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Measurements of the jet and vector boson in association with jets production, extraction of α_s and PDF constraints at CMS

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Abstract.
We present CMS results about measurements of cross sections for jet production, which allow basic tests of perturbative QCD predictions. Results include recent jet, dijet, and multijet differential cross sections, and hadronic event shape measurements in pp collisions at a centre-of-mass energy of 7 and 8 TeV, using data collected in the CMS experiment. Total and differential cross section measurements of vector bosons production in association with jets and heavy flavour quarks are also presented. The experimental results are compared to leading and next-to-leading order calculations, both at parton level and in event generators where matrix element calculations are interfaced with parton showers. Recent CMS results related to the extraction of the strong coupling constant and extraction of α_S and PDF are discussed.

1 Introduction

CMS has performed a wide range of studies of Standard Model physics using data collected at a center of mass energy of 7 and 8 TeV from 2010 to 2012 .

Jets production is the most common process in a hadron collider and cross section measurements, both inclusive and differential, can provide stringent tests of perturbative QCD (pQCD). Other measurements like hadronic shapes distributions can also extend our knowledge of hadronization, soft QCD dynamics and other non perturbative effects.

The production of Z and W bosons, which may be identified through their leptonic decays, is theoretically well described within the framework of the Standard Model. Since the electroweak part of the process is well known, precise measurement of the cross sections can provide significant constraints to the PDFs. The cross section measurement of vector bosons production is also very important for the description of background in many Beyond Standard Model (BSM) searches and in Higgs physics.

2 Jets production

2.1 Inclusive jets cross section

A fundamental quantity that can be measured and predicted within the framework of perturbative QCD (pQCD) is the inclusive jet cross section (p + p → jet + X), where every jet is counted. In

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the presented analysis [1] data from proton-proton collisions at $\sqrt{s}$ = 8 TeV, corresponding to an integrated luminosity of 10.71 fb^{-1} are analyzed, and the cross section measurement is performed double-differentially as a function of the jet transverse momentum p_T and the absolute jet rapidity $|y|$. In figure 1 the double-differential jet cross section is shown, and it is compared with NLO predictions using the NNPDF2.1 PDF times the correction factor for non-perturbative (NP) effects.

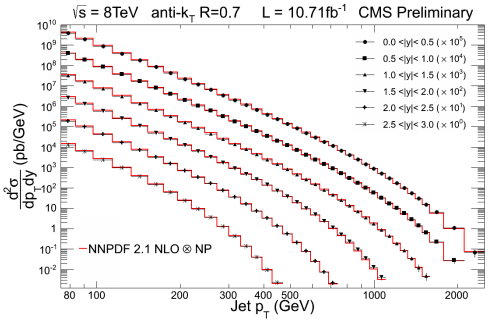

Figure 1: Double-differential inclusive jet cross section in comparison to NLO predictions using NNPDF2.1 PDF set times the NP correction factor.

Jets are reconstructed with the anti-k$_T$ clustering algorithm for a jet size parameter R = 0.7 in a phase space region ranging up to jet transverse momenta of p_T = 2.5 TeV and an absolute rapidity of $|y|$ = 3.0. The measured jet cross section is corrected for detector effects and compared to predictions of perturbative QCD at next-to-leading order using various sets of parton distribution functions.

Detailed studies of experimental and theoretical sources of uncertainty have been carried out. The dominant source of experimental systematic uncertainty arises due to the jet energy scale, unfolding and luminosity measurement uncertainty. These leads to about 15-40% uncertainty in the cross section measurement across various rapidity bins. In comparison, the theory predictions are most affected by PDF uncertainties, which amount to 10% to 50% depending on the rapidity bin, whereas choices of renormalization and factorization scales contribute 5% to 10% at central rapidity and 40% in the outer rapidity bins.

CMS has also published a study of the PDF constraints and the strong coupling constant α_s using the inclusive jet cross section measured from proton-proton collision data at $\sqrt{s}$ = 7 TeV. The data corresponds to 5.0 fb^{-1} of integrated luminosity recorded in 2011 [2]. The PDFs obtained from the fit using both CMS and HERA data are compared with HERA only. The results adding CMS data show that for the gluon distribution a significant improvement of precision in the high-x region x>0.01 is observed (see figure 2). At the same time CMS jet data favour a larger gluon PDF at high x compared to the DIS data.

2.2 Dijet cross section

A measurement of the double-differential dijet cross section is presented using 9.2 fb^{-1} of data collected with the CMS detector in proton-proton collisions at $\sqrt{s}$ = 8 TeV [3]. The measurement covers the dijet-mass range from 0.35 TeV to 5.5 TeV in five rapidity bins up to $|y_{max}|$ = 2.5. The measured cross sections agree with the predictions of perturbative QCD at NLO obtained with five different PDF sets. Theoretical and experimental uncertainties are comparable (see figure 3), even at the highest M_{jj} masses, so these results may be used to constrain global PDF fits.

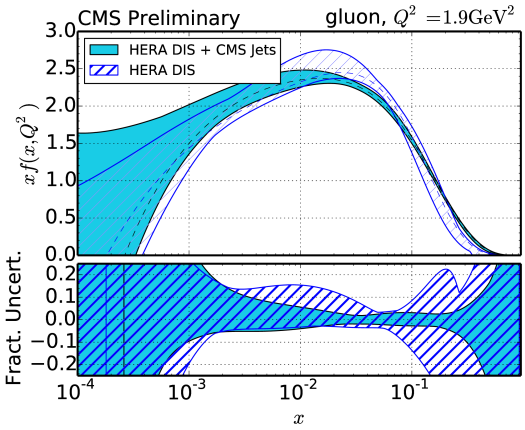

Figure 2: The gluon PDF as a function of x as derived from HERA inclusive DIS data alone (hatched) and in combination with CMS inclusive jet data from 2011. The PDFs are shown at the starting scale Q^2 = 1.9 GeV^2. Only the total uncertainty of the PDFs is shown.

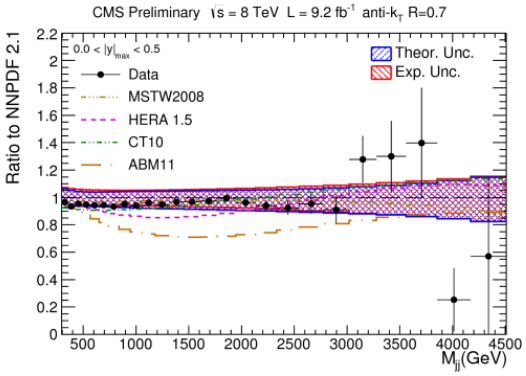

Figure 3: Ratio of the dijet cross section to the theoretical prediction using the central value of the NNPDF2.1 PDF set for the one of the five bins of $|y_{max}|$. The solid histograms show the ratio of the cross sections calculated with the other PDF sets to that calculated with NNPDF2.1. The experimental and theoretical systematic uncertainties are shown.

2.3 Multijet and hadronic shapes distributions

A study of inclusive topological distributions of three- and four-jet events has been conducted by the CMS Collaboration at the LHC with a data sample corresponding to an integrated luminosity of 5.1 fb^{-1} at a centre of mass energy of 7 TeV [4]. Kinematic and angular distributions in inclusive multijet final states serve as a natural probe of quantum chromodynamics and can reveal its inner dynamics. The corrected data are compared with predictions from four leading order Monte Carlo models: PYTHIA 6, PYTHIA 8, MADGRAPH + PYTHIA 6 and HERWIG++. The PYTHIA 6 sample shows the largest discrepancy with the data while predictions from MADGRAPH + PYTHIA

6 are the closest to the data. Predictions from HERWIG++ give a good description of the angular distributions in the four-jet events. Hadronization or PDF uncertainties cannot explain the level of disagreement between the data and the model predictions.

CMS published also a dedicated study of event shape variables which are sensitive to the structure of QCD radiation in hadron collisions [5]. Five infrared- and collinear-safe event shape variables, each sensitive to the different features of multi-jet production, are measured using hadronic jet data collected with the CMS detector from pp collisions at $\sqrt{s}$ = 7 TeV, corresponding to a total integrated luminosity of 5 fb^{-1}. The measurements are compared to predictions of PYTHIA 6, PYTHIA 8, HERWIG++ and MADGRAPH MC generators. The generator that consistently reproduces all distributions within the uncertainties is the MADGRAPH matrix-element calculator combined with PYTHIA 6-tuneZ2 for multiparton interactions and parton showering and hadronization. The study of infrared- and collinear-safe event-shape variables presented in this study provides detailed information to further improve the modelling of parton radiation and hadronization in event generators for high energy hadronic collisions.

2.4 Three-to-two jets ratio

A measurement of the double-differential cross section of 3-jet events is performed at a center of mass energy of $\sqrt{s}$ = 7 TeV, using data corresponding to an integrated luminosity of 5 fb^{-1} collected with the CMS detector in 2011 [6]. The cross section is measured as a function of the invariant mass and maximum rapidity of the 3-jet system and is unfolded for detector effects. A comparison between the measurement and the prediction from perturbative QCD at next-to-leading order is performed. Within uncertainties, data and theory are in agreement. The sensitivity of the observable to parameters of the theory like the PDFs of the proton and the strong coupling α_s is studied.

A measurement of α_s has been determined in multiple regions of 3-jet mass m_3 at scales $Q = m_{3/2}$ between 0.26 TeV and $\approx$ 1.4 TeV. Figure 4 shows the running of α_s: the results of CMS analyses are well aligned with other experiments and extend the measurement to higher momentum scale.

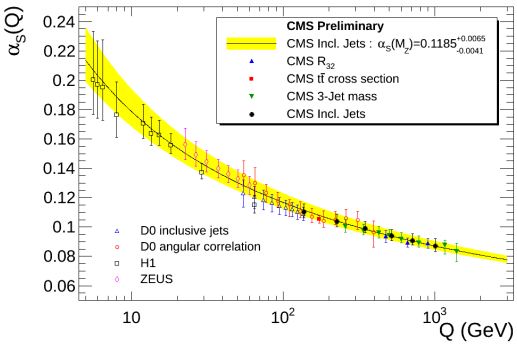

Figure 4: The strong coupling α_s(Q) (solid line) and its total uncertainty (band) as determined in this analysis using a 2-loop solution to the RGE as a function of the momentum transfer Q=p_T. The extractions of α_s(Q) in six separate ranges of Q are shown together with results from the H1, ZEUS, and D0 experiments at the HERA and Tevatron colliders. Recent other CMS measurements are displayed as well [2][6][7][8]

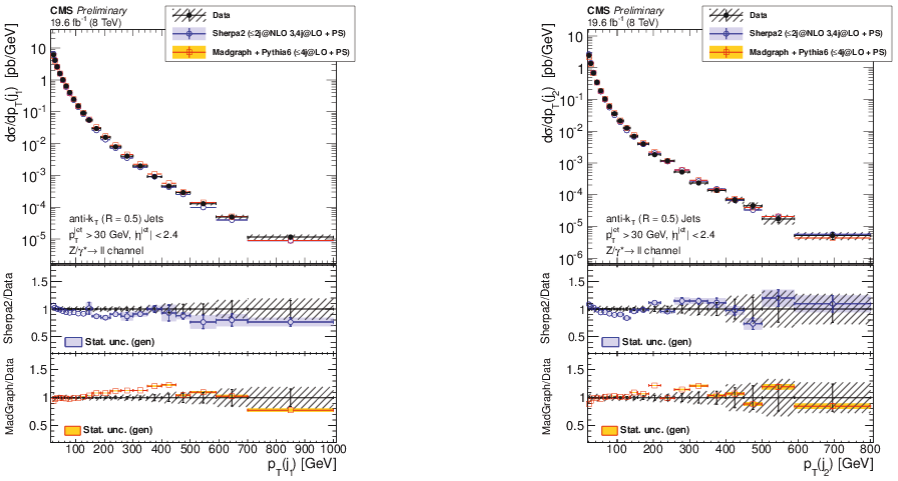

Figure 5: Differential cross section measured as a function of the (left) 1st and (right) 2nd jet p_T compared to the Sherpa and MADGRAPH Monte Carlo predictions. The lower panels show the ratio of theory prediction to data. Error bars around the experimental points show the statistical uncertainty, while the crosshatched bands indicate the statistical plus systematic uncertainties added in quadrature. The colored filled band around theory represents the statistical uncertainty of the generated sample.

3 Vector boson + light flavor jets

3.1 W/Z + jets

The differential cross section of Z boson production in association with jets, in the muon and electron decay channels, is measured in pp collisions at a center of mass energy of $\sqrt{s} = 8$ TeV with 19.6 fb^{-1} of data collected by the CMS experiment in 2012 [9]. The differential cross section is presented as a function of the jet multiplicity, the transverse momentum of the Nth jet, the absolute pseudo-rapidity of the Nth jet and the scalar sum of the jet transverse momenta, for N = 1,...,5. The differential cross sections are then compared to theoretical predictions from MADGRAPH + PYTHIA 6 and SHERPA (see figure 5). The matrix elements of SHERPA include the five processes pp → Z + N jet, N = 0...4, with an NLO accuracy for N ≤ 2 and LO accuracy for N = 3, 4. The measurement phase space is defined as: mass of Z/γ^* in the ± 20 GeV window around 91 GeV; lepton pseudorapidity, $|\eta| < 2.4$; lepton transverse momenta, $p_T > 20$ GeV. The jets are reconstructed with the anti-kt algorithm with distance parameter R = 0.5. Only jets with $p_T > 30$ GeV and $|\eta| < 2.4$ are considered. The leptons are dressed by adding to their momentum the momenta of the photons with direction closer in ΔR where $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ than 0.1 from the lepton direction in order to include the final state radiation.

The study of Z+jets is extended to the forward region $|y| < 4.7$ identifying the Z bosons via their decays to $\mu^+\mu^-$ pairs [10]. The measurement is compared to LO + PS predictions from MADGRAPH and NLO + PS predictions from SHERPA 2. Discrepancies are observed between MADGRAPH and the measurements, mainly for jet p_T above 100 GeV roughly independent of the jet rapidity. An overall agreement is seen between SHERPA 2 predictions and the data except some discrepancies in different y and p_T regions that will have to be investigated further.

Thr CMS collaboration recently published the Z + jets differential cross section measurements at $\sqrt{s} = 7$ TeV using a data sample corresponding to an integrated luminosity of 4.9 fb^{-1}. The jet mul-

tiplicity distribution is measured for up to six jets [11]. The differential cross sections are measured as a function of jet transverse momentum and pseudorapidity for the four highest transverse momentum jets. The distribution of the scalar sum of jet transverse momenta is also measured as a function of the jet multiplicity. All measured differential cross sections are corrected for detector effects and compared with theoretical predictions at particle level. The measured jet multiplicity distributions and their NLO theoretical predictions from the SHERPA and POWHEG generators are consistent within the experimental and theoretical uncertainties. However, SHERPA predicts softer p_T and H_T spectra than the measured ones, while POWHEG shows an excess compared to data in the high p_T and H_T regions. In particular, the POWHEG spectra are harder for the highest jet multiplicities, which are described only by parton showers. The tree level calculation based on MADGRAPH predicts harder p_T spectra than the measured ones for low jet multiplicities.

The corresponding measurements for the associated production of W bosons and jets are presented, for pp collisions at $\sqrt{s}$ = 7 TeV, in association with jets, in [12]. The data were collected with the CMS detector during the 2011 pp run of the LHC, and correspond to an integrated luminosity of 5.0 fb^{-1}. Cross sections have been determined using the muon decay mode of the W boson and are presented as functions of the jet multiplicity, the transverse momenta and pseudorapidities of the four leading jets, and the difference in azimuthal angle between each jet and the muon. The results, corrected for all detector effects with an unfolding procedure, have been compared with particle-level simulated predictions from pQCD. The data are compared with predictions based on LO matrix elements, from the generators MADGRAPH+PYTHIA6 and SHERPA, and from parton-level predictions at NLO, as provided by BLACKHAT+SHERPA. The latter are corrected for non-perturbative effects before comparing with data results unfolded at particle level. The jet multiplicity distribution is described by all the calculations, within uncertainties. The cross section as a function of the p_T of the leading jet is overestimated by MADGRAPH + PYTHIA and SHERPA, especially at high-p_T. Some overestimation from MADGRAPH + PYTHIA can also be observed in the second- and third-leading jet p_T distributions. The cross sections as a function of p_T predicted by BLACK-HAT + SHERPA agree with the measurements within uncertainties. Similar levels of agreement have been observed in the distributions of H_T for $N_{jet} \geq 1$, 2, 3 and 4.

3.2 Photon + jets

Differential cross sections are measured for Z/γ^* and γ final states as a function of the transverse boson momentum with a lower threshold of p_T>100 GeV and for central vector bosons ($|y| < 1.4$), using data collected by CMS at $\sqrt{s}$ = 8 TeV corresponding to an integrated luminosity of 19.7 fb^{-1} [13]. The measurement is performed in four different phase-space regions: $N_{jets} \geq 1$, 2, 3 and $H_T >$ 300 GeV, $N_{jets} \geq 1$. These regions are of interest for searches of physics beyond SM as the processes studied are used for SM background estimation. The predictions from the MC generator programs MADGRAPH and SHERPA (LO calculation) and from BLACK-HAT (NLO) are compared to the data. The NLO BLACK-HAT prediction is corrected for non-perturbative effects (hadronization and underlying event) using MADGRAPH plus PYTHIA 6 and these corrections are typically around 2%. The Z/γ^* + jets MC predictions from SHERPA and MADGRAPH + PYTHIA 6 are rescaled by a constant NNLO k-factor of k = 1.197 provided by FEWZ 3.1. At leading order the ratio of MC to data for Z/γ^* + jets and γ + jets is not well reproduced by these MC models at high vector boson p_T (see figure 6). Furthermore, this discrepancy increases approximately linearly as function of Z or γ p_T. However, at NLO, a reduction in the discrepancy between data and MC is found, indicating that it might be related to missing higher orders.

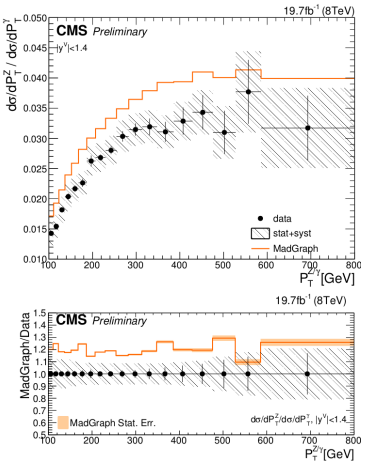

Figure 6: Differential cross-section ratio of Z over γ as a function of the total transverse momentum cross-section and for central bosons ($|y_V| < 1.4$). Here is reported the inclusive measurement ($N_{\text{jets}} \geq 1$). The black error bars reflect the statistical uncertainty of the ratio, the hatched band represents the total uncertainty of the measurement. The data points are compared to predictions from MADGRAPH 5.1.3.30 + PYTHIA 6.4.26 using LO cross-sections for both processes. The shaded band around the MADGRAPH to data ratio represents the statistical uncertainty of the MC prediction.

4 Vector boson + heavy flavor jets

4.1 Z + b, bb

The production of a Z boson, decaying into two leptons and produced in association with one or more b jets, is studied using proton-proton collisions delivered by the LHC at a centre-of-mass energy of 7 TeV [14]. The data were recorded in 2011 with the CMS detector and correspond to an integrated luminosity of 5 fb^{-1}. The Z(ll) + b-jets cross sections (where = $\mu\mu$ or ee, with leptons $p_T > 20$ GeV, $|\eta| < 2.4$, the dilepton invariant mass $76 < M < 106$ GeV, jets with $p_T > 25$ GeV and $|\eta(j)| < 2.1$, and a separation between the leptons and the jets of $\Delta R(l, j) > 0.5$) are measured separately for a Z boson produced with exactly one jet and with at least two b jets.

The cross section measurements are in agreement with the expectations from MADGRAPH and aMC@NLO in the five-flavour scheme, both combined with PYTHIA6. A difference of approximately two standard deviations is observed when comparing the cross sections with the predictions from MCFM at the parton level, and the comparison with the cross section ratio indicates that the difference is specific to the modelling of the Z + b-jets final state. Comparisons with the predictions in the four- flavour scheme, in particular from aMC@NLO, show a disagreement of more than two standard deviations in the Z + 1b-jet final state. Comparisons of the kinematic properties of Z+2b-jets production with the predictions from MADGRAPH in the five-flavour scheme show potential limitations of the existing MC event generators that employ the matrix element plus parton shower approach at leading order with massless b quarks. While these observations should be confirmed with more data, next-to- leading-order simulations and/or simulations with massive quarks could possibly provide a better description of the data in certain regions of phase space.

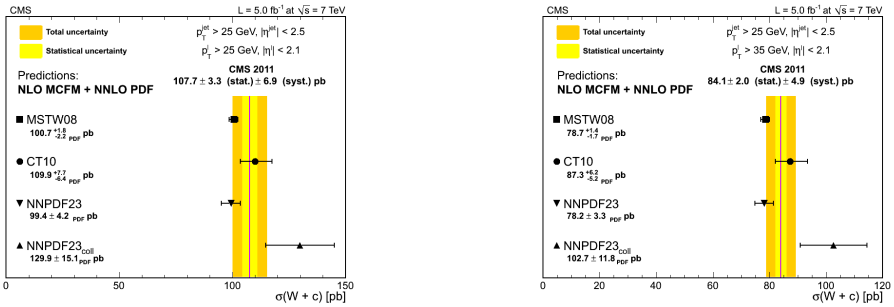

Figure 7: Comparison of the theoretical predictions for $\sigma(W + c)$ computed with MCFM and several sets of PDFs with the average of the experimental measurements. On the left is plotted the cross section of $W \to \mu\nu$ with $p_t^{\mu} > 25$ GeV, on the right the cross section of $W \to l\nu$ with $p_t^{l} > 35$ GeV

4.2 W + c

The associated production of a W boson and a charm-quark jet (W + c) is studied in pp collisions at a center of mass energy of 7 TeV [15]. The analysis is conducted with a data sample corresponding to a total integrated luminosity of 5 fb^{-1}. W boson candidates are identified by their decay into a charged lepton (muon or electron) and a neutrino. The W + c measurements are performed for charm-quark jets in the kinematic region $p_T^j > 25$ GeV, $|\eta^j| < 2.5$, for two different thresholds for the transverse momentum of the lepton from the W-boson decay, and in the pseudorapidity range $|\eta| < 2.1$.

Hadronic and inclusive semileptonic decays of charm hadrons are used to identify jets as coming from c quark fragmentation, and to measure the total cross sections $\sigma(pp \to W + c + X) \times B(W \to l\nu)$ (see figure 7) and the cross section ratios $\sigma(pp \to W^+ + c + X)/\sigma(pp \to W^- + c + X)$.

Cross sections and cross section ratios are also measured differentially with respect to the absolute value of the pseudorapidity of the lepton from the W-boson decay. These are the first measurements from the LHC directly sensitive to the strange quark and antiquark content of the proton. Results are compared with theoretical predictions and are consistent with the predictions based on global fits of parton distribution functions.

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