Parity restoration and long-range contributions to $0\nu 2\beta$

Juan Carlos Vasquez

UMass, Amherst

This work supported by US Department of Energy, Office of Science, Nuclear Physics under the Nuclear Theory Topical Collaboration program.

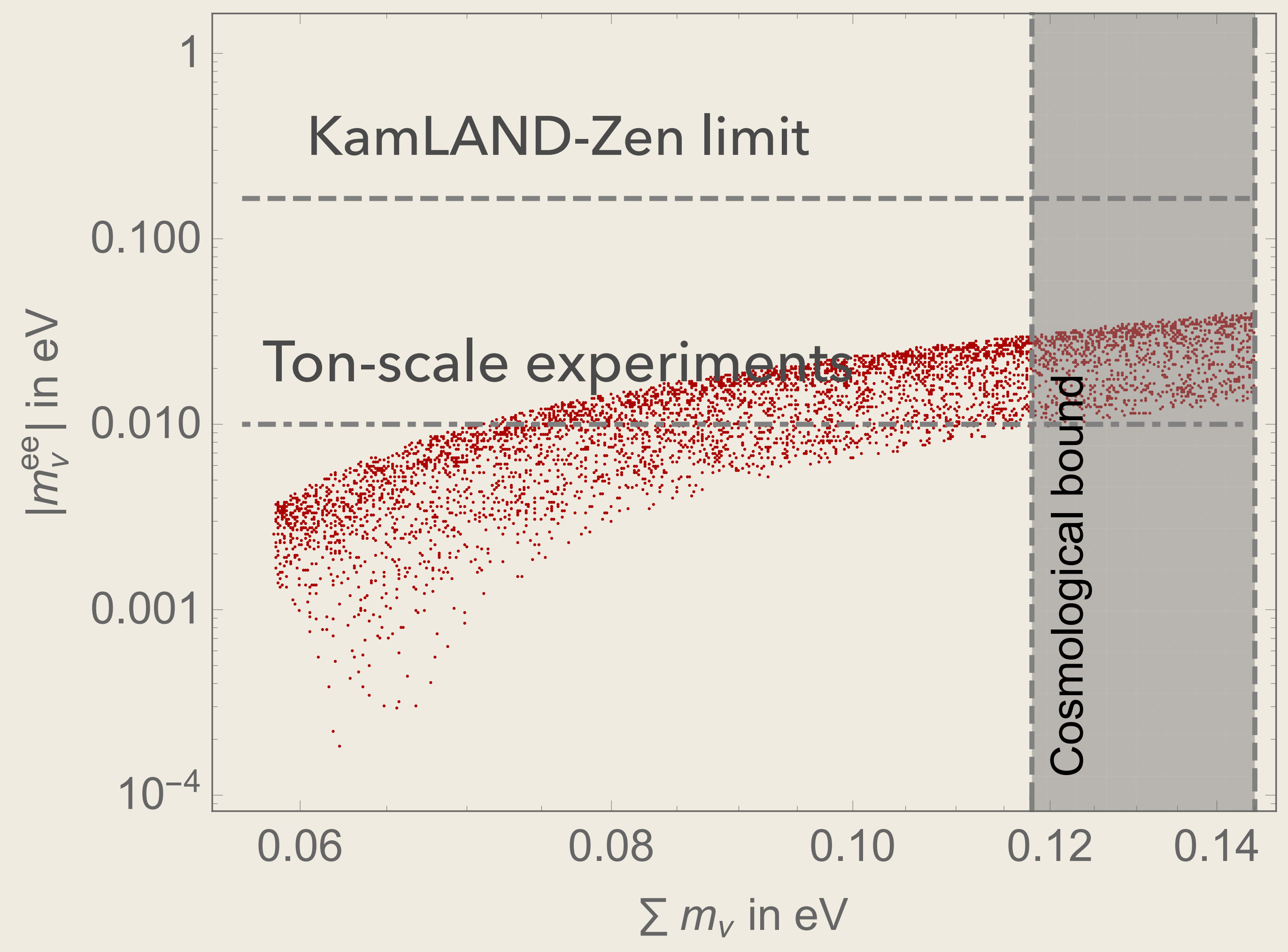
(based on an ongoing work in collaboration with Michael Ramsey-Musolf and Gang Li)

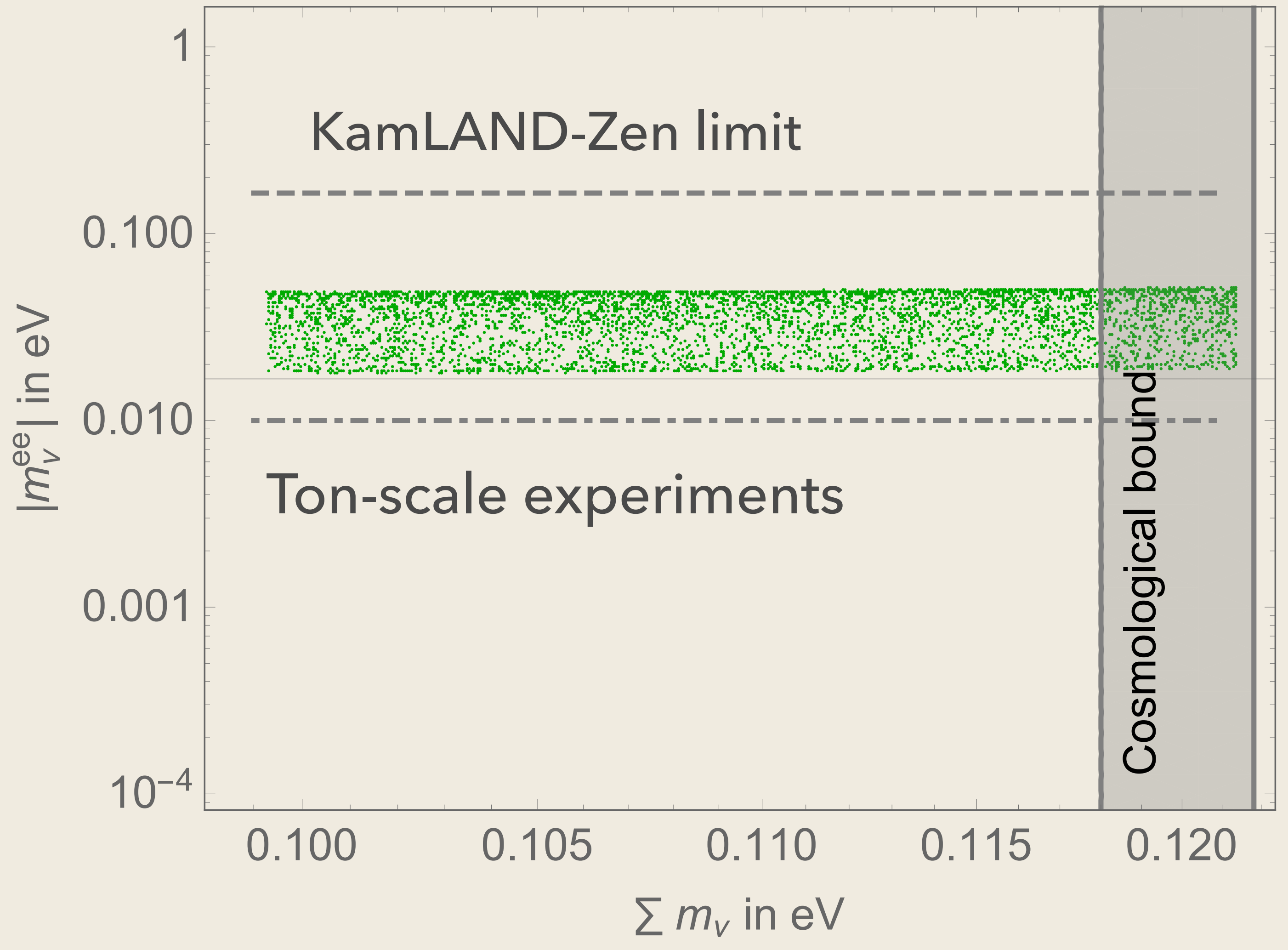
AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

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





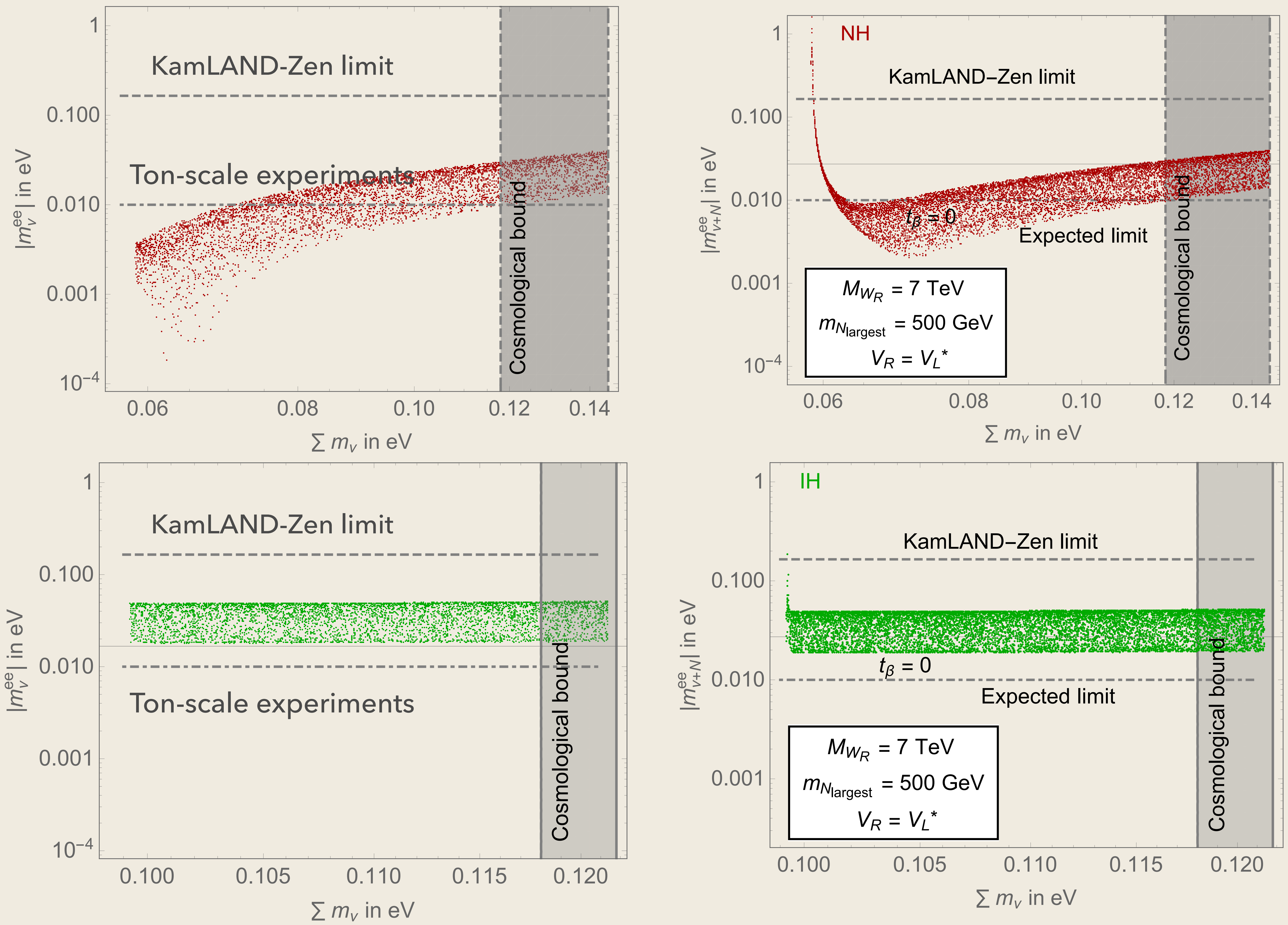
Current cosmological

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

Bound arXiv:1806.10832

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

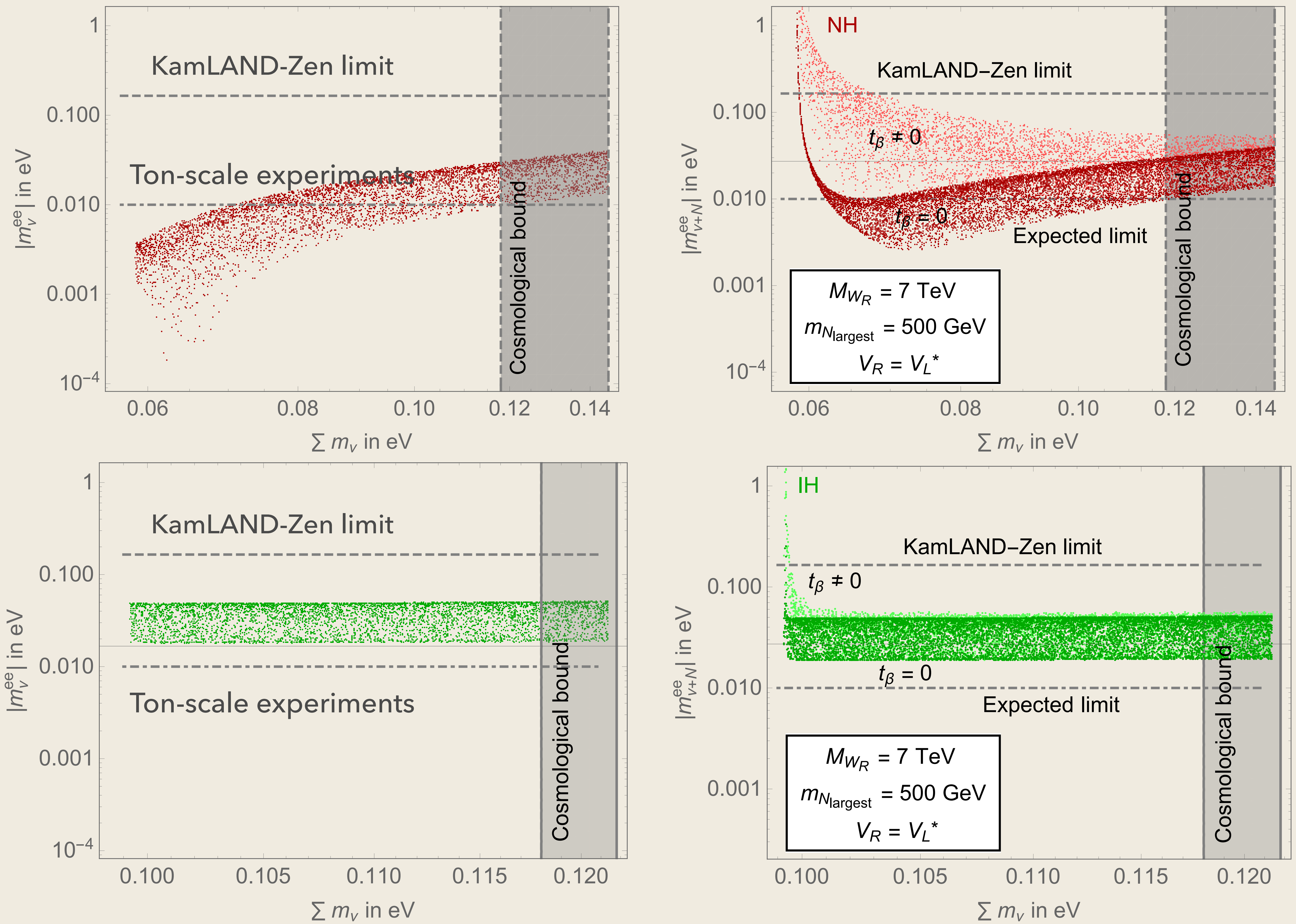
mLRSM contribution without

Including long-range interactions

(Tello and Senjanovic. ArXiv: 1011.3522)

JUAN CARLOS VASQUEZ. EMAIL: JVASQUEZCARM@UMASS.EDU

Confronting light neutrino exchange with the LR scenario



With long-range contributions

Current cosmological

Bound arXiv:1806.10832

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

Near future bound

ACTpol and SPTpol

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

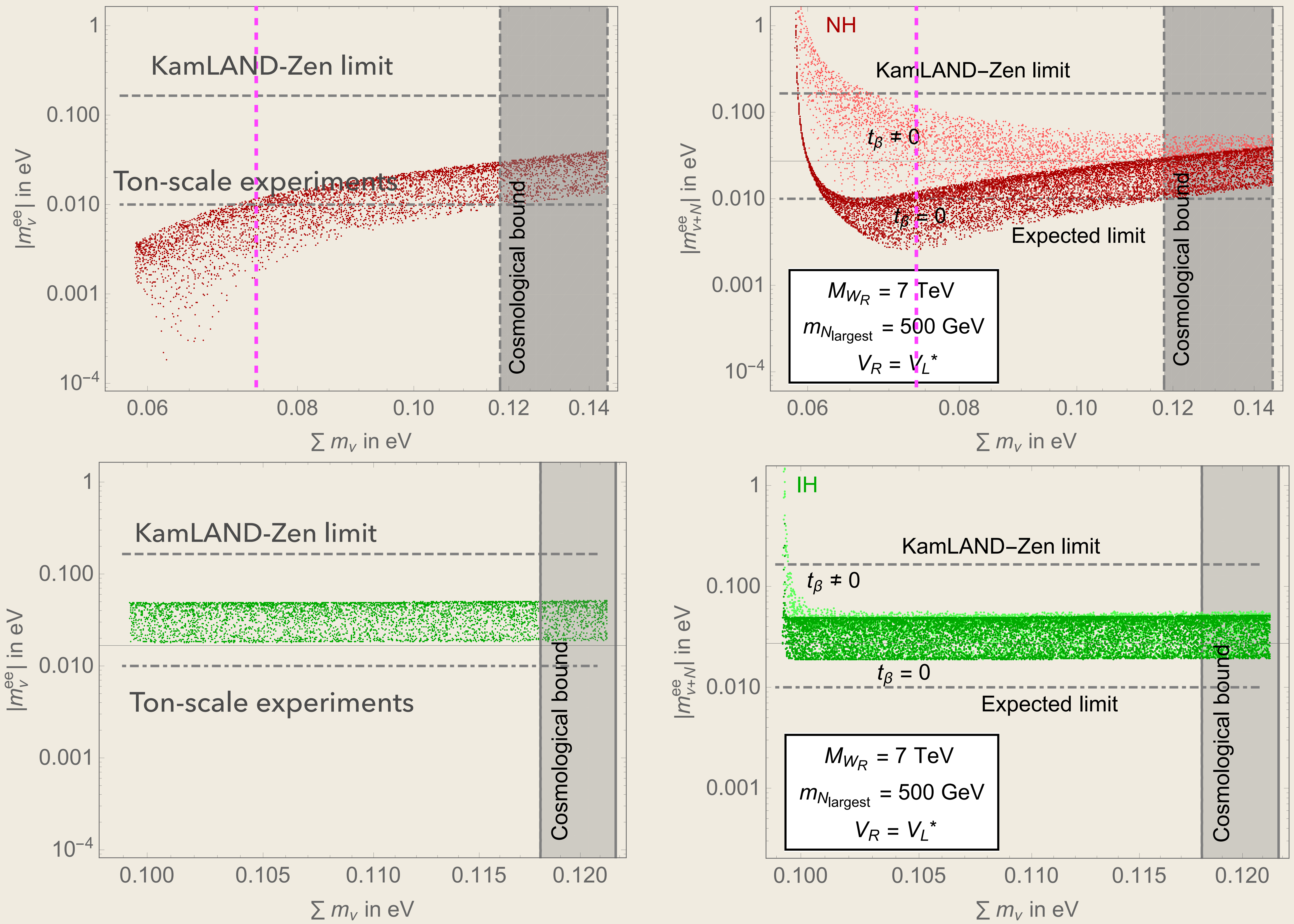
SPT-3G forecast

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

Projections taken from Kevork Abazajian ACFI talk 2015

JUAN CARLOS VASQUEZ. EMAIL: JVASQUEZCARM@UMASS.EDU

Confronting light neutrino exchange with the LR scenario



Current cosmological

Bound arXiv:1806.10832

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

Near future bound

ACTpol and SPTpol

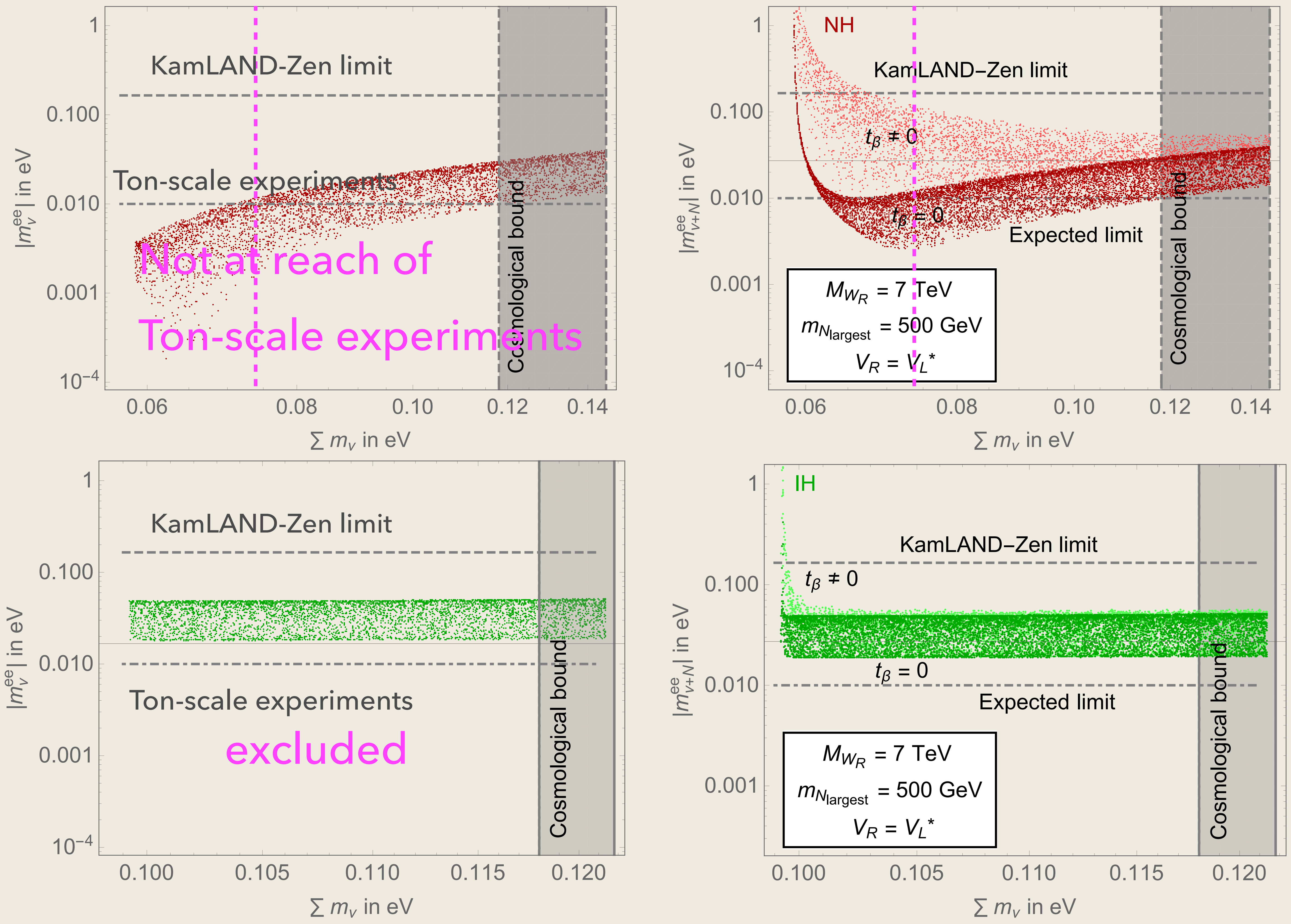
$$\sum m_\nu < 0.1 \text{ eV}$$

SPT-3G forecast Mid-future

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

Projections taken from Kevork Abazajian ACFI talk 2015

Confronting light neutrino exchange with the LR scenario



Current cosmological

Bound arXiv:1806.10832

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

Near future bound

ACTpol and SPTpol

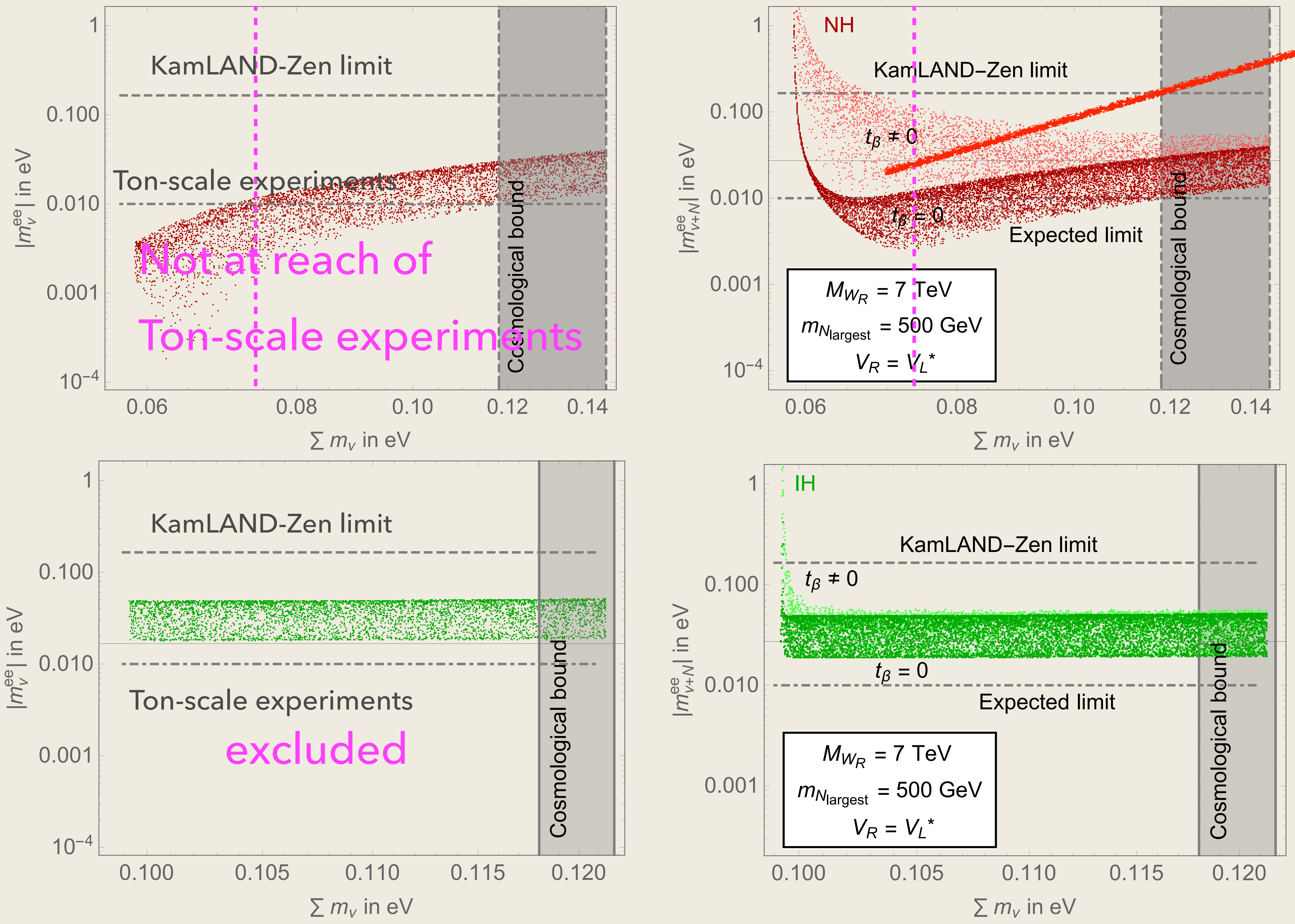
$$\sum m_\nu < 0.1 \text{ eV}$$

SPT-3G forecast Mid-future

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

Projections taken from Kevork Abazajian ACFI talk 2015

Confronting light neutrino exchange with the LR scenario



Accessible in Ton scale Experiments

Current cosmological Bound arXiv:1806.10832

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

Near future bound ACTpol and SPTpol

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

SPT-3G forecast Mid-future

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

Projections taken from Kevork Abazajian ACFI talk 2015

Confronting light neutrino exchange with the LR scenario

$|m_\nu^{ee}|$ in eV

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.

$|m_\nu^{ee}|$ in eV

This highlight the importance of measuring the chiralities of outgoing electrons and possible interplay with other process at low and/or high energies.

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

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

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

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

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

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

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

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

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).
)

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

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

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).
)

- 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)

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).
)

- 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

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

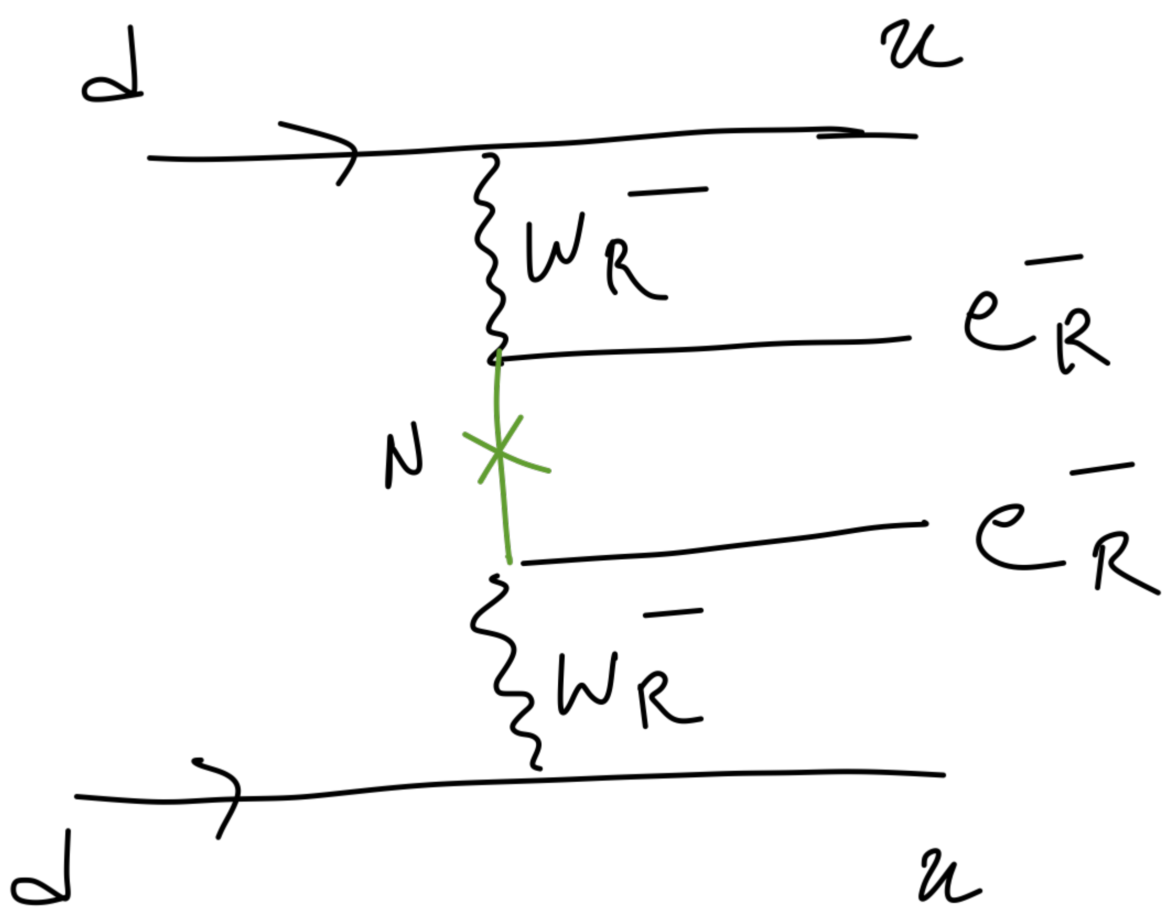
$$V_L = V_R^*$$

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

(Tello and Senjanovic. ArXiv: 1011.3522)

Feynman diagrams contributing to the decay rate in the mLRSM

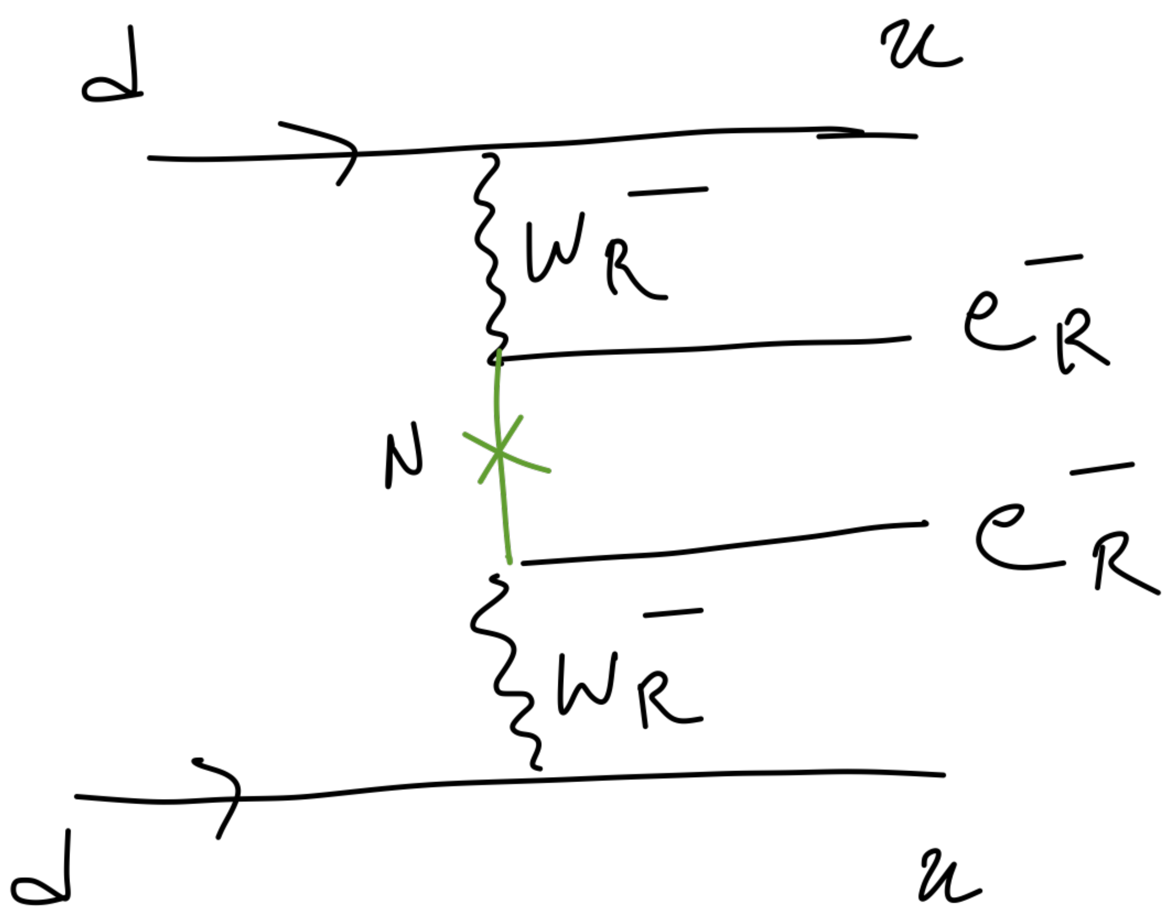
- There are the following contributions (on top of the usual light neutrino contribution)



RR contribution

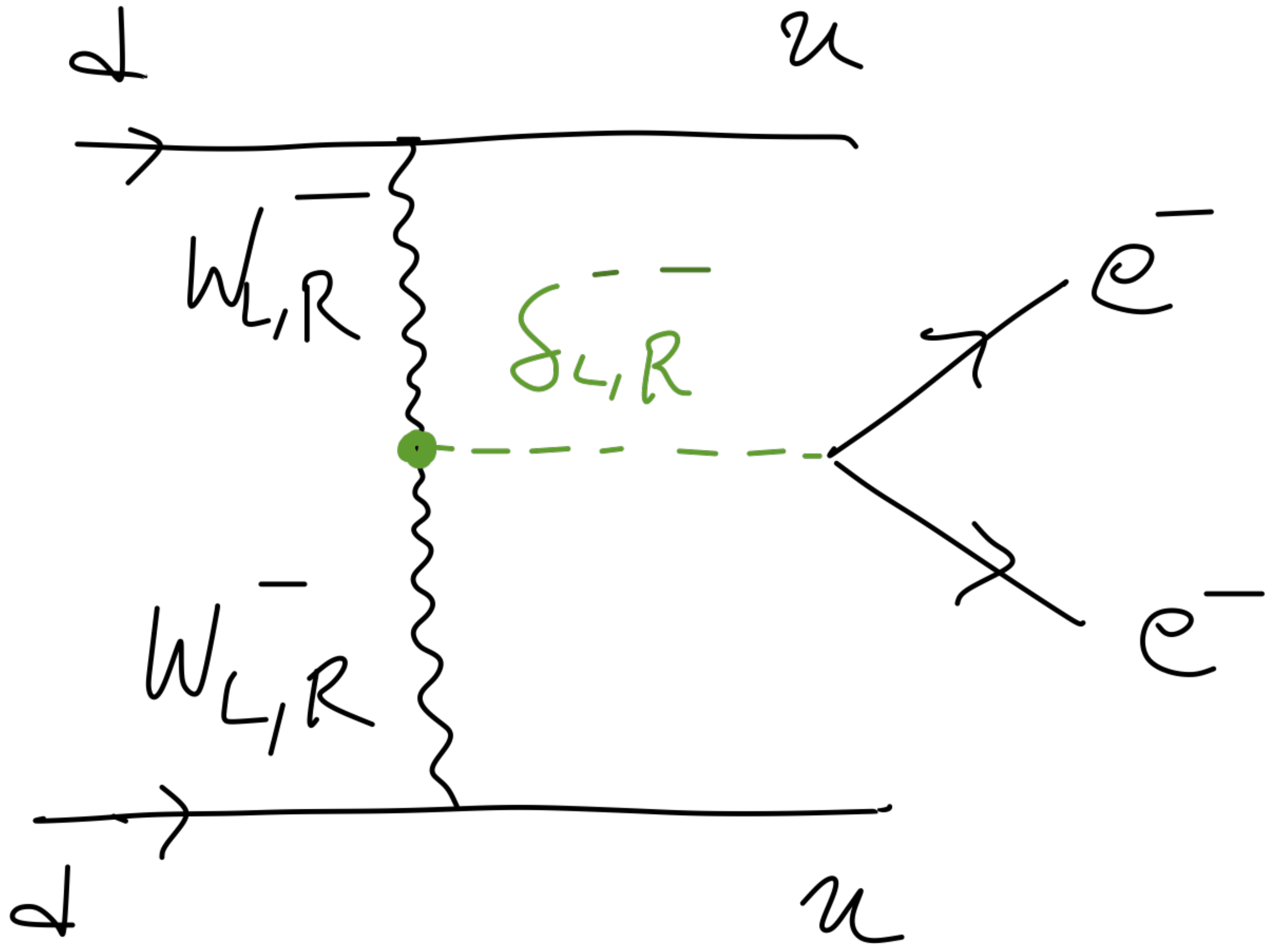
Feynman diagrams contributing to the decay rate in the mLRSM

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



RR contribution

LL or RR



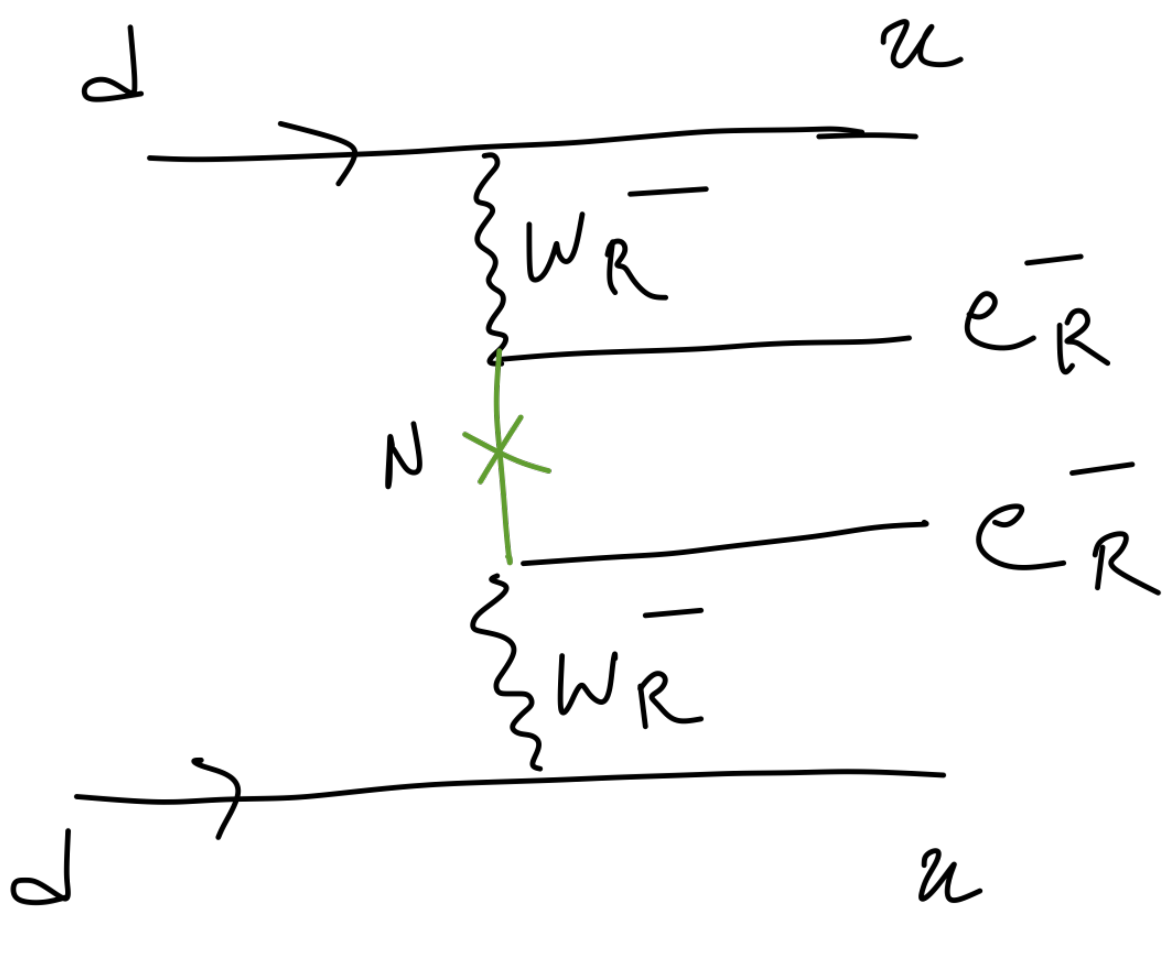
Suppressed by heavy

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

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

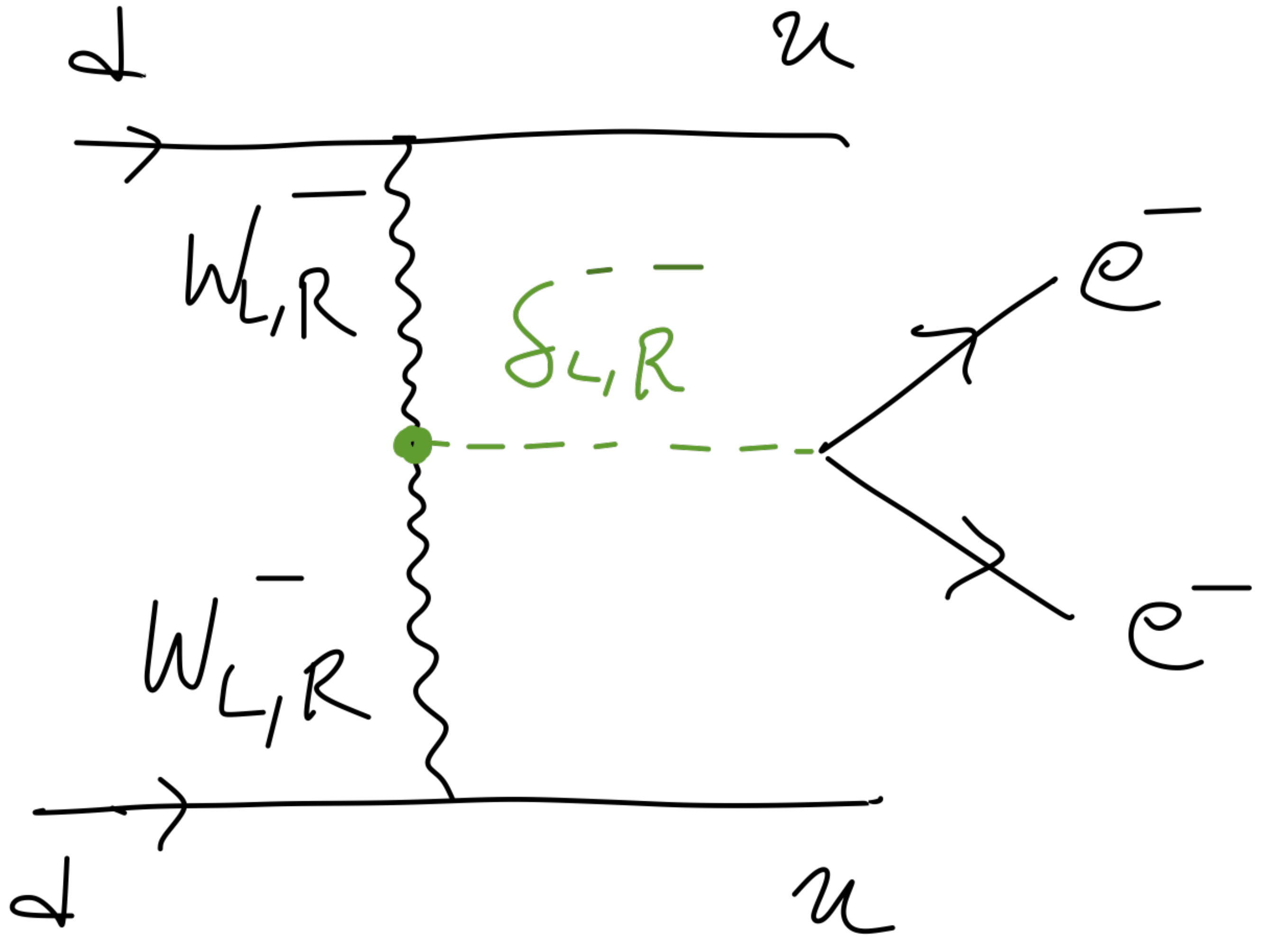
Feynman diagrams contributing to the decay rate in the mLRSM

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



RR contribution

LL or RR

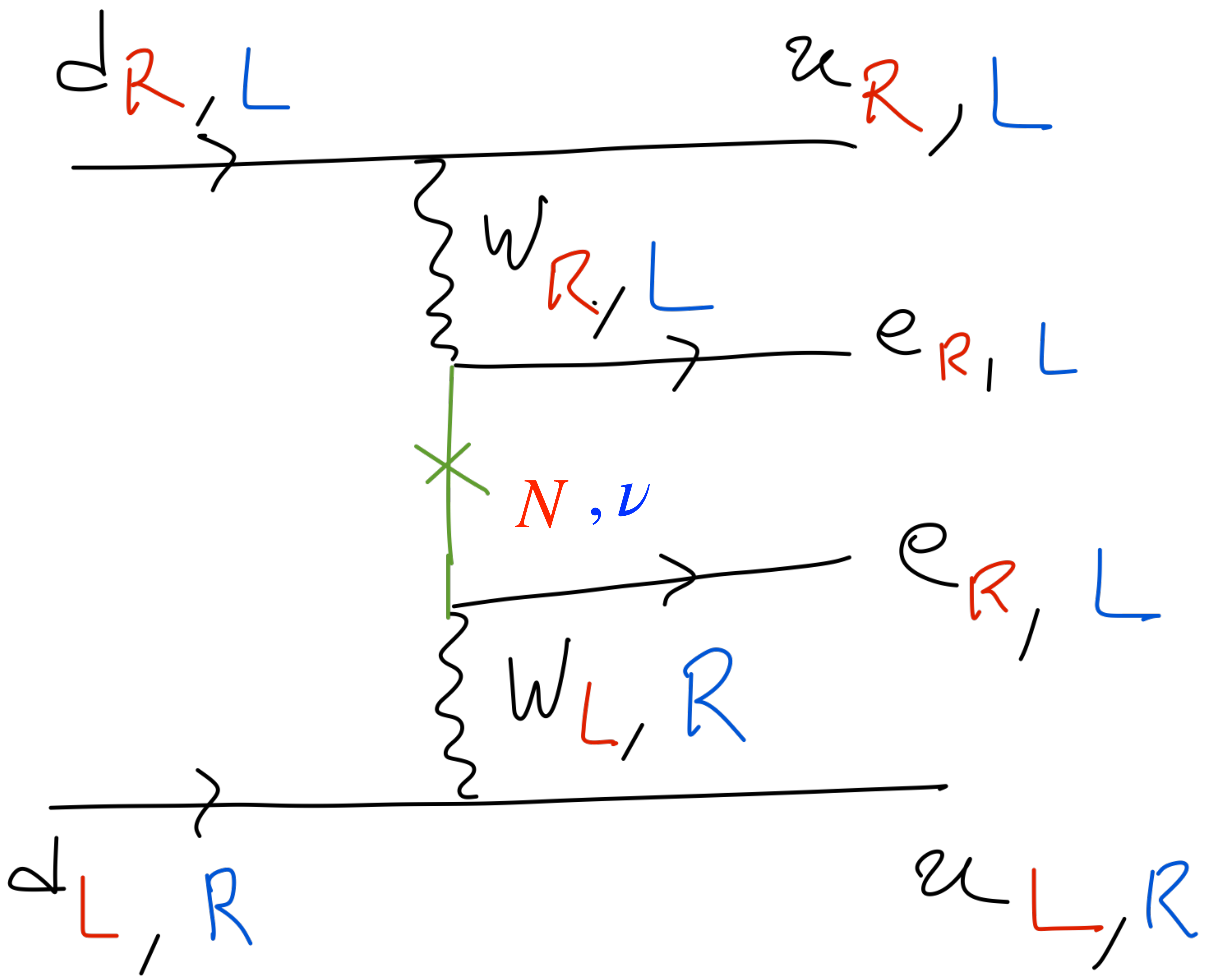


Suppressed by heavy

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

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

LR contribution



The Blue contributions are

Suppressed by small heavy-light

Neutrino mixing

Effective Lagrangian in the mLRSM

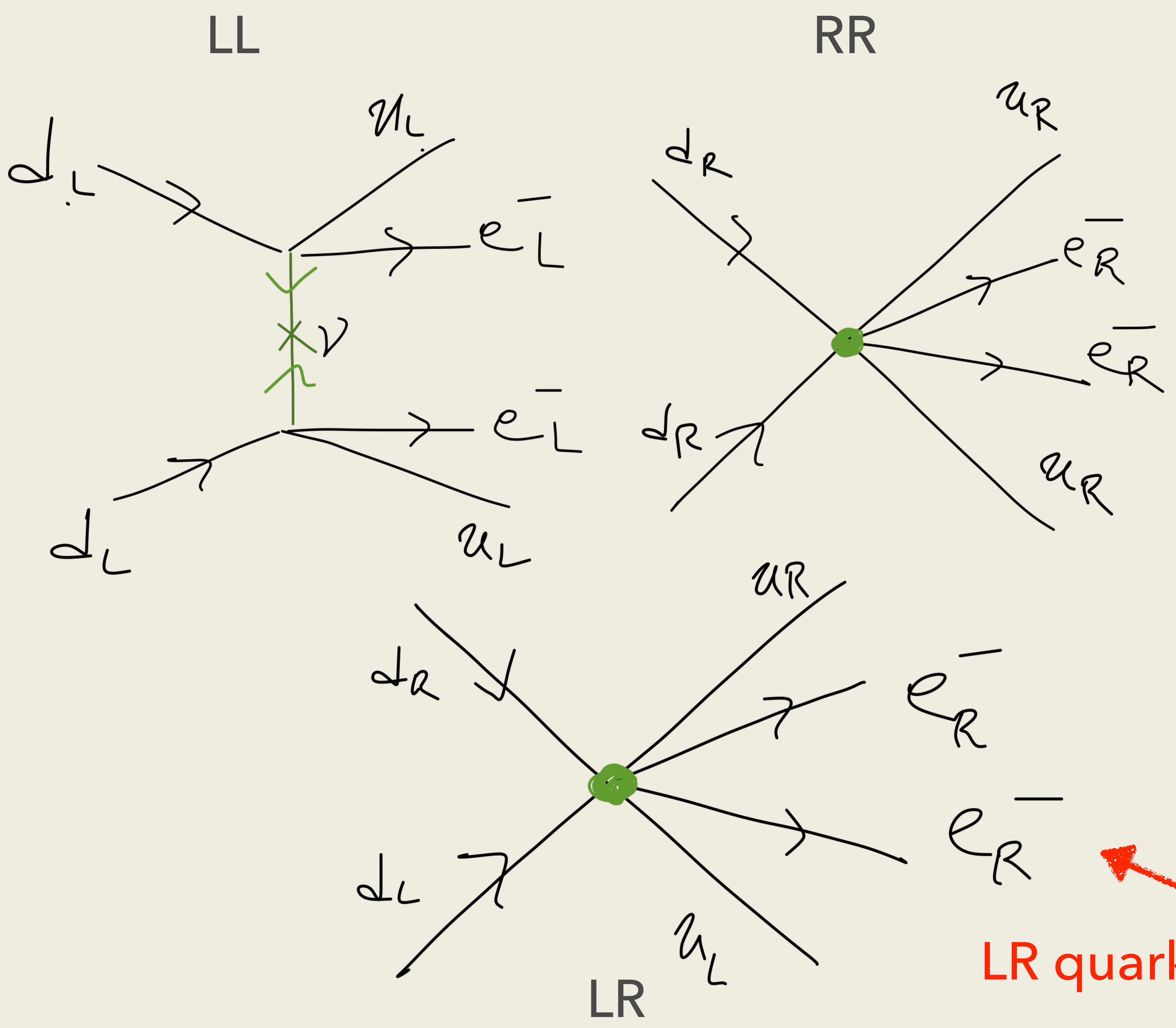
- The effective Lagrangian for $0\nu2\beta$

$$\mathscr{L}^q_{0\nu2\beta,LR} = 2G_F^2 \frac{m_{\beta\beta}}{p^2}\left(\mathcal{O}^{++}_{3+} + \mathcal{O}^{++}_{3-}\right)\bar{e}_L e^c_L$$

$$+2G_F^2\left(\frac{M_W}{M_{W_R}}\right)^2\left(\sum_{j=1}^{3} \frac{V^2_{Rje}}{m_{N_j}}\right)\left(\xi\mathcal{O}^{++}_{1+} + \left(\frac{M_W}{M_{W_R}}\right)^2\left(\mathcal{O}^{++}_{3+}-\mathcal{O}^{++}_{3-}\right)\right)\bar{e}_R e^c_R\,.$$

$$\mathcal{O}^{++}_{1+} = \left(\bar{q}_{\rm L}\tau^+\gamma^\mu q_{\rm L}\right)\left(\bar{q}_{\rm R}\tau^+\gamma_\mu q_{\rm R}\right)$$

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



LR quark currents

The chiral Lagrangian induced by the effective interaction

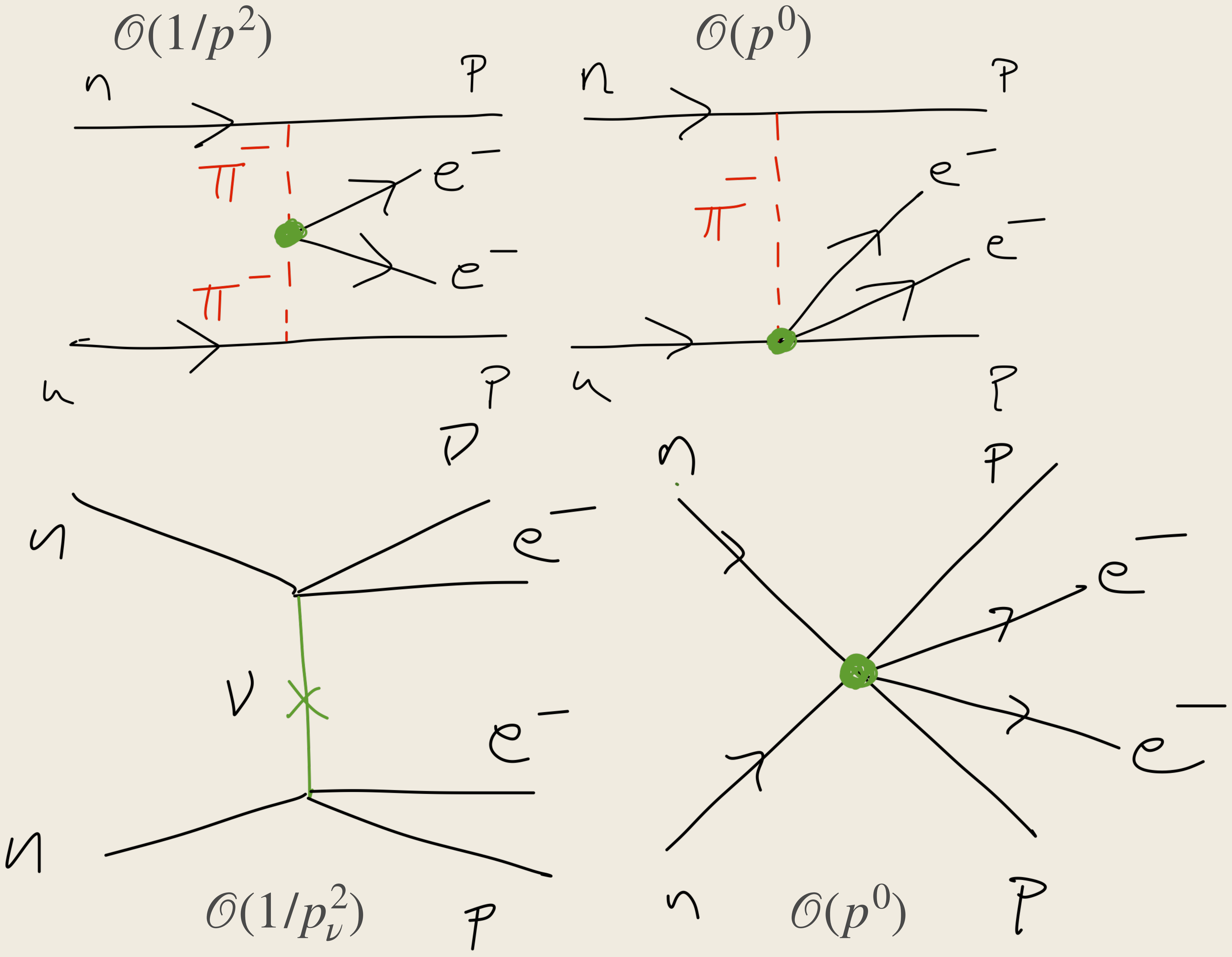
- At the hadronic level $\mathcal{O}_{1+}^{++}$ and using Weinberg's power counting, it gives a LO contribution to $\pi\pi e e^c$ vertex

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

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

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

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



The minimal left-right symmetric model

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

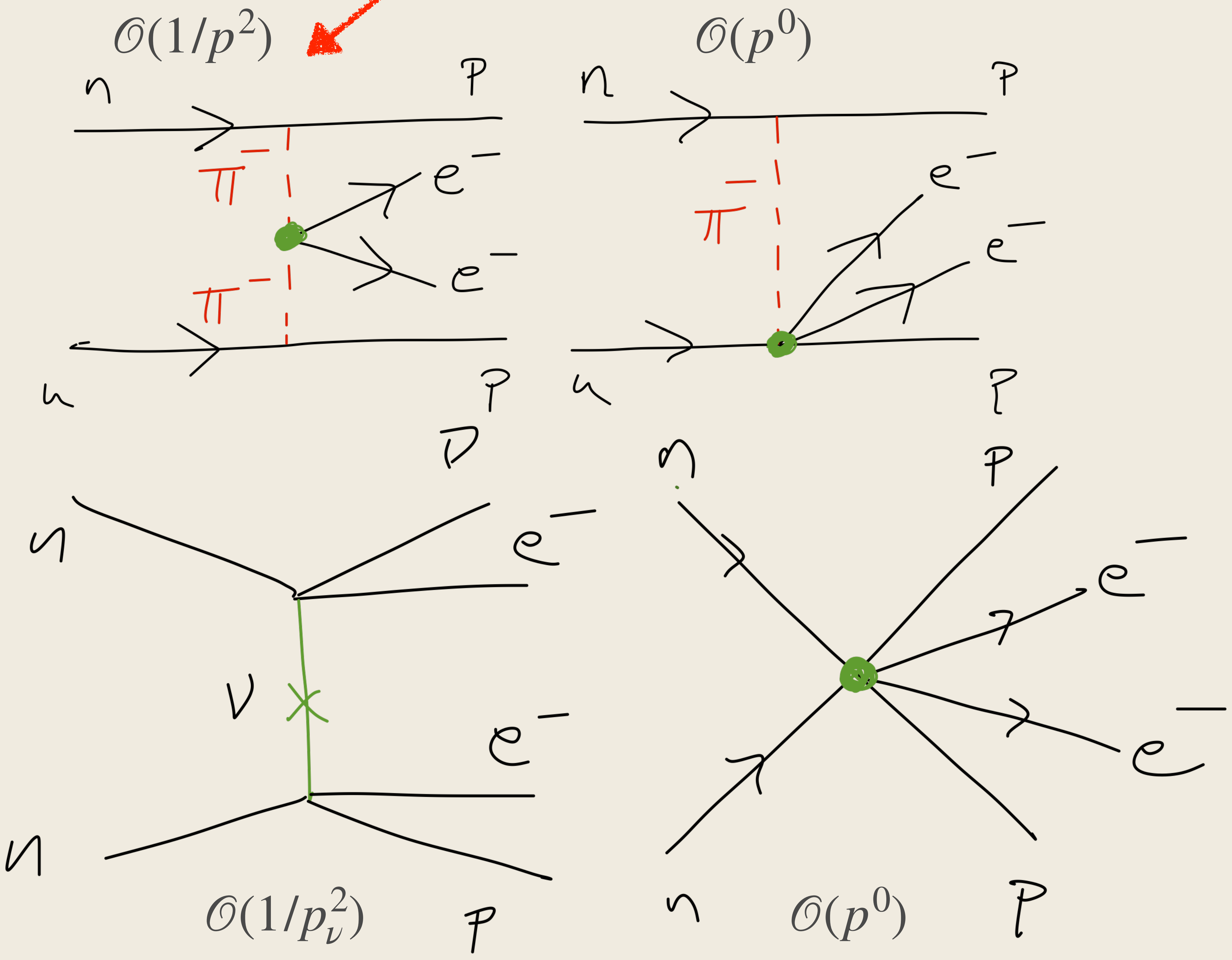
- At the hadronic level $\mathcal{O}_{1+}^{++}$ and using Weinberg's power counting, it gives a LO contribution to $\pi\pi ee^c$ vertex

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

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

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

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



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

$$m^{ee}_N \simeq \frac{2}{3} g^{\pi\pi}_4 \left[-\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \mathrm{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m^2_\pi}{g^{\pi\pi}_4} \right] \left(\frac{M_W}{M_{W_R}} \right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j}, \qquad \Delta \equiv 6 g^{\pi N}_1 \mathcal{M}_1 + 5 g^{\pi\pi}_1 \mathcal{M}_2$$

We use $\mathcal{M}_0 = 4.74$, $\mathcal{M}_1 = 9.30$ and $\mathcal{M}_2 = 6.93$,

$g^{\pi\pi}_4 = -1.9$ GeV^2, $g^{\pi\pi}_1 = 0.36$ and $g^{\pi N}_1 = \mathcal{O}(1)$

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

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m_\nu^{ee}\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m_N^{ee}\right|^2$$

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

- The new physics contribution

$$m_N^{ee} \simeq \frac{2}{3} g_4^{\pi\pi} \left[\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \mathrm{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m_\pi^2}{g_4^{\pi\pi}} \right] \left(\frac{M_W}{M_{W_R}} \right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j}, \qquad \Delta \equiv 6 g_1^{\pi N} \mathcal{M}_1 + 5 g_1^{\pi\pi} \mathcal{M}_2$$

Hadronic matrix elements

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_\nu\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m^{ee}_N\right|^2$$

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

- The new physics contribution

$$m^{ee}_N \simeq \frac{2}{3} g^{\pi\pi}_4 \left[-\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \mathrm{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m^2_\pi}{g^{\pi\pi}_4} \right] \left(\frac{M_W}{M_{W_R}}\right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j}, \qquad \Delta \equiv 6 g^{\pi N}_1 \mathcal{M}_1 + 5 g^{\pi\pi}_1 \mathcal{M}_2$$

$W_L - W_R$ mixing

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_\nu\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m^{ee}_N\right|^2$$

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

- The new physics contribution

$$m_N^{ee} \simeq \frac{2}{3} g_4^{\pi\pi} \left[-\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \mathrm{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m_\pi^2}{g_4^{\pi\pi}} \right] \left(\frac{M_W}{M_{W_R}}\right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j}, \qquad \Delta \equiv 6 g_1^{\pi N} \mathcal{M}_1 + 5 g_1^{\pi\pi} \mathcal{M}_2$$

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

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_\nu\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m^{ee}_N\right|^2$$

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

- The new physics contribution

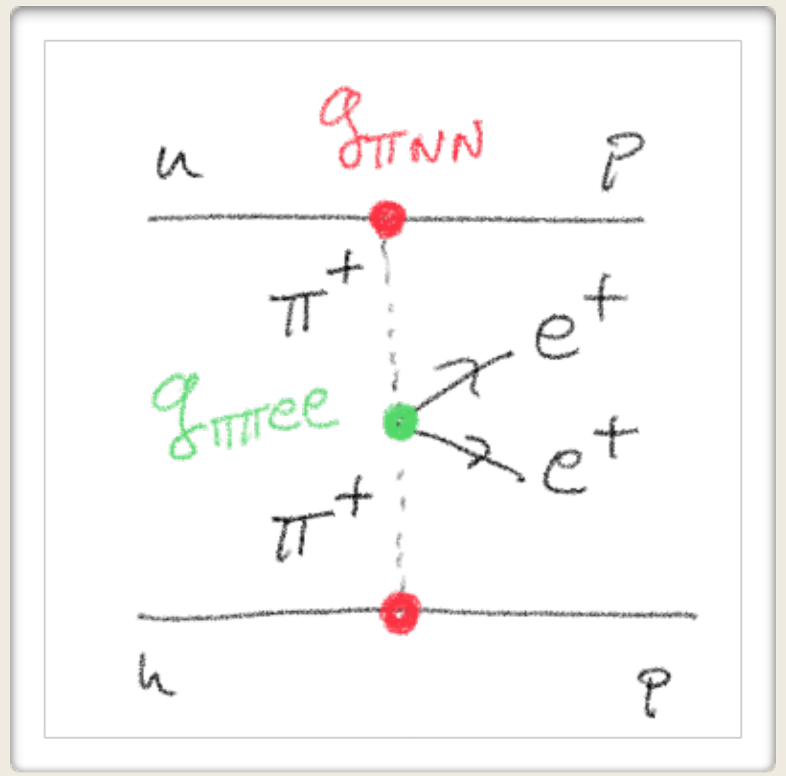
mLRSM contribution

$$m^{ee}_N \simeq \frac{2}{3} g_4^{\pi\pi} \left[-\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \mathrm{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m_\pi^2}{g_4^{\pi\pi}} \right] \left(\frac{M_W}{M_{W_R}}\right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j},$$

$$\Delta \equiv 6 g_1^{\pi N} \mathcal{M}_1 + 5 g_1^{\pi\pi} \mathcal{M}_2$$

The decay rate including “long-range” contributions

LO



- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m_\nu^{ee}\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m_N^{ee}\right|^2$$

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

- The new physics contribution

$$m_N^{ee} \simeq \frac{2}{3} g_4^{\pi\pi} \left[-\frac{|\mathcal{M}_0|}{|\mathcal{M}_\nu|} \operatorname{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{|\mathcal{M}_\nu|} \frac{m_\pi^2}{g_4^{\pi\pi}} \right] \left(\frac{M_W}{M_{W_R}} \right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j}, \qquad \Delta \equiv 6 g_1^{\pi N} \mathcal{M}_1 + 5 g_1^{\pi\pi} \mathcal{M}_2$$

+ counter term (see ahead)

The decay rate including “long-range” contributions

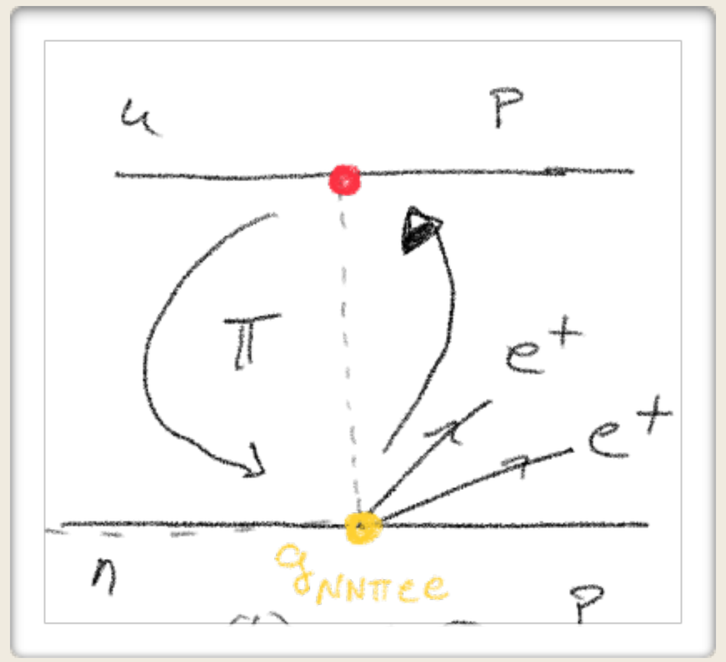
- In the mLRSM the decay rate is

$$(T^{0\nu}_{1/2})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m^{ee}_\nu\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m^{ee}_N\right|^2$$

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

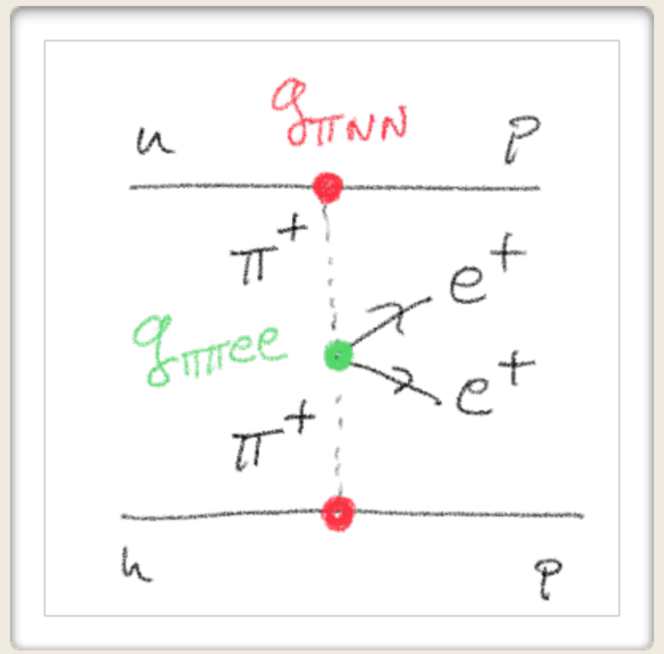
- The new physics contribution

NLO



+

NNLO



$$m^{ee}_N \simeq \frac{2}{3} g_4^{\pi\pi} \left[-\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \operatorname{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m_\pi^2}{g_4^{\pi\pi}} \right] \left(\frac{M_W}{M_{W_R}} \right)^4 \sum_{j=1}^{3} (V_R)^2_{ej} / m_{N_j},$$

$$\Delta \equiv 6 g_1^{\pi N} \mathcal{M}_1 + 5 g_1^{\pi\pi} \mathcal{M}_2$$

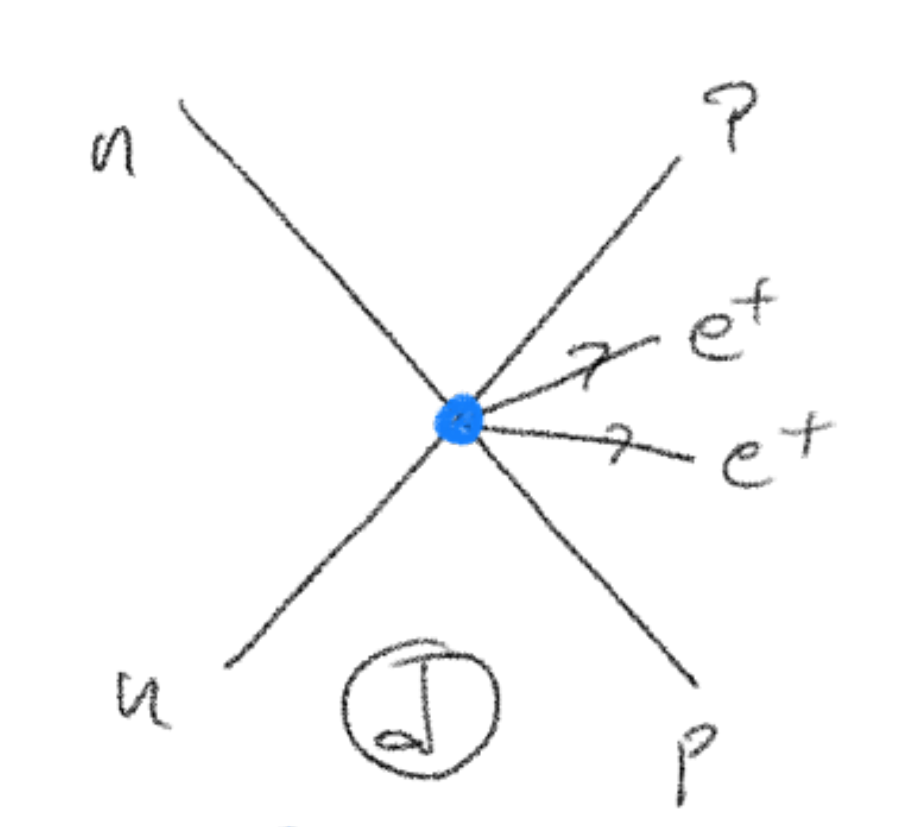
The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

$$(T_{1/2}^{0\nu})^{-1} = G \cdot \left|\mathcal{M}_\nu\right|^2 \left|m_\nu^{ee}\right|^2 + \left|\mathcal{M}_0\right|^2 \left|m_N^{ee}\right|^2$$

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

- The new physics contribution



Not quantified yet

$$m_N^{ee} \simeq \frac{2}{3} g_4^{\pi\pi} \left[-\frac{\left|\mathcal{M}_0\right|}{\left|\mathcal{M}_\nu\right|} \mathrm{sgn}(\Delta) t_\beta + \frac{2}{3} \frac{|\Delta|}{\left|\mathcal{M}_\nu\right|} \frac{m_\pi^2}{g_4^{\pi\pi}} \right] \left(\frac{M_W}{M_{W_R}}\right)^4 \sum_{j=1}^{3} (V_R)_{ej}^2 / m_{N_j},$$

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

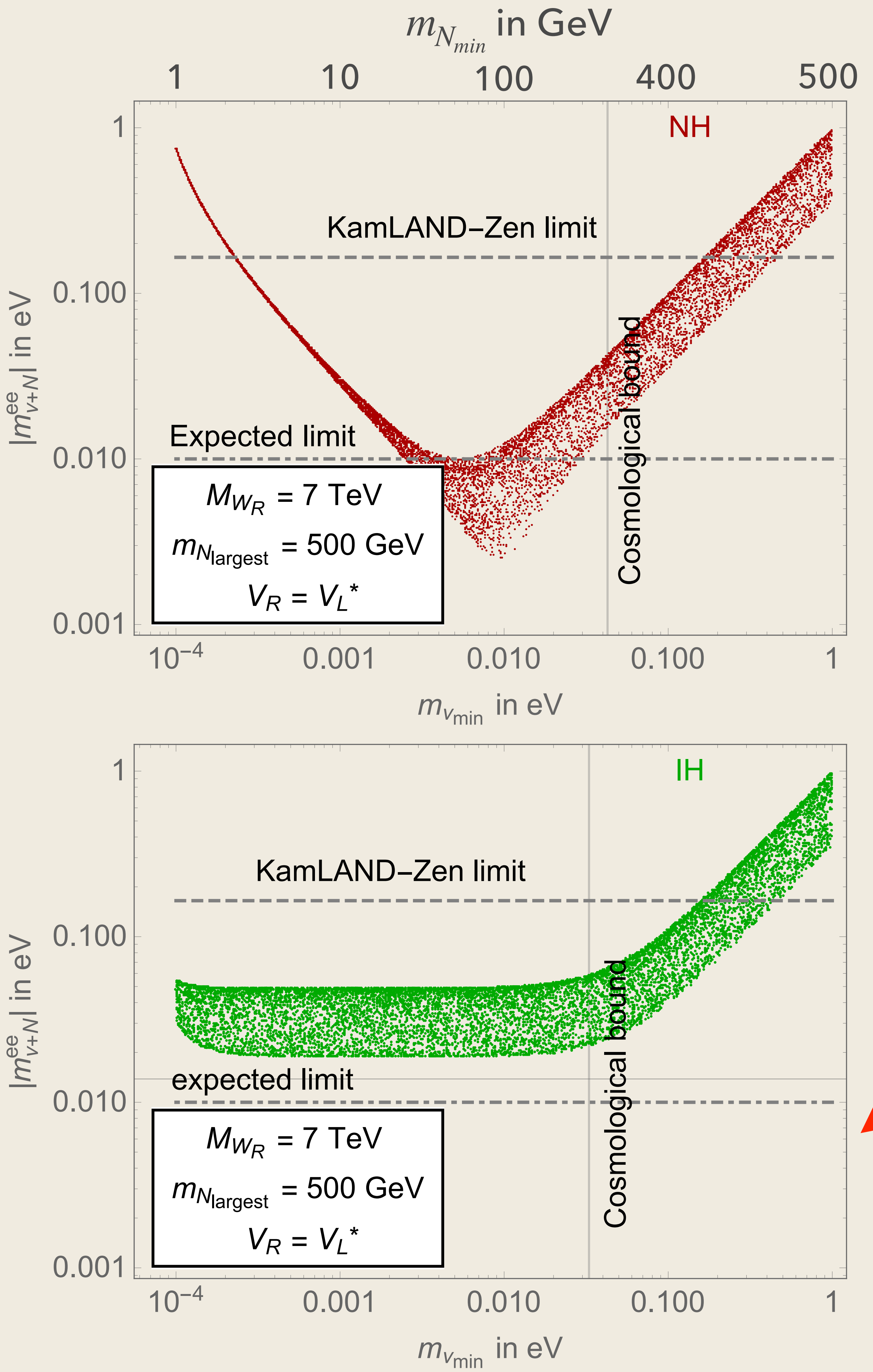
Since it have to be used as

A counterterm of the two loop

Divergent diagram.
(arXiv:1806.02780, 1802.10097 and 1907.11254)

- (Prezeau-Ramsey-Musolf-Vogel 2003. ArXiv: 0303205)

- We use $\left|\mathcal{M}_\nu\right| \sim 3.2$ for Xe-136 and $\left|\mathcal{M}_{LR}\right| = 2$



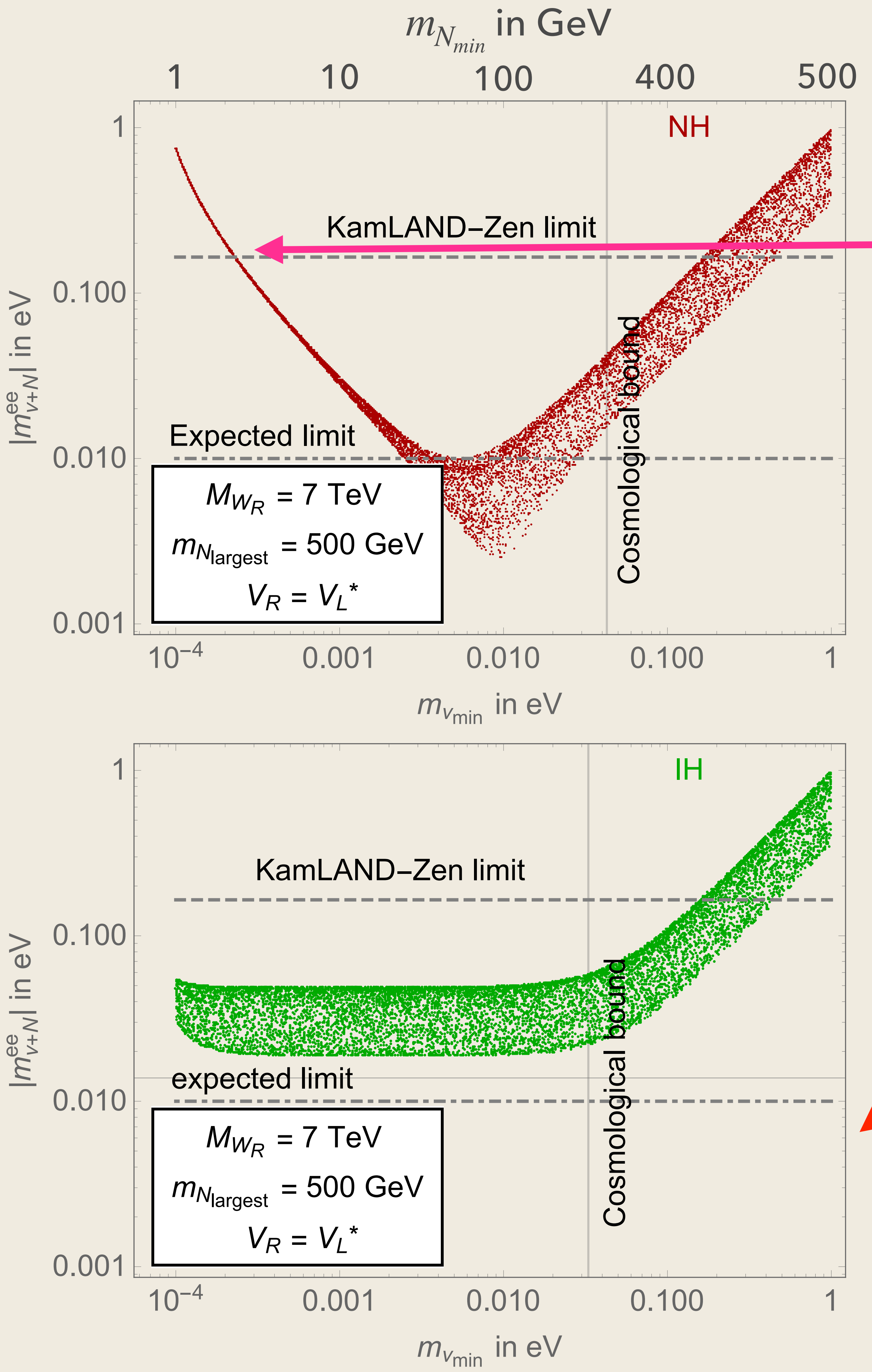
$m_{N_{min}}$ in GeV

1 10 100 400 500

No long range
Contributions

(Tello and Senjanovic. ArXiv: 1011.3522)

- We use $\left|\mathscr{M}_{\nu}\right| \sim 3.2$ for Xe-136 and $\left|\mathscr{M}_{LR}\right| = 2$



$m_{N_{min}}$ in GeV

1 10 100 400 500

EFT not reliable here

(Kaori's talk addressed this light N regime

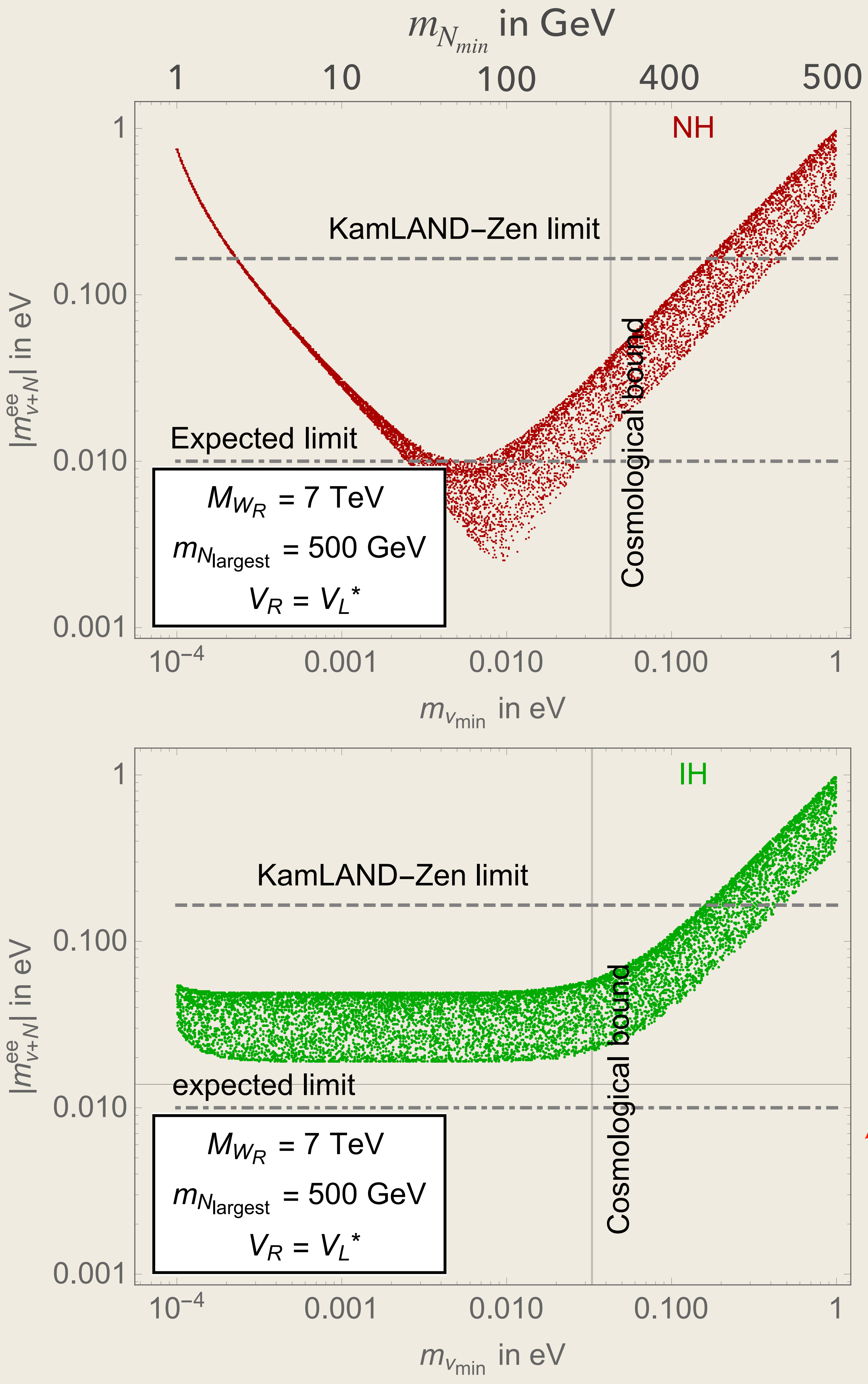
ArXiv: 2002.07182)

No long range

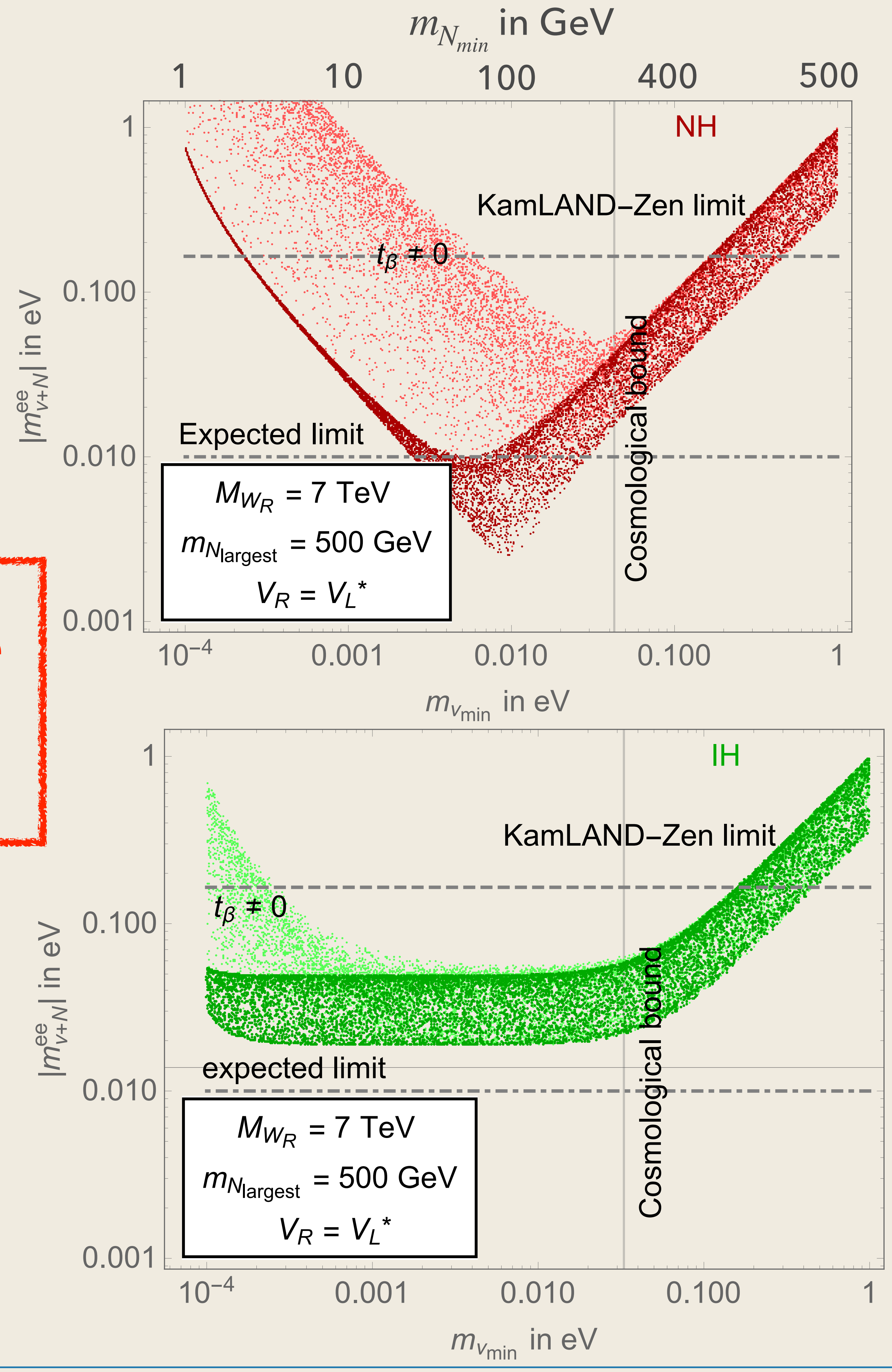
Contributions

(Tello and Senjanovic. ArXiv: 1011.3522)

- We use $\left|\mathcal{M}_\nu\right| \sim 3.2$ for Xe-136 and $\left|\mathcal{M}_{LR}\right| = 2$



No long range Contributions

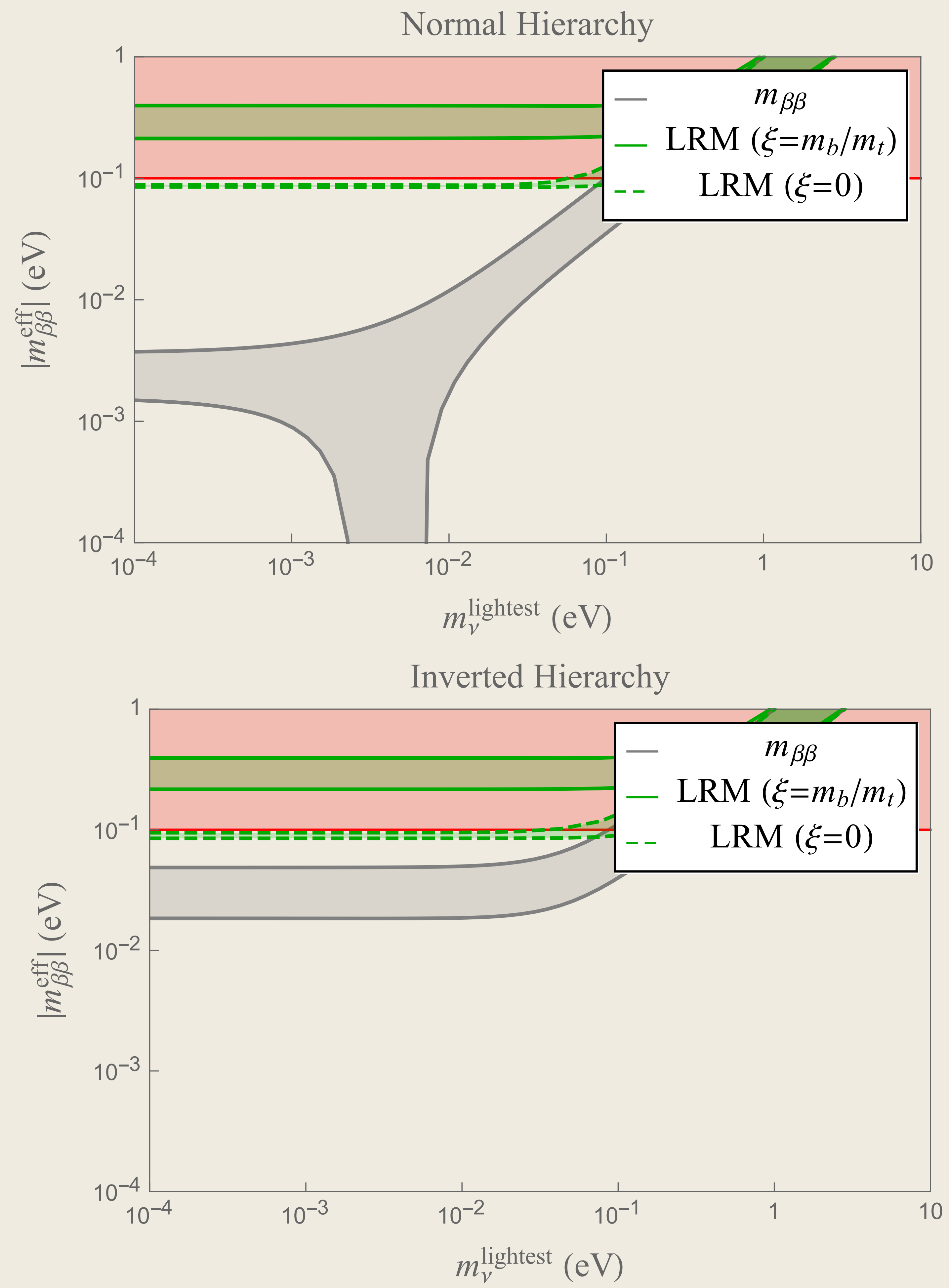


Long range Contributions

(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 assumes
- 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



Conclusions

- Since current cosmological bounds are getting more constraining, we should be ready to the possibility that new physics at the TeV dominate the 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

The decay rate including "long-range" contributions

- We use $\left|\mathscr{M}_{\nu}\right| \sim 3.2$ for Xe-136 and $\left|\mathscr{M}_{LR}\right| = 2$

Displaced vertices at the LHC

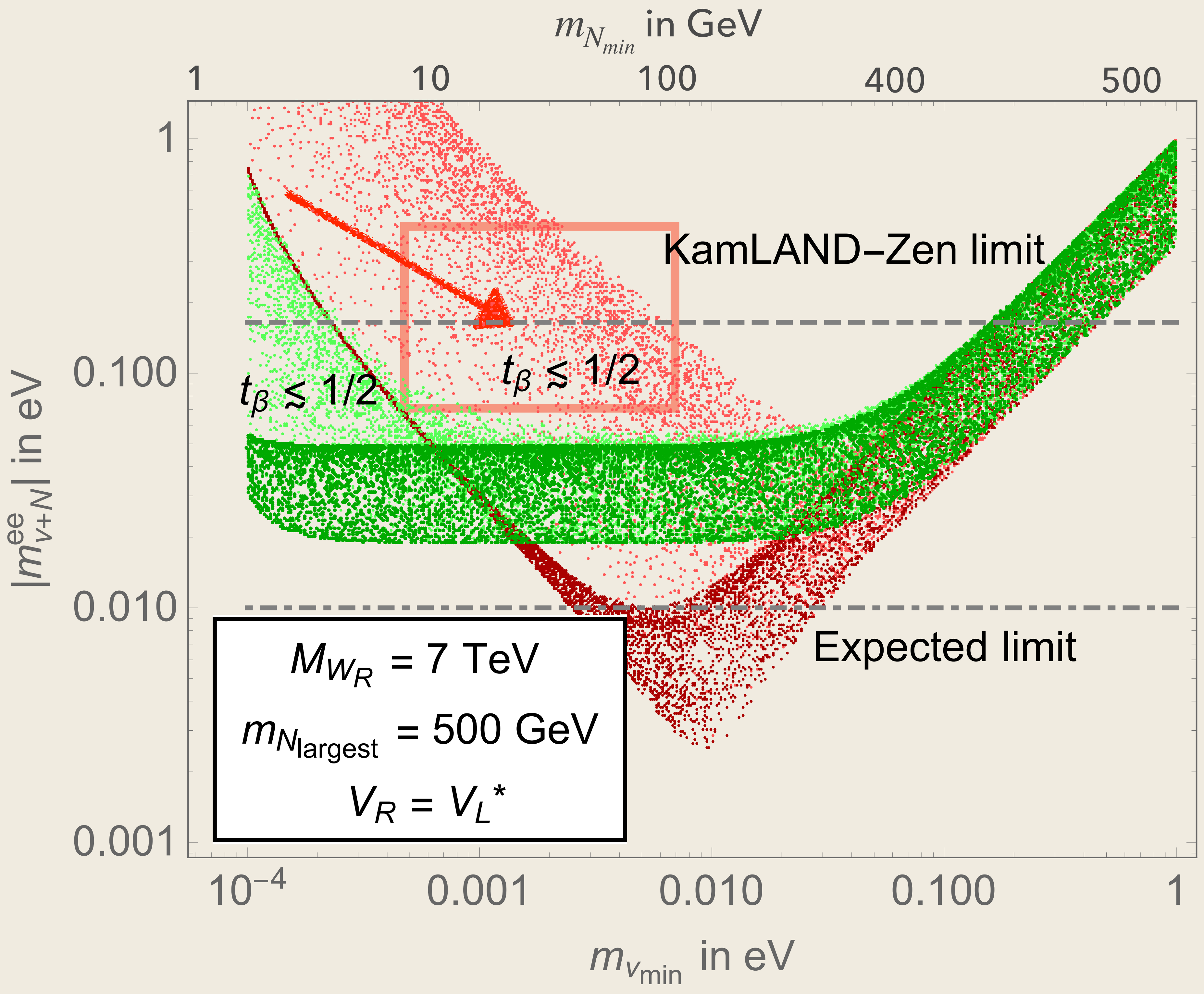
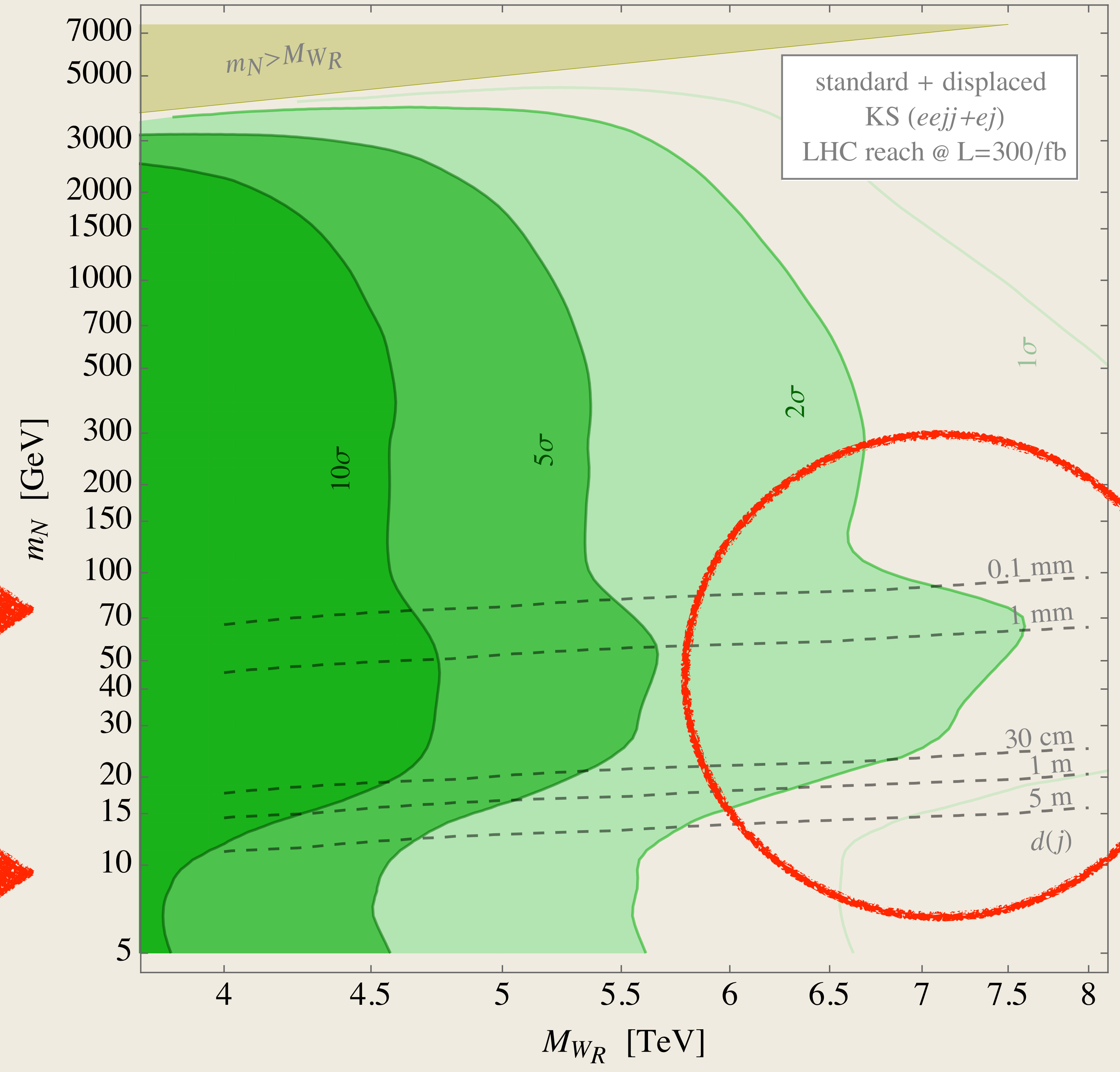


Image taken from Nemevsek, Nesti, Popara arXiv: 1801.05813



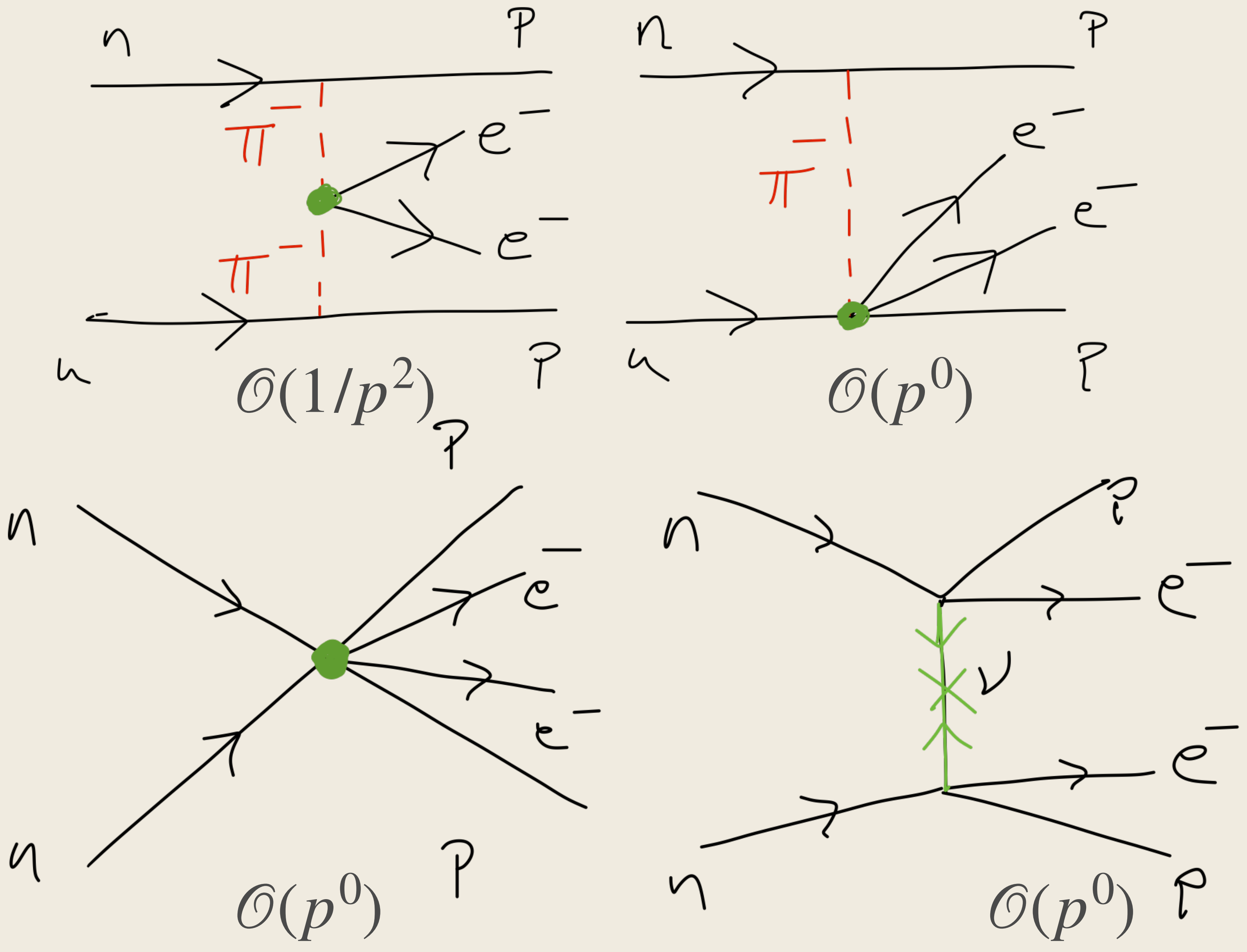
Weinberg's power counting

- $\mathscr{L}_{eff}$ 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)

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

- 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)