

FORWARD PROTON TAGGING AS A WAY TO IDENTIFY A LIGHT HIGGS BOSON AT THE LHC*

A.D. MARTIN, V.A. KHOZE AND M.G. RYSKIN

Institute for Particle Physics Phenomenology, University of Durham
South Road, Durham DH1 3LE, UK

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We show that exclusive double-diffractive Higgs production, $pp \rightarrow p + H + p$, followed by the $H \rightarrow b\bar{b}$ decay, could play an important role in identifying a ‘light’ Higgs boson at the LHC, provided that the forward outgoing protons are tagged. We predict the cross sections for the signal and for all possible $b\bar{b}$ backgrounds.

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1. Introduction

The identification of the Higgs boson(s) is one of the main goals of the Large Hadron Collider (LHC) being built at CERN. There are expectations that there exists a ‘light’ Higgs boson with mass $M_H \lesssim 130$ GeV. In this mass range, its detection at the LHC will be challenging. There is no obvious perfect detection process, but rather a range of possibilities, none of which is compelling on its own. Some of the processes are listed in Table I, together with the predicted event rates for the integrated luminosity of 30 fb^{-1} expected over the first two or three year period of LHC running. We see that, *either* large signals are accompanied by a huge background, *or* the processes have comparable signal and background rates for which the number of Higgs events is rather small.

Here we wish to draw particular attention to process (c), which is often disregarded; that is the exclusive signal $pp \rightarrow p + H + p$, where the $+$ sign indicates the presence of a rapidity gap. It is possible to install proton taggers so that the ‘missing mass’ can be measured to an accuracy $\Delta M_{\text{missing}} \simeq 1$ GeV [3]. Then the exclusive process will allow the mass of the Higgs to be measured in two independent ways. First the tagged protons

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give $M_H = M_{\text{missing}}$ and second, via the $H \rightarrow b\bar{b}$ decay, we have $M_H = M_{b\bar{b}}$, although now the resolution is much poorer with $\Delta M_{b\bar{b}} \simeq 10$ GeV. The existence of matching peaks, centered about $M_{\text{missing}} = M_{b\bar{b}}$, is a unique feature of the exclusive diffractive Higgs signal. Besides its obvious value in identifying the Higgs, the mass equality also plays a key role in reducing background contributions. Another advantage of the exclusive process $pp \rightarrow p + H + p$, with $H \rightarrow b\bar{b}$, is that the leading order $gg \rightarrow b\bar{b}$ background subprocess is suppressed by a $J_z = 0$ selection rule [3, 9].

TABLE I

The number of signal and background events for various methods of Higgs detection at the LHC. The significance of the signal, $S/\sqrt{S+B}$, is also given. The mass of the Higgs boson is taken to be 120 GeV and the integrated luminosity is taken to be 30 fb^{-1} . The notation gg^{PP} is to indicate that the gluons originate within overall colour-singlet (hard Pomeron) t -channel exchanges. The entries for the various processes are computed from references (a) [1], (b) [2], (c) [3, 4], (d) [1, 5] and (e) [3, 6]. For (a) we show the CMS value without the NLO K factor. Including the K factors for both the signal and the background increases the $H \rightarrow \gamma\gamma$ significance to about 9σ [7].

Higgs signal	number of events		S/B	signif.
	signal	backgd.		
(a) $H \rightarrow \gamma\gamma$	313	5007	$0.06 \left(\frac{1 \text{ GeV}}{\Delta M_{\gamma\gamma}} \right)$	4.3σ
(b) $t\bar{t}H$ $\quad \quad \quad \hookrightarrow b\bar{b}$	26	31	$0.8 \left(\frac{10 \text{ GeV}}{\Delta M_{b\bar{b}}} \right)$	3σ
(c) $gg^{PP} \rightarrow p + H + p$ $\quad \quad \quad \hookrightarrow b\bar{b}$	11	4	$3 \left(\frac{1 \text{ GeV}}{\Delta M_{\text{missing}}} \right)$	3σ
(d) WBF $qWWq \rightarrow jHj \rightarrow j\tau\tau j$	25	8	3	4.4σ
(e) WBF with rap. gaps $qWWq \rightarrow j + H + j$ $\quad \quad \quad \hookrightarrow b\bar{b}$	250	1800	$0.14 \left(\frac{10 \text{ GeV}}{\Delta M_{b\bar{b}}} \right)$	5.5σ

2. Calculation of the exclusive Higgs signal

The basic mechanism for the exclusive process, $pp \rightarrow p + H + p$, is shown in Fig. 1. Since the dominant contribution comes from the region $\Lambda_{\text{QCD}}^2 \ll Q_t^2 \ll M_H^2$ the amplitude may be calculated using perturbative QCD techniques [8, 9]

$$\mathcal{M} = \frac{(\sqrt{2}G_F)^{\frac{1}{2}}\pi^2\alpha_S}{3} \int \frac{d^2Q_t}{Q_t^4} f_g \left(x_1, x'_1, Q_t^2, \frac{M_H^2}{4} \right) f_g \left(x_2, x'_2, Q_t^2, \frac{M_H^2}{4} \right), \quad (2.1)$$

where the skewed unintegrated gluon densities, f_g , are given in terms of the conventional integrated density $g(x)$. The f_g 's embody a Sudakov suppression factor T , which is effectively the survival probability that the gluon remains untouched in the evolution from Q_t up to the hard scale $M_H/2$.

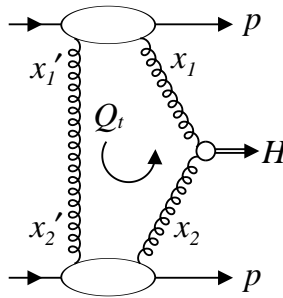


Fig. 1. Schematic diagram for the exclusive process $pp \rightarrow p + H + p$.

The radiation associated with the $gg \rightarrow H$ hard subprocess is not the only way to populate and to destroy the rapidity gaps. There is also the possibility of soft rescattering in which particles from the underlying event populate the gaps. The probability, $S^2 = 0.02$, that the gaps survive the soft rescattering was calculated using a two-channel eikonal model, which incorporates high mass diffraction [10]. Including this factor, and the NLO K factor, the cross section is predicted to be [4]

$$\sigma(pp \rightarrow p + H + p) \simeq 3 \text{ fb} \quad (2.2)$$

for the production of a Standard Model Higgs boson of mass 120 GeV at the LHC¹. It is estimated that there may be a factor two uncertainty in this prediction [3].

¹ Cross section (2.2) at the Tevatron, 0.2 fb, is too low to provide a viable signal.

The event rate in entry (c) of Table I includes a factor 0.6 for the efficiency associated with proton tagging, 0.6 for b and \bar{b} tagging, 0.5 for the b, \bar{b} jet polar angle cut, $60^\circ < \theta < 120^\circ$, (necessary to reduce the $b\bar{b}$ QCD background) and 0.67 for the $H \rightarrow b\bar{b}$ branching fraction [3]. Hence the original $(\sigma = 3 \text{ fb}) \times (\mathcal{L} = 30 \text{ fb}^{-1}) = 90$ events is reduced to an observable signal of 11 events, as shown in Table I.

3. Background to the exclusive Higgs signal

The advantage of the $p + (H \rightarrow b\bar{b}) + p$ signal is that there exists a $J_z = 0$ selection rule, which requires the leading order $gg^{PP} \rightarrow b\bar{b}$ background subprocess to vanish in the limit of massless quarks and forward outgoing protons². However, in practice, LO background contributions remain. The prolific $gg^{PP} \rightarrow gg$ subprocess may mimic $b\bar{b}$ production since we may misidentify the outgoing gluons as b and \bar{b} jets. Assuming the expected 1% probability of misidentification, and applying $60^\circ < \theta < 120^\circ$ jet cut, gives a background-to-signal ratio $B/S \sim 0.06$. Secondly, there is an admixture of $|J_z| = 2$ production, arising from non-forward going protons which gives $B/S \sim 0.08$. Thirdly, for a massive quark there is a contribution to the $J_z = 0$ cross section of order m_b^2/E_T^2 , leading to $B/S \sim 0.06$, where E_T is the transverse energy of the b and \bar{b} jets.

Next, we have the possibility of NLO $gg^{PP} \rightarrow b\bar{b}g$ background contributions. Of course, the extra gluon may be observed experimentally and these background events eliminated. However, there are exceptions. The extra gluon may go unobserved in the direction of a forward proton. This background may be effectively eliminated by requiring the equality $M_{\text{missing}} = M_{b\bar{b}}$. Then we may have soft gluon emission. First, we note that emission from an outgoing b or \bar{b} is not a problem, since we retain the cancellation between the crossed and uncrossed graphs. Emission from the virtual b line is suppressed by at least a factor of ω/E (in the amplitude), where ω and E are the energies of the outgoing soft gluon and an outgoing b quark in the $gg^{PP} \rightarrow b\bar{b}$ centre-of-mass frame. The potential danger is gluon emission from an incoming gluon, see Fig. 2. The first two diagrams no longer cancel, as the $b\bar{b}$ system is in a colour-octet state. However, the third diagram has precisely the colour and spin structure to restore the cancellation. Thus soft gluon emissions from the initial colour-singlet gg^{PP} state factorise and, due to the overriding $J_z = 0$ selection rule, QCD $b\bar{b}$ production is still suppressed. The remaining danger is large angle hard gluon emission which is collinear with either the b or \bar{b} jet, and therefore unobservable. If the cone

² In the $m_b \rightarrow 0$ limit, the two Born-level diagrams (Figs. 2(a,b) *without* the emission of the gluon) cancel each other.

angle needed to separate the g jet from the b (or \bar{b}) jet is $\Delta R \sim 0.5$ then the expected background from unresolved three jet events leads to $B/S \simeq 0.06$.

The NNLO $b\bar{b}gg$ background contributions are found to be negligible (after requiring $M_{\text{missing}} \simeq M_{b\bar{b}}$), as are soft Pomeron–Pomeron fusion contributions to the background (and to the signal) [3]. So, in total, double-diffractive Higgs production has a signal-to-background ratio of about three, after including the K factors.

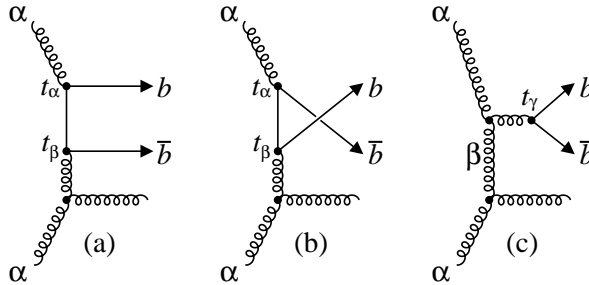


Fig. 2. The background from colour-singlet NLO $gg \rightarrow b\bar{b}g$ production, where α , β and γ are gluon colour labels and where the t_i are the colour matrices for the quark–gluon vertices.

4. Discussion

Identifying a ‘light’ Higgs will be a considerable experimental challenge. All detection processes should be considered. From Table I we see that valuable information can be obtained from weak boson fusion, where the Higgs and the accompanying jets are produced at high p_t . For example, process (d) is based on the $H \rightarrow \tau\tau$ decay for which the background is small [1, 5], whereas process (f) exploits rapidity gaps so that the larger $H \rightarrow b\bar{b}$ signal may be isolated [6], provided the pile-up problems can be overcome [3].

Here we have drawn attention to the exclusive $pp \rightarrow p + H + p$ signal, process (c). The process has the advantage that the signal exceeds the background. The favourable signal-to-background ratio is offset by a low event rate, caused by the necessity to preserve the rapidity gaps so as to ensure an exclusive signal. Nevertheless, entry (c) of Table I shows that the signal has reasonable significance in comparison to the standard $H \rightarrow \gamma\gamma$ and $t\bar{t}H$ search modes. Moreover, the advantage of the matching Higgs peaks, $M_{\text{missing}} = M_{b\bar{b}}$, cannot be overemphasised³.

³ This may be contrasted with the search for a Higgs peak sitting on a huge background in the $M_{\gamma\gamma}$ spectrum, see process (a) of Table I.

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