# Probing doubly-charged scalar with leptons at low and high energies

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第十届海峡两岸粒子物理和宇宙学研讨会

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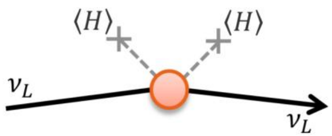
# Seesaw mechanism

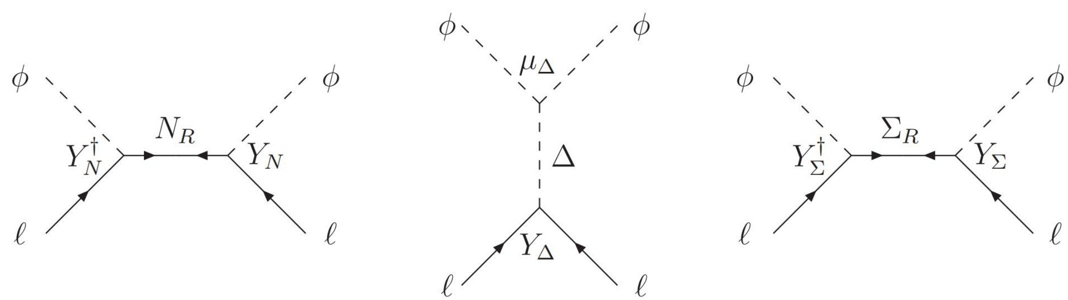
- The masses of neutrinos can be described by the dimension-5 operator




$$\mathcal{L}_M = \frac{C_5}{\Lambda}\left(\bar{L}^c \tilde{H}^*\right)\left(\tilde{H}^\dagger L\right) + \text{ h.c.}$$

lepton number violation (LNV)

- Tree-level realizations: seesaw mechanism in three types




| | | | |
|---|---|---|---|
| key ingredients: | $N_R$ | $\Delta$ | $\Sigma_R$ |
| | singlet | triplet | triplet |

# Type-II seesaw

- Triplet scalar:

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} \qquad \langle \Delta^0 \rangle = v_\Delta/\sqrt{2}$$

- Yukawa interactions and neutrino masses

$$\mathcal{L}_Y = -\bar{L}_L^c i\tau_2 \Delta f_L L_L + \text{ h.c.} \qquad M_\nu = \sqrt{2} f_L v_\Delta$$

- Electroweak $\rho$ pameter:

$$\rho = 1 - 2v_\Delta^2/v^2$$

$$\rho = 1.00031 \pm 0.00019$$

$$v_\Delta \lesssim 1.45 \text{ GeV}$$

PDG 2024

No constraint on $f_L$ from $M_\nu/v_\Delta$

# Type-II seesaw

- Scalar potential:

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}\left(H^\dagger H\right)^2 + M_\Delta^2 \,\mathrm{Tr}\left(\Delta^\dagger \Delta\right) + \left[\mu\left(H^T i\sigma^2 \Delta^\dagger H\right) + \text{ h.c. }\right]$$

$$+ \lambda_1 \left(H^\dagger H\right) \mathrm{Tr}\left(\Delta^\dagger \Delta\right) + \lambda_2 \left(\mathrm{Tr}\,\Delta^\dagger \Delta\right)^2 + \lambda_3 \,\mathrm{Tr}\left(\Delta^\dagger \Delta\right)^2 + \boxed{\lambda_4 H^\dagger \Delta \Delta^\dagger H}$$

- Physical states:

A. Arhrib, et al., 1105.1925 (PRD)

$$H^{++} \simeq \Delta^{++}, H^{+} \simeq \Delta^{+} \qquad H \simeq \sqrt{2}\,\mathrm{Re}\,\Delta^0,\ A \simeq \sqrt{2}\,\mathrm{Im}\,\Delta^0$$

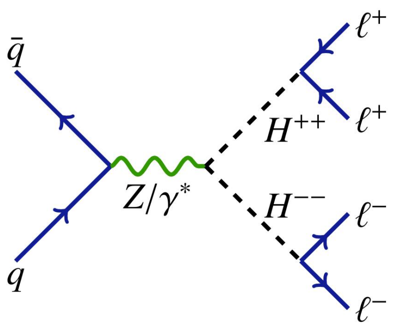
- Scalar masses

$$m_H^2 \simeq m_A^2 \simeq m_{H^+}^2 + \frac{\lambda_4 v^2}{4} \simeq m_{H^{++}}^2 + \frac{\lambda_4 v^2}{2}$$

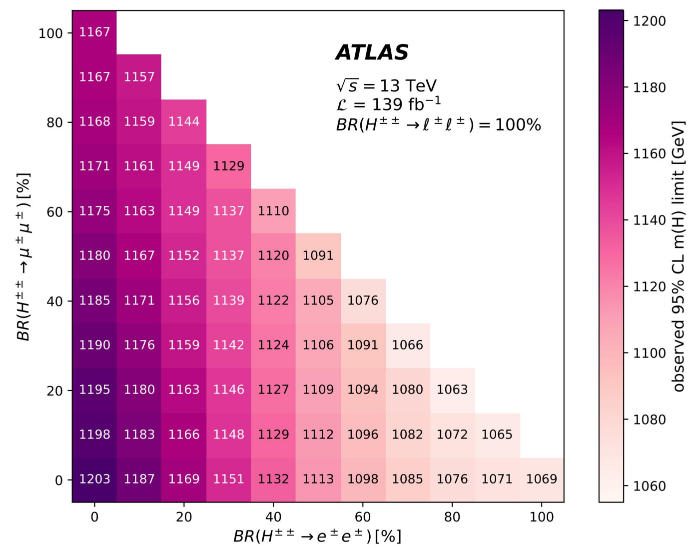
By asssuming $\lambda_4 \ll 1$, new scalars are nearly degenerate in mass

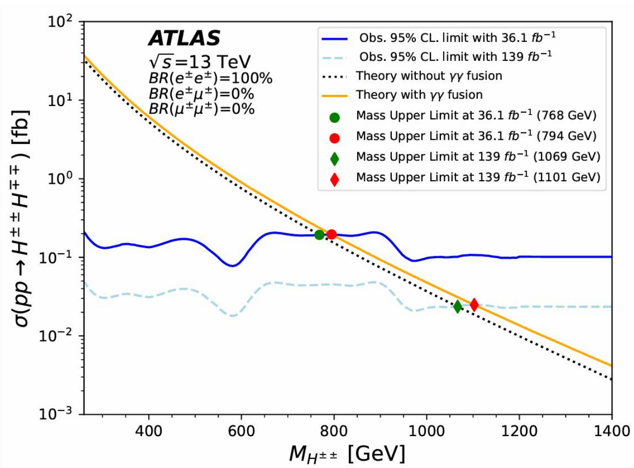
# Type-II seesaw

- LHC direct searches for doubly-charged scalar




$$H^{\pm\pm} \to e^\pm e^\pm,\ \mu^\pm\mu^\pm,\ e^\pm\mu^\pm$$



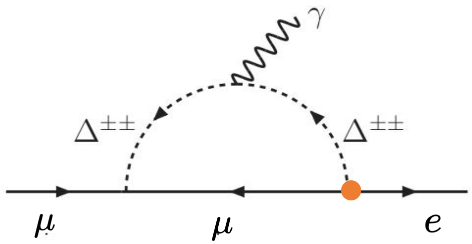

L. Guedes, et al., 2601.00083

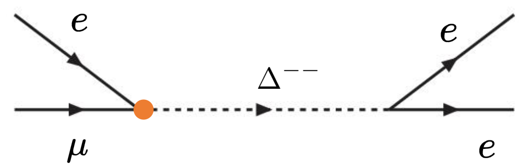
Universal constraint:

$$M_{H^{\pm\pm}} \gtrsim 1.2\ \text{TeV} \quad \text{irrespective of } f_L$$

# Type-II seesaw

- Charged lepton flavor violation (CLFV) searches




$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{27\alpha_{\mathrm{em}}}{64\pi G_F^2} \frac{\left|\left(f_L^\dagger f_L\right)_{e\mu}\right|^2}{m_{H^{\pm\pm}}^4} \qquad \mathrm{BR}(\mu \to \bar{e}ee) = \frac{1}{4G_F^2} \frac{\left|f_L^{ee} f_L^{\mu e}\right|^2}{m_{H^{\pm\pm}}^4}$$

$$\Rightarrow \quad \frac{m_{\Delta^{\pm\pm}}}{\sqrt{\left|\sum_\ell (f_L)^\dagger_{\mu\ell}(f_L)_{e\ell}\right|}} > 65\ \mathrm{TeV} \qquad \frac{m_{\Delta^{\pm\pm}}}{\sqrt{\left|(f_L)^\dagger_{ee}(f_L)_{e\mu}\right|}} > 208\ \mathrm{TeV}$$

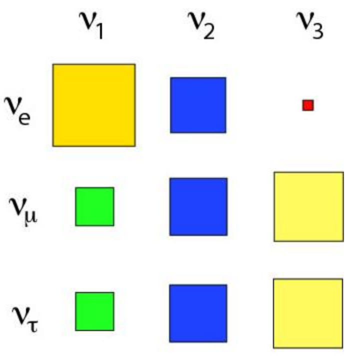
Akeroyd, Aoki, Sugiyama, 0904.3640 (PRD)
Dev, Ramsey-Musolf, Yongchao Zhang, 1806.08499 (PRD)

# Type-II seesaw

- Charged lepton flavor violation (CLFV) searches

flavor correlation:

$$M_\nu^{ij} = \sqrt{2} f_L^{ij} v_\Delta$$




- Yukawa coupling matrix $f_L$ cannot be flavor diagonal
- If $m_{\Delta^{\pm\pm}} \sim O(1)$ TeV, Yukawa couplings satisfy $f_L^{\alpha\beta} \lesssim 10^{-3}$
- To achieve sizable Yukawa couplings, $\Delta^{\pm\pm}$ should be decoupled from the neutrino mass generation

# Left-right symmetric model

- Field content:

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix} \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R \qquad \Phi = \begin{pmatrix} \phi^0_1 & \phi^+_2 \\ \phi^-_1 & \phi^0_2 \end{pmatrix}$$

- Gauge symmetry

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Yukawa interactions

$$\mathcal{L}_Y = -\left(\bar{L}^c_L i\tau_2 \Delta_L f_L L_L + \bar{L}^c_R i\tau_2 \Delta_R f_R L_R\right) + \text{ h.c.}$$

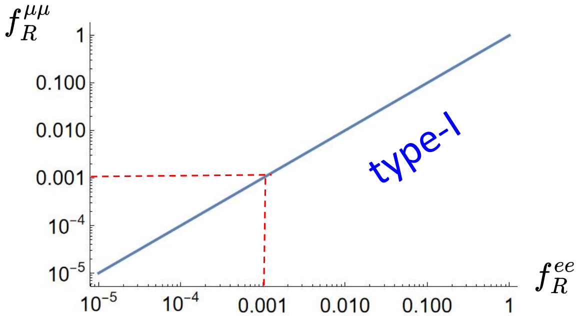
- What is good for?
    - Hybrid neutrino mass
    - Parity restoration
    - Grand unification

$$M_\nu = M_L - M_D^T \frac{1}{M_R} M_D$$

G. Senjanovic, Riv.Nuovo Cim. 34 (2011) 1, 1-68

# Left-right symmetric model

- Minimal LRSM [Mohapatra, Senjanovic, 1980&1981]
  - Left-right symmetry is imposed in the Yukawa sector: $f_L = f_R$
  - Yukawa couplings of the LH and RH doubly-charged scalars are equal
  - Depending on the neutrino mass generation:




type-II

type-II: CLFV constraints and flavor correlation are applied

type-I:

$$m_\nu = -M_D M_R^{-1} M_D^T, \quad M_R = \sqrt{2} f_R v_R$$

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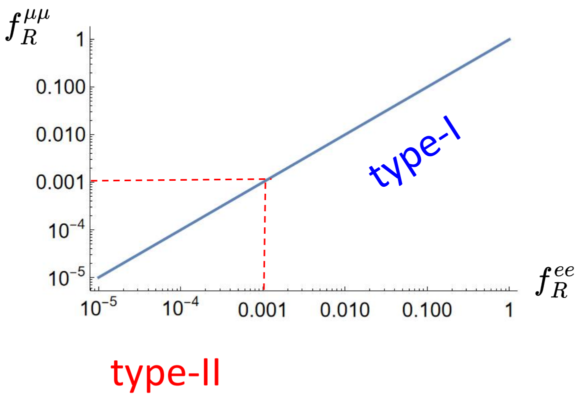


type-II: CLFV constraints and flavor correlation are applied

type-I:

$$m_\nu = -M_D M_R^{-1} M_D^T, \quad M_R = \sqrt{2} f_R v_R$$

  - RH triplet scalar is responsible for the dynamic generation of $M_R$
  - $M_D$ is generally complex, thus $f_R$ can be diagonal and sizable with the CLFV constraints being avoided

# Left-right symmetric model

- LRSM with $D$-parity breaking [Chang, Mohapatra, Parida, 1984]

$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes P \to \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$$

  - The mass of the RH doubly-charged scalar $\Delta_R^{\pm\pm}$ can be $O(1)$ TeV

$$\mu_{\Delta_L}^2 = \mu_\Delta^2 + M\langle\eta\rangle + \lambda_2\langle\eta\rangle^2$$
$$\mu_{\Delta_R}^2 = \mu_\Delta^2 - M\langle\eta\rangle + \lambda_2\langle\eta\rangle^2$$

$\Delta_L^{\pm\pm}$ is at the $D$-parity breaking scale $\gtrsim 10^9$ GeV

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  - Neutrinos acquire masses in type-I seesaw mechanism with the RH doubly-charged scalar being a key byproduct
  - Similarly, $f_R$ can be diagonal and sizable with the CLFV constraints being avoided

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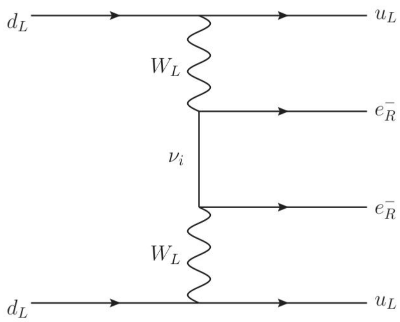
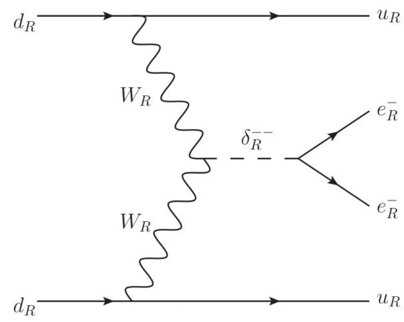
  - Neutrinos acquire masses in type-I seesaw mechanism with the RH doubly-charged scalar being a key byproduct
  - Similarly, $f_R$ can be diagonal and sizable with the CLFV constraints being avoided

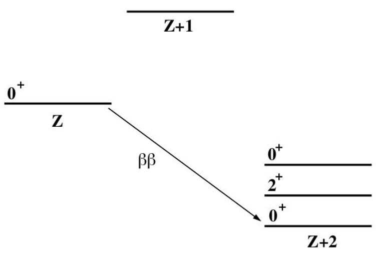
Presumably, no CLFV signal would be observed

# Nuclear Femto Laboratory

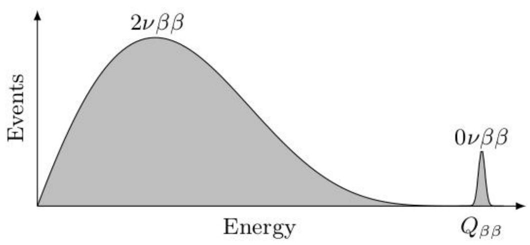
- Neutrinoless double beta decay ($0\nu\beta\beta$ decay)




$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

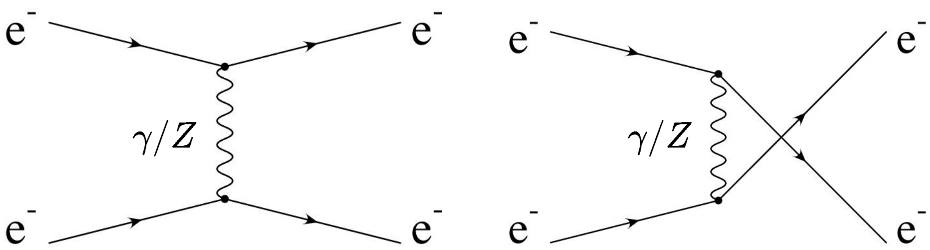


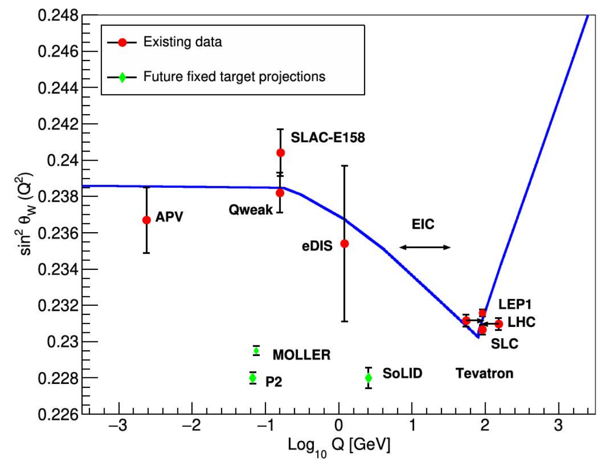

KamLAND-Zen (current): $T_{1/2}^{0\nu} > 3.8 \cdot 10^{26}$ yr

nEXO and LEGEND (tonne-scale) : $T_{1/2}^{0\nu} \gtrsim 10^{28}$ yr

# Fixed-target experiment

- Moller scattering




Jefferson Lab SoLID, J.Phys.G 50 (2023) 11, 110501

Parity-violating asymmetry:

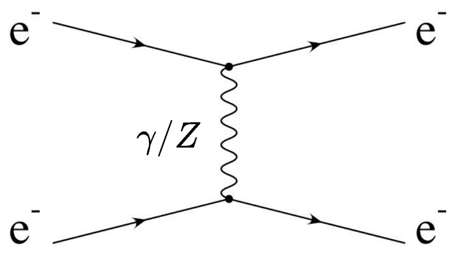
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e \qquad Q_W^e = 1 - 4\sin^2\theta_W$$

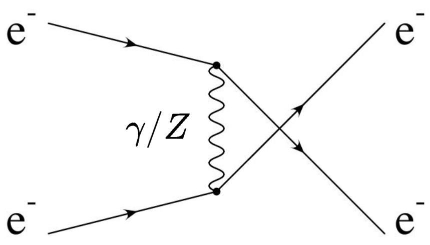
MOLLER experiment: MOLLER, 1411.4088

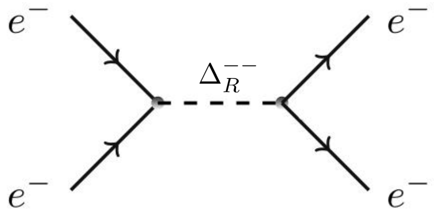
polarized electrons scattering off unpolarized electrons at $\sqrt{s} = 11$ GeV with the precision $\delta(\sin^2\theta_W)\sim 0.1\%$

# Fixed-target experiment

- Moller scattering




$$\mathcal{L}_{eff} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{e}_j \gamma_\mu e_j)$$

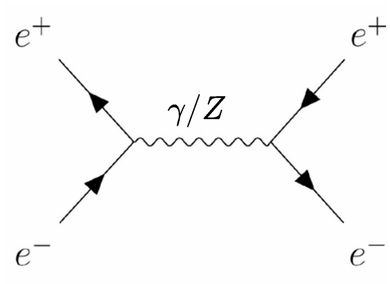
$$\mathcal{L}_\Delta = \frac{|(f_R)_{ee}|^2}{M^2_{\Delta_R^{\pm\pm}}} (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma_\mu e_R)$$

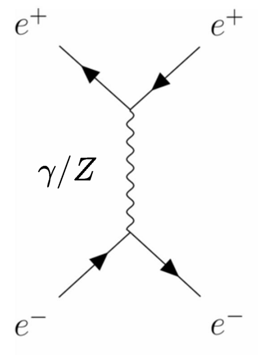
MOLLER sensitivity:

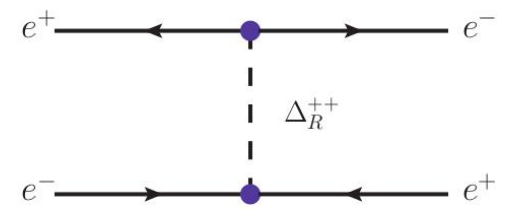
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} \simeq 7.5\ \mathrm{TeV}$$ MOLLER, 1411.4088

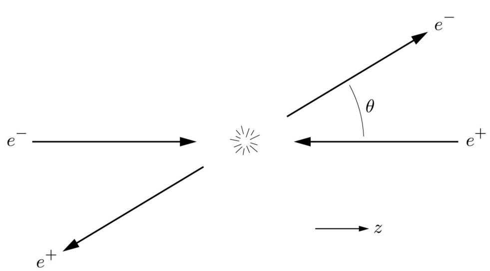
# Electron-positron colliders

- Bhabha scattering




$\theta \to 0$ in the SM

$$\mathcal{M}_{\text{int}}^2 = \frac{e^2 \left(f_R^{ee}\right)^2 u^2 [g(s) - g(t)]}{4\left[\left(u - m_{\Delta^{++}}^2\right)^2 + \Gamma_\Delta^2 m_{\Delta^{++}}^2\right]}$$

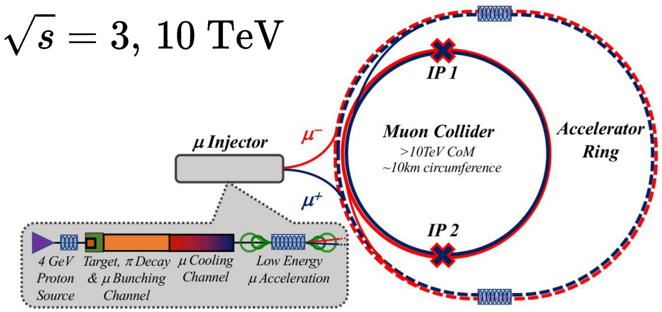
LEP: $\sqrt{s} = 195.6$ GeV, $745\ pb^{-1}$, $|\cos\theta| < 0.90$

CEPC/FCC-ee: $\sqrt{s} = 240$ GeV, $5\ ab^{-1}$, $|\cos\theta| < 0.9998$

# High-energy muon colliders

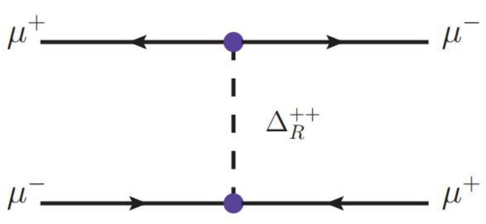
- Muon collider (MuC):

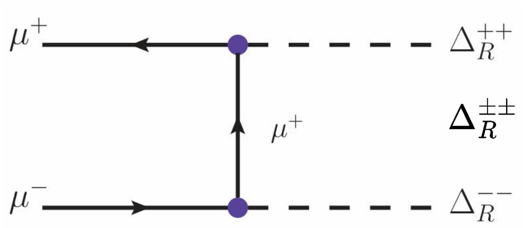
$\sqrt{s} = 3,\ 10$ TeV




- cleaner than the proton collider
- opportunities for muon-specific physics: EDM, CLFV

C. Accettura, et al., 2303.08533 (EPJC)



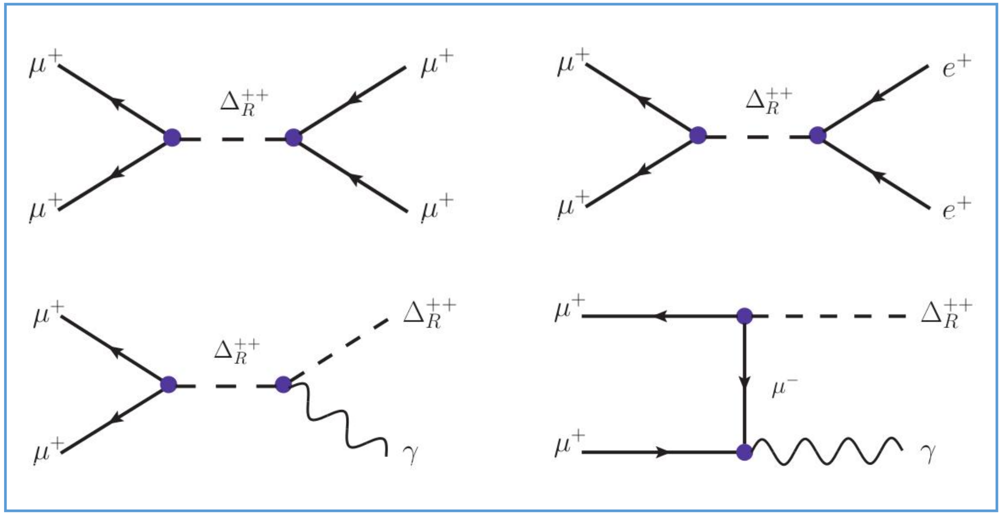

$\Delta_R^{\pm\pm} \to \ell^\pm \ell^\pm$

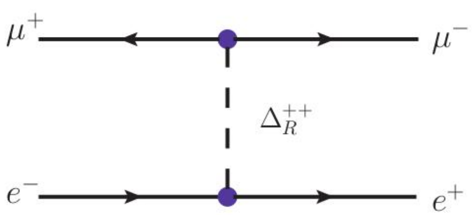
Final state: $\mu^+\mu^-$ $4\mu,\ 4e,\ 2e2\mu$

# High-energy muon colliders

- $\mu$TRISTAN:
  - $\mu^+$ beam obtained from ultra-cold muon technology at J-PARC is accelerated up to 1 TeV
  - $\mu^+\mu^+$ beams: $\sqrt{s} = 2$ TeV; $\mu^+e^-$ beams: $\sqrt{s} = 346$ GeV

Y. Hamada, et al., Prog. 2201.06664 (PTEP)



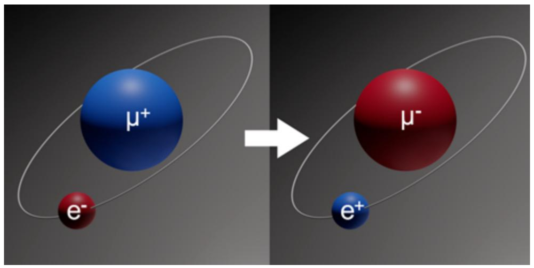



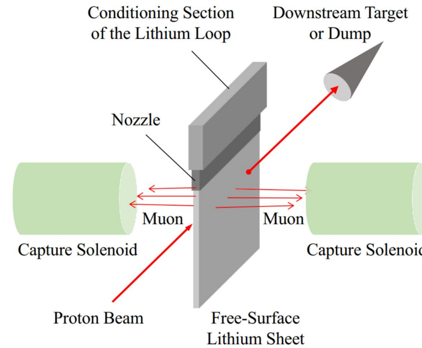

LNV ✓ YES

LFV ✗ NO

# Conversion experiment

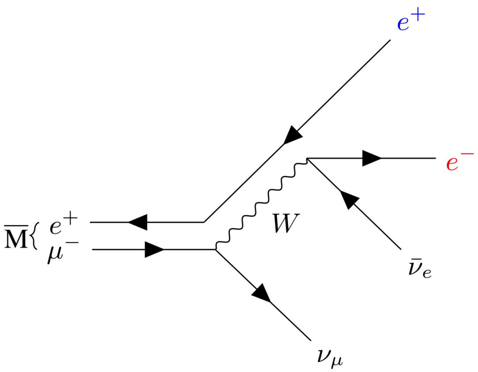
- Muonium-antimuonium transition

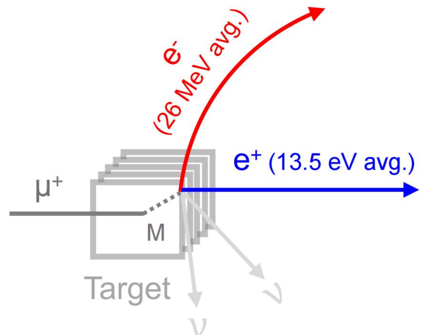


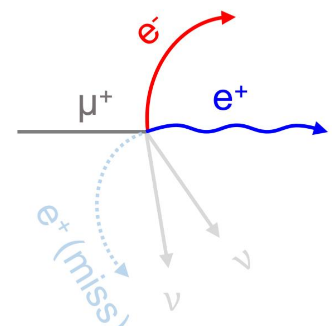




signal:

background: $\mu^+ \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$




Jian Tang, et al., 2410.18817

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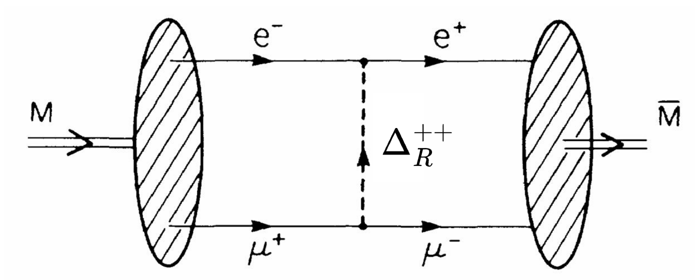



LNV — YES

LFV — NO

$$G_{M\bar{M}} = \frac{f_R^{ee} f_R^{\mu\mu}}{4\sqrt{2} m_{\Delta^{++}}^2}$$

D. Chang, W.-Y. Keung, Phys. Rev. Lett. 62, 2583 (1989)
Chengcheng Han, Da Huang, Jian Tang, Yu Zhang, 2102.00758 (PRD)

Transition probabilities:

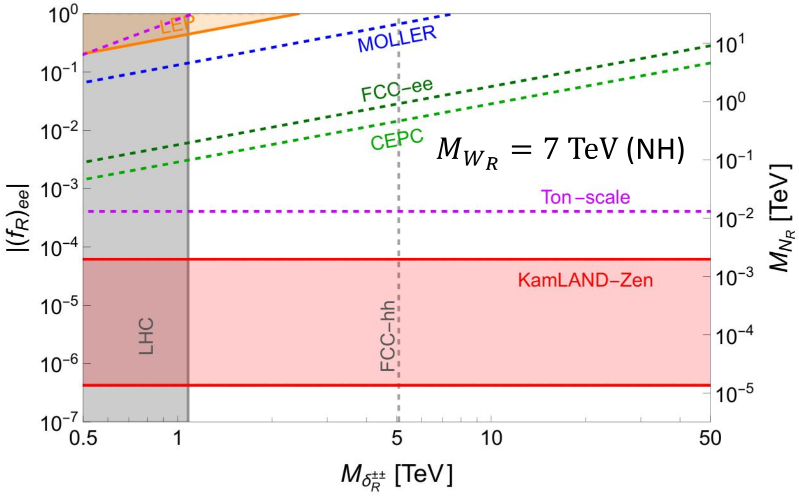
$$P(M \to \bar{M}) = \sum_{i=P,V} f_i P\left(M_i \to \bar{M}_i\right) \propto \left(\frac{G_{M\bar{M}}}{G_F}\right)^2$$

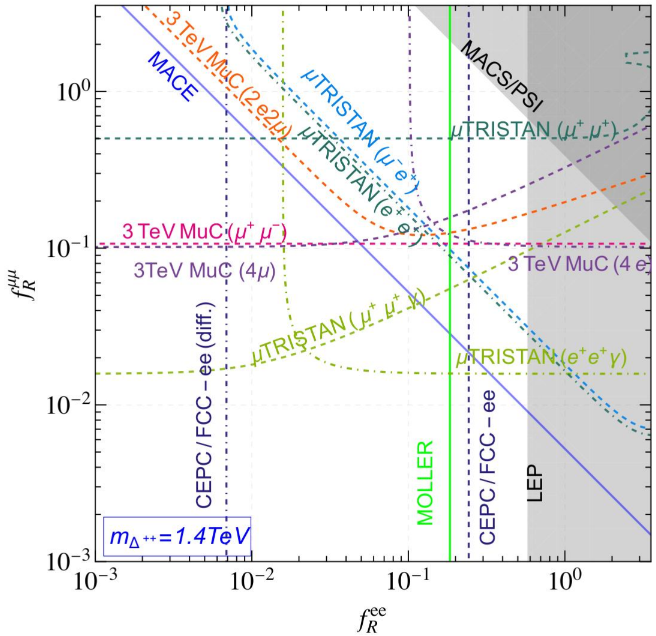
MACS/PSI (current): $G_{M\bar{M}}/G_F < 3 \times 10^{-3}$

MACE (projected): $G_{M\bar{M}}/G_F < 4 \times 10^{-5}$

# Results and discussions

- Probing the flavor-diagonal Yukawa couplings:




**GL**, M. J. Ramsey-Musolf, S. Urrutia Quiroga, J. C. Vasquez, 2408.06306 (PLB)

**GL**, Jin Sun, 2512.07255

TeV-scale doubly-charged scalar with the Yukawa couplings $f_R^{ee}, f_R^{\mu\mu} \gtrsim 10^{-3}$ is within the reach of future experiments

# Summary

- We have studied the right-handed doubly-charged scalar within the left-right symmetric model
- It can be at the TeV scale while possessing sizable and (nearly) flavor-diagonal Yukawa couplings
- Our comprehensive analysis of various low-energy precision experiments and high-energy colliders shows that future facilities will be sensitive to the Yukawa couplings $f_R^{ee}$ and $f_R^{\mu\mu}$ down to the level of $10^{-3}$

*Thank you*