Centrality dependence of high energy jets in $p+\mathrm{Pb}$ collisions at energies available at the CERN Large Hadron Collider

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The recently measured centrality dependence of high energy jets in proton-lead collisions at the CERN Large Hadron Collider (LHC) is investigated. We hypothesize that events with jets of very high energy (a few hundred GeV) are characterized by a suppressed number of soft particles, thus shifting these events into more peripheral bins. This naturally results in the suppression (enhancement) of the nuclear modification factor, R_{pA}, in central (peripheral) collisions. Our calculations suggest that a moderate suppression of the order of 20%, for 10^3 GeV jets, can quantitatively reproduce the experimental data. We further extract the suppression factor as a function of jet energy and test our conjecture using available R_{pA} data for various centralities.

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I. INTRODUCTION

Jet physics has proved to be very useful in uncovering properties of the hot medium created in heavy-ion ($A+A$) collisions [1]. A valuable baseline to study jet quenching in $A+A$ collisions is provided by proton-nucleus ($p+A$) collisions, where final state effects in the hot medium are expected to be suppressed. However, recent results on the centrality dependence of high energy jets in proton-lead ($p+\mathrm{Pb}$) collisions at the CERN Large Hadron Collider (LHC) seem to challenge our understanding of jet physics in nuclear reactions.

To characterize the centrality dependence of jet production in $p+A$ collisions and to compare to baseline proton-proton ($p+p$) collisions, one usually relies on the nuclear modification factor defined as

$$R_{pA} = \frac{1}{\langle N_{\mathrm{coll}}\rangle} \frac{dN_{\mathrm{jet}}^{pA}/dp_{\perp}dy}{dN_{\mathrm{jet}}^{pp}/dp_{\perp}dy}, \tag{1}$$

where $\langle N_{\mathrm{coll}}\rangle$ is the number of nucleon-nucleon collisions and $dN_{\mathrm{jet}}/dp_{\perp}dy$ is the average number of jets in $p+p$ or $p+A$. Both $\langle N_{\mathrm{coll}}\rangle$ and $dN_{\mathrm{jet}}^{pA}/dp_{\perp}dy$ are computed at a given centrality. R_{pA} provides a quantitative value of the nuclear modification of the jet production rate relative to $p+p$ collisions, and deviations of R_{pA} from unity indicate nontrivial nuclear effects. Following experimental collaborations, we will also consider the ratio of central-to-peripheral R_{pA}, defined as

$$R_{cp} = \frac{R_{pA}|_{\mathrm{cent.}}}{R_{pA}|_{\mathrm{periph.}}}. \tag{2}$$

For jets of high transverse momenta, R_{pA} is expected to be close to unity based on perturbative QCD. A review of quantitative predictions is given in Ref. [2].

Recently the ATLAS Collaboration reported the dependence of the jet R_{pA} on centrality, rapidity, and transverse momentum [3]. Here we provide a brief overview of their findings. The measurements were performed for jets of very high $p_{\perp}$ and energies ranging from 40 to roughly 2000 GeV. The main points are the following:

(a) R_{pA} is consistent with unity for minimum bias collisions (the centrality class 0–90%) and does not demonstrate any systematic dependence on rapidity and transverse momentum.
(b) For proton-going rapidities ($y>0$), $R_{pA}<1$ in central collisions and $R_{pA}>1$ for peripheral ones. The effect increases as a function of the jet transverse momentum and energy.
(c) For backward rapidities (nucleus-going), R_{pA} for $y<-0.8$ shows little dependence on transverse momentum and centrality, and is consistent with unity.
(d) R_{pA} of jets with $y>0$ approximately scales only with the total jet energy.

Recently the PHENIX Collaboration studied the bias from the increased multiplicity of the underlying event when a hard trigger particle is present [4]. Its effect on R_{pA} is 5% or less in central events at Relativistic Heavy Ion Collider (RHIC) energy and 20% at LHC energy. However, it enhances R_{pA} in central events, and is thus opposite to the effect observed by ATLAS.

Alternatively, color fluctuations have been discussed as having an influence on the correlation between a hard trigger and the number of binary collisions in $p+A$ collisions [5,6]. Also, it has been argued that centrality estimators based on multiplicity measurements introduce a bias on the hardness of the $p+N$ collisions such that low multiplicity $p+A$ corresponds to lower than average number of hard scatterings [7].

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After our manuscript was submitted to the journal several researchers studied different effects on jet observables. For example in [8] the effect of energy momentum conservation was reported. The energy loss in cold nuclear matter was investigated in [9]. In neither of these approaches can the authors reproduce the enhancement of R_{pA} in peripheral collisions, which is the key feature of the ATLAS data. The impact of a positive correlation between the hard scattering and the underlying event multiplicity was also investigated in [10].

We will argue that the surprising observations of the ATLAS experiment can be naturally understood assuming that events with jets of very high energy (a few hundred GeV) are characterized by a suppressed number of soft particles. We would like to illustrate this idea in an extreme case. Let us assume that events with high energy jets are characterized by a strong suppression of soft particle production, so that the number of soft particles is of order 1. Possible mechanisms of this suppression are of no relevance for this illustration and will be discussed at the end of this article. In the case of this strong suppression, all events with high energy jets will be counted as the most peripheral ones, by the usual procedure of centrality definition based on minimum bias events (the most central events are defined as events with the largest number of soft particles). By construction, no jet events would fall into the most central class and R_{pA} for central collisions will be exactly zero. All events with high energy jets are counted as peripheral, independently of the number of participants, and in this case $R_{pA} > 1$. It is also important to note that, in minimum bias events, the suppression of soft particle production does not influence R_{pA} and consequently $R_{pA} = 1$, unless there is another mechanism that modifies R_{pA}.

In the following we discuss our model and present quantitative results for R_{pA}. We argue that a moderate suppression of soft particle production of the order of 20%, for the highest measured jet energies, allows to understand the data. Further we extract the suppression factor as a function of jet energy and test our hypothesis using available R_{pA} data for various centralities.

We finish with a discussion of possible mechanisms and conclusions.

II. MODEL

In this article we assume the presence of anti-correlation between soft and very hard particle production, characterized by the suppression of soft particles in events with high energy jets. We introduce the suppression in a general way, independently of the microscopic details of this effect, and demonstrate its effect on R_{pA} and R_{cp}. The main points of our approach are listed below.

(i) Using the standard Glauber model [11], we evaluated the number of inelastic nucleon-nucleon collisions, $N_{\rm coll}$, in each $p+\mathrm{Pb}$ event. The distribution of nucleons inside a Pb nucleus is given by the standard Woods-Saxon distribution. The nucleon-nucleon inelastic cross section is taken to be 70 mb [12].

(ii) We introduce the parameter $\epsilon \ll 1$, the probability of producing a high energy (or transverse momentum) jet in a *single* nucleon-nucleon interaction. It is evident that, in $p+\mathrm{Pb}$ events with large $N_{\rm coll}$, the probability of producing a jet of high energy is larger. Mathematically, this probability is given by[1]

$$1-(1-\epsilon)^{N_{\rm coll}} \approx \epsilon N_{\rm coll}, \tag{3}$$

where we assume that $\epsilon N_{\rm coll} \ll 1$ to make our point clear. Naturally, the value of ϵ depends on the jet energy, $E_{\rm jet}$: the higher $E_{\rm jet}$ the smaller the value of ϵ. For high energy jets (so that the probability of producing more than one dijet is negligible) ϵ can be related to the jet yield according to $\epsilon(p_\perp,y) \propto \Delta p_\perp \Delta y dN_{\rm jet}/dydp_\perp$, where $\Delta p_\perp$ and Δy are narrow $p_\perp$ and y bins around the measured $p_\perp$ and y. Consequently, the probability of producing a high energy jet is given by $\epsilon \propto \int dydp_\perp dN_{\rm jet}/dydp_\perp$, where the integration is over high values of $E_{\rm jet}$. In this article we are interested in jets with energies of order 1000 GeV, thus indeed ϵ is much smaller than 1.

(iii) Now we determine the number of soft particles produced in a $p+\mathrm{Pb}$ collision. In our model, the mean number of soft particles scales linearly with the number of wounded nucleons [13,14], $N_{\rm part} = N_{\rm coll}+1$. Possible deviations from this assumption, for instance originating from gluon saturation (see, e.g., [15]), do not change our conclusions. We further assume that each participant populates soft particles according to a negative binomial distribution (NBD), which is known to approximate well measured multiplicity distributions in $p+p$ interactions. The parameters of the NBD are chosen as follows: in an event without a high energy jet the parameters for each participant are $\langle n_{pp}\rangle/2$ and $k_{pp}/2$ (so that in $p+p$ we have $\langle n_{pp}\rangle$ and k_{pp}), where $\langle n_{pp}\rangle$ and k_{pp} are taken from fits to proton-proton collisions. In our calculation we use $\langle n_{pp}\rangle = 5$ and $k_{pp} = 1.1$. In an event with a high energy jet we assume that the mean number of soft particles from each participant is reduced by a factor of s as follows:

$$\langle n_{pp}\rangle \to \langle n_{pp}\rangle(1-s). \tag{4}$$

Clearly $0 \leqslant s \leqslant 1$, ranging from no suppression to the total suppression of soft particle production in events with high energy jets. The suppression factor s is a growing function of energy or transverse momentum of a jet. The dependence of s on jet energy will be discussed later.

(iv) Finally, we compute the centrality classes using the minimum bias multiplicity distribution with $s = 0$ ($s > 0$ for events with jets would not change the centrality cuts since the probability of producing a high energy jet, ϵ, is very small) and for each

[1] $1-\epsilon$ is the probability that no high-energy jet is produced in a single nucleon-nucleon scattering. Thus $(1-\epsilon)^{N_{\rm coll}}$ is the probability that no jet is produced in $N_{\rm coll}$ nucleon-nucleon scatterings. Consequently, Eq. (3) is the probability of producing at least one jet in $p+A$ interactions with $N_{\rm coll}$ nucleon-nucleon scatterings.

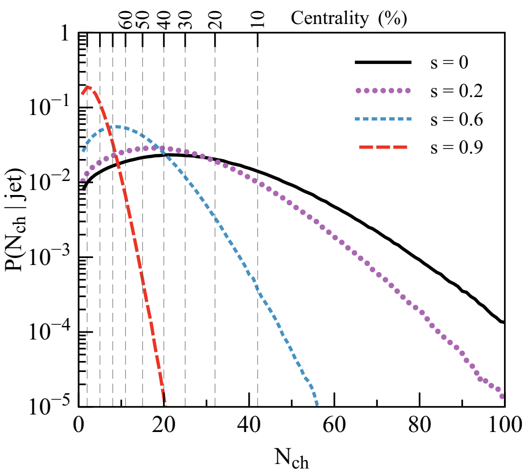

FIG. 1. The probability distribution of the number of charged particles for events with high energy jets $P(N_{\mathrm{ch}}|\mathrm{jet})$ for the different suppression factors s. The centrality classes are defined according to the minimum bias probability distribution.

centrality calculate R_{pA} as a function of the suppression factor s.[2]

III. RESULTS

The results of our model calculation are presented in Figs. 1 and 2. It is worth noting that the results do not depend on the value of ϵ, provided $\epsilon N_{\mathrm{coll}}$ is much smaller than 1. The only physics that can modify R_{pA} is the postulated suppression of soft particle production and thus R_{pA} depends only on s.[3]

In Fig. 1 we show the multiplicity distribution of charged particles produced in events with jets. The indicated centrality classes are computed from the minimum bias multiplicity distribution at $s = 0$ and are unchanged throughout our analysis. The suppression $s > 0$ modifies the multiplicity distributions by shifting them into more peripheral classes, as we discussed before.

This figure illustrates our mechanism. It is clear that jet events with, say, $s = 0.9$ are unlikely to be classified as central ones and most likely will be classified as most peripheral. Thus R_{pA} for the 0–10% class is practically zero and is larger than 1 for the peripheral centrality class.

As illustrated in Fig. 2, the case with no suppression results in $R_{pA} = 1$, because our model does not account for physics beyond soft particle suppression. For $s > 0$ we observe the expected enhancement for peripheral collisions and suppression for central events. For larger values of $s \to 1$ (strong suppression of soft particle production) we reach the limit where all events are classified as peripheral and $R_{pA} \to 0$ for all bins, except the most peripheral one.

The ATLAS data [3] are in qualitative agreement with the results from our Fig. 2.

To further check the model, we performed a fit of the available data for R_{cp} (the ratio of 0–10% to 60–90%) as a function of $E_{\mathrm{jet}} = p_\perp \cosh(y)$ for proton-going rapidities to extract the dependence of the suppression factor on E_{jet}. This is illustrated in Fig. 3. We conclude that the current data for jets of 1000 GeV can be understood with a moderately low suppression factor of the order of 0.2. Having extracted $s(E_{\mathrm{jet}})$ we can confront the model with the available experimental

[2]To determine centrality, ATLAS uses the energy deposited in the forward region of the Pb-going side, whereas in our studies we use the number of soft particles as a proxy for the same.

[3]We explicitly checked that our results are practically unchanged for values of ϵ ranging from 10^{-3} to 10^{-5}.

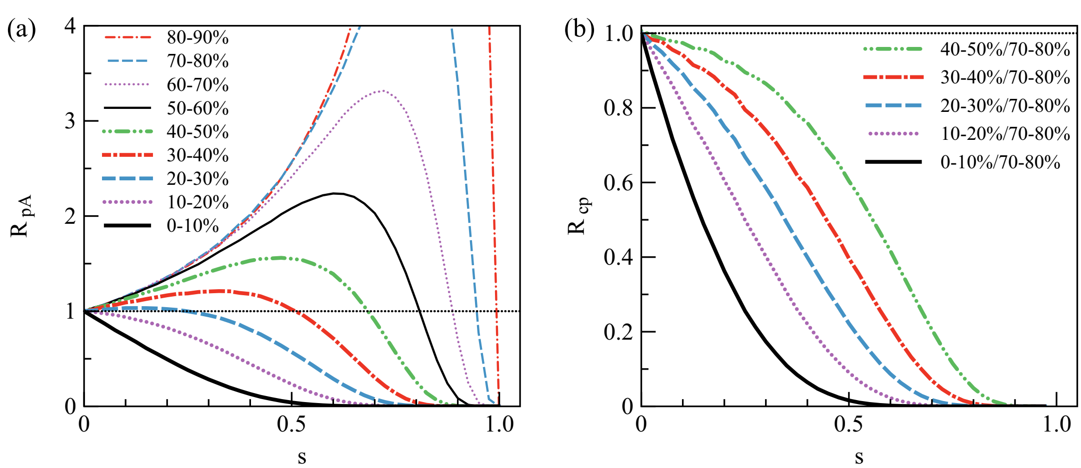

FIG. 2. (a) The nuclear modification factor R_{pA} in $p + \mathrm{Pb}$ collisions as a function of the soft particle suppression factor s, see Eq. (4), for various centrality classes defined by the number of soft particles in minimum bias events. (b) The central-to-peripheral ratio R_{cp}, Eq. (2), where the peripheral class is taken to be 70–80% centrality, as a function of the suppression factor s. In our model events with high energy jets are characterized by a suppressed number of soft particles, thus shifting these events into more peripheral bins. This naturally results in the suppression (enhancement) of R_{pA} in central (peripheral) collisions, respectively. The suppression factor is expected to grow with jet energy or transverse momentum.

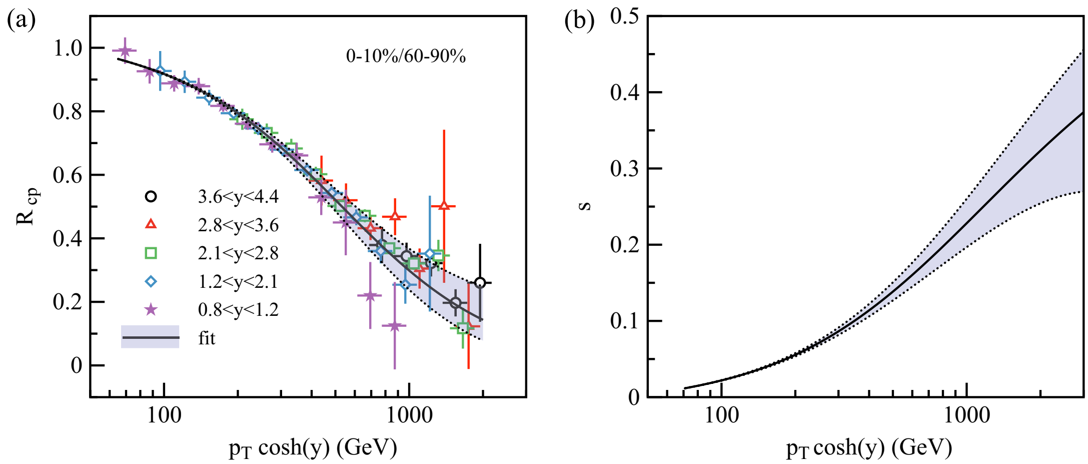

FIG. 3. (a) The experimental data [3] for R_{cp} (the ratio of 0–10% central to 60–90% peripheral) as a function of $E_{\rm jet} = p_\perp \cosh(y)$ at different values of rapidity. The black line and the shaded area shows our fit with uncertainties. (b) The corresponding suppression factor s dependence on $E_{\rm jet}$ extracted from the experimental data shown in the left plot.

data on R_{pA}. In Fig. 4 we compare our model with R_{pA} as a function of $p_\perp$ in the jet rapidity range $2.1 < y < 2.8$ for three different centrality classes. We observe satisfactory agreement. We would like to emphasize that we extracted $s(E_{\rm jet})$ from the ratio of 0–10% to 60–90% R_{pA}. But this does not guarantee that the denominator and the numerator separately are correctly described by the model. In fact, as seen in Fig. 4, the description of the data is not ideal.

IV. DISCUSSION

To this point, we entertained the idea of suppression of soft particle production in events with high energy jets without providing a possible mechanism for this suppression. We want to stress that the problem at hand is highly nontrivial since it couples large (jets) and small (soft particles) x physics, which is under poor theoretical control. Here, we will speculate about a possible mechanism that naturally explains the forward-backward rapidity dependence of the ATLAS result. Let us consider the nuclear wave function as a function of x. Originally large x partons evolve towards smaller x by splitting (into smaller x partons). During a collision the partons are liberated and eventually form final-state particles. To produce a very large energy jet close to mid-rapidity, the nuclear wave functions of both colliding objects should contain a large x parton that suffered almost no splittings owing to a rare fluctuation in the evolution. Since in a projectile proton one of the large x partons is effectively removed from the evolution, it cannot contribute to the production of small x partons, and this results in the suppression of soft particle production. Thus the events with high energy jets effectively remove a large x parton from a projectile proton, with the energy proportional to the energy of the jet. Consequently, for jets of very high energy, we expect the reduction of soft particles to be roughly 1/3 in agreement with our previous discussion.

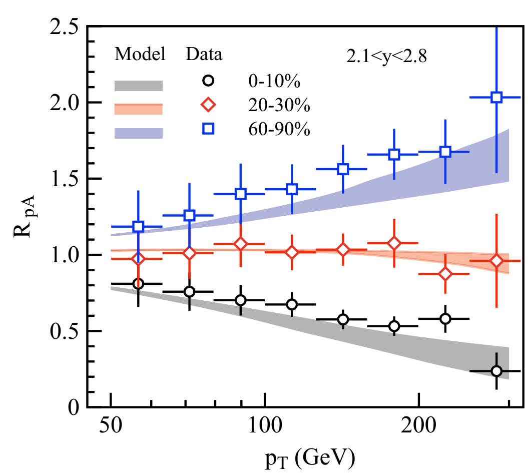

FIG. 4. The comparison of the model results (bands) with the experimental data [3] (points) on R_{pA} as a function of $p_\perp$ in the rapidity range $2.1 < y < 2.8$ for three centrality classes.

The suggested mechanism of the suppression of soft particle production, in events with high energy jets, depends on the amount of energy removed from a projectile proton and thus should depend on the energy of a jet. This could explain the observed scaling of R_{pA} and R_{cp} with energy for different values of rapidity and transverse momentum. For a jet going into the forward direction (proton-going side) we expect the suppression to be stronger: in order to produce such a jet one needs to remove a large x parton from a proton, whereas jets going into the nucleus direction would require a large x parton from a nucleus wave function. The latter does not activate the mechanism of suppression of soft particle production. Removing a large x parton form a nucleus can easily be neglected since the number of participants is of the order of 10.

Very recently similar experimental results were obtained in deuteron-gold (d + Au) collisions at RHIC [16]. It would be interesting to repeat our calculations in d + Au, and in particular to test whether the PHENIX data could be described with a similar suppression factor as presented in Fig. 3.

V. SUMMARY

In conclusion, we propose a mechanism explaining the recently observed dependence of R_{pA} and R_{cp} on centrality in $p + A$ collisions. We show that a possible suppression of soft particles in events with high energy jets naturally leads to the observed suppression (enhancement) of R_{pA} in central (peripheral) collisions. We found that a moderate soft particle suppression of the order of 20% can provide a quantitative understanding of the ATLAS data. We compared the model with the data and found satisfactory agreement.

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