A Double Parton Scattering Background to Associate $W H$ and $ZH$ Production at the LHC

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Higgs boson production in association with $W$ and $Z$ bosons at high luminosity CERN Large Hadron Collider (LHC, $\sqrt{s}=14$ TeV), is one of the most promising discovery channel for a SM Higgs particle with a mass below 135 GeV, where the Higgs decays into $b\bar{b}$ final states is dominant. The experimental capability of recognizing the presence of $b$ quarks in a complex hadronic final state has brought attention towards the final states with pairs for observing the production of the Higgs at the LHC. We point out that double parton scattering processes are going to represent a sizable background to the process.

1. INTRODUCTION

The Standard Model beautifully describes all the observed properties of elementary particles and their interactions. According to this model, the fundamental particles are either matter particles (the quarks and leptons) or force particles (the gauge bosons corresponding to the EM, Weak and Strong forces).

If nature had chosen the most elegant and symmetric mathematical construct for the SM, all fundamental particles would have zero mass. Experiments show that this is not the case: all particles have a small mass.

The Standard Model has no mechanism that would account for any of these masses, unless we supplement it by adding additional fields, of a type known as scalar fields.

One of the greatest achievements of twentieth-century theoretical physics was the discovery of how to incorporate particle masses into the Standard Model theory without spoiling the symmetry and mathematical consistency. The most straightforward way to do that is through what is known as “Higgs mechanism” [1].

An important by-product of this mass generating addition to the Standard Model is the prediction of the existence of a totally new type of particle-the as-yet- undiscovered “Higgs boson”. The discovery of the Higgs boson would solve the mystery of how particles get their masses. The spontaneous breakdown of the weak-electromagnetic gauge group can be accomplished in only one known way “Higgs fields”.

The Higgs is elusive and plays a negligible role in low energy phenomenology because it couples with particles according to their masses, and so couples very weakly coupled to the lepton and quark constituents of ordinary matter.

There are a few production mechanisms for the Higgs boson which lead to detectable cross section at the LHC. Each of them makes use of the preference of the SM Higgs which couples to the heavy particles, either massive vector boson or massive quark.

Here we discuss the production of Higgs particle more relevant to an experimental search “association production of an intermediate vector boson $W$ or $Z$ and a Higgs particle”.

The $bb$ channel is the most favorable Higgs boson decay mode when the Higgs mass is below the $W^+ W^-$ threshold, and since $b$ quark jets are identified with high efficiency final state then $bb$ pairs have a great potential for discovering the Higgs boson at the LHC, if the Higgs mass is in the range $80 \text{ GeV} \leq m_H \leq 150 \text{ GeV}$ [2].

An effective way to reduce the huge QCD background is to look for $bb$ pairs accompanied by isolated lepton resulting from the decay of a $W$
bosons.

At the LHC, Higgs boson production in association with $W$ and $Z$ bosons is the most interesting process for detecting the Higgs boson production through the $bb$ decay channel is therefore: $p + p \rightarrow W^\pm (or \ Z) + X$, with $W \rightarrow l\nu$, $Z \rightarrow ll$, $H \rightarrow bb$, where $l = e, \mu$.

The purpose of the present work is to point out that the same $l, bb$ final state can be produced also by double parton scattering collision processes, which represents therefore a further background to be taken into account in addition to the other background processes.

2. DOUBLE PARTON SCATTERING MECHANISM

Multiple parton interaction processes, where two different pairs of partons interact independently at different points in the transverse space, in the same inelastic hadronic event, become experimentally important at high energies and with the growing flux of partons. Double parton scattering has been recently observed by CDF [2]. The parton distribution function depends on the fractional momenta of all the interacting partons and on their distance in transverse space which has to be the same for both the target and the projectile partons in order for the collisions to occur. The inclusive cross-section of a double parton scattering can be expressed, as [3]:

$$\sigma_{DS} = \sum_q \int dx_1 dx_2 dx_3 dx_4 \Gamma_A(x_1, x_2; \hat{b}) \Gamma_B(x_3, x_4; \hat{b}) \hat{\sigma}^a(x_1, x_3) \hat{\sigma}^b(x_2, x_4) d^2 b$$

(1)

Where, $\hat{\sigma}^a(x_1, x_3)$, $\hat{\sigma}^b(x_2, x_4)$ are two distinguishable partonic cross sections and $\Gamma_A(x_1, x_2; \hat{b})$ represents the distribution function with fractional momenta $(x_1, x_2)$ and transverse relative distance with in the hadron $\hat{b}$. Double parton distribution functions, contain in principle detailed information on the hadronic structure and probes correlations between partons in the hadron in the transverse structure. These correlations can be assumed to be negligible if a scattering event is characterized by high center-of-mass energy. The two-body parton distribution functions factorize as $\Gamma(x_1, x_2; \hat{b}) = f(x_1) f(x_2) F(\hat{b})$, where $f(x)$ is the parton distribution function and $F(\hat{b})$ describes the distribution of parton in the transverse plane. With these assumptions the cross-section for a double parton collision leads in the case of two distinguishable parton interactions to the simplest factorized expression as:

$$\sigma_{DS} = \frac{\sigma^a \sigma^b}{\sigma_{eff}} \quad (2)$$

Here $\sigma^a$ represents the single scattering cross section

$$\sigma^a = \sum_{ij} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij \rightarrow a}$$

(3)

where $f_i(x_1)$ is the standard parton distribution function and $\hat{\sigma}_{ij \rightarrow a}$ represents the subprocess cross section.

The parameter $\sigma_{eff} = 1/ \int d^2 b F(\hat{b})$, is the effective cross section and it enters as a simple proportionality factor in the integrated inclusive cross section for a double parton scattering $\sigma_{DS}$.

The experimental value measured by CDF yields $\sigma_{eff} = 1.45 \pm 1.7_{-1.3}^{+1.7}$ mb [5]. It is believed that it is largely independent of the center-of-mass energy of the collision and of the nature of the partonic interactions.

3. CROSS-SECTION RESULTS

For the production of Higgs boson at hadron colliders, we consider the simplest spontaneous broken gauge boson involving exactly one physical Higgs boson. The elementary cross section for the process $q\bar{q} \rightarrow V^* \rightarrow W^\pm (or \ Z) + H$ is convoluted with the appropriate quark and antiquark distribution functions and integrated over all appropriate final state variables [6].

$$\sigma(pp \rightarrow V^* \rightarrow W^\pm \ or \ Z + H + X) = \sum_{ij} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}(q\bar{q} \rightarrow V^*)$$

(4)

The sub process cross sections are obtained:

$$\hat{\sigma}(q\bar{q} \rightarrow WH) = \frac{(G_F M_W^2)^2}{9\pi} |V_{qq'}|^2 \frac{p_W}{\sqrt{s}} \frac{3M_W^2 + p_W^2}{(s - M_W)^2}$$
\[ \sigma(q\bar{q} \to ZH) = \frac{(G_F M_Z^2)^2}{9\pi} \left| V_{q\bar{q}}^2 + A_{q\bar{q}}^2 \right|^2 \frac{p_Z}{\sqrt{s}} \frac{3M_Z^2 + p_Z^2}{(s - M_Z)^2}, \]

Where \( p_Z^2 = \frac{1}{4}(s^2 + M_V^4 + M_H^4 - 2sM_V^2 - 2sM_H^2 - 2M^2 V M_H^2) \) for \( V = W, Z \).

In order to devise search strategies for the Higgs boson, it is important to know the dominant decay channels for different Higgs boson masses. If the Higgs mass is below the \( WW \) threshold then \( H \to b\bar{b} \) decay is dominant, as shown in Fig 1.

The total cross section for the processes \( p + p \to WH + X \) and \( p + p \to ZH + X \) times the branching ratios of the decay mode \( H \to b\bar{b}, W \to l\nu_l \), \( Z \to l^+l^- \) (\( l = e, \mu \)), as a function of Higgs mass, is plotted in Fig. 2. In our calculation the integration was performed by VEGAS with MRST parton distributions.

The cross sections for Higgs production in association with \( W \) and \( Z \) bosons are not large, but may be useful if high luminosity is available, since the Higgs can be “tagged” by triggering on the weak boson.

A background to the process \( p + p \to W^\pm (or Z) + X \) with \( W \to l\nu_l \) and \( H \to b\bar{b} \), is represented by the double scattering interactions. The corresponding integrated rate is evaluated by combining the expected cross section for \( W \) and \( b\bar{b} \) production at LHC energy. Using equation (2) one obtain the cross section for a double parton collision production background.

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It is clear that one obtains a cross section in double scattering background three orders of magnitude larger than the expected signals from Higgs decay.

The large rate of \( b\bar{b} \) pairs expected at the LHC gives rise to a relatively large production of pair in the process underlying the \( W \) production as a
very promising channel to detect the production of the Higgs boson.

Figure 3 shows the double parton scattering background to the Higgs boson production as a function of the $b\bar{b}$ invariant mass compared to the expected signal for three possible values of the Higgs mass. The double parton scattering process remains a rather substantial component of the background to Higgs production.

4. SUMMARY

In this work we have computed the most promising channel to detect the production of the SM Higgs particle at the LHC with a mass below about 135 GeV, where the Higgs decays into $b\bar{b}$ final states is dominant.

The production of the Higgs boson, in the intermediate mass range, namely the final state with a $b\bar{b}$ pair and with isolated lepton, is affected by a sizable background due to double parton collision process.

Although the double parton scattering background cross section is a decreasing function of the invariant masses of the $b\bar{b}$ pair, the relatively large value of the invariant mass required to the $b\bar{b}$ pair to be assigned to the Higgs decay is not large enough, at LHC energies, to allow one to neglect the double parton scattering background.

However, in the hadron collider environment, the large QCD backgrounds may cause the observation impossible for those events if one or more of the gauge bosons decay hadronically. Individual channels with hadronic decays should be studied on case by case.

It is useful to point some of the inherent uncertainties which affect the final results. The most significant are: (i) the lack of precise knowledge of the parton distribution at small $x$, which is important for the intermediate mass Higgs and (ii) the effect of unknown higher order perturbation QCD corrections.

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