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ATLAS and CMS Physics prospects for High-Luminosity LHC

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Abstract

With a start of data-taking scheduled in 2029, the High-Luminosity LHC (HL-LHC) will extend the LHC program to the first half of the 2040's with pp collisions at $\sqrt{s} = 14$ TeV, with an expected integrated luminosity of 3000 fb^{-1} for each of the ATLAS and CMS experiments. Their physics programme will directly benefit from the large luminosity to be collected, improved systematic uncertainties as well as from new trigger and reconstruction techniques made possible thanks to the detector Phase-2 upgrades. The most recent physics prospects from the ATLAS and CMS collaborations are summarized in this contribution, covering in particular Higgs physics, Standard Model precision measurements and Beyond the Standard Model searches.

1 Introduction

The High-Luminosity LHC (HL-LHC) is expected to operate from 2029, with an instantaneous luminosity up to 7.5 cm^{-2}s^{-1} and an average number of inelastic proton collisions per bunch crossing ($\langle\mu\rangle$) up to 200, compared to a peak instantaneous luminosity around 2.0 cm^{-2}s^{-1} and $\langle\mu\rangle$ up to 55 achieved during the 2022 LHC run. Those data-taking conditions will present unprecedented challenges for the ATLAS and CMS detectors, motivating ambitious detector upgrade programmes [1, 2], aimed at guaranteeing equivalent or better performance as during the previous LHC runs.

In order to improve the assessment of the physics potential of the HL-LHC dataset and to identify in advance potential limiting factors requiring dedicated efforts, the ATLAS and CMS collaborations are regularly updating prospect physics results for various key HL-LHC analyses. Comprehensive studies of the HL-LHC physics potential were published in 2019 (CERN Yellow Report [3] for the European Strategy update) and in 2022 (Snowmass Energy Frontier Report [4] and ATLAS and CMS White

Paper [5]). Those projections highlight in particular the impact of the 20-fold increase in integrated luminosity ($\mathcal{L}$) with respect to the Run-2 dataset, which will significantly improve the sensitivity of statistically-limited measurements, with statistical uncertainties reducing as $1/\sqrt{\mathcal{L}}$. In addition, as an increasing amount of measurements will be limited by the systematic uncertainties, an effort to determine realistic HL-LHC estimates for those uncertainties has also been carried out. In the baseline scenario, theory uncertainties are in particular expected to be scaled down by a factor two, both for cross-section and modeling uncertainties, thanks to improved fixed-order calculations and Monte Carlo generators. In addition, uncertainties related to the limited size of Monte-Carlo simulation samples should become negligible, relying on the expected software improvements. Some experimental uncertainties will also be improved thanks to the large HL-LHC dataset, in particular for the statistical components of the uncertainties derived from auxiliary measurements in data, and the luminosity uncertainty is expected to reach 1% for the full HL-LHC dataset.

2 Higgs physics

In the Higgs sector, the HL-LHC dataset will be the opportunity to improve the precision of the measurements of the Higgs boson couplings to other Standard Model (SM) particles, illustrated in Fig. 1a). Couplings to gauge bosons and third-generation fermions are in particular expected to be measured with a precision better than 4%, getting limited by the theory uncertainties. Couplings to second-generation fermions will also be probed with good precision, offering more insight on the structure of the Higgs Yukawa couplings. Higgs boson mass measurements are also expected to reach an unprecedented precision, down to 30 MeV in the $H \to 4\ell$ channel [7], and will start getting limited by systematics uncertainties. Higgs Simplified Template Cross-Sections (STXS) and other differential measurements will also be carried to constrain the kinematics of the Higgs boson and provide model-independent measurements which can be compared to predictions from various physics models. For those measurements, systematics will also start playing an important role, except at high transverse momentum or for sub-dominant modes.

One of the key measurements to be carried at HL-LHC concerns the Higgs self-coupling, which will improve our understanding of the Higgs potential and of the electroweak symmetry breaking. The main sensitivity for this measurement will be provided through the search for di-Higgs (HH) production, complemented by constraints from single-Higgs measurements. The latest combined ATLAS and CMS projection [3], covering several HH channels, was highlighting an expected 4σ significance for the observation of the HH production and a 50% uncertainty for the Higgs self-coupling modifier. Since then, updated projections from ATLAS and CMS, benefiting from improvements developed in the context of Run 2 analyses, have been released [5]. Those updated numbers bring strong confidence that a 5σ observation could be achieved combining 3000 fb^{-1} datasets from ATLAS and CMS.

3 Standard Model

Beyond the study of the Higgs sector, the ATLAS and CMS physics programmes for HL-LHC encompass many precision measurements related to the electroweak sector, top quark properties, QCD or B-physics. The combination of such measurements as inputs for Standard Model Effective Field Theory global fits [8] could then shed light on some potential deviations from the SM predictions associated with Beyond-the-Standard-Model (BSM) particles beyond the mass scales accessible with the LHC.

Vector boson scattering (VBS) processes are quite sensitive to potential BSM effects, in particular

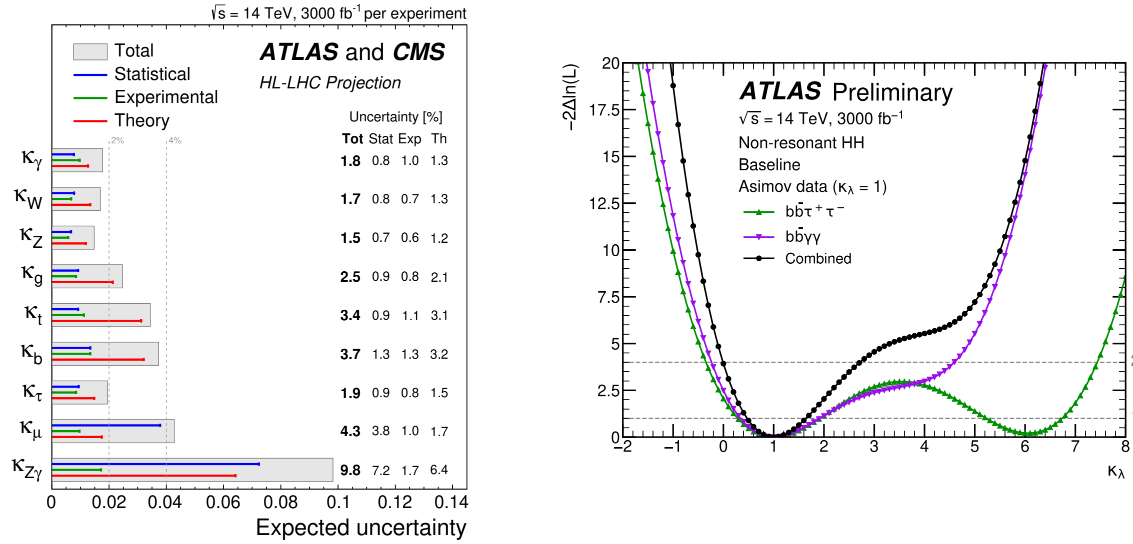

Figure 1: *a) Expected uncertainties on the Higgs coupling modifier parameters (κ), for the combination of ATLAS and CMS HL-LHC extrapolations* [3]. *b) Likelihood distributions as a function of the Higgs self-coupling modifier κ_λ for the latest ATLAS HL-LHC projection of the $HH \to b\bar{b}\tau^+\tau^-$ and $HH \to b\bar{b}\gamma\gamma$ results and their combination* [6].

for the case of longitudinally-polarized vector bosons. In the SM, this process is unitarized thanks to the presence of Higgs boson contributions, and deviations from this would indicate the presence of BSM physics. The cross-section for the longitudinally-polarized state is small (6-7% of the total cross-section), making this a challenging but important part of the HL-LHC physics program. Based on several sets of projection results [5], a combination of ATLAS and CMS data, whose sensitivity is driven by leptonic final states, is expected lead to an observation of the same-sign longitudinal WW scattering at HL-LHC, illustrated in Fig. 2a).

Precision electroweak measurements will also be carried at HL-LHC. The electroweak mixing angle $\sin^2\theta_{eff}$ is for instance expected to be measured through the forward-backward asymmetry in di-lepton events with a unprecedented precision [5]. A small dataset of 1 fb^{-1} collected at low pileup could also be exploited to improve the precision of the W mass measurement [10], benefiting in particular from the improved PDF determination expected with the HL-LHC dataset, as illustrated in Fig. 2b). An uncertainty as small as 5 MeV could thus be achieved. As for the top quark, the best precision in its mass measurement is expected to be achieved through the kinematic reconstruction of lepton+jets $t\bar{t}$ events, with a precision of 170 MeV on the MC mass parameter dominated by theoretical modeling uncertainties. Alternative methods, impacted by different systematic uncertainties, could further improve the precision of this measurement when combined [11]. Finally, measurements of the top-quark pole mass, better defined theoretically, can be achieved thanks to $t\bar{t}$ cross-section measurements and could reach an uncertainty better than 500 MeV [12].

Precision measurements in the QCD sector will also represent major components of the HL-LHC physics programme. Thanks to the large amount of events collected, the reach of differential jet and photon cross-section measurements will be significantly increased, which will directly benefit to the determination of proton PDFs, since large differences can be observed between different PDF predictions

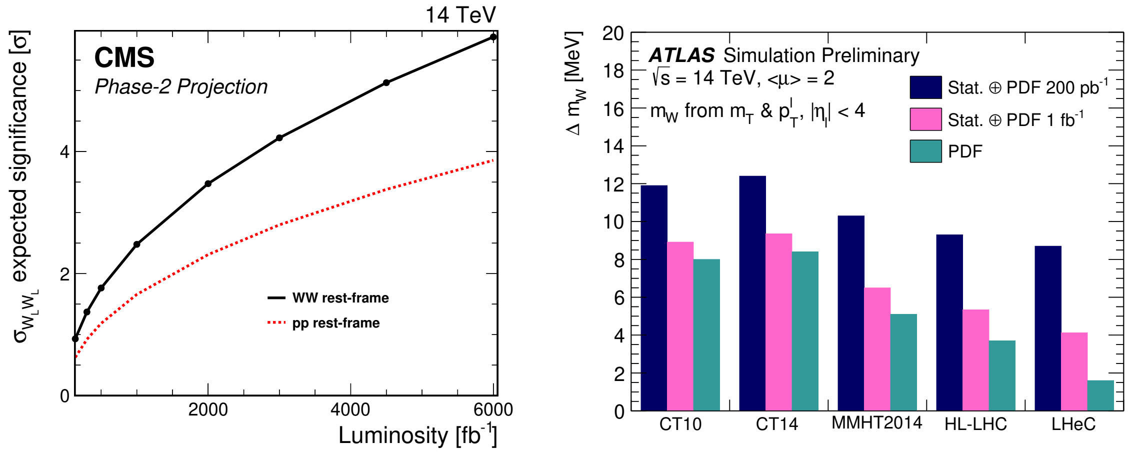

Figure 2: *a) Expected significance for the VBS* $W_L^{\pm}W_L^{\pm}$ *process as a function of the integrated luminosity obtained with the latest CMS projection* [9]*. b) W mass measurement uncertainty expected by ATLAS for* 200 pb^{-1} *and* 1 fb^{-1} *of low pileup data collected at* $\sqrt{s} = 14$ TeV*, for difference PDF predictions and uncertainties* [10]*.*

at high p_T [13]. The precision of the gluon PDFs will also be strongly improved thanks to differential $t\bar{t}$ cross-section measurements [14].

4 Beyond the Standard Model

An important set of BSM projection results from ATLAS and CMS, covering a large variety of scenarios, has been summarized in [5] and a small selection of those results is presented here. Among all of the existing BSM models, many predict heavy resonances manifesting as high-mass excesses in the tail of invariant mass distributions. Those can for instance correspond to heavy gauge bosons, excited leptons or heavy Majorana neutrinos. The corresponding searches will be continued at HL-LHC, with the best sensitivities typically achieved in leptonic channels. Thanks to the increase in the center-of-mass energy and the large luminosity, HL-LHC will improve the sensitivity of those searches towards weaker couplings and higher masses, as illustrated in Fig. 3a) with limits expected to reach 7 TeV for Z' bosons predicted in the Sequential Standard Model [15].

Run 2 Supersymmetry (SUSY) searches have already set stringent limits on squark and gluino production in scenarios with large mass differences between the SUSY particles. On the other hand, processes with smaller cross-sections , like the production of electroweakinos, will directly benefit from the large HL-LHC dataset. New analysis techniques can also significantly boost the sensitivity of scenarios with compressed mass spectrum. The new capabilities offered by the Phase-2 detector upgrades and dedicated reconstruction algorithms will also benefit to the searches for long-lived particles, predicted in a wide range of BSM models. The sensitivity to long-lived dark photons decaying into muons and produced in Higgs boson decays [16], which can be improved thanks to optimized new muon trigger algorithms, is for instance illustrated in Fig. 3b).

Dark matter (DM) searches will also be carried over a large variety of final states. As DM particles are not expected to interact with the detector, those searches are typically targeting production modes in

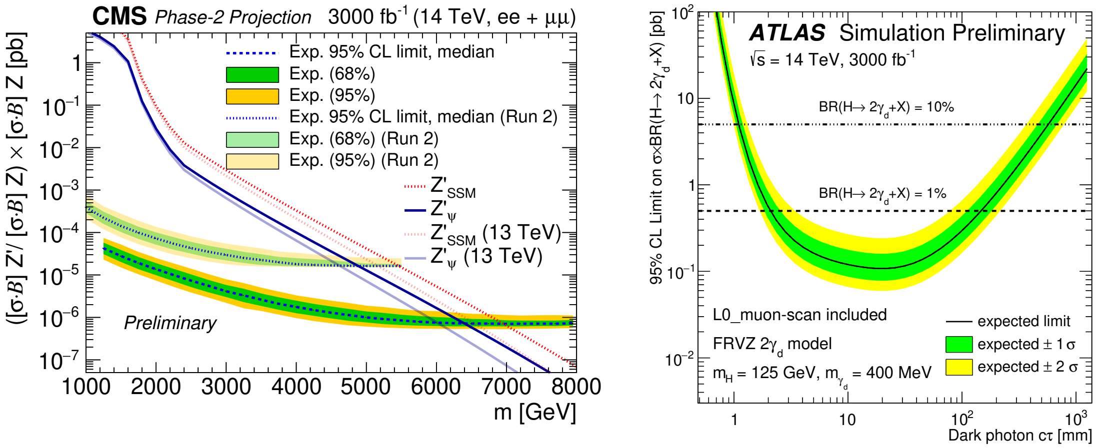

Figure 3: *a) Expected limits in the search for a heavy Z' boson for the full CMS HL-LHC dataset, compared to the expected limits for the CMS Run 2 analysis* [15]*. b) Expected HL-LHC ATLAS limits in the search for dark photons decaying into muons, through $H \to 2\gamma_d + X$ decays as a function of the γ_d lifetime, considering 45% dark photon branching ratio to muons* [16].

association with SM detectable particles, where the DM presence can be inferred through a large amount of missing transverse energy. Interpretations are often carried in simplified models, with a BSM boson coupling to SM particles and decaying into DM particles. For those searches as well, large improvements are expected thanks to the large HL-LHC dataset and complementary limits with respect to direct detection experiments can be derived [17].

5 Conclusion

The HL-LHC data-taking will represent an unprecedented challenge for the ATLAS and CMS experiments, considering the major detector upgrades scheduled, the updates required to face the large pile-up in the object reconstruction and identification algorithms and the huge amount of data to be analysed, all of this to be prepared in parallel to the Run 3 data-taking. A major effort from the collaborations has therefore been initiated to make this a success, as some strong positive impact is expected for their physics programmes. The sensitivity of HL-LHC analyses will in particular directly benefit from the large 3000 fb^{-1} luminosity expected to be collected by each experiment, the improved systematic uncertainties and the new trigger and reconstruction techniques possible thanks to the detector upgrades. Thanks to those improvements, the properties of the Higgs boson and other Standard Model properties will be measured with an unprecedented precision, while searches for BSM scenarios will be able to probe unexplored regions of phase space, either at high mass or in challenging final states. Flavor and heavy-ion physics, unfortunately not covered in this report, will also represent a large fraction of the new physics results expected during the HL-LHC phase.

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