PROCEEDINGS OF SCIENCE

Vector boson plus jets measurements at CMS

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The associated production of a vector boson and jets allows confronting measurements with QCD inspired models and calculations. The precise understanding of the vector boson plus jets channel is essential for many searches beyond standard model physics. We present the recent results of both light and heavy-flavor quark jets in association with a vector boson using LHC data at a center of mass energy of 7 TeV recorded by the CMS experiment.

The European Physical Society Conference on High Energy Physics -EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

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1. Introduction

The vector boson (V=W,Z and γ) production in association with jets (V+jets) offers an excellent opportunity for precise studies of QCD due to small theoretical and experimental uncertainties in this particular channel. Since V+jet itself is a main background in many searches for new physics phenomena an accurate understanding of it is crucial. In this report recent results from the CMS experiment[1] at the LHC are described. For a complete list of results in the V+Jets channel we refer to [2].

2. Photon plus jets and double parton scattering in W plus jets

The final state of a photon plus jets is sensitive to the gluon parton distribution function. A precise understanding of photons is important for many searches and measurements most notably $H \to \gamma\gamma$. The differential cross-section of photon plus jets is measured as function of $p_T(\gamma)$ in eight bins of $|\eta(j1)|$ and $|\eta(\gamma)|$ [3]. The photon purity corrected unfolded distributions are compared to full next-to-leading (NLO) parton-level calculations from JETPHOX 1.2.2 [4] and to the Monte Carlo (MC) generator SHERPA 1.3 [5], which provides multi-leg tree-level matrix element calculations (ME) matched with QCD+QED parton showers (PS). Predictions from JETPHOX agree slightly better with data than SHERPA predictions, both are consistent with data within uncertainties (see left Fig. 2).
Double parton scattering (DPS) is studied in the W+2 jet final state[6]. One of several DPS sensitive variables considered is ΔS, the azimuthal angle between W and the dijet system as shown in right Fig. 2. For DPS events the dijet system and the W boson originate from two separate scatters. Consequently they are randomly oriented. In the case of single parton scattering events the dijet system is correlated with the W boson and both tend to be back-to-back. The data is compared with particle level predictions from MADGRAPH 5.1 [7] in conjunction with PYTHIA 6.4 [8] for the modeling of underlying event, parton shower and hadronization and PYTHIA 8[9]. A second version of MADGRAPH is produced switching of the multi parton interactions (MPI) in the parton showering and hadronization step of PYTHIA6. The MC predictions are scaled with a global k-factor to match the NNLO cross-section. The right Fig. 2 shows that both shape and rate of data and MADGRAPH with MPI are in agreement. The MC predictions of MADGRAPH without MPI underestimates the amount of data, shape wise the distribution is shifted to higher values of ΔS. PYTHIA8 underestimates the data due to missing matrix elements beyond the $2 \to 2$ process.

3. Z and light jets

The measurement of normalized rapidity distributions of the Z and the leading jet agree with NLO parton calculations from MCFM[10] and ME+PS predictions from SHERPA and MADGRAPH and within 5 %[11]. Correlations between these two quantities, the sum $Y_{\text{sum}} = |Y_Z + Y_{j1}|/2$ and $Y_{\text{dif}} = |Y_Z - Y_{j1}|/2$ are differently reproduced by theory as shown in Fig.3. MCFM and SHERPA show a good agreement with data, while MADGRAPH disagrees with the measurement. The different behavior between SHERPA and MADGRAPH is introduced in the matching step between the parton shower and the matrix element calculation.

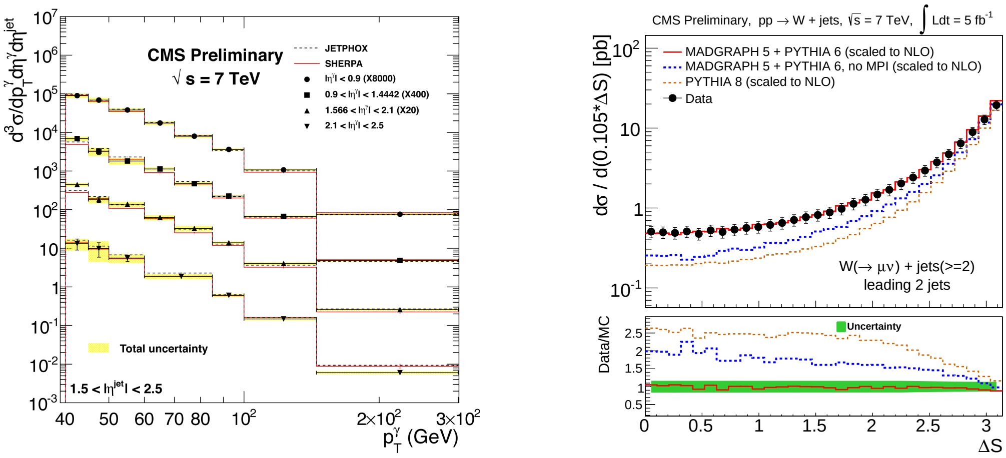

Figure 1: Differential cross-sections for $1.5 < |\eta^{\mathrm{jet}}| < 2.5$ (left) in photon plus jets events in four different ranges of η^{γ} compared with distributions from SHERPA and JETPHOX (left). Fully corrected differential cross-section for the DPS-sensitive observable ΔS for W+2 jets events compared to MC predictions from MADGRAPH with and without MPI and PYTHIA8 (right).

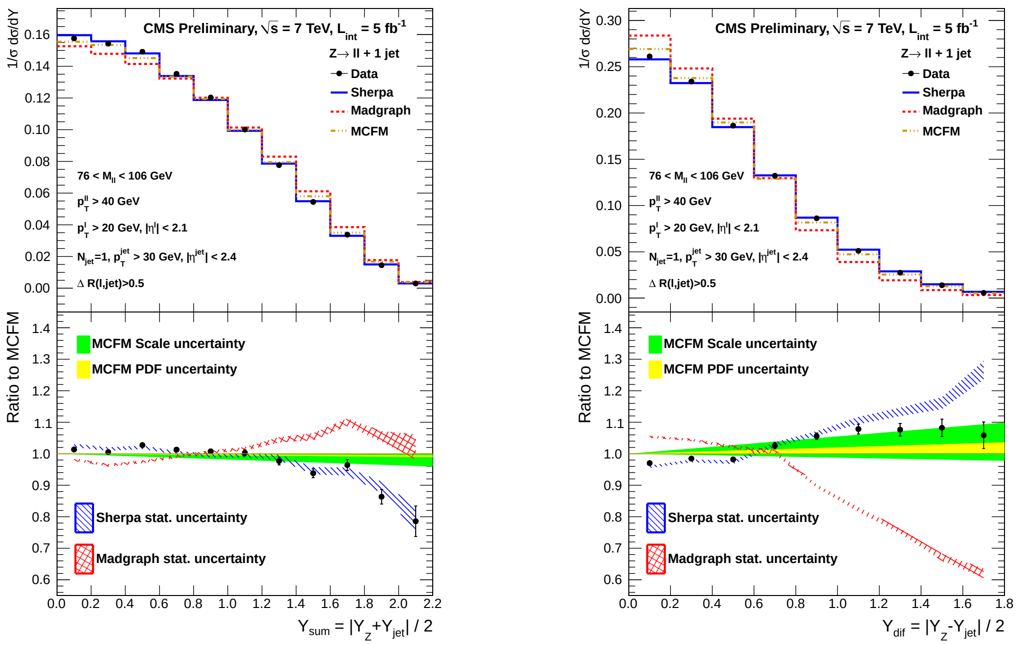

Figure 2: Rapidity distributions Y_{sum} (left) and Y_{diff} (right) for Z+jets from data corrected for detector effects compared to predictions from MCFM, MADGRAPH and SHERPA.

Angular topologies are studied through the transverse thrust variable τ_T[12] and the azimuthal observable $\Delta\phi(Z, j_1)$ for various inclusive jet multiplicities [13]. These distributions are of interest in physics searches for new physics in jet plus missing transverse energy signatures. These have $Z \to \nu\nu$ as irreducible background and the azimuthal angle between the Z and the leading jet translates into the azimuthal angle between the leading jet and the transverse missing energy vector. MADGRAPH 5.1. and POWHEG[14] describe the data well. SHERPA 3.1 gives a good description of data in the 2 and 3 jet bin, but is off by roughly 10 % for the inclusive 1 jet phasespace as displayed in Fig.3. The expected failure of PYTHIA 6.4 shows the importance of additional ME calculations. MADGRAPH and SHERPA ME calculation include up to 4 jets in the ME calculation, POWHEG provides NLO calculations for Z+1 jet. Though the additional radiation beyond the leading jet comes solely from PS POWHEG provides good predictions for high jet multiplicity regions. The agreement of the transverse thrust distribution in a regime with a highly boosted Z ($p_T^Z > 150$ GeV) shows an analogous agreement of data and predictions (Fig. 3): while MADGRAPH and POWHEG provide adequate predictions, SHERPA and PYTHIA6 are shifted towards the dijet region of low thrust values.

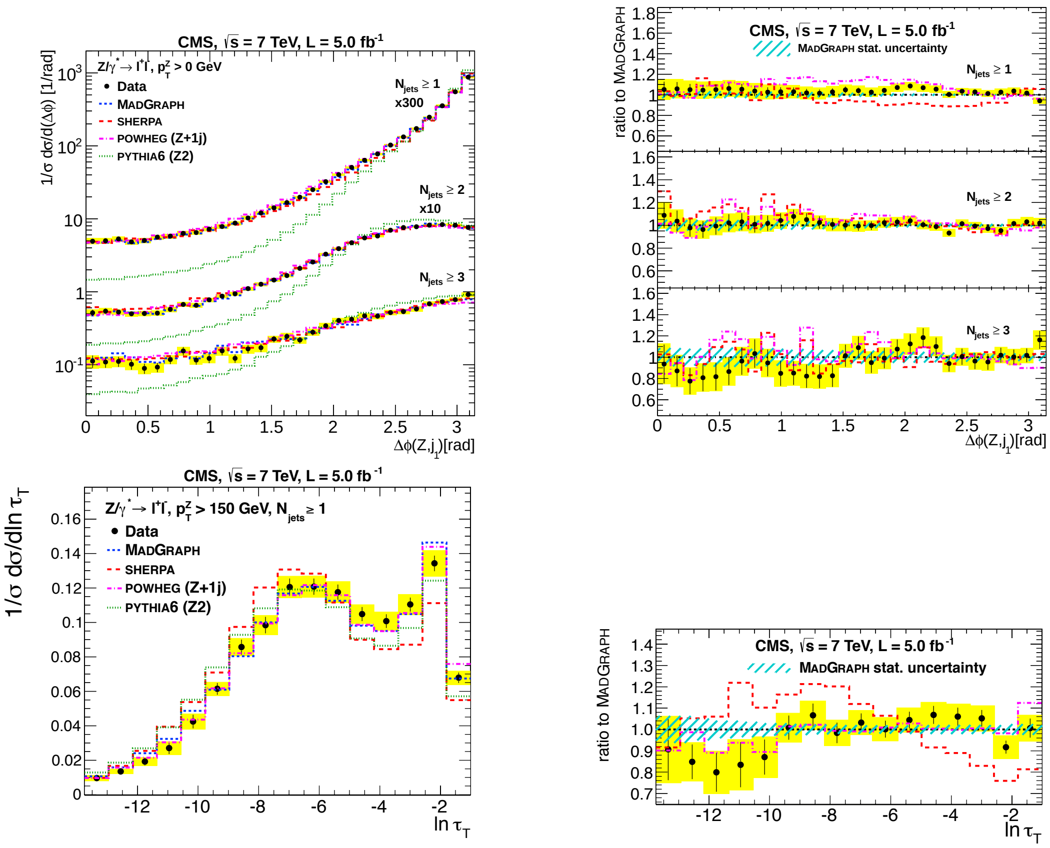

Figure 3: The distribution of $\Delta\phi(Z, j1)$ for three different inclusive jet multiplicities (left) and the distribution of the logarithm of the transverse thrust for $p_T^Z > 150$ GeV (right) from data and MC simulations from SHERPA, PYTHIA6, POWHEG and MADGRAPH in Z+jets events.

4. Z and heavy flavor quark production

Production of Z+heavy flavor quarks is studied using two different methods of heavy flavor identification both in the Z+1b and Z+2b final state. The first method relies on the identification of heavy quark jets through flight distance criteria[15]. The second b-tagging method is based on the identification of secondary vertices of B-hadrons independent of jets[16]. Thus it is possible in contrary to the b-jet identification method to access the phasespace where $\Delta R(b,\bar{b})$ is small in the Z+2 b case. This gives access to a region of collinear b-quark production which is sensitive to gluon-splitting. MADGRAPH offers two schemes of heavy flavor schemes. The five flavor (5F) scheme considers the five lightest quarks (including the b) within the proton PDF. The four flavor (4F) scheme considers the b only as massive final-state particle in the matrix element. The measured cross-section in Z+b(b) jets at particle level agrees with MADGRAPH for both schemes, after a rescaling with a constant NNLO k-factor (see Tab.1). The 4F scheme provides a better description of the collinear region of B-hadrons, whereas the 5F scheme underestimates the rate (see Fig. 4).

Table 1: Cross sections at the particle level for the production of a Z boson in association with exactly 1 b jet and at least 2 b jets, and the combination of the two (at least 1 b jet), showing the statistical and systematic uncertainties. The expectation from MadGraph includes the statistical uncertainty.

Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)+b)$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03

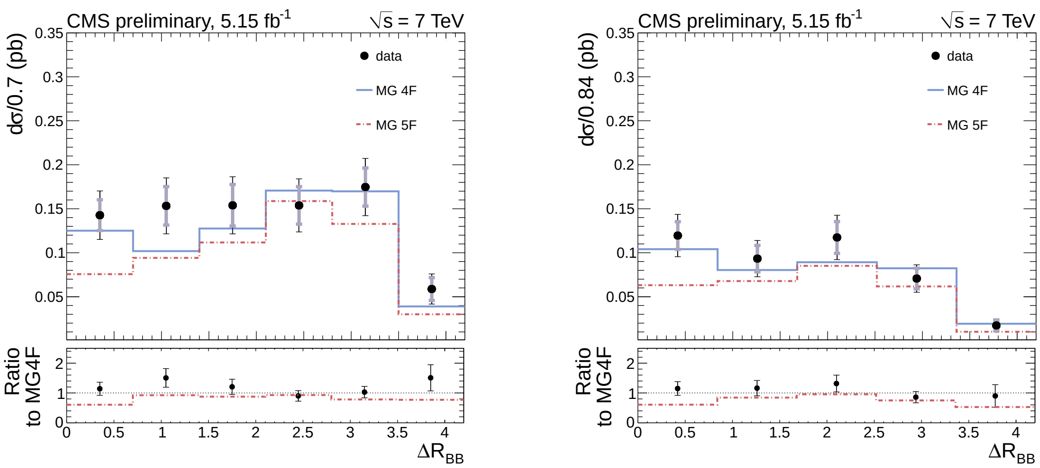

Figure 4: Differential cross-sections in Z+2 B hadron events in an inclusive selection (left) and a selection with $p_T^Z > 50\,\mathrm{GeV}$ (right) as a function of ΔR_{BB}. The measurements are compared to hadron-level predictions by MADGRAPH in the four- and five-flavor schemes

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5. Conclusion

The unprecedented amount of data delivered by the LHC makes it possible studying extreme configurations of V plus jets with high precision, which are also interesting for new physics searches. Several predictions have been compared with data in various distributions. The different level of agreement reflect the current understanding of QCD dynamics.

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, JINST **3** S08004 (2008).

[2] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP#Vector_Boson_Jets_Production.

[3] CMS Collaboration, *Measurement of triple-differential cross section of gamma+jet production production in proton-proton collisions at* $\sqrt{s} = 7\,\text{TeV}$, CMS-PAS-QCD 11-005 (2013).

[4] S. Catani et al., *Cross section of isolated prompt photons in hadron-hadron collisions*, JHEP **05** (2002) 028.

[5] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **05** (2009) 007.

[6] CMS Collaboration, *Study of observables sensitive to double parton scattering in W + 2 jets process in p-p collisions at* $\sqrt{s} = 7\,\text{TeV}$, CMS-PAS-FSQ-12-028 (2013)

[7] J. Alwall et al., *MadGraph5: Going Beyond* , JHEP **06** (2011) 128.

[8] T. Sjöstrand, S. Mrenna and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026.

[9] T. Sjöstrand, S. Mrenna and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput.Phys.Commun **178** (2008) 852.

[10] J.M. Campbell and R.K. Ellis, *MCFM for the Tevatron and the LHC*, Nucl.Phys.Proc.Suppl **205-206**, (2010) 10

[11] CMS Collaboration, *Measurement of rapidity distributions for a Z boson or a photon in association with a single jet in pp collisions at* $\sqrt{s} = 7\,\text{TeV}$, CMS-PAS-SMP-12-004 (2013)

[12] A. Banfi, G.P. Salam and G. Zanderighi, *Phenomenology of event shapes at hadron colliders*, JHEP **06** (2010) 038.

[13] CMS Collaboration, *Event shapes and azimuthal correlations in Z + jets events in pp collisions at* $\sqrt{s} = 7\,\text{TeV}$, Phys.Lett.B **722** (2013) 238

[14] S. Alioli et al., *Vector boson plus one jet production in POWHEG*, JHEP **01** (2001) 095

[15] CMS Collaboration, *Measurement of the production cross section of a Z boson in association with b jets in pp collisions at* $\sqrt{s} = 7\,\text{TeV}$, CMS-PAS-SMP-13-004 (2013)

[16] CMS Collaboration, *Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons in pp collisions at* $sqrt(s) = 7\,\text{TeV}$, arXiv:1310.1349 [hep-ex], https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015.