Observation of Ξ_{cc}^{++} at LHCb

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On behalf of the LHCb collaboration
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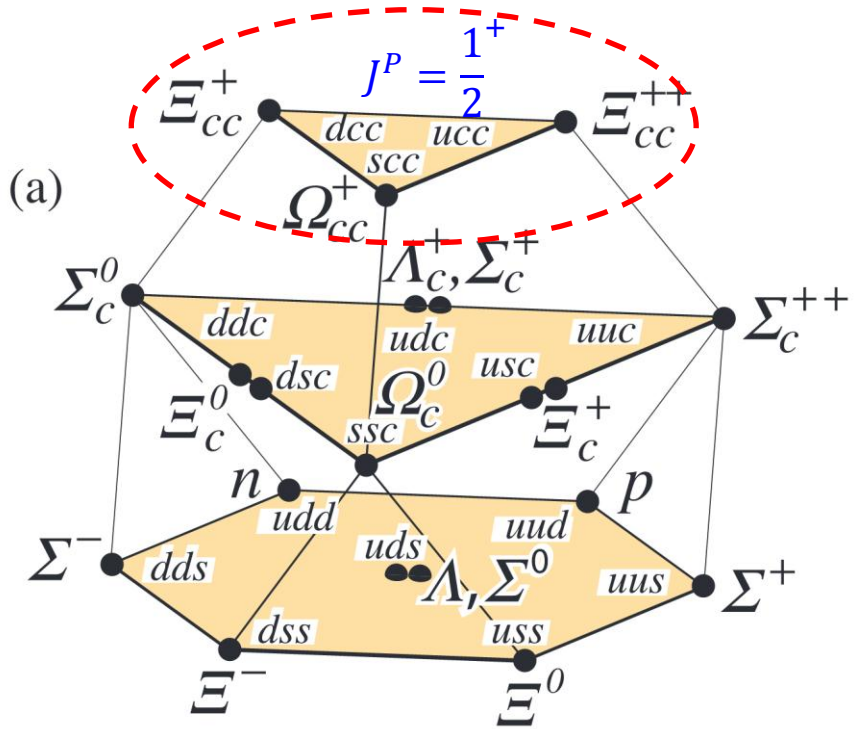
CLHCP , 22th Dec 2017

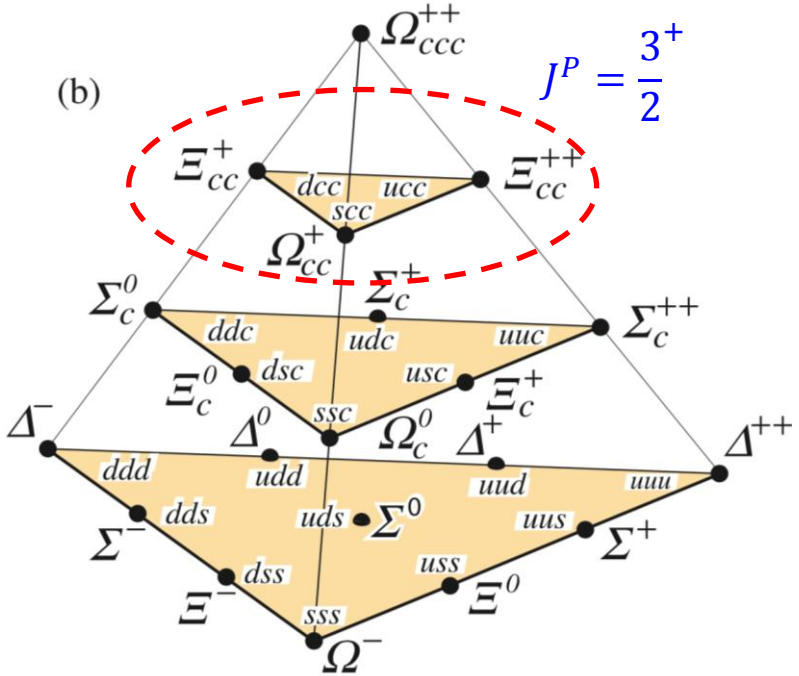
Outline

- Introduction and physics motivation
- LHCb observation of doubly charmed baryon Ξ_{cc}^{++}
- Summary

The doubly charm baryons

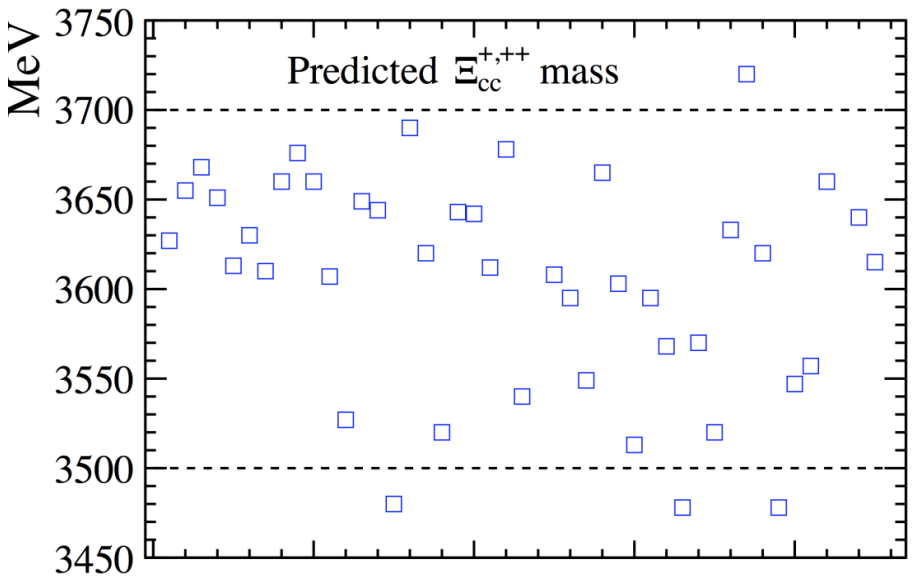
- Two SU(4) baryon 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, each contains a SU(3) triplet with two charm quarks: $\Xi_{cc}^+(ccd),\ \Xi_{cc}^{++}(ccu),\ \Omega_{cc}^+(ccs)$
- $J^P = \frac{3}{2}^+$ expected to decay to $\frac{1}{2}^+$ states via strong/electromagnetic interaction
- $J^P = \frac{1}{2}^+$ states decay weakly with a c quark transformed to lighter quarks





Masses

- Many models have been applied to determine masses of ground state and excitations: (non-) relativistic QCD potential models, bag model or quark model …
  - Predicted $M(\Xi_{cc}^{+,++}) \in [3.5,3.7\text{GeV}]$, $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}) + 0.1$ GeV
  - $M(\Xi_{cc}^{++}) \approx M(\Xi_{cc}^{+})$ due to u, d symmetry



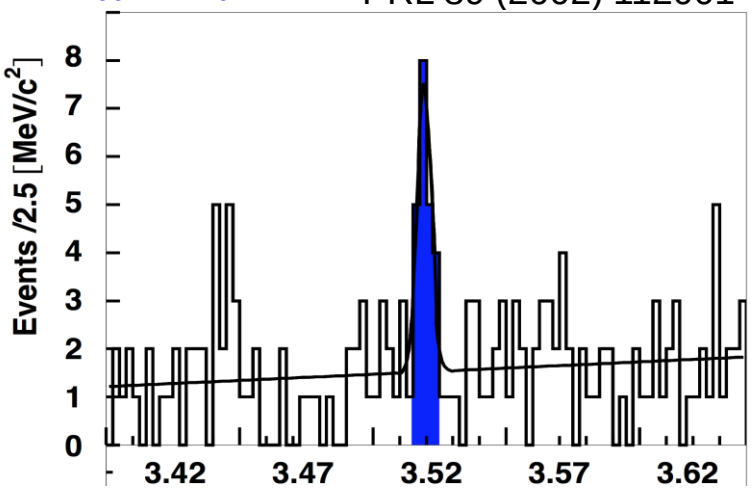
- Lattice QCD computations: Refs.[1-30]

$M(\Xi_{cc}) \approx 3.6$ GeV, $M(\Omega_{cc}^{+}) \approx 3.7$ GeV Refs.[31-46]

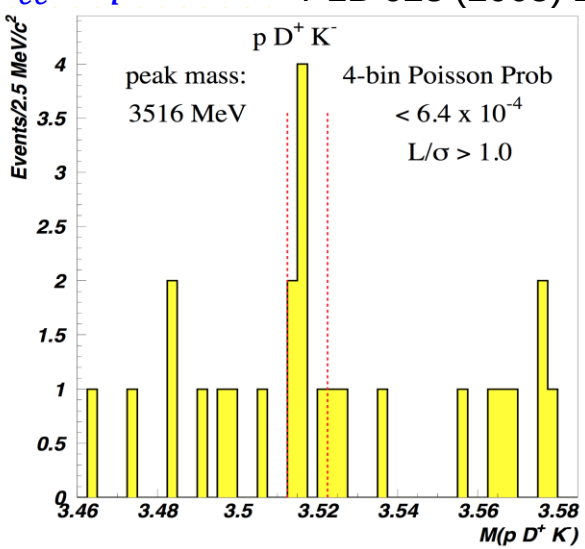
Studies of Ξ_{cc} by SELEX experiment

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to p D^+ K^-$ decays
  - **Signal yields**: 15.9 $(\Lambda_c^+ K^- \pi^+)$ and 5.62 $(p D^+ K^-)$
  - **Short lifetime**: $\tau(\Xi_{cc}^+) < 33$ fs @90% CL, but not zero
  - **Large production:** $R = \frac{\sigma(\Xi_{cc}^+ \to \Lambda_c^+ X)}{\sigma(\Lambda_c^+)} \sim 20\%$
  - **Mass (combined):** 3518.7 ± 1.7 MeV

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ PRL 89 (2002) 112001



$\Xi_{cc}^+ \to p D^+ K^-$ PLB 628 (2005) 18



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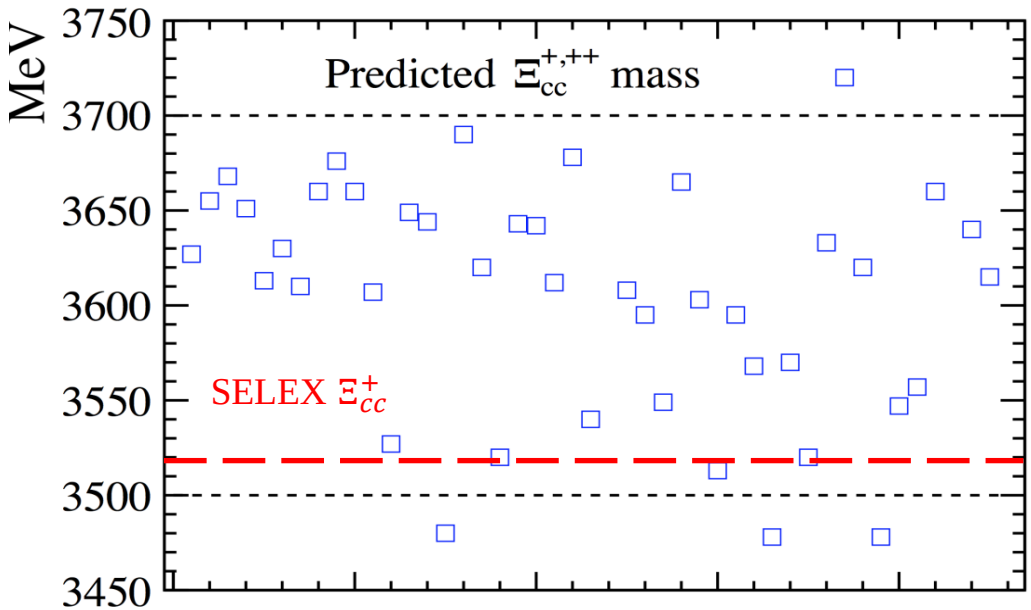
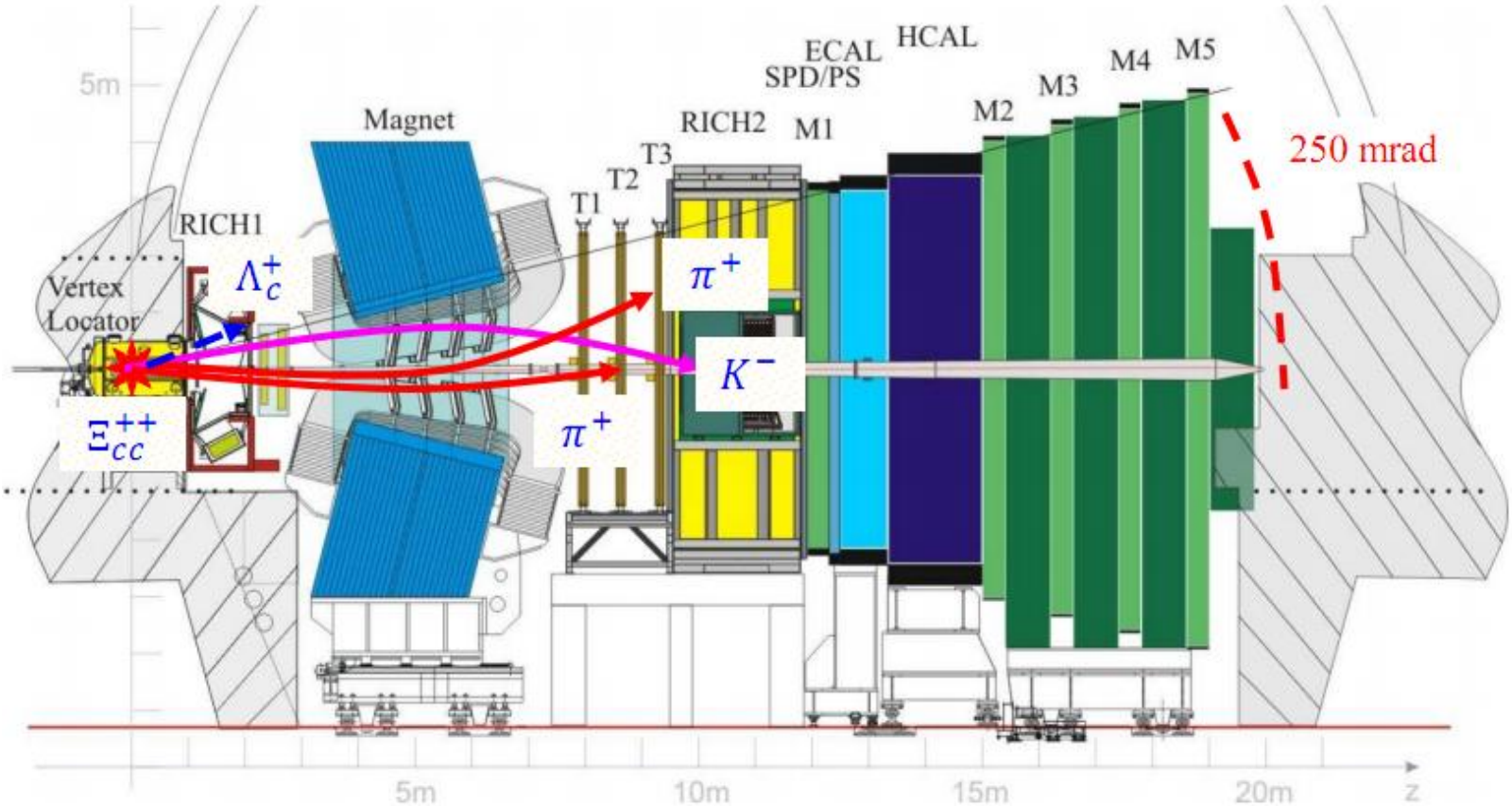
Very puzzling



LHCb experiment

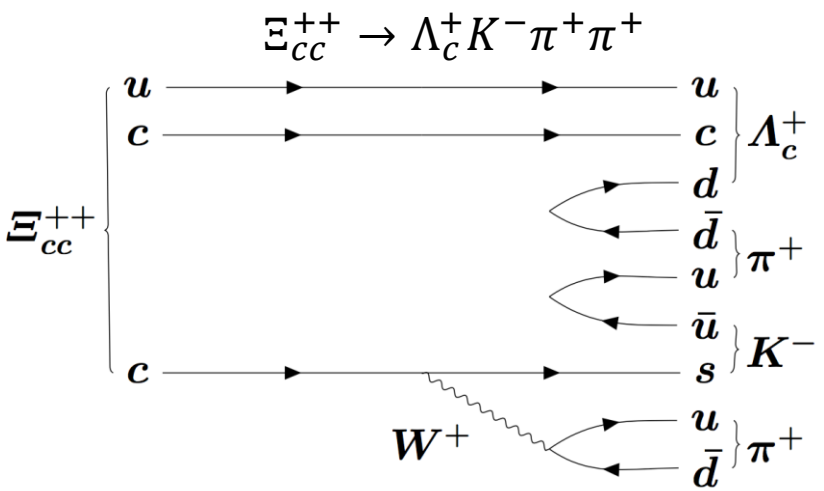
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

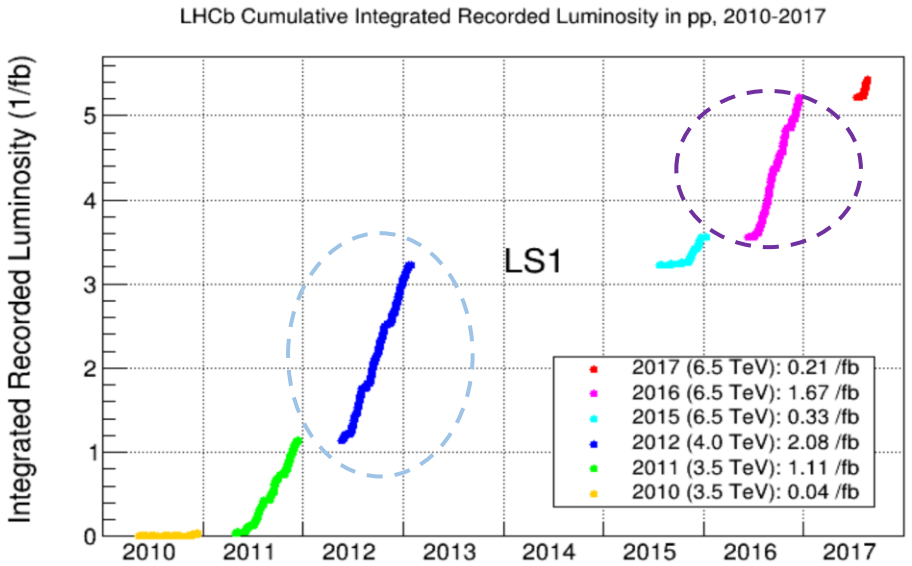
Aiming for precision measurements in b, c flavor sectors
Acceptance: $2 < \eta < 5$



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

- Expected to have longer lifetime than Ξ_{cc}^{+}, higher sensitivity at LHCb
- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, branching fraction up to 10% Refs. [56]
- Data sample: LHCb run II at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}
  - Dedicated exclusive trigger ensuring high efficiency, full event reconstruction at trigger level
  - Run I data (2012) also analyzed for cross-check

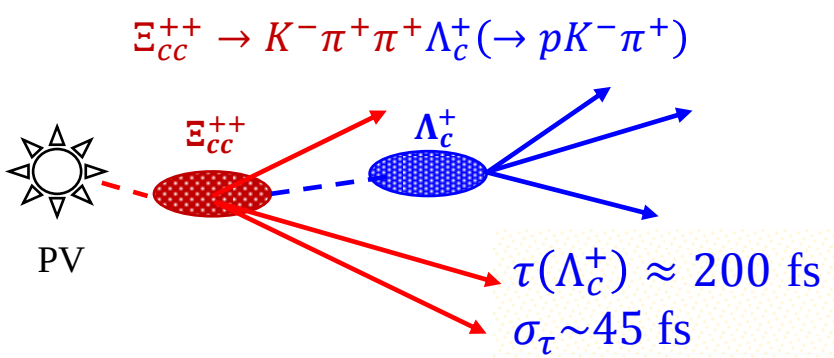


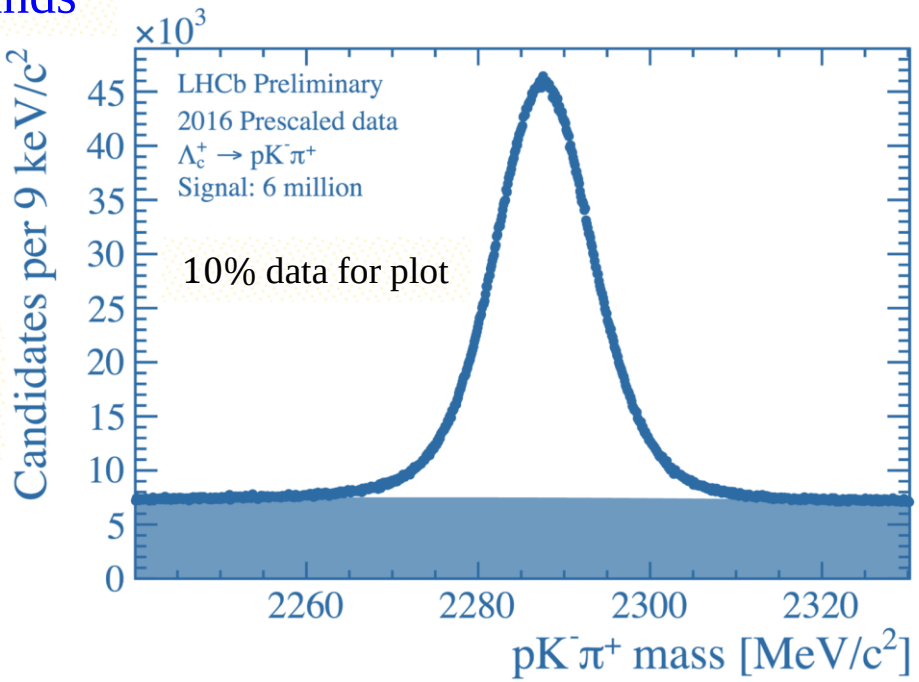


Candidate selection

- Ξ_{cc} cross-section much smaller ($\sim \times 10^{-5}$) than inelastic cross-section in pp collisions, expecting large hadronic backgrounds Refs.[5, 53-56]
- $\Lambda_c^+ \to pK^-\pi^+$:
  - p, K^-, π^+ tracks: positive particle ID, not produced from primary vertices
  - Λ_c^+: good vertex quality, separated from primary vertices
  - p, K^-, π^+ tracks and Λ_c^+ have large p_T

Strongly suppressing the backgrounds



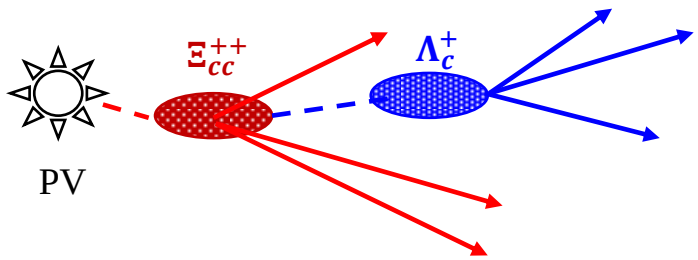


60 M fully reconstructed $\Lambda_c^+ \to pK^-\pi^+$ signal decays

The machine learning

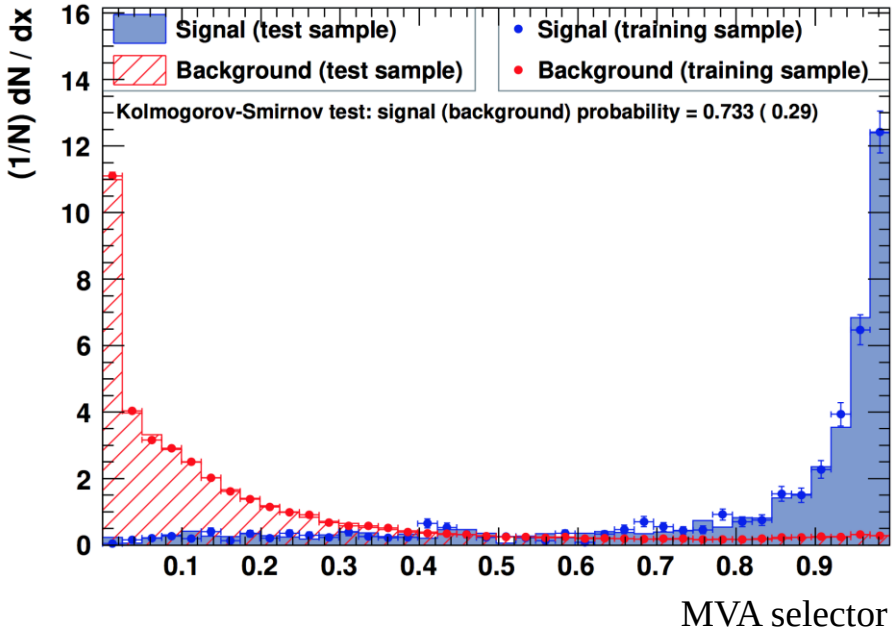
- Λ_c^+ combined with PID-selected $K^-\pi^+\pi^+$ tracks to form Ξ_{cc}^{++} candidates
- Multivariate selector further explores
  - Decay fit quality
  - Kinematics of final states
  - Ξ_{cc}^{++} vertex separation from PV

$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$



❑ More sensitive to long lived particles

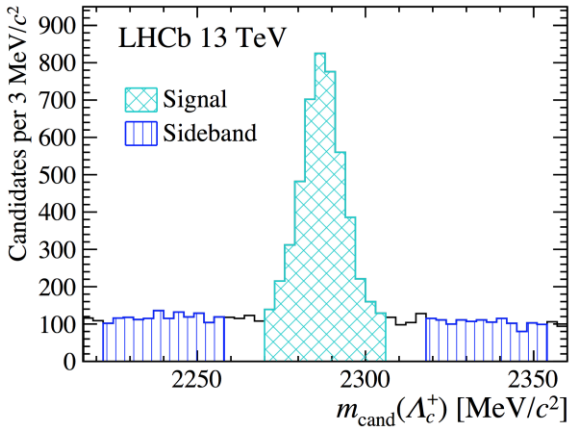
Selector optimized using simulated decays for signals and a wrong-sign control sample representing backgrounds: $\Xi_{cc}^{++} \to K^-\pi^+\pi^-\Lambda_c^+$

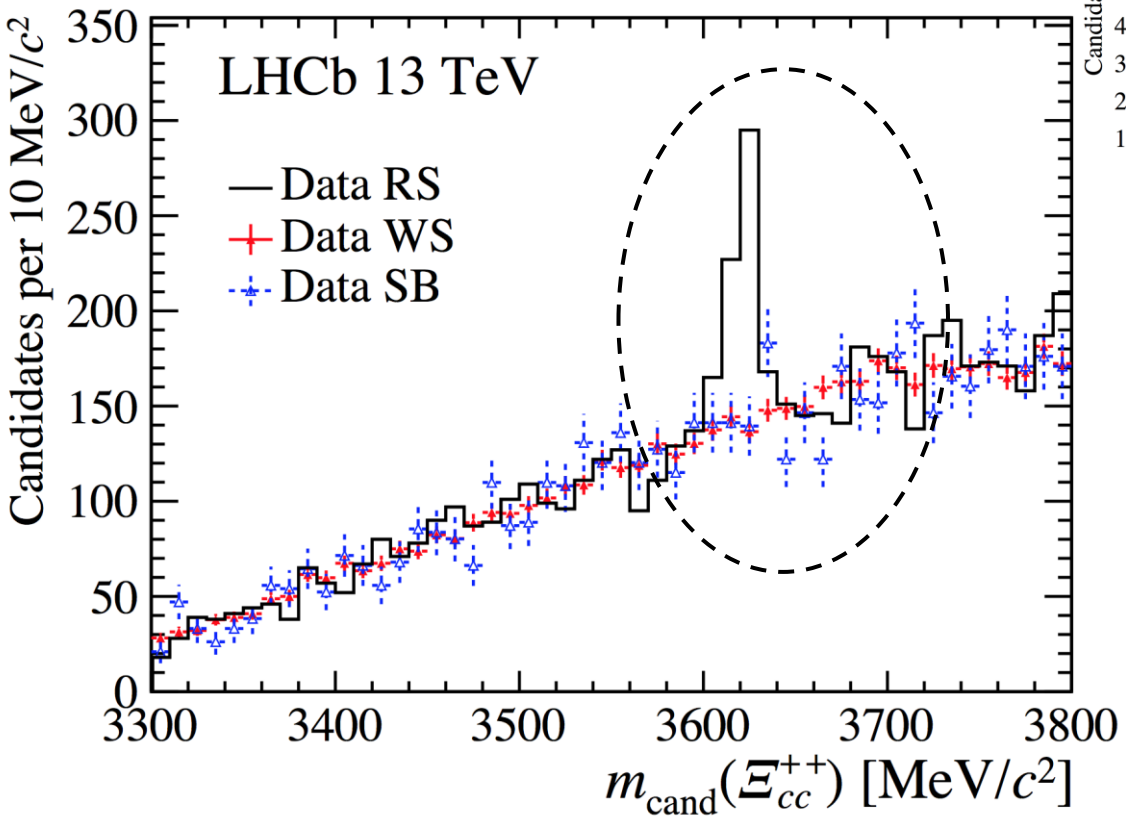


$\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum

PRL 119 (2017) 112001

- A significant structure in right sign (RS) combinations
- Not present in wrong sign (WS) combinations
- Not observed for Λ_c^+ background candidates





A significant peak!

More tests

$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$

- Signal candidates only present in Λ_c^+ signal region

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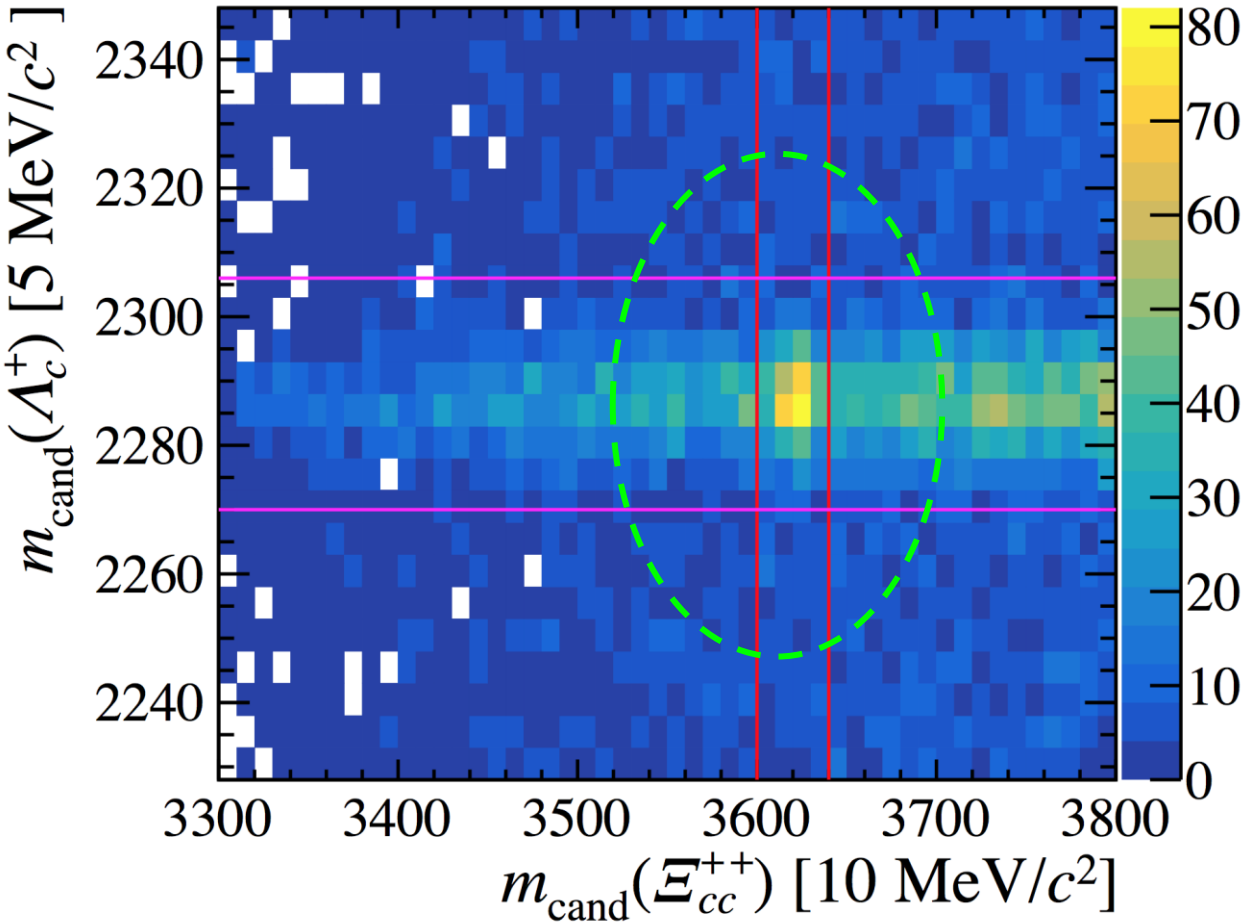

Signal yield

- Studying Λ_c^+-mass corrected mass: $m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$
  - Signal yield: 313 ± 33
  - Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
  - Local significance $> 12\sigma$

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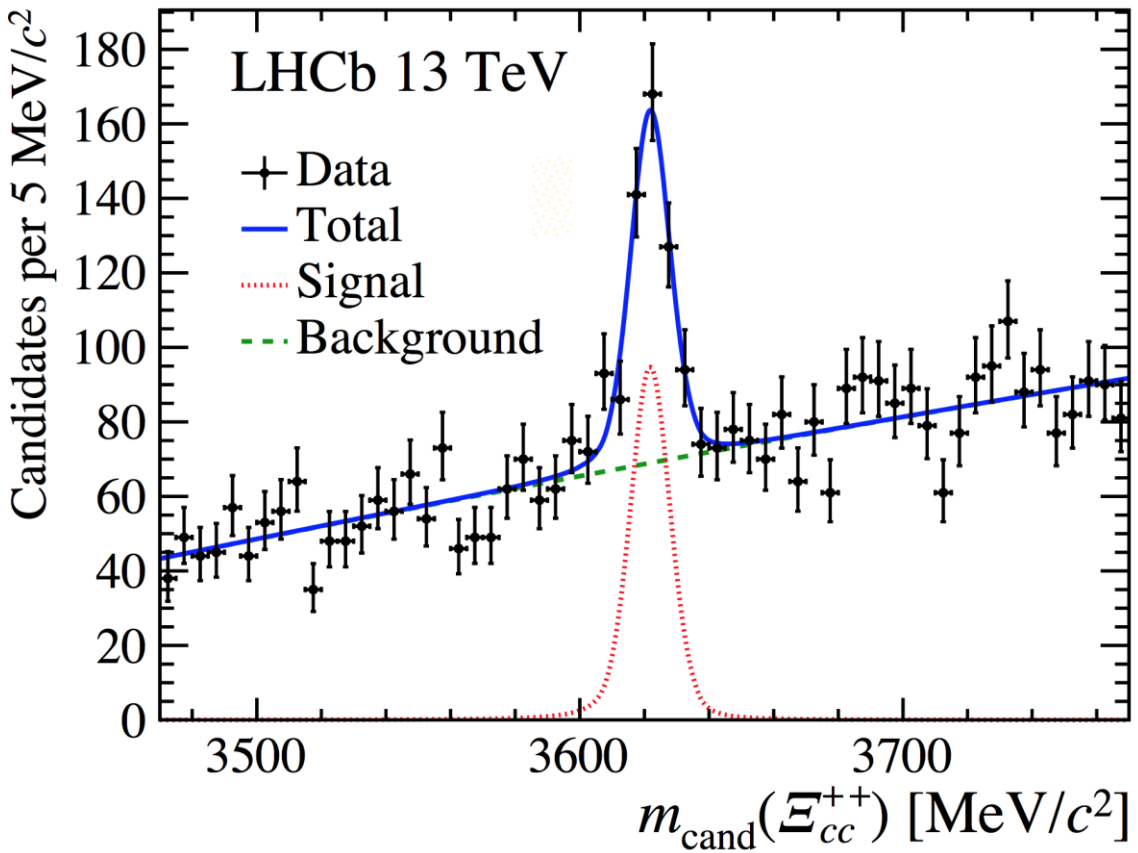
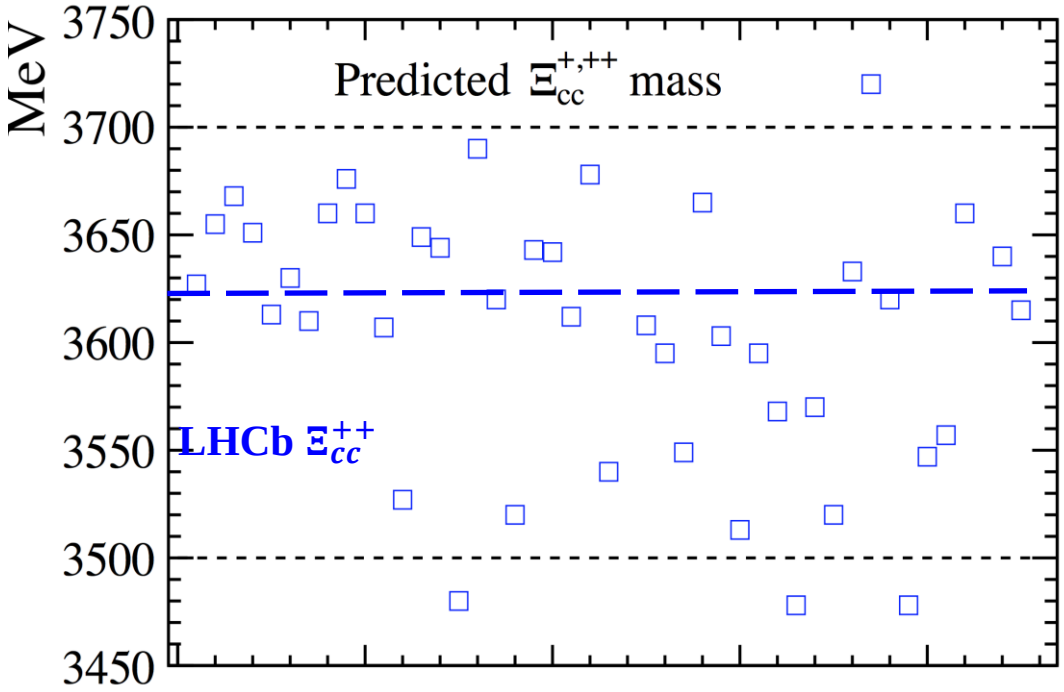


Mass measurement

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

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

Value consistent with many theoretical calculations



RunI data

$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$

- Signal peak presents in run I data sample with significance $> 7\sigma$

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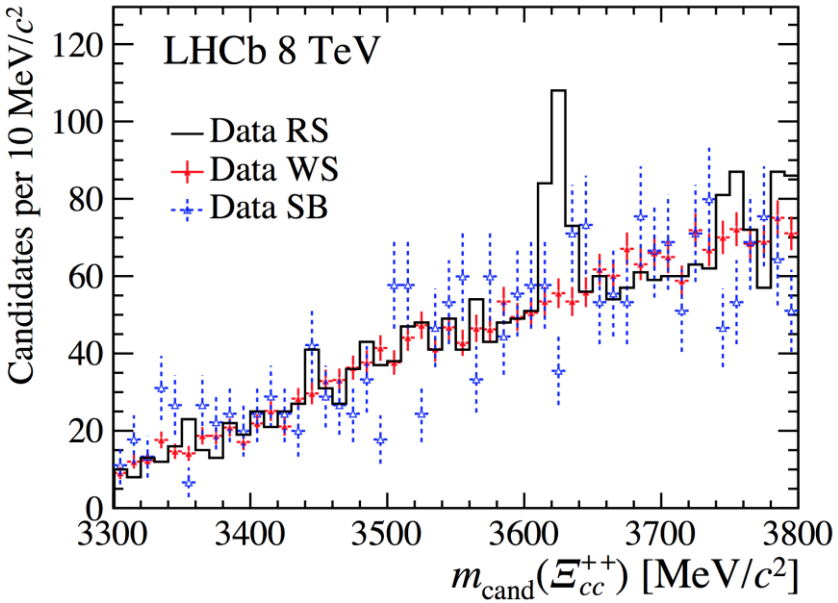

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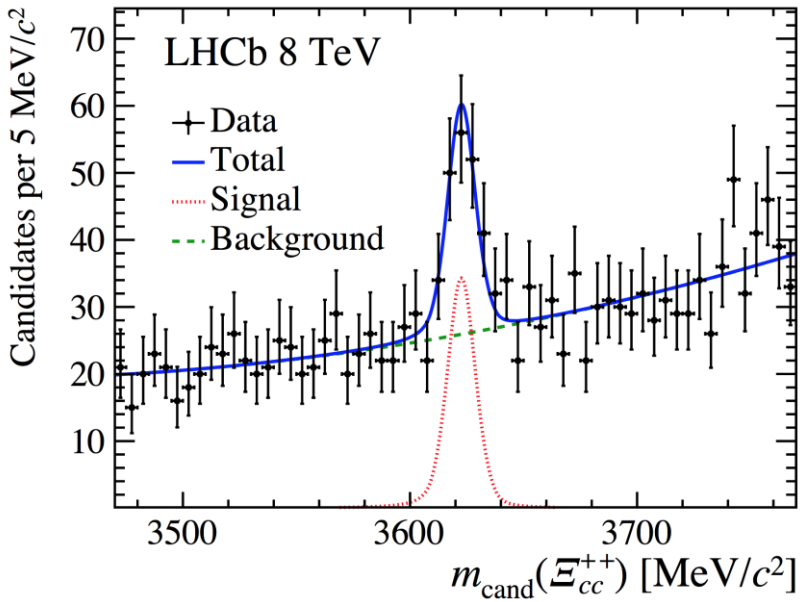

$N(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) = 113 \pm 21$

Resolution: 6.6 ± 1.4 MeV

$\delta M(\text{run I, run II}) = 0.8 \pm 1.4$ MeV

Consistent between two samples

It is a weak decay

- Peaking structure remains significant ($> 12\sigma$) after requiring minimum decay time, $t > 5\sigma_t$. It is indeed a weak decay.

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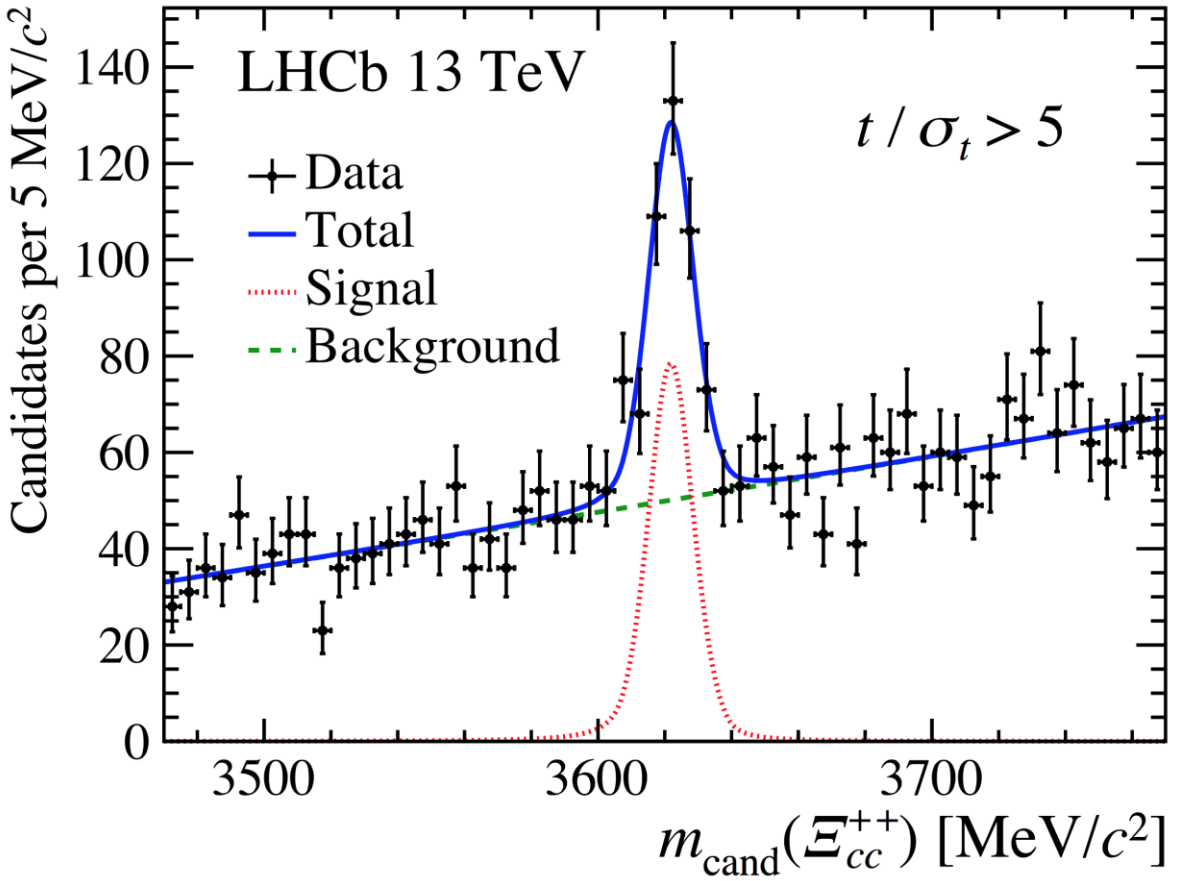

Comparison with SELEX

- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV
  - ➢ Inconsistent with being isospin partners

Refs. [46-48]

- Production: $N(\Xi_{cc})/N(\Lambda_c^+)$ much smaller in LHCb result

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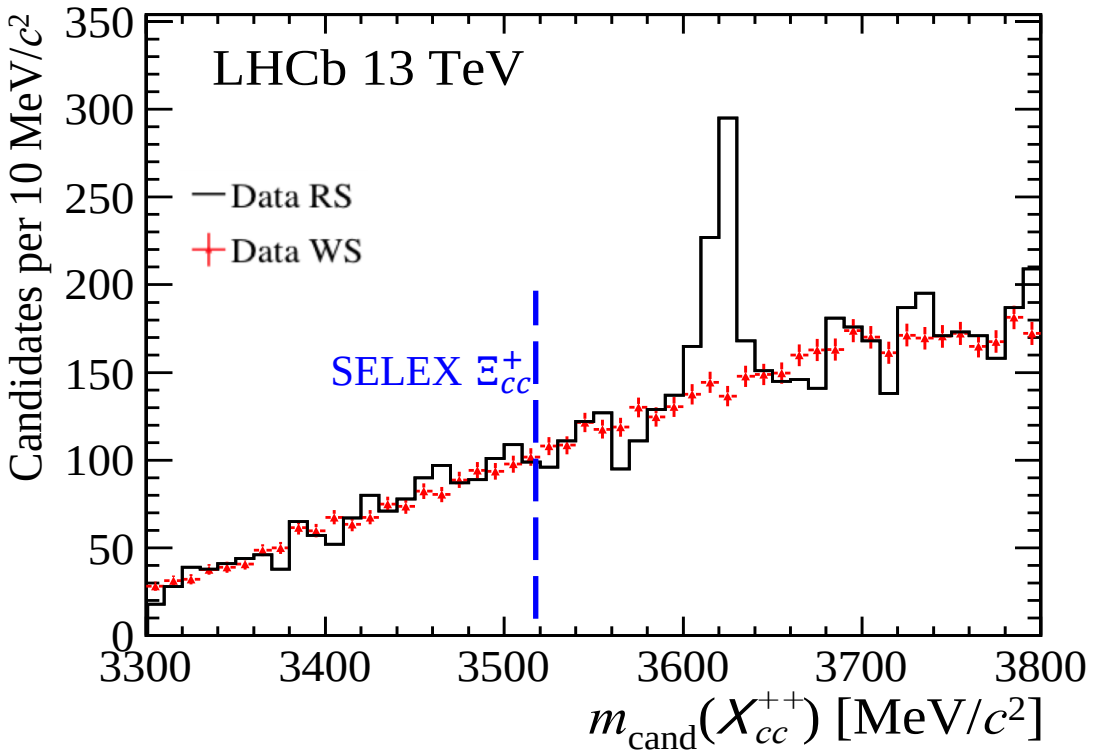
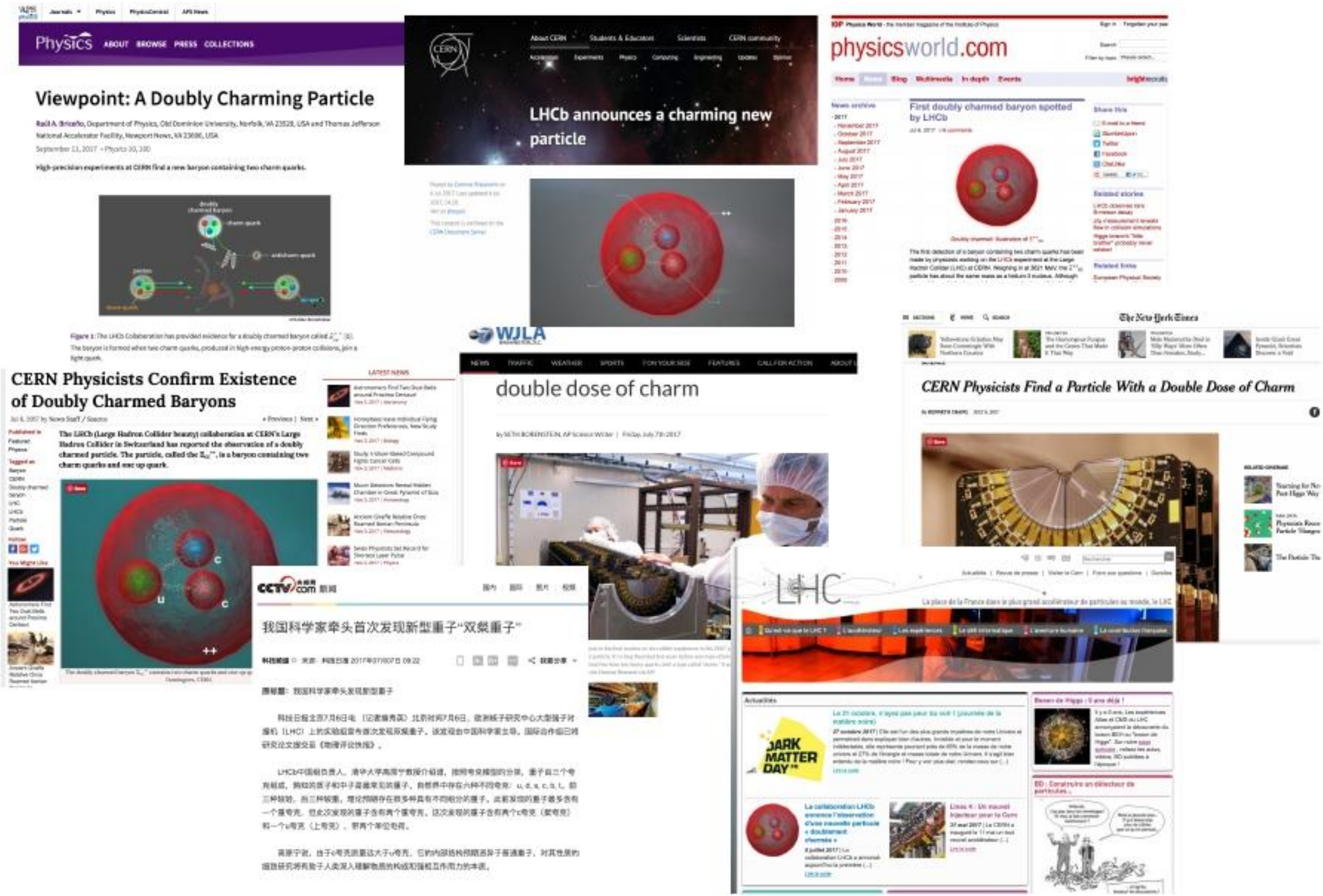


The “news”



Physics
Viewpoint: A Doubly Charming Particle
High-precision experiments at CERN find a new baryon containing two charm quarks.
LHCb announces a charming new particle
physicsworld.com
First doubly charmed baryon spotted by LHCb
CERN Physicists Confirm Existence of Doubly Charmed Baryons
WJLA
double dose of charm
The New York Times
CERN Physicists Find a Particle With a Double Dose of Charm
我国科学家牵头首次发现新型重子“双粲重子”
LHC
DARK MATTER DAY

Summary

- LHCb observed the $\Xi_{cc}^{++}(ccu)$ state in the $\Lambda_c^+ K^- \pi^+ \pi^+$ decay
  - Mass 3621.40 ± 0.78 (tot) MeV inconsistent with Ξ_{cc}^+ observed by SELEX being its isospin partner
  - Opens new window for heavy flavour studies

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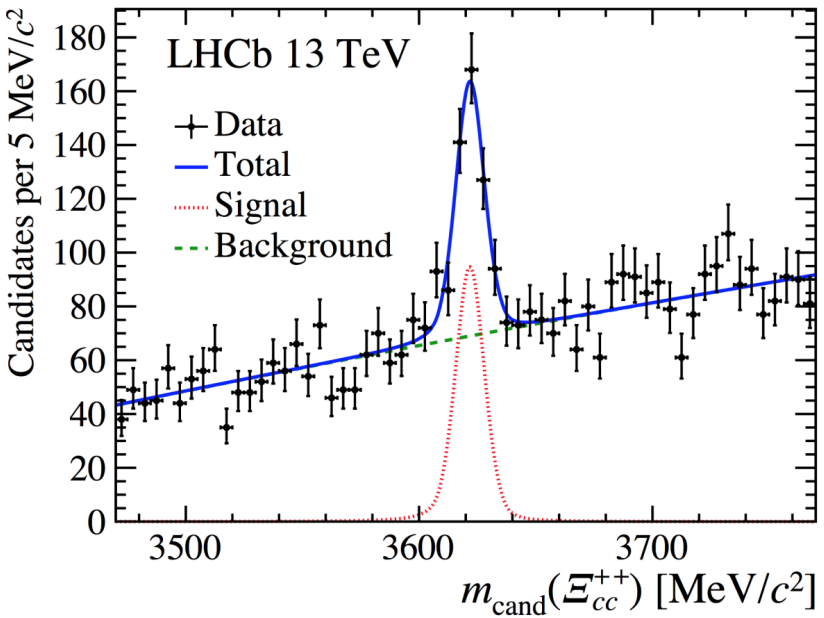
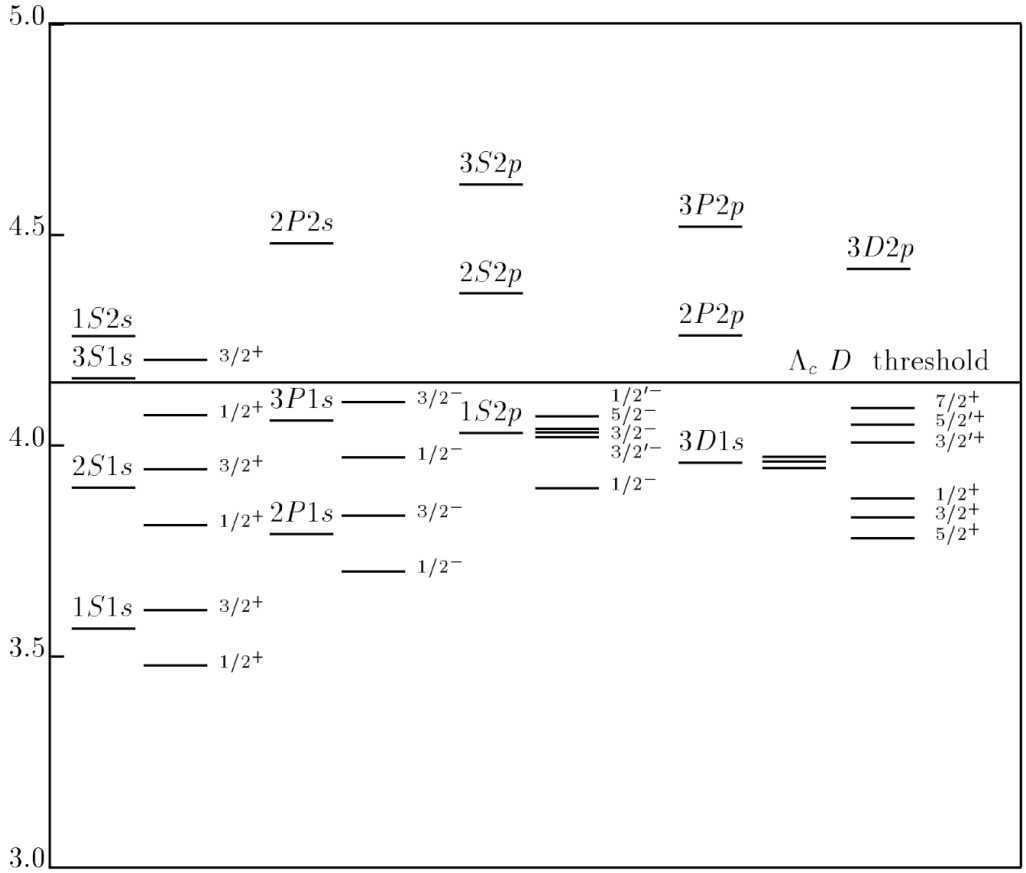
- Stay tuned for upcoming results:
  - Searching for Ξ_{cc}^{++} with more channels: $\Xi_c^+ \pi^+$, $\Lambda_c^+ \pi^+, pD^+ K^- \pi^+ \ldots$
  - Measurement of the Ξ_{cc}^{++} lifetime
  - Measurement of the production cross-section
  - …

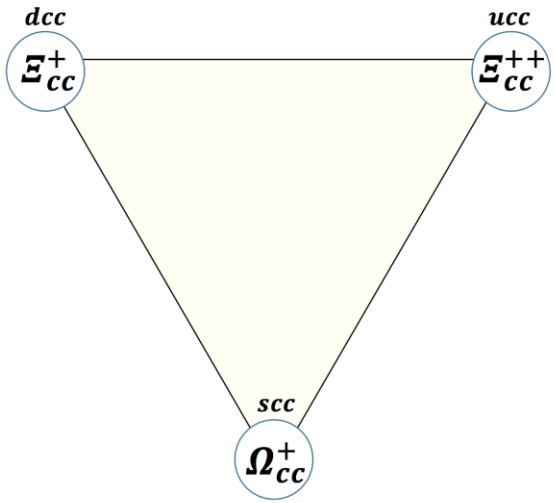


Thank you

Backup slides

Ξ_{cc} spectroscopy

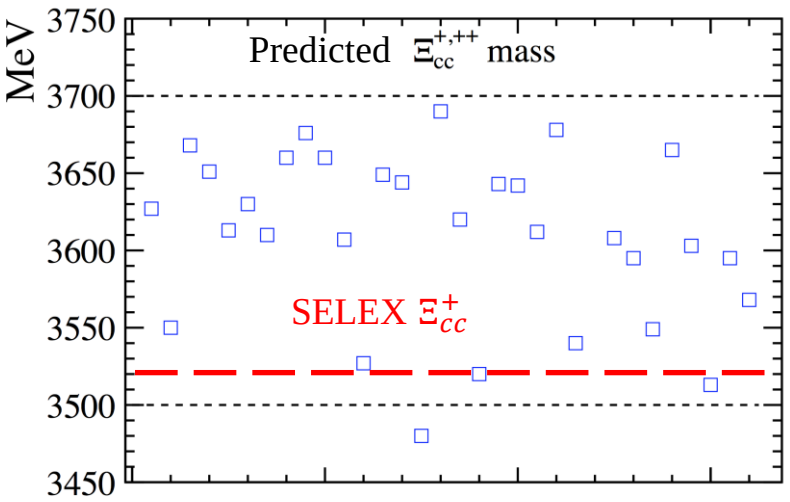




Studies of Ξ_{cc} by SELEX experiment

- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$
  - Number of inclusive Λ_c^{+} signals: ≈ 1650
  - 15.9 signals over 6.1 ± 0.5 background candidates with significance of 6.3σ
  - Mass: $m(\Xi_{cc}^{+}) = 3519 \pm 2$ MeV
  - Lifetime: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but non zero lifetime
  - Production: $R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} \sim 20\%$, much large than most model predictions of $\sim 0.1\%$
- $\Xi_{cc}^{+} \to p D^{+} \pi^{-}$
  - 5.62 signals over 1.38 ± 0.18 background candidates with 4.8σ
  - Mass: $m(\Xi_{cc}^{+}) = 3518 \pm 3$ MeV
  - Confirms the observed small lifetime
  - A few percent of D^{+} produced from $\Xi_{cc}^{+} \to p D^{+} \pi^{-}$ decay

Combined mass: 3518.7 ± 1.7 MeV



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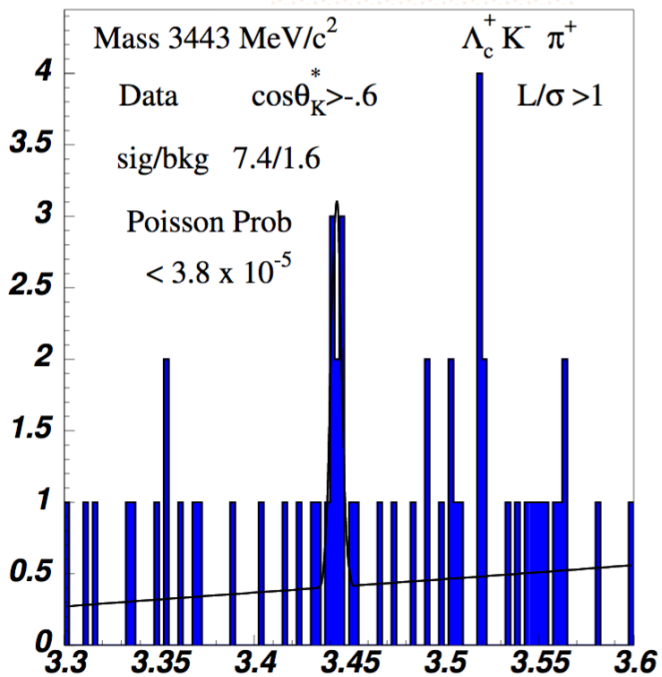
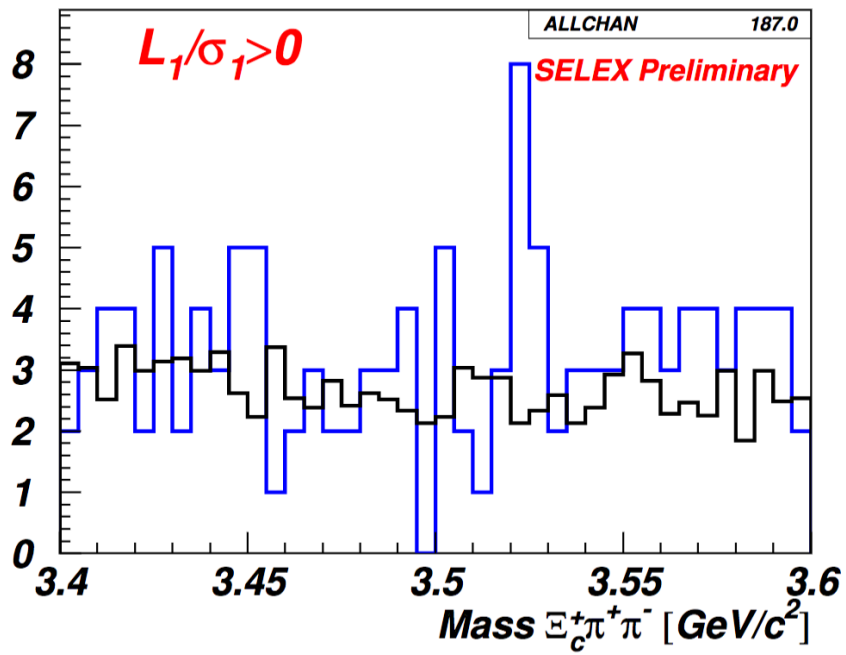
- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Claims by SELEX (conference reports)
  - Evidence of lower mass $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$
  - Evidence of $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$ decay

https://www-selex.fnal.gov/

$M \approx 3.45$ GeV



$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+ \pi^-$



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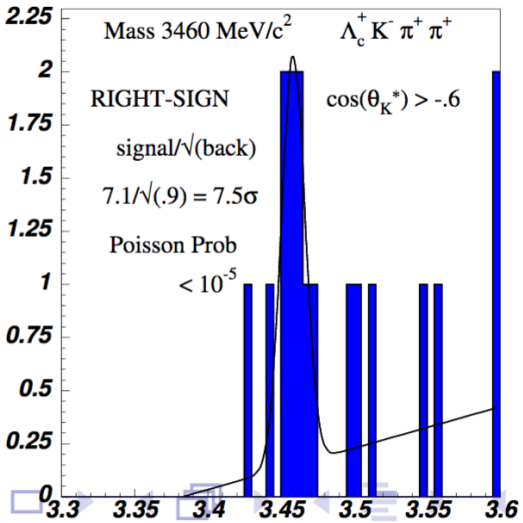
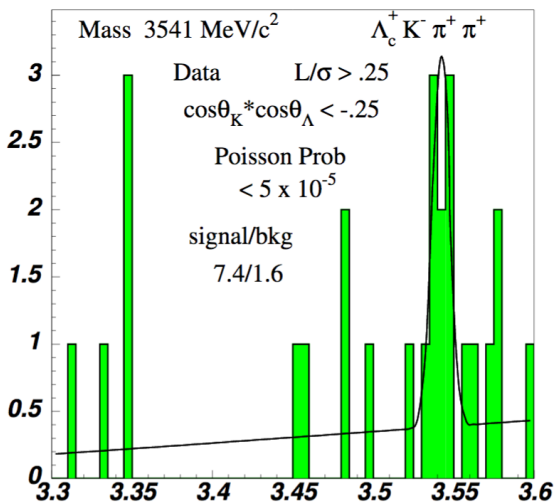
  - Evidence of lower mass $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$
  - Evidence of $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$ decay
  - Evidence of $\Xi_{cc}^{(*)++} \to \Lambda_c^+ K^- \pi^+ \pi^+$: three of them

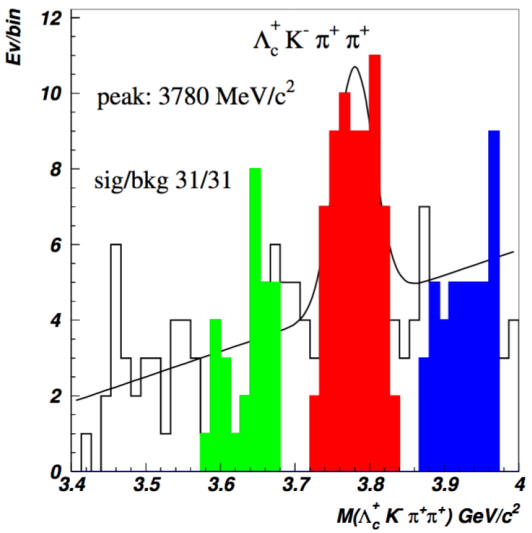
https://www-selex.fnal.gov/



$M \approx 3.46$ GeV



$M \approx 3.54$ GeV

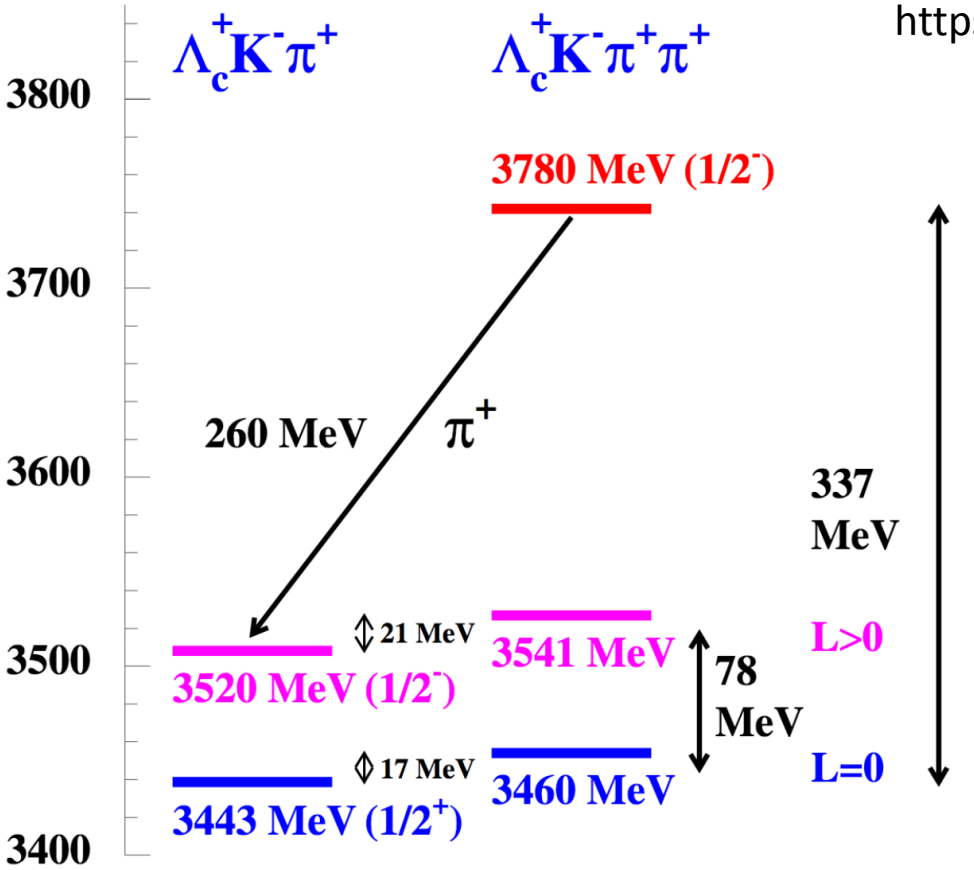


$M \approx 3.78$ GeV

Studies of Ξ_{cc} by SELEX experiment

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Claims by SELEX: consistent spectroscopy

https://www-selex.fnal.gov/



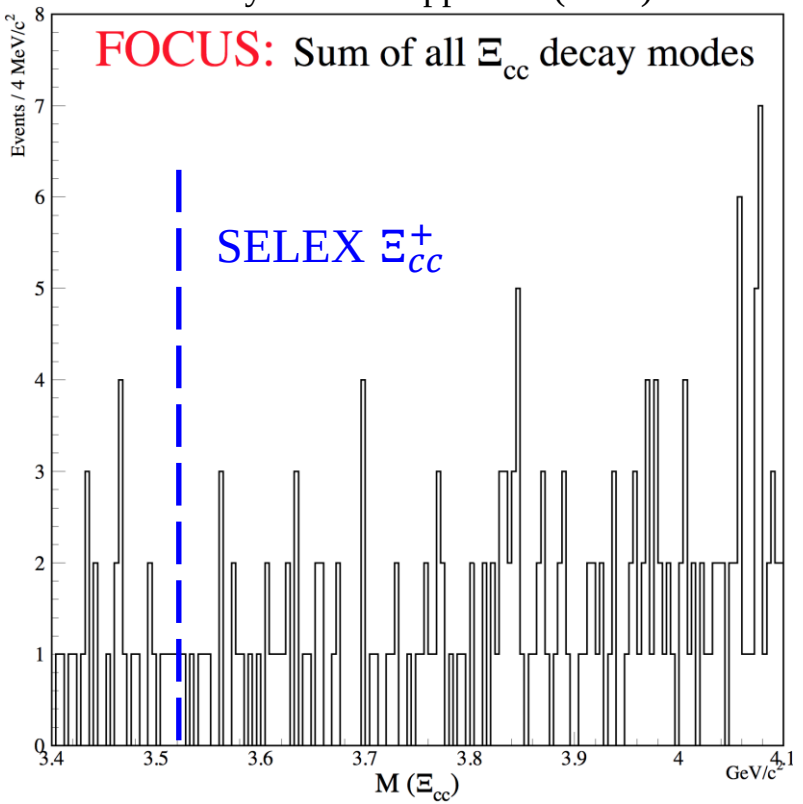
Studies of Ξ_{cc} by FOCUS

- FOCUS (Fermilab E831) studies charm hadrons produced in photon-nuclear fixed target collisions
- FOCUS didn't confirm Ξ_{cc}^{+} observed by SELEX in $\Lambda_c^+ K^- \pi^+$ decay

Decay Mode	$\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$	
Experiment	FOCUS	SELEX
Ξ_{cc} Events	<2.21 @ 90%	15.8
Reconstructed Λ_c	$19,444 \pm 262$	1650
Relative Efficiency	5%	10%
Ξ_{cc}/Λ_c^+	$<0.23\%$ @ 90%	9.6%
$\frac{\text{SELEX}}{\text{FOCUS}}$ Rel $\frac{\Xi_{cc}}{\Lambda_c}$ Prod	>42 @ 90%	

- Other modes also studied: $\Xi_{cc}^{+} \to \Lambda_c^+ X$, $D^0 X$ $D^+ X$, no SELEX-like signal peak observed

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

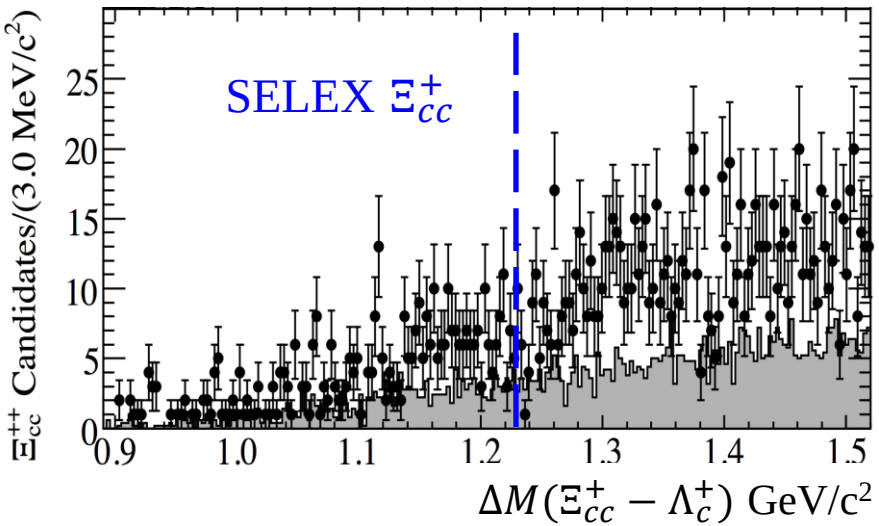


Studies of Ξ_{cc} by BaBar and Belle

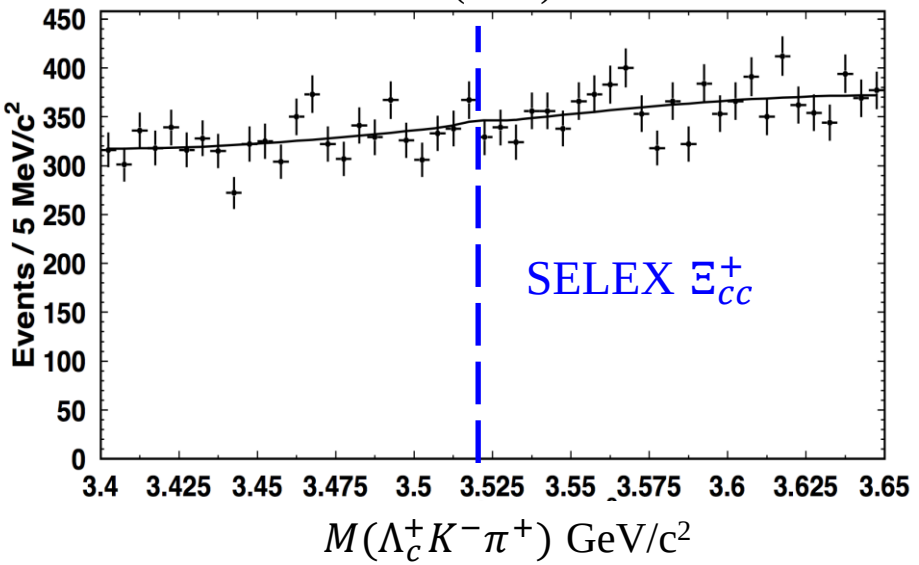
- e^+e^- colliders working at $\Upsilon(4S)$ mass $\sqrt{s} = 10.58$ GeV
- Large Λ_c^+ yields: ≈ 0.6 M at BaBar, ≈ 0.8 M at Belle
- SELEX-like Ξ_{cc}^+ signal not confirmed in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays

$$R = \frac{\sigma(\Xi_{cc}^+) \times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 2.7 \times 10^{-4} \text{ (BaBar)} \quad 1.5 \times 10^{-4} \text{ (Belle)} \quad @\ 95\%\ \mathrm{CL}$$

BaBar: PRD 74 (2006) 011103



Belle: PRL 97 (2006) 162001



Studies of Ξ_{cc}^{+} by LHCb

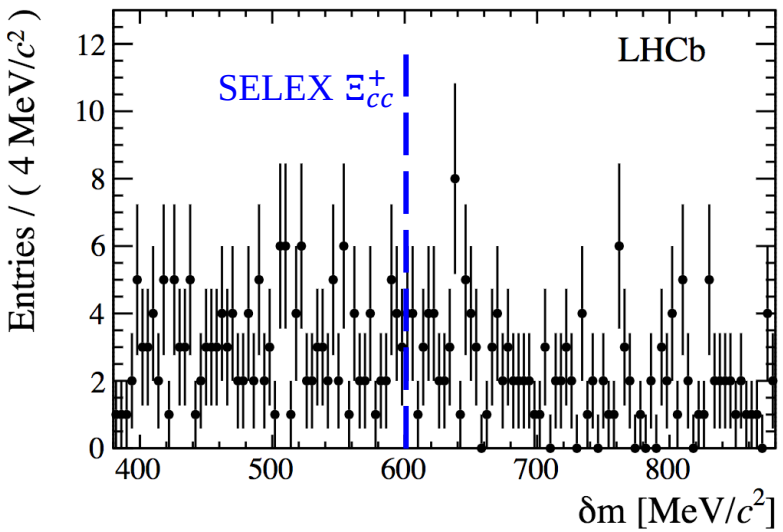
JHEP 12 (2013) 090

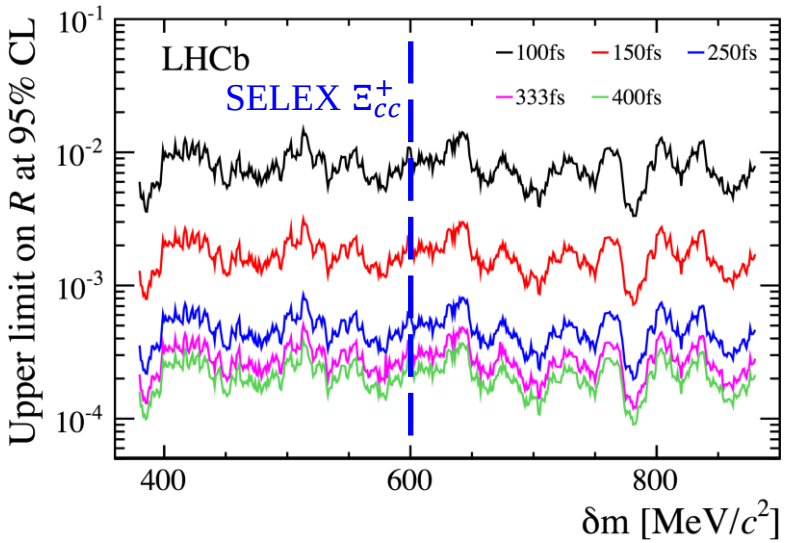
- LHCb searched for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decay with 0.65 fb^{-1} of 7 TeV data
  - $N(\Lambda_c^+) \approx 0.8$ M, requiring high-p_T
  - No significant peaking structure observed with $m \in [3.3, 3.8]$ GeV
  - Experiment sensitivity strongly depends on Ξ_{cc}^{+} lifetime

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 0.013 \text{ for } \tau = 100 \text{ fs},$$

$$< 3.3 \times 10^{-4} \text{ for } \tau = 400 \text{ fs} \quad @95\%$$

Increased by ~40 from 100 fs to 400 fs

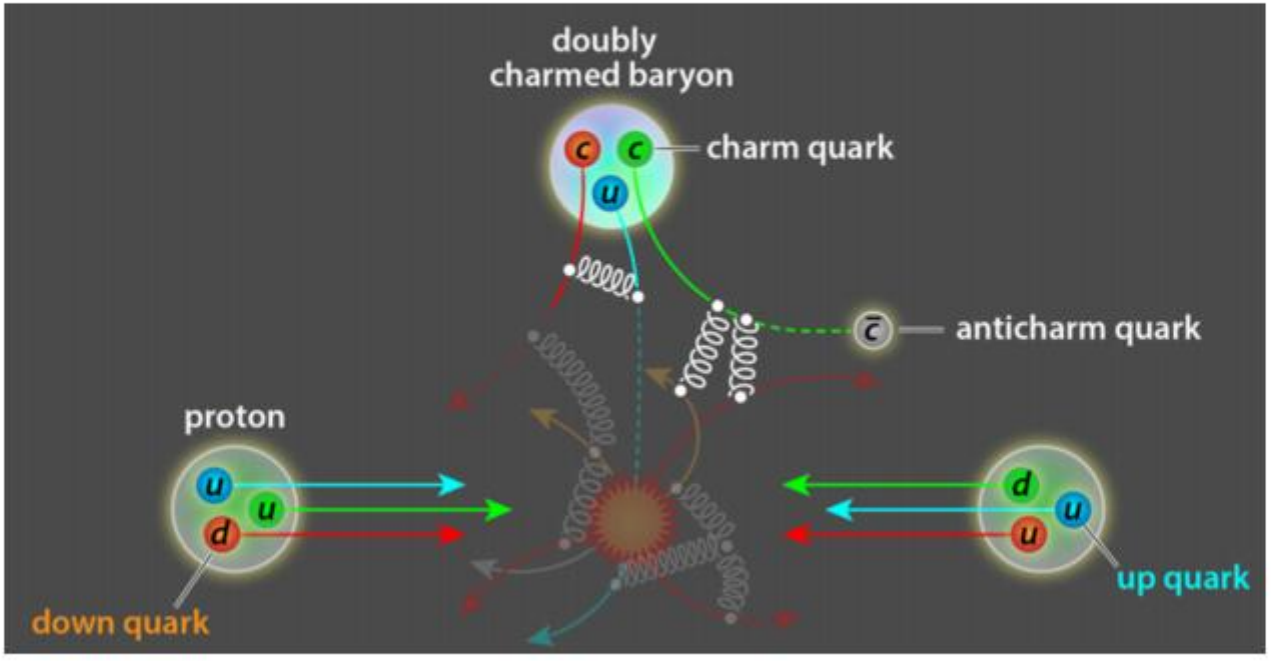




$$\delta m = m\left([pK^-\pi^+]_{\Lambda_c^+} K^-\pi^+\right) - m\left([pK^-\pi^+]_{\Lambda_c^+}\right) - m(K^-) - m(\pi^+)$$

LHCb experiment

- Since Ξ_{cc} states are not stable, not available around us, we need to produce them before studying their properties.
- LHCb produces them in proton-proton collisions
  - Small cross-section: $\sigma(\Xi_{cc}) \sim 1\mu b$ or 1 in 10^5 pp collisions, huge backgrounds



- Many different ways of transformations with weak decay, LHCb uses $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ to search for Ξ_{cc}^{++} $(\Lambda_c^+: cud)$

Fitting the mass peak

- Studying Λ_c^+-mass corrected mass: $m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$
  - Signal yield: 313 ± 33
  - Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
  - Local significance $> 12\sigma$

arXiv: 1707.01621

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

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

Systematic uncertainties

Source	Value $[\text{MeV}/c^2]$
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14

More tests

$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$

1. Multiple candidates: not creating fake narrow structure

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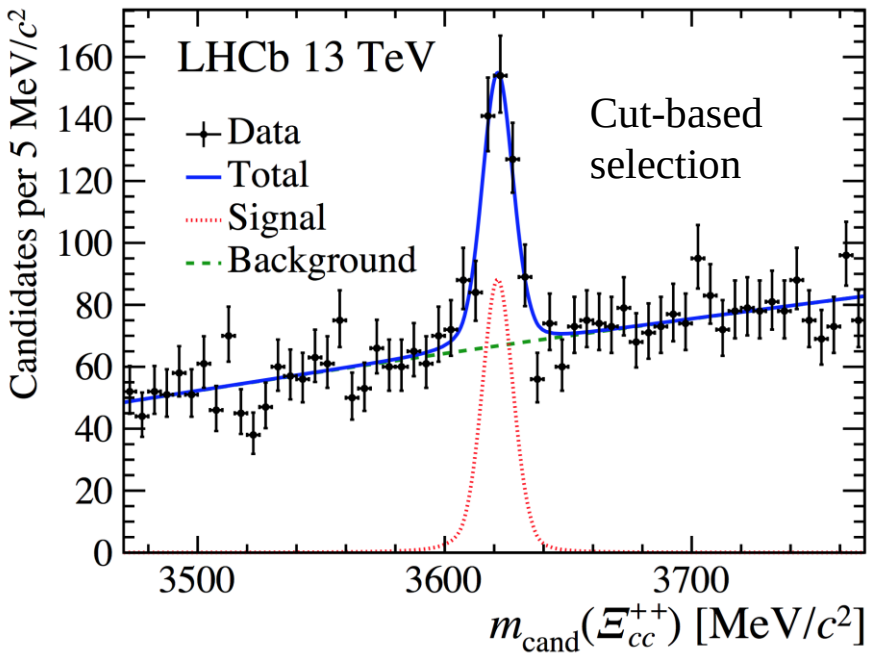
arXiv: 1707.01621

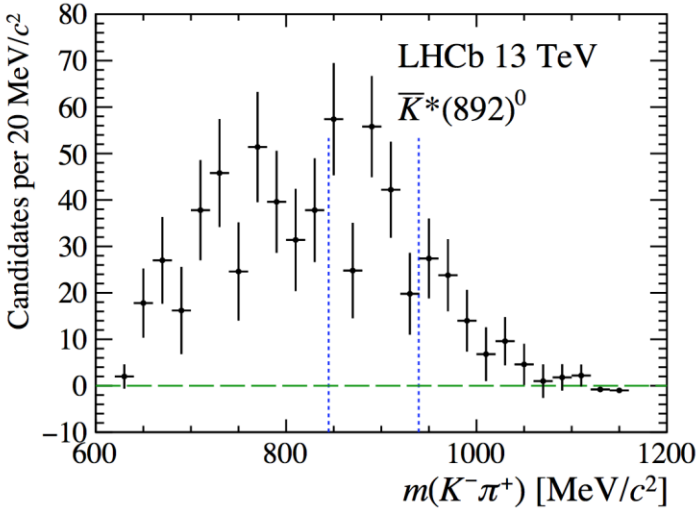
6. Using a cut based selection instead of using MVA, requiring good vertex fit quality, Ξ_{cc}^{++} vertex displaced and tracks are not produced from PV: peak significance $> 12\sigma$

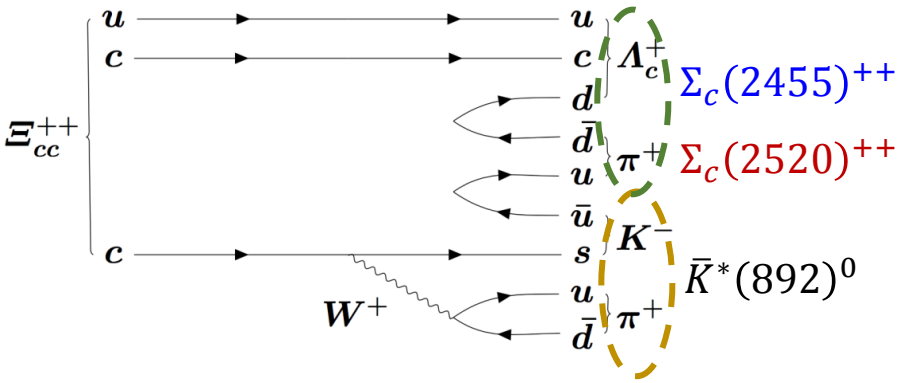


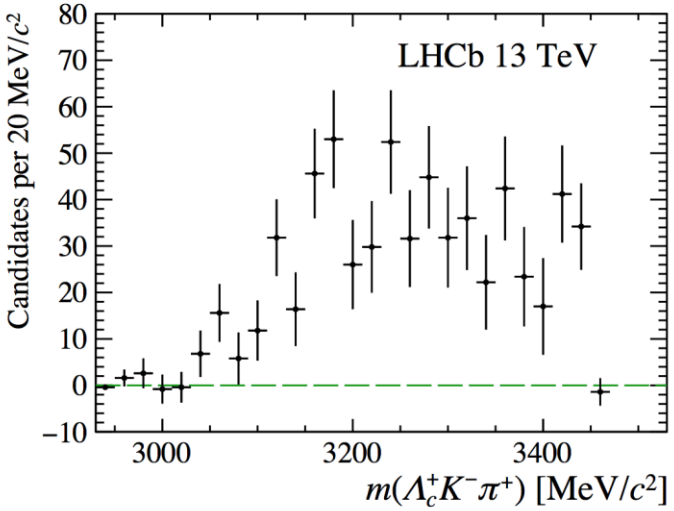
Signal properties

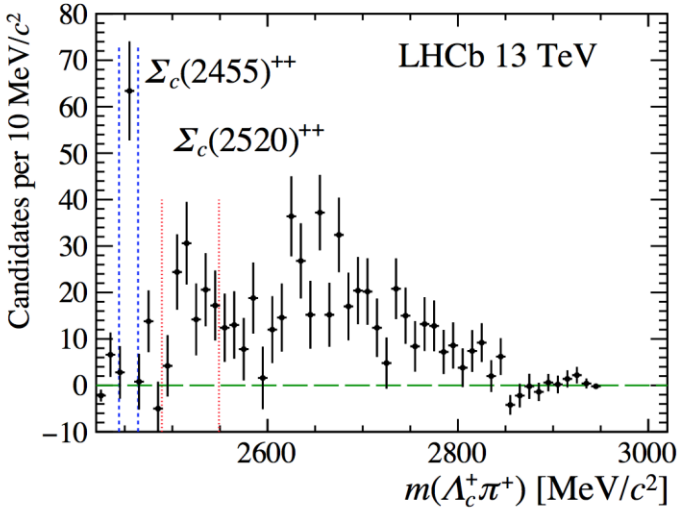
- Intermediate resonances: $\overline{K}^*(892)^0, \Sigma_c(2455)^{++}, \Sigma_c(2520)^{++}$

arXiv: 1707.01621









Prospects

- Searching for Ξ_{cc}^{++} with more channels: $\Xi_c^+\pi^+,\ \Lambda_c^+\pi^+, pD^+K^-\pi^+\ldots$
- Measurement of the Ξ_{cc}^{++} lifetime
- Measurement of the production cross-section
- Confirming its spin-parity: $½^+$
- Searching for its isospin partner Ξ_{cc}^{+} in a larger sample than the previous measurement
- Searching for Ω_{cc}^{+}
- Doubly heavy baryons with bottom quark: $\Xi_{bc}, \Omega_{bc}, \Xi_{bb}\ \ldots$
- The excited states?
- And new systems for CP violations

A long list of programs

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