Azimuthal Angular Decorrelation of Jets at Future High Energy Colliders

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Abstract

The azimuthal angular decorrelation that is relevant to small-x QCD physics is studied in this paper to show the BFKL effect with a recent event generator. Events are generated at $\sqrt{s} = 100$ TeV with proton-proton collisions and jets, that are reconstructed by the Anti-$k_T$ algorithm ($R = 0.7$), with $p_T > 35$ GeV and in the rapidity range of $|y| < 6$ are selected for the study. The azimuthal-angle difference between Mueller-Navelet Jets ($\Delta \Phi$) in the rapidity separation ($\Delta y$) up to 12 is analysed. The distributions of $< \cos n(\pi - \Delta \Phi) >$ for $n = 1, 2, 3$ and their ratio are also presented as a function of $\Delta y$. 

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I. INTRODUCTION

The strong interaction between quarks and gluons, called partons, are defined by the theory of Quantum Chromodynamics (QCD). According to QCD, quarks carry colour charges (blue, red and green) and can not be observed as free particles but in colourless states. This behaviour is named as confinement. To study partons experimentally, one needs to consider jets described by QCD in terms of pp scattering.

The momentum distribution functions of partons within the proton are described by the evaluation equations, when running coupling as one moves from one momentum scale to another. One of these evolution equations is BFKL (Balitsky, Fadin, Kuraev, Lipatov) which describes the dependence on \( x \), the parton momentum fraction. BFKL equations require strong ordering of fractional momentum. An ideal observable to study sensitivity of low-x QCD evolution and a test of BFKL, is the distribution of azimuthal angle between two jets in the same event. At the leading order calculations two jets are back-to-back in xy-plane and perfectly correlated. However when energy of collision increases the correlation of two jets break down by the emission of an extra jet and the two selected jets are no longer back-to-back in the xy-plane.

At Fermilab Tevatron, the studies of BFKL effect are performed at \( \sqrt{s} = 1.8 \text{ TeV} \), 1800 and 630 GeV by D0 experiment. At both studies, \( \Delta \eta \) is selected up to 6, which could limit the observation of decorrelation effect.

The experiments at LHC provide larger rapidity separation and higher center-of-mass energy for the studies. The publication from ATLAS Collaboration is performed at \( \sqrt{s} = 7 \text{ TeV} \) using jets with \( p_T > 20 \text{GeV} \) and rapidity separation of \( |\Delta y| < 6 \). and concludes that PYTHIA and HERWIG give best description of data as function of mean transverse momentum, \( \bar{p}_T \), while PYTHIA gives the best description of data as a function of \( \Delta y \). CMS publications report the measurements at 7 TeV and with jets \( p_T > 35 \text{GeV} \) and in the rapidity region of \( |y| < 4.7 \). These publications indicate that one can observe the BFKL effect at higher center-of-mass energies.

Recently, new projects based on higher collision energies are considering to extend the search being performed in LHC. As one of these projects, Future Circular Collider (FCC) is planning to be built on 80-100 km tunnel to reach the 100 TeV collision energy. FCC is hosted by CERN and planned to develop three accelerator facilities; FCC-hh, FCC-he
and FCC-ee. Another future collider project is Circular Electron Positron Collider (CEPC) with the design of Super Proton-Proton Collider (SPPC) [11, 12]. The CEPC-SPPC is planned to have baseline of 100km circumference and to reach the center-of-mass energy of 100 TeV. Since there is no available data at 100 TeV, to see the BFKL effect at such center-of-mass energies one can simulate hard QCD events and use jet reconstruction algorithms to investigate kinematic distributions.

II. SMALL-X PHYSICS

According to Quark-Parton Model, protons are made of point-like particles, called partons. Thus when two hadrons collide, quarks and gluons inside incoming hadrons interact with each other, indeed. The decrease of the dependence of the structure functions on energy scale $Q^2$ is predicted by increasing center-of-mass energies. Later, structure functions become the function of $x$ alone. The probability of finding a parton carrying a fraction $x$ of the momentum of the proton is defined by parton distribution functions (PDFs). The change in parton distributions with variation in momentum scale is described by evolution equations, which are calculated as perturbatively. The BFKL evolution equation becomes valid at small-$x$ values. BFKL allows the resummation of terms with $(\alpha_s \log \left(\frac{1}{x}\right))^n$ (where $\alpha_s$ is strong coupling) so it is valid at $\log \left(\frac{Q^2}{Q_0^2}\right) \ll \log \left(\frac{1}{x}\right)$.

Jets are particle sprays emitted from hadron-hadron collisions. The measurement of jet shapes allows one to study the transition between a parton, coming from hard scattering, and a hadron, observed experimentally. Mueller Navelet jets (MN Jets) [13] are produced during hadron-hadron collisions at high energies. These jets carry the longitudinal momentum fraction of their parent hadrons. Thus, each jet is closed to its parent hadron and that cause a large rapidity separation between jets. Such process allows to study the BFKL evidence. During the collision, dijets are correlated and can be observed back-to-back or with different angles. Back-to-back jets are balanced in transfer momentum and perfectly correlated. But when an extra jet is emitted in such process, the decorrelation begins to appear and break down of back-to-back topology increase.

There are two main observables can show the effect of BFKL. One is azimuthal angle between MN Jets ($\Delta\Phi$) with respect to rapidity separation between jets as suggested at [14]. If jets are highly correlated and back-to-back there should be a sharp peak in the
distribution of $\Delta \Phi$. However by increasing rapidity separation between jets, the $\Delta \Phi$ peak decrease and distribution becomes wider. The second observable is average cosine value of $\Delta \Phi$ ($<\cos(\pi - \Delta \Phi)>)$ [4, 15]. When jets are back-to-back and perfectly correlated, one should expect a flat distribution at 1 in the plot of $<\cos(\pi - \Delta \Phi) >$. When decorrelation arise with extra jet emission, $<\cos(\pi - \Delta \Phi) >$ value start to decrease with increasing rapidity seperation. And third observable can be ratio of $<\cosn(\pi - \Delta \Phi) >$ for different $n$ values. That plot can show a clear change of $<\cos(\pi - \Delta \Phi) >$.

III. EVENT AND JET SELECTION

Pythia8 [16] is used to generate the hard QCD events with proton-proton collisions at $\sqrt{s} = 100$ TeV. $30 \times 10^6$ events are generated and during the generation of events, FastJet [17] is used to reconstruct the jets by Anti-$k_T$ [18] jet algorithm with cone radius of 0.7. 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 jets:

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

By that selection, in each event these two jets would have largest rapidity seperation and can be named as Mueller-Navelet jets. The control plots are produced to see the effect of selection criteria. Figure 1 shows $p_T$ distributions of forward and backward jets of which have $p_T$ higher than 35 GeV. It is clear that during the analysis both most forward and most backward jets have $p_T > 35 GeV$ are used. In Figure 2, rapidity of MNJets is plotted, while phi distribution is shown in Figure 3. 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. Table 2 shows the number of jets at each $\Delta \Phi$ distribution at $\sqrt{s} = 100$ TeV. The number of jets decrease with large rapidity seperation.
Table I. Number of events and number of jets before and after cuts at $\sqrt{s} = 100$ TeV

| @$\sqrt{s} = 100$ TeV | Before Cuts | Events with at least 2 jets & jet $p_T > 35$ GeV | After MNJets Selection Criteria |
|------------------------|-------------|-----------------------------------------------|---------------------------------|
| Number of Events       | 3e+07       | 4.3733e+06                                   | 3442                            |
| Number of Jets         | 1.92805e+12 | 3.28932e+10                                  | 1.41547e+07                     |

Table II. Number of jets at each $\Delta \Phi$ distribution at $\sqrt{s} = 100$ TeV

| $|\Delta y| < 3$. | 3. < $|\Delta y| < 6$. | 6. < $|\Delta y| < 9$. | 9. < $|\Delta y| < 12$. |
|-----------------|------------------|-----------------|-----------------|
| Number of Jets  | 3427680          | 4465153         | 3353053         | 2904755 |

IV. ANALYSIS

After being sure about selection of MN Jets, the result plots are produced. The first observable to see the signs of BFKL effect, the azimuthal-angle difference between MNjets ($\Delta \Phi$) as a function of the rapidity separation of MNJets, is shown in Figure 4. As described in previous section, the decorrelation will rise by increasing rapidity separation between jets. To see the effect clear, the distribution is plotted for four rapidity separations: $|\Delta y| < 3.$, 3. < $|\Delta y| < 6.$, 6. < $|\Delta y| < 9.$, and 9. < $|\Delta y| < 12$. If one check first binning of the histogram, then can see clearly $|\Delta y| < 3.$ is in the top while in the last binnings it is in the bottom and 9. < $|\Delta y| < 12.$ appears in the top. That shows with increasing rapidity between

Figure 1. Forward jet $p_T$ vs backward jet $p_T$
jets, the peak of $\Delta \Phi$ distribution decrease and the distribution becomes wider comparing to the distributions with narrower $\Delta y$.

The second observable to see the BFKL effect, $\langle \cos(\pi - \Delta \Phi) \rangle$ distribution between MN Jets, is shown in Figure 5. $\langle \cos n(\pi - \Delta \Phi) \rangle$ is presented for $n = 1, 2$ and $3$ with different line colors. The distribution start around 1 and then decreases for larger rapidity separation. When $n$ increase, the change in the distribution becomes more significant. There
are some statistical fluctuations in the distributions are observed.

Figure 6 shows the ratio of \( \langle \cos 2(\pi - \Delta \Phi) \rangle \) to \( \langle \cos(\pi - \Delta \Phi) \rangle \) \((\frac{C_3}{C_1})\), left plot) and \( \langle \cos 3(\pi - \Delta \Phi) \rangle \) to \( \langle \cos 2(\pi - \Delta \Phi) \rangle \) \((\frac{C_2}{C_1})\), right plot) as a function of the rapidity separation \( \Delta y \). Except the bins with low statistics, the general behaviour of distribution is decreasing as a function of \( \Delta y \).

V. CONCLUSION

In the analysis, we have showed a significant difference between the kinematic distributions of MNjets that are selected to have largest rapidity seperation with \( p_T > 35 GeV \) at \( \sqrt{s} = 100\ TeV \) using Pythia8 event generator and FastJet clustering algorithm which are considered as one of the most realistic and updated tools in data analysis. In Figure 4, one can see that the peak of azimuthal-angle distributions of MNJets are decreasing with selected rapidity regions (\( \Delta y \)) up to 12 and getting wider by the function of \( \Delta y \). We have found that the distributions of jets for rapidity regions of \( |\Delta y| < 3., 3. < |\Delta y| < 6., 6. < |\Delta y| < 9., 9. < |\Delta y| < 12. \) are 24.2%, 31.6%, 23.7% and 20.6%, respectively. The average cosine value of \( \Delta \Phi \) is also decreases with the increasing \( \Delta y \). In figure 5, same effect can be seen in the ratio plots of \( \langle \cos n(\pi - \Delta \Phi) \rangle \) for \( n = 1, 2, 3 \) except the bins suffering from low statistic.
Figure 5. $< \cos(\pi - \Delta \Phi) >$, $< \cos 2(\pi - \Delta \Phi) >$ and $< \cos 3(\pi - \Delta \Phi) >$ as a function of $\Delta y$ at $\sqrt{s} = 100$ TeV

Figure 6. Ratio of average cosine $\frac{C_k}{C_1}$ (left) and $\frac{C_k}{C_2}$ (right) as a function of $\Delta y$ at $\sqrt{s} = 100$ TeV

In conclusion with increasing center-of-mass energies, the observables of BFKL effects become significant for jet based analysis particularly in forward regions of detectors and can only be justified by collected data at future high energy colliders such as FCC and CEPC-SPPC. Therefore one should consider the BFKL evolution equation and parton momentum fraction ($x$) dependency in the parton distribution functions in the analysis of experimental
data in order to achieve more accurate results from jet based analyses.

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