SciPost Phys. Proc. 8, 111 (2022)

Future Physics Prospects with the CMS Detector at the High-Luminosity LHC

Conor Henderson⋆ on behalf of the CMS Collaboration

University of Alabama, Tuscaloosa, AL, USA

⋆ conor.henderson@cern.ch

Proceedings for the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects, Stony Brook University, New York, USA, 12-16 April 2021
doi:10.21468/SciPostPhysProc.8

Abstract

The High-Luminosity Large Hadron Collider is expected to deliver up to 3000 fb^{-1} of proton-proton collisions at 14 TeV center-of-mass energy. We present prospects for selected heavy-ion, Standard Model and Higgs sector measurements with the CMS detector at the HL-LHC, and discuss potential sensitivity to several beyond-Standard Model new physics scenarios.

Received 22-07-2021
Accepted 09-03-2022
Published 13-07-2022
Check for updates
doi:10.21468/SciPostPhysProc.8.111

1 Introduction

The LHC plans a future 'High-Luminosity' (HL-LHC) phase, with proton-proton collisions at a center-of-mass energy of 14 TeV and an instantaneous luminosity projected to reach a peak of up to 7.5×10^{34} cm^{-2}s^{-1}, a factor of roughly four increase beyond Run 2. The HL-LHC goal is to collect an integrated luminosity of at least 3000 fb^{-1} in ten years of operations [1]. The CMS experiment [2] is preparing for a set of major detector upgrades for the HL-LHC [3]. In these proceedings, we present prospects for selected heavy-ion, Standard Model (SM) and Higgs sector measurements with the CMS detector at the HL-LHC, and discuss potential sensitivity to several beyond-Standard Model (BSM) new physics scenarios. The complete set of public CMS physics projections for the HL-LHC are available at Ref [4].

2 Heavy-Ion Physics Projections for the HL-LHC

The suppression or modification of high-energy jets observed in heavy-ion collisions, known as jet quenching, is interpreted as being caused by strong interactions between the high-energy parton and the deconfined colored medium created in the heavy-ion collision. Heavy-ion collisions at the HL-LHC will allow for more detailed measurements of this phenomenon. Figure 1 shows the projection by CMS for a measurement at the HL-LHC of the ratio of the density of particles produced at a radius r from the central axis of a photon-tagged jet in central PbPb collisions, relative to pp collisions [5]. The projected significant reduction in systematic uncertainties on this measurement at the HL-LHC will allow for more detailed probes of the underlying parton-medium interaction.

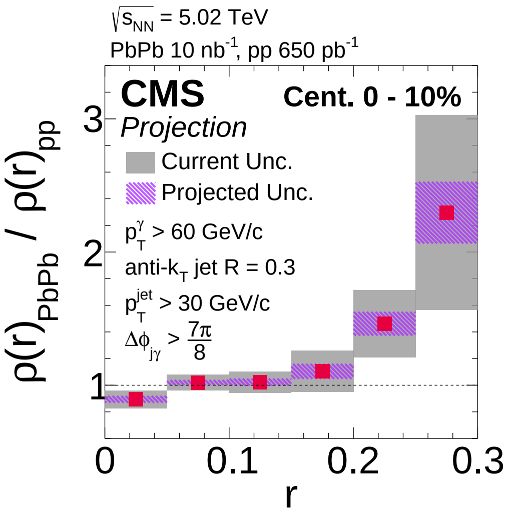

Figure 1: Ratio of the density of particles as a function of the radius r from the central axis of a photon-tagged jet in central PbPB collisions relative to pp collisions [5]. Projected systematic uncertainties on the HL-LHC measurement are shown compared to current uncertainties.

Heavy-ion collisions at the HL-LHC can also constrain more precisely the parton density functions (PDFs) within the nucleus. For instance, the photoproduction of $\Upsilon(1S)$ is proportional to the gluon density, and therefore a measurement can constrain the gluon shadowing factor (the ratio of gluon density in a nucleus compared to a proton). A CMS projection for PbPb collisions at the HL-LHC [6] shows that this measurement could constrain the gluon shadowing factor down to a Bjorken-x value around 10^{-4}, which would be a significant extension of the current x range probed.

3 Higgs Sector Projected Results for the HL-LHC

A crucial test for our understanding of the Higgs sector is to measure the Higgs boson coupling strengths to other SM particles, which are all constrained precisely in the SM, and therefore any observed deviations from the predicted values would represent evidence for beyond-SM physics. CMS has performed a projection of the precision expected for these measurements with 3000 fb^{-1} at the HL-LHC [7], and the results are shown in Figure 2, in terms of μ, the coupling strength parameter per channel. Overall, the total uncertainty is projected to be around 5% for most channels, with a larger value of $\sim$ 10% for the rarer $H \to \mu\mu$ channel; thus these HL-LHC measurements should be a signficant test of the SM predictions for the Higgs channel couplings. A comparable level of experimental precision is projected for measurements of the Higgs boson production mechanisms as shown in the second plot of the same figure.

In the SM, the Higgs potential is $V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$, where λ represents the Higgs field self-coupling, and the SM parameter values are determined once the Higgs boson mass is known. The Higgs field self-coupling contributes to di-Higgs production – observation of this

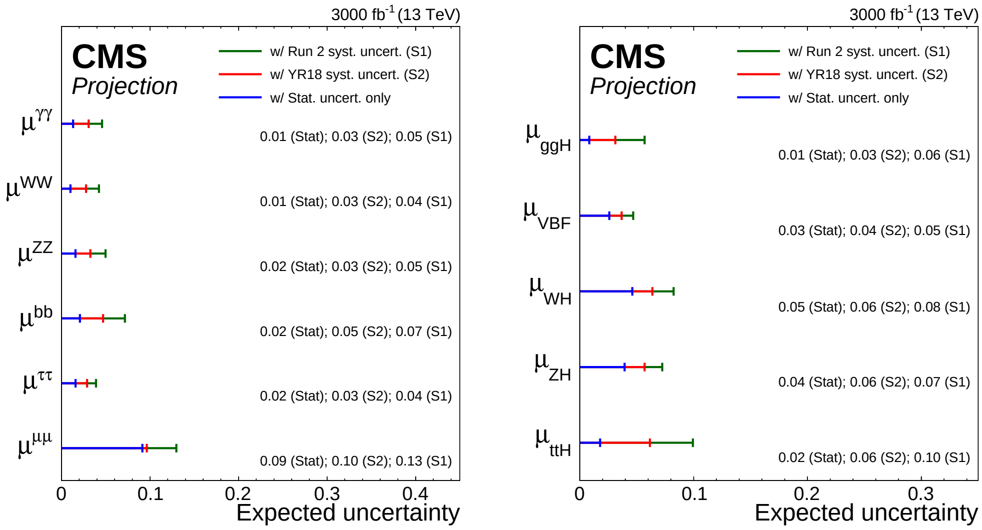

Figure 2: Projected CMS uncertainties from the HL-LHC on the Higgs coupling strength parameters for various channels (left) and production mechanisms (right) [7].

rare process can therefore probe the self-coupling parameter and would act as an important independent test of the actual Higgs potential and hence the overall Higgs sector. CMS has performed a projection for its ability to measure di-Higgs production at the HL-LHC [8]. Five HH decay channels have been considered ($HH \to bbbb, bb\tau\tau, bbWW, bbZZ$ and $bb\gamma\gamma$), and the combination is projected to yield 2.6 sigma significance for SM HH production. In terms of the coupling modifier κ_λ (the ratio of the parameter relative to the SM expectation), it is projected that, at 95% CL, κ_λ could be constrained within the range $[-0.18, 3.6]$.

4 Projected Top Quark Measurements at the HL-LHC

An illustration of the potential capability of the HL-LHC for precision physics in the top quark sector comes is the CMS projection for $t\bar{t}$ differential cross section measurements [9]. Figure 3 shows the projected results as a function of the top quark p_T and rapidity. The systematic uncertainties on this measurement are projected to be in the range 5-10%, representing about a factor of two improvement over the equivalent LHC Run 2 results, and will allow for a precision test of the SM top quark theoretical predictions at the HL-LHC.

The large luminosity obtained from the HL-LHC will also allow probes of even rarer top quark processes, such as the production of four top quarks, where observed differences relative to the SM expectation for this rare process could indicate contributions from BSM physics. For the HL-LHC, CMS projects that the cross section for SM $t\bar{t}t\bar{t}$ production could be constrained to the level of 18-28% [10].

5 Searches for Dark Matter and Heavy Resonances at the HL-LHC

One way to search for Dark Matter (DM) at the LHC is to look for new invisible particles in events containing a Z boson and missing transverse momentum. CMS has performed a projection for this analysis at the HL-LHC [11]. A benchmark scenario is considered with a vector

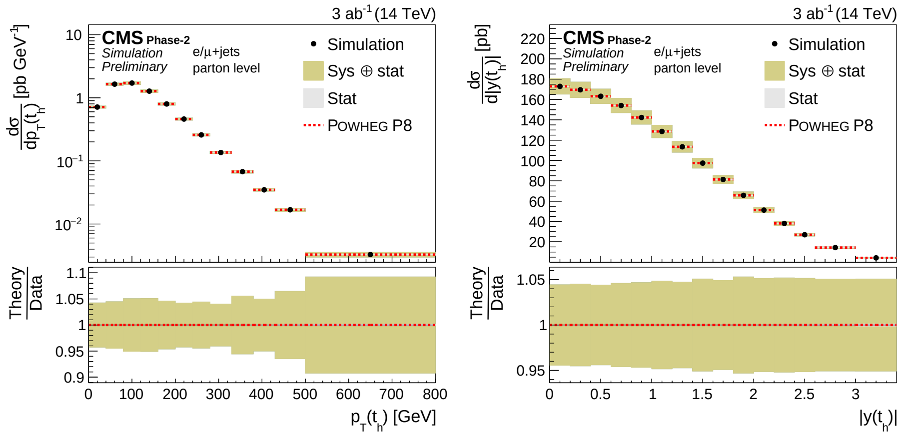

Figure 3: Projected $t\bar{t}$ differential cross sections as a function of the top quark transverse momentum (left) and rapidity (right) [9].

mediator for Dirac DM, assuming the DM particle has mass 1 GeV and the SM/DM coupling parameters are fixed to certain values. Figure 4 shows the projected discovery potential as a function of the integrated luminosity at the HL-LHC; it can be seen that for 3000 fb^{-1}, 5σ discovery is possible for DM vector mediators with mass up to about 1 TeV.

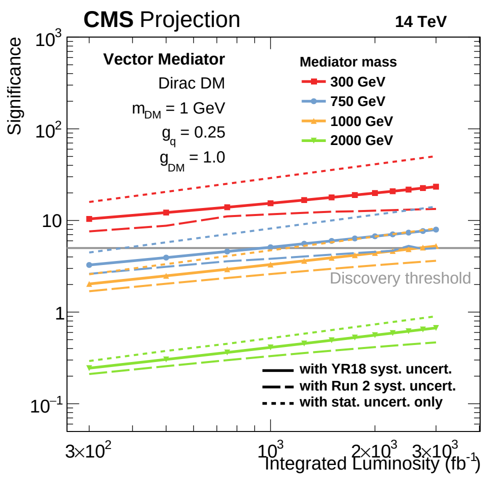

Figure 4: Discovery potential as a function of the HL-LHC integrated luminosity, for Dark Matter vector mediators of various masses in the Z boson +missing energy search channel [11].

Projections have also been performed for new heavy resonances decaying to ZZ [12] and $t\bar{t}$ [13]. In the former, the final state considered is $ZZ \rightarrow 2\ell 2q$, including both resolved and merged-jet categories. Assuming a scalar resonance with a natural width much smaller than the experimental resolution, the analysis projects to be able to exclude at 95% CL cross sections for this signal process of approximately $0.1-2$ fb, in the M_{ZZ} range $1-3$ TeV. For a $t\bar{t}$ resonance, the decay of an excited state of a gluon in a Randall-Sundrum extra dimension model is considered as a benchmark scenario. The analysis projects to have discovery potential with 5σ significance for masses of the Randall-Sundrum gluon up to 5.7 TeV

6 Conclusion

In conclusion, the High-Luminosity Large Hadron Collider aims to collect an integrated luminosity of 3000 fb^{-1} in ten years of operations, at a collision energy of 14 TeV. We have presented here a selection of projections by the CMS experiment that illustrate the broad physics capabilities from the HL-LHC, across heavy-ion physics, the Higgs sector, top quark physics and beyond-Standard Model searches. The complete set of public CMS physics projections for the HL-LHC are available at Ref [4].

Acknowledgements

The author is supported by the DOE under award DE-SC0012447.

References

[1] G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont and L. Rossi, *High-Luminosity Large Hadron Collider (HL-LHC) : Preliminary Design Report* (2015), doi:10.5170/CERN-2015-005, 10.2172/1365580.

[2] S. Chatrchyan *et al.*, *The CMS experiment at the CERN LHC*, J.Inst. **3**, S08004 (2008), doi:10.1088/1748-0221/3/08/S08004.

[3] CMS Collaboration, *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, Tech. Rep. CERN-LHCC-2015-010 (2015), http://cds.cern.ch/record/2020886.

[4] CMS Collaboration, *CMS Projected Physics Results*, http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html.

[5] CMS Collaboration, *Performance of jet quenching measurements in pp and PbPb collisions with CMS at the HL-LHC*, Tech. Rep. CMS-PAS-FTR-18-025 (2018), https://cds.cern.ch/record/2651892.

[6] CMS Collaboration, *Constraining nuclear parton distributions with heavy ion collisions at the HL-LHC with the CMS experiment*, Tech. Rep. CMS-PAS-FTR-18-027 (2018) https://cds.cern.ch/record/2652030.

[7] CMS Collaboration, *Sensitivity projections for Higgs boson properties measurements at the HL-LHC*, Tech. Rep. CMS-PAS-FTR-18-011 (2018), https://cds.cern.ch/record/2647699.

[8] CMS Collaboration, *Prospects for HH measurements at the HL-LHC*, Tech. Rep. CMS-PAS-FTR-18-019 (2018), https://cds.cern.ch/record/2652549.

[9] CMS Collaboration, *Projection of measurements of differential ttbar production cross sections in the e/u+jets channels in pp collisions at the HL-LHC*, Tech. Rep. CMS-PAS-FTR-18-015 (2018), https://cds.cern.ch/record/2651195.

[10] CMS Collaboration, *Projections of sensitivities for tttt production at HL-LHC and HE-LHC*, Tech. Rep. CMS-PAS-FTR-18-031 (2018), https://cds.cern.ch/record/2650211.

[11] CMS Collaboration, *Projection of the Mono-Z search for dark matter to the HL-LHC*, Tech. Rep. CMS-PAS-FTR-18-007 (2018), https://cds.cern.ch/record/2644529.

[12] CMS Collaboration, *Search for a new scalar resonance decaying to a pair of Z bosons at the High-Luminosity LHC*, Tech. Rep. CMS-PAS-FTR-18-040 (2019), https://cds.cern.ch/record/2658263.

[13] CMS Collaboration, *Search for ttbar resonances at the HL-LHC and HE-LHC with the Phase-2 CMS detector*, Tech. Rep. CMS-PAS-FTR-18-009 (2018), https://cds.cern.ch/record/2649032.