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Soft masses in SUSY SO(10) GUTs with low intermediate scales

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Introduction and Motivations

We study the leading-log RGE evolution of the MSSM soft SUSY breaking parameters for four different SUSY SO (10) GUT models, with mSugra boundary conditions.

Our main motivations are neutrino masses...
Neutrino oscillation experiments have shown that at least two neutrino masses are non-zero.
SO(10) automatically contain the necessary ingredients to generate them.

SO(10) can then be broken in a variety of ways; breaking chains containing a left-right symmetry show particle spectra which contain right-handed neutrinos and thus can accommodate a seesaw mechanism, generating neutrino masses quite naturally.

...and the possibility that LHC (or a ILC) will soon discover sparticles, whose mass spectra will contain hints for these new scales due to the changes in the RGEs.

SUSY SO(10) GUT MODELS

All the models considered show :

- SUSY SO(10) unification with a sliding intermediate scale;
- a left-right symmetry at some stage, in order to motivate neutrino masses;
- Renormalizable SO(10) into MSSM gauge symmetry breaking;
- Potentially realistic fermionic spectra;
- MSSM Higgs doublet structure suitable for the implementation of the standard radiative symmetry breaking.

Within the mSugra boundary framework, we show that *particular combinations of soft masses can allow to distinguish between these models.*

It has already been pointed out(*) that these quantities show a characteristic deviation from their mSugra expectations, if seesaw mediators are added to the MSSM spectrum.

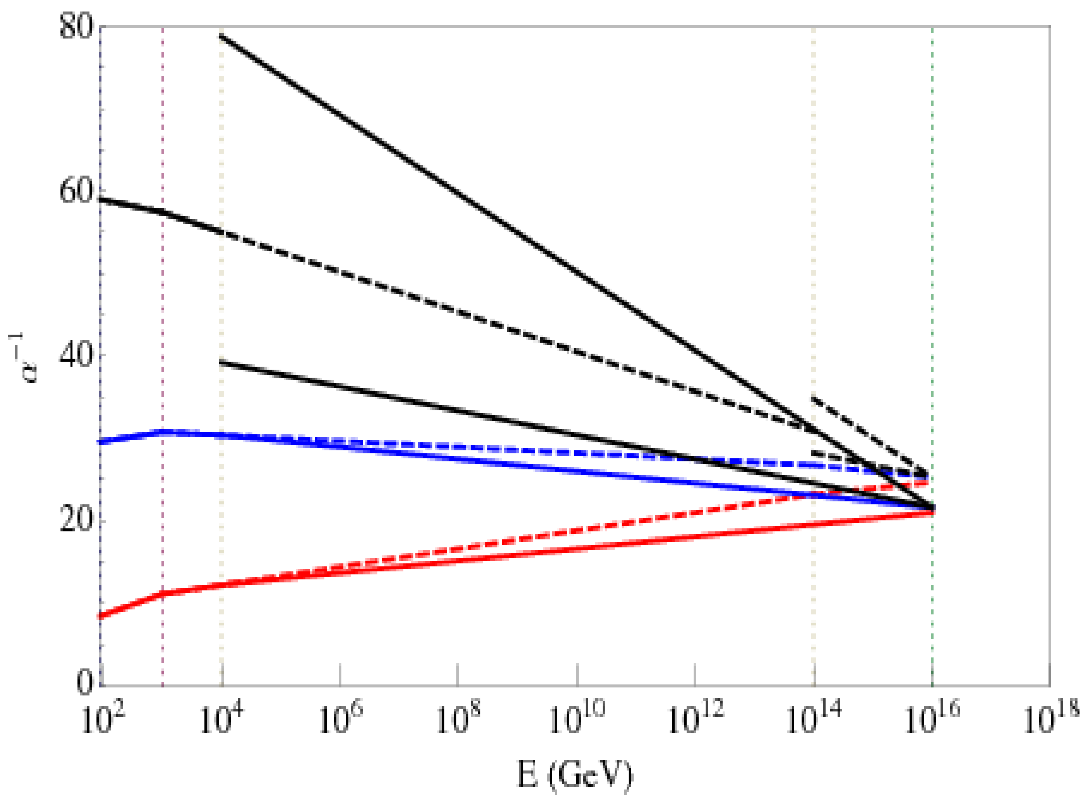
(Ref: M. R. Buckley and H. Murayama, Phys. Rev. Lett. 97, 231801 (2006))*

Model I: SUSY SO(10) with a sliding $SU(2)_R$ scale

Original model:
P. S. B. Dev and R. N. Mohapatra, Phys. Rev. D 81 013001 (2010)

The original SO(10) gauge symmetry is broken down to the MSSM in two steps via an intermediate $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	$SO(10)$ origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	16
L	3	$(1, 2, 1, -1)$	16
L^c	3	$(1, 1, 2, +1)$	16
S	3	$(1, 1, 1, 0)$	1
$\delta_d,\ \bar{\delta}_d$	1	$(3, 1, 1, -\frac{2}{3}),\ (\bar{3}, 1, 1, +\frac{2}{3})$	10
Φ	1	$(1, 2, 2, 0)$	10, 120
$\chi,\ \overline{\chi}$	1	$(1, 2, 1, \pm 1)$	$\overline{16}$, 16
$\chi^c,\ \overline{\chi}^c$	3	$(1, 1, 2, \mp 1)$	$\overline{16}$, 16



The b coefficients:

$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ level 1

$b_3 = -2,\ b_L = 2,\ b_R = 4$ and $b^c_{B-L} = 13$

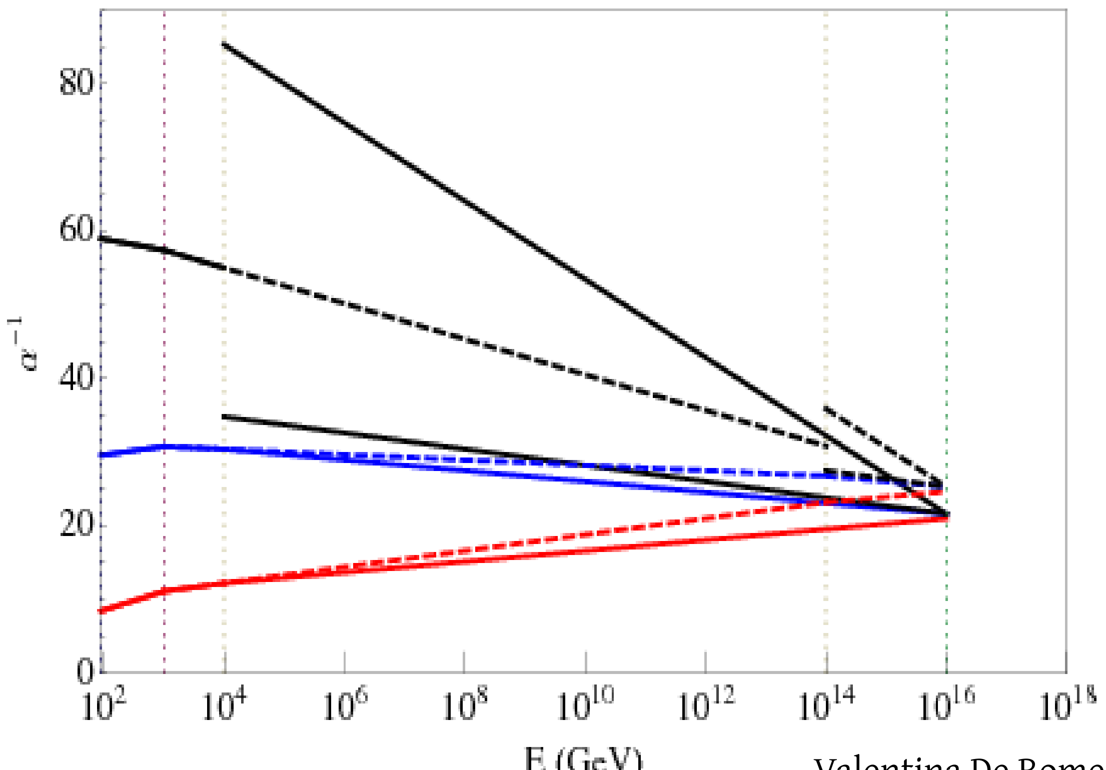
Solid lines: $V_R = 10^4$ GeV

Dashed lines : $V_R = 10^{14}$ GeV

Model II:SUSY SO(10) with a sliding $SU(2)_R$ scale

The main variation with respect to Model I is the B – L charge of the vector-like colour triplet pair owing to its different SO(10) origin.

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	$SO(10)$ origin
Q	3	$(3,2,1,+\frac{1}{3})$	16
Q^c	3	$(\bar{3},1,2,-\frac{1}{3})$	16
L	3	$(1,2,1,-1)$	16
L^c	3	$(1,1,2,+1)$	16
S	3	$(1,1,1,0)$	1
δ_u, $\bar{\delta}_u$	1	$(3,1,1,+\frac{4}{3})$, $(\bar{3},1,1,-\frac{4}{3})$	45
Φ	1	$(1,2,2,0)$	10, 120
χ, $\overline{\chi}$	1	$(1,2,1,\pm 1)$	$\overline{16}$, 16
χ^c, $\overline{\chi}^c$	2	$(1,1,2,\mp 1)$	$\overline{16}$, 16



$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ level

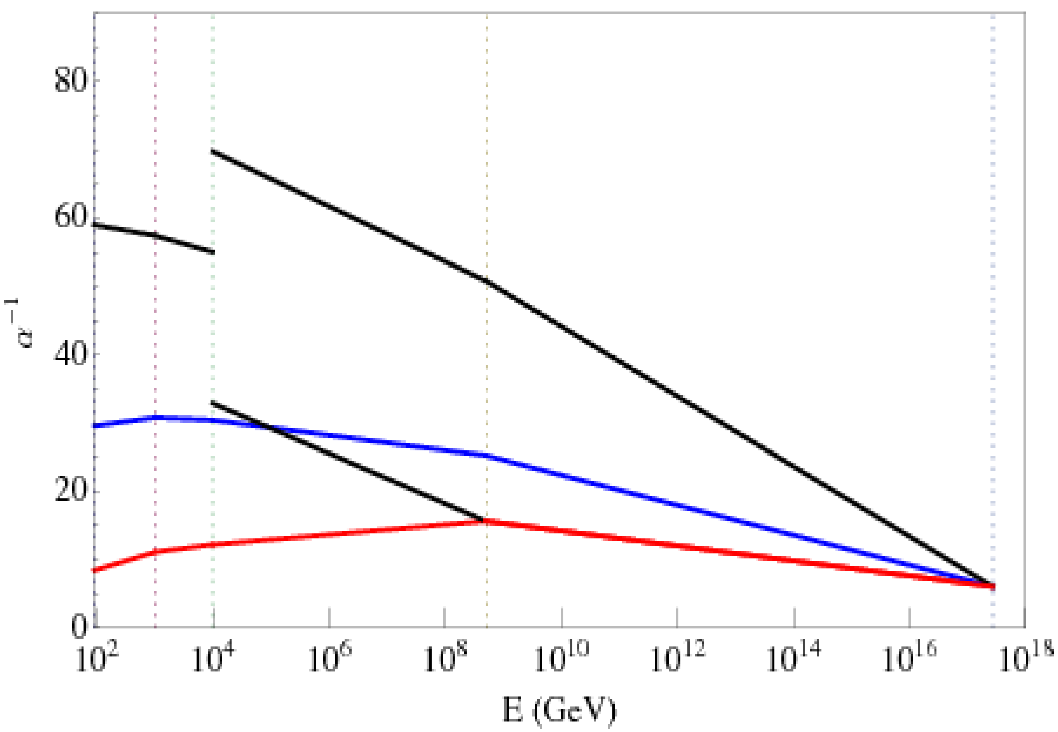
$b_3 = -2, \quad b_L = 2, \; b_R = 3$ and $b^{\rm can}_{B-L} = 29/2$

Solid lines: $V_R = 10^4$ GeV

Dashed lines : $V_R = 10^{14}$ GeV

Model III: sliding $SU(2)_R$ and Pati-Salam scales

The sliding nature of the $SU(2)_R \times U(1)_{B-L}$ scale is achieved via an interplay with another intermediate scale, namely, the Pati-Salam $SU(4)_C \times SU(2)_L \times SU(2)_R$



Field	Mult.	$3_c 2_L 2_R 1_{B-L}$	Pati-Salam	$SO(10)$
Q	3	$(3, 2, 1, +\frac{1}{3})$	$(4, 2, 1)$	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	$(\bar{4}, 1, 2)$	16
L	3	$(1, 2, 1, -1)$	$(4, 2, 1)$	16
L^c	3	$(1, 1, 2, +1)$	$(\bar{4}, 1, 2)$	16
Σ^c	3	$(1, 1, 3, 0)$	$(1, 1, 3)$	45
δ_d, $\bar{\delta}_d$	1	$(3, 1, 1, \mp\frac{2}{3})$	$(6, 1, 1)$	10
Φ	2	$(1, 2, 2, 0)$	$(1, 2, 2)$	10
Ω	1	$(1, 1, 3, 0)$	$(1, 1, 3)$	45
χ, $\bar{\chi}$	1	$(1, 2, 1, \pm 1)$	$(\bar{4}, 2, 1)$,$(4, 2, 1)$	$\overline{16}$, 16
χ^c, $\bar{\chi}^c$	1	$(1, 1, 2, \mp 1)$	$(4, 1, 2)$,$(\bar{4}, 1, 2)$	$\overline{16}$, 16
Ψ	1	absent	$(15, 1, 1)$	45

Pati-Salam $b_4 = 3,\ b_L = 6,\ b_R = 14$

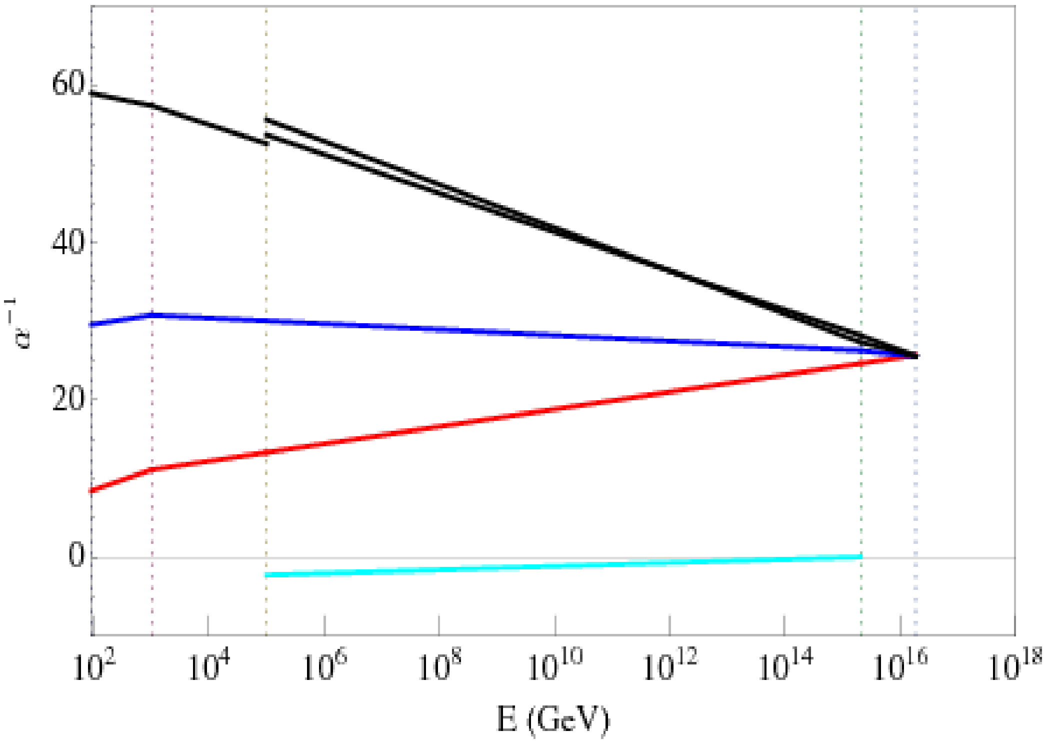
$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ level

$b_3 = -2,\ b_L = 3,\ b_R = 11$ and $b^{\rm can}_{B-L} = 10.$

Model IV:SUSY SO(10) with a sliding $U(1)_R$ scale

Original model:
M. Malinsky, J. C. Romao and J. W. F. Valle, Phys. Rev. Lett. 95, 161801 (2005)

An extended intermediate $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ stage follows a short $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ phase.



Field	Mult.	$3_c 2_L 1_R 1_{B-L}$	$3_c 2_L 2_R 1_{B-L}$	$SO(10)$
Q	3	$(3, 2, 0, +\frac{1}{3})$	$(3, 2, 1, +\frac{1}{3})$	16
Q^c	3	$(\bar{3}, 1, \pm\frac{1}{2}, -\frac{1}{3})$	$(\bar{3}, 1, 2, -\frac{1}{3})$	16
L	3	$(1, 2, 0, -1)$	$(1, 2, 1, -1)$	16
L^c	3	$(1, 1, \pm\frac{1}{2}, +1)$	$(1, 1, 2, +1)$	16
S	3	$(1, 1, 0, 0)$	$(1, 1, 1, 0)$	1
Φ	2	$(1, 2, \pm\frac{1}{2}, 0)$	$(1, 2, 2, 0)$	10
Ω	1	absent	$(1, 1, 3, 0)$	45
$\chi, \overline{\chi}$	1	absent	$(1, 2, 1, \pm 1)$	$\overline{16}$, 16
$\chi^c, \overline{\chi}^c$	1	$(1, 1, \pm\frac{1}{2}, \mp 1)$	$(1, 1, 2, \mp 1)$	$\overline{16}$, 16

$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$b_3 = -3,\ b_L = 2,\ b_R = 5 \quad \text{and } b^{\rm can}_{B-L} = 15/2.$$

$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ stage

$$b_3 = -3,\ b_L = 1 \qquad \gamma^{\rm phys} = \begin{pmatrix} 15/2 & -1 \\ -1 & 18 \end{pmatrix}$$

Squark and slepton spectra

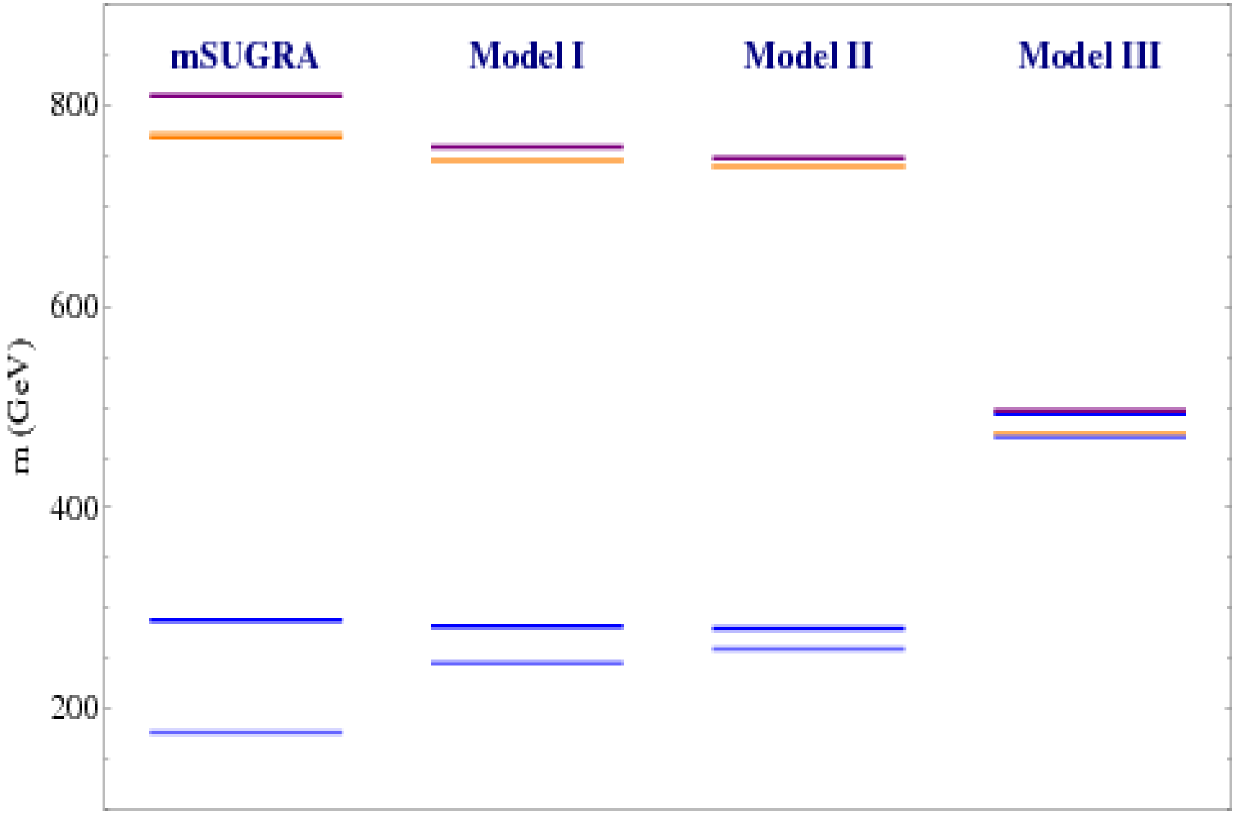
Illustrative example of the shapes of the MSSM squark and slepton spectra:

calculated for the SPS3 benchmark point, i.e. for m_0 = 90 GeV and $M_{1/2}$ = 400 GeV.

The horizontal lines (bottom to up) correspond to:

$m_{\tilde{e}}$ (light blue),
$m_{\tilde{l}}$ (blue),
$m_{\tilde{u}}$ (orange),
$m_{\tilde{d}}$ (light orange)
$m_{\tilde{q}}$ (purple).

The v_R scale has been in all cases chosen very low, namely, $v_R = 10^3$ GeV.



LEADING-LOG RGE INVARIANTS

Using mSugra boundary conditions at the 1-loop level, one can devise a simple set of analytic equations for the soft terms.
The gaugino masses at the low scale:

$$M_i(m_{SUSY}) = \frac{\alpha_i(m_{SUSY})}{\alpha(M_G)} M_{1/2}.$$

Neglecting the Yukawa couplings, for the soft mass parameters of the first two generations of sfermions:

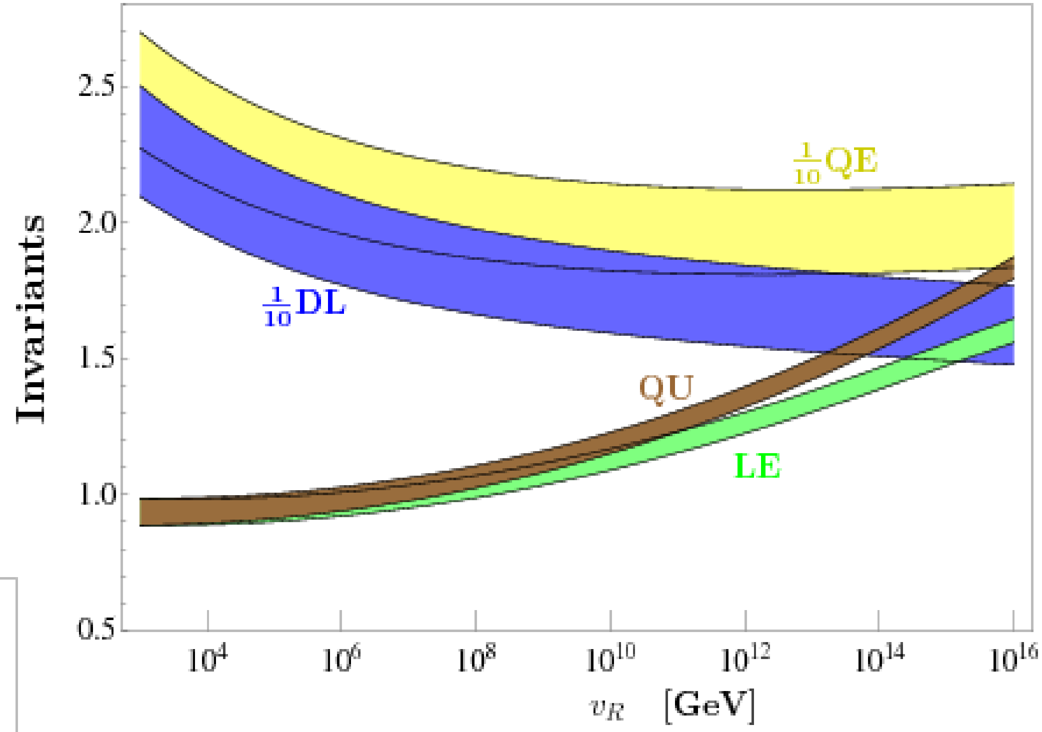
$$m_{\tilde{f}}^2 = m_0^2 + \frac{M_{1/2}}{\alpha(M_G)^2} \sum_{R_j} \sum_{i=1}^{N} \tilde{f}_i^R \alpha_i(v_{R_j})^2 .$$

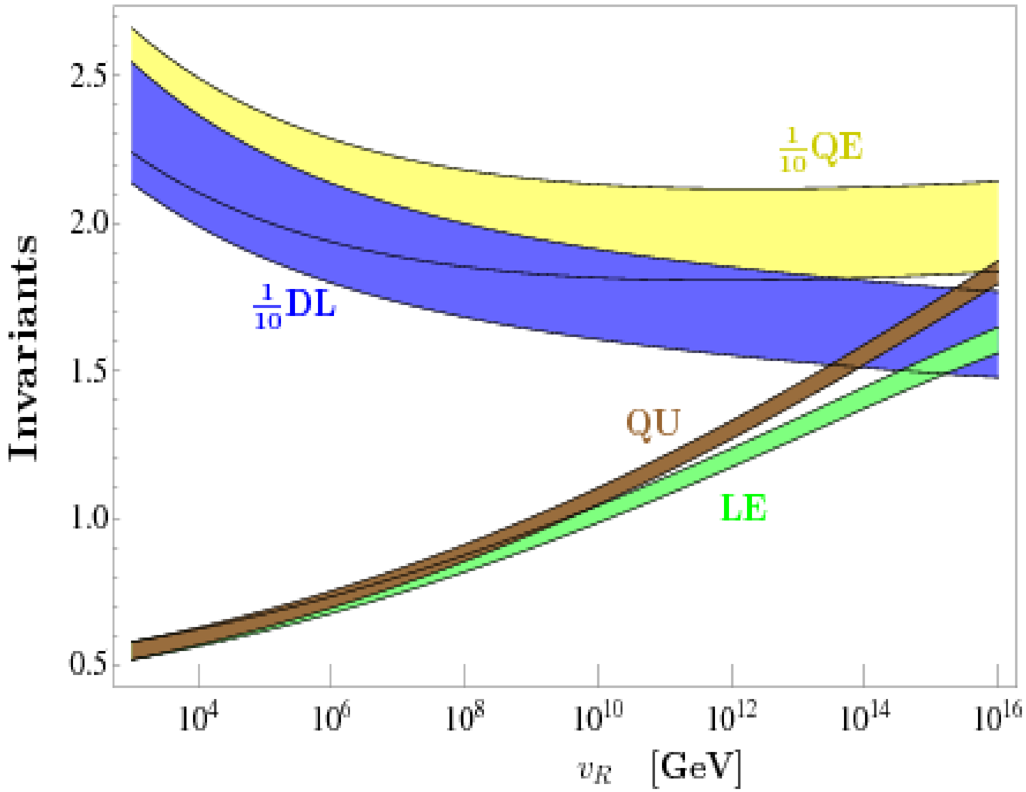
Individual SUSY masses depend strongly on the initial values for m_0 and $M_{1/2}$.
However, one can form four different combinations

$$LE \equiv (m_{\tilde{L}}^2 - m_{\tilde{E}}^2)/M_1^2$$
$$QE \equiv (m_{\tilde{Q}}^2 - m_{\tilde{E}}^2)/M_1^2$$
$$DL \equiv (m_{\tilde{D}}^2 - m_{\tilde{L}}^2)/M_1^2$$
$$QU \equiv (m_{\tilde{Q}}^2 - m_{\tilde{U}}^2)/M_1^2$$

V_R dependence of the RGE invariants in Models I, II

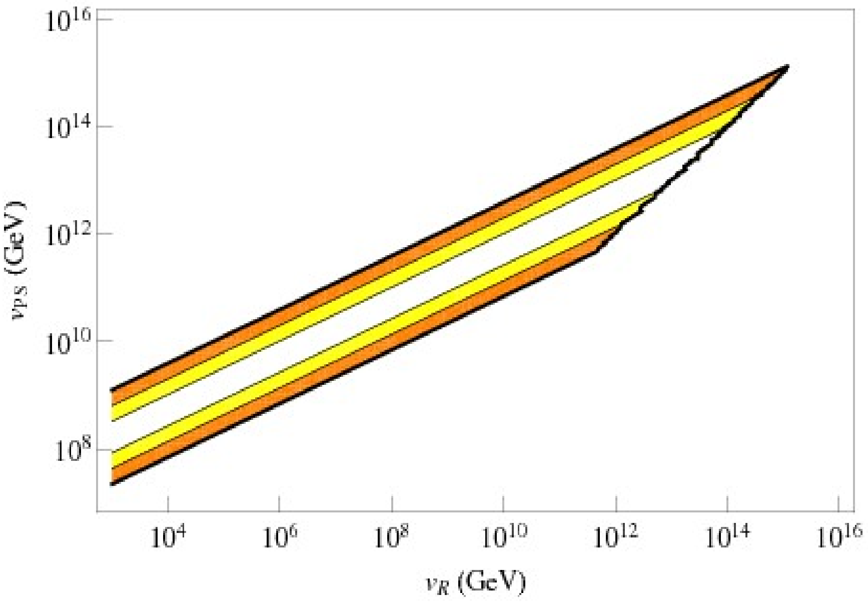
The bands represent the error due to the non-exact gauge-coupling unification (scan over the non unification triangle).





- Log dependence on v_R
- QU and LE overlap for $v_R \rightarrow$ MSSM scale
- mSugra values for $v_R \rightarrow M_G$
- QE and DL tend to increase with v_R departing from M_G

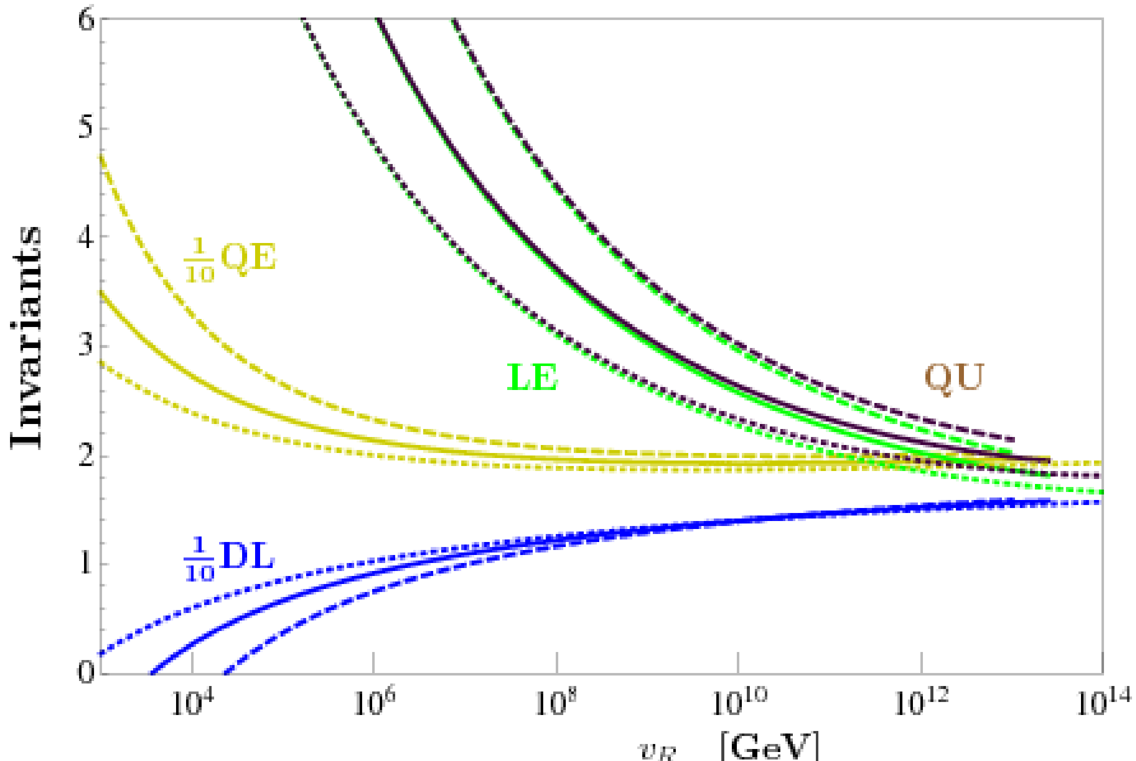
Model III with sliding $SU(2)_R$ & PS scales



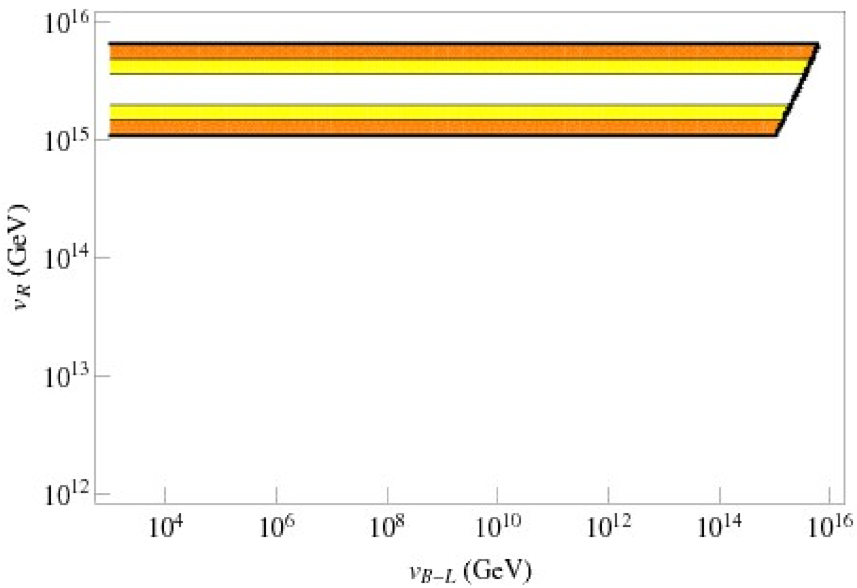
The LR and PS intermediate scales can be always adjusted so that one gets an exact one-loop unification for v_R stretching up to about 10^{14} GeV

$$t_{PS} = \frac{1}{2}t_{LR} - \frac{1}{12}\Big(14t_{SUSY} + 20t_Z + \pi(18\alpha_S(t_Z)^{-1} - 33\alpha_L(t_Z)^{-1} + 15\alpha_Y(t_Z)^{-1})\Big)$$

The invariants show a stronger v_R-dependence than in Models I and II

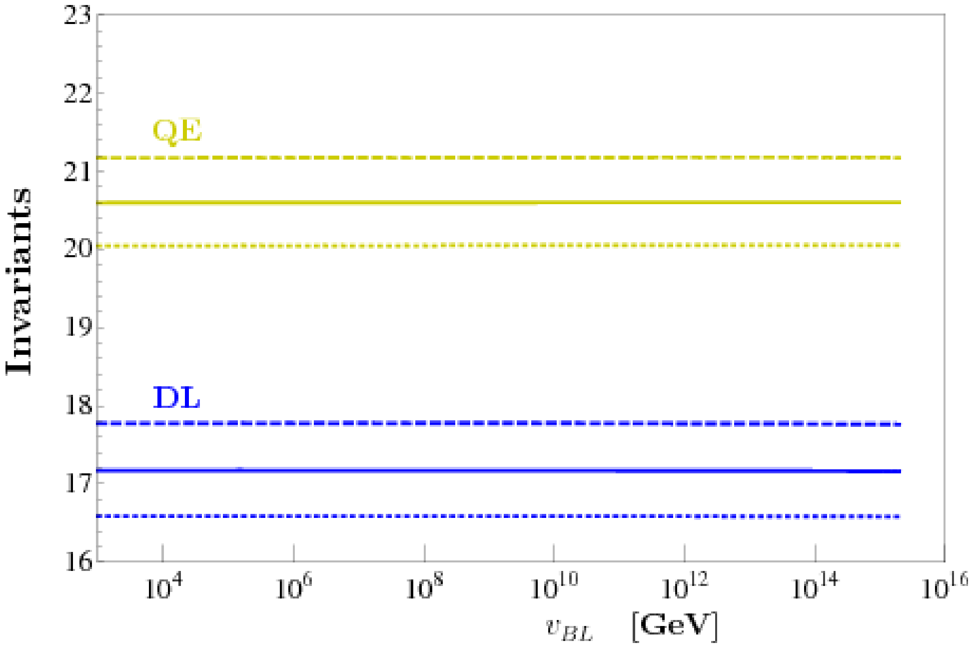


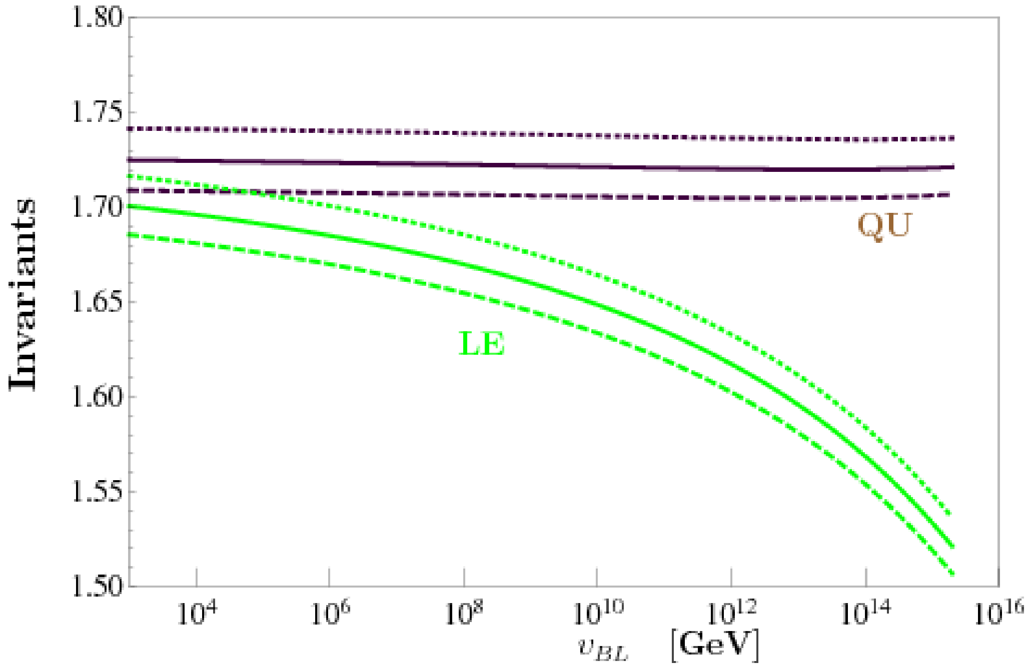
Model IV with sliding $U(1)_R \times U(1)_{B-L}$ scale



The main uncertainty at this level comes from the experimental error in $\alpha_S(M_Z)$ which translates into small shifts in v_R.

All four invariants exhibit only a very mild v_{BL} dependence: the strongest effect of the order of few per cent observed in the LE case.





DISCUSSION AND OUTLOOK

We considered four different models, all based on the unified SO(10) gauge group, but which differ at the level of intermediate scale symmetry groups and/or particle content below the GUT scale.

We defined combinations of the soft masses, called invariants, which although contain only a logarithmic dependence on the new physics scales, behave qualitatively different in different models.

The RGE invariants are good model discriminators, at least in principle. Indeed, Model IV is an example of how a new scale can be effectively "hidden" from the RGE invariants in special constructions.

There are errors to take into account, though:

- ✗ uncertainties in the values of the input parameters (the largest, m_{SUSY})
- ✗ important higher order effects such as genuine 2-loop corrections and 1-loop thresholds can emerge.
- ✗ conversion of the invariants into the measured sparticle masses requires additional experimental input.

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Thanks for the attention

Backup slides

LEADING-LOG RGE INVARIANTS

$$M_i(m_{SUSY}) = \frac{\alpha_i(m_{SUSY})}{\alpha(M_G)} M_{1/2}.$$

$$m_i^2(\mu) = m_i^2(\mu_0) - 2\sum_{\alpha=1}^{3} \frac{C_{\alpha,i}}{b_\alpha^{(1)}} |M_\alpha^2(\mu_0)| \left[\frac{g_\alpha^2(\mu)}{g_\alpha^2(\mu_0)} - 1\right] + \frac{Y_i}{22} S_Y(\mu_0) \left[\frac{g_Y^2(\mu)}{g_Y^2(\mu_0)} - 1\right]$$

$$m_{\tilde{f}}^2 = m_0^2 + \frac{M_{1/2}}{\alpha(M_G)^2} \sum_{R_j} \sum_{i=1}^{N} \tilde{f}_i^R \alpha_i(v_{R_j})^2$$

$$\tilde{f}_i^R = \frac{c_i^{f,R}}{b_i} \left[1 - \left(\frac{\alpha_i(v_x)}{\alpha_i(v_y)}\right)^2\right]$$

$$c_i^{f,R} = 2C_G(R_f).$$

$$C_G(R)d(R) = T_2(R)d(G)$$

$\tilde{f}$	$\tilde{E}$	$\tilde{L}$	$\tilde{D}$	$\tilde{U}$	$\tilde{Q}$
MSSM					
$c_1^{f,MSSM}$	$\frac{6}{5}$	$\frac{3}{10}$	$\frac{2}{15}$	$\frac{8}{15}$	$\frac{1}{30}$
$c_2^{f,MSSM}$	0	$\frac{3}{2}$	0	0	$\frac{3}{2}$
$c_3^{f,MSSM}$	0	0	$\frac{8}{3}$	$\frac{8}{3}$	$\frac{8}{3}$
$U(1)_R \times U(1)_{B-L}$					
$c_{BL}^{f,BL}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$
$c_L^{f,BL}$	0	$\frac{3}{2}$	0	0	$\frac{3}{2}$
$c_R^{f,BL}$	$\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	0
$c_3^{f,BL}$	0	0	$\frac{8}{3}$	$\frac{8}{3}$	$\frac{8}{3}$
LR					
$c_{BL}^{f,LR}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$
$c_L^{f,LR}$	0	$\frac{3}{2}$	0	0	$\frac{3}{2}$
$c_R^{f,LR}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	0
$c_3^{f,LR}$	0	0	$\frac{8}{3}$	$\frac{8}{3}$	$\frac{8}{3}$
Pati-Salam					
$c_L^{f,PS}$	0	$\frac{3}{2}$	0	0	$\frac{3}{2}$
$c_R^{f,PS}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	0
$c_4^{f,PS}$	$\frac{15}{4}$	$\frac{15}{4}$	$\frac{15}{4}$	$\frac{15}{4}$	$\frac{15}{4}$

Models I & II with a sliding $SU(2)_R$ scale

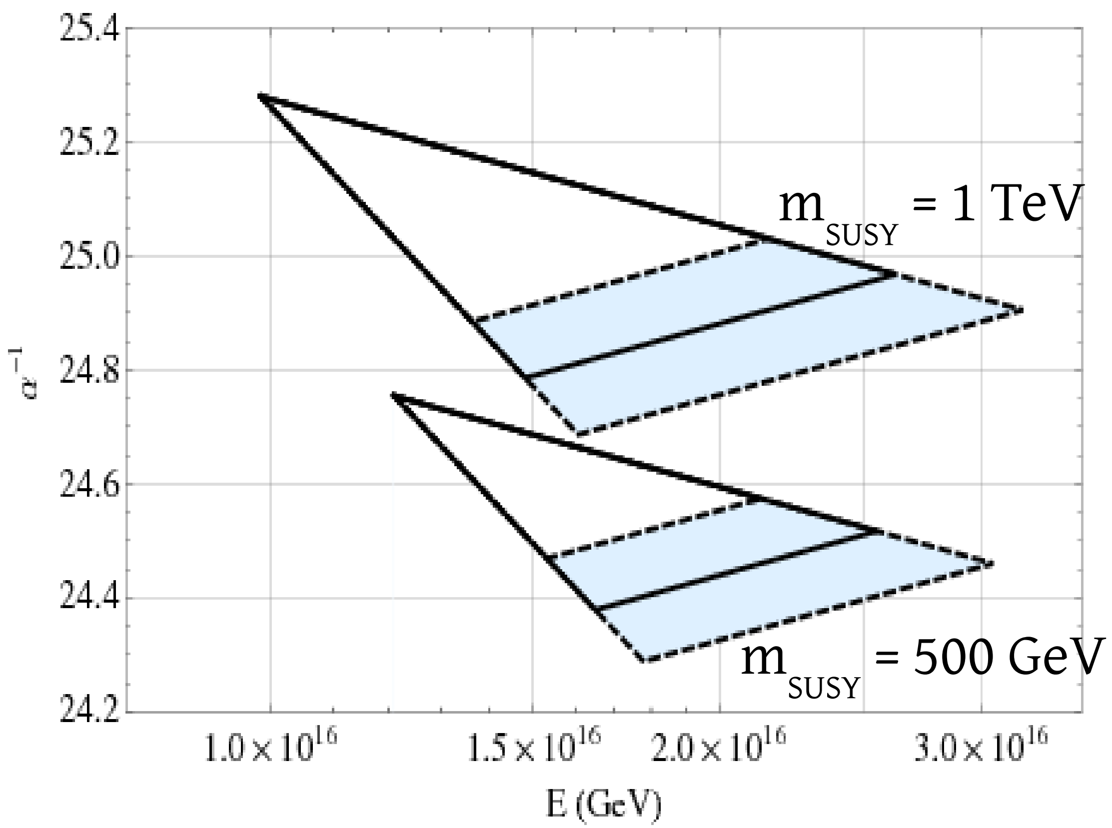
The sliding nature of the $SU(2)_R$ scale makes it impossible to get an exact unification, in analogy with the MSSM.

We parametrize our ignorance of the "true values" of the unification scale position and the unified gauge coupling in terms of a pair of small "offset" parameters scanning over the area of the relevant non-unification triangle

The upper sides of the triangles corresponds to α^{-1}_L while the lower-left sides depict the "effective" α^{-1}_Y defined as $\frac{3}{5}\alpha_R^{-1} + \frac{2}{5}\alpha_{B-L}^{-1}$

The light blue area surrounding the α^{-1}_s line represents the 1σ uncertainty in $\alpha_s(MZ)$

$$\Delta(\alpha_S(M_Z)) = 0.002$$



U(1) Mixing

arXiv:1107.2670

Some technical details of the one-loop evolution of gauge couplings and soft-SUSY breaking terms in Model IV.
It is convenient to work with a matrix of gauge couplings rather than with each of them individually.

$$G = \begin{pmatrix} g_{RR} & g_{RX} \\ g_{XR} & g_{XX} \end{pmatrix}$$

The evolution equation can be written as $\frac{\mathrm{d}}{\mathrm{d}t} A^{-1} = -\gamma$

where $A^{-1} \equiv 4\pi (G G^T)^{-1}$ and $t = \frac{1}{2\pi} \log(\mu/\mu_0)$.

$\gamma \equiv \sum_f Q_f Q_f^T$ Is the relevant matrix of anomalous dimensions.

The matching condition between such high-energy gauge couplings (corresponding to U(1)R x U(1)B–L in the case of our interest) and the effective-theory one (i.e., U(1)Y of the MSSM) at scale t

$$\alpha_Y^{-1}(t_0) = p_Y^T A^{-1}(t_0) p_Y$$

$$p_Y^T = \left(\sqrt{\tfrac{3}{5}}, \sqrt{\tfrac{2}{5}}\right) ;$$

$$g_Y^{-2} = (g_{RR} g_{XX} - g_{RX} g_{XR})^{-2} \left[\frac{3}{5} \left(g_{XX}^2 + g_{XR}^2 \right) + \frac{2}{5} \left(g_{RR}^2 + g_{RX}^2 \right) - \frac{2}{5} \sqrt{6} \left(g_{RR} g_{XR} + g_{RX} g_{XX} \right) \right] . \quad \text{(A5)}$$

DISCUSSION AND OUTLOOK

Comparison with "standard" seesaws:

Type-I seesaw adds only singlets to the MSSM and thus, just like our Model IV, can not be distinguished from the pure mSugra case by means of the invariants only.
Type-II and type-III seesaw, on the other hand, change the b -coefficients with respect to the MSSM, but do not extend the gauge group.

As a result, for minimal seesaws all four invariants are larger than their mSugra limit if the seesaw scale is below the GUT scale, as indicated by neutrino data.

Thus, the invariants should allow to distinguish our SO (10)-based Models I to III from type-II and type-III seesaw.