# Radiative Lepton Masses

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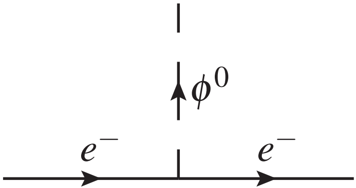
# Overview

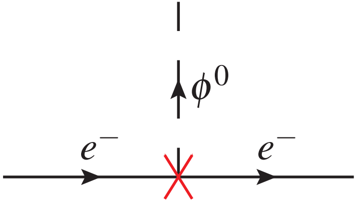
# The Standard Model




$$\sum_{i=e,\mu,\tau} f_i \overline{L_i} \Phi l_i + h.c. \in \mathcal{L}_{SM} \tag{1}$$

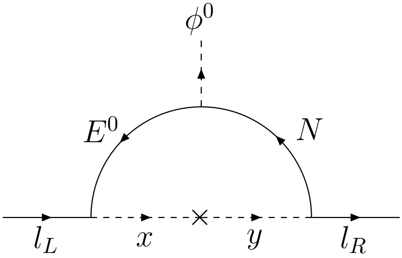
# Adding the $A_4$ Symmetry

$$\begin{aligned} \underline{3} \times \underline{3} &= \underline{1}\,(11+22+33)+... \\ \underline{1}' \times \underline{1}'' &= \underline{1} \end{aligned} \tag{2}$$




$$(\nu_i, l_i)_L \sim \underline{3}, \quad l_{iR} \sim \underline{1}, \underline{1}', \underline{1}'', \quad \Phi \sim \underline{1} \tag{3}$$

# New Particles




$$\begin{aligned}(\nu_i, l_i)_L \sim \underline{3}, \quad l_{iR} \sim \underline{1}, \underline{1}', \underline{1}'', \quad \Phi \sim \underline{1} \\ (E^0, E^-)_{L,R} \sim \underline{1}, \quad y_i^- \sim \underline{1}, \underline{1}', \underline{1}'', \quad N_{L,R} \sim \underline{1}, \quad x_i^- \sim \underline{3}.\end{aligned} \tag{4}$$

Radiative mass → No $16\pi^2$ suppression factor for radiative processes!

# Breaking $A_4$

Soft term $x_i y_j^*$ breaks $A_4$ to $\mathbb{Z}_3$:

$$\begin{array}{ll} A_4 & : \underline{1}, \quad \underline{1}', \quad \underline{1}'', \qquad \underline{3} \\ & \quad \downarrow \quad \downarrow \quad \downarrow \qquad \downarrow \\ \mathbb{Z}_3 & : 1, \quad \omega, \quad \omega^2, \quad 1\,, \omega\,, \omega^2 \end{array} \tag{5}$$

with $\omega = \exp\,(2\pi i/3)$.

$$(x_1, x_2, x_3) \sim \underline{3} \quad \longrightarrow \quad \begin{array}{l} 1.x_1 + 1.x_2 + 1.x_3 \sim 1 \\ 1.x_1 + \omega^2.x_2 + \omega.\,x_3 \sim \omega \\ 1.x_1 + \omega.\,x_2 + \omega^2.x_3 \sim \omega^2 \end{array} \tag{6}$$

$$y_1^* \sim 1, \quad y_2^* \sim \omega^2, \quad y_3^* \sim \omega. \tag{7}$$

# Charged Lepton Mass Matrix

$x_i y_j^*$ coefficients:

$$U_\omega \begin{pmatrix} \mu_e^2 & 0 & 0 \\ 0 & \mu_\mu^2 & 0 \\ 0 & 0 & \mu_\tau^2 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} \begin{pmatrix} \mu_e^2 & 0 & 0 \\ 0 & \mu_\mu^2 & 0 \\ 0 & 0 & \mu_\tau^2 \end{pmatrix} \tag{8}$$

The charged-lepton mass matrix is given by

$$\mathcal{M}_l = U_\omega^\dagger \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \tag{9}$$

where $m_e, m_\mu, m_\tau$ are generated via the loop diagram.

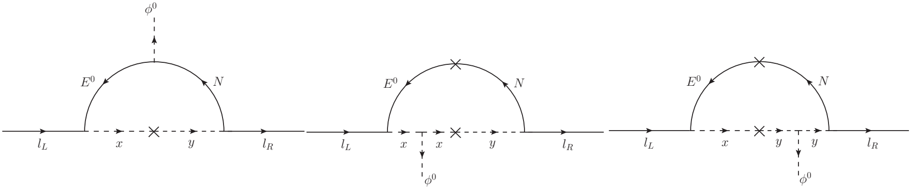
$x - y$ mixing matrix:

$$\begin{matrix} & \hat{x} & y_1 & \tilde{x} & y_2 & x & y_3 \end{matrix}$$

$$\mathcal{M}_{xy} = \begin{pmatrix} m_{11} & \mu_e^2 & 0 & 0 & 0 & 0 \\ \mu_e^2 & m_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{33} & \mu_\mu^2 & 0 & 0 \\ 0 & 0 & \mu_\mu^2 & m_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{55} & \mu_\tau^2 \\ 0 & 0 & 0 & 0 & \mu_\tau^2 & m_{66} \end{pmatrix} \quad (10)$$

Crucial for avoiding flavor violation.

# Anomalous Higgs Yukawa Couplings




$$\frac{f_D}{\sqrt{2}} h \bar{N}_L E_R^0 + \frac{f_F}{\sqrt{2}} h \bar{E}_L^0 N_R, \qquad (\lambda_x v) h x^* x, \qquad (\lambda_y v) h y^* y \tag{11}$$

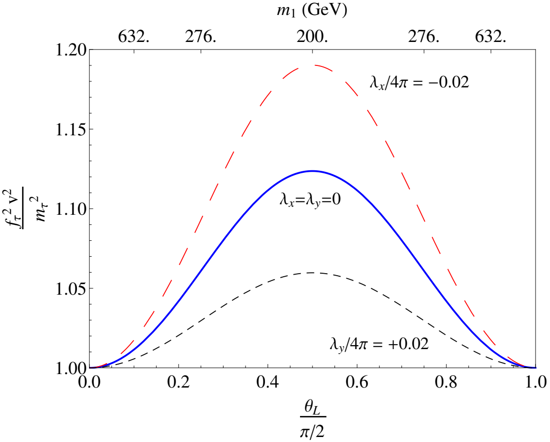
$$f' E_L^0 l_L x + f'_\tau N_R \tau_R y_3^* \tag{12}$$

# Anomalous Higgs Yukawa Couplings

$$
\begin{aligned}
N, E &\quad\rightarrow\quad \theta_L, \theta_R, m_1, m_2. \\
(x_1, x_2, x_3) &\quad\rightarrow\quad (\hat{x}, \tilde{x}, x) \sim (1, \omega, \omega^2) \\
x, y_3 &\quad\rightarrow\quad \lambda_x, \lambda_y, \theta_\tau, m_{1\tau}, m_{2\tau}.
\end{aligned} \tag{13}
$$

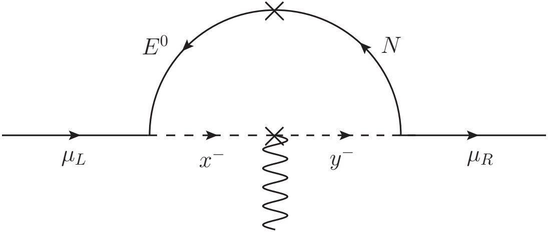
$$
\frac{f_D}{\sqrt{2}} h \bar{N}_L E_R^0 + \frac{f_F}{\sqrt{2}} h \bar{E}_L^0 N_R, \qquad (\lambda_x v) h x^* x, \qquad (\lambda_y v) h y^* y \tag{14}
$$

$$
f' E_L^0 l_L x + f'_\tau N_R \tau_R y_3^* \tag{15}
$$



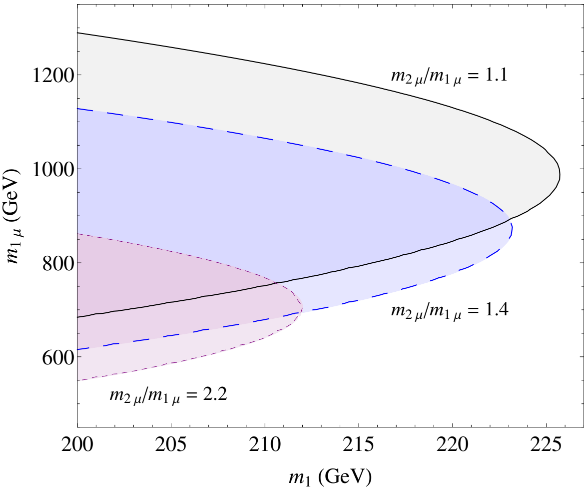

$$\theta_L = \theta_R, \quad \frac{m_2}{m_1} = 2.2, \quad \theta_\tau = 0.8 \quad \frac{m_{1\tau}}{m_1} = 5.7, \quad \frac{m_{2\tau}}{m_1} = 1.1,$$
$$\frac{f'}{4\pi} = -0.6, \quad \frac{f_D}{4\pi} = -0.19, \quad \frac{f'_\tau}{4\pi} = -0.54. \tag{16}$$

# Muon Anomalous Magnetic Moment



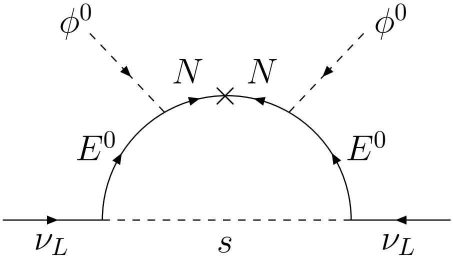

$$\Delta a_\mu = 39.35 \pm 5.21_{\text{th}} \pm 6.3_{\text{exp}} \times 10^{-10} \tag{17}$$

Note that this diagram doesn't generate LFV.




$$\theta_L = \theta_R, \quad \rightarrow \quad \Delta a_\mu \text{ is independent of } \theta_{L,R}$$
$$\frac{m_2}{m_1} = 2.2. \tag{18}$$

# Adding Real Scalars

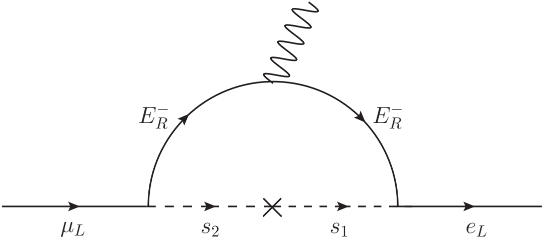



$$s_{1,2,3} \sim \underline{3} \quad \rightarrow \quad \text{Diagonal Mass Matrix} \tag{19}$$

$$U_{l\nu} = U_\omega \mathcal{O} \quad \rightarrow \quad U_{\mu i} = U^*_{\tau i} \tag{20}$$

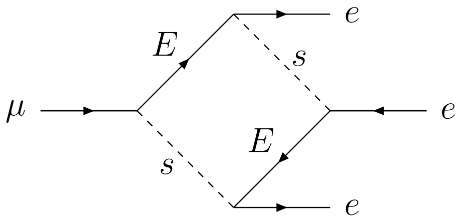
$$\text{Cobimaximal Mixing} \quad \longrightarrow \quad \theta_{13} \neq 0,\ \theta_{23} = \frac{\pi}{4},\ \delta_{CP} = \pm\frac{\pi}{2} \tag{21}$$

# $\mu \to e\gamma$




$$Br(\mu \to e\gamma) < 5.7 \times 10^{-13} \tag{22}$$

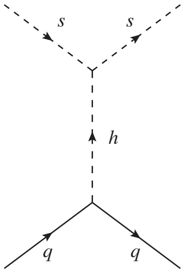
# $\mu \to eee$




$$Br(\mu \to eee) < 1.0 \times 10^{-12} \tag{23}$$

# Direct Detection

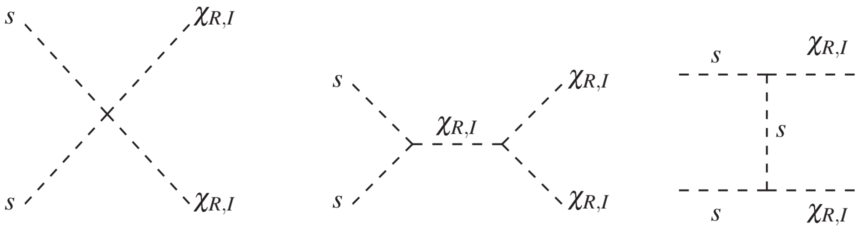
Lightest of the $s_{1,2,3}$ is odd under $\mathbb{Z}_2$ and can be a dark matter candidate.




$$(\lambda v)\, hs^2 \quad \longrightarrow \quad \lambda < 3.3 \times 10^{-4} \text{ for } m_s = 200\,\text{GeV} \tag{24}$$

# Annihilation

We add a complex neutral singlet scalar, $\chi \sim \underline{1}'$



# Conclusion

- $A_4$ symmetry can be used to explain the pattern in lepton masses.
  $\longrightarrow$ The $A_4$ symmetry breaking is also important for the neutrino mixing.
- For radiative masses, there is no $16\pi^2$ suppression factor in radiative processes.
  $\longrightarrow$ Muon $g-2$ anomaly.
  $\longrightarrow$ Anomalous Higgs yukawa couplings.

Thank You!

# References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