Study on charmed–baryon production with the ALICE experiment at the LHC

Xiuxiu Jiang for the ALICE Collaboration

Institute of Particle Physics, CCNU, Wuhan, China
17th Chinese Nuclear Physics Conference
CCNU, Wuhan, 08. - 12.10.2019
Outline

- Introduction
- The ALICE detector
- Reconstruction strategy
- Results on $\Lambda_c^+$
- Summary and outlook
Motivations: Probing the Quark–Gluon Plasma

The aim of heavy-ion collisions is to study the properties of the colour-deconfined medium, Quark–Gluon Plasma (QGP).
Motivations: Heavy quarks in pp, p–Pb and Pb–Pb collisions

- Heavy quarks are excellent probes to characterise QGP medium.
  - Early production in hard-scattering processes at the early stage of heavy-ion collisions.
  - Experience the entire evolution of the medium.
  - Strongly interacting with QGP.
Motivations: Heavy quarks in pp, p–Pb and Pb–Pb collisions

- Heavy quarks are excellent probes to characterise QGP medium.
  - Early production in hard–scattering processes at the early stage of heavy–ion collisions.
  - Experience the entire evolution of the medium.
  - Strongly interacting with QGP.

**Energy loss**

Mechanisms: gluon radiation, elastic collisions

Key Observables: 

\[ R_{AA}(p_T) = \frac{1}{<T_{AA}>} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \]

- \( R_{AA} = 1 \), if there is no medium modification

\[ \Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow R_{AA} \text{(light hadron)} < R_{AA}(D) < R_{AA}(B)? \]
Motivations: Heavy quarks in pp, p–Pb and Pb–Pb collisions

- Heavy quarks are excellent probes to characterise QGP medium.
  - Early production in hard-scattering processes at the early stage of heavy-ion collisions.
  - Experience the entire evolution of the medium.
  - Strongly interacting with QGP.

Energy loss

Collectivity

- Azimuthal anisotropy of produced particles.
- At low $p_T$ information on the transport properties of the medium, collectivity and thermalisation of heavy quarks.

Key Observables: $v_2 = \langle \cos2(\varphi - \psi_2) \rangle$
Motivations: Heavy quarks in pp, p–Pb and Pb–Pb collisions

- Heavy quarks are excellent probes to characterise QGP medium.
  - Early production in hard-scattering processes at the early stage of heavy-ion collisions.
  - Experience the entire evolution of the medium.
  - Strongly interacting with QGP.

Energy loss

Collectivity

Modification to hadron formation
  - Hadronisation via quark coalescence.
Motivations: Heavy quarks in pp, p–Pb and Pb–Pb collisions

- Heavy quarks are excellent probes to characterise QGP medium.
  - Early production in hard-scattering processes at the early stage of heavy-ion collisions.
  - Experience the entire evolution of the medium.
  - Strongly interacting with QGP.

Energy loss

Collectivity

Modification to hadron formation

pp collisions:
- Study hadronization mechanism
- Set a reference for p–Pb and Pb–Pb

p–Pb collisions:
- Study cold nuclear matter (CNM) effects
- Set a reference for Pb–Pb measurements
Motivations: Charm–baryon measurements

Charm–baryon measurements could provide unique insights into hadronisation in the QGP.

- Enhancement of baryon-to-meson ($\Lambda_c^+ / D^0$) ratio is predicted in coalescence models.
- Further enhancement of baryon-to-meson ratio is expected if light di-quark states exist in the QGP.
- $\Lambda_c^+ / D^0$ is a good tool to disentangle different hadronization mechanisms.

A Large Ion Collider Experiment

**ITS**: tracking; primary and secondary vertexing; $|\eta| < 0.9$

**TPC**: tracking and PID via $dE/dx$; $|\eta| < 0.9$

**V0,T0**: trigger and centrality

**TOF**: PID (time of flight); $|\eta| < 0.9$

High precision tracking, good vertexing capabilities and excellent particle identification
Reconstruction of $\Lambda_c^+$

- Invariant mass analysis of the decays
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR=6.3%)
  - $\Lambda_c^+ \rightarrow pK_s^0 \rightarrow \pi^+\pi^-p$ (BR=1.1%)

- Candidates build combining triplets of tracks reconstructed at mid-rapidity ($|\eta| < 0.8$) with proper charge.

- Reduction of the combinatorial background

- Different method for signal selection of the decay topological variables:
  - Rectangular topological cuts.
  - BDT based TMVA method used for cut optimization.
For the $\Lambda_c^+$, different machine-learning algorithms were exploited in p–Pb and Pb–Pb analyses.

Training variables.

Background used for training taken from side-bands in data.

The invariant mass distribution was obtained after selecting on the ML algorithm response.
$\Lambda_c^+$ cross section in Pb–Pb collisions (2018)

$\Lambda_c^+$ are measured in the range $2 < p_T < 24$ GeV/c for the 0–10% and 30–50% most central Pb–Pb collisions at 5.02 TeV.
nuclear modification factor $R_{AA}$ (2018)

Suppression observed for the $\Lambda_c^+$ baryon in Pb–Pb collisions.
\( \Lambda_c^+ \) nuclear modification factor \( R_{AA} \) (2018)

- Suppression observed for the \( \Lambda_c^+ \) baryon in Pb–Pb collisions.
- Comparison to theory favours[4] a scenario where both fragmentation and recombination are present in Pb–Pb and pp collisions, for both centrality ranges.
- The same conclusion for semi-central collisions see backup.

---

Baryon-to-meson ratio: $\Lambda_c^+/D^0$ (2018)

- Hint to a higher $\Lambda_c^+/D^0$ ratio in Pb–Pb (0–10% and 30%–50%) collisions w.r.t. pp collisions.
  - Understanding of pp data is fundamental. Ratio is underestimated by models with fragmentation parameters derived from e$^+e^-$ collision data.
- More precision needed to investigate a pp $\rightarrow$ p–Pb $\rightarrow$ Pb–Pb trend.
Outlook: $\Xi^0_c$ production

- First measurement of $\Xi^0_c$ production in pp collisions at $\sqrt{S_{NN}} = 7$ TeV[6]
  - $\Xi^0_c \rightarrow e^+\Xi^-\nu$ ($\Xi^- \rightarrow \pi^-\Lambda$)
  - Event generators PYTHIA8[7],[8] underestimate data.
  - The same conclusion with DIPSY[9] and HERWIG7[10] models see backup.

- The investigation under $\Xi^0_c$ with hadronic decay and the $\Sigma_c$ work in processing.

Summary

\( \Lambda_c^+/D^0 \) and \( \Lambda_c^+ \) are measured in the range \( 2 < \rho_T < 24 \text{ GeV/c} \) for the 0–10% and 30–50% most central Pb–Pb collisions.

- Different machine-learning algorithms are used for the \( \Lambda_c^+ \) analysis.
- \( \Lambda_c^+/D^0 \) Compatible with p–Pb within statistical uncertainties.
- The Results of \( R_{AA} \) in agreement with models that foresee both fragmentation and recombination.

Upgrade:

- ALICE upgrade for Run3+4: (new ITS and TPC)
  - It will offer the opportunity to explore, with more precision, a wide \( \rho_T \) range of open HF measurements.
Motivations: Charm–baryon measurements

- Enhancement of baryon-to-meson (Lc/D0) ratio is predicted in recombination (or coalescence models)

- Further enhancement of baryon-to-meson ratio is expected if light di-quark states exist in the QGP
  - The baryon-to-meson ratio is expected to be enhanced if charm quarks hadronise via recombination with the surrounding light quarks in the QGP.

PRL 100, 222301 (2008)

A Large Ion Collider Experiment

**ITS**: tracking; primary and secondary vertexing; $|\eta| < 0.9$

**TPC**: tracking and PID via $dE/dx$; $|\eta| < 0.9$

**TOF**: PID (time of flight); $|\eta| < 0.9$

**VO**: trigger and centrality

Data samples (Run-2):
- **pp**, 5.02 TeV: 980M MB events.
- **P–Pb**, 5.02 TeV: 600M MB events.
- **Pb–Pb**, 5.02 TeV: 100M MB events.
  - 76M 30–50% events
  - 89M 0–10% events

High precision tracking, good vertexing capabilities and excellent particle identification
MLHEP python-based package

General purpose Python package for performing parallelised analysis over large datasets and Machine Learning (ML) optimisation with Scikit, Keras, and XGBoost.

ML optimisation:
1. ML sample preparation
2. Training/testing
3. ML performance studies (ROC, cross validation, learning curves...)
4. Significance optimisation

Reconstructed objects (eg: Lc candidates stored in ROOT TTree format)

Pandas dataframes

Skimmed Pandas DataFrames (eg: selected on $p_T$, preselected on PID and/or topological cuts)

Randomised data subset

Trained model

Pandas dataframes with ML decision and probability ready for final analysis
Merging strategy: introduction

- Similar strategy as analyses that were statistically correlated (other Lc analysis: BDT/standard)
  - Treat statistical uncertainties as fully correlated.
  - Weighted average according to the uncorrelated uncertainties (in this case, assumed to just be the yield extraction systematic)
    -> Ok assumption given different background shape, cut on response, etc.
  - Corrected yield given weight
    -> $1/a^2$ where $a = \Delta\sigma_{\text{uncor.sys.}}/\sigma$ ($\sigma =$ yield)
  - So yield and uncertainties are worked out as follows:

$$
\sigma_{\text{averaged}} = \frac{\sum w_i \sigma_i}{\sum w_i} \quad \Delta\sigma_{\text{corr}} = \frac{\sum w_i \Delta\sigma_i}{\sum w_i} \quad \Delta\sigma_{\text{nucorr}} = \frac{\left(\sum w_i^2 \Delta\sigma_i^2\right)^{1/2}}{\sum w_i}
$$

- Note - this averaging does not reduce uncertainties expect for yield extraction uncertainties - but means not 1 analysis is favoured.
Reconstruction of $\Lambda_c^+$

- Invariant mass analysis of the decays
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR=6.3%)
  - $\Lambda_c^+ \rightarrow pK^0_s\pi^+\pi^-p$ (BR=1.1%)

- Candidates build combining triplets of tracking reconstructed at Mid–rapidity ($|\eta| < 0.8$) with proper charge.

- Reduction of the combinatorial background by:
  - Kinematical and geometrical selection of displaced decay–topology ($c_\tau \sim 60 \mu m$).
  - Particle identification of decay tracks.

- Corrected for:
  - Selection efficiency using MC simulations.
  - Feed–down subtraction using FONLL predictions.

- Two analysis methods used:
  - Rectangular topological cuts.
  - Multivariate analysis exploiting BDTs.
ML to extract $\Lambda^+_c$ in p–Pb and Pb–Pb

For the $\Lambda^+_c$, different machine-learning algorithms were exploited in p–pb and Pb–Pb analyses.

- The TMVA package using AdaBoost.
- New developed MLHEP (python–based fast analysis framework) using XGBoost. (more details in the backup)

- Topological, kinematical and PID training variables.
- Background used for training taken from side–bands in data.
- The invariant mass distribution was obtained after selecting on the ML algorithm response.
- Average results obtained by weighting the different results by the inverse of the sum in quadrature of the relative uncorrelated systematics.
Previous result by ALICE:

- $\Lambda_c^+$, $|y|<0.5$, 0–80%
- p–Pb reference from JHEP 04 (2018) 108
- Average $D^0$, $D^+$, $D^{*+}$, $|y|<0.5$, 0–10% (arXiv:1804.09083)
- $D^0$, $|y|<0.5$, 0–10% (arXiv:1804.09083)
- Charged particles, $|y|<0.8$, 0–10% (arXiv:1802.09145)

$\Lambda_c^+$, $|y|<0.5$, 0–80% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $|y|<0.5$

- 0–80% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $|y|<0.5$

- Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $-0.96<y<0.04$

nuclear modification factor $R_{AA}$ (2018)

- Despite the compatibility within uncertainties, hint of larger suppression for central collisions by ~1.5x up to $p_T = 12$ GeV/c.
- Suppression observed for the $\Lambda_c^+$ baryon in Pb–Pb collisions.
- Comparison to theory favours[4] a scenario where both fragmentation and recombination are present in Pb–Pb and pp collisions, for both centrality ranges.

Hint to a higher $\Lambda_c^+/D^0$ ratio in Pb–Pb (0–10% and 30%–50%) collisions w.r.t. pp collisions.

Same behaviour w.r.t. p–Pb collisions

More precision needed to investigate a pp -> p–Pb -> Pb–Pb trend.

Comparison to Catania theory favours[4] a scenario where both fragmentation and recombination are present, for both centrality ranges.

Good agreement with statistical hadronization model[5].

---


Results on $\Xi_c^0$

First measurement of $\Xi_c^0$ production in pp collisions at $\sqrt{s_{NN}} = 7$ TeV[6]

- $\Xi_c^0 \rightarrow e^+ \Xi^- \nu$ ($\Xi^- \rightarrow \pi^- \Lambda$) BR currently unknown, and can not measure neutrino.
- Event generators PYTHIA8[7][8], DIPSY[9] and HERWIG7[10] underestimate data.