Investigation of the properties of jets from p-Pb and Pb-Pb collisions with ALICE

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Abstract. Jets from hard scattering processes allow to study the properties of strongly interacting matter produced in ultra-relativistic heavy-ion collisions. The hot and dense medium created in such collisions is expected to cause energy loss of hard-scattered partons via elastic scattering and gluon radiation. Eventually, these processes modify the parton fragmentation. We report measurements of charged jets from lead-lead (Pb-Pb) and proton-lead (p-Pb) collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV. To estimate cold nuclear matter effects, the jet production in p-Pb collisions is studied for different centrality classes and is compared to that in proton-proton (pp) collisions via the nuclear modification factor. In addition, we discuss the measurement of (charged) jets recoiling from a high-$p_T$ trigger hadron, which allows to remove the contribution of combinatorial jets without introducing a bias on the jet population. Furthermore, we report about the measurement of strange hadrons ($\Lambda$, $K^0_S$) in association with charged jets from Pb-Pb and p-Pb collisions. The results are expected to clarify the role of the fragmentation process in the anomalous baryon-to-meson ratio observed at intermediate $p_T$ in A-A collisions. In particular, the measurement allows disentangling the contributions from jet fragmentation and other hadronisation processes.

1. Introduction

Jets are phenomenological objects representing partons originating from hard scattering processes. They are defined and on an equal footing for both experimental measurement and theoretical models, thus allowing a direct comparison. Jets are a powerful tool to investigate the properties of the hot medium created in ultra-relativistic heavy-ion collisions. Since the hard scattering process occurs in the initial stage of a nucleus-nucleus collision, the hard-scattered partons interact with the medium and lose energy. The investigation of the jet-medium interaction is therefore a key tool to assess the properties of this hot medium.

Besides such final state interactions there can also be cold nuclear matter effects due to the presence of a nucleus in both initial and final state. They can be studied separately in, e.g., proton-lead collisions, where no hot medium is expected to be created.

2. Jet measurements with ALICE

The ALICE detector at the CERN LHC is described in detail in [1, 2]. Here, only a brief overview of the detectors relevant for the present analysis will be given. Charged particle tracking is performed via the six layers of silicon detectors in the Inner Tracking System (ITS) and the large Time Projection Chamber (TPC). Both detectors are located inside the L3 solenoid magnet,
which provides a magnetic field of $B = 0.5\, \text{T}$. This detector set covers the full azimuth and $|\eta_{\text{lab}}| < 0.9$, where $\eta_{\text{lab}}$ denotes the pseudo-rapidity in the ALICE laboratory frame.

The event and centrality selection for this analysis is based on the two scintillator detectors V0A and V0C, which cover $2.8 < \eta_{\text{lab}} < 5.1$ and $-3.7 < \eta_{\text{lab}} < -1.7$, respectively, and the Zero Degree Calorimeters (ZDCs). The latter consist of two sets of neutron (ZNA and ZNC) and proton calorimeters (ZPA and ZPC) located at a distance of $\pm 112.5\, \text{m}$ from the interaction point.

In this analysis, charged jets have been studied, i.e. jets that are reconstructed from charged tracks only. The jet reconstruction is performed with the anti-$k_T$ and $k_T$ algorithms [3] with a resolution parameter $R$. The jet axis is required to lie within $|\eta_{\text{jet}}| < 0.9 - R$, such that each jet is fully contained in the detector acceptance. In particular in lead-lead (Pb-Pb) and proton-lead (p-Pb) collisions, the jet reconstruction algorithm assigns tracks to the jet that stem from the so-called underlying event, i.e. bulk hadrons from soft interactions. This biases the reconstructed jet momentum $p_{T,\text{ch}\, \text{jet}}^\text{raw}$ towards higher values. The contribution from the underlying event can be subtracted as follows:

$$ p_{T,\text{ch}\, \text{jet}} = p_{T,\text{ch}\, \text{jet}}^\text{raw} - A_{\text{ch}\, \text{jet}} \cdot \rho_{\text{ch}}, $$

where $A_{\text{ch}\, \text{jet}}$ denotes the jet area and $\rho_{\text{ch}}$ is the event-by-event background density [4]. For p-Pb collisions, the estimation of $\rho_{\text{ch}}$ needs an additional occupancy correction to take into account the sparse environment, see [5] for more details. On top of the average background, instrumental effects and background fluctuations can smear the reconstructed jet momentum. The impact of both sources on the jet spectrum is corrected via an unfolding technique [6].

In the following, the measurement of charged jets from p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02\, \text{TeV}$ and $2.76\, \text{TeV}$, respectively, will be reported.

3. Centrality dependence of charged jet production in p-Pb collisions

Proton-lead collisions can be used to study cold nuclear matter effects in the initial and final state, in particular to disentangle them from effects due to the hot medium created in the final state of Pb-Pb collisions. The nuclear modification is quantified by comparing the $p_T$-differential per-event yields in p-Pb collisions to those in proton-proton ($pp$) at the same centre-of-mass energy per nucleon pair and scaled by the number of binary collisions $N_{\text{coll}}$. Accordingly, the centrality-differential nuclear modification factor in p-Pb collisions, $Q_{pPb}$, is defined as [6]:

$$ Q_{pPb} = \frac{d^2N_{pPb}^c/dydp_T}{\langle N_{\text{coll}}^c \rangle \cdot d^2N_{pp}^c/dydp_T}, $$

where the superscript $c$ indicates that the corresponding quantity is evaluated for a certain centrality class $c$.

The centrality selection uses a hybrid approach, which performs the centrality classification based on the zero-degree energy measured in the lead-going neutron detector ZNA and connects it with the charged particle multiplicity measurement in lead-going direction via the V0A detector. The hybrid approach is described in detail in [7].

The reconstructed jet momentum needs to be corrected for the underlying event contribution via Eq. 1. In case of p-Pb collisions, the background density $\rho_{\text{ch}}$ reaches values not larger than $1.60\, \text{GeV}/c$ in the $0 - 20\%$ ZNA centrality class and is $0.98\, \text{GeV}/c$ for minimum bias collisions [6]. These values are small compared to the jet momentum of $p_{T,\text{ch}\, \text{jet}} > 20\, \text{GeV}/c$ used in the analysis.

In Fig. 1, the nuclear modification factors $Q_{pPb}$ of charged jets are shown for various ZNA centrality classes. The jets have been reconstructed with the anti-$k_T$ algorithm with resolution parameters $R = 0.2$ and $0.4$. The $Q_{pPb}$ factors are found to be consistent with unity for all centrality classes, which indicates the absence of a strong centrality-dependent nuclear
modification of the jet yield in the probed kinematic regime. The result is consistent with single charged particle measurements [7].

The ratio of jet production cross-sections reconstructed with different resolution parameters contains information about the radial structure of the jet. In the following, the ratio between $R = 0.2$ and 0.4 in the common rapidity interval $|\eta_{\text{lab}}| < 0.5$ is considered:

$$R(0.2, 0.4) = \frac{d\sigma_{\text{p-Pb}, R=0.2}}{d\sigma_{\text{p-Pb}, R=0.4}} / d\sigma_{\text{p-Pb}, R=0.4} / d\sigma_{\text{p-Pb}, R=0.2}.$$ 

The more collimated a jet is, the larger the ratio $R(0.2, 0.4)$. In the extreme case, when all particles are contained in the jet with smaller radius, the ratio is unity.

In Fig. 2, the ratio $R(0.2, 0.4)$ is shown for several centrality classes and minimum bias events. As expected, the ratio rises with increasing jet momentum indicating the stronger collimation of jets with rising $p_T$. The ratio for all centrality classes is consistent with the ratio for minimum bias p-Pb collisions. The latter was found to be consistent with the ratio in pp collisions [5]. It is interesting to note that the cross-section ratio was found to be unchanged with respect to pp even in central Pb-Pb collisions [8], where a significant jet suppression was observed. Since we do not observe a strong nuclear modification in p-Pb collision, the unaltered jet production cross-section in p-Pb is in agreement with the expectation.

4. Hadron-jet coincidence measurements

In Pb-Pb collisions, jets are embedded in the huge background of the underlying event. The reconstructed jet spectrum is dominated by combinatorial jets at low $p_T$, where "low" can mean
several 10 GeV/c depending on the jet resolution parameter \( R \), the lower track \( p_T \) cut, etc.. Combinatorial jets consist solely of hadrons generated by soft production processes. They can be suppressed by requiring a high-\( p_T \) track in each jet. This, however, introduces a fragmentation bias. A more elegant solution is to use hadron-jet coincidence measurements [9] that allow to suppress combinatorial jets without introducing fragmentation biases, i.e. the method is infrared and collinear safe. This enables measurements of jets with large \( R \) and/or low \( p_T \).

The basic idea is to select events with a high-\( p_T \) Trigger Track (TT) and analyse jets on the away side (azimuthal distance \( \Delta \phi \sim \pi \)). Combinatorial jets are independent of the trigger \( p_T \). This is visible in Fig. 3, in which the semi-inclusive distributions of charged jets recoiling from a TT from two different \( p_T \) classes are shown. Jets have been reconstructed with the anti-\( k_T \) algorithm. The distributions are similar for low and negative \( p_T \), where combinatorial jets dominate, but the yield of the higher TT class shows an excess towards higher \( p_T \), due to the contribution of jets originating from hard-scattered partons. The \( p_T \) becomes negative if the background subtraction term in Eq. 1 becomes larger than the raw jet \( p_T \).

To eliminate the contribution from combinatorial jets, the per-trigger-yield of the low TT class is subtracted from that of the high TT class:

\[
\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp_T^{ch} d\eta} \bigg|_{\text{TT\{20,50\}}} - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp_T^{ch} d\eta} \bigg|_{\text{TT\{8,9\}}}
\]

where \( N_{\text{trig}} \) is the number of trigger tracks in a given TT class, with TT\{20,50\} being used as an abbreviation for \( p_T, \text{trig} \in [20,50] \text{ GeV/c} \) and similarly for TT\{8,9\}. Furthermore, a scale factor \( c_{\text{Ref}} \approx 1 \) has been introduced to normalise the spectra in Fig. 3 around the peaks, see [9] for more details. The resulting \( \Delta_{\text{recoil}} \) spectrum for central Pb-Pb collisions is shown in Fig. 4 for jet resolution parameters \( R = 0.2, 0.4 \) and 0.5.

To investigate possible medium modifications of the spectra in Pb-Pb collisions, the \( \Delta_{\text{recoil}} \) spectrum needs to be compared to the corresponding pp reference. At the time when this analysis was performed, no pp reference at the same centre-of-mass energy with sufficient statistics was available. Therefore, simulations with the PYTHIA Perugia tunes 2010 and 2011 [10] have been utilised instead. As was verified in [9], these tunes reproduce the \( \Delta_{\text{recoil}} \) spectra measured in pp at \( \sqrt{s} = 7 \text{ TeV} \).
The medium modification is quantified by the ratio $\Delta I_{AA}$ between the $\Delta_{\text{recoil}}$ spectra in (central) Pb-Pb collisions and the PYTHIA (pp) reference:

$$\Delta I_{AA} = \frac{\Delta_{\text{PbPb}}}{\Delta_{\text{PYTHIA}}}. $$

The resulting $\Delta I_{AA}$ is shown in Fig. 5 for charged jets with $R = 0.5$. The value of $\Delta I_{AA}$ is found to be around 0.5 – 0.6 for all momenta, which indicates a strong suppression of the recoil jet yield for central Pb-Pb collisions. Similar results are found for jets with $R = 0.2$ and 0.4 [9].

This raises the question whether a radial redistribution of the energy inside the jet takes place. To investigate such an effect, the $\Delta_{\text{recoil}}$ ratios for different values of $R$ are calculated for central Pb-Pb collisions and compared to predictions for pp obtained via the PYTHIA Perugia tunes 2010 and 2011. The resulting ratio between $R = 0.2$ and 0.5 is shown in Fig. 6. It is consistent with the PYTHIA (pp) prediction, i.e. there is no evidence for intra-jet broadening for a jet resolution parameter up to $R = 0.5$. Note that the observations are similar for $R = 0.2$ and 0.4 [9].

5. Neutral strange particle production in charged jets

The $p_T$-differential baryon/meson ratios ($p/\pi$, $\Lambda/K^0_S$) were found to exhibit a qualitatively similar evolution with event multiplicity in pp, p-Pb and Pb-Pb collisions, with an enhanced production of baryons at mid-$p_T$ for high multiplicity [11]. This observation suggests similar production mechanism in all three collision systems. Since it cannot be explained solely by fragmentation, other hadronisation mechanisms like coalescence and parton recombination have been proposed [12, 13, 14, 15]. It has to be studied whether the hadronisation in jets exhibits similar features or it is purely a feature of the bulk.

For this the $p_T$-differential $\Lambda/K^0_S$ ratio in jets can be compared to the inclusive ratio. The analysis is performed on data from p-Pb and Pb-Pb collisions. Jets have been reconstructed with the anti-$k_T$ algorithm with resolution parameters $R = 0.2, 0.3$ and $0.4$. In particular for Pb-Pb, the jet algorithm does not only cluster particles from real jets, that are produced by
fragmentation of hard-scattered partons, but also reconstructs combinatorial jets consisting of particles from the underlying event. To reduce the contribution of purely combinatorial jets, only jets containing a leading track with $p_T > 5$ GeV/c are accepted for analysis.

The $K^0_S$ meson and $\Lambda$ ($\bar{\Lambda}$) baryons do not have electric charge and decay into a pair of charged daughter particles by weak interaction. They are referred to as "$V^0$ particles". They are reconstructed and identified via the decay topology of their most frequent decay channels:

\[ K^0_S \rightarrow \pi^+ + \pi^- , \]
\[ \Lambda \rightarrow p + \pi^- , \quad \bar{\Lambda} \rightarrow \bar{p} + \pi^+ . \]

Jets and $V^0$ particles are reconstructed independently of each other. The charged decay daughters of the $V^0$ particles are secondary tracks and, thus, excluded from the jet reconstruction procedure. To associate the $V^0$ candidates to a jet, the $V^0$ candidate is matched to a cone around the jet axis:

\[ \sqrt{\Delta \phi^2_{jet,V^0} + \Delta \eta^2_{jet,V^0}} < R , \]

where $\Delta \phi_{jet,V^0}$ and $\Delta \eta_{jet,V^0}$ denote the azimuthal and pseudo-rapidity distance between the momentum of the $V^0$ candidate and the jet axis, and $R$ is the resolution parameter for the jet reconstruction. Finally, the extracted $V^0$ yield in jets is corrected for reconstruction efficiency and the expected contribution from the underlying event is subtracted. The $\Lambda$ baryon yields are corrected for the feed-down contribution from $\Xi^0$ baryons and correspondingly for $\bar{\Lambda}$.

The $\Lambda/K^0_S$ ratio is shown in Figs. 7 and 8 for Pb-Pb and p-Pb collisions, respectively. In both cases, the results for $0 - 10\%$ most central collisions are shown, whereas for p-Pb collisions the $40 - 100\%$ centrality class is shown in addition. It is clearly visible that, while the inclusive ratio around $p_T \sim 3$ GeV/c is strongly enhanced, the ratio in jets is significantly lower in both collision systems. In the case of p-Pb, the analysis has been repeated with different jet resolution
Figure 7. $p_T$-differential $\Lambda/K_S^0$ ratio in charged jets with $R = 0.2$ and with transverse momentum larger than 10 GeV/c (red boxes) and 20 GeV/c (blue crosses), respectively, measured in 0 − 10% most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For comparison, the corresponding inclusive ratio is also shown (black dots).

Figure 8. $p_T$-differential $\Lambda/K_S^0$ ratio in charged jets with transverse momentum larger than 10 GeV/c measured in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with a centrality of 0 − 10% (left) and 40 − 100% (right), respectively. The inclusive ratio (black dots) is compared with the ratio in jets reconstructed with resolution parameters $R = 0.2, 0.3$ and 0.4 (coloured boxes and discs).
parameters $R = 0.2, 0.3$ and 0.4. The $\Lambda/K^0_S$ ratio in jets is found to be very similar for all $R$. Also, the ratios for centrality $0 - 10\%$ and $40 - 100\%$ are similar for jets, in contrast to the inclusive ratio. These observations suggest that the enhancement of the baryon/meson ratio is a feature of the bulk and the hadronisation in jets is not significantly modified with respect to the one observed in pp collisions.

6. Summary

We reported on measurements with ALICE of properties of jets from p-Pb and Pb-Pb collisions. Jets are an important probe to investigate the properties of the hot medium created in ultrarelativistic heavy-ion collisions. Their study can also help to disentangle the final state hot medium effects from cold nuclear matter effects in the initial and final state.

In our measurement of the charged jet production in p-Pb collisions, we do not observe a significant centrality-dependent nuclear modification. The jet cross-section ratio for $R = 0.2$ and 0.4 is observed to be independent of centrality, which indicates that the degree of collimation of jets at different centralities is not modified. Altogether, we do not observe strong cold nuclear matter effects in the probed kinematic regime.

Jet measurements in Pb-Pb collisions suffer from the huge underlying event leading to a significant contribution from combinatorial jets. The latter can be strongly suppressed by an analysis method based on the measurement of jets recoiling from a high-$p_T$ trigger hadron and which does not introduce a fragmentation bias on quenched jets. The differential recoil jet yield in central Pb-Pb collisions is found to be suppressed with respect to pp by up to a factor two in charged jets with resolution parameter $0.2 \leq R \leq 0.5$. At the same time, we do not observe a significant change of the intra-jet energy profile for $R \leq 0.5$.

In order to clarify the role of the fragmentation process in the anomalous baryon-to-meson ratio at intermediate $p_T$ that is observed in high-multiplicity Pb-Pb, p-Pb and pp collisions [11], we studied the $p_T$-differential $\Lambda/K^0_S$ ratio in charged jets from Pb-Pb and p-Pb collisions. The comparison to the corresponding inclusive ratios indicates that the hadronisation in jets does not significantly contribute to the observed anomaly, but that it seems to emerge from processes with low momentum transfer.

Acknowledgments

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