Towards predictive flavour models in SUSY SU(5) GUTs with doublet-triplet splitting

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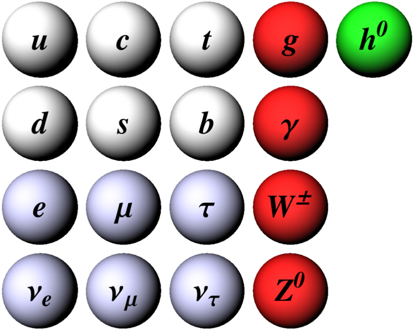
Based on Antusch, de Medeiros Varzielas, V.M., Sluka & Spinrath arXiv:1405.6962

Motivation: Playing Particle Zoo Keeper

1. particles



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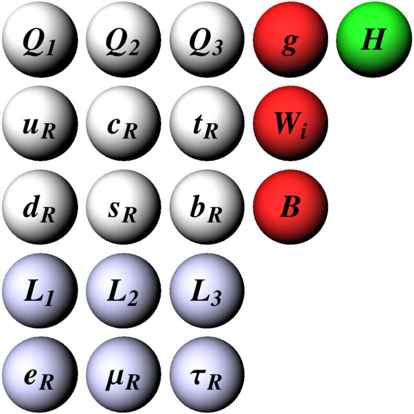
1. particles
2. SM multiplets



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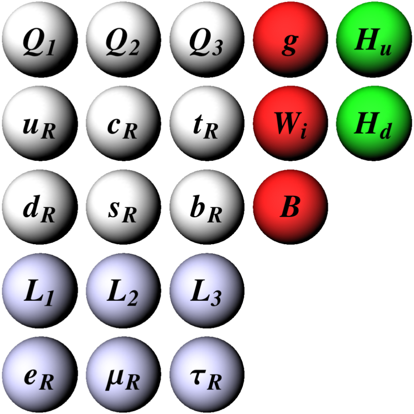
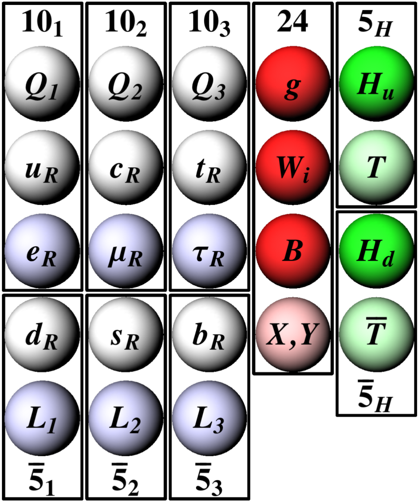


Motivation: Playing Particle Zoo Keeper

1. particles
2. SM multiplets
3. MSSM multiplets
4. GUT multiplets



Challenges

GUT Symmetry Breaking

Make new states heavy enough to suppress proton decay

- X, Y $\Rightarrow$ GUT scale $\gtrsim 10^{16}$ GeV ☑
- T, $\overline{T}$ $\rightarrow$ Doublet-Triplet splitting problem ☐

Solution(s) in 4D SU(5): (Double) Missing Partner Mechanism

[Masiero, Nanopoulos, Tamvakis, Yanagida '82; Grinstein '82; Hisano, Moroi, Tobe, Yanagida '95]

Correct Relations for Flavour Observables

- Yukawa couplings and mixing angles
- Georgi-Jarlskog relations $y_\mu / y_s = 3 = y_d / y_e$ disfavoured

Solved with effective Yukawa couplings from higher dim. operators

$$\Rightarrow y_\mu = 6\, y_s,\ y_e = \tfrac{1}{2}\, y_d \text{ and } y_\tau = \tfrac{3}{2}\, y_b$$

[Antusch, Spinrath '09]

Strategy

The Missing Partner Mechanism

Observation in GUT ⊃ SM embedding

$$\mathbf{5} \to (\mathbf{1},\mathbf{2})_{-\frac{1}{2}} + (\mathbf{3},\mathbf{1})_{\frac{1}{3}}$$

$$\mathbf{50} \to (\mathbf{1},\mathbf{1})_2 + (\mathbf{3},\mathbf{1})_{\frac{1}{3}} + (\bar{\mathbf{3}},\mathbf{2})_{\frac{7}{6}} + (\mathbf{6},1)_{-\frac{4}{3}} + (\bar{\mathbf{6}},\mathbf{3})_{\frac{1}{3}} + (\mathbf{8},\mathbf{2})_{-\frac{1}{2}}$$

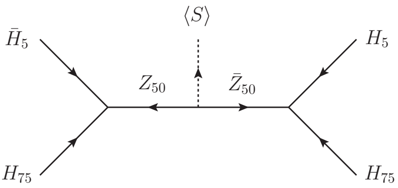
[Masiero, Nanopoulos, Tamvakis, Yanagida '82; Grinstein '82]

$$W_{\text{MPM}} = \bar{H}_5 H_{75} Z_{50} + \bar{Z}_{50} H_{75} H_5 + \langle S \rangle Z_{50} \bar{Z}_{50}$$

$$\Rightarrow$$

$$m_D = (0)$$

$$m_T = \begin{pmatrix} 0 & V \\ V & \langle S \rangle \end{pmatrix}$$



- $\langle H_{75} \rangle$ breaks SU(5) → SM
- Non-trivial charge of S, otherwise $W \supset H_5 H_{75}^2 \bar{H}_5 / M_{\text{Pl}}$

The Missing Partner Mechanism

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$$\mathbf{5} \to (\mathbf{1},\mathbf{2})_{-\frac{1}{2}} + (\mathbf{3},\mathbf{1})_{\frac{1}{3}}$$

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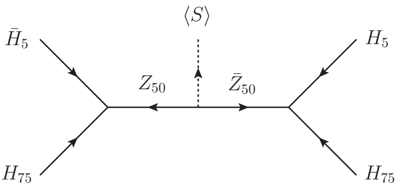

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The Missing Partner Mechanism

$$W_{\text{Yukawa}} = \mathcal{T}_i \mathcal{F}_j \bar{H}_5 + \mathcal{T}_i \mathcal{T}_j H_5$$

Integrate out all colour triplets (T_5, $\bar{T}_5$, T_{50}, $\bar{T}_{50}$) $\Rightarrow$

$$W_{\text{eff}} \supset \frac{1}{M_T^{\text{eff}}} \overbrace{(Q_i Q_j + \bar{U}_i \bar{E}_j)}^{\mathcal{T}_i \mathcal{T}_j} \overbrace{(Q_m L_n + \bar{U}_m \bar{D}_n)}^{\mathcal{T}_m \mathcal{F}_n}$$

with

$$M_T^{\text{eff}} = (m_T^{-1})_{11}^{-1} = \frac{V^2}{\langle S \rangle}$$

Some numbers: $M_T^{\text{eff}} \gtrsim 10^{17}$ GeV, $V \approx 10^{16}$ GeV $\Rightarrow \langle S \rangle \lesssim 10^{15}$ GeV

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Left-overs from 50 and $\overline{\mathbf{50}}$ in RGEs at 10^{15} GeV

Theory becomes non-perturbative much below M_{Pl} ☹

The Double Missing Partner Mechanism

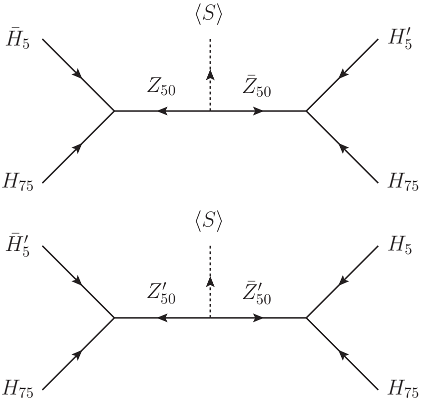
Double the **5**'s and **50**'s with H'_5, $\bar{H}'_5$, Z'_{50}, $\bar{Z}'_{50}$!

[Hisano, Moroi, Tobe, Yanagida '95]

$$\begin{aligned} W_{\text{DMPM}} &= \bar{H}_5 H_{75} Z_{50} + \bar{Z}_{50} H_{75} H'_5 \\ &+ \bar{H}'_5 H_{75} Z'_{50} + \bar{Z}'_{50} H_{75} H_5 \\ &+ \langle S \rangle Z_{50} \bar{Z}_{50} + \langle S \rangle Z'_{50} \bar{Z}'_{50} \\ &+ \langle S_{\mu'} \rangle H'_5 \bar{H}'_5 \\ &\Rightarrow \end{aligned}$$

$$m_D = \begin{pmatrix} 0 & 0 \\ 0 & \langle S_{\mu'} \rangle \end{pmatrix}$$

$$m_T = \begin{pmatrix} 0 & 0 & 0 & V \\ 0 & \langle S_{\mu'} \rangle & V & 0 \\ V & 0 & \langle S \rangle & 0 \\ 0 & V & 0 & \langle S \rangle \end{pmatrix}$$



Again only H_5, $\bar{H}_5$ couple to SM matter

The Double Missing Partner Mechanism

Analogous to MPM

$$M_T^{\text{eff}} = (m_T^{-1})_{11}^{-1} = \frac{V^4}{\langle S \rangle^2 \langle S_{\mu'} \rangle}$$

Some numbers:

$$M_T^{\text{eff}} \sim 10^{17}\ \text{GeV},\ V \approx 10^{16}\ \text{GeV},\ \langle S_{\mu'} \rangle \approx 10^{11}\ \text{GeV}$$

$$\Rightarrow \langle S \rangle \approx 10^{18}\ \text{GeV}$$

50 and $\overline{\mathbf{50}}$ in RGEs at 10^{18} GeV

Theory perturbative up to (almost) M_{Pl} ☺

The Double Missing Partner Mechanism

Analogous to MPM

$$M_T^{\text{eff}} = (m_T^{-1})_{11}^{-1} = \frac{V^4}{\langle S \rangle^2 \langle S_{\mu'} \rangle} \approx \frac{M_T^2}{\mu'}$$

Some numbers:

$$M_T^{\text{eff}} \sim 10^{17}\ \text{GeV},\ V \approx 10^{16}\ \text{GeV},\ \langle S_{\mu'} \rangle \approx 10^{11}\ \text{GeV}$$

$$\Rightarrow \langle S \rangle \approx 10^{18}\ \text{GeV}$$

$\mathbf{50}$ and $\overline{\mathbf{50}}$ in RGEs at 10^{18} GeV

Theory perturbative up to (almost) M_{Pl} ☺

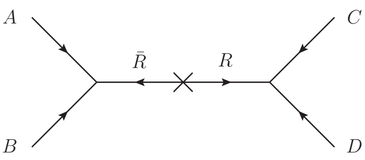
Yukawa Coupling Ratios

- Higher dim. effective operators for Yukawa couplings with $\langle H_{24} \rangle$
  $\Rightarrow$ GUT breaking effects proportional to hypercharge
- Only predictive if index contraction is fixed:

$$W \supset (AB)_{\mathbf{R}}(CD)_{\bar{\mathbf{R}}}$$

  using messenger fields in SU(5) irrep **R**
- Used ratios:

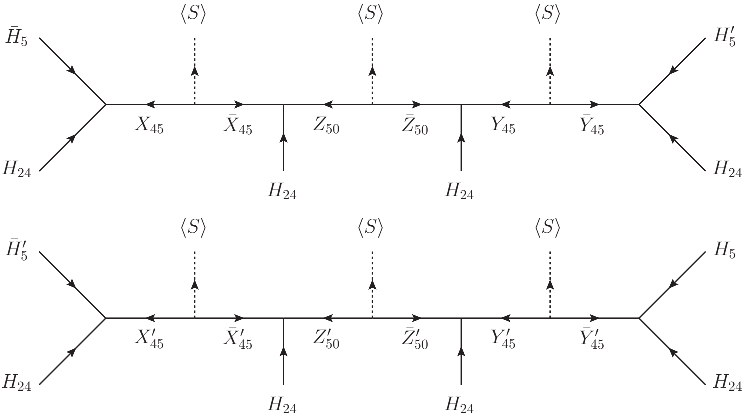
$A\,B$	$C\,D$	$\mathbf{R}$	$(Y_e)_{ji}/(Y_d)_{ij}$
$H_{24}\,\mathcal{F}$	$\mathcal{T}\,\bar{H}_{45}$	$\overline{\mathbf{45}}$	$-\frac{1}{2}$
$H_{24}\,\mathcal{F}$	$\mathcal{T}\,\bar{H}_{5}$	$\bar{\mathbf{5}}$	$-\frac{3}{2}$
$H_{24}\,\mathcal{T}$	$\mathcal{F}\,\bar{H}_{5}$	$\mathbf{10}$	6



[Antusch, Spinrath '09]

Double Missing Partner with a **24**

Replace $H_{75} \to H_{24}^2/\Lambda$



Additional messenger sector: X_{45}, $\bar{X}_{45}$, Y_{45}, $\bar{Y}_{45}$, X'_{45}, $\bar{X}'_{45}$, Y'_{45}, $\bar{Y}'_{45}$

[Zhang, Zheng '12]

Grand Unification and its Breaking

The Need for two **24**'s

Minimal SU(5):

- Single **24** contains one SU(2) triplet and one SU(3) octet that obtain equal masses
- Gauge coupling unification needs $M_T \sim 10^{15}$ GeV ☹

[Murayama, Pierce '02]

- Non-renormalizable terms for **24** $\Rightarrow$ split triplet and octet $\Rightarrow$ higher M_T possible

[Bajc, Perez, Senjanovic '02]

$\rightarrow$ generate higher dim. operator with second **24**

The Need for two **24**'s

Not taking the limit where one **24** is heavy and the other isn't:

- Additional SU(2) triplet and SU(3) octet (and leptoquark superfield) gives more freedom in GUT threshold corrections
- More possible choices for superpotentials that do not reduce to non-renormalizable single **24** versions

Intended Yukawa coupling ratios require **24** with non-trivial charge under some "shaping symmetry"

- Single **24** renormalizable superpotential that breaks SU(5) has no shaping symmetry
- Adding another **24** allows for shaping symmetry and VEV

Introduce H'_{24} in addition to H_{24}

[Antusch, de Medeiros Varzielas, VM, Sluka, Spinrath arXiv:1405.6962]

GUT Breaking Superpotentials with two **24**'s

Requirements:

renormalizable, VEVs for both **24**'s, no massless states in vacuum

(a) $W = M_{24}\ \mathrm{tr}\, H_{24}^2 + M'_{24}\ \mathrm{tr}\, H'^2_{24} + \kappa'\ \mathrm{tr}\, H_{24} H'^2_{24} + \lambda\ \mathrm{tr}\, H_{24}^3$,
$\mathbb{Z}_2$ with $Q(H_{24}) = 0$ and $Q(H'_{24}) = 1$.

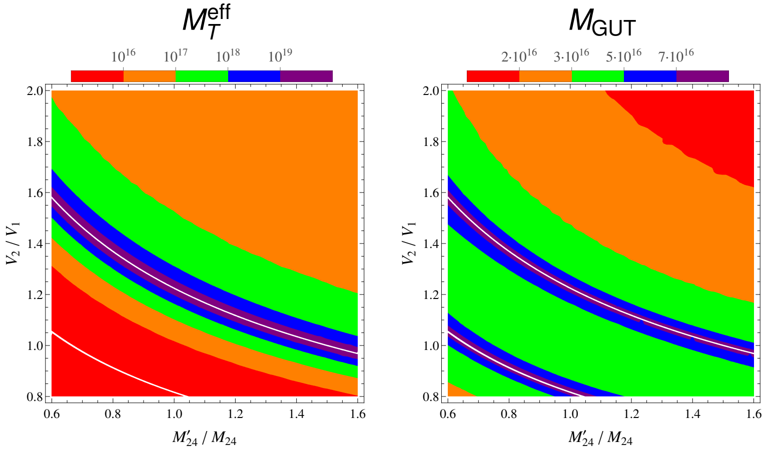
(b) $W = \tilde{M}_{24}\ \mathrm{tr}\, H_{24} H'_{24} + \lambda\ \mathrm{tr}\, H_{24}^3 + \lambda'\ \mathrm{tr}\, H'^3_{24}$,
$\mathbb{Z}_3$ with $Q(H_{24}) = 2$ and $Q(H'_{24}) = 1$.

(c) $W = \tilde{M}_{24}\ \mathrm{tr}\, H_{24} H'_{24} + \lambda\ \mathrm{tr}\, H_{24}^3 + \kappa'\ \mathrm{tr}\, H_{24} H'^2_{24}$,
$\mathbb{Z}_4^R$ with $Q(H_{24}) = 2$ and $Q(H'_{24}) = 0$ (and $Q(\theta) = 1$).

(d) The trivial case with no additional shaping symmetry.

Grand Unification: Two Loop Analysis

(a) $W = M_{24}\ \mathrm{tr}\, H_{24}^2 + M'_{24}\ \mathrm{tr}\, H'^2_{24} + \kappa'\ \mathrm{tr}\, H_{24} H'^2_{24} + \lambda\ \mathrm{tr}\, H_{24}^3$



$M_{\mathrm{SUSY}} = 1$ TeV, $M = \sqrt{|M_{24}|^2 + |M'_{24}|^2} = 10^{15}$ GeV and equal phases for V_1, V_2 and M_{24}, M'_{24}

White stripes: $M_{T(24)}$ or $M_{O(24)} < 10^{13}$ GeV

Grand Unification: Two Loop Analysis

(b) $W = \tilde{M}_{24}\ \mathrm{tr}\, H_{24} H'_{24} + \lambda\ \mathrm{tr}\, H_{24}^3 + \lambda'\ \mathrm{tr}\, H'^3_{24}$

(c) $W = \tilde{M}_{24}\ \mathrm{tr}\, H_{24} H'_{24} + \lambda\ \mathrm{tr}\, H_{24}^3 + \kappa'\ \mathrm{tr}\, H_{24} H'^2_{24}$

$$M_T^{\text{eff, 2-loop}} = \left(\frac{M_{\text{SUSY}}}{1\ \text{TeV}}\right)^{0.74} \cdot \begin{cases} 5.4 \cdot 10^{16}\ \text{GeV} \left(\frac{M}{10^{15}\ \text{GeV}}\right)^{-0.15} & \text{(b)} \\ 7.1 \cdot 10^{15}\ \text{GeV} \left(\frac{M}{10^{15}\ \text{GeV}}\right)^{-0.19} & \text{(c)} \end{cases}$$

$$M_{\text{GUT}}^{\text{2-loop}} = |\sin 2\beta_V|^{-0.48} \left(\frac{M_{\text{SUSY}}}{1\ \text{TeV}}\right)^{-0.41} \cdot \begin{cases} 2.95 \cdot 10^{16}\ \text{GeV} \left(\frac{M}{10^{15}\ \text{GeV}}\right)^{-0.62} & \text{(b)} \\ 4.89 \cdot 10^{16}\ \text{GeV} \left(\frac{M}{10^{15}\ \text{GeV}}\right)^{-0.64} & \text{(c)} \end{cases}$$

with $\tan\beta_V \equiv \frac{V_1}{V_2}$.

Some numbers: $M_T^{\text{eff}} \gtrsim 10^{17}$ GeV

$$\Rightarrow M_{\text{SUSY}} \gtrsim 2.3\ \text{TeV (b)}, 35\ \text{TeV (c)}$$

Flavour GUT Models with DMPM

Model: Diagonal Y_d and Y_e Yukawa Matrices

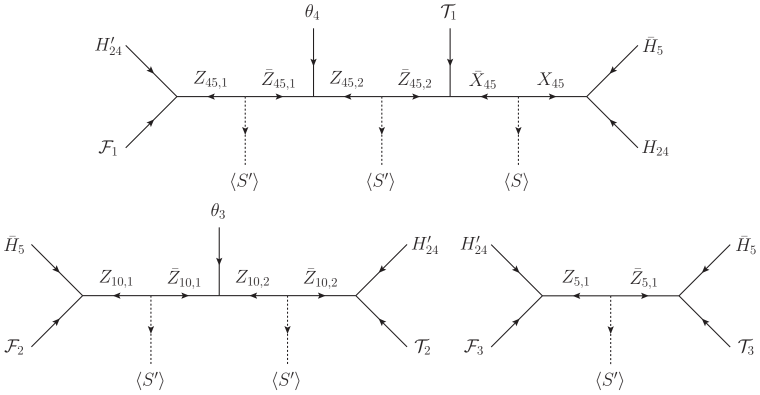
- Yukawa matrix structure:

$$Y_d = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}, \quad Y_e = \begin{pmatrix} -\frac{1}{2} y_d & 0 & 0 \\ 0 & 6 y_s & 0 \\ 0 & 0 & -\frac{3}{2} y_b \end{pmatrix}$$

$$Y_u = \begin{pmatrix} \epsilon_1^2 \epsilon_2^2 & \epsilon_1^2 \epsilon_2 & \epsilon_1 \epsilon_2 \\ \epsilon_1^2 \epsilon_2 & \epsilon_1^2 & \epsilon_1 \\ \epsilon_1 \epsilon_2 & \epsilon_1 & y_{33} \end{pmatrix}$$

- Hierarchy via $\epsilon_i = \frac{\theta_i}{\Lambda}$ with some messenger scale Λ
- For explicit W_u, W_d, see arXiv:1405.6962

Model: Diagonal Y_d and Y_e Yukawa Matrices



- Messenger masses via $\langle S \rangle$, $\langle S' \rangle \Rightarrow$ no corrections to ratios
- Superpotential (a) $\rightarrow \mathbb{Z}_2$ charged H'_{24}, more free M_T^{eff}

Model: Diagonal Y_d and Y_e Yukawa Matrices

Effective/Planck-scale suppressed operators generate μ and μ' with:

$$\mu = \frac{\langle\theta_3\rangle\langle\theta_4\rangle^4}{M_{\text{Pl}}^4}, \; \mu' = \frac{\langle\theta_3\rangle^4}{M_{\text{Pl}}^4},$$

Number example:

$$\langle H_{24}\rangle \sim 2\cdot 10^{16}\ \text{GeV}$$

$$\langle S\rangle \sim 10^{18}\ \text{GeV}$$

$$y_b \sim \frac{\langle H'_{24}\rangle}{\langle S'\rangle} \approx 0.18$$

$$y_s \sim \frac{\langle H'_{24}\rangle\langle\theta_3\rangle}{\langle S'\rangle^2} \approx 3\cdot 10^{-3}$$

$$y_d \sim \frac{\langle H_{24}\rangle\langle H'_{24}\rangle\langle\theta_4\rangle}{\langle S'\rangle^2\langle S\rangle} \approx 1.6\cdot 10^{-4}$$

$$M_T^{\text{eff}} \approx 2\cdot 10^{18}\ \text{GeV}$$

$$\mu \approx \mathcal{O}(100)\ \text{GeV}$$

$$\mu' \approx \mathcal{O}(10)\ \text{TeV}$$

$$M_T \approx 2\cdot 10^{11}\ \text{GeV}$$

[Numbers from Antusch, VM ’13 for tan $\beta = 30$]

Model: Cabibbo Angle θ_C from Y_d (and Y_e)

- Yukawa matrix structure:

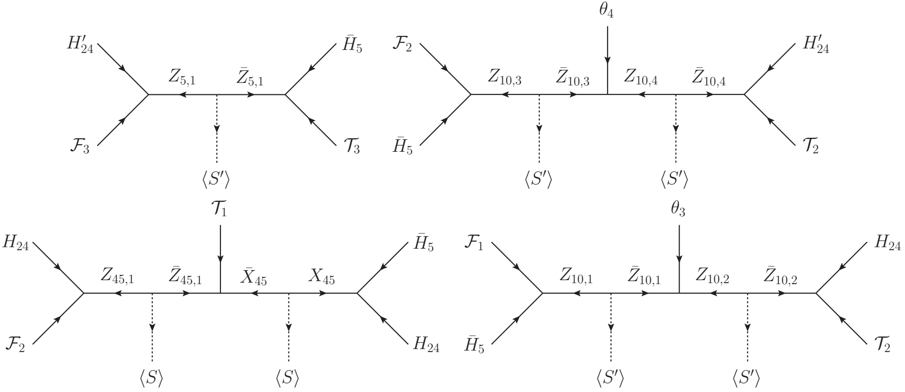
$$Y_d = \begin{pmatrix} 0 & y_{d,12} & 0 \\ y_{d,21} & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}, \quad Y_e = \begin{pmatrix} 0 & 6y_{d,21} & 0 \\ -\frac{1}{2}y_{d,12} & 6y_s & 0 \\ 0 & 0 & -\frac{3}{2}y_b \end{pmatrix}$$

$$Y_u = \begin{pmatrix} y_{11} & y_{12} & 0 \\ y_{12} & y_{22} & y_{23} \\ 0 & y_{23} & y_{33} \end{pmatrix}$$

- $\mathcal{T}_2$ couples to $\mathcal{F}_1$ and $\mathcal{F}_2$ $\Rightarrow$ superpotential (b) to forbid $(Y_d)_{11}$

[Motivated by Antusch, King, Malinsky, Spinrath ’09; Antusch, Gross, VM, Sluka ’13]

Model: Cabibbo Angle θ_C from Y_d (and Y_e)



Number example:

$$M_T^{\text{eff}} \approx 2 \cdot 10^{18}\ \text{GeV}, \qquad M_T \approx 2 \cdot 10^{11}\ \text{GeV}$$
$$\mu \approx \mathcal{O}(300)\ \text{GeV}, \qquad \mu' \approx \mathcal{O}(10)\ \text{TeV}$$

Proton Decay

Proton Decay via Dimension Five Operators

Colour triplets in H_5, $\bar{H}_5$ couple to matter:

$$W_T = \epsilon_{\alpha\beta}\left(-\frac{1}{2}(Y_{qq})_{ij}\epsilon_{abc}T^a Q_i^{\alpha b} Q_j^{\beta c} + (Y_{ql})_{ij}\bar{T}^a Q_i^{\alpha a} L_j^{\beta}\right) + (Y_{ue})_{ij} T^a \bar{U}_i^a \bar{E}_j - (Y_{ud})_{ij}\epsilon_{abc}\bar{T}^a \bar{U}_i^b \bar{D}_j^c + M_T T^a \bar{T}^a \,.$$

Messenger sector also generates specific ratios between

$$Y_{ql}, Y_{ud} \leftrightarrow Y_d \text{ and } Y_{qq}, Y_{ue} \leftrightarrow Y_u$$

Y_{ql}, Y_{ud}, Y_{qq}, Y_{ue} predicted from fit of Y_d, Y_e, Y_u

Proton Decay via Dimension Five Operators

Model with diagonal Y_d and Y_e:

$$Y_{ql} = \text{diag}\left(y_d, y_s, -\frac{3}{2}y_b\right) \qquad Y_{ud} = \text{diag}\left(\frac{2}{3}y_d, -4y_s, y_b\right)$$

$$Y_{qq} = Y_u \qquad Y_{ue} = Y_u$$

Model with Cabibbo angle from Y_d, Y_e:

$$Y_{ql} = \begin{pmatrix} 0 & y_{d,12} & 0 \\ y_{d,21} & y_s & 0 \\ 0 & 0 & -\frac{3}{2}y_b \end{pmatrix} \qquad Y_{ud} = \begin{pmatrix} 0 & \frac{2}{3}y_{d,12} & 0 \\ -4y_{d,21} & -4y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

$$Y_{qq} = Y_u \qquad Y_{ue} = Y_u$$

Extensive table of ratios to triplet Yukawa couplings $\rightarrow$ arXiv:1405.6962

Proton Decay via Dimension Five Operators

$$W_{\not{B}} = \frac{1}{M_T^{\text{eff}}} \left[\frac{1}{2} Y_{qq}^{ij} Y_{ql}^{mn} Q_i Q_j Q_m L_n + Y_{ue}^{ij} Y_{ud}^{mn} \bar{U}_i \bar{E}_j \bar{U}_m \bar{D}_n \right]$$

- $M_T^{\text{eff}} \gtrsim 10^{17}$ GeV due to two **24**'s
- Full control over all 3+4 Yukawa matrices
- Diagonal Y_{ql} and $Y_{ud} \to$ suppressed flavour transitions

RGE running/matching and dressing with superpartner fields:

$$A_{LLLL} \sim \tan\beta \text{ and } A_{RRRR} \sim (\tan\beta)^2$$

$\rightarrow$ $\boxed{\frac{y_\tau}{y_b} = -\frac{3}{2} \text{ needs } \tan\beta \approx 25}$ vs. $\boxed{y_\tau = y_b = y_t \text{ needs } \tan\beta \approx 50}$

Summary and Conclusions

Summary and Conclusions

- DMPM can be successfully combined with predictive Yukawa coupling ratios using novel CG factors
- Adding another **24** allows for high enough M_T^{eff} to avoid problems with proton decay
- Adjoint field charged under shaping symmetry allows predictive Yukawa coupling ratios
- No danger from M_{Pl} suppressed operators due to charge assignment and messenger UV completion

End of the Talk

Thank you for your attention!