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Electroweak Physics in LHC Run2

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We present a summary of the studies of the electroweak sector of the Standard Model at LHC after the first year of data taking of Run2, focusing on possible results to be achieved with the analysis of full 2015 and 2016 data. We discuss the measurements of W and Z boson production, with particular attention to the precision determination of basic Standard Model parameters, and the study of multi-boson interactions through the analysis of boson-boson final states. This work is the result of the collaboration between scientists from the ATLAS, CMS and LHCb experiments.

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1. Introduction

Standard Model (SM) electroweak processes span a range of cross sections about seven orders of magnitude wide, and have been studied in detail, based on LHC Run 1 data set[1]. The agreement between measured cross sections and predictions is good, with only a few channels showing discrepancies at two standard deviations level. This summary describes the present state of measurements of these processes after the first year of data taking in Run 2, and discusses the perspectives for possible improvements with the 2016 data set.

The increased centre of mass energy causes most SM cross sections to increase by roughly a factor two. As LHC is expected to deliver to both ATLAS and CMS around 30 fb^{-1} in 2016, the new data set will allow a gain in sensitivity of SM measurements, compared to Run 1. In addition, due to the variation of parton luminosities, the fraction of gluon-initiated processes is expected to increase at $\sqrt{s} = 13$ TeV, implying that the low-x region of phase space will have larger importance. A more accurate measurement of PDF at low-x is then desirable to obtain the precision needed by future SM measurements.

Therefore, an important contribution to ATLAS and CMS efforts may come from the LHCb experiment: even if electroweak physics is not the main goal of the LHCb program, its forward coverage makes it sensitive to low-x parton induced processes and final states with outgoing forward particles, which are not fully accessible to ATLAS and CMS.[2] Combinations of results between the three experiments will then take advantage of measurements in different phase spaces.

2. W / Z physics: testing our understanding of Standard Model

W and Z boson production are very well known processes, and they can be used to test our basic understanding of SM. Cross section measurements for these processes were repeated with first Run 2 data by ATLAS ([6]), CMS ([7, 8]) and LHCb ([9]), providing comparisons with predictions obtained using different PDF sets. Analogous comparisons were shown, by ATLAS and CMS, for cross sections ratios $\sigma_{W^+}/\sigma_{W^-}$ and $\sigma_{W^\pm}/\sigma_Z$, useful to reduce systematic uncertainties. Cross sections vary about 5% with PDFs, and disagreement between PDF sets is visible in ATLAS for $\sigma_{W^+}/\sigma_{W^-}$ (figure 1 (c)). Analogous results are obtained by the three collaborations, despite different decay channels or phase space definitions (for instance, figure 1 (a) and (b)).

Improvements of our knowledge of PDFs may come from other studies, as forward-backward asymmetry in Drell-Yan events or W charge asymmetry analysis ([10], [11], [12], [13]), expected to be measured again at 13 TeV.

Besides total cross section, differential cross section measurements as a function of several kinematic observables allow a better understanding of the underlying physics mechanisms. Recently differential results were provided for the $Z/\gamma^* \rightarrow l^+l^-$ channel: CMS and LHCb produced first 13 TeV results ([8] and [9] respectively), while ATLAS published a very detailed study on 8 TeV data [14]. A variety of kinematic variables were investigated: among them, here we focus on

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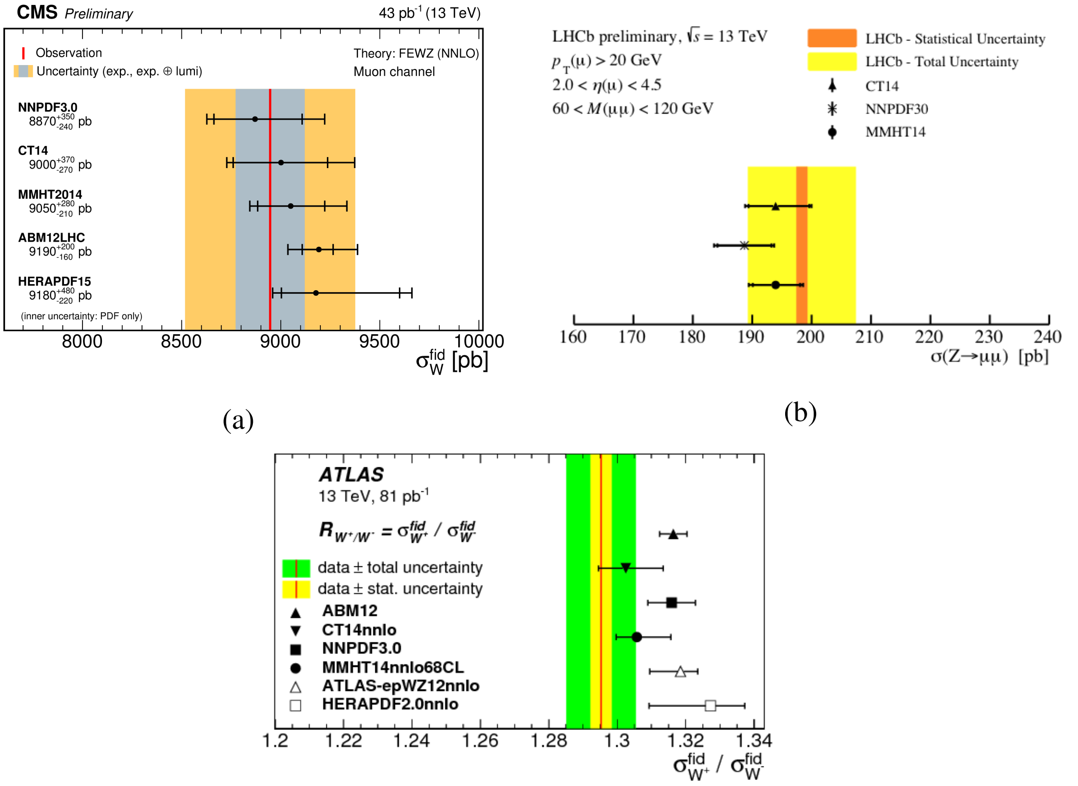
[1] For a summary of electroweak results of ATLAS and CMS see. All public results from ATLAS, CMS and LHCb can be fount respectively in [1], [2], [3]

[2] Clarifying plots can be found at [4], [5].



(a)

(b)

(c)

Figure 1: *(a): Comparison of measured fiducial inclusive $W \to \mu\nu$ cross sections with predictions for five PDF sets: NNPDF3.0, CT14, MMHT2014, ABM12LHC, and HERAPDF15 [7]. (b): The fiducial $Z \to \mu\mu$ cross-section compared between theory and data [9]. (c): Ratios (red line) of W^+ to W^- boson combined production cross sections in the fiducial region compared to predictions based on different PDF sets [6].*

the transverse momentum p_T and the related variable ϕ^*_η, correlated with p_T but experimentally dependent on angles only[3].

The Z boson p_T is highly sensitive to QCD higher order corrections and PDFs. Differential cross sections were compared to Monte Carlo (MC) generated events. Depending on the variable under study and methodological choices, the studied MCs include fixed-order (NLO) or p_T-resummed calculations, and matrix elements interfaced with parton-shower generators[4].

None of the studied generators is able to correctly reproduce data throughout the all kinematic range, examples from the ATLAS paper are shown in figure 2, showing the need for further theoretical improvements.

A complete study of W and Z properties will be replicated at 13 TeV, exploiting a W and Z boson data sample even larger than the Run 1 set. Larger statistics in boson high-p_T region will be fundamental for studies aiming to properly evaluate and model background sources in new physics searches at 13 TeV. At the same time, an increase in statistics will allow finer binning in differential

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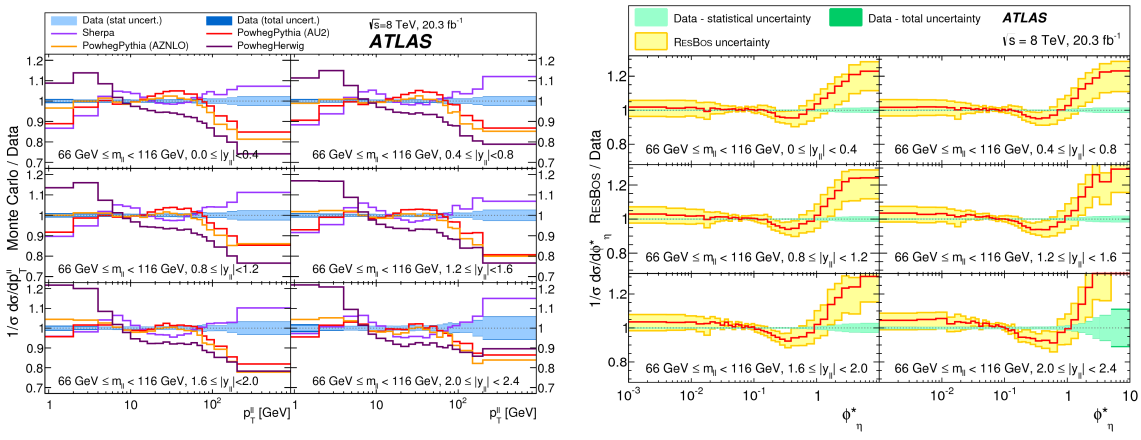
[3] ϕ^*_η is defined as $\phi^*_\eta \equiv \tan\left(\frac{\pi-\Delta\phi}{2}\right)/\cosh\left(\frac{\Delta\eta}{2}\right)$, η, ϕ being the pseudorapidity and the azimuthal angle of a particle

[4] For complete reference of adopted MCs, see Section 3.2 of the ATLAS paper [14] and its bibliography.



(a)

(b)

Figure 2: *The ratio of* $(1/\sigma_Z)d\sigma_Z/dp_T^{l^+l^-}$ *as predicted by various MC generators to the combined data (a) and the ratio of* $(1/\sigma_Z)d\sigma_Z/d\phi^*_\eta$ *as predicted by ResBos to the combined data (b). Both for six* $|y^{l^+l^-}|$ *regions at the Z-boson mass peak. The data have been unfolded for experimental resolution effects using a Born-level definition [14].*

cross sections in the soft region: hence providing better systematic constraint to SM precision measurements as the W mass.

3. Precision measurements of Standard Model parameters

The electroweak sector of the SM may be further probed by LHC experiments through measurements of its fundamental paramenters. Two of them are accessible and of particular interest: the W boson mass and the electroweak mixing angle $\sin^2\theta_W$.

The determination of the W mass (M_W) is an important consistency check of the Standard Model. A 1.4 standard deviations discrepancy exists between the experimental measurement of M_W at collider experiments [15] and the determination of M_W through the global electroweak fit [16], where the W, top and Higgs masses are indirectly determined simultaneously. In order to better assess possible deviations from SM, it is necessary to achieve an experimental precision of about 10 MeV on M_W. Both the Jacobian peak of the $W \to l\nu$ transverse mass spectrum or the W boson p_T spectrum are sensitive to M_W. In order to achieve the needed precision, a permille resolution on the lepton transverse momentum is necessary, as shown in Ref. [17].

The ATLAS and CMS collaborations aim to perform this measurement in the near future. The CMS collaboration assessed the experimentally achievable precision using the state of the art calibrations by measuring Z boson mass in a “W-like” configuration, where a muon is removed from the event to mimic a neutrino in a $Z \to \mu\mu$ event sample [18]. This study demonstrated that a precision of 20 MeV on M_W is at reach, but there are still several open issues related to theoretical systematic uncertainties. The LHCb experiment could possibly contribute to this measurements thanks to its complementary acceptance: the study [19] demonstrated that combining LHCb data with those from ATLAS and CMS might improve the precison on M_W by about 30% .

The electroweak mixing angle θ_W gauges the relative strength of the electromagnetic and the weak forces in the SM Lagrangian. By studying the forward-backward lepton asymmetry A_{FB} of the $Z \to ll$ decay, it is possible to measure the so called effective weak mixing angle $\sin^2\theta_W^{\rm eff}$, related to $\sin^2\theta_W$ through radiative corrections. All the ATLAS [20], CMS [21] and LHCb [22] collaborations determined $\sin^2\theta_W^{\rm eff}$ using the data collected during the LHC Run 1. At LHC the direction of the incoming parton is not known: the direction of the Z boost is assumed to correspond to that of the incoming quark. Indeed, in the main mechanisms for Z boson production, a valence quark interacts with a sea anti-quark with generally lower longitudinal momentum fraction. As the Z boson in the forward direction has a larger boost, the LHCb experiment, measuring a larger $A_{\rm FB}$, has a better sensitivity to $\sin^2\theta_W^{\rm eff}$ with respect to ATLAS and CMS. The asymmetry A_{FB} as a function of the dimuon mass in the $Z \to \mu\mu$ decay, measured by LHCb, is displayed in fig. 3 (left). $\sin^2\theta_W^{\rm eff}$ is obtained with a fit to these data points. The summary of $\sin^2\theta_W^{\rm eff}$ measurements [23] is reported in fig. 3 (right).

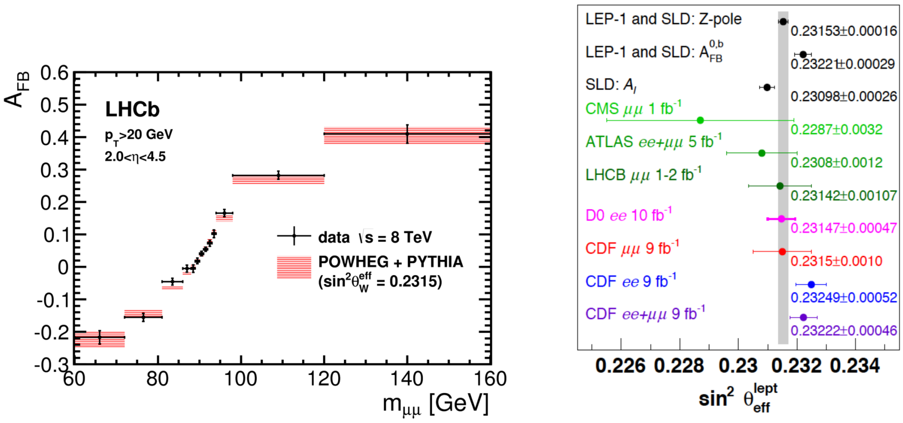


Figure 3: *A_{FB} measured by LHCb experiment and theoretical prediction in bins of dimuon invariant mass, for the 8* TeV *dataset (left) and summary of* $\sin^2\theta_W^{\rm eff}$ *measurements (right).*

The two most precise measurements, at LEP and at SLAC, differ at three standard deviations level: a greater precision is needed to solve this puzzle. The LHCb measurement is at present limited by the available statistics while the ATLAS result is limited by systematic uncertainties.

Measurements of M_W and $\sin^2\theta_W^{\rm eff}$ are expected to be improved in the next LHC data taking. These improvements rely on the increased statistics, on new PDFs sets constrained with LHC data and on more precise detector calibrations. In the long term we may expect big improvements from new colliders [24], as can be seen in fig. 4.

4. Multi-bosons physics

Studies of associated production of two or three gauge bosons, collectively indicated as multi-boson final states, are a key feature to understand interactions between gauge bosons. Deviations from SM prediction in vertexes coupling three or four gauge bosons (Triple/Quartic Gauge Couplings or TGC/QGC) could be an indication of interactions with undiscovered non-SM physics. Multi-boson processes are commonly categorized in diboson, Vector Boson Fusion (VBF), Vector Boson Scattering (VBS) and tri-boson production.

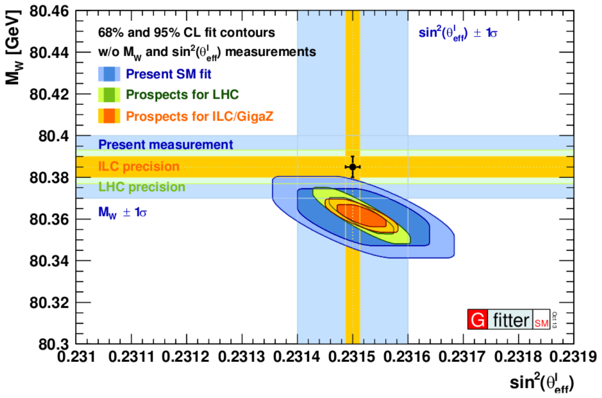


Figure 4: *Current* M_W *and* $\sin^2\theta_W^{\rm eff}$ *measurements and predicted precision for LHC and for future proposed colliders .*

4.1 Diboson

Diboson processes, namely the associated production of a pair of gauge bosons, have been widely studied in Run 1 by ATLAS and CMS. First 13 TeV results are also available for the $ZZ \to l^+l^-l^+l^-$ channel [25, 26]. Figure 5 (a) shows the ZZ cross section results from ATLAS and CMS at 8 and 13 TeV. The new 13 TeV measurements agree with the expectations, but the statistics available is still limited and such result needs improvements from 2016 data.

Concerning WW and WZ 8 TeV measurements, an order of two standard deviations disagreement with respect to MC was observed in the $WZ \to l\nu l^+l^-$ channel, by both ATLAS [27] and CMS [28], as shown in fig. 5 (a). A first 13 TeV result from CMS [29] seems not to confirm the 8 TeV discrepancy, but the statistics is still limited to reach a firm conclusion. Most likely, missing higher order corrections for the p_T spectrum of the diboson system may play a significant role in such a discrepancy. This is the case also in $WW \to l\nu l\nu$ channel, where a similar discrepancy was observed by ATLAS [30]. In leptonic WW, a veto on events with jets is applied: the jet veto enhances contributions beyond fixed order calculations, possibly causing the disagreement. CMS, on the other hand, reweights MC to p_T-resummed calculation and does not observe an analogous effect [31].

The semi-leptonic WW/WZ channel should be considered separately ($W \to l\nu$, $W/Z \to qq$[5]). Only 7 TeV results are currently published by both ATLAS and CMS. The channel is indeed characterized by a poor signal over background ratio and large systematic uncertainties due to jet contributions: for this reasons, it is not a preferred channel for future SM precision measurements.

On the other hand, the semi-leptonic WW/WZ channel is connected with the developing sector of boosted object tagging. A variety of algorithms is being developed to identify boosted W decaying hadronically and resulting in a single large-radius jet [32, 33], with the aim of improving searches of physics beyond SM. Semi-leptonic WW/WZ production is measured selecting events with a leptonic W decay and fitting the jet-jet invariant mass spectrum for the W/Z peak: it then offers an interesting opportunity for testing such tools on the detection of a known resonance of small cross

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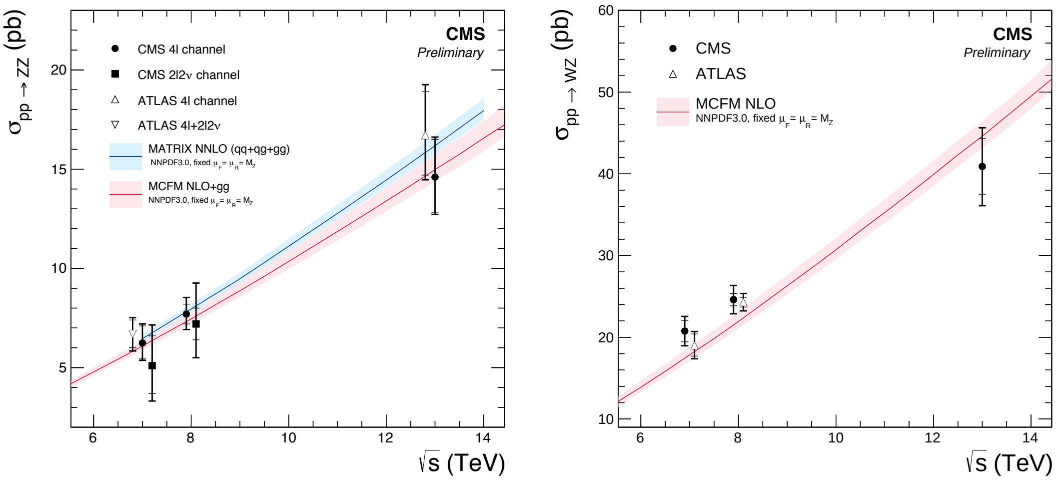
[5] Because of jet energy resolution, it is impossible to discriminate between W and Z hadronic resonances.



(a) (b)

Figure 5: *The total ZZ (a) and WZ (b) cross section as a function of the proton-proton center-of-mass energy. Results from CMS and ATLAS are compared to predictions from MATRIX (a) and MCFM with nnpdf3.0 PDF sets (a/b). From [26] (a) and [29] (b).*

section.

Diboson production channels, in summary, have all been measured and are entering the phase of precision measurements and modelling testing, as was already the case for single bosons. First differential cross sections are indeed being produced, an example is the data-MC comparison for differential cross section shown in ATLAS $Z\gamma$ analysis [34].

4.2 Anomalous Triple Gauge Coupling (aTGC)

Searches for aTGC were performed in all shown diboson studies. New physics contributions are expected to enhance the high-end tail of the mass spectrum m_{VV} [6]. The effect is described adding model independent terms to the SM Lagrangian. Such non-SM terms are dependent on unknown parameters quantifying the strenght of the interaction. A fit of the m_{VV} (or other kinematic variable) spectrum is used to set limits on these parameters. A full representation of current aTGC limits can be found at [35]. In summary, all observed limits are consistent with no anomalous contribution, ATLAS and CMS provide in most cases the world most sensitive limits. The main source of uncertainty in aTGC search is at present the limited statistics in the sensitive region of the studied observables. An increase in precision is therefore expected with 2016 data. Another possible improvement may come from purposed combination between electroweak and Higgs results on aTGCs [36].

4.3 Vector Boson Fusion and Vector Boson Scattering

VBF and VBS consist of two gauge bosons irradiated by incoming quarks, that interact creating other either one (VBF) or two (VBS) gauge bosons. The experimental signature is then defined

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[6] Related variables as p_T^V are also investigated to avoid uncertainties in mass reconstruction due to possible neutrinos.

by two high rapidity jets, separated by a wide rapidity gap. The products from the boson or bosons decays are located inside the rapidity gap. Both QCD and purely electroweak diagrams contribute to the final state: interference between electroweak and QCD diagrams should be taken into account when measuring VBS cross section. Both ATLAS and CMS chose to measure the purely electroweak contribution and treat the QCD as a background: the adopted fits are designed to take into account the interference terms. This approach provides a good electroweak signal significance. The VBS is of particular interest as it provides sensitivity to Quartic Gauge Couplings (QGC) at LHC. In addition, the VBS cross section is highly dependent on Higgs-exchange diagrams and any possible deviation from SM prediction might indicate new physics in the Higgs sector.

The golden channel for VBS measurement is represented by $W^{\pm}W^{\pm}jj$. The two leptonically decaying Ws from the VBS are required to have the same charge, strongly reducing the background. Evidence of electroweak production of same-sign $W^{\pm}W^{\pm}jj$ has been observed by ATLAS and CMS in Run 1 [37, 38]. Both measurements have large uncertainties due to the small statistic in the signal region and will benefit from results of 2016 data analysis.

Other VBS channels have been investigated. The study of production of $W^{\pm}W^{\mp}jj$ in which Ws are of opposite sign (dominated by $\gamma\gamma \to WW$ VBS) was published by CMS, showing a 3.4 σ excess over the non-VBS contribution only. $WZjj$ were searched by both ATLAS and CMS as additional result to other diboson (ATLAS, [27]) and VBS (CMS, [38]) analyses. CMS reported a cross section measurement, while ATLAS only set a limit. Finally, evidences of $W\gamma jj$ and $Z\gamma jj$ electroweak production were reported by CMS [39, 40], where the electroweak contribution is observed with a significance of 2.7 σ and 3.0 σ respectively over the other production processes, treated as background sources. In both cases the resulting signal yield is anyway extremely small.

4.4 Tri-bosons

QGC may be also observed directly via tri-boson production. With this signature, three out of four interacting bosons are identified in the final state, allowing a better knowledge of the involved diagrams without the need of treating interference terms. Cross sections for tri-bosons production are anyway very small and first Run 1 results were published only recently.

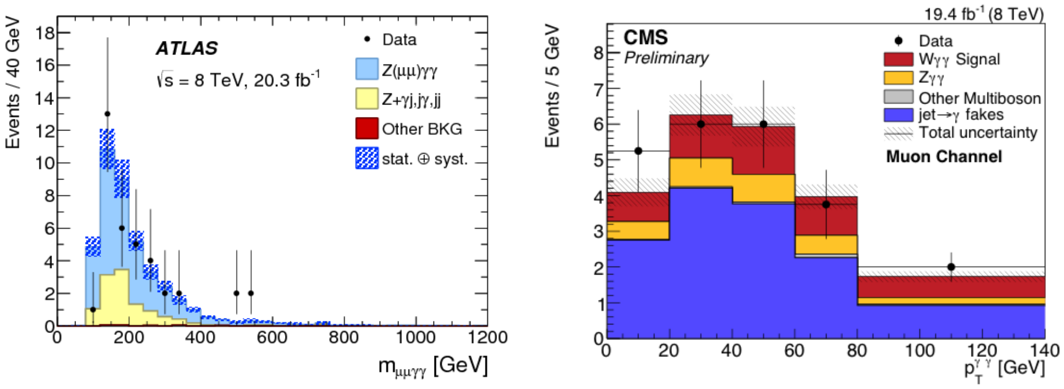
Both ATLAS and CMS observed evidence for the production of $W\gamma\gamma$ ([41] and [42] respectively) and $Z\gamma\gamma$ ([34], [42]). Figure 6 shows the distribution of kinematic observable for $Z\gamma\gamma$ (ATLAS) and $W\gamma\gamma$ (CMS): despite the small statistics, signal contributions are clearly present.

4.5 Anomalous Quartic Gauge Couplings (aQGC)

The search strategy for aQGC is analogous to the one adopted for aTGC, described in section 4.2. Limits have been set in the analysis of all described VBS and tri-bosons channels. A complete summary of aQGC results can be found at [35]. No deviation with respect to SM is observed, the best precision is obtained by CMS $\gamma\gamma \to WW$ analysis. In most cases the precision is anyway still quite small, due to the low statistics of these channels in Run 1: this sector of experimental investigation is still fully open.

4.6 Future prospects

Improving the precision of the measurement of VBS and tri-boson production is expected to be a major goal of ATLAS / CMS Run 2 analysis in the electroweak physics sector. The upgrade to



(a) (b)

Figure 6: *(a): The four-body invariant mass ($m_{\mu\mu\gamma\gamma}$) distribution from inclusive (Njet ≥ 0) $l^+l^-\gamma\gamma$ events for the muon channel [34]. (b): The p_T of the diphoton system for the $W^{\pm}\gamma\gamma$ analysis. [42].*

HL-LHC will anyway be necessary to get precision measurements in this field. Studies have been done to evaluate possible improvements in electroweak analysis with upgraded ATLAS and CMS detectors at HL-LHC [24, 43, 44].

Concerning LHCb, up to now it did not contribute to multi-bosons analysis because the statistics available in Run 1 was too low. With the expected Run 2 statistics, diboson measurements in the forward region will be possible, providing an interesting completion of ATLAS / CMS results in a complementary phase space region.

5. Conclusion

Experimental data now allow us to test full consistency of SM: LHC experiments will provide fundamental contribution through $\sin\theta_W$ and M_W measurements. In addition, detailed measurements of differential cross sections of SM processes such as W, Z or diboson production will provide a fundamental handle to improve theoretical description and modelling of SM physics at colliders, being a major test of emerging frountier calculations. Rare processes as VBS and triboson channel will be fully investigated by future analysis. Study of gauge bosons interactions is an important field in Run 2 and will be a key target for HL-LHC.

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