Nuclear modification of hadron production measured by ALICE

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Abstract. The Large Hadron Collider (LHC) collides lead nuclei at an unprecedented centre of mass energy of 2.76 TeV/nucleon to measure the properties of the strongly interacting matter when partons are liberated from nucleons and create a Quark Gluon Plasma. The highly energetic partons propagating through medium are absorbed and thus probe its characteristics. The highly energetic hadrons produced by fragmentation of these partons, provide information about the energy loss of the original quarks and gluons. The energy loss can be studied by measuring the modification of hadron spectra and correlations produced in heavy ion collisions with respect to proton-proton. The ALICE experiment is one of 4 large LHC experiments. It is dedicated to the study of the strong force by colliding heavy ions. The modifications of high momentum particle spectra and their correlation, measured by ALICE experiment, are presented. The consequences of these measurements on the evolution of strongly interacting matter are discussed.

1. Introduction
The strong force which binds nucleons in nuclei and quarks in nucleons is believed to be due to the colour charge. There is experimental evidence that there are three types of colour charge and they correspond to the components of SU(3) triplet. The observed hadrons are colour singlets. The dynamics between quarks can be described in the theory which is invariant under independent rotations of the colour charge at all space-time points. The quanta which mediate strong force are called gluons. The theory which describes the interaction between quarks is Quantum Chromodynamics (QCD).

The strong interaction has two remarkable features. The strength of the interaction decreases with increased transferred four momentum. This phenomenon is called asymptotic freedom. It enables us to use perturbation theory to describe the scattering of partons. The cross section for production of highly energetic partons in pp collisions can be factorised to a non-perturbative probability of finding a parton of type \( a \) with fractional momentum \( x_a \) and a parton of type \( b \) with fractional momentum \( x_b \) of the proton and a perturbative (Rutherford) cross section for the scattering of two partons \( ab \rightarrow cd \), where \( c \) and \( d \) are final state partons. Partons in final state hadronise forming a jet of hadrons. The QCD calculations of jet production are in excellent agreement with data [1, 2, 3]. Opposite to asymptotic freedom at large distances (small transferred four momenta) there is infrared slavery. This is due to the linear increase of the potential between the colour charges. Lattice QCD is an appropriate tool to study this soft region. It predicts that there is a phase transition between the system with hadronic degrees of...
freedom to a system with quark and gluon degrees of freedom \cite{4}, the so called Quark Gluon Plasma (QGP).

In 1982 Bjorken \cite{5} suggested that production of jets in nuclear collisions would be modified due to the presence of QGP. He argued that a parton propagating through a medium would suffer differential energy loss via elastic scattering from quanta in plasma. Later Gyulassy and Plumer \cite{6} showed that radiative energy loss is also important at temperatures close to the phase transition temperature. This energy loss of quarks and gluons in a coloured medium is known as jet quenching.

The measurement of jet quenching is based on comparison of hard parton production in nuclear collisions to the same processes in pp collisions using different observables:

- high $p_T$ hadron spectra,
- two particle hadron correlations,
- jet asymmetry and fragmentation.

In the following sections the results on transverse momentum spectra and two particle correlations are presented. The status of jet studies can be found elsewhere \cite{7}. The presented results are based on minimum bias Pb-Pb events collected in the first LHC heavy ion run in November 2010, where ALICE recorded about 30M minimum bias Pb-Pb events. The reference pp measurements are obtained from the analysis of a dedicated pp run at $\sqrt{s}=2.76$ TeV at the LHC in March 2011, where ALICE collected about 70M minimum bias events.

The Pb-Pb results are often presented in different centrality bins. The centrality is expressed in percentile of inelastic cross section. The estimate of centrality is based on the correlation between the geometry of the nuclear collision and activity in the event, for details see \cite{8}.

## 2. High $p_T$ hadron spectra

It is observed that that high $p_T$ particles are suppressed in Pb-Pb collisions with respect to pp collisions. This observation is best expressed in terms of the nuclear modification factor which is defined as a ratio of the charged particle yield in Pb-Pb to pp collisions scaled by the number of binary collisions:

$$R_{AA}(p_T) = \frac{1/N_{\text{evt}}^{AA}dN_{ch}^{AA}/dp_T}{\langle N_{\text{coll}} \rangle (1/N_{\text{evt}}^{pp}dN_{ch}^{pp}/dp_T)}$$

Thus $R_{AA} = 1$ corresponds to the absence of nuclear effects.

Fig. 1 (left panel) shows fully corrected $p_T$ spectrum of unidentified charged particles measured in pp collisions at $\sqrt{s} = 2.76$ TeV. The details of the analysis can be found in \cite{8, 9, 10, 11}. Due to the limited statistics the pp reference for $R_{AA}$ was constructed using the measured yield only below $p_T = 5$ GeV/c. At larger $p_T$ the pp reference was approximated by a modified Hagedorn function. This functional form provides the best fit to the measured pp spectrum between $p_T = 5$ and 30 GeV/c and was extrapolated to $p_T = 50$ GeV/c. The estimated uncertainty on the pp reference due to the parametrisation and extrapolation procedure increases with $p_T$ and reaches 25% at $p_T = 50$ GeV/c.

Figure 1 (right panel) shows the corrected $p_T$ distributions of inclusive charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in different centrality intervals \cite{11}. Also shown are the pp reference spectra derived from the pp data at $\sqrt{s} = 2.76$ TeV \cite{1, 11} and scaled by the number of collisions $\langle N_{\text{coll}} \rangle$. The scaled pp reference spectra reveal the typical power law shape at high $p_T$, characteristic of hard scattering. In contrast, a marked depletion of the Pb-Pb spectra develops gradually as centrality increases, indicating a significant suppression of particle production in central Pb-Pb collisions.

The nuclear modification factors $R_{AA}$ up to $p_T = 50$ GeV/c are shown in Fig. 2 (left panel) for different centrality intervals. At all centralities, a pronounced minimum at about $p_T = 6\text{-}8$
Figure 1. Left: $p_T$ spectrum of pp collisions at $\sqrt{s} = 2.76$ TeV together with the parametrisation. For $p_T > 30$ GeV/c the extrapolation is shown. The lower panel shows the data-to-fit ratio where the grey area denotes the $p_T$ dependent systematic uncertainties. Right: $p_T$ spectra of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in 3 centrality bins. Results from different centrality intervals are separated by successive factors of 100 for clarity. Also shown (dashed lines) are the reference spectra derived from pp collisions and scaled by $\langle N_{coll}\rangle$

Figure 2. Left: $R_{AA}$ of inclusive charged particles. Error bars indicate the statistical uncertainties. The error boxes contain the systematic uncertainties on the Pb-Pb data and on the pp reference. Normalisation uncertainties are indicated by the bars at $R_{AA} = 1$. Right: $R_{AA}$ in central (0-5%) Pb-Pb collisions compared to model calculations [14, 15, 16, 17].
GeV/c is observed, above which $R_{AA}$ rises monotonically up to about $p_T = 50$ GeV/c. The suppression observed in central collisions at the LHC is stronger than at RHIC [12, 13].

Figure 2 (right panel) shows a comparison of $R_{AA}$ in central (0-5%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV to calculations from energy loss models [14, 15, 16, 17]. All model calculations in Fig. 2 have been constrained to match $R_{AA}$ results from RHIC. The qualitative features of our data are described by all models, including the strong rise of $R_{AA}$ between $p_T = 7$ and 50 GeV/c. A quantitative comparison of the model calculations to the present data will help to put tighter constraints on the underlying energy loss mechanisms and their parametric dependencies.

3. Two particle correlations
Two particle correlation of high $p_T$ particles allows us to study hard scattering phenomena. They present an alternative to full jet reconstruction. The correlations are created between pairs of particles from two non-intersecting windows in transverse momentum. The particles in the higher momentum window are termed trigger particles while the others are termed associated particles. The example of per-trigger yield $1/N_{\text{trig}} dN_{\text{assoc}}/d\Delta \phi$ in the windows $(8 \text{ GeV/c} < p_T, \text{trig} < 15 \text{ GeV/c}; 4 \text{ GeV/c} < p_T, \text{assoc} < 6 \text{ GeV/c})$ can be seen in fig. 3.

Figure 3. Left: The corrected per-trigger yield from pp collisions used for $I_{AA}$ (black crosses). Data is compared with Pythia Perugia-0 simulation (red crosses). Right: The corrected per-trigger yield from Pb-Pb collisions for central (black crosses) and peripheral (blue crosses) collisions.

The effect of the medium on the yield of particles in a jet is studied by calculating ratios $I_{AA}$ of yields in Pb-Pb with respect to pp collisions

$$I_{AA}(p_T,\text{trig}; p_T,\text{assoc}) = \frac{Y^{AA}(p_T,\text{trig}; p_T,\text{assoc})}{Y^{pp}(p_T,\text{trig}; p_T,\text{assoc})}$$

where yield $Y = 1/N_{\text{trig}} \int (dN_{\text{assoc}}/d\Delta \phi)d\Delta \phi$ is integrated on near or away side. Details of the analysis can be found in [18]. Fig. 4 shows $I_{AA}$ for central and peripheral collisions. In central collisions, away-side suppression from in-medium energy loss is seen ($I_{AA} \approx 0.6$), as
expected. Moreover, there is an unexpected enhancement above unity ($I_{AA} \approx 1.2$) on the near-side that was not observed with significance at lower collision energies [19]. It is attributed to the enhanced relative abundance of quarks w.r.t. gluons escaping the medium: gluons couple stronger to the medium due to their different colour charge and their abundance is reduced. The quarks fragment harder and thus produce an enhanced associated yield. In addition, energy loss of the near-side parton causes that trigger particles with similar $p_T$ stem from partons with higher $p_T$ in Pb-Pb collisions than in pp collisions. Consequently, more energy is available for particle production on near and away side. In peripheral collisions, both near and away side are consistent with unity.

![Graph](https://example.com/graph.png)

**Figure 4.** $I_{AA}$ for central and peripheral collisions using the flat pedestal (data points) and flow ($v_2$) subtracted yields (lines). Left side corresponds to near side yield. Right side corresponds to away side yield.

Fig. 5 shows $I_{AA}$ compared to theory predictions. Shown are calculations with different energy loss scenarios [20, 21]. The near-side enhancement is reproduced by energy loss following AdS/CFT (cubic path length dependence) and ASW (quadratic dependence). YaJEM (linear dependence) as well as YaJEM-D yield too large values. The away-side suppression is reproduced by AdS/CFT, ASW and YaJEM-D; YaJEM is too high and the calculation from X. N. Wang yields slightly too low values.

4. Summary
The new data from the LHC provides unprecedented experimental information on jet quenching in heavy-ion collisions. The results presented by ALICE indicate strong suppression of charged particles in Pb-Pb collisions and a characteristic centrality and $p_T$ dependence of the nuclear modification factor $R_{AA}$. The suppression observed in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC is stronger than in central Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV at RHIC. However, the results are compatible if compared in terms of the charged particle density. This emphasises the strong relation between medium density and partonic energy loss. A comparison to model calculations indicates a high sensitivity of high-$p_T$ LHC data to details of the energy loss mechanism. The suppression of the away-side jet-particle yield is also consistent with strong in-medium energy loss. An interesting near-side enhancement shows that the effect of the
medium on the near side is measurable at the LHC. These measurements - both high transverse momentum suppression and jet particle yield modification will provide stringent constraints to the energy loss models and pave the way for a detailed extraction of the relevant medium parameters.

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