EXPLORING THE **NEUTRINO SECTOR** OF THE MINIMAL **LEFT-RIGHT** SYMMETRIC MODEL

Gustavo F. S. Alves

In collaboration with:
Chee Sheng Fong
Luighi P. S. Leal
Renata Zukanovich Funchal

FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA
DO ESTADO DE SÃO PAULO

IFUSP
Instituto de Física da USP

arXiv:2208.07378

Introduction to the MLRSM:

- The Minimal Left Right Symmetric Model is an extension of the Standard Model that makes it parity invariant at higher energies.

- Therefore, it is based on the group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

R. N. Mohapatra and G. Senjanovic (1980)
N. G. Deshpande, J. F. Gunion, B. Kayser, and F. I. Olness (1991)

Setting the stage

Particle Content: Scalar Sector

- We have more scalars to get a symmetry breaking pattern that recovers the SM at lower energies:

Bidoublet: $\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$

LH Triplet: $\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}$

RH Triplet: $\Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$

Symmetry breaking proceeds as the scalars acquire a vev

$$< \phi_2^0 >= \kappa_2 \qquad < \phi_1^0 >= \kappa_1$$

$$< \delta_{\mathrm{LR}}^0 >= v_{\mathrm{LR}}$$

Physical Scalars:

$\delta_{L,R}^{++}$ δ_L^+ A^0

H H^+

Setting the stage

Particle Content: Gauge Sector

$$W^{\pm}_{L,R} \; W^{3}_{L,R} \quad B' \longrightarrow Z \; Z' \quad W \; W' \quad \gamma$$

LR and RH W's can mix!!

F. del Aguila, et al., arXiv:1005.3998.
M. Lindner, et al., arXiv:1604.07419.
CMS Collaboration, A. Tumasyan et al., arXiv:2112.03949.
A. Maiezza, G. Senjanovic, and J. C. Vasquez, arXiv:1612.09146.
S. Bertolini, A. Maiezza, and F. Nesti, arXiv:1911.09472.
W. Dekens, L. Andreoli, J. de Vries, E. Mereghetti, and F. Oosterhof, arXiv:2107.10852.
M. Nemevsek, G. Senjanovic, and V. Tello, arXiv:1211.2837.
G. C. Branco and G. Senjanovic, Phys. Rev. D 18 (1978) 1621.

Setting the stage

Particle Content: Leptonic Sector

Dirac mass term

LH & RH neutrino Majorana mass term

$$\mathcal{L}_l = -\bar{L}_L(h_l\Phi + \tilde{h}_l\tilde{\Phi})L_R - \overline{L_L^c} i\sigma_2\Delta_L h_M L_L - \overline{L_R^c} i\sigma_2\Delta_R \tilde{h}_M L_R + \mathrm{h.c.}$$

Charged Lepton masses:

$$U_L \mathcal{M}_l U_R^\dagger = \hat{\mathcal{M}}_l$$

Neutrino masses:

$$\mathcal{M}_\nu = \begin{pmatrix} M_L^\dagger & M_D \\ M_D^T & M_R \end{pmatrix} \approx \begin{pmatrix} M_L^\dagger - M_D M_R^{-1} M_D^T & 0 \\ 0 & M_R \end{pmatrix}$$

The neutrino sector at its finest

- Mixing matrix:

$$\mathcal{U} = \begin{pmatrix} \mathcal{U}_{LL} & \mathcal{U}_{LR} \\ \mathcal{U}^*_{RL} & \mathcal{U}^*_{RR} \end{pmatrix}$$

Active-active neutrino mixing ($\mathcal{U}_{LL}$)

Active-Sterile neutrino mixing ($\mathcal{U}_{LR}$)

- The light neutrino mass formula:

$$m_\nu = \underbrace{M_L^\dagger}_{\text{Type-II}} - \underbrace{M_D M_R^{-1} M_D^T}_{\text{Type-I}}$$

$$|\mathcal{U}_{LR}|^2 \approx |m_I M_R^{-1}|$$

$$m_I = M_D M_R^{-1} M_D^T$$

The neutrino sector at its finest

- Three regimes:
  - Type-I dominated:

$$m_\nu \approx -M_D M_R^{-1} M_D^T$$
$$|\mathcal{U}_{LR}|^2 \sim m_\nu M_R^{-1}$$

J. Barry and W. Rodejohann, arXiv:1303.6324.
P. S. Bhupal Dev, S. Goswami, and M. Mitra, arXiv:1405.1399.
G. Bambhaniya, P. S. B. Dev, S. Goswami, and M. Mitra, arXiv:1512.00440.
S. Goswami and K. N. Vishnudath, arXiv:2011.06314.
D. Borah and A. Dasgupta, arXiv:1606.00378.
V. Tello, M. Nemevsek, F. Nesti, G. Senjanovic, and F. Vissani, arXiv:1011.3522.
G. Li, M. Ramsey-Musolf, and J. C. Vasquez, arXiv:2009.01257.

  - Type-II dominated:

$$m_\nu \approx M_L^\dagger$$

  - Hybrid:

$$M_L^\dagger \sim M_D M_R^{-1} M_D^T >> m_\nu$$
$$|\mathcal{U}_{LR}|^2 \sim v_L / v_R$$

The neutrino sector at its finest

- Three regimes:
  - Type-I dominated:

$$m_\nu \approx -M_D M_R^{-1} M_D^T$$
$$|\mathcal{U}_{LR}|^2 \sim m_\nu M_R^{-1}$$

J. Barry and W. Rodejohann, arXiv:1303.6324.
P. S. Bhupal Dev, S. Goswami, and M. Mitra, arXiv:1405.1399.
G. Bambhaniya, P. S. B. Dev, S. Goswami, and M. Mitra, arXiv:1512.00440.
S. Goswami and K. N. Vishnudath, arXiv:2011.06314.
D. Borah and A. Dasgupta, arXiv:1606.00378.
V. Tello, M. Nemevsek, F. Nesti, G. Senjanovic, and F. Vissani, arXiv:1011.3522.
G. Li, M. Ramsey-Musolf, and J. C. Vasquez, arXiv:2009.01257.

  - Type-II dominated:

$$m_\nu \approx M_L^\dagger$$

  - Hybrid:

$$M_L^\dagger \sim M_D M_R^{-1} M_D^T >> m_\nu$$
$$|\mathcal{U}_{LR}|^2 \sim v_L / v_R$$

Our work explored in detail this scenario!

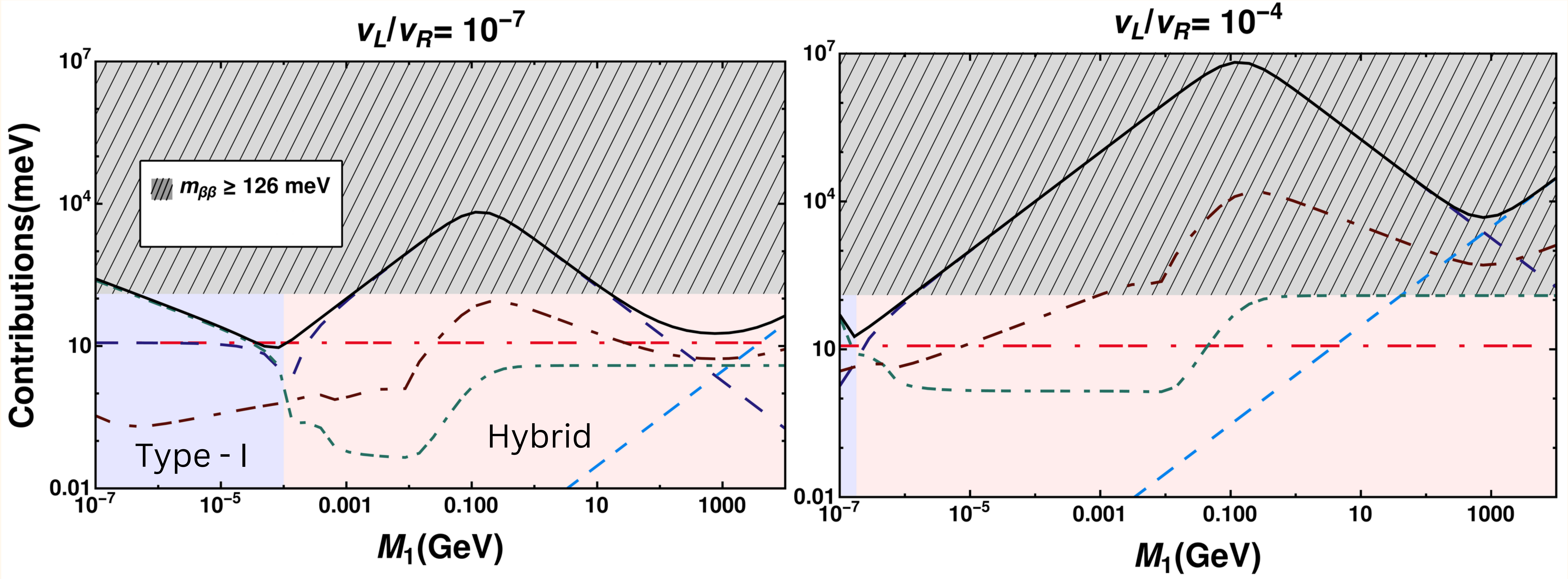
Phenomenology

Neutrinoless Double Beta Decay

$$M_1/M_3 = M_1/M_3 = 1$$

$$U_L = \mathbf{1}$$

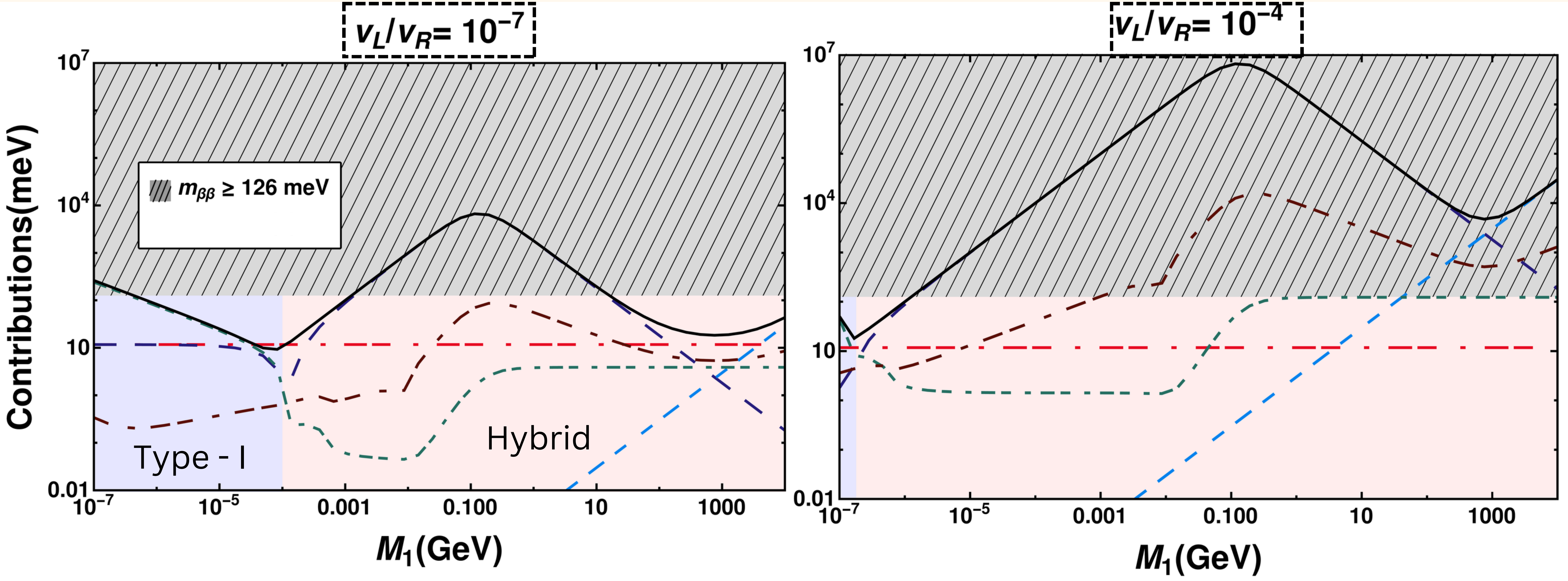
$$\xi = 3 \times 10^{-8}$$



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

Neutrinoless Double Beta Decay

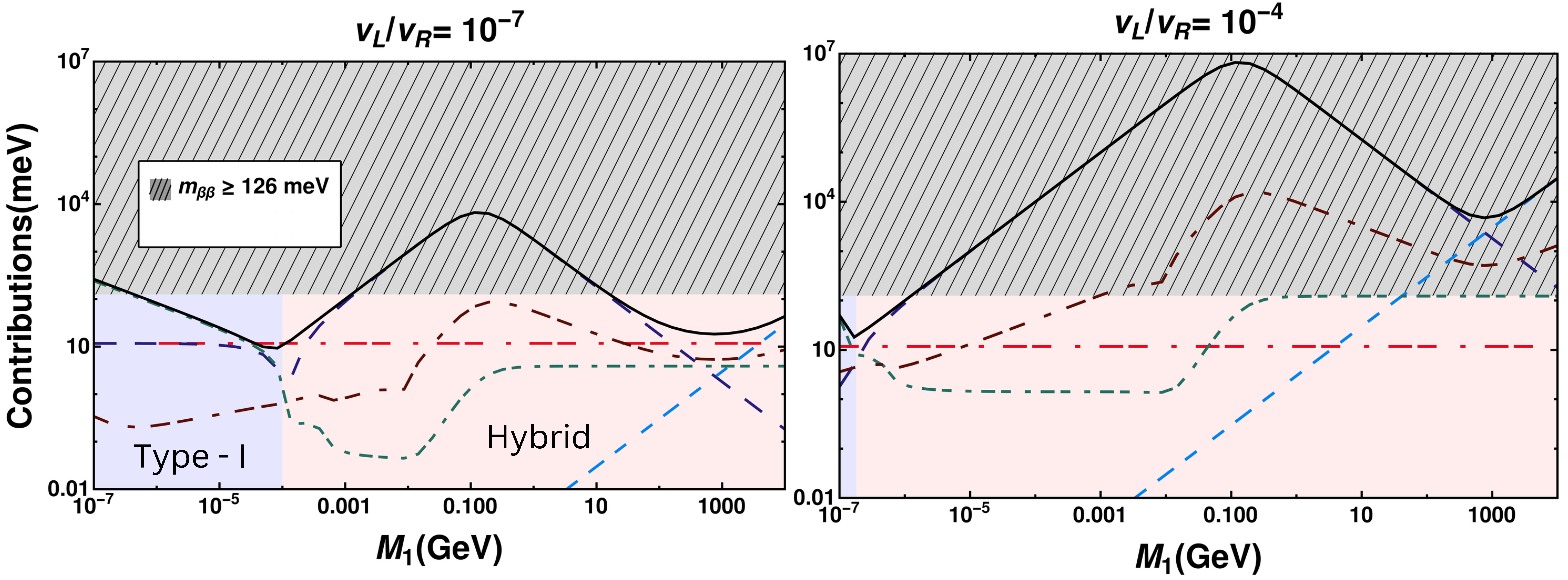
$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

Neutrinoless Double Beta Decay

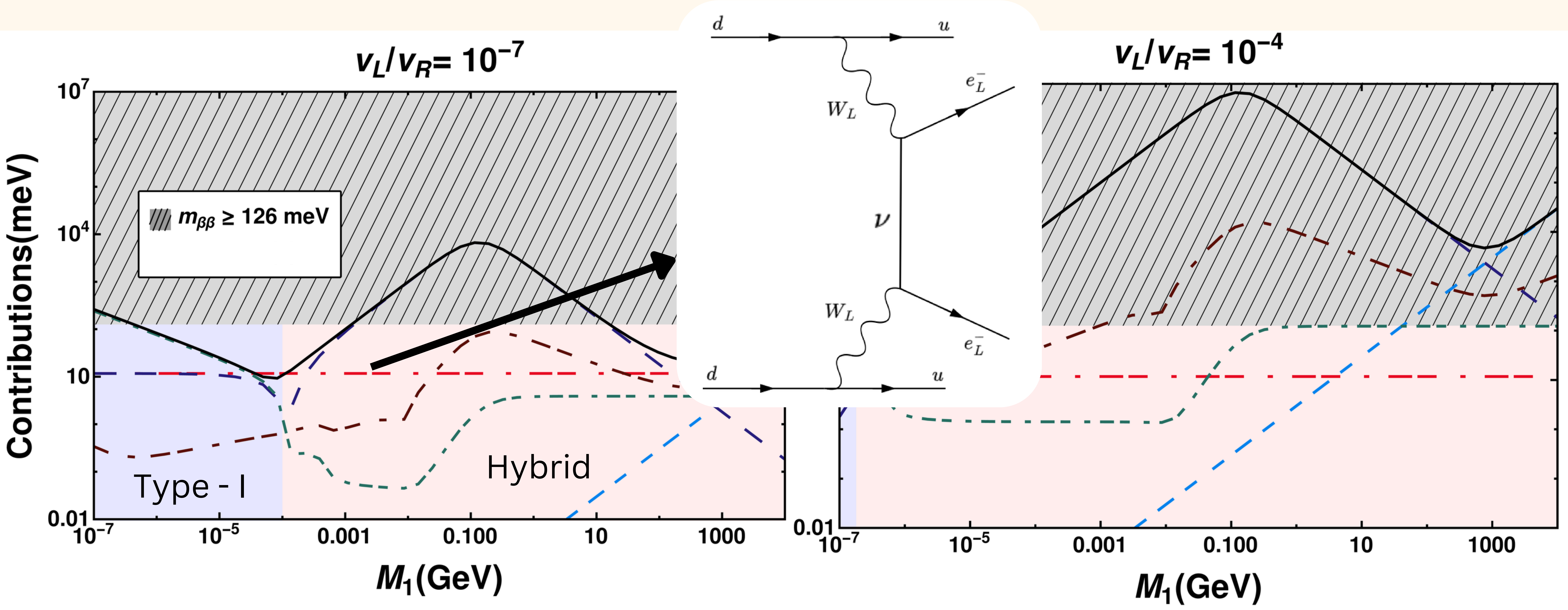
$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

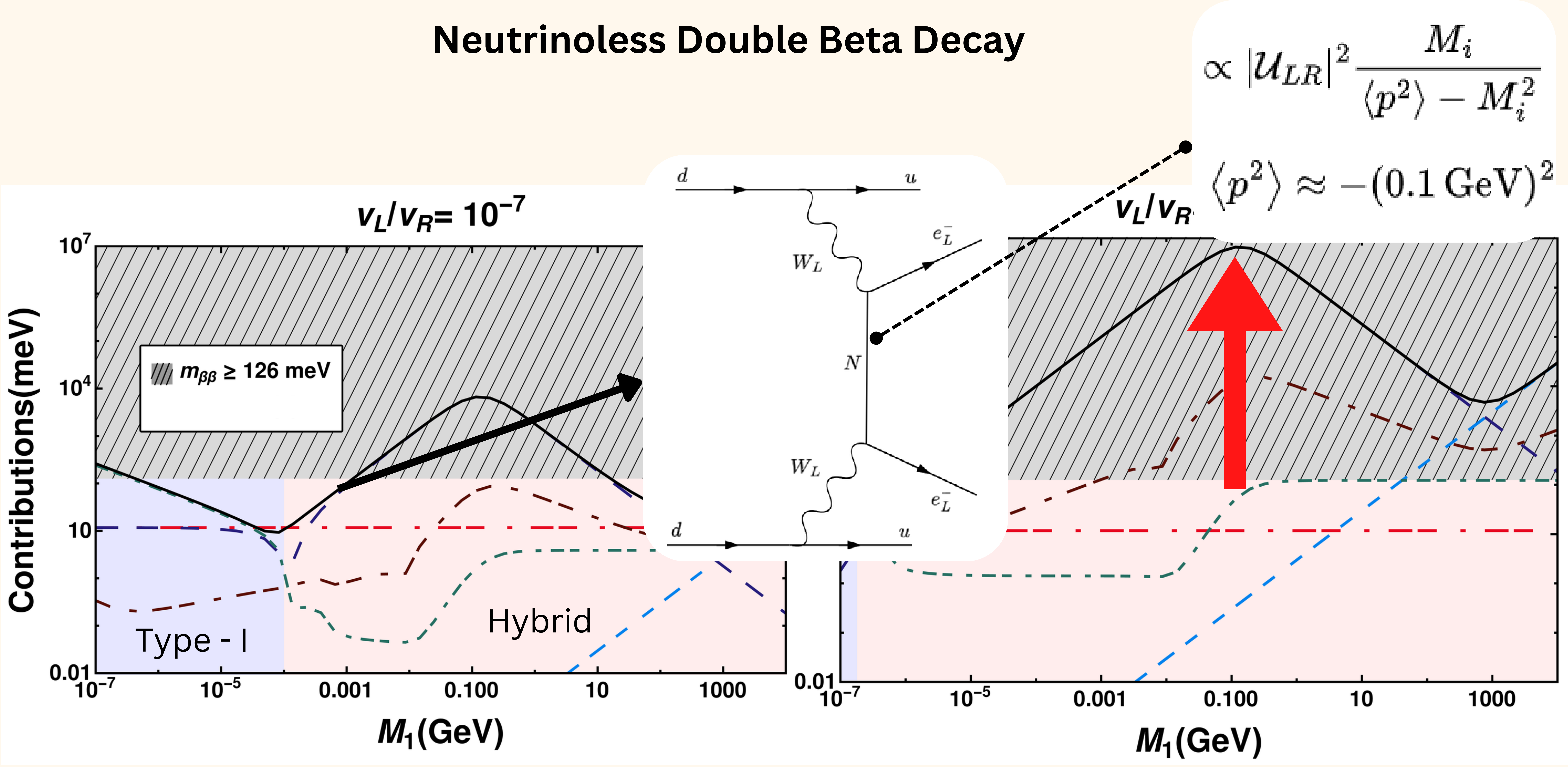
Neutrinoless Double Beta Decay

$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

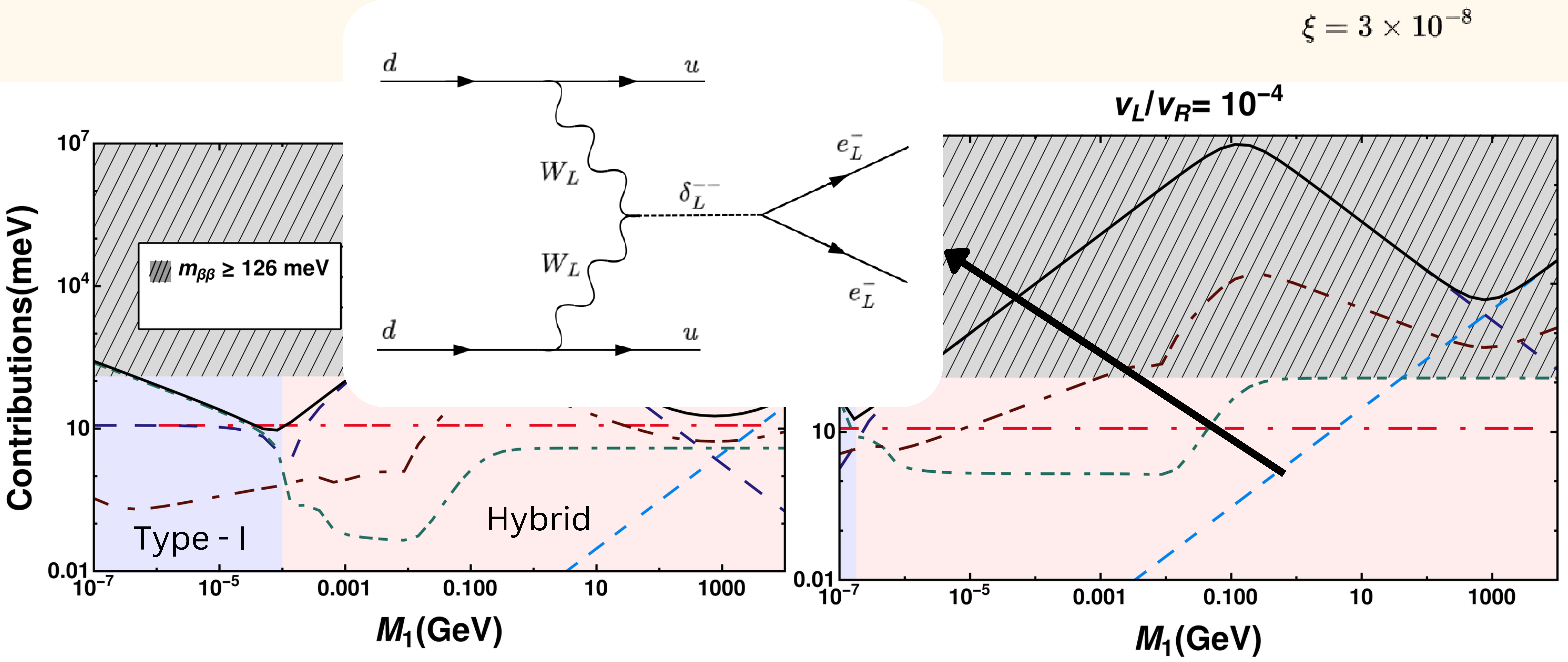
Neutrinoless Double Beta Decay



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

Neutrinoless Double Beta Decay

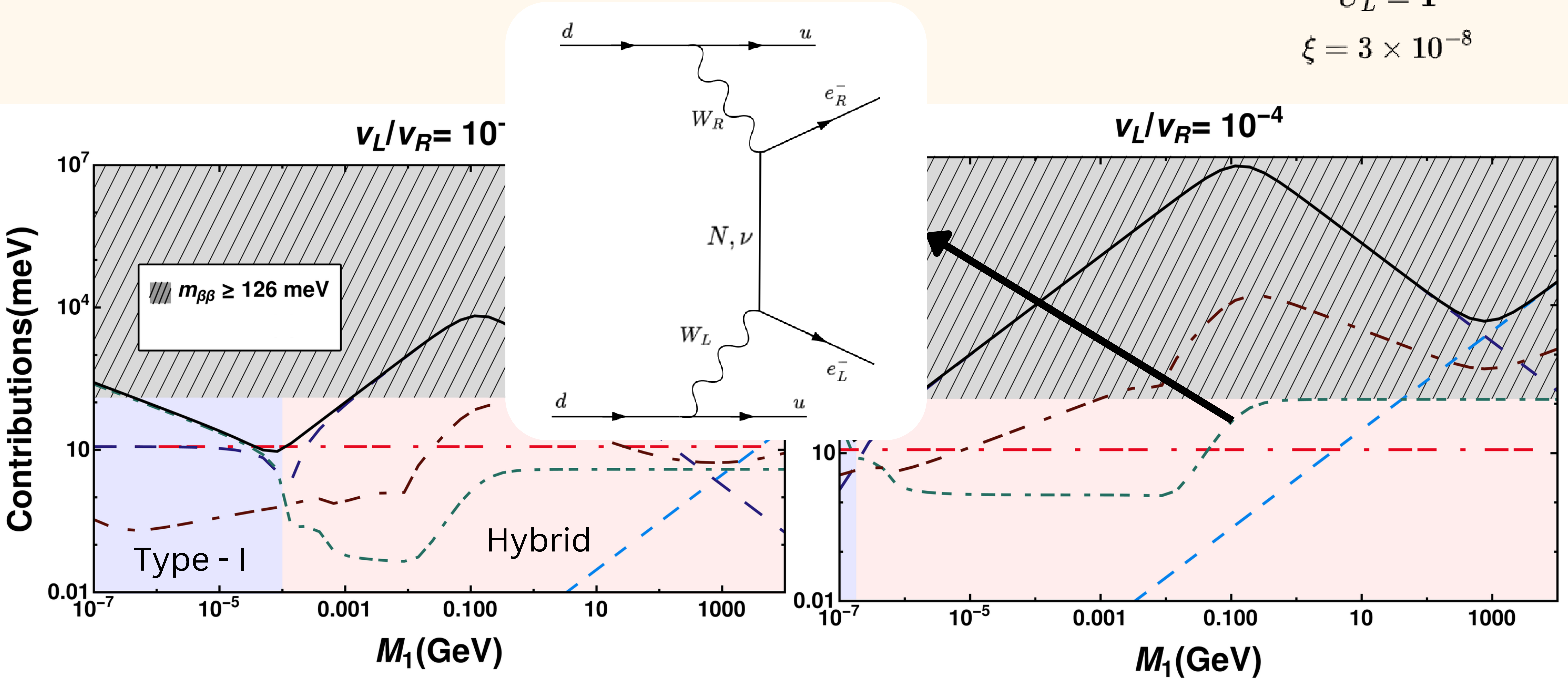
$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

Neutrinoless Double Beta Decay

$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$

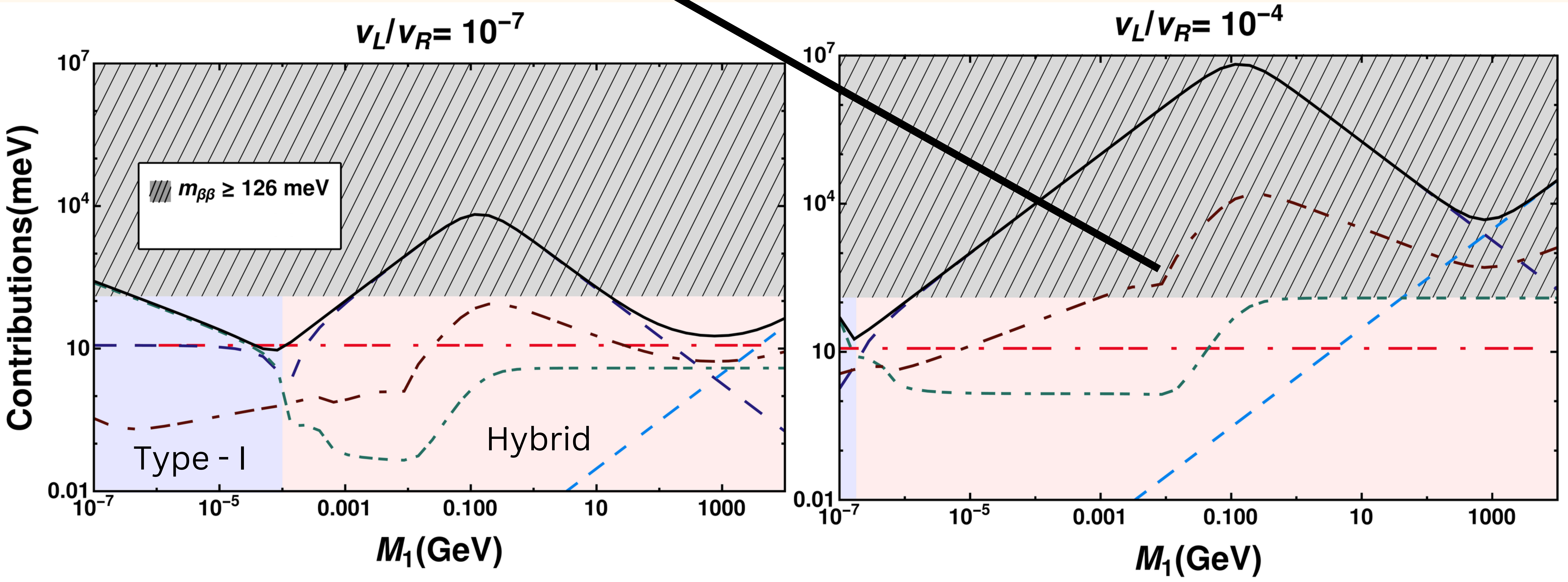


KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

Neutrinoless Double Beta Decay

$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$

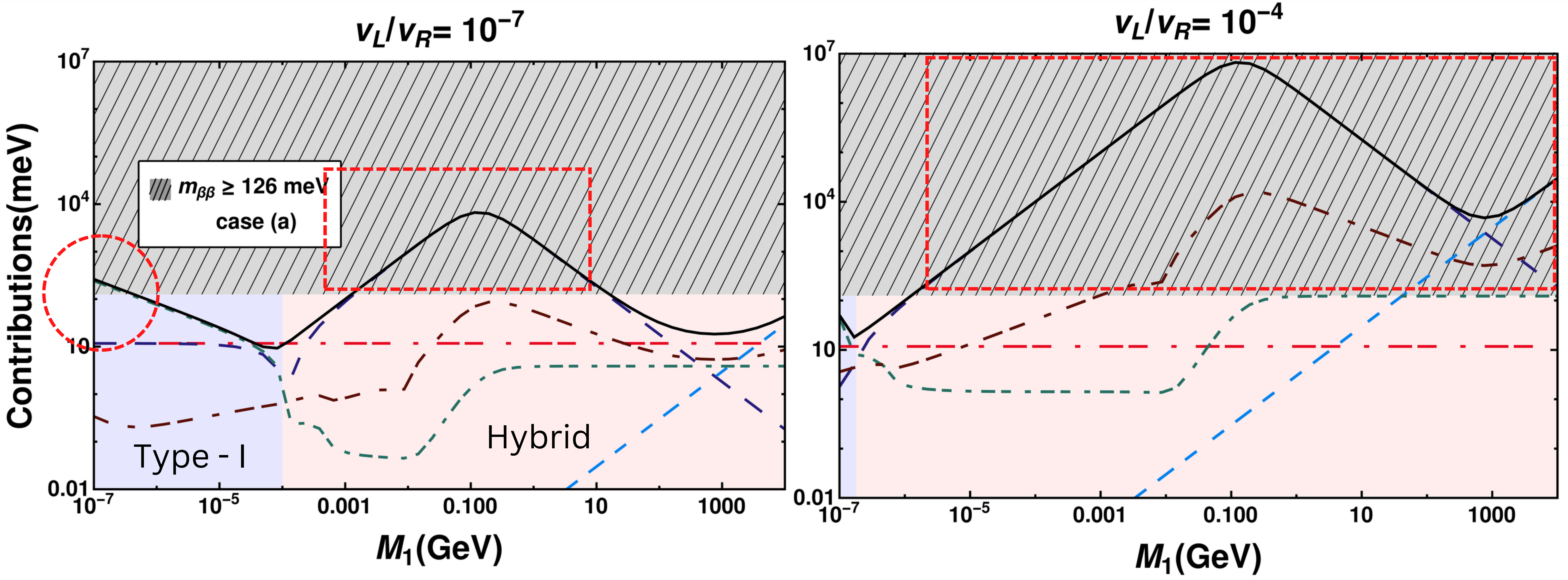
Amplitude interference contribution



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

Neutrinoless Double Beta Decay

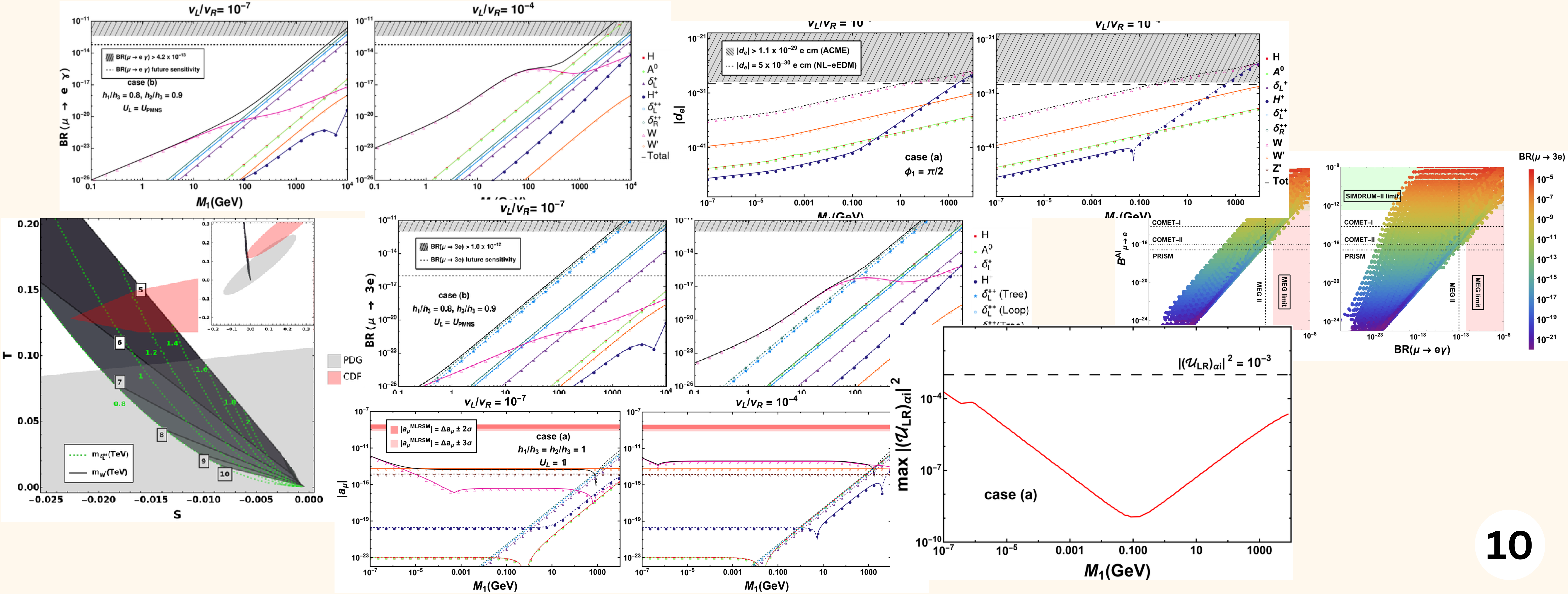
$$M_1/M_3 = M_1/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$



KamLAND-Zen Collaboration, S. Abe et al. arXiv:2203.02139 (2022).

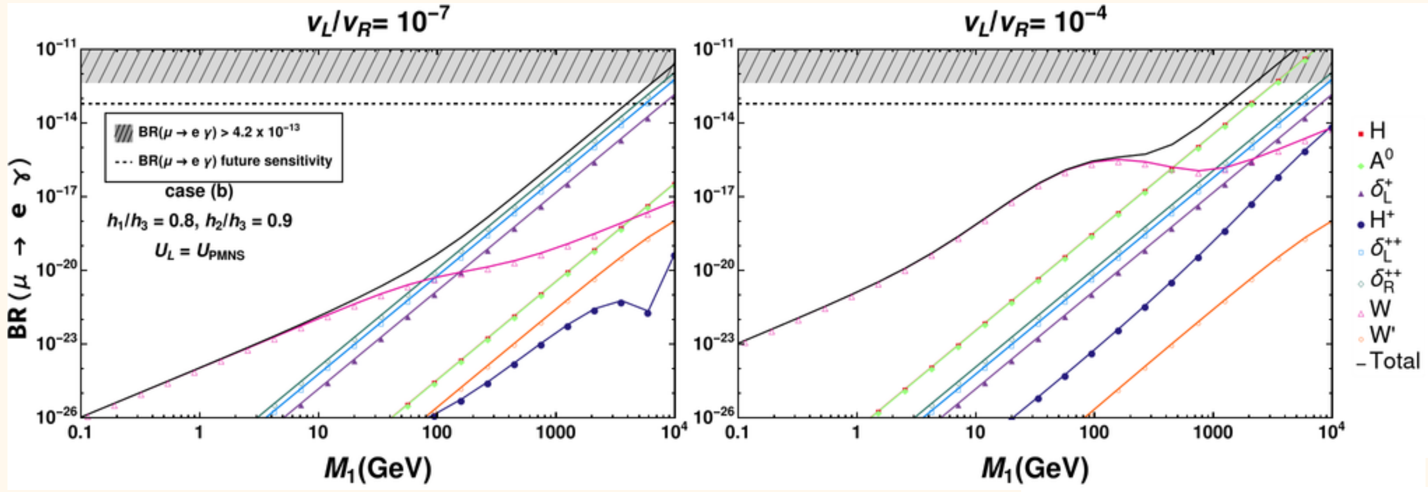
Not only Lepton Number but also Lepton Flavor

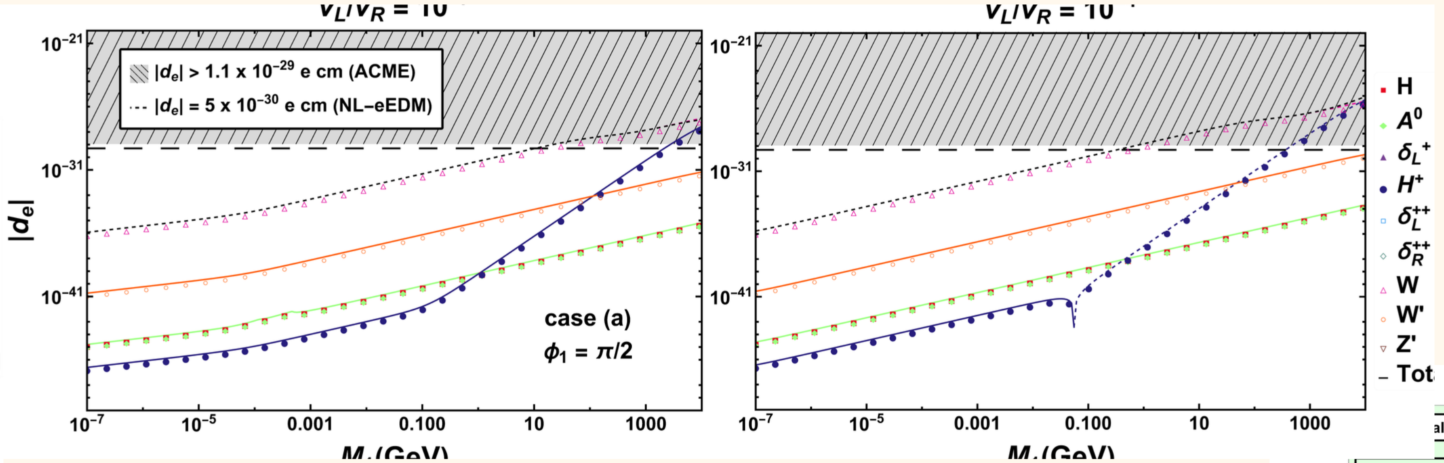
- We have studied several Lepton Flavor Violating processes:
  - Mu to e gamma;
  - Mu to 3e;
  - Mu to e in nuclei;
  - Correlations between LFV observables;
  - EDM + g-2;
- Extra: Unitarity and W mass.

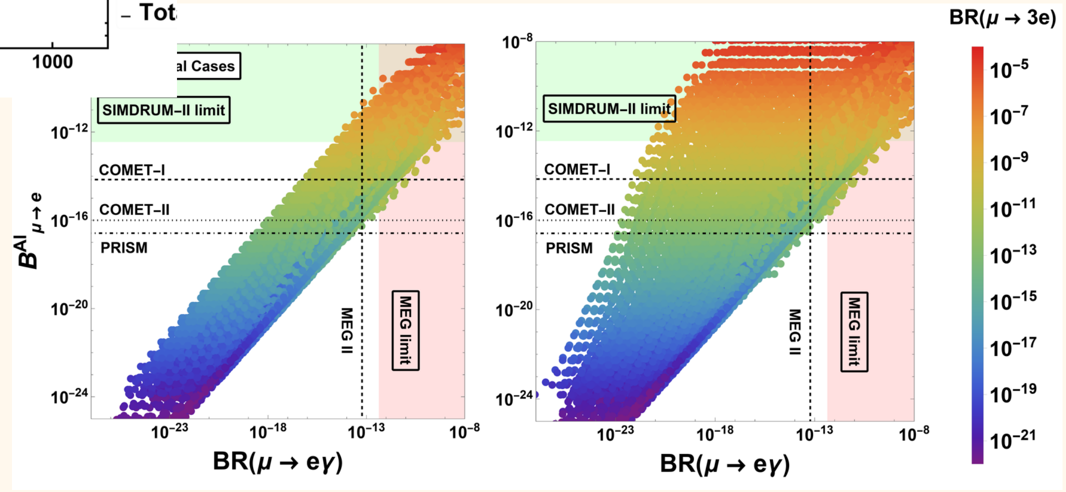


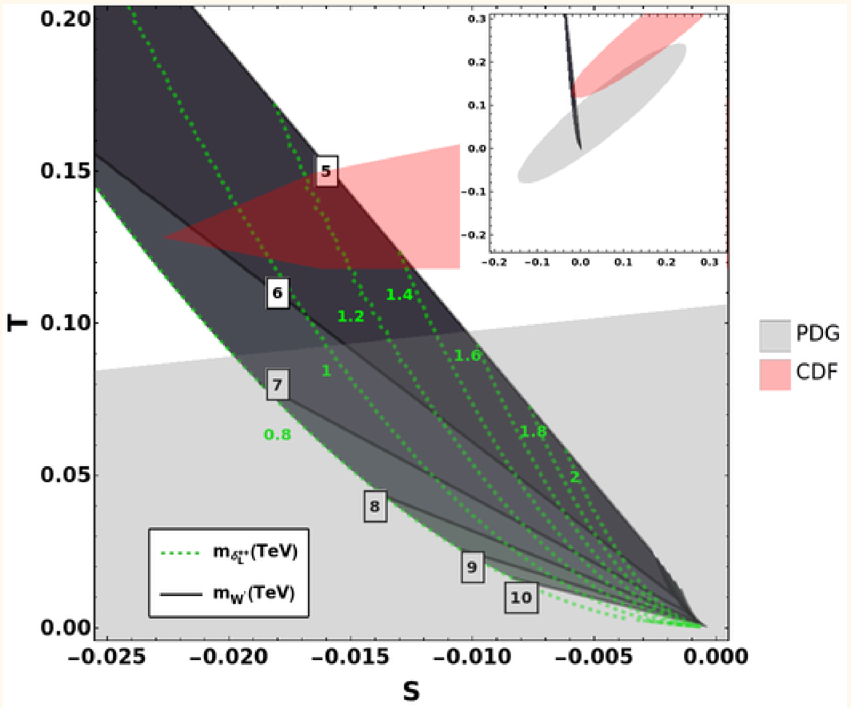
Not only Lepton Number but also Lepton Flavor

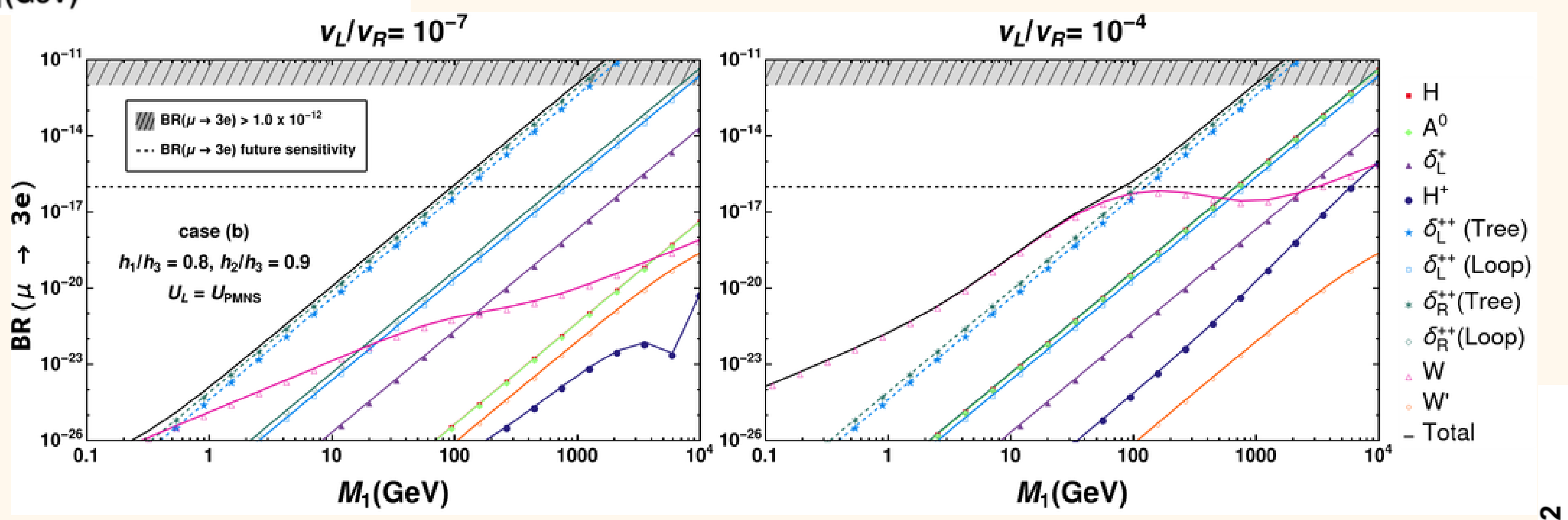
- The LFV processes constrain our parameter space for **bigger values** of heavy neutrinos masses.
- Only for **specific choices** they are all **suppressed at the same time**.

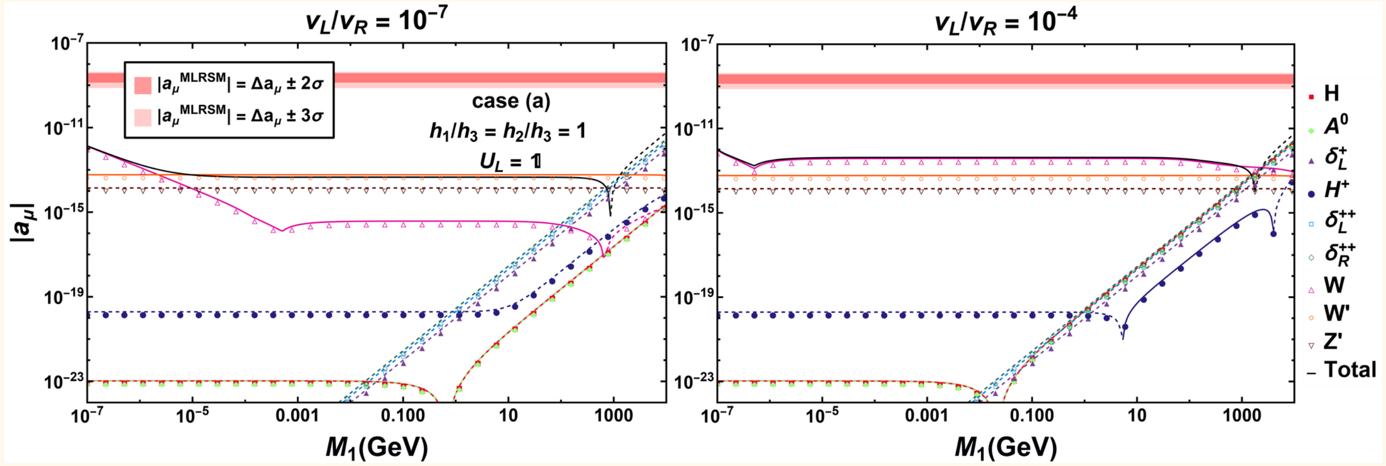


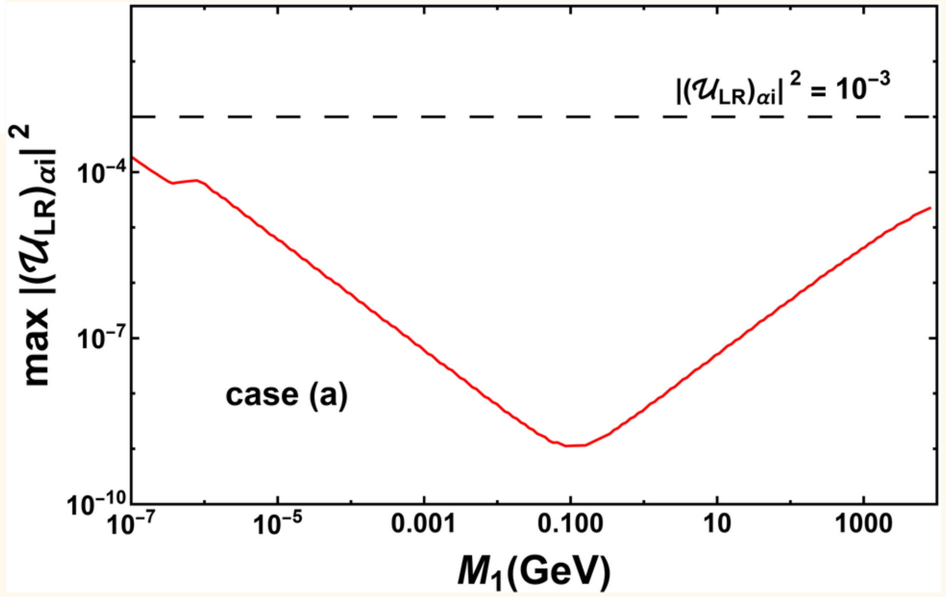




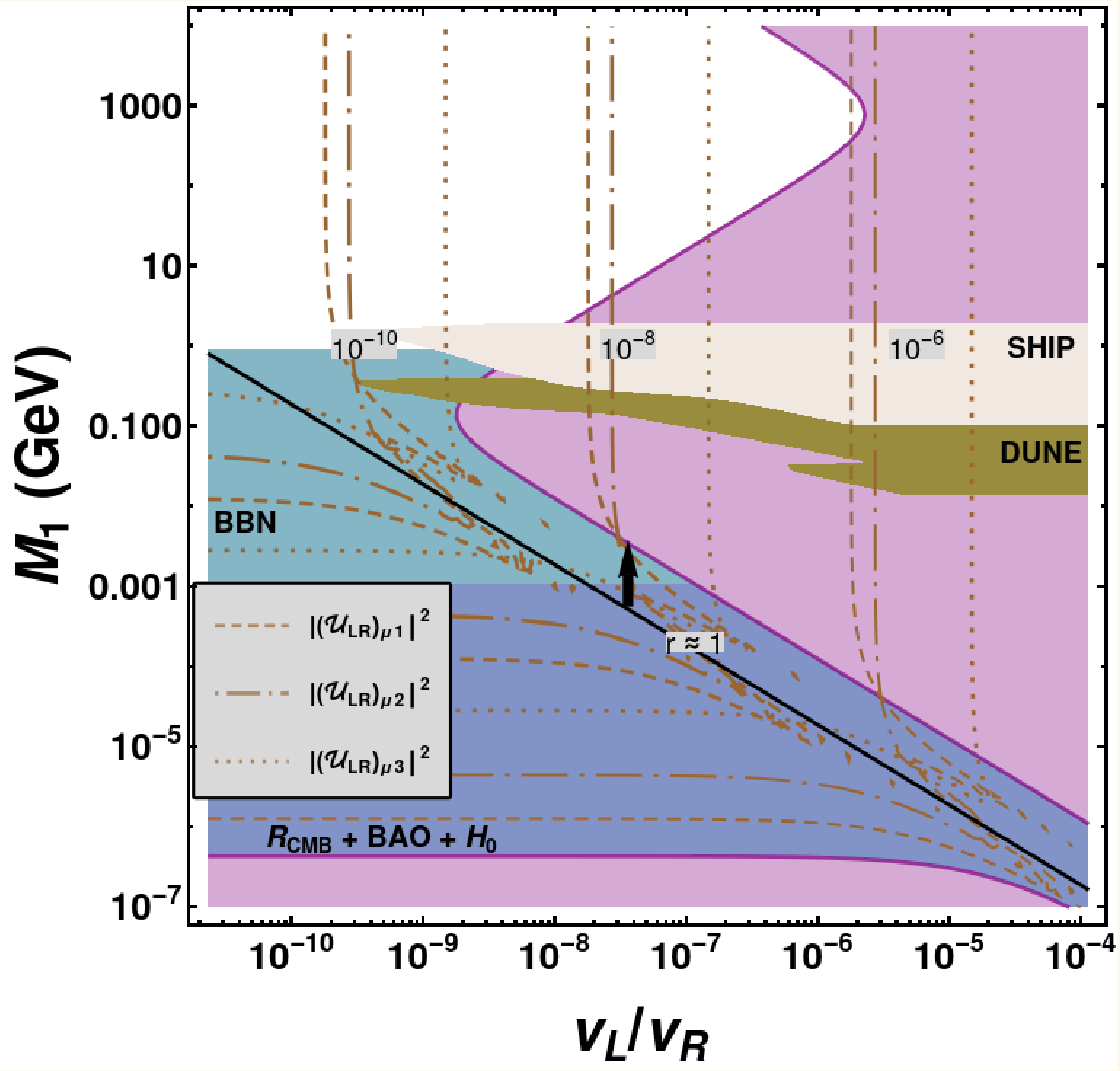








Results

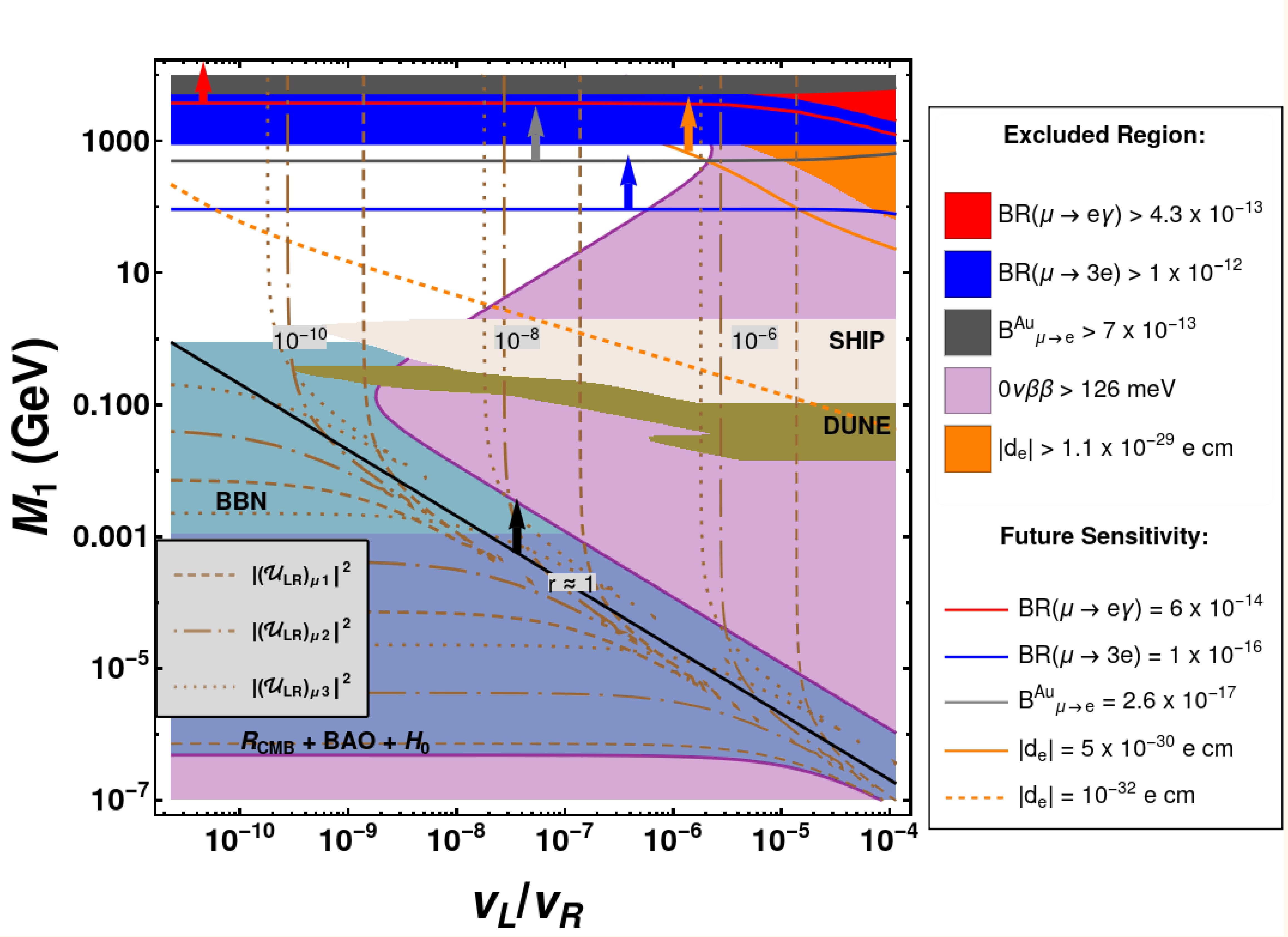


Conservative choice of parameters such that new processes **constrain the least** the parameter space! **It just gets even more restricted**!

$$M_1/M_3 = M_2/M_3 = 1$$
$$U_L = \mathbf{1}$$
$$\xi = 3 \times 10^{-8}$$

A. de Gouvêa and A. Kobach, arXiv:1511.00683 (2015).
N. Sabti, A Magalich , and A. Filimonova, arXiv: 2006.07387 (2006).
A. C. Vicent, et al., arXiv:1408.1956.
P. Ballet, T. Boschi, and S. Pascoli, arXiv:1905.00284 (2019).

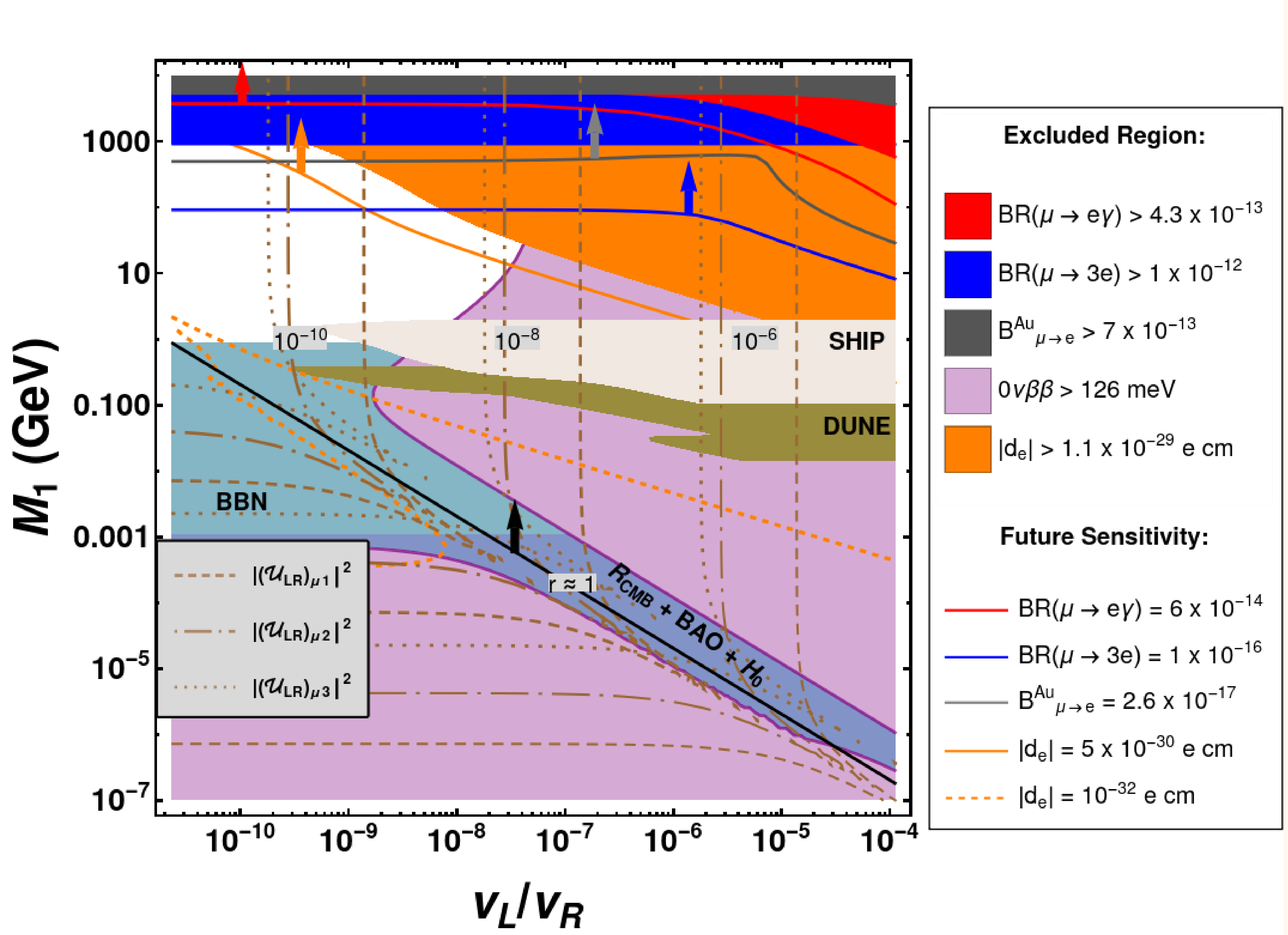
Results



$$M_1/M_3 = 0.8,\ M_2/M_3 = 0.9$$
$$U_L = U_{\text{PMNS}}$$
$$\xi = 3 \times 10^{-8}$$

A. de Gouvêa and A. Kobach, arXiv:1511.00683 (2015).
N. Sabti, A Magalich , and A. Filimonova, arXiv: 2006.07387 (2006).
A. C. Vicent, et al., arXiv:1408.1956.
P. Ballet, T. Boschi, and S. Pascoli, arXiv:1905.00284 (2019).

Results



$$M_1/M_3 = 0.8, M_2/M_3 = 0.9$$

$$U_L = U_{\text{PMNS}}$$

$$\xi = 3 \times 10^{-6}$$

A. de Gouvêa and A. Kobach, arXiv:1511.00683 (2015).
N. Sabti, A Magalich , and A. Filimonova, arXiv: 2006.07387 (2006).
A. C. Vicent, et al., arXiv:1408.1956.
P. Ballet, T. Boschi, and S. Pascoli, arXiv:1905.00284 (2019).

Conclusions

- The LR Model is an extension of the SM that links parity violation to a UV completed theory.
- Our work went beyond previous as we explored the **hybrid** regime where the active-sterile mixture **behaves differently** in comparison to either type-I or II dominance.
- This will be **severely** probed by future LFV experiments for **several** combination of parameters present in the model:
  - Mu2e;
  - Mu3e;
  - MEG-II;
  - COMET;
  - PRISM;
- Neutrinoless beta decay searches are also going to **push even more** the current excluded regions.

Thank you all!

Backup

Scalar Sector Parameters

Vev parameters must satisfy:

$$\kappa_+ = \sqrt{\kappa_1^2 + \kappa_2^2} = 246\,\mathrm{GeV}$$

$$v_R >> \kappa_+ >> v_L$$

→

The resulting scalar masses must respect bounds from Kaon mixing, electroweak precision tests and direct searches.

→

We fixed the RH vev to 44 TeV and the bidoublet vevs respect

$$\frac{\kappa_1}{\kappa_2} = 10^3$$

Scalar Sector	
m_H (GeV)	15×10^3
m_{A^0} (GeV)	15×10^3
$m_{\delta_L^+}$ (GeV)	780
m_{H^+} (GeV)	15×10^3
$m_{\delta_L^{++}}$ (GeV)	780
$m_{\delta_R^{++}}$ (GeV)	660

Y. Zhang, et al., arXiv:0712.4218.
ATLAS Collaboration, arXiv:1710.09748.
G. C. Branco and G. Senjanovic, Phys. Rev. D 18 (1978) 1621.
M. Nemevsek, et al., arXiv:1211.2837.

Gauge Sector Parameters

Parameters in the Gauge sector:

- Masses fixed respecting collider and electroweak bounds (fixed).
- Mixing angle respects lower bound from electroweak radiative corrections and upper bound (free).

F. del Aguila, et al., arXiv:1005.3998.
M. Lindner, et al., arXiv:1604.07419.
CMS Collaboration, A. Tumasyan et al., arXiv:2112.03949.
A. Maiezza, G. Senjanoví c, and J. C. Vasquez, arXiv:1612.09146.
S. Bertolini, A. Maiezza, and F. Nesti, arXiv:1911.09472.
W. Dekens, L. Andreoli, J. de Vries, E. Mereghetti, and F. Oosterhof, arXiv:2107.10852.

Leptonic Sector Parameters

Parameters in the light neutrino sector:

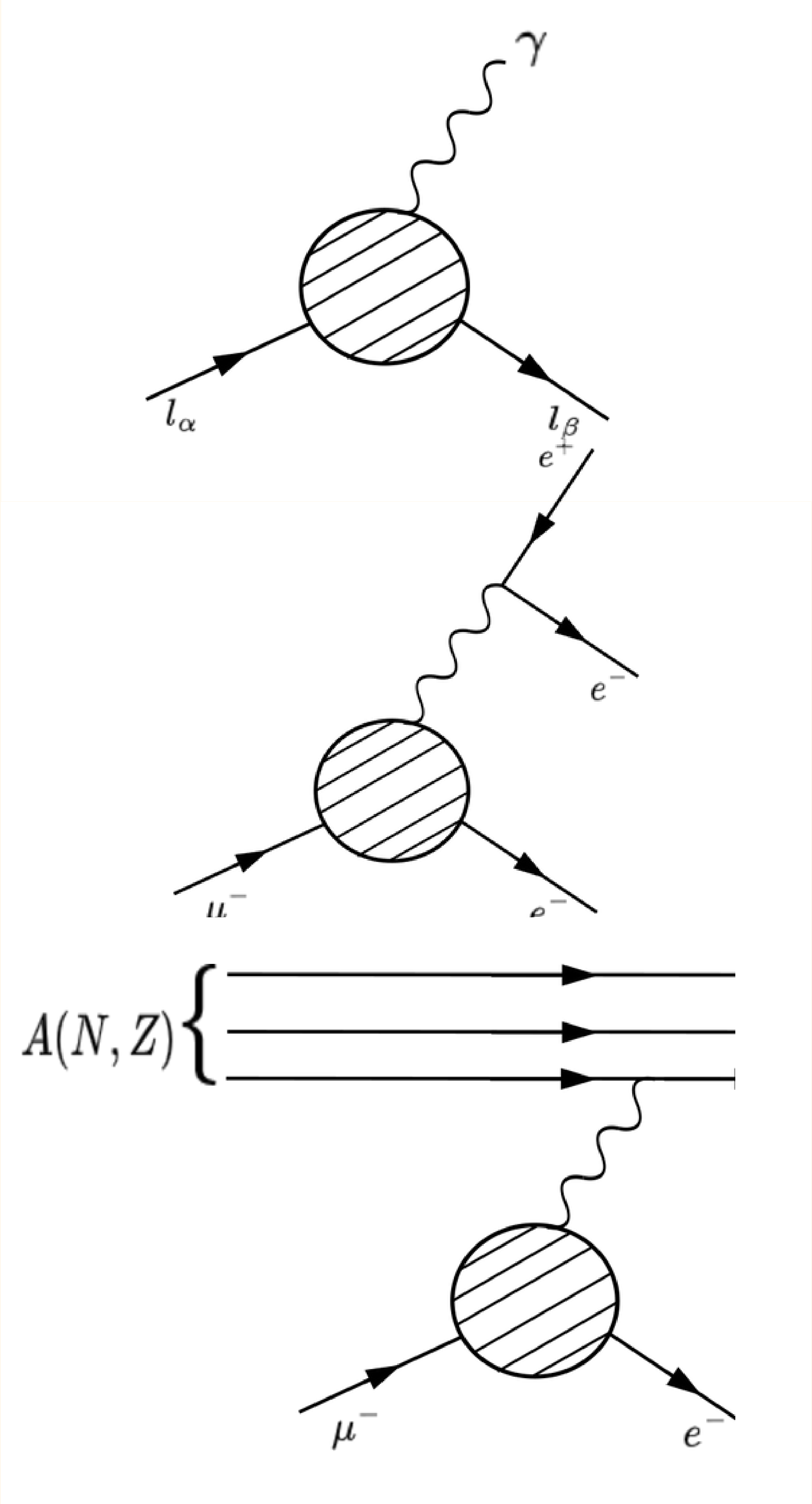
- Ordering fixed to NO
- PMNS angles to best fit from NuFIT.
- Majorana phases set to zero.
- Lightest neutrino mass set to 0.01 eV.

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, JHEP 09 (2020) 178, arXiv:2007.14792.

Parameters in the **Heavy** neutrino sector:

- Ordering fixed by ratio of their masses (free).
- Phases in the mass matrix (free).
- Their mass scale is set by RH vev (fixed).
- U_L (free)

Lepton Flavor Violating processes

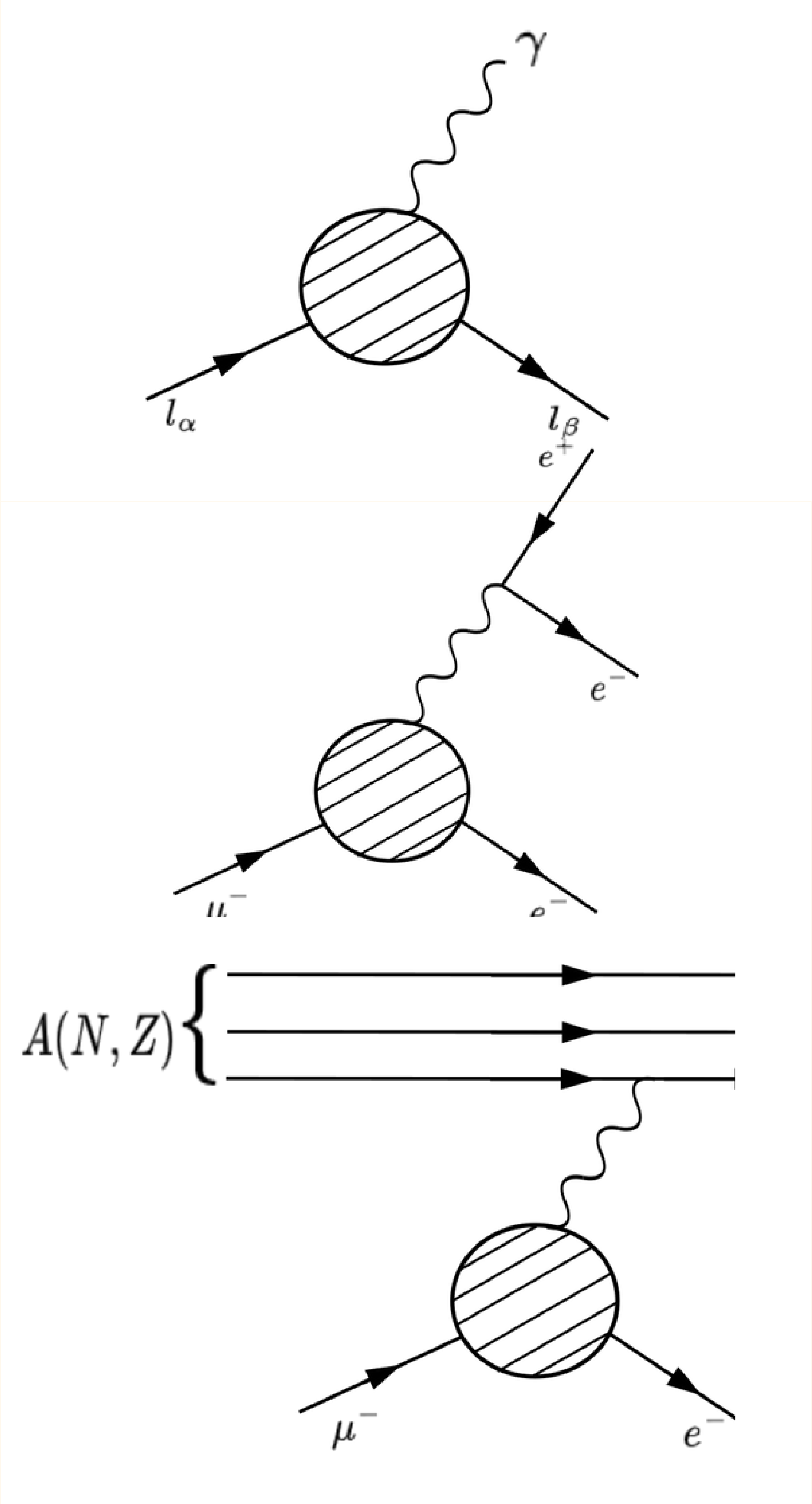


$$\mathcal{M}^\mu = -e\bar{u}(p_\beta)\left[F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m}\right.$$
$$\left.+G_1(q^2)(q^2\gamma^\mu - 2mq^\mu)\frac{\gamma^5}{2m} + G_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu\gamma^5}{2m}\right]u(p_\alpha)$$

- EDM
- Magnetic Moment

Yoshitaka Kuno and Yasuhiro Okada, arXiv:9909265 (1999).
Claudia Cornella, Paride Paradisi, and Olcyr Sumensari arXiv:1911.06279 (2021).

Lepton Flavor Violating processes

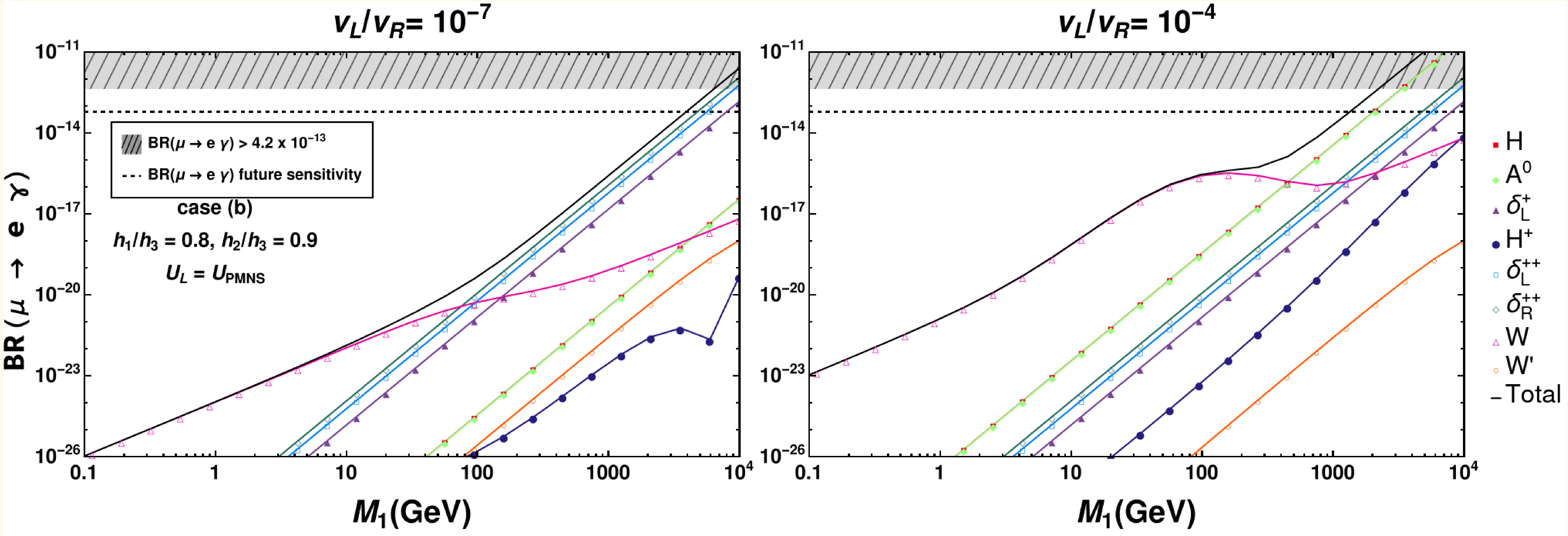


$$\mathcal{M}^\mu = -e\bar{u}(p_\beta)\left[F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m} + G_1(q^2)(q^2\gamma^\mu - 2mq^\mu)\frac{\gamma^5}{2m} + G_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu\gamma^5}{2m}\right]u(p_\alpha)$$

We derived approximate formulas for all of those form factors - for all diagrams - in our work

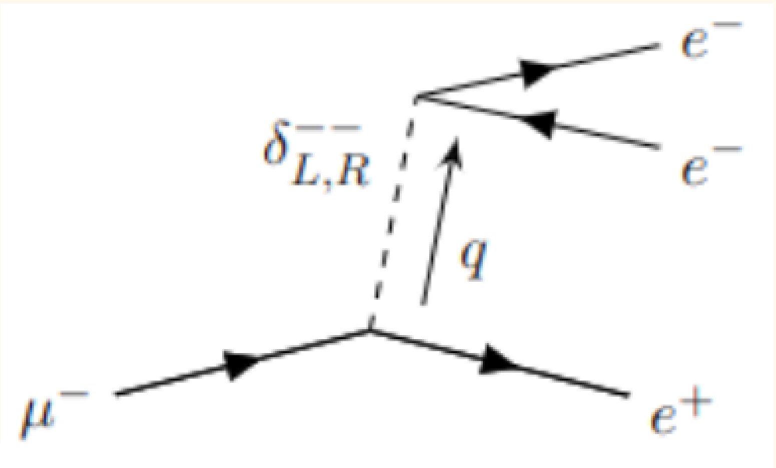
Yoshitaka Kuno and Yasuhiro Okada, arXiv:9909265 (1999).
Claudia Cornella, Paride Paradisi, and Olcyr Sumensari arXiv:1911.06279 (2021).

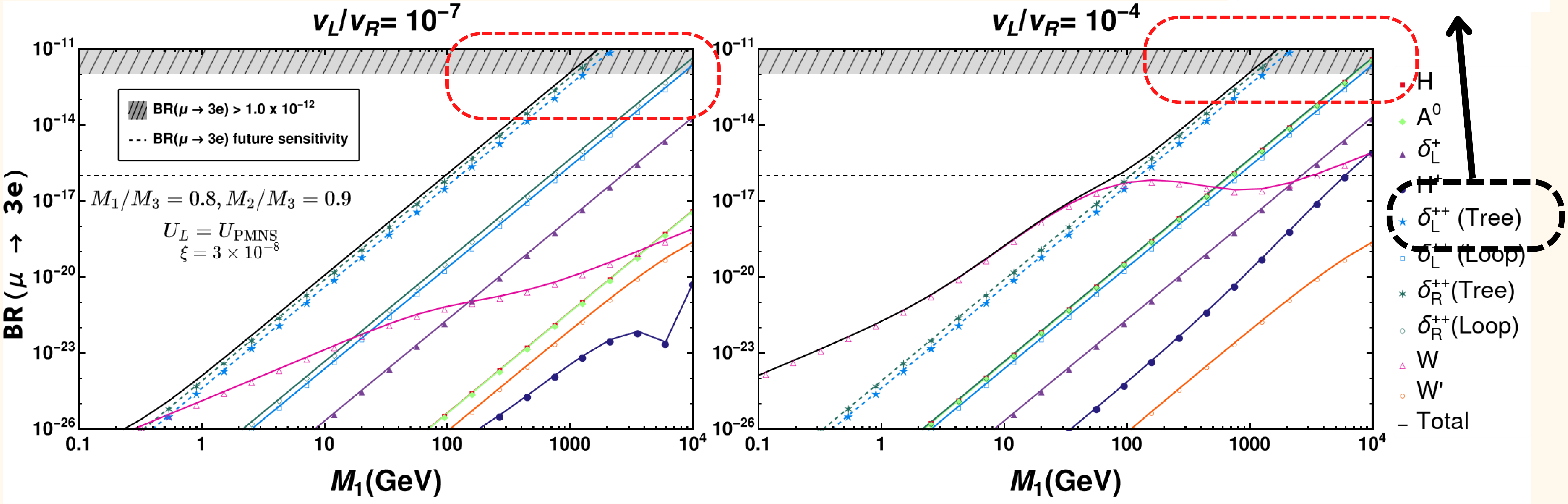
LFV



MEG Collaboration, A. M. Baldini et al. (2016).
A. M. Baldini et al. (2013).

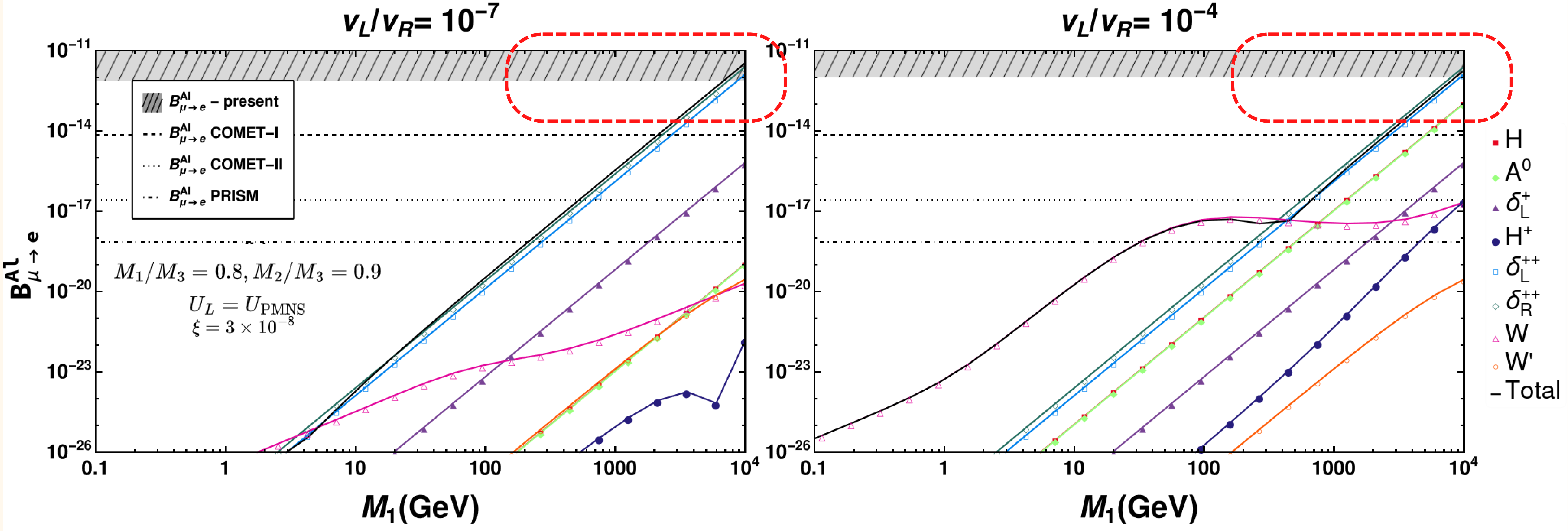
LFV





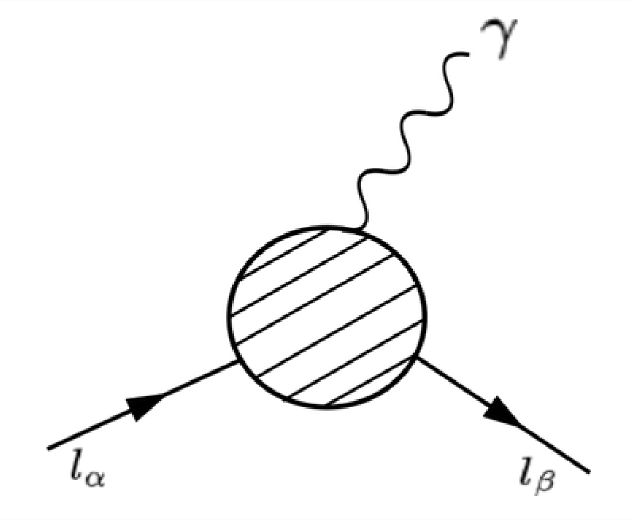
SINDRUM Collaboration, U. Bellgardt et al. (1988).
Mu3e Collaboration, K. Arndt et al. (2021).

LFV



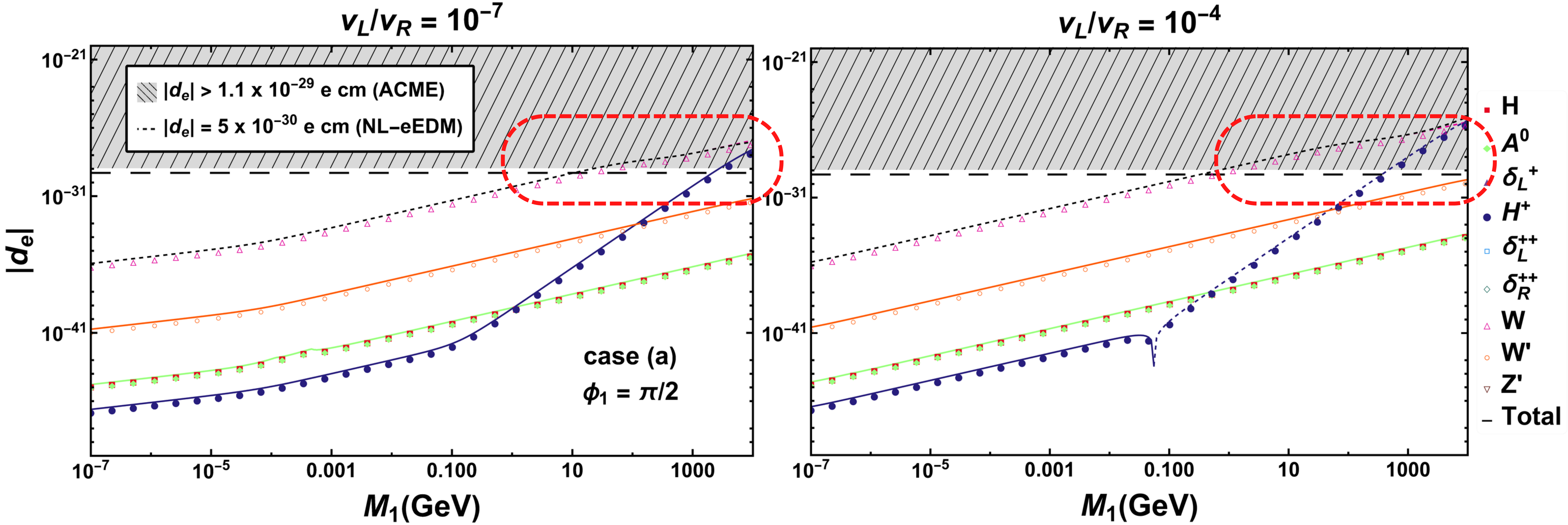
COMET Collaboration, R. Abramishvili et al. (2020).
SINDRUM II Collaboration, W. H. Bertl et al., (2006).
Mu2e Collaboration, arXiv: 1501.05241 (2015).

Electric Dipole Moment



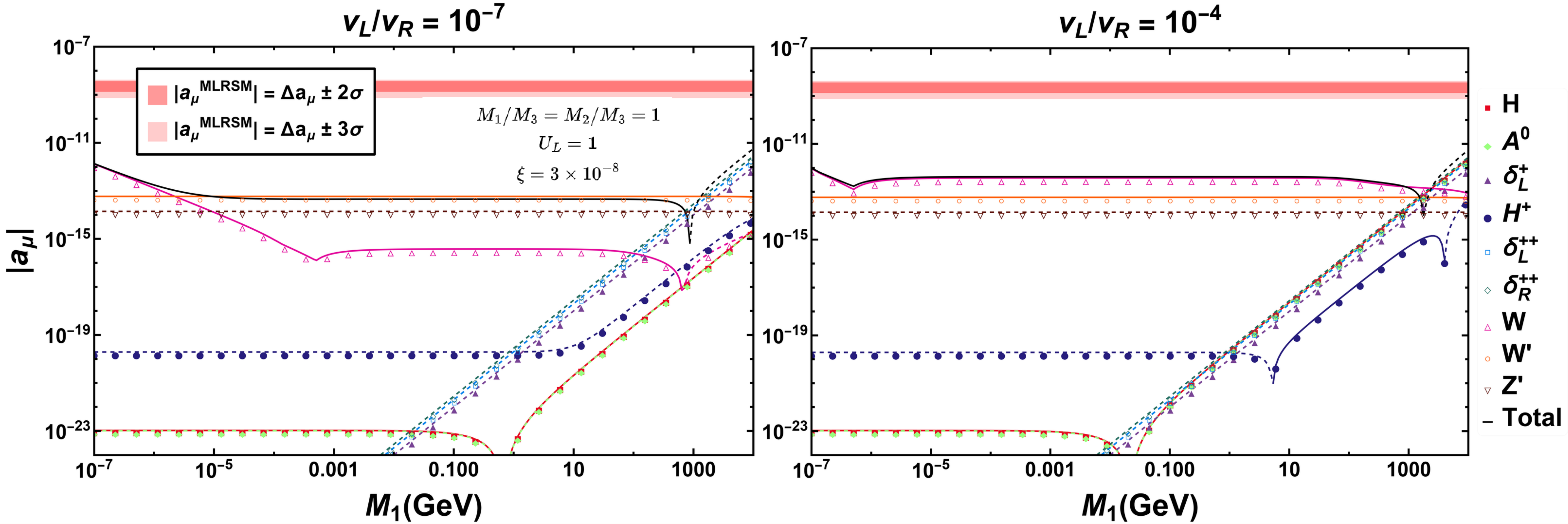
Also contributes to the EDM of charged leptons.

ACME Collaboration, V. Andreev et al., (2018).
NL-eEDM Collaboration, P. Aggarwal et al., (2018).



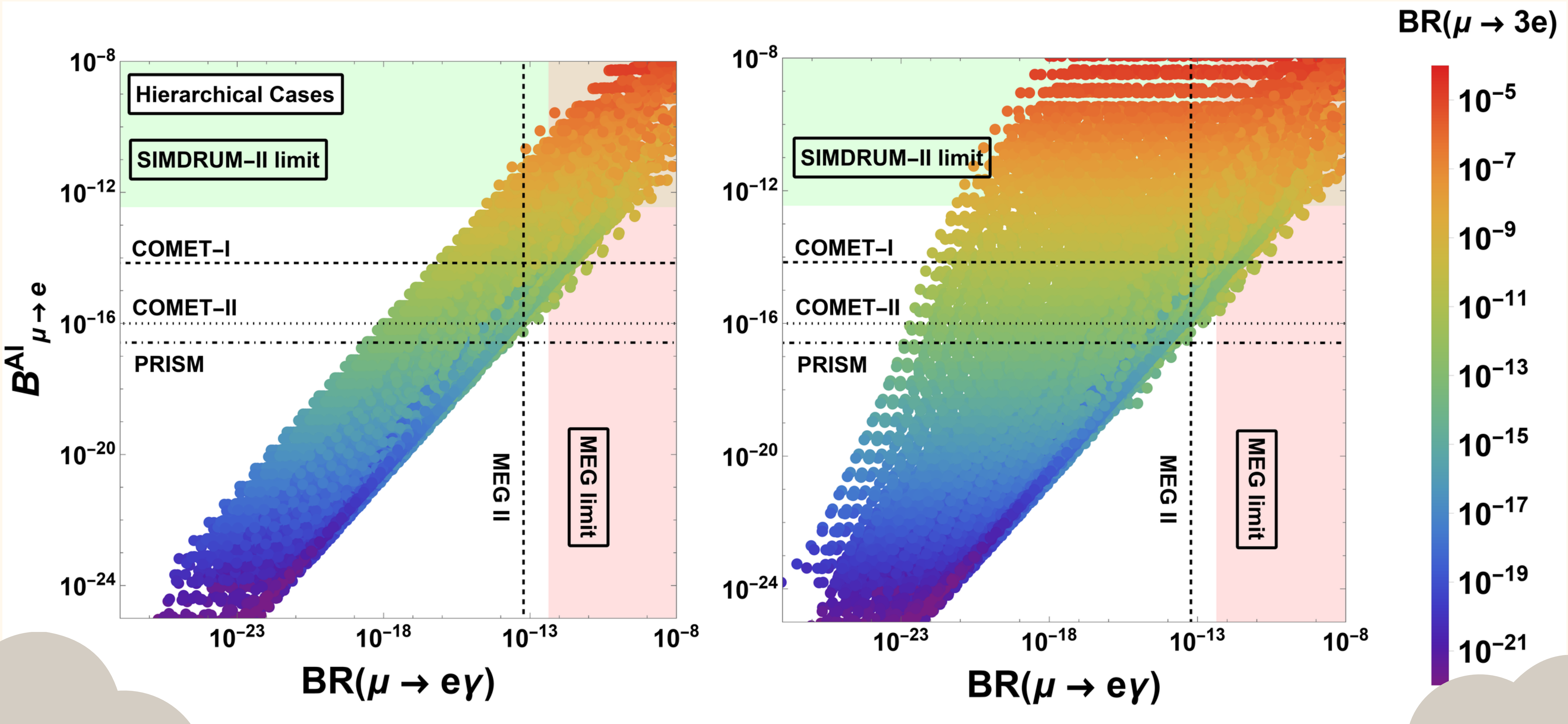
Anomalous magnetic moment

- We also studied the contribution to the anomalous magnetic moment.



T. Aoyama et al., Phys. Rept. 887 (2020), arXiv:2006.04822
Muon g-2 Collaboration, Phys. Rev. Lett. 126 (2021), arXiv:2104.03281.

As the several LFV processes have different form factors their correlation can be rather non trivial.



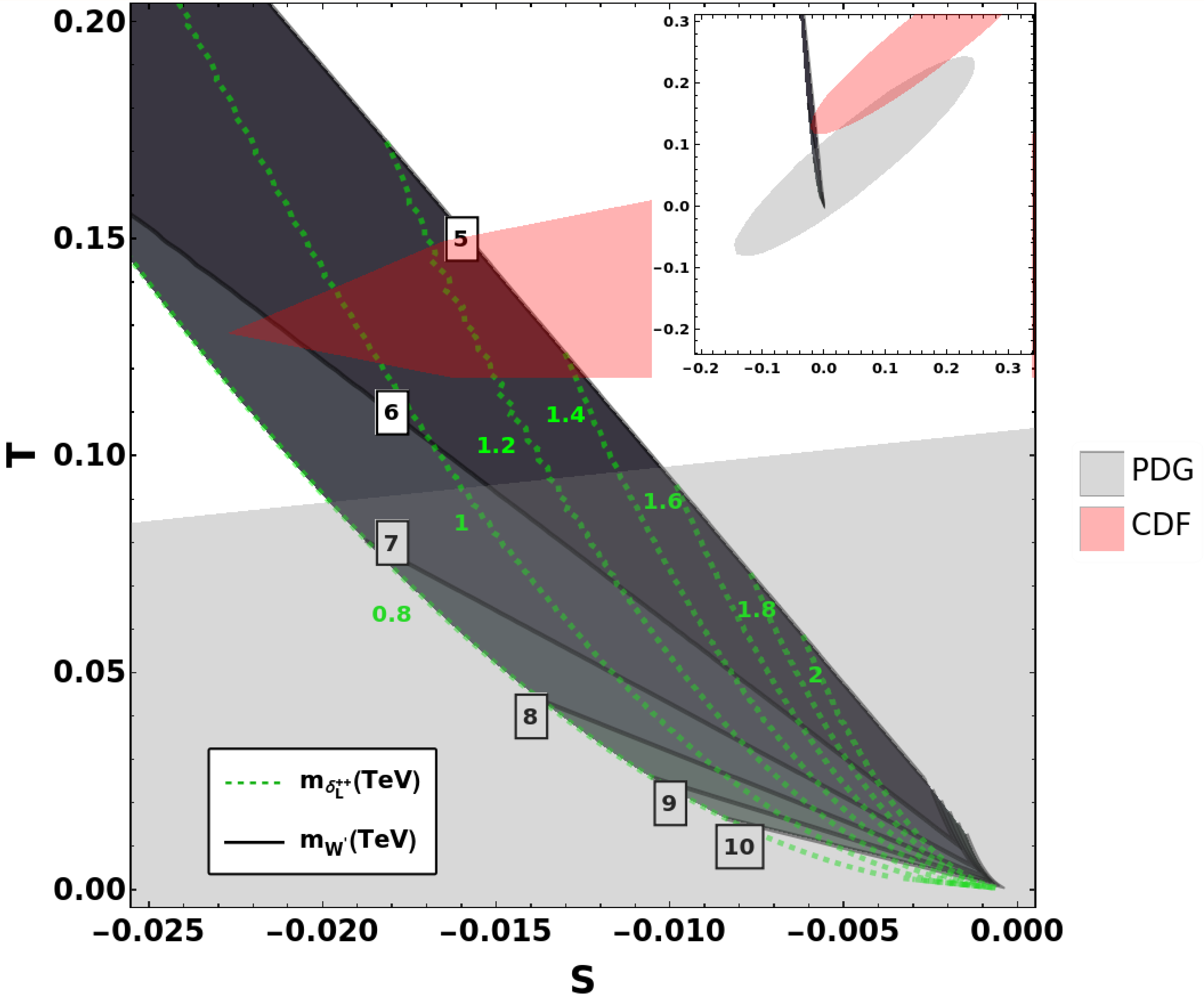
Varying the neutrino hierarchy, the right hand vev, the LR mixing and the mixing matrix.

Here we did the same but including degenerate heavy neutrinos.

Backup - Additional Remarks

- As a side note we have also checked the model impact on the oblique parameters in the light of the new CDF-II data.

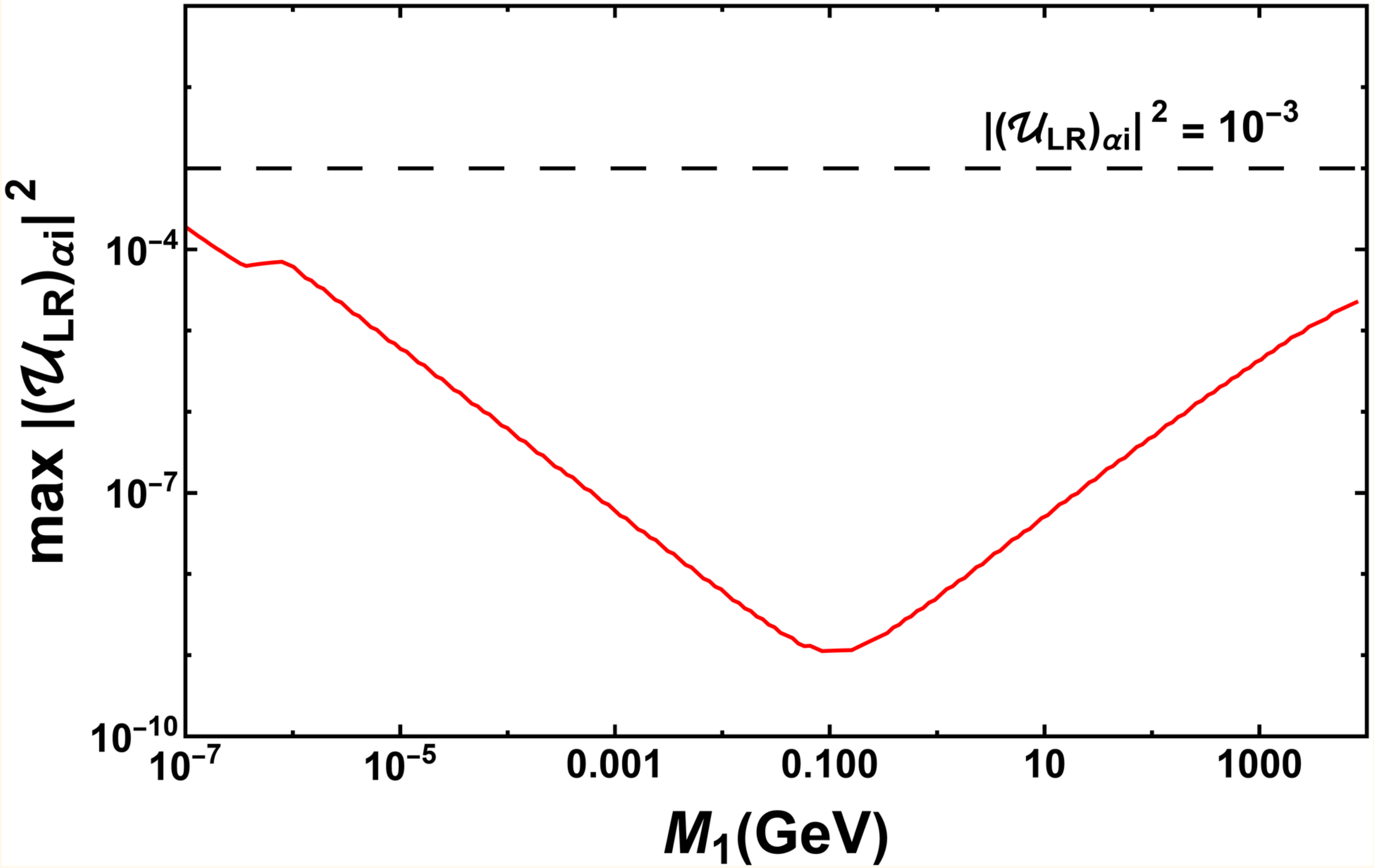
M. E. Peskin and T. Takeuchi, Phys. Rev. D 65 (1990).
M. E. Peskin and T. Takeuchi, Phys. Rev. D 46 (1992).
I. Maksymyk, C. P. Burgess, and D. London, Phys. Rev. D 50 (1994), hep-ph/9306267.
M. Awramik, et al., Phys. Rev. D 69 (2004), hep-ph/0311148.
L. Lavoura and L. F. Li, Phys. Rev. D 49 (1994), hep-ph:9309262.
S. Bertolini, et al., Phys. Rev. D 89 (2014), arXiv:1403.7112.
A. Maiezza et al., Phys. Rev. D 94 (2016), arXiv:1603.00360.
R. Balkin, et al., JHEP 05 (2022) 133, arXiv:1603.00360.
P. Asadi, et al., arXiv:2204.05283.

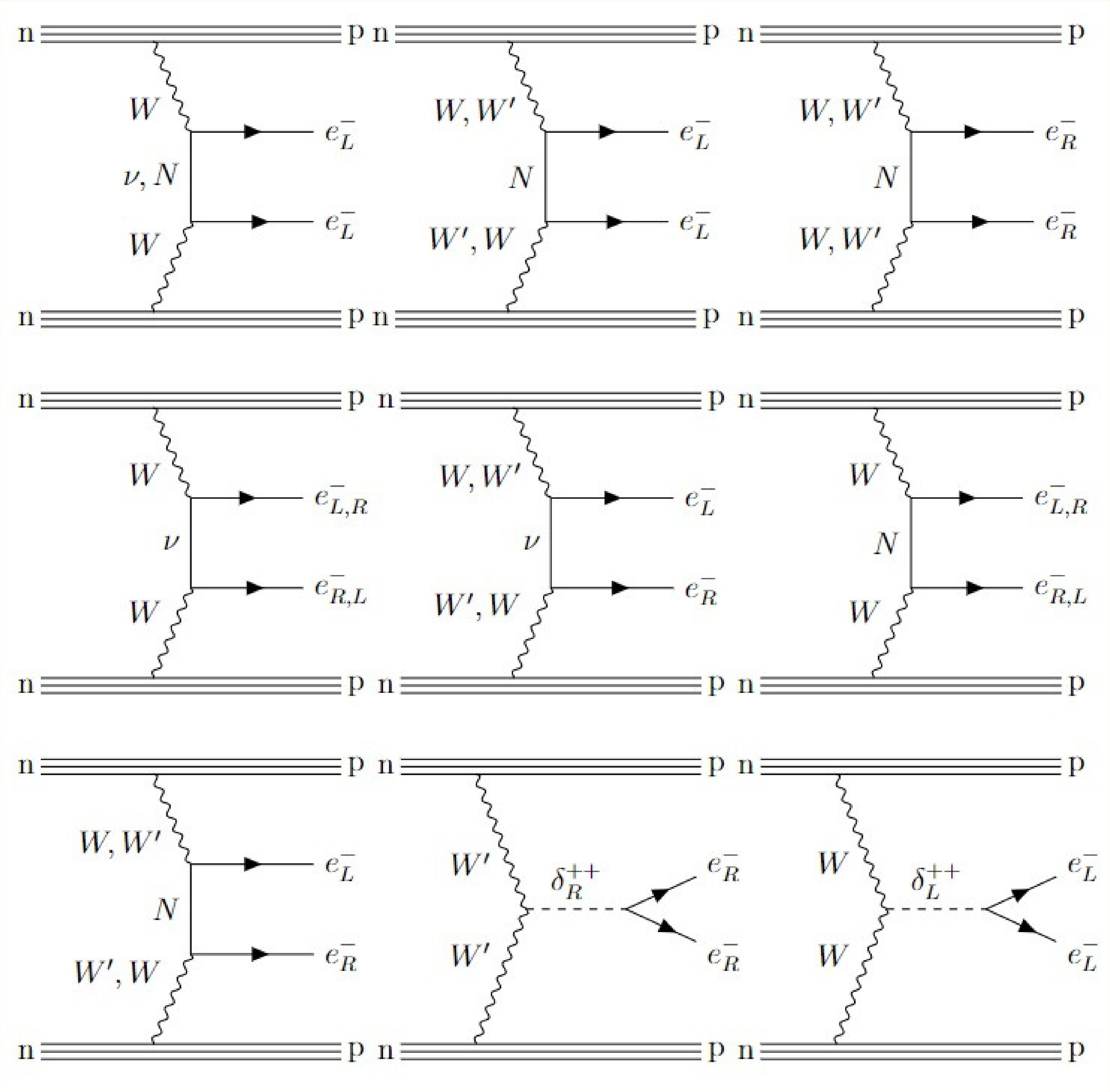


Backup - Additional Remarks

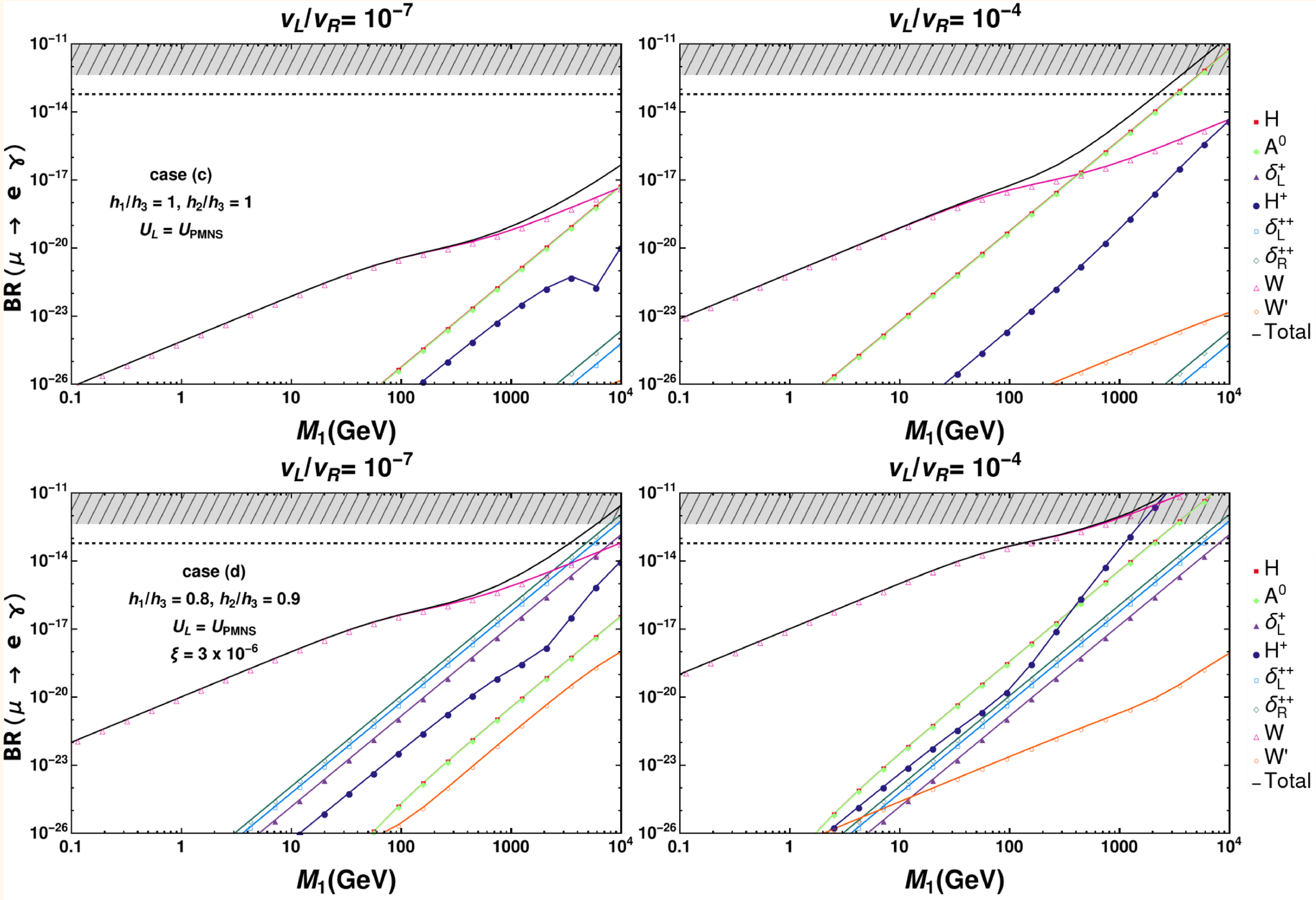
- We have also checked if the non unitarity introduced in the light neutrino mixing can impact the determination of the Fermi constant in muon decays.

Mattias Blennow, Pilar Coloma, Enrique Fernández-Martínez, and Manuel González-López Phys. Rev. D 106, (2022), arXiv:2204.04559

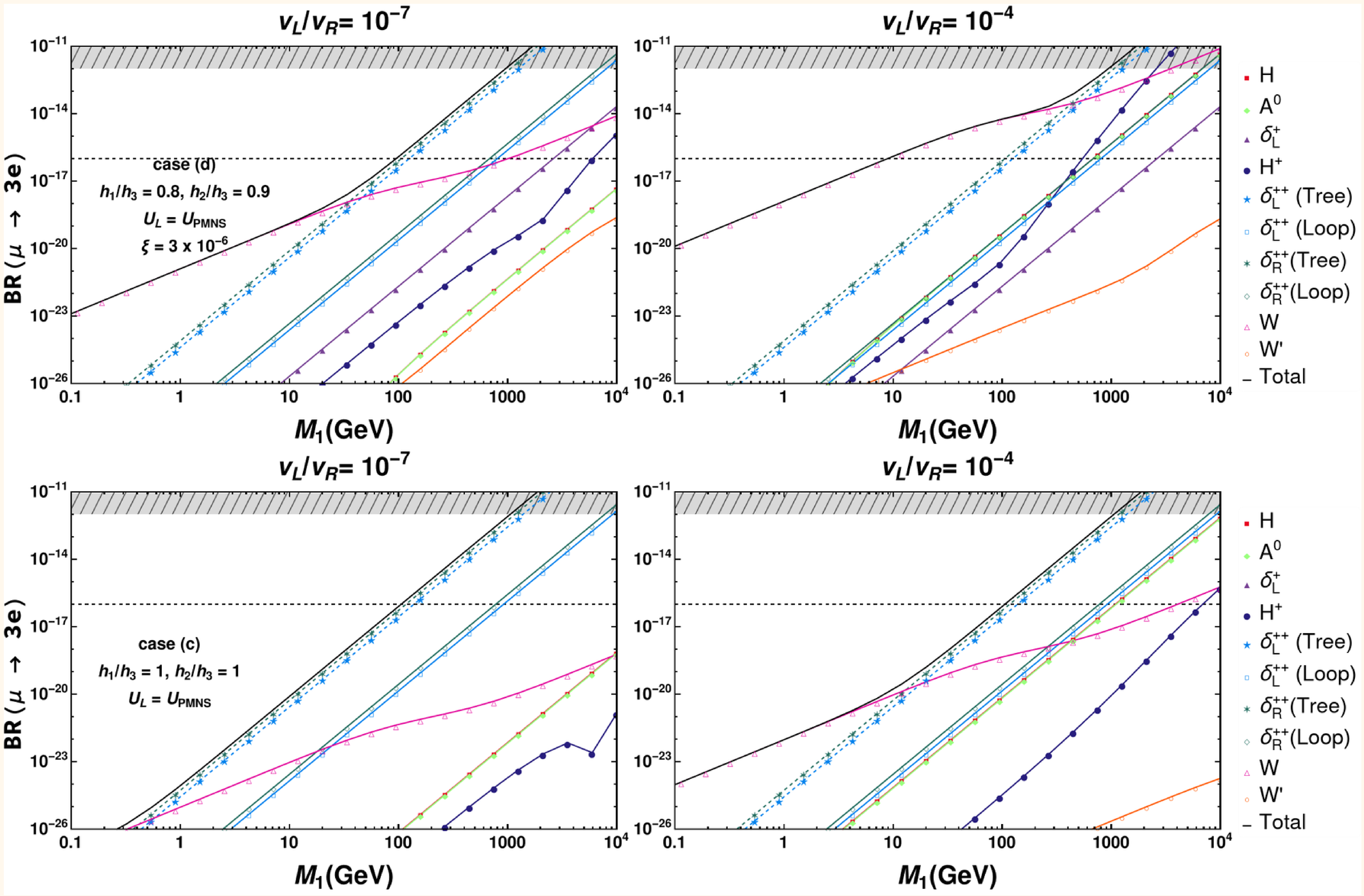




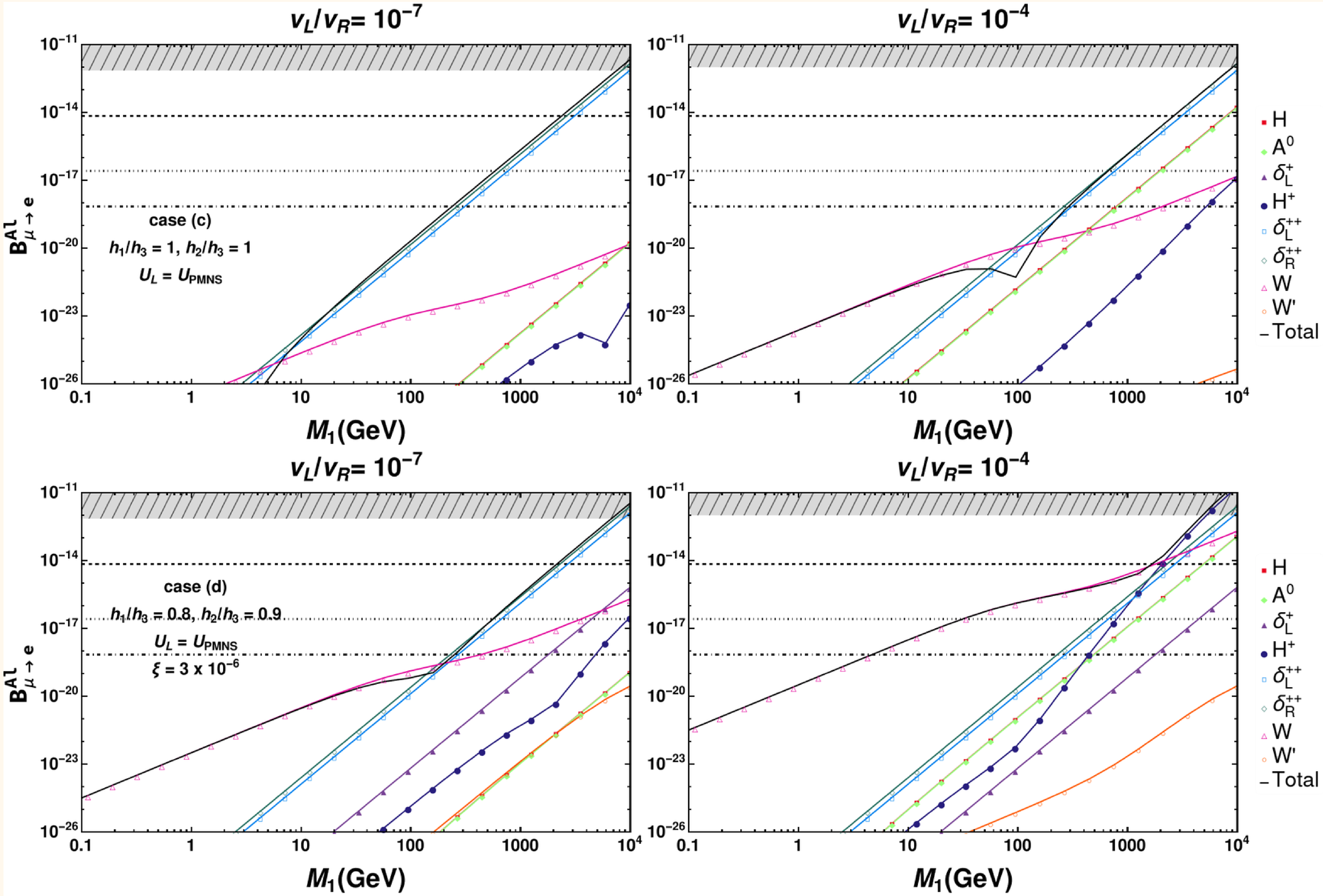
n
p
W
W
ν, N
e$_L^-$
e$_L^-$
W, W′
W′, W
N
e$_L^-$
e$_L^-$
W, W′
W, W′
N
e$_R^-$
e$_R^-$
W
W
ν
e$_{L,R}^-$
e$_{R,L}^-$
W, W′
W′, W
ν
e$_L^-$
e$_R^-$
W
W
N
e$_{L,R}^-$
e$_{R,L}^-$
W, W′
W′, W
N
e$_L^-$
e$_R^-$
W′
W′
δ$_R^{++}$
e$_R^-$
e$_R^-$
W
W
δ$_L^{++}$
e$_L^-$
e$_L^-$



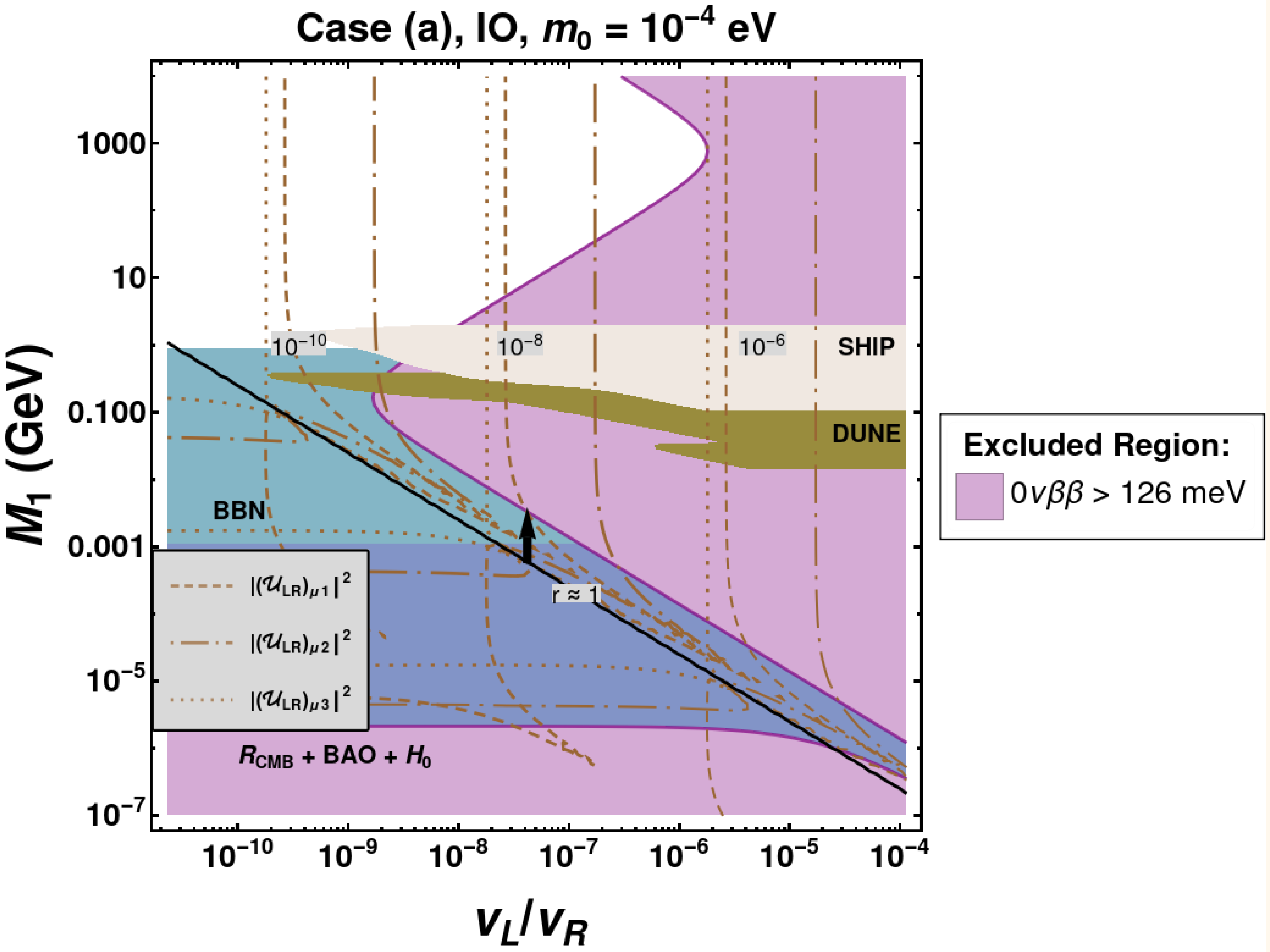
v_L/v_R= 10^{-7}
v_L/v_R= 10^{-4}
BR ($\mu \to e\ \gamma$)
M_1(GeV)
case (c)
h_1/h_3 = 1, h_2/h_3 = 1
U_L = $U_{\rm PMNS}$
case (d)
h_1/h_3 = 0.8, h_2/h_3 = 0.9
U_L = $U_{\rm PMNS}$
ξ = 3 x 10^{-6}
H
A^0
δ_L^+
H^+
δ_L^{++}
δ_R^{++}
W
W'
Total

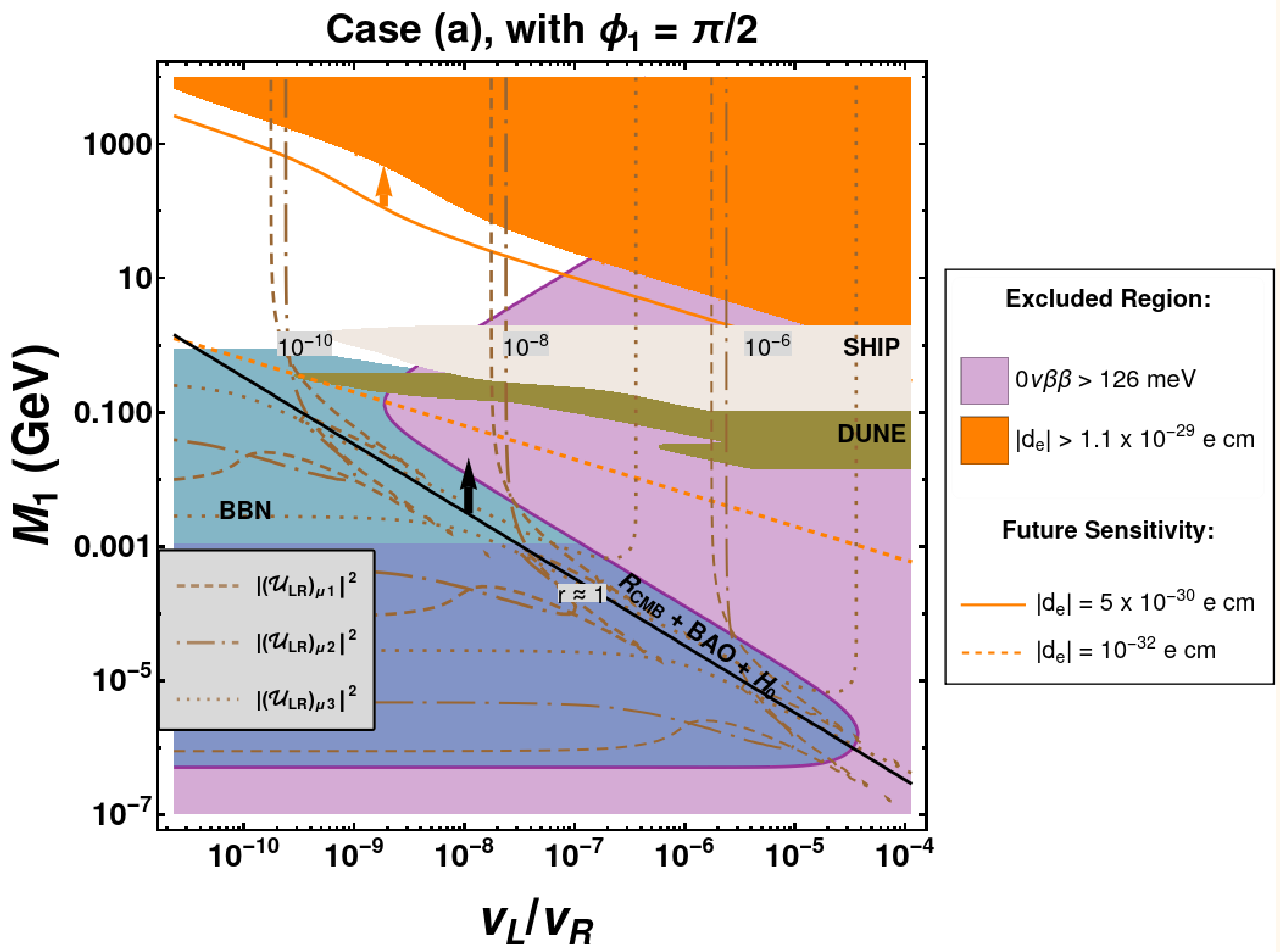


$v_L/v_R = 10^{-7}$
$v_L/v_R = 10^{-4}$
case (d)
$h_1/h_3 = 0.8$, $h_2/h_3 = 0.9$
$U_L = U_{PMNS}$
$\xi = 3 \times 10^{-6}$
case (c)
$h_1/h_3 = 1$, $h_2/h_3 = 1$
$U_L = U_{PMNS}$
BR ($\mu \to 3e$)
M_1(GeV)
H
A^0
δ_L^+
H^+
δ_L^{++} (Tree)
δ_L^{++} (Loop)
δ_R^{++}(Tree)
δ_R^{++}(Loop)
W
W'
Total

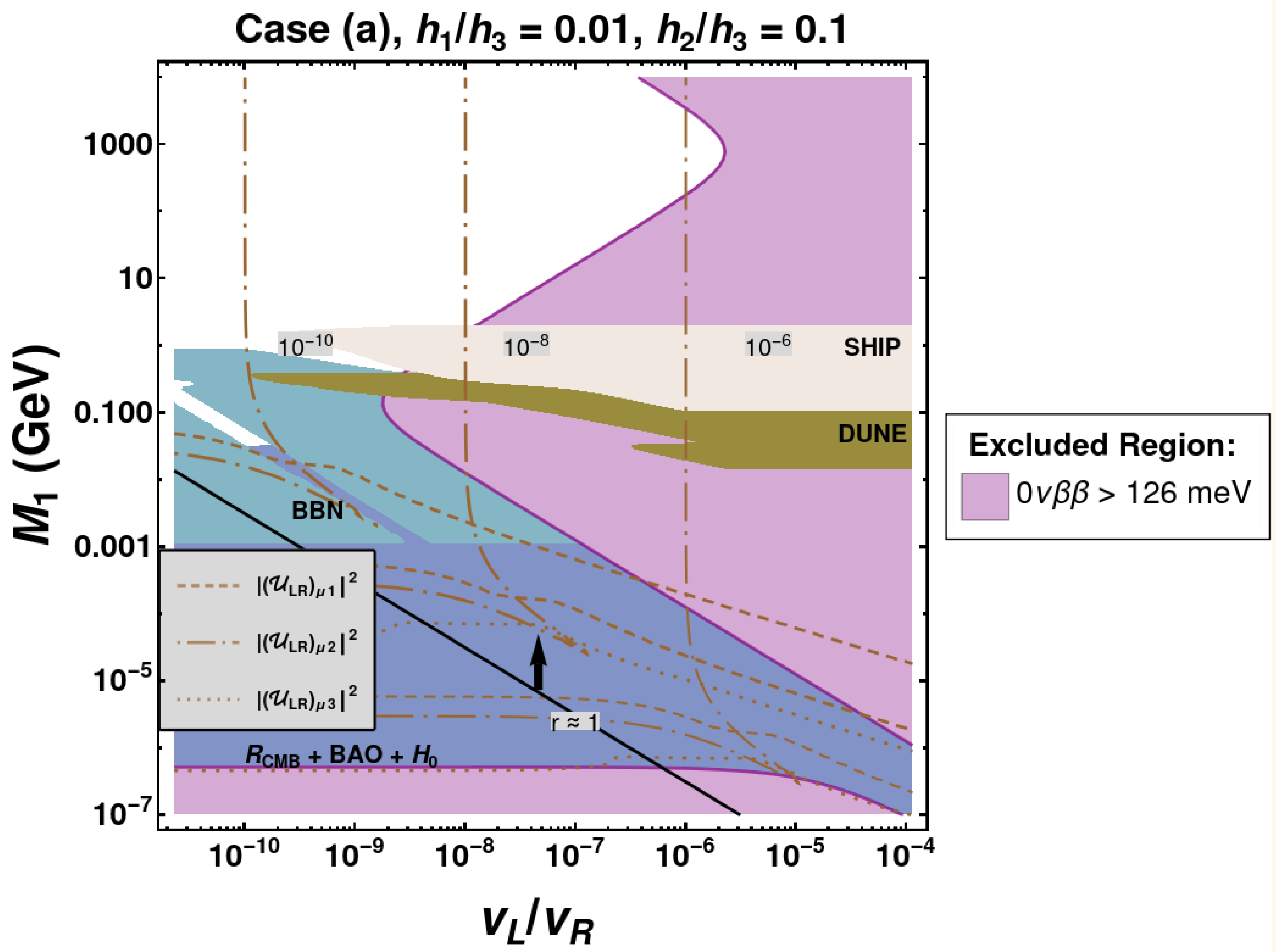


$v_L/v_R = 10^{-7}$
$v_L/v_R = 10^{-4}$
case (c)
$h_1/h_3 = 1$, $h_2/h_3 = 1$
$U_L = U_{PMNS}$
case (d)
$h_1/h_3 = 0.8$, $h_2/h_3 = 0.9$
$U_L = U_{PMNS}$
$\xi = 3 \times 10^{-6}$
$B^{Al}_{\mu \to e}$
M_1(GeV)
H
A^0
δ_L^+
H^+
δ_L^{++}
δ_R^{++}
W
W'
Total

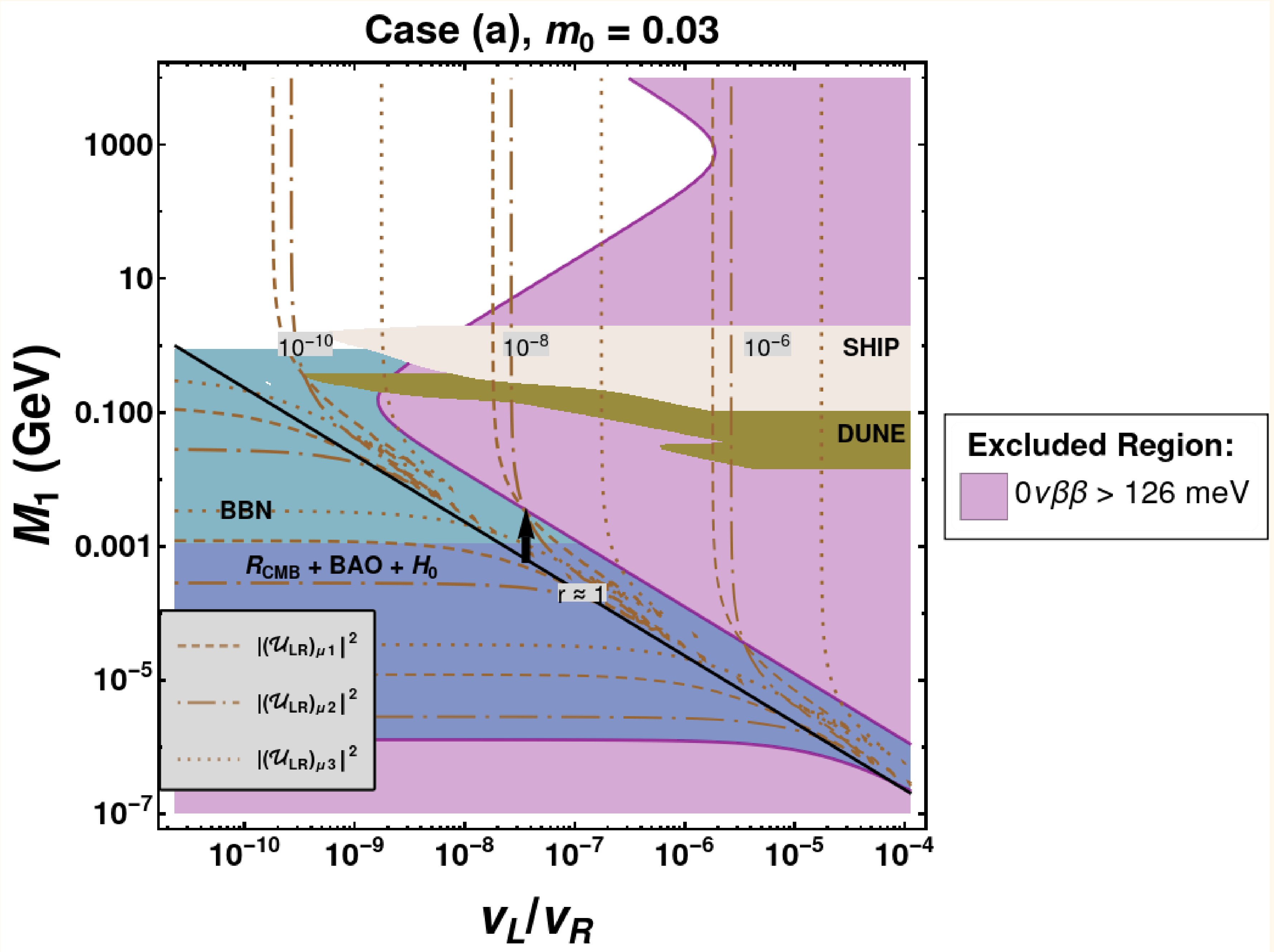

Case (a), IO, $m_0 = 10^{-4}$ eV
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
$r \approx 1$
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
R_{CMB} + BAO + H_0
Excluded Region:
$0\nu\beta\beta > 126$ meV



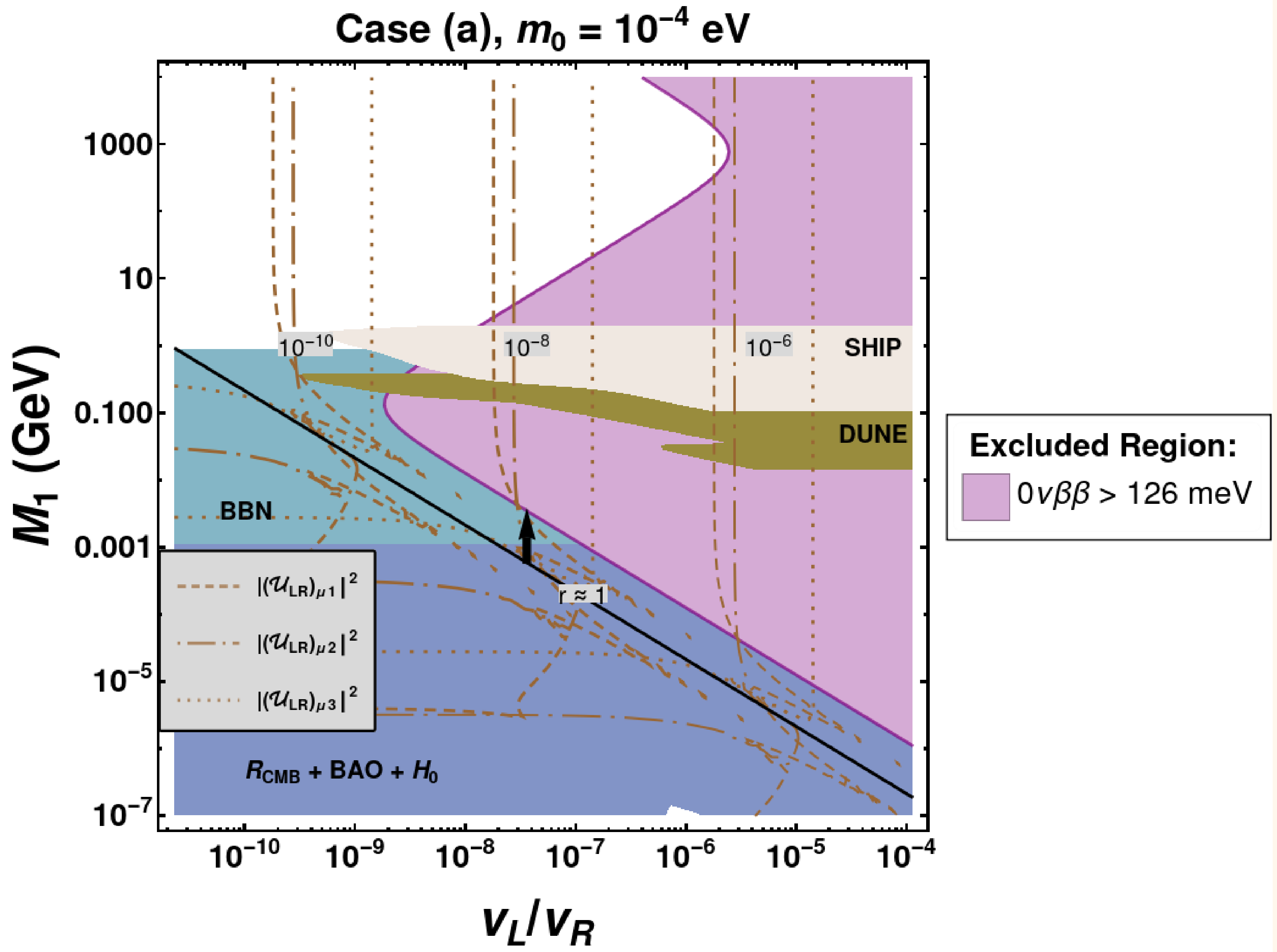
Case (a), with $\phi_1 = \pi/2$
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
$r \approx 1$
R_{CMB} + BAO + H_0
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
Excluded Region:
$0\nu\beta\beta$ > 126 meV
$|d_e| > 1.1 \times 10^{-29}$ e cm
Future Sensitivity:
$|d_e| = 5 \times 10^{-30}$ e cm
$|d_e| = 10^{-32}$ e cm



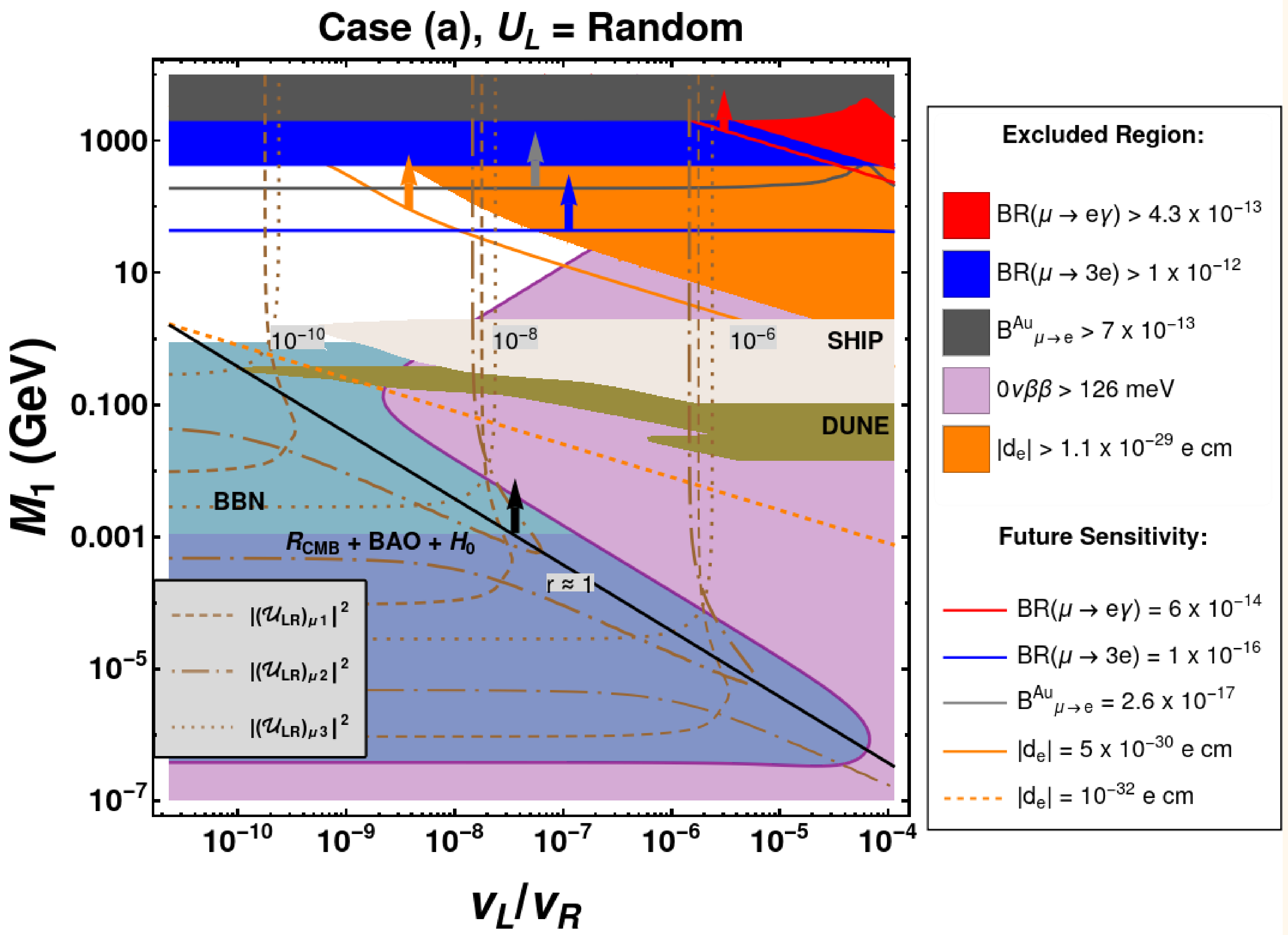
Case (a), $h_1/h_3 = 0.01$, $h_2/h_3 = 0.1$
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
$r \approx 1$
R_{CMB} + BAO + H_0
Excluded Region:
$0\nu\beta\beta > 126$ meV



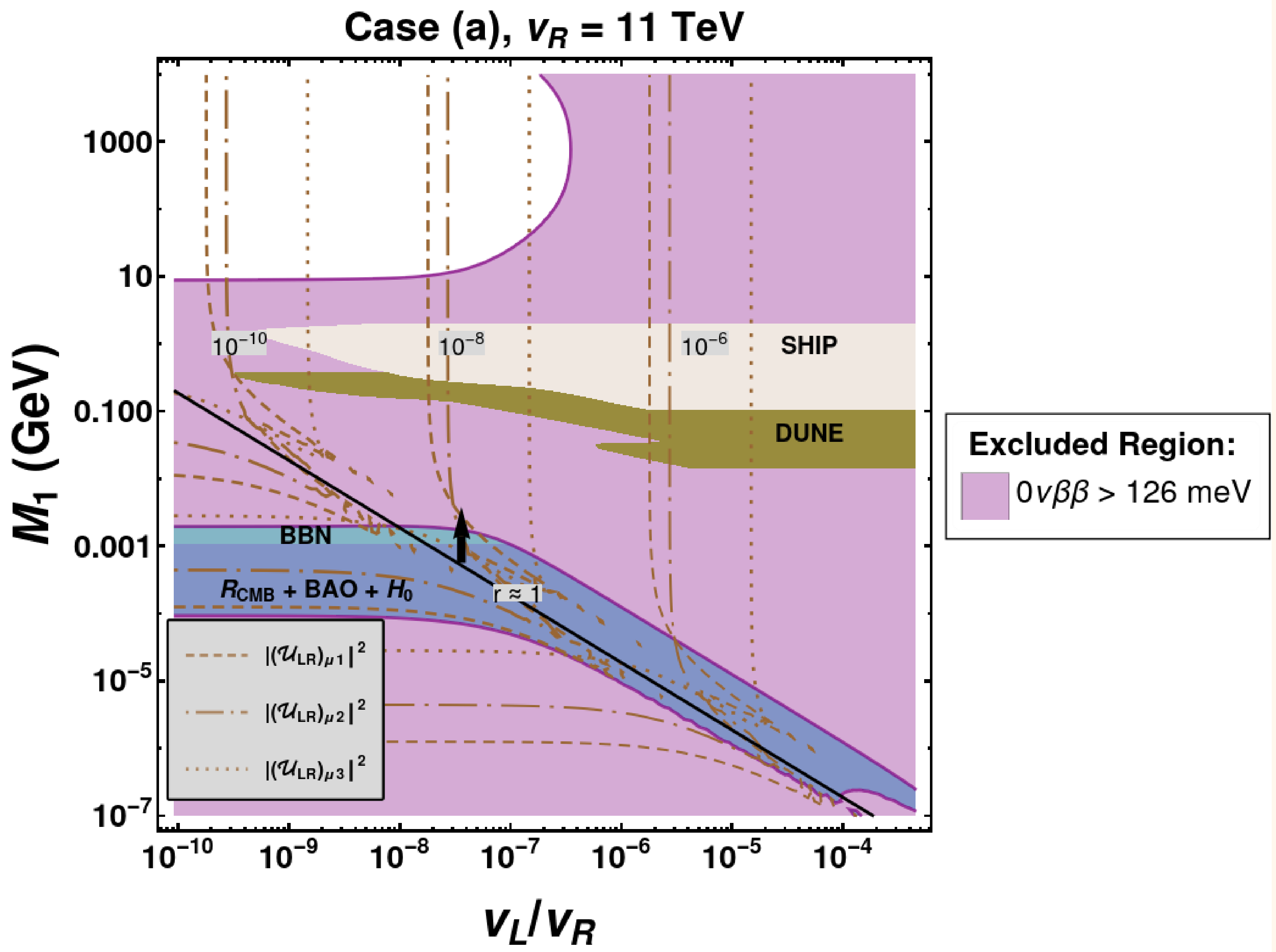
Case (a), m_0 = 0.03
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
R_{CMB} + BAO + H_0
r ≈ 1
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
Excluded Region:
$0\nu\beta\beta$ > 126 meV



Case (a), $m_0 = 10^{-4}$ eV
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
$r \approx 1$
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
R_{CMB} + BAO + H_0
Excluded Region:
$0\nu\beta\beta > 126$ meV



Case (a), U_L = Random
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
R_{CMB} + BAO + H_0
r ≈ 1
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
Excluded Region:
BR($\mu \to e\gamma$) > 4.3 x 10^{-13}
BR($\mu \to 3e$) > 1 x 10^{-12}
$B^{Au}_{\mu \to e}$ > 7 x 10^{-13}
$0\nu\beta\beta$ > 126 meV
$|d_e|$ > 1.1 x 10^{-29} e cm
Future Sensitivity:
BR($\mu \to e\gamma$) = 6 x 10^{-14}
BR($\mu \to 3e$) = 1 x 10^{-16}
$B^{Au}_{\mu \to e}$ = 2.6 x 10^{-17}
$|d_e|$ = 5 x 10^{-30} e cm
$|d_e|$ = 10^{-32} e cm



Case (a), v_R = 11 TeV
M_1 (GeV)
v_L/v_R
1000
10
0.100
0.001
10^{-5}
10^{-7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-10}
10^{-8}
10^{-6}
SHIP
DUNE
BBN
R_{CMB} + BAO + H_0
r ≈ 1
$|(\mathcal{U}_{LR})_{\mu 1}|^2$
$|(\mathcal{U}_{LR})_{\mu 2}|^2$
$|(\mathcal{U}_{LR})_{\mu 3}|^2$
Excluded Region:
$0\nu\beta\beta$ > 126 meV