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Fiducial cross sections for Higgs boson production in association with a jet at next-to-next-to-leading order in QCD

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Abstract

We extend the recent computation of Higgs boson production in association with a jet through next-to-next-to-leading order in perturbative QCD by including decays of the Higgs boson to electroweak vector bosons. This allows us to compute fiducial cross sections and kinematic distributions including realistic selection criteria for the Higgs boson decay products. As an illustration, we present results for $pp \to H + j \to \gamma\gamma + j$ closely following the ATLAS 8 TeV analysis and for $pp \to H + j \to W^+W^- + j \to e^+\mu^-\nu\bar{\nu} + j$ in a CMS-like 13 TeV setup.

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I. INTRODUCTION

Studies of the Higgs boson discovered by the ATLAS and CMS collaborations [**? ?**] will be at the focus of the experimental program during Run II of the LHC. The interpretation of future measurements of Higgs boson production and decay rates in terms of Higgs boson couplings to matter and gauge fields and Higgs boson quantum numbers will rely on the comparison of measured event rates and kinematic distributions with results of theoretical modelling of such processes in the Standard Model. It is hoped that such comparisons will help to elucidate the nature of the Higgs particle and explore the mechanism of electroweak symmetry breaking in detail [**? ?**].

Recently, the ATLAS collaboration made an important step forward in presenting the results of analysis of the Higgs boson production and decay at the LHC. Indeed, in contrast to many other Run I LHC measurements, the ATLAS collaboration measured fiducial volume cross sections and a variety of kinematic distributions in the process $pp \to H + \text{jets}$ [**?**]. The Higgs boson was identified through its decay to photons, $H \to \gamma\gamma$.

Fiducial volume measurements allow for a direct comparison between data and theoretical predictions minimizing extrapolation uncertainties. Although many of the ATLAS fiducial volume measurements are currently limited by statistical uncertainties, this will certainly change in the current run of the LHC. Therefore, the important issue for the near future is the availability of highly accurate theoretical predictions that can be used to describe complicated fiducial volume measurements.

We will now summarize the most advanced fixed order computations related to Higgs boson production and decay at the LHC. The inclusive production cross section of the Higgs boson has recently been computed through next-to-next-to-next-to leading order in perturbative QCD [**?**]. This computation refers to the total cross sections and can not be used for the direct comparison with fiducial volume measurements without extrapolation. The computation of $H + j$ production at the LHC has recently been extended to next-to-next-to leading order (NNLO) in perturbative QCD, in a fully differential manner [**? ?**][1]. Unfortunately, in Refs. [**? ?**] decays of the Higgs boson were not considered; for this reason the comparison of the results of Refs. [**? ?**] with the results of the fiducial measurements is

[1] For earlier partial results, see [**? ?**].

also not possible. When the Higgs boson is produced in association with two and three jets, the NLO QCD computations provide the state-of-the-art results [? ? ?]. In those NLO QCD computations decays of the Higgs bosons are routinely taken into account. We note that the NNLO QCD computations of $pp \to H + j$ [? ?] combine the NNLO prediction for the *exclusive* $H + j$ cross section with the NLO QCD prediction for the exclusive $H + 2j$ cross section and the LO prediction for the $H + 3j$ cross section, making them particularly suitable for studying Higgs boson production in association with different number of jets in a consistent way.

It is relatively straightforward to extend the fully-differential $pp \to H + j$ computation reported in Ref. [?] to include decays of the Higgs boson into electroweak gauge bosons since the Higgs boson is a spin-zero particle and no spin correlations need to be considered. This is what we do in this paper for a variety of the Higgs boson decay modes. Once this is done, it becomes possible to calculate fiducial volume cross sections and kinematic distributions and directly compare with experimental measurements. The very fact that it is possible to do that through next-to-next-to-leading order in the expansion in the strong coupling constant, represents an impressive milestone in an application of perturbative QCD to the description of hard collisions at the LHC.

Our paper is organized as follows. In Section ??, we briefly summarize the theoretical and experimental setup. In Section ??, we present the results for fiducial volume cross sections and kinematic distributions at the 8 TeV LHC for the $H \to \gamma\gamma$ decay mode and at the 13 TeV LHC for the $H \to WW^* \to e^+\mu^-\nu\bar{\nu}$ decay mode. We also compare the results of the fiducial volume computation for the $\gamma\gamma$ final state with the results of the ATLAS measurement. We conclude in Section ??.

II. THE SETUP

A. Theory

We begin by summarizing the theoretical framework that we use in the computation. We work in an effective field theory obtained by integrating out the top quark. We employ the method of improved sector decomposition developed in Refs. [? ? ?]. This method is based on the factorization of scattering amplitudes in soft and collinear limits and on particular way of splitting the phase-space into sectors, where soft and collinear singularities are easily identified. For this calculation, we require a large number of matrix elements that are used to construct differential cross sections. In particular, we need the two-loop virtual corrections to the partonic channels $gg \to Hg$ and $qg \to Hq$; the one-loop virtual corrections to $gg \to Hgg$, $gg \to Hq\bar{q}$, $qg \to Hqg$, $q\bar{q} \to HQ\bar{Q}$ and the double real emission processes $gg \to Hggg$, $gg \to Hgq\bar{q}$, $qg \to Hqgg$ and $qg \to HqQ\bar{Q}$, where the $Q\bar{Q}$ pair can be of any flavor. The helicity amplitudes for all of these processes are available in the literature. The two-loop amplitudes were computed in Ref. [?]. The one-loop corrections to the four-parton processes are known [?]. For five-parton tree-level amplitudes, we use compact results obtained using BCFW recursions [?].

It is non-trivial to combine processes with different particle multiplicities as required for any NNLO QCD computation. Our method for doing that is described in [?]; we do not repeat that discussion here. As already mentioned in the Introduction, the inclusion of Higgs boson decays is straightforward since the Higgs boson is a spin-zero particle. The only technical issue that arises is a significantly larger phase space that needs to be considered and the ensuing difficulties with the Monte-Carlo integration. However, the numerical challenges that appear in fiducial volume computations turn out to be not prohibitive. In particular, we find that for the $H \to \gamma\gamma$ decay mode we need roughly the same amount of statistics as for the stable Higgs case, while for $H \to 4l$ the amount of statistics should be increased by a factor between 2 and 4.

B. $H \to \gamma\gamma$

We continue by listing the selection criteria employed by the ATLAS collaboration [?]. We are interested in the process $pp \to H + j$, where the Higgs boson decays to two photons. Final state jets are defined using the anti-$k_\perp$ algorithm [?] with $\Delta R = 0.4$ and $p_{\perp,j} > 30$ GeV. Jets are required to have rapidities y_j in an interval $-4.4 < y_j < 4.4$. The two photons from the Higgs decay must have the transverse momenta $p_{\perp,\gamma_1} > \max(25\ \text{GeV}, 0.35\ m_{\gamma\gamma})$ and $p_{\perp,\gamma_2} > \max(25\ \text{GeV}, 0.25\ m_{\gamma\gamma})$, respectively, where $m_{\gamma\gamma}$ is the invariant mass of the two photons. In our calculation, the Higgs boson decays are described in the narrow width approximation, so that we always have $m_{\gamma\gamma} = m_H = 125$ GeV. Then, the above conditions imply $p_{\perp,\gamma_1} > 43.75$ GeV and $p_{\perp,\gamma_2} > 31.25$ GeV. ATLAS requires that the two photons are in the central region of the detector $|y_\gamma| < 2.37$, but no photons are allowed to be in the rapidity interval $1.37 < |y_\gamma| < 1.56$. However, when presenting the results of the measurements [?], the ATLAS collaboration corrects for the second condition and, for this reason, we do not account for it in our calculation.[2] It is required that photons and jets are well-separated $\Delta R_{\gamma j} > 0.4$. Finally, we take the branching ratio for the Higgs boson decay to two photons to be $\mathrm{Br}(H \to \gamma\gamma) = 2.35 \times 10^{-3}$.

C. $H \to W^+W^- \to e^+\mu^-\nu\bar{\nu}$

As the second example, we consider $H + j$ production at the 13 TeV LHC. The Higgs boson decays to $e^+\mu^-\nu\bar{\nu}$ final state through a pair of W bosons. To identify selection criteria, we apply kinematic cuts similar to those employed by the CMS collaboration in their studies of the $H \to W^+W^-$ production at the 8 TeV LHC [?]. We define jets using the anti-$k_\perp$ algorithm with $\Delta R = 0.4$. Jets are required to have transverse momentum $p_{\perp,j} > 30$ GeV and be in the rapidity interval $-4.7 < y_j < 4.7$. The harder of the two charged leptons must have transverse momentum $p_{\perp,l} > 20$ GeV; the softer one must have $p_{\perp,l} > 10$ GeV. The transverse missing energy in the event should exceed $E_{\perp,\mathrm{miss}} > 20$ GeV. Other cuts that we employ are i) the cut on the dilepton invariant mass $m_{ll} > 12$ GeV; ii) the cut on the transverse momentum of the dilepton pair $p_{\perp,ll} > 30$ GeV and iii) the cut on the transverse mass of the two W bosons $m_\perp = \sqrt{2p_{\perp,ll}E_{\perp,\mathrm{miss}}(1 - \cos\Delta\phi_{ll,\mathrm{miss}})} > 30$ GeV.

III. THE RESULTS

A. $H \to \gamma\gamma$

We consider production of the Higgs boson in association with a jet at the 8 TeV LHC and compute the fiducial volume cross section and the kinematic distributions using the ATLAS selection criteria described in Section ??. We begin with the fiducial volume cross section. For events that contain the Higgs boson and at least one jet, the ATLAS collaboration

[2] We note that it is unclear to us why correcting for the missing rapidity region is a worthwhile thing to do since such theoretical correction defies the original goal of comparing theoretical fiducial volume cross sections with the results of experimental *measurements*.