Insight into New Physics with Tagged Forward Protons at the LHC

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Abstract

The addition of forward proton detectors to LHC experiments will significantly enlarge the potential for studying New Physics. We discuss a topical example of Higgs production by the central exclusive diffractive process, $pp \rightarrow p + H + p$. Special attention is paid to the backgrounds to the $H \rightarrow b\bar{b}$ signal.

1 Introduction

The use of diffractive processes to study the Standard Model (SM) and New Physics at the LHC has only been fully appreciated within the last few years; see, for example [1–6]. By detecting protons that have lost only about 1-3% of their longitudinal momentum [7], a rich QCD, electroweak and BSM programme becomes accessible experimentally, with the potential to study phenomena which are unique to the LHC, and difficult even at a future linear collider. Particularly interesting are the so-called central exclusive production (CEP) processes which provide an extremely favourable environment to search for, and identify the nature of, new particles at the LHC. The first that comes to mind are the Higgs bosons, but there is also a rich, more exotic, physics menu including (light) gluino and squark production, searches for extra dimensions, gluinonia, radions, and indeed any new object which has 0^{++} (or 2^{++}) quantum numbers and couples strongly to gluons. By "central exclusive" we mean a process of the type $pp \rightarrow p+X+p$, where the + signs denote the absence of hadronic activity (that is, the presence of rapidity gaps) between the outgoing protons and the decay products of the centrally produced system X. The basic mechanism driving the process is shown in Fig. 1. There are several reasons why CEP is
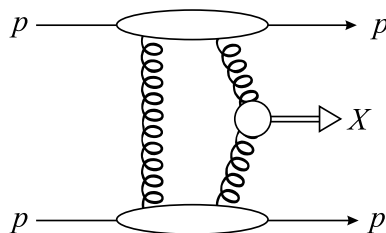

Fig. 1: The basic mechanism for the exclusive process $pp \rightarrow p + X + p$. The system X is produced by the fusion of two active gluons, with a screening gluon exchanged to neutralize the colour.

especially attractive for searches for new heavy objects. *First*, if the outgoing protons remain

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intact and scatter through small angles then, to a very good approximation, the primary active di-gluon system obeys a $J_z = 0$, C-even, P-even, selection rule [8]. Here J_z is the projection of the total angular momentum along the proton beam axis. This selection rule readily permits a clean determination of the quantum numbers of the observed new (for example, Higgs-like) resonance, when the dominant production is a scalar state. *Secondly*, because the process is exclusive, the energy loss of the outgoing protons is directly related to the mass of the central system, allowing a potentially excellent mass resolution, irrespective of the decay mode of the centrally produced system. *Thirdly*, in many topical cases, in particular, for Higgs boson production, a signal-to-background ratio of order 1 (or even better) is achievable [3, 9–11]. In particular, due to $J_z = 0$ selection, leading-order QCD $b\bar{b}$ production is suppressed by a factor $(m_b/E_T)^2$, where E_T is the transverse energy of the $b, \bar{b}$ jets. Therefore, for a low mass Higgs, $M_H \lesssim 150$ GeV, there is a possibility to observe the main $b\bar{b}$ decay mode and to directly measure the $H \to b\bar{b}$ Yukawa coupling constant. The signal-to-background ratio may become significantly larger for a Higgs boson in certain regions of the MSSM parameter space.

It is worth mentioning that, by tagging both of the outgoing protons, the LHC is effectively turned into a gluon-gluon collider. This will open up a rich, QCD physics menu, which will allow the study of the skewed, unintegrated gluon densities, as well as the details of rapidity gap survival. Note that CEP provides a source of practically pure gluon jets; that is we effectively have a 'gluon factory' [8]. The forward-proton-tagging approach also offers a unique programme of high-energy photon-interaction physics at the LHC.

2 Central Exclusive Higgs production

The 'benchmark' CEP new physics process is Higgs production. Studies of the Higgs sector are at the heart of the recent proposal [7] to complement the LHC central detectors with proton taggers placed at 420 m either side of the interaction point.

Our current understanding is, that if a SM-like Higgs boson exists in Nature, it will be detected at the LHC. However, various extended models predict a large diversity of Higgs-like bosons with different masses, couplings and CP-parities. The best studied extension of the SM up to now is the MSSM, in which there are three neutral Higgs bosons, the scalars h and H, and the pseudoscalar A.

The forward proton tagging mode is especially advantageous for the study of the MSSM sector. Note that when using the "standard" non-diffractive production mechanisms, there is usually an important region of MSSM parameter region, where the LHC can detect only the Higgs boson with SM-like properties. To check that a discovered state is indeed a scalar Higgs boson, and to distinguish between the Higgs boson(s) of the SM or the MSSM and those from of extended Higgs theories will be highly non-trivial task. Without forward proton tagging, it would require interplay with observations at the Next Linear Collider. Moreover, within the MSSM, the weak-boson-fusion channel becomes of no practical use for the production of the heavier scalar H or the pseudoscalar A boson. On the other hand, in the forward proton mode the pseudoscalar A is practically filtered out, and the detection of the H boson should be achievable [9, 10]. In addition, in some MSSM scenarios, CEP provides an excellent opportunity for probing the CP-structure of the Higgs sector by measuring directly the azimuthal asymmetry of the outgoing protons [12]. In Fig. 2 we show, for reference purposes, the total CEP cross section for the SM Higgs boson
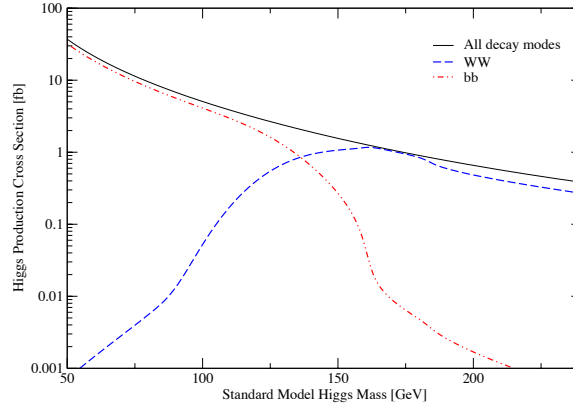
Fig. 2: The cross section times branching ratio for CEP of the SM Higgs [13].

times branching ratio for the WW and $b\bar{b}$ channels, as a function of the Higgs mass. We see that the expected total cross section for the CEP of a SM Higgs, with mass 120 GeV, is 3 fb, falling to just less than 1 fb for a mass of 200 GeV. With a good understanding of the detectors and favourable experimental conditions, the rate for the SM Higgs of mass 120 GeV for the integrated LHC luminosity of $\mathcal{L} = 60$ fb^{-1} would be quite sizeable (around 100 events). However, with the presently envisaged LHC detectors, there are various experimental problems. First of all, trigger signals from protons detected at 420 m cannot reach the central detector in time to be used in the Level 1 trigger. For this, we have to rely on the central detector. Other factors may also strongly reduce the current expectations for the detected signal rate, in particular, the b-tagging efficiency, the jet energy resolution etc. At high luminosities there is also a potentially dangerous problem of backgrounds due to the overlapping events in the same bunch crossing (the so-called "pile-up" events). In summary, with the current hardware, the expectation is that there will be not more than a dozen SM Higgs signal events for an integrated LHC luminosity of $\mathcal{L} = 60$ fb^{-1}. Whether experimental ingenuity will increase this number remains to be seen. Indeed, it is quite possible that "clever" hardware and the use of optimized cuts will increase the rate.

As we already mentioned, in the MSSM, the CEP cross sections can be an order-of-magnitude or more higher. This is illustrated in Fig. 3, which shows the contours for the ratio R of signal events in the MSSM over those in the SM in the CEP of $H \rightarrow b\bar{b}$ in the M_A–$\tan\beta$ plane, see [10].

As discussed above, the exclusive Higgs signal is particularly clean, and the signal-to-background ratio is quite favourable, at least, at an instantaneous luminosity $L \sim 2 \times 10^{33}$ cm^{-2} s^{-1}, when the effect of pile-up can be kept under full control, see [10, 11] and references therein. However, without improving the LHC hardware, the expected event rate in the SM case is quite limited, and so it is important to test various ingredients of the adopted theoretical scheme [1, 2, 8] by studying the related processes at HERA and the Tevatron. Various such tests have been performed so far,
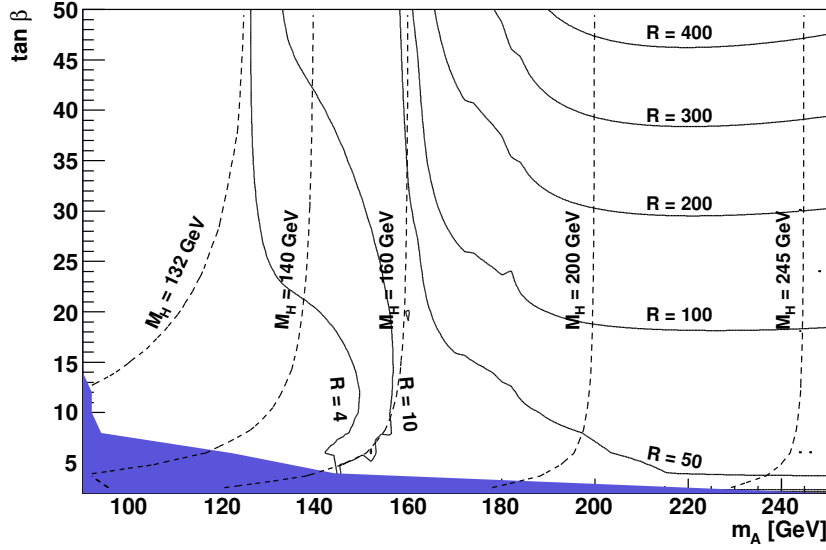
Fig. 3: Contours for the ratio R of the $H \rightarrow b\bar{b}$ signal events in the MSSM over those in the SM in CED process in the M_A–$\tan\beta$ plane. The ratio is shown for the M_h^{max} benchmark scenario (with $\mu = +200$ GeV). The values of the mass of the Higgs boson are indicated by dashed contour lines. The dark shaded region is excluded by the LEP Higgs searches.

see for example, [14, 15] and references therein.

The straightforward checks come from the study of processes which are mediated by the same mechanism as CEP of the Higgs boson, but with rates which are sufficiently high, so that they may be observed already at the Tevatron. The most obvious examples are those in which the Higgs is replaced by either a dijet system, or a χ_c meson, or a $\gamma\gamma$ pair. The reported preliminary CDF data on these CEP processes (see for example, [16]) show a good agreement with the theoretical expectations by Durham group.

Especially impressive are the recent CDF data [16] on exclusive production of a pair of high E_T jets, $p\bar{p} \rightarrow p + jj + \bar{p}$. The corresponding cross section was evaluated to be about 10^4 times larger than that for the production of a SM Higgs boson. Since the dijet CEP cross section is rather large, this process appears to be an ideal 'standard candle'. A comparison of the data with analytical predictions [1, 2] is given in Fig. 4. It shows the E_T^{min} dependence for the dijet events with $R_{jj} \equiv M_{\mathrm{dijet}}/M_{\mathrm{PP}} > 0.8$, where M_{PP} is the invariant energy of the incoming Pomeron-Pomeron system. The agreement with the theoretical expectations [1, 2] lends credence to the predictions for the CED Higgs production [16].

3   The backgrounds to the $p + (h, H \rightarrow b\bar{b}) + p$ signal

The importance of the $p + (h, H \rightarrow b\bar{b}) + p$ process means that the physical backgrounds to this reaction must be thoroughly addressed. Recall that the unique advantage of the $b\bar{b}$ CEP process
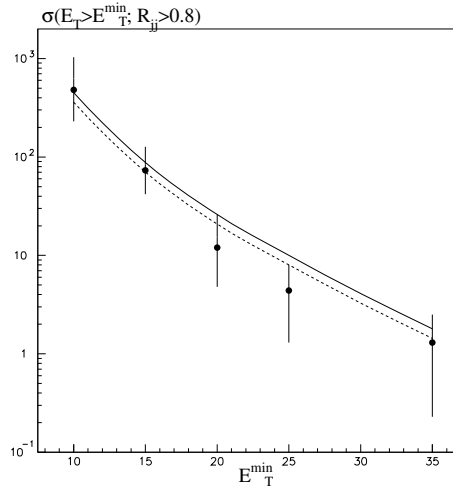
Fig. 4: The cross section for 'exclusive' dijet production as a function $E_T^{\min}$ as measured by CDF [16]. The data correspond to the cross section integrated over the domain $R_{jj} \equiv M_{\mathrm{dijet}}/M_{\mathrm{PP}} > 0.8$ and $E_T > E_T^{\min}$. A jet cone of $R < 0.7$ is used. The curves are the exclusive cross section calculated [2] using the CDF event selection. The solid curve is obtained by rescaling the parton transverse momentum p_T to the measured jet transverse energy E_T by $E_T = 0.8p_T$. The dashed curve assumes $E_T = 0.75p_T$. The rescaling procedure effectively accounts for the hadronization and radiative effects, and for jet energy losses outside the jet cone.

is the $J_z = 0$ selection rule, which requires the LO $gg^{PP} \to b\bar{b}$ background to vanish in the limit of massless quarks and forward going protons. However, there are still four main sources of background [3, 17].

   (i) The prolific (LO) $gg^{PP} \to gg$ subprocess can mimic $b\bar{b}$ production since we may misidentify the gluons as b and $\bar{b}$ jets.

 (ii) An admixture of $|J_z| = 2$ production, arising from non-forward going protons, which contributes to the LO $gg^{PP} \to b\bar{b}$ background.

(iii) Because of non-zero mass of the quark there is a contribution to the $J_z = 0$ cross section of order m_b^2/E_T^2. This term currently raises the main concern. The problem is that the result is strongly affected by the large higher-order QCD effects. In particular, the one-loop double logarithmic contribution exceeds the Born term, and the final result becomes strongly dependent on the NNLO effects. There is no complete calculation of these effects for the $gg^{PP} \to b\bar{b}$ process. The validity of estimates given in [17] has an accuracy not better than a factor of 2-4. The good news is that this contribution decreases with increasing E_T much faster than the other backgrounds.

(iv) Finally, there is a possibility of NLO $gg^{PP} \to b\bar{b}g$ background contributions, which for large angle, hard gluon radiation do not obey the selection rules. In particular, the extra gluon may go unobserved in the direction of a forward proton. This background is reduced by requiring the approximate equality $M_{\mathrm{missing}} = M_{b\bar{b}}$. Calculations [18] show that this

background may be safely neglected. The remaining danger is large-angle hard gluon emission which is collinear with either the b or $\bar{b}$ jet, and, therefore, unobservable. This background source results in a sizeable contribution, see [17].

There are also other (potentially worrying) background sources, which after a thorough investigation [17, 18], have been neglected. This is either because their contributions are numerically small from the very beginning, or because they can be reduced to an acceptable level by straightforward experimental cuts.

Next, a potential background source can arise from the collision of two soft Pomerons. Such backgrounds were carefully evaluated in [18], and it was found that they are quite small.

In summary, the main background contributions come from exclusive dijet production as listed in the items (i)-(iv) above. Within the accuracy of the existing calculations [3, 8, 17], the overall background to the 0^+ Higgs signal in the $b\bar{b}$ mode can be approximated by the following formula, see [10]

$$\frac{\mathrm{d}\sigma^B}{\mathrm{d}M} \approx 0.5 \,\mathrm{fb/GeV} \left[0.92 \left(\frac{120}{M} \right)^6 + \frac{1}{2} \left(\frac{120}{M} \right)^8 \right].$$ (1)

Note that this approximate expression may be used only for the purposes of making quick estimates of the background, since no detector simulation has been performed.

4 Conclusion

The installation of proton-tagging detectors in the distant forward regions around the ATLAS and/or CMS central detectors would add unique capabilities to the existing LHC experimental programme. The calculation of the rates of CEP processes show that there is a good chance that new heavy particle production could be observed in this mode. For a Higgs boson this would amount to a direct determination of its quantum numbers. For certain MSSM scenarios, the tagged-proton channel may even be the Higgs discovery channel. Moreover, with sufficient luminosity, proton tagging may provide direct evidence of CP-violation within the Higgs sector. There is also a rich QCD, electroweak, and more exotic physics, menu.

Here we focused on the unique advantages of CEP Higgs production. The events are clean, but the predicted yield for the SM Higgs for an integrated luminosity of $\mathcal{L} = 60\,\mathrm{fb}^{-1}$ is comparatively low, after experimental cuts and acceptances. Further efforts to optimize the event selection and cut procedure are very desirable. In the MSSM there are certain regions of parameter space which can be especially 'proton tagging friendly' [9–11]. Here the signal-to-background ratios in the $b\bar{b}$ channel can exceed the SM by up to two orders of magnitude. Moreover, the observation of the decay of Higgs to $b\bar{b}$ would allow a direct determination of the $H \to b\bar{b}$ Yukawa coupling. From the experimental perspective, the simplest exclusive channel in which to observe a SM Higgs boson with mass between 140 GeV and 200 GeV is the WW decay mode. However, contrary to the $b\bar{b}$ case, no dramatic rise in the rate is expected within the MSSM [10].

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