

# Small-x QCD physics probed with jets in CMS \*

Pedro Cipriano<sup>†</sup>

Deutsches Elektronen-Synchrotron, Notkestrasse 85, 22761 Hamburg, Germany

September 15, 2013

## Abstract

The latest CMS jet measurements in p-p collisions at  $\sqrt{s} = 7$  TeV, sensitive to small-x QCD physics, are discussed. These include inclusive forward jet and simultaneous forward-central jet production, as well as production ratios and azimuthal angle decorrelations of jets widely separated in rapidity.

## 1 Introduction

The measurement of forward jets provides an important testing ground for QCD predictions of the Standard Model in the low-x region. The LHC (Large Hadron Collider) can reach  $Q^2$  and  $x$  values previously inaccessible to Hera as displayed in figure 1. To access the low-x region one must look at high rapidity. For such task the rapidity coverage of up to  $|\eta| = 5.2$  in CMS [1] has been used.

The jet-rapidity and transverse-momenta is well described by the calculations at next-to-leading-order (NLO) in perturbative quantum chromodynamics (QCD) using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) [2–6] approach and collinear factorization. The dijet cross-section is also well described [7]. When the collision energy  $\sqrt{s}$  is considerably larger than the hard scattering scale given by the jet transverse momentum,  $p_T$ , calculations in perturbative QCD require a resummation of large  $\log(1/x)$  terms. This leads to the prediction of new dynamic effects, expected to be described by Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution [8–10] and  $k_T$  factorization [11–13]. An effective theory has been developed which describes strong interactions in this kinematic domain [14]. This description is particularly useful in events with several jets with large rapidity separation, which are not well described by DGLAP predictions.

To extend the study of the parton evolution equations, the azimuthal angle differences were also measured. This observable has a sensitivity to BFKL effects when both jets are widely separated in rapidity (eg: Mueller-Navelet jets).

---

\*Presented at the Low x workshop, May 30 - June 4 2013, Rehovot and Eilat, Israel

<sup>†</sup>pedro.cipriano@desy.de

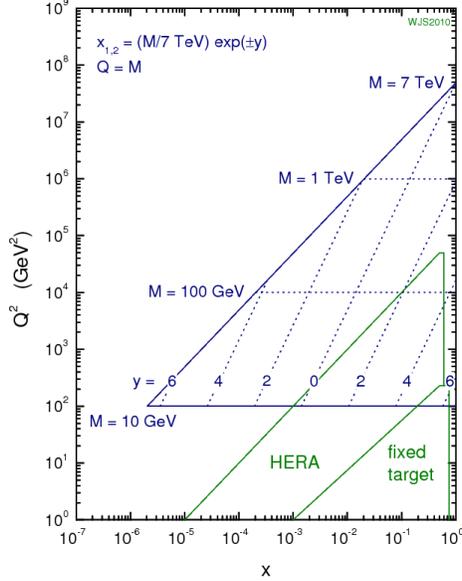


Figure 1: Kinematic phase-space accessible to Hera and LHC.

## 2 Inclusive forward jet production

The inclusive forward jet cross-section was measured from an integrated luminosity of  $3.14 \text{ pb}^{-1}$  [15]. Jets were reconstructed with the anti- $k_T$  clustering algorithm [16, 17] with a distance parameter  $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ . The energy depositions in the calorimeter cells were used as input for the clustering. Assuming massless jets, a four-momentum is associated with them by summing the energy of the cells above a given threshold.

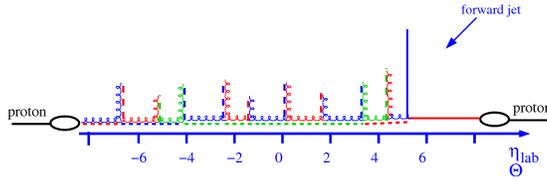


Figure 2: Feynmann diagram for inclusive forward jet production

The forward region is defined as  $3.2 < |\eta| < 4.7$ . The jets are required to have a transverse momentum above  $p_T = 35 \text{ GeV}$ . If more than one jet is present, the one with highest  $p_T$  is considered, as is illustrated in figure 2. The jets are corrected for the following systematic effects:  $p_T$  and  $\eta$ -dependent response of the calorimeters, overlap with other proton-proton interactions and

the migration of events across the  $p_T$  bins due to jet energy resolution.

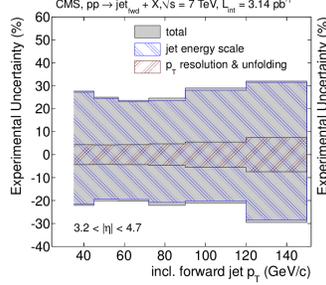


Figure 3: Inclusive forward jet production uncertainty

In figure 3 the experimental systematic uncertainties are show for the leading forward jet as function of  $p_T$ . The jet energy scale is the dominant systematic uncertainty and the total uncertainty is around  $-25+30\%$ .

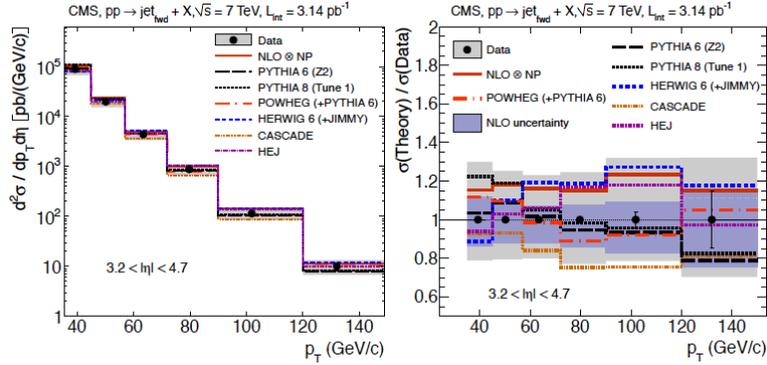


Figure 4: Inclusive forward jet cross-section compared with different Monte Carlo predictions.

The inclusive forward jet production cross-section corrected to hadron level is presented in figure 4. Although all predictions describe the data within the uncertainty band, some of them do better. POWHEG + PYTHIA 6 gives the best description. PYTHIA 6 and PYTHIA 8 describe the data reasonably well. CASCADE underestimates the cross-section while HERWIG tends to overestimate. NLOJET++ overestimates the data but is still within the large theoretical and experimental uncertainties.

### 3 Forward-central dijet production

The selection procedure for the simultaneous forward–central dijet production is similar to the one for the inclusive forward jet production. In addition, a central jet within  $|\eta| < 2.8$  with a transverse momentum above  $p_T = 35$  GeV is required. A Feynmann diagram of the process is shown in figure 5.

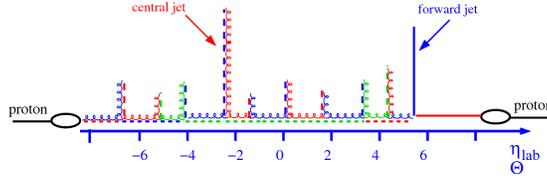


Figure 5: Feynmann diagram for forward–central dijet production

Several MC predictions compared to the data cross-section is presented in figures 6 and 7 [15]. Forward jet cross-section is steeper than the central jet. The shape of the forward jet is poorly described when compared with the central jet. HEJ provides the best description being followed closely by HERWIG6 and HERWIG++. Both PYTHIA6, PYTHIA8 and the CCFM CASCADE have troubles describing the data for the central jets and for low  $p_T$  forward jets. POWHEG + PYTHIA6, which was the best prediction for inclusive forward jet production, yields similar result as PYTHIA6 alone.

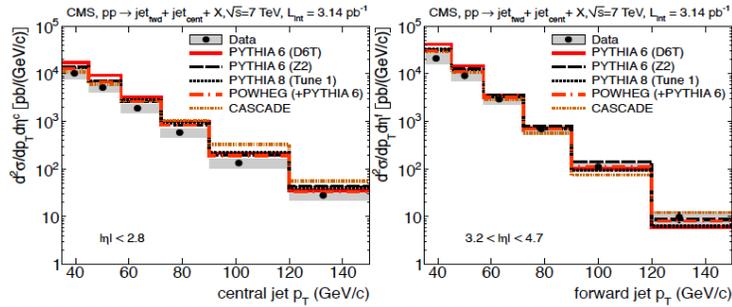


Figure 6: Forward–central dijet production compared with different Monte Carlo predictions [15].

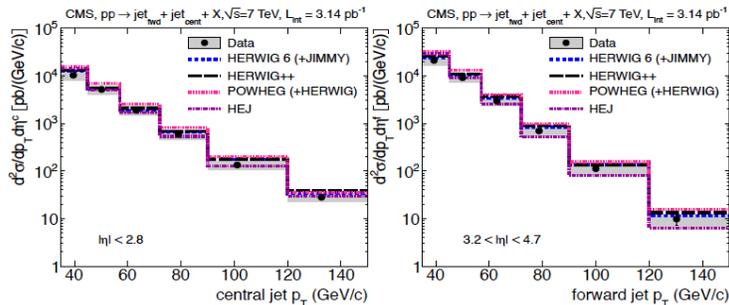


Figure 7: Forward–central dijet production compared with different Monte Carlo predictions [15].

## 4 Azimuthal–angle decorrelations of jets widely separated in rapidity

The reconstruction and correction procedure is similar as for the inclusive forward jet production [18]. Mueller-Navelet jets are the dijet pair with the highest rapidity separation. In this analysis only jets with  $p_T$  above 35 GeV and  $|\eta| < 4.7$  were considered. The azimuthal angle decorrelations of jets widely separated in rapidity is presented in figures 8 and 9 as function of rapidity separation.

The first row of figure 8 displays the azimuthal angle difference  $\Delta\phi$  for jets with a rapidity separation  $\Delta y$  less than 3. PYTHIA6 and HERWIG++ describe the data within uncertainties, while PYTHIA8 and SHERPA 1.4 with parton matrix elements matched show deviations at small and intermediate  $\Delta\phi$ . The second row shows  $\Delta\phi$  for a rapidity separation between 3 and 6. Herwig++ provides the best description, but all predictions show deviation beyond the experimental uncertainties. The last row shows the azimuthal–angle difference for  $\Delta y$  between 6 and 9. The dijets are strongly decorrelated. HERWIG++ provides the best description while PYTHIA6 and PYTHIA8 fail for the lower  $\Delta\phi$  region.

The figure 9 shows  $\Delta\phi$  for Mueller-Navelet jets with different rapidity separations compared with with different PYTHIA6 predictions. The contributions of the angular ordering (AO) and multi–parton interactions (MPI) are very similar. The intermediate  $\Delta y$  region is better described without MPI. Overall the data is better described with AO and MPI.

## 5 Fourier coefficients ratio of the average azimuthal cosines

Using the same selection as in the previous section, the Fourier coefficients of the average cosines have been measured [18] and is presented in the figure 10.

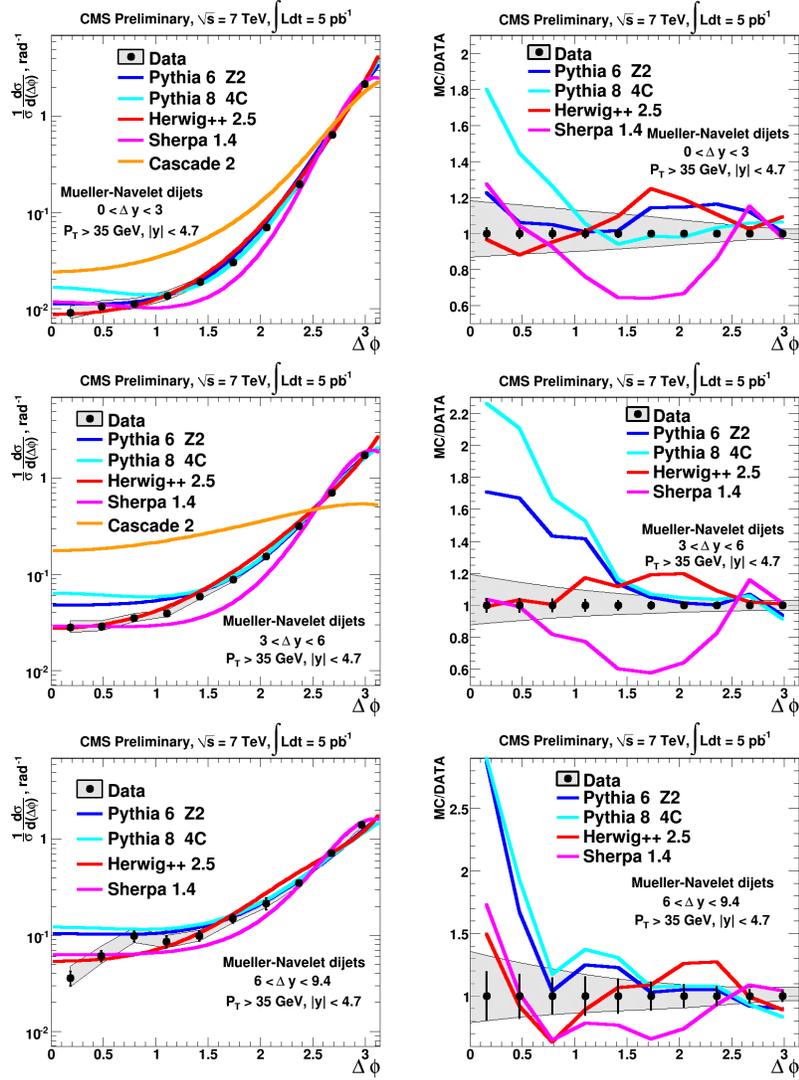


Figure 8: Azimuthal-angle decorrelations of jets widely separated in rapidity compared with different Monte Carlo predictions [18].

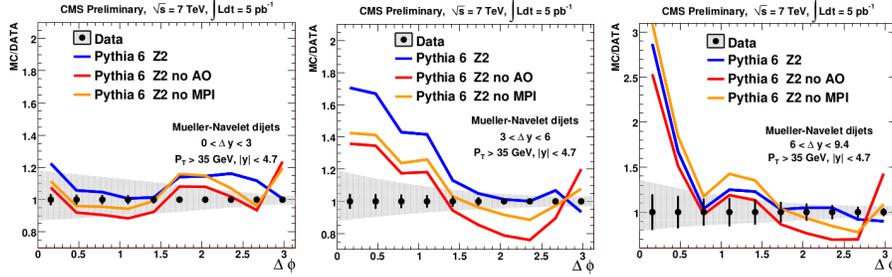


Figure 9: Azimuthal angle decorrelations of jets widely separated in rapidity compared with different PYTHIA6 predictions [18].

$$C_n : d\sigma/d(\Delta\phi) \sim \sum C_n; \quad C_n = \langle \cos(n(\pi - \Delta\phi)) \rangle \quad (1)$$

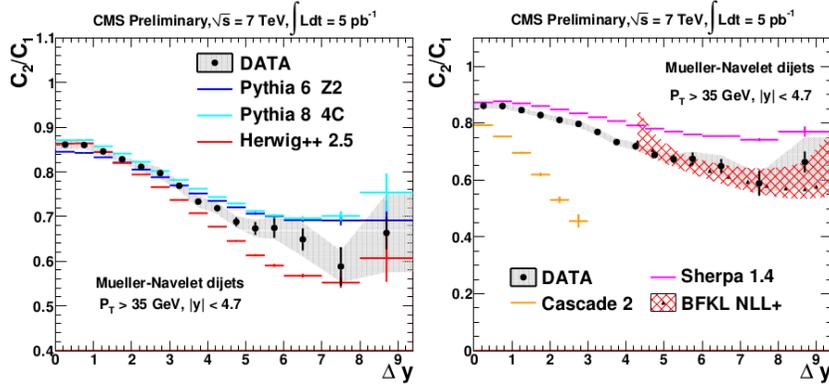


Figure 10: Fourier coefficients ratio of the average azimuthal cosines compared with different Monte Carlo predictions [18].

DGLAP contributions are expected to partly cancel in the  $C_{n+1}/C_n$  ratio, which are described by LL DGLAP-based generators towards low  $\Delta y$ . SHERPA, PYTHIA8 and PYTHIA6 overestimate  $C_2/C_1$  while HERWIG underestimate it. The CCFM-based CASCADE predicts too small  $C_{n+1}/C_n$ . At  $\Delta y > 4$ , a BFKL NLL calculation describe  $C_2/C_1$  within uncertainties.

## 6 Ratios of dijets production

Using jets with  $p_T > 35$  GeV and  $|\eta| < 4.7$  the ratio of the inclusive to exclusive dijet production was measured as a function of  $\Delta y$  [19]. With increasing  $\Delta y$  a

larger phase-space for radiation is opened. The inclusive dijet sample consists of events with at least 2 jets over the threshold and exclusive requires exactly two jets. The ratio of inclusive to exclusive dijet production is shown in the figure 11. PYTHIA6 and PYTHIA8 agree well with the data while HERWIG++ and HEJ+ARIADNE overestimate the data at higher  $\Delta y$ . CASCADE is completely off. MPI gives only a small contribution.

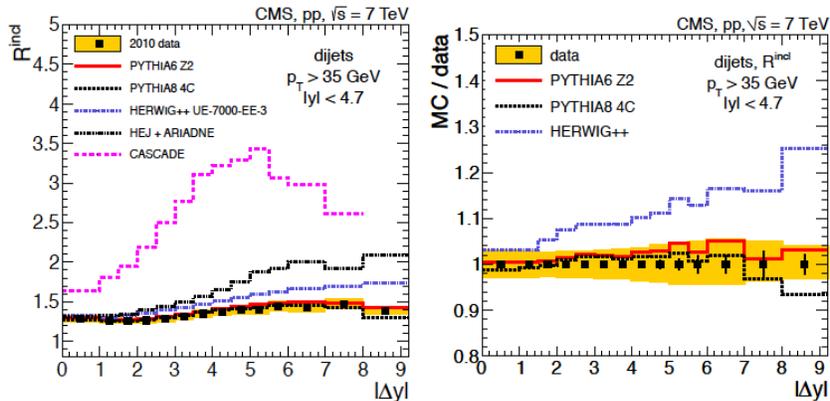


Figure 11: Ratios of inclusive/exclusive dijets production compared with different Monte Carlo predictions [19].

The ratio of inclusive to exclusive Mueller-Navalet dijets is presented in 12. At low  $\Delta y$  the ratio of Muller-Navelet over exclusive is, by definition, smaller than inclusive over exclusive and at higher  $\Delta y$  it is the same. The conclusions of the comparison between data and MC are the same as for the ration inclusive over exclusive.

## 7 Summary

Inclusive measurements of forward and central-forward jets, are reasonably well described by the MC predictions while more exclusive measurements are poorly described. A summary of the MC description is presented in table 1. The DGLAP-based generators, PYTHIA and HERWIG, seem to do a better job than the BFKL-inspired CASCADE. The effort of description of the underlying events, development of the parton showers and tuning of PYTHIA and HERWIG play an huge role into this result.

## References

- [1] CMS Collaboration, “The CMS experiment at the CERN LHC, JINST 03 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

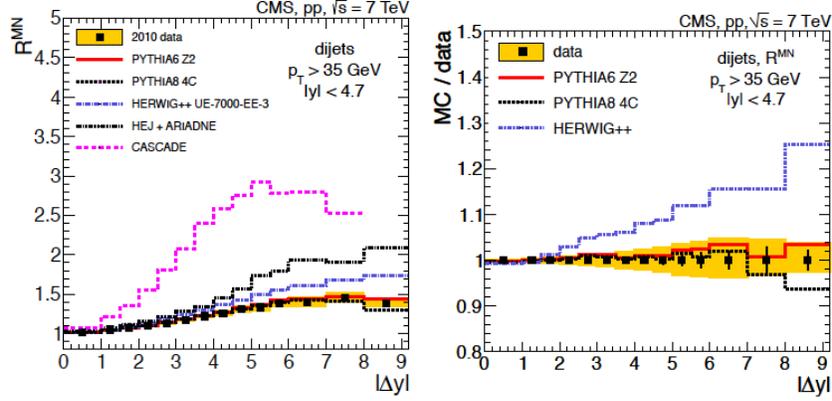


Figure 12: Ratios of Mueller-Navelet/exclusive dijets production compared with different Monte Carlo predictions [19].

Observable	Pythia	Herwig	Cascade	HEJ
Forward jet $p_T$	Good	Acceptable	Acceptable	Good
Central-forward jet $p_T$	Bad	Acceptable	Bad	Good
Azimuthal correlations	Acceptable	Good	Bad	–
Fourier coefficients ratio	Acceptable	Bad	Bad	–
Dijet ratios	Good	Acceptable	Bad	Bad

Table 1: Monte Carlo description of the measurements

- [2] V.N. Gribov and L.N. Lipatov, “Deep inelastic ep scattering in perturbation theory, Sov. J. Nucl. Phys. 15 (1972) 438.
- [3] V.N. Gribov and L.N. Lipatov, “e+ e- pair annihilation and deep inelastic ep scattering in perturbation theory, Sov. J. Nucl. Phys. 15 (1972) 675.
- [4] L.N. Lipatov, “The parton model and perturbation theory, Sov. J. Nucl. Phys. 20 (1975) 94.
- [5] G. Altarelli and G. Parisi, “Asymptotic freedom in parton language, Nucl. Phys. B 126 (1977) 298, doi:10.1016/0550-3213(77)90384-4.
- [6] Yu.L. Dokshitzer, “Calculation of the structure functions for deep inelastic scattering and e+ e- annihilation by perturbation theory in quantum chromodynamics, Sov. Phys. JETP 46 (1977) 641.
- [7] CMS Collaboration, “Measurement of the differential dijet production cross section in proton-proton collisions at  $\sqrt{s} = 7$  TeV, Phys. Lett. B 700 (2011) 187, arXiv:1104.1693, doi:10.1016/j.physletb.2011.05.027.

- [8] E.A. Kuraev, L.N. Lipatov and V.S. Fadin, “Multi-reggeon processes in the Yang-Mills theory, Sov. Phys. JETP 44 (1976) 443.
- [9] E.A. Kuraev, L.N. Lipatov and V.S. Fadin, “The Pommeranchuk singularity in nonabelian gauge theories, Sov. Phys. JETP 45 (1977) 199.
- [10] I.I. Balitsky and L.N. Lipatov, “The Pommeranchuk singularity in quantum chromodynamics, Sov. J. Nucl. Phys. 28 (1978) 822.
- [11] E.M. Levin et al., “Heavy quark production in semihard nucleon interactions, Sov. J. Nucl. Phys. 53 (1991) 657.
- [12] S. Catani, M. Ciafaloni and F. Hautmann, “High-energy factorization and small-x heavy flavour production, Nucl. Phys. B 366 (1991) 135, doi:doi:10.1016/0550-3213(91)90055-3.
- [13] J.C. Collins and R.K. Ellis, “Heavy quark production in very high-energy hadron collisions, Nucl. Phys. B 360 (1991) 3, doi:10.1016/0550-3213(91)90288-9.
- [14] L.N. Lipatov, “Small x physics in perturbative QCD, Phys. Rept. C 286 (1997) 131. doi:10.1016/S0370-1573(96)00045-2.
- [15] CMS Collaboration, “Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at  $\sqrt{s} = 7$  TeV”, JHEP 1206 (2012) 036, doi:10.1007/JHEP06(2012)036, arXiv:1202.0704
- [16] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-kt jet clustering algorithm”, JHEP 04 (2008) 063, arXiv:0802.1189, doi:10.1088/1126-6708/2008/04/063.
- [17] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, arXiv:1111.6097.
- [18] CMS Collaboration, “Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at  $\sqrt{s} = 7$  TeV”, FSQ-12-002.
- [19] CMS Collaboration, “Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton-proton collisions at  $\sqrt{s} = 7$  TeV” Eur.Phys.J.C72(2012)2216, arXiv:1204.0696.