Supersymmetric Dark Matter at XENON100 and the LHC: No-Scale $F$-$SU(5)$ Stringy Correlations

Tianjun Li,1, 2 James A. Maxin,2 Dimitri V. Nanopoulos,2, 3, 4, 5 and Joel W. Walker5

1 State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China
2 George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
3 Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, TX 77381, USA
4 Academy of Athens, Division of Natural Sciences, 28 Panepistimiou Avenue, Athens 10679, Greece
5 Department of Physics, Sam Houston State University, Huntsville, TX 77341, USA

We complete an investigation of the observable signatures of No-Scale flipped $SU(5) \times U(1)_X$ grand unified theory with TeV-scale vector-like particles (No-Scale $F$-$SU(5)$) at the LHC and dark matter direct detection experiments. We feature a dark matter candidate which is over 99% bino due to a comparatively large Higgs bilinear mass $\mu$ term around the electroweak scale, and hence automatically satisfies the present constraints from the XENON100 and CDMS/EDELWEISS experiments. We do however expect that the continued XENON100 run and extension to 1-ton may begin to probe our model. Similarly, our model is also currently under probe by the LHC through a search for events with ultra-high multiplicity hadronic jets, which are a characteristic feature of the distinctive No-Scale $F$-$SU(5)$ mass hierarchy.

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The search for supersymmetry (SUSY) and dark matter at the Large Hadron Collider (LHC) has been progressing since March 2010, steadily accumulating data from $\sqrt{s} = 7 - 8$ TeV proton-proton collisions by the CMS and ATLAS Experiments, and has reached an integrated luminosity of 15 fb$^{-1}$ to date, with possibly over 25 fb$^{-1}$ anticipated by the end of 2012. Nonetheless, early results have produced no definitive signal of supersymmetry or dark matter, drastically constraining the experimentally viable parameter space of the CMSSM and mSUGRA, in addition to the entire landscape of supersymmetric models. The lack of convincing evidence of supersymmetry thus far has increased the constraints on the viable CMSSM and mSUGRA model space, posing the question whether there exist SUSY and/or superstring post-Standard Model extensions that can elude the currently enforced LHC constraints, though surviving within the 2012 reach of the LHC.

The search for dark matter (DM) is being led on the direct detection front by the XENON100 collaboration [1], whose expansion in the last year to a fiducial detector mass of 62 kg of ultra-pure liquid xenon has promptly captured a near ten-fold improvement over the CDMS and EDELWEISS experiments [2] in the upper bound on the spin-independent cross section for scattering WIMPs against nucleons. This limit likewise begins to cut incisively against the favored regions of the CMSSM.

The exploration of the existence of dark matter persists not only between parallel experimental search strategies, but also between alternative theoretical proposals. We have studied in comprehensive detail a promising model name by the No-Scale $F$-$SU(5)$ [3–22], which is constructed from the merger of the $F$-flipped $SU(5)$ Grand Unified Theory (GUT) [23–25], two pairs of hypothetical TeV scale vector-like supersymmetric multiplets with origins in $F$-theory [26–30], and the dynamically established boundary conditions of No-Scale Supergravity [31–35]. The experimentally viable parameter space of No-Scale $F$-$SU(5)$ has been comprehensively mapped [9], which satisfies the “bare minimal” phenomenological constraints, possesses the correct cold DM (CDM) relic density, and is consistent with a dynamic determination by the secondary minimization of the Higgs potential via the “Super No-Scale” mechanism [8, 9, 14].

The No-Scale $F$-$SU(5)$ construction inherits all of the most beneficial phenomenology [30] of flipped $SU(5)$ [23–24], as well as all of the valuable theoretical motivation of No-Scale Supergravity [31–35], including a deep connection to the string theory infrared limit (via compactification of the weakly coupled heterotic theory [37] or M-theory on $S^1/Z_2$ at the leading order [38]), and a mechanism for SUSY breaking which preserves a vanishing cosmological constant at the tree level (facilitating the observed longevity and cosmological flatness of our Universe [31]).

Mass degenerate superpartners for the known SM fields have not been observed, therefore SUSY must itself be broken near the TeV scale. In mSUGRA, this begins in a hidden sector, and the secondary propagation by gravitational interactions into the observable sector is
parameterized by universal SUSY-breaking “soft terms” which include the gaugino mass $M_{1/2}$, scalar mass $M_0$ and the trilinear coupling $A$. The ratio of the low energy Higgs vacuum expectation values (VEVs) $\tan\beta$ and the sign of the SUSY-preserving Higgs bilinear mass term $\mu$ remain undetermined, while the magnitude of the $\mu$ term and its bilinear soft term $B_0$ are determined by the $Z$-boson mass $M_Z$ and $\tan\beta$ after electroweak symmetrization (EWSB). In the simplest No-Scale scenario, $M_0=A=B_0=0$ at the unification boundary, while the entire set of low energy SUSY breaking soft-terms evolve down from a single non-zero parameter $M_{1/2}$. As a result, the particle spectrum is proportional to $M_{1/2}$ at leading order, rendering the bulk “internal” physical properties invariant under an overall rescaling.

The (formerly negative) one-loop $\beta$-function coefficient of the strong coupling $\alpha_s$ becomes precisely zero, flattening the RGE running, and generating a wide gap between the large $\alpha_{32} \simeq \alpha_3(M_3) \simeq 0.11$ and the much smaller $\alpha_\chi$ at the scale $M_{32}$ of the intermediate flipped $SU(5)$ unification of the $SU(5) \times SU(2) \times U(1)$ subgroup. This facilitates a very significant secondary running phase up to the final $SU(5) \times U(1)_X$ unification scale $M_\chi$, which may be elevated by 2-3 orders of magnitude into adjacency with the Planck mass, where the $B_\mu = 0$ boundary condition fits well $\exists \beta \in \{39, 40\}$. We denote this final $SU(5) \times U(1)_X$ unification scale as $M_\chi$ for the experimentally viable parameter space, $M_{1/2}$ transpires at about $4-6 \times 10^{17}$ GeV, right near the string scale of $\sim 5 \times 10^{17}$ GeV, providing a very natural solution to the “little hierarchy” problem.

The modifications to the $\beta$-function coefficients from introduction of the vector-like multiplets have a comparable effect on the RGEs of the gauginos. Specifically, the color-charged gaugino mass $M_3$ likewise evolves down from the high energy boundary flat, obeying the relation $M_3/M_{1/2} \simeq \alpha_3(M_3)/\alpha_3(M_{32}) \simeq O(1)$, which precipitates a conspicuously light gluino mass assignment. The $SU(2)_L$ and hypercharge $U(1)_Y$ associated gaugino masses are by contrast driven downward from the $M_{1/2}$ boundary value by roughly the ratio of their corresponding gauge couplings ($\alpha_2, \alpha_Y$) to the strong coupling $\alpha_s$. The large mass splitting expected from the heaviness of the top quark via its strong coupling to the Higgs (which is also key to generating an appreciable radiative Higgs mass shift $\Delta m_h^2 \equiv 41$) is responsible for a rather light stop squark $\tilde{t}_1$. The distinctively predictive $m_{\tilde{t}_1} < m_{\tilde{g}} < m_{\tilde{q}}$ mass hierarchy of a light stop and gluino, both much lighter than all other squarks, is stable across the full No-Scale $F-SU(5)$ model space, but is not precisely replicated in any phenomenologically favored CMSSM constructions of which we are aware.

The spectrum associated with this mass hierarchy generates a unique event topology starting from the pair production of heavy squarks $\tilde{g}\tilde{q}$, except for the light stop, in the initial hard scattering process, with each squark likely to yield a quark-gluino pair $\tilde{q} \rightarrow \tilde{g}\tilde{q}$. Each gluino may be expected to produce events with a high multiplicity of virtual stops or tops, via the (possibly off-shell) $\tilde{g} \rightarrow \tilde{t}_1\tilde{\tau}$ or $\tilde{g} \rightarrow \tilde{t}_1t$ transitions, which in turn may terminate into hard scattering products such as $\rightarrow W^+W^-b\tilde{\chi}_1^0$ and $W^+b\tau^+\nu_\tau\tilde{\chi}_1^0$, where the $W$ bosons will produce mostly hadronic jets and some leptons. The model described may then consistently produce a net product of eight or more jets emergent from a single squark pair production event, passing through a single intermediate gluino pair, resulting after fragmentation in an impressive signal of ultra-high multiplicity final state jet events.

The entirety of the viable $F-SU(5)$ parameter space naturally features a dominantly bino LSP, at a purity greater than 99%, as is exceedingly suitable for direct detection. There exists no direct bino to wino mass mixing term. This distinctive and desirable model characteristic is guaranteed by the relative heaviness of the Higgs bilinear mass $\mu$, which in the present construction generically traces the the universal gaugino mass $M_{1/2}$ at the boundary scale $M_{F}$, and subsequently transmutes under the RGEs to a somewhat larger value at the electroweak scale.

A majority of the bare-minimally constrained $\mathbb{B}$ parameter space of No-Scale $F-SU(5)$, as defined by consistency with the world average top-quark mass $m_t$, the No-Scale boundary conditions, radiative EWSB, the centrally observed WMAP7 CDM relic density limits 0.1088 $\leq \Omega h^2 \leq 0.1158$ [46] (we assume a thermal relic), and precision LEP constraints on the lightest CP-even Higgs boson $m_h$ and other light SUSY chargino and neutralino mass content, remains viable. The intersection of these experimental bounds is quite non-trivial, as the tight theoretical constraints, most notably the vanishing of $B_\mu$ at the high scale boundary, render the residual parameterization insufficient for arbitrary tuning of even isolated predictions, not to mention the union of all predictions.

![FIG. 1: The bare-minimally constrained parameter space of No-Scale $F-SU(5)$ is depicted as a function of the gaugino boundary mass $M_{1/2}$ and the vector-like mass $M_V$. The WIMP mass, top quark mass $m_t$, and $\tan\beta$ are demarcated via the solid, dashed, and dotted contour lines, respectively.](image-url)
The bare-minimal constraints set lower bounds at about $d$ of top quark mass, $\tan \beta$ uniquely formed profile situated in the minimal constraints shapes the parameter space into the with a lower bound of $\tan \beta$ exhibited in Fig. (1), from a tapered light mass region around $\tan \beta$ that ceases sharply with the charged stau LSP exclusion LEP constraints, into a more expansive heavier region.

FIG. 2: Direct dark matter detection diagram associating the WIMP mass with the spin-independent annihilation cross-section $\sigma_{SI}$.

minimal constraints shapes the parameter space into the uniquely formed profile situated in the $M_{1/2}, M_V$ plane exhibited in Fig. (1), from a tapered light mass region with a lower bound of $\tan \beta = 19.4$ demanded by the LEP constraints, into a more expansive heavier region that ceases sharply with the charged stau LSP exclusion around $\tan \beta \simeq 23$, where we overlay smooth contour gradients of top quark mass, $\tan \beta$, and the WIMP mass. The bare-minimal constraints set lower bounds at about $M_{1/2} \simeq 385$ and $M_V \simeq 925$ GeV correlated to the lower bound on $\tan \beta$ of around 19.4, and upper bounds near $M_{1/2} \simeq 900$ and $M_V \simeq 9.7$ TeV, correlated to the upper bound on $\tan \beta$ at about 23. The parameter space in Fig. (1) does not include the most recent constraint on the Higgs mass, though when applying the mass limits 125 $\lesssim m_h \lesssim 126$, the large region of model space in Fig. (1) is reduced to a narrow strip of space along the lower edge of the region [17, 18].

The proportional rescaling associated with the single massive input $M_{1/2}$ explains the ability to generate the WMAP7 successfully and generically, where we assume a thermal relic. The correct DM relic density can be generated by the LSP neutralino and light stau coannihilation. All considered, it indicates how finely naturally adapted (not finely tuned) No-Scale $\mathcal{F}$-$SU(5)$ is with regards to the question of relic density. Although currently safe, it does appear that the full model space may be effectively probed in the near future by the extended reach of the ongoing data collection at XENON100 and the expansion to the 1-ton XENON. The relevant scale dependent sensitivity contours to spin-independent DM-nucleon scattering are depicted in Fig. (2), along with their relation to the putative $\mathcal{F}$-$SU(5)$ signal. In Fig. (2), we include the latest results from the XENON100 experiment released in 2012 [47], as well as the expected sensitivity for the 1-ton version of the XENON experiment.

The LHC has begun running at a beam collision energy of 8 TeV in 2012, though the analysis of these 8 TeV data observations is still progressing. However, we have completed a thorough examination of the complete 5 fb$^{-1}$ at 7 TeV [19, 21], and discovered tantalizing correlations between the 7 TeV observations and the Monte-carlo predictions of No-Scale $\mathcal{F}$-$SU(5)$, particularly in the realm of the large multijet events, which as we discussed earlier, is expected to be a clear signature of $\mathcal{F}$-$SU(5)$ as larger amounts of data are collected.

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[1] E. Aprile et al. (XENON100), “Dark Matter Results from 100 Live Days of XENON100 Data,” (2011), 1104.2549.
[2] CDMS, “Combined Limits on WIMPs from the CDMS and EDELWEISS Experiments,” (2011), 1105.3377.
[3] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “The Golden Point of No-Scale and No-Parameter $\mathcal{F}$-$SU(5)$,” Phys. Rev. D83, 056015 (2011), 1007.5100.
[4] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “The Golden Strip of Correlated Top Quark, Gaugino, and Vectorlike Mass In No-Scale, No-Parameter F-SU(5),” Phys. Lett. B699, 164 (2011), 1009.2981.
[5] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Super No-Scale $\mathcal{F}$-$SU(5)$: Resolving the Gauge Hierarchy Problem by Dynamic Determination of $M_{1/2}$ and $\tan \beta$,” Phys. Lett. B 703, 469 (2011), 1010.4550.
[6] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Blueprints of the No-Scale Multiverse at the LHC,” Phys. Rev. D84, 056016 (2011), 1101.2197.
[7] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Ultra High Jet Signals from Stringy No-Scale Supergravity,” (2011), 1103.2362.
[8] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “The Ultrahigh jet multiplicity signal of stringy no-scale $\mathcal{F}$-$SU(5)$ at the $\sqrt{s} = 7$ TeV LHC,” Phys.Rev. D84, 076003 (2011), 1103.4160.
[9] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “The Unification of Dynamical Determination and Bare Minimal Phenomenological Constraints in No-Scale F-
SU(5),” Phys.Rev. D85, 056007 (2012), 1105.3988.
[10] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “A Two-Tiered Correlation of Dark Matter with Missing Transverse Energy: Reconstructing the Lightest Supersymmetric Particle Mass at the LHC,” JHEP 02, 129 (2012), 1107.2375.
[11] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Prospects for Discovery of Supersymmetric No-Scale F-SU(5) at The Once and Future LHC,” Nucl.Phys. B859, 96 (2012), 1107.3825.
[12] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Has SUSY Gone Undetected in 9-jet Events? A Ten-Fold Enhancement in the LHC Signal Efficiency,” (2011), 1108.5169.
[13] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Natural Predictions for the Higgs Boson Mass and Supersymmetric Contributions to Rare Processes,” Phys.Lett. B708, 93 (2012), 1109.2110.
[14] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “The F-Landscape: Dynamically Determining the Multiverse,” Int.Jour.Mod.Phys. A27, 1250121 (2012), 1111.0236.
[15] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Profumo di SUSY: Suggestive Correlations in the ATLAS and CMS High Jet Multiplicity Data,” (2011), 1111.4294.
[16] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “A Higgs Mass Shift to 125 GeV and A Multi-Jet Supersymmetry Signal: Miracle of the Flippons at the LHC,” Phys.Lett. B710, 7 TeV LHC, (2012), 1207.1051.
[17] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Testing No-Scale F-SU(5)/SU(5): A 125 GeV Higgs Boson and SUSY at the 8 TeV LHC,” (2012), 1207.1051.
[18] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “A 125.5 GeV Higgs Boson in F-SU(5): Imminently Observable Proton Decay, A 130 GeV Gamma-ray Line, and SUSY Multijets & Light Stops at the LHCs,” (2012), 1208.1999.
[19] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “A Multi-Axis Best Fit to the Collider Supersymmetry Search: The Aroma of Stops and Gluinos at the $\sqrt{s} = 7$ TeV LHC,” (2012), 1203.1918.
[20] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Chanel N$^5$/(fb$^{-1}$): The Sweet Fragrance of SUSY,” (2012), 1205.3052.
[21] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Non-trivial Supersymmetry Correlations between ATLAS and CMS Observations,” (2012), 1206.0293.
[22] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Correlating LHCh $B^0_d \rightarrow \mu^+\mu^-$ Results with the ATLAS-CMS Multijet Supersymmetry Search,” (2012), 1206.2633.
[23] S. M. Barr, “A New Symmetry Breaking Pattern for SO(10) and Proton Decay,” Phys. Lett. B112, 219 (1982).
[24] J. P. Derendinger, J. E. Kim, and D. V. Nanopoulos, “Anti-SU(5),” Phys. Lett. B139, 170 (1984).
[25] I. Antoniadis, J. R. Ellis, J. S. Hagelin, and D. V. Nanopoulos, “Supersymmetric Flipped SU(5) Revitalized,” Phys. Lett. B194, 231 (1987).
[26] J. Jiang, T. Li, and D. V. Nanopoulos, “Testable Flipped SU(5) $\times U(1)_X$ Models,” Nucl. Phys. B772, 49 (2007), hep-ph/0610054.
[27] J. Jiang, T. Li, D. V. Nanopoulos, and D. Xie, “F-SU(5),” Phys. Lett. B677, 322 (2009).
[28] J. Jiang, T. Li, D. V. Nanopoulos, and D. Xie, “Flipped SU(5) $\times U(1)_X$ Models from F-Theory,” Nucl. Phys. B830, 195 (2010), 0905.3394.
[29] T. Li, D. V. Nanopoulos, and J. W. Walker, “Elements of F-ast Proton Decay,” Nucl. Phys. B846, 43 (2011), 1003.2570.
[30] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “Dark Matter, Proton Decay and Other Phenomenological Constraints in F-SU(5),” Nucl.Phys. B848, 314 (2011), 1003.4186.
[31] E. Cremmer, S. Ferrara, C. Kounnas, and D. V. Nanopoulos, “Naturally Vanishing Cosmological Constant in $N = 1$ Supergravity,” Phys. Lett. B133, 61 (1983).
[32] J. R. Ellis, A. B. Lahanas, D. V. Nanopoulos, and K. Tamvakis, “No-Scale Supersymmetric Standard Model,” Phys. Lett. B134, 429 (1984).
[33] J. R. Ellis, C. Kounnas, and D. V. Nanopoulos, “Phenomenological SU(1, 1) Supergravity,” Nucl. Phys. B241, 406 (1984).
[34] J. R. Ellis, C. Kounnas, and D. V. Nanopoulos, “No Scale Supersymmetric Guts,” Nucl. Phys. B247, 373 (1984).
[35] A. B. Lahanas and D. V. Nanopoulos, “The Road to No Scale Supergravity,” Phys. Rept. 145, 1 (1987).
[36] D. V. Nanopoulos, “F-enomenology,” (2002), hep-ph/0211128.
[37] E. Witten, “Dimensional Reduction of Superstring Models,” Phys. Lett. B155, 151 (1985).
[38] T.-j. Li, J. L. Lopez, and D. V. Nanopoulos, “Compactifications of M theory and their phenomenological consequences,” Phys.Rev. D56, 2602 (1997), hep-ph/9704247.
[39] J. R. Ellis, D. V. Nanopoulos, and K. A. Olive, “Lower limits on soft supersymmetry breaking scalar masses,” Phys. Lett. B525, 308 (2002), arXiv:0109298.
[40] J. Ellis, A. Mustafayev, and K. A. Olive, “Resurrecting No-Scale Supergravity Phenomenology,” Eur. Phys. J. C69, 219 (2010), 1004.5399.
[41] Y. Okada, M. Yamaguchi, and T. Yanagida, “Upper bound of the lightest Higgs boson mass in the minimal supersymmetric standard model,” Prog.Theor.Phys. 85, 1 (1991).
[42] Y. Okada, M. Yamaguchi, and T. Yanagida, “Renormalization group analysis on the Higgs mass in the softly broken supersymmetric standard model,” Phys.Lett. B262, 54 (1991).
[43] H. E. Haber and R. Hempfling, “Can the mass of the lightest Higgs boson of the minimal supersymmetric model be larger than m(Z)?,” Phys.Rev.Lett. 66, 1815 (1991).
[44] J. R. Ellis, G. Ridolfi, and F. Zwirner, “Radiative corrections to the masses of supersymmetric Higgs bosons,” Phys.Lett. B257, 83 (1991).
[45] J. R. Ellis, G. Ridolfi, and F. Zwirner, “On radiative corrections to supersymmetric Higgs boson masses and their implications for LEP searches,” Phys.Lett. B262, 477 (1991).
[46] E. Komatsu et al. (WMAP), “Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation,” Astrophys.J.Suppl. 192, 18 (2010), 1001.4538.
[47] E. Aprile et al. (XENON100 Collaboration), “Dark Matter Results from 225 Live Days of XENON100 Data,” (2012), 1207.5988.