Centrality Dependence of Particle Production in p–A collisions measured by ALICE

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Abstract. We present the centrality dependence of particle production in p–Pb collisions at √sNN = 5.02 TeV measured by the ALICE experiment, including the pseudo-rapidity and transverse momentum spectra, with a special emphasis on the event classification in centrality classes and its implications for the interpretation of the nuclear effects.

1. Introduction
Nuclear modification factors measured by ALICE in minimum bias (MB) p–Pb collisions for charged particles [1], heavy flavor and jets show no deviations from unity at high-pT, demonstrating that the observed strong suppression in Pb–Pb collisions is due to final state effects. However, several measurements [2, 3, 4, 5] of particle production in the low and intermediate pT region can not be explained by an incoherent superposition of pp collisions, but rather call for coherent and collective effects. As their strength increases with multiplicity, a more detailed characterisation of the collision geometry is needed. Moreover, a knowledge of the geometry dependence is necessary to interpret the suppression pattern of J/ψ in Pb–Pb collisions relative to the effects observed in the nuclear medium produced in p–Pb collisions.

ALICE has carried out detailed studies of the centrality determination in p–Pb collisions, and the possible biases induced by the event selection on the scaling of hard processes in a selected event sample. The centrality determination consists in relating a Glauber model, which calculates the geometric properties of the event (Ncoll), to a measured observable related to the event activity in a specific rapidity region [6], via the conditional probability to observe a certain activity for a given Ncoll. Specifically, particle production measured by detectors at mid-rapidity can be modeled with a negative binomial distribution (NBD). The zero-degree energy is related to the number of the slow nucleons emitted in the nucleus fragmentation process, which we model with a Slow Nucleon Model (SNM) [7]. However, the connection of the measurement to the collision geometry has to be validated, eg by correlating observables from kinematic regions causally disconnected after the collision, or by comparing a Glauber MC with data for a known process, as eg the deuteron dissociation probability at RHIC [8].

In addition, the consistency of the approach must be demonstrated. As in general the selection in a system with large relative fluctuations can induce a bias, one needs to identify the physics origin of the bias in order to correct centrality dependent measurements. In p–Pb collisions, the relative large size of the multiplicity fluctuations has the consequence that a centrality selection based on multiplicity may select a biased sample of nucleon-nucleon collisions. In essence,
by selecting high (low) multiplicity one chooses not only large (small) average $N_{\text{part}}$ but also positive (negative) multiplicity fluctuations per nucleon-nucleon collision. These fluctuations are partly related to qualitatively different types of collisions, described in all recent Monte Carlo generators by impact parameter dependence of the number of particle sources via multi-parton interaction. However also other types of biases have an influence on the nuclear modification factor: the jet-veto effect, due to the trivial correlation between the centrality estimator and the interaction. However also other types of biases have an influence on the nuclear modification factor: the jet-veto effect, due to the trivial correlation between the centrality estimator and the presence of a high-$p_T$ particles in the event; the geometric bias, resulting from the mean impact parameter between nucleons rising for the most peripheral events.

2. The ALICE approach

The ALICE approach aims to a centrality selection with minimal bias and, therefore, uses the signal in the Zero Degree Calorimeter (ZNA). In this case we cannot establish a direct connection to the collision geometry but we can study the correlation of two or more observables that are causally disconnected after the collision, e.g. because they are separated in rapidity. In centrality classes selected by ZNA, we study the dependence of various observables in different $\eta$ and $p_T$ regions on the charged particle density at mid-rapidity. Fig.1 indicate a monotonic change of the scaling with rapidity. The correlation between the ZDC energy and any variable in the central part shows unambiguously the connection of these observables to geometry. Exploiting the findings from the correlation analysis described, we make use of observables that are expected to scale as a linear function of $N_{\text{coll}}$ or $N_{\text{part}}$, to calculate $N_{\text{coll}}$:

- $N_{\text{coll}}^{\text{mult}}$: the multiplicity at mid-rapidity proportional to the $N_{\text{part}}$;
- $N_{\text{coll}}^{\text{Ph-side}}$: the target-going multiplicity proportional to $N_{\text{target}}$;
- $N_{\text{coll}}^{\text{high-}p_T}$: the yield of high-$p_T$ particles at mid-rapidity is proportional to $N_{\text{coll}}$.

These scalings are used as an ansatz, in the ALICE so-called hybrid method to calculate $N_{\text{coll}}$, rescaling the MB value $N_{\text{coll}}^{\text{MB}}$ by the ratio of the normalized signals to the MB one. We therefore obtain 3 sets of values of $N_{\text{coll}}$. The relative difference does not exceed 10%. We have performed a consistency check, correlating ZNA and V0A centrality measurements, to establish their relation to the centrality. The $N_{\text{coll}}$ distributions for centrality classes selected with ZNA, obtained from the SNM-Glauber fit, are convolved with the NBD from the fit to the V0A distribution. These
Figure 2. $Q_{pPb}$ calculated with CL1 estimator (left), the lines are the G-PYTHIA calculations; with the hybrid method (right), spectra are measured in ZNA-classes and $N_{coll}$ are obtained with the assumption that forward multiplicity is proportional to $N_{target}$.

are compared to the data and a good agreement is found. Moreover, a good agreement is also achieved with an unfolding procedure, where the $N_{coll}$ distributions have been fitted to the data using the parameters from the NBD-Glauber fit. For each V0A distribution selected by ZNA, we find the $N_{coll}$ distribution that, convolved with the NBD$_{MB}$, fits the data, i.e. the parameters of the fit are the relative contributions of each $N_{coll}$ bin. The existence of $N_{coll}$ distributions that folded with NBD agree with measured signal distributions is a necessary condition for ZNA to behave as an unbiased centrality selection. This procedure, which actually does not work for a biased centrality selection (eg CL1) shows that the energy measured by ZN is connected to the collision geometry.

3. Physics Results

3.1. Nuclear Modification Factors

The nuclear modification factors $Q_{pPb}$ calculated with multiplicity based estimator (shown in Fig.2 for CL1, where centrality is based on the tracklets measured in $|\eta| < 1.4$) widely spreads between centrality classes. They also exhibit a negative slope in $p_T$, mostly in peripheral events, due to the jet veto bias, as jet contribution increases with $p_T$. The $Q_{pPb}$ compared to G-PYTHIA, a toy MC which couples Pythia to a p-Pb Glauber MC, show a good agreement, everywhere in 80-100%, and in general at high-$p_T$, demonstrating that the proper scaling for high-$p_T$ particle production is an incoherent superposition of pp collisions, provided that the bias introduced by the centrality selection is properly taken into account, as eg in G-PYTHIA. With the hybrid method, using either the assumption on mid-rapidity multiplicity proportional to $N_{part}$, or forward multiplicity proportional to $N_{target}$, the $Q_{pPb}$ shown in Fig. 2, are consistent with each other, and also consistent with unity for all centrality classes, as observed for MB collisions, indicating the absence of initial state effects. The observed Cronin enhancement is stronger in central collisions and nearly absent in peripheral collisions. The enhancement is also weaker at LHC energies compared to RHIC energies.

3.2. Charged particle density

Charged particle density is also studied as a function of $\eta$, for different centrality classes, with different estimators. In peripheral collisions the shape of the distribution is almost fully
Figure 3. Left: Asymmetry of particle yield, as a function of the pseudorapidity density at mid-rapidity. Right: Pseudorapidity density of charged particles at mid-rapidity per participant as a function of \(N_{\text{part}}\) for various centrality estimators.

symmetric and resembles what is seen in proton-proton collisions, while in central collisions it becomes progressively more asymmetric, with an increasing excess of particles produced in the direction of the Pb beam. We have quantified the evolution plotting the asymmetry between the proton and lead peak regions, as a function of the yield around the midrapidity (see Fig. 3, left): the increase of the asymmetry is different for the different estimators. Fig. 3 right shows \(N_{\text{ch}}\) at mid-rapidity divided by \(N_{\text{part}}\) as a function of \(N_{\text{part}}\) for various centrality estimators. For Multiplicity-based estimators (CL1, V0M, V0A) the charged particle density at mid rapidity increases more than linearly, as a consequence of the strong multiplicity bias. This trend is absent when \(N_{\text{part}}\) is calculated with the Glauber-Gribov model, which shows a relatively constant behavior, with the exception of the most peripheral point. For ZNA, there is a clear sign of saturation above \(N_{\text{part}} = 10\), due to the saturation of forward neutron emission. None of these curves points towards the pp data point. In contrast, the results obtained with the hybrid method, using either \(N_{\text{part}}^{\text{target}}\)-scaling at forward rapidity or \(N_{\text{coll}}\)-scaling for high-\(p_T\) particles give very similar trends, and show a nearly perfect scaling with \(N_{\text{part}}\), which naturally reaches the pp point. This indicates the sensitivity of the \(N_{\text{part}}\)-scaling behavior to the Glauber modeling, and the importance of the fluctuations of the nucleon-nucleon collisions themselves.

4. Conclusions

Multiplicity Estimators induce a bias on the hardness of the pN collisions. When using them to calculate centrality-dependent \(Q_{p\text{Pb}}\), one must include the full dynamical bias. However, using the centrality from the ZNA estimator and our assumptions on particle scaling, an approximate independence of the mid-rapidity multiplicity on the number of participants is observed. Furthermore, at high-\(p_T\) the p–Pb spectra are found to be consistent with the pp spectra scaled by the number of binary collisions for all centrality classes. Our findings put strong constraints on the description of particle production in high-energy nuclear collisions.

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