Unification with TeV Scale Lepton Number Violation

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Work with I. Gogoladze and C. Kolda

Structure of Matter Multiplets

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = (u_1^c \quad u_2^c \quad u_3^c) \sim (\bar{3}, 1, \frac{-2}{3})$$

$$d^c = (d_1^c \quad d_2^c \quad d_3^c) \sim (\bar{3}, 1, \frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

$$e^c \sim (1, 1, +1)$$

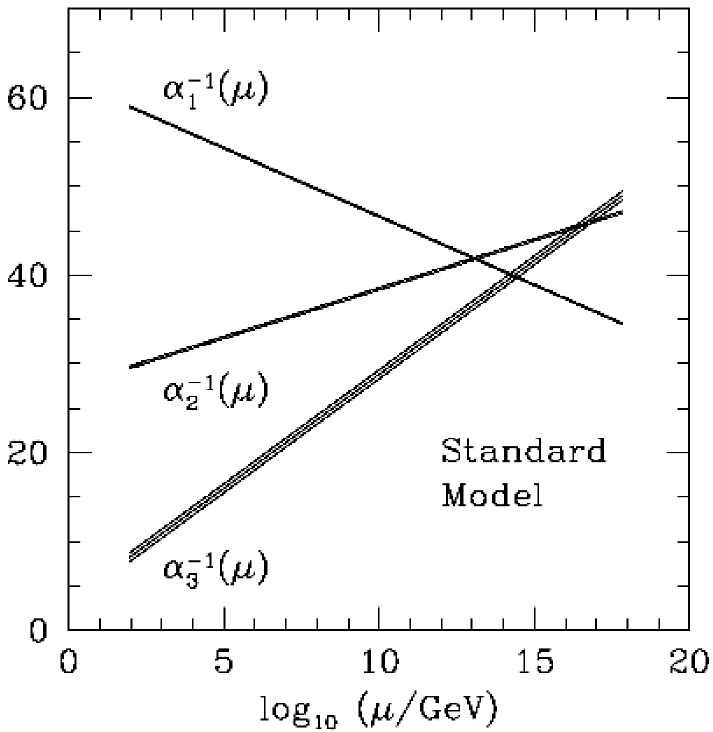
$$\nu^c \sim (1, 1, 0)$$

Matter Unification

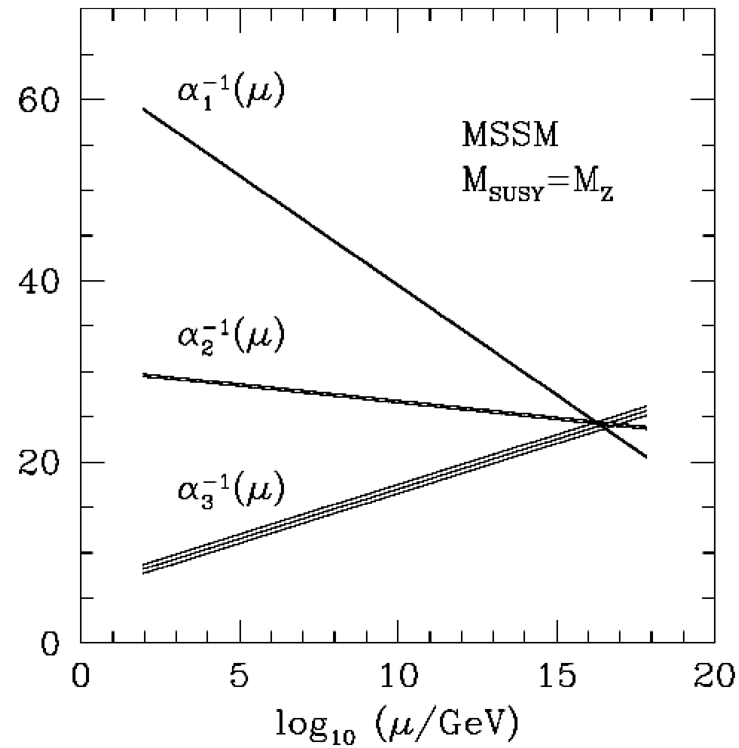
in 16 of SO(10)

u_1	:	$\vert\uparrow\downarrow\uparrow\uparrow\downarrow>$
u_2	:	$\vert\uparrow\downarrow\uparrow\downarrow\uparrow>$
u_3	:	$\vert\uparrow\downarrow\downarrow\uparrow\uparrow>$
d_1	:	$\vert\downarrow\uparrow\uparrow\uparrow\downarrow>$
d_2	:	$\vert\downarrow\uparrow\uparrow\downarrow\uparrow>$
d_3	:	$\vert\downarrow\uparrow\downarrow\uparrow\uparrow>$
u_1^c	:	$\vert\downarrow\downarrow\uparrow\downarrow\downarrow>$
u_2^c	:	$\vert\downarrow\downarrow\downarrow\uparrow\downarrow>$
u_3^c	:	$\vert\downarrow\downarrow\downarrow\downarrow\uparrow>$
d_1^c	:	$\vert\uparrow\uparrow\uparrow\downarrow\downarrow>$
d_2^c	:	$\vert\uparrow\uparrow\downarrow\uparrow\downarrow>$
d_3^c	:	$\vert\uparrow\uparrow\downarrow\downarrow\uparrow>$
ν	:	$\vert\uparrow\downarrow\downarrow\downarrow\downarrow>$
e	:	$\vert\downarrow\uparrow\downarrow\downarrow\downarrow>$
e^c	:	$\vert\downarrow\downarrow\uparrow\uparrow\uparrow>$
ν^c	:	$\vert\uparrow\uparrow\uparrow\uparrow\uparrow>$

Evolution of Gauge Couplings

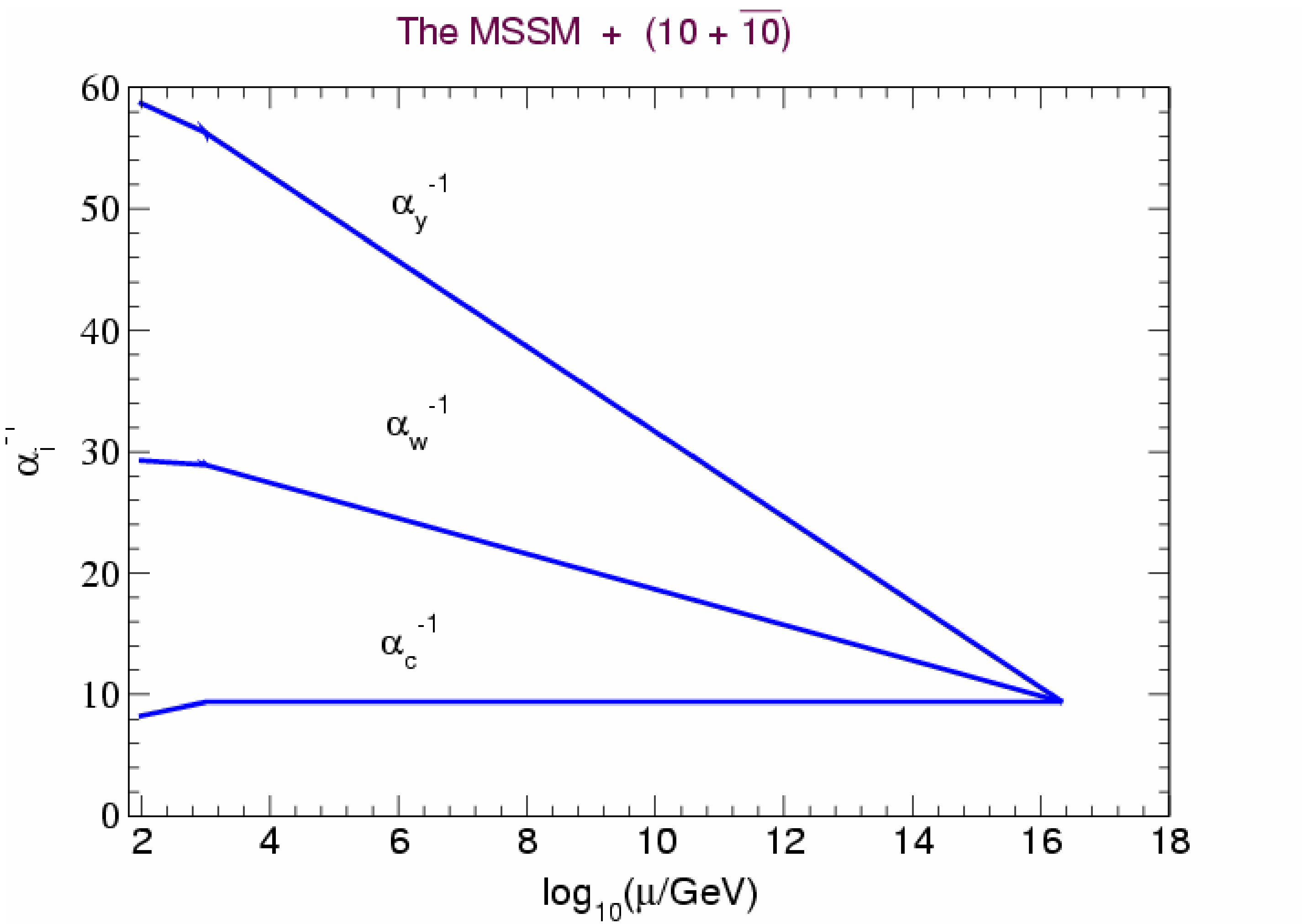


Standard Model



Minimal Supersymmetry

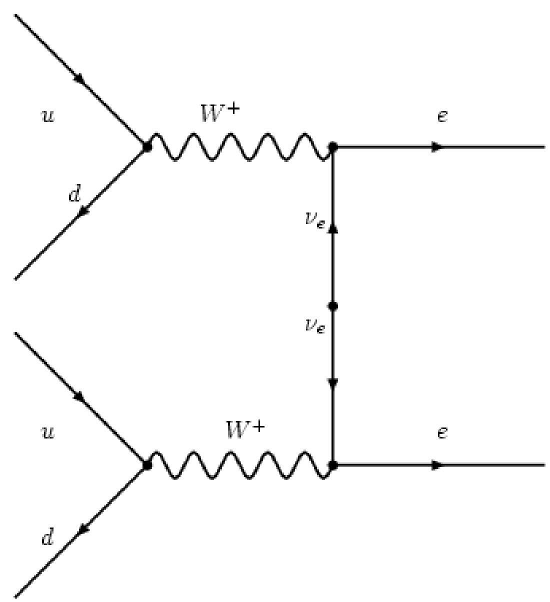
Unification with additional 10+10*



Lepton Number Violation

- In the standard scenario L violation occurs near the GUT scale, $M_R \sim 10^{14}$ GeV
- Testable indirectly via soft SUSY masses
- Can L violation occur at TeV scale consistent with unification, LSP dark matter, and small neutrino masses?
- Motivations:
  Observable neutrinoless double beta decay,
  Collider signals

Neutrinoless double beta decay



$$m_{\beta\beta} = \left|\sum U_{ei}^2 m_i\right| \quad \begin{array}{l} \sim 0.006 \text{ eV(Hierarchical)} \\ \geq 0.018 \text{ eV (Inverted)} \\ \geq 0.06 \text{ eV (Quasi-degenerate)} \end{array}$$

When combined with cosmology

$$m_{\beta\beta} < 0.15 - 0.2 \text{ eV}$$

- If $m_{\beta\beta}$ is observed at the level of 0.5 eV, new interactions will be needed

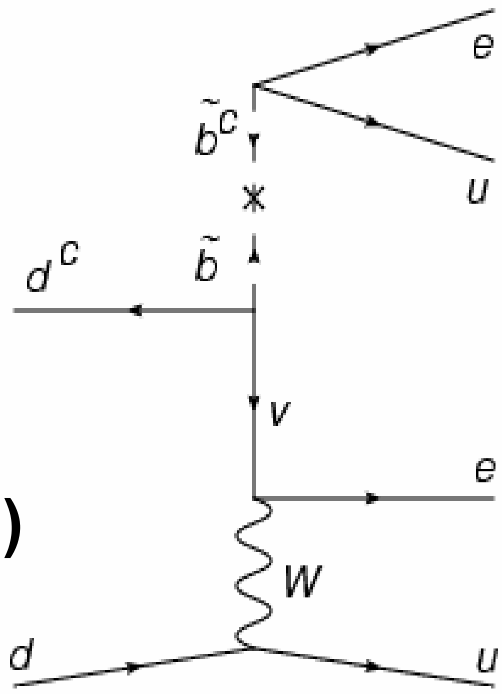
- If so, what are the consequences?

- Vector-scalar exchange seems very promising [R.Mohapatra, KB (1995)]

- $W' = \lambda'_{ijk} L_i L_j e^c_k + ..$

$$\Rightarrow$$

$$\lambda'_{113}\lambda'_{131} < 1.6 \times 10^{-7} \left(\frac{M_{\rm SUSY}}{100 \ \rm GeV}\right)^3$$



Pas et al (1999)

- Can we realize similar effects without R parity violation?

Unifiable model for neutrinoless double beta decay

- Add complete multiplet $\{10 + \overline{10}\}$ of $SU(5)$ to MSSM
- Since $B - L$ is likely a gauge symmetry, a Z_2 subgroup of I_{3R} remains unbroken
- Assign:

$$I_{3R} = +1 \text{ for } 10, \ -1 \text{ for } \overline{10}$$

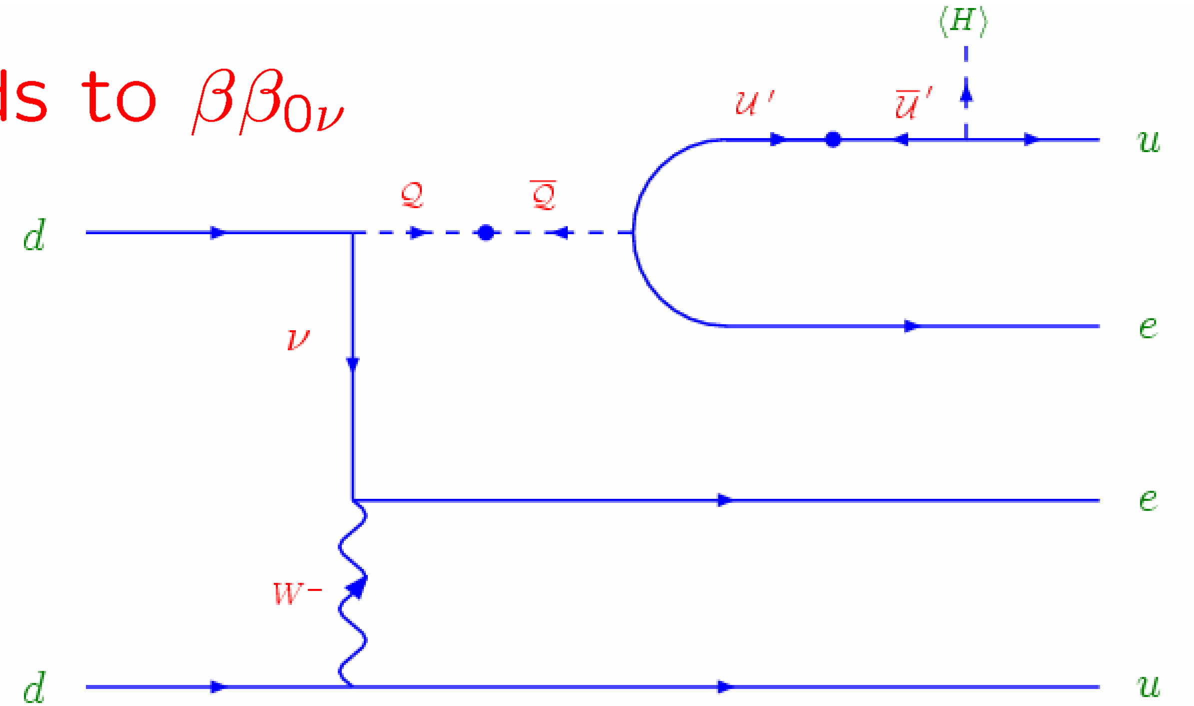
- $$10 : \{\mathcal{Q} = \begin{pmatrix} \mathcal{U} \\ \mathcal{D} \end{pmatrix}, \ \overline{\mathcal{U}}', \ \overline{E} \ \}$$

$$\overline{10} : \{\overline{\mathcal{Q}} = \begin{pmatrix} \overline{\mathcal{D}} \\ -\overline{\mathcal{U}} \end{pmatrix}, \ \mathcal{U}', \ E \ \}$$

Addition to MSSM superpotential:

$$W' = Q\overline{\mathcal{U}}' H_u + LQd^c + L\overline{Q}\mathcal{U}' + M_{10}\overline{10}10$$

- Leads to $\beta\beta_{0\nu}$



- $$\mathcal{L}_{\text{eff}} \simeq -\frac{1}{4}(\overline{d}_R \sigma_{\mu\nu} u_L)(\nu^T C \sigma^{\mu\nu} e_L)$$
- For couplings of order 10^{-2} and masses of order 300 GeV, this yields observable $\beta\beta_{0\nu}$

Why are 10+10* light?

Similar to μ problem

King, Shafi
Mohapatra, Dutta, KB
Kitano, Okada
Nomura, Hall

- A simple solution:

- $W = X(\Delta\overline{\Delta} - M^2) + H_u H_d X + 10.\overline{10}X + \nu^c \nu^c \Delta$

- In SUSY limit, $\langle\Delta\rangle = \left\langle\overline{\Delta}\right\rangle = M$, $\langle X\rangle = 0$

- After SUSY breaking, $\langle X\rangle \sim M_{\text{SUSY}}$

  $\Rightarrow$ μ erm and vector family masses are of order M_{SUSY}

- Low energy theory has no singlet field X

- W enforced by a discrete Z_4 symmetry

Anomay free Z(4) symmetry

$X:2 \quad H_u:2 \quad H_d:2 \quad \Delta:2 \quad \overline{\Delta}:2$
$Q:2 \quad \overline{Q}:2 \quad \lambda_i:1 \quad W:2$
Other fields: 0

- Discrete Anomalies:

$$SU(3)^2 \times Z_4 = 3 + \frac{1}{2}(-1)[3 \times 4 + 2 - 4] = -2$$
$$SU(2)_L^2 \times Z_4 = 2 + \frac{1}{2}(-1)[3 \times 4 - 6 - 2] = 0$$

- Z_4 is anomaly free

Flavor structure

- Use "Lopsided mass matrices" [S. Barr, KB (1995)] with a $U(1)$ flavor symmetry
- $10_i : (4, 2, 0) \quad \overline{5}_i : (3, 2, 2) \quad 1_i : (1, 0, 0)$
  $10 : 0 \quad \overline{10} : 0 \quad H_u : 0 \quad H_d : 0 \quad S : -1$

$$M_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^6 & \epsilon^4 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \qquad M_d \sim \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix}$$

$$M_\nu^D \sim \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix} \qquad M_\ell \sim \begin{pmatrix} \epsilon^5 & \epsilon^3 & \epsilon \\ \epsilon^4 & \epsilon^2 & 1 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix}$$

$$M_\nu^M \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

$$W' = f_i Q_i \overline{\mathcal{U}}' H_u + g_{ij} L_i \mathcal{Q} d_j^c + h_i \overline{\mathcal{Q}} \mathcal{U}' L_i$$

$$f_i = \begin{bmatrix} \epsilon^4 \\ \epsilon^2 \\ 1 \end{bmatrix}, \quad g_{ij} = \begin{bmatrix} \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^5 & \epsilon^4 & \epsilon^4 \end{bmatrix}, \quad h_i = \begin{bmatrix} \epsilon^3 \\ \epsilon^2 \\ \epsilon^2 \end{bmatrix}$$

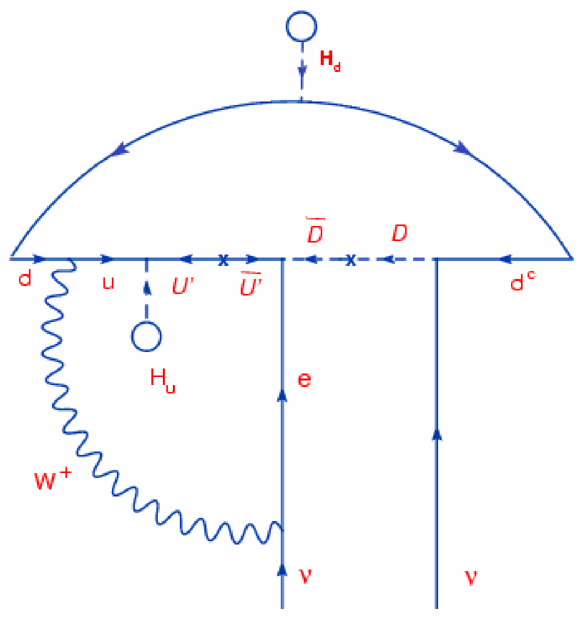
- $$A_{\beta\beta} \sim \frac{\epsilon^{13}}{M^3} \sim 10^{-8} G_F$$

Near current experimental limit
if $M = 10^2 - 10^3$ GeV

Other constraints

- ν-mass
- $D^0 - \overline{D}^0$ mixing
- $\mu \to e\gamma$

Neutrino mass



$$\mathcal{L} = \frac{\epsilon^6}{M^3}(\overline{d}_R \sigma_{\mu\nu} u_L)(\nu_L^T C \sigma^{\mu\nu} e_L) H_u^0 + \ldots$$

$$m_{\nu_\tau} \sim \frac{g^2}{(16\pi^2)^2}\epsilon^6 \left(\frac{m_b v_u}{M}\right)$$

$$\sim 0.1 \text{ eV}$$

$D^0 - \overline{D}^0$ mixing

- GIM violation in up–quark sector:

$$\epsilon^6 \overline{u}_L \gamma^\mu c_L Z^\mu$$

$$\Delta m_D < 4 \times 10^{-14} \text{ GeV} \Rightarrow$$

$$\epsilon^6 \leq 6 \times 10^{-5}$$

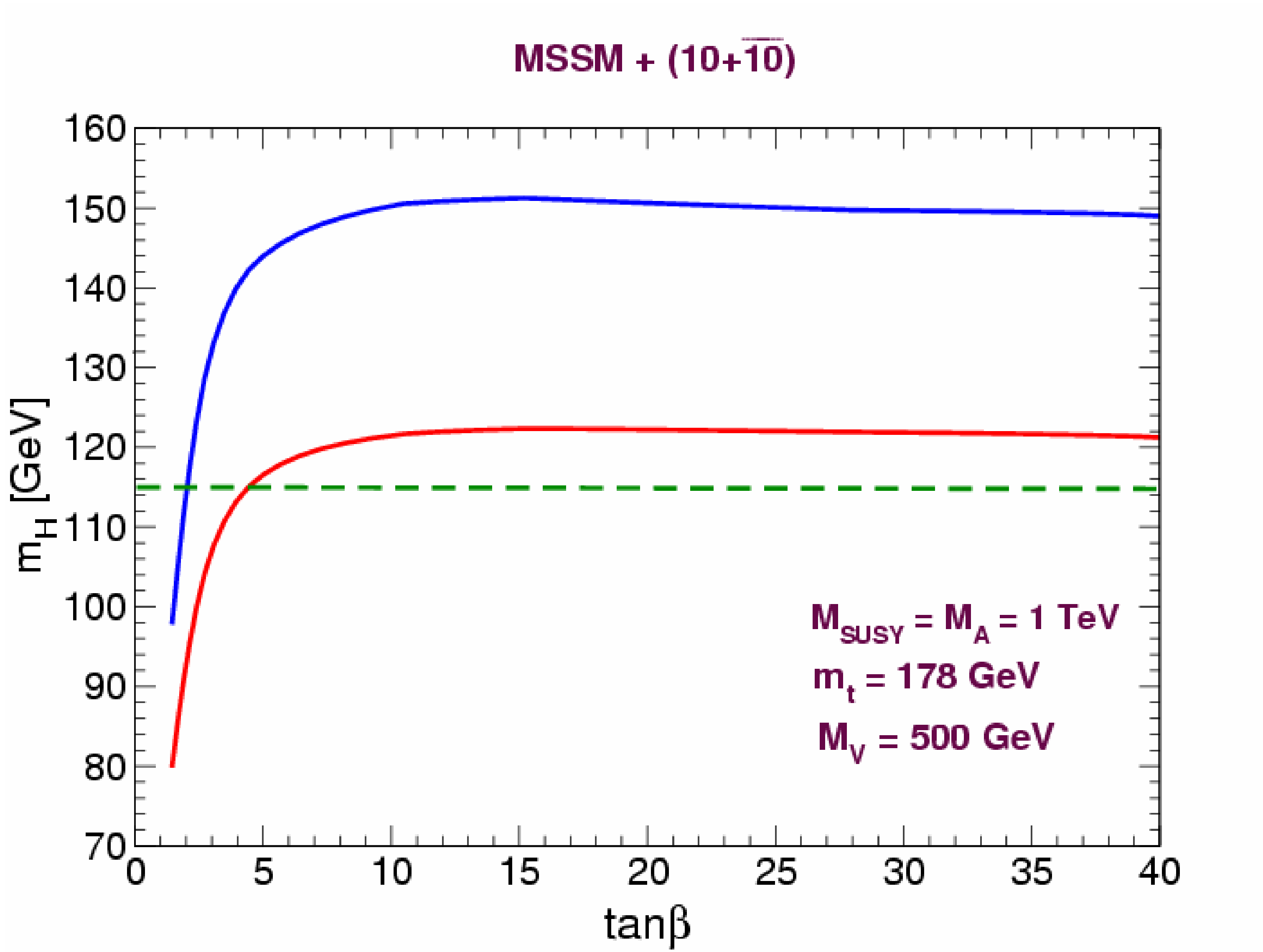
For $\epsilon \sim 0.2$, mixing close to current limit

$\mu \to e\gamma$

$$\Gamma_{\mu \to e\gamma} \sim \frac{\alpha}{8\pi} \frac{\epsilon^{10}}{(4\pi)^3} \frac{m_\mu^5}{M^4}$$

$\text{Br}(\mu \to e\gamma) \sim 10^{-12}$ for $M \sim 1$ TeV

Lightest Higgs mass limit



Conclusions

- Lepton number violation can occur naturally at the TeV scale consistent with unification, dark matter, and neutrino mass limits
- Neutrinoless double beta decay is prominent and within experimental reach
- Simple symmetries can explain the vector-particle masses, including the mu term
- D mixing and mu to e gamma are other tests of the Specific model