Physics with forward protons at hadron colliders\textsuperscript{1}

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Abstract

We emphasize the importance of tagging the outgoing forward protons to sharpen the predictions for New Physics at the LHC. 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.

1 Introduction

Recently there has been much interest in studying events with tagged forward protons at present and forthcoming hadronic colliders, see, for example, [1, 2]. This may not only allow the luminosity of the colliding protons to be monitored with high accuracy [3], but also can provide new ways to investigate the subtle issues of QCD and to search for the manifestations of the New Physics. As discussed in [1] the programme with the tagged forward protons is in many aspects complementary to both the standard physics at hadron colliders and to studies at a future linear collider.

The physics potential of high energy proton colliders can be significantly increased by studying exclusive double-diffractive-like processes of the type $pp \rightarrow p + M + p$. Here $M$ represents

\textsuperscript{1}Presented at the 31st International Conference on High Energy Physics (ICHEP02), Amsterdam, Netherlands, 24–31 July 2002.
a system of invariant mass $M$, and the + signs denote the presence of rapidity gaps which separate the system $M$ from the protons. Such processes allow an exceptionally clean experimental environment to identify New Physics signals (such as the Higgs boson, SUSY particles, etc., see [1]). In such events we produce a colour-singlet state $M$ which is practically free from soft secondary particles. Moreover, if forward going protons are tagged we can reconstruct the ‘missing’ mass $M$ with good resolution, and so have an ideal means to search for new resonances and to study threshold behaviour phenomena. We have to pay a price for ensuring such a clean diffractive signal. In particular, the diffractive event rate is suppressed by the small probability, $\hat{S}^2$, that the rapidity gaps survive soft rescattering effects between the interacting hadrons, which can generate secondary particles which populate the gaps, see, for example, [4, 5] and references therein.

2 Exclusive Higgs Production

Double-diffractive Higgs production, $pp \to p+H+p$, at the LHC, is a good example to illustrate the pros and cons of exclusive processes. Let us assume a Higgs boson of mass $M_H = 120$ GeV and consider detection in the $b\bar{b}$ channel. It is possible to install proton taggers so that the ‘missing mass’ can be measured to an accuracy $\Delta M_{\text{missing}} \approx 1$ GeV [2]. Then the exclusive process will allow 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 $H \to b\bar{b}$ decay, we have $M_H = M_{b\bar{b}}$, although now the resolution is much poorer with $\Delta M_{b\bar{b}} \approx 10$ 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 this exclusive process, with $H \to b\bar{b}$, is that the leading order $gg \to b\bar{b}$ background subprocess is suppressed by a $J_z = 0$ selection rule [6, 7]. The disadvantage is that, to ensure the survival of the rapidity gaps, the predicted $H \to b\bar{b}$ cross section is low, $\sigma \approx 2$ fb, corresponding to a soft survival factor $\hat{S}^2 = 0.02$. It is estimated that there is a factor two uncertainty in this prediction [2].

For an integrated luminosity of 30 fb$^{-1}$ the number of signal (background) events for this method of Higgs detection at the LHC is expected to be 11 (4). These include a factor 0.6 for the efficiency associated with proton tagging, 0.6 for $b$ and $\bar{b}$ tagging and 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) [2].

There exists a huge spread of predictions of the cross sections for diffractive Higgs production, see, for example, [8, 9, 10, 11], which can differ from [1, 2] by orders of magnitude. A critical comparison between these predictions, and an explanation of their differences with our results, is given in [12].

A way to check experimentally the reliability of the predictions of exclusive production is to measure the much larger cross section for an analogous process: double-diffractive central production of a pair of high-$E_\perp$ jets [13]. Some of the existing approaches overshoot the
current CDF dijet data [14] by a few orders of magnitude; others are just normalized to the experimental rates in order to account for the survival effects. However, the latter procedure is not unambiguous, since there is no direct way of using the dijet overshoot factors to correct the expectations for Higgs production. The perturbative approach [13] predicts about 1 nb [6] for the exclusive central production of dijets with $E_\perp > 7$ GeV, corresponding to the CDF kinematics [14] to be compared with the observed exclusive dijet bound of less than 3.7 nb. Moreover, in the case of central inelastic production (when secondaries are allowed in some central rapidity interval), our estimates give about 40 nb (with a factor two uncertainty) for the cross section in the CDF kinematical range, while the observed value [14] is $43.6 \pm 4.4 \pm 21.6$ nb. Bearing in mind that the accuracy of the theoretical predictions for $E_\perp > 7$ GeV jets at the Tevatron energy is far from perfect, we find this preliminary comparison quite encouraging.

Another valuable check of the calculations of the soft survival factor $\hat{S}^2$ (which originates from the non-perturbative sector) is the description of diffractive dijet production at the Tevatron [15] in terms of the diffractive structure functions measured at HERA [5]. The remarkably good agreement of these predictions with the CDF measurements is a confirmation that our calculations of $\hat{S}^2$ [4, 5, 13] are trustworthy. Moreover, the new fit to the H1 diffractive data [16] makes the agreement with the CDF results even better².

Details of the calculation of exclusive Higgs production are given in Ref. [1]. The main sources of the $b\bar{b}$ background are, at leading order, caused by gluon jets being misidentified as a $b\bar{b}$ pair, by a $J_z = 2$ admixture due to non-forward protons and by a $J_z = 0$ contribution arising from $m_b \neq 0$. Also there is a background contribution from $b\bar{b}g$ events in which the emitted gluon is approximately collinear with a $b$ jet. These backgrounds were considered in detail in Ref. [2], leading to a prediction of the signal-to-background ratio of about 3. Note that in [2] only the $gg \to b\bar{b}g$ hard subprocess was considered at NLO, and radiation for the spectator, screening gluon was not discussed. However, this latter process is numerically small because of the additional suppression of colour-octet $b\bar{b}$ production around 90°; rotational invariance around the $b$ quark direction causes the cross section to be proportional to $\cos^2 \theta$ in the $b\bar{b}$ c.m. frame.

The cross sections for inclusive and central inelastic diffractive Higgs production are larger than for exclusive production. However, for these non-exclusive processes it is hard to suppress the QCD $b\bar{b}$ background and the signal-to-background ratio is small. Second, we cannot improve significantly the accuracy of the measurement of the mass of the Higgs boson by tagging the forward protons and measuring the missing mass.

Recall that, at medium and high luminosity at the LHC, the recorded events will be plagued by overlap interactions in the same bunch crossing. For example, at the medium luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$, an average of 2.3 inelastic events are expected for each bunch crossing. Hence the rapidity gaps occurring in one interaction may be populated by particles created in an

²Another probe of the calculations of $\hat{S}^2$ could come from the experimental studies of the central $Z$ production by $WW$ fusion, see, for instance, [17].
accompanying interaction. It is, however, possible to use detector information to locate the vertices of the individual interactions and, in principle, to identify hard scattering events with rapidity gaps. For the exclusive and central inelastic processes, the use of proton taggers makes it much more reliable to select the rapidity gap events.

3 Conclusion

The Physics menu for LHC studies with tagged forward protons looks quite attractive and promising [1]. In particular, the exclusive $pp \to p + H + p$ 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, as shown in [2], the signal for a ‘light’ Higgs has reasonable significance in comparison to the standard $H \to \gamma\gamma$ and $t\bar{t}H$ search modes. Moreover, the advantage of the matching Higgs peaks, $M_{\text{missing}} = M_{bb}$, cannot be overemphasized.

We stress that the predicted value of the exclusive cross section can be checked experimentally. All the ingredients, except for the NLO correction to the $gg \to H$ vertex, are the same for our signal as for exclusive double-diffractive dijet production, $pp \to p + \text{dijet} + p$, where the dijet system is chosen in the same kinematic domain as the Higgs boson, that is $M(jj) \sim 120$ GeV. Therefore by observing the larger dijet production rate, we can confirm, or correct, the estimate of the exclusive Higgs signal.

Acknowledgements

We thank Albert De Roeck, Aliosha Kaidalov and Risto Orava for valuable discussions, and the EU, PPARC and the Leverhulme Trust for support.

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