Searches for doubly charmed baryons at LHCb

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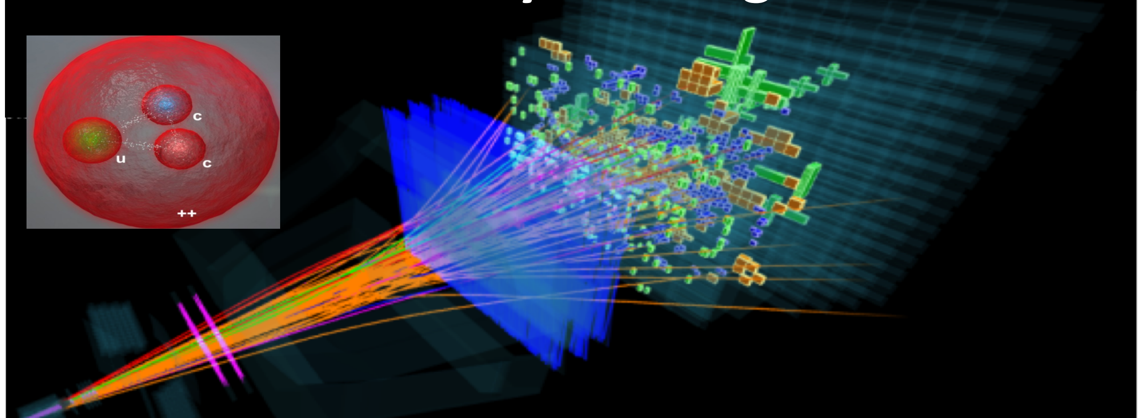

IOP APP and HEPP Annual Conference 2018

Bristol 26-28th March

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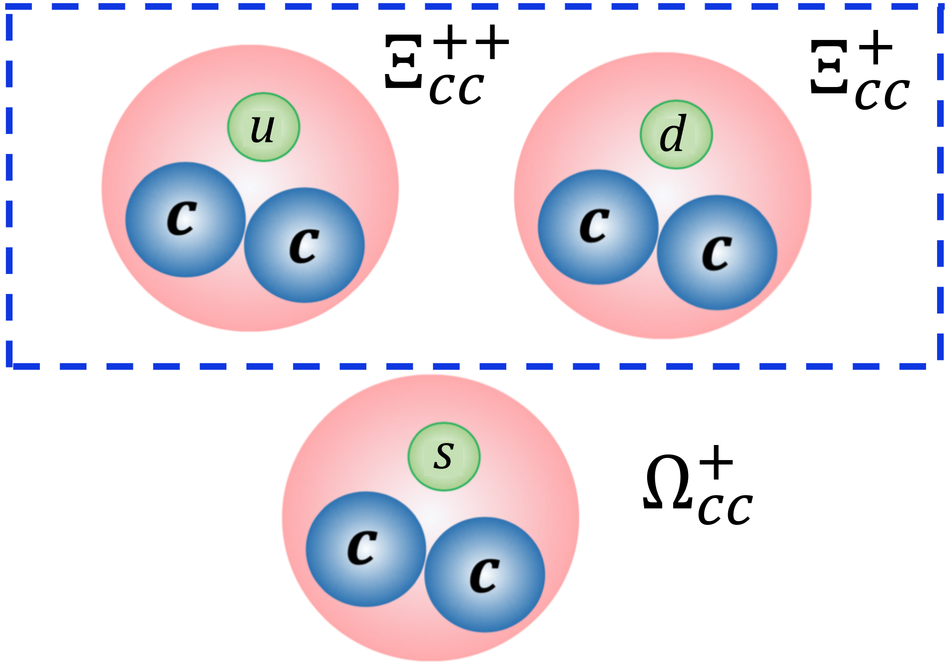
Overview

- Quark model predicts the existence of three SU(3) quasi-stable Doubly Charmed Baryons (DCBs): Ξ_{cc}^{++}(ccu), Ξ_{cc}^{+}(ccd) + Ω_{cc}^{+}(ccs)



- $\sigma(pp \to DCB + X)$ are predicted to be low and with large uncertainties: 60-1800nb @13TeV LHC [1]

- Decay to high multiple-body final states
  $\Longrightarrow$ reconstruction of decays is challenging

$$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-}\pi^{+} \quad \hookrightarrow p\, K^{-}\pi^{+}$$

$$\Xi_{cc}^{+} \to D^{+} p\, K^{-}\pi^{+} \quad \hookrightarrow K^{-}\pi^{+}\pi^{+}$$

$$\Omega_{cc}^{+} \to \Omega_c^{0}\, \pi^{+} \quad \hookrightarrow p\, K^{-}K^{-}\pi^{+}$$

- No unambiguous evidence† for any doubly (or triply) charmed baryons before 2017
  (LHCb observe thousands of $B_c^{+}(c\bar{b})$ mesons)

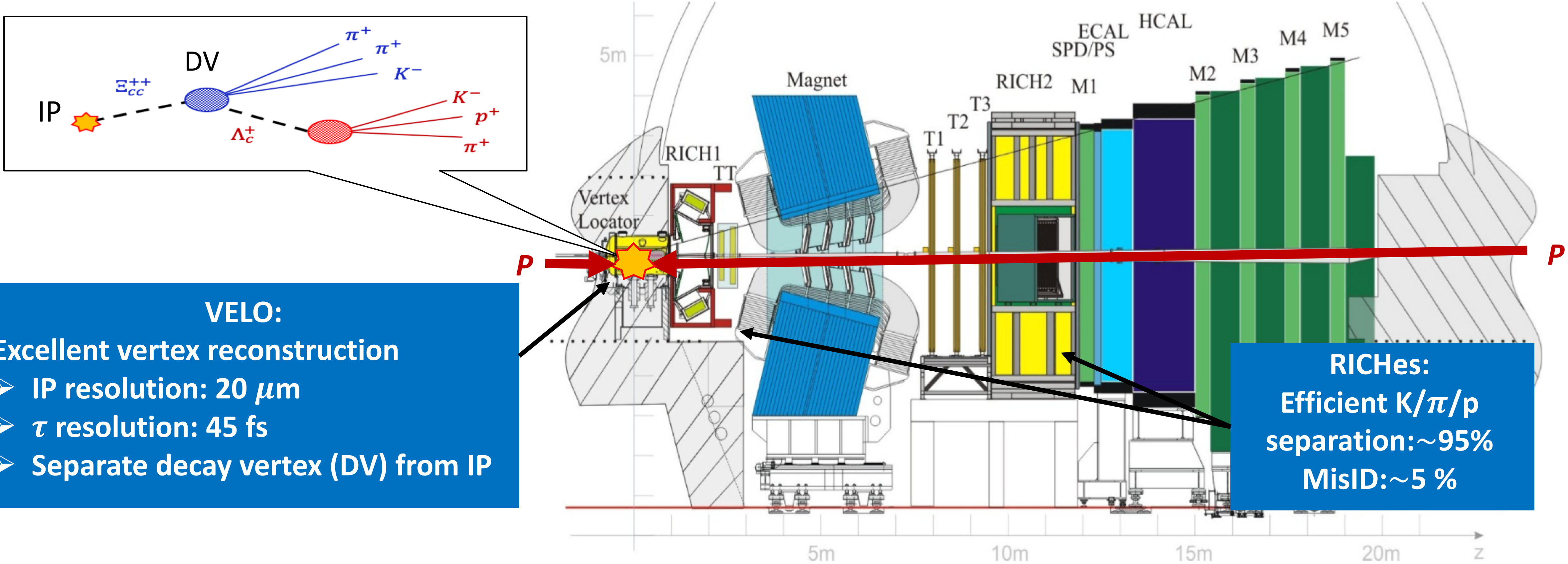
† SELEX Collaboration's discovery claims of the Ξ_{cc}^{+} state not widely accepted

- What is the motivation for finding them?
  Great testing grounds for non-perturbative QCD techniques and are unexplored systems for CP violation

LHCb detector

- Why do LHCb believe they could detect doubly charmed baryons?
- Mainly due to its excellent tracking and efficient particle identification techniques

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



VELO:
Excellent vertex reconstruction
- **IP resolution: 20 μm**
- **τ resolution: 45 fs**
- **Separate decay vertex (DV) from IP**

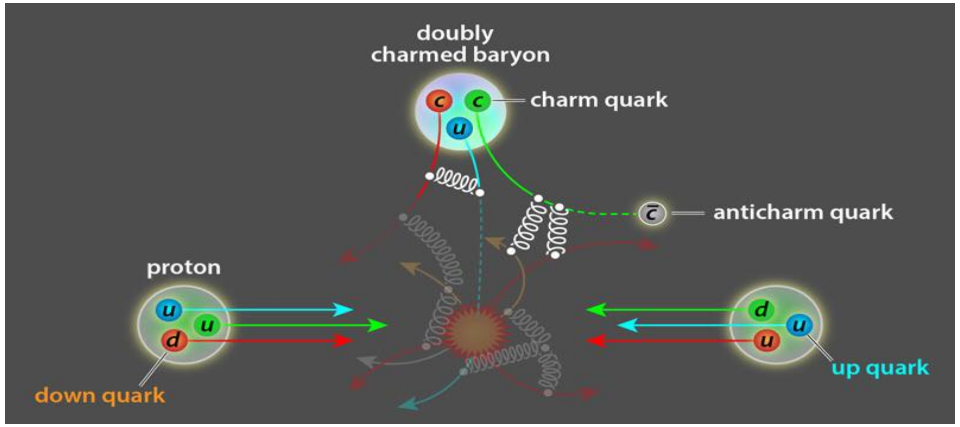
RICHes:
Efficient K/π/p separation:~95%
MisID:~5 %

- Belle2 in Japan will begin data taking soon and could be competitive with LHCb in these searches

Production and decay properties

Production mechanisms

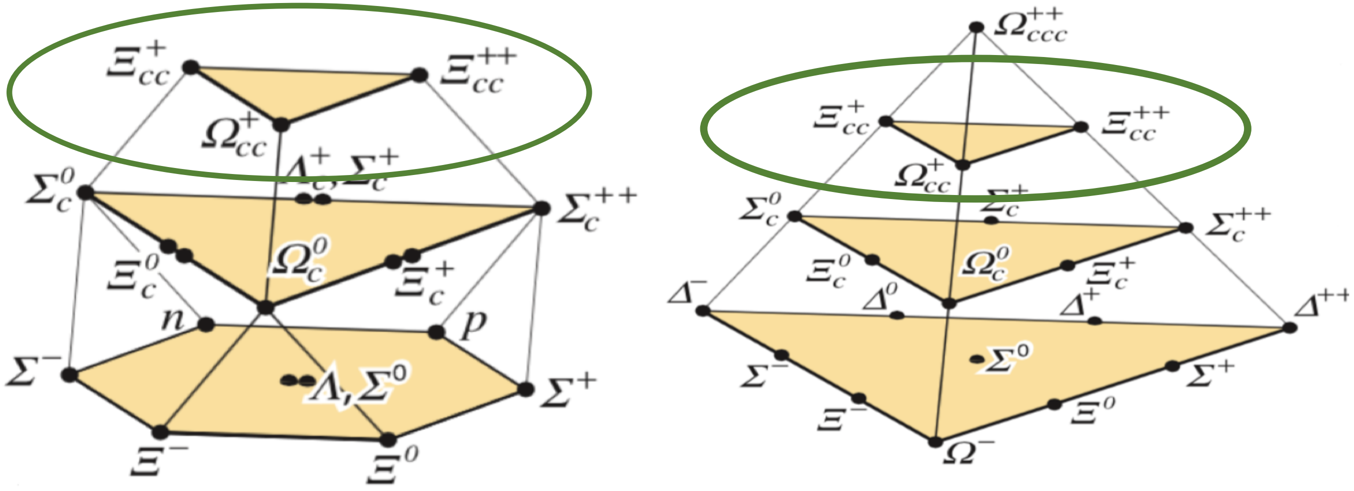
- Double parton scattering believed to be dominant source of double heavy production (LHCb measurements of: $pp \rightarrow J/\psi$ + D and $pp \rightarrow \Upsilon$ + D)
- Formation: Production of two $c\bar{c}$ quark pairs
  → Bind into di-quark structure
  → Hadronization
- Dedicated GenXicc generator used to produce DCBs in MC for LHCb analyses [2]



Decays properties

- Excitations decay to ground states via Strong/EM interaction
- Ground states decay weakly with a charm quark transitioning into lighter quarks

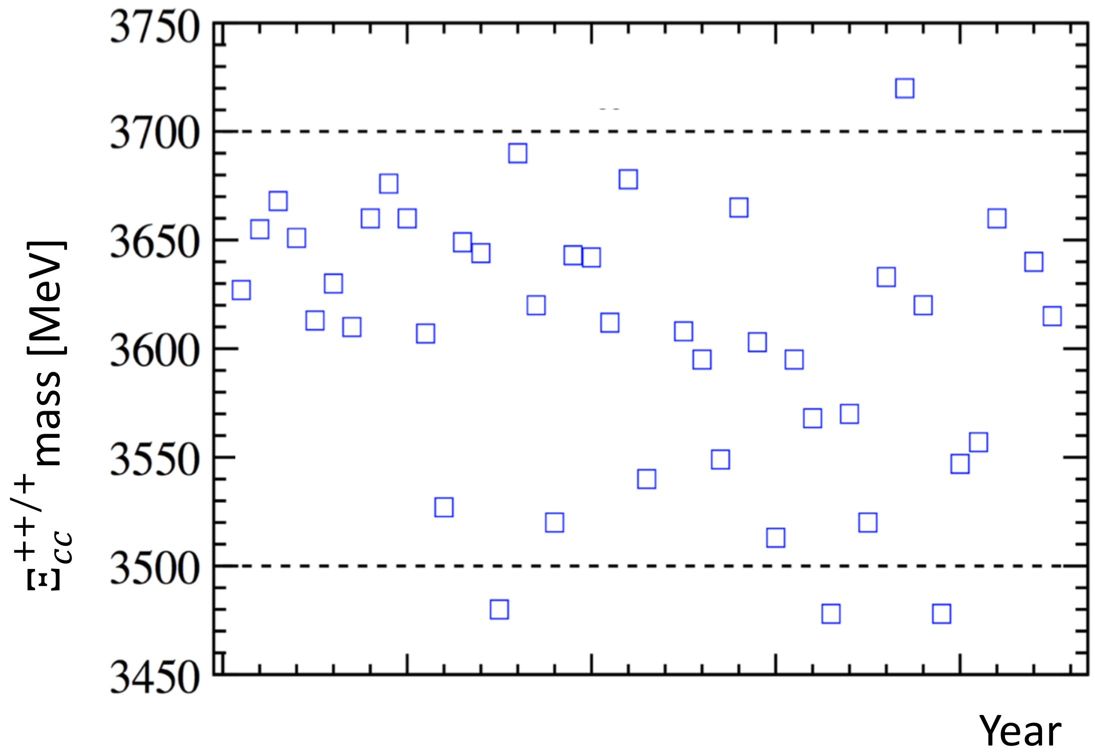
Ground states $J^P = \frac{1^+}{2}$ Excited states $J^P = \frac{3^+}{2}$



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

Mass and lifetime of ground states

- Many models on the market to determine masses of ground states: QCD sum rules, (non-)relativistic QCD potential models, quark model etc



- $m(\Xi_{cc}) \approx$ 3.5-3.7 GeV, $m(\Omega_{cc}^{+}) \approx m(\Xi_{cc})$ + 0.1 GeV [3]
- Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++} only few MeV due to approx. isospin symmetry

Sources	Ξ_{cc}^{++}	Ξ_{cc}^{+}	Ω_{cc}^{+}
Karliner, & Rosner 2014	185 *fs*	53 fs	-
Kiselev & Likhoded 2002	460±50 *fs*	160±50 *fs*	270±60 *fs*
Guberina, Melic, Stefancic, 1998	1550 *fs*	220 *fs*	250 *fs*
Chang, Li , Wang 2007	670 *fs*	250 *fs*	210 *fs*

$\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+}) \sim \tau(\Omega_{cc}^{+})$

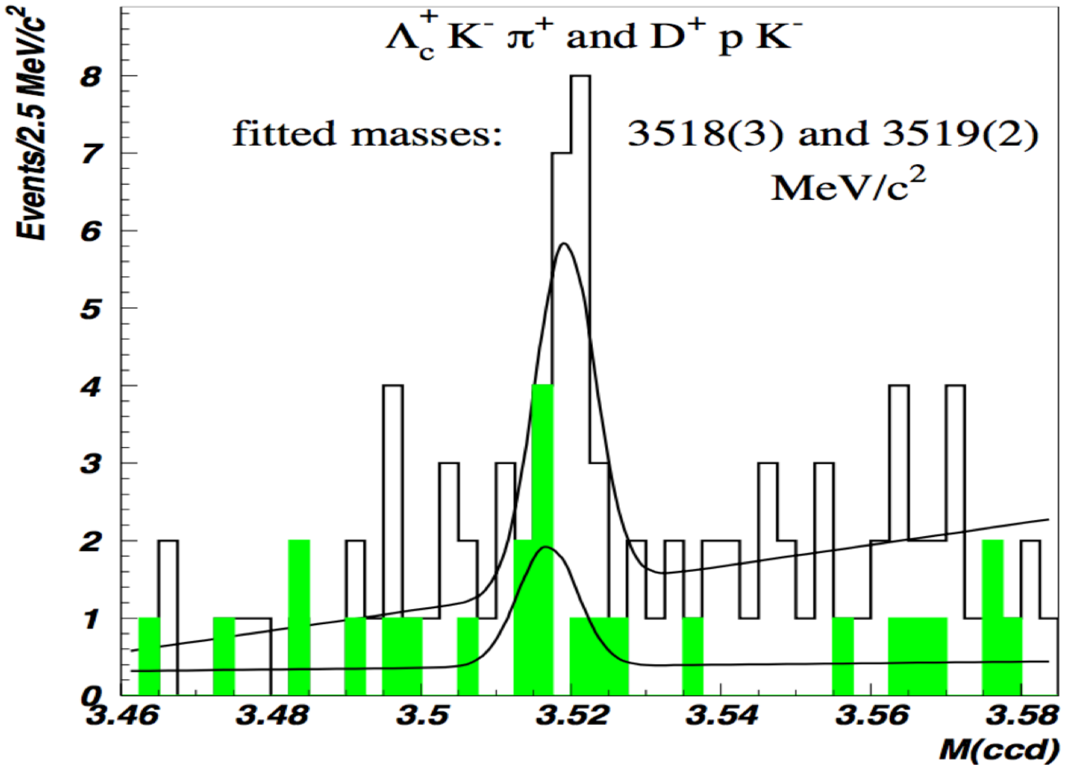
$\tau(\Xi_{cc}^{++}) \in$ 200-700 *fs*

$\tau(\Xi_{cc}^{+}) \in$ 50-250 *fs* [4]

- Charm lifetimes vary a lot: explained by non-spectator decays and interference effects
- Theoretically large uncertainties for DCB lifetimes – difficult to calculate

SELEX and Ξ_{cc}^{+} arXiv:hep-ex/0406033

- SELEX, fixed-target Fermilab experiment, observed Ξ_{cc}^{+} state in 2 channels:
  - ➢ $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-}\pi^{+}$ in 2002 (6.3σ)
  - ➢ $\Xi_{cc}^{+} \rightarrow D^{+}p^{+} K^{-}$ in 2004 (4.8σ)
- Signal had very unexpected properties:
  - ➢ Short lifetime: τ < 33 fs (@90% CL) ⟹ Strong decay!?
  - ➢ Large production: 20% Λ_c^{+} came from Ξ_{cc}^{+} decays
- SELEX state never found by other groups including LHCb when analysing 2011 data [5]
- SELEX has a different production environment:
  - ➢ 600 GeV beam of hyperons on fixed target of Cu/diamond
  - ➢ Production cross-section could be very different than in pp colliders



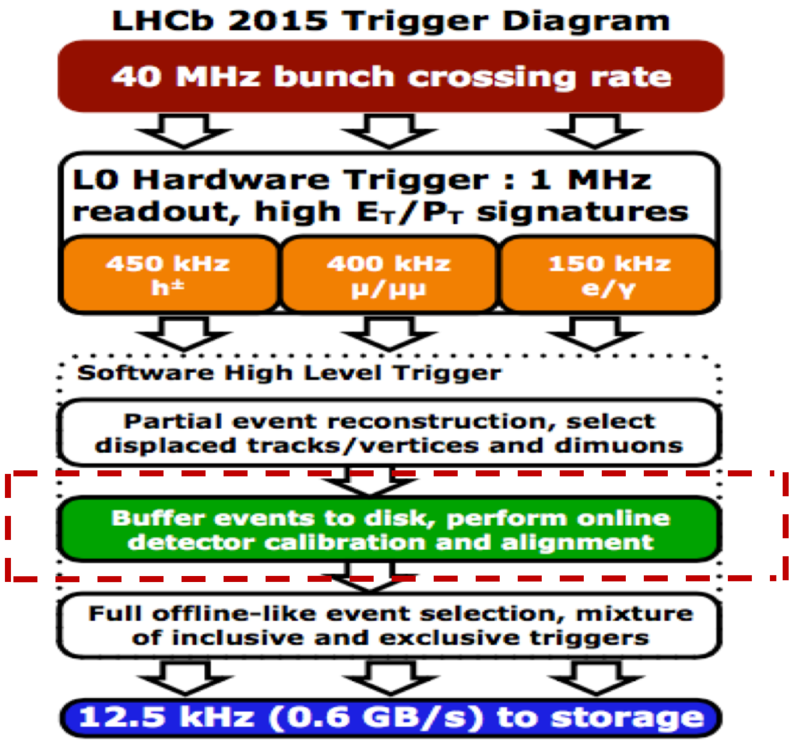
SELEX $\Lambda_c^{+} K^{-}\pi^{+}$and $D^{+}p^{+} K^{-}$distributions superposed

Phys.Lett. B628 (2005) 18-24

$3518.7 \pm 1.7(\text{stat})\ \text{MeV}/c^2$

Analysis strategy

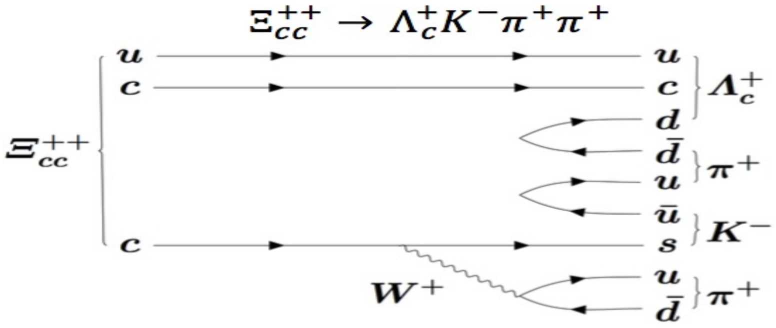
- Searches for Ξ_{cc}^{++} and Ξ_{cc}^{+} are done blindly in Run2 data
  $\Longrightarrow$ Do not look at candidates with mass between 3.3-3.8 GeV
- Selections built around simulated decays and data with an unphysical combination of charged tracks
- Candidates are reconstructed at the trigger level saved for offline analyses (Run 2 "Turbo" stream)



arXiv:1604.05596

Initial focus on Ξ_{cc}^{++}

- LHCb focused on searching for Ξ_{cc}^{++} particularly in decays of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ due its expectantly high *BF* [6]
- $\tau(\Xi_{cc}^{++})$ >> $\tau(\Xi_{cc}^{+})$ so Ξ_{cc}^{++} travels further from IP
  $\Longrightarrow$ trigger and offline cuts better at removing background
- Searches for Ξ_{cc}^{+} continue in parallel in many different decays



Candidate selection

- $\sigma(pp \to \Xi_{cc}^{++} X)$ << inelastic cross-section in pp so expecting large hadronic backgrounds
- Selections of candidates for all analyses:
  1) Loose cut based preselection
  2) Multivariate techniques
  3) Removal of clones and duplications

e.g. $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
$\hookrightarrow p^+ K^- \pi^+$

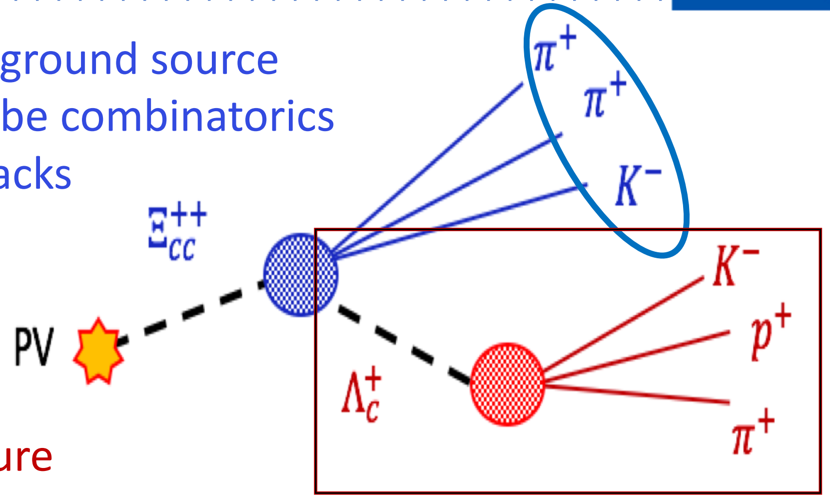
Preselection cuts selects tracks with high p_T and that are displaced largely from IP

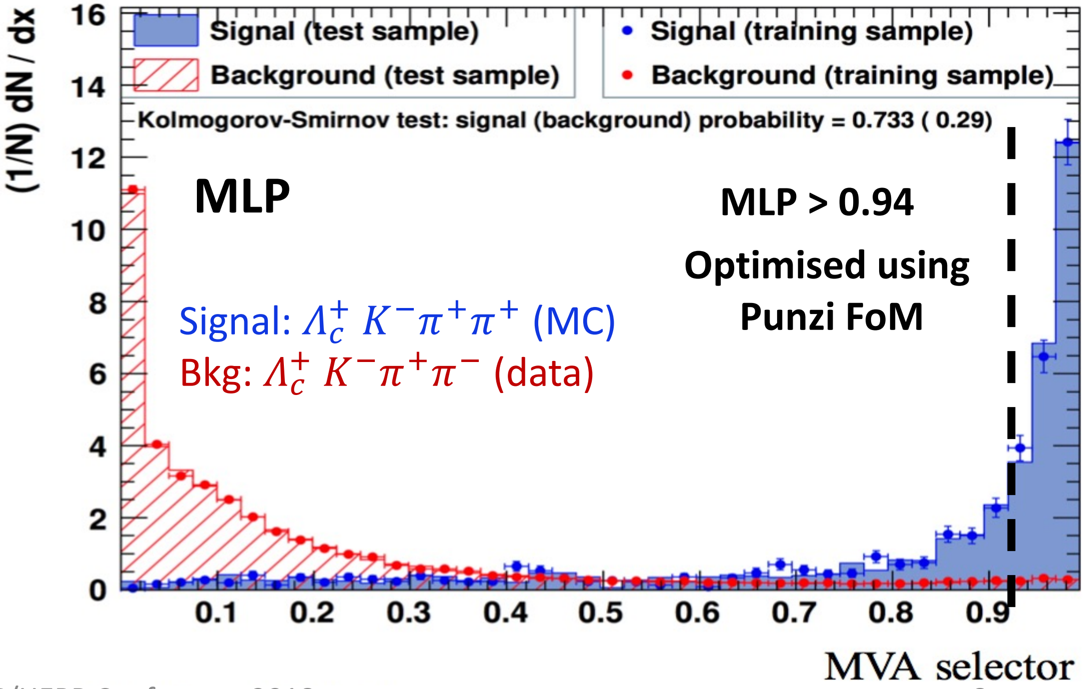
MVA selector makes use of quality, topological and dynamical information from decays:

- ➢ Decay fit quality of Ξ_{cc}^{++} candidates
- ➢ Kinematics of final states
- ➢ Ξ_{cc}^{++} vertex separation from PV

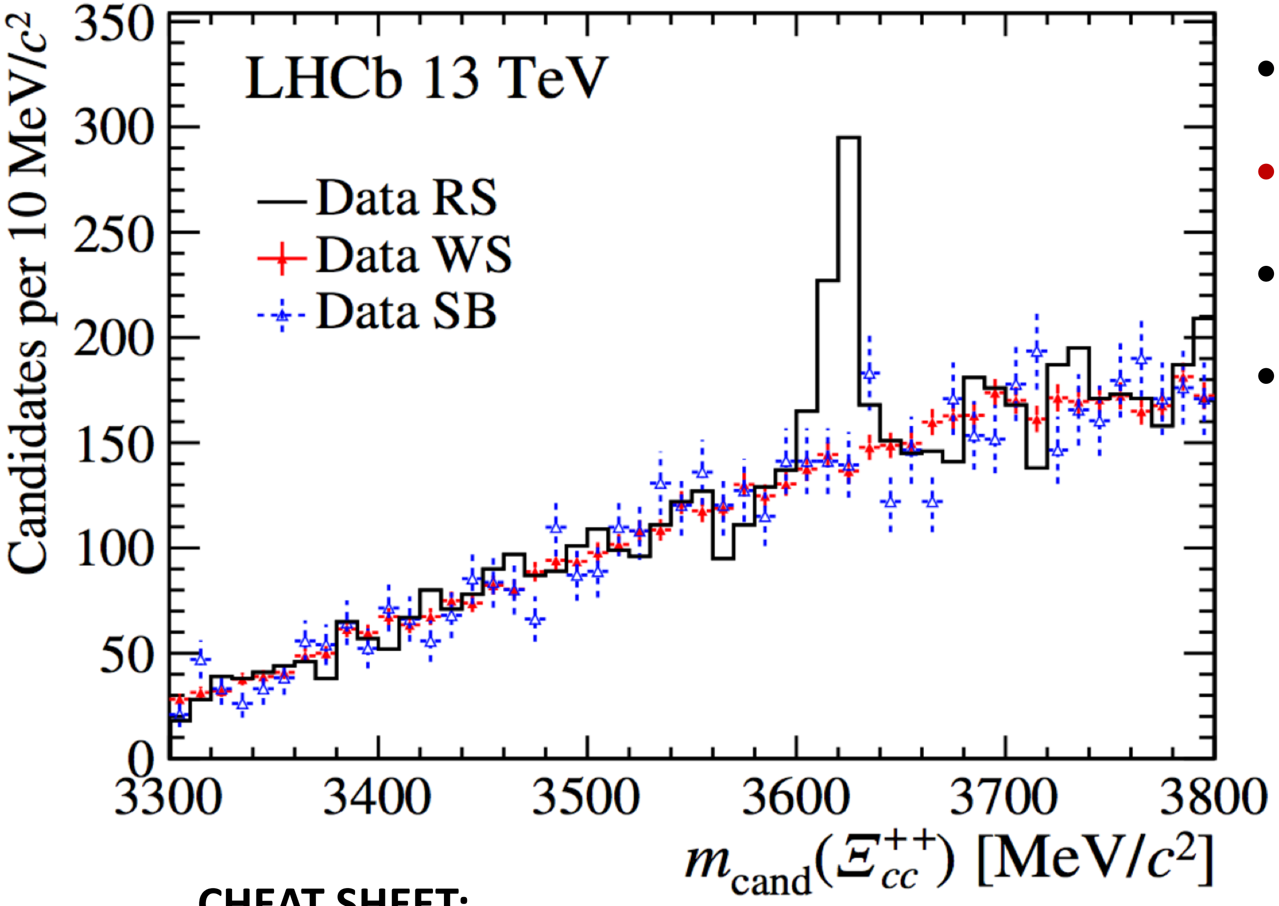
Largest background source expected to be combinatorics from Ξ_{cc}^{++} tracks

Open charm decays should already be pure





$\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum PRL 119, 112001 (2017)



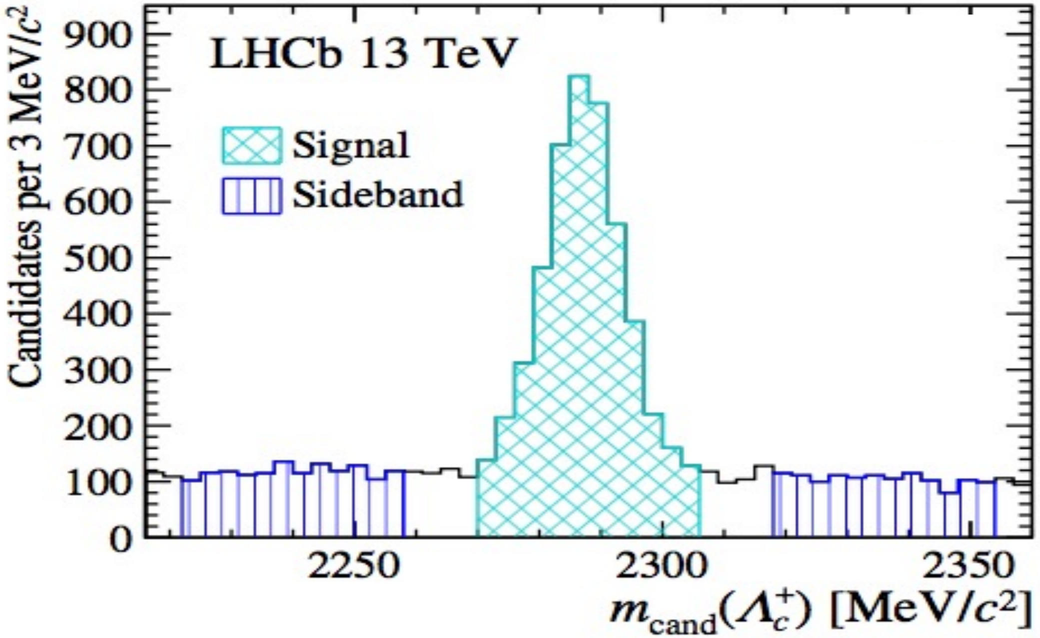
- A significant structure in right sign (RS) data
- Not present in wrong sign (WS) combinations
- Not observed for Λ_c^+ background candidates
- Distributions similar except the peak in RS

CHEAT SHEET:

RS: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+)\, K^- \pi^+ \pi^+$

WS: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+)\, K^- \pi^+ \pi^-$

SB: $\Xi_{cc}^{++} \rightarrow [\Lambda_c^+(\rightarrow p^+ K^- \pi^+)]_{SB}\, K^- \pi^+ \pi^+$



Ξ_{cc}^{++} discovery [PRL 119, 112001 (2017)]

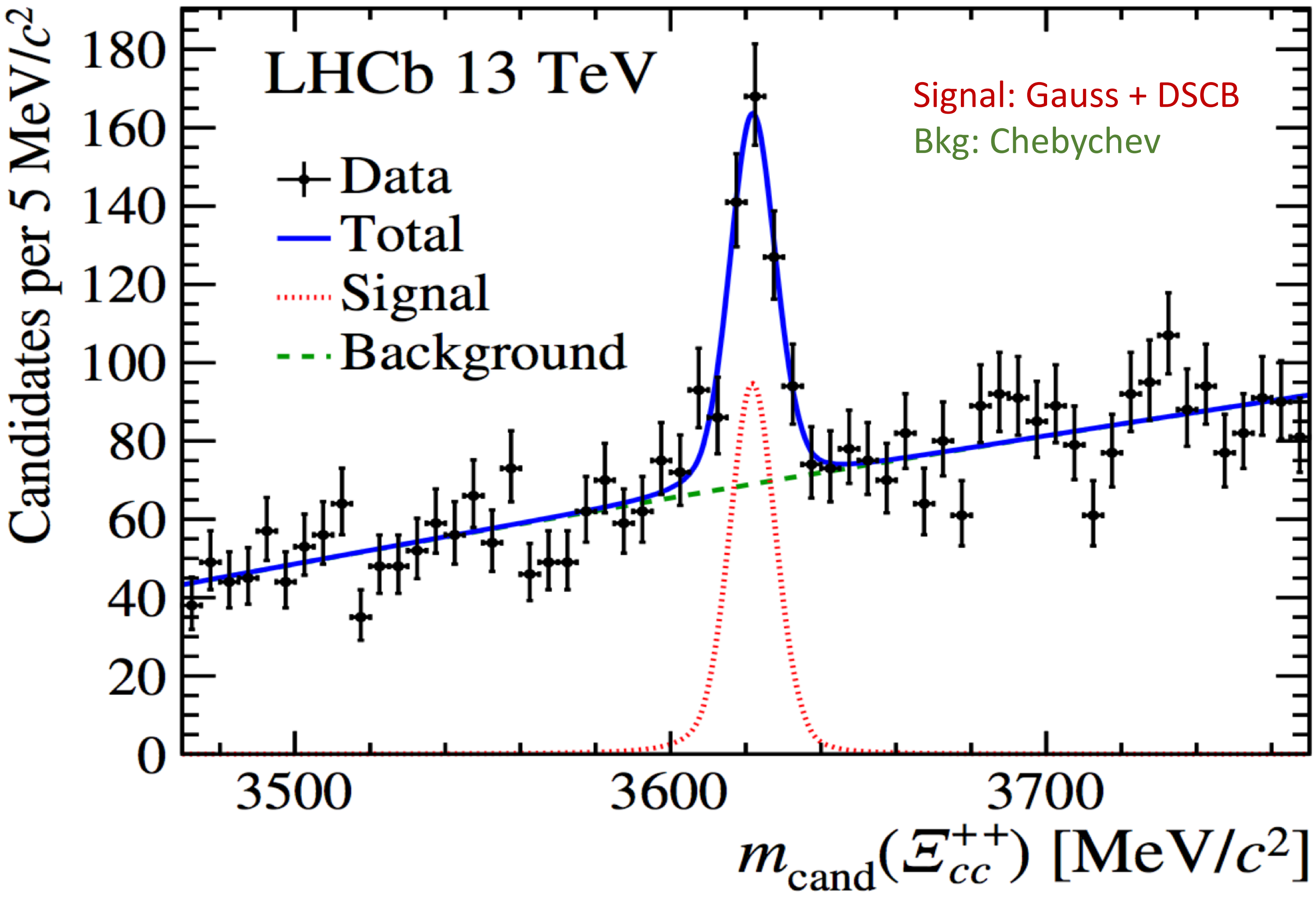
Local significance > 12σ

Resolution = 6.6 ± 0.8 MeV (consistent with expected detector resolution)

Signal yield = 313 ± 33 events

Systematics of mass measurement

Source	Value [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



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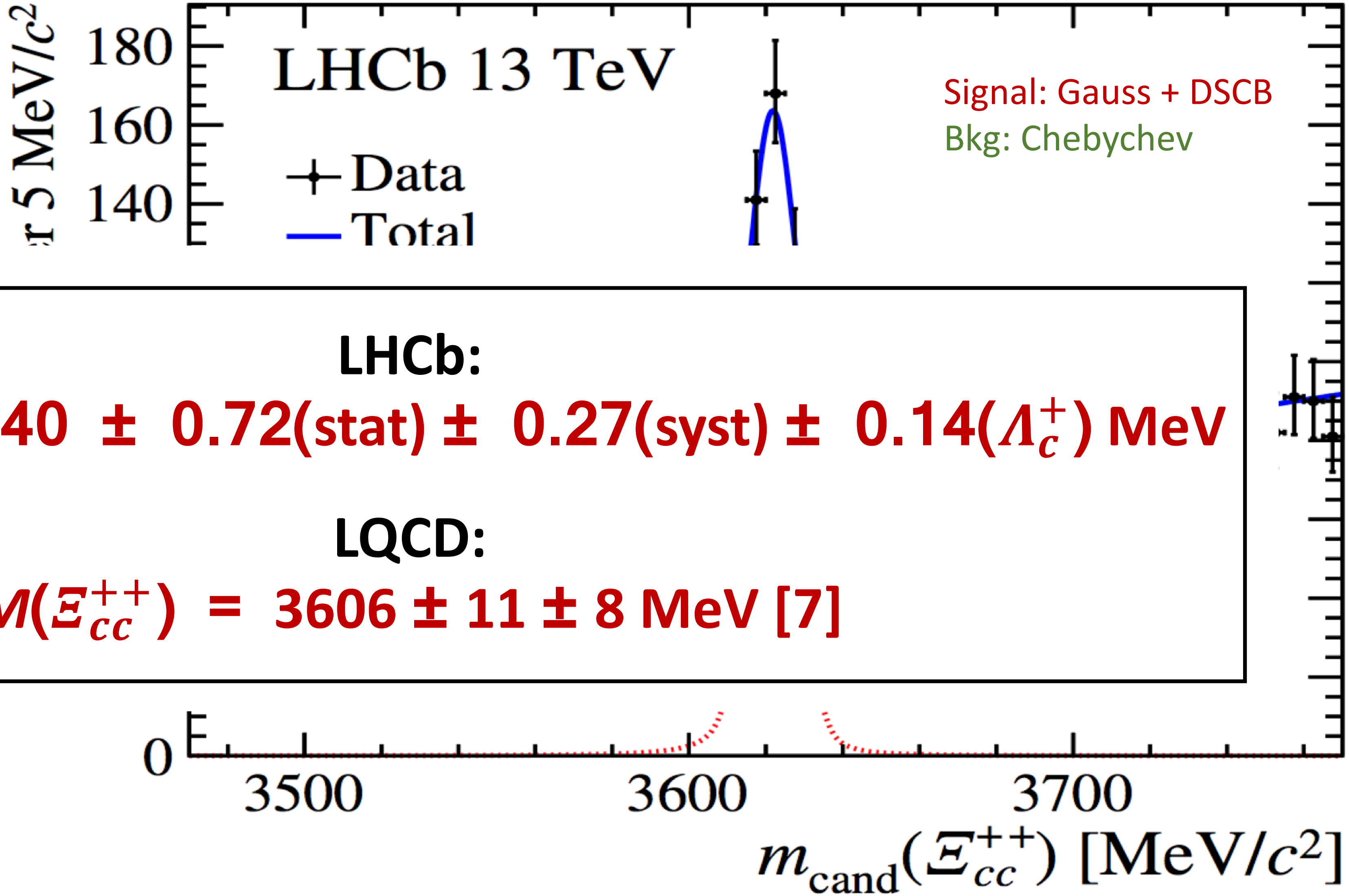


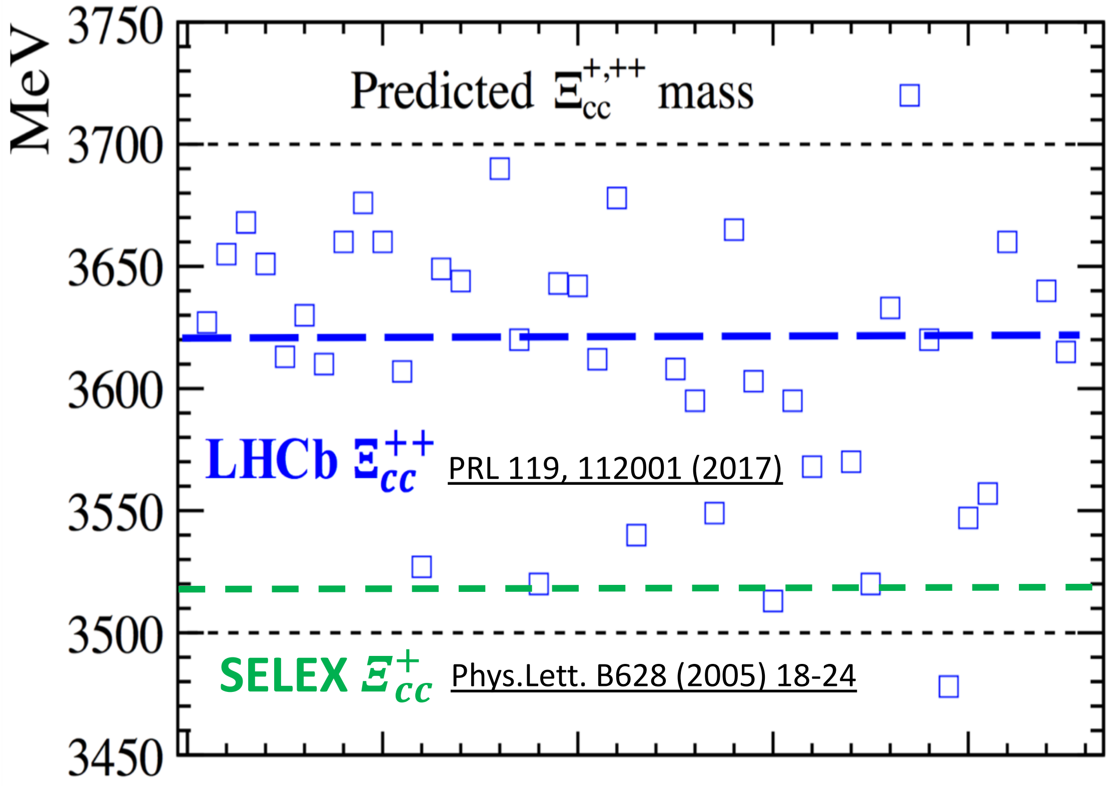
LHCb:

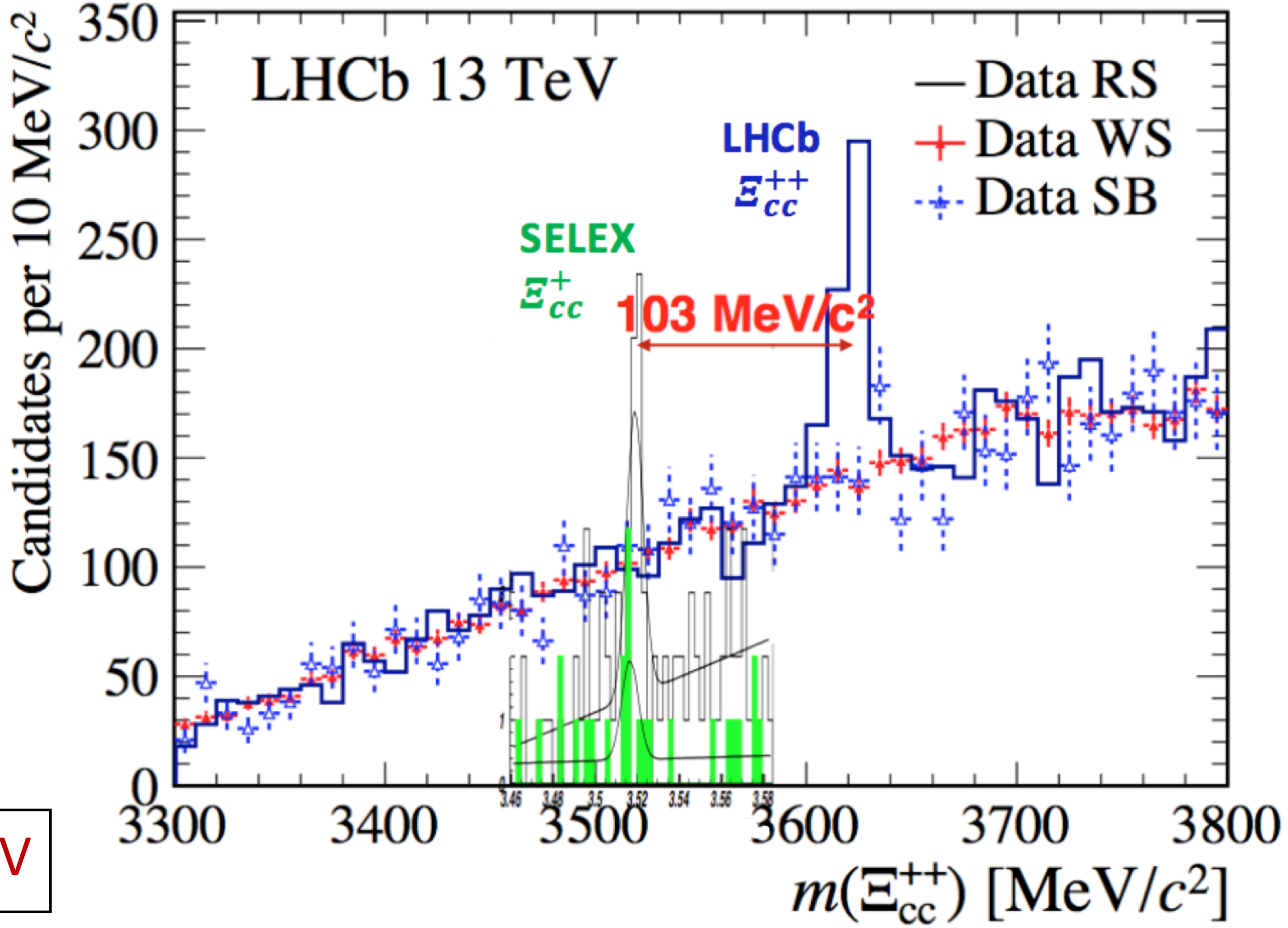
$M(\Xi_{cc}^{++})$ = 3621.40 ± 0.72(stat) ± 0.27(syst) ± 0.14(Λ_c^+) MeV

LQCD:

$M(\Xi_{cc}^{++})$ = 3606 ± 11 ± 8 MeV [7]

Comparison with SELEX





Large mass difference:

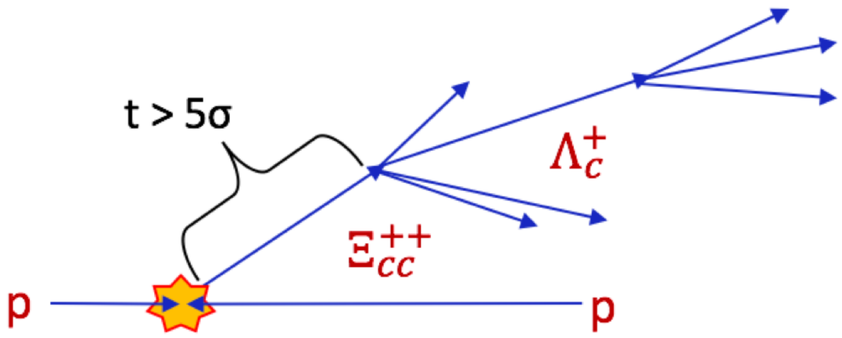
$$m(\Xi_{cc}^{++})_{LHCb} - m(\Xi_{cc}^{+})_{SELEX} = 103 \pm 2 \text{ MeV}$$

Inconsistent with being isospin partners: (Guo, Hanhart & Meissner, PLB 698 251-255; Karliner & Rosner, arXiv:1706.06961)

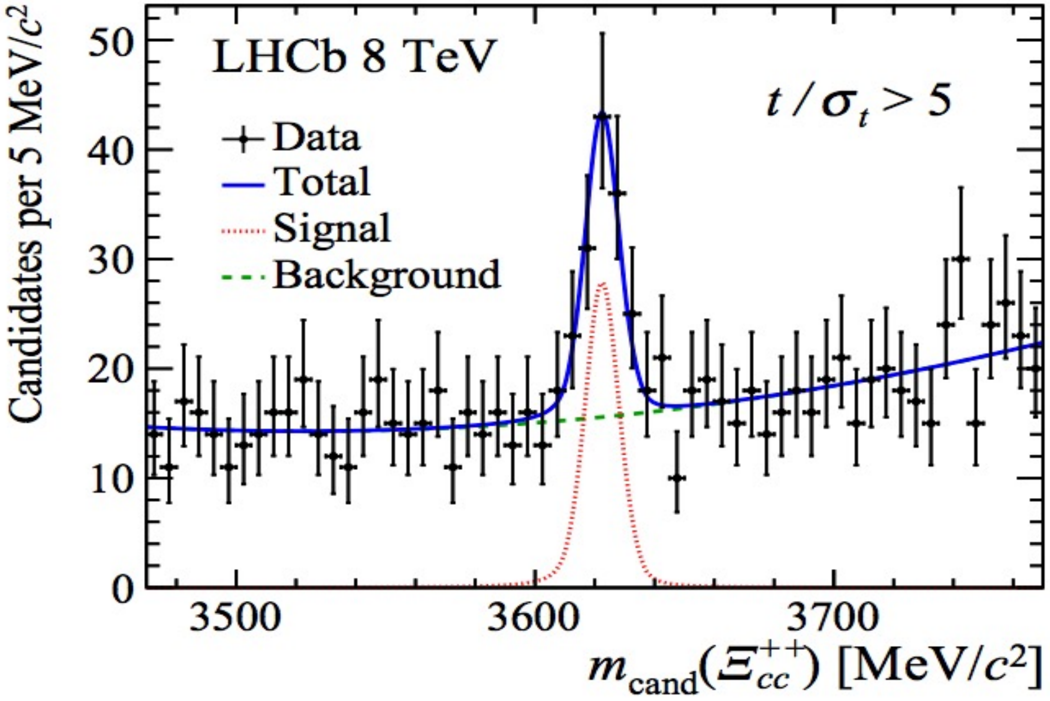
Papers attempting to reconcile LHCb with SELEX e.g arXiv:1709.09903 (Assumes LHCb's Ξ_{cc}^{++} is 3/2 spin state)

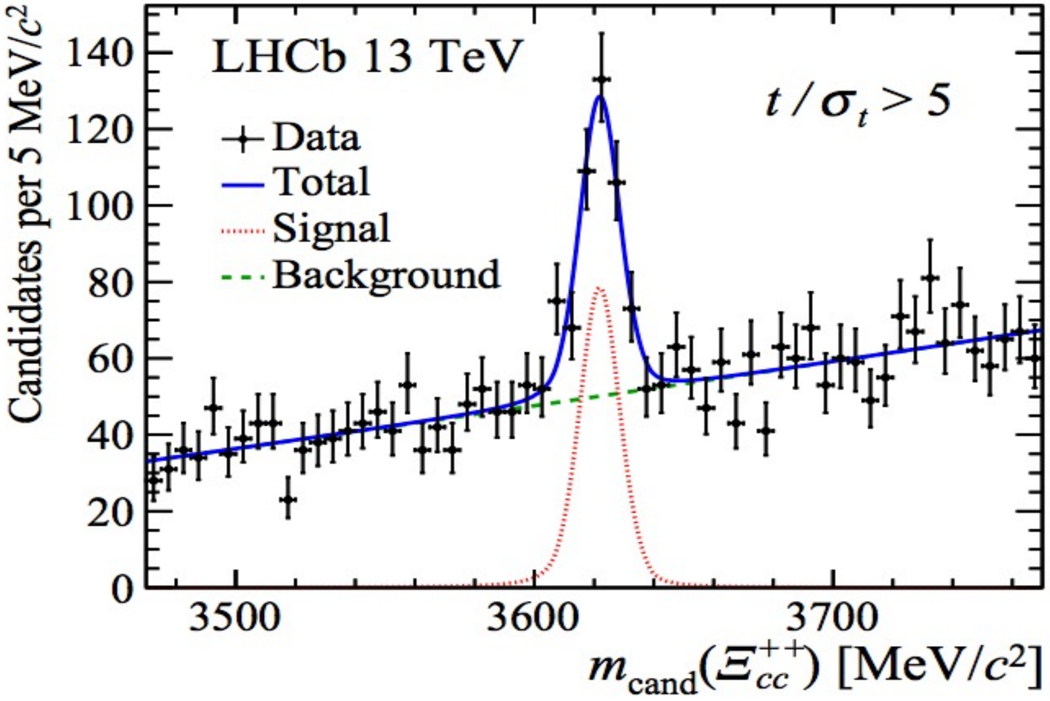
Weak decay PRL 119, 112001 (2017)

- Peaking structure remains significant after requiring minimum decay time, $t > 5\sigma$ w.r.t PV:
  - ➢ Run I significance: >7σ
  - ➢ Run II significance: >12σ



Inconsistent with a strong decay ⟹ not the excited 3/2 spin state

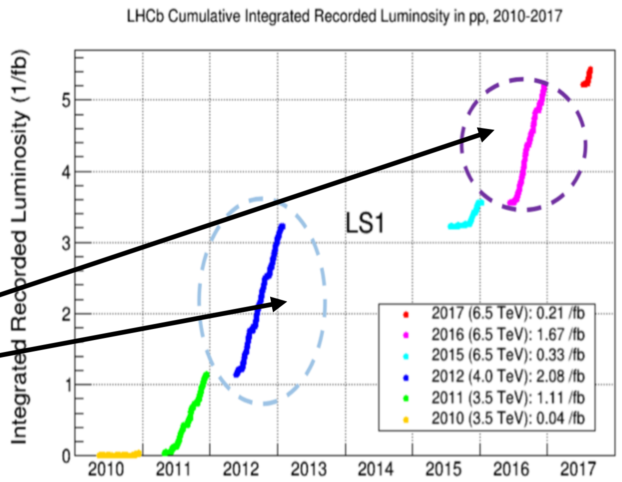




Future work

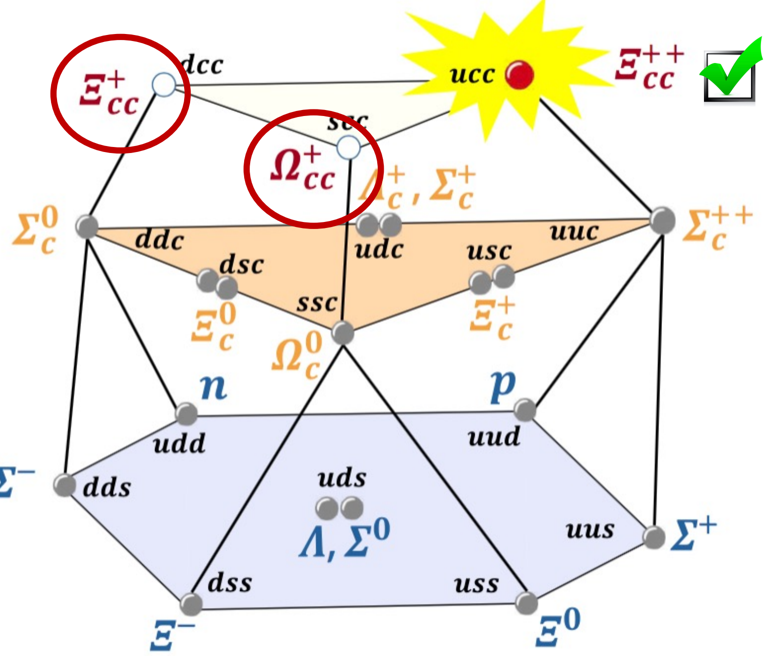
- Mass measurement of Ξ_{cc}^{++} baryon only the start:
  - Lifetime, production cross section, spin etc still need to be found
- Searching for Ξ_{cc}^{++} in other final states including:
  - $\Xi_{cc}^{++} \rightarrow D^{+}p^{+}K^{-}\pi^{+}$
  - $\Xi_{cc}^{++} \rightarrow D^{0}p^{+}K^{-}\pi^{+}\pi^{+}$

$$R = \frac{BF(\Xi_{cc}^{++} \rightarrow D^{+}K^{-}p^{+}\pi^{+})}{BF(\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+}\ K^{-}\pi^{+}\pi^{+})}$$



- Searching for isospin partner Ξ_{cc}^{+} in larger data samples than previous LHCb measurement in multiple channels:
  - $\Xi_{cc}^{+} \rightarrow D^{+}p^{+}K^{-}$
  - $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}\ K^{-}\pi^{+}$

  Same as SELEX search modes

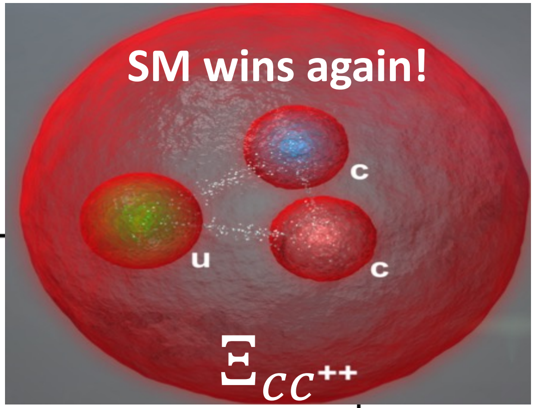


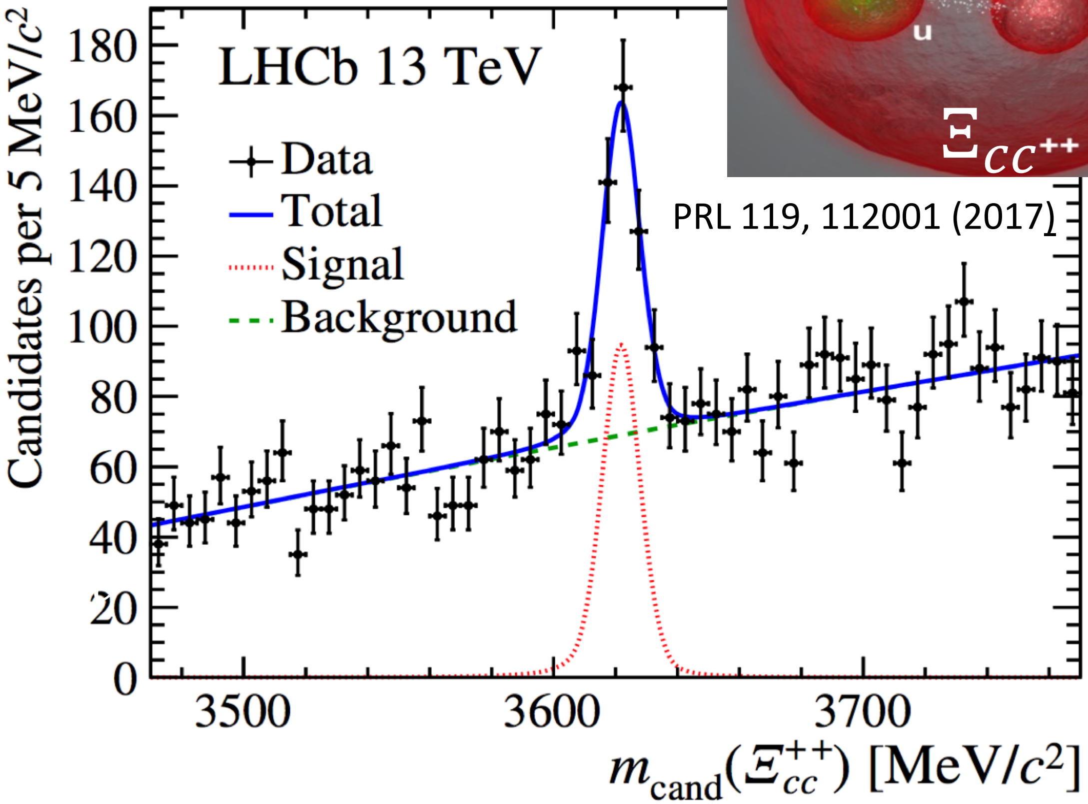
- Improvements in triggers being made:
  - Developing inclusive MVA $\Xi_{c}^{+}, \Xi_{c}^{0}, \Omega_{c}^{+}, \Omega_{c}^{0}$ triggers for 2018
  - In future hope to have dedicated lines for excited states
- Work has started on Ω_{cc}^{+} searches – analysis strategy will be similar

Summary

LHCb very active in doubly charmed baryon studies

- Observed narrow structure in $\Lambda_c^+ K^-\pi^+\pi^+$ mass spectrum
  - ➢ Significant displacement consistent with a weakly decaying particle
  - ➢ Consistent with $\Xi_{cc}^{++}(ccu)$
- Searching for other hadronic decay modes of Ξ_{cc}^{++} to obtain relative BF measurements
- Search for Ξ_{cc}^{+} continues in LHCb data
- DCBs are important systems to study: better understanding of strong force, spectroscopy, CPV… more than just stamp collecting



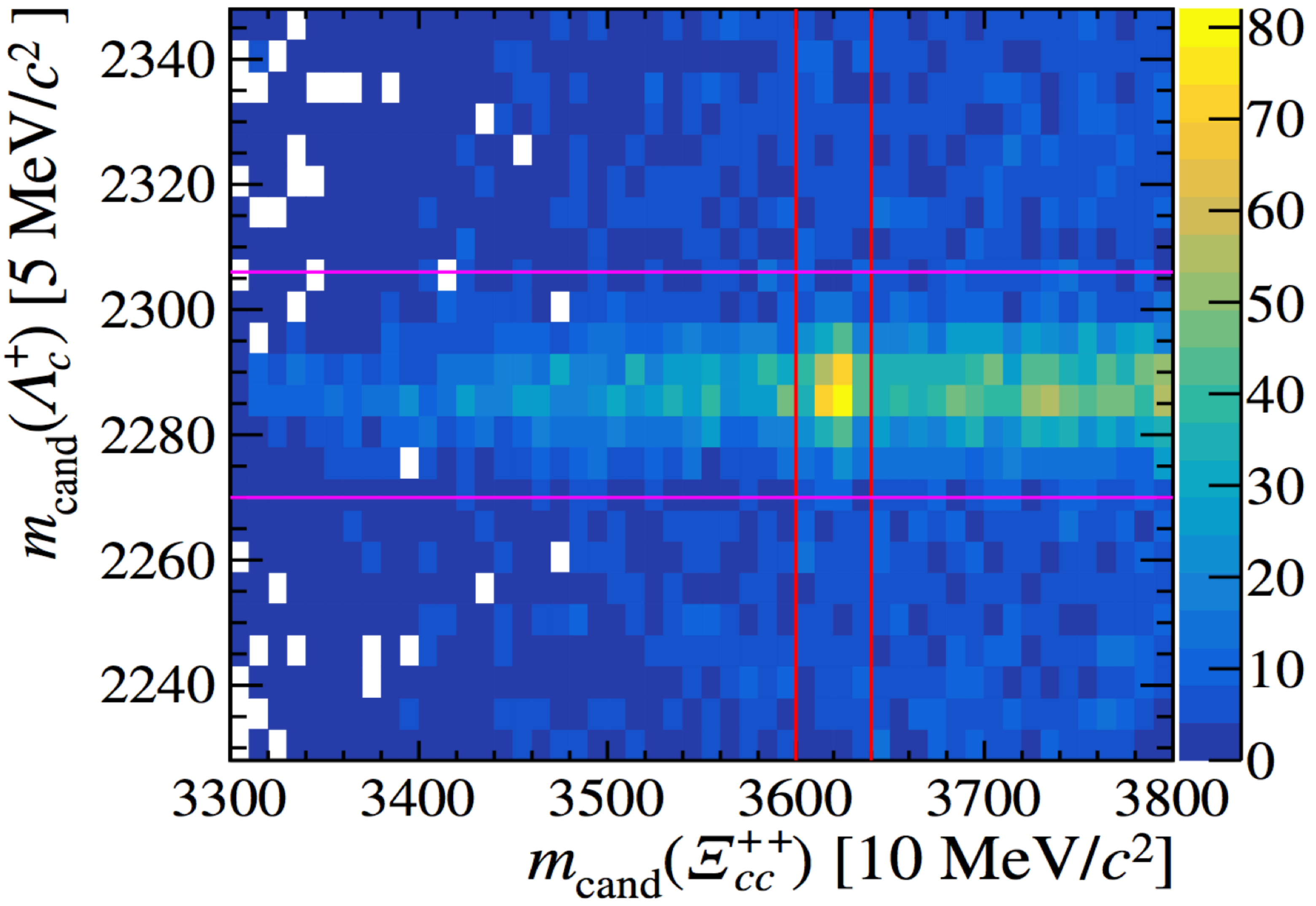


PRL 119, 112001 (2017)

$M(\Xi_{cc}^{++})$= 3621.40 $\pm$ 0.78 MeV/c^2

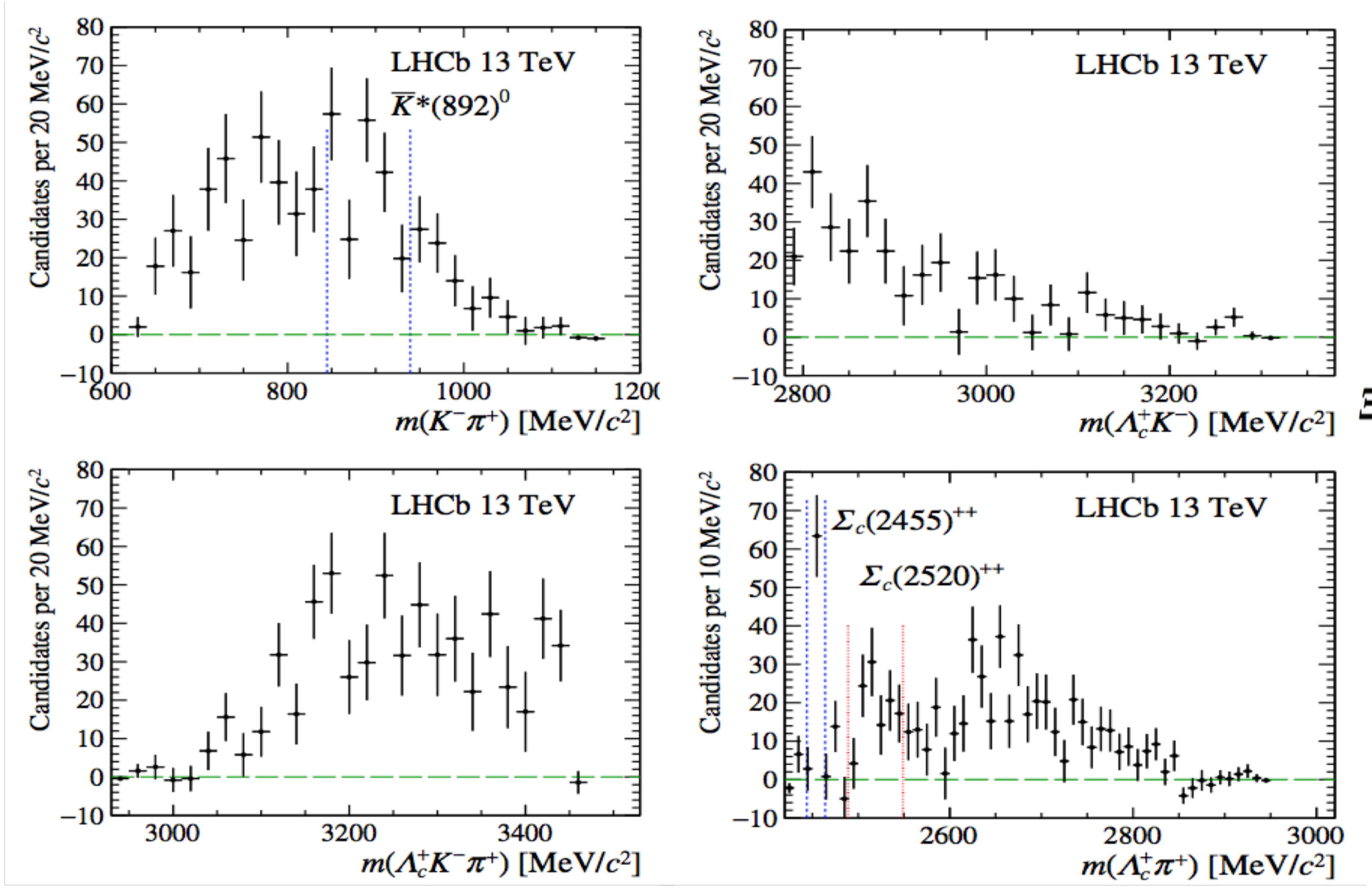
Back-up

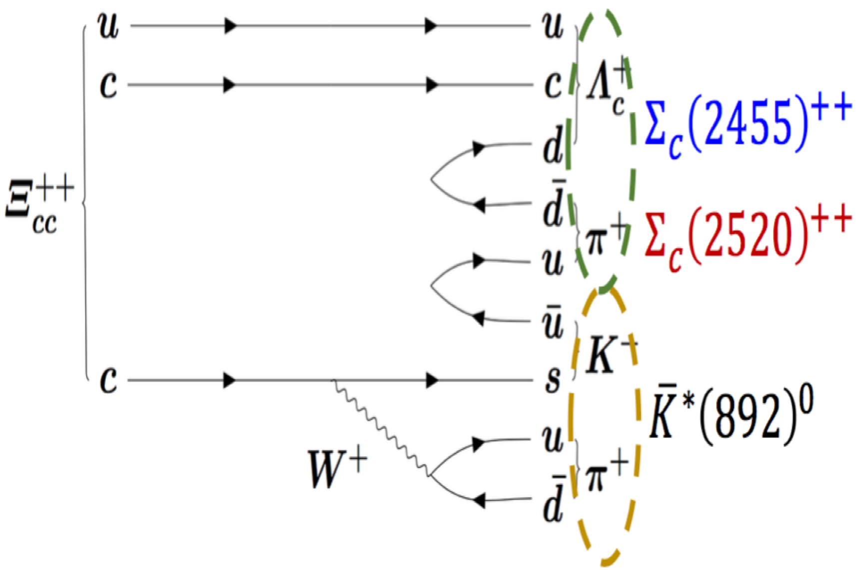
$M(\Lambda_c^+)$ vs. $M(\Xi_{cc}^{++})$ PRL 119, 112001 (2017)



Intermediate resonances [PRL 119, 112001 (2017)](#)

RS, sideband-subtracted





References

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[2] *C.H. Chang, J.-X. Wang, and X.-G. Wu, GENXICC2.0: Comput.Phys.Commun.181:1144-1149, 2010*

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[5] *Search for the doubly charmed baryon Ξ_{cc}^{+}, The LHCb Collaboration, R. Aaij et el, JHEP12(2013)090*

[6] *Discovery potentials of Doubly Charmed Baryons, Fu-Heng, Hua-Yu Jiang. arXiv:1703.09086*

[7] *Low lying baryon masses using N_f=2 twisted mass clover-improved fermions directly at the physical point, Constantia Alexandrou, Christos Kallidonis, arXiv: 1704.02647v1*