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Absence of jet quenching in peripheral nucleus–nucleus collisions

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ABSTRACT

Medium effects on the production of high-p_T particles in nucleus–nucleus (AA) collisions are generally quantified by the nuclear modification factor (R_{AA}), defined to be unity in absence of nuclear effects. Modeling particle production including a nucleon–nucleon impact parameter dependence, we demonstrate that R_{AA} at midrapidity in peripheral AA collisions can be significantly affected by event selection and geometry biases. Even without jet quenching and shadowing, these biases cause an apparent suppression for R_{AA} in peripheral collisions, and are relevant for all types of hard probes and all collision energies. Our studies indicate that calculations of jet quenching in peripheral AA collisions should account for the biases, or else they will overestimate the relevance of parton energy loss. Similarly, expectations of parton energy loss in light–heavy collision systems based on comparison with apparent suppression seen in peripheral R_{AA} should be revised. Our interpretation of the peripheral R_{AA} data would unify observations for lighter collision systems or lower energies where significant values of elliptic flow are observed despite the absence of strong jet quenching.

Medium effects on the production of high-p_T particles are in general quantified by the nuclear modification factor

$$R_{AA} = \frac{Y_{AA}}{N_{coll} Y_{pp}} = \frac{Y_{AA}}{T_{AA}\,\sigma_{pp}} \quad (1)$$

defined as the ratio of the per-event yield Y_{AA} measured in nucleus–nucleus (AA) collisions to the yield of an equivalent incoherent superposition of N_{coll} binary pp collisions. The number of binary collisions depends on the overlap between the two colliding nuclei quantified by the nuclear overlap T_{AA}. It is expected that in the absence of nuclear effects R_{AA} is unity. However, strictly speaking this holds only for centrality integrated measurements. In this case N_{coll} is given by $N_{coll} = A^2\sigma_{pp}/\sigma_{AA}$, where σ_{pp} and σ_{AA} are, respectively, the pp and AA inelastic cross-sections. As will be outlined in the following in more detail, centrality classification can lead to the selection of AA event samples for which the properties of the binary NN collisions deviate from unbiased pp collisions. In this case R_{AA} can deviate from unity even in the absence of nuclear effects. There are two main origins for selection biases. Firstly, the spatial distribution of nucleons bound in nuclei in the plane transverse to the beam direction differs from those of protons in a beam leading to a bias on the NN impact parameter. Secondly, centrality selection is based on measurements related to bulk, soft particle production. The selection can bias the mean multiplicity of individual NN collisions and in case of a correlations between soft and hard particle production the yield of hard processes in AA collisions.

In the optical Glauber model [1], the nuclear overlap is obtained from the nuclear density distributions and the impact parameter b between two nuclei, which is the only parameter characterizing a collision. Instead, Monte Carlo (MC) Glauber models [1] take into account collision-by-collision fluctuations at fixed impact parameter by allowing the positions of the nucleons in the nuclei to vary. The number of binary collisions is obtained by assuming that the nucleons move on straight trajectories and a collision is counted if the nucleon–nucleon (NN) impact parameter b_{NN} is below a certain threshold (usually given by the inelastic NN cross section). For each simulated AA collision the MC Glauber determines N_{coll}, and for each of the N_{coll} nucleon–nucleon collisions the impact parameter b^i_{NN} and the respective collision position (x^i, y^i) in the transverse plane. In this way, such calculations provide important information about the energy density distribution including its event-by-event fluctuations in the initial state of AA collisions, which can be used as input for hydrodynamic calculations. However, for the evaluation of the nuclear modification factor the information about the individual NN collisions is usually ignored. An impact parameter dependent NN profile can also

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be enabled in the GLISSANDO model [2], but is not (yet) available in the widely-used standard Glauber MC [3,4].

In variance to the standard MC Glauber approach, the HIJING model [5] takes into account the possibility of multiple hard scatterings (multiple parton interactions) in the same NN collision. As in MC models for pp collisions like for example PYTHIA [6], the mean number of hard scatterings per collision depends on the NN impact parameter. While the NN collisions are still modeled as incoherent, the production rate of hard processes is not proportional to $N_{\rm coll}$ but to

$$N_{\rm hard} = N_{\rm coll} \cdot N_{\rm NN}^{\rm hard}\Big|_{\rm C} / \left\langle N_{\rm NN}^{\rm hard}\right\rangle, \tag{2}$$

where $N_{\rm NN}^{\rm hard}\Big|_{\rm C}$ is the average number of hard scatterings in a NN collision for a given centrality selection and $\left\langle N_{\rm NN}^{\rm hard}\right\rangle$ is its unbiased average value. Similarly, Ref. [7] describes an extension of the optical Glauber model, in which the nuclear overlap function is obtained from a convolution between the product of the thickness functions of the two nuclei and the nucleon–nucleon overlap function.

These extensions have important consequences for the AA impact parameter dependence of hard processes. With respect to standard Glauber $N_{\rm coll}$ scaling, the number of hard processes is suppressed in peripheral collisions due to a simple geometrical bias. With increasing AA impact parameter the phase space for collisions increases $\propto b$ whereas the nuclear density decreases leading to an increased probability for more peripheral than average NN collisions.

A further consequence arises if the yield of hard and soft processes are correlated via the common $b_{\rm NN}$ and centrality selection is based on soft particle production (multiplicity or summed energy) [8,9]. In this case for a given centrality class, the NN collisions can be biased towards higher or lower than average impact parameters. The event selection bias is in particular important when fluctuations of the centrality estimator due to $b_{\rm NN}$ are of similar size as the dynamic range of $N_{\rm coll}$, as in pA collisions.

In contrast, centrality measurements based on zero-degree energy should not introduce any selection bias, while the geometric bias could still play a role. In the so called hybrid method, described in Ref. [9], the pPb centrality selection is based on zero-degree neutral energy in the Pb-going directions (slow neutrons) and $N_{\rm coll}$ is determined from the measured charged particle multiplicity M according to $N_{\rm coll} = \langle N_{\rm coll}\rangle \cdot M/\langle M\rangle$, where $\langle N_{\rm coll}\rangle$ and $\langle M\rangle$ are, respectively, the centrality averaged number of collisions and multiplicity. In case soft and hard particle yields are affected in the same way, the selection bias would cancel in the nuclear modification factor.

In peripheral AA collisions, one can expect the selection bias to be relevant, in addition to the geometric bias. To illustrate its potential effect on peripheral $R_{\rm AA}$ we use PHENIX data in 80–92% central AuAu collisions at $\sqrt{s_{\rm NN}} = 0.2$ TeV [10,11] and CMS data in 70–90% central PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [12]. Above 5.25 GeV/c the PHENIX data from 2008 and 2012 were averaged using the quadratic sum of statistical and systematic uncertainties of the original measurements as weights. The PHENIX data are shown in Fig. 1 up to 10 GeV/c and the CMS data in Fig. 2 up to 30 GeV/c. The error bars represent statistical, while the shaded boxes the systematic uncertainties. The vertical box around 1 at 0.5 GeV/c denotes the global normalization uncertainty, which is dominated by the uncertainties on determining the centrality and $N_{\rm coll}$ (or $T_{\rm AA}$) from Glauber. As indicated in the figures, constant functions were fit to the PHENIX and CMS data between 3–17 GeV/c and between 10–100 GeV/c, respectively, yielding a value of 0.80 ± 0.03 GeV/c and 0.74 ± 0.02 GeV/c with a reduced

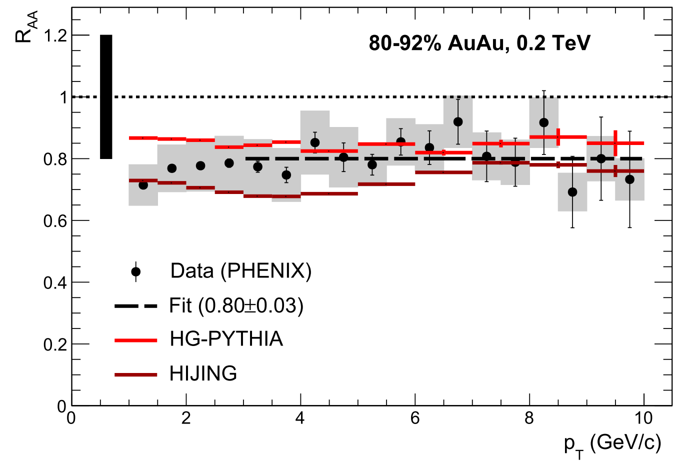

Fig. 1. $R_{\rm AA}$ versus $p_{\rm T}$ in 80–92% central AuAu collisions at $\sqrt{s_{\rm NN}} = 0.2$ TeV. The PHENIX data from [10,11], which were averaged as explained in the text, are compared to HG-PYTHIA and HIJING calculations. For details, see text.

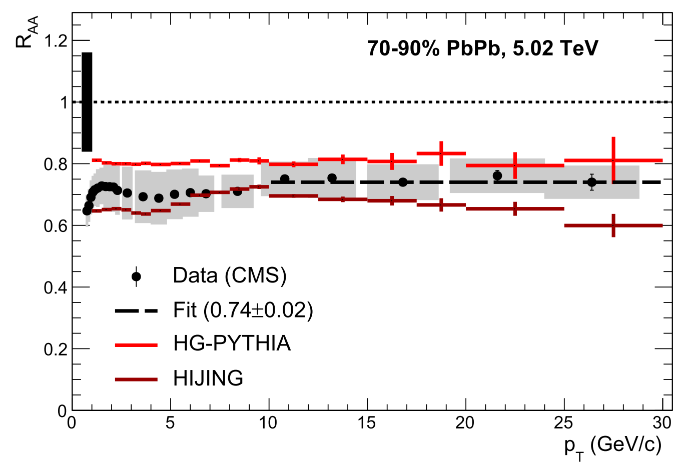

Fig. 2. $R_{\rm AA}$ versus $p_{\rm T}$ in 70–90% central PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The CMS data from [12] are compared to HG-PYTHIA and HIJING calculations. For details, see text.

$\chi^2 < 1$ using statistical and systematic uncertainties (ignoring the normalization uncertainty) added in quadrature. Using a linear fit instead of a constant would in both cases result in a slope consistent with 0. For PbPb at 5.02 TeV, this is distinctively different for the 50–70% centrality class, where $R_{\rm AA}$ exhibits a significant slope of about 0.003 GeV$^2/c^2$, indicating that $R_{\rm AA} \sim 1$ is reached at around 125 GeV/c, although parton energy loss should play a stronger role than in the more peripheral class.

The data are compared to HIJING (v1.383) calculations without jet quenching and shadowing and a toy model called HG-PYTHIA, which is based on the HIJING Glauber model for the initial state and PYTHIA [6] as explained below. Besides the jet quenching and shadowing settings, all other settings in HIJING were used as set by default, except the minimum $p_{\rm T}$ of hard or semi-hard scatterings, which was set to 2.3 (instead of 2.0) GeV for PbPb collisions at 5.02 TeV.

HIJING accounts for fluctuations of $N_{\rm NN}^{\rm hard}$ via an NN overlap function $T_{\rm NN}$ that depends on $b_{\rm NN}$. The probability for an inelastic NN collision is given by

$$d\sigma_{\rm inel} = 2\pi\, b_{\rm NN}\, db_{\rm NN} \left[1 - e^{-(\sigma_{\rm soft}+\sigma_{\rm hard})\, T_{\rm NN}(b_{\rm NN})}\right], \tag{3}$$

where $\sigma_{\rm soft}$ is the geometrical soft cross-section of 57 mb related to the nucleon size and $\sigma_{\rm hard}$ the energy-dependent pQCD cross-