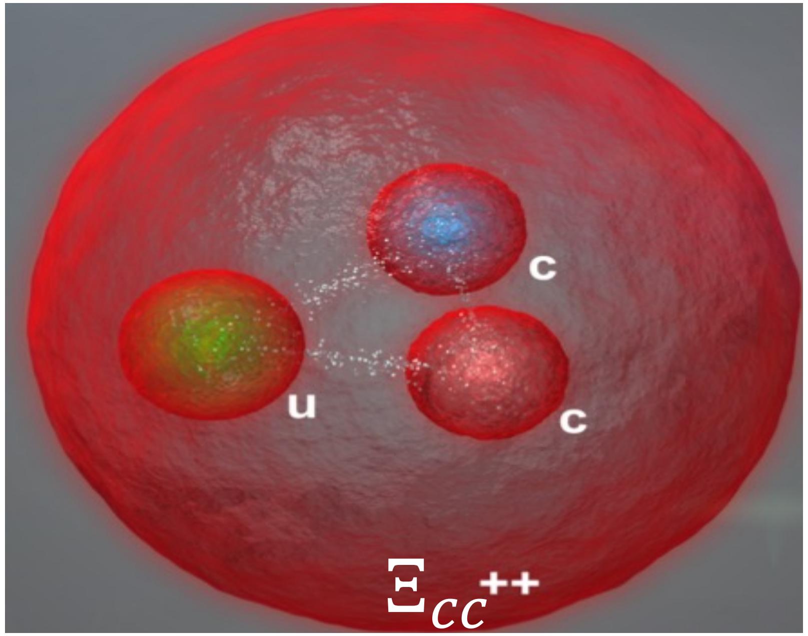
Doubly charmed hadrons at LHCb

Murdo Traill

on behalf of the LHCb collaboration

University of Glasgow



HF@LHC workshop, 6th - 8th September 2017
Durham, UK

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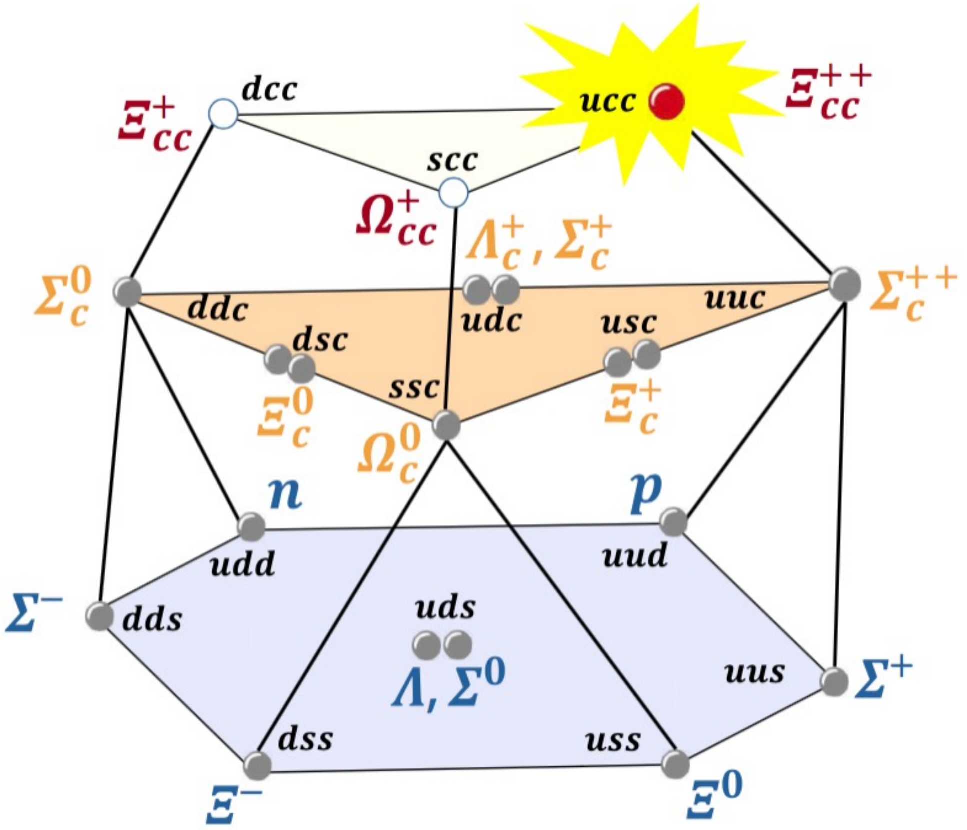


LHCb detector

Main challenges in hadron spectroscopy include hadronic background and particle mis-ID

LHCb is well equipped to handle both!

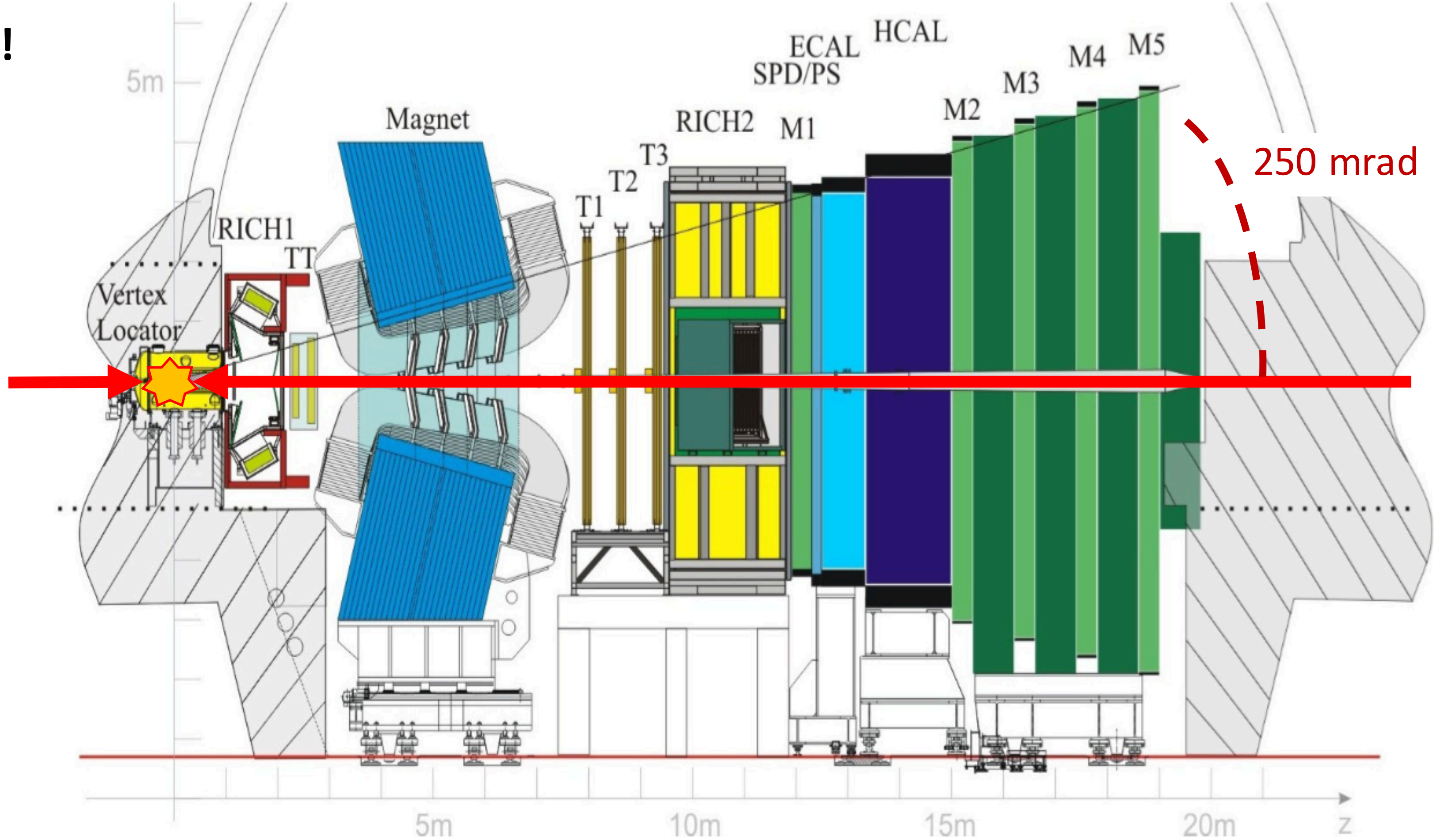
VErtex LOcator (VELO):
- Vertex reconstruction
- Impact parameter resolution: 20 μm
- Decay time resolution: 45 fs
- Allows identification of weak decays

RICH sub-detectors:
- K/π/p separation
- $\epsilon(K \to K)$~95% with $\epsilon(\pi \to K)$~5%
- $\epsilon(p \to p)$~95% with $\epsilon(\pi \to p)$~5%
- Effectively distinguish K *and* p *from* π

Tracking system:
- $\epsilon(Tracking)$~96%
- δp/p~0.5-1% (5-200 GeV)
- Easily separate neighboring structures

Aiming for precision measurements in b and c flavor physics

Single forward arm detector covering $2 < \eta < 5$



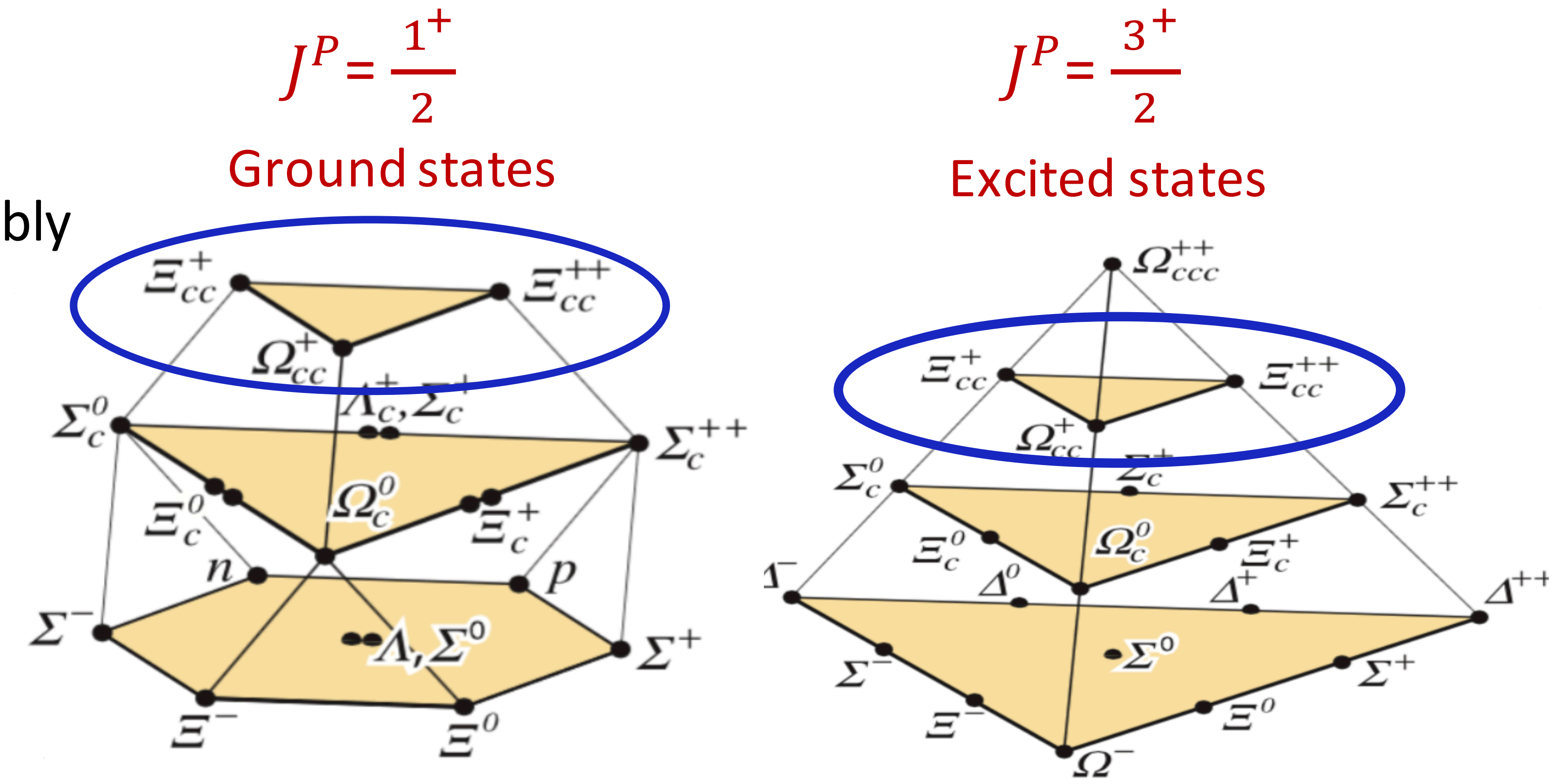
The LHCb Detector at the LHC 2008 JINST 3 S08005

Doubly charmed baryons

- Constituent-quark model predicts 3 SU(3) triplets with C=2; $\Omega_{cc}^{+}(ccs)$, $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$
- Excited decay to ground states via strong/electromagnetic interactions
- Ground states decay weakly with a charm quark transitioning into lighter quarks

- (QQq) baryons are not exotic – predicted by SM
- No unambiguous evidence for doubly charmed baryons before 2017
- Ξ_{cc} are the lightest doubly heavy baryon
- Ξ_{cc} offered best chance of discovery;

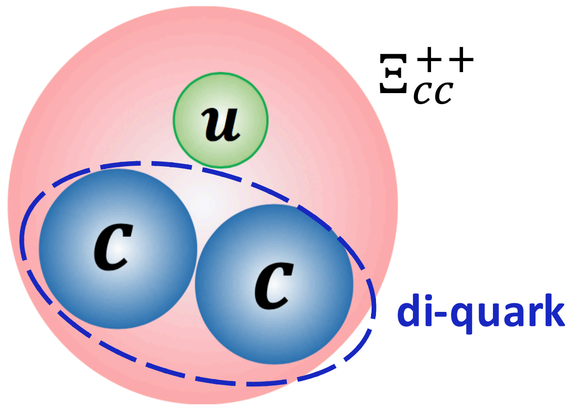
$\sigma(c\bar{c}, c\bar{c}) >> \sigma(b\bar{b}, c\bar{c}) >> \sigma(b\bar{b}, b\bar{b})$



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

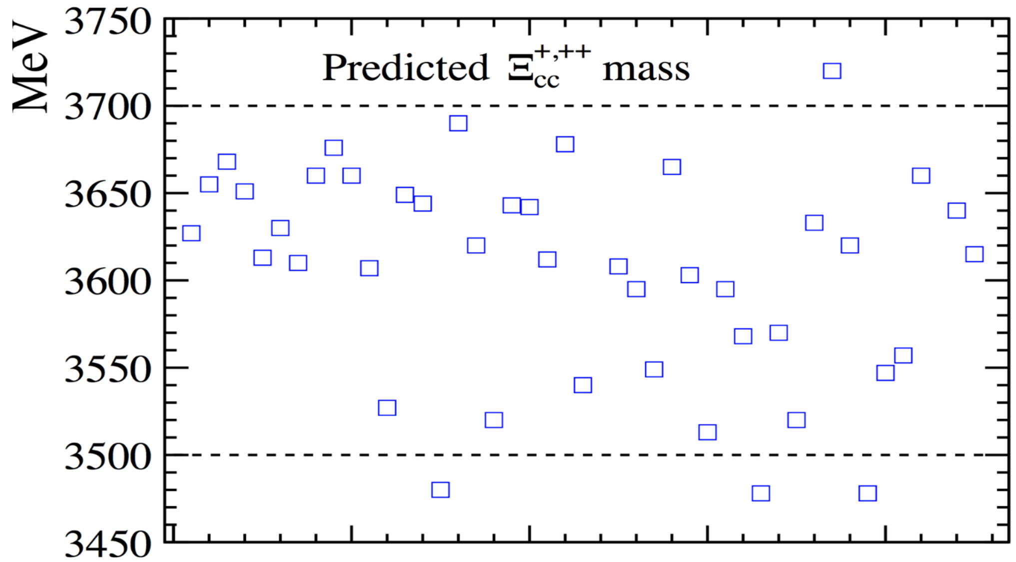
Masses and lifetime of ground states

- Many models been applied to determine masses of ground state and excitations: QCD sum rules, (non-)relativistic QCD potential models, etc



Great for testing HQET where two c quarks considered as heavy di-quark and baryon is similar to heavy meson $Q\bar{q}$

- Most agree Ξ_{cc}^{+} and Ξ_{cc}^{++} states between 3.5 - 3.7 GeV and $\Omega_{cc}^{+}(ccs) \approx \Xi_{cc}$+ 0.1 GeV



- Mass splitting between $\Xi_{cc}^{+}/\Xi_{cc}^{++}$ is only a few MeV due to approximate isospin symmetry

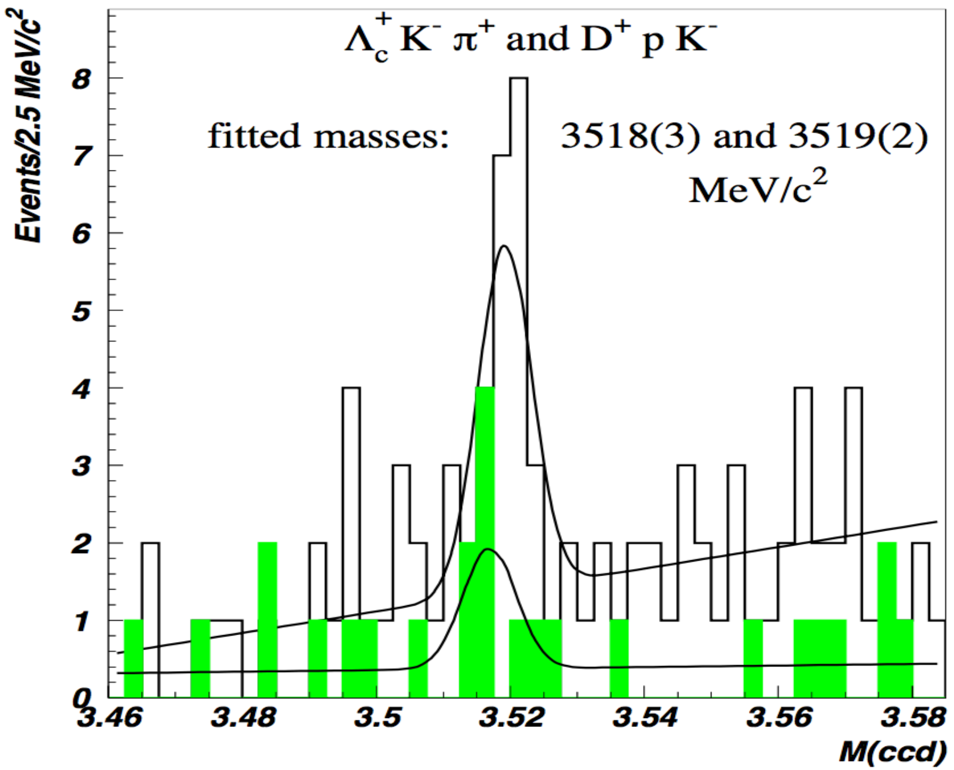
- Recent lattice QCD computations: m($\Xi_{cc}^{+}/\Xi_{cc}^{++}$) ≈ 3.6 GeV, m($\Omega_{cc}^{+}$) ≈ 3.7 GeV

- Lifetimes: expect $\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+}) > \tau(\Omega_{cc}^{+})$
  - $\tau(\Xi_{cc}^{+}) \in$ 50-250 fs
  - $\tau(\Xi_{cc}^{++}) \in$ 200-700 fs
  - $\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{+})$

All references shown in back-up slides

SELEX and Ξ_{cc}^{+}

- SELEX, a fixed-target Fermilab experiment, claimed first observation of Ξ_{cc}^{+} state in $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-}\pi^{+}$ decays in 2002
- Followed by a confirmation in $D^{+}p^{+} K^{-}$mode in 2004:
  - $\Lambda_c^{+} K^{-}\pi^{+}$: 15.9 signals over 6.1 bkg (6.3σ)
  - $D^{+}p^{+} K^{-}$: 5.62 signals over 1.38 bkg (4.8σ)
- Unexpected properties of this observation:
  - Short lifetime: τ < 33 fs at 90% C.L. (Strong decay?)
  - Large production of Λ_c^{+} with 20% from Ξ_{cc}^{+} decays
- Main problem with SELEX findings; never reproduced by other groups
- Unique production environment:
  - Hyperon beam is admixture of $\Sigma^{-}, p^{+}, \pi^{-}$ and target was Cu/diamond
  - Production cross-section could be much different than in p-p colliders



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

Combined mass:
3518.7 ± 1.7(stat) MeV/c^2

LHCb search for Ξ_{cc}^{+}

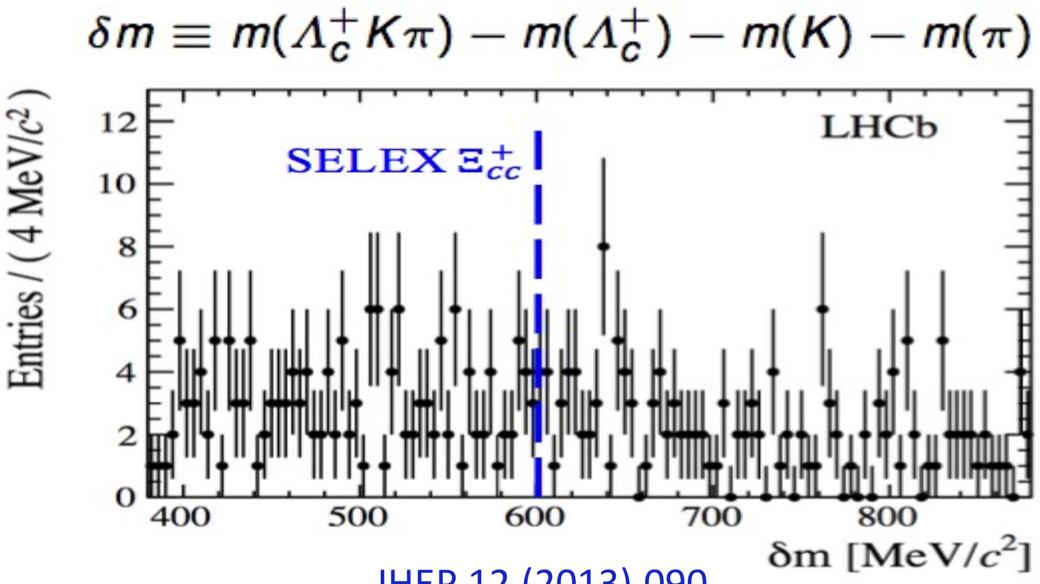
- In 2013, LHCb searched for $\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$ decays with 0.65 fb^{-1} of 2011 data
- Initial SELEX mode with a large expected BF
- Examined mass range 3.3-3.8 GeV but found no evidence of Ξ_{cc}^{+} production
- Experiment sensitivity strongly depends on Ξ_{cc}^{+} lifetime however

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times BF(\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

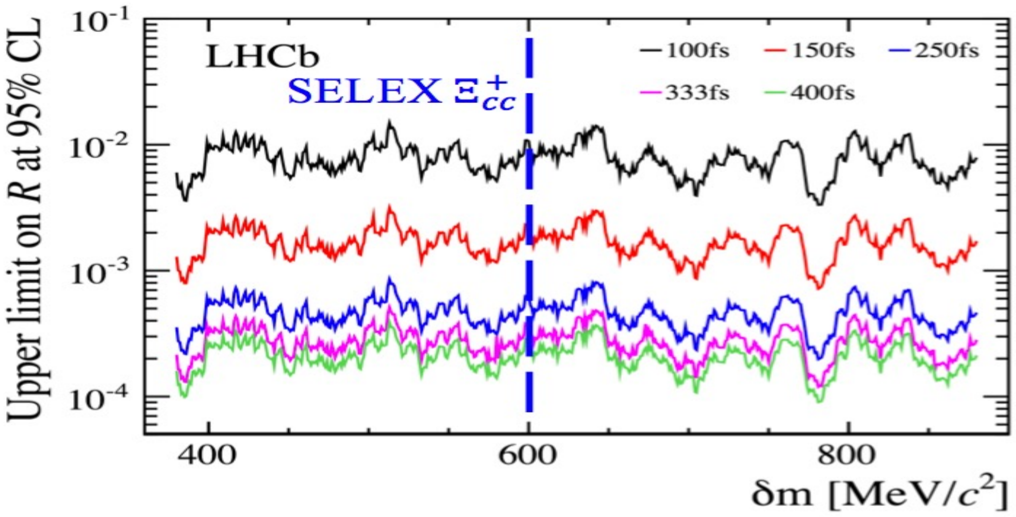
R < 0.013 for $\tau(\Xi_{cc}^{+})$ = 100fs

R < 3.3×10^{-4} for $\tau(\Xi_{cc}^{+})$ = 400fs

- Due to limited sensitivity at short lifetimes, this non-observation is not inconsistent with the SELEX claim

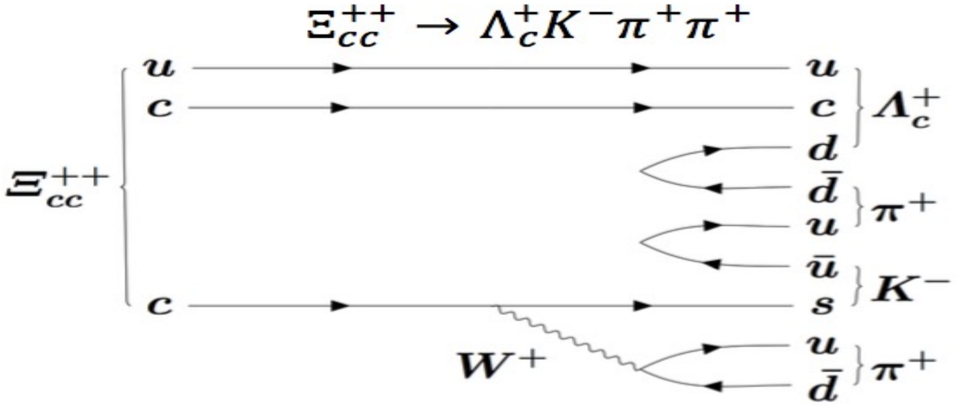


JHEP 12 (2013) 090



Switch to Ξ_{cc}^{++}

- Searching for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays: theorists suggest BF could as high as ~10%, see arXiv:1703.09086

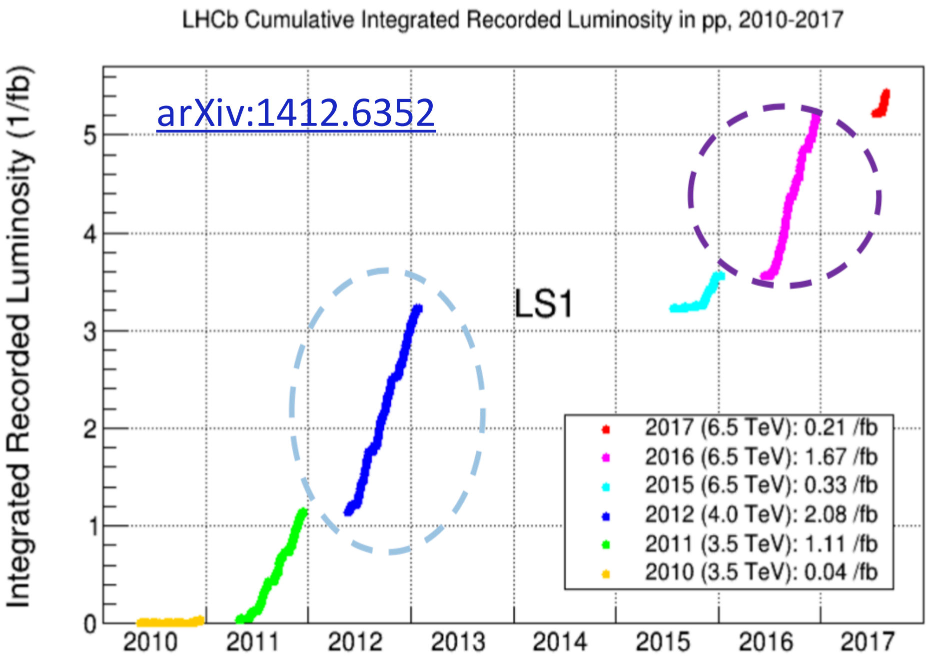


- $\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+})$; Ξ_{cc}^{++} travels further from PV making online selection better at observing Ξ_{cc}^{++} state

- Reconstruct Λ_c^+ through $p^+ K^- \pi^+$ final state

Analysis strategy:

- Use ~1.7 fb^{-1} 2016 Run2 data at $\sqrt{s}$ = 13 TeV
- Dedicated exclusive trigger ensuring high efficiency
- Full event reconstruction done at trigger level
- 2 fb^{-1} 2012 Run1 data also analysed to check results



Candidate selection

- Ξ_{cc}^{++} cross-section much smaller ($\sim\times10^{-5}$) than inelastic cross-section in pp so expecting large hadronic backgrounds
- Expect high-pure sample of $\Lambda_c^+ \to p^+ K^- \pi^+$

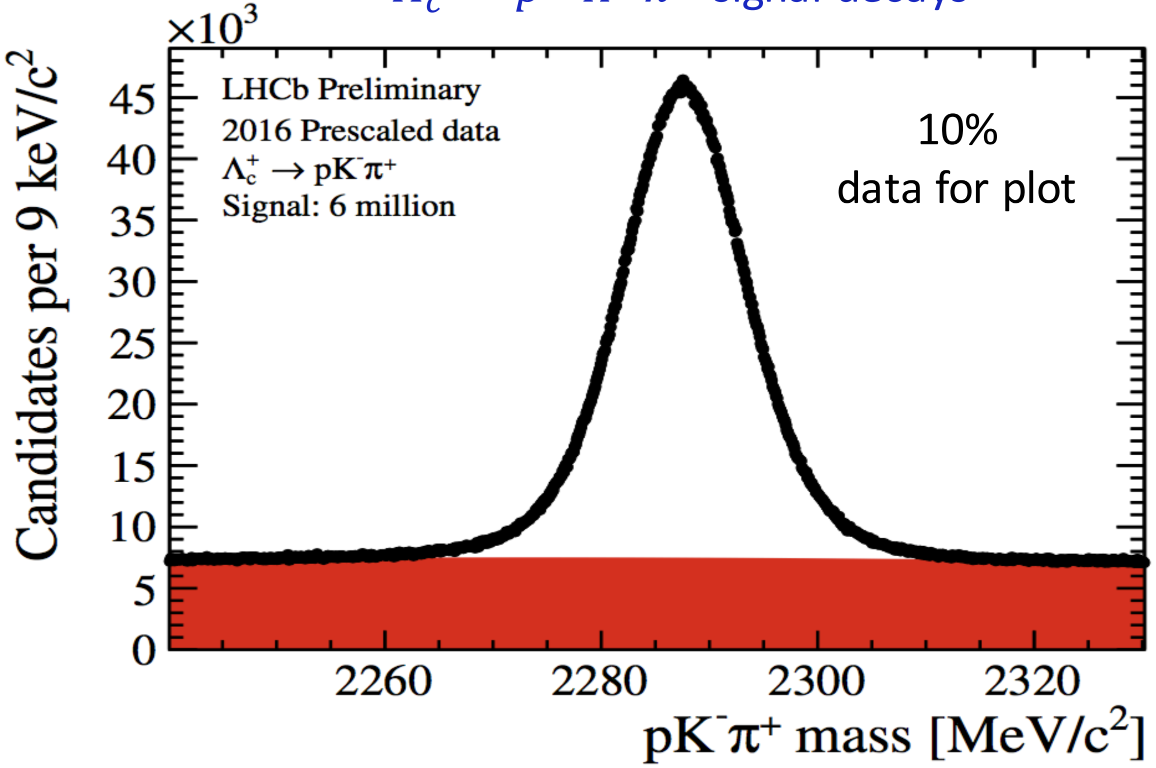
LHCb has some of largest charm data sets in the world

$\sigma(pp \to c\bar{c}X;$ 13TeV) LHCb =2369$\pm$3 $\pm$ 192 μb JHEP 1603 (2016) 159

$\Lambda_c^+ \to p^+ K^- \pi^+$ selection:

- p^+, K^-,π^+tracks: positive particle ID and not produced from primary vertices
- Λ_c^+: good vertex quality, separated from primary vertices
- Λ_c^+, p^+, K^-,π^+ tracks must have large p_T

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



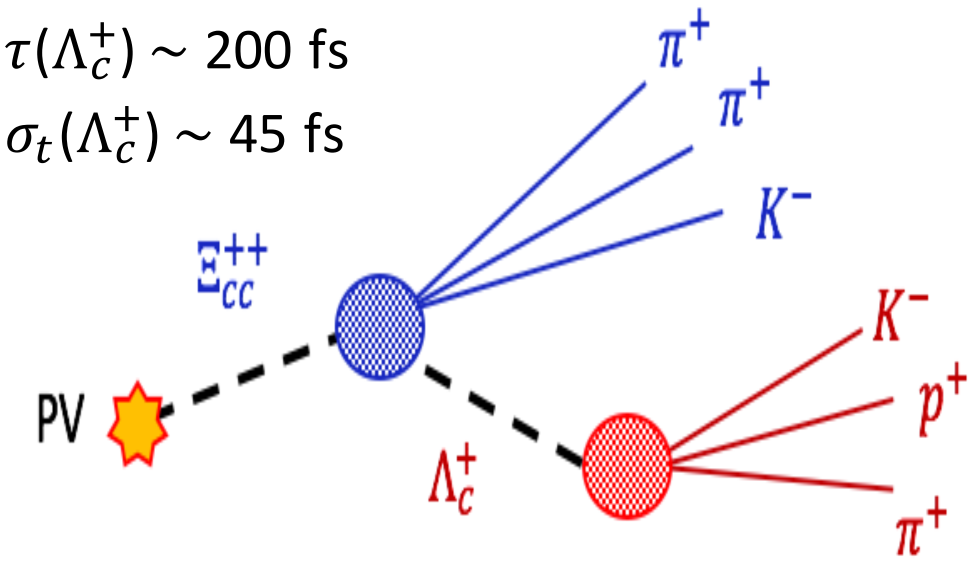
Machine learning

- Λ_c^+ combined with PID-selected $K^-\pi^+\pi^+$ tracks to form Ξ_{cc}^{++} candidates
- Candidates with cloned tracks are removed

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

$\tau(\Lambda_c^+) \sim 200$ fs

$\sigma_t(\Lambda_c^+) \sim 45$ fs

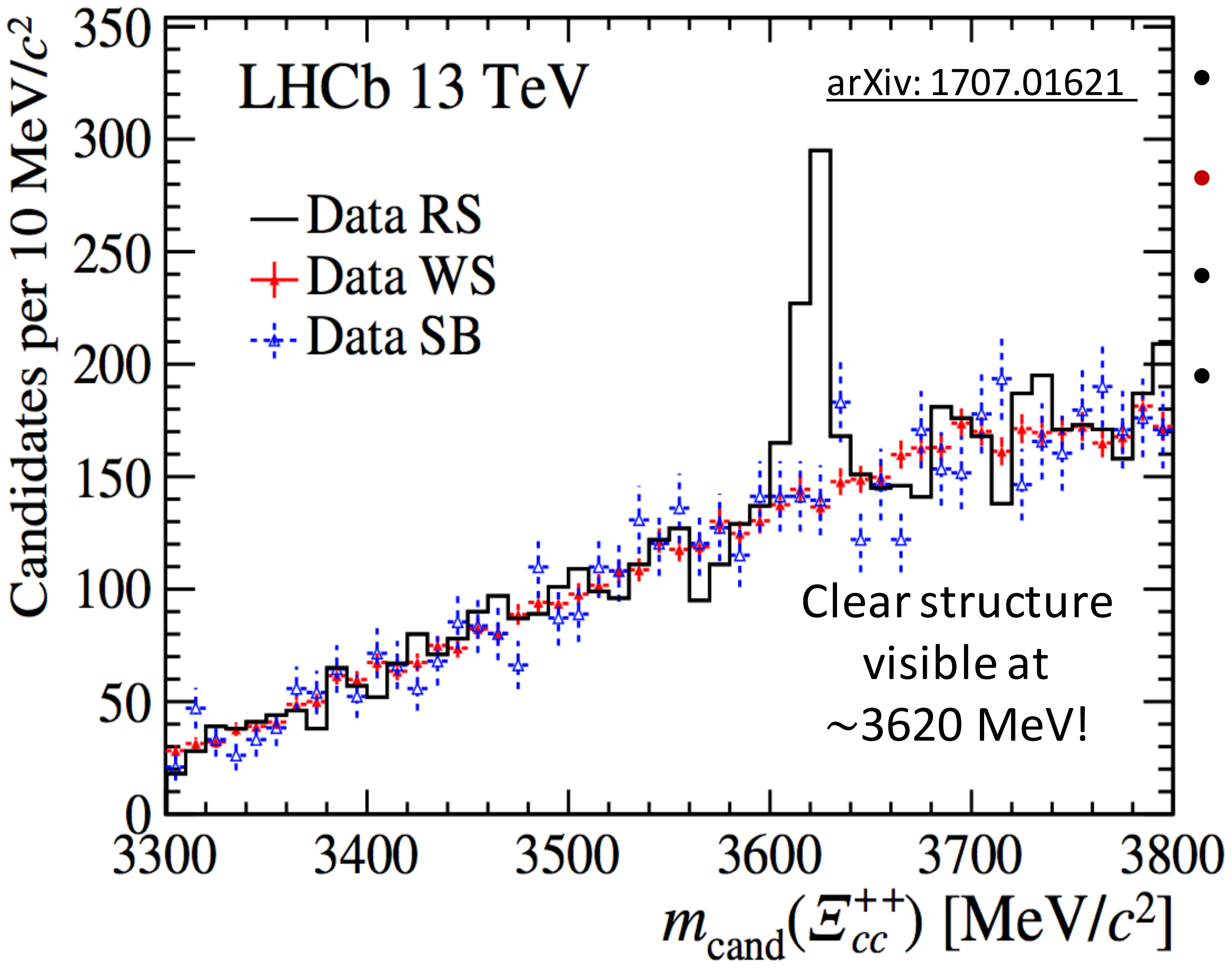


- Multivariate selector further explores:
  - Decay Fit quality of Ξ_{cc}^{++} candidates
  - Kinematics of final states
  - Ξ_{cc}^{++} vertex separation from PV

Neural-network selector trained on simulated signal and un-physical wrong-sign (WS) data represented background as:

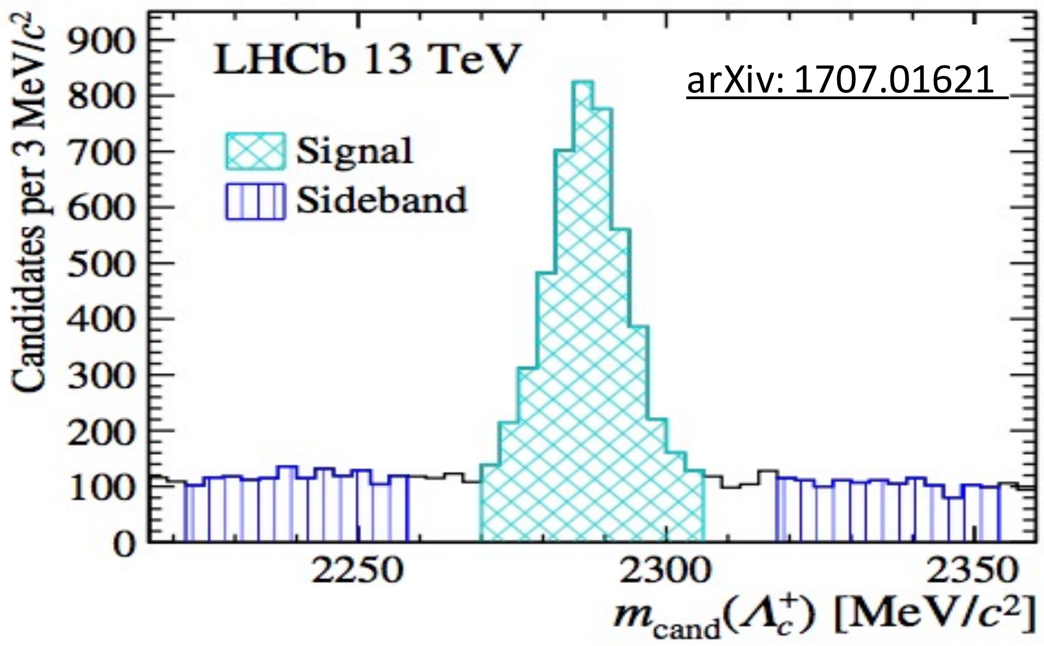
$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^-$$

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



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

- 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

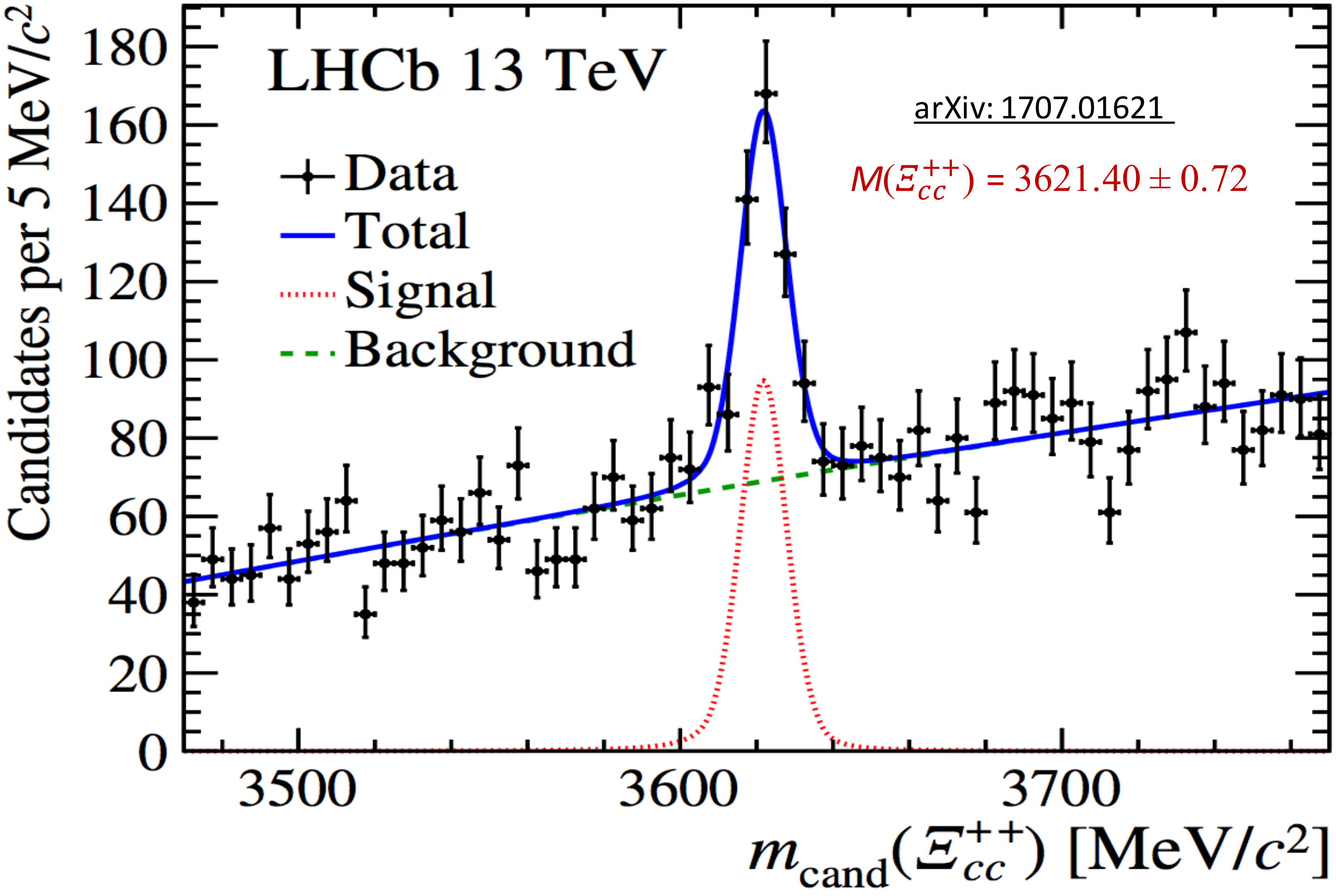


Fitting the mass peak

Signal yield = 313 ± 33

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

Local significance > 12σ



Mass measurement

Systematics

arXiv: 1707.01621

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

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

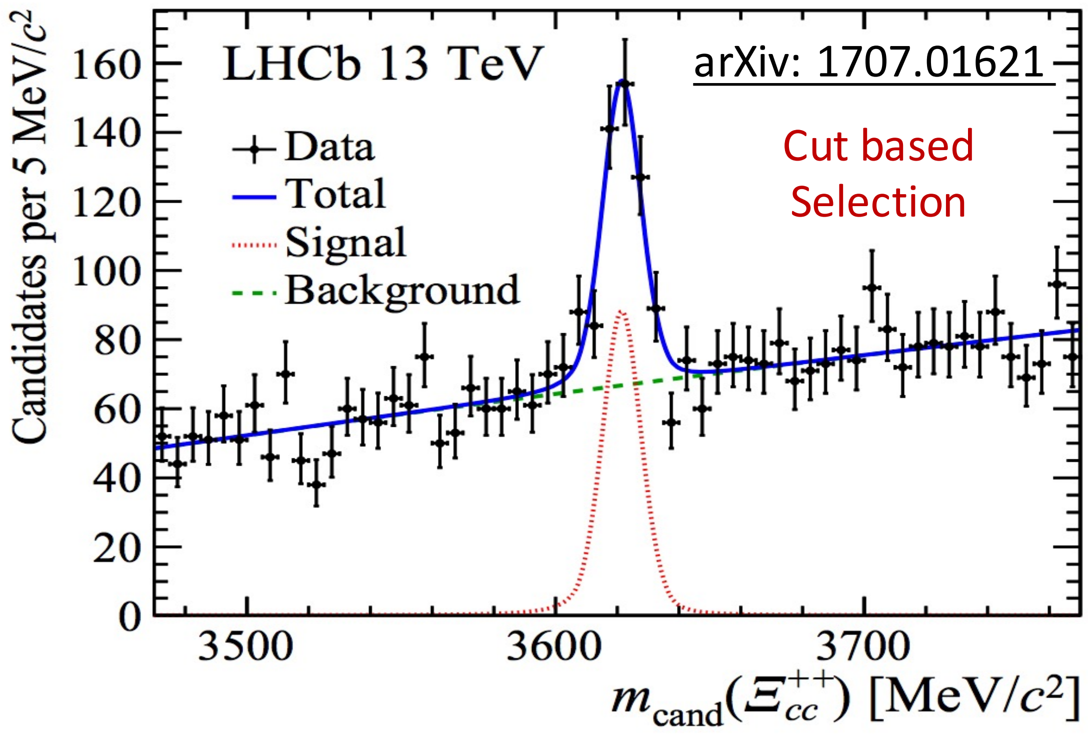
$$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\ (\text{stat}) \pm 0.27\ (\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$

Cross-checks

- Varying threshold value of MVA selector has no effect on signal significance
- MVA efficiency as a function of mass: very smooth, no biasing
- Multiple candidates do not create fake narrow structures
- Checking combinations of tracks from Λ_c^+ and Ξ_{cc}^{++}: again no peaking structures

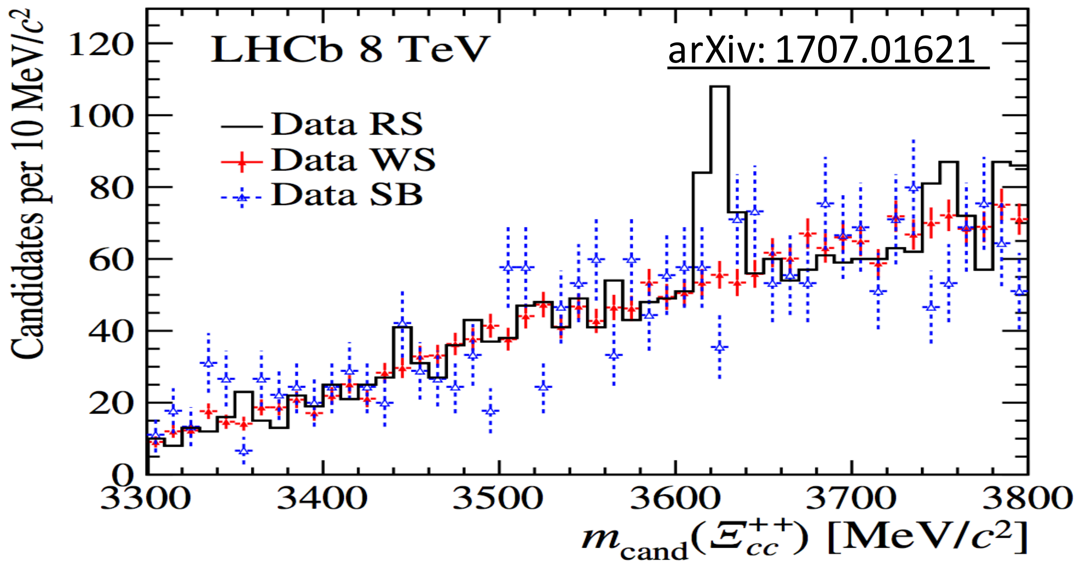
- Varying particle ID selections: no peaking structure emerge in WS combinations but structure remains in RS sample

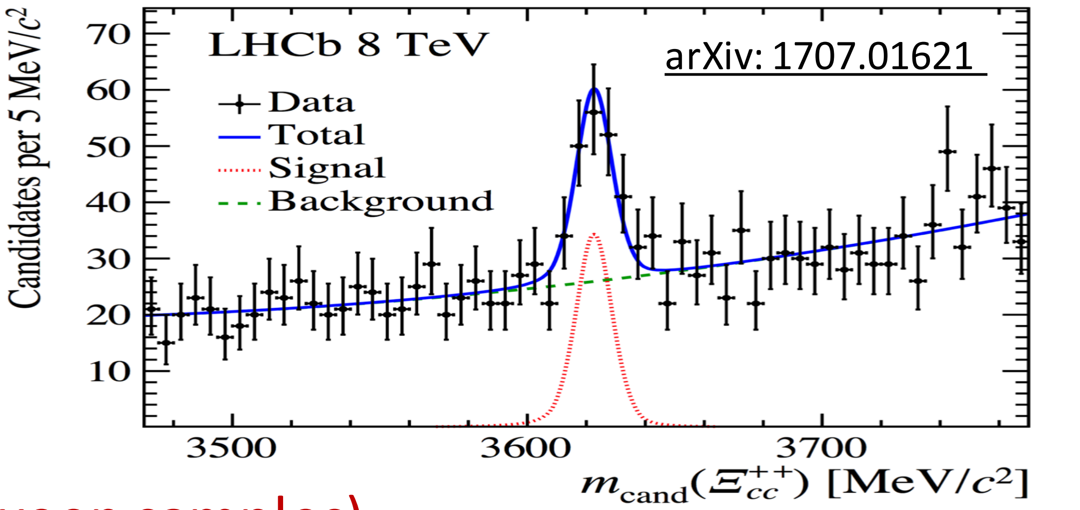
- Tried cut based selection instead of MVA:
  - ➢ requiring good vertex fit quality
  - ➢ Ξ_{cc}^{++} vertex displaced
  - ➢ tracks are not produced from PV
  - ➢ Peak significance still > 12σ



Confirmation in Run 1

- Similar search done with 2 fb^{-1} of Run1 data recorded in 2012, $\sqrt{s}$ = 8 TeV
- Different trigger and data processing configuration than in Run2
- But again a clear peak is seen in $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum
- Signal yield: 113 ± 21
- Local significance: $>7\sigma$
- Resolution: 6.6 ± 1.4 MeV

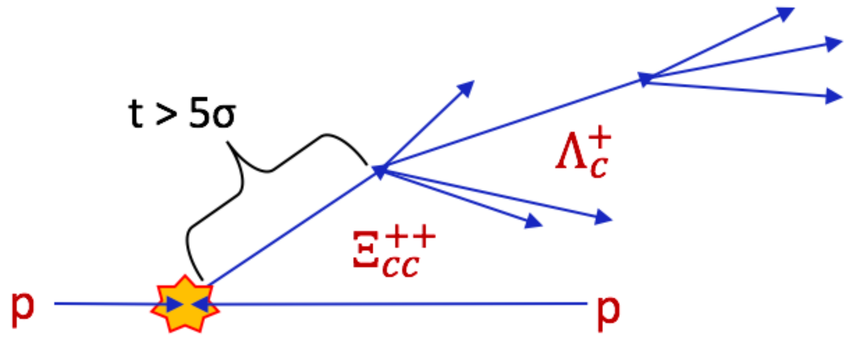




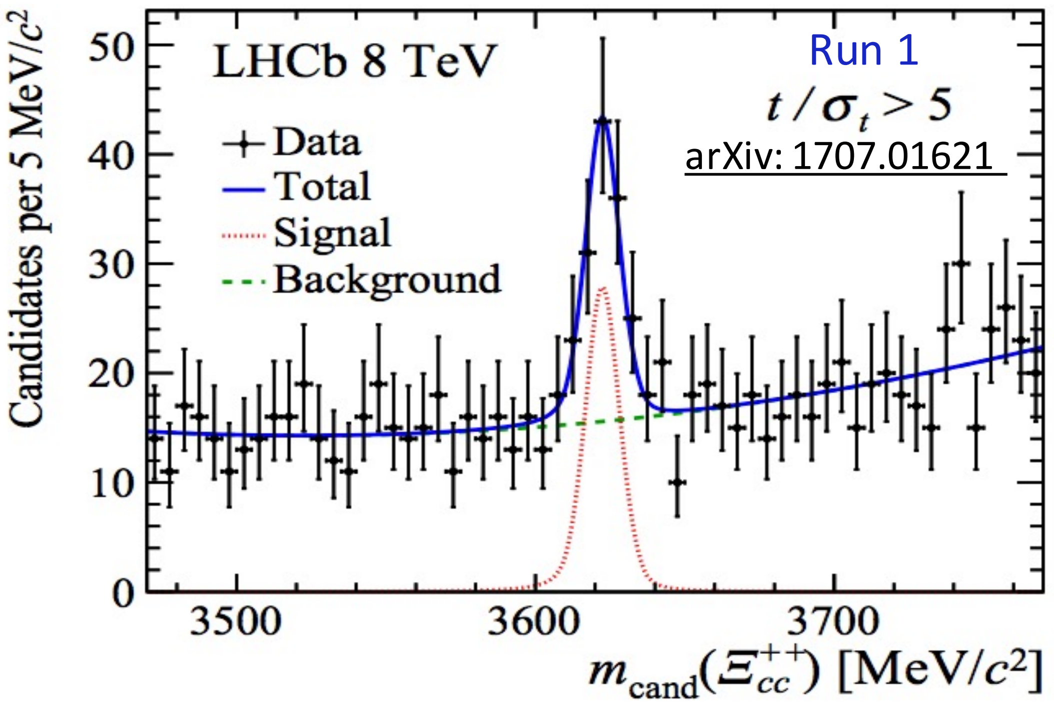
- Δm(Run1, Run2) = 0.8 ± 1.4 MeV (consistent between samples)

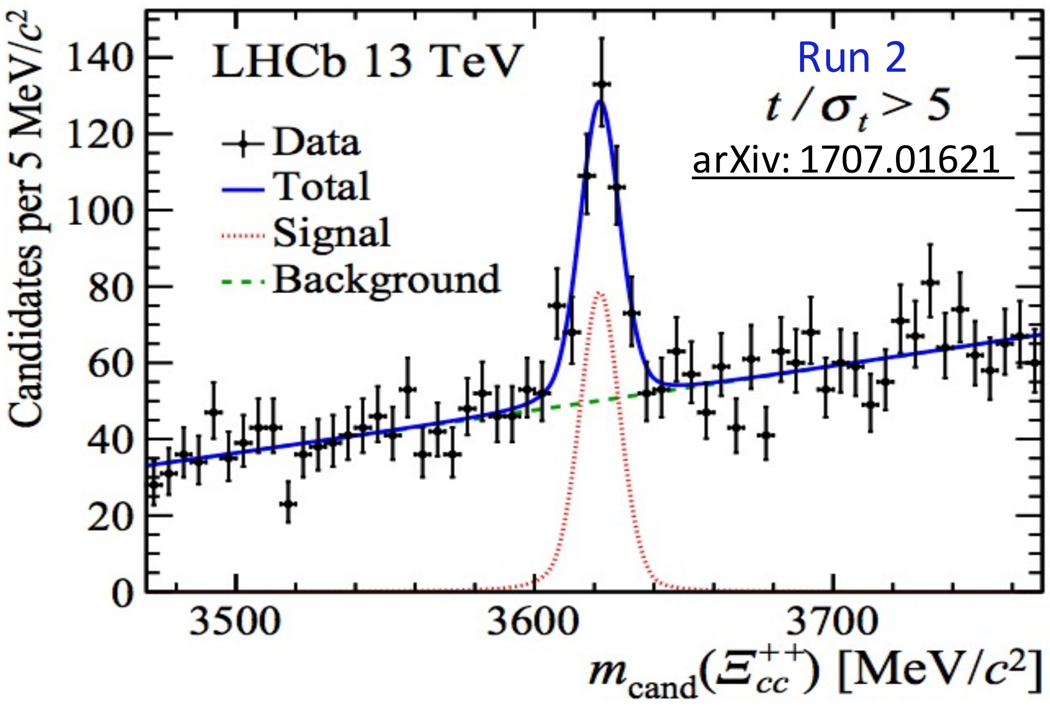
Weak Decay

- Peaking structure remains significant after requiring minimum decay time, $t > 5\sigma$ w.r.t PV:
  - ➢ Run1 significance: >7σ
  - ➢ Run2 significance: >12σ

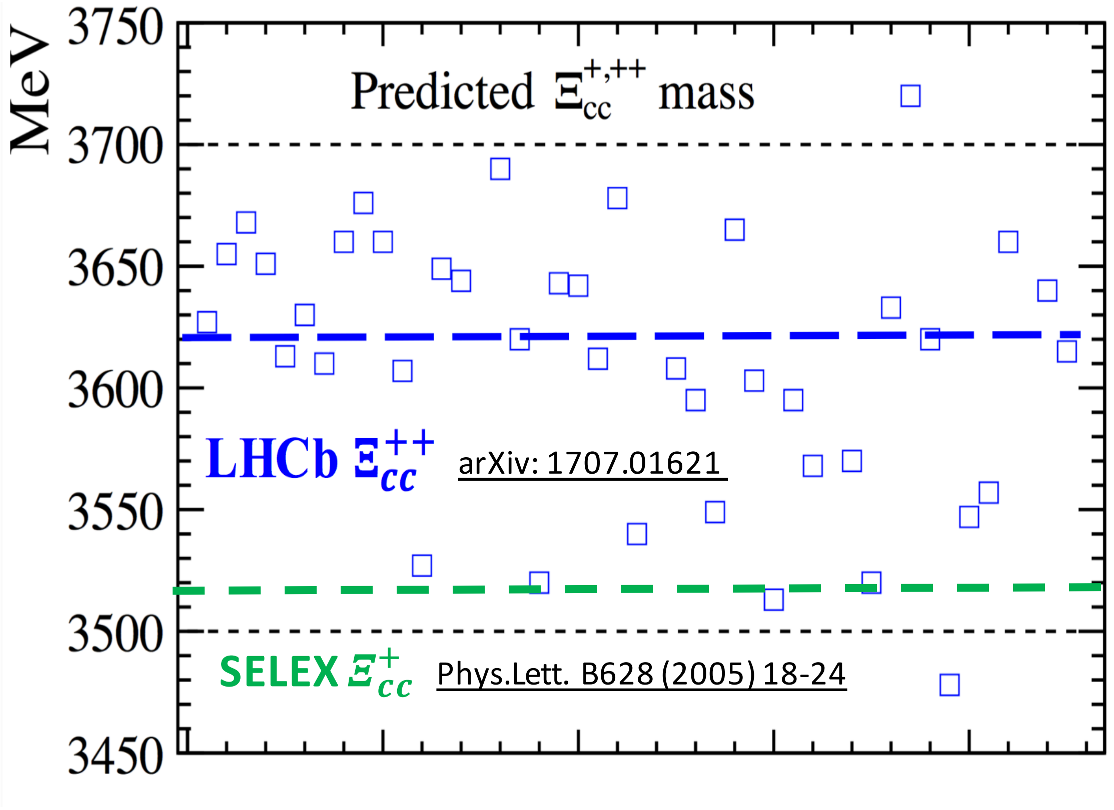


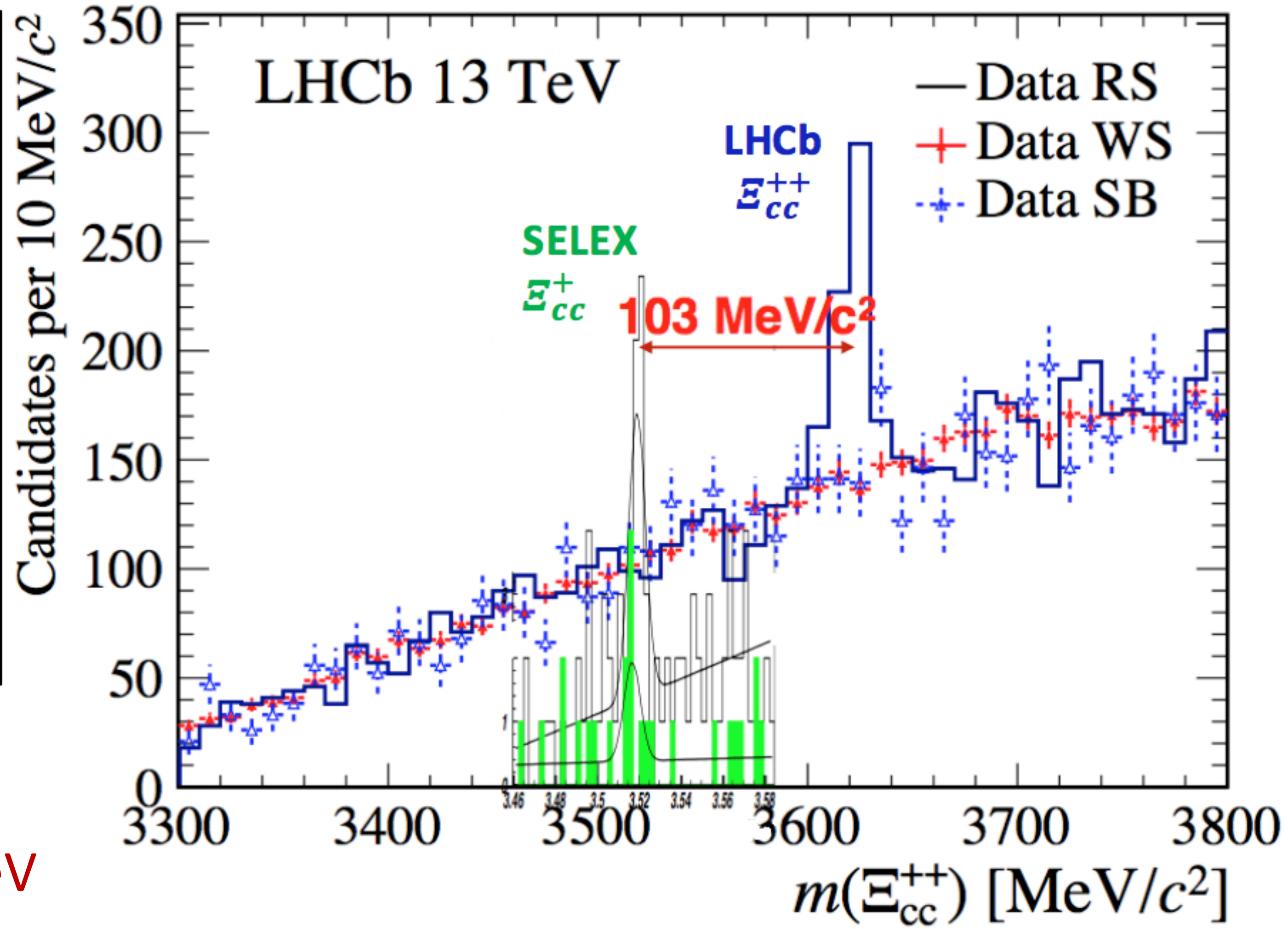
Inconsistent with a strong decay





Comparison with SELEX





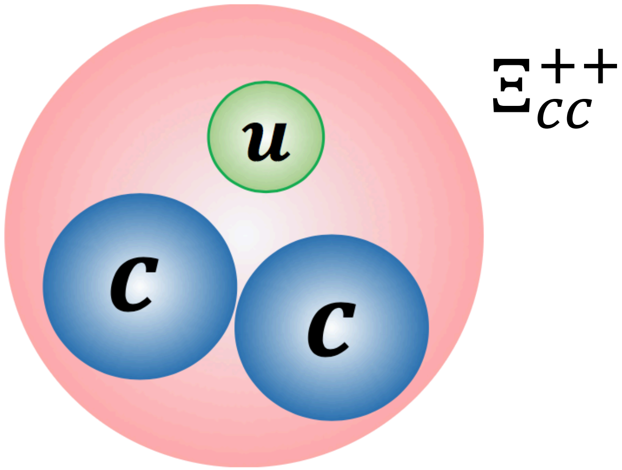
- Large mass difference:

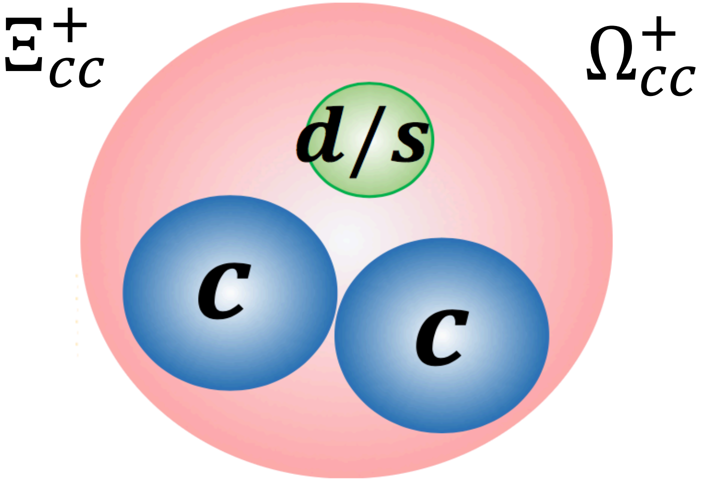
$m(\Xi_{cc}^{++})_{LHCb} - m(\Xi_{cc}^{+})_{SELEX}$ = 103 ± 2 MeV

Inconsistent with being isospin partners: E.g. Guo, Hanhart, and Meissner, PLB 698 251-255; Karliner and Rosner, arXiv:1706.06961

Prospects

- Searching for Ξ_{cc}^{++} in additional decay modes:
  $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$, $\Xi_{cc}^{++} \to D^{+}p^{+}K^{-}\pi^{+}$, $\Xi_{cc}^{++} \to \Lambda_c^{+}\pi^{+}$
- Measurement of Ξ_{cc}^{++} lifetime is making good progress
- Production cross-section
- Confirming its spin-parity is $J^P = {1^+}/{2}$





- Searching for its isospin partner Ξ_{cc}^{+} in larger sample than previous LHCb measurement
  - Also searching for Ω_{cc}^{+} in the near future
  - The excited states?
- Now a new sector to study strong force and CP violation

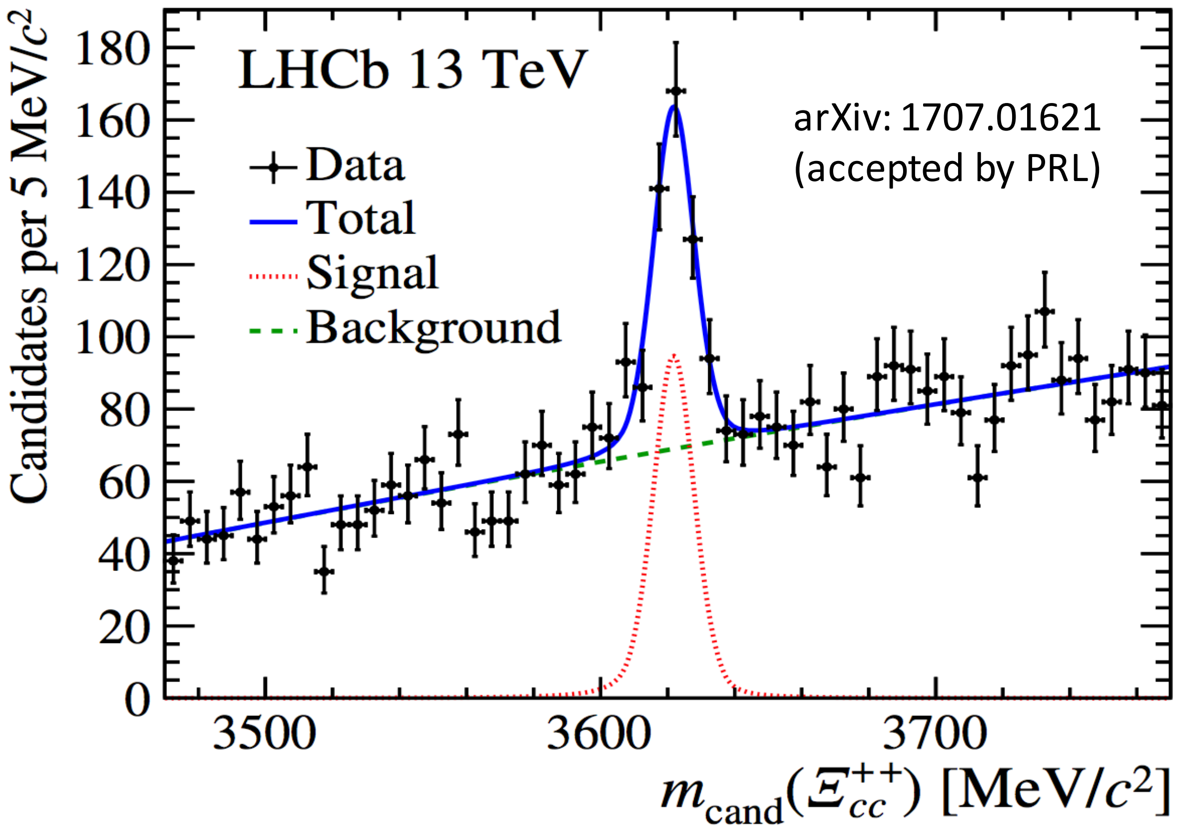
Just the beginning. A long list of studies ahead.

Summary

- LHCb very active in hadron spectroscopy studies
- Observed narrow structure in the $\Lambda_c^+ K^-\pi^+\pi^+$ mass spectrum this year
- Significant displacement consistent with a weakly decaying particle
- Observed in two LHCb data sets
- Consistent with $\Xi_{cc}^{++}(ccu)$
- Inconsistent with Ξ_{cc}^{+} observed by SELEX being its isospin partner

Stay tuned for more doubly charming results

Thank you.

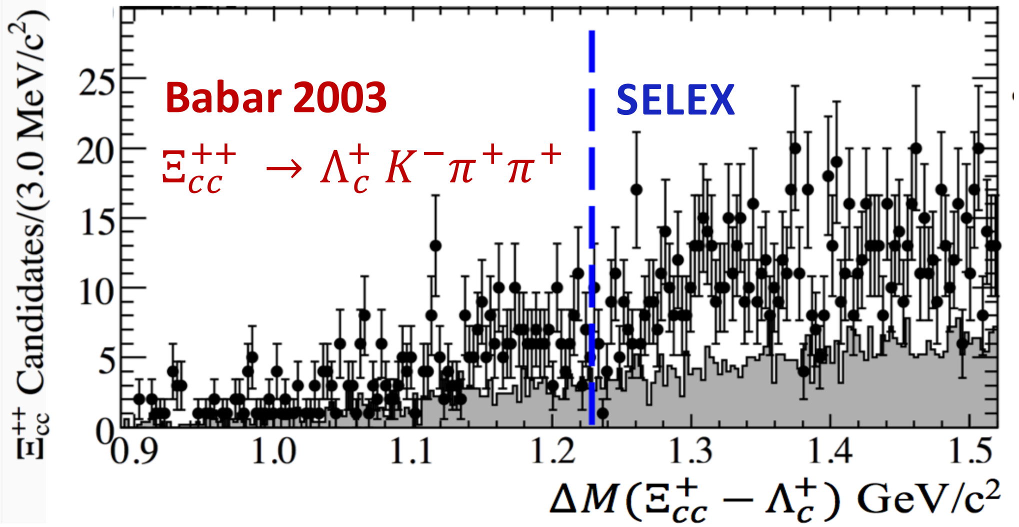


$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ (tot) MeV

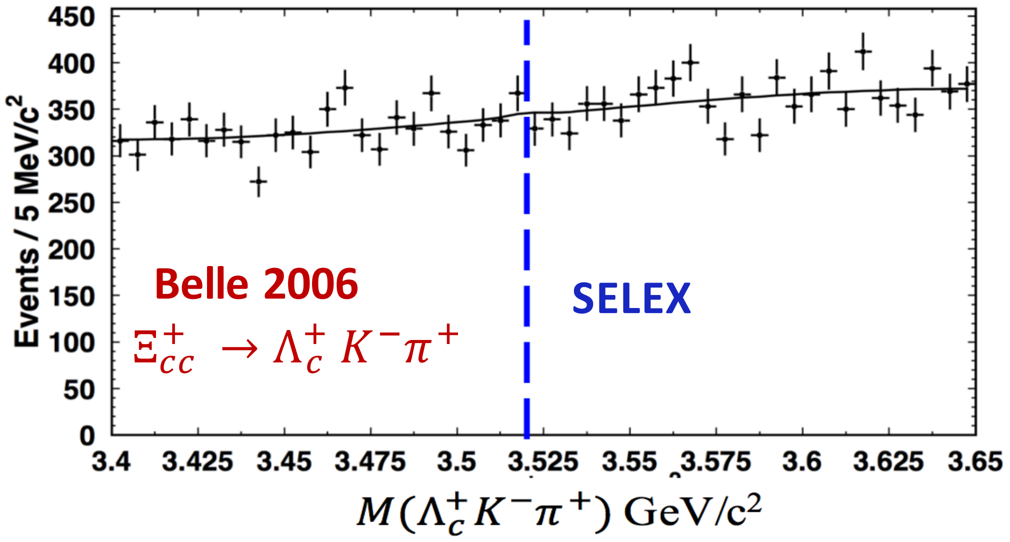
Back-up

Searches by other experiments

Phys.Rev. D74 (2006) 011103



Phys.Rev.Lett. 97 (2006) 162001

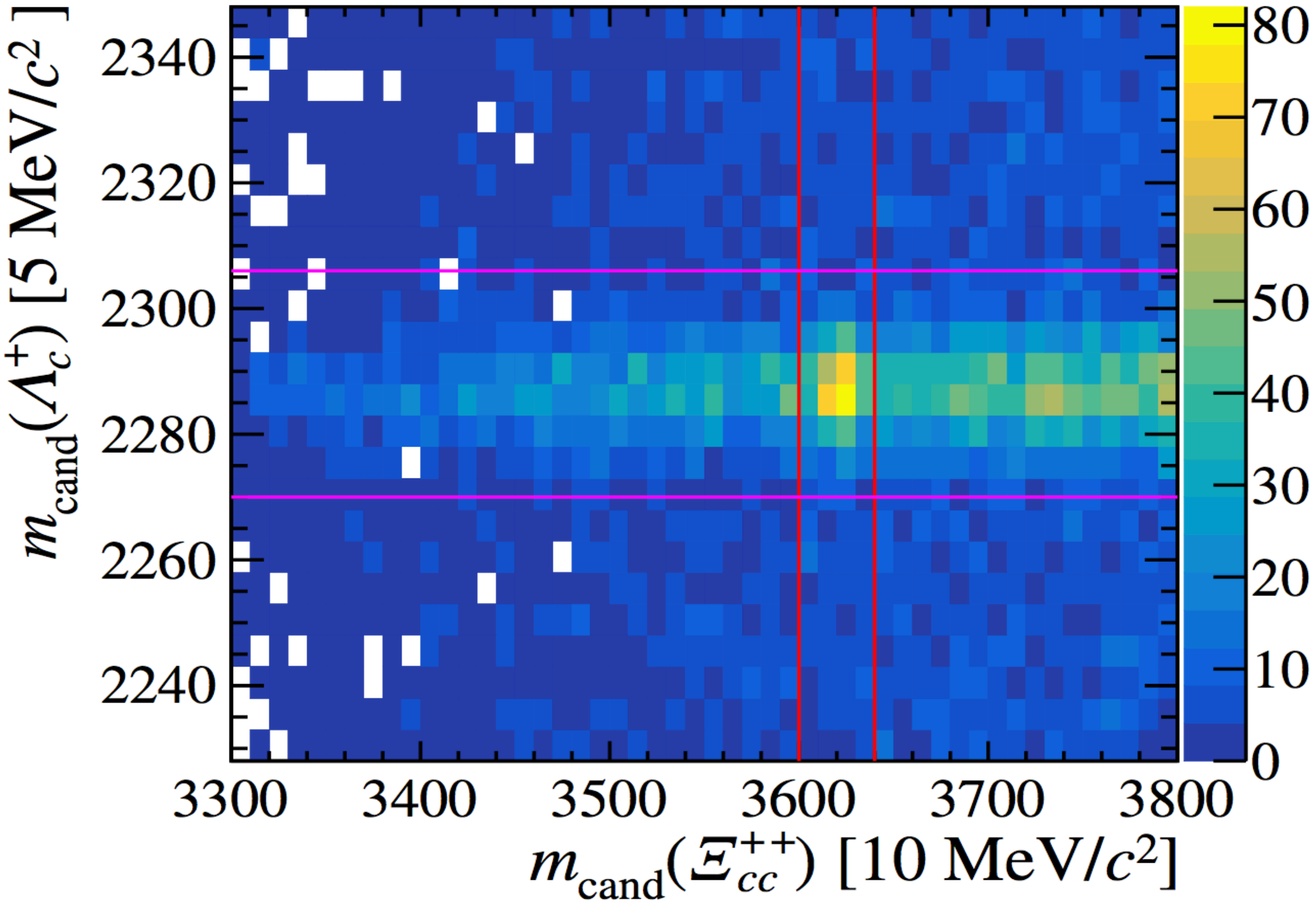


- FOCUS@Fermilab: Photon beam on Be fixed target
  - Searched for both Ξ_{cc}^+ and Ξ_{cc}^{++} states
  - 7 exclusive $\Xi_{cc} \rightarrow \Lambda_c^+ X$ modes
  - 14 exclusive $\Xi_{cc} \rightarrow D^{0,+} Y$ modes
  - **No evidence of a Ξ_{cc} state**

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

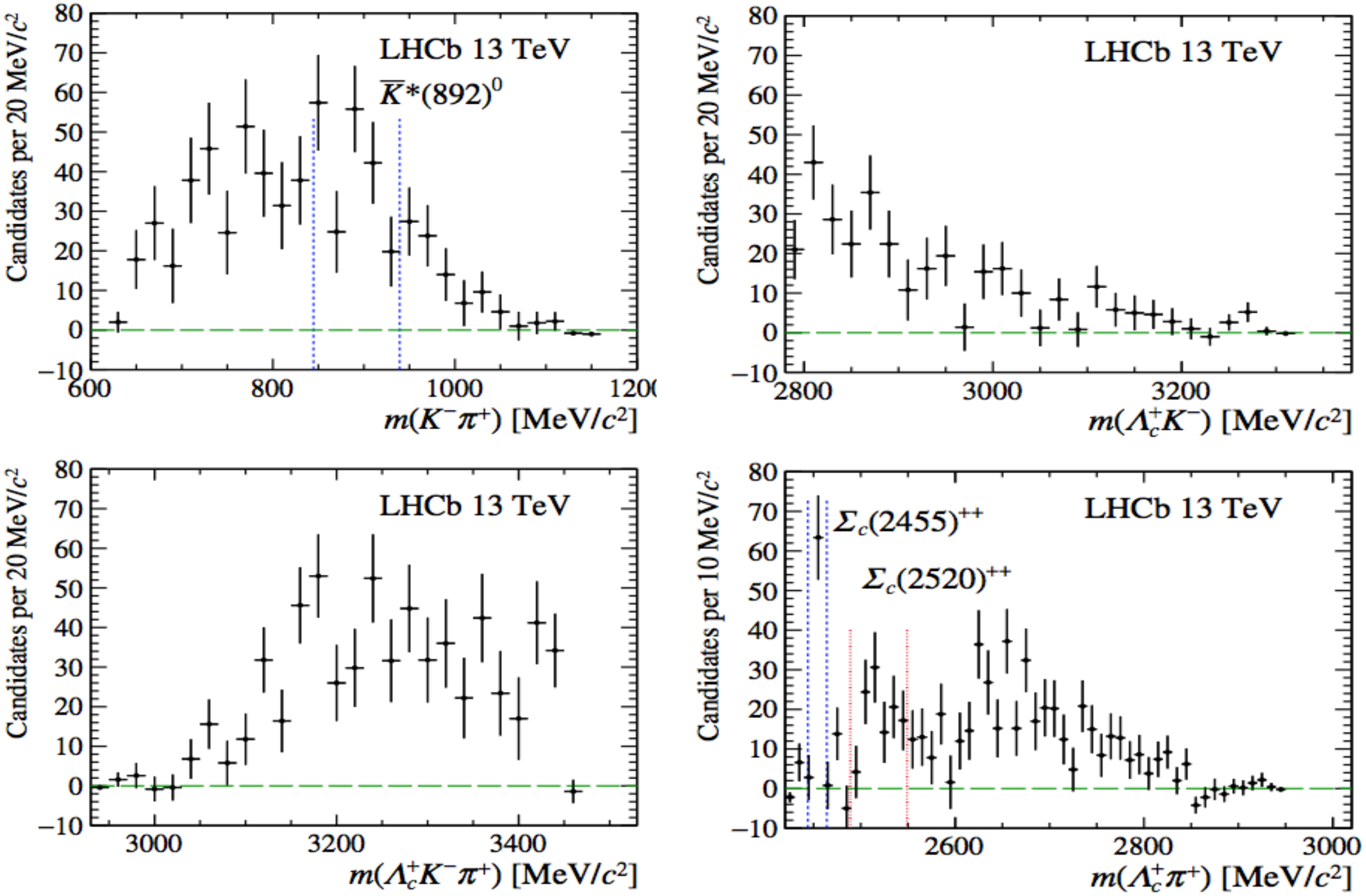
- BaBar@SLAC: $e^- e^+$ at $\sqrt{s}$ = 10.58 GeV
  - Searched for both Ξ_{cc}^+ and Ξ_{cc}^{++} states
  - Searched for $\Xi_{cc}^{+(+)} \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+)$
  - Searched for $\Xi_{cc}^{+(+)} \rightarrow \Xi_c^0 \pi^+ (\pi^+)$
  - **No evidence of Ξ_{cc} states**
- Belle@KEK: $e^- e^+$ at $\sqrt{s}$ = 10.58 GeV
  - Searched for $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$
  - Found new Ξ_c^+ resonance decaying to $\Lambda_c^+ K^- \pi^+$
  - **But still no evidence of a Ξ_{cc} state**

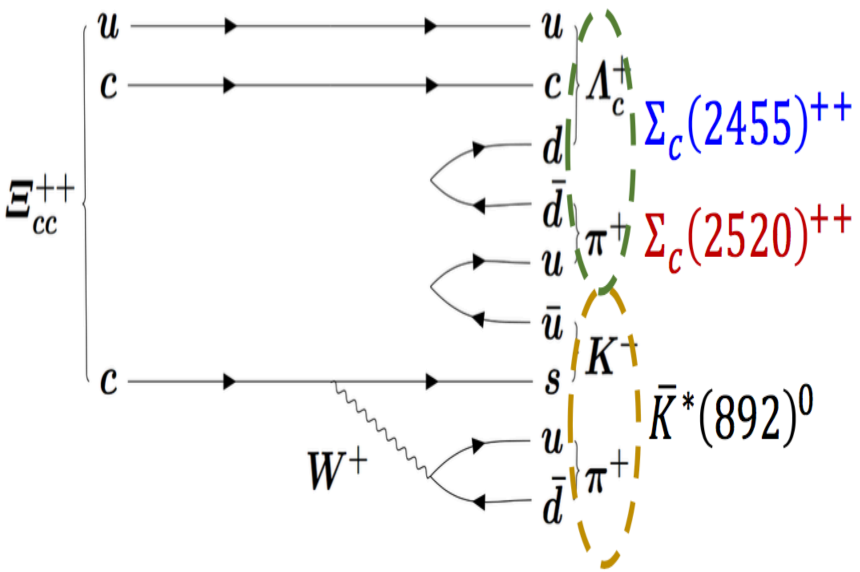
M(Λ_c^+) vs. M(Ξ_{cc}^+)



Intermediate resonances

RS, sideband-subtracted





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