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Present and future investigations of hadron formation mechanisms in Pb–Pb collisions at the LHC with the ALICE experiment

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Abstract. The present status and the future of hadron production characterization in Pb–Pb collisions at LHC by measuring the p_{T} dependence of baryon over meson ratios is presented. The current RHIC and LHC results showing a strong enhancement of the $\Lambda/\mathrm{K}^0_{\mathrm{S}}$ ratio in Pb–Pb collisions with respect to proton-proton collisions at intermediate p_{T} and their interpretation in terms of coalescence processes are discussed. A crucial extension of these studies to heavy flavor hadrons (D, B mesons and Λ_c, Λ_b baryons) will be enabled by the foreseen reforging of the ALICE Inner Tracking System (ITS). The main performance objectives and technological ingredients of the ITS upgrade are summarized.

1 Introduction

An enhancement of baryon over meson ratios has been observed in the intermediate transverse momentum (p_{T}) region of central heavy-ion collisions at RHIC [1, 2] and at the LHC [3]. These measurements reveal strong hints of the formation of a deconfined state of nuclear matter: the so called Quark Gluon Plasma (QGP). Indeed they suggest that parton recombination [4] or coalescence [5] mechanisms represent a major actor, in competition with parton fragmentation processes, in the hadron formation scenario, thus evidencing a high level of partonic degrees of freedom in the created medium. Weak decaying strange particles play a key role in these investigations since they can be measured in a wide p_{T} range thanks to the topological recontruction of their decay. The current results of ALICE concerning the $\Lambda/\mathrm{K}^0_{\mathrm{S}}$ ratio will be reported and compared to the ones extracted at RHIC. Their interpretation in terms of the parton recombination/coalescence picture will be discussed.

In order to answer the question whether this picture also applies to heavy quarks and get novel and complementary information on the hadronisation characteristics (i.e., the respective weigths of coalescence and fragmentation processes as a function of p_{T}), it will be crucial in the future to extend these studies to the behaviour of heavier flavors, i.e. charm and bottom quarks, by measuring simultaneously the D, B mesons, the Λ_c baryon (as a first step and benchmark) and even the Λ_b baryon (much more challenging), thus enabling the extraction of the correponding baryon/meson ratios. Unfortunately, these objectives are beyond the capabilities of the present set-up and technologies of the ALICE detector. Indeed, if D mesons are already succesfully measured today in their hadronic decay channels (by a recognition, as for strange hadrons, of their weak decay topology) as well as B mesons (however only in their semi-leptonic decay channel), on the other hand, the Λ_c and the Λ_b stay outside

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the scope of any measurement in Pb–Pb. A global upgrade of ALICE is presently foreseen, aiming at improving the current measurements and getting access to many new signals. The detector design will have to cope with the high luminosity beams that are planned to be delivered by the LHC after 2018 and to allow the signal measurements (especially those having a poor statistics, among them the Λ_c and Λ_b signals) to benefit from these high interaction rates. The ALICE upgrade project includes a full reforging of the present Inner Tracking System (ITS) of the experiment. The mandatory performance of the new ITS for improving the D meson reconstruction and enabling the one of the Λ_c will be described. The simulation results for this later benchmark analysis will be given. The ingredients of the ITS, in terms of layout-out and silicon detector technologies, foreseen to reach this goals will finally be presented.

2 The present: Λ/K^0_S ratios

The RHIC experiments first evidenced an excess of baryon over meson ratios at intermediate p_T in heavy-ion collisions with respect to pp collisions, and a strong increase of this effect with the collision centrality [1]. The Λ/K^0_S ratio measured in ALICE in Pb–Pb and pp collisions at LHC, shown in figure 1 confirms those effects [3].

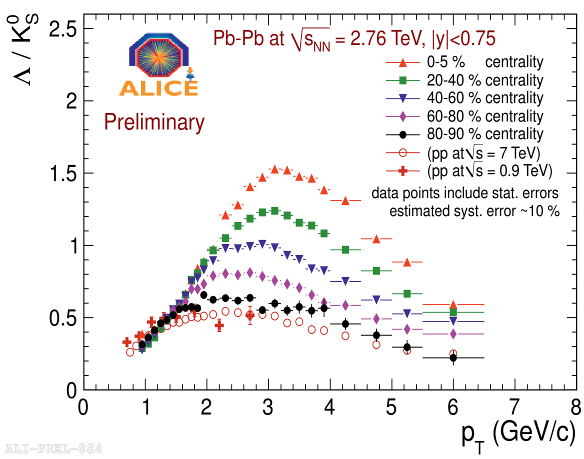

Figure 1. Λ/K^0_S ratios measured as a function of p_T in ALICE at the LHC. The ratios are given for different centralities in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and for minimum bias pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV [3].

The maximum value of the Λ/K^0_S ratio is about 1.6 for the 0-5 % most central events and located at a p_T slightly larger than 3 GeV/c, whereas in the most peripheral collisions, the maximum is shifted to lower p_T (2.5 GeV/c) and drops to 0.6, coming close to the behaviour observed in pp collisions. When going from RHIC to the LHC (see figure 2), an increase of the maximum value of 15 % for all centrality classes and a shift in p_T (+0.6 GeV/c) of the maximum are observed.

The main idea to explain this baryon excess is that parton recombination or coalescence mechanisms could play a major role for hadron formation [4, 5], based on the following arguments. In pp collisions, the standard picture of hadron production at high p_T involves fragmentation of energetic partons described by factorised fragmentation functions in pQCD-improved parton models. Fast partons propagate in the vacuum connected to each other via colour strings and finally hadronise via string fragmentation. In high-energy heavy-ion collisions, where many partons populate the phase space, multi-parton processes become important and potentially even dominant. In such conditions, it may be more effective to create new hadrons by recombining partons that are already present and close to each other. Recombination yields more baryons than mesons at a given hadron p_T since the three quarks recombining into a baryon have a larger yield at $p_T/3$ than the two quarks at $p_T/2$ which recombine to form a meson. This can explain why more baryons than mesons are produced in the intermediate p_T region.

Beside these interpretations, there exists an alternative and more complex explanation for the baryon over meson enhancement at intermediate transverse momentum. It is based on the existence of topological gluon field configurations called baryon junctions, predicting long-range baryon number transport in rapidity as well as hyperon enhancement and considerable p_T enhancement relative to conventional diquark-quark string fragmentation [6]. In order to discrimate between these scenarii, differential studies are needed, namely correlations between baryon/meson ratios and jets as well as flavour dependence of baryon/meson ratios.

3 The future: Λ_c/D ratios and the ITS upgrade

Coalescence model predictions [7] for the Λ_c/D^0 ratio at RHIC energy are shown in figure 3. In this model, partons produced in hard scatterings can combine with quarks and anti-quarks in the QGP. But in addition, there is the possibility of recombination of a heavy quark with di-quarks present in the QGP (blue curve in figure 3).

When compared to standard coalescence of three quarks (red curve), it produces an additionnal enhancement of the Λ_c yields, especially at low p_T. In this region this would lead to a significant increase with respect to thermal models where the relative abundance of particles depends only on their masses. Unfortunately, the measurement of such ratios cannot be performed in ALICE for the time being. Heavy flavor baryons are clearly beyond the present ALICE capabilities. The flight distance of the Λ_c ($c\tau \sim 60\ \mu$m) is a factor of 2 smaller than that of the D^0. This would need a very precise tracking and track impact parameter resolution (the decay tracks typically have displacements of a few tens of microns from the primary vertex) that can be achieved only with an upgraded ITS.

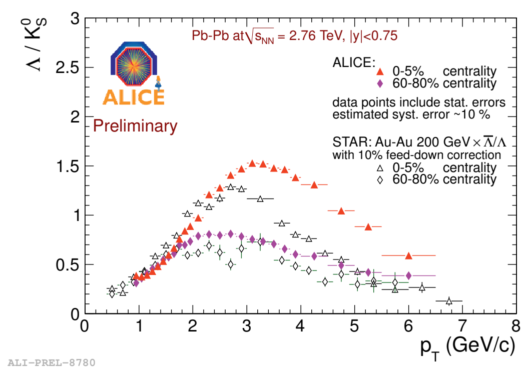

Figure 2. Λ/K^0_S ratios measured as a function of p_T in ALICE for Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [3] and compared with those measured in Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR experiment at RHIC [1].

The ITS upgrade project [8] is elaborated in the perspective of the high luminosity LHC beams (from 2018) and the frame of the global reforging of ALICE. Beside the physics objectives described in the previous section, there are several other strong physics motivations for the ITS upgrade, among them the study of heavy quark thermalization in the medium via elliptic flow measurement for charm mesons and baryons, and the study of the quark mass dependence of in-medium energy loss via the measurement of nuclear modification factors of D and B mesons separately. The conclusion of the performance studies conducted for the ITS upgrade is that the layout and the technologies of the future ITS must be optimized to reach the following performance:

- A track position resolution at the primary vertex (pointing resolution) improved by a factor ∼ 3.
- A standalone tracking efficiency comparable to what is presently achieved by combining ITS and TPC.
- A relative momentum resolution of about 2% up to 2 GeV/c and remaining below 3% up to 20 GeV/c.
- The capability to read the data corresponding to each interaction individually up to a rate of 50 kHz for Pb–Pb collisions and 2 MHz for pp collisions.

To get the required pointing resolution and tracking quality, there are three essential ingredients:

- The first ITS layer has to be closer to the beam pipe. A new beam pipe with an outer radius of 19.8 mm is foreseen. The first detection layer can then be moved from 39 mm (the current radius) to 22 mm.
- The material budget must be reduced. The challenge is to reach a thickness of 0.3 - 0.4 % of the radiation length per detection layer.
- The geometry and the granularity have to be improved.

The baseline scenario involves a completely new ITS with 2 options:

- Option a) 7 silicon pixel detector layers with excellent intrinsic resolutions (a few microns) both in the transverse plane ($r\phi$) and along the beam axis (z).

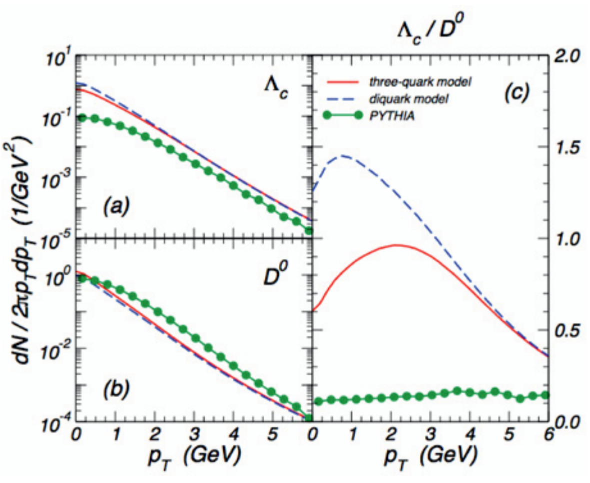

Figure 3. Λ_c/D^0 ratio predicted by the coalescence model described in [7] for Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

- Option b) 3 silicon pixel detector layers (the innermost ones) and 4 silicon micro-strip detector layers (outermost) with a worse granularity but good PID capabilities.

The pointing resolution obtained within this baseline scenario, considering the two options is given in figure 4 (red curves for the first option, green curves for the second one) and compared to the current ITS performances (black curves). The details of the simulation are given in [8]. Resolutions $(\sigma_{r\phi}, \sigma_z) = (4, 4)$ μm are considered here for the pixel detectors and $(\sigma_{r\phi}, \sigma_z) = (20, 830)$ μm for the strip detectors. The two options lead to a similarly good improvement with respect to the current ITS over the whole p_{T} range : at 400 MeV/c for example, the gain is of about a factor 3 in the $r\phi$-plane and a factor 5 along the z axis. But, as shown in [8], for what concerns standalone tracking efficiency and momentum resolution, the first option offers better results.

A comparison between the Λ_c invariant mass spectrum presently measured in ALICE for a statistics of 1.9×10^8 minimum bias pp collisions at $\sqrt{s} = 7$ TeV (see figure 5, left panel) and the distribution expected with the upgraded ITS for the same event statistics (figure 5, right panel) shows that a signal-to-background ratio (S/B) five times higher and a significance twice higher should be reached.

For Pb–Pb collisions, the expected improvement on the signal-to-background ratio and on the significance per event are given as a function of p_{T}, for different assumptions on the material budget, in figure 6 (left and right panels respectively). In the $2 < p_{\mathrm{T}} < 4$ GeV/c range, the signal-to-background ratio increases by a factor 400 when going from the current ITS situation to the upgraded ITS (considering a material budget of 0.3% of the radiation lenght per detection layer), while the significance improves by a factor 5-10 above 2 GeV/c.

Figure 7 shows the statistical uncertainties on the measurement of the Λ_c/D^0 ratio estimated for 1.7×10^{10} central Pb–Pb collisions (0-20%), corresponding to an integrated luminosity of 10 nb^{-1}. The points are located on a curve that corresponds to the trend and the magnitude of the $\Lambda/\mathrm{K}^0_{\mathrm{S}}$ ratio shown in figure 1. The conclusion of this study is that the Λ_c measurement in central Pb–Pb collisions with the above conditions, should be possible down to a transverse momentum of 2 GeV/c.

Concerning the technologies that are foreseen for the ITS upgrade, two types of silicon pixel detectors are under consideration: hybrid and monolithic pixel detectors. In the hybrid pixel detector concept the sensor and the front-end electronics are implemented in two separate silicon chips connected by bump bonding. This offers the advantage of allowing the optimization of both parts

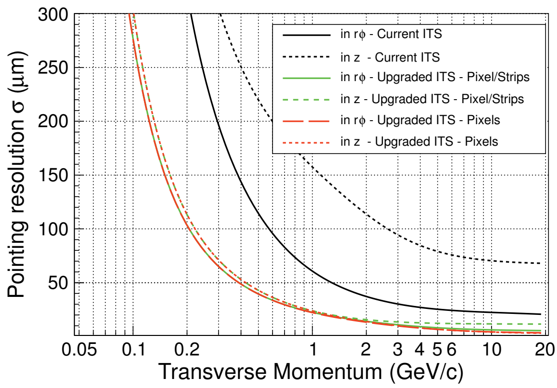

Figure 4. Pointing resolution to the primary vertex of charged pions versus transverse momemtum for the current ITS and the upgraded ITS (with an ITS standalone tracking) [8].

separately. In the case of monolithic pixel detectors, the sensing part (an epitaxial layer grown on a silicon substrate) and the front end readout electronics are incorporated in a same chip. This chip can be currently thinned down to 50 μm, offering a significant advantage in terms of material budget. In addition pitches of 20 μm are standard with this technology while the hybrid pixel size reduction is limited due to the bump bonding. Nevertheless the evolution of this connection technology is expected to enable soon cells sizes of 30 μm $\times$ 30 μm. A detailed description of the R&D activities ongoing on these technologies is given in [8].

4 Conclusion

A new silicon tracker will be built in ALICE, with greatly improved features in terms of track pointing resolution, standalone tracking efficiency, momentum resolution and readout rate capabilities. This upgrade is enabled by the progress made in the field of silicon detector technologies over the last years as well as the possibility to build a smaller radius beampipe in ALICE. The new ITS will put many novel observables within reach, among them the measurement of charm baryons in Pb–Pb collisions as well as exclusive measurements of beauty production. These opportunities are essential in order to understand the hadronisation processes and the thermalization of heavy quarks and thus crucial for the long-term goal of the ALICE experiment that is to provide a precise determination of the Quark Gluon Plasma properties.

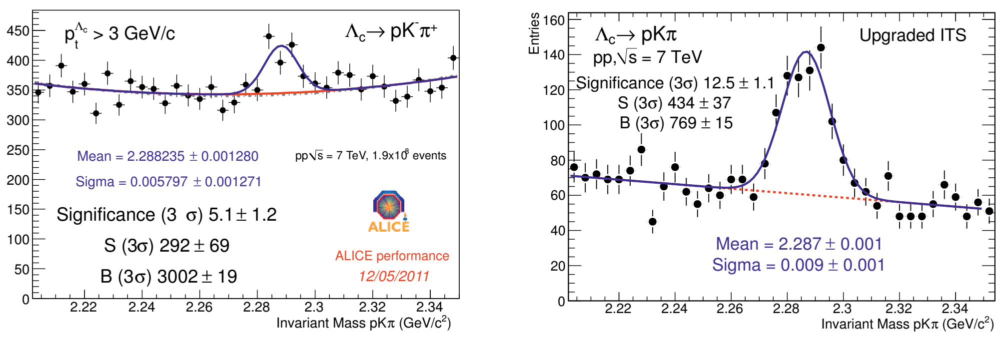

Figure 5. Left: Invariant mass distribution of Λ_c candidates (with $p_T > 3$ GeV/c) measured in pp collisions at $\sqrt{s}$ = 7 TeV. Right: Λ_c invariant mass distribution simulated with the first option (7 pixel layers) of the ITS upgrade and the same sample statistics as in the data [8].

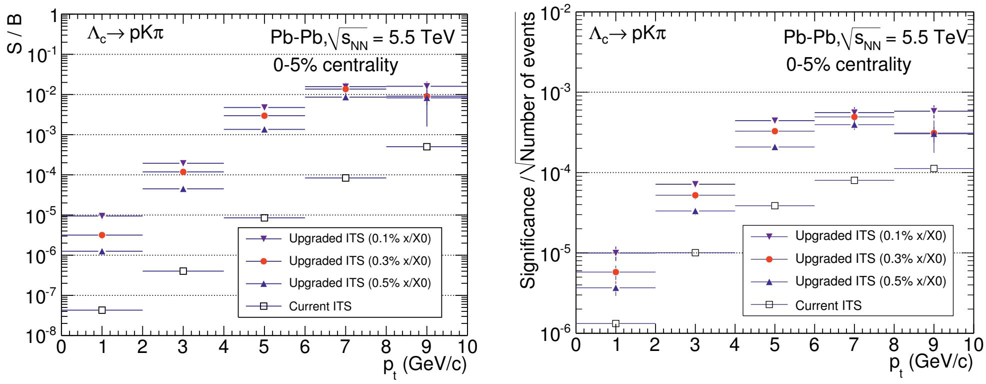

Figure 6. Signal-to-background ratio (left panel) and significance per event (right panel) as a function of p_T for the Λ_c measurement in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV. Different material budget configurations are considered: the label 0.3 % corresponds to the baseline scenario. The label 0.1 % corresponds to a variation of the two innermost layers only to a thickness of 0.1% of the radiation lenght while in the case 0.5%, all layers have a thickness of 0.5% of the radiation lenght [8].

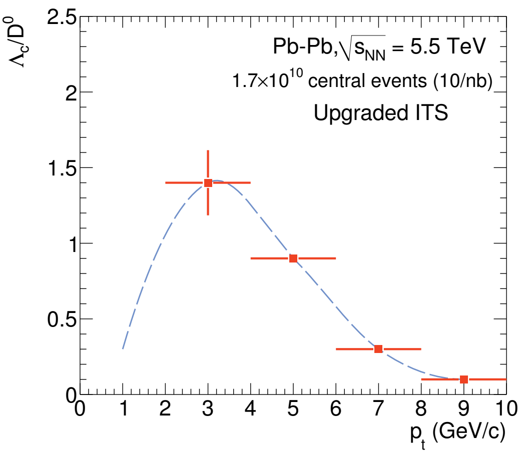

Figure 7. Estimation of the statistical errors expected on the measurement of the Λ_c/D^0 ratio for 1.7×10^{10} central Pb–Pb collisions (0-20%) [8].

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