A Search for Doubly Charmed Baryons at LHCb

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Outline

- Introduction
- Experimental status
- Analysis strategy
- Generator level cuts
- Study of offline selection
- Plan
Introduction

• Theoretical motivation
  • The quark model proposed by Gell-Mann and Zweig in 1964 revolutionized our understanding of the structure of matter with strong interactions.
  • It predicts several doubly heavy flavor baryons, but none of them is solidly observed.
  • Doubly charmed baryons are interesting places for the study of non-perturbative QCD.

• Production
  • Formation
    • Production of two c quarks
    • Binding into di-quark structure
    • Hadronization
  • $\sigma(pp \rightarrow \Xi_{cc}^{\pm}X) \approx 110$ nb
  • Theoretical predictions of $\Xi_{cc}^{\pm}$ mass and lifetime
    • $m_{\Xi_{cc}^{\pm}}$: ranges from 3500 to 3700 MeV/$c^2$
    • $\tau_{\Xi_{cc}^{\pm}}$: ranges from 110 to 250 fs
  • LHCb is a good place to search for $\Xi_{cc}^{\pm}$ and other doubly heavy flavor baryons.
Experimental status

- SELEX reported observation of $\Xi_{cc}^+$ with more than $5\sigma$ significance in 2002. But observed $\Xi_{cc}^+$ has much smaller lifetime and much larger cross-section than theoretical predictions.
- FOCUS, Belle and BaBar failed to repeat this observation.

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Experimental status

• Search @LHCb in 2013
  • In $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^-\pi^+$ decay mode using 2011 data of 0.65 fb$^{-1}$
  • No significant signal is found.
  • Upper limits on $R$ (@95% CL) are given as a function of $\delta m$ for different lifetime hypotheses, where $R \equiv \frac{\sigma(\Xi_{cc}^+ B(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^-\pi^+))}{\sigma(\Lambda_c^+)}$,

$$\delta m \equiv m([pK^-\pi^+]_{\Lambda_c^+} K^-\pi^+) - m([pK^-\pi^+]_{\Lambda_c^+}) - m(K^-) - m(\pi^+).$$
Analysis strategy

- Larger data sample
  - Run1: 1 fb\(^{-1}\) in 2011 and 2 fb\(^{-1}\) in 2012

- Combined decay modes to improve sensitivity, considering branching ratio and detection efficiency

- Improved stripping cuts
Generator level cuts of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

- **Motivation**
  - **Generator level cuts** are criteria designed to filter candidates with desired properties during Monte Carlo event generation.
  - Useful generator level cuts are needed to improve MC selection efficiency and optimize computing resources usage.
  - **MC selection efficiency**: efficiency for candidates to pass certain requirements in reconstruction.
  - MC selection efficiency of current sample is about 0.2%.

- **MC sample used**
  - Sample size: 510,338 events
  - Each event contains one $\Xi_{cc}^+$ candidate within LHCb detector acceptance.
Generator level cuts of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

- Generator level cuts are determined by comparing the distributions of generator level candidates with that of reconstructed candidates.
  - Red: truth value of generator level candidates
  - Blue: truth value of reconstructed candidates

$\Lambda_c^+ p_T$ Distribution

$\Xi_{cc}^+ p_T$ Distribution

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Generator level cuts of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

- Cuts with discrimination power can be determined in a similar way.

Generator level cuts to be applied in the new MC sample generation

<table>
<thead>
<tr>
<th>Particle</th>
<th>$p_T$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+$</td>
<td></td>
<td>$\geq 2$ GeV/c</td>
</tr>
<tr>
<td>Flight distance</td>
<td></td>
<td>$\geq 20$ GeV/c</td>
</tr>
<tr>
<td>$\Xi_{cc}^+$</td>
<td>$p_T$</td>
<td>$\geq 3$ GeV/c</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$p$</td>
<td>$\geq 30$ GeV/c</td>
</tr>
<tr>
<td>$K^-$ (from $\Xi_{cc}^+$)</td>
<td>$p_T$</td>
<td>$\geq 0.2$ GeV/c</td>
</tr>
<tr>
<td>$\pi^+$ (from $\Xi_{cc}^+$)</td>
<td>$p_T$</td>
<td>$\geq 0.2$ GeV/c</td>
</tr>
<tr>
<td>$K^-$ (from $\Lambda_c^+$)</td>
<td>$p_T$</td>
<td>$\geq 0.2$ GeV/c</td>
</tr>
<tr>
<td>$\pi^+$ (from $\Lambda_c^+$)</td>
<td>$p_T$</td>
<td>$\geq 0.2$ GeV/c</td>
</tr>
<tr>
<td>Proton</td>
<td>$p_T$</td>
<td>$\geq 0.2$ GeV/c</td>
</tr>
</tbody>
</table>

Expected Efficiency $0.55\%$
Study of offline selection of $\Xi^{+}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+}$

- **Preselection**: relatively loose rectangular cuts to reduce background

- **Multivariate analysis (MVA)** is developed to further suppress background.

- **Signal sample**: MC sample of size 1449 events, half for training and the other half for testing

- **Background sample**: 2012 data reconstructed with wrong charge decay chain $\Xi^{+}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{-}$ of size 13559 events, which is a good description of combinatorial background distribution. Half sample are used for training and the other half for testing.
Input variables of MVA for $E_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

- Nine input variables are used, including kinematics variables of $E_{cc}^+$ and its daughters and the topological variables of the decay chain.
Output of MVA training and testing

- **BDTG algorithm** is adopted.
- Evident overtraining is observed possibly due to:
  - the small sample size
  - real overtraining which can be avoided by further algorithm configuration

![Background rejection versus Signal efficiency](image1)

![TMVA overtraining check for classifier: BDTG](image2)

- Kolmogorov-Smirnov test: signal (background) probability = 0.016 (0.431)
- U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
Plan

• Apply generator level cuts to new MC sample generation with GenXicc generator
• Conduct offline selections using new MC sample
• Determine optimal MVA cut by maximizing the sensitivity
Plan

1. Signal simulation
2. Selection
   - Efficiency and sensitivity study
   - Yield measurement method development
   - Systematic error
   - Unblind real data
Acknowledgment

- My supervisors Yuanning Gao and Patrick Spradlin for patient instructions
- My colleagues Paul Soler, Murdo Traill and Zhenwei Yang for inspiring discussions
- The summer student program for an exciting summer
Back up
Monte Carlo production chain

Event Generation
simulate the physics process.

Detector Simulation
simulate the interaction of the particles with the detector material.

Digitization
Translate interactions with detector into realistic signals.

Reconstruction
Go from signals back to particles, as for real data.
LHCb detector

- A single-arm forward spectrometer
Generator level study of $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$

- Decay Chain
  - $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$
    $\leftrightarrow \Xi^- \pi^+ \pi^+$
    $\leftrightarrow \Lambda^0 \pi^-$
    $\leftrightarrow p \pi^-$

- MC sample: 571,447 events
- Five truth matched $\Xi_{cc}^+$ and 30 truth matched $\Lambda^0$
- Inefficiency due to the long flight distance of $\Lambda^0$
- Not a promising decay mode
Information about MC and data sample

- MC sample for generator level study of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$
  - Event Type: 26265012
  - 2012 MagDown sample with Sim08f and Reco14a
  - StrippingXiccPlusToLcKPi line of Stripping21
- MC sample for generator level study of $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$
  - Event Type: 26167110
  - 2012 MagDown sample with Sim08f and Reco14a
  - StrippingXiccXiccPlusToXicPlusPiPi line of Stripping21
- Data sample for MVA
  - Collision12, Beam4000GeV and Reco14
  - StrippingXiccXiccPlusToLcKPiWC line in Stripping21
MVA input variables definition

- Input variables
  - $\Xi_{cc}^+ \text{ MAXDOCA}$: Maximum distance of the closest approach between all possible pairs of daughters
  - $\Xi_{cc}^+ \text{ IP } \chi^2$: Difference between the PV fit $\chi^2$ with and without candidate included in the track set
  - $\Xi_{cc}^+ \text{ ENDVX } \chi^2$: Decay vertex fit $\chi^2$
  - $\Xi_{cc}^+ \text{ PV } \chi^2$: Primary vertex fit $\chi^2$
  - $\Xi_{cc}^+ \text{ minDaughtersPT}$: Minimum $p_T$ of daughters
  - $\Lambda_{c}^+ \text{ MAXDOCA}$
  - $\Lambda_{c}^+ \text{ IP } \chi^2$
  - $\Lambda_{c}^+ \text{ ENDVX } \chi^2$
  - $\Lambda_{c}^+ \text{ FD } \chi^2$: Difference between the PV fit $\chi^2$ with and without candidate included in the track set