

## Is Nature Standard like the Model? Experimental results on Standard Model and Higgs boson physics

A. MASSIRONI for the ATLAS and CMS COLLABORATIONS  
*Northeastern University - Boston, MA, USA*

received 21 April 2018

**Summary.** — Recent results on Standard Model and Higgs boson measurements performed by ATLAS and CMS Collaborations will be reported. The presentation will include results based on LHC Run II data, with particular relevance on the most recent ones. Vector boson production, Jets, Photons, Top physics, and different Higgs production mechanisms will be overviewed. Precision measurements reachable with Run II data are discussed as well, such as the most updated differential distributions.

### 1. – Introduction

After almost  $70\text{ fb}^{-1}$  collected at 7, 8 and 13 TeV of center-of-mass energy both by ATLAS [1] and CMS [2] experiments, the precision era for LHC concerning measurements and tests of the Standard Model (SM) of particle physics has started.

With the discovery of the 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 is sometimes required, and 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 contribution the procedures followed by experimentalists to perform measurements and searches in SM, including top and 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 towards 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.

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

$$(1) \quad \sigma = (\text{DATA} - \text{Background}) / \left( \varepsilon \int \text{Luminosity} \right),$$

where “DATA” is the number of events observed, “Background” is the number of expected background events, “ $\varepsilon$ ” is the acceptance of the selections, “ $\int \text{Luminosity}$ ” is the integrated luminosity, and  $\sigma$  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 Monte Carlo (MC) generators. The results are usually reported for different center-of-mass energies, thanks to data collected with different proton beams configurations.

With increased integrated luminosity collected, some of the measurements become systematically limited, in particular due to the theoretical uncertainty on the extrapolation ( $\varepsilon$ ) from a particular phase space defined by reconstruction level selections to the inclusive cross-section. A way to avoid these limitations is to measure the cross-section in fiducial phase spaces, where the uncertainty in the extrapolation is reduced. In addition, these results are quite useful to the theorists 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.

The third step is looking for deviations with respect to SM expectations in the high-energy regimes: 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 a hand to probe it indirectly. Results based on anomalous couplings are reported in different ways and for many final states.

Eventually, in order to remove additional 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.

An important interplay among different analyses is essential: precise knowledge of SM processes is needed to model the backgrounds for new physics searches. As an example, improvements in the parton distribution functions (PDF) knowledge from collider data have been achieved using jets, vector boson(s), and top measurements, as shown in [3] and [4], respectively from  $W^+$ ,  $W^-$ ,  $Z/\gamma^*$  and top analyses.

### 3. – Standard Model

The first SM measurements that are performed typically concern single Vector Boson production,  $Z$  and  $W$ . The main final states for  $Z$  boson are di-electron and di-muon

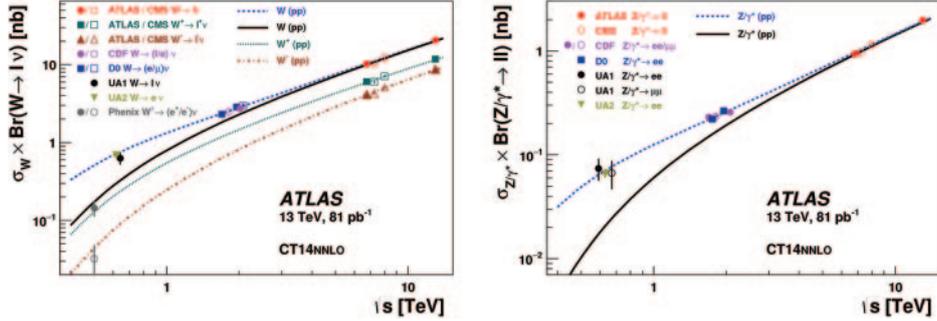


Fig. 1. – The  $W$  (left) and  $Z$  (right) boson cross-section for different center-of-mass energies [7].

ones [5,6]. The  $Z$  analysis is considered a standard candle that is used for different purposes such as tag and probe for trigger efficiency measurements, lepton reconstruction checks in data, and modeling for high-energy resonances decaying into two leptons. Inclusive cross-section, reconstruction level distributions, fiducial cross-section measurement, differential unfolded distributions, and anomalous couplings searches are performed. The electron and muon final states are analysed for  $W$  boson decay [7,8], and also in this case the aforementioned complete list of measurements is performed. In addition, the measured cross-sections have been compared among different center-of-mass energies, and among different experiments, as shown in fig. 1: good agreement between theory and observation is found.

The associated production of two vector bosons is another set of SM processes being investigated at LHC. The main categories considered are  $ZZ$  [9,10],  $WZ$  [11,12], and  $WW$  [13,14]. Different final states have been considered, and the control of several backgrounds is needed for these analyses due to the increased ratio of background over signal yields for some of them. Even in this case the precision era started: since some measurements are systematically limited, fiducial and differential measurements are provided in addition to the inclusive cross-section. Good agreement between data and MC is found and limits on anomalous couplings are set, reducing the phase space for new physics and superseding the results based on lower energies (7 and 8 TeV) achieved during the LHC Run 1 operations.

A summary table of the SM cross-sections measurement is reported in [15] and [16], respectively from ATLAS and CMS results, and shown in fig. 2. The measurements have been performed over several order of magnitudes, showing the big challenge for many analyses to cope with the very small expected signal yield.

#### 4. – Top physics

A big sector of SM physics searches is particularly aiming at measuring the properties of the top quark, its production mechanisms and possible anomalies. Many results from ATLAS and CMS Collaborations have been released with 13 TeV data, exploiting the increase in cross-section for the signals by about a factor 4 with respect to the Run 1 one.

Fully leptonic, semi-leptonic and all-hadronic decays for top pair production have been considered. Many measurements have been performed [17,18]: cross-section, inclusive, differential and fiducial, top mass, polarization, asymmetries, width, and rare decays. In addition, cross-section measurements with limited statistics have been performed in

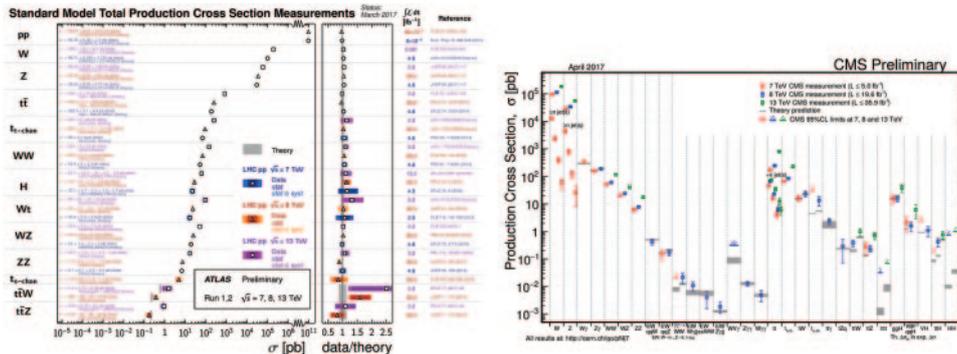


Fig. 2. – The ATLAS (left) [15] and CMS (right) [16] summary table for SM cross-section measurements.

special LHC running conditions, used mainly to commission the detector for lead collisions, but still delivering enough luminosity to allow, for example, the cross-section measurement of top pair production at 5 TeV of center-of-mass energy [4]. These results have also been exploited to improve the knowledge on the PDF.

The control and good modeling of the top samples is essential for several SM measurements and for Higgs boson physics studies.

## 5. – Higgs boson physics

In the SM of particle physics, the origin of the masses of the  $Z$  and  $W$  bosons is based on the spontaneous breaking of the electroweak symmetry. This symmetry breaking is achieved through the introduction of a complex doublet scalar field, leading to the prediction of the existence of one physical neutral scalar particle, commonly known as the Higgs boson. The presence of the Higgs boson has been confirmed by both ATLAS and CMS experiments with 7 and 8 TeV data. Measurements at 13 TeV have been performed, aiming to measure the properties of the newly discovered particle and to look for rarer production mechanisms and decay channels.

A rare production mechanism, but extremely important to explore the nature of the Higgs boson and its couplings with SM particles, is the one in association with a pair of top quarks. Although the  $5\sigma$  discovery has not been reached yet, both ATLAS [19] and CMS [20] experiments see an excess of about  $3\sigma$  with respect to the background only hypothesis.

Also in the Higgs field precision measurements in the high-resolution final states, such as di-photon [21,22] and  $ZZ$  [23,24], started: fiducial cross-section and differential distributions are obtained and compared with several MC predictions.

## 6. – Conclusions

To answer the original question about how “standard” is the Nature, several measurements have been performed by ATLAS and CMS. The SM seems to hold in all the tests so far. Limits on anomalous couplings are obtained and the precision era for the LHC experiments has started in different fields, from vector boson measurements, top and Higgs boson. More data are needed to reduce statistical and systematic uncertainties

on the current results. A great positive feedback from the theory community in the last years allowed big improvements in MC generators, where, for example, next-to-leading order is now the default accuracy used by experiments, and higher-order calculations and reduced uncertainties are becoming available. Rarer processes are currently under study and more results based on 2016 and 2017 data will be soon released.

## REFERENCES

- [1] ATLAS COLLABORATION (AAD G. *et al.*), *JINST*, **3** (2008) S08003.
- [2] CMS COLLABORATION (CHATRCHYAN S. *et al.*), *JINST*, **3** (2008) S08004.
- [3] ATLAS COLLABORATION (AABOUD M. *et al.*), *Precision measurement and interpretation of inclusive  $W^+$ ,  $W^-$  and  $Z/\gamma^*$  production cross sections with the ATLAS detector*, arXiv:1612.03016 [hep-ex].
- [4] CMS COLLABORATION, *Measurement of the inclusive  $t\bar{t}$  cross section at  $\sqrt{s} = 5.02$  TeV*, CMS-PAS-TOP-16-023.
- [5] ATLAS COLLABORATION (AABOUD M. *et al.*), *Measurements of the production cross section of a Z boson in association with jets in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, arXiv:1702.05725 [hep-ex].
- [6] CMS COLLABORATION, *Measurement of the differential Drell-Yan cross section in proton-proton collisions at 13 TeV*, CMS-PAS-SMP-16-009.
- [7] ATLAS COLLABORATION (AAD G. *et al.*), *Phys. Lett. B*, **759** (2016) 601, arXiv:1603.09222 [hep-ex].
- [8] CMS COLLABORATION, *Measurement of the differential cross section for the production of a  $W (\rightarrow \mu\nu)$  boson in association with jets at  $\sqrt{s} = 13$  TeV*, CMS-PAS-SMP-16-005.
- [9] ATLAS COLLABORATION (AAD G. *et al.*), *Phys. Rev. Lett.*, **116** (2016) 101801, arXiv:1512.05314 [hep-ex].
- [10] CMS COLLABORATION, *Measurement of the  $pp \rightarrow ZZ$  production cross section,  $Z \rightarrow 4\ell$  branching fraction and constraints on anomalous triple gauge couplings at  $\sqrt{s} = 13$  TeV*, CMS-PAS-SMP-16-017.
- [11] ATLAS COLLABORATION (AABOUD M. *et al.*), *Phys. Lett. B*, **762** (2016) 1, arXiv:1606.04017 [hep-ex].
- [12] CMS COLLABORATION (KHACHATRYAN V. *et al.*), *Phys. Lett. B*, **766** (2017) 268, arXiv:1607.06943 [hep-ex].
- [13] ATLAS COLLABORATION (AABOUD M. *et al.*), *Measurement of the  $W^+W^-$  production cross section in pp collisions at a centre-of-mass energy of  $\sqrt{s} = 13$  TeV with the ATLAS experiment*, arXiv:1702.04519 [hep-ex].
- [14] CMS COLLABORATION, *Measurement of the WW cross section pp collisions at  $\sqrt{s} = 13$  TeV*, CMS-PAS-SMP-16-006.
- [15] <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/>.
- [16] <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined>.
- [17] ATLAS COLLABORATION (AABOUD M. *et al.*), *Eur. Phys. J. C*, **77** (2017) 292, arXiv:1612.05220 [hep-ex].
- [18] CMS COLLABORATION, *Measurement of particle level differential  $t\bar{t}$  cross sections in the dilepton channel at  $\sqrt{s} = 13$  TeV*, CMS-PAS-TOP-16-007.
- [19] THE ATLAS COLLABORATION, *Search for the Associated Production of a Higgs Boson and a Top Quark Pair in Multilepton Final States with the ATLAS Detector*, ATLAS-CONF-2016-058.
- [20] CMS COLLABORATION, *Search for Higgs boson production in association with top quarks in multilepton final states at  $\sqrt{s} = 13$  TeV*, CMS-PAS-HIG-17-004.
- [21] THE ATLAS COLLABORATION, *Measurement of fiducial, differential and production cross sections in the  $H \rightarrow \gamma\gamma$  decay channel with  $13.3 \text{ fb}^{-1}$  of 13 TeV proton-proton collision data with the ATLAS detector*, ATLAS-CONF-2016-067.

- [22] CMS COLLABORATION, *Measurement of differential fiducial cross sections for Higgs boson production in the diphoton decay channel in pp collisions at  $\sqrt{s} = 13$  TeV*, CMS-PAS-HIG-17-015.
- [23] THE ATLAS COLLABORATION, *Study of the Higgs boson properties and search for high-mass scalar resonances in the  $H \rightarrow ZZ^* \rightarrow 4\ell$  decay channel at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, ATLAS-CONF-2016-079.
- [24] CMS COLLABORATION, *Measurements of properties of the Higgs boson decaying into four leptons in pp collisions at  $\sqrt{s} = 13$  TeV*, CMS-PAS-HIG-16-041.