PROCEEDINGS OF SCIENCE

Single inclusive jet production at very forward rapidity in proton-proton collisions with $\sqrt{s}$ = 7 and 13 TeV

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We report on recent result [1] of calculations of differential cross sections for single inclusive jet production at forward rapidity ($5.2 < y < 6.6$) in proton-proton collisions with $\sqrt{s} = 7$ and 13 TeV. Calculations based on high-energy factorization and k_T-dependent parton densities are compared to simulations using the PYTHIA event generator.

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects
3-7 April 2017
University of Birmingham, UK

*Speaker.

PoS(DIS2017)055

1. Introduction

The study of single inclusive forward jet production allows to investigate various aspects of hadron-hadron scattering. Jets resulting from a hard parton interaction are boosted forward if the incoming partons have a large imbalance in the fractional hadron's momenta, x, carried by the partons. Such processes are therefore ideal to test approaches that allow for studies of both high-x and low-x phenomena. Moreover, at large rapidity, the transverse momentum of the jet is kinematically bound to small values, making this process very sensitive to the modeling of the underlying event, regularization of the partonic cross section, and saturation [2] of parton densities. In particular this last phenomenon, i.e. saturation of gluons in hadrons, is one of the open problems in QCD [3]. It is related to perturbative unitarity of the QCD evolution equations and follows from constraints on the rate of growth of the cross section as the energy of the collision increases. Microscopically, saturation is an outcome of the competition between gluon splitting and gluon fusion processes, and can be theoretically described by nonlinear QCD evolution equations. Here we presents predictions of single inclusive energy, and Feynman-x spectra with rapidity $5.2 < y < 6.6$ in proton-proton collisions at $\sqrt{s} = 7$ and 13 TeV. This rapidity range allows to probe values of x as low as 10^{-6}, and corresponds to the acceptance of the CASTOR calorimeter installed at the CMS experiment [4], which has collected data at the LHC with pp collisions at various center-of-mass energies. The spectra are obtained using two frameworks: high-energy factorization (HEF) [5, 6] and collinear factorization as implemented in PYTHIA [7]. The comparison of these two frameworks offers a hint of where the predicted phenomena are universal and where they differ.

2. Numerical results

We start with calculation of the cross section single inclusive jet transverse momentum spectrum is shown in Figure 1 for center-of-mass energies $\sqrt{s} = 7$ and 13 TeV. The p_T spectrum can not be measured in the CASTOR calorimeter but it allows us to visualize the basic differences and similarities between collinear and HEF frameworks. In particular calculations with the HEF framework are compared to simulations using the PYTHIA Monte Carlo event generator for "Hard QCD" processes with only ISR included. The HEF calculations predict a suppression of the low p_T part of the spectrum with the nonlinear parton densities w.r.t. the linear ones. We attribute this effect to saturation of the unintegrated gluon density, which is indeed expected to manifest itself at low x and p_{T}. In the hybrid HEF framework justified by the boosted forward final state jet with one off-shell initial state parton, the p_{T} of the produced jet directly corresponds to the transverse momentum of the incoming parton. When one lowers the jet p_{T}, the sensitivity to the saturation scale becomes more visible. Moreover, in a fixed rapidity window, the fractional momentum x that is probed is also smaller for small jet p_{T}. The region of high jet p_{T} probes the parton densities at a scale that is much larger than the saturation scale, and the predictions based on the KS-linear gluon density and KS-nonlinear parton density [8] are therefore consistent, with both exhibiting a power law dependence. The HEF calculation does not include final state radiation and hadronization effects, while initial state radiation is taken into account via the p_{T} dependence of parton densities, as an outcome of the evolution in rapidity of the unintegrated parton density. MPI processes are also not included in this configuration. The PYTHIA predictions are remarkably parallel to the HEF

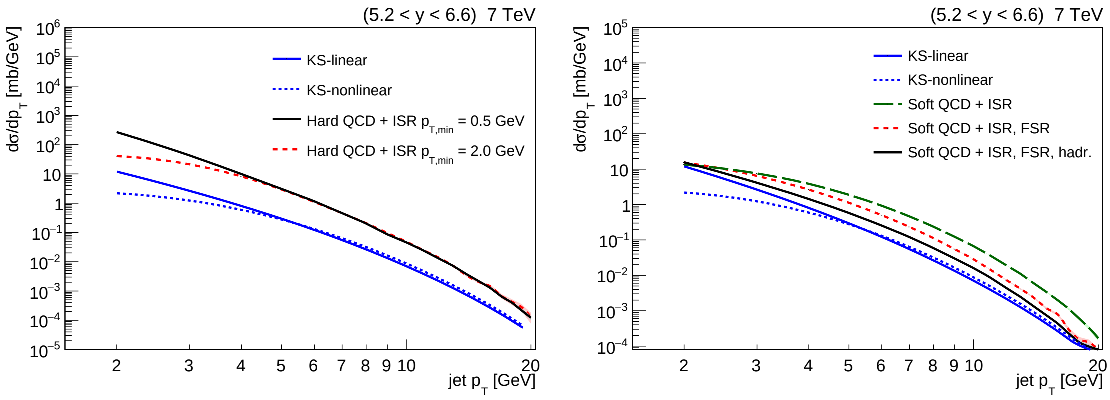

Figure 1: Differential jet cross sections as function of jet $p_{\rm T}$ at forward rapidity $5.2 < y < 6.6$ and for $\sqrt{s} = 7$ TeV (left) and 13 TeV (right). Calculations obtained with the HEF framework (labeled "KS-linear" and "KS-nonlinear") are compared to simulations obtained with PYTHIA for hard QCD processes with ISR and two different lower cutoffs on $\hat{p}_{\rm T}$, the transverse momentum scale of the hard subprocess.

calculations, and are reminiscent of the $1/\hat{p}_{\rm T}^4$ dependence of the partonic cross section. There exists however an important difference in normalization of the two calculations. It should be noted that the total inelastic cross section reported by PYTHIA is compatible with measurements only after all effects discussed below (soft regularization, MPI, etc.) are included. We observe that introducing a lower cutoff of 2 GeV on $\hat{p}_{\rm T}$ has a very similar effect as using the nonlinear KS gluon density. The qualitative agreement in the small and moderate transverse momentum domain of the HEF prediction with PYTHIA points at the consistency between the considered frameworks in re-summation of logarithms of transverse momenta when the momenta are moderate. In general one could expect that the hybrid formalism should provide relatively more high energy jets than the collinear framework. However, the results show that the predictions are rather comparable in shape. This is due to the inclusion of higher orders in the used unintegrated gluon densities following the used her KMS prescription [9] for including terms of higher orders [9]: kinematic constraints and complete splitting functions that limit the phase space for energetic emissions render the result similar to collinear factorization with initial state parton showers as implemented in PYTHIA. A more realistic description of QCD processes is available in PYTHIA via the generation of "soft QCD" collisions, including a smooth regularization of the partonic cross section and MPIs. The shape of the energy spectrum for soft QCD events is drastically different, and the resulting total inelastic cross section is much more compatible with measurements. Figures 2 and 3 also show the effect of final state radiation and hadronization as modeled in PYTHIA. Adding FSR to the simulation results in a suppression of the high energy tail of the spectrum because energy is radiated outside the jet cone. Adding hadronization effects softens the spectrum even further, which can be explained by the presence of softer particles originating from the fragmentation of partons. Some care in interpreting the results should be taken: in a fixed rapidity window, the highest-energy jets tend to be the most forward. We note that, after all effects in PYTHIA are included, the resulting spectra become remarkably similar to the prediction obtained within the HEF framework with the linear evolution equation, especially for $\sqrt{s} = 7$ TeV.

Measuring cross section ratios helps to substantially reduce experimental uncertainties, and

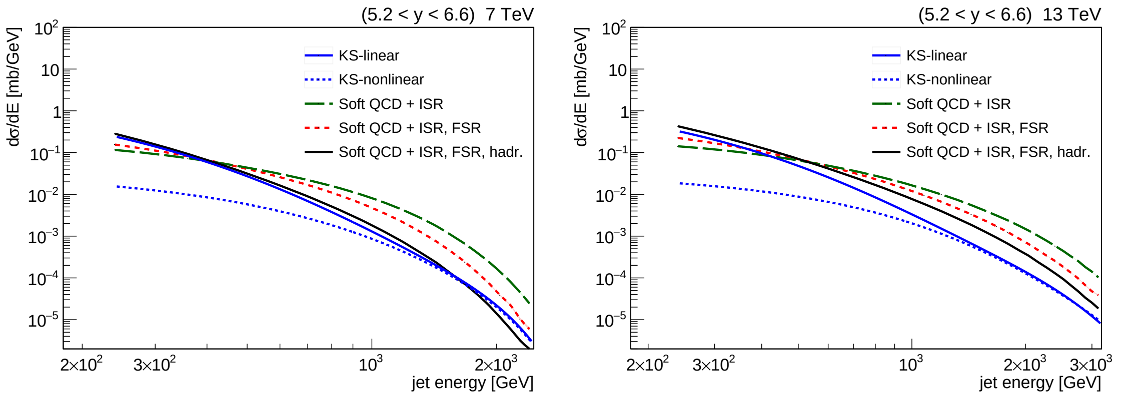

Figure 2: Differential jet cross sections as function of jet energy at forward rapidity $5.2 < y < 6.6$ and for $\sqrt{s} = 7$ TeV (left) and 13 TeV (right). Calculations obtained with the HEF framework (labeled "KS-linear" and "KS-nonlinear") are compared to simulations obtained with PYTHIA for soft QCD processes with ISR, adding subsequently FSR and hadronization.

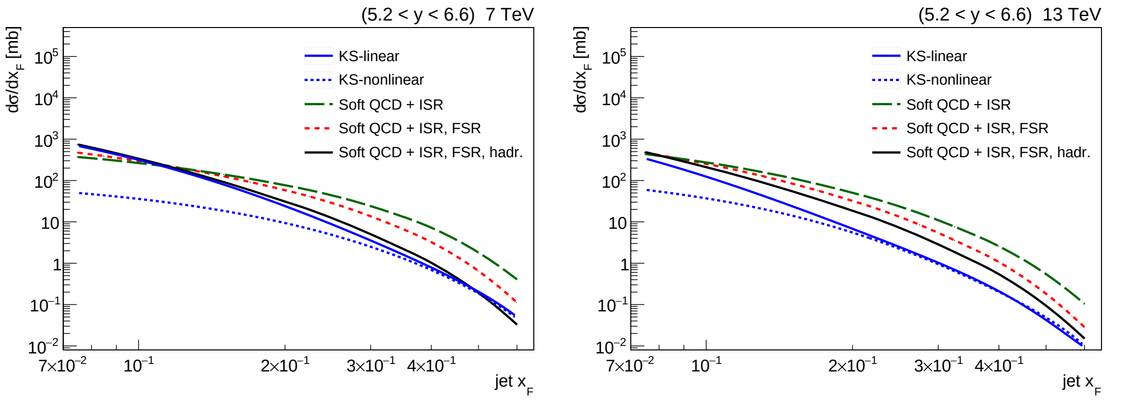

Figure 3: Differential jet cross sections as function of jet x_{F} at forward rapidity $5.2 < y < 6.6$ and for $\sqrt{s} = 7$ TeV (left) and 13 TeV (right). Calculations obtained with the HEF framework (labeled "KS-linear" and "KS-nonlinear") are compared to simulations obtained with PYTHIA for soft QCD processes with ISR, adding subsequently FSR and hadronization.

may also help to disentangle various physical phenomena because some effects cancel in the ratio while others do not. Figure 4 (left) shows the ratio of the differential cross sections at $\sqrt{s} = 13$ and 7 TeV as function of jet energy. The cross section at $\sqrt{s} = 13$ TeV is larger than the cross section at $\sqrt{s} = 7$ TeV. The ratio also increases with jet energy. As can be seen from both the HEF calculations and from the simulation of hard QCD events with PYTHIA (Fig. 4, left), the effect of saturation will largely cancel in the cross section ratio. The cross section ratio as function of x_{F} is shown in Fig. 4(right). The HEF calculation with KS-linear gluon density predicts a more or less constant cross section ratio around 0.2–0.3, with an increase at very low $x_{\mathrm{F}} \sim 0.1$. Both the HEF calculation with nonlinear evolution, and the PYTHIA simulations with regularization show a dramatic increase of the ratio below $x_{\mathrm{F}} \sim 0.3$. Of course, by taking the cross section ratio at a fixed value of x_{F}, one compares the jet cross section at very different values of p_{T} or energy for the two center-of-mass energies. For x_{F} values below 0.3 this means that one compares the jet cross

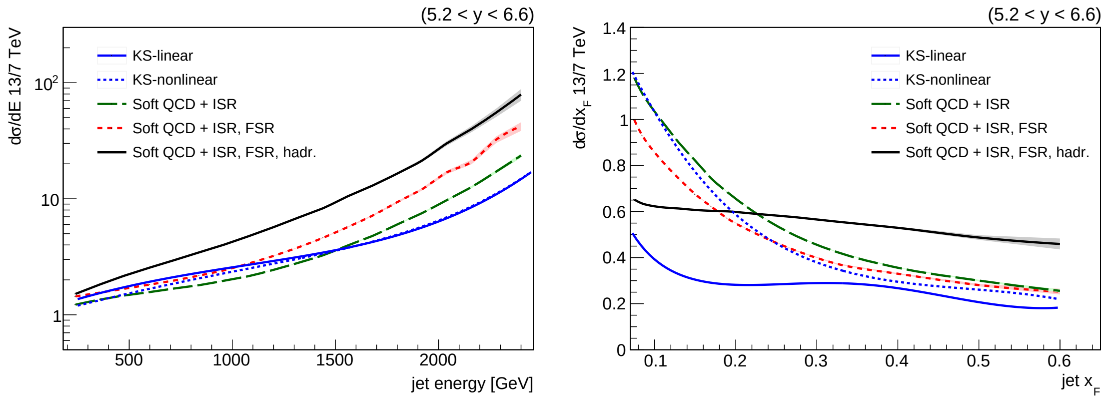

Figure 4: Ratio of the differential jet cross section at $\sqrt{s} = 13$ TeV w.r.t. $\sqrt{s} = 7$ TeV as function of jet energy (left) and x_F (right), at forward rapidity $5.2 < y < 6.6$. Calculations obtained with the HEF framework (labeled "KS-linear" and "KS-nonlinear") are compared to simulations obtained with PYTHIA for soft QCD processes with ISR, FSR, and hadronization.

section at 7 TeV in the saturation/regularization domain to the jet cross section at 13 TeV at larger p_T, hence the sharp increase of the ratio. Remarkably, this effect is smoothed out by hadronization, because the softening of the spectrum at larger p_T by hadronization is less pronounced at $\sqrt{s} = 13$ TeV. The cross section ratio predicted by PYTHIA with all effects included is therefore again flat as a function of x_F, albeit at a larger value of around 0.5–0.6.

Acknowledgements

I would like to thank the conveneers and in particular Anna Stasto for inviting me to present the results. The research was supported by common FWO-PAS grant.

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