$\pi^0$-hadron correlations in pp, p-Pb and Pb-Pb collisions at ALICE

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Abstract. We present the status of the analyses and latest results on $\pi^0$-hadron correlations measured with the ALICE experiment in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Results are compared with transport models and pQCD calculations.

1. Introduction

Two-particle correlations are a powerful and widely accepted tool \cite{1-3} to study jet-quenching phenomena in high-energy heavy-ion collisions. The energy loss of partons in dense and hot nuclear matter is caused by gluon radiation and multiple elastic and inelastic scatterings in the final state. A quantitative description within various theoretical models \cite{4} can be improved with experimental data. Observables to study jet-quenching in heavy-ion collisions include the nuclear modification factor $R_{AA}$ which was reported by ALICE to show large suppression by a factor $\sim 10$ for $\pi^0$ at $5 \lesssim p_T \lesssim 7$ GeV/c in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV \cite{5}. One can calculate the nuclear modification factor for jets \cite{6}, but this requires jet reconstruction which is complicated in high multiplicity environments such as central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV – here, two-particle correlations are advantageous due to their simplicity. By taking a high-energy trigger particle and correlating its angle and pseudorapidity values with corresponding values of charged particles from the same event, one can study both the jet going in the same direction as the trigger particle and the one in the opposite direction. By comparing per-trigger yields in pp collisions and Pb-Pb collisions at the same center-of-mass energy, we can study the modification of the fragmentation in the QGP medium. Results on $\pi^0$-hadron correlations presented on pp and Pb-Pb collisions have previously been shown in \cite{7}.

Similarly to pp and Pb-Pb collisions, two-particle correlations technique can be applied to p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV performed at the LHC in 2013, which can bring valuable insight into Cold Nuclear Matter effects \cite{8}.

2. Experimental setup

The ALICE experiment \cite{9} is one of four major experiments at LHC, its main goal being to study nuclear matter at extreme temperatures and energy densities occurring in high-energy heavy-ion collisions. Here we present measurements by ALICE with the data sample from pp collisions...
and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and p-Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV collected in 2011 and 2013, respectively.

Charged-particle tracking and identification is performed by the central tracking system which includes the Time-Projection Chamber (TPC) [10] and the Inner Tracking System (ITS) [11]. Charged particles can be measured in a wide $p_T$ range down to 100 MeV in full azimuthal angle and the pseudorapidity range $|\eta| < 0.9$.

Photon and neutral meson measurements are obtained with three complementary systems: Photon Spectrometer (PHOS) [12], Electromagnetic Calorimeter (EMCal) [13] and Photon Conversion Method (PCM) [14]. All three methods successfully proved consistency in results published by the ALICE collaboration on measurements of $\pi^0$ spectra [15–17]. We have used EMCal (for pp and Pb-Pb) and PHOS (for p-Pb) for the measurements reported here. PHOS is based on lead tungstate (PbWO$_4$) scintillating crystals and is dedicated to high-precision photon and neutral meson measurements through its high granularity and excellent energy resolution, but PHOS acceptance is limited to $|\eta| < 0.13$ and $260^\circ < \phi < 320^\circ$. EMCal utilizes lead-scintillator design and covers $|\eta| < 0.7$ and $80^\circ < \phi < 180^\circ$ making it a perfect detector for neutral jets measurements and correlation studies with high-$p_T$ $\pi^0$ mesons or photons.

The V0 detector [18] is used for centrality determination in Pb-Pb and p-Pb collision and for minimum bias triggering both in pp and Pb-Pb collisions. V0 covers the pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$.

### 3. Neutral pion reconstruction

$\pi^0$ mesons are reconstructed by measuring their decay photons in electromagnetic calorimeters [15, 16, 19] and constructing the two-photon invariant mass. In PHOS the background from combinatorial pairs originating not from the same $\pi^0$ and contamination of photons by other particles is estimated and subtracted with the mixed-events method [15,16] and then the number of $\pi^0$ mesons is calculated from the resulting signal distribution. Thanks to the high granularity of PHOS the two $\pi^0$ decay photons can be separated up to $p_T \sim 50$ GeV. For p-Pb collisions ALICE recorded events with a special PHOS trigger [20] which selected events with high-energy cells in a $2 \times 2$ cells region in PHOS (with threshold equal to 7 GeV for p-Pb data periods in 2013). With the data sample obtained with the PHOS trigger the $\pi^0$ peak in the very high-$p_T$ (30-40 GeV/c) invariant mass distribution is clearly seen (figure 1, left).

In the EMCal, high-$p_T$ $\pi^0$'s (above 6 GeV/c) mostly produce one merged cluster instead of two for each photon and a special procedure is called for to produce two-photon invariant mass. First, the cluster spatial dispersion parameter $\sigma_{\text{long}}$ is calculated [7, 21] for separation of merged clusters from the one-photonic clusters which generally have a smaller values of this parameter. For better performance, ranges of $\sigma_{\text{long}}$ parameter where obtained as a function of cluster $p_T$ and used to select merged clusters. A merged cluster is then split into two new clusters with 3 $\times$ 3 cells around two local maxima (which is generally possible for cluster energy below 15 GeV). The two-photon invariant mass is calculated with energies of these new clusters. Both experimentally observed $\sigma_{\text{long}}$ distribution and two-photon invariant mass distribution are reproduced by Monte Carlo simulations (figure 1, middle and right).

### 4. $\pi^0$-hadron correlations in pp, p-Pb and Pb-Pb collisions

The correlation function under investigation is:

$$C(\Delta \phi, \Delta \eta) = \frac{1}{N_{\text{trig}}} \frac{d^2 N(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta},$$

(1)

where $N_{\text{trig}}$ is the number of trigger particles ($\pi^0$), $N(\Delta \phi, \Delta \eta)$ is the number of $\pi^0$-hadron pairs depending on the difference between the particles’ $\phi$ and $\eta$. The $\pi^0$ candidate is taken in
Figure 1. Left plot: Two-photon invariant mass distributions with PHOS for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for $30 < p_T^{\gamma\gamma} < 40$ GeV/c. Blue points – invariant mass distribution of all cluster pairs with the fit of a Gaussian plus a second order polynomial (red curve), orange points – combinatorial background obtained with mixed-event technique. Two-photon invariant mass (middle) and shower shape parameter $\sigma_{\text{long}}$ (right) distributions with EMCal for central (0-10% centrality) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $8.0 < E^{\gamma\gamma} < 16$ GeV. Comparison of experimental data (black points) and Monte Carlo simulations (red points) is shown [7].

The 3$\sigma$ range around the parameterized $\pi^0$ peak in the two-photon invariant mass distribution. A correction on the non-uniform detector acceptance effects is applied using a mixed-event technique [7]. Also corrections for track efficiency and contamination from the secondary particles, $\pi^0$ purity and efficiency and pair $p_T$ resolution are applied. The pseudorapidity integrated distribution $C(\Delta \phi)$ for pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for different ranges of associated particles $p_T$ ($p_T^{\text{assoc}}$) is shown in figure 2. $C(\Delta \phi)$ for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in figure 3.

Figure 2. $C(\Delta \phi)$ distribution for pp (right) and Pb-Pb (left, centrality class – 0-10%) collisions at $\sqrt{s_{NN}} = 2.76$ TeV [7]. Trigger $\pi^0$ is measured with EMCal within $8 < p_T < 16$ GeV/c. Associated charged hadrons are in four $p_T$ bins from 0.5 to 6 GeV/c. Backgrounds obtained with ZYAM (for pp) and $v_n$ subtraction (for Pb-Pb) procedures are shown with dotted lines.

Per-trigger yields, $Y$, are defined as the number of associated particles per trigger in the near or away side peak, after background subtraction. For the subtraction of the background...
commonly two approaches are used: flat background subtraction (ZYAM method) [22] or subtraction of anisotropic flow coefficients \(v_n\). With flat background subtraction one calculates background parameter \(B_0\) in the region outside peaks \((1.0 < \Delta \phi < \frac{\pi}{2})\). In the \(v_n\) subtraction procedure one subtracts \(B(\Delta \phi) = B_0(1 + 2 \sum n V_n \cos(n \Delta \phi))\), where \(V_n\) can approximately be given as the product [23] of the \(v_n\) of associated and trigger particles, \(V_n \approx v_n^{\text{trig}} v_n^{\text{assoc}}\). The per-trigger yields are then calculated by integration within \(-0.7 < \Delta \phi < 0.7\) (Near side) or \(-1.1 < \Delta \phi - \pi < 1.1\) (Away side).

The modification of per-trigger yields is studied by producing the ratio of the per-trigger yields in AA collisions to the ones in pp collisions \(I_{AA} = Y_{AA}/Y_{pp}\) for both the near and away side in several \(p_T^{\text{assoc}}\) bins. The \(I_{AA}\) measured by ALICE is shown on figure 4 for both near side (left) and away side (right). The per-trigger yield is calculated with \(v_n\) subtraction (for Pb-Pb) and flat background subtraction (pp). \(v_n\) coefficients \((v_2 - v_3)\) are taken from ALICE measurements [23,24]. Systematic uncertainties both for \(Y(\Delta \phi)\) and \(I_{AA}\) measurements are summarized in table 1 from [7]. The largest uncertainty in the \(Y(\Delta \phi)\) measurement is due to tracking efficiency uncertainty and the largest uncertainty in \(I_{AA}\) is due to background subtraction in Pb-Pb.

The away side yield at high \(p_T\) is suppressed with \(I_{AA}\) close to 0.6 which is due to jet interaction with medium while for the near side yield at high \(p_T\) there is a hint of a moderate enhancement. Both near side and away side yields show significant enhancement by the factor of 1.8 and 5 at low \(p_T\), correspondingly, which is speculated to be due to several possible effects, e.g. modification of the fragmentation function, change of the quark vs gluon jet ratio or bias on the parton \(p_T\) spectrum for the near side modification and \(k_T\) broadening, medium excitation or fragments from radiated gluons on the away side [7].

Model predictions within JEWEL [25] and AMPT [26] as well as pQCD calculations [27] are shown on figure 4. All models can describe suppression of the away peak yield at high-\(p_T\) but only the AMPT model can qualitatively describe the low-\(p_T\) enhancement both in the away-side and the near-side which is attributed to the increase of soft particles as a result of the jet-medium interactions. The models underestimate the \(I_{AA}\) value for the high-\(p_T\) range for the near side.

5. Conclusions

We report the measurements of \(\pi^0\) - charged hadron correlation distributions for pp and central Pb-Pb collisions (0-10% centrality class) at \(\sqrt{s_{NN}} = 2.76\) TeV in several \(p_T^{\text{assoc}}\) ranges and \(8 < p_T^{\text{trig}} < 16\) GeV/c as well as performance plots for p-Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV. In p-Pb collisions PHOS triggered data sample was used in order to obtain high-\(p_T\) \(\pi^0\) sample.

The \(I_{AA}\) factor for Pb-Pb collisions was obtained for wide \(p_T^{\text{assoc}}\) range \(0.5 < p_T^{\text{assoc}} < 10\) GeV/c which extends the range measured in [1] to the lower \(p_T^{\text{assoc}}\) values. \(I_{AA}\) for the near side is found to have an enhancement at low \(p_T^{\text{assoc}}\) by a factor \(\approx 1.8\) and a hint of a moderate
Figure 4. $I_{AA}$ for near side (left) and away side (right) measured for central (0-10% centrality) Pb-Pb collisions and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV with a $\pi^0$ in the range $8 < p_T < 16$ GeV/$c$. Comparison to predictions by JEWEL and AMPT models and pQCD calculation is shown [7].

enhancement at high $p_T^{assoc}$. $I_{AA}$ for the away side is found to have large enhancement at low $p_T^{assoc}$ by a factor $\approx 5$ and suppression at the level $\approx 0.6$ at high $p_T^{assoc}$. These values are consistent with di-hadron correlations measurements by ALICE [1]. The obtained $I_{AA}(p_T^{assoc})$ values were compared to the predictions with AMPT and JEWEL models and pQCD calculations.

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