Distinguishing Majorana and Dirac 
Gluinos and Neutralinos

A. Freitas

Department of Physics and Astronomy, University of Pittsburgh, PA 15260, USA

Abstract. While gluinos and neutralinos are Majorana fermions in the MSSM, they can be Dirac fermion fields in extended supersymmetry models. The difference between the two cases manifests itself in production and decay processes at colliders. In this contribution, results are presented for how the Majorana or Dirac nature of gluinos and neutralinos can be extracted from di-lepton signals at the LHC.

PACS: 12.60.Jv, 14.80.Ly, 13.85.-t

MAJORANA AND DIRAC FERMIONS IN SUPERSYMMETRY

In the Minimal Supersymmetric Standard Model (MSSM), the fermionic partners of the neutral, self-conjugate gauge bosons are self-conjugate Majorana fields with two degrees of freedom each. For example, the relation between the gluon and gluino fields and their charge conjugate fields is given by $g^c = -g^T$, $\tilde{g}^c = -\tilde{g}^T$, where color indices have been suppressed. Massive Majorana particles are known to mediate fermion-number violating production and decay processes, such as

$$q_Lq_L \rightarrow \tilde{q}_L\tilde{q}_L, \quad q_Rq_R \rightarrow \tilde{q}_R\tilde{q}_R, \quad \tilde{q}_L \rightarrow q \ell^\pm \ell'^\mp. \quad (1)$$

These processes thus are central for experimentally testing the Majorana nature of gluinos.

To study the characteristic differences between Majorana and Dirac fields, we will focus on a well-defined framework where the gauge fields are embedded in $N = 2$ superfields [1]. Each $N = 2$ gauge hypermultiplet contains one vector field, two two-component fermion fields, and one complex scalar fields, see Tab. 1. Depending on the structure of supersymmetry (SUSY) breaking, the two fermion components can form two distinct Majorana fields or one Dirac field. The scalar component could lead to interesting phenomenology on its own [2], but will not be discussed here. The two MSSM Higgs doublets can be joined into an $N = 2$ chiral/anti-chiral hypermultiplet, but the quark and lepton fields will be restricted to $N = 1$ representations as in the MSSM for the purpose of this work. The results presented here are based on Ref. [3]. Some earlier work on the observability of the Majorana nature may be found in Ref. [4], and consequences for the density of cold dark matter have been elaborated in Ref. [5].
the second eigenvalue changes from
with a bino LSP,
Majorana gluino mass eigenstates ˜
Majorana and Dirac limits, respectively, while for any value in-between we obtain two
matrix. A few examples for the
squark production are shown in Fig. 1.
As
y
squark production are shown in Fig. 1.

\[ L_{\text{gluino interactions}} = g_s \text{Tr}(\bar{g} \gamma^\mu [g_{\mu}, g]) + \bar{g} \gamma^\mu [g_{\mu}, g']) - g_s [\bar{\tau}_L \bar{\tau}_L - \bar{\tau}_R \bar{\tau}_R + \text{h.c.}] \].

(2)
The soft supersymmetry breaking mass terms are given by

\[ L_{\text{soft gluino masses}} = -\frac{1}{2} [M'_3 \text{Tr}(\bar{g} g') + M_3 \text{Tr}(\bar{g} g) + M_D^2 \text{Tr}(\bar{g} g + \bar{g} g')] \],

(3)
so they form a 2 × 2 matrix in the ˜g, ˜g'-space. In the limit \( M'_3 \rightarrow \infty \) the ˜g' decouples and
the MSSM gluino sector is recovered. On the other hand, if \( M_3 = M'_3 = 0 \) and \( M_D^2 \neq 0 \),
the mass matrix has two degenerate eigenvalues. In this case, the two Majorana states
are paired into one Dirac field ˜g_D = \( \frac{1}{2}(1 + \gamma_5)g + \frac{1}{2}(1 - \gamma_5)g' \) with Dirac mass \( M_D^2 \).

A smooth path can be defined that interpolates between the Majorana and Dirac limits:

\[ M'_3 = m_{\tilde{g}_1} \frac{y}{1 + y}, \quad M_D^3 = m_{\tilde{g}_1}, \quad M_3 = m_{\tilde{g}_1} M'_3/(M_3 - m_{\tilde{g}_1}). \]

(4)
As \( y \) is varied between −1 and 0, one of the mass eigenvalues is kept fixed at \( m_{\tilde{g}_1} \), while
the second eigenvalue changes from \( \infty \) to \( m_{\tilde{g}_1} \). Therefore \( y = -1, 0 \) correspond to the
Majorana and Dirac limits, respectively, while for any value in-between we obtain two
Majorana gluino mass eigenstates ˜g_{1,2} that are related to ˜g and ˜g' by a non-trivial mixing
matrix. A few examples for the \( y \)-dependence of partonic cross sections for gluino and
squark production are shown in Fig. [1]

Since, therefore, the ratio of gluino and squark production rates is different in the
Majorana and Dirac limits, this leads to observable effects for di-lepton SUSY signatures
at the LHC. In particular, assuming a standard scenario (such as the SPS1a' scenario [6])
with a bino LSP, \( m_{\tilde{g}} > m_{\tilde{q}} \), and the dominant decay chains

\[ \tilde{q}_L \rightarrow q \tilde{\chi}_i^\pm \rightarrow q l^\pm v_l \tilde{\chi}_i^0, \quad \tilde{q}_R \rightarrow q \tilde{\chi}_i^0, \]

(5)
the charge of the lepton is related to the charge of the L-squark. This results in a net
difference in the ratio of \( l^+ l^+ \) and \( l^- l^- \) rates between the Majorana and Dirac case,
see Tab. [2]. After applying the cuts of Ref. [7] to reduce the Standard Model (SM)
background and by combining information of the total di-lepton rates and the jet \( p_T \)
distributions, the two cases can be distinguished with a statistical significance of 11
standard deviations, for an integrated luminosity of 300 fb⁻¹. As we have checked in

\[ \begin{array}{cccc}
\text{Group} & \text{Spin 1} & \text{Spin 1/2} & \text{Spin 0} \\
\text{SU(3)} & g & \tilde{g}; \tilde{g}' & \sigma_g \\
\text{SU(2)} & W^\pm, W^0 & \tilde{W}^\pm, \tilde{W}^0 & \sigma_{W} \sigma_{W'} \\
U(1) & B & \tilde{B}; \tilde{B}' & \sigma_B \\
\end{array} \]

(1)

\textbf{THE SUSY-QCD SECTOR}

In our setup, the two gluino components ˜g and ˜g' in the gluon vector hypermultiplet each
have the usual kinetic terms, but only the standard gluino interacts with matter:

\[ \tilde{L} \quad \tilde{g} \quad \tilde{B} \quad \tilde{W}^\pm \quad \tilde{W}^0 \quad \tilde{Z} \quad \tilde{H}^0 \quad \tilde{H}^0 \quad \tilde{c} \quad \tilde{t} \quad \tilde{b} \quad \tilde{d} \quad \tilde{u} \quad \tilde{e} \quad \tilde{\mu} \quad \tilde{\tau} \]

(1)

\[ \begin{array}{cccc}
\text{Group} & \text{Spin 1} & \text{Spin 1/2} & \text{Spin 0} \\
\text{SU(3)} & g & \tilde{g}; \tilde{g}' & \sigma_g \\
\text{SU(2)} & W^\pm, W^0 & \tilde{W}^\pm, \tilde{W}^0 & \sigma_{W} \sigma_{W'} \\
U(1) & B & \tilde{B}; \tilde{B}' & \sigma_B \\
\end{array} \]
FIGURE 1. Partonic cross sections for $\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{g}$ production at a function of the Dirac/Majorana control parameter $y$. The plot corresponds to a fixed partonic center-of-mass energy $\sqrt{s} = 2000$ GeV, and $m_{\tilde{g}_1} = 500$ GeV and $m_{\tilde{g}_1} = 600$ GeV.

Ref. [3] this result is not deteriorated significantly by including realistic uncertainties for the squark and gluino masses, the missing higher-order corrections, and the parton distribution functions.

THE ELECTROWEAK SECTOR

The electroweak $N = 2$ gauge multiplets can form Dirac neutralinos in a similar fashion as explained for Dirac gluinos in the previous section. The matching of the two Majorana neutralinos is straightforward if the mixing between gauginos and higgsinos due to electroweak symmetry breaking can be neglected.

The difference between the Dirac and Majorana theory leads to interesting consequences for decay chains involving neutralinos at the LHC. Owing to its self-conjugate nature, a Majorana neutralino can decay into R-sleptons of either charge,

$$\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q l_n^- \tilde{l}_R^+ \rightarrow q l_n^- l_f^+ \tilde{\chi}_1^0.$$  \hspace{1cm} (6)

Here $l_n$ stands for the “near” lepton emitted in the first decay stage of the neutralino.

| Majorana | Dirac | $N(t^+t^+)/N(t^+\tilde{t}^*)$ |
|---------|-------|------------------|
| $\tilde{q}_L \tilde{q}_L^{(1)}$ | 2.1 pb | 0.6 fb | 2.5 | 1.5 |
| $\tilde{q}_L \tilde{q}_L^{(1)*}$ | 1.4 pb | 3.1 fb | 3.1 fb | 1.4 | 1.4 |
| $\tilde{q}_L \tilde{g}_L^{(1)}$ | 7.0 pb | 7.6 fb | 7.6 fb | 1.5 | 1.5 |
| $\tilde{g}_L^{(1)} \tilde{g}_L^{(1)*}$ | 3.2 pb | 1.4 fb | 3.2 fb | 1.0 | 1.0 |
| SM | 800 pb | <0.6 fb | 800 pb | <0.6 fb | 1.0 |
while \( l_f \) denotes the “far” lepton stemming from the slepton decay. On the other hand, the corresponding Dirac neutralino \( \tilde{\chi}^0_{D2} \) decays only to negative R-sleptons, while its charge conjugate \( \tilde{\chi}^{0*}_{D2} \) decays only to positive R-sleptons:

\[
\tilde{q}_L \rightarrow q \tilde{\chi}^0_{D2} \rightarrow q l_+^R \tilde{\chi}_1^0, \quad \tilde{q}_L^* \rightarrow q \tilde{\chi}^{0*}_{D2} \rightarrow q l_-^R \tilde{\chi}_1^0. \quad (7)
\]

As a result, the \( q l^\pm \) distributions arising from these decay chains are markedly different for the Majorana and Dirac cases. This is shown in Fig. [2] for the SPS1a’ scenario. The kink in the plots corresponds to the kinematic endpoint for the \( q l_f \) system, while the \( q l_n \) endpoint is larger in this scenario and coincides with the right edge of the plots.

**SUMMARY**

SUSY extensions of the SM predict fermions in the adjoint gauge group representations, which can be Majorana or Dirac fermions, depending on the details of the model. Experimental distinction between the two cases is thus of central interest for the physics program at future colliders. Here it was shown how the Majorana or Dirac nature of gluinos can be determined from SUSY production processes at the LHC, while neutralinos can be analyzed in leptonic SUSY decay chains.

**REFERENCES**

1. K. Benakli and C. Moura, in M. M. Nojiri et al., arXiv:0802.3672 [hep-ph].
2. S. Y. Choi, M. Drees, J. Kalinowski, J. M. Kim, E. Popenda and P. M. Zerwas, Phys. Lett. B 672, 246 (2009).
3. S. Y. Choi, M. Drees, A. Freitas and P. M. Zerwas, Phys. Rev. D 78, 095007 (2008).
4. R. M. Barnett, J. F. Gunion and H. E. Haber, Phys. Lett. B 315 (1993) 349; M. M. Nojiri and M. Takeuchi, Phys. Rev. D 76 (2007) 015009.
5. G. Belanger, K. Benakli, M. Goodsell, C. Moura and A. Pukhov, arXiv:0905.1043 [hep-ph].
6. J. A. Aguilar-Saavedra et al., Eur. Phys. J. C 46 (2006) 43.
7. A. Freitas, P. Z. Skands, M. Spira and P. M. Zerwas, JHEP 0707 (2007) 025.