Long range contributions to the $0\nu2\beta$ decay rate in the minimal left-right symmetric model

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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

- The parameter's space of visible $0\nu2\beta$ decay rate for the TeV scale mLRSM is bigger than previous studies showed

1. Introduction
2. Neutrinoless double beta decay.
3. Experimental searches and limits
4. The minimal left-right symmetric model (mLRSM)
5. Effective Lagrangian in chiral perturbation theory from the mLRSM
6. The decay rate including long range contributions in the mLRSM
7. Conclusions and outlook

Introduction. Neutrinoless double beta decay

- Lepton number is an accidental symmetry of the SM
- Neutrino have zero electric charge. In 1937 Majorana raised the possibility of the neutrino being its own antiparticle
- This implies that Lepton number is not conserved
- In 1937, 1939 Racah and Furry proposed the possibility of a beta decay with no neutrinos and $\Delta L = 2$ for this process
- This is not the only mechanism. New physics could be dominant (G. Feinberg and M. Goldhaber 1959)

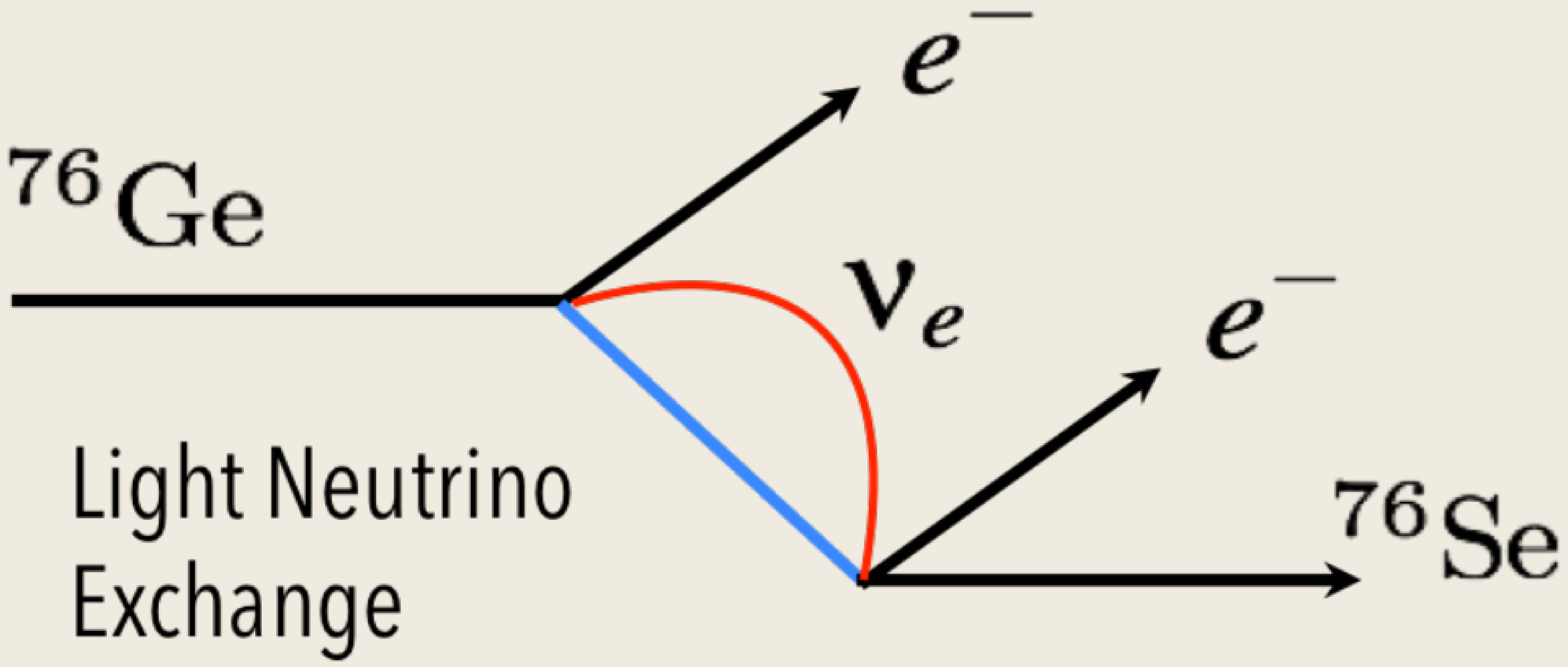
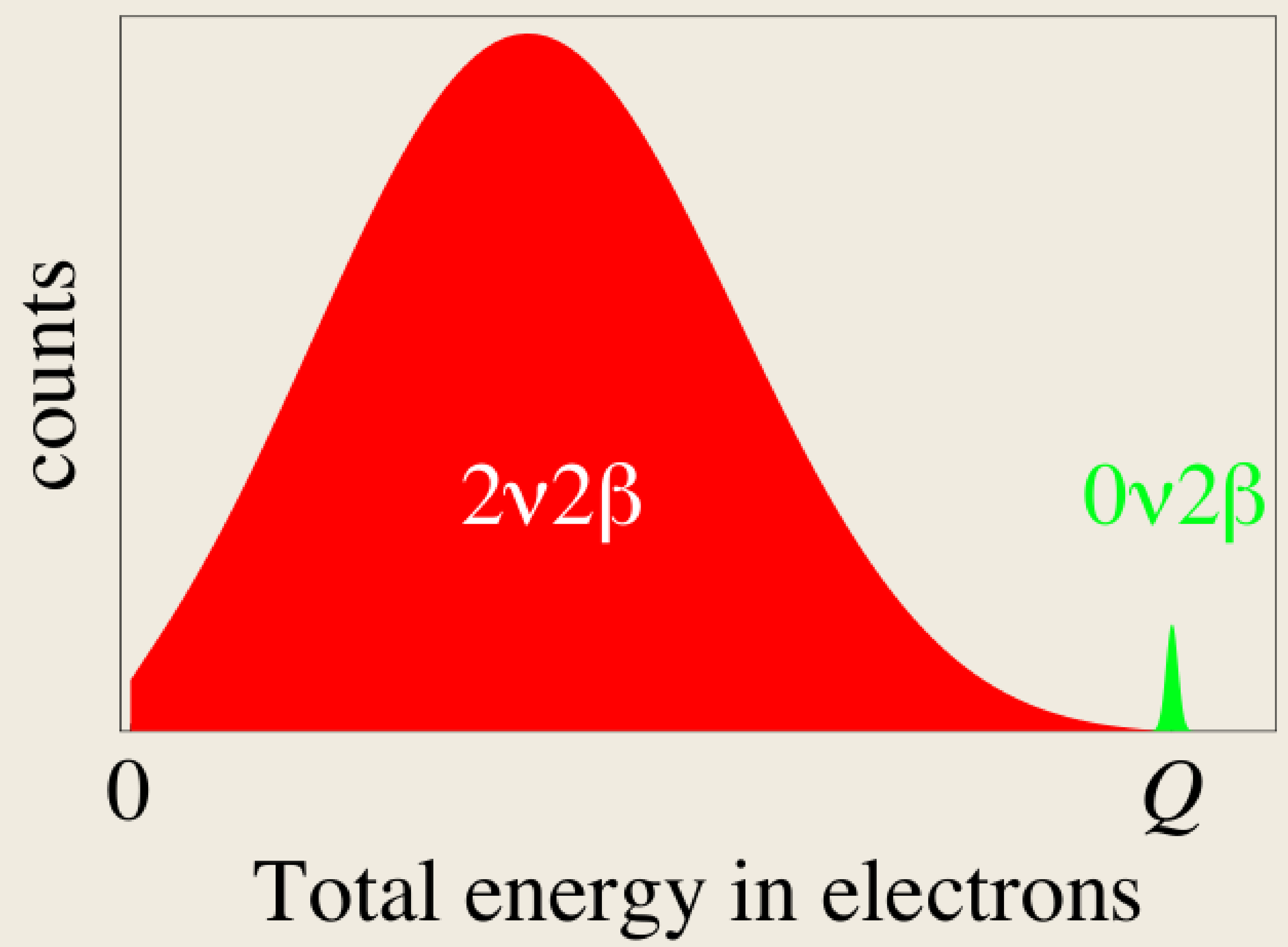


Image taken from https://www.npl.washington.edu/majorana/majorana-experiment

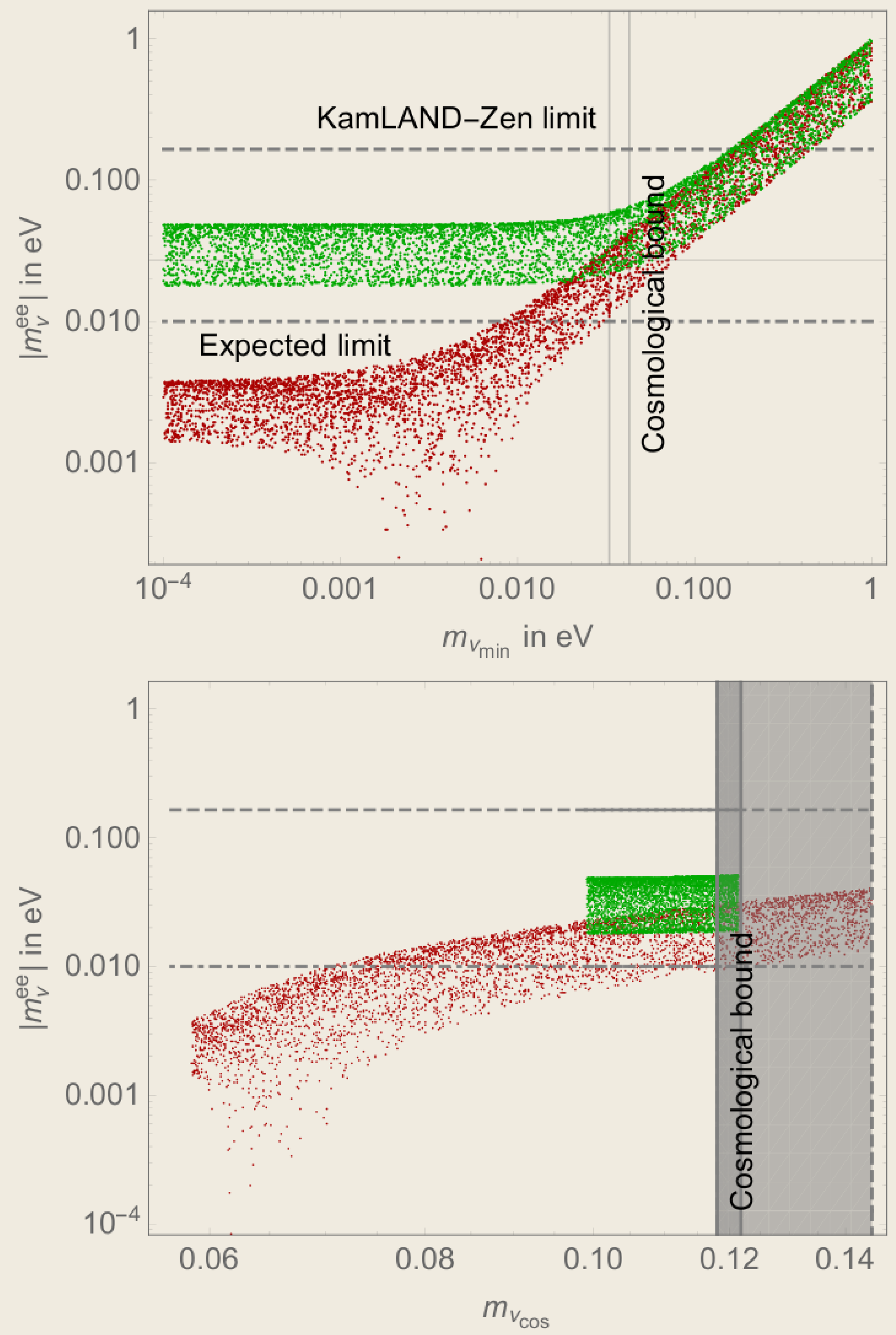
$$^{76}\text{Ge} \to {}^{76}\text{Se}\, ee\, \bar{\nu}_e \bar{\nu}_e \qquad (Q = 2038.6\,\text{keV}).$$



Experimental searches and limits

- Limits on $\langle m_{\beta\beta} \rangle = | m_\nu^{ee} |$ and the lifetime for the light ν exchange mechanism
- Cosmological bound $\sum m_\nu < 0.118$ eV.

(taken from: arXiv:1806.10832)



Isotope	$T_{1/2}^{0\nu}$ ($\times 10^{25}$ years)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment
^{48}Ca	$>5.8 \times 10^{-3}$	<3.5–22	ELEGANT-IV
^{76}Ge	>8.0	<0.12–0.26	GERDA
	>1.9	<0.24–0.52	Majorana Demonstrator
^{82}Se	$>3.6 \times 10^{-2}$	<0.89–2.43	NEMO-3
^{96}Zr	$>9.2 \times 10^{-4}$	<7.2–19.5	NEMO-3
^{100}Mo	$>1.1 \times 10^{-1}$	<0.33–0.62	NEMO-3
^{116}Cd	$>2.2 \times 10^{-2}$	<1.0–1.7	Aurora
^{128}Te	$>1.1 \times 10^{-2}$	NE	C. Arnaboldi et al.
^{130}Te	>1.5	<0.11–0.52	CUORE
^{136}Xe	>10.7	<0.061–0.165	KamLAND-Zen
	>1.8	<0.15–0.40	EXO-200
^{150}Nd	$>2.0 \times 10^{-3}$	<1.6–5.3	NEMO-3

- (image taken from: arXiv:1902.04097)

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

$$\mathcal{L}^W = -\frac{g}{\sqrt{2}}\bar{u}_{Li}\gamma^\mu V^L_{ud}\left(\cos\xi W^+_{1\mu} - \sin\xi e^{-i\alpha}W^+_{2\mu}\right)d_{Li}$$

$$-\frac{g}{\sqrt{2}}\bar{u}_{Ri}\gamma^\mu V^R_{ud}\left(\sin\xi e^{i\alpha}W^+_{1\mu} + \cos\xi W^+_{2\mu}\right)d_{Ri}$$

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

- $\tan\beta_{max} \sim 0.5$ 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)

$W^+_R = \sin\xi e^{i\alpha}W^+_{1\mu} + \cos\xi W^+_{2\mu}$

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

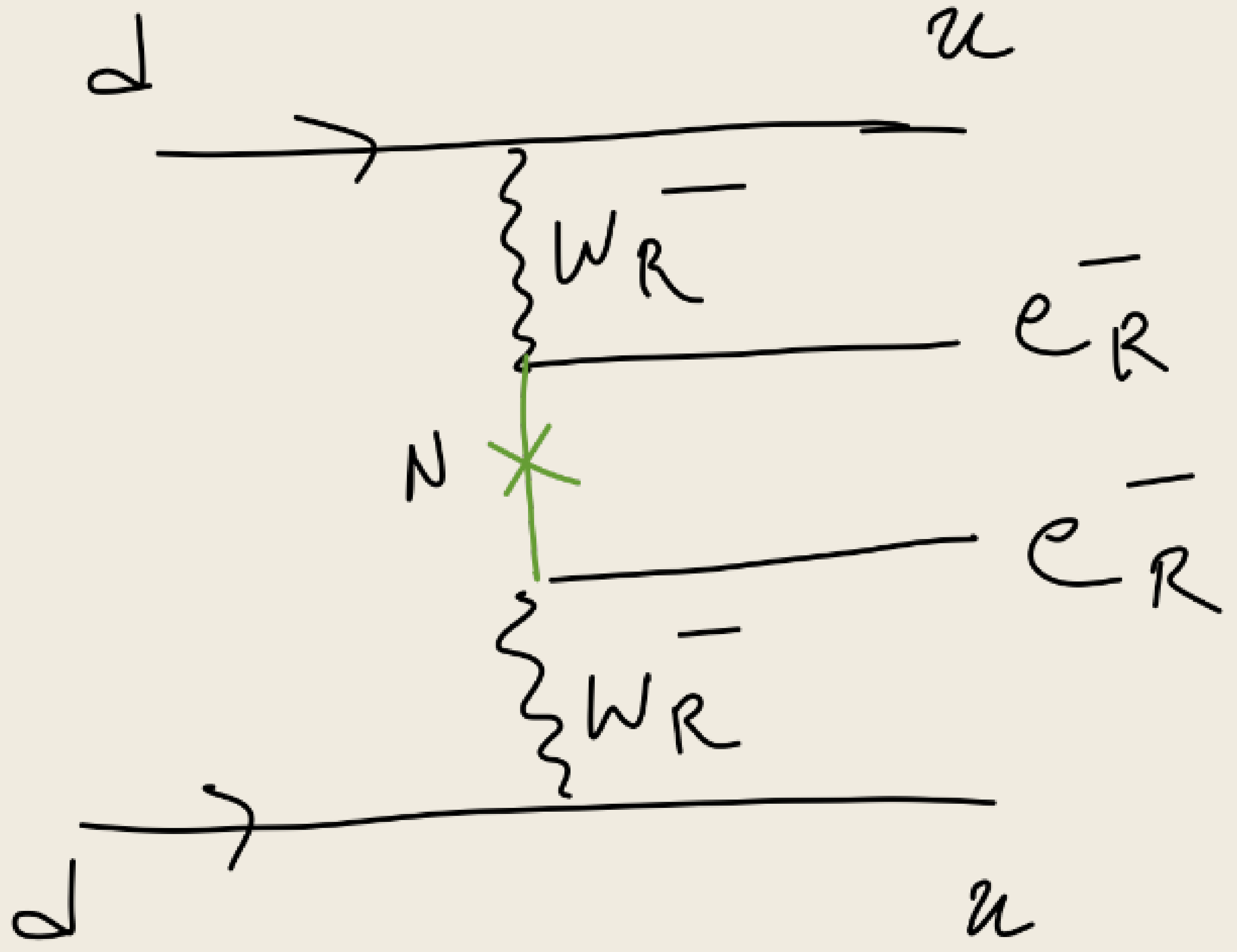
$V_L = V_R^*$

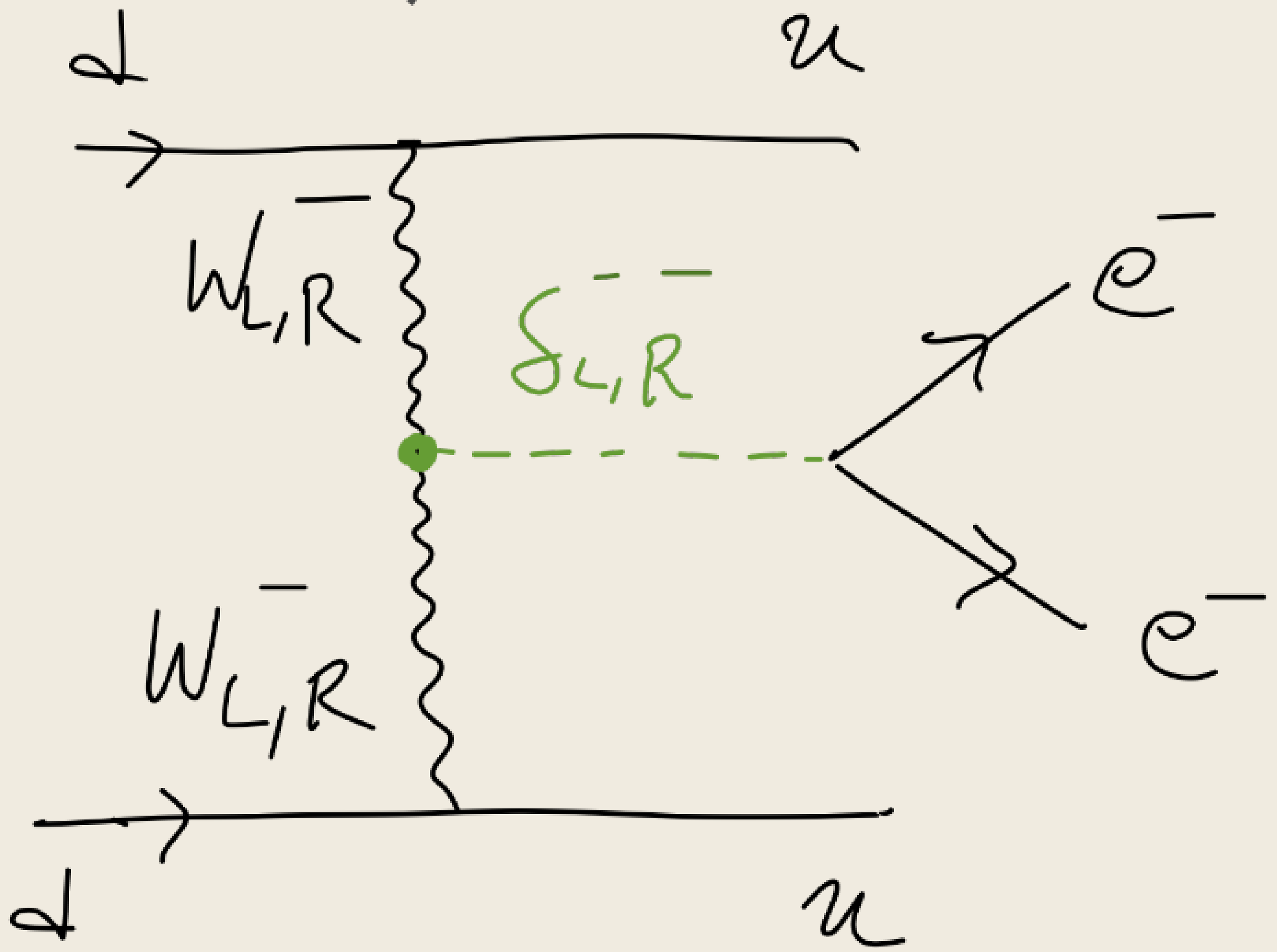
and the $m_{N_{min}} = m_{N_{min}}(m_{\nu_{min}})$

(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)

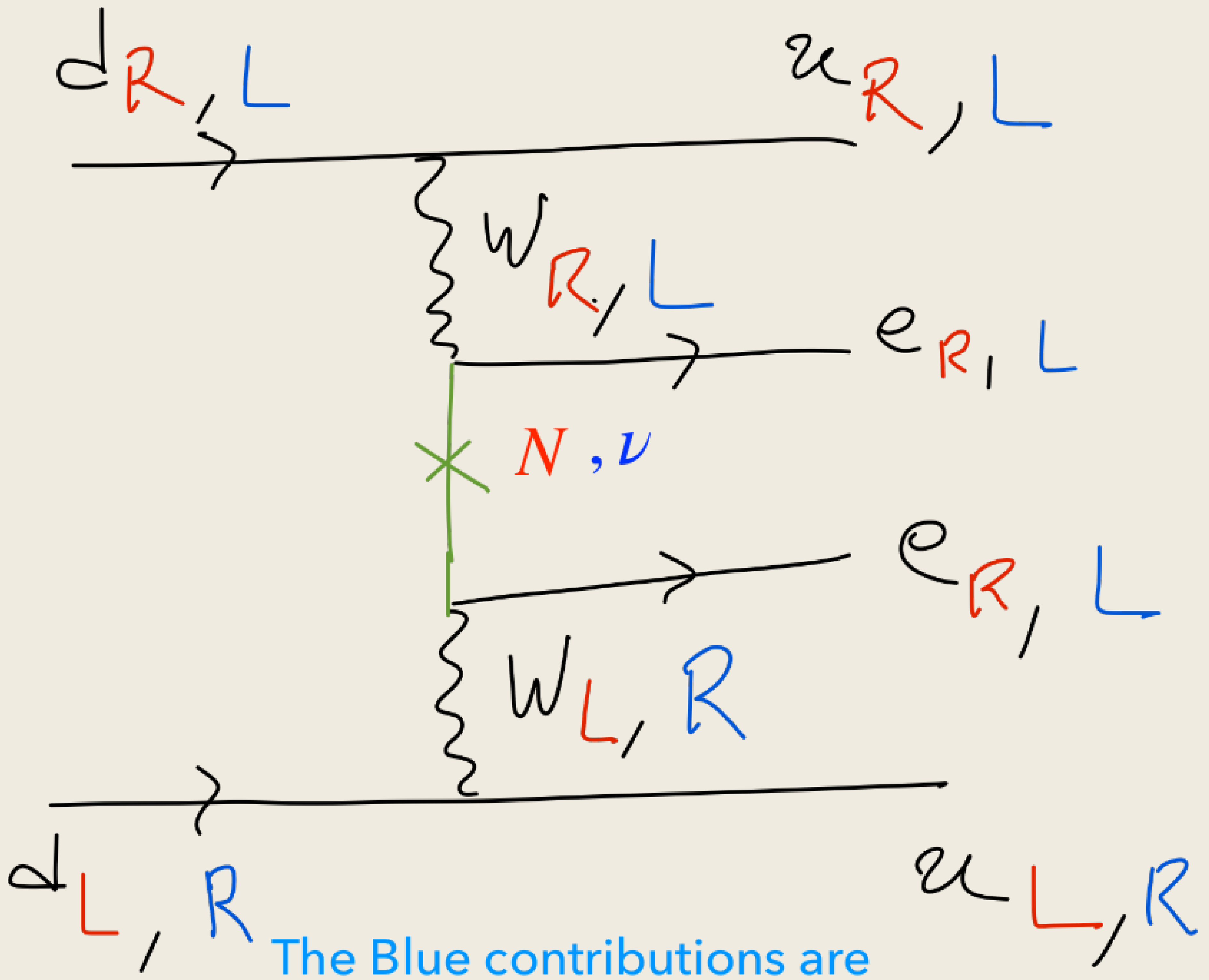




Suppressed by heavy

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

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The minimal left-right symmetric model

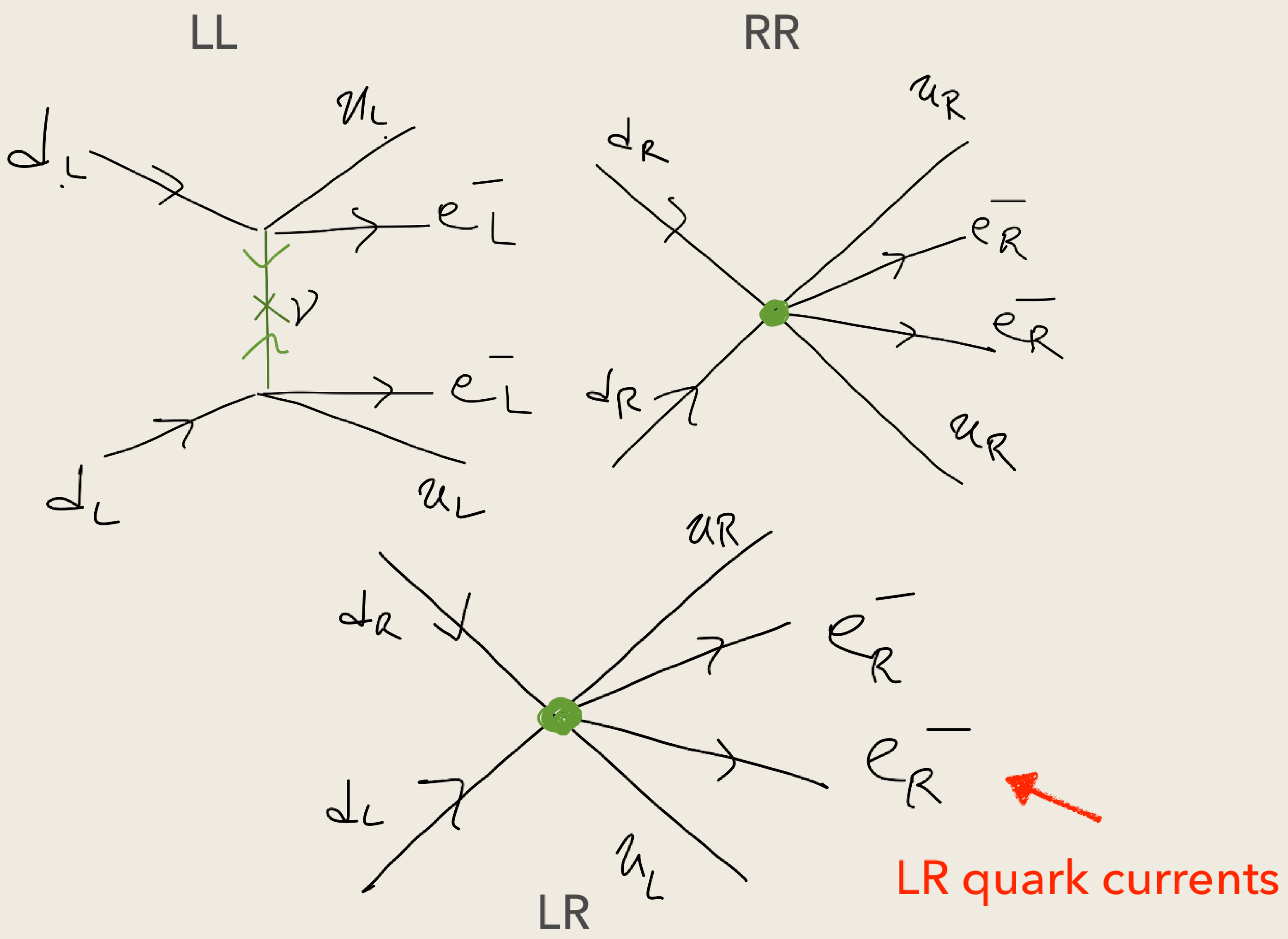
- The effective Lagrangian for $0\nu 2\beta$

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

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

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

$$\mathcal{O}^{++}_{3\pm} = \left(\bar{q}_L\tau^+\gamma^\mu q_L\right)\left(\bar{q}_L\tau^+\gamma_\mu q_L\right) \pm \left(\bar{q}_R\tau^+\gamma^\mu q_R\right)\left(\bar{q}_R\tau^+\gamma_\mu q_R\right).$$



The chiral Lagrangian induced by the effective interaction

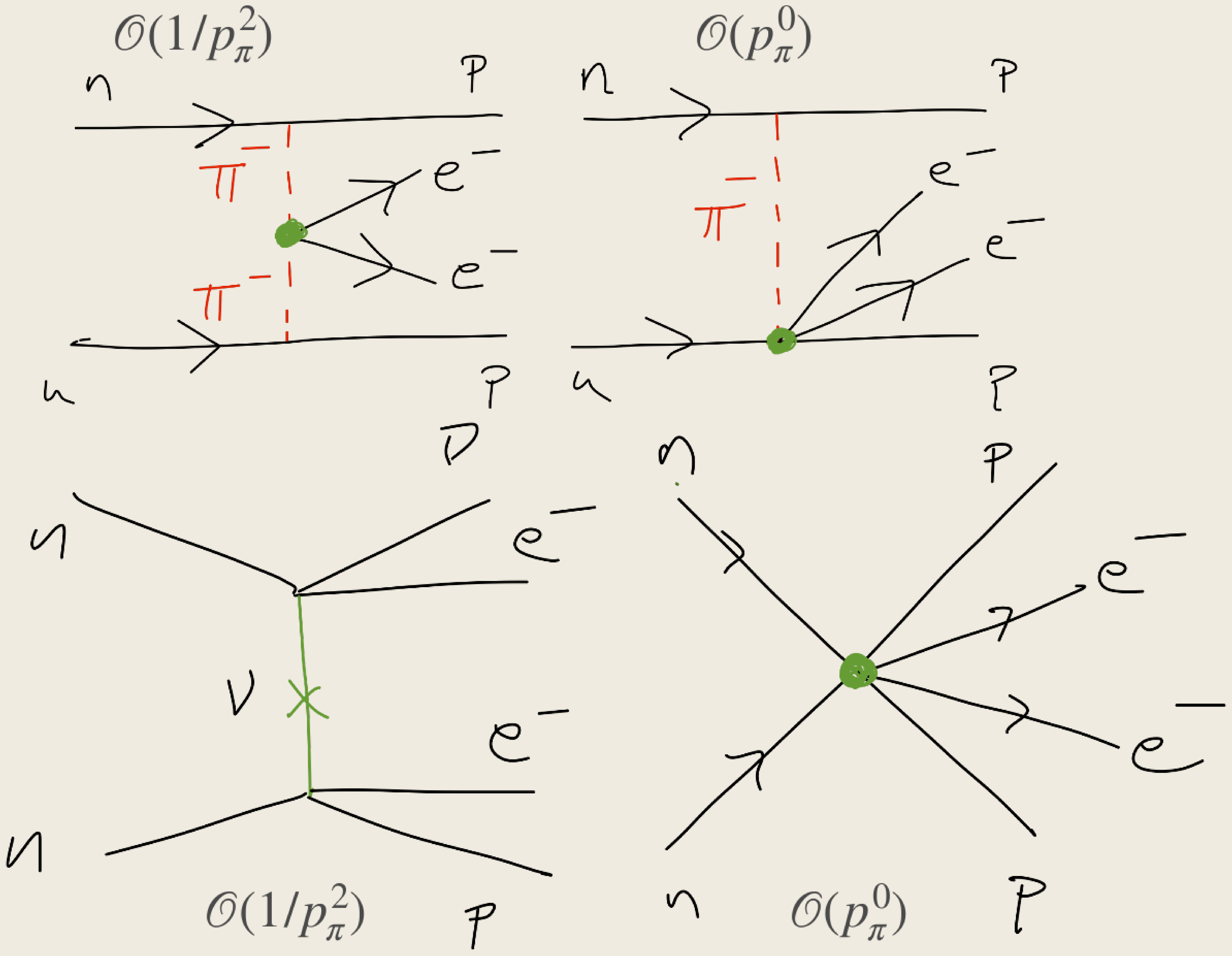
- At the hadronic level $\mathcal{O}_{1+}^{++}$ five a LO contribution to $\pi\pi e e^c$ vertex

$$\mathcal{O}_{1+}^{\pm\pm} \to \frac{4}{f_\pi^2}\pi^\mp\pi^\mp + \cdots,$$ 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 $\Lambda_H^2/p_\pi^2 \sim 10^2$

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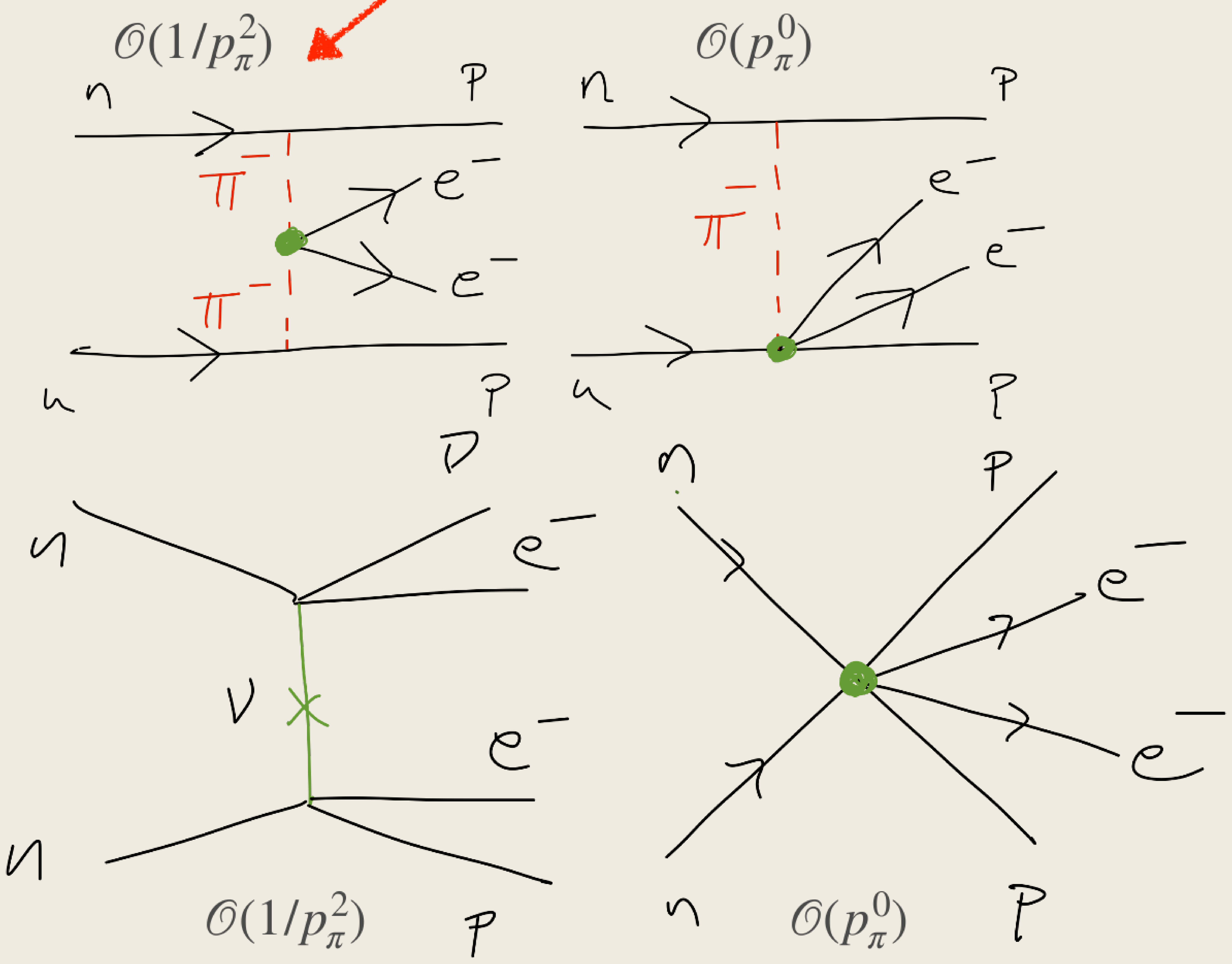

The decay rate including "long-range" contributions

- In the mLRSM the decay rate is

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

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

- The NME $\left|\mathcal{M}_{LR}\right|^2 = 2$ (Prezeau-Ramsey-Musolf-Vogel 2003. ArXiv: 0303205.
- The new physics contribution

$$m^{ee}_N \simeq \sqrt{\frac{2}{9}} \Lambda^2_H (2t_\beta + \delta) \left(\frac{M_W}{M_{W_R}} \right)^4 \sum_{j=1}^{3} \frac{(V_R)^2_{ej}}{m_{N_j}} .$$

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Hadronic matrix elements

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$W_L - W_R$ mixing $\tan\beta_{max} \sim 0.5$

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chiral suppression of the RR and LL contributions $\delta \approx 1/30$

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mLRSM contribution

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

The decay rate including "long-range" contributions

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

Displaced vertices at the LHC

EFT not so reliable here

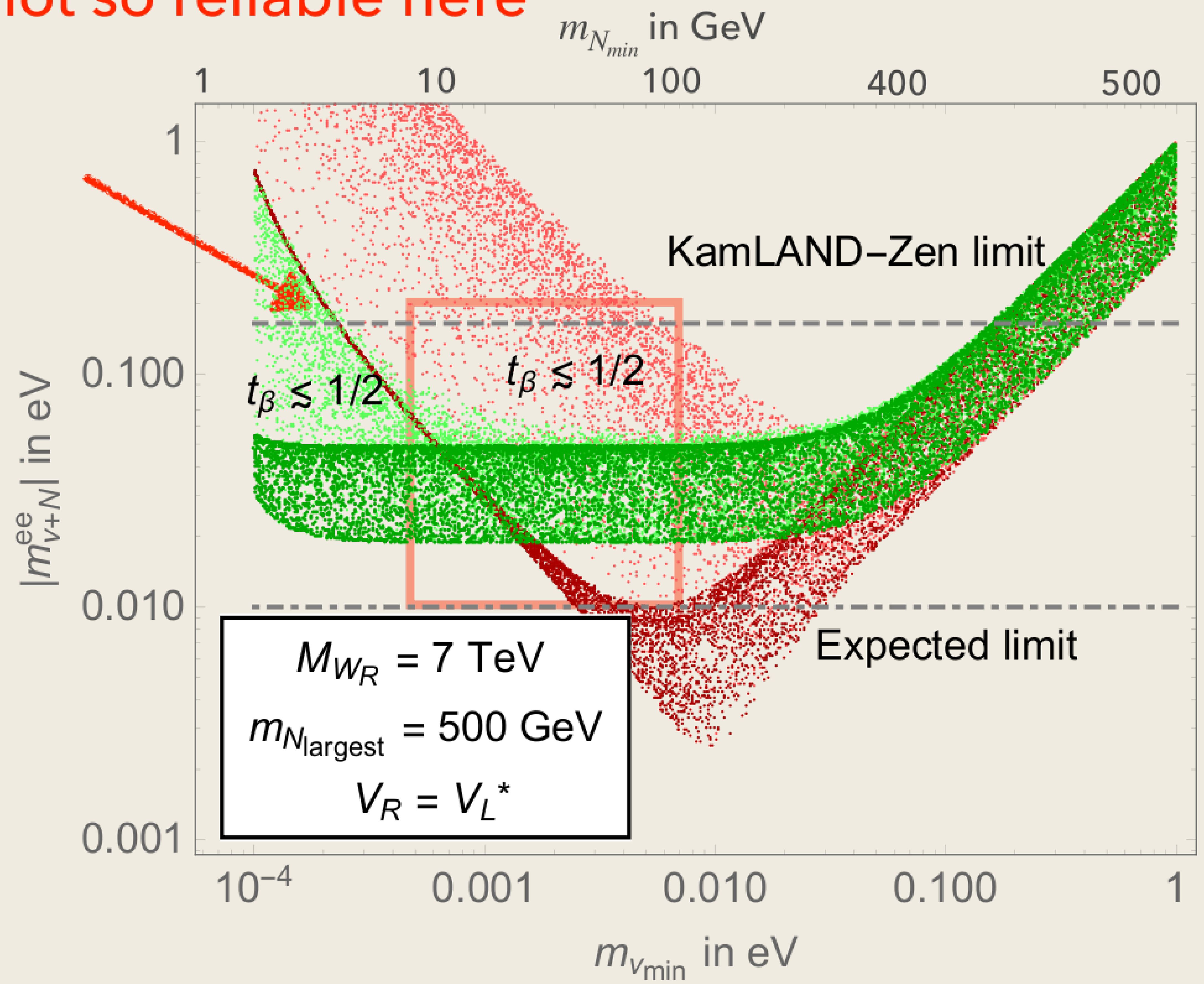
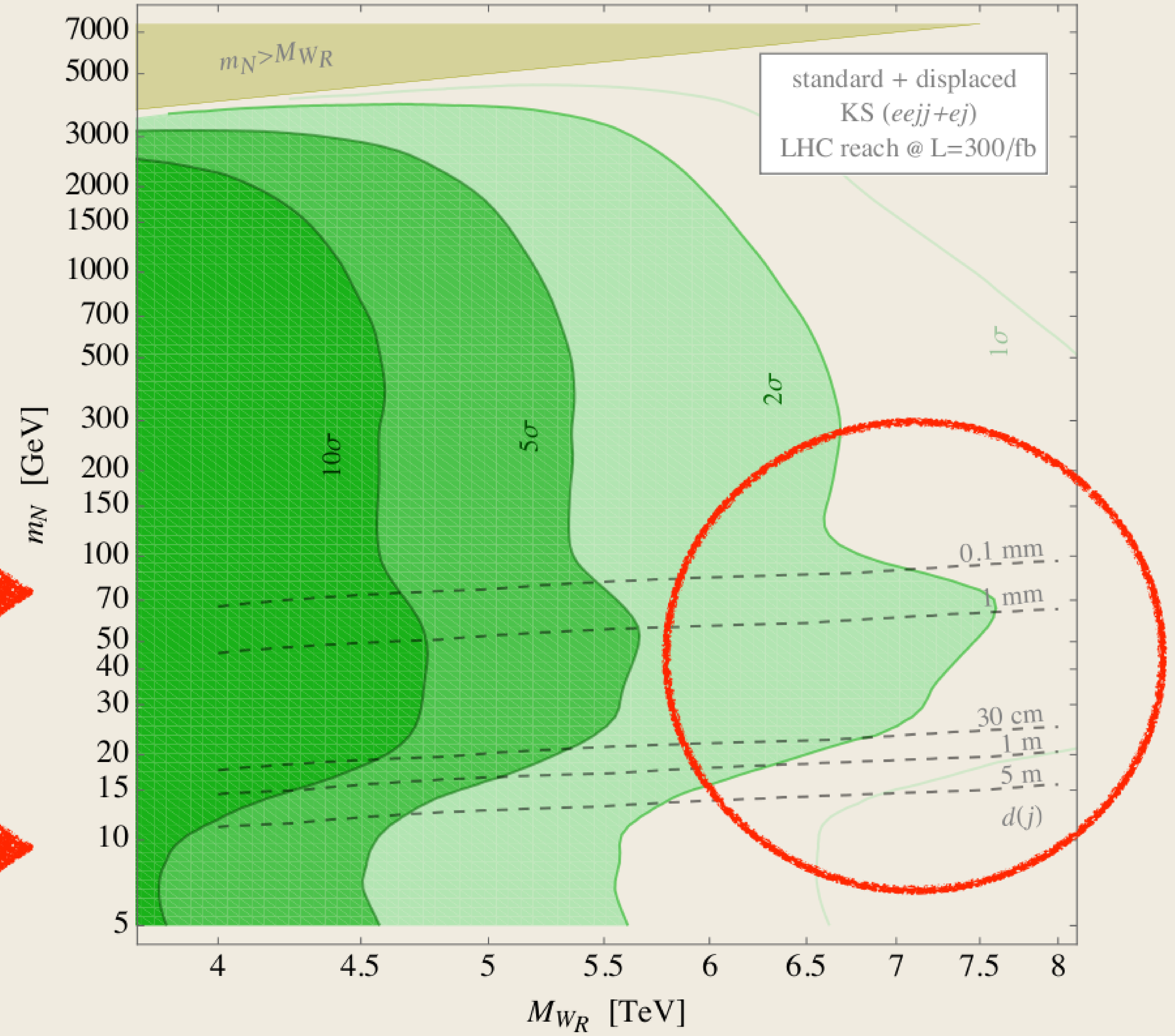
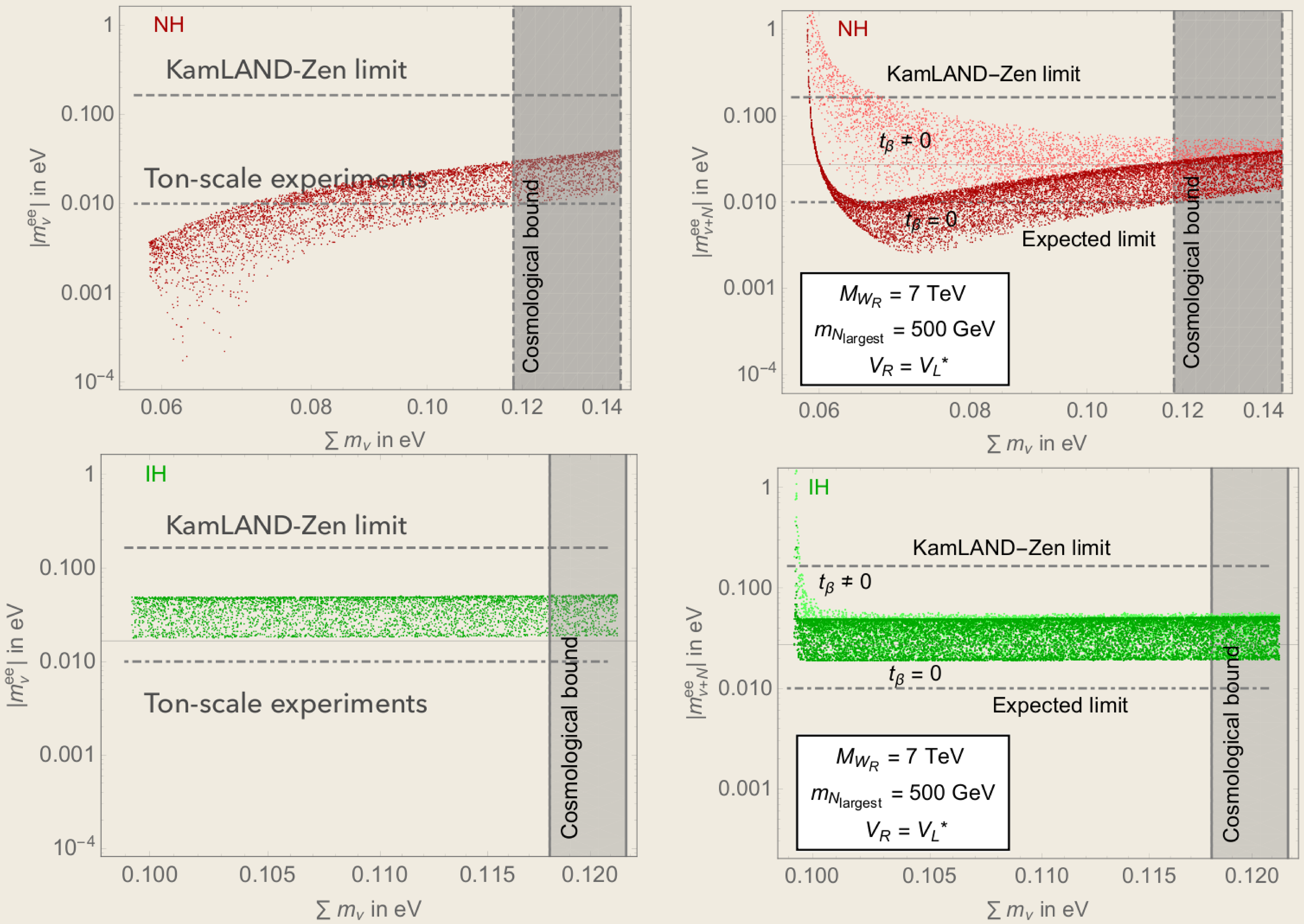


Image taken from Nemevsek, Nesti, Popara

arXiv: 1801.05813



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

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

Projections taken from Kevork Abazajian ACFI talk 2015

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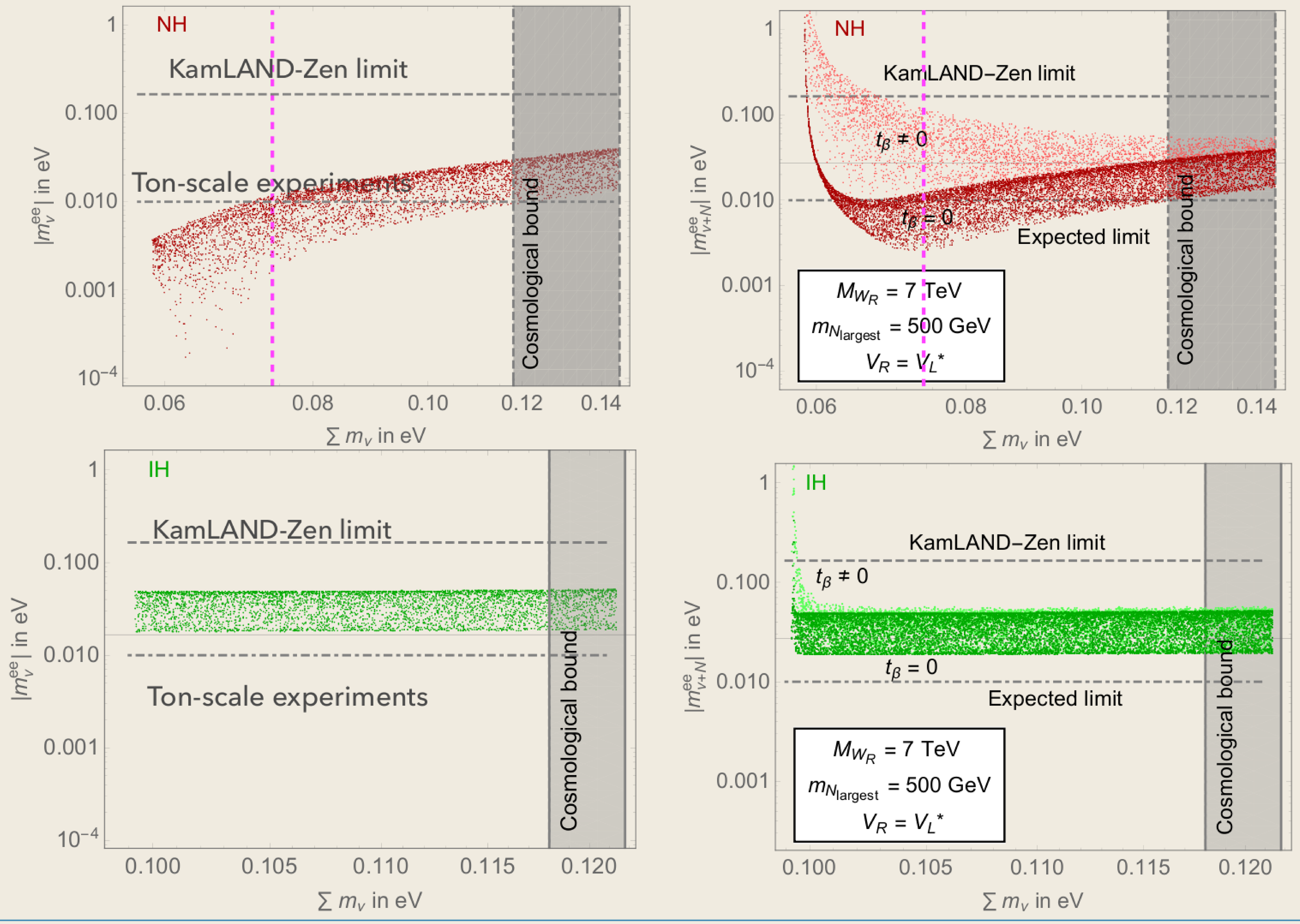

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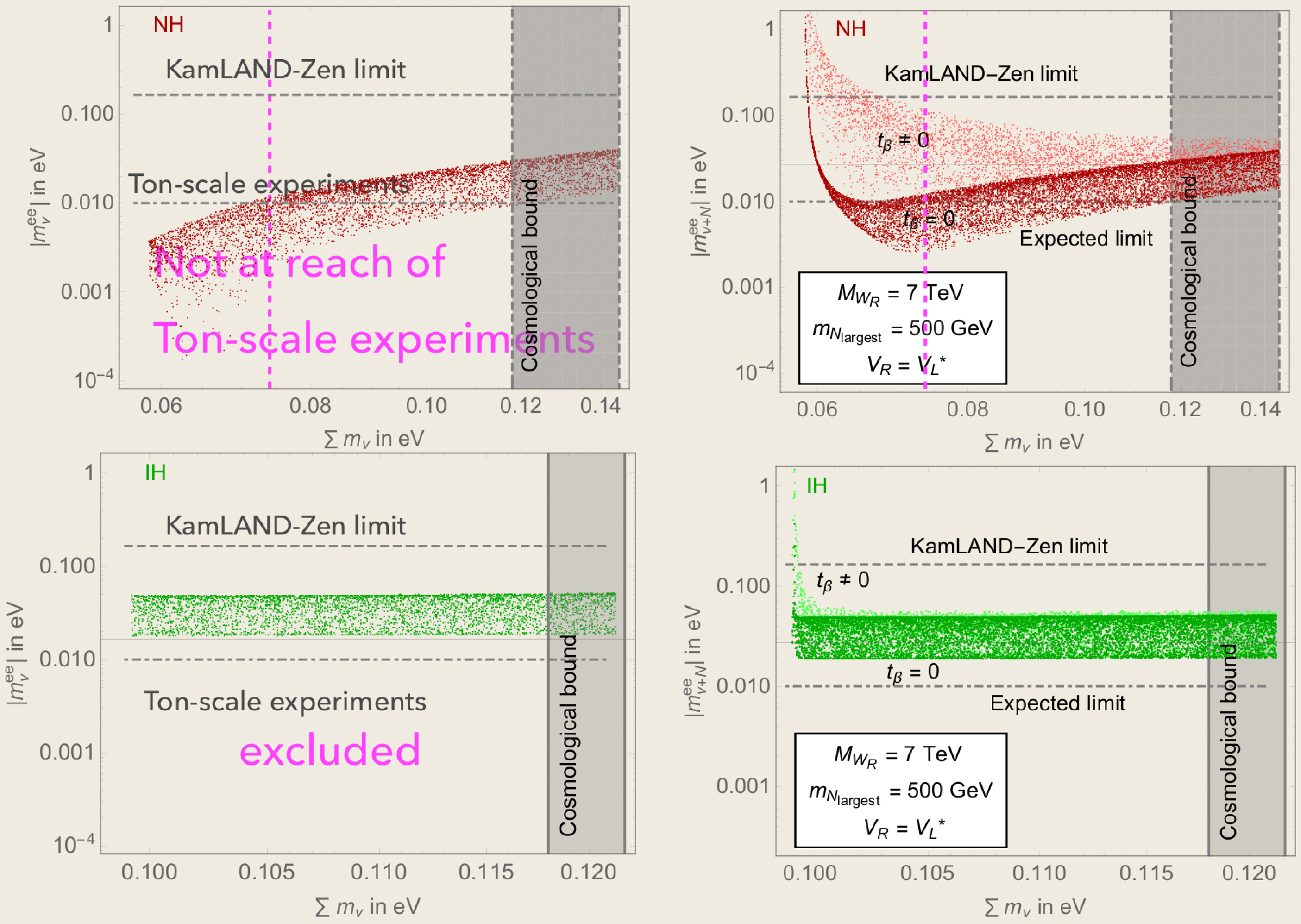

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Conclusions

- Since current cosmological bounds are getting more constraining, we should be ready to the possibility that new physics at the TeV dominates 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 $0\nu2\beta$ decay experiments
- In contrast to the light neutrino exchange scenario, in this scenario the parameter space of visible decay rate is bigger than previous analysis have reported

Thank you

Backup slides

Future directions

- 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)

Light neutrino exchange decay rate

- Nuclear Matrix elements for different atoms

(image taken from: arXiv:1902.04097)

- The decay rate

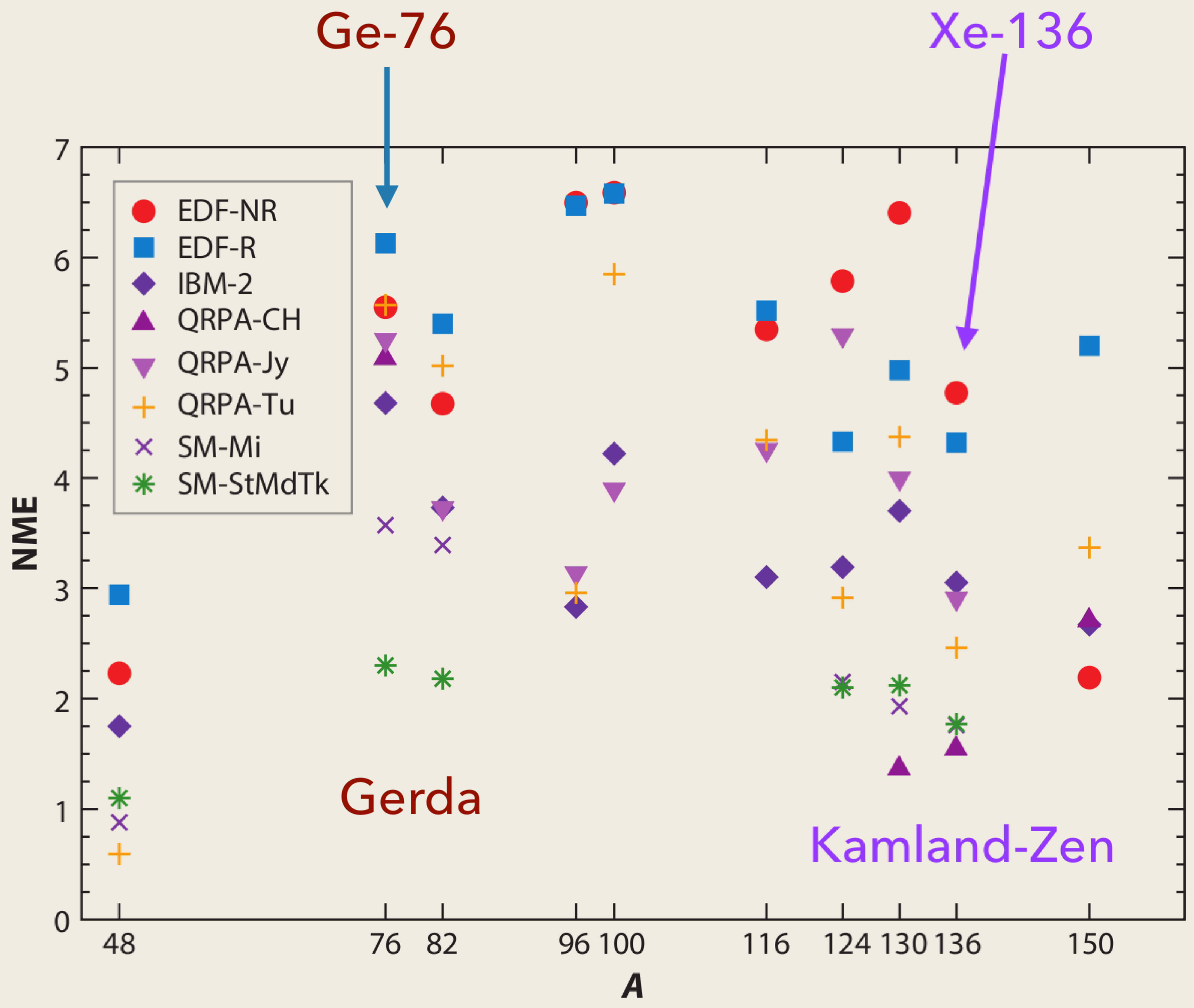
NME^2

$$T^{0\nu}_{1/2} = \left(G\, |\mathscr{M}|^2 \langle m_{\beta\beta} \rangle^2 \right)^{-1}$$

where Phase space factor

$$m_{\beta\beta} \equiv \sum_{i=1}^{3} V_{ei}^2\, m_{\nu_i}$$ (effective neutrino mass)

$$(G^{\text{Ge}}_{0\nu})^{-1} = 4.09 \times 10^{25} \text{eV}^2 \text{ yrs}$$



Type II seesaw dominance

- In this analysis we will assume Type-II seesaw dominance
- $M_\nu = Y_{\Delta_L} v_L - M_D^T M_N^{-1} M_D$
- Then $M_\nu = \frac{v_L}{v_R} M_N$
- $\Delta m_{21}^2 = \Delta m_\odot^2 \sim 10^{-5}$ eV^2 and $\Delta m_{31}^2 = \Delta m_{atm}^2 \sim 10^{-3}$ eV^2 fixed by oscillation experiments
- Constraints

$m_{\nu_l}, m_{\nu_m}, m_{\nu_h}$

$m_{N_l}, m_{N_m}, m_{N_h}$

$\Delta m_\odot$ Δm_{atm}

Fixed to 500 GeV

Fixed again by mass differences

- From the atmospheric mass difference

$$\left|v_L\right| = \frac{M_{W_R}}{g} \frac{\Delta m_{atm}^2}{\sqrt{|m_{N_3}^2 - m_{N_1}^2|}}$$

- Using

$$m_{\nu_1} + m_{\nu_2} + m_{\nu_3} = \frac{v_L}{v_R}(m_{N_1} + m_{N_2} + m_{N_3})$$

- One can get $m_{N_1} = m_{N_1}(m_{\nu_1})$

The chiral Lagrangian

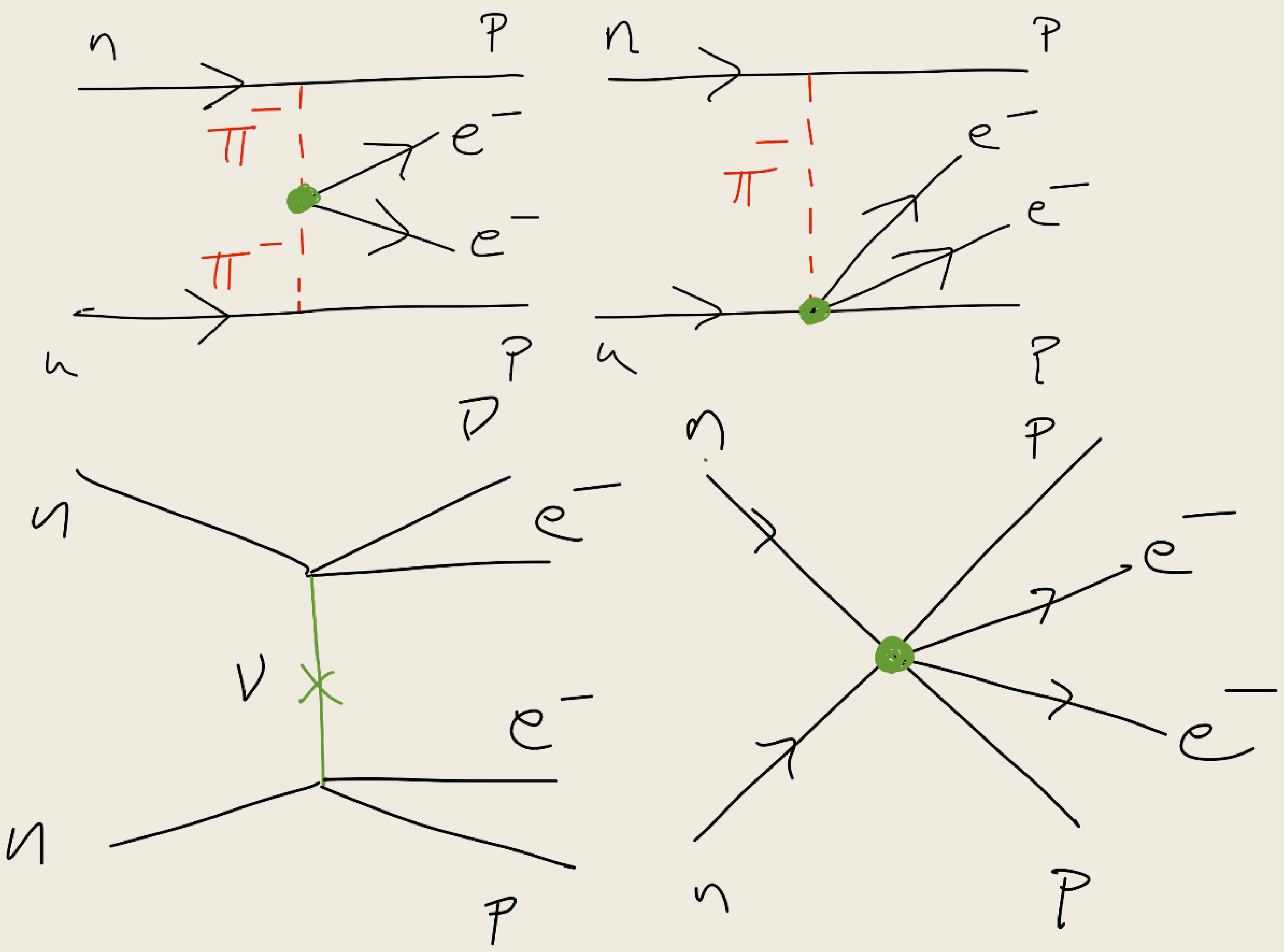
- The effective Lagrangian hadronic scale

$$\mathscr{L}^{\pi\pi ee}_{(0)} = \frac{G_F^2 f_\pi^2}{\Lambda_{\beta\beta}} \pi^- \pi^- \bar{e} \left(\beta_1 + \beta_2 \gamma^5\right) e^c + h.c.$$

$$\mathscr{L}^{NN\pi ee}_{(1)} = \frac{G_F^2 \Lambda_H f_\pi}{\Lambda_{\beta\beta}} \bar{N} \gamma^5 \tau^+ \pi^- N \bar{e} \left(\zeta_5 + \zeta_6 \gamma^5\right) e^c + \mathrm{h.c.}$$

$$\mathscr{L}^{NNNNee}_{0} = \frac{G_F^2}{\Lambda_{\beta\beta}} \left\{ \xi_3 \mathfrak{N}^{++}_{3+} \bar{e} e^c + \xi_6 \mathfrak{N}^{++}_{3+} \bar{e} \gamma^5 e^c \right\},$$

$$\mathfrak{N}^{\pm\pm}_{3+} = \left(\bar{N} \tau^\pm \gamma^5 \gamma^\mu N\right) \left(\bar{N} \tau^\pm \gamma^5 \gamma_\mu N\right).$$



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The minimal left-right symmetric model

- So we see a relative enhancement of the $\pi\pi e e^c$ contribution
- The enhancement goes as $\Lambda_H^2/p^2 \sim 10^2$