Introduction to Forward Physics and Cosmic Rays at the
Symposium on Multiparticle Dynamics ISMD 2010

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We give a brief introduction to the topics discussed at the ISMD 2010 Symposium (Antwerp, 2010) on forward physics at the LHC and its interplay with cosmic rays physics.

1 Introduction

Particle production in the forward region at hadron colliders (Fig. 1) is traditionally dominated by low-p_T physics. At the Large Hadron Collider (LHC), due to the large center-of-mass energy, the phase space opens up for high-p_T forward production. By exploiting the unprecedented reach in rapidity of the experimental instrumentation, it becomes possible, for the first time at hadron-hadron colliders, to carry out a program of high-p_T physics and jets in the forward region [1, 2, 3], involving both new particle discovery processes (e.g., Higgs searches for vector boson fusion channels, jet studies in decays of highly boosted heavy states) and new aspects of standard model physics (e.g., QCD at small x, searches for new states of strongly interacting matter at high density).
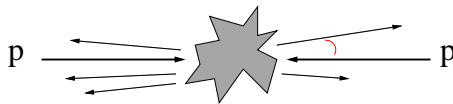

Figure 1: *Particle production at forward rapidities in hadronic collisions.*

Measurements of forward particle production (both soft and hard) at the LHC are expected to provide input to Monte Carlo models of high-energy air showers [4] for experiments on cosmic rays (Fig. 2), as LHC pp interactions correspond to fixed-target collisions in air in the midst of the measured cosmic ray spectrum.

LHC forward physics poses new challenges to both experiment and theory. On one hand, measurements of final states boosted to forward rapidities call for new experimental tools and techniques. On the other hand, the evaluation of QCD theoretical predictions is made complex
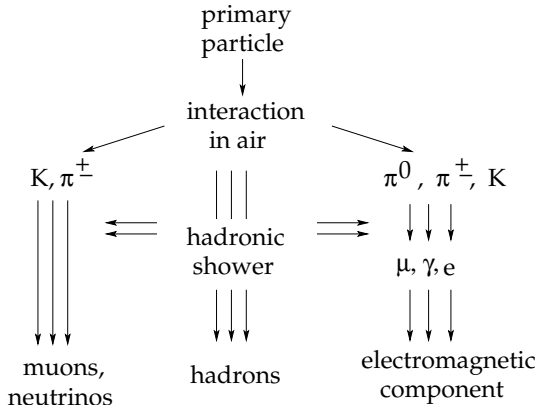
Figure 2: *High-energy air showers.*

by the fact that the forward kinematics forces high-p_T production into a region characterized by multiple energy scales, possibly widely disparate from each other.

In this article we start in Sec. 2 with a concise overview of general issues in the QCD treatment of forward hard processes. In Sec. 3 we discuss a selection of the first measurements in the forward region at the LHC presented at this meeting. In Sec. 4 we address connections of collider measurements with cosmic ray physics. In Sec. 5 we describe further collider studies discussed at the meeting and give final remarks.

2   General issues

This section presents briefly QCD theory issues in the description of hard processes in the forward region, introducing the role of perturbative resummations, of corrections beyond single parton scattering, and of methods that aim to extend the theory towards infrared-sensitive regions. See discussion in [5] for an introduction to low-p_T phenomena.

Fig. 3 pictures a forward hard event in which a forward jet (or some other high-p_T probe, such as b-quark jets or Drell Yan pairs) is produced in association with hard final state X. See e.g. contributions [6, 7, 8, 9] for specific examples of such events. The kinematics of the process in Fig. 3 is characterized by the large ratio of sub-energies $s_2/s_1 \gg 1$ and highly asymmetric longitudinal momenta in the partonic initial state ($x_A \to 1$, $x_B \to 0$).

In this multiple-scale region, one is probing the partonic phase space near its boundaries, and a first, basic question in the QCD treatment of these processes is whether fixed-order perturbative calculations accurately describe QCD theoretical predictions, or significant contributions arise beyond fixed order which call for perturbative QCD resummations.

In the case of jets at forward rapidity, it has long been recognized [10] that reliable theoretical predictions, unlike the case of inclusive jet production in the central region, require the resummation of logarithmically enhanced QCD corrections, becoming large for asymptotically high energies. This early observation has given rise to an ample literature of calculations based on the use [10] of the BFKL equation. See [11] for results at next-to-leading-logarithmic order.

On the other hand, in forward hard production at collider energies both logarithmic corrections in the large rapidity interval (of BFKL, or high-energy, type) and logarithmic corrections
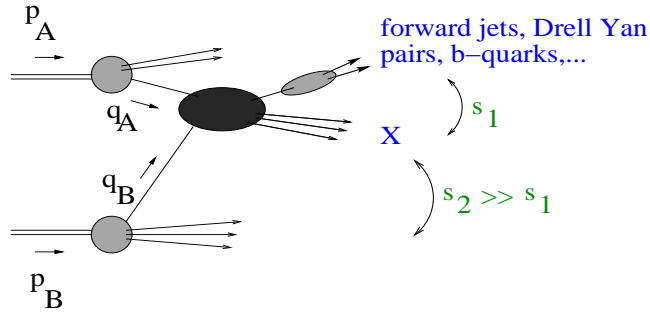
Figure 3: *Forward hard production processes in hadron-hadron collisions.*

in the hard transverse momentum (of collinear type) are phenomenologically important [3]. A pictorial representation of these radiative contributions in the rapidity and transverse momentum plane is sketched in Fig. 4. The theoretical framework to sum consistently both kinds of logarithmic corrections to all perturbative orders is based on QCD high-energy factorization with both longitudinal momentum fraction x and transverse momentum k_T fixed [12]. This factorization program is carried through in [13] for the case of forward jet hadroproduction. Applications of this framework to forward physics at the LHC are discussed in the contribution [9].

The factorization in x and k_T in Fig. 4 is valid to single-logarithmic accuracy [12]. In particular, it is consistent with the all-order factorization of collinear singularities [14], allowing one to fully control the dependence on the factorization scheme and scale. Conversely, it enables one to obtain logarithmically enhanced terms in rapidity that are not associated to any collinear logarithm. This in contrast with calculations in double-logarithmic approximations.
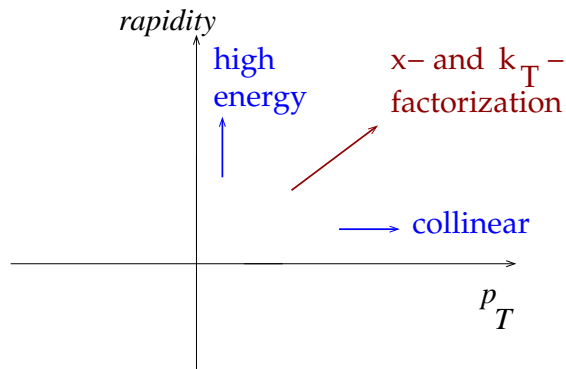

Figure 4: *QCD radiative contributions to forward hard processes in the rapidity and transverse momentum plane.*

Besides the different classes of all-order radiative corrections to single parton scattering illustrated in Fig. 4, and the corresponding perturbative QCD resummation methods, another
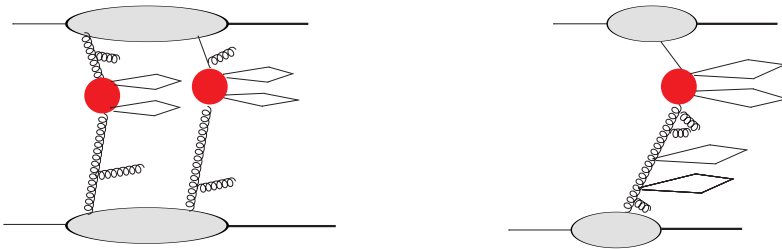
Figure 5: *Multi-jet production by (left) multiple parton chains; (right) single parton chain.*

type of dynamical effects which it has been argued may have non-negligible impact on forward processes involves contributions from multiple parton interactions [15], and is depicted in Fig. 5. This picture illustrates that the production of final states with multiple jets may occur by interactions from a single parton chain or by interactions from multiple chains. The multi-parton interactions are essential if one is to describe minimum-bias collider processes; but they may also affect significantly events involving a hard trigger [15, 16]. Multi-parton interactions are modeled in the parton-shower event generators used to simulate final states at the LHC [15, 16], and are the subject of a number of current efforts [17] to construct approaches capable of incorporating multiple scatterings in a partonic framework.

A basic question for phenomenology is to what extent current Monte Carlo generators can provide realistic event simulations of forward particle production. Detailed measurements of forward-region observables, such as those discussed in Sec. 3, should enable one to make comparative studies of the different mechanisms in Fig. 5 for multi-jet production and investigate whether QCD effects are well described by current Monte Carlo tools. Examples of such studies are given in Sec. 5.

As noted earlier, the forward region implies asymmetric parton kinematics and is sensitive to the structure of the initial state near small x. Measurements of forward high-p_T production processes could in principle be used for PDF determinations [7]. As they probe the gluon density function for small x, they could naturally be used also to investigate possible nonlinear effects [18, 19] at high parton density. The formulation [13] of forward jets, based on the factorization in both x and $k_\perp$ in Fig. 4, although it cannot by itself be used in the high-density saturation region, is however well-suited for describing the approach to this region, since it is designed to take into account both the effects from high-energy (BFKL) evolution associated with the increase in rapidity and also the effects from increasing p_T described by renormalization group, which are found to be also quantitatively significant [20] for studies of parton saturation. First Monte Carlo calculations along these lines, attempting to include saturation effects, are given in [21]. An important role will be played by studies of the forward region in collisions of dense systems. See [22] for recent work on high-density effects in jet production in proton-nucleus collisions.

Finally, we note that many of the theoretical issues that underlie forward physics, from QCD resummations to parton showering beyond leading order to potential effects of parton saturation, depend on the notion of transverse momentum dependent, or unintegrated, parton

distribution functions. See contribution [23] at this meeting and [24] for recent overviews. Transverse momentum dependent distributions are currently at the center of much activity, see e.g. [25], and their uses cover a broad range of QCD applications. Here we limit ourselves to observing that, in the context of forward physics, formulations at unintegrated level may provide a natural framework if we are to extend the theory towards the soft, low-p_T region [16], and treat phenomena such as diffraction and the physics of multiple gluon rescattering. An example is the discussion [26, 27] of hard-diffractive processes. Another example is the study [22] of unintegrated PDFs for scattering on dense targets. Also note that techniques are being developed [28] to incorporate the treatment of multiple-gluon rescattering graphs at small x in the operator matrix-element formalism [14, 29] for parton distribution functions. We finally recall that unintegrated parton distributions are a building block in QCD models for central exclusive production processes [30], which will complement, at later stages of the LHC program when near-beam proton taggers are installed [31], studies of forward high-p_T production such as those discussed above.

3   First LHC measurements

The earliest LHC runs yielded first results on forward physics. This section describes a sample of these early results.

The CMS Collaboration reported measurements of forward energy and particle flow [6, 32, 33] for pseudorapidity $3.15 < |\eta| < 4.9$ at three different center-of-mass energies $\sqrt{s}$ of 0.9 TeV, 2.36 TeV and 7 TeV. The energy flow in the forward region is measured for minimum bias events and for events with central ($|\eta| < 2.5$) dijets. Fig. 6 [6] shows results for $\sqrt{s} = 7$ TeV.
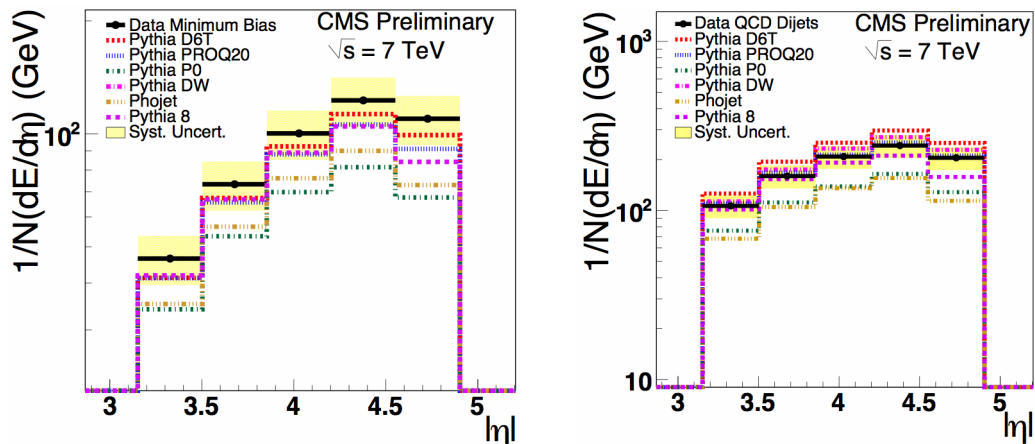

Figure 6: *Energy flow in the minimum bias sample (left) and in the central dijet sample (right) as a function of pseudorapidity [6].*

The energy flow is observed to increase with increasing $\sqrt{s}$. It is found [6, 33] that the observed energy flow in the forward region is not well described by tunes of the PYTHIA Monte Carlo generator based on charged particle spectra in the central region, especially for the

minimum bias sample.

CMS also reported first results on reconstruction of jets at forward rapidities [6, 34], with 35 GeV < p_T < 120 GeV and 3.2 < $|\eta|$ < 4.7. This is the first time that jets are observed in hadron-hadron collisions at such forward rapidities $\eta > 3$. Fig. 7 [6] shows the detector level forward jet pseudorapidity spectrum.
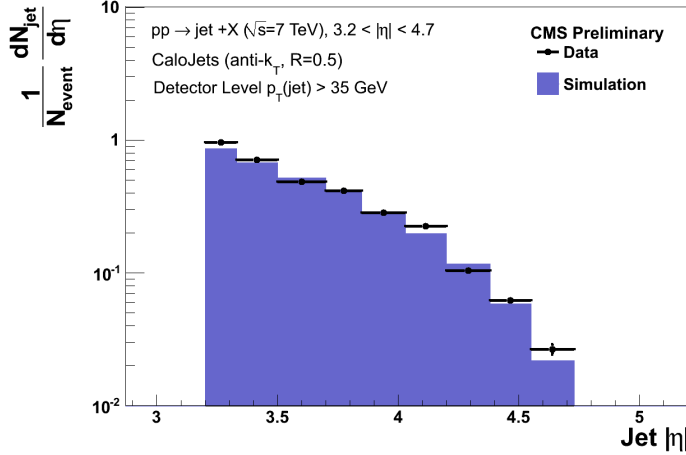

Figure 7: *Detector level forward jet pseudorapidity spectrum [6].*

The absence of energy deposition in the forward region was used by ALICE, ATLAS and CMS to identify diffractive events [35, 36, 37]. Fig. 8 [35] shows the ATLAS track distributions in transverse momentum p_T and rapidity gap $\Delta\eta$ for the diffractive fraction in minimum bias events [36, 38]. Prospects for diffraction in LHCb are discussed in [39].
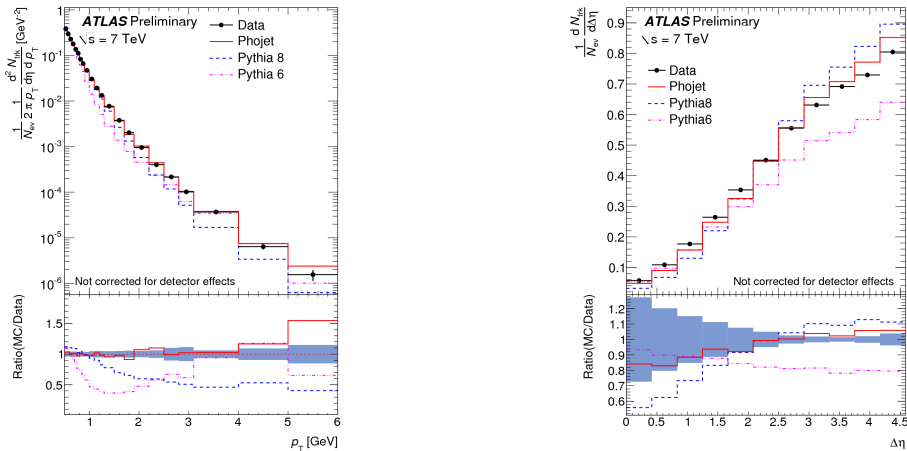

Figure 8: *Track transverse momentum and rapidity gap distributions for a diffraction enhanced sample in minimum bias events [35].*

The CMS Collaboration performed measurements of b-jet cross sections [40, 41]. The com-

parison with results of the MC@NLO Monte Carlo event generator in Fig. 9 [40] indicates potentially interesting effects in the b-jet transverse momentum spectra for the most forward rapidity bins. Reconstruction of b-jets at forward rapidities will also be feasible in LHCb [42]. These studies will impact measurements of the Higgs to $b\bar{b}$ decay channel in Higgs production associated with vector bosons.
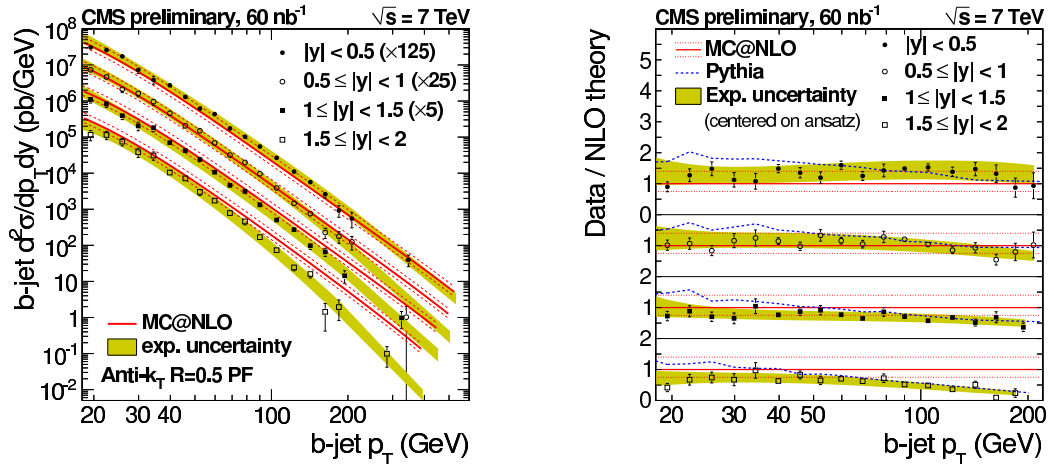

Figure 9: *CMS b-jet cross section versus p_T [40].*

4   High energy cosmic rays

In this section we consider the impact of collider measurements on investigations of high-energy cosmic rays (CR).

The high-energy CR spectrum has been measured to laboratory energies in excess of 10^{11} GeV [43, 44, 45]. The observed CR spectrum is shown in Fig. 10. However, winning in the maximal energy, Nature cannot compete with human-made accelerators regarding the luminosity, which is especially true for ultra-high energy cosmic rays (UHECR) at $E > 10^{10}$ GeV, whose flux is of the order of a particle per km^2 per century. Hence, one is forced to use the atmosphere of the Earth as the target, inferring the properties of the primary CR particles from the characteristics of huge nuclear-electromagnetic cascades (Fig. 2) - extensive air showers (EAS), induced by them in the air [4, 43, 46]. Primarily one is interested in the CR arrival directions, the energy spectrum, and the elemental composition (protons, nuclei, possible admixtures of photons and neutrinos). In fact, it is the latter which allows one to choose between various models for the origin of high and ultrahigh energy cosmic rays, providing in particular a decisive discrimination between astrophysical explanations of UHECR and scenarios which involve physics beyond the Standard Model [47, 48].

The classical air shower technique is to study the products of air shower development in ground-based detectors, as performed, for example, by the KASCADE experiment [49]. The most important observables in such a case are densities of all charged particles (mainly electrons and positrons) and of muons at the ground level. While the energy of the primary cosmic ray
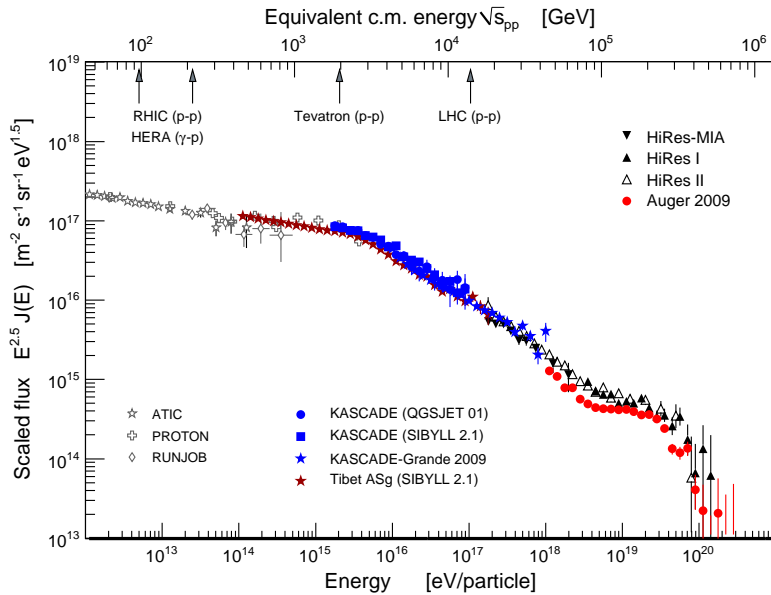
Figure 10: *The observed flux of high energy cosmic rays (from Ref. [53]).*

is typically reconstructed from the charged particle signal, the nuclear mass of the primary is inferred from the relative strength of the measured muon component, based on a higher multiplicity of charged hadrons, hence, of muons produced by pion and kaon decays, in nucleus-air collisions, compared to the case of the primary proton. Alternatively, one can study the longitudinal EAS development detecting the fluorescence light emitted by air molecules which are excited by charged particles propagating through the atmosphere, the corresponding technique introduced by the Fly's Eye experiment [50]. In such a case, the primary CR energy can be rather precisely deduced from the estimated total amount of fluorescence light while the type of the primary particle influences strongly the so-called shower maximum position – the depth (in g/cm^2) in the atmosphere where the maximal number of ionizing particles is observed. Modern experiments, like the Pierre Auger Observatory [51], combine both techniques and use them to cross-calibrate the results.

Naturally, the so-obtained spectrum and, especially, the composition of the primary cosmic rays depend crucially on the validity of the cascade description by the corresponding Monte Carlo codes. The least certain part of such simulation programs is the treatment of hadronic interactions, which has to be extrapolated over many orders of magnitude beyond the energies studied at accelerators [4, 52]. Besides, as in any thick target experiment, particle densities at ground are most influenced by the forward spectra of secondaries in hadron-air and nucleus-air collisions and by the corresponding inelastic cross sections. Similarly, the longitudinal shower development is very sensitive to the magnitude of the inelastic proton-air cross section and to the very forward spectra of produced particles, in particular, to the relative fraction of diffractive collisions.

Both the already obtained and the forthcoming LHC data have a great potential for improv-

ing EAS simulation procedures. In Ref. [53] the predictions of hadronic Monte Carlo generators used in the CR field have been compared to the results of the CMS [54] and ALICE [55] collaborations on soft multiparticle production. While none of the models considered provided a sufficiently good description of the complete set of the available LHC data, the experimental results on the pseudorapidity density of produced charged hadrons appeared to be well bracketed by the CR model predictions. As discussed in Ref. [53], the experimentally observed smooth energy behavior of the multiplicity of charged hadrons in the $\sqrt{s} = 0.9 \div 7$ TeV range supports conventional astrophysical interpretations of cosmic ray data in the discussed energy range, in particular concerning the "knee" around $3 \cdot 10^6$ GeV [56], in contrast with claims on exotic physics (e.g. [57]) being responsible for the observed features of the CR spectrum.

On the other hand, the LHC results provide a firm ground for extrapolating existing hadronic interaction models to ultra-high energies. The accuracy of the description of air shower development will be further enhanced by the forthcoming LHC data. Especially important results are expected from the TOTEM experiment [58] designed for high accuracy measurements of the total, inelastic, and diffractive proton-proton cross sections and from the studies of forward particle and energy flows by the LHCf experiment [59, 60]. The LHCf experiment concentrates on investigations of forward spectra of neutrons and photons [61, 62] and has a good potential to improve significantly model predictions for the spectra of leading baryons and mesons [63], which are presently extrapolated from fixed target energies. In turn, the good knowledge of the inelastic cross section and of forward hadron spectra in pp collisions will significantly enhance the accuracy of the calculations of the longitudinal EAS development and will offer an opportunity for precise studies of the CR composition by means of the fluorescence technique.

As LHC forward production measurements probe the structure of the initial state at very low x, they can potentially also impact predictions for the scattering of ultra-high energy neutrinos that are expected to accompany UHECRs [64]. See [65, 66, 67] for recent evaluations of structure function effects on UHE ν cross sections. Given the size of the theoretical uncertainties estimated on the neutrino cross sections [65] from the gluon distribution, it can be relevant to exploit both the experimental information on low-x PDFs that can be gleaned from LHC forward probes [7] and the theoretical constraints on the sea quark distribution associated with multi-gluon rescattering (see [68] and first reference in [28]).

5   Further collider studies

As discussed in the previous two sections, the LHC forward physics program is underway and is already providing useful results based on data collected in the earliest machine runs. In this section we consider further aspects of this program which can be investigated in the near future based on the full 2010 data yield. We do not address here issues concerning overlaid pile-up events from the increase in luminosity in 2011 runs.

One area of investigation concerns correlations of forward and central jets. The jet reconstruction capabilities of forward + central detectors at the LHC give the possibility to study these correlations in rapidity, azimuth and transverse momentum (Fig. 11). These studies should allow one to probe effects of multi-gluon radiation across the large rapidity interval and in particular make a comparative investigation of finite-angle, noncollinear corrections to parton showers and multi-parton interaction corrections [69].

Measurements of forward-central jet correlations can be used for the QCD tuning of Monte Carlo event generators. (For the counterpart of this in the case of central jet pairs see the first

LHC measurements [70].) Specific information on jet distributions is to be gained by going to the forward region. We observe that this will be relevant also in the case of heavy particle production, if one is to use jets as a tool to analyze potential effects of new physics at the LHC from highly boosted massive states [71].
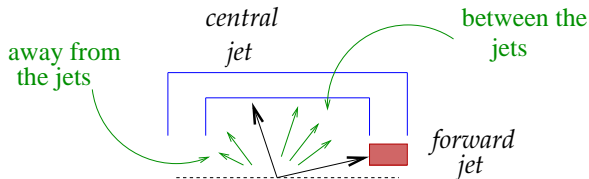

Figure 11: *Production of forward and central jets.*

An example is shown in Fig. 12 (from [69]), where we see the cross section as a function of the azimuthal separation $\Delta\phi$ between central and forward jets reconstructed with the Siscone algorithm [72] ($R = 0.4$) for different rapidity separations. The solid blue curve is the prediction based on implementing the factorization [13] in the parton-shower event generator [73] (CASCADE); the red and purple curves are the predictions based on calculations with collinear parton-showering [74] (PYTHIA), respectively including multiple interactions and without multiple interactions. See comments in Sec. 2 around Fig. 5. It is found in [69] that while the average of the azimuthal separation $\Delta\phi$ between the jets is not affected very much as a function of rapidity by finite-angle gluon emissions, the detailed shape of the $\Delta\phi$ distribution is. In particular we see in Fig. 12 that the decorrelation as a function of $\Delta\eta$ increases in CASCADE as well as in PYTHIA, but while in the low E_T region (Fig. 12 (left)) this is similar between CASCADE and PYTHIA with multiparton interactions for $\Delta\eta < 4$, in the higher E_T region (Fig. 12 (right)) the influence of multiparton interactions in PYTHIA is small and CASCADE predicts everywhere a larger decorrelation as a result of finite-angle gluon radiation in single-chain parton shower.

It is worth noting that jets in the forward region are relevant not only for LHC physics but also in the case of leptoproduction [75] for the physics program at the proposed future lepton facilities [76] (LHeC, EIC) and for further analyses of ep HERA data [77, 78]. It can be of interest to examine forward + central jets, similarly to what is described above for the LHC case, also in leptoproduction; due to the phase space available for multiple jet radiation, such studies are likely to prove more relevant at a future high-energy lepton collider than at HERA. (For related discussions of central jet leptoproduction see [79].) A further, interesting possibility is to examine forward jets associated with diffractive DIS [78].

Another set of potentially interesting studies at the LHC concerns measurements of particle and energy flow in the regions both between the jets and away from the jets in Fig. 11. As noted in [9], the inter-jet and the outside flows would allow one to gain more insight into the single-chain and multiple-chain mechanisms of Fig. 5. Especially, one may investigate quantitatively to what extent the multiple-interaction case shifts a significant amount of gluon radiation to larger values of x in the initial-state decay chains, as a result of less energy being available to each of the sequential parton chains [69]. See also the analyses [80] of energy flow observables.

An extension of the studies discussed above will involve forward and backward jets. Here one can look for Mueller-Navelet effects [2, 3, 10, 11]. Investigating QCD radiation associated with forward-backward jets will serve to analyze backgrounds in Higgs searches from vector boson fusion channels [81]. In particular, one may be able to extract information on Higgs
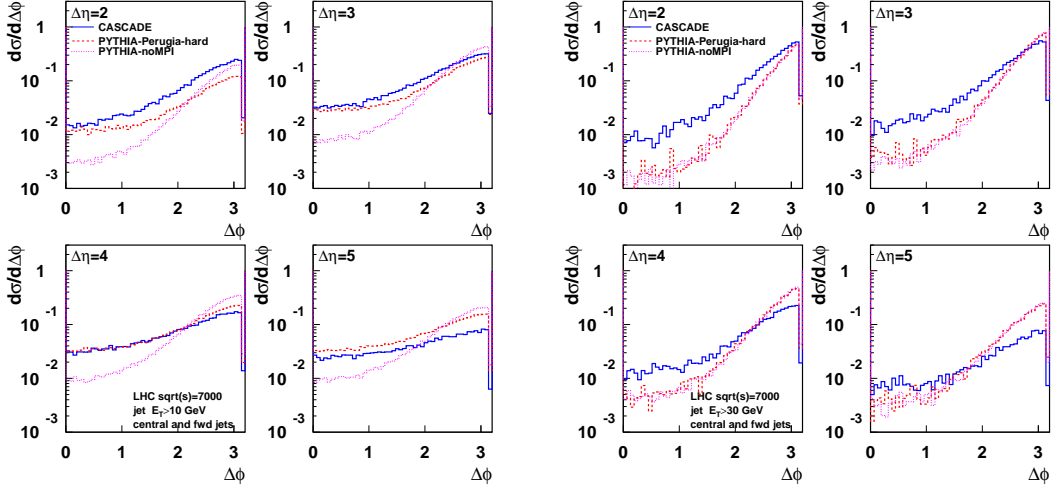
Figure 12: *Cross section versus azimuthal separation $\Delta\phi$ between central and forward jet, at different rapidity separations $\Delta\eta$, for jets with transverse energy $E_T > 10$ GeV (left) and $E_T > 30$ GeV (right) [69].*

couplings by studying the dependence on a central jet veto [82]. In this case too finite-angle radiative contributions to single-chain showers, extending across the whole rapidity range, affect the underlying jet activity accompanying the Higgs [83] and may give competing effects to multiple-parton interactions.

Note that, besides the case of jet production, also for minimum bias processes measurements of forward-backward correlations may provide useful information on event structure [84] and properties of multi-particle production.

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