Early SUSY discovery at LHC via sparticle cascade decays to same-sign and multimuon states

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Abstract

In the very early stages of LHC running, uncertainties in detector performance will lead to large ambiguities in jet, electron and photon energy measurements, along with inferred missing transverse energy $E_T^{\text{miss}}$. However, muon detection should be quite straightforward, with the added benefit that muons can be reliably detected down to transverse energies of order 5 GeV. Supersymmetry discovery through multimuon channels has been extensively explored in the literature, but always relying on hard $E_T^{\text{miss}}$ cuts. Here, we quantify signal and background rates for same-sign (SS) dimuon and multimuon production at the LHC without any $E_T^{\text{miss}}$ cuts. The LHC, operating at $\sqrt{s} = 10$ TeV, should be able to discover a signal over expected background consistent with gluino pair production for $m_{\tilde{g}} \lesssim 450$ (550) GeV in the SS dimuon plus $\geq 4$ jets state with just 0.1 (0.2) fb$^{-1}$ of integrated luminosity.

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With the recent circulation of proton beams around the entire CERN Large Hadron Collider (LHC) ring, the era of LHC physics has begun. Meaningful data is now expected starting in fall 2009, when LHC will likely start up with $pp$ collisions at $\sqrt{s} \simeq 10$ TeV.

In the LHC ramping up process, it will be essential to observe many familiar Standard Model (SM) processes—multi-jet production as predicted by QCD, $W$ and $Z$ production as predicted by the electroweak theory, $t\bar{t}$ production, vector boson pair production—all at their expected rates, and with distributions and mass peaks at previously measured values\textsuperscript{[1]}. Conventional wisdom holds that once confidence in the Atlas and CMS detectors has been established, then the search for physics beyond the Standard Model will begin. In this letter, we explore the possibility of searching for new physics in parallel with the calibration phase. We will show that even with relatively poor knowledge of the detector, new physics searches may still be possible, at least in the case of weak scale supersymmetry.

Weak scale supersymmetry—wherein each particle state of the Standard Model has a TeV-scale superpartner differing by $1/2\hbar$ units of spin—is perhaps the most motivated new physics theory\textsuperscript{[2]}. Theories with supersymmetry (SUSY) broken at the weak scale actually enjoy indirect experimental support in that the measured values of the three SM gauge couplings at energy scale $Q \simeq M_Z$, when extrapolated to very high energies under renormalization group (RG) evolution, meet at a point as predicted by grand unified theories (GUTs) under Minimal Supersymmetric Standard Model (MSSM) evolution (while they miss badly under SM evolution)\textsuperscript{[3]}. SUSY theories also predict a SM-like Higgs boson $h$ with mass below $\sim 135$ GeV—a scenario which is consistent with global analyses of precision electroweak measurements\textsuperscript{[4]}.

While the idea of supersymmetry is theoretically very appealing, the mechanism behind SUSY breaking is a complete mystery. One very elegant SUSY breaking mechanism occurs in local SUSY—or supergravity (SUGRA)—theories. It is possible to embed the SM into a supergravity theory, and then set up a hidden sector which serves as an arena for SUSY breaking via the super-Higgs mechanism. The SUSY breaking is communicated from the hidden sector to the visible sector via Planck-scale suppressed operators, and a judicious choice of parameters leads to weak scale soft SUSY breaking (SSB) parameters, exactly as needed by gauge coupling evolution, and which serve to stabilize the weak scale-GUT scale energy hierarchy without too much fine-tuning. The simplest such model, the minimal supergravity or mSUGRA model, thus posits a common (universal) mass $m_0$ for all SSB
scalar masses, a common SSB gaugino mass $m_{1/2}$, and common trilinear SSB terms $A_0$. (Here, the gaugino is the spin-$\frac{1}{2}$ superpartner of the gauge bosons.) Motivated by gauge coupling unification, these common masses are assumed valid at the GUT scale $M_{\text{GUT}} \simeq 2 \times 10^{16}$ GeV. All weak-scale Lagrangian parameters can be calculated in terms of this parameter set using the power of the RG equations. Thus, all physical superpartner masses and mixings may be calculated in terms of the parameter set

$$m_0, \ m_{1/2}, \ A_0, \ \tan \beta, \ \text{sign} (\mu),$$

(1)

wherein $\tan \beta$ is the ratio of the two Higgs field vacuum expectation values (vevs) needed for electroweak symmetry breaking, and $\mu$ is a quadratic superpotential term. While many other well-motivated SUSY models exist, the mSUGRA model has emerged as a sort of paradigm choice for exploring basic SUSY phenomena expected at collider experiments.

The strongly interacting sparticles-- the gluinos $\tilde{g}$ and squarks $\tilde{q}$-- often end up with the largest of all the sparticle masses due to the influence of the strong interactions on their RG mass evolution. Sparticles such as charginos, neutralinos and sleptons are frequently much lighter. The strongly interacting $\tilde{g}$ and $\tilde{q}$-- produced through QCD interactions-- usually have the largest production cross sections. Once the $\tilde{g}$ and $\tilde{q}$s are produced, they decay through a cascade of possibly several stages until the state with the lightest SUSY particle-- or LSP-- is reached[5]. The LSP in mSUGRA usually turns out to be the lightest neutralino, $\tilde{Z}_1$, which if $R$-parity is conserved, is absolutely stable and serves as a good candidate for cold dark matter (CDM) in the universe[6].

The classic signature for $\tilde{g}$ and $\tilde{q}$ production at hadron colliders consists of events containing jets plus large missing transverse energy $E_T^{\text{miss}}$, wherein the $E_T^{\text{miss}}$ arises due to the $\tilde{Z}_1$s completely escaping the detector, much as neutrinos do. This signature channel should serve sparticle-hunters well once the detectors are fully calibrated so that SM backgrounds for jets+$E_T^{\text{miss}}$ events are well-understood[7]. Experience with similar jets+$E_T^{\text{miss}}$ searches at the Fermilab Tevatron suggest that it may well take some time to fully understand detector performance, so that $E_T^{\text{miss}}$ can be reliably measured. For this reason, several of us recently proposed that early searches for SUSY matter at the LHC may be better served by looking for events containing multiple (2,3,4,...), high transverse momentum ($p_T \geq 20$ GeV) isolated leptons (e$+$s and/or $\mu$s) along with jets, instead of $E_T^{\text{miss}}+$jets events[8]. Requiring high lepton multiplicity rejects SM background at a large rate, while maintaining much of the expected
signal, since isolated leptons are expected to be produced frequently in the sparticle cascade decays \( [9] \).

Since publication of Ref. \( [8] \), it has been pointed out that reliable \textit{electron} identification may also be a major issue during the early phase of LHC running. If so, this could jeopardize the results of Ref. \( [8] \), which summed over both muons and electrons in order to establish the multi-lepton signal and background rates. In addition, the SM background calculation of Ref. \( [8] \) included only \( 2 \rightarrow 2 \) processes that were pre-programmed into Isajet. However, various SM \( 2 \rightarrow n \) BG processes potentially may be larger than the lowest order processes considered in Ref. \( [8] \).

In this letter, we show \( i \) that it is sufficient to focus only on isolated \textit{multimuon} plus jets events during the earliest SUSY searches at LHC. The lack of electron channels can be partially compensated for by the lower \( p_T \) values which are allowed for isolated muon searches. Secondly, \( ii \) we evaluate a variety of additional \( 2 \rightarrow n \) background processes beyond those presented in Ref. \( [8] \), thus putting our results on a more firm foundation. Thirdly, we re-evaluate all signal and background channels for the anticipated start-up energy of \( \sqrt{s} = 10 \text{ TeV} \), instead of design energy \( \sqrt{s} = 14 \text{ TeV} \). Finally, \( iii \) we scan over a wide swath of mSUGRA model parameter space, and present the LHC reach plot on the \( m(\text{squark}) \) vs. \( m(\text{gluino}) \) plane for various low levels of integrated luminosity. In the same-sign dimuon plus jets channel, some reach is possible even for integrated luminosities as low as 0.1 fb\(^{-1} \), where squark and gluino masses up to \( \sim 450 \text{ GeV} \) may be probed.

There are several advantages to a SUSY search via multimuon plus jets events.

- Reliable electron identification may be difficult in the early stages of LHC running. Electrons will need to be readily distinguishable from QCD jets and also from high \( p_T \) photon production. As an example, a jet with a single soft charged pion plus several \( \pi^{0} \)'s can give a track pointing to a mainly electromagnetic calorimeter deposition, which may well fake an electron signal.

- Muon identification should be straightforward even in the very early stages of LHC running \( [10] \). In fact, cosmic ray muons have already been seen at both Atlas and CMS. Muons with \( p_T \lesssim 5 \text{ GeV} \) should readily penetrate the electromagnetic calorimeter (ECAL) and hadronic calorimeter (HCAL), yielding easily-seen tracks in the muon chambers. Since muons are so heavy, they produce minimal bremsstrahlung and show-
erating in the ECAL or HCAL.

- Muons can be readily identified at $p_T$ values much lower than electrons. Reliable $e$ tagging typically needs $p_T(e) \gtrsim 20$ GeV, while $p_T(\mu) \gtrsim 5$ GeV is sufficient for muon identification. Thus, the lower $p_T$ muons emerging from cascade decays will be easily detected, while this is not so for electrons.

- Superparticle cascade decays tend to be rich in $b$s and $\tau$s. While $b \rightarrow c\mu\bar{\nu}_\mu$ decay yields mainly non-isolated muons, $\tau \rightarrow \nu_\tau\mu\bar{\nu}_\mu$ decay leads to rather soft, but isolated, muon production. The rather low $p_T(\mu)$ requirements allows one to detect muons from $\tau$ decay, while $e$s from tau decay are often too soft to reliably identify.

The large rate for $b$ and $\tau$ production in sparticle cascade decay events has three sources\[11\]: 1. the large $b$ and $\tau$ Yukawa couplings, especially at large $\tan\beta$ values, enhance chargino and neutralino branching fractions into $b$ and $\tau$ states, 2. third generation sparticle masses are often much lighter than their first/second generation counterparts due to Yukawa coupling effects pushing the third generation SSB masses to low values, and also due to large mixing effects, which are proportional to the corresponding fermion mass. This latter effect also enhances sparticle decay rates into third generation fermions. 3. Higgs bosons, especially $h$, can be produced at large rates in sparticle cascade decays. For instance, if the decay $\tilde{Z}_2 \rightarrow \tilde{Z}_1 h$ is kinematically allowed, this usually dominates the $\tilde{Z}_2$ branching fraction. Since $h$ and the other Higgs subsequently decay dominantly into third generation fermions, one gets enhanced $b$ and $\tau$ production from cascade decays of sparticles into Higgs bosons.

The search for multi-muon events has been proposed much earlier with regards to the search for fourth generation quarks\[12\], which also decay via a cascade to the lightest flavor states. Multimuon detection has been proposed in the old idea of an “iron ball detector”, wherein the interaction region is completely surrounded by iron absorber, and one only detects the penetrating muons\[13\]. LHC detectors are vastly more complex than the iron ball detector. But in the very early stages of running, wherein calorimeter and other detector response is not well understood, their initial performance may approximate the iron-ball idea.

We adopt the Isajet 7.78 program for sparticle mass calculations and simulation of signal events at the LHC\[14\]. A toy detector simulation is employed with calorimeter cell size $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ and $-5 < \eta < 5$. (here, $\eta = -\log \tan \frac{\theta}{2}$ is pseudorapidity and
\( \phi \) is angle transverse to beamline. The HCAL (hadronic calorimetry) energy resolution is taken to be 80\%/\( \sqrt{E} + 3\% \) for \(|\eta| < 2.6 \) and FCAL (forward calorimetry) is 100\%/\( \sqrt{E} + 5\% \) for \(|\eta| > 2.6 \). The ECAL (electromagnetic calorimetry) energy resolution is assumed to be 3\%/\( \sqrt{E} + 0.5\% \). We use the Isajet\[14\] jet finding algorithm with jet cone size \( R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4 \) and require that \( E_T(jet) > 50 \text{ GeV} \) and \(|\eta(jet)| < 3.0 \). Muons are considered isolated if they have \( p_T(\mu) > 5 \text{ GeV} \) and \(|\eta(\mu)| < 2 \) with visible activity within a cone of \( \Delta R < 0.2 \) of \( \sum E_T^{cells} < 5 \text{ GeV} \). The isolation criterion helps reduce multi-lepton backgrounds from heavy quark (\( c\bar{c} \) and \( b\bar{b} \)) production.

For our initial analysis, we adopt the well-studied SPS1a' benchmark point\[15\], which occurs in the minimal supergravity (mSUGRA) model with parameters \( m_0 = 70 \text{ GeV} \), \( m_{1/2} = 250 \text{ GeV} \), \( A_0 = -300 \text{ GeV} \), \( \tan \beta = 10 \), \( \mu > 0 \) and \( m_t = 172.6 \text{ GeV} \). The SPS1a' point leads to a spectrum with \( m_{\tilde{g}} = 608 \text{ GeV} \), while squark masses tend to be in the 550 GeV range. The gluinos and squarks then cascade decay via a multitude of modes leading to events with high jet, \( b \)-jet, isolated lepton and tau lepton multiplicity.

Since the gluino and squark cascade decay events will be rich in jet activity, we first require events with \( \geq 4 \) jets, with \( E_T(j1, j2, j3, j4) \geq 100, 50, 50, 50 \text{ GeV} \). We also require sphericity (restricted to the transverse plane) \( S_T \geq 0.2 \) to reject QCD-like events at little cost to signal. We do not apply the traditional cut on missing transverse energy, since at this stage we are working towards early SUSY discovery, when \( E_T^{miss} \) may not yet be well-established. In Fig. 1 we show the muon \( p_T \) distribution from point SPS1a' along with dominant SM BGs (see discussion below) in same-sign (SS) dimuon plus \( \geq 4 \) jet events (each muon in a SS-dimuon event will have an entry in the plot). The signal muons tend to populate the 5 – 40 GeV regime, and so should be easily measured by the bend of their tracks in the detector magnetic field. The BG muons come dominantly from \( t\bar{t} \) production, and have a hard component (from \( W \) decay) and a soft component (from rare \( b \) and \( c \) decays to isolated muons). The soft component exceeds signal in the 5-10 GeV range. Hence, we require \( p_T(\mu) > 10 \text{ GeV} \) in our multi-muon signal events, which eliminates much of the BG from \( t\bar{t} \) production.

Next, we plot the multiplicity of muons in the SUSY cascade decay events. The results are shown for point SPS1a' in Fig. 2 for \( pp \) collisions at \( \sqrt{s} = 10 \text{ TeV} \). We also plot a variety of SM backgrounds. The dominant backgrounds for the dimuon signal were calculated using AlpGen/Pythia and AlpGen’s matching algorithm (MLM scheme\[16\]) to include multiple jet
FIG. 1: $p_T(\mu)$ distribution from the SPS1a' mSUGRA study, along with SM BG, for SS dimuon plus $\geq 4$ jet events at LHC with $\sqrt{s} = 10$ TeV.

emission. In particular, the $t\bar{t}$ channel includes $t\bar{t}+0,1,2,3$ jets, $Z+\text{jet}$ includes $Z+0,1,2,3$ jets, the $t\bar{t}+Z$ channel includes $t\bar{t}+Z+0,1,2$ jets and $b\bar{b}+Z$ includes $b\bar{b}+Z+0,1,2$ jets (in all cases the full matrix element $\gamma^*,Z^* \to l^+l^-$ was used). The presence of hard additional jets increases the BG quite a bit from our earlier estimates using just the Isajet parton shower.\textsuperscript{1}

In addition, we have calculated using MadGraph/Pythia\textsuperscript{17, 18} a variety of exact $2 \to n$ processes: $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$, $b\bar{b}b\bar{b}$, $ttV$, $t\bar{t}V$, $VV$, $W+\text{jet}$, $b\bar{b}$, QCD dijets, $VV$ and $VVVV$ production, where $V = W^\pm$ or $Z^0$. The summed BG histogram along with component contributions are also shown in Fig. 2. We adopt a renormalization/factorization scale choice $Q = \sqrt{\hat{s}}/6$ ($\hat{s}$ is the parton-parton CM frame squared energy) which brings our background (BG) cross sections into close accord with NLO QCD results.\textsuperscript{2}

\textsuperscript{1} Our BG from $b\bar{b}$ production comes from Alpgen/Pythia, but with just LO $b\bar{b}$ production along with jets from the parton shower. We expect the BG from $b\bar{b}+$jets production to be sub-dominant because we would need to obtain one isolated lepton from a $b$ decay, and another from a $c$ decay, while producing four hard jets at the same time, and that sort of event is extremely rare. This reaction, with exact 4-jet emission matrix elements, is extremely hard to generate with reliable statistics.

\textsuperscript{2} The dominant BG for SS dimuon plus $\geq 4$-jet events comes from $t\bar{t}$ production. Using the MCFM code\textsuperscript{19}, we find $\sigma^{LO}(pp \to t\bar{t})(Q = m_{top}) \approx 255$ pb, while $\sigma^{NLO}(pp \to t\bar{t})(Q = m_{top}) \approx 347$ pb. If instead we take
FIG. 2: Muon multiplicity cross sections expected from the SPS1a’ mSUGRA case study, along with SM background, for ≥ 4 jet plus n-muon events (p_T(μ) ≥ 10 GeV) at LHC with √s = 10 TeV.

At n(μ) = 0, signal is about three orders of magnitude below SM background. As we increase the isolated muon multiplicity, BG falls off faster than signal, and signal exceeds BG already at n(μ) = 3, where signal is at the ∼ 5 fb level. The dimuon signal can be broken up into opposite sign μ^+μ^- events (OS) and same sign μ^±μ^± events (SS) [9, 20, 21]. In order to suppress the large contribution from the Z peak to the OS events we required 10 GeV ≤ m(μ^+μ^-) ≤ 75 GeV. The SS signal is due in part to the Majorana nature of the gluinos, in that a gluino is as likely to decay via ˜g → ˜W^+ ˜u d as via the charge conjugate mode. Thus, ˜g ˜g production is likely to lead to equal amounts of ++ and −− SS dileptons. Now, ˜g ˜q or ˜q ˜q production depends on the quark content of the colliding beams, and since LHC is a pp collider, we expect more ++ dileptons than −− dileptons from squark production.

For OS dimuons and case study SPS1a’, the OS signal is just slightly above OS BG, while SS signal well exceeds SS BG, and is at the ∼ 10 fb level. As we move to higher and higher muon multiplicity, the signal rates diminish, although signal-to-background ratio steadily improves. For instance, at n(μ) = 3, signal is ∼ 5 fb, while the summed SM background, arising mainly from t ̅t and t ̅tZ production, occurs at the ∼ 0.1 fb level. Using these results,

\[ Q = \sqrt{s}/6, \text{ then } \sigma^{LO}(pp \rightarrow t ̅tX)(Q = \sqrt{s}/6) \simeq 337 \text{ pb}. \]
we can now see that if case study SPS1a’ describes SUSY, then the first clear signal may emerge in the SS dimuon plus multi-jet channel, with corroborating signals in the OS and tri-muon channels.

Another discriminating variable for SUSY events has been proposed by Randall and Tucker-Smith[22], albeit applied to dijet events coming from squark pair production. They propose using \( \alpha = p_T(jet_2)/m(jet_1, jet_2) \). Here we plot \( \alpha(\mu) = p_T(\mu_2)/m(\mu^\pm\mu^\pm) \) in Fig. 3 and do find that the SUSY event shape is discriminated from the SM event shape. We do not apply an \( \alpha(\mu) \) cut at this time for very low luminosity studies, but merely note that this distribution will add additional confidence in any possible SS dimuon signal.

As higher integrated luminosities are reached, trimuon and later four muon plus jet events should emerge at rates far above expected background. Of course, also as higher integrated luminosities are achieved, reliable electron ID should become available, and ultimately also reliable \( E_T^{miss} \) measurements. Thus, the real utility of multi-muon plus jets events will be for a possible early discovery of SUSY, when muon ID is possible, but electron ID and \( E_T^{miss} \) resolution are still works in progress.

In Fig. 4 we scan over \(~200\) choices of \( m_0 \) and \( m_{1/2} \) values for fixed \( A_0 = 0, \mu > 0 \) and \( \tan \beta = 45 \). We test to see if the SS dimuon plus jets signal is greater than a nominal
discovery threshold of 5σ, and require at least five signal events as well, for various integrated luminosity choices: 0.1, 0.2 and 1 fb⁻¹. We plot the results in the physical \( m_{\tilde{g}} \) vs. \( m_{\tilde{u}_L} \) plane. The lower-right region gives a chargino mass less than 103.5 GeV, and so is already excluded by LEP2 new particle searches. The left side of the plot gives a \( \tilde{\tau}_1 \) slepton as the LSP, and is excluded by null searches for stable, charged relics from the Big Bang. For just 0.1 fb⁻¹ of integrated luminosity, eleven points are accessible, with \( m_{\tilde{g}} \lesssim 480 \) GeV and \( m_{\tilde{u}_L} \lesssim 580 \) GeV. For 0.2 fb⁻¹, \( m_{\tilde{g}} \lesssim 550 \) and \( m_{\tilde{q}} \lesssim 700 \) GeV are being probed. The SS di-muon reach increases to \( m_{\tilde{g}} \sim 650 \) GeV for 1 fb⁻¹ of integrated luminosity. If we move to a lower \( \tan \beta = 10 \) value, then the dimuon reach diminishes only slightly from that presented in the \( \tan \beta = 45 \) case.

**Conclusions:** In the early stages of LHC running, electron ID, ECAL and HCAL calibration and \( E_T^{miss} \) resolution may all be works in progress. However, muon ID and momentum resolution, obtained from track bending in the magnetic field, should be quite reliable, and allow muon \( p_T \) measurement down to the \( \sim 5 - 10 \) GeV range. SS dimuon and, later, OS dimuon and \( \geq 3\mu \) plus multi-jet signals, without any \( E_T^{miss} \) discrimination, should allow for good signal-to-background resolution for gluino masses up to about 550 GeV with just 0.2 fb⁻¹ of data. Thus, SS dimuon and multi-muon plus jets production offer excellent possi-

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**FIG. 4:** Reach of the \( \sqrt{s} = 10 \) TeV LHC for mSUGRA models with \( A_0 = 0 \) and \( \tan \beta = 45 \) via SS dimuon + \( \geq 4 \) jet events in the \( m_{\tilde{g}} \) vs. \( m_{\tilde{q}} \) plane, for various integrated luminosity values.
bilities for an early SUSY discovery at LHC, even if $E_T^{miss}$ and electron ID are not initially well-understood.

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