Frascati Physics Series Vol. 70 (2019)
LFC19: Strong dynamics for physics within and beyond the Standard Model at LHC and Future Colliders
September 9-13, 2019

Physics at the High-Luminosity LHC

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Abstract

The High-Luminosity LHC (HL-LHC) is scheduled to start operation in 2027. By the end of the 2030s it is expected to deliver to upgraded LHC experiments a factor 20 more data than collected so far. To further refine the expectations of the physics potential of the HL-LHC, the "Workshop on the Physics of the HL-LHC and Perspectives for the HE-LHC" took place from October 2017 to December 2018. The whole LHC community, theorists and experimentalists, collaborated closely and produced detailed studies of HL-LHC measurements towards ultimate precision, and of searches for new phenomena. The updated experimental projections are generally based on recent publications of the LHC Run-2 data. The results are presented in a comprehensive document [1]. An executive summary of the report was also submitted to the European Particle Physics Strategy Group [2]. Here, a small selection of the projections of the physics at the HL-LHC is presented.

1 Introduction

For the HL-LHC, the ATLAS and CMS collaborations are preparing a major upgrade, with significantly improved detector resolutions, larger acceptance, enhanced triggering capabilities and increased recording rate. The tracking detectors cover an enhanced acceptance up to a pseudo-rapidity $|\eta| < 4$ and are complemented by extended or new muon systems and calorimeters, as well as novel precision timing detectors. Detector upgrades for the experiments LHCb and Alice are taking place during the current shutdown.

Two examples for the improved detector performance of ATLAS and CMS are shown in Fig. 1. Due to the improvements in tracking, the expected resolution for the reconstruction of the Higgs boson mass in the decay into two muons is significantly improved (Fig. 1a), leading to better signal significance

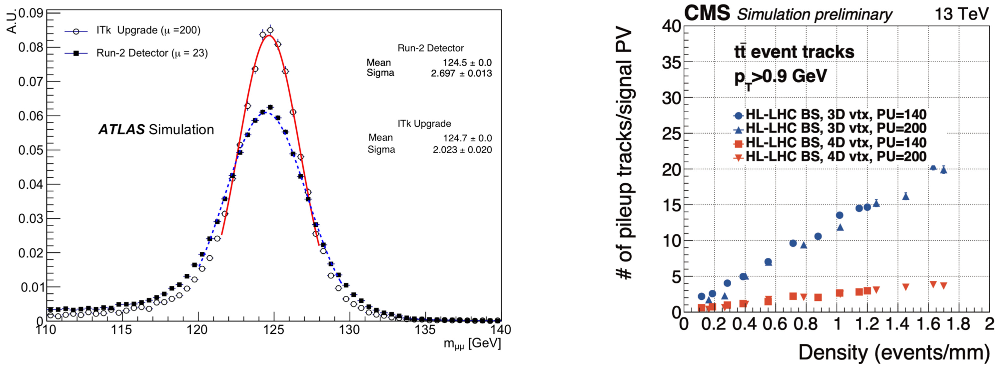

Figure 1: *a) Signal resolution for $H \rightarrow \mu\mu$ signal events. The Run-2 resolution is compared to that at the HL-LHC (from [3]), b) Rate of tracks from pileup vertices, incorrectly associated with the primary vertex of the hard interaction, normalized to the total number of tracks in the vertex (from [4]).*

and smaller statistical uncertainties for the measurement of the invariant mass. The high instantaneous luminosity at the HL-LHC, will produce up to 200 proton–proton collisions per bunch crossing (pile-up), and consequently very high densities of the collision vertices. The fraction of pile-up tracks associated with the primary vertex is expected to increase proportionally (Fig. 1b). With additional timing layers around the tracker volume, precision measurements of the track timing, with target resolution 30 ps, become possible. Including the time information as a fourth dimension the number of pile-up tracks associated to the primary vertex is substantially reduced, almost to the level of Run-2.

In addition to better detectors and large luminosity, significant improvements over current LHC results are also expected from the continuous refinement of analysis techniques and theory calculations. To determine the physics yield of the HL-LHC as precisely as possible, a main goal of the workshop was to produce projections of the uncertainties of the future measurements that are as realistic as possible. ATLAS and CMS agreed on the following common approach [5, 4]: statistical uncertainties are expected to scale as $1/\sqrt{L}$; theory uncertainties are assumed to be reduced by a factor of two; and Monte Carlo simulations are expected to give no uncertainty. For the experimental uncertainties, the statistical component of such systematics is naturally expected to scale with $1/\sqrt{L}$. In contrast, systematic components of the uncertainties may be hard, and ultimately impossible, to overcome. ATLAS and CMS estimated these 'floors' individually for each experimental input. Good general agreement was found.

The relevance on the assumptions for the evolution of the systematic uncertainties is illustrated in

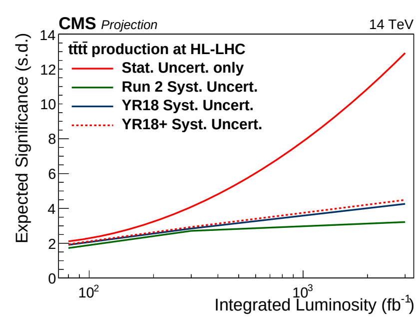

Figure 2: *Expected significance of a search for 4-top production with CMS at HL-LHC. The expected significance of the 4-top signal over a background-only hypothesis in standard deviations is given for various HL-LHC systematic uncertainty scenarios (from [6]).*

Fig. 2, using the example of the 4-top analysis. With current uncertainties, additional signal statistics would barely lead to further improvements. In contrast, if the total uncertainty was purely statistical, a measurement with very high significance would become possible. It is worth noting that, in many areas, the actual results from LHC Run-2 data proved to be significantly better than original expectations prior to Run-2. Beyond-design detector performance could be achieved, theory uncertainties could be constrained and refined analysis techniques were developed, e.g. using novel machine learning approaches. The coming two decades are likely to bring about further improvements beyond current projections.

2 Standard Model Physics

Due to much better detectors and refined analysis techniques, measurements of standard model (SM) processes are expected to improve significantly beyond the already precise results from the LHC. Such measurements are key to determining SM parameters, such as the masses of the top quark and the W boson, as well as the strong coupling constant α_s and the proton structure functions, just to name a few. In electroweak and QCD fits, rigorous consistency tests of the SM will be performed. Ultimately, the W boson mass is expected to be measured with an uncertainty as small as 5 MeV. For the measurement of the top quark mass, a precision of better than 200 MeV is expected. For a theoretically well-defined interpretation of such top quark mass measurements, theory developments are ongoing. At the HL-LHC, a precision of 1% is envisaged for the measurement of the integrated luminosity, a crucial input to cross section measurements, which are also used to determine the parton distribution functions. Due to the large statistics, jet cross sections can be measured up to transverse jet momenta of 4 TeV. In addition to SM physics at medium and high energy scales, better detectors will also open a new realm of forward physics as well as hadron spectroscopy.

3 Higgs Physics

Since the discovery of a scalar boson at 125 GeV in 2012, the precision determination of its properties is a primary target of the LHC and the HL-LHC. A guiding question is whether the boson is identical to the one expected in the SM or whether it carries signs of new physics. The Higgs program at the HL-LHC comprises measurements of the discovered particle in all accessible production and decay channels. In the κ-framework, scale factors quantifying the agreement of the measured Higgs Yukawa couplings with expectations are determined (assuming SM structure). In Fig. 3a) the expectations for the achievable precision are presented. In combination, the ATLAS and CMS measurements are expected to reach a precision as low as 1 to 1.5% for the most precise channels. Within the κ-framework, contributions from non-SM couplings can be constrained at the level of 2.5%.

Differential measurements are expected to achieve a precision that allows to constrain the couplings of the Higgs boson also from shape analysis. The direct measurement of the coupling to charm depends directly on the efficiency to disentangle charm quarks and b quarks in the experiments. Already now LHC experiments are exceeding original expectations by a large amount. In Fig. 3b) a summary of the expectations for the HL-LHC for the coupling to light quarks is presented.

Inclusive and differential measurements of vector boson scattering (VBS) processes involving triple and quartic gauge couplings, are going to probe the Higgs boson as virtual particle, providing insight into the Higgs mechanism. While electroweak multiboson production involving W, such as WW, WZ and WWW, are expected to be measured at uncertainties as low as 6%, the measurements of electroweak ZZ, WWZ and WZZ processes will be much less precise. However, better analysis techniques, e.g. for the

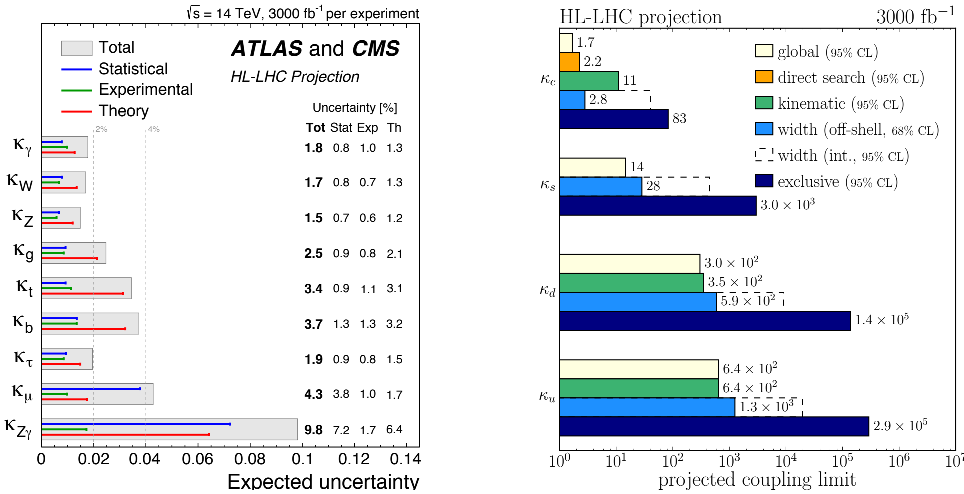

Figure 3: *a) Projected uncertainties on κ_i, combining ATLAS and CMS (from [2]), b) Summary of the projected HL-LHC limits on the quark Yukawa couplings (from [2]).*

reconstruction of forward jets, could possibly improve future measurements beyond current projections.

One important goal of Higgs physics is to measure the self-coupling of the Higgs as predicted in the SM. At the HL-LHC, about 120k events with two Higgs bosons (HH) will be produced per experiment. The HH cross section is driven by a negative interference between the Higgs self-coupling diagram and a diagram involving a top-quark box. Direct measurements of HH production have been performed using a combination of several final states. Best sensitivity is expected for events where one H decays into bb (large branching ratio) and the other one decays into a pair of photons (clear signature), as shown in Fig. 4a), or τ-leptons. Other final states have also been investigated [1]. Current projections indicate that CMS and ATLAS will be able to measure the cross section with a significance of 4 standard deviations. The expected likelihood profile of the self-coupling modifier κ_λ is shown in Fig. 4b).

4 Direct Searches

The potential of the HL-LHC to directly observe physics beyond the standard model has been studied for a large variety of scenarios. Only a very small selection of the studies can be presented here. Arguably the simplest approach is to look for high-mass resonances. In Fig. 5a) the upper limit is shown for a heavy vector boson Z', as predicted e.g. in the Sequential SM or the E_6 GUT model, decaying into a pair of leptons. At the HL-LHC, a Z' with a mass of about 6 TeV can be excluded. For this, as for many other resonance searches, the HL-LHC extends the reach in mass by typically 2 TeV w.r.t. current limits.

New physics could also occur in a dark sector of new particles, connected with standard model particles through a portal described by a kinetic mixing parameter ϵ. In Fig. 5b), a summary of searches for dark photons from Higgs decays is presented. If ϵ is very small, dark photons can be long-lived, with a lifetime between a few millimeters up to several meters.

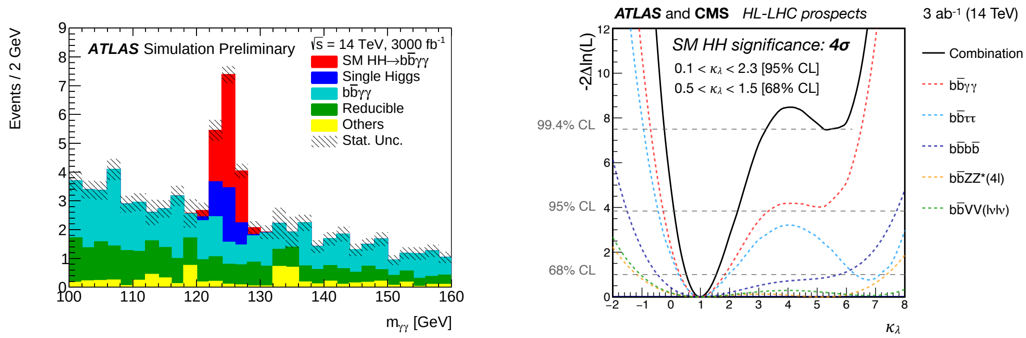

Figure 4: *a) Distribution of $m_{\gamma\gamma}$ following the BDT response cut (from [1]), b) Projected combined HL-LHC sensitivity to Higgs trilinear coupling from direct search channels (from [2]).*

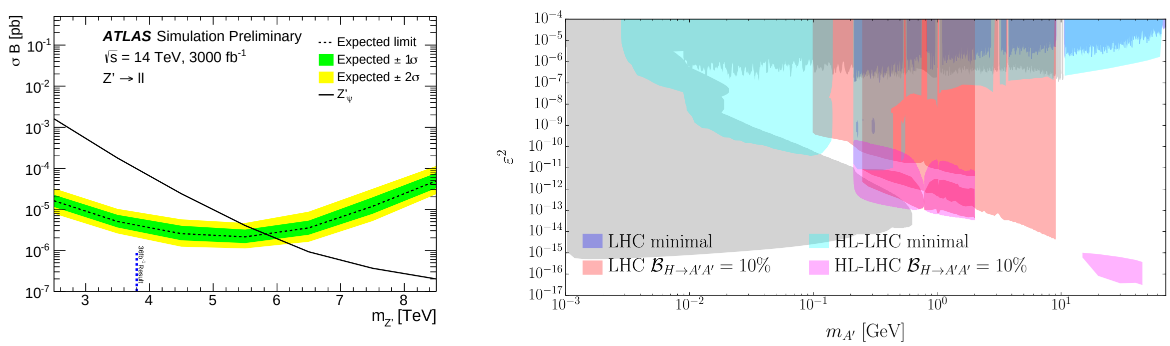

Figure 5: *a) Expected upper limit for a Z', and the prediction for a Z'$_\psi$ in the E_6 model (from [2]), b) Projections for dark photons from Higgs decays, assuming a branching ratio of 10% (from [1]).*

Long-lived particles could also arise when phase space is small, e.g. in scenarios of mass-degenerate supersymmetric particles. While SUSY particles produced in strong interactions have largely been excluded up to masses of 1 TeV or above, the cross sections for supersymmetric particles produced via electro-weak processes are too small for current LHC data to have sensitivity. Scenarios involving electroweakinos with masses above about 500 GeV are still consistent with current data, and compatible with SUSY naturalness. In Fig. 6a), limits are shown for the search of pairs of higgsino-like electroweakinos.

The search for leptoquarks (LQ) involving 2nd or 3rd generation particles has recently received enhanced interest, as their existence is suggested in models addressing the tensions observed in B-factory data, often referred to as 'flavour anomalies'. It is expected that LHCb and Belle II experiments will clarify the situation in the next few years. ATLAS and CMS can also have an impact at low momenta, in final states with muons, and also exploiting new track trigger systems that are able to reconstruct tracks, vertices and invariant masses at first trigger level. If deviations from standard model expectations in low-momentum flavour physics persist at high significance, ATLAS and CMS provide complementarity at high mass scales, as they are able to discover, or exclude, exotic heavy particles, such as LQ. In Fig. 6b) upper limits on the LQ pair-production cross section at 95% CL as a function of the LQ mass and the branching fraction are shown for LQ decaying into a top quark and a muon or τ-lepton. With HL-LHC,

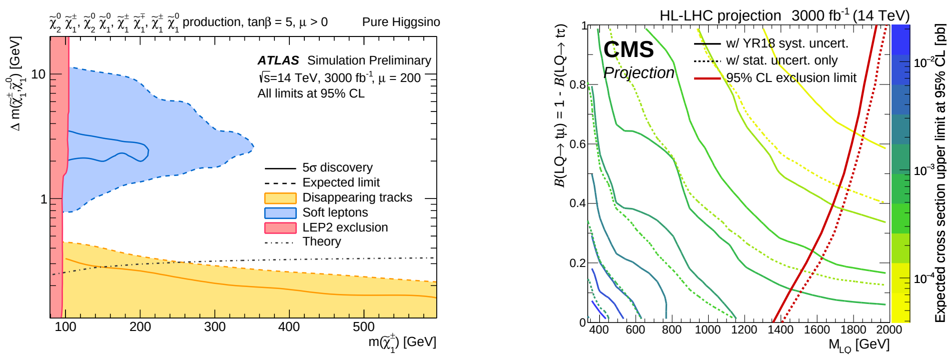

Figure 6: *a) Expected 95% CL exclusion / discovery reach from disappearing-track and low-momentum lepton pair searches in higgsino-like electroweakino models (from [1]), b) Expected upper limits on the LQ pair-production cross section at 95% CL as function of LQ mass and branching fraction (from [1]).*

the presence of such LQ can be excluded up to almost 2 TeV.

5 Conclusions

In conclusion, upgraded machine and detectors at the HL-LHC are expected to produce an excellent and diverse physics yield. With the expected statistics and precision, stringent tests will be performed of the Standard Model and of the properties of the Higgs boson. In searches for heavy resonances, the HL-LHC increases the reach in mass by typically 2 TeV w.r.t. current limits. With the greatly improved HL-LHC detectors, exotic signatures, e.g. of long-lived particles, can be studied in much more detail. Possible indirect discoveries in the flavour sector could turn out to be complementary to findings at high mass scales. Using collisions with heavy ions (HI), the LHC and the HL-LHC also pursue a comprehensive and rich program for the study of QCD in media, not covered in this report.

References

1. A. Dainese et al., "Physics of the HL-LHC, and perspectives at the HE-LHC", CERN Yellow Reports: Monographs Vol 7 (2019) doi:http://dx.doi.org/10.23731/CYRM-2019-007

2. A. Dainese et al,, "The physics potential of HL-LHC", Input to the European Particle Physics Strategy Update 2018-2020, https://indico.cern.ch/event/765096/contributions/3295995/

3. The ATLAS Collaboration, "Technical Design Report for the ATLAS Inner Tracker Strip Detector", ATLAS-TDR-025, https://cds.cern.ch/record/2257755

4. CMS Collaboration, "Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC", Technical Report CMS-NOTE-2018-006, https://cds.cern.ch/record/2650976

5. ATLAS Collaboration, "Expected performance of the ATLAS detector at the High-Luminosity LHC", ATL-PHYS-PUB-2019-005, http://cds.cern.ch/record/2655304

6. CMS Collaboration, "Projections of sensitivities for 4-top production at HL-LHC and HE-LHC", CMS PAS-FTR-18-031, http://cds.cern.ch/record/2650211