Testing No-Scale $\mathcal{F}$-SU(5) with LHC, Planck, and XENON

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The Tripodal Foundation of No-Scale $\mathcal{F}$-SU(5)

1) The Flipped SU(5) GUT

2) Extra TeV scale Vectorlike Multiplets
   with F-theory origin

3) No-Scale Supergravity
   Boundary Conditions

Pillar Number I

The Flipped SU(5) GUT

The Standard and Flipped SU(5) Particle Representations

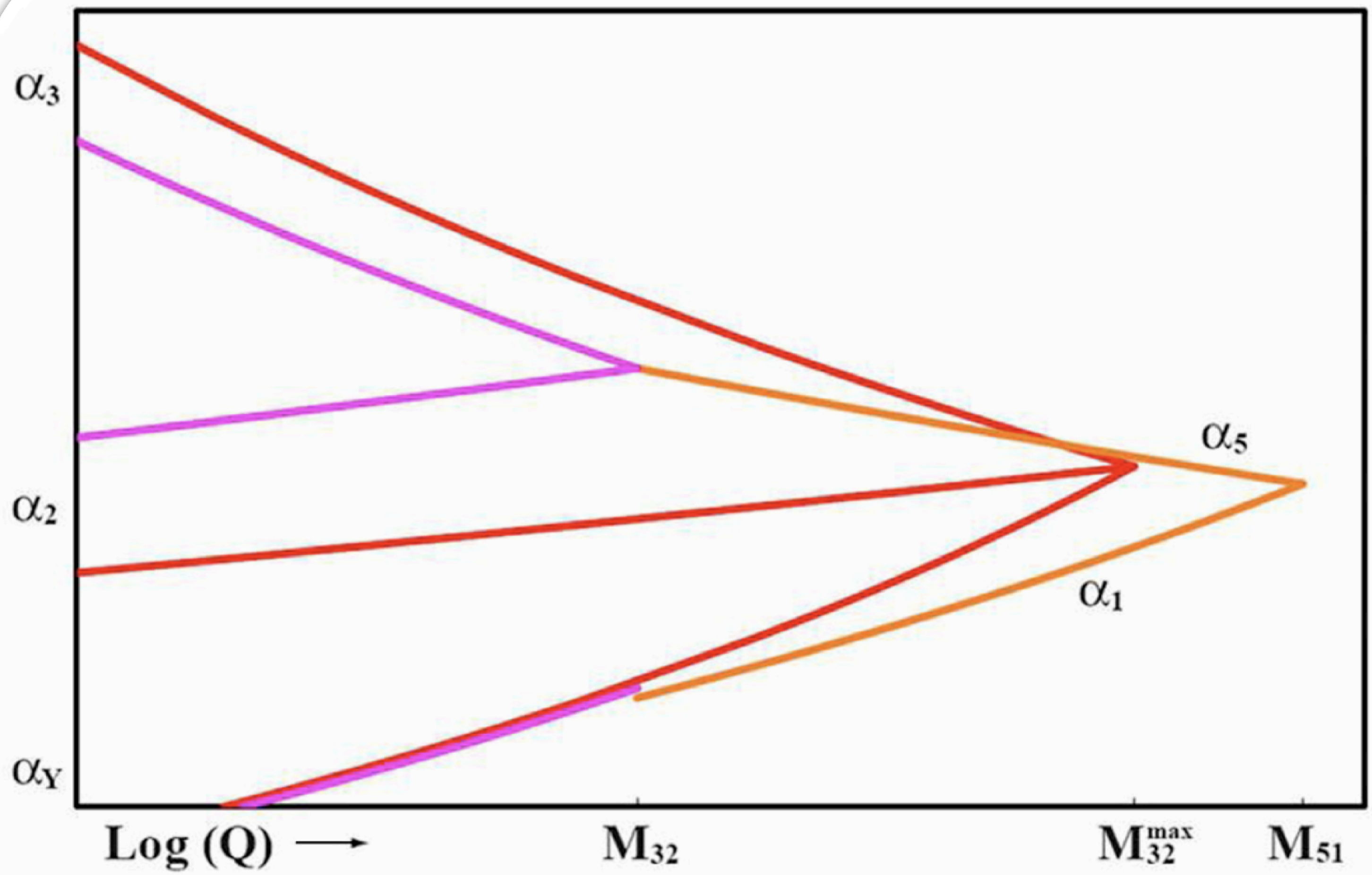
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \;;\; u_L^c \;;\; d_L^c \qquad \underset{\text{RIGHT}}{\overset{\text{JUST}}{\longrightarrow}} \qquad \underset{\bar{\mathbf{5}}}{\begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ \nu_e \end{pmatrix}_L} \;;\; \underset{\mathbf{10}}{\left(\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_L^c \;\; e_L^c \right)} \;;\; \underset{\boxed{\mathbf{1}}}{\boxed{\nu_L^c}}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \;;\; e_L^c \;;\; \boxed{\nu_L^c}$$

$$f_{\bar{5}} = \begin{pmatrix} u_1^c \\ u_2^c \\ u_3^c \\ e \\ \nu_e \end{pmatrix}_L \;;\quad F_{10} = \left(\begin{pmatrix} u \\ d \end{pmatrix}_L \; d_L^c \;\; \nu_L^c \right) \;;\quad l_1 = e_L^c$$

Upper: Each generation of the Standard Model fits perfectly into a fundamental **5-bar** and an antisymmetric 10 of SU(5). The RH neutrino is “out”. Lower: The RH up/down quarks, and the electron/neutrino can “flip” places relative to standard SU(5).

Flipped Unification



$$\frac{1}{\alpha_i(Q)} - \frac{1}{\alpha_{GUT}} = \frac{b_i}{2\pi} \ln \frac{M_{GUT}}{Q}$$

$$M_{Pl} = 2 \times 10^{19}\ \mathrm{GeV}$$

A heuristic graphical representation of Flipped SU(5) in purple Vs. Standard SU(5) in red. Note that Flipped SU (5) is not fully unified at M_{32}. It "waits" for Super Unification at M_{51}, which may be closer to M_{Planck} .

Motivations for Flipped SU(5)

Why is the complication of 'Flipped' SU(5) preferred?

- Natural and Essential accomodation of the RH neutrino, along with see-saw type mass terms
- Antisymmetric 10 of GUT Higgs, rather than adjoint
- Doublet-Triplet SM Higgs Splitting
- No dimension five proton decay operators
- Able to satisfy the strong coupling at the Z-mass
- 'Waits' on Super-Unification

The Missing Partner Mechanism

$$H\,H\,h \text{ and } \bar{H}\,\bar{H}\,\bar{h} \quad \Rightarrow \quad \langle \nu^c_H \rangle d^c_H H_{\mathbf{3}}$$

There is no such partner for H_2 , so it then remains light

$$M h_{\mathbf{5}} h_{\bar{\mathbf{5}}} \qquad \text{vs.} \qquad h_{\mathbf{5}} h_{\bar{\mathbf{5}}} \Sigma_{\mathbf{24}}$$

In standard SU(5), these terms must play against each other to finely tune two distinct scales

We achieve a Natural splitting between the double and triplet Higgs. We avoid fine tuning and the overly rapid dimension 5 proton decay!

A Lesson from History

SU(2) [Georgi-Glashow '72] • "grand" unified • $W^{\pm}, \gamma$: γ inside $SU(2)$ • Higgs triplet (adjoint) • Neutral currents exist (1973) • Wrong!	SU(2)×U(1) [Glashow '61, Weinberg '67, Salam '68] • unified • $W^{\pm}, Z, \gamma$: $\gamma = \{W^3\ [SU(2)],\ B\ [U(1)]\}$ • Higgs *doublet*, *à la* quarks, leptons • $SU(3)$ not accounted for; grand unification later • Right!
SU(5) [Georgi-Glashow '74] • grand unified • $W^{\pm}, W^3, B, X, Y$ γ inside $SU(5)$ • Higgs **24** (adjoint) • $\alpha_3(M_Z) > 0.13$; $\tau\ (p \rightarrow K^+ \bar{\nu})$ *too short* • Wrong!	SU(5)×U(1) [Barr '82, Derendinger-Kim-Nanopoulos '84, Antoniadis-Ellis-Hagelin-Nanopoulos '87] • unified • $W^{\pm}, W^3, B, X, Y, \widetilde{B}$ γ: $(W^3, B)\ [SU(5)],\ \widetilde{B}\ [U(1)]$ • Higgs $\mathbf{10}, \overline{\mathbf{10}}$ (antisymmetric), *à la* quarks, leptons • Gravity* not accounted for; grand unification later • Right?

Nature repeats her favorite themes, in delicate reprise.

Pillar Number II

Extra TeV scale Vectorlike Multiplets
with F-theory origin

Grand Unification and String Phenomenology

- **GUTs extend the successes of particle physics, covariantly encoding gauge interactions**
- Well grounded in low energy experiments (precision LEP data + logarithmic renormalization)
- Reductionism: relations between masses and couplings, plus charge quantization
- Highly predictive and testable: requires SUSY & probes that parameter space; proton decay (essential to matter dominance); strong coupling at Z-mass
- BUT this is a symmetry, not a system of dynamics in itself
- HOWEVER, it can offer the string a reasoned starting point for model building

- **String Theory offers a unified origin for gravity, supersymmetry and chiral replicated families of gauged matter**
- Contains multiple techniques for constructing exactly what particle physics orders (Free Fermionic Constructions, Intersecting D-Branes, Calabi-Yau Compactifications)
- BUT the parameter space is too large, and the mechanisms for selecting a vacuum are unknown
- HOWEVER, it can offer to particle physics origin, context, dynamics and potentially added calculability of input quantities

These distinct points of view are natural symbiotic partners.

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

- To separate the mass scales M_{23} and M_U and realize the decoupling scenario, 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.

TeV Scale Vector Multiplets

$$\Delta b^{XQ+XQ^c} = (\frac{1}{5}, 3, 2) \ ; \ \Delta b^{XU+XU^c} = (\frac{8}{5}, 0, 1) \ ; \ \Delta b^{XD+XD^c} = (\frac{2}{5}, 0, 1)$$

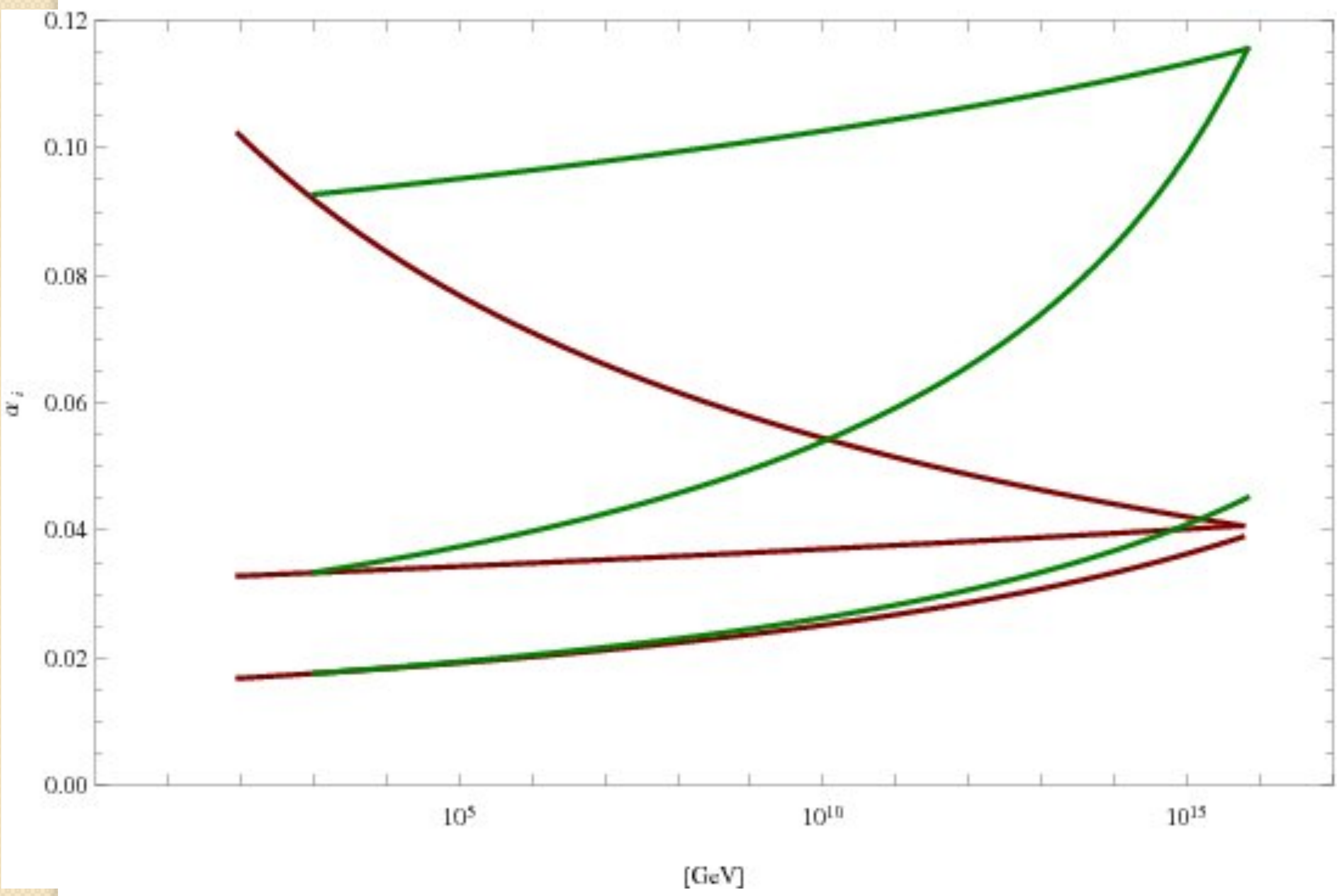
$$\Delta b^{XL+XL^c} = (\frac{3}{5}, 1, 0) \ ; \ \Delta b^{XE+XE^c} = (\frac{6}{5}, 0, 0) \ ; \ \Delta b^{XN+XN^c} = (0, 0, 0)$$

$$\Delta b^{XY+XY^c} = (5, 3, 2) \ ; \ \Delta b^{XT_i+\overline{XT}_i} = (\frac{6}{5}, 0, 0)$$

Scenario	Vector Super-Multiplets	b_Y	b_2	b_3
$\mathrm{SU}(5)_0$	None	6.6	1	-3
$\mathrm{SU}(5)_\mathrm{A}$	$(YF \equiv \{XQ, XU^c, XE^c\}_{\mathbf{10}}, \overline{YF})$	9.6	4	0
$\mathrm{SU}(5)_\mathrm{B}$	$3 \otimes (Yf \equiv \{XD^c, XL\}_{\mathbf{5}}, \overline{Yf})$	9.6	4	0
$\mathcal{F}$-$\mathrm{SU}(5)_0$	None	6.6	1	-3
$\mathcal{F}$-$\mathrm{SU}(5)_\mathrm{A}$	$(XF \equiv \{XQ, XD^c, XN^c\}_{\mathbf{10}}, \overline{XF}) \oplus (Xl \equiv \{XE\}_{\mathbf{1}}, \overline{Xl})$	8.4	4	0
$\mathcal{F}$-$\mathrm{SU}(5)_\mathrm{B}$	$(XF \equiv \{XQ, XD^c, XN^c\}_{\mathbf{10}}, \overline{XF})$	7.2	4	0

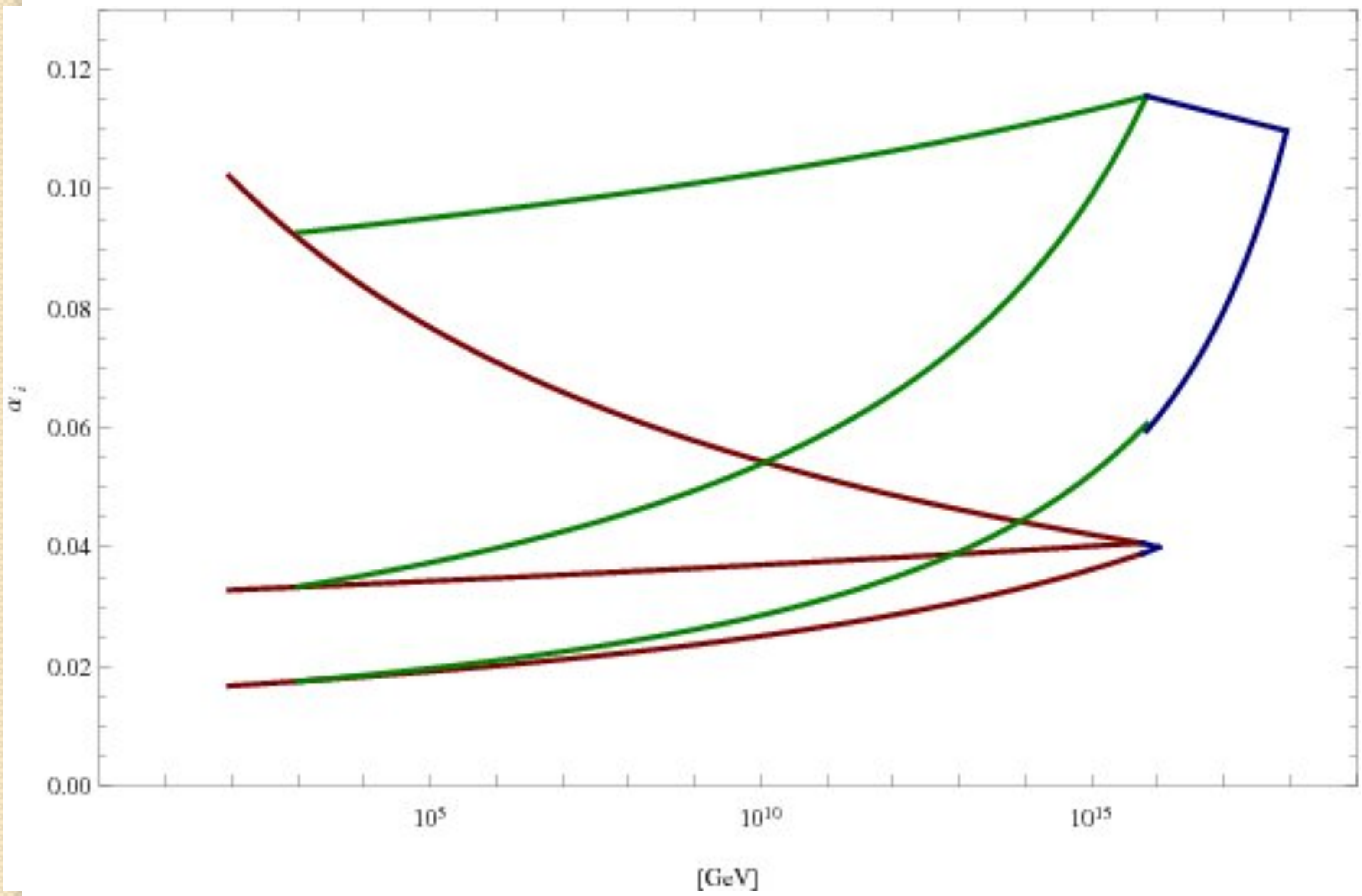
Inclusion of TeV scale Vector Multiplets, as motivated by F-theory, creates a dramatic early adjustment to the running of the gauge couplings.

Flipped Unification with & without Vector Multiplets



Inclusion of TeV scale Vector Multiplets levels out the renormalization of the strong coupling, driving up the SU(5) coupling, and speeding proton decay. The gap between the M_{32} scale couplings becomes extreme.

Natural ~ Planck Scale GUT Unification



Continuing the two-loop renormalization beyond the 3,2 partial unification can result in a super unification near the reduced Planck scale. The wide coupling separation at M_{32} which was produced by the F-theory fields allows sufficient room to run.

Pillar Number III

No-Scale Supergravity

Boundary Conditions

Motivations for Supersymmetry

- The SM has a scale stabilization problem: SUSY fixes quadratic scalar Higgs divergences with ‘chirality transmission’ and counter-balanced loops
- The SM has too many free parameters: SUSY offers a highly confining principle of constraint; one potential produces masses and Yukawa couplings
- The price: Doubling the known particle spectrum, an extra doublet of Higgs, and a new mechanism to break SUSY.
- New predictions: a very light Higgs, improved GUT unification => longer proton lifetime, dark matter candidate
- Also: A new proton decay mode that is more dangerous

Detection of Supersymmetric Particles is a key motivating goal of the Large Hadron Collider.

Minimal Supergravity (mSUGRA)

M_0	Universal soft scalar mass
$M_{1/2}$	Universal soft gaugino mass
μ	Higgsino bilinear mass parameter
A	Trilinear soft SUSY breaking coupling
B_μ	Higgs Bilinear soft SUSY breaking term
$\tan\beta$	Ratio of Higgs VEVs

$|\mu|$ and B can be determined by the requirement for REWSB,
so we are left with only five parameters:

M_0, $M_{1/2}$, A, $\tan\beta$, and $\mathrm{sgn}(\mu)$

Supergravity & the No-Scale Formulation

- Connection to String Theory in IR limit
- Natural incorporation of general coordinate invariance (Gravity)
- Suppression of CP violation and FCNCs
- Mechanism for SUSY breaking with cosmological constant vanishing at tree level (Flatness)
- Dynamic determination of gravitino & gaugino masses and SUSY breaking scale at loop level
- Dramatic Reduction in Parameter Freedom

$$M_0 = B_\mu = A = 0$$

But …. Implementation is Difficult

- Simplest and most generic Universal Boundary Conditions possible – But fails to give consistent results applied at M_{GUT}

- The major problem is the non trivial consequences of setting $B_{\mu}=0$ at the GUT scale. The theory is so highly constrained that it fights against attempts at fine tuning. This tension is alleviated if the boundary conditions are instead applied closer to the Planck scale. (Ellis et. al)

Three Ideas Fit Hand to Glove

- The Flipped SU(5) GUT has a two stage unification. The lower stage sets the proton decay scale, but the upper scale may be associated with the reduced Planck Mass and gravitational physics.
- This association is possible only if the RGEs are modified, as occurs naturally with the F-theory vectorlike multiplets.
- With both these pieces in place, the No-Scale boundary conditions have extra baseline to run (and run in a modified way), realizing a perfect fit to phenomenology.

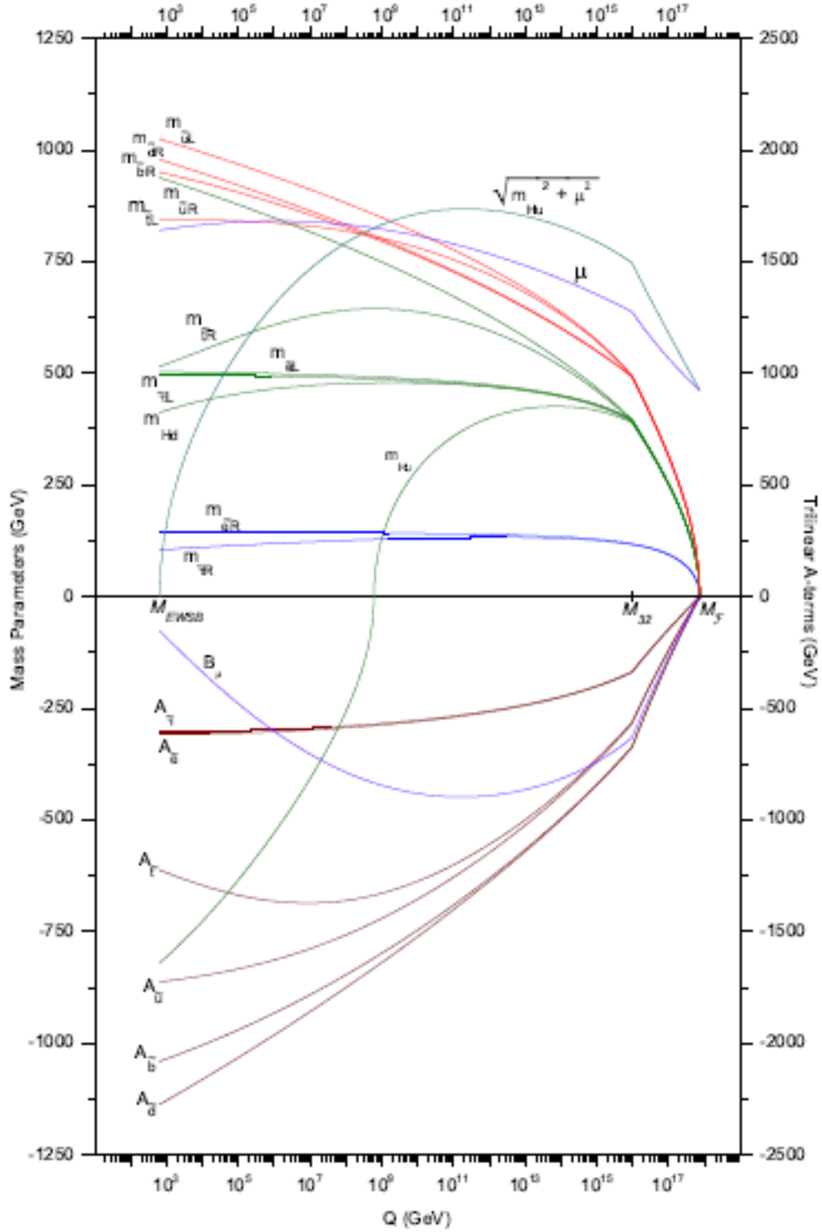


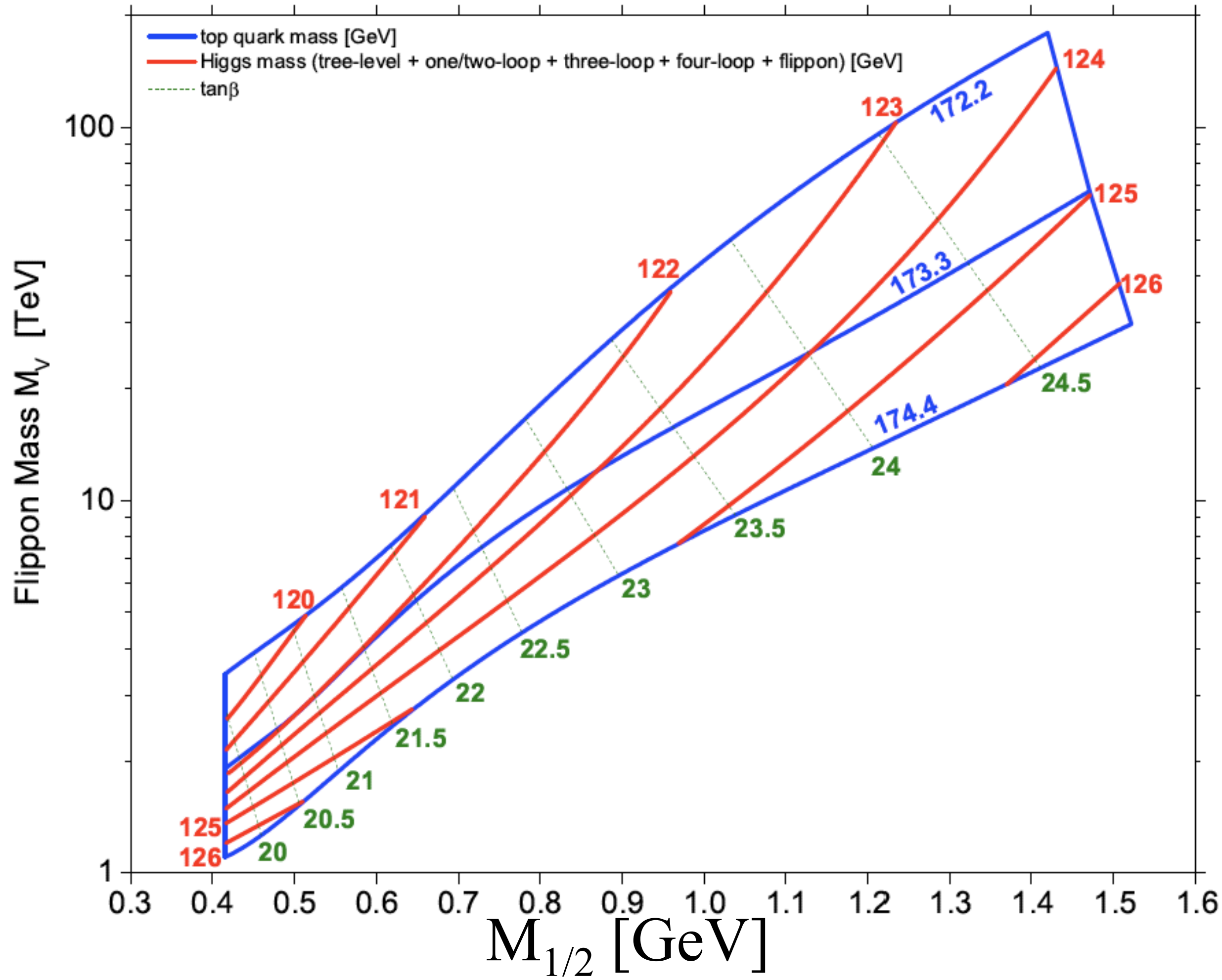
FIG. 3: RGE Running of the μ term and SUSY breaking soft terms from the EW scale to the unification scale $M_{\mathcal{F}}$.

“Bare Minimal” Experimental Constraints

- 7-Year WMAP Cold Dark Matter Relic Density Measurement (Now Planck)
- World average top quark mass 173.3±1.1GeV
- No Scale B.C. matching on $B_{\mu} = 0 \pm 1.0$ GeV
- Radiative EWSB
- LEP limits on the light CP even Higgs mass and light SUSY content (Pre-LHC)
- Compliance with all precision electroweak measurements (M_z, α_s, Θ_W, α_{em}, m_b)

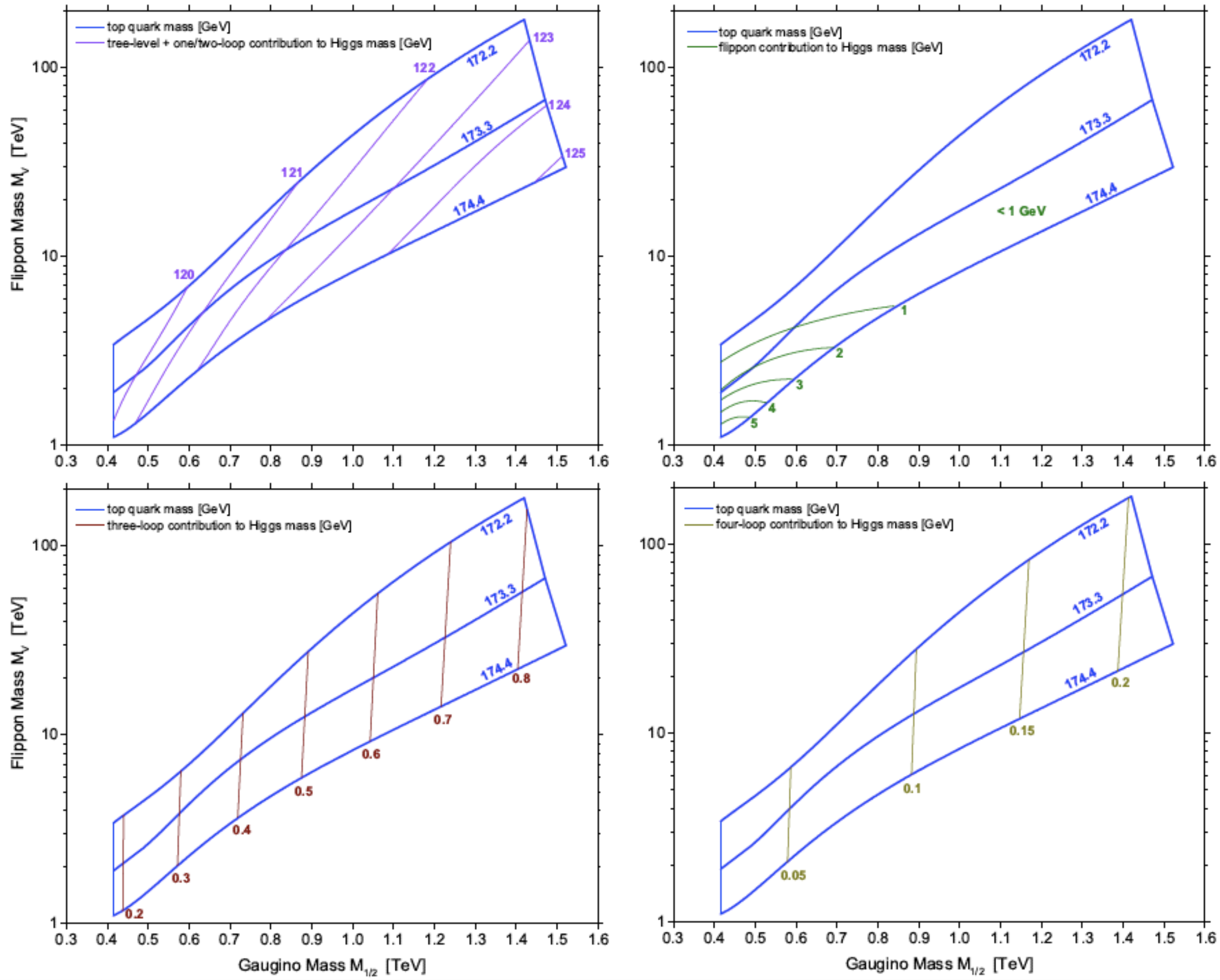
* The Weinberg angle floats mildly according to original program design.

Wedge of "Bare Minimal" Constraints



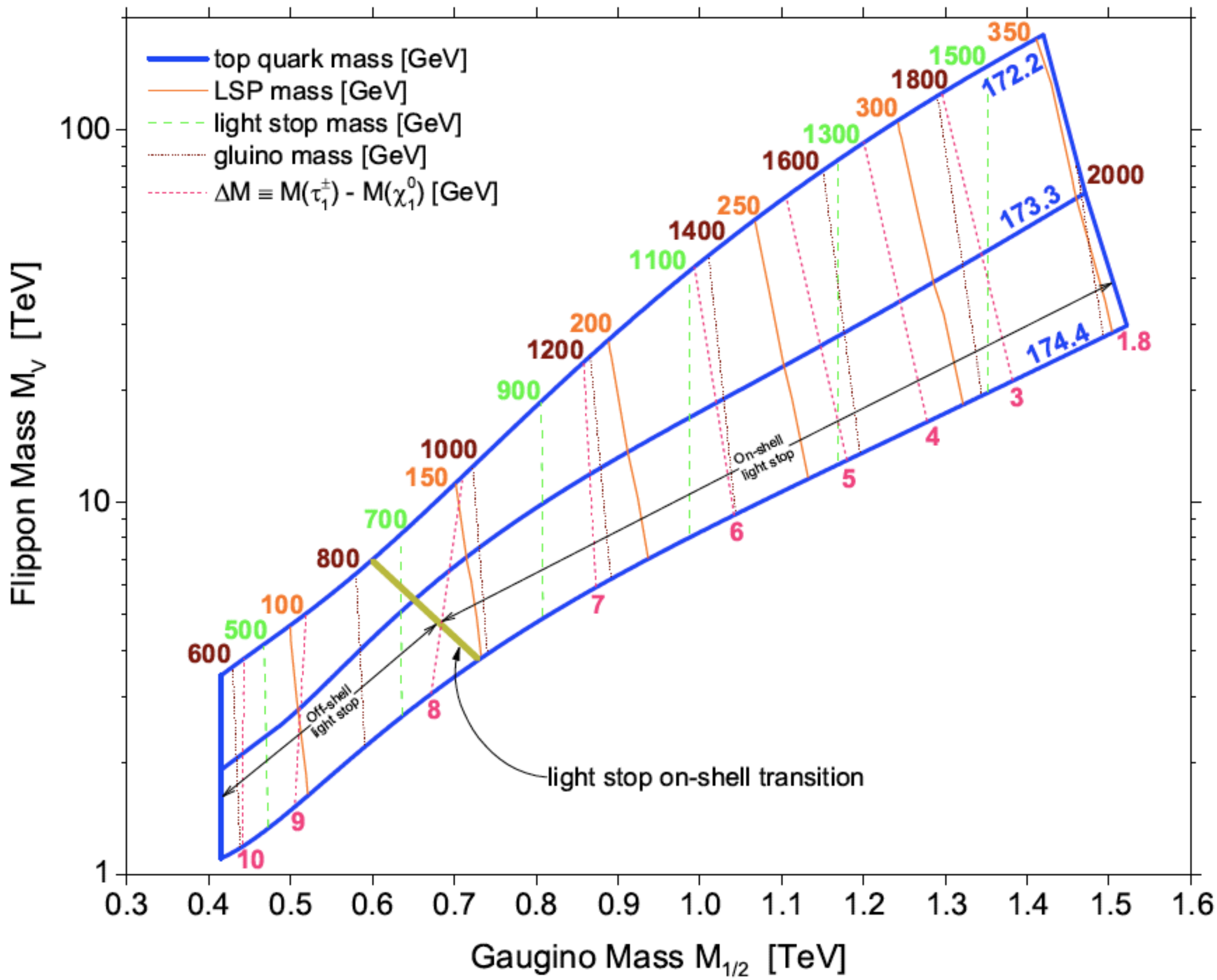
A two-dimensional wedge is cut out of the 4-D scanning hypervolume. Reducing α_s will lower the blue lines, effectively raising m_h.

Higgs Mass Components



There is complementarity between reduction in the “flippon” sector and increase in the squark sector. 3,4 loops scale as geometric mean of stops α $M_{1/2}$

SUSY Mass Spectrum



Testability at the Upper $M_{1/2}$ Boundary

- The wedge terminates at $M_{1/2} \approx 1.5$ TeV, where the stau-neutralino mass difference at 1.8 GeV is equal to the tau mass
- Heavy squarks are about 2.7 TeV
- Gluino about 2 TeV
- Light stop is about 1.6 TeV
- LSP neutralino is about 350 GeV
- Nominally, this is testable at the 14 TeV LHC
- Note: Heavy M_V is vector-like & may have Dirac mass contributions

$\mathcal{F}$-SU(5) Multijet Events at LHC

CMSSM

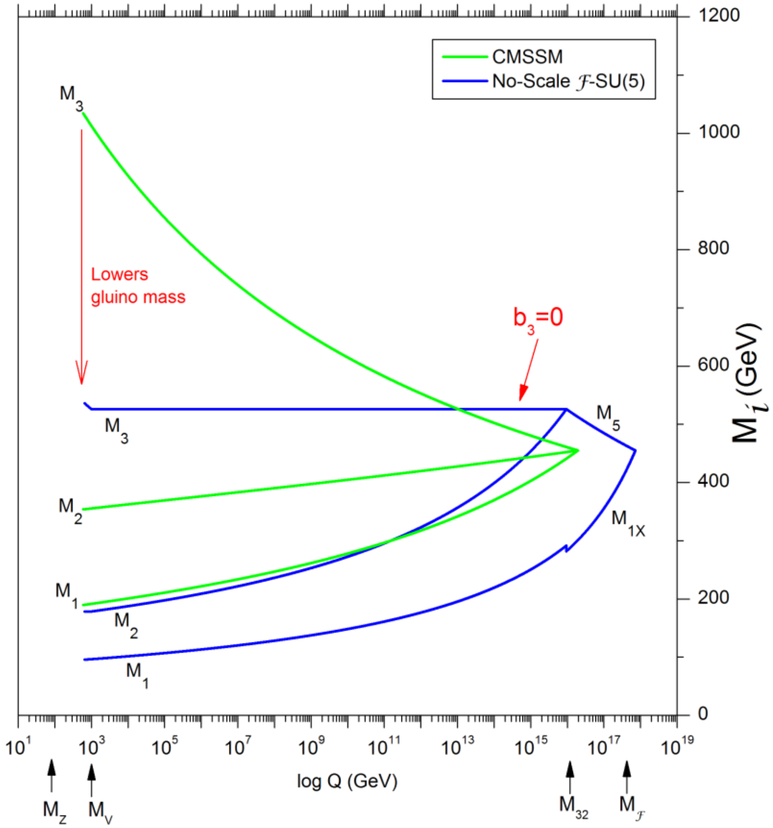
$\tilde{g}$, $\tilde{d}_L$, $\tilde{u}_L$, $\tilde{d}_R$, $\tilde{u}_R$, $\tilde{b}_2$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{t}_1$

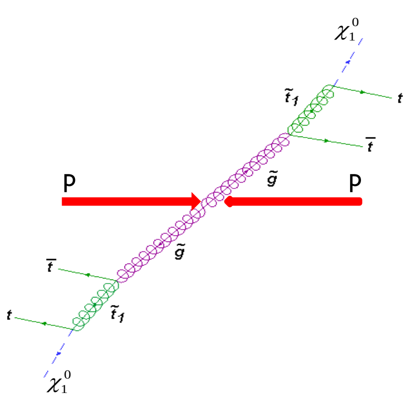
$\mathcal{F}$-SU(5)

$\tilde{d}_L$, $\tilde{u}_L$, $\tilde{d}_R$, $\tilde{u}_R$, $\tilde{b}_2$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{g}$, $\tilde{t}_1$

Just right for Multijets!

Large Branching Fraction





$$\tilde{g} \to \tilde{t}_1 \bar{t} \to t\bar{t}\chi_1^0$$

$$\Rightarrow \tilde{g}\tilde{g} \to t\bar{t} + t\bar{t} + 2\chi_1^0 \quad \text{(4-top multijet SUSY signal)}$$

Real Love* $\longrightarrow$ $\geq$9j, p_T>20, lepton

* Description courtesy of Lubos Motl, "The Reference Frame"

SUSY Multijet w/lepton Search at 7-8 TeV LHC

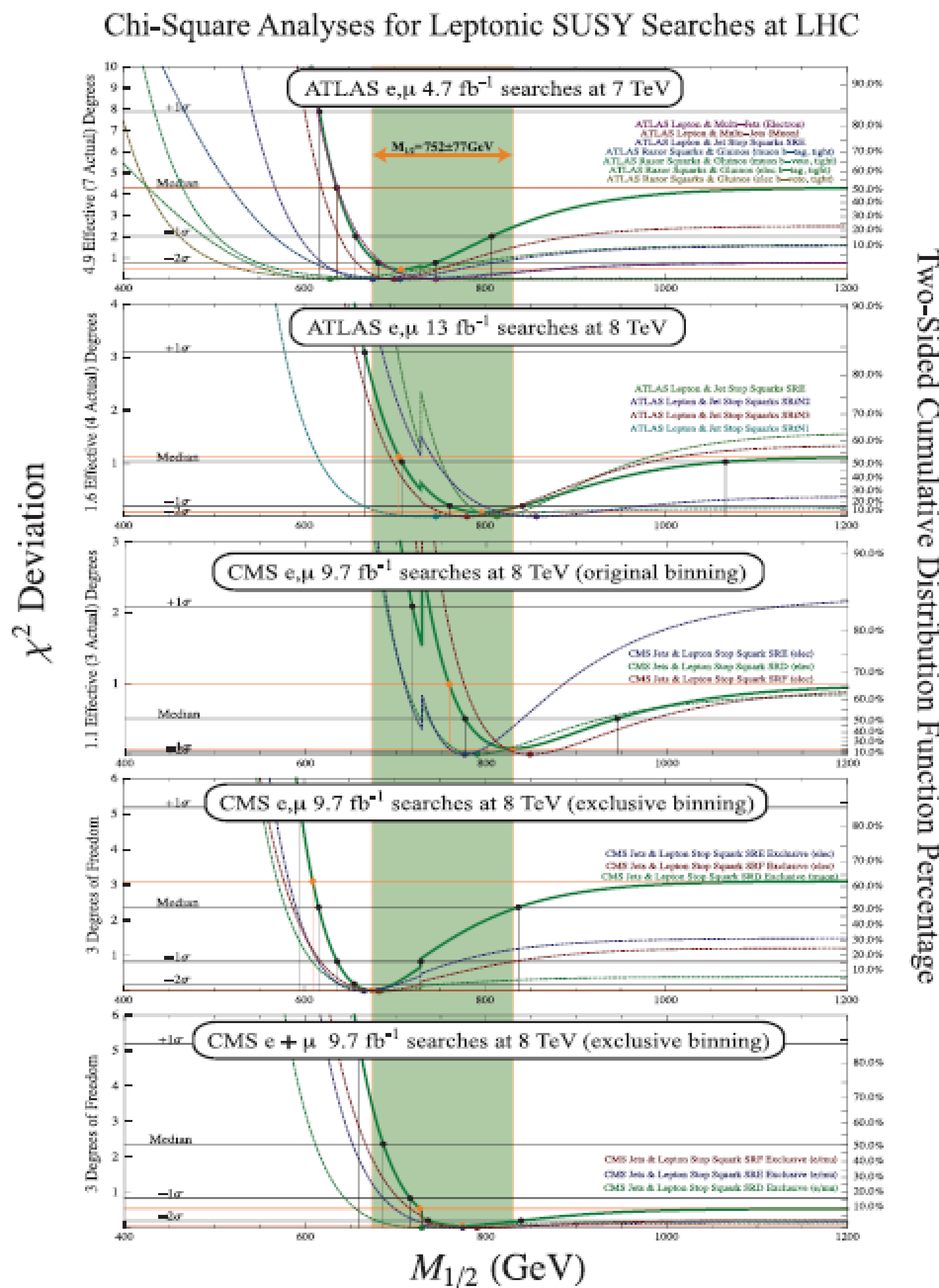
- Numerous Multijet+lepton SUSY search regions at 7-8 TeV by both ATLAS & CMS with p_T>20-30 GeV

- Target gluino mediated light stops and light stop pair-production

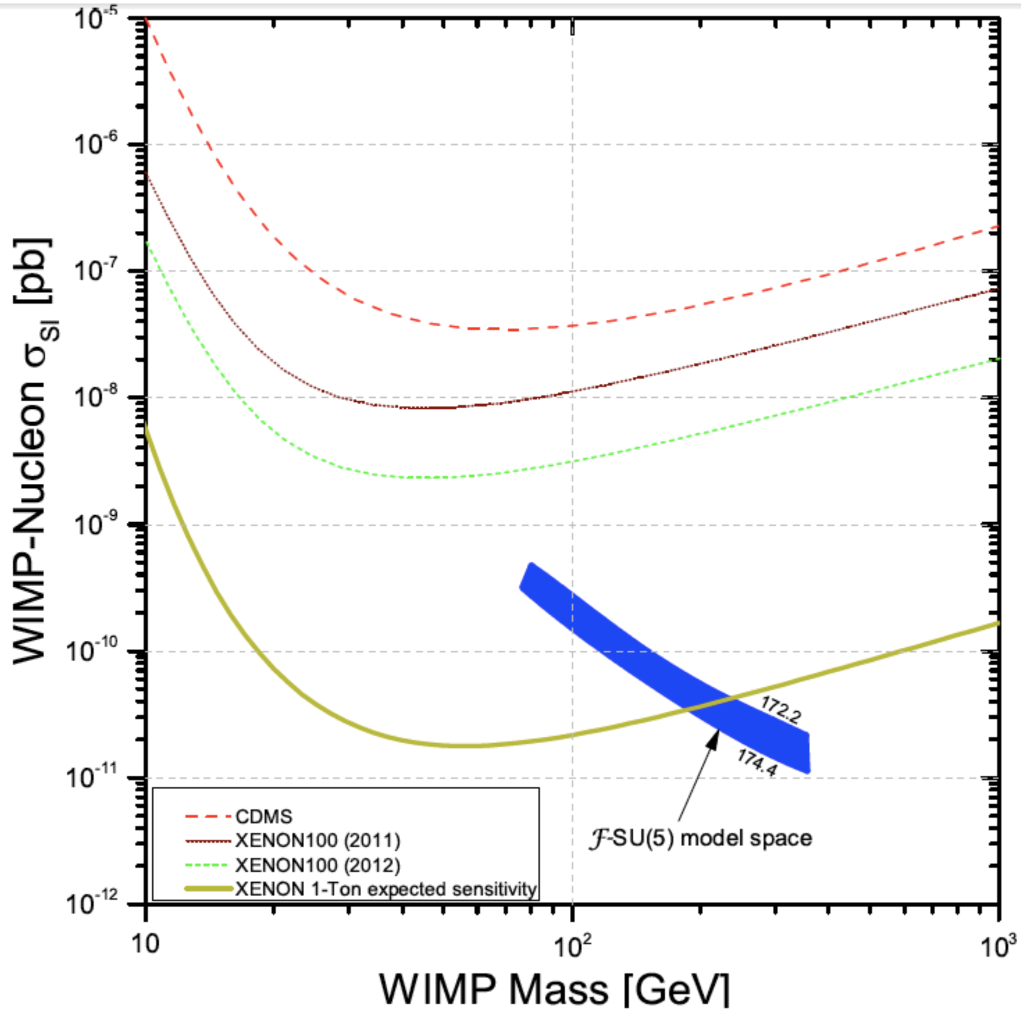
- $\mathcal{F}$-$SU(5)$ 2σ range: $M_{1/2} \geq 680$ GeV

$\mathcal{F}$-$SU(5)$ Best Fit SUSY Mass:

$M_{1/2}$=675-829 GeV

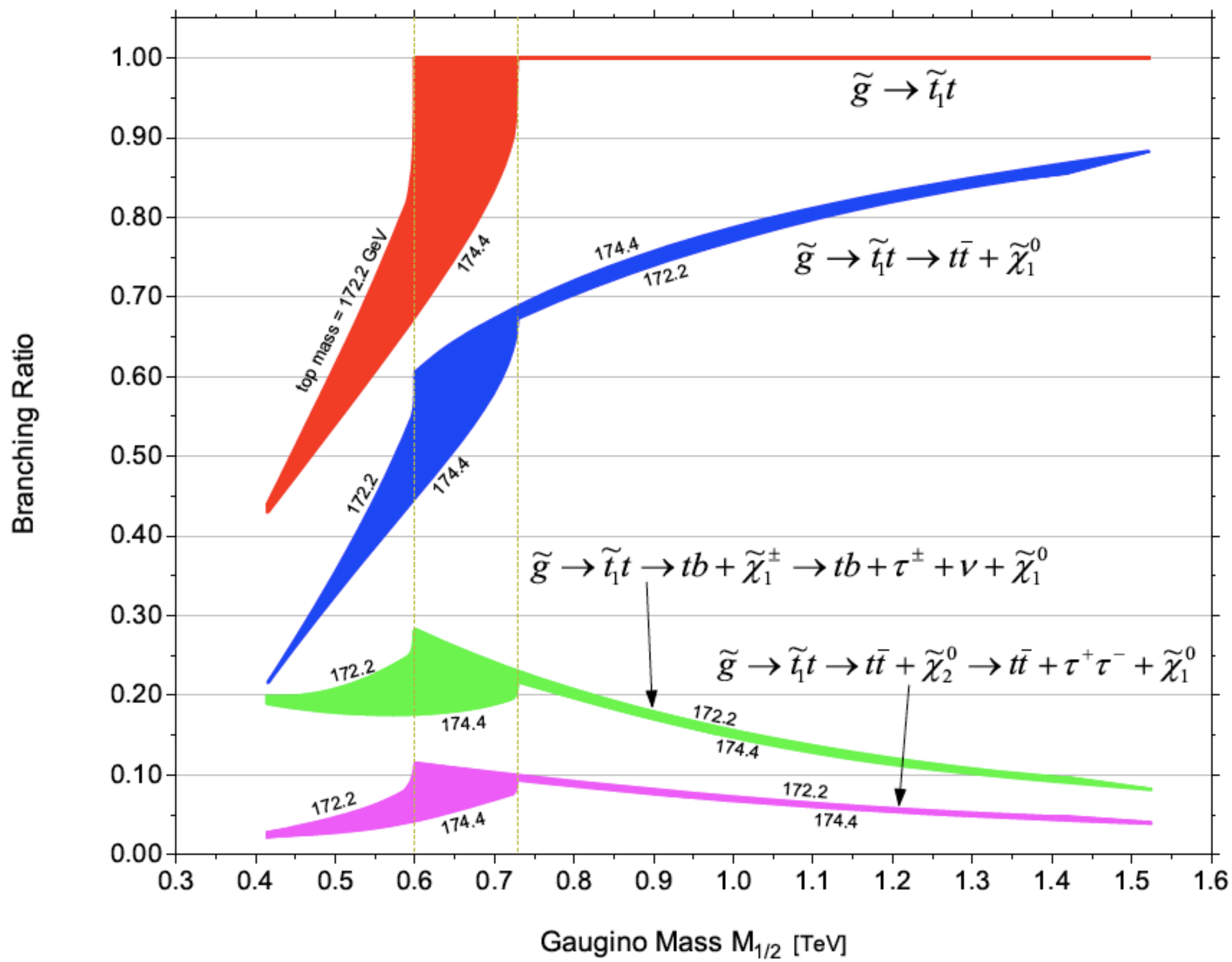


XENON Direct Detection Prospects



About ½ of the model wedge may be probed by XENON 1T, up to a wimp mass around 200 GeV ($M_{1/2} \approx$ 900 GeV). Most of this region is increasingly disfavored by the LHC.

On/Off-Shell Branching Ratios



Rare-decay process constraints

($b \longrightarrow s\gamma$): Combining experimental & theoretical errors in quadrature (2σ)

$2.86\times10^{-4} \leq Br(b \longrightarrow s\gamma) \leq 4.18\times10^{-4}$

$\mathcal{F}$-SU(5) $\longrightarrow M_{1/2} \geq 545$ GeV

$(g-2)_\mu$: Including new computation of 10th order QED terms (2σ); ~3σ from zero

$5.5\times10^{-10} \leq \Delta a_\mu \leq 39.5\times10^{-10}$

$\mathcal{F}$-SU(5) $\longrightarrow M_{1/2} \leq 850$ GeV

($B_s^0 \longrightarrow \mu^+\mu^-$): First evidence of events at LHCb; 3.5σ above SM expectations

$Br(B_s^0 \longrightarrow \mu^+\mu^-) = 3.2 +1.5 -1.2 \times 10^{-9}$ at 95% CL

$\mathcal{F}$-SU(5) $\longrightarrow M_{1/2} \geq 400$ GeV

Proton Decay: Super-Kamiokande $e^+\pi^0$ mode; highly dependent on $M_{32} \leftrightarrow \alpha_s$

$\tau_p \geq 1.4 \times 10^{34}$ yrs

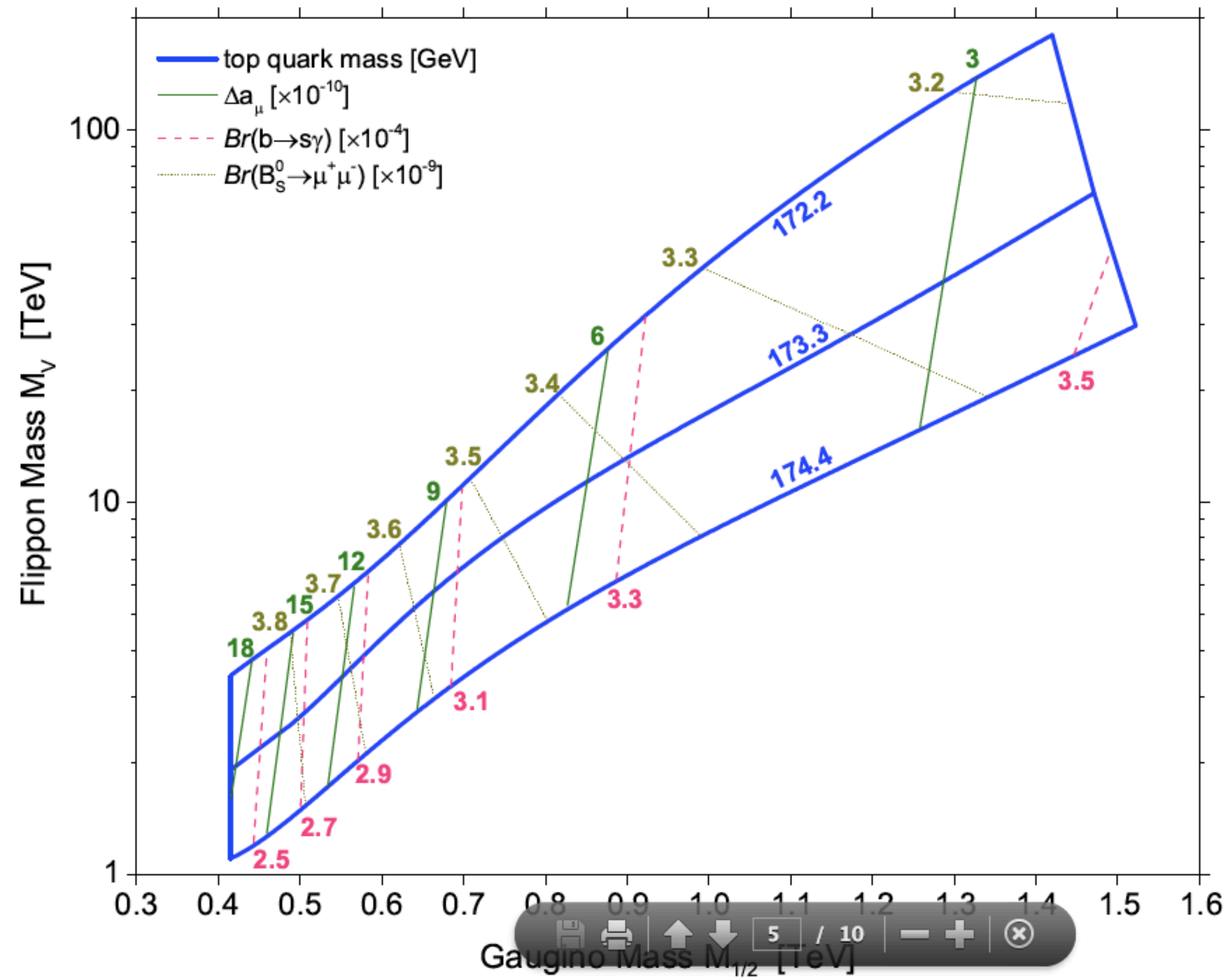
$\mathcal{F}$-SU(5) $\longrightarrow \alpha_s = 0.1172$, $M_{1/2} \geq 400$ GeV

$\mathcal{F}$-SU(5) $\longrightarrow \alpha_s = 0.1145$, $M_{1/2} \gtrsim 600$ GeV

Rare-decay intersection of all $M_{1/2} \longrightarrow$ Golden Strip $\in$ [545, 850] GeV

"Bottom Up" approach

Rare Process Contributions



Rare process contributions are generically “small”.

A Brief Commercial Interruption

CutLHCO: A Consumer-Level Tool for Implementing Generic Collider Data Selection Cuts in the Search for New Physics

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A new computer program named CutLHCO is introduced, whose function is the implementation of generic data selection cuts on collider event specification files in the standardized *.lhco* format. This software is intended to fill an open market niche for a lightweight yet flexible "consumer-level" alternative to the Root data analysis framework. The primary envisioned application is as a filter on output produced by the PGS4 and Delphes detector simulations, which are themselves lightweight alternatives to the Geant4 based solutions favored by the large LHC experiments. All process control instructions are provided via a compact and powerful card file input syntax that efficiently facilitates the reasonable approximation of most event selection strategies and specialized discovery statistics commonly employed by the CMS and ATLAS collaborations. The structure, function, invocation and usage of the most recent CutLHCO 2.0 program version are documented thoroughly, including a detailed deconstruction of several example card file specifications. The associated software is simultaneously being made available for free public download.

PACS numbers: 02.70.Uu, 07.05.Kf, 29.85.Fj

arXiv: 1207.3383

CutLHCO Card for Jets + Lepton

```
****** cut_card.dat 2.0 ******
* ATLAS Jets and Lepton (3J1L)
* ATLAS-CONF-2012-041
*** Object Reconstruction ****
OBJ_ALL = PRM:[0.0,4.9]
OBJ_ELE = PTM:10, PRM:[0.0,2.47]
OBJ_MUO = PTM:10, PRM:[0.0,2.4]
OBJ_LEP_001 = SRC:+000, EMT:+1, PTM:25
OBJ_LEP_002 = SRC:+000, EMT:+2, PTM:20
OBJ_JET_002 = SRC:+000, CMP:+001, PTM:20, PRM:[0.0,4.5], CDR:0.2
OBJ_LEP_003 = SRC:[+001,+002], CMP:+002, CDR:0.4, CUT:[1,1]
OBJ_JET_003 = SRC:+002, PTM:25, PRM:[0.0,2.5], CUT:3
OBJ_LEP_004 = SRC:[+000,-003], EMT:-3, CUT:[0,0]
OBJ_JET_004 = SRC:+003, CUT:[3,UNDEF,-1]
OBJ_JET_005 = SRC:+003, PTM:80, CUT:[0,3]
OBJ_JET_006 = SRC:+005, PTM:100, CUT:1
****** Event Selection *******
EVT_MET = CUT:250
EVT_MHT_001 = LEP:003, JET:004
EVT_MEF_001 = MET:000, MHT:001
EVT_REF_001 = NUM:000, DEN:001, CUT:0.3
EVT_LTM_001 = LEP:003, MET:000, CUT:100
EVT_MHT_002 = LEP:003, JET:003
EVT_MEF_002 = MET:000, MHT:002, CUT:1200
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