The Impact of Jet Azimuthal Angular Decorrelation Observations at FCC-ep

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Abstract

Higher collision energies at future colliders will eventually lead to the falsification of standard fixed-order perturbation theory and linear evolutions due to non-linear structure of QCD at small-x. New physics researches that is strictly based on accurate jet measurements will undoubtedly have this observation known as BFKL effect via angular jet decorrelations taking into account the Mueller-Navelet jets. As one of the frontier colliders, FCC-ep, has a great observation potential on parton densities through asymmetrical collisions. We aim to test the observability of azimuthal angular jet decorrelations with the recent event generators (HERWIG, PYTHIA) at the particle level for FCC-ep centre of mass energies √s = 3.5 TeV in proton-electron collisions. Jets are reconstructed by the Anti-\textit{k}_T algorithm (R = 0.5), with \textit{p}_T > 35 GeV and selected in the rapidity range of |\textit{y}| < 6. Relevant rapidity regions has been analyzed with the azimuthal-angle difference between Mueller-Navelet Jets (\textit{ΔΦ}) in the rapidity seperation (\textit{Δy}) and the distributions of \textit{< cosn(π − ΔΦ) >} are presented in comparison as the result.

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I. INTRODUCTION

The strong interaction between quarks and gluons, called partons, are defined by the theory of Quantum Chromodynamics (QCD). The behavior of the QCD interactions with respect to different momentum scales can be considered as one of the most puzzling questions within the SM theory. If one is considering an experimental setup to collide energetic non-point particles (e.g: protons), Parton Distribution Functions (PDFs) should be granted as a known fact. In experimental data analysis, MC generators use built-in PDFs that are strictly depended on momentum scales and can be recalculated for each center of mass energies to reconstruct background data. However, recent observations show that as the collision energies and collected data increase, the kinematic observables reveal some anomalies in comparison of background and signal [1, 2]. Especially in large rapidity distributions, ATLAS and CMS Collaborations announced that a good agreement between signal and background can be provided only if the multiple MC generators are assigned for the analysis [3, 4]. In the past experiments (e.g: D0), a similar effect was hinted with \( \sqrt{s} = 1.8 \) TeV, 1800 and 630 GeV at Fermilab Tevatron [2, 5]. At those studies, \( \Delta \eta \) is selected up to 6, to limit the observation of the decorrelation effect.

In this work, we aim to present the observation of azimuthal angular jet decorrelations through multiple MC generators, namely HERWIG7 [7] and PYTHIA 8 [8], at FCC-ep. As a part of the huge project in the FCC framework, ep collider offers asymmetrical collisions to researchers to analyze topics such as high precision QCD, Top&Electroweak Physics, Supersymmetry and Higgs Physics. According to recent concept design report of FCC [9], it is planned to be built on 80-100 km tunnel under CERN campus to reach the 50 TeV proton beam energy. For the electron beam, it is aimed to reach 60 GeV energy with boosting particles in the energy recovery linac. In the physics program of FCC-ep collider that became evident before CDR report [10, 11], QCD studies take an utmost important place as the complementary to hadron collider studies.

The outline of the paper is as follows: a numerical approach to the problem using BFKL and DGLAP evolutions is mentioned in the section II with the theoretical considerations. We explain event generation setup and jet selection to obtain Mueller-Navelet Jets (MN-Jets) in the section III. Then we mention the analysis results and comparisons in the section IV. And in the final section, we basically present the quantitative outputs of the analysis that
may be possible to observe in the FCC-ep experiments.

II. THEORITICAL CONSIDERATIONS

In the hadronic collisions, Mueller-Navelet Jets (MN-Jets) are some jets that carry the longitudinal momentum fraction of their parent hadrons in the forward direction and that cause a large rapidity separation between each others. If one can measure the transverse momenta of the forward jets as $k_1$ and $k_2$, total collision energy should be sufficiently large to observe MN-Jets in the large rapidity interval $\Delta \eta \sim \ln(s/k_1k_2)$ where $s$ is the center of mass energy. On the other hand, one can explain jets in the fixed-order perturbative QCD calculations considering a fixed value for the running strong coupling $\alpha_s$. More specifically, in order to calculate cross section, one should obtain the partonic momenta from structure functions within the energy scale $Q^2$ and solve the Dokshitzer, Gribov, Lipatov, Altarelli, Parisi (DGLAP) equation as mentioned in ref [12, 13]. Recently, these structure functions have been well-studied within the PDF studies solving DGLAP equation that allows resummation of the large logarithms coming from the strong ordering between the hadrons scale and the jets transverse momenta using mathematical methods [14]. Note that recent MC event generators use built-in PDF datasets although various calculation tools are developed based on the DGLAP analytical solutions. However, in the DGLAP perspective, a dijet is correlated changing of parton densities with varying spatial resolution of the detector. With contrary the observations, that leads to end up with low $p_T$ emissions via strong ordering of transverse momenta.

In the high-energy regime, the Balitsky-Fadin-Kuraev-Lipatov (BFKL) [15–17] approach states that a dijet can be decorrelated with large parton emissions and allows the resummation of terms with $\alpha_s\log(1/x)^n$ at leading (LL) and next-leading (NLL) logarithmic accuracies. Thus, one can calculate the cross section values that are independent of the parton densities but for higher accuracy one should calculate the NLL-BFKL [18, 19] predictions since it is reported LL-BFKL is underestimating data [20].

One can calculate the normalized MN-Jets cross section analytically as a function of azimuthal-angle difference ($\Delta \phi$) with $p_T > p_{T,min}$ in Fourier series expansion as follows [21]:

$$
\[
\frac{1}{\sigma} \frac{d\sigma}{d(\Delta\phi)}(\Delta y, p(T, min)) = \frac{1}{2\pi} [1 + 2 \sum_{n=1}^{\infty} C_n(\Delta y, p(T, min)) \cos(n(\pi - \Delta\phi))] \tag{1}
\]

Here, \( C_n \) parameters are Fourier coefficients and equal to average cosines of the decorrelation angle, \(< \cos(n(\pi - \Delta\phi)) >\), where \( \Delta\phi = \phi_1 - \phi_2 \) is the difference between azimuthal angles of MN-Jets. Phenomenologically the reason of choosing average cosine observable has a direct effect on differential MN-Jets cross section as well as it’s a kinematically measurable variable.

### III. EVENT AND JET SELECTION

Pythia8 (version of 8.243) and Herwig7 (version of 7.1.2) are used to generate events with electron-proton collisions at \( \sqrt{s} = 3.5 \text{ TeV} \). \( 30 \times 10^6 \) events are generated with Pythia8 and these events are used to reconstruct jets with Anti-\( k_T \) [23] jet algorithm (cone radius of 0.5) within FastJet (version of 3.3.0) [22]. The number of events generated by Herwig7 is \( 20 \times 10^6 \). Then jets are reconstructed by FastJet (version of 3.2.1) with Anti-\( k_T \) [23] jet algorithm (cone radius of 0.5). As the preselection criteria, events with at least two jets are used and jets are required to pass \( p_T \) cut of 10 GeV and to be in the rapidity region of \( |y| < 7 \).

In the analysis, following criteria are applied to select the MN-Jets:

- \( p_T \) higher than 35 GeV
- in the rapidity region of \( |y| < 6 \).
- apply rapidity ordering of jets for each event
- choose the jets with highest rapidity and lowest rapidity value
- name them most forward jet and most backward jet, respectively.

Two jets in each events with the largest rapidity seperation are obtained. Some kinematic distributions of these jets are produced to see the selection of jets. Figure 1 shows \( p_T \) (top left), rapidity (top right), phi (bottom left) distribution of all jets including MN-Jets and \( p_T \) (bottom right) distribution of leading jets in each event for Herwig7. Figure 2 shows \( p_T \) distributions of forward and backward jets of which have \( p_T \) higher than 35 GeV. It is clear
Table I. Number of events and number of jets before and after cuts at \( \sqrt{s} = 3.5 \) TeV

| @\( \sqrt{s} = 3.5 \) TeV | Before Cuts | After Cuts* | After MNJets Selection Criteria |
|---------------------------|-------------|-------------|---------------------------------|
| Pythia8                   |             |             |                                 |
| Number of Events          | 2.99999e+07 | 401722      | 137642                          |
| Number of Jets            | 5.50625e+09 | 1.15873e+08 | 3.95394e+07                     |
| Herwig7                   |             |             |                                 |
| Number of Events          | 2.04497e+07 | 1.12609e+07 | 142993                          |
| Number of Jets            | 1.81002e+08 | 1.56032e+07 | 889652                          |

* Events with at least 2 jets & jet \( p_T > 35 \) GeV

Table II. Number of jets at each \( \Delta \Phi \) distribution at \( \sqrt{s} = 3.5 \) TeV

| \(|\Delta y| < 3, 3. < |\Delta y| < 6, 6. < |\Delta y| < 9, 9. < |\Delta y| < 12.\) | Pythia 8 | Herwig7 |
|-------------------------------------------------|----------|---------|
| \(|\Delta y| < 3\)                                  | 23032683 | 128025  |
| \(|\Delta y| < 6\)                                  | 14895265 | 196614  |
| \(|\Delta y| < 9\)                                  | 1611430  | 361324  |
| \(|\Delta y| < 12\)                                 | 0        | 0       |

that during the analysis both most forward and most backward jets have \( p_T > 35\) GeV are used. In Figure 3, rapidity of MN-Jets is plotted, while phi distribution is shown in Figure 4. These two figures show most of the jets are in back-to-back in \( xy \) plane.

The number of events and number of jets before and after cuts are presented in Table 1 for Pythia 8 and Herwig7 separately.

IV. ANALYSIS

The azimuthal-angle difference between MNjets (\( \Delta \Phi \)) as a function of the rapidity separation is plotted in Figure 5. Left plot show the distribution for Pythia8 while right plot is representing the distribution for Herwig7. The distributions are plotted for four rapidity separations: \(|\Delta y| < 3\), \(3. < |\Delta y| < 6\), \(6. < |\Delta y| < 9\), and \(9. < |\Delta y| < 12\). At the first binning of the histogram, \(|\Delta y| < 3\), is in the top while in the third binning, \(6. < |\Delta y| < 9\), is in the bottom. Then the situtation reversed in the last binnings of histogram. Table 2 shows the number of jets at each \( \Delta \Phi \) distribution at \( \sqrt{s} = 3.5 \) TeV. The number of jets decrease with large rapidity seperation for Pythia8 while it increases for Herwig7. There are no MNJets observed for the range of \(9. < |\Delta y| < 12\) as indicated in Table 2. The peak of
Figure 1. $p_T$ (top left), rapidity (top right), phi (bottom left) distribution of all jets and $p_T$ (bottom right) distribution of first two leading jets for Herwig7

Figure 2. Forward jet $p_T$ vs backward jet $p_T$ for Pythia8 (left) and Herwig7 (right)

$\Delta \Phi$ distribution decrease and the distribution becomes wider comparing to the distributions with narrower $\Delta y$ with increasing rapidity between jets. That behavior becomes significant for Herwig7 MC event generator.

Figure 6 represents the distribution of $<\cos(\pi - \Delta \Phi)>$ for both MC event generators. Distribution of Pythia 8 (left plot) shows fluctuations as a function of $\Delta y$ and entries at
Figure 3. Forward jet rapidity vs backward jet rapidity for Pythia8 (left) and Herwig7 (right)

Figure 4. Forward jet phi vs backward jet phi for Pythia8 (left) and Herwig7 (right)

first binning is out of the range of the histogram. Herwig7 distribution, right plot in Figure 6, shows a decrease with increasing of $\Delta y$ which indicates a better sign of decorrelation.

The ratio of $<\cos 2(\pi - \Delta \Phi)>$ to $<\cos (\pi - \Delta \Phi)> (\frac{C_2}{C_1}$, left plot) and $<\cos 3(\pi - \Delta \Phi)>$ to $<\cos 2(\pi - \Delta \Phi)> (\frac{C_3}{C_2}$, right plot) as a function of the rapidity separation $\Delta y$ are plotted for Pythia8 (top) and Herwig7 (bottom) in Figure 7. The distribution of Herwig7 shows a smooth decrease downwards versus the higher values of $\Delta y$ and last binnings of histograms are suffering from low statistics.

V. CONCLUSION

We have presented azimuthal angular deccorelation of most forward and most backward jets in ep collisions at $\sqrt{s} = 3.5$ TeV with Pythia8 and Herwig7 MC event generators. Azimuthal-angle difference between MNjets ($\Delta \Phi$), average cosine value of $\Delta \Phi$
Figure 5. The azimuthal-angle difference between MNjets ($\Delta \Phi$) in the rapidity of $|\Delta y| < 3.$, $3. < |\Delta y| < 6.$, $6. < |\Delta y| < 9.$, and $9. < |\Delta y| < 12.$ at $\sqrt{s} = 100$ TeV for Pythia8 (left) and Herwig7 (right).

Figure 6. $< \cos(p - \Delta \Phi) >$, $< \cos2(p - \Delta \Phi) >$ and $< \cos3(p - \Delta \Phi) >$ as a function of $\Delta y$ at $\sqrt{s} = 100$ TeV for Pythia8 (left) and Herwig7 (right).

($< \cos(n(p - \Delta \Phi) >$) for $n = 1, 2, 3$ and ratio of $< \cos(n(p - \Delta \Phi) >$ for different $n$ values as a function of the rapidity separation up to 12 are plotted. It’s produced $3 \times 10^7$ events with both MC generators individually that roughly corresponds to the integrated luminosity at the order of $(nb)^{-1}$. We have not observed significant change on the behaviour of event generators for different multi-parton interaction (MPI) schemes. At this point, we should also reveal the differences in how both event generators handle the generation processes. Although both are the general-purpose event generators to simulate the high-energy lepton-
Figure 7. Ratio of average cosine \( \frac{C_2}{C_1} \) (left) and \( \frac{C_3}{C_2} \) (right) as a function of \( \Delta y \) at \( \sqrt{s} = 100 \text{ TeV} \) for Pythia8 (top) and Herwig7 (bottom).

In previous experiments it is shown that colour coherence can effect the ratio of the difference in rapidity over the difference in azimuthal angle between leading jets [24]. Due to the properties of Herwig, we see a clearer decorrelation effects with the obtained observables. Note that MC modelling uncertainty is the dominant systematic uncertainties in the jet energy detection and both ATLAS and CMS detectors have recently used above mentioned event generators for forward-backward jet calibration taking the full difference between Pythia8 and Herwig7 as the uncertainty. As a preliminary study to FCC, we have executed the
related simulations in the particle level without systematic uncertainties. For $|\Delta y| > 4$ and a few $(nb)^{-1}$ integrated luminosities, one can roughly predict %70 MC modelling difference in measuring $C_1/C_2$ and %50 MC modelling difference in measuring $C_2/C_3$ at FCC-ep. However, with the higher luminosities at the order of $(fb)^{-1}$ and $(ab)^{-1}$, difference will decrease by a factor of 10 and 100 respectively. We have not observed entries for rapidity interval $|\Delta y| > 9$ due to the asymmetric collisions, but comparing with FCC-hh, one can expect higher decorrelation signs for dijets at FCC-ep.

[1] ATLAS Collaboration, “Measurements of jet vetoes and azimuthal decorrelations in dijet events produced in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector.” The European physical journal. C, Particles and fields vol. 74,11 (2014): 3117. doi:10.1140/epjc/s10052-014-3117-7

[2] ATLAS Collaboration, “Measurement of dijet production with a veto on additional central jet activity in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector”, JHEP 09 (2011) 053, doi:10.1007/JHEP09(2011)053, arXiv:1107.1641

[3] CMS Collaboration, “Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton-proton collisions at $\sqrt{s} = 7$ TeV”, Eur. Phys. J. C 72 (2012) 2216, doi:10.1140/epjc/s10052-012-2216-6, arXiv:1204.0696

[4] The CMS collaboration, “Azimuthal decorrelation of jets widely separated in rapidity in pp collisions at $\sqrt{s}= 7$ TeV”, J. High Energ. Phys. (2016) 2016: 139. https://doi.org/10.1007/JHEP08(2016)139.

[5] D0 Collaboration, “The azimuthal decorrelation of jets widely separated in rapidity”, Phys. Rev. Lett. 77 (1996) 595, doi:10.1103/PhysRevLett.77.595, arXiv:hep-ex/9603010

[6] D0 Collaboration, “Probing BFKL Dynamics in the Dijet Cross Section at Large Rapidity Intervals in ppbar Collisions at $\sqrt{s}=1800$ and 630 GeV”, Phys. Rev. Lett. 84 (2000) 5722, doi: 10.1103/PhysRevLett.84.5722, arXiv:hep-ex/9912032

[7] Bellm, Johannes et al., Herwig 7.0/Herwig++ 3.0 release note , Eur.Phys.J. C76 (2016) no.4, 196, DOI: 10.1140/epjc/s10052-016-4018-8.

[8] T. Sjostrand et al, “An Introduction to PYTHIA 8.2”, Comput. Phys. Commun. 191 (2015) 159, DOI: 10.1016/j.cpc.2015.01.024.
[9] Abada, A., Abbrescia, M., AbdusSalam, S.S. et al. FCC Physics Opportunities. Eur. Phys. J. C 79, 474 (2019). https://doi.org/10.1140/epjc/s10052-019-6904-3

[10] The Future Circular Collider Study Group, Kickoff Meeting, 12-15 February 2014, University of Geneva, Switzerland, https://indico.cern.ch/event/282344/. More information is available on the FCC Web site: http://cern.ch/fcc.

[11] A. Ball et al., Future Circular Collider Study Hadron Collider Parameter s, FCC-ACC-SPC-0001 (2014).

[12] Altarelli, G. and G. Parisi, “Asymptotic Freedom in Parton Language”, Nucl. Phys., B126:298–318, 1977.

[13] Dokshitzer Y. L., Sov. Phys. JETP, 46(1977) 641, [Zh. Eksp. Teor. Fiz.73, 1216 (1977)].

[14] M. M. Block, L. Durand, P. Ha, and D.W. McKay, “Analytic solution to leading order coupled DGLAP evolution equations: A new perturbative QCD tool” Phys. Rev. D 83, 054009 (2011).

[15] E. A. Kuraev, L. N. Lipatov and V. S. Fadin, “Multi-reggeon processes in the Yang-Mills theory”, Sov. Phys. JETP 44 (1976) 443.

[16] E. A. Kuraev, L. N. Lipatov and V. S. Fadin, “The Pomeronchuk singularity in nonabelian gauge theories”, Sov. Phys. JETP 45 (1977) 199.

[17] I. I. Balitsky and L. N. Lipatov, “The Pomeronchuk singularity in quantum chromodynamics”, Sov. J. Nucl. Phys. 28 (1978) 822.

[18] B. Ducloue, L. Szymanowski, and S. Wallon, Confronting Mueller-Navelet jets in NLL BFKL with LHC experiments at 7 TeV, J. High Energy Phys. 05 (2013) 096

[19] B. Ducloue, L. Szymanowski, and S. Wallon, Evidence for High-Energy Resummation Effects in Mueller-Navelet Jets at the LHC, Phys. Rev. Lett. 112, 082003 (2014)

[20] D0 Collaboration, B. Abbott et al, Phys. Rev. Lett.84(2000) 5722

[21] A. H. Mueller and H. Navelet, “An inclusive minijet cross-section and the bare pomeron in QCD”, Nucl. Phys. B 282 (1987) 727, doi:10.1016/0550-3213(87)90705-X.

[22] Cacciari, M., Salam, G.P. & Soyez, “FastJet User Manual”, G. Eur. Phys. J. C (2012) 72: 1896. https://doi.org/10.1140/epjc/s10052-012-1896-2.

[23] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-kt jet clustering algorithm”, JHEP 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063. [arXiv:0802.1189]

[24] Lee, Jason. (2017). Multi-jet correlations and colour coherence phenomena. EPJ Web of Conferences. 141. 04003. 10.1051/epjconf/201714104003.
