PROCEEDINGS OF SCIENCE

Measurement of four-jet production including two heavy-flavour jets in pp collisions at 7 TeV with the CMS experiment

PoS(DIS2015)165

Paolo Gunnellini[*†]
Deutsches Elektronen Synchrotron (DESY), Notkestrasse 85, 22761 Hamburg (Germany)
E-mail: paolo.gunnellini@desy.de

Measurements of differential cross sections for the production of at least four jets, two of them initiated by a b-quark, in proton-proton collisions are presented as a function of the transverse momentum p_{T} and pseudorapidity η, together with the correlations in azimuthal angle and the p_{T}-balance among the jets. The data sample was collected in 2010 at a center-of-mass energy of 7 TeV with the CMS detector at the LHC with an integrated luminosity of 3 pb^{-1}. The measurement, compared to predictions from different models, shows that the addition of parton showers to fixed-order matrix element calculations describe the measured differential cross sections in only some regions of phase space. Including a contribution from double parton scattering in the models improves the predictions.

The XXIII International Workshop on Deep Inelastic Scattering and Related Subjects
April 27 - May 1, 2015
Southern Methodist University
Dallas, Texas 75275

[*]Speaker.
[†]on behalf of the CMS Collaboration.

1. Introduction

The production of jets with large transverse momenta p_{T} in high energy proton-proton (pp) collisions originates from a scattering of partons which is well-described within the theory of strong interactions, Quantum Chromodynamics (QCD). The cross section of such a proton-proton collision process is factorized in a convolution of the cross section for a partonic subprocess and the parton distribution functions (PDF). At the Large Hadron Collider (LHC), the inclusive cross section for high p_{T} jets has been measured by CMS and ATLAS [1, 2] and is in good agreement with predictions obtained at next-to-leading order (NLO) QCD.

Multijet measurements allow further features of QCD to be investigated and studied. An exclusive four-jet final state has been measured at CMS [3], where it has been shown that the present calculations describe the data only in some regions of the phase space and might be improved through the use of higher order matrix elements. By selecting jets originating from bottom quarks (denoted as "b-jets") in a multijet scenario along with other jets, the same calculations can be tested in the heavy-flavour sector. The hard scattering produces a pair of partons at high p_{T}, and their evolution may result in additional jets at lower momenta. This partonic process, referred to as single parton scattering SPS, is a crucial test for higher order QCD calculations as well as for the description of high p_{T} jets within a parton shower formalism, along the line of the studies described in [3]. At high centre-of-mass energies the gluonic parton densities become large at low values of longitudinal momentum fraction. Hence, the probability to have more than one partonic interaction becomes non-negligible, leading to the production of pairs of different flavoured jets via double parton scattering (DPS). Resulting in different distributions of angular correlations, SPS and DPS processes can be disentangled as discussed in [4]. In fact, a final state arising from SPS tends to have strongly correlated configuration in the azimuthal angle and p_{T}-balance between the two jet systems, while a DPS event has a preferred back-to-back topology. The measurement of the correlation observables is a crucial baseline for future investigations of DPS contributions.
The measurement of differential cross sections is presented in the following as a function of the jet p_{T} and as a function of the jet correlation observables in an inclusive four-jet final state.

2. Event selection, definition of the observables and systematic effects

The inclusive production of two b-jets and two other jets for $p_{\mathrm{T}} > 20$ GeV is measured [5] at $\sqrt{s}$ = 7 TeV using an integrated luminosity of 3.03 pb^{-1} recorded with the CMS detector at the LHC. The jets are reconstructed with the anti-k_T algorithm [6] with a distance parameter R of 0.5 in the pseudorapidity range of $|\eta| < 4.7$. Events with at least four jets with $p_{\mathrm{T}} > 20$ GeV are selected; two of them are the highest transverse momentum (leading) jets classified as originated by b-quarks, while the other two are the remaining highest p_{T} jets, regardless of their flavour. The former two jets are associated in the "b-quark jet pair" (bottom), while the latter two ones compose the "light-quark jet pair" (light). About 60,000 events are selected after the four-jet requirement in the data. The jets have been reconstructed with the Particle-Flow algorithm [7], which combines information from several sub-detectors. A jet p_{T} correction was applied to both data and simulation at the reconstruction level to account for the non-linear response of the calorimeters to the particle energies and other instrumental effects.

PoS(DIS2015)165

The b-jets are identified by using information about the secondary decay vertex of the b-hadrons, impact parameter significance of the tracks and jet kinematics [8] through the so-called "Combined Secondary Vertex" (CSV) discriminant. A loose selection has been chosen for the b-tag algorithm which assures a high b-tagging efficiency, of the order of 75-85%, and a jet misidentification efficiency of 20, 10 and 15% for, respectively, $p_{\mathrm{T}} \sim 20$, 75 and 300 GeV, increasing up to 35% for jets in $2.0 < |\eta| < 2.4$. The b-jet purity, namely the percentage of selected events where both tagged jets originate from b-quarks, is of about 12%. Relative differences in b-jet purity of the order of 2-7% have been obtained between data and simulation and they have been corrected in the simulation by means of scale factors ($SF_{\text{b-purity}}$), depending on the true flavour of the b-tagged jets. Additional scale factors ($SF_{\text{b-tag}}$) have been also applied to the simulation in order to match the b-tag efficiencies in data and MC [8]. They depend on the jet p_{T}, η and flavour and range between 1.1 and 0.9.

Differential cross sections as a function of the transverse momenta of each of the four jets are presented in absolute value. In addition, the differential cross section normalized to the total number of selected events is measured as a function of correlation variables, defined from the bottom and light pair of jets. The considered correlation observables are very similar to the ones measured for the four-jet scenario [3] and are defined as:

- the azimuthal angular difference between the jets belonging to the light-jet pair:

$$\Delta\phi^{\text{light}} = |\phi_{\text{light}_1} - \phi_{\text{light}_2}| \tag{2.1}$$

- the balance in transverse momentum of the two light jets:

$$\Delta^{\text{rel}}_{\text{light}} p_{\mathrm{T}} = \frac{|\vec{p}_{\mathrm{T}}^{\,\text{light}_1} + \vec{p}_{\mathrm{T}}^{\,\text{light}_2}|}{|\vec{p}_{\mathrm{T}}^{\,\text{light}_1}| + |\vec{p}_{\mathrm{T}}^{\,\text{light}_2}|} \tag{2.2}$$

- the azimuthal angle ΔS between the two dijet pairs, defined as:

$$\Delta \mathrm{S} = \arccos\left(\frac{\vec{p}_{\mathrm{T}}(\text{bottom}_1, \text{bottom}_2) \cdot \vec{p}_{\mathrm{T}}(\text{light}_1, \text{light}_2)}{|\vec{p}_{\mathrm{T}}(\text{bottom}_1, \text{bottom}_2)| \cdot |\vec{p}_{\mathrm{T}}(\text{light}_1, \text{light}_2)|}\right) \tag{2.3}$$

where bottom_1 (bottom_2) and light_1 (light_2) are respectively the leading (subleading) jets of the bottom and light jet pairs. With $\vec{p}_{\mathrm{T}}(\text{bottom}_1, \text{bottom}_2)$ and $\vec{p}_{\mathrm{T}}(\text{light}_1, \text{light}_2)$ are indicated the vector sum of the two bottom and of the two light jets. All measured cross sections are unfolded to the stable particle level.

The jet cross sections are well described at detector level by predictions obtained with PYTHIA [9] and HERWIG [10] in the whole jet p_{T} spectrum and in the central region [5]; they exhibit differences of up to 20–40% at the most forward pseudorapidities ($|\eta| > 3$).

The kinematic variables as well as the correlation observables are corrected for selection efficiencies and detector effects. The data are corrected to stable particle level applying an iterative unfolding. Particles are considered stable if their mean path length $c\tau$ is greater than 10 mm. Jets are identified as "b-jets" at the stable particle level if evidence of a b-quark is found within a cone of radius R = $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ equal to 0.3 around the jet axis. The unfolding to stable particle level includes corrections for jet resolution, flavour misidentification and pileup effects.

Various systematic uncertainties have been investigated and the corresponding uncertainty has been calculated for each of the distributions. The total uncertainties have been obtained by summing quadratically the single contributions. The systematic effects are shown in Table 1.

Table 1: Systematic and statistical uncertainties affecting the absolute and the normalized cross-section distributions for each presented observable. The 4% uncertainty from the luminosity measurement is included in the total uncertainty affecting the absolute cross sections. This is obtained by summing the individual uncertainties quadratically.

Measured observable	Model	JES	JER	$SF_{\text{b-tag}}$	$SF_{\text{b-purity}}$	Trigger efficiency	Stat.	Total incl. luminosity
Absolute cross sections								
b-tagged jet p_T	20%	25%	4%	15%	4%	6%	4%	35%
light-jet p_T	10%	25%	4%	15%	4%	6%	4%	32%
Jet $\|\eta\| \leq 3$	10%	25%	4%	15%	4%	5%	4%	32%
Jet $\|\eta\| > 3$	20%	35%	4%	15%	4%	5%	4%	44%
Normalized cross sections								
$\Delta\phi^{\text{light}}$	13%	5%	1%	2%	1%	1%	4%	15%
$\Delta^{\text{rel}}_{\text{light}} p_T$	13%	5%	7%	2%	1%	1%	4%	16%
ΔS	20%	5%	10%	2%	2%	1%	4%	23%

3. Results and comparison to various predictions

The cross section for an inclusive four-jet scenario with heavy-flavour jets has been measured to be σ(pp$\rightarrow$ 2 b + 2 j + X) = 64.6 $\pm$ 2.4 (stat.) $\pm$ 21.6 (syst.) nb [5]. Predictions from different event generators at the stable particle level have been considered for comparison (see Table 2). While predictions from PYTHIA 8 Tune CUETP8S1 are above the measured cross section, the best agreement is achieved by HERWIG ++ Tune UE-EE-5C, POWHEG+PYTHIA 6 Tune Z2', and PYTHIA 6 Tune CUETP6S1, which are compatible with the data. Predictions obtained with MADGRAPH+PYTHIA 6 Tune Z2* tend to underestimate the measured cross section.

The measured absolute differential cross sections as a function of the jet p_T, along with the normalized cross sections as a function of the jet correlation observables are presented in the following. In Figure 1, the differential absolute cross sections as a function of the p_T of the selected jets are shown. The p_T of the jets is rapidly decreasing over 5-6 orders of magnitude up to 500 GeV. The measured differential cross sections have been compared to predictions of various Monte Carlo event generators. Predictions obtained with PYTHIA 8 overestimate the data in the low p_T region. Instead, predictions of MADGRAPH and POWHEG, interfaced with the parton shower and UE simulation provided by respectively PYTHIA 6 tune Z2* and PYTHIA 6 tune Z2', and predictions of PYTHIA 6 are closer to the measurement in the whole p_T spectrum. The HER-

Table 2: Cross sections for MC predictions and measured data for pp $\rightarrow$ 2b+2j+X.

Sample	PDF	Cross section (nb)
PYTHIA 6 Tune CUETP6S1	CTEQ6L1	76.66
HERWIG ++ Tune UE-EE-5-CTEQ6L1	CTEQ6L1	47.39
PYTHIA 8 Tune CUETP8S1-CTEQ6L1	CTEQ6L1	95.58
POWHEG+PYTHIA 6 Tune Z2'	CT10	54.91
MADGRAPH+PYTHIA 6 Tune Z2*	CTEQ6L1	39.33
DATA	-	64.6 $\pm$ 2.4 (stat.) $\pm$ 21.6 (syst.)

WIG ++ event generator is not able to reproduce the observed cross sections at $p_{\mathrm{T}} > 50$ GeV, by underestimating the measurement by up to 40-50%.

Figure 2 shows the differential normalized cross sections as a function of the correlation observables between the selected jets. The $\Delta\phi$ variable is rather flat with a small increase towards high values ($\sim \pi$ rad) corresponding to a back-to-back configuration for the jet pairs. A small peak at values around $\Delta\phi \sim$ 0.5-0.8 is present for both distributions: this is due to collinear jet emission which starts to be resolved at $\Delta\phi > 0.5$ because of the width of the jet clustering cone. The $\Delta^{rel} p_{\mathrm{T}}$ increases towards 1, which corresponds to a configuration where the jets are emitted collinearly. The ΔS variable, which is the most DPS-sensitive observable, has a falling distribution from correlated configurations at high values, down to uncorrelated jet topologies at low values.

The differential cross sections as a function of the correlations observables have been also compared to the previously considered MC predictions. A comparison with predictions from PYTHIA 8 without the simulation of the MPI is also provided. A good agreement between all the predictions is observed for $\Delta\phi^{light}$. For low values of the $\Delta^{\mathrm{rel}}_{light} p_{\mathrm{T}}$ observable, the predictions from PYTHIA 8 without the simulation of the MPI are far below the data; this is a clear indication for the need for MPI contributions, since this is the region where a DPS signal is expected. In these regions, the data are in agreement with the predictions from PYTHIA 8 with MPI and MADGRAPH+PYTHIA 6. The POWHEG event generator interfaced with the parton shower provided by PYTHIA 6, tune Z2', also underestimates the data. ΔS is not well described by any prediction: in particular, all of them, except HERWIG ++ and PYTHIA 8 in a lesser extent, underestimate the region at values of ΔS < 2, and do not well follow the decreasing shape towards lower values. This study shows the need for MPI contributions in the simulation in order to describe correlation observables between jets. However, the considered models which implement a simulation of the UE tuned to soft MPI, are not able to describe at a good level measurements sensitive to the harder part of the MPI spectrum. This outcome has been observed also in [11] and might be an indication that a better simulation of the hard part of the UE needs to be implemented.

4. Conclusions

A measurement of the production cross section of events with at least four jets, two of which originated from a b-quark, has been performed using data collected with the CMS experiment in 2010. The cross section has been measured to be σ(pp$\rightarrow$ 2 b + 2 j + X) = 64.6 $\pm$ 2.4 (stat.) $\pm$

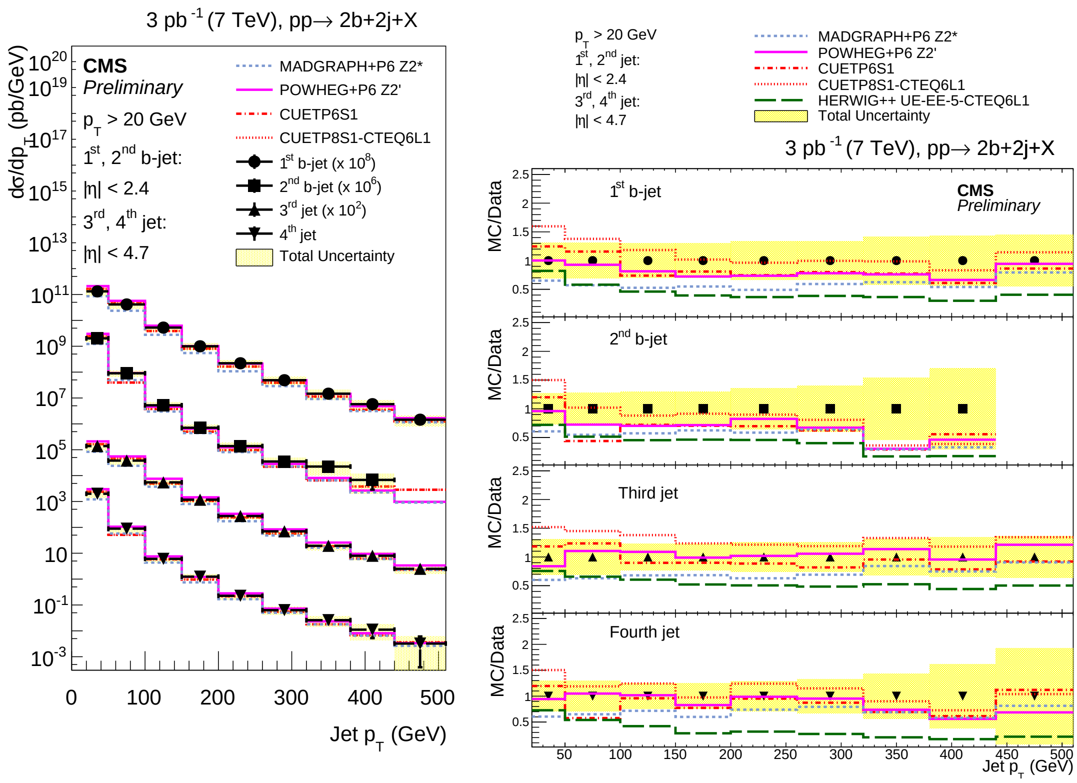

Figure 1: (a) Differential cross sections unfolded to the stable particle level as a function of the jet transverse momenta p_{T}. Scale factors of 10^8, 10^6 and 10^2 are applied to the measurement of the leading, subleading and third jet, respectively. (b) Ratios of predictions of POWHEG, MADGRAPH, PYTHIA 6, PYTHIA 8 and HERWIG ++ to data unfolded to the stable particle level as a function of the jet transverse momenta p_{T} for each specific jet. The yellow band represents the total uncertainty, including the statistical and systematic components added quadratically.

21.6 (syst.) nb. The differential cross sections as a function of the p_{T} of each of the four jets together with the cross section as a function of correlation variables have been presented and compared to several theoretical predictions. A correct estimation of the total cross section is provided only by some models. The NLO dijet calculation (POWHEG) and the LO 2→4 matrix element (MADGRAPH) matched with parton showers describe well the shape of the differential cross sections as a function of p_{T} in the whole region of the phase space. The differential cross sections as a function of the correlation observables between the jets of the final state are not optimally described by any of the considered theoretical models, which use a simulation of the UE tuned to soft MPI. The fully unfolded distributions of the correlation observables may serve for further tuning of the simulation, as described in [11]. Results from tuning in the heavy-flavour sector, compared to the light-flavour scenario, might also indicate a possible flavour dependence of the DPS contribution.

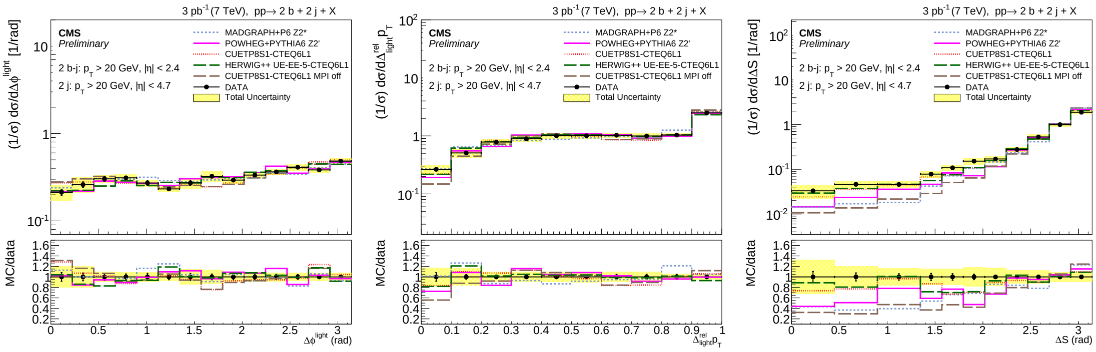

Figure 2: Normalized cross sections unfolded to the stable particle level as a function of $\Delta\phi^{\text{light}}$ (a), $\Delta^{\text{rel}}_{\text{light}} p_{\text{T}}$ (b) and ΔS (c), compared to predictions of POWHEG, MADGRAPH, PYTHIA 6, PYTHIA 8 and HERWIG ++. A comparison with the PYTHIA 8 CUETP8S1-CTEQ6L1 predictions without the simulation of the MPI is also shown. The lower panel shows the ratios of the predictions to the data. The yellow band represents the total uncertainty, including the statistical and systematic components added quadratically.

References

[1] S. Chatrchyan *et al.* [CMS Collaboration], "Measurements of differential jet cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV with the CMS detector," Phys. Rev. D **87** (2013) 11, 112002 [arXiv:1212.6660 [hep-ex]].

[2] G. Aad *et al.* [ATLAS Collaboration], "Measurement of inclusive jet and dijet production in *pp* collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector," Phys. Rev. D **86** (2012) 014022 [arXiv:1112.6297 [hep-ex]].

[3] S. Chatrchyan *et al.* [CMS Collaboration], "Measurement of four-jet production in proton-proton collisions at $\sqrt{s} = 7$ TeV," Phys. Rev. D **89** (2014) 9, 092010 [arXiv:1312.6440 [hep-ex]].

[4] E. L. Berger, C. B. Jackson and G. Shaughnessy, "Characteristics and estimates of double parton scattering at the Large Hadron Collider," Phys. Rev. D **81** (2010) 014014 [arXiv:0911.5348 [hep-ph]].

[5] CMS Collaboration, "Studies of 2 b-jet + 2 jet production in proton-proton collisions at 7 TeV," CMS-PAS-FSQ-13-010.

[6] M. Cacciari, G. P. Salam and G. Soyez, "The Anti-k(t) jet clustering algorithm," JHEP **0804** (2008) 063 [arXiv:0802.1189 [hep-ph]].

[7] CMS Collaboration, "Particle-flow event reconstruction in CMS and performance for jets, taus, and MET," CMS-PAS-PFT-09-001.

[8] S. Chatrchyan *et al.* [CMS Collaboration], "Identification of b-quark jets with the CMS experiment," JINST **8** (2013) P04013 [arXiv:1211.4462 [hep-ex]].

[9] T. Sjöstrand, S. Mrenna and P. Z. Skands, "PYTHIA 6.4 physics and manual," JHEP **0605** (2006) 026 [hep-ph/0603175].

[10] J. Bellm *et al.*, "Herwig++ 2.7 release note," arXiv:1310.6877 [hep-ph].

[11] CMS Collaboration, "Underlying event tunes and double parton scattering," CMS-PAS-GEN-14-001.