Journal of Physics: Conference Series **623** (2015) 012010 doi:10.1088/1742-6596/623/1/012010

Recent Standard Model results from CMS

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March 2015

Abstract. The data recorded by the Compact Muon Solenoid experiment during the first LHC run (2010-2012) has allowed to refine our knowledge on the production of jets and vector boson using the proton-proton collisions at $\sqrt{s}$= 7 or 8 TeV. Representative studies concerning the PDF and α_s extractions, the study of inclusive vector boson production, of production vector bosons in association with jets, and some recent results on anomalous gauge couplings evaluation are discussed.

1. Introduction

These proceedings are devoted to a few representative Standard Model (SM) measurements, which were performed by the CMS experiment using data collected during the LHC Run I operation. In Sec. 2 the impact of the CMS measurements on the parton density function (PDF) constraints as well as on the strong coupling constant $\alpha_{\rm s}$ extraction is discussed. In Sec 3, studies of the inclusive vector boson (V=W,Z,γ) production as well as V production in association with light or heavy jets (V+jets) are presented. In Sec. 4, the latest results on the extraction of anomalous triple/quartic gauge couplings (aTGC/aQGC) are reviewed. Full list of publications discussing SM-related results are accessible through [1].

2. PDF and α_s determination

The PDFs are essential ingredients to estimate the inclusive and differential cross-sections of all types of processes in proton-proton (p-p) collisions at the LHC. Several of them are needed to constrain the valence quarks, sea quarks and gluon PDFs: while QCD production of jets allows to refine the gluon PDF, the inclusive production of a W boson is more specifically sensitive to the valence- and sea-quarks PDFs, and that of the W boson in association with a charm quark has a large sensitivity to the strange-quark PDF. The data collected by the CMS collaboration in 2010 and 2011 was successfully used to refine our knowledge of these PDFs.

First, the inclusive jet production study [2] has allowed to add additional constraints especially on the gluon PDF. Final state is defined by the presence of at least two anti-$k_{\rm T}$ jets [3] with size parameter R=0.7, $p_{\rm T}$ >114 GeV and |y| <2.5. The full integrated luminosity (5fb^{-1}) of the 7 TeV p-p collisions is used. The difference between the gluon PDF uncertainty with HERA-I DIS data only [4] and with HERA-I

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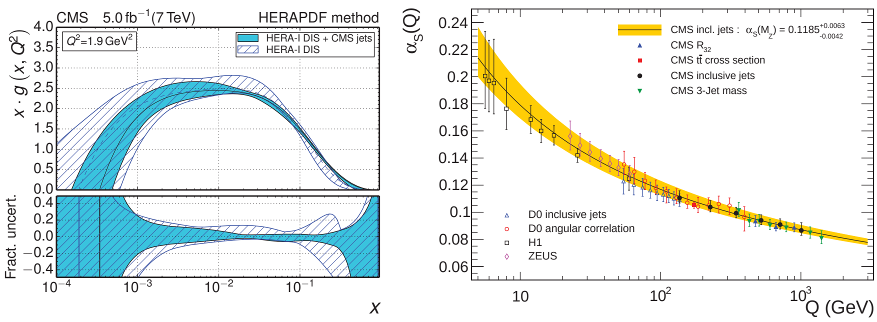

(a) (b)

Figure 1: (a) Comparison of the gluon PDF from HERA-I DIS data only, and after combining with CMS multijets analysis result. The error band represent the total (experimental, statistical, modeling) uncertainties. (b) Evolution of α_s with the scattering scale Q.

DIS and CMS measurement added is shown in Fig. 1a: the uncertainty on the gluon PDF is significantly reduced for fractional parton momenta x>0.01. More modest, although measurable, improvements on the u and d valence quarks PDFs are also present.The measurement of α_s was performed as well, found to be

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})^{+0.0053}_{-0.0024}(\text{scales}),$$

where NP stands for the uncertainties related to the non-perturbative corrections brought to the data to correct the measured quantities to the parton level, scales for the factorization and renormalization scale uncertainties. The running of α_s was also evaluated in several ranges of scattering scale Q^2 and is shown to be inline with previous measurements, as shown in Fig. 1b

The quarks PDFs were also extracted using the muon charge asymmetry and W+c measurements. The muon charge asymmetry measurement [5] especially impacts the quark PDFs in the Bjorken scaling variable from 0.001 to 0.1, while the W+c measurement allows to probe in particular the s-quark pdf [6] . Both measurements have been combined together, with the HERA e-p cross-section measurement, see [7] for the details and conclusions.

3. Production of a W or Z boson

The study of W and Z bosons production is essential for two reasons. First, these processes are large backgrounds for numerous searches and measurements. A precise estimate of the corresponding differential cross-sections is therefore essential in this context. Second, the understanding of their production mechanism is important to refine our knowledge of QCD and QED. The p-p collisions data taken during the Run I allowed to compare data with predictions from theory to a unprecedented level, both in terms of statistics and range of energy.

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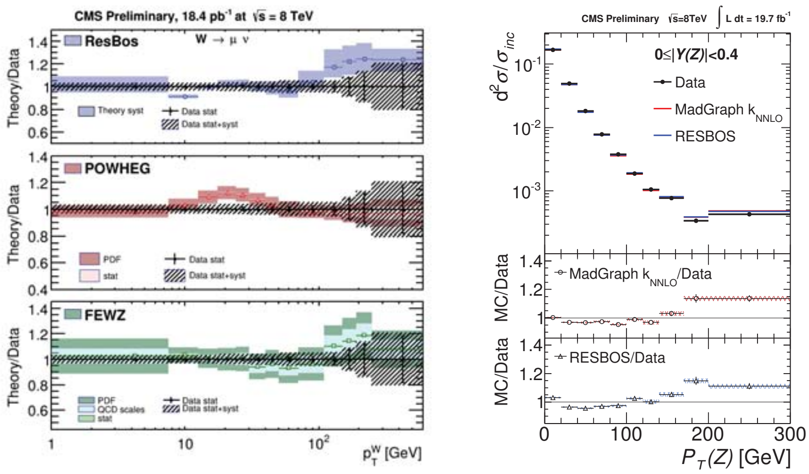
3.1. Differential W bosons and Z bosons production cross-section at $\sqrt{s}$= 8 TeV

Theoretical predictions for the production of a vector boson W or Z in hadron collisions are computed to the next-to-next-to-leading-order (NNLO) in perturbative quantum chromodynamics (pQCD). The uncertainties are essentially related to the PDFs, α_s and the scales choice. The complication in the prediction of vector boson spectra, independently of the number of jets from initial-state radiation (ISR), is the necessity to describe production mechanisms simultaneously at soft and hard scales, including the transition region. These studies therefore constitute stress tests of sophisticated event generation/calculation techniques. Here below the example of the study of the W and Z vector bosons transverse momenta with the full integrated luminosity ($\sim$ 20fb^{-1}) of the 8 TeV p-p collisions are given. The measurement of the W boson transverse momentum (see Fig. 2a) is compared with different theoretical predictions: `POWHEG` [8] (NLO in QCD), `FEWZ` [9] (NNLO QCD), `RESBOS` [10] (NNLL/NLO QCD).



(a) (b)

Figure 2: (a) Transverse momentum of the W boson. The uncertainties in the data points are systematical and statistical errors added in quadrature. The uncertainties in the theory predictions represent the scale, PDF, and statistical errors, also added in quadrature. (b) Transverse momentum of the Z boson for $|y| < 0.4$. The error bars represent the statistical uncertainty of data and predictions, while the shaded band represent the systematic uncertainties from data only.

The comparison is done in a phase-space region defined by the presence of one pre-FSR muon (electron) with p_T >20 (25) GeV, $|\eta|$ <2.1 (2.5). Correction of the detector effects is performed with the SVD technique [11]. The measurement of the Z boson $d\sigma/dp_T|dy|$ (see Fig. 2b) is compared with `RESBOS` and the tree-level multi-leg event generator `Madgraph` [12]. The comparison is done in a phase-space defined by the presence of two muons. The leading (second) with p_T >25 (10) GeV, $|\eta|$ <2.1 (2.4). Correction of the detector effects is performed with the D'Agostini technique [13].

Both `Madgraph` and `RESBOS` predictions severely overshoot the data in the high

p_T^Z region (>100 GeV). A similar effect is observed with `RESBOS` and `FEWZ` for the transverse momentum of the W boson, while `POWHEG` exhibits an event excess in the region between 10 and roughly 30 GeV. More details concerning these studies can be found in [14, 15], and other CMS studies can be found elsewhere [1].

3.2. V + jets

The modeling of the production of V+jets processes is sensitive to several effects: the presence of higher order QCD or QED corrections, the choice of factorization and renormalization scales, the merging procedure used to get the leading jets from the matrix-element (ME) calculation (see e.g. [16–19]), and the characteristics of the parton shower (PS).

The CMS collaboration has published several results concerning the V+jets processes. Comparison between data and prediction from theory is shown for the production of a Z boson in association with jets [20, 21] in Fig. 3. The comparison is done in a phase-space region defined by the presence of two same-flavour and opposite-charge leptons (e or μ) with $\mathrm{p_T}$ >20 GeV, $|\eta|$ <2.4. Each lepton is dressed, i.e. is defined from the clustering of a final state lepton and FSR photons in a cone with 0.1 radius centered on this final state lepton. In addition, the lepton invariant mass $\mathrm{M_{ll}}$ must fulfill de condition $|\mathrm{M_Z} - \mathrm{M_{ll}}| < 20$ GeV. Jets are defined at particle level using anti-$\mathrm{k_T}$ (R=0.5) algorithm, $\mathrm{p_T}$ >30 GeV and $|\eta|$ <2.4. A minimal ΔR of 0.5 between the jets and the leptons is required. The correction of detector effects is performed using the D'Agostini method. The number of jets shown in Fig. 3a turns out to be reasonably described by both `Sherpa2` [22] and `Madgraph`. Deviations are observed essentially for $\mathrm{N_{jet}}$ >5, where the parton shower prediction is dominant. That means the ME calculation are performing well, both at tree-level and NLO. In Fig. 3b, the transverse momentum of the leading jet turns out to be better described by the NLO prediction, although a trend is visible, especially in the low $\mathrm{p_T}$ region. The scalar sum of jet $\mathrm{p_T}$ shown in Fig. 3c is very well described by `Sherpa2`, while a `Madgraph` undershoot the data in the low $\mathrm{H_T}$ region.

The comparison and ratio of momenta of Z boson and photon produced in association with jets [23] is shown in Fig. 3d and 3e, respectively. The Z+jets events selection is essentially the same as described above. For the γ+jets, a minimal transverse momentum of 100 GeV is required for the photon, as well as $|\eta|$ <1.4. It turns out that `Madgraph` predicts the good shape, but fails at estimating the normalization. One possible source for this deviation is the missing QCD and QED higher order terms. This is particularly important for searches for supersymmetric particles, where the $\mathrm{Z} \to \nu\nu$ background processes can be deduced by estimating the normalization and shape of γ+jet process. Other results which concern the jets production in association with a W boson, the azimuthal and longitudinal correlation in Z+jets, can be found in [1].

3.3. W and Z + heavy flavour quark pairs

The production of a Z or W boson in association with a heavy flavour quark pair c or b constitute a subclass of the V+jets events copiously produced in the p-p collisions at the LHC. Due to their much smaller cross-section, the production mechanisms of the heavy quarks are only scarcely known and large uncertainties remain up to now. Dominant uncertainties are related to the choice of factorization and renormalization

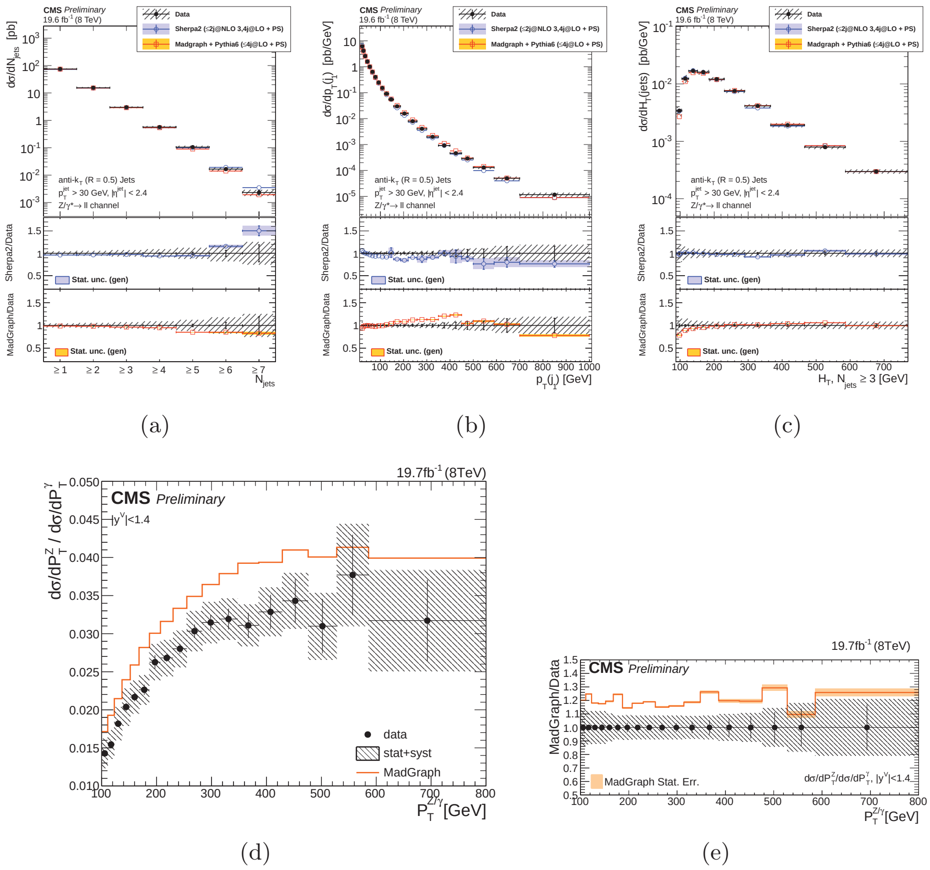
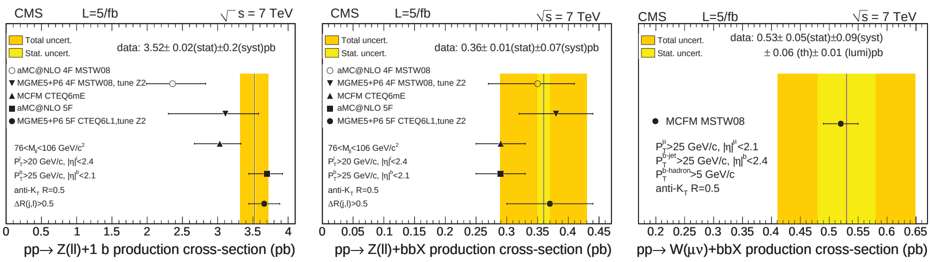
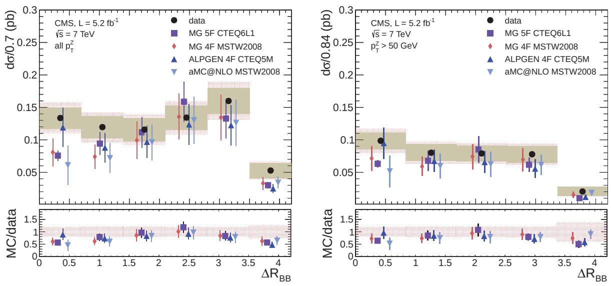


Figure 3: (a) Number of jets produced in association with the Z boson (b) p_T of the leading jet produced in association with the Z boson. (c) Scalar sum of the jets p_T, assuming the presence of at least three jets. The uncertainty band associated to the predictions from theory show the statistical uncertainty. (d) Differential cross-section ratio of leptonic Z/γ w.r.t. p_T^V for $N_{jet} > 0$. (e) Ratio of the Z and γ+jets predictions from theory and data. The error bars reflect the statistical uncertainty of the ratio, the hatched band is the total uncertainty.

scales, flavour numbering scheme and related ME-PS merging approach (which includes the treatment of FSR gluons radiated off the heavy quark states), and the b-quark mass. Several analyses were completed by the CMS collaboration, all related to the production of a Z or W boson in association with a b-jet pair [24, 25]. The cross-sections are given for the events with exactly one b-jet (Fig. 4a) and events with at least two b-jets (Fig. 4b and 4c). Comparisons with `aMC@NLO` [26] and `Madgraph` in both the four flavour (4F) and five-flavour (5F) numbering schemes, and with `MCFM` (5F) were done. For the Z+b-jet(s) analysis, the phase-space is defined by the leptons: $p_T > 20$ GeV, $|\eta| < 2.4$, $|M_Z - M_{ll}| < 15$ GeV, the presence of one or at least two b-jet:



(a) (b) (c)



(d) (e)

Figure 4: (a), (b) and (c): cross-sections for Z+1 b-jet, Z+>1 b-jet and W+2 b-jets, respectively. Both statistical and total uncertainties are represented. (d) and (e): differential cross-section of Z+2 B-hadrons w.r.t. the ΔR separation between the hadrons. The darker band is the statistical uncertainty, the brighter one is total uncertainy.

anti-k_T(R=0.5), p_T >25 GeV, $|\eta|$ <2.4, ΔR(j, l) >0.5 and the presence of a b-hadron inside the jet. For the W+2 b-jets analysis, the phase-space definition is the same apart that the lepton selection is defined from the presence of one muon with p_T >25 GeV, $|\eta|$ <2.1.

For Z + exactly one b-jet, the 4F predictions from both `Madgraph` and `aMC@NLO` tend to undershoot the data, while the 5F predictions are more inline with the data. For Z and W + at least two b-jets all predictions are in agreement (within the uncertainties) with the data.

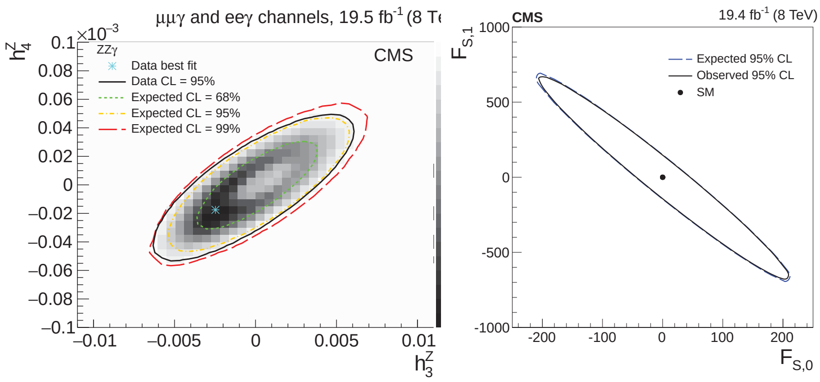
Besides the inclusive measurements, the differential cross-section of the production of a Z boson in association with a pair of B-hadron (identified through the presence of secondary vertices) was measured [27]. Several variables are studied, including the ΔR between the B-hadrons, which is the most sensitive variable to test the modeling of the collinear production of B-hadrons and suffers from large theoretical uncertainties. In Fig. 4d (4e) the ΔR between the B-hadrons is shown for events with p_T^Z > 0 (50) GeV. There the phase-space is defined by the presence of two leptons with p_T >20 GeV, $|\eta|$ <2.4, $|M_Z - M_ll|$ <10 GeV, and two B-hadrons with p_T >15 GeV and $|\eta|$ <2.0.

These first studies of the production of a vector boson in association with b-quark pairs shows that as soon as the two heavy states are sufficiently separated, i.e. if the production mechanism of the b-quarks is not likely identified as from a gluon splitting, the prediction do behave well, while the collinear region is generally poorly described.

4. Anomalous gauge couplings

The study of anomalous triple (quartic) gauge couplings aTGC (aQGC) is of prime importance to test the dimension-4 SM hypothesis: besides the searches for the presence of new resonances, a seducing idea is to consider the SM as an effective field theory described by a higher dimensional (6 or 8) lagrangian with as consequence a change of gauge-couplings strengths. Recent results concerning the aTGC Z$Z\gamma$ and $Z\gamma\gamma$ [28, 29] as well as WWWW [30] aQCG are quoted here. In the first case, The experimental final state is a dilepton final state and a photon, while in the second case, the hypothesis of the aQCG is tested using the vector-boson-scattering process leading to a pair of same-sign W bosons.

Exclusion limits on the operator strength were established, as shown in Fig. 5a and 5b.



(a) (b)

Figure 5: (a) Best fit between data and model of anomalous ZZ? couplings [28]. The blue marker indicates the point of highest probability. The level of gray represents the exclusion probability and the black line corresponds to the 95% CL limit. Several expected contours from SM simulation are also shown.(b)Observed and expected 2D limit on FS_0 and FS_1 for the WWWW aQGC [30] .

The general conclusion from the diverse aTGC/QCG searches is that as for today there is no observed deviation from the dimension-4 SM hypothesis. All CMS results concerning searches for anomalous triple (WWZ, WWγ, ZZγ, Z$\gamma\gamma$) and quartic ($\gamma\gamma$WW, γZWW) gauge couplings can be found elsewhere [1].

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