Photoproduction of $WH$ signal at electron-proton Colliders

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ABSTRACT

We present the photoproduction of an intermediate mass Higgs (IMH) boson associated with a $W$ boson at the future electron-proton colliders using bremsstrahlung photon beam or laser backscattered photon beam. With bremsstrahlung photon beam the search for the IMH boson is unfavorable because of the small signal rate. But with laser photon beam the search is viable due to a much larger rate, and provided that the $B$-identification is efficient and $m(b\bar{b})$ measurement has a good resolution.

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I. INTRODUCTION

Standard Model (SM) Higgs boson has been searched at LEP and the negative results put a lower bound of about 60 GeV [1] on the Higgs-boson mass. With the highest center-of-mass energy of LEP II the search can push the limit to about 90 GeV. The discovery of a heavy Higgs boson, on the other hand, should be viable using the $H \rightarrow ZZ$, $WW$ decay channels at the future hadronic supercolliders [2]. But so far there are still controversies on identifying the intermediate mass Higgs (IMH) boson at the hadronic supercolliders. On the other hand, the whole intermediate mass range should be covered at the future linear $e^+e^-$ colliders of $\sqrt{s} = 300 - 500$ GeV [3]. Besides, the linear $e^+e^-$ colliders operating in $\gamma\gamma$ or $e\gamma$ modes, where the photon beams are realized by the laser backscattering method [4], have also been shown to be possible for the IMH discovery [5,6]. The feasibility for IMH discovery has also been explored at $ep$ colliders via $ep \rightarrow \nu HX$ production channel [7], however, a detector of high performance is necessary for reasonable signal-to-background ratios. Another possibility will be the associated photoproduction of an IMH boson with a $W$ boson at $ep$ colliders via the subprocess

$$q\gamma \rightarrow q'W^\pm H,$$  \hspace{1cm} (1)

where the initial photon is obtained by the bremsstrahlung off the incoming electron or by the laser backscattering method [4]. This production channel has the advantage of an additional $W$ boson which can be tagged by its leptonic or hadronic decays to eliminate the QCD backgrounds. In this paper we will investigate this possibility and will show that this channel can only give a small cross section for the bremsstrahlung photons but a much larger cross section for the laser backscattered photons at the future $ep$ colliders. We will also discuss the corresponding backgrounds in the search of the IMH boson at the LEP×LHC.
II. PHOTOPRODUCTION

HERA is at present the only ep collider running. One of its goals is to provide data for accurate determination of the proton structure function at the small $x$ region. Another ep collider [8] being contemplated is the combination of the LEP and the LHC (LEP×LHC), in which an 60 GeV electron beam collides with a 7.7 TeV proton beam, and the center-of-mass energy $\sqrt{s}$ of the collision is 1.36 TeV. The luminosity under consideration is about $2.8 \times 10^{32}$ cm$^{-2}$ s$^{-1}$. If we assume a 30% duty cycle (same as the SSC), then in one year of running it can accumulate about 2.65 fb$^{-1}$. For the following discussion we will assume a yearly luminosity of 3 fb$^{-1}$.

Photoproduction [9] at ep (HERA, LHC×LEP) colliders is a part of the neutral-current (NC) scattering, $ep \rightarrow eX$, with the exchange photon being almost on-shell $Q^2 \approx 0$. In this type of events the scattered electron is tagged in the direction of the incoming electron beam within a certain angle, and its energy is measured. Using this scattered electron as a trigger, a lot of charged-current (CC) backgrounds can be eliminated. Nevertheless, there are still large backgrounds coming from the NC photoproduction of jets.

We will use the Weizsäcker-Williams approximation (WWA) of the form

$$f^{\text{WWA}}_{\gamma/e}(x) = \frac{\alpha}{2\pi} \frac{1 + (1 - x)^2}{x} \log \frac{Q^2_{\text{max}}}{Q^2_{\text{min}}},$$

for the luminosity function of the bremsstrahlung photons. The $Q^2_{\text{min}} = m_e^2 x^2/(1 - x)$ is determined by the kinematic limit. The $Q^2_{\text{max}}$ is expected to be less than the maximum virtuality of the photon, and is taken to be one quarter the square of the center-of-mass energy of the ep system. For the proton structure function we will use the HMRS (set b) [10] with the scale $\mu^2 = M^2(WH) + p_T^2(WH)$, the transverse mass of the WH pair. The effective $\gamma p$ luminosity is equal to the ep luminosity in the approximation of one photon bremsstrahlung.

On the other hand, the laser backscattered photons are obtained by directing a low-energy but intense laser beam almost head-to-head to the incident electrons. The resulting
photon beam carries most of the energy of the electron beam and therefore has the advantage that its spectrum is much harder than that of the bremsstrahlung photons. The spectrum for the unpolarized beam is given by

\[ f_{\gamma/e}^\text{laser}(x) = \frac{1}{D(\xi)} \left[ 1 - x + \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right], \]

\[ D(\xi) = (1 - \frac{4}{\xi} - \frac{8}{\xi^2}) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2}, \]

where \( \xi = 4E_e\omega_0/m_e^2 \), and \( \omega_0 \) is the energy of the incident laser photon. \( \xi \) is chosen to be about 4.8 and \( x_{\text{max}} \) is then about 0.83. In this method, if the converted electron can be removed efficiently the charged-current backgrounds will be eliminated, and resulting in pure \( \gamma p \) collision. The effective \( \gamma p \) luminosity depends on how efficient the conversion \( e \to \gamma \) is. According to Ref. [4], the effective \( \gamma \gamma \) luminosity can be achieved higher than the original \( e^+e^- \) collider, but for \( e\gamma \) collision the effective \( e\gamma \) luminosity was shown to be limited [4]. So far the use of laser backscattering method to convert \( e \to \gamma \) in \( ep \) environment has not been studied. For the calculation we are going to present we assume that the effective \( \gamma p \) luminosity is the same as the \( ep \) luminosity.

The contributing Feynman diagrams for the subprocess

\[ d(p_1) \gamma(p_2) \to u(q_1) W^-(k_1) H(k_2), \]

are shown in Fig. [4]. The helicity amplitudes for the matrix elements have been given for a similar process \( e^-\gamma \to W^-H\nu \) in Ref. [6]. Simple adaptation from those formulas by changing the corresponding photon coupling to quarks should be made. The matrix elements for the charge-conjugate process

\[ u(p_1) \gamma(p_2) \to d(q_1) W^+(k_1) H(k_2) \]

can be obtained simply by charge-conjugation. The total cross section is obtained by convoluting the subprocess cross section with the proton structure function and the luminosity function for the bremsstrahlung photons or for the laser backscattered photons.
III. RESULTS

We used the input parameters of $M_Z = 91.175$ GeV and $\sin^2 \theta_W = 0.23$. The total cross section of the photoproduction of $ep \rightarrow WHX$ using the WWA for the bremsstrahlung photons versus the center-of-mass energies of the $ep$ system for a range of Higgs masses from 60 – 140 GeV is shown in Fig. 2. The cross section starts off with a very small value, and increases quite rapidly around $\sqrt{s} = 1 – 2$ TeV because the phase space factor to produce $WH$ final state is very limited at small $\sqrt{s}$ but increases favorably with $\sqrt{s}$. At $\sqrt{s} = 3$ TeV the cross section for $m_H = 60$ GeV can reach 32 fb. On the other hand, using the laser backscattered photons the production cross section is more than an order of magnitude larger, as shown in Fig. 3. Therefore, the plausibility of using the $WH$ channel to search for the IMH boson improves substantially. For the following discussions we will concentrate on the LEP×LHC of $\sqrt{s} = 1.36$ TeV. The production rates for $\sqrt{s} = 1.36$ TeV using the bremsstrahlung photons and laser photons are listed in Table I.

IV. DISCUSSIONS

So far the studies on the IMH search at $ep$ collision are not so ideal because of the presence of huge QCD backgrounds from NC and CC scatterings [7]. In our study we can tag on the charged lepton from the leptonic $W$ decay or on the pair of jets from the hadronic $W$ decay. This can help suppressing the QCD backgrounds. The dominant decay of the IMH is the $b \bar{b}$ mode, which is chosen to maximize the number of signal events. Therefore, in the final state we have

$$ep \rightarrow WHX \rightarrow \ell \nu (b \bar{b}) X ,$$

or

$$ep \rightarrow WHX \rightarrow (jj)(b \bar{b}) X .$$
The irreducible backgrounds from $ep \rightarrow WZX \rightarrow W(b\bar{b})X$ and $ep \rightarrow t\bar{t}X \rightarrow b\bar{b}WX$ are always present, no matter which decay mode of the $W$ boson is chosen. Besides, photoproductions of multi-jet events, $W+$jets events, $Z+$jets events, and $t\bar{t}$ events are all potential backgrounds. $B$-tagging should be very useful in rejecting a lot of non-$b$ events.

A. Bremsstrahlung Photons

The cross section using the bremsstrahlung photons is $1.5 - 5$ fb for $m_H = 60 - 140$ GeV. Multiplying with the corresponding branching ratios we have about $3 - 9$ events for the $jjb\bar{b}$ decay mode, and $1 - 3$ events for the $\ell\nu b\bar{b}$ decay mode per each year running. The largest irreducible background $ep \rightarrow t\bar{t}X$ has a production rate of $2$ pb for $m_t = 150$ GeV\cite{11}, and $ep \rightarrow t\bar{t}X$ background is much smaller in the order of $0.1$ pb\cite{11}. In these backgrounds the $m(b\bar{b})$ forms a continuum but in our signal the $m(b\bar{b})$ centers at $m_H$. So by binning on the $m(b\bar{b})$, these backgrounds could be reduced to a 5% level. The $ep \rightarrow t\bar{t}X$ background is reduced to the level of the signal, but $ep \rightarrow t\bar{t}X$ is still about two order of magnitudes larger. Further reduction can be made if we restrict on the invariant mass $m(bW) \neq m_t$. However, it is unlikely that this constraint can bring the $t\bar{t}X$ background down to the level of the signal due to the smearing of the momenta of all the particles, and also it is not applicable for the $\ell\nu b\bar{b}$ decay mode. The $ep \rightarrow WZX$ background is the same order as the signal in terms of coupling constant, and should therefore be under control as long as the $m_H$ is not close to $m_Z$. Overall, the $ep \rightarrow t\bar{t}X$ remains a major obstacle to the observation of the $WH$ signal, but the most important is the very small signal rate that makes the search via $WH \rightarrow jjb\bar{b}$ or $\ell\nu b\bar{b}$ almost impossible.

B. Laser Backscattered Photons

The situation for the laser photons is different because it is in principle pure $\gamma p$ collision. The cross section of the $WH$ signal ranges from 23 to 63 fb. Assuming a yearly luminosity of 3 fb$^{-1}$, we have about 40–110 events for the $jjb\bar{b}$ decay mode or 13–35 events for the
$\ell v b\bar{b}$ decay mode. The $t\bar{b}X$ and $tbX$ backgrounds only come from the subprocesses $q\gamma \rightarrow q'W^*\gamma \rightarrow q't\bar{b}$ and $q'\bar{t}b$, respectively. Unlike the case of bremsstrahlung photons, in which the $t\bar{b}X$ mainly comes from the subprocess $eg \rightarrow \nu W^*g \rightarrow t\bar{b} \nu$, the $tbX$ and $\bar{t}bX$ productions using the laser photons should then be of the same order as the $WH$ signal. It should also be true for the $WZX$ production via the subprocess $q\gamma \rightarrow q't^\pm Z$. These backgrounds, however, have not been calculated. The $WH$ signal search in $\gamma p$ collision under the presence of $\bar{t}bX$, $tbX$, and $WZX$ backgrounds is very similar to the $WH$ search in the $\gamma e$ collision \[6\]. According to Ref. \[6\], the $W^-H$ signal search using the $jjb\bar{b}$ mode in the $e^-\gamma$ collision is viable under the presence of $t\bar{b} \nu$, $W^-Z\nu$, and $WW e^-$ backgrounds, with or without considering $B$-tagging, and provided that all the signal lies within $|m(b\bar{b}) - m_H| < 10$ GeV. Likewise, the discovery of the $WH$ signal in $\gamma p$ collision should likely be viable, provided that the $m(b\bar{b})$ measurement has a resolution better than $m_H \pm 10$ GeV.

Since the $\gamma p \rightarrow t\bar{b}X$ and $tbX$ are of the same order as the signal, the binning on the $m(b\bar{b})$, say $|m(b\bar{b}) - m_H| < 10$ GeV, can reduce these backgrounds to a manageable level. Similarly, $\gamma p \rightarrow tlX$ can be brought down to a level much smaller than the $WH$ signal. The $\gamma p \rightarrow WZX$ background is under control as long as $m_H$ is not close to $m_Z$. When $m_H$ is in the vicinity of $m_Z$, the discovery of the signal is made possible by a precise calculation of the normalization of the $Z$-peak, plus there should be sufficient number of signal events under the $Z$-peak. Also efficient $B$-tagging is necessary to get rid of the $W$+jets, $Z$+jets, and multi-jets backgrounds. A full analysis will be presented elsewhere \[12\].

V. CONCLUSIONS

We have presented total cross sections of the associated photoproduction of a Higgs boson with a $W$ boson via $\gamma q \rightarrow WHq'$ at electron-proton colliders with the photon beam obtained by electron bremsstrahlung and by the laser backscattering method. At the LEP×LHC ($\sqrt{s} = 1.36$ TeV) under consideration, the search for an IMH boson via the photoproduction of $WH \rightarrow \ell v b\bar{b}$ or $j j b\bar{b}$ with bremsstrahlung photons is almost impossible due to the very
small signal rate. But with the laser backscattered photon beam there are a sizeable number
of signal events. Providing that the invariant mass $m(b\bar{b})$ resolution can be made better than
$m_h \pm 10$ GeV and the $B$-identification is good, the search using $\ell\nu b\bar{b}$ or $jjb\bar{b}$ modes should
be viable. But a thorough analysis taking into account of the full background is needed to
confirm this. Finally, the laser backscattering option to perform pure $\gamma p$ collision is favorable
in the future $ep$ colliders.

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TABLE I. Production cross sections in fb for $\gamma p \rightarrow W^\pm HX$ at $\sqrt{s_{ep}} = 1.36$ TeV, using (i) the bremsstrahlung photons, and (ii) laser backscattered photons, with $m_H = 60, 80, 100, 120, \text{ and } 140$ GeV. The HMRS(B) is used for the proton structure function.

| $m_H$ | (i) Bremsstrahlung photons | (ii) Laser photons |
|-------|----------------------------|-------------------|
| 60    | 4.9                        | 63                |
| 80    | 3.4                        | 47                |
| 100   | 2.5                        | 37                |
| 120   | 1.9                        | 29                |
| 140   | 1.5                        | 23                |
FIGURES

FIG. 1. Contributing Feynman diagrams for the process $d(p_1) \gamma(p_2) \rightarrow u(q_1) W^-(k_1) H(k_2)$ in the general $R_\xi$ gauge.

FIG. 2. Total cross sections for the photoproduction of $ep \rightarrow WHX$ versus the center-of-mass energies of the $ep$ system using the WWA for the bremsstrahlung photons.

FIG. 3. Total cross sections for the photoproduction of $ep \rightarrow WHX$ versus the center-of-mass energies of the $ep$ system using the luminosity function of Eqs. (3a) and (3b) for the laser backscattered photons.