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Future prospects of Higgs Physics at CMS

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ABSTRACT

The Higgs boson physics reach of the CMS detector with 300(0) fb^{-1} of proton-proton collisions at $\sqrt{s} = 14$ TeV is presented. Precision measurements of the Higgs boson properties, Higgs boson pair production and self-coupling, rare Higgs boson decays, and the potential for additional Higgs bosons are discussed.

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1 Introduction

The standard model (SM) predicts the existence of a Higgs boson responsible for the spontaneous electroweak symmetry breaking [1, 2]. In July 2012, the ATLAS and CMS [3] Collaborations announced the discovery of a new boson [4, 5] with a mass around 126 GeV. From that moment one of the highest priorities of the CMS Collaboration was to establish the nature of this new partible by studying its properties using the current dataset. In parallel, the physics goals of the future LHC running are clear [6], including the measurement of the Higgs boson properties to the highest precision, the Higgs self-coupling, and the search for additional Higgs bosons and exotic decays.

The LHC is currently in the first long shutdown in order prepare for running in 2015. A second long shutdown in 2018 will be used to upgrade de detectors for running at double the design luminosity and an average number of interactions per pp crossing (pile-up) of 50. The next phase of planned LHC operation, referred to as the High Luminosity LHC (HL-LHC), will begin with the third long shutdown in the period 2022-2023, where machine and detectors will be upgraded to allow for pp running at a luminosity of 5×10^{34} cm^{-2} s^{-1}, with the goal of accumulating 3000 fb^{-1}.

In order to deal with the increased luminosity that the LHC will deliver in the next runs, several modifications in the CMS detector are required. The improvements are referred to as to "Phase 1" and "Phase 2" upgrades.

The results presented in this document are extrapolated to 300 and 3000 fb^{-1} at $\sqrt{s} = 14$ TeV by scaling signal and background event yields. In the particular case of the precision measurements, the extrapolations were made assuming that future CMS upgrades will provide the same level of detector and trigger performances achieved with the current detector. Two different scenarios are presented. In Scenario 1, all systematic uncertainties are left unchanged. In Scenario 2, the theoretical uncertainties are scaled by a factor 1/2, while other systematic uncertainties are scaled by the squared root of the integrated luminosity.

2 SM Higgs precision measurements

The signal strength modifier $\mu = \sigma/\sigma_{SM}$, obtained in the combination of all search channels, provides a first compatibility test. Figure 1 shows the μ uncertainties obtained in different sub-combinations of search channels, organized by decay modes for an integrated dataset of 300 fb^{-1} and 3000 fb^{-1}. We predict a precision 614% for 300 fb^{-1} and 4-8% for a dataset of 3000 fb^{-1}. Studies show that future measurements of the signal strength will be limited by theoretical uncertainty of the signal cross section, which is included in the fit.

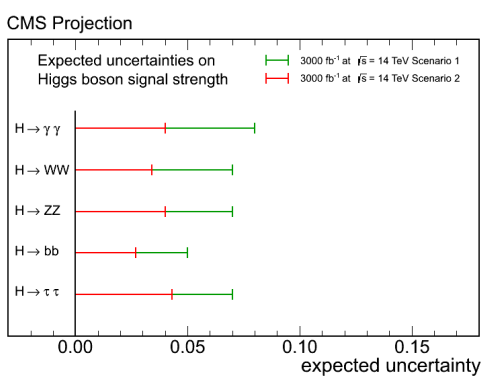

Figure 1: Estimated precision on the measurements of the signal strength for a SM-like Higgs boson. The projections assume $\sqrt{s} = 14$ TeV and an integrated dataset of 3000 fb^{-1}.

The event yield for any (production) $\times$ (decay) mode is related to the production cross section and the partial and total Higgs boson decay widths via the narrow-width approximation:

$$(\sigma \times BR)(x \to H \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{total}}, \tag{1}$$

where σ_x is the production cross section through the initial state x, Γ_{ff} is the partial decay width into the final state ff, and Γ_{tot} is the total width of the Higgs boson. The possibility of Higgs boson decays to BSM particles, with a partial width Γ_{BSM}, is accommodated by keeping Γ_{tot} as a dependent parameter so that $\Gamma_{tot} = \sum \Gamma_{ii} + \Gamma_{BSM}$, where the Γ_{ii} stand for the partial width of decay to all SM particles. The partial widths are proportional to the square of the effective Higgs boson couplings to the corresponding particles. To test for possible deviations in the data from the rates expected in the different channels for the SM Higgs boson, factors k_i corresponding to the coupling modifiers are introduced and fit to the data [7].

Figure 2 shows the uncertainties obtained on k_i for an integrated dataset of 3000 fb^{-1}. The expected precision ranges from 2-10%. The measurements will be limited by systematic uncertainties on the cross section, which is included in the fit for the signal strength. The statistical uncertainties on k_i are below one percent.

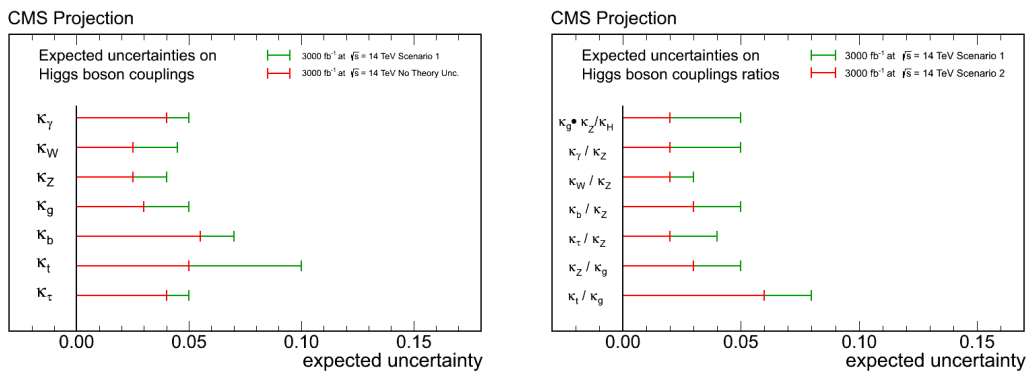

Figure 2: Estimated precision on the measurements of $k_\gamma, k_W, k_Z, k_g, k_b, k_t$, and k_τ (right) and its ratios (left). The projections assumes $\sqrt{s} = 14$ TeV and an integrated dataset of 3000 fb^{-1}.

Besides testing Higgs boson couplings, it is important to determine the spin and quantum numbers of the new particle as accurately as possible. The full case study has been presented by CMS with the example of separation of the SM Higgs boson model and the pseudoscalar (0^-) model. Studies on the prospects of measuring CP-mixing of the Higgs boson are presented using the $H \to ZZ^* \to 4l$ channel. The decay amplitude for a spin-zero boson defined as

$$A(H \to ZZ) = v^{-1}(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}, \tag{2}$$

where $f^{(i),\mu\nu}, (\tilde{f}^{(i),\mu\nu})$ is the (conjugate) field strength tensor of a Z boson with polarization vector ϵ_i and v the vacuum expectation value of the Higgs field. The spin-zero models 0^+ and 0^- correspond to the terms with a_1 and a_3, respectively.

Four independent real numbers describe the process in Eq. (2), provided that the overall rate is treated separately and one overall complex phase is not measurable. For a vector-boson coupling, the four independent parameters can be represented by two fractions of the corre- sponding cross-sections (f_{a2} and f_{a3}) and two phases (ϕ_{a2} and ϕ_{a3}). In particular, the fraction of CP-odd contribution is defined under the assumption $a_2 = 0$ as

$$f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_3|^2 \sigma_3}, \tag{3}$$

where σ_i is the effective cross section of the process corresponding to $a_i = 1$, $a_{j \neq i} = 0$. Given the measured value of f_{a3}, the coupling constants can be extracted in any parameterization.

Projections of the expected $-2ln\mathcal{L}$ values from the fits assuming 300 fb^{-1} and 3000 fb^{-1} are shown in figure 3.

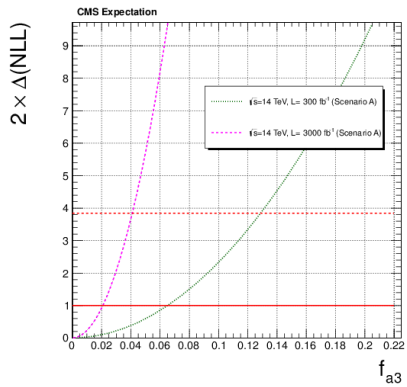

Figure 3: Distribution of expected $-2ln\mathcal{L}$ for f_{a3} for the projection to 300 fb^{-1} (green, dotted) and 3000 fb^{-1} (magenta, dot-dashed).

3 Higgs boson pair production and self-coupling

In the SM, the Higgs boson mass itself fixes the value of the self-coupling in the scalar potential whose form is determined by the global symmetries and the requirement of renormalisability. Direct information on the Higgs three- and four-point interactions could provide a indication of the scalar potential structure. To answer some of these questions the Higgs boson pair production will play a major role. First through the simplest production process, sensitive to the self-coupling λ, and second probing the existence of heavier states coupled to the SM Higgs boson. However, even in most optimistic scenario in terms of energy and integrated luminosity at the future HL-LHC, the measurement of the Higgs boson pair production remains extremely challenging. The SM cross section for HH production at 14 TeV is of the order of tens of femtobarns. Several new physics scenarios could enhance the HH production, opening the possibility for a BSM discovery before the SM HH measurement.

4 SM rare decays

We present two different cases of rare SM decays, $H \to \mu\mu$ and $H \to Z\gamma$.

The dimuon decay channel has the advantage of a clean signature in the CMS detector, but the disadvantage in the SM of a small branching ratio (BR), 2.2×10^{-4} , for a SM Higgs boson with $m_H = 125$GeV. The search is also motivated by the fact that the BR of the SM Higgs boson decay in the dimuon channel measures the second generation fermion Higgs-Yukawa coupling constant, the muon coupling, g_μ. Compared to the $H \to \gamma\gamma$ channel, the BR is ten times smaller, but certain non-SM Higgs models predict enhanced branching ratios.

Figure 4 shows the extrapolated CMS $H \to \mu\mu$ search performance for high luminosities at $\sqrt{s} =$ 14 TeV from the current analyses and $\sqrt{s} = 8$ TeV MC. No additional optimization for the higher energy or luminosity is performed, and effects of higher pile-up, detector upgrades, and detector aging are neglected. This is justified by assuming that future degradation in detector performance will be counteracted by future analysis optimization. Based on this extrapolation a 5σ expected significance will be reached with 1200 fb^{-1}.

The $H \to Z\gamma$ decay channel is important because its partial width is induced by loops of heavy charged particles, making it sensitive to physics beyond the standard model, just as the $H \to \gamma\gamma$ decay channel. Despite its small branching fraction, which in the SM varies between 0.111% and 0.246% in the mass range of $120 < m_H < 150$ GeV, the LHC experiments should be sensitive to this channel in the near future.

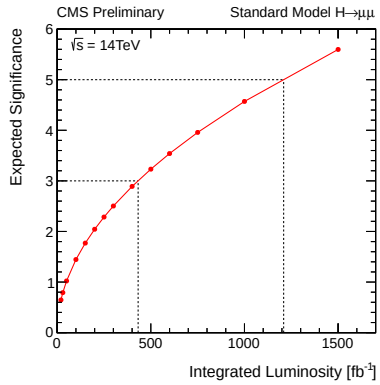

Figure 4: Expected significance versus luminosity for $\sqrt{s} = 14$ TeV

5 BSM rare decays

The Higgs field is theorized to interact with all the fundamental particles, making the particles massive (except the photon and gluon). One can postulate that there are additional particles beyond the standard model that thus far escape our detectors, to which the Higgs boson can couple. This will enhance the Higgs boson invisible branching fraction significantly, compared to $O(0.1\%)$ as predicted in the SM via $H \to ZZ^* \to 4\nu$ decay. At a mass of 125 GeV, the invisible branching fraction of the Higgs boson is especially sensitive to new particles at electroweak scale. Many extensions to the SM, such as supersymmetry, extra dimension models or dark matter singlet models, postulate the existence of such invisible particles.

6 Additional Higgs bosons

Two Higgs doublet models (2HDM) provide an effective theory description for many extensions of the electroweak symmetry breaking sector, allowing compact relations between couplings of the observed Higgs boson and the production rates and branching fractions (BR) of additional scalars. 2HDMs contain five physical Higgs bosons: two CP-even scalars h and H, a CP-odd pseudo-scalar A, and a charged pair $H^{\pm}$. While the general parameter space of 2HDMs is large, it may be constrained by a variety of well-motivated assumptions about CP conservation and the absence of new tree-level sources of flavor violation. Subject to these constraints, 2HDMs may be parametrized in terms of nine variables: the physical masses m_h, m_H, m_A, and $m_{H^{\pm}}$; the CP-even mixing angle α; the ratio of Higgs vacuum expectation values $\tan(\beta)$; and three scalar couplings λ_5, λ_6, and λ_7. The number of variables may be further reduced by assuming the tree-level MSSM values of the three scalar couplings, $\lambda_{5,6,7}$. The absence of tree-level flavor violation is guaranteed by four discrete choices of couplings between SM fermions and the Higgs doublets; this leads to four types of 2HDMs corresponding to the possible discrete coupling assignments. Of these, type I and II 2HDMs are the most familiar; the former can give rise to a fermiophobic Higgs boson, while the latter includes minimal supersymmetric extensions of the SM Higgs sector.

Here we extend a recent analysis completed in the context of the Snowmass process, focusing on the resonant production and decay of the heavy CP-even scalar H boson and the pseudo-scalar A boson, which possess large gluon fusion production cross sections at the LHC as well as decays to distinctive final states such as $H \to ZZ$ and $A \to Zh$. For these projections (figure 5) , we assume a total integrated luminosity of 3000 fb^{-1}, collected at a center of mass energy $\sqrt{s}$ TeV with an average of 140 pile-up interactions per bunch crossing. The expected performance of the so-called "configuration 3" Compact Muon Solenoid (CMS) PhaseII detector upgrade proposal is used throughout. In configuration 3, the main upgrades consist of a new central silicon tracker, new forward electromagnetic and hadronic calorimeters and a completed muon system, with a detection acceptance similar to that of the present CMS detector.

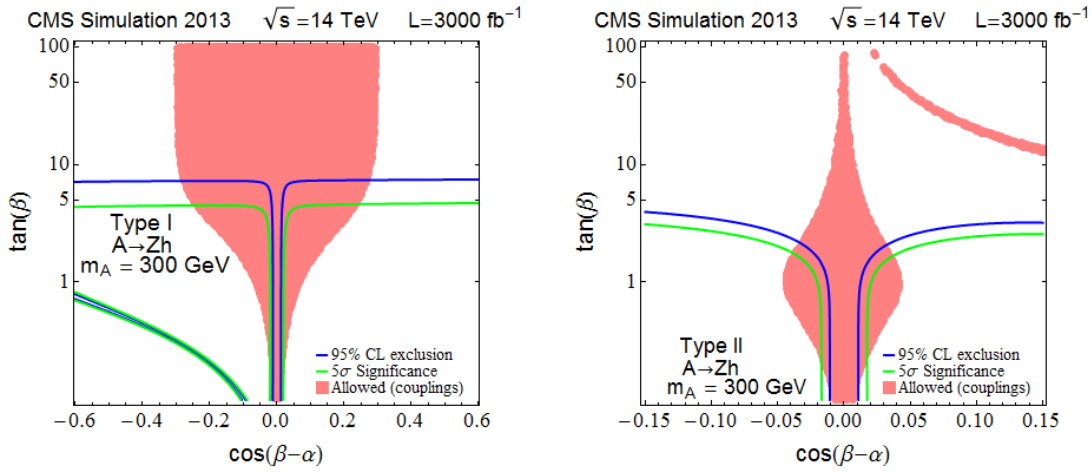

Figure 5: The region of parameter space for which a 300 GeV A boson could be excluded at 95% CL (blue), and the region of parameter space which could yield a 5σ observation of a heavy pseudo-scalar A boson (green) in the Zh channel, in the context of Type I (left) and II (right) 2HDMs. The colored regions correspond to the expected 95% CL allowed region from Higgs boson precision measurements with 3000 fb^{-1}

7 Conclusions

We present results extrapolated to 300 and 3000 fb^{-1} at $\sqrt{s} = 14$ TeV. Precision measurements of the Higgs boson properties, Higgs boson pair production and self-coupling, rare Higgs boson decays, and the potential for additional Higgs bosons are discussed in the context of "Phase 1" and "Phase 2" CMS upgrades, aimed for the next LHC runs.

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