UV completion of the radiative neutrino mass models

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Hrvatska zaklada za znanost

GOALS :

- BOTTOM-UP approach to address m_ν (and DM) problems (in the SM gauge group context)
- LHC rationale: focusing on mechanisms whose required states can get tested @ LHC
- possible UV completions of such models: embedding into GUT scenarios

Open problems of Standard Model

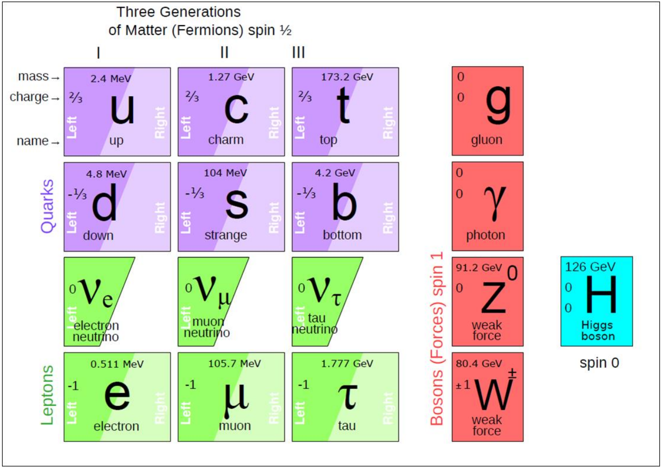
- neutrino masses (neutrino oscillations: existence, lightness)
- dark matter
- hierarchy problem - Higgs naturalness problem
- ...

Motivates search for BSM physics: requires introducing new “heavy” particles (no gauge anomaly: e.g. vector-like matter)

Open problems of Standard Model

"accidental" SM matter (used representations seemingly arbitrary)

SM Periodic Table



Top-down BSM approach: GUTs

PROs :

- unified framework → less parameters, connection between different quantities
- electric charge quantization
- prediction of new phenomena (proton decay, ...)
- "explanation" for the heavy spectrum

CONs :

- simplest models ruled out (e.g. no unification, massless neutrinos in Georgi-Glashow minimal non-SUSY $SU(5)$)
- infinitely many possibilities (GUT gauge group, representations, scalar potential): no clear selection rule
- phenomenology (neutrino masses, DM, proton decay, light fermion mass relations ...)

Bottom-up BSM approach: neutrino mass models

Focusing on established deficiencies of SM: construction of mechanisms which try to explain experimental findings

Seesaw mechanism

Weinberg dim 5 effective operator *LLHH* after integrating out BSM particles (M)

$$\Delta\mathcal{L} = \frac{\lambda}{M} LLHH + \mathcal{O}(\frac{1}{M^2}) \quad \rightarrow \quad m_\nu \sim \lambda \frac{v^2}{M} \sim 0.1\,\mathrm{eV}$$

@ tree-level: only 3 possible realizations (with single BSM particle) :

- **type I**: $3 \times N_R^f \sim (1,1,0)$
  [Minkowski '77; Yanagida '79; Glashow '79; Gell-Mann, Ramond, Slansky '79; Mohapatra, Senjanović '79]
- **type II**: $1 \times \Delta^s \sim (1,3,-1) \equiv \begin{pmatrix} \Delta^- & -\sqrt{2}\Delta^0 \\ \sqrt{2}\Delta^{--} & -\Delta^- \end{pmatrix}$
  [Magg, Wetterich '80; Schechter, Valle '80; Lazarides et al. '80; Mohapatra, Senjanović '80; Gelmini, Roncadelli '80]
- **type III**: $3 \times \Sigma^f \sim (1,3,0) \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 \end{pmatrix}$
  [Foot, Lew, He, Joshi '89]

Seesaw mechanism

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If $\lambda \sim \mathcal{O}(1)$ and $v = \langle H \rangle = 246\,\mathrm{GeV}$, scale of new physics (seesaw scale) $M \sim 10^{14}\,\mathrm{GeV} \rightarrow$ out of reach of LHC.

Either lowering seesaw scale by going to higher dimensional operators:

$$m_\nu \sim v \left(\frac{v}{M}\right)^{dim-4}$$

- dim 7: $(LLHH)(H^\dagger H)$
- dim 9: $(LLHH)(H^\dagger H)(H^\dagger H) \rightarrow M \sim \mathrm{TeV}$
- ...

or ...

Zee model

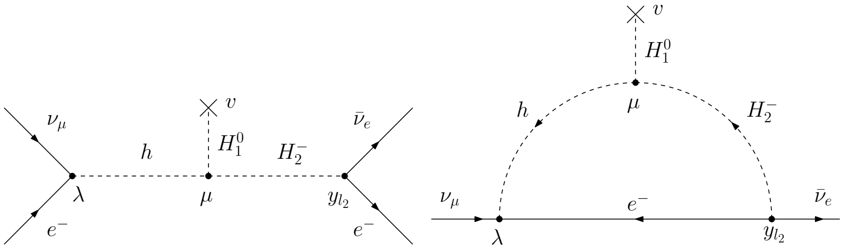
... or consider radiative neutrino mass models (mass suppression by loop factor)

Zee '80: realization of radiative neutrino mass by 2HD + charged Higgs singlet

$$\mathrm{SM} + H_2 \sim (1, 2, +\tfrac{1}{2}) \subset 5_{H_2} + h^+ \sim (1, 1, +1) \subset 10_H$$
$$V_{Zee} \sim \lambda L L h^+ + y_{l_a} \bar{L} H_a e + \mu H_1 H_2 h^- + h.c.$$

(where λ is antisymmetric in flavour space) breaks global $B - L$

$\Delta L = 2$ processes (e.g. $\nu_\mu e^- \to \bar{\nu}_e e^-$) break L_e, L_μ, L_τ and contribute to Majorana neutrino mass (oscillation of neutrino into antineutrino; Majorana neutrino is its own antineutrino):



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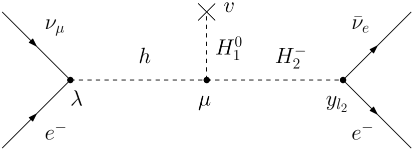
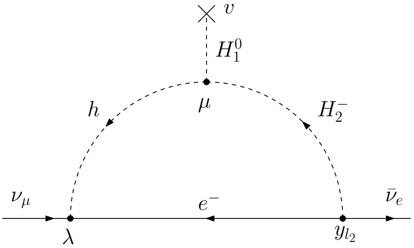
(where λ is antisymmetric in flavour space) breaks global $B-L$

$$m_\nu \sim m_e \, \lambda \, y_{l_2} \, \mu \, v \, m_h^{-2} \log \frac{m_h^2}{m_{H_2}^2}$$





Synthesis: UV complete neutrino mass models

Potentially realistic extensions of Georgi-Glashow model :

▷▷▷ Georgi, Glashow '74:
minimal non-SUSY $SU(5)$: $24_H \oplus 5_H \oplus 3 \times (10_F \oplus \bar{5}_F)$ ✗

- no unification, massless neutrinos

Synthesis: UV complete neutrino mass models

Potentially realistic extensions of Georgi-Glashow model :

▷▷▷ $SU(5) + 3 \times 1_F$ + type I seesaw ✗

- no unification

Synthesis: UV complete neutrino mass models

Potentially realistic extensions of Georgi-Glashow model :

▷▷▷ Doršner, Fileviez Perez et al. '05:
$SU(5) + 15_H \supseteq (1,3,+1) \oplus (3,2,+\frac{1}{6}) \oplus (6,1,-\frac{2}{3})$ + type II seesaw ✓

- unification - light leptoquarks
- non-renormalizable model - higher dimensional operators needed to correct $SU(5)$ fermion mass relations

Synthesis: UV complete neutrino mass models

Potentially realistic extensions of Georgi-Glashow model :

▷▷▷ Bajc, Nemevšek, Senjanović '07: $SU(5) + 24_F \supset (1,3,0)_F \oplus (1,1,0)_F \oplus \dots$
$+$ combination of type I and type III seesaw $+$ 1 massless neutrino ✓

- unification - $m_{(1,3,0)_{H,F}} \lesssim \mathrm{TeV}$
- non-renormalizable model - higher dimensional operators needed to correct the $SU(5)$ fermion mass relations & to split fields in 24_F
- fine-tuned but predictive: proton decay & unification constraints

Synthesis: UV complete neutrino mass models

Potentially realistic extensions of Georgi-Glashow model :

▷▷▷ Fileviez Perez, Murgui '16: $SU(5) + 10_H + 45_H \supseteq (1,2,+\frac{1}{2}) \oplus (3,1,-\frac{1}{3}) \oplus (3,3,-\frac{1}{3}) \oplus (\bar{3},1,+\frac{4}{3}) \oplus (\bar{3},2,-\frac{7}{6}) \oplus (\bar{6},1,-\frac{1}{3}) \oplus (8,2,+\frac{1}{2})$ ✓

- unification & proton decay (main contribution from gauge boson mediation) - $m(8,2,+\frac{1}{2}) \sim 1 - 10\,\mathrm{TeV}$
- 45_H - correct mass relations between charged leptons & down-type quarks @ renormalizable level

$$M_d = Y_1^T \frac{v_5}{\sqrt{2}} - \frac{1}{3} Y_2^T \frac{v_{45}}{\sqrt{2}}$$
$$M_e = Y_1 \frac{v_5}{\sqrt{2}} + Y_2 \frac{v_{45}}{\sqrt{2}}$$

$+$ contains 2^{nd} Higgs doublet - generates neutrino masses @ quantum level through Zee mechanism

$$V_{Zee} \supseteq \lambda \bar{5}_F \bar{5}_F 10_H + \bar{5}_F 10_F (Y_1^* 5_H^* - \frac{1}{6} Y_2^* 45_H^*) - \frac{1}{6}\mu 5_H 45_H 10_H^* + h.c.$$

Brdar, Picek, Radovčić '13: 1-loop radiative neutrino mass model - variant of Zee model: triplet instead of 2^{nd} Higgs doublet

$$\Delta \sim (1,3,0) = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^0 & \Delta^+ \\ \Delta^- & -\frac{1}{\sqrt{2}}\Delta^0 \end{pmatrix}$$
$$h^+ \sim (1,1,+1)$$

and 3 generations of vector-like lepton doublets: $E_{L,R} \sim (1,2,-\frac{1}{2})$

$$\begin{aligned} \mathcal{L} &= M\overline{E_L}E_R + \tilde{M}\overline{L_L}E_R + y\overline{E_L}Hl_R + y_1\overline{L_L^c}E_L h^+ + \\ &+ y_2\overline{L_L}\Delta E_R + y_3\overline{E_L}\Delta E_R + y_4\overline{L_L^c}L_L h^+ + h.c. \\ V(H,\Delta,h^+) &= -\mu_H^2 H^\dagger H + \lambda_1(H^\dagger H)^2 + \mu_h^2 h^- h^+ + \lambda_2(h^- h^+)^2 \\ &+ \mu_\Delta^2 \,\mathrm{Tr}\big[\Delta^2\big] + \lambda_3(\mathrm{Tr}\big[\Delta^2\big])^2 + \lambda_4 H^\dagger H h^- h^+ + \lambda_5 H^\dagger H\,\mathrm{Tr}\big[\Delta^2\big] \\ &+ \lambda_6 h^- h^+\,\mathrm{Tr}\big[\Delta^2\big] + (\lambda_7 H^\dagger \Delta \tilde{H} h^+ + h.c.) + \mu H^\dagger \Delta H \end{aligned}$$

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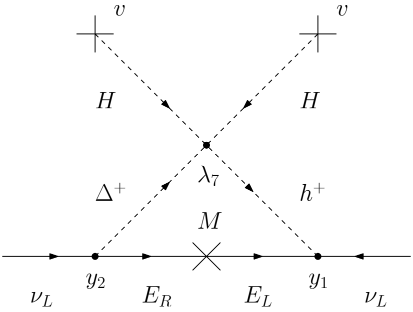
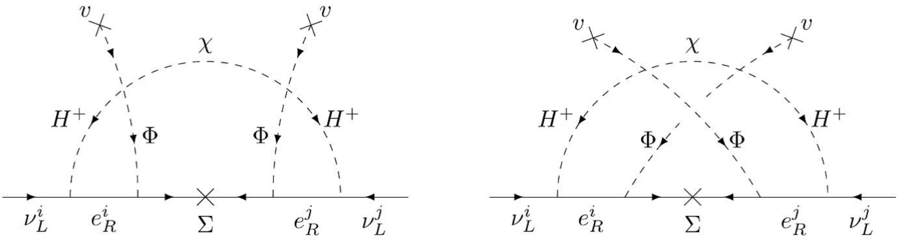


$$m_\nu \propto \frac{1}{4\pi^2}\, y_1\, y_2\, \lambda_7\, M\, v^2 \times (\text{loop factor})$$

Čuljak, Kumerički, Picek '15: 3-loop radiative neutrino mass model - Yukawas of order $\mathcal{O}(1)$: 2HD + exotic matter

$$\phi^s \sim (1,5,-1)$$
$$\chi^s \sim (1,7,0)$$
$$\Sigma^f \sim (1,5,0)$$



multiplets	$\subset SU(5)$	$\subset SU(5)'_{Z'}$	$\subset SO(10)$
$\mathbf{m}_\nu$ @ 1-loop			
$\Delta = (1,3,0)$	24	24_0, 15_1, $\overline{15}_{-1}$, 175_1	45, 54, 144, 210, 560
$h^+ = (1,1,+1)$	10	1_5, 24_5, $\overline{10}_4$, 10_6, 50_3, $\overline{50}_7$, 75_5	16, 45, 120, 126, 144, 210, $560^{(3)}$, $\overline{560}$
$E_{L,R} = (1,2,-\frac{1}{2})$	$\bar{5}$, $\overline{45}$, $\overline{70}$	5_{-2}, $\bar{5}_{-3}$, 40_{-4}, $\overline{40}_{-1}$, 45_{-2}, $\overline{45}_{-3}$, 70_{-2}, $\overline{70}_{-3}$	10, 16, $120^{(2)}$, 126, $\overline{126}$, $144^{(2)}$, $\overline{144}$, 210, $210'$, $320^{(3)}$, $560^{(3)}$, $\overline{560}$
$\mathbf{m}_\nu$ @ 3-loops			
$H_{1,2} = (1,2,+\frac{1}{2})$	5, 45, 70	$\bar{5}_2$, 5_3, $\overline{40}_4$, 40_1, $\overline{45}_2$, 45_3, $\overline{70}_2$, 70_3	10, $\overline{16}$, $120^{(2)}$, 126, $\overline{126}$, 144, $\overline{144}^{(2)}$, 210, $210'$, $320^{(3)}$, 560, $\overline{560}^{(3)}$
$\phi = (1,5,-1)$	> 75	$70'_{-7}$, $\overline{70}'_{-3}$	> 560
$\chi = (1,7,0)$	> 75	> 75	> 560
$\Sigma = (1,5,0)$	> 75	$70'_{-2}$, $\overline{70}'_{2}$	> 560

SM singlets $(1,1,0)$ with potentially non-zero VEVs $\in$ 24, 75 ($SU(5)$); 1_0, 10_1, $\overline{10}_{-1}$, 24_0, 50_{-2}, $\overline{50}_2$, 75_0 ($SU(5)'_{Z'}$); 16, $45^{(2)}$, 54, 126, 144, $210^{(3)}$, $560^{(3)}$ ($SO(10)$)

$SU(5)$ embedding of the 1-loop (BPR) model

Particle content:

	SM multiplets	$\subset SU(5)$
scalar	$H = (1, 2, +\frac{1}{2})$	$5^a = (1, 2, +\frac{1}{2}) \oplus (3, 1, -\frac{1}{3})$; or 45, 70
	$\Delta = (1, 3, 0)$ $h^+ = (1, 1, +1)$	$24^a_b = (1, 3, 0) \oplus (8, 1, 0) \oplus (1, 1, 0) \oplus (3, 2, -\frac{5}{6}) \oplus (\bar{3}, 2, +\frac{5}{6})$ $10^{ab} = (1, 1, +1) \oplus (\bar{3}, 1, -\frac{2}{3}) \oplus (3, 2, +\frac{1}{6})$
fermion	$3 \times Q = (3, 2, +\frac{1}{6})$ $3 \times u^c = (\bar{3}, 1, -\frac{2}{3})$ $3 \times e^c = (1, 1, +1)$ $3 \times L = (1, 2, -\frac{1}{2})$ $3 \times d^c = (\bar{3}, 1, +\frac{1}{3})$	$3 \times 10^{ab} = (3, 2, +\frac{1}{6}) \oplus (\bar{3}, 1, -\frac{2}{3}) \oplus (1, 1, +1)$ $3 \times \bar{5}_a = (1, 2, -\frac{1}{2}) \oplus (\bar{3}, 1, +\frac{1}{3})$
	$3 \times E_R = (1, 2, -\frac{1}{2})$ $3 \times E_L = (1, 2, -\frac{1}{2})$	$3 \times \bar{5}_a = (1, 2, -\frac{1}{2}) \oplus (\bar{3}, 1, +\frac{1}{3})$; or $\overline{45}$, $\overline{70}$ $3 \times \bar{5}_a = (1, 2, -\frac{1}{2}) \oplus (\bar{3}, 1, +\frac{1}{3})$; or $\overline{45}$, $\overline{70}$
gauge	$G_\mu = (8, 1, 0)$ $W_\mu = (1, 3, 0)$ $B_\mu = (1, 1, 0)$	$24^a_b = (1, 3, 0) \oplus (8, 1, 0) \oplus (1, 1, 0) \oplus (3, 2, -\frac{5}{6}) \oplus (\bar{3}, 2, +\frac{5}{6})$

Realistic GUT scenarios

Potential problems of $SU(5)$:

- unification of gauge couplings (non-SUSY!!!)
- proton decay bounds: $\tau_p(p^+ \to \pi^0 e^+) \to M_{\rm GUT} \gtrsim 10^{15.6}\,{\rm GeV}$
  (if unification scale $M_{\rm GUT}$ too low, $X,\overline{X}$ gauge bosons of masses $M_g \sim g_{\rm GUT}\, v$ which mediate proton decay are too light + colour charged particles need to be sufficiently heavy)
- realistic mass relations between down-type quarks & charged leptons
  (@ renormalizable level 45_H is needed)
- doublet-triplet splitting (not only in 5_H, but also in 45_H or whenever some multiplets are required to be light):
  fine-tuning, missing partner mechanism, ...?

RGEs (@ 1-loop): B test

$$\frac{d\alpha_i^{-1}(m)}{d\ln\frac{m}{\mu_r}} = -\frac{b_i}{2\pi} \to \alpha_i^{-1}(m) = \alpha_i^{-1}(m_Z) - \frac{1}{2\pi}\underbrace{\left(b_i^{(SM)} + \sum_{m_k<m}\Delta b_i^{(k)}\overbrace{\frac{\ln\frac{m}{m_k}}{\ln\frac{m}{m_Z}}}^{r_k}\right)}_{B_i \text{ for } m=M_{\mathrm{GUT}}}\ln\frac{m}{m_Z}$$

$$\frac{B_{23}}{B_{12}} \equiv \frac{B_2 - B_3}{B_1 - B_2} = \frac{\alpha_2^{-1}(m_Z) - \alpha_3^{-1}(m_Z)}{\alpha_1^{-1}(m_Z) - \alpha_2^{-1}(m_Z)} = \frac{5}{8}\,\frac{\sin^2\theta_w - \frac{\alpha_{EM}(m_Z)}{\alpha_3(m_Z)}}{\frac{3}{8} - \sin^2\theta_w} = 0.718$$

$$= 0.528 + (\mathrm{BSM})$$

$$M_{\mathrm{GUT}} = m_Z\,\exp\left(\frac{2\pi(\alpha_1^{-1}(m_Z) - \alpha_2^{-1}(m_Z))}{B_{12}}\right) = m_Z\,\exp\left(\frac{184.87}{B_1 - B_2}\right)$$

$$= 10^{13}\,\mathrm{GeV} + (\mathrm{BSM})$$

$$\alpha_{\mathrm{GUT}}^{-1} = -\frac{\frac{3}{5}B_3}{B_1 + \frac{3}{5}B_2 - \frac{8}{5}B_3}\alpha_{EM}^{-1}(m_Z) + \frac{B_1 + \frac{3}{5}B_2}{B_1 + \frac{3}{5}B_2 - \frac{8}{5}B_3}\alpha_3^{-1}(m_Z)$$

$$= 41.48 + (\mathrm{BSM})$$

BSM contributions to running

SCALARS:

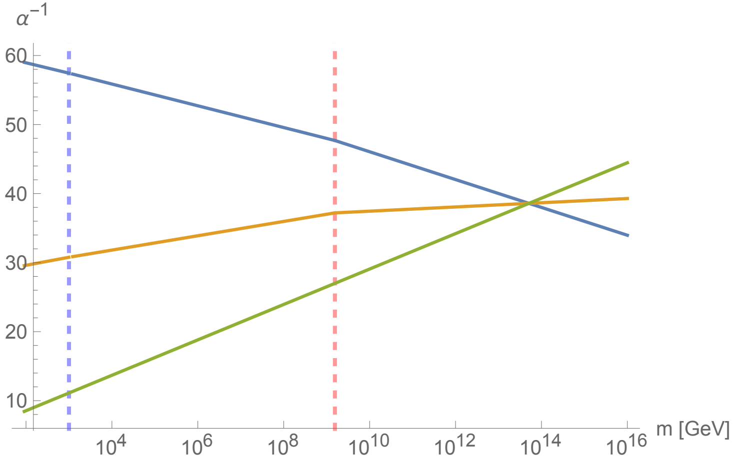
k	5_H: H	5_H: T_5	24_H: Δ	24_H: O_{24}	24_H: S_{24}	24_H: LQ_{24}	24_H: $\overline{LQ}_{24}$	10_H: h^+	10_H: $\overline{T}_{10}$	10_H: LQ_{10}
ΔB_{23}	$+\frac{1}{6}$	$-\frac{1}{6}r_k$	$+\frac{1}{3}r_k$	$-\frac{1}{2}r_k$	0	$+\frac{1}{12}r_k$	$+\frac{1}{12}r_k$	0	$-\frac{1}{6}r_k$	$+\frac{1}{6}r_k$
ΔB_{12}	$-\frac{1}{15}$	$+\frac{1}{15}r_k$	$-\frac{1}{3}r_k$	0	0	$+\frac{1}{6}r_k$	$+\frac{1}{6}r_k$	$+\frac{1}{5}r_k$	$+\frac{4}{15}r_k$	$-\frac{7}{15}r_k$

FERMIONS:

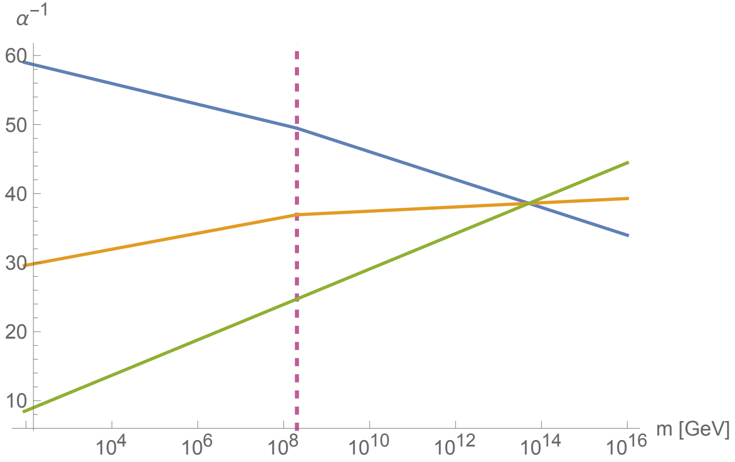
k	$\bar{5}_F$: $E_{L,R}$	$\bar{5}_F$: $\overline{T}_{\bar{5}}$
ΔB_{23}	$+\frac{1}{3}r_k \times n_{\rm gen}$	$-\frac{1}{3}r_k \times n_{\rm gen}$
ΔB_{12}	$-\frac{2}{15}r_k \times n_{\rm gen}$	$+\frac{2}{15}r_k \times n_{\rm gen}$

GAUGE BOSONS:

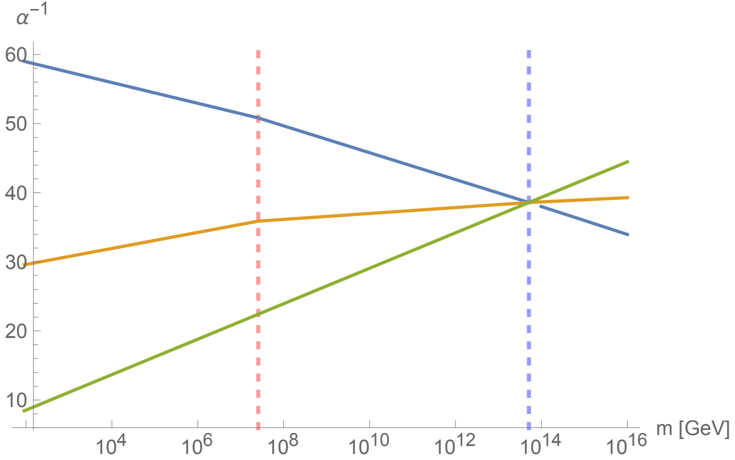
k	24_g: LQ_{24}	24_g: $\overline{LQ}_{24}$
ΔB_{23}	$-\frac{11}{6}r_k$	$-\frac{11}{6}r_k$
ΔB_{12}	$-\frac{11}{3}r_k$	$-\frac{11}{3}r_k$



$$m_\Delta = m_{h^+} = 10^3\,\mathrm{GeV}\,, \quad m_{E_{L,R}} = 1.55 \times 10^9\,\mathrm{GeV}\,, \quad M_{\mathrm{GUT}} = 5.11 \times 10^{13}\,\mathrm{GeV}$$



$$m_\Delta = m_{h^+} = m_{E_{L,R}} = 2.03 \times 10^8\,\mathrm{GeV}\,, \quad M_{\mathrm{GUT}} = 5.11 \times 10^{13}\,\mathrm{GeV}$$



$$m_{E_{L,R}} = 2.55 \times 10^7 \, \mathrm{GeV} \,, \quad m_\Delta = m_{h^+} = M_{\mathrm{GUT}} = 5.11 \times 10^{13} \, \mathrm{GeV}$$