Gauge Coupling Unification in Radiative Neutrino Mass Models

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Outline

- Motivation
- RG running in radiative neutrino mass models
  1. Minimal UV completion models with d=7
  2. Models with DM
  3. Models with adjoint representation of SU(3)
- Summary and conclusions

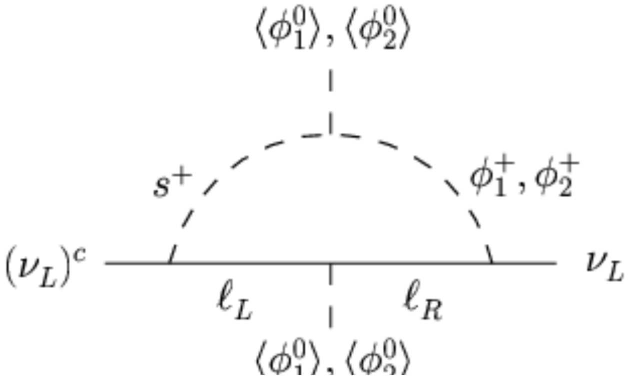
Motivation

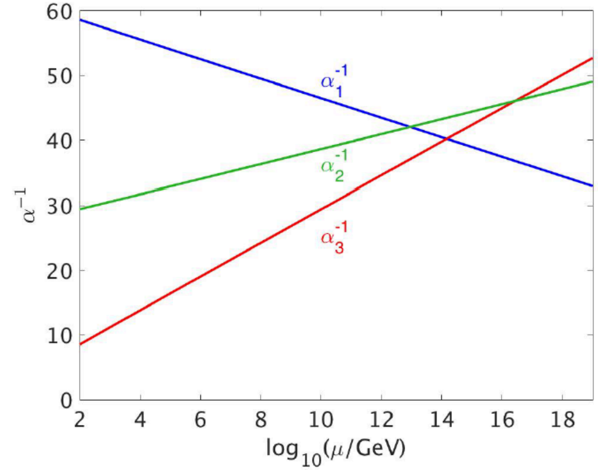
Address two of the problems with the SM:

- Neutrino mass
- Grand unification

Bonus: dark matter

Idea: RG running in radiative neutrino mass models. Can there be unification?





Choice of models

- ”Minimal” extensions to the seesaw mechanism
- SM + additional representations
- SM gauge group

Three classes of models:

I. Minimal UV completions of dimension-7 operators + DM
II. Models with dark matter
III. Models with particles in the adjoint representations of SU(3) + DM

Assumptions:

- New particle masses: 1 TeV
- Only gauge coupling running → Error margin on unification
- Only top yukawa
- Non-perturbative models

Running in radiative models

$$\frac{dg_l}{dt} = \beta_l(g) = b_l \frac{g_l^3}{16\pi^2} + \sum_k \left(b_{lk} \frac{g_k^2 g_l^3}{(4\pi)^4} + \frac{g_l^3}{(4\pi)^4} Tr(C_k^u Y_u^\dagger Y_u + C_k^d Y_d^\dagger Y_d + C_k^e Y_e^\dagger Y_e) \right)$$

[Machacek, Vaughn, 1983]

Determine contribution to gauge coupling running and solve RGE analytically (one-loop) and numerically using PyR@TE (two-loop)
[Lyonnet, Schienbein, Staub, Wingerter, 2014]

Model categories:

1. Those unifying
2. Those which doesn't unify but also doesn't diverge
3. Those which doesn't unify and contain a Landau pole

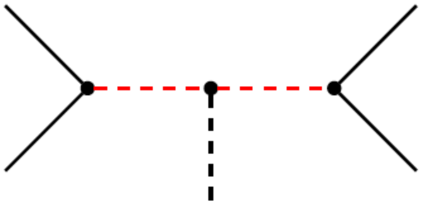
I. Minimal UV completions of d=7 operators

[Cai, Clarke, Schmidt, Volkas, 2015]

- 15 models with d=7 operators
  - $\triangle L = 2$
  - Three topologies
- Two new particles. Two scalars or one scalar + one fermion
- We assume 1 to 6 generations of each new particle.

Models SI-J

Scalar	Scalar	Operator
$(1, 2, \frac{1}{2})$	$(1, 1, 1)$	$\mathcal{O}_{2,3,4}$ [28]
$(3, 2, \frac{1}{6})$	$(3, 1, -\frac{1}{3})$	$\mathcal{O}_{3,8}$ [38, 44]
$(3, 2, \frac{1}{6})$	$(3, 3, -\frac{1}{3})$	$\mathcal{O}_3$



$$\mathcal{O}_2 = LLL\bar{e}H, \qquad \mathcal{O}_3 = LLQ\bar{d}H,$$

$$\mathcal{O}_4 = LLQ^\dagger\bar{u}^\dagger H, \qquad \mathcal{O}_8 = L\bar{d}\bar{e}^\dagger\bar{u}^\dagger H,$$

I. Minimal UV completions of d=7 operators

Analytical study

$$n_1 = \frac{2\pi}{L} \frac{B^2_{23}\,\alpha^{-1}_{1,\mathrm{SM}}(\Lambda) + B^2_{31}\,\alpha^{-1}_{2,\mathrm{SM}}(\Lambda) + B^2_{12}\,\alpha^{-1}_{3,\mathrm{SM}}(\Lambda)}{B^1_{23}\,B^2_{31} - B^2_{23}\,B^1_{31}},$$

$$n_2 = \frac{2\pi}{L} \frac{B^1_{23}\,\alpha^{-1}_{1,\mathrm{SM}}(\Lambda) + B^1_{31}\,\alpha^{-1}_{2,\mathrm{SM}}(\Lambda) + B^1_{12}\,\alpha^{-1}_{3,\mathrm{SM}}(\Lambda)}{B^2_{23}\,B^1_{31} - B^1_{23}\,B^2_{31}}.$$

$$B^i_{kl} = b^i_k - b^i_l \quad , \quad L = \ln\left(\frac{\Lambda}{\Lambda_{\mathrm{NP}}}\right)$$

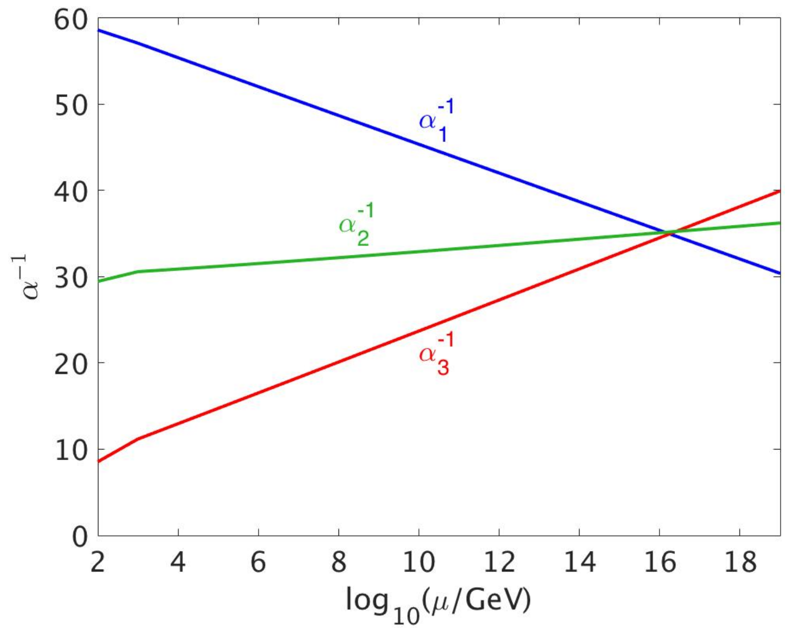
- Two new particles in $1 \leq n_1 \leq 6$ and $1 \leq n_2 \leq 6$ generations
- Models unify if range in Λ overlap

→ S1-2, S2-4, S2-6 and S2-11.

I. Minimal UV completions of d=7 operators

Numerical analysis

- Unification in 4 models
- Unification scale 10^{14}-10^{16} GeV
- One ”basic” model



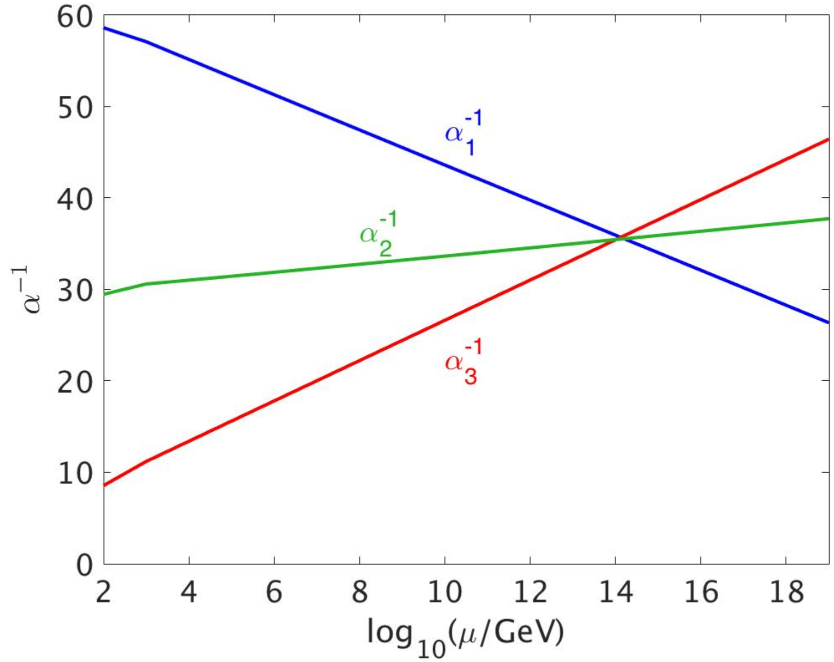
Model	P1	P2	Λ (GeV)	$\alpha^{-1}(\Lambda)$	$\frac{\Delta \log_{10}(\Lambda)}{\log_{10}(\Lambda)}$ (%)	$\frac{\Delta\alpha^{-1}}{\alpha^{-1}}$ (%)
S1-2	$3\,(3,2,\frac{1}{6})_S$	$(3,1,-\frac{1}{3})_S$	$2.4\cdot 10^{15}$	37.5	1.0	0.52
S1-2	$4\,(3,2,\frac{1}{6})_S$	$4\,(3,1,-\frac{1}{3})_S$	$1.8\cdot 10^{16}$	35.1	1.6	0.80
S2-4	$(3,1,\frac{2}{3})_F$	$5\,(3,2,\frac{1}{6})_S$	$4.3\cdot 10^{15}$	32.3	1.8	0.87
S2-11	$(1,2,-\frac{1}{2})_F$	$(3,2,\frac{1}{6})_S$	$1.2\cdot 10^{14}$	38.4	1.2	0.61

Adding dark matter

[Goodman, Witten 1985], [Cirelli, Fornengo, Strumia, 2006], [Cirelli, Strumia 2009]

Add 1 to 6 generations of DM to "basic model"

Scalar	Fermion	Scalar
$(1,3,0)_S$	$(1,3,0)_F$	$(1,2,\frac{1}{2})_S$
$(1,5,0)_S$	$(1,5,0)_F$	$(1,4,\frac{1}{2})_S$
$(1,7,0)_S$		

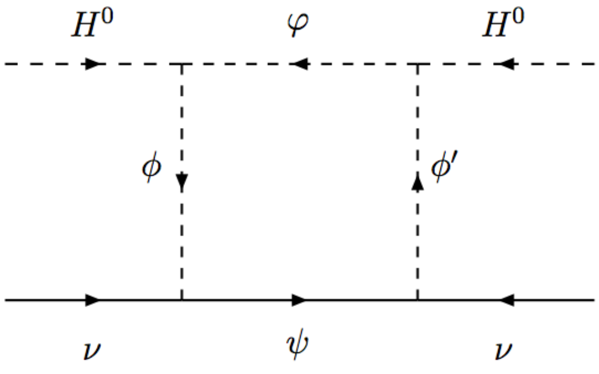


- Unification in 15 models
- Lower unification scale
- Gauge coupling same ball park

Model	P1	P2	DM	Λ (GeV)	$\alpha^{-1}(\Lambda)$	$\frac{\Delta \log_{10}(\Lambda)}{\log_{10}(\Lambda)}$ (%)	$\frac{\Delta\alpha^{-1}}{\alpha^{-1}}$ (%)
S2-9	$(3,1,-\frac{1}{3})_F$	$(1,1,1)_S$	$(1,3,0)_F$	$2.6\cdot 10^{14}$	37.9	0.54	0.28

II. Models with dark matter [Restrepo, Zapata, Yaguna, 2013]

T1-1-X



Model	m	P1	P2	P3	P4	Λ (GeV)	$\alpha^{-1}(\Lambda)$
T1-1-D	1	$(1,2,\frac{1}{2})_S$	$(1,1,0)_S$	$(1,2,\frac{1}{2})_F$	$(1,3,1)_S$	$1.3\cdot 10^{13}$	38.4
	-1	$(1,2,-\frac{1}{2})_S$	$(1,1,-1)_S$	$(1,2,-\frac{1}{2})_F$	$(1,3,0)_S$	$3.1\cdot 10^{13}$	38.2
T1-2-A	0	$(1,1,0)_F$	$(1,2,\frac{1}{2})_S$	$(1,1,0)_S$	$(1,2,\frac{1}{2})_F$	$5.3\cdot 10^{13}$	39.4
T1-2-B	0	$(1,1,0)_F$	$(1,2,\frac{1}{2})_S$	$(1,3,0)_S$	$(1,2,\frac{1}{2})_F$	$4.6\cdot 10^{13}$	38.4
	-2	$(1,1,-1)_F$	$(1,2,-\frac{1}{2})_S$	$(1,3,-1)_S$	$(1,2,-\frac{1}{2})_F$	$3.2\cdot 10^{12}$	35.9
T1-3-A	0	$(1,1,0)_F$	$(1,2,\frac{1}{2})_F$	$(1,1,0)_S$	$(1,2,-\frac{1}{2})_F$	$2.8\cdot 10^{13}$	37.7
T3-A	0	$(1,1,0)_S$	$(1,3,1)_S$	$(1,2,\frac{1}{2})_F$	-	$1.6\cdot 10^{13}$	37.3
	-2	$(1,1,-1)_S$	$(1,3,0)_S$	$(1,2,-\frac{1}{2})_F$	-	$4.0\cdot 10^{13}$	38.7
T1-3-A	0	$(1,1,0)_F$	$(1,2,\frac{1}{2})_F$	$2\ (1,1,0)_S$	-	$6.9\cdot 10^{13}$	39.8
T1-3-B	0	$(1,1,0)_F$	$(1,2,\frac{1}{2})_F$	$2\ (1,3,0)_S$	-	$5.7\cdot 10^{13}$	38.9

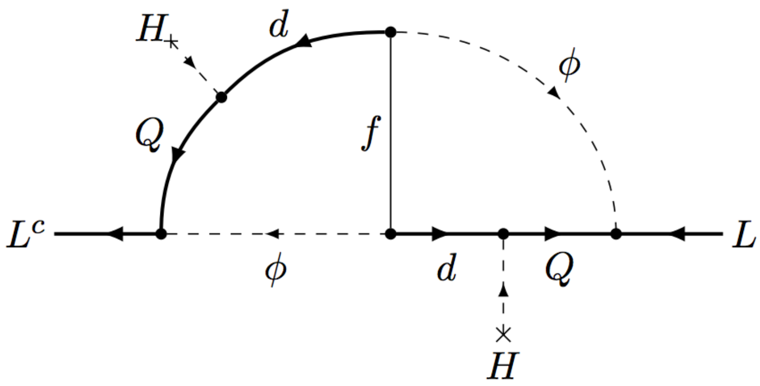
- One-loop realization of Weinberg operator
- 4 topologies
- 2-4 new particles
- Color neutral

- 10 models with unification
- Low unification scale

III. Models with particles in adjoint representation of SU(3)

[Angel, Cai, Rodd, Schmidt, Volkas, 2013], [Fileviez Pérez, Wise, 2009]

Model	Scalar	Fermion
U1	$(\overline{3}, 1, \frac{1}{3})_S$	$(8, 1, 0)_F$
U2	$(8, 2, \frac{1}{2})_S$	$(8, 1, 0)_F$
U3	$(8, 2, \frac{1}{2})_S$	$(8, 3, 0)_F$



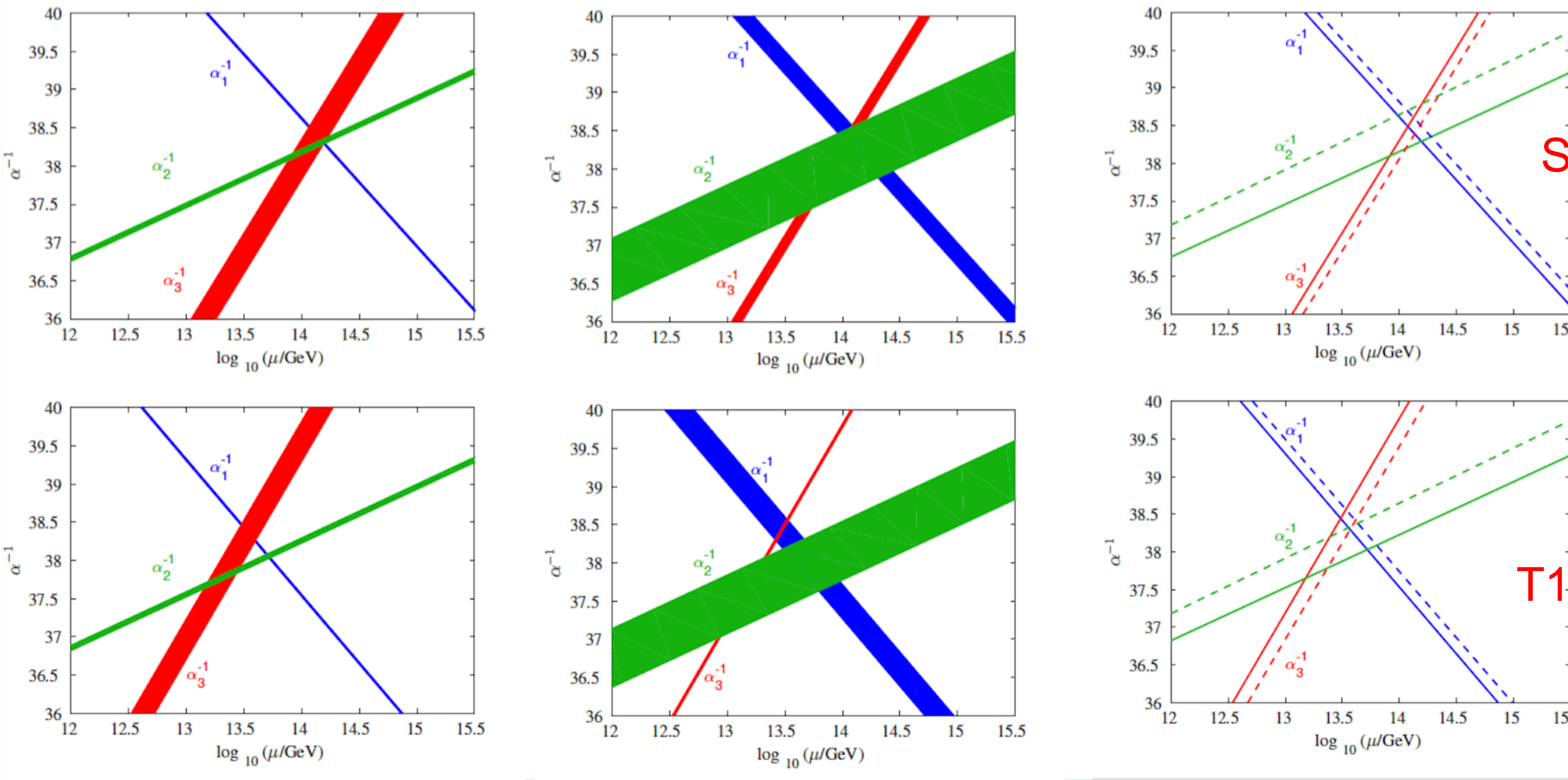
- Large representations = large contribution to the RG running
- Only one model, U1, without LP
- No model with unification (even if DM added)

Sources of uncertainty

Uncertainty at Z-mass scale

New particle mass

One-loop vs two-loop effect



S2-11

T1-1-D

Effects of the order of 1-10 %

Summary and conclusions

- Connect low-energy radiative neutrino mass models with high energy GUTs.
- Gauge unification is possible
- Unification scale in general low
  - Can be pushed up by colored particles
- Further investigation necessary considering other couplings and other models
- arXiv:1605.03986

THANK YOU!