Doubly-charged scalar from the right-handed sector: complementary tests from $0\nu\beta\beta$ decay, parity-violating Møller scattering, and colliders

DPF Meeting @ Pheno 2024

May 15, 2024

Sebastián Urrutia Quiroga 🇨🇱

suq90@uw.edu

In collaboration with Gang Li, Juan Carlos Vasquez, Michael Ramsey-Musolf

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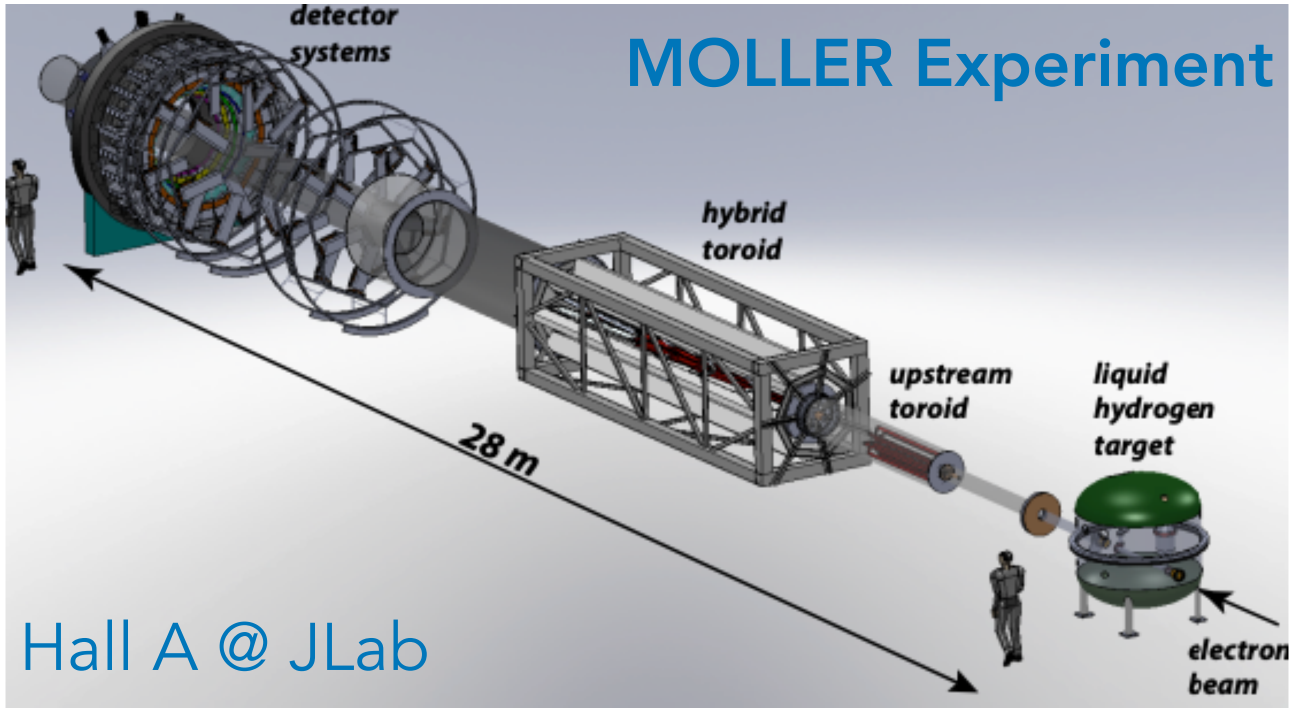
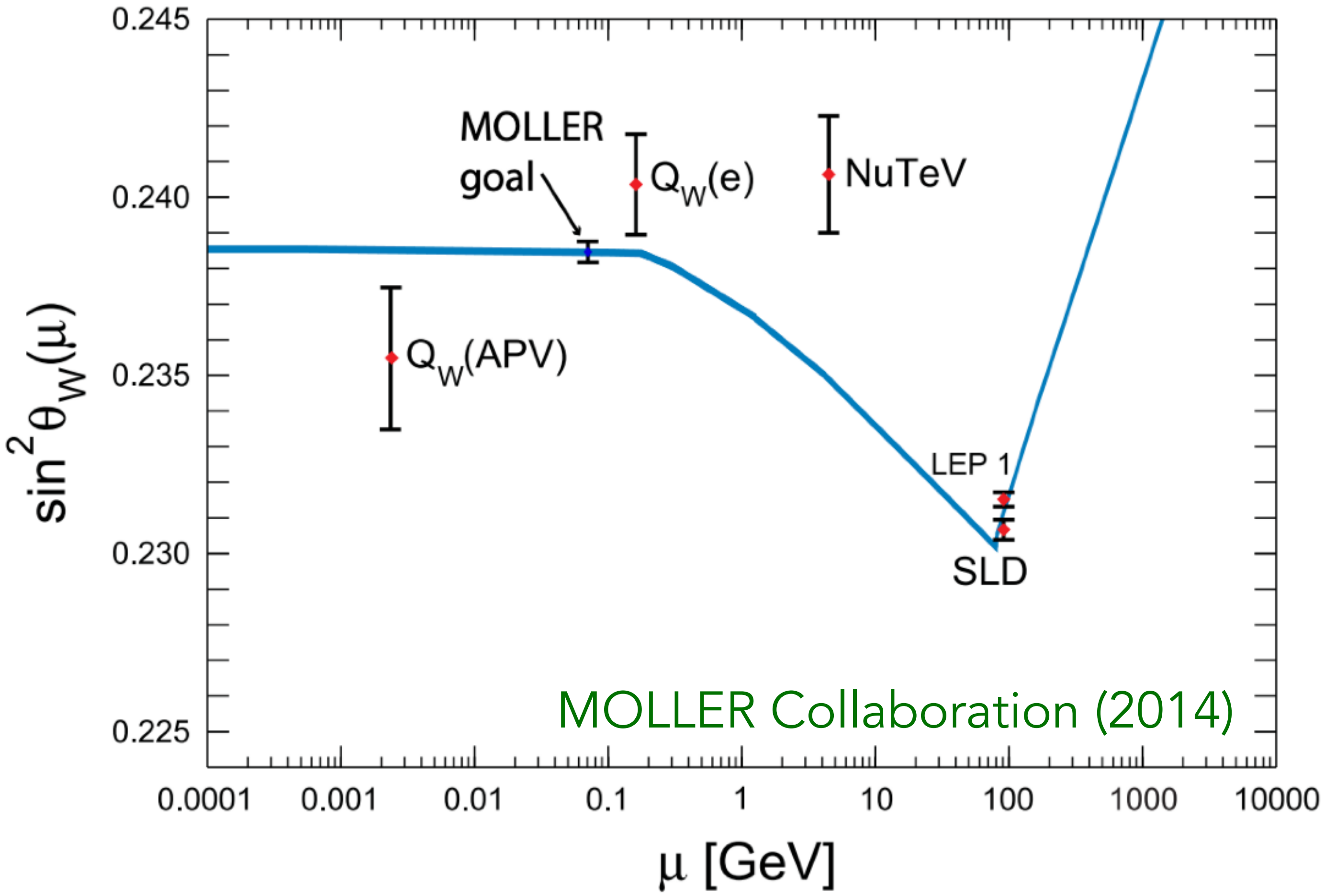
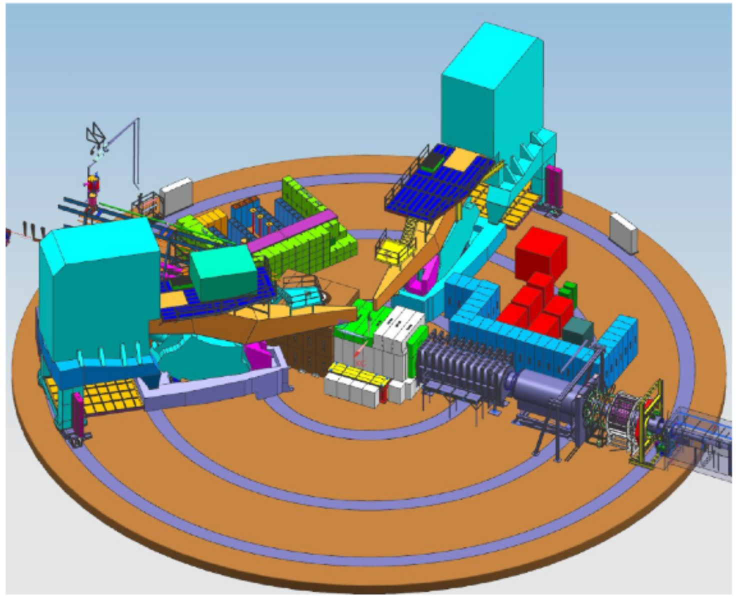
Motivation





CRITICAL DECISION-3A CLEARS WAY TOWARD STANDARD MODEL TEST



With designs of many of the MOLLER experiment elements finalized, DOE has granted Critical Decision-3A, allowing procurements of key elements to begin

NEWPORT NEWS, VA – The U.S. Department of Energy has given the greenlight for the MOLLER experiment to begin procurement of key components with its granting of Critical Decision-3A (CD-3A): Approve Long Lead Procurements. The determination allows the MOLLER project at DOE's Thomas Jefferson National Accelerator Facility to begin spending $9.14 million for long-lead procurements of critical items for which designs are complete.

After imagining what it would look like for 17 years, Krishna Kumar felt chills the first time he saw fully engineered drawings of the MOLLER experiment.

PV Møller scattering

- Scattering of longitudinally polarized e^- off unpolarized e^-

$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

- **MOLLER goal:** $\delta A_{\mathrm{PV}} = 0.7\,\mathrm{ppb}$ ($\times\,5$ better than SLAC E158)

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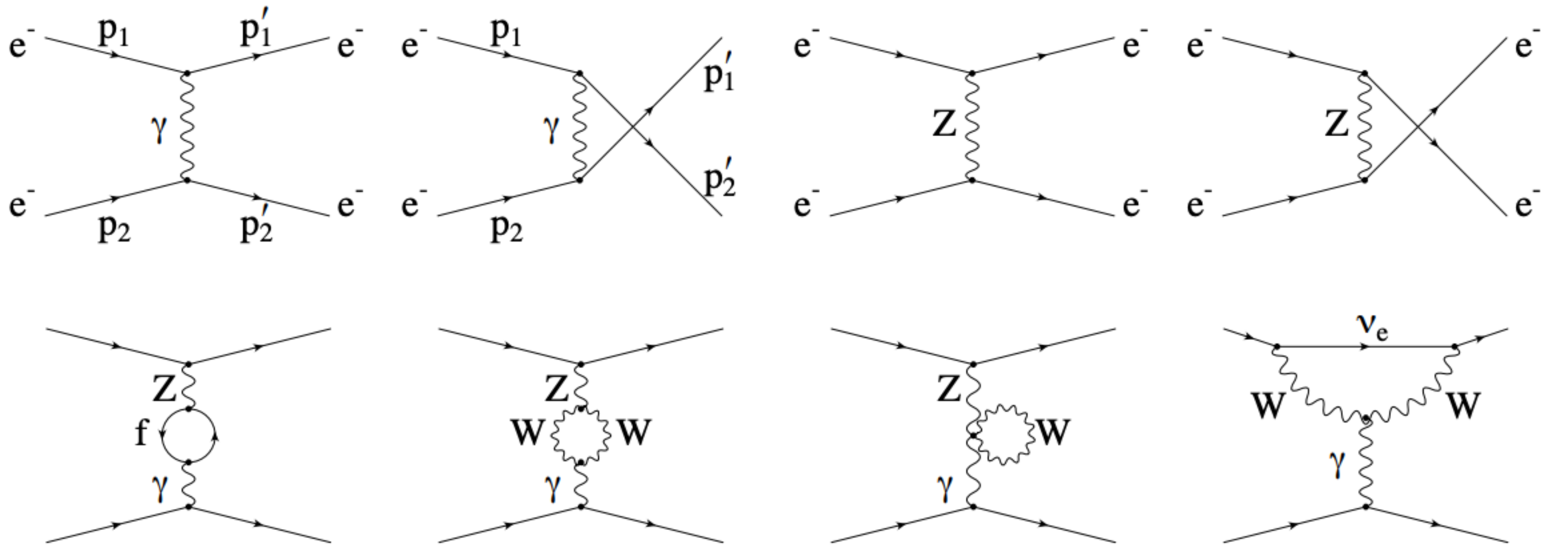

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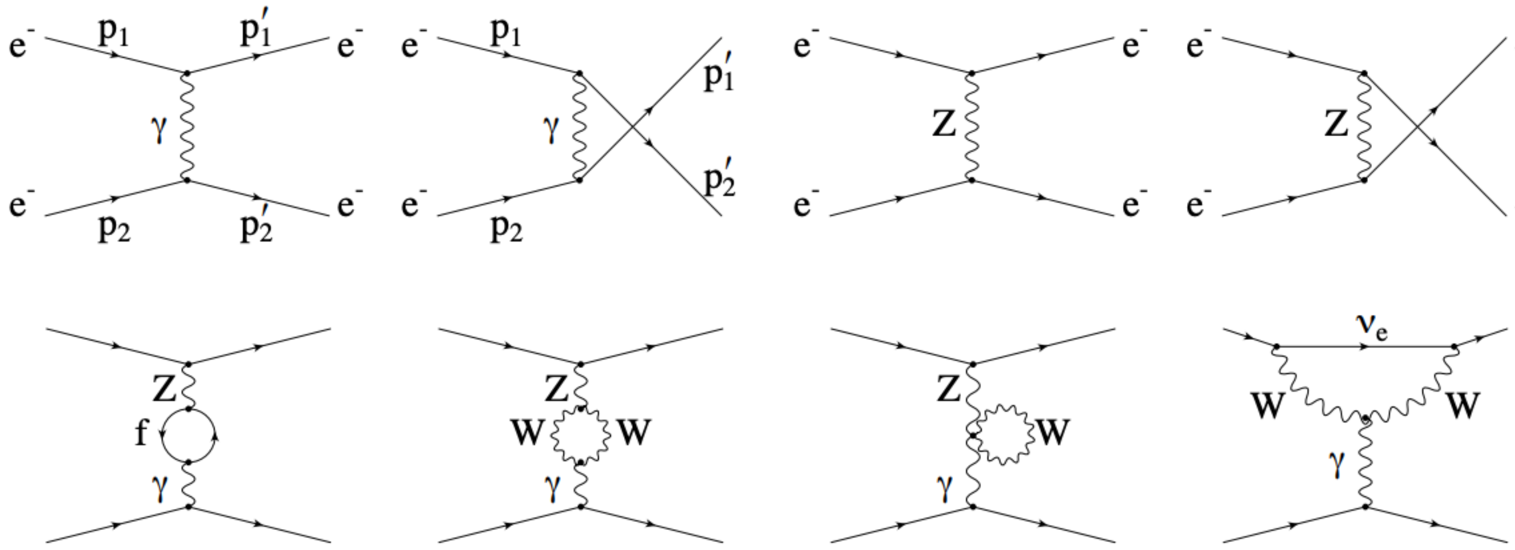

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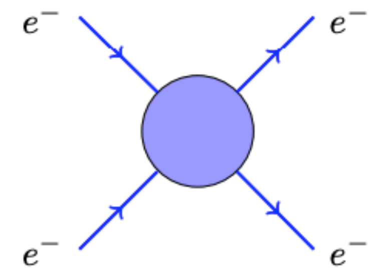

$$\mathscr{L}_{eff} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{e}_j \gamma_\mu e_j)$$

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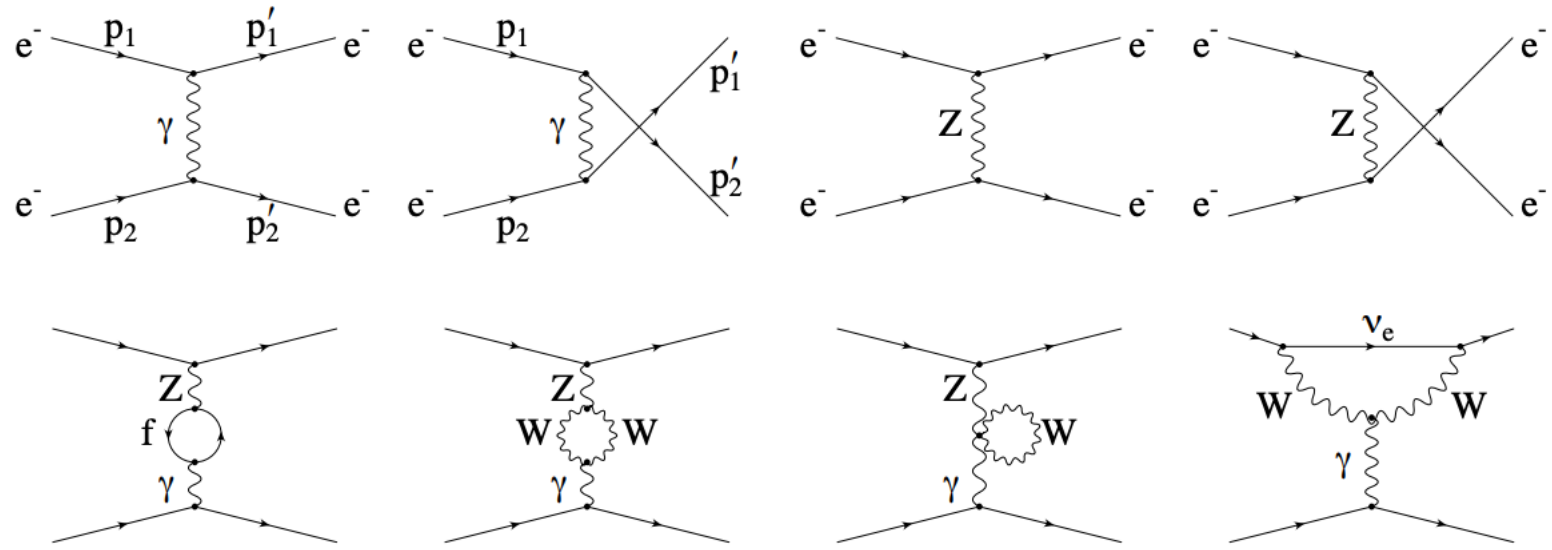

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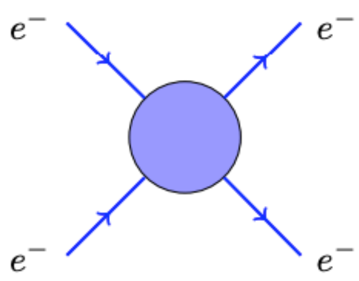

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- Sensitivity to New Physics: $\dfrac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} \simeq 7.5\,{\rm TeV}$

MOLLER Collaboration (2014)

The minimal Left-Right Symmetric Model

Key aspects of the mLRSM

Mohapatra & Senjanovic (1980, 1981)

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

Scalar triplets and bidoublet:

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix} \qquad \Phi = \begin{pmatrix} \phi^0_1 & \phi^+_2 \\ \phi^-_1 & \phi^0_2 \end{pmatrix}$$

$W_L - W_R$ mixing:

$$\begin{pmatrix} W^\pm_L \\ W^\pm_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W^\pm_1 \\ W^\pm_2 \end{pmatrix}$$

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mLRSM & Parity Violation

PV Møller scattering

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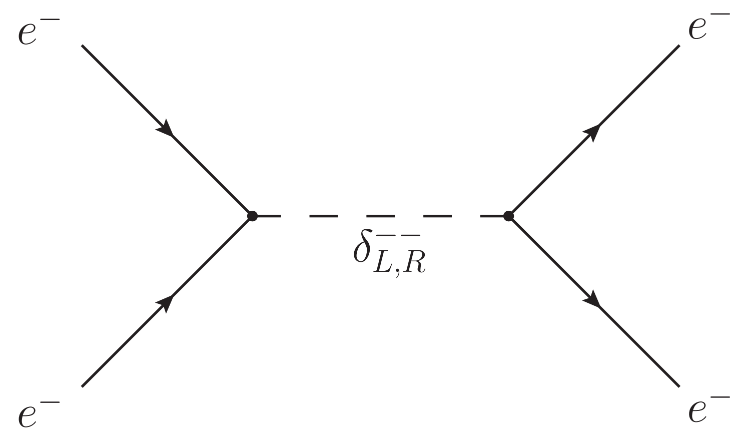

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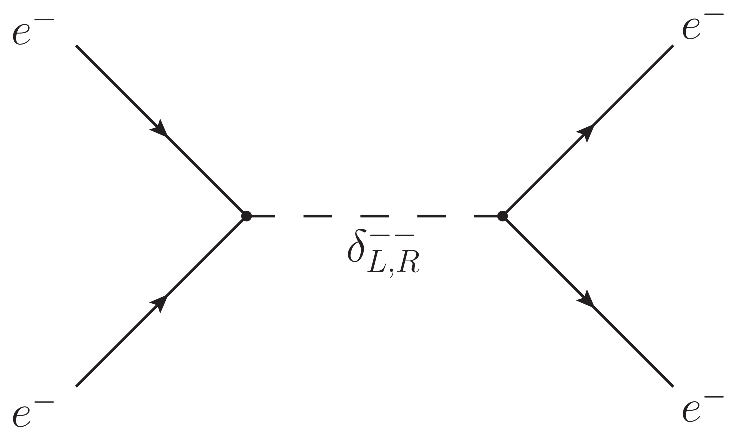

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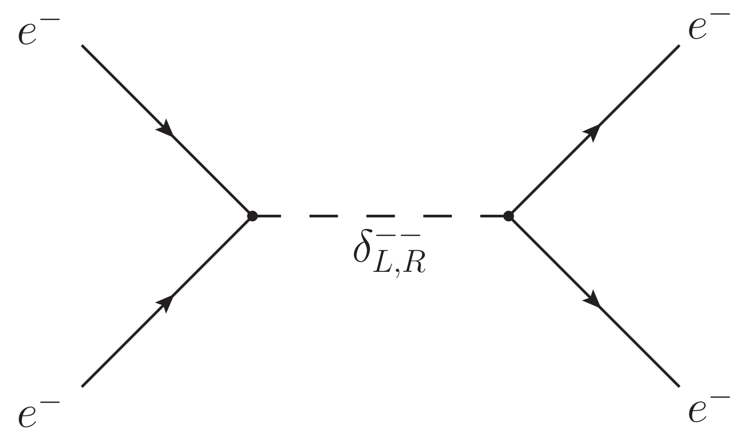

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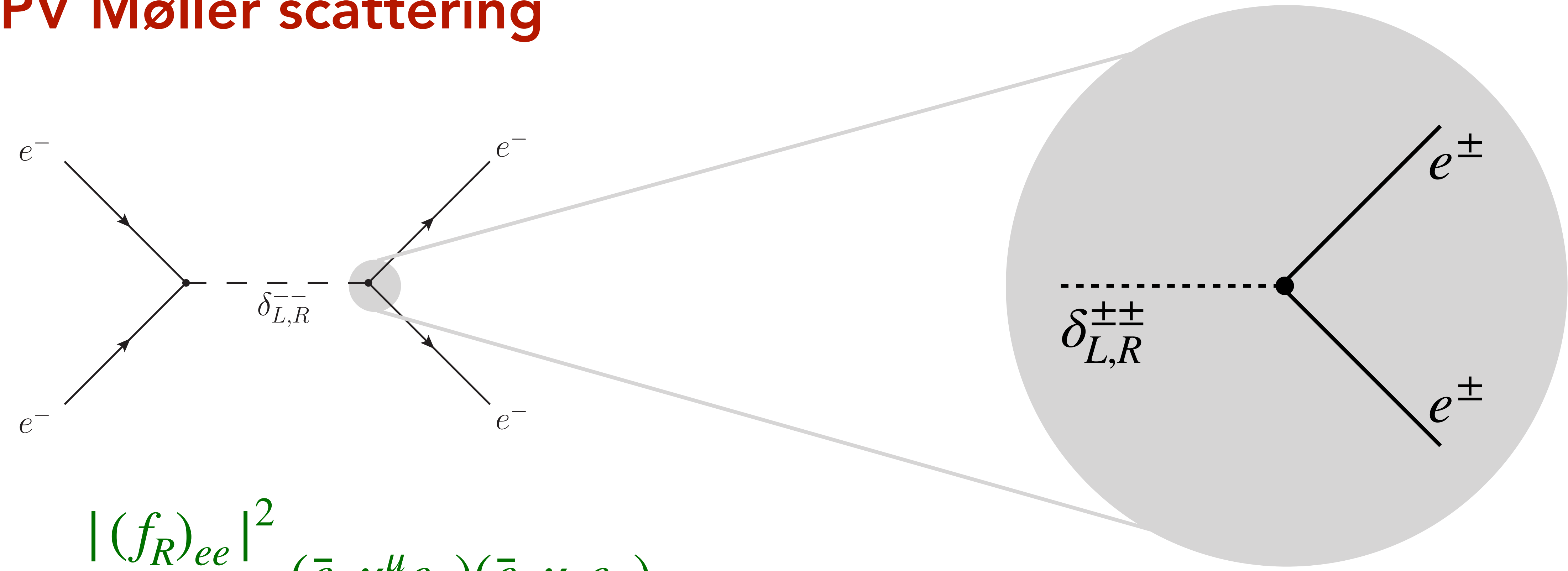

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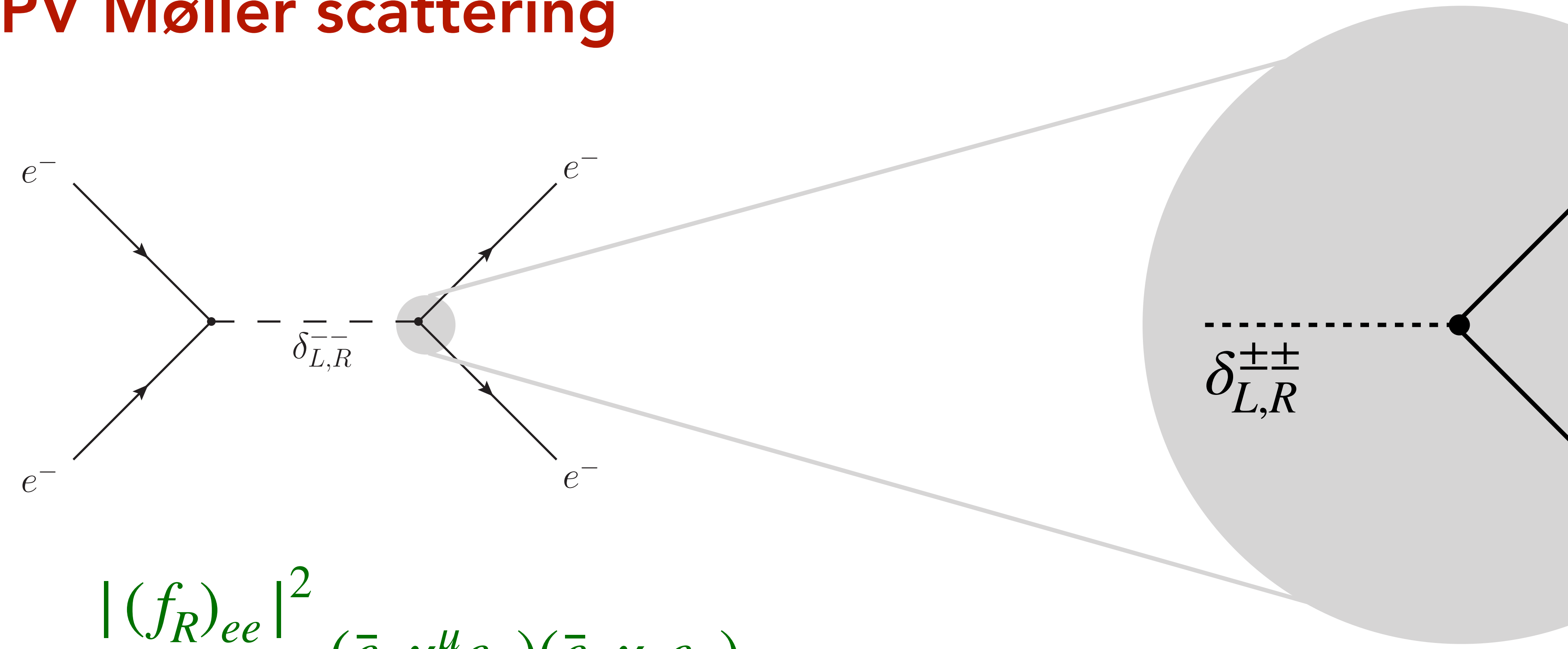

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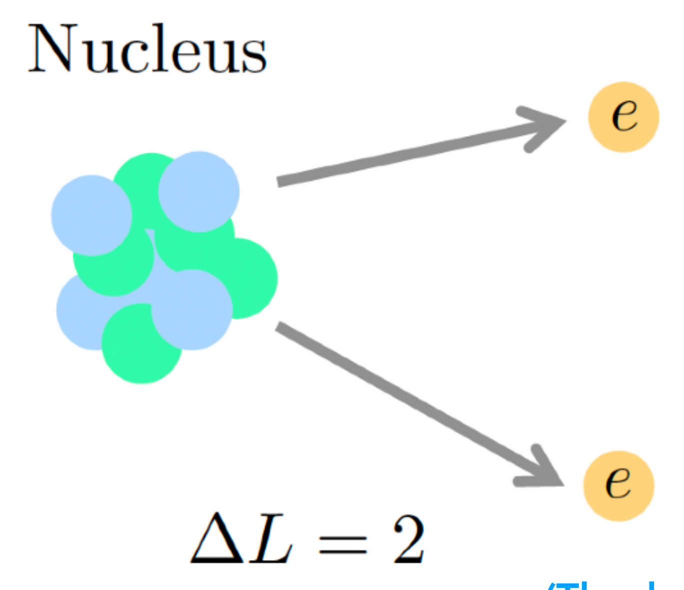

(Thanks! K. Fuyuto)

mLRSM & $0\nu\beta\beta$ decay

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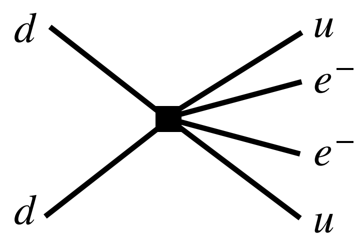

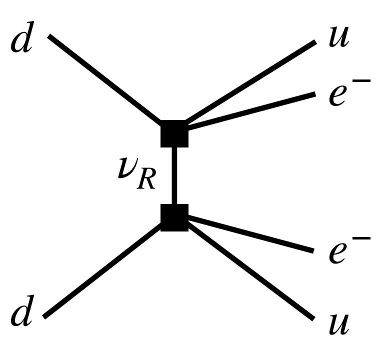

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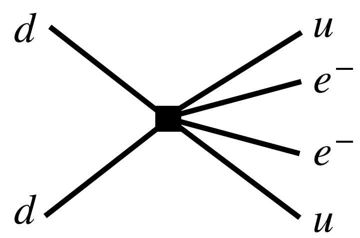
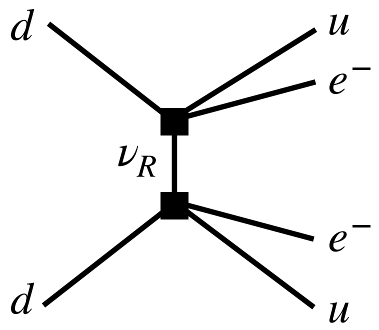
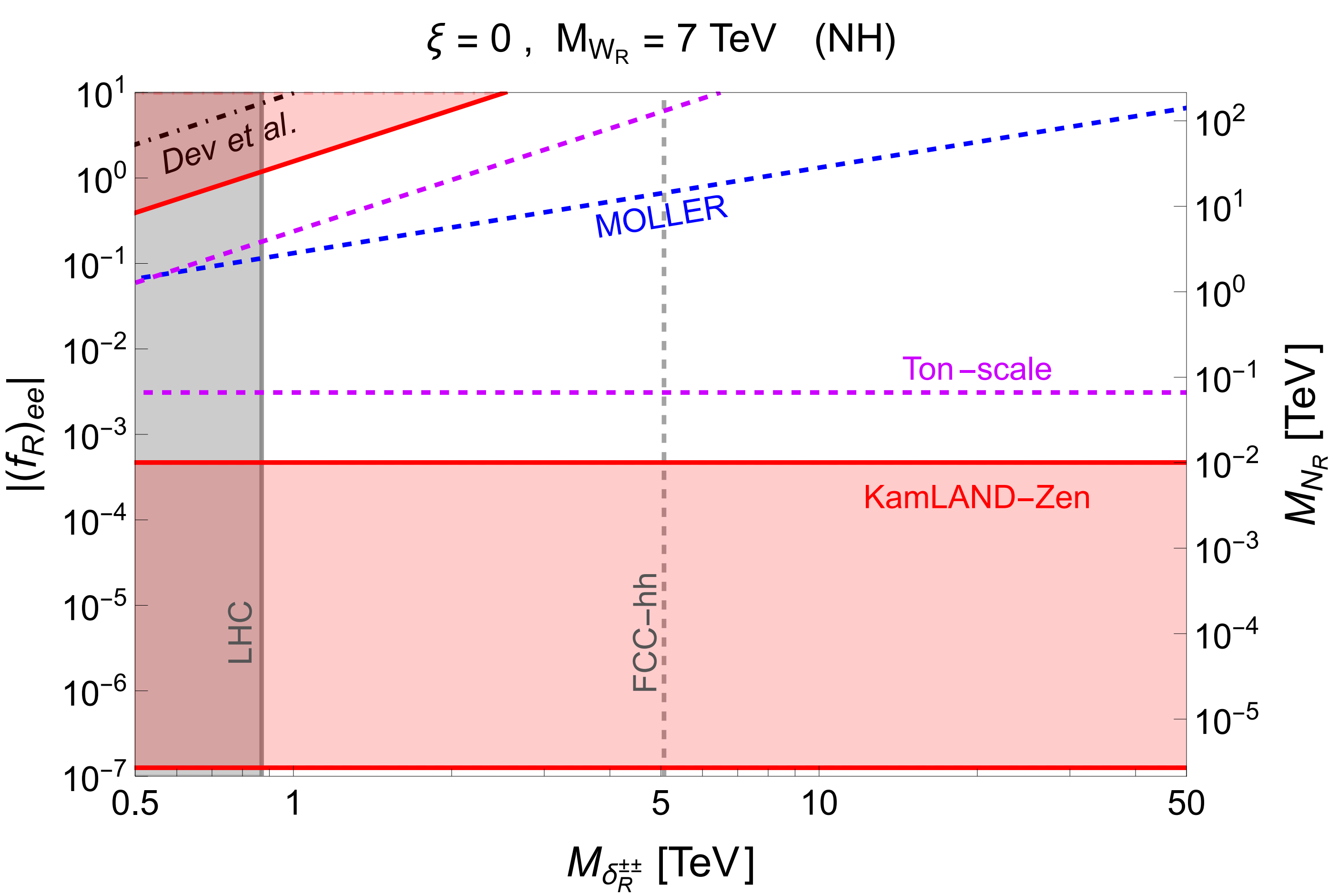




Small $\mathbf{f}_R \leftrightarrow$ Small $\mathscr{M}_N$

- $(T^{0\nu}_{1/2})^{-1}$ depends on a few parameters: $\{\xi, M_{W_R}\}$ and $\{(f_R)_{ee}, M_{\delta_R^{\pm\pm}}\}$

Results: $0\nu\beta\beta$ decay & PV scattering



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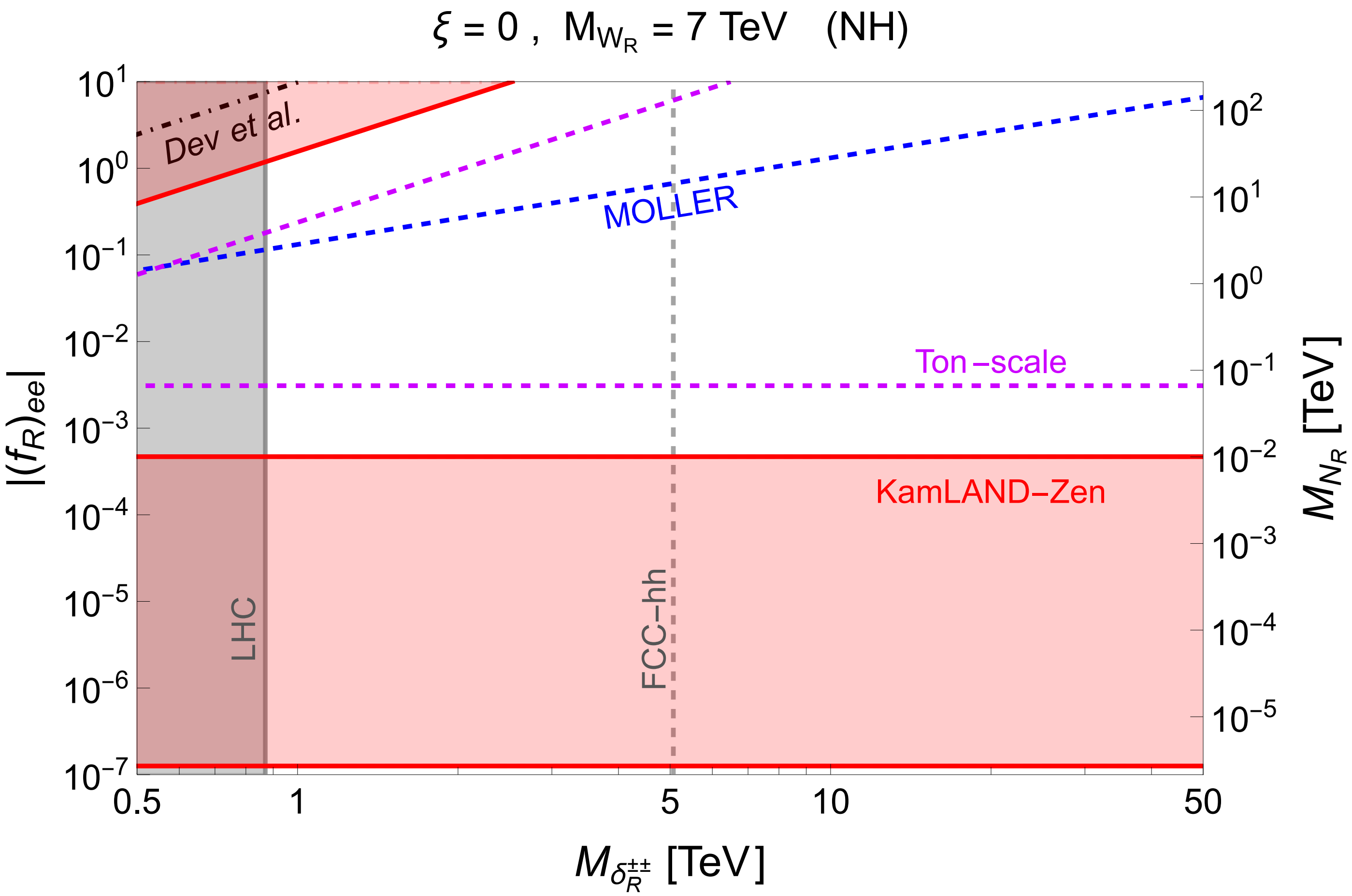
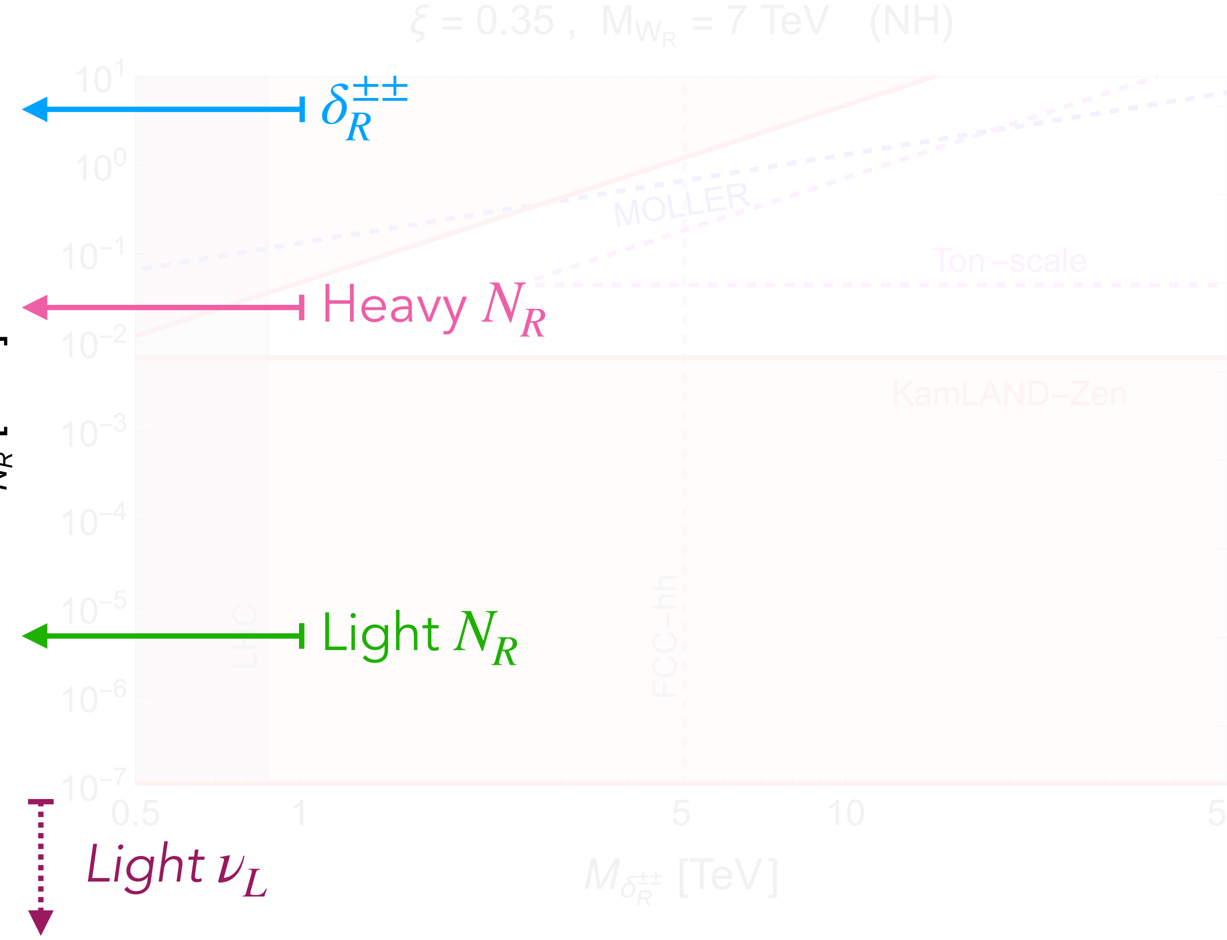
$\mathscr{A}_{0\nu2\beta}$ dominated by:





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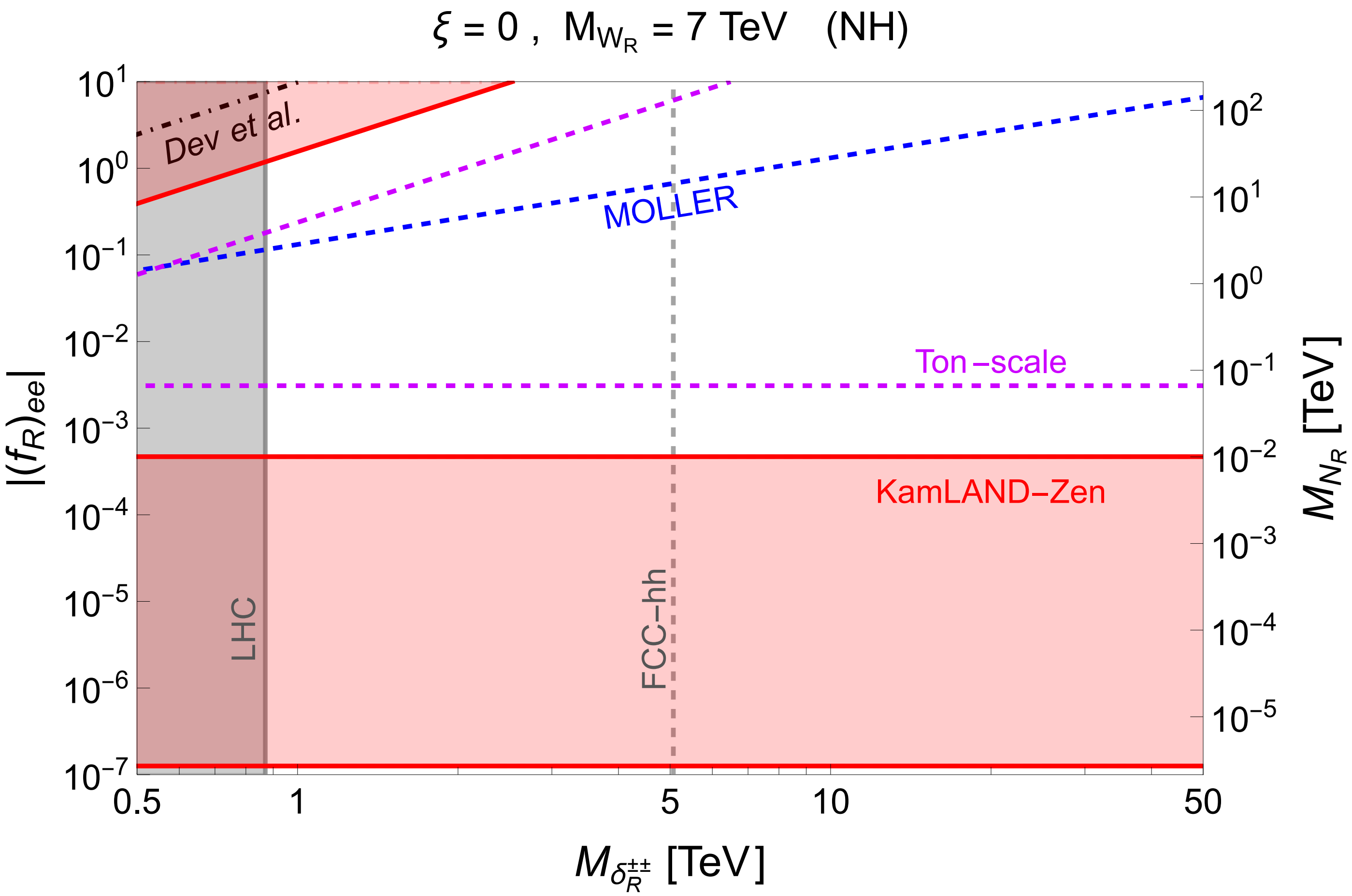

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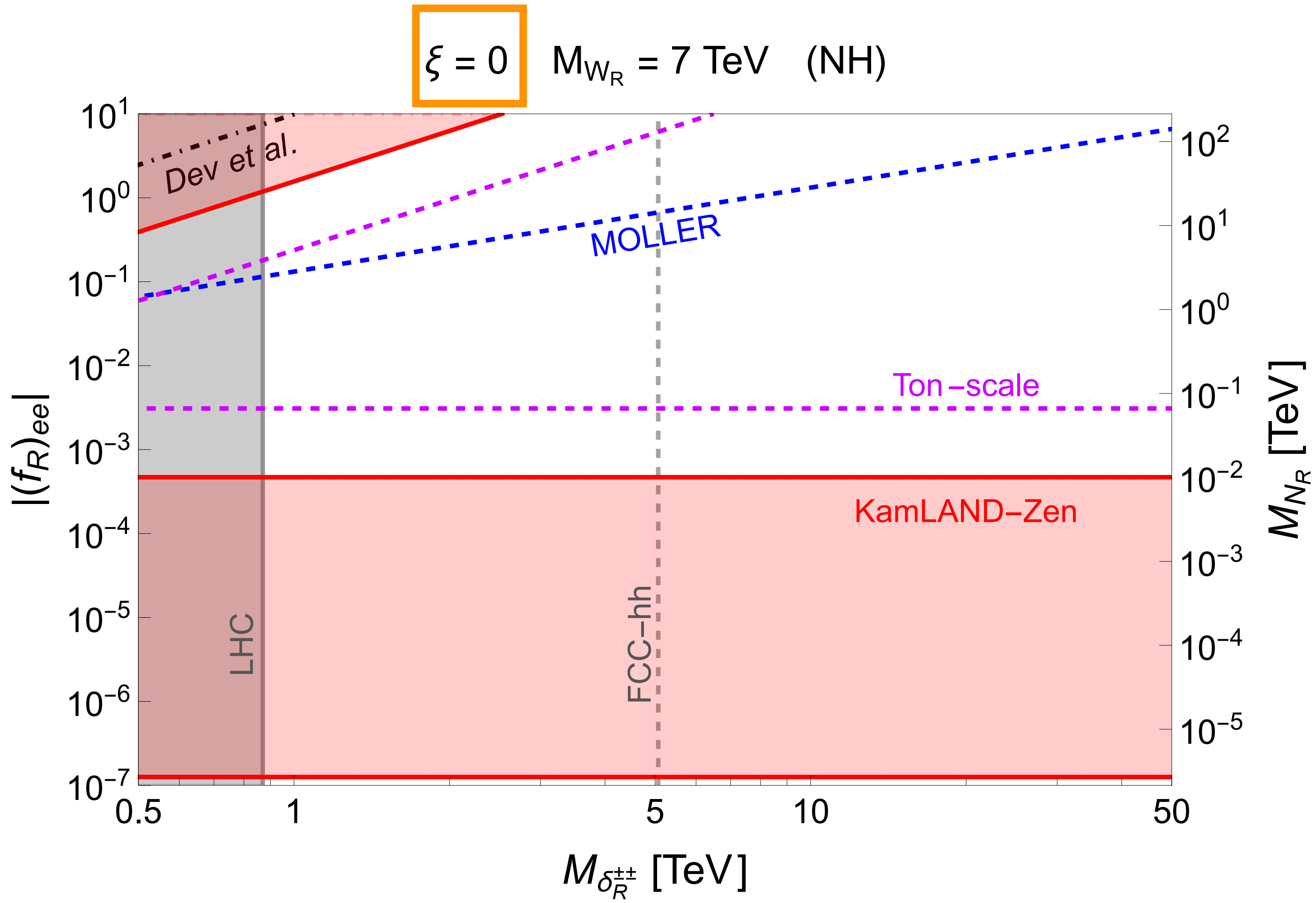

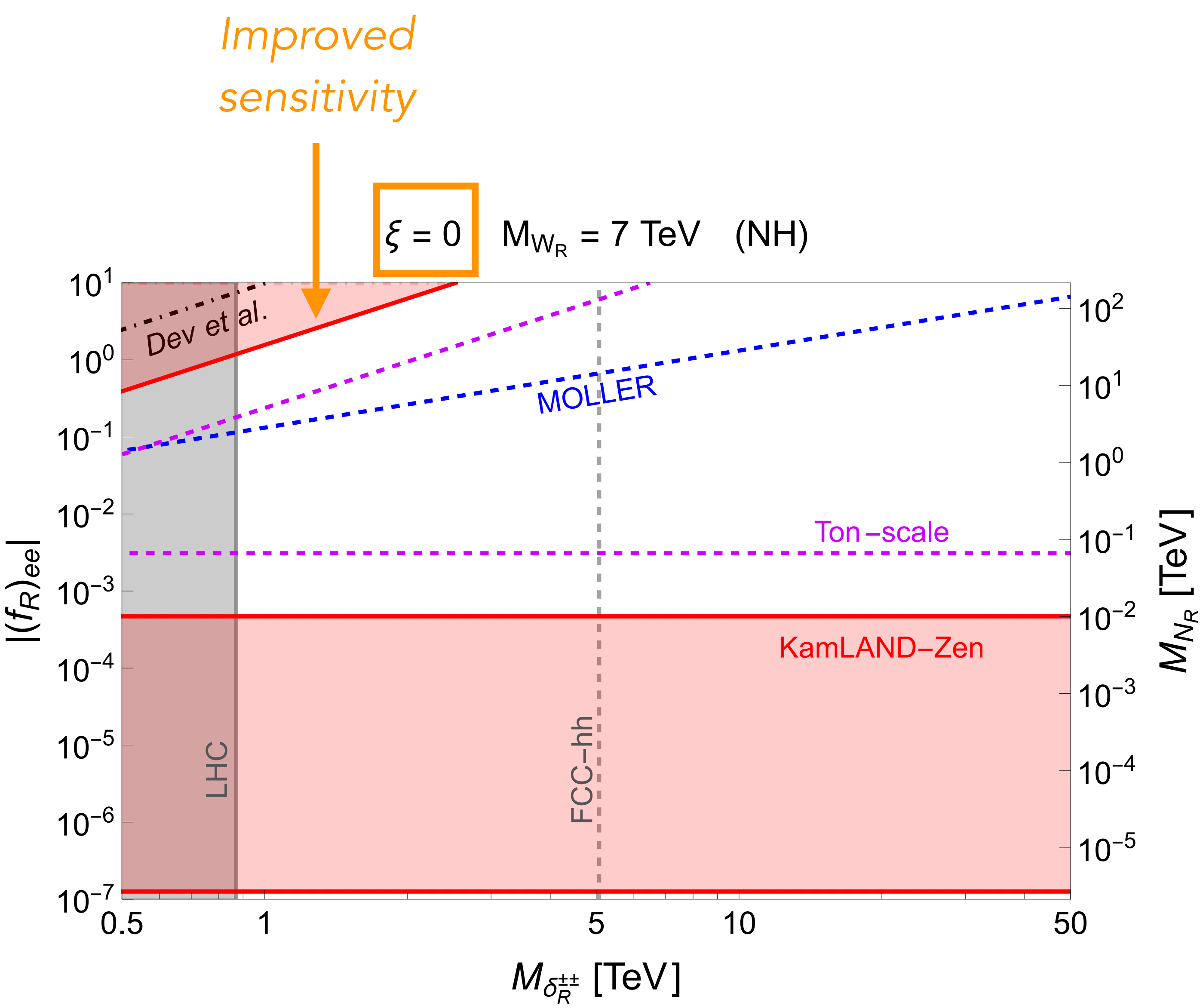
Improved
sensitivity
ξ = 0
M_{W_R} = 7 TeV (NH)
Dev et al.
MOLLER
Ton−scale
KamLAND−Zen
LHC
FCC−hh
|(f_R)_{ee}|
M_{N_R} [TeV]
M_{δ_R^{±±}} [TeV]

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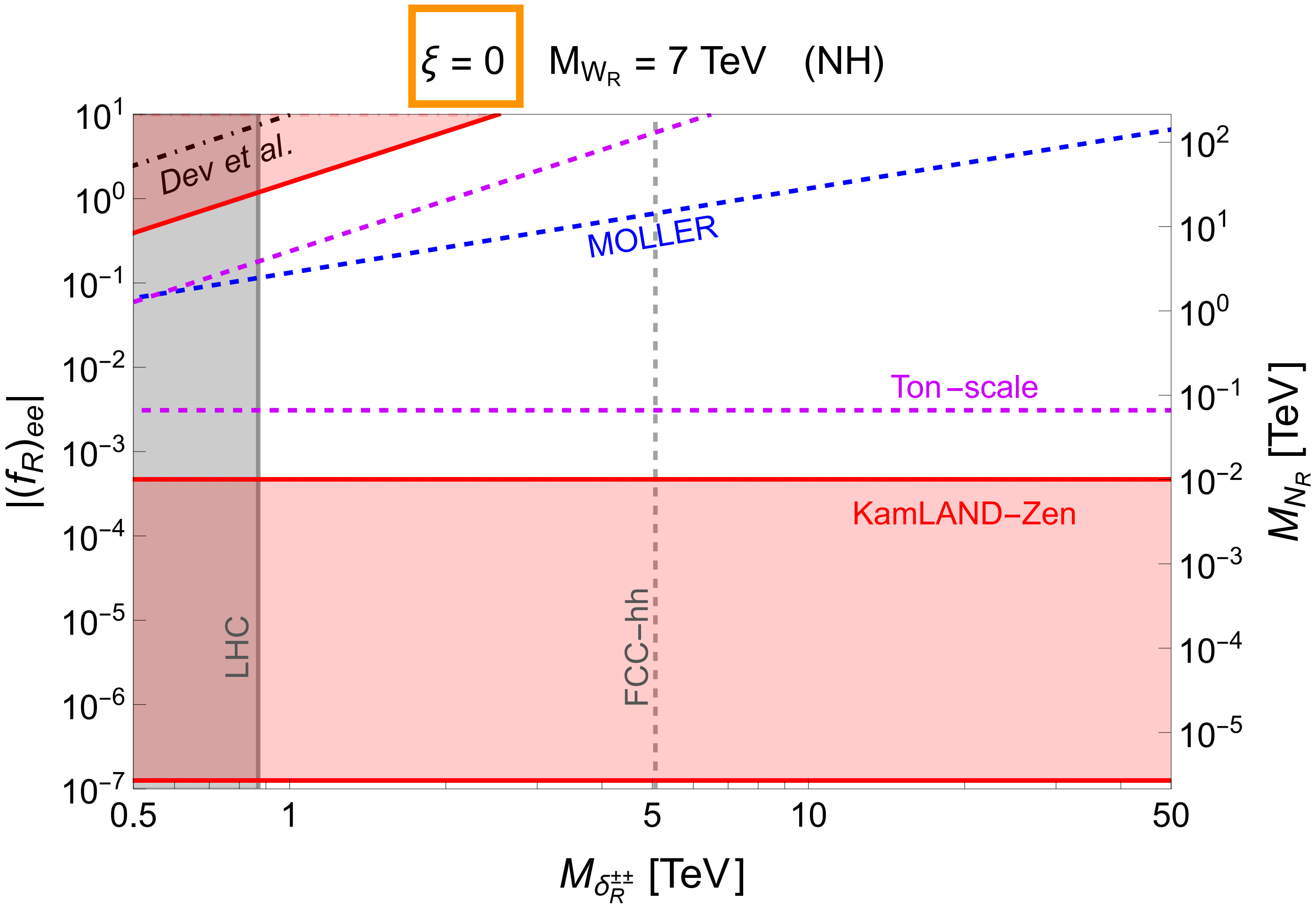

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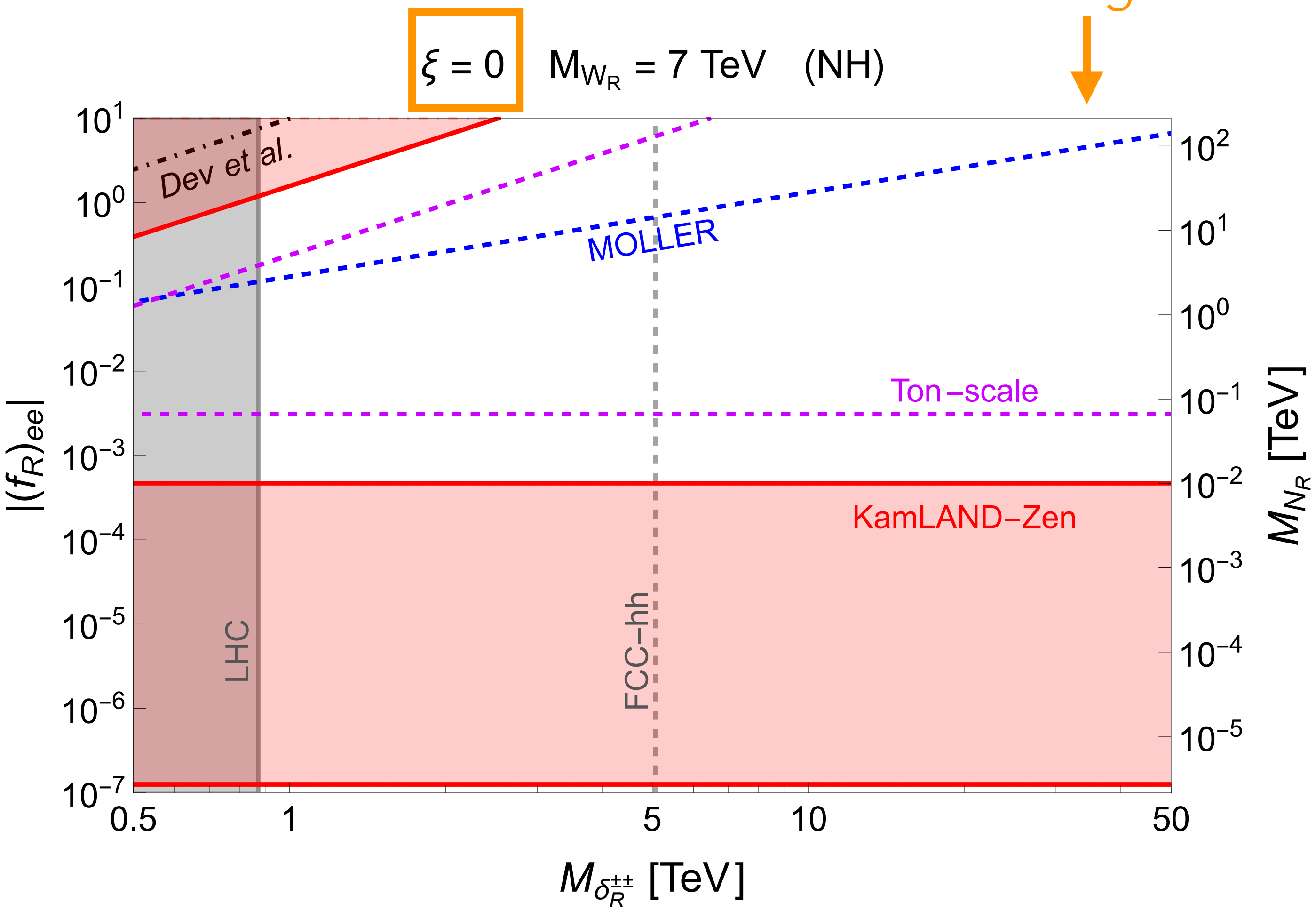
MOLLER consistently stronger



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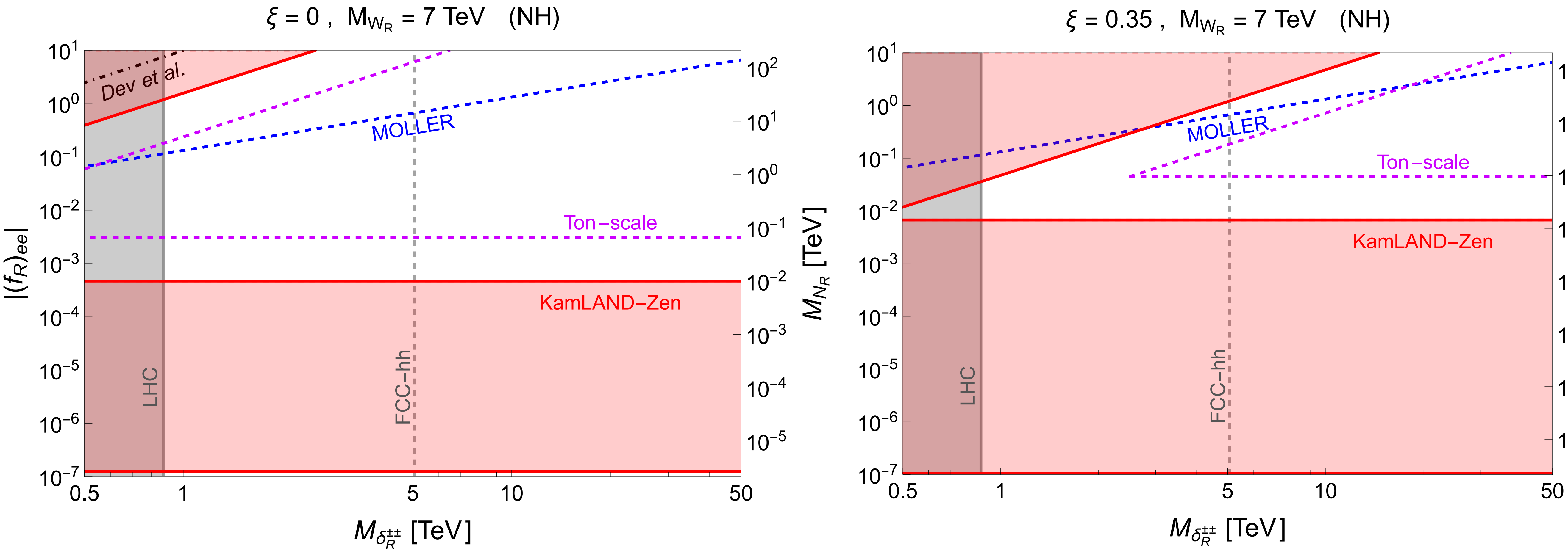

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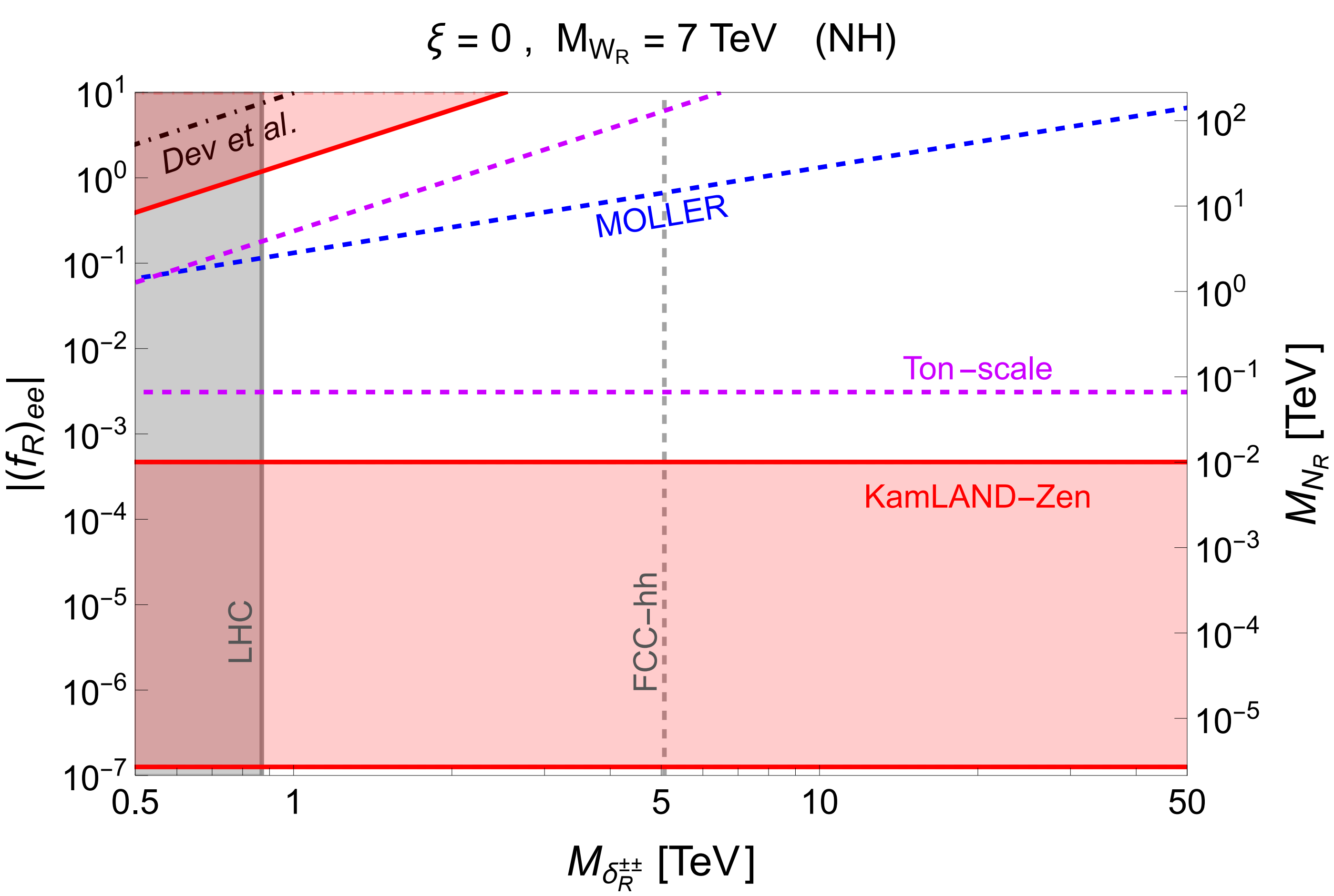

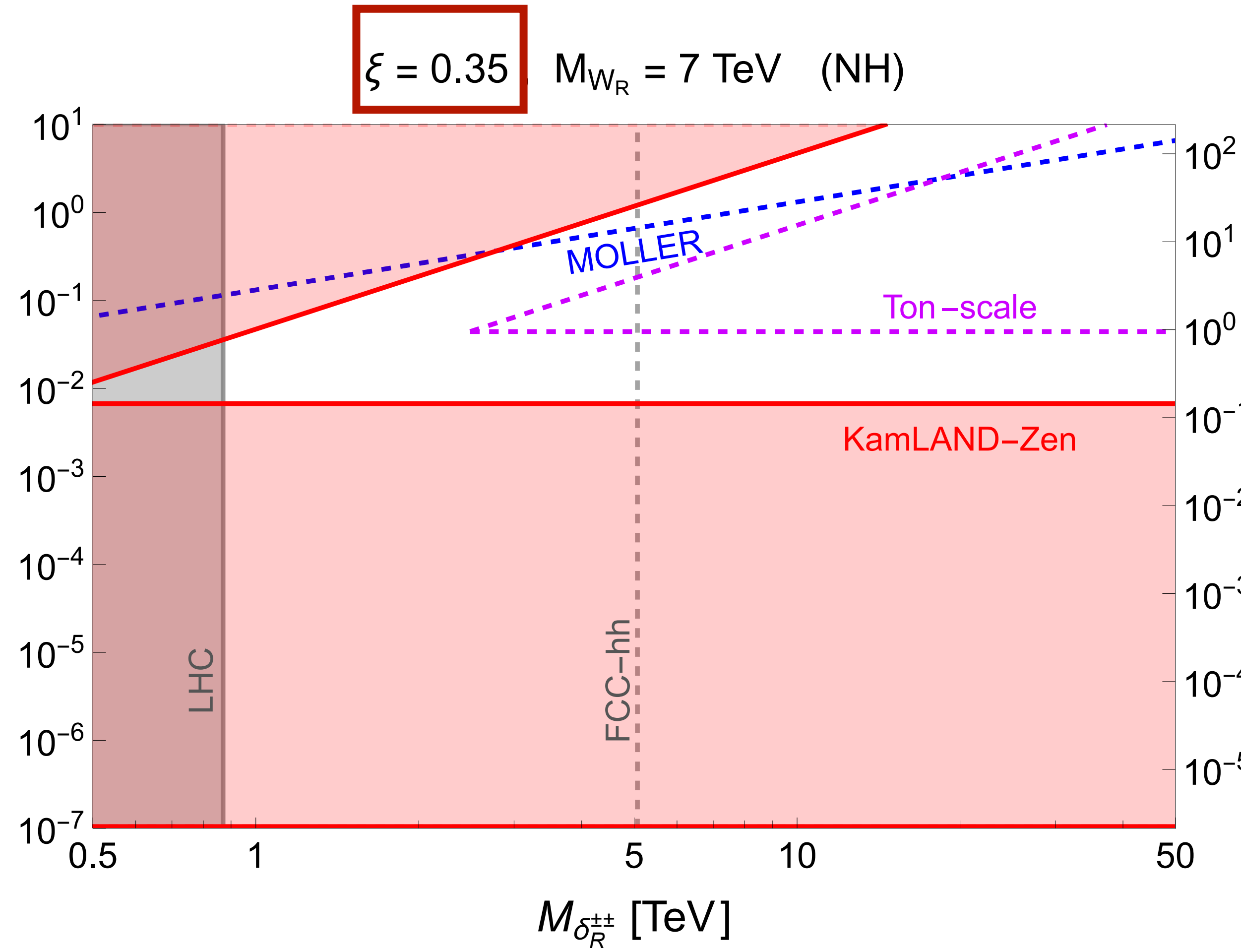

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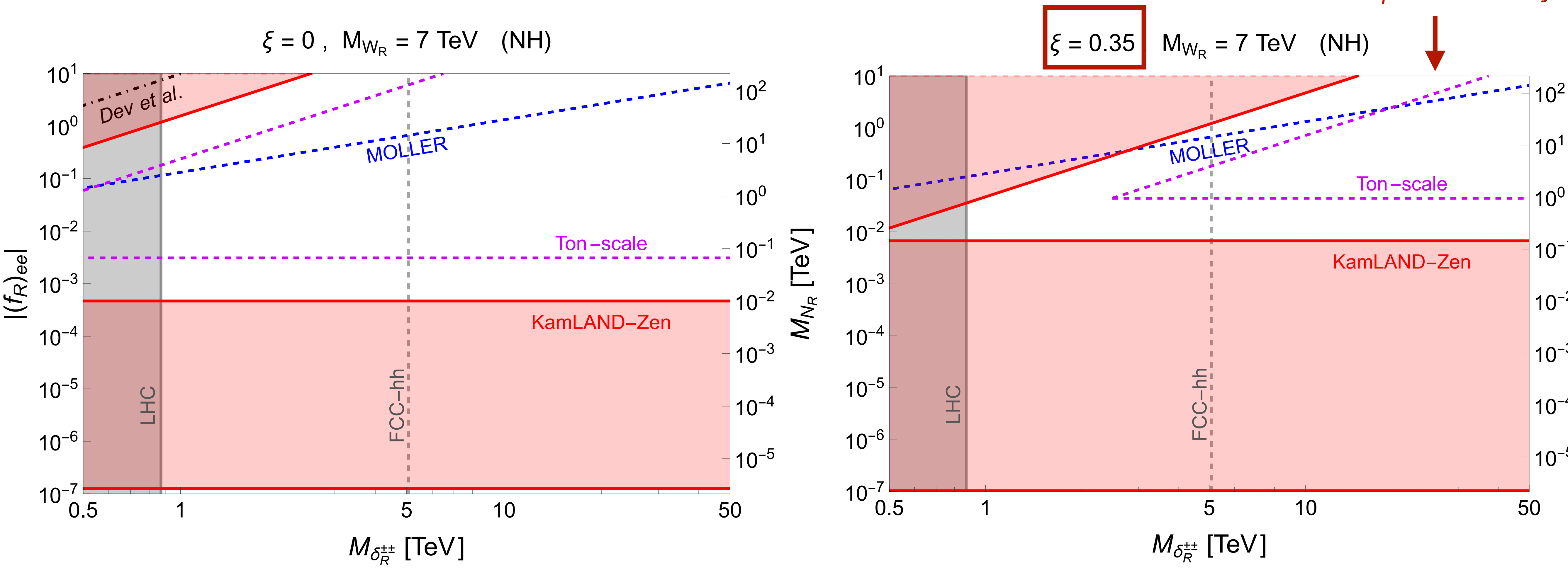
Complementarity



Take away messages

- The use of an EFT description provides a significant improvement in the $0\nu\beta\beta$-decay calculations and their corresponding sensitivity

- The interplay between $0\nu\beta\beta$ decay and parity-violating Møller scattering processes is influenced by the value of W_L-W_R mixing

- The MOLLER experiment may hold important implications for the understanding of $0\nu\beta\beta$-decay experiments. In essence, the interplay between these two experiments may shed light on the underlying mechanism behind $0\nu\beta\beta$ decay, should future searches yield a positive result

INSTITUTE for NUCLEAR THEORY

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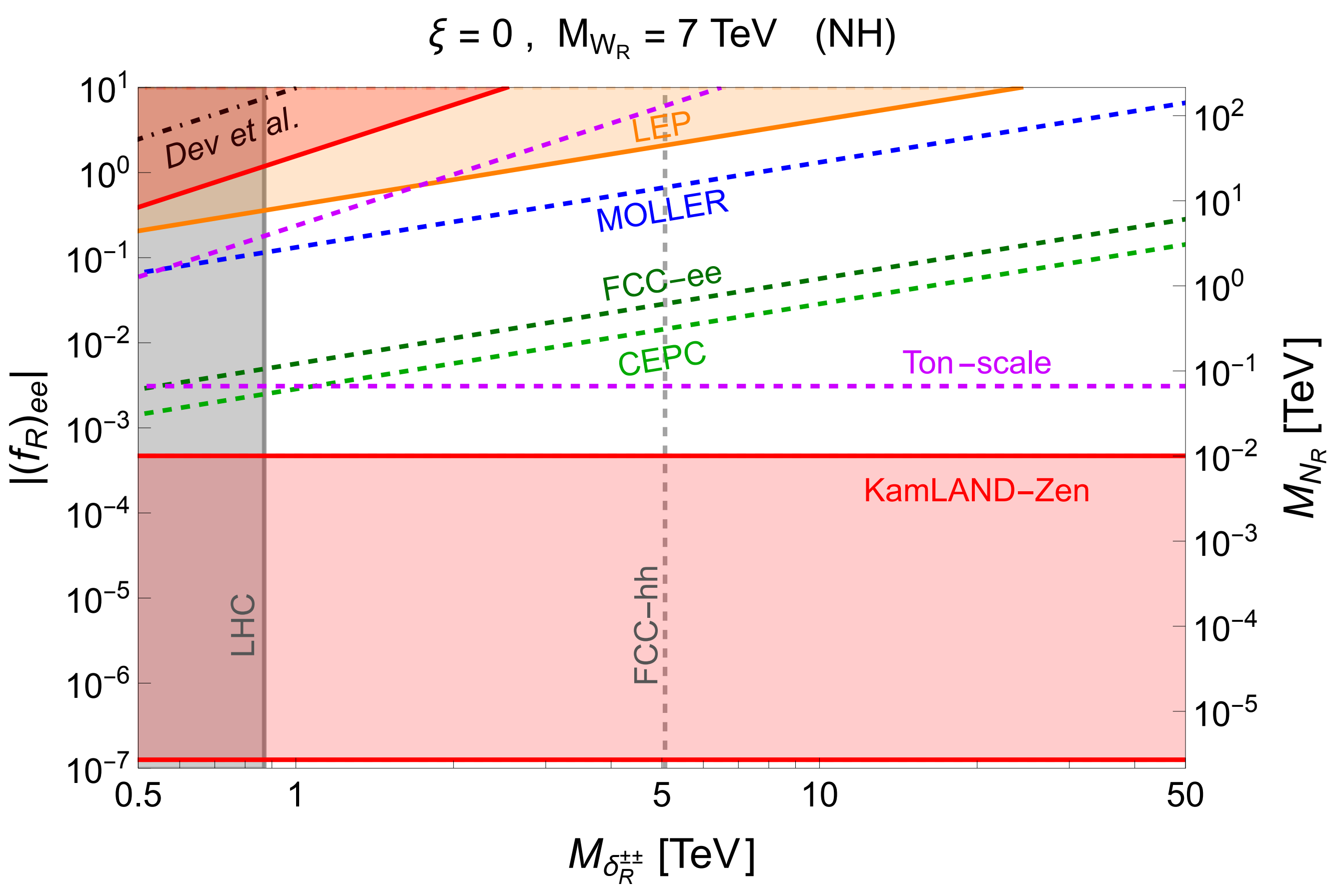
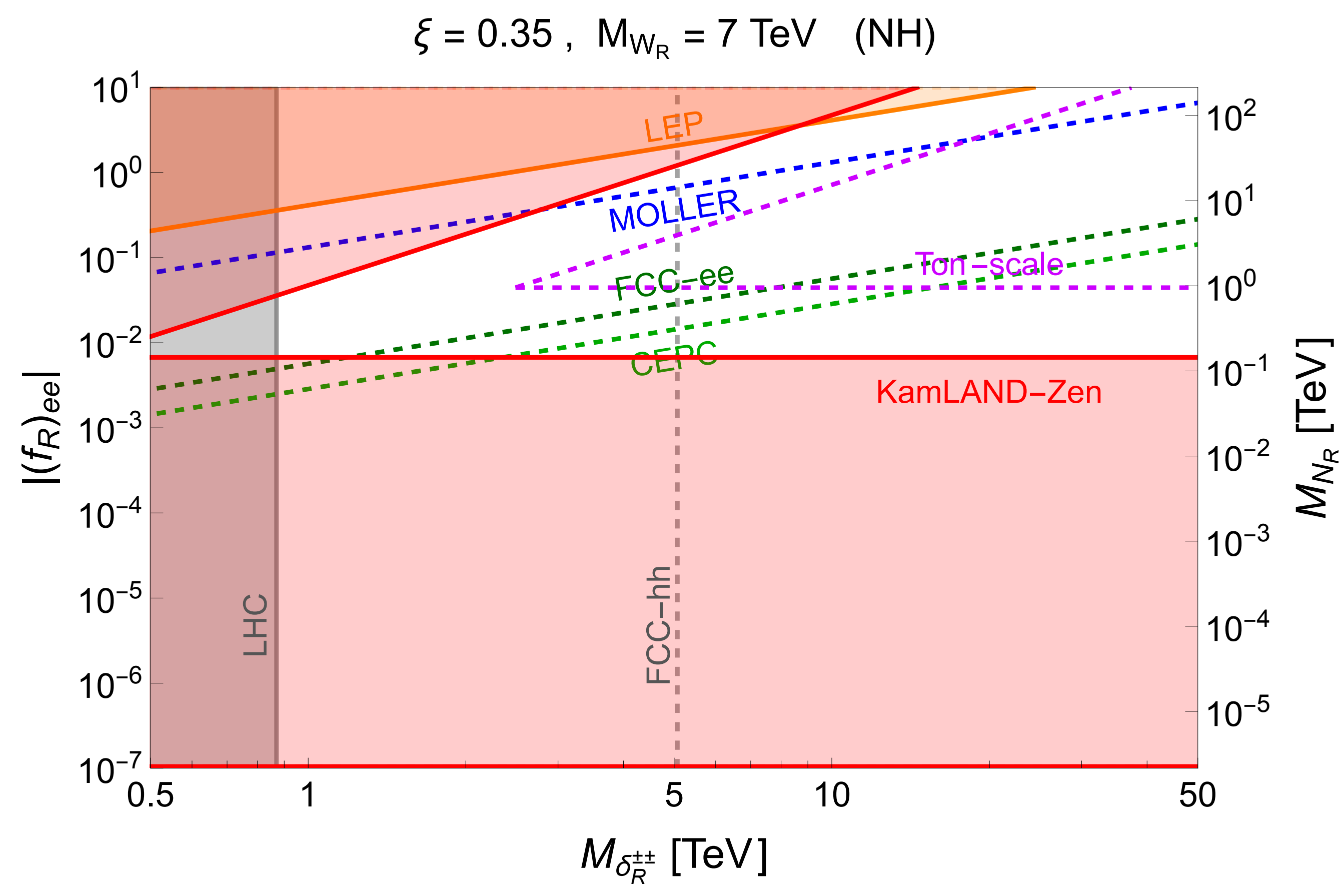
Backup Slides

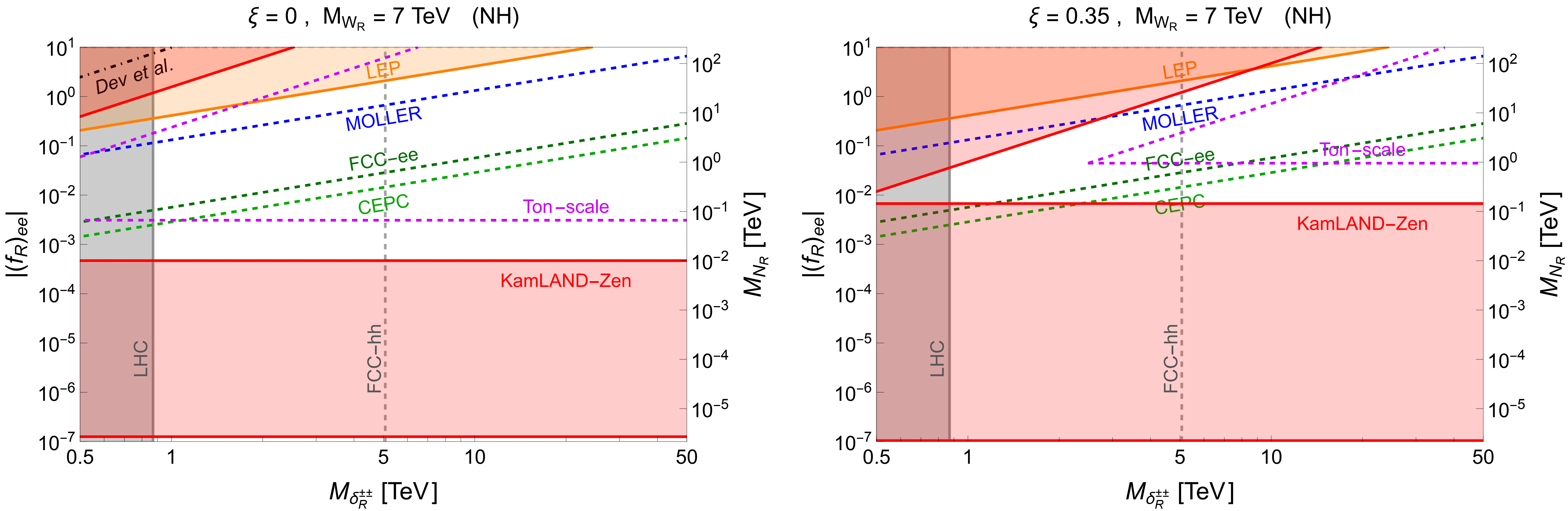
[...] and colliders





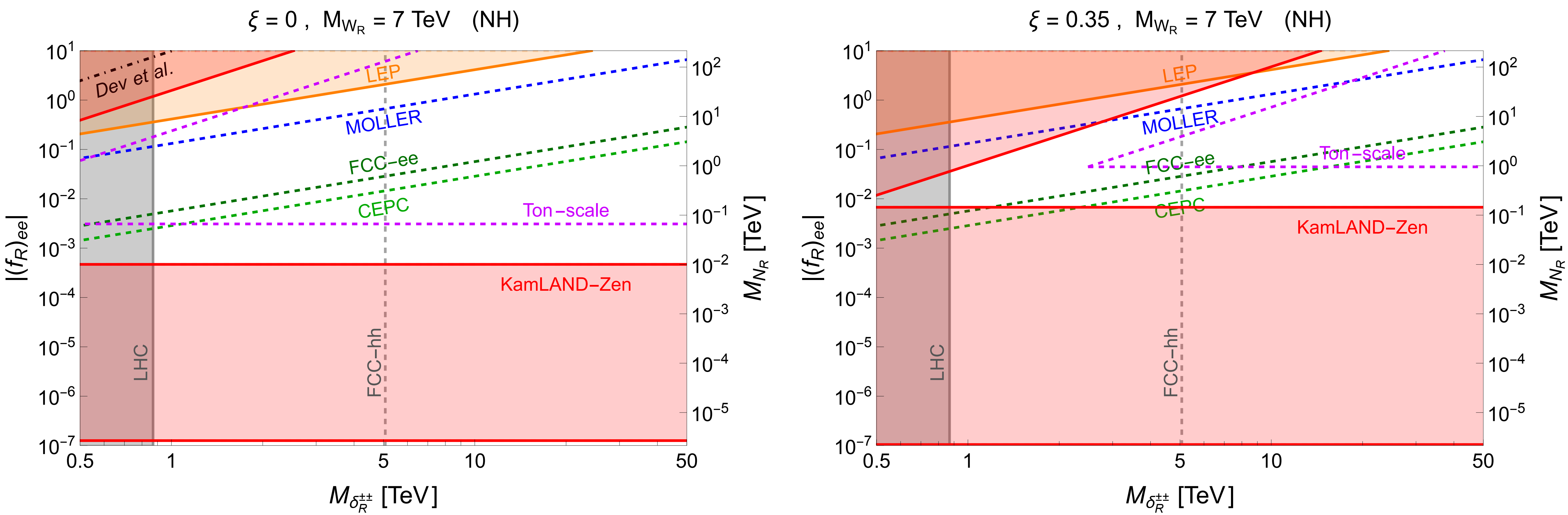
[...] and colliders

- Interplay between $0\nu\beta\beta$-decay **and** LNC experiments



[...] and colliders

- Interplay between $0\nu\beta\beta$-decay **and** LNC experiments
- Both searches provide complementary sensitivity!



mLRSM & $0\nu\beta\beta$ decay — Diagrams

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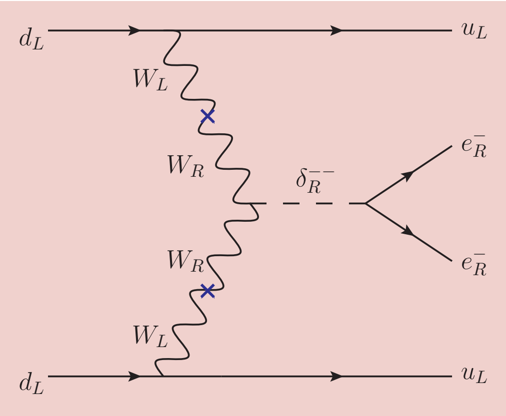
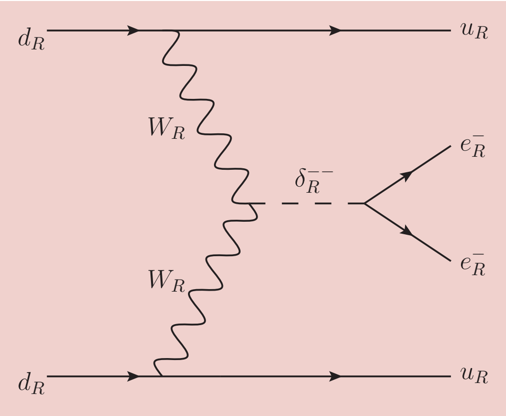
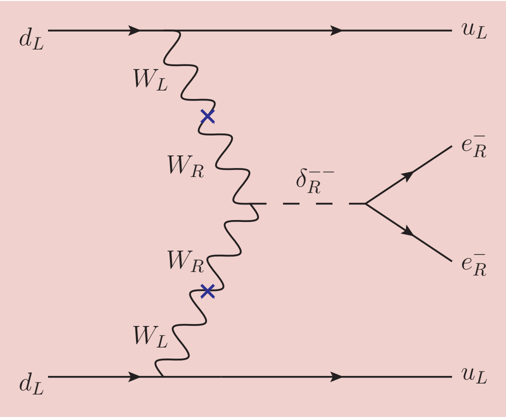
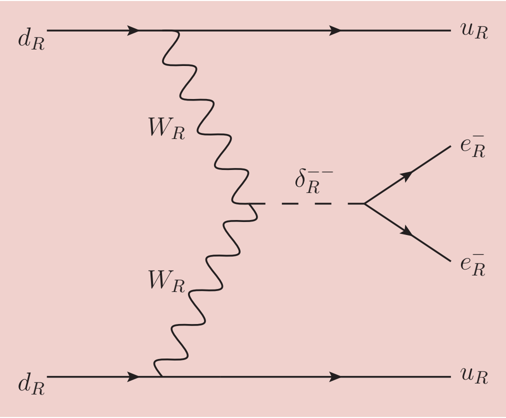
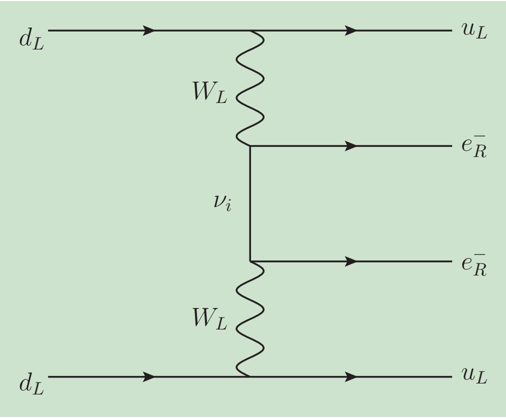




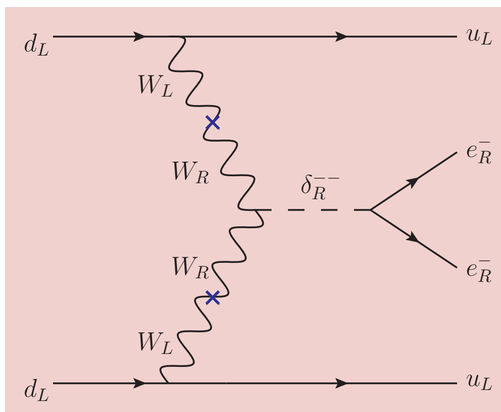
mLRSM & $0\nu\beta\beta$ decay — Diagrams

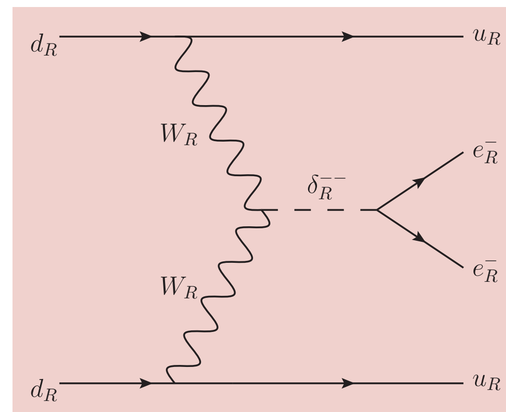


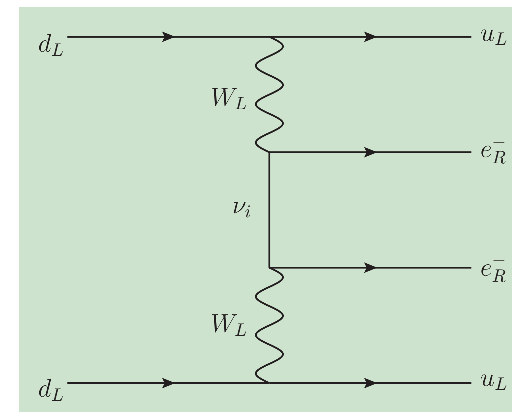


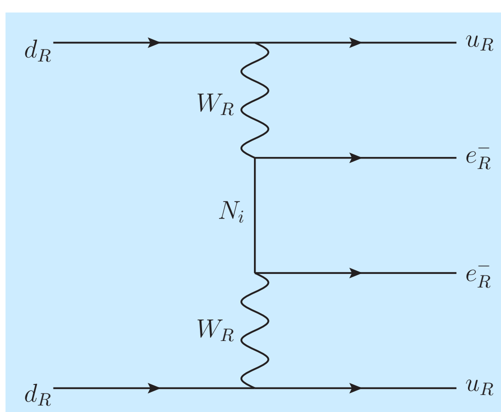


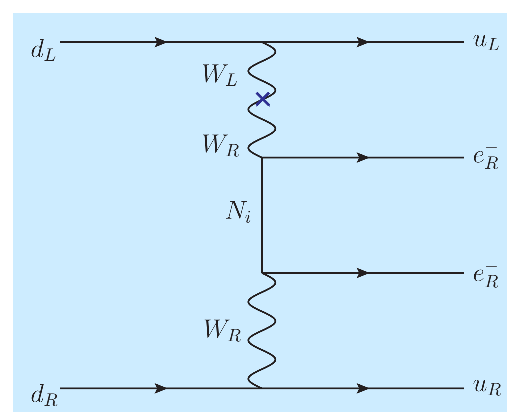
mLRSM & $0\nu\beta\beta$ decay — Diagrams

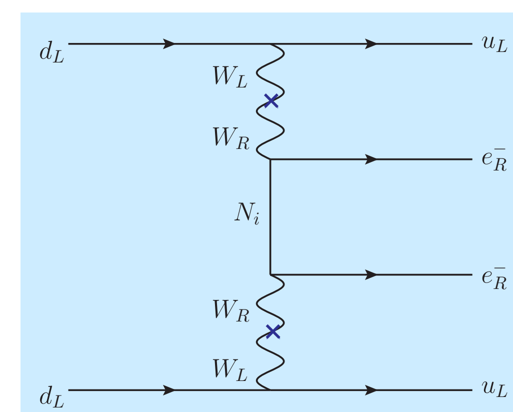












Neutrino masses (mLRSM)

$$M_n \equiv \begin{pmatrix} M_L & M_D \\ M_D^{\top} & M_R \end{pmatrix}$$

$$M_D = (\kappa \mathbf{\Gamma_l} + \kappa' \widetilde{\mathbf{\Gamma}}_{\mathbf{l}})/\sqrt{2}$$
$$M_{L,R} = \sqrt{2}\ \mathbf{f_{L,R}}\, v_{L,R}$$

$$m_\nu = \mathrm{diag}(m_1, m_2 \ldots, m_6) = U^{\top} M_n^{\dagger} U$$

$$U = \mathscr{U}_1 \mathscr{U}_2$$
$$\mathscr{U}_1 = \begin{pmatrix} 1 & R \\ -R^{\dagger} & 1 \end{pmatrix}, \quad \mathscr{U}_2 = \begin{pmatrix} U_{\mathrm{PMNS}} & 0 \\ 0 & U_R \end{pmatrix}$$

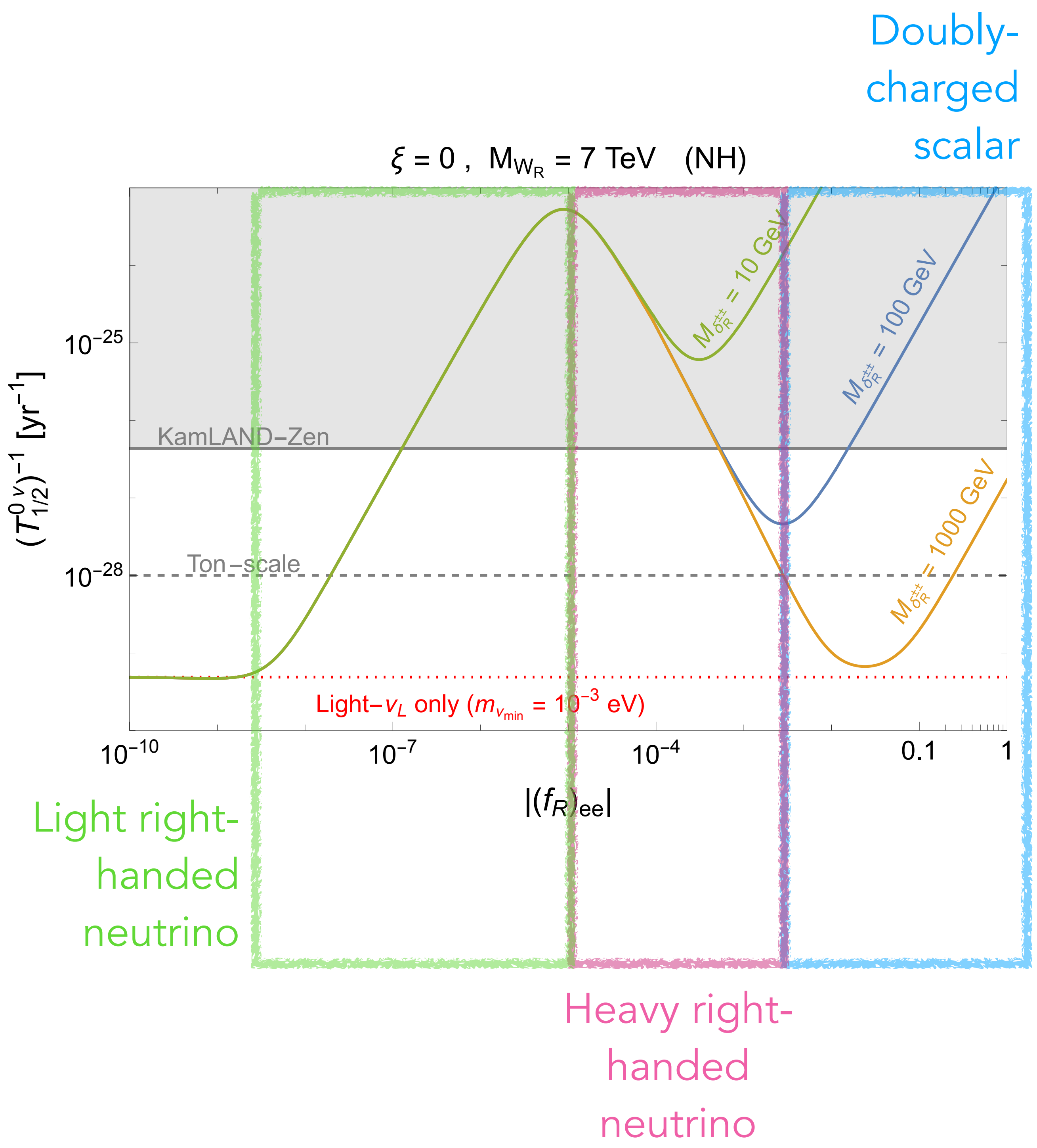
$$\mathscr{U}_1^{\dagger} M_n \mathscr{U}_1^{*} = \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

$$M_\nu = M_L - M_D M_R^{-1} M_D^{\top},$$
$$M_N = M_R .$$

$$\mathscr{U}_2^{\dagger} \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix} \mathscr{U}_2^{*} = \begin{pmatrix} \widehat{M}_\nu & 0 \\ 0 & \widehat{M}_N \end{pmatrix}$$

$$\widehat{M}_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$$
$$\widehat{M}_N \equiv \mathrm{diag}(m_4, m_5, m_6)$$

Coupling effects



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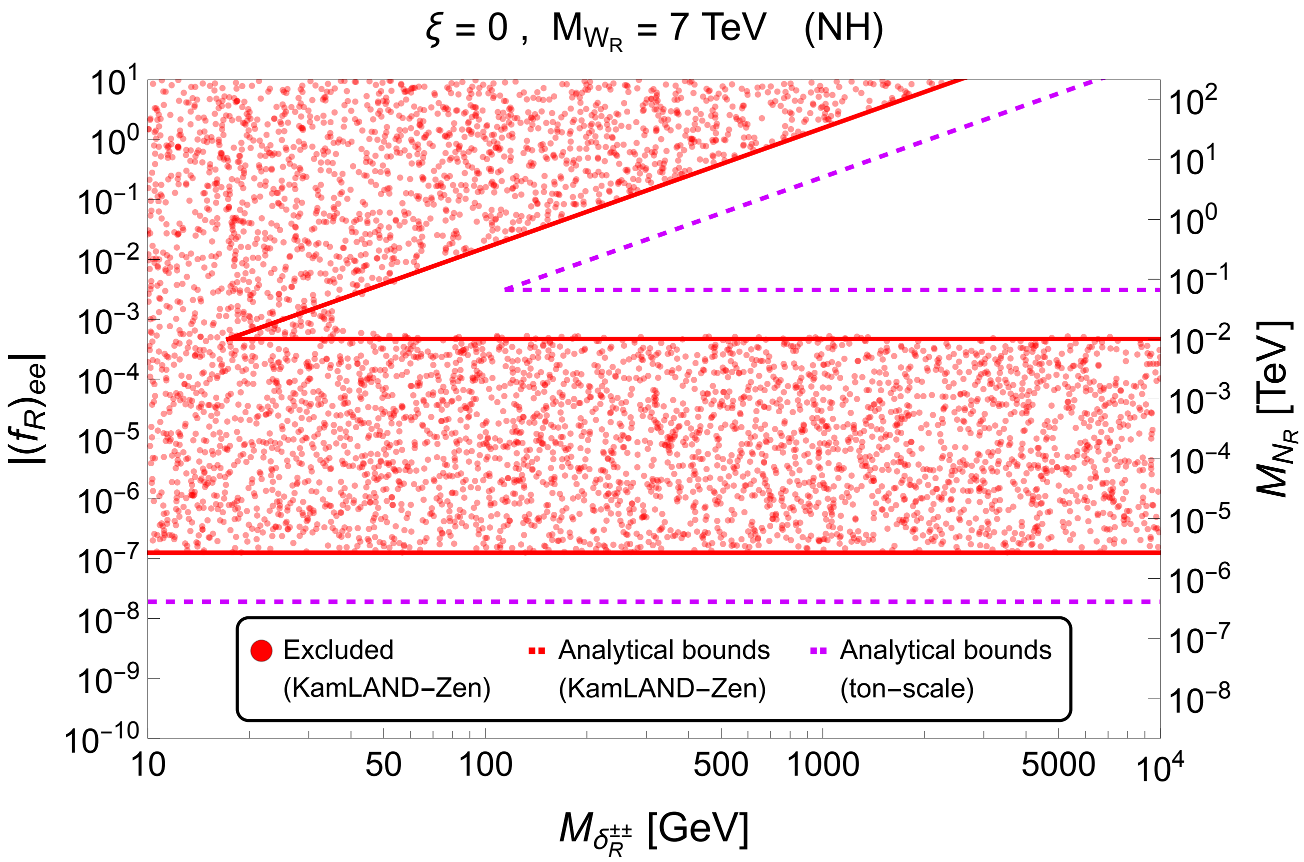

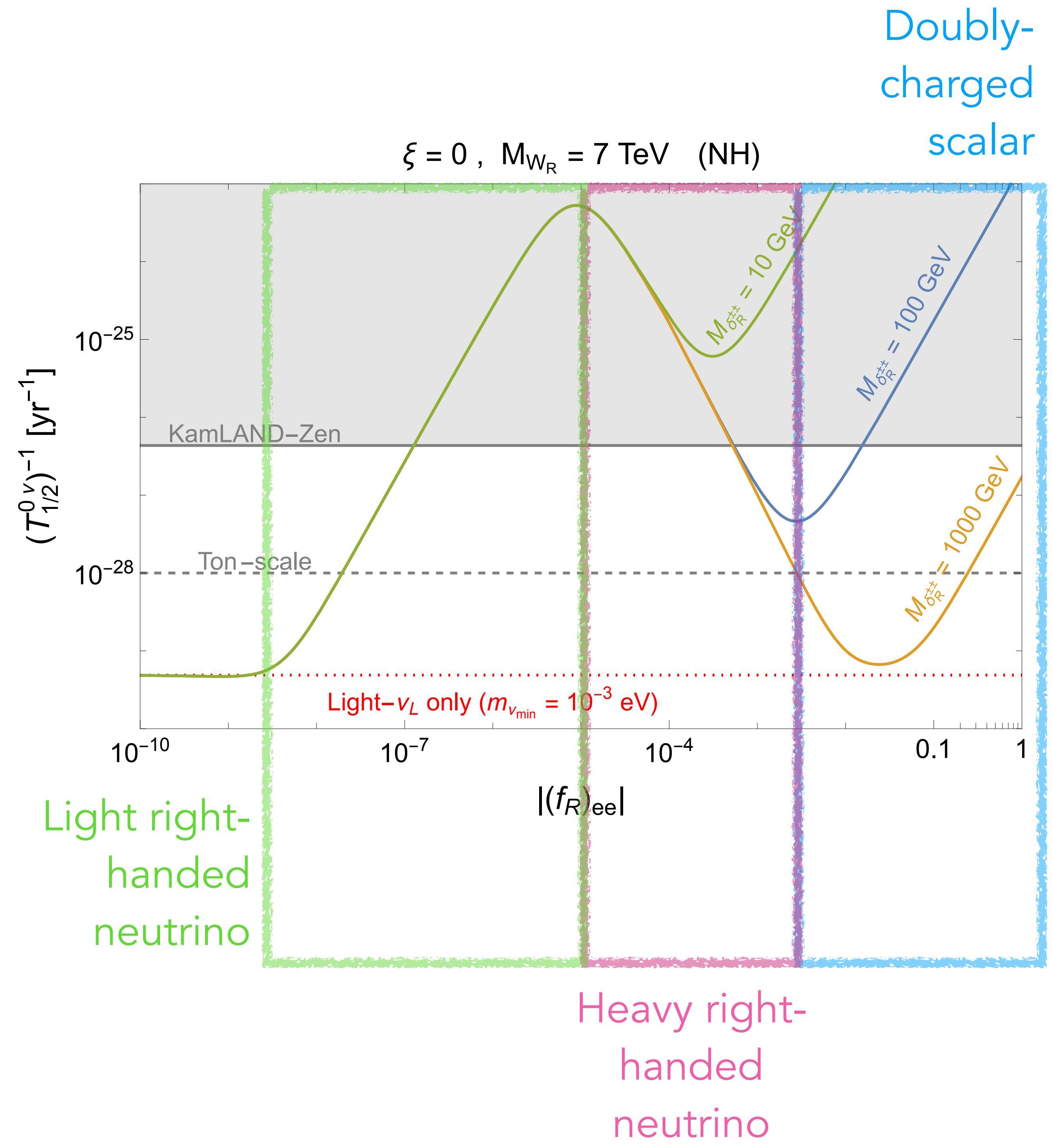

Mixing and mass effects

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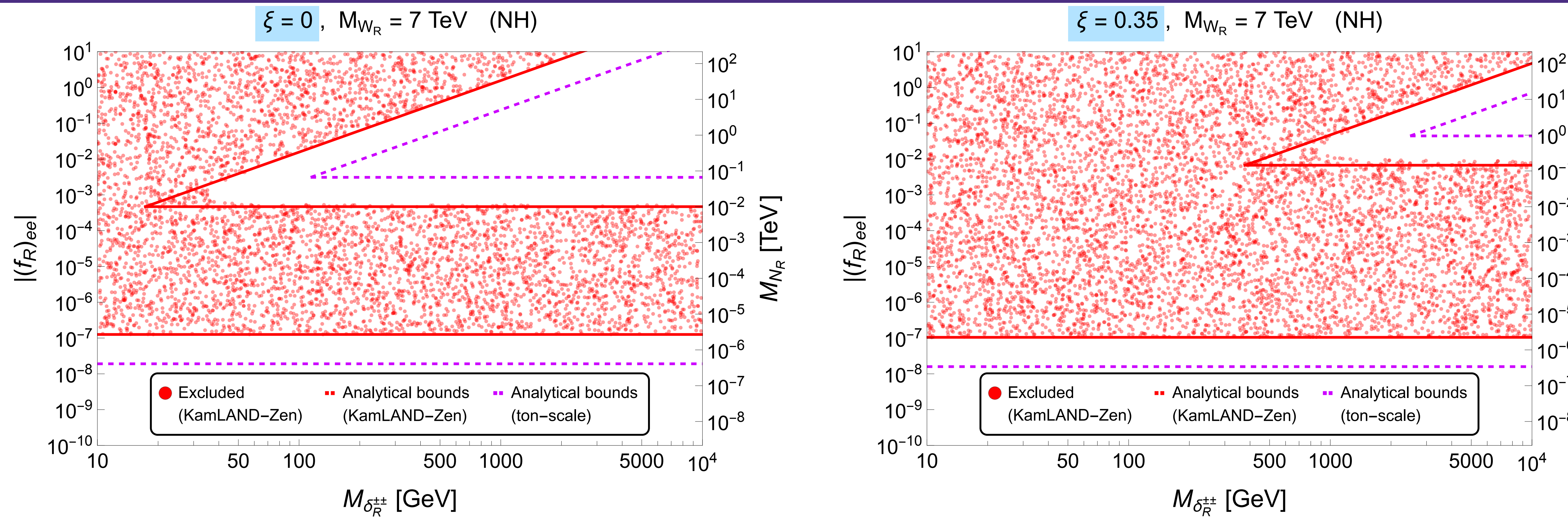

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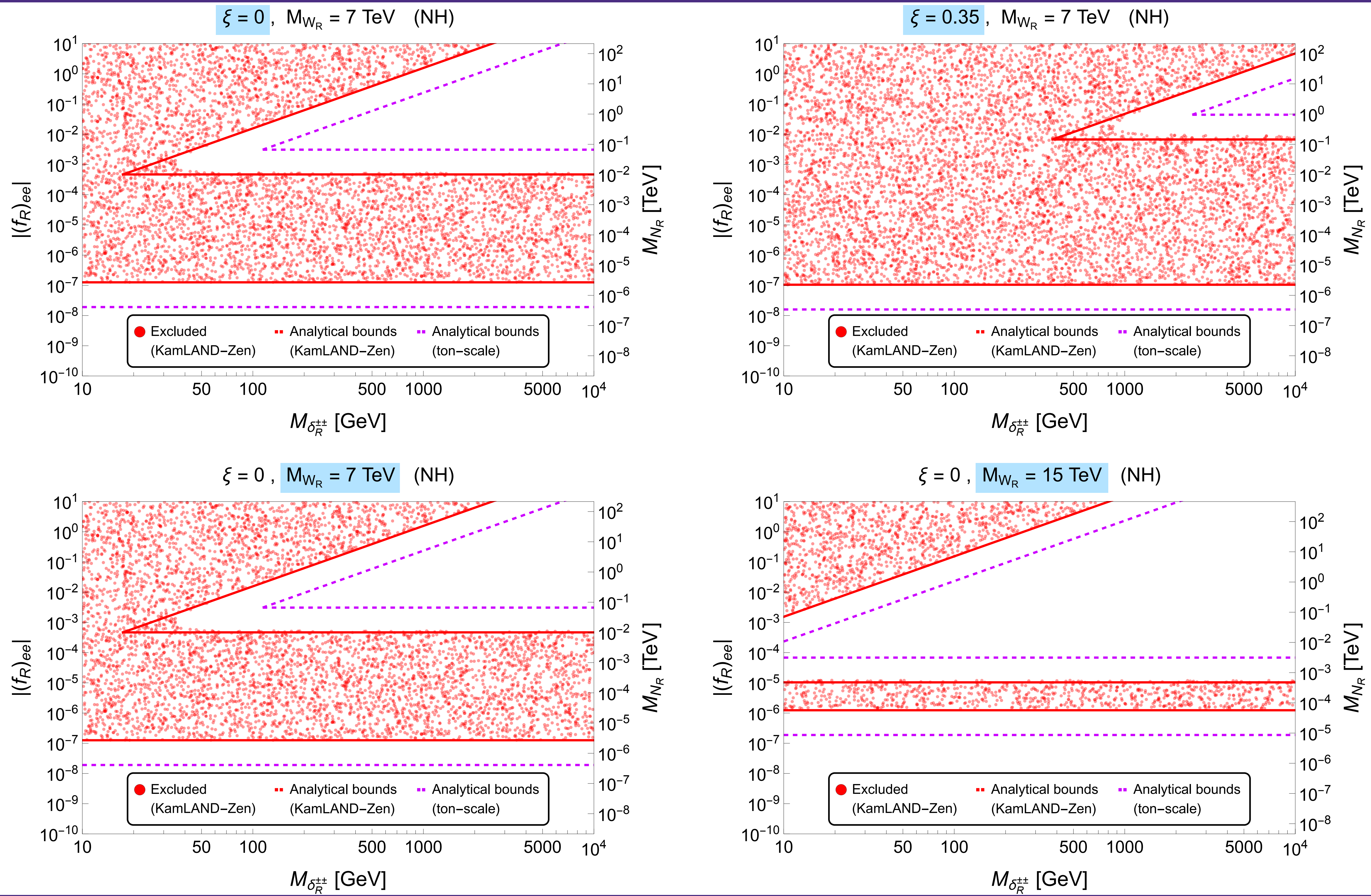
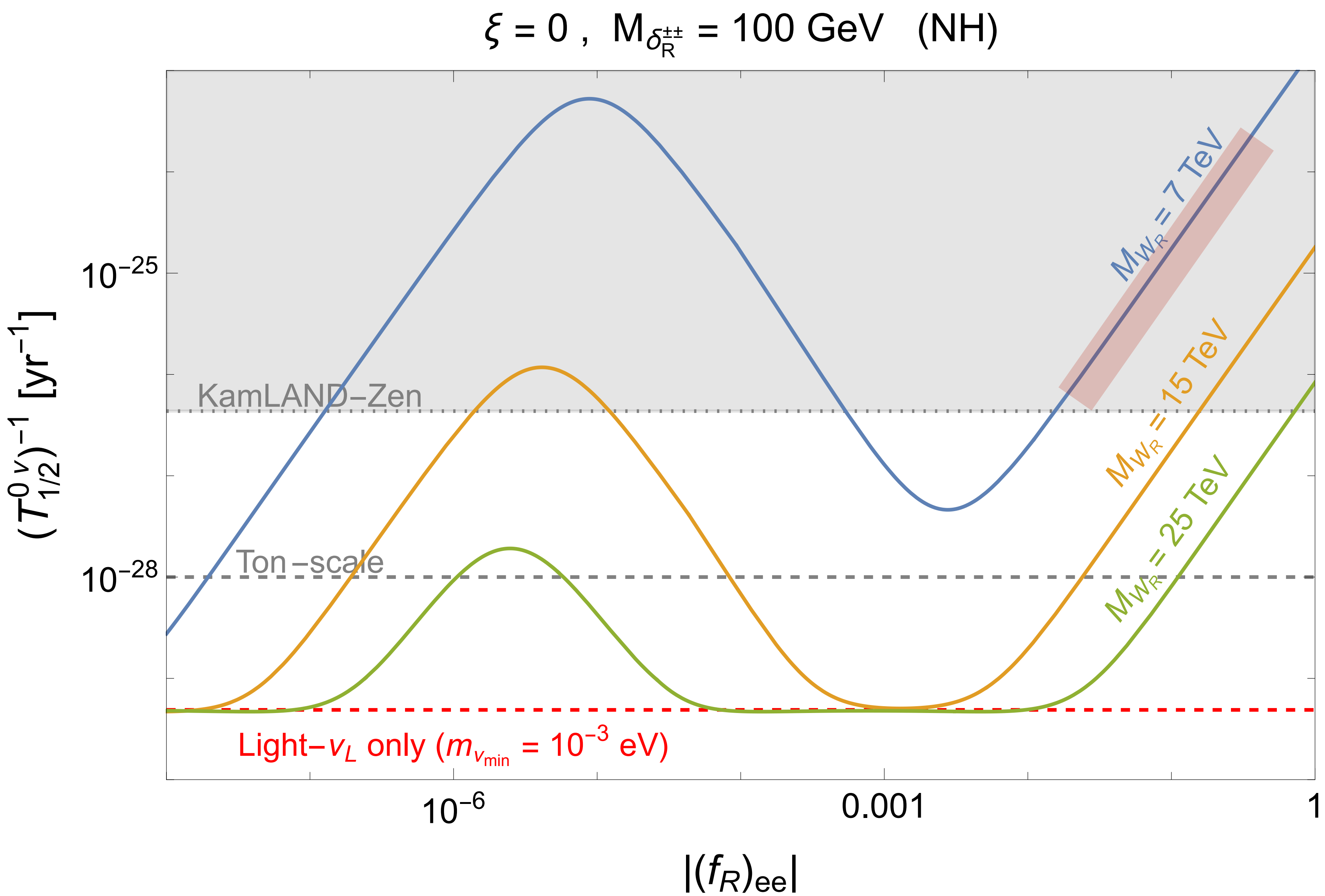
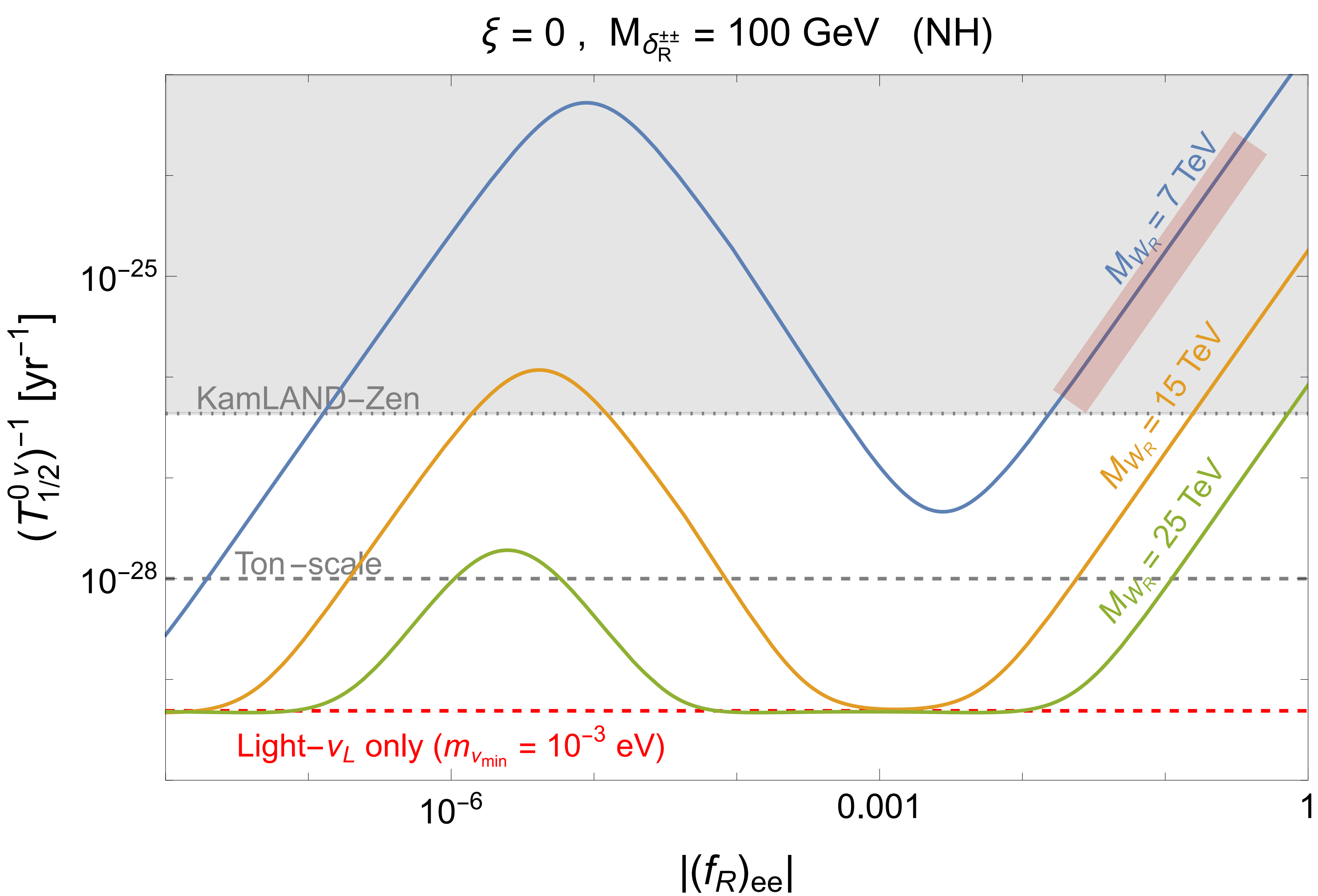


Coupling dependence



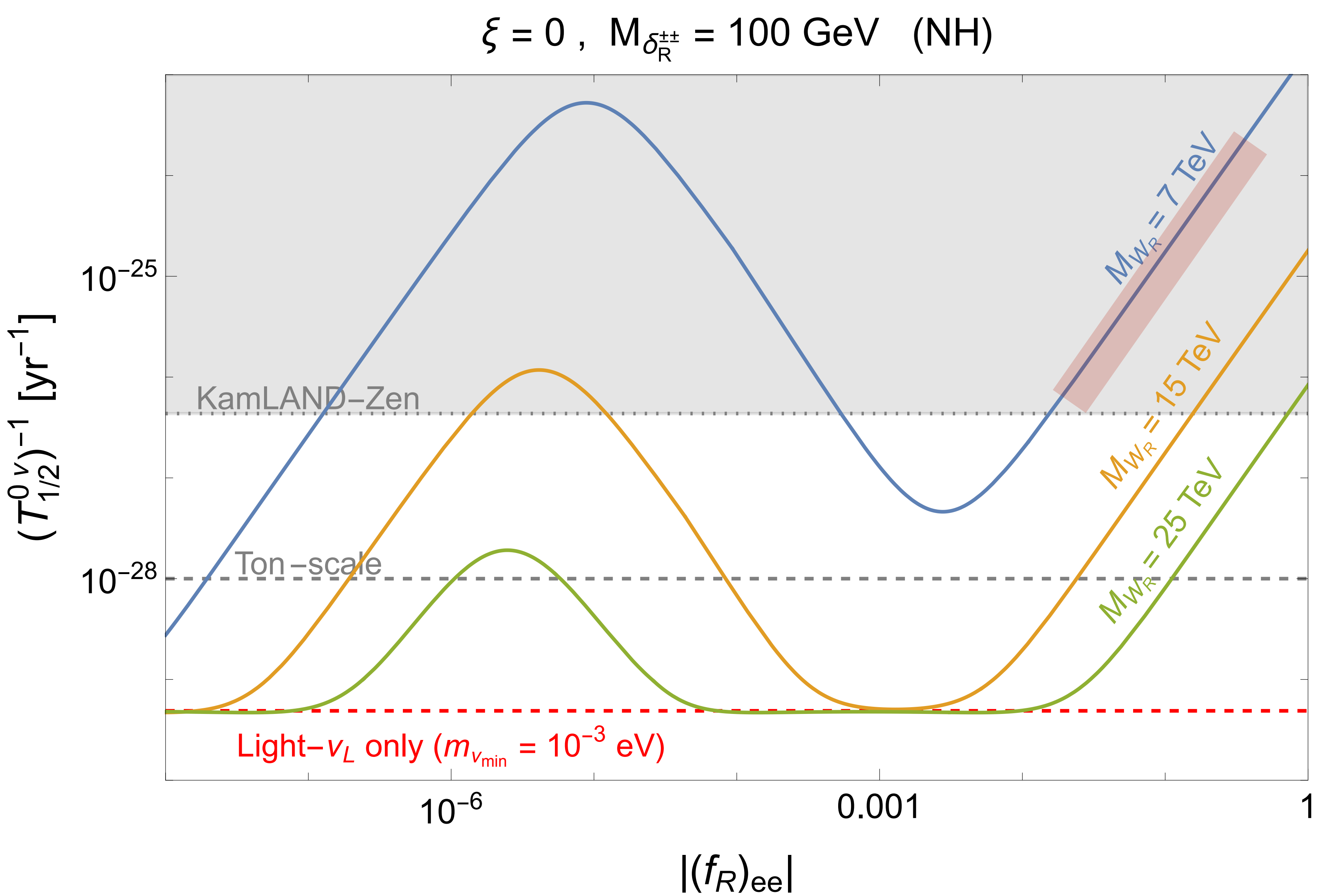
Coupling dependence

- Dominant contributions:



Coupling dependence

- Dominant contributions:
  - Doubly-charged scalar
  - Right-handed neutrino (heavy)
  - Right-handed neutrino (light)



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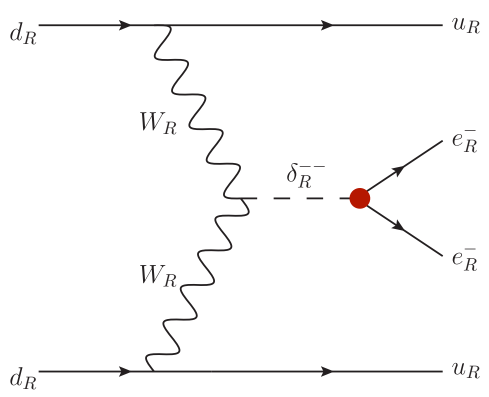

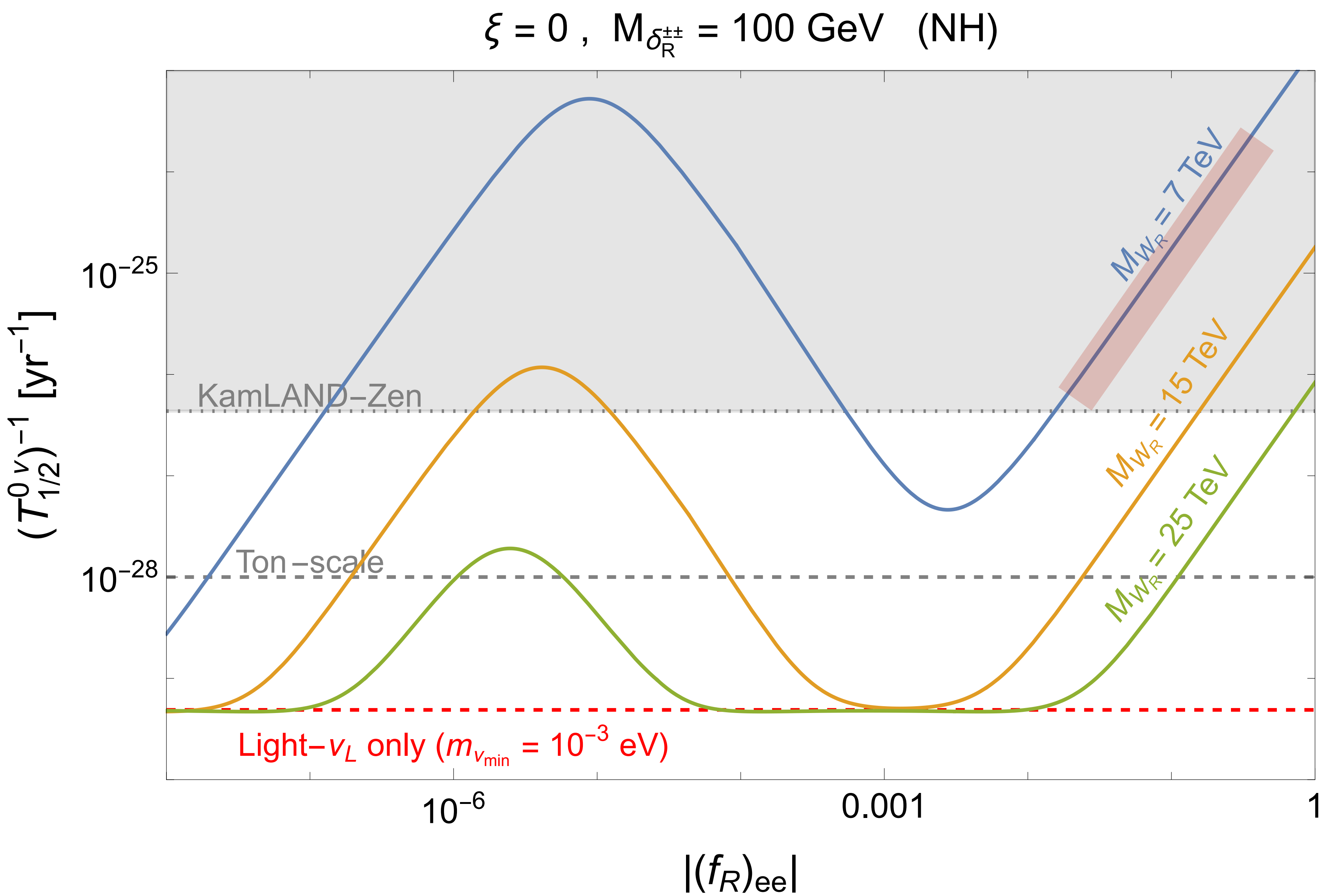

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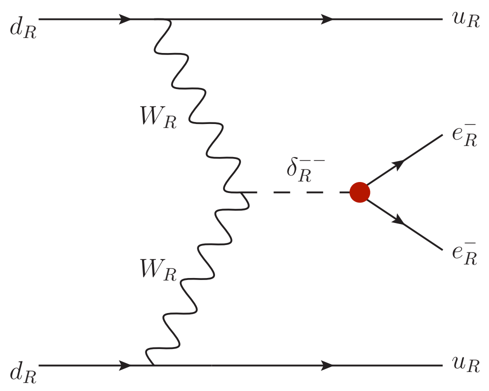
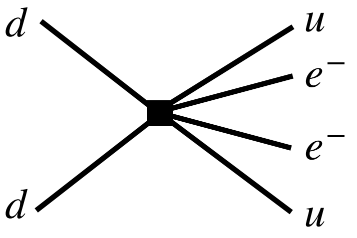
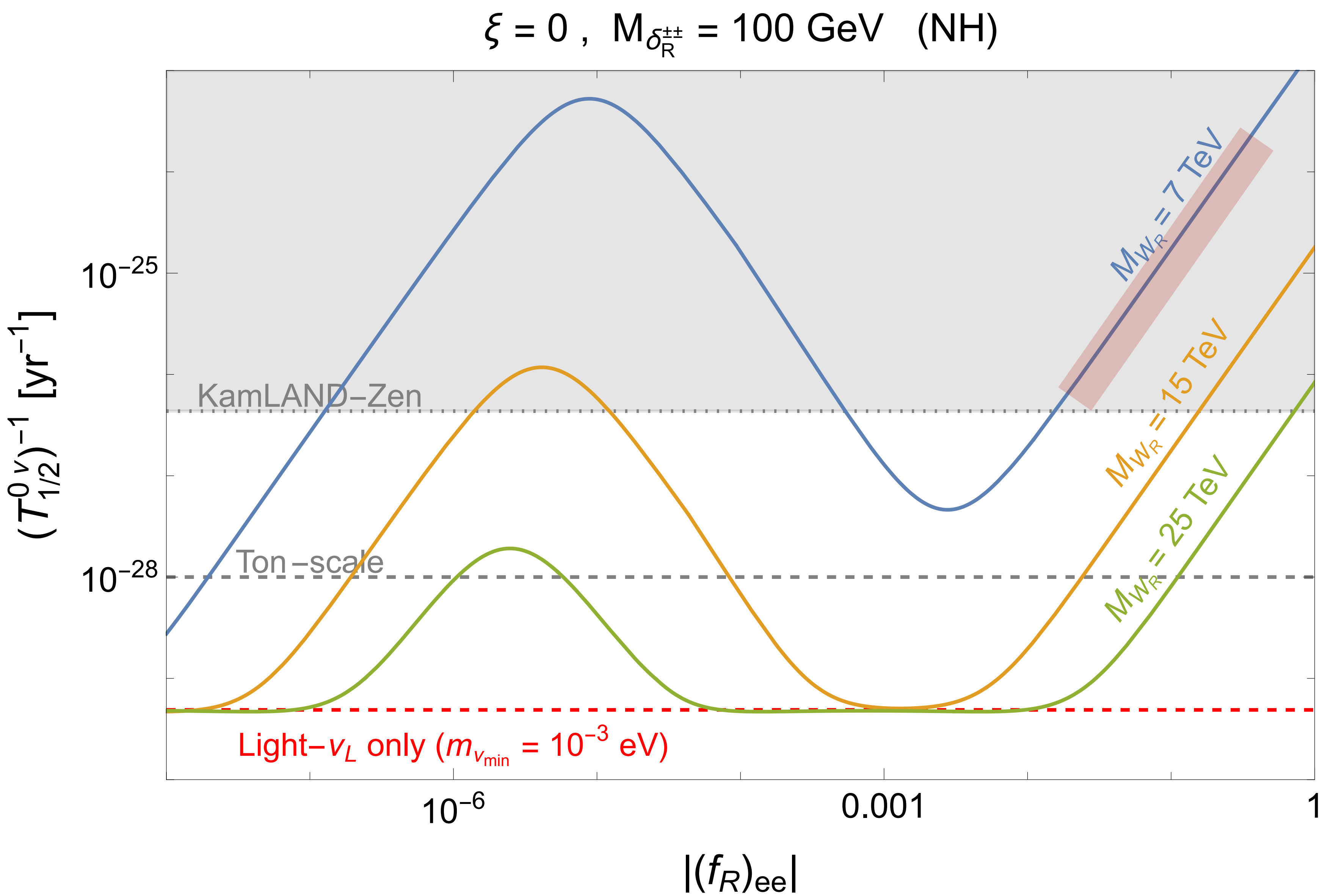




$$(T_{1/2}^{0\nu})^{-1} \propto \left| \frac{(f_R)_{ee}}{M^2_{\delta_R^{\pm\pm}}} \frac{v_R}{M^4_{W_R}} \right|^2$$

$$\propto \frac{1}{M^4_{\delta_R^{\pm\pm}} M^6_{W_R}} \, |(f_R)_{ee}|^2$$



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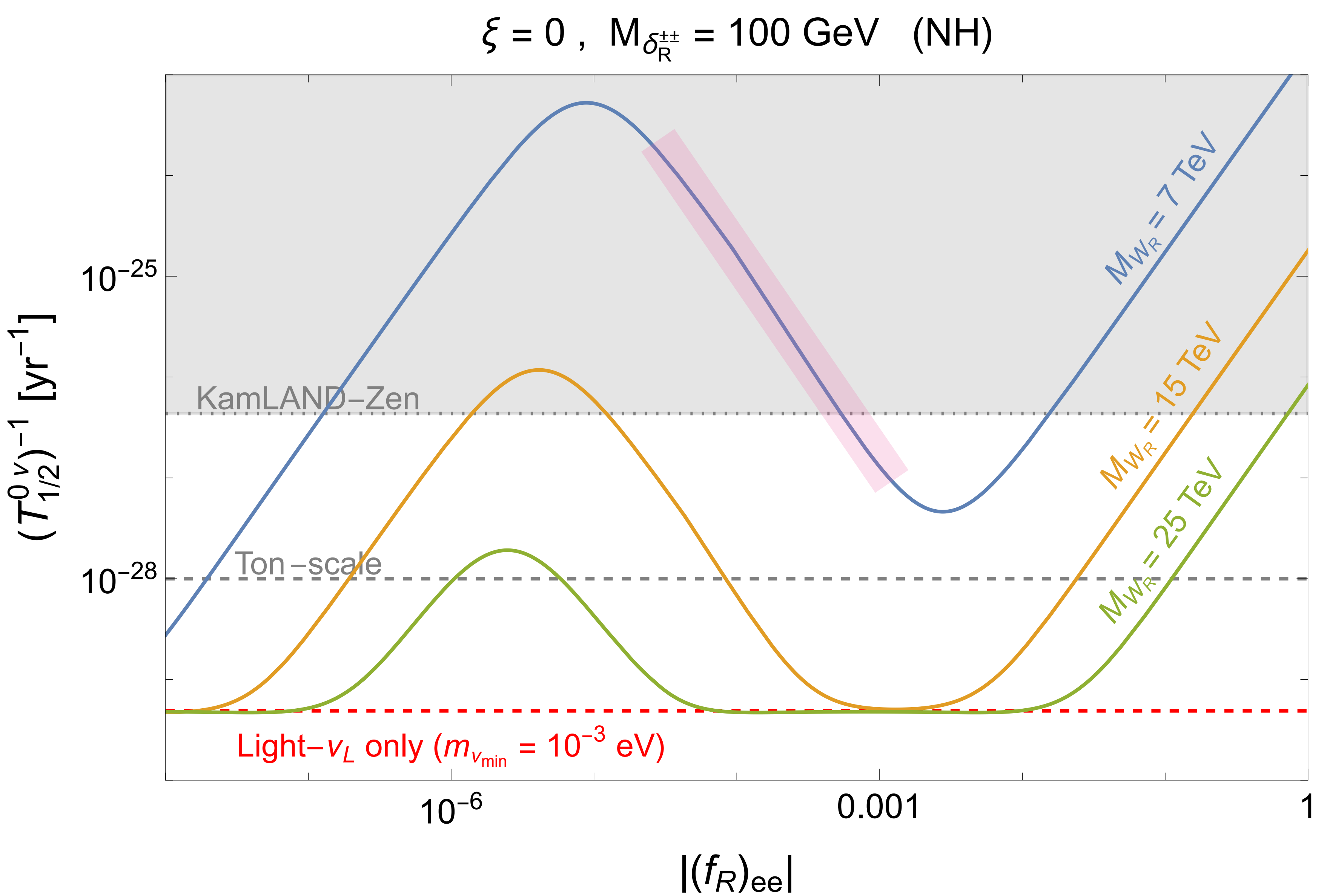

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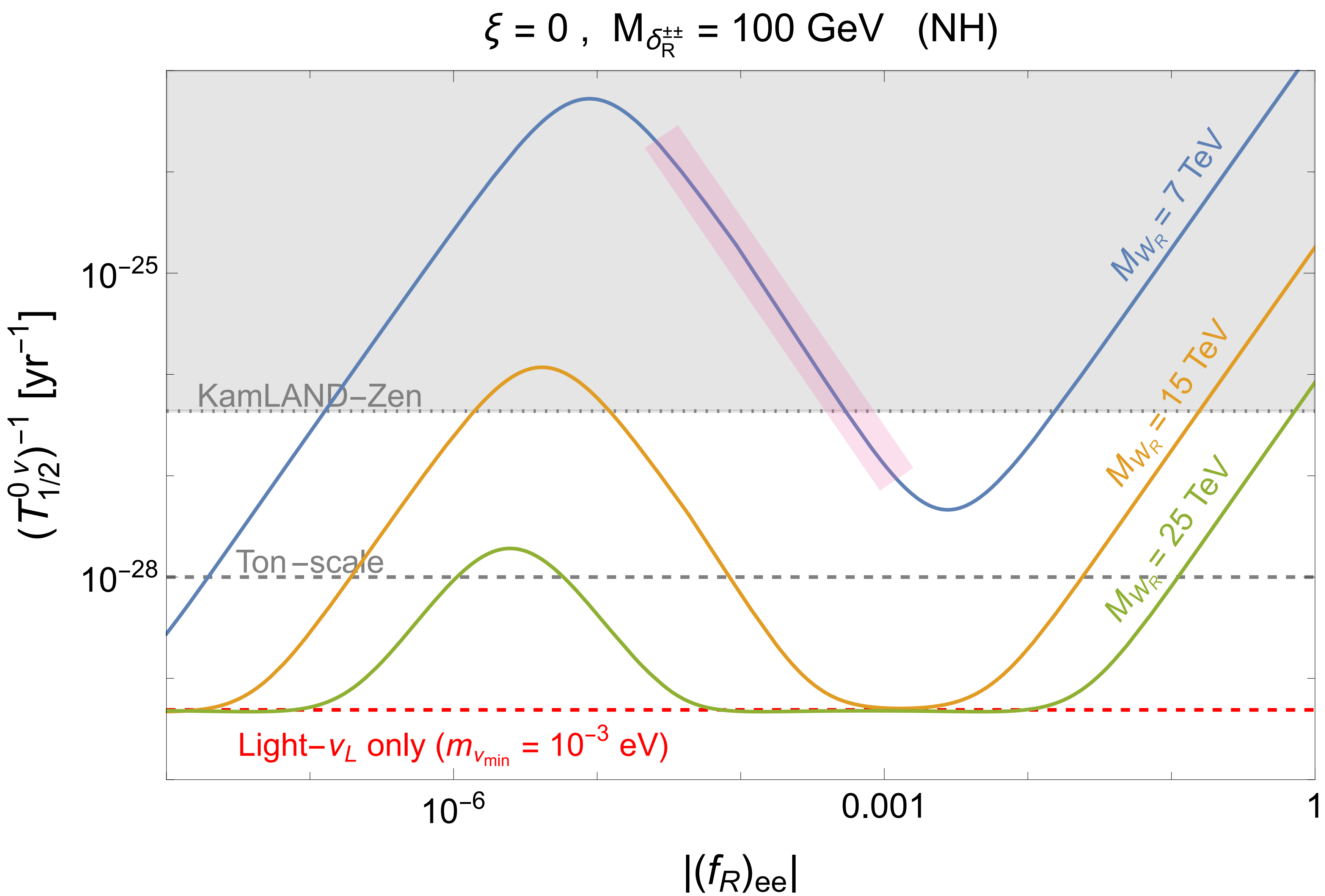

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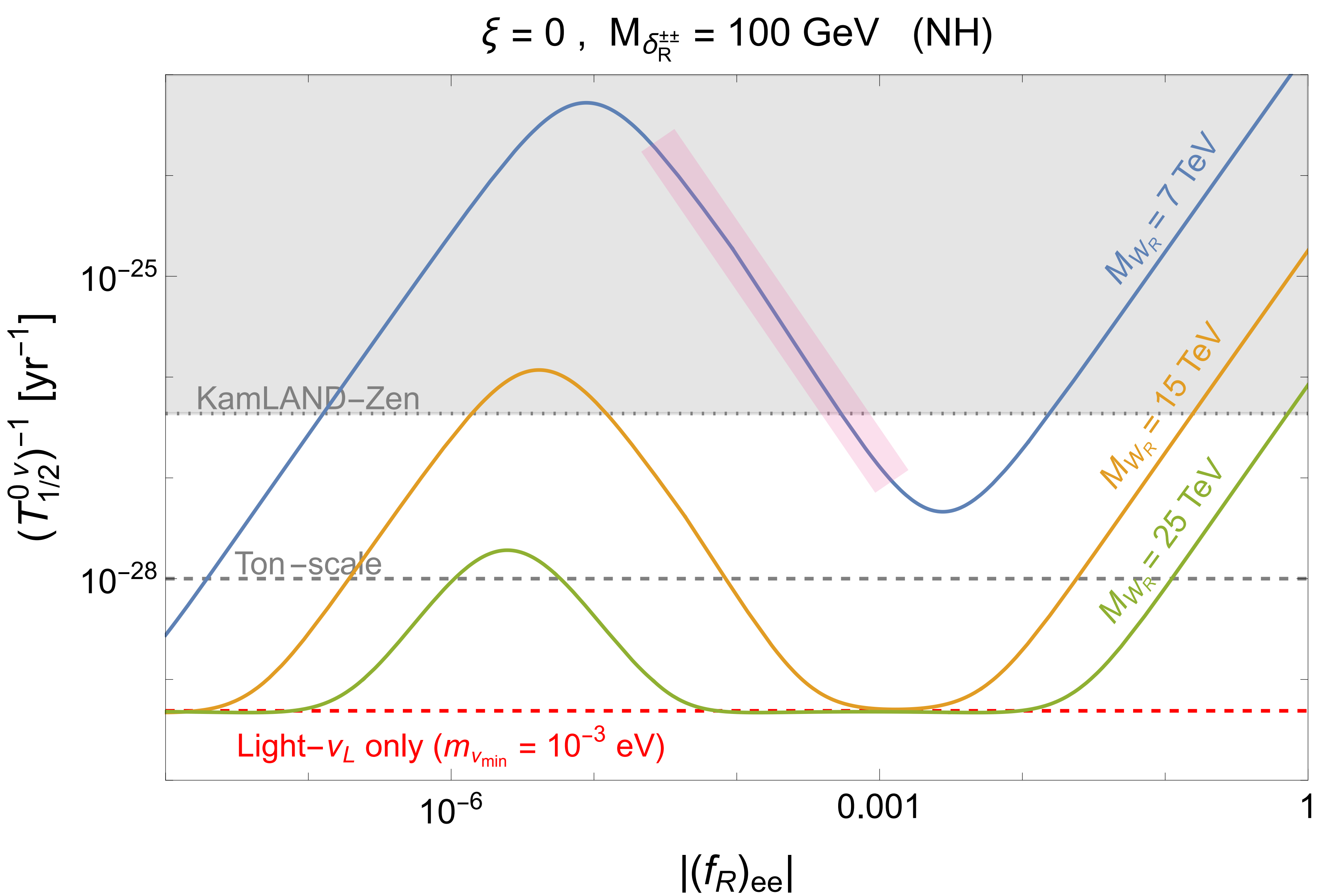

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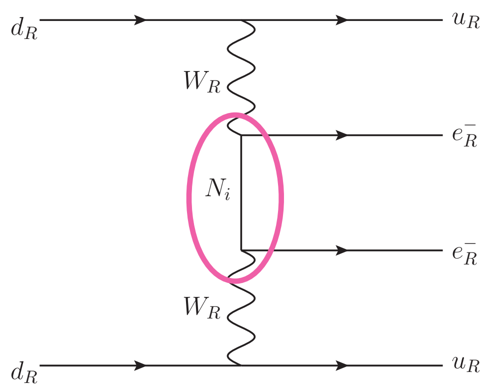

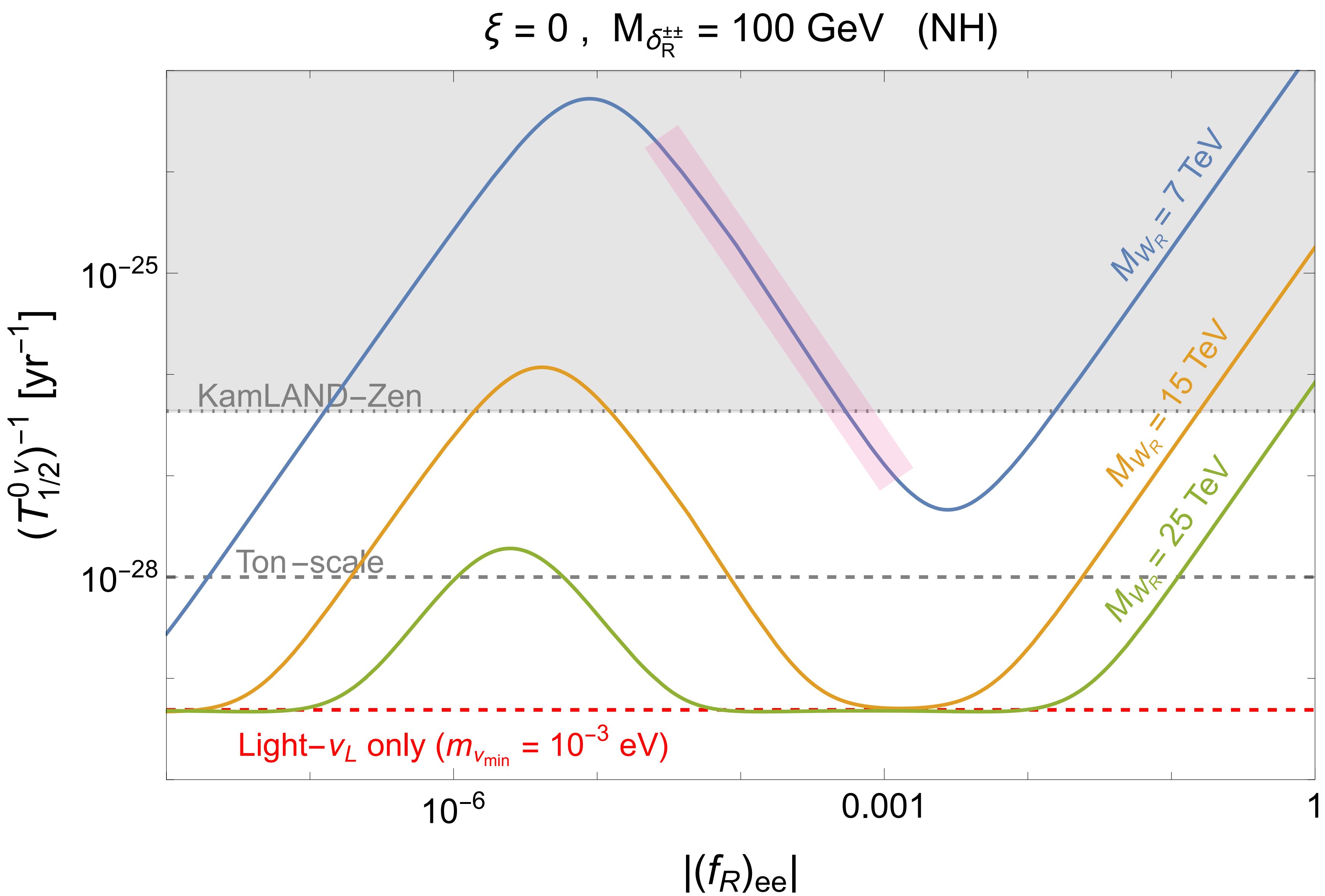

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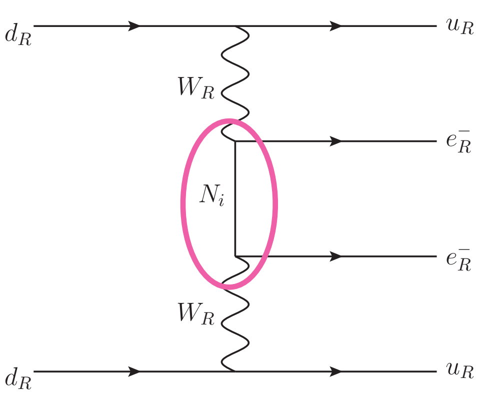
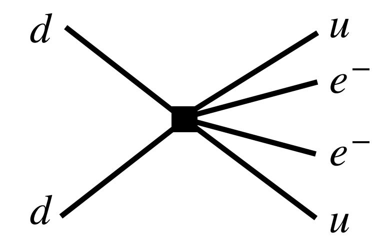
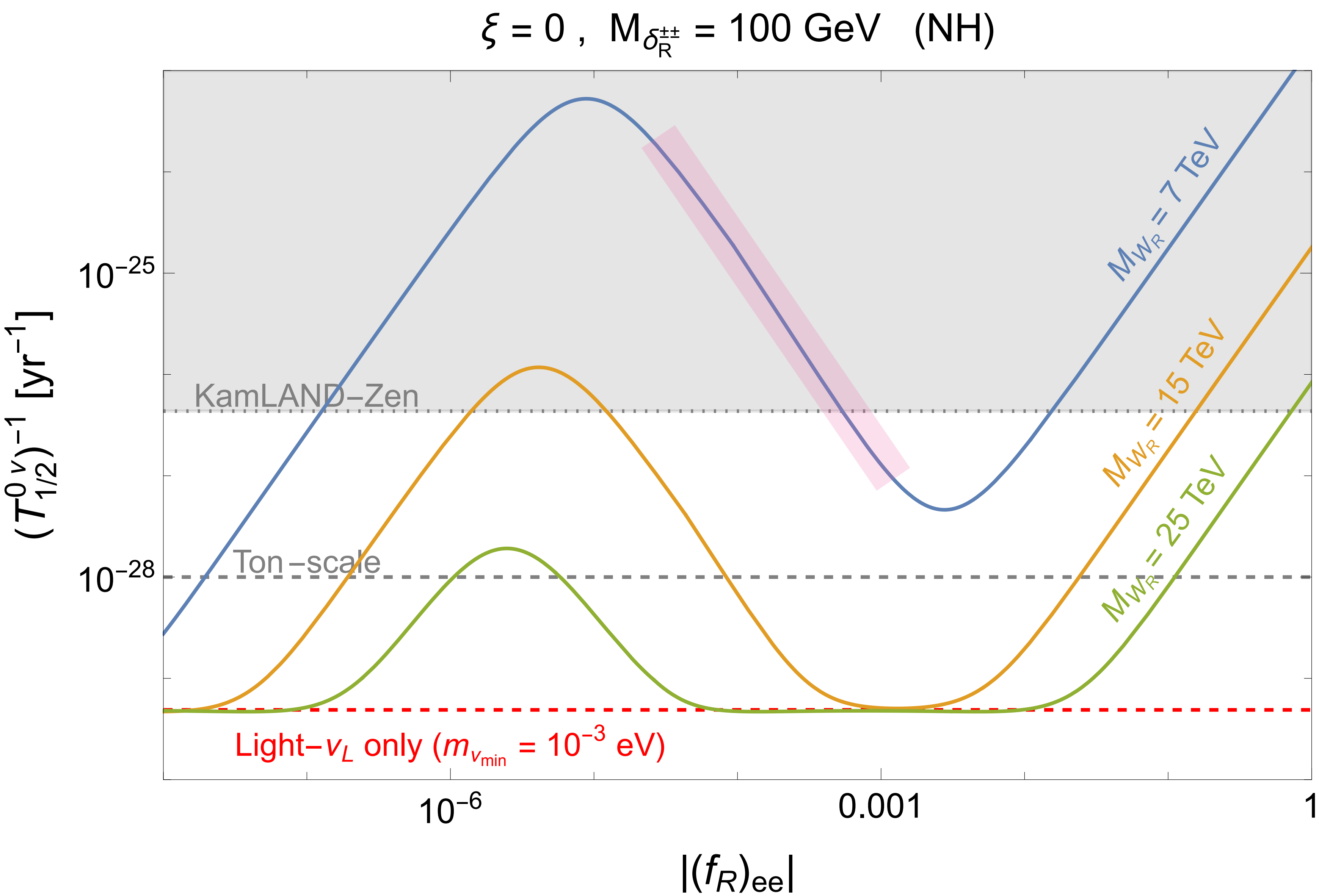




$$(T^{0\nu}_{1/2})^{-1} \propto \left| \frac{1}{M_{N_R}} \frac{1}{M^4_{W_R}} \right|^2$$

$$\propto \frac{1}{M^{10}_{W_R}} \frac{1}{|(f_R)_{ee}|^2}$$



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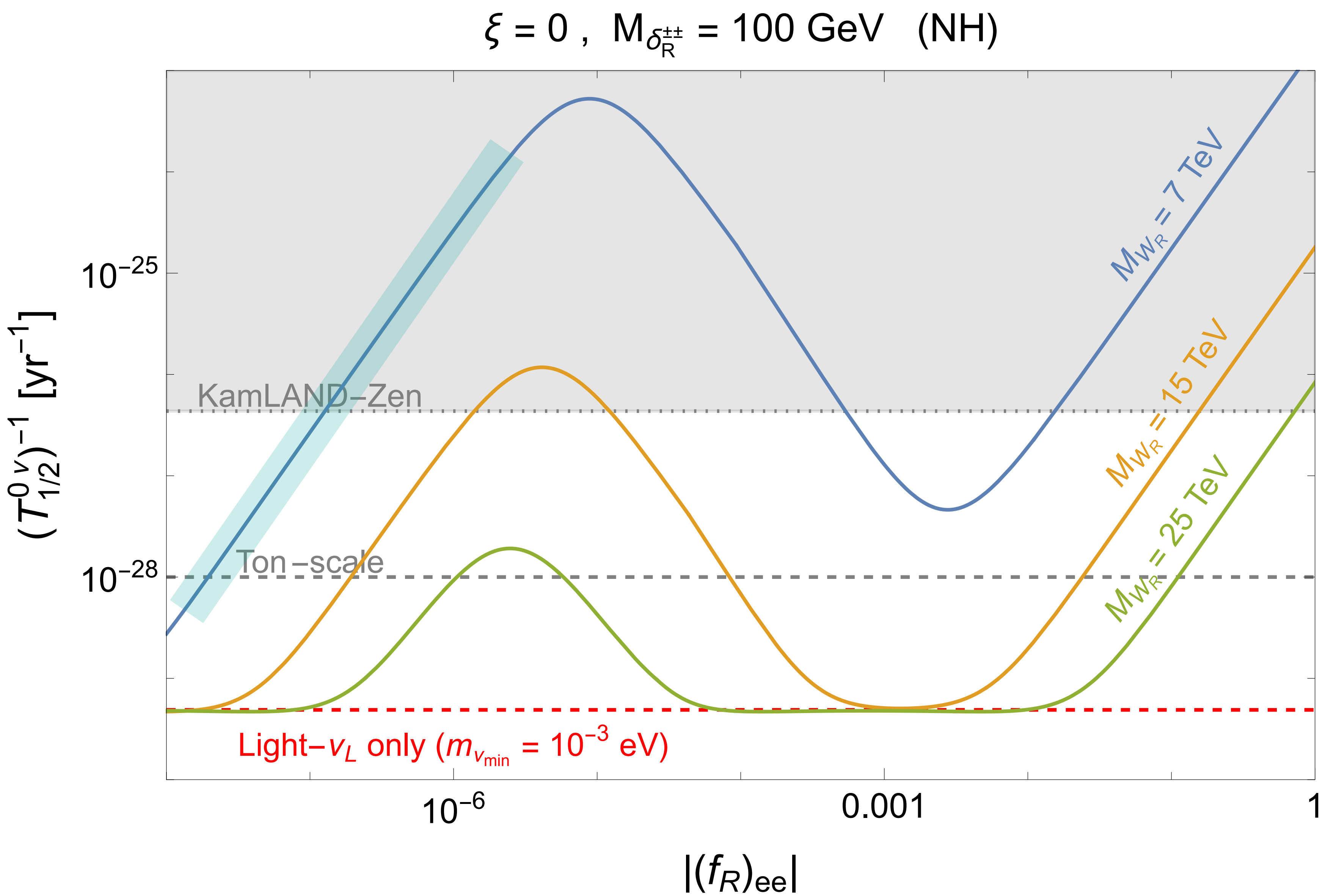

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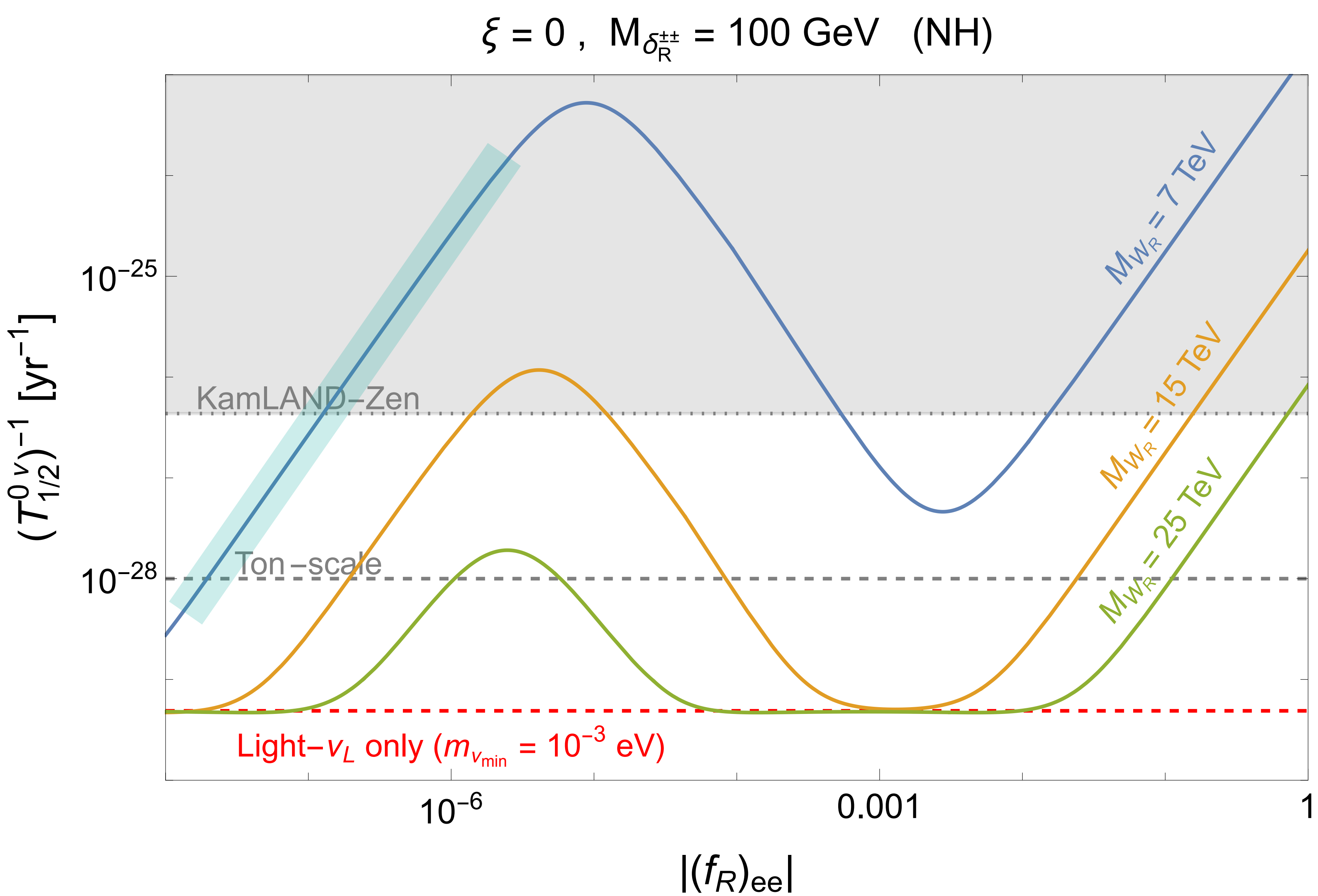

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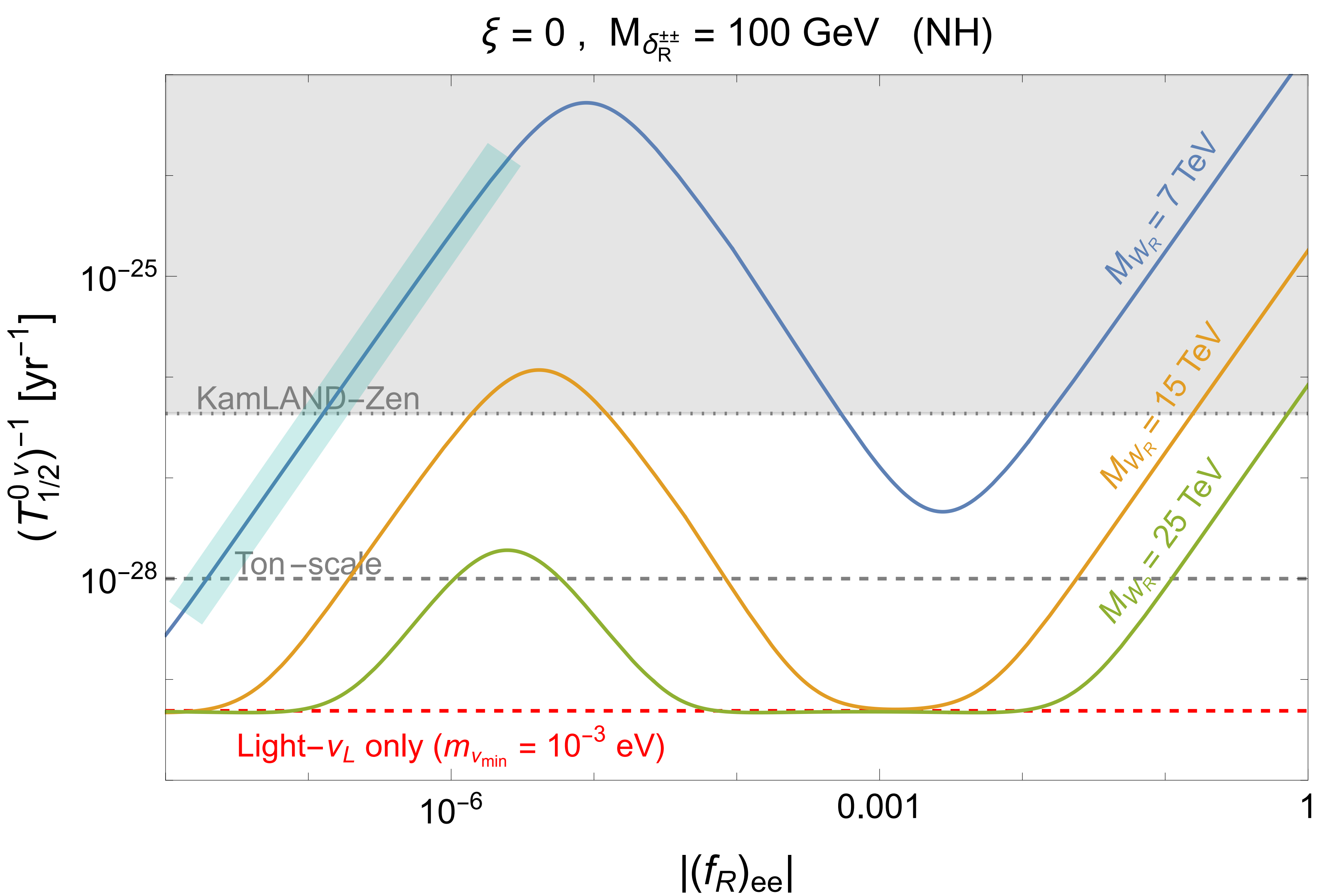

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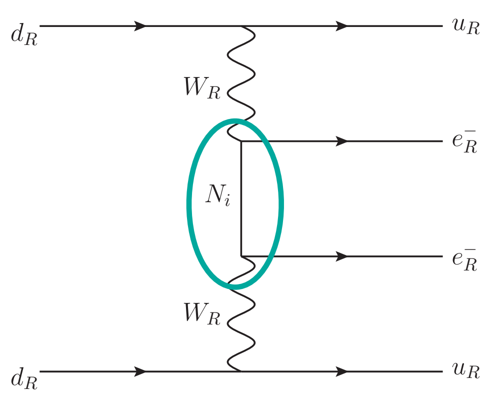

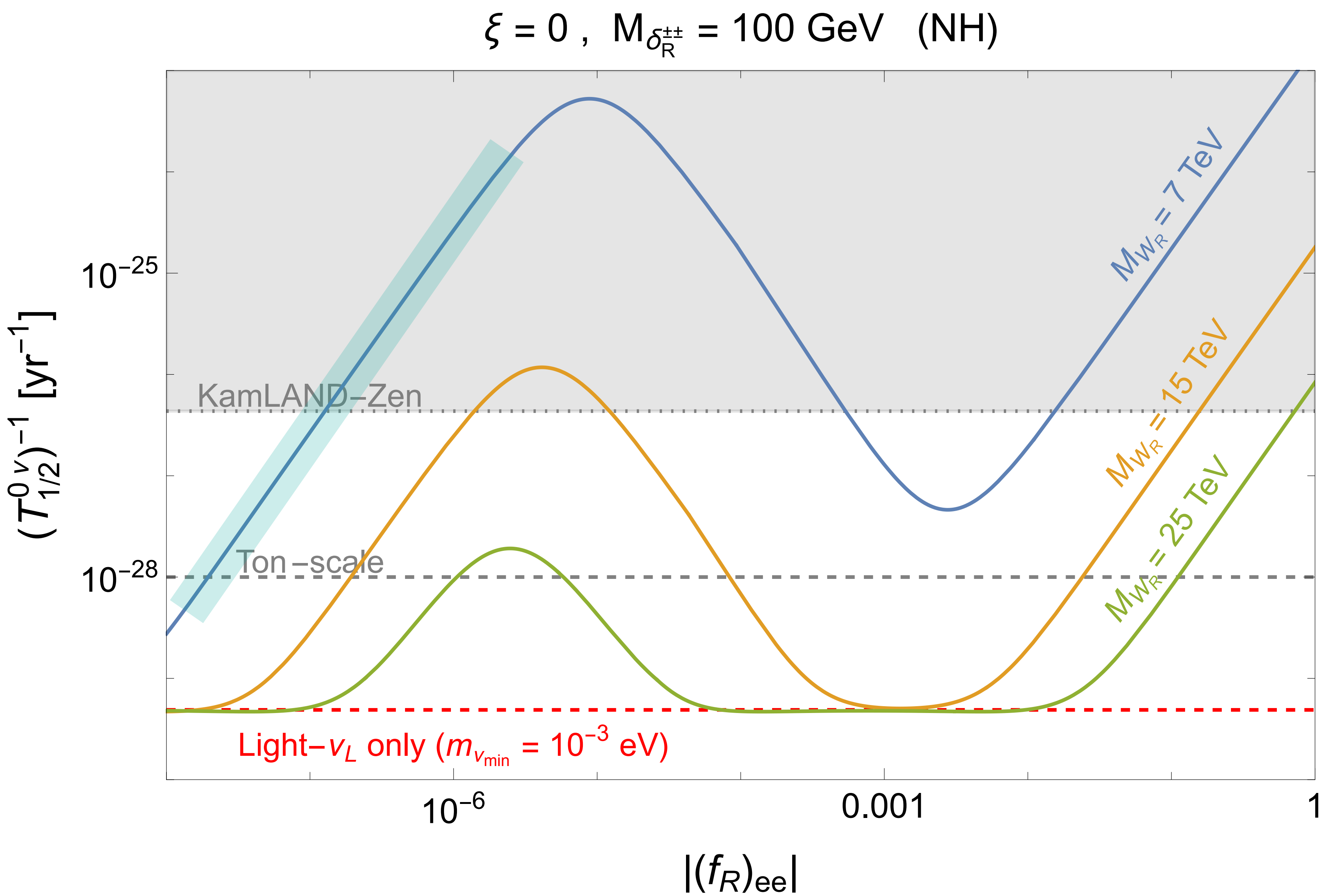

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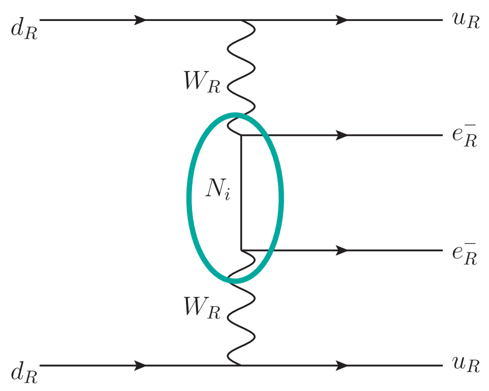

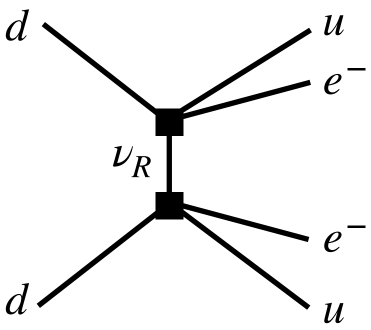

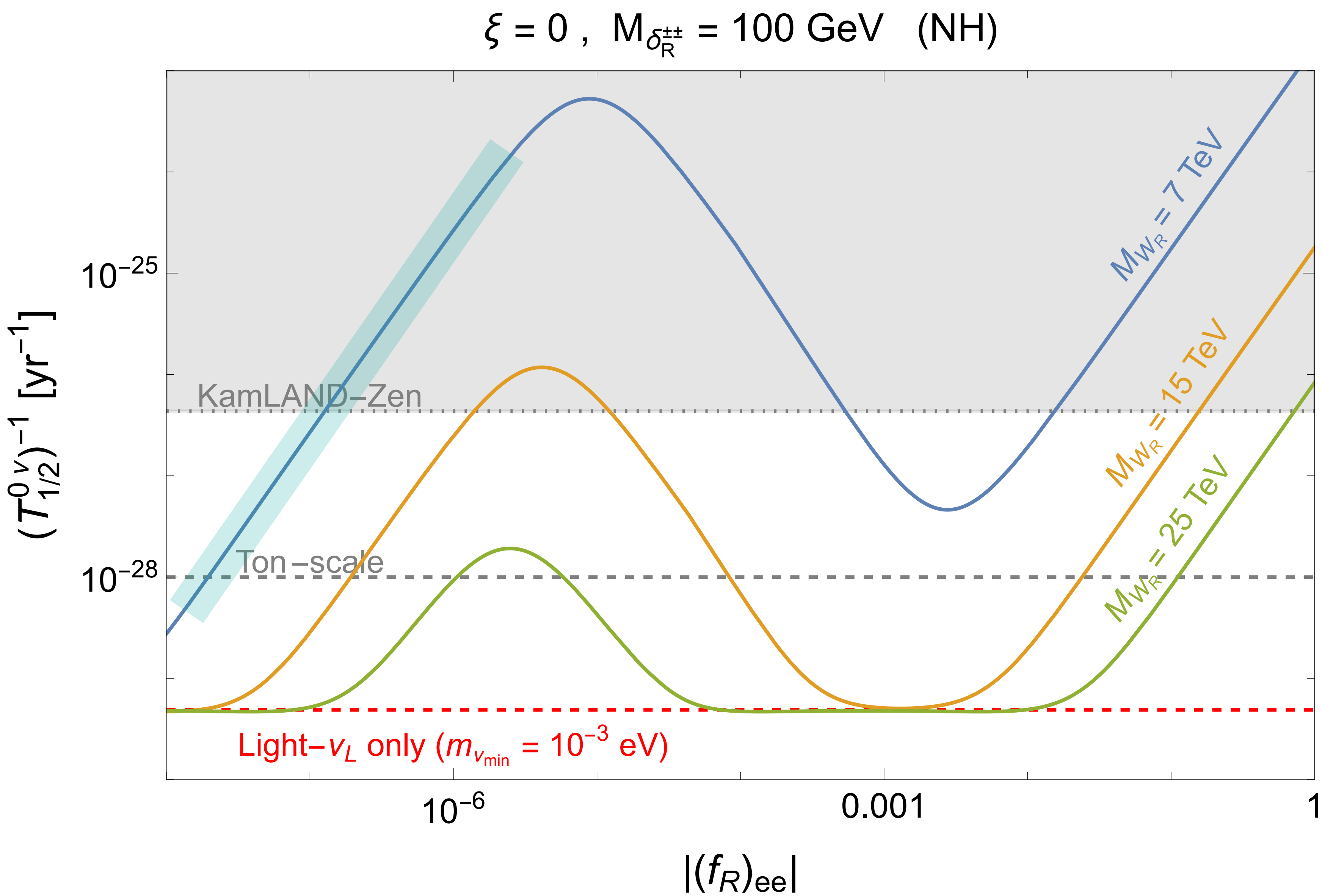

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