Doubly charmed baryons at LHCb

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On behalf of the LHCb collaboration

QWG 2022, GSI Darmstadt
30 Sept 2022

How it started ...

PRL 119 (2017) 112001

PRL **119,** 112001 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

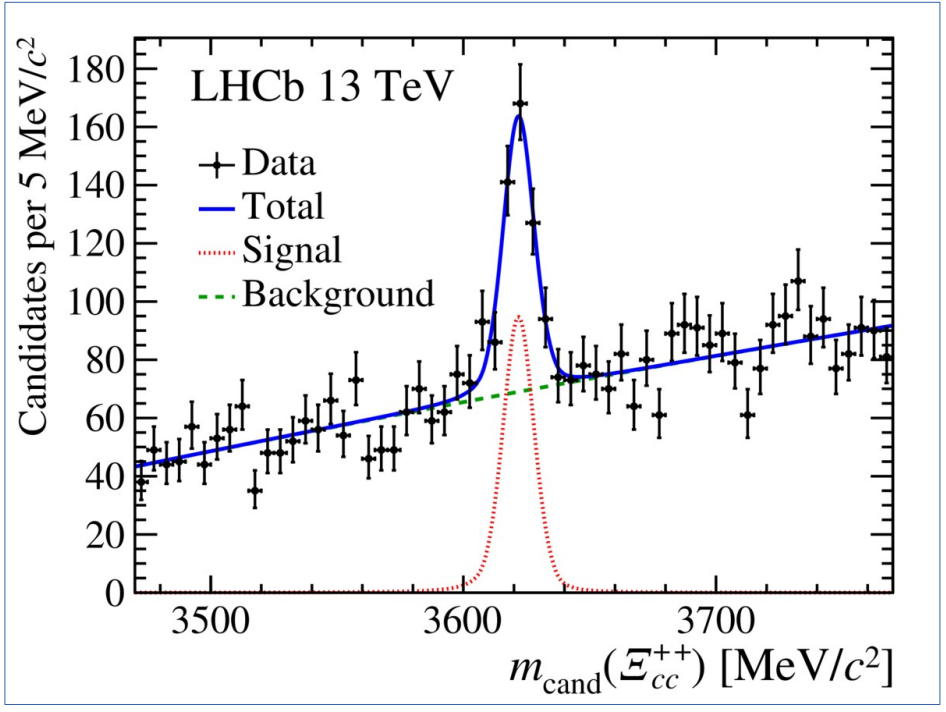
Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})$ MeV/c^2, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)$ MeV/c^2, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001



Summer 2017:

LHCb discovers Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^-$ final state

Summer 2022:

What's new since then?

How it’s going

- Other decay modes
  - $\Xi_c^{(')+}\pi^+$, $D^+pK^-\pi^+$
- Mass, lifetime & production rate measurements
- Searches for double charm partners
  - Ξ_{cc}^+, Ω_{cc}^+
- Searches for other double heavies
  - $\Xi_{bc}^{+/0}$, Ω_{bc}^0 [in back up, feel free to ask!]

The LHCb experiment

- Huge charm and beauty production cross-section in the forward direction in pp collisions at LHC energies
  - Essentially all hadrons produced
- Require superb detection capability to separate signal from potentially overwhelming background
  - LHCb strengths in vertexing, tracking and charged particle identification
  - Ideal signature:
    - displaced vertex
    - all track final state (no neutral particles to reconstruct)
    - containing at least some protons and/or kaons
  - Capability for online selection (trigger) also crucial

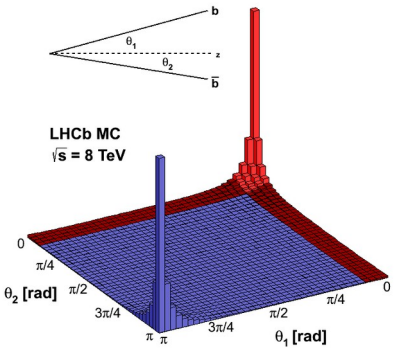
Example:

- $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-$
  - $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\tau(\Xi_{cc}^{++}) \sim O(ps)$

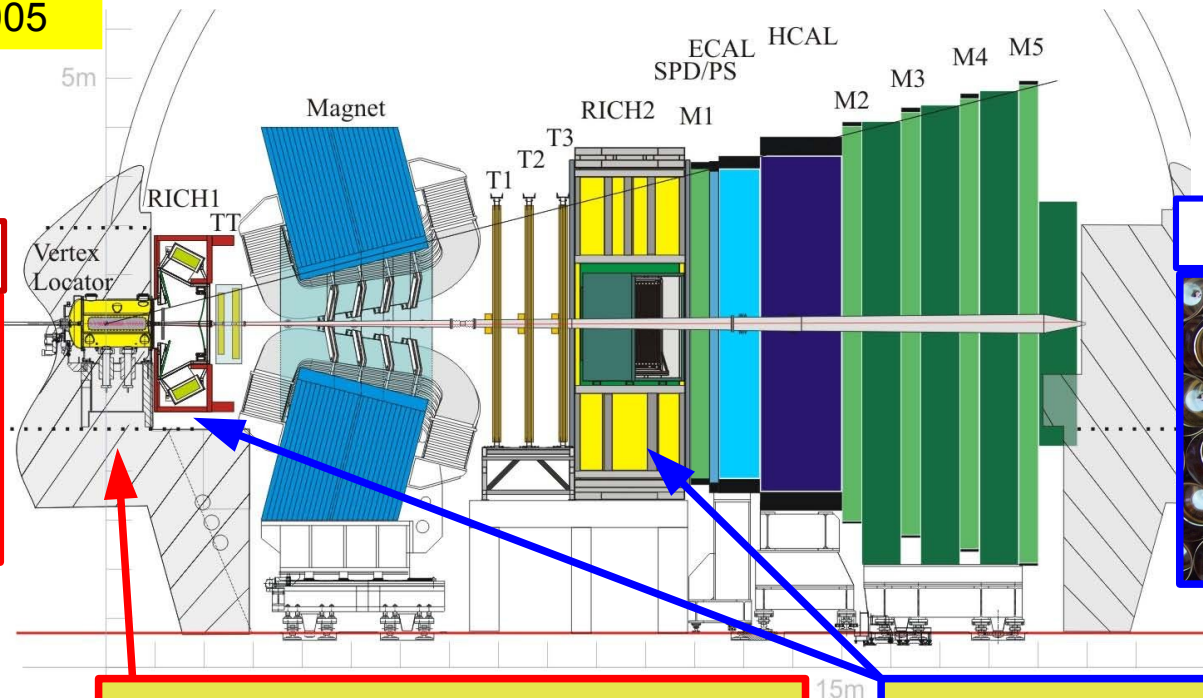
The LHCb detector

(2011-18 edition)

The LHCb Detector
JINST 3 (2008) S08005



VELO silicon strips



RICH PMTs

Precision primary and secondary vertex measurements

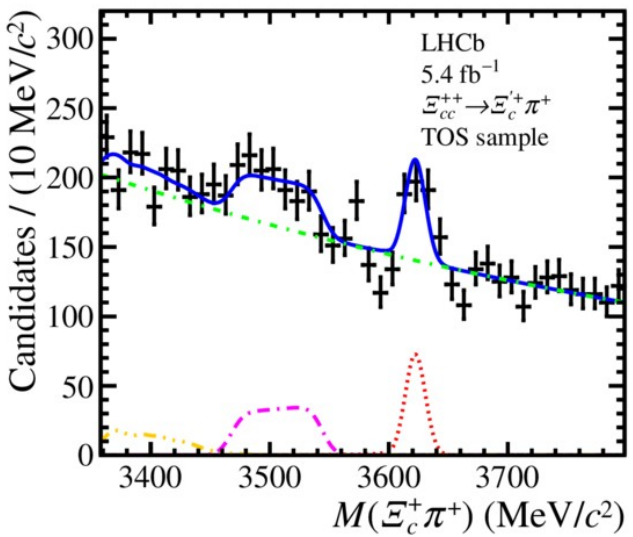
Excellent K/π separation capability

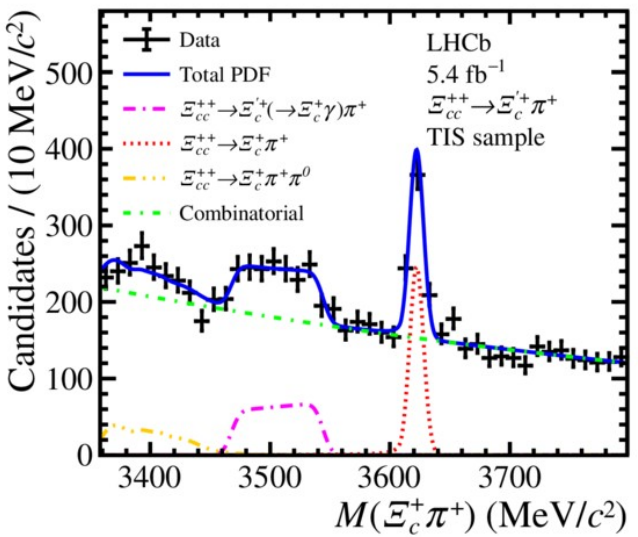
$\Xi_{cc}^{++} \rightarrow \Xi_c^{(')+}\pi^+$

PRL 121 (2018) 162002
JHEP 05 (2022) 038

- $\Xi_{cc}^{++} \rightarrow \Xi_c^{'+}\pi^+$ appears as partially reconstructed peak in $m(\Xi_c^+\pi^+)$ spectrum
  - missing photon from $\Xi_c^{'+} \rightarrow \Xi_c^+\gamma$ decay
- Reconstruct $\Xi_c^+ \rightarrow pK^-\pi^+$ decay
  - Cabibbo-suppressed but good efficiency (3 tracks)

Separate hardware trigger decision samples
- on signal (TOS)
- independent of signal (TIS)





$\Xi_{cc}^{++} \rightarrow \Xi_c^{(')+}\pi^+$

PRL 121 (2018) 162002
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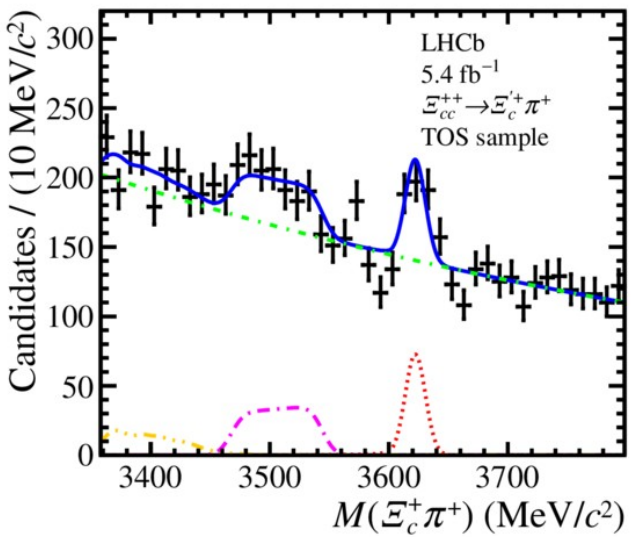
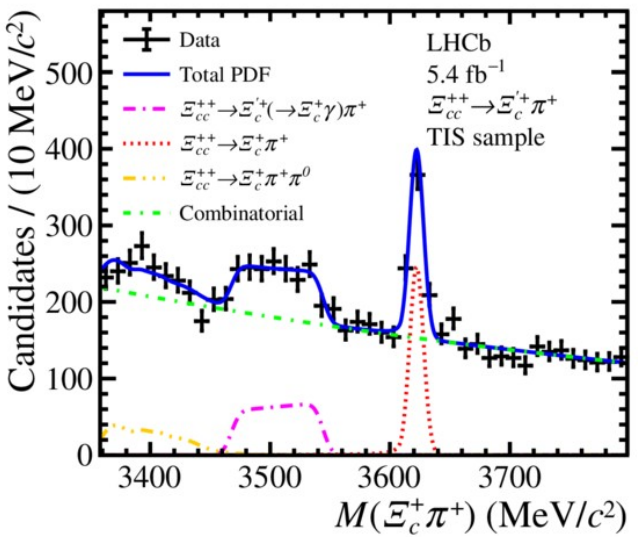
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009\,(\text{stat}) \pm 0.003\,(\text{syst}).$$

Separate hardware trigger decision samples
- on signal (TOS)
- independent of signal (TIS)



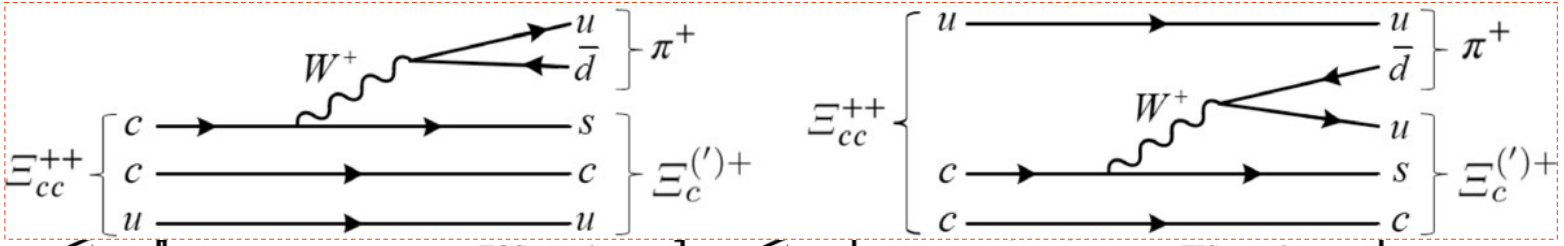


$\Xi_{cc}^{++} \to \Xi_c^{(\prime)+}\pi^+$

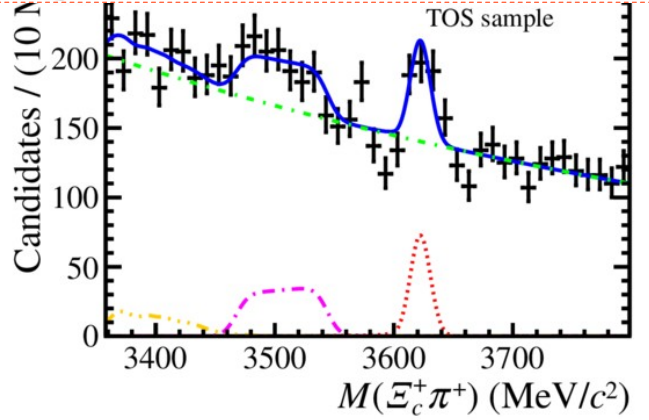
PRL 121 (2018) 162002
JHEP 05 (2022) 038

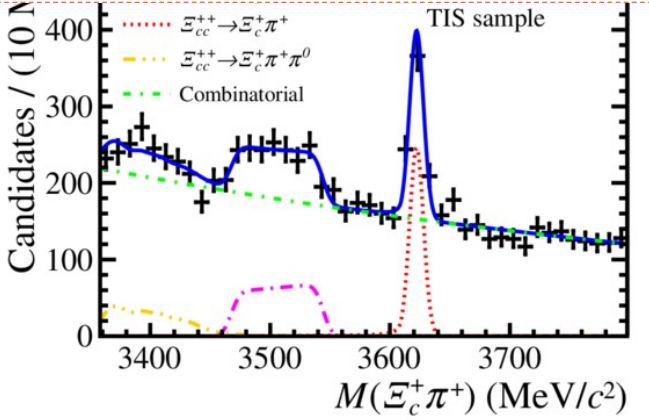
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10.$$

Theory predictions range from 0.4 – 7 depending on relative contributions of two amplitudes



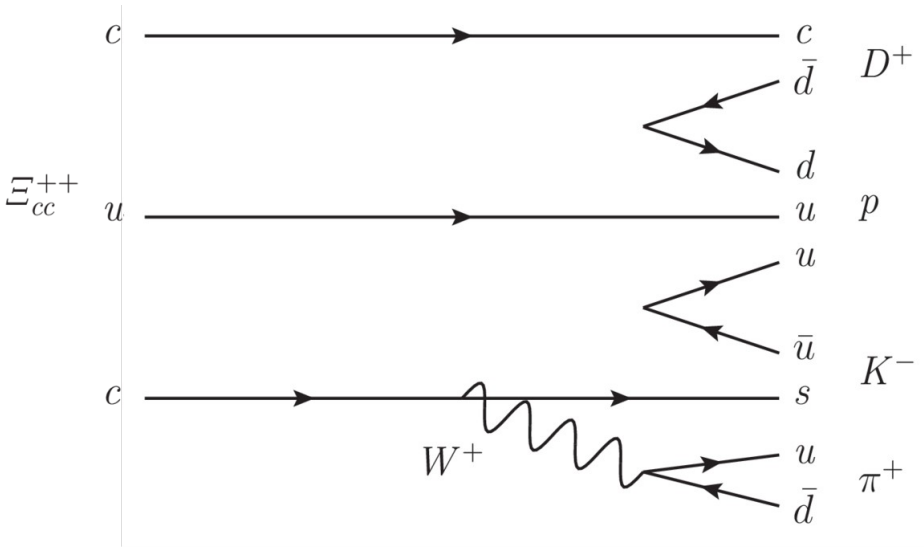
Separate hardware trigger decision samples
- on signal (TOS)
- independent of signal (TIS)

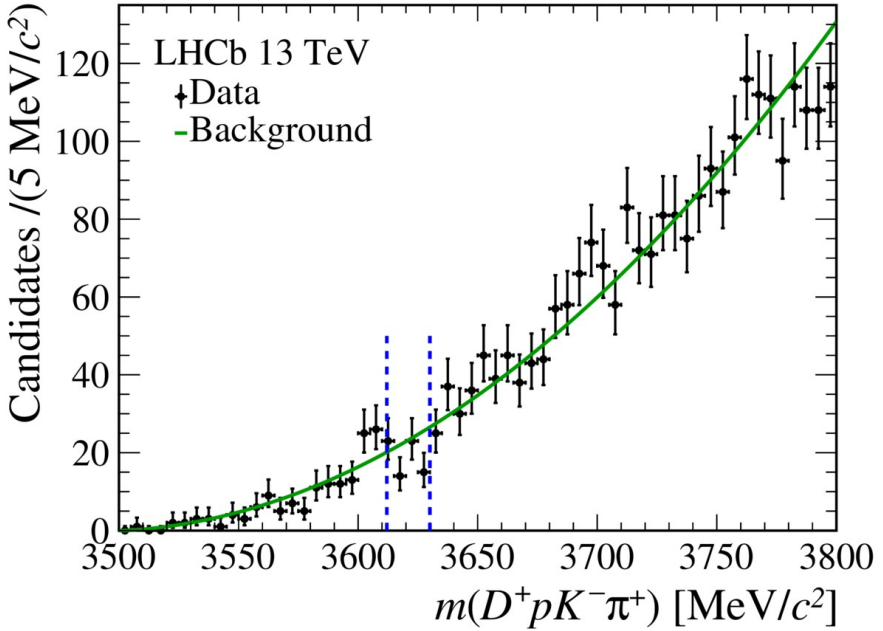




$\Xi_{cc}^{++} \to D^+pK^-\pi^+$

JHEP 10 (2019) 124

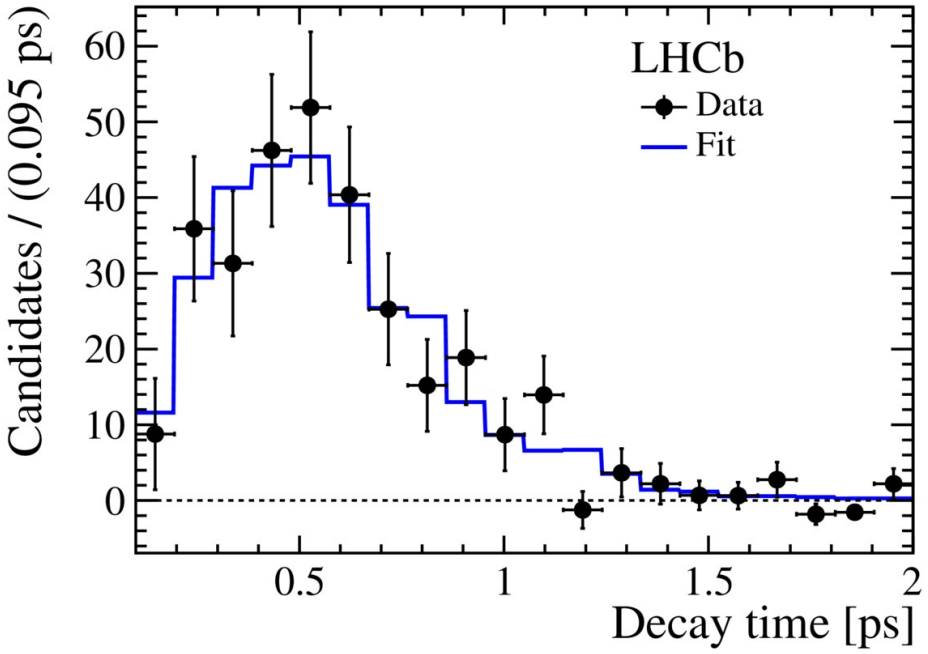


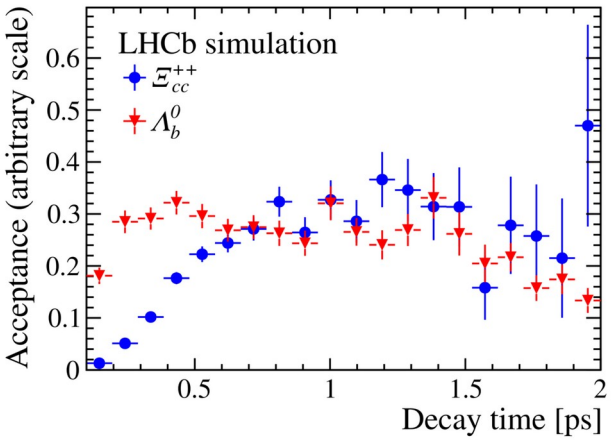


$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)} < 1.7\,(2.1) \times 10^{-2} \text{ at } 90\%\ (95\%)\ \text{CL}$$

Lifetime measurement

PRL 121 (2018) 052002





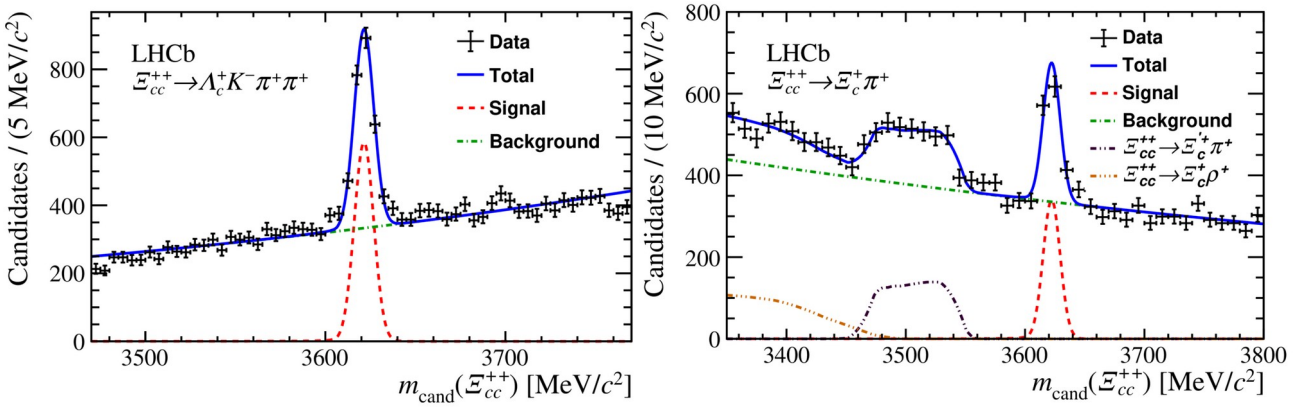
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ channel

Non-trivial decay-time acceptance

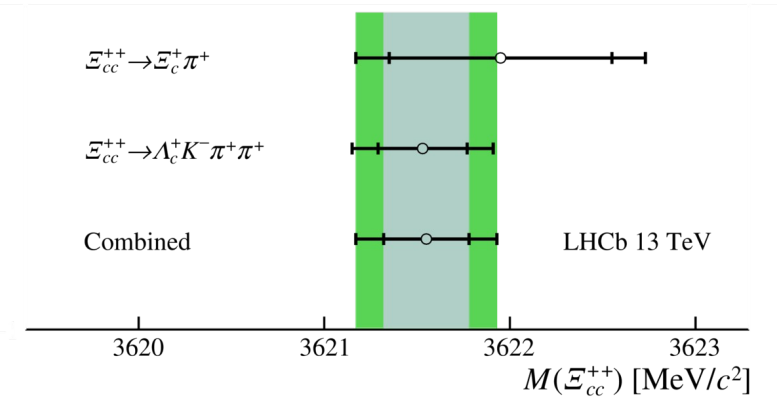
- use $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ as control channel

$\tau(\Xi_{cc}^{++}) = 0.256\ ^{+0.024}_{-0.022}$ (stat) ± 0.014 (syst) ps

Mass measurement & production rate



JHEP 02 (2020) 049
CP C44 (2020) 022001



$$\frac{\sigma(\Xi_{cc}^{++})\times\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+)}{\sigma(\Lambda_c^+)} = (2.22\pm0.27\pm0.29)\times10^{-4}$$

- in LHCb acceptance:
  4 < pT < 15 GeV/c & 2.0 < y < 4.5
- for pp collisions at √s = 13 TeV
- assuming central value of τ(Ξ_{cc}^{++})

Both $\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^-$ and $\Xi_c^+\pi^+$ channels

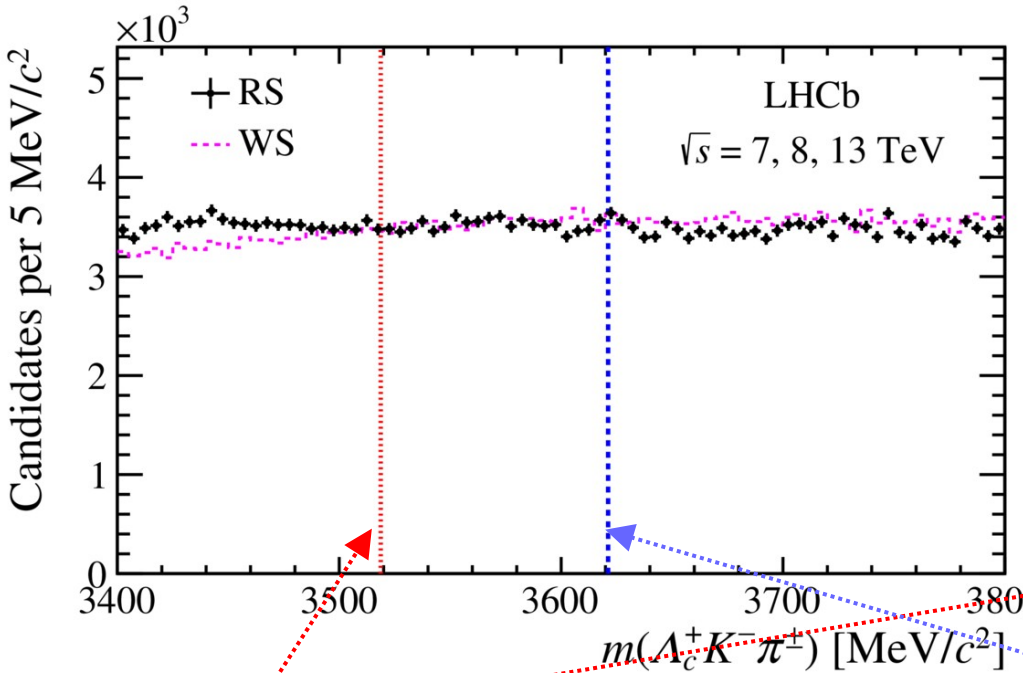
$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23$ (stat) ± 0.30 (syst) MeV/c^2

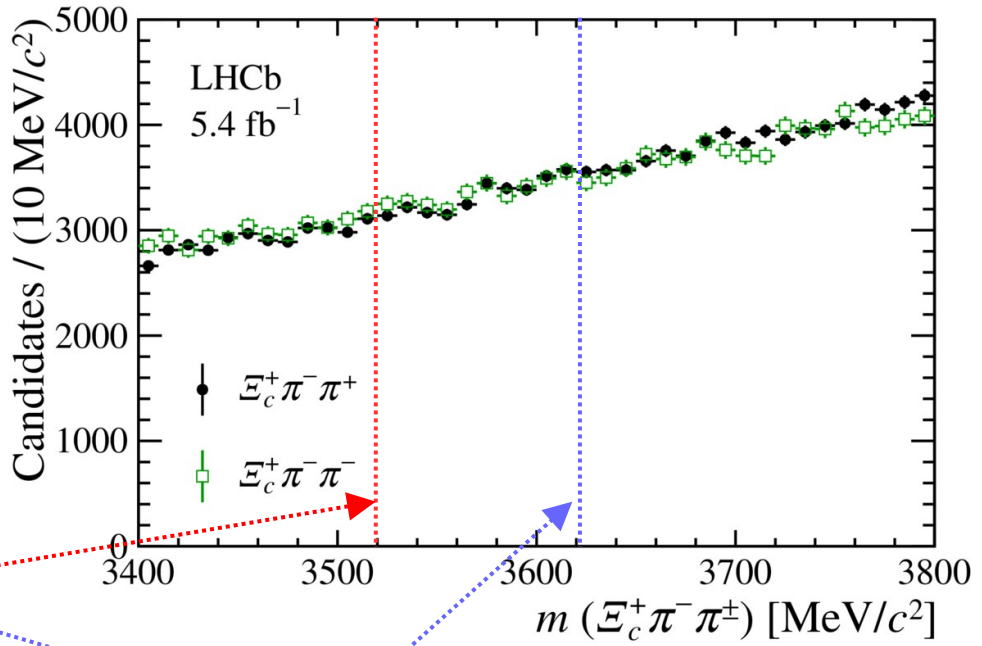
Largest systematic uncertainties from

- momentum scale
- Λ_c^+ and Ξ_c^+ masses

Searches for Ξ_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107



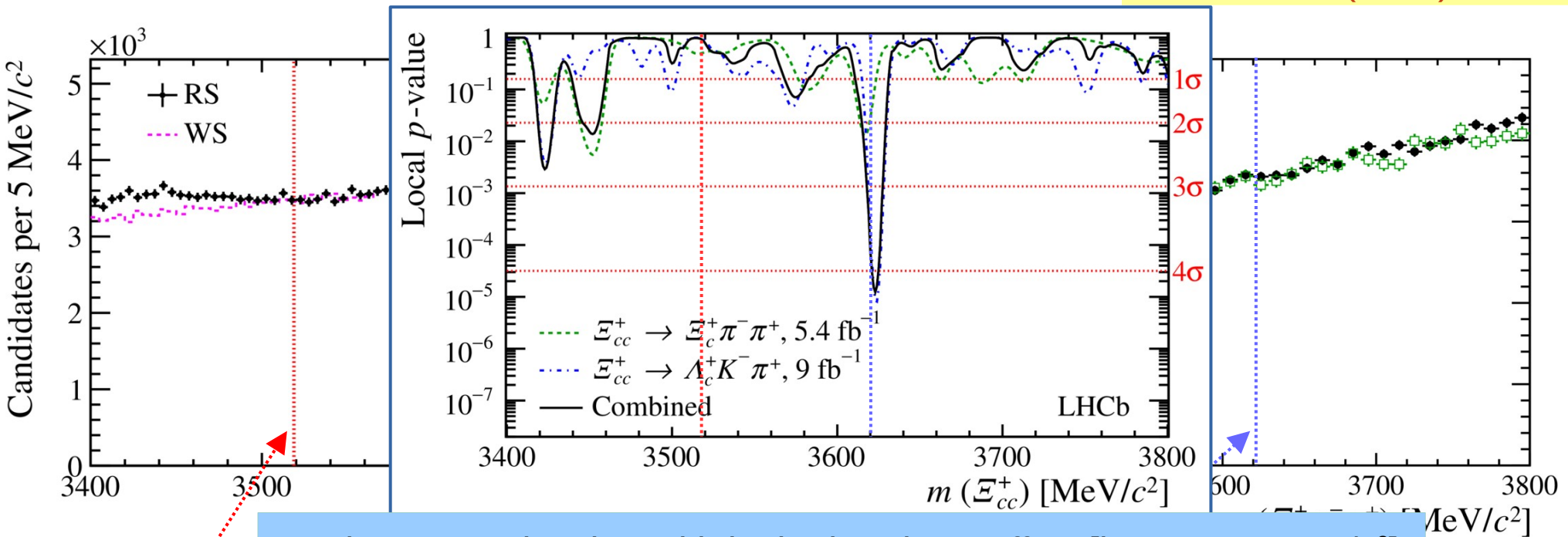


Mass of SELEX claim

Mass of Ξ_{cc}^{++}

Searches for Ξ_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107

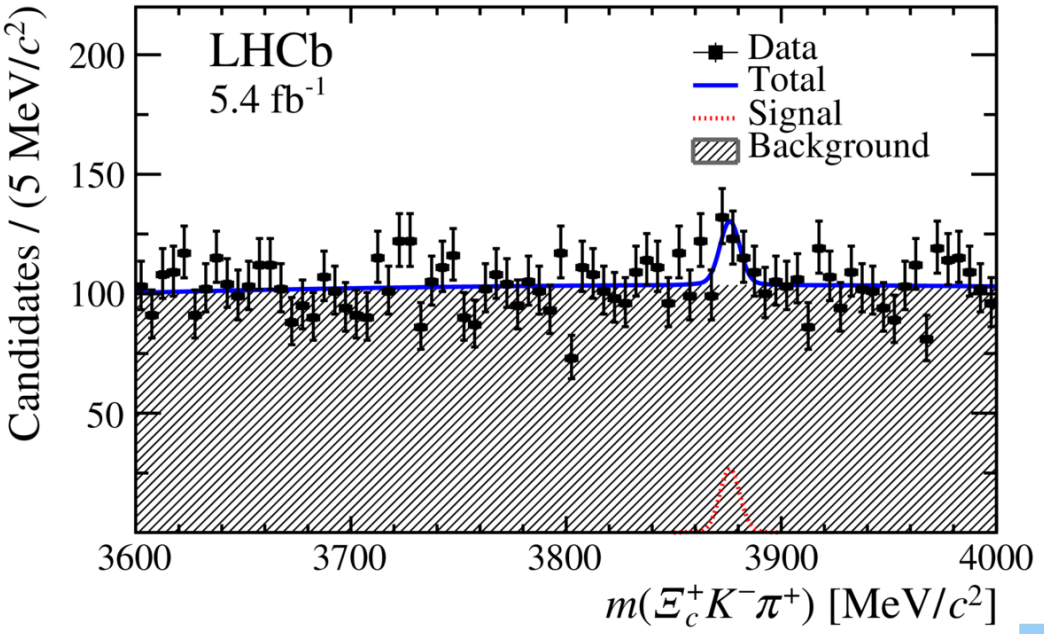


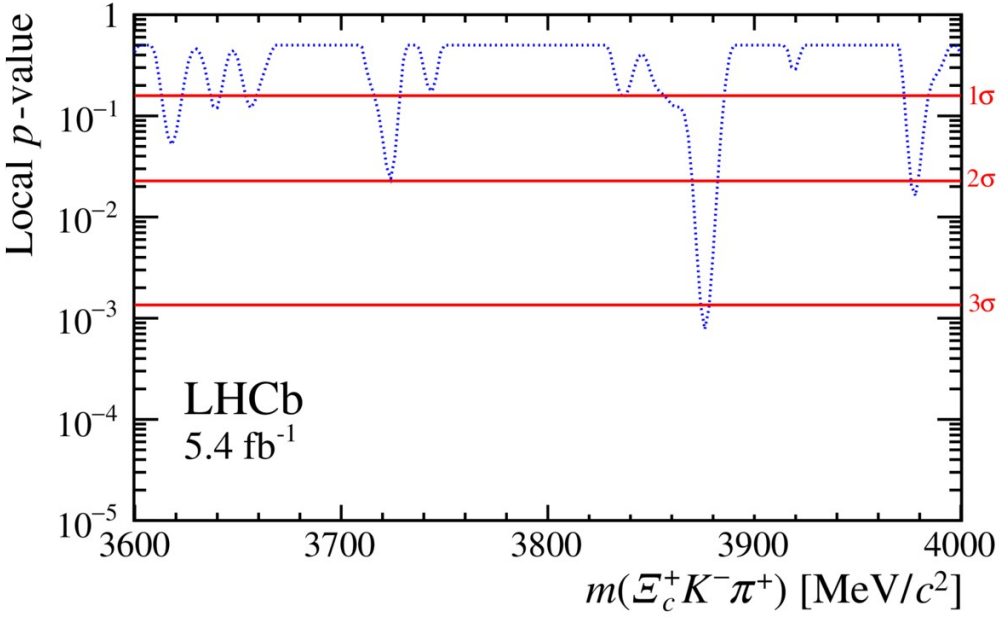
Mass of SE

Looks suggestive, but with look-elsewhere-effect [in 3.5−3.7 GeV/c²] global significance is 2.9 σ

Search for Ω_{cc}^{+}

SCPMA 64 (2021) 101062

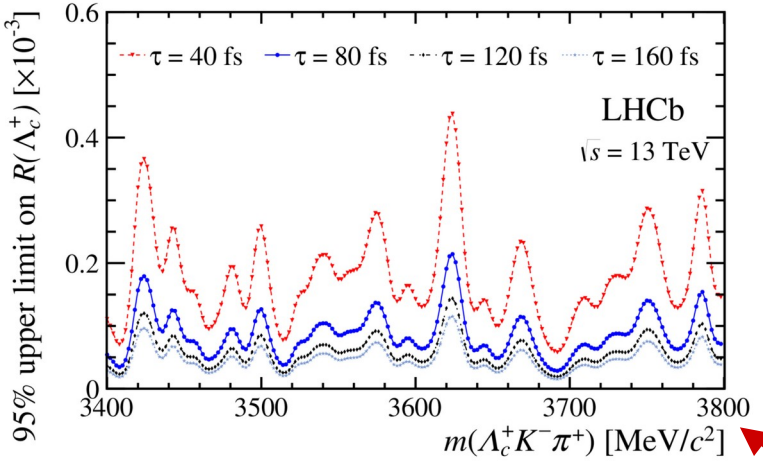


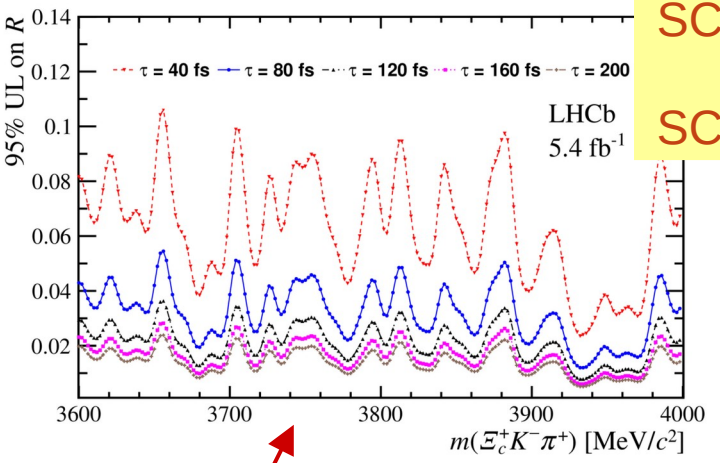


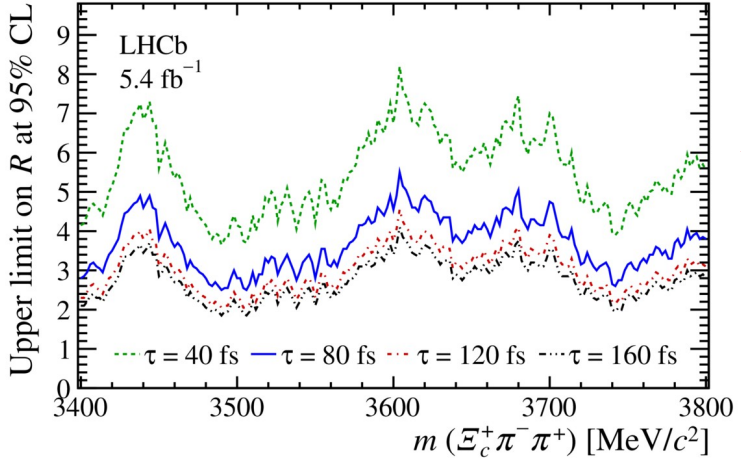
With look-elsewhere-effect [in 3.6−4.0 GeV/c^2] global significance is 1.8 σ

Production rate limits for Ξ_{cc}^+ and Ω_{cc}^+

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107
SCPMA 64 (2021) 101062







- $\Omega_{cc}^+ \rightarrow \Xi_c^+K^-\pi^+$ relative to $\Xi_{cc}^{++} \rightarrow \Lambda_c^+K^-\pi^+\pi^+$
- $\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+$ relative to Λ_c^+
- $\Xi_{cc}^+ \rightarrow \Xi_c^+\pi^+\pi^-$ relative to $\Xi_{cc}^{++} \rightarrow \Xi_c^+\pi^+$
- Strong dependence on assumed lifetime
  - Little sensitivity for low lifetimes

To the future, and beyond!

- More yet to be learned from the Run 1+2 data sample
- But fundamental limits due to sample size and detector performance
  - improve both in Runs 3 (2022-25) & 4 (2029-32)
  - reasons to be optimistic for further doubly charmed hadron discovery
- No reason to think that should be the end of the road
  - ambitious plans for LHCb Upgrade 2
  - aim for the ultimate LHC flavour experiment
  - reasons to be optimistic for further doubly heavy hadron discovery?

The LHCb detector

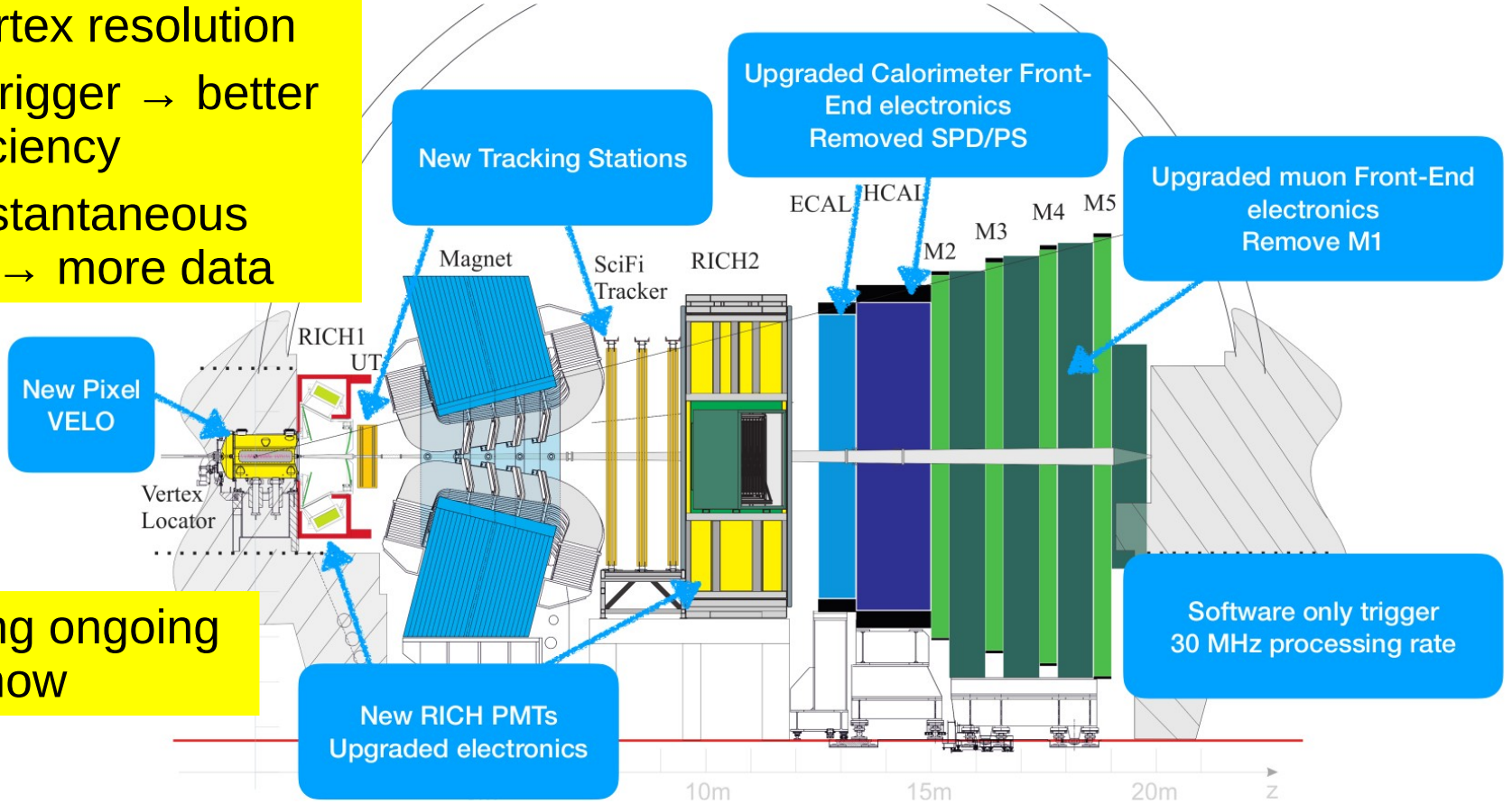
(2022-32 edition)

VELO pixels & thinned RF foil → better vertex resolution

All software trigger → better efficiency

Higher instantaneous luminosity → more data

Commissioning ongoing right now



The LHCb detector

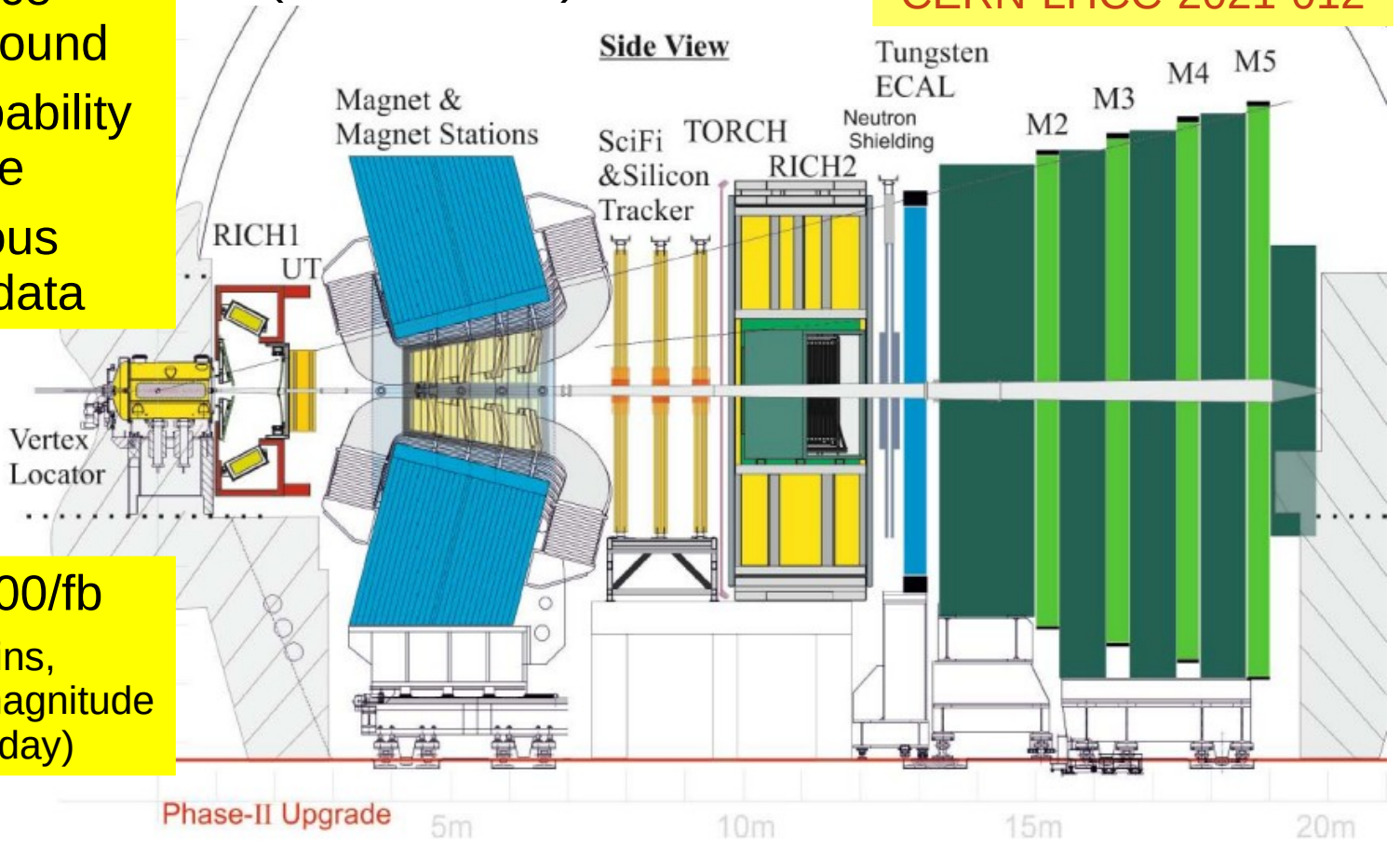
(final edition)

CERN-LHCC-2017-003
CERN-LHCC-2021-012

Use timing to reduce combinatorial background

Improve detection capability wherever possible

Higher instantaneous luminosity → more data



Aim to record over 300/fb

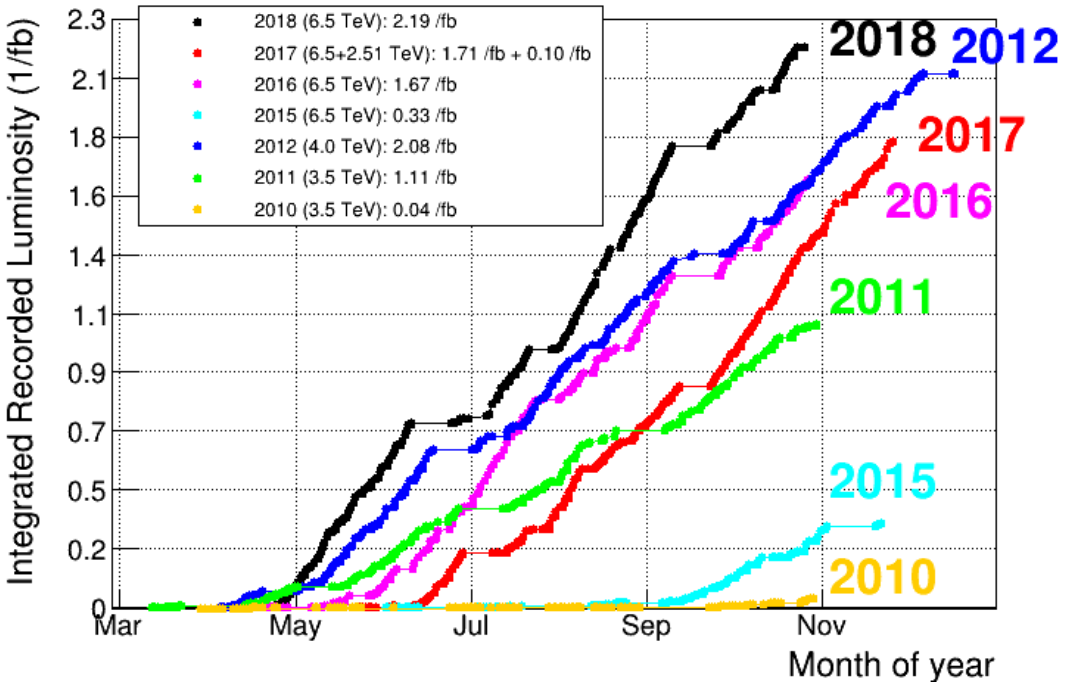
(Including efficiency gains, approximately two order of magnitude increase compared to today)

Summary

- We have learned a lot about double charm baryons since the 2017 Ξ_{cc}^{++} discovery
  - e.g. precision mass and lifetime measurements
    - $m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23\ (stat) \pm 0.30\ (syst)\ MeV/c^2$
    - $\tau(\Xi_{cc}^{++}) = 0.256\ ^{+0.024}_{-0.022}\ (stat) \pm 0.014\ (syst)\ ps$
- No 5σ discovery of other double heavies yet, but ...
- Great prospects for further discoveries in the near future
  - even more exciting prospects for Upgrade 2

Back it up

LHCb Run 1+2 integrated luminosity

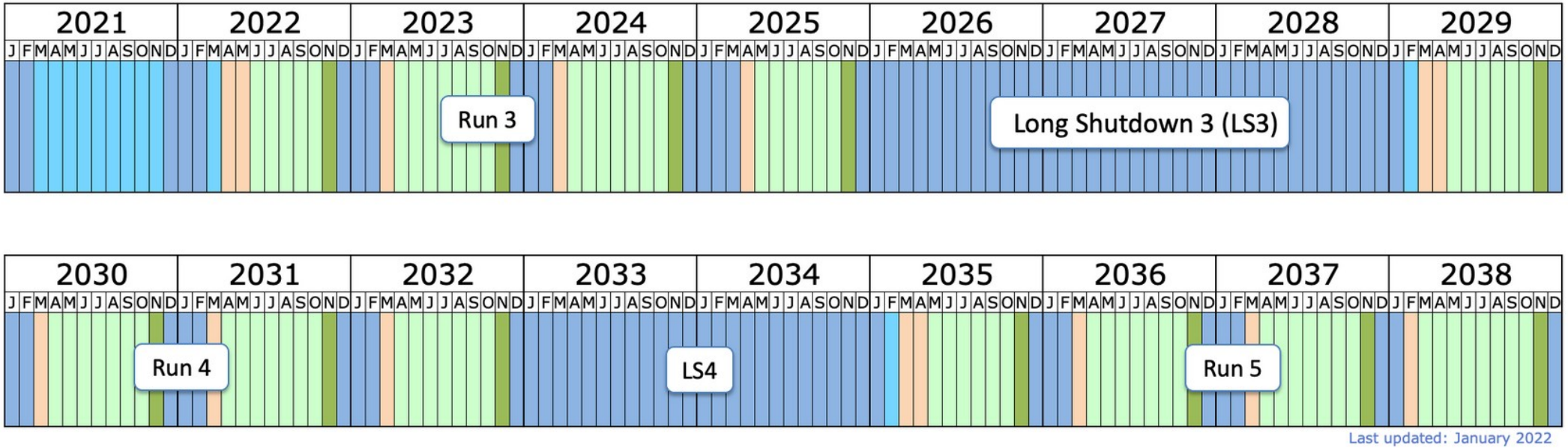


Unprecedented samples of charm and beauty

Dependence of production rate on √s means (for LHCb)

2015+16 ≈ 2 x Run 1 (2011+12); 2017+18 ≈ 2 x 2011–16

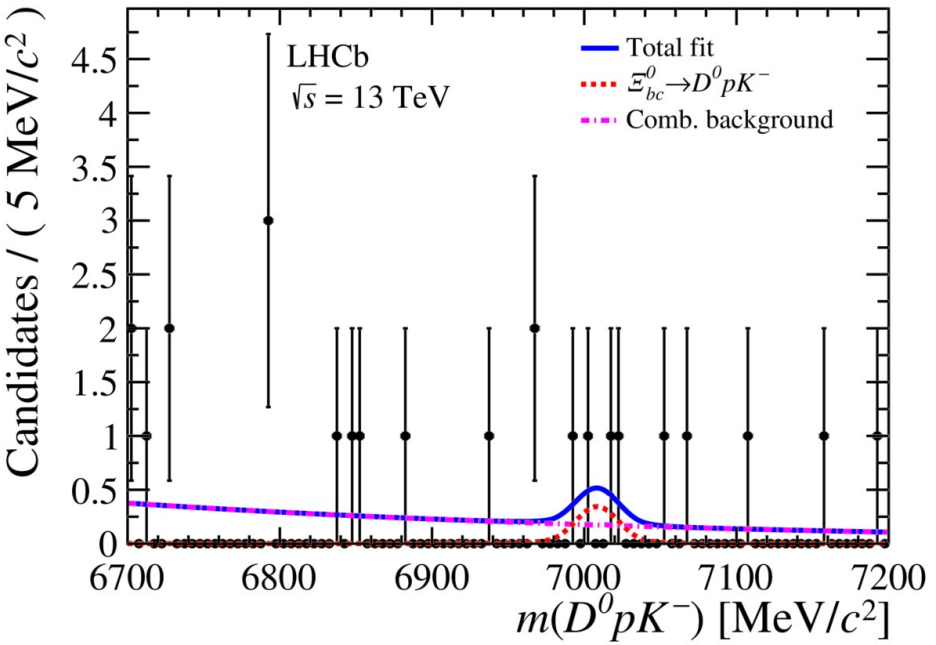
HL-LHC schedule

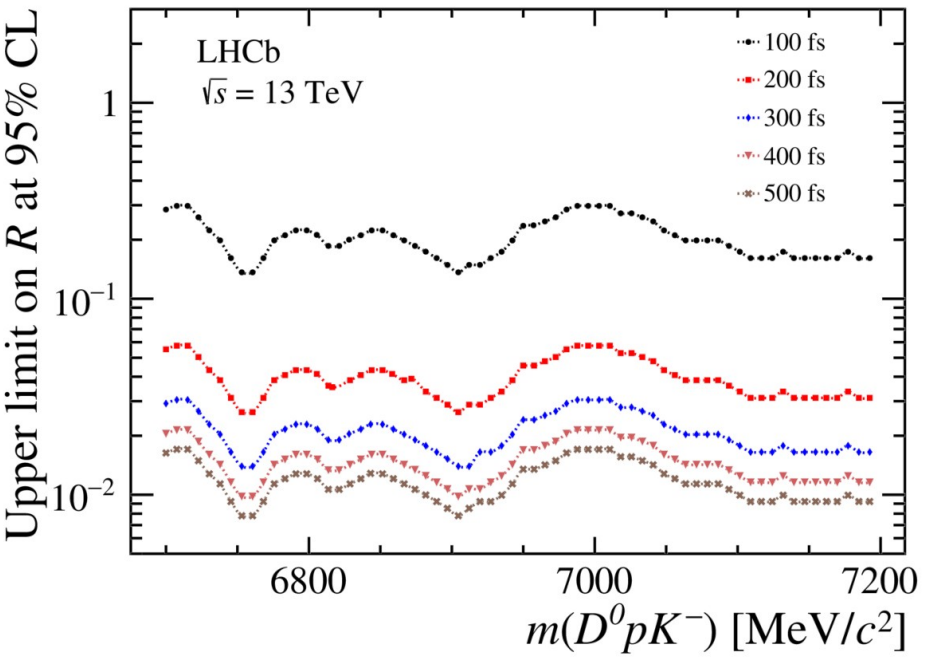


to be followed by LS5 (1-2 years) and Run 6

JHEP 11 (2020) 095

Search for $\Xi_{bc}^0 \rightarrow D^0pK^-$

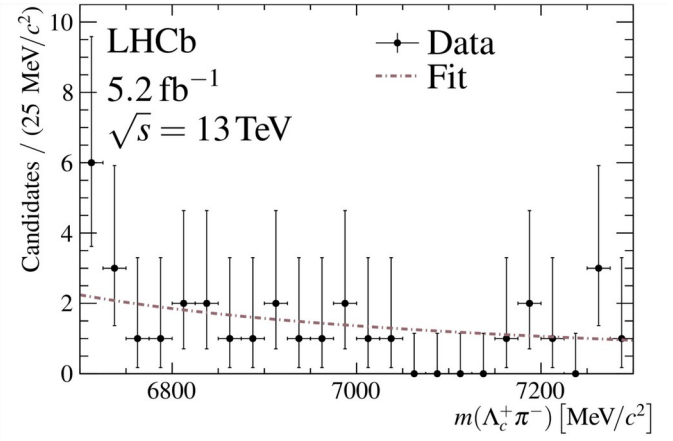


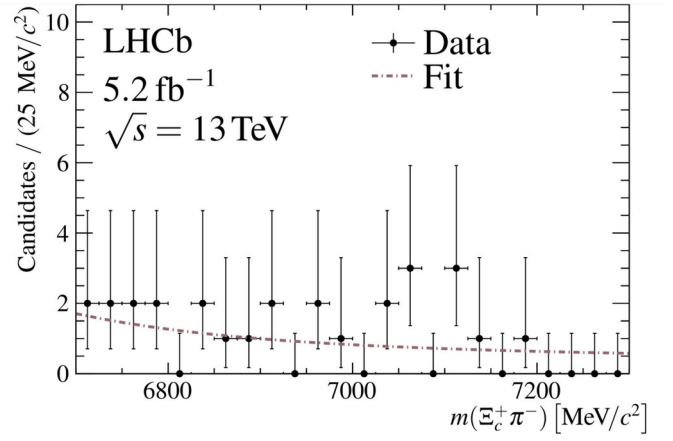


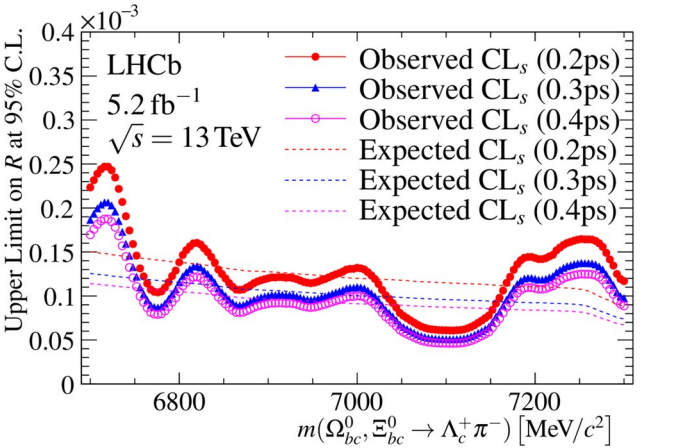
Limits on ratio R of production cross-section x branching fraction, relative to $\Lambda_b^0 \rightarrow D^0pK^-$

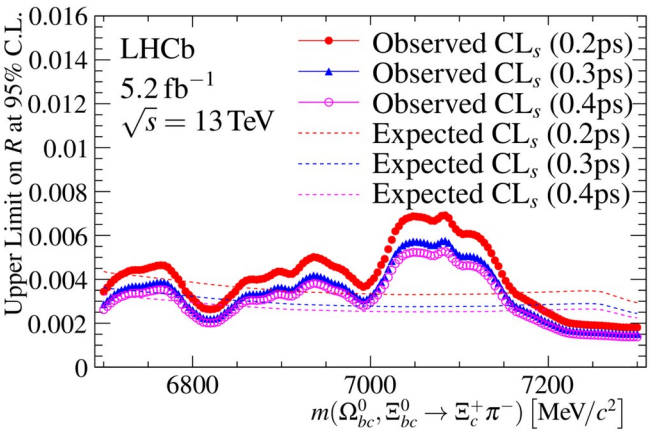
CPC 45 (2021) 093002

Ξ_{bc}^0 and $\Omega_{bc}^0 \to \Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$





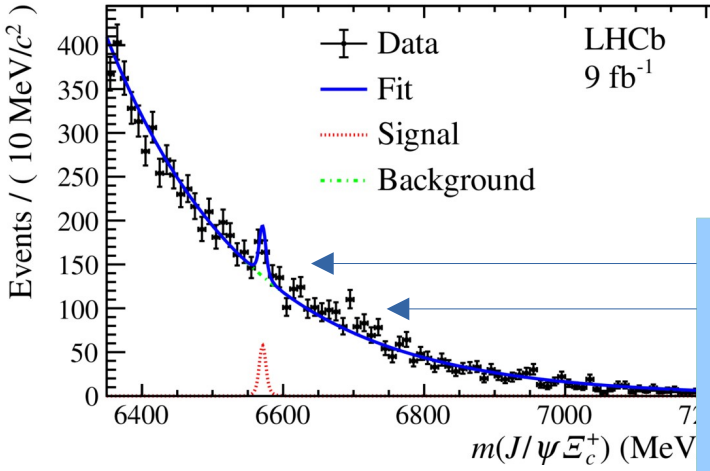


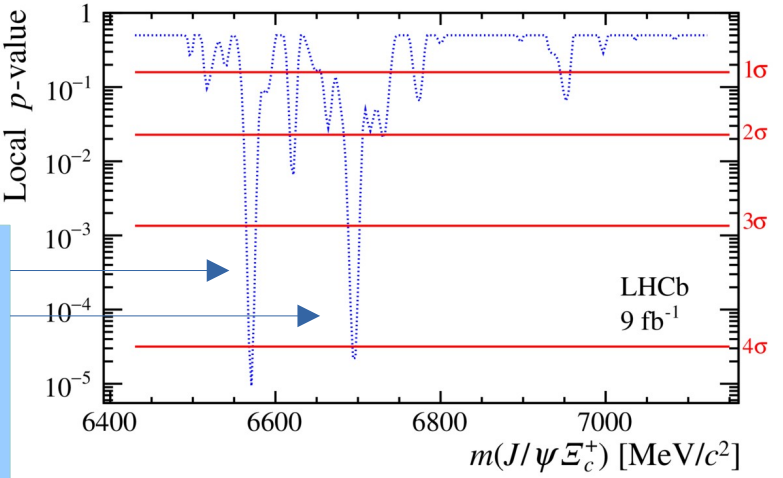


Limits on ratios R of production cross-section x branching fraction, relative to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Xi_b^0 \to \Xi_c^+\pi^-$

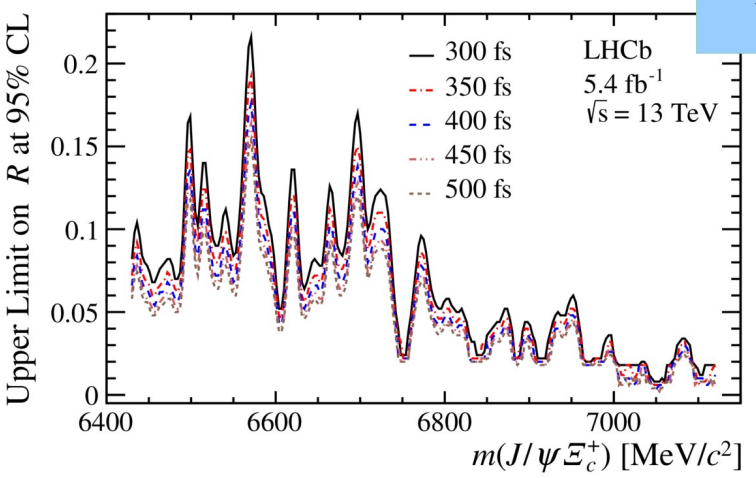
arXiv:2204.09541

$\Xi_{bc}^{+} \rightarrow J/\psi\, \Xi_{c}^{+}$





Suggestive peaks, but with look-elsewhere-effect [in 6.43−7.12 GeV/c²] global significance is 2.8 σ



Limits on ratios R of production cross-section x branching fraction, relative to $B_c^+ \rightarrow J/\psi\, D_s^+$