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Can an invisible Higgs boson be seen via diffraction at the LHC?

K. Belotsky[1,2], V.A. Khoze[3,4], A.D. Martin[3], M.G. Ryskin[3,4]

[1] Moscow Engineering Physics Institute, Moscow, Russia
[2] Center for Cosmoparticle Physics "Cosmion" of Keldysh Institute of Applied Mathematics, Moscow, 125047, Russia
[3] Department of Physics and Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, UK
[4] Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, 188300, Russia

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Abstract. We study the possibility of observing an "invisible" Higgs boson in central exclusive diffractive production at the LHC. We evaluate the cross section using, as a simple example, the standard model with a heavy fourth generation, where the invisible decay mode $H \to \nu_4\bar{\nu}_4$ dominates, with the heavy neutrino mass $M(\nu_4) \simeq 50\,\text{GeV}$. We discuss the possible requirements on trigger conditions and the background processes.

1 Introduction

There exist several extensions of the standard model (SM) in which the Higgs boson decays dominantly into particles which cannot be directly detected. One example is the standard model with a fourth generation [1–3], where the invisible decay mode $H \to \nu_4\bar{\nu}_4$ may occur with a large branching fraction [2]. In the case of supersymmetry, the Higgs can decay with a large branching ratio into gravitinos or neutralinos or other neutral supersymmetric particles; see, for example [4]. Yet another possibility are models with large extra dimensions; see, for example, [5–9]

Searches for an invisible Higgs at the LHC have been addressed recently in [10–13]. One proposal is to observe such an "invisible" Higgs in inelastic events with large missing transverse energy, $\not{E}_T$, and two high E_T jets [14, 10]. Here the Higgs boson is produced by WW fusion and therefore has large transverse momentum. However, in such a process, it is not possible to measure the mass of the boson. Moreover even the quantum numbers are not known. Other undetected neutral particles (for example, neutrinos, photinos) may be produced which carry away a large $\not{E}_T$. From this viewpoint central exclusive diffractive production, $pp \to p + H + p$ looks like a much more favourable process; see, for example, [15,16]. First, the mass M_H can be accurately determined by observing the forward going protons and measuring the missing mass [15,17]. The existence of the sharp peak in the missing mass spectrum dramatically reduces any background contributions. Second, we have information about the quantum numbers of the object produced by pomeron–pomeron fusion: the boson must be neutral, colourless, flavourless and have natural parity, $P = (-1)^J$, with $J^P = 0^+$ being by far the most likely [18,19][1].

Moreover, in some popular models (in particular, the minimal supersymmetric model (MSSM) with large values of $\tan\beta$ [21]) the coupling of the Higgs to W, Z bosons is suppressed while the coupling to gluons is enhanced [22]. Thus the inelastic production cross section with large missing E_T is suppressed, while the exclusive signal is enhanced by about an order-of-magnitude as compared to the SM prediction [24].

2 A typical cross section

To illustrate the possibility of using central exclusive diffractive production, $pp \to p+H+p$, to observe an invisible Higgs H we take a simple example. We consider the SM with an additional fourth generation of heavy fermions[2]. The mass of the heavy neutrino must be greater than $M_Z/2$, since it has not been seen in Z decays at LEP[3]. On the other hand cosmological constraints imply that it cannot be too heavy; a mass greater than a few TeV is likely to be excluded. Data on direct searches for weakly interacting massive particles (WIMP) in underground installations suggest that the fourth neutrino mass is not much above 50 GeV [25].

We therefore take $M(\nu_4) = 50\,\text{GeV}$ for our numerical estimates, and assume that all the other (charged)

[1] The spin-parity may be studied in more detail by measuring the angular correlation between the transverse momenta of the outgoing protons [20].

[2] There are arguments, both from cosmology and astrophysics [1,25] and from precision fits of electroweak data [26], in favour of the presence of a heavy fourth generation.

[3] A recent detailed analysis of the Z-resonance shape shows that the fourth generation is excluded at 95% C.L. for $M(\nu_4) < 46.7 \pm 0.2\,\text{GeV}$ [23].

Table 1. The total cross section, σ, for the exclusive double-diffractive production of a Higgs boson of mass M_H at the LHC, assuming that a fourth heavy generation of fermions exists. Most of the cross section corresponds to the invisible decay $H \to \nu_4 \bar{\nu}_4$. We take $M(\nu_4)$ to be 50 GeV. The component $\sigma(b\bar{b})$ corresponding to the visible $H \to b\bar{b}$ decay is also given. The $H \to gg$ and $H \to bb$ decay widths and branchings have been calculated using the HDECAY code [29]

M_H (GeV)	120	150	180	210
$\Gamma(H \to gg)$ (MeV)	2.2	4.1	6.9	10.8
σ (fb)	21	11	5.9	3.6
Br($b\bar{b}$)	11%	4%	0.5%	0.2%
$\sigma(b\bar{b})$ (fb)	2.3	0.4	0.03	0.007

fermions of the fourth generation have masses above the experimental lower limits; to be specific we assume that they are heavier than the top quark.

In such a scenario the branching fractions of the Higgs boson into the usual visible decay channels are suppressed due to the large $H \to \nu_4 \bar{\nu}_4$ decay width. In particular, for a Higgs of mass 120 GeV, the $H \to b\bar{b}$ decay is reduced from the SM fraction of 68% to about 10% if there is a heavy fourth generation[4]. On the other hand the $gg \to H$ coupling becomes about three times larger, as we now have three types of heavy quarks (U and D quarks of the fourth generation and the top quark) with $m_Q > M_H/2$. Thus the central exclusive Higgs production cross section is enhanced by up to a factor of 9 from the SM expectation; see, for example, [27,2]. To calculate the cross sections for a range of Higgs masses, we use the method described in [18,20,28,16]. The results, at the LHC energy, are presented in Table 1. We show the total exclusive cross section, $\sigma = \sigma(pp \to p + H + p)$, and the visible component, $\sigma(b\bar{b})$, going through the $b\bar{b}$ decay.

Interestingly, for a Higgs mass of 120 GeV, $\sigma(b\bar{b})$ remains close to the conventional SM prediction, even though the branching fraction is reduced by a factor of about 7. The suppression is compensated by the enhancement of the $H \to gg$ width by a factor of up to 9. Using the cuts and efficiences of [17], we see, from the estimates given in that paper, that we expect about 10 $p + H(\to b\bar{b}) + p$ events with a QCD $b\bar{b}$ background of four events[5], for a luminosity $\mathcal{L} = 30\,\text{fb}^{-1}$.

However for higher Higgs masses ($M_H > 150$ GeV), the cross section, $\sigma(b\bar{b})$, for the visible $b\bar{b}$ signal appears to be too small to be observable at the LHC, at least for an integrated lumionsity of the order of $30\,\text{fb}^{-1}$. On the other hand, the exclusive cross section in the invisible Higgs mode is still large enough to give a detectable event rate; even for $M_H = 210$ GeV we have a cross section of nearly 4 fb.

3 Triggering for an invisible Higgs

At first sight the best signal for an invisible Higgs decay mode would be an "empty event" trigger with no deposition in the central detector (CD). However elastic pp scattering gives a huge number of such events. For a luminosity of $\mathcal{L} = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$ we would anticipate more than 20 million background events/s, since $\sigma_{\text{el}} \geq 20$ mb. Thus the only way to isolate signal events is to use information from the forward proton detectors, which register protons with a fraction $x_p = 1-\xi$ of their incoming energy. If events are selected where both forward protons have lost some small fraction, $\xi \sim 0.001$–0.01, of their initial energy, then, first, the elastic interaction is eliminated, and, next (just by kinematics), rapidity gaps ($y_i > \ln 100 \sim 4.5$) are generated around the protons. In this case, the main background is generated by "soft" inelastic pomeron–pomeron fusion. Up to a factor of two uncertainty, the cross section for the production of the central system of low p_t particles, with the invariant mass M in the range of 100–200 GeV, is [28,18]

$$\frac{\mathrm{d}\sigma^{\text{CD}}}{\mathrm{d}y_1 \mathrm{d}y_2} = 4\,\mu\text{b}, \tag{1}$$

with a weak mass dependence[6]. Here $y_i = \ln(1/\xi_i)$ are the rapidity intervals which separate the centrally produced system from the outgoing protons[7]. The mass and the CM rapidity of the centrally produced system are

$$M^2 \simeq \xi_1 \xi_2 s \quad \text{and} \quad y = (y_1 - y_2)/2. \tag{2}$$

If we integrate over the available rapidity interval, $-2.5 < y < 2.5$ ($\Delta y \sim 5$), and account for the mass bin, $M = 100$–200 GeV, we find

$$\sigma^{\text{CD}} \sim 30\,\mu\text{b}.$$

For a luminosity of $\mathcal{L} = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$, we thus have a rate of about 30 kHz.

For the off-line analysis we would need to know only the momenta of the two tagged protons and that no other secondaries are produced. This is rather a limited amount of information and, ideally, we may even contemplate accumulating the information at 30 kHz. Moreover, one could decrease the rate by installing a veto detector to reject events containing secondaries in the central rapidity

[4] Note that for a wide range of Higgs masses, the existence of a fourth generation would induce a significant reduction of the two-photon decay width of the Higgs; see, for example, [27,2].

[5] Note that in [17] the quantity ΔM_{miss}, which was called the mass resolution, is not the dispersion, σ_{mass}, of the Gaussian distribution over the missing mass, but rather the integration range for the signal. In order to detect 95% of the signal ΔM_{miss} should be equal to $4\sigma_{\text{mass}}$. Therefore, if σ_{mass} were equal to 1 GeV, then the ratio of the signal will decrease by a factor of about 4.

[6] Note that this estimate is in a qualitative agreement with the old results [30] obtained within both, the triple-pomeron approach and the one-pion-exchange model

[7] Strictly speaking the y_i are the rapidity intervals between the respective proton (with energy E_0) and the most energetic hadron in the central system with the same transverse mass ($m_{\text{T}} = \sqrt{m_{\text{had}}^2 + p_t^2} = m_p$) and energy $E = \xi_i E_0$. For a light hadron at low p_t, the intervals will be smaller by the constant amount $\ln(m_p/m_{\text{T}})$

region. Unfortunately, in practice, such an ideal experimental set-up is very difficult to achieve. The LHC general purpose detectors – CMS and ATLAS – are designed, and optimised, for "discovery physics" with a high p_t trigger in the central rapidity region. It is not possible to trigger on "nothing" with these detectors. In particular, there will always be noise in the calorimeters.

On the other hand, for the present purpose, it is not necessary to measure the momenta of these secondaries. At the trigger level, it would be sufficient to supplement the Central Detector with an additional simple detector just to suppress events in which new particles are emitted. Indeed, at the trigger level, it would be enough to detect only charged (or only neutral, say, photons) particles in a limited rapidity interval, $|y| = 3$–6, not currently covered by the central calorimeter[8]. At the final stage, in the offline analysis the information from the Central Detector can be used to suppress the physical background more effectively.

Can we use information from the proton taggers for triggering? This issue is under study by the experimental collaborations. Various LHC beam optics are being considered [33], one of which would require forward proton detectors (roman pots or microstations) to be installed at about 300–400 m from the interaction point. Due to their distant position, the signals from these proton taggers are delayed, and it is difficult to use them as a Level-1 trigger. However future electronics may allow an extension of the trigger latency (decision making time) to 300–400 m. Alternative beam optics, currently under investigation, which would avoid the above problem, is based on roman pots at about 200 m or less from the interaction point [34]. So the situation is not resolved yet.

Note that due to "pile-up" events – that is, several independent pp interactions in a single bunch crossing – it would be better to work at a relatively low luminosity. Indeed, we need to collect only events which have no inelastic interaction in a bunch crossing. Thus, assuming that a supplementary detector is used as a veto trigger, the effective luminosity appropriate for the Level-1 trigger would be

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_0 \exp(-n(\mathcal{L}_0)), \tag{3}$$

where $n(\mathcal{L}_0)$ is the average number of pile-up events at collider luminosity $\mathcal{L}_0$. For $\mathcal{L}_0 = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$ we expect $n(\mathcal{L}_0) \simeq 2.3$, which gives $\mathcal{L}_{\text{eff}} = 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$. As a result even at the level-one, the expected detection rate of the events with the rapidity gaps will be 10 times less, and the effective integrated luminosity would be $\mathcal{L}_{\text{eff}} \simeq 3\,\text{fb}^{-1}$, and not $30\,\text{fb}^{-1}$ (as it is expected for the run with $\mathcal{L}_0 = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$). If we would assume that the efficiency of tagging both the forward protons is $\epsilon = 0.6$ [17], then about 10 events should be registered for $\mathcal{L}_{\text{eff}} = 3\,\text{fb}^{-1}$ and $M_H = 180\,\text{GeV}$. Note that the maximal value of the effective luminosity, $\mathcal{L}_{\text{eff}} = 1.5 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$, is reached at a collider luminosity of $\mathcal{L}_0 = 4 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$.

[8] Such particles will be missed by the central CMS and ATLAS detectors, but charged particles may be detected by the planned TOTEM T1 and T2 detectors [31,32]. Moreover, a combination of the signal from the forward proton detectors and the veto from the T1 and T2 detectors can help to reduce the rate of background events and to improve the trigger budget. The rate limit of about 1 kHz could be set within the present Level-1 trigger budget for this channel.

4 Background to the invisible Higgs signal

The crucial point for detecting an invisible Higgs boson is the size of the background. The only signal which is detected for the process is the registration of the two outgoing protons with a fraction $x_p = 1 - \xi$ of the initial proton momentum just less than 1; typically $\xi \simeq 0.01$. Unfortunately an outgoing proton can lose part of its energy simply by QED radiation [16]. The probability to emit a photon of energy ω is [35]

$$\frac{2\alpha}{3\pi} \frac{\langle q_{\text{T}}^2 \rangle}{m_p^2} \frac{\text{d}\omega}{\omega}, \tag{4}$$

where $q_{\text{T}} \ll m_p$ is the transverse momentum of the outgoing proton of mass m_p and $\alpha = 1/137$ is the QED coupling. Thus the cross section for quasi-elastic scattering, $pp \to (p\gamma) + (p\gamma)$, which may mimic a missing mass invisible Higgs event, is

$$\left.\frac{\text{d}\sigma}{\text{d}y}\right|_{y=0} \sim \left(\frac{2\alpha}{3\pi} \frac{\langle q_{\text{T}}^2 \rangle}{m_p^2} \right)^2 \frac{\Delta M^2}{M^2} \sigma_{\text{el}}(pp) \simeq 3\,\text{pb}. \tag{5}$$

To obtain this numerical estimate we assume an integration range of $\Delta M = 1\,\text{GeV}$ [17] and $M_H = 120\,\text{GeV}$. We have also taken $\sigma_{\text{el}} = 25\,\text{mb}$ and $\langle q_{\text{T}}^2 \rangle = 1/B_{\text{el}} = 0.05\,\text{GeV}^2$ at the LHC energy [28]. To compare the background with the cross sections presented in Table 1 we have to integrate (5) over the rapidity interval in which the Higgs signal is collected. For instance, for a Higgs of mass $M_H \sim 150\,\text{GeV}$ this interval is $|y| < 2.5$. The cross section of (5) therefore has to be integrated over the rapidity interval $\Delta y \simeq 5$. Thus we see the QED background cross section $\sigma_{\text{QED}} \simeq 15\,\text{pb}$ exceeds the invisible Higgs signal, $\sigma \simeq 10\,\text{fb}$ by almost a factor of 1500. Thus to suppress the QED background it is necessary to have forward veto electromagnetic calorimeters to detect the forward photons, with energies about $M_H/2 \simeq 75\,\text{GeV}$, with an efficiency better than about 1–$1/\sqrt{1000}$, that is 97%[9]. This may be achieved, at least to some extent, by the CMS detector by using its zero degree calorimeter (ZDC), which may allow the detection of forward photons with energies above 50 GeV.

Another source of background is double-diffractive dissociation, $pp \to X + Y$, where both the excited X and Y systems contain a proton with $\xi \sim 0.01$. The selection $\xi_{1,2} \sim 0.01$ means that we already have rapidity gaps between the forward protons and the central system. The main danger is to have "quasi-elastic" pomeron–pomeron scattering in the central region, $PP \to h_1 h_2$ where the

[9] Also it is necessary to allow for the radiative tail which will spread out the shape of the Higgs peak.

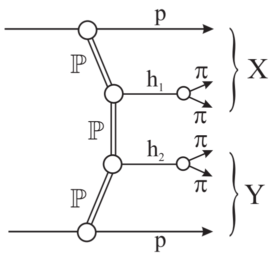

Fig. 1. A schematic diagram of the double-diffractive dissociation background $pp \to X + Y$, to an invisible Higgs signal

hadrons h_i may be, for example, the $f_0(0^{++})$ or $f_2(2^{++})$ mesons or even a glueball. Quantum numbers prevent a h_i from being a single pion. The quasi-elastic process produces low multiplicity events (typically at least four pions) with a third rapidity gap in the central region, as shown in Fig. 1. To estimate this background we use the model of [28]. The cross section of the process shown in Fig. 1 is given by

$$\frac{\mathrm{d}\sigma^{\mathrm{DD}}}{\mathrm{d}y_1 \mathrm{d}y_2} \sim \mathcal{L}_{PP} \frac{\sigma_{PP}^2}{32\pi^3 B_{PP}} = 1\text{–}100\,\mathrm{nb}, \tag{6}$$

where the effective pomeron–pomeron luminosity is [28]

$$\mathcal{L}_{PP} \sim 0.4 \times 10^{-3},$$

the pomeron–pomeron cross section in a low mass (resonance) region is $\sigma_{PP} = 1\text{–}10\,\mathrm{mb}$, and the "elastic" pomeron–pomeron scattering slope is $B_{PP} \sim 1\text{–}2\,\mathrm{GeV}^{-2}$. When we integrate over the available rapidity interval of the central system, $\Delta y \sim 5$, and account for the mass resolution,

$$\Delta M^2/M^2 = 2\Delta M/M \sim 0.02,$$

we find a background of

$$\sigma^{\mathrm{DD}} \sim 0.1\text{–}10\,\mathrm{nb}.$$

An even more conservative[10] evaluation, based on the effective pomeron–pomeron cross section $\sigma_{PP} \simeq 1.5\,\mathrm{mb}$ measured by the UA8 collaboration [36], gives $\sigma^{\mathrm{DD}} \sim 300\,\mathrm{nb}$. The centrally produced $h_1 h_2$ system will decay into at least four pions. Thus we need to be sure that at least one of the four pions will be observed. That is, the probability to detect one pion must be better than

$$1 - \left(\frac{S}{B}\right)^{\frac{1}{4}} = 1 - \left(\frac{\sigma(pp \to p + H + p)}{\sigma^{\mathrm{DD}}}\right)^{\frac{1}{4}}$$

$$\sim 1 - \left(\frac{10\,\mathrm{fb}}{300\,\mathrm{nb}}\right)^{\frac{1}{4}} \sim 99\%, \tag{7}$$

where S/B is the ratio of the invisible Higgs signal to the double-diffractive dissociation background. Since, here, we have used $\sigma^{\mathrm{DD}} = 300\,\mathrm{nb}$, it is a very conservative estimate. Even so, it appears to be a realistic requirement for the detection of the background. Of course the suppression of the background will depend on the coverage of the detectors. In this connection, we note, that in the "worst" possible decay configuration, at least one pion must have rapidity $|y_\pi| < 5$, simply from kinematic considerations[11]. Of course, a detailed evaluation of the size of the background will require a Monte Carlo simulation of the response of the available detectors to the double-diffractive dissociation events.

5 Summary

We have shown that there is a good chance to observe a Higgs boson which decays invisibly via central exclusive diffractive production, $pp \to p + H + p$. Contrary to conventional inelastic production, the mass of the Higgs boson can be accurately measured by the missing mass method. This is a crucial ingredient in reducing the background to the level of the signal. Moreover for exclusive process, it is known that the produced object is flavourless and is a colour singlet. Due to the "pile-up" problem, it will be most effective to work at luminosities in the range $\mathcal{L}_{\mathrm{eff}} = 10^{32}\text{–}10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

To suppress the background arising from QED radiation and/or soft double-diffractive dissociation, the Central Detector should be supplemented with forward calorimeters able to reject events with additional high energy photons and charged pions with energies in the range 5–200 GeV. In order to reach a signal-to-background ratio $S/B > 1$, these detectors should have an efficiency of photon or pion registration of typically 98%.

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[10] The analysis of [36] does not account for the gap survival probability, $\hat{S}^2$. Therefore the value $\sigma_{PP}^{\mathrm{eff}} = 1.5\,\mathrm{mb}$ claimed by UA8 should be considered as the product $\hat{S}^2 \sigma_{PP}$ corresponding to a "corrected" $\sigma_{PP} \sim 10\text{–}20\,\mathrm{mb}$. Also note that the UA8 evaluation [36], $\sigma^{\mathrm{DD}} \sim 300\,\mathrm{nb}$, does not take into account the decrease in the survival probability of the rapidity gaps of the three-gap process (by a factor 2–3) as we go from the energy, $\sqrt{s} = 630\,\mathrm{GeV}$, of the UA8 experiment up to the LHC.

[11] The typical energy of the two fast pions is about $(M_H/4)\mathrm{e}^{y_H}$, where M_H and y_H denote the mass and rapidity of the central system measured by the forward detectors (see (2)). For the two slow pions the energies are around $(M_H/4)\mathrm{e}^{-y_H}$. The expected CM rapidities of these four pions are in the region of $|y_\pi| \sim 4\text{–}8$.

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