Flavored color scalars for neutrino masses

Brda 2025: Selected topics in (B)SM

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Motivation

- Neutrino oscillations

  $\Rightarrow$evidence that neutrinos have **masses**

  $\Rightarrow$the only laboratory evidence of physics beyond the Standard Model

- Unresolved puzzles:

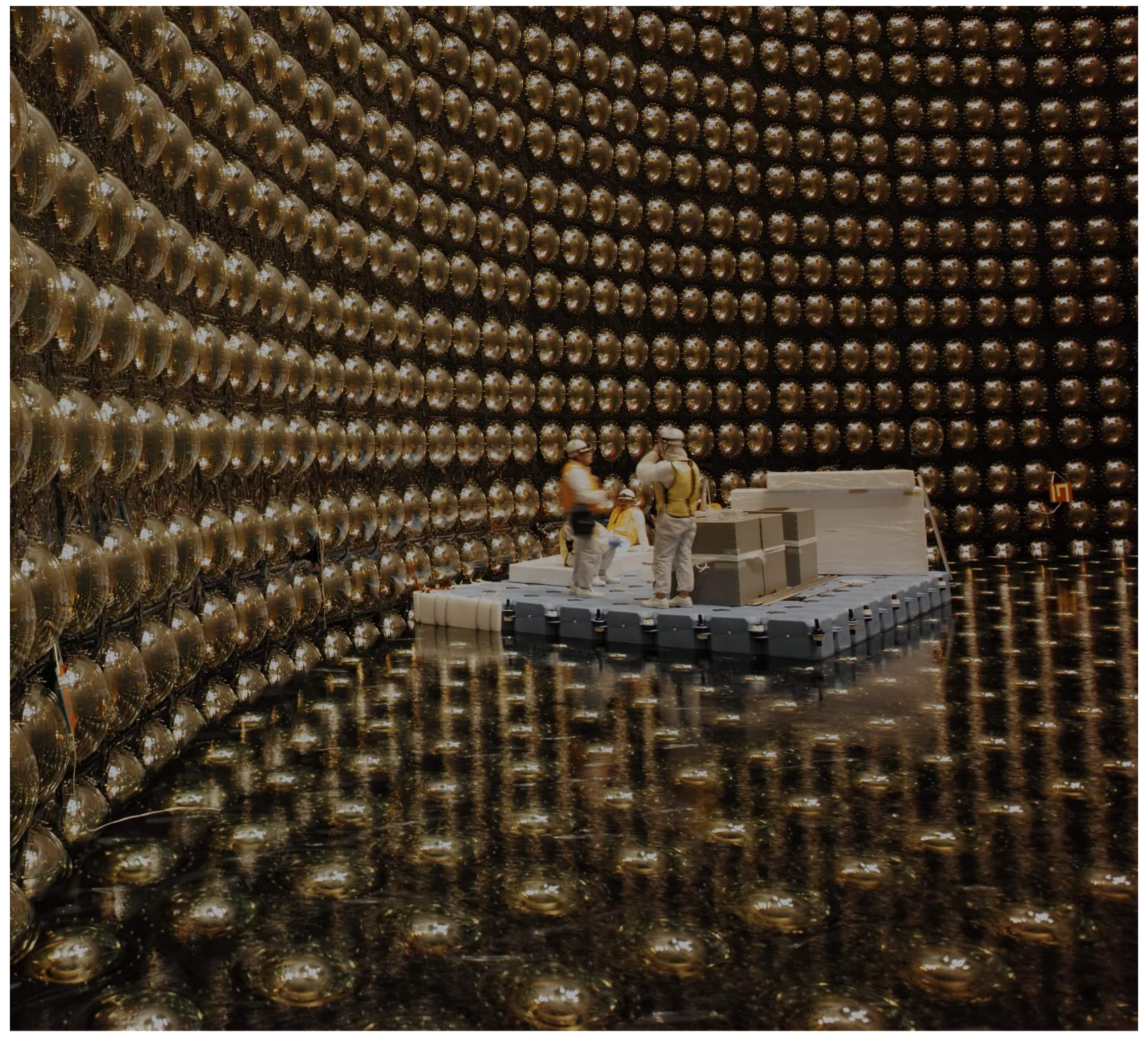
  $\Rightarrow$absolute **mass scale**?

  $\Rightarrow$**Majorana** or **Dirac**?

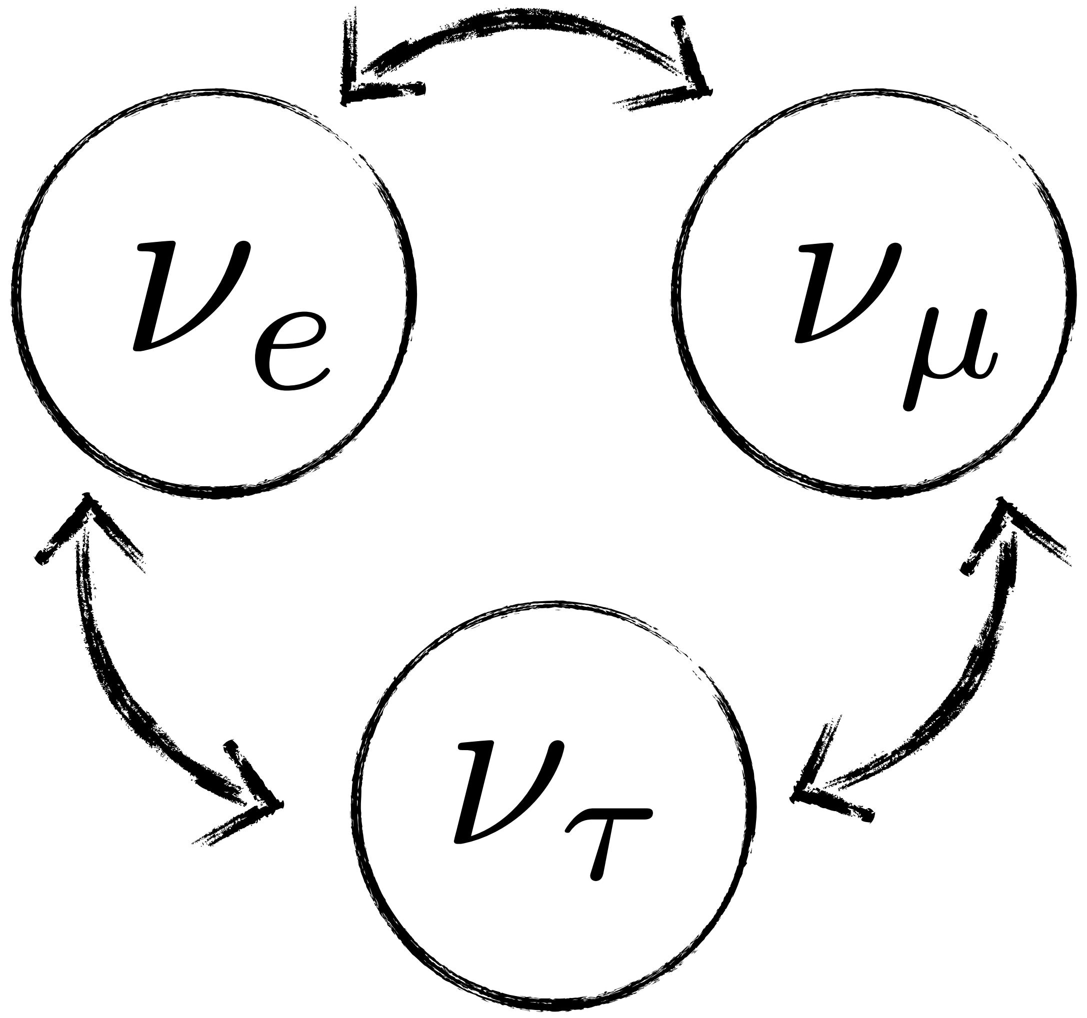
  $\Rightarrow$is **lepton number** conserved?

  $\Rightarrow$mass ordering (**NO** or **IO**)?

  $\Rightarrow$Leptonic **CP violation**?



Super Kamiokande experiment



Neutrino masses

- Two possibilities for the neutrino mass term:

1. Dirac term $\mathcal{L}_{\rm eff} \supset m_\nu \, \overline{\nu}_L \nu_R$ **?**

   - Like other SM fermions
   - Needs new states ν_R, i.e. right-handed neutrinos

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    - Using only the SM spectrum
    - Unique possibility for neutrinos since they are the only known neutral fermions

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   - Using only the SM spectrum
   - Unique possibility for neutrinos since they are the only known neutral fermions
   - Emerges from the effective **Weinberg operator**

$$\mathcal{L}_{\text{d=5}} = \frac{c_{ij}}{2\Lambda} H^T i\tau^2 \vec{\tau} H \cdot \overline{\ell_i^C} i\tau^2 \vec{\tau} \ell_j$$

$$c_{ij} = c_{ji}$$

Flavor symmetries

- One of the ways to address the **flavor puzzle** is to impose a $U(N)$ flavor symmetry
- We consider the $U(2)$ symmetry

  $\Longrightarrow$ can explain the quark and charged lepton hierarchies

  Antusch, Greljo, Stefanek, Thomsen - Phys. Rev. Lett. 132 (2024)
  Greljo, Thomsen, Tiblom - JHEP 08 (2024)
  Barbieri, Isidori, Jones-Perez, Lodone, Straub - Eur. Phys. J. C. 71 (2011)
  ...

Flavor symmetries

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- We consider the $U(2)$ symmetry
  - $\Longrightarrow$ can explain the quark and charged lepton hierarchies
- Specifically, we focus on the $U(2)_\ell \cong SU(2) \otimes U(1)_\ell$
  - $\Longrightarrow \ell_\alpha = 2_1,\ \alpha = 1{,}2$
  - $\Longrightarrow$ it forbids the Weinberg operator in the first two generations
  - $\Longrightarrow$ to restore the symmetry, we introduce *spurions* and identify the minimal set;
    - $D_\alpha = 2_1 \quad T_A = 3_2$

$$c_{ij}\, \overline{\ell_i^C} \ell_j$$

$$\Downarrow$$

$$\kappa \overline{\ell_3^C} \ell_3 + 2\kappa_D \frac{D_\alpha^*}{\Lambda} \overline{\ell_3^C} \ell_\alpha + \kappa_T \frac{T_A^*}{\Lambda} \overline{\ell_\alpha^C} (i\sigma_2 \sigma_A)_{\alpha\beta} \ell_\beta$$

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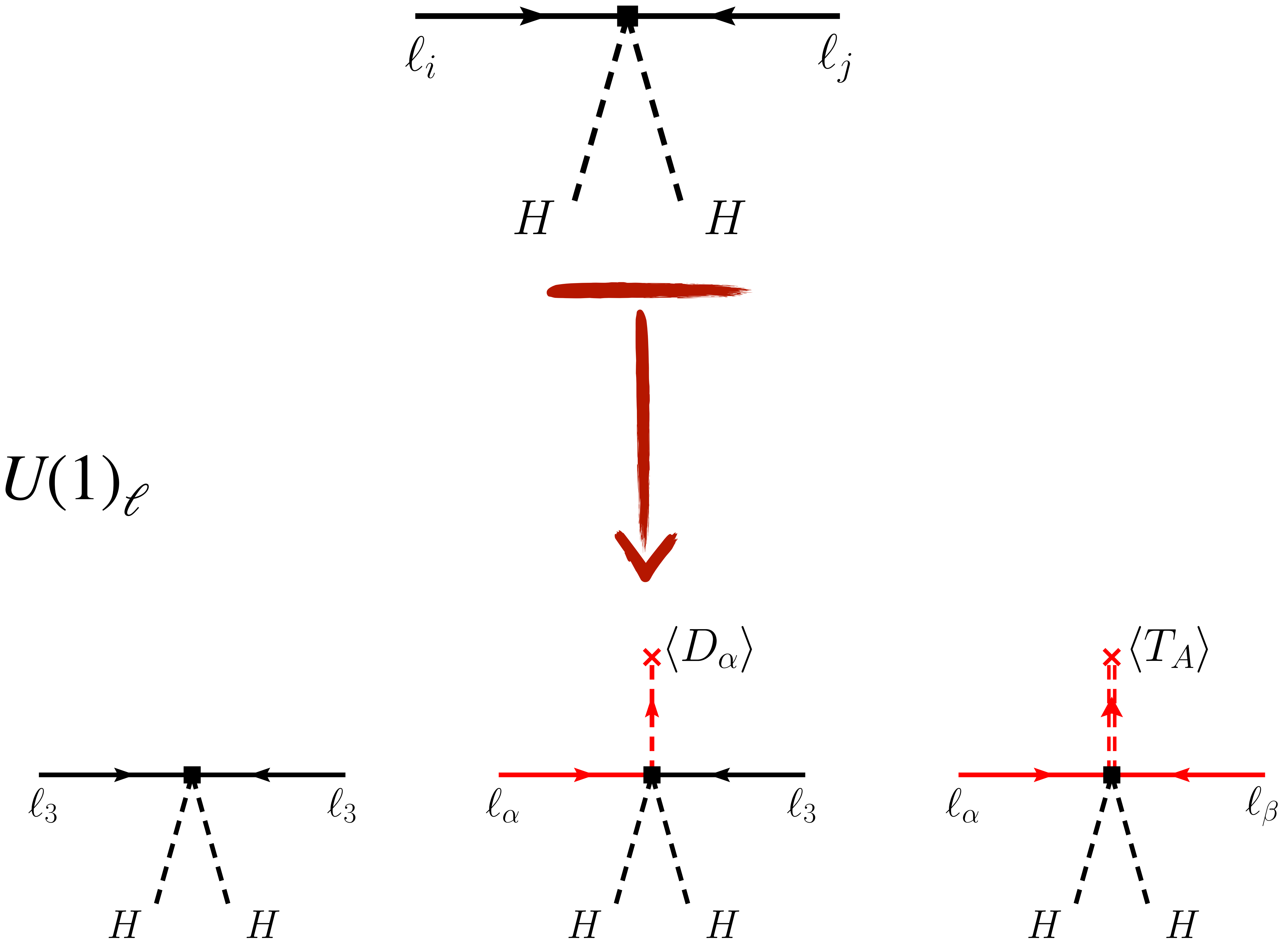

Neutrino mass matrix

UV

$\mu \sim \Lambda$

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$\mu \sim v_{\mathcal{F}} \Rightarrow$ Flavor symm. breaking

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- The spurions acquire a **VEV** $\Longrightarrow \begin{cases} \langle D_\alpha \rangle = (0, v_D)\,, \\ \langle T_A \rangle = (v_{T_1}, v_{T_2} e^{i\phi_2}, v_{T_3} e^{i\phi_3}) \end{cases}$

*We used $U(2)$ symmetry to rotate away unphysical degrees of freedom

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$\mu \sim v_{\mathrm{EW}}$

EW symm. breaking

$$(M_\nu)_{ij} \overline{\nu_i^C} \nu_j$$

Neutrino mass matrix

- The mass matrix depends on the spurion VEVs

  $\Rightarrow$ which gives the neutrino mass matrix a **specific shape**: $$(M_\nu)_{ij} = \begin{pmatrix} \tilde{v}_{T_1} + i\tilde{v}_{T_2}e^{i\phi_2} & -\tilde{v}_{T_3} & 0 \\ -\tilde{v}_{T_3} & -\tilde{v}_{T_1} + i\tilde{v}_{T_2}e^{i\phi_2} & \tilde{v}_D \\ 0 & \tilde{v}_D & \tilde{v} \end{pmatrix}$$

$$\tilde{v}_i \equiv \frac{\kappa_i v_i v^2}{\Lambda^2}. \qquad \tilde{v} \equiv \frac{\kappa v^2}{\Lambda}$$

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  - The **PMNS matrix:** $M_\nu \approx U_{\mathrm{PMNS}}^T D_\nu U_{\mathrm{PMNS}}$ $\quad D_\nu = \mathrm{diag}(m_1, m_2, m_3)$

  - The **mass splittings:** $\begin{cases} \Delta m_{21}^2 = m_2^2 - m_1^2 \\ \Delta m_{3\ell}^2 = m_3^2 - m_\ell^2 \end{cases}$

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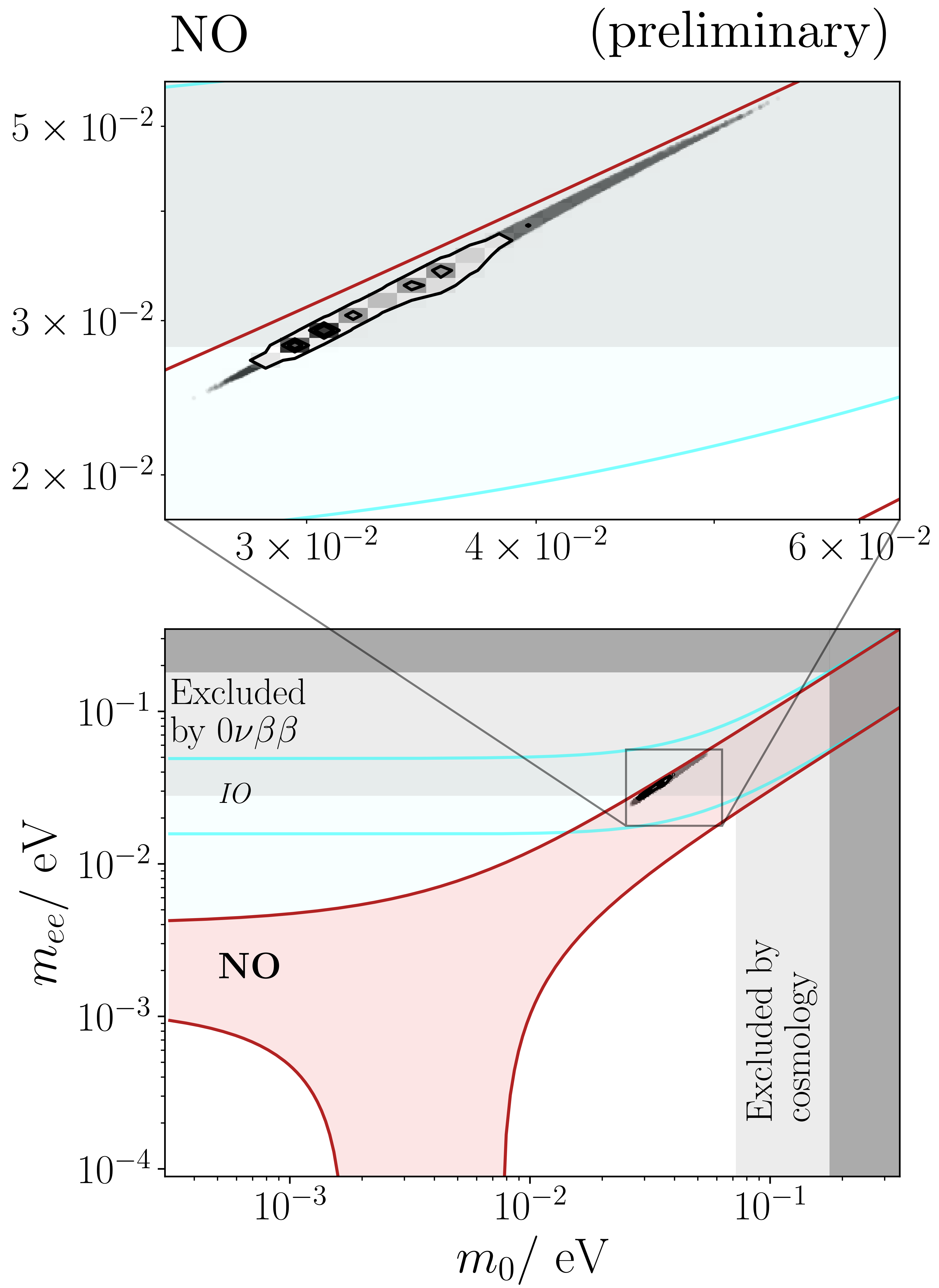
- Relation to the charged lepton masses?

Neutrino mass matrix

- The model successfully reproduce the observed values!
  $\Longrightarrow$ furthermore, it predicts the **lightest neutrino mass**

$$m_0 = \begin{cases} 0.0292 \pm 0.0016\,\mathrm{eV} & \textbf{NO} \\ 0.0264^{+0.012}_{-0.0052}\,\mathrm{eV} & \textbf{IO} \end{cases}$$

Quasi-degenerate spectrum, accessible at the future neutrino experiments



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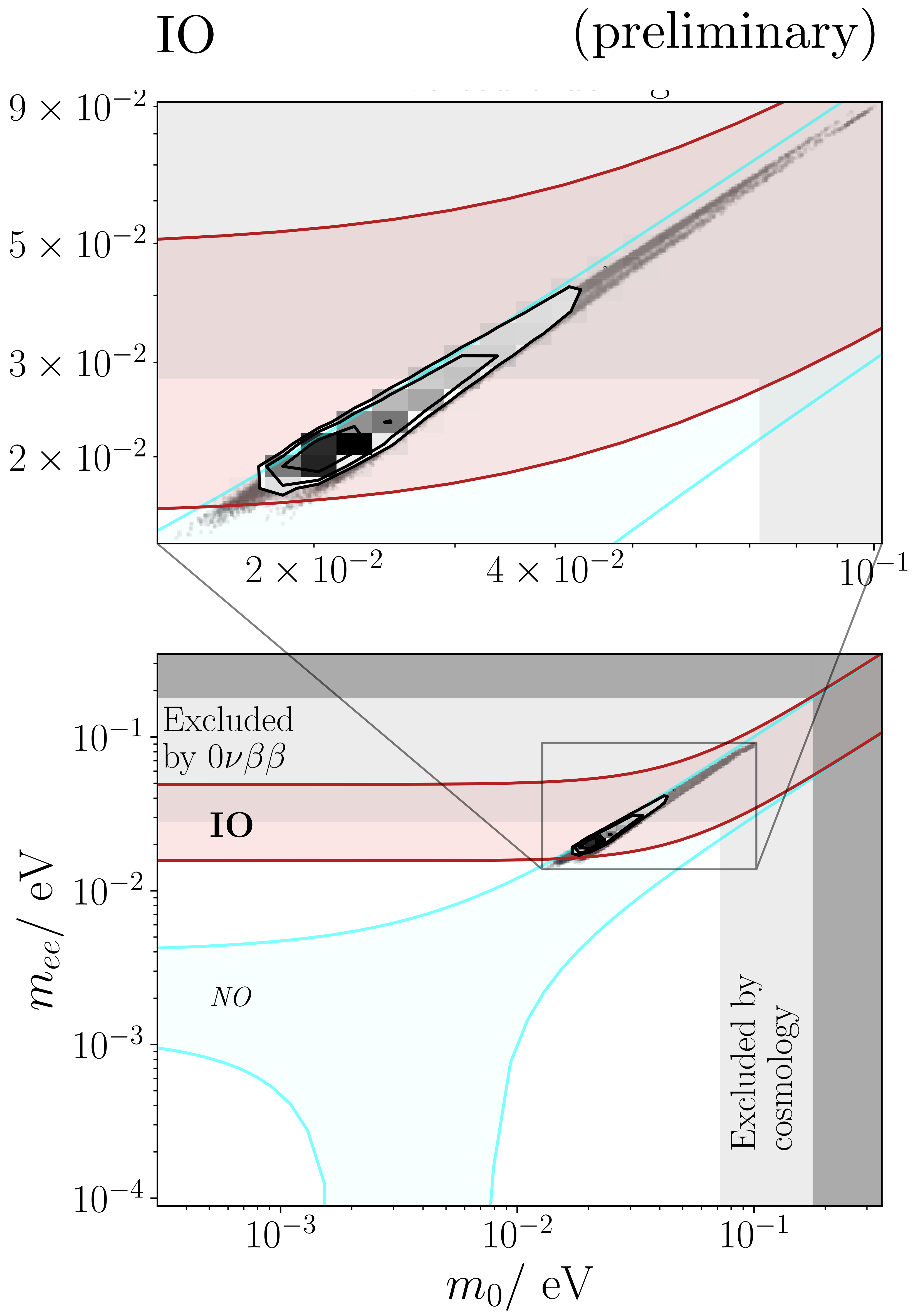
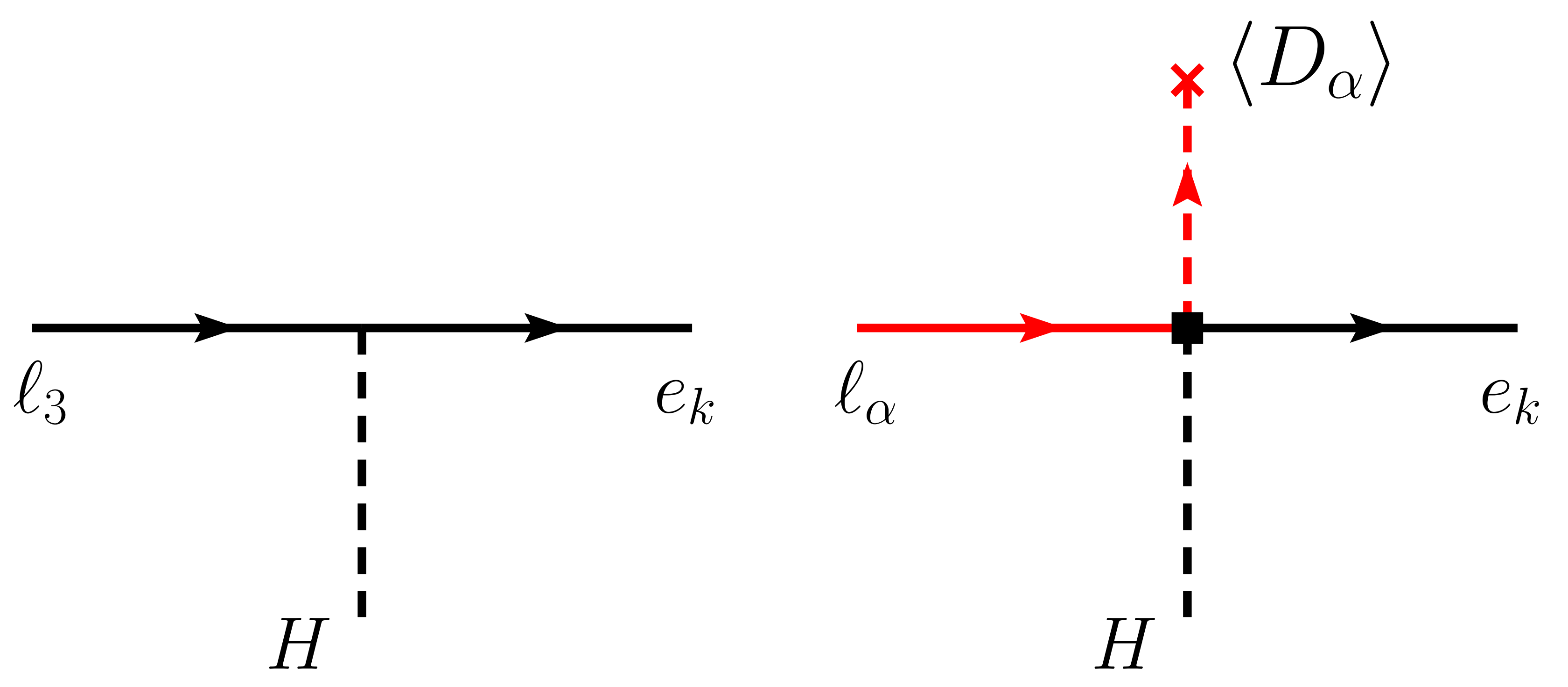
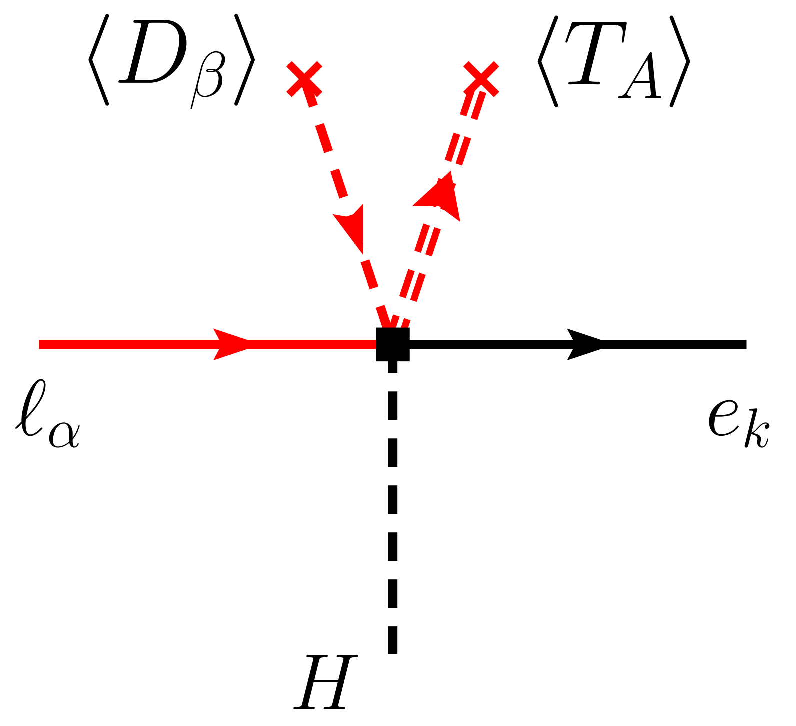


Charged lepton masses



- Lagrangian in the charged lepton sector:

$$\mathcal{L}^{\text{lep.}}_{\text{Yuk}} = -x_k\,\bar{\ell}_3 e_k H - \frac{z_k}{\Lambda} D_\alpha\,\bar{\ell}_\alpha e_k H - \frac{w_k}{\Lambda^2} T_A\,\bar{\ell}_\alpha (i\sigma_2\sigma^A)_{\alpha\beta} D^{*\beta} e_k H + \text{h.c.}$$



$$Y_e = \begin{pmatrix} w_1\,\epsilon_D\epsilon_3 & w_2\,\epsilon_D\epsilon_3 & w_3\,\epsilon_D\epsilon_3 \\ z_1\,\epsilon_D - w_1\,\epsilon_-\epsilon_D & z_2\,\epsilon_D - w_2\,\epsilon_-\epsilon_D & z_3\,\epsilon_D \\ x_1 & x_2 & x_3 \end{pmatrix}$$

$$\epsilon_i = v_i/\Lambda$$

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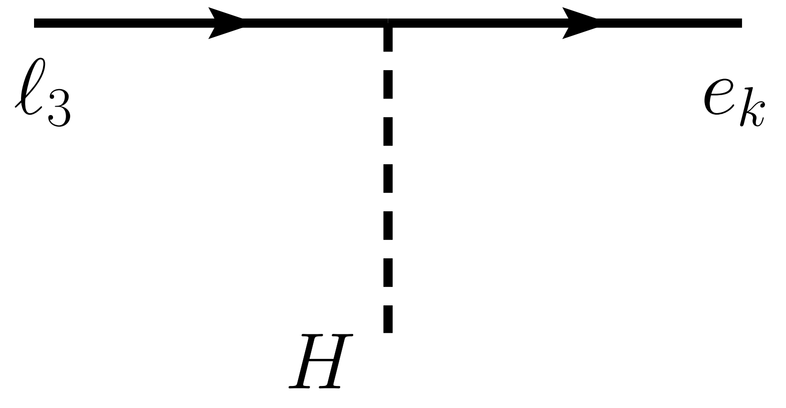
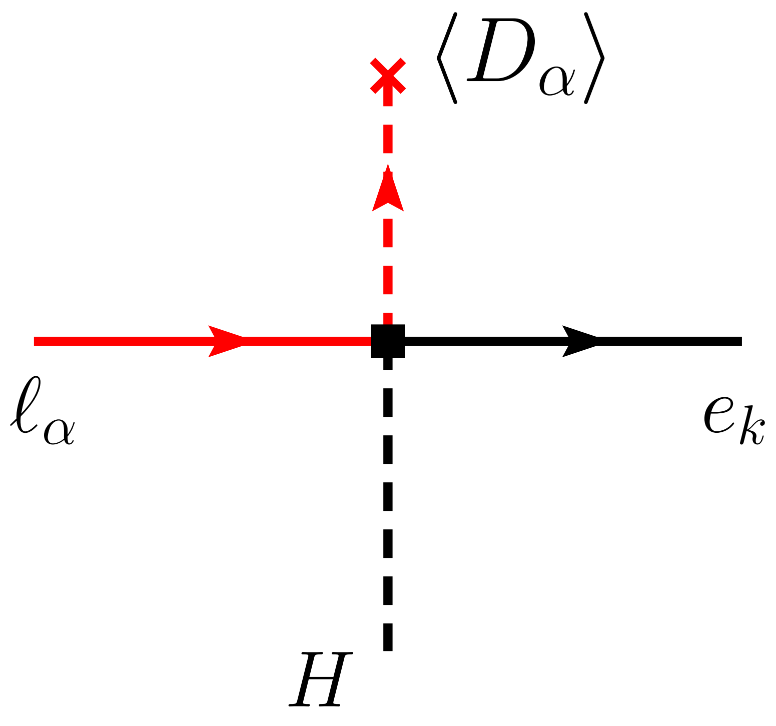
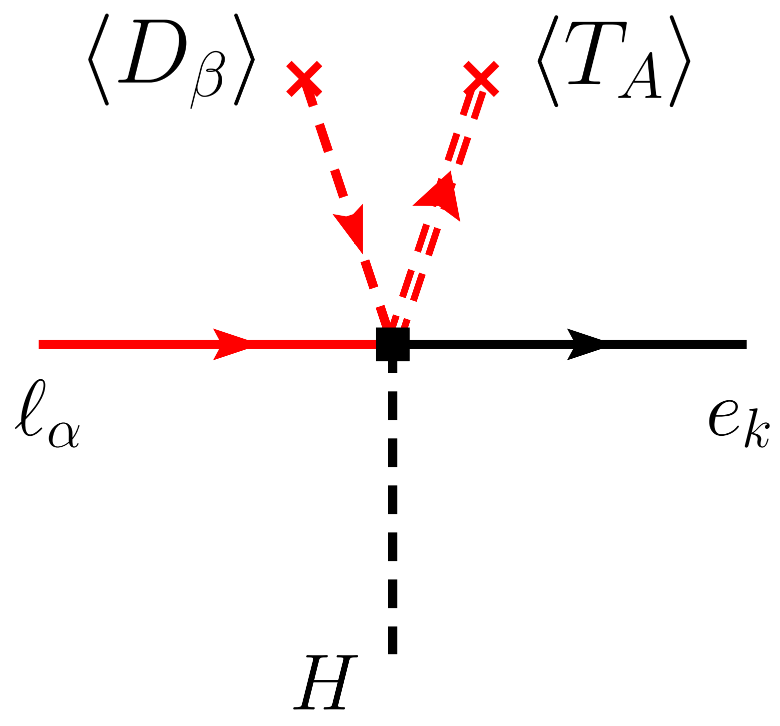






After diagonalization: $Y_e = \begin{pmatrix} \epsilon^2 & & \\ & \epsilon & \\ & & 1 \end{pmatrix} \times \mathcal{O}(1)$ couplings (x_i, z_i, w_i)

$\epsilon \sim \epsilon_D, \epsilon_i$

$\Rightarrow$we see a clear **hierarchy** in the charged lepton Yukawa couplings

UV completion

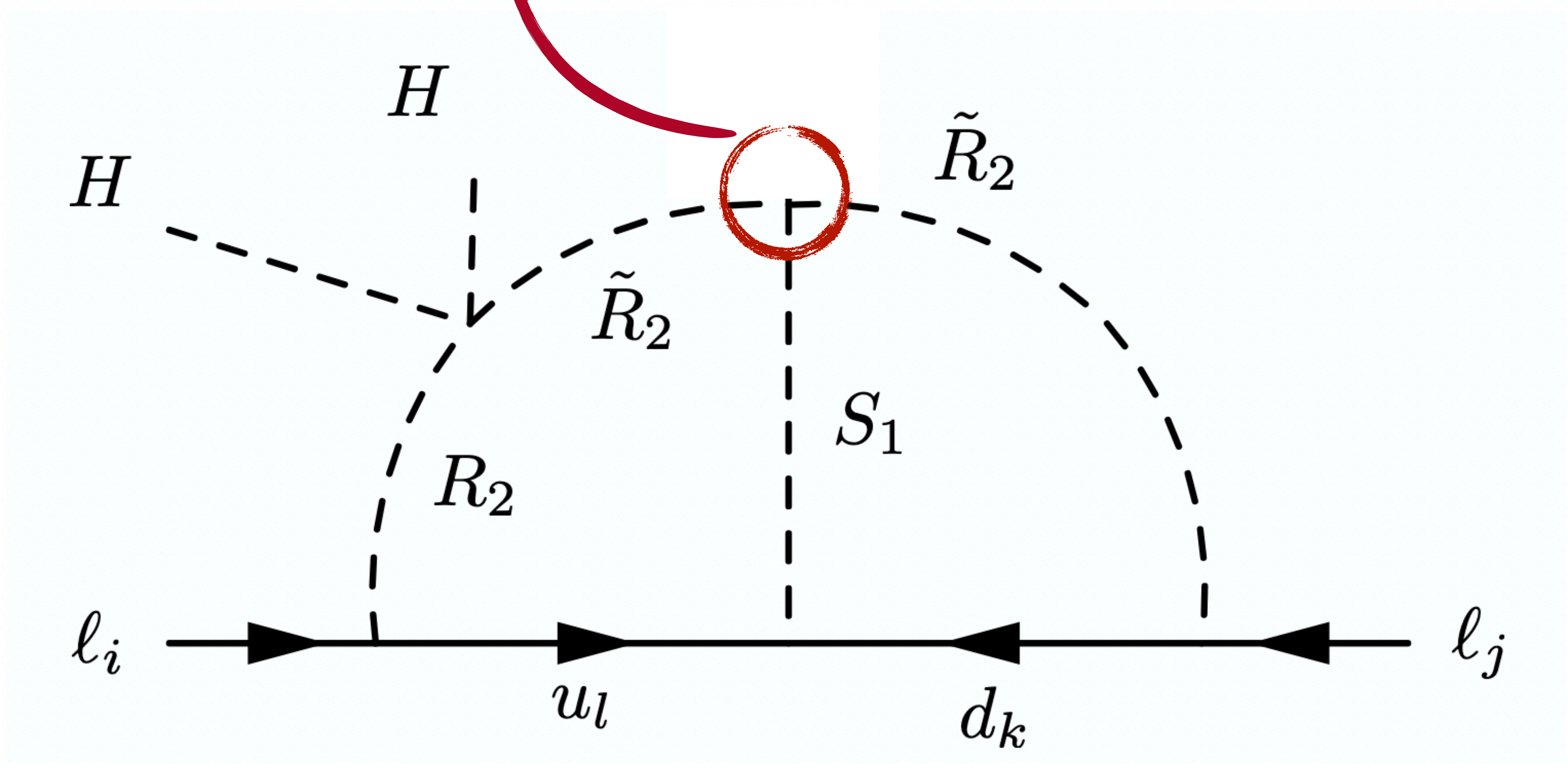
- The Weinberg operator is **radiatively** completed
- To do so, we introduce the following:

  $\Rightarrow$Leptoquarks $R_2 = (3, 2, 7/6)$

  $\tilde{R}_2 = (3, 2, 1/6)$

  $\Rightarrow$Diquark $S_1 = (\overline{3}, 1, 1/3)$
- This setup can in principle complete the Weinberg operator on the **2-loop** level

$\kappa S_1 \tilde{R}_2^T (i\sigma_2) \tilde{R}_2$ $\Rightarrow$Mechanism that provides $\Delta L = 2$



UV completion

- We expand the flavor symmetry group:

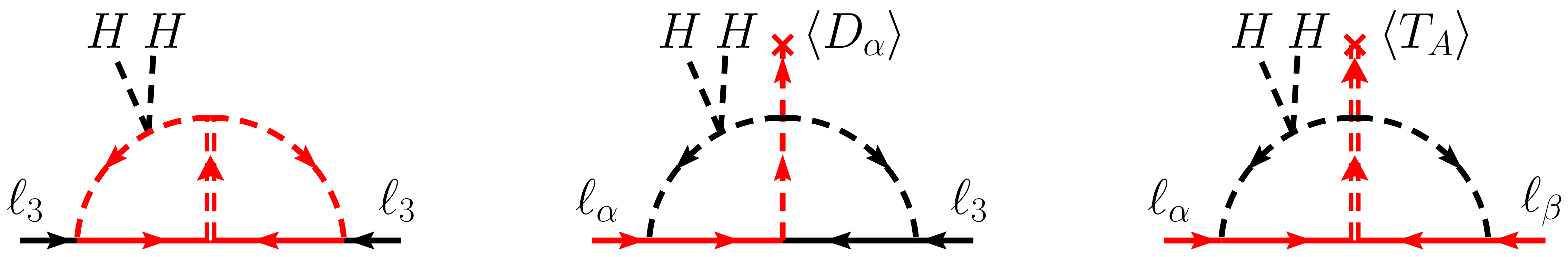
$$U(2)_\ell \to U(2)_{\ell+u+d}$$

- Leptoquarks/diquark get also the flavor number;

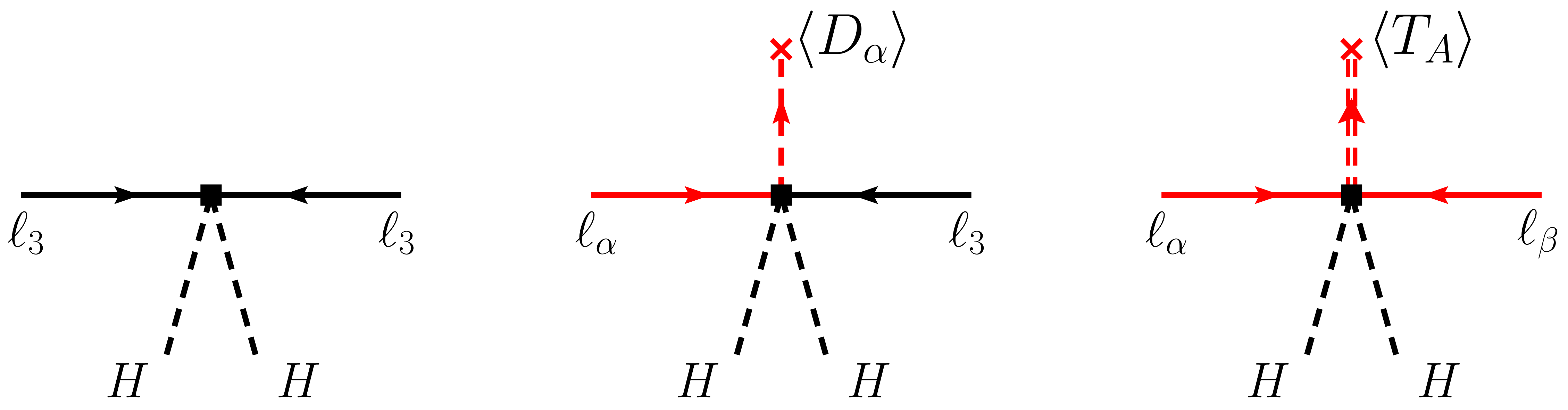
$$R_2 \to R_{2S} = 1_0 \text{ and } R_{2D} = 2_1$$
$$\tilde{R}_2 \to \tilde{R}_{2S} = 1_0 \text{ and } \tilde{R}_{2D} = 2_1$$
$$S_1 \to S_{1S} = 1_0 \text{ and } S_{1T} = 3_2$$

\+ the flavons $D = 2_1$ and $T = 3_2$

- The **baryon number** is conserved



Spontaneous flavor symm. breaking and integrating out $R_2, \tilde{R}_2$ and S_1



UV completion

- The scalars are completing the Weinberg operator at the **2-loop** level

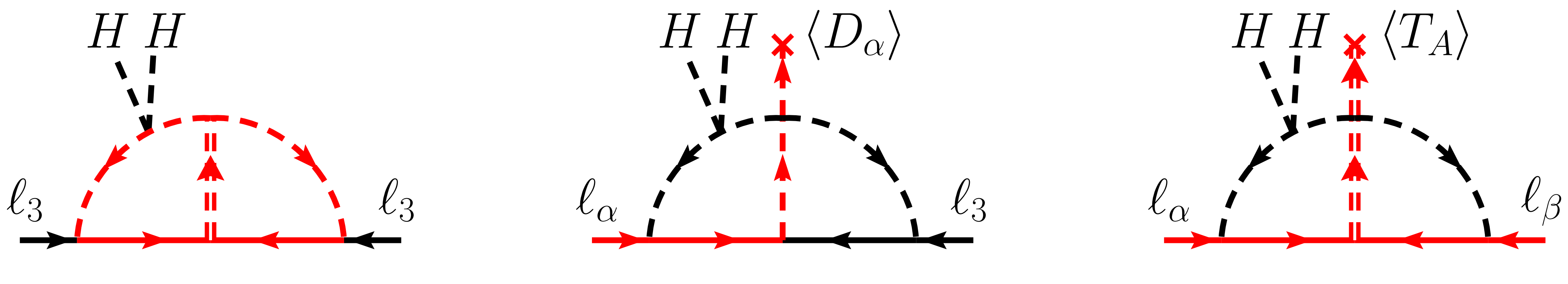
- The scales are predicted to be

$$v_{\mathcal{F}} \sim 10^8 \text{ GeV}$$

$$m_R \sim 10^{10} \text{ GeV}$$

m_{S_1} can be light ($\lesssim$ 100 TeV)

*with the assumptions that the couplings are order of magnitude $\mathcal{O}(1)$



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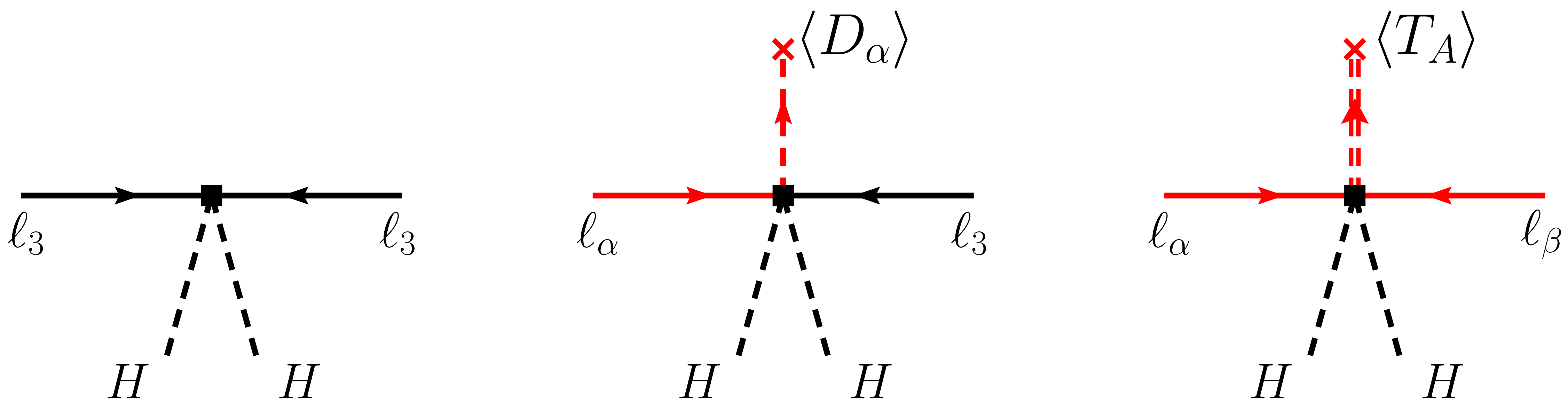

$\Rightarrow$Leptoquark R_2 can be potentially tested in LFV experiments

$\Rightarrow$Diquark S_1 can be potentially tested via meson-mixing

Conclusions

- The model based on the $U(2)_\ell$ flavor symmetry is proposed in order to accommodate for the measured neutrino observables

- The effective model predicts the lightest neutrino mass to be fairly high, making the spectra quasi-degenerate

  $\Longrightarrow$available for the next generation neutrino experiments

- The hierarchy in the charged lepton sector is also predicted

- A radiative UV model based on 2 leptoquarks and a diquark is proposed, completing the Weinberg operator on 2-loop level

Thank you for your attention!