SEE-SAW

@

LHC

Goran Senjanović

Bajc, G. S. hep-ph/0612029

Bajc, Nemevšek, G.S. , yesterday

- $m_\nu \neq 0$, $\theta_\ell \neq 0$ $\quad l = \begin{pmatrix} \nu \\ e \end{pmatrix}$, $\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

$m_\nu \lesssim 10^{-1}\,eV$

Weinberg '79

- SM
  - $\mathcal{L}_Y(\text{eff}) \sim Y_{\text{eff}} \dfrac{l\,C\,l\;\Phi\,\Phi}{M_\nu}$

neutrino: $m_\nu \simeq Y_{\text{eff}} \dfrac{M_W^2}{M_\nu}$

charged fermions: $m_f \simeq Y_f M_W$

$M_\nu \gg M_W \Rightarrow$

$m_\nu \ll m_f$ $\quad (M_\nu \lesssim 10^{14}\,\text{GeV})$

$Y_{\text{eff}} = ?$ $\quad M_\nu = ?$ $\quad$ NO predictions m_ν, θ_ℓ

SM: no predictions m_f, θ_q

NO PROBLEM in SM

issue

(large) $\theta_\ell \longleftrightarrow \theta_q$ (small)

$m_\ell \longleftrightarrow m_q$

How to generate Weinberg's effective operator?

$$M_\nu \gg M_W$$

Ma '98

3 ways (see-saw)

I) add ν_R (≥ 2 for at least two massive ν's)

$$\mathcal{L}_Y = Y_D \bar{\nu}_L \Phi \nu_R + M_R \nu_R^T C \nu_R + h.c.$$

$$y_{eff}/M_\nu \simeq Y_D^2/M_R$$

Minkowski; '77
Gell-Mann et al;
Glashow; Mohapatra, G.S. '79

[redacted]

II) add Δ_H : $SU(2)_L$ triplet, $Y = 2$

$$\mathcal{L}_Y = Y_\nu \Delta \ell \ell + \mu \Delta^* \Phi \Phi + M_\Delta \Delta^2$$

$$\mu \simeq M_\Delta \Rightarrow \langle \Delta \rangle \simeq M_W^2/M_\Delta$$

$$Y_{eff}/M_\nu \simeq Y_\nu/M_\Delta$$

Lazarides, Shafi, Wetterich
Mohapatra, G.S. '80

NO useful information if $M_{new} \gg M_W$

Weinberg more useful

Analogy : • Fermi theory of weak int.

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \bar{\mu}_L \gamma^\mu \nu_{\mu L} \, \bar{\nu}_{eL} \gamma^\mu e_L$$

• $\mathcal{L}_{int} = g/\sqrt{2} \; \bar{e}_L \gamma^\mu \nu_L W_\mu^- + h.c.$

small energy: $E \ll M_W$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}$$

↖ tells you nothing; instead of coupling between e, ν → couplings with unknown, unreachable W^-

• if $E \simeq M_W \Rightarrow$ useful (~ Shaposhnikov)

• or if a theory of W exists

e.g. $SM = SU(2)_L \times U(1)_Y$

⇓

neutral current – correlated with charged

See-saw useful iff one has a theory of Y_D, M_R, ...

Connect neutrino mass, mixing with new physical phenomena

- e.g. **L-R** theory : restoration of parity (W_R^+, Z_R..)

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

Minkowski, Mohapatra, G.S.

I + II naturally present

- scales, couplings?

GRAND UNIFICATION

G.S., see-saw 25

SO(10) : compute m_ν, θ_ℓ

e.g. SUSY SO(10) : normal hierarchy

$\theta_{13} \simeq 10^\circ$

Connection with proton decay

but M_R, $M_\Delta \simeq M_{GUT}$ only indirect tests

Similar in ordinary SO(10) :

$M_R \to 10^{10}$ GeV

III) add T_F : SU(2) fermion triplet, $Y = 0$

$$\mathcal{L}_Y = Y_D\, T_F\, \Phi\, \ell + M_T\, T_F\, C\, T_F$$

Foot et al '89

$$Y_D^2 / M_T = Y_{eff} / M_\nu$$

(analogy type I)

$\Rightarrow$ at least two T_F ; or III + I

baroque? little studied, almost nothing

If $m_T <$ TeV $\Rightarrow$ real exciting

GUT : grand unification to fix m_T?

- <u>Minimal</u>: SU(5)

Minimal SU(5) fails (SM ⊆ SU(5)) { $m_\nu = 0$; no unification

I) add $1_F = \nu_R$: fails (also expect: $m_{1_F} > M_{GUT}$)

II) add $15_H \ni \Delta_H$ $\Rightarrow$ ok, but no interesting prediction

Dorsner, Fileviez-Perez '06

III) $24_F \ni T_F$ (need two?)

$$24_F = 1_F + 3_F + 8_F^c + (2, 3_c)_F$$

1_F → I, 3_F → III: sufficient

prediction: $m_1 = 0$

(one neutrino massless)

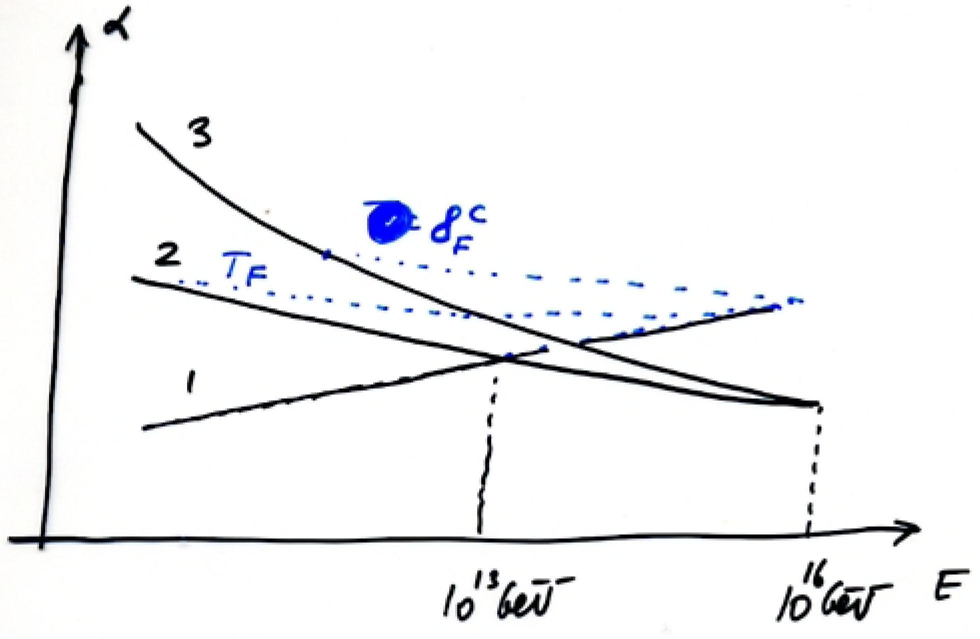
Bajc, G.S. '06

Bajc, Nemevšek, G.S.

(yesterday)

- UNIFICATION

SM



new states: raise α, unless Y=0

T_F (Y=0) ideal ⇒ $m_T \leq$ TeV

$m_8 \simeq 10^7 - 10^9$ GeV

$$\mathcal{L}_F = m_F \, \mathrm{Tr}\, 24_F^2 + \lambda \, \mathrm{Tr}\, 24_F^2 \, 24_H + 1/\Lambda \; \mathrm{Tr}\, 24_F^2 \, 24_H^2 \quad (*)$$

$$\langle 24_H \rangle = v \,\mathrm{diag}\,(2, 2, 2, -3, -3)$$

↑ higher dimensional operator

$$\mathcal{L}_Y = Y_d \, 10_F \, \bar{5}_F \, 5_H^* + Y_u \, 10_F \, 10_F \, 5_H$$

$$+ \, 1/\Lambda \; 10_F \, \bar{5}_F \, 5_H^* \, 24_H$$

$$\Downarrow$$

$$Y_d = Y_e$$

- $Y_b = Y_\tau + O\left(\frac{M_{GUT}}{\Lambda}\right)$ at M_{GUT}

but $Y_b \leq .6 \, Y_\tau$

and $Y_b \sim 1/100 \Rightarrow \underline{\underline{\Lambda \simeq 100 \, M_{GUT}}}$

(*)

$$m_0^F = m_F - \lambda_F v_{GUT} + O(v_{GUT}^2/\Lambda)$$

$$m_3^F = m_F - 3\lambda_F v_{GUT} + O(\text{-- '' --})$$

$$m_8^F = m_F + 2\lambda_F v_{GUT} + O(\text{-- '' --})$$

fine-tuning

$$m_{(3,2)}^F = m_F - \frac{\lambda_F v_{GUT}}{2} + O(\text{-- '' --}) \Rightarrow \boxed{m_{(3,2)} \simeq \frac{M_{GUT}^2}{\Lambda}}$$

1 - loop

$$\exp\left[30\pi\left(\alpha_1^{-1}-\alpha_2^{-1}\right)\Big|_{M_Z}\right] =$$

$$= \left(\frac{M_{GUT}}{M_Z}\right)^{84}\left(\frac{(m_3^F)^4\, m_3^B}{M_Z{}^5}\right)^5\left(\frac{M_{GUT}}{m^F_{(3,2)}}\right)^{20}\frac{M_{GUT}}{m_{\text{color triplet}}}$$

(m_3^B ← 24_H; $m_{\text{color triplet}}$ → 24_H)

SM: $m_3 \simeq M_{GUT} \Rightarrow$

light triplet ↗ M_{GUT} as needed

$m_3 \leq$ TeV

$$\exp\left[20\pi\left(\alpha_1^{-1}-\alpha_3^{-1}\right)\Big|_{M_Z}\right] =$$

$$= \left(\frac{M_{GUT}}{M_Z}\right)^{86}\left(\frac{(m_8^F)^4\, m_8^B}{M_Z{}^5}\right)^5\left(\frac{M_{GUT}}{m^F_{(3,2)}}\right)^{20}\left(\frac{M_{GUT}}{m_{\text{color triplet}}}\right)^{-1}$$

SM: $m_8 \simeq M_{GUT}$; but 1-3 meet after 1-2

$\Rightarrow$ $m_8 \simeq 10^7$ GeV

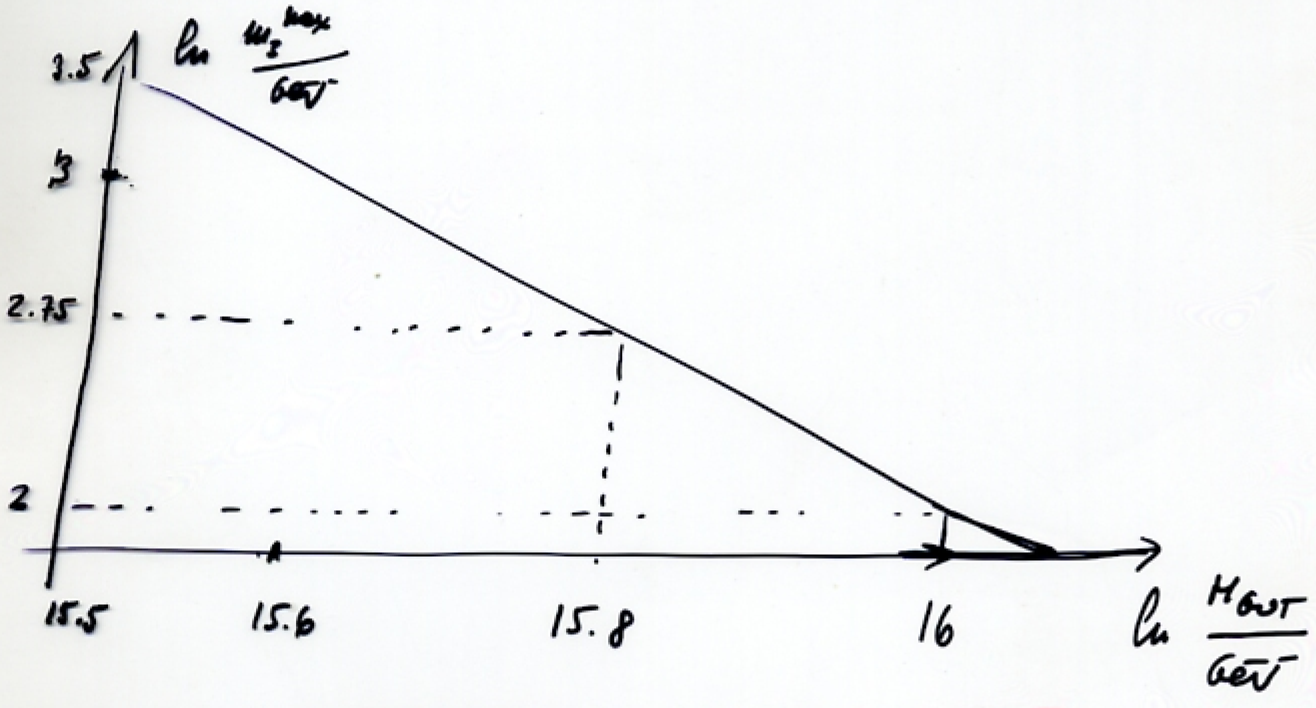
(2-loop)

- $m_{\text{color triplet}} > 10^{12}$ GeV (proton decay)
- $M_{GUT} > 10^{15.5}$ GeV (proton decay)
- $m^F_{(3,2)} \simeq \frac{M_{GUT}}{100}$ $\left(M_{GUT}^2/\Lambda \right)$

⇓

$M_{GUT} \lesssim 10^{16}$ GeV (hard prediction)

$\tau_p < 10^{36}$ yr observable?



$M_{GUT} \simeq 10^{16}$ GeV $\quad m_F \simeq 200$ GeV

$m_F^8 \simeq 10^7 - 10^8$ GeV

- $\mathcal{L}_Y = y\, 24_F\, \bar{5}_F\, 5_H^* + 24_F\, \bar{5}_F\, 5_H^*\, 24_H / \Lambda$

T_F, S_F — ℓ — Φ^* — necessary

would not split y_T, y_S

$$\mathcal{L}_Y(\text{eff}) = y_T^i\, T_F\, \Phi^*\, l_i + y_S^i\, S_F\, \Phi^*\, l_i + m_T\, T_F T_F + m_S\, S_F S_F \quad i = 1, 2, 3$$

3 + 3 complex Yukawas

↳ make real by phase convention

⇓

3 + 6 = 9 real couplings

→ 2 masses ($m_1 = 0$)

3 mixings

1 + 1 = 2 phases (only one Majorana phase)

Light triplets

LHC : $m_T < 500$ GeV (~ winos)

- weakly produced, ~ winos

- decays $T^- \to W^- + \nu$ $\qquad T^0 \to Z + \nu$

  $\qquad Z + l \qquad\qquad \to W^+ + l$

directly through Yukawa

$$\mathcal{L}_Y = Y_T^k \, T \, \Phi \, l_k + Y_S^k \, S \, \Phi \, l_k \qquad k = 1,2,3 \quad (3+6=9)$$

$$\Gamma(T^- \to Z l_k^-) = \frac{m_T}{32\pi} |Y_T^k|^2 \left(1 - \frac{m_Z^2}{m_T^2}\right)\left(1 + 2\frac{m_Z^2}{m_T^2}\right)$$

$$\sum_k \Gamma(T^- \to W^- \nu_k) = \frac{m_T}{16\pi} \left(\Sigma |Y_T^k|^2\right) \quad -\text{''}-$$

and similar for T_0

- $m_T \simeq 300$ GeV : $|Y_T^{max}| \gtrsim 5 \times 10^{-7} \Rightarrow$

  $(10^{-11}\,\text{mm} \leq)\ \tau_T \lesssim 10^{-1}\,\text{mm}$

- one massless neutrino

e.g. normal hierarchy $m_1^\nu = 0$

$$\frac{v_w y_T^{i*}}{i\sqrt{2 m_T}} = U_{i2}\sqrt{m_2^\nu}\cos z \pm U_{i3}\sqrt{m_3^\nu}\sin z$$

$$\frac{i\, v_w y_S^{i*}}{\sqrt{2 m_S}} = U_{i2}\sqrt{m_2^\nu}\sin z \mp U_{i2}\sqrt{m_3^\nu}\cos z$$

$z \in \mathbb{C}$, U = PMNS (1 + 1 phase only)
↑ Majorana

- Im(z) ≫ 1 (large Yukawa's) ⟶ LFV

$\theta_{13} = 5°$: $\left\{ \begin{array}{l} .25 \leq \frac{\Gamma(\mu)}{\Gamma(\tau)} \leq 4.3 \\ .02 \leq \frac{\Gamma(e)}{\Gamma(\mu,\tau)} \lesssim .5 \end{array} \right\}$

$\theta_{13} = 0°$ $\{ \Gamma(e) \simeq \Gamma(\mu) \simeq \Gamma(\tau) \}$

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inverse hierarchy: $\Gamma(\mu) = \Gamma(\tau)$

$$.07 \leq \frac{\Gamma(e)}{\Gamma(\mu)} \leq 50$$

no θ_{13} dependence!

• COSMOLOGICAL IMPLICATIONS

• LEPTOGENESIS

$$\varepsilon_{max} \simeq \frac{1}{16\pi} \frac{m_T \left(m_3^\nu - m_2^\nu\right)}{v^2} \qquad m_T \ll m_S$$

↑ rigorous — no assumptions as in the three ν_R case (Davidson, Ibarra) Raidal, Strumia, Turzynski '04

$m_T \simeq$ TeV

⇓

$\varepsilon_{max} \lesssim 10^{-12}$ – far too small

⇓

Only resonant leptogenesis: $m_T \simeq m_S$

S hard to produce!

$|Y_S| \lesssim 1/10$

unitarity of PMNS ⇔ LFV

Biggio et al '06

• NO DARK MATTER CANDIDATE

e.g. T_F (unlike wino) decays through Y_T

OUTLOOK

Minimal SU(5) (type III seesaw)

⊕ 24_F → III

T_F (SU(2) triplet ~ wino) ∴ $m_T \lesssim$ TeV

$M_{GUT} \leq 10^{16}$ GeV ⇒ $\tau_p \lesssim 10^{36}$ yr

LHC - proton decay connection

↓ measure directly see-saw

- comparison with supersymmetry

~ : light wino ($\lesssim$ TeV)

heavy gluino ($10^7 - 10^9$ GeV)

decoupled Higgsino ($m_{\tilde{h}} > M_{GUT}$)

➡ consistent with unification :

gluino $M_W - 10^9$ GeV

higgsino $M_W - M_{pl}$

split (more) supersymmetry

*

- loophole : leptogenesis ?

$$\nu_R \to \left.\begin{array}{l} \phi + l \\ \phi^* + l^c \end{array}\right\} \Delta L \neq 0 \Rightarrow$$

$\Delta B \neq 0$ (sphalerons)

↓

lightest right-handed neutrino

$\Rightarrow \quad M_R \gtrsim 10^9$ GeV — Davidson, Ibarra '02

↓ needs assumptions about Yukawas

$m_\nu \propto Y^T Y \quad , \quad \varepsilon \propto Y^* Y$

⇓

even TeV ok! — Raidal, Strumia, Turzynski '04

(or resonant – Pilaftsis)