ONE-LOOP NEUTRINO MASS IN $SU(5)$*

Ilja Doršner

University of Split

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Selected topics in flavor and collider physics

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*I. Doršner, S. Fajfer, N. Košnik, work in progress.

OUTLINE

• **ONE-LOOP NEUTRINO MASS WITH LEPTOQUARKS**

• **ONE-LOOP NEUTRINO MASS MECHANISM IN $SU(5)$**

• **CONCLUSIONS**

<u>ONE-LOOP NEUTRINO MASS MECHANISM</u>

STANDARD MODEL + TWO SCALAR LEPTOQUARK MULTIPLETS [◎]

◎C.-K. Chua, X.-G. He, W.-Y. P. Hwang, Phys. Lett. B479 (2000).

SCALAR LEPTOQUARKS[©]

LEPTOQUARK (LQ) MULTIPLETS:

$$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$(\mathbf{3}, \mathbf{2}, 7/6)$$

$$(\mathbf{3}, \mathbf{2}, 1/6)$$

$$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$$

$$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$$

$$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$$

[©]I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik, N. Košnik, Phys. Rept. 641 (2016).

SCALAR LEPTOQUARKS

LQ NOMENCLATURE[©]:

$$S_3 \equiv \quad (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$R_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\tilde{R}_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 1/6)$$

$$S_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$$

$$\tilde{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$$

$$\bar{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, -2/3)$$

[©]W. Büchmuller *et al.*, Phys. Lett. B 191, 442 (1987).

SCALAR LEPTOQUARKS VS. ν MASS

ν MASS LQs: $\tilde{R}_2 + (\ S_3 \vee \ S_1\ )$

$$\boxed{S_3 \equiv \quad (\overline{\mathbf{3}}, \mathbf{3}, 1/3)}$$

$$R_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\boxed{\tilde{R}_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 1/6)}$$

$$\boxed{S_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 1/3)}$$

$$\tilde{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$$

$$\bar{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, -2/3)$$

SCALAR LEPTOQUARKS VS. p DECAY

p DECAY LQs: ($S_3,\ \tilde{R}_2,\ S_1,\ \tilde{S}_1,\ \bar{S}_1$)

$$\boxed{S_3 \equiv \quad (\overline{\mathbf{3}}, \mathbf{3}, 1/3)}$$

$$R_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\boxed{\tilde{R}_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 1/6)}$$

$$\boxed{S_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 1/3)}$$

$$\boxed{\tilde{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 4/3)}$$

$$\boxed{\bar{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, -2/3)}$$

ν MASS VS. p DECAY

$$\boxed{S_3 \equiv \quad (\overline{\mathbf{3}}, \mathbf{3}, 1/3)}$$

$$R_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\boxed{\tilde{R}_2 \equiv \quad (\mathbf{3}, \mathbf{2}, 1/6)}$$

$$\boxed{S_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 1/3)}$$

$$\boxed{\tilde{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, 4/3)}$$

$$\boxed{\bar{S}_1 \equiv \quad (\overline{\mathbf{3}}, \mathbf{1}, -2/3)}$$

A(NOTHER) WORD ABOUT NOMENCLATURE

$$\mathcal{L} \supset -\tilde{y}^{RL}_{2\,ij}\bar{d}^{i}_{R}\tilde{R}^{a}_{2}\epsilon^{ab}L^{j,b}_{L}$$

a, b (= 1, 2) are $SU(2)$ indices

i, j (= 1, 2, 3) are flavor indices

$\tilde{y}^{RL}_{2}$ ≡ Yukawa coupling matrix

A(NOTHER) WORD ABOUT NOMENCLATURE

$$\mathcal{L} \supset -\tilde{y}^{RL}_{2\,ij}\bar{d}^{i}_{R}\tilde{R}^{a}_{2}\epsilon^{ab}L^{j,b}_{L}$$

$$\mathcal{L} \supset -\tilde{y}^{RL}_{2\,ij}\bar{d}^{i}_{R}e^{j}_{L}\tilde{R}^{2/3}_{2} + (\tilde{y}^{RL}_{2}U)_{ij}\bar{d}^{i}_{R}\nu^{j}_{L}\tilde{R}^{-1/3}_{2}$$

a, b (= 1, 2) are $SU(2)$ indices

i, j (= 1, 2, 3) are flavor indices

$\tilde{y}^{RL}_{2}$ ≡ Yukawa coupling matrix

U ≡ Pontecorvo-Maki-Nakagawa-Sakata unitary mixing matrix

ONE-LOOP NEUTRINO MASS

$$\tilde{y}_2^{RL} \bar{d}_R \nu_L \tilde{R}_2^{-1/3}$$

ONE-LOOP NEUTRINO MASS

$\tilde{y}_2^{RL}\bar{d}_R\nu_L\tilde{R}_2^{-1/3}$

$y_1^{LL}\bar{d}_L^C\nu_L S_1$

$y_3^{LL}\bar{d}_L^C\nu_L S_3^{1/3}$

ONE-LOOP NEUTRINO MASS

$$\begin{tikzcd}
 & m_D \bar{d}_L d_R \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\
\tilde{y}_2^{RL} \bar{d}_R \nu_L \tilde{R}_2^{-1/3} & & \begin{array}{c} y_1^{LL} \bar{d}_L^C \nu_L S_1 \\ y_3^{LL} \bar{d}_L^C \nu_L S_3^{1/3} \end{array} \\
 & m_D \bar{d}_L d_R \arrow[ul, leftrightarrow] \arrow[ur, leftrightarrow] &
\end{tikzcd}$$

ONE-LOOP NEUTRINO MASS

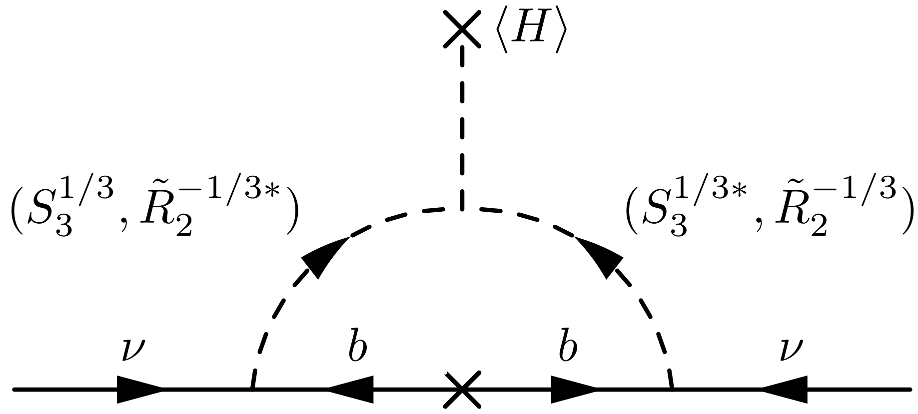
$$
\begin{tikzcd}
 & m_D \bar{d}_L d_R & \\
 & \tilde{R}_2 H S_1 \arrow[r, leftrightarrow] & y_1^{LL} \bar{d}_L^C \nu_L S_1 \arrow[ul, leftrightarrow] \\
\tilde{y}_2^{RL} \bar{d}_R \nu_L \tilde{R}_2^{-1/3} \arrow[uur, leftrightarrow] \arrow[ur, leftrightarrow] \arrow[dr, leftrightarrow] \arrow[ddr, leftrightarrow] & & \\
 & \tilde{R}_2 H S_3 \arrow[r, leftrightarrow] & y_3^{LL} \bar{d}_L^C \nu_L S_3^{1/3} \arrow[dl, leftrightarrow] \\
 & m_D \bar{d}_L d_R &
\end{tikzcd}
$$

$$H \equiv (\mathbf{1}, \mathbf{2}, -1/2)$$

ONE-LOOP NEUTRINO MASS

$$\begin{tikzcd}
& \tilde{R}_2 H S_3 \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\
\tilde{y}_2^{RL}\bar{d}_R\nu_L\tilde{R}_2^{-1/3} \arrow[r, leftrightarrow] & m_D\bar{d}_L d_R \arrow[r, leftrightarrow] & y_3^{LL}\bar{d}_L^C\nu_L S_3^{1/3}
\end{tikzcd}$$

ONE-LOOP NEUTRINO MASS



IMPORTANT ISSUES

WHAT HAPPENED WITH THE LQ DIQUARK COUPLINGS?

LQ MASSES ARE FREE PARAMETERS…

$\tilde{y}_2^{RL}$, y_1^{LL}, y_3^{LL} ARE ALL *A PRIORI* UNKNOWN MATRICES…

RECENT DEVELOPMENTS [◎]

"A testable radiative neutrino mass model without additional symmetries and explanation for the $b \to s\ell^+\ell^-$ anomaly"

[◎] K. Cheung, T. Nomura, H. Okada, arXiv:1610.02322.

ONE-LOOP ν MASSES IN $SU(5)$

SCALAR LQs	$SU(5)$
$S_3 \equiv (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{\mathbf{45}}$
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{\mathbf{45}}$
$\tilde{R}_2 \equiv (\mathbf{3}, \mathbf{2}, 1/6)$	$\mathbf{10}, \mathbf{15}$
$\tilde{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\mathbf{45}$
$S_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{\mathbf{5}}, \overline{\mathbf{45}}$
$\bar{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	$\mathbf{10}$

ONE-LOOP ν MASSES IN *SU*(5)

SCALAR REPRESENTATIONS IN *SU*(5):

5 [⦿]	**10** [◎]	**15** [⊙]	**45** [◆]
(S_1)	$(\tilde{R}_2)$	$(\tilde{R}_2)$	$(S_3,\, S_1)$
THE STANDARD MODEL SYMMETRY BREAKING		UNIFICATION	THE STANDARD MODEL SYMMETRY BREAKING
CHARGED FERMION MASSES	UNIFICATION OF GAUGE COUPLINGS	TYPE II SEE-SAW ν MASSES	CHARGED LEPTON & DOWN-TYPE QUARK MASSES

[⦿] H. Georgi, S. L. Glashow, Phys. Rev. Lett. 32 (1974). [◎] H. Murayama, T. Yanagida, Mod. Phys. Lett. A7 (1992). [⊙] I. Doršner, P. Fileviez Perez, Nucl. Phys. B723 (2005). [◆] H. Georgi, C. Jarlskog., Phys. Lett. B86 (1979).

ONE-LOOP ν MASSES IN *SU*(5)

SCALAR REPRESENTATIONS IN *SU*(5):

$\mathbf{5}$	$\mathbf{15}$	$\mathbf{45}$
(S_1)	$(\tilde{R}_2)$	$(S_3,\ S_1)$
$y_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{5}}$	$y_{ij}\overline{\mathbf{5}}_i\overline{\mathbf{5}}_j\mathbf{15}$	$y_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}}$
$y_{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{5}$		$y_{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{45}$

$\mathbf{10}_i$ & $\overline{\mathbf{5}}_i$ $(i = 1, 2, 3)$ COMPRISE THE STANDARD MODEL FERMIONS

ONE-LOOP ν MASSES IN $SU(5)$

A POSSIBLE $SU(5)$ SET-UP:

$\mathbf{5}$	$\mathbf{15}$	$\mathbf{45}$
(S_1)	$\boxed{(\tilde{R}_2)}$	$\boxed{(S_3)}$ $(R_2,\ S_1,\ \tilde{S}_1)$
$y_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{5}}$	$\boxed{y_{ij}\overline{\mathbf{5}}_i\overline{\mathbf{5}}_j\mathbf{15}}$	$\boxed{y_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}}}$
$y_{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{5}$		$y_{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{45}$

ONE-LOOP NEUTRINO MASS

$$\begin{tikzcd}
 & m_D \bar{d}_L d_R \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\
\tilde{y}_2^{RL} \bar{d}_R \nu_L \tilde{R}_2^{-1/3} \arrow[r, leftrightarrow] & \tilde{R}_2 H S_3 \arrow[r, leftrightarrow] & y_3^{LL} \bar{d}_L^C \nu_L S_3^{1/3}
\end{tikzcd}$$

ONE-LOOP ν MASSES IN *SU*(5)

$$\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{5}} \quad \& \quad \mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}}$$

$$\begin{tikzcd}
 & m_D \bar{d}_L d_R \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\
\tilde{y}_2^{RL} \bar{d}_R \nu_L \tilde{R}_2^{-1/3} \arrow[r, leftrightarrow] & \tilde{R}_2 H S_3 \arrow[r, leftrightarrow] & y_3^{LL} \bar{d}_L^C \nu_L S_3^{1/3} \\
\overline{\mathbf{5}}_i\overline{\mathbf{5}}_j\mathbf{15} & \lambda\, \overline{\mathbf{5}}\mathbf{10}\overline{\mathbf{45}} & \mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}}
\end{tikzcd}$$

λ $\equiv$ dimensionful parameter

p DECAY

$$y_3^{LL}\bar{d}_L^C \nu_L S_3^{1/3}$$

$$\boxed{y_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}}}$$

p DECAY

S_3 LEPTOQUARK MULTIPLET COULD BE LIGHT IF NEEDED…

$$-y_{ij}\bar{u}^C_{L\,i}\nu_{L\,j}S_3^{-2/3}$$

$$2^{-1/2}y_{ij}\bar{u}^C_{L\,i}e_{L\,j}S_3^{1/3}$$

$$2^{-1/2}y_{ij}\bar{d}^C_{L\,i}\nu_{L\,j}S_3^{1/3}$$

$$y_{ij}\bar{d}^C_{L\,i}e_{L\,j}S_3^{4/3}$$

$$\boxed{y_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}}}$$ ◎

◎I. Doršner, S. Fajfer, N. Košnik, Phys. Rev. D 86, 015013 (2012).

p DECAY

Q	$\mathbf{5}$	$\mathbf{15}$	$\mathbf{45}$
$-2/3$		$\tilde{R}_2^{2/3\,*}$	$R_2^{2/3\,*}$ $S_3^{-2/3}$
$1/3$	S_1	$\tilde{R}_2^{-1/3\,*}$	$S_3^{1/3}$ S_1
$4/3$			$S_3^{4/3}$ $\tilde{S}_1$
$5/3$			$R_2^{5/3}$

p DECAY

$$\left[\; S_1 \quad S_1 \quad \tilde{R}_2^{-1/3\,*} \quad S_3^{1/3} \;\right] \; \boxed{\quad 4 \times 4 \quad} \; \begin{bmatrix} S_1 \\ S_1 \\ \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix}^{*}$$

p DECAY

$$
\begin{bmatrix} S_1 & S_1 & \tilde{R}_2^{-1/3\,*} & S_3^{1/3} \end{bmatrix}
\left[\begin{array}{cc|cc}
 & & 0 & 0 \\
 & & 0 & 0 \\
\hline
0 & 0 & & \\
0 & 0 & &
\end{array}\right]
\begin{bmatrix} S_1 \\ S_1 \\ \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix}^{*}
$$

ONE-LOOP ν MASSES

$$\begin{bmatrix} \tilde{R}_2^{-1/3\,*} & S_3^{1/3} \end{bmatrix} \begin{bmatrix} m_{11}^2 & m_{12}^2 \\ m_{12}^2 & m_{22}^2 \end{bmatrix} \begin{bmatrix} \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix}^*$$

$$\begin{bmatrix} \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix} \rightarrow \begin{bmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{bmatrix} \begin{bmatrix} \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix} \qquad \begin{bmatrix} m_{11}^2 & m_{12}^2 \\ m_{12}^2 & m_{22}^2 \end{bmatrix} \rightarrow \begin{bmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{bmatrix}$$

ONE-LOOP ν MASSES

$$(m_\nu)_{ij} = \frac{3 s_\theta c_\theta}{16\pi^2} \sum_{k=d,s,b} m_k [B_0(0, m_k^2, m_1^2) - B_0(0, m_k^2, m_2^2)]\{y_{ik} y'_{jk} + y_{jk} y'_{ik}\}$$

$$B_0(0, m_k^2, m_1^2) - B_0(0, m_k^2, m_2^2) = \frac{m_2^2[\ln m_2^2 - \ln m_k^2]}{m_2^2 - m_k^2} - \frac{m_1^2[\ln m_1^2 - \ln m_k^2]}{m_1^2 - m_k^2}$$

B_0 – Passarino-Veltman function

ONE-LOOP ν MASSES

$$(m_\nu)_{ij} = \frac{3 s_\theta c_\theta}{16\pi^2} \sum_{k=d,s,b} m_k [B_0(0, m_k^2, m_1^2) - B_0(0, m_k^2, m_2^2)] \{y_{ik} y'_{jk} + y_{jk} y'_{ik}\}$$

$$y_{ij} \overline{\mathbf{5}}_i \overline{\mathbf{5}}_j \mathbf{15} \qquad y'_{ij} \mathbf{10}_i \overline{\mathbf{5}}_j \overline{\mathbf{45}}$$

ONE-LOOP ν MASSES

$$(m_\nu)_{ij} = \frac{3 s_\theta c_\theta}{16\pi^2} \sum_{k=d,s,b} m_k [B_0(0, m_k^2, m_1^2) - B_0(0, m_k^2, m_2^2)] \{ y_{ik} y'_{jk} + y_{jk} y'_{ik} \}$$

$y_{ij} \overline{\mathbf{5}}_i \overline{\mathbf{5}}_j \mathbf{15}$ $\qquad$ $y' \sim (M_e^T - M_d)/v_{45}$

M_e – charged lepton mass matrix $\qquad$ M_d – down-type quark mass matrix

A LIST OF BENEFITS

p DECAY CONSTRAINTS CAN BE ACCOMMODATED

RELEVANT YUKAWA COUPLING MATRICES ARE RELATED ◎
TO FERMION MASSES AND/OR POSSESS ADDITIONAL
SYMMETRY. THIS NOT ONLY REDUCES THE TOTAL
NUMBER OF PARAMETERS BUT HELPS RELATE
LEPTOQUARK DECAY PATTERNS TO NEUTRINO MASSES…

LQ MASSES COULD BE CONSTRAINED THROUGH THE
GAUGE COUPLING UNIFICATION…

◎P. Fileviez Perez, T. Han, Gui-Yu Huang, T. Li, K. Wang, Phys. Rev. D 78, 071301, (2008).

CONCLUSIONS

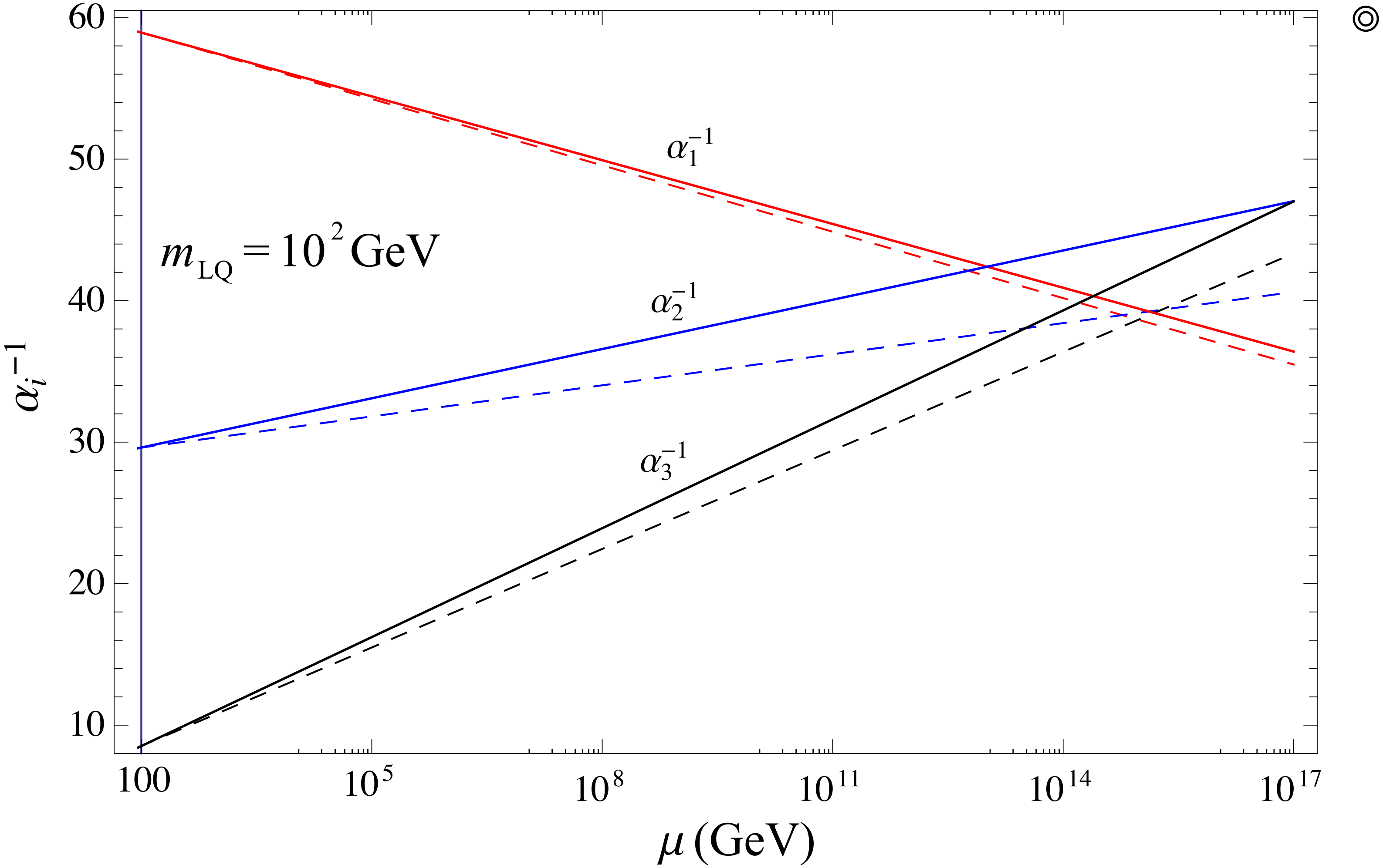
$SU(5)$ CAN ACCOMMODATE WITH EASE THE ONE-LOOP NEUTRINO MASS MECHANISM THAT IS BASED ON THE LEPTOQUARK MULTIPLET MIXING.

THE USE OF $SU(5)$ CAN INCREASE PREDICTIVITY OF THE SET-UP. THIS COULD ESPECIALLY BE REFLECTED IN THE DECAY PATTERNS OF THE RELEVANT LEPTOQUARK MULTIPLETS.

THANK YOU

dorsner@fesb.hr

STANDARD MODEL + (2 × **10**)



◎H. Murayama, T. Yanagida, Mod. Phys. Lett. A7 (1992).