Doubly charmed baryon @ LHCb

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On behalf of the LHCb Collaboration

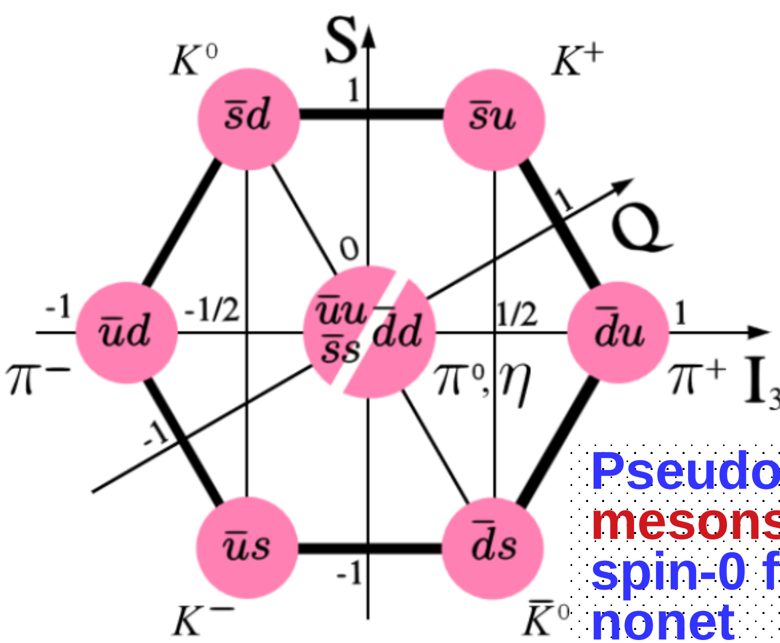
第十届中国高能物理年会 2018年6月20-24日 上海

Outline

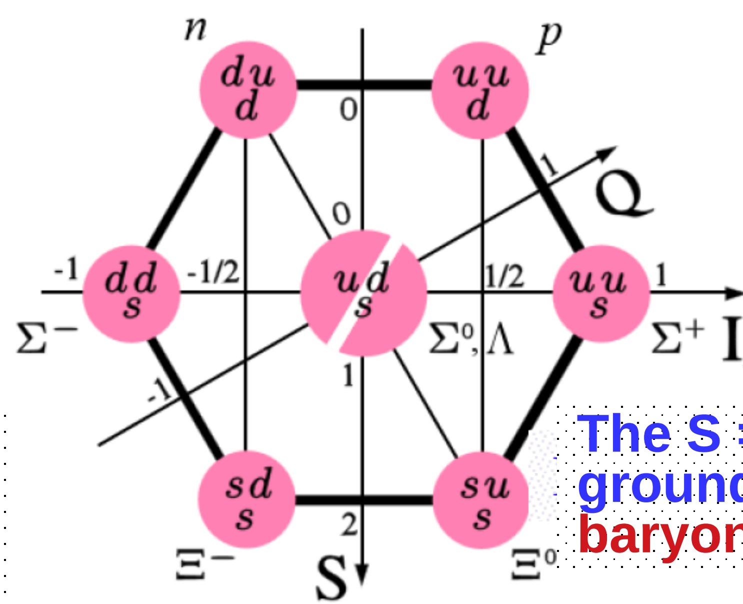
- Motivation & history
- LHCb experiment
- Experimental details
- Observation of Ξ_{cc}^{++} [PRL 119, 112001 (2017)]
- The Ξ_{cc}^{++} lifetime [arXiv:1806.02744]
- Search for $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+} \pi^{+}$ [LHCP talk]

Quark model

- In 1964, Quark Model was proposed as a classification scheme for hadrons using quarks
- Hadrons were organized into SU(3) representation multiplets using the then known three (u,d,s) quarks
- The quarks and antiquarks give rise to the quantum numbers of the hadrons
- Quark model has been successful in predicting new hadron states



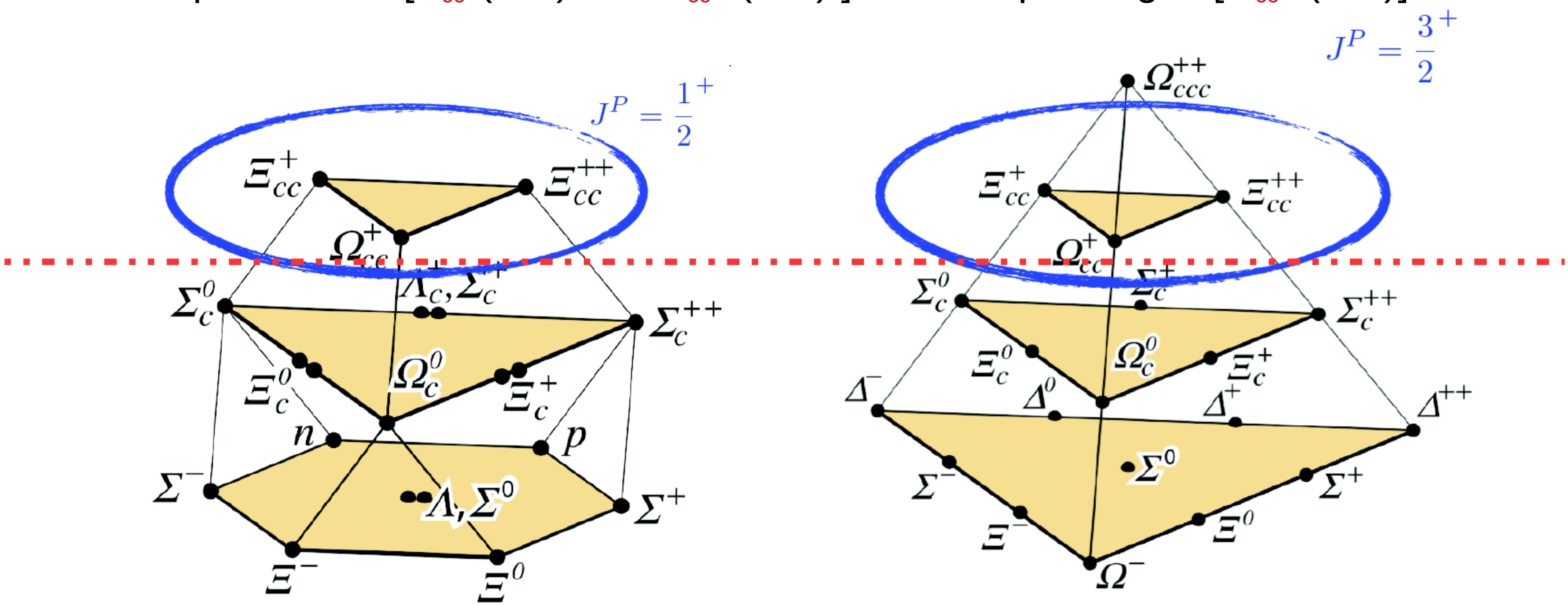
Pseudoscalar mesons of spin-0 form a nonet



The S = 1/2 ground state baryon octet

Quark model & doubly heavy baryons

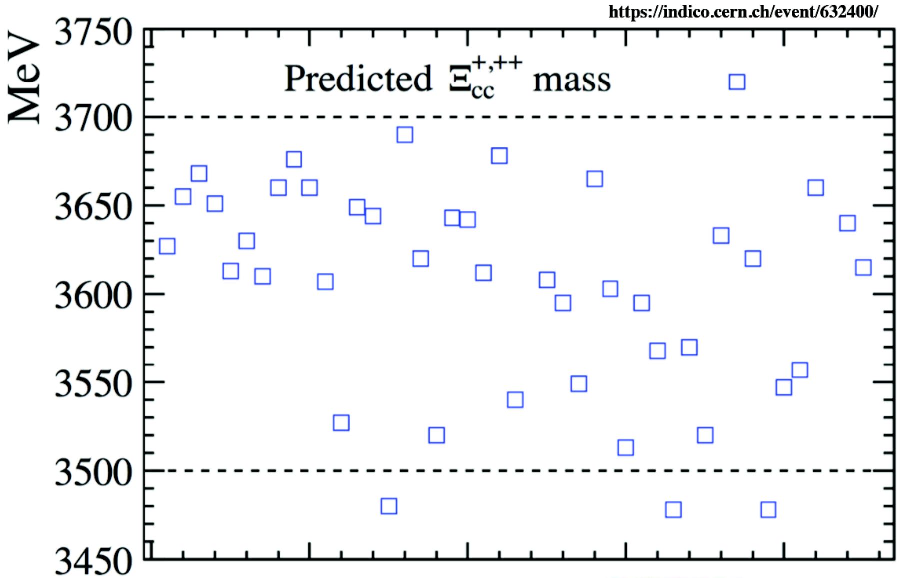
- Since 1970s, with the discovery of a new quark c, hadrons form SU(4) multiplets
  - The first of three “heavy” quarks
- By mid 2017, all C = 0 and C = 1 ground states were observed
- Predicted C = 2 (doubly charm) baryons
  - Isospin doublet [Ξ_{cc}^{+}(ccd) and Ξ_{cc}^{++}(ccu)] and Isospin singlet [Ω_{cc}^{++}(ccu)]



Predictions on Ξ_{cc} properties

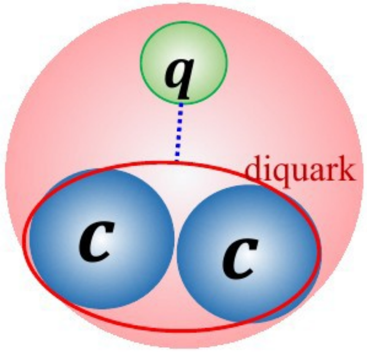
- Many models have been applied to determine the Ξ_{cc} masses, e.g. (non-) relativistic QCD potential models, QCD sum rules, bag model…
  - $m(\Xi_{cc}^{+,++}) \in (3.5, 3.7)\, GeV$
  - Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++}: a few MeV

    See Refs. [6-33] of PRL 119, 112001 (2017)



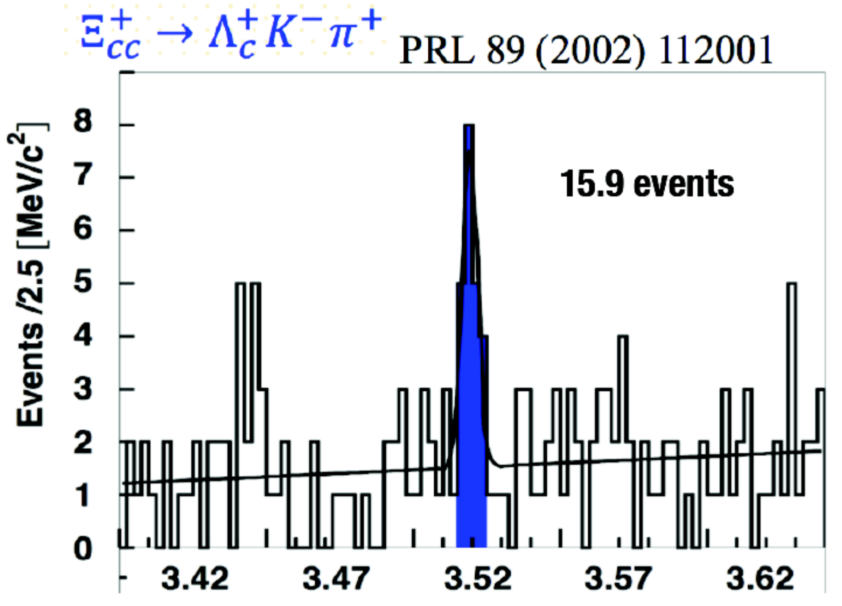
- Expected lifetime: $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$
  - $\tau(\Xi_{cc}^{++}) \in (200, 1050)\, fs$
  - $\tau(\Xi_{cc}^{+}) \in (50, 250)\, fs$

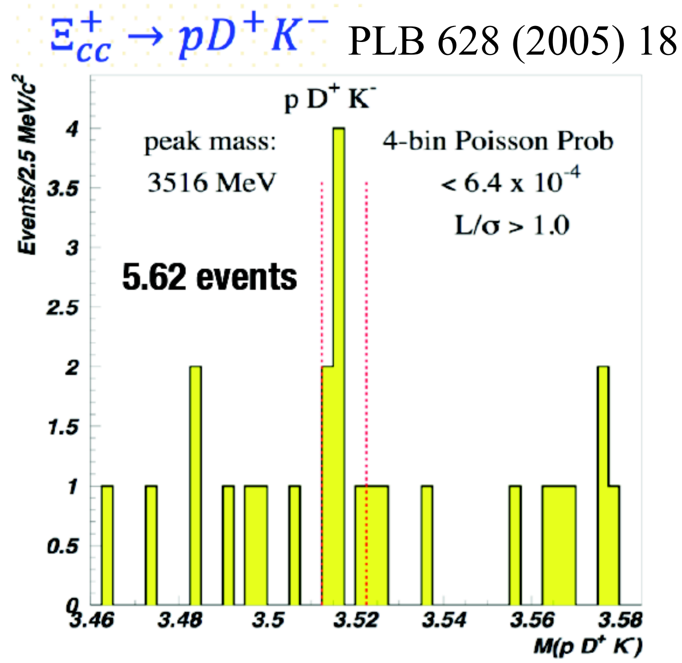
See Refs. [1-10] of arXiv:1806.02744



Past searches: SELEX and Ξ_{cc}^{+}

- SELEX observed Ξ_{cc}^{+} in two decay channels:



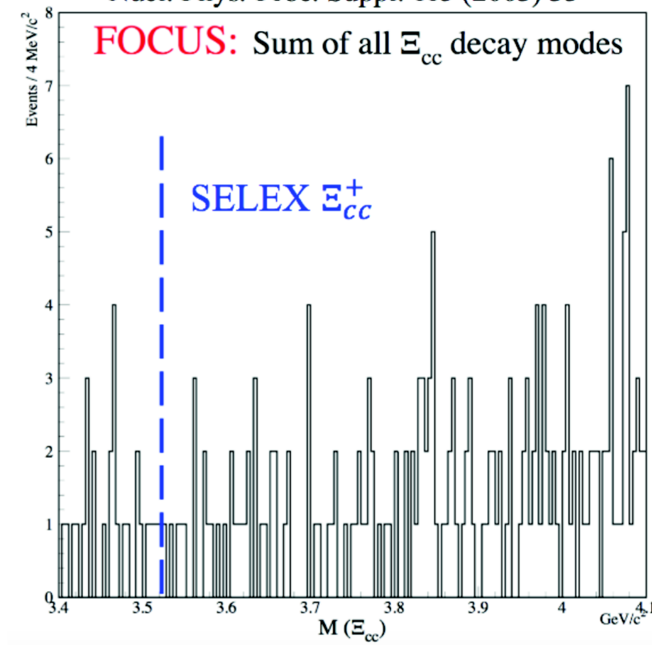


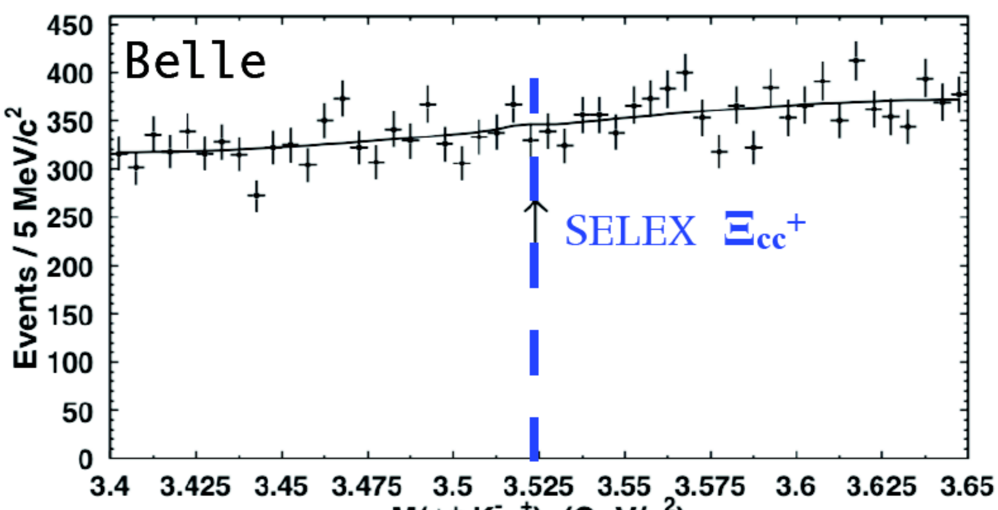
  - Short yet nonzero lifetime: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL
  - Unexpectedly large production: 20% of all Λ_c production
  - Mass (combined): 3518.7 ± 1.7 MeV

Past searches: other experiments

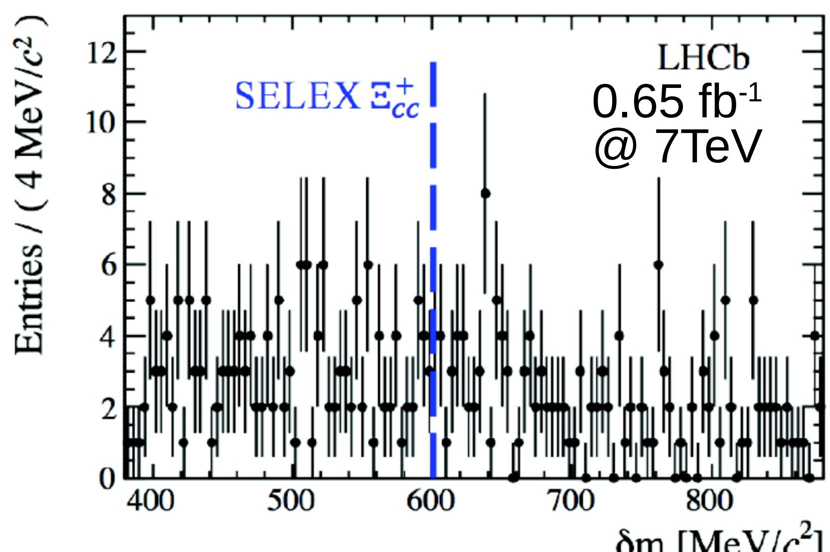
- SELEX's Ξ_{cc}^{+} observation NOT confirmed by other experiments (FOCUS, BABAR, BELLE and LHCb)

Nucl. Phys. Proc. Suppl. 115 (2003) 33





PRL **97**, 162001 (2006)



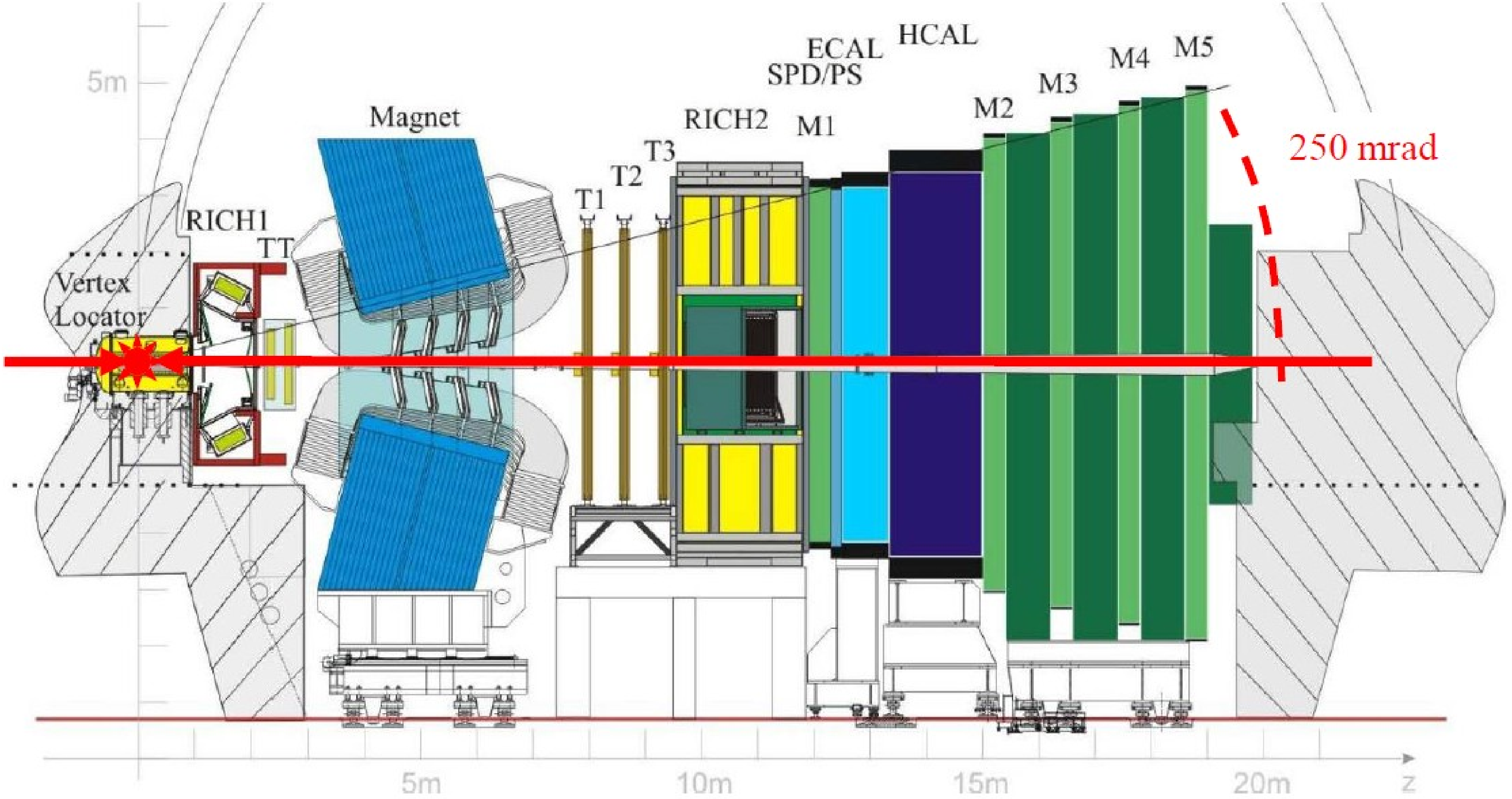
JHEP 12 (2013) 090

LHCb experiment

Aiming for precision measurements in b, c flavor sectors

Acceptance: $2 < \eta < 5$

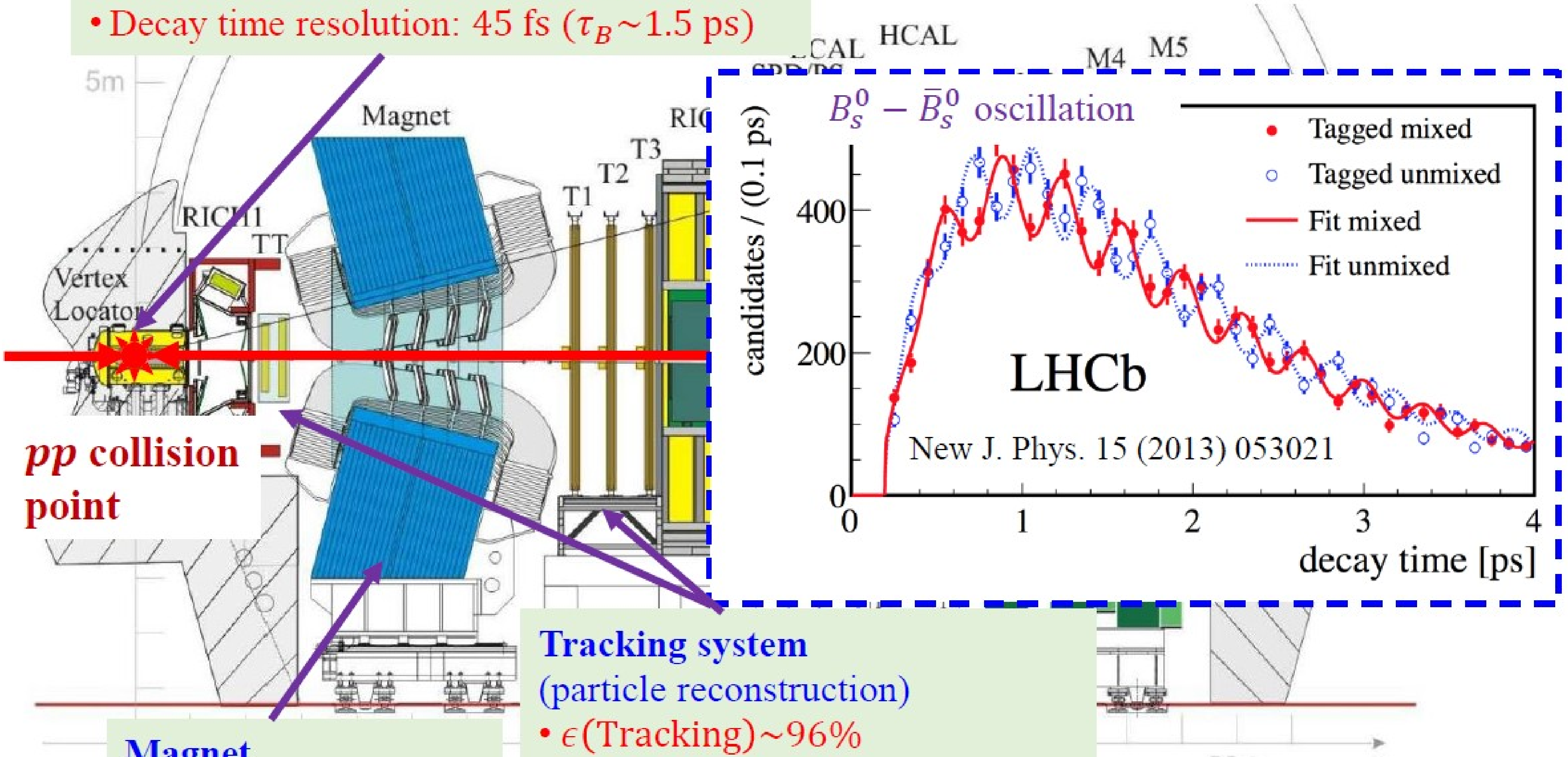
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



LHCb experiment

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator (vertex reconstruction)
- Impact parameter resolution: 20μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)

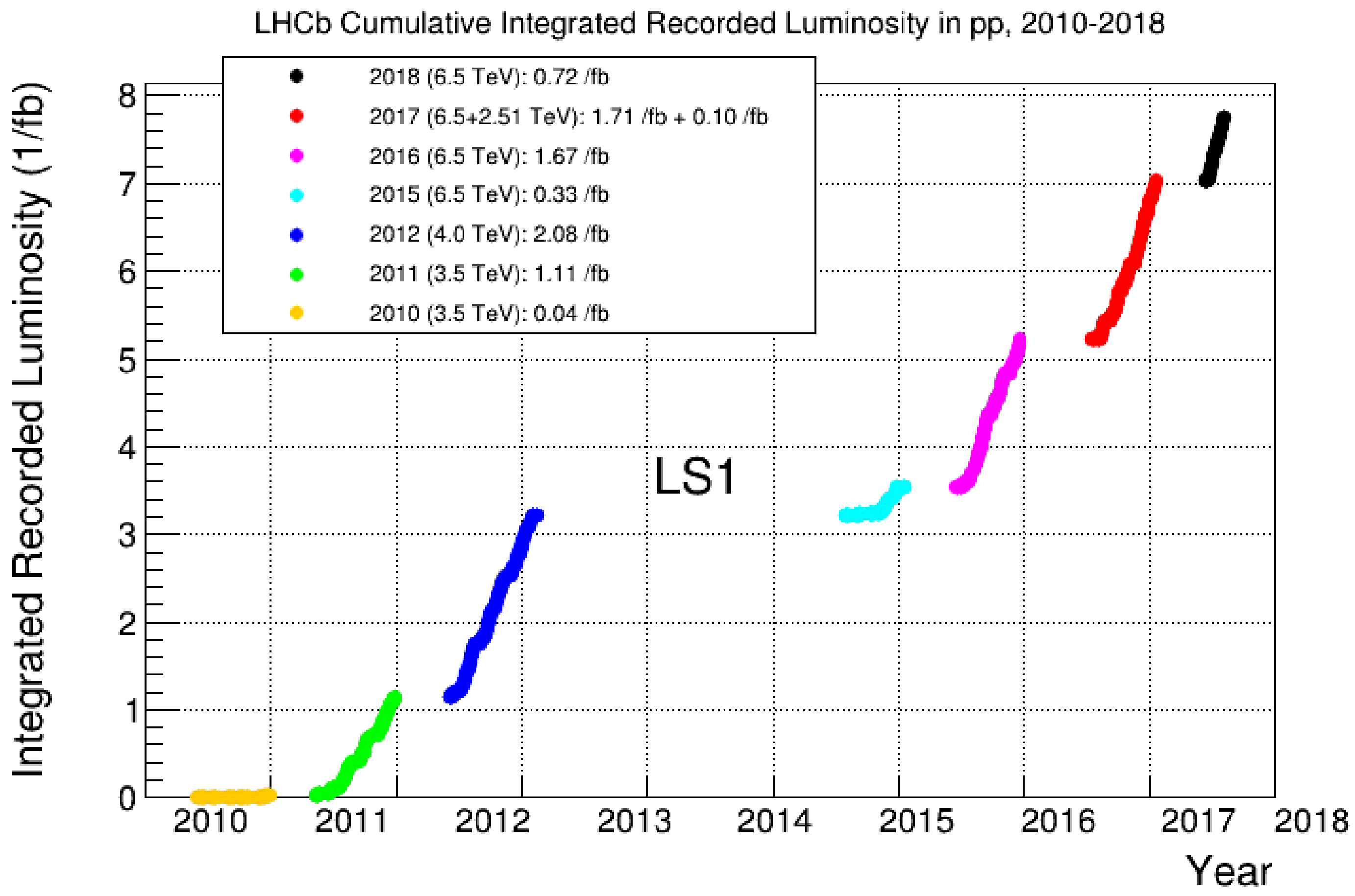


***pp* collision point**

Magnet
Bending power: 4 Tm

Tracking system
(particle reconstruction)
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx$ 22 MeV

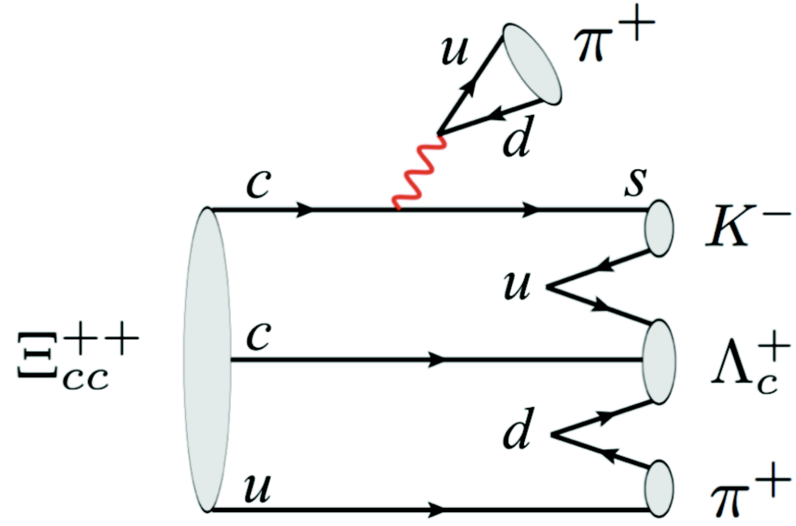
LHCb data-taking

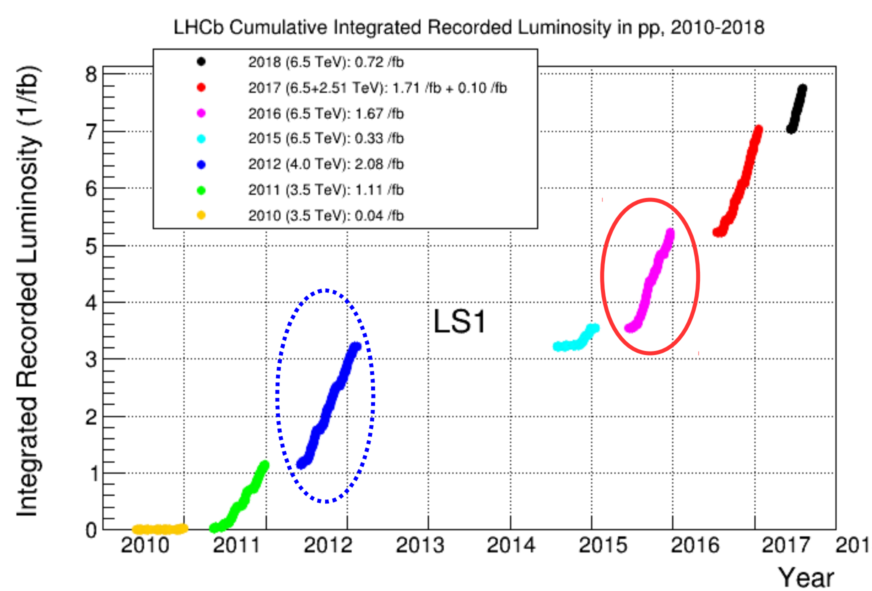


- Run I: 1.0 fb^{-1} @ 7 TeV (2011) + 2.0 fb^{-1} @ 8 TeV (2012)
- Run II: 0.3 fb^{-1} (2015) + **1.7 fb^{-1} (2016)** + 1.7 fb^{-1} (2017) @ 13 TeV

Search for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ @ LHCb

- Ξ_{cc}^{++} with longer lifetime than Ξ_{cc}^{+} → higher sensitivity @ LHCb
- $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ branching ratio expected to be ~10% [F-S. Yu et al. arXiv:1703.09086]
  - Reconstructing $\Lambda_c^+ \rightarrow p K^- \pi^+$
- Used dataset: LHCb Run-II (2016) ~1.7 fb^{-1} @ 13 TeV
  - Run-I (2012) 2 fb^{-1} data @ 8TeV as crosscheck

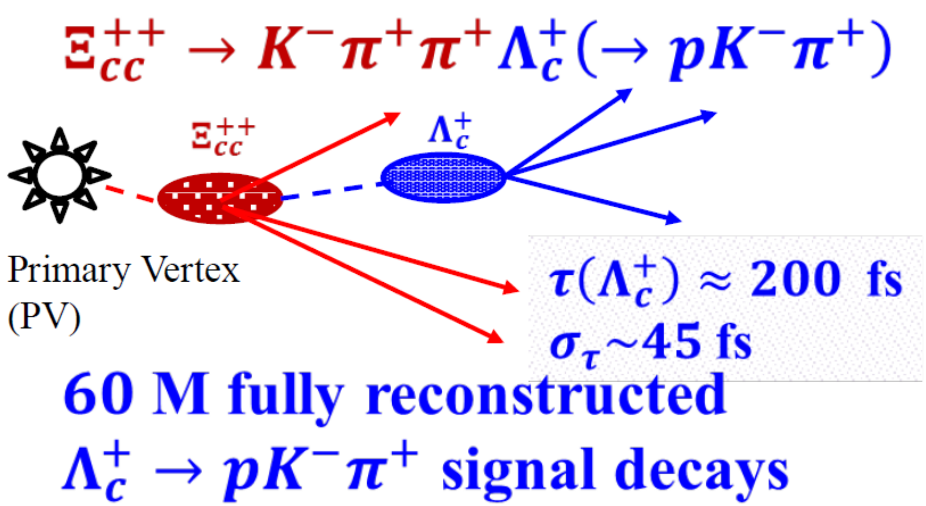




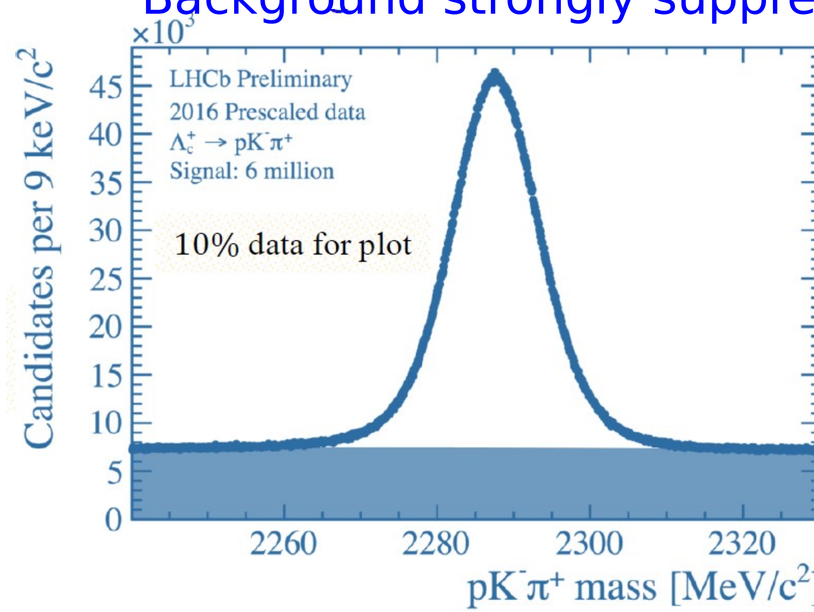
PRL119(2017)112001

$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$: event selection

- Selection highlights:
  - Online selection of clean $\Lambda_c^+ \rightarrow p K^- \pi^+$ signals
  - $\Lambda_c^+ K^- \pi^+ \pi^-$ wrong-sign (WS) events as control sample for background study
  - MVA based on kinematic & topological variables to suppress the copious hadronic background



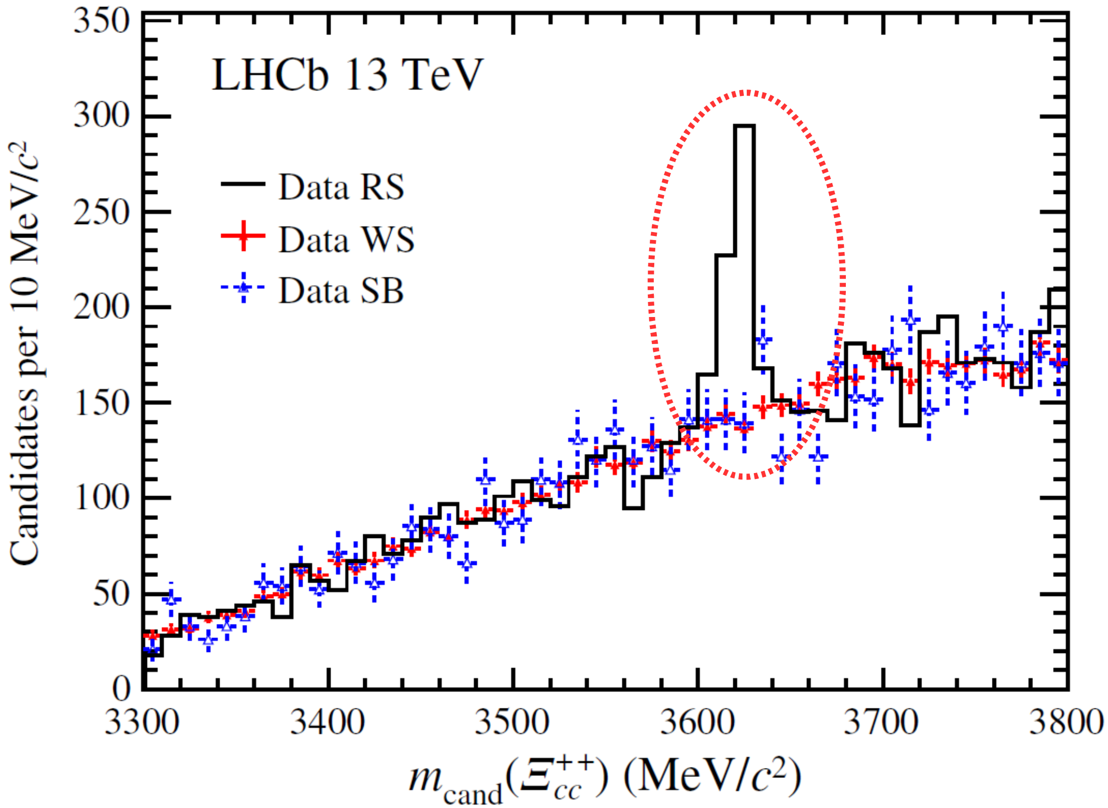
Background strongly suppressed

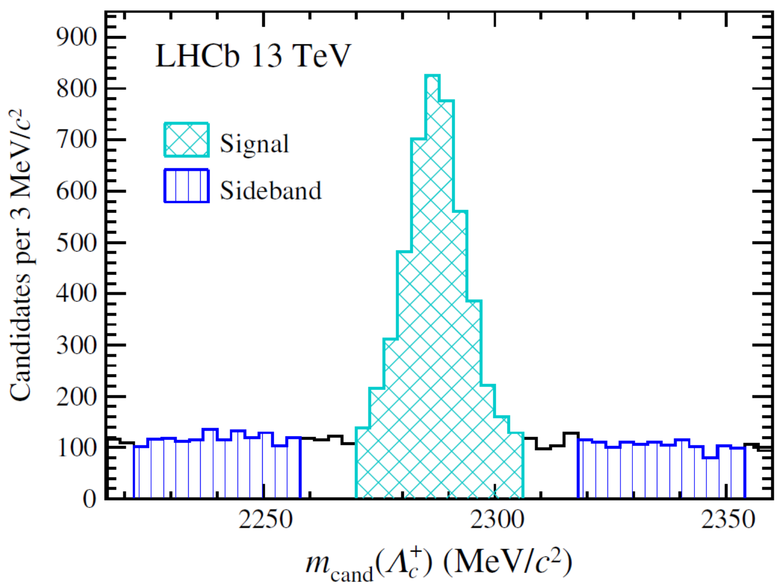


$\Lambda_c^+ K^- \pi^+ \pi^{(+,-)}$ invariant mass spectrum

$$m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+ \pi^+) - m_{\text{cand}}(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$$

- A clear structure (peak) is visible at ~3.62 GeV for **right-sign (RS)** combinations
- No peak found for either wrong-sign (WS, $\Lambda_c^+ K^- \pi^+ \pi^-$) combinations or events in the **Λ_c^+ sidebands (SB)**
- Similar distributions except for RS around the peak





PRL119(2017)112001

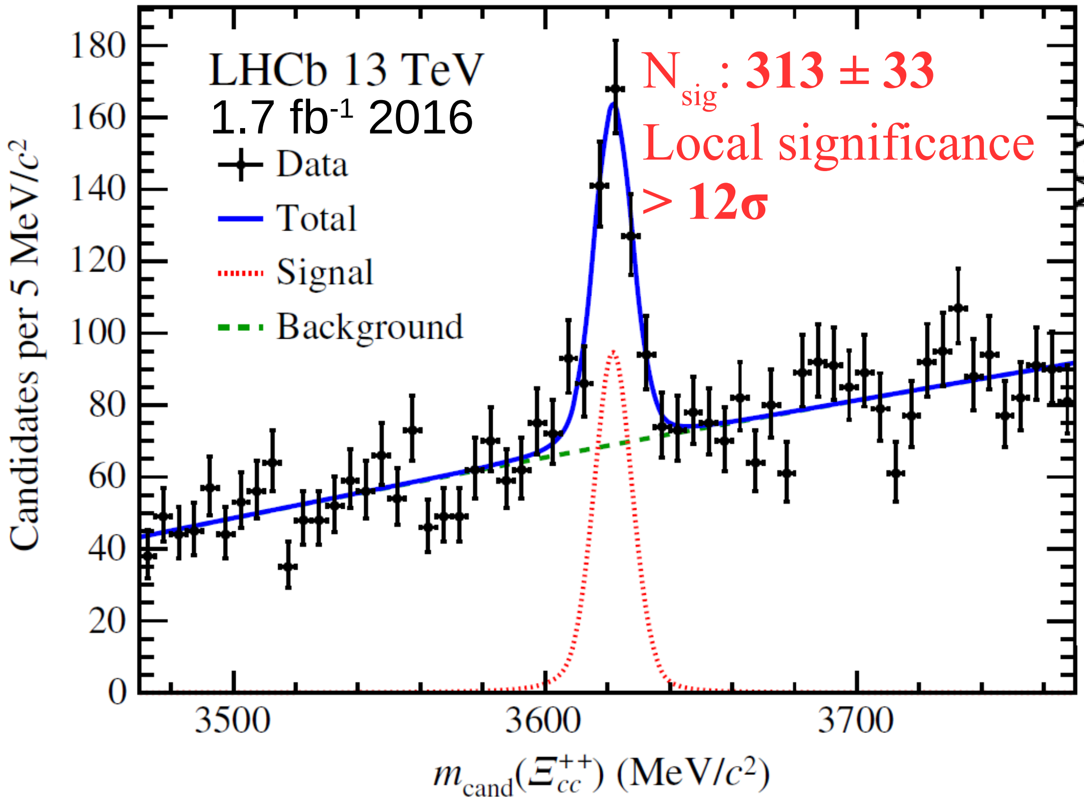
Mass fit to extract Ξ_{cc}^{++} signals

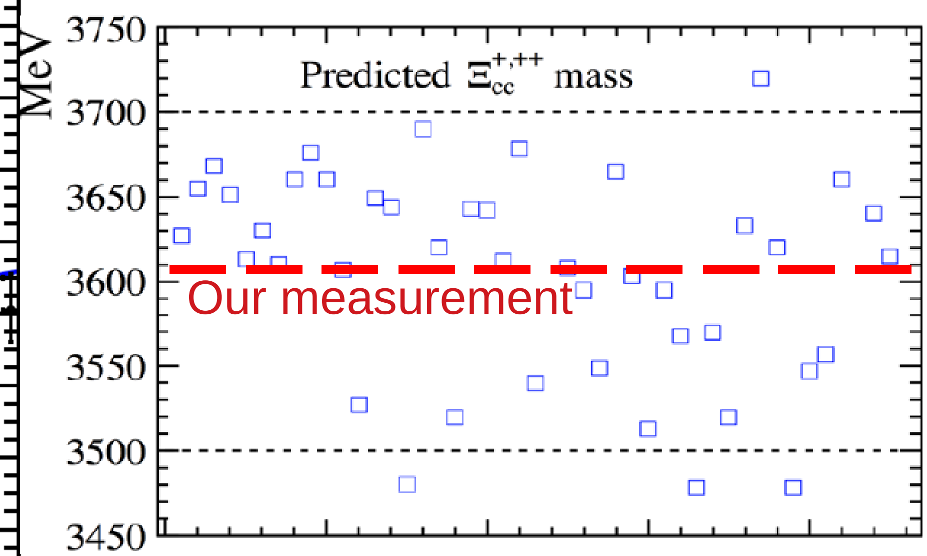
$$m_{\rm cand}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+ \pi^+) - m_{\rm cand}(\Lambda_c^+) + m_{\rm PDG}(\Lambda_c^+)$$

- Likelihood fit in mass range 3620 ± 150 MeV
- Measured Ξ_{cc}^{++} mass using 13 TeV data:

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72({\rm stat}) \pm 0.27({\rm syst}) \pm 0.14(\Lambda_c^+)\ {\rm MeV}$$

$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72({\rm stat}) \pm 0.27({\rm syst})\ {\rm MeV}$$





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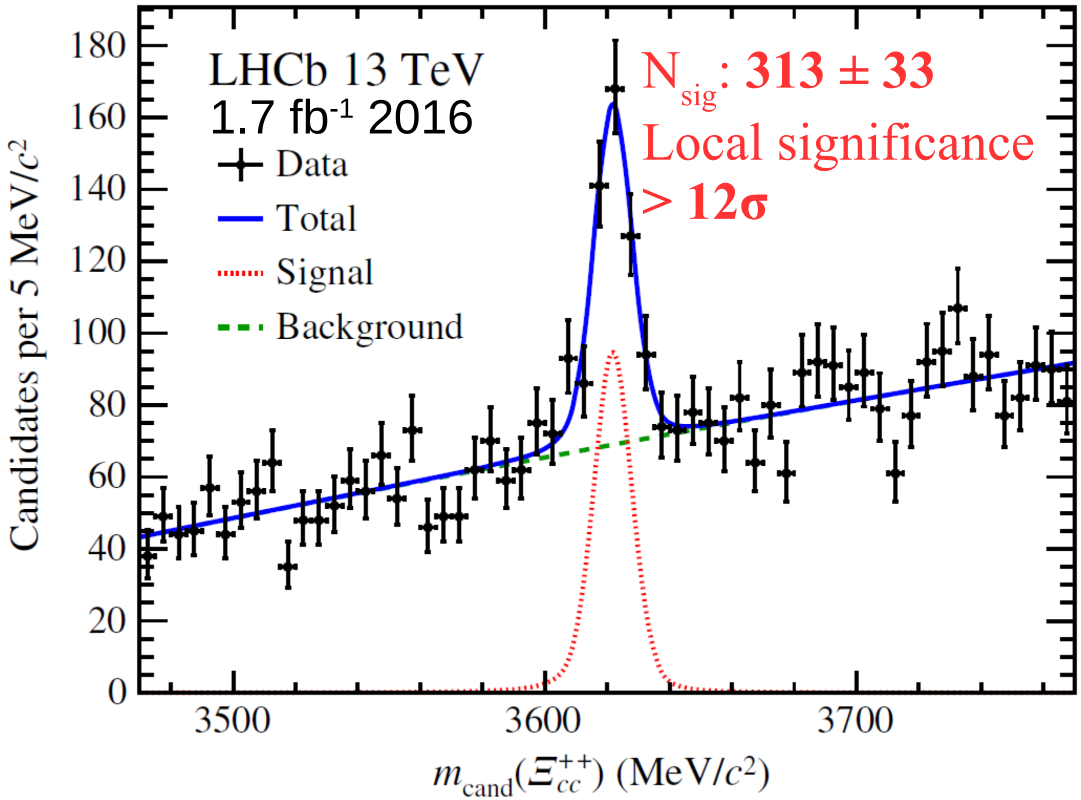
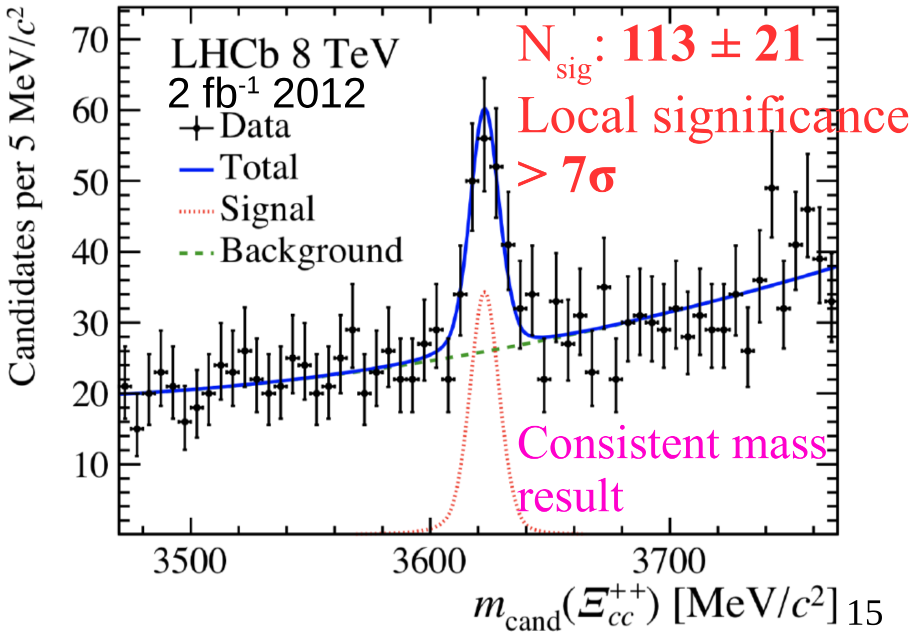
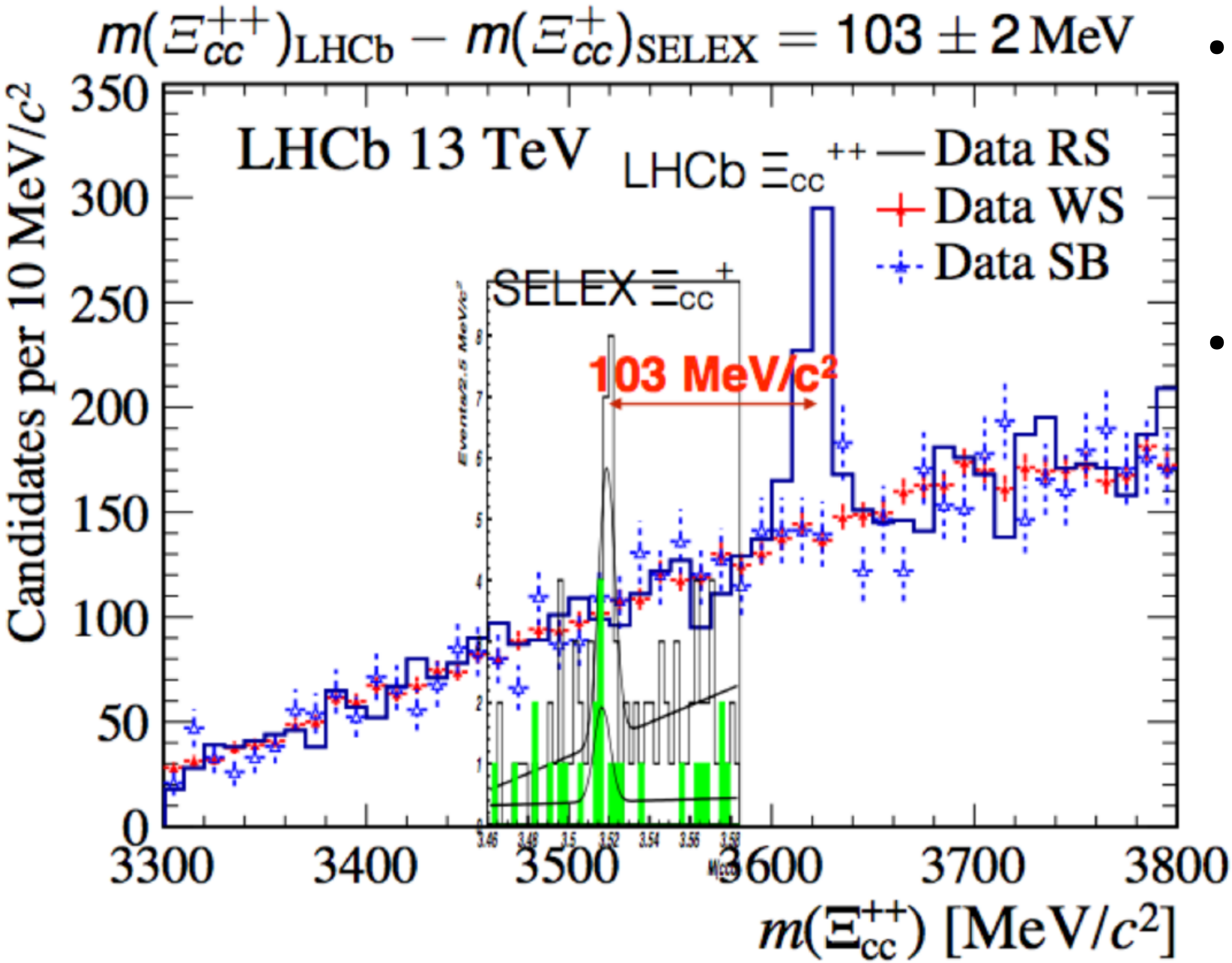


Validation with Run-I data:



PRL119(2017)112001

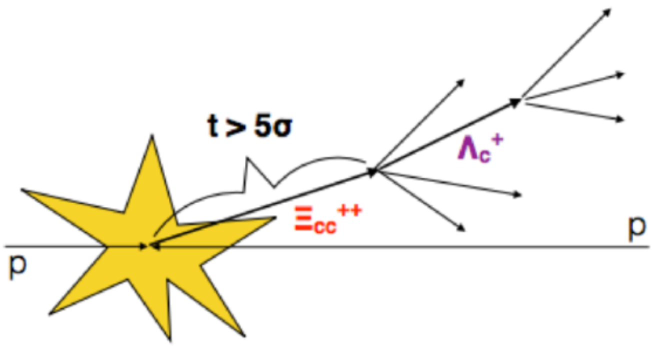
Inconsistency with SELEX results

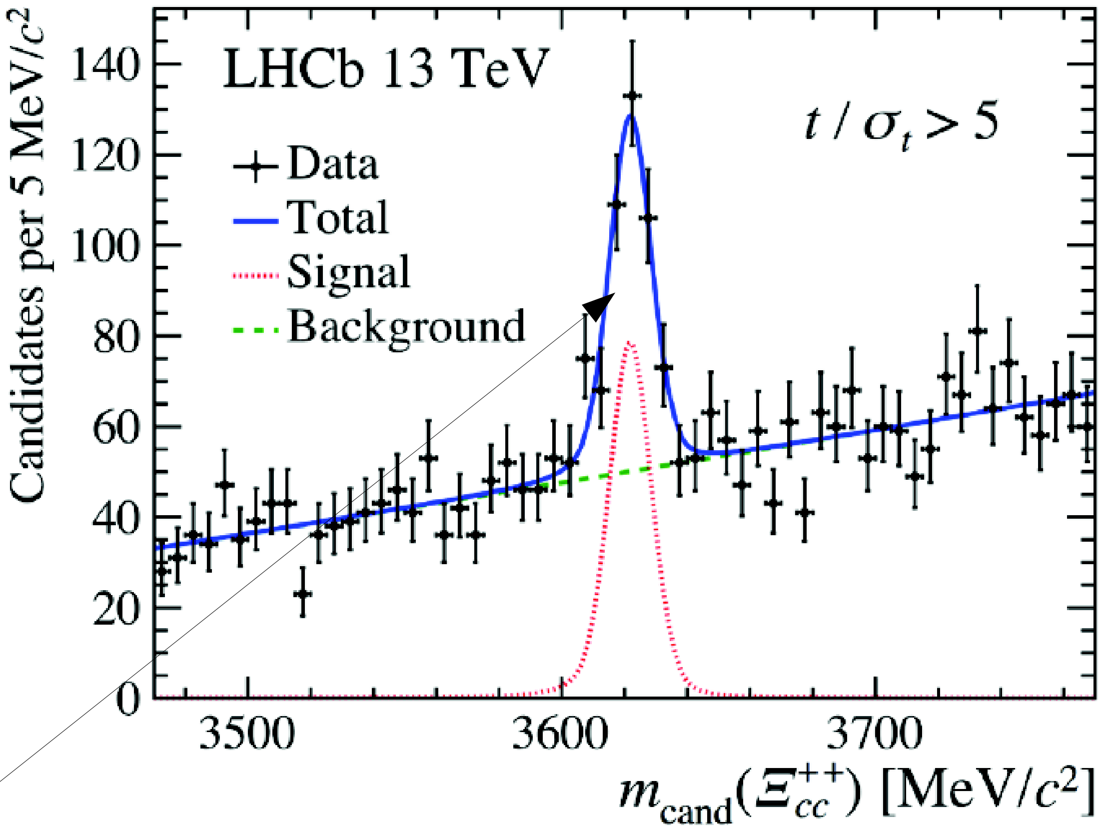


- Too large mass difference, cannot be isospin partners!
- Production: $N(\Xi_{cc})/N(\Lambda_c)$ much smaller in LHCb result

PRL119(2017)112001

Signal properties: weak decay





Peaking structure remains significant (>12σ) after requiring decay time $t > 5\sigma_t$: inconsistent with the strong decay

The new particle's lifetime is measurable, so how large is it?

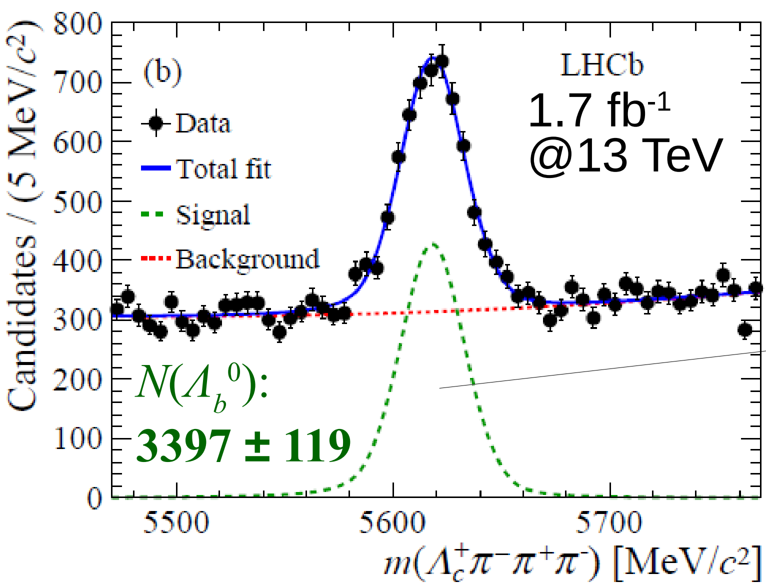
Lifetime measurement

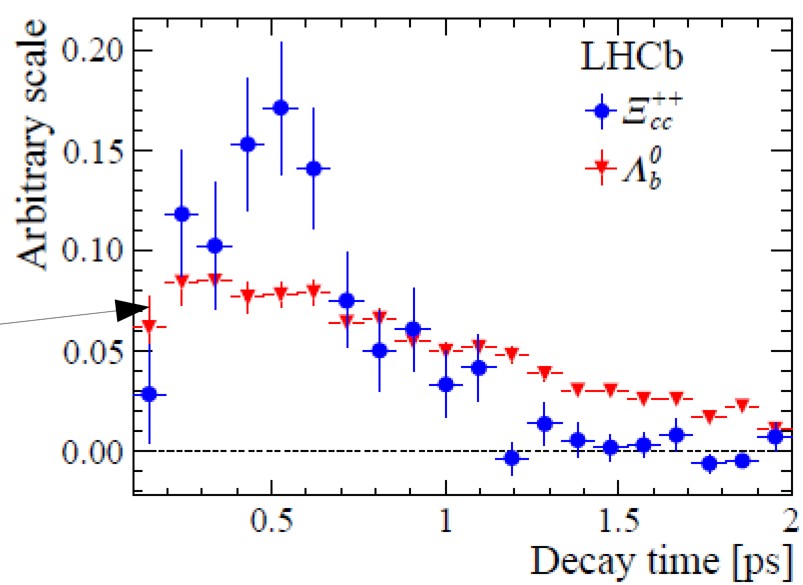
- The lifetime measurement uses the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay, relative to the control channel of the same topology, $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$
- Unbinned maximum likelihood fit of the background subtracted Ξ_{cc}^{++} decay time distribution (sFit [arXiv:0905.0724]), using PDF:

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

$\tau(\Lambda_b^0)$: 1.47 ± 0.01 ps from PDG

  - Background-subtracted decay-time distribution of the Λ_b^0 data





arXiv:1806.02744, submitted to PRL

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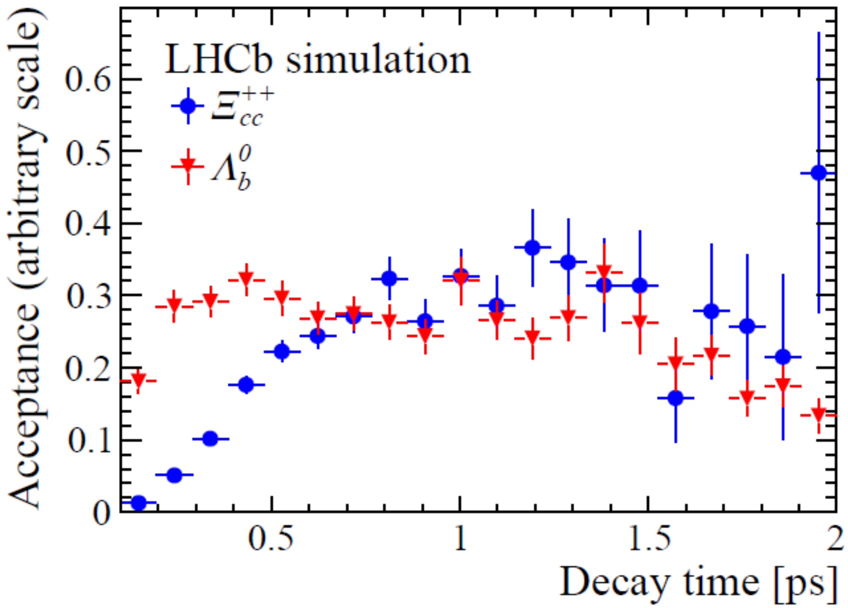
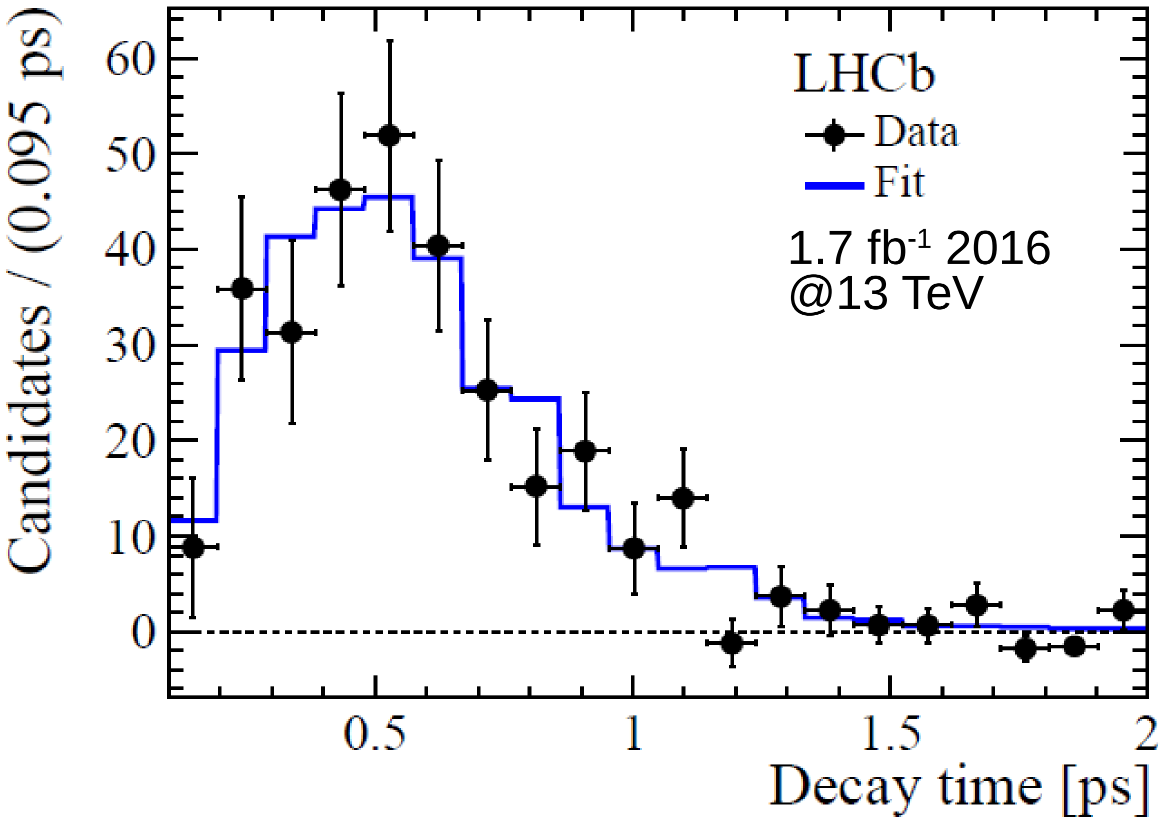
$\tau(\Lambda_b^0)$: 1.47 ± 0.01 ps from PDG

  - Background-subtracted decay-time distribution of the Λ_b^0 data
  - Decay time acceptance distributions from MC samples reweighted to match p_T distributions in data



Lifetime result

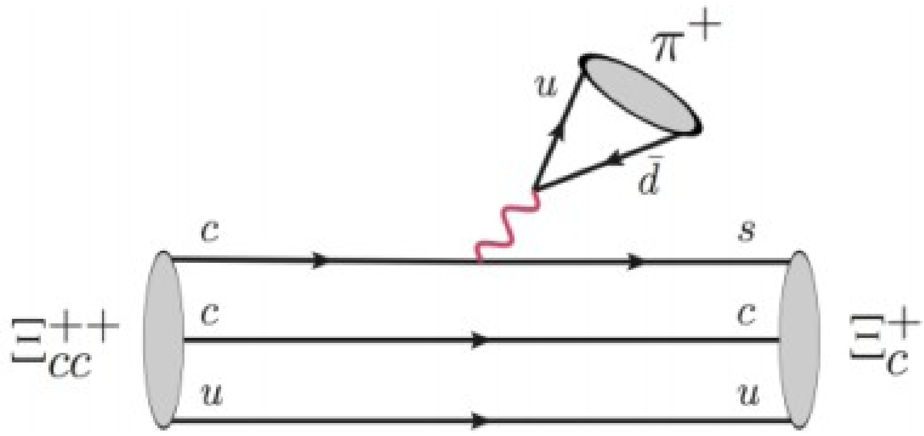


Fit to background-subtracted Ξ_{cc}^{++} decay-time distribution yields:

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

Search for $\Xi_{cc}^{++} \rightarrow \Xi_c^{+} \pi^{+}$

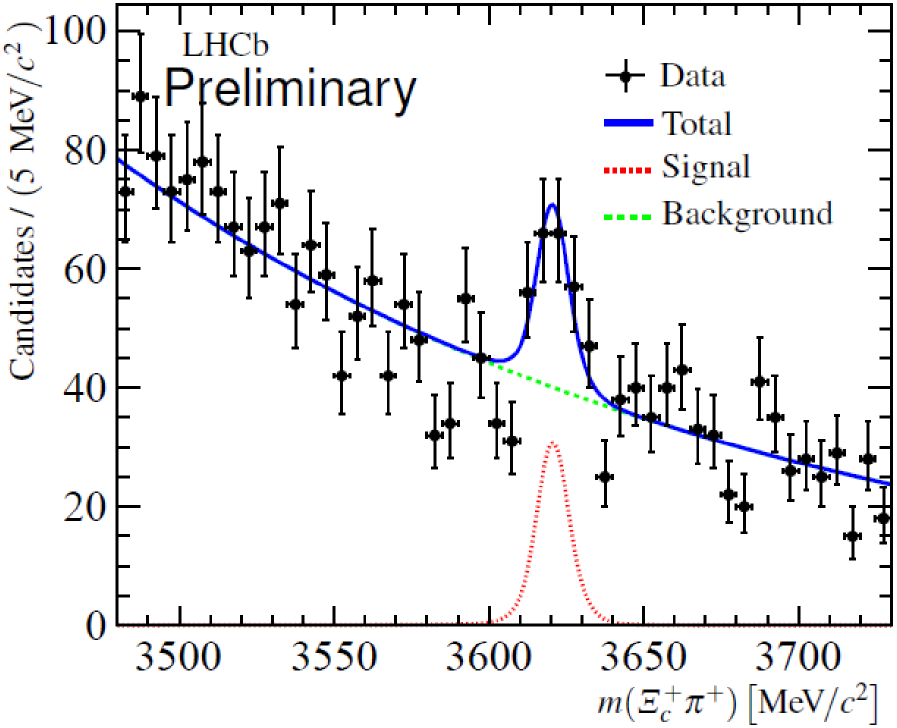
- One of the two “golden” channels originally proposed by F-S Yu et al. [arXiv:1703.09086] for the Ξ_{cc}^{++} search
  - Both channels expected to have absolute branching fractions of a few percent
  - BR($\Lambda_c^+ \rightarrow p^+ K^- \pi^+$)~(6.35%), BR($\Xi_c^+ \rightarrow p^+ K^- \pi^+$)~(2%)
  - The $\Xi_c^+\pi^+$ channel has fewer tracks → higher reconstruction efficiency



LHCb preliminary

Search for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

- Data sample: LHCb Run-II (2016) ~1.7 fb-1 @ 13 TeV
- Normalization channel: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
- MVA to suppress hadronic background
- Signal yield is **91 ± 20** with significance of ~6σ



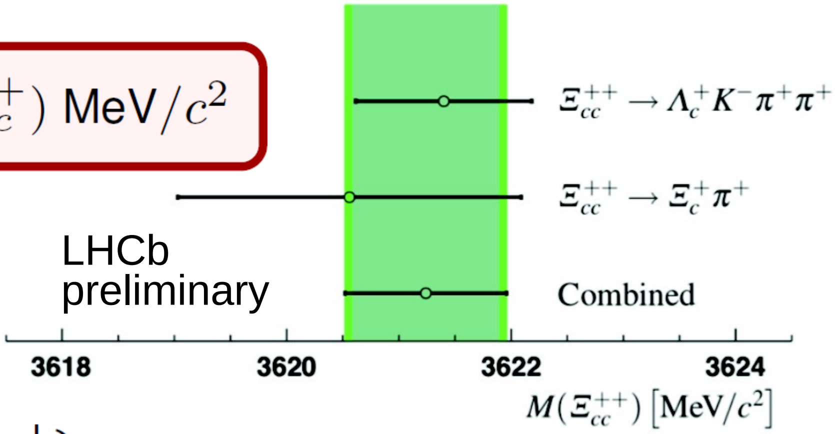
$$\mathbf{M(\Xi_{cc}^{++}) = M(\Xi_c^+\pi^+) - M(\Xi_c^+) + M_{PDG}(\Xi_c^+)}$$

Search for $\Xi_{cc}^{++} \to \Xi_c^{+} \pi^{+}$

- The mass is measured to be

$$m(\Xi_{cc}^{++}) = 3620 \pm 1.5\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.3(\Xi_c^{+})\ \text{MeV}/c^2$$

consistent with the previous result



- The ratio of branching fractions is

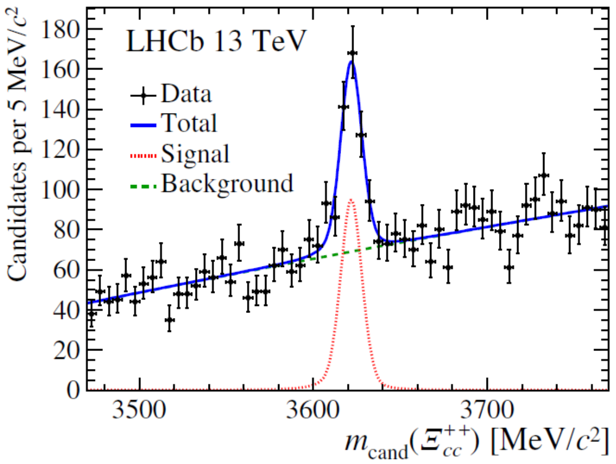
$$\mathcal{R} \equiv \frac{B(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)}{B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{B(\Xi_c^+ \to p^+ K^- \pi^+)}{B(\Lambda_c^+ \to p^+ K^- \pi^+)}$$

$$= \mathbf{0.035 \pm 0.009\,(stat) \pm 0.003\,(syst)}$$

consistent with the prediction by F-S Yu et al. [arXiv:1703.09086]

Summary and outlook

- LHCb observed the $\Xi_{cc}^{++}(ccu)$ state in the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay and measured its mass & lifetime
- Observation confirmed in decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
- New window now opened for charm/bottom hadron spectroscopy studies
- A long and growing to-do list with current & future LHCb data
  - More channels: $\Lambda_c^+\pi^+$, $pD^+K^-\pi^+$, ...
  - Production cross-section
  - The isospin partner $\Xi_{cc}^{+}(ccd)$ and $\Omega_{cc}^{+}(ccs)$
  - Doubly heavy baryons with bottom quark
  - The excited states



- Stay tuned for exciting results in the pipeline!