INCLUSIVE FORWARD-JET AND DIJET PRODUCTION AT THE LHC*

Marcin Bury

The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland

(Received April 6, 2017)

We present a study of inclusive forward-jet and dijet production in the high-energy factorization framework. We examine several physical effects not included in previous analyses *i.e.* contributions coming from off-shell quarks, double-parton scattering and final-state radiation. We compare our results with the available LHC data at $\sqrt{s} = 7$ and 13 TeV and with collinear factorization.

DOI:10.5506/APhysPolB.48.939

1. Introduction

Production of particles with large rapidities in high-energy hadronic collisions provides a unique opportunity to access the region of phase space where one of the incoming partons carries almost full longitudinal momentum of the proton, while the other has a very small fraction of it, $x \ll 1$. The latter gives rise to large logarithms of the form of $\alpha_{\rm s} \ln(1/x)$, coming from initial state emissions, which needs to be resummed by means of BFKL or BK equations. The resummation results in parton distributions that depend on the transverse component of parton's four-momentum, $k_{\rm t}$, in addition to the longitudinal momentum fraction x, and the hadronic cross section factorizes into a convolution of such unintegrated parton distributions and the corresponding off-shell matrix elements. This approach is commonly known as $k_{\rm t}$*-factorization* or *high-energy factorization* (HEF) [1] and it is the basic framework used to study forward-jet production in this work. An alternative approach is to use general-purpose Monte Carlo (MC) programs, such as PYTHIA or Herwig, which are based on the collinear factorization supplemented with an initial- and a final-state parton shower (PS). This

* Presented at the Cracow Epiphany Conference "Particle Theory Meets the First Data from LHC Run 2", Kraków, Poland, January 9–12, 2017.

method allows one to include a range of important physicall effects, such as multi-parton interactions and non-perturbative corrections, it lacks, however, formal resummation of $\alpha_{\mathrm{s}}\ln(1/x)$ terms, so the behaviour at low x is only modeled by appropriate initial condition for evolution of collinear parton densities.

2. Inclusive forward-jet production

The inclusive jet production process is unique in the sense that it can be calculated already at leading order in high-energy factorization. This is not possible in collinear factorization, where $2 \to 1$ emission vertex vanishes identically and one has to include higher order corrections.

The high-energy factorization formula for the calculation of single-jet production cross section reads

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\mathrm{jet}}\mathrm{d}p_{\mathrm{t,jet}}} = \frac{1}{2}\frac{\pi\, p_{\mathrm{t,jet}}}{(x_1 x_2 s)^2}\sum_{a,b,c}\overline{|\mathcal{M}_{ab^*\to c}|}^2 x_1 f_{a/A}\left(x_1,\mu^2\right)\,\mathcal{F}_{b/B}\left(x_2,p_{\mathrm{t,jet}}^2,\mu^2\right)\,, \tag{1}$$

where $\mathcal{F}$ denotes the transverse momentum-dependent parton density (TMD). The fractions of the longitudinal momenta of the incoming partons can be expressed in terms of the rapidity y_{jet} and the transverse momentum $p_{\mathrm{t,jet}}$ of the leading final-state jet as

$$x_1 = \frac{1}{\sqrt{s}}\, p_{\mathrm{t,jet}}\, e^{y_{\mathrm{jet}}}\,, \qquad x_2 = \frac{1}{\sqrt{s}}\, p_{\mathrm{t,jet}}\, e^{-y_{\mathrm{jet}}}\,, \tag{2}$$

where $s = (p_A + p_B)^2$ is the total squared energy of the colliding hadrons.

TMDs, in general, depend on three variables — the longitudinal momentum fraction x, transverse momentum k_{t} and the factorization scale μ. There are several methods to obtain them, in particular they can be constructed from collinear parton densities using the KMR procedure [2] or they can be obtained as solutions of low-x evolution equations. The function $x_1 f_{a/A}(x_1,\mu^2)$ denotes the collinear parton distribution function. The matrix elements $|\mathcal{M}_{ab^*\to c}|^2$ can be calculated using the helicity-based formalism [3] or the *parton reggezation approach* [4]. The explicit expressions for the corresponding matrix elements can be found in Ref. [5].

Let us now turn to predictions for the transverse momentum spectra of the single inclusive forward jets at the LHC. The calculations were performed at the center-of-mass energies of $\sqrt{s} = 7$ and 13 TeV, with the events selected following the cuts used in the CMS analyses of Refs. [6, 7], *i.e.* the leading jet with $p_{\mathrm{t,jet}} > 35\,\mathrm{GeV}$ in the rapidity window of $3.2 < |y_{\mathrm{jet}}| < 4.7$. For on-shell partons, we used the distribution from the CT10 NLO set [8] and for off-shell partons, we tested several different distributions, which we will now shortly describe. The *KS nonlinear* unintegrated gluon density [9] comes from an extension of the BK equation. It includes kinematic constraint on the gluons in the chain, non-singular pieces of the splitting functions and contributions from sea quarks. The *KShardscale nonlinear* [10] adds on top of that Sudakov resummation of soft emissions. Another two distributions are linearized analogues of the above two. The *DLC2016* (Double Log Coherence) [11] are unintegrated quarks and gluon densities obtained from the standard collinear PDFs (CT10 NLO [8]) using KMR prescription [2].

All TMD sets, apart from DLC2016, deliver only off-shell gluons assuming that the contribution from off-shell quarks is much smaller. The DLC2016 distributions allow us to examine this assumption. The calculations performed for individual channels showed that the off-shell quark contributions can be effectively neglected and we can proceed just with the off-shell gluons in the initial state.

Since the off-shell quark contributions are negligible, it is justified to use all of the TMD gluon sets listed above to calculate predictions of single inclusive jet spectra. The results are shown in Fig. 1. We see a good agreement between the predictions and the 7 and 13 TeV CMS data for all of the unintegrated gluon distributions.

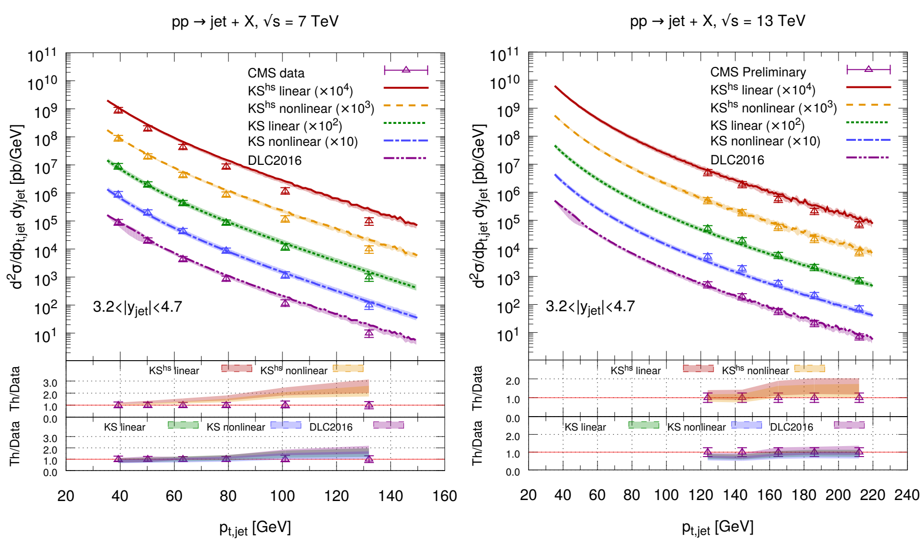

Fig. 1. Transverse momentum distribution in single inclusive forward-jet production — comparison between various gluon TMDs and the CMS data at 7 [6] and 13 TeV [7]. The error bands arise from varying the hard scale by a factor of two with respect to the central value equal to $p_{t,\text{jet}}$. Data and predictions with various gluons TMDs were multiplied by factors of 10^n.

3. Forward-dijet production

Dijets can be produced in *single-parton scattering* (SPS) or in *double-parton scattering* (DPS). In SPS, each of incoming hadrons radiates one parton which then interact through a $2 \to 2$ process, whereas in DPS, each of hadrons provides two partons that undergo two $2 \to 1$ scatterings. The good description of the inclusive jet production motivated us to study DPS effects in forward-dijet production.

3.1. Results within HEF formalism

The cross-section formula for SPS forward-dijet production reads

$$\frac{\mathrm{d}\sigma_{\mathrm{SPS}}^{pA\to\mathrm{dijets}+X}}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}p_{1\mathrm{t}}\mathrm{d}p_{2\mathrm{t}}\mathrm{d}\Delta\phi} = \frac{p_{1\mathrm{t}}p_{2\mathrm{t}}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/p}\left(x_1,\mu^2\right)\left|\overline{\mathcal{M}_{ag^*\to cd}}\right|^2 \mathcal{F}_{g/A}\left(x_2,k_\mathrm{t}^2\right)\frac{1}{1+\delta_{cd}}\,, \quad (3)$$

where

$$x_1 = \frac{1}{\sqrt{s}}\left(|p_{1\mathrm{t}}|e^{y_1}+|p_{2\mathrm{t}}|e^{y_2}\right)\,, \qquad x_2 = \frac{1}{\sqrt{s}}\left(|p_{1\mathrm{t}}|e^{-y_1}+|p_{2\mathrm{t}}|e^{-y_2}\right) \quad (4)$$

are the fractions of the longitudinal momenta of the incoming partons and

$$k_\mathrm{t}^2 = |\boldsymbol{p_{1\mathrm{t}}}+\boldsymbol{p_{2\mathrm{t}}}|^2 = p_{1\mathrm{t}}^2+p_{2\mathrm{t}}^2+2p_{1\mathrm{t}}p_{2\mathrm{t}}\cos\Delta\phi \quad (5)$$

is the transverse momentum imbalance of the jet pair, equal to the off-shellness of the gluon in the HEF formalism. $\Delta\phi$ is the azimuthal angle between the two leading jets.

A proper description of DPS requires taking into account the correlations between the two partons coming from the same hadron, contained in a set of double-parton distribution functions. Nevertheless, the recent study of Ref. [12] showed that at high scales ($Q^2 > 10^2$ GeV^2), the factorized assumption for DPS is justified, therefore, we can write

$$\frac{\mathrm{d}\sigma_{\mathrm{DPS}}^{pA\to\mathrm{dijets}+X}}{\mathrm{d}y_1\mathrm{d}^2p_{1\mathrm{t}}\mathrm{d}y_2\mathrm{d}^2p_{2\mathrm{t}}} = \frac{1}{\sigma_{\mathrm{effective}}}\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\mathrm{d}^2p_{1\mathrm{t}}}\frac{\mathrm{d}\sigma}{\mathrm{d}y_2\mathrm{d}^2p_{2\mathrm{t}}}\,, \quad (6)$$

where $\sigma_{\mathrm{effective}}$ can be interpreted as a measure of transverse correlation between two partons and is equal to 15 mb according to the recent measurement of the LHCb Collaboration [13].

The SPS contribution is expected to be dominant in high-p_{t} region of phase space, whereas the potential window to observe significant DPS effects opens for lower transverse momenta. To evaluate the impact of the DPS in forward-dijet production, we compared SPS and DPS contributions to the azimuthal-angle dependence. We used the same parton densities as for single-jet production. The expressions for matrix elements contained in (3) and (6) can be found in Ref. [9]. We expect that in the approximation we use, the DPS contribution will be just of pedestal type, changing only the overall normalization.

Calculations reveal that the relative contribution of DPS increases with softening the tranverse momentum jet cut, but it is significantly smaller than the SPS at the experimentally relevant value of 35 GeV, as shown in Fig. 2.

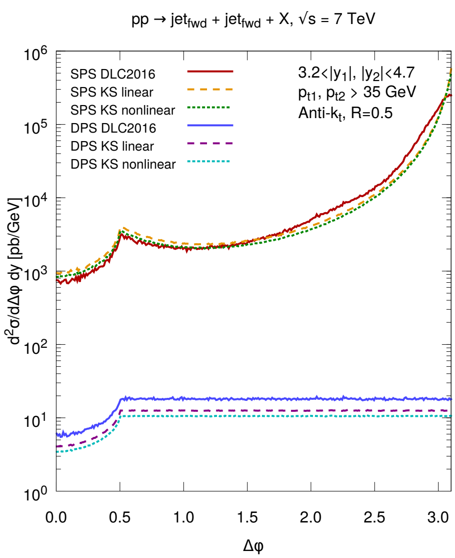

Fig. 2. SPS and DPS contribution to forward-dijet production for 35 GeV transverse momentum cut.

3.2. HEF vs. collinear factorization

In the following subsection, we compare predictions for the forward-dijet production calculated within HEF and collinear factorization. The latter were obtained using PYTHIA 8.2 MC generator.

The calculations were carried out for 7 and 13 TeV, with the cuts on the jets' momenta set to $p_{\mathrm{t},1,2} > 20$ GeV in the rapidity window $3.2 < y_1,\ y_2 < 4.9$ and CT10 NLO PDFs [8]. Jets were reconstructed using the anti-k_{t} algorithm with radius $R = 0.5$. PYTHIA generated two sets of data for each energy, distinguished by the final-state radiation (FSR) option switch on or off.

The comparison between the HEF and the collinear factorization at 13 TeV is shown in Fig. 3. The two formalisms are consistent in description of the p_{t} spectra when the FSR is turned off, while turning it on leads to a change in normalization. The spectra decrease by a factor of approx. 2 for moderate and large p_{t} values, the low-p_{t} part of the distribution seems to be almost not affected by FSR. The possible explanation of this difference in normalization is the energy loss of the leading hard parton that emits the radiation. The parton originating from the hard collision splits into two partons separated by an angle sufficient to produce two lower-p_{t} jets. As a result, the high-p_{t} events from the tail of the spectrum without FSR are moved to the region below the jet cut and they effectively do not contribute to the cross section.

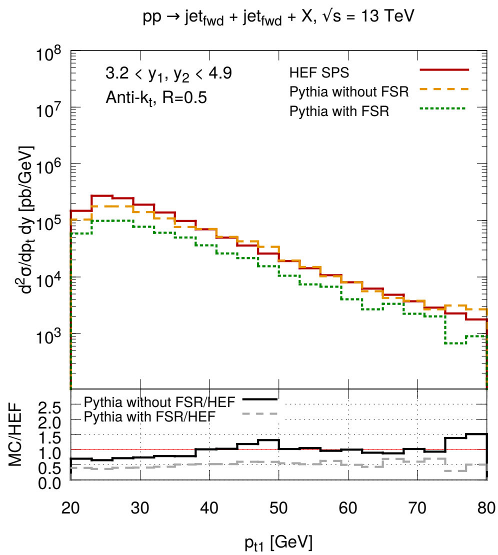

Fig. 3. Transverse momentum distribution in forward-dijet production — comparison between HEF (DLC2016) and PYTHIA.

4. Conclusions

In the present work, we studied single and double inclusive forward-jet production within two formalisms: the high-energy factorization (HEF) and the collinear factorization.

We showed that the HEF framework gives a good description of the single-jet production at the LHC at the center-of-mass energies of 7 and 13 TeV, and the main uncertainty comes from the unintegrated parton distributions. We found that for typical experimental cuts used in the forward-dijet production, the DPS contribution is very small. Finally, our study demonstrates that the effect of the final-state radiation cannot be neglected and it leads to a change of normalization of differential distributions. A more complete treatment of the subjects addressed in this proceeding can be found in [5].

The work of M.B. has been supported by the Polish National Science Centre (NCN) with Sonata Bis grant DEC-2013/10/E/ST2/00656 and by the M. Smoluchowski Cracow Scientific "Consortium Matter–Energy–Future".

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