Charged particle production in Pb-Pb and p-Pb collisions at ALICE

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Abstract. Global event observables are of fundamental importance in characterizing the properties of the strongly interacting medium created in heavy-ion collisions. The ALICE experiment at LHC measured charged particle multiplicity distributions in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV in a wide pseudo-rapidity range \((-5 < \eta < 5.5)\) exploiting different techniques. The production of high transverse momentum particles in Pb-Pb relative to pp is studied to characterize the in-medium energy loss. The pseudorapidity distribution of charged particles and the nuclear modification factor for Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV and for p-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV are discussed. The ALICE results are compared to experimental results at lower energies and to theoretical predictions.

1. Introduction
Heavy ion collisions are the best experimental tool to study the phase transition to the Quark Gluon Plasma state predicted by lattice QCD. The RHIC experimental programme has established in the last decade that the hot medium formed in Au-Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV behaves as a perfect liquid [1] [2]. The ALICE (A Large Ion Collider Experiment) experiment at LHC has studied Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV extending the experimental reach towards extreme energy densities. The ALICE experimental programme includes the study of proton-proton interactions as a benchmark for the observables studied in nucleus-nucleus collisions. Moreover proton-nucleus collisions are of crucial importance to disentangle Cold Nuclear Matter (CNM) effects and as a tool to assess QCD in the low x and high gluon density domain reached at LHC energies [3].

Global event properties allow the characterization of the collisions by describing the initial state and the following dynamical evolution. In nucleus-nucleus collisions the centrality is usually defined through the impact parameter \( b \), the distance between the centers of the colliding nuclei in the plane transverse to their direction. The centrality is directly related to the geometry of the collisions and hence to the number of participating nucleons \( (N_{part}) \) and to the number of binary collisions \( (N_{coll}) \). The observables are usually studied as a function of centrality: the more central the collision, the higher the energy density. The particle multiplicity produced in A-A or p-A collisions is linked to the initial energy density and it can provide constraints on the particle production mechanisms, allowing the discrimination of the soft \( (\sim N_{part}) \) from the hard \( (\sim N_{coll}) \) regime [4].

The medium formed can also be characterized by studying the probes that propagate through it. High transverse momentum partons, produced during the very early stages of the collisions
in initial hard scattering, are an ideal tool to study the properties of the medium. Hard partons lose energy by interacting with partons from the medium or by medium-induced gluon radiation [5] [6]. The nuclear modification factor ($R_{AA}$), defined as the ratio of the particle yield in A-A over p-p yield scaled by the number of collisions, characterizes the in-medium effects:

$$R_{AA} = \frac{d^2N_{AA}/d\eta}{d^2N_{pp}/d\eta}. \tag{1}$$

In the hard regime, where particle production scales with the number of binary collisions, $R_{AA}$ is expected to approach unity if the nucleus-nucleus interactions are a simple superposition of $N_{coll}$ hadron collisions. Modifications due to the presence of a hot and dense medium result in $R_{AA}$ different from unity.

In the following, results on the charged particle multiplicity and on the charged hadron nuclear modification factor, measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in p-Pb interactions at $\sqrt{s} = 5.02$ TeV, are presented and compared to results at lower energies and to predictions.

2. Detectors

ALICE is the dedicated heavy ion experiment at LHC. The experimental apparatus is constituted of a central ($|\eta| < 0.9$) barrel placed on a solenoidal magnetic field where different detectors track and identify particles down to $p_T = 200$ MeV/c, a forward ($2.5 < \eta < 4$) muon spectrometer to detect muons from heavy-quarkonia decays and very forward detectors which characterize the collision and provide the trigger. A comprehensive description of the experimental apparatus can be found in [7]. For the results that will be discussed in the following, four detectors are considered:

- the Silicon Pixel Detector (SPD): the 2 innermost layers of the Inner Tracking System (ITS), consisting of two cylindrical layers of hybrid silicon pixel assemblies covering $\eta < 2.0$ and $\eta < 1.4$ for the inner and outer layers, respectively. Besides the trigger, the SPD provides the interaction vertex and the charged particle multiplicity at midrapidity.
- the VZERO counters: two arrays of 32 scintillator tiles placed at $z = 3.3$ m and $z = -0.9$ m from the nominal interaction point (IP), covering the full azimuth within $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$. (VZERO-C).
- the Forward Multiplicity Detector (FMD): a silicon strip detector composed of three sub-detectors, each made by an inner and an outer ring, covering $2\pi$ in azimuth and $-3.4 < \eta < -1.7$ (FMD3), $1.7 < \eta < 5.0$ (FMD1-2) in pseudorapidity.
- the Zero Degree Calorimeters (ZDC): quartz fiber calorimeters placed at about 113 m from the IP, each set consisting of a neutron (ZN) and proton (ZP) ZDC. They detect the energy carried in the forward direction by nucelons that do not interact (spectators). The ZDC are used in Pb-Pb collisions to determine the centrality, to reject the background due to purely electromagnetic interactions and to identify satellite collisions.

3. Pb-Pb results

3.1. Charged particle multiplicity

The charged particle multiplicity, measured by ALICE in Pb-Pb collisions at midrapidity $|\eta| < 0.9$, has been compared to the existing measurements with different colliding systems [8] [9]. The charged particle multiplicity per participant pair at LHC is $\sim 2.2$ times the value measured at RHIC and a factor of 1.9 larger than in Non Single Diffractive (NSD) pp interactions at $\sqrt{s_{NN}} = 2.36$ TeV (see fig. 1). This measurement provides some basic constraints on theoretical models predicting particle production. The logarithmic increase of multiplicity as a function of
\( \sqrt{s} \), valid for data up to the highest RHIC energy [10], had to be replaced by a power law growth \( \sim s^{0.15} \). The ALICE measurement, together with the ATLAS [11] and CMS [12] results, draw a coherent picture that shows a very weak dependence on centrality going from 0.2 to 2.76 TeV (see fig. 2). Such a behavior is reproduced only by models that include saturation [13].

Figure 1. Charged particle multiplicity per participant pair as a function of \( \sqrt{s} \) for different colliding systems [8].

ALICE extended the multiplicity measurement to forward rapidities, covering nearly 10 units of pseudorapidity, using the VZERO and the FMD. Since these detectors do not allow the rejection of secondary particles, a special technique has been developed to avoid large Monte Carlo dependent corrections and to extend the rapidity coverage. Interactions of the main Pb bunch with the satellite bunches from the other beam are selected, to identify the interaction vertices for which the produced particles only cross the beam pipe before reaching the VZERO.

Figure 2. Charged particle multiplicity per participant pair as a function of centrality (expressed here in number of participating nucleons). LHC and RHIC data show the same weak centrality dependence [13].
and FMD detectors. In this way, the secondary production and the corresponding correction are minimized. The satellite vertices are selected using the timing information provided by the neutron ZDCs that measure the arrival time of the emitted neutrons with a resolution of about 0.5 ns. The sum (interaction time) and the difference ($Z_{\text{vertex}}$) of the arrival time on the two ZN are simultaneously used to select the interactions vertices of interest (see fig. 3).

**Figure 3.** Sum vs. difference of the timing measured by the two ZN detectors positioned on both sides relative to ALICE IP. Interactions between the main bunches are at (0, 0). Interactions of main-satellite bunches are displaced by 2.5 ns with the corresponding vertices spatially displaced by 37.5 cm.

**Figure 4.** VZERO (left) and FMD (right) pseudorapidity coverage for the satellite vertices.

In fig. 4 the pseudorapidity coverage for the two detectors is shown for the different satellite vertices used in the analysis. Monte Carlo simulations are used to relate the VZERO signal amplitude to the true charged particle multiplicity. The VZERO absolute response is calibrated in the $\eta$ range where VZERO and SPD detectors overlap. Finally, the charged particle multiplicity is extracted using the ratio from different vertex positions in order to cancel out contributions due to secondaries. The FMD detects the energy deposited by crossing particles, a statistical approach is used to determine the charged particle multiplicity. The absolute
measurement is then corrected for the secondary contribution estimated through a Monte Carlo simulation. The FMD and VZERO measurements agree within 10% and they are both in agreement with the SPD results in the overlapping region. The combined results are shown in fig. 5. The centrality classes have been defined using the ZDC since their distance from the IP makes their response weakly dependent on the interaction vertex position (the same is not true for other estimators such as the VZERO or the SPD multiplicity). The distributions are then symmetrized between positive and negative pseudorapidities and fitted with a double Gaussian. The results are compared to predictions from different models: predictions based on Color Glass Condensate [14] [15] seem to reproduce the data around midrapidity but are only available over a limited pseudorapidity range. AMPT [16] and UrQMD [17] models provide a reasonable description of the forward region but they are unable to describe the overall magnitude and the shape on the whole \( \eta \) range.

![Figure 5. Combined \( dN_{ch}/d\eta \) distributions in 4 centrality bins compared to model predictions.](image)

In fig. 6 the charged particle distribution is plotted in the rest frame of one of the colliding nuclei for LHC and RHIC energies. This measurement is consistent with the validity of longitudinal scaling [19] within the errors, arising mainly from the extrapolation of the charged particle pseudorapidity density from the measured region to the rapidity region of the projectile.

### 3.2. Nuclear modification factor \( R_{AA} \)

The nuclear modification factor for charged particles has been measured in Pb-Pb collisions at \( \sqrt{s} = 2.76 \) TeV [20]. While a weak parton energy loss is observed in peripheral events, the high \( p_T \) particle production is strongly suppressed for central events. The pattern of \( R_{AA} \) as a function of \( p_T \) is qualitatively similar to that observed at RHIC (see fig. 7). At LHC the production is more suppressed, providing evidence for strong parton energy loss in a very dense medium.
4. p-Pb results

4.1. Charged particle multiplicity distributions

Particle production in p-Pb collisions is sensitive to the nuclear effects in the initial state. Therefore p-A interactions are an essential tool to discriminate between initial (already present in p-A interactions) and final (presumably accessible only in A-A collisions) state effects. ALICE measured the charged particle multiplicity in NSD p-A interactions with $|\eta_{LAB}| < 2$ [21]. The charged particle multiplicity is compared with several models (see fig. 8). Most of the models including either shadowing or saturation are able to predict the result within 20%. DPMJET [22]
and HIJING [23] with gluon shadowing are closer to the data. The charged particle multiplicity per participant (compared to existing data in fig. 8) is consistent with inelastic pp collisions interpolated to the same energy. This measurement has provided the first constraint on the description of particle production in proton-nucleus collisions at LHC energies.

![Figure 8](image-url)

**Figure 8.** Left: charged particle pseudorapidity distribution measured in NSD p-A collisions. Right: Multiplicity per participant as a function of beam energy for different systems [21].

4.2. Nuclear modification factors $R_{pA}$

The nuclear modification factor in p-A collisions is a crucial tool to assess whether the initial state of the colliding system plays a role in the suppression of high transverse momentum particles observed in central Pb-Pb collision. $R_{pPb}$ as a function of $p_T$ is shown in fig. 9, compared with $R_{AA}$ for top 5% central and for peripheral Pb-Pb collisions. $R_{pPb}$ is compatible with unity for hard processes ($p_T > 2$ GeV/c), providing evidence that the strong suppression in central A-A collisions is due to the hot and dense medium formed in the collision. The Cronin enhancement observed at RHIC has a lower magnitude at LHC. The centrality dependence of $R_{pPb}$ will help in understanding the cold nuclear matter effects and will provide constraints for the theoretical models describing particle production.

5. Conclusions

ALICE has measured the charged particle pseudorapidity distribution in Pb-Pb collisions in more than 10 units of pseudorapidity. The $\sqrt{s}$ dependence follows a power law. A weak centrality dependence of produced multiplicity is observed, indicating a strong shadowing of nuclear Parton Distribution Functions. Longitudinal scaling seems to persist at LHC energies. Currently no available model is able to describe ALICE data over the whole $\eta$ range. A strong suppression of high transverse momentum particle production has been observed in Pb-Pb collisions, indicating that a dense and opaque medium is formed in A-A collisions at LHC.

First p-Pb data have provided an insight into cold nuclear matter effects. $R_{pPb}$ is found to be compatible with unity, providing evidence that the suppression observed in Pb-Pb collisions is the fingerprint of an in-medium effect.
**Figure 9.** $R_{pPb}$ (blue circles) compared to $R_{AA}$ for top 5% central (red squares) and a more peripheral (green triangles) bin [24].

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