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Detecting an invisible Higgs boson at Fermilab Tevatron and CERN LHC

S.-H. Zhu[a]

Institute of Theoretical Physics, School of Physics, Peking University, Beijing 100871, P.R. China

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Abstract. In this paper, we study the observability of an invisible Higgs boson at Fermilab Tevatron and CERN LHC through the production channel $q\bar{q} \to ZH \to \ell^+\ell^- + \not{P}_{\rm T}$, where $\not{P}_{\rm T}$ is reconstructed from the $\ell^+\ell^-$ with $\ell = e$ or μ. A new strategy is proposed to eliminate the largest irreducible background, namely $q\bar{q} \to Z(\to \ell^+\ell^-)Z(\to \nu\bar{\nu})$. This strategy utilizes the precise measurements of $q\bar{q} \to Z(\to \ell^+\ell^-)Z(\to \ell^+\ell^-)$. For $m_H = 120$ GeV and with luminosity 30 fb^{-1} at Tevatron, a 5σ observation of the invisible Higgs boson is possible. For $m_H = 114 \sim 140$ GeV with only 10 fb^{-1} luminosity at LHC, a discovery signal over 5σ can be achieved.

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1 Introduction

Understanding the mechanism of electroweak symmetry breaking (EWSB) is a primary goal of the Fermilab Tevatron, CERN LHC and the proposed ILC. In the standard model (SM) of high energy physics, EWSB is realized via a weak-doublet fundamental Higgs field. After spontaneous EWSB, namely the Higgs field acquiring a vacuum expectation value (VEV), only one neutral Higgs boson is left in the particle spectrum. The Higgs boson mass is theoretical unknown within the SM. Therefore searching the whole mass region is necessary and great efforts have been made on it since the establishment of the SM. The latest direct search at LEP sets the lower bound of the SM Higgs boson of 114.4 GeV at 95% confidence level (CL) [1]. The Higgs boson can also affect electroweak observables through radiative corrections. Therefore precise measurements of these observables can predict the Higgs boson mass. Studies show that data from LEP, SLD and Tevatron are in good agreement with SM predictions[1]. Based on the global fit of those data, the Higgs boson mass is predicted to be $m_H = 98^{+52}_{-36}$GeV and $m_H < 208$ GeV at 95% CL using the latest preliminary top quark mass $m_{\rm t} = 174.3 \pm 3.4$GeV [2].

The Higgs boson decay width in the SM varies dramatically within the experiment's preferable mass region $114.4 \sim 208$ GeV. For example, for $m_H = 120$ GeV, $\Gamma(H) \simeq 3.65$ MeV while for $m_H = 200$ GeV, $\Gamma(H) \simeq 1.425$ GeV [5]. The tiny decay width for the light Higgs ($< 2m_W$) is due to the suppressed coupling among Higgs boson and fermion, which is proportional to m_f/m_W with m_f the light fermion mass. Therefore the *light* Higgs boson ($< 2m_W$) can possibly decay into non-SM particles with a large branching ratio. For example the Higgs boson may decay dominantly into scalar dark matter in the simplest cold dark matter model [6]. The study in [6] shows that the correct cold dark matter relic abundance within 3σ uncertainty ($0.093 < \Omega_{\rm dm}h^2 < 1.129$) and the experimentally allowed Higgs boson mass ($114.4 \le m_H \le 208$ GeV) constrain the scalar dark matter mass within $48 \le m_{\rm S} \le 78$ GeV. This result is in excellent agreement with that of de Boer et al. ($50 \sim 100$ GeV) [7]. Such a kind of dark matter annihilation can account for the observed gamma ray excess (10σ) at EGRET for energies above 1 GeV in comparison with the expectations from conventional galactic models. The most important phenomenological consequence of this model is that the Higgs boson decays dominantly into scalar cold dark matter if its mass lies within $48 \sim 64$ GeV. In [8] $O(1 \sim 100)$MeV scalar dark matter was proposed to account for the observation of a 511 keV bright γ ray line from the galactic bulge [9]. From a theoretical point of view, containing a stable singlet scalar which interacts possibly with an SM Higgs boson is a generic feature of models of scalar dark matter [6, 10]. In other models beyond the SM, it is not rare that the Higgs boson can decay into dark matter. For example in supersymmetrical models with R-parity, the Higgs boson can decay into a neutralino pair if kinematically allowed.

Another reason why the light Higgs boson is especially interesting is due to the aspect of experiments. It has been known for a long time that hadronic asymmetry meas-

[a] e-mail: huald@th.phy.pku.edu.cn

[1] The notorious three 3σ anomalies [3] may indicate new dynamics beyond the SM; moreover, even without these anomalies the global fit shows a certain tension with a direct search limit at LEP [4].

urements, namely $A^b_{\rm FB}$, $A^c_{\rm FB}$ and $Q_{\rm FB}$, prefer the heavier Higgs mass with central value around 400 GeV, while the leptonic ones, m_W, F_Z and R_ℓ, prefer the very light Higgs, which already indicates a certain tension with the direct search limit 114.4 GeV [4]. While such a situation may be totally due to statistical fluctuations, it is not unreasonable to suspect that some unknown systematic errors lie in hadronic asymmetry measurements. If this is true, the SM Higgs boson tends to lie just above the current direct search limit; otherwise the tension will become stronger.

In this paper we will study the invisible Higgs boson in the ZH associated production channel in which the Higgs boson decays *invisibly*, i.e. we cannot tag the Higgs decay products, and $Z \to \ell^+\ell^-$ with $\ell = e, \mu$. The signal is $\ell^+\ell^- \not{p}_{\rm T}$ where $\not{p}_{\rm T}$ is reconstructed from the $\ell^+\ell^-$. This channel has been widely discussed in the literature [11–15]. As one of the characteristics of this mode, we cannot get a Higgs boson invariant mass peak out of a continuum background. Therefore it is quite interesting to know how to get Higgs boson mass information from the experimental measurements. As pointed out by [14], this process may provide an interesting handle on the Higgs boson mass at LHC. The Higgs mass can be extracted from the production cross section and the uncertainty is 35–50 GeV (15–20 GeV) with integrated luminosity 10(100) $\rm fb^{-1}$ at LHC [14][2]. Therefore, precise understanding of the backgrounds is essential. At hadron colliders the precise predictions for the backgrounds are commonly thought to be difficult because of the uncertainty in the parton distribution function (PDF), large QCD radiative corrections etc. However for this channel, we only care about charged lepton final states, and the backgrounds seem to be less severe than those of hadronic final states. Another interesting question is how to suppress the background efficiently. In the literature, lots of techniques are proposed [11–15]. However the largest irreducible ZZ background, with one Z decay into neutrinos and the other into a charged lepton pair, cannot be eliminated by kinematical cuts. In this paper, we will propose a method, i.e. utilizing the precise measurement of $Z(\to \ell^+\ell^-)Z(\to \ell^+\ell^-)$, to reduce the largest irreducible ZZ background.

2 Detail simulation

In this paper, we consider the production of a Higgs boson in association with a Z boson, and the Higgs decays 100% invisibly. Therefore the signal is

$$p\,p(\text{or } \bar{p}) \to Z(\to \ell^+\ell^-) + h_{\rm inv}\,; \quad \ell = e, \mu\,. \tag{1}$$

As the signal is $\ell^+\ell^- \not{p}_{\rm T}$ where $\not{p}_{\rm T}$ is reconstructed from the $\ell^+\ell^-$, the most significant sources of background are

$$Z(\to \ell^+\ell^-)Z(\to \nu\bar{\nu}), \quad W^+(\to \ell^+\nu)W^-(\to \ell^-\bar{\nu}),$$
$$Z(\to \ell^+\ell^-)W(\to \ell\nu), \tag{2}$$

with the lepton (e, μ and τ, and here we only consider the τ lepton) from the W decay in ZW missed, and $Z +$ jets final states with fake $\not{p}_{\rm T}$ [12, 13]. We simulate the signal and the three backgrounds in (2) using Pythia [17] without initial and final QCD and QED radiation corrections. In order to reduce the fake $\not{p}_{\rm T}$ background to an insignificant level, we set $\not{p}_{\rm T} > 85, 100$ GeV for LHC [14] and $\not{p}_{\rm T} > 55, 75, 100$ GeV for Tevatron [13].

We adopt the following "LHC cuts" from [14]:

$$p_{\rm T}(\ell^\pm) > 10\,{\rm GeV}, \quad |\eta(\ell^\pm)| < 2.5, \quad \Delta R(\ell^+\ell^-) > 0.4, \tag{3}$$

where η denotes the pseudo-rapidity and ΔR is the separation between the two particles in the detector, $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$; ϕ is the azimuthal angle. The WW background can be largely eliminated by

$$|m_{\ell^+\ell^-} - m_Z| < 10\,{\rm GeV}, \quad \Delta\phi_{\ell^+\ell^-} < 2.5\,. \tag{4}$$

In order to reduce the third background in (2), we veto events with

$$p_{\rm T}(\ell) > 10\,{\rm GeV}, \quad |\eta(\ell)| < 3.0\,. \tag{5}$$

At Tevatron we adopt the following "Tevatron cuts" from [13]:

$$p_{\rm T}(\ell^\pm) > 12\,{\rm GeV}, \quad |\eta(\ell^\pm)| < 2.0, \quad \Delta R(\ell^+\ell^-) > 0.4, \tag{6}$$

$$|m_{\ell^+\ell^-} - m_Z| < 7\,{\rm GeV}, \quad \Delta\phi_{\ell^+\ell^-} < 2.7\,, \tag{7}$$

and veto events with

$$p_{\rm T}(\ell) > 10\,{\rm GeV}, \quad |\eta(\ell)| < 2.5\,. \tag{8}$$

The signal and background are shown in Figs. 1 and 2 as a function of $\not{p}_{\rm T}$ for the e^+e^- final states at Tevatron and LHC. Our results are consistent with those of [13] and [14].

After imposing cuts in (3)–(8), the remaining largest irreducible background is ZZ, as shown in Figs. 1 and 2. This background cannot be eliminated via kinematical cuts. Therefore we propose to utilize the measurement of $Z(\to \ell^+\ell^-)Z(\to \ell^+\ell^-)$ (in short, $ZZ \to 4\ell$, hereafter) to reduce this background. This idea is quite natural because of two reasons. The first one is that $ZZ \to 4\ell$ is almost background free [18][3] due to the excellent leptonic reconstruction efficiency and mass resolution of the Z boson (decays to a pair of charged leptons). For example with integrated luminosity 30 $\rm fb^{-1}$ cross section of this channel can be measured to an accuracy of 5% at LHC [18]. The second reason is that the ZZ background and $ZZ \to 4\ell$ share almost the same kinematics, the same higher order QCD radiative correction and PDF uncertainties, as well as the uncertainty of the luminosity etc. We can then get

[2] The precise measurement of $ZZ \to 4\ell$ can reduce the largest ZZ background, and it may also improve the Higgs mass determination.

[3] Due to the large gg luminosity at LHC, $gg \to H \to ZZ^{(*)} \to 4\ell$ can act as the background to $ZZ \to 4\ell$ especially for heavier Higgs, say 140 GeV. However we can apply an invariant mass cut to eliminate such a kind of background.

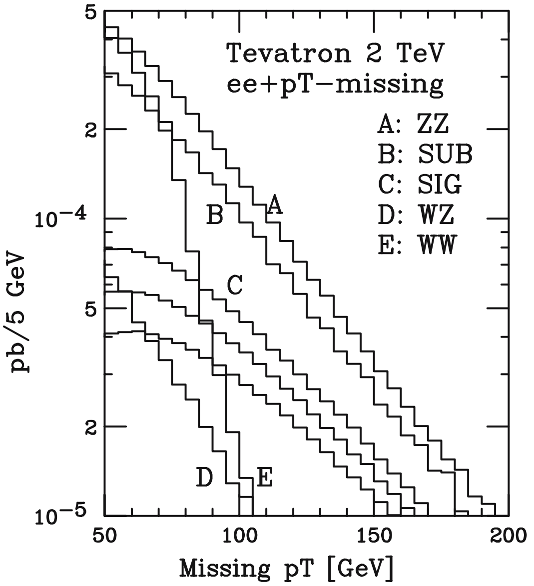

Fig. 1. Missing $p_{\rm T}$ distribution for $Z(\to e^+e^-)+h_{\rm inv}$ signal and backgrounds at Tevatron with $\sqrt{s}=2\,{\rm TeV}$ after applying the "Tevatron cuts" in (6)–(8). Here "C" represents signal with $m_h=120, 130$ and $140\,{\rm GeV}$ from top to bottom, and "SUB" stands for $R\times\sigma_{4\ell}/2$ (see text)

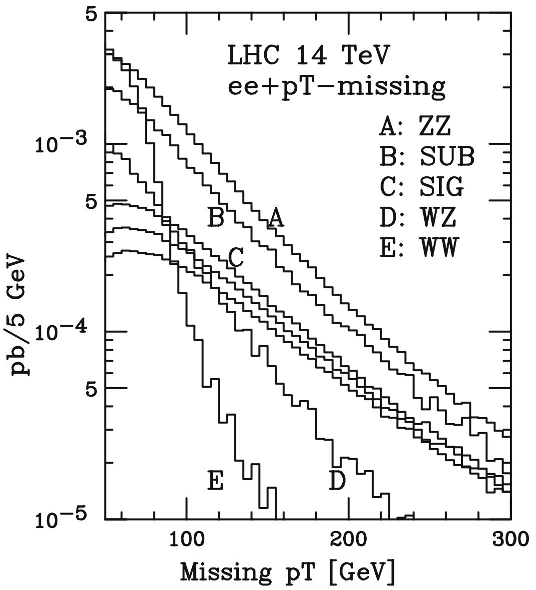

Fig. 2. Same conventions as Fig. 1 but at the LHC with $\sqrt{s}=14\,{\rm TeV}$ after applying the "LHC cuts" in (3)–(5)

an improved ZZ background by subtracting contributions from $ZZ\to 4\ell$

$$\sigma_{\rm bkg}^{ZZ,{\rm improved}}=\sigma_{\rm bkg}^{ZZ}-R\times\sigma_{4\ell}\,, \tag{9}$$

where $\sigma_{4\ell}$ is the cross section for $ZZ\to 4\ell$ with each pair of leptons satisfying "LHC cuts" or "Tevatron cuts" in (3)–(8). Actually the $ZZ\to 4\ell$ event does not have a missing $P_{\rm T}$ if we run through all the final state particles. However in our case $\not{P}_{\rm T}$ is reconstructed via the momentum of a charged lepton pair, the invariant mass of which is effectively around m_Z. Thus $ZZ\to 4\ell$ yields the extra data set which is not included in that of $\ell^+\ell^-\not{P}_{\rm T}$. Note that the purity of $ZZ\to 4\ell$ is the most crucial factor for the subtraction purpose. Thus besides "LHC cuts" or "Tevatron cuts" (e.g. the invariant mass of each pair is effectively around m_Z), we can further require that the missing $P_{\rm T}$ of four leptons should be small, in order to guarantee that they do come from ZZ. A detailed study of $ZZ\to 4\ell$ can be found in [18]. In (9) R is the ratio defined as

$$R=\frac{2}{3}\frac{\sum_{i=1}^{3}{\rm Br}(Z\to\nu_i\bar{\nu}_i)}{{\rm Br}(Z\to e^+e^-)}. \tag{10}$$

It is obvious that $\sigma_{\rm bkg}^{ZZ,{\rm improved}}\approx 0$ if we can measure all four charged lepton final states in any kinematical region. Though this ratio at tree level can be expressed as

$$R=2\times\frac{\left(g_V^{(\nu)}\right)^2+\left(g_A^{(\nu)}\right)^2}{\left(g_V^{(\ell)}\right)^2+\left(g_A^{(\ell)}\right)^2}, \tag{11}$$

omitting the final state lepton mass, with $g_V^{(f)}=T_{w3}^{(f)}-2\sin^2\theta_{\rm W}Q^{(f)}$ and $g_A^{(f)}=T_{w3}^{(f)}$. The higher order radiative corrections can be included by replacing the couplings g_V and g_A by the effective ones. In this paper we alternatively adopt the experimental central values as input: $\Gamma(Z\to{\rm inv})=499\,{\rm MeV}$ and $\Gamma(Z\to\ell^+\ell^-)=83.984\,{\rm MeV}$ [19] and get

$$R=\frac{2}{3}\frac{\Gamma(Z\to\ {\rm inv})}{\Gamma(Z\to\ell^+\ell^-)}=3.961\,. \tag{12}$$

In Figs. 1 and 2, we also show the $\not{P}_{\rm T}$ distribution for the 4ℓ process (in fact, one can reconstruct two equal $\not{P}_{\rm T}$ based on two pairs of leptons, and the invariant mass of each lepton pair is around the Z mass peak). The shape of the ZZ background and the $ZZ\to 4\ell$ process is very similar, and the difference represents the incomplete cancelation due to the kinematical cuts on charged leptons.

Our results for the background and signal cross sections are tabulated in Table 1 for Tevatron and Table 2 for LHC.

Table 1. Background and signal cross sections for associated $Z(\to\ell^+\ell^-)+h_{\rm inv}$ production at the Tevatron, combining the ee and $\mu\mu$ channels

$\not{p}_{\rm T}$ cut	$B(ZZ)$	improved $B(ZZ)$	$B(WW)$	$B(ZW)$
55 GeV	6.73	1.78 fb	2.96 fb	0.70 fb
75 GeV	3.96	0.97 fb	0.71 fb	0.35 fb
100 GeV	1.96	0.45 fb	0.10 fb	0.15 fb
		$S(Z+h_{\rm inv})$		
$\not{p}_{\rm T}$ cut	$m_h=120$	130	140 GeV	
55 GeV	2.07 fb	1.62 fb	1.27 fb	
75 GeV	1.46 fb	1.18 fb	0.95 fb	
100 GeV	0.88 fb	0.73 fb	0.61 fb	

Table 2. Same as Table 1 but at the LHC

$\not{p}_T$ cut	$B(ZZ)$	improved $B(ZZ)$	$B(WW)$	$B(ZW)$
85 GeV	30.4	9.1 fb	2.6 fb	6.2 fb
100 GeV	22.0	6.4 fb	1.1 fb	4.1 fb
		S$(Z+h_{\rm inv})$		
$\not{p}_T$ cut	$m_h = 120$	130	140 GeV	
85 GeV	10.5 fb	8.8 fb	7.4 fb	
100 GeV	8.3 fb	7.1 fb	6.0 fb	

Table 3. Signal significance for associated $Z(\to \ell^+\ell^-) + h_{\rm inv}$ production at the Tevatron, combining the ee and $\mu\mu$ channels. The numbers in parentheses correspond to a ZZ background without improvement (see text)

		$m_h = 120$ GeV	
$\not{p}_T$ cut	S/B	$S/\sqrt{B}$ (10 fb^{-1})	$S/\sqrt{B}$ (30 fb^{-1})
55 GeV	0.38(0.25)	2.81(2.26)	4.86(3.91)
75 GeV	0.72(0.29)	3.20(2.06)	5.61(3.57)
100 GeV	1.26(0.40)	3.32(1.87)	5.76(3.24)
		$m_h = 130$ GeV	
$\not{p}_T$ cut	S/B	$S/\sqrt{B}$ (10 fb^{-1})	$S/\sqrt{B}$ (30 fb^{-1})
55 GeV	0.30(0.19)	2.20(1.77)	3.80(3.06)
75 GeV	0.58(0.24)	2.62(1.67)	4.54(2.88)
100 GeV	1.04(0.33)	2.76(1.55)	4.78(2.70)
		$m_h = 140$ GeV	
$\not{p}_T$ cut	S/B	$S/\sqrt{B}$ (10 fb^{-1})	$S/\sqrt{B}$ (30 fb^{-1})
55 GeV	0.23(0.15)	1.72(1.39)	2.98(2.40)
75 GeV	0.47(0.19)	2.11(1.34)	3.65(2.32)
100 GeV	0.87(0.28)	2.31(1.30)	3.99(2.25)

Table 4. Same as Table 3 but at the LHC

		$m_h = 120$ GeV	
$\not{p}_T$ cut	S/B	$S/\sqrt{B}$ (10 fb^{-1})	$S/\sqrt{B}$ (30 fb^{-1})
85 GeV	0.59(0.27)	7.8(5.3)	13.6(9.2)
100 GeV	0.72(0.31)	7.7(5.0)	13.3(8.7)
		$m_h = 130$ GeV	
$\not{p}_T$ cut	S/B	$S/\sqrt{B}$ (10 fb^{-1})	$S/\sqrt{B}$ (30 fb^{-1})
85 GeV	0.49(0.22)	6.6(4.4)	11.4(7.7)
100 GeV	0.61(0.26)	6.6(4.3)	11.4(7.5)
		$m_h = 140$ GeV	
$\not{p}_T$ cut	S/B	$S/\sqrt{B}$ (10 fb^{-1})	$S/\sqrt{B}$ (30 fb^{-1})
85 GeV	0.41(0.19)	5.5(3.7)	9.6(6.5)
100 GeV	0.52(0.22)	5.6(3.6)	9.6(6.3)

The corresponding signal to background ratio, S/B, and significance, $S/\sqrt{B}$, are tabulated in Table 3 for Tevatron and Table 4 for LHC.

From Tables 1–4, we can see that the ZZ background is greatly eliminated after including the measurement of $ZZ \to 4\ell$. Accordingly S/B and $S/\sqrt{B}$ are improved significantly. At Tevatron, for $m_H = 120$ GeV and with luminosity 30 fb^{-1}, observation of Higgs boson over 5σ is possible through this channel, while one can only achieve a significance less than 4σ without input from the measurement of $ZZ \to 4\ell$. For the heavier Higgs mass, even for $m_H = 140$ GeV, this channel can yield a signal of 3σ significance with 30 fb^{-1} luminosity. At LHC, our results show that for a 114–140 GeV Higgs boson and with only 10 fb^{-1} luminosity, this channel can provide an observation with over 5σ significance of the invisible Higgs boson.

3 Discussion and open questions

In this paper we studied the invisible Higgs boson at Fermilab Tevatron and CERN LHC, i.e. $q\bar{q} \to ZH \to \ell^+\ell^- + \not{P}_T$, where $\not{P}_T$ is reconstructed from the $\ell^+\ell^-$ with $\ell = e$ or μ. Moreover, in order to reduce the largest $Z(\to \ell^+\ell^-)Z(\to \nu\bar{\nu})$ background, we propose to utilize a precise measurement of $Z(\to \ell^+\ell^-)Z(\to \ell^+\ell^-)$ as input. Our study shows that at Tevatron, for $m_H = 120$ GeV and with luminosity 30 fb^{-1}, the observation over 5σ of the Higgs boson is possible via this channel. At LHC, for a 114–140 GeV Higgs boson and with only 10 fb^{-1} luminosity, this channel can achieve over 5σ discovery. We should note that the feasibility of this discovery mode depends crucially on the understanding of the backgrounds. Therefore the simulation incorporated with at least NLO QCD radiative correction for signal [20] and background [21] is very important and will put the analysis on a firmer ground. Moreover we are aware that the simulation presented here is very rough, and the full detector simulation, which is beyond the scope of this paper, is a natural further investigation.

It is worthwhile to mention that the invisible Higgs boson can also be investigated through weak boson fusion (WBF), provided that events with two energetic forward–backward jets of high dijet invariant mass and with substantial missing transverse momentum can be triggered efficiently [22]. The study shows that it is possible to discover an invisible Higgs boson with masses up to 480 GeV at the 5 sigma level if the invisible branching ratio is close to 100% [22]. While WBF can detect the invisible Higgs boson with higher mass, the ZH channel may provide a better handle on the mass determination [14]. Moreover the combined analysis of WBF and ZH modes allows for a relatively model-independent determination of the invisible Higgs boson mass.

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