What if the LHC does not find supersymmetry in the $\sqrt{s} = 7$ TeV run?

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We investigate the implications for supersymmetry from an assumed absence of any signal in the first period of LHC data taking at 7 TeV center-of-mass energy and with 1 to 7 fb^{-1} of integrated luminosity. We consider the zero-lepton plus four jets and missing transverse energy signature, and perform a combined fit of low-energy measurements, the dark matter relic density constraint and potential LHC exclusions within a minimal supergravity model. A non-observation of supersymmetry in the first period of LHC data taking would still allow for an acceptable description of low-energy data and the dark matter relic density in terms of minimal supergravity models, but would exclude squarks and gluinos with masses below 1 TeV.

INTRODUCTION

The Higgs sector of the Standard Model (SM) of elementary particle physics suffers from the hierarchy problem between the weak scale and the Planck scale. Extending the SM through supersymmetry (SUSY) is a very promising solution [1]. The new supersymmetric particles must then have masses of order 1 TeV. Furthermore, supersymmetric particles can contribute to low-energy observables via radiative quantum corrections. In fact, SUSY models provide an excellent fit to the extensive data, see for example Refs. [2–6]. The fits generically prefer a light SUSY spectrum, typically below 1 TeV.

The ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN have so far analyzed 35 pb^{-1} of integrated luminosity at 7 TeV center-of-mass energy. A total integrated luminosity of 1 to 7 fb^{-1} can realistically be achieved at this energy through 2012. These data will significantly extend the search reach for SUSY [7, 8].

The minimal supersymmetric SM has 124 free parameters. However, current precision observables and direct search limits only provide sensitivity to very restricted SUSY models with a small number of parameters, like minimal supergravity (mSUGRA) [1] which only has 5 free parameters beyond those of the SM. In the following, we thus focus on mSUGRA models. Specifically, they are characterized by a common supersymmetric scalar mass M_0, a common gaugino mass $M_{1/2}$, a universal trilinear coupling A_0, the ratio of the two Higgs vacuum expectation values, $\tan \beta$, and the sign of the Higgs mixing mass parameter, sign(μ).

At the LHC, supersymmetry can be searched for in channels with jets, leptons and missing transverse energy [21]. Studies by ATLAS and CMS reveal that squarks and gluinos with masses up to about 700 GeV could be discovered at 7 TeV energy and 1 fb^{-1} integrated luminosity [7, 8]. If no signal is found, one can significantly constrain supersymmetric models and exclude squarks and gluinos with masses close to 1 TeV.

To obtain consistent limits on the SUSY parameter space and the resulting mass spectrum in the absence of a SUSY signal at the LHC, one needs to combine potential LHC exclusion limits and current low energy precision observables in a global fit. In the following we employ the FITTINO framework [6, 9] to study such a scenario.

FIT OBSERVABLES

We follow the FITTINO analysis in Ref. [6] and consider the following set of low-energy observables and existing collider limits in light of the mSUGRA model: *(i)* rare decays of B- and K-mesons; *(ii)* the anomalous magnetic moment of the muon, a_μ; *(iii)* electroweak precision measurements from LEP, SLC and the Tevatron and the Higgs boson mass limit from LEP; and *(iv)* the relic density of cold dark matter in the universe, Ω_χ. In contrast to Ref. [6], we employ the program HIGGSBOUNDS [10] and not a rigid Higgs mass

limit. We refer to Ref. [6] for a detailed discussion of the low-energy inputs and the collider limits.

At the LHC, the most stringent limits on supersymmetric models with R-parity conservation can be expected from searches in channels with jets, leptons and missing transverse energy, E_T^{miss}. We follow the analysis presented in Ref. [7] and consider the search channel with four jets, zero leptons and E_T^{miss}. This channel drives the sensitivity, in particular for large $M_{1/2}$. The selection cuts are

– four or more central jets with the pseudorapidity $|\eta(\text{jet})| < 2.5$, and with the transverse momentum $p_T > 100\,\text{GeV}$ for the leading jet, and $p_T > 40\,\text{GeV}$ for the other jets;

– an opening angle between the transverse momentum of the three leading jets and $\vec{p}_T^{\text{miss}}$ satisfying $\Delta\phi(\vec{p}_T^{\text{jet},i}, \vec{p}_T^{\text{miss}}) > 0.2$;

– the missing transverse energy $E_T^{\text{miss}} > 80\,\text{GeV}$;

– the ratio of the missing transverse energy and the effective mass satisfying $E_T^{\text{miss}}/M_{\text{eff}} > 0.2$;

– the transverse sphericity [11] $S_T > 0.2$;

– no leptons with $p_T > 20\,\text{GeV}$.

The effective mass is defined as the scalar sum of the transverse momenta of all main objects, *i.e.*

$$M_{\text{eff}} = \sum_{i=1}^{N_{\text{jets}}=4} p_T^{\text{jet},i} + E_T^{\text{miss}}. \tag{1}$$

The SM background processes have been described in detail in Ref. [7]. After the cuts listed above, the combined SM cross section has been estimated to $\sigma_{\text{SM}} = 2.42\,\text{pb}$ at 7 TeV. The signal cross section is dominated by squark and gluino pair production, $pp \to \tilde{q}\tilde{q}^*, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$, but all SUSY pair production processes are included in our numerical analysis. We use HERWIG++ [12] in combination with the parameterised fast detector simulation DELPHES [13] to obtain the detector response and, in particular, the shape of the M_{eff} distribution for a given point in the supersymmetric parameter space [22]. The signal estimate is normalized to the NLO+NLL QCD prediction for the inclusive squark and gluino cross sections [14].

To obtain good sensitivity to a SUSY signal, the full distribution of M_{eff} is included in the statistical analysis. We consider ten bins in the range $0 < M_{\text{eff}} < 4\,\text{TeV}$ and calculate the χ^2 contribution to the SUSY parameter fit from the number of signal and background events in each bin of the M_{eff} distribution. We define a test statistic $t = -2\ln Q$ with Q being the likelihood ratio

$$Q = \prod_{i=1}^{N_{\text{bins}}} \frac{\mathcal{L}(\mu_i = s_i + b_i; n_i)}{\mathcal{L}(\mu_i = b_i; n_i)}. \tag{2}$$

Here $\mathcal{L}(\mu; n) = \mu^n e^{-\mu}/n!$ is the Poisson probability to observe n events if μ are expected. s_i and b_i are the expected number of signal and background events in bin i, and n_i is the observed event count in this bin. s_i is a function of the SUSY parameters, whereas b_i is fixed. We consider a signal excluded with 95% confidence level (CL) if

$$\text{CL}_{s+b} = \int_{t_{\text{obs}}}^{\infty} P_{s+b}(t)\, dt < 0.05. \tag{3}$$

Here $P_{s+b}(t)$ is the probability density function of t assuming the presence of a signal and t_{obs} the actually observed value of t. Uncertainties on the cross-sections are taken into account by a correlated smearing of the expected event numbers. A given CL_{s+b} value can be approximately translated into a χ^2 contribution using the formula [15]

$$\chi^2 = 2[\,\text{erf}^{-1}(1 - 2\,\text{CL}_{s+b})]^2. \tag{4}$$

To obtain expected exclusion limits we use the Asimov data set $n_i = b_i$, $i = 1, \ldots, N_{\text{bins}}$.

NUMERICAL RESULTS

We present results from a global fit of the mSUGRA model to low-energy precision observables, the dark matter relic density, existing collider data from LEP, SLC and the Tevatron, and potential LHC exclusion limits. We consider LHC scenarios corresponding to $35\,\text{pb}^{-1}$, and 1, 2 and 7 fb^{-1} integrated luminosity.

In Fig. 1 we show the mSUGRA parameter region in M_0 and $M_{1/2}$ compatible with the existing low energy observables, the existing collider limits from LEP, SLC and the Tevatron, and the cold dark matter relic density, but no LHC exclusions imposed. Note that a positive sign of μ is preferred to describe the anomalous magnetic moment of the muon, so we have fixed $\text{sign}(\mu) = +$ and determined M_0, $M_{1/2}$, A_0, and $\tan\beta$ from the fit. Including the 1σ uncertainty, we find $M_0 = 75^{+115}_{-29}\,\text{GeV}$, $M_{1/2} = 329^{+92}_{-83}\,\text{GeV}$, $A_0 = 417^{+715}_{-725}\,\text{GeV}$ and $\tan\beta = 13^{+10}_{-7}$, in good agreement with Ref. [6]. The minimum χ^2 value is 19 for 20 degrees of freedom. Note that in regions with small M_0 and large $M_{1/2}$ the $\tilde{\tau}$ may be the lightest supersymmetric particle; such regions are thus excluded from the fit. In Fig. 1 we also show our estimate of the LHC exclusion limits in the four-jet, zero-lepton and missing transverse energy channel for different integrated luminosities. The area below the curves can be excluded at 95% CL. We assign 30% systematic uncertainty to the SUSY signal cross-section, and 20% systematic uncertainty to the background event rate in the signal-enriched region, which is dominantly electroweak [7]. The LHC signal estimate for the four jets, zero leptons and E_T^{miss} channel is insensitive to variations in $\tan\beta$ and A_0 within the systematic uncertainty. Our
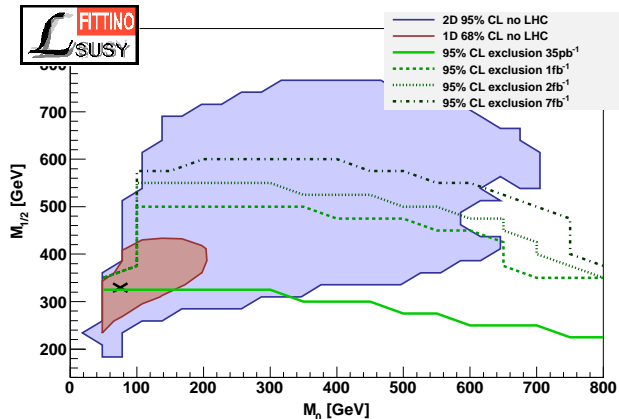
FIG. 1: mSUGRA parameter region in M_0 and $M_{1/2}$ compatible with low-energy observables, current collider data from LEP, SLC and the Tevatron, and the dark matter relic density. Shown are the two-dimensional 95% and one-dimensional 68% CL regions. Also shown is our estimate of the potential LHC 95% CL exclusion limits in the four-jet, zero-lepton and E_T^{miss} channel for different integrated luminosities.

FIG. 2: mSUGRA parameter region in M_0 and $M_{1/2}$ compatible with low-energy observables, current collider data from LEP, SLC and the Tevatron, the dark matter relic density, and a potential LHC exclusion limit in the four-jet, zero-lepton and E_T^{miss} channel for $2\,\mathrm{fb}^{-1}$ integrated luminosity. Also shown is the the potential LHC 95% CL exclusion limit.

results are in good agreement with current LHC limits at $35\,\mathrm{pb}^{-1}$ [16, 17], and with the projected ATLAS discovery potential at higher luminosities [7], bearing in mind that we use an improved signal estimate including the NLO+NLL QCD corrections.

We now combine the potential LHC exclusion limits, the current low-energy precision and collider observables, and the dark matter relic density constraint in a global fit. We assume $2\,\mathrm{fb}^{-1}$ integrated luminosity as our base scenario, but also discuss the impact of the LHC exclusions at $35\,\mathrm{pb}^{-1}$, and at 1 and $7\,\mathrm{fb}^{-1}$ below. The result of our combined mSUGRA fit assuming no SUSY signal at the LHC with $2\,\mathrm{fb}^{-1}$ is shown in Fig. 2. The best fit now corresponds to $M_0 = 270\,^{+423}_{-143}$ GeV, $M_{1/2} = 655\,^{+150}_{-81}$ GeV, $A_0 = 763\,^{+1238}_{-879}$ GeV and $\tan\beta = 32\,^{+18}_{-21}$, with a minimum χ^2 value of 24 for 21 degrees of freedom. The corresponding sparticle mass spectrum is presented in Fig. 3 and features most probable squark and gluino masses beyond 1 TeV.

An LHC exclusion in the zero-lepton, four-jet plus E_T^{miss} channel is mainly sensitive to the squark and gluino masses and would drive M_0 and $M_{1/2}$ to larger values. The low-energy precision observables and the relic density, on the other hand, are mainly constraining the masses of colour-neutral sparticles. Supersymmetric models with common scalar and gaugino masses like mSUGRA connect these two, leading to a tension between the two sets of observables. In addition, for larger M_0 and $M_{1/2}$ both a_μ and Ω_χ require an increased $\tan\beta$. It is also noteworthy that the global fit allows areas in the SUSY parameter space at 95% CL, which are located in the
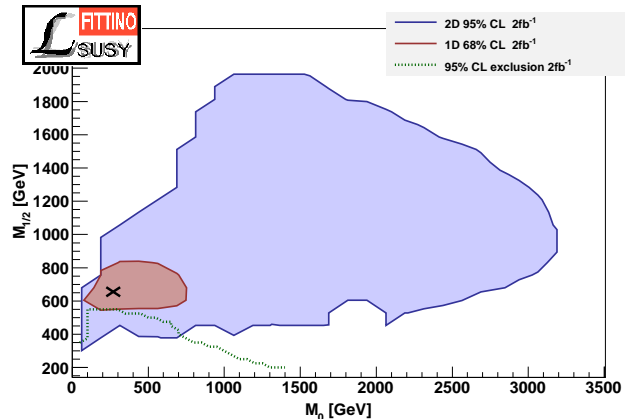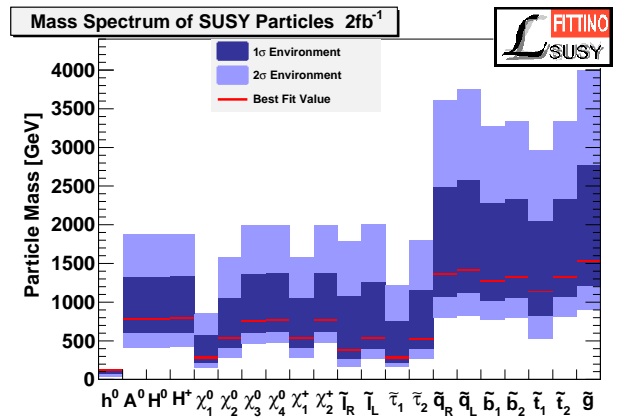

FIG. 3: SUSY mass spectrum as predicted by a combined mSUGRA fit of low-energy observables, current collider data from LEP, SLC and the Tevatron, the dark matter relic density, and a potential LHC exclusion limit in the four-jet, zero-lepton and E_T^{miss} channel for $2\,\mathrm{fb}^{-1}$ integrated luminosity.

region of 95% CL exclusion of the LHC, see Fig. 2. This is due to the weak dependence of the LHC contribution to the χ^2 on $M_{1/2}$. Furthermore values of M_0 and $M_{1/2}$ below the direct LHC limit allow for a significantly better χ^2 from the low energy data, compensating the contribution from the LHC. Thus the lower limits on the SUSY masses from the global fit including the LHC are significantly lower than the direct exclusion limits.

Fig. 4 presents the impact of the LHC exclusions on the $\tilde{q}_R$ and $\tilde{l}_R$ mass spectrum from the global mSUGRA fit, assuming $35\,\mathrm{pb}^{-1}$, and 1, 2 and $7\,\mathrm{fb}^{-1}$. Already with $1\,\mathrm{fb}^{-1}$ the LHC exclusion would push the lower limit on the squark mass above the TeV-
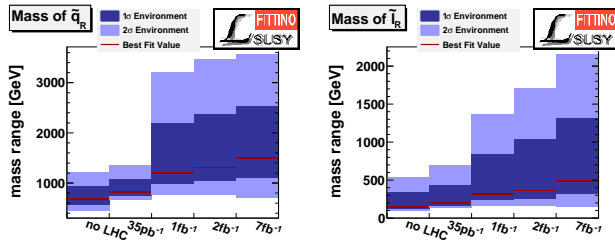
FIG. 4: $\tilde{q}_R$ and $\tilde{l}_R$ masses as predicted by a combined mSUGRA fit of low-energy observables, current collider data from LEP, SLC and the Tevatron, the dark matter relic density, and a potential LHC exclusion limit in the four-jet, zero-lepton and E_T^{miss} channel for $35\,\text{pb}^{-1}$, and 1, 2 and $7\,\text{fb}^{-1}$ integrated luminosity.

scale. The $\tilde{l}_R$ mass, which is mainly determined from the low-energy observables, is predicted in the range between $300\,\text{GeV}$ and $500\,\text{GeV}$. Note that a combined mSUGRA fit without the constraints on a_μ and Ω_χ results in very large sparticle mass uncertainties.

CONCLUSIONS

We have presented a first global mSUGRA analysis of supersymmetric models which includes the current low-energy precision measurements, the dark matter relic density as well as potential LHC exclusion limits from direct SUSY searches in the zero-lepton plus jets and missing transverse energy channel.

We conclude that it is, in principle, possible to reconcile the supersymmetric description of low-energy observables and the dark matter relic density with a non-observation of supersymmetry in the first phase of the LHC, despite some tension building up in a combined fit within the mSUGRA framework. Moreover, we find that a global mSUGRA fit including potential LHC exclusion limits would yield lower bounds on squark and gluino masses of about 1 TeV already with $1\,\text{fb}^{-1}$ integrated LHC luminosity.

While our study is exploratory in the sense that it is based on one search channel only, and on a simplified description of the LHC detectors, it clearly demonstrates the potential of the first phase of LHC running at 7 TeV in 2011/12 to constrain supersymmetric models and the sparticle mass spectrum.

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