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Abstract

A high-luminosity running period is planned for the LHC, in which up to 3000 fb^{-1} of integrated luminosity to be collected, enabling many Higgs properties to be measured at high precision. Projections are given for the expected performance of an upgraded CMS detector for various Higgs property measurements, including modified couplings, rare decays, and spin-parity. Parameterized simulation is used to estimate CMS performance with an extended tracker and of the potential to observe Two Higgs Doublet Models.

Keywords:

1. Introduction

With the discovery of a 125 GeV Higgs boson in 2012 at the Large Hadron Collider (LHC), the standard model (SM) and its Brout-Englert-Higgs Mechanism have been shown to give a good description of all high-energy particle behavior that has thus far been observed. However, the Higgs sector has not yet been tested to any great precision, and future precision measurements may reveal deviations from SM predictions that point the way toward studies of new particles and fields. In order to realize the full potential of the LHC, a High Luminosity LHC (HL-LHC) is planned that will produce up to 3000 fb^{-1} of integrated luminosity. The phase of running will begin in the mid-2020's after a period of upgrades.

The Compact Muon Solenoid (CMS) is a large general purpose detector at the LHC that, along with ATLAS, discovered the Higgs boson and has measured its properties. In order to continue operating successfully as the LHC luminosity increases, the CMS detector will require a series of upgrades. Parts of the detector will also have to be replaced, even if not upgraded, in order to maintain performance after radiation damage in the LHC collision environment. A series of Phase I upgrades, already begun and continuing through the end of the present decade, will enable the CMS detector to take data efficiently through the first 300 fb^{-1} of LHC data. In order to take data in the HL-LHC environment, the phase II upgrades are proposed.

In this document, the requirements for Higgs boson studies at the HL-LHC are outlined. The possible upgrades to the CMS detector and their potential impact on Higgs boson measurements are discussed, including signal strengths, couplings, spin-parity measurements, and searches for rare decays and physics beyond the SM.

2. High-Luminosity Higgs physics

A key goal of the HL-LHC is to gather a sufficient number of collisions so that very rare Higgs processes can be observed. Such rare processes are essential for verifying that Higgs couplings are proportional to fermion mass, as predicted by the SM, and di-Higgs boson production is especially important for direct tests of the Higgs tri-linear coupling. Any deviation from SM predictions observed in these channels will be an important clue to new physics.

A few illustrative examples of the number of events that will be produced in 3000 fb^{-1} of HL-LHC data with 14 TeV center-of-mass energy for particular production and/or decay modes are shown in Table 2, with production cross sections and decay branching fractions from Ref. [1]. Even very rare decays such as $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu$ will be measurable, as discussed in Section 5.2.

Some di-Higgs boson channels, will be detectable but challenging, while others such as $HH \to \gamma\gamma\gamma\gamma$ will be beyond the reach of even the HL-LHC.

Table 1: Number of Higgs events in different production/decay modes. All lines except the first refer to 3000 fb^{-1} 14 TeV HL-LHC data. Detector efficiency and acceptance are not included. Production cross sections and branching fractions are from Ref. [1]

SM Higgs Process	Number of events
All, LHC Run 1	660k
All, HL-LHC, 3000 fb^{-1}	170M
VBF Production (all decays)	13M
ttH Production (all decays)	1.8M
H $\to \gamma\gamma$	390k
H $\to$ Zγ	260k
H $\to \mu\mu$	37k
HH (all decays)	121k
HH $\to$ WWWW	5580
HH $\to$ bb$\gamma\gamma$	320
HH $\to \gamma\gamma\gamma\gamma$	0.6

3. High-Luminosity LHC Environment

In order to achieve an integrated luminosity of 3000 fb^{-1} at the HL-LHC, an instantaneous luminosity of $5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, is anticipated. Although final details of the required luminosity leveling techniques and beamspot shape have not yet been finalized, some basic estimates [2] indicate that an average of 130 proton-proton collisions per event (so-called "pileup") will occur over a region with length about 5 cm along the beam pipe. Upgrade studies assume that detector performance should remain excellent in events with at least 140 collisions; at the HL-LHC, it is estimated that 8% of events will have at least this amount of pileup.

4. Requirements and upgrades for CMS

The Phase I upgrade program for the CMS detector is already ongoing and will continue through LHC Run II and into the shutdown immediately afterward. It will include:

- major upgrades to the calorimeter readout and electronics to cope with high pileup [3];
- the replacement of the current pixel detector, which will sustain significant radiation damage, with a 4-layer version in order to improve tracking and b-tagging precision even at higher luminosity than planned for the original design [4];
- and upgrades of the L1 trigger system to allow greater flexibility and interplay between systems (e.g. for object isolation) to give faster decisions at very high rate [5].

The Phase I upgrade will allow the CMS detector to operate at high efficiency through the end of LHC Run III in the early 2020's.

In order to prepare for HL-LHC running, with its 140 collisions, additional upgrades will be required. The forward calorimeters will need to be replaced due to radiation damage and to improve performance at very high occupancy. The pixel detector will once again require replacement, and an extended design providing tracking to $|\eta|$[1] up to 4.0 is under consideration; this would allow significant improvements in b-tagging and pileup mitigation, particularly in the context of CMS's particle flow algorithm. A corresponding extension of the muon system is also under study. Studies of the Higgs boson, particularly in lepton acceptance (Section 6.1) and Vector Boson Fusion tagging, will be a major factor in these decisions.

5. Extrapolated measurements

Estimates of the precision for which Higgs boson properties can be measured at the LHC can be extrapolated from the results for existing channels. This method takes advantage of the existing framework for combining Higgs boson analyses; a complete list of the inputs used is given in Ref. [6]. In order to extrapolate to future 14 TeV data, the number of events in the signal and background regions for each existing analysis is scaled according to the change in cross section and greater recorded luminosity. The systematic uncertainties in each analysis are adjusted according to two possible scenarios: Scenario 1 pessimistically assumes all uncertainties will remain the same, whereas Scenario 2 optimistically assumes that theory uncertainties will be halved and experimental uncertainties based on control region measurements will scale by $1/\sqrt{\mathcal{L}}$.

Several assumptions of this procedure may impact the accuracy of extrapolations both positively and negatively. Analyses are not re-optimized for changes in collision energy, nor for the possibility of analysis regions with higher signal-to-background ratios that become accessible only with very high statistics. However, it is assumed that detector resolutions will be maintained after

[1] The pseudorapidity η is defined by $\eta = -\ln(\tan(\frac{\theta}{2})$, where θ is the polar angle from the LHC beam axis.

upgrades, even in a much higher-pileup environment, by improved detectors and advances in reconstruction techniques. Although past experience in collider detector development demonstrates that such optimistic assumptions are often achieved or even exceeded, such performance has yet to be fully demonstrated using detailed detector simulation and reconstruction.

5.1. Signal strengths and couplings

The signal strength for each Higgs boson decay mode, defined as σ/σ_{SM}, can be extracted from the combined fit. The uncertainties on this quantity given 300 (3000) fb^{-1} of data are shown in Figure 1 (2). Both Scenario 1 and Scenario 2, as described in the previous section, are shown. The signal strengths can be determined to a precision of roughly 10% (5%).

Given these results, deviations from SM couplings can then be extracted within a framework of modified Higgs boson couplings [7], in which cross sections and decay widths are scaled by a series of factors κ_i, with a separate factor given for each particle interacting with the Higgs. For example, κ_τ and κ_t area defined by the modification of the partial decay width of $H \rightarrow \tau\tau$ and the cross section for associating production with $t\bar{t}$ respectively:

$$\frac{\Gamma_{\tau-\tau+}}{\Gamma^{SM}_{\tau-\tau+}} = \kappa_\tau^2 \tag{1}$$

$$\frac{\sigma_{t\bar{t}}}{\sigma^{SM}_{t\bar{t}}} = \kappa_t^2 \tag{2}$$

The uncertainties for the κ_i determination with 300 (3000) fb^{-1} of data are shown in Figure 3 (4).

5.2. Rare decays

The extrapolation framework can also be applied to measurements of the rare decays $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$, and to setting limits on the Higgs branching ratio to invisible particles. κ_μ can be determined to within 23% (8%) for 300 (3000) fb^{-1} of data, as shown in Figure 7. $\kappa_{Z\gamma}$ can be determined to within 40% (10%), and a limit on the invisible branching ratio of 17% (6%) can be set, with an integrated luminosity of 300 (3000) fb^{-1}.

5.3. Spin-parity

Limits can further be set on f_{a3}, which parameterizes the fraction of the Higgs interaction that is CP-odd, predicted to be 0 in the SM. It is measured from a simultaneous fit to the Higgs mass and the kinematics of the 4-lepton system, as detailed in Ref. [8]. As shown in Figure 8, at 3000 fb^{-1} a 95% CL limit of 0.04 can be placed on this parameter.

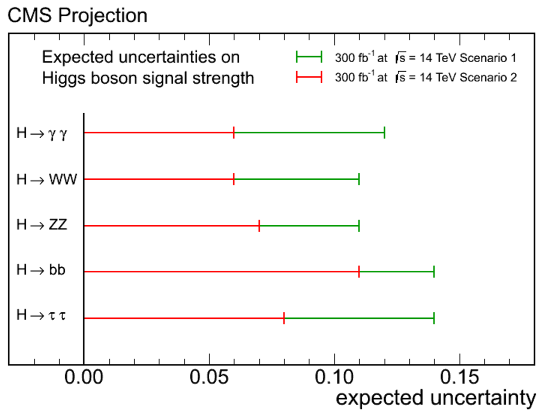

Figure 1: Predicted uncertainty on the measurement of signal strength for each decay channel for 300 fb^{-1} on 14 TeV LHC data.

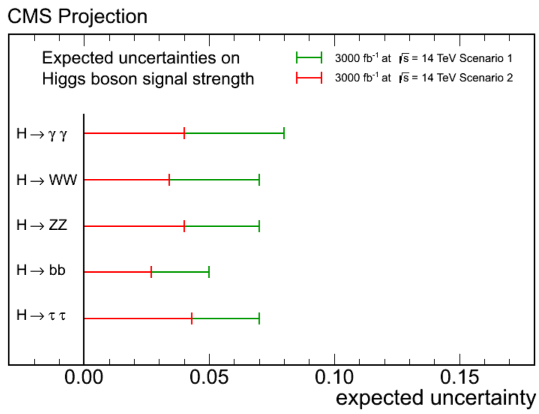

Figure 2: Predicted uncertainty on the measurement of signal strength for each decay channel for 3000 fb^{-1} on 14 TeV LHC data .

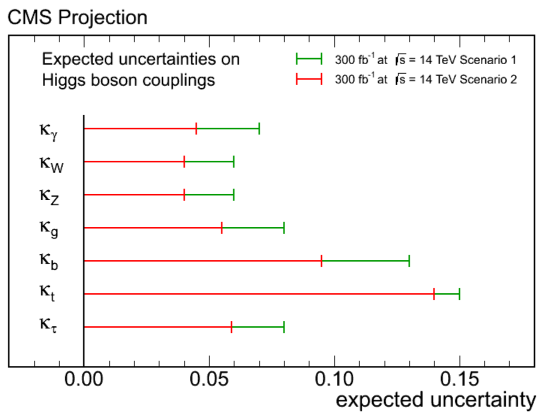

Figure 3: Predicted uncertainty on the measurement of the coupling modifiers κ_i, as defined in the text, for 300 fb^{-1} on 14 TeV LHC data.

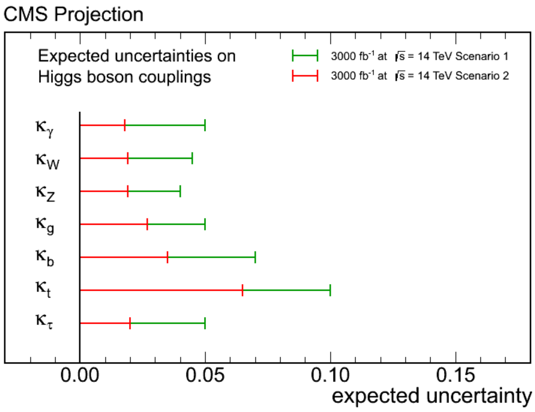

Figure 4: Predicted uncertainty on the measurement of the coupling modifiers κ_i, as defined in the text, for 3000 fb^{-1} on 14 TeV LHC data.

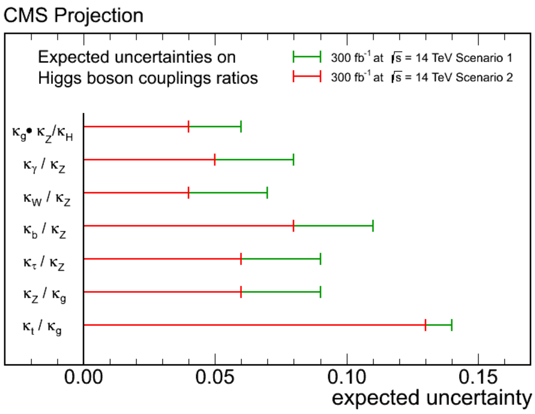

Figure 5: Predicted uncertainty on the measurement of ratios of the coupling modifiers κ_i, as defined in the text, for 300 fb^{-1} on 14 TeV LHC data.

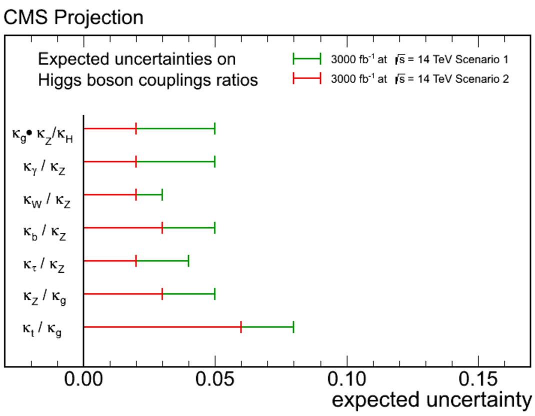

Figure 6: Predicted uncertainty on the measurement of ratios of the coupling modifiers κ_i, as defined in the text, for 3000 fb^{-1} on 14 TeV LHC data.

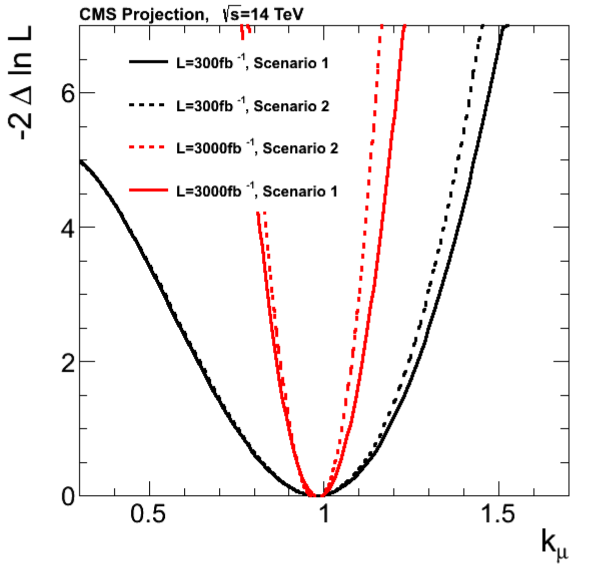

Figure 7: Extrapolated log likelihood fit to κ_μ as defined in the text, for scenarios 1 and 2 and for 300 and 3000 fb^{-1}.

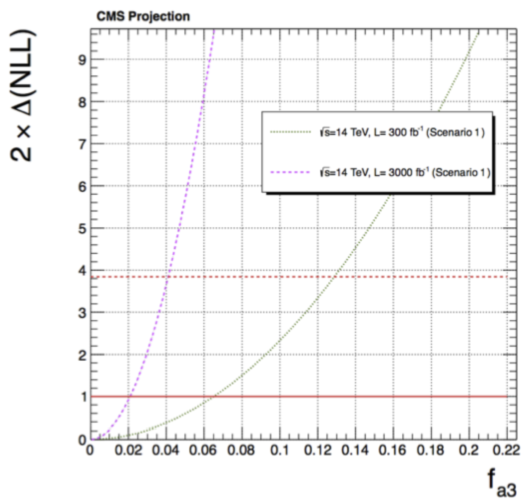

Figure 8: Extrapolated likelihood fit to f_{a3} as discussed in the text, for scenario 1 at 300 and 3000 fb^{-1}.

6. Parameterized simulation

Parameterized simulation is used for additional analyses, in order to produce large background samples that cannot be quickly simulated for practical reasons. Using the DELPHES 3 package [9], event generator-level objects are smeared according to the resolution and efficiency anticipated for the upgraded CMS detector. These smearings are applied to the stable particles produced by generating events in MadGraph 5.1 [10], with parton showering performed by Pythia 6.4 [11]. A simple model of a particle flow-based calorimeter is subsequently applied, which automatically accounts for the impact of pileup on jet resolution and object isolation; for objects other than jets, resolution and identification efficiency are derived from fully simulated samples with the appropriate level of pileup.

6.1. $H \to ZZ \to 4\mu$ with extended acceptance

The impact of the tracker extension to $|\eta|$ of 4.0 can be shown in studies of $H \to ZZ$ using parameterized simulation. In so-called Configuration 3, events with 140 pileup collisions are modeled with a tracker extending to $|\eta| < 2.5$; in Configuration 4, similar events are modeled with the tracker extension to $|\eta|$ ¡ 4.0. Events are required to have two opposite-sign dimuon pairs, with dimuon masses between 40 and 120 GeV for one and between 12 and 120 GeV in the other. At least one lepton must have $p_T > 20$ GeV, and another $p_T > 10$ GeV. In Figure 9, the four-lepton mass distribution for Higgs signal and background are shown for both configurations, illustrating the improvement in acceptance due to the tracker extension.

6.2. Two Higgs Doublet Models

To illustrate the potential performance of the upgraded CMS detector for beyond-the-SM Higgs physics, limits can be placed on Two Higgs Doublet Models (2HDM) by searching for a heavy neutral Higgs boson decaying to a pair of on-shell Z bosons. [12]. In Figure 10, the distribution of ZZ invariant masses in 3000 fb^{-1} is shown for inclusive SM backgrounds and for neutral Higgs bosons at three different masses in the context of the 2HDM. The discovery potential in the plane of 2HDM parameters $\tan(\beta)$ and $\cos(\beta - \alpha)$ is shown in Figure 11.

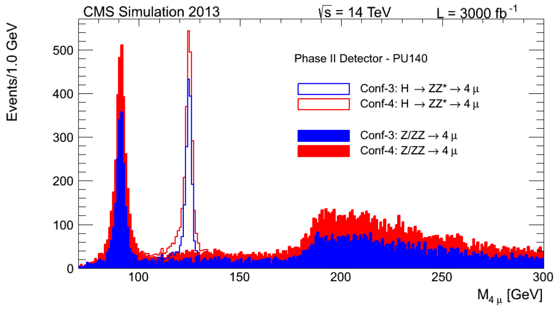

Figure 9: Mass distribution of 4μ events in a 3000 fb^{-1} sample.

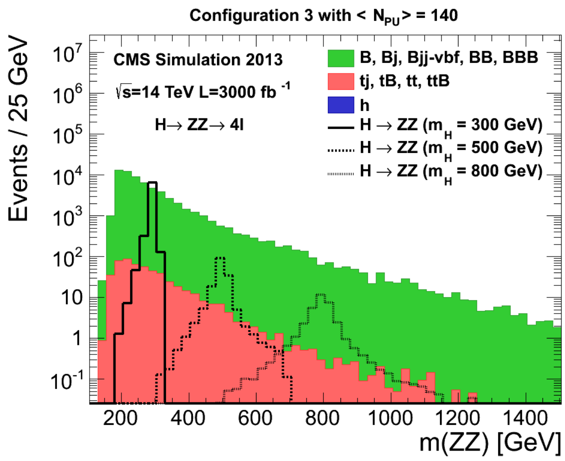

Figure 10: Distribution of ZZ invariant masses in 3000 fb^{-1} is shown for inclusive SM backgrounds and for neutral Higgs bosons at three different masses.

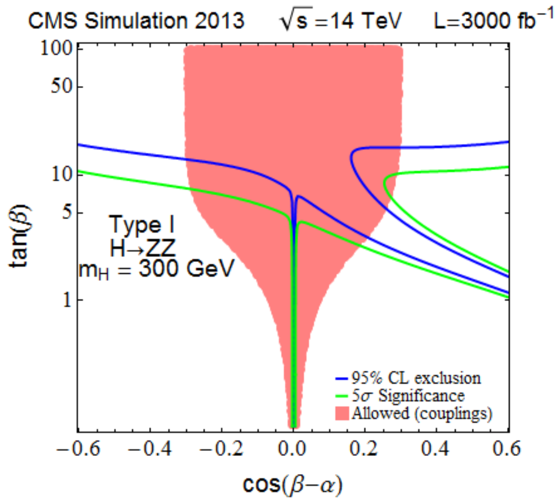

Figure 11: Limits and discovery potential in 2HDM parameter space, using 3000 fb^{-1} of data, as estimated from parameterized simulation.

7. Conclusions

Studies of the Higgs boson are a major driver in planning the details of CMS running upgrades for HL-LHC running. Using parameterized simulation and extrapolation from existing analyses, the potential of an upgraded CMS detector to measure Higgs boson properties, and to search for rare decays and physics beyond the SM, has been shown. Couplings can be measured to a precision of 2 – 5%, providing a very strong test of the SM. Neutral Higgs bosons can be discovered or excluded within a large range of 2HDM parameter space. Multiple options such as the tracker extension can be compared based on their performance for Higgs measurements. Further study of Higgs performance with an upgraded CMS detector is ongoing and will be part of the Phase II upgrade technical proposal, to be released in 2015.

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