

Correlating $0\nu\beta\beta$ decays and flavor observables in leptoquark models

Luighi P. S. Leal (University of São Paulo, University Paris-Saclay)

In collaboration with Svjetlana Fajfer, Olcyr Sumensari and Renata Z. Funchal
[arXiv: 2406.20050]



Neutrino masses

❖ Neutrinos are massive and oscillate

Evidence of Physics
Beyond Standard
Model (BSM)

❖ Standard Model effective field theory (SMEFT)

$$\mathcal{L}_{\text{SMEFT}} = \sum_{d \geq 5} \sum_a \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{O}_a^{(d)}$$

Operators invariant under
 $SU(3)_C \times SU(2)_L \times U(1)_Y$

EFT cutoff

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EFT cutoff

❖ Neutrino masses described by the Weinberg operator (d = 5)

$$\mathcal{L}^{d=5} = \frac{C_{ij}^{(5)}}{\Lambda} (\bar{L}_i^C \tilde{H}^*) (\tilde{H}^\dagger L_j) + h.c.$$

$$(m_\nu)_{ij} = \frac{C_{ij}^{(5)} v^2}{\Lambda}$$

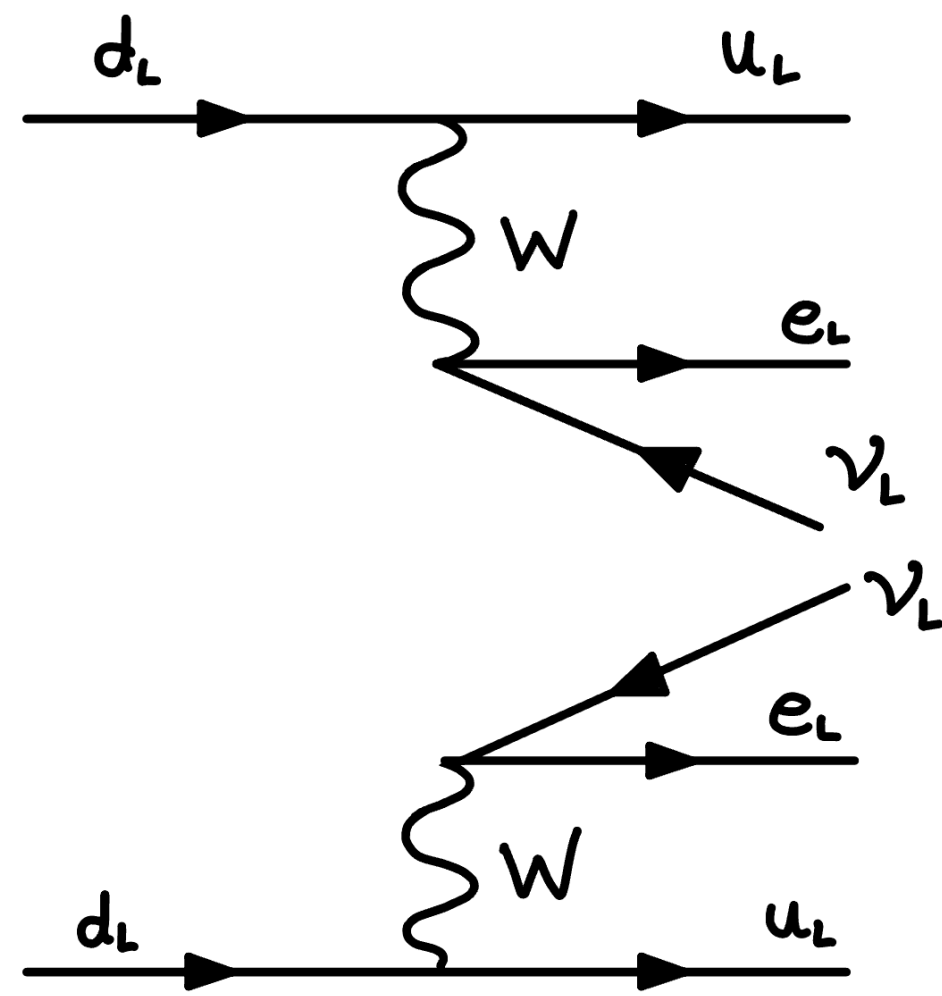
Lepton Number
(L) is broken

Majorana
Neutrino Masses

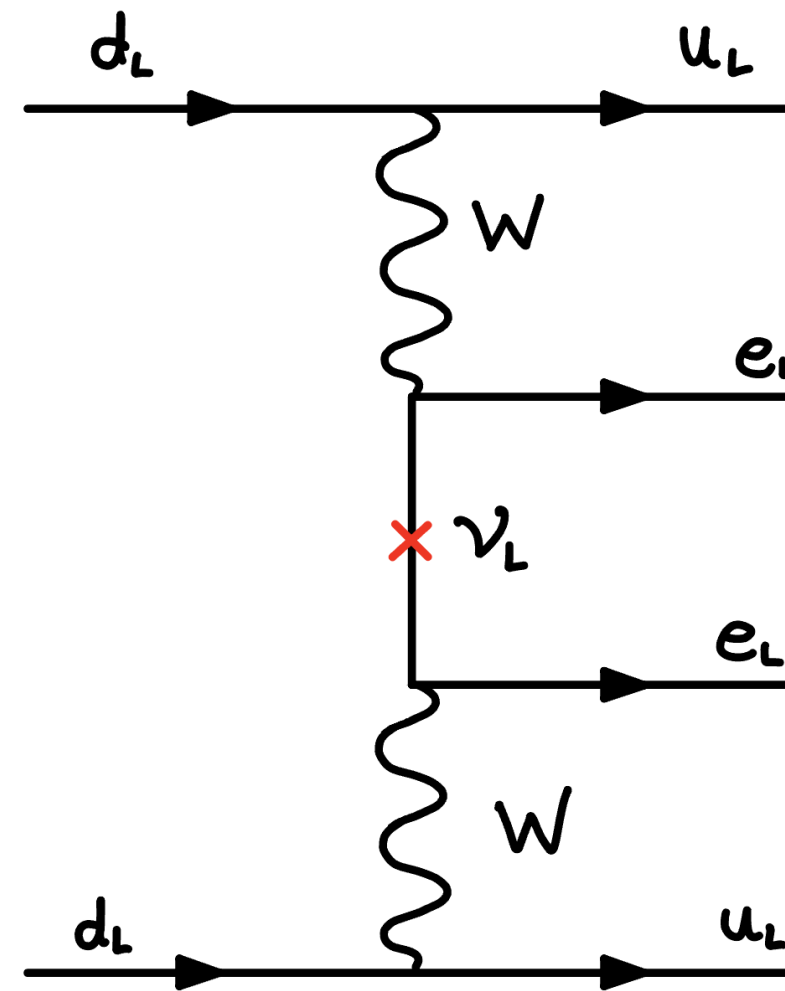
Lepton Number Violation (LNV)

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

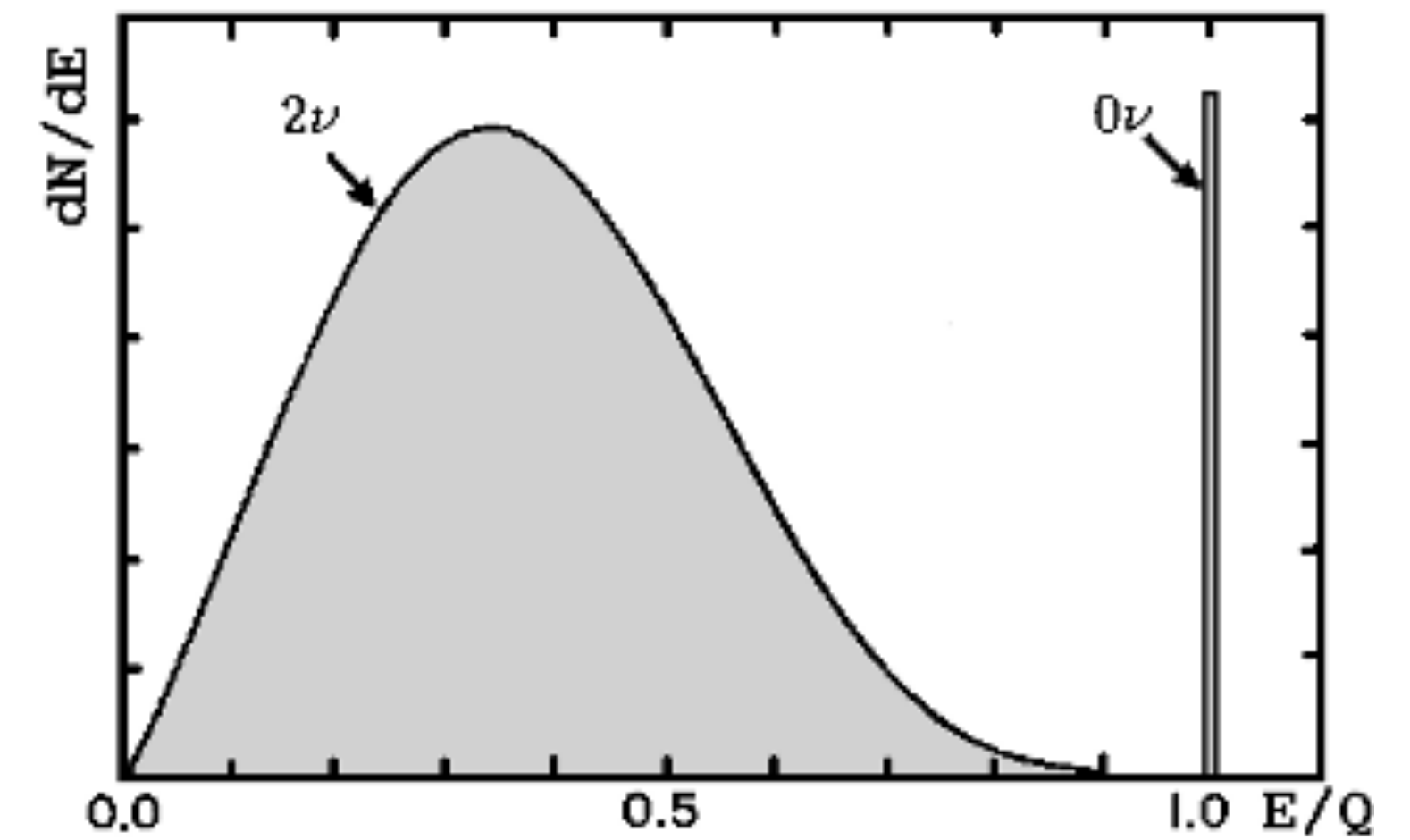
Induced by $d = 5$ operator



VS



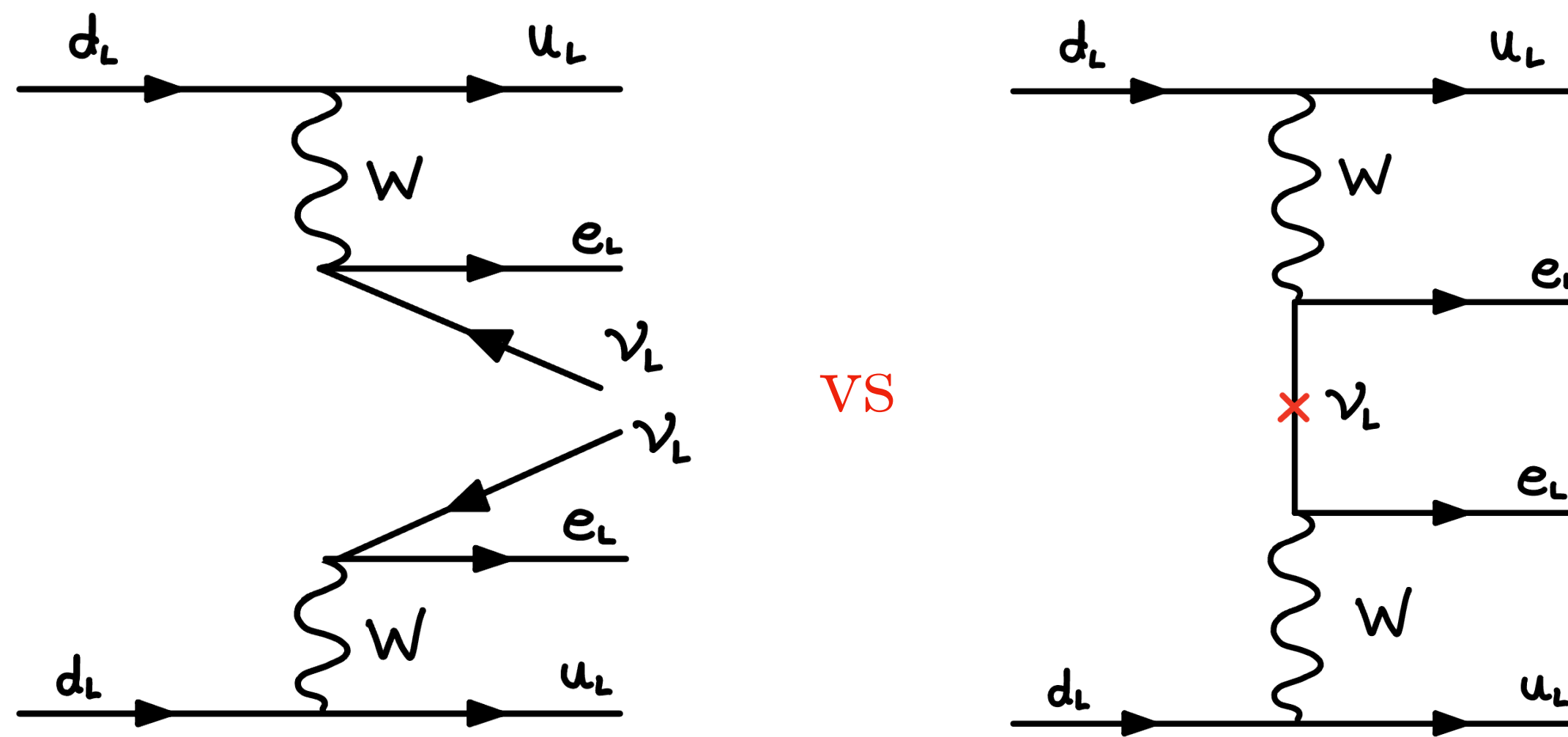
Experimental searches



Lepton Number Violation (LNV)

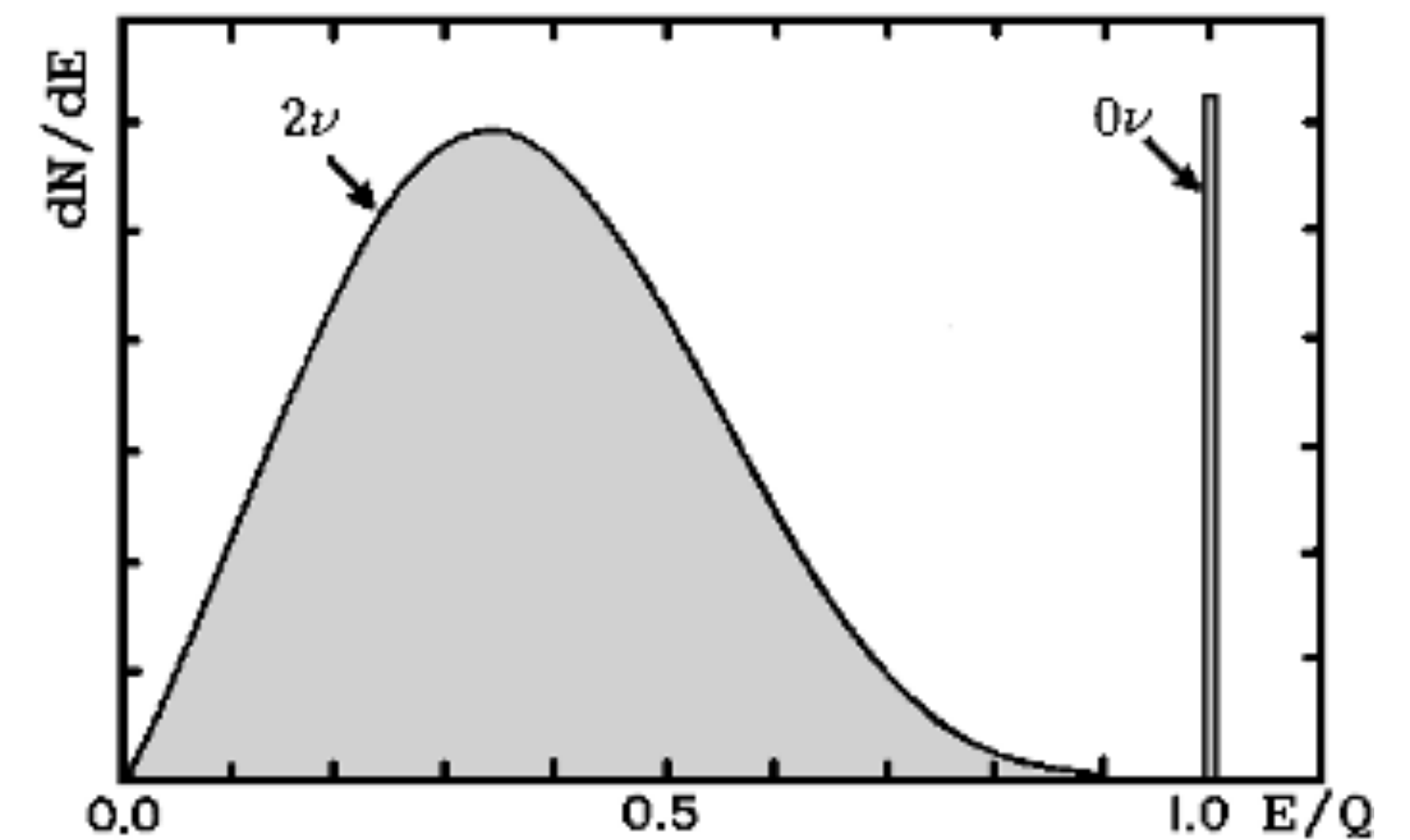
❖ Neutrinoless double-beta decay ($0\nu\beta\beta$)

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VS

Experimental searches



Half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{g_A^4 G_{01}}{m_e^2} |m_{\beta\beta}|^2 |\mathcal{M}_\nu^{(3)}|^2$$

Phase space factor

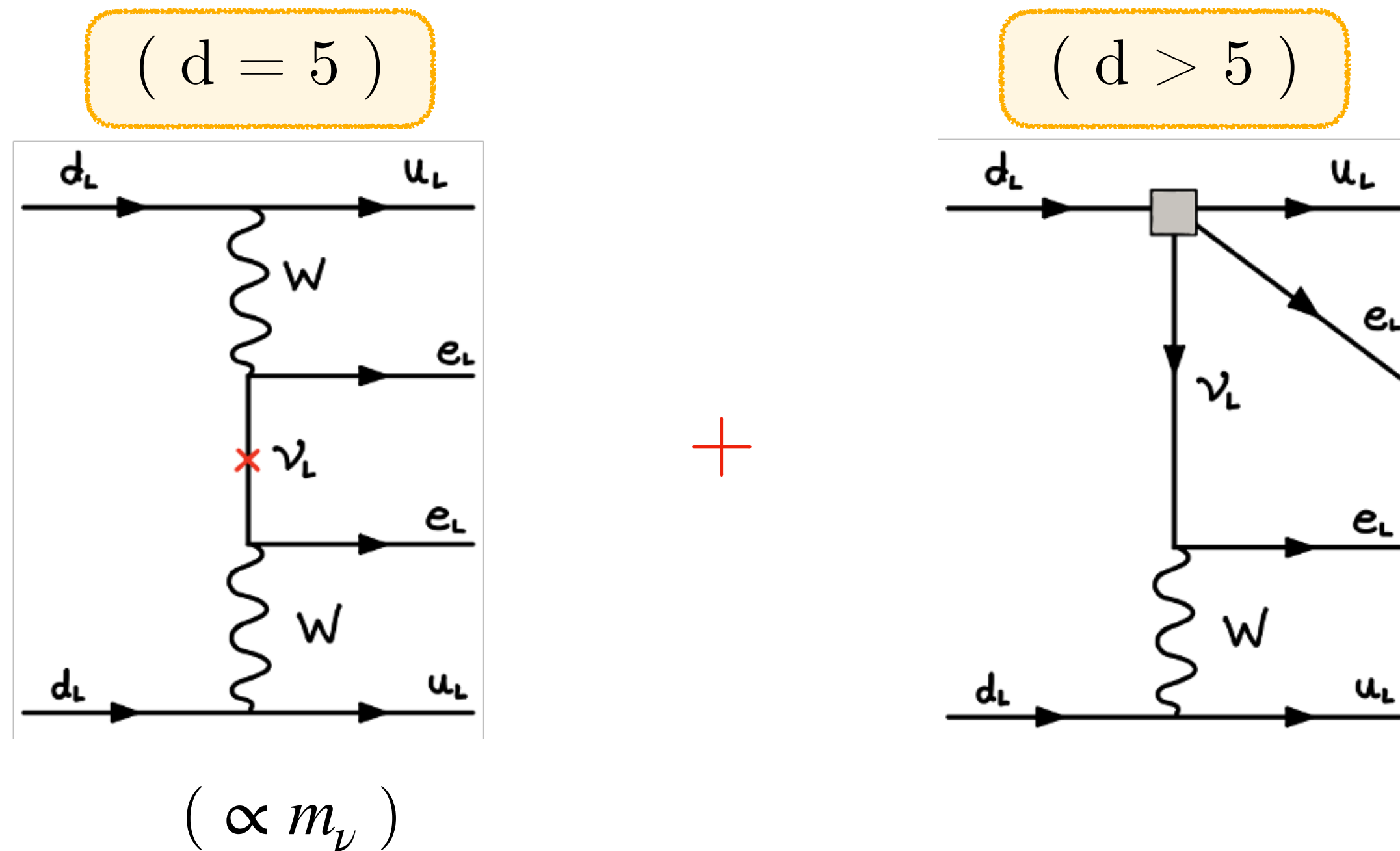
Nuclear Matrix Element

with $m_{\beta\beta} = \sum_i m_{\nu_i} U_{ei}^2$

PMNS

Lepton Number Violation (LNV)

❖ Concrete BSM models for neutrino masses can induce additional contributions to $0\nu\beta\beta$:

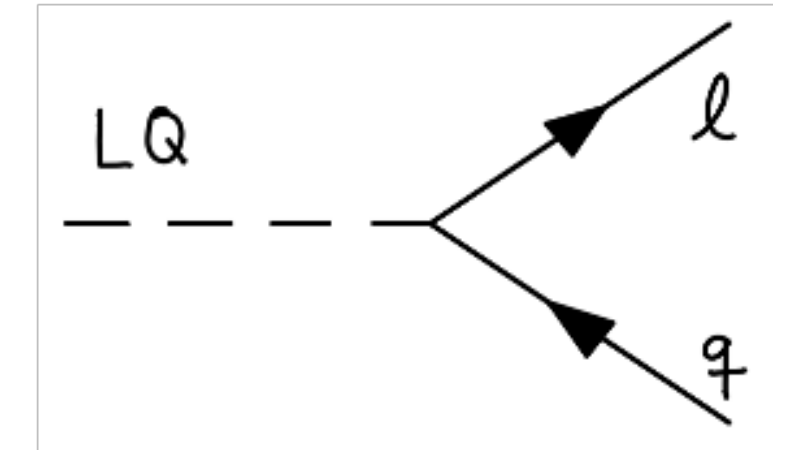


Are $d > 5$ operators suppressed with respect to $d = 5$?

❖ We are going to explore these effects in a minimal Leptoquark (LQ) model

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Leptoquarks and $0\nu\beta\beta$



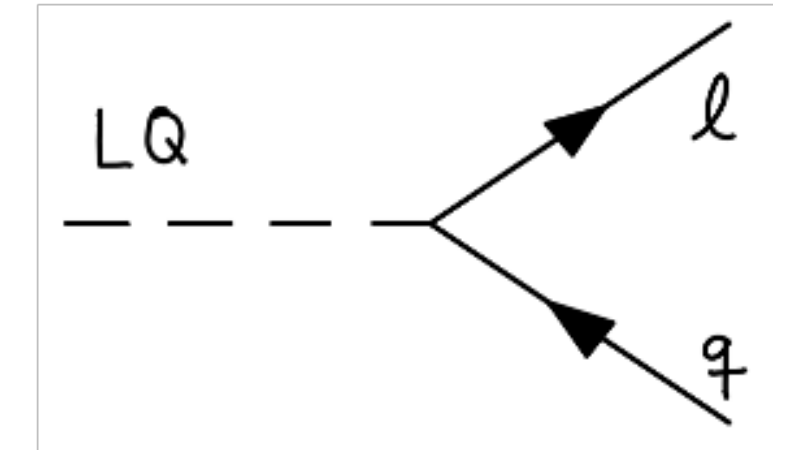
❖ Leptoquarks: colored particles that couple to quarks and leptons

❖ Models: $S_3 \sim (\bar{3}, 3, 1/3)$ and $\tilde{R}_2 \sim (3, 2, 1/6)$ or $S_1 \sim (\bar{3}, 1, 1/3)$ and $\tilde{R}_2 \sim (3, 2, 1/6)$

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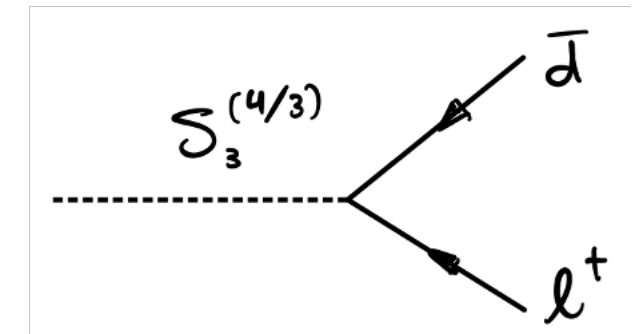
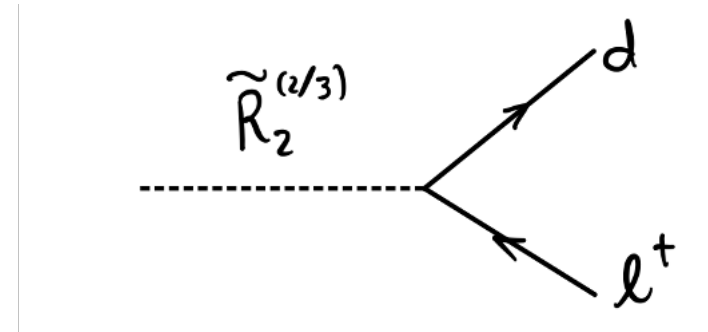
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$$\mathcal{L}_{\tilde{R}_2 \& S_3} \supset (D_\mu \tilde{R}_2)^\dagger (D_\mu \tilde{R}_2) + (D_\mu S_3^a)^\dagger (D_\mu S_3^a) - m_{\tilde{R}_2}^2 \tilde{R}_2^\dagger \tilde{R}_2 - m_{S_3}^2 S_3^{a\dagger} S_3^a$$

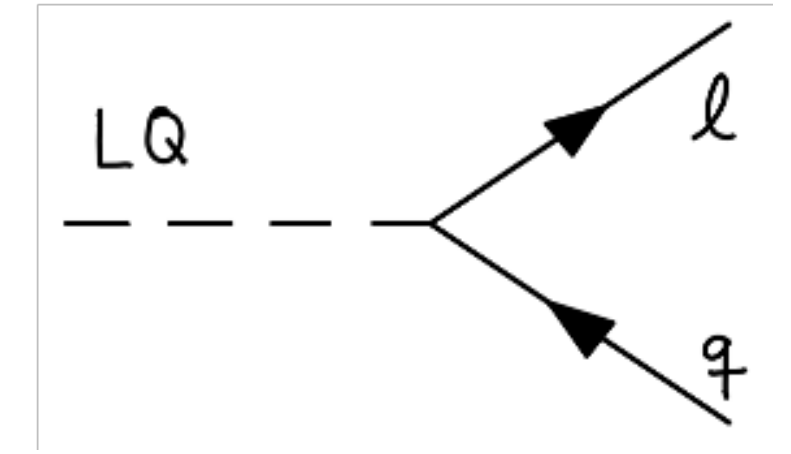
$$y_{3L}^{ij} \overline{Q}_i^C i\tau_2 (\tau^a S_3^a) L_j - y_{2L}^{ij} \bar{d}_{Ri} \tilde{R}_2 i\tau_2 L_j - \lambda_3 \tilde{R}_2^\dagger (\tau^a S_3^a)^\dagger H + \text{h.c.}$$

Mixing induces
Lepton Number Violation



$$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad L = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \quad \tilde{R}_2 = \begin{pmatrix} \tilde{R}_2^{(2/3)} \\ \tilde{R}_2^{(-1/3)} \end{pmatrix} \quad S_3 = \begin{pmatrix} S_3^{(4/3)} \\ S_3^{(1/3)} \\ S_3^{(-2/3)} \end{pmatrix}$$

Leptoquarks and $0\nu\beta\beta$

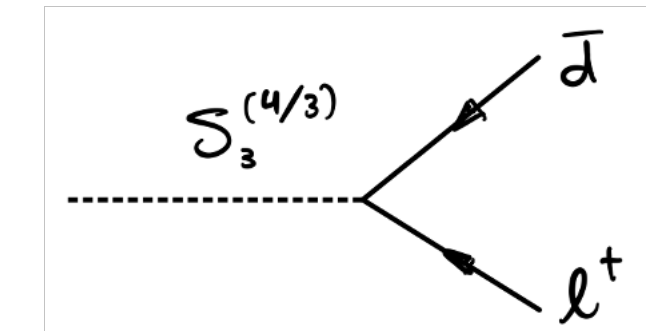
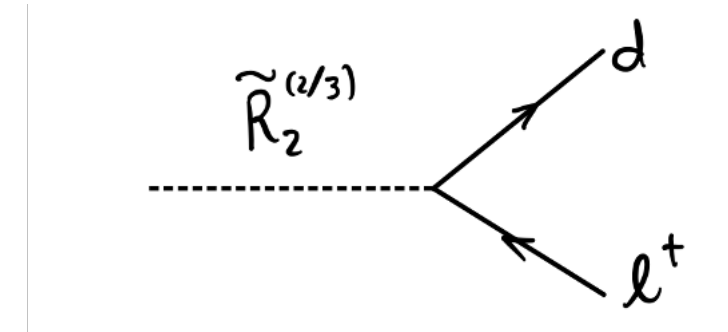


❖ Leptoquarks: colored particles that couple to quarks and leptons

❖ Models: $S_3 \sim (\bar{3}, 3, 1/3)$ and $\tilde{R}_2 \sim (3, 2, 1/6)$ or $S_1 \sim (\bar{3}, 1, 1/3)$ and $\tilde{R}_2 \sim (3, 2, 1/6)$

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Mixing induces
Lepton Number Violation

❖ Interaction to mass basis:

$$f_L \rightarrow U_{f_L} f_L, \quad f_R \rightarrow U_{f_R} f_R, \quad \text{where } f \in \{\nu, \ell, d, u\}$$

$$V_{\text{CKM}} \equiv V = U_{u_L}^\dagger U_{d_L}$$

$$U_{\text{PMNS}} \equiv U = U_{\ell_L}^\dagger U_{\nu_L}$$

$$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad L = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \quad \tilde{R}_2 = \begin{pmatrix} \tilde{R}_2^{(2/3)} \\ \tilde{R}_2^{(-1/3)} \end{pmatrix} \quad S_3 = \begin{pmatrix} S_3^{(4/3)} \\ S_3^{(1/3)} \\ S_3^{(-2/3)} \end{pmatrix}$$

[C. K Chua et al. Phys. Lett. B, 479]
[U. Mahanta Phys. Rev D, 62]

Neutrino masses

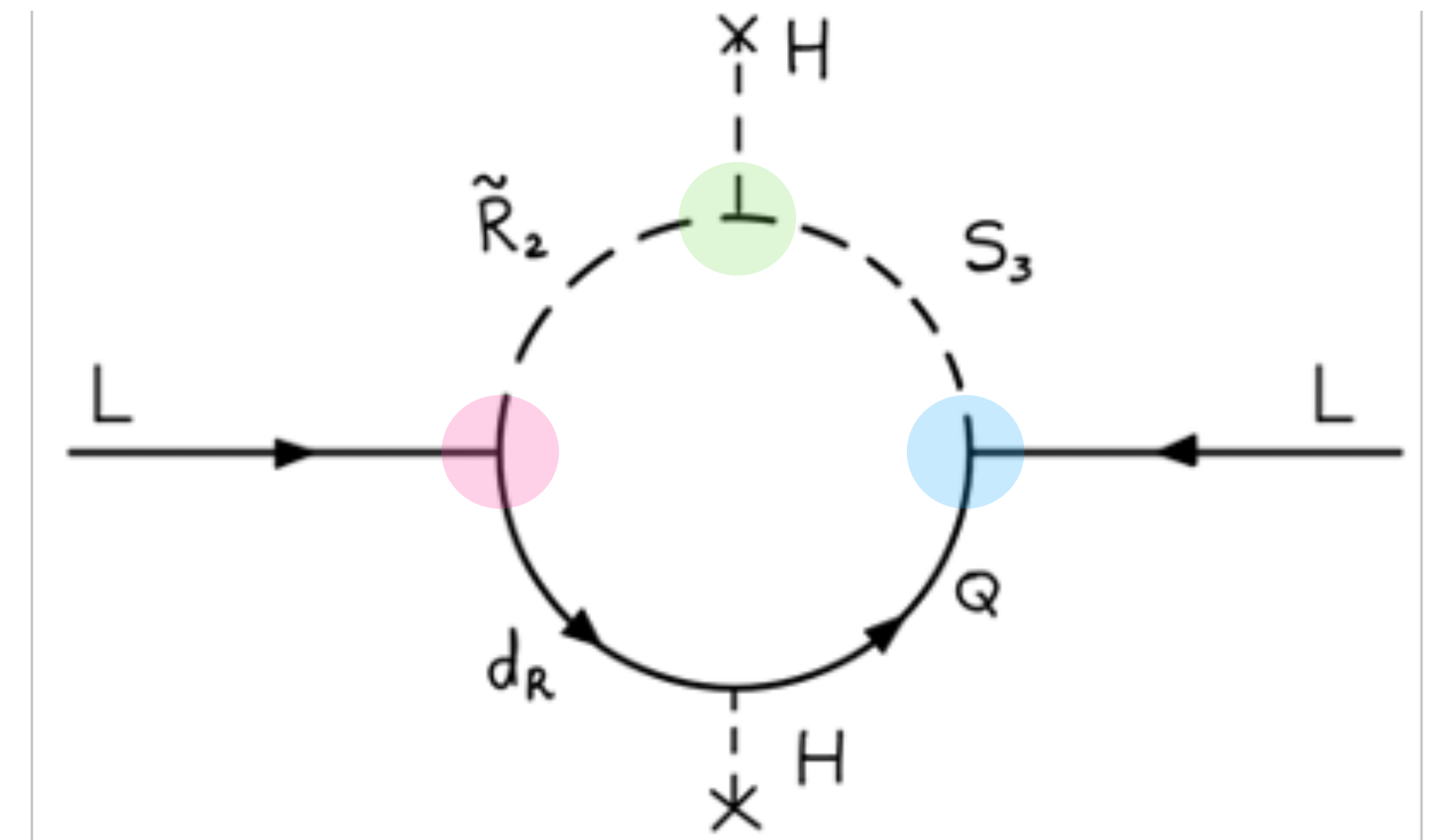
❖ $Q = -1/3$ components of LQs can mix to generate neutrino masses

$$\mathcal{L}_{\tilde{R}_2 \& S_3} \supset (D_\mu \tilde{R}_2)^\dagger (D_\mu \tilde{R}_2) + (D_\mu S_3^a)^\dagger (D_\mu S_3^a) - m_{\tilde{R}_2}^2 \tilde{R}_2^\dagger \tilde{R}_2 - m_{S_3}^2 S_3^{a\dagger} S_3^a$$

$$y_{3L}^{ij} \overline{Q_i^C} i\tau_2 (\tau^a S_3^a) L_j - y_{2L}^{ij} \bar{d}_{Ri} \tilde{R}_2 i\tau_2 L_j - \lambda_3 \tilde{R}_2^\dagger (\tau^a S_3^a)^\dagger H + \text{h.c.}$$

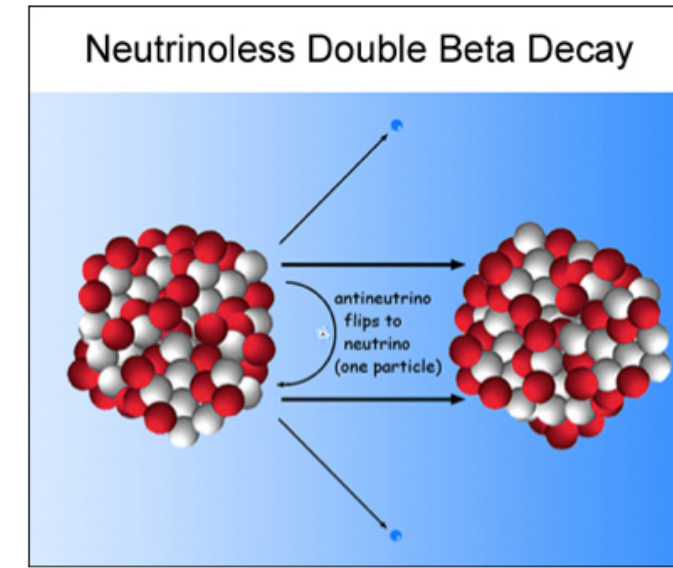
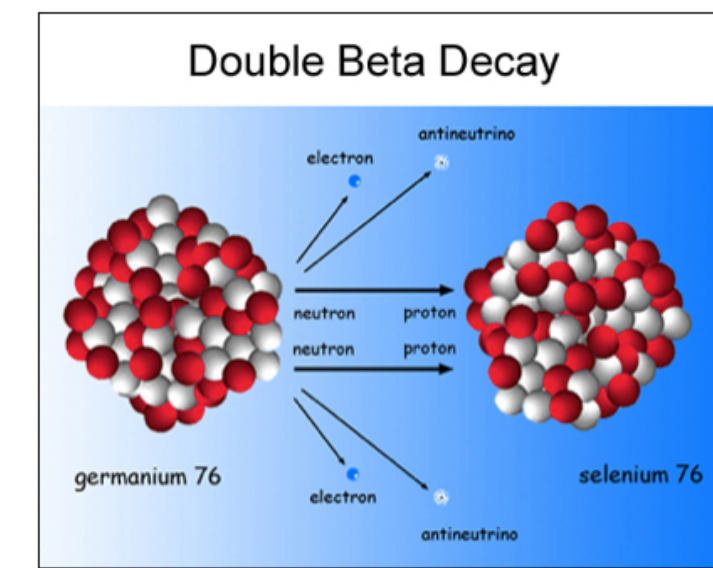
$$m_\nu \simeq - \frac{3\lambda_3}{16\sqrt{2}\pi^2} \frac{v^2}{M^2} \left(y_{2L}^T \cdot \hat{y}_d \cdot y_{3L} + y_{3L}^T \cdot \hat{y}_d \cdot y_{2L} \right)$$

$$m_{\tilde{R}_2} \sim m_{S_{1,3}} \sim M \gg v$$

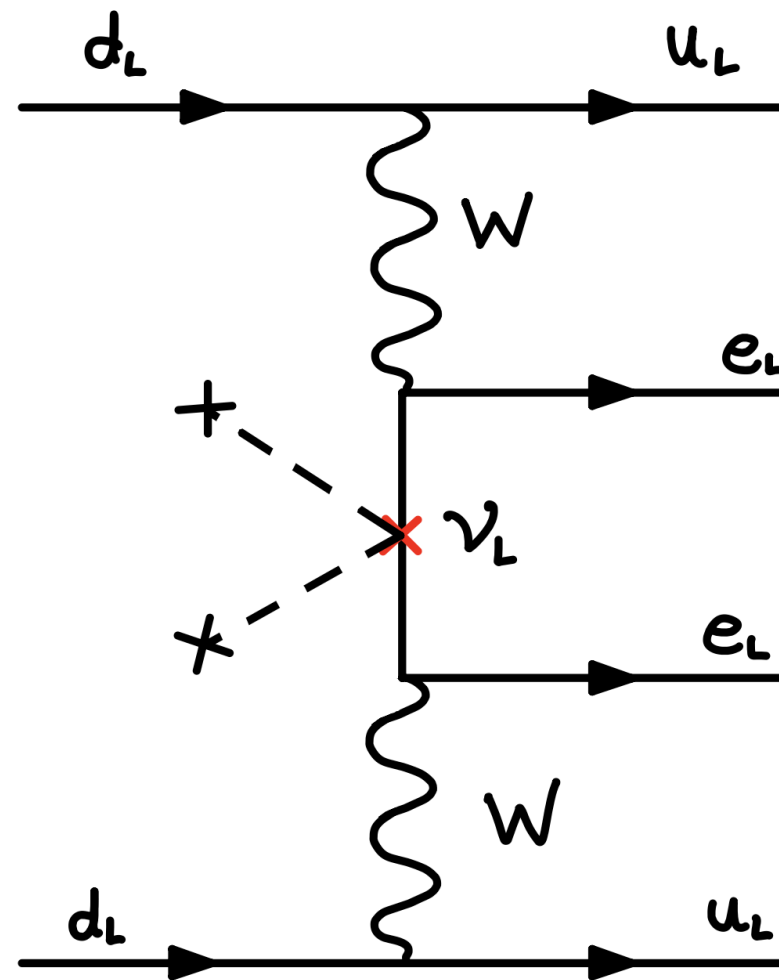


Neutrinoless double-beta decay

❖ Contributions from $d = 5$ and $d = 7$ effective operators

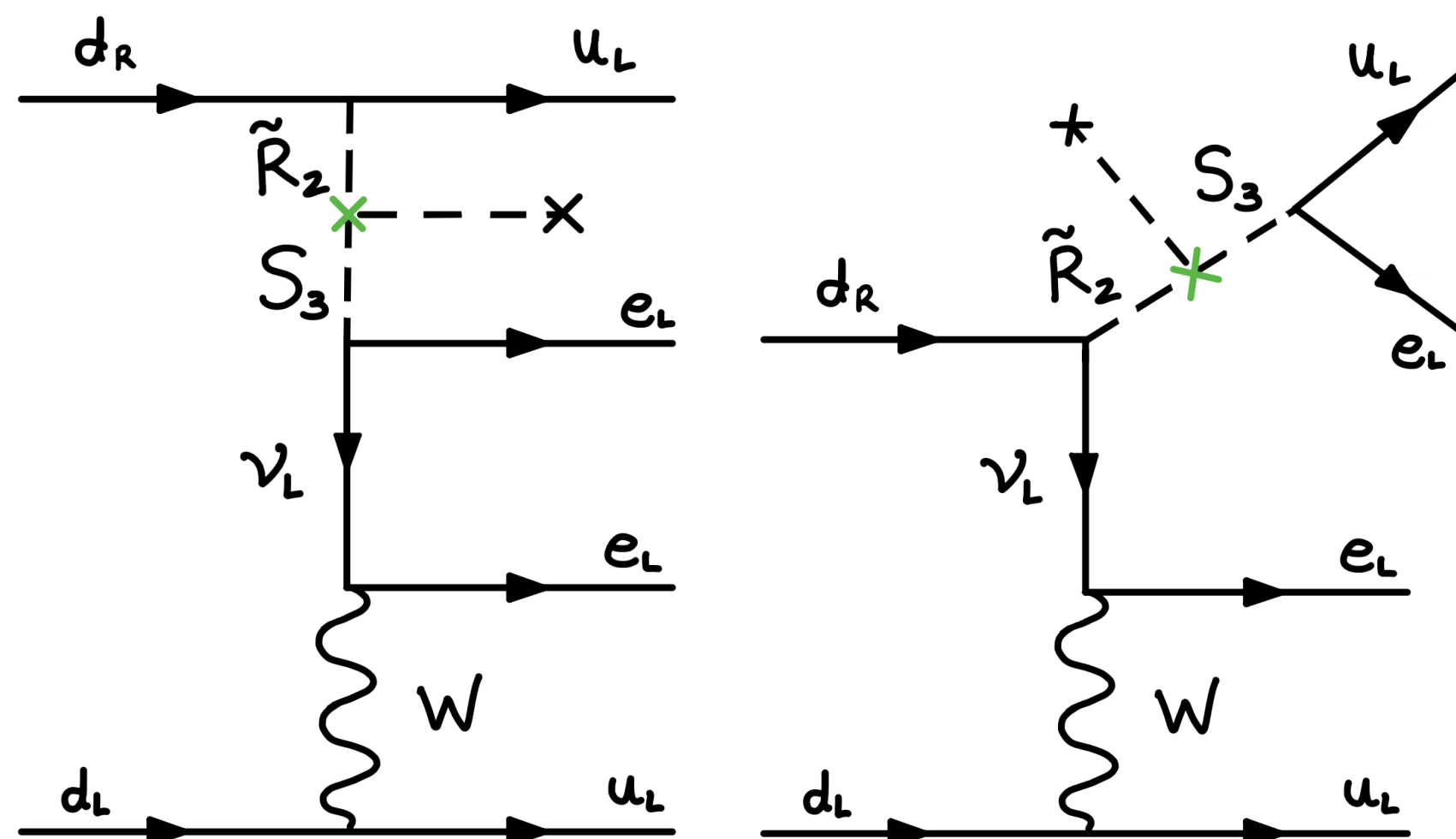


$d = 5$ contribution
(loop - level)



$(\propto m_\nu)$

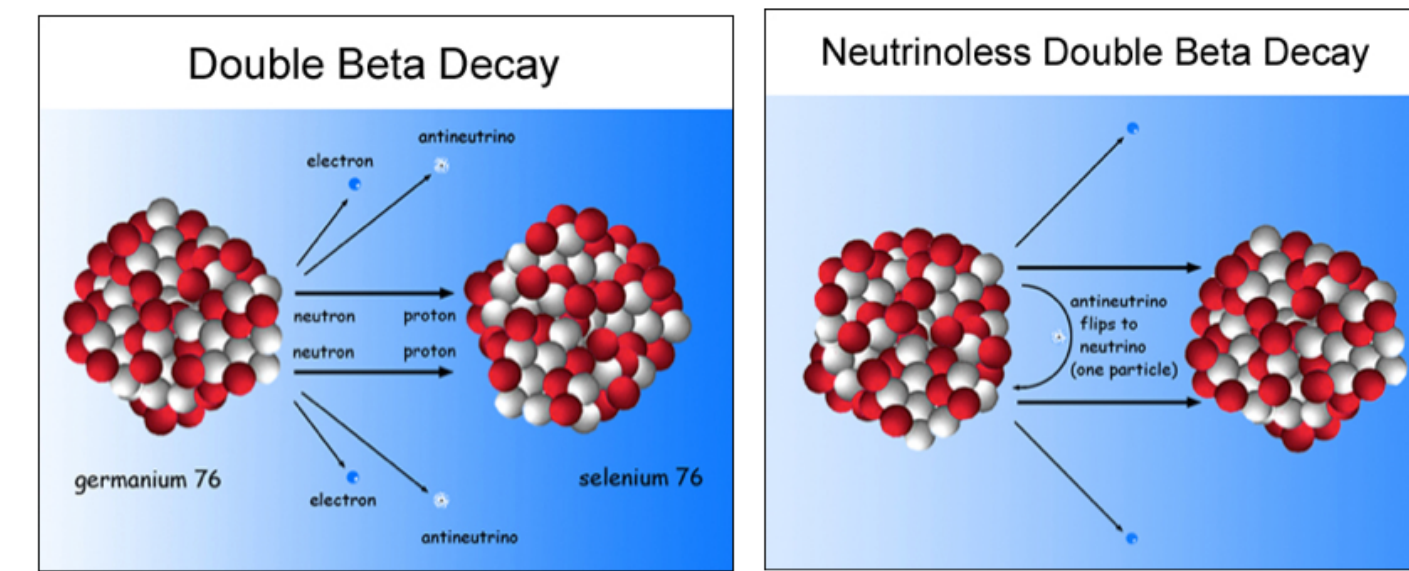
$d = 7$ contributions
(Tree - level)



Chirality-enhanced ($\propto E/m_\nu$) contributions
to $0\nu\beta\beta$, with $E \sim 100$ MeV

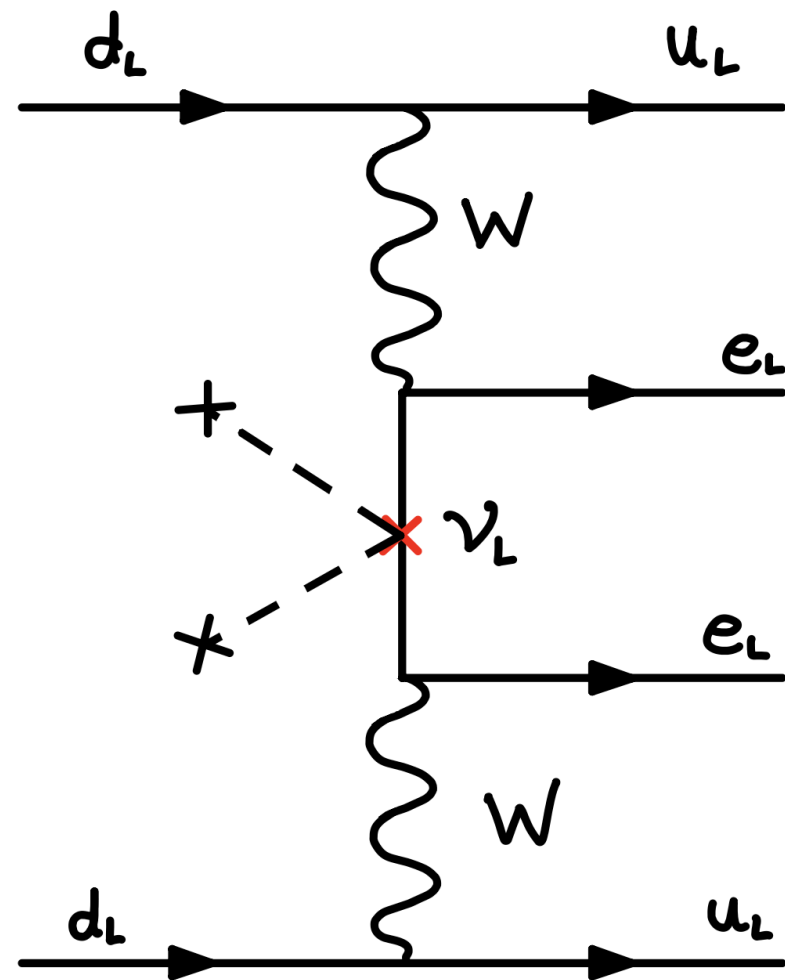
$S_3 - \tilde{R}_2$
Leptoquark mixing
through λ_3 breaks
lepton number

Neutrinoless double-beta decay



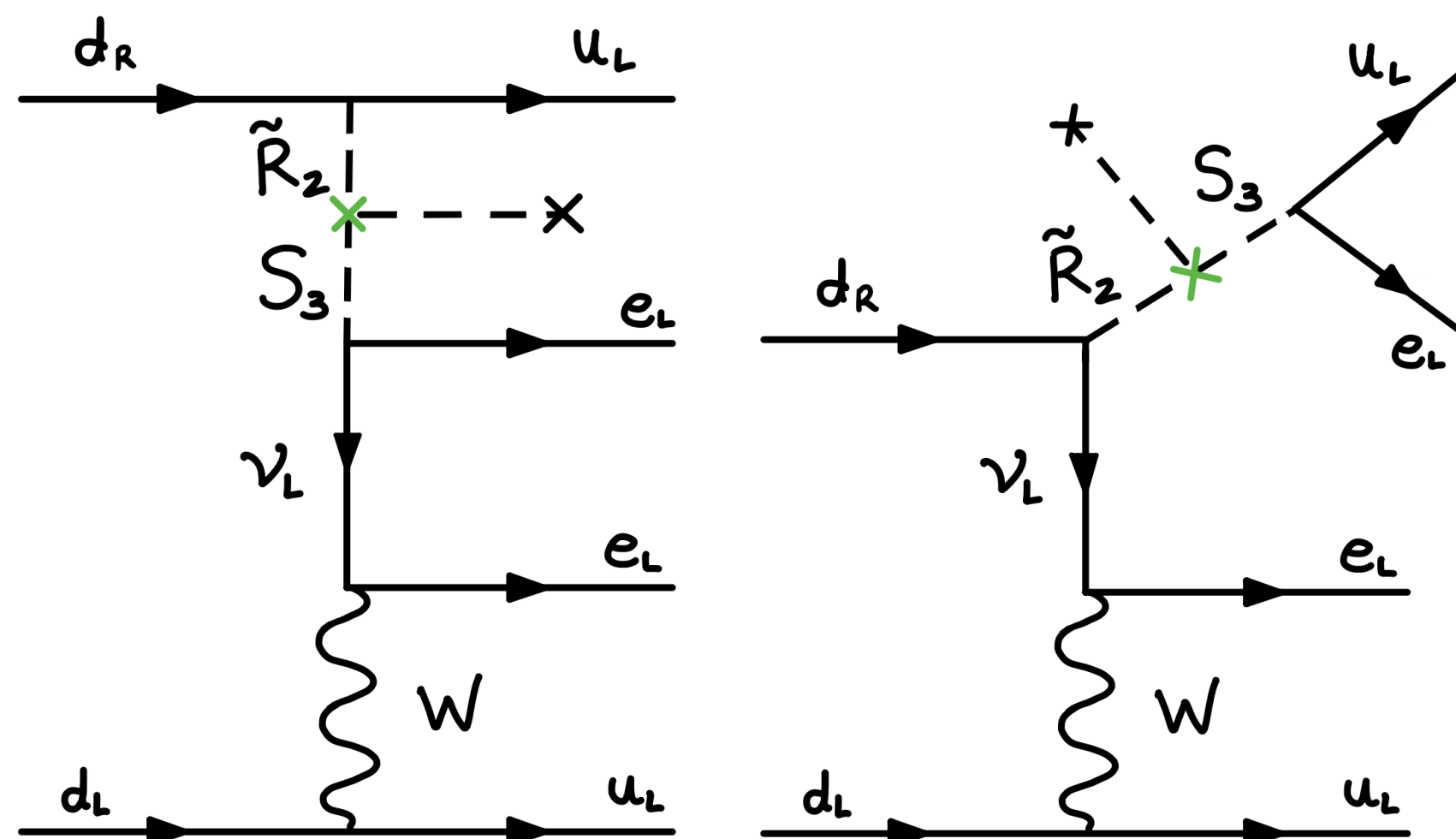
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$S_3 - \tilde{R}_2$
Leptoquark mixing
through λ_3 breaks
lepton number

Upper limits:
 $S_3 - \tilde{R}_2$ model:
 $\frac{|\lambda_3 y'_{3L}{}^{11} y'_{2L}{}^{11}|}{M^4} \lesssim (340 \text{ TeV})^{-3}$

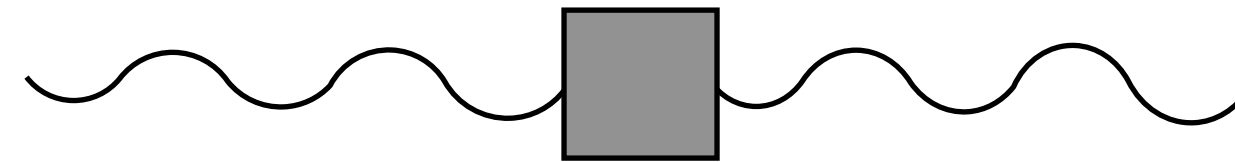
$y'_L = y_L U_{eL}$ where U_{eL} is the
left-handed charged lepton

❖ Effective Field theory approach

Phenomenology

❖ Electroweak Precision Tests

- T parameter: corrections to the gauge-boson two point functions



Scalar Leptoquarks

- Mass splitting between leptoquarks induces additional contributions to T

Bounds:

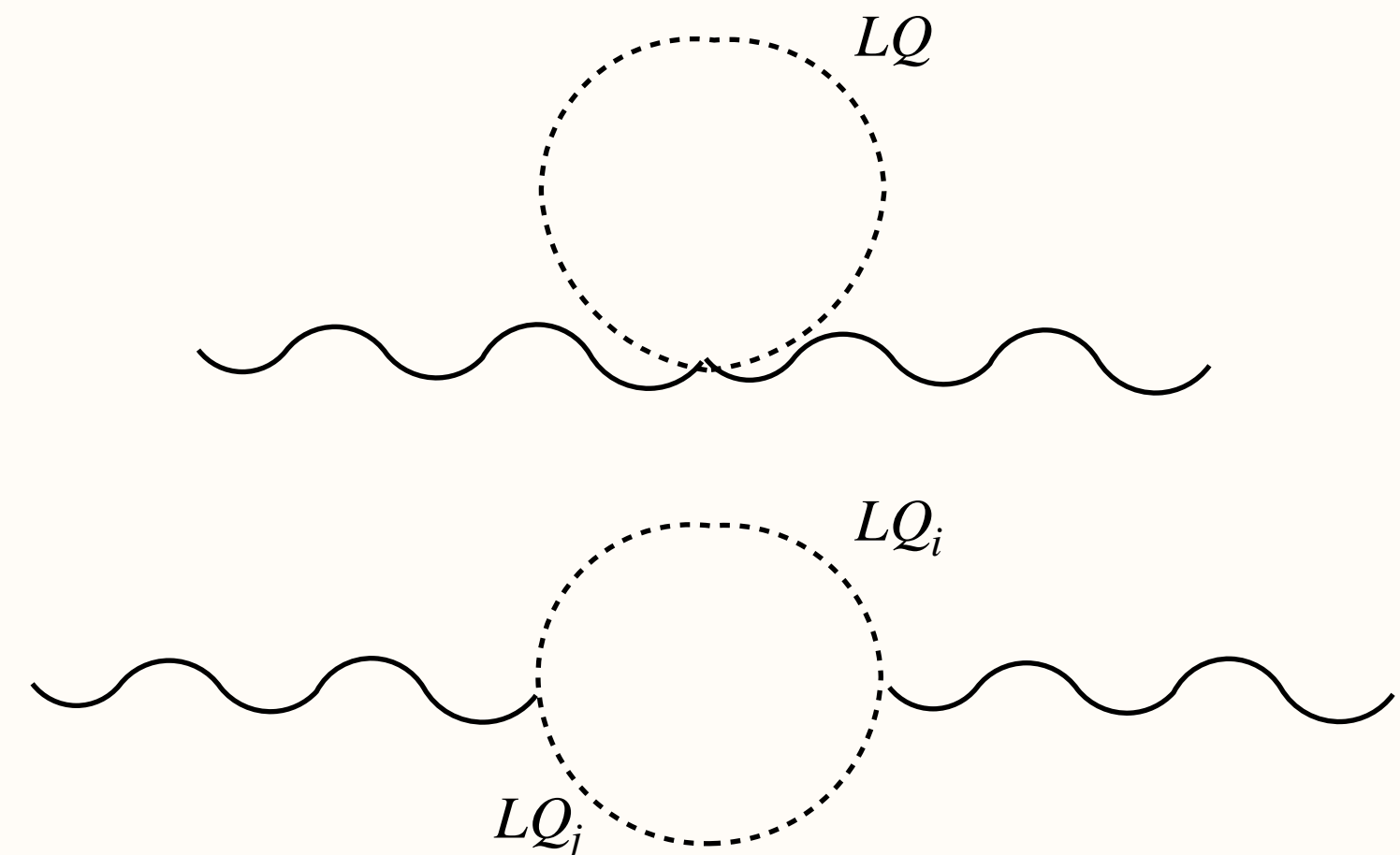
$$T = 0.05 \pm 0.12 \quad \Rightarrow \quad \frac{|\lambda_3|}{M} \lesssim 0.7$$

(Electroweak fit)

\Rightarrow

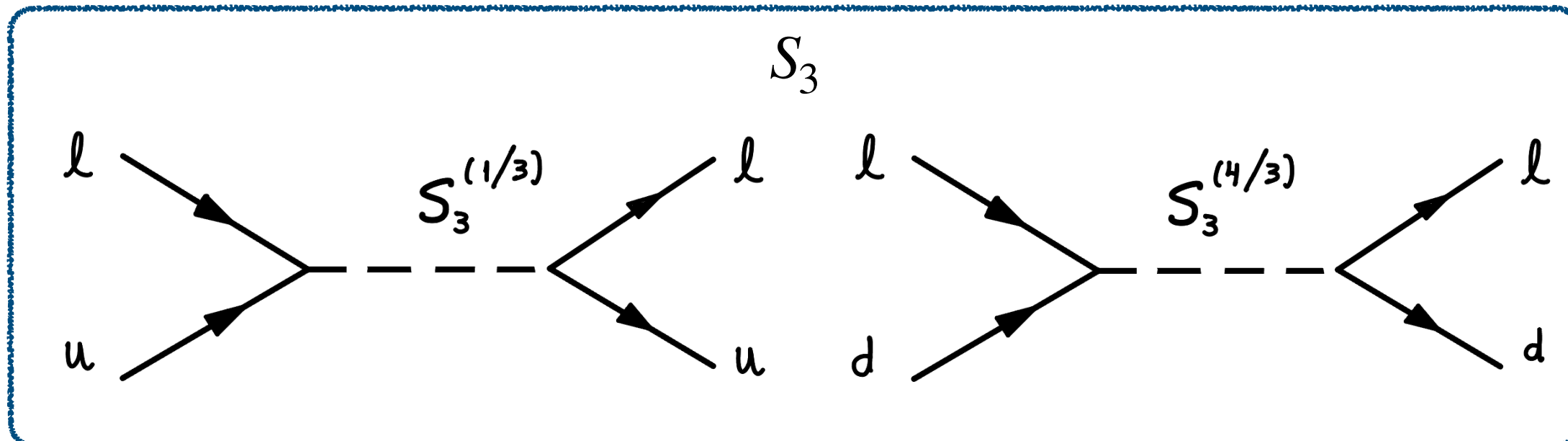
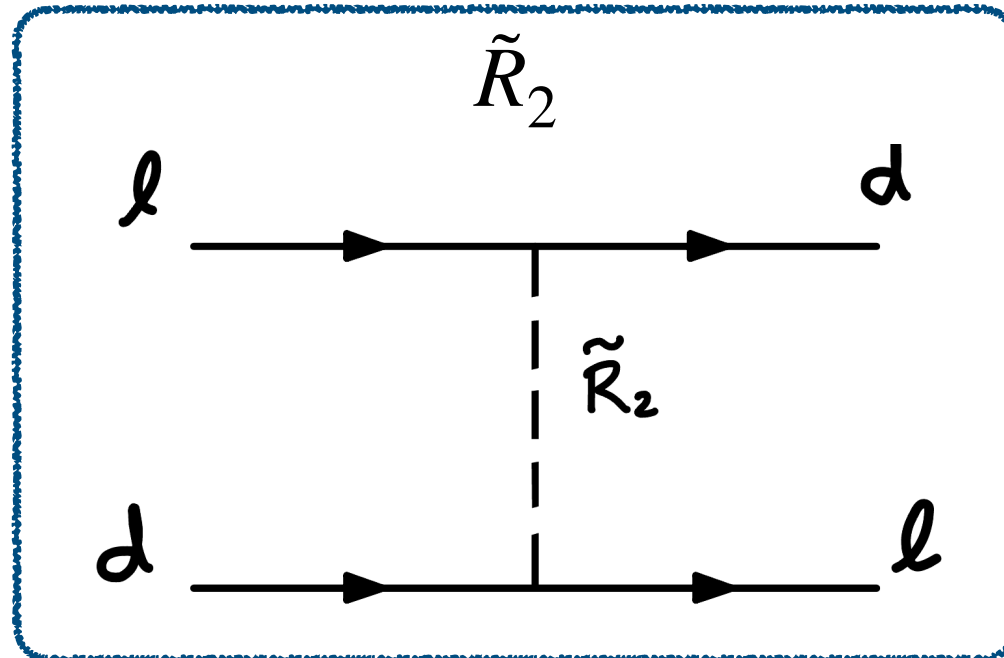
We choose $\lambda_3 = M/2$
in our analysis

New Contributions



Flavor Physics

$$\mu N \rightarrow e N$$



Bounds:

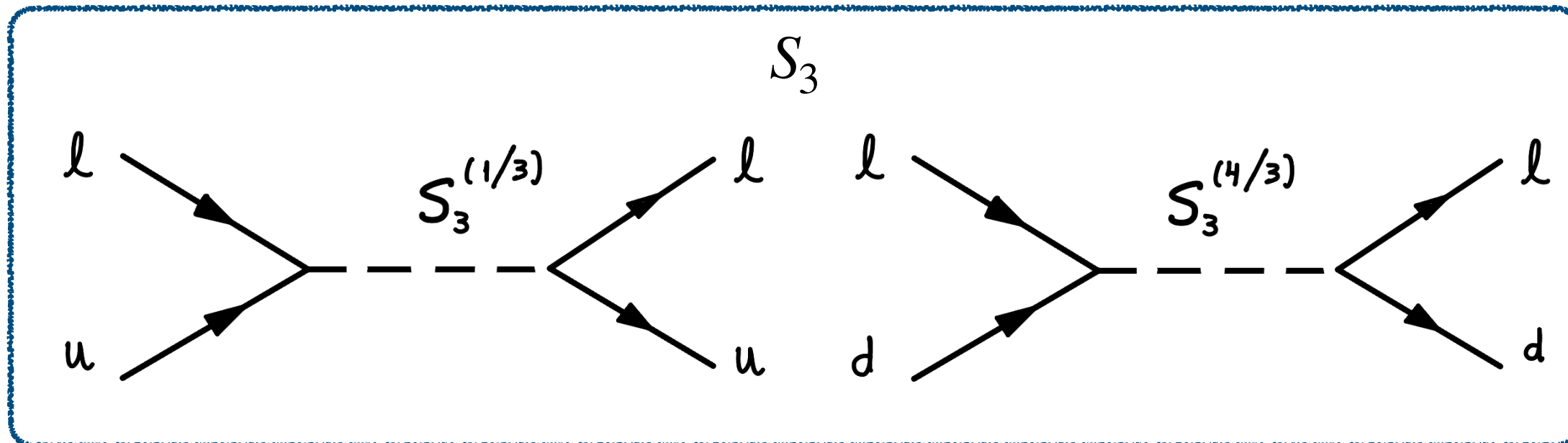
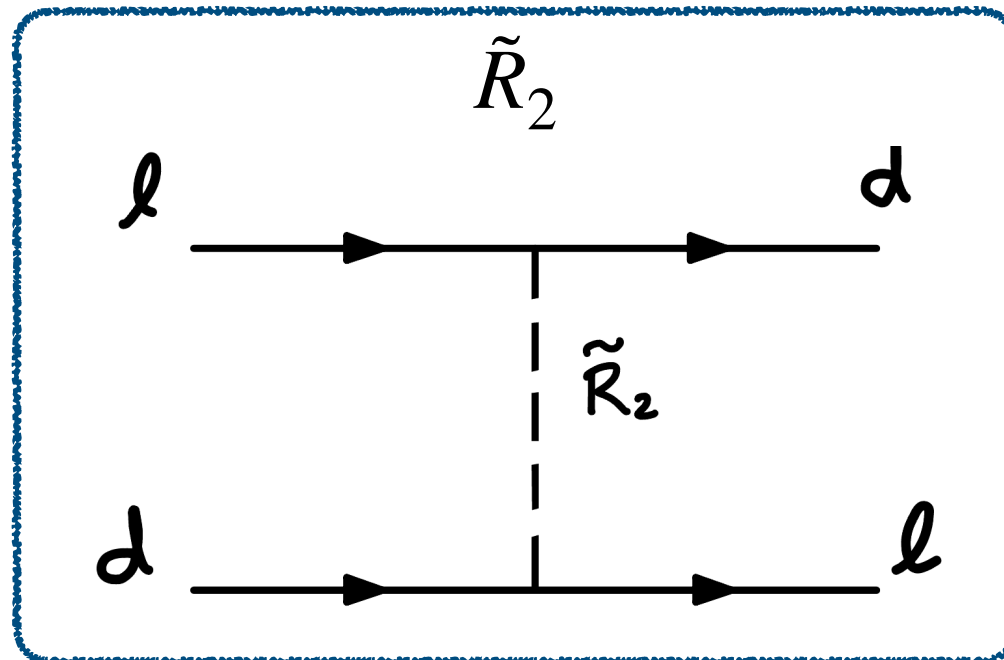
SINDRUM II : $B_{\mu e}^{(Au)} < 7 \times 10^{-13}$ (90% C.L)

$$\frac{|y'_{2L}{}^{12} y'_{2L}{}^{11*}|}{M^2} < (500 \text{ TeV})^{-2}, \quad \frac{|y'_{3L}{}^{12} y'_{3L}{}^{11*}|}{M^2} < (830 \text{ TeV})^{-2},$$

Future Experiments: $B_{\mu e}^{(Al)} < \mathcal{O}(10^{-17})$ (Mu2E and COMET)

Flavor Physics

$$\mu N \rightarrow e N$$



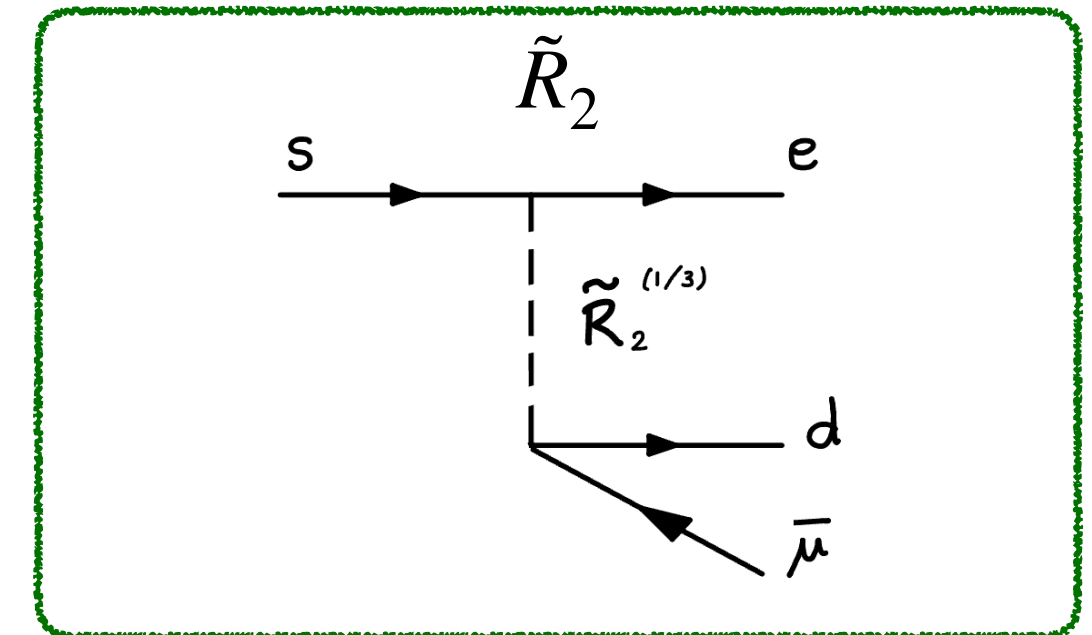
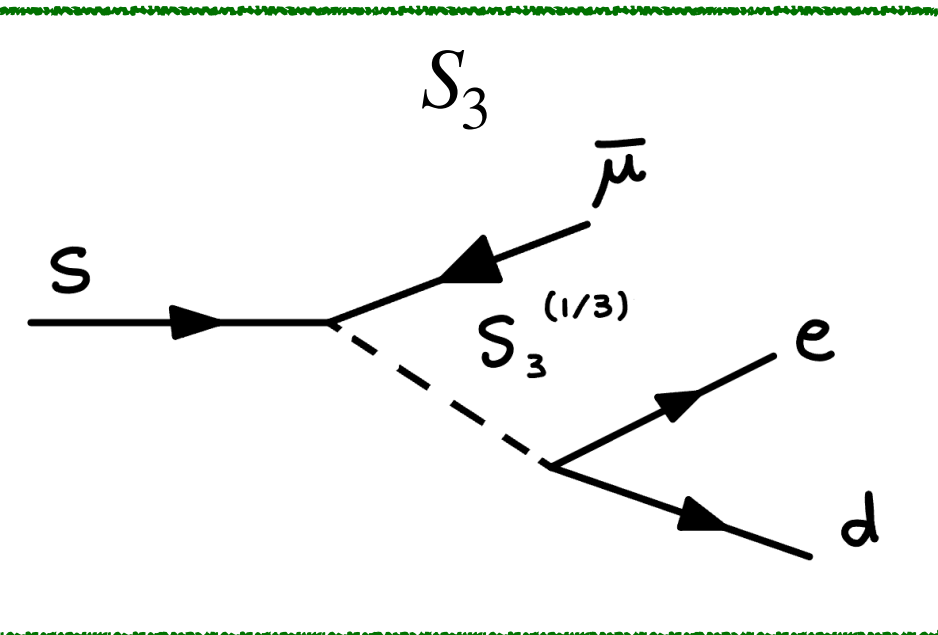
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Future Experiments: $B_{\mu e}^{(Al)} < \mathcal{O}(10^{-17})$ (Mu2E and COMET)

$$K_L \rightarrow \mu^\pm e^\mp \text{ and } K^+ \rightarrow \pi^+ \mu^+ e^-$$



Bounds:

$$B(K_L \rightarrow \mu^\pm e^\mp) < 4.7 \times 10^{-12} \text{ (90\% C.L.)}$$

$$B(K^+ \rightarrow \pi^+ \mu^+ e^-) < 1.3 \times 10^{-11} \text{ (90\% C.L.)}$$

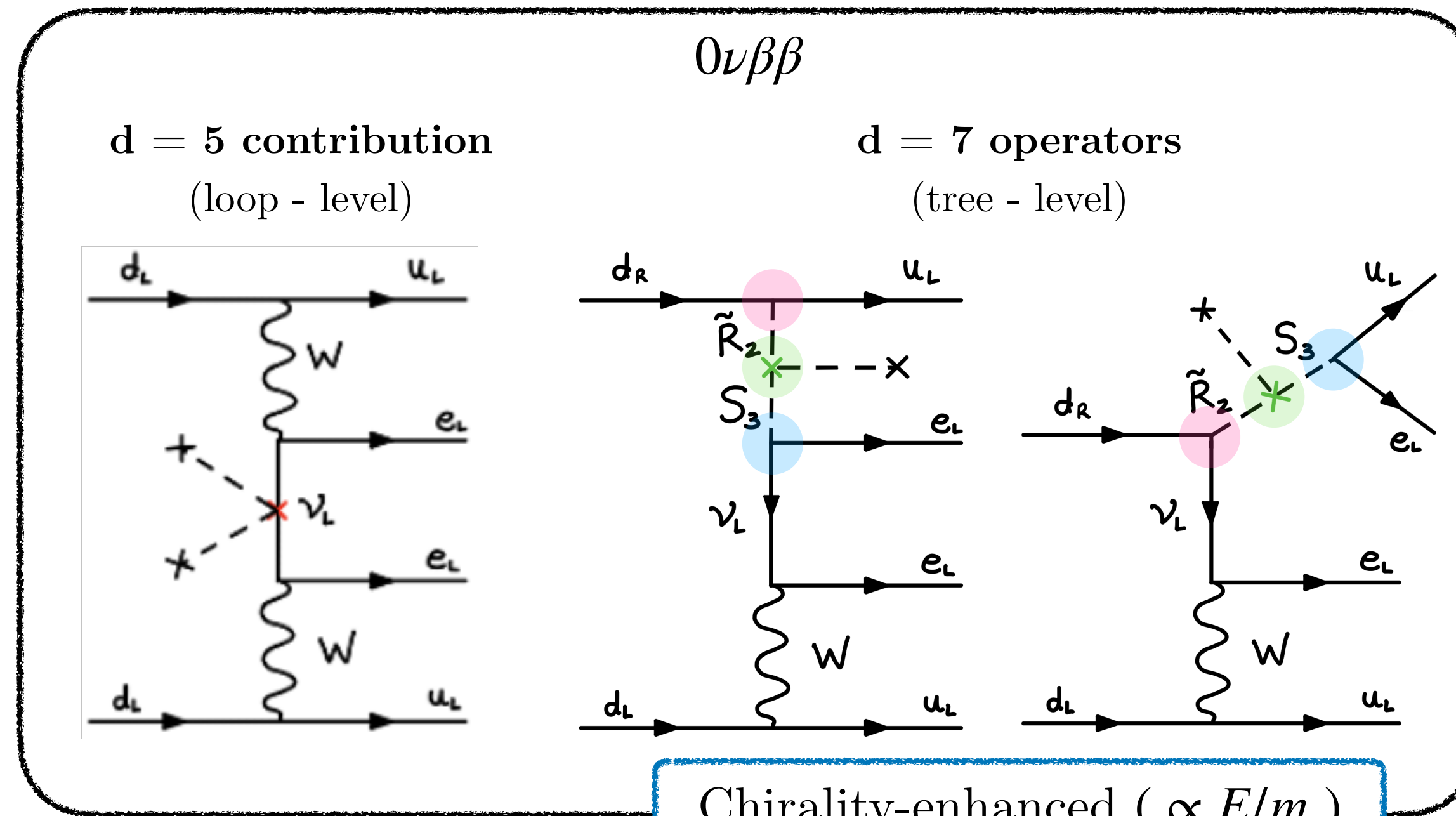
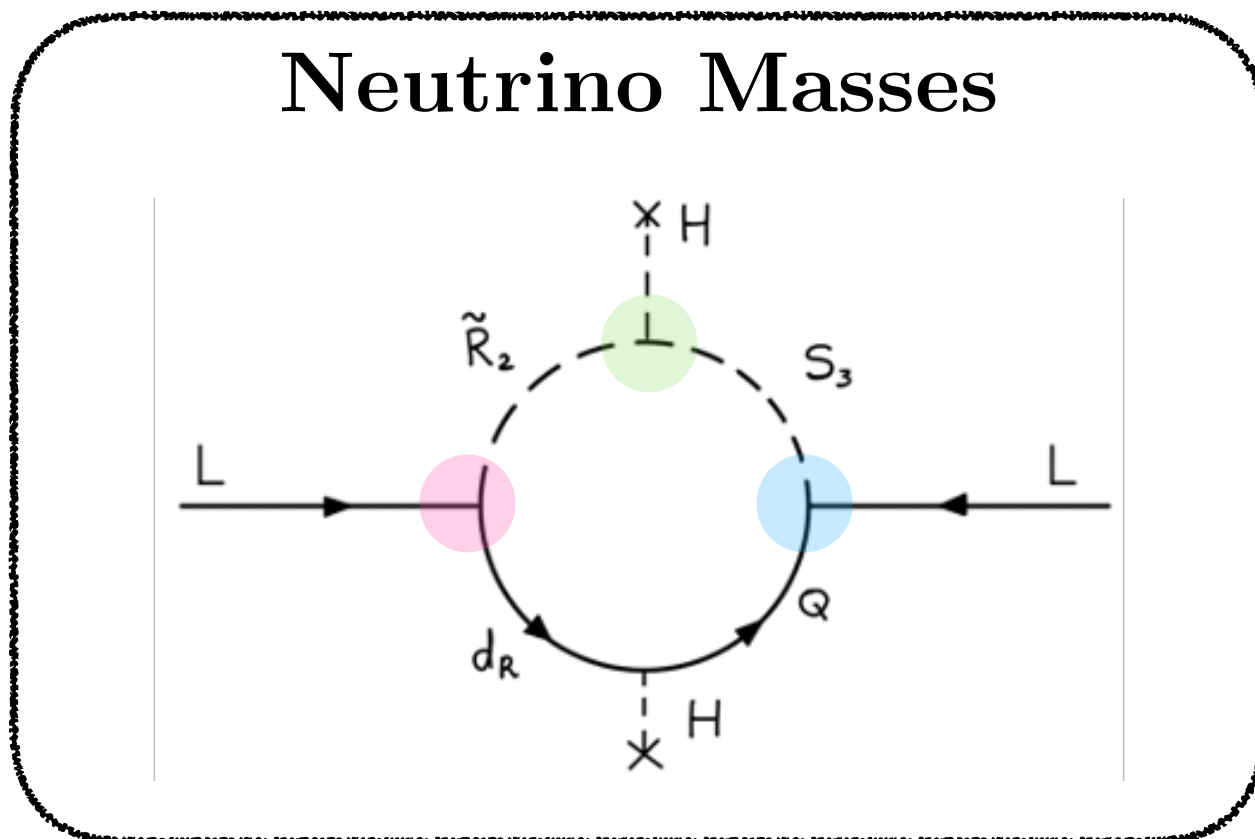
$$\frac{|y'_{2L}{}^{21} y'_{2L}{}^{12*}|}{M^2} < (208 \text{ TeV})^{-2}, \quad \frac{|y'_{3L}{}^{21} y'_{3L}{}^{12*}|}{M^2} < (290 \text{ TeV})^{-2}$$

Recap

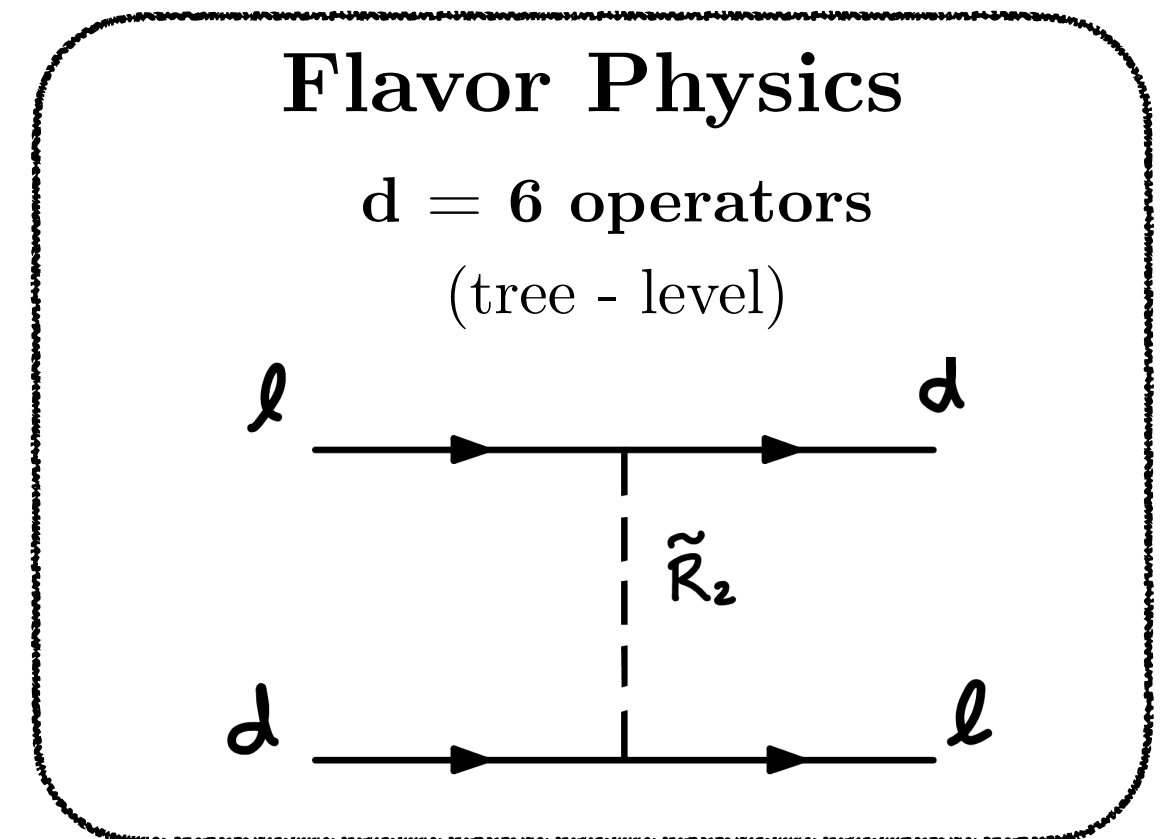
❖ Scalar Leptoquarks with mixing

$$\mathcal{L}_{\tilde{R}_2 \& S_3} \supset (D_\mu \tilde{R}_2)^\dagger (D_\mu \tilde{R}_2) + (D_\mu S_3^a)^\dagger (D_\mu S_3^a) - m_{\tilde{R}_2}^2 \tilde{R}_2^\dagger \tilde{R}_2 - m_{S_3}^2 S_3^{a\dagger} S_3^a$$

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Chirality-enhanced ($\propto E/m_\nu$)
contributions to $0\nu\beta\beta$, with
 $E \sim 100 \text{ MeV}$

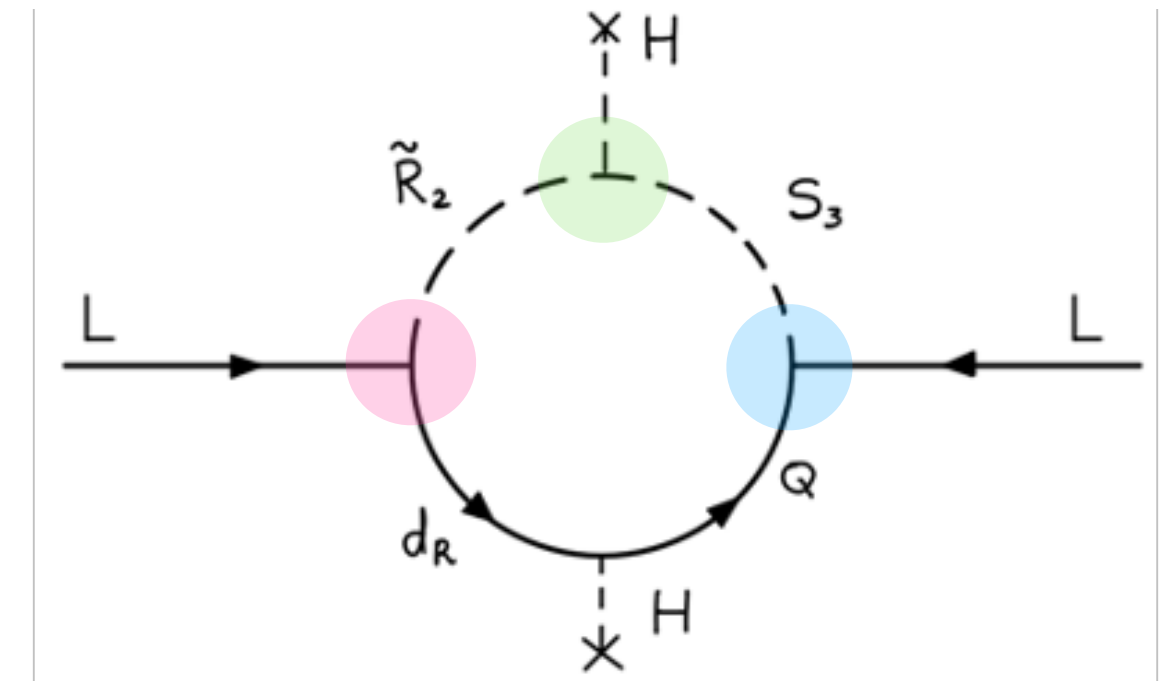


Numerical Results

❖ Neutrino masses

$$m_\nu = -\frac{3\lambda_3}{16\sqrt{2}\pi^2} \frac{v^2}{M^2} \left(y_{2L}^T \cdot \hat{y}_d \cdot y_{3L} + y_{3L}^T \cdot \hat{y}_d \cdot y_{2L} \right)$$

❖ $\lambda_3 = M/2$ and $M = 100$ TeV

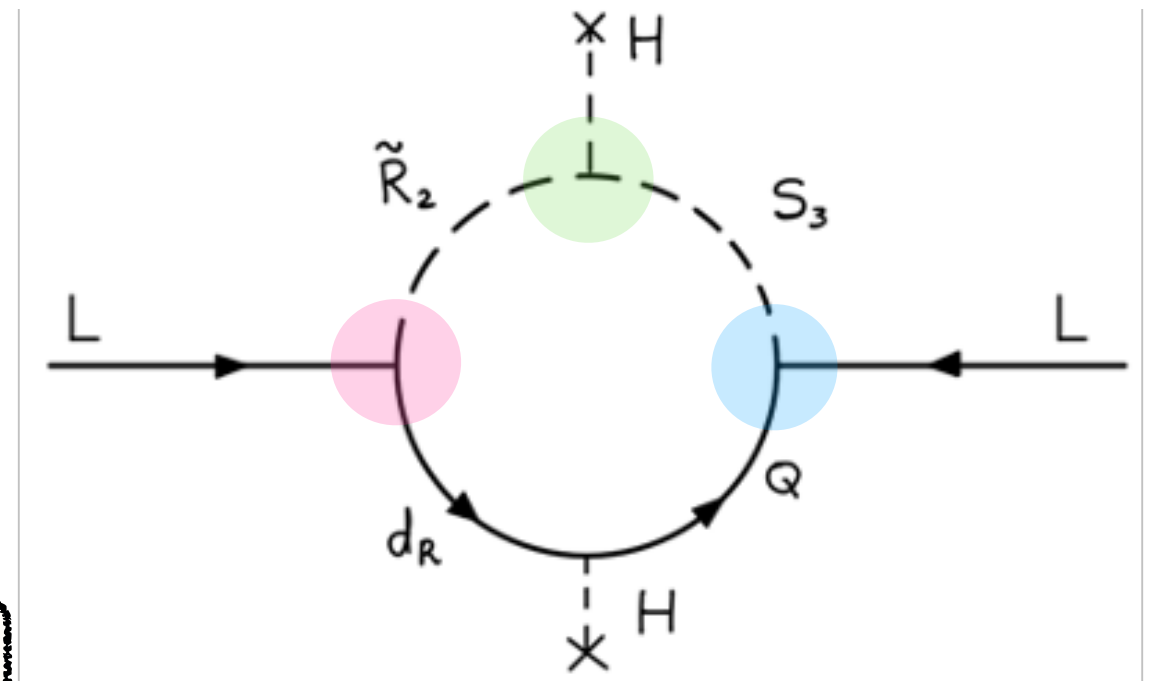


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varied within perturbativity range



❖ $\lambda_3 = M/2$ and $M = 100$ TeV

❖ Requirement that we need to reproduce results from oscillation experiments:

$$\Delta m_{21}^2 = (7.4 \pm 0.2) \times 10^{-5} \text{ eV}^2, \quad |\Delta m_{3\ell}^2| = (2.51 \pm 0.03) \times 10^{-3} \text{ eV}^2, \quad \text{with } \ell = 1 \text{ (2) for NO (IO)}$$

❖ PMNS matrix within the allowed 3σ range

❖ Random Majorana phases in the range $0 \leq \alpha_{1,2} \leq \pi$

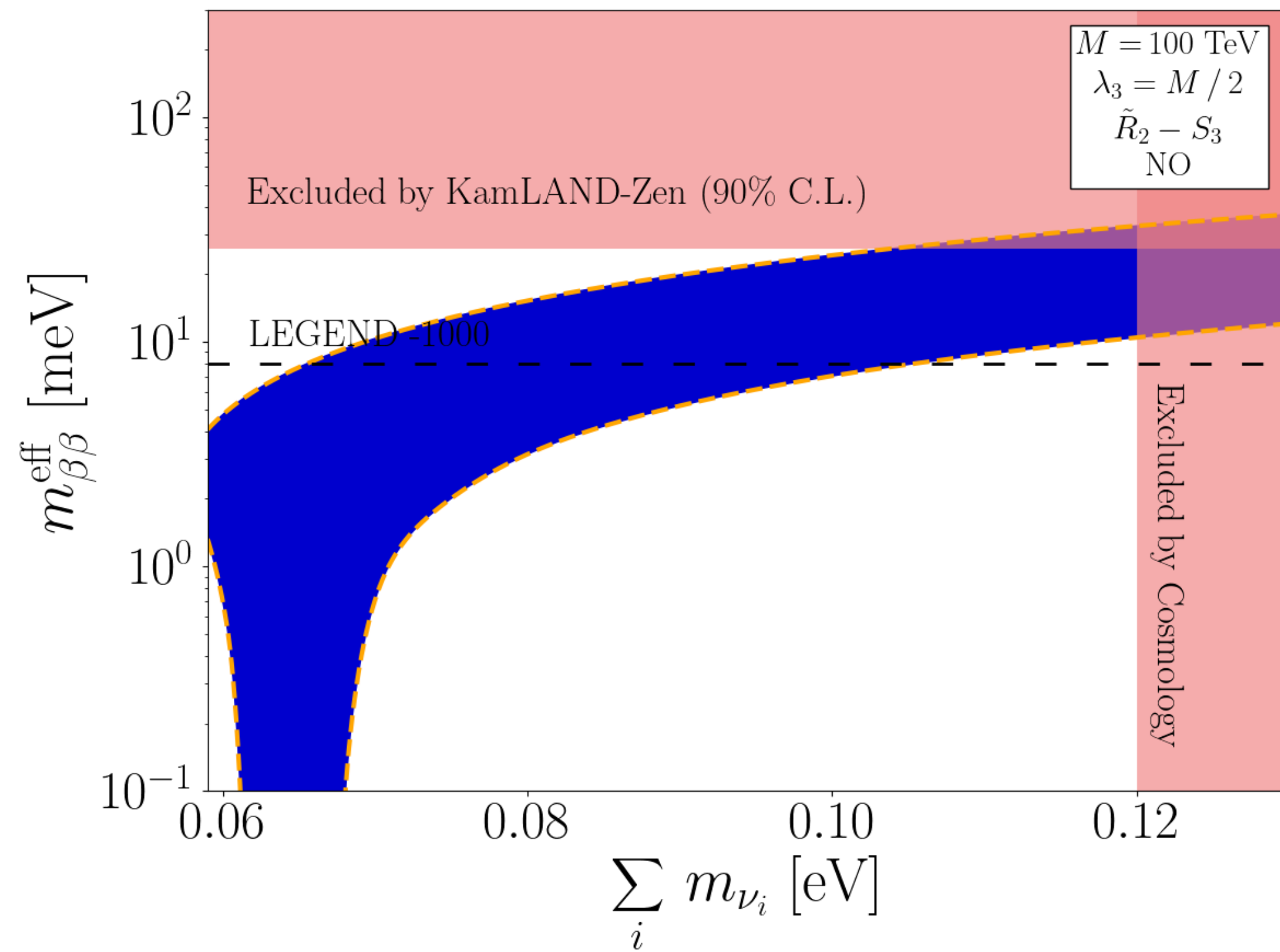
❖ Cosmology: $\sum_i m_{\nu_i} \lesssim 0.12 \text{ eV}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

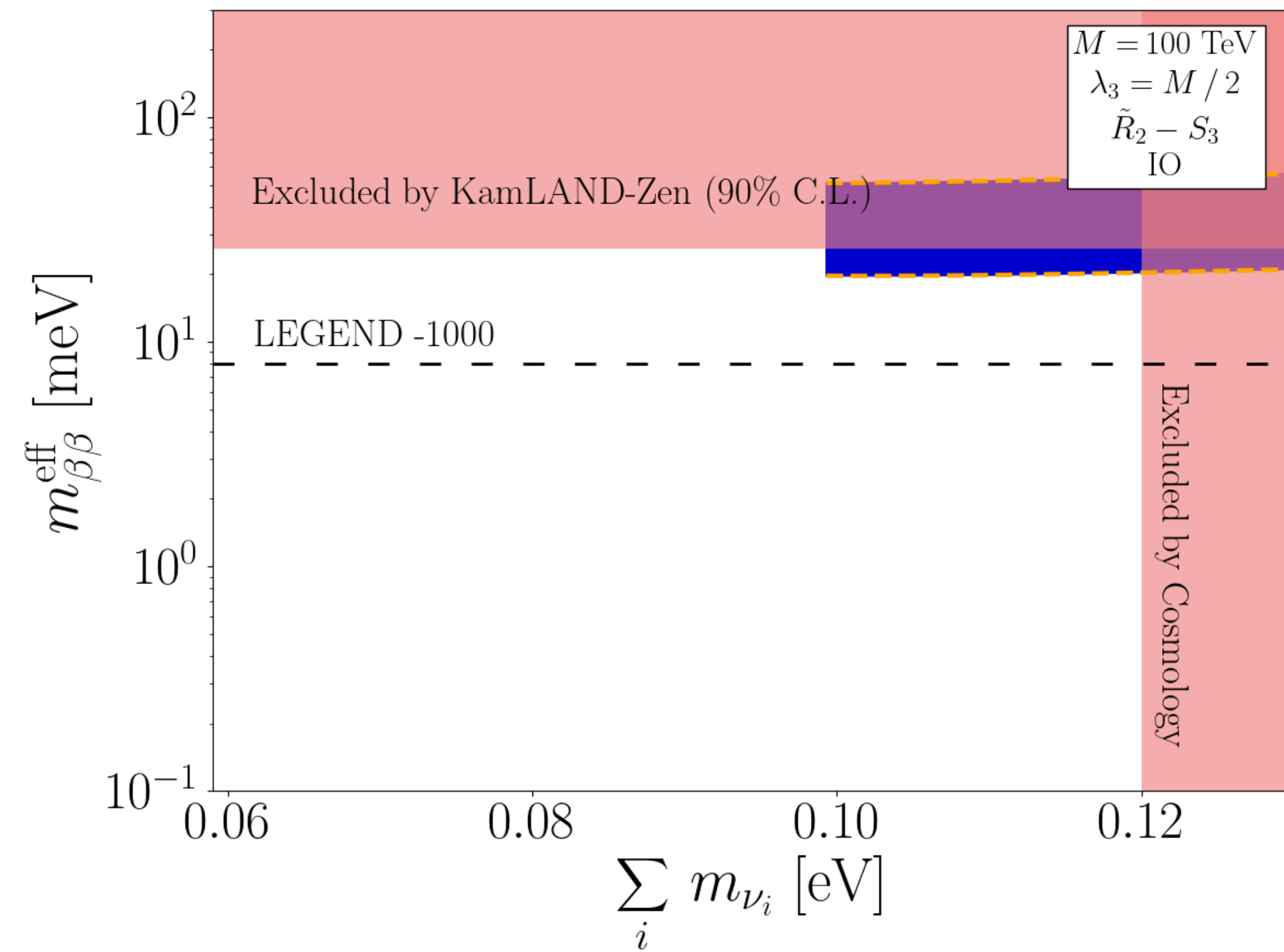
Neutrinoless double-beta decay

$$(m_{\beta\beta}^{\text{eff}})^2 \equiv m_{\beta\beta}^2 + \delta m_{\beta\beta}^{2(\text{int})} + \delta m_{\beta\beta}^{2(\text{LQ})} \quad ; \quad m_{\beta\beta} = \sum_i U_{ei}^2 m_{\nu_i}$$

$$d = 5$$



NO: $m_1 < m_2 < m_3$
 $\Delta m_{21}^2 = (7.4 \pm 0.2) \times 10^{-5} \text{ eV}^2$
 $\Delta m_{31}^2 = (2.51 \pm 0.03) \times 10^{-3} \text{ eV}^2$

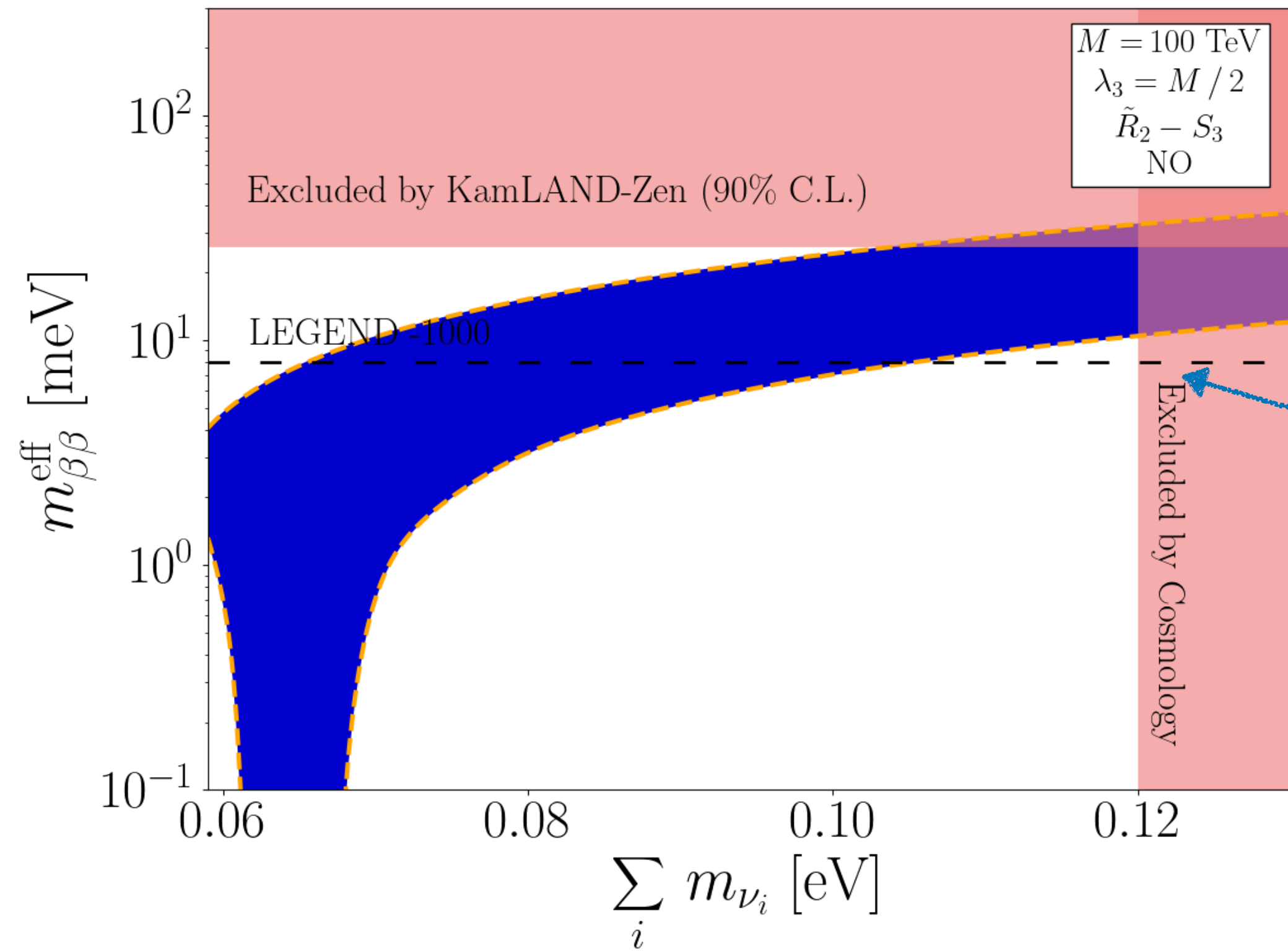


IO: $m_3 < m_1 < m_2$
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 $\Delta m_{23}^2 = (2.51 \pm 0.03) \times 10^{-3} \text{ eV}^2$

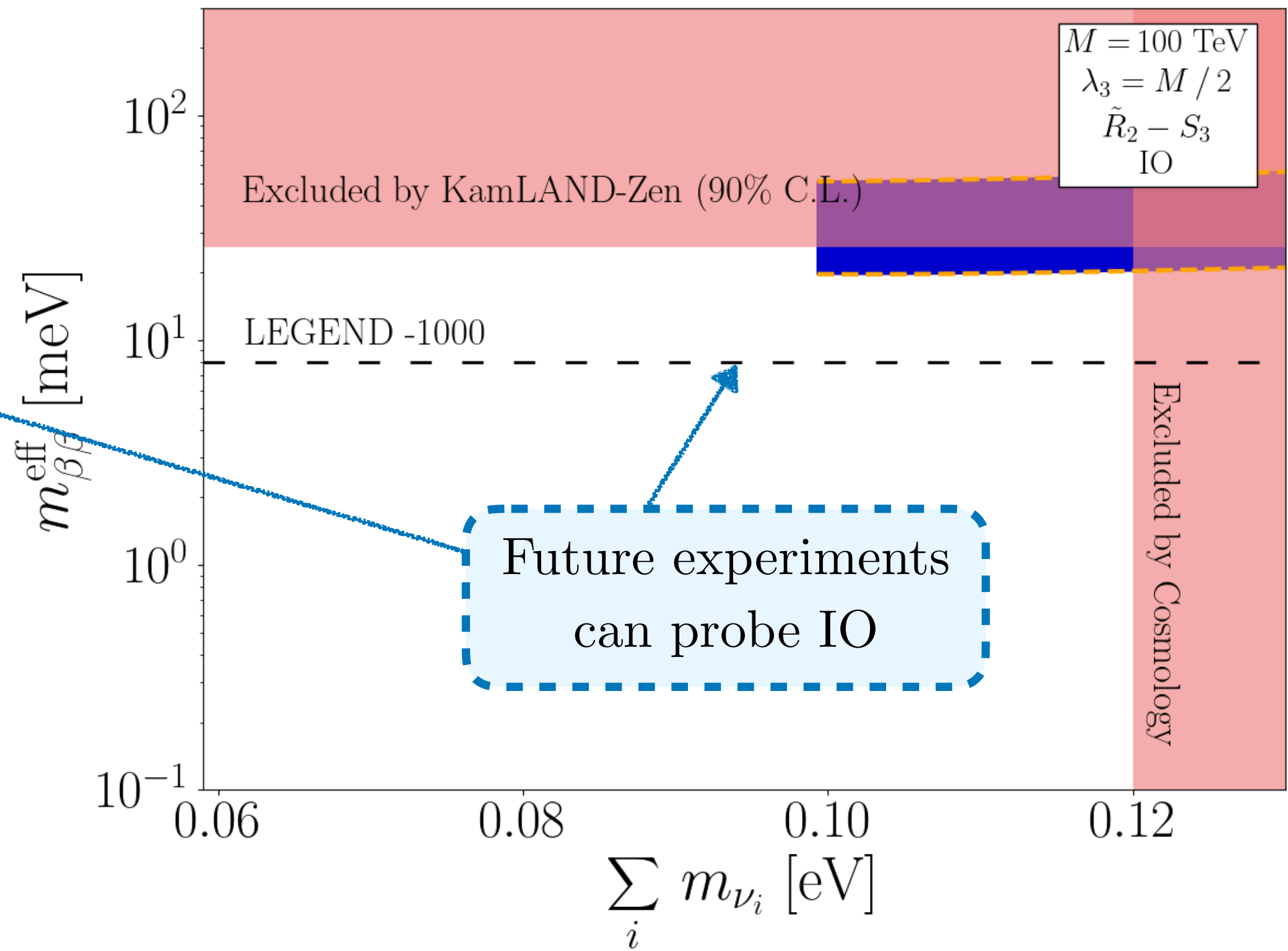
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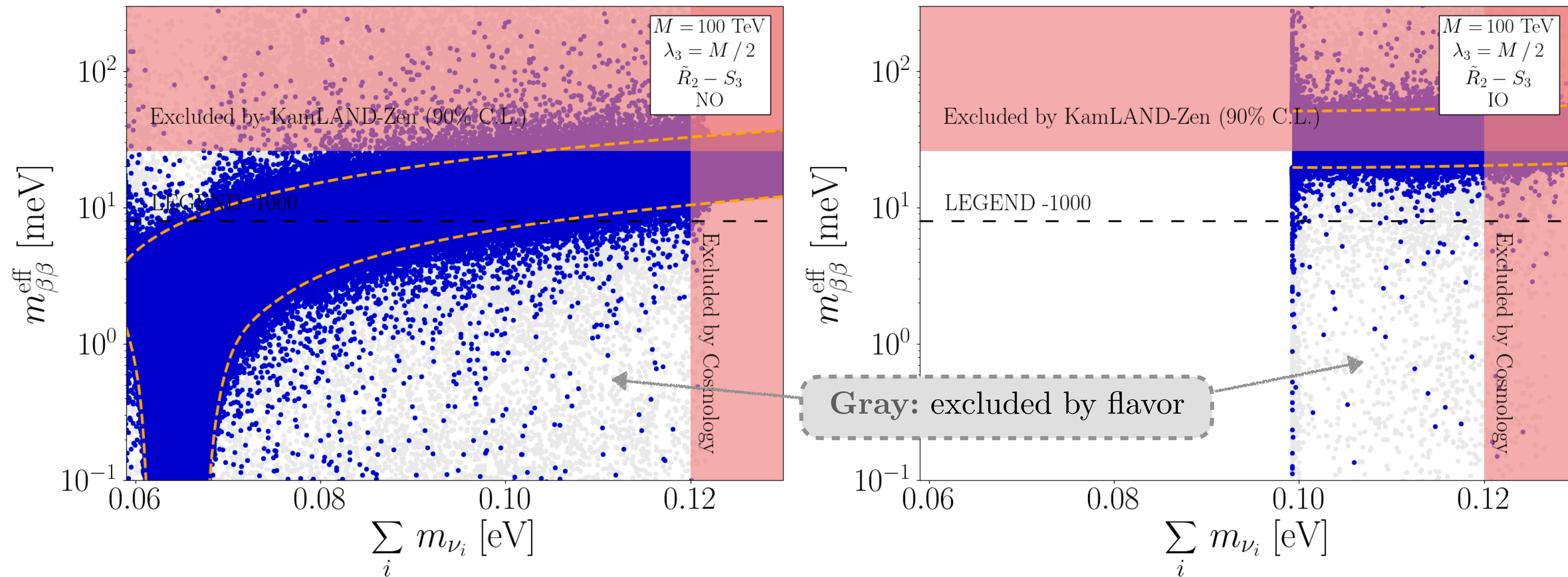


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Neutrinoless double-beta decay

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Contributions
up to $d = 7$

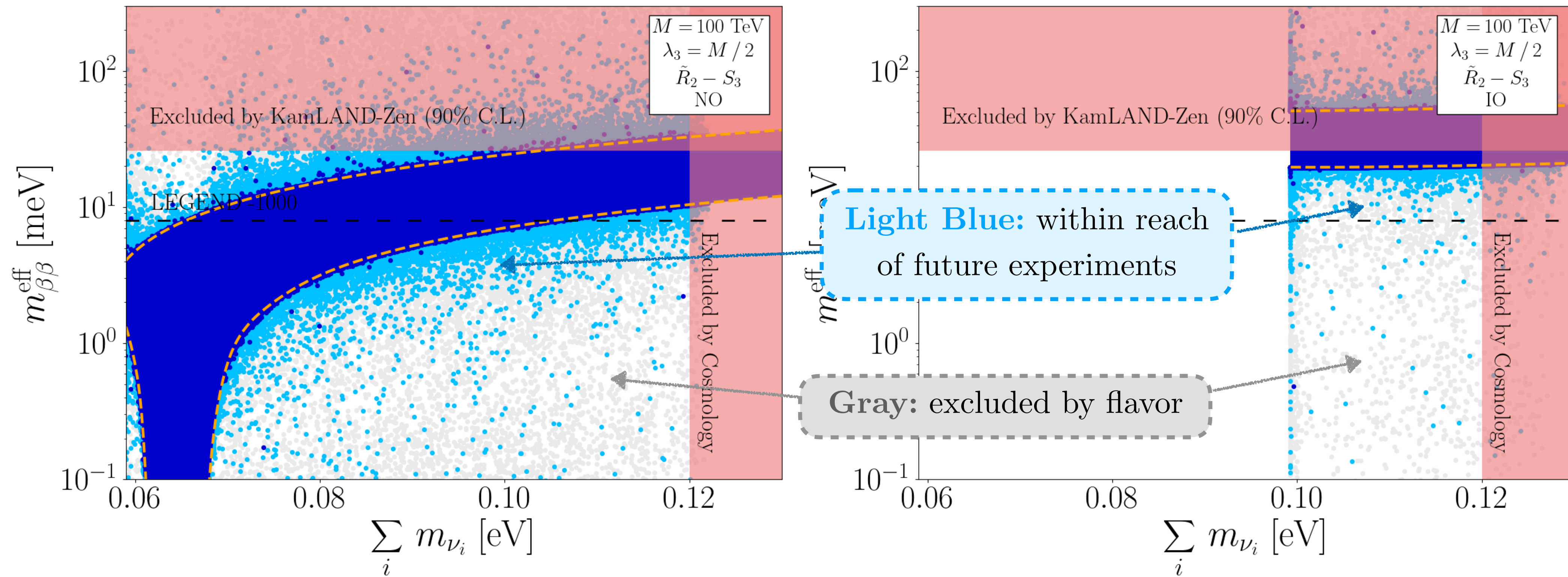


⇒ Ambiguity between NO and IO (more information needed, e.g. oscillation determination of ordering)

Neutrinoless double-beta decay

$$(m_{\beta\beta}^{\text{eff}})^2 \equiv m_{\beta\beta}^2 + \delta m_{\beta\beta}^{2(\text{int})} + \delta m_{\beta\beta}^{2(\text{LQ})}; \quad m_{\beta\beta} = \sum_i U_{ei}^2 m_{\nu_i}$$

Contributions
up to $d = 7$



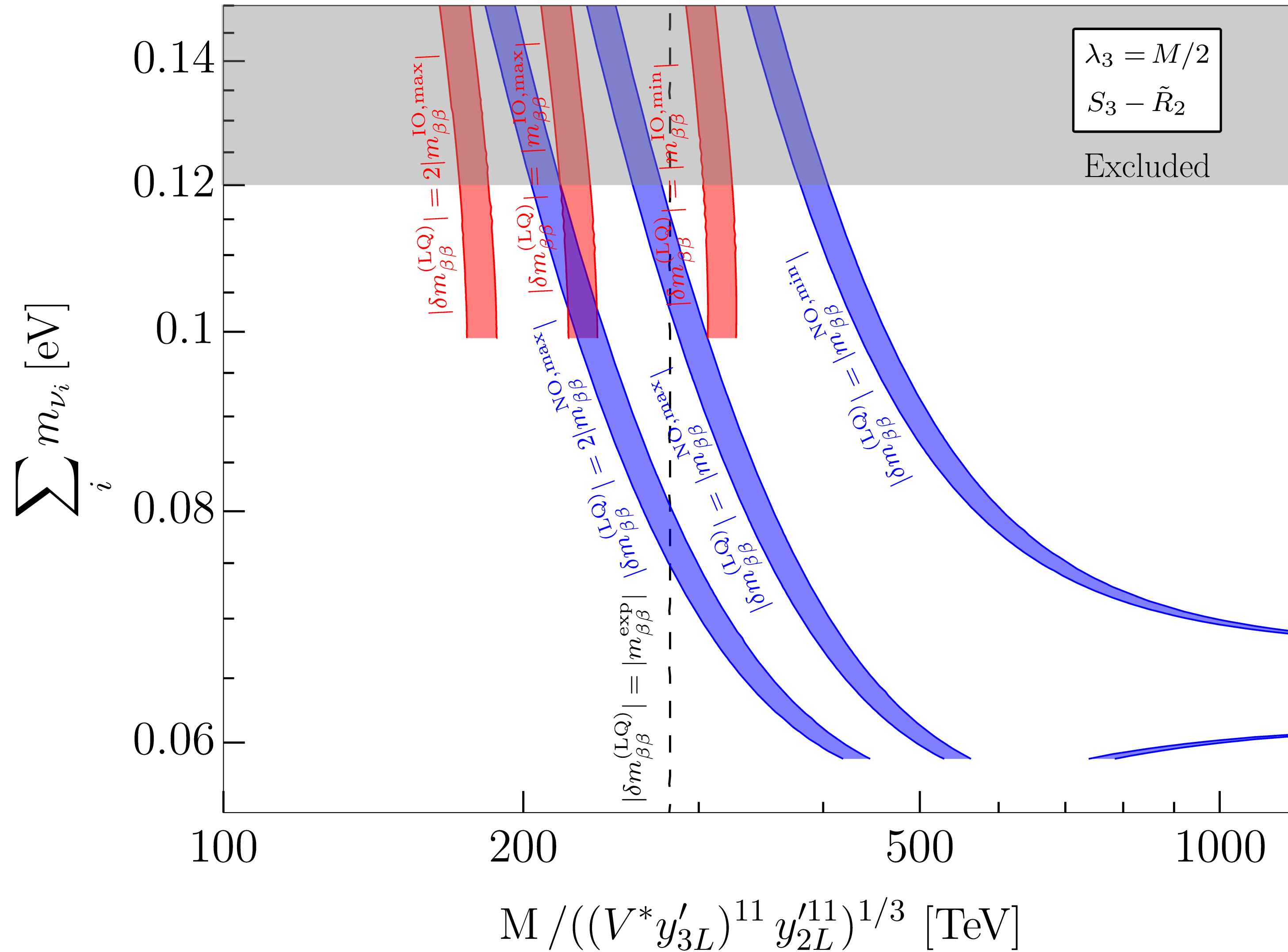
Complementarity between $0\nu\beta\beta$ and LFV probes!

Conclusions

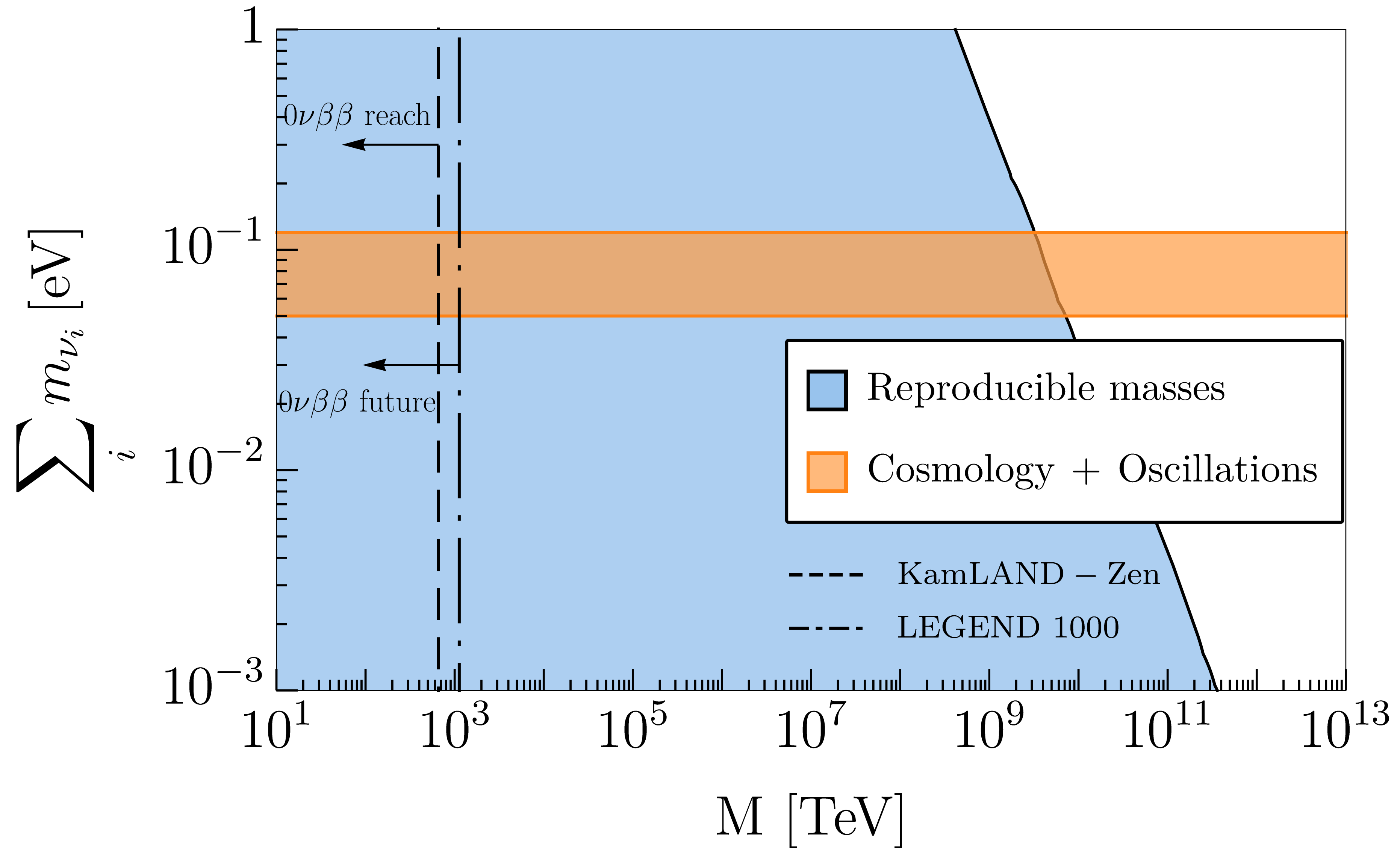
- ❖ Neutrino masses and oscillation are clear evidence of physics BSM
- ❖ Majorana neutrino masses can be **generated at one loop** in scalar Leptoquark models:
 - ⇒ New **chirality-enhanced** ($\propto E/m_\nu$) **d = 7 contributions** to $0\nu\beta\beta$ at tree-level!
- ❖ **Ambiguity between NO and IO** (more info is needed, e.g. oscillation)!
- ❖ **Flavor constraints** can probe a substantial part of the parameter space
 - ⇒ Large exp. improvements in $\mu \rightarrow e$ conversion in nuclei in the near future
 - ⇒ **Complementarity to future searches of $0\nu\beta\beta$**

Thank you!

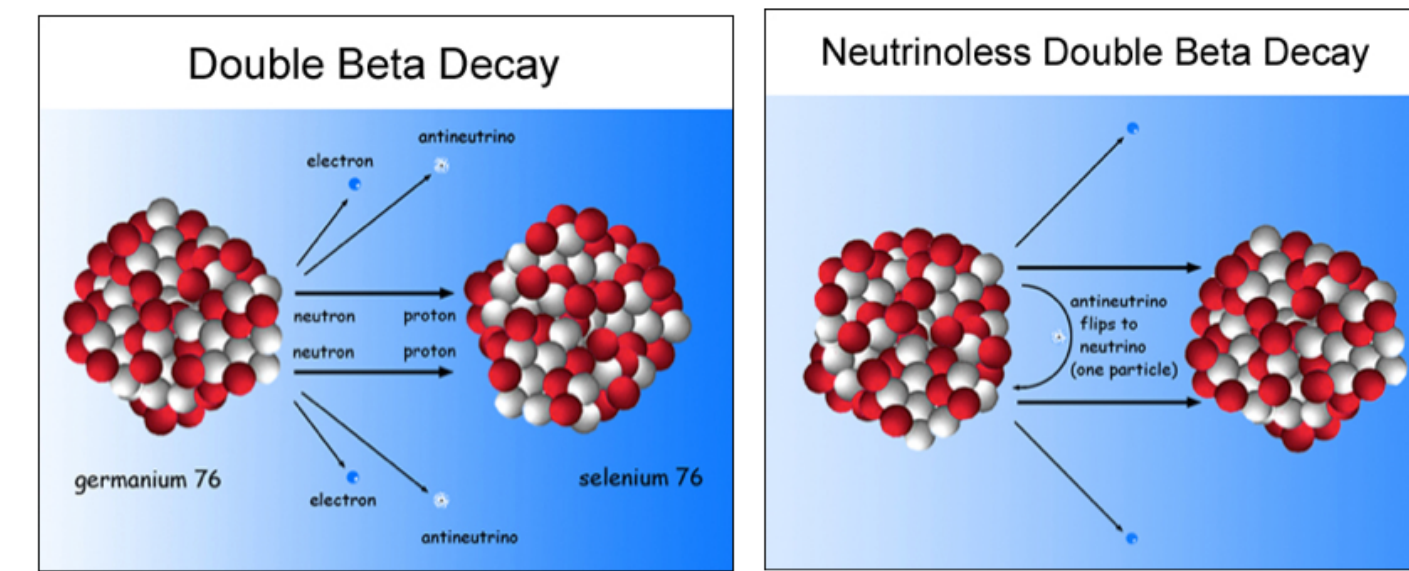
Neutrinoless double-beta decay and m_ν



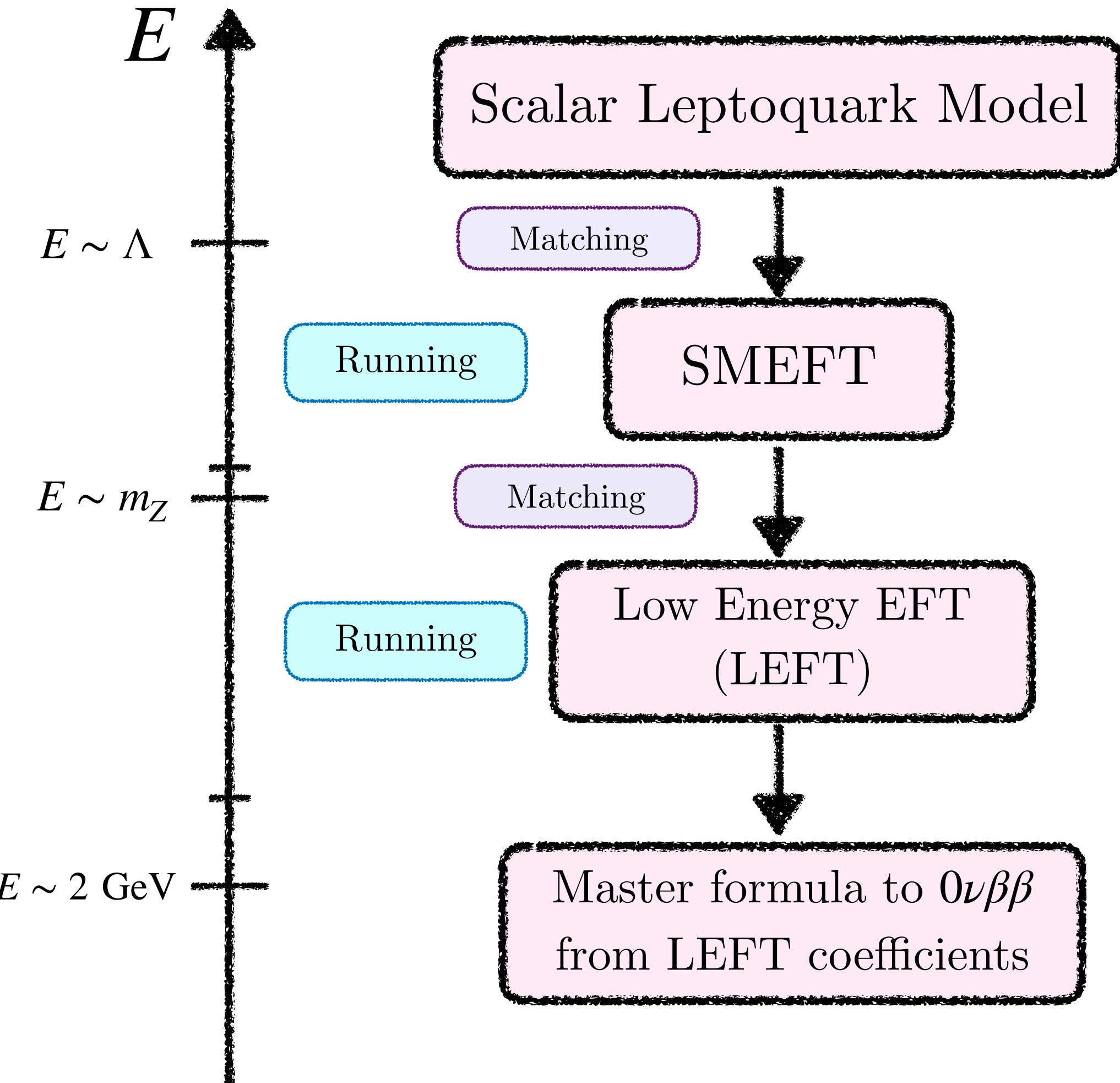
Reproducible m_ν



Neutrinoless double-beta decay

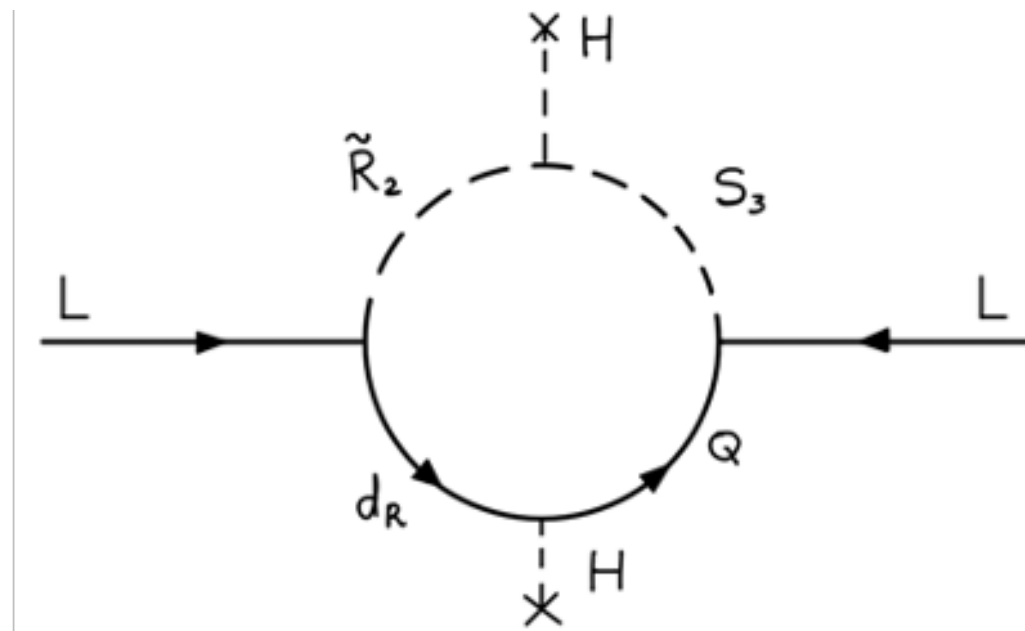


❖ Effective Field theory approach



d = 5 operator at loop-level

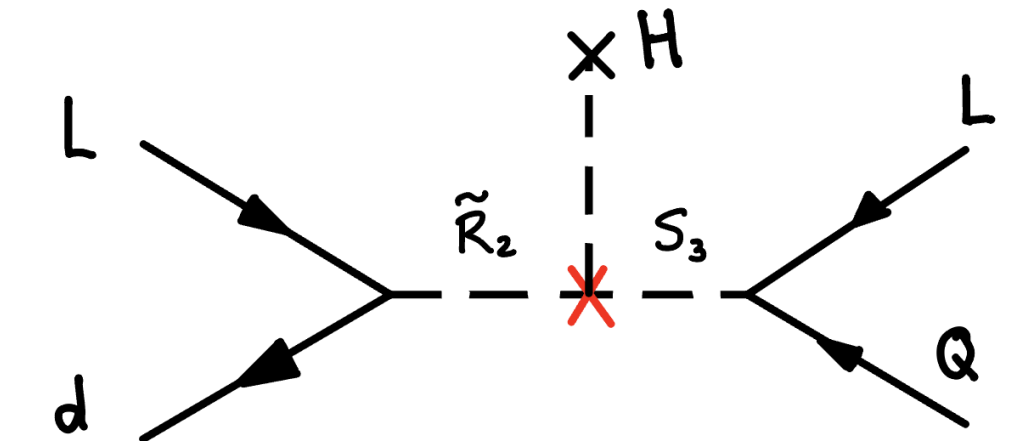
$$\mathcal{O}^{d=5} = \frac{C_{ij}^{(5)}}{\Lambda} (\bar{L}_i^C \tilde{H}^*) (\tilde{H}^\dagger L_j)$$



d = 7 operators at tree-level

$$[\mathcal{O}_{LLQ\bar{d}H}^{(1)}]_{ijkl} = \epsilon_{ab}\epsilon_{mn} (\bar{d}_{Rk} L_i^a) (\bar{L}_j^m C Q_l^b) H^n,$$

$$[\mathcal{O}_{LLQ\bar{d}H}^{(2)}]_{ijkl} = \epsilon_{am}\epsilon_{bn} (\bar{d}_{Rk} L_i^a) (\bar{L}_j^m C Q_l^b) H^n$$



Upper limits:

$S_3 - \tilde{R}_2$ model:

$$\frac{|\lambda_3 y_{3L}'^{11} y_{2L}'^{11}|}{M^4} \lesssim (340 \text{ TeV})^{-3}$$

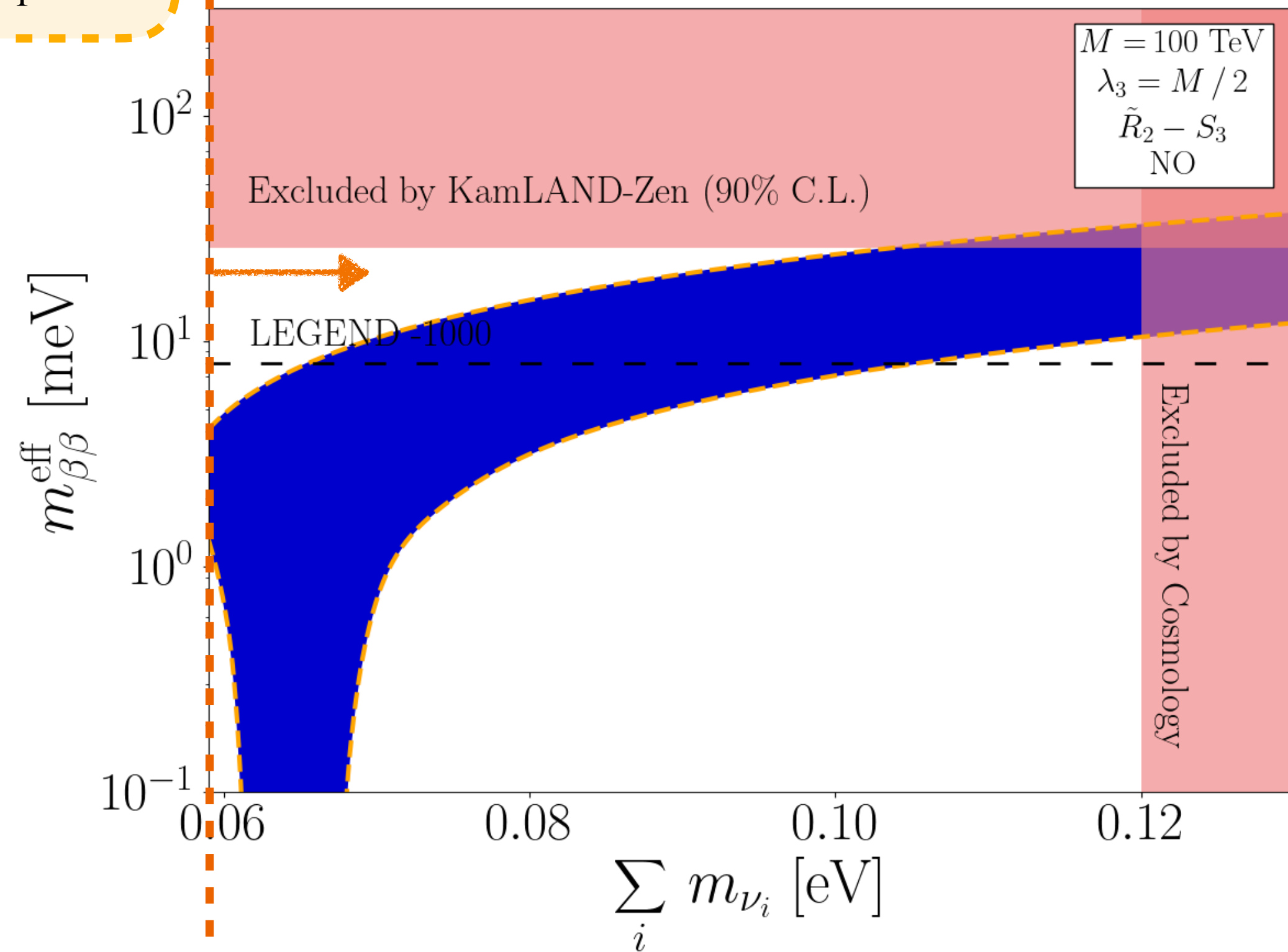
$y'_L = y_L U_{\ell L}$ where $U_{\ell L}$ is the left-handed charged lepton

Neutrinoless double-beta decay

$$(m_{\beta\beta}^{\text{eff}})^2 = m_{\beta\beta}^2 + \delta m_{\beta\beta}^{2(\text{int})} + \delta m_{\beta\beta}^{2(\text{LQ})} \quad ; \quad m_{\beta\beta} = \sum_i U_{ei}^2 m_{\nu_i}$$

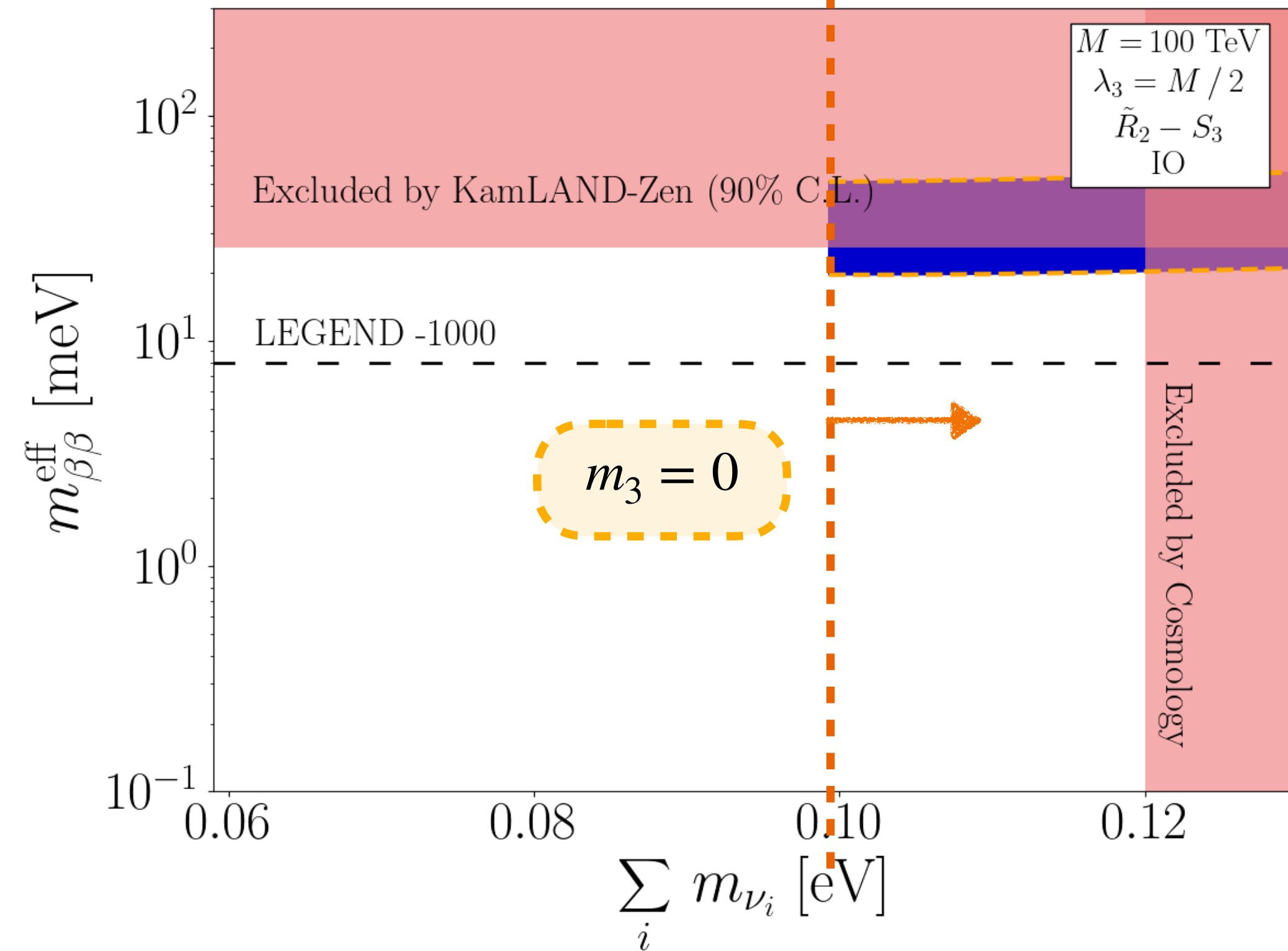
$$d = 5$$

$$m_1 = 0$$



NO: $m_1 < m_2 < m_3$
 $\Delta m_{21}^2 = (7.4 \pm 0.2) \times 10^{-5} \text{ eV}^2$
 $\Delta m_{31}^2 = (2.51 \pm 0.03) \times 10^{-3} \text{ eV}^2$

$$m_3 = 0$$

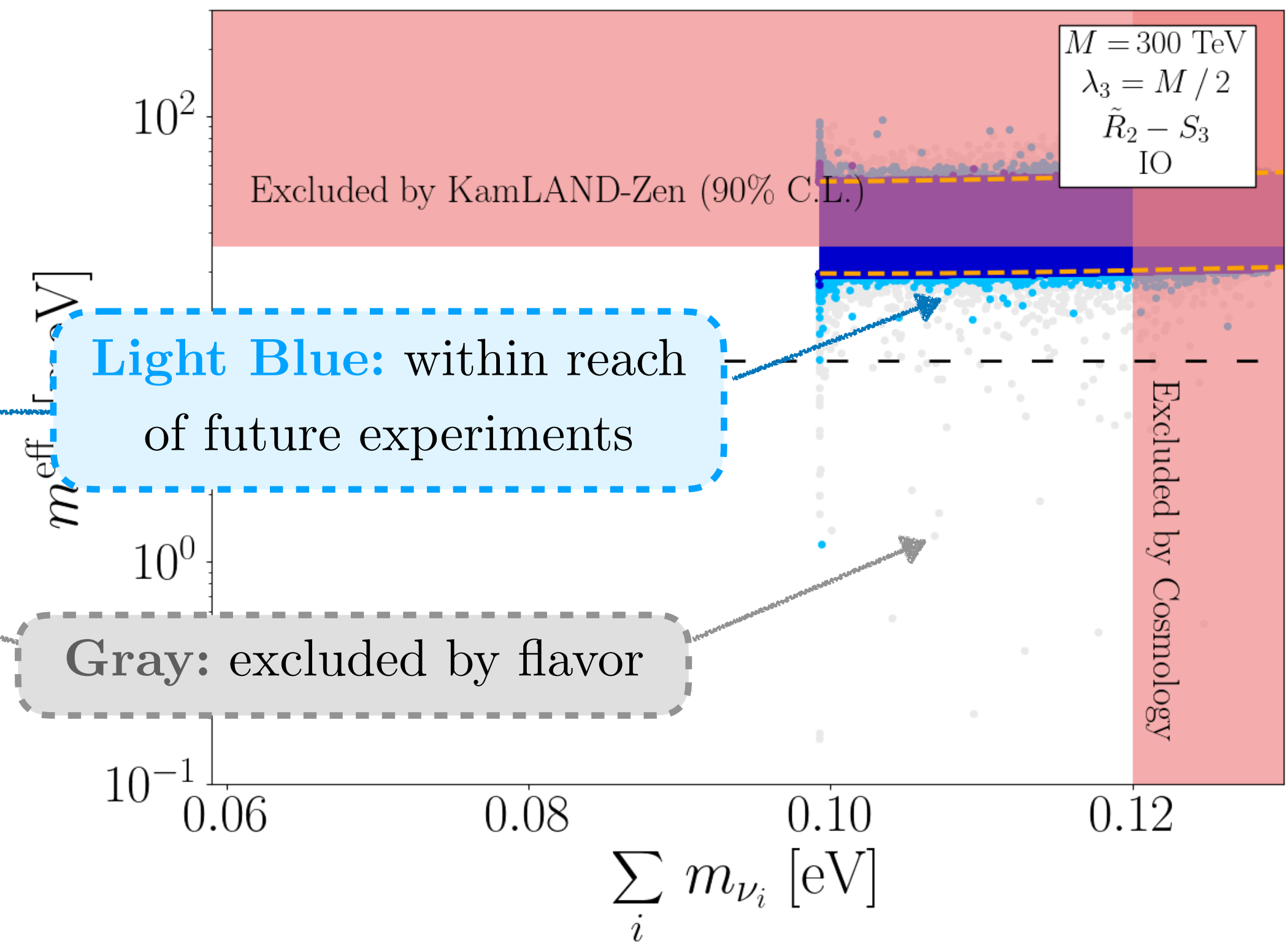
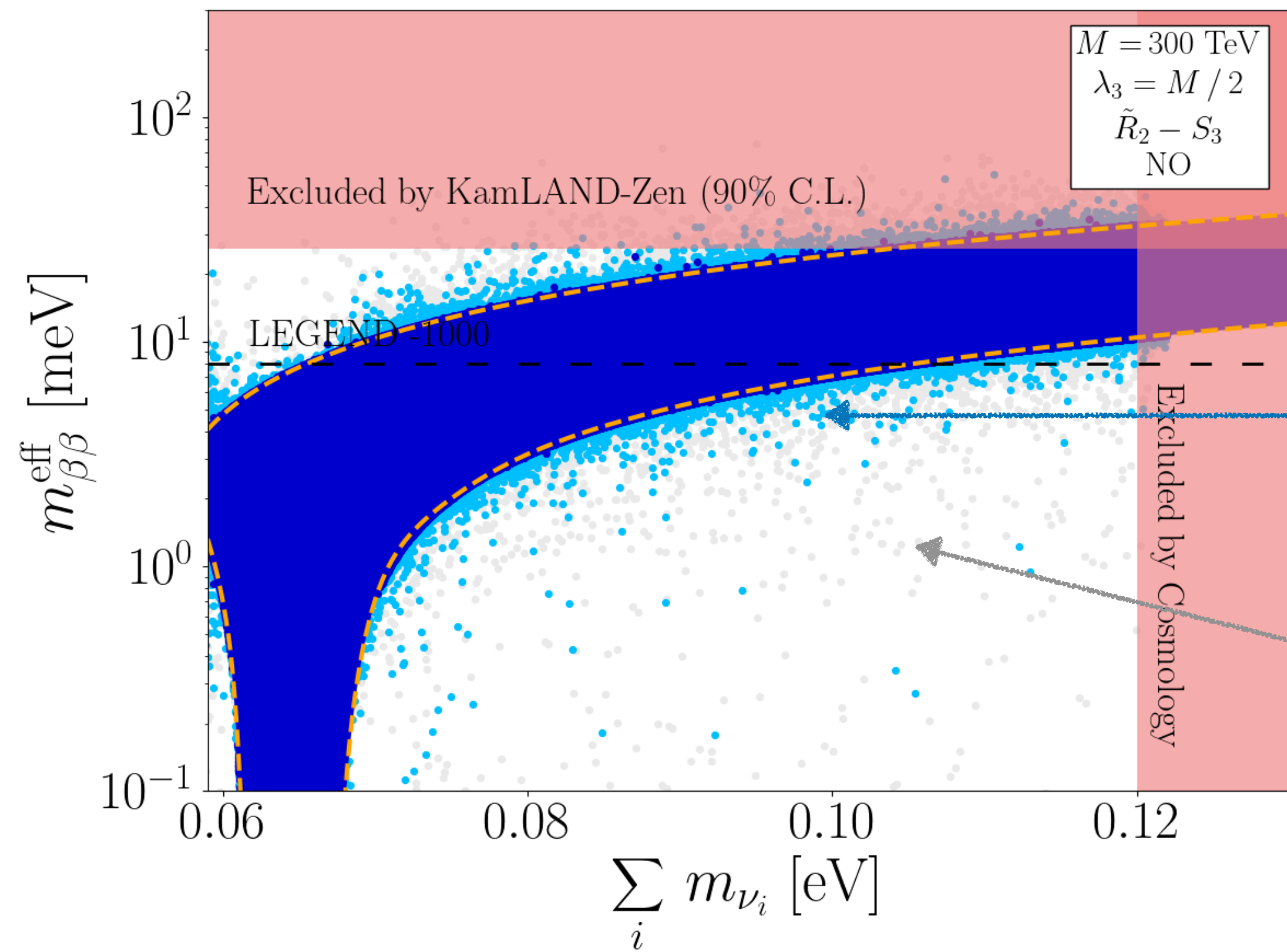


IO: $m_3 < m_1 < m_2$
 $\Delta m_{21}^2 = (7.4 \pm 0.2) \times 10^{-5} \text{ eV}^2$
 $\Delta m_{23}^2 = (2.51 \pm 0.03) \times 10^{-3} \text{ eV}^2$

Neutrinoless double-beta decay

$M = 300 \text{ TeV}$

$$(m_{\beta\beta}^{\text{eff}})^2 \equiv m_{\beta\beta}^2 + \delta m_{\beta\beta}^{2(\text{int})} + \delta m_{\beta\beta}^{2(\text{LQ})} ; m_{\beta\beta} = \sum_i U_{ei}^2 m_{\nu_i}$$



Correlation $0\nu\beta\beta$ vs. $\mu N \rightarrow eN$

❖ Huge improvement in $\mu N \rightarrow eN$ experimental sensitivity

- Present: $B(\mu\text{Au} \rightarrow e\text{Au}) < 7 \times 10^{-13}$ (90% C.L.)
- Future: $B(\mu\text{Al} \rightarrow e\text{Al}) \sim \mathcal{O}(10^{-17})$

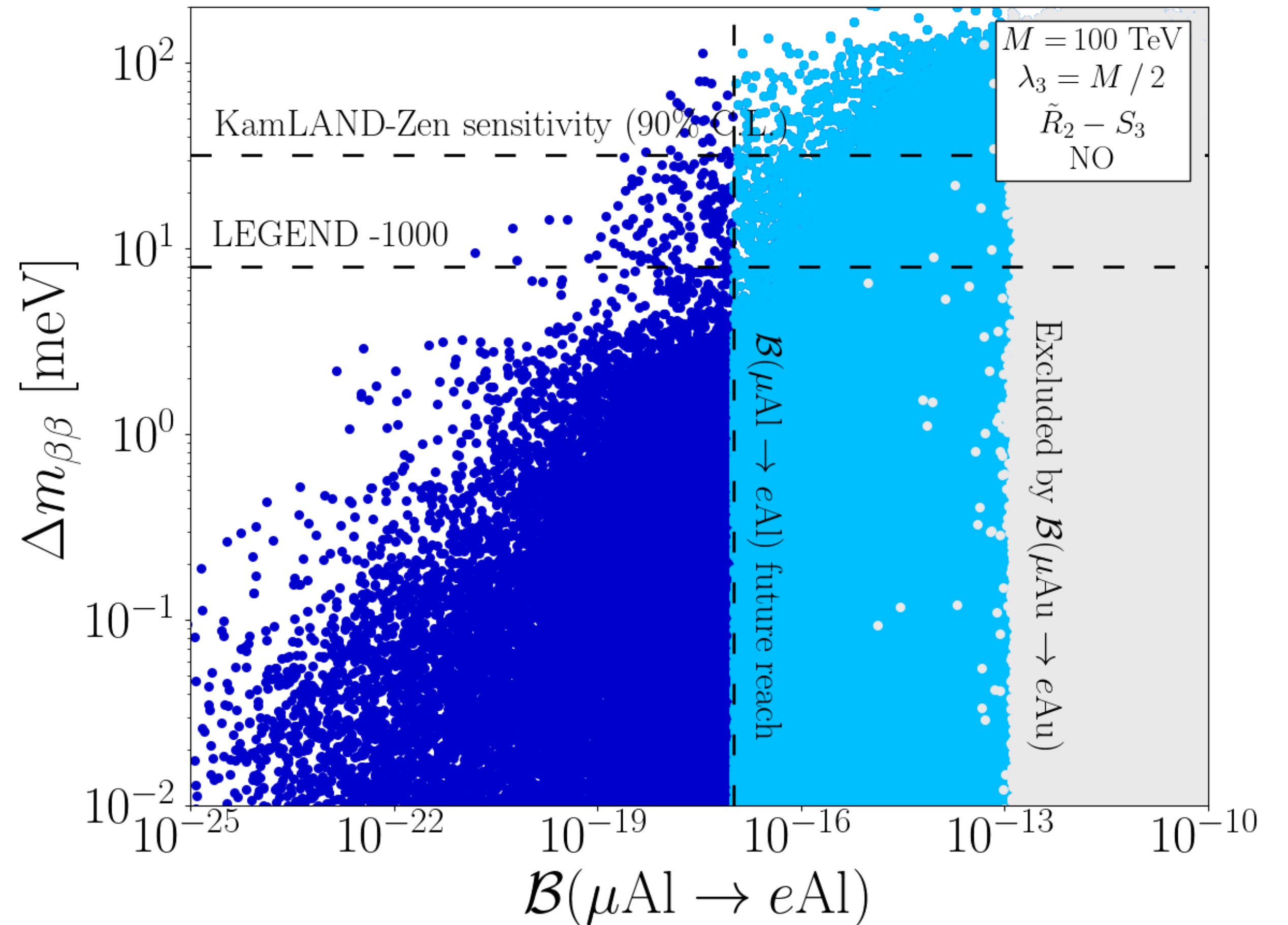
$$\Delta m_{\beta\beta} \equiv |m_{\beta\beta}^{\text{eff}2} - m_{\beta\beta}^2|^{1/2}$$

▸ Main contributions to $\mu N \rightarrow eN$ comes from spin-independent rates

$$\mathcal{B}_{\mu e}^{(N)} \Big|_{\text{SI}} = \frac{2 G_F^2 m_\mu^5}{\Gamma_{\text{capt}}^N \pi^2} (Z\alpha_{\text{em}})^3 \left| Z F_p^N(m_\mu) c_{VL}^{(p)} + (A - Z) F_n^N(m_\mu) c_{VL}^{(n)} \right|^2 + (L \leftrightarrow R)$$

▸ Scales with atomic number Z

Complementarity between $0\nu\beta\beta$ and LFV probes!

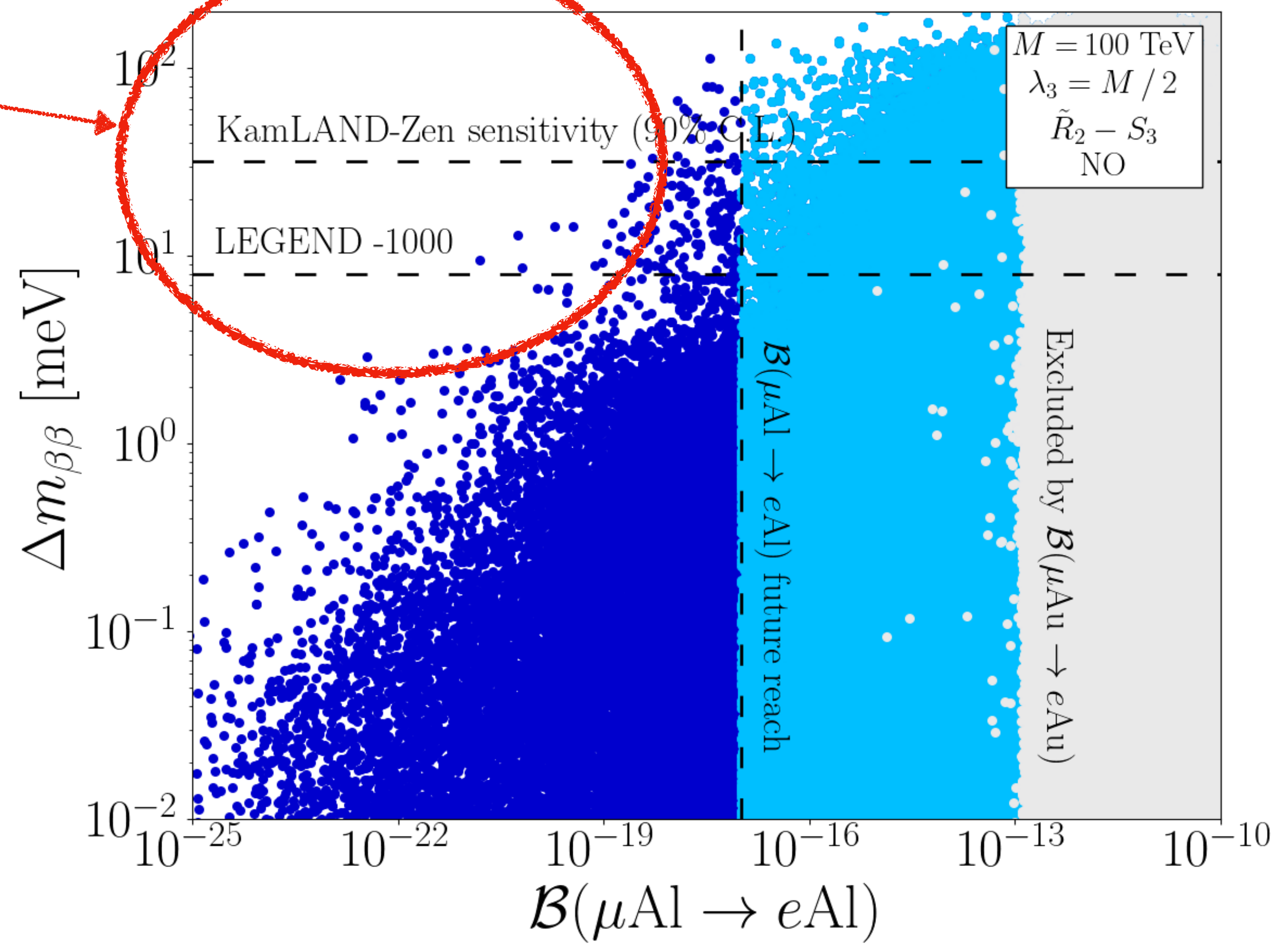


Correlation $0\nu\beta\beta$ vs. $\mu N \rightarrow eN$

❖ Huge improvement in $\mu N \rightarrow eN$ experimental sensitivity

$$\Delta m_{\beta\beta} \equiv |m_{\beta\beta}^{\text{eff}2} - m_{\beta\beta}^2|^{1/2}$$

Can we have suppressed $\mu N \rightarrow eN$ while $m_{\beta\beta}$ is large?



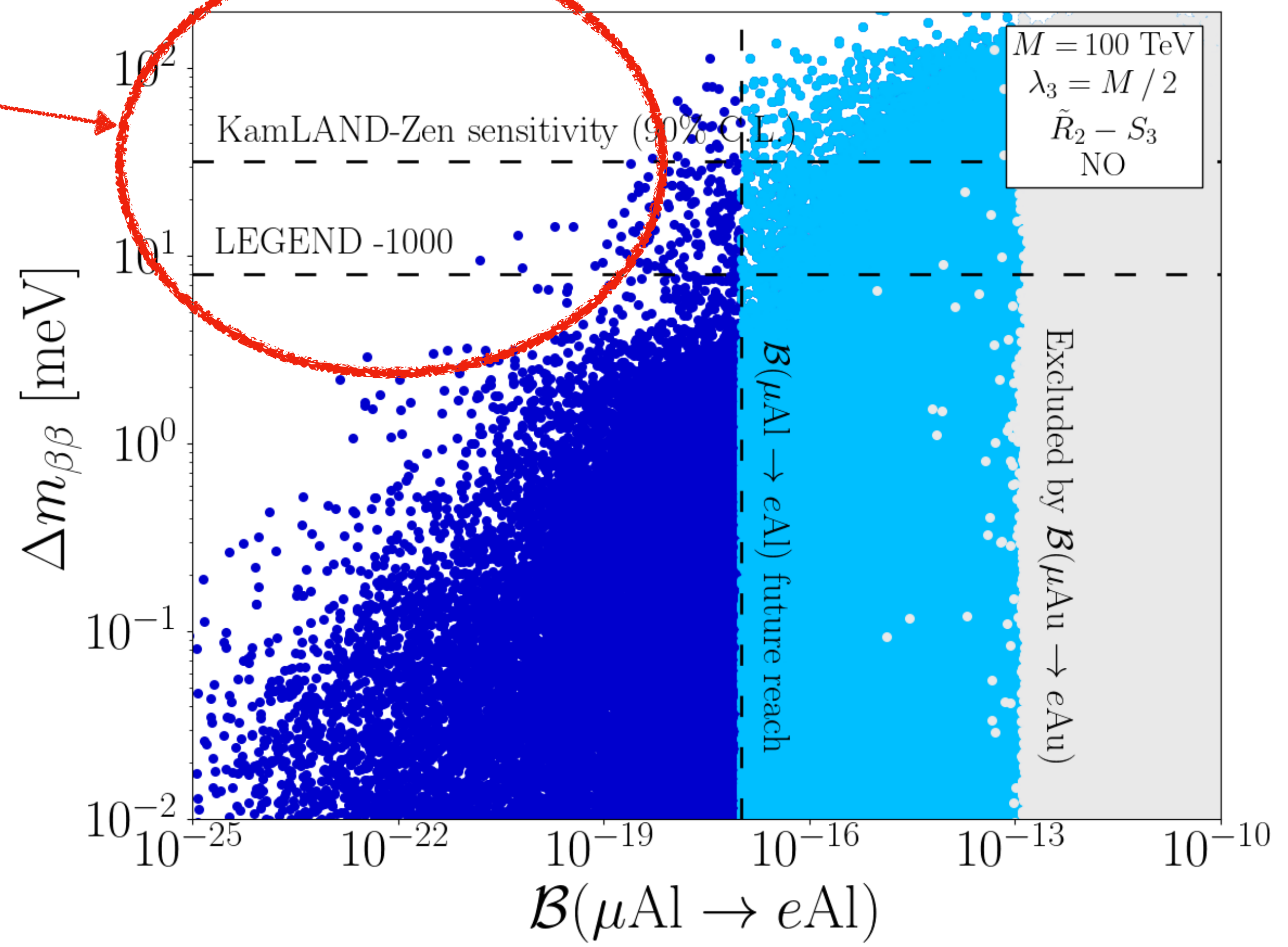
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Can we have suppressed $\mu N \rightarrow eN$ while $m_{\beta\beta}$ is large?

- 1) Cancellation between S_3 and \tilde{R}_2 contributions
- 2) Coupling to muons vanish in physical basis



Correlation $0\nu\beta\beta$ vs. $\mu N \rightarrow eN$

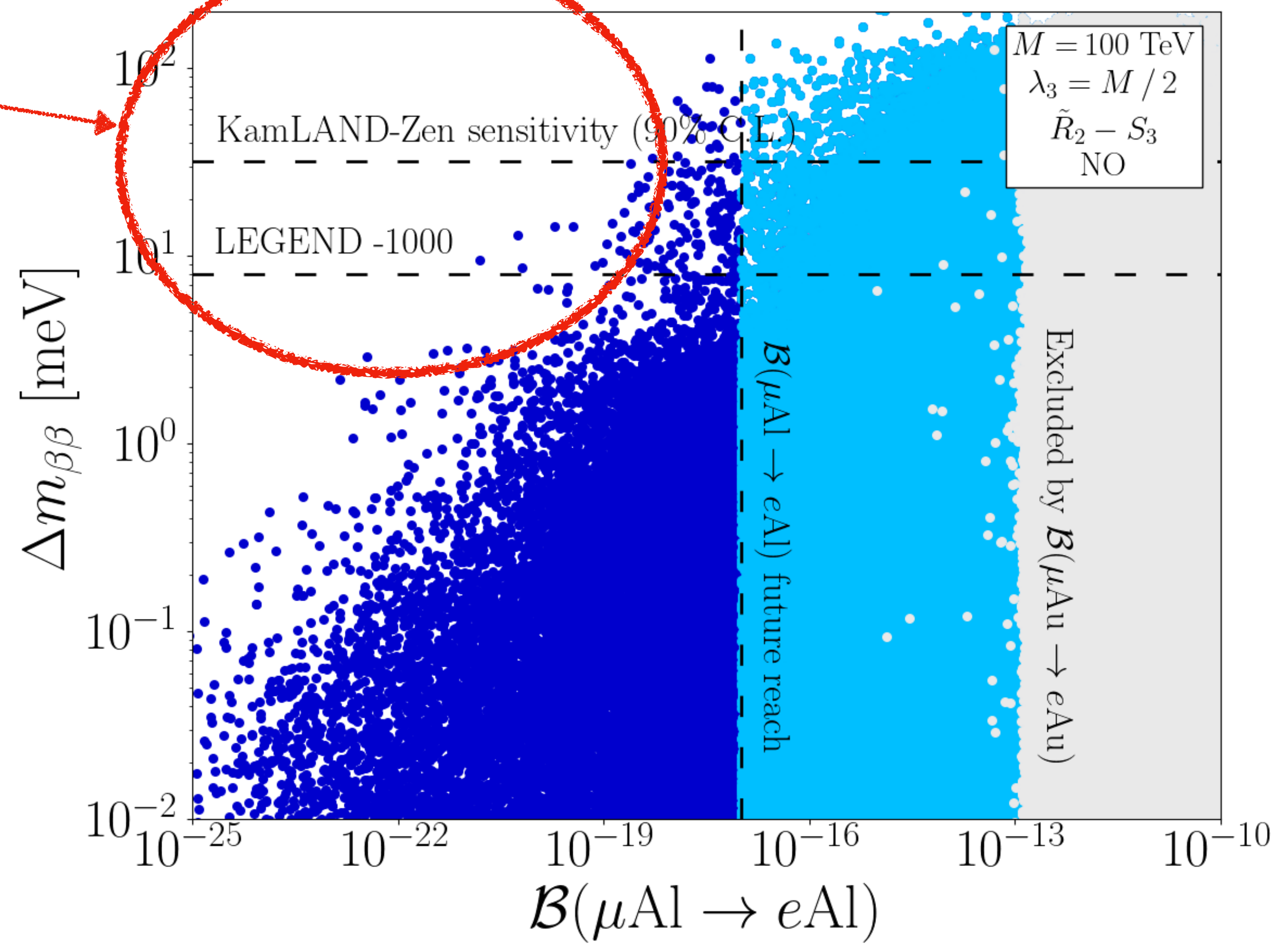
❖ Huge improvement in $\mu N \rightarrow eN$ experimental sensitivity

$$\Delta m_{\beta\beta} \equiv |m_{\beta\beta}^{\text{eff}2} - m_{\beta\beta}^2|^{1/2}$$

Can we have suppressed $\mu N \rightarrow eN$ while $m_{\beta\beta}$ is large?

Condition 1: Cancellation between S_3 and \tilde{R}_2 contributions

▸ Additional spin-dependent contributions.
 \implies enhanced when we have cancellations in SI part



Correlation $0\nu\beta\beta$ vs. $\mu N \rightarrow eN$

❖ Huge improvement in $\mu N \rightarrow eN$ experimental sensitivity

$$\Delta m_{\beta\beta} \equiv |m_{\beta\beta}^{\text{eff}2} - m_{\beta\beta}^2|^{1/2}$$

Condition 2: Coupling to muons vanish in physical basis



- $S_3 - \tilde{R}_2$: $(y'_{2L})_{12} = (V^* y'_{3L})_{12} = (y'_{3L})_{12} = 0$
- Consequences to neutrino mass matrix structure

$$m_\nu = -\frac{3\lambda_3}{16\sqrt{2}\pi^2} \frac{v^2}{M^2} \left(y_{2L}^T \cdot \hat{y}_d \cdot y_{3L} + y_{3L}^T \cdot \hat{y}_d \cdot y_{2L} \right)$$

- We did not find solutions compatible with neutrino oscillations

