Absence of jet quenching
in peripheral nucleus–nucleus collisions

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October 11, 2022

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

\[
R_{AA} = \frac{Y_{AA}}{N_{\text{coll}} Y_{pp}} = \frac{Y_{AA}}{T_{AA} \sigma_{pp}} \tag{1}
\]
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 \( N_{\text{coll}} \) 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 \( N_{\text{coll}} \) is given by \( N_{\text{coll}} = A^2 \sigma_{pp}/\sigma_{AA} \), where \( \sigma_{pp} \) and \( \sigma_{AA} \) 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 characterising 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 \( b_{\text{NN}} \) is below a certain threshold (usually given by the inelastic NN cross section). For each simulated AA collision the MC Glauber determines \( N_{\text{coll}} \), and for each of the \( N_{\text{coll}} \) nucleon–nucleon collisions the impact parameter \( b_{\text{NN}} \) 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 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 $N_{\text{coll}}$ but to

$$N_{\text{hard}} = N_{\text{coll}} \cdot N_{\text{NN hard}} |_{C} / \langle N_{\text{NN hard}} \rangle,$$

(2)

where $N_{\text{NN hard}} |_{C}$ is the average number of hard scatterings in a NN collision for a given centrality selection and $\langle N_{\text{NN hard}} \rangle$ 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 $N_{\text{coll}}$ 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 $b_{\text{NN}}$ 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 $b_{\text{NN}}$ are of similar size as the dynamic range of $N_{\text{coll}}$, 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 $N_{\text{coll}}$ is determined from the measured charged particle multiplicity $M$ according to $N_{\text{coll}} = \langle N_{\text{coll}} \rangle \cdot M / \langle M \rangle$, where $\langle N_{\text{coll}} \rangle$ 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, as demonstrated in figure 8 of [9], which quantifies the ratio between the average multiplicity of the centrality estimator and the average multiplicity per average ancestor of the Glauber fit. To illustrate its potential effect on peripheral $R_{\text{AA}}$ we use PHENIX data.
in 80–92% central AuAu collisions at $\sqrt{s_{NN}} = 0.2$ TeV [10,11] and CMS data in 70–90% central PbPb collisions at $\sqrt{s_{NN}} = 5.02$ 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 $N_{coll}$ (or $T_{AA}$) 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 $\pm$ 0.03 and 0.74 $\pm$ 0.02 with a reduced $\chi^2 < 1$ 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 $R_{AA}$ exhibits a significant slope of about 0.003 GeV$^2$/c$^2$, indicating that $R_{AA} \sim 1$ 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 $p_T$ 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 $N_{NN}^{hard}$ via an NN overlap function $T_{NN}$ that depends on $b_{NN}$. The probability for an inelastic NN collision is given by

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

where $\sigma_{soft}$ is the geometrical soft cross-section of 57 mb related to the nucleon size and $\sigma_{hard}$ the energy-dependent pQCD cross-section for $2 \rightarrow 2$ parton scatterings. At $\sqrt{s_{NN}} = 0.2$ and 5.02 TeV, $\sigma_{hard} = 11.7$ and 166.2 mb, respectively, while below 0.04 TeV it is only about 1 mb. The NN overlap is approximated by the Eikonal function as $T_{NN} \propto \xi^3 K_3(\xi)$ with $\xi \propto b_{NN}/\sqrt{\sigma_{soft}}$. If there is at least one hard NN collision, the number of hard scatterings or multiple parton interactions (MPI) per NN interactions is distributed as

$$P(N_{NN}^{hard}) = \left( N_{NN}^{hard} \right)^{N_{NN}^{hard}} \frac{N_{NN}^{hard}}{N_{NN}^{hard}} e^{-(N_{NN}^{hard})}, \quad (4)$$
Figure 1: $R_{AA}$ versus $p_T$ in 80–92% central AuAu collisions at $\sqrt{s_{NN}} = 0.2$ 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.

with the average number of hard scatterings determined by $b_{NN}$ as

$$\langle N_{NN}^{\text{hard}} \rangle = \sigma_{\text{hard}} T_{NN}(b_{NN})$$

(5)

For a soft NN collision $N_{NN}^{\text{hard}} = 0$. The average number of hard collisions per NN collisions decreases from $\langle N_{NN}^{\text{hard}} \rangle = 1.77$ at $\sqrt{s_{NN}} = 5.02$ TeV to 0.28 at 0.2 TeV and becomes negligible (<0.05) below 0.04 TeV. The total number of hard scatterings for a AA collision is then obtained by looping over all NN collisions in the MC Glauber, i.e.

$$N_{\text{hard}} = \sum_{i=1}^{N_{\text{coll}}} N_{NN}^{\text{hard}}(b_{NN})$$

In HIJING, $R_{AA}$ at high $p_T$ for central collisions is not unity even in absence of jet quenching and shadowing, possibly due to the implementation of adhoc energy–momentum conservation for large $N_{NN}^{\text{hard}}$ and due to the treatment of multiple scattering to model the “Cronin” effect [13]. This is illustrated in Fig. 4, which shows $R_{AA}$ versus $p_T$ in 0–5% central AuAu and PbPb collisions at $\sqrt{s_{NN}} = 0.2$ and 5.02 TeV, respectively, calculated using HIJING without jet quenching and without shadowing. At high $p_T$, a suppression by about a factor 2 is obtained. Such a strong suppression despite nuclear effects in the model calculation is not consistent with direct photon measurements [14,15] which find $R_{AA} \approx 1$ with an uncertainty of about ±25% in central collisions.
To overcome these features and to study a baseline corresponding to an incoherent and unconstrained superposition of NN collisions, we developed HG-PYTHIA. For a given MC Glauber event calculated in HIJING, we run PYTHIA (v6.28 with Perugia 2011 tune) to generate pp events with exactly \( N_{\text{hard}} \) multiple parton interactions for each NN collision \( i \), where \( i \) runs from 0 to \( N_{\text{coll}} \). The generated particles from all PYTHIA events are then combined and treated like a single AA event in the further analysis.

The model calculations were performed at \( \sqrt{s_{\text{NN}}} = 0.2 \text{ TeV} \) for AuAu and \( 5.02 \text{ TeV} \) for PbPb collisions. The respective pp references were obtained with the same MPI model from HIJING as for AA collisions. The centrality selection was done similarly to the data, namely by ordering events based on the charged particle multiplicity in \( 3 < |\eta| < 4 \) for the low and \( 2.5 < |\eta| < 5 \) for the high energy data, respectively. The multiplicity in the models approximately scales with \( N_{\text{hard}} \) and hence can not be expected to be in agreement with the data. However, by ordering the events according to multiplicity for the centrality selection, this deficiency is not relevant for the present study. The average number of binary collisions needed for the calculation of \( R_{\text{AA}} \) was obtained directly from the model for the selected range...
Figure 3: $R_{AA}$ versus centrality for AuAu and PbPb collisions at $\sqrt{s_{NN}} = 0.2$ and $\sqrt{s_{NN}} = 5.02$ TeV, respectively, calculated with HG-PYTHIA, where $R_{AA} \equiv N_{\text{hard}}/(N_{\text{coll}} \langle N_{\text{hard}}^{\text{NN}} \rangle)$ by construction. For details, see text.

in multiplicity and was found to be about $N_{\text{coll}} = 4.1$ and 8.6, respectively, similar to the values reported by the experiments.

The results of the model calculations are compared to the data in Figs. 1 and 2. As expected due to the selection bias, both calculations are below 1 even in absence of any initial or final state effect in the model. The models describe the data at both collision energies, despite a factor of 25 difference in their center-of-mass energies. HG-PYTHIA has the tendency to overshoot the data, while HIJING to undershoot the data, and appears to decrease with increasing $p_T$. Presumably this originates from the adhoc energy–momentum conservation and strong multiple scattering implemented in HIJING, which is purposely neglected in HG-PYTHIA, and hence the difference between the two models may be taken as a extreme range of model predictions. The experimental results have large global normalization uncertainties of about 15 to 20%, which however are largely correlated with those of the calculations, since in all cases the same types of MC Glauber simulation are used. However, the PHENIX data may be affected by finite trigger inefficiency in the peripheral bin, whose correction as in the case of dA collisions \footnote{16} would work in the opposite direction than the multiplicity bias \footnote{17}.

Finally, we discuss the relative importance of the geometry and selection biases on $R_{AA}$. In HG-PYTHIA, $R_{AA}$ at high $p_T$ approaches $N_{NN}^{\text{hard}}|_C =$
\( \frac{N_{\text{hard}}}{N_{\text{coll}}} / \langle N_{\text{NN}}^{\text{hard}} \rangle \) from Eq. 2 by construction. The ratio of \( \frac{N_{\text{hard}}}{N_{\text{coll}}} \) for AuAu and PbPb collisions divided by the average number of \( N_{\text{hard}} \) in pp collisions at \( \sqrt{s_{\text{NN}}} = 0.2 \) and \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV, respectively, was calculated, and plotted versus centrality class in 5% intervals in Fig. 3. The events were either ordered according to impact parameter probing only the geometry bias, or according to charged particle multiplicity in the same rapidity ranges as before, probing both the geometry and the selection biases. It turns out that the geometry bias sets in at mid-central collisions, reaching up to 10 to 20% for most peripheral collisions. The additional effect of the selection bias becomes noticeable above the 60% percentile and is significant above the 80% percentile, reaching up to 75% and 40% for most peripheral collisions. The onset of the selection bias is steeper for the lower collision energy, as expected if the fluctuations of the multiplicity and the dynamic range of \( N_{\text{coll}} \) are similar. For peripheral classes of 85% and beyond, another bias becomes increasingly important, namely the multiplicity selection in AA collisions effectively cuts into the pp cross section, suppressing the rate of hard processes relative to minimum bias pp collisions. While at center-of-mass energies of below 40 GeV [18,19], the effect from multiple interactions can be neglected, the latter, so called “jet-veto” [9], bias is strongly enhanced due to auto-correlations, since centrality estimators at mid-rapidity were used. Hence, the ratio of yields in central to peripheral collisions, \( R_{\text{CP}} \), which is intended to quantify nuclear modification in absence of pp reference data, would be larger than unity in absence of nuclear effects.

In conclusion, our model studies which employ particle production including a nucleon–nucleon impact parameter dependence in AA collisions but no nuclear effects, demonstrate that \( R_{\text{AA}} \) at midrapidity in peripheral AA collisions can be significantly affected by event selection and geometry biases, similar to those previously discussed in the context of pPb collisions at the LHC [9]. The apparent suppression induced by the biases for peripheral \( R_{\text{AA}} \) results are present at all high energy collisions, and for very peripheral collisions expected to be stronger for lower energy collisions. In principle, all hard probes should be similarly affected; examples are the most peripheral \( R_{\text{AA}} \) of inclusive \( J/\psi \) [20] or jets [21] at LHC energies. Furthermore, the discussion of the onset of parton energy loss studied with the RHIC beam energy scan [18,19] should take the biases into account when considering the ratio of yields in central to peripheral collisions, which may lead to an artificial enhancement of \( R_{\text{CP}} \) in absence of nuclear effects. Calculations that attempt to address parton energy loss in peripheral collisions have to account for the effect, or else they will overestimate the suppression caused by parton energy loss. In particular, to assess the multiplicity bias, the correlation between soft and hard particle production has to be modelled and centrality selection
has to be performed in the same way as in the experiment. For example, in
the model calculation [22], the extracted transport coefficient changes by an
order of magnitude from 0.1 GeV²/fm, i.e. similar to cold nuclear matter, for
$R_{AA} \sim 1$ in 80–92% to 1 GeV²/fm, i.e. hot nuclear matter, for $R_{AA} \sim 0.8$ in
60–70% AuAu collisions at $\sqrt{s_{NN}} = 0.2$ TeV. Hence, our studies indicate that
expectations of parton energy loss in light-heavy collision systems [23–25],
which were perhaps guided by comparing with apparent suppression seen in
peripheral $R_{AA}$, should be revisited.

Our interpretation of the peripheral $R_{AA}$ data also implies that large
values of elliptic flow ($v_2$), as measured in peripheral AA collisions [26], can
arise in a system that does not exhibit jet quenching, and hence in accordance
with similar observations in low-energy heavy-ion collisions [27], or in light–
heavy or even light–light collisions (see references in [28]).

To further study the effect of the biases, it would be useful measure pe-
ripheral $R_{AA}$ (or integrated values above $\sim 10$ GeV/c) in finer (5% wide)
centrality intervals. The trend of the progressively more peripheral $R_{AA}$ val-
ues should clearly demonstrate the effect of the biases, as one would expect
the $R_{AA}$ values to decrease, and not to rise, as expected if parton energy
loss decreases. Further experimental studies, such as measurements of $R_{AA}$
for reference processes like photon and intermediate vector boson for which
no medium modification is expected, in peripheral AA collisions, would be
needed to experimentally constrain the biases, but they are not straightfor-
ward due to the reduced parton luminosity, and due to significant contamina-
tion from ultra-peripheral collisions and electro-magnetic processes. Finally,
semi-inclusive measurements as [29][30] can be used to constrain the energy
loss in peripheral AA and light–heavy collision systems, as they do not rely
on the modeling of the Glauber parameters.

Acknowledgments

We thank Jamie Nagle and Yen-Jie Lee for fruitful discussions. We thank
Austin Baty for making available his code of HG-PYTHIA (which he derived
from our ROOT-macro-based code end of 2019). The work of C. Loizides
is supported by the U.S. Department of Energy, Office of Science, Office of
Nuclear Physics, under contract number DE-AC02-05CH11231.
Figure 4: $R_{AA}$ versus $p_T$ in 0–5% central AuAu and PbPb collisions at $\sqrt{s_{NN}} = 0.2$ and 5.02 TeV, respectively calculated using HIJING without jet quenching and without shadowing.

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Appendix

Values for $R_{AA}$ are provided for numerous collisions systems (AuAu at 0.2 TeV, PbPb at 2.75 and 5.02 TeV, XeXe at 5.44 TeV and OO at 7 TeV) in Tab. 1 and shown in Fig. 5. To obtain the values for other centralities the computed suppression factors must be weighted with $N_{\text{coll}}$. If you need values for a different collision system or centrality, please ask the authors or use the provided code.

Figure 5: $R_{AA}$ versus centrality for various collision systems calculated with HG-PYTHIA as $R_{AA} \equiv N_{\text{hard}}/(N_{\text{coll}} \langle N_{\text{NN}}^{\text{hard}} \rangle)$. 
| System $\sqrt{s_{\text{NN}}}$ (TeV) | AuAu | PbPb | PbPb | XeXe | OO |
|-------------------------------|------|------|------|------|----|
| Centrality | $R_{\text{AuAu}}$ | $R_{\text{PbPb}}$ | $R_{\text{PbPb}}$ | $R_{\text{XeXe}}$ | $R_{\text{OO}}$ |
| 0–5% | 1.006 | 1.011 | 1.013 | 1.021 | 1.107 |
| 5–10% | 1.001 | 1.007 | 1.008 | 1.013 | 1.059 |
| 10–15% | 1.000 | 1.005 | 1.005 | 1.008 | 1.038 |
| 15–20% | 0.998 | 1.003 | 1.003 | 1.003 | 1.018 |
| 20–25% | 0.997 | 1.000 | 1.000 | 0.997 | 1.005 |
| 25–30% | 0.995 | 0.997 | 0.996 | 0.989 | 0.989 |
| 30–35% | 0.993 | 0.993 | 0.991 | 0.981 | 0.973 |
| 35–40% | 0.989 | 0.987 | 0.984 | 0.969 | 0.954 |
| 40–45% | 0.986 | 0.980 | 0.975 | 0.955 | 0.937 |
| 45–50% | 0.980 | 0.969 | 0.962 | 0.940 | 0.919 |
| 50–55% | 0.973 | 0.957 | 0.948 | 0.923 | 0.894 |
| 55–60% | 0.965 | 0.943 | 0.930 | 0.904 | 0.864 |
| 60–65% | 0.954 | 0.925 | 0.909 | 0.885 | 0.825 |
| 65–70% | 0.941 | 0.905 | 0.887 | 0.864 | 0.772 |
| 70–75% | 0.927 | 0.882 | 0.858 | 0.832 | 0.711 |
| 75–80% | 0.906 | 0.853 | 0.829 | 0.792 | 0.639 |
| 80–85% | 0.873 | 0.809 | 0.771 | 0.730 | 0.560 |
| 85–90% | 0.834 | 0.741 | 0.697 | 0.649 | 0.496 |
| 90–95% | 0.593 | 0.642 | 0.574 | 0.538 | 0.433 |
| 95–100% | 0.124 | 0.345 | 0.350 | 0.309 | 0.188 |
| 0–10% | 1.007 | 1.009 | 1.011 | 1.017 | 1.086 |
| 10–20% | 1.002 | 1.004 | 1.004 | 1.006 | 1.029 |
| 20–30% | 0.999 | 0.999 | 0.998 | 0.994 | 0.998 |
| 30–40% | 0.994 | 0.990 | 0.988 | 0.976 | 0.965 |
| 40–50% | 0.986 | 0.975 | 0.971 | 0.949 | 0.929 |
| 50–60% | 0.973 | 0.952 | 0.942 | 0.915 | 0.880 |
| 60–70% | 0.952 | 0.917 | 0.901 | 0.876 | 0.802 |
| 70–80% | 0.922 | 0.871 | 0.847 | 0.816 | 0.677 |
| 80–90% | 0.857 | 0.785 | 0.746 | 0.700 | 0.533 |
| 90–100% | 0.373 | 0.525 | 0.488 | 0.441 | 0.313 |
| 0–20% | 1.005 | 1.007 | 1.008 | 1.013 | 1.063 |
| 20–40% | 0.997 | 0.996 | 0.995 | 0.987 | 0.985 |
| 40–60% | 0.982 | 0.968 | 0.961 | 0.938 | 0.909 |
| 60–80% | 0.943 | 0.904 | 0.886 | 0.858 | 0.753 |
| 80–100% | 0.733 | 0.722 | 0.685 | 0.627 | 0.439 |

Table 1: Numerical values for $R_{\text{AA}}$ versus centrality for various collision systems calculated with HG-PYTHIA as $R_{\text{AA}} = N_{\text{hard}}/(N_{\text{coll}} \langle N_{\text{NN}}^{\text{hard}} \rangle)$.