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Abstract

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Full Text

Status of CMSSM in Light of Current LHC Run-2 and LUX Data

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Abstract

Motivated by the latest results from LHC Run-2 and the LUX experiments, we examine the status of the Constrained Minimal Supersymmetric Standard Model (CMSSM) by performing a global fit. We construct a likelihood function that includes electroweak precision observables, B-physics measurements, LHC Run-1 and Run-2 data from SUSY direct searches, Planck observations of the dark matter relic density, and the combined LUX Run-3 and Run-4 detection

limits. Based on profile likelihood functions from 1 billion samples, we obtain the following observations: (i) The stau coannihilation region has been mostly excluded by the latest LHC Run-2 data; (ii) The focus point region has been largely covered by the LUX-2016 limits, while the A-funnel region has been severely restricted by flavor observables such as $B \rightarrow \dots$. The remaining parts of both regions will be completely covered by the future LZ dark matter experiment; (iii) The masses of the stop, the lightest neutralino, and the gluino have been pushed up to 1033 GeV, 449 GeV, and 2285 GeV, respectively.

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Introduction

Supersymmetry (SUSY) is one of the most promising candidates for addressing the long-standing hierarchy problem in particle physics. Among various SUSY models, the Constrained Minimal Supersymmetric Standard Model (CMSSM) is particularly attractive as an effective parametrization motivated by supergravity models. In the CMSSM, there are only five free parameters at the GUT scale: the universal scalar mass M_0 , the gaugino mass parameter $M_{1/2}$, the universal trilinear coupling A_0 , the ratio of the two Higgs vacuum expectation values $\tan \beta$, and the sign of the Higgs/higgsino mass parameter $\text{sign}(\mu)$. All sparticle masses and couplings at the weak scale are determined by these five input parameters through the running of renormalization group equations (RGEs), making the CMSSM highly predictive.

Over the past decades, many efforts have been devoted to investigating the CMSSM using various collider and dark matter experiments. In particular, the discovery of the 125 GeV Higgs boson and null results from LHC direct sparticle searches provide significant constraints on the CMSSM parameter space. The value of M_0 has been pushed up to several hundred GeV or larger, leading to tension between the observed Higgs mass and the muon $g-2$ anomaly. To be compatible with the measured cold dark matter relic density, the CMSSM parameter space is further restricted to several regions: the stau coannihilation (SC) strip, the focus-point (FP) region where the annihilation rate is enhanced by a significant higgsino component in the lightest neutralino, and the A-funnel (AF) region at large $\tan \beta$ where annihilation via a heavy MSSM Higgs boson H/A is dominant.

Among these regions, the FP region was expected to have low fine-tuning due to the RGE trajectories of the Higgs doublet mass squared (m^2_H) crossing close to the electroweak scale. However, the large value of M_0 required by the Higgs mass indicates approximately 0.1% fine-tuning in the FP region.

Very recently, the ATLAS and CMS collaborations updated their sparticle search results at the 13 TeV LHC with an integrated luminosity of 13 fb⁻¹. The non-observation of excess events in multi-jets plus missing transverse momentum channels excluded gluinos up to 1.8 TeV for a massless neutralino LSP, which is significantly stronger than the bound of approximately 1.3 TeV from LHC

Run-1. Meanwhile, the LUX experiment reported limits on spin-independent dark matter-nucleon scattering using a 3.35×10 kg-day exposure. Their new limits are about four times stronger than the LUX-2013 results. All these results tightly constrain the CMSSM parameter space and illuminate the path for future CMSSM searches. Therefore, it is necessary to re-examine the CMSSM with these new experimental data.

In this work, we adopt a Bayesian approach to scan the CMSSM parameter space by constructing a global likelihood function. We implement constraints including the Higgs boson mass, dark matter relic density, flavor observables, electroweak precision data, and the muon $g-2$ measurement. We compare the currently allowed parameter space with previous results from LHC Run-1 data and present lower limits for various sparticles. We also estimate the prospects for the LUX-Zeplin (LZ) experiment and the high-luminosity LHC to cover the CMSSM parameter space.

The paper is organized as follows. In Section II we describe our scan strategy and constraints. In Section III we present the allowed parameter space under current constraints and show prospects for future experiments. We conclude in Section IV.

II. Scan Strategy and Constraints

In our scan, we use the Markov Chain Monte Carlo (MCMC) method based on the Metropolis-Hastings algorithm to obtain samples. The MCMC algorithm generates a chain of samples whose density is proportional to the posterior probability density function (PDF) $p(\theta|d)$. The PDF represents our knowledge about parameter θ after incorporating experimental data d , given by $p(\theta|d) = p(d|O(\theta))L(\theta)/p(d)$, where $O(\theta)$ stands for some experimental observable. The likelihood function $p(d|O(\theta))L(\theta)$ gives the probability density of obtaining d from experimental measurements of O . The prior PDF $p(\theta)$ parameterizes assumptions about the theory before measurements, and the evidence $p(d)$ represents assumptions on the data.

A. Prior PDF

In the prior PDF $p(\theta)$, θ represents the parameters of the CMSSM and SM. For our study, these are M , M/Λ , A , $\tan\beta$, $\text{sign}(\mu)$, and the top quark mass m_t . The prior PDF is chosen subjectively to focus on regions of interest. Two popular choices exist: Flat and Log scans. The Flat prior means the PDF is uniform over the given range, while the Log prior means the PDF is logarithmic, giving more weight to lower parameter regions. The SM parameter m_t is determined by experimental data, so we adopt a Gaussian prior $p(m_t) = \exp[-(m_t - \hat{m}_t)^2/(2\sigma^2)]$ for CMSSM parameters. Other SM parameters are taken as $m_b(m_b) = 4.18$, $\alpha_s(m_Z) = 0.1185$, $[\alpha_{EM}(m_Z)]^{-1} = 127.944$. To obtain robust conclusions with finite CPU resources, we only scan the parameter space with $\text{sign}(\mu) = +1$, which is favored by the muon $g-2$ measurement.

TABLE I: The parameter space scanned in our MCMC sampling.

Parameter	Prior PDF	Range
M (GeV)	Flat, Log	(100, 10000)
M / (GeV)	Flat, Log	(100, 4000)
A (TeV)	Flat, Log	(-10, 10)
tan	Flat	(2.0, 65.0)
sign()	Fixed	+1
m	Gaussian	172.9 \pm 0.91

B. Likelihood Function

We construct the likelihood function $L(\cdot)$ using electroweak precision observables, B-physics observables, the measured Higgs boson mass, Planck observations of the cold dark matter relic density ($L_{\text{precision}}$), null results from SUSY searches at the LHC (L_{LHC}) and LEP (L_{LEP}), and limits from LUX-2016 spin-independent DM scattering cross-section (L_{LUX}):

$$\ln L(\cdot) = \ln L_{\text{precision}} + \ln L_{\text{LHC}} + \ln L_{\text{LEP}} + \ln L_{\text{LUX}}$$

TABLE II: The experimental constraints used in the likelihood function $L_{\text{precision}}$.

[Table content would be preserved here with experimental values for various observables]

We assume a Gaussian approximation for $L_{\text{precision}}$: $\ln L_{\text{precision}} = -\frac{1}{2} \sum [\hat{O}_i(\cdot) - O_i]^2 / \sigma_i^2$, where $\hat{O}_i(\cdot)$ denotes the predicted value of observable O_i in the model, O_i is the experimental central value, and σ_i represents experimental and theoretical uncertainties. In our study, we use SOFTSUSY 3.3.1 to generate sparticle mass spectra, MicrOMEGAs 2.4.5 to calculate the dark matter relic density (assuming the lightest neutralino is the sole dark matter component), SuperIso v3.3 to evaluate flavor physics observables, FeynHiggs 2.12 to obtain the Higgs boson mass and electroweak precision observables, and GM2Calc for the muon $g-2$ calculation. We interface all these programs with EasyScan HEP and use its built-in Metropolis-Hastings algorithm to perform the MCMC scan.

Since LHC searches for jets plus missing transverse momentum (with or without leptons or b-jets) provide strong constraints on the CMSSM parameter space, we implement these bounds by recasting relevant experimental analyses. We simulate SUSY signal processes with MG5@NLO, PYTHIA, and Delphes 3.3.0, using Prospino to calculate squark and gluino production cross sections at next-to-leading order. The likelihood function L_{LHC} is evaluated assuming a Poisson distribution for expected signal events N_s , observed events N_o , and background events N_b from experimental reports.

To validate our method, we first calculate the likelihood $L_{8\text{TeV_LHC}}$ by re-casting ATLAS analyses (0 lepton + 2-6 jets + $E_{T^{\text{miss}}}$ and 0/1 lepton + 3 b-jets + $E_{T^{\text{miss}}}$) with CheckMATE 2.0 on the (m, m') plane of the CMSSM, with other parameters fixed as $\tan\beta = 30$, $A = -2m$, $\mu > 0$. In the left panel of **FIGURE:1**, we show the color map of $-2\Delta\ln L$ on the (M, M') plane for the 0 lepton + 2-6 jets + $E_{T^{\text{miss}}}$ search. The contour of $-2\ln L = 4$ (our 95% limits) is well consistent with the experimental 95% CL limits. In the middle panel of **FIGURE:1**, we validate our simulations for ATLAS 13 TeV results on the $m_{\tilde{g}}$ versus $m_{\tilde{t}}$ plane. Our 95% CL exclusion limits for simplified models are well consistent with ATLAS results. Since the signal rate is fairly insensitive to $\tan\beta$ and A , we treat the likelihood as a function of (m, m') only. The likelihood function $L_{13\text{TeV_LHC}}$ is built by interpolating the likelihood of grid points on the (m, m') plane with intervals of 300 GeV and 50 GeV for m and m' , respectively. In the right panel of **FIGURE:1**, we compare our 95% C.L. exclusion limits from 13 TeV analyses with those from 8 TeV analyses, finding that the lower values of M' are lifted from 800 GeV at 8 TeV LHC to 1100 GeV at 13 TeV LHC.

The likelihood function L_{LEP} from LEP direct sparticle searches is evaluated using a step function, assigning a large value of $\ln L_{\text{LEP}}$ for excluded samples and 0 for allowed samples. Our results are not sensitive to L_{LEP} because LEP limits on sparticle masses are much weaker than LHC limits.

The likelihood function $L_{\text{LUX-2013}}$ from LUX results with 85.3 live days of data (collected between April and August 2013 with a 118 kg fiducial volume) is computed using the LUXCalc package. For recent direct detection constraints from LUX using a 3.35×10 kg-day exposure, we use the likelihood function form described in [55] to estimate $L_{\text{LUX-2016}}$ with a 10% theoretical uncertainty. This likelihood function form is designed for experimental results presented as upper or lower bounds only. The spin-independent dark matter-nucleon scattering cross-section used in the likelihood function is obtained from MicrOMEGAS with $f_{T^{\text{u}}} = 0.023689$, $f_{T^{\text{d}}} = 0.03906$, and $f_{T^{\text{g}}} = 0.363$.

To show the impact of recent LHC 13 TeV direct searches and LUX dark matter detections on the CMSSM parameter space, we use two likelihood functions:

$$\begin{aligned} \ln L(_)_{\text{old}} &= \ln L_{\text{precision}} + \ln L_{8\text{TeV_LHC}} + \ln L_{\text{LEP}} + \ln L_{\text{LUX-2013}} \\ \ln L(_)_{\text{new}} &= \ln L(_)_{\text{old}} + \ln L_{13\text{TeV_LHC}} + \ln L_{\text{LUX-2016}} \end{aligned}$$

C. Profile Likelihood Function

There are two statistical approaches to present global fit results: the marginal posterior PDF and the profile likelihood function. The marginal posterior PDF of a parameter θ_i is defined by integrating out other parameters from the posterior distribution $p(\theta|\mathcal{d})$: $p(\theta_i|\mathcal{d}) = \int p(\theta|\mathcal{d}) d\theta_{i-1} d\theta_{i+1} \dots d\theta_n$, which includes volume effects and peaks of highest posterior mass. However, marginal posterior results depend on prior probability assumptions.

The frequentist profile likelihood function is defined as $L(\hat{\theta}_i) = \max_{\theta} L(\theta) = L(\hat{\theta}_i, \hat{\theta}_{-i})$, where $L(\theta)$ is the likelihood function from Eq.(1), $\theta = \{\theta_1, \dots, \theta_{i-1}, \theta_{i+1}, \dots, \theta_n\}$, and $\hat{\theta}_i$ maximizes $L(\theta)$. By definition, the profile likelihood function is independent of scan method, allowing samples from MCMC scans with Flat or Log priors to be merged. Since the frequentist approach yields well-defined probabilities, we present our results using the profile likelihood. Confidence intervals/regions from resulting 1D/2D profile likelihood maps are given by the profile likelihood ratio $-2\ln(\hat{\theta}_i) = -2\ln(L(\hat{\theta}_i)/L(\hat{\theta}_i, \hat{\theta}_{-i}))$, which follows a χ^2 distribution, with $L(\hat{\theta}_i, \hat{\theta}_{-i})$ corresponding to the maximum likelihood (the best-fit point).

III. Results

In this section, we present the allowed CMSSM parameter space from profile likelihood functions of 1 billion samples.

In **FIGURE:2**, we show allowed parameter regions on the $(m_{\tilde{g}}, m_{\tilde{t}})$, $(\tan\beta, A)$, and $(m_{\tilde{L}}, \sqrt{s} \hat{\sigma}_p)$ planes. Red and black contours correspond to 68% and 95% CL regions. Left and right columns depict 2D profile likelihood functions obtained from $L(\theta)_{\text{old}}$ and $L(\theta)_{\text{new}}$, respectively. Four regions with different DM annihilation mechanisms are distinguished by colors: the SC region (green), where neutralino relic density is set by neutralino-stau coannihilation with $m_{\tilde{L}}/m_{\tilde{L}} - 1 < 0.15$; the AF region (blue), characterized by $|m_{\tilde{A}}/2m_{\tilde{L}} - 1| < 0.2$, where a relatively light pseudoscalar mediates DM annihilation via s-channel; the FP region (yellow), requiring $|m_{\tilde{L}} - 1| < 0.4$, where the lightest neutralino has significant higgsino component. Additionally, two hybrid regions exist: SC&AF (gray) and AF&FP (pink), satisfying two conditions simultaneously.

From **FIGURE:2**, we find that parameter spaces of these four regions are sensitive to different experiments:

- In the SC region, $M < 2$ TeV and $M_{\tilde{L}} < 1.5$ TeV with negative A required, corresponding to $m_{\tilde{g}} < 3$ TeV and $m_{\tilde{t}} < 1.8$ TeV. Most of this parameter space is excluded by recent LHC-13 TeV SUSY direct searches. The small surviving region can be further probed at high-luminosity LHC. Notably, the best point, previously located in the SC region, has been pushed into the FP region by new LHC-13 TeV results. The 95% CL lower limits on M and $M_{\tilde{L}}$ become 1041 GeV and 856 GeV, respectively. Consequently, lower masses of \tilde{g} and \tilde{t} are pushed up to 2.2 TeV and 1 TeV. $\tan\beta$ must be larger than 30 to enhance stau coannihilation cross-section. When \tilde{L} is bino-dominated, LUX constraints on this region become weak.
- Contrary to the SC region, the FP region exists at large M and $M_{\tilde{L}}$ values, allowing it to escape LHC SUSY search limits. However, the \tilde{L} -nucleon scattering cross-section is sizable here. We see that one-third of this parameter space is excluded by LUX-2016. The whole region lies within expected exclusion limits of the future LZ experiment.

- In the AF region, $\tilde{\chi}^0$ pairs mostly annihilate into b-quarks through A boson in the s-channel, preferring large $\tan\beta$ to enhance the A-b coupling. The preferred parameter space is scarcely changed between $L(\)_{old}$ and $L(\)_{new}$. A special feature is that the profile likelihood is not as flat as in SC and FP regions on the $(M_h, M_{\tilde{g}})$ plane. The 95% CL and 68% CL contours are very close in SC and FP regions, while the 95% CL region is much larger than the 68% CL region in the AF region, primarily because the observable $Br(B \rightarrow \tilde{\chi}^0 b)$ is proportional to $\tan\beta$. The whole AF region can also be covered by the LZ experiment. Additionally, studies show the AF region would be covered by $Br(B \rightarrow \tilde{\chi}^0 b)$ measurements at 14 TeV LHC with 50 fb^{-1} luminosity.
- The two “hybrid” regions have properties similar to the AF region: moderate M_h and $M_{\tilde{g}}$, large $\tan\beta$, and positive A.

In **FIGURE:3**, we display predictions for low-energy observables (left panel) and sparticle mass spectra (right panel) in the preferred parameter space. Light and dark green (blue) bars indicate 95% and 68% CL 1D intervals from $L(\)_{old}$ ($L(\)_{new}$), while red points show the overall best-fit point. The main contribution to the likelihood comes from muon $g-2$, a_{μ}^{SUSY} . Due to new LHC strong constraints on the SC region, the SUSY contribution to Δa_{μ} becomes rather small. The 95% CL upper limit on a_{μ}^{SUSY} is reduced from 6×10^{-1} ($L(\)_{old}$) to 3×10^{-1} ($L(\)_{new}$).

Compared with LHC Run-1, null results from 13 TeV LHC SUSY searches also push 95% CL lower mass bounds: gluino and first two generations of squarks from ~ 1.6 TeV to 2.3 TeV, lightest stop from 700 GeV to 1 TeV, and LSP from 320 GeV to 450 GeV. Consequently, SUSY contributions to B-physics observables approach the decoupling limit. The Higgs mass more easily satisfies experimental measurements. Except for electroweakinos, upper mass limits on sparticles are determined by input parameter scan ranges (the prior PDF).

TABLE III presents properties of benchmark points from SC, FP, and AF regions with local $L(\)_{new}$ (SC' represents the SC region with local $L(\)_{old}$). Each point is the best point in its region. Δ is the fine-tuning measure. All masses are in GeV.

[Table content showing Point, M_h , $M_{\tilde{g}}$, A, $\tan\beta$, $m_{\tilde{h}}$, $m_{\tilde{A}}$, $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^{\pm}}$, $\Omega_{\tilde{\chi}^0}^2$, \tilde{a}_{SI} , Δa_{μ} , and Δ values for FP, AF, SC, and SC' regions]

The local best point in the SC region has smaller Higgs mass but larger muon $g-2$ than FP and AF regions. Conversely, the spin-independent cross-section of the local best point in the FP region is much larger. We compute fine-tuning using SOFTSUSY 3.3.1 with the definition $\Delta = \max |\ln M_{Z^2} / \ln a|$, where a represents fundamental parameters $\{M_h, M_{\tilde{g}}, A, \tan\beta, B\}$ at the GUT scale. The fine-tuning value for the SC region's local best point is about two thousand, much smaller than in FP and AF regions.

IV. Conclusion

In this paper, we examined the CMSSM status by performing a global fit under currently available constraints, particularly LHC-13 TeV SUSY direct searches and combined LUX Run-3 and Run-4 dark matter direct detection limits. From profile likelihood functions of 1 billion samples, we obtained the following 95% confidence level results for CMSSM parameter space: (i) The stau coannihilation region has been mostly excluded by latest Run-2 data, with the remaining part to be completely covered by Run-2' s end; (ii) The focus point region has been largely cut off by LUX-2016 limits, while the A-funnel region has been severely restricted by flavor observables like $B \rightarrow \dots$. Surviving parts of both regions will be completely covered by the future LZ dark matter experiment, while current and future LHC Run-2 data provide weaker constraints; (iii) Current lower mass bounds for the stop, neutralino dark matter, and gluino are 1033 GeV, 449 GeV, and 2285 GeV, respectively.

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