Higgs mass saturation effect and the LHC discovery potential

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Abstract

In view of recent perturbative and nonperturbative evidence that the peak of the Higgs resonance saturates as the coupling increases, we examine the potential of the future Large Hadron Collider to discover a heavy Higgs resonance by gluon fusion.

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Abstract

In view of recent perturbative and nonperturbative evidence that the peak of the Higgs resonance saturates as the coupling increases, we examine the potential of the future Large Hadron Collider to discover a heavy Higgs resonance by gluon fusion.

No doubt, the main goal of the Large Hadron Collider is a better understanding of the electroweak spontaneous symmetry breaking mechanism. At present, the constraints on the mass of a standard Higgs boson obtained from radiative corrections are quite loose, and depend strongly on which data are taken into account \cite{1}. Even values of the order of 1 TeV cannot be excluded with certainty. For this reason one should keep an eye open to the possibility of a heavy Higgs particle. On the other hand, the LHC ought to be able to observe a standard Higgs resonance in the mass range under $\sim 1$ TeV \cite{2}.

The physics of light Higgs particles is well understood, and a lot of work was done on radiative corrections. For a mass approaching the 1 TeV scale, the situation is more complicated because the Higgs field becomes strongly coupled and the radiative corrections blow up.

Recent nonperturbative results \cite{3} which involve a higher order $1/N$ expansion of the $O(N)$–symmetric sigma model indicate an interesting behaviour of the Higgs

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sector at strong coupling. As the coupling increases, a saturation effect takes place. The mass of the Higgs resonance does not increase beyond a saturation value under 1 TeV, and only its width increases.

We illustrate the saturation effect in fig. 1. One can see that the saturation effect is suggested already by the two-loop perturbative result, and is confirmed by the $1/N$ expansion. In this figure we plot an effective mass and width of the standard Higgs particle, $M_{\text{PEAK}}$ and $\Gamma_{\text{PEAK}}$. These parameters are defined based on the fermion scattering process $f \bar{f} \rightarrow H \rightarrow f' \bar{f}'$. $M_{\text{PEAK}}$ and $\Gamma_{\text{PEAK}}$ are extracted from the line shape of the Higgs resonance in this scattering process as if the resonance was of Breit–Wigner type [3].

The perturbative results shown in fig. 1 are accurate in the low coupling limit, and become progressively unreliable numerically as the coupling increases. On the contrary, the convergence of the $1/N$ series is independent of the value of the coupling; it only depends on the value of $N$, which is four in the case of the standard model. The striking feature of fig. 1 is that both expansions appear to converge towards a common result. In fact, the agreement between the next-to-leading order $1/N$ result and two-loop perturbation theory is remarkable. This convinces us that one has reached a good numerical understanding of the behaviour of the Higgs sector rather deep in the saturation zone, up to about $m_H \sim 1.1$ TeV.

Of course, the mass and the width defined from the line shape of the resonance are process dependent. This is in contrast to the position of the pole in the complex plane [4], which is universal. Nevertheless, fig. 1 is conclusive for the occurrence of the mass saturation effect, and for the degree of accuracy provided by perturbation theory and the $1/N$ expansion in different orders which are available.

It is clear from fig. 1 that the properties of the Higgs particle differ considerably from the perturbative leading order and one-loop results. The low order results can be substantially misleading in the range above 700—800 GeV.

In view of the mass saturation effect, it is the purpose of this letter to reevaluate the gluon fusion process, which is the main Higgs production mechanism at LHC, and to estimate the LHC potential to discover a strongly interacting Higgs resonance. On the one hand, the mass saturation effect shifts the resonance towards lower energy, which tends to increase the production rate. On the other hand, also the width is increased, which decreases the production rate.

The Higgs boson production by gluon fusion is dominated by the top quark loop contribution. This process was studied in detail at leading order [2, 3]. The full $Z$ pair production process $pp \rightarrow ZZ$ is available, including the coherent $gg \rightarrow ZZ$ and incoherent $q\bar{q} \rightarrow ZZ$ backgrounds to Higgs production. The incoherent background is meanwhile known to order $\mathcal{O}(\alpha_s)$ [3]. The perturbative corrections of enhanced electroweak strength up to NNLO were calculated in ref. [7]. The next-to-leading order nonperturbative $1/N$ result for the resonant diagram $gg \rightarrow H \rightarrow ZZ$ is in principle already contained in the results of refs. [3]. Nevertheless, one notes that this

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1 Notice that the next-to-leading order $1/N$ correction to the $H \rightarrow zz$ decay width is given by the
Figure 1: The saturation effect. The parameters $M_{\text{PEAK}}$ and $\Gamma_{\text{PEAK}}$ are extracted from the position and the height of the Higgs resonance in fermion scattering as if the resonance was of Breit–Wigner type. We give the relation between $M_{\text{PEAK}}$ and $\Gamma_{\text{PEAK}}$ in perturbation theory (LO, NLO and NNLO) and in the nonperturbative $1/N$ expansion (LO and NLO). For the perturbation theory curves we give the corresponding values of the on–shell mass parameter $m_H$. 
is not sufficient for calculating the process $gg \to ZZ$ nonperturbatively in the Higgs coupling because also the phase factor of the decay amplitude $H \to ZZ$ is needed. This is because of interference effects with the nonresonant box diagrams. To perform this calculation one needs therefore the next–to–leading order $1/N$ correction to the $Hzz$ vertex, which is not available yet. Therefore, for the purposes of this letter, we rely on the NNLO perturbative result in the on–shell renormalization scheme. We expect this to be a sensible approximation up to a coupling corresponding to $m_H \sim 1.1$ TeV due to the good agreement with the NLO $1/N$ width (fig. 1).

In the following we consider the gluon fusion process $gg \to H \to ZZ$, with the subsequent $Z$ pair decay into purely leptonic channels, which provide a clean signal. We will not deal with jet channels in this paper; they have a larger branching ratio and thus have the potential of probing heavier Higgs resonances, but the analysis is complicated by the presence of a heavy QCD background and is strongly dependent on the detector’s energy and position resolution. Therefore we will consider for the decay of the $Z$ pair only the channels $(l^+l^-)(l^+l^-)$ and $(l^+l^-)(\nu\bar{\nu})$, where $l$ can be either the electron or the muon. We note that compared to the four muon channel, $(l^+l^-)(l^+l^-)$ has a branching ratio 4 times larger, and $(l^+l^-)(\nu\bar{\nu})$ 24 times larger.

In the $(l^+l^-)(l^+l^-)$ channel the Higgs mass can be reconstructed completely, and the Higgs boson is observed as a peak in the invariant mass of the $Z$ pair. In the $(l^+l^-)(\nu\bar{\nu})$ channel the Higgs particle is observed as a Jacobian peak in the missing transverse momentum distribution. Details of the leading order gluon fusion calculation can be found in ref. [5]. The NNLO radiative corrections of enhanced electroweak strength can be derived from existing two–loop calculations [8] by using the procedure explained in ref. [7]. We work in the on–shell renormalization scheme to facilitate comparison with existing calculations. The radiative corrections were incorporated into a Monte Carlo program which calculates the complete $ZZ$ production in $pp$ collisions with the subsequent $Z$ decay taken into account in the narrow width approximation.

We plot in fig. 2 the distributions for the invariant mass $m_{ZZ}$ of the $Z$ pair and for the transverse momentum $p_t$ of the $Z$ bosons which can be constructed from the purely leptonic channels. We considered the CM energy of the LHC $\sqrt{s} = 14$ TeV. We used the parton distribution functions of Martin, Roberts and Stirling [9]. For a crude simulation of the detector acceptance, we impose a rapidity cut on the final state charged leptons $\eta < 2.5$, and also require a minimum transverse momentum for the charged leptons of 20 GeV.

Figure 2 shows the effect of the mass saturation on the gluon fusion process. As the coupling is increased, the position of the peak of the distributions barely changes, but the resonance becomes wider.

As the Higgs coupling is increased, the signal becomes weaker, and the resonance imaginary part of the next–to–leading order Higgs self–energy. This is in contrast to perturbation theory, where the imaginary part of the self–energy needs to be calculated one loop higher than the vertex correction.
Figure 2: Distributions of the invariant mass of the $Z$ pairs (above) and of the transverse momentum of the $Z$ bosons (below). We show both the full cross section and the Higgs signal after the subtraction of the background. The background is defined by the absence of the resonant Higgs production diagram. For the $m_{ZZ}$ distribution we use the branching ratio of the $(l^+l^-)(l^+l^-)$ channels, and for the $p_T$ distribution we use the $(l^+l^-)(\nu\bar{\nu})$ channel. The LHC CM energy is 14 TeV, and $m_t = 180$ GeV.
becomes more difficult to observe. To fully exploit the discovery potential of the machine, it is of advantage to isolate the whole resonance region by cuts and to compare the event rate with the expected background. In the following we will assume an integrated luminosity of 100 $fb^{-1}$. We impose suitable cuts separately on the invariant mass of the $Z$ pair and on the transverse momentum of the $Z$ bosons, and give the background and the signal for different values of the on–shell mass parameter $m_H$ in table 1. For comparison, we give also the event rates corresponding to the measurement of the Jacobian peak of the transverse momentum of the $Z$ bosons as it can be observed in the $(l^+l^-)(l^+l^-)$ events, but note that this is not competitive with the invariant mass analysis of this decay channel.

For the $(l^+l^-)(l^+l^-)$ channel it has been proposed $[5]$ to use an additional cut:

$$p_t > m_{ZZ}/4 \sqrt{1 - 4m_Z^2/m_{ZZ}^2}$$

in order to improve the signal to background ratio of the $m_{ZZ}$ distribution. This idea is based on the observation that the Higgs boson decays isotropically in the center of mass frame, while the background $Z$ pairs are radiated mainly at low transverse momentum. We give in table 1, in brackets, the results obtained by using this cut. It can be seen that this cut improves to some extent the signal to background ratio.

Keeping in mind that we have taken into account the properties of the detector only by a rapidity cut as explained above, the discovery potential of the LHC is summarized in fig. 3. It can be seen that by observation of the neutrinoless leptonic channels, and for a five sigma effect, one can reach the zone up to about $m_H \sim 830$ GeV, where the saturation effect only starts to play a role. As expected, the discovery

| $m_H$ [GeV] | 700 | 800 | 900 | 1000 | 1100 | 1200 | background |
|------------|-----|-----|-----|------|------|------|------------|
| 4l: $m_{ZZ}$ distrib. | 103 | 83  | 70  | 62   | 57   | 54   | 47         |
| (additional $p_t$ cut) | (87) | (68) | (56) | (49) | (44) | (41) | (34)       |
| 4l: $p_t$ distrib. | 81  | 64  | 53  | 46   | 41   | 38   | 32         |
| 2l/2$\nu$: $p_t$ distrib. | 546 | 443 | 373 | 328  | 298  | 279  | 240        |

Table 1: The number of events to be expected from a 100 $fb^{-1}$ sample by imposing a cut $582 \text{ GeV} < m_{ZZ} < 1372 \text{ GeV}$ on the $m_{ZZ}$ distribution of $(l^+l^-)(l^+l^-)$ events; $240 \text{ GeV} < p_t < 590 \text{ GeV}$ on the $p_t$ distribution of $(l^+l^-)(l^+l^-)$; and $240 \text{ GeV} < p_t < 590 \text{ GeV}$ on the $p_t$ distribution of $(l^+l^-)(\nu\bar{\nu})$ events. In brackets we give the event rates corresponding to $(l^+l^-)(l^+l^-)$ events when the cut $p_t > m_{ZZ}/4 \sqrt{1 - 4m_Z^2/m_{ZZ}^2}$ is imposed in addition to $582 \text{ GeV} < m_{ZZ} < 1372 \text{ GeV}$. For the outgoing charged leptons we request $\eta < 2.5$, and a transverse momentum larger than 20 GeV. The LHC CM energy is 14 TeV, and $m_t = 180 \text{ GeV}$. 


Figure 3: Discovery limits of a heavy Higgs resonance at LHC. We give the limits which can be obtained from the invariant mass of the $Z$ pairs ($(l^+l^-)(l^+l^-)$ channel), and from the transverse momentum of the $Z$ ($(l^+l^-)(\nu\bar{\nu})$ channel). We use the cuts $582 \text{ GeV} < m_{ZZ} < 1372 \text{ GeV}$ and $240 \text{ GeV} < p_t < 590 \text{ GeV}$, respectively, to isolate the resonance from each distribution. For the $(l^+l^-)(l^+l^-)$ channel we include the cut of eq. 1. We also show the leading order results (dashed lines). The LHC CM energy is $14 \text{ TeV}$, and $m_t = 180 \text{ GeV}$. 
potential is increased by using the missing $p_t$ channels, and the mass saturation zone becomes accessible up to about $m_H \sim 1030$ GeV for a five sigma effect. Roughly speaking, the inclusion of quantum effects increases the discovery range by 40–60 GeV with these cuts. It can be expected that by using jet decay modes the discovery range can be increased further in the saturation region, but then a careful analysis of the QCD background is needed.

At this point we would like to make a few remarks regarding the interplay of electroweak and QCD corrections. The one–gluon corrections to the Higgs boson production by gluon fusion are available \[10\] for a narrow Higgs resonance. It has been shown that these corrections can be quite large, at the 50% — 70% level. This final enhancement effect is the result of several contributions from virtual and real gluon diagrams, some of them tending to enhance the cross section, and other to decrease it. It is hard to infer from these results even the sign of the effect for a wide resonance because the full $gg \to ZZ$ process must be considered. This includes the one–gluon corrections to nonresonant quark box diagrams, which are not available so far. Given the size of the narrow width QCD corrections, it can be expected that they be substantial for wide resonances as well.

To conclude, we reached a good quantitative understanding of electroweak effects for heavy Higgs resonances over the whole range relevant for the LHC, by combining two–loop perturbation theory and next–to–leading order nonperturbative $1/N$ expansion. The mass saturation effect is important for the gluon fusion Higgs signal at LHC for values of the on–shell mass above 700—800 GeV. By including the leptonic missing $p_t$ decay modes one can probe into the mass saturation region. Given that the identification of a heavy Higgs resonance depends crucially on a good theoretical calculation of the background, better control is needed of the interplay of electroweak and QCD corrections for a wide resonance.

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