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# Centrality dependence of particle production in p–A collisions measured by ALICE

Alberica Toia (for the ALICE Collaboration) [1]

*Goethe University Frankfurt, GSI Darmstadt, Germany*

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**Abstract**

We present the centrality dependence of particle production in p–A collisions at $\sqrt{s_{NN}} = 5.02$ 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.

*Keywords:* pA; Centrality; Nuclear modification factor

## 1. Introduction

Studies of nuclear effects in minimum bias (MB) p–Pb collisions for charged particles [1], heavy flavor and jets show that the observed strong suppression in Pb–Pb collisions is due to final state effects. Centrality dependent measurements of the nuclear modification factor require the determination of the average number of binary collisions, $N_{\text{coll}}$, for each centrality class. Moreover, it has been recognized that the study of p–Pb collisions is interesting on its own, with several measurements [3–6] of particle production in the low and intermediate $p_T$ region that cannot be explained by an incoherent superposition of pp collisions, but rather call for coherent and collective effects.

To determine centrality in ALICE we use as many detectors as possible [2], in various rapidity regions [7]. Particle production measured by detectors at mid-rapidity can be modeled

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[1] A list of members of the ALICE Collaboration and acknowledgements can be found at the end of this issue.

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with a negative binomial distribution (NBD), while the zero-degree energy measures the slow nucleons emitted in the nucleus fragmentation process, which we model with a Slow Nucleon Model (SNM) [8]. These models (NBD and SNM) are coupled to a p–Pb Glauber MC and $N_{\mathrm{coll}}$ are obtained for each centrality class determined by slicing the experimental distribution in percentiles of the hadronic cross-section. The $N_{\mathrm{coll}}$ values are similar for different estimators within the systematic error from the Glauber parameters and a MC closure test with HIJING.

However, in order to use these $N_{\mathrm{coll}}$ values in a $R_{\mathrm{pPb}}(p_{\mathrm{T}}, \mathrm{cent}) = \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\langle N^{\mathrm{cent}}_{\mathrm{coll}}\rangle \mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$ calculation, one needs to take into account the bias arising when sampling the p–A events in centrality classes. In p–Pb collisions, the range of multiplicities used to select a centrality class is of similar magnitude as the fluctuations, with 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 $N_{\mathrm{part}}$, but also positive (negative) multiplicity fluctuations. These fluctuations are partly related to qualitatively different types of collisions, described in all recent Monte Carlo generators by fluctuations of the number of particle sources via multi-parton interaction. Concerning the nuclear modification factor other types of bias have been discussed: the jet-veto effect, due to the trivial correlation between the centrality estimator and the presence of a high-$p_{\mathrm{T}}$ particles in the event; the geometric bias, resulting from the mean impact parameter between nucleons rising for most peripheral events. Studies of particle production and centrality determination have already been presented by ALICE [8]; here we focus on the results obtained with a new approach, described in the following sections.

## 2. The hybrid method

The hybrid method aims at providing a data driven and unbiased centrality determination. We give priority to a centrality selection with minimal bias and, therefore, use 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 well separated in rapidity.

Charged particle multiplicity is dominated by soft particles while hard processes are expected to scale with $N_{\mathrm{coll}}$. In centrality classes selected by ZNA, we study the dependence of various observables in different $\eta$ and $p_{\mathrm{T}}$ regions on the charged particle density at mid-rapidity. In order to compare different observables on the same scale and also to neglect efficiency and acceptance, we normalize the values in different classes by the corresponding MB value. The correlation of the signals to the mid-rapidity particle density (Fig. 1 left) exhibits a clear dependence on the rapidity. The slope of the signals with $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ decreases towards the proton direction (C-side). In the Wounded Nucleon Model, $N_{\mathrm{part}}$ is expressed in terms of target and projectile participants. The particle density at mid-rapidity is proportional to $N_{\mathrm{part}}$, whereas at higher rapidities the model predicts a dependence on a linear combination of the number of target and projectile participants with coefficients which depend on the rapidity. Close to Pb-rapidity a linear wounded target nucleon scaling ($N^{\mathrm{target}}_{\mathrm{part}} = N_{\mathrm{part}} - 1$) is expected.

In order to further quantify the trends of the observables and to relate them with geometrical quantities, such as $N_{\mathrm{part}}$, one can adopt the WNM model and make the assumption that the charged particles density at mid-rapidity is proportional to $N_{\mathrm{part}}$ and relate the other observables to $N_{\mathrm{part}}$ assuming linear dependence, parameterized with $N_{\mathrm{part}} \simeq \alpha$. The results for $\alpha$ (Fig. 1 right) indicate a monotonic change of the scaling with rapidity. The red horizontal lines show the ideal geometrical scalings. In Pb-going direction (negative $\eta_{\mathrm{CMS}}$ in the figure) the

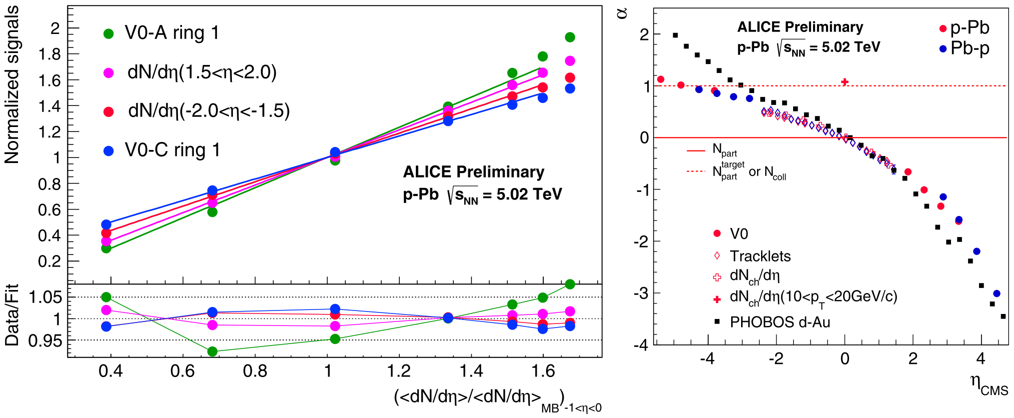

Fig. 1. Left: Normalized signal from various observables versus the normalized charged-particle density, fit with a linear function of $N_{\text{part}}$. Right: Results from the fits as a function of the pseudorapidity covered by the various observables. The red horizontal lines indicate the ideal $N_{\text{part}}$ and $N_{\text{coll}}$ geometrical scalings. The most central point is excluded from the fit, to avoid pile-up effects.

values of $\alpha$ reach the ones obtained for charged-particle production at high-$p_{\text{T}}$. In contrast, in the proton-going direction, $\alpha$ is much lower, indicating strong suppression of the charged-particle production with centrality with respect to $N_{\text{part}}$-scaling. The correlation between the ZDC energy and any variable in the central part shows unambiguously the connection of these observables to geometry. Our data are overlaid with the corresponding fit parameters derived from PHOBOS in d–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The comparison shows a good agreement over a wide $\eta$ range, with some deviations at large negative pseudorapidity. In particular, the $\eta$ region covered by the innermost ring of the VZERO-A detector corresponds to the target fragmentation region where extended longitudinal scaling was observed at RHIC [9].

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

These scalings can be used as an ansatz 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 $N_{\text{coll}}$, whose relative difference does not exceed 10%. This confirms the consistency of the used assumptions, although it does not constitute a proof that any or all of the assumptions are valid.

## 3. Physics results

### 3.1. Nuclear modification factors

As already discussed in [8], the $Q_{\text{pPb}}$ calculated with multiplicity based estimator (shown in Fig. 2 for CL1, where centrality is based on the tracklets measured in $|\eta| < 1.4$) widely spread between centrality classes. They also exhibit a negative slope in $p_{\text{T}}$, mostly in peripheral events,

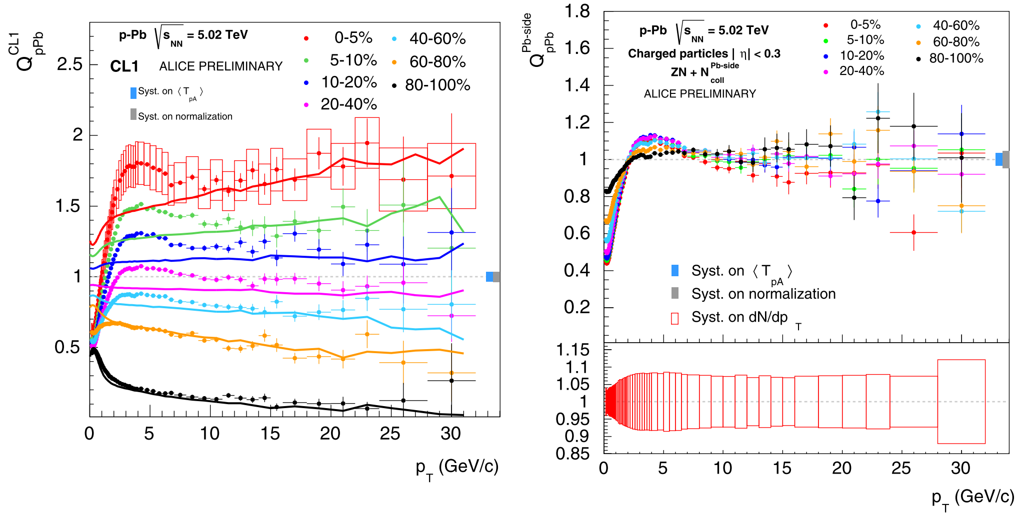

Fig. 2. $Q_{\mathrm{pPb}}$ calculated with CL1 estimator (left), the lines are the G-PYTHIA calculations; with the hybrid method (right), spectra are measured in ZNA-classes and $N_{\mathrm{coll}}$ are obtained with the assumption that forward multiplicity is proportional to $N^{\mathrm{target}}_{\mathrm{part}}$.

due to the jet veto bias, as jet contribution increases with $p_{\mathrm{T}}$. The $Q_{\mathrm{pPb}}$ 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-$p_{\mathrm{T}}$, demonstrating that the proper scaling for high-$p_{\mathrm{T}}$ particle production is an incoherent superposition of pp collisions, provided that the bias introduced by the centrality selection is properly taken into account, as e.g. in G-PYTHIA. For ZNA centrality classes, no bias on the multiplicity or high-$Q^2$ processes is expected and indeed the classes present spectra which are much more similar to each other. However the absolute values of the spectra at high-$p_{\mathrm{T}}$ indicate the presence of a bias, not due to the event selection but because of inaccurate $N_{\mathrm{coll}}$ values calculated with the SNM.

With the hybrid method, using either the assumption on mid-rapidity multiplicity proportional to $N_{\mathrm{part}}$, or forward multiplicity proportional to $N^{\mathrm{target}}_{\mathrm{part}}$, the $Q_{\mathrm{pPb}}$ 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 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 center of mass (see Fig. 3, left): the increase of the asymmetry is different for the different estimators. Fig. 3 right shows $N_{\mathrm{ch}}$ at mid-rapidity divided by $N_{\mathrm{part}}$ as a function of $N_{\mathrm{part}}$ for various centrality estimators.

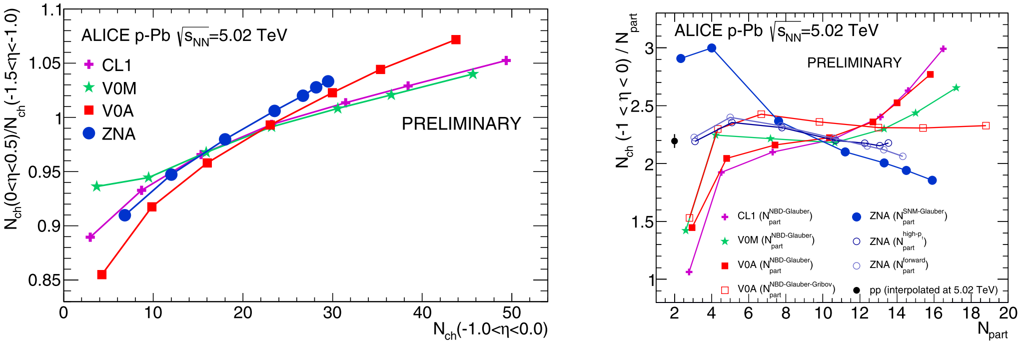

Fig. 3. Left: asymmetry of particle yield, as a function of the pseudorapidity density at mid-rapidity for various centrality classes and estimators. Right: pseudorapidity density of charged particles at mid-rapidity per participant as a function of $N_{\text{part}}$ for various centrality estimators.

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-$p_{\text{T}}$ 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 $Q_{\text{pPb}}$, 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 multiplicity measured at mid-rapidity on the number of participating nucleons is observed. Furthermore, at high-$p_{\text{T}}$ the p–Pb spectra are found to be consistent with the pp spectra scaled by the number of binary nucleon–nucleon 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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