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Dijet azimuthal correlations in p-p and p-Pb collisions at forward LHC calorimeters

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Abstract: We present a state-of-the-art computation for the production of dijets in proton-proton and proton-lead collisions at the LHC, in forward rapidity domains covered by the ATLAS calorimeter and the planned FoCal extension of the ALICE detector. We use the small-x improved TMD (ITMD) formalism, together with collinearly improved TMD gluon distributions and full b-space Sudakov resummation, and discuss nonperturbative corrections due to hadronization and showers using the Pythia event generator. We observe that the production of forward dijets in proton-nucleus collisions at moderately low p_T is an excellent probe of saturation effects, and demonstrate that the Sudakov resummation does not alter the suppression of the cross section.

Keywords: Deep Inelastic Scattering or Small-x Physics, Quark-Gluon Plasma

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1 Introduction

A current experimental challenge in Quantum Chromodynamics (QCD) is the search for clean signals of gluon saturation, i.e. gluon recombination in dense nuclear systems. Gluon saturation has been predicted from QCD long time ago [1] and has been systematically studied over the years, in particular using the Color Glass Condensate (CGC) effective theory (see e.g. [2]). Although there is no doubt that the growth of gluon distributions has to be tamed at some point due to the unitarity of the scattering matrix, and while there are strong hints for the occurrence of saturation in data [3–10] (see [11] for a review), there is no full consensus on how the very small x limit is reached. Moreover, Balitsky-Fadin-Kuraev-Lipatov (BFKL) dynamics [12, 13] is expected to manifest itself even before the onset of saturation dynamics in processes like Mueller-Navelet jet production [14–16], heavy quark production at mid rapidities [17] (see also [18] for recent developments), inclusive processes [19], or central-forward inclusive jets at the LHC [20–22].

However, there is an important difference between BFKL and saturation physics, which could potentially allow for saturation to be seen more directly. Saturation phenomena are described by high energy evolution equations, such as the Balitsky-Kovchegov (BK) [23, 24] or the B-JIMWLK equations [23, 25–31]. These are similar to the BFKL evolution equations, but include nonlinear terms that tame the growth of gluon distributions. The strength of these nonlinear terms depends on the target size; for large systems with A nucleons it is expected to be enhanced by roughly $A^{1/3}$. Therefore, comparing observables computable within the high energy QCD limit for protons and for large nuclear targets is potentially the best way to find evidence for saturation. One example is the suppression of the cross section for the forward production of π^0 mesons in p+A collisions that was recently reported in [32], providing a strong hint for saturation. Nontheless, it is important to mention that there might be other mechanisms leading to a suppression of nuclear parton distribution functions (PDFs), notably the so-called leading twist nuclear shadowing [33] within collinear factorization. However, at present its connection to saturation is unclear, although one has to keep in mind that saturation in dijet production is also a leading power effect.

In our work, we are interested in dijet final states as a probe of saturation in hadroproduction (see [34–39] for earlier works on this subject). We thus require the final state partons to have rather large transverse momenta P_T. Naturally, the scale set by the jets is larger than the saturation scale but not asymptotically larger, so that saturation effects cannot be neglected. Such limit is well defined within the CGC theory, and is precisely the leading power limit $k_T/P_T \ll 1$, where k_T is the dijet imbalance [40]. In our computations we go beyond the leading power, by including the kinematic twists. Such an approach gives more precise predictions for dijet correlation spectra. The adequate formalism is known as the small-x improved Transverse Momentum Dependent (ITMD) factorization [41, 42] (for further developments of both the ITMD and the leading power limit see [43–53]).

The description of dijet imbalance observables requires to perform a suitable resummation of the Sudakov logs. This can be done in at least two ways. A first method relies on including the Sudakov form factor as a source of the hard scale evolution, similar to what is being done in parton shower algorithms. Such an approach has been used for instance in [38, 54–56]. Another approach relies on the soft gluon resummation technique in b-space [57, 58], which in general provides resummation beyond simple double Sudakov logs (see e.g. [9, 59, 60]). In this paper, we apply the full b-space resummation approach, as a current state-of-the-art result.

Forward jets have been measured at LHC, however with inconclusive results regarding saturation. For example, the CMS-CASTOR calorimeter [61] was used to measure single inclusive jets [62] in proton-lead collisions, but the lack of an analogous study in proton-proton collisions makes it very difficult to assess if saturation is present. This is mainly due to the fact that all saturation-based calculations are performed on parton-level and thus the comparison with data is burdened with large uncertainties [63–65]. Furthermore, the ATLAS collaboration measured forward-forward and forward-central dijets [66] in both proton-proton and proton-lead collisions, but no measurement of the absolute cross section or nuclear modification ratio was provided. The observed nuclear broadening was claimed to be negligible w.r.t. uncertainties, despite being consistent with saturation and Sudakov resummation [56]. Finally, the CMS collaboration recently measured exclusive dijet production [67] in ultra-peripheral collisions, where, again, only the photon-lead sample is studied, without a photon-proton reference. Interestingly, a comparison with a Monte Carlo describing the photoproduction on proton targets seems to imply strong nuclear broadening.

In the present work we provide predictions for a new study of forward dijets with ATLAS FCal kinematics, as well as for the planned FoCal upgrade of ALICE [68], assuming that both proton-proton and proton-lead cross sections will be measured. Our paper is organized as follows. In the next section we briefly review the ITMD framework and modify it accordingly to include the Sudakov resummation. Next, in section 3, we specify our kinematic cuts in detail and present our results. We delegate the discussion of the results to section 4.

2 Small-x improved TMD factorization

The ITMD factorization formula for the production of two jets reads as follows:

$$\frac{d\sigma^{\mathrm{pA}\to j_1 j_2+X}}{d^2P_T d^2k_T dy_1 dy_2} = \sum_{a,c,d} x_{\mathrm{p}} f_{a/\mathrm{p}}\left(x_{\mathrm{p}},\mu\right) \sum_{i=1}^{2} \mathcal{K}^{(i)}_{ag^*\to cd}\left(P_T,k_T;\mu\right) \Phi^{(i)}_{ag\to cd}\left(x_{\mathrm{A}},k_T\right) , \qquad (2.1)$$

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where we define $\vec{P}_T = \vec{p}_{T1} - \vec{p}_{T2}$ and $\vec{k}_T = \vec{p}_{T1} + \vec{p}_{T2}$ for jets with transverse momenta $\vec{p}_{T1}$ and $\vec{p}_{T2}$, with y_1 and y_2 being the jet rapidities. The longitudinal fractions of partons extracted from proton and nucleus are, respectively, $x_{\rm p}$ and x_A. Equation (2.1) applies to the region where $x_A \ll x_{\rm p}$. Furthermore, $f_{a/{\rm p}}$ are collinear PDFs, $\mathcal{K}_{ag^*\to cd}$ are off-shell gauge invariant hard factors and $\Phi^{(i)}_{ag\to cd}$ are the TMD gluon distributions that correspond to distinct color flows for each partonic channel. The hard factors and the TMD gluon distributions were computed in [41].

The resummation of the Sudakov logarithms is performed following the perturbative calculation presented in [57]. That calculation was done in impact parameter space (the impact parameter b_T is the Fourier conjugate to the gluon k_T) and in the back-to-back regime, that is to leading power. Since the Sudakov factors are negligible for $k_T \sim P_T$, the calculation can be straightforwardly extended to the ITMD formula (2.1).

$$\frac{d\sigma^{{\rm pA}\to j_1 j_2 + X}}{d^2P_T d^2k_T dy_1 dy_2} = \sum_{a,c,d} x_{\rm p} \sum_{i=1}^{2} \mathcal{K}^{(i)}_{ag^*\to cd}(P_T, k_T; \mu) \times \int db_T b_T J_0(b_T k_T) f_{a/{\rm p}}(x_{\rm p}, \mu_b)\, \widetilde{\Phi}^{(i)}_{ag\to cd}(x_{\rm A}, b_T)\, e^{-S^{ag\to cd}(\mu, b_\perp)}, \tag{2.2}$$

where $\widetilde{\Phi}^{(i)}_{ag\to cd}$ is the Fourier transform of the TMD gluon distributions and $S^{ag\to cd}$ are the Sudakov factors defined below. The scale μ_b is essentially the inverse of the impact parameter:

$$\mu_b = 2e^{-\gamma_E}/b_* \tag{2.3}$$

with

$$b_* = b_T/\sqrt{1 + b_T^2/b_{\rm max}^2}\,. \tag{2.4}$$

With such a choice, the scale μ_b freezes in the limit of large b_T, where it takes the value $2e^{-\gamma_E}/b_{\rm max} \gg \Lambda_{\rm QCD}$. Following ref. [69], in our calculation we shall use the value $b_{\rm max} = 0.5\,{\rm GeV}^{-1}$.

For each channel, the Sudakov factors can be written as

$$S^{ab\to cd}(\mu, b_\perp) = \sum_{i=a,b,c,d} S^i_p(\mu, b_\perp) + \sum_{i=a,c,d} S^i_{np}(\mu, b_\perp), \tag{2.5}$$

where S^i_p and S^i_{np} are the perturbative and non-perturbative contributions. It was argued in ref. [60], that the non-perturbative Sudakov should not be included for a small-x parton b. The perturbative Sudakov factors, including double and single logarithms, are given by [57, 58]

$$S^{qg\to qg}_p(\mu, b_\perp) = \int_{\mu_b^2}^{\mu^2} \frac{dq_T^2}{q_T^2}\left[2(C_F + C_A)\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu^2}{q_T^2}\right) - \left(\frac{3}{2}C_F + C_A\beta_0\right)\frac{\alpha_s}{\pi}\right], \tag{2.6}$$

$$S^{gg\to gg}_p(\mu, b_\perp) = \int_{\mu_b^2}^{\mu^2} \frac{dq_T^2}{q_T^2}\left[4C_A\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu^2}{q_T^2}\right) - 3C_A\beta_0\frac{\alpha_s}{\pi}\right], \tag{2.7}$$

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where $\beta_0 = (11 - 2n_f/N_c)/12$. The $gg \to q\bar{q}$ channel is negligible for the kinematic domain of this study.[1]

We note that in (2.2) the collinear PDF depends on the impact parameter. This complicates the Monte Carlo implementation of the factorization approach. Therefore we investigate a choice of the factorization scale, which is independent on b_T. As argued for example in [71] this formally introduces a threshold-type logarithmic term. The real impact of this term in the kinematic domain under study is however difficult to judge, without concrete computations. Setting $\mu_b = \mu$, the collinear PDF factorizes outside the b-space integral and we can define the hard scale-dependent TMD gluon distribution as

$$\Phi^{(i)}_{ag\to cd}(x, k_\perp, \mu) = \int db_\perp \int dk'_\perp \, b_\perp \, k'_\perp \, J_0(b_\perp \, k'_\perp) \, J_0(b_\perp \, k_\perp) \\ \times \mathcal{F}_{g^*/B}(x, k'_\perp) \, e^{-S^{ag\to cd}(\mu, b_\perp)} \, . \tag{2.8}$$

The above TMD gluon distribution can then be straightforwardly used in the ITMD factorization formula (2.1). The hard scale μ in the dijet production process is provided by the jet transverse momentum. Specifically, in our computations we shall use the the average p_T of the two leading jets.

In order to compare the above approach to the full b-space resummation, we apply the following *reweighting* procedure, that can be relatively easily implemented in a Monte Carlo program (see for example [72]). First one generates events in the simplified approach with $\mu_b = \mu$. Then, just for the generated space phase points, one calculates the following quantity:

$$\left(f_{a/\mathrm{p}} \otimes \Phi^{(i)}_{ag\to cd}\right)(x_\mathrm{p}, x, k_\perp, \mu) = \int db_\perp \int dk'_\perp \, b_\perp \, k'_\perp \, J_0(b_\perp \, k'_\perp) \, J_0(b_\perp \, k_\perp) \\ \times f_{a/\mathrm{p}}(x_\mathrm{p}, \mu_b) \, \mathcal{F}_{g^*/B}(x, k'_\perp) \, e^{-S^{ag\to cd}(\mu, b_\perp)} \, . \tag{2.9}$$

Finally, in order to obtain the full b-space resummation, one reweighs the events with a ratio

$$\frac{\left(f_{a/\mathrm{p}} \otimes \Phi^{(i)}_{ag\to cd}\right)(x_\mathrm{p}, x, k_\perp, \mu)}{f_{a/\mathrm{p}}(x_\mathrm{p}, \mu) \; \Phi^{(i)}_{ag\to cd}(x, k_\perp, \mu)} \, . \tag{2.10}$$

As we shall see in the next section, both approaches give very similar results, validating the simplified approach for forward dijet production processes.

The ITMD approach was previously applied, for example, to study shapes of forward dijet azimuthal correlation spectra [56], measured by the ATLAS collaboration [66]. It was demonstrated that the saturation effects and the Sudakov resummation together seem to describe the shapes better then either effect alone. However, the Sudakov resummation method used in [56] was a simplified procedure, as described in [73], where it was tested against the forward-central dijet production.

[1] The single logarithm accuracy terms have been recently obtained at leading power within the small-x CGC formalism for di-jet production in e-A at NLO accuracy [70].

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3 Numerical results

In this section we present our results for:

- differential cross sections as a function of the azimuthal angle $\Delta\Phi$ between the leading and sub-leading jets, both for p-p and p-Pb collisions at $\sqrt{s} = 8.16\,\mathrm{TeV}$;
- nuclear modification ratios, necessary to quantify saturation effects, defined as:

$$R_{\mathrm{p-Pb}} = \frac{\frac{d\sigma^{p+Pb}}{d\mathcal{O}}}{A\frac{d\sigma^{p+p}}{d\mathcal{O}}}\,. \tag{3.1}$$

The partonic cross sections are calculated using the KaTie Monte Carlo program [74] within the ITMD factorization scheme introduced above. The following set of cuts is applied on the transverse momenta p_{T1}, p_{T2} of the two leading jets, defined using the anti-k_T jet clustering algorithm [75] with a radius parameter $R = 0.4$:

i) $28\,\mathrm{GeV} < p_{T1}, p_{T2} < 35\,\mathrm{GeV}$,

ii) $35\,\mathrm{GeV} < p_{T1}, p_{T2} < 45\,\mathrm{GeV}$,

iii) $35\,\mathrm{GeV} < p_{T1} < 45\,\mathrm{GeV}$ and $28\,\mathrm{GeV} < p_{T2} < 35\,\mathrm{GeV}$,

iv) $p_{T1}, p_{T2} > 10\,\mathrm{GeV}$.

The first three cuts are tailored to the FCal calorimeter of the ATLAS detector for which jets were considered in the rapidity range $2.7 < y_1^\star, y_2^\star < 4.0$ in both the proton-proton and the proton-nucleon center of mass frame. The last set of cuts is adapted for the planned ALICE upgrade FoCal and is used for jets in the rapidity range $3.8 < y_1^\star, y_2^\star < 5.1$ (positive rapidity corresponds to the direction of the proton momentum in p-Pb collisions). The factorization and renormalization scales are set to $(p_{T1} + p_{T2})/2$. The shaded bands in figure 3 represent the error due to the variation of this value by a factor of 1/2 and 2.

In our computation within the ITMD framework, we include the following partonic channels, for five quark flavors:

$$qg^* \longrightarrow qg, \qquad gg^* \longrightarrow gg\,, \tag{3.2}$$

where the $*$ represents the off-shell gluon. The channel $gg^* \longrightarrow \bar{q}q$ is neglected as the contribution of this channel is small for the considered kinematic domains [36, 43]. The gluon distributions necessary for the ITMD framework were calculated in [43] and are based on the Kutak-Sapeta (KS) fit of the dipole gluon density [36]. We use the CTEQ10NLO PDF set [76] from LHAPDF6 [77] for the collinear PDFs in the ITMD framework.

The cross sections computed in the ITMD framework are obtained at the parton level. In order to estimate the effects due to the final state shower as well as hadronization, we use the Pythia Monte Carlo event generator [78, 79] version 8.307 with default tunes. We use the NNPDF23NLO set [80] to describe the proton structure, and nCTEQ15WZ set [81] for the nuclear PDF in the simulation of p-Pb collisions. The detailed procedure is as follows:

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1. we simulate p-p collisions at parton level using Pythia with the Initial State (IS) showers only; such setup is supposed to include similar physics as in the KaTie simulation, because the TMD gluon distributions mimic the IS showers,

2. we turn on the Final State (FS) shower, hadronization and MPI effects; by comparing this with the previous calculation we estimate the correction factors,

3. we use the same procedure for p-Pb collisions,

4. we apply the correction factors to the KaTie results to obtain hadron-level cross sections.

The correction factor is not very sensitive to the actual PDF used. Therefore using the correction factor extracted from nuclear PDFs that do not — at least explicitly — have saturation effects on the top of the ITMD saturation framework is a rough but realistic estimate.

In figure 1 we show the results of the calculations using the ITMD factorisation formula with the Sudakov resummation in the simplified scheme of eq. (2.1), as compared to calculations based on the full b-space resummation of eq. (2.2). The calculations are done for the p-p and p-Pb systems and for the ATLAS and ALICE kinematic regions. We see that, overall, the results are similar; the full b-space resummation gives slightly less decorrelation than the factorized approach. However, within the accuracy of our LO predictions, both approaches can be treated on equal footing. This is evident from figure 3, where we see that within the uncertainties obtained by varying the factorization/renormalization scales, the difference between full b-space and the factorized Sudakov form factor calculations washes out. In addition, the difference between both Sudakov resummation schemes cancels to large extent in the ratio of p-Pb and p-p cross sections.

In figure 2 we compare results obtained within the ITMD approach to Pythia calculations. We use only the factorized Sudakov resummation for simplicity. We observe that parton-level Pythia results, with only the initial-state shower applied, are above the ITMD results, and attribute this to the difference between linear and nonlinear evolutions. One can also see that the ITMD results for the p-p and p-Pb spectra approach each other at small $\Delta\Phi$, while the Pythia results are shifted by a constant value for all values of $\Delta\Phi$. The behavior of the ITMD result is an expected manifestation of saturation effects. They are larger at large $\Delta\Phi$, leading to a more pronounced difference between the p-p and p-Pb curves at larger values of $\Delta\Phi$. The final state shower, hadronization and MPI, essentially decrease the cross section, not changing the distribution shape too much, especially for larger transverse momenta.

The extracted correction factors are applied to the KaTie results, see figure 3 (see also comparison with Pythia results in figure 2). The error bands for calculations with the correction factor are combinations of the scale variation error and the statistical error from Pythia.

In figure 4 we show the results for nuclear modification ratio R_{pA} which determines the strength of suppression due to the saturation effects as one goes from a proton to a nuclear

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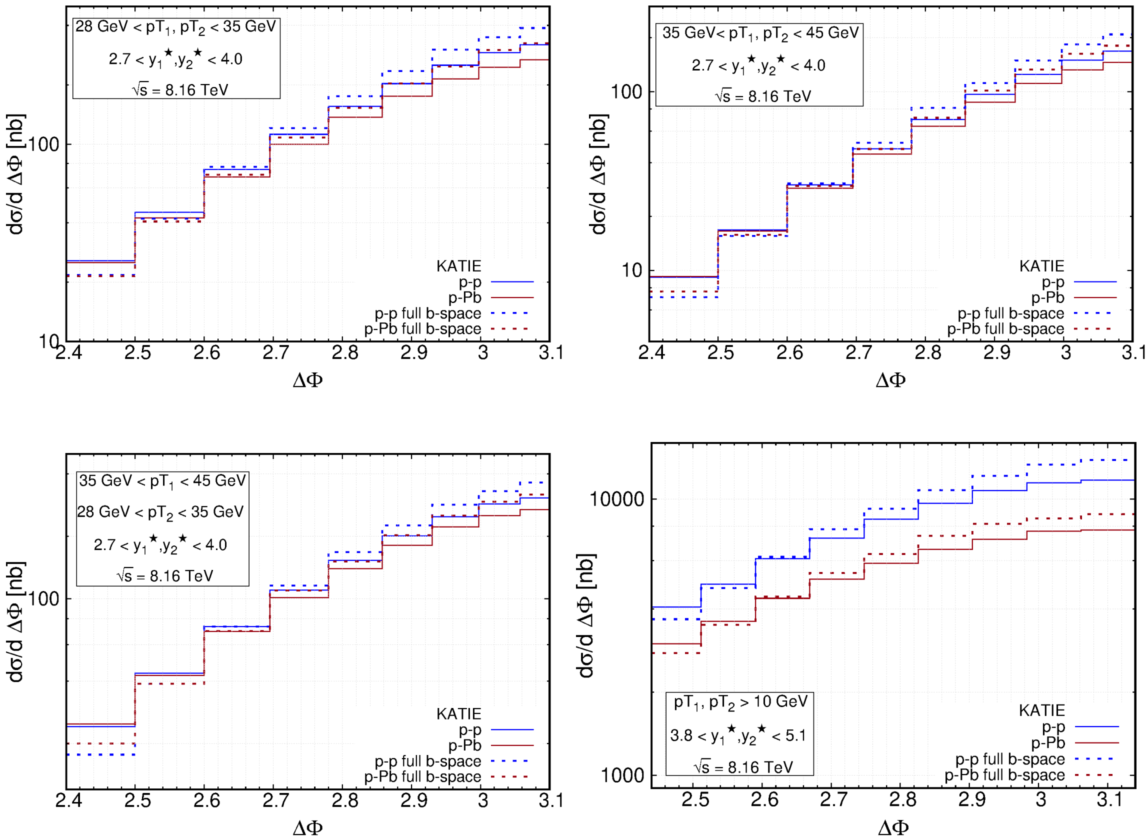

Figure 1. The differential cross sections in the azimuthal angle between the two hardest jets, $\Delta\Phi$, for p-p and p-Pb collisions computed from KATIE using the ITMD factorisation formula with: the simplified Sudakov resummation eq. (2.1) (solid lines), the full b-space resummation eq. (2.2) (dotted lines). The top two and the bottom left plots correspond to FCal ATLAS kinematics, while the bottom right plot corresponds to the FoCal upgrade of ALICE.

target. First of all we see that the suppression is quite large, about 20%, for the FoCal upgrade of ALICE. The saturation signal persists even after including the correction due to the hadronization and other effects, which is an important result. The second important observation is that the difference between the full b-space Sudakov resummation and the simplified approach cancels out to large degree in the nuclear modification ratio. Thus, the saturation signal is not much affected by the details of the Sudakov suppression of the back-to-back peak. For ATLAS kinematics, which is restricted to a slightly more central region, we see similar trends as for ALICE kinematics but the suppression due to saturation is smaller.

4 Summary

We provided state-of-the-art predictions for the cross sections and the nuclear modification ratio R_{pA} for forward dijet production in kinematic domains covered by the FCal ATLAS

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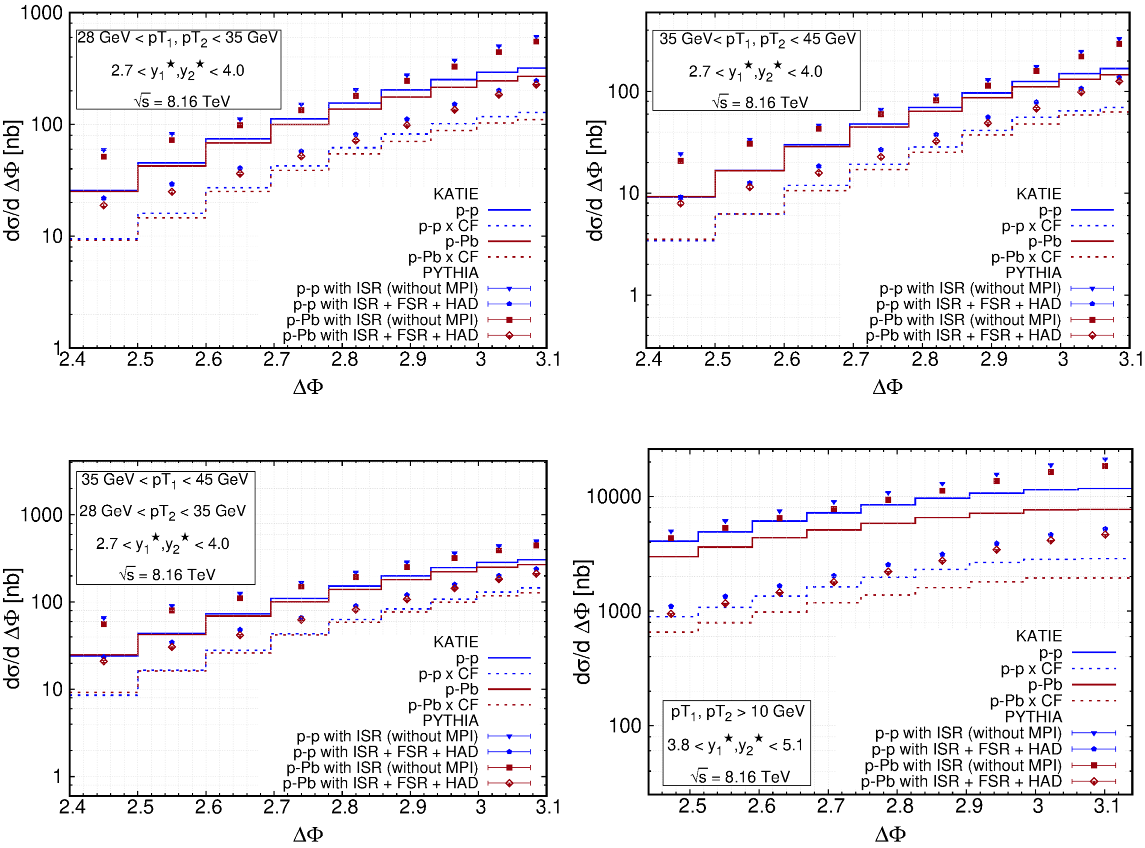

Figure 2. The differential cross sections in the azimuthal angle between the two hardest jets, $\Delta\Phi$, for p-p and p-Pb collisions computed using KaTie with the ITMD approach (solid lines), Pythia with various components (points) and the KaTie with the non-perturbative correction factor extracted from Pythia (dotted lines). The top two and the bottom left plots correspond to the FCal ATLAS kinematics, the bottom right plot corresponds to the FoCal upgrade of the ALICE.

detector and the planned FoCal upgrade of the ALICE experiment. The calculation is based on the application of the ITMD factorization approach implementing the saturation and kinematic twist corrections, together with the Sudakov resummation necessary for realistic description of azimuthal observables in jet production processes. The Sudakov form factor was implemented using two approaches: a simplified approach, where the collinear PDF describing the dilute projectile is factorized, and the full b-space resummation. Both frameworks give results that are close to each other for the considered kinematic domain with the ITMD result being below the Pythia result. As the ITMD calculation is a parton level calculation, we used Pythia in order to estimate corrections for hadronization, FSR shower and MPI effects. We conclude that, taking into the account all the uncertainties, the measurement of the nuclear modification ratio will allow to determine the suppression due to saturation effects.

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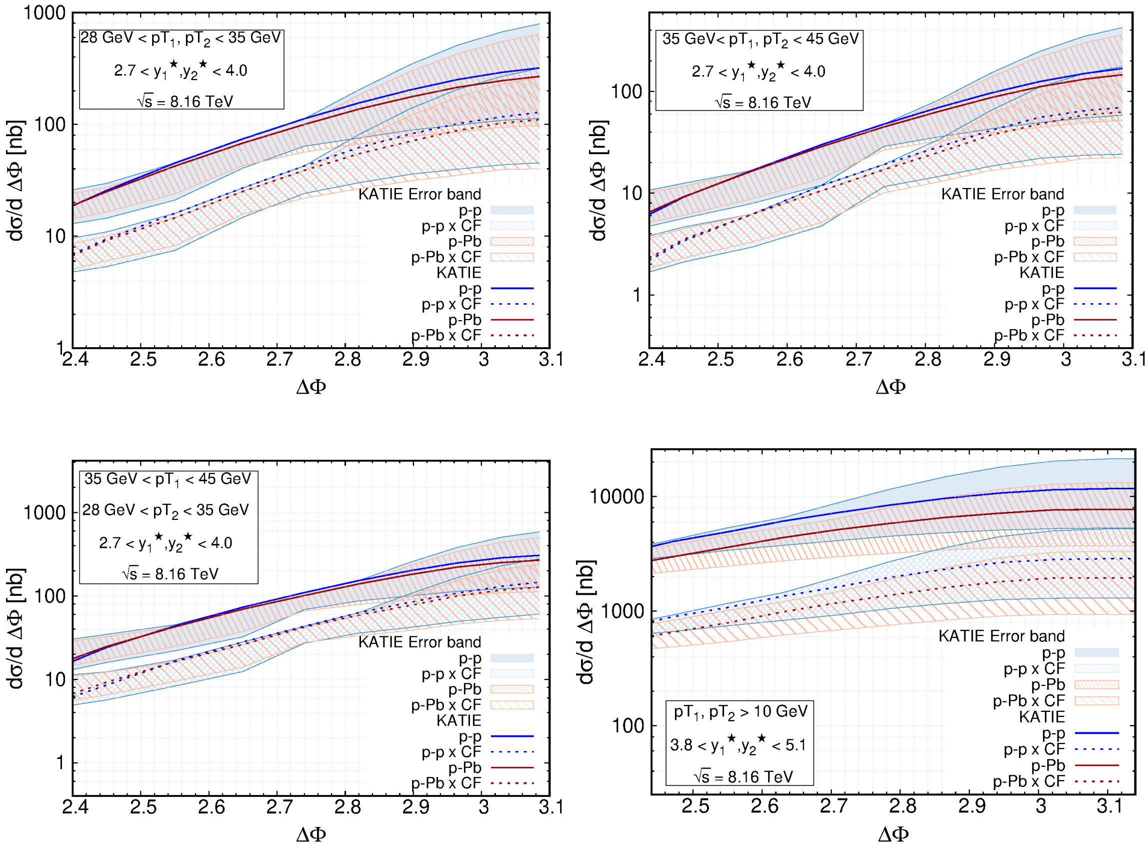

Figure 3. The solid lines represent the differential cross sections in the azimuthal angle between the two hardest jets, $\Delta\Phi$, for p-p and p-Pb collisions computed using KaTie and the ITMD approach. The error bands represents uncertainty due to scale variation from $(p_{T1} + p_{T2})/2$ by a factor of $1/2$ and 2. The dotted lines represent the differential cross sections taking into account the non-perturbative correction factors from Pythia. Similarly, the lower band represent uncertainty due to scale variation multiplied by the correction factor, taking into account statistical errors from Pythia. The top two and the bottom left plots correspond to the FCal ATLAS kinematics, the bottom right plot corresponds to the FoCal upgrade of the ALICE.

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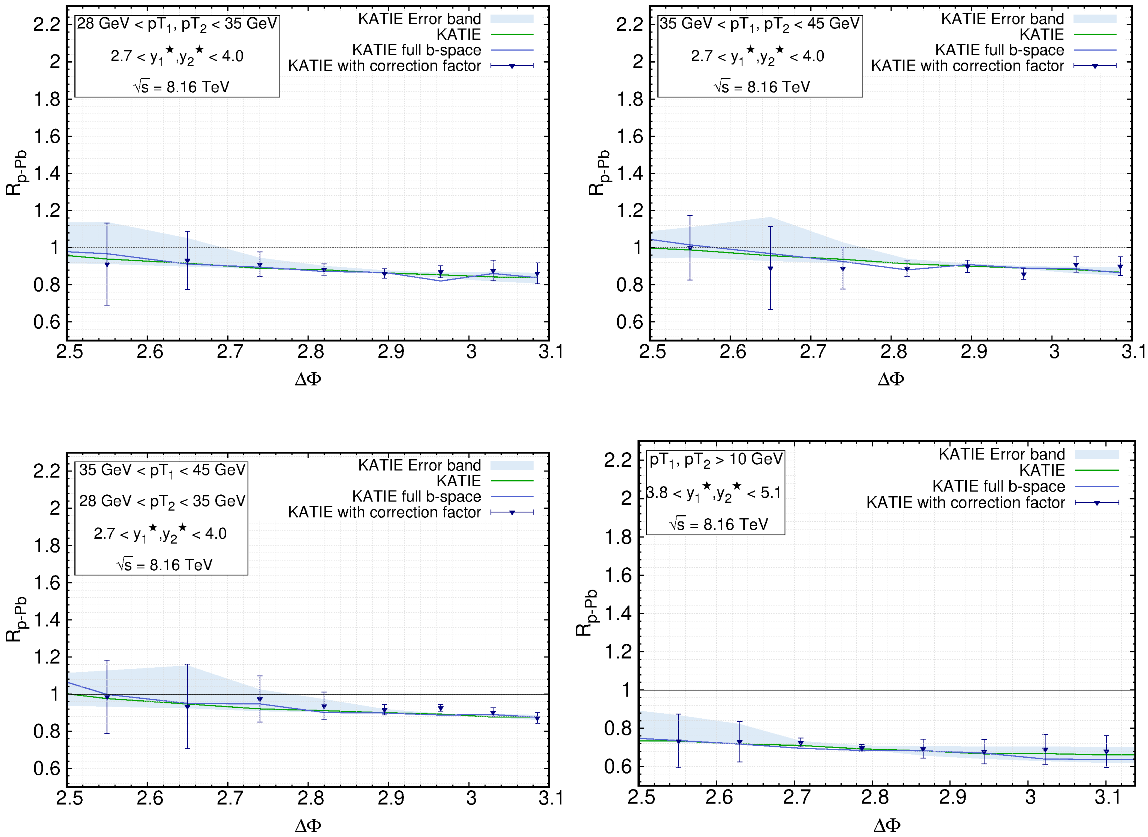

Figure 4. Nuclear modification ratio $R_{\mathrm{p-Pb}}$ as a function of the azimuthal angle between the jets $\Delta\Phi$ for the FCal ATLAS and ALICE FoCal kinematics. The error bands represents uncertainty associated with the KaTie ITMD results due to the variation of the factorization scale from $(p_{T1} + p_{T2})/2$ by a factor of 1/2 and 2. The $\triangledown$ points represent $R_{\mathrm{p-Pb}}$ obtained from KaTie multiplied by the non-perturbative correction factors from Pythia. The error bars associated with these account for both the error in KaTie via the variation of factorization scale plus the statistical uncertainties associated with the correction factors.

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