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Constraints on Supersymmetry using 5/fb LHC data

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The ATLAS and CMS experiments did not find evidence for Supersymmetry using close to 5/fb of published LHC data at a center-of-mass energy of 7 TeV. We combine these LHC data with data on $B_s^0 \to \mu^+\mu^-$ (LHCb experiment), the relic density (WMAP and other cosmological data) and upper limits on the dark matter scattering cross sections on nuclei (XENON100 data). The excluded regions in the constrained Minimal Supersymmetric SM (CMSSM) lead to gluinos excluded below 1370 GeV and dark matter candidates below 230 GeV. If a Higgs mass of 125 GeV is imposed in the fit, the preferred SUSY region is above this excluded region, but the size of the preferred region is strongly dependent on the assumed theoretical error.

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1. Introduction

Supersymmetry (SUSY) remains the best candidate for physics beyond the Standard Model (SM) because of its exceptional properties, unification paradigm and a plausible dark matter (DM) candidate. Unfortunately, direct searches for the predicted SUSY particles at the LHC running at 7 TeV were unsuccessful. Also direct DM searches in deep underground experiments were contradictory. Combining all data from the LHC, cosmology and direct DM searches leads to strong constraints on the predicted SUSY masses, as discussed in recent papers. This report is based on the papers [1],[2], where a complete set of references can be found.

To restrict the number of independent SUSY masses one usually assumes the universality at the GUT scale and the particles get different masses at lower energies because of radiative corrections. In the constrained Minimal Supersymmetric SM (CMSSM) the many parameters of SUSY models are reduced to only four: the two mass parameters m_0, $m_{1/2}$ and two parameters related to the Higgs sector: the trilinear coupling at the GUT scale A_0, and $\tan\beta$, the ratio of the vacuum expectation values of the two neutral components of the two Higgs doublets. Electroweak symmetry breaking (EWSB) fixes the scale of μ, so only its sign is a free parameter. The positive sign is taken, as suggested by the muon anomalous magnetic moment.

In this letter we combine the newest data from LHC, WMAP, XENON100, flavor physics and g-2. The specific observables are detailed in Table 1. The combination of all constraints differs from the results from other groups, which is attributed to different fitting techniques.

Constraint	Data
Ωh^2	0.113 ± 0.004
$b \to X_s\gamma$	$(3.55 \pm 0.24) \cdot 10^{-4}$
$B_u \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$
Δa_μ	$(302\ \pm\ 63(exp)\ \pm\ 61(theo)) \cdot 10^{-11}$
$B_s^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^- < 4.5 \cdot 10^{-9}$
m_h	$m_h > 114.4$ GeV
m_A	$m_A > 510$ GeV for $\tan\beta \approx 50$
ATLAS	$\sigma_{had}^{SUSY} < 0.001 - 0.03$ pb
CMS	$\sigma_{had}^{SUSY} < 0.003 - 0.03$ pb
XENON100	$\sigma_{\chi N} < 1.8 \cdot 10^{-45} - 6 \cdot 10^{-45} cm^2$

Table 1: Constraints used in the fit to determine the excluded region of the CMSSM parameter space.

2. Excluded region by direct searches for SUSY at the LHC

In proton-proton collisions strongly interacting supersymmetric particles can be produced in pairs in strong and weak processes and decay via cascade chains. The cross section for the "strong" production of $\tilde{q}\bar{\tilde{q}}$ and $\tilde{g}\tilde{q}$ is large for low values of m_0 and $m_{1/2}$, the gluino production $\tilde{g}\tilde{g}$ is strongest at small values of $m_{1/2}$ and the electroweak production of gauginos starts to increase at large values of m_0. The reason for the increase of the electroweak production at large m_0 is the decrease of the Higgs mixing parameter μ, as determined from EWSB, which leads to a stronger mixing of

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the Higgsino component in the gauginos and so the coupling to the weak gauge bosons and Higgs bosons increases, thus increasing the amplitudes.

The strong production cross sections are characterized by a large number of jets from long decay chains and missing energy from the escaping neutralino. These characteristics can be used to efficiently suppress the background. For the electroweak production, both the number of jets and the missing transverse energy is low, hence, the electroweak gaugino production needs leptonic decays to reduce the background, so these signatures need more luminosities and cannot compete at present with the sensitivity of the strong production of squarks and gluinos.

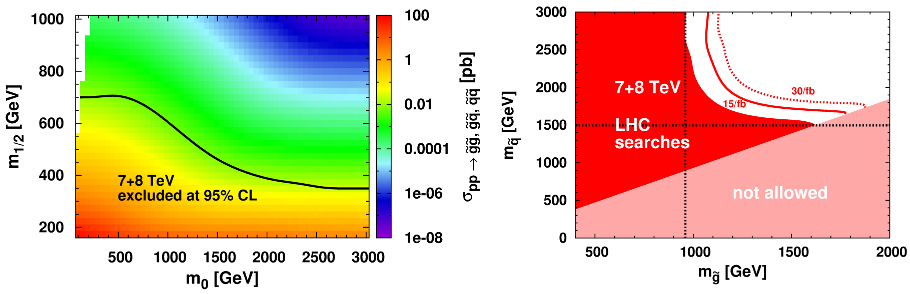

Figure 1: Left: Total production cross section of strongly interacting particles in comparison with the LHC excluded limits for 7 TeV. One observes that a cross section of 0.1 to 0.2 pb is excluded at 95% confidence level. Right: The same but in the $m_{\tilde{q}}, m_{\tilde{g}}$ plane. The red area corresponds to excluded regions for an integrated luminosity slightly above 1/fb; the expectations for higher luminosities are indicated as well.

The total cross section for the strongly interacting particles are shown in Fig. 1 together with the excluded region from direct searches at the LHC for SUSY particles. One observes that the excluded region (below the solid line) follows rather closely the total cross section, indicated by the colour shading. From the colour coding one observes that the excluded region corresponds to a cross section limit of about 0.1 -0.2 pb. The excluded region was obtained by combining the ATLAS and CMS limits. We only consider limits from LHC data based on jets and missing energy and do not include the less sensitive limits from leptonic data.

These limits can be translated to squark and gluino masses and lead to the excluded regions indicated in the right panel of Fig. 1. Note that these regions are not specific to the CMSSM and are valid in other models. Squark masses below 1.5 TeV and gluino masses below 0.96 TeV are excluded for the LHC data at 7 TeV. Expected sensitivities for higher integrated luminosities have been indicated as well. One observes that increasing the energy is much more effective than increasing the luminosity.

3. Combination of all Constraints

3.1 Excluded region by $B_s^0 \to \mu^+\mu^-$

The upper limit on the branching ratio of $B_s^0 \to \mu^+\mu^-$ can give significant constraints on the SUSY parameter space, since the $B_s^0 \to \mu^+\mu^-$ rate varies as $tan^6\beta$. In addition $B_s^0 \to \mu^+\mu^-$ is sensitive to the stop mixing which is a function of A_0. $B_s^0 \to \mu^+\mu^-$ can be suppressed if $m_{\tilde{t}_1} \approx m_{\tilde{t}_2}$ or even gets values below SM. Hence the χ^2 is sensitive to the chosen $\tan\beta$ and A_0 value. The combination with the relic density, which requires a large $\tan\beta$ value in a large region of parameter space (see Fig. 3) causes tension with the $B_s^0 \to \mu^+\mu^-$ constraint. This tension can be reduced by large values of A_0 but with the recent upper limit near the SM value from LHCb this tension increased and both constraints cannot be fulfilled at the same time in the whole parameter space. This leads to two excluded regions shown in Fig. 2. Compared to the other constraints the $B_s^0 \to \mu^+\mu^-$ rate leads only to a tiny increase of the excluded region at small m_0.

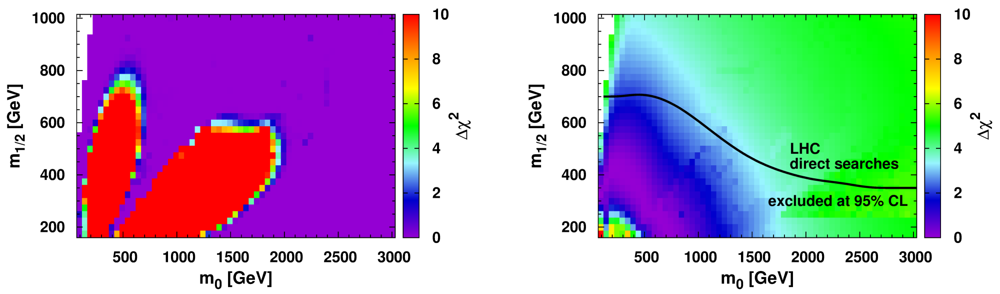

Figure 2: Left: constraints from the $B_s^0 \to \mu^+\mu^-$ in the $m_0, m_{1/2}$ plane after optimizing $\tan\beta$ and A_0. The red shaded area is excluded at 95 % C.L. Right: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ distribution of the g-2 observable alone under the constraint that $\tan\beta$ and A_0 are still fixed by all other constraints. One observes a shallow increase of the χ^2 value for large SUSY masses, because g-2 prefers light SUSY particles.

3.2 Influence of the anomalous magnetic moment of the muon

If the value of g-2 is included into the fit, one finds the preferred region of parameter space indicated by blue (dark shaded) area in Fig.2, if one adds the experimental and theoretical errors in quadrature. However, this region is still excluded by the direct searches at the LHC, so the observed three sigma deviation of the anomalous magnetic moment of the muon above the SM prediction may either be a statistical fluctuation or has an origin different from SUSY, if we assume the theoretical and experimental errors have been estimated correctly.

3.3 Excluded region by the relic density

The observed relic density of DM corresponds to $\Omega h^2 = 0.113 \pm 0.004$, which is about a factor six higher than the baryonic density. This number is inversely proportional to the annihilation cross section. The dominant annihilation contribution comes from A-boson exchange in most of the parameter space, if one excludes the narrow co-annihilation regions. The correct relic density requires $< \sigma v >= 2 \cdot 10^{-26}\ cm^3/s$, which implies that the annihilation cross section σ is of the order of a few pb. Such a high cross section can be obtained only close to the resonance. This constraint can be fulfilled with $\tan\beta$ values around 50 in the whole $m_0, m_{1/2}$ plane, except for the narrow co-annihilation regions, as we showed previously.

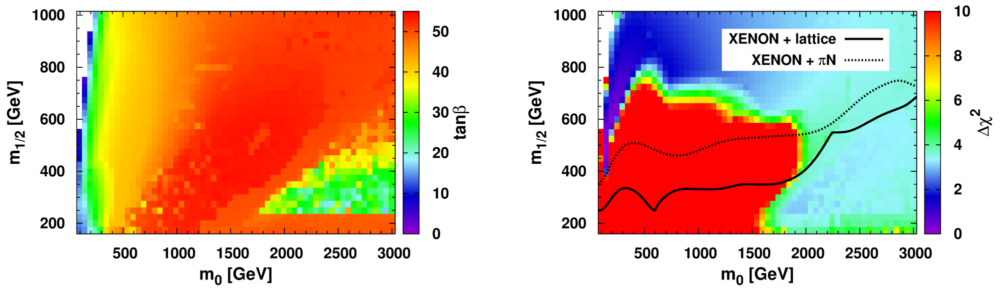

Figure 3: Left: Fitted values of $\tan\beta$ from relic density and EWSB constraints in the $m_0, m_{1/2}$ plane after optimizing A_0 at every point. The relic density requires $\tan\beta \approx 50$ in most of the parameter space, where pseudo-scalar Higgs exchange dominates. Right: $\Delta\chi^2$ distribution in the $m_0, m_{1/2}$ plane in comparison with the XENON100 limits on the direct WIMP-nucleon cross section for two values of the form factors (dotted line: πN scattering, solid line: lattice gauge theories).

3.4 Excluded region by direct DM searches

The cross section for direct scattering of WIMPS on nuclei has an experimental upper limit of about 10^{-8} pb, i.e. many orders of magnitude below the annihilation cross section. This is naturally explained in the MSSM by the fact that both cross sections are dominated by Higgs exchange. Due to the smallness of the Yukawa couplings most of the scattering cross section comes from the heavier sea-quarks the density of which inside the nuclei is small. For low momentum transfer, the scattering can be written in terms of an effective coupling, which can be determined either from πN scattering or from lattice QCD calculations.

To get conservative estimates for the excluded regions, we take the lowest possible values of the local DM density and the low couplings from lattice QCD calculations. The excluded region from the XENON100 cross section limit is shown on the right panel of Fig. 3. At large values of m_0 EWSB forces the higgsino component of the WIMP to increase and consequently the amplitude proportional to the bino-higgsino mixing, starts to increase. This leads to an increase in the excluded region at large m_0 and has here a similar sensitivity as the LHC.

3.5 Excluded region by the pseudo-scalar Higgs mass m_A

The pseudo-scalar Higgs boson mass is constrained by the relic density, because the dominant neutralino annihilation contribution comes from A-boson exchange in the region outside the small co-annihilation regions. One expects $m_A \propto m_{1/2}$ from the relic density constraint, which can be fulfilled with $\tan\beta$ values around 50 in the whole $(m_0, m_{1/2})$-plane. Since the m_A production cross section at the LHC is proportional to $\tan^2\beta$, the pseudo-scalar mass limit increases up to 496 GeV for the large values of $\tan\beta$ preferred by the relic density.

Combining all constraints from the LHC data with data on $B_s^0 \to \mu^+\mu^-$, the relic density (WMAP and other cosmological data) and upper limits on the dark matter scattering cross sections on nuclei (XENON100 data) (without 125 GeV Higgs mass) leads to the excluded region below the solid black line in Fig.4 (left).

3.6 Effect of a SM Higgs mass m_h around 125 GeV

In the fit we use the 95% C.L. LEP limit of 114.4 GeV on the Higgs mass instead of the limits published by CMS and ATLAS with about 5/fb. If a Higgs mass of 125 GeV is included in the fit, the best-fit point moves to higher SUSY masses, but there is a rather strong tension between the relic density constraint, $B_s^0 \to \mu^+\mu^-$ and the Higgs mass, so the best-fit point depends strongly on the error assigned to the Higgs mass. We have plotted the best-fit point for Higgs uncertainties of 2 GeV in Fig.4 (right panel). The region below the white line (for small $m_{1/2}$) and above the white line (for large $m_{1/2}$) is excluded at 95% C.L. A negative sign of the mixing parameter μ shows similar results.

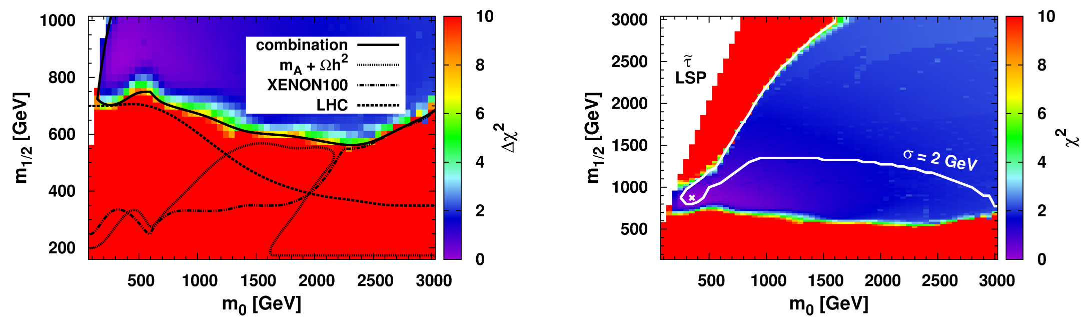

Figure 4: The total $\Delta\chi^2$ distribution without (left) and with (right) account of the 125 GeV Higgs mass

4. Summary

If one combines the limits from the direct searches at the LHC, heavy flavor constraints, WMAP and XENON100 we exclude values of $m_{1/2}$ below 525 GeV in the CMSSM for $m_0 < 1500$ GeV, which implies a lower limit on the WIMP mass of 230 GeV and a gluino mass of 1370 GeV, respectively.

If a Higgs mass of the lightest Higgs boson of 125 GeV is imposed, the preferred region is well above this excluded region, but the size of the preferred region is strongly dependent on the size of the assumed theoretical uncertainty. However, in models with an extended Higgs sector, like NMSSM, a Higgs mass of 125 GeV can be obtained for lower values of $m_{1/2}$, in which case the regions excluded in the MSSM become viable.

References

[1] C. Beskidt, W. de Boer, D.I. Kazakov, and F. Ratnikov, *Where is SUSY?*, JHEP 1205 (2012) 094, arXiv:1202.3366 [hep-ph]

[2] C. Beskidt, W. de Boer, D.I. Kazakov, and F. Ratnikov, *Constraints on Supersymmetry from LHC data on SUSY searches and Higgs bosons combined with cosmology and direct dark matter searches*, Eur.Phys.J. C72 (2012) 2166, arXiv:1207.3185 [hep-ph].