Physics Letters B 703 (2011) 469–474

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Super-No-Scale $\mathcal{F}$-$SU(5)$: A dynamic determination of $M_{1/2}$ and $\tan\beta$

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ARTICLE INFO

Article history:
Received 10 May 2011
Received in revised form 19 July 2011
Accepted 10 August 2011
Available online 16 August 2011
Editor: M. Cvetič

Keywords:
No-scale supergravity
$\mathcal{F}$-theory
Vector-like multiplets
Flipped $SU(5)$
Grand unification
Higgs potential
Gauge hierarchy

ABSTRACT

We study the Higgs potential in No-Scale $\mathcal{F}$-$SU(5)$, a model built on the tripodal foundations of the $\mathcal{F}$-lipped $SU(5)\times U(1)_X$ Grand Unified Theory, extra $\mathcal{F}$-theory derived TeV scale vector-like particle multiplets, and the high scale boundary conditions of no-scale supergravity. $V_{\min}$, the minimum of the potential following radiative electroweak symmetry breaking, is a function at fixed Z-boson mass of the universal gaugino boundary mass $M_{1/2}$ and $\tan\beta$, the ratio of Higgs vacuum expectation values. The so-scale nullification of the bilinear Higgs soft term B_μ at the boundary reduces $V_{\min}(M_{1/2})$ to a one-dimensional dependency, which may be secondarily minimized. This "Super-No-Scale" condition dynamically fixes $\tan\beta$ and $M_{1/2}$ at the local *minimum minimorum* of $V_{\min}$. Fantastically, the walls of this theoretically established secondary potential coalesce in descent to a striking concurrency with the previously phenomenologically favored "Golden Point" and "Golden Strip".

1. Introduction and background

We have recently demonstrated [1,2] the unique phenomenological consistency and profound predictive capacity of a model dubbed No-Scale $\mathcal{F}$-$SU(5)$, constructed from the merger of the $\mathcal{F}$-lipped $SU(5)$ Grand Unified Theory (GUT) [3–5], two pairs of hypothetical TeV scale vector-like supersymmetric multiplets with origins in $\mathcal{F}$-theory [6–10], and the dynamically established boundary conditions of no-scale supergravity [11–15]. It appears that the no-scale scenario, particularly vanishing of the Higgs bilinear soft term B_μ, comes into its own only when applied at an elevated scale, approaching the Planck mass [16]. $M_{\mathcal{F}}$, the point of the second stage $SU(5)\times U(1)_X$ unification, emerges in turn as a suitable candidate scale only when substantially decoupled from the primary GUT scale unification of $SU(3)_C\times SU(2)_L$ via the modification to the renormalization group equations (RGEs) from the extra $\mathcal{F}$-theory vector multiplets [1,2].

Taking a definition of $M_V=1$ TeV for the new vector-like fields as an elemental model feature, we showed [1] that the viable parameter space consistent with radiative electroweak symmetry breaking (EWSB), limits on the flavor changing neutral current $(b\to s\gamma)$ process and on contributions to the muon anomalous magnetic moment $(g-2)_\mu$, runs sufficiently perpendicular to both the $B_\mu(M_{\mathcal{F}})=0$ and centrally observed WMAP 7 cold dark matter (CDM) relic density contours that the non-trivial mutual intersection is a narrowly confined "Golden Point" with a universal gaugino boundary mass $M_{1/2}$ around 455 GeV, and a ratio $\tan\beta=15$ of Higgs vacuum expectation values (vevs). Insomuch as the collision of top-down model based constraints with bottom-up experimental data effectively absorbs the final dynamic degree of freedom, this was labeled a No-Parameter Model.

Advancing from the "Golden Point" to the "Golden Strip" [2], we relaxed the definition of the vector-like mass and studied the impact of fluctuating key electroweak reference data (α_s, M_Z) and the top quark mass m_t about the error margins. The most severe variation occurred for m_t, via its connection to the large Yukawa coupling essential to radiative EWSB. We recognized this dependence by effectively treating m_t as an additional input, selecting the appropriate value to restore a vanishing $B_\mu(M_{\mathcal{F}})$ at each point in the $(M_{1/2}, \tan\beta, M_V)$ volume. The $(g-2)_\mu$ and $(b\to s\gamma)$ constraints, both at their lower limits, were found to exert opposing pressures on $M_{1/2}$ due to operation of the former in alignment with, and the latter in counter-balance of, the Standard Model (SM) leading term. Cross cutting by the WMAP CDM

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doi:10.1016/j.physletb.2011.08.025

measurement completed demarcation of the strip, running diagonally from about $(M_{1/2}, M_{\mathrm{V}}) = (455, 1020)$ GeV, to $(481, 691)$ GeV, with $\tan\beta = 15$ independently enforced for the full space. With parameterization freedom exhausted, the model was finally required to make a correlated postdiction for the top quark mass. The result, $m_{\mathrm{t}} = 173.0$–174.4 GeV, is in fine accord with the measured value 173.1 ± 1.3 GeV [17]. The predicted range of M_{V} is testable at the LHC, and the partial lifetime for proton decay in the leading $(e|\mu)^+\pi^0$ channels is 4.6×10^{34} years, testable at the future Hyper-Kamiokande [18] and DUSEL [19] experiments.

2. The Super-No-Scale mechanism

In the present work we volunteer a small step backward to emphasize a giant leap forward. Having established practical bounds on the vector-like mass, we revert to a single conceptual universe, ostensibly our own or one of sufficient phenomenological proximity, with $M_{\mathrm{V}} = 1000$ GeV, and $m_{\mathrm{t}} = 173.1$ GeV. Minimization of the Higgs potential with respect to the neutral up-like and down-like Higgs components H_u and H_d imposes a pair of constraint equations which may be used to eliminate any two free parameters of the set $M_{1/2}, B_\mu$, $\tan\beta \equiv \langle H_u\rangle / \langle H_d\rangle$, and the supersymmetry (SUSY) preserving bilinear Higgs mass term μ. The overall magnitude of the Higgs vev $v \equiv \sqrt{\langle H_u\rangle^2 + \langle H_d\rangle^2} \simeq 174$ GeV is considered to be experimentally constrained by measurement of the gauge couplings and Z-boson mass. Typically, one will solve for $\mu(M_{\mathrm{Z}})$ and $B_\mu(M_{\mathrm{Z}})$ in terms of the constrained Higgs vevs and $\tan\beta$, at fixed $M_{1/2}$. We consider though that the no-scale boundary condition $B_\mu(M_{\mathcal{F}}) = 0$ fixes the value of B_μ at all other scales as well via action of the renormalization group. Restricting then to just the solution subset for which $B_\mu(M_{\mathrm{Z}})$ given by EWSB stitches cleanly onto that run down under the RGEs from $B_\mu(M_{\mathcal{F}}) = 0$, $\tan\beta$ (or alternatively μ) becomes an implicit function of the single modulus $M_{1/2}$. Concretely, we shall consider that the first EWSB constraint absolutely establishes μ, and that the second gives a line of parameterized solutions for the functional relationship between $M_{1/2}$ and $\tan\beta$. We therefore distinguish the residual freedom in the dynamic modulus $M_{1/2}$ and parameter $\tan\beta$ by the ability to exert direct influence on the Higgs potential within a single physical parameterization.

The crucial observation is that the minimization of the Higgs potential is therefore at this stage incomplete. In no-scale supergravity, the specific structure of the Kähler potential K leads to a contribution to the scalar potential which is zero and flat at tree level, so that the gravitino mass $M_{3/2}$, or by proportional equivalence $M_{1/2}$, is to be determined dynamically by radiative corrections. In order to finish specification of the physical vacuum, we must then *secondarily* minimize the Higgs potential with respect to the dependency on $M_{1/2}$, a dependency which is embodied in the bulk proportionality of the full low energy mass spectrum to this SUSY breaking parameter [12,15]. At this locally smallest value of $V_{\min}(M_{1/2})$, which we dub the *minimum minimorum*, the dynamic determination $M_{1/2}$ is established. Moreover, the implicit dependence of the parameter $\tan\beta$ on $M_{1/2}$ means that its value is also simultaneously provided by the system dynamics. Henceforth, the imposition of $dV_{\min}/dM_{1/2} = 0$ on the Higgs potential will be referred to as the "Super-No-Scale" condition.

We emphasize that the justification for this procedure traces back to the fact that the soft SUSY breaking mass $M_{1/2}$ is related to the F-term of a dynamic modulus. For example, in the weakly coupled heterotic $E_8 \times E_8$ string theory, or in M-theory on S^1/Z_2, $M_{1/2}$ is related to the F-term of a Kähler modulus T. In string models, there exists a fundamental question of how any such moduli are to be stabilized. Thus, the physical motivation of the Super-No-Scale condition is the stabilization of the F-term of the modulus. Again, for each $M_{1/2}$, we will have an electroweak symmetry breaking vacuum corresponding to minimization of the scalar Higgs potential. Among these minima, the *minimum minimorum* is the dynamically preferred locally smallest minimum of the Higgs potential.

We openly recognize that the potential affords an additional dimensionality along the degree of freedom which has been locked out by the fixing of v, and that minimization with respect to this additional parameter remains a question of interest. However, this is a delicate point of ongoing research, and beyond the scope of the current study. If one accepts, for the sake of argument, that the current model fairly represents the physics of our Universe, then current experimental measurements guarantee that the potential along this direction is indeed bounded, not running away from the adopted constant value of v. It is therefore only the secondary bounding along the degree of freedom associated with $M_{1/2}$ which is experimentally unknown to us, and which may be predicted according to model formulations such as the one here presented.

3. $\mathcal{F}$-*SU*(5) models

In the flipped $SU(5)$ GUTs, the gauge group is $SU(5) \times U(1)_X$, which embeds in $SO(10)$. Gauge coupling unification near 10^{16} GeV strongly suggests the existence of a Grand Unified Theory (GUT). In minimal SUSY $SU(5)$ models there are problems with doublet–triplet splitting and dimension five proton decay by colored Higgsino exchange [5]. These difficulties are elegantly overcome in Flipped $SU(5)$ GUT models via the missing partner mechanism [5]. The generator $U(1)_{Y'}$ is defined for fundamental five-plets as $-1/3$ for the triplet members, and $+1/2$ for the doublet. The hypercharge is given by $Q_Y = (Q_X - Q_{Y'})/5$. There are three families of Standard Model (SM) fermions, a pair of ten-plet Higgs for breaking the GUT symmetry, and a pair of five-plet Higgs for EWSB.

Historically, the first flipped F-theory $SU(5)$ GUT was constructed in Ref. [20], and further aspects of flipped $SU(5)$ F-theory GUTs have been considered in [21–23]. We introduce in addition, vector-like particle multiplets, derived likewise in the context of F-theory model building [6], to address the "little hierarchy" problem, altering the beta coefficients of the renormalization group to dynamically elevate the secondary $SU(5) \times U(1)_{\mathrm{X}}$ unification at $M_{\mathcal{F}}$ to near the Planck scale, while leaving the $SU(3)_C \times SU(2)_L$ unification at M_{32} close to the traditional GUT scale. In other words, one obtains true string-scale gauge coupling unification in free fermionic string models [6,24] or the decoupling scenario in F-theory models [7,8]. To avoid a Landau pole for the strong coupling constant, we are restricted around the TeV scale to one of the following two multiplet sets [6]:

$$\begin{aligned}
&\big(XF_{(\mathbf{10},\mathbf{1})} \equiv (XQ, XD^c, XN^c), \overline{XF}_{(\overline{\mathbf{10}},-\mathbf{1})}\big), \\
&\big(Xl_{(\mathbf{1},-\mathbf{5})}, \overline{Xl}_{(\mathbf{1},\mathbf{5})} \equiv XE^c\big). \qquad (1)
\end{aligned}$$

Prior, XQ, XD^c, XE^c, XN^c have the same quantum numbers as the quark doublet, right-handed down-type quark, charged lepton, and neutrino, respectively. We have argued [2] that the eminently feasible near-term detectability of these hypothetical fields in collider experiments, coupled with the distinctive flipped charge assignments of the multiplet structure, represents a smoking gun signature for flipped $SU(5)$, and have thus coined the term *flippons* to collectively describe them. Immediately, our curiosity is piqued by the announcement [25] of the DØ Collaboration that vector-like quarks have been excluded up to a bound of 693 GeV, corresponding to the lower edge of our golden strip. We here consider only the $Z2$ set, although discussion for the $Z1$ set, if supplemented by heavy threshold corrections, will be similar.