Suppression of the nuclear modification factor with a hybrid model based on perturbative QCD and hadronic rescattering

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One of the key signatures of the presence of a hot and dense medium in nucleus-nucleus (AA) collisions is the suppression of high transverse momentum (p_{T}) particles with respect to a scaled proton-proton (pp) baseline, quantified by the nuclear modification factor R_{AA}. In this paper, we study R_{AA} predictions from the PYTHIA/Angantyr model coupled to UrQMD as a hadronic cascade simulator and compare to ALICE data from Pb-Pb collisions at √s_{NN} = 2.76 TeV and Xe-Xe at √s_{NN} = 5.44 TeV. This coupling is made possible due to a new implementation of the hadron vertex model in PYTHIA/Angantyr. We find that the high-p_{T} suppression and its subsequent rise at very high momenta may be a consequence of a combination of a violation of binary scaling and hadron cascade dynamics, with the high-p_{T} rise taking place as very high-momentum particles are produced at increasingly displaced positions and interact less with the system. These findings suggest that significant jet-quenching-like effects may still originate in the hadronic, as opposed to the partonic phase.

The ultra-relativistic heavy ion (AA) collisions measured at the LHC and RHIC experiments produce the hottest, densest state of matter available in the laboratory. Such collisions are expected to lead to a deconfined state of quarks and gluons, denoted the Quark–Gluon Plasma (QGP) [1–4]. An important evidence for this phase of matter consists in comparing the yields of high-p_{T} particles produced in AA collisions to that of proton–proton (pp) collisions. Since high-p_{T} particles will be sensitive to partonic energy loss while traversing the QGP, a modification of the high-p_{T} yield in AA collisions compared to pp is in general taken as a sign of a QGP phase. This is quantified by the nuclear modification factor:

\[ R_{AA} = \frac{d^{2}N_{ch}/dp_{T}dy|_{AA}}{N_{coll}d^{2}N_{ch}/dp_{T}dy|_{pp}}, \]  

(1)

where y is the rapidity and N_{coll} is a scaling factor corresponding to the number of binary nucleon–nucleon collisions calculated using the Glauber model [5, 6].

The standard picture of high-p_{T} modification can be phrased in terms of the QGP transport coefficient, which denotes the broadening of the transverse momentum distribution per unit length \( \hat{q} = \langle p_{T}^{2} \rangle_{L}/L \). According to the JETSCAPE approach [7], a high virtuality Q^{2} ≫ \sqrt{E} (where E is the parton energy) will undergo a medium-modified DGLAP evolution [8] and at lower Q^{2} the shower modifications can be calculated by transport theory [9, 10]. The JEWEL approach [11] treats high to intermediate virtuality by a combination of partonic rescattering and the Landau-Pomeranchuk-Migdal effect [12]. In both cases the relevant degrees of freedom are partonic.

Recently, other effects normally associated with the formation of a QGP phase, such as multi-particle flow [13] and enhanced strangeness production [14], were also observed in pp collisions. The discovery that the demarcation between QGP-producing and no-QGP-producing collision systems is not as clear as previously thought should naturally lead to questions regarding the no-QGP baseline used in jet quenching searches in AA collisions. Not only is it unclear that a given pp collision can be taken as a pure baseline result, it is also unclear that an AA collision can be taken as a simple superposition of pp collisions, even without considering QGP effects. It has recently been shown by the ALICE experiment [15] that the charged-particle multiplicity in very central AA collisions breaks the scaling with number of participating nucleons. Furthermore, a correct description of basic quantities must take into account effects not arising from the QGP phase, but rather from nuclear shadowing or diffractive contributions. Additionally, it is well known that compared to pp collisions, the large geometry of an AA collision also potentially allows hadronic rescattering effects to affect relative production rates and kinematics [16], another effect in AA collisions not linked to QGP production.

Dynamical models based on perturbative QCD coupled to either string or cluster hadronization [17–18], have worked very well to describe most features of e^{+}e^{-}, ep and pp collisions. Such models are implemented in so-called General Purpose Monte Carlo event

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I. MODEL SETUP

The PYTHIA/Angantyr+UrQMD hybrid model is outlined in Fig. 1. On the right side of the figure, the standard view on a heavy ion collision is sketched. Importantly, this includes the formation of a strongly coupled, nearly thermal QGP phase. This phase can be described by relativistic hydrodynamics, and is observed to "quench" jets by comparing the single particle yields at high \( p_{\perp} \) to that of \( pp \) collisions. On the left side of Fig. 1, the alternative, QGP free, description is sketched. Instead of assuming the formation of a QGP, that part of the evolution is carried out using just the PYTHIA/Angantyr model, which will be presented below. The right and left sides of Fig. 1 share the final phase of the evolution, consisting of hadronic interactions.

The PYTHIA model for MPIs

In a \( pp \) collision, MPIs are generated under the assumption that different partonic interactions are almost independent. As such, MPIs are selected according to the 2 \( \rightarrow \) 2 perturbative parton–parton cross section:

\[
\frac{d\sigma_{2\rightarrow 2}}{dp_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2) p_{\perp}^4}{p_{\perp}^4 + p_{\perp,0}^4} \rightarrow \frac{\alpha_s^2(p_{\perp}^2 + p_{\perp,0}^2)}{(p_{\perp}^2 + p_{\perp,0}^2)^2}.
\]

Since the cross section diverges like \( 1/p_{\perp}^4 \), it is regularised using a parameter \( p_{\perp,0} \). This value can be interpreted as being proportional to the inverse of a maximal (colour) screening length of a proton. MPIs are interleaved with the initial state and final state parton showers (ISR and FSR), which are also ordered in \( p_{\perp} \). This implies that MPIs, ISR and FSR obey a combined evolution equation that determines the \( p_{\perp} \) of the next step in the evolution, whether that is the generation of a new MPI, and ISR or an FSR emission.

The final step before hadronization concerns color reconnection of partonic systems. The idea originates in the notion that having many MPIs leads to many color strings, which moving from the \( N_c \rightarrow \infty \) limit to \( N_c = 3 \), can be connected in many different ways. Since nature is expected to favour configurations with the lowest potential energy – and thus the smallest total string length – this is the guiding principle for present models. The current default model for color reconnection, the one used in this paper, gives each MPI system a probability to reconnect with a harder system which is:

\[
\mathcal{P} = \frac{p_{\perp,\text{Rec}}^\perp}{p_{\perp,\text{Rec}}^\perp + p_{\perp}^\perp}, \quad p_{\perp,\text{Rec}} = R \times p_{\perp,0},
\]

where \( R \) is a tunable parameter, and \( p_{\perp,0} \) is the same parameter as in Eq. (2). This makes it easier to connect low-\( p_{\perp} \) systems with high \( p_{\perp} \) ones, essentially making high-\( p_{\perp} \) systems "sweep up" some of the low-\( p_{\perp} \) ones.

PYTHIA/Angantyr for heavy ion collisions

In a heavy ion collision, each (projectile) nucleon can interact with several (target) nucleons. The amount of interacting nucleons can be determined by a Glauber model, to which PYTHIA/Angantyr makes several additions. Most importantly, for this paper, there is a distinction between different types of nucleon–nucleon interactions: elastic, diffractive and...
absorptive (ie. inelastic, non-diffractive) sub-collisions. In PYTHIA/Angantyr this is done by parametrizing the nucleon–nucleon elastic amplitude in impact parameter space \( T(\vec{b}) \), and its fluctuations. Details of the parametrization can be studied in ref. [24], but crucially, it allows for a) determination of all parameters from fits to semi-inclusive \( pp \) cross sections, and b) calculation of the amplitude \( T_{kl}(b) \) for any combination of projectile state \( k \) and target state \( l \). Once it is determined which nucleons may interact and their type of interaction, it is then determined if they will interact, and, for absorptive sub-collisions, if the interaction will be considered primary or secondary. This final distinction is based on the wounded nucleon model [32], according to which a wounded nucleon in a \( pA \) or \( AA \) collision contributes to the final state multiplicity as:

\[
\frac{dN_{ch}}{d\eta} = w_p F(\eta) + w_t F(-\eta),
\]

where \( w_i \) denotes the number of wounded nucleons in projectile and target respectively, and \( F(\eta) \) is a single-nucleon emission function (of pseudo-rapidity). For a \( pp \) collision \( w_p = w_t = 1 \). A proton–deuteron collision with all nucleons wounded will thus reduce to a \( pp \) collision, plus an additional wounded nucleon contributing only on the deuteron side. In the language of PYTHIA/Angantyr: one primary absorptive collision and one secondary absorptive collision. The primary collision is modelled as a normal inelastic, non-diffractive collision, whereas the secondary absorptive one is treated with inspiration from the Fritiof model [33]. In Fritiof, a single string with a mass distribution \( \propto dM^2/M^2 \), similar to diffractive excitation, was used. In PYTHIA/Angantyr such sub-systems are allowed to have MPIs in secondary collisions, following the interleaved MPI/shower prescription described above. This procedure can be generalized to an arbitrary \( AA \) collision. In PYTHIA/Angantyr this is done by first ordering all possible interaction in increasing local impact parameter. Going from smallest to largest impact parameter, an interaction is labelled primary if neither of the participating nucleons have participated in a previous interaction and secondary otherwise.

On the conceptual level, there are some differences between \( pp \) events generated with the PYTHIA 8.2 MPI model and \( pA \) or \( AA \) events generated with the PYTHIA/Angantyr model. Most importantly, color reconnection is in PYTHIA/Angantyr only applied at the level of individual nucleon–nucleon collisions. As seen from Eq. (3), the current color reconnection model includes no dependence on impact parameter, but has instead the implicit assumption that a soft MPI will have a large spatial spread, and thus be easier to reconnect. While this may be reasonable for a \( pp \) collision where everything is confined to the transverse size of a single nucleon, it is inappropriate for heavy ion collisions. In that case, possible reconnections across separate nucleon–nucleon interactions are therefore neglected altogether. Other more recent developments in string models, such as color ropes [34] and string shoveling [35], are also not considered in this work. Furthermore the concept of interleaved evolution is also only followed for individual nucleon–nucleon collisions, and not the full \( AA \) collision.

**Hadron production vertices**

After construction of a parton-level event, as outlined above, the color reconnected strings hadronize. This is done using the Lund string hadronization model [17, 36–38], as implemented in PYTHIA 8.2. A string represents the gluonic flux tube stretched between a quark–anti-quark pair. At distances larger than \( \approx 1 \text{ fm} \), the confinement potential is linear \( V(r) = \kappa r \), with the string tension \( \kappa \approx 1 \text{ GeV/fm} \), cf. lattice calculations [39]. As the string grows, energy is transferred from endpoint momenta to potential energy until the string breaks into hadrons [40]. A crucial feature of the Lund model is that the string hadronization time in the string rest frame can be calculated. This time signifies directly the end of the pre-hadronic phase, and start of the hadronic cascade. The hadronization time follows a Gamma distribution with the average:

\[
\langle \tau^2 \rangle = \frac{1 + a}{b\kappa^2},
\]

The two parameters \( a \) and \( b \) also enters the Lund symmetric fragmentation function, which determines the longitudinal momentum fraction taken away from the string by each hadron. As such, they are strongly correlated with total charged multiplicity and momentum fraction, and can be fitted to \( e^+e^- \) collider data. The standard values [41] gives \( \tau^2 \approx 2 \text{ fm}/c \). In order to couple the output from PYTHIA/Angantyr to UrQMD, space–time information of hadron production vertices is necessary. It was recently shown [42] that production vertices of even complicated multi-parton systems can be extracted in the Lund model and implemented in PYTHIA 8.2. The key component of this translation comes from noting that the linear confinement potential gives rise to a linear relationship between space-time and momentum quantities. The space-time location of a string breakup vertex on a simple \( qq \) string can there-
Hadronization rate in PYTHIA

\[ v = \frac{x^+p^+ + x^-p^-}{\kappa}, \]  

where \( p^\pm \) are the \( q \) and \( \bar{q} \) four-momenta, and \( x^\pm \) are (normalized) light-cone coordinates of the break-up point. The production vertex of the hadron is then taken to be the average of the two break-up vertices producing it. It should be stressed that this simple explanation of a \( q\bar{q} \) system does not give justice to the many complications arising from treatment of multiparton geometries, gluon loops, massive quarks or junction topologies, but the reader is referred to ref. [42] for details about complicated systems.

The application to PYTHIA/Angantyr is straightforward. In each nucleon–nucleon collision, each MPI parton is assigned a primordial vertex randomly from the overlap of two 2D Gaussian distributions (the nucleon mass distribution), and each nucleon assigned an overall position in the event according to the initial Glauber simulation.

Coupling to \( rQMD \)

Immediately after hadronization, 99.8% of all particles are propagated using \( rQMD \) 3.4 and may interact elastically and inelastically or decay if unstable, while the remaining 0.2% are treated separately due to technical limitations. Since hadrons containing charm quarks, which correspond to approximately 0.2% of all produced particles, are not adequately treated by \( rQMD \), these particles are exceptionally decayed by PYTHIA and only their decay products are used in the hadronic cascade simulation. Photons and leptons make up 0.01% of all particles produced by PYTHIA/Angantyr and are discarded prior to the simulation of the hadronic phase as they would not be recognized or not interact in \( rQMD \).

A notable difference in this coupling compared to the usual application of \( rQMD \) with hydrodynamics-based event generators is that the latter evolve the system by \( O(10 \text{ fm/c}) \), while PYTHIA/Angantyr provides a significant fraction of final hadrons already after 1-2 \text{ fm/c} \ after the initial hard scatterings even in central collisions, as can be seen in Fig. 2. Another significant distinction is that, while hydrodynamics-based simulation chains produce hadrons at a particlization surface, PYTHIA/Angantyr provides for a position distribution over a three-dimensional volume and considers jet-like physical correlations between space and time that are not taken into account in hydro-based models. Remarkably, in this model, small-\( p_\perp \) hadrons are all created at low radii in central Pb-Pb collisions, high-\( p_\perp \) hadrons will have their production vertices offset from the nucleon–nucleon collision, as can be seen in Fig. 3. Ultimately, all these effects lead to an average hadron density in PYTHIA/Angantyr that is approximately 2-3 times larger than the one observed in hydrodynamic simulations and the resulting hadronic phase lasts significantly longer, as can be seen in the hadron interaction time distribution in Fig. 2. Therefore, the effects of hadronic interactions may be more significant in the PYTHIA/Angantyr+\( rQMD \) simulation chain compared to hydrodynamics-based models.

In order to study simulated events as a function of collision centrality, a number of different options, such as selecting on impact parameter or charged-particle multiplicity in different rapidity ranges, were considered. These options are found to be largely consistent within 0-70% centrality. The analysis is performed with centrality estimated using charged-particle multiplicities calculated for the rapidity range \(-3.7 < \eta < -1.7 \) and \( 2.8 < \eta < 5.1 \), corresponding to the acceptance of the V0M detector of the ALICE experiment and therefore matching what is done in real data analysis. All results presented in what follows were produced using a sample of \( 1.3 \times 10^6 \) Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) generated with the PYTHIA/Angantyr+\( rQMD \) simulation chain.

II. RESULTS

The charged-particle multiplicity density obtained with the full PYTHIA/Angantyr+\( rQMD \) simulation is within approximately 20% of the corresponding ALICE measurements [43], as

![Figure 2. Time \( \tau = \sqrt{t^2 - x^2} \) distribution of hadrons created by PYTHIA/Angantyr in 0-5% central Pb-Pb collisions at 2.76 TeV shown together with the time distribution of \( rQMD \) scatterings (solid symbols).](image-url)
shown in Fig. 4. In order to isolate the effect coming from hadronic scattering, the simulation is also re-run with interactions disabled, leading to no more than a 2-3% difference in charged-particle multiplicity densities and therefore no significant change in how simulations compare to data.

The effect of the hadronic phase can be further characterized by calculating the $p_{\perp}$ distributions of identified particle spectra, shown in Fig. 5 for various centrality classes.

The effect of hadronic interactions can be quantified by calculating the ratio of the $p_{\perp}$ distributions obtained with and without scatterings, as seen in Fig. 6. While yields are modified by no more than 10-15% below 2 GeV/c, the effect is more pronounced at mid- to high-$p_{\perp}$, with a maximum suppression of 60% taking place at approximately 5 GeV/c for 0-10% collisions. The suppression due to hadronic interactions becomes progressively smaller for higher $p_{\perp}$ and more peripheral collisions.

The results seen in Fig. 6 are reminiscent of the suppression of high-$p_{\perp}$ particles seen in the nuclear modification factor $R_{AA}$. To calculate the $R_{AA}$ from the PYTHIA/Angantyr+UQMD model, pp collisions were generated using the exact same settings and simulation chain and the average number of binary collisions $N_{\text{coll}}$ is assumed to be the one calculated by the ALICE Collaboration using the Glauber model [44]. The simulated $R_{AA}$ with and without hadronic interactions can be seen in Fig. 7 for Pb-Pb at $\sqrt{s_{\text{NN}}} = 5.02$, respectively, for two selected centrality classes. With interactions disabled, the model overestimates the $R_{AA}$ at mid- and high-$p_{\perp}$, especially for central collisions, while data and simulation are within uncertainties of each other for 6 GeV/c $< p_{\perp} < 30$ GeV/c when interactions are enabled.

In order to determine if the agreement of the high-$p_{\perp}$ $R_{AA}$ between simulation and measurement is coincidental, we perform the same calculation for Xe-Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV, shown in Fig. 8. Also in this case, the PYTHIA/Angantyr+UQMD model succeeds in describing measurements within uncertainties for 6 GeV/c $< p_{\perp} < 30$ GeV/c.

III. CONCLUSION

The successful description of the nuclear modification factor for the intermediate $p_{\perp}$ region from around 6 GeV/c to around 30 GeV/c by PYTHIA/Angantyr+UQMD is a significant
As explained in the introduction, values for $R_{AA}$ below unity are generally taken as a clear indication of QGP formation, and models incorporating QGP formation are, as a general rule, needed to describe the data. In PYTHIA/Angantyr+UrQMD there is no assumption of a QGP phase, but nevertheless several effects contribute to the description of $R_{AA}$.

The high-$p_T$ part of the spectra generated by PYTHIA/Angantyr deviates from the simple binary scaling which is normally expected [6], as seen also in the fact that the $R_{AA}$ is constant but below unity for high $p_T$ even without hadronic interactions. As previously explained, PYTHIA/Angantyr makes a distinction between various types of nucleon–nucleon interactions, which will contribute differently to high-$p_T$ particle yields, and as a result the high-$p_T$ $R_{AA}$ does not converge to unity even if hadronic interactions are disabled. This effect is responsible for the majority of the deviation from unity, as seen in Fig. 7. There are, however, model uncertainties associated with this effect. While the treatment of secondary absorptive sub-collisions similar to diffractive excitations can be theoretically and numerically motivated [24], it is, as mentioned earlier, not clear that it will exactly reproduce the phenomenology of an interleaved shower plus color reconnection. An obvious next step would be to study the (absence of) nuclear modification in p-Pb collisions within PYTHIA/Angantyr+UrQMD. However, in that case, model uncertainties are much larger than in $AA$ collisions. It was shown in ref. [24] that secondary collisions contribute between 25-40% in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, while for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV they contribute between 50-85%.

An equally important conclusion from this work is the influence of the hadronic rescattering phase on $R_{AA}$. Since strings have an average life-time $\langle \tau^2 \rangle \approx 2$ fm/c, the hadronic phase is longer, and with a more dense initial condition, than for hydrodynamic simulations where a QGP phase lives for up to an order of magnitude longer. We have shown that a hadronic rescattering phase with such an early starting time modifies $R_{AA}$ up to a factor 3 for intermediate $p_T$ particles in central Pb-Pb events. From this model, we can interpret that at intermediate $p_T$, hadronic interactions lead to a suppression of particle yields as hadrons lose significant momentum to more abundant low-$p_T$ particles. However, this effect subsides for very large transverse momentum, such that the $R_{AA}$ will eventually converge to the value without hadronic interactions. This is because, in the hadron vertex model, higher-$p_T$ values correlate with more displaced hadron creation vertices due to the linear relationship between space-time and momentum in Eq. (6), visible result.
also in Fig. 3. Since higher-$p_{\perp}$ particles are then increasingly displaced, these are less likely to interact with the remainder of the system. While this effect is smaller in magnitude than the deviation from binary scaling, it is crucial to recover the minimum of the nuclear modification factor at around 5 GeV/$c$ and the subsequent rise at high momenta. It should be noted here that the main model uncertainty in this part lies in the determination of the vertex position. The relation in Eq. (6) leads directly to a hadron production point as the average of two subsequent break-up points. As noted in ref. [42], this definition is not unique, but could differ from the average up to $\pm p_h/2\kappa$, where $p_h$ is the hadron four-momentum. Taking this at face value, the uncertainty of the final value for $R_{AA}$ would be large enough that the high-$p_{\perp}$ rise is not visible within uncertainties.

It has to be noted that the intermediate to high-$p_{\perp}$ suppression studied in this paper is fundamentally different than the one that would result from models such as JETSCAPE or JEWEL. In the latter, jet quenching is a phenomenon associated to partonic energy loss, which would lead to the suppression of an entire high-momentum jet, while in the former, individual hadrons lose momentum after hadronization. Experimentally, these two scenarios can be distinguished using techniques such as two-particle correlations and dijet asymmetry measurements. The findings of this paper prompts present and future experimental studies to put more emphasis on such techniques, as well as including a full no-QGP baseline for comparison.

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