Diffractive Higgs production and related processes

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We review the signal, and the $b\bar{b}$ background, for Higgs production by the exclusive double-diffractive process, $pp \to p + H + p$, and its subsequent $H \to bb$ decay, at the LHC. We discuss the production of Higgs bosons in both the SM and MSSM. We show how the predicted rates may be checked at the Tevatron by observing the exclusive double-diffractive production of dijets, or $\chi_c$ or $\chi_b$ mesons, or $\gamma\gamma$ pairs.

Key words: Higgs, diffraction, LHC

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. 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 attention to the exclusive signal $pp \to p + H + p$, where the + sign indicates the presence of a rapidity gap. It may be possible to install proton taggers so that the ‘missing mass’ can be measured very accurately. The experimental challenge is to provide a set-up in which the bulk of the proton-tagged signal is deposited in a small missing mass window $\Delta M_{\text{missing}}$ [1]. The exclusive process allows the mass of the Higgs to be measured in two independent ways. First the tagged protons give $M_H = M_{\text{missing}}$ and second, via the $H \to bb$ decay, we have $M_H = M_{bb}$, although now the resolution is much poorer with $\Delta M_{bb} \simeq 10$ GeV or more. The existence of matching peaks, centered about $M_{\text{missing}} = M_{bb}$, 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 crucial advantage of the exclusive process $pp \to p + H + p$, with $H \to bb$, is that the leading order $gg \to bb$ background subprocess is suppressed by a $J_z = 0$, P-even selection rule [2, 1].

2 Calculation of the exclusive Higgs signal

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

\[ \mathcal{M}_H \simeq N \int \frac{dQ^2_\perp}{Q^2_\perp} V_H f_g(x_1, x'_1, Q^2_1, \mu^2) f_g(x_2, x'_2, Q^2_2, \mu^2), \]

where the overall normalization constant \( N \) can be written in terms of the \( H \to gg \) decay width, and where the \( gg \to H \) vertex factors for \( \text{CP} = \pm 1 \) Higgs production are, after azimuthal-averaging,

\[ V_{H(0^+)} \simeq Q^2_1, \quad \text{and} \quad V_{A(0^-)} \simeq (\vec{p}_{1t} \times \vec{p}_{2t}) \cdot \vec{n}_0, \]

Expressions (1,2) hold for small \( p_{it} \), where the \( \vec{p}_{it} \) are the transverse momenta of the outgoing protons, and \( \vec{n}_0 \) is a unit vector in the beam direction. The \( f_g \)'s are the skewed unintegrated gluon densities at the hard scale \( \mu \), taken to be \( M_H/2 \). Since \( (x' \sim Q_1/\sqrt{s}) \ll (x \sim M_H/\sqrt{s}) \ll 1 \), it is possible to express \( f_g(x, x', Q^2_1, \mu^2) \), to single log accuracy, in terms of the conventional integrated density \( g(x) \). The \( f_g \)'s embody a Sudakov suppression factor \( T \), which ensures that the gluon does not radiate in the evolution from \( Q_1 \) up to the hard scale \( M_H/2 \), and so preserves the rapidity gaps. The apparent infrared divergence of (1) is nullified for \( H(0^+) \) production by these Sudakov factors. However the amplitude for \( A(0^-) \) production is much more sensitive to the infrared contribution. Indeed let us consider the case of small \( p_{it} \) of the outgoing protons. Then we see, from (2), that the \( dQ^2_\perp/Q^2_1 \) integration for \( H(0^+) \) is replaced by \( p_{1t} p_{2t} dQ^2_\perp/Q^2_1 \) for \( A(0^-) \), and now the Sudakov suppression is not enough to prevent a significant contribution from the \( Q^2_1 \lesssim 1 \text{ GeV}^2 \) domain.

![Schematic diagram for exclusive Higgs production at the LHC, \( pp \to p + H + p \). The presence of Sudakov form factors ensures the infrared stability of the \( Q_t \) integral over the gluon loop. It is also necessary to compute the probability, \( S^2 \), that the rapidity gaps survive soft rescattering.](image)

Fig. 1. Schematic diagram for exclusive Higgs production at the LHC, \( pp \to p + H + p \). The presence of Sudakov form factors ensures the infrared stability of the \( Q_t \) integral over the gluon loop. It is also necessary to compute the probability, \( S^2 \), that the rapidity gaps survive soft rescattering.
probability, $S^2 = 0.026$ at the LHC, that the gaps survive the soft rescattering was calculated using a two-channel eikonal model, which incorporates high mass diffraction. Including this factor, and the NLO $K$ factor, the cross section is predicted to be $\sigma(pp \to p + H + p) \simeq 3 \text{ fb}$ for the production of a Standard Model Higgs boson of mass 120 GeV at the LHC. It is estimated that there may be a factor of 2.5 uncertainty (up or down) in this prediction.

If we include a factor 0.6 for the efficiency associated with proton tagging, 0.67 for the $H \to b\bar{b}$ branching fraction, 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) then, for a luminosity of $L = 30 \text{ fb}^{-1}$, the original $3 \times 30 = 90$ events are reduced to an observable signal of 11 events.

3 Background to the exclusive Higgs signal

The advantage of the $p + (H \to b\bar{b}) + p$ signal is that there exists a $J_z = 0$ selection rule, which requires the leading order $gg^{\text{PP}} \to b\bar{b}$ background subprocess to vanish in the limit of massless quarks and forward outgoing protons. (The $\text{PP}$ superscript is to note that each gluon comes from colour-singlet $gg$ $t$-channel exchange.) However, in practice, LO background contributions remain. The prolific $gg^{\text{PP}} \to gg$ 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 $B/S \sim 0.06$. (Here, for reference, we assume that the bulk of the Higgs signal can be collected within an interval $\Delta M_{\text{missing}} = 1 \text{ GeV}$.) 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 $m_{b\bar{b}}^2/E_T^2$, 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 $gg^{\text{PP}} \to b\bar{b}g$ 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 $M_{\text{missing}} = M_{b\bar{b}}$. Moreover, soft gluon emissions from the initial $gg^{\text{PP}}$ state factorize and, due to the overriding $J_z = 0$ selection rule, these contributions to the QCD $b\bar{b}$ production are also 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 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). Also note that radiation off the screening gluon, in Fig. 4, is numerically small.
4 The signal-to-background ratio

So, in total, for the exclusive production of a 120 GeV (SM) Higgs boson at the LHC with the integrated luminosity $L = 30 \text{ fb}^{-1}$, the signal-to-background ratio is

$$S/B \simeq \left(1\text{GeV}/\Delta\text{M}_{\text{missing}}\right) 11/4 \text{ events},$$

(4) after cuts and acceptance. This corresponds to a statistical significance of roughly $3.7\sigma \sqrt{1\text{GeV}/\Delta\text{M}_{\text{missing}}}$. That is, if almost the whole Higgs signal can be collected within the interval $\Delta\text{M}_{\text{missing}} = 1\text{ GeV}$, then $S/B \simeq 3$, corresponding to a $3.7\sigma$ signal. In the case of a Gaussian missing mass distribution of width $\sigma$, about 87% of the signal is contained in a bin $\Delta\text{M}_{\text{missing}} = 3\sigma$, that is $M_{\text{missing}} = M_H \pm 1.5\sigma$.

We could consider Higgs production in other diffractive channels, such as diffractive production accompanied by proton dissociation ($pp \to M_1 + H + M_2$), or central inelastic production ($pp \to p + (M \to HX) + p$). However they are worse than the usual totally inclusive production – there is no precise missing mass measurement, no selection rule to suppress the background and more serious pile-up problems. The somewhat smaller density of soft secondary hadrons in the Higgs rapidity region does not compensate for the much smaller statistics (cross sections) in diffractive processes.

5 Exclusive SUSY Higgs signals

To be specific, we discuss the three neutral Higgs bosons of the MSSM model: $h$, $H$ with CP = 1 and $A$ with CP = −1. There are regions of MSSM parameter space where the conventional signals ($\gamma\gamma$, $WW$, $ZZ$ decays) are suppressed, but where the exclusive subprocess $gg \to H \to b\bar{b}$ is strongly enhanced[6]. For example, for $M_A = 130 \text{ GeV}$ and $\tan\beta = 50$, we have $M_h = 124.4 \text{ GeV}$ with $S/B = 71/3$ events, $M_H = 135.5 \text{ GeV}$ with $S/B = 124/2$ events and $M_A = 130 \text{ GeV}$ with $S/B = 1/2$ events, so both $h$ and $H$ should be clearly visible. (Again, for reference, we assume that $\Delta\text{M}_{\text{missing}} = 1 \text{ GeV}$ can be achieved.) The decoupling regime ($M_A \gtrsim 2M_Z$ and $\tan\beta \gtrsim 5$) is another example where the exclusive signal is of great value. In this case $h$ is indistinguishable from a SM Higgs, and so the discovery of $H$ is crucial to establish the underlying dynamics. The plot of Fig. 2, with $\tan\beta = 30$, shows that a $5\sigma$ signal is possible up to quite large values of $M_H$.

If the exclusive cross sections for scalar and pseudoscalar Higgs production were comparable, it would be possible to separate them readily by a missing mass scan, and by the study of azimuthal correlations between the outgoing protons. Unfortunately pseudoscalar exclusive production is strongly suppressed by the $P$-even selection. Maybe the best chance to identify the $A(0^-)$ boson is through the double-diffractive process, $pp \to X + A + Y$, where both protons dissociate[6].

6 Related processes: checks of the predicted exclusive Higgs yield

The exclusive Higgs signal is particularly clean, and the signal-to-background ratio is especially favourable, in comparison with the other proposed detection...
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Fig. 2. The cross sections predicted for the exclusive diffractive production of \( h(0^+) \), \( H(0^+) \) and \( A(0^-) \) MSSM Higgs bosons at the LHC, for \( \tan\beta = 30 \). The superimposed lines show the cross section required for a 5\( \sigma \) signal for integrated LHC luminosities of 30 and 300 fb\(^{-1} \). The figure is taken from Ref. [6].

modes. However the expected number of events is low. Therefore it is important to check the predictions for exclusive Higgs production by studying processes mediated by the same mechanism, but with rates which are sufficiently high that they may be observed at the Tevatron (as well as at the LHC). The most obvious examples are those in which the Higgs of Fig. 1 is replaced by either a dijet system, a \( \chi_c \) or \( \chi_b \) meson, or by a \( \gamma\gamma \) pair.

First, we discuss the exclusive production of a pair of high \( E_T \) jets, \( p\bar{p} \to p+jj+\bar{p} \) [3, 5]. This would provide an effective \( ggPP \) ‘luminosity monitor’ just in the kinematical region of the Higgs production. The corresponding cross section was evaluated to be about \( 10^4 \) times larger than that for the SM Higgs boson. Thus, in principle, this process appears to be an ideal ‘standard candle’. The expected cross section is rather large, and we can study its behaviour as a function of the mass of the dijet system. Unfortunately, in the present CDF environment, the background from ‘inelastic Pomeron-Pomeron collisions’ is large as well. Theoretically the exclusive dijets should be observed as a narrow peak, sitting well above the background, in the distribution of the ratio

\[
R_{jj} = \frac{E_{\text{dijet}}}{E_{PP}}
\]

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at $R_{jj} = 1$, where $E_{PP}$ is the energy of the incoming Pomeron-Pomeron system. In practice the peak is smeared out due to hadronization and the jet-searching algorithm. For jets with $E_T = 10$ GeV and a jet cone $R < 0.7$, more than 1 GeV will be lost outside the cone, leading to (i) a decrease of the measured jet energy of about 1-2 GeV, and, (ii) a rather wide peak ($\Delta R_{jj} \sim \pm 0.1$) in the $R_{jj}$ distribution. The estimates based on Ref. 5 give an exclusive cross section for dijet production with $E_T > 25$ GeV (and CDF cuts) of about 40 pb, which is very close to the recent CDF measurement 8.

$$\sigma(R_{jj} > 0.8, E_T > 25 \text{ GeV}) = 34 \pm 5(\text{stat}) \pm 10(\text{syst}) \text{ pb}. \quad (6)$$

However there is no ‘visible’ peak in the CDF data for $R_{jj}$ close to 1. The contribution from other channels (called Central Inelastic in Ref. 5) is too large, and matches with the expected peak smoothly $^1$).

An alternative possibility is to measure exclusive double-diffractive $\gamma \gamma$ production with high $E_T$ photons, that is $p\bar{p} \rightarrow p + \gamma \gamma + \bar{p}$ $^5$ $^10$. Here there are no problems with hadronization or with the identification of the jets. On the other hand the exclusive cross section is rather small. As usual, the perturbative QCD Pomeron is described by two (Reggeized) gluon exchange. However the photons cannot be emitted from the gluon lines directly. We need first to create quarks. Thus a quark loop is required, which causes an extra coupling $\alpha_s(E_T)$ in the amplitude. The predictions of the cross section for exclusive $\gamma \gamma$ production are shown in Fig. 3.

Recently the first ‘preliminary’ result on exclusive $\chi_c$ production has been reported 8. Although it is consistent with perturbative QCD expectations 11, the mass of the $\chi_c$-boson, which drives the scale of the process, is too low to justify just the use of perturbative QCD $^2$. However, in Ref. 11, it was found that both a Regge formalism and perturbative QCD predict essentially the same qualitative behaviour for the central double-diffractive production of ‘heavy’ $\chi_c(0^{++})$ and $\chi_b(0^{++})$ mesons. Due to the low scale, $M_{\chi_c}/2$, there is a relatively small contribution coming from the process in which the incoming protons dissociate. Therefore simply selecting events with a rapidity gap on either side of the $\chi$, almost ensures that they will come from the exclusive reaction, $p\bar{p} \rightarrow p + \chi + \bar{p}$. Although exclusive $\chi$ production is expected to dominate, the predicted 11 event rates are large enough to select double-diffractive dissociative events with large transverse energy flows in the proton fragmentation regions. Such events are particularly interesting. First, in this case, the large value of $E_T$ provides the scale to justify the validity, and the reasonable accuracy, of the perturbative QCD calculation of the cross section. Next, by measuring the azimuthal distribution between the two $E_T$ flows, the parity of the centrally produced system can be determined.

$^1$ We hope that applying the $k_t$ jet searching algorithm, rather than the jet cone algorithm, would improve the selection of the exclusive events. This is in accord with the studies in Ref. 9.

$^2$ Even lower scales correspond to the fixed target central double diffractive meson resonance production observed by the WA102 collaboration at CERN 12. Therefore, it is intriguing that the qualitative features of the observed $p_t$ and azimuthal angular distributions appear to be in good agreement with the perturbatively based expectations 13.
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| $|\eta| < 2$ | $|\eta| < 1$ |
|---|---|
| $gg \to \gamma\gamma$ | $gg \to \gamma\gamma$ |
| $gg/qq$ interf. | $gg/qq$ interf. |
| $q\bar{q} \to \gamma\gamma$ | $q\bar{q} \to \gamma\gamma$ |

Fig. 3. The contributions to the cross section for exclusive $\gamma\gamma$ production from $gg$ and $q\bar{q}$ exchange at the Tevatron and the LHC. Also shown is the contribution from the QED subprocess $\gamma\gamma \to \gamma\gamma$. For each component we show the cross section restricting the emitted photons to have $E_T > E_{\text{cut}}$ and to lie in the centre-of-mass rapidity interval $|\eta_\gamma| < 1$ (or $|\eta_\gamma| < 2$). The figure is taken from Ref. [10].

Another possible probe of the exclusive double-diffractive formalism would be to observe central open $b\bar{b}$ production; namely $b,\bar{b}$ jets with $p_t \gtrsim m_b$. Again, this would put the application of perturbative QCD on a sounder footing. It would allow a check of the perturbative formalism, as well as a study of the dynamics of $b\bar{b}$ production.

7 Conclusion

If the Higgs is light, $M_H \lesssim 135$ GeV, it will be experimentally challenging to study it in detail at the LHC. All possible processes should be considered. Here we have emphasised the unique advantages of exclusive double-diffractive Higgs
production, provided the forward outgoing protons can be precisely tagged. The missing mass, \( M_{\text{missing}} \), measured by the forward proton detectors can then be matched with the mass \( M_{b \bar{b}} \) from the main decay mode, \( H \to b \bar{b} \). Moreover the QCD \( b \bar{b} \) background is suppressed by a \( J_z = 0 \) selection rule. The events are clean, but the predicted yield is low: about 10 events, after cuts and acceptance, for an integrated luminosity of \( \mathcal{L} = 30 \text{ fb}^{-1} \). The signal-to-background ratio is about 1 or better, depending crucially on the accuracy with which \( M_{\text{missing}} \) can be measured. We have emphasized the importance of checking these perturbative QCD predictions by observing analogous double-diffractive processes, with larger cross sections, at the Tevatron.

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References
[1] A. De Roeck, V.A. Khoze, A.D. Martin, R. Orava and M.G. Ryskin, Eur. Phys. J. C25 (2002) 391.
[2] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C19 (2001) 477.
[3] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C14 (2000) 525.
[4] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C18 (2000) 167.
[5] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C23 (2002) 311.
[6] A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C33 (2004) 261.
[7] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C26 (2002) 229.
[8] M. Gallinaro (representing the CDF Collaboration), FERMILAB-CONF-03-403-E, November 2003, arXiv:hep-ph/0311192.
[9] B. Cox, J.R. Forshaw and A. Pilkington, in preparation.
[10] V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Stirling, arXiv:hep-ph/0409037.
[11] V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. C35 (2004) 211.
[12] WA102 Collaboration: D. Barberis et al., Phys. Lett. B467 (1999) 165; ibid. B474 (2000) 423; ibid. B484 (2000) 198; ibid. B488 (2000) 225; ibid. B453 (1999) 305,316.
[13] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C24 (2002) 581.