THE TESTABLE FLIPPED $SU(5) \times U(1)_X$ MODELS

Tianjun Li
Institute of Theoretical Physics, Chinese Academy of Sciences

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USTC, Hefei, May 20, 2011

I. INTRODUCTION

The Standard Model (SM) is a model that describes the elementary particles in the nature and the fundamental interactions between them.

Fundamental Interactions

Interactions	Invariant	Symmetry	Fields	Spin
Gravity	Diffeomorphism		Graviton	2
Strong	Gauge	$SU(3)_C$	Gluon	1
Weak	Gauge	$SU(2)_L$	$W^{\pm}, W^0$	1
Hypercharge	Gauge	$U(1)_Y$	B^0	1

Properties for the theories:

Gauge theory is renormalizable, and described by quantum field theory which is consistent with both quantum mechanics and special relativity. However, gravity theory is non-renormalizable, and we do not have a correct quantum gravity theory.

Elementary Particles

- Three families of SM fermions:

$$\textbf{Quarks}: \quad Q_1 = \begin{pmatrix} U & U & U \\ D & D & D \end{pmatrix}_{\mathrm{L}}, \quad (U \;\; U \;\; U)_R\,, \quad (D \;\; D \;\; D)_R\,.$$

$$\textbf{Leptons}: \quad L_1 = \begin{pmatrix} \nu \\ E \end{pmatrix}_{\mathrm{L}}, \quad E_R\,.$$

- One Higgs doublet

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}.$$

$$
\begin{aligned}
\mathcal{L}_{MSM} = &-\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
&-\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
&+|D_\mu H|^2 + \bar{Q}_i i\not{D}Q_i + \bar{U}_i i\not{D}U_i + \bar{D}_i i\not{D}D_i \\
&+\bar{L}_i i\not{D}L_i + \bar{E}_i i\not{D}E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
&-\left(h_u^{ij}Q_iU_j\tilde{H} + h_d^{ij}Q_iD_jH + h_l^{ij}L_iE_jH + c.c.\right) \;,
\end{aligned}
$$

where $\tilde{H} \equiv i\sigma_2 H^*$.

The SM has 20 parameters (19 without gravity).

The Higgs potential is

$$V_{\text{Higgs}} = \frac{\lambda}{2}\left(H^{\dagger}H - \frac{v^{2}}{2}\right)^{2} ,$$

At minimum, Higgs field has a non-zero VEV

$$\langle H^{0}\rangle = \frac{v}{\sqrt{2}} .$$

All the gauge symmetries, under which H^{0} is charged, are broken after Higgs mechanism.

Symmetry Breaking

- $SU(2)_L \times U(1)_Y$ is broken down to the $U(1)_{\rm em}$ symmetry.
- $W^\pm$ and Z^0 become massive, and γ is massless

$$Z^0 \; = \; \cos\theta_W W^0 - \sin\theta_W B^0 \; , \quad \gamma \; = \; \sin\theta_W W^0 + \cos\theta_W B^0 \; .$$

- The SM quarks and leptons obtain masses via Yukawa couplings, except the neutrinos.
- Unknown: Higgs boson and its mass.

The SM explains existing experimental data very well, including electroweak precision tests.

Standard Model:

- Fine-tuning problems: cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...
- Aesthetic problems: interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters; ...

Supersymmetric Standard Model:

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking

  Large top quark mass
- Natural dark matter candidates

  Neutralino, sneutrino, gravitino, ...
- Electroweak baryogenesis
- Electroweak precision: R parity

Problems in the MSSM:

- μ problem

  $\mu H_u H_d$

- Little hierarchy problem:

  Fine-tuning for the lightest CP even Higgs mass

- CP violation and EDMs

- FCNC

- Dimension-5 proton decays

The Grand Unified Theories: $SU(5)$, and $SO(10)$, etc.

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa unification $y_t = y_b = y_\tau$
- Radiative electroweak symmetry breaking due to the large top quark Yukawa coupling
- Weak mixing angle at weak scale M_Z
- Neutrino masses and mixings by seesaw mechanism

Problems:

- Gauge symmetry breaking
- Doublet-triplet splitting problem

  Higgs particles do not form complete GUT multiplet at low energy
- Proton decay problem
- Fermion mass problem

  GUT relation $m_e/m_\mu = m_d/m_s$

String Models:

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory

  Grand Unified Theory (GUT) can be realized naturally through the elegant E_8 breaking chain: $E_8 \supset E_6 \supset SO(10) \supset SU(5)$
- D-brane models on Type II orientifolds

  N stacks of D-branes gives us $U(N)$ gauge symmetry: Pati-Salam Models
- Free fermionic string model builing

  Realistic models with clean particle spectra can only be constructed at the Kac-Moody level one: the Standard-like models, Pati-Salam models, and flipped $SU(5)$ models.

$\mathcal{F}$-Theory Model Building

- The models are constructed locally, and then the gravity should decoupled, *i.e.*, $M_{\rm GUT}/M_{\rm Pl}$ is a small number.
- The $SU(5)$ and $SO(10)$ gauge symmetries can be broken by the $U(1)_Y$ and $U(1)_X$/$U(1)_{B-L}$ fluxes.
- Gauge mediated supersymmetry breaking can be realized via instanton effects. Gravity mediated supersymmetry breaking predicts the gaugino mass relation.
- All the SM fermion Yuakwa couplings can be generated in the $SU(5)$ and $SO(10)$ models.
- The doublet-triplet splitting problem, proton decay problem, μ problem as well as the SM fermion masses and mixing problem can be solved.

String Phenomenology:

- String models can solve the problems in GUTs naturally.
- Realistic string models with moduli stabilization.
- Unique predictions: testable at the LHC, ILC and other experiments.

Flipped $SU(5) \times U(1)_X$ Models: [a]

- Doublet-triplet splitting via missing partner mechanism [b].
- No dimension-five proton decay problem.
- Little hierarchy problem in string models: $M_{\rm String} \sim 20 \times M_{\rm GUT}$

$$M_{\rm String} \;=\; g_{\rm String} \times 5.27 \times 10^{17}\ {\rm GeV}\ .$$

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[a] S. M. Barr, Phys. Lett. B **112**, 219 (1982); J. P. Derendinger, J. E. Kim and D. V. Nanopoulos, Phys. Lett. B **139**, 170 (1984).

[b] I. Antoniadis, J. R. Ellis, J. S. Hagelin and D. V. Nanopoulos, Phys. Lett. B **194**, 231 (1987).

- Testable flipped $SU(5) \times U(1)_X$ models: TeV-scale vector-like particles [a]
- Free-fermionic string construction [b]
- F-theory model building [c]

$\mathcal{F}$-$SU(5)$ **Models**:

Orbifold GUTs [d]; Heterotic String Constructions [e]; ...

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[a] J. Jiang, T. Li and D. V. Nanopoulos, Nucl. Phys. B **772**, 49 (2007).

[b] J. L. Lopez, D. V. Nanopoulos and K. j. Yuan, Nucl. Phys. B **399**, 654 (1993).

[c] C. Beasley, J. J. Heckman and C. Vafa, JHEP **0901**, 059 (2009); J. Jiang, T. Li, D. V. Nanopoulos and D. Xie, Phys. Lett. B **677**, 322 (2009); Nucl. Phys. B **830**, 195 (2010).

[d] S. M. Barr and I. Dorsner, Phys. Rev. D **66**, 065013 (2002)

[e] A. E. Faraggi, R. S. Garavuso and J. M. Isidro, Nucl. Phys. B **641**, 111 (2002).

II. $\mathcal{F}$-$SU(5)$ MODELS

- The gauge group $SU(5) \times U(1)_X$ can be embedded into $SO(10)$ model.

- Generator $U(1)_{Y'}$ in $SU(5)$

$$T_{\mathrm{U(1)_{Y'}}} = \mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right) \ .$$

- Hypercharge

$$Q_Y = \frac{1}{5}\left(Q_X - Q_{Y'}\right) \ .$$

- SM fermions

$$F_i = (\mathbf{10},\mathbf{1}),\ \bar{f}_i = (\bar{\mathbf{5}},-\mathbf{3}),\ \bar{l}_i = (\mathbf{1},\mathbf{5})\ ,$$

$$F_i = (Q_i, D^c_i, N^c_i),\ \overline{f}_i = (U^c_i, L_i),\ \overline{l}_i = E^c_i\ .$$

- Higgs particles:

$$H = (\mathbf{10},\mathbf{1}),\ \overline{H} = (\overline{\mathbf{10}},-\mathbf{1}),\ h = (\mathbf{5},-\mathbf{2}),\ \overline{h} = (\bar{\mathbf{5}},\mathbf{2})\ ,$$

$$H = (Q_H, D^c_H, N^c_H)\ ,\ \overline{H} = (\overline{Q}_{\overline{H}}, \overline{D}^c_{\overline{H}}, \overline{N}^c_{\overline{H}})\ ,$$

$$h = (D_h, D_h, D_h, H_d)\ ,\ \overline{h} = (\overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, H_u)\ .$$

Symmetry Breaking:

- Superpotential

$$W_{\rm GUT} = \lambda_1 H H h + \lambda_2 \overline{H H h} + \Phi(\overline{H} H - M_{\rm H}^2) ~.$$

- There is only one F-flat and D-flat direction along the N^c_H and $\overline{N^c_{\overline{H}}}$ directions: $< N^c_H >=< \overline{N^c_{\overline{H}}} >= M_{\rm H}$.

- The doublet-triplet splitting due to the missing partner mechanism

  The superfields H and $\overline{H}$ are eaten and acquire large masses via the supersymmetric Higgs mechanism, except for D^c_H and $\overline{D^c_{\overline{H}}}$. And the superpotential $\lambda_1 H H h$ and $\lambda_2 \overline{H H h}$ couple the D^c_H and $\overline{D^c_{\overline{H}}}$ with the D_h and $\overline{D}_{\overline{h}}$, respectively, to form the massive eigenstates with masses $2\lambda_1 < N^c_H >$ and $2\lambda_2 < \overline{N^c_{\overline{H}}} >$.

- No dimension-5 proton decay problem.

  Because the triplets in h and $\overline{h}$ only have small mixing through the μ term, the Higgsino-exchange mediated proton decay are negligible.

$\mathcal{F}$-$SU(5)$ Models:

- To achieve the string scale gauge coupling unification, we introduce sets of vector-like particles in complete $SU(5) \times U(1)_X$ multiplets, whose contributions to the one-loop beta functions of the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ gauge symmetries, Δb_1, Δb_2 and Δb_3 respectively, satisfy $\Delta b_1 < \Delta b_2 = \Delta b_3$.
- To avoid the Landau pole problem for the gauge couplings, we can only introduce the following two sets of vector-like particles around the TeV scale, which could be observed at the LHC

$$Z1 : XF = (\mathbf{10}, \mathbf{1}) \ , \ \overline{XF} = (\overline{\mathbf{10}}, \mathbf{-1}) \ ;$$
$$Z2 : XF \ , \ \overline{XF} \ , \ Xl = (\mathbf{1}, \mathbf{-5}) \ , \ \overline{Xl} = (\mathbf{1}, \mathbf{5}) \ .$$

- We define the flipped $SU(5) \times U(1)_X$ models with $Z1$ and $Z2$ sets of vector-like particles as Type I and Type II models, respectively.

Models	M_V	M_S	M_{23}	$g_{\rm U}$	$M_{\rm U}$
Type II	200	360	1.21×10^{16}	1.289	6.79×10^{17}
Type II	200	1000	1.25×10^{16}	1.194	6.29×10^{17}
Type II	1000	360	1.13×10^{16}	1.207	1.20×10^{18}
Type II	1000	1000	1.18×10^{16}	1.143	9.33×10^{17}
Type II	2.0×10^4	800	1.15×10^{16}	1.051	5.54×10^{17}

Table 1: Mass scales in GeV unit and gauge couplings in the $\mathcal{F}$-$SU(5)$ models for gauge coupling unification.

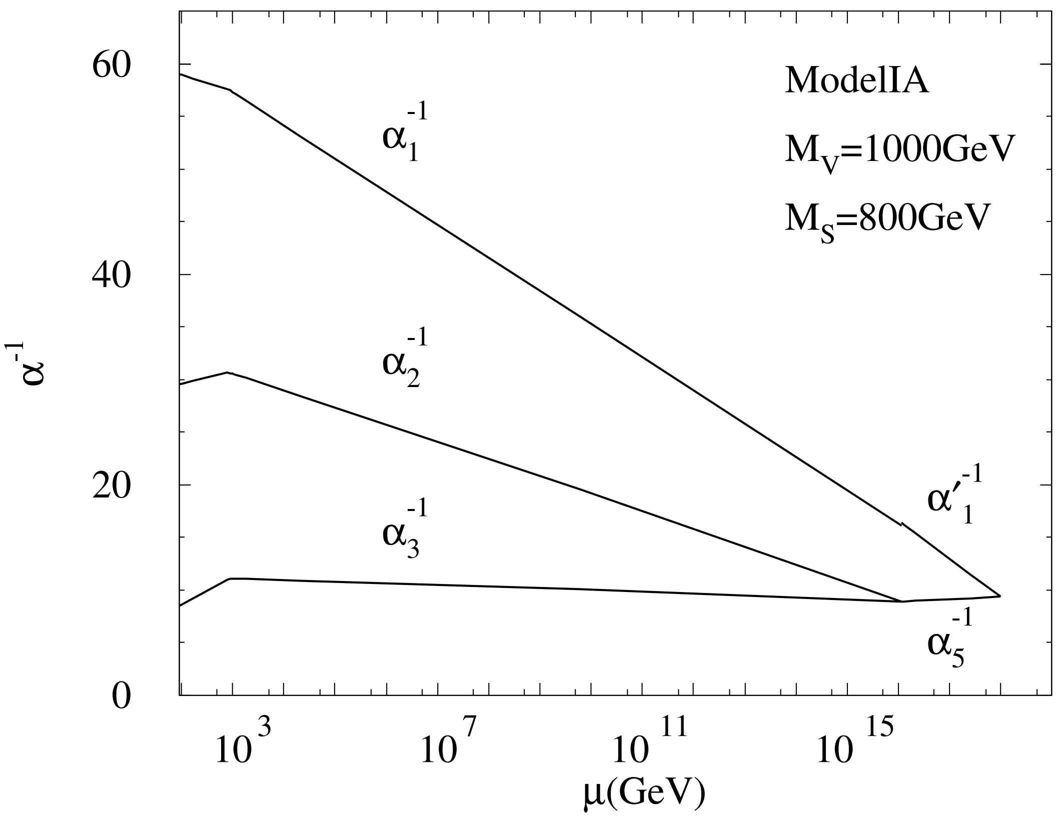

Figure 1: Gauge coupling unification in the Type II model.

III. $\mathcal{F}$-AST PROTON DECAY

Proton decay experiments:

- Super-Kamiokande, a 50-kiloton (kt) water Cherenkov detector, has set the current lower bounds of 8.2×10^{33} and 6.6×10^{33} years at the 90% confidence level for the partial lifetimes in the $p \longrightarrow e^{+}\pi^{0}$ and $p \longrightarrow \mu^{+}\pi^{0}$ modes.
- Hyper-Kamiokande is a proposed 1-Megaton detector, about 20 times larger volumetrically than Super-Kamiokande, which we can expect to explore partial lifetimes up to a level near 2×10^{35} years for $p \longrightarrow e^{+}\pi^{0}$ across a decade long run.

- The proposal for the DUSEL experiment features both 500 kt water Cherenkov and 100 kt liquid Argon detectors, with the stated goal of probing partial lifetimes into the order of 10^{35} years for both the $p \to e^+\pi^0$ and $p \to K^+\bar{\nu}_\mu$ channels.
- LAGUNA is a European collaboration which is considering three possible technologies; water Cherenkov, liquid argon or liquid scintillators. These detectors, if built, have similar goals to any DUSEL detector, *i.e.*, to reach a lifetime sensitivity of 10^{35} years.

Proton decay in flipped $SU(5) \times U(1)$:

- After integrating out the heavy gauge boson fields, we obtain the effective dimension-six operator for proton decay

$$\mathcal{L} \ = \ \frac{g_{23}^2 \epsilon^{ijk}}{2M_{32}^2} \left[((\bar{d}_k^c \cos\theta_c + \bar{s}_k^c \sin\theta_c)\gamma^\mu P_L u_j) \times (u_i \gamma_\mu P_L e_L) + h.c. \right] \ .$$

- The decay amplitude is proportional to the overall normalization of the proton wave function at the origin. Relevant matrix elements have been calculated in a lattice approach with quoted errors below 10%, corresponding to an uncertainty of less than 20% in the proton partial lifetime. Thus, this uncertainty is negligible.

- Proton lifetime is sensitive to M_{23} and g_{23}

$$\tau(p \to e^+\pi^0) \ \sim \ \left(\frac{M_{23}}{g_{23}} \right)^4 \ .$$

Proton decay: [a]

- We consider two-loop RGE running for gauge couplings and one-loop RGE running for top and bottom Yukawa couplings.
- For the light M_Z-scale threshold corrections from the supersymmetric particles, we consider the CMSSM benchmark scenarios, which respect all the available experimental constraints.
- For the M_{23} scale threshold corrections from the triplet Higgs fields and heavy gauge fields of $SU(5)$, from naturalness we assume

$$\frac{\sqrt{\lambda_1 \lambda_2}}{3} \leq g_{23} \leq 3\sqrt{\lambda_1 \lambda_2}\ .$$

- Because XF and $\overline{XF}$ form complete $SU(5) \times U(1)_X$ multiplets and Xl and $\overline{Xl}$ are $SU(5)$ singlets, we can assume degeneracy of these vector-like particles' masses at a central value of 1 TeV.

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[a] T. Li, D. V. Nanopoulos and J. W. Walker, arXiv:0910.0860 [hep-ph]; arXiv:1003.2570 [hep-ph].

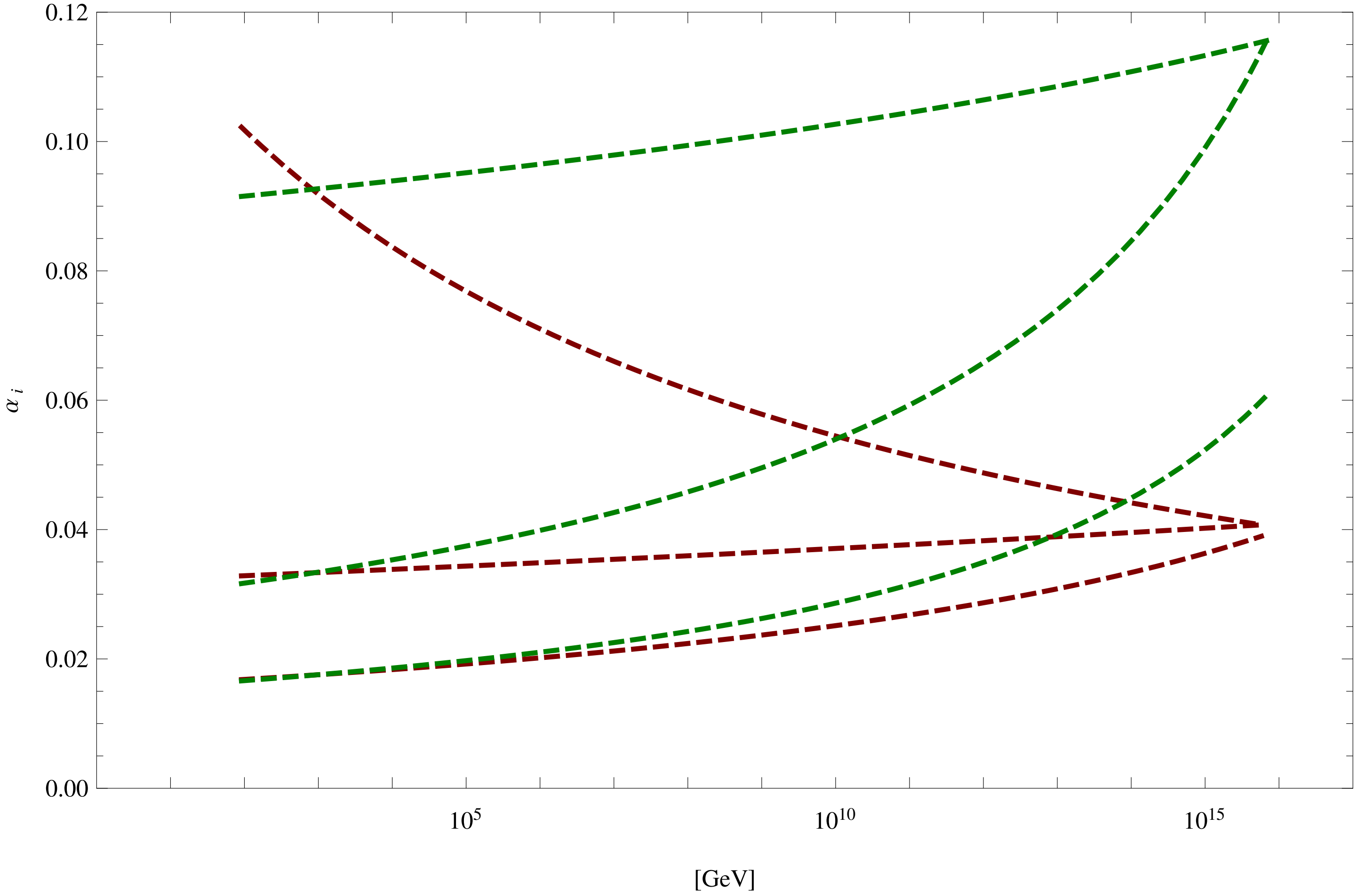

Figure 2: Gauge coupling unification in the minimal (red dashed lines) and Type II (green dashed lines) flipped $SU(5) \times U(1)_X$ models for benchmark scenario B'.

Model	g_1	g_{23}	M_{23} (GeV)	τ_p (Years)
Minimal	0.70	0.72	5.8×10^{15}	4.3×10^{34}
Type I	0.75	1.21	6.8×10^{15}	1.0×10^{34}
Type II	0.87	1.20	6.8×10^{15}	1.0×10^{34}

Table 2: Proton decay for benchmark scenario B'.

The central prediction of the proton partial lifetime for the minimal, Type I and Type II models is well below 10^{35} years, within the reach of the future Hyper-Kamiokande and DUSEL experiments. However, the uncertainty from heavy threshold corrections ever threatens to undo this promising result.

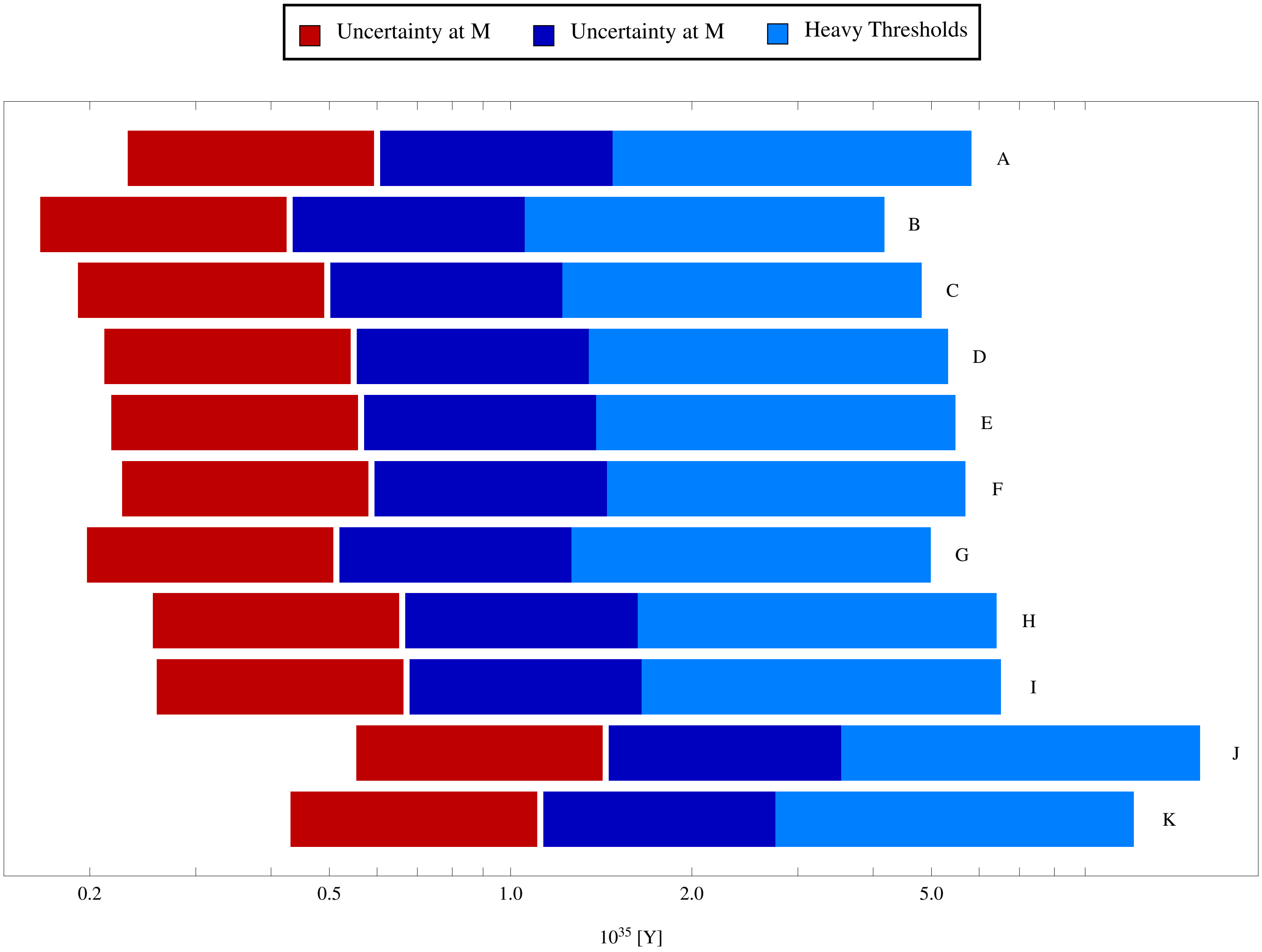

Figure 3: Including uncertainties from threshold corrections at the M_Z and M_{23} scales, the proton partial lifetime in the minimal flipped $SU(5) \times U(1)_X$ model.

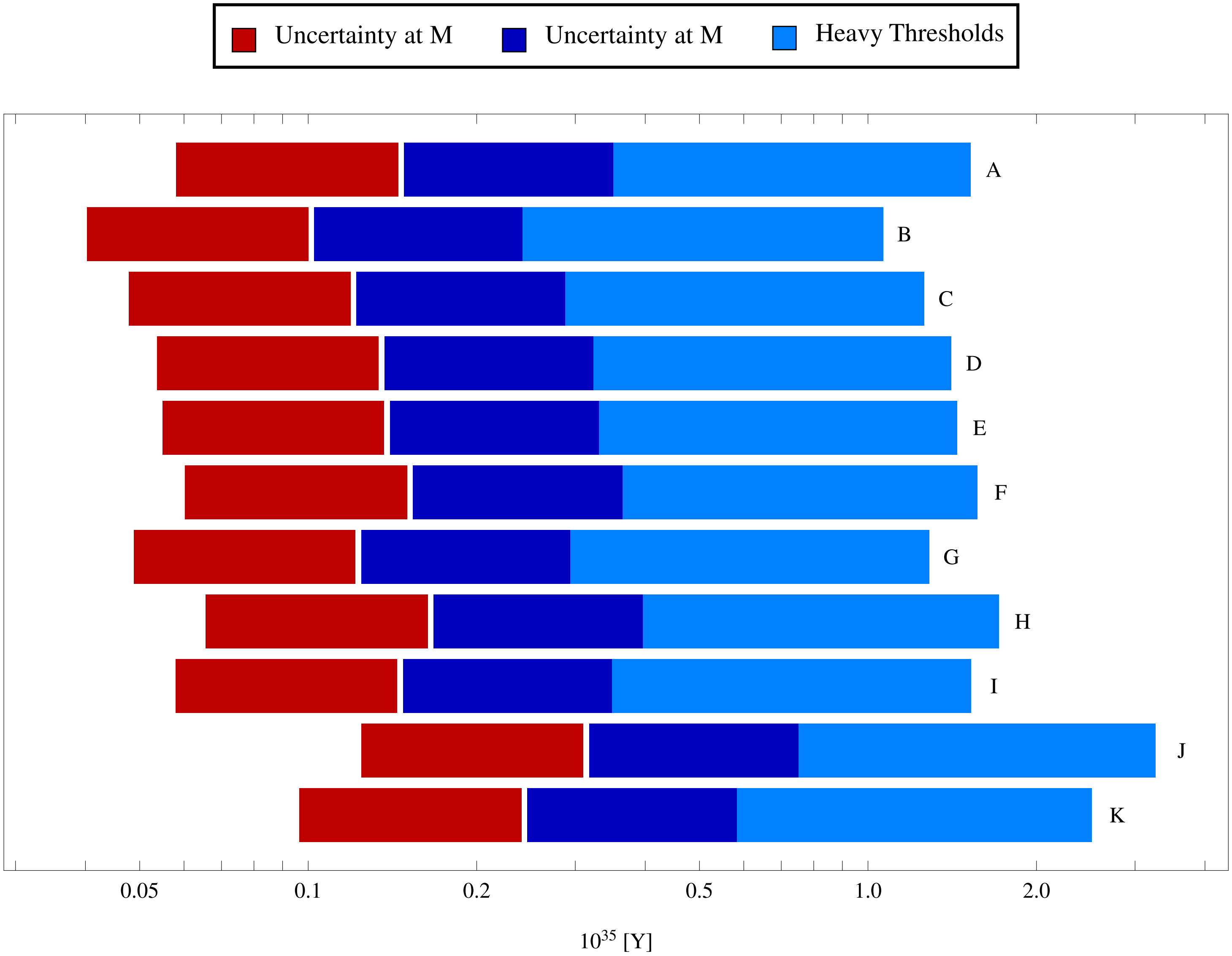

Figure 4: Including uncertainties from threshold corrections at the M_Z and M_{23} scales, the proton partial lifetime in the Type II flipped $SU(5) \times U(1)_X$ model.

Summary on Proton Decay:

- In the minimal model, the central partial lifetime is in the range of $4 - 7 \times 10^{34}$ years for benchmark scenarios from A' to I', and about $1 - 2 \times 10^{35}$ years for benchmark scenarios J' and K'. However, the uncertainties from the heavy threshold corrections at M_{23} are indeed quite large. Proton decay appears to be within the reach of the future Hyper-Kamiokande, DUSEL, and LAGUNA experiments if the heavy threshold corrections are more modest.

- For Type II flipped $SU(5) \times U(1)_X$ model, the central values for the partial lifetime are about $1 - 2 \times 10^{34}$ years for benchmark scenarios from A' to I', and about $2 - 3 \times 10^{34}$ years for benchmark scenarios J' and K'. Even including uncertainties from the light and heavy threshold corrections, the lifetime is still less than $2 - 3 \times 10^{35}$ years for all scenarios considered. A strong majority of the parameter space for proton decay does indeed appear to be within the reach of the future Hyper-Kamiokande and DUSEL experiments for the Type II flipped $SU(5) \times U(1)_X$ model. This basic conclusion holds also for the Type I flipped $SU(5) \times U(1)_X$ model.

IV. NO-SCALE $\mathcal{F}$-$SU(5)$

No-Scale Supergravity: [a]

- The vacuum energy vanishes automatically due to the suitable Kähler potential;
- At the minimum of the scalar potential, there are flat directions which leave the gravitino mass $M_{3/2}$ undertermined;
- The super-trace quantity $\mathrm{Str}\mathcal{M}^2$ is zero at the minimum.

$$K = -3\ln(T + \overline{T} - \sum_i \overline{\Phi}_i \Phi_i) \ .$$

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[a] E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, Phys. Lett. B **133**, 61 (1983); A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. **145**, 1 (1987).

No-Scale Supergravity:

- mSUGRA: $M_{1/2}$, M_0, A, $\tan\beta$
- No-Scale boundary condition: $M_{1/2} \neq 0$, $M_0 = A = B_\mu = 0$
- Natural solution to CP violation and FCNC problem.
- Disfavored by phenomenology: $M_0 = 0$ at traditional GUT scale
- No-scale $\mathcal{F}$-$SU(5)$

No-scale supergravity can be realized in the compactification of the weakly coupled heterotic string theory [a] and the compactification of M-theory on S^1/Z_2 at the leading order [b].

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[a] E. Witten, Phys. Lett. B **155**, 151 (1985).

[b] T. Li, J. L. Lopez and D. V. Nanopoulos, Phys. Rev. D **56**, 2602 (1997).

Constraints:

- The WMAP 2σ measurements of the cold dark matter density: $0.1088 \leq \Omega_\chi \leq 0.1158$.
- The experimental limits on the Flavor Changing Neutral Current (FCNC) process for $b \rightarrow s\gamma$: $2.86 \times 10^{-4} \leq Br(b \rightarrow s\gamma) \leq 4.18 \times 10^{-4}$.
- The anomalous magnetic moment of the muon, $g_\mu - 2$: $11 \times 10^{-10} < a_\mu < 44 \times 10^{-10}$.
- The process $B_s^0 \rightarrow \mu^+\mu^-$: $Br(B_s^0 \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8}$.
- The LEP limit on the lightest CP-even Higgs boson mass $m_h \geq 114$ GeV.

No-Scale $\mathcal{F}$-$SU(5)$: [a]

- $M_0 = A = B_\mu = 0$, $\tan\beta$ is a function of $M_{1/2}$ and μ.
- Choosing $\tan\beta$ (equivalent to μ) and $M_{1/2}$ as free parameters, we determine the no-scale parameter space by requiring that $B_\mu = 0$.
- Taking $M_V = 1$ TeV, the $B_\mu(M_{\mathcal{F}}) = 0$ contour runs sufficiently perpendicular to the WMAP strip, which gives the observed dark matter density.

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[a] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1007.5100 [hep-ph].

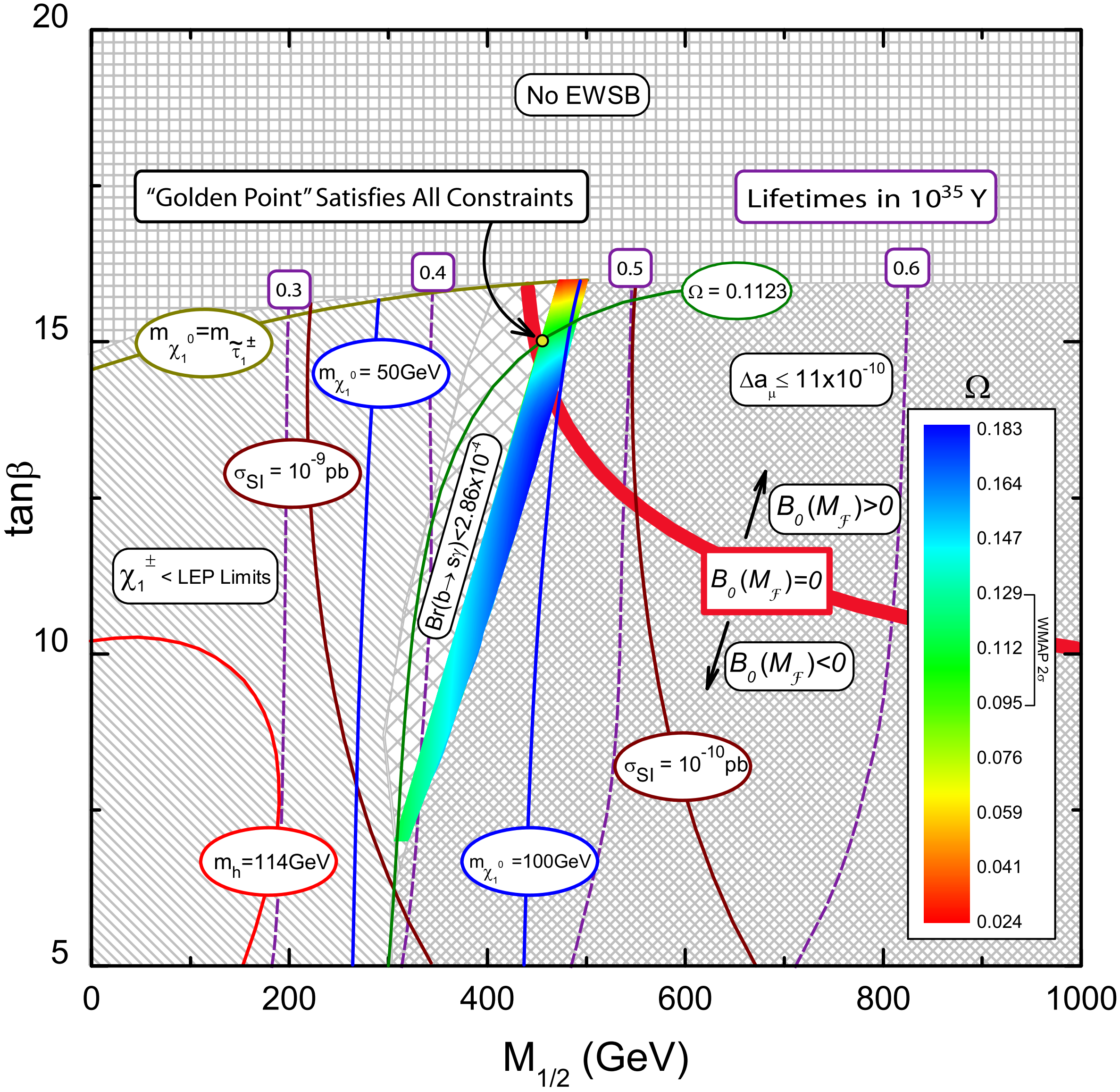

Figure 5: Viable parameter space in the $\tan\beta - M_{1/2}$ plane.

No-Scale $\mathcal{F}$-$SU(5)$: [a]

- To realize radiative EWSB and match the observed CDM density, $\tan\beta \simeq 15$ (equivalent to fix μ).
- B_μ at M_Z is very sensitive to m_t, but not sensitive to α_3 and M_Z.
- We choose $M_{1/2}$, M_V, m_t as free parameters and require that $B_\mu = 0$ at the GUT scale.

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[a] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1009.2981 [hep-ph].

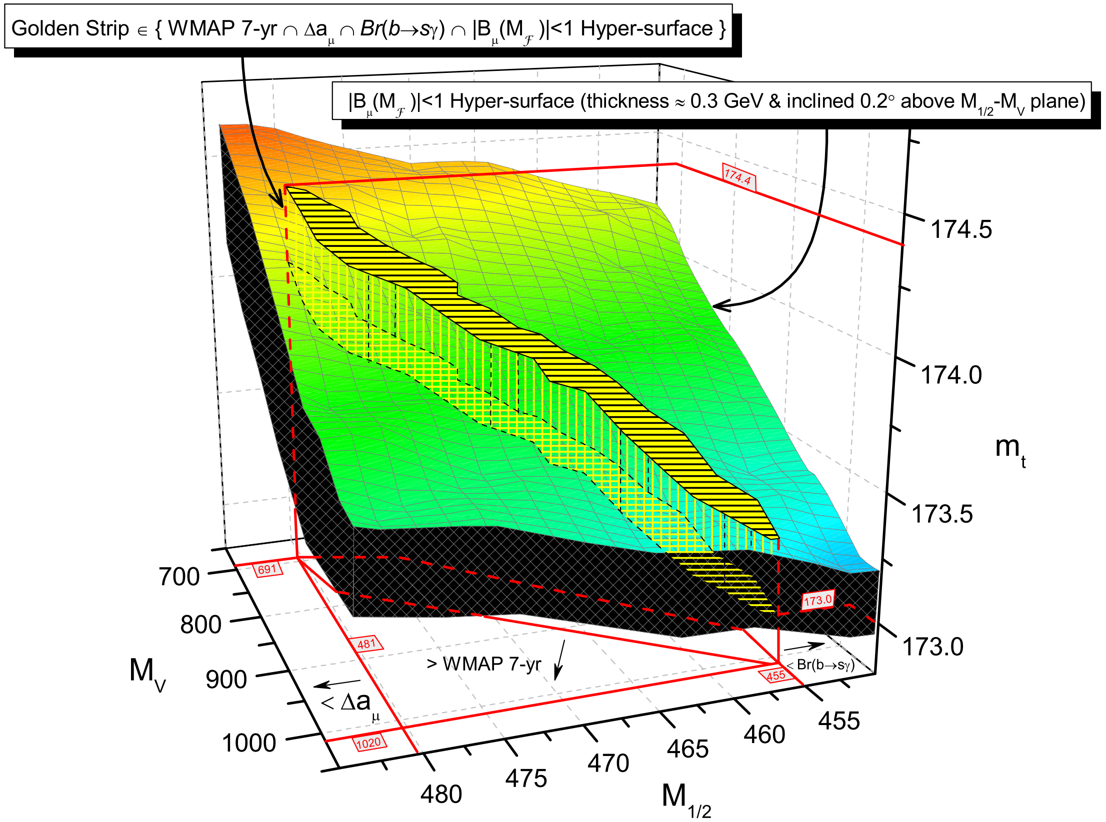

Figure 6: With $\tan\beta \simeq 15$ fixed by WMAP-7, the residual parameter volume is three dimensional in $(M_{12}, M_{\rm V}, m_{\rm t})$, with the $|B_\mu(M_{\mathcal{F}})| \leq 1$ (slightly thickened) surface forming a shallow (0.2°) incline above the $(M_{12}, M_{\rm V})$ plane.

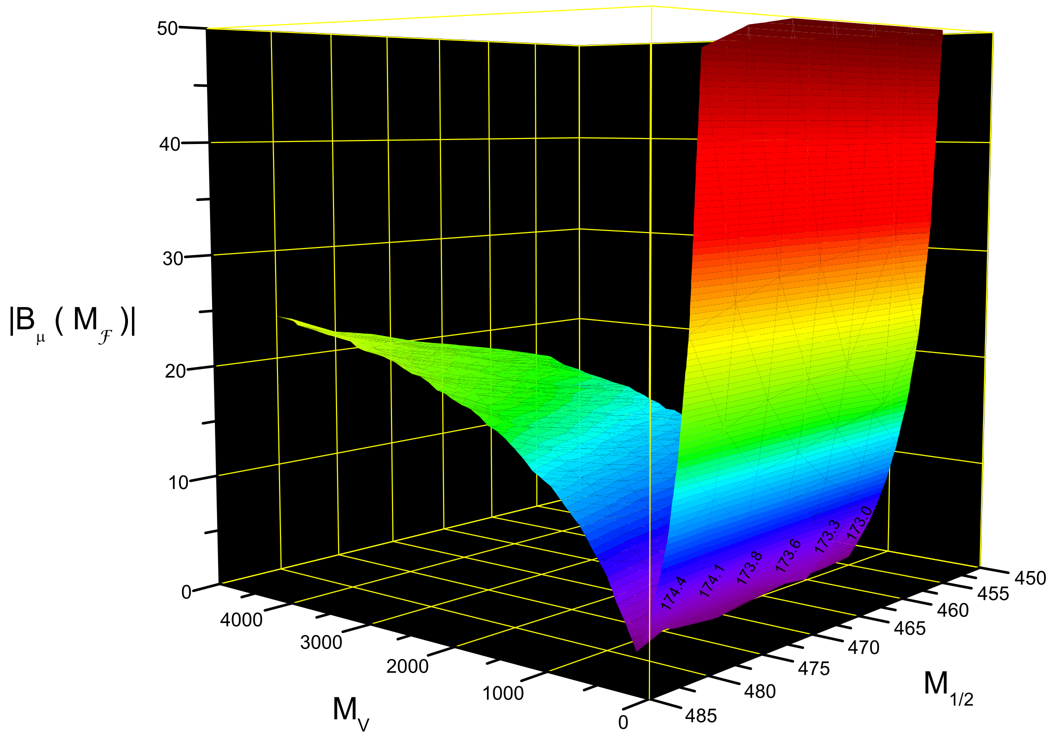

Figure 7: The $B_\mu = 0$ target for variations in $(M_{1/2}, M_{\rm V})$, with $\tan\beta = 15$. The specific $m_{\rm t}$ which is required to minimize $|B_\mu(M_{\mathcal{F}})|$ is annotated along the solution string.

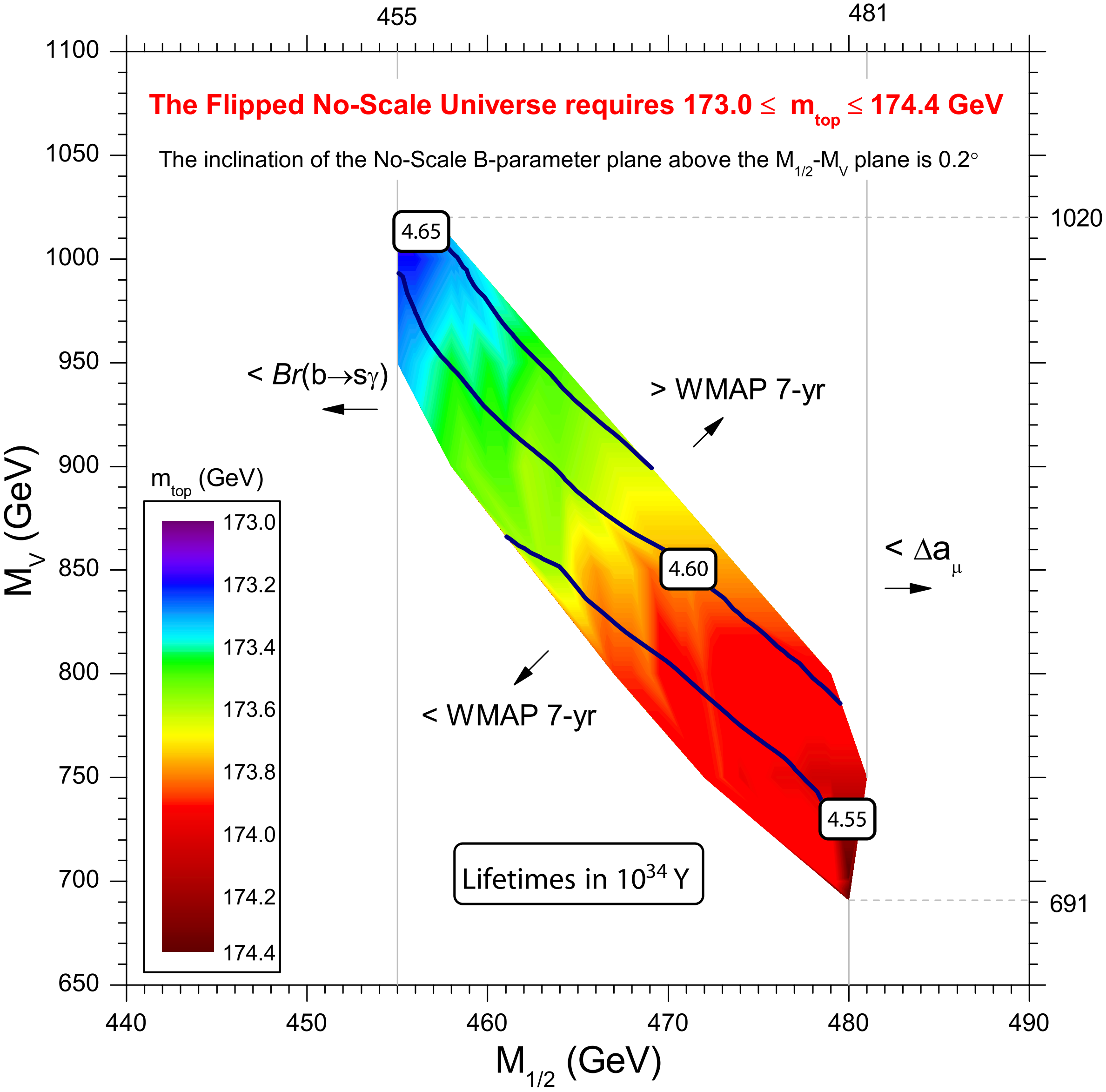

Figure 8: With $\tan\beta \simeq 15$ fixed by WMAP-7, the residual parameter volume is three dimensional in $(M_{12}, M_{\rm V}, m_{\rm t})$, with the $|B_\mu(M_{\mathcal{F}})| \leq 1$ (slightly thickened).

Results:

- A highly non-trivial "golden strip" with $\tan\beta \simeq 15$, $m_{\rm t} = 173.0\text{-}174.4$ GeV, $M_{1/2} = 455\text{-}481$ GeV, and $M_{\rm V} = 691\text{-}1020$ GeV.
- Postdicting the correct top quark mass.
- The predicted range of $M_{\rm V}$ is testable at the LHC.
- The partial lifetime for proton decay in the leading $(e|\mu)^+\pi^0$ channels falls around 4.6×10^{34} Y.
- $B_\mu = 0$ constraint is highly non-trivial.

- The golden strip is further consistent with the CDMSII and Xenon100 upper limits, with the spin-independent cross section extending from $\sigma_{SI} = 1.3\text{-}1.9 \times 10^{-10}$ pb. Likewise, the allowed region satisfies the Fermi-LAT space telescope constraints with the photon-photon annihilation cross section $\langle \sigma v \rangle_{\gamma\gamma}$ ranging from $\langle \sigma v \rangle_{\gamma\gamma} = 1.5\text{-}1.7 \times 10^{-28}\ cm^3/s$.

Benchmark Point:

Table 3: Spectrum (in GeV) for the benchmark point. Here, $M_{1/2}$ = 464 GeV, M_V = 850 GeV, m_t = 173.6 GeV, Ω_χ = 0.112, $\sigma_{SI} = 1.7 \times 10^{-10}$ pb, and $\langle \sigma v \rangle_{\gamma\gamma} = 1.7 \times 10^{-28}\ cm^3/s$. The central prediction for the $p \rightarrow (e|\mu)^+ \pi^0$ proton lifetime is 4.6×10^{34} years. The lightest neutralino is 99.8% Bino.

$\widetilde{\chi}_1^0$	96	$\widetilde{\chi}_1^\pm$	187	$\widetilde{e}_R$	153	$\widetilde{t}_1$	499	$\widetilde{u}_R$	975	m_h	120.6
$\widetilde{\chi}_2^0$	187	$\widetilde{\chi}_2^\pm$	849	$\widetilde{e}_L$	519	$\widetilde{t}_2$	929	$\widetilde{u}_L$	1062	$m_{A,H}$	946
$\widetilde{\chi}_3^0$	845	$\widetilde{\nu}_{e/\mu}$	513	$\widetilde{\tau}_1$	105	$\widetilde{b}_1$	880	$\widetilde{d}_R$	1018	$m_{H^\pm}$	948
$\widetilde{\chi}_4^0$	848	$\widetilde{\nu}_\tau$	506	$\widetilde{\tau}_2$	514	$\widetilde{b}_2$	992	$\widetilde{d}_L$	1065	$\widetilde{g}$	629

Super-No-Scale $\mathcal{F}$-$SU(5)$:

- $M_{1/2}$ as a modulus parameter.
- Fixing M_V, m_t, and μ at $M_{\mathcal{F}}$, for a particular $M_{1/2}$, we can determine an EWSB vacuum with potential V_{min}.
- Super-No-Scale Condition: *minimum minimorum*, $dV_{\text{min}}/dM_{1/2} = 0$
- Moduli Stabilization and Complete Solution to the Gauge Hiearchy Problem

Super-No-Scale $\mathcal{F}$-$SU(5)$:

- Fixing M_Z: [a]
- Fixing M_V, m_t, and μ at M_U: M_{32} [b]

Dynamically Determination of $M_{1/2}$ and the electroweak scale in the Golden Strip.

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[a] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1010.4550 [hep-ph].

[b] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1101.2197 [hep-ph].

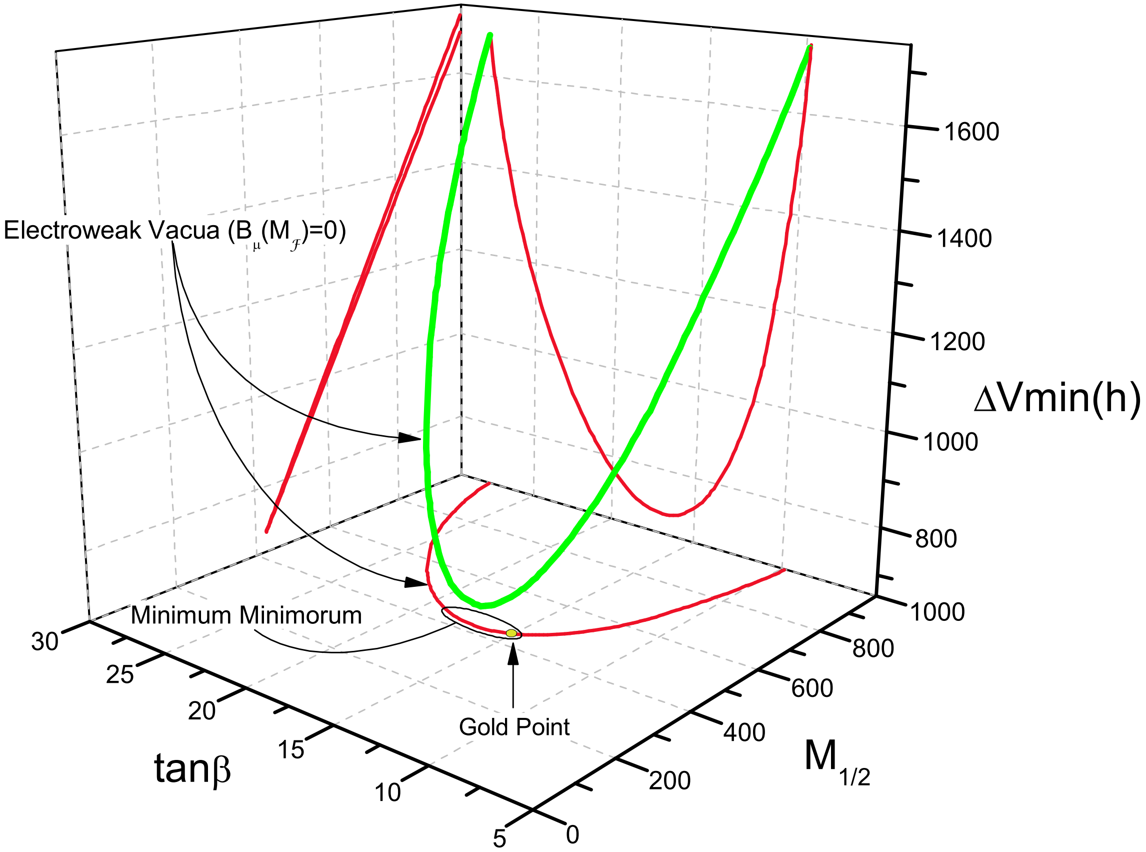

Figure 9: Dynamical determination of $M_{1/2}$: fixing M_Z.

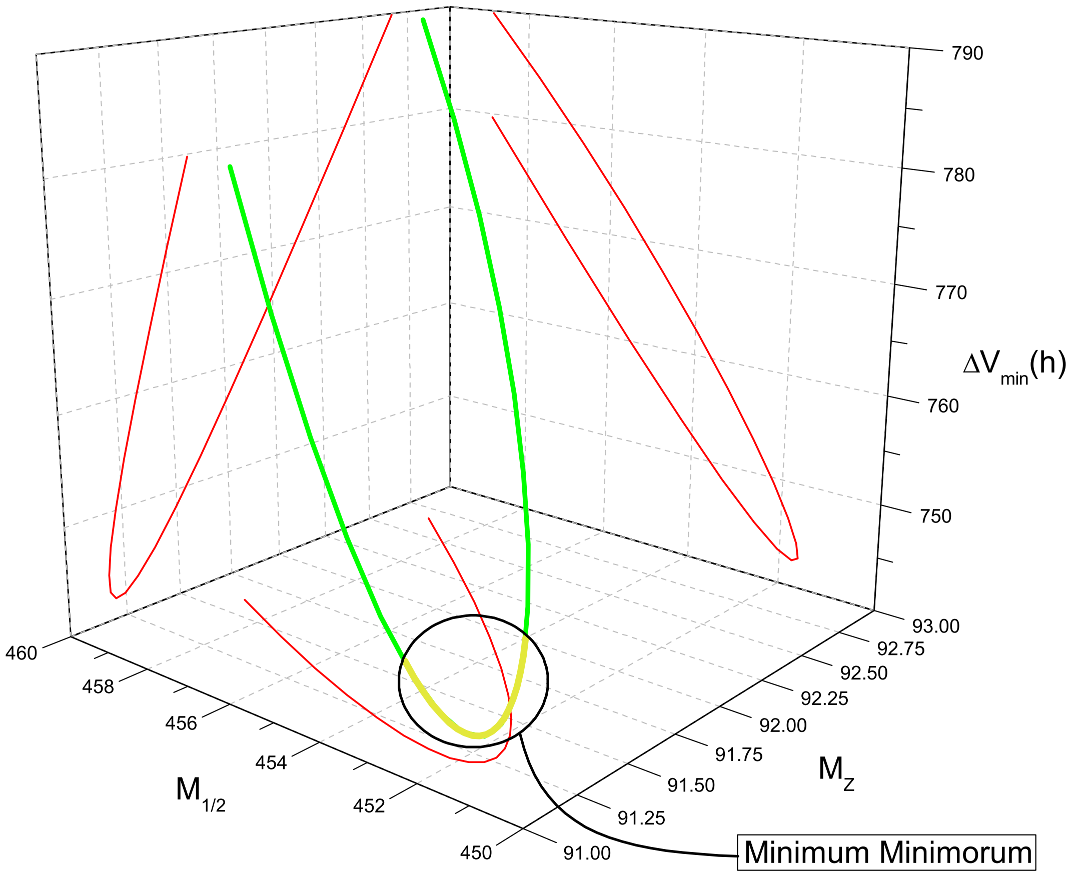

Figure 10: Dynamical determination of $M_{1/2}$: fixing M_V, m_t, and μ at M_U.

LHC Search at the Early Run: [a]

- Vector-like particles are difficult.
- Specific feature: Lighter stop and gluino.
- Looking for the multiple jets: four tops, > 8 jets.
- LHC: 7 TeV and 1-3 fb^{-1}.

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[a] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1103.2362 [hep-ph], and arXiv:1103.4160 [hep-ph].

LHC Search: Benchmark Point

Table 4: Spectrum (in GeV) for $M_{1/2}$ = 410 GeV, M_V = 1 TeV, m_t = 174.2 GeV, tanβ = 19.5. Here, Ω_χ = 0.11 and the lightest neutralino is 99.8% bino.

$\widetilde{\chi}_1^0$	76	$\widetilde{\chi}_1^\pm$	165	$\widetilde{e}_R$	157	$\widetilde{t}_1$	423	$\widetilde{u}_R$	865	m_h	120.4
$\widetilde{\chi}_2^0$	165	$\widetilde{\chi}_2^\pm$	756	$\widetilde{e}_L$	469	$\widetilde{t}_2$	821	$\widetilde{u}_L$	939	$m_{A,H}$	814
$\widetilde{\chi}_3^0$	752	$\widetilde{\nu}_{e/\mu}$	462	$\widetilde{\tau}_1$	85	$\widetilde{b}_1$	761	$\widetilde{d}_R$	900	$m_{H^\pm}$	820
$\widetilde{\chi}_4^0$	755	$\widetilde{\nu}_\tau$	452	$\widetilde{\tau}_2$	462	$\widetilde{b}_2$	864	$\widetilde{d}_L$	942	$\widetilde{g}$	561

Property of Particle Spectra:

- Both the particle spectra and the sparticle branch ratio are similar in the (updated) “Golden Strip” up to a small rescale since $M_{1/2}$ is the only supersymmetry breaking parameter.
- Light gluino due to $b_3 = 0$.
- The distinctive mass pattern: $m_{\widetilde{t}_1} < m_{\widetilde{g}} < m_{\widetilde{q}}$.
- Different from the ten “Snowmass Points and Slopes” (SPS) benchmark points.

Collider Physics:

- MadGraph and MadEvent: Low order Feymann Diagram and Monte Carlo simulated parton level scattering events.
- PYTHIA: the cascaded fragmentation and hadronization of these events into final state showers of photons, leptons, and mixed jets.
- PGS4: simulating the physical detector environment.
- MLM matching: avoid double counting.
- CTEQ6L1: parton distribution functions .
- The updated b-tag efficiency $\sim 60\%$.

Event Veto Conditions:

- $p_T < 100$ GeV for the two leading jets.
- $p_T < 350$ GeV for all jets.
- Pseudorapidity $|\eta| > 2$ for the leading jet.
- Missing energy $\not{E}_T < 150$ GeV.
- Isolated photon with $p_T > 25$ GeV.
- Isolated electron or muon with $p_T > 10$ GeV.
- Any single jet with $|\eta| > 3$

Decaying Chains:

- $\widetilde{g} \longrightarrow \widetilde{t}_1\bar{t} \longrightarrow t\bar{t}\widetilde{\chi}_1^0 \longrightarrow W^+W^-b\bar{b}\widetilde{\chi}_1^0.$
- $\widetilde{g} \longrightarrow \widetilde{t}_1\bar{t} \longrightarrow b\bar{t}\widetilde{\chi}_1^+ \longrightarrow W^-b\bar{b}\widetilde{\tau}_1^+\nu_\tau \longrightarrow W^-b\bar{b}\tau^+\nu_\tau\widetilde{\chi}_1^0.$
- $\widetilde{g} \longrightarrow \widetilde{\bar{t}}_1 t \longrightarrow t\bar{t}\widetilde{\chi}_1^0.$
- $\widetilde{g} \longrightarrow \widetilde{\bar{t}}_1 t \longrightarrow \bar{b}t\widetilde{\chi}_1^-.$

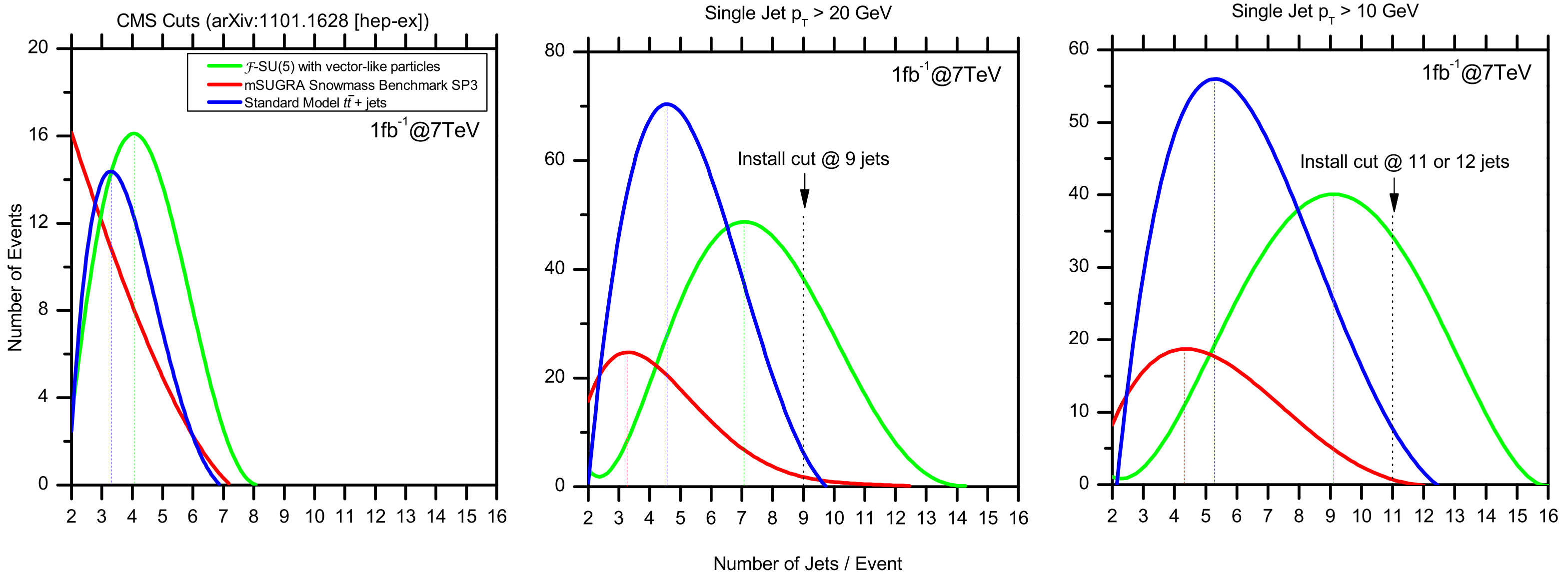

Figure 11: Distribution of events per number of jets. For clarity of the peaks, polynomials have been fitted over the histograms. $P_T > 20$ GeV.

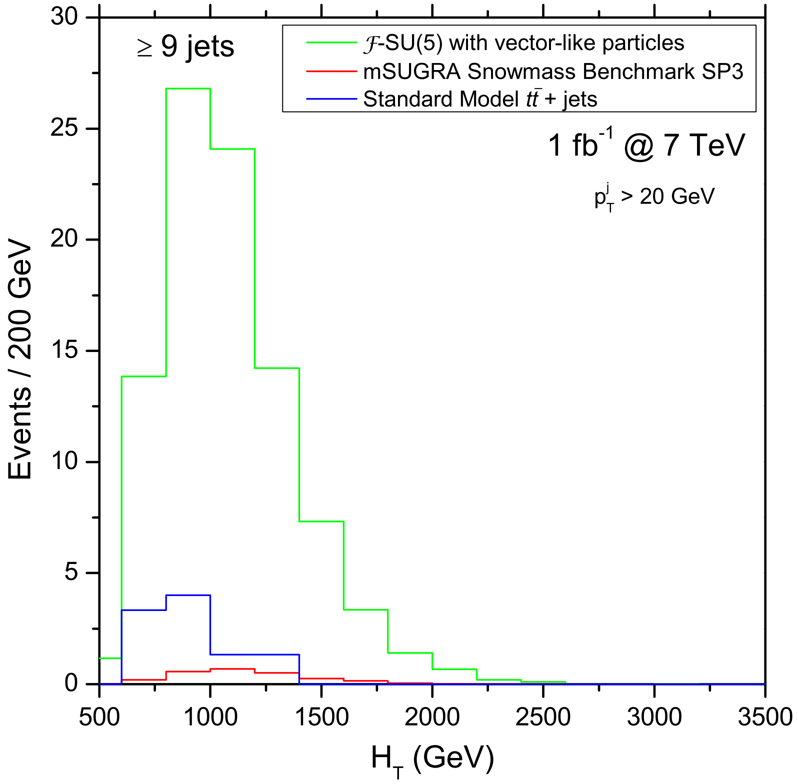

Figure 12: Counts for events with ≥ 9 jets. $H_T = \sum_{i=1}^{N_{jet}} E_T^{j_i}$.

Table 5: Total number of events for 1 fb^{-1} and $\sqrt{s}$ = 7 TeV. Minimum p_T for a single jet is $p_T > 20$ GeV.

	$\mathcal{F}$-$SU(5)$	$SP3$	$t\bar{t} + jets$
$Events$	93.2	2.4	10
$\frac{S}{\sqrt{B}}$	29.5	0.76	

The benchmark point can be tested at the early LHC run.

PHENOMENOLOGICAL CONSEQUENCES

- The lightest CP-even Higgs boson mass is larger than the MSSM due to the additional Yukawa interactions between the MSSM Higgs fields and these vector-like particles [a]

$$-\mathcal{L} \;=\; y^{d}_{XF} XFXFh + y^{u}_{XF}\overline{XFXFh}\,.$$

- The neutrino masses and mixings can be generated via seesaw mechanism. And the observed baryon asymmetry can be explained via leptogenesis.

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[a] Y. J. Huo, T. Li, D. V. Nanopoulos and C. L. Tong, in preparation.

- We can naturally have the hybrid inflation where Φ is the inflaton field. The inflation scale is related to the scale M_{23}. Because M_{23} is at least one order smaller than M_U, we solve the monopole problem. Interestingly, we can generate the correct cosmic primordial density fluctuations [a]

$$\frac{\delta\rho}{\rho} \sim \left(\frac{M_{23}}{g_{23} M_{\rm Pl}}\right)^2 \sim 1.7 \times 10^{-5} \, .$$

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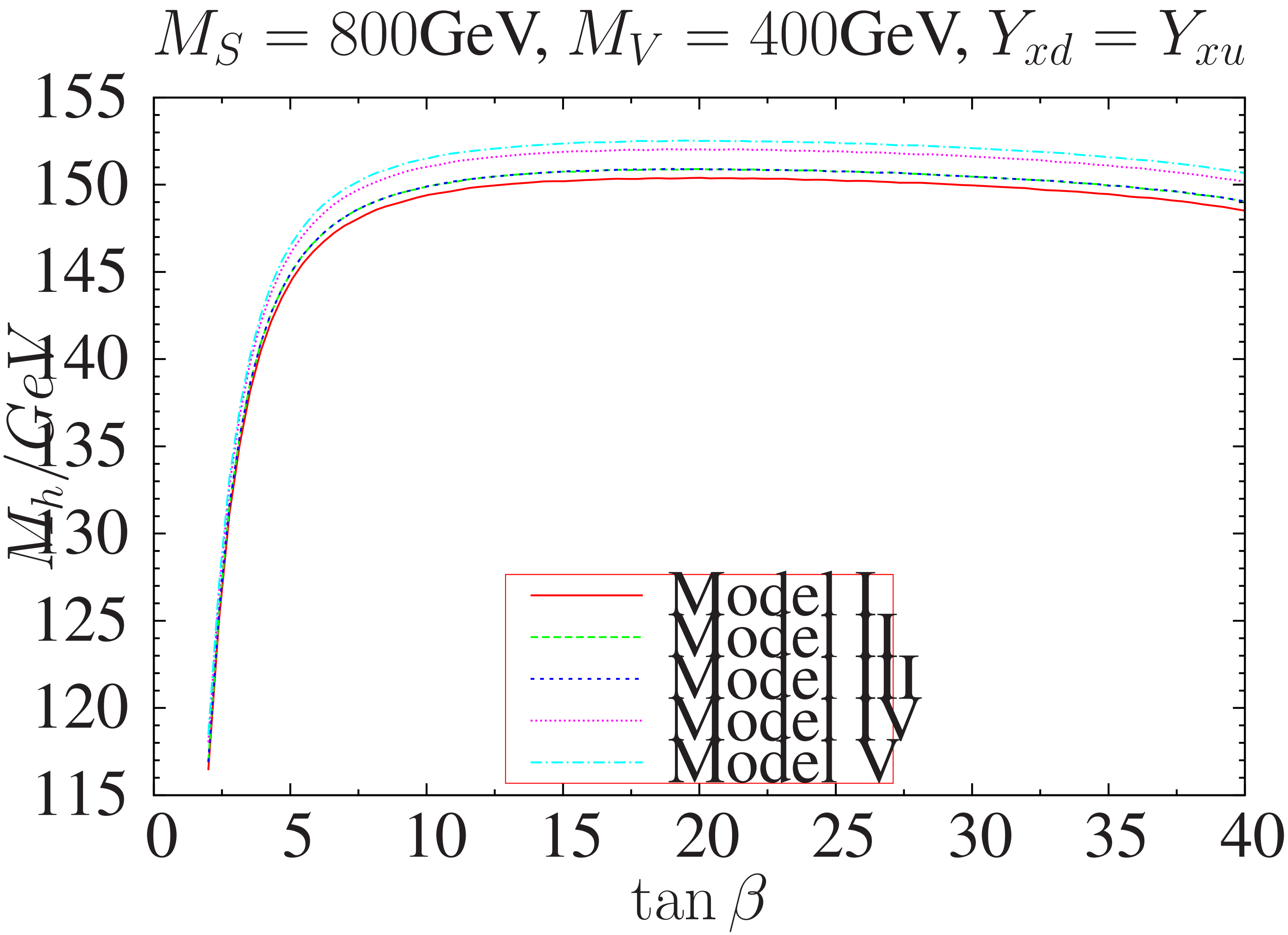
[a] B. Kyae and Q. Shafi, Phys. Lett. B **635**, 247 (2006).



For $M_S = 800$ GeV and $M_V = 800$ GeV, the lightest CP-even Higgs boson mass versus $\tan\beta$.

CONCLUSION

$\mathcal{F}$-$SU(5)$

- These models can be realized in free fermionic string constructions and F-theory model building.
- Lighter stop and gluino can be observed at the LHC early run.
- The models may be tested in the early LHC run. And the TeV-scale vector-like particles can be produced and observed at the next LHC run.
- The proton decay $p \to e^+\pi^0$ from the heavy gauge boson exchange is within the reach of the future DUSEL and Hyper-Kamiokande experiments for a majority of the most plausible parameter space.

- A strong correlation between the most exciting particle physics experiments of the coming decade.
- The phenomenological consequences are pretty interesting.