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Double-diffractive processes in high-resolution missing-mass experiments at the Tevatron

V.A. Khoze[a], A.D. Martin[a] and M.G. Ryskin[a,b]

[a] Department of Physics, University of Durham, Durham, DH1 3LE
[b] Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, 188300, Russia

Abstract

We evaluate, in a model-independent way, the signal-to-background ratio for Higgs→ $b\bar{b}$ detection in exclusive double-diffractive events at the Tevatron and the LHC. For the missing-mass approach to be able to identify the Higgs boson, it will be necessary to use a central jet detector and to tag b quark jets. The signal is predicted to be very small at the Tevatron, but observable at the LHC. However we note that the background, that is double-diffractive dijet production, may serve as a unique gluon factory. We also give estimates for the double-diffractive production of χ_c and χ_b mesons at the Tevatron. We emphasize that a high-resolution missing-mass measurement, on its own, is insufficient to identify rare processes.

1 Introduction

¿From several points of view it looks appealing to study processes with two large rapidity gaps in high energy hadron collisions. Applications of such processes, generated, for example, by 'Pomeron-Pomeron' collisions, embrace both searches for New Physics (such as the Higgs boson) and dedicated analyses of conventional physics, including the investigation of subtle aspects of QCD. The attractiveness of the approach is motivated by the spectacularly clean experimental signatures and the possibility to clearly differentiate between different production mechanisms.

Events with large rapidity gaps may be selected either by using a calorimeter or by detecting leading protons with beam momentum fractions x close to 1. If the momenta of the leading protons can be measured with very high accuracy then a particle (or system) produced by the double-diffractive mechanism may be observed as a peak in the spectrum of the missing-mass (M) distribution. Indeed, it has recently been proposed to search for the Higgs boson[1] by measuring the outgoing fast proton and antiproton in Run II of the Tevatron with extremely good precision corresponding to a missing-mass resolution $\Delta M \simeq 250$ MeV [2]. To ascertain whether the sought after Higgs signal can be seen, it is crucial to evaluate the background. Recall that the inclusive search for an intermediate mass Higgs, that is pp or $p\bar{p} \to HX$ with $H \to b\bar{b}$, has an extremely small signal-to-background ratio, which makes this process impossible to observe.

In Section 2 we briefly recall the QCD mechanism for the double-diffractive production of a system of large invariant mass M. We use this formalism in Section 3 to study the background for double-diffractive $H \to b\bar{b}$ production, and to show that the signal-to-background ratio can be estimated in a practically model-independent way. Then in Section 4 we discuss double-diffractive production of χ_b (and χ_c) mesons. We present their expected cross sections at the Tevatron. In Section 5 we discuss another attractive possibility. That is, to use the double-diffractive production of a dijet system as a "gluon factory", which generates huge numbers of essentially pure gluon jets in a clean environment. In Section 6 we emphasize that a high-resolution missing-mass measurement on its own may not yield a sharp peak for a rare process, if care is not taken to account for QED radiation. Finally, in Section 7, we present our conclusions.

2 The mechanism for double-diffractive production

We wish to estimate the cross section for high energy reactions of the type

$$pp \;\to\; p \,+\, M \,+\, p, \tag{1}$$

and similarly for $p\bar{p}$, where the 'plus' signs indicate the presence of large rapidity gaps. To be precise, we calculate the rate for the double-diffractive exclusive production of a system of

[1]The possibility of a high resolution missing-mass search for the Higgs boson in exclusive double rapidity gap events was considered in Ref. [1].

large invariant mass M, for example, a Higgs boson. In all models [3]–[8] the amplitude for the double-diffractive process is described by Fig. 1, where the hard subprocess $gg \to M$ is initiated by gluon-gluon fusion and the second t-channel gluon is needed to screen the colour flow across the rapidity gap intervals. In other words the Pomeron is modelled by two-gluon exchange.

One major difference between the various theoretical approaches concerns the specification of the exchange gluons. *Either* non-perturbative gluons are used in which the propagator is modified so as to reproduce the total cross section [4, 6], *or* a perturbative QCD estimate is made [8] using an unintegrated, skewed gluon density that is determined from conventional gluons obtained in global parton analyses. However it has been emphasized [9] (see also [5, 8]) that the non- perturbative normalisation based on the value of the elastic or total cross section fixes the diagonal gluon density at $\hat{x} \sim \ell_T/\sqrt{s}$ where the transverse momentum ℓ_T is small, namely $\ell_T < 1$ GeV. Thus the value of $\hat{x}$ is even smaller than

$$x' \;\approx\; \frac{Q_T}{\sqrt{s}} \;\ll\; x \;\approx\; \frac{M}{\sqrt{s}}, \tag{2}$$

where the variables are defined in Fig. 1. However, the gluon density grows as $x \to 0$ and so the use of a non-perturbative normalisation will lead to an overestimation of double-diffractive cross sections.

Of course the fusion of the two energetic gluons into the high mass state in Fig. 1 is generally accompanied by the emission of soft gluons which may populate the rapidity gaps. The basic mechanism to suppress this effect is shown in Fig. 1, where the second t-channel gluon, which screens the colour, does not couple to the produced state of mass M and has typical values of Q_T which are much smaller than M but yet are large enough (for sufficiently large M) to screen soft gluon emission and to justify the applicability of perturbative QCD.

Recently the $p\overset{(}{\bar{p}}\overset{)}{} \to p + H + \overset{(}{\bar{p}}\overset{)}{}$ cross section has been calculated to single log accuracy [8]. The amplitude is

$$\mathcal{M} \;=\; A\pi^3 \int \frac{d^2Q_T}{Q_T^4}\, f_g(x_1, x_1', Q_T^2, M_H^2/4)\, f_g(x_2, x_2', Q_T^2, M_H^2/4), \tag{3}$$

where the $gg \to H$ vertex factor A^2 is given by (7) below, and the unintegrated gluon densities are related to the conventional distributions by

$$f_g(x, x', Q_T^2, M_H^2/4) \;=\; R_g \,\frac{\partial}{\partial \ln Q_T^2}\left[\sqrt{T(Q_T, M_H/2)}\, xg(x, Q_T^2)\right]. \tag{4}$$

The factor R_g is the ratio of the skewed $x' \ll x$ integrated gluon distribution to the conventional one. $R_g \simeq 1.2(1.4)$ at LHC (Tevatron) energies. The bremsstrahlung survival probability T^2 is given by

$$T(Q_T, \mu) \;=\; \exp\left(-\int_{Q_T^2}^{\mu^2} \frac{dk_T^2}{k_T^2}\, \frac{\alpha_S(k_T^2)}{2\pi} \int_0^{1-k_T/\mu} dz \left[z\, P_{gg}(z) \;+\; \sum_q\, P_{qg}(z)\right]\right), \tag{5}$$

and strongly suppresses the infrared contribution to the Q_T integration of (3). The factor $\sqrt{T}$ arises in (4) because the survival probability is only relevant to the hard gluon exchanges in Fig. 1. In addition to this suppression due to the probability "T^2" that the $pp \to p + H + p$ rapidity gaps survive population by extra gluons from the hard process, we must also include the probability S^2 that the gaps are not filled by secondaries produced in soft rescattering between the protons, that is by an underlying interaction. We estimate the $p\bar{p} \to p + H + \bar{p}$ event rate at the Tevatron in Section 3.3.

3 Dijet background to double-diffractive Higgs production

To use the 'missing-mass' method to search for an intermediate mass Higgs boson, via the $H \to b\bar{b}$ decay mode, we have to estimate the QCD background which arises from the production of a pair of jets with invariant mass about M_H. If we assume that the Higgs boson is produced by the $gg \to H$ fusion mechanism then the signal-to-background ratio is just given by the ratio of the appropriate matrix elements squared for the $gg \to H$ and $gg \to$ dijet subprocesses.

3.1 Gluon dijet background

We begin by considering the double-diffractive colour-singlet production of a pair of high E_T gluons with rapidities η_1 and η_2. The $gg \to gg$ subprocess cross section is [3, 10]

$$\begin{aligned} \frac{d\hat{\sigma}}{d^2 p_T} &= \frac{9\alpha_S^2}{4p_T^4}\,\frac{1}{2p_T^2\,\sinh\,\Delta\eta}\,\frac{dM^2}{d(\Delta\eta)} \\ &= \frac{9\alpha_S^2}{8p_T^6}\left(\frac{M^4}{4p_T^4} - \frac{M^2}{p_T^2}\right)^{-\frac{1}{2}}\,\frac{dM^2}{d(\Delta\eta)}, \end{aligned} \tag{6}$$

where M is the invariant mass of the dijet system, p_T is the transverse momentum of the jets, and $\Delta\eta = |\eta_1 - \eta_2|$ is the jet rapidity difference. Note that, since the outgoing proton and antiproton are at small angles relevant to the respective beams, $\boldsymbol{p}_{1T} = -\boldsymbol{p}_{2T}$.

The background (6) should be compared to the double-diffractive $gg \to H$ signal

$$\frac{A^2}{4} = \frac{\sqrt{2}}{4}\,G_F\,\alpha_S^2\,\frac{N}{9\pi^2} \simeq \frac{\sqrt{2}}{36\pi^2}\,G_F\,\alpha_S^2, \tag{7}$$

where G_F is the Fermi coupling and $N \simeq 1$ since we assume M_H lies well below the $t\bar{t}$ threshold. Here we use the framework and the notation of Refs. [5, 3][2].

[2]To be specific the signal-to-background ratio is given by comparing eqs. (8,10) of [5] with eqs. (8,17,19) of [3].

Immediately we see a problem. The small p_T divergence of the dijet cross section, (6), means that the background will be huge if just a missing-mass measurement on its own is performed. We thus also require a central detector to impose a jet p_T(or E_T) cut. With such an additional detector we may select events with jets, say, with $E_T^2 > (3/16)M_H^2$. In other words we trigger on double-diffractive events containing a pair of jets with angles $\theta > 60^\circ$ from the beam direction in the Higgs rest frame. For a scalar Higgs boson this cut kills one half of the events, whereas the dijet cross section (6) is reduced to

$$\frac{d\hat{\sigma}}{dM^2} = \frac{9\alpha_S^2}{8} \int_{3M^2/16}^{M^2/4} \frac{dp_T^2}{p_T^6} \left(\frac{M^4}{4p_T^4} - \frac{M^2}{p_T^2} \right)^{-\frac{1}{2}} = 9.73\, \frac{9\alpha_S^2}{8M^4}. \tag{8}$$

With the same scale in the couplings α_S in (7) and (8), and neglecting the NLO corrections[3], we obtain the signal-to-background ratio

$$\begin{aligned} \frac{S}{B_{gg}} &= \frac{\sqrt{2}G_F}{9.73(81\pi^2)}\, \frac{M^3}{\Delta M}\, \frac{1}{2}\, \mathrm{Br}(H \to b\bar{b}) \\ &\simeq (4.3 \times 10^{-3})\, \mathrm{Br}(H \to b\bar{b}) \left(\frac{M}{100\ \mathrm{GeV}} \right)^3 \left(\frac{250\ \mathrm{MeV}}{\Delta M} \right). \end{aligned} \tag{9}$$

The factor $\frac{1}{2}\mathrm{Br}(H \to b\bar{b})$ accounts for the branching ratio of the $H \to b\bar{b}$ decay and the $\theta > 60^\circ$ cut of the low p_T jets. (The $H \to b\bar{b}$ branching ratio is about 0.7 if $M_H = 120$ GeV.)

The ratio $S/B_{gg} \sim 5 \times 10^{-3}$ appears too small for the above approach to provide a viable signal for the Higgs boson. However the situation is greatly improved if we are able to identify the b and $\bar{b}$ jets. If we assume that there is only a 1% chance to misidentify a gluon jet as a b jet, then tagging *both* b and $\bar{b}$ will suppress the gluon background by 10^4. In this case only the true $b\bar{b}$ background will pose a problem.

3.2 Signal-to-background ratio for b quark dijets

For the double-diffractive central production of a $b\bar{b}$ pair, the $H \to b\bar{b}$ signal/$b\bar{b}$ background ratio is much larger than that of Section 3.1. Here the ratio is strongly enhanced due to the colour factors, gluon polarisation selection and the spin $\frac{1}{2}$ nature of the quarks. First, the cross sections for inclusive colour-singlet dijet production are [3]

$$\begin{aligned} \frac{d\hat{\sigma}}{d\hat{t}}\,(gg \to gg) &= \frac{9\pi\alpha_S^2}{2p_T^4} \left(1 - \frac{p_T^2}{M^2} \right)^2 \\ \frac{d\hat{\sigma}}{d\hat{t}}\,(gg \to b\bar{b}) &\simeq \frac{\pi\alpha_S^2}{6p_T^2 M^2} \left(1 - \frac{2p_T^2}{M^2} \right). \end{aligned} \tag{10}$$

[3]The NLO correction is not yet known for double- diffractive dijet production from a colour-singlet state. The corresponding K-factor is expected to be about the same, or a little larger, than that for Higgs production.

Since $p_T^2 < M^2/4$ the $b\bar{b}$ background is suppressed relative to the gg background by

$$\frac{d\hat{\sigma}(gg \to b\bar{b})}{d\hat{\sigma}(gg \to gg)} \; < \; \frac{1}{4 \times 27} \; < \; 10^{-2}. \qquad (11)$$

Moreover, we emphasize that for the exclusive process the initial gg state obeys special selection rules. Besides being a colour-singlet, for forward outgoing protons the projection of the total angular momentum is $J_z = 0$ along the beam axis[4]. On the other hand, the Born amplitude for light fermion pair production[5] vanishes in this $J_z = 0$ state, see, for example, [12]. This result follows from P- and T-invariance and fermion helicity conservation of the $J_z = 0$ amplitude [13]. Thus, if we were to neglect the b-quark mass m_b, then at leading order we would have no QCD $b\bar{b}$-dijet background at all. Even beyond LO, the interference between the signal and background amplitudes is negligibly small, since they have different helicity structure. Therefore the form of the peak, observed in double- diffractive exclusive $H \to b\bar{b}$ production, will not be affected by interference with $b\bar{b}$ jets produced by the pure QCD background process.

Of course, a non-vanishing $b\bar{b}$ rate is predicted when we allow for the quark mass or if we emit an extra gluon. Nevertheless in the former case we still have an additional suppression to (11) of about a factor of $m_b^2/p_T^2 \simeq 4m_b^2/M_H^2 < 10^{-2}$, whereas in the latter case the extra suppression is about $\alpha_S/\pi \simeq 0.05$. Note that events containing the third (gluon) jet may be experimentally separated from Higgs decay, where the two jets are dominantly co-planar[6].

Up to now we have discussed forward outgoing protons in the idealized case where their transverse momenta $\boldsymbol{q}_{1T}, \boldsymbol{q}_{2T} \to 0$. In reality there is a strong correlation between these transverse momenta. In particular, it implies that factorization (whereby the cross section is a product of Pomeron emission factors multiplied by the Pomeron-Pomeron fusion subprocess) is not valid [11]. It is thus remarkable that the suppression of the double-diffractive $b\bar{b}$ dijet production (the QCD background process) is still valid for non-zero q_{1T} and q_{2T}. Indeed, the polarization vectors ε_j of the 'hard' gluons in Fig. 1 are directed along $(Q+q_i)_j$, where $j = 1, 2$ denotes the two transverse components of the momenta. In the case where we neglected $\boldsymbol{q}_{iT}$ and averaged over the direction of $\boldsymbol{Q}_T$ we obtained the polarization tensor

$$\varepsilon_j \varepsilon_k \;\sim\; Q_j Q_k \;\sim\; \delta_{jk}^{(2)} \frac{Q_T^2}{2}, \qquad (12)$$

which corresponds to the $J_z = 0$ di-gluon state. However, for non-zero $\boldsymbol{q}_{it}$ the tensor becomes

$$\varepsilon_j \varepsilon_k \;\sim\; (Q + q_1)_j \, (Q + q_2)_k \;\sim\; \delta_{jk}^{(2)} \frac{Q_T^2}{2} \;+\; q_{1j} \, q_{2k}. \qquad (13)$$

[4]This statement remains valid even when the blobs in Fig. 1, which describe the radiation of two t-channel gluons by the protons, include leading order BFKL or DGLAP ladders.

[5]For light quark pair exclusive production, $p+p \to p+q\bar{q}+p$, with forward outgoing protons, the cancellation was first observed by Pumplin [11], see also [10, 3].

[6]The situation here is similar to the signal-to-background ratio for intermediate mass Higgs production in polarised $\gamma\gamma$ collisions, which was studied in detail in [13, 14].

The linear term in Q_T vanishes after the $\boldsymbol{Q}_T$ angular integration. In this way we obtain an admixture of $J_z = \pm 2$ di-gluon states, which leads to a contribution of the order of $4q_{1T}^2 q_{2T}^2/Q_T^4$ to the $gg \to b\bar{b}$ cross section. Thus the integral over the Q_T loop in the amplitude (that is the dijet counterpart to (3)) becomes less infrared safe. However the Sudakov-like form factor (5) and the effective anomalous dimension, $\gamma > 0$, of the gluon $(xg(x, Q_T^2) \sim (Q_T^2)^\gamma)$ still suppress the contribution from the infrared domain [5]. If we use the MRS gluon [15], we find the integral typically samples Q_T values in the region $Q_T^2 \simeq 1.5(3)$ GeV^2 at the Tevatron (LHC) energy. Thus the $|J_z| = 2$ admixture does not contribute more than 5% (1.5%) of the dijet cross section; here we take a mean q_T of 400 MeV. Of course the $|J_z| = 2$ contribution may be suppressed by selecting forward protons with smaller q_T.

So finally we see that identifying the $H \to b\bar{b}$ signal allows the background to be suppressed by more than a factor 3000. The signal is thus in excess of the background, even for a mass resolution of $\Delta M \sim 4$ GeV. There is therefore an opportunity to see a clear peak at $M = M_H$, *provided* the cross section for double-diffractive Higgs production is large enough.

3.3 The cross section for $p\overset{(}{\bar{p}}\overset{)}{} \to p + H + \overset{(}{\bar{p}}\overset{)}{}$

The cross section for double-diffractive Higgs production at Tevatron and LHC energies has been calculated by several authors[7] [4, 5, 6, 8]. If our recent perturbative QCD determination [8] is updated to incorporate the latest rapidity gap survival probability estimates[8] of Ref. [16], then

$$\sigma_H \;\equiv\; \sigma(p\bar{p} \to p + H + \bar{p}) \;\simeq\; 0.06\,\text{fb} \quad \text{at} \quad \sqrt{s} \;=\; 2 \text{ TeV} \tag{14}$$

for a Higgs boson of mass 120 GeV. Note that the value of cross section (14) is comparable to the cross section generated by the $\gamma\gamma \to H$ fusion subprocess. Recall that this QED contribution comes from large impact parameters, where the corresponding gap survival probability $S^2 = 1$ [8]. $\sigma(\gamma\gamma \to H)$ is estimated to be about 0.03 fb at $\sqrt{s} = 2$ TeV and 0.3 fb at $\sqrt{s} = 14$ TeV. Note that the strong and electromagnetic contributions have negligible interference, because they occur at quite different values of the impact parameter:

$$\begin{aligned} \langle \rho_T^2 \rangle_{\text{em}} \;&\gg\; B_{\text{el}} \;\sim\; 20 \text{ GeV}^{-2}, \\ \langle \rho_T^2 \rangle_{\text{str}} \;&\sim\; 4 \text{ GeV}^{-2}, \end{aligned} \tag{15}$$

where B_{el} is the t-slope of the elastic pp cross section.

Prediction (14) is lower than estimates made by other authors. However it may be checked experimentally, since exactly the same mechanism, and calculation, is relevant to double-diffractive dijet production. Indeed, double-diffractive dijet production, for jets with $E_T >$

[7] A more complete set of references to related theoretical papers can be found in Ref. [2].

[8] The gap survival probability for the double-diffractive processes is estimated to be $S^2 = 0.05$ at $\sqrt{s} = 2$ TeV and $S^2 = 0.02$ at $\sqrt{s} = 14$ TeV.

7 GeV, has been studied by CDF collaboration [17]. They find an upper limit for the cross section, $\sigma(\text{dijet}) < 3.7$ nb, as compared to our prediction of about 1 nb [18]. Using the dijet process as a monitor thus rules out the much larger predictions for $\sigma(p\bar{p} \to p + H + \bar{p})$ which exist in the literature. Unfortunately the prediction $\sigma_H \simeq 0.06$ fb of (14) means that Run II of the Tevatron, with an integrated luminosity of $\mathcal{L} = 15\text{fb}^{-1}$, should yield less than an event. We should add that the double-diffractive Higgs search can also be made in the $\tau^+\tau^-$ and WW^* decay channels [2], but, due to the small branching ratios, then the event rate is even less.

On the other hand, the cross section σ_H, calculated in the perturbative QCD approach [5, 8, 16], grows with energy and at $\sqrt{s} = 14$ TeV reaches $\sigma_H \simeq 2.2$fb (corresponding to $d\sigma_H/dy \simeq 0.6$ fb at $y = 0$). In fact, if we were to ignore the rapidity gap survival probability, S^2, then σ_H would have increased by more than a factor of 100 in going from $\sqrt{s} = 2$ TeV to $\sqrt{s} = 14$ TeV. However at larger energies the probability to produce secondaries which populate the gap increases and so $\sigma(pp \to p + H + p)$ increases only by a factor of 40. Nevertheless there is a real chance to observe double-diffractive Higgs production at the LHC[9], since both the cross section and the luminosity are much larger than at the Tevatron.

4 Double-diffractive χ meson production

Of course, the missing-mass method may be used, not only for Higgs searches, but for many other double-diffractive exclusive reactions. Particularly relevant examples are the production of scalar (0^{++}) χ_c and χ_b mesons [2, 19]. These processes will allow another check, albeit qualitative, of our perturbative QCD techniques[10] for calculating double-diffractive processes [8]. In addition there are two reasons why χ production processes are of interest in their own right. First, the production of χ mesons with a rapidity gap on either side ensures the selection of pure colour-singlet states, so there can be no admixture from a colour-octet production mechanism. This should illuminate the dynamics of the hadroproduction of mesons containing heavy quarks. Second, the data on inclusive $b\bar{b}$ production at the Tevatron lies about a factor of 3 above the conventional NLO QCD prediction. A measurement of χ_b diffractive production is thus of interest.

As mentioned above, the cross section for double-diffractive χ meson production may be calculated by the same perturbative QCD approach that was applied to Higgs and dijet production [8]. The $gg \to \chi$ vertex is given in terms of the width of the χ meson. We assume $\Gamma(\chi \to gg) \simeq \Gamma_{\text{tot}}(\chi)$, with an observed width of $\Gamma_{\text{tot}} = 14.9$ MeV [20] for the $\chi_c(0^{++})$ meson. For $\chi_b(0^{++})$ we used the QCD lattice result [21] for the leading order $\Gamma(\chi \to gg)$ width

[9]Note that Refs. [5, 8, 16] do not address the complications caused by multiple (or ‘pile-up’) interactions at the high luminosities at the LHC.

[10]We also have to include a suppression factor which represents the survival probability of the rapidity gaps. This probability S^2 has been calculated for a range of diffractive processes in, for example, Ref. [16].

of 354 keV. To be more precise, we included the standard NLO correction $(1 + 9.8\alpha_S/\pi)$ for $\chi_b(0^{++})$, see, for example, [22]. We assume that the amplitude for χ production behaves as

$$\mathcal{M} \;\propto\; e^{b(t_1+t_2)/2} \tag{16}$$

with slope $b = 4\ \mathrm{GeV}^{-2}$, where t_i are the momentum transfer squared at the proton (antiproton) vertices. For $\sqrt{s} = 2$ TeV we take the rapidity gap survival probability to be $S^2 = 0.05$ [16]. With these input values, the double-diffractive cross sections estimated for Run II of the Tevatron are

$$\begin{aligned} \sigma\left(\chi_c(0^{++})\right) &\simeq 600\ \mathrm{nb}, \\ \sigma\left(\chi_b(0^{++})\right) &\simeq 110\ \mathrm{pb}. \end{aligned} \tag{17}$$

The corresponding rapidity distributions $d\sigma/dy$ are shown in Fig. 2.

Note that the double-diffractive production of exclusive axial vector (1^{++}) and tensor (2^{++}) quarkonium states are strongly suppressed[11]. The former results from the Landau-Yang theorem [24] which forbids the $1^{++} \to 2g$ transition for massless gluons. The latter is directly related to the helicity-zero selection rule which we have discussed above. It was known for a long time that in the non-relativistic limit the $J_z = 0$ amplitude for the $\gamma\gamma$ decay of the $2^{++}\ {}^3P_2$ positronium state vanishes [25]. This, of course, remains valid for the helicity-zero transition of a heavy tensor quarkonium state into two gluons [26].

In reality, exclusive tensor χ-meson production will occur due to corrections caused by relativistic effects (which are expected to be numerically small [27]), as well as by the off-mass-shell corrections to the helicity-zero transition and by the admixture of $|J_z| = 2$ di-gluon states, which we explained in Section 3.2. The largest contribution is expected from non-forward corrections, arising from the second term on the right-hand-side of (13). The $\chi(2^{++})$ rate may therefore be as large as the fraction $0.2\Gamma(2^{++})/\Gamma(0^{++})$ of the $\chi(0^{++})$ production cross sections of (17). As a consequence we anticipate a decrease of the $\chi(2^{++})$ cross section in the very forward region. Note that the $J_z = 0$ selection rule becomes redundant for *inclusive* double-diffractive processes, so, for example, 2^{++} χ-production will become more significant.

Of course the estimates of double-diffractive χ production are much less infrared stable than those for Higgs production. For example, using GRV partons [28] down to $Q^2 = 0.36\ \mathrm{GeV}^2$, rather than MRS partons [15] with frozen anomalous dimension for $Q^2 < 1\ \mathrm{GeV}^2$, to calculate the gluon loop contribution at low virtuality[12], enlarges the cross section by about a factor of 3 for χ_b, and even larger for χ_c. It is known that the GRV gluon is rather too large in this domain. However the comparison does demonstrate the infrared sensitivity of the estimates,

[11] The vanishing of the forward double-diffractive 1^{++} and 2^{++} quarkonium production was recently pointed out by F. Yuan [23] who used a non-relativistic formula for the evaluation of P-wave quarkonium decays.

[12] The contribution from the $Q^2 > 1\ \mathrm{GeV}^2$ is approximately independent of whether GRV or MRS partons are used.

which for such low mass particles should only be considered as an indication of the size of the cross section. Nevertheless the χ cross sections are huge. For an integrated luminosity of $\mathcal{L} = 15$ fb^{-1} in Run II of the Tevatron we expect about 10^6 χ_b events with a large rapidity gap on either side of the meson.

5 Gluon factory

The high event rate and the remarkable purity of the di-gluon system, that is generated in the exclusive double-diffractive production process, provides a unique[13] environment to make detailed studies of high energy gluon jets. Indeed we may speak of a 'gluon factory', since, as discussed in Section 3.2, double-diffractive quark di-jet production is strongly suppressed (by the $J_z = 0$ selection rule). Recall that a precise comparison of quark and gluon jets requires that the two isolated gluon jets are produced from a point-like colour-singlet state[14] — the counterpart of the celebrated $e^+e^- \to q\bar{q}$ process — see [30, 32] for recent reviews.

Note that for QCD studies of gluon jets, the requirement of high resolution on the dijet mass is not essential. Based on the estimates performed in Ref. [8], we expect, for example, about 10^5 gg events per day with $45 < E_T(\text{jet}) < 55$ GeV, at the LHC, assuming a luminosity of 1 fb^{-1}/day and neglecting corrections for acceptance and efficiency. This number should be compared with the present experimental studies of the so-called unbiased gluon jets performed by the OPAL collaboration at LEP1 [33]. Here gluon jets are identified in double-tagged $Z \to b\bar{b}g$ events. Over about five years of running only 439 pure gluon events were identified.

6 Problems with a high-resolution pure missing-mass method

At first sight it looks attractive to use the missing-mass approach to search for (non-Standard Model) Higgs bosons which decay into invisible modes, such as gravitinos, neutralinos or gravitons. The possibility of observing such an invisible Higgs in inclusive processes at the LHC was discussed recently in Ref. [34]. Indeed in the exclusive channel, $pp \to p + H + p$, one should observe just two outgoing protons and nothing else but a sharp peak in the missing-mass distribution. Unfortunately it is not clear how accurately it is possible to eliminate the background

[13]Rather we should say it is almost unique, since sometime ago it was proposed [29] that a polarized $\gamma\gamma$ facility at a photon linear collider could also allow an experimental study of gluon jets via the process $\gamma\gamma \to gg$ in the $J_z = 0$ initial state.

[14]It is often said that a detailed study of the properties of gluon jets can be made by separating out the contribution of the $gg \to gg$ subprocess to a hadronic reaction. In many cases this approach could be misleading since the gg events do not originate from a pure colour-singlet system. The interference between emissions from incoming and outgoing gluons leads to coherence effects which can strongly affect the final hadronic system, see, for example, [30, 31].

caused, for example, by QED radiation from the protons, or maybe even from radiative decays of low mass proton excitations. The problem is that the probability to lose some energy by radiating photons of energy ω in the interval $d\omega$ is of order $(2\alpha/3\pi)(\langle q_T^2\rangle/m^2)(d\omega/\omega)$ [35], where q_T is the transverse momentum of the outgoing proton of mass m. Therefore the cross section for $pp \to (p\gamma) + (p\gamma)$, which may mimic a missing-mass event, is about

$$\left.\frac{d\sigma}{dy}\right|_{y=0} \sim \left(\frac{2\alpha}{3\pi}\frac{\langle q_T^2\rangle}{m^2}\right)^2 \left(\frac{dM^2}{M^2}\right) \sigma_{\rm el} \sim 0.8 \text{ pb}, \tag{18}$$

where we have assumed $M = 120$ GeV, $\Delta M = 250$ MeV, and taken $\sigma_{\rm el} \simeq 25$ mb and $\langle q_T^2\rangle = 1/B_{\rm el} \simeq 0.05$ GeV^2 at LHC energies. This is huge in comparison to the cross section $d\sigma/dy_H \simeq$ 0.6 fb for $pp \to p + H + p$. Of course some of the QED radiation may be detected by an additional dedicated forward electromagnetic calorimeter[15]. Also it is necessary to allow for the radiative tail which will spread out the shape of the Higgs peak.

This illustrates a basic problem in searching for *rare* processes using *high-resolution* missing-mass measurements which observe *only* the forward protons. There will always be the possibility that part of the proton energy will escape undetected down, or near, the beam pipe. Of course this deficiency would not exist if we were able to measure the products of the rare process with sufficient accuracy to confirm that their invariant mass coincides with the missing-mass measurement. In this case the main purpose of the forward proton missing-mass detector would be to considerably improve the ΔM resolution. For the gluon factory there is no problem, since high resolution is not essential and the event rate is enormous. The missing-mass detector is used just to select large rapidity gap events. Similarly there is no problem for double-diffractive χ meson production if the various decay modes are observed.

7 Conclusion

We have studied the proposal of triggering on forward going protons and antiprotons to perform a high resolution missing-mass search for the Higgs boson at the Tevatron, that is the process $p\bar{p} \to p + H + \bar{p}$ where a 'plus' denotes a large rapidity gap. However, we find that there is a huge QCD background arising from double-diffractive dijet production. A central detector to trigger on large E_T jets is essential. Even so, the signal-to-background ratio is too small for a viable 'missing-mass' Higgs search. The situation is much improved if we identify b and $\bar{b}$ jets. The $gg \to H \to b\bar{b}$ signal is now in excess of the QCD $gg \to b\bar{b}$ background, even for a mass resolution of $\Delta M \sim 4$ GeV. The only problem is that, when proper account is taken of the survival probability of the rapidity gaps, the $p\bar{p} \to p + H + \bar{p}$ event rate is too small at the Tevatron. Recall that the experimental limit on the cross section for double-diffractive dijet production confirms the predicted small rates.

[15] We thank A. Rostovtsev for discussions about photon detection.

The pessimistic expectations of the missing-mass Higgs search at the Tevatron are, however, compensated by an interesting by-product of the double-diffractive proposal. The double-diffractive production of dijets offers a unique *gluon factory*, generating huge numbers of essentially pure gluon jets from a colour-singlet state in an exceptionally clean environment. Recall that the exclusive production of $q\bar{q}$ dijets, with a large rapidity gap on either side, is strongly suppressed by the $J_z = 0$ selection rule.

Finally, we give estimates for the double-diffractive production of χ_b and χ_c mesons at the Tevatron. These mesons have smaller mass than the Higgs boson or dijet systems that we have considered, and so the QCD cross section estimates are much more qualitative. Nevertheless the rates are huge, and the observation of χ_b and χ_c production (from colour-singlet states) should illuminate intriguing features of heavy flavour dynamics.

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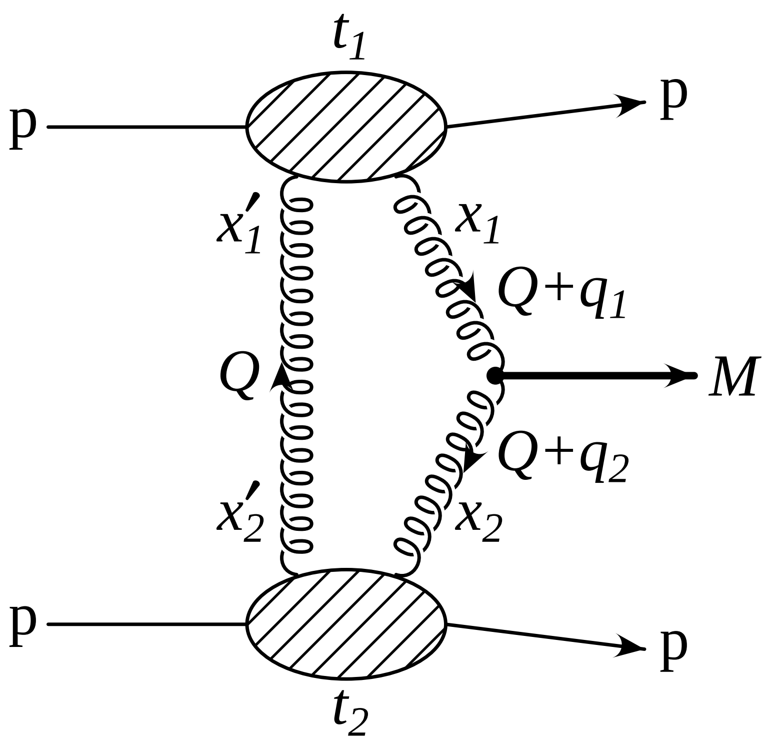

Figure 1: Schematic diagram of double-diffractive production of a system of invariant mass M, that is the process $pp \to p + M + p$.

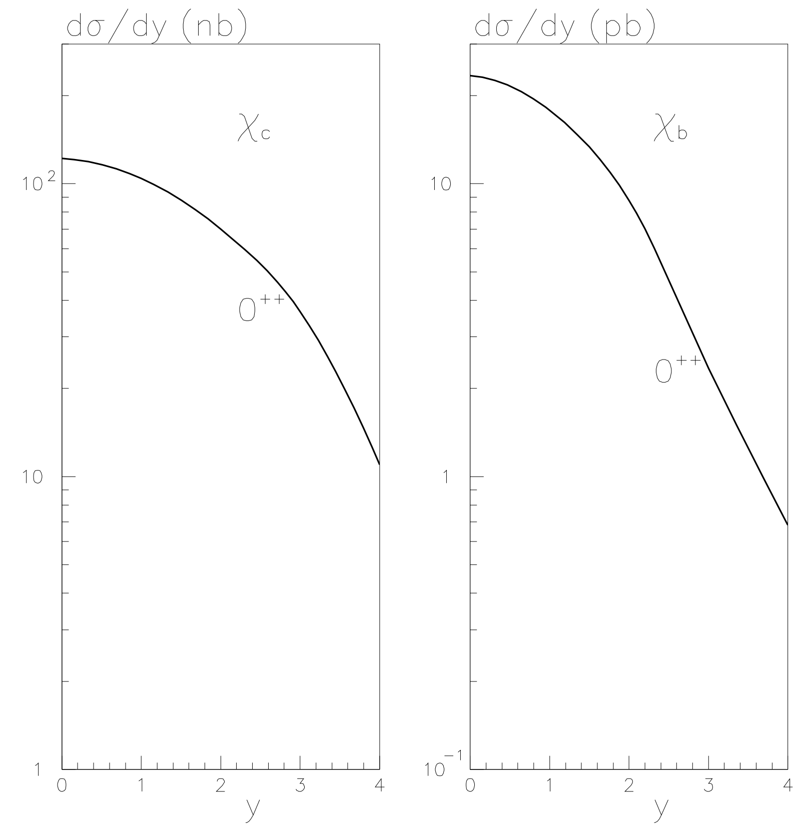

Figure 2: The rapidity distributions for double diffractive χ_c and χ_b (0^{++}) production at the Tevatron.