

Exploring Dirac neutralinos and EW adjoint scalars of N=1/N=2 hybrid SUSY at colliders*

Jan Kalinowski[†]

Faculty of Physics, University of Warsaw, Hoza 69, 00681 Warsaw, Poland

E-mail: Jan.Kalinowski@fuw.edu.pl

Properties of Dirac neutralinos and the corresponding EW scalar gauge bosons, as predicted by the N=1/N=2 hybrid supersymmetric model, and prospects for their discovery at colliders are discussed.

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[†]Speaker.

1. Introduction.

In the simplest N=1 supersymmetric extension of the Standard Model each particle is accompanied by a sparticle that differs in spin by half a unit. Thus the gaugino partners \tilde{G}_K^α of the gauge bosons G_K^μ are self-conjugate Majorana fields (with $K = C, I, Y$ for SU(3), SU(2) and U(1)). In non-minimal models additional gauginos \tilde{G}'^α together with the original N=1 gauginos \tilde{G}_K^μ can be combined to Dirac fields. For example, in [1, 2, 3] the usual super-multiplets $\mathcal{G}_K = \{\tilde{G}_K^\alpha, G_K^\mu\}$ are supplemented by additional N=1 chiral super-multiplets $\hat{\Sigma}_K = \{\sigma_K, \tilde{G}'^\alpha\}$ of extra gauginos \tilde{G}'^α and scalar partners σ_K in the adjoint representation of the corresponding gauge group to form a vector hyper-multiplet of N=2 SUSY [4]. To keep the theory chiral, masses of new matter multiplets are assumed heavy implying an hybrid N=1/N=2 structure of the model.

The transition from Majorana to Dirac fields renders the theory [partially] R -symmetric with important consequences: the baryon and lepton number violating operators are naturally suppressed and SUSY flavor-changing and CP-violating contributions are reduced significantly, widening the parameter space for supersymmetric theories [5]. The Dirac nature of gauginos alters significantly the collider phenomenology and has implications for the relic density of the Universe [6]. Last, not least, since adjoint scalars σ_K are R -parity even, they can be produced not only pairwise with large cross section but also singly in particle collisions making searches at colliders very interesting.

2. Dirac gauginos and adjoint scalars

Apart from kinetic $\int d^4\theta \hat{\Sigma}^\dagger \exp[\hat{G}] \hat{\Sigma}$, new terms in the hybrid model appear: the Majorana mass M' for the new gauge superfields $\int d^2\theta M' \hat{\Sigma} \hat{\Sigma}$ as well as the Dirac mass M^D coupling the original and new gauge superfields $\int d^2\theta M^D \theta^\alpha \text{tr} \hat{G}_\alpha \hat{\Sigma}$ (with gauge group indices understood), and new trilinear terms $W'_H = \int d\theta^2 \hat{H}_u \cdot (\lambda_I \hat{\Sigma}_I + \lambda_Y \hat{\Sigma}_Y) \hat{H}_d$ that couple new electroweak chiral to Higgs superfields.¹ Soft N=1 breaking terms complete the definition of the hybrid model.

New fields imply new couplings. New gauginos \tilde{G}' and sigma fields σ couple minimally to the gauge fields, as required by the gauge symmetry. Also gauge symmetry dictates tree level couplings of the sigma fields to the gaugino and sfermion-fermion fields. Fermion and sfermion fields interact only with the standard gaugino since only their mirror partners (assumed to be heavy) couple to \tilde{G}' . The tri-linear terms W'_H in the superpotential imply Yukawa-type interactions of the EW sigma fields with higgsinos, while the Dirac gaugino mass generates, via the D -term, new tri- and quadri-linear scalar couplings between σ field(s) and sfermion pair

$$\mathcal{L}_{\sigma(\sigma)\tilde{f}\tilde{f}} = \left[-\sqrt{2}gM^D(\sigma^a + \sigma^{a*}) + ig^2 f^{abc} \sigma^{b*} \sigma^c \right] (\tilde{f}_L^\dagger T^a \tilde{f}_L - \tilde{f}_R^\dagger T^a \tilde{f}_R)$$

where M^D , g , T and f are the Dirac masses, couplings, generators and structure functions of the corresponding gauge group [note the minus sign in front of the quartic \tilde{f}_R term, which corrects Eq.(2.16) in Ref. [3]]. Since sfermions couple directly to gauge bosons and fermions, the above coupling, via sfermion/gaugino loops, generates effective couplings of σ fields to gauge bosons and fermions. Note however that L - and R -sfermion contributions to the effective coupling come with opposite signs. For colored σ_C they cancel each other for mass-degenerate squarks. In the EW sector only L sfermions couple to σ_I , while for σ_Y only partial cancellation occurs due to different

¹ M' and M^D can be generated by contact terms, $\int d^4\theta X^\dagger \hat{\Sigma} \hat{\Sigma}$ and $\int d^2\theta W'^\alpha W_\alpha \hat{\Sigma}$, when hidden sector spurion fields get vacuum expectation values, $\langle X \rangle = F\theta^2$ and $\langle W'^\alpha \rangle = D'\theta^\alpha$, respectively.

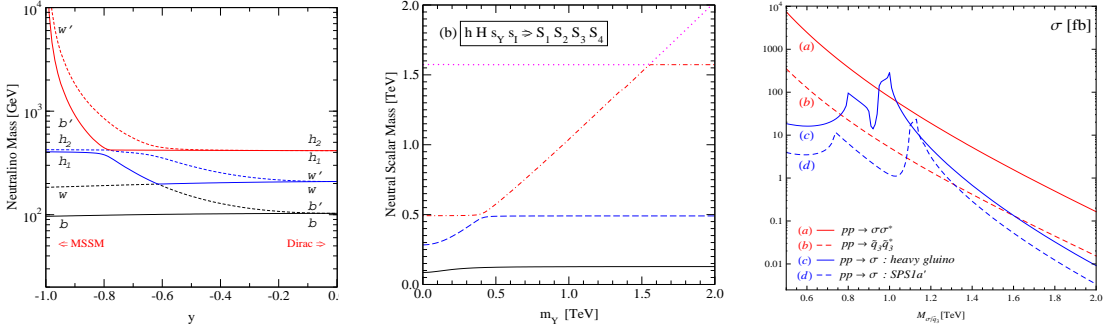


Figure 1: Left: Evolution of the neutralino masses as a function of the parameter y from the MSSM to the Dirac case. Middle: Neutral scalar masses as a function of the hypercharge soft scalar mass m_Y . Right: Cross sections for σ_C -pair (a), \tilde{q} -pair (b) and single σ_C (c,d) production at the LHC.

hypercharges of L and R sfermions. The fermion-antifermion-sigma coupling is also suppressed by the fermion mass, as evident from general chirality rules.

In the \tilde{G}, \tilde{G}' basis the 2×2 gaugino mass matrix has on the diagonal the soft SUSY breaking Majorana mass M for the usual gaugino and the supersymmetric Majorana M' for the new one, and on the off-diagonal the Dirac mass M^D . Its diagonalization gives rise to two Majorana mass eigenstates, \tilde{G}_1 and \tilde{G}_2 . There are two limiting cases of interest that can smoothly be connected by an auxiliary parameter $y \in [-1, 0]$ setting $M' = yM^D / (1 + y)$, $M = -yM^D$. Keeping $M^D = m_{\tilde{G}_1}$ fixed, the standard Majorana gaugino is reached for $y = -1$ (with the other infinitely heavy), while for $y = 0$ two degenerate Majorana states are combined to one Dirac $\tilde{G}_D = \tilde{G} \oplus \tilde{G}'$.

In the electroweak sector this simple picture complicates once the gauge symmetry is broken. EW gauginos get coupled to higgsinos extending the chargino mass matrix to the 3×3 and the neutralino to 6×6 . Nevertheless, for the couplings λ_I and λ_Y as dictated by N=2 SUSY, in the limit $y = 0$ three Dirac neutralinos are obtained as illustrated in Fig. 1(left).

The scalar electroweak sector, apart from the usual Higgses, includes also the iso-triplet and hypercharge fields. Expanding the fields around vev 's and eliminating the Goldstone modes, and diagonalising the mass matrices one ends up with 3 parity-odd neutral a_i , 4 parity-even neutral s_i and 3 charged scalar s_i^\pm mass-eigenstates. The small value of the iso-triplet vev , $v_I \leq 3$ GeV, to comply with constraints on the ρ parameter, can be met assuming the soft mass of σ_I of order TeV. On the other hand, the hypercharge v_Y and the σ_Y soft mass can be arbitrary. Fig.1(middle) illustrates the masses of the four parity-even eigenstates as a function of soft mass parameter m_Y .

3. Collider signatures

The phenomenology of the hybrid model is very rich. Here we show only a few examples; more can be found in [1, 2, 3].

Since sgluons σ_C , scalar partners of gluons, have a large color charge they might be more copiously produced than squarks at the LHC. In addition they can be produced singly as an s -channel resonance in gg fusion via the loop induced coupling. Fig.1(right) shows the expected cross section at the LHC in specific scenarios considered in ref.[1]. Such processes would be really spectacular given the fact that the σ decays give rise to signatures with multi-jets and large E_{miss} that should easily be detectable.

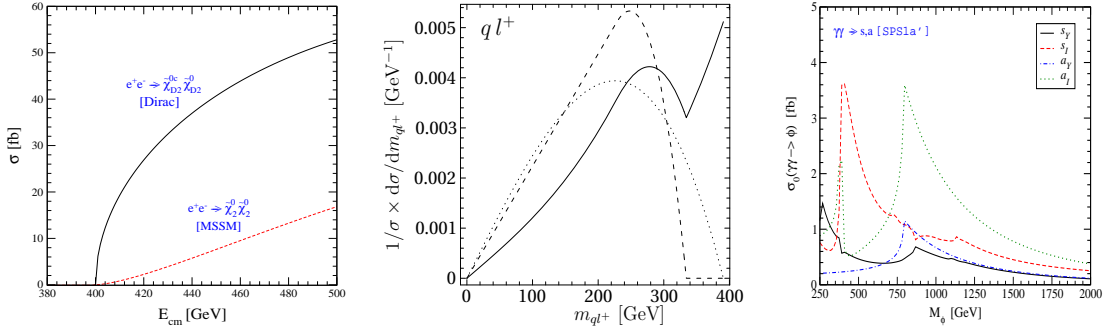


Figure 2: Left: Cross sections for pair production of wino-like neutralinos near threshold in the MSSM and the Dirac theory. Middle: ql^+ invariant mass distributions for squark decay chains involving Majorana or Dirac neutralinos: in the MSSM \tilde{q} and \tilde{q}^* decay chains lead to identical distributions (solid), in contrast to the Dirac case (dashes and dots, respectively). Right: Cross sections $\sigma_0(\gamma\gamma \rightarrow \phi)$ for $\phi = s_{Y,I}$ and $a_{Y,I}$.

Lepton colliders are ideal laboratories to study the properties of EW gauginos. The phenomenology of Dirac gauginos is characteristically different from Majorana. First, Dirac pair production is not forward-backward symmetric. Second, near threshold the diagonal neutralino pair is excited in P -waves for Majorana while in S -waves for Dirac, see Fig.2(left). The enhanced production for Dirac neutralinos may extend the search reach at colliders. By the same token, the neutralino annihilation cross section in the MSSM shows a P -wave, while in the Dirac case only an S -wave suppression into a fermion and anti-fermion pair and non-vanishing even for massless fermions. Thus, if the lightest neutralino is the LSP and stable, its nature has important consequences for cold dark matter phenomenology [6]. At hadron colliders the nature of the neutralino can be tested in the celebrated cascade squark decay. The decay chains differ: $\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow ql^\pm \tilde{l}_R^\mp \rightarrow ql^\pm l^\mp \tilde{\chi}_1^0$ for MSSM, $\tilde{q}_L \rightarrow q \tilde{\chi}_{D2}^0 \rightarrow ql^+ \tilde{l}_R^- \rightarrow ql^+ l^- \tilde{\chi}_1^0$ for Dirac, which will leave a characteristic imprint on the angular distributions of visible decay jets and leptons, as seen in Fig. 2(middle) for $SPS1a'$ -like scenario.

As a final example we consider the production processes of EW adjoint scalars. Since Q , I_3 and Y of neutral scalars vanish, they cannot be pair-produced at e^+e^- . However, the charged pairs $\sigma_I^+ \sigma_I^-$ can be excited through γ, Z exchanges with cross sections exceeding the charged Higgs states due to their larger EW charge. Resonant s -channel formation in fermion-antifermion annihilation is strongly suppressed since the tree level couplings are suppressed by the fermion mass. However, they can be excited in $\gamma\gamma$. Adopting the $SPS1a'$ scenario, the reduced $\sigma_0(\gamma\gamma \rightarrow \phi)$ cross section (the luminosity factor removed) can be of order 1 fb, see Fig.2(right).

Summary

In extended SUSY models, the gauginos can be of Majorana or Dirac type. Their nature can be tested at the LHC and linear colliders in a variety of production and decay channels. In addition, the accompanying adjoint scalars make the collider phenomenology very exciting.

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