Suppression of Charged Particle Production at Large Transverse Momentum in Central Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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INTRODUCTION

The dominant production mechanism for high transverse momentum ($p_T$) hadrons in central nucleus-nucleus collisions at relativistic energies is the fragmentation of high-$p_T$ partons that originate in hard scatterings in the early stage of the nuclear reaction. At RHIC, in central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV the high-$p_T$ hadron production was observed to be suppressed by a factor 4–5 compared to expectations from an independent superposition of nucleon–nucleon collisions [1–5]. Such a suppression was generally attributed to energy loss of the partons as they propagate through the hot and dense QCD medium [6–10].

The degree of the nuclear medium effects at high $p_T$ is estimated by using the nuclear modification factor:

$$R_{AA} = (Y_{NN}/Y_{pp})^{<N_{coll}};$$

where $<N_{coll}>$ is the number of binary nucleon–nucleon collisions, given by the product of the nuclear overlap function $<T_{AA}>$ [11] and the inelastic nucleon–nucleus cross section.

In the $R_{AA}$ expression, $Y_{NN}$ is the charged particle yield in nucleus-nucleus reactions:

$$Y_{NN} = (\frac{d^2N_{AA}}{d\eta dp_T})/M_{AA}$$

and $Y_{pp}$ is the charged particle yield in pp reactions:

$$Y_{pp} = (\frac{d^2N_{pp}}{d\eta dp_T})/M_{pp}$$

where $\eta = \ln(\theta/2)$ is the pseudo-rapidity, $\theta$ the polar angle, $M_{NN}$ and $M_{pp}$ the number of events in nucleus-nucleus and pp collisions respectively.

At LHC energies the parton energy loss is expected to be different than at RHIC because of both a higher medium density and a greater high-$p_T$ partons production. So the measurement of $R_{AA}$ and its dependence on $p_T$ can give information on the characteristics of the medium, the gluon shadowing and the saturation effects.

EXPERIMENTAL DETAILS

The ALICE experiment [12] measured the inclusive primary charged particle transverse momentum distributions at mid-rapidity in central and peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In these measurements the primary particles include also the decay products, except the weak decay of strange particles. For the charged particle tracking we utilized the Inner Tracking System (ITS) [13] and the Time Projection Chamber (TPC) [14] both of which cover the central region in the pseudo-rapidity range $|\eta| < 0.9$. The sum of the signal amplitudes of two forward scintillator hodoscopes [15], covering the pseudo-rapidity ranges $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$ (VZERO-C), were used to measure the event centrality. The VZERO detectors also provide a fast signal which, together with the SPD [16] signal and the LHC bunch-crossing signal, forms the minimum bias trigger for the ALICE experiment. During the heavy-ion data-taking period, up to 114 bunches, each containing about $7 \times 10^{12}$ ions of $^{208}$Pb, collided at $\sqrt{s_{NN}} = 2.76$ TeV in the ALICE interaction region. The rate of hadronic events was about 100 Hz, corresponding to an estimated luminosity of $1.3 \times 10^{30}$ cm$^{-2}$ s$^{-1}$.

The present analysis is based on $2.3 \times 10^{6}$ minimum-bias Pb–Pb events, which passed the offline event selection based on VZERO timing information and the correlation between TPC tracks and hits in the SPD. Additionally, a minimal energy deposit in the Zero Degree Calorimeters (ZDC) [17] is required to further suppress electromagnetic interactions. Only events with reconstructed vertex at $|z_{vtx}| < 10$ cm were used.

The definition of the event centrality is based on the sum of the amplitudes measured in the VZERO detectors. The VZERO amplitude distribution is fitted by using a Glauber model [18] to determine percentage intervals of the hadronic cross section. We used a Glauber model Monte Carlo simulation assuming $\sigma_{NN}$(inel) = 64 ± 5 mb, a Woods–Saxon nuclear density with radius 6.62 ± 0.06 fm and surface diffuseness 0.546 ± 0.010 fm [19] and a minimum inter-nucleon distance of 0.4 ± 0.4 fm. The Glauber Monte Carlo allows one to relate the event classes to the mean numbers of participating nucleons $<N_{part}>$ and binary collisions $<N_{coll}>$ by geometrically ordering events according to the impact parameter distribution.

Track quality cuts in the TPC are based on the number of reconstructed space points (at least 70 out of a maximum of 159) and the $\chi^2$ per space point of the momentum fit (lower than 4). The TPC track candidates are projected to the ITS and used for further analysis, if at least two matching hits in the ITS are found, including at least one in the SPD. The event vertex is reconstructed by extrapolating the particle tracks to the interaction region. Tracks are rejected from the final sample if their distance of closest approach to the reconstructed vertex in longitudinal and radial direction, $d_L$ and $d_R$, satisfies $d_L > 2$ cm or $d_R > 0.018$ cm + 0.035 cm $\cdot p_T^{-1.0}$, with $p_T$ in GeV/c.
The efficiency and purity of primary charged particles using these cuts are estimated using a Monte Carlo simulation including HIJING events and a GEANT3 model of the detector response. The momentum of charged particles is reconstructed from the track curvature measured in the ITS and TPC. The momentum resolution can be parametrized as \( \sigma(p_T) / p_T = A^2 + (B p_T)^2 \). It is estimated from the track residuals to the momentum fit and verified by cosmic muon events and the width of the invariant mass peaks of \( \Lambda, \Xi \) and \( K_0^* \). While \( A = 0.01 \) for all the centrality bins, there is a weak centrality dependence of \( B \). This was accounted for by introducing a \( p_T \) dependent correction factor to the \( p_T \) spectra.

The determination of \( R_{AA} \) requires a pp reference at \( \sqrt{s} = 2.76 \) TeV, where no pp measurement exists. Different approaches are at hand which allow a prediction of the \( p_T \) spectrum at a given \( \sqrt{s} \) by scaling existing data at different energies. Such approaches assume general scaling properties of perturbative QCD (pQCD) or rely on next-to-leading order (NLO) pQCD calculations.

The present analysis follows a data-driven approach with minimal theoretical assumptions where, in order to minimize systematic uncertainties, only measurements by ALICE are considered. In this approach, the pp reference spectrum is obtained by interpolating the differential pp yields \( dN_{ch}/dp_T \) of charged particles measured in inelastic pp collisions at \( \sqrt{s} = 0.9 \) and 7 TeV by ALICE [20]. The interpolation is performed in bins of \( p_T \), based on the assumption that the increase of the yield with \( \sqrt{s} \) follows a power law. Systematic uncertainties on the pp reference spectrum arise from the parametrization, the experimental errors of the measured spectra at 0.9 and 7 TeV and from the interpolation procedure in \( \sqrt{s} \). The combined statistical and systematic data errors result in a 9–10\% uncertainty on the pp reference spectrum at \( \sqrt{s} = 2.76 \) TeV, depending on \( p_T \). Finally, the scaled pp yield in a given centrality class is obtained by multiplication of the pp reference spectrum with \( <N_{coll}> \).

**RESULTS**

Fig. 1a shows the nuclear modification factor \( R_{AA} \) for central and peripheral Pb–Pb collisions. The nuclear modification factor deviates from one in both samples. At high \( p_T \), where production from hard processes is expected to dominate, there is a marked difference between peripheral and central events. In peripheral collisions, the nuclear modification factor reaches about 0.7 and shows no pronounced \( p_T \) dependence for \( p_T > 2 \) GeV/c. In central collisions, \( R_{AA} \) is again significantly different from one, reaching a minimum of \( R_{AA} = 0.14 \) at \( p_T = 6–7 \) GeV/c. In the intermediate region there is a strong dependence on \( p_T \) with a maximum at \( p_T = 2 \) GeV/c. This may reflect a variation of the particle composition in heavy-ion collisions with respect to pp, as observed at RHIC. A significant rise of \( R_{AA} \) by a factor of two is observed for \( 7 < p_T < 20 \) GeV/c.

In fig. 1b the ALICE result in central Pb–Pb collisions at the LHC is compared to measurements of \( R_{AA} \) of charged hadrons (\( \sqrt{s_{NN}} = 200 \) GeV) by the PHENIX and STAR experiments at RHIC. At 1 GeV/c the measured value of \( R_{AA} \) is similar to those from RHIC. The position and shape of the maximum at \( p_T \approx 2 \) GeV/c and the subsequent decrease are similar at RHIC and LHC, contrary to expectations from a recombination model. Despite the much flatter \( p_T \) spectrum in pp at the LHC, the nuclear modification factor at \( p_T = 6–7 \) GeV/c is smaller than at RHIC. This suggests an enhanced energy loss at LHC and therefore a denser medium. A quantitative determination of the energy loss and medium density will require further investigation of gluon shadowing and saturation.

![Fig. 1. a) \( R_{AA} \) in central (0-5%) and peripheral (70-80%) collisions. b) Comparison of \( R_{AA} \) in central Pb-Pb collisions at LHC to measurements at \( \sqrt{s_{NN}} = 200 \) GeV by the PHENIX and the STAR experiments at RHIC.](image-url)