Doubly charmed baryons searches and studies at LHCb

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Overview

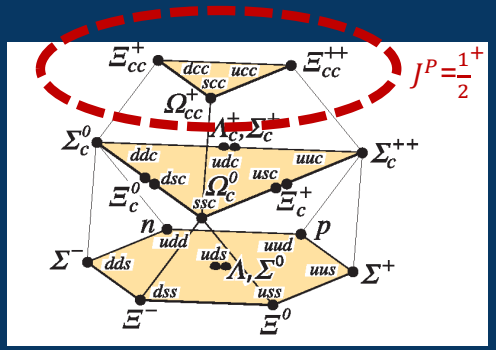
Doubly charmed baryons

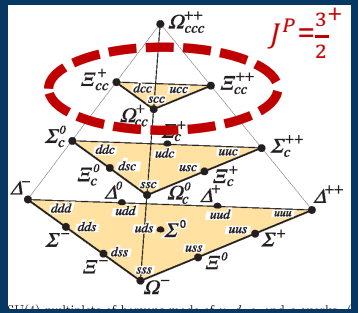
- Introduction & Motivation
- Experimental status
  - Ξ_{cc}^{++} baryon studies
  - Ξ_{cc}^{+} baryon searches
- My contribution
- Summary & future prospects

Introduction

Doubly charmed baryons

- Doubly charmed baryons - baryons containing two charm quarks and one lighter quark
- Quark model predicts the existence of three doubly charmed baryons:
  - Ξ_{cc} isodoublet (ccu and ccd states)
  - Ω_{cc}^{+} isosinglet (ccs)

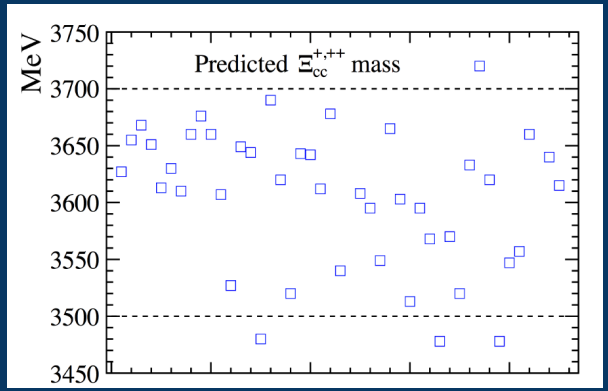




Doubly heavy baryons provide a unique platform to study the nonperturbative dynamics in the presence of heavy quarks.

Motivation

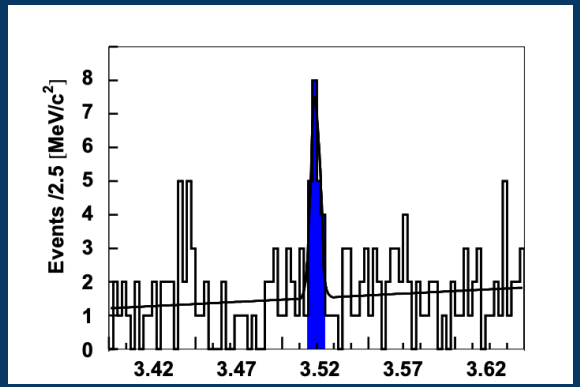
- Experimental results (masses, lifetimes, branching fractions) are an important input for testing QCD predictions based on different calculation techniques (HQET, lattice QCD, etc.)
- Many potential decay channels, however branching fractions difficult to predict
- Theory predictions for lifetimes and are in wide range (Eur. Phys. J.C13,551(2000)):
  - $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$
  - $\tau(\Xi_{cc}^{++}) \approx$ 200-700 fs
  - $\tau(\Xi_{cc}^{++}) \approx$ 3-4 times $\tau(\Xi_{cc}^{+})$
- Many theory predictions for masses (Phys. Rev. D 90, 094007 (2014))

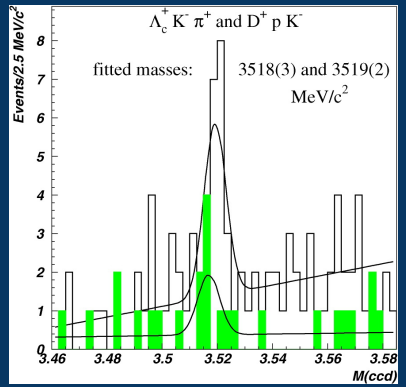


Experimental status

First results on Ξ_{cc}^{+} baryon

- The first published evidence of the doubly charmed baryons existence (Phys.Rev.Lett.89:112001,2002, Phys.Lett.B628:18-24,2005) was the observation of the Ξ_{cc}^{+} baryon reported by the SELEX collaboration in 2002
  - Some unexpected properties were reported - very low UL on the measured lifetime (33 fs at 90% CL) and unexpectedly high production rate;
  - Not confirmed by any other experiment (BaBar, Belle, FOCUS, LHCb).



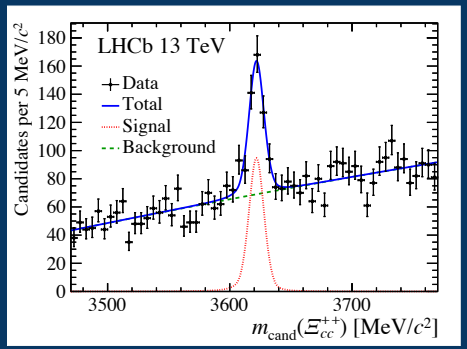


First observation of the Ξ_{cc}^{++} baryon by the LHCb

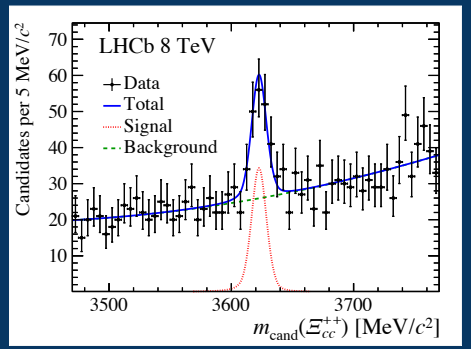
- In 2017, the first observation of the doubly charmed baryon Ξ_{cc}^{++} (ccu) in the final state of $\Lambda_c^+ K^- \pi^+ \pi^+$ was announced by the LHCb collaboration (Phys.Rev.Lett.119,112001(2017))
- Candidates saved by the Turbo[1] stream
- 313 ± 33 signal candidates observed, local significance of >12σ using 2016 data (1.67 fb^{-1})
- Measured mass:

  $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\ (stat) \pm 0.27\ (syst) \pm 0.14\ (\Lambda_c^+)\ MeV/c^2$

2016 dataset ⇒



Confirmation by the Run 1 dataset ⇒

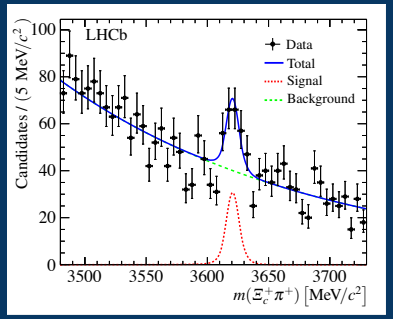


[1]Candidates fully reconstructed and ready for offline analysis already at the trigger level

Ξ_{cc}^{++} baryon studies

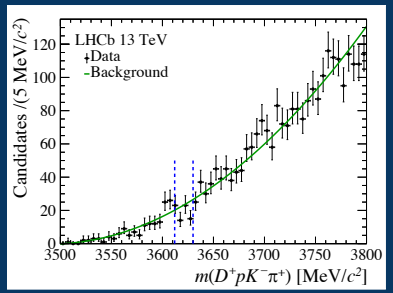
Ξ_{cc}^{++} decays

- More searches for the Ξ_{cc}^{++} baryon performed at the LHCb using 2016 data to confirm the observation and better understand decay dynamics of the Ξ_{cc}^{++} baryon



- Confirmation in $\boldsymbol{\Xi_{cc}^{++} \to \Xi_c^+ \pi^+}$ decay mode (Phys.Rev.Lett.121,162002(2018))
  - Significance of 5.9σ, measured mass in agreement with observation decay channel

$$\frac{\mathfrak{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathfrak{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathfrak{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathfrak{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009\ (\text{stat}) \pm 0.003\ (\text{syst})$$



- Search for $\boldsymbol{\Xi_{cc}^{++} \to D^+ pK^-\pi^+}$ decays (arXiv:1905.02421v3)
  - Search motivated by the excellent $D^+ \to K^-\pi^+\pi^+$ trigger and long D^+ lifetime
  - No significant Ξ_{cc}^{++} signal observed
  - Upper limit on the BF ratio using CLs method:

$$\frac{\mathfrak{B}(\Xi_{cc}^{++} \to D^+ pK^-\pi^+) \times \mathfrak{B}(\Xi_c^+ \to K^-\pi^+\pi^+)}{\mathfrak{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathfrak{B}(\Lambda_c^+ \to pK^-\pi^+)} < 1.7\%\ (2.1\%)\ \text{at}\ 90\%\ (95\%)\ \text{CL}$$

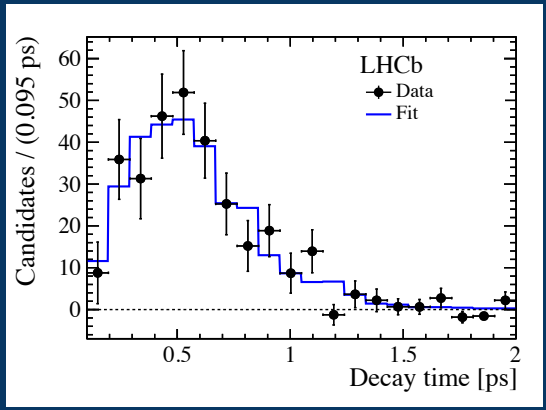
  - Theoretical understanding needed to explain a surprisingly large difference in branching fractions

Ξ_{cc}^{++} lifetime measurement

- First lifetime measurement of the doubly charmed baryon (Phys.Rev.Lett.121,052002(2018))
- Using observation decay channel $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- Decay time measured relatively to Λ_b^0 baryon which has a well known lifetime of 1.470 ± 0.010 ps
- Acceptance correction based on MC
- Weighted unbinned maximum likelihood fit

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\varepsilon_{\Xi_{cc}^{++}}}{\varepsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$

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



Confirmation of the weak nature of this decay.

Ξ_{cc}^{++} production measurement

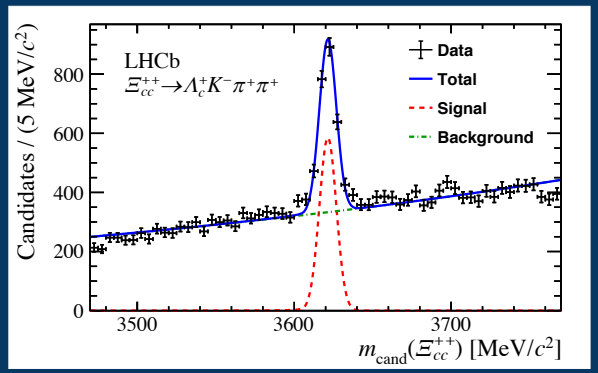
- Production of the Ξ_{cc}^{++} baryon relatively to prompt Λ_c^+ production using 2016 data (1.7 fb^{-1}) (arXiv:1910.11316v1)
- Measurement performed in the transverse momentum range of $4 < p_T < 15$ GeV/c and the rapidity range of $2.0 < y < 4.5$
- Separation of prompt and non-prompt Λ_c^+ decays challenging
  - Two steps fit - mass spectrum fit, followed by the log χ^2_{IP} fit of background subtracted data

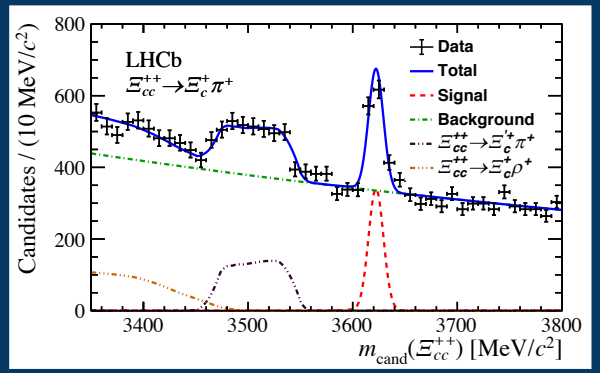
$$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27(\text{stat}) \pm 0.29\ (\text{syst})) \times 10^{-4}$$

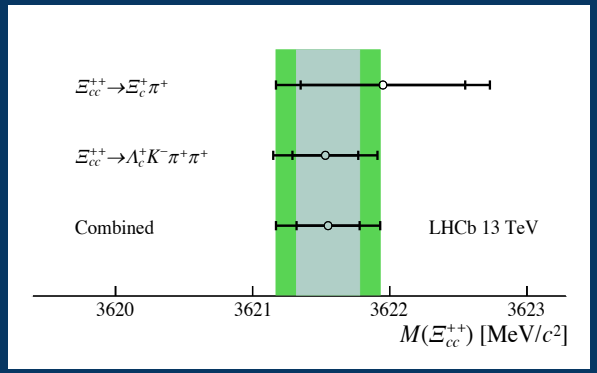
Ξ_{cc}^{++} mass measurement

- The most precise mass measurement of the doubly charmed baryon mass to date (arXiv:1911.08594)
- Using 2016-2018 data and combination of both observed decay modes of Ξ_{cc}^{++} baryon
- Signal selection optimised on 2016 data with $S/\sqrt{(S+B)}$ merit and applied on full dataset
- Each decay mode fitted independently, results combined by the BLUE method:

$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23\ (stat) \pm 0.30(syst)\ MeV/c^2$$





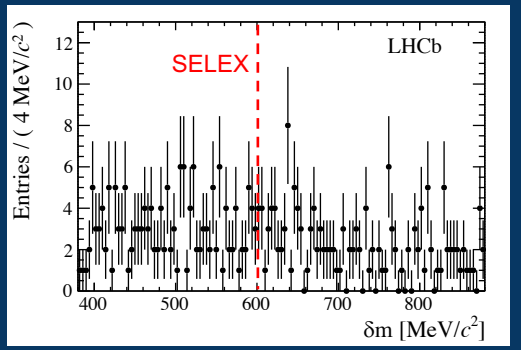


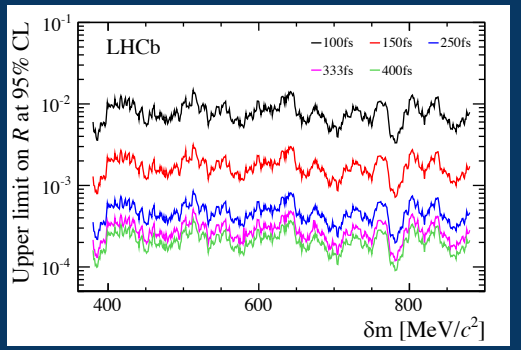
Ξ_{cc}^{+} baryon searches

Search for the Ξ_{cc}^{+} baryon

- Production cross-section and mass of the Ξ_{cc}^{+} baryon are expected to be similar to its isospin partner Ξ_{cc}^{++}
- Ξ_{cc}^{+} lifetime is predicted to be ~3-4 times shorter than the lifetime of Ξ_{cc}^{++} (measured to be 256 fs) – more experimentally challenging
- Shorter lifetime of the Ξ_{cc}^{+} baryon is due to the:
  - Destructive Pauli interference in Ξ_{cc}^{++} decays;
  - W^{+} exchange between c and d quarks only in Ξ_{cc}^{+} decays.

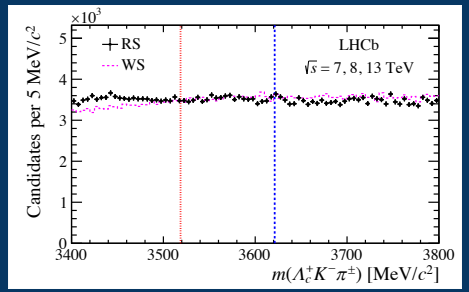
- First search for the Ξ_{cc}^{+} baryon in the decay to $\Lambda_c^{+}\ K^{-}\pi^{+}$ performed by the LHCb using 2011 data (0.65 fb^{-1}) reported no signal observation (JHEP 1312 (2013) 090)

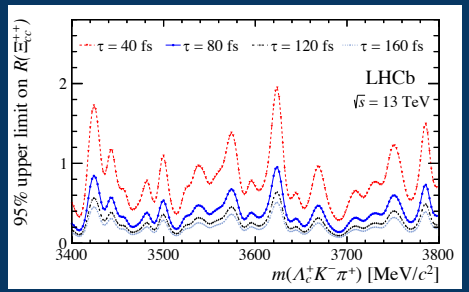


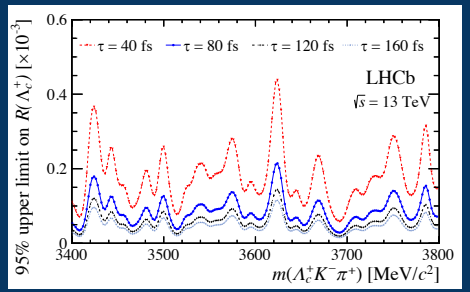


New results on search for the Ξ_{cc}^{+} baryon

- Subsequent search in the same decay channel ($\Lambda_c^+ K^-\pi^+$) using significantly larger dataset (arXiv:Sci.China-Phys.Mech.Astron.63,221062(2020)):
  - Selection A : Signal search & mass measurement (using all available data – 2011, 2012, 2015–2018)
    Selection B : Production rate measurement (2012, 2016–2018 data)
- No significant signal observed
  - Global significance (evaluated in the 3.5–3.7 GeV/c² mass range) 1.7σ
- Upper limit on the ratio of production cross-section times branching fraction to Λ_c^+ and Ξ_{cc}^{++} has been set as a function of lifetime and mass hypotheses
- The limits are significantly below the value of R(Λ_c^+) reported by the SELEX collaboration

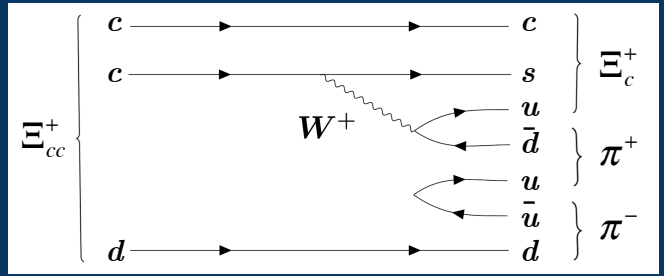






My contribution

Main focus of my analysis



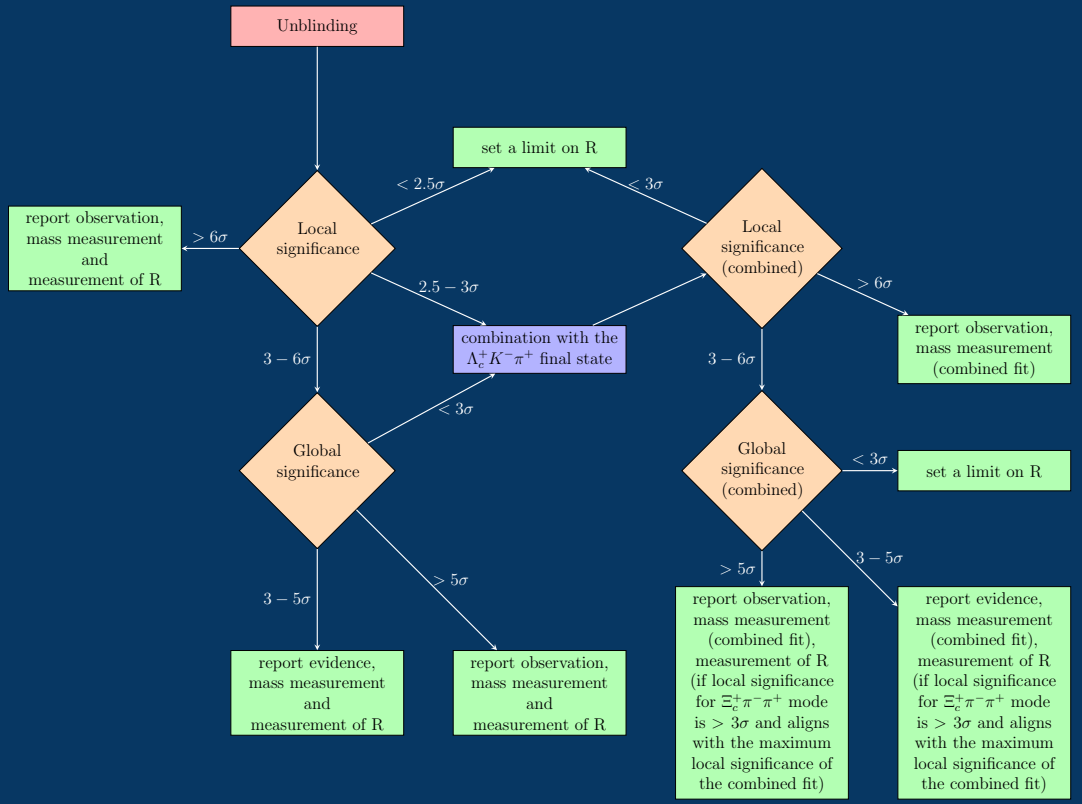
- Search for the Ξ_{cc}^{+} baryon in two decay modes:
  - $\Xi_{cc}^{+} \to (\Xi_{c}^{+} \to pK^{-}\pi^{+})\,\pi^{-}\pi^{+}$
  - $\Xi_{cc}^{+} \to (\Xi_{c}^{0} \to pK^{-}K^{-}\pi^{+})\,\pi^{+}$
- Normalisation channel - already observed decay of the doubly charged state:
  - $\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$
- According to some theoretical prediction, studied modes could have a relatively large branching fraction (Eur.Phys.J.C77(2017)no.11,781, Eur.Phys.J.C78(2018)no.11,961)

$\Xi_{cc}^{+} \rightarrow (\Xi_{c}^{+} \rightarrow pK^{-}\pi^{+})\,\pi^{-}\pi^{+}$ analysis overview

- Blinded analysis using 2016-2018 data (blinded mass window 3.3-3.8 MeV/c^2)
- Studies of the Ξ_{cc}^{+} baryon selection and efficiency based on a simulated Monte Carlo (MC) data, wrong sign (unphysical) combinations of final state particles used as a background proxy
- The final two stage selection for the Ξ_{cc}^{+} baryon in the $\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+}\,\pi^{-}\pi^{+}$ decay channel is developed:
  - Cut based pre-selection (based on kinematic, vertex, PID cuts)
  - Multivariate analysis (MVA) based selection (using discriminatory kinematic and vertexing variables)
- Mass / lifetime of the Ξ_{cc}^{+} baryon a priori unknown - efficiency (needed for the UL measurement) evaluated as a function of different mass and lifetime hypotheses

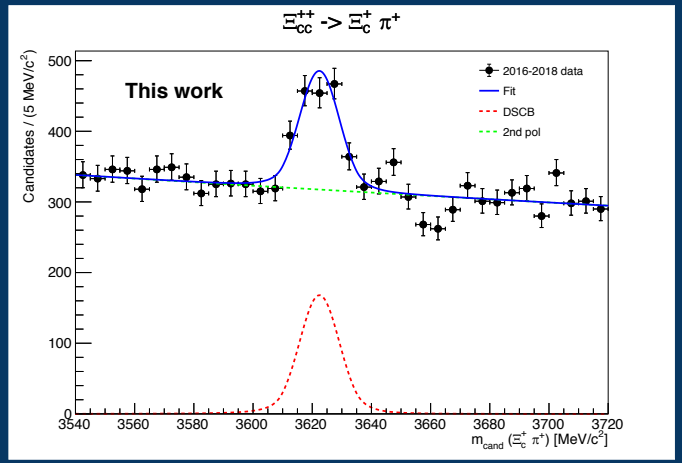
Analysis Strategy

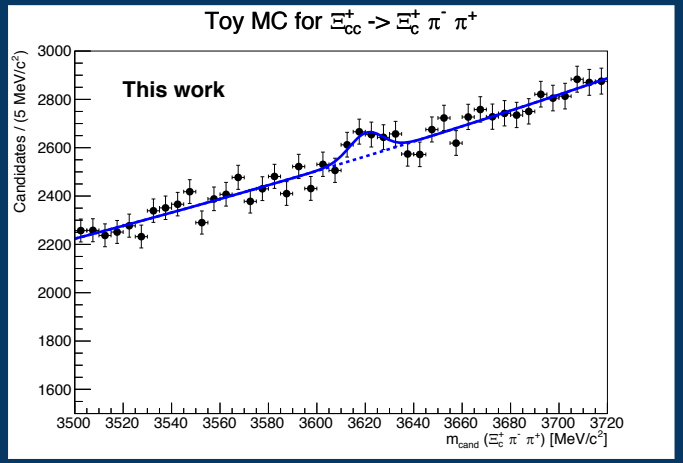
- Two cases:
  - Observation/Evidence: measurements of the mass and production branching fraction w.r.t. the control channel
  - Non-significant signal: Setting an upper limit on the production cross section times branching fraction relative to the control channel
- Strategies defined and procedures developed for both cases prior to unblinding



Sensitivity studies

- Toy MC for the $\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+}\,\pi^{-}\pi^{+}$ decay channel:
  - Based on the efficiency studies of the signal and normalisation modes;
  - Number of expected background events and background shape based on a study of the WS sample;
  - Assumption for the same BF as $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+}\pi^{+}$ decay.





Summary

Summary and outlook

- LHCb is building a comprehensive picture of the doubly charmed baryons
  - Observation and confirmation of the Ξ_{cc}^{++} baryon state, followed by its lifetime, mass and production studies
  - Searches for the Ξ_{cc}^{+} and Ω_{cc}^{+} baryons performed in several decay modes are in progress
- More to do with a larger dataset accumulated in Run 3
  - Increase of the luminosity by a factor of 5 with a fully software trigger – trigger studies ongoing to ensure full potential for doubly charmed baryons searches and studies is in place for Run3 data taking
  - Searches for the excited states, measurement of quantum numbers, ...

Stay tuned for more doubly charmed baryon results from LHCb this year and in a near future!

Thank you for your attention!