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LHC discovery potential for supersymmetry with $\sqrt{s}$ =7 TeV and 5-30 fb^{-1}

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Abstract: We extend our earlier results delineating the supersymmetry (SUSY) reach of the CERN Large Hadron Collider operating at a centre-of-mass energy $\sqrt{s}$ = 7 TeV to integrated luminosities in the range 5 - 30 fb^{-1}. Our results are presented within the paradigm minimal supergravity model (mSUGRA or CMSSM). Using a 6-dimensional grid of cuts for the optimization of signal to background ratio – including missing E_T– we find for $m_{\tilde{g}} \sim m_{\tilde{q}}$ an LHC 5σ SUSY discovery reach of $m_{\tilde{g}} \sim 1.3,\ 1.4,\ 1.5$ and 1.6 TeV for 5, 10, 20 and 30 fb^{-1}, respectively. For $m_{\tilde{q}} \gg m_{\tilde{g}}$, the corresponding reach is instead $m_{\tilde{g}} \sim 0.8,\ 0.9,\ 1.0$ and 1.05 TeV, for the same integrated luminosities.

Keywords: Supersymmetry Phenomenology, Supersymmetric Standard Model, Large Hadron Collider.

1. Introduction

In 2011, the CERN Large Hadron Collider has produced proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV (LHC7) and has enabled both ATLAS and CMS experiments to each accumulate over 5 fb^{-1} of useful data. The current plan is to resume running with pp collisions in early 2012, with a goal to amass in the vicinity of 10-30 fb^{-1} of usable data. The 2012 run will likely be followed by a shut down for ~ 2.5 years so that various upgrades may be implemented; turn-on at or near design energy of $\sqrt{s} = 14$ TeV is then expected around 2015.

While many LHC analyses are focused on the elusive Higgs boson, the search for weak scale supersymmetry (SUSY) [1] remains an important part of the LHC program. In a previous paper[2], we presented projections for the LHC7 5σ discovery reach for SUSY in the paradigm minimal supergravity (mSUGRA or CMSSM) model[3]. In that study, we presented discovery strategies for early SUSY discovery and made projections for the LHC7 reach for a variety of integrated luminosities ranging from 100 pb^{-1} up to 2 fb^{-1}, well beyond what was then expected to be delivered in the entire 7 TeV run. LHC reach projections for $\sqrt{s} = 14$ TeV (LHC14) have been reported in earlier studies [4].

Recent analyses (performed within the mSUGRA model) of the LHC7 data by the ATLAS[5] and CMS[6] experiments based on just ~ 1 fb^{-1} of integrated luminosity have found no indication of SUSY so far, yielding 95% CL lower limits of $m_{\tilde{q}} \sim m_{\tilde{g}} \gtrsim 1$ TeV for comparable gluino and squark masses, and $m_{\tilde{g}} \gtrsim 0.6$ TeV for the case where $m_{\tilde{q}} \gg m_{\tilde{g}}$. It is worth emphasizing that although all squarks are by assumption degenerate within the mSUGRA framework, the squark mass limit cited above arises mostly from signals for first generation squarks that are much more copiously produced from qq and qg initial states than their second and third generation cousins. In other words, the LHC7 squark limit really applies to up and down type squarks – other squark flavors may be significantly lighter than the quoted bounds. These LHC7 bounds *do not apply* to third generation squarks or to electroweak-inos, the only sparticles with significant couplings to the Higgs sector and to which the naturalness arguments that yield upper mass bounds on sparticles apply. Indeed models with $\mathcal{O}(10-100)$ TeV gluinos and first generation sfermions but with sub-TeV third generation sfermions and electroweak-inos [7] that have been proposed to ameliorate the SUSY flavour and CP problems are not in conflict with these LHC7 data.

The LHC has performed spectacularly and has already delivered an integrated luminosity of 5 fb^{-1} and, as we mentioned, is expected to deliver a comparable or larger data set in 2012. This motivated us to extend our earlier projections[2] of the LHC7 reach for SUSY to integrated luminosities up to 30 fb^{-1}. As before, we work within the mSUGRA framework, the parameter space of which is given by,

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)\ . \tag{1.1}$$

Here, m_0 is a common GUT scale soft SUSY breaking (SSB) scalar mass, $m_{1/2}$ is a common GUT scale soft supersymmetry breaking (SSB) gaugino mass, A_0 is a common GUT scale trilinear SSB term, $\tan\beta$ is the ratio of Higgs field vevs, and μ is the superpotential higgsino mass term, whose magnitude, but not sign, is constrained by the electroweak symmetry breaking minimization conditions.

For each model parameter space point, many simulated collider events are generated and compared against SM backgrounds with the same experimental signature [8]. A 6-dimensional grid of cuts[2] is then employed to enhance the SUSY signal over SM backgrounds, and the signal is deemed observable if it satisfies pre-selected criteria for observability. Based on previous studies [4], we include in our analysis the following channels:

- $jets + E_T^{\rm miss}$ (no isolated leptons),
- $1\ell + jets + E_T^{\rm miss}$,
- two opposite-sign isolated leptons (OS)$+jets + E_T^{\rm miss}$,
- two same-sign isolated leptons (SS)$+jets + E_T^{\rm miss}$,
- $3\ell + jets + E_T^{\rm miss}$.

For the simulation of the background events, we use AlpGen[9] to compute the hard scattering events and Pythia [10] for the subsequent showering and hadronization. For the final states containing multiple jets (namely $Z(\to ll, \nu\nu) + jets$, $W(\to l\nu) + jets$, $b\bar{b} + jets$, $t\bar{t} + jets$, $Z + b\bar{b} + jets$, $Z + t\bar{t} + jets$, $W + b\bar{b} + jets$, $W + t\bar{t} + jets$ and QCD), we use the MLM matching algorithm to avoid double counting. All the processes included in our analysis are shown in Table 1 of Ref. [2] as well as their total cross-sections, number of events generated and event generator used. Here, we show in Table 1 the various backgrounds along with k-factors[1] used to normalize the generator cross sections to NLO QCD results where available. The background k-factors were computed using MCFM[11] for the NLO cross sections, and AlpGen for the LO ones.

The signal events were generated using Isajet 7.79[12] which, given a mSUGRA parameter set, generates all $2 \to 2$ SUSY processes in the right proportion, and decays the sparticles to lighter sparticles using the appropriate branching ratios and decay matrix elements, until the parent sparticle cascade decay[13] terminates in the stable lightest supersymmetric particle (LSP), assumed here to be the lightest neutralino. Total gluino and squark production cross sections have been presented

[1] By k-factor, here we actually mean σ^{NLO}/σ^{LO}. Normally, one compares the two cross sections using an identical renormalization/factorization scale for the two cases. Here, we merely compute σ^{LO} using AlpGen and σ^{NLO} using MCFM, using the pre-programmed default scale choices for the latter.

in Ref. [2] at NLO QCD using Prospino[14], and will not be repeated here. It is worth noting that for $m_{\tilde{q}} \sim m_{\tilde{g}}$, $\tilde{g}\tilde{q}$ associated production is the dominant strongly interacting SUSY production mechanism, while for $m_{\tilde{q}} \gg m_{\tilde{g}}$, $\tilde{g}\tilde{g}$ pair production tends to dominate.

For event generation, we use a toy detector simulation with calorimeter cell size $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ and $-5 < \eta < 5$. The HCAL (hadronic calorimetry) energy resolution is taken to be $80\%/\sqrt{E} \oplus 3\%$ for $|\eta| < 2.6$ and FCAL (forward calorimetry) is $100\%/\sqrt{E} \oplus 5\%$ for $|\eta| > 2.6$, where $\oplus$ denotes a combination in quadrature. The ECAL (electromagnetic calorimetry) energy resolution is assumed to be $3\%/\sqrt{E} \oplus 0.5\%$. We use the cone-type Isajet [12] jet-finding algorithm to group the hadronic final states into jets. Jets and isolated lepton are defined as follows:

- Jets are hadronic clusters with $|\eta| < 3.0$, $R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq 0.4$ and $E_T(jet) > 50$ GeV.

- Electrons and muons are considered isolated if they have $|\eta| < 2.0$, $p_T(l) > 10$ GeV with visible activity within a cone of $\Delta R < 0.2$ about the lepton direction, $\Sigma E_T^{cells} < 5$ GeV.

- We identify hadronic clusters as b-jets if they contain a B hadron with $E_T(B) >$ 15 GeV, $\eta(B) < 3$ and $\Delta R(B, jet) < 0.5$. We assume a tagging efficiency of 60% and light quark and gluon jets can be mis-tagged as a b-jet with a probability 1/150 for $E_T \leq 100$ GeV, 1/50 for $E_T \geq 250$ GeV, with a linear interpolation for 100 GeV $\leq E_T \leq$ 250 GeV [15].

As in Ref. [2], we define the signal to be observable if

$$S \geq max\left[5\sqrt{B},\ 5,\ 0.2B\right]$$

where S and B are the expected number of signal and background events, respectively, for an assumed value of integrated luminosity. The requirement $S \geq 0.2B$ is imposed to avoid the possibility that a *small* signal on top of a *large* background could otherwise be regarded as statistically significant, but whose viability would require the background level to be known with exquisite precision in order to establish a discovery. For cases with very low signal and BG event numbers, we require the Poisson probability to correspond to the 5σ level.

The grid of cuts used in our optimized analysis is:

- $E_T^{\rm miss} > 50$,100 - 1000 GeV (in steps of 100 GeV),

- $n(jets) \geq 2$, 3, 4, 5 or 6,

- $n(b-jets) \geq 0$, 1, 2 or 3,

SM process	k-factor	SM process	k-factor
$t\bar{t}$	0.99	$QCD, b\bar{b}$	–
Z/γ + jets	1.47	$Z + t\bar{t}$	–
W + jets	1.53	$W + t\bar{t}$	–
$Z(\to \nu\bar{\nu}) + b\bar{b}$	1.18	$W + b\bar{b}$	–
$Z/\gamma(\to l\bar{l}) + b\bar{b}$	1.03	$W + tb$	–
WW	1.38	$t\bar{t}t\bar{t}$	–
WZ	1.47	$t\bar{t}b\bar{b}$	–
ZZ	1.35	$b\bar{b}b\bar{b}$	–

Table 1: Background processes included in this LHC7 study, along with the k-factor (from MCFM and AlpGen) used (when available) to normalize to NLO QCD. For $t\bar{t}$ production, the renormalization scale is chosen to match the NLO cross section. The event generator used, total cross sections and number of generated events are listed in Table 1 of Ref. [2]. All light (and b) partons in the final state are required to have $E_T > 40$ GeV. For QCD, we generate the hardest final parton jet in distinct bins to get a better statistical representation of hard events.

- $E_T(j_1) >$ 50 - 300 GeV (in steps of 50 GeV) and 400-1000 GeV (in steps of 100 GeV) (jets are ordered $j_1 - j_n$, from highest to lowest E_T),
- $E_T(j_2) >$ 50 - 200 GeV (in steps of 30 GeV) and 300, 400, 500 GeV,
- $n(\ell) =$ 0, 1, 2, 3, OS, SS and inclusive channel: $n(\ell) \geq 0$. (Here, $\ell = e,\ \mu$).
- 10 GeV$\leq m(\ell^+\ell^-) \leq$ 75 GeV or $m(\ell^+\ell^-) \geq$ 105 GeV (for the OS, same flavor (SF) dileptons only),
- transverse sphericity $S_T > 0.2$.

We show in Fig. 1 the optimized 5σ discovery reach of LHC7 for various choices of integrated luminosity in the m_0 *vs.* $m_{1/2}$ plane. We also take $A_0 = 0$, $\tan\beta = 45$ and $\mu > 0$, with $m_t = 172.6$ GeV.[2] Gluino iso-mass contours are shown, as obtained using the ISASUGRA routines[16] in Isajet. We see from Fig. 1 that with ~ 1 fb^{-1} of integrated luminosity, the LHC7 sensitivity does indeed extend to $m_{\tilde{g}} \sim 1.1$ TeV for $m_{\tilde{q}} \sim m_{\tilde{g}}$, and to $m_{\tilde{g}} \sim 0.65$ TeV for $m_{\tilde{q}} \gg m_{\tilde{g}}$[3]. For 5 fb^{-1} of integrated

[2]Recent evidence from Atlas[17] and CMS[18] using 5 fb^{-1} of data show some evidence for a Higgs scalar h with $m_h \sim 125$ GeV. For $A_0 = 0$, it is very difficult to accommodate such a Higgs mass in the mSUGRA model. For $A_0 \sim \pm 2m_0$, then $m_h \sim 125$ GeV can be accommodated, but mainly at rather high $m_0 \sim 2 - 10$ TeV. For more details, see *e.g.* Ref. [19]. Our reach projections are largely insensitive to variation in A_0 (and subsequent small changes in m_h) as explained below.

[3]We stress that the curves presented here include an optimization over several search channels and correspond to a 5σ discovery reach. Care must be taken when comparing these results with experimental bounds, which are usually presented for single channels at 95% C.L. ($\sim 2\sigma$).

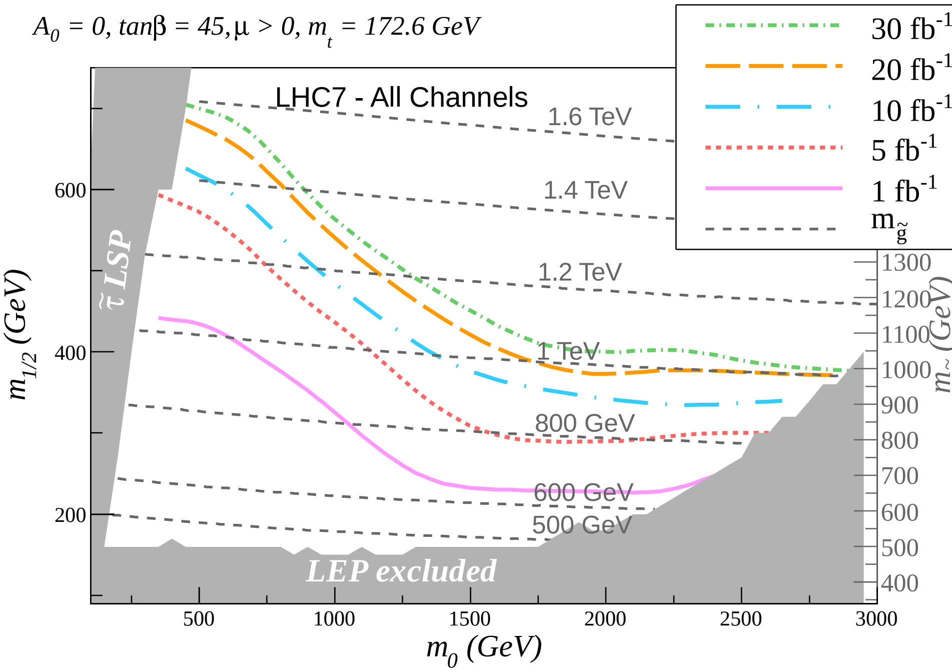

Figure 1: The optimized SUSY reach of LHC7 for different integrated luminosities combining the different channels described in the text. The signal is observable if it falls below the solid contour for the corresponding integrated luminosity. The fixed mSUGRA parameters are $A_0 = 0$, $\tan\beta = 45$ and $\mu > 0$. Gluino mass contours are shown by the dashed, dark grey curves. The shaded grey area is excluded due to stau LSPs (left side of figure) or no electroweak symmetry breaking (right side of figure), while the shaded grey area marked "LEP excluded" is excluded by non-observation of a sparticle signal from LEP2 searches. All sparticle and background cross sections are normalized to NLO QCD values via k-factors.

luminosity (for which we expect ATLAS and CMS analyses in Spring 2012), the LHC discovery reach extends to $m_{\tilde{g}} \sim 1.3$ TeV for $m_{\tilde{q}} \sim m_{\tilde{g}}$, and to $m_{\tilde{g}} \sim 0.8$ TeV for $m_{\tilde{q}} \gg m_{\tilde{g}}$. As integrated luminosity moves into the 20-30 fb^{-1} regime, the LHC7 reach for $m_{\tilde{q}} \sim m_{\tilde{g}}$ moves up to $m_{\tilde{g}} \sim 1.5 - 1.6$ TeV. For the case where $m_{\tilde{q}} \gg m_{\tilde{g}}$, the 20-30 fb^{-1} LHC reach approaches $m_{\tilde{g}} \sim 1$ TeV. We stress that – as discussed above – while non-observation of the signal at LHC7 may qualitatively point toward very heavy gluinos and first generation squarks, *this does not* in and of itself preclude SUSY as the new physics that stabilizes the weak scale [7] because third generation squarks and electroweak-inos could still be at the sub-TeV scale.

While our results are presented for the particular choice of mSUGRA parameters $A_0 = 0$ and $\tan\beta = 45$, we emphasize here that we expect these results to hold also for other choices of A_0 and $\tan\beta$, and also for $\mu < 0$. Variation of A_0 mainly affects third generation sparticle masses, while the reach is determined mostly by $m_{\tilde{g}}$ and the first generation squark masses. Moreover, variation of $\tan\beta$ mainly affects the size of b and τ Yukawa couplings, and these feed only weakly into the reach plots: for instance, sparticle decays to third generation matter are enhanced at large $\tan\beta$[20] where b-tagging may somewhat enhance the LHC reach for gluinos [21] as already demonstrated by ATLAS [22].

To give the reader an idea of the dominant event topologies in which experiments at LHC7 will be able to probe SUSY in the 2012 run, we show in Fig. 2 the optimized 5σ reach via the 0ℓ, 1ℓ, OS dilepton, SS dilepton and the trilepton channels for 20 fb^{-1}. The striking feature of the figure is that while the reach is dominated by the low multiplicity ($n_\ell = 0, 1$) lepton channels for $m_0 \lesssim 1.5$ TeV, the reach in the low background but rate-limited trilepton channel becomes competitive with that in other channels if squarks are essentally decoupled at LHC7 as could well be the case. We have checked that this is true also for an integrated luminosity of 10 fb^{-1}.

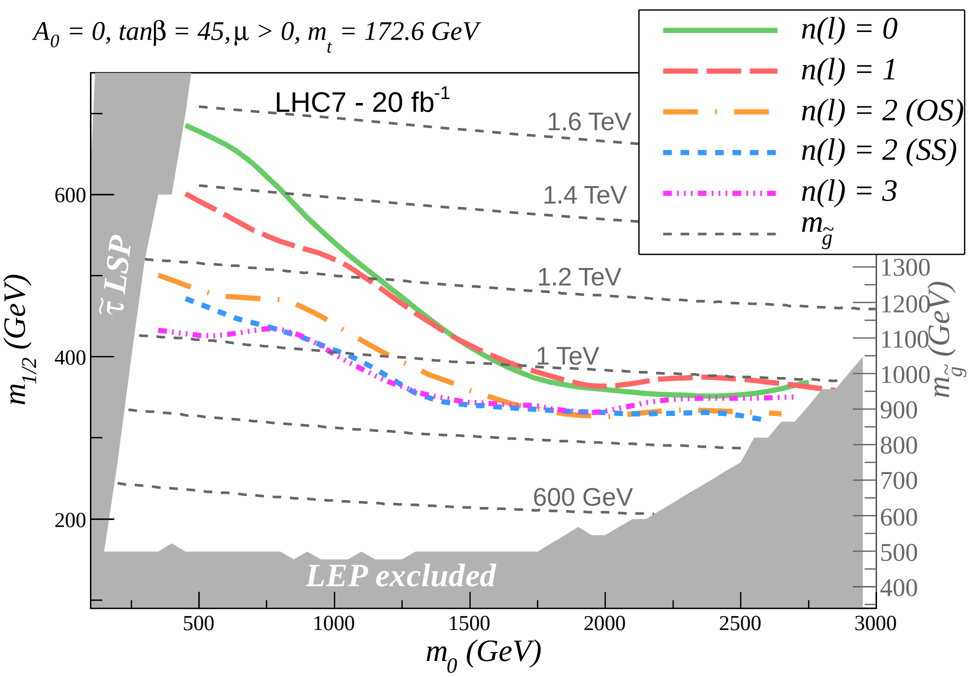

Figure 2: The optimized 5σ SUSY reach of LHC7 in various channels classified by lepton multiplicity: 0ℓ, 1ℓ, SS dilepton, OS dilepton and trilepton for an integrated luminosity of 20 fb^{-1}. Any mSUGRA point will be observable if it falls below the corresponding contour. The fixed mSUGRA parameters are $A_0 = 0$, $\tan\beta = 45$ and $\mu > 0$. Gluino mass contours are shown by the dashed, dark grey curves. The shaded grey area is excluded due to stau LSPs (left side of figure) or no electroweak symmetry breaking (right side of figure), while the shaded grey area marked "LEP excluded" is excluded by non-observation of a sparticle signal from LEP2 searches. All sparticle and background cross sections are normalized to NLO QCD values via k-factors.

In summary, we have presented updated 5σ discovery contours for the paradigm mSUGRA/CMSSM SUSY model for LHC7 with 5-30 fb^{-1} of integrated luminosity. These results help to understand the capabilities of LHC7 for discovering supersymmetry in 2012-2013. Within mSUGRA, for integrated luminosity 20-30 fb^{-1}, we expect LHC7 to probe $m_{\tilde{g}}$ up to ~ 1.6 TeV for $m_{\tilde{q}} \simeq m_{\tilde{g}}$, while we expect LHC7 to probe up to $m_{\tilde{g}} \sim 1$ TeV for $m_{\tilde{q}} \gg m_{\tilde{g}}$. If squarks are much heavier than gluinos, the reach at LHC7 via the inclusive trilepton channel will be competitive in reach with the canonical jets plus $E_T^{\rm miss}$ channel.

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