Electroweak measurements with the CMS experiment

Gabriella Pasztor on behalf of the CMS Collaboration

Abstract

The CMS Collaboration pursues a rich program of electroweak measurements using the W and Z particles. Its latest results are presented using the data collected at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of almost 20 fb$^{-1}$. The cross-sections of electroweak $\ell\ell jj$ and $\ell\nu jj$ production and the properties of the additional jets in the event are measured. The forward-backward asymmetry and angular coefficients in Drell-Yan $\ell\ell$ production, as well as the transverse momentum distribution of the W and Z bosons are studied and compared to theoretical calculations. The charge asymmetry in $W$ production is determined and used to constrain the parton distribution functions of light quarks.

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1 Introduction

Electroweak (EW) measurements coupled with precise theoretical calculations provide a critical test of the Standard Model (SM) and allow to constrain models predicting New Physics. The EW gauge and Higgs sector can be described by four parameters: the fine-structure constant, the Fermi coupling constant, the masses of the Z boson and the Higgs boson. Other parameters like the weak mixing angle ($\theta_W$) and the mass of the W boson ($m_W$) are then predicted, making the theory over-constrained.

The precise measurement of the weak mixing angle and the W mass requires and excellent understanding of the experimental and theoretical uncertainties, including those coming from the imperfect knowledge of parton distribution functions (pdf’s). Leading to that, a rich program of W and Z boson measurements is executed and presented here: the determination of forward-backward asymmetry and angular coefficients in Drell-Yan $\ell\ell$ production, the charge asymmetry in W production constraining the pdf’s of light quarks, as well as differential distributions of W and Z production in particular the transverse momentum spectra that provide crucial tests of both non-perturbative and perturbative effects due to quantum chromodynamics (QCD). Gauge boson self-interactions are studied via the measurement of the electroweak production of Z + 2 jets and W + 2 jets and complement the di-boson measurements at the LHC.

All results presented here are based on the data collected in 2012 by the CMS detector at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of almost 20 fb$^{-1}$.

2 Electroweak production of $\ell\ell jj$ and $\ell\nu jj$

The measurement of EW triple gauge boson couplings (TGC’s) in vector boson fusion (VBF) processes tests the SM description of gauge boson self-interactions. VBF signatures, featuring...
two energetic jets ($j$) with large rapidity separation and large dijet invariant mass, are also important for Higgs boson property measurements.

For EW $\ell\ell jj$ and $\ell\nu jj$ production ($\ell$ denoting an electron or muon), large background comes from $Z/\gamma^*$ and W production accompanied by quark and gluon emission via strong couplings. Large negative interference arises for VBF, radiative and multi peripheral EW $\ell\ell jj$ diagrams.

The EW $\ell\ell jj$ signal strength is measured in a fiducial region defined by requirements on the dilepton mass $m_{\ell\ell} > 50$ GeV, the jet transverse momentum $p_{Tj} > 25$ GeV and pseudorapidity $|\eta_j| < 5$, as well as the dijet mass $m_{jj} > 120$ GeV and angular separation $\Delta R_{jj} > 0.5$, as shown in Figure 1(a). The cross-section $\sigma_{\mathrm{LO}}(\text{EW } \ell\ell jj) = 208 \pm 18 \text{ fb}$ is then derived using the SM prediction of $\sigma_{\mathrm{LO}}(\text{EW } \ell\ell jj) = 174 \pm 15 \text{ (stat.)} \pm 40 \text{ (syst.)}$ fb.

A good agreement is found for the EW $\ell\nu jj$ cross-section in the region defined by the leading and subleading jet transverse momentum $p_{T1} > 60$ GeV and $p_{T2} > 50$ GeV, the jet pseudorapidity $|\eta_j| < 4.7$ and the dijet mass $m_{jj} > 1000$ GeV. The observed value $\sigma_{\text{EW } \ell\nu jj} = 0.42 \pm 0.04 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.01 \text{ (lumi)} \text{ pb}$ is compared to the SM prediction of $\sigma_{\text{LO}}(\text{EW } \ell\nu jj) = 0.5 \pm 0.02 \text{ (scale)} \pm 0.02 \text{ (pdf)} \text{ pb}$. The EW signal is observed at the 4$\sigma$ level.

The dominant uncertainties in both cases come from limited statistics, the interference between the EW and Drell-Yan $\alpha_s^2 \alpha_{em}^2$ diagrams, the contribution from the DY background as well as from the jet energy scale calibration.

The $\ell\ell jj$ data is also used to study the properties of the additional jets, in particular the fraction of events which do not have reconstructed kinematics above a given threshold (also called gap fraction). This provides a measurement of the efficiency of extra jet veto in VBF-like topologies which seems to be reliably modelled by simulation, as shown in Figure 1.

![Figure 1](attachment:image1.png)

Figure 1 – (a) Fitted signal strength for $\ell\ell jj$ EW and DY production. Fraction of events which do not have (b) a third jet and (c) the scalar sum of jet $p_T$ above a given threshold.

3 Forward-backward asymmetry in Drell-Yan lepton pair production

The lepton angular distribution in Drell-Yan production with respect to the incoming quark in the dilepton restframe is given in the SM by $P(\cos \theta) \propto (1+\cos^2 \theta) + 0.5 A_0 (1-3 \cos^2 \theta) + A_4 \cos \theta$. The last term due to the presence of both vector and axial vector couplings gives a forward-backward asymmetry $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$, where $\sigma_F$ and $\sigma_B$ are the forward ($\cos \theta > 0$) and backward ($\cos \theta < 0$) total cross-sections. $A_{FB}$ depends on the dilepton mass, the initial quark flavour and $\sin^2 \theta_W$. Indeed studying $A_{FB}$ around $m_{\ell\ell} \sim m_Z$ gives a measurement of $\sin^2 \theta_W$. A discrepancy of $A_{FB}$ could signal new physics, such as the presence of new neutral gauge bosons, quark-lepton compositeness, supersymmetric particles or extra spatial dimensions.

The measurement is made in the Collins-Soper (CS) frame to reduce uncertainty due to the incoming quark transverse momenta. This measurement – benefitting from the electrons reconstructed in the hadronic forward calorimeter and the larger statistics – extends the phase space to dilepton rapidities of $|y_{\ell\ell}| < 5$ and invariant masses of $40 \text{ GeV} < m_{\ell\ell} < 2 \text{ TeV}$. The measured distributions shown in Figure 2(a-b) are consistent with the SM. They show the dilution of $A_{FB}$ at low rapidities as the quark direction is not always along the positive
direction defined by the boost of the $\ell\ell$ system. The main systematic uncertainties arise from the background contribution and the lepton energy scale especially for forward electrons.

![Figure 2](image)

Figure 2 – Forward-backward asymmetry as a function of the dilepton mass at (a) low and (b) high rapidity values\(^6\). The measured $A_0 - A_2$ angular coefficient difference as a function of the dilepton transverse momentum.

4 Angular coefficients in Drell-Yan lepton pair production

The accurate modelling of QCD effects is crucial for precision EW measurements. To test the description provided by various calculations, one can factorise the DY cross-section by decay kinematics. The lepton ($\ell^-$) angular distribution in the boson ($\ell\ell$) rest frame is given by

$$
\frac{d^2\sigma}{d\cos\theta d\phi} \propto (1 + \cos^2\theta) + 0.5A_0(1 - 3\cos^2\theta) + A_1\sin(2\theta)\cos\phi + 0.5A_2\sin^2(\theta)\cos(2\phi)
$$

$$
+ A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin(\phi) + A_7\sin\theta\sin\phi
$$

The coefficients $A_1, A_2, A_3$ are related to the Z boson polarisation and $A_3, A_4$ to the V-A structure of lepton couplings. $A_4$ is the EW parity violation term, the only non-vanishing coefficient when the Z boson transverse momentum $q_T$ goes to zero. $A_5, A_6, A_7$ are small and set to zero.

The coefficients are derived from template fits to the 2-dimensional $(\cos\theta, |\phi|)$ distributions in bins of rapidity and $q_T$. The results are compared to various theoretical calculations. As an example Figure 2(c) shows $A_0 - A_2$ that violates the Lam-Tung relation ($A_0 = A_2$) as anticipated in perturbative QCD calculations beyond leading order due to the presence of non-planar processes. Within the large statistical uncertainties the models provide a reasonable description of the data with a few known deficiencies\(^7\). Statistics is the dominant uncertainty at high values of the boson $p_T$ while lepton efficiencies dominate at lower $p_T$. At the lowest $p_T$ bins muon momentum scale and resolution and template systematics give the largest contribution.

5 Charge asymmetry in W production

In pp collisions the dominant production modes for W bosons are $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$. Due to the valence quark content (uud) of the proton, more $W^+$ bosons are produced. The charge asymmetry of W boson production can thus be used to constrain the $u(x)/d(x)$ pdf ratio for Bjorken $x = 0.001 − 0.1$. Including the CMS measurement\(^8\) shown in Figure 3 in a HERAPDF type fit improves the uncertainties by about 20%.

6 W and Z boson transverse momentum distribution

The transverse momentum ($p_T^\ell$) distribution of weak bosons provides a crucial test of QCD with the low $p_T$ region being sensitive to initial state radiation and non-perturbative effects, and the high $p_T$ region being primarily affected by perturbative effects.

The data corresponding to 18.4 pb\(^{-1}\) integrated luminosity were collected in a special low luminosity run with the number of collisions per bunch crossing (pile-up) being around four. The low pile-up condition allows to have an improved resolution and lower background than the
Figure 3 – (a) Charge asymmetry of W boson production as a function of the muon pseudorapidity, showing also (b) the differences wrt. various pdf predictions. (c) Improvement for the u valence quark distribution when the CMS W data is included.  

previously published CMS results\textsuperscript{9}, allowing an extended reach down to $p_T = 20$ GeV and finer binning at low values. The statistical uncertainty is below the systematic contribution for the Z boson and comparable with it for the W boson. The results\textsuperscript{10} agree with theoretical calculations within 20%. Cross-section ratios provide a partial cancellation of systematics, in particular for theoretical pdf and scale uncertainties as demonstrated in Figure 4.  

Figure 4 – (a) W boson transverse momentum distribution. (b) Z-to-W boson production cross-section ratio showing also (c) the differences wrt. various theoretical predictions.\textsuperscript{10}  

7 Conclusion

The results presented here provide important tests of the Standard Model, improve the understanding of the detector performance and the modelling of QCD corrections, as well as decrease the uncertainties on the parton distribution functions. These are important to determine the W boson mass with a precision similar to that coming from EW fits\textsuperscript{11}. Statistical uncertainties are still significant, thus the LHC Run 2 data will improve the attainable precision.

References

2. R. Covarelli, in this proceedings.