Unification without supersymmetry

R. Frezzotti[a)b)], M. Garofalo[c)], G.C. Rossi[a)b)d)]

[a)]Dipartimento di Fisica - Università di Roma *Tor Vergata*
[b)]INFN - Sezione di Roma *Tor Vergata*
[c)]University of Edinburgh
[d)]Centro Fermi

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Outline of the talk

1. **Motivation & Introduction**
   - expose a non-Susy model with a level of unification as in MSSM
2. **The model**
   - SM matter + superstrongly interacting extra matter $\rightarrow$
   - a kind of BSMM with
     - NP generation of all elementary particle masses
     - natural mass hierarchy
3. **Unification**
   - strong & electro-weak coupling unification owing to
     - new matter (superstrongly interacting quarks and leptons)
     - with unusual hypercharge assignment (half-integer charges)
   - superstrong, strong & electro-weak coupling unification owing to
     - further extra fermions endowed with only superstrong interactions
     - and masses around the unification scale Λ_{GUT}
4. **Conclusions & Outlook**
   - lattice checks of the NP mass generation mechanism
   - look for a GUT group

Motivation

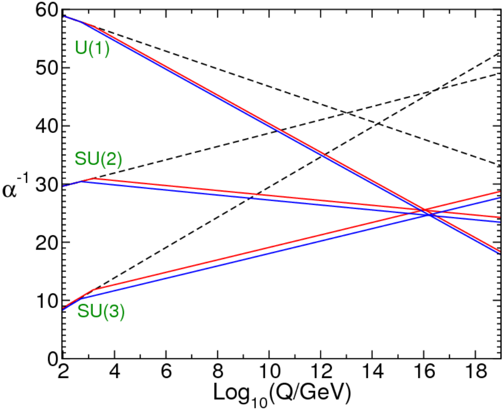


Figure : Running of electro-weak and strong couplings in SM (black dotted lines) and MSSM. Displacement of blue and red curves at small scales is associated to the opening of the SUSY threshold, either 0.5 TeV (blue curve) or 1.5 TeV (red curve) with initial conditions $\alpha_s(m_Z) = 0.117$ and $\alpha_s(m_Z) = 0.121$, respectively.

A non-supersymmetric model

$$\mathcal{L}^{BSMM} = \frac{1}{4}\left(F^B F^B + F^W F^W + F^A F^A\right) +$$

$$+ \sum_{f=1}^{n_g} \Big[\bar{q}_L^f \not{D}^{BWA} q_L^f + \bar{q}_R^{f\,u} \not{D}^{BA} q_R^{f\,u} + \bar{q}_R^{f\,d} \not{D}^{BA} q_R^{f\,d} +$$

$$+ \bar{\ell}_L^f \not{D}^{BW} \ell_L^f + \bar{\ell}_R^{f\,u} \not{D}^{B} \ell_R^{f\,u} + \bar{\ell}_R^{f\,d} \not{D}^{B} \ell_R^{f\,d} \Big] + \text{SM masses} +$$

$$+ \frac{1}{4} F^G F^G + \sum_{s=1}^{\nu_Q} \Big[\bar{Q}_L^s \not{D}^{BWAG} Q_L^s + \bar{Q}_R^{s\,u} \not{D}^{BAG} Q_R^{s\,u} + \bar{Q}_R^{s\,d} \not{D}^{BAG} Q_R^{s\,d} \Big] +$$

$$+ \sum_{t=1}^{\nu_L} \Big[\bar{L}_L^t \not{D}^{BWG} L_L^t + \bar{L}_R^{t\,u} \not{D}^{BG} L_R^{t\,u} + \bar{L}_R^{t\,d} \not{D}^{BG} L_R^{t\,d} \Big] + \text{O(TeV) masses}$$

$$D_\mu^{BWAG} = \partial_\mu - iYg_Y B_\mu - ig_w \tau^r W_\mu^r - ig_s \frac{\lambda^a}{2} A_\mu^a - ig_T \frac{\lambda_T^\alpha}{2} G_\mu^\alpha$$

A non-supersymmetric BSM model

$$\mathcal{L}^{BSMM} = \frac{1}{4}\left(F^B F^B + F^W F^W + F^A F^A\right) +$$
$$+ \sum_{f=1}^{n_g} \Big[\bar{q}_L^f \not{D}^{BWA} q_L^f + \bar{q}_R^{f\,u} \not{D}^{BA} q_R^{f\,u} + \bar{q}_R^{f\,d} \not{D}^{BA} q_R^{f\,d} +$$
$$+ \bar{\ell}_L^f \not{D}^{BW} \ell_L^f + \bar{\ell}_R^{f\,u} \not{D}^{B} \ell_R^{f\,u} + \bar{\ell}_R^{f\,d} \not{D}^{B} \ell_R^{f\,d}\Big] +$$
$$+ \frac{1}{4} F^G F^G + \sum_{s=1}^{\nu_Q} \Big[\bar{Q}_L^s \not{D}^{BWAG} Q_L^s + \bar{Q}_R^{s\,u} \not{D}^{BAG} Q_R^{s\,u} + \bar{Q}_R^{s\,d} \not{D}^{BAG} Q_R^{s\,d}\Big] +$$
$$+ \sum_{t=1}^{\nu_L} \Big[\bar{L}_L^t \not{D}^{BWG} L_L^t + \bar{L}_R^{t\,u} \not{D}^{BG} L_R^{t\,u} + \bar{L}_R^{t\,d} \not{D}^{BG} L_R^{t\,d}\Big] +$$
$$+ \ldots$$

$$m_Q = \mathrm{O}(\alpha_T \alpha_T)\Lambda_T \quad m_{\mathrm{top}} = \mathrm{O}(\alpha_s \alpha_T)\Lambda_T \quad m_\tau = \mathrm{O}(\alpha_Y \alpha_T)\Lambda_T$$
$$M_W = \mathrm{O}(\sqrt{\alpha_W})\Lambda_T$$
$$\Lambda_T \sim \mathrm{O}(TeV)$$

SM hypercharge assignments

q	ℓ
$y_{u_L} = \frac{2}{3} - \frac{1}{2} = \frac{1}{6}$	$y_{\nu_L} = 0 - \frac{1}{2} = -\frac{1}{2}$
$y_{u_R} = \frac{2}{3} - 0 = \frac{2}{3}$	$y_{\nu_R} = 0$
$y_{d_L} = -\frac{1}{3} + \frac{1}{2} = \frac{1}{6}$	$y_{e l_L} = -1 + \frac{1}{2} = -\frac{1}{2}$
$y_{d_R} = -\frac{1}{3} - 0 = -\frac{1}{3}$	$y_{e l_R} = -1 - 0 = -1$
$\sum y_q^2 = \frac{22}{36}$	$\sum y_\ell^2 = \frac{3}{2}$

Table : Hypercharges of SM fermions

- $\mathcal{Q} = T^3 + Y$
- Anomaly cancellation occurs between quarks and leptons

Non-standard hypercharge assignments $\to$ unique

Q	L
$y_{U_L} = \frac{1}{2} - \frac{1}{2} = 0$	$y_{N_L} = \frac{1}{2} - \frac{1}{2} = 0$
$y_{U_R} = \frac{1}{2} - 0 = \frac{1}{2}$	$y_{N_R} = \frac{1}{2} - 0 = \frac{1}{2}$
$y_{D_L} = -\frac{1}{2} + \frac{1}{2} = 0$	$y_{L_L} = -\frac{1}{2} + \frac{1}{2} = 0$
$y_{D_R} = -\frac{1}{2} - 0 = -\frac{1}{2}$	$y_{L_R} = -\frac{1}{2} - 0 = -\frac{1}{2}$
$\sum y_Q^2 = \frac{1}{2}$	$\sum y_L^2 = \frac{1}{2}$

Table : Non-standard hypercharge assignments

- Anomalies separately zero for quarks and leptons $\to Y_L = 0$
- L-handed doublets $\to \mathcal{Q}_L = T_L^3 = \pm 1/2$
- R-handed singlets $\to \mathcal{Q}_R = Y_R$
- $\mathcal{Q}_R = \mathcal{Q}_L = \pm 1/2$
- The above is the only possible choice

BSMM β-functions

Table 2 assignment for SIP hypercharges $\to$ above TeV scale we get

$$\beta_T^{BSMM} = -\left[\frac{11}{3}N_T - \frac{4}{3}(N_c\nu_Q + \nu_L)\right]\frac{g_T^3}{(4\pi)^2}$$

$$\beta_s^{BSMM} = -\left[\frac{11}{3}N_c - \frac{4}{3}(N_T\nu_Q + n_g)\right]\frac{g_s^3}{(4\pi)^2}$$

$$\beta_w^{BSMM} = -\left[2\frac{11}{3} - \frac{1}{3}n_g(N_c+1) - \frac{1}{3}N_T(N_c\nu_Q + \nu_L)\right]\frac{g_w^3}{(4\pi)^2}$$

$$\beta_Y^{BSMM} = \left\{\frac{2}{3}\left[\left(\frac{22}{36}N_c + \frac{3}{2}\right)n_g + \frac{1}{2}N_T(N_c\nu_Q + \nu_L)\right]\right\}\frac{g_Y^3}{(4\pi)^2}$$

Alternatively with the standard assignment one would have

$$\beta_{Y\,st}^{BSMM} = \left\{\frac{2}{3}\left[\left(\frac{22}{36}N_c + \frac{3}{2}\right)n_g + \frac{1}{2}N_T\left(\frac{22}{18}N_c\nu_Q + 3\nu_L\right)\right]\right\}\frac{g_Y^3}{(4\pi)^2}$$

with $n_g, \nu_Q, \nu_L = \#$ of generations of (q, ℓ), Q and L

SM β-functions

$$\beta_s^{SM} = -\left(\frac{11}{3}N_c - \frac{4}{3}n_g\right)\frac{g_s^3}{(4\pi)^2}\,,$$

$$\beta_w^{SM} = -\left[2\frac{11}{3} - \frac{1}{3}n_g(N_c+1) - \frac{1}{6}\right]\frac{g_w^3}{(4\pi)^2}\,,$$

$$\beta_Y^{SM} = \left[\frac{2}{3}\left(\frac{22}{36}N_c + \frac{3}{2}\right)n_g + \frac{1}{6}\right]\frac{g_Y^3}{(4\pi)^2}\,.$$

GUT normalization conditions - BSSM

If all the fermions must belong to an irreducible G_{GUT} representation, one must have

$$\mathrm{Tr}\left[(g_Y Y)^2\right] = \mathrm{Tr}\left[(\frac{1}{2}g_w\tau^3)^2\right] = \mathrm{Tr}\left[(\frac{1}{2}g_s\lambda^3)^2\right] = \mathrm{Tr}\left[(\frac{1}{2}g_T\lambda^3_T)^2\right]$$

An explicit computation reveals that the unifying couplings are

- non-standard hypercharge assignments

$$g_1^2 := \frac{4}{3}\, g_Y^2\,, \qquad g_2^2 := g_w^2\,, \qquad g_3^2 := g_s^2\,, \qquad g_4^2 := \frac{2}{3}\, g_T^2$$

- standard hypercharge assignments

$$g_1^2 := \frac{5}{3}\, g_Y^2\,, \qquad g_2^2 := g_w^2\,, \qquad g_3^2 := g_s^2\,, \qquad g_4^2 := \frac{2}{3}\, g_T^2$$

We took for concreteness $N_T = N_c = n_g = 3 \quad \& \quad \nu_Q = \nu_L = 1$

GUT normalization conditions - SM

$$\mathrm{Tr}\left[(g_Y Y)^2\right] = \mathrm{Tr}\left[(\frac{1}{2}g_w\tau^3)^2\right] = \mathrm{Tr}\left[(\frac{1}{2}g_s\lambda^3)^2\right]$$

$$g_1^2 := \frac{5}{3}g_Y^2\,, \qquad g_2^2 := g_w^2\,, \qquad g_3^2 := g_s^2$$

Evolution equations

$$\frac{dg_i}{d\log\mu} = \beta_{g_i}\,, \quad i = 1, 2, 3, 4$$

- BSMM 1-loop β-functions with GUT normalization

$$\beta_{g_1} = 8\frac{g_1^3}{(4\pi)^2}\,, \qquad \beta_{g_2} = \frac{4}{6}\frac{g_2^3}{(4\pi)^2}\,,$$
$$\beta_{g_3} = -3\frac{g_3^3}{(4\pi)^2}\,, \qquad \beta_{g_4} = -\frac{17}{2}\frac{g_4^3}{(4\pi)^2}$$

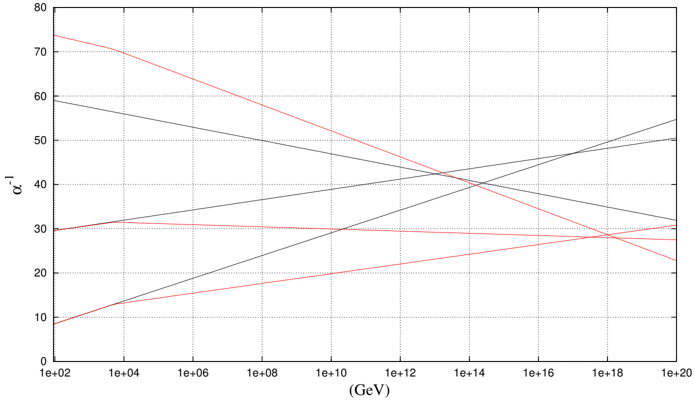
Standard and non-standard Y assignments yield the same β_{g_1}

- SM 1-loop β-functions with GUT normalization

$$\beta_{g_1} = \frac{41}{10}\frac{g_1^3}{(4\pi)^2}\,, \qquad \beta_{g_2} = -\frac{19}{6}\frac{g_2^3}{(4\pi)^2}\,, \qquad \beta_{g_3} = -7\frac{g_3^3}{(4\pi)^2}$$

Note - β_{g_2} is positive in the BSMM and negative in the SM.

BSMM vs. SM



SM

$\alpha_1^{-1}(m_Z) = 59.01 \pm 0.02$

$\alpha_2^{-1}(m_Z) = 29.57 \pm 0.02$

$\alpha_3^{-1}(m_Z) = 8.45 \pm 0.05$

BSSM

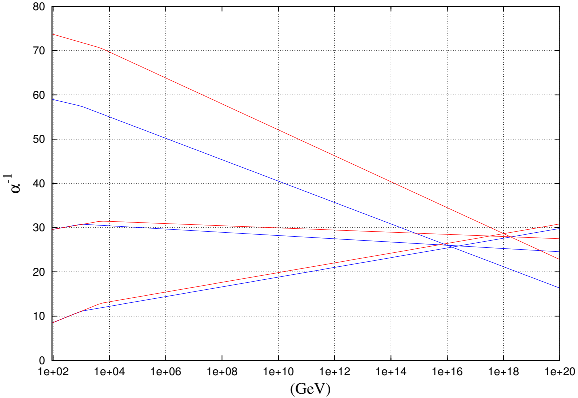
$\alpha_1^{-1}(m_Z) = 73.76 \pm 0.02$

$\alpha_2^{-1}(m_Z) = 29.57 \pm 0.02$

$\alpha_3^{-1}(m_Z) = 8.45 \pm 0.05$

Figure : The 1-loop running of electro-weak and strong couplings in the BSMM (red curves) and in the SM (black curves). The visible change of slope of red curves at “low” scales is associated with the opening of the superstrong threshold that we take at $\Lambda_T = 5$ TeV

BSMM vs. MSSM



MSSM

$\alpha_1^{-1}(m_Z) = 59.01 \pm 0.02$

$\alpha_2^{-1}(m_Z) = 29.57 \pm 0.02$

$\alpha_3^{-1}(m_Z) = 8.45 \pm 0.05$

BSSM

$\alpha_1^{-1}(m_Z) = 73.76 \pm 0.02$

$\alpha_2^{-1}(m_Z) = 29.57 \pm 0.02$

$\alpha_3^{-1}(m_Z) = 8.45 \pm 0.05$

Figure : The 1-loop running of electro-weak and strong couplings in the BSMM (red curves) and in the MSSM (blue curves). The superstrong and supersymmetry thresholds have been set at $\Lambda_T = 5$ and $\Lambda_{MSSM} = 1$ TeV, respectively

Changing hypercharge assignment to SIPs

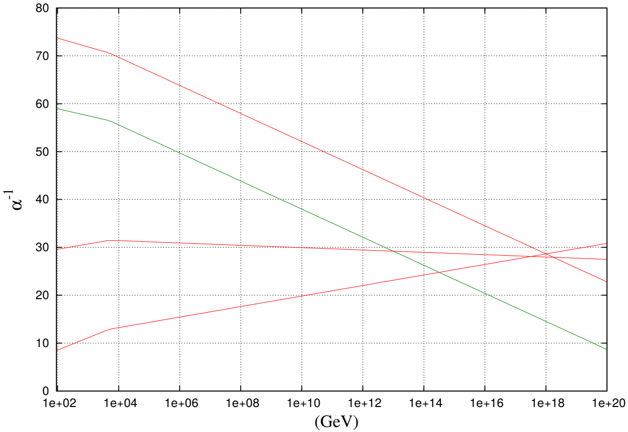


Figure : The 1-loop running of electro-weak and strong couplings in the BSMM with the hyperchage assignment of Table 2 (red curves) and the "standard" hyperchage assignment of Table 1 (green curve)

A full unification in BSMM?

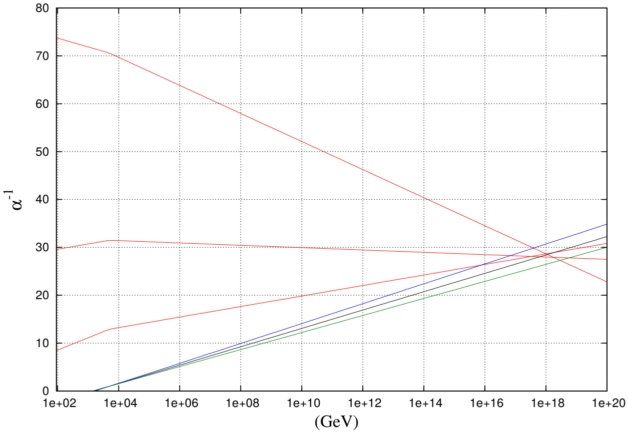
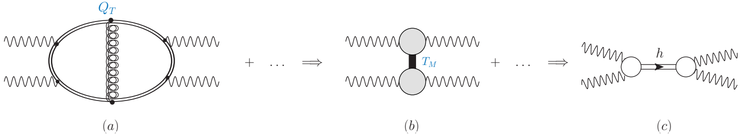


Figure : The 1-loop running of electro-weak strong and superstrong couplings in the BSMM with N_S extra particles having purely superstrong vector interactions and masses $O(\Lambda_{GUT})$. $N_S = 4$ (blue line) $N_S = 5$ (black line), $N_S = 6$ (green line)

Conclusions

- A non-SUSY BSMM model with unification at the level of MSSM
- The salient features of the BSMM outlined in slide 5 are
  - elementary particle masses generated by a NP mechanism
  - triggered by irrelevant $d = 6$ chiral breaking op's in $\mathcal{L} \to$ no Higgs
  - a neat solution of "naturalness" & "hierarchy" problems
    - at the price of giving up a bit of universality
  - correct order of magnitude of the NP-ly generated *top* mass $\Longrightarrow$
    - SIPs with an RGI scale $\Lambda_T \gg \Lambda_{QCD}$, $\Lambda_T \sim$ O(TeV)
  - SIPs (must) have unusual hypercharge assignments
    - electric charge quantized in units of $e/2$.
    - neutral SIP bound states with non-zero fermion number $\to$ CDM?
  - 125 resonance is a WW/ZZ state bound by superstrong forces



- Existence of NP effects needs a numerical confirmation

Thank you for your attention