理论与实验联合研讨会：粲物理”专题研讨会

2019.11.22-24，暨南大学

Recent results of charmed baryons at LHCb

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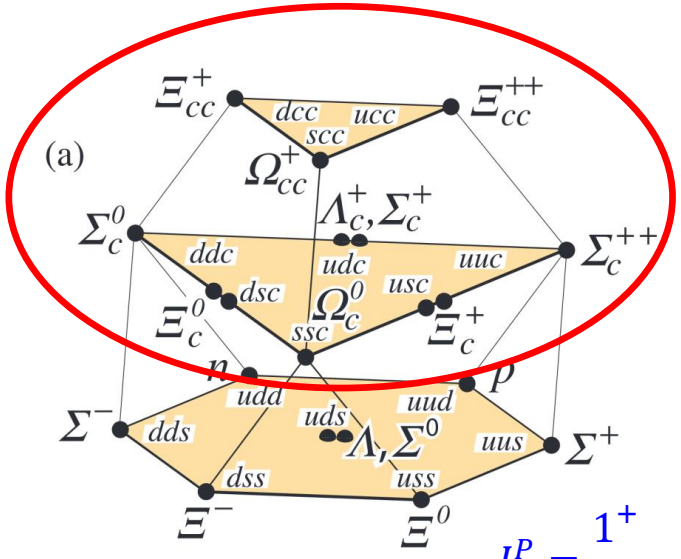
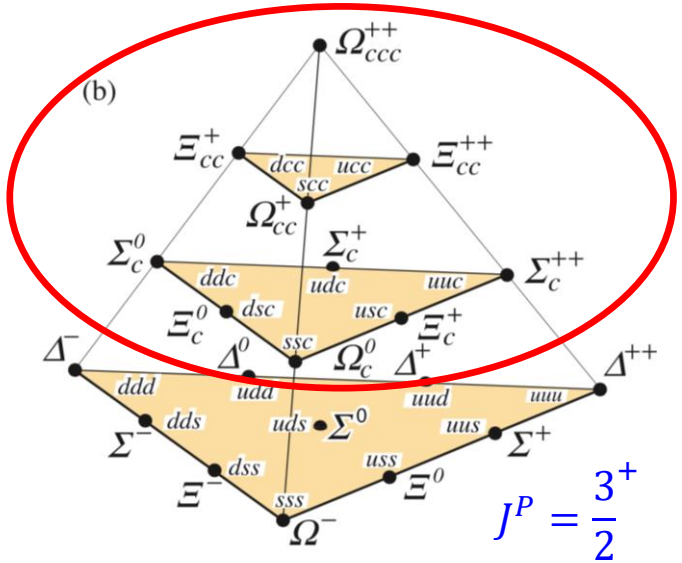
2019.11.23

Outline

- Introduction
- Singly charmed baryons
- Doubly charmed baryons
- Prospects and summary



$J^P = \frac{1}{2}^+$



$J^P = \frac{3}{2}^+$

The LHCb experiment

Origin of LHCb: 1995

LHC-B

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

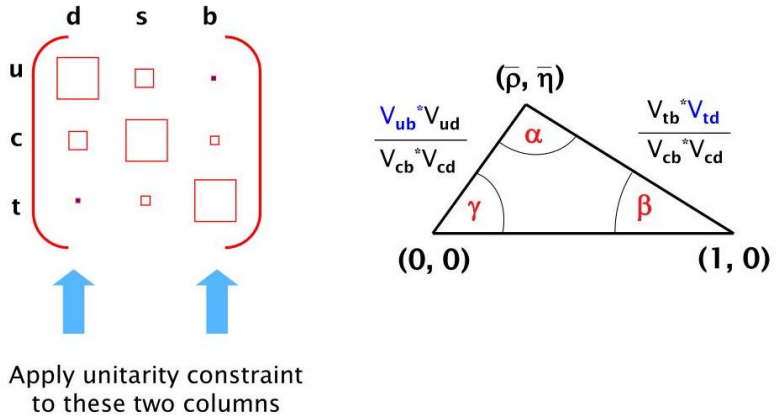
LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

CKM matrix (quark-mixing matrix) & the unitarity triangles



... dedicated to the study of CPV and other rare phenomena in the decays of Beauty particles.

... precise measurements of the CKM angles ...

Physics at LHCb (now)

- **Indirect search of BSM via precision measurements**
  - CKM, CPV and rare decays in b and c hadrons
- Precise measurements of QCD + EW at large rapidity
- Hadron spectroscopy
- Direct searches of New Physics
- Heavy-ion and fixed-target physics

The LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

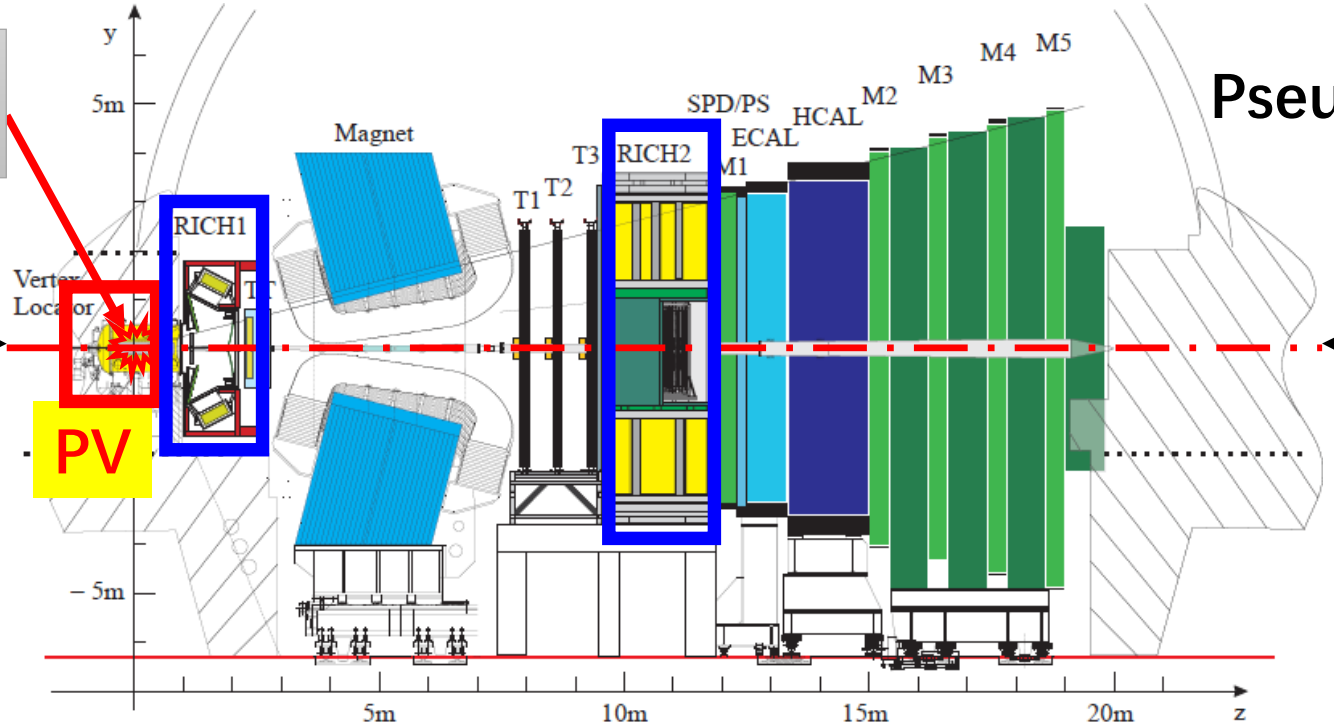
Collision point

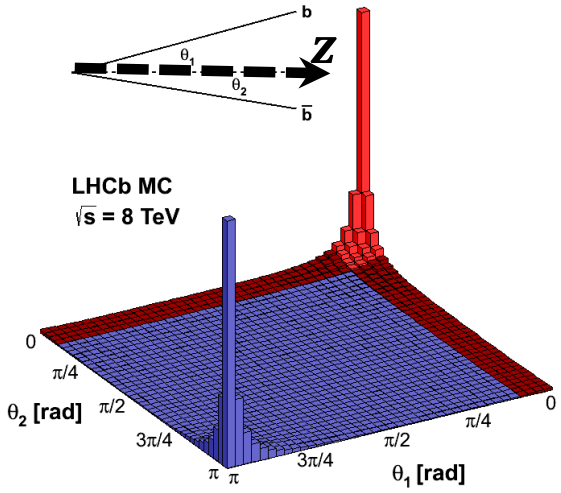
Beam1

Beam2

Pseudorapidity coverage
$2 < \eta < 5$

VELO silicon strips

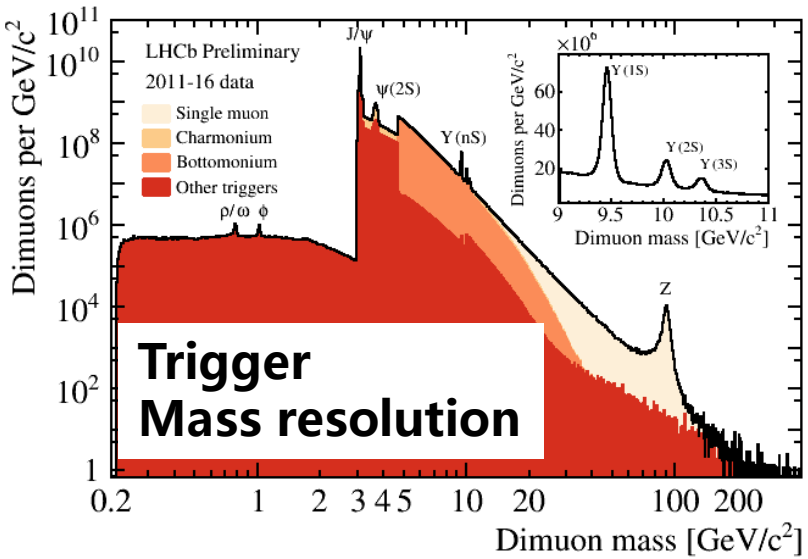


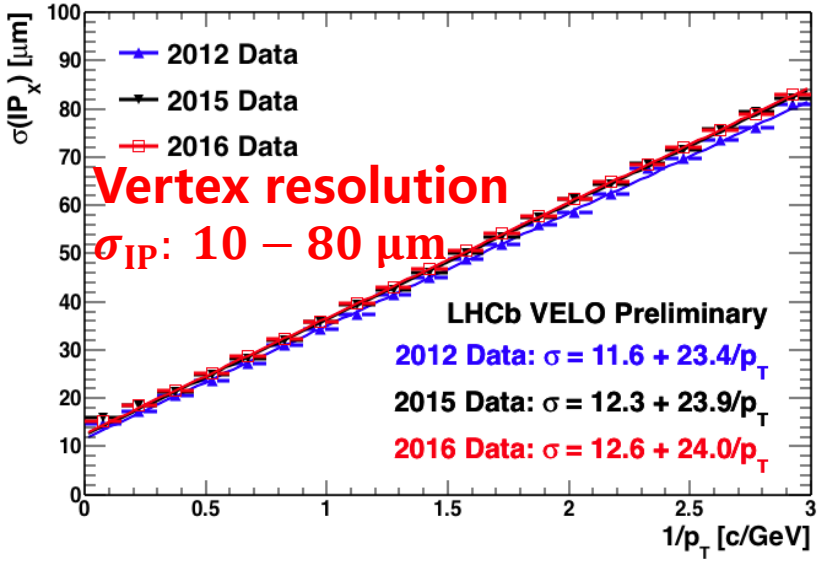


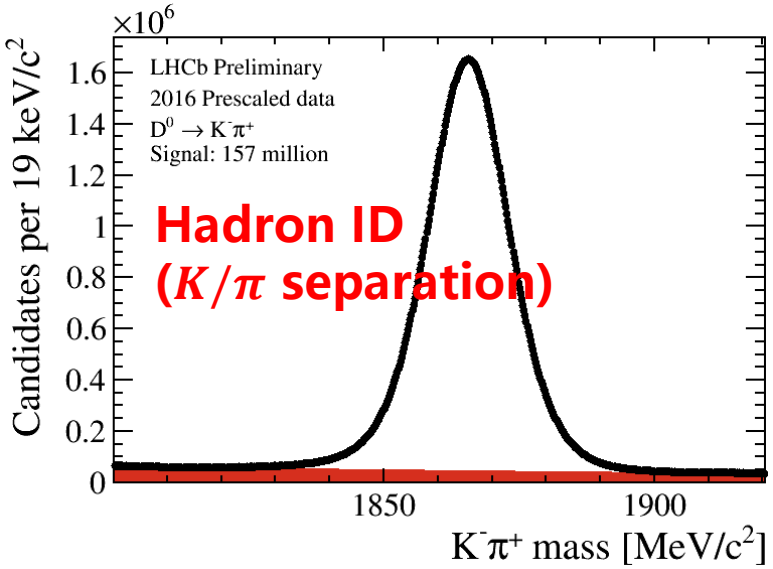
Vertex:	$\sigma_{IP} = 20\ \mu m$
Time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\sigma_m = 8$ MeV/c^2 for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

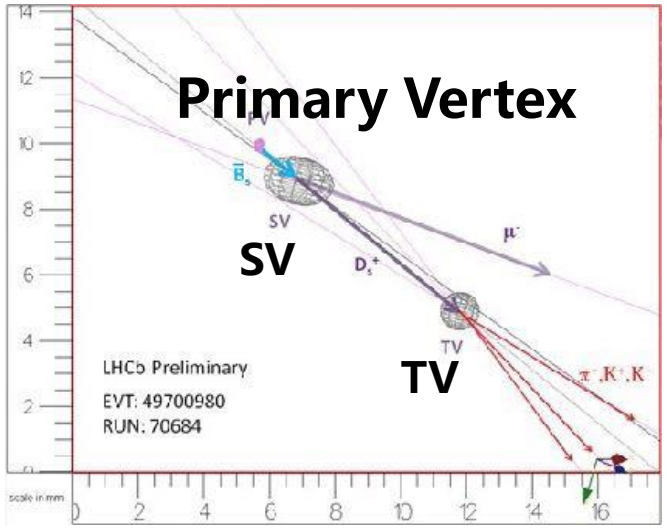
A detector at the collider which looks like one for fixed-target experiment

Pros of hadron spectroscopy at LHCb





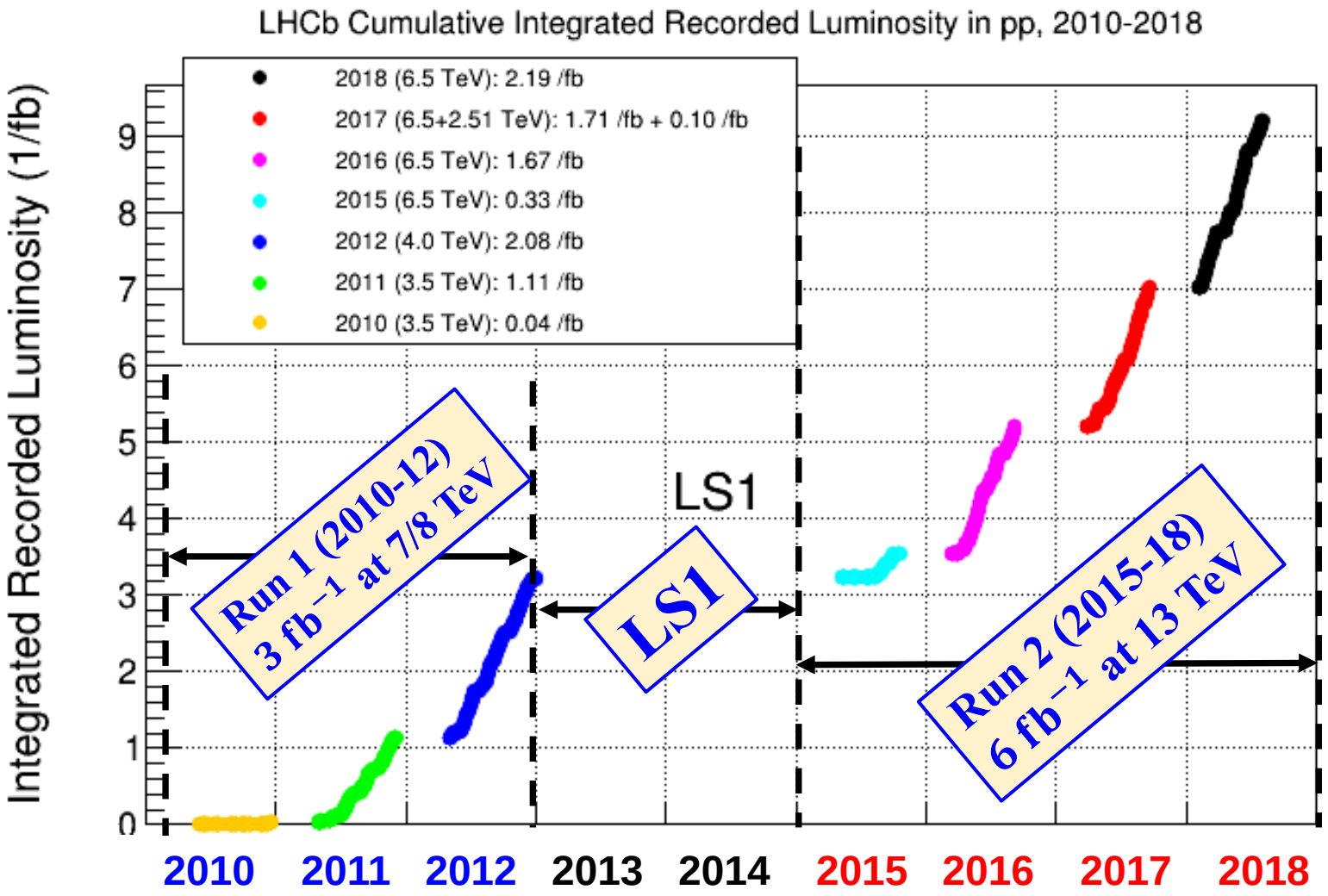




- Large production cross-section
- Efficient trigger
- Vertex locator with high precision
- High precision tracking system
- Powerful hadron identification
- Efficient muon system

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2016
https://twiki.cern.ch/twiki/bin/view/LHCb/ConferencePlots

Data taking (run1+run2)



- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- Many impressive results have been achieved

More than 9 fb^{-1} accumulated in Run1+Run2

Large $b\bar{b}$ ($c\bar{c}$) cross-sections at the LHC

$\sigma(b\bar{b}X) \sim 0.2\% \times \sigma_{pp}^{\text{inesl}}$,

$\sim 10^{11}$ b-hadrons per fb^{-1}

$\sigma(c\bar{c}X) \sim 4\% \times \sigma_{pp}^{\text{inesl}}$,

$\sim 10^{12}$ c-hadrons per fb^{-1}

All species of heavy flavour hadrons:

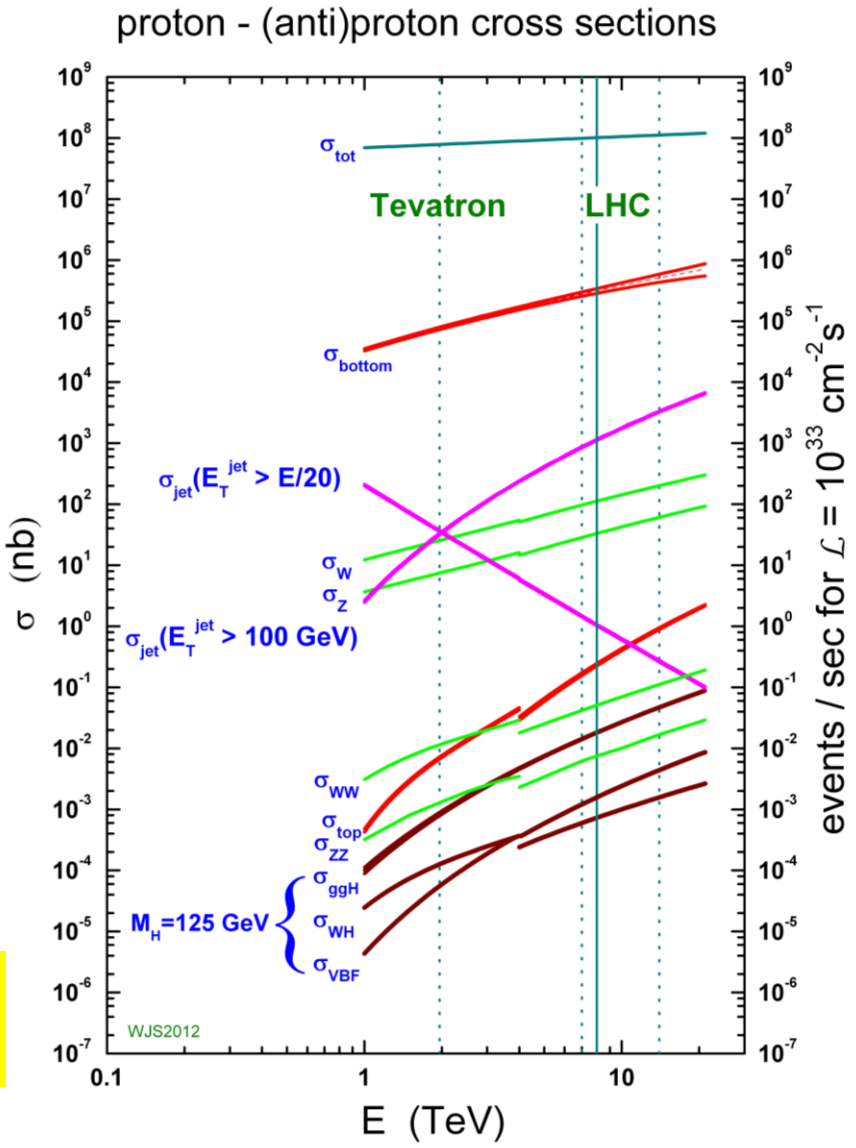
$B^0, B_s^0, B^\pm, B_c^+, \Lambda_b^0,$

$D^0, D^\pm, D_s^\pm, \Lambda_c^\pm, \Xi_{cc}^{++}, P_c^+,$

$J/\psi, \psi(2S),$

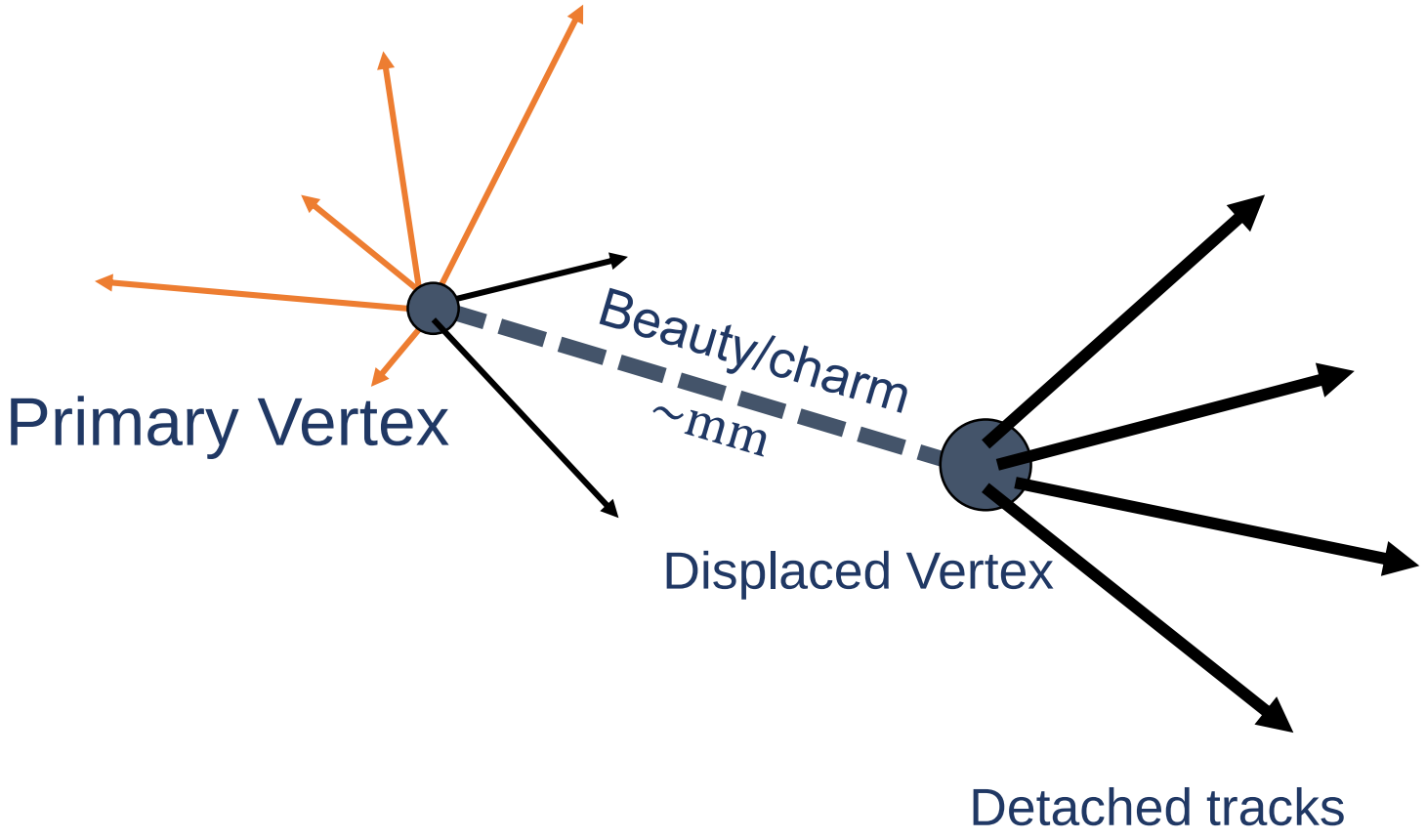
$\Upsilon(\text{n}S), \ldots$

A huge charm factory



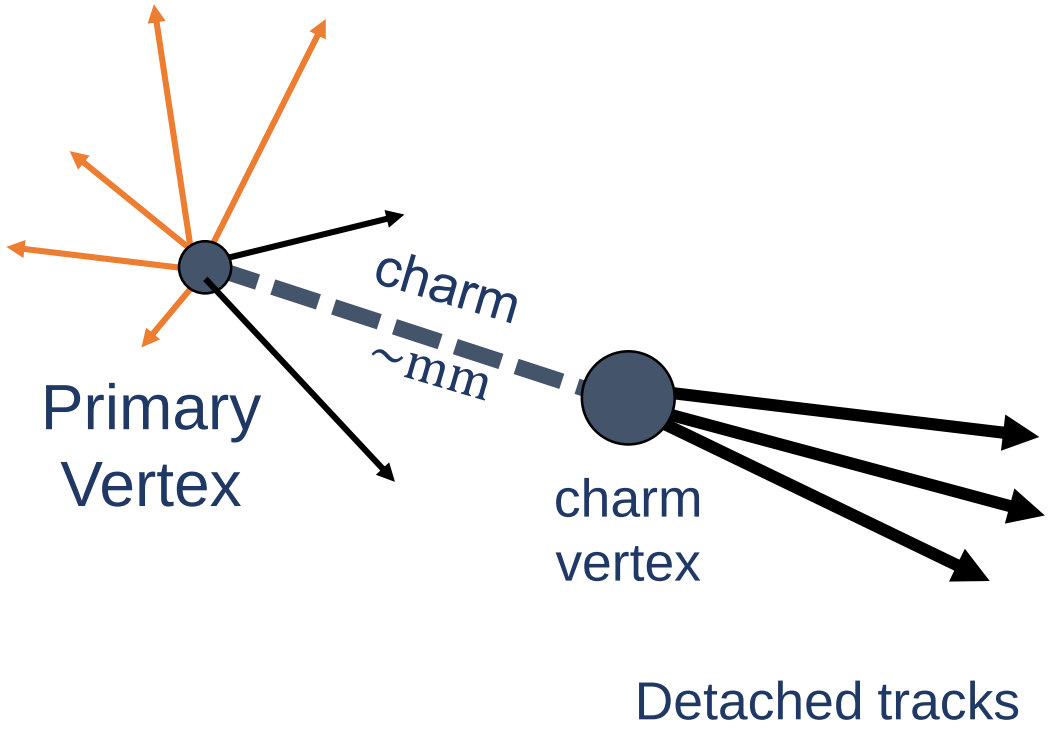
Reconstruct heavy flavour decays at LHCb

~200 prompt tracks in acceptance

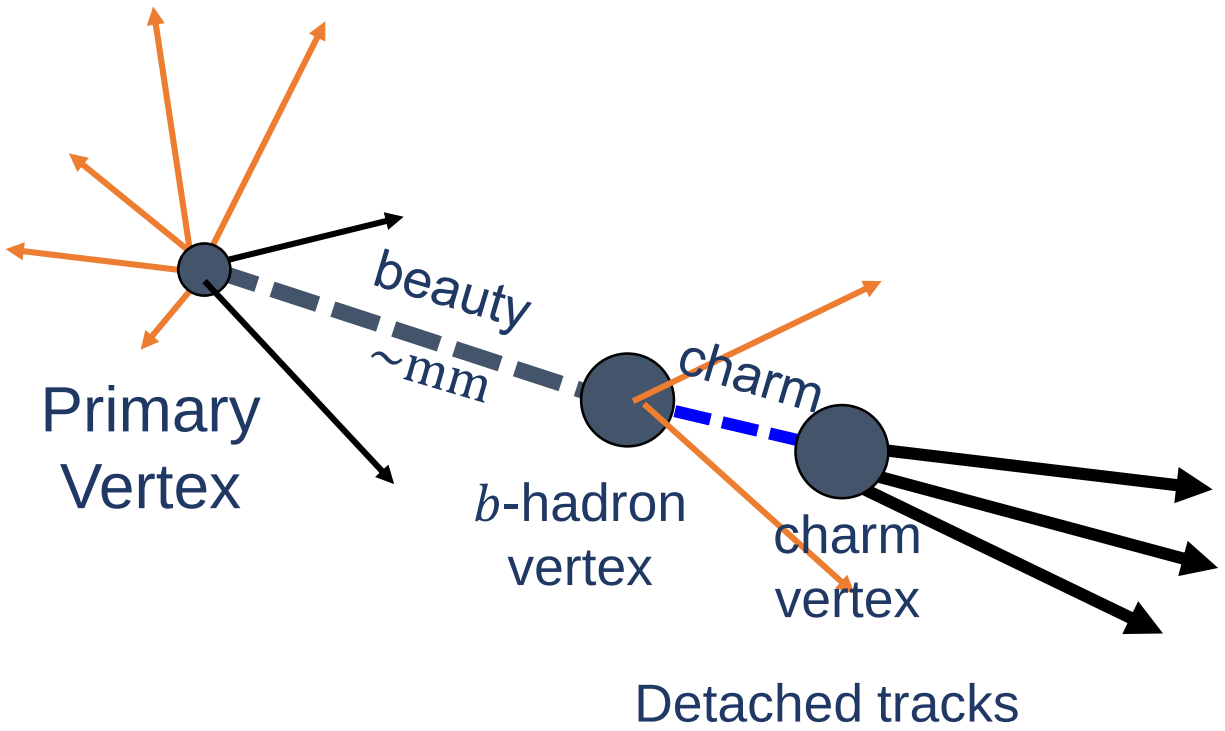


Charmed baryons at LHCb

- Prompt production
  - Large cross-section ➔ Large sample size
  - Background level usually high



- From b-hadron decays
  - Sample size relatively small
  - Background level relatively low



Singly charmed baryon

Lifetimes of charmed baryons

- Known much less precisely than lifetimes of charmed mesons
- Test of HQE in particular on higher-order terms
- Expected lifetime hierarchy

$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

  - Consistent with measurements by previous experiments
- LHCb can significantly improve these measurements

Charmed baryon	Lifetime [fs]
Ξ_c^+	442 ± 26
Λ_c^+	200 ± 6
Ξ_c^0	112^{+13}_{-10}
Ω_c^0	69 ± 12

PDG2018

Measurement of the Ω_c^0 lifetime

PRL 121 (2018) 092003

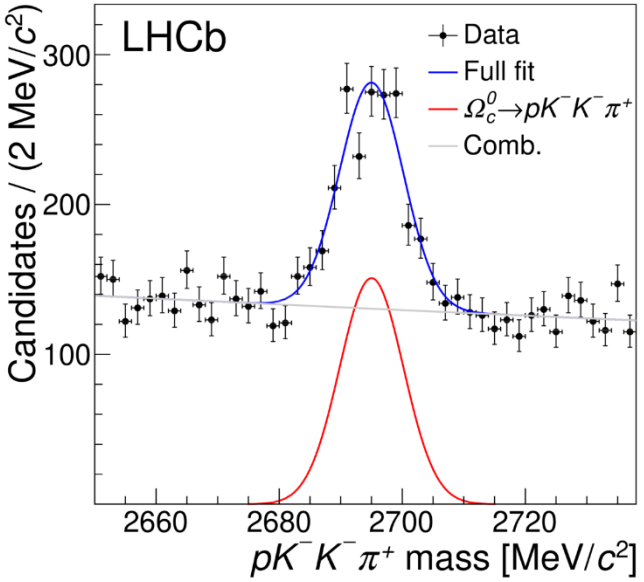
Measurement of the Ω_c^0 lifetime

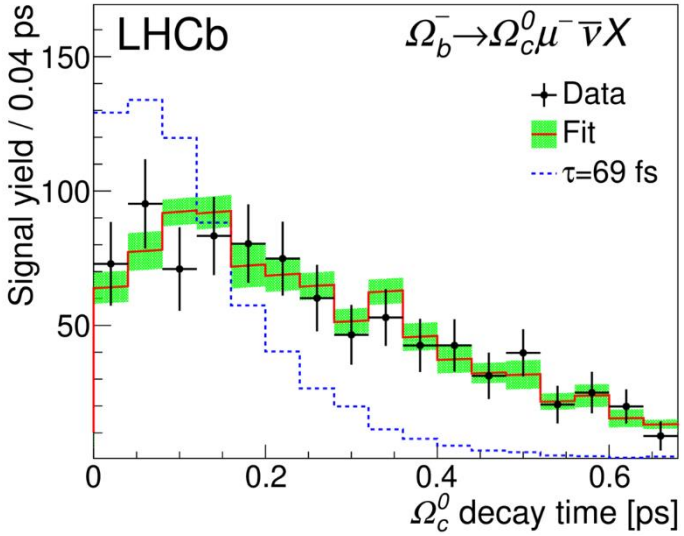
PRL 121 (2018) 092003

- Data sample: Run1 (3 fb^{-1})
- Ω_c^0 from semileptonic decay $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$
  - $\Omega_c^0 \to pK^-K^-\pi^+$ decays used to reconstruct Ω_c^0
- 10 times larger signal yield (978 ± 60) compared to previous experiments
- D^+ from $B \to D^+(K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$ used for reference, measuring the lifetime ratio

$$r_{\Omega_c^0} \equiv \tau_{\Omega_c^0}/\tau_{D^+}$$

to reduce systematic uncertainties
- Result incompatible with the PDG value (69 fs)





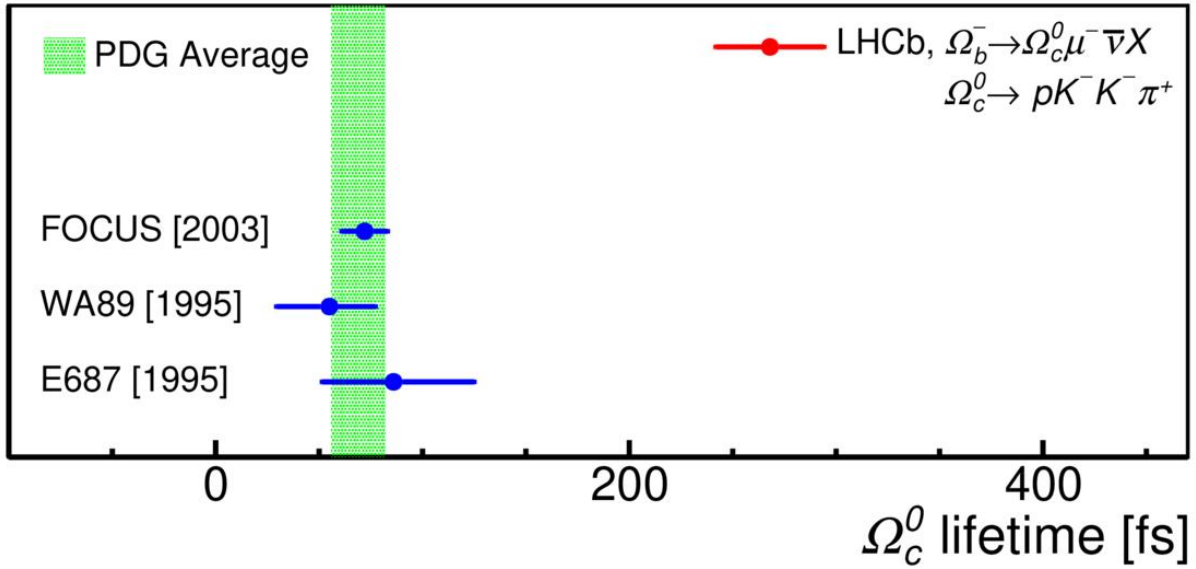
Measurement of the Ω_c^0 lifetime

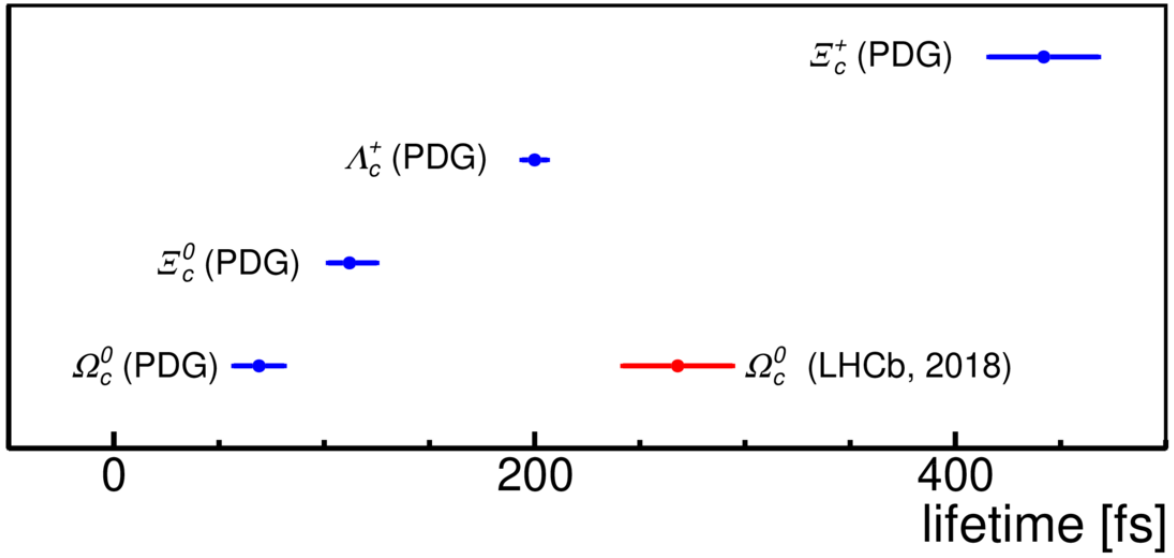
PRL 121 (2018) 092003

$$\frac{\tau(\Omega_c^0)}{\tau(D^+)} = 0.258 \pm 0.023 \pm 0.010 \quad \Rightarrow \quad \tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2\ \mathrm{fs}$$

- New charmed baryon lifetime hierarchy

$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$





Measurement of the Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetimes

PRL 121 (2018) 092003

Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetimes: strategy

PRD 100 (2019) 032001

- Same strategy as Ω_c^0 lifetime measurement
- Data sample: Run1 + Run2
- H_c from semileptonic decay $H_b \to H_c \mu^- \bar{\nu}_\mu X$
  - $H_c \equiv \Lambda_c^+, \Xi_c^+$ or Ξ_c^0
  - $H_b \equiv \Lambda_b^0, \Xi_b^0$ or Ξ_b^-
- D^+ from $B \to D^+(K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$ used for reference, measuring the lifetime ratio

$$r_{\Omega_c^0} \equiv \tau_{\Omega_c^0}/\tau_{D^+}$$

to reduce systematic uncertainties

$\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu X$

$- \Lambda_c^+ \to pK^-\pi^+$

$\Xi_b^0 \to \Xi_c^+ \mu^- \bar{\nu}_\mu X$

$- \Xi_c^+ \to pK^-\pi^+$

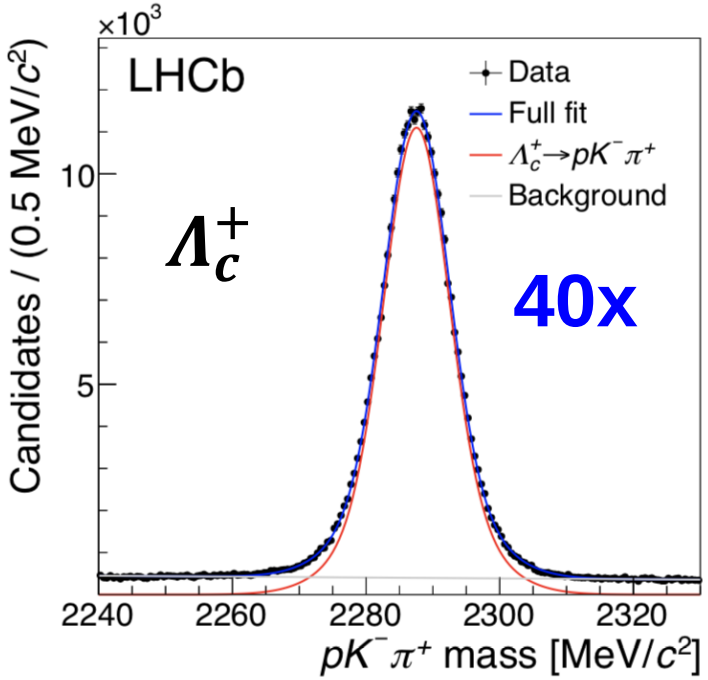
$\Xi_b^- \to \Xi_c^0 \mu^- \bar{\nu}_\mu X$

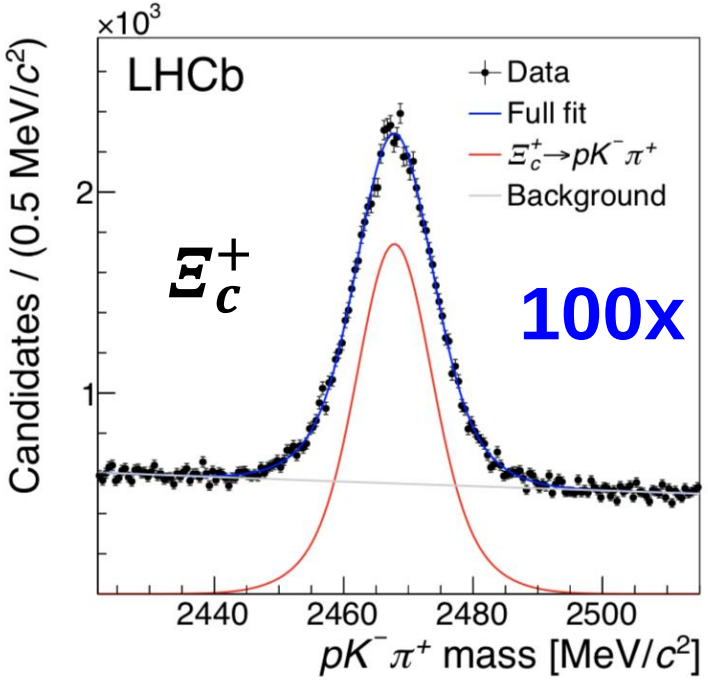
$- \Xi_c^0 \to pK^-K^-\pi^+$

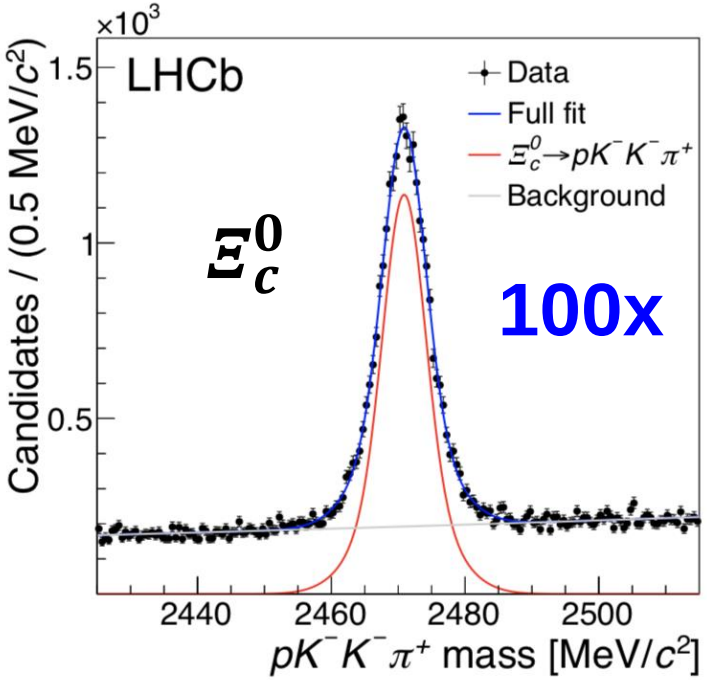
PRD 100 (2019) 032001

Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetime: mass fits

- Signal: sum of two Gaussian
- Background: exponential
- Much larger signal yields than previous measurements





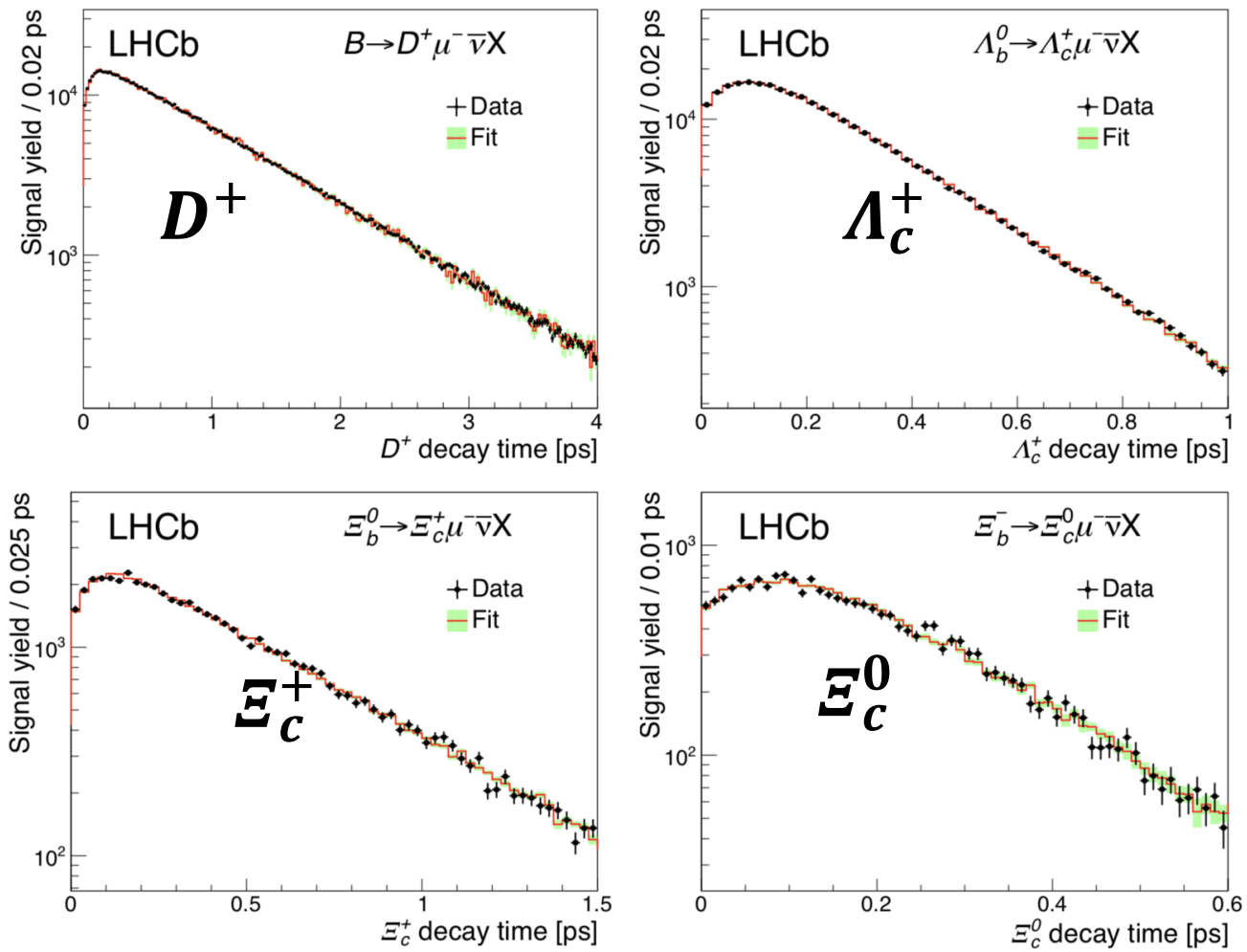


PRD 100 (2019) 032001

Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetime: decay time fits

$$r_{\Lambda_c^+} = 0.1956 \pm 0.0010 \pm 0.0013$$
$$r_{\Xi_c^+} = 0.4392 \pm 0.0034 \pm 0.0028$$
$$r_{\Xi_c^0} = 0.1485 \pm 0.0017 \pm 0.0016$$

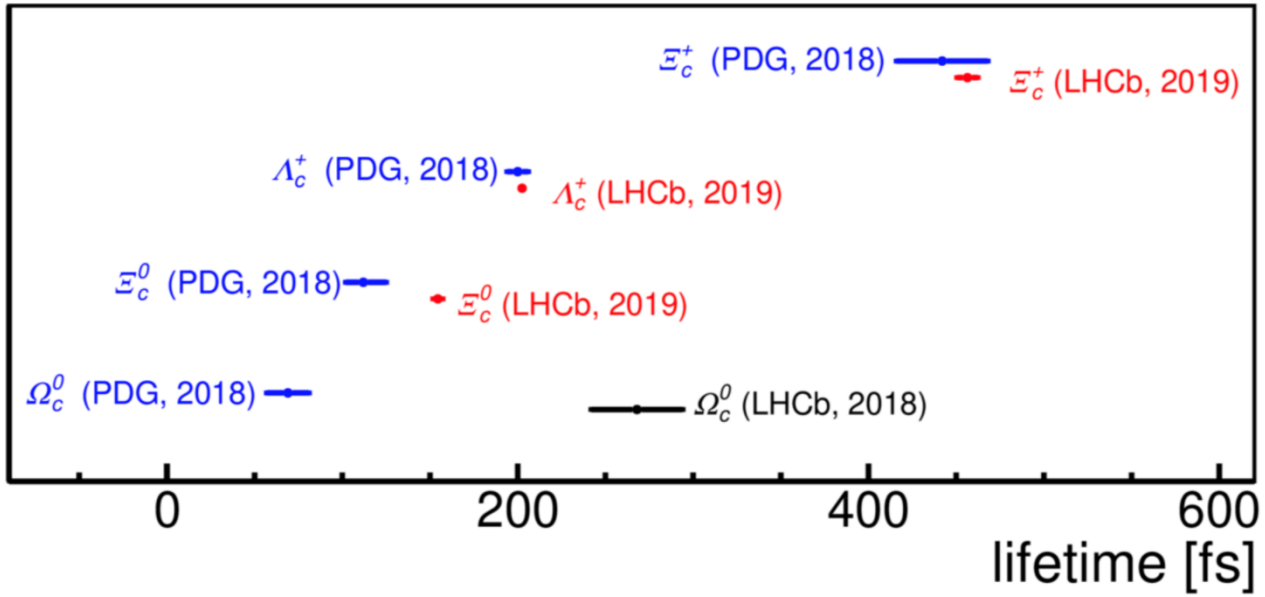
$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs}$$
$$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs}$$
$$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs}$$



PRD 100 (2019) 032001

Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetime: decay time fits

Baryon	Lifetime [fs] (old)	Lifetime [fs] (new)
Ξ_c^+	442 ± 26	$456.8 \pm 3.5 \pm 2.9 \pm 3.1$
Λ_c^+	200 ± 6	$203.5 \pm 1.0 \pm 1.3 \pm 1.4$
Ξ_c^0	112^{+13}_{-10}	$154.5 \pm 1.7 \pm 1.6 \pm 1.0$
Ω_c^0	69 ± 12	$268 \pm 24 \pm 10 \pm 2$



- 3-4x smaller uncertainties for $\tau_{\Lambda_c^+}$, $\tau_{\Xi_c^+}$, $\tau_{\Xi_c^0}$ than previous world average
- $\tau_{\Xi_c^0}$ is 3.3σ larger than previous world average
- $\tau_{\Omega_c^0}$ is 6.9σ larger than previous world average

$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

Observation of excited Ω_c^0 baryons

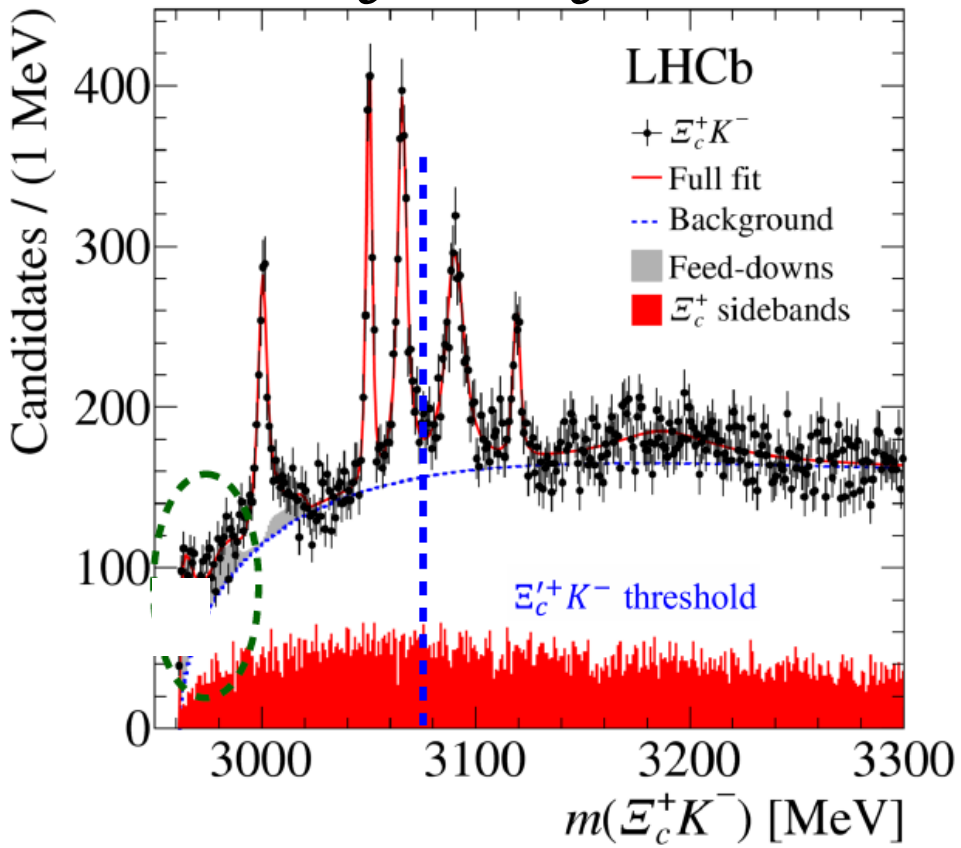
PRL 121 (2018) 092003

Five narrow excited Ω_c^0 states all at once

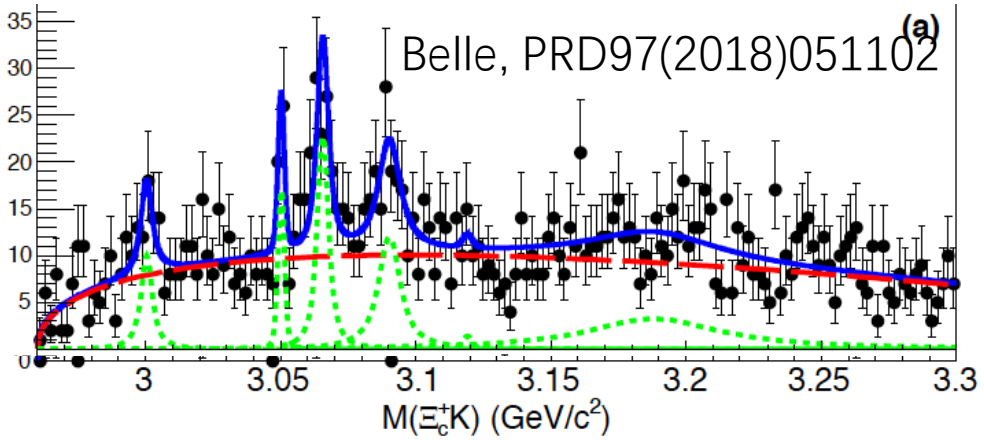
PRL118(2017)182001

+ an evidence for 6th broad state at high mass

$\Omega_c^{*0} \to \Xi_c^+ K^-$



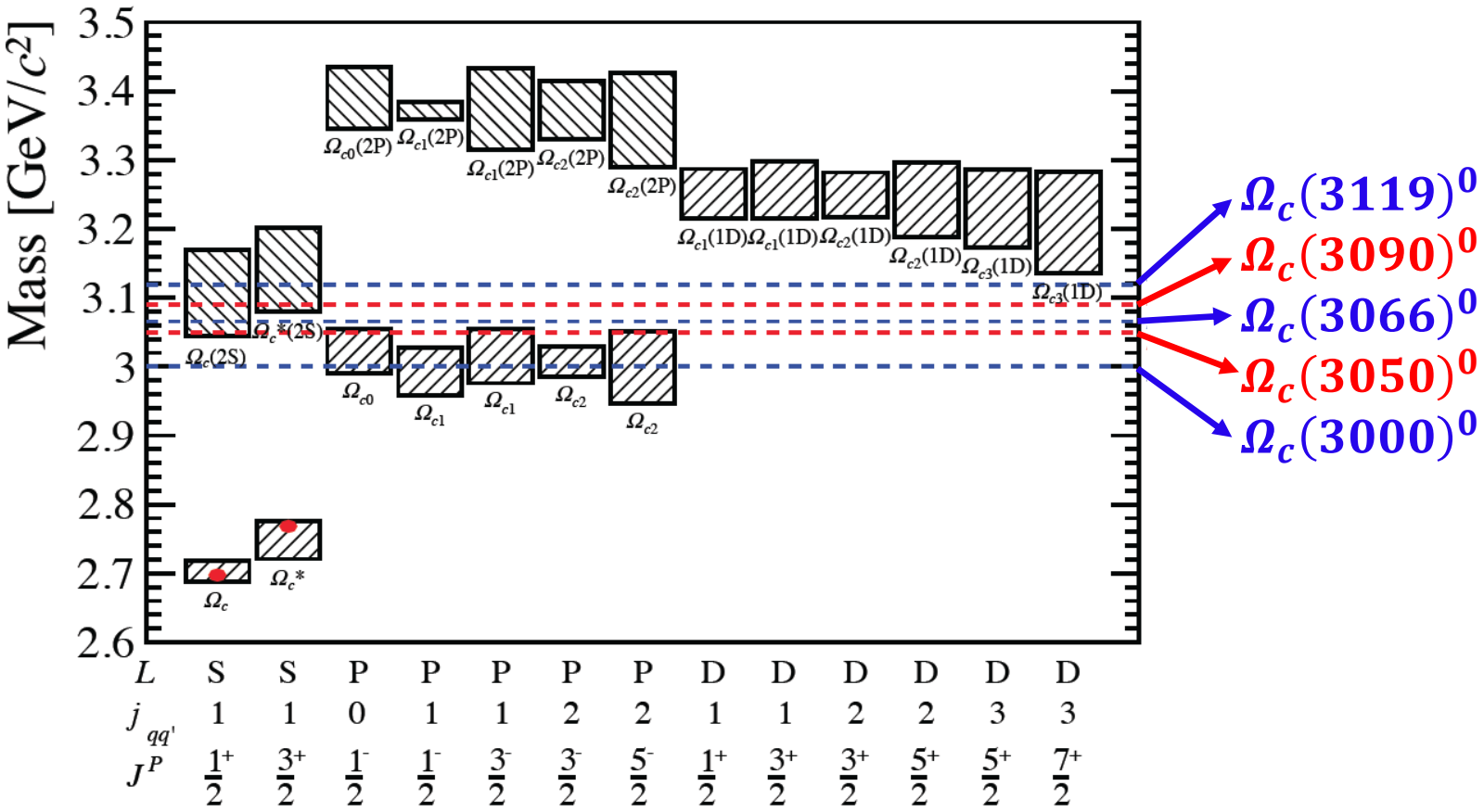
Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		< 1.2 MeV, 95% CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$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



New excited Ω_c^0 states in $\Xi_c^+ K^-$

PRL118(2017)182001

- Not clear which state is which
- Spin and parity need to be determined



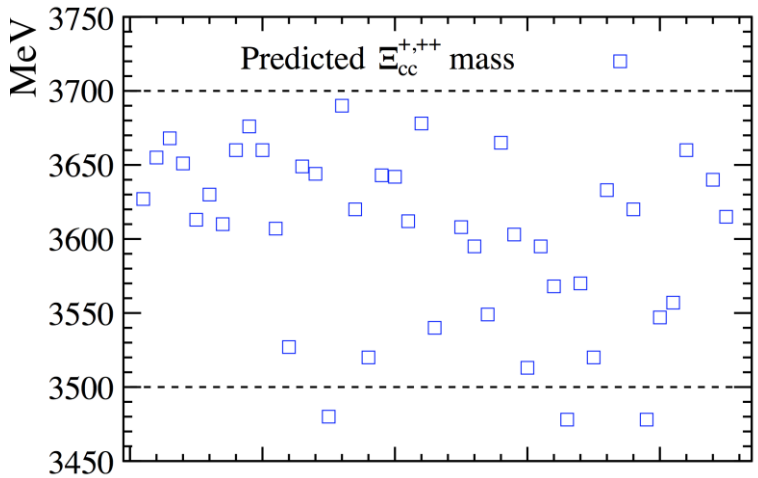
Doubly charmed baryons

Theoretical calculations of Ξ_{cc}

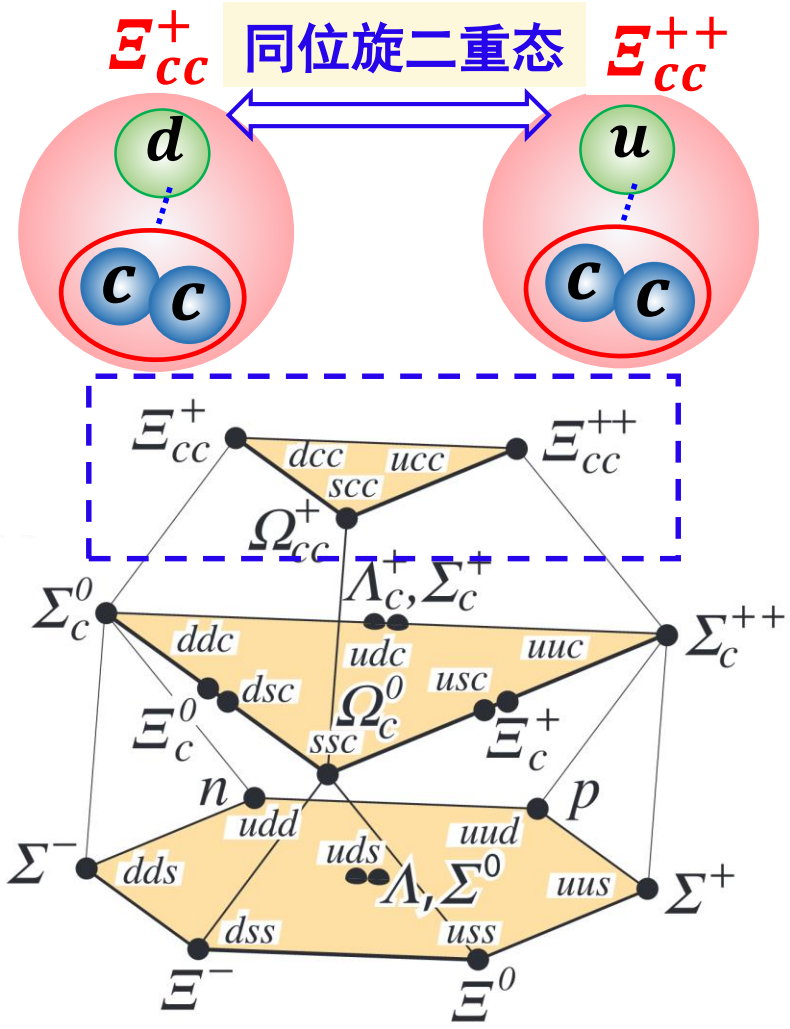
- **Many models calculated the masses**
  - $m(\Xi_{cc}^{+,++}) \in (3.5, 3.7)$ GeV, $m(\Omega_{cc}^{+}) \approx m(\Xi_{cc}) + 0.1$ GeV
  - **Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++}: a few MeV**

$$M(\Xi_{cc}) \approx 3.6 \text{ GeV}, \quad M(\Omega_{cc}^{+}) \approx 3.7 \text{ GeV}$$

- **Lifetime: $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$**
  - $\tau(\Xi_{cc}^{++}) \in (200 - 700)$ fs
  - $\tau(\Xi_{cc}^{+}) \in (50 - 250)$ fs



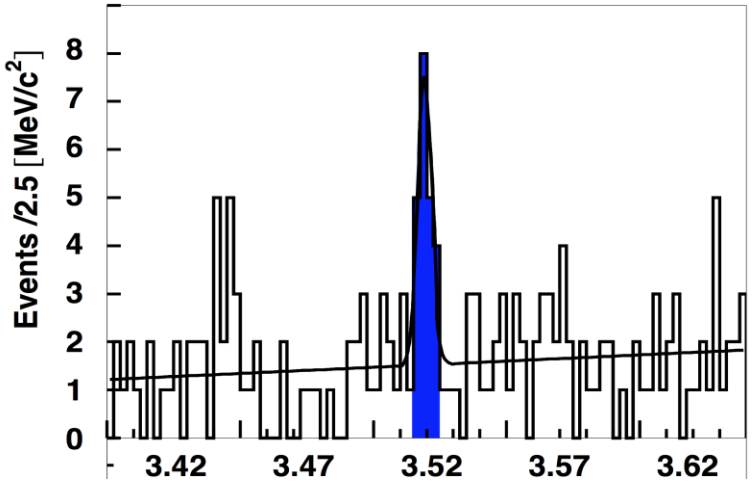
HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson Qq



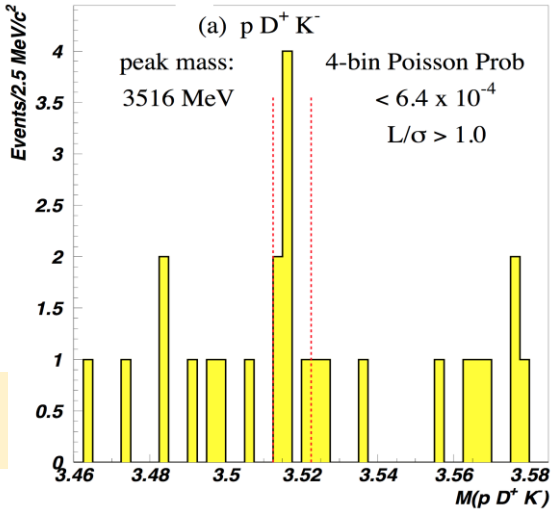
Experimental efforts: SELEX

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with targets, dedicated to study charm baryons
- Observed Ξ_{cc}^+ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ ($N_s = 15.9$) and $\Xi_{cc}^+ \to p D^+ K^-$ ($N_s = 5.62$) decays
  - Mass (combined): $3518.7 \pm 1.7\ \mathrm{MeV/c^2}$

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ PRL89(2002)112001



$\Xi_{cc}^+ \to p D^+ K^-$ PLB628(2005)18



Some significant puzzles of SELEX results

- Too short lifetime: $\tau(\Xi_{cc}^+) < 33$ fs @90% CL, but not zero
- Too large production: $R = \dfrac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$
- Mass lower than expected

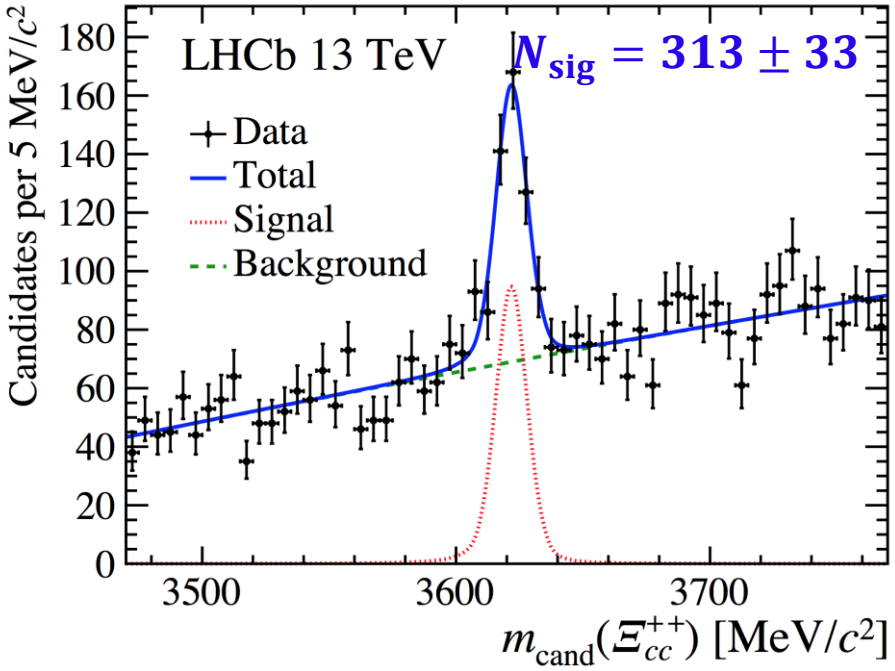
No evidence observed by FOCUS, BaBar, Belle, and LHCb

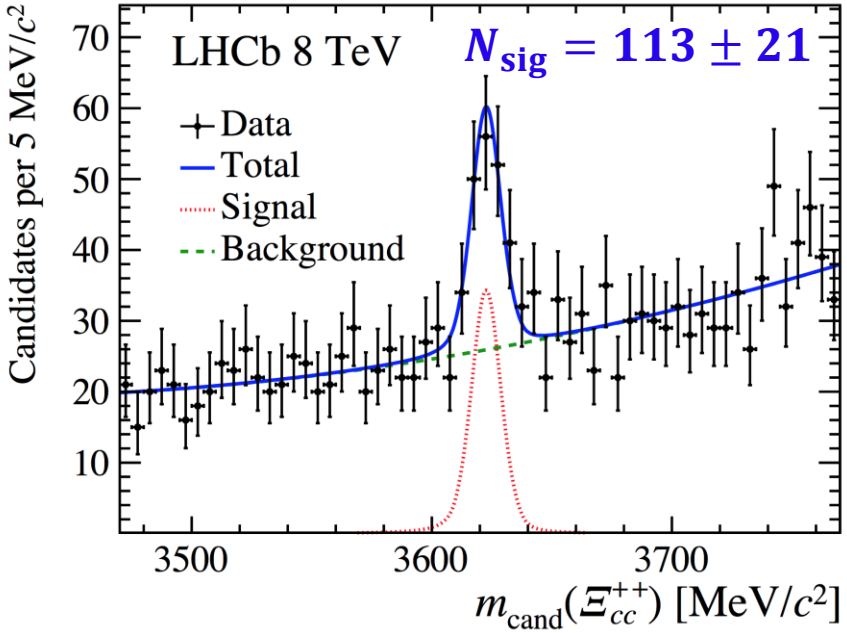
Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

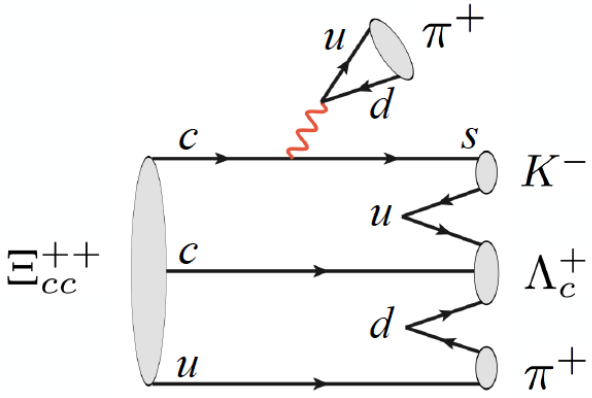
PRL 119 (2017) 112001

- Suggested by theorists [Yu et al., Chin.Phys.C 42 (2018) 051001]
- Significant structure around $\mathbf{3620\ MeV/c^2}$ in the 2016 data ($> 12\sigma$)
- Confirmed in the 2012 data ($> 7\sigma$)

$$m = 3621.80 \pm 0.72\ \mathrm{MeV}/c^2$$
$$\sigma = 6.63 \pm 0.82\ \mathrm{MeV}/c^2$$





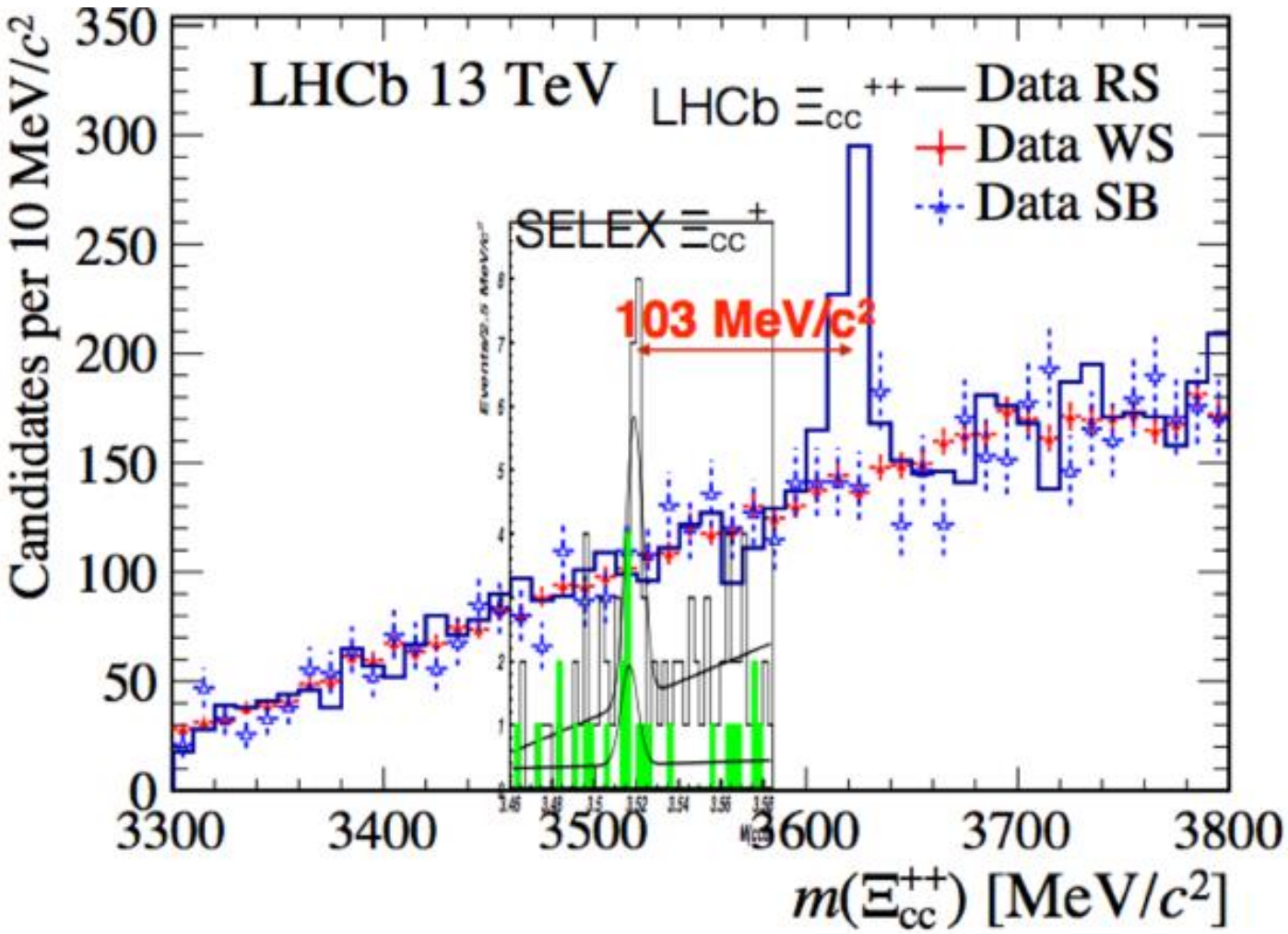


Comparison with SELEX

PRL119(2017)112001

- Large mass difference, inconsistent with being isospin partners：
  $\Delta m = 103 \pm 2\ \mathrm{MeV}/c^2$
- Production: $N(\Xi_{cc})/N(\Lambda_c^+)$ much smaller in the LHCb result than that in SELEX

$$\Delta m \equiv m(\Xi_{cc}^{++})_{\mathrm{LHCb}} - m(\Xi_{cc}^{+})_{\mathrm{SELEX}}$$



Measurement of the Ξ_{cc}^{++} lifetime

PRL 121 (2018) 052002

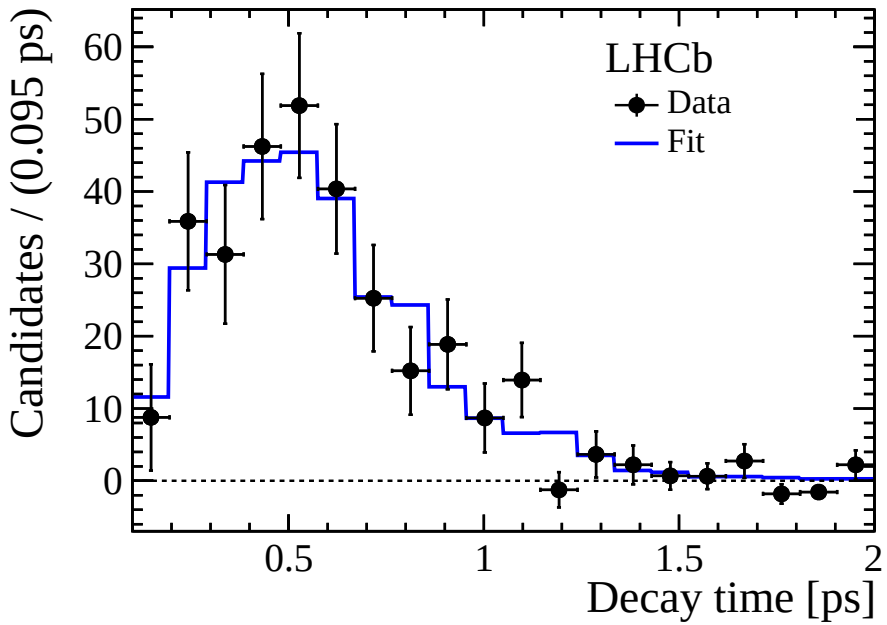
- Use the same sample as the observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- The $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ decay used as reference

$$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14 \text{ fs}$$

Confirmed it is the weakly decaying ground state

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

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014



Measurement of Ξ_{cc}^{++} production

arXiv:1910.11316
Submitted to Chin.Phys.C

- Data sample: 2016 (1.7 fb^{-1})
- Selections almost the same as those used in the observation
- Relative to Λ_c^+ production

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

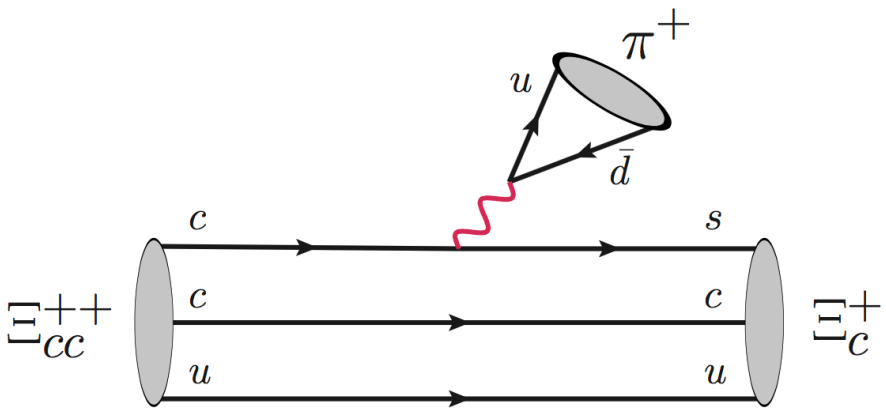
- Three lifetime hypotheses used

Category	$R\ [10^{-4}]$		
	$\tau_{\Xi_{cc}^{++}} = 0.230$ ps	$\tau_{\Xi_{cc}^{++}} = 0.256$ ps	$\tau_{\Xi_{cc}^{++}} = 0.284$ ps
TOS	$2.90 \pm 0.57 \pm 0.49$	$2.57 \pm 0.51 \pm 0.43$	$2.31 \pm 0.46 \pm 0.39$
exTIS	$2.41 \pm 0.35 \pm 0.34$	$2.11 \pm 0.31 \pm 0.30$	$1.88 \pm 0.27 \pm 0.27$
Combined	$2.53 \pm 0.30 \pm 0.33$	$2.22 \pm 0.27 \pm 0.29$	$1.98 \pm 0.23 \pm 0.26$

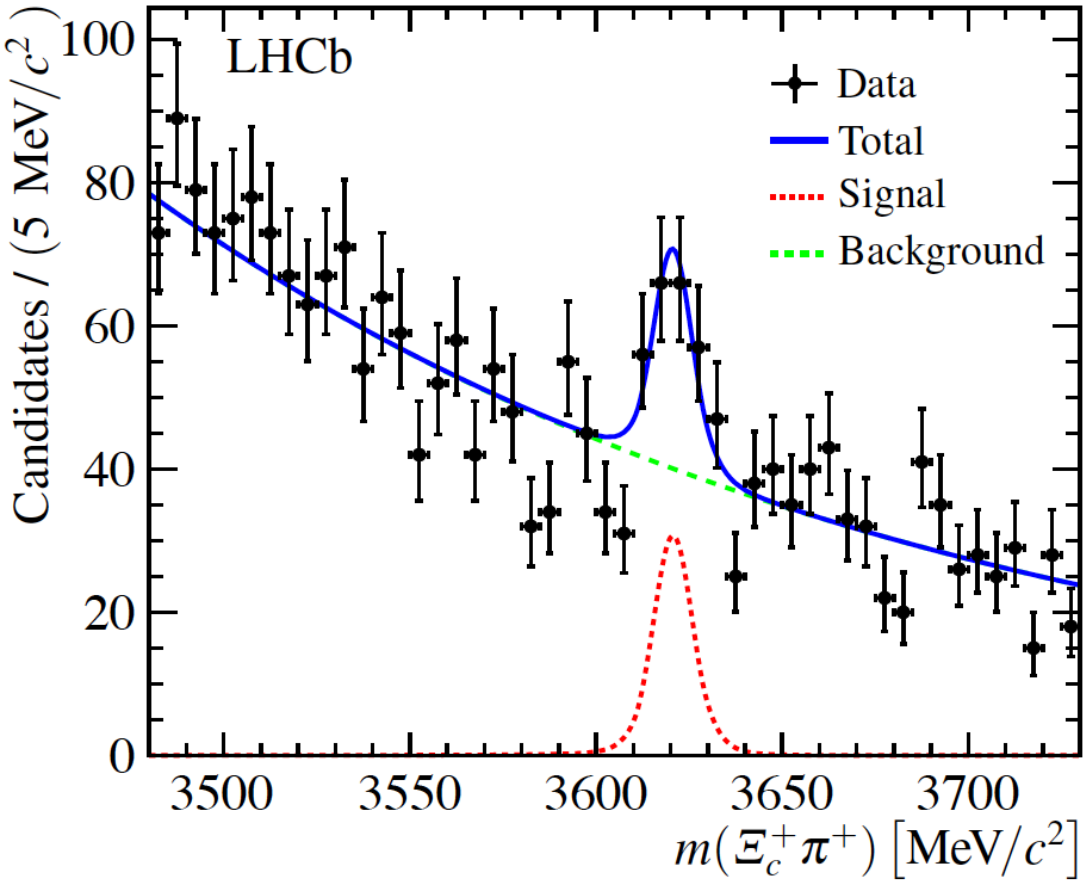
Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

PRL 121 (2018) 162002

- Another decay possibly with large BR suggested by theorists [Yu et al., Chin.Phys.C 42 (2018) 051001]
- Significance: 5.9σ
- Mass and resolution consistent with those of the $\Lambda_c^+ K^- \pi^+ \pi^+$ channel



$N_{\mathrm{sig}} = 91 \pm 20$



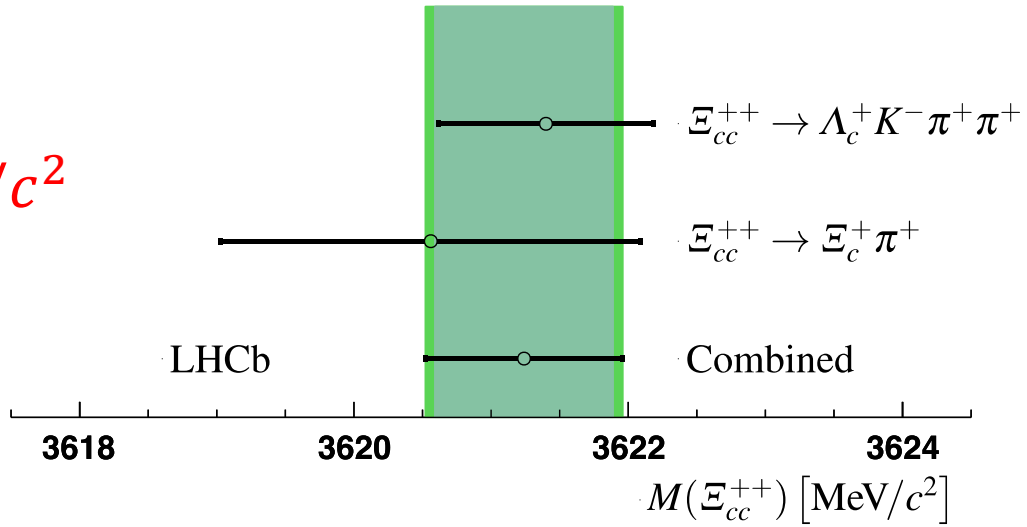
PRL 121 (2018) 162002

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

- Branching fraction ratio

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+; \Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+; \Lambda_c^+ \to pK^-\pi^+)} = (3.5 \pm 0.9 \pm 0.3) \times 10^{-2}$$

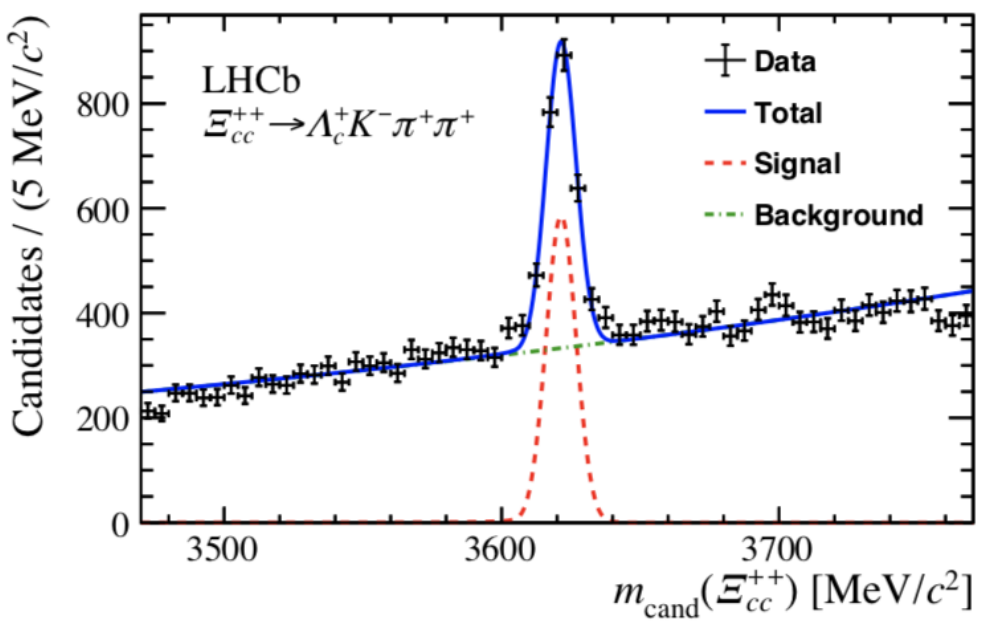
  - Consistent with predictions [Yu et al., Chin.Phys.C 42 (2018) 051001]
- Mass and resolution consistent between the two channels
  - Combined mass: $3621.24 \pm 0.65 \pm 0.31\ \mathrm{MeV}/c^2$
- **Mass difference between the LHCb Ξ_{cc}^{++} and the SELEX Ξ_{cc}^{+}**
  - $m(\Xi_{cc}^{++})_{\mathrm{LHCb}} - m(\Xi_{cc}^{+})_{\mathrm{SELEX}} = 103 \pm 2\ \mathrm{MeV}/c^2$
  - **They could not be isospin partners**

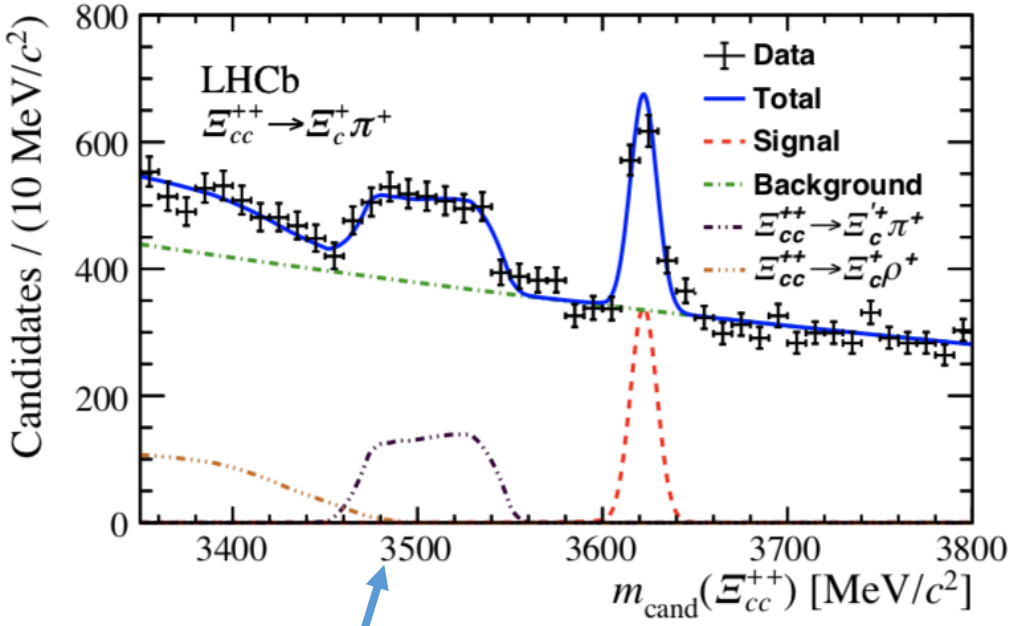


Ξ_{cc}^{++} mass measurement

arXiv:1911.08594
Submitted to JHEP

- Data sample: 2016-2018 ($5.6\ \mathrm{fb}^{-1}$)
- Decay mode $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ used





Partially reconstructed

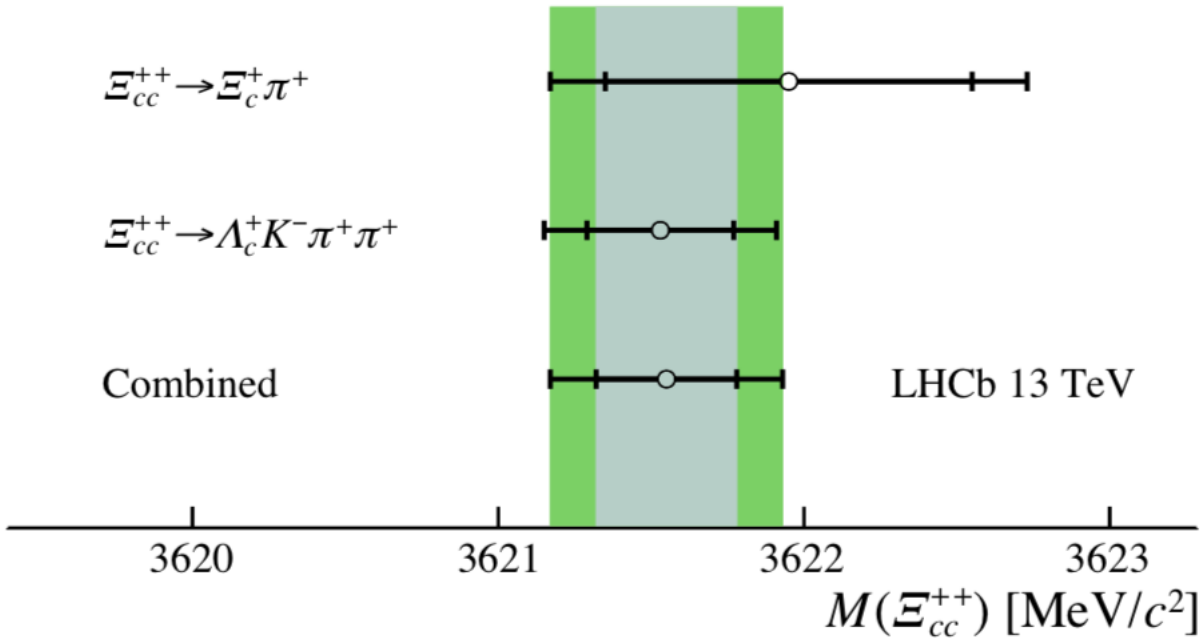
$$\Xi_{cc}^{++} \to \Xi_c^+ \rho^+ (\to \pi^+ \pi^0)$$
$$\Xi_{cc}^{++} \to \Xi_c'^+ (\to \Xi_c^+ \gamma) \pi^+$$

Ξ_{cc}^{++} mass measurement: results

arXiv:1911.08594
Submitted to JHEP

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

Previous result: $\mathbf{3621.24 \pm 0.65 \pm 0.31\ MeV/c^2}$



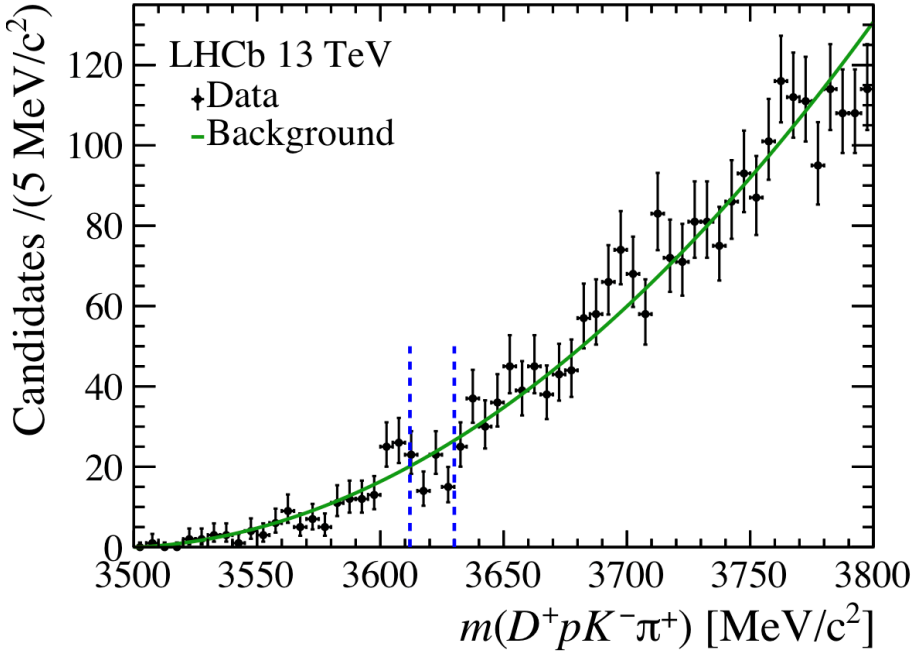
Results of $\Xi_{cc}^{++} \to D^+pK^-\pi^+$

JHEP 10 (2019) 124

- Helpful to further understand the dynamics of Ξ_{cc}^{++}
  - Efficient D^+ trigger at LHCb
  - Low branching fraction (and also low background) due to small phase space
- No signal observed
  - Relative branching fraction measured

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

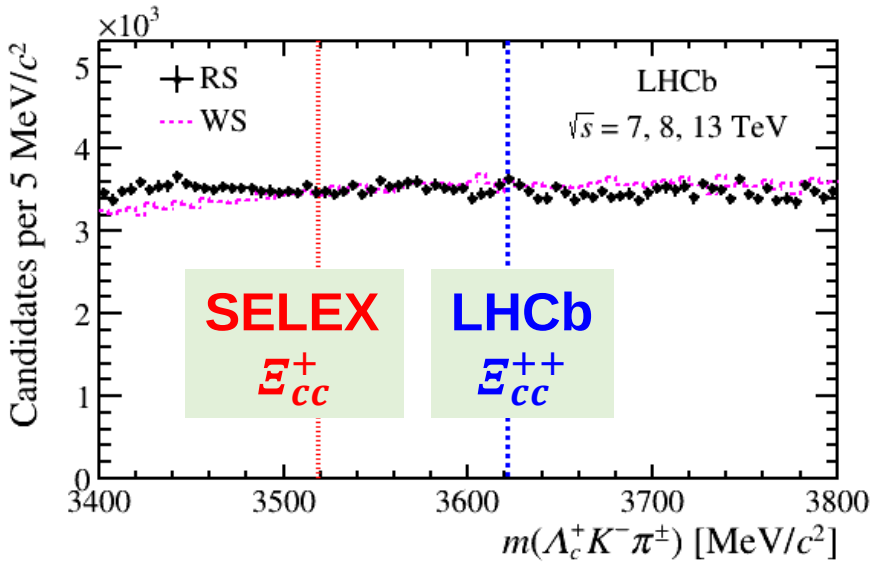
$$\mathcal{R} < 1.7\ (2.1) \times 10^{-2} \text{ at } 90\%\ (95\%)\ \text{CL}$$



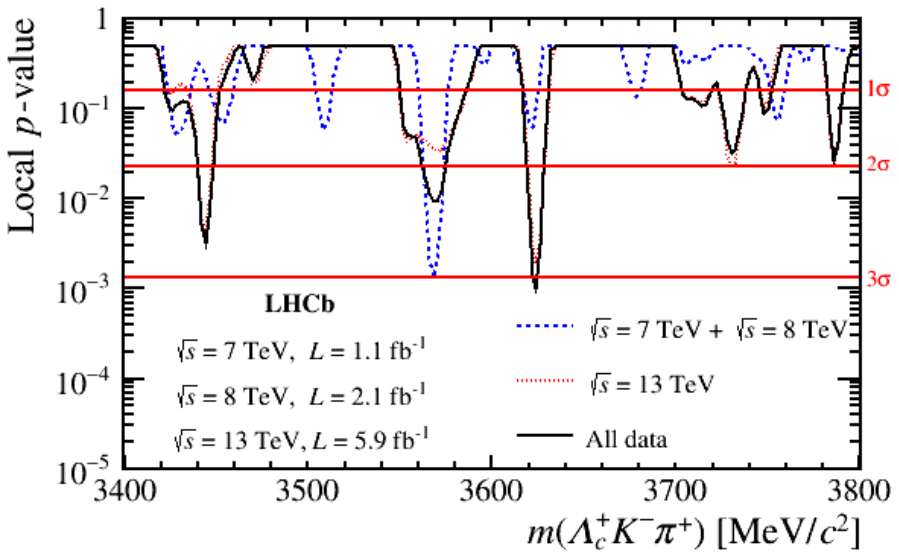
双粲重子$\Xi_{cc}^{+}(ccd)$的寻找

Sci. China Phys. Mech. Astron. 63 (2020) 221062

- **2009年开始寻找**
  - **2013年发表首次结果，未发现信号（2011数据）**
  - **2019年更新（全部数据）**



- **一期 + 二期数据**
- **仍未发现信号**

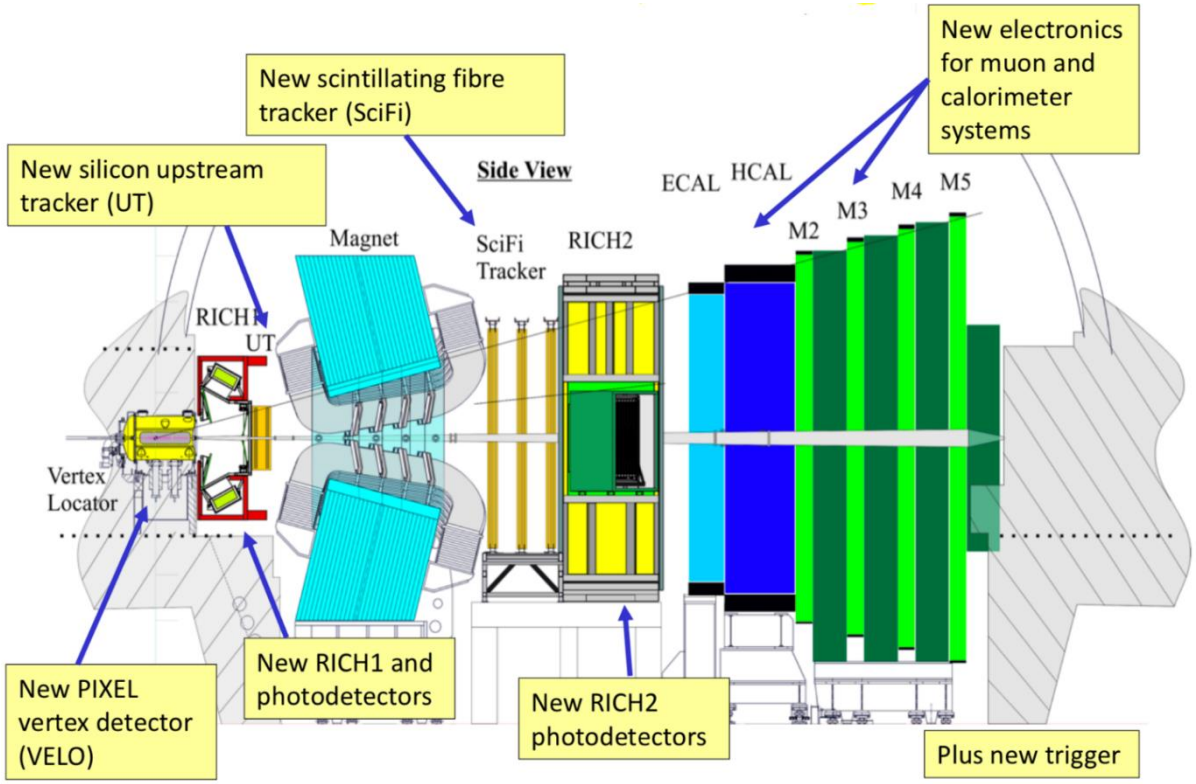


- **最大局域统计显著性：3.1σ**
  - **$3620\ \mathrm{MeV}/c^2$附近**
- **全局显著性： 1.7σ**

Prospects

LHCb Upgrade (2019-2020)

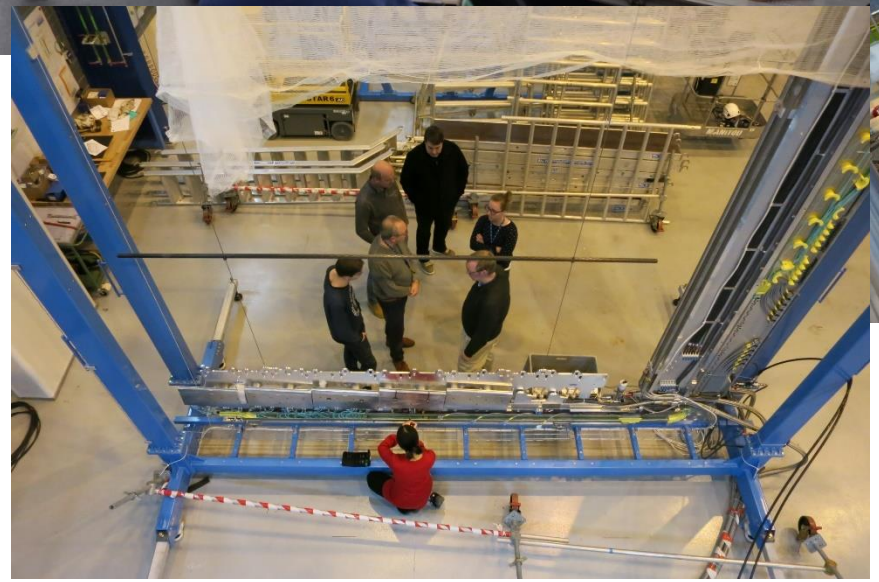
[LHCB-TDR-017]



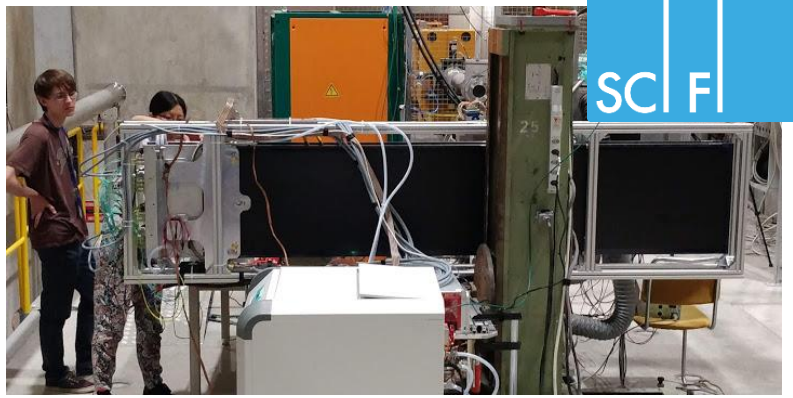
CERN-LHCC-2012-007

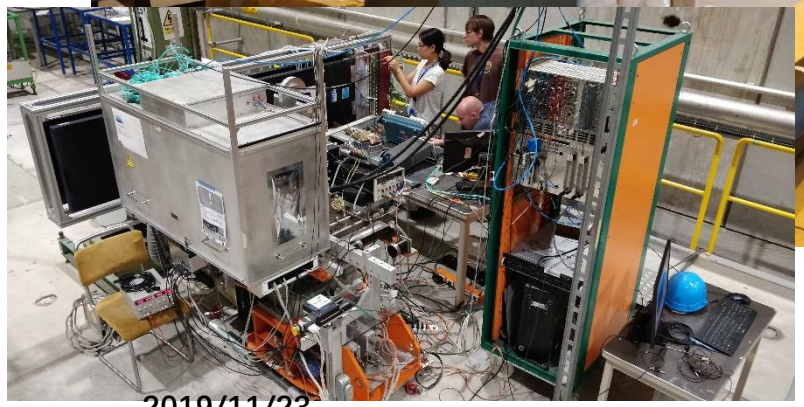
- **Increase luminosity to $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$**
  - **5 times larger than current maximum instantaneous luminosity**
- **All sub-detectors read out at 40 MHz for a full software trigger**
  - Record with 10 GB/s
- **All subdetector apart from muon and calorimeter systems will be fully replaced**

Scintillating Fibre (SciFi) tracker installation



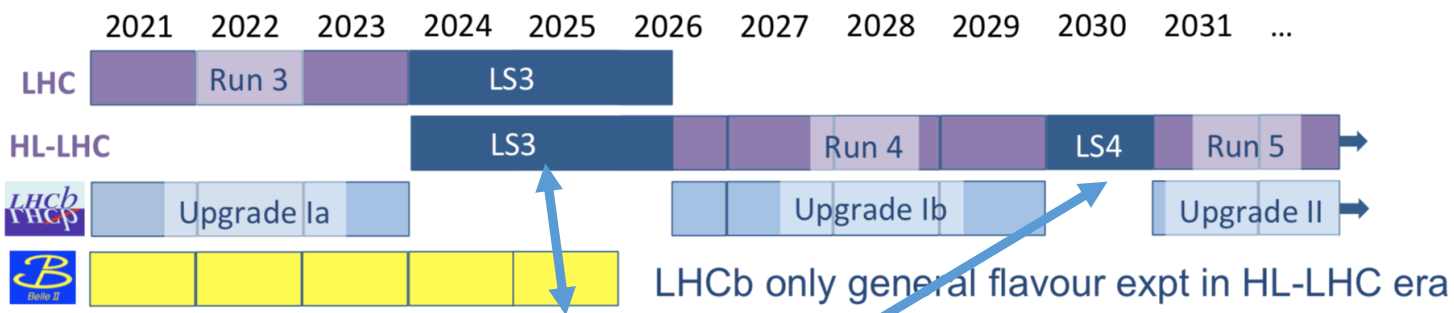
Scintillating Fibre (SciFi) tracker installation





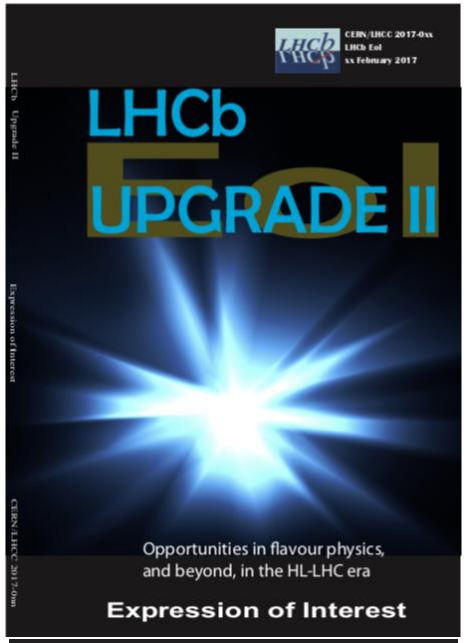
LHCb Upgrade 2

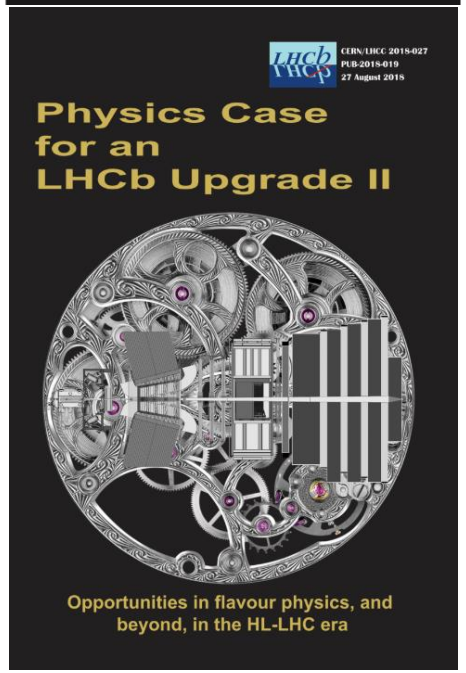
- Upgrade 2 proposed to take full profit of HL-LHC
  - $\mathcal{L} = 1 - 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, 10 times larger than Upgrade 1
  - Aiming at $300\ \mathrm{fb}^{-1}$ after Run5



- **Consolidate in LS3**
- **Major upgrade in LS4**

- **EOI submitted in 2017 (CERN-LHCC-2017-003)**
- **Physics document submitted in 2018 (arXiv:1808.08865)**



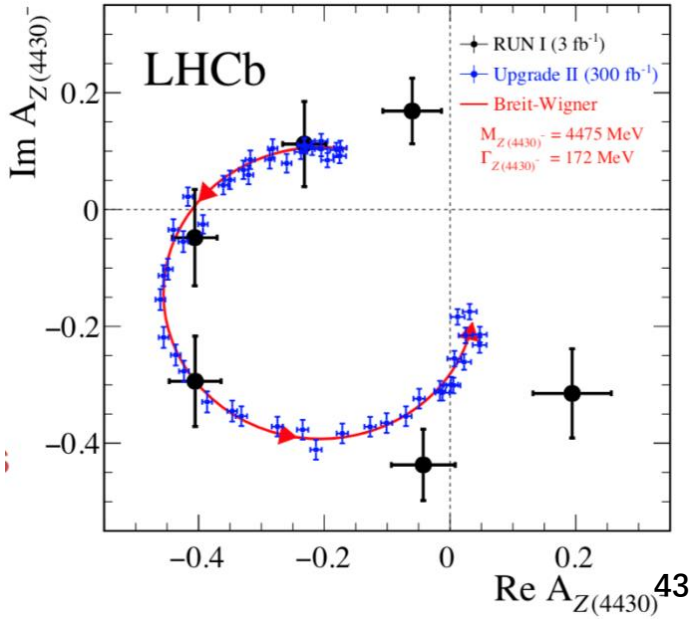


Physics case: hadron spectroscopy

arXiv:1808.08865

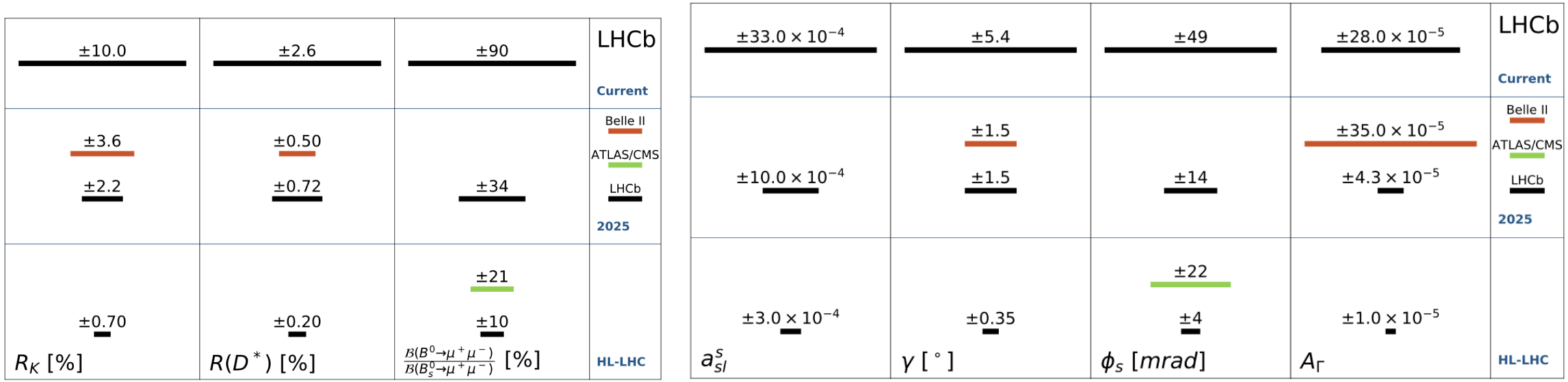
- Much more b- and c-hadrons would be produced with the Upgrade
- More precision measurements for SM tests and NP searches with heavy flavour, CKM, CPV, RD, spectroscopy,...
  - Observation of new states
  - Double heavy flavour production, e.g. $\Upsilon(nS) + \Upsilon(nS)$
  - Detailed studies of $\chi_c \to J/\psi\mu^+\mu^-$

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600	—



Physics cases: RD and CPV

arXiv:1808.08865



Summary

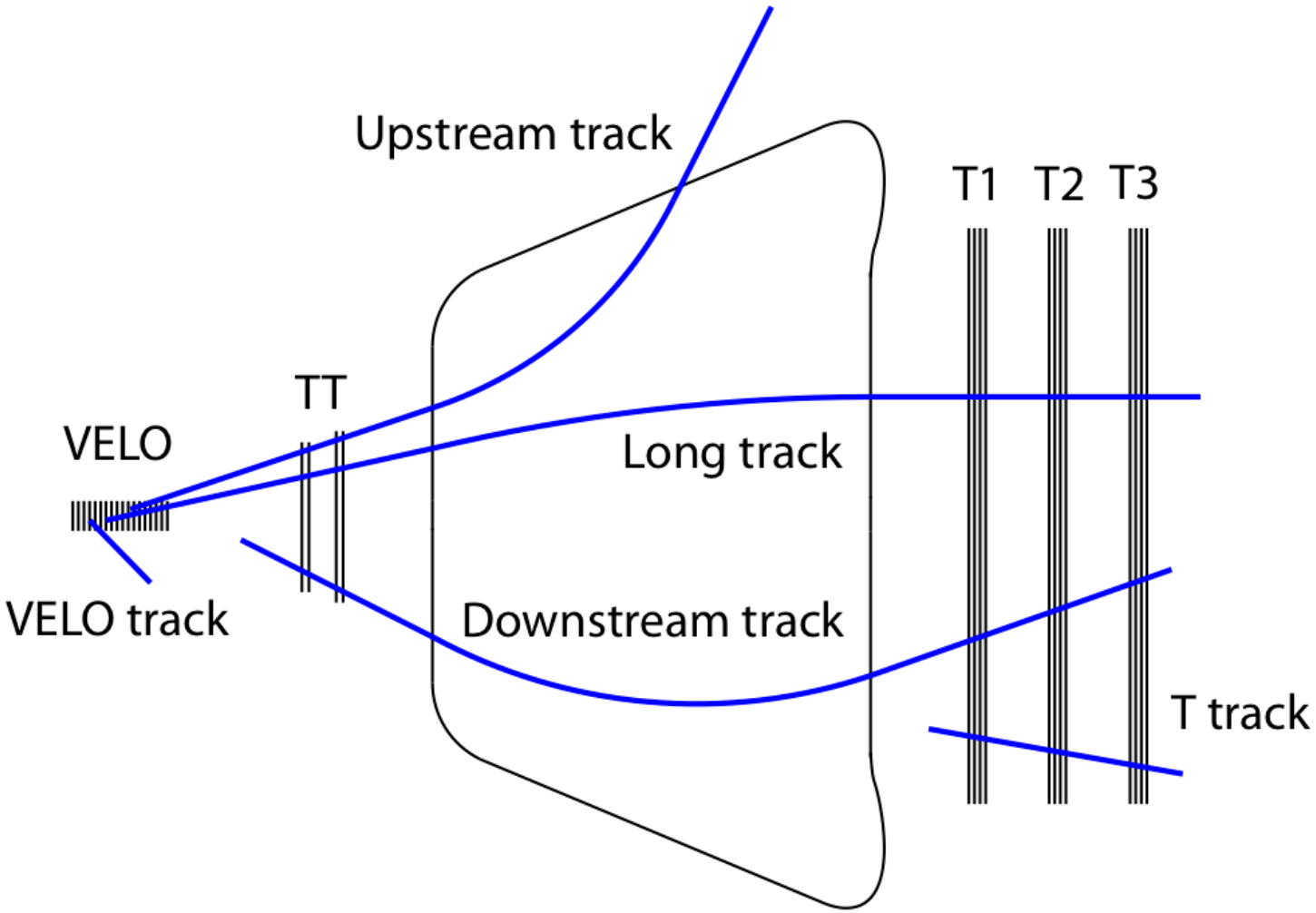
- LHCb has been operated well in run1+run2 and produced nice results in charmed baryons

- LHCb Upgrade is under construction
  - Expect to accumulate data of $50\ \mathrm{fb}^{-1}$ after Run4 (2019)

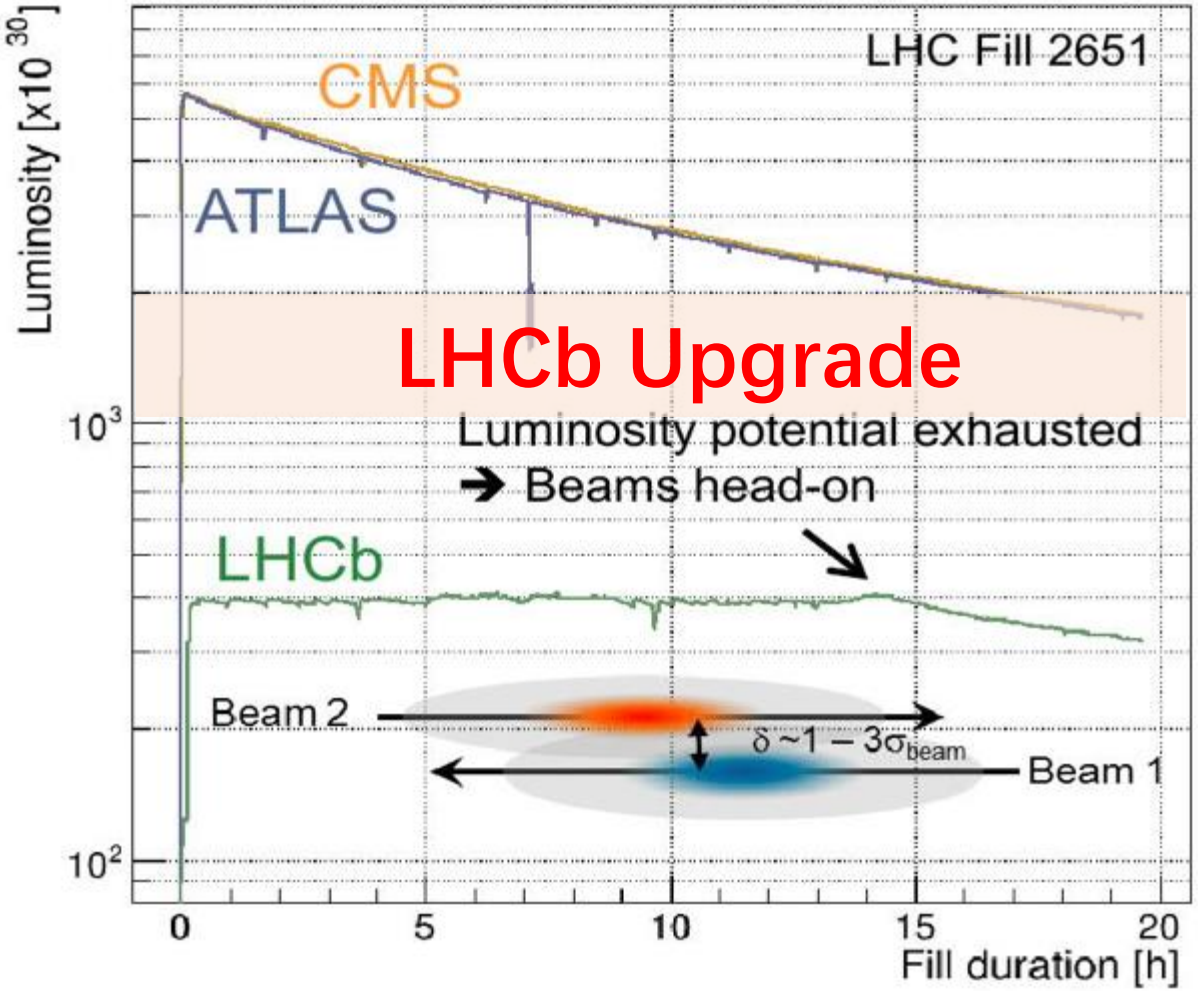
- LHCb Upgrade 2 aiming at $300\ \mathrm{fb}^{-1}$ with fully new detector to deepen our understanding of heavy flavour physics
  - You inputs are essential

Backup slides

Track types for the LHCb Run I and II



How to increase the LHCb statistics significantly?

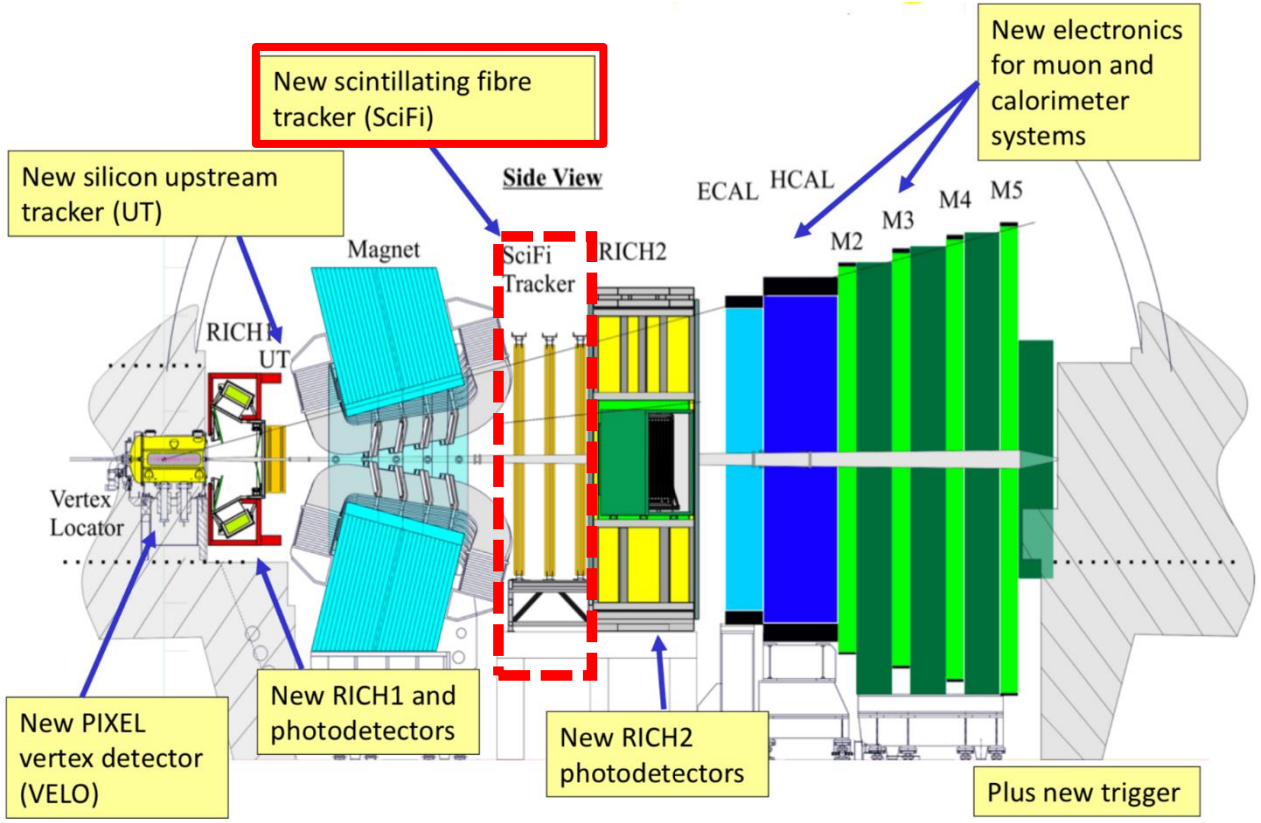


- **LHCb up to LS2 (2018)**
  - Running at levelled luminosity of $\sim 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, pile-up~1
  - First level hardware trigger running at event rate ~1 MHz
  - Record ~12 kHz (0.6 GB/s)
- **LHCb Upgrade I (2021-)**
  - Increase luminosity to a levelled $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, pile-up~5
  - Run fully flexible and efficient software trigger up to 40 MHz
  - Record with 10 GB/s

The most severe bottlenecks:
- Hardware trigger limited to ~ 1 MHz
- Tracking reconstruction

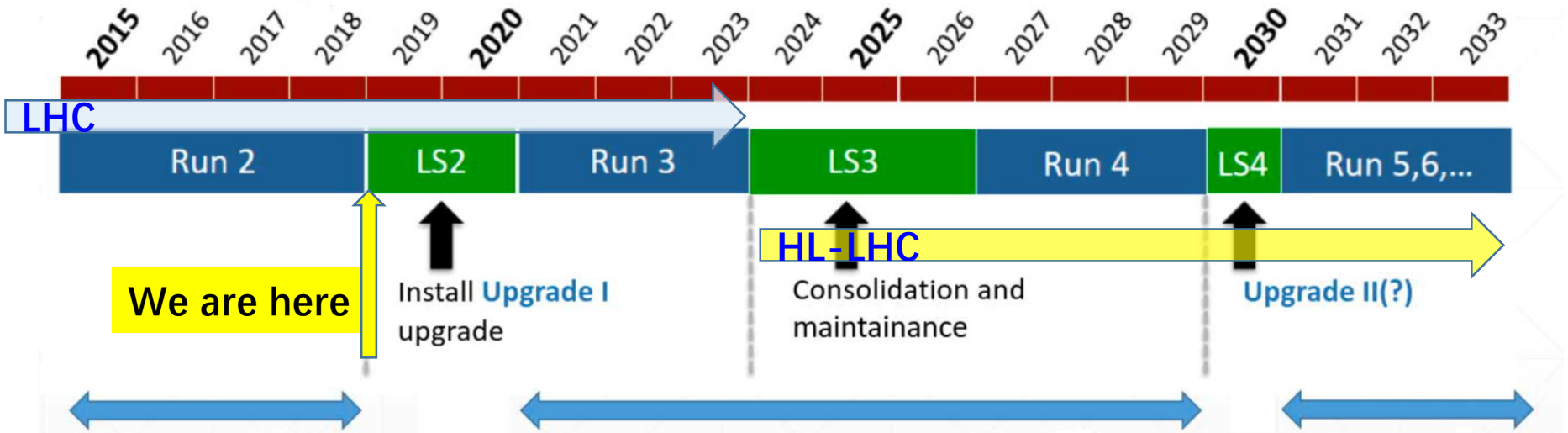
The LHCb Upgrade I detector

- A complete new detector
  - All sub-detectors read out at 40 MHz for a fully software trigger



- **Tracking system**
  - VELO: Silicon strip → $55 \times 55\ \mu m^2$ PIXEL
  - TT→ UT: Silicon strip → Silicon microstrip
  - T1-T3→SciFi: Straw + silicon microstrip
    → Scintillating Fibre Tracker
- PID system
  - RICH: HPD → MaPMT
    improved optics + mechanics
  - ECAL/HCAL: remains the same
    ECAL inner modules replaced in LS3
  - Muon: increased granularity

Plan of the LHC(b) upgrade



$\mathcal{L}^{\max} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
1.1 visible interactions per bunch crossing

$\rightarrow 5\mathcal{L}^{\max}$

$\mathcal{L}^{\max} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
5.5 visible interactions per bunch crossing

$\rightarrow 50\mathcal{L}^{\max}$

$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
55 visible interactions per bunch crossing

LHCb up to 2018→ $9\ \mathrm{fb}^{-1}$

- ✓ Demonstrated feasibility of high precision flavour physics at hadron colliders
- ➢ Find/rule out large sources of NP at the TeV scale

LHCb Upgrade I → $\geq 50\ \mathrm{fb}^{-1}$

- ✓ Increase trigger efficiency
- ➢ Aim at experimental sensitivities comparable to theoretical uncertainties

LHCb Upgrade II → $\geq 300\ \mathrm{fb}^{-1}$

- ✓ Take full profit of HL-LHC
- ➢ Physics document has been submitted to LHCC arXiv:1808.08865

Charmed baryon lifetimes: systematic uncertainties

Source	$r_{\Omega_c^0}$ (10^{-4})
Decay-time acceptance	13
Ω_b^- prod. spectrum	3
Ω_b^- lifetime	4
Decay-time resolution	3
Background subtraction	18
$H_c(\tau^-, D)$, random μ^-	8
Simulated sample size	98
Total systematic	101
Statistical uncertainty	230

Source	$r_{\Lambda_c^+}$	$r_{\Xi_c^+}$	$r_{\Xi_c^0}$
Decay-time acceptance	6	13	4
H_c lifetime	4	4	12
H_b lifetime	1	3	0
H_b production spectra	2	4	1
Background subtraction	8	17	7
$H_c(\tau^-,\ D$, random $\mu^-)$	5	11	3
Simulated sample size	4	13	5
Total systematic	13	28	16
Statistical uncertainty	10	34	17

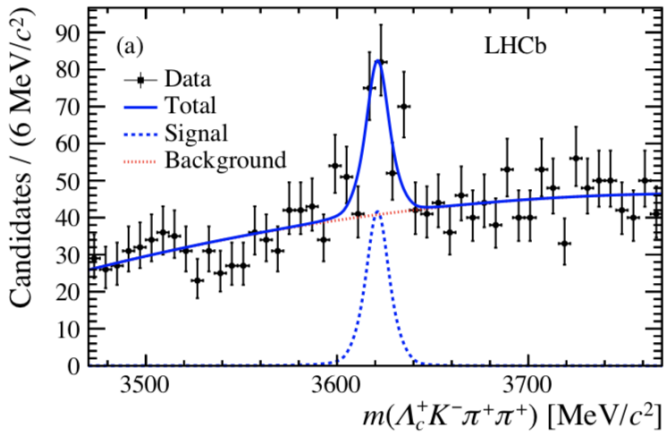
Ξ_{cc}^{++} mass measurement: systematics

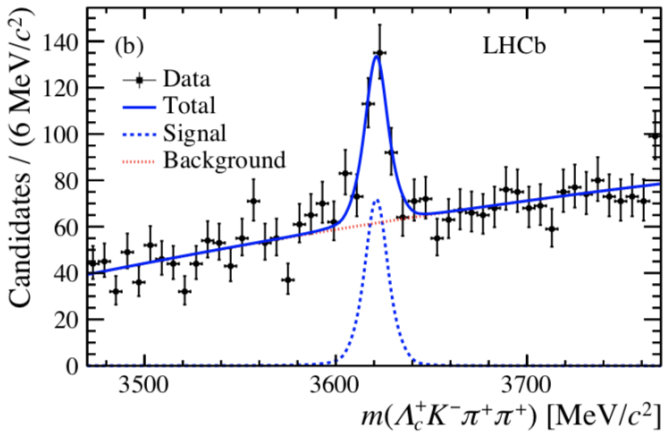
$$3621.55 \pm 0.23\,(\text{stat}) \pm 0.30\,(\text{syst})\ \text{MeV}/c^2.$$

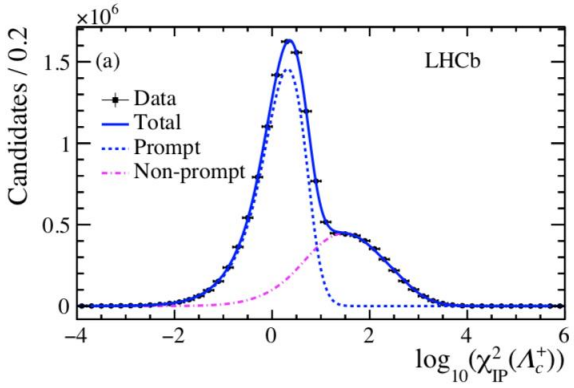
	Uncertainty [MeV/c^2]	
Source	$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
Momentum-scale calibration	0.21	0.34
Energy-loss correction	0.05	0.03
Simulation/data agreement	0.09	0.05
Selection-induced bias on the Ξ_{cc}^{++} mass	0.09	0.09
Final-state radiation	0.05	0.16
Background model	0.01	0.04
Λ_c^+, Ξ_c^+ mass	0.14	0.22
Total	0.29	0.49

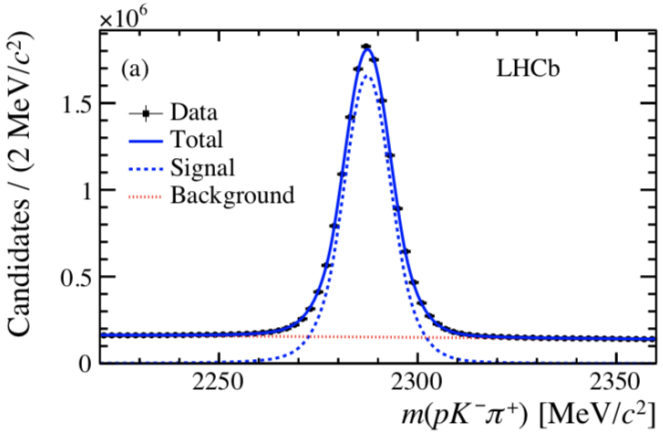
Measurement of Ξ_{cc}^{++} production

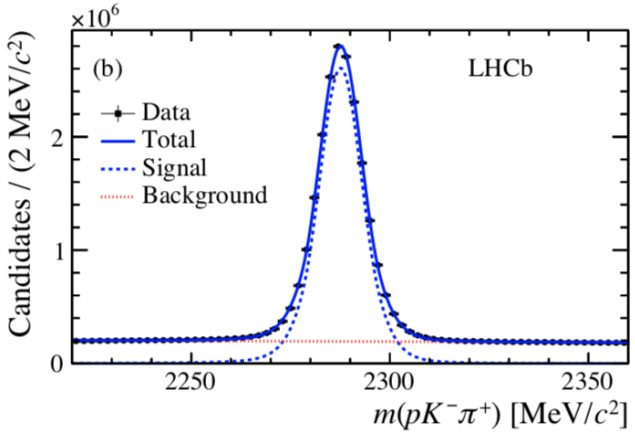
arXiv:1910.11316
Submitted to Chin.Phys.C

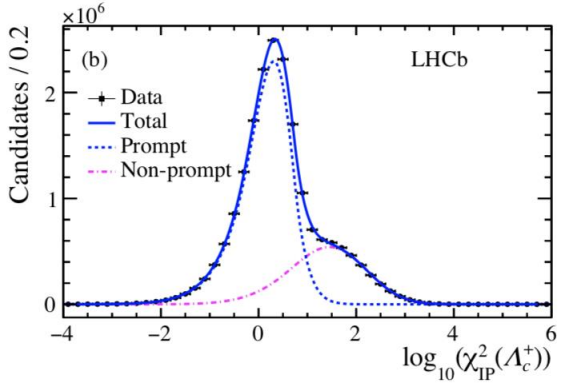












Measurement of Ξ_{cc}^{++} production: systematic uncertainties

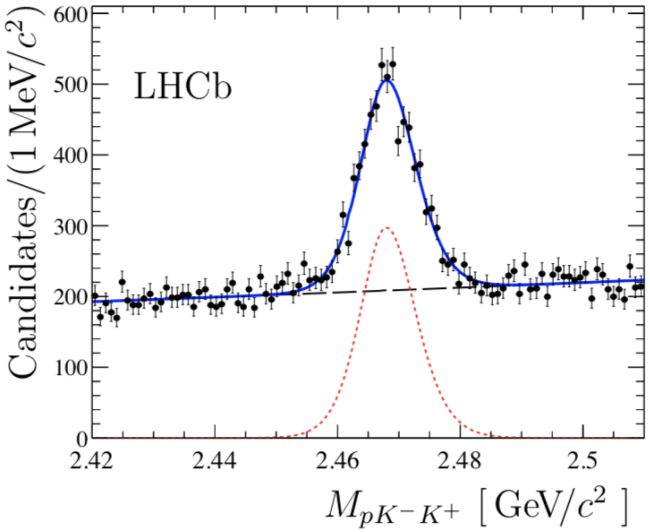
arXiv:1910.11316
Submitted to Chin.Phys.C

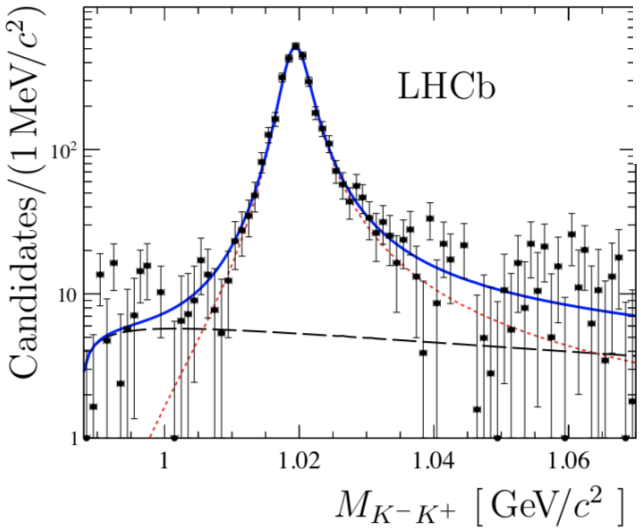
Source	TOS [%]	exTIS [%]
Simulation sample size	8.8	7.3
Fit model	5.4	5.3
Hardware trigger	9.0	6.3
Tracking	3.4	3.4
Particle identification	5.5	5.4
Kinematic correction	7.3	6.0
Sum in quadrature	16.8	14.1

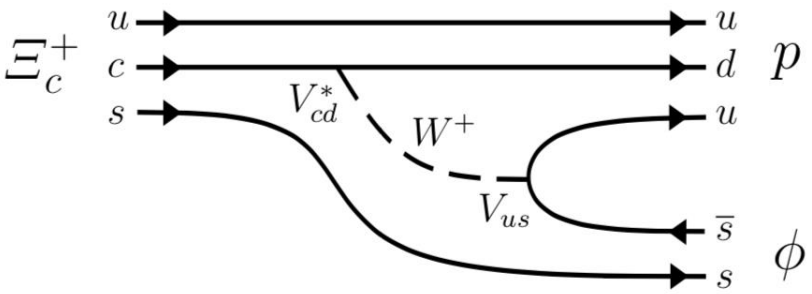
Doubly suppressed $\Xi_c^+ \to p\phi$

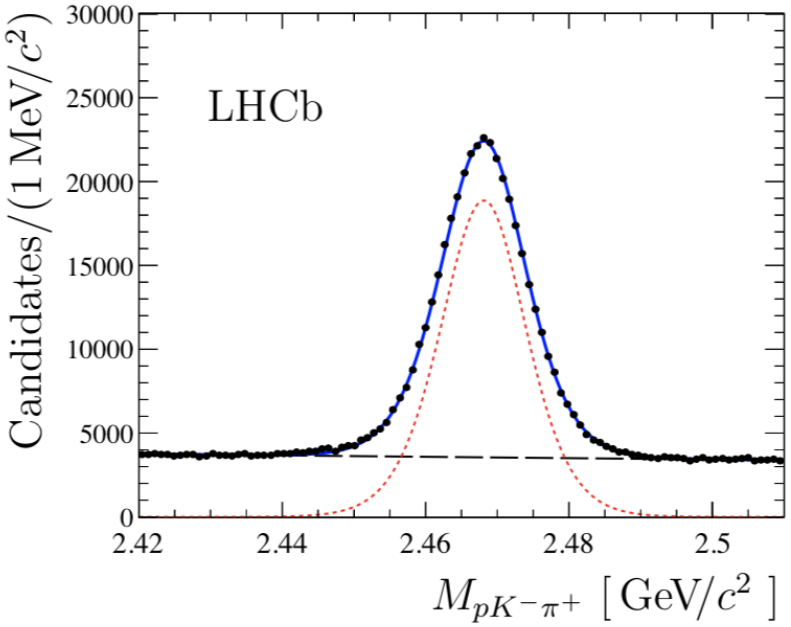
JHEP 04 (2019) 084

2012 data used









$$R_{p\phi} = \frac{N_{pKK} f_\phi}{\mathcal{B}(\phi \to K^+K^-)} \times \frac{1}{N_{pK\pi}} \times \frac{\epsilon_{\text{total}}^{pK\pi}}{\epsilon_{\text{total}}^{p\phi}}$$

$$R_{p\phi} = (19.8 \pm 0.7 \pm 0.9 \pm 0.2) \times 10^{-3}$$

Doubly suppressed $\Xi_c^+ \to p\phi$

JHEP 04 (2019) 084

Source	Uncertainty (%)
Signal fit model	0.5
Background fit model	0.5
sPlot-related uncertainty	1.0
Trigger efficiency	3.0
PID efficiency	2.2
Tracking	1.0
(p_{T},y) binning	1.3
Size of simulation sample	0.7
Selection requirements	0.8
Total	4.4