Type-II Seesaw Triplet Scalar Effects on Neutrino Trident Scattering

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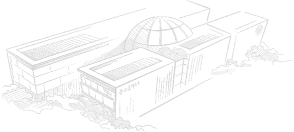
Otranto
September 4, 2024



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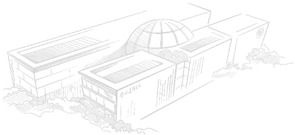
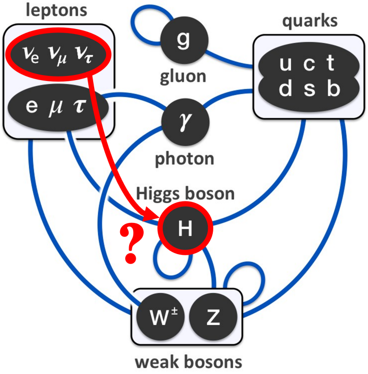
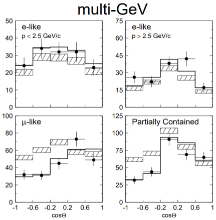


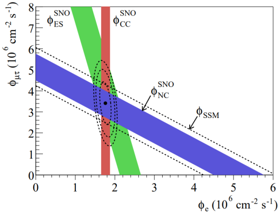
Non-zero Neutrino Mass



- Super-Kamiokande: atmospheric ν_μ disappearance.
- ν_e flux and total neutrino $\nu_{e,\mu,\tau}$ flux from the Sun.



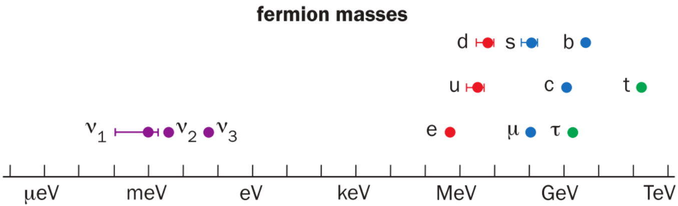
(a) Super-K, 1998



(b) SNO, 2002

Neutrinos have non-zero mass, 2015 Nobel Prize

Non-zero Neutrino Mass



To explain the tiny neutrino mass,

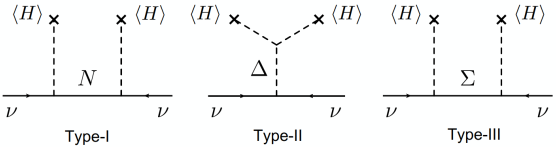


Figure 1: Seesaw Mechanism

1. $M_\nu = M_D M_R^{-1} M_D^T$
2. $M_\nu = \sqrt{2} Y_\Delta \nu_\Delta = \frac{\mu_\Delta Y_\Delta v_d^2}{m_\Delta^2}$
3. $M_\nu = M_D M_\Sigma^{-1} M_D^T$

Type-II Seesaw

In type-II seesaw model, one heavy triplet Higgs boson Δ is added[1],

		$SU(2)_L$	$U(1)_Y$
L_{L_i}	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	2	$-\frac{1}{2}$
Φ	$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	2	$\frac{1}{2}$
Δ	$\begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$	3	1

[1] Konetschny and Kummer, 1977; Magg and Wetterich,1980; Schechter and Valle, 1980; Cheng and Li, 1980; Lazarides et al., 1981; Mohapatra and Senjanovic, 1981.

Type-II Seesaw

Covariant derivative,

$$
\begin{aligned}
D_\mu \Phi =& \partial_\mu \Phi - i\frac{g}{2} W_\mu^a \sigma^a \Phi - i\frac{g'}{2} B_\mu \Phi \\
D_\mu \Delta =& \partial_\mu \Delta - i\frac{g}{2}\left[W_\mu^a \sigma^a, \Delta\right] - ig' B_\mu \Delta.
\end{aligned}
$$

The Higgs sector is extended

$$
\mathcal{L}_{\text{Higgs}} = \left(D^\mu \Phi\right)^\dagger \left(D_\mu \Phi\right) + \operatorname{Tr}\left[\left(D^\mu \Delta\right)^\dagger \left(D_\mu \Delta\right)\right] - V(\Phi, \Delta).
$$

where

$$
\begin{aligned}
V(\Phi, \Delta) =& -m_\Phi^2 \Phi^\dagger \Phi + M^2 \operatorname{Tr} \Delta^\dagger \Delta + \left(\mu \Phi^T i\sigma^2 \Delta^\dagger \Phi + \text{ h.c. }\right) \\
&+ \frac{\lambda}{4}\left(\Phi^\dagger \Phi\right)^2 + \lambda_1 \Phi^\dagger \Phi \operatorname{Tr} \Delta^\dagger \Delta + \lambda_2 \left(\operatorname{Tr} \Delta^\dagger \Delta\right)^2 \\
&+ \lambda_3 \operatorname{Tr}\left(\Delta^\dagger \Delta\right)^2 + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi.
\end{aligned}
$$

Type-II Seesaw Modification on W Mass

After SSB,

$$\langle\Phi\rangle \overset{SSB}{\Longrightarrow} \begin{pmatrix} 0 \\ v_d/\sqrt{2} \end{pmatrix} \qquad \langle\Delta\rangle \overset{SSB}{\Longrightarrow} \begin{pmatrix} 0 & 0 \\ v_\Delta/\sqrt{2} & 0 \end{pmatrix}.$$

$$m_\Phi^2 = \frac{\lambda}{4}v_d^2 + \frac{\lambda_1+\lambda_4}{2}v_\Delta^2 - \sqrt{2}\mu v_\Delta$$

$$M^2 = -\frac{\lambda_1+\lambda_4}{2}v_d^2 - (\lambda_2+\lambda_3)\, v_\Delta^2 + \frac{\mu v_d^2}{\sqrt{2}v_\Delta} \sim m_\Delta^2 \equiv \frac{\mu v_d^2}{\sqrt{2}v_\Delta}.$$

we can generate the mass of gauge bosons and Higgs bosons

$$m_W^2 = \frac{g^2(v_d^2+2v_\Delta^2)}{4} \qquad m_Z^2 = \frac{(g^2+g'^2)(v_d^2+4v_\Delta^2)}{4}.$$

so we can easily acquire

$$\rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = 1 + \Delta\rho = 1 - \frac{2v_\Delta^2}{v_d^2+4v_\Delta^2}.$$

Type-II Seesaw Modification on W Mass

Considering $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{v^2}{2}$, we derive that

$$\rho = 1 - \frac{2v_\Delta^2}{v_d^2 + 4v_\Delta^2} = 1 - \frac{2v_\Delta^2}{v^2 + 2v_\Delta^2} = \frac{1}{1 + 2\left(\frac{v_\Delta}{v}\right)^2}$$

which is evidently smaller than 1, and significant effect on ρ needs $v_\Delta \sim \mathcal{O}(1)$GeV.

In 2022, CDF Collaboration announced the W mass measurement results

$$m_W^{\rm CDF} = 80,433.5 \pm 9.4 \text{MeV},$$

which is 7σ level above the SM prediction $m_W^{\rm SM} = 80,357 \pm 6$MeV, implies

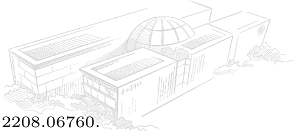
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1.0019.$$

Type-II seesaw modification is in the wrong direction, so v_Δ should be little small.

Type-II Seesaw Modification on W Mass

To make the model in right direction,

1. Introduce some new scalar Higgs bosons.
2. Consider the loop level contribution.[2]



[2] Y. Cheng, X. G. He, F. Huang, J. Sun and Z.P. Xing, Nucl.Phys.B 989 (2023) 116118, arXiv: 2208.06760.

Type-II Seesaw Modification on W Mass

To make the model in right direction,

1. Introduce some new scalar Higgs bosons.
2. Consider the loop level contribution.[2]

Consider the multi-scalars $H_i$with vevs v_i, the mass of W and Z are changed as

$$m_W = g^2 \sum_i \frac{v_i^2}{2}(I_i(I_i+1) - Y_i^2), \quad m_Z = (g^2 + g'^2) \sum_i (Y_i^2 v_i^2)$$

$$\Rightarrow \rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i v_i^2 (I_i(I_i+1) - Y_i^2)}{2\sum_i (Y_i^2 v_i^2)}.$$

If new scalar Higgs bosons Y is 0, they would give a positive contribution to ρ.

[2] Y. Cheng, X. G. He, F. Huang, J. Sun and Z.P. Xing, Nucl.Phys.B 989 (2023) 116118, arXiv: 2208.06760.

Type-II Seesaw Modification on W Mass

For example[3], we can introduce a triplet ξ whose $Y = 0$, then

$$\rho = \frac{\frac{v_d^2}{2} + v_\Delta^2 + 2v_\xi^2}{2(\frac{v_d^2}{4} + v_\Delta^2)} = 1 - \frac{2v_\Delta^2}{v_d^2 + 4v_\Delta^2} + \frac{4v_\xi^2}{v_d^2 + 4v_\Delta^2}.$$

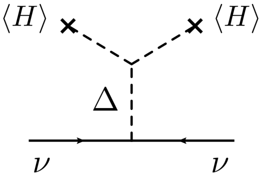
If the contribution of v_Δ is small enough to neglect, with $\Delta\rho = 0.0019$ we can estimate that

$$v_\xi \approx 5.36\text{GeV}.$$

[3] J.-Y. Cen, J.-H. Chen, X.-G. He, and J.-Y. Su, 2018. (arXiv:1803.05254)

Majorana Neutrino Mass in Type-II Seesaw Model

Meanwhile, the extra Yukawa coupling term could generate the Majorana neutrino mass after SSB.



$$-\mathcal{L}_{M_\nu} = \sum_{\alpha,\beta=e,\mu,\tau} Y_{\alpha\beta} L_\alpha^T C i\sigma^2 \Delta P_L L_\beta + \text{h.c.}$$

$$= -Y_{\alpha\beta}\overline{\ell_\alpha^c} P_L \ell_\beta \Delta^{++} - \sqrt{2} Y_{\alpha\beta}\overline{\nu_\alpha^c} P_L \ell_\beta \Delta^{+} + Y_{\alpha\beta}\overline{\nu_\alpha^c} P_L \nu_\beta \Delta^{0} + \text{h.c.}\ ,$$

where the last term would induce a Majorana-type mass matrix, ie.

$$m_{\alpha\beta} = (M_\nu)_{\alpha\beta} = \sqrt{2} Y_{\alpha\beta} \nu_\Delta = \frac{\mu Y_{\alpha\beta} v_d^2}{m_\Delta^2},$$

Majorana Neutrino Mass in Type-II Seesaw Model

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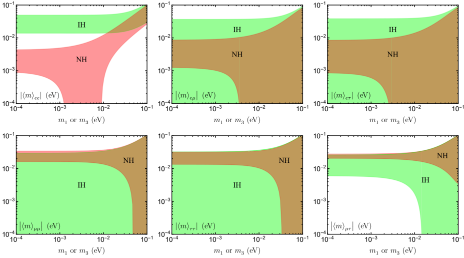
Majorana mass matrix could be diagonalized by a similarity transformation

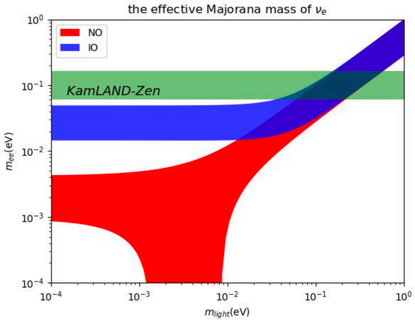
$$U^T M_\nu U = \widehat{M}_\nu = \mathrm{diag}\{m_1, m_2, m_3\} \Rightarrow M_\nu = U^* \widehat{M}_\nu U^\dagger = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix},$$

where U is PMNS matrix and $m_{\alpha\beta} = m_{\beta\alpha}$. With the oscillation parameter data, we can reconstruct the Majorana neutrino mass matrix (Z. Z. Xing, 1909.0961)



Majorana Neutrino Mass in Type-II Seesaw Model

Due to the Majorana feature, $0\nu\beta\beta$ process constrain the model with $m_{ee} < 61 - 165$meV.



which means $m_{\text{light}} < 180 - 480$meV.

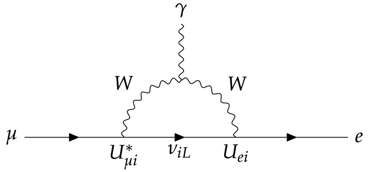
Besides, there're also other mass constraints

- Tritium neutrino mass from KATRIN: $m_\nu < 0.8$eV.
- Cosmic constraint from Planck: $\sum m_i < 0.12$eV, which means NO: $m_{\text{light}} < 0.03$eV, IO: $m_{\text{light}} < 0.016$eV.

Content

Charged Lepton Flavor Violation in SM

In SM, Charged Lepton Flavor Violation process is mediated by massive neutrinos.



The predicted rates for CLFV are typically GIM suppressed,

$$\mathrm{Br_{SM}}(\mu \to e\gamma) = \frac{3\alpha_e}{32\pi}\left|\sum_i U_{ei}^* U_{\mu i}\frac{m_i^2}{M_W^2}\right|^2 = 10^{-55} - 10^{-54}$$

Due to the tiny neutrino mass, this decay width is beyond current experimental reach.

$$\mathrm{Br_{exp}}(\mu \to \mathrm{e}\gamma) < 4.2 \times 10^{-13}$$

CLFV in Type-II Seesaw Model

1. $\ell_i^- \to \ell_j^+ \ell_k^- \ell_l^-$, mediated by Δ^{++}.
2. $\ell_i^- \to \ell_j^- \gamma$, mediated by Δ^{++} or Δ^+.

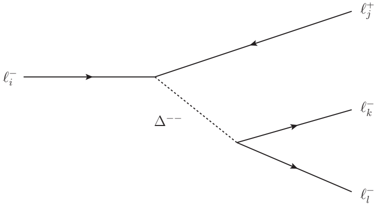


Figure 2: $\ell_i^- \to \ell_j^+ \ell_k^- \ell_l^-$.

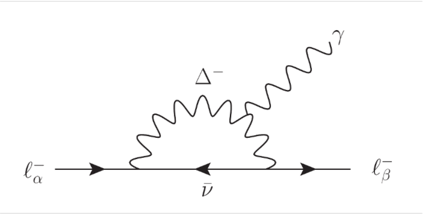


Figure 3: $\ell_i^- \to \ell_j^- \gamma$.

CLFV Three Body Decay

The decay rate of $\ell_i^- \to \ell_j^+ \ell_k^- \ell_l^-$ is found to be

$$\Gamma\left(\ell_i^- \to \ell_j^+ \ell_k^- \ell_l^-\right) = \frac{1}{2\left(1+\delta_{kl}\right)} \frac{m_{\ell_i}^5}{192\pi^3} \left|\frac{Y_{ij}Y_{kl}}{m_\Delta^2}\right|^2 = \frac{1}{8\left(1+\delta_{kl}\right)} \frac{m_{\ell_i}^5}{192\pi^3} \left|\frac{m_{ij}m_{kl}}{m_\Delta^2 v_\Delta}\right|^2 .$$

With the upper bound of branching ratio, we can give the lower bound of $m_\Delta^2 v_\Delta^2$.

Process	Branching	Constraint
$\mu^- \to e^+ e^- e^-$	1.0×10^{-12}	$m_\Delta v_\Delta > \left\|(M_\nu)_{\mu e} (M_\nu)_{ee}\right\|^{1/2} \times 145\text{TeV}$
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	$m_\Delta v_\Delta > \left\|(M_\nu)_{\tau\mu} (M_\nu)_{ee}\right\|^{1/2} \times 8.6\text{TeV}$
$\tau^- \to \mu^+ \mu^- e^-$	2.7×10^{-8}	$m_\Delta v_\Delta > \left\|(M_\nu)_{\tau\mu} (M_\nu)_{\mu e}\right\|^{1/2} \times 8.8\text{TeV}$
$\tau^- \to \mu^+ \mu^- \mu^-$	2.1×10^{-8}	$m_\Delta v_\Delta > \left\|(M_\nu)_{\tau\mu} (M_\nu)_{\mu\mu}\right\|^{1/2} \times 7.9\text{TeV}$

CLFV Three Body Decay

Due to the mass matrix element could be very small, these three body decay constraints are weak.

Eg, for $\mu^- \to e^+e^-e^-$, the constraint is

$$m_\Delta v_\Delta > |m_{\mu e} m_{ee}|^{1/2} \times 145\text{TeV} .$$

So the lower bound of $m_\Delta^2 v_\Delta^2$ is significant only when lightest neutrino mass m_0 is smaller that 10^{-3}eV for normal ordering case.

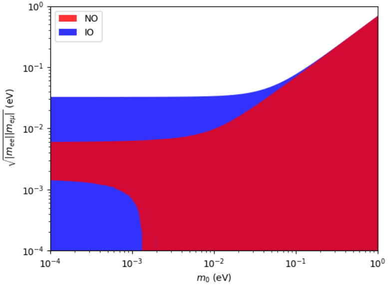


Figure 4: The range of $|m_{\mu e} m_{ee}|^{1/2}$.

CLFV Radiative Decay

Neglected all internal lepton masses, we can get decay rate of $\ell_i^- \to \ell_j^- \gamma$,

$$\Gamma\left(\ell_i^- \to \ell_j^- \gamma\right) = \frac{m_{\ell_i}^5 \alpha_{em}}{(192\pi^2)^2} \left|f^\dagger f\right|_{ij}^2 \left(\frac{1}{m_{\Delta^+}^2} + \frac{8}{m_{\Delta^{++}}^2}\right)^2 = \frac{m_{\ell_i}^5 \alpha_{em}}{(192\pi^2)^2} \left(\frac{9\left|M_\nu^\dagger M_\nu\right|_{ij}}{2m_\Delta^2 v_\Delta^2}\right)^2 .$$

Lower bound of $m_\Delta^2 v_\Delta^2$ could be

Process	Branching	Constraint
$\mu^- \to e^- \gamma$	4.2×10^{-13}	$m_\Delta v_\Delta > \sqrt{9\left\|M_\nu^\dagger M_\nu\right\|_{\mu e}} \times 15.3\text{TeV}$
$\tau^- \to e^- \gamma$	3.3×10^{-8}	$m_\Delta v_\Delta > \sqrt{9\left\|M_\nu^\dagger M_\nu\right\|_{\mu e}} \times 0.6\text{TeV}$
$\tau^- \to \mu^- \gamma$	4.4×10^{-8}	$m_\Delta v_\Delta > \sqrt{9\left\|M_\nu^\dagger M_\nu\right\|_{\mu e}} \times 0.56\text{TeV}$

CLFV Radiative Decay

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These constrains are much stronger, as the $\sqrt{\left|M_\nu^\dagger M_\nu\right|_{ji}}$ has lower bound

$$\sqrt{\left|M_\nu^\dagger M_\nu\right|_{ji}} = \left|U_{j2}U_{i2}^*\Delta m_{21}^2 + U_{j3}U_{i3}^*\Delta m_{31}^2\right| \text{ , eg: } 0.041\text{eV} < 3\sqrt{\left|M_\nu^\dagger M_\nu\right|_{\mu e}} < 0.054\text{eV}.$$

With experimental lower limit of a few hundred GeV of m_Δ, we can estimate the range of v_Δ

$$m_\Delta v_\Delta > \sqrt{9\left|M_\nu^\dagger M_\nu\right|_{\mu e}} \times 15.3\text{TeV} \Rightarrow v_\Delta > (6.25 - 8.39)\text{eV}\left(\frac{100\text{GeV}}{m_\Delta}\right),$$

So v_Δ could be very small, which means the Type-II seesaw contribution to m_W could be negligible.

Content

Background

Neutrino Trident Scattering (NTS) is a weak process:

A neutrino, scattering off a heavy nucleus, generates a pair of charged leptons.

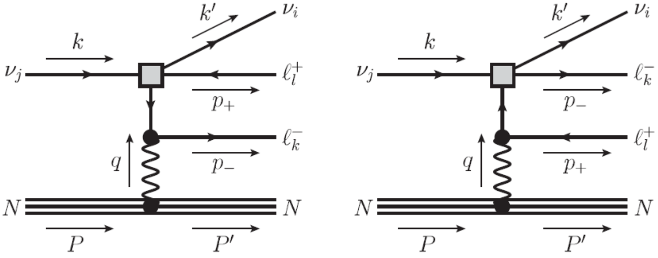


Figure 5: Diagrams for the $\nu_j \to \nu_i \ell_k^- \ell_l^+$.

Background

1964 Trident scattering to examine the V-A theory.
(Czyz, Sheppey, and Walecka)

1971 Momentum and angular distribution of the NTS.
(Lovseth and Radomiski, Koike et al, Fujikawa)

1972 Trident scattering to examine the W-S theory.
(Brown, Hobbs, Smith and Stanko)

Measurements of $\nu_\mu \to \nu_\mu \mu^+ \mu^-$.

1990 $\frac{\sigma_{\text{exp}}}{\sigma_{\text{SM}}} = 1.58^{+0.64}_{-0.64}$ CHARM-II. (Geiregat et al., 1990.)

1991 $\frac{\sigma_{\text{exp}}}{\sigma_{\text{SM}}} = 0.82^{+0.28}_{-0.28}$ CCFR. (S. R. Mishra et al., 1991.)

1999 $\frac{\sigma_{\text{exp}}}{\sigma_{\text{SM}}} = 0.72^{+1.73}_{-0.72}$ NuTeV. (T. Adams et al., 2000)

The weighted average value $\frac{\sigma_{\text{exp}}}{\sigma_{\text{SM}}} = 0.95^{+0.25}_{-0.25}$

Revival

2014 Trident scattering to constrain new physics.
(Altmannshofer, Gori, Pospelov, and Yavin)

SM contribution

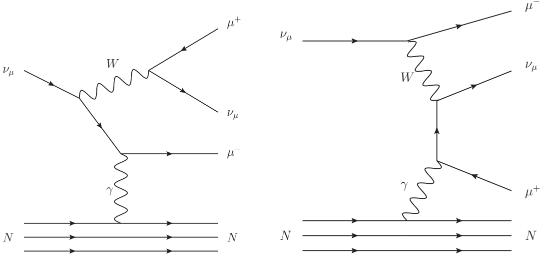


Figure 6: W contribution.

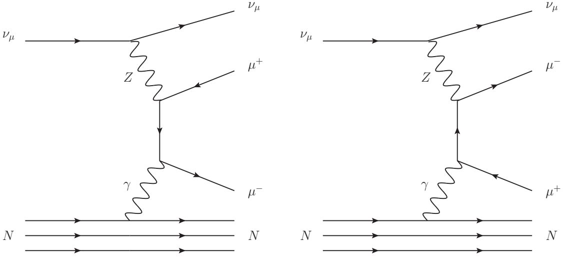


Figure 7: Z contribution.

In SM, a $\mu^+\mu^-$ pair can be generated by W and Z exchange from the operator

$$-\frac{g^2}{16m_W^2}\bar{\nu}_\mu\gamma^\alpha\left(1-\gamma^5\right)\nu_\mu\bar{\mu}\gamma_\alpha\left(1-\gamma^5+4\sin^2\theta_W\right)\mu$$

Type-II modification

In type-II seesaw model, a $\mu^+\mu^-$ pair can be generated by Δ^+,

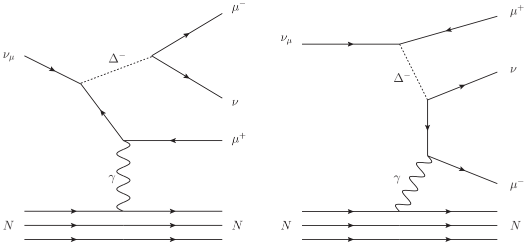


Figure 8: Type-II Seesaw contribution to NTS.

The effective operator would be

$$\frac{2Y_{ij}Y^*_{kl}}{m^2_\Delta}\bar{\nu}^c_i P_L \ell_j \bar{\ell}_l P_R \nu^c_k = \frac{m_{ij}m^*_{kl}}{2m^2_\Delta v^2_\Delta}\bar{\nu}_k \gamma^\mu P_L \nu_i \bar{\ell}_l \gamma_\mu P_L \ell_j$$

Type-II modification

Notice that we should sum over all flavor neutrinos in final states. Then we get the final modification

$$\frac{\sigma}{\sigma_{SM}} = \frac{1}{(1+4s_w^2)^2+1}\left(\left(1+4s_w^2-\frac{2m_W^2}{g^2}\frac{|m_{\mu\mu}|^2}{m_\Delta^2 v_\Delta^2}\right)^2+\left(1-\frac{2m_W^2}{g^2}\frac{|m_{\mu\mu}|^2}{m_\Delta^2 v_\Delta^2}\right)^2 + 2\left(\frac{2m_W^2|m_{\mu\mu}|^2}{g^2 m_\Delta^2 v_\Delta^2}\right)^2\left(\frac{|m_{e\mu}|^2+|m_{\tau\mu}|^2}{|m_{\mu\mu}|^2}\right)\right),$$

Treat the ratio as a quadratic function of $\frac{1}{m_\Delta^2 v_\Delta^2}$, $\quad (m_\Delta^2 v_\Delta^2 \to \infty \Rightarrow \frac{\sigma}{\sigma_{SM}} \to 1)$

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} = a\left(\frac{1}{m_\Delta^2 v_\Delta^2}\right)^2 + b\left(\frac{1}{m_\Delta^2 v_\Delta^2}\right)+1,$$

where

$$a = \frac{\left(v^2|m_{\mu\mu}|^2\right)^2\left(1+\frac{|m_{e\mu}|^2+|m_{\tau\mu}|^2}{|m_{\mu\mu}|^2}\right)}{2\left((1+4s_w^2)^2+1\right)}, \quad b = -\frac{v^2|m_{\mu\mu}|^2(2+4s_w^2)}{(1+4s_w^2)^2+1}.$$

Type-II modification

With the property of quadratic function, we can draw the figure,

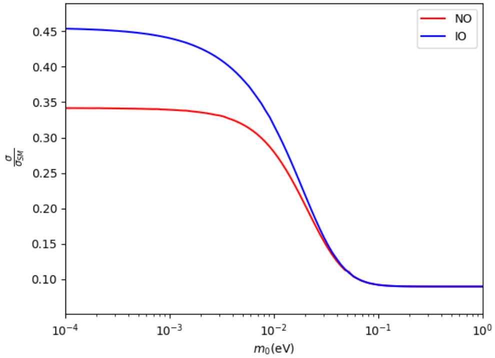
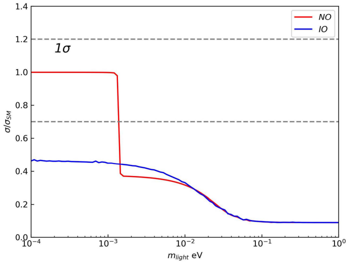


Figure 9: The rough lower bound of the ratio $\dfrac{\sigma}{\sigma_{\text{SM}}}$.

Combined with CLFV constraints

Use upper bound of $\frac{1}{m_\Delta^2 v_\Delta^2}$ from CLFV, we can constrain $\frac{\sigma}{\sigma_{SM}}$ better.

Figure 10: The lower bound of the ratio $\frac{\sigma}{\sigma_{\rm SM}}$ with the constraint from $\mu^- \to e^+ e^- e^-$.



As the constraint from $\mu^- \to e^+ e^- e^-$ is weak, the range of ratio is still very large.

Combined with CLFV constraints

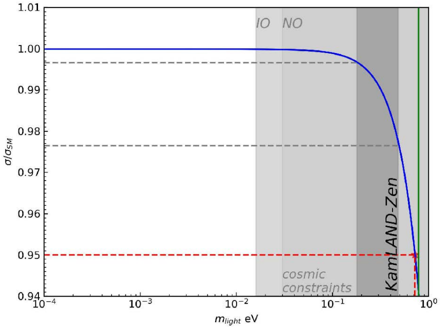
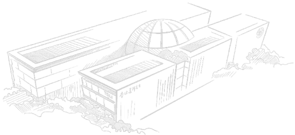


Figure 11: Combined with the constrain from $\mu^- \to e^-\gamma$.

1. Combining constraints from $0\nu\beta\beta$, $\frac{\sigma}{\sigma_{\rm SM}} > 0.977$. Close to the current experimental central value.
2. From cosmic constraint (based on ΛCDM), the effect of Δ on $\frac{\sigma}{\sigma_{\rm SM}}$ is limited to be less than 0.1%. A challenge to experimental test.

Thanks

Thanks



Question

Questions?

Backup

In, future DUNE Near Detector precision,[4]

$$\frac{\delta\langle\sigma^{e^\pm\mu^\mp}\rangle}{\langle\sigma^{e^\pm\mu^\mp}\rangle} = 1.8\%(1.6\%), \quad \frac{\delta\langle\sigma^{e^+e^-}\rangle}{\langle\sigma^+e^-\rangle} = 3.4\%(3.3\%) \quad \text{and} \quad \frac{\delta\langle\sigma^{\mu^+\mu^-}\rangle}{\langle\sigma^{\mu^+\mu^-}\rangle} = 5.5\%(5.1\%).$$

[4] JHEP 01 (2019) 119, arXiv:1807.10973