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# Electroweak measurements at the High-Luminosity LHC

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A set of selected standard model measurements proposed for the ATLAS and CMS experiments after the high-luminosity upgrade of the LHC is discussed. The measurements are separated into two categories: precise measurements that benefit from both improved systematic uncertainties and increased luminosity, like W or top masses, or weak mixing angle measurements; measurements of low cross section production that benefit mainly from luminosity increase and detector improvements, like diboson (VV) VBS polarized cross section measurements or study of triboson (VVV) production.

*7th Annual Conference on Large Hadron Collider Physics - LHCP2019*
*20-25 May, 2019*
*Puebla, Mexico*

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PoS(LHCP2019)242

## 1. Introduction

The HL-LHC project aims to achieve instantaneous luminosity a factor of five larger than the nominal LHC value. With this modification the LHC will be able to deliver 3000 fb$^{-1}$ of integrated luminosity over 10 years of operation, 2028 - 2038, to be compared to 300 fb$^{-1}$ expected to be collected by the end of 2023 [1]. The HL-LHC relies on a number of key innovative technologies, including cutting-edge 11-12 Tesla superconducting magnets, compact superconducting crab cavities with precise phase control for beam rotation, etc. There are plans that the HL-LHC will be followed by High-Energy LHC (HE-LHC) with increased $\sqrt{s}$ up to 27 TeV.

The experiments are also planning to upgrade their detectors: muon systems in ATLAS [2], CMS [3]; trackers in ATLAS [4], CMS [5] with extending pseudorapidity coverage $|\eta| < 4(3.8)$; improved trigger systems in ATLAS [6], CMS [7]; new endcap calorimeter in the CMS case [8].

There are many existing and new measurements that can be performed with such luminosity and improved detector capabilities, we present here only few selected proposals for electroweak measurements that benefit from improved systematic uncertainties and increased luminosity of the HL-LHC data. The electroweak (EW) measurements are playing an important role at the LHC. The global standard model (SM) parameters like W and top masses, and $sin\theta_W$ are measured and provide important input to the models and global fits. The multiboson VVV and EW VV production, where V=(W, Z), can only be studied with reasonable data samples at the HL-LHC. These and other measurements are summarized in the Yellow Report WG1 summary [9].

To make a proper projection to the future measurements a reliable assumption about experimental and theoretical systematic uncertainties is important. The major assumptions that are referred later to as “YR18” are the following:

- *Trigger.* Most of the trigger thresholds for common objects are expected to either remain similar to current ones or to even decrease.
- *Theoretical uncertainties* are assumed to be reduced by a factor of two with respect to the current knowledge, thanks to both higher-order calculation and reduced parton density function (PDF) uncertainties. All the MC uncertainties related to the limited number of simulated events are neglected. The statistical uncertainty in the measurement is reduced by a factor $1/\sqrt{L}$, where $L$ is the projected integrated luminosity divided by that of the reference Run-2 analysis.
- *Systematic uncertainties driven by intrinsic detector limitations* are left unchanged, or revised according to detailed simulation studies of the upgraded detector. Uncertainties on methods are kept at the same value as in the latest public results available, assuming that the harsher HL-LHC conditions will be compensated by method improvements.
- *Luminosity* uncertainty is expected to be reduced down to 1% .

## 2. The W mass measurement

Leptonic W boson decays are characterised by an energetic, isolated electron or muon, and significant missing transverse momentum reflecting the decay neutrino. With special low pile-up pp collision data at the HL-LHC (and HE-LHC) with two collisions per bunch crossing on average, about $2 \times 10^6$ W boson events per week of operation should be collected. Increasing the acceptance of the new inner detectors from $|\eta| < 2.5$ to $|\eta| < 4$ allows further constraints on the PDFs thus reducing the corresponding uncertainties in the measurement of W mass. An energy increase at the HE-LHC to $\sqrt{s}$ = 27 TeV could play a similar role. For the current estimate only statistical and PDF uncertainties are considered. The present study considers measurements of W mass in separate categories, corresponding to $W^+$ and $W^-$ events; five pseudorapidity bins; $p_T^\ell$ and $m_T$ distribution fits; and two centre-of-mass energies (14 and 27 TeV). The expected measurement uncertainties, together with their statistical and PDF components, are summarised in Fig. 1 (left) for CT10 PDF. The numbers quoted for $0 < |\eta| < 2.4$ correspond to the combination of the four pseudorapidity bins in this range. Moderate or negative PDF uncertainty correlations, leading to reduced combined uncertainties, are observed between categories of different W-boson charges, and between central and forward pseudorapidities. With 200 $\text{pb}^{-1}$ of data collected at each energy, a total uncertainty of about 10 MeV is obtained. The uncertainties obtained for different PDF sets are presented in Fig. 1 (right). The CT10 and CT14 sets display similar uncertainty correlations, the MMHT2014 uncertainties are about 30% lower. The three projected HL-LHC PDF sets give very similar uncertainties, compared to CT10 and CT14, and a reduction in PDF uncertainty of about a factor of two is obtained.

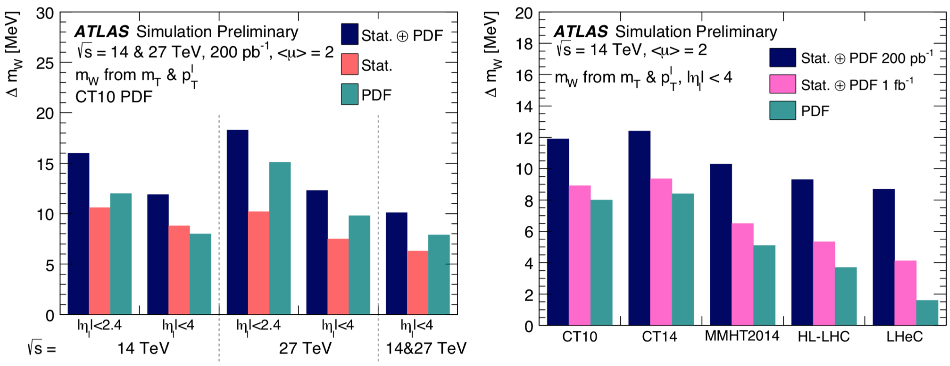


**Figure 1:** (left) Measurement uncertainty for combined fits to the $p_T^\ell$ and $m_T$ distributions in different lepton acceptance regions and for different centre-of-mass energies, using the CT10 PDF set and (right) for different PDF sets.

## 3. Effective weak mixing angle

The presence of both vector and axial-vector couplings of electroweak bosons to fermions lead to a forward-backward asymmetry $A_{FB}$ in the production of Drell–Yan lepton pairs that is used to extract the effective weak mixing angle. Figure 2 (left) shows the $A_{FB}$ distributions in bins of dimuon mass and rapidity for different energies and pseudorapidity acceptances. As expected, at higher centre-of-mass energies the observed $A_{FB}$ is smaller because the interacting partons have smaller $x$-values, which results in a smaller fraction of dimuon events produced by the valence quarks, which also means more dilution. The samples are normalised to the integrated luminosities of 19 $\text{fb}^{-1}$ for $\sqrt{s}$ = 8 TeV and to 3000 $\text{fb}^{-1}$ for $\sqrt{s}$ = 14 TeV and the simulated data are shown for $\sqrt{s}$ = 8 and 14 TeV for two different selection requirements, $|\eta| < 2.4$ and 2.8. Extending the pseudorapidity acceptance significantly increases the coverage for larger $x$-values in the production and reduces both the statistical and PDF uncertainties, as shown below. After improvement in statistical uncertainty, as shown in Fig. 2 (right), the PDF uncertainty becomes the dominating factor that restricts the precision of the measurement. This uncertainty is estimated by repeating the analysis with 100 replicas of NNPDF 3.0 PDF and is shown in the plot as “nominal”. Since the shape of the $A_{FB}$ distribution changes for different replicas, it results in large PDF uncertainty in the extraction of the weak mixing angle, which is performed at Z-boson mass. The effect is reduced by assigning higher weight to replicas that describe the data in the regions of low and high dimuon masses, far from the Z-boson mass, in the region that is not so sensitive to the weak-mixing-angle value. Such a way of treatment of different replicas not only reduces the PDF uncertainty, but also makes it luminosity dependent, since with increased luminosity the weight assignment to different replicas becomes more accurate. The “constrained” method reduces the PDF uncertainty of the measurement as presented in the same plot.

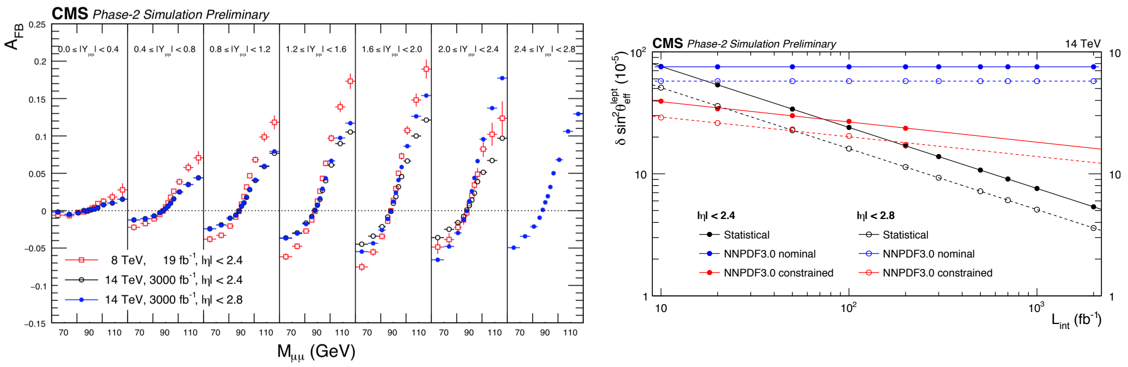


**Figure 2:** (left) Forward-backward asymmetry distribution, $A_{FB}$, in dimuon events at $\sqrt{s}$ = 8 and 14 TeV. (right) The statistical and PDF uncertainties of the weak mixing angle measurement as a function of integrated luminosity.

## 4. Top mass measurement

The top mass at the LHC is measured with so called “direct measurements”, where information from the kinematic reconstruction of the measured top quark decay products, and their corresponding combinations are used. The typical uncertainty of such methods are of the order of 500 – 600 MeV as shown in Fig. 3 (left) where the summary of recent measuremens is presented [10]. A variety of alternative methods are exploited to supplement the top quark mass measurements from direct mass reconstruction based on jet observables. One source of alternative observables is the usage of the b-jet information in the $t\bar{t}$ decay, e.g. via final states featuring $J/\Psi$ produced in the b-hadron decays or secondary vertices in b-jets. With the alternative approaches, a large variety of other measurements can be done, which have different sensitivities to the top quark production and decay mechanisms and making therefore different contributions to the systematic uncertainties. The comparison of extrapolated uncertainties on the top quark mass measurements to the HL-LHC using different methods is presented in Fig. 3 (right). The less precise, currently, is the “$J/\Psi$”

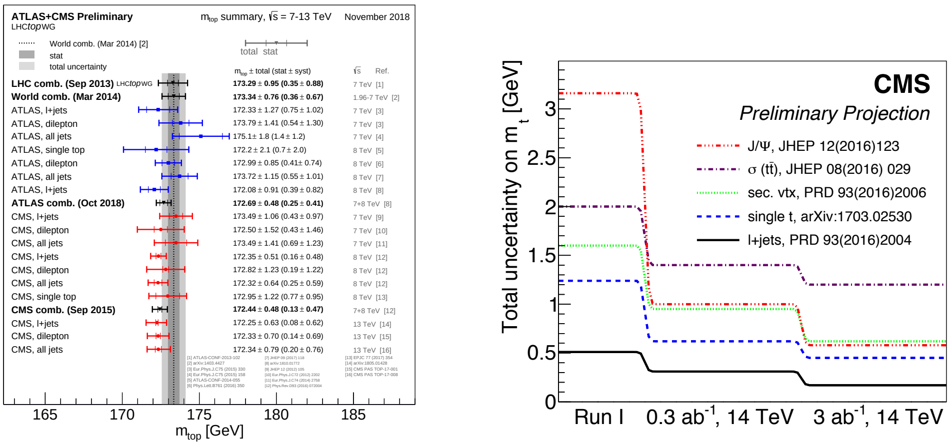


**Figure 3:** (left) The summary of the recent top mass measurements from [10]. (right) The top mass measurement uncertainty for different methods as a function of integrated luminosity.

approach that is based on a correlation between lepton from W decay and $J/\Psi$ from the b-quark decay in a process $t \to Wb$. With more data and improved systematic uncertainties it is expected that the $J/\Psi$ method will significantly improve its precision and together with other methods will allow the measurement of the top mass with accuracy of a few hundred MeV at the HL-LHC.

## 5. VV Vector Boson Scattering and VVV production

Electroweak production of vector bosons is another important measurement that requires large data samples. This production is characterized by presence of two vector bosons, WW, WZ, or ZZ in the central part of the detector with two jets in backward/forward directions separated by a large rapidity gap. The total EW production is composed of three possible polarization states, when both vector bosons are longitudinally polarized (LL), and when one or both of them are polarized transversely. The LL component is interesting as a direct probe of the unitarization mechanism of the VBS amplitude through Higgs boson production and possible new physics. It can possibly be observed using angular separation between jets. Figure 4 (left) demonstrates the expected significance of the LL cross section measurement as a function of integrated luminosity for the WW channel. It demonstrates that by combining the ATLAS and CMS results, and possibly by adding WZ and ZZ, the LL process will become observable at the HL-LHC.

The HL-LHC offers a large improvement to multi-boson production, as shown in Fig. 4 (right) for the WWW channel. A simple cut-and-count approach provides sensitivities larger than $3\sigma$. It should be noted that more mature analysis techniques such as multivariate analysis would likely improve these results further. However, high level of background control, mainly diboson background as well as instrumental background arising from fake-leptons, will be needed in order to maintain the desired level of precision.

## 6. Summary

The high-luminosity upgrade of the LHC will allow the collection of an amount of proton-

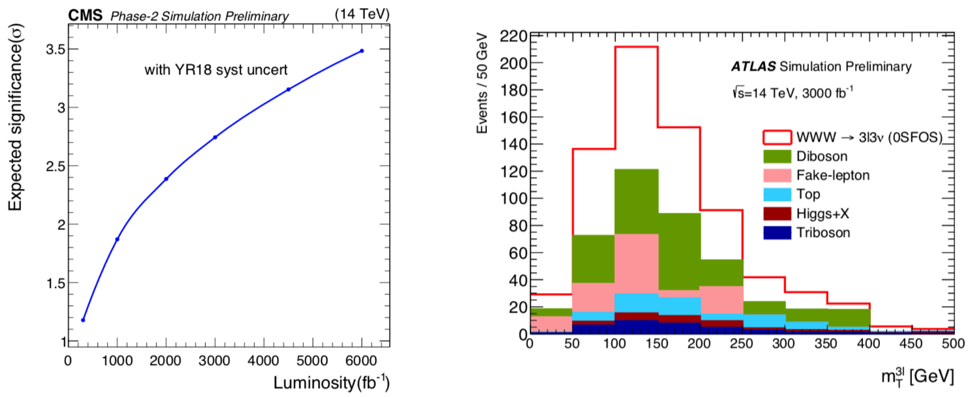


**Figure 4:** (left) Significance of the observation of the scattering of a pair of longitudinally polarized W bosons as a function of the integrated luminosity at CMS. (right) The distribution of $m_T^{3\ell}$ for the $W^{\pm}W^{\pm}W^{\mp} \rightarrow 3\ell 3\nu$ channel.

proton collisions factor of ten larger than the currently planned one by the end of 2023. An important part of the project is the upgrade of the detectors. Improved parts of the detectors, increase in the pseudorapidity coverage together with large amounts of data should lead to the new very precise electroweak measurements, and as a result better understanding of the underlying physics processes.

The University of Wisconsin – Madison would like to acknowledge the U.S. Department of Energy (DOE) and the National Science Foundation (NSF) for funding their contribution to this research.

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