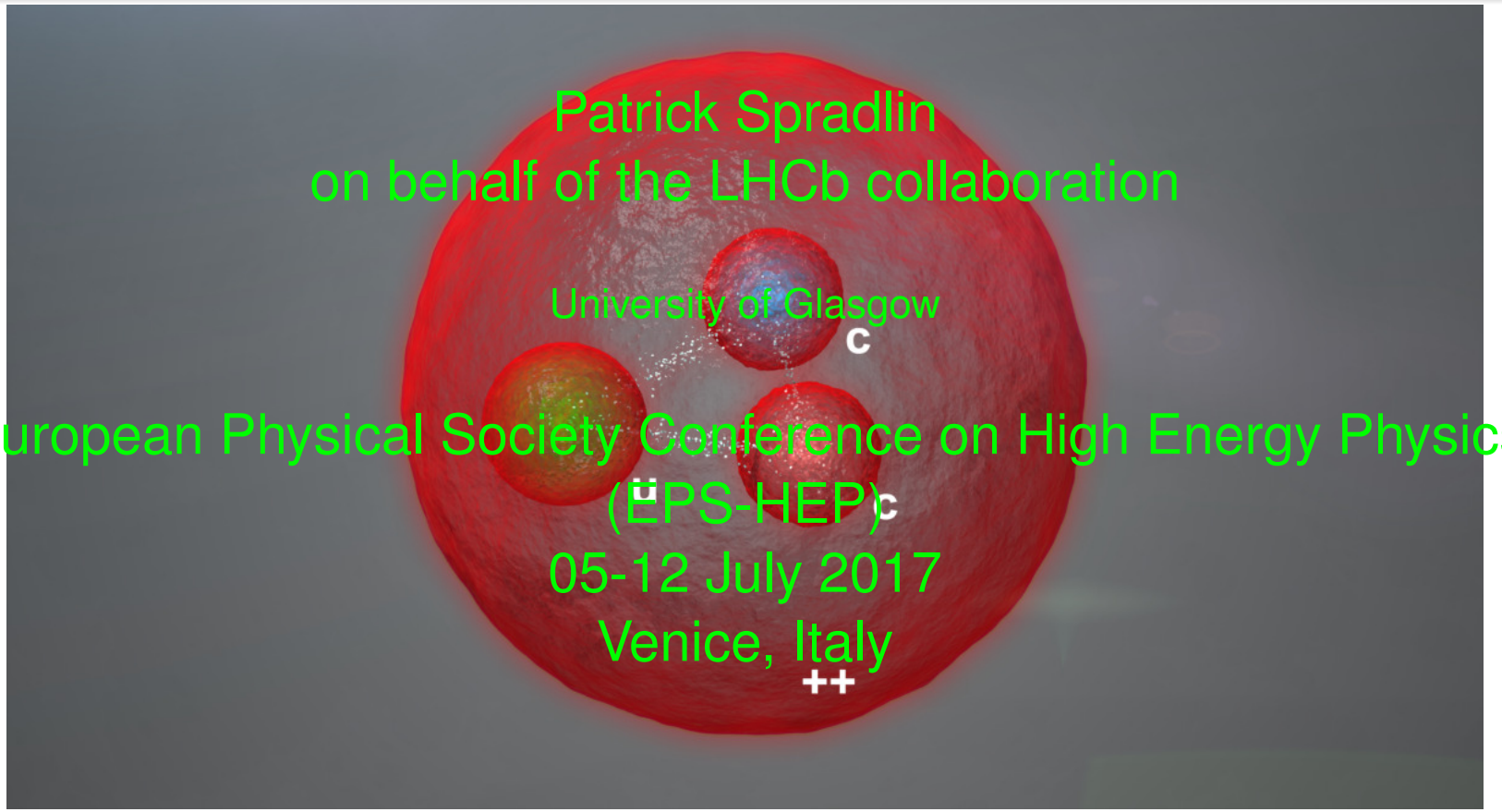
Discovery of the doubly charmed baryon Ξ_{cc}^{++} at LHCb

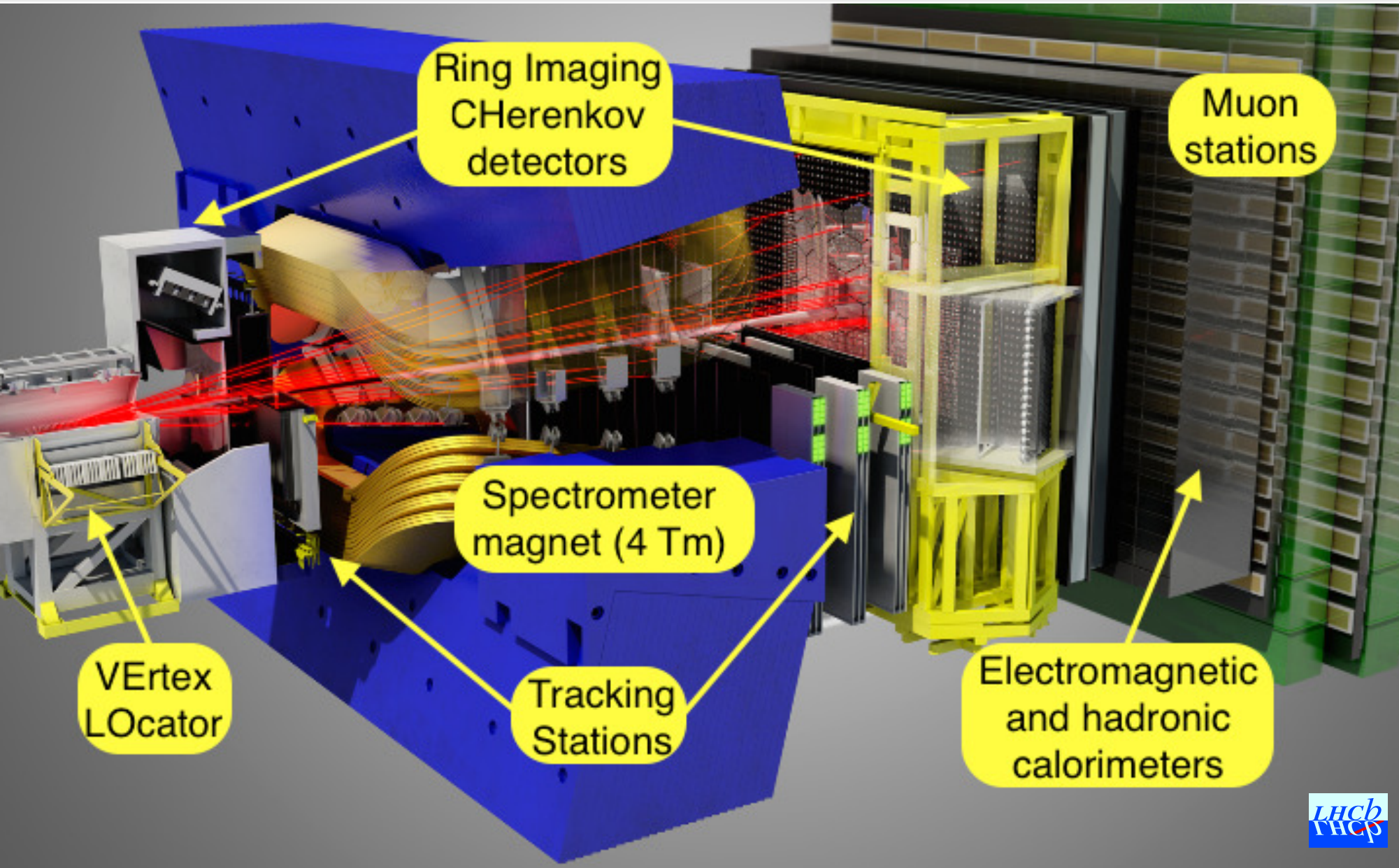


Patrick Spradlin
on behalf of the LHCb collaboration

University of Glasgow

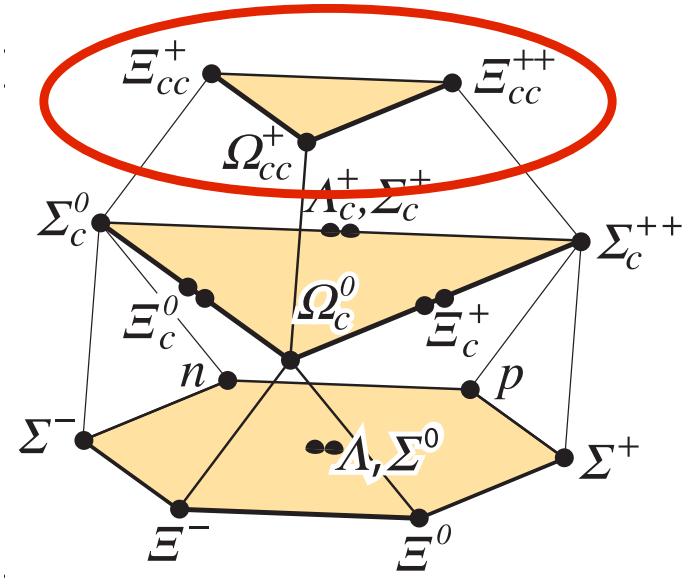
European Physical Society Conference on High Energy Physics
(EPS-HEP)
05-12 July 2017
Venice, Italy

THE LHCb DETECTOR



DOUBLY CHARMED BARYONS

The constituent-quark model predicts three weakly decaying $C = 2$, $J^P = \frac{1}{2}^+$ states: Ξ_{cc}^+ (ccd), Ξ_{cc}^{++} (ccu), and Ω_{cc}^+ (ccs).



SU(4) flavor multiplets, PDG Review of Particle Physics, Phys.Rev. D86, 010001.

There are several theoretical predictions of their properties on the market:
References in backup slides.

- Masses: 3500-3700 MeV, (broad range of predictions)
- Lifetimes: $\tau(\Xi_{cc}^+) \approx \tau(\Omega_{cc}^+) < \tau(\Xi_{cc}^{++})$
  - $\tau(\Xi_{cc}^+) \approx 50$ to 250 fs
  - $\tau(\Xi_{cc}^{++}) \approx 200$ to 700 fs

SELEX AND Ξ_{cc}^{+}

PHYS.REV.LETT. 89 (2002) 112001, PHYS.LETT. B628 (2005) 18-24

In 2002, SELEX, a fixed-target charm hadroproduction experiment at Fermilab, claimed the first observation of Ξ_{cc}^{+} in decays to $\Lambda_c^+ K^- \pi^+$.

Followed by a confirmation in 2004 in $D^+ pK^-$,

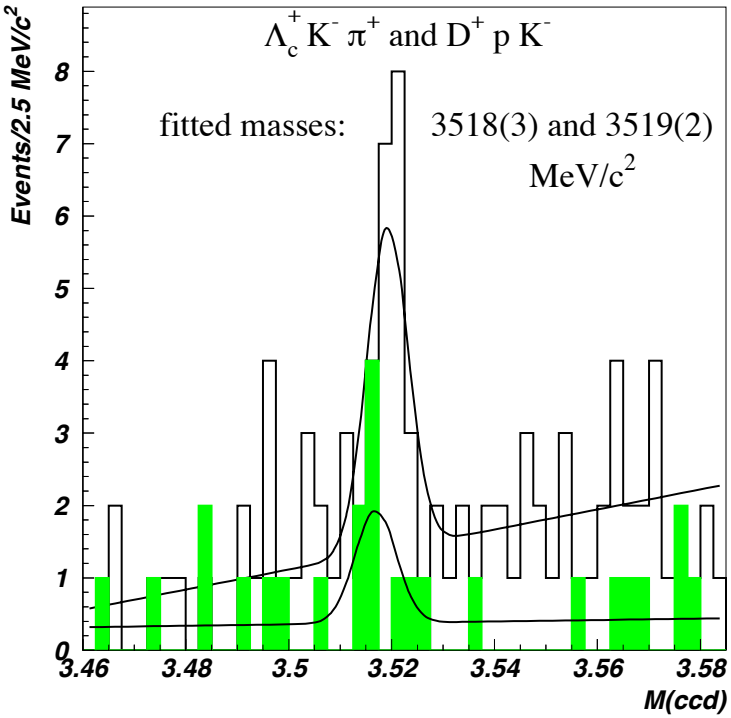
- $\Lambda_c^+ K^- \pi^+$: 15.9 sig over 6.1 bkg (6.3σ),
- $D^+ pK^-$: 5.62 sig over 1.38 bkg (4.8σ).

Combined mass:

$m(\Xi_{cc}^{+}) = 3518.7 \pm 1.7\,\mathrm{MeV}/c^2$.

Unexpected properties of the observation:

- Short lifetime, $\tau < 33\,\mathrm{fs}$ at 90% C.L.
- 20% of all Λ_c^+ production with baryon beams.

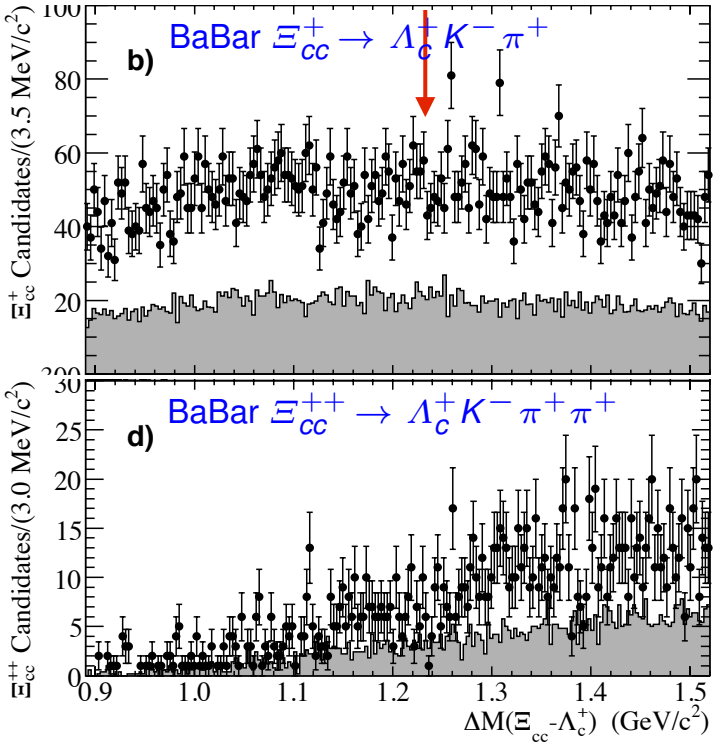


SELEX $\Lambda_c^+ K^- \pi^+$ and $D^+ pK^-$ distributions superposed
Phys.Lett. B628 (2005) 18-24

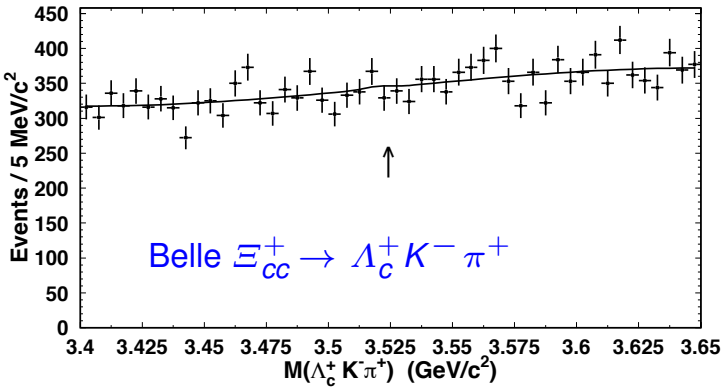
Unique production environment:

- Hyperon beam: admixture of Σ^- (68%), proton (18%), and π^- (13%),
- Thin foil target: Cu or diamond.

DOUBLY CHARMED BARYONS AT OTHER EXPERIMENTS



BaBar: Phys.Rev. D74 (2006) 011103



Belle: Phys.Rev.Lett. 97 (2006) 162001

FOCUS: Photon beam on Be fixed target

Nucl.Phys.Proc.Suppl. 115 (2003) 33-36

- Search for both Ξ_{cc}^+ and Ξ_{cc}^{++},
- 7 exclusive $\Xi_{cc} \to \Lambda_c^+ X$ modes,
- 14 exclusive $\Xi_{cc} \to D^{0,+} Y$ modes,
- No evidence of Ξ_{cc}.

BaBar: e^+e^- at $\Upsilon(4S)$ Phys.Rev. D74 (2006) 011103

- Search for both Ξ_{cc}^+ and Ξ_{cc}^{++},
- $\Xi_{cc}^{+(+)} \to \Lambda_c^+ K^- \pi^+ (\pi^+)$
- $\Xi_{cc}^{+(+)} \to \Xi_c^0 \pi^+ (\pi^+)$
- No evidence of Ξ_{cc}.

Belle: e^+e^- at $\Upsilon(4S)$ Phys.Rev.Lett. 97 (2006) 162001

- Searched for $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$,
- Found new Ξ_c^+ resonance decaying to $\Lambda_c^+ K^- \pi^+$
- No evidence of Ξ_{cc}.

LHCb'S FIRST SEARCH FOR Ξ_{cc}^{+}

Initial search at LHCb in $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$:

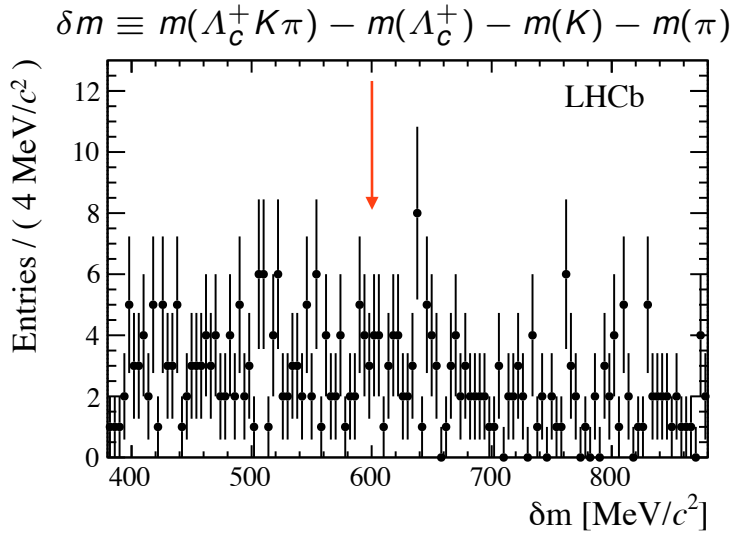
- The initial SELEX mode with a large expected BF.
- Based on 0.65 fb^{-1} of 2011 data.

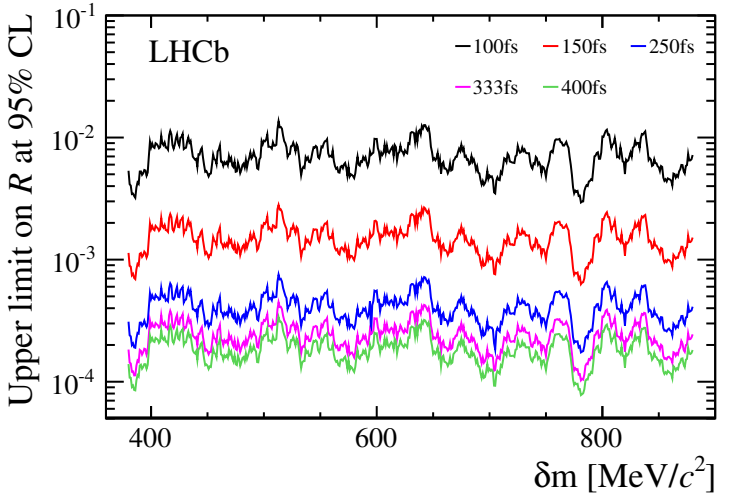
No evidence of Ξ_{cc}^{+} production.

- Set upper limits on production
  $R \equiv \frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$
  as function of mass and lifetime,

  $R < 0.013$ for $\tau = 100$ fs

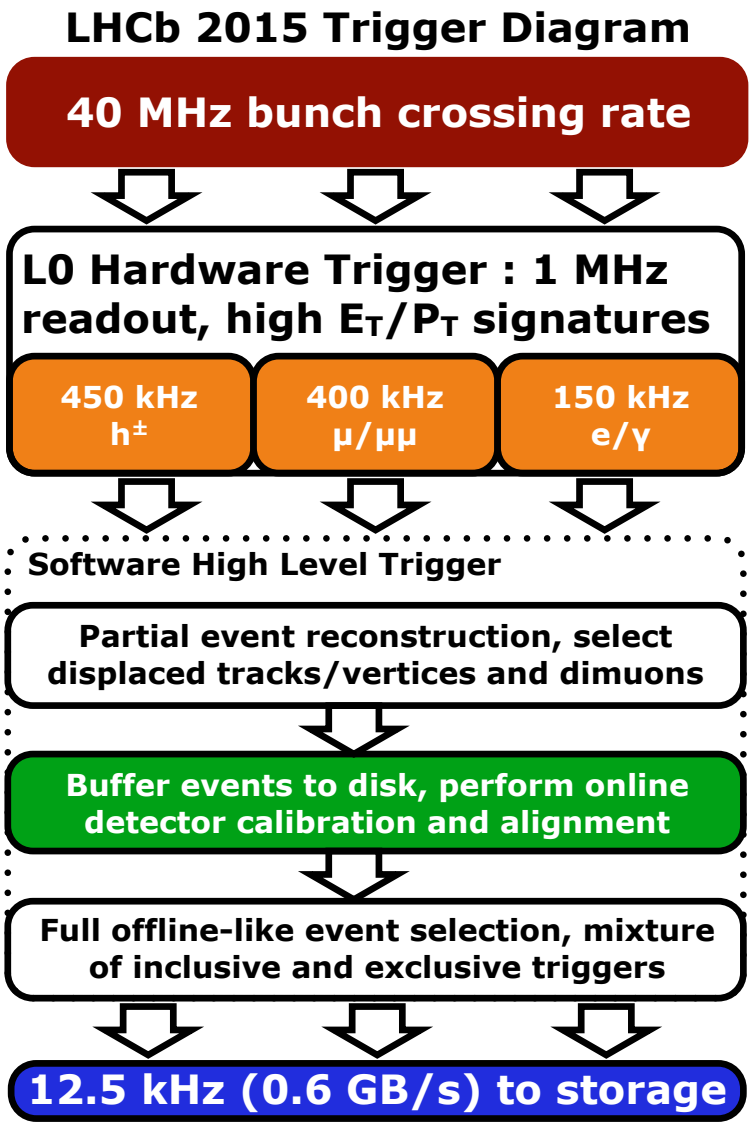
  $R < 3.3 \times 10^{-4}$ for $\tau = 400$ fs
- Due limited sensitivity at short lifetimes, this non-observation is not inconsistent with the SELEX claim.





LHCb RUN 2 DATA COLLECTION

COMPUT.PHYS.COMMUN. 208 (2016) 35-42



Searches for Ξ_{cc} in Run 2 utilize LHCb's Turbo stream.

After LHCb's hardware trigger, events are bufferred.

LHCb's automated real-time alignment and calibration runs, LHCb-PROC-2015-011

- Full detector alignment and calibration in minutes.

Full event reconstruction in software trigger

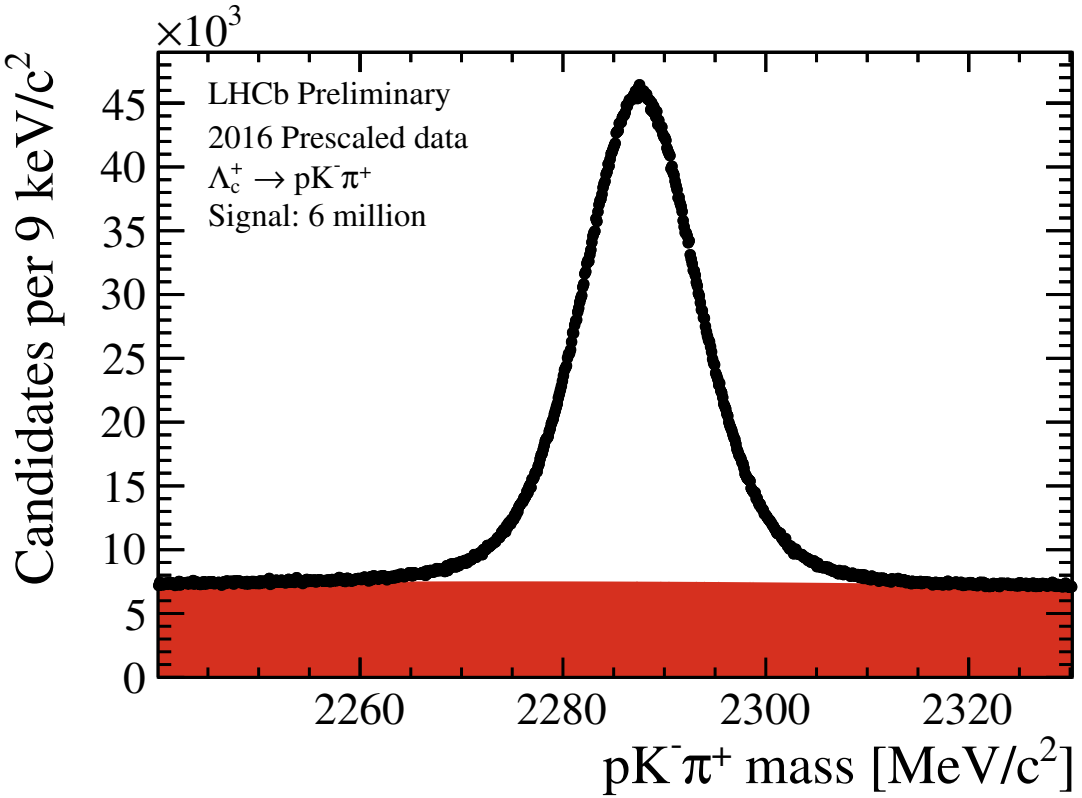
- Exclusive decay modes and calibration modes full reconstructed,
- Results stored and used as basis for analysis.

CHARM PRODUCTION AT $\sqrt{s} = 13\,\text{TeV}$

LHCb has some of the world's largest charm data sets,

$$\sigma(pp \to c\bar{c}X; 13\,\text{TeV})_{\text{LHCb}} = 2369 \pm 3 \pm 192\,\mu\text{b}$$

JHEP 1603 (2016) 159, erratum JHEP 1705 (2017) 074



~10% of 2016 data.

Large, high-purity samples of $\Lambda_c^+ \to pK^-\pi^+$

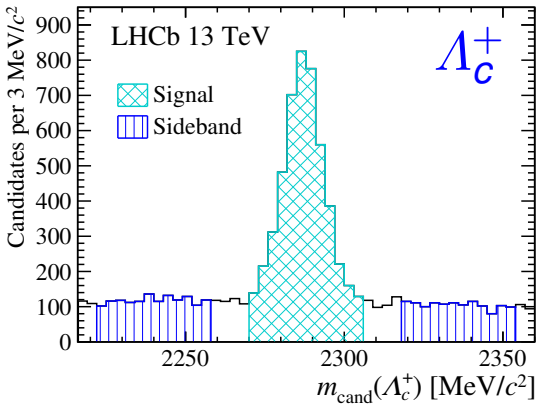
- 2016 search dataset: $\int \mathcal{L} = 1.7\,\text{fb}^{-1} \Rightarrow \sim$60 million $\Lambda_c^+ \to pK^-\pi^+$.

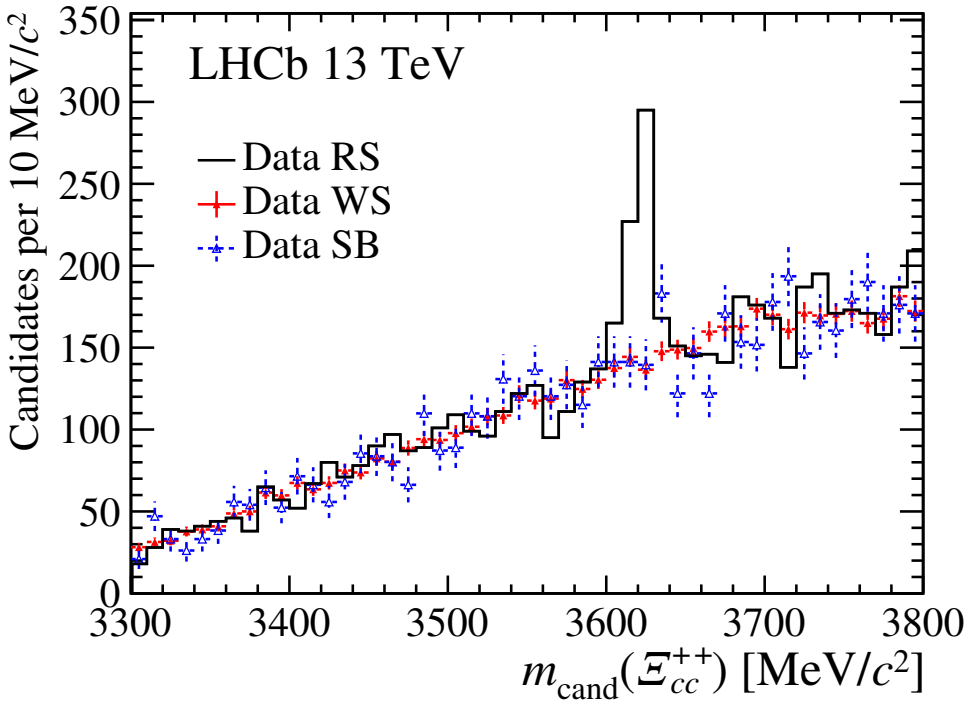
RECONSTRUCTION OF $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

Λ_c^+ combined with K^- and $2 \times \pi^+$ candidates,

- Unphysical 'wrong-sign' (WS) mode $\Lambda_c^+ K^- \pi^+ \pi^-$ also reconstructed.

Neural-network selector trained on simulated signal and wrong-charge data.





$$m(\Xi_{cc}^{++}) \equiv m[(pK^-\pi^+)_{\Lambda_c^+} K^-\pi^+\pi^+] - m[(pK^-\pi^+)_{\Lambda_c^+}] + m(\Lambda_c^+)_{\rm PDG}$$

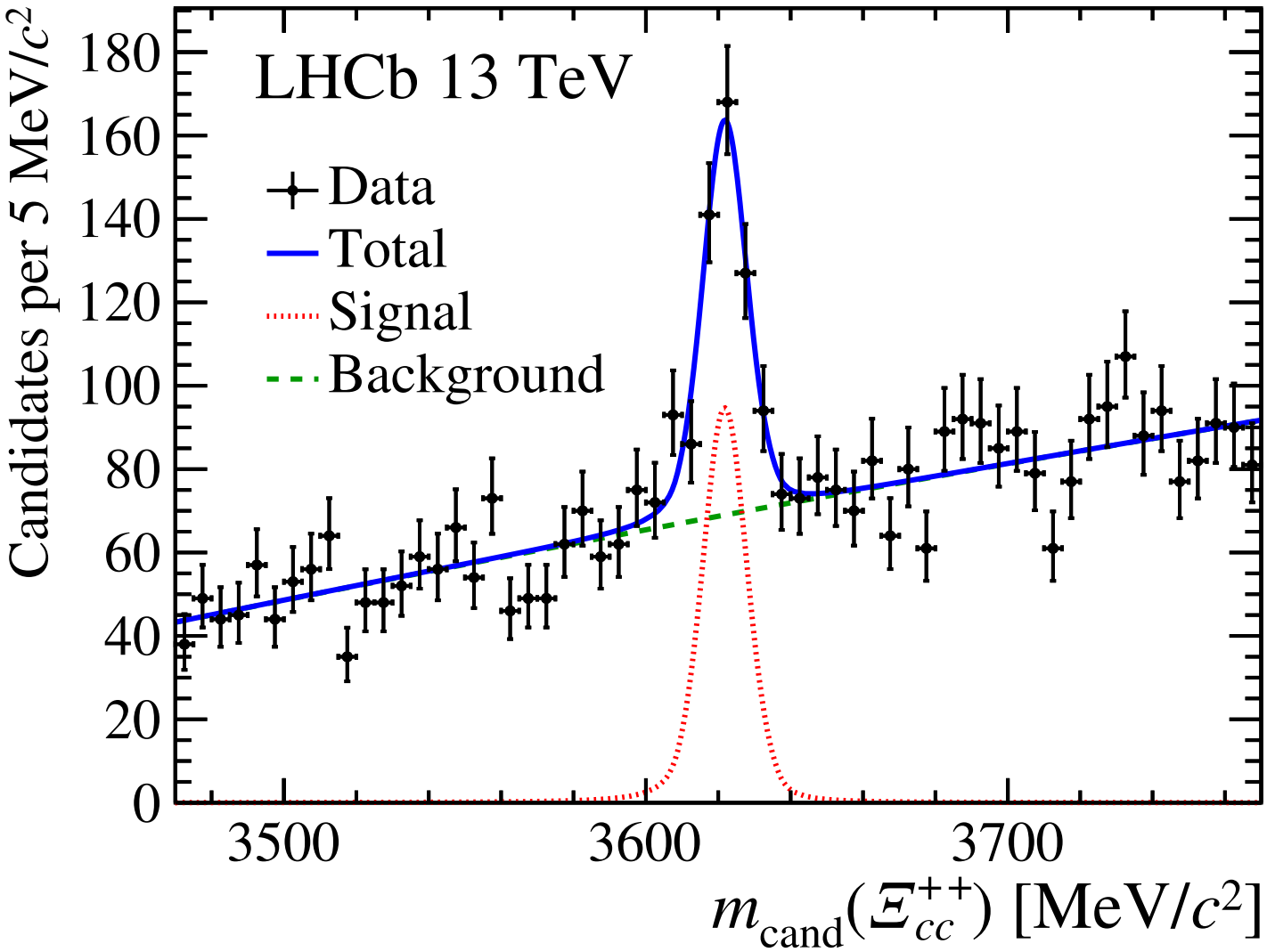
Clear structure visible at ~ 3620 MeV!

- No corresponding structure in WS nor in Λ_c^+ sidebands.

Likelihood fit in the range 3620 ± 150

- Yield: 313 ± 33 decays,
- Local significance: $> 12\sigma$ (likelihood ratio).

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

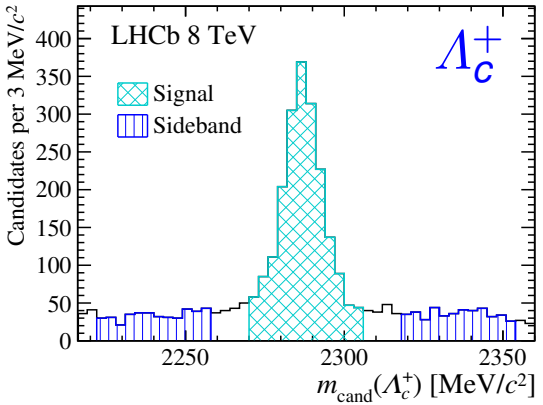


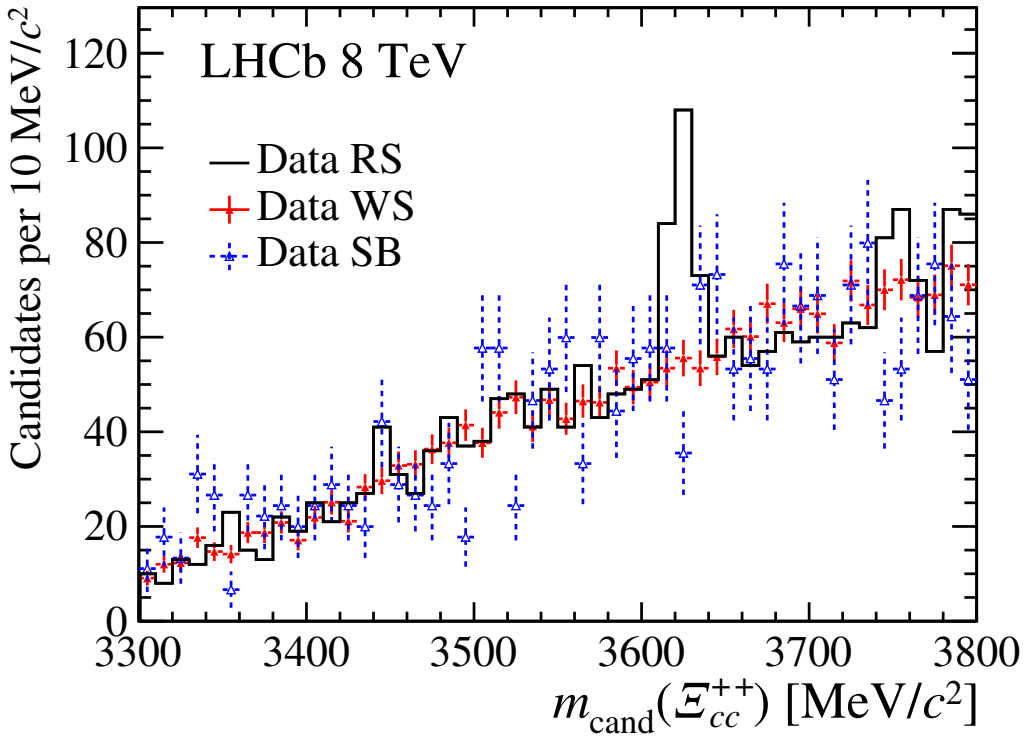
$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV

CONFIRMATION IN RUN 1 DATASET

Similar search in Run 1 data collected in 2012,

- $\int \mathcal{L} = 2\,\text{fb}^{-1}$ in pp collisions at 8 TeV,
- Different trigger and data processing configuration.





Again, clear structure visible,

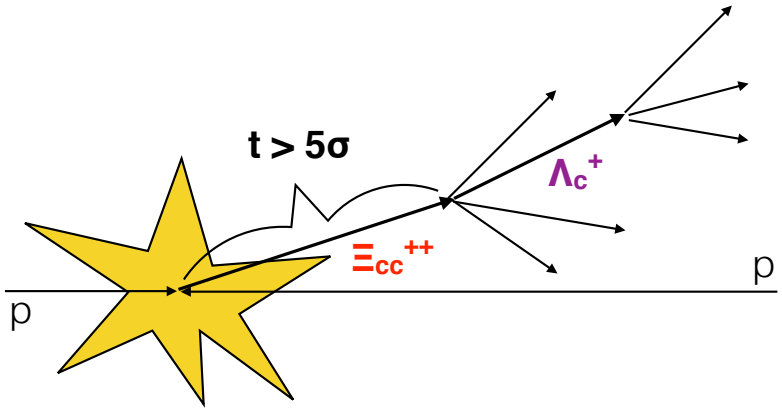
- Yield: 113 ± 21 decays,
- Local significance: $> 7\sigma$ (likelihood ratio).

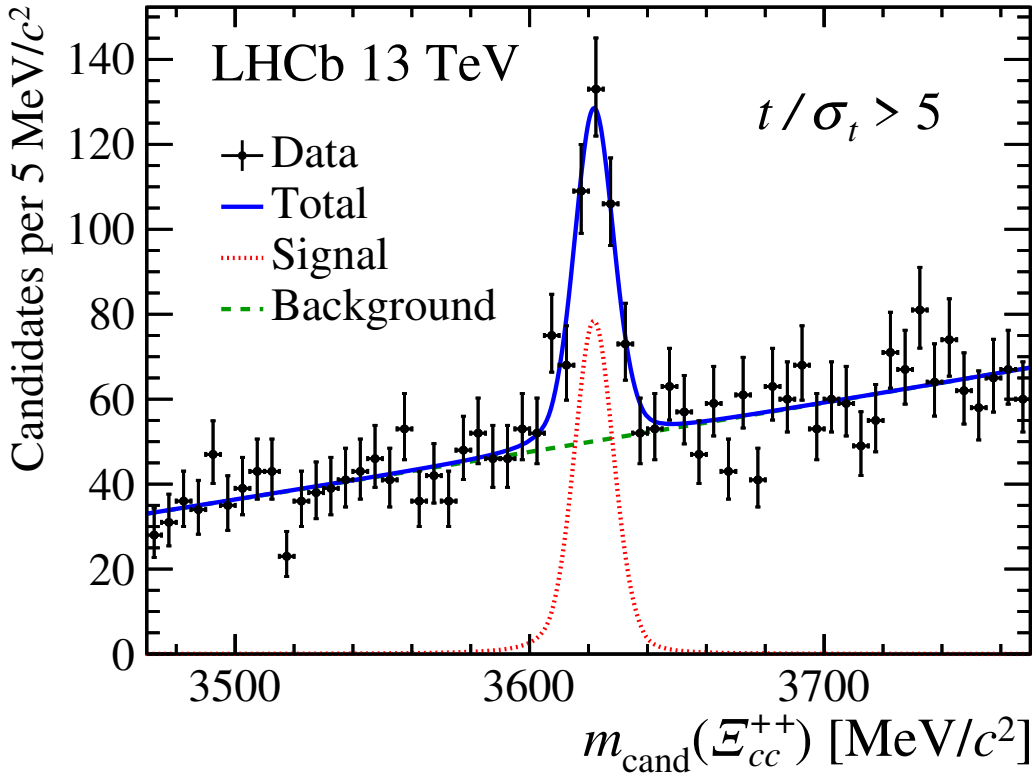
Fitted mass consistent with structure in Run 2 data:

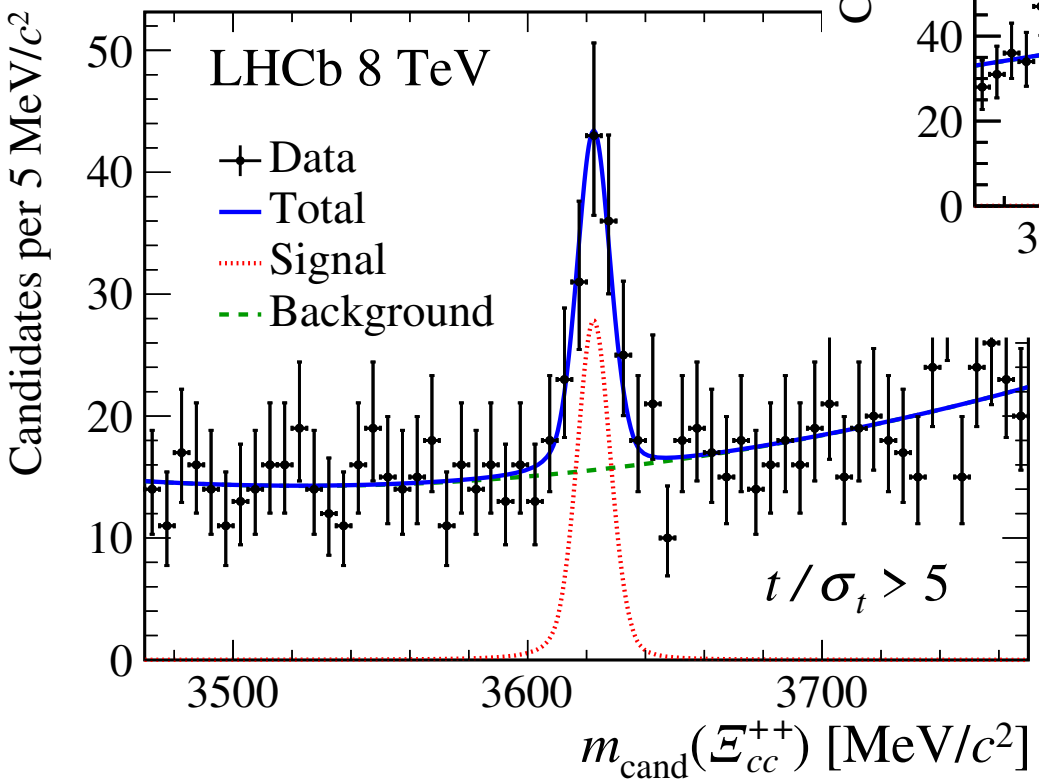
$$m(\Xi_{cc}^{++})_{\text{R1}} - m(\Xi_{cc}^{++})_{\text{R2}} = 0.8 \pm 1.4\,\text{MeV}.$$

(statistical uncertainty only)

WEAK DECAY





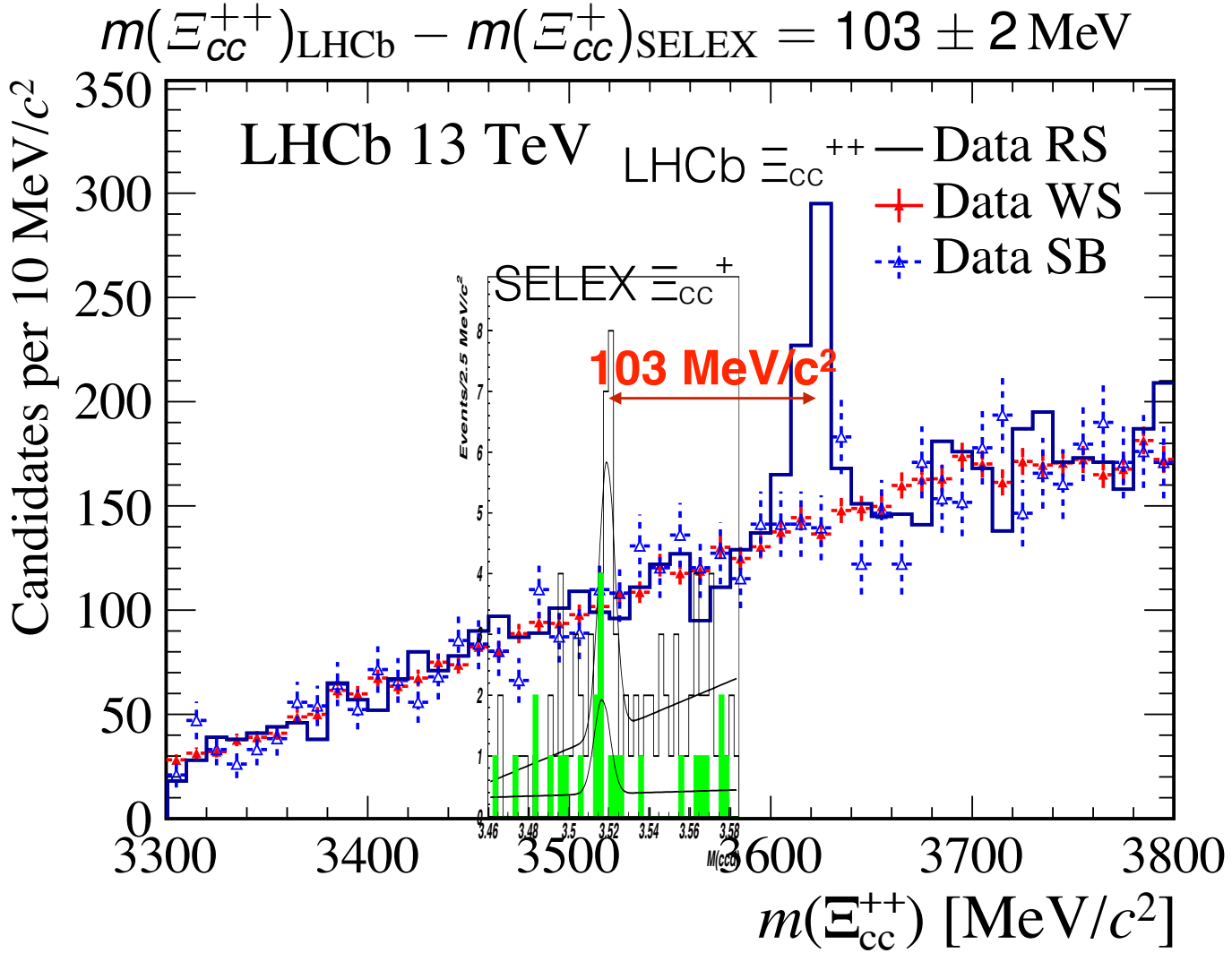


Decay time $> 5\sigma$ wrt the primary interaction vertex

- Run 1 significance: 7σ,
- Run 2 significance: 12σ.

Inconsistent with strong decay.

COMPARISON WITH SELEX



Inconsistent with being isospin partners.

[E.g., Hwang and Chung, PRD 78 073013; Brodsky, Guo, Hanhart, and Meissner, PLB 698 251-255; Karliner and Rosner, arXiv:1706.06961]

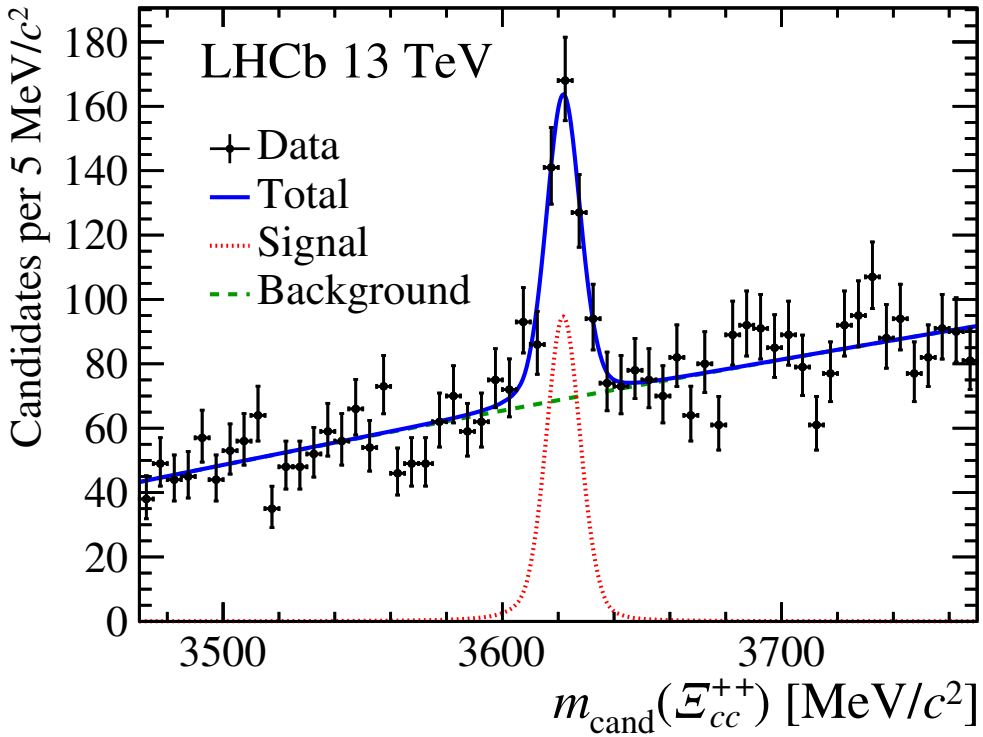
SUMMARY

Narrow structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum.

Significant displacement consistent with a weakly decaying particle.

Observed in two LHCb data sets.

Consistent with Ξ_{cc}^{++} (ccu).



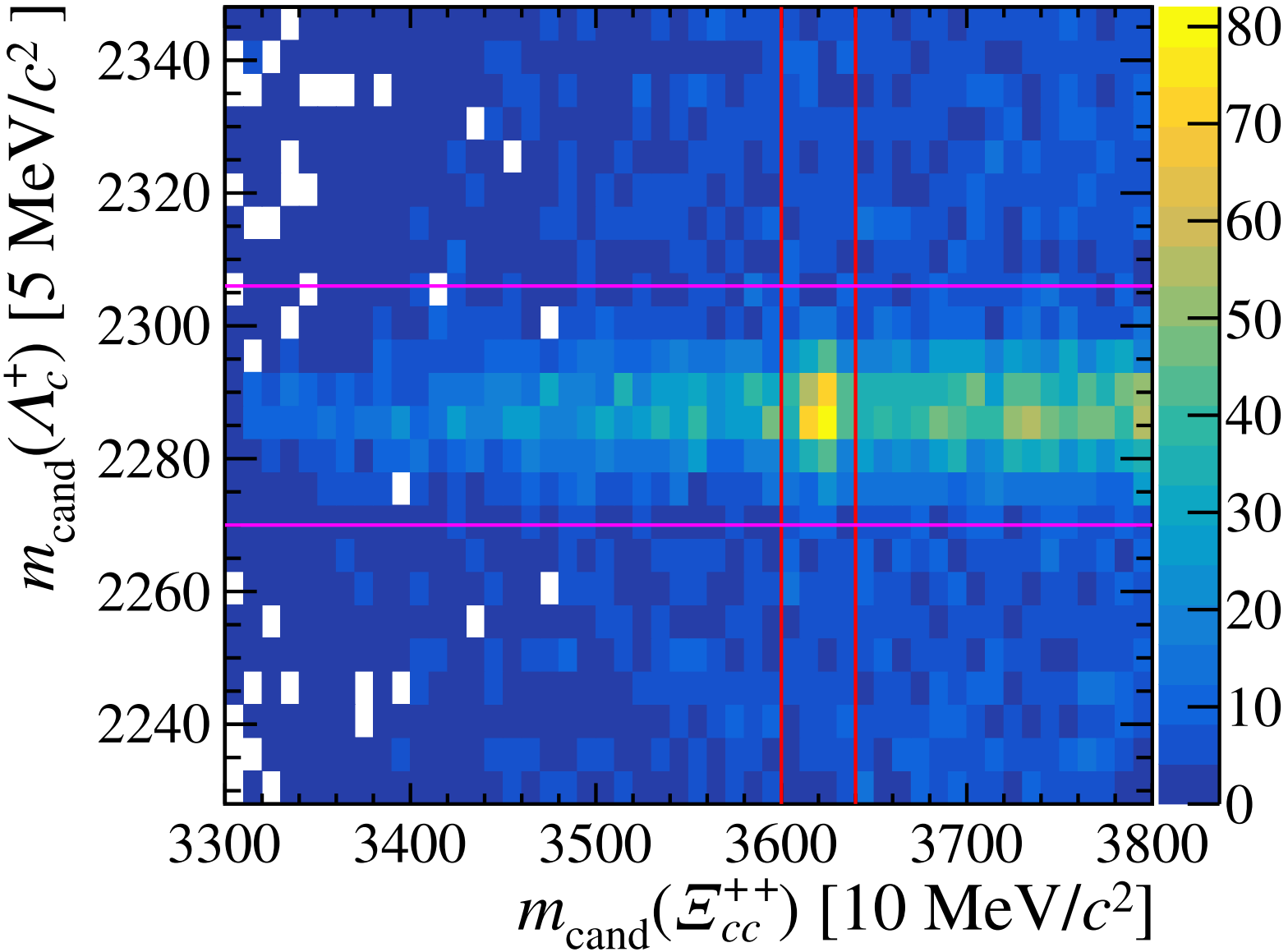
Mass: $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)\,\text{MeV}$

Many follow-up analyses are in progress

- Lifetime and production rate measurements,
- Searches in additional decay modes,
- Searches for isospin partner.

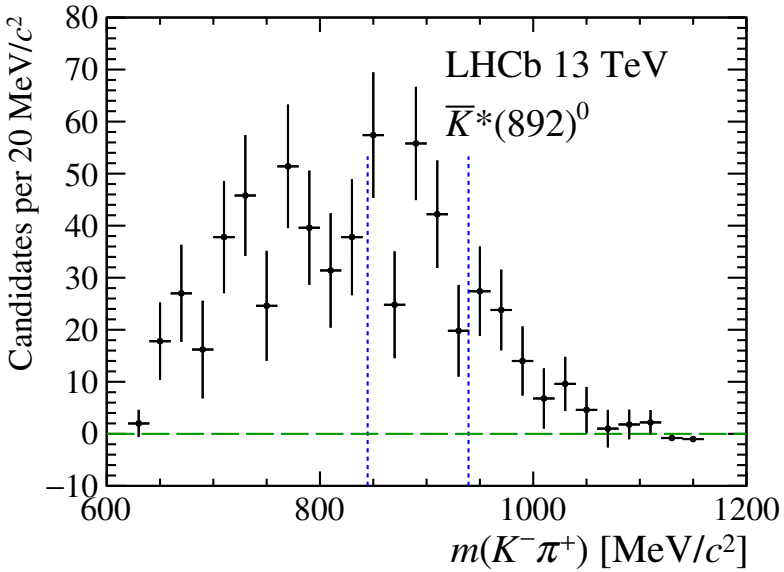
Backup

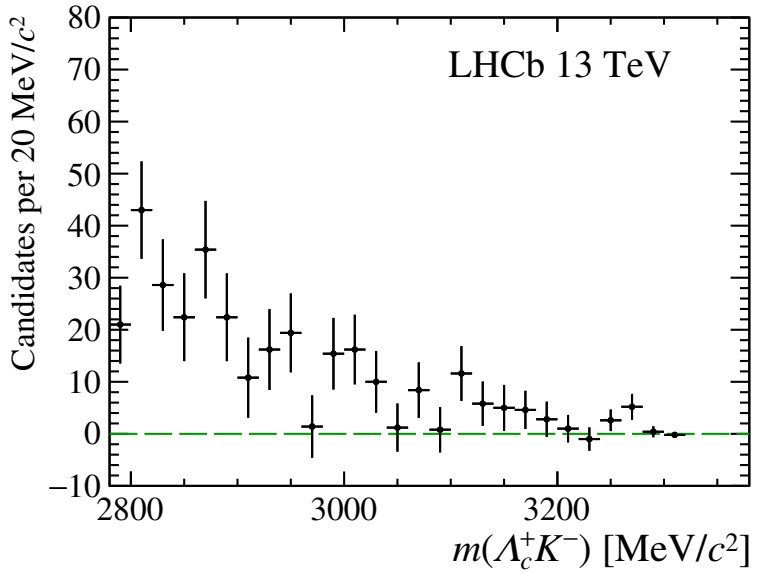
M(Λ_c^+) VS. M(Ξ_{cc}^{++})

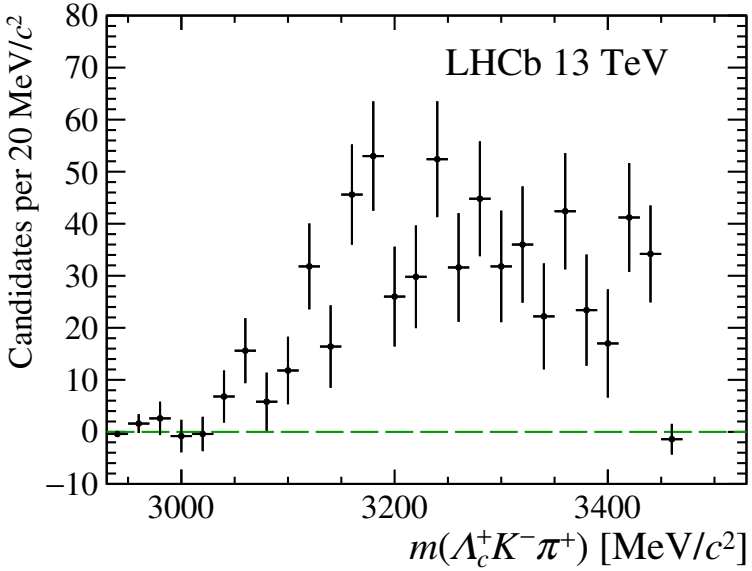


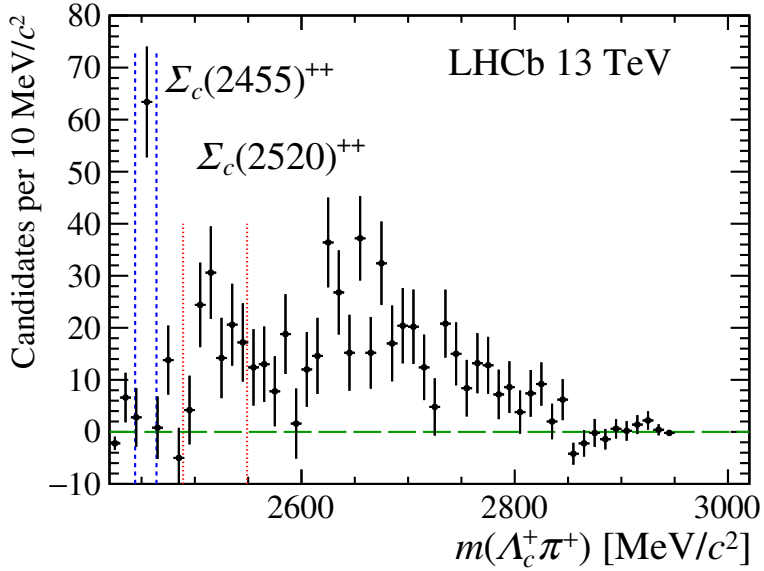
MASS PROJECTIONS

SIDEBAND SUBTRACTED









SELEX AND Ξ_{cc}^{++}

NEVER PUBLISHED

In unpublished work that was shown at several conferences, the SELEX collaboration did claim to have seen two *ccu* states in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum.

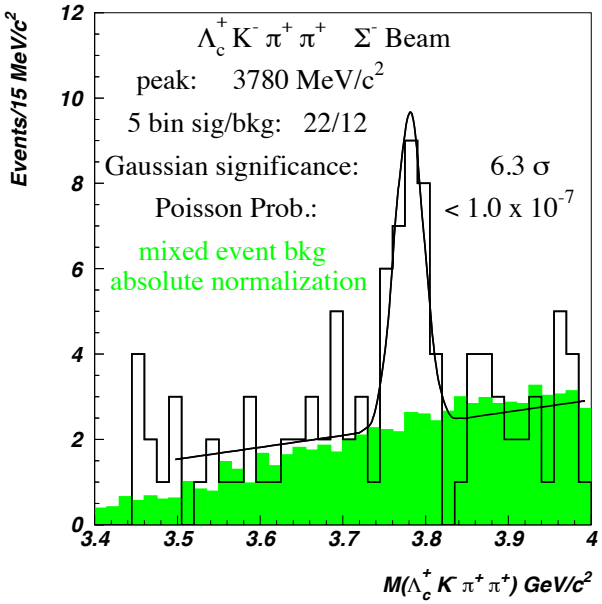
$\Xi_{cc}(3780)^{++}$:

- Width greater than detector resolution,
- Contained $\Lambda_c^+ K^- \pi^+$ combinations from the Ξ_{cc}^+ observation,
- Interpreted as an excited state.

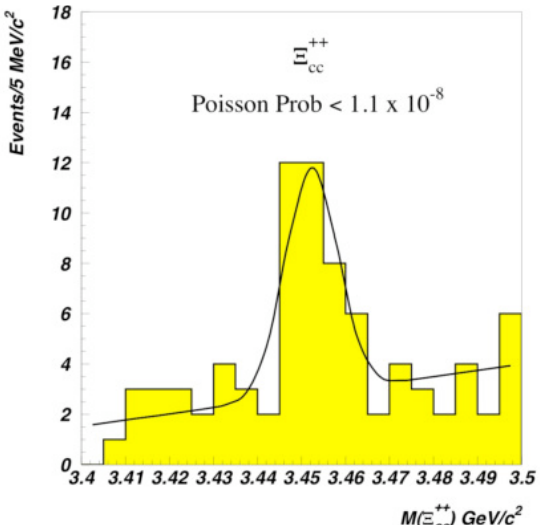
$\Xi_{cc}(3452)^{++}$:

- Also claimed evidence in $\Xi_c^+ \pi^+ \pi^- \pi^+$,
- $67 \pm 3\,\mathrm{MeV}$ below their Ξ_{cc}^+ mass.

See the talks and proceedings linked from the SELEX web pages.



J. Engelfried for the SELEX collaboration, proceedings of HQL06, hep-ex/0702001.



P. Cooper, slides in proceedings of Charm2007.

SOME THEORY REFERENCES

NOT NECESSARILY EXHAUSTIVE

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Spectroscopy of doubly heavy baryons*, Phys. Atom. Nucl. **63** (2000) 274, arXiv:hep-ph/9811212.

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K. Anikeev *et al.*, *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999*, 2001. arXiv:hep-ph/0201071.

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C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, *Estimate of the hadronic production of the doubly charmed baryon Ξ_{cc} in the general-mass variable-flavor-number scheme*, Phys. Rev. **D73** (2006) 094022, arXiv:hep-ph/0601032.

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NOT NECESSARILY EXHAUSTIVE

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Z.-G. Wang, *Analysis of the $\frac{1}{2}^+$ doubly heavy baryon states with QCD sum rules*, Eur. Phys. J. **A45** (2010) 267, arXiv:1001.4693.

M. Karliner and J. L. Rosner, *Baryons with two heavy quarks: masses, production, decays, and detection*, Phys. Rev. **D90** (2014) 094007, arXiv:1408.5877.

K.-W. Wei, B. Chen, and X.-H. Guo, *Masses of doubly and triply charmed baryons*, Phys. Rev. **D92** (2015) 076008, arXiv:1503.05184.

Z.-F. Sun and M. J. Vicente Vacas, *Masses of doubly charmed baryons in the extended on-mass-shell renormalization scheme*, Phys. Rev. **D93** (2016) 094002, arXiv:1602.04714.

C. Alexandrou and C. Kallidonis, *Low-lying baryon masses using $N_f = 2$ twisted mass clover-improved fermions directly at the physical point*, arXiv:1704.02647.

C.-W. Hwang and C.-H. Chung, *Isospin mass splittings of heavy baryons in heavy quark symmetry*, Phys. Rev. **D78** (2008) 073013, arXiv:0804.4044.

EVEN MORE THEORY REFERENCES

NOT NECESSARILY EXHAUSTIVE

S. J. Brodsky, F.-K. Guo, C. Hanhart, and U.-G. Meißner, *Isospin splittings of doubly heavy baryons*, Phys. Lett. **B698** (2011) 251, arXiv:1101.1983.

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A. V. Berezhnoy and A. K. Likhoded, *Doubly heavy baryons*, Phys. Atom. Nucl. **79** (2016) 260.

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K. Kolodziej, A. Leike, and R. Ruckl, *Production of B_c^+ mesons in hadronic collisions*, Phys. Lett. **B355** (1995) 337, arXiv:hep-ph/9505298.

A. V. Berezhnoy, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Doubly charmed baryon production in hadronic experiments*, Phys. Rev. **D57** (1998) 4385, arXiv:hep-ph/9710339.