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Overview of Standard Model and Higgs results at ATLAS and CMS

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Recent results on Standard Model and Higgs boson measurements performed by ATLAS and CMS collaborations are reported. The presentation includes results based on LHC Run II data, with particular relevance on most recent ones. Precision measurements reachable with Run II data are discussed, such as the most up-to-date differential distributions.

The 15th International Conference on Flavor Physics & CP Violation
5-9 June 2017
Prague, Czech Republic

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PoS(FPCP2017)032

1. Introduction

After almost 70 fb^{-1} collected at 7, 8 and 13 TeV of center of mass energy both by ATLAS [1] and CMS [2] experiments, the precision era for Large Hadron Collider (LHC) concerning measurements and tests of the Standard Model (SM) of particle physics has started.
With the discovery of one new particle, compatible with the SM Higgs boson, the foreseen particles by the current model have all been observed. However, some discrepancies are observed and fine tuning of the parameters are sometimes required: they may be explained by extensions of the SM or by radical new models. In order to test possible deviations from the SM, precise measurements of the processes foreseen at LHC are required.
In this presentation the procedures followed by experimentalists to perform measurements and searches in SM, including Higgs boson physics, are highlighted. A critical review of the current results from ATLAS and CMS experiments is reported, emphasizing the most recent results from the two collaborations.

2. Steps in measurements

The following steps have been identified as a common guideline for most measurements and searches performed with LHC data:

- Inclusive cross section
- Fiducial and differential cross sections
- High energy regimes for anomalous couplings
- Ratio measurements to reduce systematic uncertainties
- Special measurements

In the next sections the different steps will be described, with examples from the most recent results from ATLAS and CMS.

3. Inclusive cross section

The first step is the measurement of the inclusive cross section. It is based on the simple formula:

$$\sigma = (\text{DATA} - \text{Background})/(\varepsilon \int \text{Luminosity}) \tag{3.1}$$

where "DATA" is the number of events observed, "Background" is the number of expected background events, "ε" is the acceptance and efficiency of the selections, "$\int$ Luminosity" is the integrated luminosity, and σ is the measured cross section. Although apparently simple, these results include many ancillary measurements, like trigger efficiency calculations in data, object reconstruction scale factors, and careful tuning of the MonteCarlo (MC) generators. The results are usually reported for different center of mass energies, thanks to data collected with different proton beams configurations. In addition, the background estimation is essential for precision measurements:

there is a close connection between analyses, and improvements in the description of a specific final state lead to the reduction of the uncertainties on background subtraction. For example, jets, single vector boson, and double vector bosons measurements are key ingredients for Higgs boson searches and precision studies.
Measurements of the SM ZZ production into 4-leptons final states have been performed at 13 TeV [3][4], as well as 7 and 8 TeV, of center of mass energy. A selection requiring di-muon or di-electron events to have an invariant mass close to the Z one is applied, and a good agreement between data and MC is observed. However the analyses are still statistically dominated.
The good agreement observed is essential to measure rarer processes, like ZZ-electroweak production [5]. In this case a more complex analysis by means of a multivariate technique is performed, selecting events with 2 Z bosons and 2 jets with high invariant mass: the cross section ratio with respect to the one predicted by the SM has been measured to be $1.39\,^{+0.86}_{-0.65}$. Rarer final states, like the electroweak Z + 2 jets production and the electroweak $Z\gamma$ + 2 jets [6] have been investigated as well.

4. Fiducial and differential cross sections

With increased integrated luminosity collected, some of the measurements become systematically limited, in particular due to the model-dependence introduced by the extrapolation (ε) from a particular phase space defined by reconstruction level selections to the inclusive cross section. A way to avoid these limitations is to measure cross section in fiducial phase spaces, where the uncertainty in the extrapolation is reduced. In addition, these results are quite useful to the theory community, since they can be compared with different MC calculations and help in an improved tune of the MC. The fiducial phase space is defined by means of generator level selections that mimic the reconstruction level ones. Differential measurements are usually reported as well. However, they usually rely on some level of regularization, that is carefully checked in order to reduce as much as possible the bias due to the MC generator used to construct the response matrix used in this procedure.
Many measurements have been performed by ATLAS and CMS, such as Single jet, Di-jet, Single Vector Boson (W, Z), Double Vector Boson (WW, WZ, ZZ, W/Z γ), Triple Vector Boson, and Vector Boson Scattering. As an example, in Figure 1 the reconstruction level distribution in ZZ events [3] of the transverse momentum of the leading Z boson and the unfolded distribution are shown.

5. Anomalous couplings

The next step is looking for deviations with respect to SM expectations: although new physics scale could be un-reachable with the current center of mass energy, an indirect probe of it is possible by means of deviations in the high energy tails of the distributions. New physics could modify slightly the SM couplings among particles, thus giving the experiments an handle to probe it indirectly. Results based on anomalous couplings are reported in different ways and for many final states. Several limits in terms of anomalous couplings are set for different kind of vertices, namely Charged Anomalous Triple Gauge Couplings (charged aTGC), Neutral Anomalous Triple

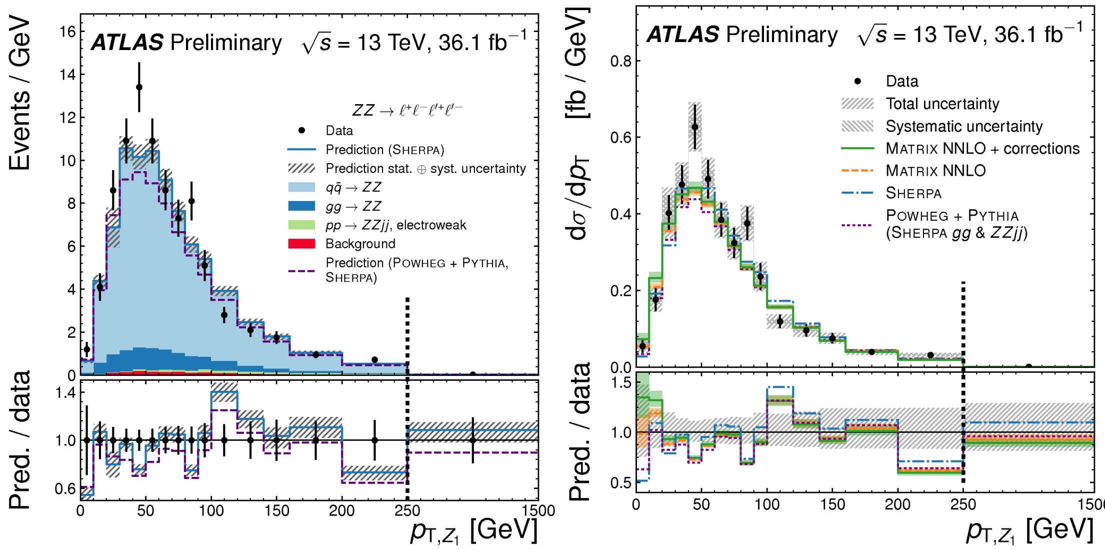

Figure 1: The reconstruction level distribution in ZZ events of the transverse momentum of the leading Z boson (left) and the unfolded distribution (right) [3].

Gauge Couplings (neutral aTGC), and Anomalous Quartic Gauge Couplings (aQGC). The effects of anomalous couplings can be divided in two: on one side some vertices are not allowed in SM at tree-level, on the other changes in the couplings can alter the kinematic distributions. In Figure 2 the results of the Vector Boson Scattering WW same sign analysis are reported [7]. The SM process of the electroweak WW has been observed with more than 5σ significance, and by looking for excesses in the very high di-jet invariant mass it is possible to probe new physics and set limits to anomalous couplings.

6. Ratios

In order to remove some of the systematic limitations on the results, measurements of ratios of cross sections are performed: for example, by means of considering the ratio of cross sections for different processes, the uncertainty related to the precise knowledge of the luminosity cancels out. The ratio of top pair production to Z boson [8] has been measured, also among different center of mass energies, allowing to reduce the systematic uncertainty on the results.

7. Special measurements

Measurements from ATLAS and CMS can be used also to improve our knowledge of proton parton distribution functions (PDF). Ratio measurements, like the one referred in the previous section [8], are sensitive to the tuning of the PDF. Another example is the measurement of the triple-differential di-jet cross section as a function of jet transverse momentum (p_T), rapidity difference (Δy), and system boost (y_b) [9]. In this analysis not only a measurement of the PDF has been performed, but also a measurement of strong coupling constant α_S. These in-situ measurements allow the experiments to reduce the systematic uncertainty in precision analyses and searches.
The different steps described so far are usually reported in a single analysis. For example in the

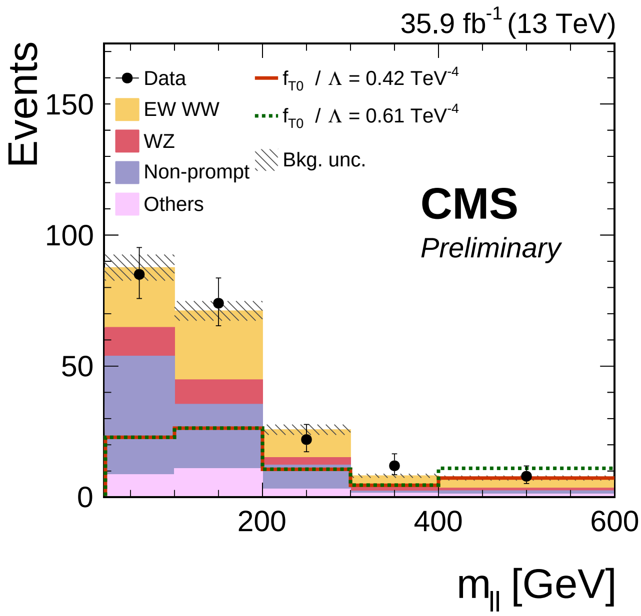

Figure 2: The di-lepton invariant mass after selecting two same-sign leptons, looking for WW Vector Boson Scattering signatures [7].

precision measurement of W^+, W^- and Z/γ^* [10] different results are reported: inclusive cross section, differential cross section, ratios between different final states, comparison with different PDF sets, and precision measurements that allow to have some handle on proton PDF, and even the measurement of strange quark density and CKM matrix elements $|V_{cs}|$.
It's worth to mention also the recent result on W mass measurement at the LHC [11], m_W = 80370 $\pm$ 19 MeV. The impressive level of precision that has been achieved is the result of an extensive work to keep experimental and theoretical uncertainties as small as possible.

8. Higgs measurements

All the improvements in the SM results reflect in a better control of the backgrounds for Higgs boson searches and precision measurements. Also in this sector the different steps described before have been followed: inclusive cross sections, fiducial and differential measurements, anomalous couplings, up to high precision in Higgs properties measurements, like the Higgs boson mass. Different final states have been considered, such as the so called golden channels: ZZ [12] [13] [14] [15] and $\gamma\gamma$ [16] [17] [18]. With more luminosity available, rarer final states, rarer production mechanisms, such as top pair associated production of a Higgs boson [19] [20] [21] [22], and single top + Higgs production [23] have been investigated, as well as di-Higgs boson searches, aiming to the measurement of the Higgs self coupling parameter, but being also a key to look for new resonances that decay in two Higgs bosons [24] [25].

In order to reduce the main theoretical uncertainties, a new paradigm has been also followed, namely the Simplified Template Cross Section (STXS) [26]. It consists in common phase spaces defined by ATLAS, CMS and theorists, that will allow for possible re-interpretation of experimental results given new theoretical predictions. The first results in the main final states have been already released by ATLAS [16] [27] and CMS [17].

9. Conclusions

The most recent LHC results from ATLAS and CMS have been highlighted, and the standard approaches for measurements have been described. So far the results are compatible with SM predictions. The precision measurement era at LHC has started, but more data are needed to reduce statistical and systematic uncertainties. New results based on 2016 data are expected in the next months, as well as first outcomes from 2017 data.

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PoS(FPCP2017)032