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Prospects for di-Higgs measurements in the $b\bar{b}\gamma\gamma$ final state at the High-Luminosity LHC with the phase-II CMS detector

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Summary. — The prospects for the study of the production of a pair of Higgs bosons (HH), where one decays into two photons and the other one into a bottom quark-antiquark pair, are presented for a center-of-mass energy of 14 TeV at the High-Luminosity LHC. The analysis is developed using a parametric simulation of the Phase-II upgraded CMS detector and optimized for an integrated luminosity of 3000 fb^{-1}. The projected statistical sensitivity of this decay channel for the standard model HH signal is about 1.8σ, the highest among the decay channels considered for HH searches. Projections are also presented for the measurement of the Higgs boson self-coupling λ_3.

1. – Motivations for the HH search at HL-LHC

The production of Higgs boson pairs is one of the key measurements for the physics program of the HL-LHC, since it allows a direct measurement of the Higgs boson self-coupling λ_3 and is sensitive to the existence of new phenomena beyond the standard model [1]. Being the standard model (SM) HH production cross section only about 40 fb, an observation of this phenomenon will be possible only exploiting the huge amount of data collected at HL-LHC. During this phase, the upgraded LHC machine will provide a peak luminosity of 5–7.5 $\times$ 10^{34} cm^{-2} s^{-1}, which is 3–4 times larger than the current achievable value. This will provide 3000 fb^{-1} of integrated luminosity in 10 years of operation, starting from 2026. The components of the CMS detector [2] will be properly upgraded or replaced [3] to handle the expected increase of the number of simultaneous interactions per bunch crossing (pileup), and the radiation damage. This paper will focus on the analysis of HH $\rightarrow b\bar{b}\gamma\gamma$ channel. The result is combined with the other main sensitive channel [4] and included in the report of Higgs physics prospects at HL-LHC and HE-LHC [5].

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2. – Analysis strategy

The analysis was performed using Monte Carlo event generators interfaced with the Delphes [6] software to model the upgraded CMS detector response, and optimized for $3000\,\mathrm{fb}^{-1}$ of integrated luminosity. Whereas the $\mathrm{HH} \rightarrow b\bar{b}\gamma\gamma$ decay channel has a branching ratio of only 0.26%, the sensitivity to HH signal is large thanks to the clean signature of two photons with an invariant mass $m_{\gamma\gamma}$ consistent with the Higgs boson mass, and two heavy-flavour jets.

The $\mathrm{H} \rightarrow \gamma\gamma$ candidate is built using the two photons with the highest transverse momentum p_T, satisfying isolation and identification criteria. The pseudorapidity η of the selected photons is required to be smaller than 2.5, and $m_{\gamma\gamma}$ is required to be between 100 GeV and 180 GeV. The $\mathrm{H} \rightarrow b\bar{b}$ candidate is built using the reconstructed jets with the highest output score of the algorithm for heavy-flavour jet identification [7] (b tag). The selected jets are required to have the transverse momentum $p_T > 25\,\mathrm{GeV}$, $|\eta| < 2.5$, the di-jet invariant mass $90\,\mathrm{GeV} < m_{jj} < 200\,\mathrm{GeV}$, and to satisfy at least the loose b tag working point, corresponding to an efficiency of 90% on a genuine b jet, and a misidentification rate for light-flavour jets of about 10%. After the selections, the background can be classified in continuum background and single Higgs boson background. The main contribution to the continuum background comes from the associated production of jets with a pair of photons ($\gamma\gamma$ + jets), or with a single photon (γ + jets) with one jet misidentified as a photon. The main contribution to the single Higgs boson background comes from the associated production of a Higgs boson with a $t\bar{t}$ pair ($t\bar{t}$H), with the Higgs boson decaying to a pair of photons.

A multivariate analysis classifier based on a boosted decision tree (BDT) algorithm was developed to identify and reject the $t\bar{t}$H events. The selection on the BDT score allows the rejection of about 75% of the $t\bar{t}$H events with an efficiency of about 90% on the HH signal. Another BDT classifier was developed to separate the signal from the $\gamma\gamma$ + jets and γ+jets events. The BDT score and the variable $M_X = m_{\gamma\gamma jj} - m_{\gamma\gamma} - m_{jj} + 250\,\mathrm{GeV}$, are used to classify the events in six exclusive categories. The signal is extracted from a parametric maximum likelihood fit of the distributions of $m_{\gamma\gamma}$ and m_{jj} in each category.

3. – Results

Considering only the $\mathrm{HH} \rightarrow b\bar{b}\gamma\gamma$ channel, and assuming a HH signal with the properties described by the SM, the expected significance is 1.8 standard deviations, while, assuming no HH signal, the expected upper limit to the cross section σ is 1.1 σ/σ_{SM}. Combining the $\mathrm{HH} \rightarrow b\bar{b}\gamma\gamma$ channel with the other exclusive HH decay channels considered for the projections, the expected significance raises to 2.6 standard deviations while the expected upper limit on the cross section is 0.8 σ/σ_{SM}. Projections are performed also for the measurements of the λ_3 parameter, *i.e.*, assuming the SM signal hypothesis, the expected confidence interval is $-0.5 < \lambda_3/\lambda_3^{SM} < 6$ at 95% confidence level, considering only the $\mathrm{HH} \rightarrow b\bar{b}\gamma\gamma$ channel, while the interval reduces to $-0.18 < \lambda_3/\lambda_3^{SM} < 3.6$ at 95% confidence level combining all the decay channels.

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