Low-x QCD studies with forward jets in p-p at 14 TeV

Salim Cerci¹,* and David d’Enterria²,†
for the CMS collaboration

¹ Cukurova University, Adana, Turkey and
² CERN, CH-1211 Geneva 23, Switzerland

The Large Hadron Collider will provide hadronic collisions at energies in the multi-TeV range, never explored before. The parton fractional momenta probed at such energies can be as low as \( x \approx 2p_T/\sqrt{s} e^{-y} \approx 10^{-5} \) at large rapidities \( y \), opening up attractive opportunities for low-x QCD studies. The combination of the CMS HF (\( 3<|\eta|<5 \)) and CASTOR (\( 5.1<|\eta|<6.6 \)) calorimeters allows one, in particular, to reconstruct very forward jets. We present generator-level studies of the CMS capabilities to measure the single inclusive forward jet spectrum and forward-backward (Mueller-Navelet) dijets in p-p collisions at 14 TeV. Both observables are sensitive to low-x gluon densities and non-linear QCD evolution.

I. INTRODUCTION

The parton distribution functions (PDFs) in the proton have been studied in detail in deep-inelastic-scattering (DIS) \( ep \) collisions at HERA [1]. For decreasing parton momentum fraction \( x = p_{\text{parton}}/p_{\text{hadron}} \), the gluon density is observed to grow rapidly as \( xg(x, Q^2) \propto x^{\lambda(Q^2)} \), with \( \lambda \approx 0.1-0.3 \) rising logarithmically with \( Q^2 \). As long as the densities are not too high, this growth is described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) [2] or by the Balitski-Fadin-Kuraev-Lipatov (BFKL) [3] evolution equations which govern, respectively, parton radiation in \( Q^2 \) and \( x \). Eventually, at high enough centre-of-mass energies (i.e. at very small \( x \)) the gluon density will be so large that non-linear (gluon-gluon fusion) effects will become important, saturating the growth of the parton densities [4]. Studies of the high-energy (low-x) limit of QCD have attracted much theoretical interest in the last 10–15 years, in the context of DIS and of nucleus-nucleus collisions [5]. Experimentally, direct information on the parton structure and evolution can be obtained in hadron-hadron collisions from the perturbative production of e.g. jets or prompt \( \gamma \)'s, which are directly coupled to the parton-parton scattering vertex. From leading-order (LO) kinematics, the rapidities and momentum fractions of the two colliding partons are related via

\[
x_2 = (p_T/\sqrt{s}) \cdot (e^{-y_1} + e^{-y_2}) \quad \text{and} \quad x_1 = (p_T/\sqrt{s}) \cdot (e^{y_1} + e^{y_2}).
\]

The minimum momentum fractions probed in a \( 2 \rightarrow 2 \) process with a particle of momentum \( p_T \) produced at pseudo-rapidity \( \eta \) are

\[
x_2^{\text{min}} = \frac{x_T e^{-\eta}}{2 - x_T e^\eta} \quad \text{and} \quad x_1^{\text{min}} = \frac{x_2 x_T e^\eta}{2x_2 - x_T e^{-\eta}}, \text{ where } x_T = 2p_T/\sqrt{s},
\]

i.e. \( x_2^{\text{min}} \) decreases by a factor of \( \sim 10 \) every 2 units of rapidity. From Eq. (2), it follows that the measurement of jets with transverse energy \( E_T \approx 20 \text{ GeV} \) in the CMS forward calorimeters (HF, \( 3<|\eta|<5 \)) and CASTOR, \( 5.1<|\eta|<6.6 \)) will allow one to probe \( x \) values as low as \( x_2 \approx 10^{-5} \). Figure 1 shows the actual log\((x_1, x_2)\) distribution for two-parton scattering in p-p collisions at 14 TeV producing at least one jet above 20 GeV in the HF and CASTOR acceptances. We present here generator-level studies of two forward-jet measurements in CMS sensitive to small-x QCD [6].

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1. single inclusive jet cross section in HF at moderately high virtualities \( (E_T \approx 20 \text{–} 100 \text{ GeV}) \),

2. differential cross sections and azimuthal (de)correlation of “Mueller-Navelet” (MN) \cite{7} dijet events, characterized by jets with similar \( E_T \) separated by a large rapidity interval \( (\Delta \eta \approx 10) \).

The first measurement is sensitive to the low-\( x_2 \) (and high-\( x_1 \)) proton PDFs, whereas the second one yields information on BFKL- \cite{7,8,9,10} and saturation- \cite{11,12} type dynamics.

![Image](image_url)

**FIG. 1:** log(\( x_{1,2} \)) distribution of two partons producing at least one jet above \( E_T = 20 \text{ GeV} \) within HF \((3 < |\eta| < 5, \text{ left})\) and CASTOR \((5.1 < |\eta| < 6.6, \text{ right})\) in p-p collisions at \( \sqrt{s} = 14 \text{ TeV} \) \cite{6}.

### II. EXPERIMENTAL SETUP

The combination of HF, TOTEM, CASTOR and ZDC (Fig. 2) makes of CMS the largest acceptance experiment ever built at a collider. Very forward jets can be identified using the HF \cite{13} and CASTOR \cite{14} calorimeters. The HF, located 11.2 m away on both sides of the interaction point (IP), is a steel plus quartz-fiber Čerenkov calorimeter segmented into 1200 towers of \( \Delta \eta \times \Delta \phi \sim 0.175 \times 0.175 \). It has 10\( \lambda_I \) interaction lengths and is sensitive to deposited electromagnetic (EM) and hadronic (HAD) energy. CASTOR is an azimuthally symmetric EM/HAD calorimeter placed at 14.37 m from the IP, covering \( 5.1 < |\eta| < 6.6 \). The calorimeter is a Čerenkov-light device, with successive layers of tungsten absorber and quartz plates as active medium arranged in 2 EM (10 HAD) sections of about \( 22X_0 \) \((10.3\lambda_I)\) radiation (interaction) lengths.

### III. FORWARD JETS RECONSTRUCTION IN HF

Jets in CMS are reconstructed at the generator- and calorimeter-level using 3 different jet algorithms \cite{15}: iterative cone \cite{16} with radius of \( R = 0.5 \) in \((\eta, \phi)\), SISCone \cite{17} \((R = 0.5)\), and the Fast-\( k_T \) \cite{18} \( (E_{\text{seed}} = 3 \text{ GeV} \text{ and } E_{\text{thres}} = 20 \text{ GeV}) \). The Monte Carlo samples used in this analysis were part of the official CMS QCD-jets simulation using PYTHIA \cite{19} in seven 1M-events \( \hat{p_T} \) bins across the \( E_T = 15 \text{–} 230 \text{ GeV} \) range. Events are selected where at least one jet above 20 GeV falls in the forward HF acceptance. The matching radius between generated and reconstructed jets, for reconstruction performance studies, is set at \( \Delta R = 0.2 \). The \( E_T \) resolutions for the three
differing algorithms are very similar: \( \sim 18\% \) at \( E_T \sim 20 \text{ GeV} \) decreasing to \( \sim 12\% \) for \( E_T \gtrsim 100 \text{ GeV} \) (Fig. 3 left). The position \((\eta, \phi)\) resolutions (not shown here) for jets in HF are also very good: \( \sigma_{\phi,\eta} = 0.045 \) at \( E_T = 20 \text{ GeV} \), improving to \( \sigma_{\phi,\eta} \sim 0.02 \) above 100 GeV. The forward jet energy scale uncertainty is, however, expected to be relatively large (in the range 10\%–3\% in the same \( E_T \) range) [16].

IV. SINGLE INCLUSIVE FORWARD JET MEASUREMENT

Figure 3 right shows the single jet spectrum expected in both HFs for 1 pb\(^{-1}\) integrated luminosity obtained at the parton-level from PYTHIA for two different PDF sets (CTEQ5L and MRST03) compared to a NLO calculation (CTEQ6M, \( R = 0.5, \mu = 0.5E_T - 2E_T \)) [20]. The single jet spectra obtained for different PDFs are similar at high \( E_T \), while differences as large as \( \mathcal{O}(60\%) \) appear below \( \sim 60 \text{ GeV} \). The measurement of low-\( E_T \) forward jets in HF seems in principle feasible: the statistical errors are negligible and the HF energy resolution is very good (Fig. 3 left). Yet, in the “interesting” low-\( E_T \) range, the main experimental issue will be the control of the jet-energy scale whose uncertainty propagates into up to \( \pm 40\% \) differences in the final jet yield. Use of this measurement to constrain the proton PDFs in the low-\( x \) range will thus require careful studies of the HF jet calibration.

V. MUELLER-NAVELET (MN) DIJETS MEASUREMENT

Inclusive dijet production at large pseudorapidity intervals in high-energy hadron-hadron collisions has been since long considered an excellent testing ground for BFKL [7, 8, 9, 10] and also for saturation [11, 12] QCD evolutions. Both colliding partons in the MN kinematics are large-\( x \) valence quarks \((x_1, x_2 \approx 0.2)\), which produce two jets with transverse energies \( E_{T, i} \) with a large rapidity interval between them:

\[
Y = \log(x_1 x_2 s/(Q_1 Q_2)) ,
\]

where \( Q_i \approx E_{T, i} \) are the corresponding parton virtualities. The presence of a large rapidity separation \((Y = \Delta \eta)\) between jets enhances the available phase-space in longitudinal momentum for extra BFKL-type radiation. In CMS, jet rapidity separations as large as \( \Delta \eta \approx 12 \) are accessible.
combining both HF and CASTOR opposite hemispheres. As a proof of principle, we have reanalyzed the PYTHIA jet samples discussed in the previous Section, and selected events which satisfy the following Mueller-Navelet-type selection cuts:

- $E_{T,i} > 20$ GeV
- $|E_{T,1} - E_{T,2}| < 5$ GeV (similar virtuality, $Q \approx \sqrt{E_{T,1} \cdot E_{T,2}}$, to minimise DGLAP evolution)
- $3 < |\eta_{i,2}| < 5$ (both jets in HF)
- $\eta_1 \cdot \eta_2 < 0$ (each jet in a different HF)
- $||\eta_1| - |\eta_2|| < 0.5$ (almost back-to-back in pseudo-rapidity)

The data have been divided into 4 equidistant HF pseudorapidity bins and the dijet cross sections in each $\eta$ bin computed as $d^2\sigma/d\eta dQ = N_{jets}/(\Delta \eta \Delta Q \int dt)$, where $N$ is the observed number of jets in the bin and 1 pb$^{-1}$ the assumed integrated luminosity. The left plot in Fig. 4 shows the expected dijet yields passing the MN kinematics cuts as a function of $Q$ for the pseudo-rapidity separation $\Delta \eta \approx 8$. The obtained MN dijet statistics appears large enough to carry out detailed studies of the $\Delta \eta$ dependence, that would e.g. provide evidence for a possible Mueller-Navelet “geometric scaling” behaviour [12]. An enhanced azimuthal decorrelation for increasing rapidity separation between the Mueller-Navelet jets is the classical “smoking-gun” of BFKL radiation [8, 9, 10]. The generator-level $\Delta \phi$ jet distributions are plotted in the right plot of Fig. 4 for $\Delta \eta = 7.5, 8.5$ and 9.5. The peak at $\Delta \phi = (\phi_1 - \phi_2) - \pi = 0$ indicates that the two jets are highly correlated with each other. As the $\Delta \eta$ between the two jets increases, the peaks diminish and the distributions get increasingly larger, signaling a loss in correlation. Since PYTHIA is a leading-order generator without any BFKL (or saturation) effect, the observed azimuthal decorrelation is just due to parton shower effects and initial- or final-state radiation. Such a result provides, thus, a baseline of the minimal decorrelation expected in non-BFKL scenarios. Detailed simulation studies are ongoing to test the sensitivity of such forward jet measurements to signal (or not) the presence of “genuine” low-$x$ decorrelations.
FIG. 4: Dijet events passing the Mueller-Navelet cuts described in the text. Left: Expected yields (in 1 pb$^{-1}$) for a separation $\Delta \eta \approx 8$ \cite{6}. Right: $\Delta \phi$ distributions for jet separations $\Delta \eta = 7.5$, 8.5 and 9.5.

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