Studies of Λ_c production in pp and p-Pb collisions with ALICE at the LHC

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Abstract. A Large Ion Collider Experiment (ALICE) was designed to study the strongly interacting medium created in heavy-ion collisions at LHC energies, the Quark Gluon Plasma (QGP). Heavy quarks (charm and beauty), produced in the early stages of the collisions, are among the most powerful probes to study this state of matter. To study the QGP effects, it is important to establish reference data, which is done by analysing results from pp and p-Pb collisions.

We report on the charmed baryon Λ_c measurement in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE experiment, through the reconstruction of the decay channels $\Lambda_c^+ \rightarrow p K_s^0$ and $\Lambda_c^+ \rightarrow p K^- \pi^+$.

1 Introduction

Heavy quarks are a unique tool to test the QGP medium formed in heavy-ion collisions. They are produced in hard parton scattering processes occurring in the early stages of the collision, and as they traverse the QCD medium, they interact with its constituents and thus experience the whole evolution of the medium. The thermalization and hadronization of heavy quarks in the medium can be studied via the baryon/meson ratio for charm (Λ_c/D) and for beauty (Λ_b/B). Within thermal models, it is assumed that charm and beauty hadrons are produced during the QGP hadronization and that they are in thermal equilibrium with the medium. Within coalescence models, partons produced in hard scatterings can combine with quarks and anti-quarks in the QGP to form hadrons. The two different scenarios result in different yield predictions at intermediate momentum [1–3]. Moreover coalescence models consider also the possibility of recombination of a heavy quark with a di-quark [4]. It has been predicted that if [ud] di-quark exist in the QGP formed in heavy ions collisions, this would lead to a significant enhancement of Λ_c/D^0 (and Λ_b/D^0).

It is of utmost importance for ALICE to establish a firm baseline measurement in pp collisions of Λ_c production through different channels, providing a reference for results in heavy-ion collisions.

Moreover, a complete understanding of the Pb-Pb results requires an understanding of *cold nuclear matter* (CNM) effects in the initial and final state, which can be assessed by studying p-Pb collisions assuming that the QGP is not formed in these collisions. In the initial state, CNM effects include: the modification of quark and gluon distribution, depending on the parton fractional momentum x and the atomic mass number A [5] [6]; gluon saturation at low Bjorken- x [7]; multiple scattering of partons in the nucleus before and/or after the hard scattering, which can modify the kinematic distribution of the

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produced hadrons [8] [9]. The presence of significant final-state effects in high-multiplicity p-Pb collisions is suggested by different observations, e.g. the presence of long-range correlations of charged hadrons [10] [11], the evolution with multiplicity of the identified-hadron transverse-momentum distributions [12], and the suppression of the $\Psi(2S)$ production with respect to the J/Ψ one [13].

The Λ_c analysis discussed in this proceeding is the first measurement of Λ_c in mid-rapidity ($|\eta| < 0.9$) at the LHC energies. Until now Λ_c production has been measured mainly at electron-positron colliders at SLAC [14], at CLEO [15], ARGUS [16] and at HERA in electron-proton collisions [17]. Existing Λ_c cross-section measurements at hadron colliders in pp collisions are back to ISR [18], at significantly lower energies ($\sqrt{s} = 62$ GeV). At Tevatron collider, D mesons were extensively measured [19], and non-*prompt* Λ_c were reconstructed as decay products of b -hadrons [20–22]. At LHC the LHCb experiment reported the measurement of non-*prompt* Λ_c production in pp collisions at $\sqrt{s} = 7$ TeV at forward rapidity [23].

Up to now, there were not existing measurements of Λ_c in p-Pb collisions.

2 Data Sample

Λ_c is the lightest baryon carrying open charm, with a rest mass of 2.286 GeV/ c^2 and a decay length ($c\tau$) of $60 \mu\text{m}$ [24]. The Λ_c analysis reported in this proceeding is performed with ALICE at LHC on two data samples: about 3×10^8 events collected with a minimum-bias trigger during the 2010 LHC run with pp collisions at $\sqrt{s} = 7$ TeV; about 1×10^8 events collected with a minimum-bias trigger during the 2013 LHC run with p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Two hadronic decay channels of Λ_c have been studied: $\Lambda_c^+ \rightarrow p K_S^0$ and $\Lambda_c^+ \rightarrow p K^- \pi^+$.

Considering the most recent (2016) measurement made by the BESIII collaboration [25], the branching ratio (BR) taken into account for $\Lambda_c^+ \rightarrow p K_S^0$ was $(1.093 \pm 0.055)\%$. The golden channel $\Lambda_c^+ \rightarrow p K^- \pi^+$ has a branching ratio of $\text{BR} = (6.35 \pm 0.33)\%$, which includes four types of decays that are indistinguishable in this measurement: three types of decay through a coupled resonance as well as a non-resonant one.

3 ALICE detector

The ALICE detector, described in detail in [26], consists of a central barrel at mid-rapidity, a muon spectrometer at forward rapidity and a set of detectors (forward and backward rapidity) for global collision characterization and triggering purposes. In the central rapidity region, open heavy flavours are measured in several charm hadronic decay channels and via electrons from semi-leptonic decays of charm and/or beauty hadrons. At forward rapidity, open heavy-flavor production is studied in the semi-muonic decay channel.

A subset of the central barrel detectors is essential for the Λ_c analysis at mid-rapidity: the *Inner Tracking System* (ITS) for vertex reconstruction and tracking, the *Time Projection Chamber* (TPC) for tracking and Particle Identification (PID) and the *Time of Flight detector* (TOF) for PID. The main ALICE trigger detectors are the *Silicon Pixel Detector* (SPD) and VZERO scintillator arrays. The minimum bias trigger selects all the events with at least one hit in the SPD or in one of the two VZERO counters, in coincidence with the signals from the beam pickup detector.

4 Λ_c analysis strategy

4.1 $\Lambda_c^+ \rightarrow p K_S^0$

Pairs of tracks with opposite charge are selected in the invariant mass window of the K_S^0 , applying topological selections (i.e. on the transverse momentum of K_S^0 -daughters, bachelor and K_S^0 , transverse

impact parameter of proton and K_S^0 , distance of closest approach (DCA) of K_S^0 daughters and DCA of proton and K_S^0) and excluding pairs that, with the (p, π) or (e^+, e^-) mass assignments, are compatible with Λ_c decays or photon conversions. After this selection, the purity of the sample of K_S^0 is very high (see Fig. 1). The analysis is performed constructing the combinatorial pairs of the K_S^0 candidates with the bachelor (proton) track candidate. Each bachelor- K_S^0 candidate has therefore three prongs in total.

Figure 1. Invariant mass $M(\pi^+\pi^-)$ corresponding to pp data at $\sqrt{s} = 7$ TeV.

Protons are identified using a *number of sigma cut* approach, where the measured energy deposit (TPC) or time-of-flight (TOF) are compared with the expected values for protons, and candidates with PID observable within three sigma from the expected value are selected.

4.2 $\Lambda_c^+ \rightarrow pK^-\pi^+$

For the decay channel $\Lambda_c^+ \rightarrow pK^-\pi^+$, single tracks are selected at first. Pairs of tracks with opposite charge are constructed and topological selections are applied on the vertices defined for each pair of tracks, such as a cut on the distance of closest approach between the two single-tracks. A third track is finally attached to a pair, forming a Λ_c candidate and the vertex of the triplet is calculated. Λ_c candidates are selected according to the quality of the reconstructed vertices, the distance between primary and secondary vertex (Λ_c decay length) and the cosine of angle between the Λ_c flight line and its momentum. The identification of pions, kaons and protons reduces the large combinatorial background: a Bayesian approach is used to combine the response of the TPC and TOF detectors. Particle species are assigned to the tracks according to the maximum probability criterion: a track is identified as species i if the Bayesian probability $W(i)$ to be of species i is the highest.

4.3 Signal extraction in pp and p-Pb collisions

Once the Λ_c candidate are reconstructed, two different analysis techniques are used in order to improve the signal extraction.

- **Cut optimization (called *standard procedure*):** p_T -dependent kinematic and geometrical selections are applied on the final decay products. The cuts are optimized to obtain the highest signal-over-background ratio and significance, $\frac{\text{signal}}{\sqrt{\text{signal}+\text{background}}}$, by using a maximum likelihood criterion with the signal extracted on the anchored Monte Carlo (MC) productions, in terms of mean and width of the signal peak.

- **Multivariate analysis technique**, namely the Boosted Decision Trees (BDT), implemented in the software package TMVA [27]. This strategy has the advantage to consider simultaneously multiple event properties, exploiting the most of the available information through machine learning techniques.

5 Results

A clear Λ_c signal can be observed in both decay channels and both collisions systems, as shown in Figs. 2 and 3 for pp collisions, 4 and 5 for p-Pb collisions. The two decay channels allow us to cover a large p_T range, [2,12] GeV/c with a large overlap. They provide two complementary measurements but also interesting checks. The signal is fitted with a Gaussian and the background with a second order polynomial. The resolution of the invariant mass is extracted from the fit and is determined as the width of the Gaussian. It changes with the p_T of the Λ_c candidates because the momentum of the daughter particles increases with increasing momentum of the Λ_c , and this generally leads to an increase in the mass resolution. We are not able to observe a Λ_c signal for $p_T < 1$ GeV/c, because the combinatorial background is very large and the resolution on the track position is not sufficient to separate the Λ_c decay vertex from the interaction point.

Figure 2. Invariant mass distribution of $\Lambda_c^+ \rightarrow pK^0\pi^+$ in pp collisions at $\sqrt{s} = 7$ TeV, using the standard cut optimization procedure. The signal is observed in four p_T intervals in the range $2 < p_T < 6$ GeV/c.

Figure 3. Invariant mass distribution of $\Lambda_c^+ \rightarrow pK_S^0$ in pp collisions, using the standard cut optimization procedure, considering Λ_c candidates in the p_T interval $2 < p_T < 12$ GeV/c.

Figure 4. Invariant mass distribution of $\Lambda_c^+ \rightarrow pK^- \pi^+$ in p-Pb collisions, using the standard cut optimization procedure. The signal is observed in six p_T intervals in the range $2 < p_T < 10$ GeV/c.

Figure 5. Invariant mass distribution of $\Lambda_c^+ \rightarrow pK_S^0$ in p-Pb collisions using the MVA technique. The signal is observed in six p_T intervals in the range $2 < p_T < 12$ GeV/c.

6 Conclusions

For the measurement of the Λ_c production cross section, corrections for reconstruction and selection efficiency and detector acceptance are needed to be applied. These are the next steps of this analysis. The Λ_c analysis in pp and p-Pb collisions, using data from the Run I is limited by the large combinatorial background. The larger amount of data available with the increase in luminosity during the Run II, will improve the precision of our results. The observation of Λ_c in Pb-Pb collisions is challenging with the present detector. The ITS upgrade (planned for the second long LHC shutdown in the years 2018-2019) [28] will improve the track impact parameter resolution (by a factor of ~ 3), the tracking efficiency and p_T resolution at low p_T . These new features will allow us to measure Λ_c for the first time in Pb-Pb collisions.

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