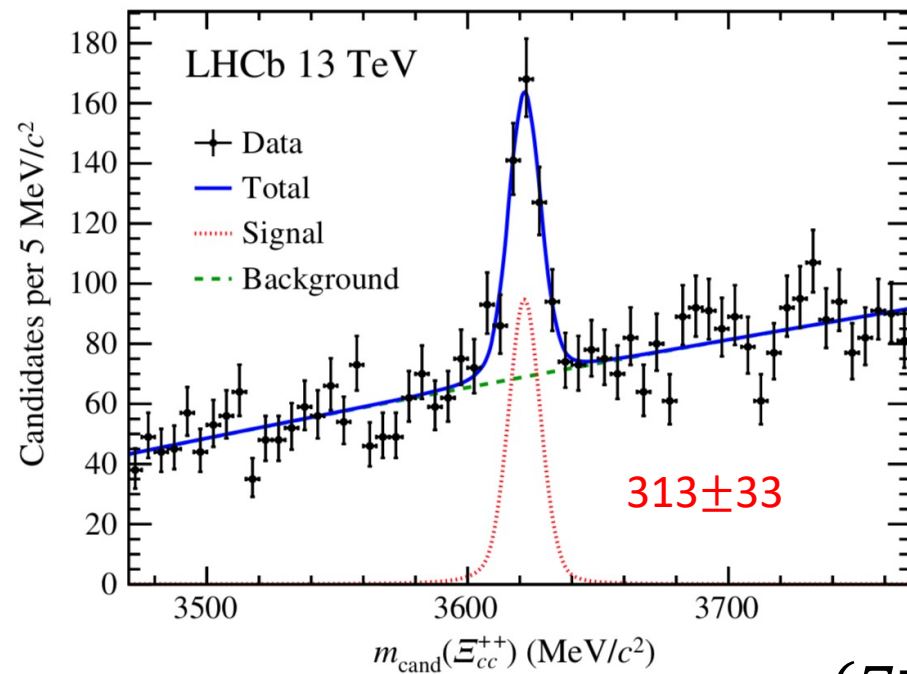
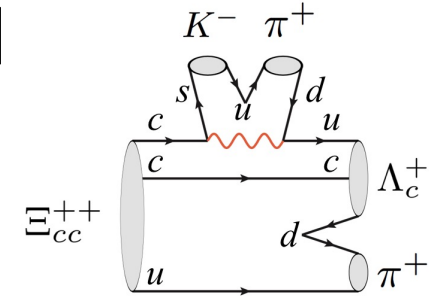
- However, LHCb already had lots of  $B_c^+$  events, and double-charm events...

# Observation of $\Xi_{cc}^{++}$

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



- $\Lambda_c^+ K^- \pi^+ \pi^+$  identified as the most promising channel
- **First observation**, in 2016 ( $>12\sigma$ ) & Run1 ( $>7\sigma$ )



$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 (\Lambda_c^+) \text{ MeV}/c^2$$

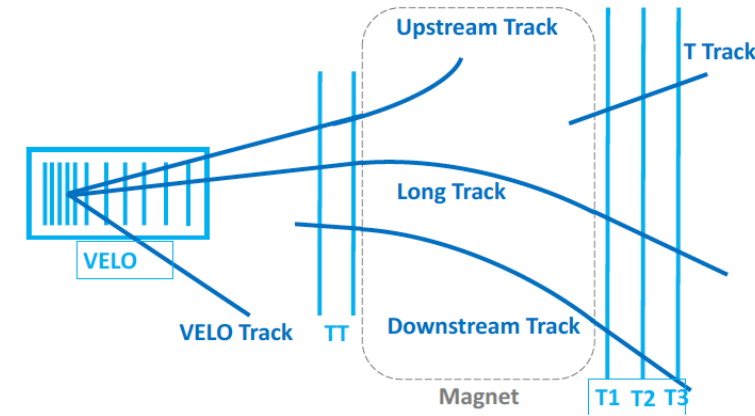
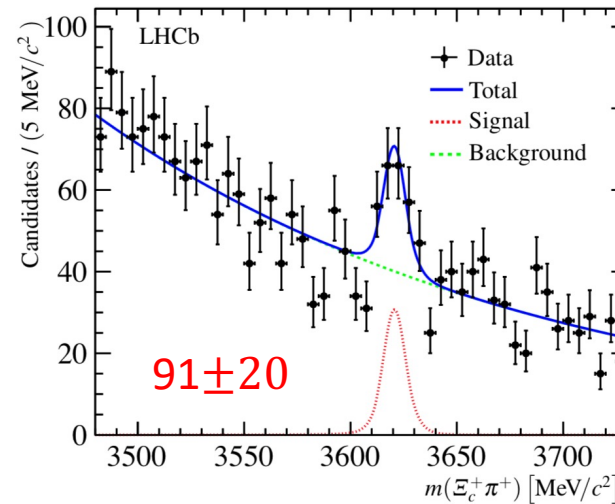
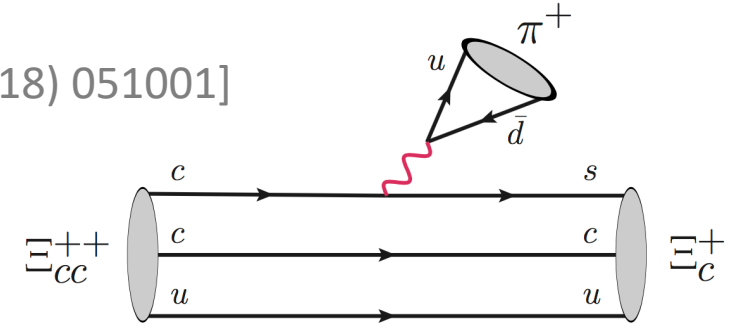
# Observation of $\Xi_{cc}^{++}$

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

- $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$  expected to have large BR
  - **Rule of thumb**: 2 less tracks, 10 times higher eff.
- Re-discovery with 2016 data,  $5.9\sigma$
- BR ratio measured

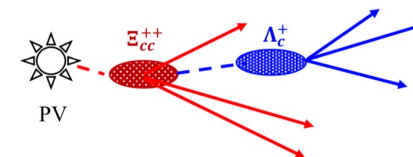
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+) \cdot \mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \cdot \mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)}$$

$$= 0.035 \pm 0.009 \pm 0.003$$

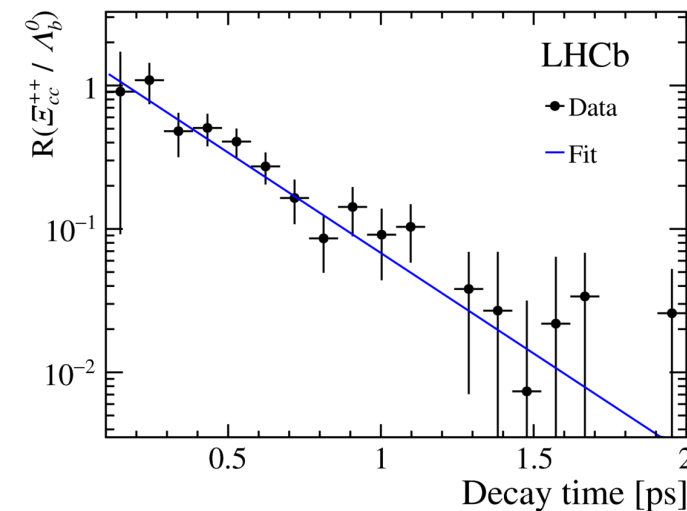
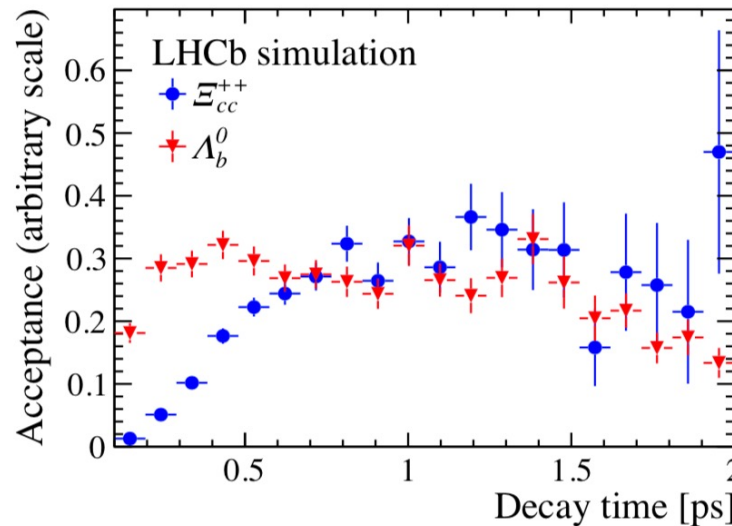
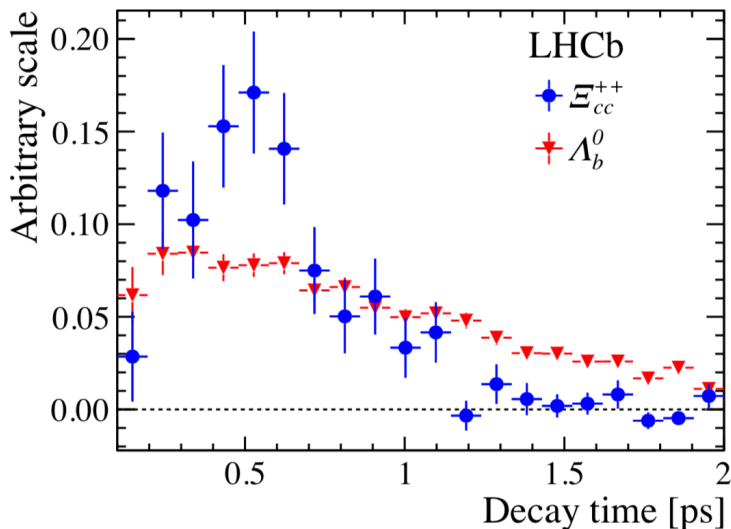


Not very good at hyperon...

# $\Xi_{cc}^{++}$ lifetime



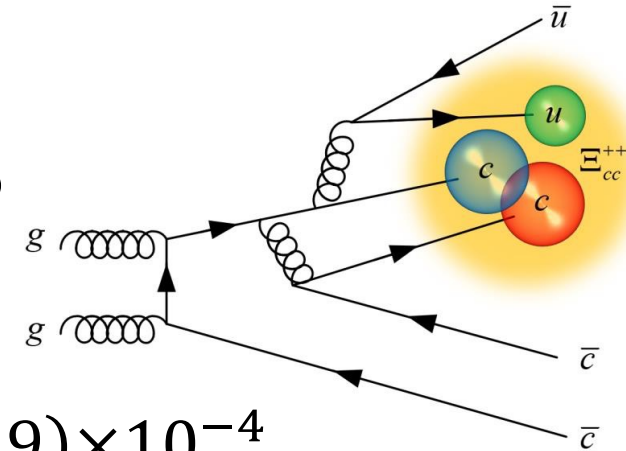
- Control mode,  $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$



- $\tau(\Xi_{cc}^{++}) = 0.256_{-0.022}^{+0.024} \pm 0.014$  ps, at lower side prediction: 0.2-1.05ps
- Weakly decay nature established!

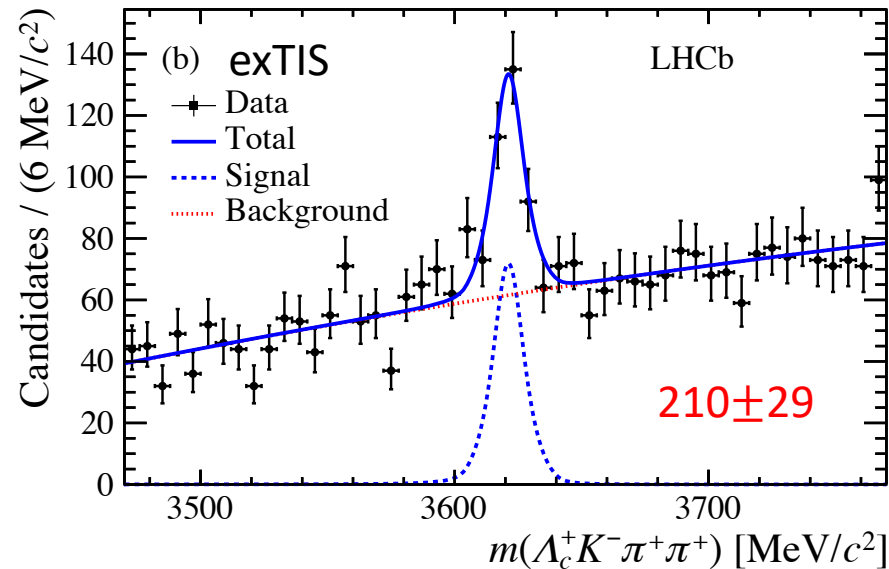
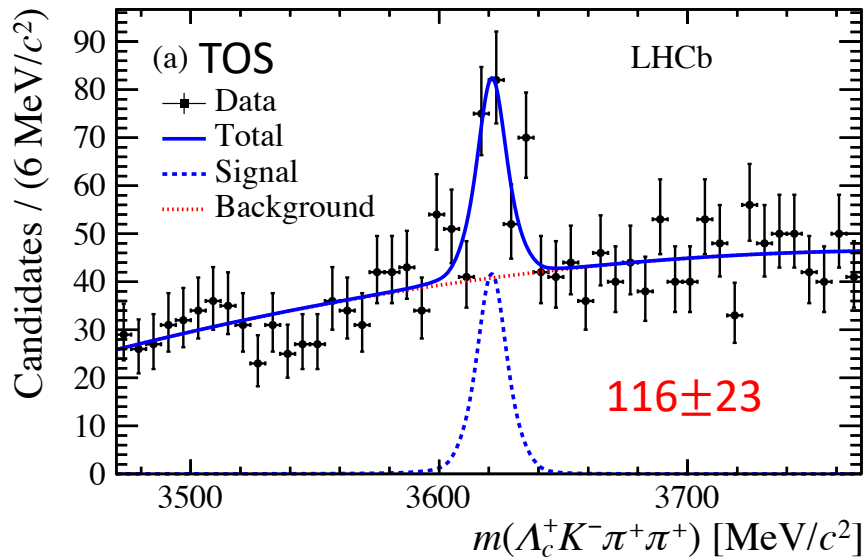
# $\Xi_{cc}^{++}$ production

- Relative to  $\Lambda_c^+$ , in  $4 < p_T < 15$  GeV,  $2 < y < 4.5$
- Accompanying  $\bar{c}\bar{c}$  dominates in trigger



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

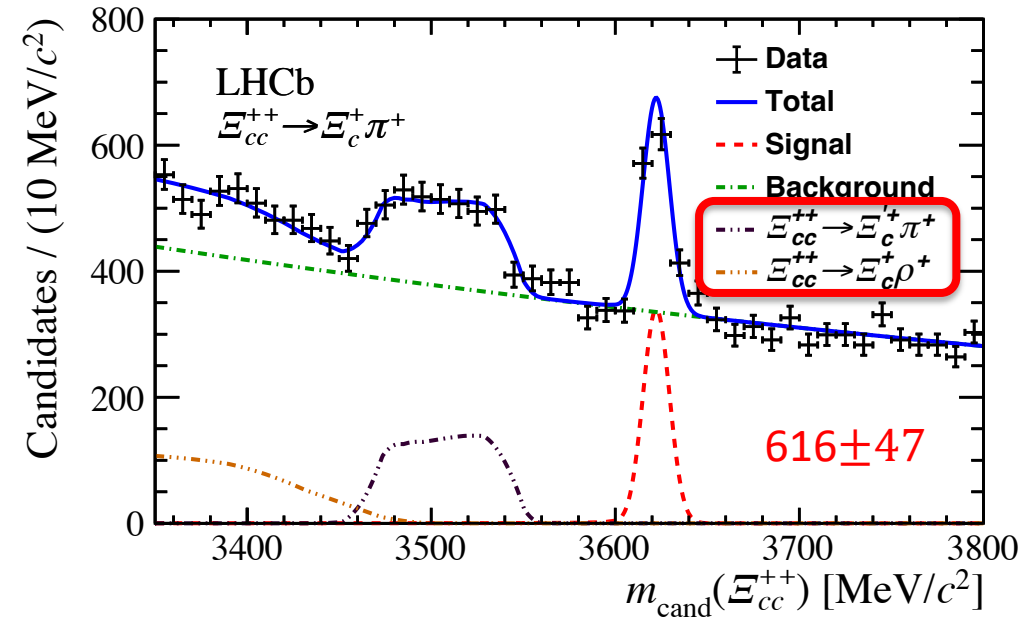
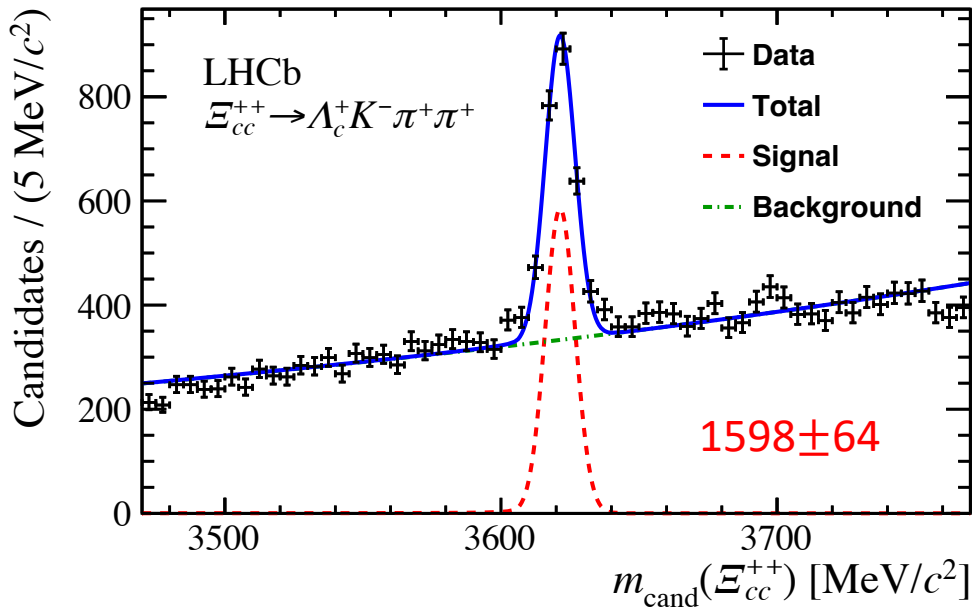
SELEX, 20%  $\Lambda_c^+$  from  $\Xi_{cc}^+$ ?



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

- Preparing to search for excited states, selection re-optimised
- 5-6 times signal yields with a factor of 3 data

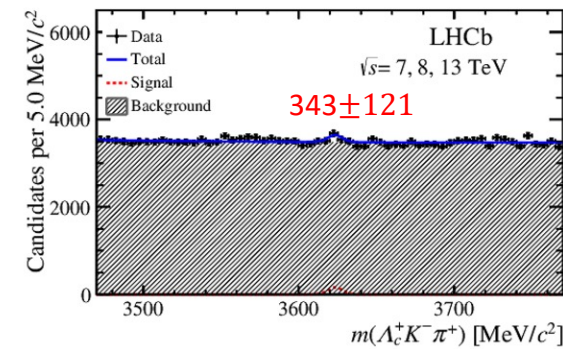
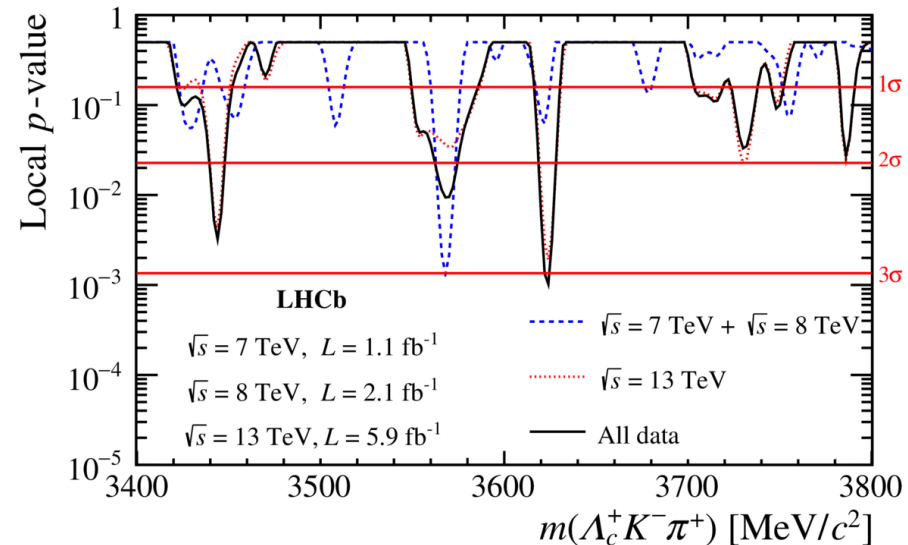
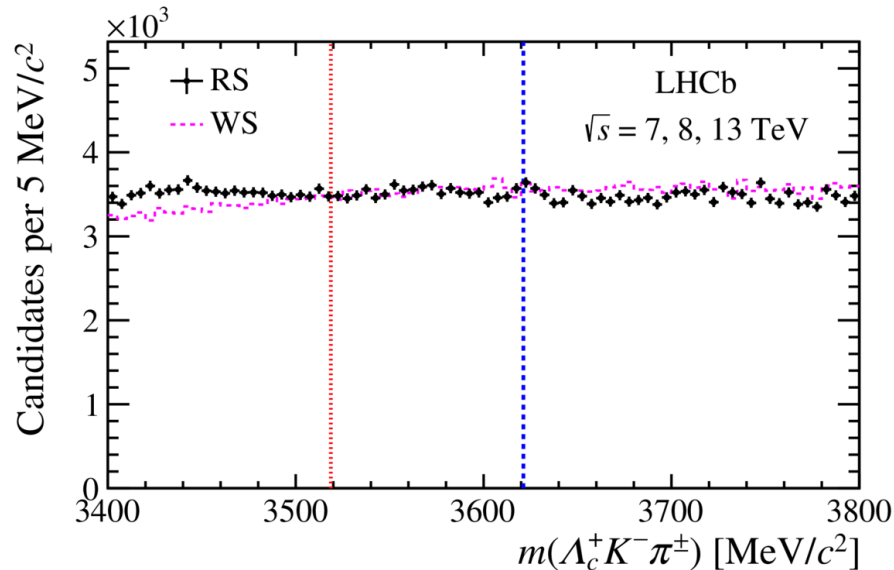
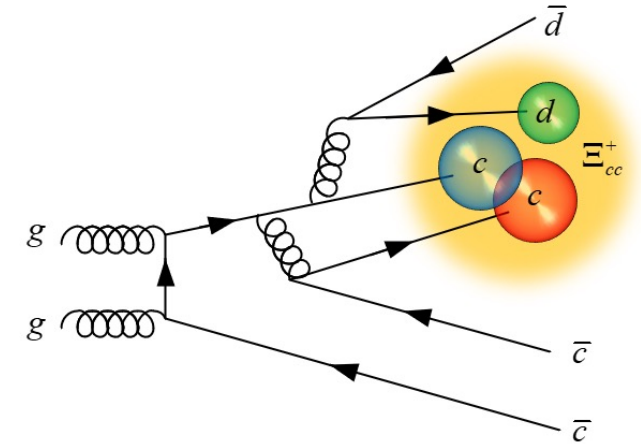
[JHEP 02 (2020) 049]



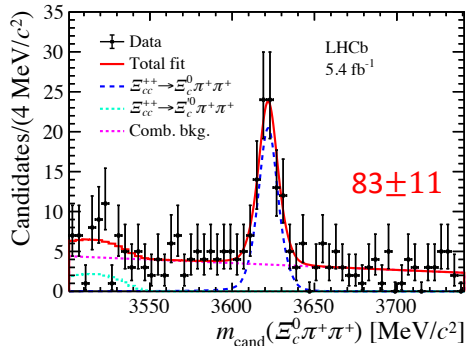
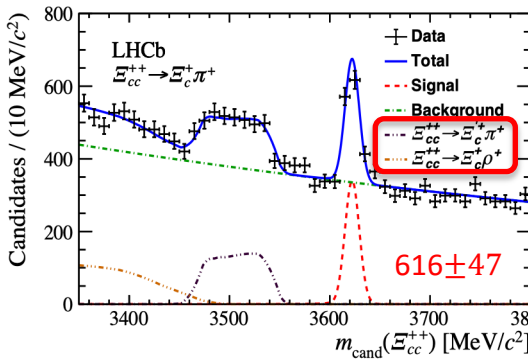
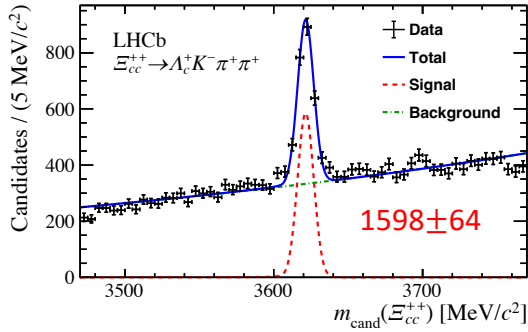
$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30 \text{ MeV}/c^2$  taken as WA by PDG

# $\Xi_{CC}^+$ search

- Updated w/  $\Lambda_c^+ K^- \pi^+$  using all Run1-2 data
- $\tau(\Xi_{CC}^+)$ : (0 fs, 80 fs)  $\times$  (non)observation
- Evidence at  $\Xi_{CC}^{++}$ , w/ local (global) significance  $3.1\sigma$  ( $1.7\sigma$ )



# Doubly heavy baryons w/ Run1-2 data

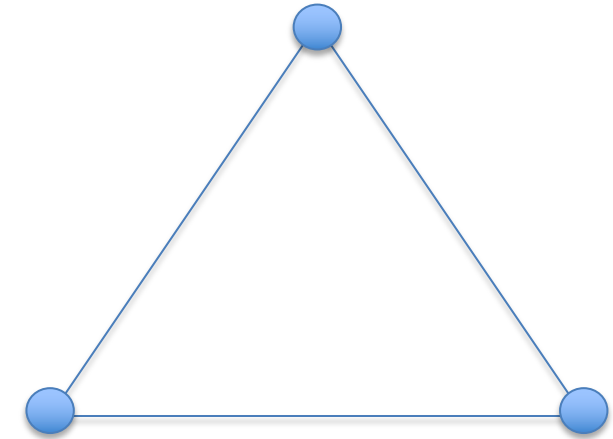
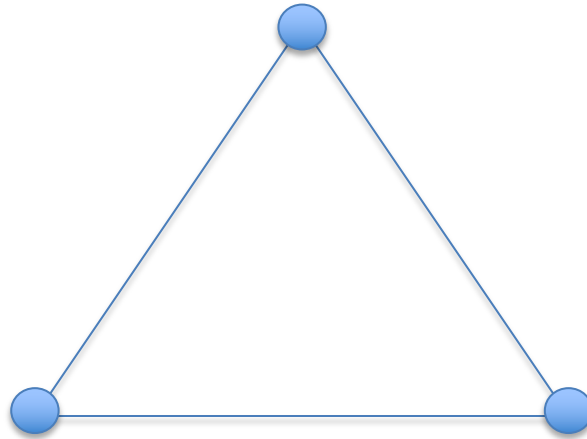


First search, Hint [SCPMA 64 (2021) 101062]

$\Omega_{cc}^+$  (ccs)

First search [CPC 45 (2021) 093002]

$\Omega_{bc}^0$  (bcs)



$\Xi_{cc}^{++}$  (ccu)

$\Xi_{cc}^+$  (ccd)

$\Xi_{bc}^+$  (bcu)

$\Xi_{bc}^0$  (bcd)

Observation [PRL 119 (2017) 112001]

Hint/Evidence

First search

First search

Mass [JHEP 02 (2020) 049]

[SCPMA 63 (2020) 221062,  
JHEP 12 (2021) 107]

Hint

[JHEP 11 (2020) 095]

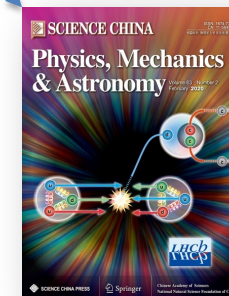
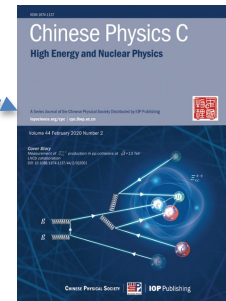
Lifetime [PRL 121 (2018) 052002]

Production [CPC 44 (2020) 022001]

Decay  $\Xi_{cc}^+ \pi^+$  [PRL 121 (2018) 162002]

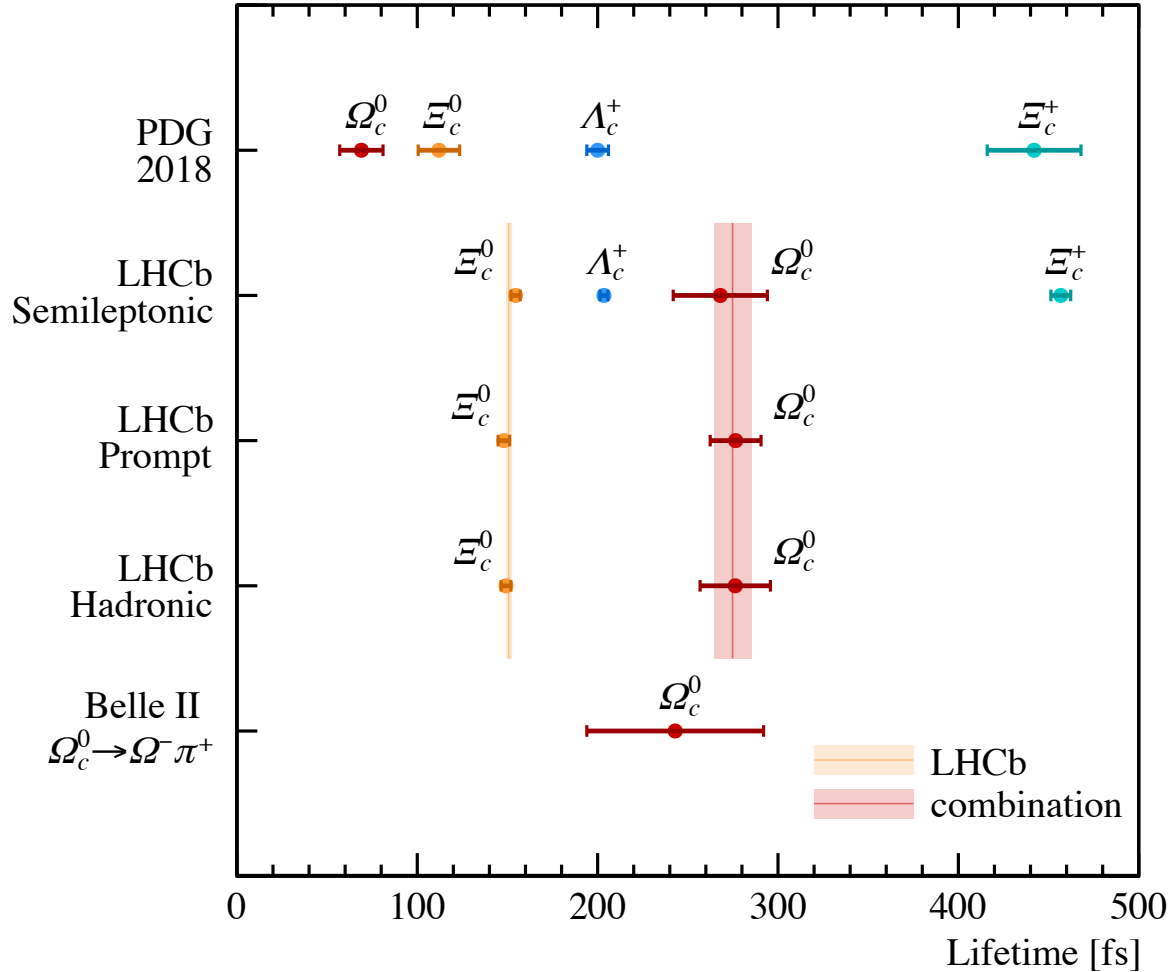
$\Xi_{cc}^{\prime+} \pi^+$  [JHEP 05 (2022) 038]

$\Xi_{cc}^0 \pi^+ \pi^+$  [JHEP 10 (2025) 136]



# Interplay between theory and exp., an example

[JHEP 09 (2025) 157]



[H.-Y. Cheng, C.-W. Liu, JHEP 07 (2023) 114]

$\mathcal{B}_Q$	BM <sup>a</sup>		NRQM		Experiment	
	$\mathcal{BF}_e^{\text{SL}}(\%)$	$\tau$	$\mathcal{BF}_e^{\text{SL}}(\%)$	$\tau$	$\mathcal{BF}_e^{\text{SL}}(\%)$	$\tau$
$\Lambda_c^+$	4.57(54)	1.92(37)	$3.80^{+0.58}_{-0.57}$	$3.04^{+1.06}_{-0.80}$	$3.95 \pm 0.35$	2.029(11)
$\Xi_c^0$	4.40(61)	1.66(32)	$4.31^{+0.87}_{-0.84}$	$2.31^{+0.84}_{-0.59}$	-	1.505(19)
$\Xi_c^+$	8.57(49)	3.27(76)	$12.74^{+2.54}_{-2.45}$	$4.25^{+1.22}_{-1.00}$	-	4.53(5)
$\Omega_c^0$	1.88(1.69)	2.30(58)	$7.59^{+2.49}_{-2.24}$	$2.59^{+1.03}_{-0.70}$	-	2.73(12)
$\Lambda_b^0$	9.90(3)	1.48(22)	$11.0^{+0.6}_{-0.5}$	$1.490^{+0.176}_{-0.207}$	-	1.471(9)
$\Xi_b^0$	9.94(6)	1.49(22)	$11.1^{+0.6}_{-0.6}$	$1.493^{+0.177}_{-0.207}$	-	1.480(30)
$\Xi_b^-$	10.38(9)	1.55(23)	$11.7^{+0.7}_{-0.6}$	$1.608^{+0.194}_{-0.230}$	-	1.572(40)
$\Omega_b^-$	10.76(14)	1.60(25)	$12.0^{+1.4}_{-1.4}$	$1.692^{+0.231}_{-0.261}$	-	$1.64^{+0.18}_{-0.17}$

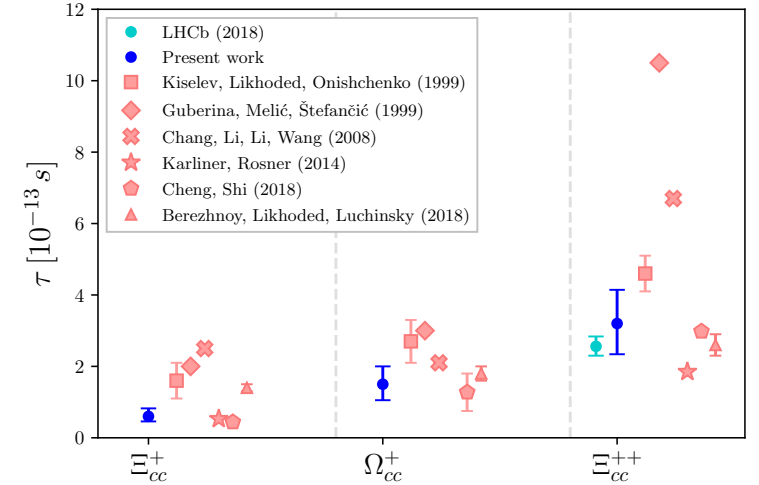
<sup>a</sup>Corresponding to the results in which the CMM is removed from the bag model.

**Table 7.** Comparison of our results with refs. [23, 24] obtained in the pole mass scheme for charmed baryons and ref. [25] in the kinetic mass scheme for bottom baryons, of which the uncertainties are added quadratically. The baryon matrix elements in refs. [23–25] are evaluated using the NRQM. Experimental results are quoted from ref. [1] and table 1. The lifetimes are in units of  $10^{-13}s$  for  $\mathcal{B}_c$  and  $10^{-12}s$  for  $\mathcal{B}_b$ .

# $\Xi_{cc}^+$ lifetime

- Theoretical predictions updated following  $\tau(\Xi_{cc}^{++})$  by LHCb
- $\tau(\Xi_{cc}^+) \approx 45$  fs, used as the baseline

PHYSICAL REVIEW D 98, 113005 (2018)



## Revisiting lifetimes of doubly charmed baryons

### Lifetimes of doubly charmed baryons

Hai-Yang Cheng<sup>1</sup> and Yan-Liang Shi<sup>2,\*</sup>

<sup>1</sup>*Institute of Physics, Academia Sinica Taipei, Taiwan 115, Republic of China*

<sup>2</sup>*C.N. Yang Institute for Theoretical Physics, Stony Brook University Stony Brook, New York 11794, USA*

(Received 25 September 2018; published 13 December 2018)

The lifetimes of doubly charmed hadrons are analyzed within the framework of the heavy quark expansion (HQE). Lifetime differences arise from spectator effects such as  $W$ -exchange and Pauli interference. The  $\Xi_{cc}^{++}$  baryon is longest-lived in the doubly charmed baryon system owing to the destructive Pauli interference absent in the  $\Xi_{cc}^+$  and  $\Omega_{cc}^+$ . In the presence of dimension-seven contributions, its lifetime is reduced from  $\sim 5.2 \times 10^{-13}$  s to  $\sim 3.0 \times 10^{-13}$  s. The  $\Xi_{cc}^+$  baryon has the shortest lifetime of order  $0.45 \times 10^{-13}$  s due to a large contribution from the  $W$ -exchange box diagram. It is difficult to make a precise quantitative statement on the lifetime of  $\Omega_{cc}^+$ . Contrary to  $\Xi_{cc}$  baryons,  $\tau(\Omega_{cc}^+)$  becomes longer in the presence of dimension-seven effects and the Pauli interference  $\Gamma_{\mp}^{\text{int}}$  even becomes negative. This implies that the subleading corrections are too large to justify the validity of the HQE. Demanding the rate  $\Gamma_{\mp}^{\text{int}}$  to be positive for a sensible HQE, we conjecture that the  $\Omega_{cc}^0$  lifetime lies in the range of  $(0.75 \sim 1.80) \times 10^{-13}$  s. The lifetime hierarchy pattern is  $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^+) > \tau(\Xi_{cc}^+)$  and the lifetime ratio  $\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^+)$  is predicted to be of order 6.7.

Lovro Dulibić, James Gratrex, Blaženka Melić and Ivan Nišandžić

*Ruder Bošković Institute,  
Bijenička cesta 54, 10000, Zagreb, Croatia*

*E-mail: ldulibic@irb.hr, jgratrex@irb.hr, melic@irb.hr,  
ivan.nisandzic@irb.hr*

ABSTRACT: We present updated predictions for lifetimes of doubly charmed baryons, within the heavy quark expansion, including available NLO  $\alpha_s$  contributions and newly-computed terms in the  $1/m_c$  series. Our improved results confirm the expected hierarchy

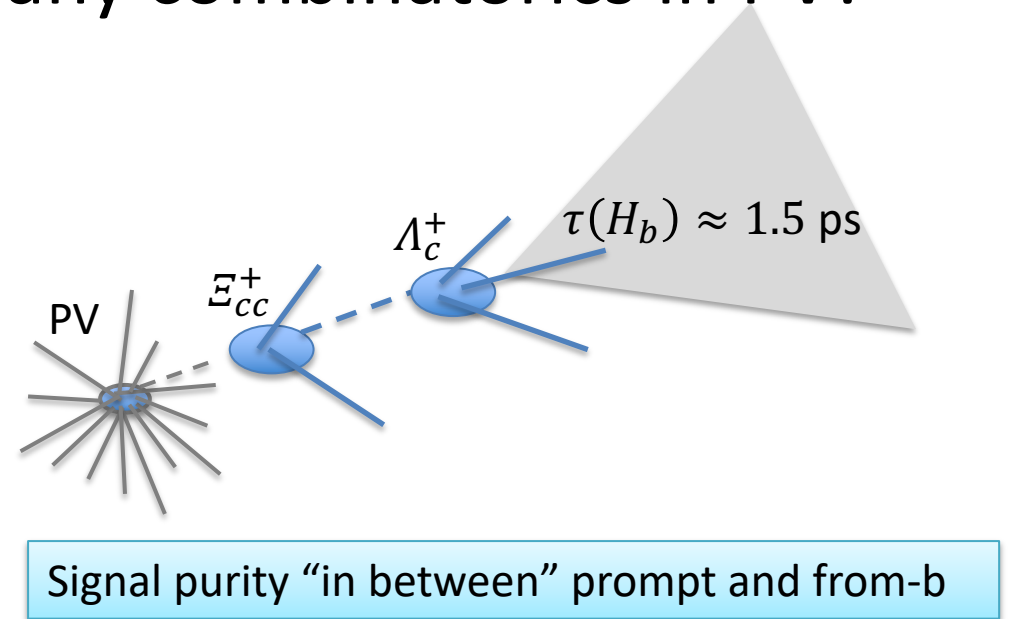
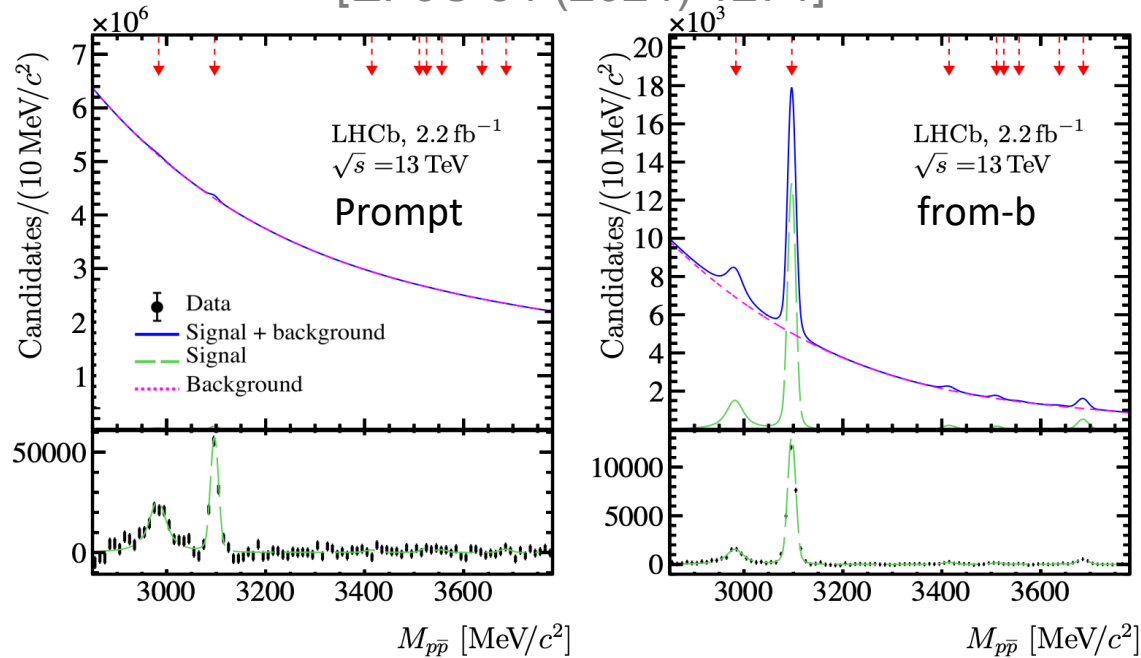
$$\tau(\Xi_{cc}^+) < \tau(\Omega_{cc}^+) < \tau(\Xi_{cc}^{++}),$$

while the predicted lifetime  $\tau(\Xi_{cc}^{++}) = 0.32 \pm 0.5_{-0.7}^{+0.8}$  ps is consistent with the recent LHCb determination. We provide predictions for the lifetime ratios of the  $\Xi_{cc}^+$  and  $\Omega_{cc}^+$  baryons relative to the  $\Xi_{cc}^{++}$  baryon, namely  $\tau(\Xi_{cc}^+)/\tau(\Xi_{cc}^{++}) = 0.22 \pm 0.05 \pm 0.04$  and  $\tau(\Omega_{cc}^+)/\tau(\Xi_{cc}^{++}) = 0.52 \pm 0.13_{-0.02}^{+0.03}$ .

# Selection strategy

- Should we still use lifetime info when  $\tau(\Xi_{cc}^+) \approx 45$  fs, which is close to  $\sigma_t \approx 50$  fs? Yes!
- $\eta_c(1S) \rightarrow p\bar{p}$  as an example, too many combinatorics in PV!

[EPJC 84 (2024) 1274]



# Preparing for Run3

- Run1-2 re-visited, undergraduate thesis of **Danyi Zhang**
- $\Lambda_c^+ K^- \pi^+$  re-optimised
  - $p_T$  cuts relaxed, w/ unparked  $\Lambda_c^+$
  - PID added in BDT training
  - $\tau(\Xi_{cc}^+) \approx 45$  fs as baseline
- New decay modes added:

$$- \Xi_{cc}^+ \rightarrow \Xi_c^0 \pi^+$$

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

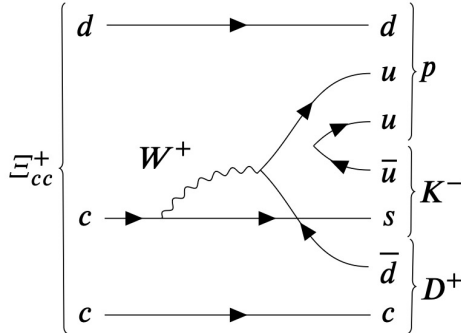
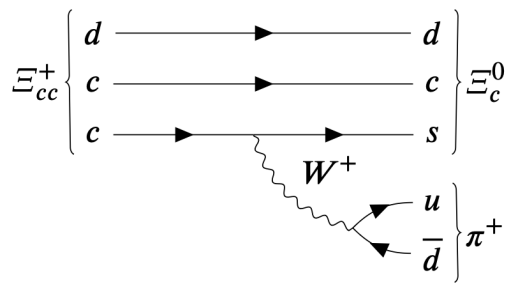
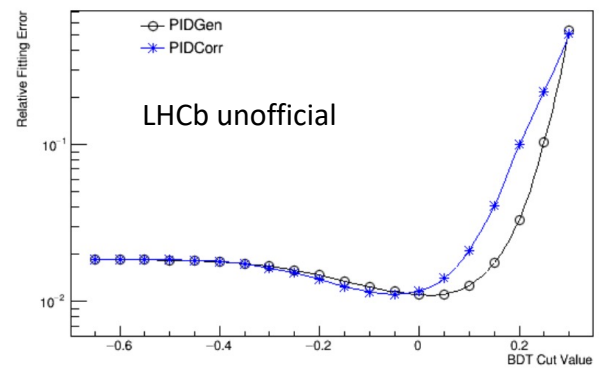


表 3.1 衰变过程  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  的遍举触发选择条件和效率。  
Table 3.1 The efficiency of the the exclusive turbo line selections for  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  decay.

Particle	Selection	Events	Efficiency
	Proton $p_T > 200$ MeV/c	121589	(99.81 ± 0.01)%
	Kaon $p_T > 200$ MeV/c	119526	(98.30 ± 0.04)%
	Pion $p_T > 200$ MeV/c	112556	(94.17 ± 0.07)%
	Proton $\chi_{IP}^2$ to own PV >6	63855	(56.73 ± 0.15)%
	Kaon $\chi_{IP}^2$ to own PV >6	43976	(68.87 ± 0.18)%
$\Lambda_c^+$ daughters	Pion $\chi_{IP}^2$ to own PV >6	33402	(75.96 ± 0.20)%
	$\Lambda_c^+$ flight distance $\chi^2$ to PV >16	33234	(99.50 ± 0.04)%
	$\Lambda_c^+$ $p_T > 1000$ MeV/c	33231	(99.99 ± 0.01)%
	Proton particle ID $DLL_{p\pi} > 10$	29778	(89.61 ± 0.17)%
	Kaon particle ID $DLL_{K\pi} > 10$	24630	(82.71 ± 0.22)%
	Pion particle ID $DLL_{K\pi} < 0$	20511	(83.28 ± 0.24)%
	<b>Kaon <math>p_T &gt; 500</math> MeV/c</b>	18251	<b>(88.98 ± 0.22)%</b>
	<b>Pion <math>p_T &gt; 500</math> MeV/c</b>	13440	<b>(73.64 ± 0.33)%</b>
	Kaon particle ID $DLL_{K\pi} > 10$	11797	(87.78 ± 0.28)%
$\Xi_{cc}^+$ daughters	Pion particle ID $DLL_{K\pi} < 0$	10620	(90.02 ± 0.28)%
	Sum of $p_T > 2000$	18296	(100.00 ± 0.00)%
	Kaon $\chi_{IP}^2$ to PV >1	15748	(86.07 ± 0.26)%
	Pion $\chi_{IP}^2$ to PV >1	14010	(88.96 ± 0.25)%
$\Xi_{cc}^+$	$\chi_{IP}^2$ to PV >25	13584	(96.96 ± 0.15)%
	DIRA > 0.99	13231	(97.40 ± 0.14)%



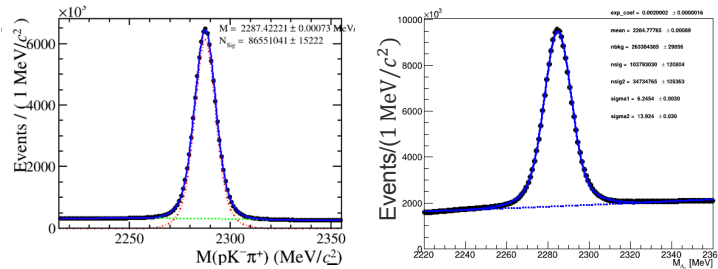
# Joined the efforts to understand **new detector**

- Linnuo Zhang, CERN summer student project

## $\Lambda_c^+$ in LHCb Run3 data

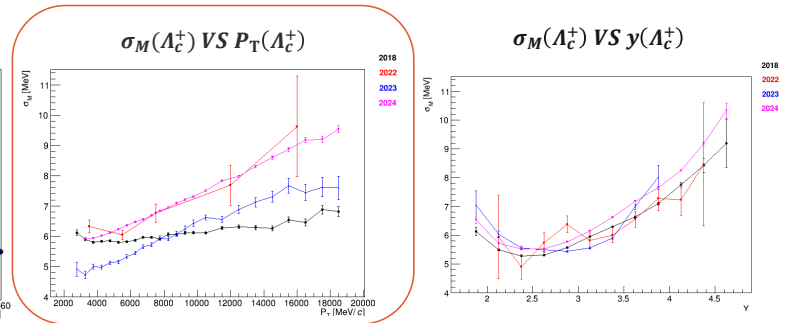
- Number of  $\Lambda_c^+$  events in **2018** data:  $8.6 \times 10^7$
- Number of  $\Lambda_c^+$  events in **part of 2024** data (before including UT):  $1.3 \times 10^8$

$\Lambda_c^+ (\rightarrow pK^- \pi^+)$  mass distribution



more  $\Lambda_c^+ \rightarrow$  expect more  $E_{cc}$

$\Lambda_c^+ (\rightarrow pK^- \pi^+)$  mass resolution (July 16)

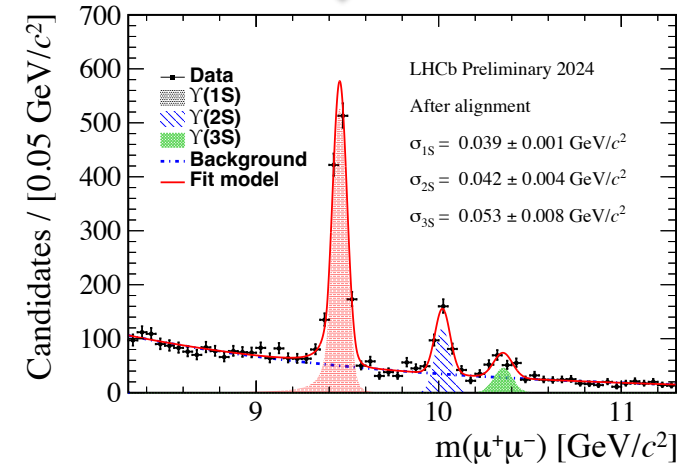
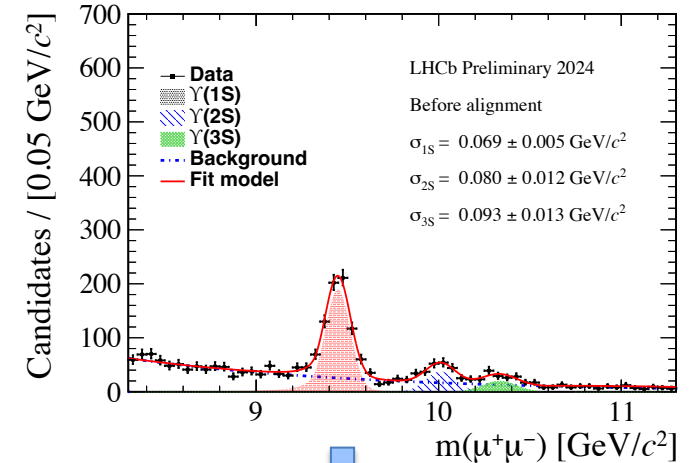


$\sigma_M(\Lambda_c^+)$  has stronger dependence on  $P_T(\Lambda_c^+)$  in Run3

Shared this result to **egroup** for alignment work

[JH | Linnuo Zhang | LHCb Run3 data](#)  
 Thursday, July 18, 2024 at 17:27  
 To: lhc-rtb-cath-and-alignment (group for work on alignment/cathodisation within RTA project).  
 Dear All,  
 Hope this is right list for discussion.  
 Following a chat with Vincenzo after the running meeting of last week, Linnuo (in CC) has made the plots of the Lambda\_c+ (to p K pi) mass resolution as a function of Lc PT and gamma for 2022/23/24 and 2018 data, as attached. So, in general, the dependence on PT is stronger for Run-3. We hope this adds a bit info on understanding the mass resolution in Run-3 data. Now this is binned in Lc PT. It might be more clear if one bins in PT of a muon from the J/psi decay.  
 BTW: Linnuo is a summer student working with Monica and me, on the discovery of Xicc in LHCb Run3 data.  
 Cheers, Jho

[LHCb-FIGURE-2024-037]

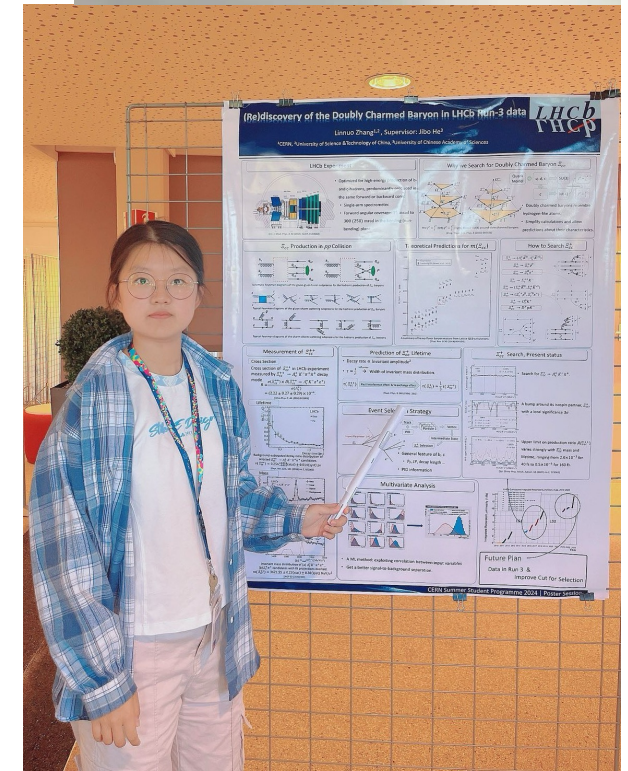
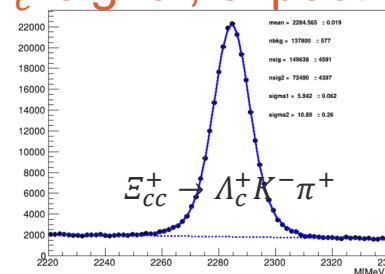
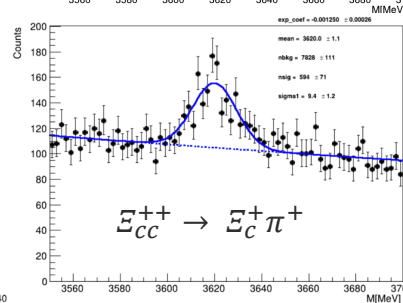
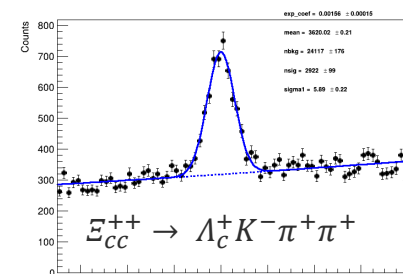
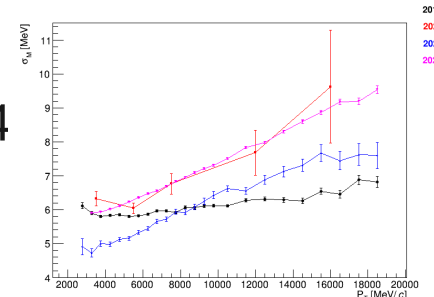


# Rediscovery of $\Xi_{CC}^{++}$ in 2024 data

- Extensive studies on  $\Xi_{CC}^{++}$  in 2024, old / new MVA

## Summary

- Studied  $\Lambda_c^+$  mass resolution as functions of  $P_T$ ,  $y$  in 2024 sent to alignment group
- Studied and optimized event selection for:
  - $\Xi_{CC}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ , twice signals in part of 2024 data, compared to signals in Run 2
  - $\Xi_{CC}^{++} \rightarrow \Xi_c^+ \pi^+$ , better sig-to-bkg ratio with new MVA model
  - $\Xi_{CC}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ , blind analysis, more  $\Lambda_c^+$  signal, expect 1st observation of  $\Xi_{CC}^+$  w/ 2024 data



First Chinese Winner of the LHCb best summer student



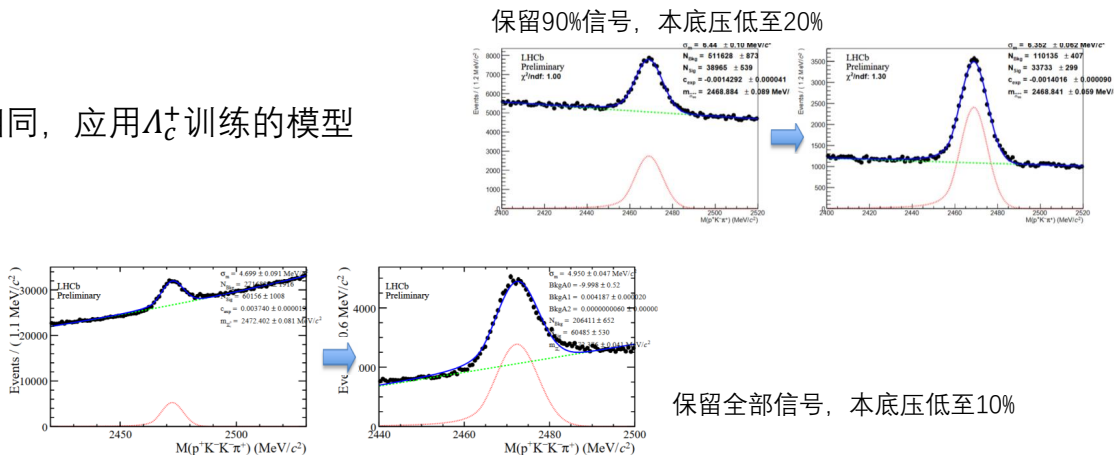
# BDT-based trigger for $H_c$

- Shuyu Han, UROP student

## 触发算法开发



- $\Xi_c^+ \rightarrow pK^- \pi^+$ :  
信号数少，与 $\Lambda_c^+$ 衰变末态相同，应用 $\Lambda_c^+$ 训练的模型
- $\Xi_c^0 \rightarrow pK^- K^- \pi^+$ :  
训练变量中增加一个 $K^-$



- 触发算法加入2024年取数；2025年经迭代进一步提高性能，可用于其他粒子（双粲重子）的重建

触发算法	带宽 (kHz)	独占带宽 (kHz)	平均事例大小 (kB)	总带宽 (GB/s)
$\Lambda_c^+$ cut-based	0.374	0.0645	72	0.0269
$\Xi_c^+$ cut-based	0.361	0.0774	48.4	0.0175
$\Xi_c^0$ cut-based	0.142	0.0516	92.9	0.0132
$\Lambda_c^+$ MVA-based	0.181	0	64	0.0116
$\Xi_c^+$ MVA-based	0.155	0	56.5	0.00874
$\Xi_c^0$ MVA-based	0.0258	0	101	0.00261

[Update] Studies on bandwidth reduction for  $\Lambda_c$  trigger lines in Run 3 (20+15')

报告人: Shuyu Han (University of Chinese Academy of Sciences (CN))

Lc2pKpi\_TMVA\_202... Charm WG meeting (2024.4.10)

[Update] MVA-based trigger lines for charmed baryons (15 + 10')

报告人: Shuyu Han (University of Chinese Academy of Sciences (CN))

MVA based Turbo li... Charm WG meeting (2024.7.17)

# $\Xi_{cc}^+$ search w/ 2024

- Shuyu Han, undergraduate thesis

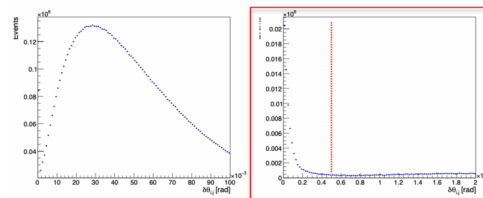
Moriond EW 2026

## 去除克隆

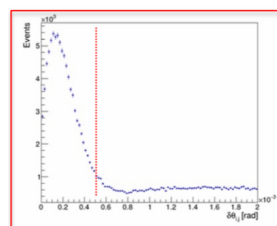
克隆事例：重建算法将一根真实径迹错误地重建为两根径迹

- 主要发生在同电荷粒子间
- 要求两条径迹张角小且动量差别不大
- 使用  $\Xi_{cc}^+$  组合本底 ( $\Lambda_c^+ K^- \pi^-$ ) 样本研究

- 二期运行中张角的选择条件定为 0.5 mrad
- 三期运行：发现张角分布变宽，条件应该加严
- 张角分布峰值右移(克隆事例增多)的原因：顶点探测器
  - 克隆径迹的  $\phi$  值分布出现三个明显峰值
  - 峰值位置与升级后顶点探测器的重叠位置吻合
  - 径迹在顶点探测器平均击中数目少而径迹数多



运行二期的 WS 样本中未态粒子张角分布 将角度范围缩小至 0 附近的情况



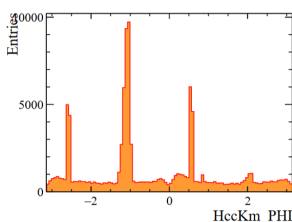
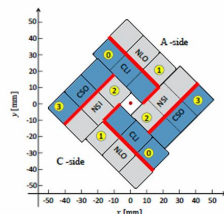
2024 年 WS 样本中未态粒子夹角分布，将角度范围缩小至 0 附近的情况



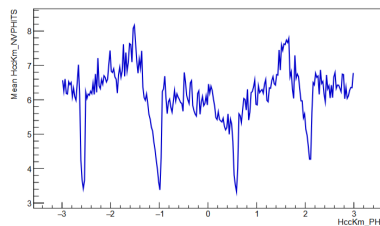
Monday Afternoon : Flavour  
Convener: Roberto Salerno

11 Search for the  $\Xi_{cc}$  baryon in the  $\Lambda_c K \pi$  final state with the LHCb Upgrade I detector  
Speaker: Shuyu Han  
1\_SHan-v1.pdf

5' YSF talk prompted to 10+5'



来自  $\Xi_{cc}^{++}$  的  $K^-$  的  $\phi$  值分布  
在最小夹角  $< 0.0007$  的条件下



来自  $\Xi_{cc}^{++}$  的  $K^-$  在 VELO 中的平均击中数目随  $\phi$  值的变化  
在最小夹角  $< 0.0007$  的条件下

Studies of opening angle and clones in 2024 data (doubly charmed baryon)

报告人: Shuyu Han (University of Chinese Academy of Sciences (CN))

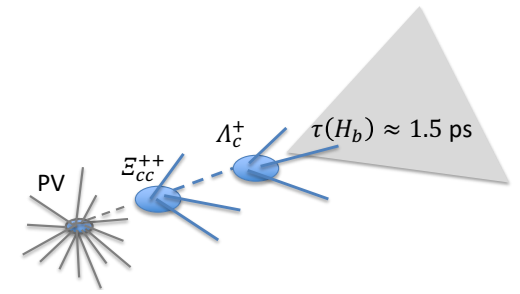
Opening\_angle\_Shu... General Performance Meeting (2025.4.7)

Studies of opening angle and clones in 2024 data (doubly charmed baryon)

报告人: Shuyu Han (University of Chinese Academy of Sciences (CN))

Opening\_angle\_Shu... RTA: Reconstruction WP2 meeting (2025.4.15)

# Control mode: $\Xi_{cc}^{++}$ in 2024



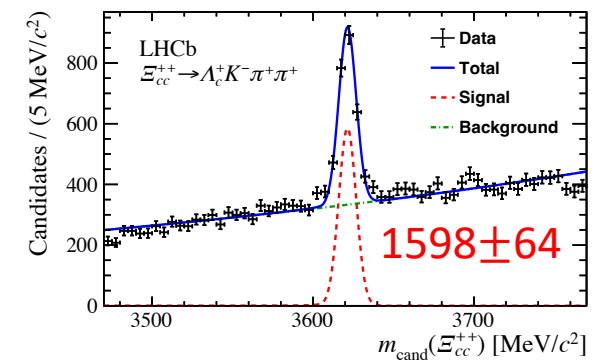
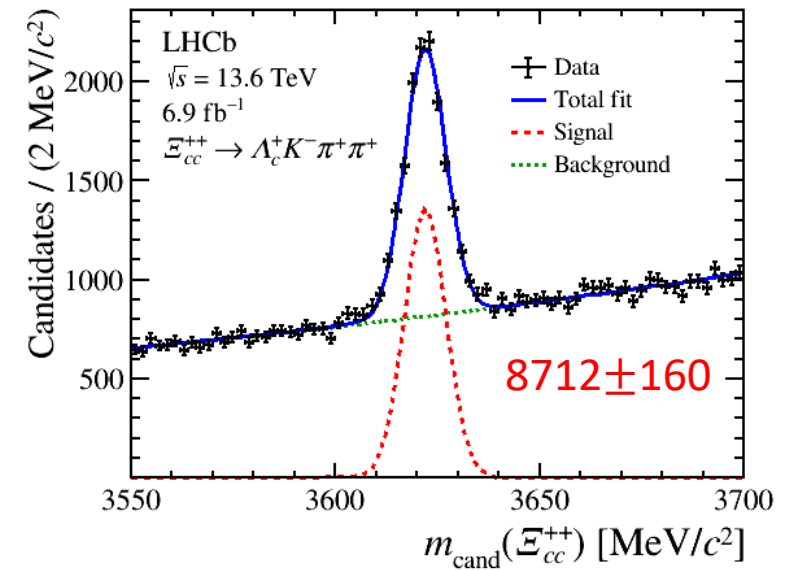
- Event-Selection (early measurement)
  - Several iterations. One BDT trained w/  $\Lambda_c^+$  in data included in BDT for  $\Xi_{cc}^{++}$  ( $p_T$ ,  $\chi_{IP}^2$ , PID)
  - BDT w/o PID as cross-check

- Efficiency increased by a factor of 4, compared with Run2

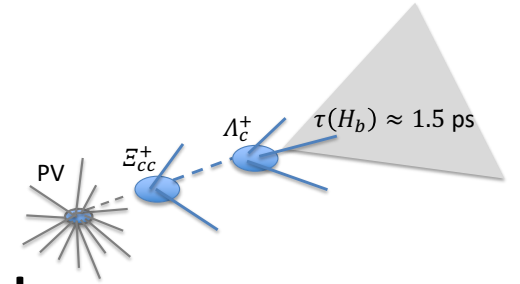
- Mass consistent with Run2

$$m(\Xi_{cc}^{++}) = 3621.74 \pm 0.10 \text{ MeV}/c^2$$

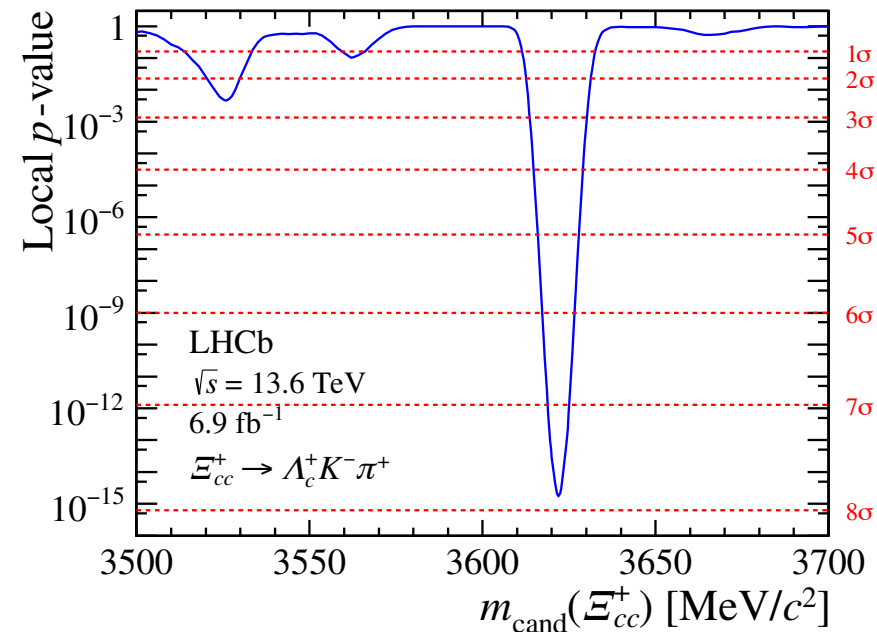
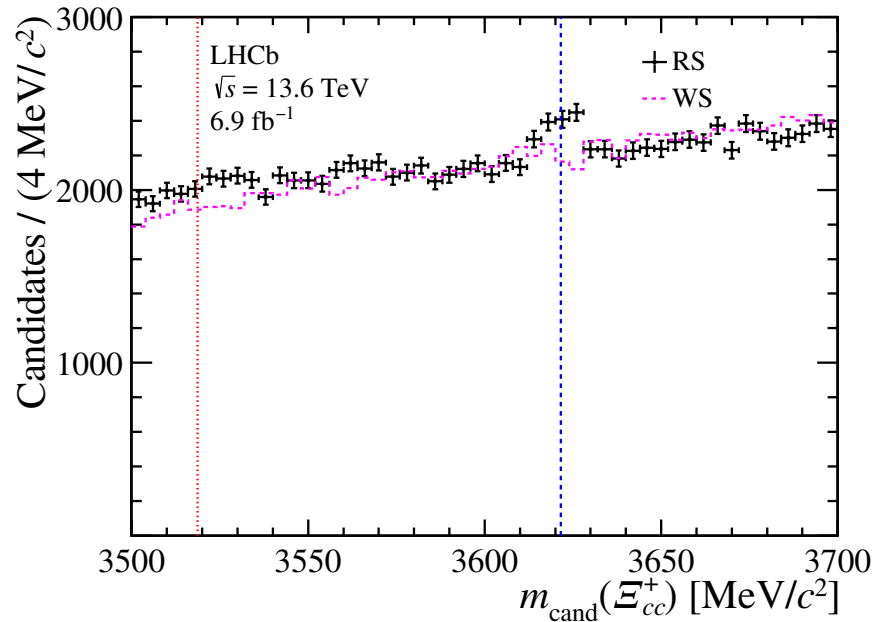
c.f.,  $3621.55 \pm 0.23 \pm 0.30 \text{ MeV}/c^2$



# Signal mode: $\Xi_{cc}^+$ in 2024



- Event-Selection, similar strategy to  $\Xi_{cc}^{++}$ , many checks
  - Effects of  $\tau(\Xi_{cc}^+)$ , no fake peaks in wrong-sign,  $\Lambda_c^+$  sideband...
- After unblinding, **first observation!**

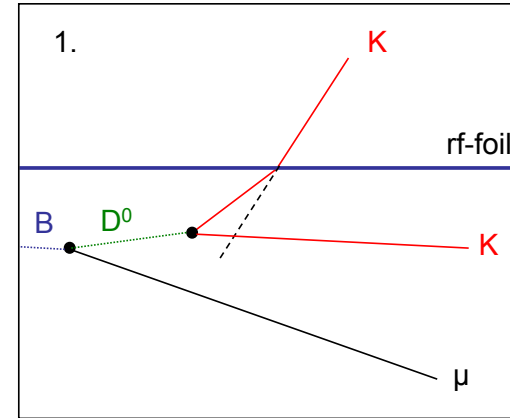


# Precision mass measurement

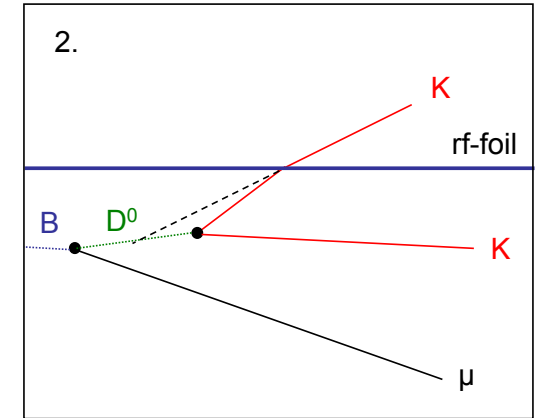
- Bias due to final-state radiation
- Bias due to event-selection
- Momentum scale, as functions of kinematics, multiplicity...

–  $\Xi_c^0$  in the same decay-time range

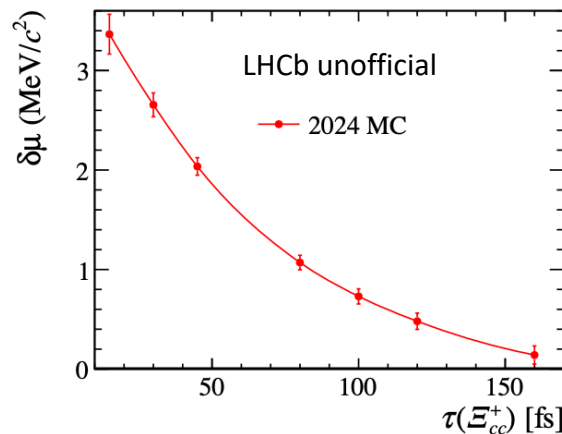
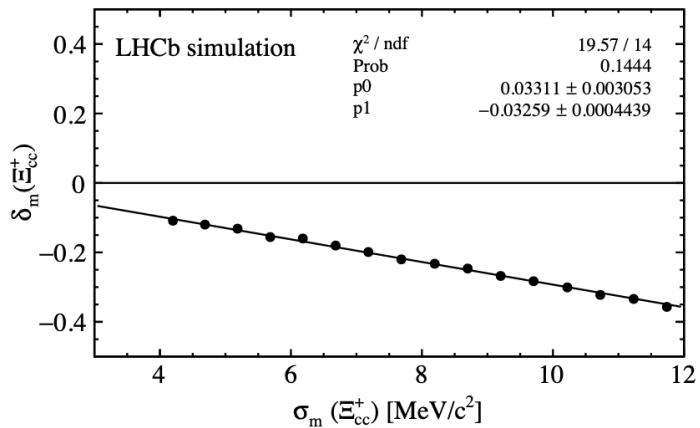
Two examples of multiple scattering Credit: J. Tiburg



- Opening angle larger  $\rightarrow$  higher mass
- Reconstructed decay distance too long



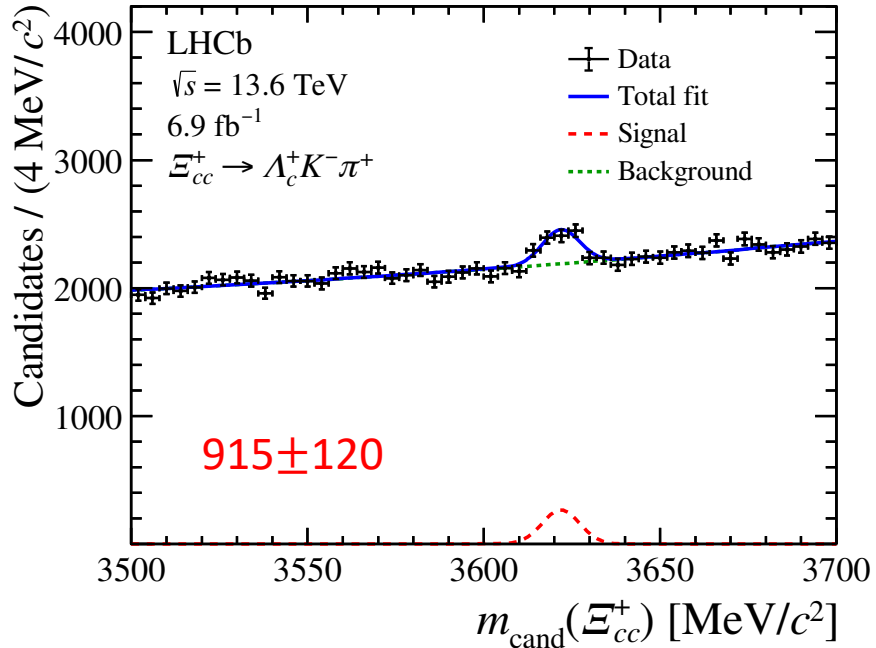
- Opening angle smaller  $\rightarrow$  lower mass
- Reconstructed decay distance too short



Reconstructed decay distance and mass are correlated

# $\Xi_{cc}^+$ mass

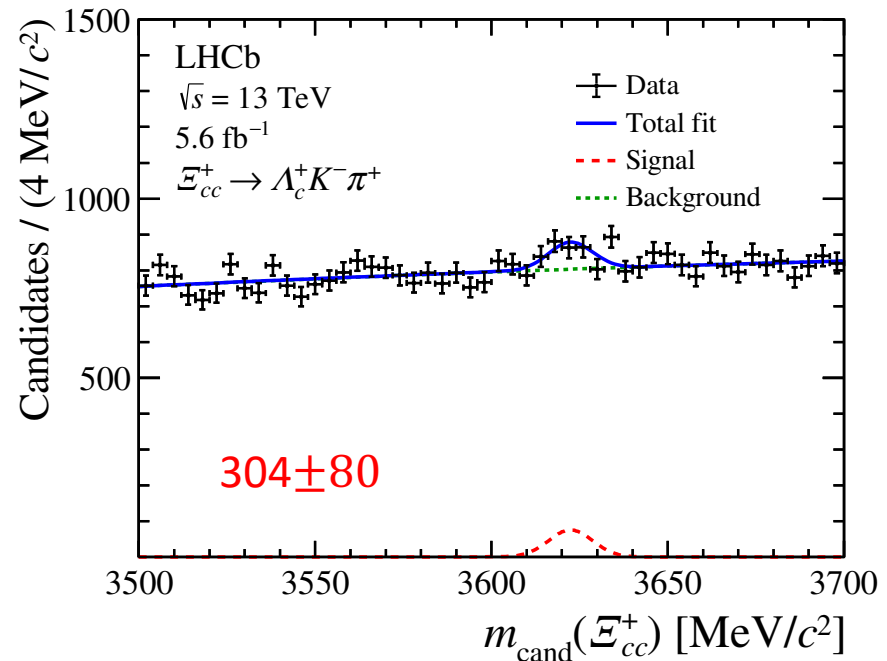
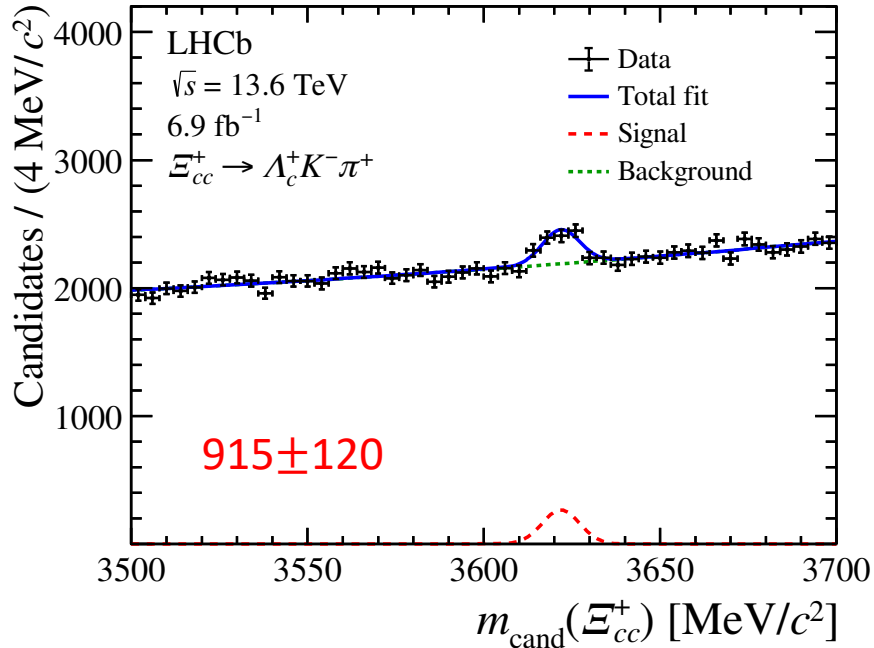
- Mass,  $m(\Xi_{cc}^+) = 3619.97 \pm 0.83 \pm 0.26_{-1.30}^{+1.90} \text{ MeV}/c^2$   
after correcting for the bias due to FSR and event-selection
- Mass diff.,  $m(\Xi_{cc}^+) - m(\Xi_{cc}^{++}) = -1.77 \pm 0.84 \pm 0.25_{-1.30}^{+1.90} \text{ MeV}/c^2$

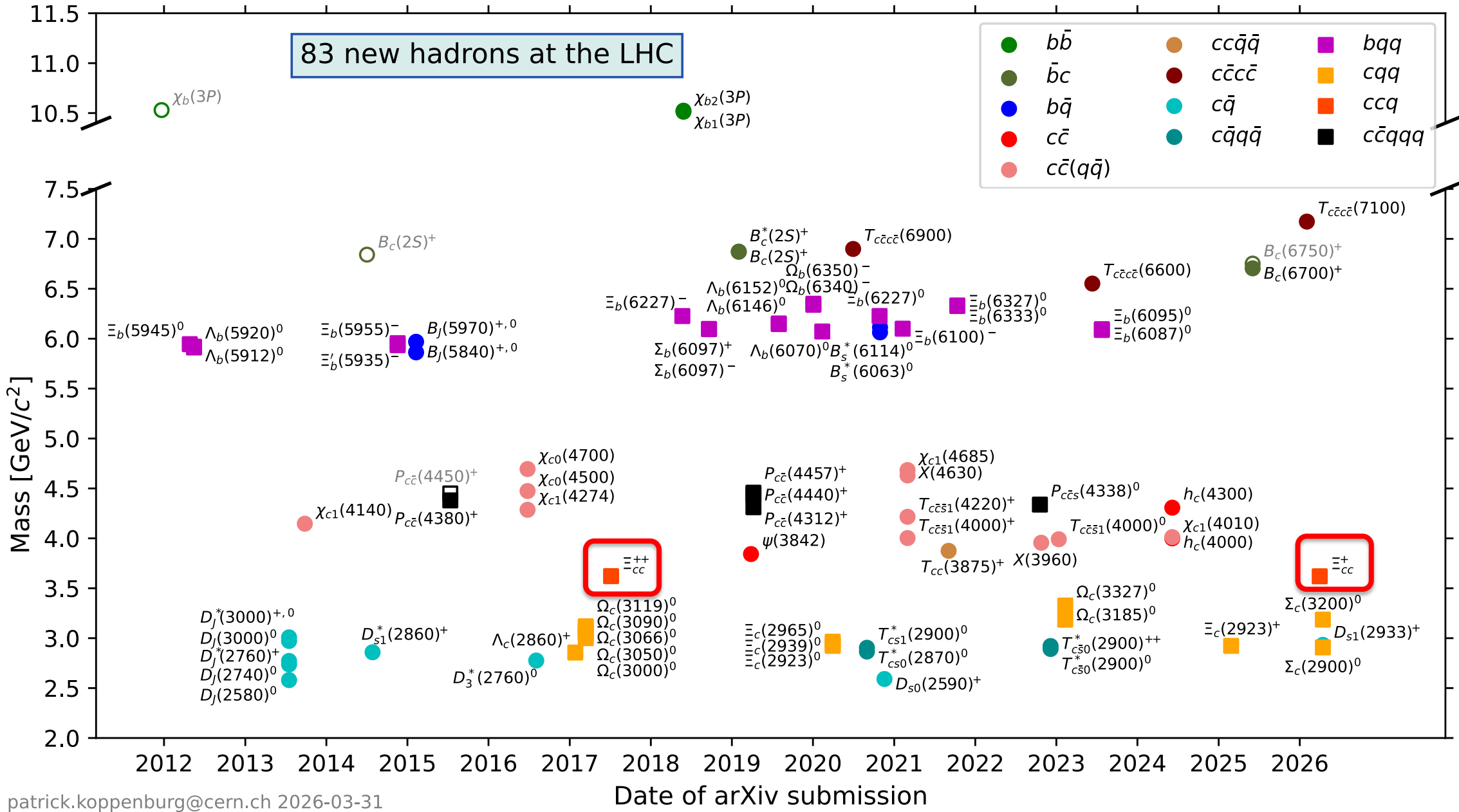


Source	$M(\Xi_{cc}^+) [\text{MeV}/c^2]$	$\Delta M [\text{MeV}/c^2]$
Momentum-scale calibration	0.14	0.03
Energy loss	0.10	0.05
Selection bias correction	0.10	0.10
Mass fit model	0.10	0.10
$\Lambda_c^+$ mass uncertainty	0.14	—
Sum in quadrature	0.26	0.15
$\Xi_{cc}^+$ lifetime	+1.90 -1.30	+1.90 -1.30

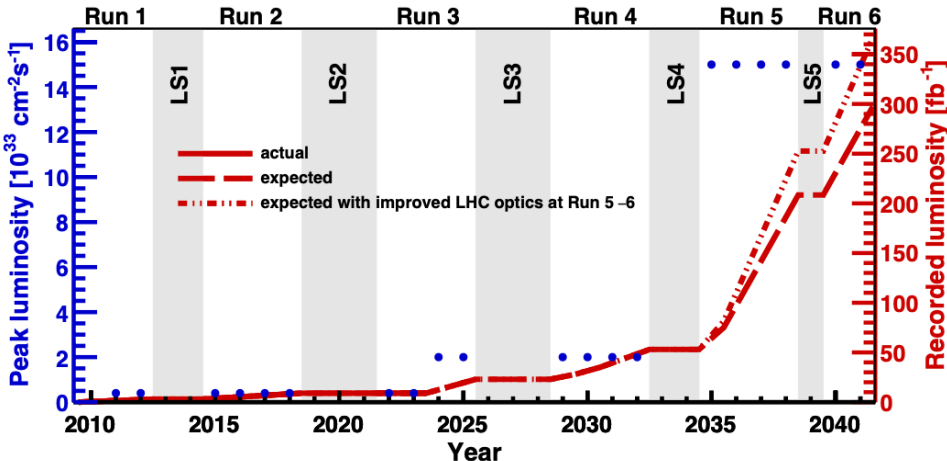
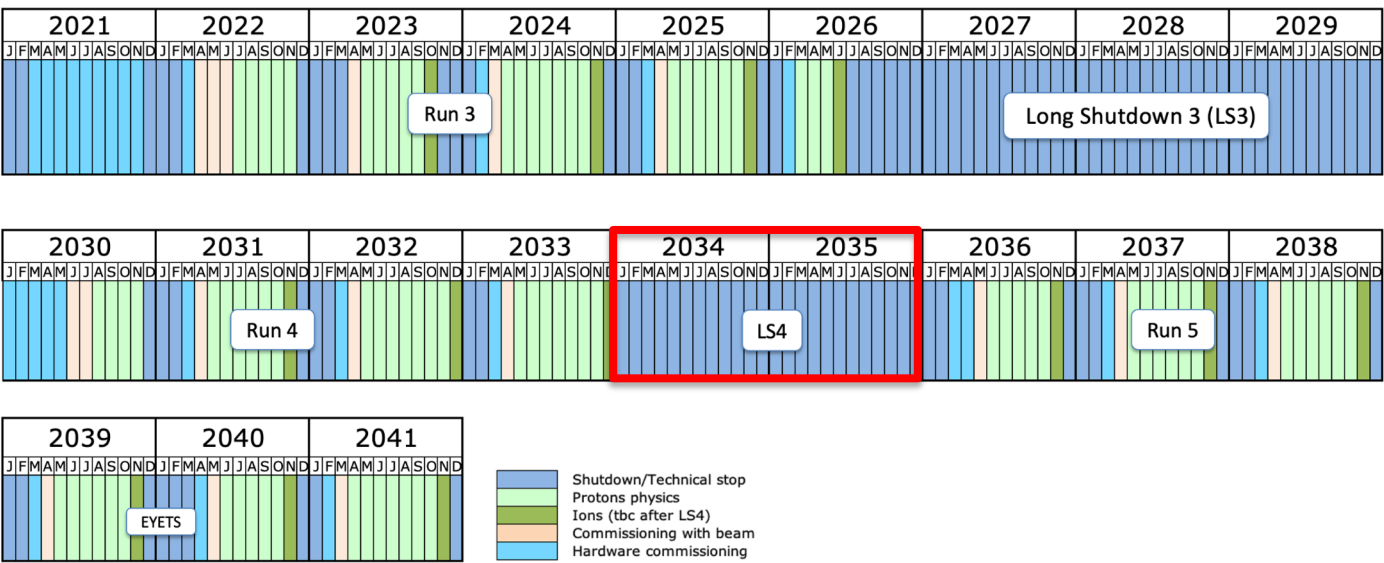
# $\Xi_{cc}^+$ in Run2

- Signal w/ a local significance of  $4\sigma$ ,  $m(\Xi_{cc}^+) = 3620.8 \pm 2.2 \text{ MeV}/c^2$ , consistent with 2024  
 $m(\Xi_{cc}^+) = 3619.97 \pm 0.83 \pm 0.26_{-1.30}^{+1.90} \text{ MeV}/c^2$
- Efficiency in 2024 **increased by a factor of 2.5**, compared w/ Run2

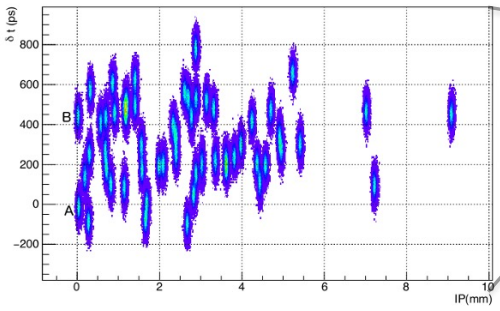




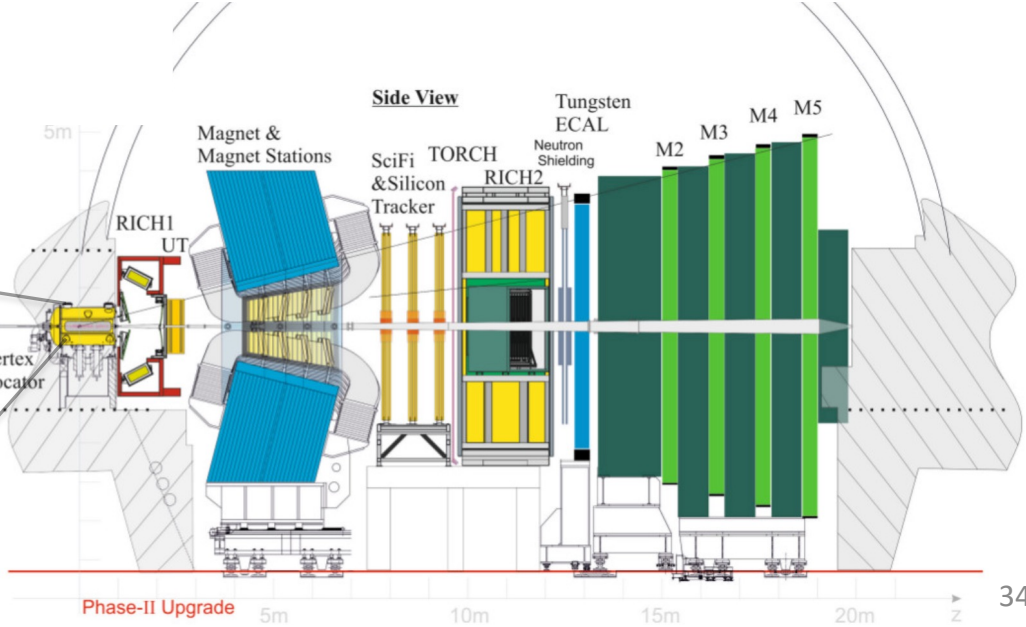
# The LHCb upgrades



Last update: September 24



Upgrade II, 4D detector, Timing,  $\mathcal{O}(10 \text{ ps})$ , is essential





# Summary

- Upgraded LHCb detector and trigger, efficiency of hadronic final states increased by a factor 2-4!
- $\Xi_{cc}^{++}$ : a factor of 4 signal yield per  $\text{fb}^{-1}$ , compared w/ Run2
- $\Xi_{cc}^+$ : **First new particle observed w/ the upgraded LHCb detector**
  - $m(\Xi_{cc}^+) = 3619.97 \pm 0.83 \pm 0.26_{-1.30}^{+1.90} \text{ MeV}/c^2$
  - $m(\Xi_{cc}^+) - m(\Xi_{cc}^{++}) = -1.77 \pm 0.84 \pm 0.25_{-1.30}^{+1.90} \text{ MeV}/c^2$consistent with theoretical predictions
- Many thanks to your continued and strong supports