Physics with forward jets in ATLAS, CMS and LHCb

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The capabilities of the ATLAS, CMS and LHCb detectors to reconstruct jets at forward rapidities ($|\eta| > 3$) in *p-p* collisions at the CERN Large Hadron Collider are reviewed. The QCD and Higgs physics motivations for such measurements are summarised. Details are given on studies that provide information on the parton structure and evolution at small values of fractional momenta in the proton.

1 Introduction

The ATLAS, CMS and LHCb experiments[1] feature detection capabilities at forward rapidities ($|\eta| > 3$, see Fig. 1 left) which allows them to reconstruct jets in a kinematic range of interest for various Higgs and QCD physics studies in *p-p* collisions at TeV energies.

On the one hand, having the possibility to reconstruct jets beyond $|\eta| \approx 3$ in ATLAS and CMS is crucial to signal Higgs boson production in vector-boson-fusion (VBF) processes, $qq \xrightarrow{VV} qqH$ (with $V = W, Z$), where the valence quarks q from each proton fragment into jets in the forward and backward hemispheres [2]. The presence of such low-angle jets is instrumental to significantly reduce the QCD backgrounds in various VBF Higgs discovery channels at the LHC, particularly for low H masses [3, 4]. In the case of LHCb, given the excellent secondary vertex capabilities of the detector, forward jet studies have focused on the reconstruction of b-jets aiming at the $H \to b\bar{b}$ decay channel in Higgs production associated with vector bosons (about one third of the cross section falls within the LHCb acceptance) [5].

On the other hand, forward jet production is in its own right an interesting perturbative QCD (pQCD) process whose study yields important information on the underlying parton structure and its dynamical evolution in the proton. In particular, it provides valuable information on the gluon density $xG(x, Q^2)$ in a regime of low momentum fraction, $x = p_{parton}/p_{hadron} < 10^{-2}$, where standard deep-inelastic *e-p* data can only indirectly constrain its value [6], and where its evolution is expected to be affected by non-linear QCD dynamics [7]. Indeed, in *p-p* collisions, the *minimum* parton momentum fractions probed in each proton in a $2 \to 2$ process with a jet of momentum p_T produced at pseudo-rapidity η are

$$x_2^{min} = \frac{x_T\, e^{-\eta}}{2 - x_T\, e^{\eta}} \;, \quad \text{and} \quad x_1^{min} = \frac{x_2\, x_T\, e^{\eta}}{2x_2 - x_T\, e^{-\eta}} \;, \text{ where } \quad x_T = 2p_T/\sqrt{s}\,, \tag{1}$$

[1]ALICE has jet reconstruction capabilities at central [1] but not forward rapidities.

i.e. x_2^{min} decreases by a factor of ∼10 every 2 units of rapidity. The extra e^{η} lever-arm motivates the interest of *forward* jet production measurements to study the PDFs at small values of x. From Eq. (1), it follows that the measurement at the LHC of jets with transverse momentum $p_T = 20$ GeV/c at rapidities $\eta \approx 5$ allows one to probe x values as low as $x_2 \approx 10^{-5}$ in partonic collisions with highly asymmetric longitudinal momenta in the initial-state (Fig. 1, right).

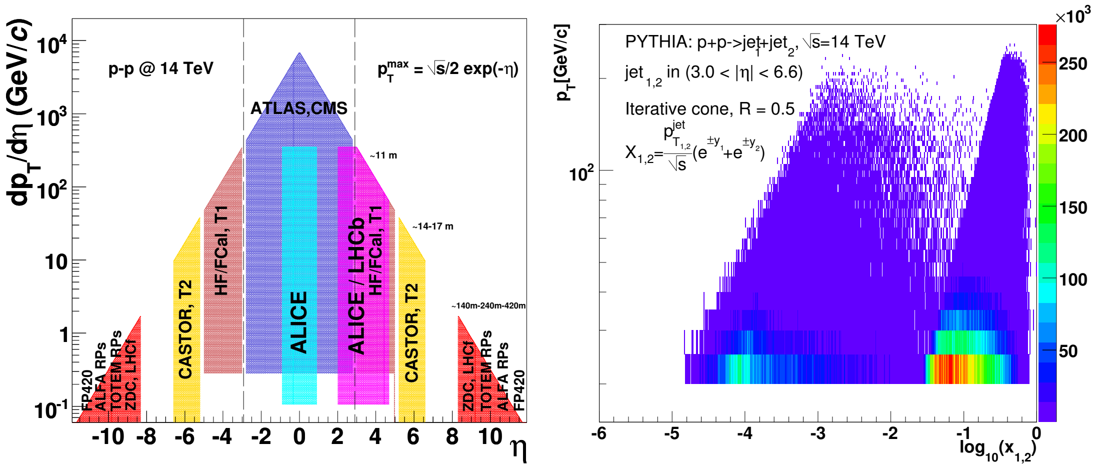

Figure 1: Left: Acceptance of the LHC detectors in the p_T–η plane ('forward' detectors are beyond the dashed vertical line) [8]. Right: Log($x_{1,2}$) distribution of two partons producing at least one jet above $p_T = 20$ GeV/c at forward rapidities in p-p collisions at $\sqrt{s} = 14$ TeV [9].

In this contribution we summarise first the forward jet reconstruction capabilities of the three LHC experiments (Section 2) and, then, in Sections 3 and 4 we present simulation studies of two CMS forward-jet measurements [9]:

1. single inclusive jet cross section at moderate transverse momenta ($p_T \approx$ 20 − 120 GeV/c),
2. azimuthal (de)correlations of "Mueller-Navelet" [10] dijet events, characterised by jets with similar p_T separated by a large rapidity interval ($\Delta\eta \approx 6 - 10$),

which are sensitive, respectively, to the small-x_2 (and high-x_1) proton PDFs, as well as to low-x QCD evolution of the BFKL [11], CCFM [12] and/or saturation [7] types.

2 Experimental Performances

In ATLAS and CMS, jets can be reconstructed calorimetrically at forward rapidities in the FCal [13] and HF [14] calorimeters[2] (3< $|\eta|$ <5), by means of standard jet algorithms of the cone or sequential-clustering types [16]. The jet radii are often chosen relatively small (e.g. $\mathcal{R} = 0.5$ for the cone and $D = 0.4$ for the k_T algorithms) so as to minimise the effects of hadronic activity inside the jet due to the underlying event and beam-remnants. Figure 2

[2] In addition, in CMS one can further extend jet reconstruction up to $|\eta| \approx 6.6$ with the CASTOR detector [15].

(left) shows the energy resolution for forward jets reconstructed in CMS with three different algorithms (iterative cone, SISCone and k_T) [9]. The obtained p_T relative resolutions are of $\mathcal{O}(20\%)$ at 20 GeV/c decreasing to 10% above 100 GeV/c. Similar results are obtained for ATLAS [17]. We note that though the forward calorimeters have a coarser granularity than the barrel and endcap ones, the energy resolution is *better* in the forward direction than at central rapidities because (i) the *total* energy of the jet is boosted at forward rapidities, and (ii) the forward jets are more collimated and, thus, the ratio of jet-size/detector-granularity is more favourable. The position (η, ϕ) resolutions (not shown here) for forward jets are also very good: $\sigma_{\phi,\eta} \approx 0.045$ at $p_T = 20$ GeV/c, improving to $\sigma_{\phi,\eta} \approx 0.02$ above 100 GeV/c [9]. Good ϕ-η resolutions are important when it comes to detailed studies of the azimuthal decorrelation as a function of the pseudorapidity separation in events with forward-backward dijets (see Section 4). Figure 2 (right) shows the efficiency and purity of forward jets reconstructed with the seeded cone finder ($\mathcal{R} = 0.4$) in the ATLAS FCal calorimeter [17]. Above ∼35 GeV/c, the efficiency saturates at around 95% with a purity below 4%.

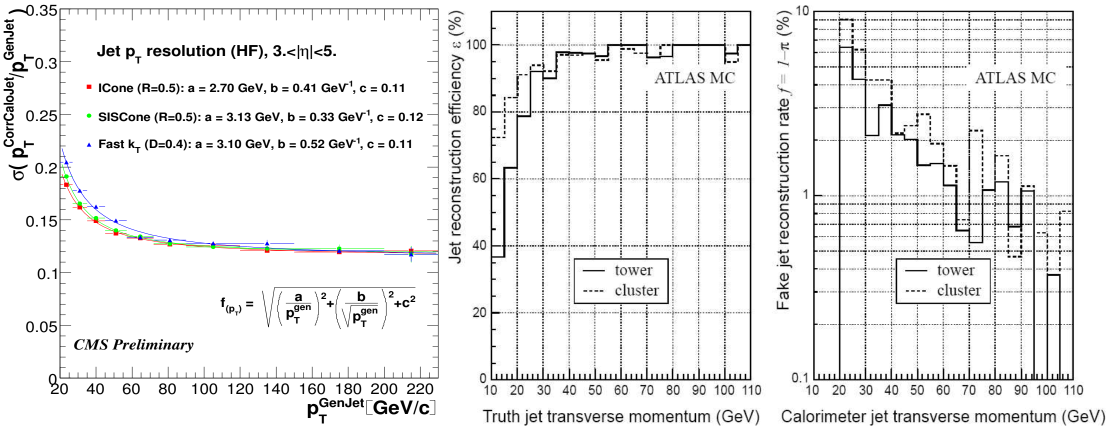

Figure 2: Left: Forward jet relative p_T resolutions for various jet algorithms in the CMS HF calorimeter [9]. Right: Forward jet reconstruction efficiency as function of the true jet p_T, and fake reconstruction rate versus the reconstructed jet p_T in the ATLAS FCal calorimeter [17].

In LHCb, jet reconstruction has focused on b-jets given the excellent vertexing capabilities of the detector. The physics motivation is so far centered on the measurement of the $H \to b\bar{b}$ channel for intermediate-mass Higgs production associated with vector bosons (30% of such a signal falls within the LHCb acceptance) [5]. Both seeded-cone- and k_T-algorithms have been tested including information from the calorimeters and the tracking devices in a "particle flow" type of approach. A neural-network is trained to identify b-jets and optimise the jet energy reconstruction. The main current limitation of the measure is the saturation of the calorimeters (designed originally mostly for single particle triggering/measurements at low and moderate p_T's) for jets with total energy beyond $E_{tot} \approx 1.5$ TeV (i.e. $p_T \approx 20 - 150$ GeV/c for $\eta \approx 3 - 5$) given the very strong $\cosh(\eta)$ energy boost at large rapidities.

3 Inclusive Forward Jet Spectrum: Low-x PDFs

Figure 3 (left) shows the forward jet p_T spectrum generated with PYTHIA and reconstructed in the CMS HF calorimeter with the SISCone finder [9]. The spectrum is compared to fastNLO jet predictions [18] with the MRST03 and CTEQ6.1M PDFs. The right plot shows the percent differences between the reconstructed spectrum and the two theoretical predictions. The single jet spectra obtained for different PDFs are similar at high p_T, while differences as large as $\mathcal{O}(60\%)$ appear below $\sim$60 GeV/c. The error bars include the statistical (a total integrated luminosity of 1 pb^{-1} is assumed) and the energy-resolution smearing errors. The thin violet band around zero is the PDF uncertainty from the CTEQ6.1M set alone. The main source of systematic uncertainty is due to the calibration of the jet energy-scale (JES). Assuming a conservative $5 - 10\%$ JES error, one finds propagated uncertainties of the order $30 - 40\%$ in the jet yields at $p_T = 35 - 60$ GeV/c (yellow band) which are similar to the theoretical uncertainty associated to the PDF choice. If the JES can be improved at the 5% level or below, and the PDF uncertainties are indeed as large as the differences between MRST03 and CTEQ6M, a forward jet measurement could help constrain the underlying PDF in global-fit analyses.

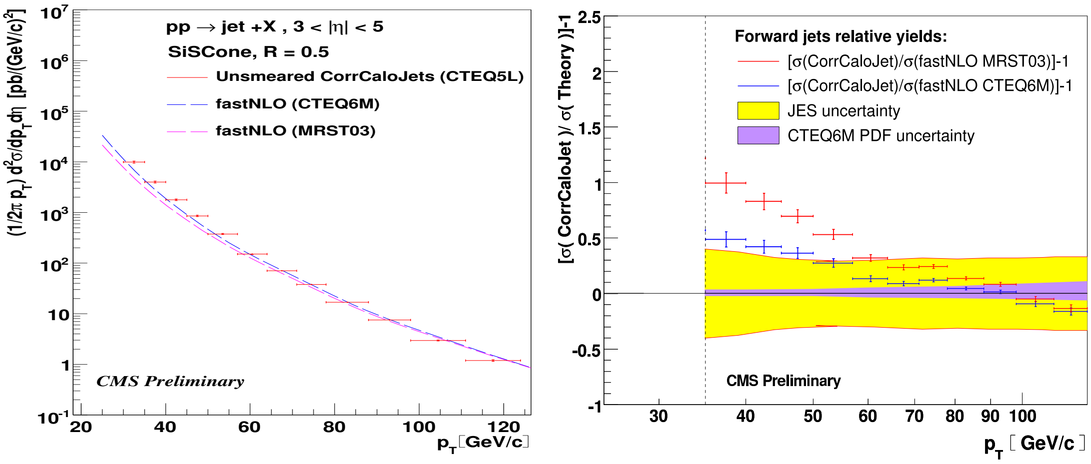

Figure 3: Left: Reconstructed forward jet spectrum (only stat errors shown) in p-p at 14 TeV compared to fastNLO predictions with MRST03 and CTEQ6.1M PDFs. Right: Percent differences between the forward jet p_T spectrum and the two fastNLO predictions. The yellow band shows the propagated yield uncertainty for a $5 - 10\%$ jet-energy scale (JES) error.

4 Forward-Backward Dijet Correlations: Low-x QCD

The interest in forward jet measurements goes beyond the *single* inclusive cross sections: the production of *dijets* with similar p_T but separated by large rapidities, the so-called "Mueller-Navelet jets" [10], is a particularly sensitive measure of non-DGLAP QCD evolutions. The large rapidity interval between the jets (e.g. up to $\Delta\eta \approx 12$ in the extremes of CMS forward calorimeters) enhances large logarithms of the type $\Delta\eta \sim log(s/p_{T,1}p_{T,2})$ which can be appropriately resummed within the BFKL [19], CCFM [12] and/or saturation [20, 21] frameworks. One of the phenomenological implications of this type of dynamics is an enhanced radiation between the two jets which results in a larger azimuthal decorrelation for increasing $\Delta\eta$ separations compared to collinear pQCD approaches. CMS [9] has carried out an analysis with PYTHIA [22] and HERWIG [23] selecting events with forward jets (ICone, $\mathcal{R} = 0.5$) which satisfy the following Mueller-Navelet (MN) type cuts:

- $p_{T,i} > 35$ GeV/c (good parton-jet matching and good jet trigger efficiencies in HF)
- $|p_{T,1} - p_{T,2}| < 5$ GeV/c (similar p_T to minimise DGLAP evolution)
- $3 < |\eta_{1,2}| < 5$ (both jets in HF)
- $\eta_1 \cdot \eta_2 < 0$ (each jet in a different HF, i.e. their separation is $\Delta\eta \gtrsim 6$)

The data passing the MN-cuts are divided into 4 equidistant pseudorapidity bins with separations $\Delta\eta$=6.5, 7.5, 8.5 and 9.5 and the dijet cross section computed as $d^2\sigma/d\eta dQ = N_{jets}/(\Delta\eta\Delta Q \int \mathcal{L}\mathrm{d}t)$, where $Q = p_{T,1} \approx p_{T,2}$ and N is the observed number of jets in the $\Delta\eta, \Delta Q$ bin. For 1 pb^{-1}, one expects a few 1000s (100s) MN jets with separations $\Delta\eta > 6$ (9). Figure 4, left, shows the expected PYTHIA yields passing the MN cuts for $\Delta\eta \approx 7.5$. The obtained dijet sample appears large enough to carry out detailed studies of the $\Delta\eta$ dependence of the yields, and look e.g. for a possible "geometric scaling" behaviour in the Mueller-Navelet yields [21].

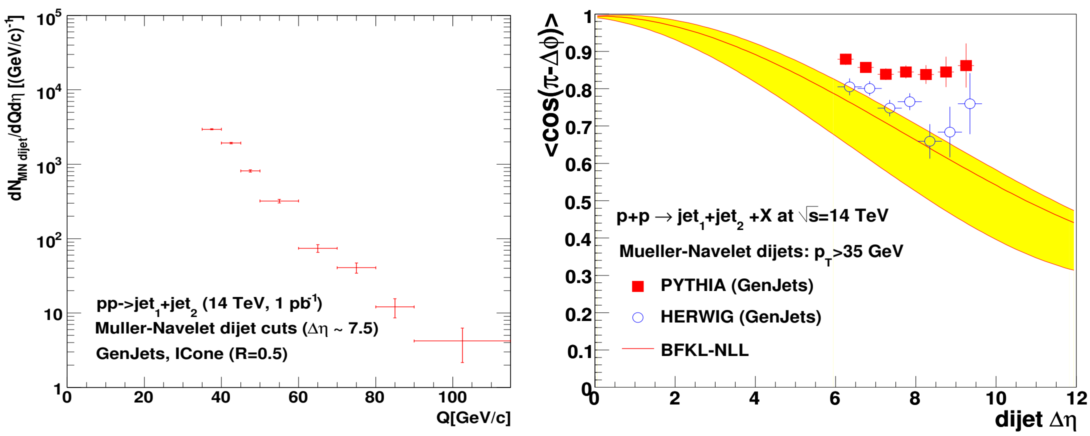

Figure 4: CMS study of dijet events passing the Mueller-Navelet cuts (see text) [9]. Left: Expected PYTHIA yields (1 pb^{-1}) for $\Delta\eta \approx 7.5$. Right: Average of $cos(\pi - \Delta\phi)$ versus $\Delta\eta$ in PYTHIA-, HERWIG-generated events compared to BFKL (yellow band) [19] analytical estimates.

An enhanced azimuthal decorrelation for increasing rapidity separation, measured e.g. by the average value (over events) of the cosine of the $\Delta\phi$ difference between the MN jets $\langle cos\,(\pi - \Delta\phi)\rangle$ versus the $\Delta\eta$ between them, is the classical "smoking-gun" of BFKL radiation [19, 20]. One expects $\langle cos(\pi - \Delta\phi)\rangle = 1$ (0) for perfect (de)correlation between the two jets. The results are shown in Fig. 4 (right) for the two highest-p_T jets in the event passing the MN cuts. Only the dominant (statistical) errors are presented. At the Monte Carlo truth level (not shown here), the originating partons in PYTHIA or HERWIG are almost exactly back-to-back for all $\Delta\eta$ in each such jet-pair events. Yet, at the *generator-level*, the $\langle cos(\pi - \Delta\phi)\rangle$ decorrelation increases to 15% (25%) for PYTHIA (HERWIG), $\langle cos(\pi - \Delta\phi)\rangle \approx 0.85$ (0.75), due to parton showering and hadronization effects. Yet, the forward dijet decorrelation observed in both MCs is smaller (and less steep as a function of $\Delta\eta$) than found in BFKL approaches (yellow band) [19, 20].

5 Summary

We have summarised the forward jet reconstruction capabilities of the ATLAS, CMS and LHCb experiments. The measurement of forward jets opens up the possibility to carry out interesting studies in the Higgs (tagging of vector-boson-fusion or Higgs-to-$b\bar{b}$ in associated $W Z$ production) and QCD (low-x parton densities and dynamics) sectors of the Standard Model.

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