Diffractive processes as a tool for searching for new physics

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Abstract: We show that the addition of detectors to tag the outgoing forward protons, at the LHC, will significantly enlarge the potential of studying New Physics. A topical example is Higgs production by the exclusive double-diffractive process, $pp \rightarrow p + H + p$. 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.

1 Introduction

The use of forward proton detectors as a means to study Standard Model (SM) and New Physics at the LHC has only been fully appreciated within the last few years; see, for example \cite{1,2,3,4,5} and references therein. By detecting protons that have lost less than about 2\% of their longitudinal momentum, a rich QCD, electroweak, Higgs and BSM programme becomes accessible, with a potential to study phenomena which are unique to the LHC, and difficult even at a future linear collider \cite{6}.

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In particular, the so-called central exclusive production (CEP) processes may provide a very friendly environment to search for, and identify the nature of, new particles at the LHC; in particular, Higgs bosons. There is also a potentially rich, more exotic, physics menu including (light) gluino and squark production, gluinonia, radions, and indeed any object which has 0++ (or 2++) quantum numbers and couples strongly to gluons \[1\]. By central exclusive, we mean the process $pp \rightarrow p + X + p$, where the + signs denote the absence of hadronic activity (that is, the presence of a rapidity gap) between the outgoing protons and the decay products of the central system $X$.

It is a pleasure to recall that the whole strategy of predicting diffractive phenomena, and, in particular, of CEP processes, is based on the ideas developed by V.N. Gribov. We list only some of these: Regge poles in particle physics, the vacuum pole (Pomeron) and its shrinkage, Glauber-Gribov theory of multiple scattering, Gribov’s reggeon calculus, Gribov’s factorization, the Abramovsky-Gribov-Kancheli cutting rules, Gribov’s theorem for bremsstrahlung at high energies, the Gribov-Lipatov (DGLAP) evolution equations, the Frolov-Gorshkov-Gribov-Lipatov approach to Regge processes in gauge theories, and much, much more.

There are three main reasons why CEP is especially attractive for searches for new heavy objects. First, if the outgoing protons remain 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 \[7,8\]. 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, which will be dominantly produced in 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 produced particle.\(^2\) Thirdly, a signal-to-background ratio of order 1 (or even better) is achievable \[9,12\]. This ratio becomes significantly larger for the lightest Higgs boson in certain regions of the MSSM parameter space \[10\].

Moreover, in some MSSM Higgs scenarios CEP provides an opportunity for a lineshape analysis \[10,11\]. Another attractive feature is the ability to directly probe the CP-structure of the Higgs sector by measuring the azimuthal asymmetry of the outgoing tagged protons \[12\]. A different strategy, to explore the manifestation of explicit CP-violation in the Higgs sector, was

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\(^2\)Recent studies suggest that the missing mass resolution $\sigma$ will be of order 1% for a 140 GeV central system, assuming both the outgoing protons are detected at 420m from the interaction point \[2,6\].
recently studied by Ellis et al. [11].

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, ‘high-rate’ QCD physics menu (especially concerning diffractive phenomena), which will allow the study of the skewed, unintegrated gluon densities, as well as the details of rapidity gap survival; see, for example, [113]. Note that CEP provides a source of practically pure gluon jets; that is we effectively have a ‘gluon factory’ [8]. This can be an ideal laboratory in which to study the properties of gluon jets, especially in comparison with the quark jets, and will even allow a search for glueballs. The forward-proton-tagging approach also offers a unique programme of high-energy photon-interaction physics at the LHC; see, for example, [3][14].

The ‘benchmark’ CEP process, for these new physics searches, is Higgs production. In the mass range around 115-130 GeV, its detection at the LHC will not be an easy task. 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. The predicted cross section for the CEP production of a SM Higgs, with mass 120 GeV, at the LHC is 3 fb, falling to 1 fb for a mass of 200 GeV; see [15].

From an experimental perspective, the $WW$ decay channel is the simplest way to observe the SM Higgs in the tagged-proton approach [16][17]. The $b\bar{b}$ decay channel is more challenging from a trigger perspective, although, in this case, the ‘useful’ event rate is more favourable for masses below about 130 GeV. Moreover, the latter decay mode becomes extremely important in the so-called intense coupling regime [18] of the MSSM, where CEP is likely to be the discovery channel [10]. In this case, we expect about $10^3$ exclusively produced double-tagged Higgs bosons for 30 fb$^{-1}$ of delivered luminosity. About 100 would survive the experimental cuts [9], with a signal-to-background ratio of the order of 10.

In the case of the exclusive process, $pp \rightarrow p+H+p$, a major experimental task is to provide a set-up in which the bulk of the proton-tagged Higgs signal is deposited in a smallest possible missing-mass window; $\Delta M_{\text{missing}}$ of about 3 GeV should be achievable. Note that for the $b\bar{b}$ channel the CEP 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 $H \rightarrow b\bar{b}$ 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 or more. 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 crucial advantage of the exclusive process $pp \to p + H + p$, with $H \to b\bar{b}$, is that the leading order $gg \to b\bar{b}$ background subprocess is suppressed by the $J_z = 0$, P-even selection rule \[8,9\].

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 $\Lambda_{QCD}^2 \ll Q_t^2 \ll M_H^2$, the amplitude may be calculated using perturbative QCD techniques \[15,8\]

$$M_H \approx N \int \frac{dQ_t^2}{Q_t^4} \frac{V_H}{Q_t^2} f_\bar{g}(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2),$$

(1)

where the overall normalization constant $N$ can be written in terms of the $H \to gg$ decay width \[11,15\], and where the $gg \to H$ vertex factors for CP $= \pm 1$ Higgs production are, after azimuthal-averaging,

$$V_{H(0+)} \approx Q_t^2, \quad \text{and} \quad V_{A(0-)} \approx (\vec{p}_1t \times \vec{p}_2t) \cdot \vec{n}_0,$$

(2)

Expressions \[11,2\] 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 $f_\bar{g}$'s are the skewed unintegrated gluon densities at the hard scale $\mu$, taken to be $M_H/2$. Since $(x' \sim Q_t/\sqrt{s}) \ll (x \sim M_H/\sqrt{s}) \ll 1$, it is possible to express $f_\bar{g}(x, x', Q_t^2, \mu^2)$, 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 $Q_t$ 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.\(^3\) 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 $dQ_t^2/Q_t^4$ integration for $H(0^+)$ is replaced by $p_{1t}p_{2t}dQ_t^2/Q_t^6$ for $A(0^-)$, and now the Sudakov suppression is not enough to prevent a significant contribution from the low $Q_t^2$ domain.

The radiation associated with the $gg \to H$ hard subprocess is not the only way to populate and to destroy the rapidity gaps. There is also the possibility \(^3\)Note also that the Sudakov factor inside the loop integration induces an additional strong decrease (roughly as $M^{-3}$ \[10\]) of the cross section as the mass $M$ of the centrally produced hard system increases. Therefore, the price to pay for neglecting this suppression effect would be to considerably overestimate the CEP cross section at large masses.
Figure 1: Schematic diagram for central exclusive production, $pp \rightarrow p + X + p$. 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.

of soft rescattering in which particles from the underlying event populate the gaps. The probability, $S^2 = 0.03$ at the LHC, that the gaps survive the soft rescattering was calculated using a two-channel eikonal model, which incorporates high mass diffraction\[19\]. Including this factor, and the NLO $K$ factor, the cross section is predicted to be $[1,15]$ \[3\]

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

for the production of a SM Higgs boson of mass 120 GeV at the LHC. We evaluated that there may be a factor of 2.5 uncertainty (up or down) in this prediction\[10\].

If we include a factor 0.6 for the efficiency associated with proton tagging, 0.67 for the $H \rightarrow b\bar{b}$ 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)\[9\], 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 $H \rightarrow b\bar{b}$ 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 protons. (The $PP$ superscript is to note that each gluon comes from colour-singlet $gg$ $t$-channel exchange.) However, in practice, LO background contributions remain. The prolific $gg^{PP} \rightarrow gg$ 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 $B/S \sim 0.18$. (Here, for reference, we assume that the mass window over which we collect the signal, $\Delta M \sim 3\sigma = 3$ GeV).

Secondly, there is an admixture of $|J_z| = 2$ production, arising from non-forward going protons which gives $B/S \sim 0.24$. 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 $B/S \sim 0.18$, where $E_T$ is the transverse energy of the $b$ and $\bar{b}$ jets.4

Next, we have the possibility of NLO $gg \to b\bar{b}$ background contributions, which for large angle, hard gluon radiation does not obey the selection rules. 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 $gg$ 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 $B/S \simeq 0.18$. 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) 9. Also note that radiation off the screening gluon, in Fig. 1 is numerically small 20.

4 The signal-to-background ratio for $H \to b\bar{b}$ mode

So, in total, for the exclusive production of a 120 GeV (SM) Higgs boson at the LHC with the integrated luminosity $\mathcal{L} = 30$ fb$^{-1}$, after cuts and acceptances we can expect about 10 events, with a signal-to-background ratio $S/B$ of the order of 1. In the case of a Gaussian missing mass distribution of width $\sigma$, about 87% of the signal is contained in a bin $\Delta M_{\text{missing}} = 3\sigma$, 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 ($pp \to p + (M \to HX) + p$) 14.

4There are reasons to hope that, due to higher-order QCD effects, this particular background contribution will be a few times smaller.
Figure 2: The cross section times the $b\bar{b}$ branching ratio for central exclusive production of $h$ and $H$ MSSM Higgs bosons at the LHC for $\tan\beta = 30$. Also shown (by the dotted curve) is the cross section times the branching ratio for SM Higgs production.

However, we do not gain much as compared to the usual totally inclusive production – there is no precise missing mass measurement, no selection rule to suppress the $b\bar{b}$ 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 $H \rightarrow b\bar{b}$ 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 [21]. There are regions of MSSM parameter space, for example, the intense coupling regime [18], where the conventional signals ($\gamma\gamma$, $WW$, $ZZ$ decays) are suppressed, but where the exclusive subprocess $gg \rightarrow H \rightarrow b\bar{b}$ is strongly enhanced [10]. This is evident from Fig. 2 which shows the cross section for CEP production of $h$, $H$ bosons as function of their mass for $\tan\beta = 30$. Here, and in what follows, we use version 3.0 of the HDECAY code [22].

Taking, for example, for $M_A = 130$ GeV and $\tan\beta = 50$, we have $M_h =$
124.4 GeV with $S/B = 71/9$ events, $M_H = 135.5$ GeV with $S/B = 124/6$ events and $M_A = 130$ GeV with $S/B = 0.17$, so both $h$ and $H$ should be clearly visible. (Again, for reference, we assume that $\Delta M_{\text{missing}} = 3$ GeV can be achieved.) Let us emphasize that the intense coupling regime of the MSSM [18] is especially forward proton friendly, and in this particular case the tagged-proton approach may well be the discovery channel.

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.

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 dissociation process, $pp \rightarrow X + A + Y$, where both protons dissociate [10].

### 6 Detecting the Higgs in the $WW$ channel

The analysis in the previous sections was focused primarily on light SM and MSSM Higgs production, with the Higgs decaying to 2 $b-$jets. The potentially copious $b-$jet (QCD) background is controlled by a combination of the spin-parity selection rules and the mass resolution from the forward proton detectors. The missing-mass resolution is especially critical in controlling the background, since poor resolution would allow more background events into the mass window around the resonance.

Whilst the $b\bar{b}$ channel is very attractive theoretically, allowing direct access to the dominant decay mode of the light Higgs boson, there are some basic problems which render it challenging from an experimental perspective, see [17] for details. First, it relies heavily on the quality of the mass resolution from the proton taggers to suppress the background. Secondly, triggering on the relatively low-mass dijet signature of the $H \rightarrow b\bar{b}$ events is a challenge for the Level 1 triggers of both ATLAS and CMS. And, thirdly, this measurement requires double $b-$tagging, with a corresponding price to pay for the tagging efficiency.

In [16,17], attention was turned to the $WW^*$ decay mode of the light Higgs, and for a Higgs mass above the $WW$ threshold, to the $WW$ decay mode. This channel does not suffer from any of the above problems: suppression of the dominant backgrounds does not rely so strongly on the mass
resolution of the detectors, and, certainly, in the semi-leptonic decay channel of the \(WW\) system, the Level 1 triggering is not a problem. The advantages of forward proton tagging are, however, still explicit. Even for the double leptonic decay channel (i.e. with two leptons and two final state neutrinos), the mass resolution will be very good, and, of course, observation of the Higgs in the double-tagged channel immediately establishes its quantum numbers. It is worth mentioning that the mass resolution should improve with increasing Higgs mass. Moreover, the semileptonic ‘trigger cocktail’ may allow a combination of signals, not only from \(H \rightarrow WW\) decays, but also from the \(\tau \tau, ZZ\) and even the semileptonic \(b-\)decay channels.

In Fig. 3 we show the cross section for the process \(pp \rightarrow p + H + p \rightarrow p + WW + p\) as a function of the Higgs mass \(M_H\) at the LHC. The increasing branching ratio to \(WW^*\) as \(M_H\) increases (see for example [21]) compensates for the falling central exclusive production cross section. For comparison, we also show the cross section times branching ratio for \(pp \rightarrow p + H + p \rightarrow p + b\bar{b} + p\). For reference purposes, the cross sections in Fig. 3 are normalized in such a way that \(\sigma_H = 3\) fb for \(M_H = 120\) GeV. In Fig. 3 we show also the results for \(\tan \beta = 2, 3, 4\). Evidently the expected CEP yield is also promising in the low \(\tan \beta\) region.

Experimentally, events with two \(W\) bosons in the final state fall into 3 broad categories — fully-hadronic, semi-leptonic and fully-leptonic — depending on the decay modes of the \(W\)’s. Events in which at least one of the \(W\)’s decays in either the electron or muon channel are by far the simplest, and Ref. [17] focuses mainly on these semi- and fully-leptonic modes. As mentioned above, one of the attractive features of the \(WW\) channel is the absence of a relatively large irreducible background, in contrast to the large central exclusive \(bb\) QCD background in the case of \(H \rightarrow bb\), suppression of which relies strongly on the experimental missing-mass resolution and di-jet identification. The primary exclusive backgrounds for the \(WW\) channel can be divided into two broad categories:

1. central production of a \(WW^*\) pair \(pp \rightarrow p + (WW^*) + p\) from either the (a) \(\gamma\gamma \rightarrow WW^*\) or (b) \(gg^{PP} \rightarrow WW^*\) subprocess,

2. the \(W\)-strahlung process \(pp \rightarrow p + Wjj + p\) originating from the \(gg^{PP} \rightarrow Wq\bar{q}\) subprocess, where the \(W^*\) is ‘faked’ by the two quarks.

As shown in [17], over a wide region of Higgs masses the photon-photon initiated backgrounds are strongly suppressed if we require that the final leptons and jets are central and impose cuts on the transverse momenta of the protons in the taggers. Moreover, our estimates show that the QCD
Figure 3: The cross section times branching ratio for the central exclusive production of the MSSM Higgs boson (for three values of $\tan \beta = 2, 3, 4$), as a function of the Higgs mass, in the $WW$ and $bb$ decay channels. The cross section for the CEP production of a SM Higgs boson is also shown.
quark-box-diagram contribution from the $gg^{PP} \to WW^*$ subprocess is very small.

The most important background, therefore, comes from the second category, i.e. from the $W$-strahlung process. Here we have to take into account the $J_z = 0$ projection of this amplitude, which requires a calculation of the individual helicity amplitudes. This was done in [16] using the spinor technique of Ref. [23]. The analysis in [16,17] shows that this background can be manageable with carefully chosen experimental cuts. For $M_H = 140$ GeV we expect 19 exclusive $H \to WW$ events for an LHC luminosity of $30 \text{ fb}^{-1}$. Note that the largest loss of events in the $WW$ case is caused by the Level 1 trigger efficiency, and we expect significant improvements here.

7 Related processes: checks of the predicted exclusive Higgs yield

As discussed above, the exclusive Higgs signal is particularly clean, and the signal-to-background ratio is favourable. However, the expected number of events in the SM case 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, so that they may be observed at the Tevatron (as well as at the LHC). The most obvious examples are those in which the Higgs is replaced by either a dijet system, a $\chi_c$ or $\chi_b$ meson, or by a $\gamma\gamma$ pair, see Fig. 1.

First, we discuss the exclusive production of a pair of high $E_T$ jets, $p\bar{p} \to p + jj + \bar{p}$ [15,11]. This would provide an effective $gg^{PP}$ ‘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. This process is being studied by the CDF collaboration. Unfortunately, in the present CDF environment, the separation of exclusive events is not unambiguous. At first sight, we might expect that the exclusive dijets form a narrow peak, sitting well above the background, in the distribution of the ratio

$$R_{jj} = M_{\text{dijet}}/M_{PP}$$

at $R_{jj} = 1$, where $M_{PP}$ is the invariant energy of the incoming Pomeron-Pomeron system. In reality the peak is smeared out due to hadronization and the jet-searching algorithm. Moreover, since $M_{\text{dijet}}$ is obtained from mea-
suring just the two-jet part of the exclusive signal, there will be a ‘radiative tail’ extending to lower values of $R_{jj}$.

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 ($\Delta R_{jj} \sim \pm 0.1$ or more) in the $R_{jj}$ distribution. The estimates based on Ref. [1] (see also [25]) give an exclusive cross section for dijet production with $E_T > 10, 25, 35, 50$ GeV, with values which are rather close to the recent CDF limits [24]. The comparison is shown in Fig. 4. In particular, for $E_T > 50$ GeV, we predict an exclusive cross section of about 1 pb [1], which agrees well with the current CDF upper limit obtained from events with $R_{jj} > 0.8$. As discussed above, one should not expect a clearly ‘visible’ peak in the CDF data for $R_{jj}$ close to 1. It is worth mentioning that the CDF measurements have already started to reach values of the invariant mass of the Pomeron-Pomeron system in the SM Higgs mass range.

An alternative ‘standard candle’ process is exclusive double-diffractive $\gamma\gamma$ production with high $E_T$ photons, that is $p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ [1,25]. 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. The predictions of the cross section for exclusive $\gamma\gamma$ production are shown in Fig. 5.

The CDF collaboration has reported [24] a preliminary result for exclusive $\chi_c$ production. Although it is consistent with perturbative QCD expectations [26], 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. 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 [28]. However, in Ref. [26], 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, $M_{\chi}/2$, 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 event rates are large enough to select double-diffractive

5Even lower scales correspond to the fixed target central double diffractive meson resonance production observed by the WA102 collaboration at CERN [27].

6Note that the results for $\chi_c(0^{++})$, given in [26], should be decreased by a factor of 1.5 due to the new value of the total $\chi_c(0^{++})$ width in PDG-2004 [29]. Thus, the predicted cross section for $\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu\mu\gamma$ is now about 300 pb; with the CDF experimental cuts, it becomes about 50 pb.
Figure 4: The cross section limit for ‘exclusive’ dijet production at the Tevatron as a function $E_{T,\text{min}}$ as measured by CDF [24]. These preliminary CDF data correspond to the cross section integrated over the domain $R_{jj} = M_{\text{dijet}}/M_{PP} > 0.8$ and $E_T > E_{T,\text{min}}$. The curves are the pure exclusive cross section calculated [1] using the CDF event selection. Different hadronization corrections were applied. The solid curve is obtained assuming that, after the hadronization, the measured jet transverse energy $E_T$ is less than the parton (gluon) transverse energy by $\Delta E_T = E_{T,\text{gluon}} - E_T = \alpha_s(E_T)E_T + 2 \text{ GeV}$; while for the dashed curve it is assumed that $\Delta E_T$ is halved, i.e. $\Delta E_T = (\alpha_s(E_T)/2)E_T + 1 \text{ GeV}$. The dotted curve is calculated assuming $E_{T,\text{gluon}} = E_T$, but with the mass of the whole central system (which determines the incoming gluon-gluon luminosity) enlarged according to the $R_{jj}$ ratio $- M_{PP} = (2E_T/\sin\theta)/0.8$, where $\theta$ is the jet polar angle in the dijet rest frame.
Figure 5: 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 $\gamma\gamma \rightarrow \gamma\gamma$. 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. [25].
dissociation 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.

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.

8 Conclusion

The installation of proton-tagging detectors in the forward region around ATLAS and/or CMS would add unique capabilities to the existing LHC experimental programme. The current calculations of the rates of CEP processes show that there is a real chance that new heavy particle production could be observed in this channel. For the Standard Model Higgs, this would amount to a direct determination of its quantum numbers, with an integrated luminosity of order $30 \text{ fb}^{-1}$. For certain MSSM scenarios, the tagged-proton channel may even be the discovery channel. At higher luminosities, 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. This includes searches for extra dimensions, gluino and squark production, gluinoia, and, indeed, any object which has $0^{++}$ or $2^{++}$ quantum numbers and couples strongly to gluons [1].

Here we focused on the unique advantages of CEP Higgs production. 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, depending crucially on the accuracy with which $M_{\text{missing}}$ can be measured.

From the experimental perspective, the simplest channel to observe a Higgs Boson of mass between 140 GeV and 200 GeV is the $WW$ decay mode. According to studies in [17], there will be a detectable signal, and the backgrounds should be controllable.

We have emphasized the importance of checking the perturbative QCD
predictions by observing analogous CEP processes, with larger cross sections, at the Tevatron.

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References

[1] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C23 (2002) 311.

[2] B.E. Cox, arXiv:hep-ph/0409144.

[3] K. Piotrzkowski, Phys. Rev. D63 (2001) 071502.

[4] V.A. Petrov, R.A. Ryutin A.E. Sobol and J.-P. Guillaud, arXiv:hep-ph/0409118 and references therein.

[5] M. Bonnekamp et al., arXiv:hep-ph/0506275 and references therein.

[6] FP-420, M. Albrow et al., CERN-LHCC-2005-025, LHCC-I-015.

[7] V.A. Khoze, A.D. Martin and M.G. Ryskin, arXiv:hep-ph/0006005, in Proc. of 8th Int. Workshop on Deep Inelastic Scattering and QCD (DIS2000), Liverpool, eds. J. Gracey and T. Greenshaw (World Scientific, 2001), p.592.

[8] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C19 (2001) 477, erratum C20 (2001) 599.

[9] A. De Roeck, V.A. Khoze, A.D. Martin, R. Orava and M.G. Ryskin, Eur. Phys. J. C25 (2002) 391.

[10] A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C33 (2004) 261.

[11] J.R. Ellis, J.S. Lee and A. Pilaftsis, Phys. Rev. D71 (2005) 075007.
[12] V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C 34 (2004) 327.

[13] M.G. Ryskin, A.D. Martin and V.A. Khoze, these proceedings, arXiv:hep-ph/0506272.

[14] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C24 (2002) 459.

[15] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C14 (2000) 525.

[16] V.A. Khoze, M.G.Ryskin and W.J. Stirling, arXiv:hep-ph/0504131.

[17] B.E. Cox et al., arXiv:hep-ph/0505220.

[18] E. Boos, A. Djouadi and A. Nikitenko, Phys.Lett. B578 (2004) 384.

[19] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C18 (2000) 167.

[20] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C26 (2002) 229.

[21] M. Carena and H. Haber, Prog. Part. Nucl. Phys. 50 (2003) 63; G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, Eur. Phys. J. C28 (2003) 133; A. Djouadi, arXiv:hep-ph/0503175.

[22] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Com. 108 (1998) 56, arXiv:hep-ph/9704448.

[23] R. Kleiss and W.J. Stirling, Nucl. Phys. B262(1985)235.

[24] M. Gallinaro (for the CDF Collaboration), arXiv:hep-ph/0311192, arXiv:hep-ph/0505159.

[25] V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. C38 (2005) 475.

[26] V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. C35 (2004) 211.

[27] 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.
[28] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C24 (2002) 581.

[29] S. Eidelman et al. (Particle Data Group), Phys. Lett. B592 (2004) 1.