Central exclusive production of longlived gluinos at the LHC

Peter J. Bussey

Department of Physics & Astronomy, University of Glasgow,
Glasgow G12 8QQ, U.K.
E-mail: p.bussey@physics.gla.ac.uk

Timothy D. Coughlin, Jeffrey R. Forshaw and Andrew D. Pilkington

School of Physics & Astronomy, University of Manchester,
Manchester M13 9PL, U.K.
E-mail: timc@hep.man.ac.uk, forshaw@mail.cern.ch, pilko@hep.man.ac.uk

ABSTRACT: We examine the possibility of producing gluino pairs at the LHC via the exclusive reaction $pp \to p + \tilde{g}\tilde{g} + p$ in the case where the gluinos are long lived. Such long lived gluinos are possible if the scalar super-partners have large enough masses. We show that it may be possible to observe the gluinos via their conversion to R-hadron jets and measure their mass to better than 1% accuracy for masses below $350\,\mathrm{GeV}$ with $300\,\mathrm{fb}^{-1}$ of data.

KEYWORDS: QCD, Hadronic Colliders.

Contents

1. Introduction

There is increasing interest in the possibility of instrumenting the LHC to measure protons, scattered through very small angles, using detectors at a distance down the beam pipe from the interaction point [1, 2]. A primary motivation for installing such detectors is to study the process $pp \rightarrow p + X + p$, where the protons and the central system, X, are separated by large rapidity gaps. This process has already been studied extensively in the literature and it is clear that it offers a unique possibility to produce and explore new physics at the LHC [1, 3–5]. In this paper, we consider the case in which X is a pair of long lived gluinos, forming either a bound state, termed gluinonium [6–9], or hadronising individually to form colour singlet states, termed R-hadrons [10].

The possibility that the gluino may be long-lived is a hallmark of the recently proposed 'Split Supersymmetry' scenario [11, 12], though long lived gluinos have been studied before, in the context of models in which the gluino is the Lightest Supersymmetric Particle (LSP) [10, 13, 14]. In Split Supersymmetry the SUSY breaking scale, m_S, is large ($m_S \gg 1\,\mathrm{TeV}$) and the scalar particles acquire masses at this scale. The sfermions of the theory are protected by chiral symmetries and so can have masses at the TeV scale as can one neutral Higgs boson whose mass is allowed to be finely tuned. As a result the gluino can be long-lived on collider timescales since it can only decay via the massive scalar particles.

The gluino lifetime is approximately given by (neglecting electroweak corrections and possible decays to a Goldstino[1]):

$$\tau_{\tilde{g}} = \frac{4\ \mathrm{sec}}{N} \left(\frac{m_S}{10^9\ \mathrm{GeV}} \right)^4 \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}} \right)^5 , \qquad (1.1)$$

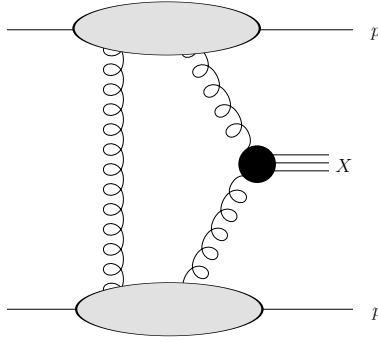[1]The inclusion of decays to a Goldstino can in some cases substantially decrease the gluino lifetime [15].

Figure 1: The central exclusive production process $pp \to pXp$.

where N depends upon m_S and $m_{\tilde{g}}$ (and very weakly on $\tan\beta$) [15], but is of order unity. If m_S is unbounded from above then so is the gluino lifetime. Cosmological considerations of long lived gluinos in the early universe [16] can place upper bounds on $\tau_{\tilde{g}}$, giving $\tau_{\tilde{g}} \lesssim 100$ s for $m_{\tilde{g}} \gtrsim 500$ GeV and $\tau_{\tilde{g}} \lesssim 10^6$ years for $m_{\tilde{g}} \lesssim 500$ GeV. Clearly these constraints do not rule out gluinos long-lived on collider timescales. In this paper we consider the case where the gluinos are sufficiently long-lived that they do not decay within the detector.[2]

Data from the Tevatron have been used to place the limit $m_{\tilde{g}} \gtrsim 170$ GeV on the mass of a long lived gluino [18], for the case in which the gluino forms only neutral hadrons which remain neutral as they pass through the detector. This limit is expected to rise to $\simeq 210$ GeV using Run II data [18]. We should stress that this is a conservative limit, since it is anticipated that these hadrons will undergo charge conversion reactions as they pass through the detector [19]. In the most optimistic case, the Tevatron may reach gluino masses of up to $\simeq 430$ GeV if no signal is observed [18].

The structure of the paper is as follows: In section 2 we give a description of the process $pp \to p + X + p$ and the model we shall use to calculate cross-sections. In section 3 we briefly consider the production of the lowest lying colour singlet bound state of two gluinos and show that the rate for bound state production is too low for it to be interesting at the LHC. In section 4 the signatures of gluino hadronisation are discussed and the cross-section for open gluino production is presented.

2. Diffractive production with forward protons

We calculate the cross-section using the model of Khoze, Martin and Ryskin (KMR) [4], in which the process $pp \to p + X + p$ takes place as illustrated in figure 1. The cross-section factorises into a hard scattering part which represents the gluon fusion sub-process, $d\hat{\sigma}(y, \hat{s})$, and an effective gluon luminosity, $d\mathcal{L}(\hat{s}, y)/(dy\, d\hat{s})$. As a result, we can write the cross-section for producing any central system at rapidity y and invariant mass $\hat{s}$ as

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[2]It means we do not consider the case where the gluinos stop and subsequently decay within the calorimeter [17].

$$\frac{d\sigma}{dyd\hat{s}} = \frac{d\mathcal{L}(\hat{s}, y)}{dyd\hat{s}} d\hat{\sigma}(y, \hat{s}) \,. \tag{2.1}$$

An overview of the details of the calculation has been given by one of us [5]. Here we just state the result:

$$\hat{s}\frac{d\mathcal{L}(\hat{s}, y)}{dyd\hat{s}} = \left[\frac{\pi}{8b} \int\limits^{M^2/4} \frac{dQ^2}{Q^4} f(x_1, Q, M) f(x_2, Q, M)\right]^2 \tag{2.2}$$

where

$$f(x, Q, M) = R_g Q^2 \frac{\partial}{\partial Q^2}\left(\sqrt{T(Q, M)} x g(x, Q^2)\right) \tag{2.3}$$

and

$$T(Q, M) = \exp\left(-\int_{Q_T^2}^{M^2/4} \frac{dp_T^2}{p_T^2} \frac{\alpha_s(p_T^2)}{2\pi} \int_0^{(1+2p_T/M)^{-1}} dz \left[zP_{gg}(z) + \sum_q P_{qg}(z)\right]\right). \tag{2.4}$$

We take the diffractive slope parameter $b = 4\,\text{GeV}^{-2}$ and $g(x, Q^2)$ is the gluon distribution function of the proton. R_g is a parameter which corrects for the fact that we really need an off-diagonal gluon distribution. We use the default value in the ExHuME Monte Carlo [20] which, at LHC energies, corresponds to $R_g \approx 1.2$ [3]. Formally the Q integral needs to be cut-off in order to avoid the pole in the running coupling. In practice the integral is peaked well above Λ_{QCD} and so the final results are insensitive to the value of the infra-red cutoff (ExHuME takes a value of $800\,\text{MeV}$).

Since we are considering scattering of the protons through very small angles there is an effective $J_z = 0$ selection rule enforced upon the sub-process. This means that the incoming gluons which fuse to produce the central system X should have equal helicities. We choose to normalise the luminosity function in (2.2) such that an average over the incoming helicities and the colour of the gluons must be included in the sub-process amplitude, i.e.

$$\mathcal{M} = \frac{1}{(N_C^2 - 1)}\frac{1}{2}\left(\mathcal{M}^{++} + \mathcal{M}^{--}\right) \tag{2.5}$$

and

$$d\hat{\sigma}(y, \hat{s}) = \frac{1}{2\hat{s}}|\mathcal{M}|^2 d(\text{PS}). \tag{2.6}$$

3. Gluinonium

Close to threshold, the final state gluinos in the process $pp \to p + \tilde{g}\tilde{g} + p$ may be produced in a colour singlet bound-state configuration. Due to the Majorana nature of the gluinos the sum of the spin and angular momentum quantum numbers, $S + L$, of the bound state must be an even number [9]. Parity conservation then implies that $^3P_0$ is the lowest accessible state. After production, the gluinonium state would decay very rapidly to two gluons, which should then be detected as a pair of jets.

Given the large mass of the gluinos, we can use a non-relativistic Coulomb potential to determine the interaction between them, i.e.

$$V(r) = -\frac{3\alpha_s}{r} , \qquad (3.1)$$

where r is the separation of the gluinos. The hard scattering cross-section we require is related simply to the width for the decay of the bound state to two gluons Γ_{gg} via

$$\frac{d\hat{\sigma}}{d\hat{s}} = 2\frac{\pi^2}{M^3}\Gamma_{gg}\delta(1 - \hat{s}/M^2). \qquad (3.2)$$

This is the usual result for the production of a bound state of mass $M \approx 2m_{\tilde{g}}$ [9] except that we need an additional factor of 2 to account for the fact that this is to be used in the exclusive cross-section formula (2.1) above.

The width for the P-wave gluinonium decay to two gluons can be computed and related to the derivative of the radial wavefunction at the origin, i.e. [3, 21]

$$\Gamma_{gg} = 648\alpha_s^2(m_{\tilde{g}})\frac{|R'(0)|^2}{M^4} = 27\left(\frac{3}{4}\right)^5 \alpha_s^2(m_{\tilde{g}})\alpha_s^5(Q)\,M \qquad (3.3)$$

where[3]

$$R(r) = \frac{1}{\sqrt{24a_0^5}}r\mathrm{e}^{-r/(2a_0)} \qquad (3.4)$$

and the Bohr radius is

$$a_0 = \frac{2}{3}\frac{1}{m_{\tilde{g}}\alpha_s(Q)}.$$

We choose the scale Q to be determined by the mean size of the gluinonium state, i.e.

$$Q = \frac{1}{\langle r \rangle} \approx \frac{1}{10a_0}. \qquad (3.5)$$

This scale is substantially smaller than the value chosen in [3] but ought to be more appropriate since the bound state is P-wave rather than the more compact S-wave.

In making our predictions we use the default soft survival factor of 3%, as appropriate to central production at the LHC [22]. Figure 2 shows the total cross-section of central exclusive gluinonium production as a function of the mass of the gluinonium. The results are presented for two choices of the scale Q and for two different choices of parton distribution function (PDF).

Even before backgrounds are considered, this rate is small. At low luminosity ($10\,\mathrm{fb}^{-1}$ per year) we can expect fewer than ~ 5 events after one year for gluino bound states of mass $\approx 340\,\mathrm{GeV}$, which corresponds to the current experimental lower limit. This number rises to ~ 45 events at high luminosity ($100\,\mathrm{fb}^{-1}$ per year) but this is still likely to be insufficient given that the backgrounds from inclusive central production ($pp \to p + jj + X + p$) and exclusive dijet production ($pp \to p + jj + p$) need also to be brought under control. We have used ExHuME v1.3.2 [20] and POMWIG [25] to model the backgrounds and confirm that they are indeed prohibitive.

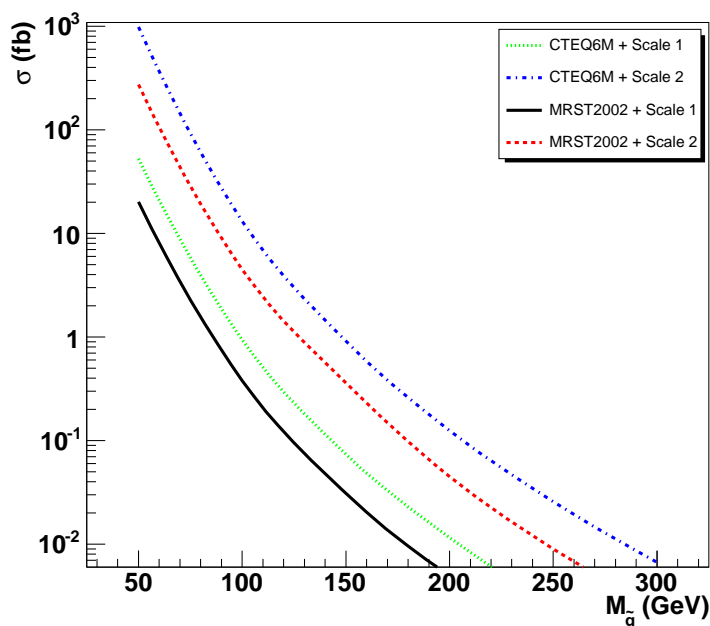[3]$R(r)$ is normalized such that $\int dr\ r^2 R(r)^2 = 1$.

Figure 2: The total cross-section for gluinonium production. Shown are results for the MRST2002nlo [23] and CTEQ6m [24] PDF sets with two different choices of scale. Scale 1 is the choice $Q^{-1} = a_0$ and Scale 2 is the choice $Q^{-1} = 10a_0$.

4. R-hadrons

4.1 Production and spectrum

The gluinos may also be produced unbound. Sufficiently far from threshold, the differential cross-section in the centre-of-mass (CM) frame given by [3]

$$\left(\frac{d\hat{\sigma}}{d\Omega}\right)_{\text{CM}} = \frac{9}{32} \frac{\alpha_s^2(\mu) m_{\tilde{g}}^2 \beta_{\tilde{g}}^3}{(m_{\tilde{g}}^2 + |\boldsymbol{p}|^2 \sin^2 \theta)^2} \, K, \tag{4.1}$$

where $\beta_{\tilde{g}}$ and $|\boldsymbol{p}|$ are the CM speed and momentum of the gluinos. Following the NLO calculations in [26], we evaluate the running coupling at scale $\mu = \frac{1}{5}m_{\tilde{g}}$. K is a threshold correction factor which we take to be [3, 14, 27]

$$K = \frac{Z_g}{1 - \exp(-Z_g)} \left(1 + \frac{Z_g^2}{4\pi^2}\right) \tag{4.2}$$

where

$$Z_g = \frac{3\pi\alpha_s(\beta_{\tilde{g}} m_{\tilde{g}})}{\beta_{\tilde{g}}}. \tag{4.3}$$

The gluino is colour octet and in the case where it is long lived will hadronise into bound states termed R-hadrons. These are colour neutral states of a single gluino bound with

gluons and/or quarks and anti-quarks. There have been several studies of the spectrum of these states and their interactions in the detector [10, 13, 14, 28 – 34, 17 – 19]. It is found that the states are nearly mass degenerate, with the R-mesons ($\tilde{g}\bar{q}q$) being slightly lighter than the lowest gluino-gluon state, R_g^0, [19, 28 – 30] and the R-baryons ($\tilde{g}qqq$) being about 0.3 GeV heavier than these [29, 19]. Only a small proportion of gluinos are expected to form R-baryons and roughly half of the R-mesons formed will be charged, with the rest neutral. The fraction forming R_g states is unknown and is therefore a free parameter.

4.2 Interaction in detectors and triggering

As a R-hadron passes through the detector, it will lose energy through ionisation (if it is charged) and via hadronic interactions in the calorimeters. R-mesons may be converted into R-baryons by scattering off nucleons in the calorimeter, but R-baryon conversion to R-mesons is likely to be negligible [19]. Also, the R_g states are expected to interact in the same way as a neutral R-meson, hence by the time the R-hadron has passed through the calorimeter it may well be an R-baryon, irrespective of how it started. Thus, 75% of all R-hadrons are expected to be charged after passing through the calorimeters (the ratio of charged to neutral R-baryon states is 3:1) [34]. These events will look like a muon within a jet (though more isolated than one resulting from a heavy quark weak decay [34]) but with the particle arriving significantly later at the muon chambers.

The difficulties in triggering on events involving R-hadrons at the ATLAS experiment have been discussed in [34]. Essentially, the level 1 triggers which make use of energy deposited in the calorimeters (including the missing energy triggers) are useless because the R-hadrons are expected to leave too little energy in the detector. The only other option is to use the muon triggers. This presents its own problems however, since the R-hadrons can be so delayed that they do not even arrive at the muon chambers within the same bunch crossing. We therefore impose the following cuts:

- The pseudo-rapidity of each R-hadron should satisfy $|\eta| < 2.4$. This is the limit of the muon trigger at ATLAS.

- The speed of the fastest of the two R-hadrons should lie in the range $0.6 < \beta < 0.9$. This is the R-hadron which triggers the muon chambers. The upper bound is chosen in order to eliminate all muon backgrounds whilst the lower bound arises in order that the R-hadron arrive in time to trigger the event.

- The speed of the slower R-hadron should lie in the range $0.25 < \beta < 0.9$ where the lower bound is determined by the requirement that the R-hadron is in the same event record as the faster R-hadron.

The ability of the $\beta > 0.6$ cut to retain the complete event information is questionable.[4] Although it is true that the R-hadron arrives in time to trigger the event, there is the possibility that the readout of the muon trigger will assign the event to the wrong bunch crossing. The wrong event would then be read out from the other sub-detectors. This does

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[4]We thank Thorsten Wengler for drawing our attention to this.

not necessarily mean that the information is unobtainable. For example, the TRT reads out in 75 ns time slices which could be long enough to contain the relevant information. Nevertheless more detailed studies are required before firm conclusions on the utility of the inner detectors can be drawn. Fortunately, the forward detector information should be available provided they are configured to take the events either side of the accepted event. We therefore propose to trigger on the fastest R-hadron and then check the pot readout to see if there are hits in the forward detectors in either the same event or the previous one. In what follows we shall assume that no information is available other than that provided by the forward detectors and the muon chambers, fortunately this should be sufficient to make an interesting measurement of the gluino mass.

The gluino mass can be determined given the mass (M) and rapidity (y) of the central system, and the lab scattering angles of the two gluinos (θ_1 and θ_2) by solving the pair of equations

$$\frac{1}{\tan\theta_1} = \frac{\gamma}{k\sin\theta_{CM}}\left(k\cos\theta_{CM} + \frac{\beta M}{2}\right), \tag{4.4}$$

$$\frac{1}{\tan\theta_2} = \frac{\gamma}{k\sin\theta_{CM}}\left(-k\cos\theta_{CM} + \frac{\beta M}{2}\right) \tag{4.5}$$

where θ_{CM} is the CM scattering angle, $\beta = \tanh y$, $\gamma = \cosh y$ and $k^2 = \hat{s}/4 - m_{\tilde{g}}^2$. The forward detectors measure the momentum loss, x_i, of the protons and hence the mass and rapidity of the central system can be reconstructed using

$$M^2 = x_1 x_2 s \quad \text{and} \quad y = \frac{1}{2}\ln\frac{x_1}{x_2}. \tag{4.6}$$

The muon spectrometer can be used to determine the angles θ_1 and θ_2 and so the gluino mass can be measured using only the muon and forward detector information.

When quoting expected numbers of events we must also remember to multiply by a factor 0.75×0.6. The 0.75 accounts for the fact that the R-hadron must be charged and the 0.6 is an estimate of the muon trigger efficiency . The efficiency of the muon trigger is usually greater than 85% at ATLAS [35]. However, it is argued in [34] that the efficiency is lower in the case of R-hadrons because the R-hadron can interact in the muon system and change to another R-hadron of different charge.

We must also account for the acceptance of the forward detectors. At present there are plans to put detectors at 220m [2] and 420m [1] from the interaction point. Due to the relatively large masses we consider, good acceptance for central masses in the range $300 - 1500\,\text{GeV}$ requires use of at least one pot at 220m. The acceptances and resolutions for the measurements in the Roman Pots have been calculated by means of the Monte Carlo program FPTRACK which tracks the protons, generated using ExHuME, through an accurate representation of the LHC beam line with the best available magnet optics. The results for the acceptance are shown in figure 3. Moving the 220m pots closer to the beam, i.e. from from 3mm to 2mm, results in an increase in acceptance in the mass range $200\,\text{GeV} < M < 800\,\text{GeV}$. Even in the most conservative scenario with 420m pots at 5mm from the beam and 220m pots at 3mm from the beam, the acceptance is more than 40% up to central masses of $950\,\text{GeV}$.
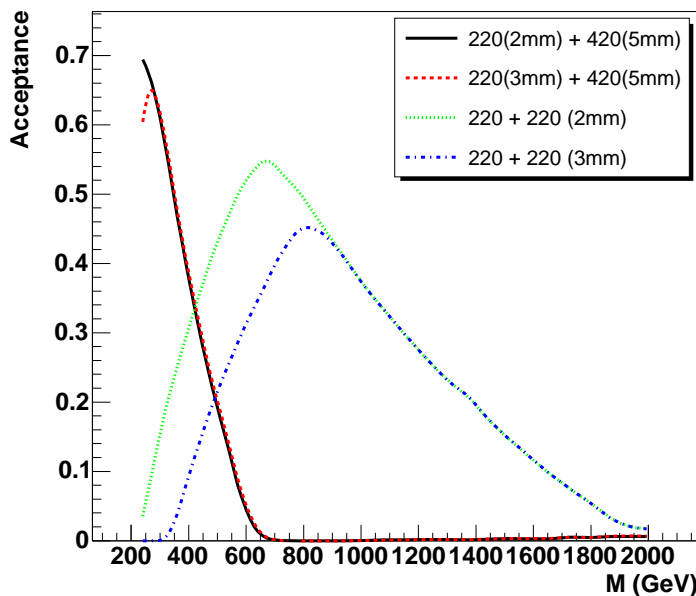
Figure 3: The acceptance of Roman Pots installed 5mm from the beam at 420m and either 2mm or 3mm at 220m.

There are two sources of background which need discussing. The first involves processes in which the protons remain intact whilst the second arises as a result of pile-up. The former comes mainly from the weak decays of exclusively produced high transverse momentum b and t quarks, and it was found in [34] that these backgrounds can be effectively reduced by the upper β cut. Finally, there is a kinematic matching constraint, arising from the requirement that the kinematics of the central system should match the kinematics measured using in the pots, which will reduce the background rate still further. We therefore believe that this type of background will be negligible.

The background from pile-up requires a different strategy for its removal. As we shall see in the next section, gluino pair production is mainly interesting when the LHC luminosity is high, i.e. $\sim 100\,\mathrm{fb}^{-1}$ per year. At high luminosity, there are expected to be around 35 overlap events in each bunch crossing and it is possible for two single diffractive events $(pp \to p + X)$ to overlap with an inclusive hard scattering event $(pp \to X)$. This could mimic the signal, with a proton from each of the single diffractive events registering in the pots and the hard scattering providing the candidate muons. However, this background can certainly be reduced very substantially in a number of ways. Firstly, good timing from the forward detectors can locate the candidate primary vertex to within 3mm [36] and this can be compared to the position of the vertex obtained from the central detector. Secondly, one can apply the kinematic matching of the previous paragraph to ensure that the central system has kinematics consistent with the measured protons. Finally, the muon candidates will only pass the $\beta < 0.9$ cut if the inclusive interaction occurs with a time
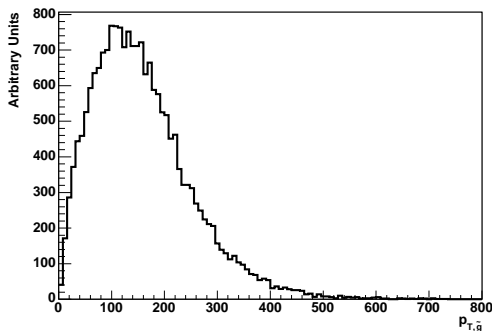
Figure 4: The p_T distribution for pair producing 300 GeV gluinos.

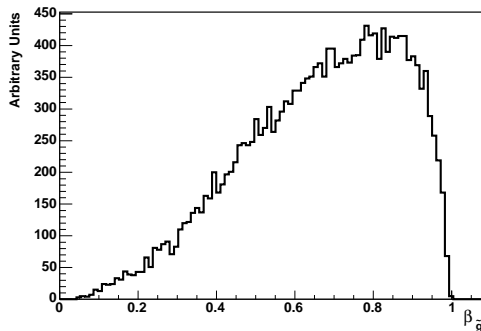**Figure 5:** The β distribution for pair producing 300 GeV gluinos.

delay relative to the LHC clock. The spread of protons in a bunch at the LHC is estimated to be $0.25 - 0.5$ ns. However, the minimum distance the muon has to travel to trigger the event at high luminosity is $\simeq 10$m, which takes some 30 ns. Therefore, in order to pass the $\beta < 0.9$ cut, the delay of the interaction with respect to the LHC clock would have to be 3 ns. We therefore conclude that backgrounds from this source will also be negligibly small.

Before moving on to present our numerical estimates, it is worth emphasising that the possibility to measure central exclusive production even in the high luminosity phase of the LHC is of much wider significance than the study presented here. Potentially all processes hitherto examined in the literature could benefit from the greatly enhanced statistics afforded if pile-up can be brought under control.

4.3 Results

The cross-section for gluino pair production has been included in the ExHuME Monte Carlo [20]. Figures 4 and 5 show the p_T and β spectra for 300 GeV gluinos. Clearly, the β cuts we use do not cut out too much signal. We do not need to worry about the p_T trigger cut because the muon trigger uses the radius of curvature of the track in the muon spectrometer. As R-hadrons are much heavier than muons they have a much larger radius of curvature for a given velocity and hence all of them will pass the trigger cut. In figure 6 we show the cross-section for the central exclusive production of a pair of gluinos after the cuts discussed in the previous section, but excluding the trigger efficiency factor and the pot acceptance factor. We show our results for two different PDFs. We also show the cross-section in the case that both R-hadrons are required to make the level 1 trigger (i.e. the slower R-hadron is also required to have $\beta > 0.6$). In figure 7 we show the effect of the threshold correction given in (4.2) for our canonical β cuts. Clearly the rate is not large. However, the smallness of the background and the precision of the detectors means that only very few events are needed in order to make an interesting measurement.

As we have seen, the gluino mass determination is possible using only the pots and the muon detector. This is in contrast to the case where the gluinos are produced inclusively (i.e. the protons break up). Inclusive production was considered in [33], where the recon-
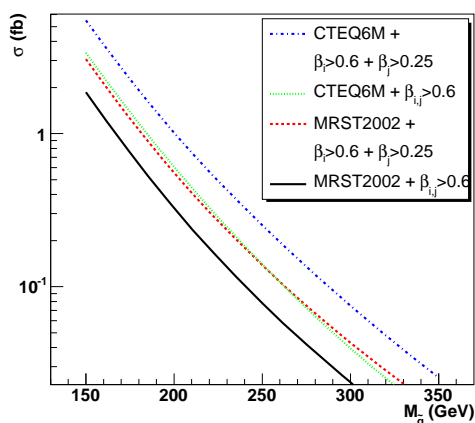
Figure 6: The cross-section for exclusive gluino pair production for the MRST2002nlo and CTEQ6m PDF sets with two different choices of β cut.
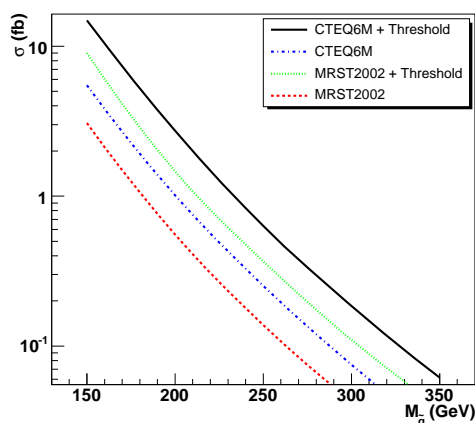

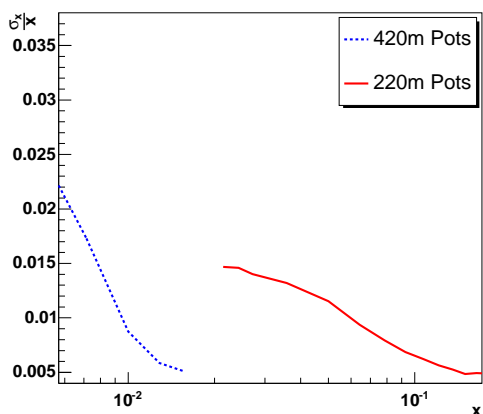**Figure 7:** The effect of the threshold enhancement for MRST and CTEQ PDF's.

Figure 8: The resolution of the fractional momentum loss, x, of protons tagged in the pots.
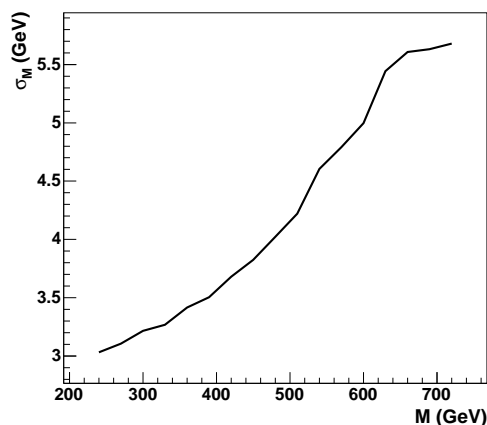

Figure 9: The resolution of the central mass M (all rapidities)

structed R-hadron mass was found to be shifted from the true mass due to interactions of the R-hadron in the calorimeter. The uncertainty of this shift was estimated to be $5\,\text{GeV}$ for a $250\,\text{GeV}$ gluino, with the systematic uncertainty becoming less important for larger gluino masses. An analysis using the forward detectors thus complements that of [33], since it is best suited to making accurate measurements at lower masses where the rate is higher.

Using FPTRACK, we obtain proton momentum resolutions as shown in figure 8, from which the gluino mass resolution is calculated. In figure 9 we show the corresponding resolution on the central mass. The resolution is dependent on the primary beam momentum spread, the beam spot size and the angle/position measurement of the proton by the pots (1μrad and 10μm). All that is required from the main detector itself are the

$m_{\tilde{g}}$ (GeV)	$\sigma_{m_{\tilde{g}}}$ (GeV)	$\frac{\sigma_{m_{\tilde{g}}}}{\sqrt{N-1}}$ (GeV)	N
200	2.31	0.19	145
250	2.97	0.50	35.0
300	3.50	1.10	10.2
320	3.61	1.54	6.5
350	3.87	2.45	3.5

Table 1: The gluino mass resolution as a function of the gluino mass.

pseudo-rapidities of each of the gluinos. We smear the gluino pseudo-rapidities using a gaussian distribution with $\sigma_\eta = 0.0038$ which is our best estimate of the resolution that can be obtained using only the muon detectors [37]. This uncertainty assumes that no inner detector information will be available as a result of read-out problems. If it transpires that some inner detector information is available, then this resolution will obviously improve. The resulting gluino mass resolution, given 3 years of high luminosity running, is shown in table 1. In particular we show the final error on the mass measurement for N events, where N is determined using figure 7 after applying the pot acceptance (0.4) and trigger efficiency (0.75×0.6) factors. We see that it should be possible to measure the gluino mass to an accuracy below 1% up to gluino masses of $\simeq 350\,\text{GeV}$.

We should comment upon the fact that the central masses we have been considering are as large as $1\,\text{TeV}$. In this region, the theory we have used should certainly be supplemented by the inclusion of quark exchange diagrams and this should serve to increase the predicted rate. We therefore regard our predictions as conservative.

5. Conclusions

We have shown that central exclusive production of gluino pairs ($pp \to p + \tilde{g}\tilde{g} + p$) could provide an accurate measurement of the gluino mass at the LHC in the case that the gluinos are light enough and sufficiently stable. Although detection of gluino bound states is not viable, open gluino production could be detected provided the gluinos have mass below $\simeq 350\,\text{GeV}$ and their mass measured to an accuracy at the 1% level after 3 years of high luminosity running. Accurate mass determination is a feature of having successfully detected and measured the scattered protons using appropriately installed forward detectors during the high luminosity phase of the LHC.

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