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Jet production and the inelastic pp cross section at the LHC

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We suggest that, if current measurements of inclusive jet production for central rapidities at the LHC are extended to lower transverse momenta, one could define a visible cross section sensitive to the unitarity bound set by the recent determination of the inelastic proton-proton cross section.

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Hadronic jet cross sections are being explored at the Large Hadron Collider (LHC) [1,2] across a kinematic range much wider than at any previous collider experiment, with the jets being measured either by calorimeters or by trackers.

The inclusive one-jet cross section at central rapidities is well described by next-to-leading order QCD calculations and shower Monte Carlo event generators [3] over a wide range in transverse momenta from 20 GeV to 2 TeV. For the case of forward rapidities and less inclusive jet observables see, e.g., discussions in Refs. [4,5].

In this note we suggest that if the jet measurement for central rapidities is extended to lower but still perturbative transverse momenta one can define a visible jet cross section sensitive to the bound set by the inelastic proton-proton rate which has recently been measured at the LHC [6–8]. We observe that this can be done within the range of acceptance of the measurement without using any extrapolation.

We start by briefly recalling the physical picture and Monte Carlo estimates [9–13] for the increase in the partonic cross section at low transverse momenta. Then we consider measuring jets in the low-momentum region, and introduce the visible jet cross section. We present numerical estimates and comment on physical implications of the proposed measurements.

To begin, consider the basic physical picture for jet production in the high-energy limit. In this limit the dynamics is driven by the growth of gluon densities at low momentum fractions $x \sim (p_T/\sqrt{s})e^{-y}$, where p_T and y are the jet transverse momentum and rapidity, and $\sqrt{s}$ is the center-of-mass energy. As the energy increases, the jet cross section rises, and eventually the perturbative prediction obtained from integrating the cross section over transverse momenta above a given p_T is higher than the inelastic pp cross section. The value of p_T at which this occurs depends on the parton density and the center-of-mass energy. At the LHC, for the first time, such a p_T value approaches the weakly coupled region, $p_T = \mathcal{O}(10)$ GeV [10], owing to the high center-of-mass energy and the associated wide rapidity phase space.

Dynamical effects slowing down the rise of the cross section go beyond the QCD parton model approximations valid at large transferred momenta. Even though at weak coupling, they involve strong fields and nonperturbative physics. At phenomenological level, this constitutes the motivation for multiparton interaction models [9–13] in shower Monte Carlo event generators for event simulation of final states. However, fundamental aspects of these processes are little known. In addition, although all collider Monte Carlo models appear to require multiparton interactions to explain various features of pp data, the experimental evidence for double parton scatterings is still weak.

We here propose appealing to the measurements [6–8] to investigate the leading jet cross section near the p_T region where the inelastic pp production rate is saturated. This region requires jets at low p_T and therefore only jets constructed from charged tracks can experimentally be employed. In addition, forward high-p_T particle production is copious at the LHC and poses special issues. On the experimental side, particle tracking capabilities decay with increasing rapidity [14]. On the theory side, QCD predictions are affected by all-order logarithmic corrections [4,5,15,16] increasing with rapidity. We thus focus on the central pseudorapidity range. In this region the *visible* inelastic cross section has been measured by ATLAS and CMS [6–8], giving a value of $\sigma_{\rm inel} \sim 60$ mb at $\sqrt{s} = 7$ TeV, depending on the precise definition of the visible phase space. No extrapolation is needed for this to be compared with the jet cross section proposed here.

First, we consider the parton-level cross section at $\sqrt{s} = 8$ TeV (calculated using PYTHIA (version 6.425) [9]). Figure 1 (left) shows the estimate obtained from the $2 \rightarrow 2$ integrated cross section as a function of the minimum transverse momentum:

$$\sigma(p_{T\min}) = \int_{p_{T\min}} dp_T^2 \int_{-\infty}^{\infty} dy \frac{d^2\sigma}{dp_T^2 dy} = \int_{p_{T\min}} dp_{T\rm jet}^2 \int_{-\infty}^{\infty} dy_{\rm jet} \frac{d^2\sigma_{\rm jet}}{dp_{T\rm jet}^2 dy_{\rm jet}}, \qquad (1)$$

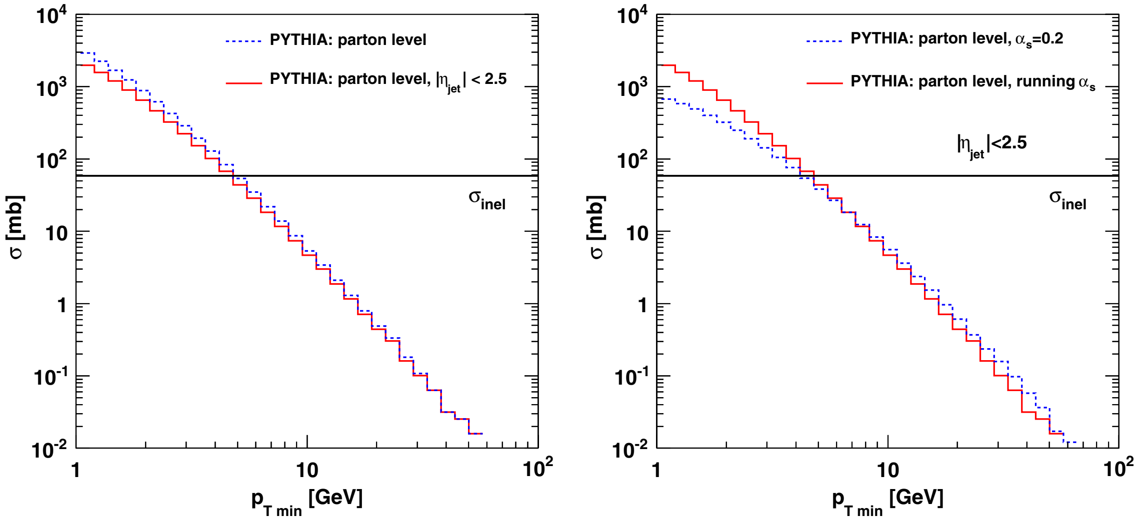

FIG. 1 (color online). Integrated cross sections at $\sqrt{s} = 8$ TeV as a function of the minimum transverse momentum: (left) inclusive cross section compared to what can be investigated within $|\eta| < 2.5$; (right) visible inclusive cross section in $|\eta| < 2.5$ compared to the prediction with fixed $\alpha_s = 0.2$.

where the last expression gives an operational definition of $\sigma(p_{T\,\mathrm{min}})$ in terms of a measurable leading jet cross section σ_{jet}. Note that the cross section defined here as the integral over the differential leading jet cross section is an event cross section, which does not depend on the jet multiplicity. In Fig. 1 (left) we define the visible range by restricting the integration to the pseudorapidity region $|\eta| < 2.5$. For comparison we plot the measurement [6–8] of the inelastic cross section as a horizontal line. One can clearly see that the partonic cross section exceeds the inelastic cross section at values of the transverse momentum at around 4–5 GeV even in the restricted η range. In Fig. 1 (right) we also show the cross section with $|\eta| < 2.5$ using a fixed value of $\alpha_s = 0.2$. This illustrates that the infrared behavior of the strong coupling does not significantly affect the physical picture in the p_T region where the jet cross section approaches the inelastic bound. The rise of the cross section is essentially coming from the $1/t^2$ pole of the partonic matrix element, as explained in Ref. [10].

We then consider the cross section of jets at particle level. We suppose measuring jets at low transverse momenta in the visible range $|\eta| < 2.5$. In order to reconstruct the jets we use the anti-k_T algorithm [17] with $R = 0.5$ down to low transverse momenta. The visible jet cross section is shown in Fig. 2 using PYTHIA [9]. The solid line corresponds to the partonic cross section (of Fig. 1). We show the effect of turning on successively intrinsic k_t, initial and final state parton showers (IFPS) and finally hadronization (using default parameters, without allowing

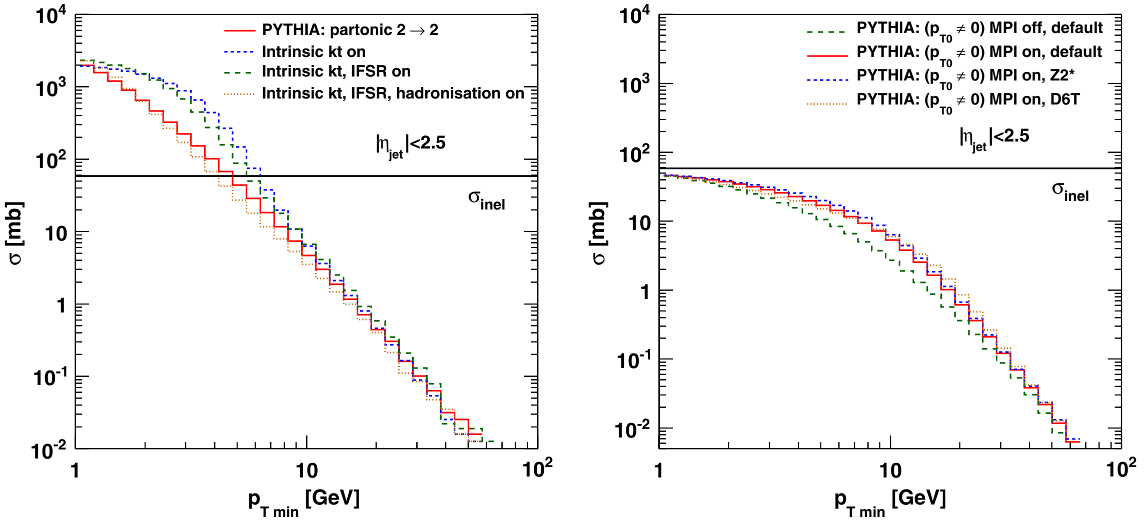

FIG. 2 (color online). (Left) Cross section from purely partonic $2 \rightarrow 2$ process, including intrinsic k_t effects, including IFPS and finally hadronization. (Right) Predicted cross section applying $p_{T0} \neq 0$ and MPI with different underlying event tunes of PYTHIA.

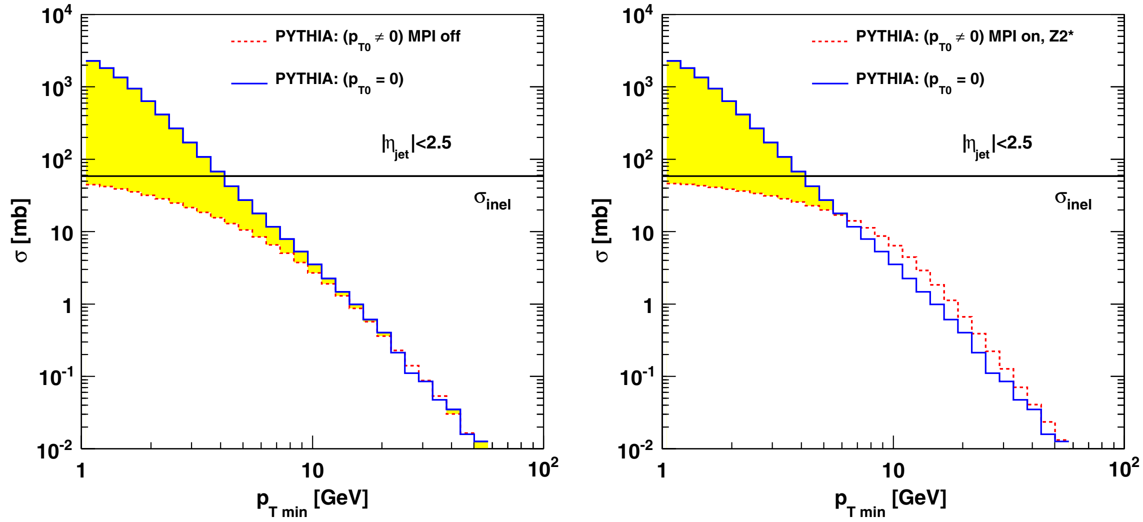

FIG. 3 (color online). The cross section as a function of $p_{T\,\mathrm{min}}$ as predicted by PYTHIA in the range $|\eta| < 2.5$. The solid (blue) line shows the prediction applying $p_{T0} = 0$ including parton shower and hadronization, while the dashed (red) line shows the prediction with $p_{T0} \neq 0$, shown without multi-parton interactions (left) and including multi-parton interactions with tune Z2* (right) [20].

a taming of the cross section). In Fig. 2 (left) the perturbative result reaches the inelastic bound [6] for minimum $p_T \simeq 4$ GeV. In the region just above this value, $p_T = \mathcal{O}(10)$ GeV, effects responsible for the taming of the cross section set in. The model [10,18] provides a phenomenological modification of the low-p_T behavior of the jet cross section within a collinearly-factorized framework; the rise of the cross section is tamed at small values of p_T by introducing a factor,

$$\frac{\alpha_s^2(p_{T0}^2 + p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}, \qquad (2)$$

where p_{T0} is a parameter obtained from a fit to describe measurements of the underlying event. In Fig. 2 (right) we show the cross section based on Eq. (2) as well as the effect of multiparton interactions (MPI). The prediction of tune D6T [19] and Z2* are also shown. The Z2* tune is an updated version of the Z1 tune [20], based on automated tuning and using the CTEQ6L PDF [21]. In the Z2* tune PARP(82) = 1.92 and PARP(90) = 0.23. Besides the leading jet cross section, it will also be interesting to measure the fraction of events with more than one jet, as a function of the cut in p_T, in the same p_T range.

Note that in approaches that go beyond the collinear approximation [11–13,15,16,22–24] the low-p_T behavior comes from two different sources: first, the perturbative matrix elements, which are computed at finite transverse momenta k_T in the initial state, have the standard collinear rise [9] at low p_T for $k_T \ll p_T$ but a slower rise for $k_T \simeq p_T$ [15,16,23,24]; second, the unintegrated parton densities enhance the relative weight of finite transverse momentum contributions compared to collinearly-ordered contributions, due to both Sudakov and Regge suppression of the low-k_T region [11,12,23,24]. The jet measurements suggested in this paper may be useful to investigate k_T-dependent dynamical effects. In Fig. 3 we show a comparison of the jet cross section for $p_{T0} = 0$, including parton shower and hadronization, with the cross section obtained from PYTHIA including the model of Eq. (2). In Fig. 3 (right) we show the effect of multiparton interactions. Especially in the region of $p_T < 10$ GeV a clear deviation from the $p_{T0} = 0$ prediction is visible. A measurement of the jet cross section in the low-p_T region would give insight into the transition from the perturbative jet cross section at large p_T to the small-p_T region where additional effects are needed to avoid unitarity violation. Besides pp collisions, the jet measurements proposed may be extended to collisions of nuclei. If the inelastic cross section is measured in AA and pA, they may be useful to characterize properties of final states in terms of jets or flows, and investigate the role of k_T-dependent effects and multiple interactions in ion collisions.

In summary, we have proposed measurements of the visible jet cross section at the LHC by using jets down to transverse momenta of the order of a few GeV. Such measurements require a handle on jet algorithms and jet reconstruction capabilities in the low-p_T region. Without extrapolation, they could be related to the measurement [6–8] of the inelastic pp cross section. The jet cross section measurement in the proposed p_T region probes weak-coupling but still nonperturbative QCD physics. It is relevant for the phenomenology of multiparton interaction models in shower Monte Carlo generators. It can provide new experimental information on transverse-momentum-dependent correlations between initial and final states of partonic collisions.

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