Parity restoration and long-range contributions to $0\nu2\beta$

Juan Carlos Vasquez

UMass & ACFI, Amherst

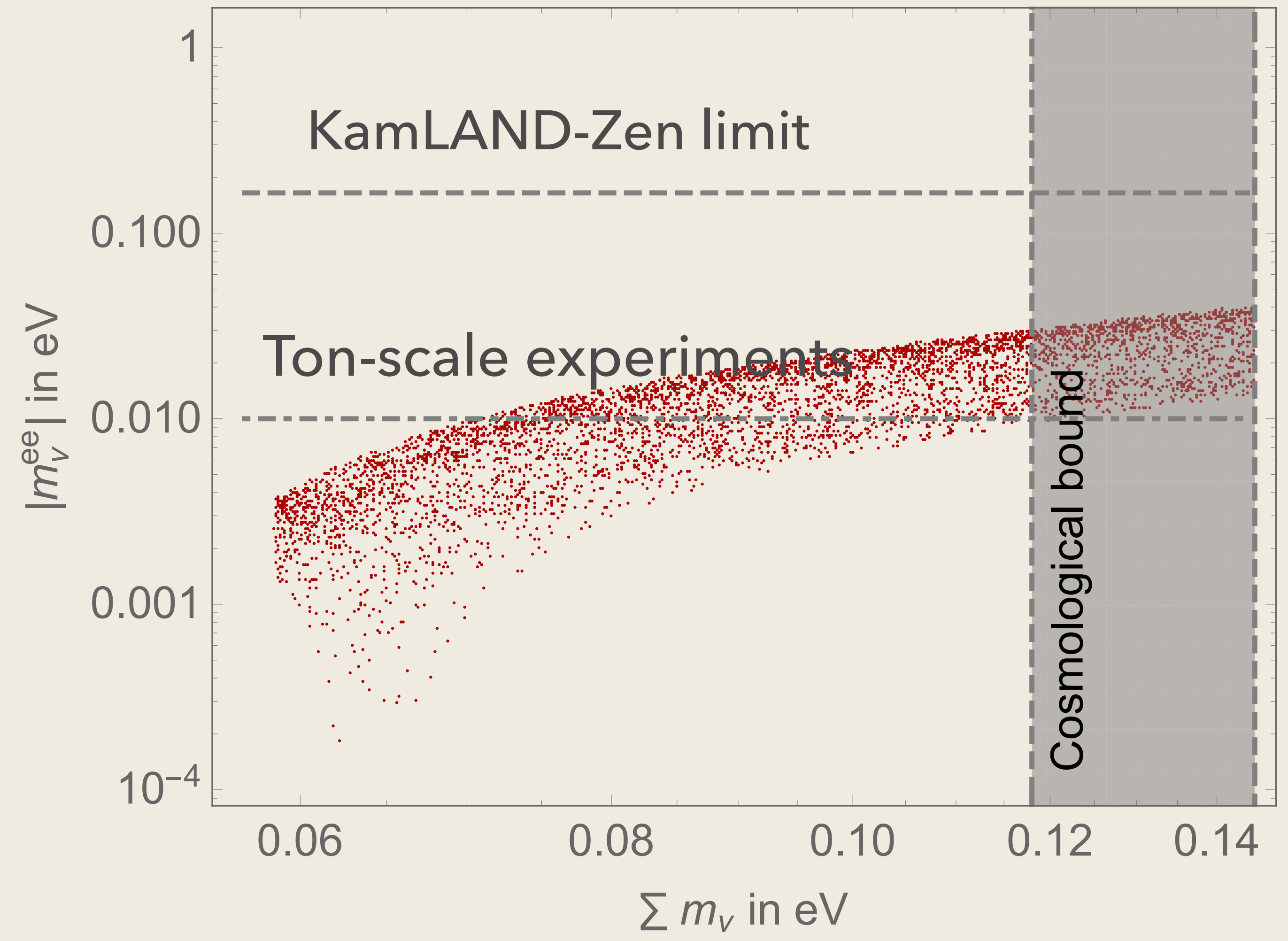
Work supported by the US Department of Energy (DoE), Office of Science, Nuclear Physics under the Nuclear Theory Topical Collaboration program

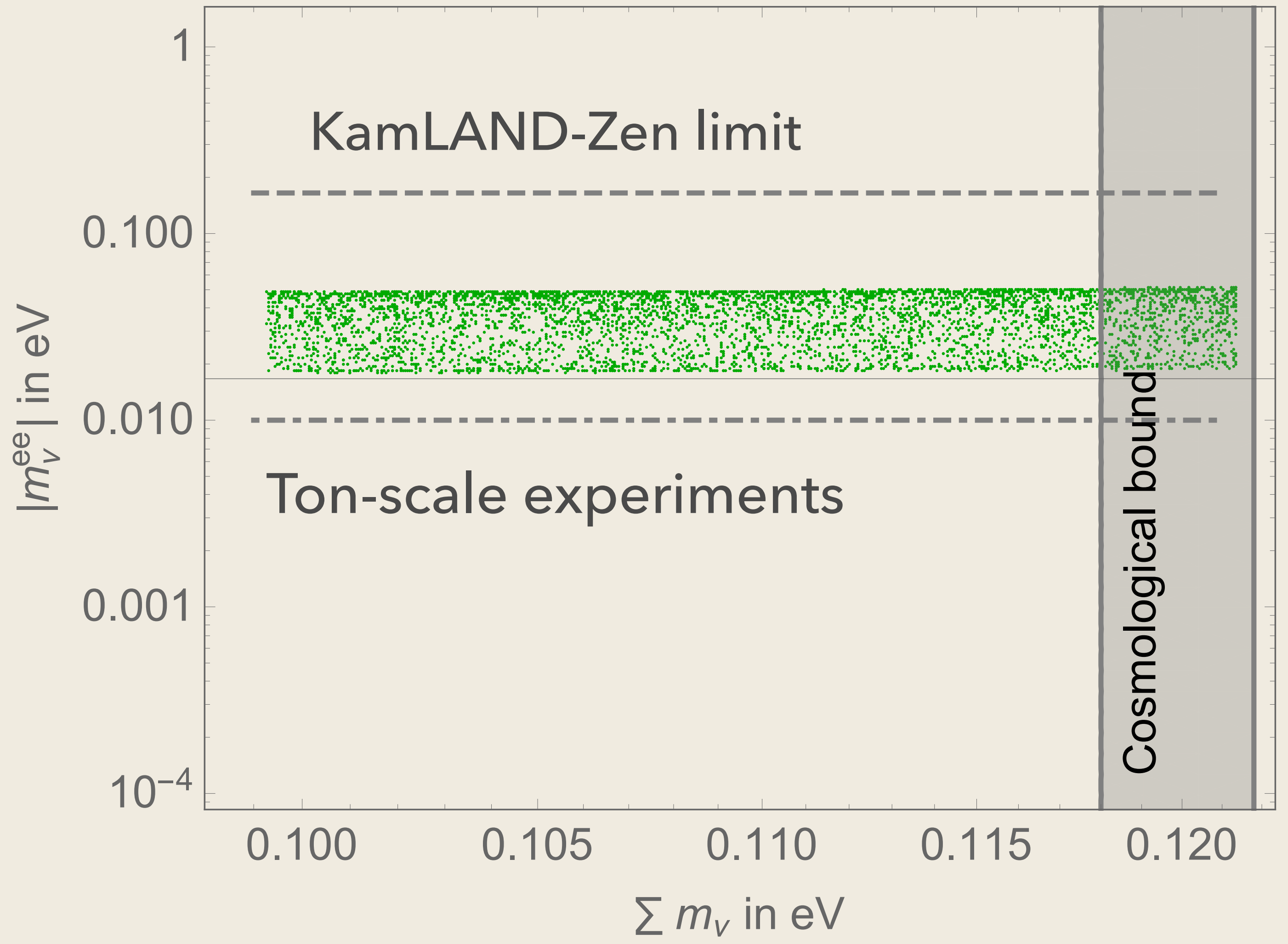
(based on an ongoing work in collaboration with Michael Ramsey-Musolf and Gang Li)

Outline of the talk

1. Results. Confronting the light-neutrino scenario with the mLRSM
2. The minimal left-right symmetric model (mLRSM)
3. Feynman diagrams contributing to the decay rate
4. Effective Lagrangian in mLRSM
5. Decay rate including the long-range contributions
6. Conclusions

Confronting light neutrino exchange with the LR scenario





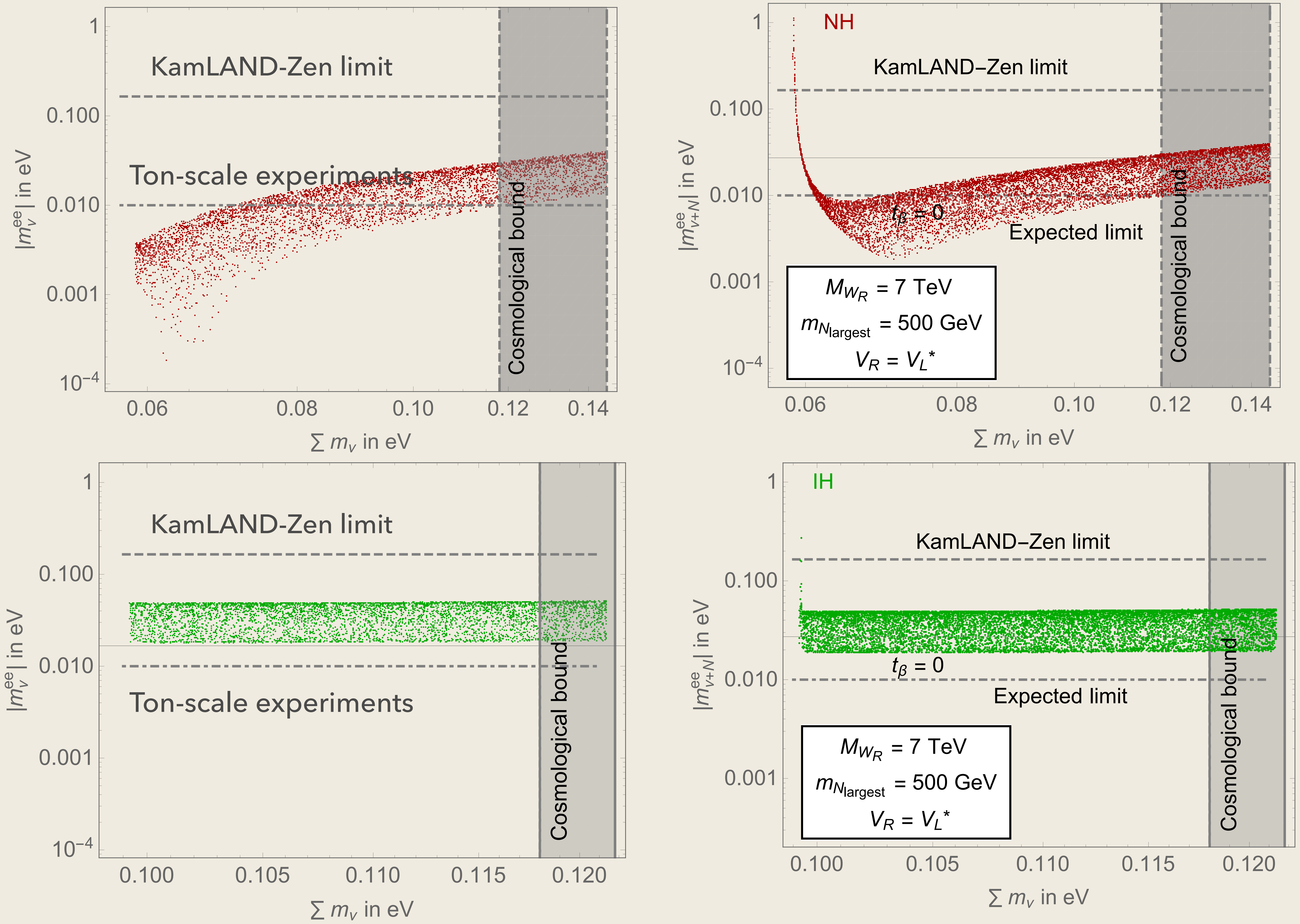
Current cosmological

Bound arXiv:1806.10832

$$\sum m_\nu < 0.118 \text{ eV}$$

Light ν exchange scenario

Confronting light neutrino exchange with the LR scenario



Current cosmological

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$$\sum m_\nu < 0.118 \text{ eV}$$

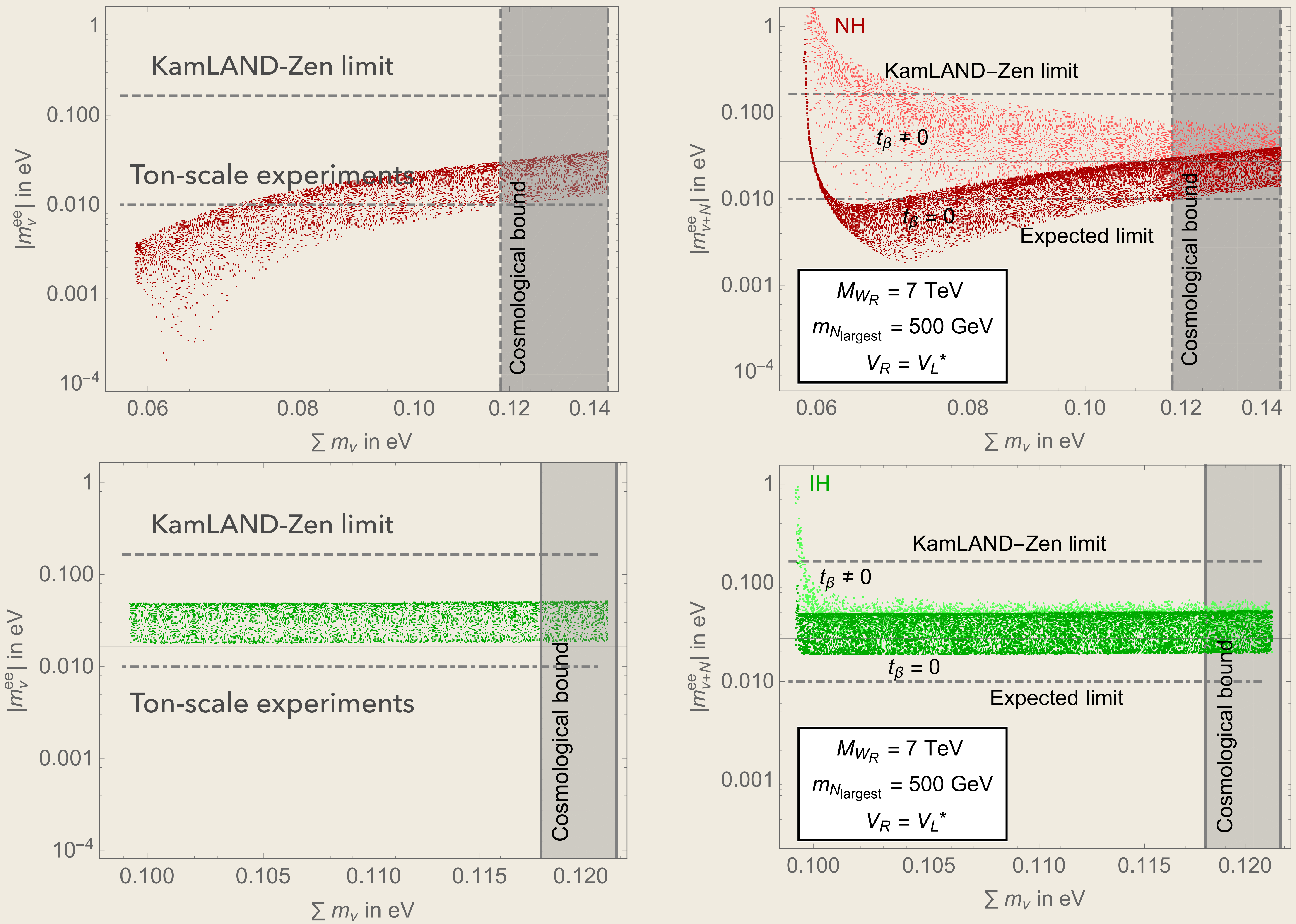
mLRSM contribution without

Including long-range interactions

(Tello, Senjanovic, Nemevsek, Nesti, Vissani

ArXiv: 1011.3522)

Confronting light neutrino exchange with the LR scenario



With long-range contributions

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Near future bound

ACTpol and SPTpol

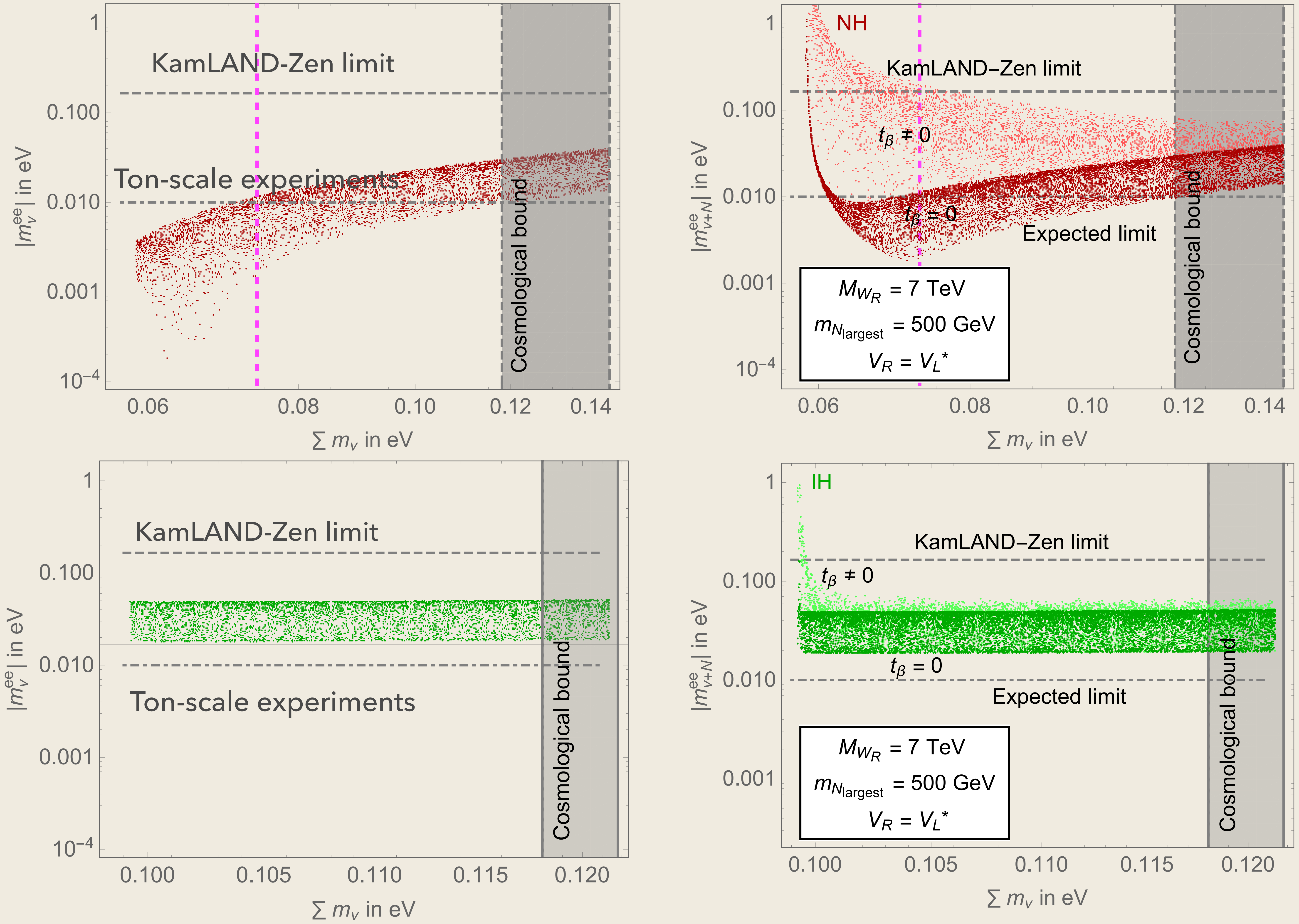
$$\sum m_\nu < 0.1 \text{ eV}$$

SPT-3G forecast

$$\sum m_\nu < 0.74 \text{ eV}$$

Projections taken from Kevork Abazajian ACFI talk 2015

Confronting light neutrino exchange with the LR scenario



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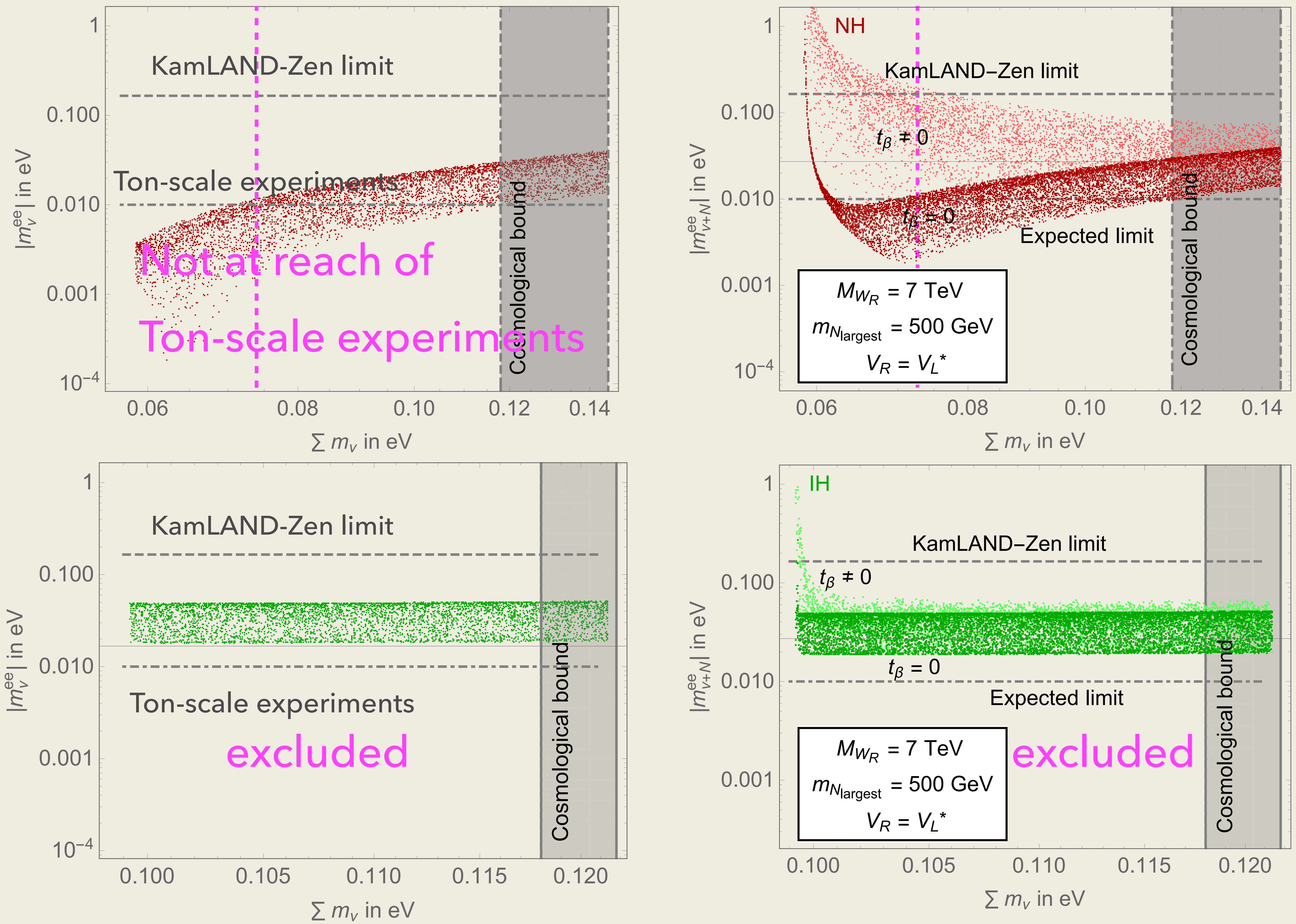

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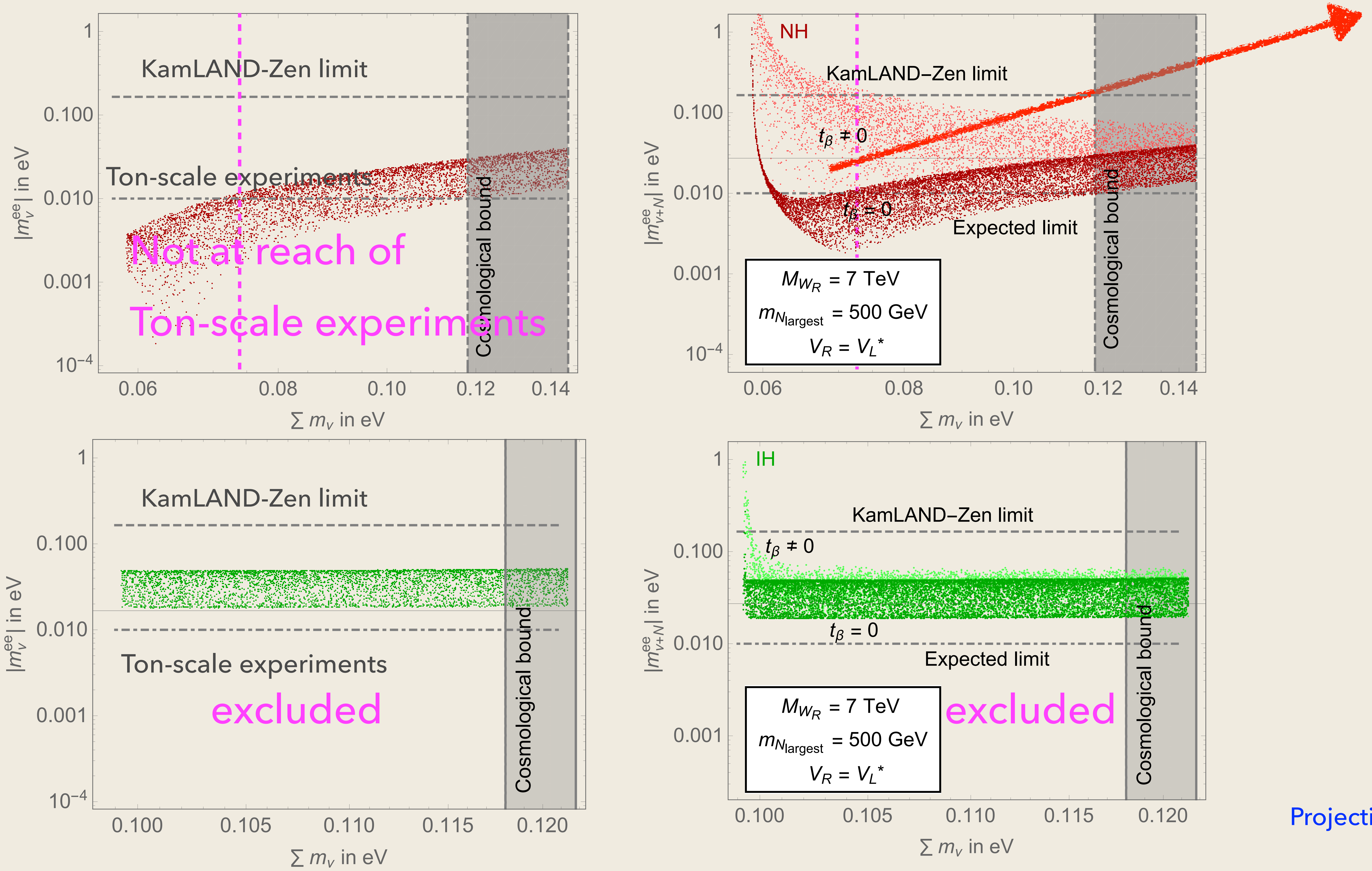

Accessible in Ton scale

Experiments

Current cosmological

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Near future bound

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Confronting light neutrino exchange with the LR scenario

It is not correct then to declare that a positive observation

In next experiments would mean that IH neutrino mass ordering

A positive observation would just mean that LNV indeed occurs but it could well be due to new physics dominating the rate.

This highlight the importance of measuring the chiralities of outgoing electrons and possible interplay with other process at low and/or high energies. (very difficult to do from the experimental side)

The minimal left-right symmetric model

(J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 2558 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975); G. Senjanovic, Nucl. Phys. B153, 334 (1979).
)

- Extends the SM gauge group

$$SU(3) \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \times Z_2$$

- Complete model of ν masses
  (Tello, Nemevsek and Senjanovic 2012 ArXiv:1211.2837 for charge conjugation)
  (Tello and Senjanovic ArXiv: 1612.05503 for parity)

- The mixing between the $W - W_R$ bosons give

$$\tan\xi = -\frac{v_1 v_2}{v_R^2} e^{-i\alpha} \simeq \left(\frac{M_W^2}{M_{W_R}^2}\right) \sin 2\beta e^{-i\alpha}, \quad \tan\beta \equiv v_2/v_1$$

v_1 and v_2 are the v.e.vs of the light and heavy doublets.

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- $\tan\beta_{max} \sim 0.5$ from K and B meson systems (Bertolini, Nesti and Maiezza 2019. ArXiv: 1911.09472)

$$W_L^+ = \cos\xi W_{1\mu}^+ - \sin\xi e^{-i\alpha} W_{2\mu}^+$$ (SM W boson)

$$W_R^+ = \sin\xi e^{i\alpha} W_{1\mu}^+ + \cos\xi W_{2\mu}^+$$

- Neutrino mass matrix (well-known see-saw formula)

$$M_\nu = Y_\Delta v_L + M_D M_N^{-1} M_D^T$$

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- Neutrino mass matrix (well-known see-saw formula)

$$M_\nu = Y_\Delta v_L + M_D M_N^{-1} M_D^T$$

We assume this piece dominates the neutrino mass contribution

- For type II dominance and $\mathscr{C}$ as the LR symmetry the Leptonic mixing matrix satisfy

$$V_L = V_R^*$$

and the $m_{N_{min}} = m_{N_{min}}(m_{\nu_{min}})$

(Tello and Senjanovic. ArXiv: 1011.3522)

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- Neutrino mass matrix (well-known see-saw formula)

$$M_\nu = Y_\Delta v_L + M_D M_N^{-1} M_D^T$$

Type-I contribution studied in

- ArXiv: 1806.02780, Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti

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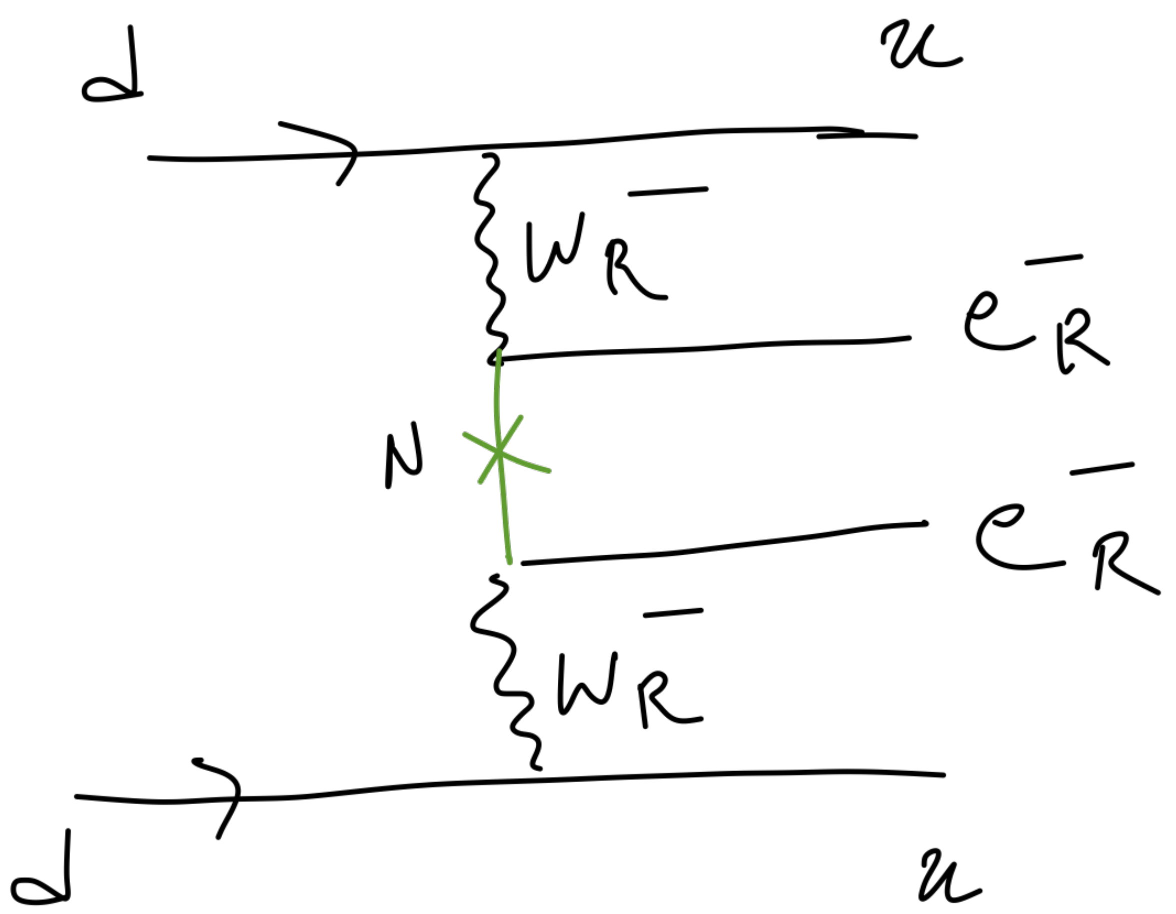
Feynman diagrams contributing to the decay rate in the mLRSM

(Mohapatra and Senjanovic 1981)

- There are the following contributions (on top of the usual light neutrino contribution)



RR contribution

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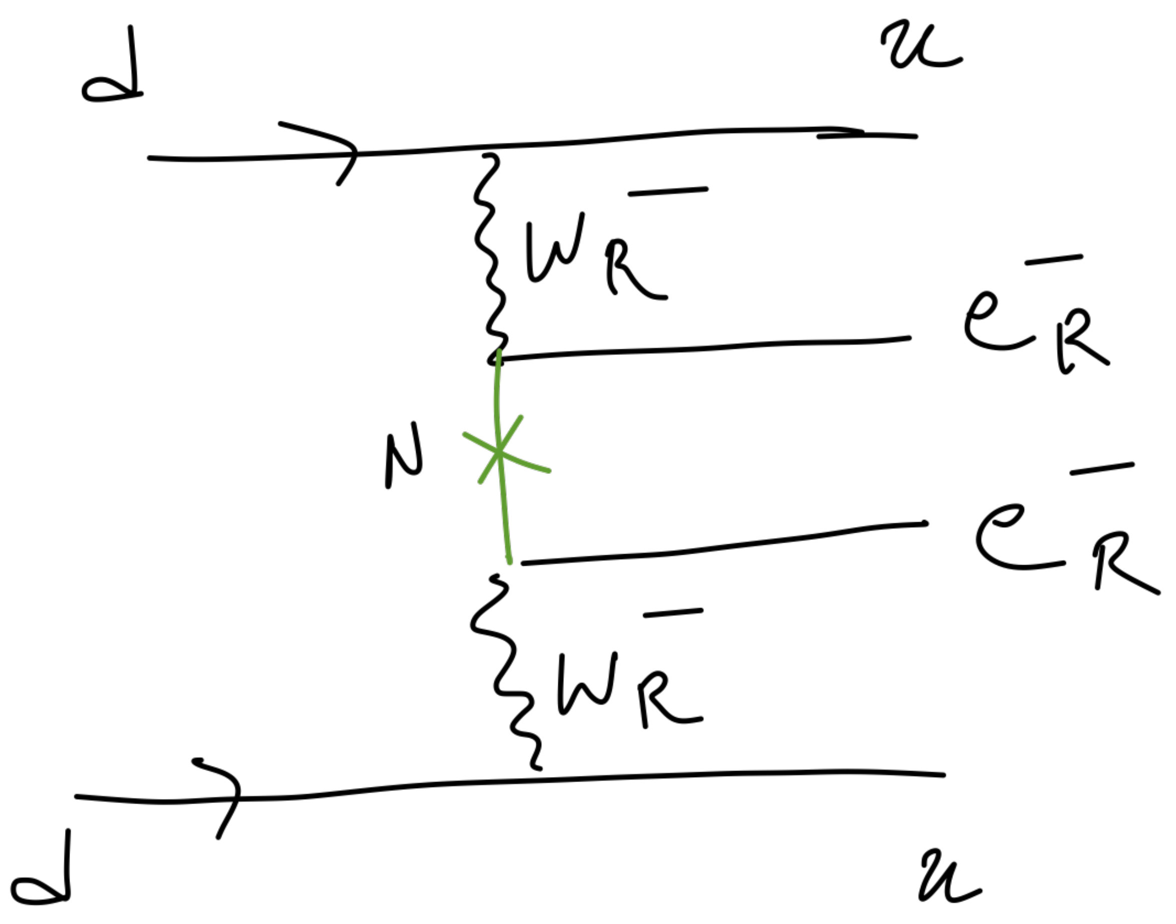
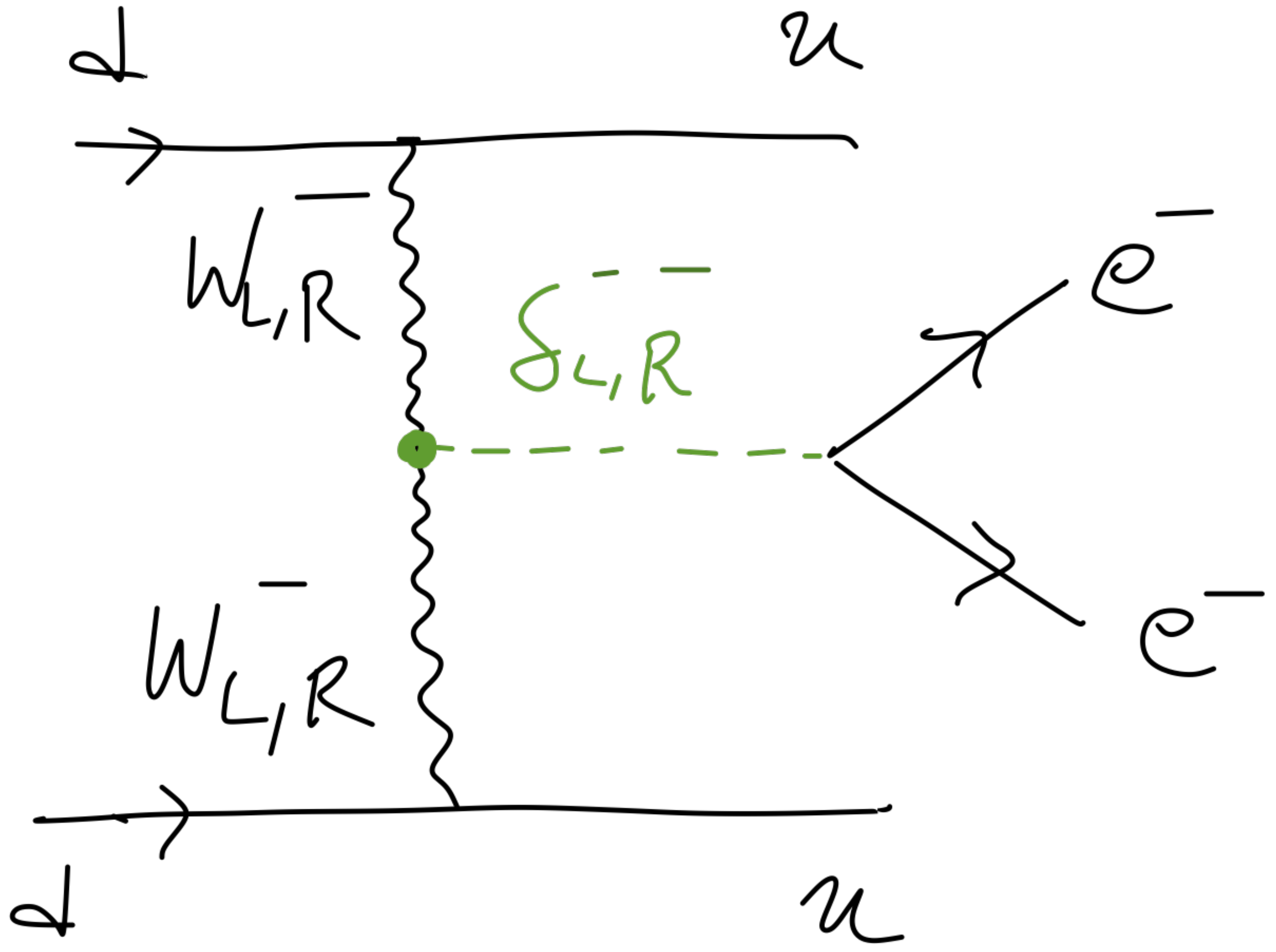
LL or RR





RR contribution

Suppressed by heavy

δ^{++} masses and LFV constraints (Tello and Senjanovic. ArXiv: 1011.3522)

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

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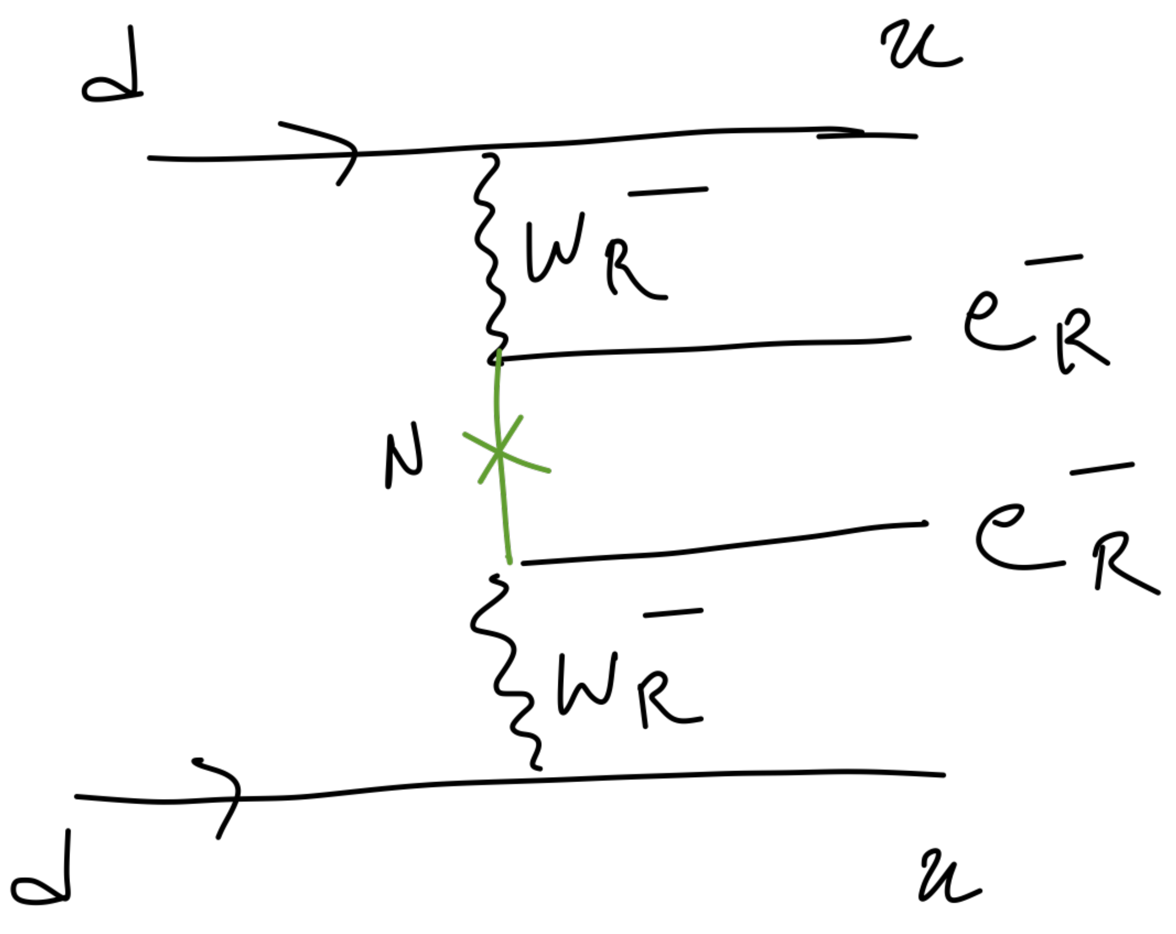
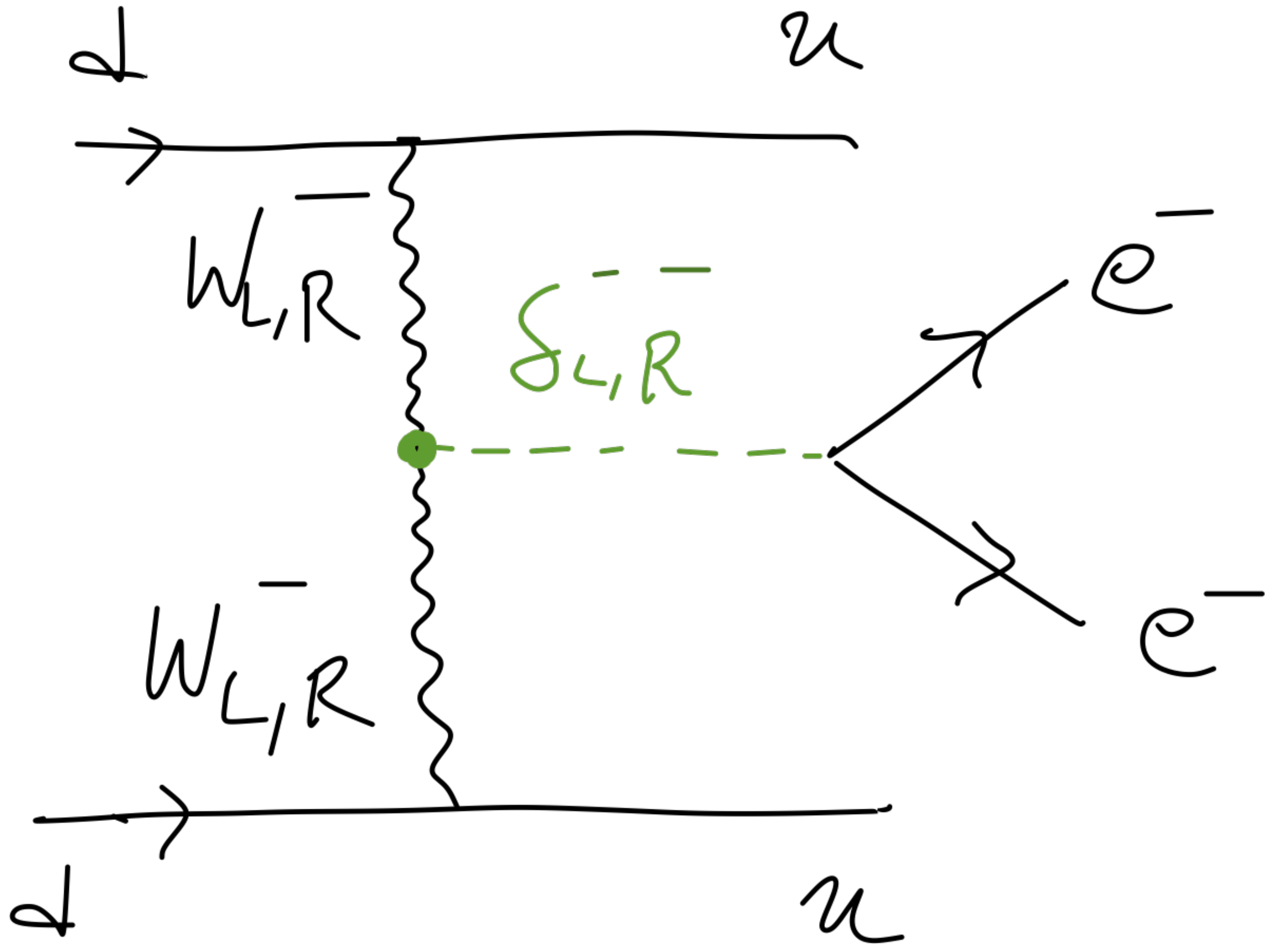
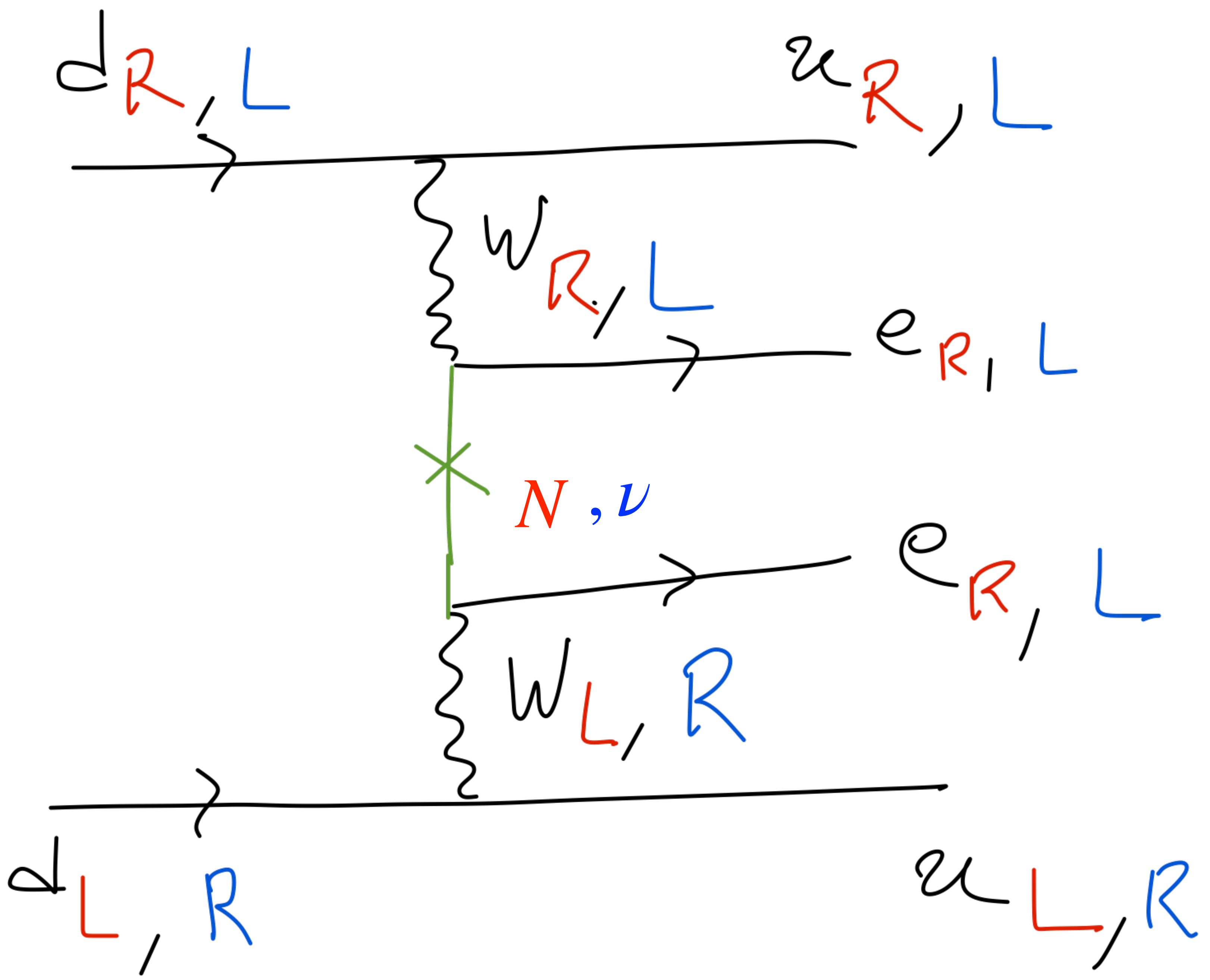
- There are the following contributions (on top of the usual light neutrino contribution)

LR contribution

LL or RR







RR contribution

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δ^{++} masses and LFV constraints (Tello and Senjanovic. ArXiv: 1011.3522)

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

The Blue contributions are

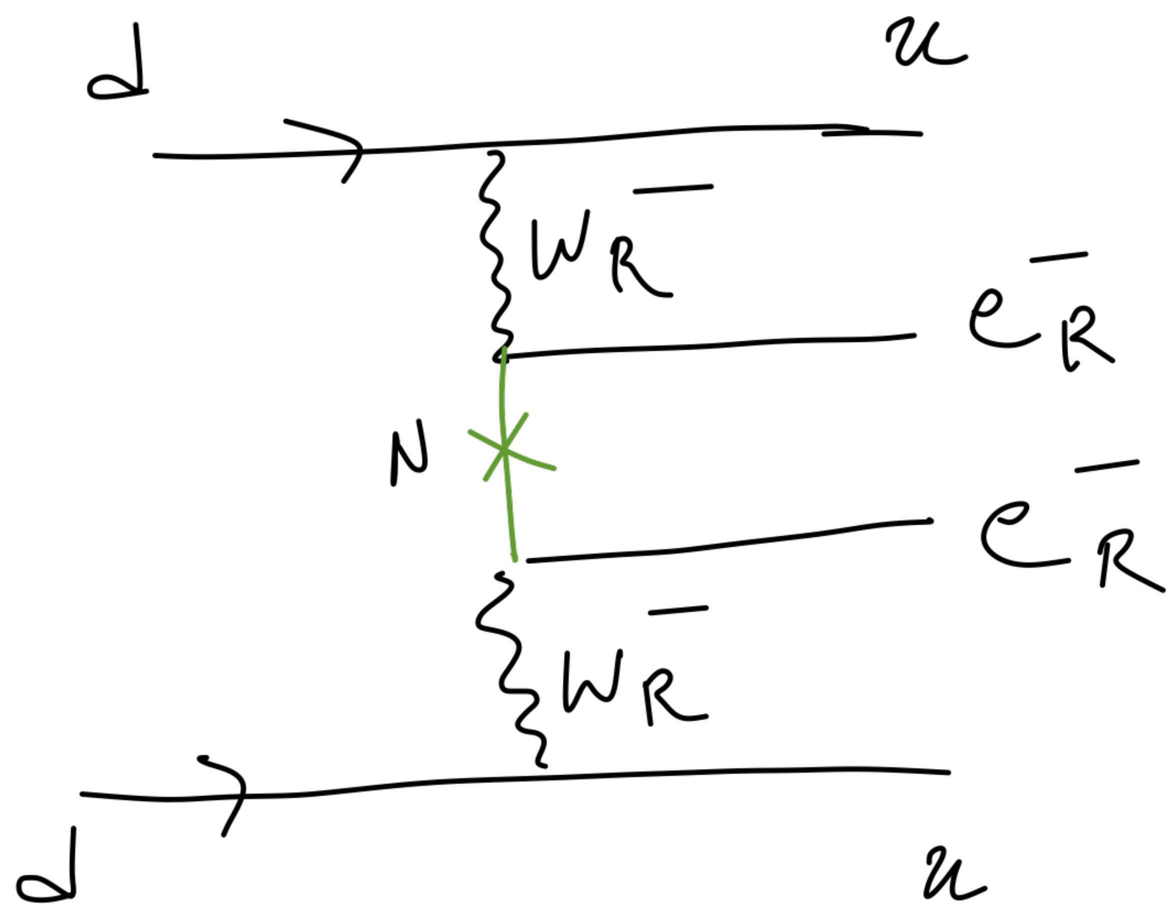
Suppressed by small heavy-light

Neutrino mixing

Feynman diagrams contributing to the decay rate in the mLRSM

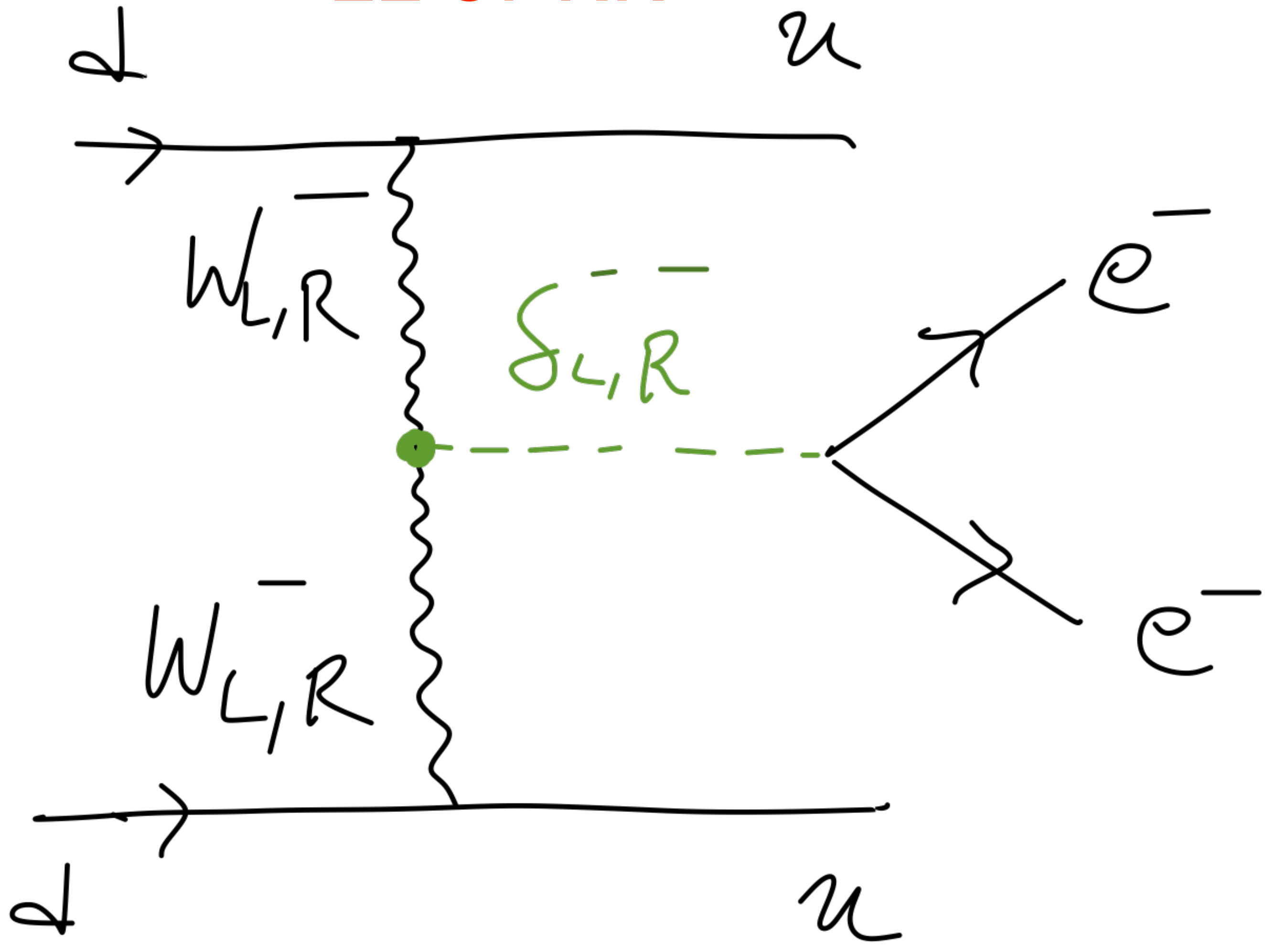
(Mohapatra and Senjanovic 1981)

- There are the following contributions (on top of the usual light neutrino contribution)



RR contribution

LL or RR



Suppressed by heavy

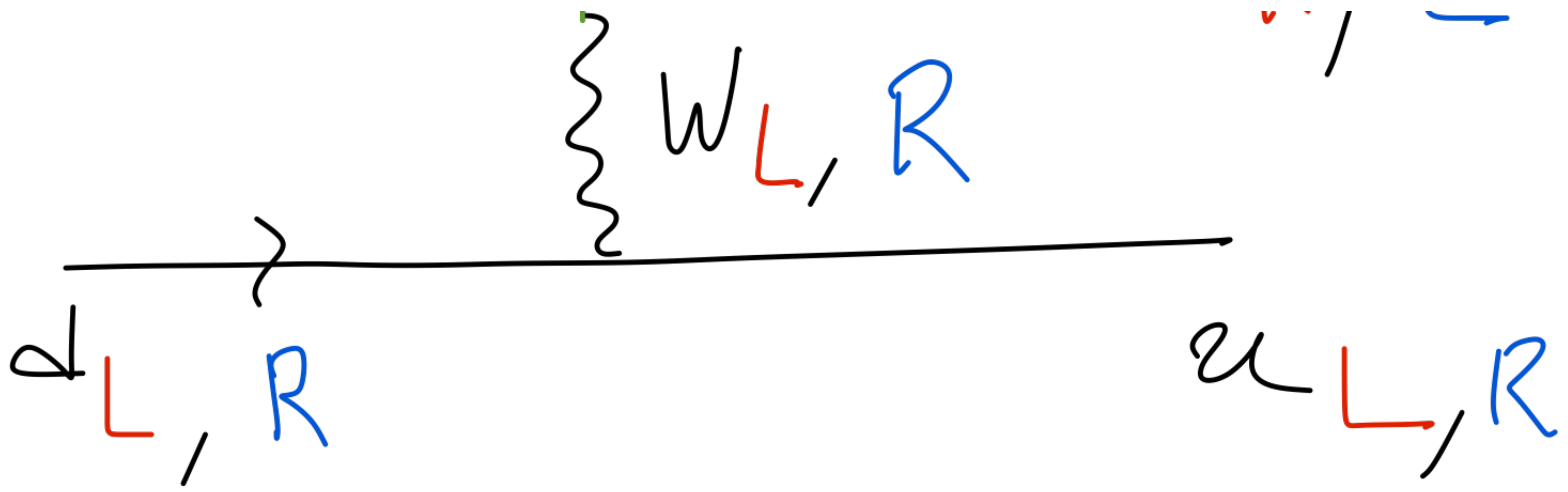
δ^{++} masses and LFV constraints (Tello and Senjanovic. ArXiv: 1011.3522)

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

See Tello's PhD thesis

For a detailed overview of

$0\nu2\beta$ in mLRSM



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Neutrino mixing

Effective Lagrangian in the mLRSM

- The effective Lagrangian for $0\nu 2\beta$

$$\mathscr{L}_{\text{eff}} = \frac{G_F^2}{\Lambda_{\beta\beta}}[C_{3R}(\mathcal{O}_{3+}^{++} - \mathcal{O}_{3-}^{++})(\bar{e}e^c - \bar{e}\gamma_5 e^c)$$

$$+C_{3L}(\mathcal{O}_{3+}^{++} + \mathcal{O}_{3-}^{++})(\bar{e}e^c - \bar{e}\gamma_5 e^c)$$

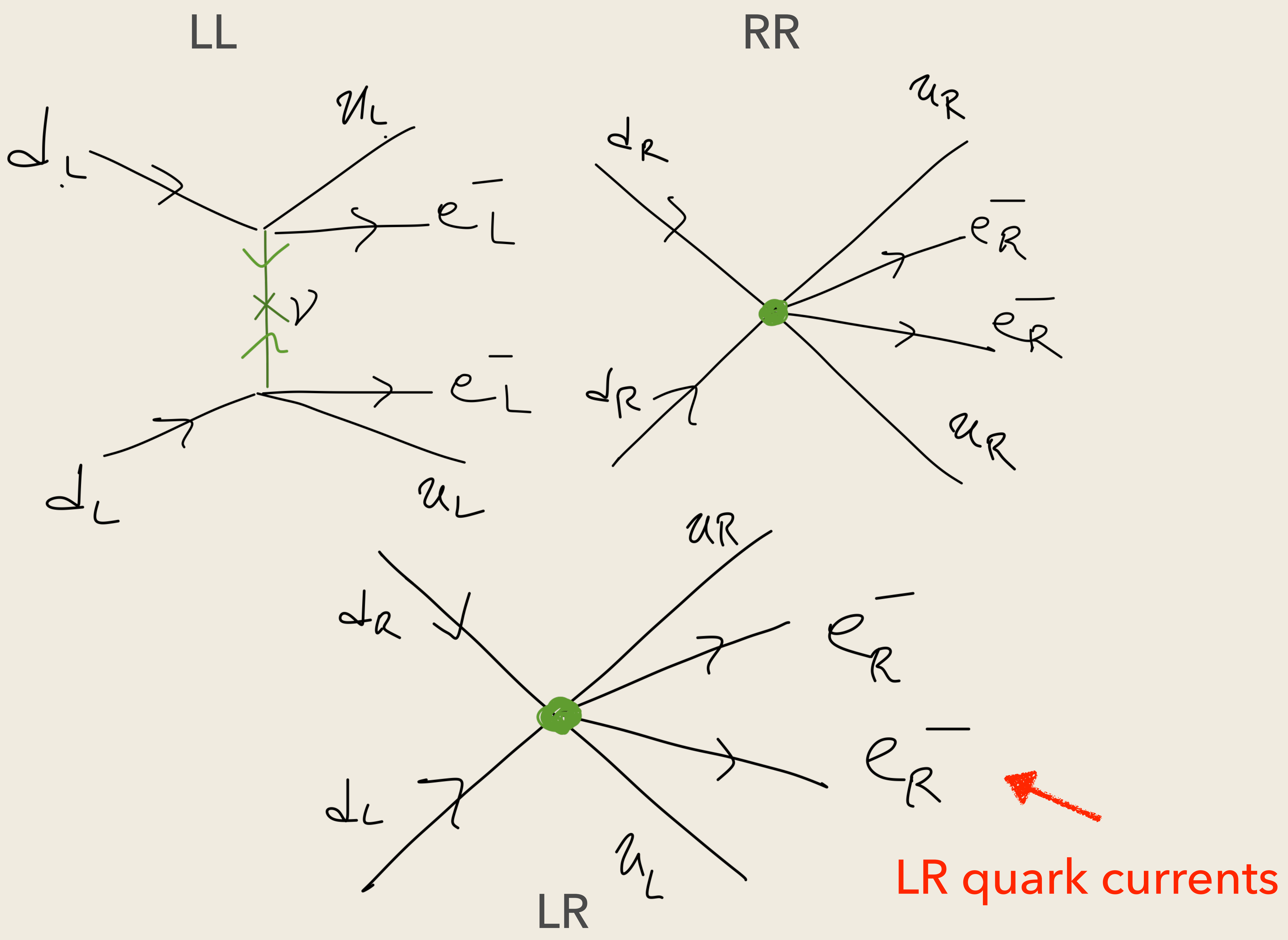
$$+C_1\mathcal{O}_{1+}^{++}(\bar{e}e^c - \bar{e}\gamma_5 e^c) + C_1'\mathcal{O}_{1+}^{++'}(\bar{e}e^c - \bar{e}\gamma_5 e^c)]$$

$$\mathcal{O}_{1+}^{++} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\alpha)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\beta)$$

$$\mathcal{O}_{1+}^{++'} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\beta)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\alpha)$$

$$\mathcal{O}_{3\pm}^{++} = (\bar{q}_{\mathrm{L}}\tau^+\gamma^\mu q_{\mathrm{L}})\left(\bar{q}_{\mathrm{L}}\tau^+\gamma_\mu q_{\mathrm{L}}\right) \pm (\bar{q}_{\mathrm{R}}\tau^+\gamma^\mu q_{\mathrm{R}})\left(\bar{q}_{\mathrm{R}}\tau^+\gamma_\mu q_{\mathrm{R}}\right).$$

$$1/\Lambda_{\beta\beta} = \sum_{j=1}^{3} V_{Rej}^2/m_{N_j}$$



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RGE generated at

$E \sim \Lambda_\chi$

$$\mathcal{O}_{1+}^{++} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\alpha)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\beta)$$

$$\mathcal{O}_{1+}^{++'} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\beta)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\alpha)$$

$$\mathcal{O}_{3\pm}^{++} = \left(\bar{q}_{\mathrm{L}} \tau^+ \gamma^\mu q_{\mathrm{L}}\right)\left(\bar{q}_{\mathrm{L}} \tau^+ \gamma_\mu q_{\mathrm{L}}\right) \pm \left(\bar{q}_{\mathrm{R}} \tau^+ \gamma^\mu q_{\mathrm{R}}\right)\left(\bar{q}_{\mathrm{R}} \tau^+ \gamma_\mu q_{\mathrm{R}}\right).$$

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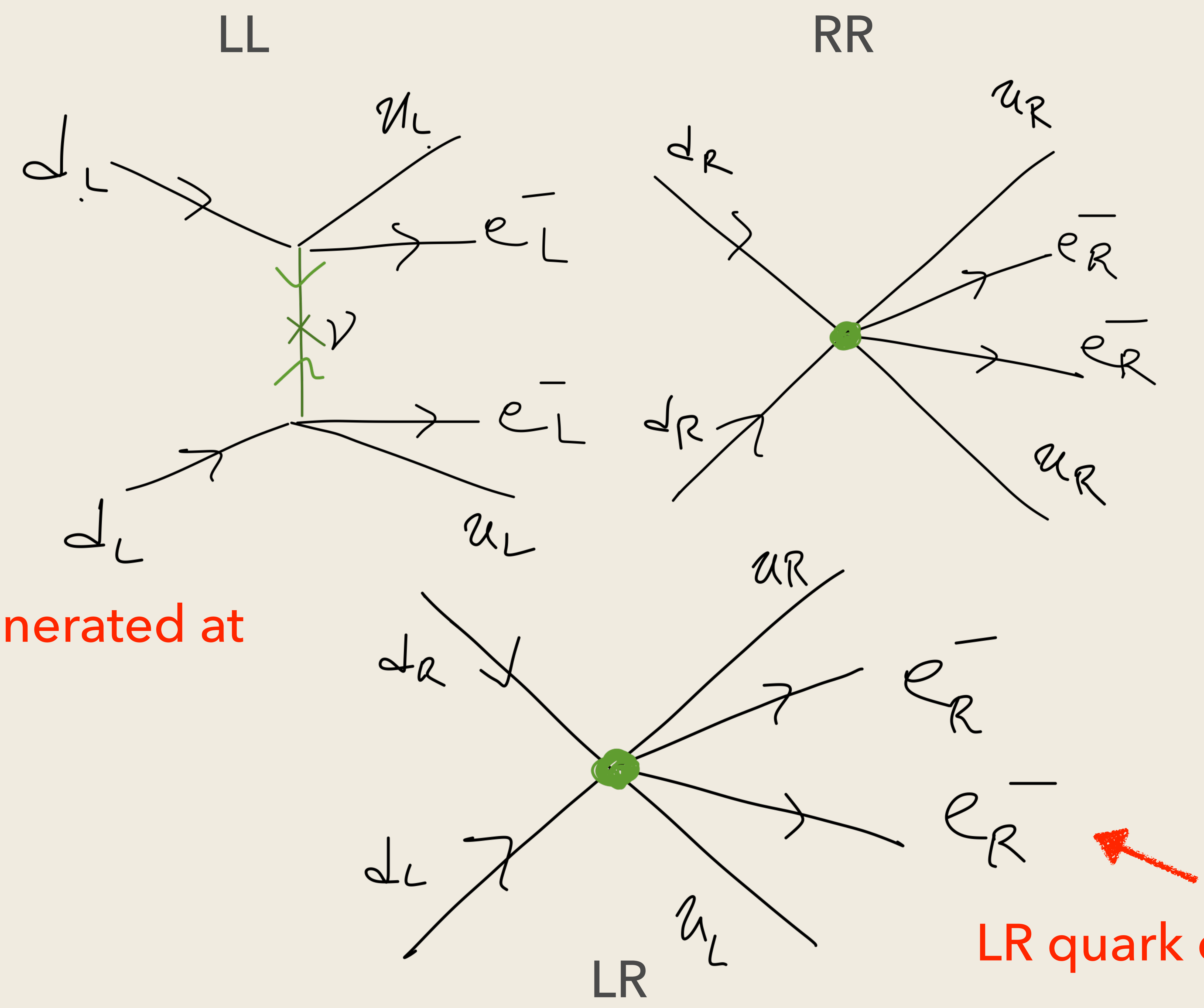


LR quark currents

Effective Lagrangian in the mLRSM

- The RGE of the Wilson coefficients are
(RGEs taken from V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti. ArXiv: 1806.02780)

$$\begin{pmatrix} C_1(2\ \mathrm{GeV}) \\ C_1'(2\ \mathrm{GeV}) \end{pmatrix} = \begin{pmatrix} 0.90 & 0 \\ 0.48 & 2.32 \end{pmatrix} \begin{pmatrix} C_1(7\ \mathrm{TeV}) \\ C_1'(7\ \mathrm{TeV}) \end{pmatrix}$$

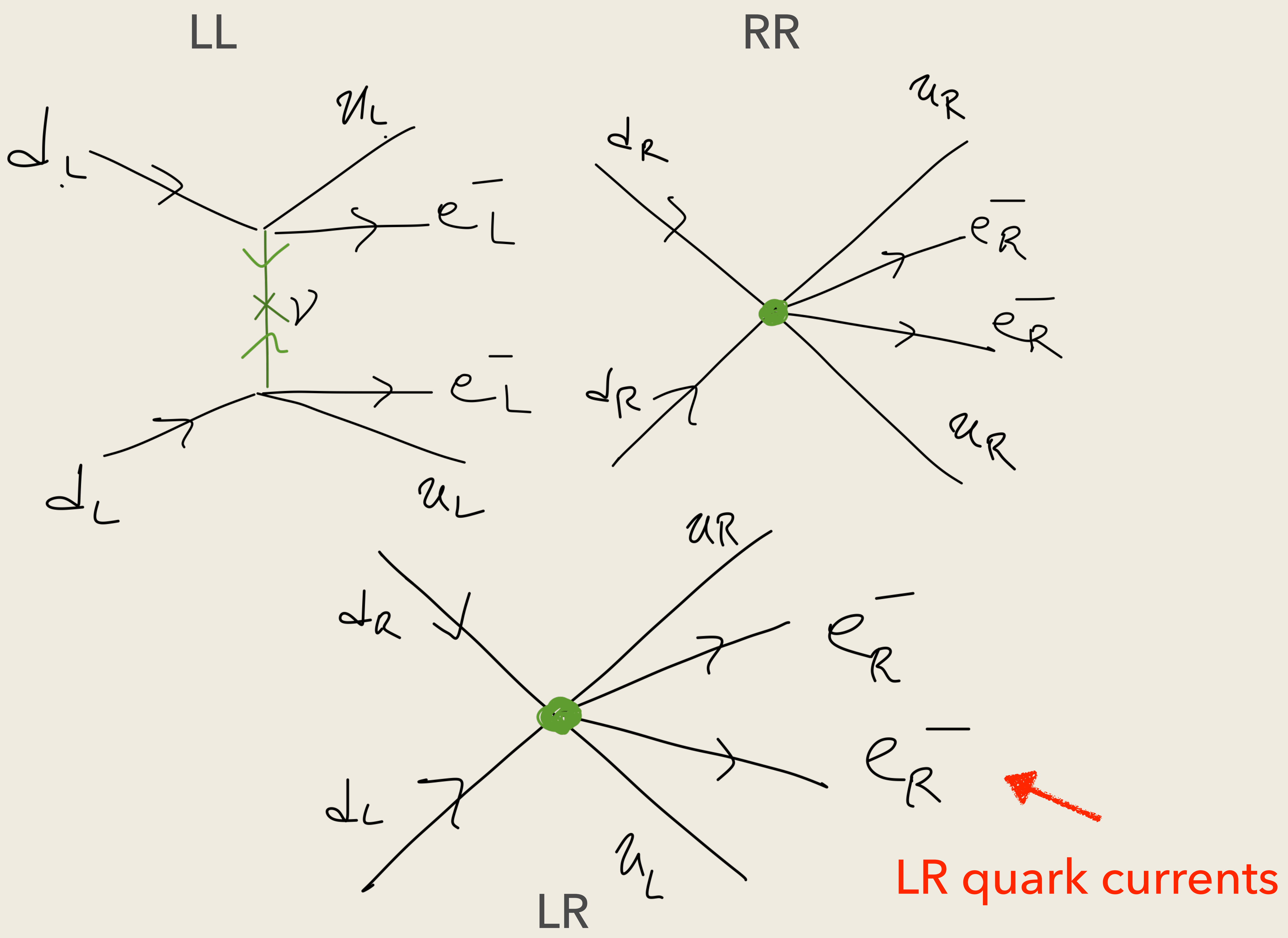
with $C_1'(M_{W_R}) = 0$ and $\lambda \equiv \dfrac{M_W^2}{M_{W_R}^2}$

$$\begin{pmatrix} C_{3L}(2\ \mathrm{GeV}) \\ C_{3R}(2\ \mathrm{GeV}) \end{pmatrix} = \begin{pmatrix} 0.71 & 0 \\ 0 & 0.71 \end{pmatrix} \begin{pmatrix} C_{3L}(7\ \mathrm{TeV}) \\ C_{3R}(7\ \mathrm{TeV}) \end{pmatrix}$$

at $\mu = M_{W_R}$

$$C_{3R} = -\lambda^2 \left(1 + \frac{4\Lambda_{\beta\beta}^2}{M_{\Delta_R}^2}\right), \qquad C_{3L} = \xi^2,$$

$$C_1 = -4\lambda\xi$$



The chiral Lagrangian induced by the effective interaction

Feinberg and Goldhaber 1959

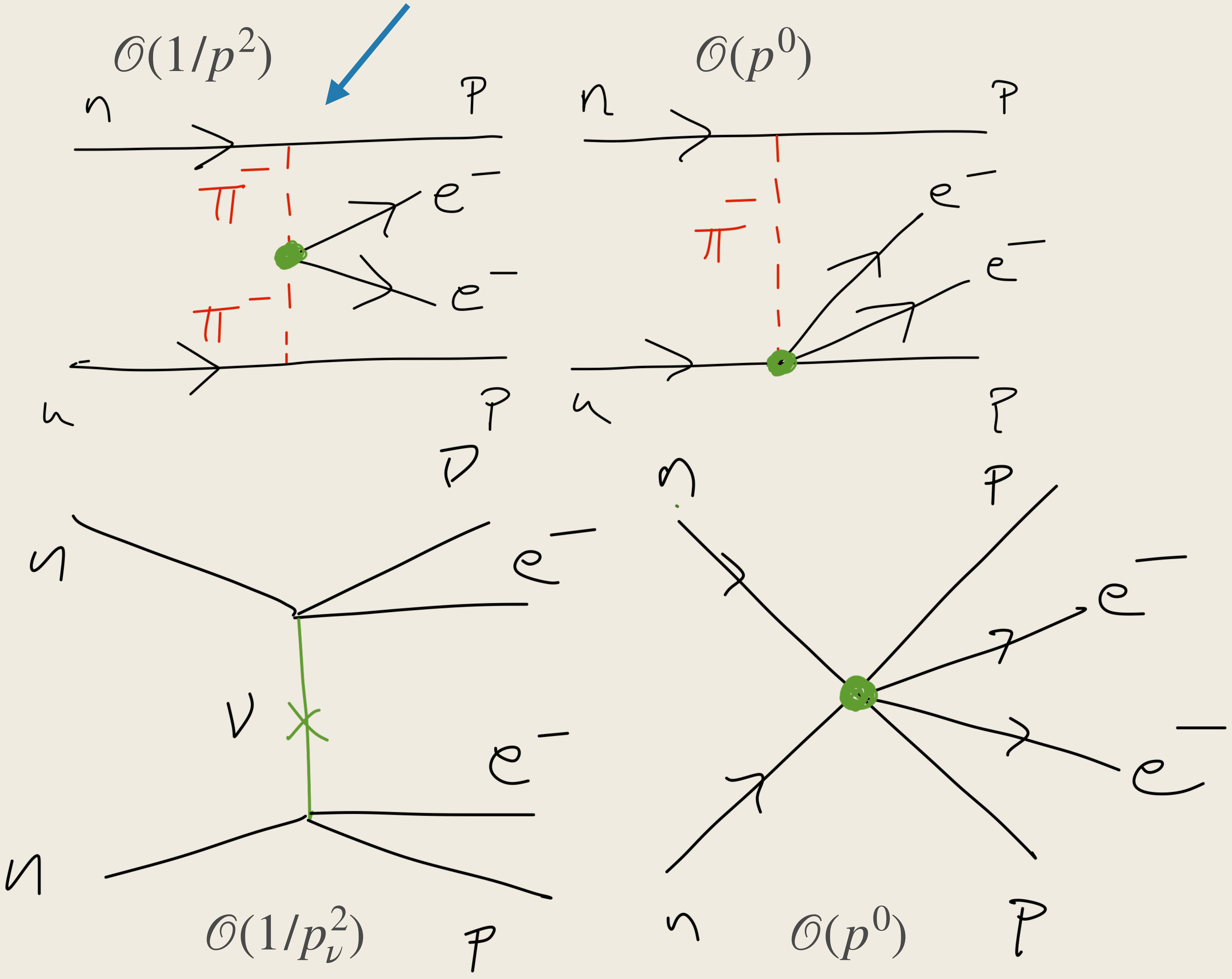
- At the hadronic level $\mathcal{O}^{++}_{1+}$ and using Weinberg's power counting, it gives a LO contribution to $\pi\pi e e^c$ vertex

$$\mathcal{O}^{\pm\pm}_{1+} \to \frac{4}{f_\pi^2}\pi^{\mp}\pi^{\mp} + \cdots,$$ LO contribution

- At NLO it induces the $NN\pi$ piece

$$\mathcal{O}^{\pm\pm}_{1+} \to \bar{N}\gamma^5\Phi^{\pm\pm}_{1-}N \to p_\pi/m_N$$ (NLO)

$\Phi^{\pm\pm}_{1-} = \Phi^{\pm\pm}_{1-}(\pi' s)$, its form is not relevant for our arguments



The minimal left-right symmetric model

- Prezeau-Ramsey-Musolf-Vogel 2003. ArXiv: 0303205.
- enhanced as $\Lambda_H^2/p^2 \sim 10^2$

- At the hadronic level $\mathcal{O}_{1+}^{++}$ and using Weinberg's power counting, it gives a LO contribution to $\pi\pi ee^c$ vertex

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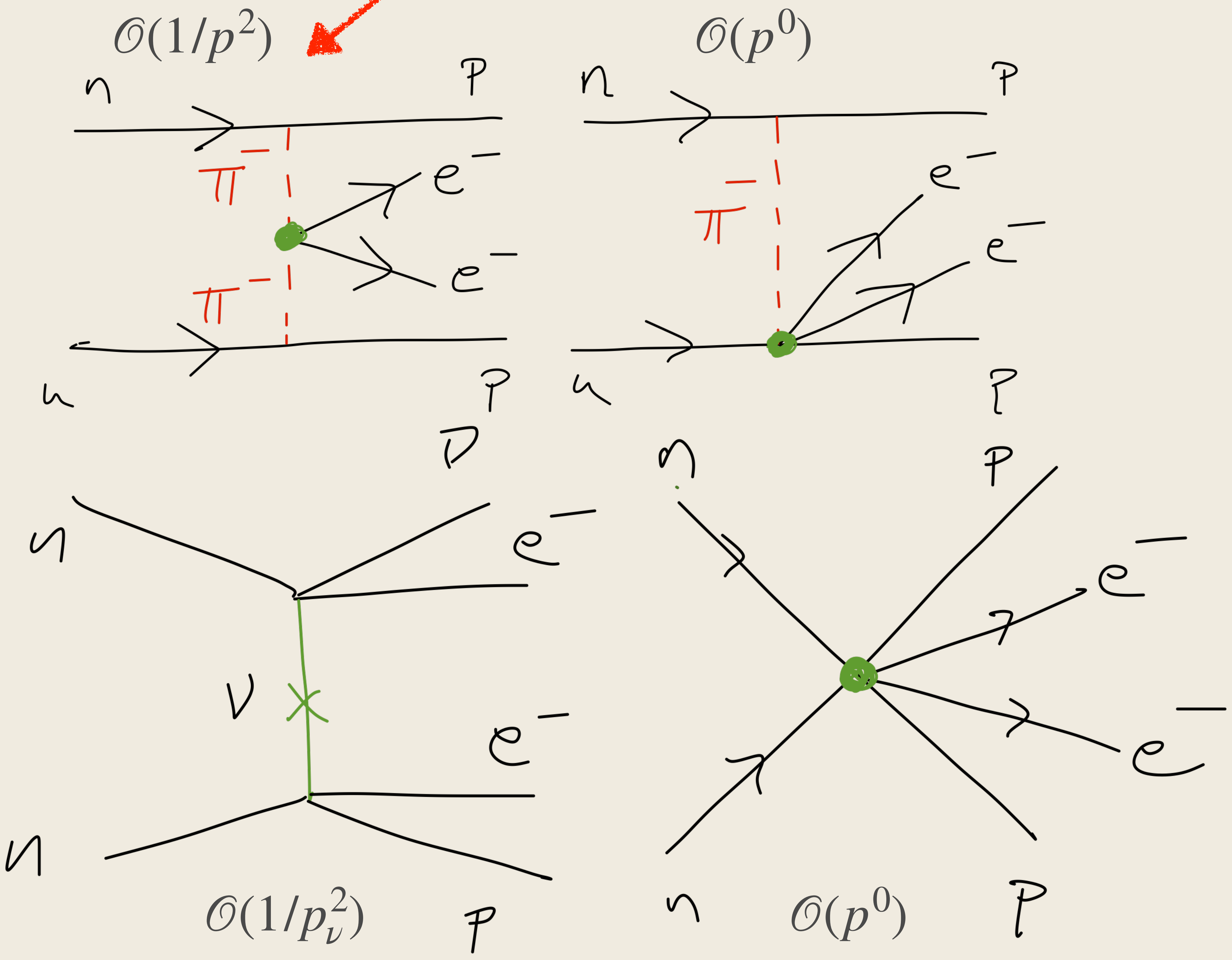

Pion interactions

- In more detail the interaction of the pions at the Λ_χ energy scale

$$\mathscr{L}^\pi = \frac{G_F^2 F_\pi^2}{\Lambda_{\beta\beta}} \Big\{ \Lambda_H^2 \pi^- \pi^- e(\beta_1 + \beta_2 \gamma^5) e^c$$

$$+ \partial_\mu \pi^- \partial^\mu \pi^- e(\beta_3 + \beta_4 \gamma^5) e^c$$

$$+ \Lambda_H / F_\pi \bar{N} \gamma_5 \tau^+ \pi^- N \bar{e}(\zeta_5 + \zeta_6 \gamma^5) e^c + \text{H.c.} \Big\},$$

Where

$$\beta_1 = -\beta_2 = \alpha_1^{\pi\pi} C_1 + \alpha_1^{\pi\pi\prime} C_1'$$

$$\beta_3 = -\beta_4 = \alpha_3^{\pi\pi} (C_{3L} + C_{3R})$$

$$\zeta_5 = -\zeta_6 = -2\sqrt{2} g_A \alpha_3^{\pi N} \frac{m_N}{\Lambda_H} (C_{3L} + C_{3R})$$

$\alpha_1^{\pi\pi} = -0.71$, $\alpha_1^{\pi\pi\prime} = -2.98$ and $\alpha_3^{\pi\pi} = 0.60$

Extracted from Lattice results in Nicholson et.al. arXiv:1805.02634

Agrees with V. Cirigliano, W. Dekens, M. Graesser and E. Mereghetti arXiv:1701.01443 using $SU(3)$ chiral symmetry

Finally

$$\alpha_3^{\pi N} \sim \mathcal{O}(1)$$

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right| \left(\left|m^{ee}_\nu\right|^2 + \left|m^{ee}_N\right|^2 \right)$$

$$\equiv G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_{\nu+N}\right|^2$$

- The new physics contribution

$$|m_N^{ee}|^2 = \frac{\Lambda_H^4}{72\Lambda_{\beta\beta}^2} \frac{\mathcal{M}_0^2}{\mathcal{M}_\nu^2} \left[(\beta_1 + \zeta_5 \delta_{NN\pi} - \beta_3 \delta_{\pi\pi})^2 + (\beta_2 + \zeta_6 \delta_{NN\pi} - \beta_4 \delta_{\pi\pi})^2 \right], \quad \delta_{\pi\pi} \equiv \frac{2m_\pi^2}{\Lambda_H^2} \frac{\mathcal{M}_2}{\mathcal{M}_0}, \quad \delta_{NN\pi} \equiv \frac{\sqrt{2} m_\pi^2}{g_A \Lambda_H m_N} \frac{\mathcal{M}_1}{\mathcal{M}_0}.$$

We use $\mathcal{M}_\nu = 2.91$ $\mathcal{M}_0 = 2.64$, $\mathcal{M}_1 = 5.52$ and $\mathcal{M}_2 = 4.20$ for ^{136}Xe.

(NME taken from V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti. ArXiv: 1806.02780)

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Hadronic matrix elements

- The new physics contribution

$$|m^{ee}_N|^2 = \frac{\Lambda^4_H}{72\Lambda^2_{\beta\beta}} \frac{\mathcal{M}^2_0}{\mathcal{M}^2_\nu} \left[(\beta_1 + \zeta_5 \delta_{NN\pi} - \beta_3 \delta_{\pi\pi})^2 + (\beta_2 + \zeta_6 \delta_{NN\pi} - \beta_4 \delta_{\pi\pi})^2 \right], \quad \delta_{\pi\pi} \equiv \frac{2m^2_\pi}{\Lambda^2_H} \frac{\mathcal{M}_2}{\mathcal{M}_0}, \quad \delta_{NN\pi} \equiv \frac{\sqrt{2}m^2_\pi}{g_A \Lambda_H m_N} \frac{\mathcal{M}_1}{\mathcal{M}_0}.$$

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$$\equiv G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_{\nu+N}\right|^2$$

- The new physics contribution

These are the leading parts

$$\beta_1 = -\beta_2 = \alpha_1^{\pi\pi} C_1 + \alpha_1^{\pi\pi\prime} C_1'$$
$$\beta_3 = -\beta_4 = \alpha_3^{\pi\pi}(C_{3L} + C_{3R})$$
$$\zeta_5 = -\zeta_6 = -2\sqrt{2} g_A \alpha_3^{\pi N} \frac{m_N}{\Lambda_H}(C_{3L} + C_{3R})$$

$$C_1 \propto \frac{m_W^4}{m_{W_R}^4} \tan\beta$$

$\propto W_L - W_R$ mixing $\qquad$ $\propto W_L - W_R$ mixing

$$|m^{ee}_N|^2 = \frac{\Lambda_H^4}{72\Lambda_{\beta\beta}^2} \frac{\mathcal{M}_0^2}{\mathcal{M}_\nu^2}\left[(\beta_1 + \zeta_5\delta_{NN\pi} - \beta_3\delta_{\pi\pi})^2 + (\beta_2 + \zeta_6\delta_{NN\pi} - \beta_4\delta_{\pi\pi})^2\right],$$

We use $\mathcal{M}_\nu = 2.91$ $\mathcal{M}_0 = 2.64$, $\mathcal{M}_1 = 5.52$ and $\mathcal{M}_2 = 4.20$ for ^{136}Xe.

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right| \left(\left|m^{ee}_\nu\right|^2 + \left|m^{ee}_N\right|^2 \right)$$

chiral suppression of the RR contributions $\sim p^2/\Lambda_H^2 \approx 1/30$

$$\equiv G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_{\nu+N}\right|^2$$

- The new physics contribution

$$|m^{ee}_N|^2 = \frac{\Lambda_H^4}{72\Lambda_{\beta\beta}^2}\frac{\mathcal{M}_0^2}{\mathcal{M}_\nu^2}\left[(\beta_1 + \zeta_5\delta_{NN\pi} - \beta_3\delta_{\pi\pi})^2 + (\beta_2 + \zeta_6\delta_{NN\pi} - \beta_4\delta_{\pi\pi})^2\right], \quad \delta_{\pi\pi} \equiv \frac{2m_\pi^2}{\Lambda_H^2}\frac{\mathcal{M}_2}{\mathcal{M}_0}, \quad \delta_{NN\pi} \equiv \frac{\sqrt{2}m_\pi^2}{g_A\Lambda_H m_N}\frac{\mathcal{M}_1}{\mathcal{M}_0}.$$

We use $\mathcal{M}_\nu = 2.91$ $\mathcal{M}_0 = 2.64$, $\mathcal{M}_1 = 5.52$ and $\mathcal{M}_2 = 4.20$ for ^{136}Xe.

(NME taken from V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti. ArXiv: 1806.02780)

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Heavy neutrino contribution

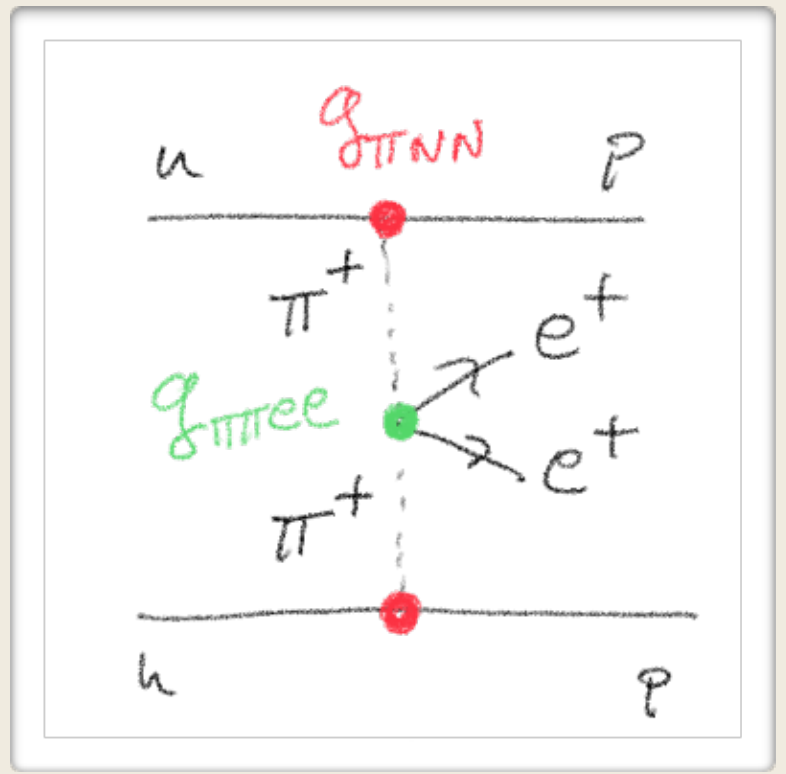
The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T_{1/2}^{0\nu})^{-1} = G \cdot \left|\mathcal{M}_\nu\right| \left(\left|m_\nu^{ee}\right|^2 + \left|m_N^{ee}\right|^2 \right)$$

$$\equiv G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m_{\nu+N}^{ee}\right|^2$$

LO



- The new physics contribution

$$|m_N^{ee}|^2 = \frac{\Lambda_H^4}{72\Lambda_{\beta\beta}^2} \frac{\mathcal{M}_0^2}{\mathcal{M}_\nu^2} \left[(\beta_1 + \zeta_5 \delta_{NN\pi} - \beta_3 \delta_{\pi\pi})^2 + (\beta_2 + \zeta_6 \delta_{NN\pi} - \beta_4 \delta_{\pi\pi})^2 \right], \quad \delta_{\pi\pi} \equiv \frac{2m_\pi^2}{\Lambda_H^2} \frac{\mathcal{M}_2}{\mathcal{M}_0}, \quad \delta_{NN\pi} \equiv \frac{\sqrt{2} m_\pi^2}{g_A \Lambda_H m_N} \frac{\mathcal{M}_1}{\mathcal{M}_0}.$$

+ counter term (see ahead)

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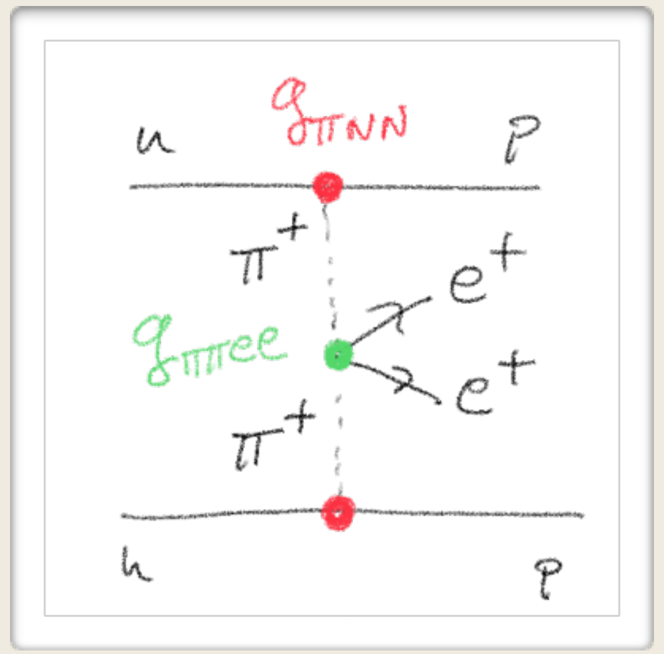
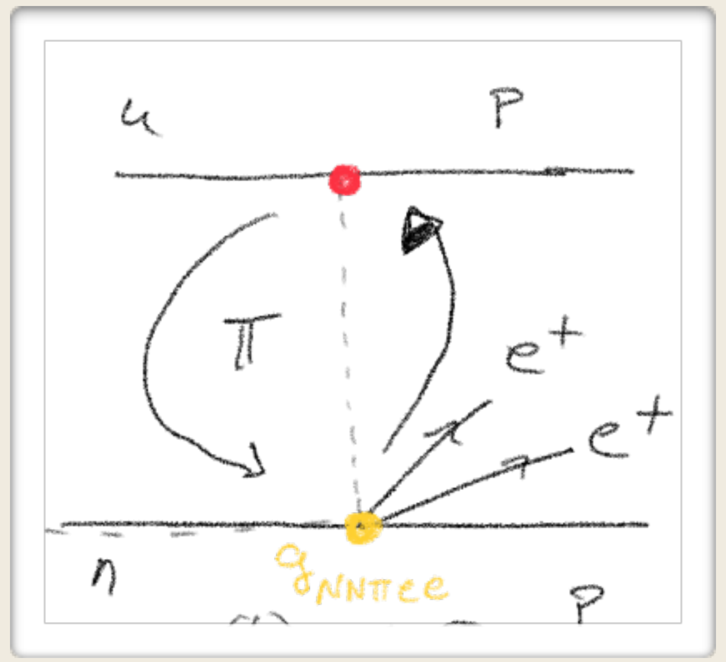
NNLO



NLO



- The new physics contribution

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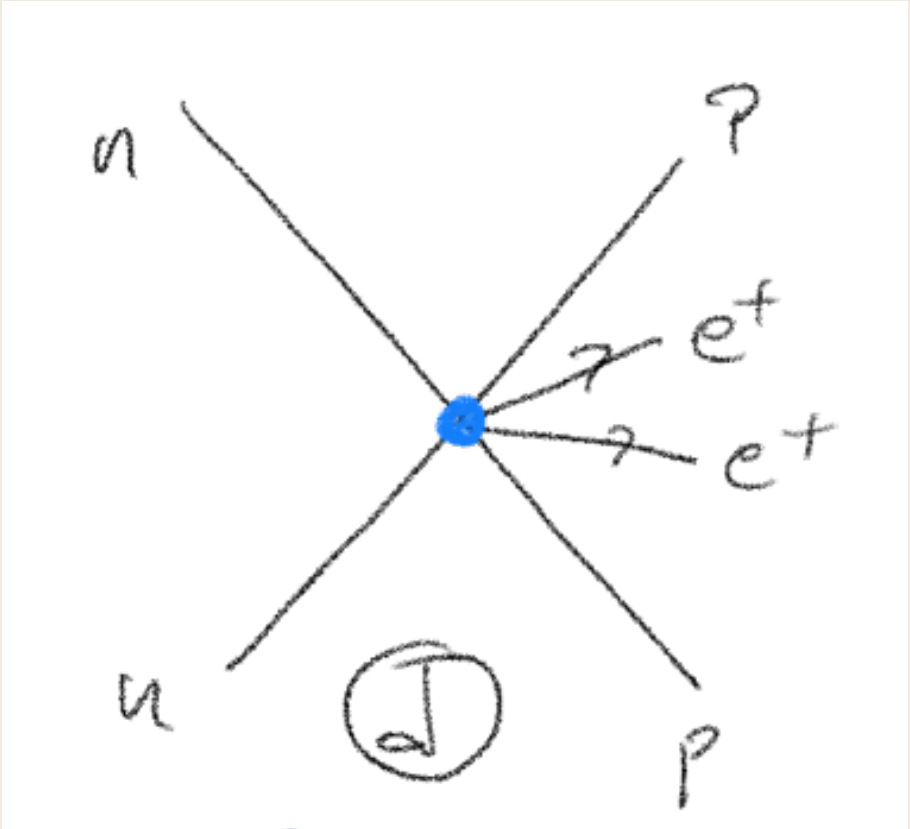
$$\equiv G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_{\nu+N}\right|^2$$

See Cirigliano

Talk on this issue



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Not quantified yet

Give an uncertainty to $\mathcal{M}_0$

Since it have to be used as

A counterterm of the two loop

Divergent diagram.

(arXiv:1806.02780, 1802.10097 and 1907.11254)

We use $\mathcal{M}_\nu = 2.91$ $\mathcal{M}_0 = 2.64$, $\mathcal{M}_1 = 5.52$ and $\mathcal{M}_2 = 4.20$ for ^{136}Xe.

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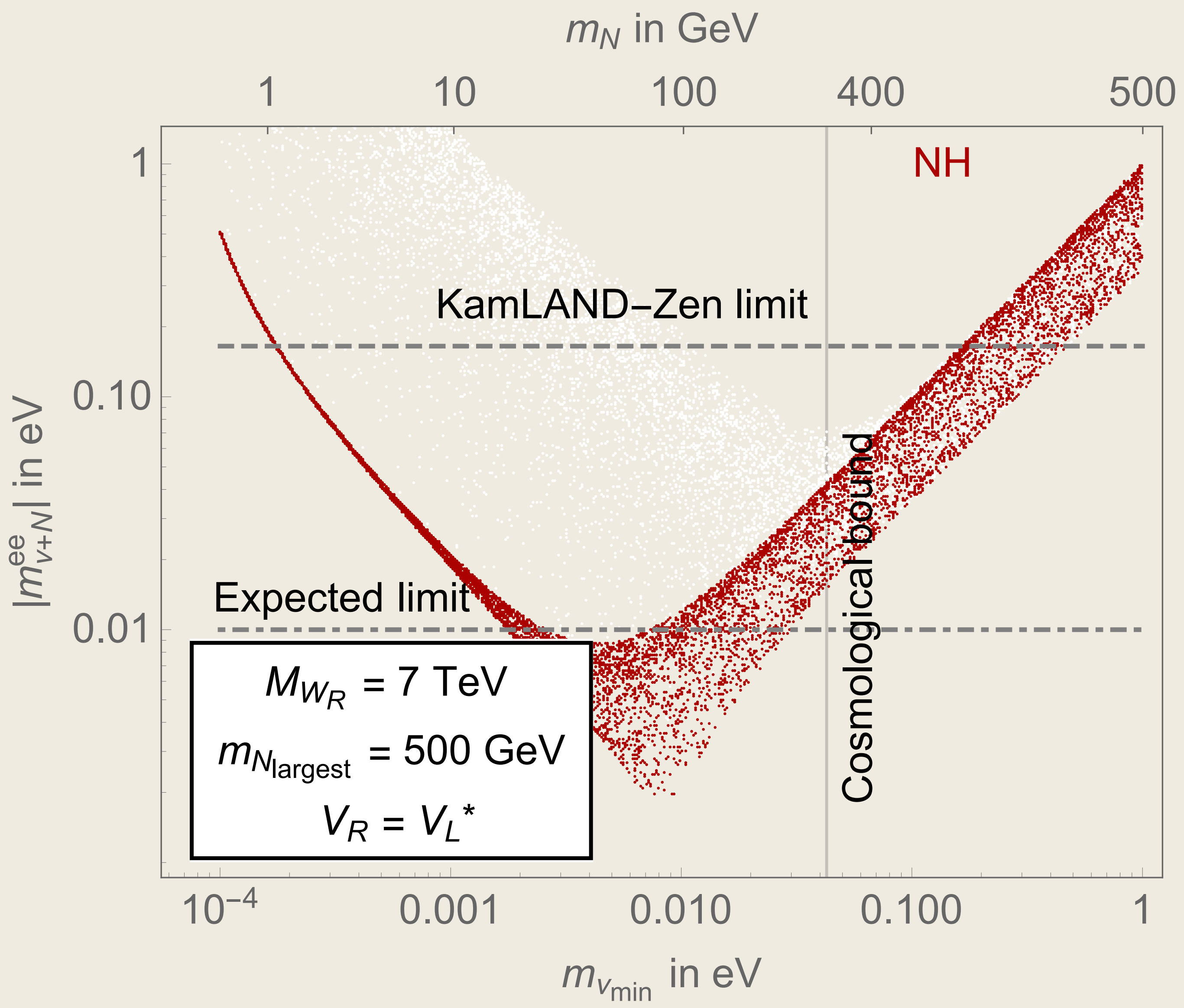
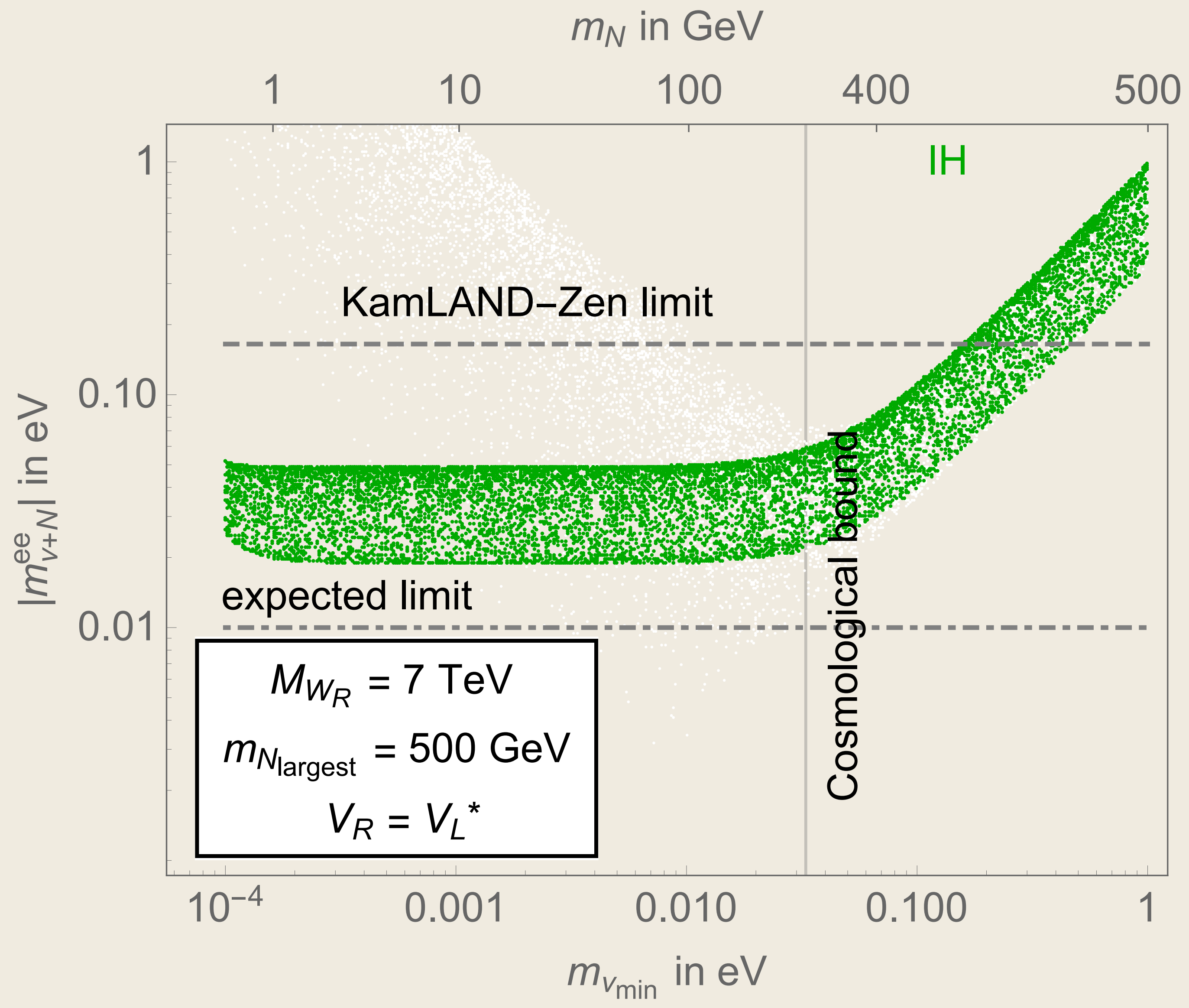
The decay rates

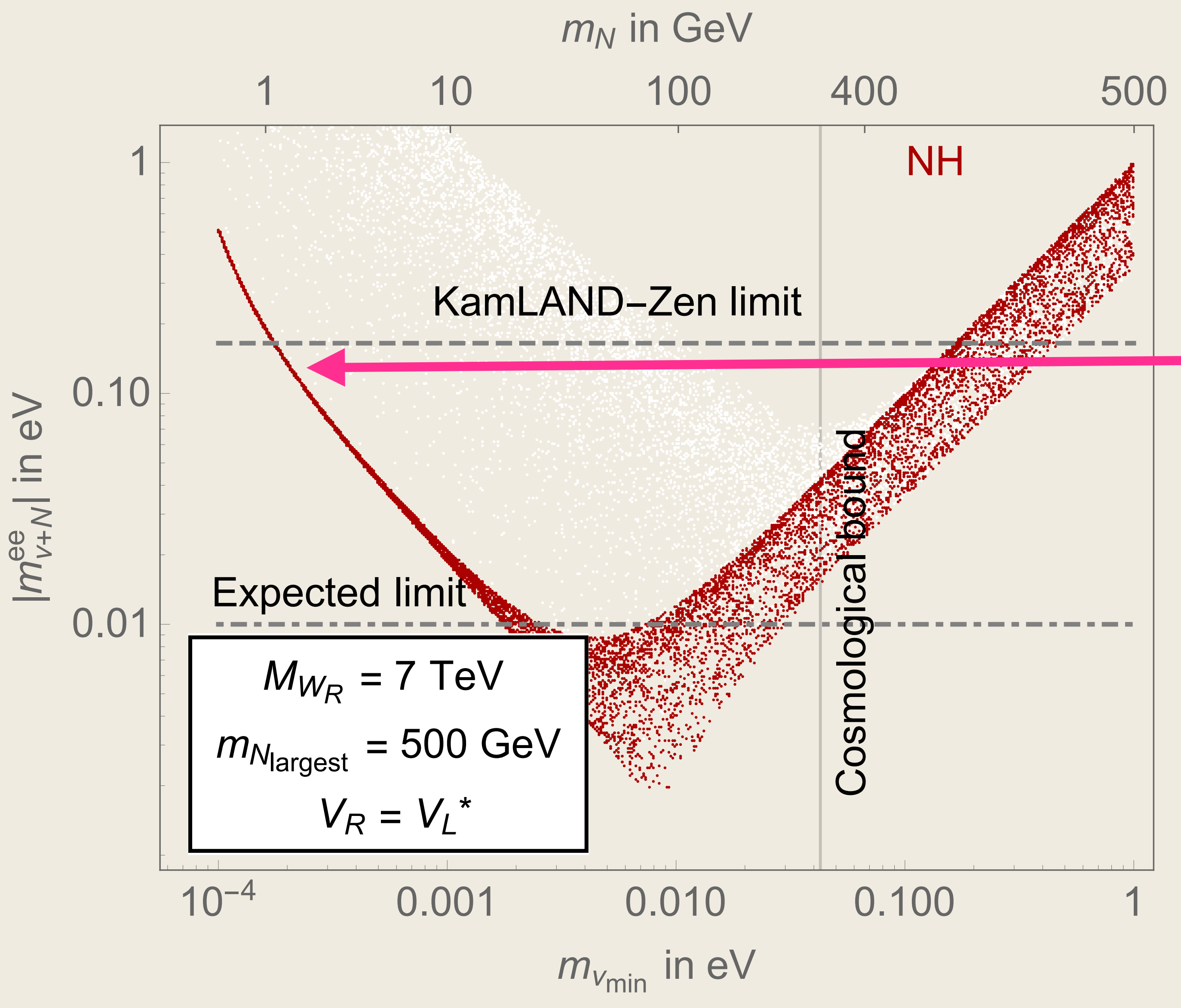




Bands come from varying the CPV phases in the mixing matrix

No long range Contributions

(Tello and Senjanovic. ArXiv: 1011.3522)



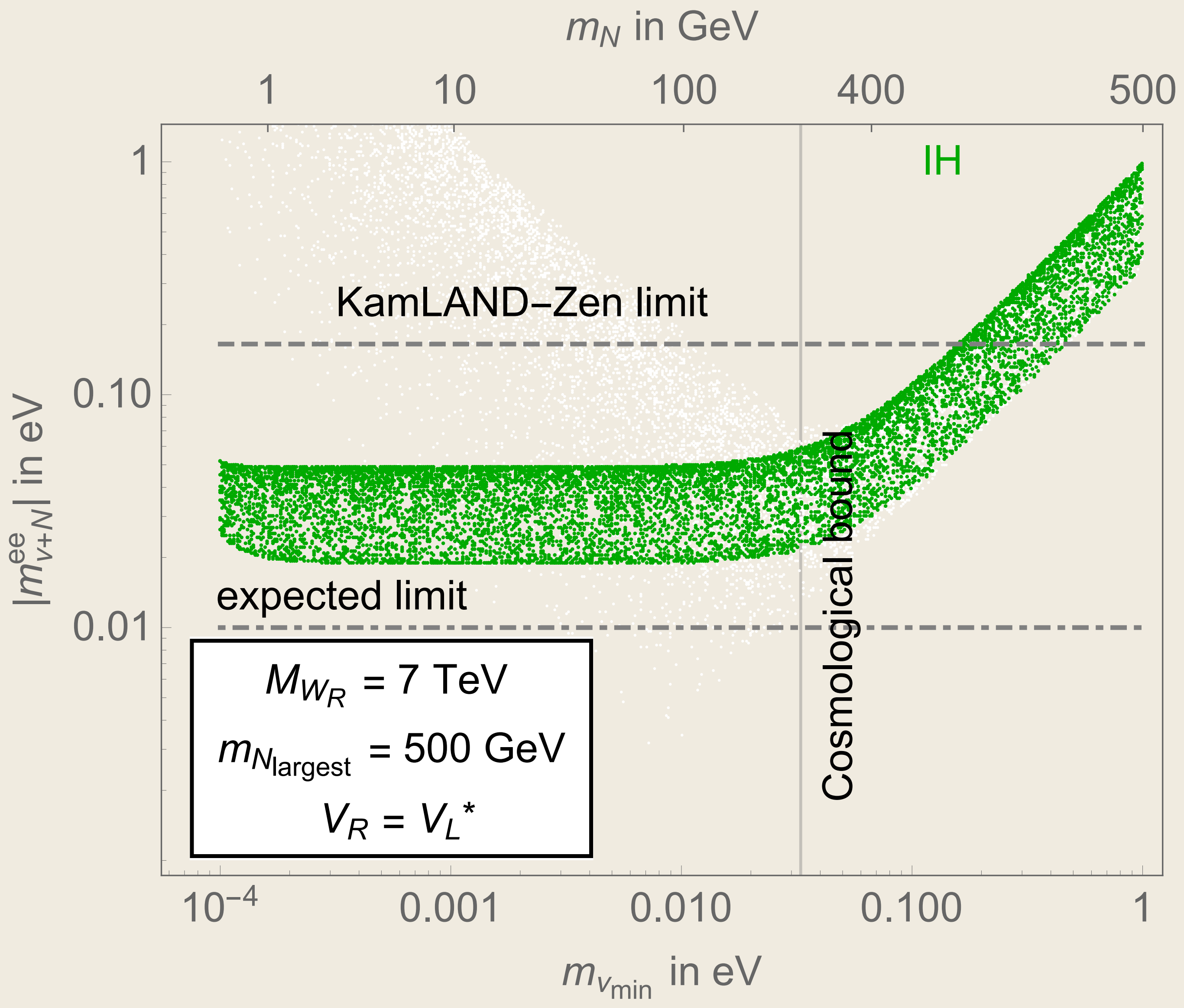
EFT not reliable here. See De Vries talk

(from De Vries, Dekens, Fuyuto, Mereghetti and Zhou

ArXiv: 2002.07182)

No long range

Contributions



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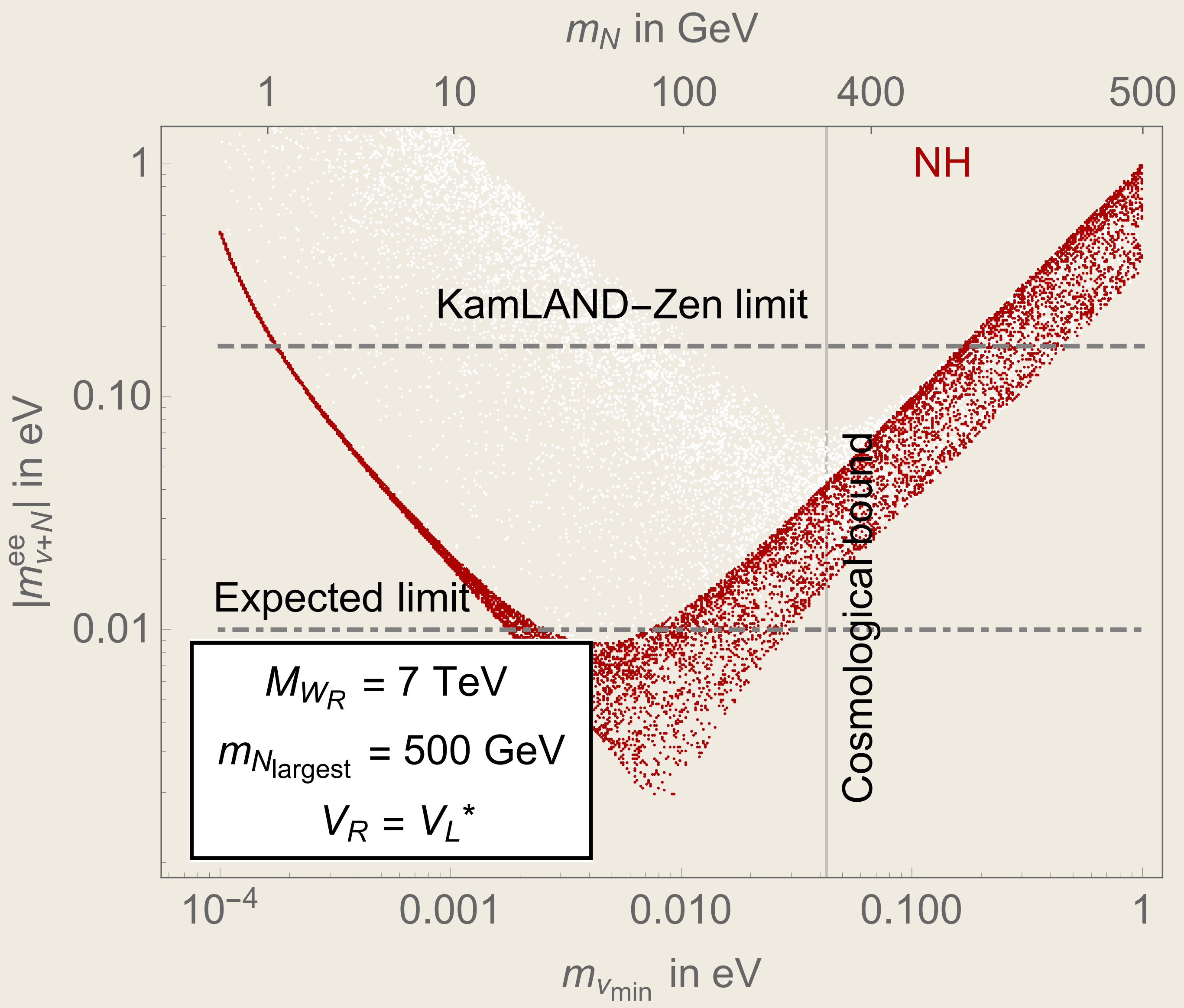
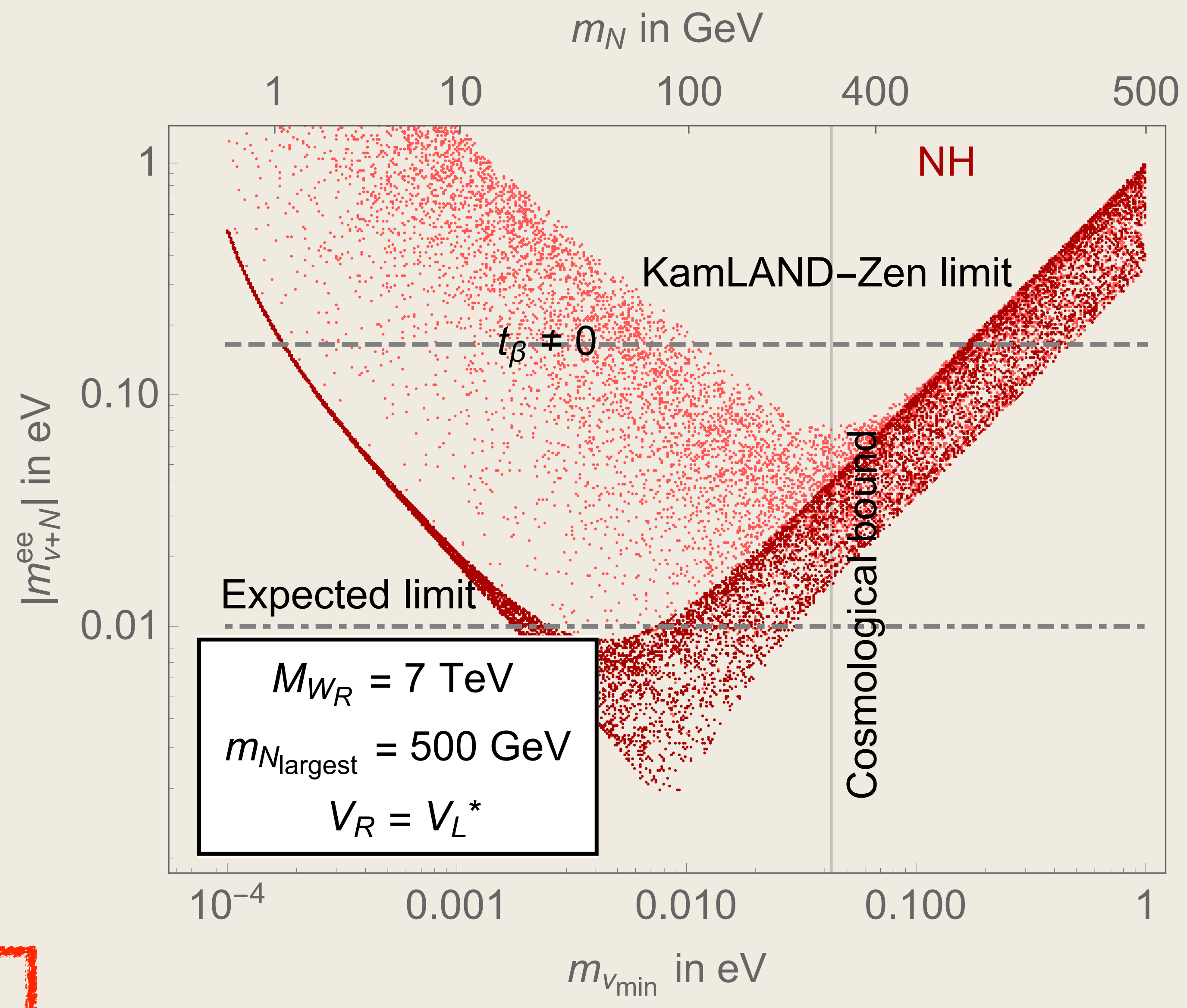
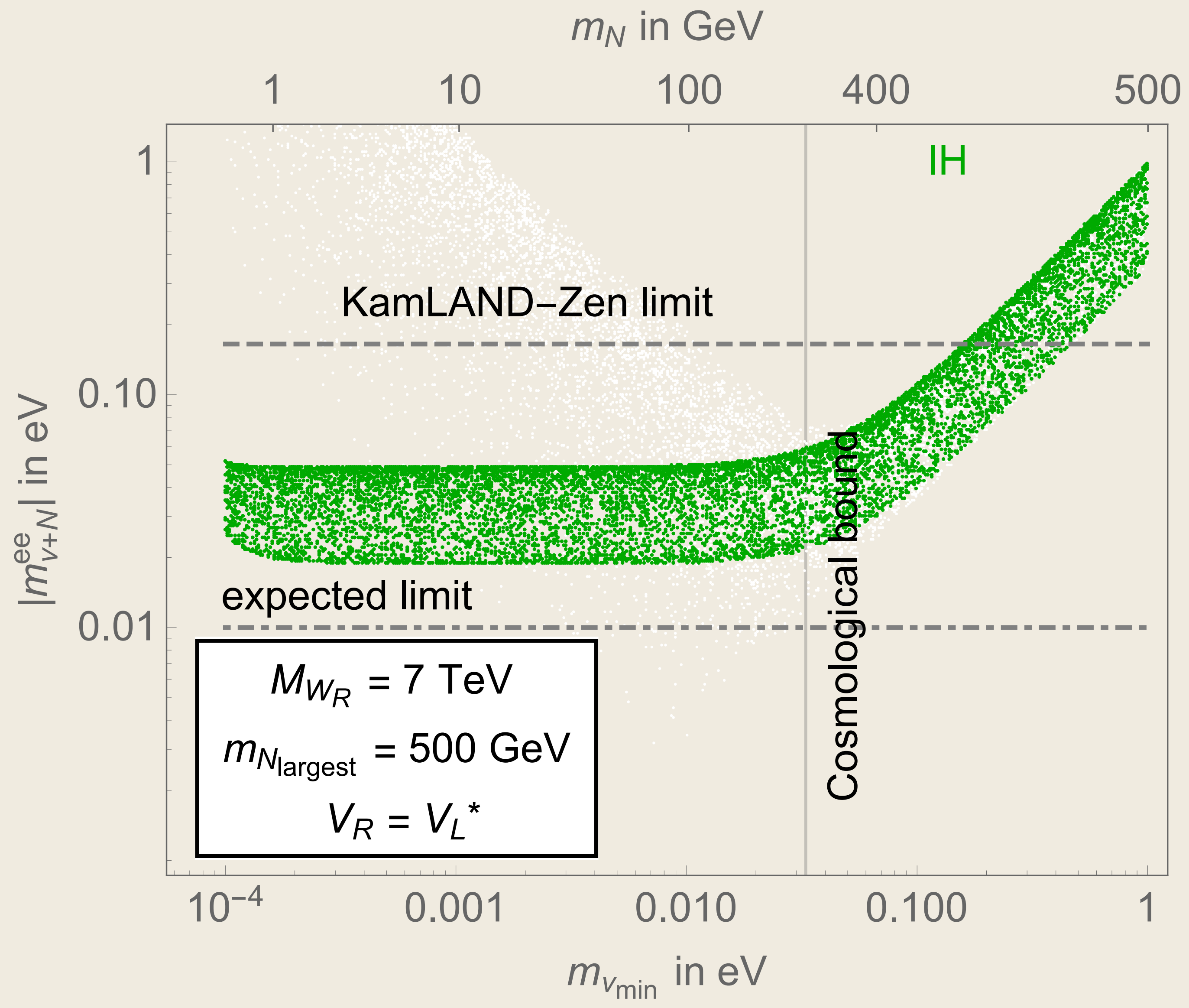


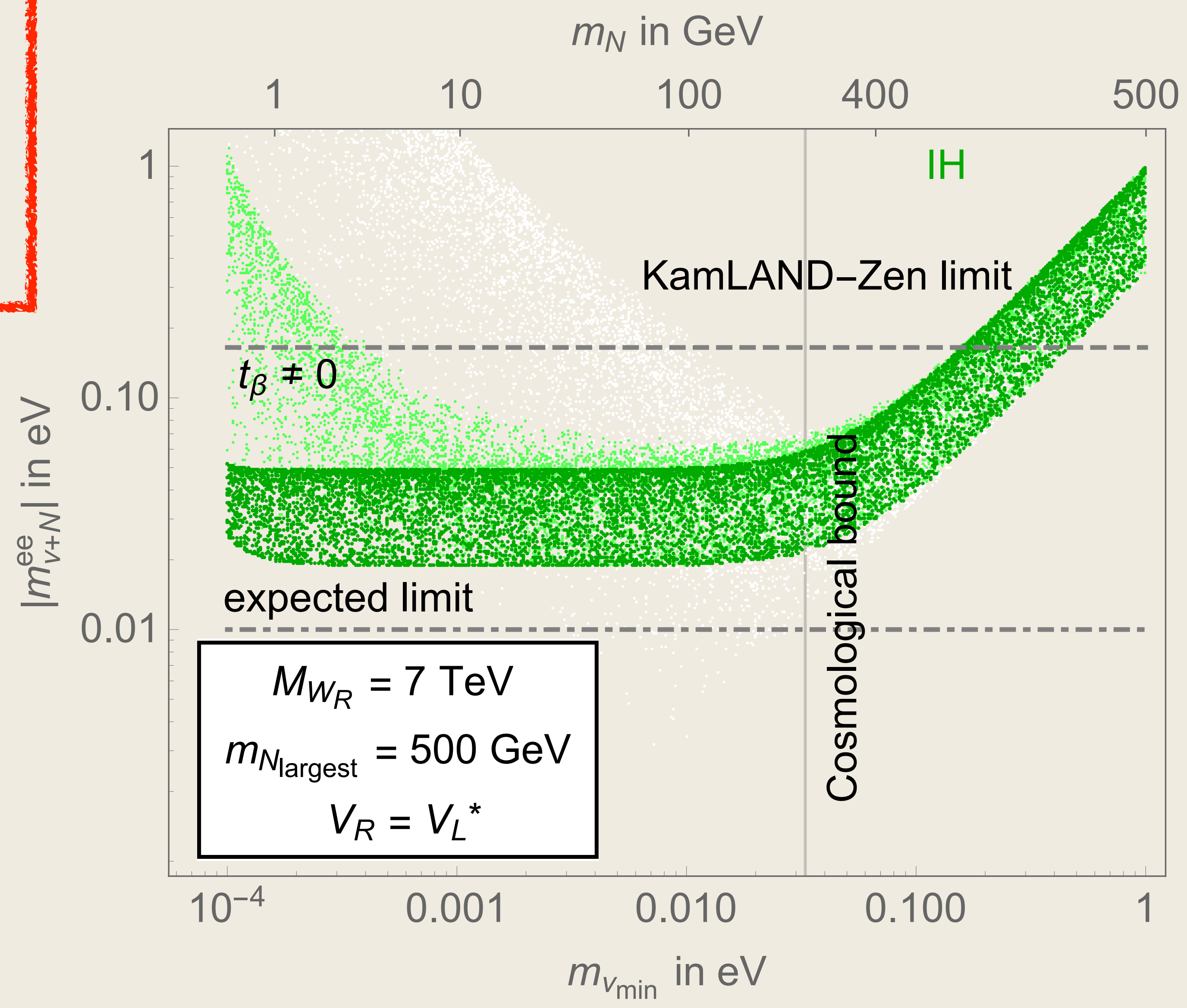


We vary the phases and $\tan\beta \in [0,0.5]$

No long range Contributions

Long range Contributions

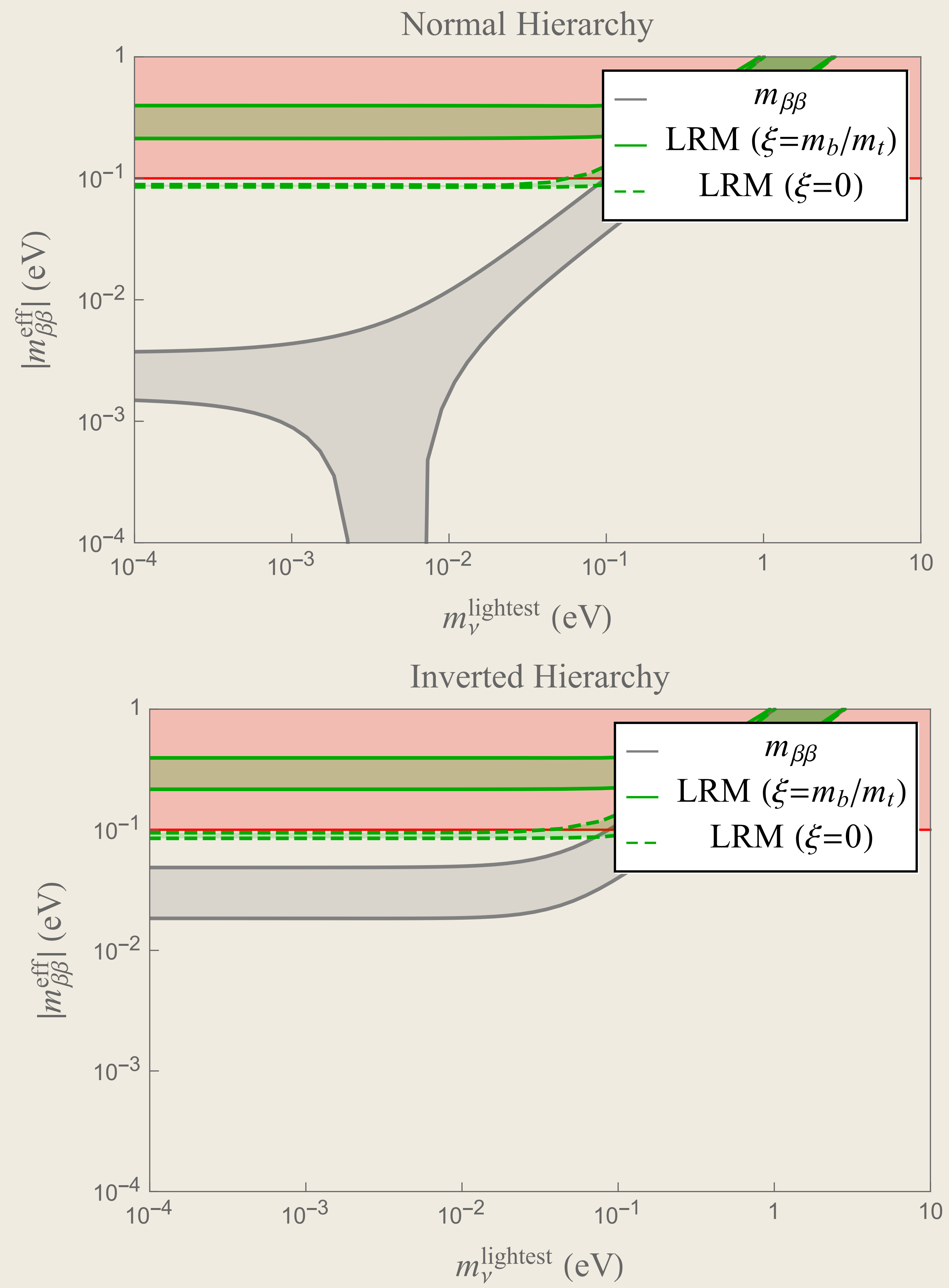




(Tello and Senjanovic. ArXiv: 1011.3522)

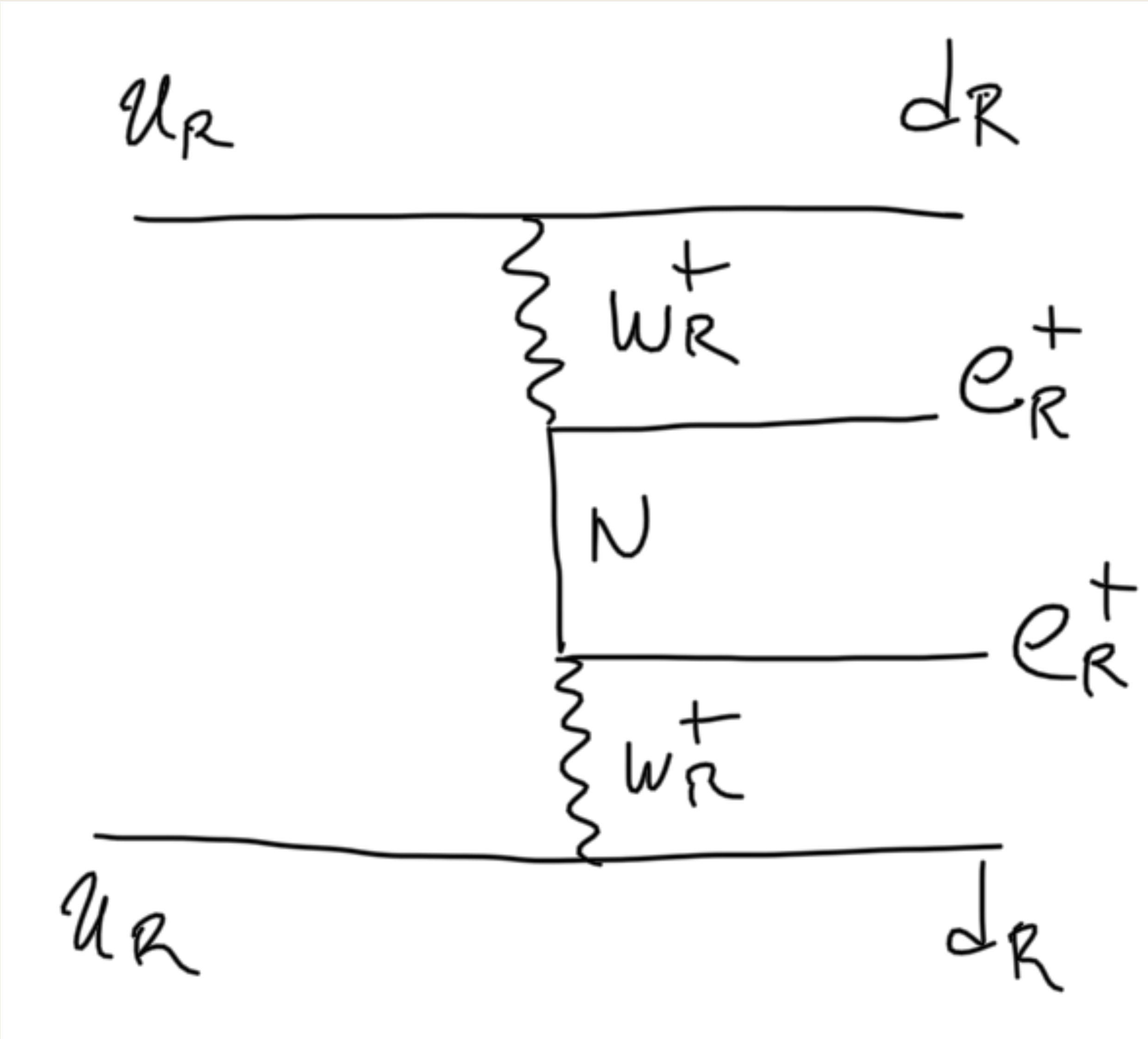
Comparison with type-I scenario

- In ArXiv: 1806.02780, Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti studied the mLRSM.
- They study the heavy neutrino regime with $m_N \sim 10$ GeV and $M_{W_R} = 4.5$ TeV
- They consider small $\tan\beta \sim m_b/m_t \simeq 0.02.$ Instead we consider large $\tan\beta \sim 0.5$
- Finally, they assume Type I dominance and also in this scenario the new physics contribution may dominate



Connection between low and high energy

- Low Energy: Netrinoless double beta decay



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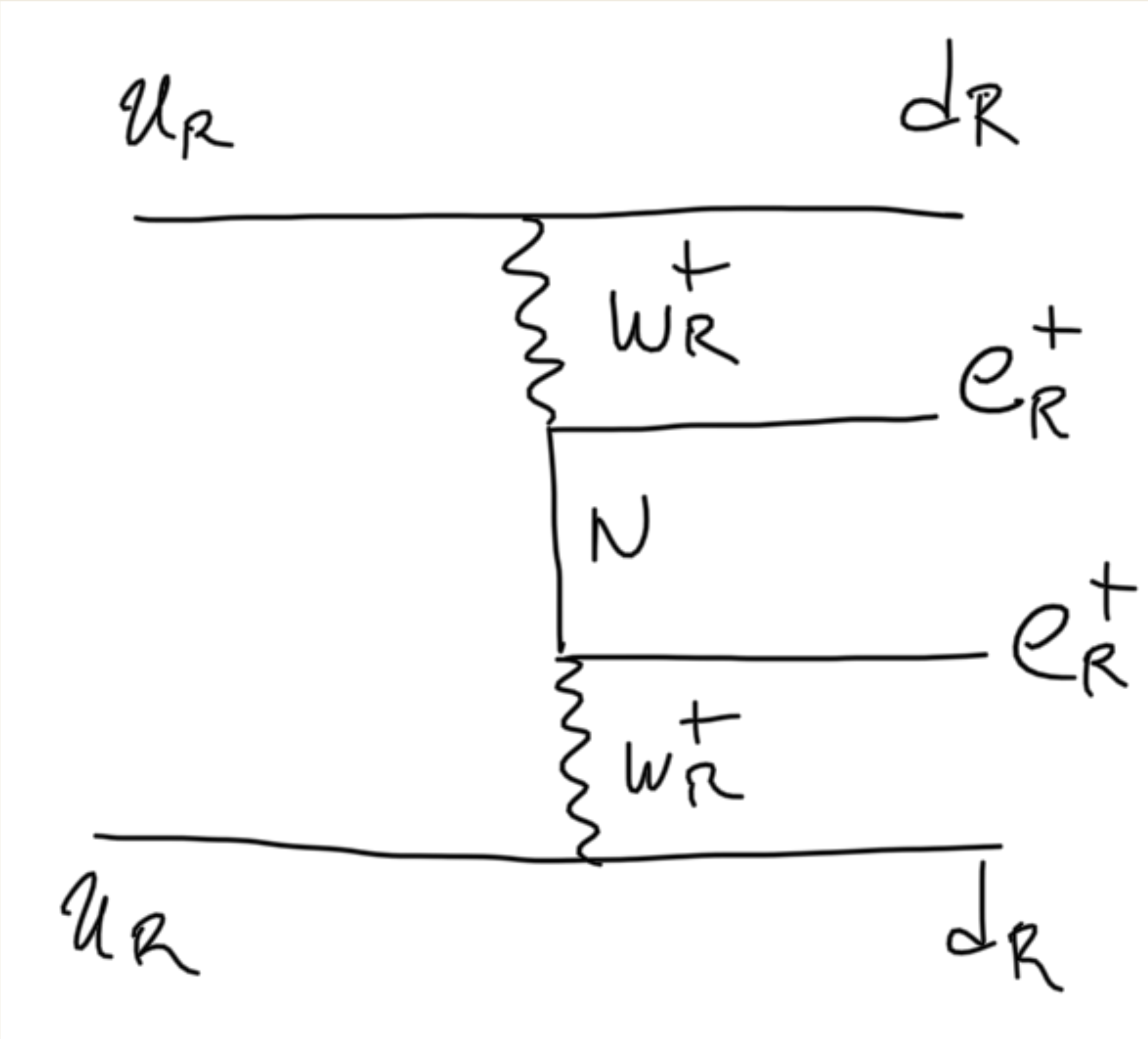
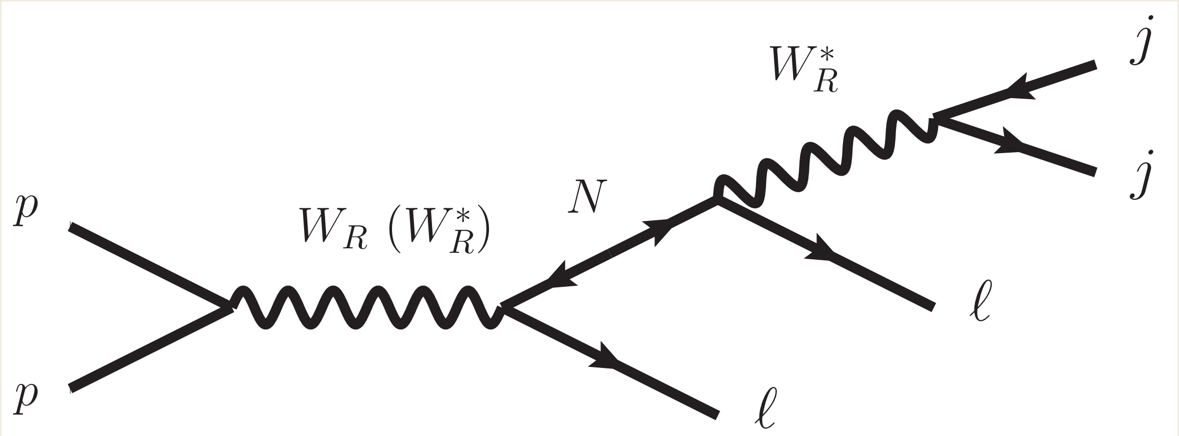


- High Energy: Keung-Senjanovic

KS process

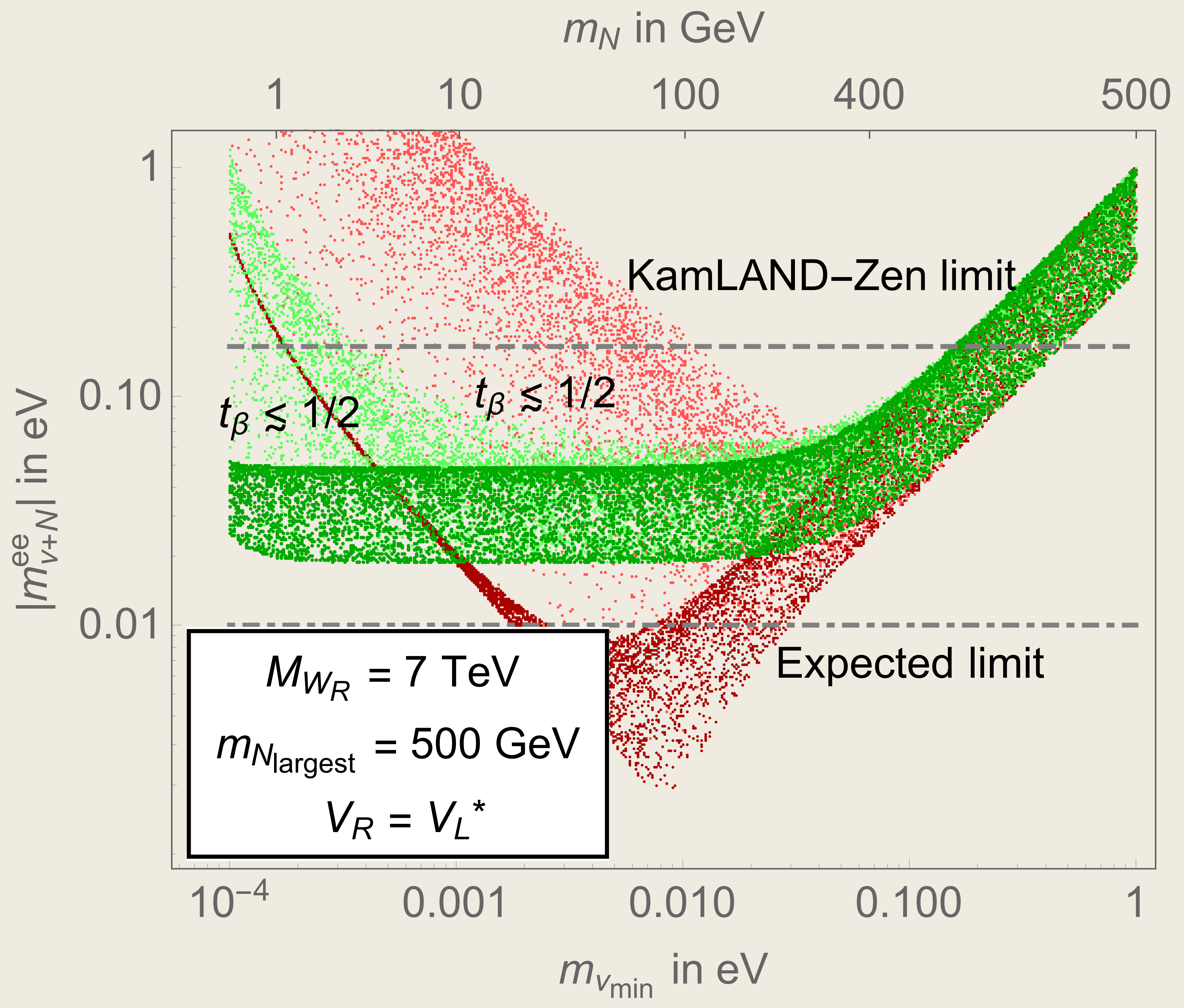
Keung-Senjanovic 1983



taken from Nemevsek, Nesti, Popara
arXiv: 1801.05813 (KS channel $\ell^\pm \ell^\pm jj$)

The decay rate including “long-range” contributions

Displaced vertices at the LHC



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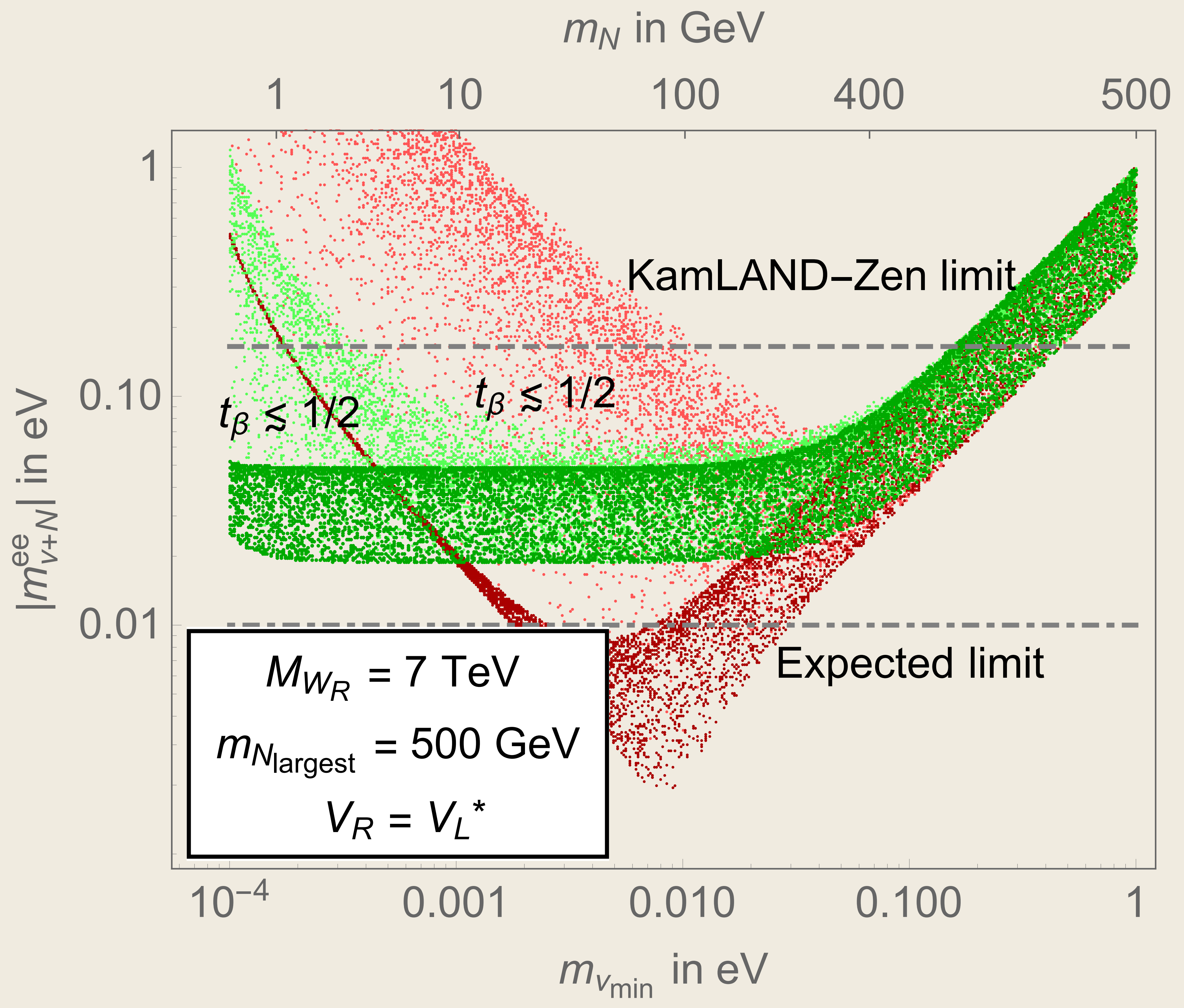

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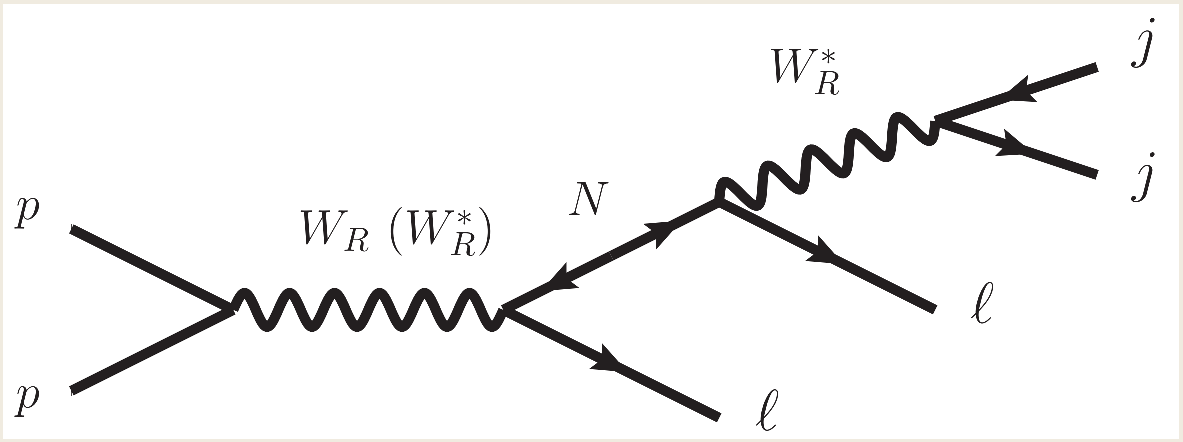

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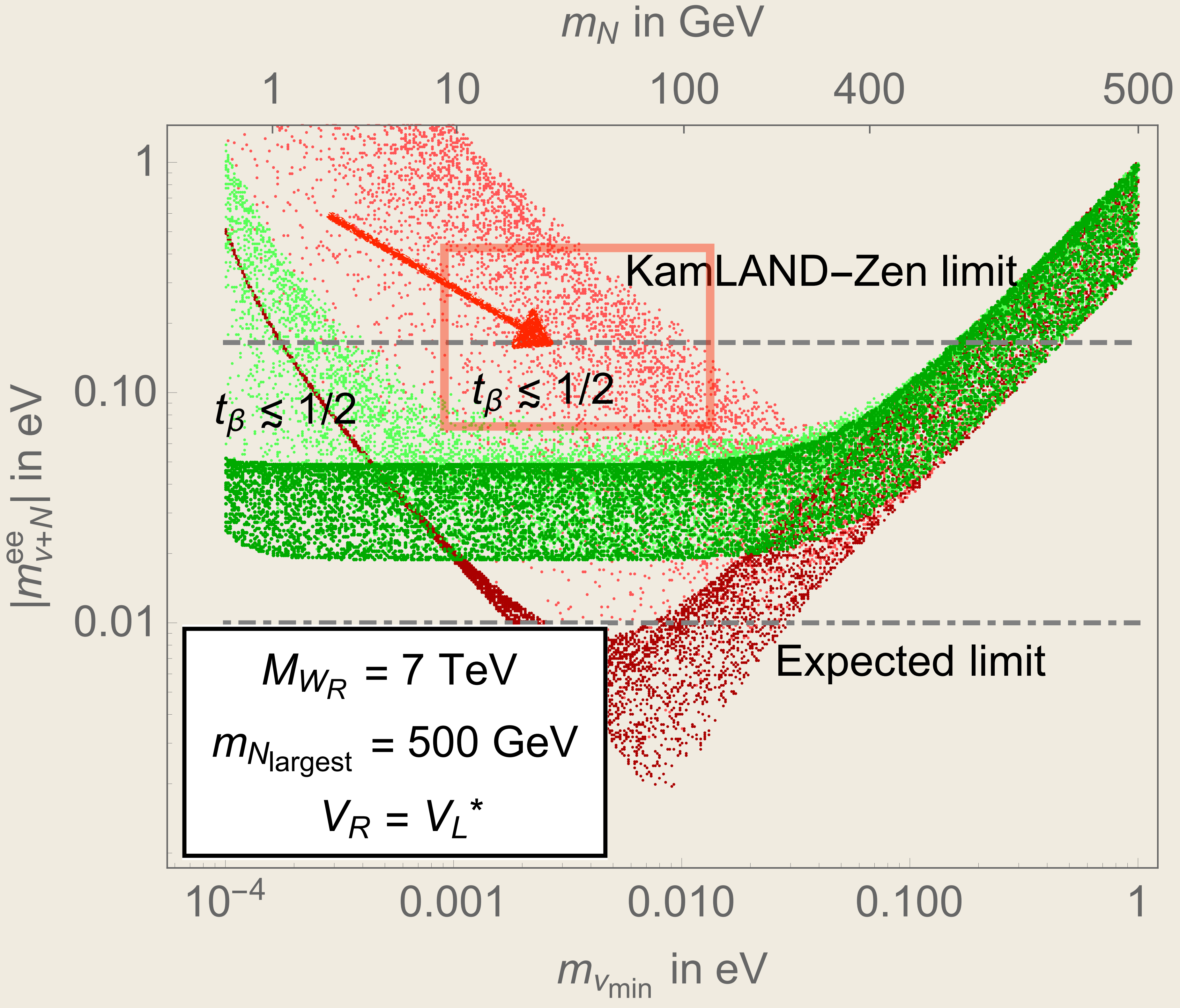

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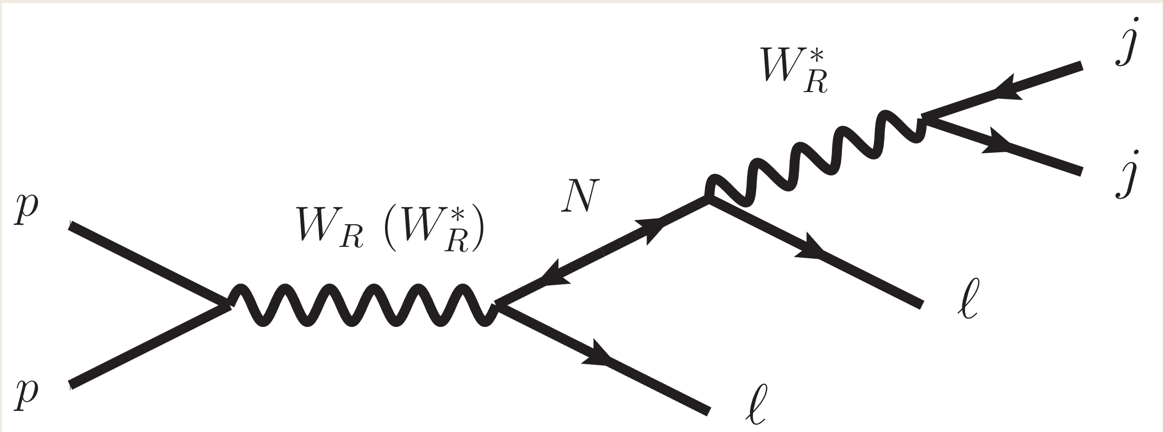

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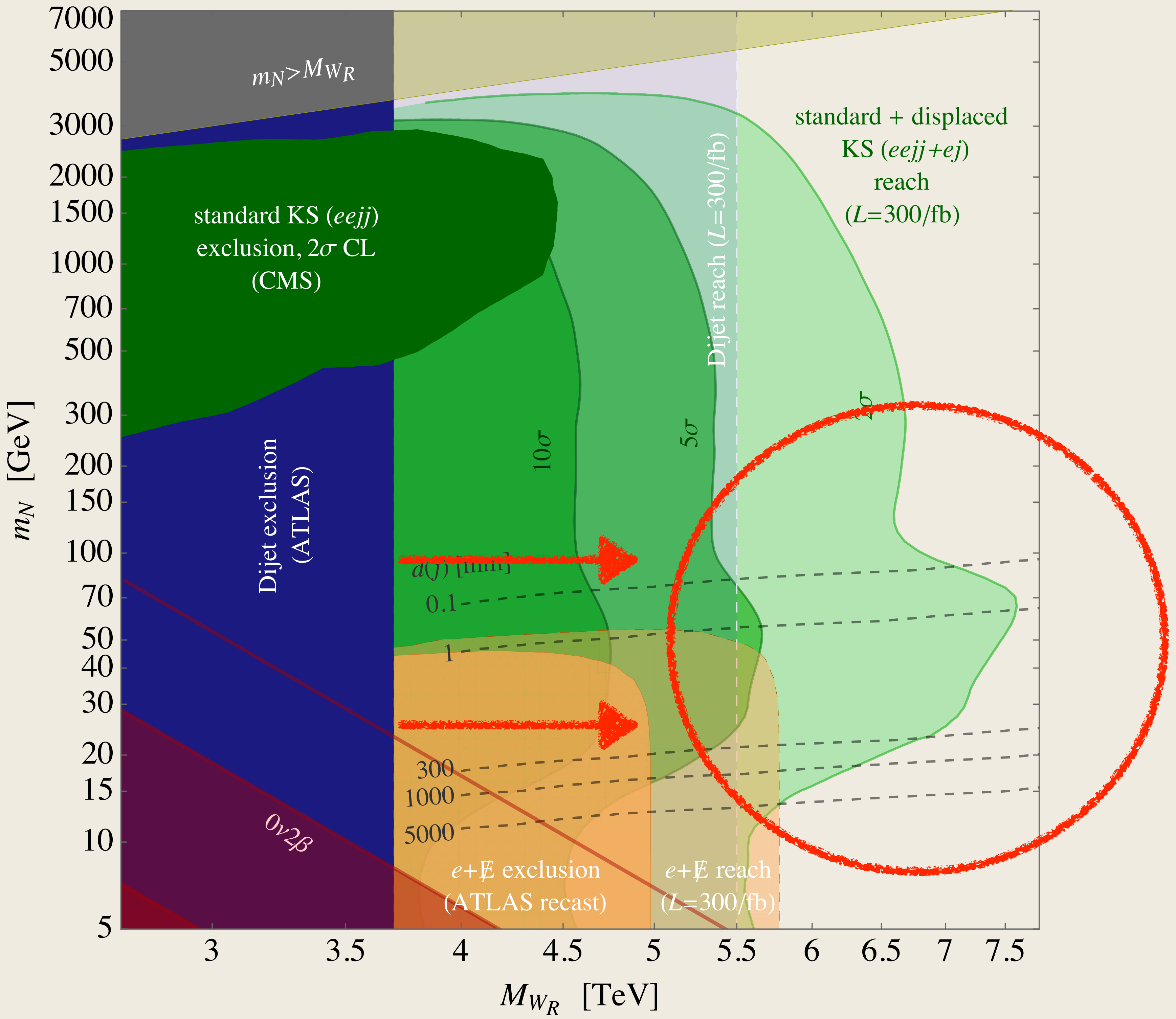


Conclusions

- Since current cosmological bounds are getting more constraining, we should be ready to the possibility that new physics at the TeV scale may dominate the decay rate
- The mLRSM is a well motivated example of the kind of new physics dominating the decay rate
- W_R boson mass ~ 10 TeV could give signals in current and next $0\nu 2\beta$ decay experiments
- It is crucial to include the long-range (pion exchange) contributions. This is what would make the mLRSM contribution to $0\nu 2\beta$ observable in the ton scale experiments, even in the light of the cosmological bounds.

Thank you

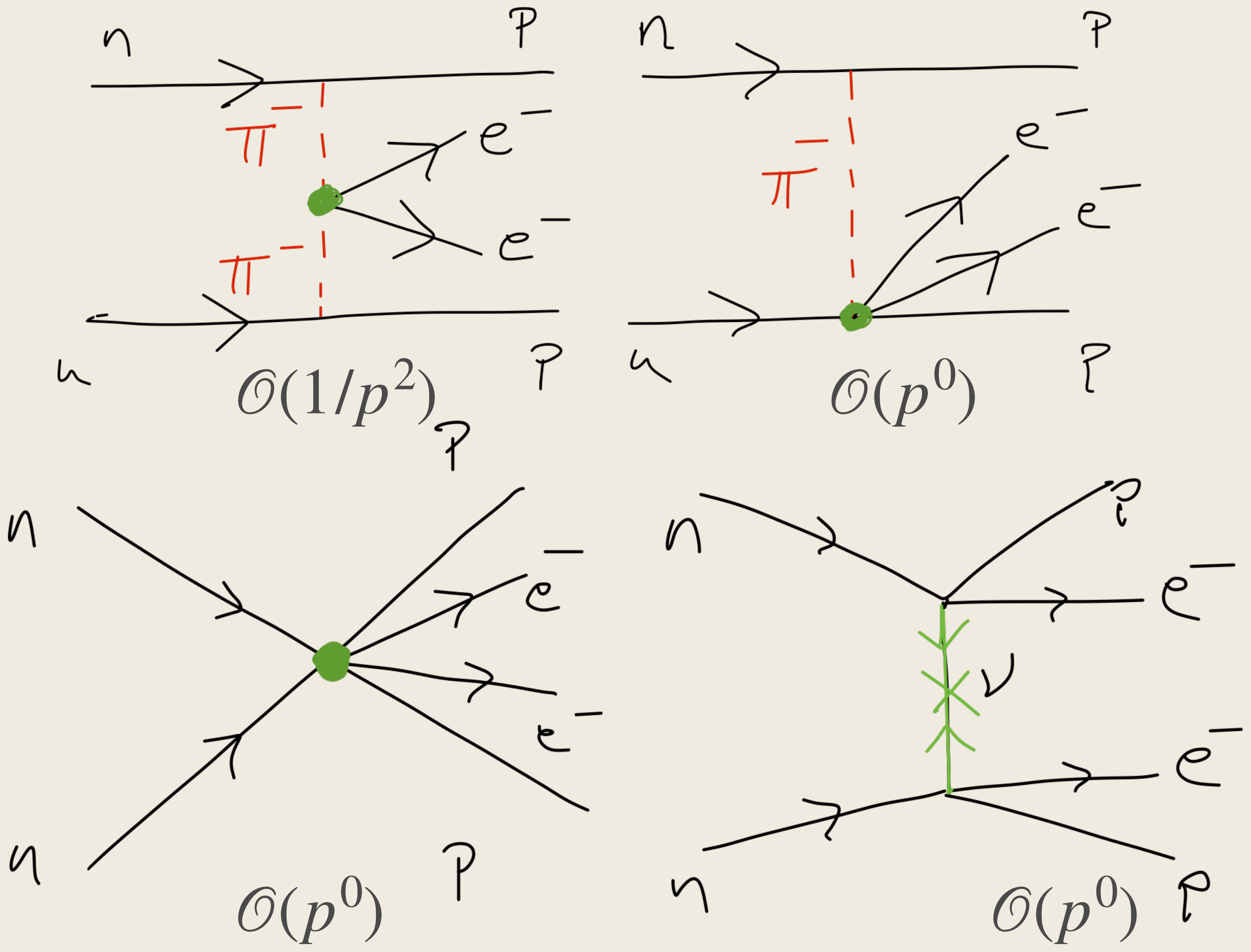
Backup slides

Weinberg's power counting

- $\mathscr{L}_{eff}$ includes an infinite tower of nonrenormalizable operators, but they are arrange according to their importance at low energies
- There is a power counting in powers of $p/\Lambda_{\rm H}, p/\Lambda_{\beta\beta}$ and $\Lambda_{\rm H}/\Lambda_{\beta\beta}$
- p is any small quantity and typically is $\sim m_\pi$

Power counting rules (Ramsey-Musolf at al 2003):

- A pion propagator is $\mathcal{O}(1/p^2)$
- Each derivative of the pion field is $\sim p$
- The strong interaction vertex $NN\pi \sim p$
- The $\pi\pi ee^c$ vertex is $\sim p^2$, where p is the pion momentum
- The $NN\pi ee^c$ vertex is $\sim p/m_N$
- The $NNNNee^c$ vertex is $\sim p^0$
- All diagrams are equally important in the light ν exchange scenario



Future plans

- We can also perform a similar analysis in the case of parity for which a new recent bound applies
- For parity and due to the new bound from θ_{QCD} (Senjanovic and Tello 2020)

$$M_N \lesssim 10^{-6/5} \left(M_{W_R}/\mathrm{GeV}\right)^{4/5} \ \mathrm{GeV}.$$

- For $M_{W_R} \sim 7$ TeV this give $m_{N_{max}} \sim 75$ GeV so EFT with Light heavy neutrinos is needed (De Vries et .al. 2020. ArXiv: 2002.07182 for the EFT study)