High Scale Supersymmetry and F-theory GUTs

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The hierarchy problem

The hierarchy problem is perhaps the primary concern for theories of beyond the standard model physics.

Proposed solutions to hierarchy problem can be classified into:

- (Low scale) Supersymmetry
- New strong dynamics (e.g. Technicolor, Extra-dimensions. . .)
- Environmental selection

Environmental selection

Assume fixed gauge and Yukawa couplings and the Higgs VEV scans.

Requiring the existence of Hydrogen and complex nuclei leads to a tight anthropic window for the Higgs VEV:

$$0.39 < \frac{v}{v_{\rm obs}} < 1.64.$$

If the Higgs VEV is too small, then $m_p > m_n$ due to EM interactions.

If the Higgs VEV is too large, then heavy nuclei disintegrate because the attractive nuclear central potential is too weak.

Damour & Donoghue [arXiv:0712.2968].

Motivation for model building

Assume environmental selection explains the hierarchy problem.

Then what motivates model building beyond the Standard Model?

- Dark matter
- Neutrino masses
- Strong CP problem
- Gauge coupling unification
- (High scale) supersymmetry

This talk will focus mainly on the latter two points.

High scale SUSY and Split SUSY

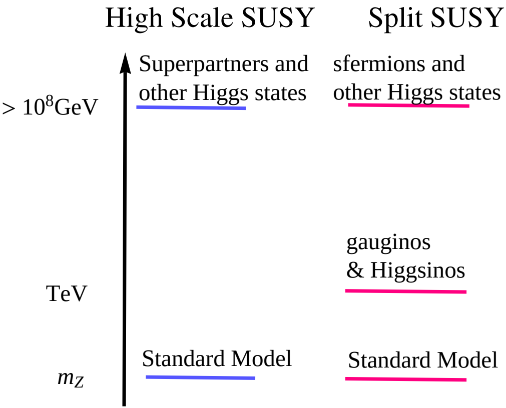
- The low energy spectra, accessible at the LHC, of these models feature only the SM states with a single Higgs.
- One linear combination of the two Higgs scalars is tuned light

$$h = \sin\beta h_u + \cos\beta h_d^*$$

- Hall & Nomura: The superpartners have masses at the SUSY breaking scale, which is assumed to be high: $M_{\rm SUSY} \gg$ TeV.
- Motivated by precision unification and an LSP DM candidate, Split SUSY has weak scale Higgsinos and gauginos.

Hall & Nomura [0910.2235]
Arkani-Hamed & Dimopoulos [0405159]
Giudice & A. Romanino [0406088]

High scale SUSY and Split SUSY



We focus here on the case of High Scale SUSY.

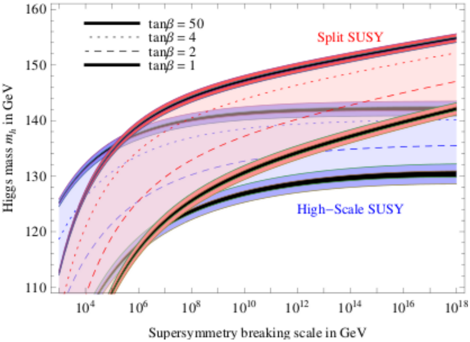
Higgs mass predictions from High Scale SUSY

Remarkably High Scale SUSY models can give predictions of m_H.

This can be calculated as the quartic Higgs coupling is fixed by the SUSY boundary condition at the scale $M_{\rm SUSY}$ (assuming MSSM)

$$\lambda_H(M_{\rm SUSY}) = \left(\frac{g^2+g'^2}{8}\right)\cos^2 2\beta$$

Then running the couplings from $M_{\rm SUSY}$ to the weak scale, to determine m_H.



Giudice & Strumia [arXiv:1108.6077]

The motivation for GUTs in High Scale SUSY

GUTs provide a strong organising principle for SM matter content.

SU(5) representations decompose into SU(3)×SU(2)×U(1) as:

$$
\begin{aligned}
\mathbf{24} &\to (8,1)_0 + (1,3)_0 + (1,1)_0 + (3,2)_{-5/6} + (\overline{3},2)_{5/6} \\
\overline{\mathbf{5}} &\to (\overline{3},1)_{1/3} + (1,2)_{-1/2} && (d \text{ and } l) \\
\mathbf{10} &\to (3,2)_{1/6} + (\overline{3},1)_{-2/3} + (1,1)_1 && (Q,\ u \text{ and } e)
\end{aligned}
$$

Consider a counter argument:

The SM matter content can arise by demands of anomaly cancellation.

$$
\mathrm{SU}(2)^2\mathrm{U}(1): \quad \sum_{\square \text{ of } \mathrm{SU}(2)} Y_i = 0\,, \qquad \mathrm{U}(1)^3: \quad \sum_{\text{all repr.}} Y_i^3 = 0\,,
$$

$$
\mathrm{SU}(3)^2\mathrm{U}(1): \quad \sum_{\square \text{ of } \mathrm{SU}(3)} Y_i = 0\,, \qquad \mathrm{G}^2\mathrm{U}(1): \quad \sum_{\text{all repr.}} Y_i = 0\,.
$$

GUTs in the absence of TeV SUSY

Restricts the combinations of representations to only the following minimal spectra

$$\mathbf{I}: \quad (3,2)_{1/6} \oplus (\overline{3},1)_{-2/3} \oplus (\overline{3},1)_{1/3} \oplus (1,2)_{-1/2} \oplus (1,1)_{1}$$

$$\mathbf{II}: \quad (3,2)_{Y} \oplus (\overline{3},1)_{-Y-1/2} \oplus (\overline{3},1)_{-Y+1/2} \oplus (1,2)_{-3Y} \oplus (1,1)_{3Y-1/2} \oplus (1,1)_{3Y+1/2}$$

$$\mathbf{III}: \quad (3,2)_{Y} \oplus (\overline{3},2)_{-Y-1/2} \oplus (\overline{3},2)_{-Y+1/2} \oplus (3,2)_{-Y} \oplus (\overline{3},2)_{Y-1/2} \oplus (\overline{3},2)_{Y+1/2} .$$

Foot, Lew, Volkas, Joshi (1989)
Knochel, Wetterich, [1106.2609]

It is easy to accept that we could live in case **I** by pure accident.

As a result, the motivation for GUTs as an organizing principle appears to be lost.

However, a puzzle remains:

If the choice is accidental, it is surprising that it is replicated thrice in the generation structure.

Instead, some combination of the different anomaly free choices above appears more likely.

On the contrary, the replicated structure is automatically in SU(5) and SO(10) GUTs.

High scale SUSY, GUTs, and String Theory

As High Scale SUSY is motivated by string theory (rather than weak scale physics) hints and constraints from the string theory should inform the model building.

Following from this point, we have argued for the importance of GUTs.

Notably, UV completion of GUTs into string theory is non-trivial.

Focusing on type IIB which are the best understood from the POV of moduli stabilisation.

It is difficult to construct realistic GUT models in type IIB.

Typically the matter content or Yukawa couplings are inappropriate to match the SM.

F-theory provides a particularly promising possibility, as it over comes these problems.

It also leads to high scale threshold corrections which are, in principle, calculable.

Ibanez, *et al* [1206.2655]
Hebecker, JU [1405.XXXX]

Pragmatic overview of F-theory models

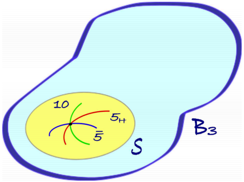
In strongly coupled type IIB theory $\tau \equiv g_s + iC_0$ can vary strongly over the internal space.

F-theory is a 12d string theory where the extra 2 dimensions describe the variation of τ.

The strength of this picture is that powerful tools from algebraic geometry can be applied.

After compactification SM matter resides on 2D sub-manifolds, *matter curves*, within a 4d manifold, the *GUT brane*, on which SU(5) gauge fields are localised.

Couplings between states are determined by the overlap of their associated wavefunctions, which describe the localisation in the compact dimensions



Beasley, Heckman, Vafa [0806.0102], [0802.3391]

Donagi and Wijnholt [0802.2969]

Ibaneza, Marchesano, Regalado, Valenzuela [1206.2655]

Reviews: Heckman [1001.0577], Weigand [1009.3497]

Unification in High Scale SUSY

In traditional weak scale MSSM the gauge coupling RGEs are of the form

$$\alpha_i^{-1}(m_Z) = \alpha_{\mathrm{GUT}}^{-1} + \frac{1}{2\pi} b_i^{\mathrm{MSSM}} \log\left(\frac{M_{\mathrm{GUT}}}{m_Z}\right)$$

High Scale SUSY introduces a new scale M_{SUSY} which affects the running

$$\alpha_i^{-1}(m_Z) = \alpha_{\mathrm{GUT}}^{-1} + \frac{1}{2\pi} b_i^{\mathrm{SM}} \log\left(\frac{M_{\mathrm{SUSY}}}{m_Z}\right) + \frac{1}{2\pi} b_i^{\mathrm{MSSM}} \log\left(\frac{M_{\mathrm{GUT}}}{M_{\mathrm{SUSY}}}\right)$$

In the limit $M_{\mathrm{SUSY}} \to M_{\mathrm{GUT}}$ unification is SM-like.

The quality of unification deteriorates as the SUSY scale is raised.

In F-theory GUTs this is perturbed by high scale threshold corrections.

F-theory threshold corrections: Tree level

Realistic F-theory models feature multiple U(1)'s with flux.

That is a non-trivial field strength for the U(1) along the compact dimensions.

The hypercharge f_Y contribution to SM gauge couplings is non-universal and breaks SU(5).

This flux breaking leads to well-defined UV threshold corrections to SM gauge coupling RGEs.

$$\delta_i^{\text{tree}} = \frac{\gamma}{g_s} b_i^H$$

Coefficient γ depends (in complicated manner) on the various fluxes and vacuum configuration

$$\gamma = -\int_S \left[\frac{1}{10} f_Y \wedge f_Y + f_Y \wedge f_S \right]$$

Flux quantisation implies f_S and f_Y are quantised and γ is naturally $\mathcal{O}(1)$.

Blumenhagen [0812.0248]

Mayrhofer, Palti, Weigand [1303.3589]

F-theory threshold corrections: Loop level

There are also loop level corrections of the form

$$\delta_i^{\text{loop}} = \frac{1}{2\pi} b_i^{5/6} \log\left(\frac{\Lambda}{M_{\text{KK}}}\right)$$

Can be given in terms of divergences of local string construction are cancelled only in the bulk.

As these divergences are logarithmic they can be recast in the form of RGE running.

Donagi, Wijnholt [0808.2223]

Conlon [0901.4350]

If the divergences are cancelled in a slightly larger neighbourhood around the local construction then $\Lambda \sim T_s \mathcal{V}_{\text{GUT}}^{1/4} l_s$ (where $T = 1/(2\pi\alpha')$ is the string tension) and

$$\log\left(\frac{\Lambda}{M_{\text{KK}}}\right) = \log\left(\frac{2\pi \mathcal{V}_{\text{GUT}}^{1/4}}{2\pi \mathcal{V}_{\text{GUT}}^{-1/4}}\right) = \frac{1}{2}\log\left(\frac{1}{2\alpha_{\text{GUT}}}\right) \simeq 1.2$$

whereas if the tadpoles are only cancelled in the complete global model $\Lambda = T_s \mathcal{V}^{1/6} l_s$ and

$$\log\left(\frac{\Lambda}{M_{\text{KK}}}\right) = \log\left(\frac{2\pi \mathcal{V}^{1/6}}{2\pi \mathcal{V}_{\text{GUT}}^{-1/4}}\right) = \frac{1}{6}\log\left(\frac{\pi}{2\alpha_{\text{GUT}}}\frac{M_{\text{Pl}}^2}{M_{\text{GUT}}^2}\right) \simeq 4.4$$

Gauge coupling RGEs with F-theory corrections

Putting this together the RGEs can be written in terms of

$$\alpha_i^{-1}(m_Z) = \alpha_{\rm GUT}^{-1} + \frac{1}{2\pi} b_i^{\rm MSSM} \log\left(\frac{M_{\rm KK}}{m_Z}\right) + \delta_i^{\rm MSSM} + \delta_i^{\rm tree} + \delta_i^{\rm loop}$$

where $M_{\rm KK} \equiv M_{\rm GUT}$ and the corrections are given by

$$\delta_i^{\rm tree} = \frac{\gamma}{g_s} b_i^H$$

$$\delta_i^{\rm loop} = \frac{1}{2\pi} b_i^{5/6} \log\left(\frac{\Lambda}{M_{\rm KK}}\right)$$

$$\delta_i^{\rm MSSM} = \frac{1}{2\pi}\left(b_i^{\rm SM} - b_i^{\rm MSSM}\right) \log\left(\frac{M_{\rm SUSY}}{m_Z}\right)$$

The signs and magnitudes of the F-theory threshold corrections can be appropriate to counter the effect of raising the SUSY scale and thus unification can be maintained in High Scale SUSY.

The GUT scale with F-theory threshold corrections

Assuming the δ_i are such that the correct low-energy values of the SM gauge couplings are reproduced, the RGEs can be solved for $M_{\rm GUT}$ in three different but equivalent ways:

$$\frac{1}{2\pi}\log\left(\frac{M_{\rm GUT}}{m_Z}\right) = \frac{1}{2\pi}\log\left(\frac{M_{\rm GUT}^{(0)}}{m_Z}\right) + \Delta_{ij}$$

Here $M_{\rm GUT}^{(0)}$ is the GUT scale in the absence of corrections (i.e. $\delta_i = 0$) and

$$\Delta_{ij} = \frac{\delta_j - \delta_i}{b_i^{\rm MSSM} - b_j^{\rm MSSM}}$$

Evaluating Δ_{ij} explicitly yields

$$\Delta_{12} \simeq \frac{5}{28}\left[\frac{5}{6\pi}\log\left(\frac{M_{\rm SUSY}}{m_Z}\right) + \frac{\gamma}{g_s}\frac{2}{5} - \frac{1}{\pi}\log\left(\frac{\Lambda}{M_{\rm GUT}^{(0)}}\right)\right]$$

$$\Delta_{23} \simeq \frac{5}{48}\left[\frac{3}{4\pi}\log\left(\frac{M_{\rm SUSY}}{m_Z}\right) - \frac{\gamma}{g_s} + \frac{1}{2\pi}\log\left(\frac{\Lambda}{M_{\rm GUT}^{(0)}}\right)\right]$$

$$\Delta_{31} \simeq \frac{1}{4}\left[\frac{1}{12\pi}\log\left(\frac{M_{\rm SUSY}}{m_Z}\right) + \frac{\gamma}{g_s}\frac{3}{5} - \frac{3}{2\pi}\log\left(\frac{\Lambda}{M_{\rm GUT}^{(0)}}\right)\right]$$

The GUT scale with F-theory threshold corrections

Evaluating δ_i^{tree} and δ_i^{loop} we find that the loop-level corrections are typically subdominant.

If the δ_i^{loop} are neglected the UV correction is strictly proportional to the vector (2/5, -1, 3/5).

We choose a linear combination of Δ_{ij} so the leading UV threshold corrections δ_i^{tree} drop out

$$\frac{1}{2\pi}\log\left(\frac{M_{\text{GUT}}}{m_Z}\right) = \frac{1}{2\pi}\log\left(\frac{M_{\text{GUT}}^{(0)}}{m_Z}\right) + \Delta_{\text{GUT}}^{\text{SUSY}} + \Delta_{\text{GUT}}^{\text{loop}}$$

with

$$\Delta_{\text{GUT}}^{\text{SUSY}} = -\frac{1}{B^{\text{MSSM}}}\left(\delta_1^{\text{MSSM}} - \frac{3}{5}\delta_2^{\text{MSSM}} - \frac{2}{5}\delta_3^{\text{MSSM}}\right)\log\left(\frac{M_{\text{SUSY}}}{m_Z}\right)$$

$$\Delta_{\text{GUT}}^{\text{loop}} \simeq -\frac{1}{B^{\text{MSSM}}}\left(\delta_1^{\text{loop}} - \frac{3}{5}\delta_2^{\text{loop}} - \frac{2}{5}\delta_3^{\text{loop}}\right)\log\left(\frac{\Lambda}{M_{\text{GUT}}^{(0)}}\right)$$

and

$$B^{\text{MSSM}} \equiv b_1^{\text{MSSM}} - \frac{3}{5}b_2^{\text{MSSM}} - \frac{2}{5}b_3^{\text{MSSM}} = \frac{36}{5}$$

nb. similar to Blumenhagen [0812.0248]

The GUT scale with F-theory threshold corrections

After some manipulation this gives us an expression for the GUT scale.

$$M_{\mathrm{GUT}} \simeq M_{\mathrm{GUT}}^{(0)} \times \left(\frac{m_Z}{M_{\mathrm{SUSY}}}\right)^{2/9} \left(\frac{M_{\mathrm{GUT}}^{(0)}}{\Lambda}\right)^{1/3}$$

Minimizing the loop effect by assuming local divergence cancellation, the GUT scale is numerically given by

$$M_{\mathrm{GUT}} \simeq 4.25 \times 10^{15}\ \mathrm{GeV} \left(\frac{10^5\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^{2/9} \left(\frac{3.3}{\Lambda/M_{\mathrm{GUT}}^{(0)}}\right)^{1/3}$$

The GUT coupling can be determined by $\alpha_3(M_{\mathrm{GUT}}) \simeq \alpha_{\mathrm{GUT}}(M_{\mathrm{GUT}})$ (neglecting F-theory correction here)

$$\begin{aligned}
\alpha_{\mathrm{GUT}}^{-1} &\simeq \alpha_3^{-1}(m_Z) + \frac{1}{2\pi}\left[b_3^{\mathrm{MSSM}} \log\left(\frac{M_{\mathrm{SUSY}}}{M_{\mathrm{GUT}}}\right) + b_3^{\mathrm{SM}} \log\left(\frac{m_Z}{M_{\mathrm{SUSY}}}\right)\right] \\
&\simeq 28 + \frac{10}{6\pi} \log\left(\frac{M_{\mathrm{SUSY}}}{10^5\ \mathrm{GeV}}\right) ,
\end{aligned}$$

Limits from proton decay

X, Y gauge boson exchange leads to dimension 6 operators which can mediate proton decay suppressed by the GUT scale.

$$\Gamma^{X,Y}_{p\to\pi^0 e^+} \simeq \mathcal{C} \times \left(\frac{\alpha^2_{\rm GUT} m_p^5}{M^4_{\rm GUT}} \right)$$

From the GUT coupling and GUT scale derived just, we can calculate the proton decay rate.

$$\tau^{X,Y}_{p\to\pi^0 e^+} \simeq 3 \times 10^{41}\ {\rm s}\ \left(\frac{30\ {\rm TeV}}{M_{\rm SUSY}}\right)^{8/9} \left(1 + \frac{10}{168\pi} \log\left[\left(\frac{M_{\rm SUSY}}{30\ {\rm TeV}}\right)\right]\right)^2$$

The relevant experimental lower bound on the proton lifetime is

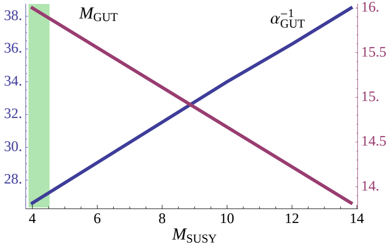
$$\tau(p \to \pi^0 e^+) > 2.5 \times 10^{41}{\rm s}$$

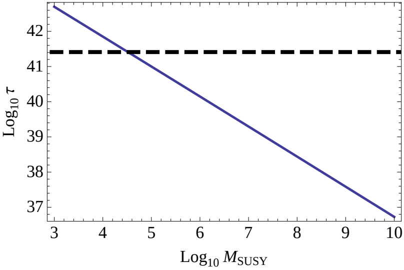
Limits from proton decay

$$\tau^{X,Y}_{p\to\pi^0 e+} \simeq 3\times 10^{41}\ \mathrm{s}\left(\frac{30\ \mathrm{TeV}}{M_{\rm SUSY}}\right)^{8/9}\left(1+\frac{10}{168\pi}\log\left[\left(\frac{M_{\rm SUSY}}{30\ \mathrm{TeV}}\right)\right]\right)^2 > 2.5\times 10^{41}\ \mathrm{s}$$

To avoid fast proton decay in F-SU(5) High Scale SUSY the SUSY scale must be sub-100 TeV.

(With a few caveats, such as non-minimal spectra, large additional UV threshold corrections, or substantial suppressions in the proton decay rate).





Suppression of ground state mediated proton decay

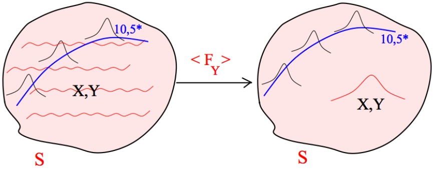
There is an interesting proposal for the suppressing proton decay in F-theory by [1206.2655].

Prior to flux breaking the X, Y gauge field propagate over the GUT 4-cycle.

Post-breaking the X, Y become localised at a point and may be separated from the SM matter.

The coupling between the X, Y bosons and the SM matter (relevant for proton decay) is determined by the wavefunction overlap and here is exponentially suppressed.

$$Y_U = \int_S \Psi_{10}\Psi_{10}\Phi_{X,Y} \qquad Y_D = \int_S \Psi_{\bar{5}}\Psi_{10}\Phi_{X,Y}$$



Ibaneza, Marchesano, Regalado, Valenzuela [1206.2655]

But this simple picture is not the whole story: it neglects flux, compactness and higher modes.

Suppression of ground state mediated proton decay

This point can be made most easily in 6d. Starting from an 8d theory on T^4, we take 2 dimensions small, reducing to a 6d gauge theory on T^2: a torus with volume $L_5 \times L_6$.

For a constant background field $F_{56} \equiv \partial_5 A_6 - \partial_6 A_5 = H$ the component fields are

$$A_5 = 0\,, \qquad\qquad A_6 = Hx_5$$

The field A_μ is periodic in x_5 up to a gauge transformation,

$$A_\mu(x_5 + L_5) = A_\mu(x_5) - ie^{-i\theta}\partial_\mu e^{i\theta}\,, \qquad\qquad \theta = HL_5 x_6$$

Demanding this is single-valued in x_6-direction leads to the quantisation condition

$$H = \frac{2\pi N}{L_5 L_6}$$

The 4d spectrum of the model is determined by the Laplacian,

$$(D_5^2 + D_6^2)\Phi_n = \left[\partial_5^2 + (\partial_6 + Hx_5)^2\right]\Phi_n = M_n^2 \Phi_n$$

The set of ground state wavefunctions $\Phi_0^{(j)}$ can be expressed as

$$\Phi_0^{(j)} = \sum_{m=-\infty}^{\infty} \exp\left[-\frac{\pi N}{L_5 L_6}\left(x_5 - \left(m + \frac{j}{N}\right)L_5\right)^2\right] \exp\left[2\pi i\,(Nm + j)\,\frac{x_6}{L_6}\right]\,.$$

Bachas [hep/th9503030]

Suppression of ground state mediated proton decay

Regarding the ground state wave function in the presence of flux

$$\Phi_0^{(j)} = \sum_{m=-\infty}^{\infty} \exp\left[-\frac{\pi N}{L_5 L_6}\left(x_5 - \left(m + \frac{j}{N}\right) L_5\right)^2\right] \exp\left[2\pi i \left(Nm + j\right) \frac{x_6}{L_6}\right]$$

By relabelling m it can be seen that the spectrum features an N-fold degeneracy: $\Phi^{(j)} = \Phi^{(j+N)}$

Wavefunctions is a superposition of N Gaussians distributed evenly along x_5 with width

$$d = \sqrt{\frac{L_5 L_6}{2\pi N}}$$

Thus the SM fields can not be located arbitrarily far from the X, Y localisation points.

To suppress proton decay must be to find regions where all of these wavefunctions vanish:

$$\frac{Nd}{L_5} = \sqrt{\frac{L_6}{L_5} \cdot \frac{N}{2\pi}} \ll 1$$

Thus forced into the effectively one-dimensional regime $L_6/L_5 \ll 1$ (a 'thin' torus).

Suppression of ground state mediated proton decay

The most promising geometry is the effectively 1-dimensional limit where $L_6 \ll L_5$.

We now focus on a 5d theory compactified on S^1 with volume L_5.

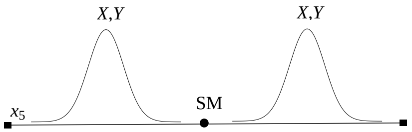
N ground state X, Y wavefunctions: Gaussians localized at N equally spaced positions along x.

Proton decay mediated by ground state suppressed for SM matter positioned between two peaks.

Fix the origin at the closest peak to SM matter curve and consider patch $|x| \leq L_5/2N$

$$\Phi_0 \sim \exp\left(-\frac{x^2}{2d^2}\right)$$

The next peak is at $x = L_5/N$.



Proton decay mediated by high modes

But now lets look at the higher modes.

Start from 1d internal Laplace equation describing the behaviour of the field in the x_5

$$\left[-\partial_x^2 - M(x)^2\right] \Phi_n(x) = m_n^2 \Phi_n(x)$$

with $M(x) = Hx$. The ground state $\Phi_0 \sim \exp\left(-Hx^2/2\right)$ is a solution, since $H = 1/d^2$.

We can make an analogy with the harmonic oscillator, from which we know the spectrum

$$m_n^2 = 2H\left(n + \frac{1}{2}\right)$$

and the higher modes can be found by operating on Φ_0 with the following ladder operators

$$a = \sqrt{\frac{d}{2}}\left(x_5 + d^2\frac{\mathrm{d}}{\mathrm{d}x_5}\right) \qquad a^\dagger = \sqrt{\frac{d}{2}}\left(x_5 - d^2\frac{\mathrm{d}}{\mathrm{d}x_5}\right)$$

to obtain the wave functions for the higher modes in terms of the Hermite polynomials H_n

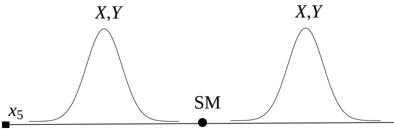
$$\Phi_n(x) \sim H_n\left(\frac{x}{d}\right)\exp\left(-\frac{x^2}{2d^2}\right)$$

Proton decay in F-theory

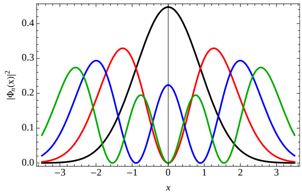
Thus the ground state and higher modes are described by

$$\Phi_0 \sim \exp\left(-\frac{x^2}{2d^2}\right)$$

$$\Phi_n(x) \sim H_n\left(\frac{x}{d}\right)\exp\left(-\frac{x^2}{2d^2}\right)$$



The Hermite polynomial acts to shift the position of the peak for each subsequent mode. The maxima are dense over x_5.



Thus even in the case that the ground state wavefunction overlap with the SM fields is negligible, some higher modes will have substantial overlap with the matter curve.

Generically, (at best) the proton decay rate can pick up an $O(1)$ suppression from localisation effects of the X, Y.

The prospect of light triplet Higgses

It is interesting to ask if the triplet Higgses can be at $M_{\rm SUSY}$.

If the triplet Higgs states survive below the GUT scale then this leads to rapid proton decay via dimension five and six effective operators.

The partial proton lifetime due to these operators involving the scalar triplet Higgs are

$$\tau^{T}_{p\to K^+\overline{\nu}} \simeq 1.2\times 10^{41}~{\rm s}~\sin^4 2\beta \left(\frac{M_{\rm SUSY}}{30~{\rm TeV}}\right)^2 \left(\frac{m_T}{3\times 10^{15}~{\rm GeV}}\right)^2 \gtrsim 2\times 10^{40}~{\rm s}$$

Recall the limit from X, Y mediated proton decay

$$\tau^{X,Y}_{p\to\pi^0 e^+} \simeq 3\times 10^{41}~{\rm s}~\left(\frac{30~{\rm TeV}}{M_{\rm SUSY}}\right)^{8/9} \left(1+\frac{10}{168\pi}\log\left[\left(\frac{M_{\rm SUSY}}{30~{\rm TeV}}\right)\right]\right)^2 > 2.5\times 10^{41}~{\rm s}$$

Thus unless there are substantial suppressions in some couplings, the triplet Higgses must be near the GUT scale.

Correlated signals

Even with heavy triplets there is still the prospect for multiple signals of proton decay.

Dimension six proton decay due to X, Y boson could be detected if $\tau^{(6)}_{p\to\pi^0 e+} \sim 10^{42\pm1}$ s.

$$\tau^{X,Y}_{p\to\pi^0 e+} \simeq 3\times10^{41}\ \mathrm{s}\ \left(\frac{30\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^{8/9}\left(1+\frac{10}{168\pi}\log\left[\left(\frac{M_{\mathrm{SUSY}}}{30\ \mathrm{TeV}}\right)\right]\right)^2 > 2.5\times10^{41}\ \mathrm{s}$$

Further, dimension five proton decay could be detected if $\tau^{(5)}_{p\to K+\overline{\nu}} \sim 10^{41\pm1}$ s

$$\tau^{T}_{p\to K+\overline{\nu}} \simeq 1.2\times10^{41}\ \mathrm{s}\ \sin^4 2\beta\left(\frac{M_{\mathrm{SUSY}}}{30\ \mathrm{TeV}}\right)^2\left(\frac{m_T}{3\times10^{15}\ \mathrm{GeV}}\right)^2 \gtrsim 2\times10^{40}\ \mathrm{s}$$

And projected limits for Hyper-K are 3×10^{42} s and 6×10^{41} s for $p\to e^+\pi^0$ and $p\to K^+\overline{\nu}$.

Summary

Models of High Scale SUSY are an interesting alternative to traditional BSM.

The generation structure of the SM may be an indication of an underlying GUT.

As High Scale SUSY is motivated by string theory hints and constraints from the string theory should inform the model building. F-theory is a promising candidate for a UV completion.

The signs and magnitudes of the F-theory threshold corrections can be appropriate to counter the effect of raising the SUSY scale and thus unification can be maintained in High Scale SUSY.

Proton decay typically can not be suppressed by localisation effects in extra dimensions.

To avoid fast proton decay in F-SU(5) High Scale SUSY the SUSY scale must be sub-100 TeV.