Dirac Gauginos in Supersymmetry – Suppressed Jets + MET Signals:
A Snowmass Whitepaper

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Abstract

We consider the modifications to squark production in the presence of a naturally heavier Dirac gluino. First generation squark production is highly suppressed, providing an interesting but challenging signal find or rule out. No dedicated searches for supersymmetry with a Dirac gluino have been performed, however a reinterpretation of a “decoupled gluino” simplified model suggests the bounds on a common first and second generation squark mass is much smaller than in the MSSM: $\lesssim 850$ GeV for a massless LSP, and no bound for an LSP heavier than about 300 GeV. We compare and contrast the squark production cross sections between a model with a Dirac gluino and one with a Majorana gluino, updating earlier results in the literature to a $pp$ collider operating at $\sqrt{s} = 14$ and 33 TeV. Associated production of squark+gluino is likely very small at $\sqrt{s} = 14$ TeV, while is a challenging but important signal at even higher energy $pp$ colliders. Several other salient implications of Dirac gauginos are mentioned, with some thought-provoking discussion as it regards the importance of the various experiments planned or proposed.
1 Introduction

Gauginos in weak scale supersymmetry could acquire dominantly Dirac masses instead of Majorana masses. Dirac gaugino masses have been considered long ago \cite{1,3} and have inspired more recent model building \cite{4,21} and phenomenology \cite{22,56}. Dirac masses for gauginos of the MSSM requires the model to be extended to include a chiral superfields in the adjoint representation of each gauge group. Some or all of the gauginos could be Dirac, Majorana, or mixed states depending on the model and the mediation of supersymmetry breaking. Among the dramatic consequences that have been studied include: gaugino contributions to scalar masses that are “supersoft” (not log-divergent) \cite{4}; substantial relief from the supersymmetric flavor problem when the low energy model includes an approximate R-symmetry \cite{11}; suppressed EDMs \cite{3,11}; heavier Dirac gauginos that are just as naturalness as lighter Majorana gauginos \cite{4,47,55}; the (suppressed) production cross sections of colored superpartners at LHC \cite{47}; and the absence of some of the historically characteristic signals of supersymmetry (same sign lepton searches). There are many other interesting consequences of Dirac (or partially Dirac) gauginos that we do not have time or space to review, but can be found in papers cited above. For this Snowmass white paper, we delineate some ideas for searches involving Dirac gauginos that provide benchmarks to understand the impact of LHC searches thus far, the gaps in the searches that persist, and the opportunities for future searches.

One of the important consequences of a Dirac gluino is that it can be several times heavier than a Majorana gluino with the same degree of naturalness with respect to the electroweak symmetry breaking scale \cite{4,47}. Once a Dirac gluino mass is above roughly 2-3 TeV, gluino pair production as well as associated squark-gluino production cross sections are negligible at the 8 TeV LHC. For a Dirac gluino of any mass, several squark production channels vanish due to the absence of a “chirality flipping” Majorana mass in t-channel exchange, namely \( pp \rightarrow \tilde{q}_L \tilde{q}_L, pp \rightarrow \tilde{q}_R \tilde{q}_R \), etc. Other squark production channels that involve the gluino in t-channel exchange, such as \( pp \rightarrow \tilde{q}_L \tilde{q}_R \), are suppressed by \(|p|/M_{\tilde{g}}^2\) in the amplitude, where \(|p|\) is the momentum in the propagator. This suggests the dominant production mode of colored superpartners is \( pp \rightarrow \tilde{q} \tilde{q}^* \) for first (and second, third) generation squarks is through s-channel gluon exchange. The total colored superpartner production cross section is therefore reduced by roughly two orders of magnitude compared with what is typical in the MSSM – a Majorana gluino roughly equal in mass to the squarks.

2 Existing Searches

There are no dedicated searches for supersymmetric models with a gluino that acquires a Dirac (or “mixed” – Dirac and Majorana) mass. Since a Dirac gluino can be a factor of several times heavier than a Majorana gluino without additional fine-tuning, one interesting scenario to consider is when the squark masses are generated dominantly from the finite contributions from the Dirac gluino. In this case, \( M_{\tilde{g}}/M_{\tilde{q}} \simeq 5 \rightarrow 10 \). For squark masses larger than 500 GeV, the Dirac gluino is sufficiently heavy \( \gtrsim 2.5 \) TeV, and with sufficiently suppressed effects at the 8 TeV LHC, that it is effectively decoupled from the spectrum. Note that this is not true of a Majorana gluino of the same mass, due to the structure of the interactions, in particular, the lower dimension operator for squark production with a Majorana mass insertion (that leads to \( 1/M_{\tilde{g}} \)-suppressed effective interactions). We can therefore map a modestly heavy Dirac gluino into the existing “decoupled
Table 1: Simplified models considered in this writeup. All masses are in TeV. Sparticles not listed are decoupled.

|          | Dirac5 | MSSM5 | MSSMequal |
|----------|--------|-------|-----------|
| $M_{\tilde{g}}$ | 5 TeV  | 5 TeV | $= M_{\tilde{q}}$ |
| $M_{\tilde{q}}$ | varies | varies | $= M_{\tilde{g}}$ |
| $\tilde{q}$     | 1st, 2nd gen | 1st, 2nd gen | 1st, 2nd gen |
| $BR(\tilde{q} \rightarrow q + \text{LSP})$ | 100%   | 100%  | 100%      |
| LSP mass        | 0      | 0     | 0         |

Squark production with a decoupled gluino is a specific simplified model in which the ATLAS and CMS collaborations have placed bounds on the cross sections within the $(M_{\tilde{q}}, M_{\text{LSP}})$ space. Here we mention only the results from the latest analyses, namely a jets plus missing energy search strategy at ATLAS using $\simeq 20$ fb$^{-1}$ of 8 TeV data at ATLAS and CMS. The simplified model used for each search assumed the first and second generation squarks have a common mass $M_{\tilde{q}}$, there is a single LSP with mass $M_{\text{LSP}}$, and the squarks are assumed to decay $100\%$ of the time via $\tilde{q} \rightarrow q + \text{LSP}$. For a nearly massless LSP, the current ATLAS results rule out $M_{\tilde{q}} \lesssim 850$ GeV while the CMS results rule out $M_{\tilde{q}} \lesssim 780$ GeV. If the LSP mass were 300 GeV, the ATLAS and CMS analyses find no bound on the squark mass. These results can be contrasted with, for example, the current bound on the MSSM simplified where a Majorana gluino is also present in the spectrum. Consider the case where $M_{\tilde{g}} = M_{\tilde{q}}$: the latest ATLAS result constrains $M_{\tilde{q}}(= M_{\tilde{g}}) \gtrsim 1.7$-1.8 TeV for an LSP up to 700 GeV in mass. Regarding the search for first and second generation squarks with a decoupled gluino, the ATLAS note stated: “the expected limits for [the decoupled gluino case] do not extend substantially beyond those obtained from the previous published ATLAS analysis because the events closely resemble the predominant $W/Z + 2$-jet background, leading the background uncertainties to be dominated by systematics.” This implies the need for innovative search strategies to uncover squark production with suppressed production cross sections.

3 Motivation for Future Collider Studies

Clearly, if the first and second generation squarks are much lighter than the standard MSSM analyses suggest, it is worthwhile to consider what future collider studies can say about this scenario. Following our earlier analysis from 2012, we consider the following scenarios: “Dirac5”, “MSSM5”, “MSSMequal” detailed in Table 1. These are not meant to represent the full spectrum of possibilities or phenomenology associated with suppressed colored sparticle production. Instead, we are interested to provide a few benchmark examples of the differences between gluinos having a Dirac mass versus a Majorana mass as it pertains to searches for (highly) suppressed colored sparticle production. Instead, we are interested to provide a few benchmark examples of the differences between gluinos having a Dirac mass versus a Majorana mass as it pertains to searches for (highly) suppressed colored sparticle production.

In Fig. 1, we show the production cross sections for three quantities: the total colored sparticle production (squark and gluino production), the cross section of $\tilde{q}\tilde{q}^*$, and the cross section of $\tilde{q}\tilde{q}$. All
allowed combinations of the first two generations of squarks are summed together. In all results we used MadGraph4 [60] at leading order, for LHC operating at $\sqrt{s} = 14$ and 33 TeV. The figures clearly show the suppression in cross sections persist at LHC collider energies of 14 and 33 TeV. Notice that $\tilde{q}\tilde{q}$ production is always subdominant to $\tilde{q}\tilde{q}^*$ production for a scenario with a 5 TeV Dirac gluino, throughout the squark mass range shown, $M_{\tilde{q}} < 2$ TeV. By contrast, $\tilde{q}\tilde{q}$ production is comparable or dominates the production cross section of squarks for either scenario involving a Majorana gluino.

3.1 Storyboard: Discovery of suppressed $M_{\tilde{q}} = 1$ TeV at LHC with $\sqrt{s} = 14$ TeV and $\simeq 100$ fb$^{-1}$.

In the spirit of the Irvine “storyboards” [61] for discovery of new physics in the next run of the LHC, we consider the possibility that the LHC has discovered a jets plus missing energy signal consistent with first and second generation squark production with squark mass $M_{\tilde{q}} = 1$ TeV, but with a highly suppressed cross section relative to the expectations from MSSM.

There are several investigations one would like to apply to the signal. The first obvious one is to try to pin down the mass scale of the squarks and obtain an upper bound on the LSP mass. This requires careful examination of the signal kinematic distributions, e.g. [62]. Searching for accompanying signals, namely in the $n \geq 3$-jet categories could uncover evidence for, or absence of, an accompanying gluino production signal. Even if there is no accompanying signals consistent with a kinematically accessible gluino, we saw above that the squark production rates are nevertheless sensitive to a kinematically inaccessible Majorana gluino. This can be seen by contrasting the squark production rates for the MSSM5 scenario against the Dirac5 scenario. If the experimental data on the the squark production rate appears to be consistent with just $\tilde{q}\tilde{q}^*$ production, the signal can be probed for consistency with this hypothesis. For example, by measuring the angular distributions of the final state decay products should allow the experiments to verify the signal is consistent with $s$-channel gluon production of $\tilde{q}\tilde{q}^*$ (versus a $t$-channel gluino-mediated production of $\tilde{q}\tilde{q}$ with a rate that happened to match the “observed” squark–anti-squark rate).

If the rate is slightly larger than what is expected from just $\tilde{q}\tilde{q}^*$ production, there are several possible culprits. One is that the gluino is not completely decoupled, and its effects on $t$-channel exchange are being (slightly) felt. Another is that the first and second generation squarks are not precisely degenerate in mass, but these kinematic differences are not readily observable.

The central goal in this scenario would be to discover the heavy gluino state. This is where a Dirac gluino becomes much more advantageous compared with a Majorana gluino (holding the squark production cross sections roughly the same). Because the Dirac gluino can be much lighter without affecting squark production channels, this suggests associated $\tilde{g} + \tilde{q}$ production can be probed by 33 TeV LHC. The leading order rates for $\tilde{g} + \tilde{q}$ production in Dirac5 scenario, with $M_{\tilde{q}} = 1$ TeV and $M_{\tilde{g}} = 5$ TeV, are

$$\sigma(\tilde{q} + \tilde{g}) \sim 0.015 \text{ fb} \quad \sqrt{s} = 14 \text{ TeV}$$

$$\sigma(\tilde{q} + \tilde{g}) \sim 12 \text{ fb} \quad \sqrt{s} = 33 \text{ TeV}.$$  

\footnote{We use CTEQ6L1 parton distribution functions and default factorization and renormalization scales for all simulations}
Figure 1: Cross sections for the simplified models considered in this writeup. For squark production, all allowed combinations of the first two generations of squarks are summed together. For total colored sparticle production, both gluino pair production and gluino-squark associated production are included. In all results we used MadGraph4 [60] at leading order, for LHC operating at \( \sqrt{s} = 14 \) and 33 TeV.
Clearly, the cross section at the LHC operating at 14 TeV is much too small to be seen at any conceivable integrated luminosity. However, at the higher center-of-mass energy of 33 TeV, it is at least conceivable to obtain evidence for a heavy gluino given that the cross section is nearly 3 orders of magnitude larger. At even higher energy machines (100 TeV), there should be no difficulty measuring and studying both associated and gluino pair production.

4 Discussion

We have focused on the narrow issue of first and second generation squark production in the presence of a heavy Dirac gluino. The highly suppressed cross section of lighter squarks is an incredibly important signal to find or rule out, to determine if supersymmetry is realized in this interesting but non-standard way. Our quick-and-dirty preliminary investigation suggests that high energy is more important that high luminosity, since kinematics may well limit the ability to probe the Dirac gluino directly. This are many more interesting issues that could be explored, and thus far, have few if any experimental analyses completed:

- What happens when there is a heavy Dirac gluino and lighter Majorana electroweak gauginos? This is an interesting scenario where the electroweak $D$-term is not suppressed (giving the ordinary tree-level Higgs mass contribution familiar from the MSSM), and does not appear to significantly affect squark production [59]. How much of the same-sign dilepton signal remains when the gluino is Dirac while the electroweakinos are Majorana?

- What happens when the first and second generation, or even up-type and down-type squarks are not degenerate in mass? A few interesting recent examples that contains a light second generation can be found in Ref. [63,64].

- What happens if there is substantial squark mixing, e.g., following the $R$-symmetric supersymmetric model [11,30]. Squark decays to heavy flavor (tops, bottoms, and $\tau$s) become generic. Are the bounds better in the case of third generation squarks (given multitude of dedicated analyses for this “natural” region)? How effective (or ineffective) are the standard jets plus missing energy strategy?

- How is $m_h = 125$ GeV realized in this scenario? In scenarios with Dirac electroweak gauginos, there are methods to raise the tree-level contribution mass (for example, [49]), that typically also require moderately heavy stops ($M_{{\tilde t}} \gtrsim 2-3$ TeV). How easily can the stops be probed with colliders? This is a common but important issue in this and most other supersymmetric scenarios.

- ILC implications? If Dirac electroweak gauginos are present, the sleptons and Higgs scalars acquire weak-coupling suppressed contributions to their masses, and thus are generically light. In addition, in models with an approximate $R$-symmetry [11], there are more “Higgs-like” states to uncover, since each Higgs supermultiplet ($H_u,H_d$) is paired up with an $R$-supermultiplet partner ($R_u,R_d$) giving many more scalars and fermions with electroweak interactions with the Standard Model.
Finally, we should emphasize that in complete models involving Dirac gauginos, there are a host of indirect methods to probe the model. These rely on intensity frontier experiments, adding to the motivation that a diverse array of experiments in particle physics that can probe new mass scales are an essential complement to the energy frontier experiments.

For example, if the low energy theory contains large squark or slepton mixing, there is the possibility to observe a flavor-changing neutral current process at a level that is expected to be probed by future experiments. One example is charged lepton flavor violation. It was shown in [36] that the-then existing bounds from the MEG experiment on $\mu \rightarrow e\gamma$ were only beginning to probe maximal lepton flavor violation in an $R$-symmetric model with Dirac gauginos. One of the interesting results is that $\mu \rightarrow e$ conversion experiments are generically more sensitive to CLFV in $R$-symmetric supersymmetry, and happily we expect the Mu2e experiment and future Project X experiments to probe between four to six orders of magnitude lower in rate than the best bound today.

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