(Global) Lepton Number Symmetry and Neutrino Masses

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Accidental symmetries of the SM

The Standard Model has accidental perturbative symmetries, arising from:
gauge group + field content + renormalizability

B	L_α	L
Baryon number	**Flavour numbers**	**Lepton number**
(Individual quark flavour numbers are violated by CKM mixing)	**α = e, μ, τ**	**$L = \Sigma_\alpha L_\alpha$**

Non perturbative effects violate both B and L, but preserve

B - L

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{N_f}{32\pi^2}\epsilon^{\mu\nu\sigma\tau}\left(-g_W^2 \,\mathrm{Tr}\, W_{\mu\nu}W_{\sigma\tau} + g_Y^2 B_{\mu\nu}B_{\sigma\tau}\right)$$

G. 't Hooft, Phys. Rev. Lett. 37 (1976) 8; Phys. Rev. D 14 (1976) 3432

Accidental symmetries: experimental status

B — **No evidence of violation**

E.g. proton mean life $> 3.6 \times 10^{29}$ years CL=90%

PDG, Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

$\not{L}_\alpha$ — **Violated in neutrino oscillations** ⬇ **New physics BSM**

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou, arXiv:2007.14792 [hep-ph]

L — **No evidence of violation**

Massive neutrinos violate it if they are Majorana particles

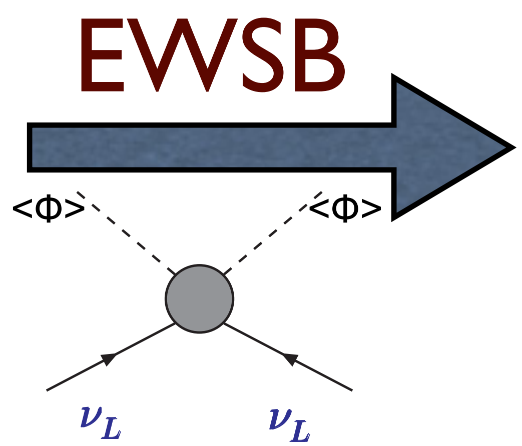
SM as an effective theory

Relaxing the renormalizability condition there is only one dim=5 gauge invariant operator (Weinberg operator) S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566

Lepton number violation

$$\frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{l^c_{L\alpha}}\tilde{\Phi}^*\right)\left(\tilde{\Phi}^\dagger l^\beta_L\right) + h.c.$$

$\Delta L = 2$



Neutrino masses and mixing

$$\frac{v^2}{2}\frac{c_{\alpha\beta}}{\Lambda}\overline{\nu^c_{L\alpha}}\nu_{L\beta} + h.c.$$

New physics scale (Λ)

$$m^\nu_{\alpha\beta} = c_{\alpha\beta}\frac{v}{\Lambda}v \lesssim \text{eV} \ll v$$

Why are neutrinos so light?

Suppression mechanisms:

- $\frac{v}{\Lambda} \ll 1$ High NP scale
- $c_{\alpha\beta} \ll 1$ Symmetry (Lepton number)
- $c_{\alpha\beta} \ll 1$ Accidental cancellations

Unveiling neutrino mass generation mechanism

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_5}{\Lambda}\mathcal{O}^{d=5} + \frac{c_6^i}{\Lambda^2}\mathcal{O}_i^{d=6} + \dots$$

ν masses and mixing common to all SM extensions with Majorana ν

New physics effects

If only Λ at work

$$\frac{c_6^i}{\Lambda^2} \approx \left(\frac{c_5}{\Lambda}\right)^2 \simeq \left(\frac{m_\nu}{v^2}\right)^2$$

New physics effects strongly suppressed by the ν mass scale

If symmetry at work

$c_5 \ll 1$ and $c_6^{\mathrm{LNV,i}} \ll 1$

$c_6^{\mathrm{LNC,i}} \approx \mathcal{O}(1)$ **possible for L conserving operators**

If accidental cancellation

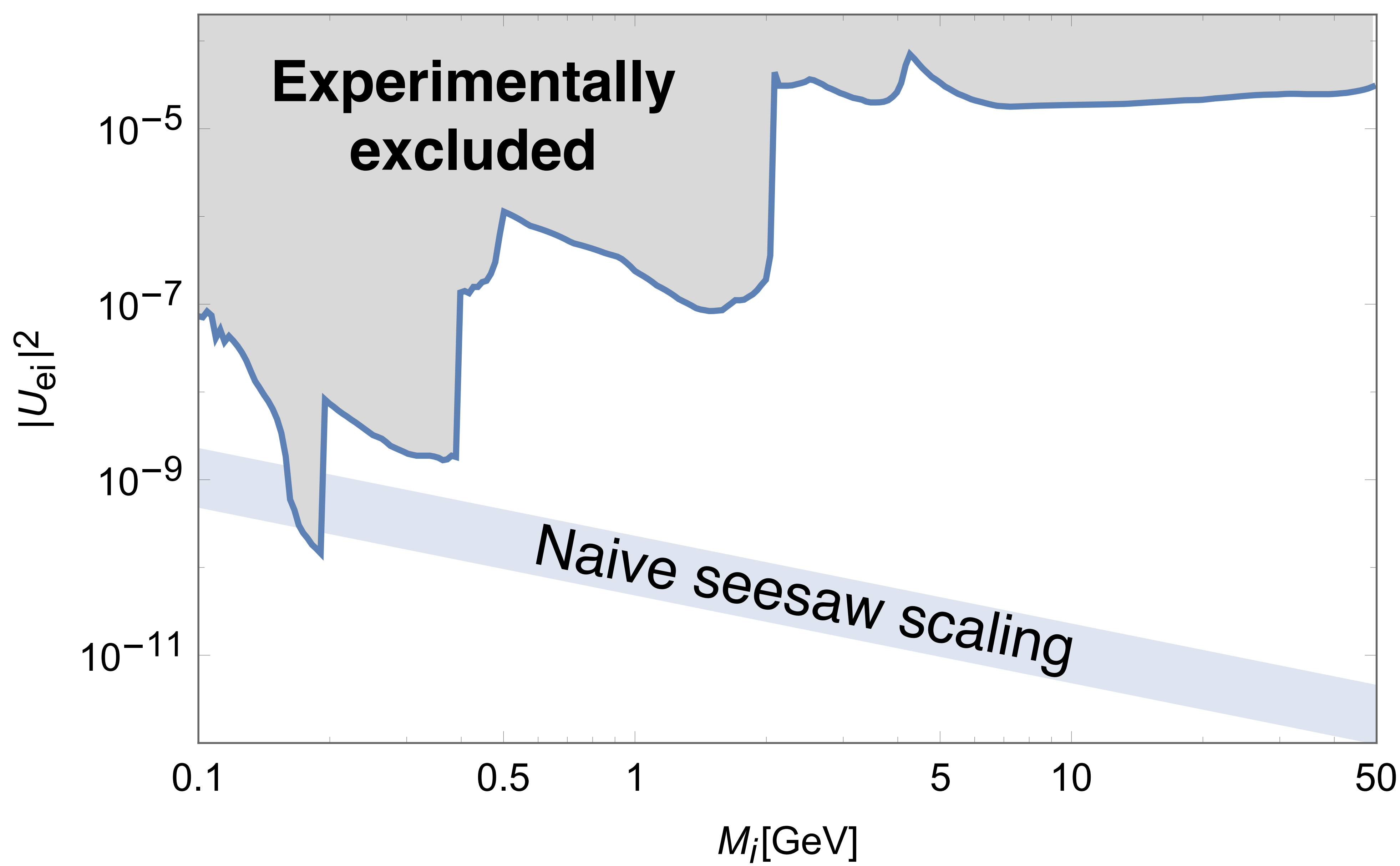
$c_5 \ll 1$

$c_6^i \approx \mathcal{O}(1)$ **possible for all operators**

Λ suppression: naive Seesaw scaling

Seesaw scaling $$m_\nu = -v^2 F \frac{1}{M} F^T$$

In the **absence** of any **structure** in the *F* and *M* matrices $$|U_{\alpha i}| \lesssim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-5}\sqrt{\frac{\text{GeV}}{M}}$$



Symmetries: L number has a special role

Theorem: SM + fermionic gauge singlets

K. Moffat, S. Pascoli and C. Weiland, arXiv:1712.07611 [hep-ph]

"The most general gauge-singlet neutrino extensions of the SM with no cancellation between different orders of the seesaw expansion, no fine-tuned cancellations between different radiative orders and which lead to three massless neutrinos are lepton number conserving"

In the SM extended with fermionic gauge singlets (e.g. Right-Handed neutrinos)

$$m_\nu = 0 \Rightarrow \Delta L = 0$$

Unless there are accidental cancellations in m_ν, the rate for Lepton number violating events is proportional to the small active neutrino masses

The theorem extends and generalises previous results: G. Ingelman and J. Rathsman, Z. Phys. C 60 (1993) 243; J. Gluza, hep-ph/0201002; J. Kersten and A. Y. Smirnov, arXiv:0705.3221 [hep-ph]

Accidental cancellations: quantify fine tuning

If a symmetry is present in the Lagrangian, it will be manifest at any order in perturbation theory → The **neutrino mass scale** is **stable** under **radiative corrections**

Compute neutrino masses m_ν at 1-loop, and quantify the level of fine-tuning of a solution as

$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left(\frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

$m_i^{\,loop}$
1-loop neutrino mass spectrum

$m_i^{\,tree}$
tree-level neutrino mass spectrum

Fermionic singlet extensions of the SM

SM + *n* gauge singlet fermions *N*$_I$

$$\mathcal{L} \;=\; \mathcal{L}_{\rm SM} + i\overline{N_I}\partial\!\!\!/ N_I - \left(F_{\alpha I}\overline{\ell^\alpha_L}\widetilde{\phi}N_I + \frac{M_{IJ}}{2}\overline{N^c_I}N_J + h.c.\right)$$

3 x n matrix
Yukawa couplings

n x n matrix
Majorana mass couplings

After electroweak phase transition < Φ > = v ≃ 174 GeV

$$-\mathcal{L}^\nu_m = \frac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{N^c} \end{pmatrix} \underbrace{\begin{pmatrix} \delta m_\nu^{\rm loop} & vF \\ vF^T & M \end{pmatrix}}_{\mathcal{M}} \begin{pmatrix} \nu^c_L \\ N \end{pmatrix} + h.c.$$

(3+n) dimensional mass matrix

Phenomenology of fermionic singlets

$$\mathcal{U}^T \mathcal{M}\, \mathcal{U} = \hat{\mathcal{M}}_{\rm diag}$$

→

- *3* light (mostly active) states
- *n* heavy (mostly sterile) states

PMNS matrix: neutrino oscillations

Couples the heavy states with SM gauge bosons

$$\mathcal{U} = \begin{pmatrix} \mathcal{U}^{\alpha,\ i=1,2,3}_{\text{active-active}} & \mathcal{U}^{\alpha,\ i\geq 4}_{\text{active-sterile}} \\ \vdots & \ddots \end{pmatrix}$$

Unobservable

L symmetry and Majorana fields

Majorana fermions violate all global symmetries, including L

How to preserve lepton number with Majorana states?

	Pair two states to form a **Dirac** state (*equal masses, maximal mixing, opposite CP*)	**Decouple** a state	Have a **massless** state
Exact symmetry	$M_1 = M_2$ $\mathcal{U}_{\alpha 1} = i\,\mathcal{U}_{\alpha 2}$	$\mathcal{U}_{\alpha i} = 0$	$M_i = 0$
Approximate symmetry	$\frac{M_2 - M_1}{M_1 + M_2} \ll 1$ $\mathcal{U}_{\alpha 1} \simeq i\,\mathcal{U}_{\alpha 2}$	$\lvert\mathcal{U}_{\alpha,i}\rvert \ll \lvert\mathcal{U}_{\alpha,j\neq i}\rvert$	$M_i \ll M_{j\neq i}$

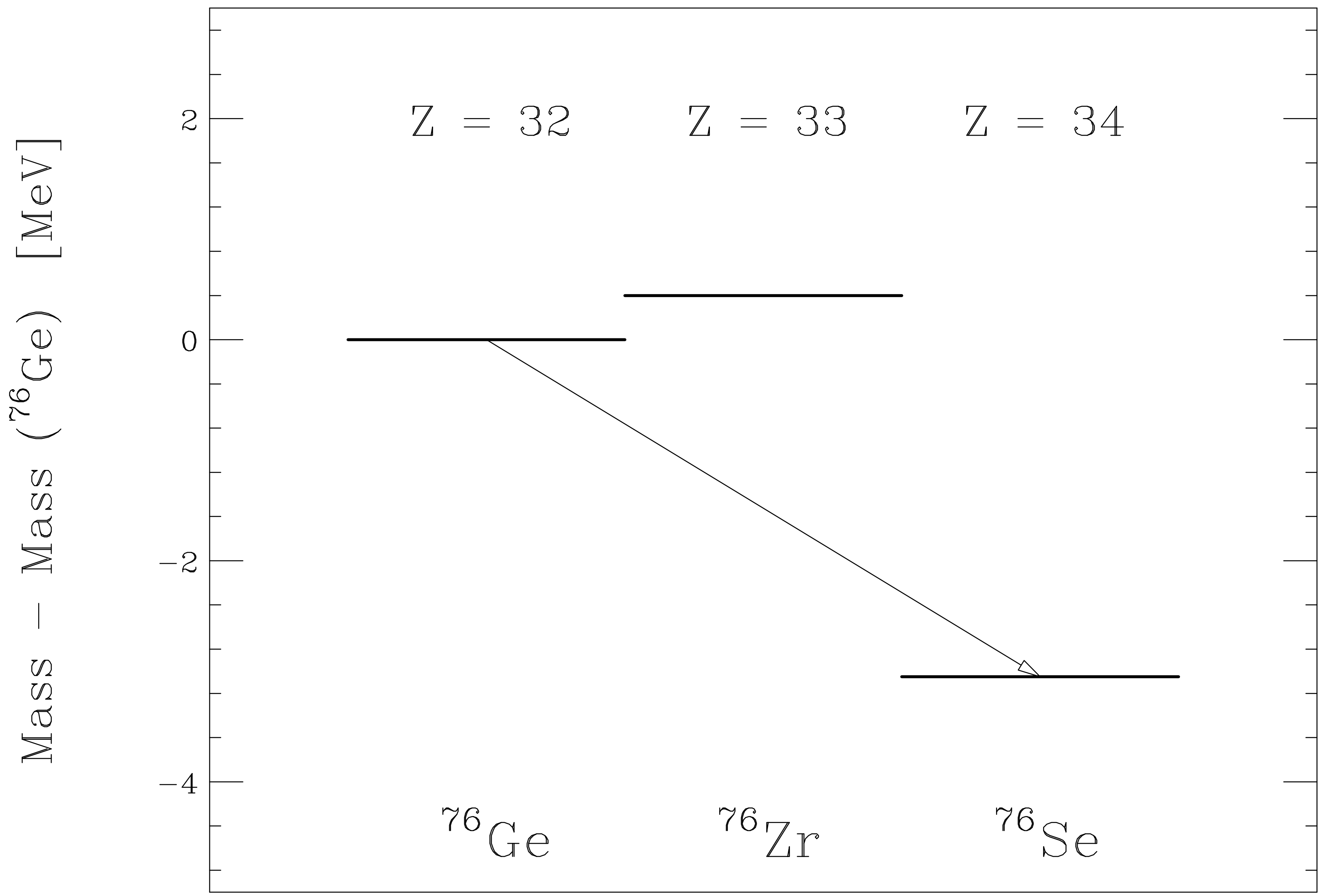
NEUTRINOLESS DOUBLE BETA DECAY

Double beta decay

2β decay: 2nd order weak process $\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + 2e^- + 2\overline{\nu_e}$

Only relevant when the single β decay is kinematically forbidden

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd



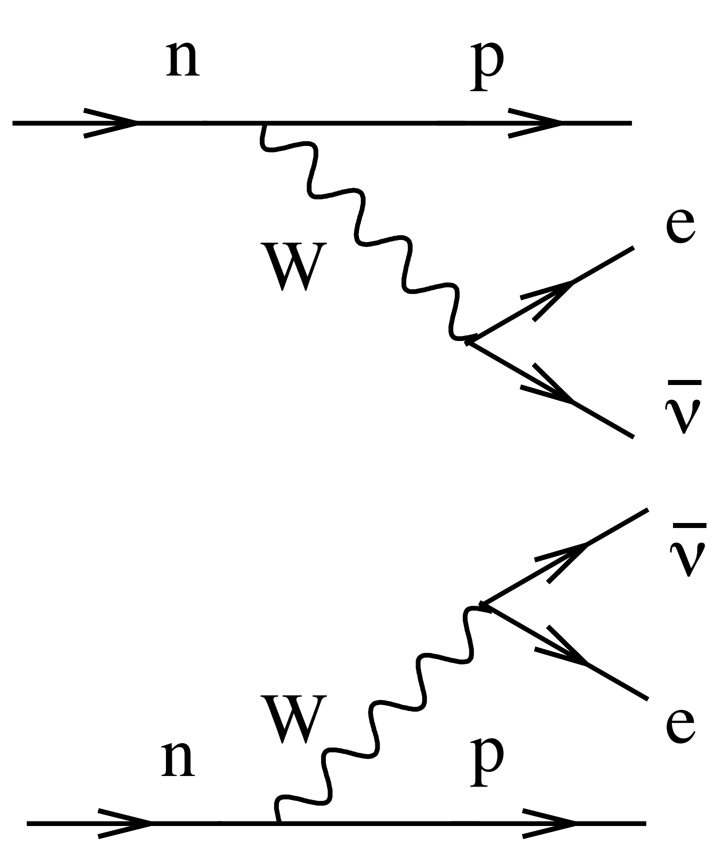


Figure from P. Lipari, Introduction to neutrino physics, in 2001 CERN-CLAF School of high-energy physics

Neutrinoless double beta decay: ΔL = 2

W. H. Furry, Phys. Rev. 56 (1939) 1184

If neutrinos are Majorana particles 0ν2β is possible

$$\mathcal{N}(A,Z) \rightarrow \mathcal{N}(A,Z+2) + 2e^-$$

Clear experimental signature

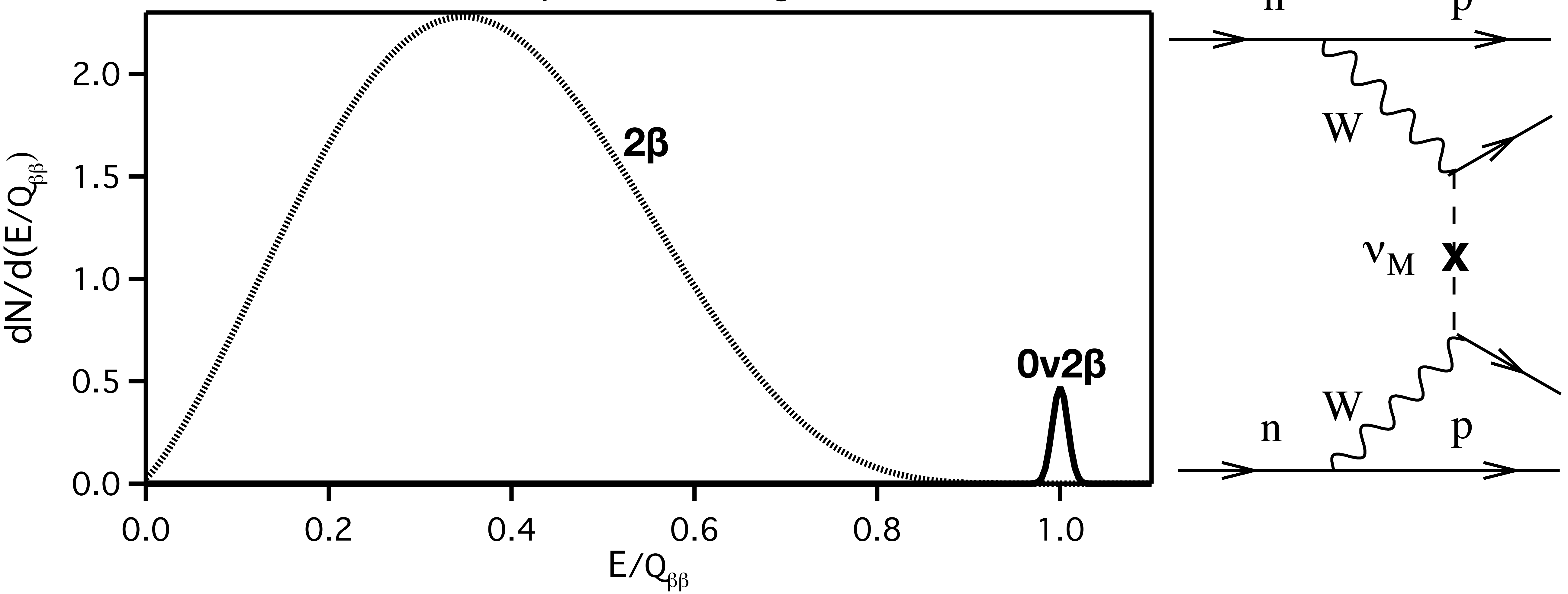


Figure modified from F. T. Avignone III, S. R. Elliott and J. Engel, arXiv:0708.1033 [nucl-ex]

The black box theorem

J. Schechter and J. W. F. Valle, Phys. Rev. D 25 (1982) 2951; E. Takasugi, Phys. Lett. 149B (1984) 372;
see also M. Duerr, M. Lindner and A. Merle, arXiv:1105.0901 [hep-ph]

Non-vanishing 0v2β amplitude

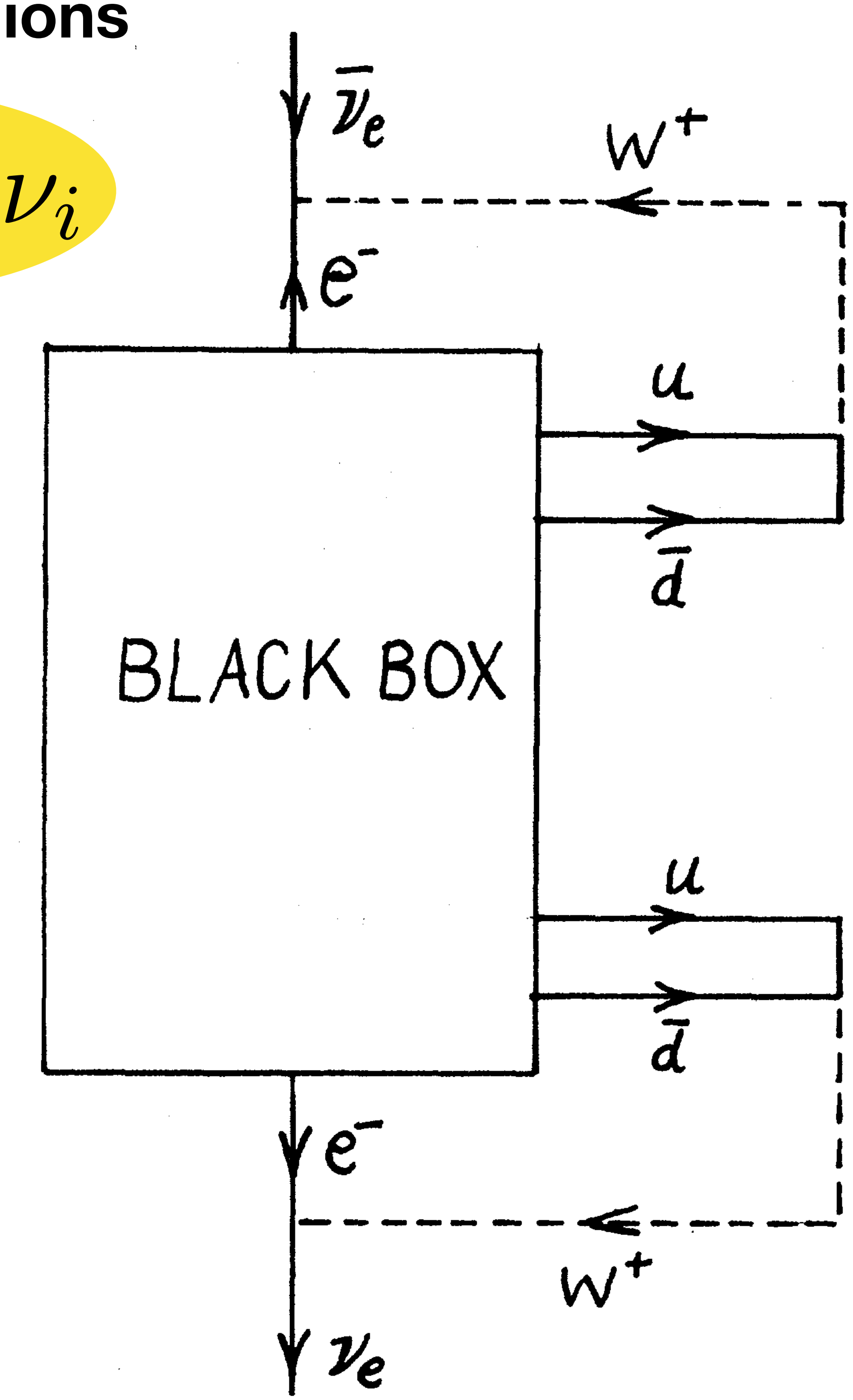
$$\Gamma_{0\nu 2\beta} \neq 0$$

⟺

Neutrinos are Majorana fermions

$$\nu_i^c = e^{i\phi}\nu_i$$

Irrespectively of the underlying mechanism, a non-vanishing 0v2β amplitude generates a Majorana mass term for the SM neutrinos



Experimental status: minimal SM

The amplitude for light neutrino exchange is proportional to $m_{2\beta} = \left| \sum_i U_{ei}^2 m_i \right|$

From current knowledge on neutrino oscillation parameters it is possible to compute $m_{2\beta}$ as a function of unknown lightest neutrino mass, ordering and CP phases

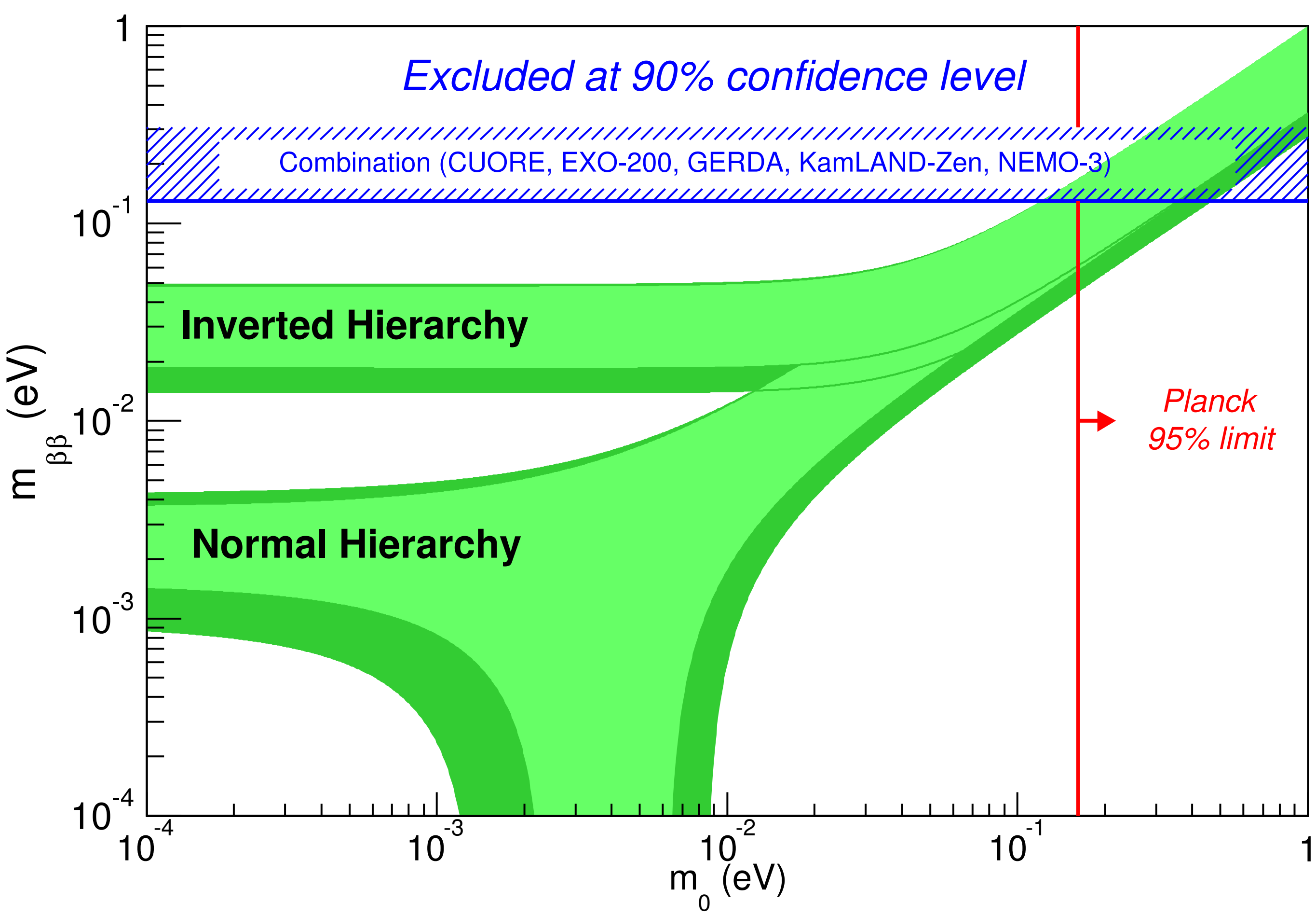


Figure from P. Guzowski, L. Barnes, J. Evans, G. Karagiorgi, N. McCabe and S. Soldner-Rembold, arXiv:1504.03600 [hep-ex]

Current bounds

Isotope	$T_{1/2}^{0\nu}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta} \rangle$ (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	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3
^{128}Te	$> 1.1 \times 10^{-2}$	—	—
^{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

Table from M. J. Dolinski, A. W. P. Poon and W. Rodejohann, arXiv:1902.04097 [nucl-ex]

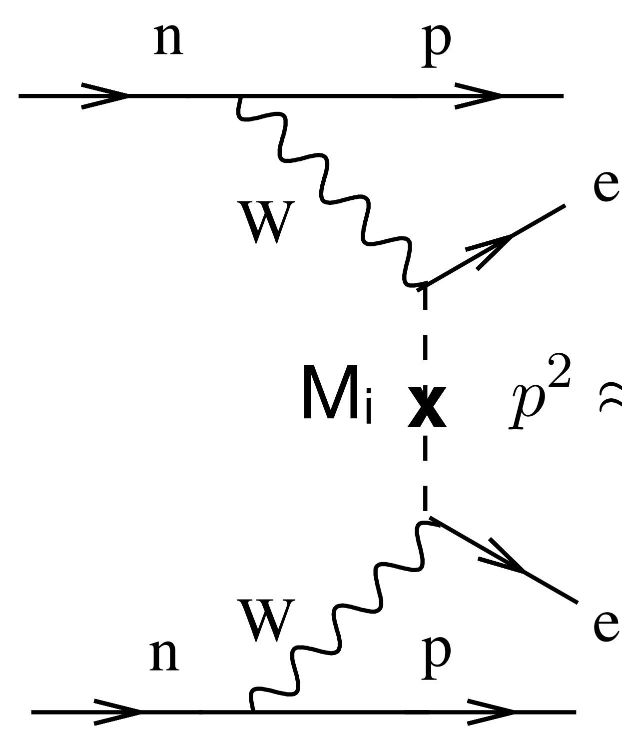
Contribution of heavy neutrinos

Heavy Majorana neutrinos contribute as well to 0ν2β amplitude

F. L. Bezrukov, hep-ph/0505247; M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon and J. Menendez, arXiv:1005.3240 [hep-ph]; A. Abada and M.L., arXiv:1401.1507 [hep-ph]; A. Faessler, M. González, S. Kovalenko and F. Šimkovic, arXiv:1408.6077 [hep-ph]; A. Abada, V. De Romeri, M.L., A. M. Teixeira and T. Toma, arXiv:1712.03984 [hep-ph]; A. Babič, S. Kovalenko, M. I. Krivoruchenko and F. Šimkovic, arXiv:1804.04218 [hep-ph]

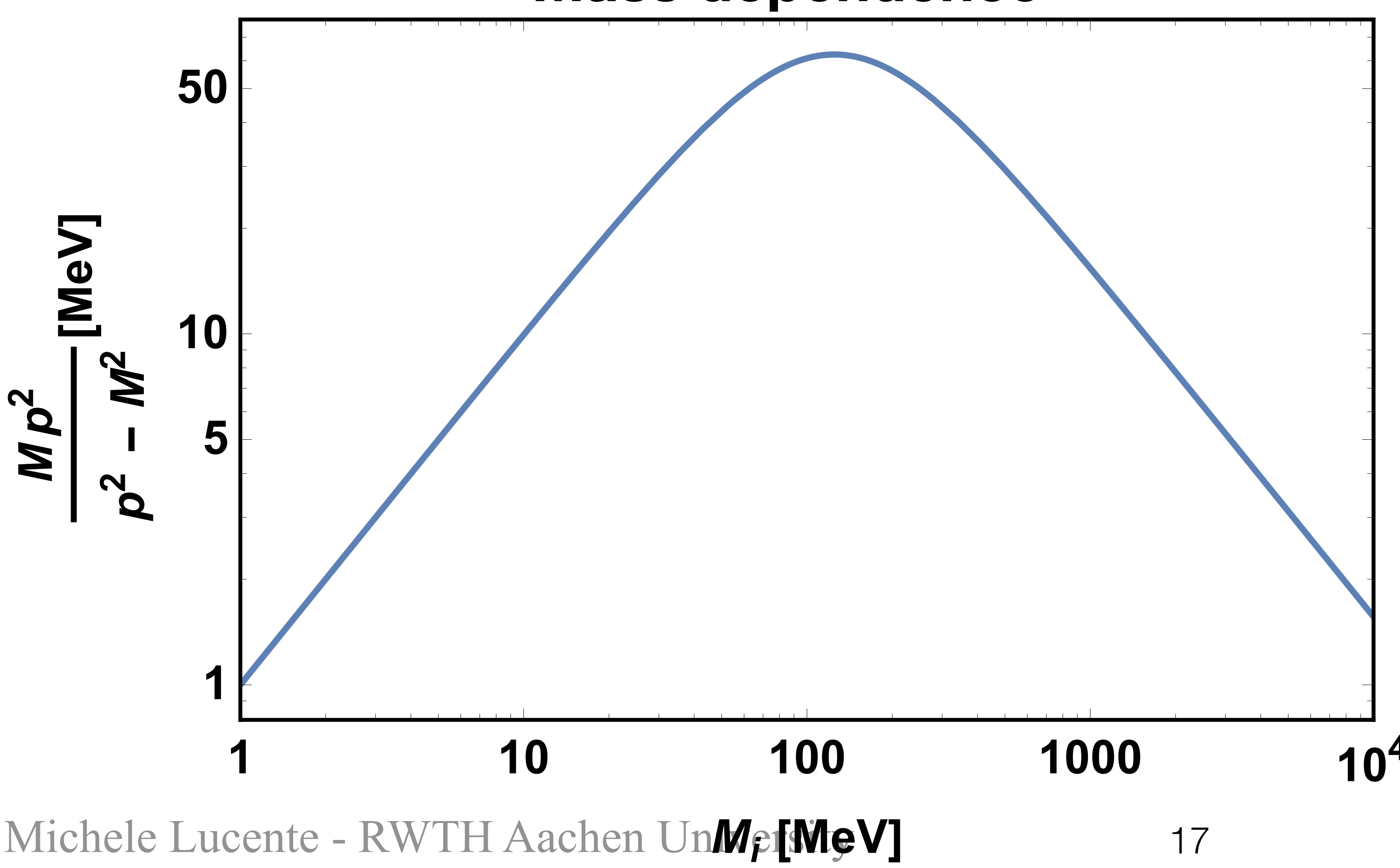
$$\mathcal{A}^{0\nu 2\beta} \propto \sum_i M_i\, \mathcal{U}_{ei}^2\; M^{0\nu 2\beta}(M_i)$$

$$M^{0\nu 2\beta}(M_i) \simeq M^{0\nu 2\beta}(0)\frac{p^2}{p^2 - M_i^2}$$



$p^2 \approx -(125\ \text{MeV})^2$

Mass dependence

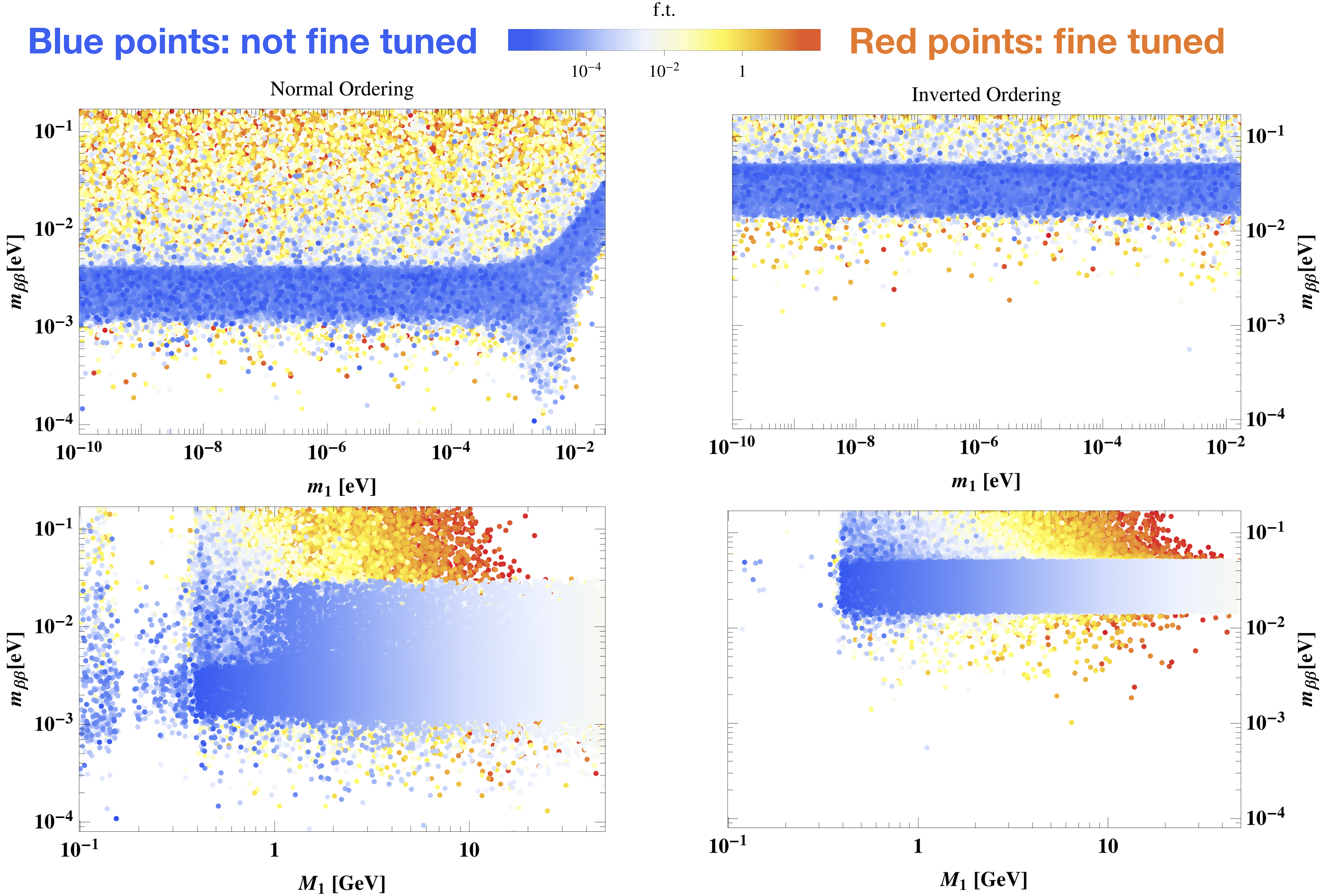


If pseudo-Dirac

$$M_1 \simeq M_2$$
$$\mathcal{U}_{e1} \simeq i\,\mathcal{U}_{e2}$$

cancellation between contributions of single Majorana states

Heavy neutrinos at GeV scale

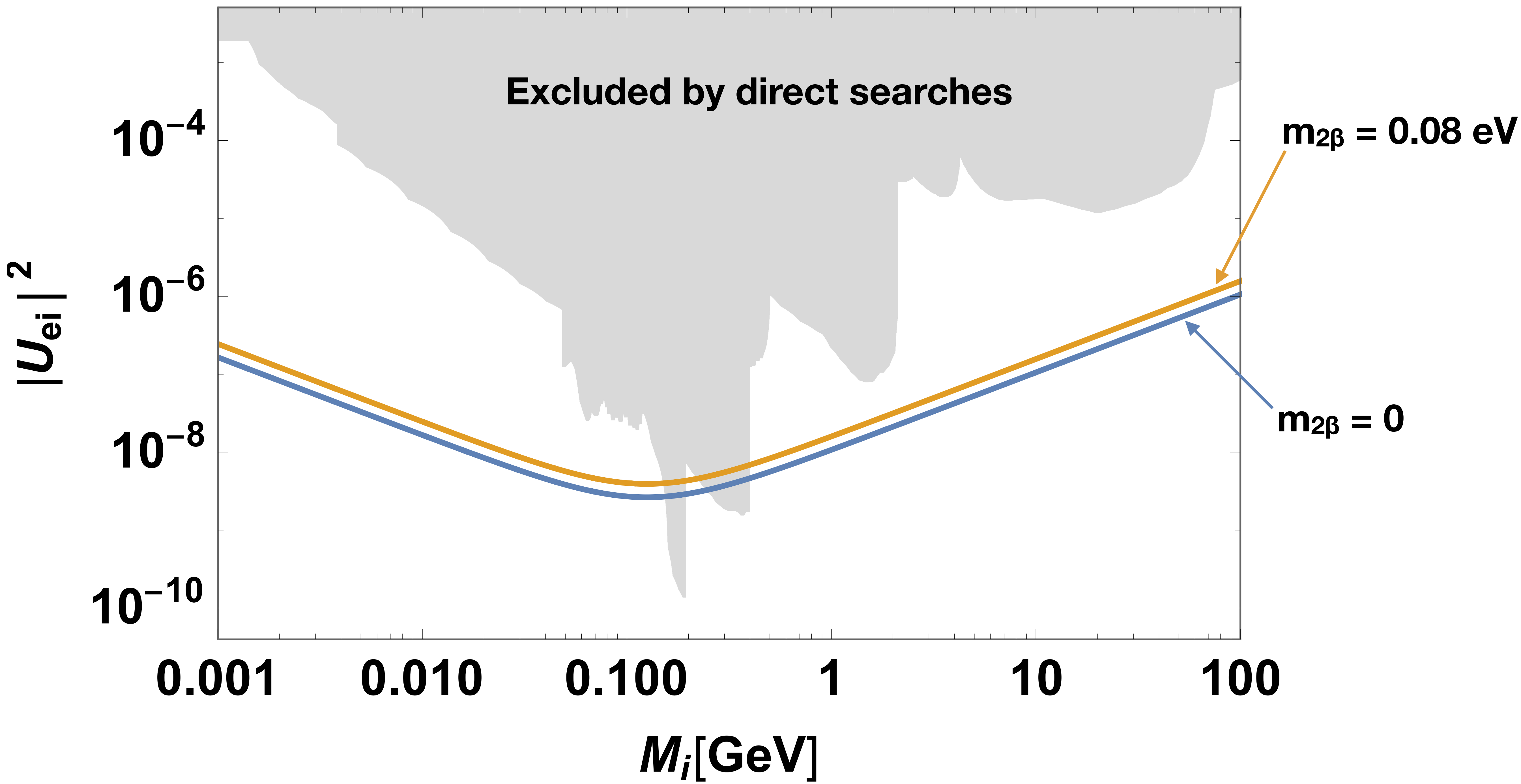


Figures from A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M. Lucente, arXiv:1810.12463 [hep-ph]; **see also** J. Lopez-Pavon, S. Pascoli and C. f. Wong, arXiv:1209.5342 [hep-ph]; J. Lopez-Pavon, E. Molinaro and S. T. Petcov, arXiv:1506.05296 [hep-ph]

Extracting contraints on heavy neutrinos

$$\mathcal{A}^{0\nu2\beta} \propto \sum_{i=1}^{3+n} M_i\, \mathcal{U}_{ei}^2\; M^{0\nu2\beta}(M_i)$$

0v2β constraints depend on the full mass spectrum (light + heavy)



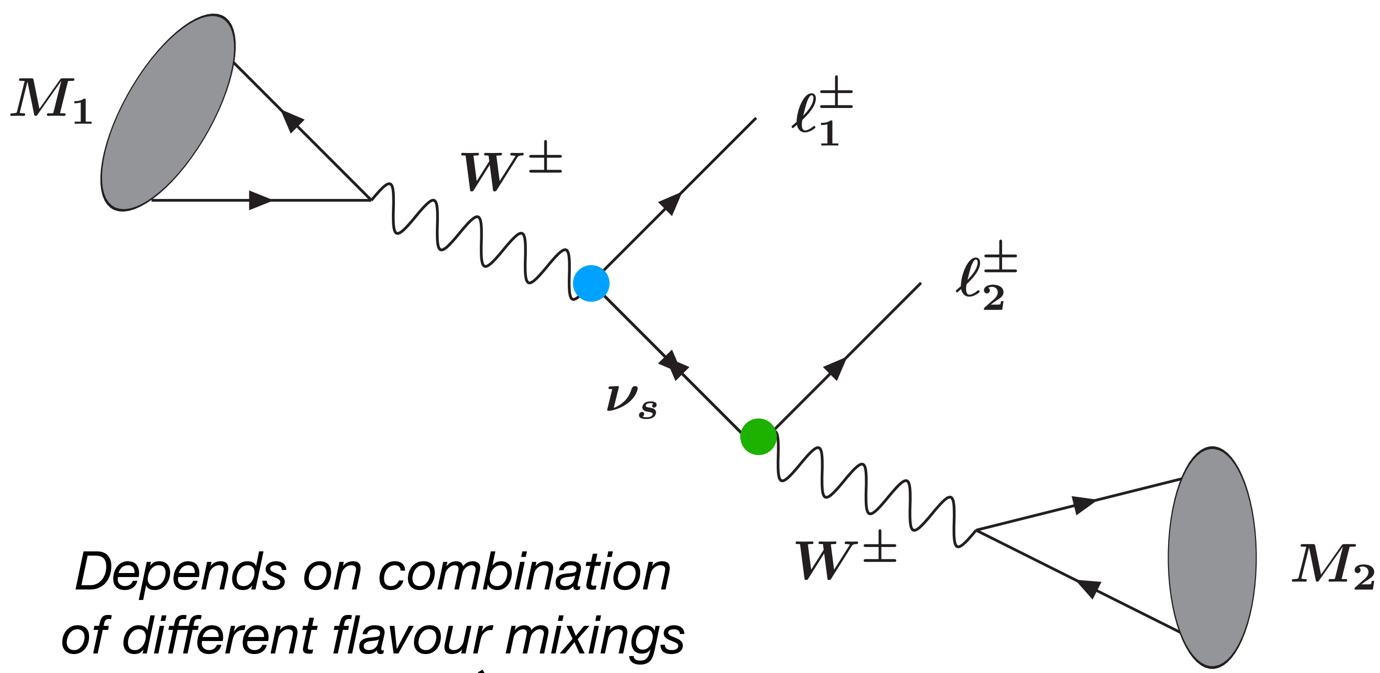
These constraints do not apply to (pseudo-)Dirac particles

Tau and meson decay

L-violating τ and meson decay

Heavy Majorana neutrinos can mediate L-violating decays of pseudo-scalar mesons and τ lepton

$$M_1(p, m_{M_1}) \rightarrow \ell_\alpha(k_1, m_{\ell_\alpha})\,\ell_\beta(k_2, m_{\ell_\beta})\,M_2(k_3, m_{M_2})$$



Depends on combination of different flavour mixings

$$i\mathcal{M}_P \equiv i\mathcal{M}_{P1} + i\mathcal{M}_{P2} = 2i\,G_F^2\,V_{M_1}\,V_{M_2}\,U_{\ell_\alpha 4}\,U_{\ell_\beta 4}\,m_4\,f_{M_1}\,f_{M_2}\left[\frac{\overline{u}(k_1)\not{k}_3\not{p}P_R v(k_2)}{m_{31}^2 - m_4^2 + i m_4\,\Gamma_4} + \frac{\overline{u}(k_1)\not{p}\not{k}_3 P_R v(k_2)}{m_{23}^2 - m_4^2 + i m_4\,\Gamma_4}\right]$$

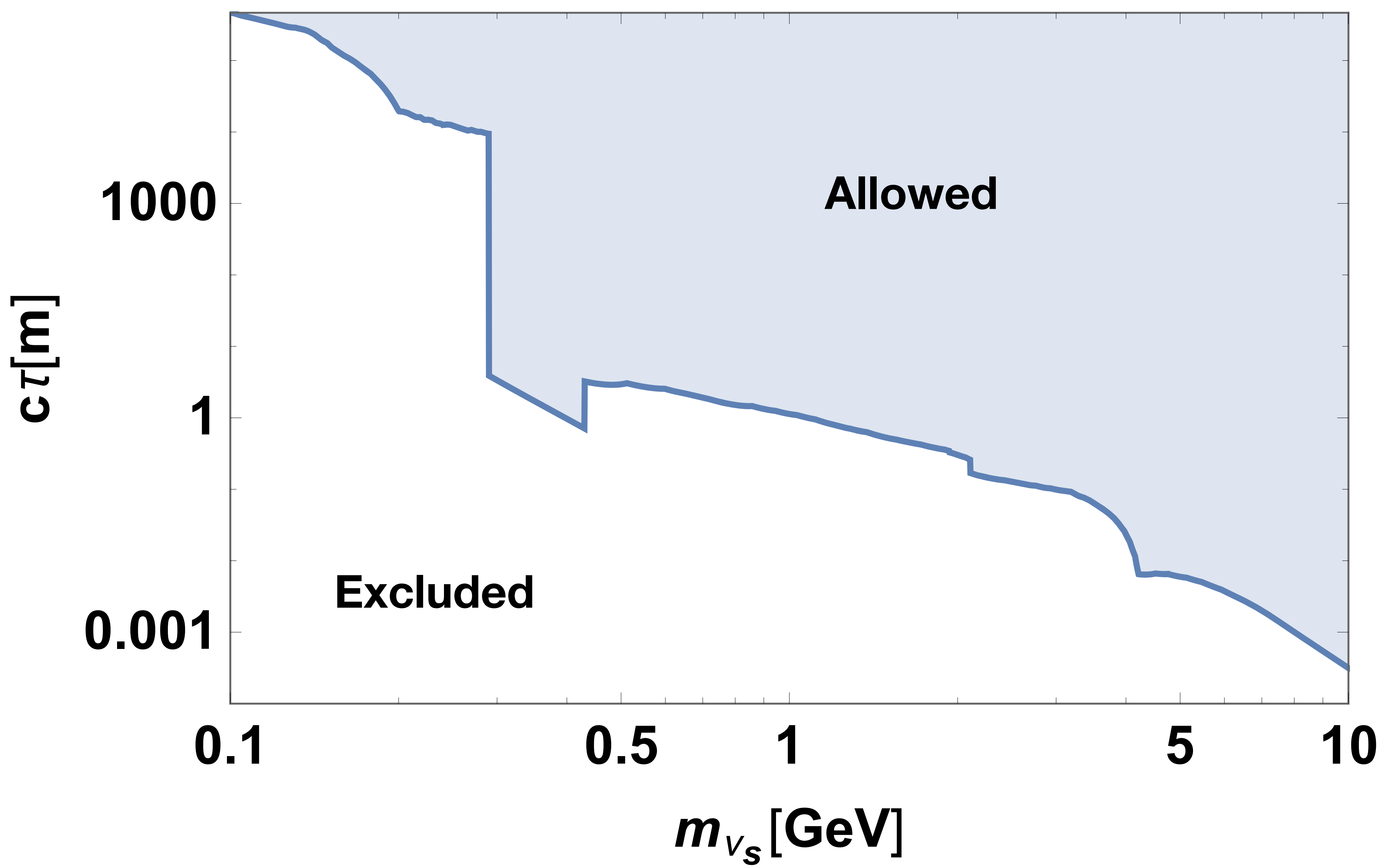
Negligible amplitude unless the intermediate state can go on-shell

$$\frac{1}{\left(m_{ij}^2 - m_4^2\right)^2 + m_4^2\Gamma_4^2} \rightarrow \frac{\pi}{m_4\Gamma_4}\delta\left(m_{ij}^2 - m_4^2\right)$$

Lifetime limitations

In the resonant regime $i\mathcal{M} \propto \frac{M_{\nu_s}}{\Gamma_{\nu_s}} \equiv M_{\nu_s}\tau_{\nu_s}$

But too long-lived heavy neutrinos decay outside the detector



Asking for observable (inside detector) decays imposes a further constraint

Current bounds

Tables (and list of references) from A. Abada, V. De Romeri, M.L., A. M. Teixeira and T. Toma, arXiv:1712.03984 [hep-ph]

Meson decay

LNV decay	Current bound		
	$\ell_\alpha = e,\ \ell_\beta = e$	$\ell_\alpha = e,\ \ell_\beta = \mu$	$\ell_\alpha = \mu,\ \ell_\beta = \mu$
$K^- \to \ell_\alpha^- \ell_\beta^- \pi^+$	6.4×10^{-10} [41]	5.0×10^{-10} [41]	1.1×10^{-9} [41]
$D^- \to \ell_\alpha^- \ell_\beta^- \pi^+$	1.1×10^{-6} [41]	2.0×10^{-6} [78]	2.2×10^{-8} [79]
$D^- \to \ell_\alpha^- \ell_\beta^- K^+$	9.0×10^{-7} [78]	1.9×10^{-6} [78]	1.0×10^{-5} [78]
$D^- \to \ell_\alpha^- \ell_\beta^- \rho^+$	—	—	5.6×10^{-4} [41]
$D^- \to \ell_\alpha^- \ell_\beta^- K^{*+}$	—	—	8.5×10^{-4} [41]
$D_s^- \to \ell_\alpha^- \ell_\beta^- \pi^+$	4.1×10^{-6} [41]	8.4×10^{-6} [78]	1.2×10^{-7} [79]
$D_s^- \to \ell_\alpha^- \ell_\beta^- K^+$	5.2×10^{-6} [78]	6.1×10^{-6} [78]	1.3×10^{-5} [78]
$D_s^- \to \ell_\alpha^- \ell_\beta^- K^{*+}$	—	—	1.4×10^{-3} [41]
$B^- \to \ell_\alpha^- \ell_\beta^- \pi^+$	2.3×10^{-8} [80]	1.5×10^{-7} [81]	4.0×10^{-9} [82]
$B^- \to \ell_\alpha^- \ell_\beta^- K^+$	3.0×10^{-8} [80]	1.6×10^{-7} [81]	4.1×10^{-8} [83]
$B^- \to \ell_\alpha^- \ell_\beta^- \rho^+$	1.7×10^{-7} [81]	4.7×10^{-7} [81]	4.2×10^{-7} [81]
$B^- \to \ell_\alpha^- \ell_\beta^- D^+$	2.6×10^{-6} [84]	1.8×10^{-6} [84]	6.9×10^{-7} [85]
$B^- \to \ell_\alpha^- \ell_\beta^- D^{*+}$	—	—	2.4×10^{-6} [41]
$B^- \to \ell_\alpha^- \ell_\beta^- D_s^+$	—	—	5.8×10^{-7} [41]
$B^- \to \ell_\alpha^- \ell_\beta^- K^{*+}$	4.0×10^{-7} [81]	3.0×10^{-7} [81]	5.9×10^{-7} [81]
LNV matrix m_ν	m_ν^{ee}	$m_\nu^{e\mu}$	$m_\nu^{\mu\mu}$

Results from

Belle [84],
BABAR [78,80,81] and
LHCb [79,82,83,85];

summarised in PDG [41]

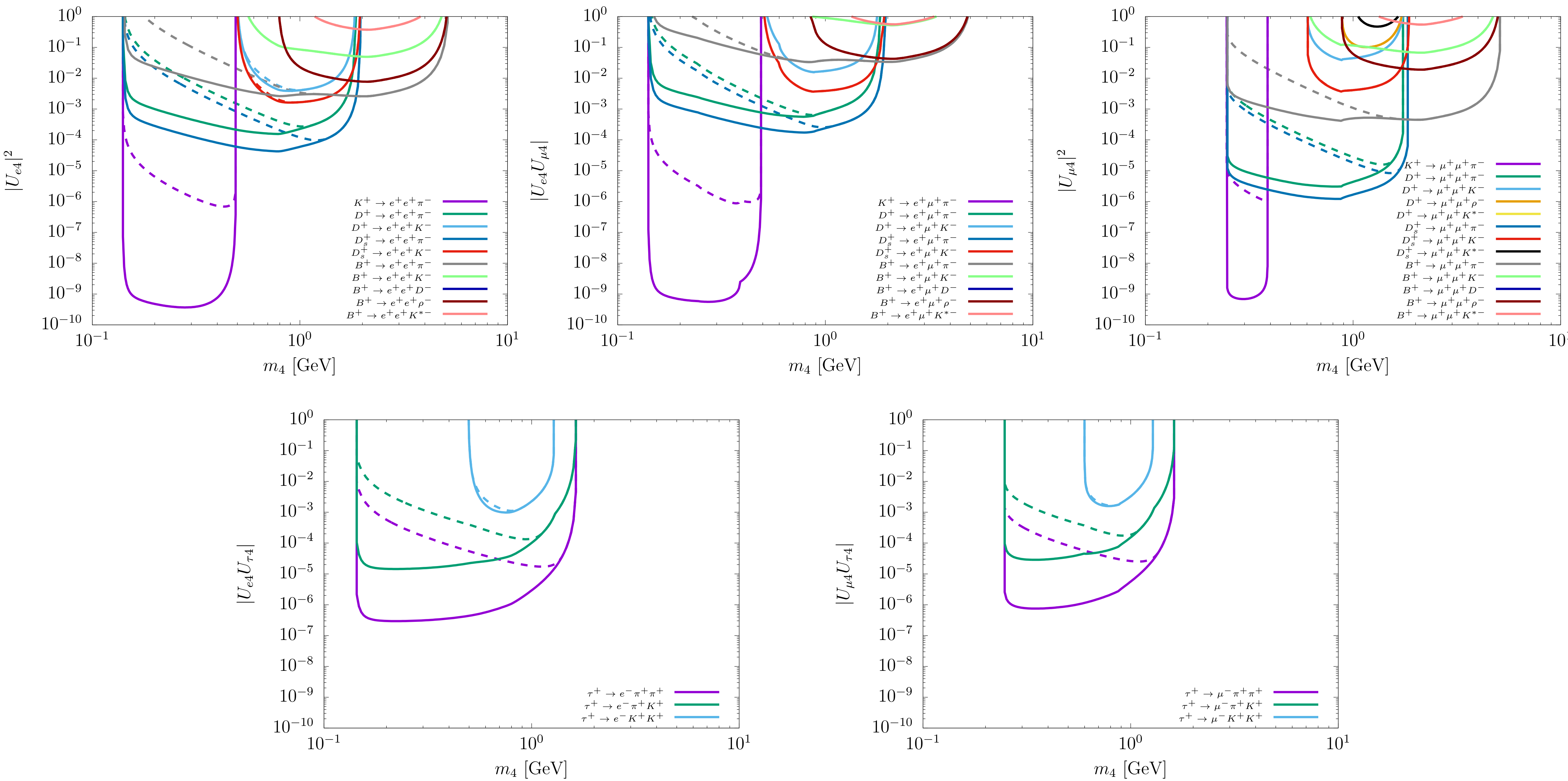
τ decay

LNV decay	Current bound	
	$\ell = e$	$\ell = \mu$
$\tau^- \to \ell^+ \pi^- \pi^-$	2.0×10^{-8}	3.9×10^{-8}
$\tau^- \to \ell^+ \pi^- K^-$	3.2×10^{-8}	4.8×10^{-8}
$\tau^- \to \ell^+ K^- K^-$	3.3×10^{-8}	4.7×10^{-8}
LNV matrix m_ν	$m_\nu^{e\tau}$	$m_\nu^{\mu\tau}$

upper bounds from the Belle

Constraints: single intermediate state

Figures from A. Abada, V. De Romeri, M.L., A. M. Teixeira and T. Toma, arXiv:1712.03984 [hep-ph];
see also A. Atre, T. Han, S. Pascoli and B. Zhang, arXiv:0901.3589 [hep-ph]

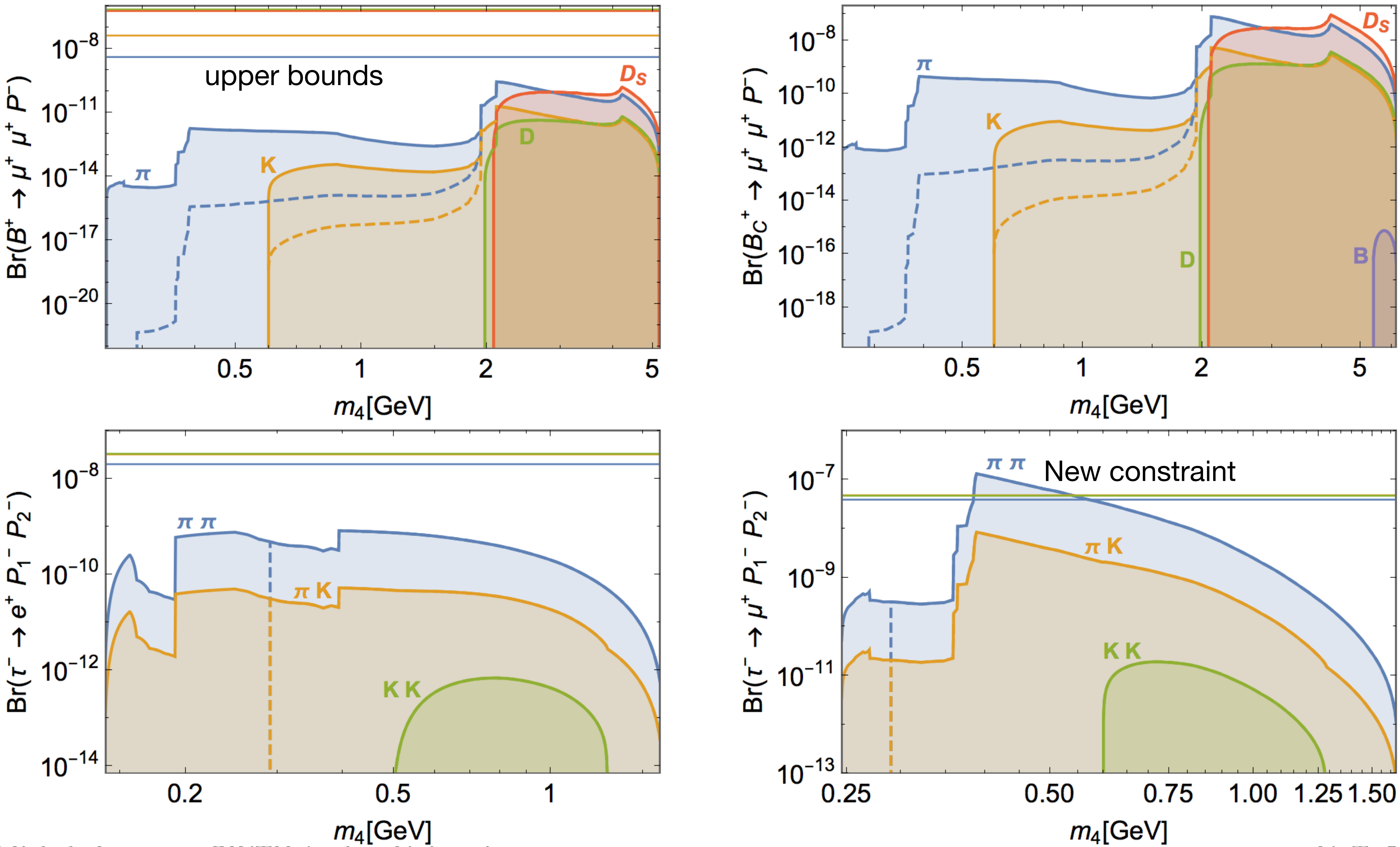


Dashed lines: the on-shell heavy neutrino travels for less than 10 m

Some predictions: single intermediate state

Comprehensive analysis for τ and pseudo-scalar mesons in 1712.03984

(all possible initial and 3-body final states)



Multiple intermediate states: interference

A. Abada, C. Hati, X. Marcano and A. M. Teixeira, arXiv:1904.05367 [hep-ph]

If more than one heavy neutrino mediate the process, and

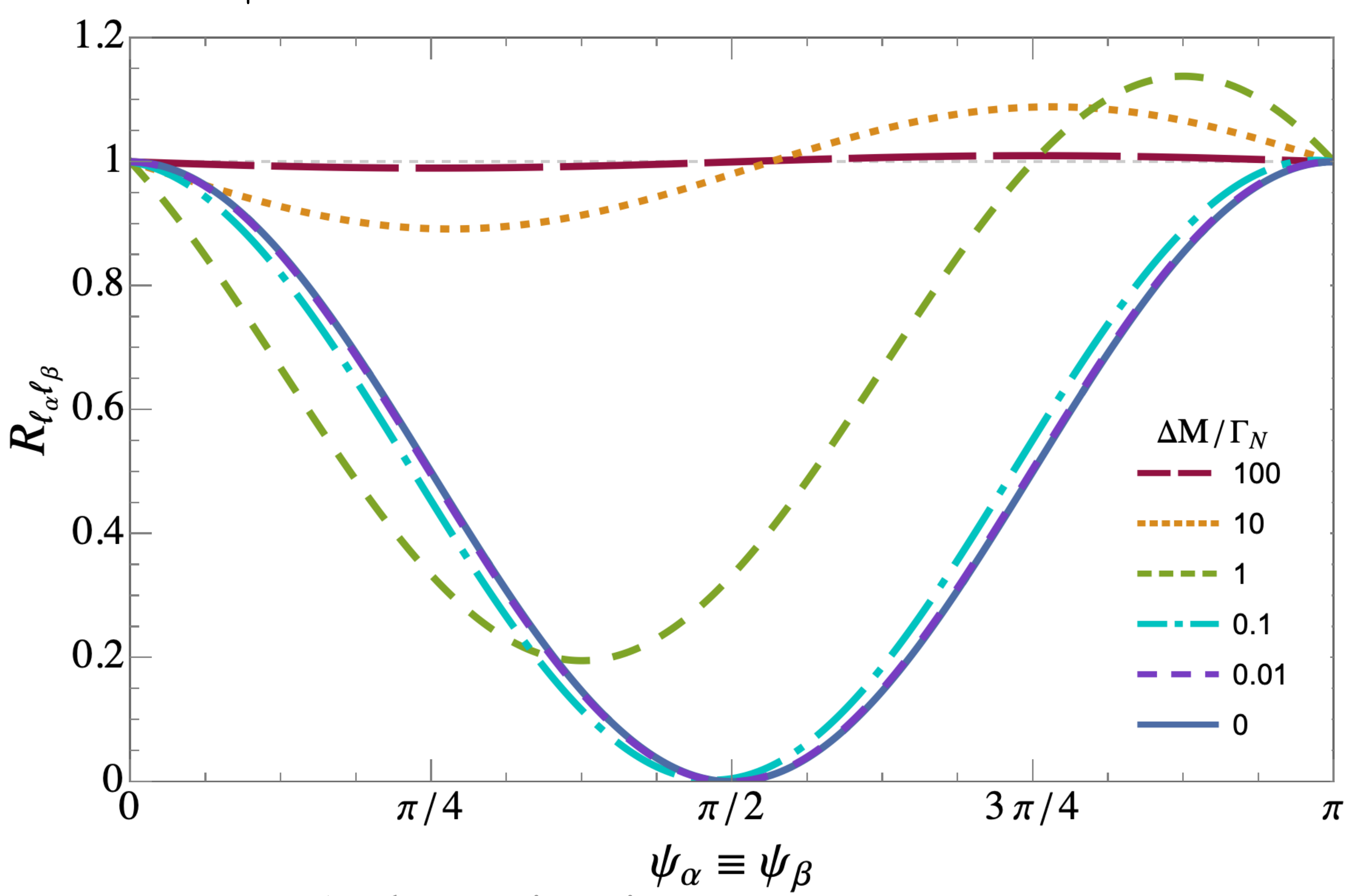
$$\Delta M \ll M \quad \text{and} \quad \Delta M < \Gamma_N$$

interference effects arise due to the CP-violating phases

$$\left|\mathcal{A}^{\rm LNC}_{M\to M'\ell^+_\alpha\ell^-_\beta}\right|^2 \propto \left|U_{\alpha 4}U^*_{\beta 4}g(m_4) + U_{\alpha 5}U^*_{\beta 5}g(m_5)\right|^2,$$

$$\left|\mathcal{A}^{\rm LNV}_{M\to M'\ell^+_\alpha\ell^+_\beta}\right|^2 \propto \left|U_{\alpha 4}U_{\beta 4}f(m_4) + U_{\alpha 5}U_{\beta 5}f(m_5)\right|^2,$$

$$R_{\ell_\alpha\ell_\beta} \equiv \frac{\Gamma^{\rm LNV}_{M\to M'\ell^\pm_\alpha\ell^\pm_\beta}}{\Gamma^{\rm LNC}_{M\to M'\ell^\pm_\alpha\ell^\mp_\beta}}$$



$$U_{\alpha i} = e^{-i\phi_{\alpha i}}|U_{\alpha i}|$$

$$\psi_\alpha \equiv \phi_{\alpha 5} - \phi_{\alpha 4}$$

Dirac limit

$$\frac{\Delta M}{\Gamma_N} = 0$$

$$\psi_\alpha = \frac{\pi}{2}$$

LHC SEARCHES

LNV at LHC

Heavy neutrinos in pp collisions produced through a variety of mechanisms

charge (neutral) current Drell-Yan

gluon fusion

W γ fusion

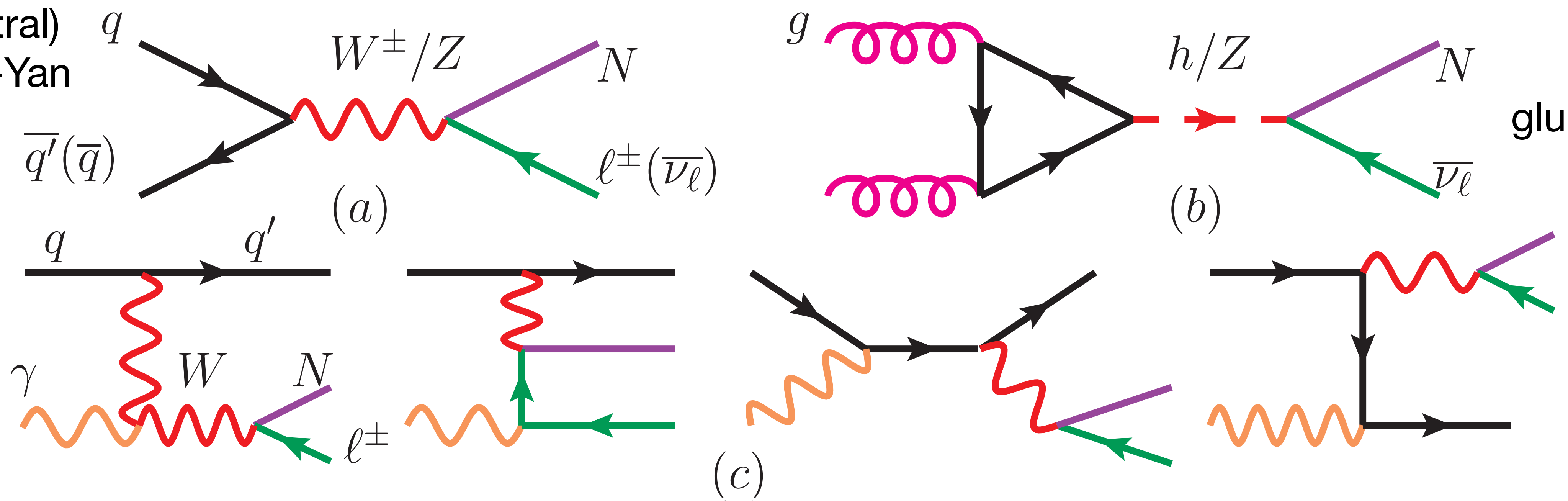


Figure from C. Degrande, O. Mattelaer, R. Ruiz and J. Turner, arXiv:1602.06957 [hep-ph];
see also Y. Cai, T. Han, T. Li and R. Ruiz, arXiv:1711.02180 [hep-ph]

LNV can manifest with clean experimental signatures:

e.g. two same-sign leptons (any flavour combination of e and μ) and at least one jet

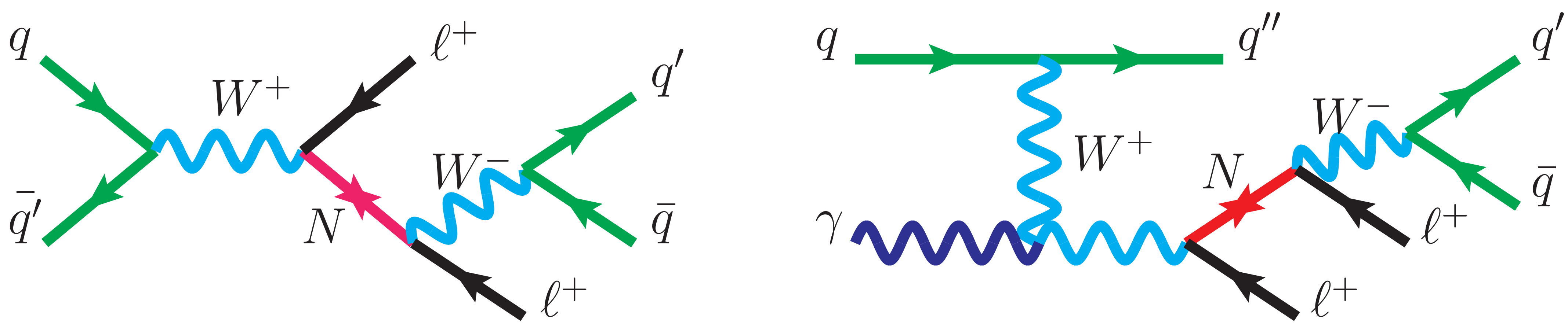
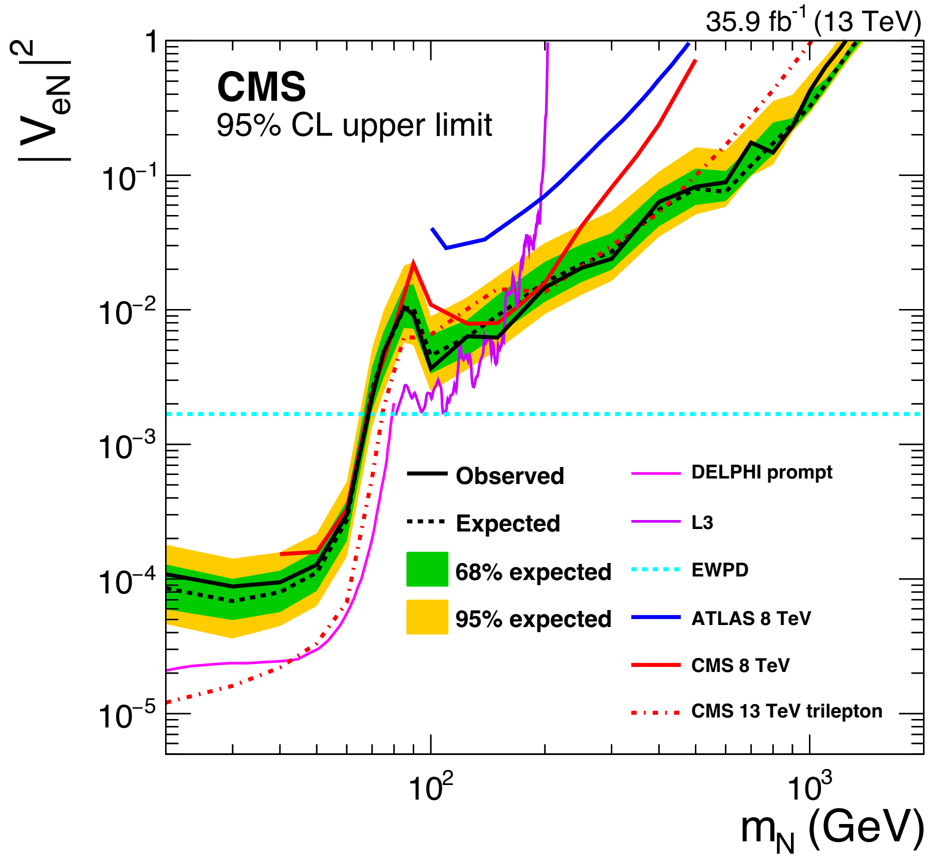
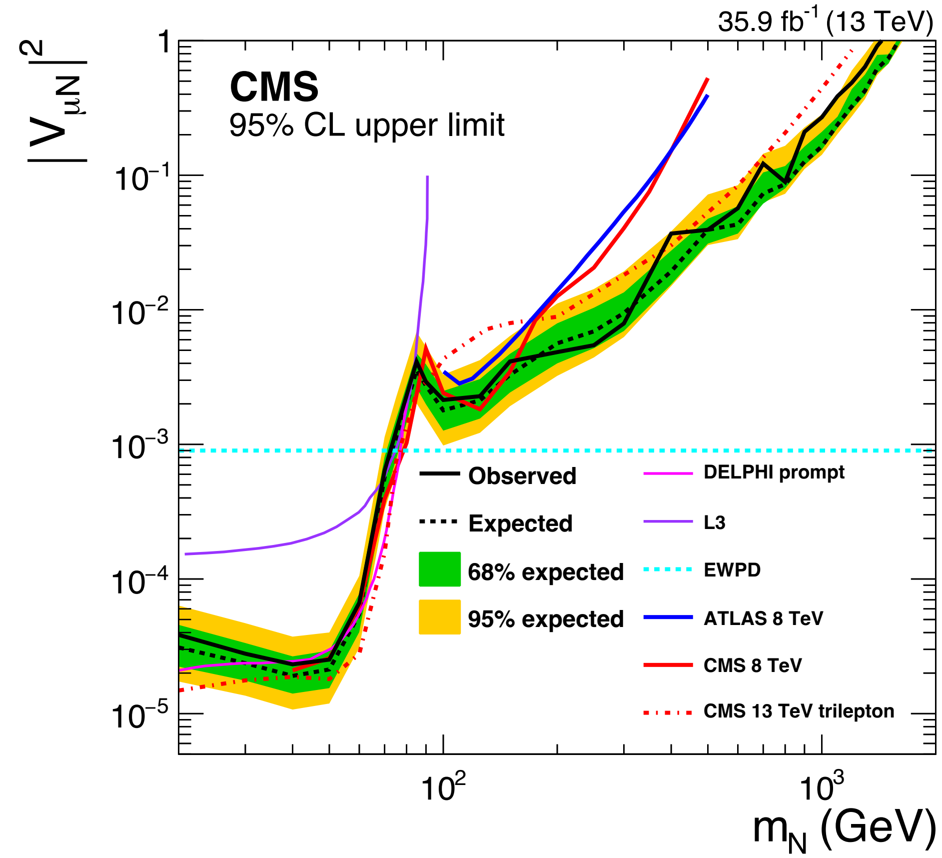


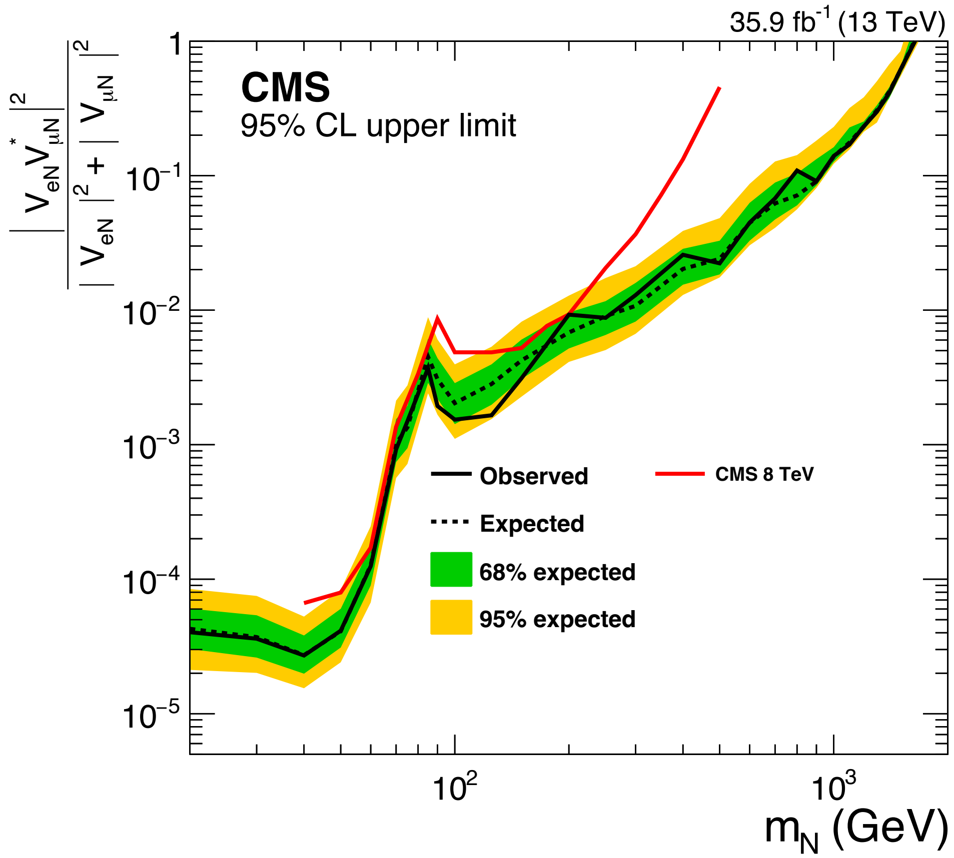
Figure from CMS Collaboration, arXiv:1806.10905 [hep-ex]

Current bounds: single mediator

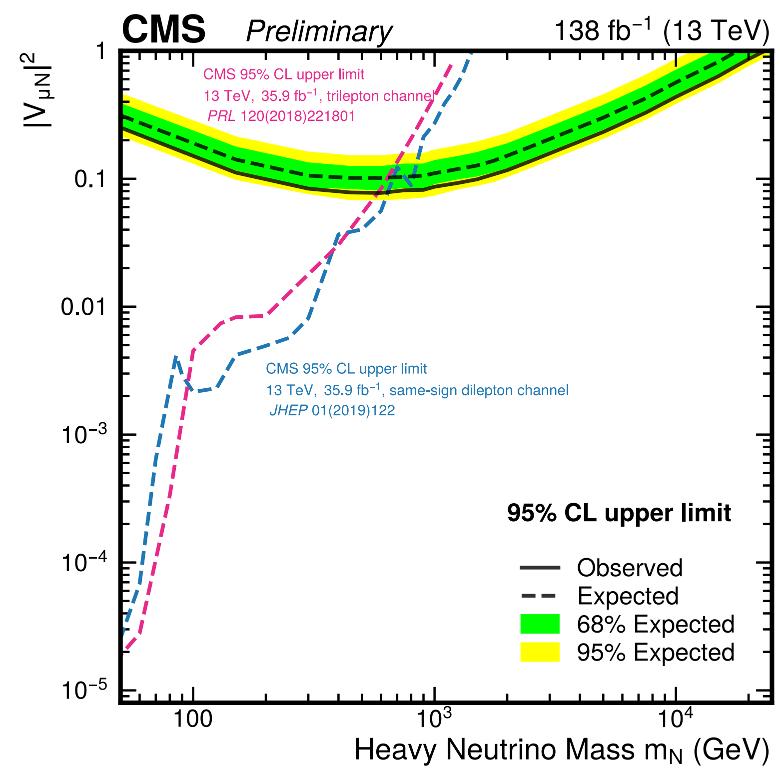
CMS Collaboration, arXiv:1806.10905 [hep-ex]; **see also** ATLAS Collaboration, arXiv:1506.06020 [hep-ex]







Vector boson fusion



CMS-PAS-EXO-21-003

LNV/LNC oscillations

Y. Nir, Conf. Proc. C9207131, 81 (1992); G. Anamiati, M. Hirsch and E. Nardi, arXiv:1607.05641 [hep-ph]

Flavour eigenstate = coherent superposition of mass eigenstates

$$\begin{cases} N_\ell = \frac{1}{\sqrt{2}}(N_+ - iN_-) \\ N_{\bar{\ell}} = \frac{1}{\sqrt{2}}(N_+ + iN_-) \end{cases}$$

evolution →

$$\begin{cases} N_\ell(t) = g_+(t)N_\ell + g_-(t)N_{\bar{\ell}} \\ N_{\bar{\ell}}(t) = g_-(t)N_\ell + g_+(t)N_{\bar{\ell}} \end{cases}$$

$$g_+(t) = e^{-iMt}e^{-\frac{\Gamma}{2}t}\cos\left(\frac{\Delta M}{2}t\right)$$

$$g_-(t) = i\,e^{-iMt}e^{-\frac{\Gamma}{2}t}\sin\left(\frac{\Delta M}{2}t\right)$$

$$\Delta M = M^+ - M^-$$

Timescales

$\Delta M \gg \Gamma$	**decay after decoherence (Majorana limit)**
$\Delta M \approx \Gamma$	**oscillations**
$\Delta M \ll \Gamma$	**oscillations do not develop (Dirac limit)**

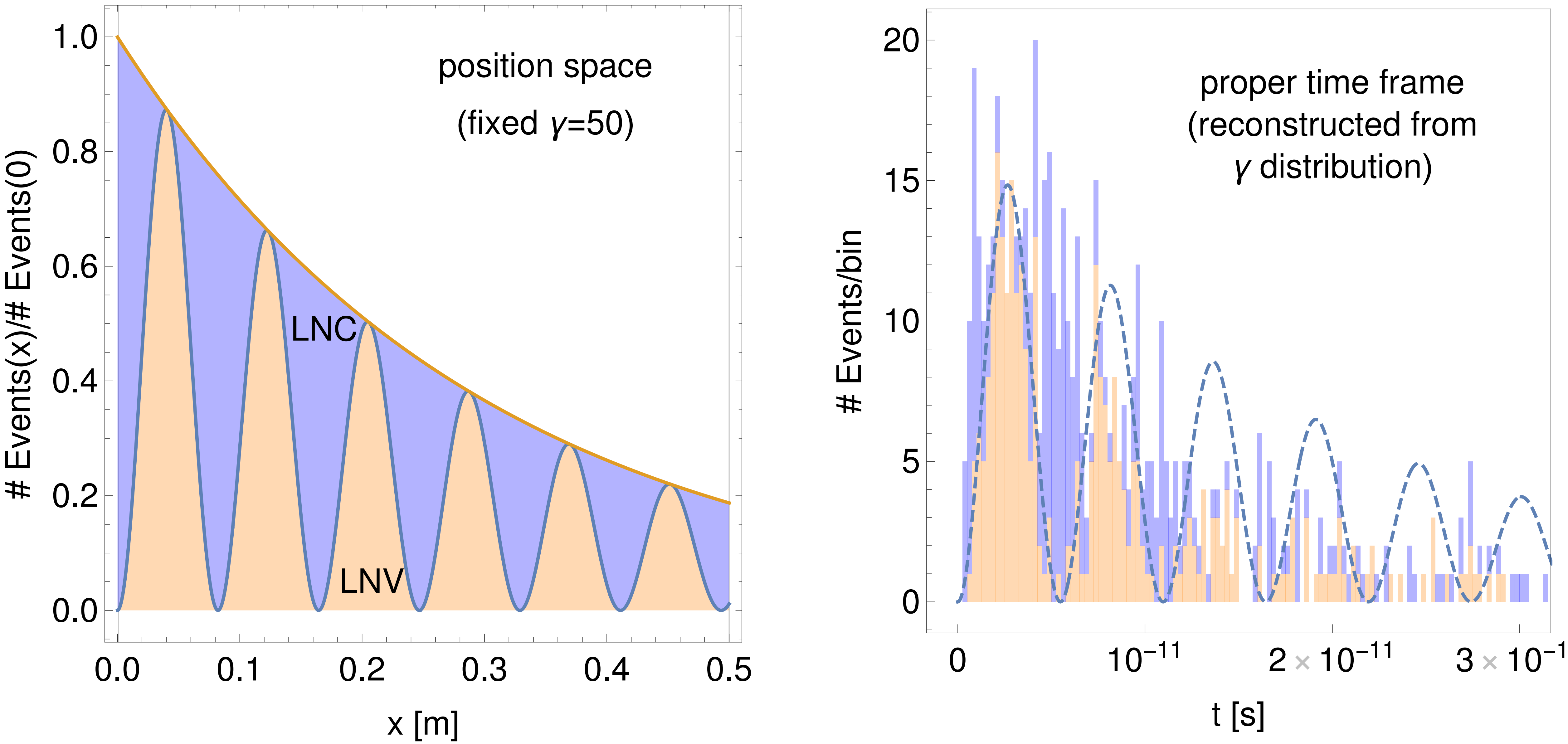
$$R_{\ell\ell}(t_1,t_2) = \frac{\int_{t_1}^{t_2}|g_-(t)|^2 dt}{\int_{t_1}^{t_2}|g_+(t)|^2 dt} = \frac{\#(\ell^+\ell^+) + \#(\ell^-\ell^-)}{\#(\ell^+\ell^-)}$$

$$R_{ll}(0,\infty) = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

Are these oscillations observable?

S. Antusch, E. Cazzato and O. Fischer, arXiv:1709.03797 [hep-ph]

E.g. LHCb experiment for
Linear Seesaw with M = 7 GeV, $U^2 = 10^{-5}$, Inverted Ordering



However, for heavy neutrinos with γ=50

- very forward rapidity
- very small track separation of decay products

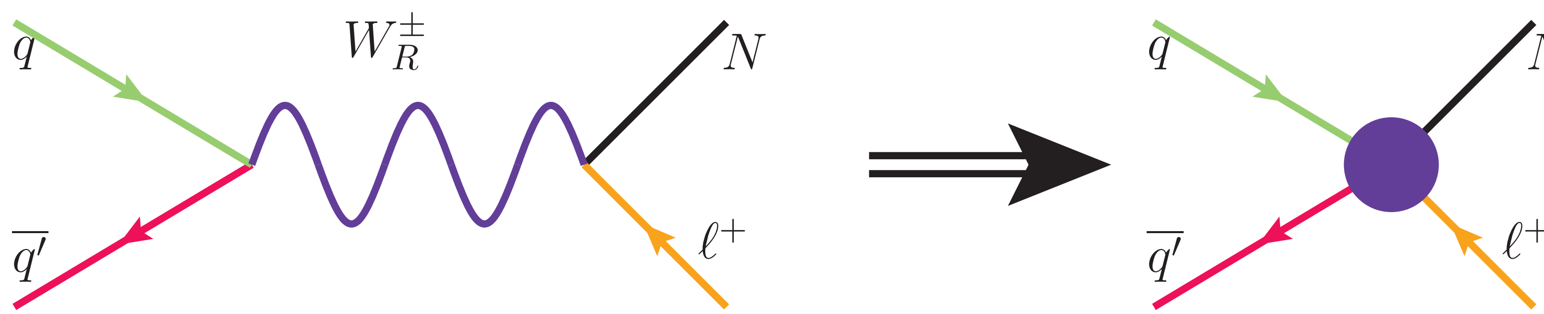
Richard Ruiz, private communication

Why to look for LNV if $m_\nu \simeq 0$?

Equivalence between L conservation and massless neutrinos only holds in SM + singlet fermions

E.g. Left-right symmetric model

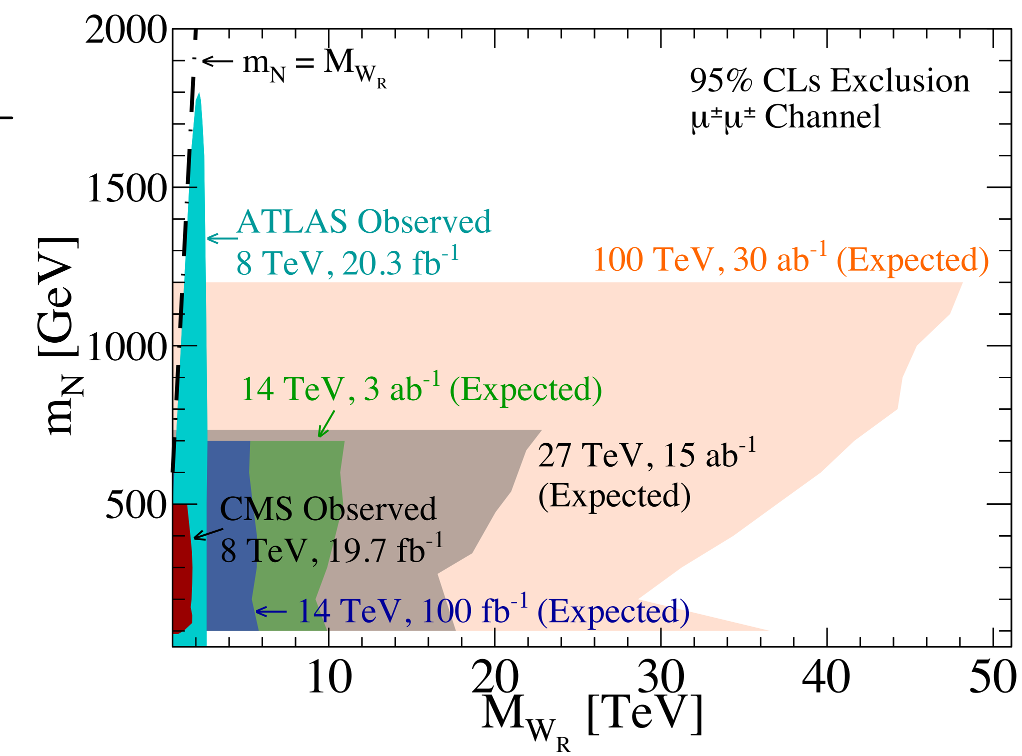
If new gauge mediators are too heavy, light N are still accessible



Courtesy of Richard Ruiz

When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ production in the LRSM and minimal Type I Seesaw are not discernible[11]

- **Signature:** $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N)$ + no MET
- At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab^{-1}, $M_{W_R} \lesssim 9$ (40) TeV probed
- **DO NOT STOP SEARCHING FOR TYPE I LNV**

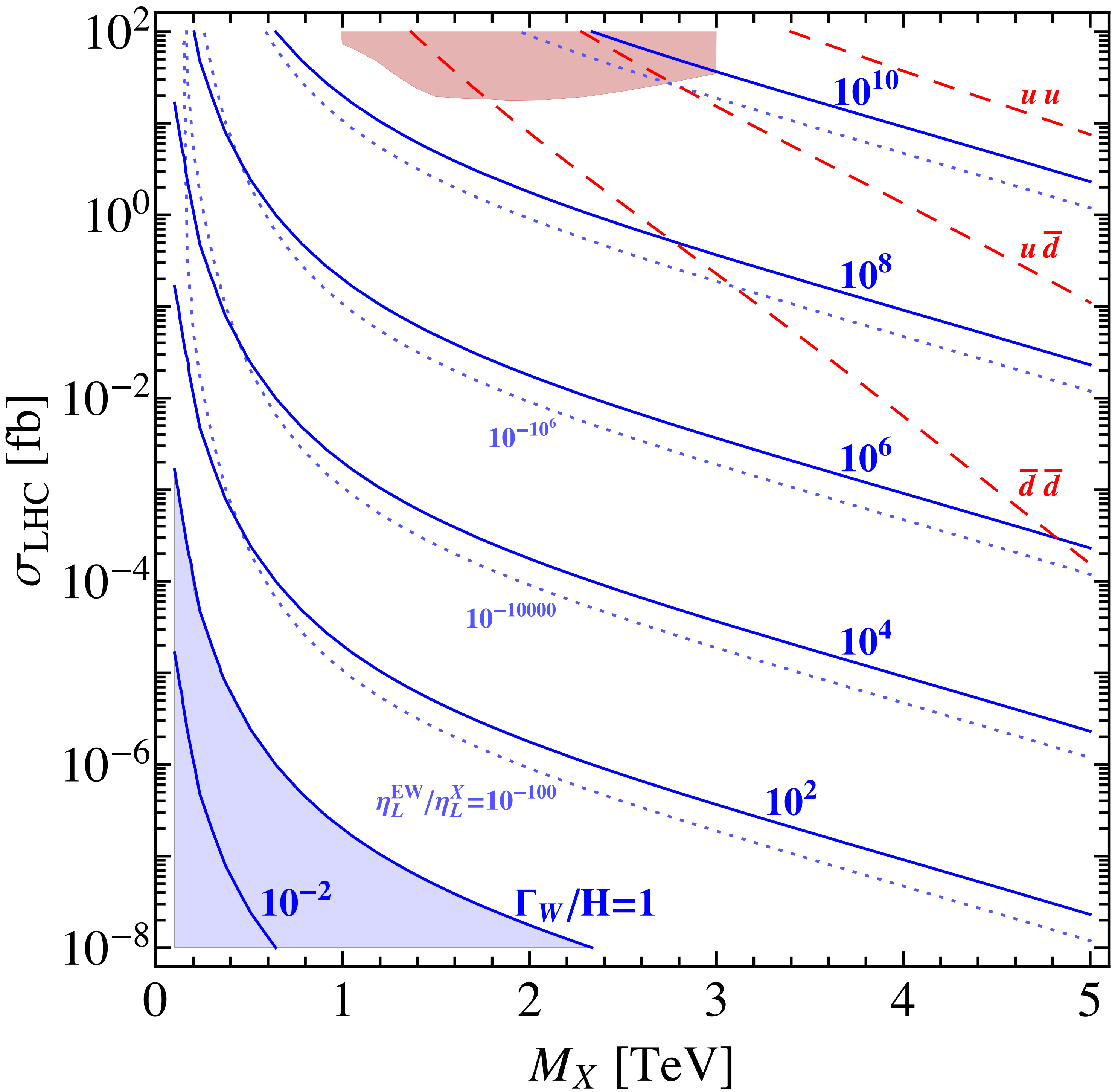


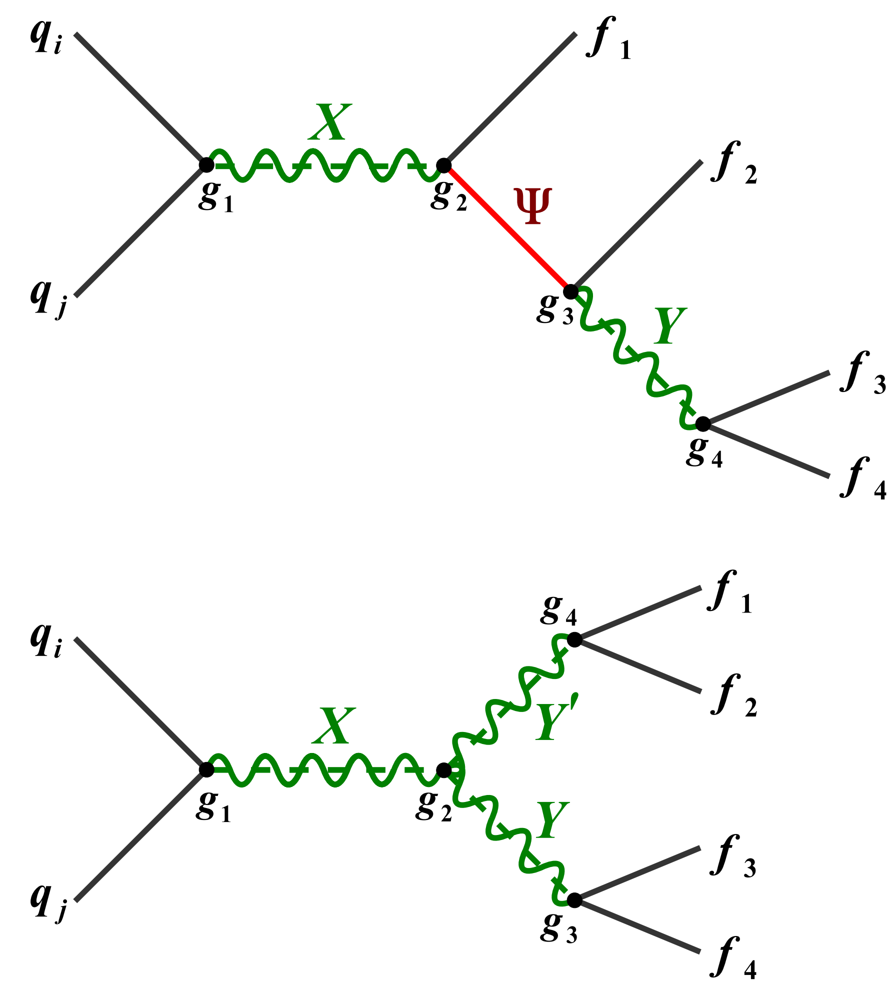
[11] Han, Lewis, **RR**, Si, [1211.6447]; **RR**, [1703.04669]

R. Ruiz - CP3, Universite Catholique de Louvain | Heavy N: From Beam Dumps to Colliders - Melbourne Uni. 28 / 38

Falsify high-scale leptogenesis with LNV

J. M. Frere, T. Hambye and G. Vertongen, arXiv:0806.0841 [hep-ph];
F. F. Deppisch, J. Harz and M. Hirsch, arXiv:1312.4447 [hep-ph]





$$\frac{\Gamma_W}{H} = \frac{0.028}{\sqrt{g_*}}\frac{M_{\rm P} M_X^3}{T^4}\frac{K_1\left(M_X/T\right)}{f_{q_1 q_2}\left(M_X/\sqrt{s}\right)} \times \left(s\sigma_{\rm LHC}\right)$$

A LNV observation at LHC likely falsifies high-scale leptogenesis

Early Universe

Low Scale Leptogenesis with 2 RHN

The approximate L conservation forces the **HNL** to be **degenerate in mass**

$$M_0 = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}}Yv & 0 \\ \frac{1}{\sqrt{2}}Yv & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \quad \Rightarrow \quad m_\nu = 0\,, \quad M_{1,2} = \sqrt{|\Lambda|^2 + \frac{1}{2}|Yv|^2}$$

$$\Delta M_{ISS} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \xi\,\Lambda \end{pmatrix} \quad \Delta M_{LSS} = \begin{pmatrix} 0 & 0 & \frac{\epsilon}{\sqrt{2}}Y'v \\ 0 & 0 & 0 \\ \frac{\epsilon}{\sqrt{2}}Y'v & 0 & 0 \end{pmatrix} \quad \Rightarrow \quad m_\nu \simeq 2\epsilon\frac{m_D^2}{M_{1,2}}\,, \quad \Delta m^2 \simeq 2\xi M_{1,2}^2$$

This allows to account for BAU via freeze-in leptogenesis with low-scale NHL

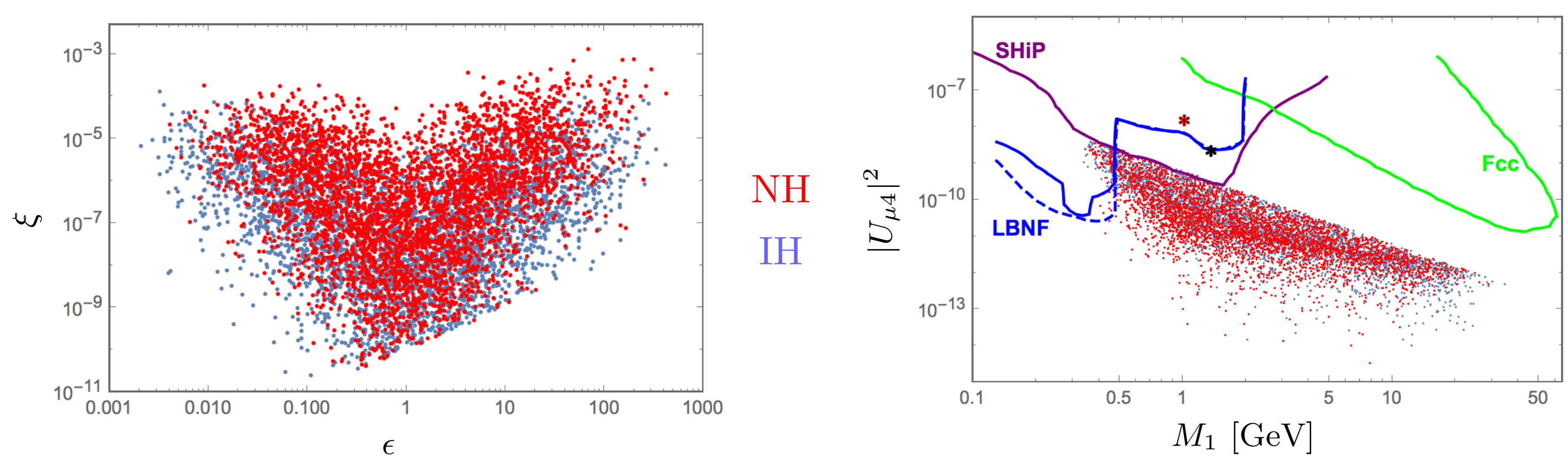
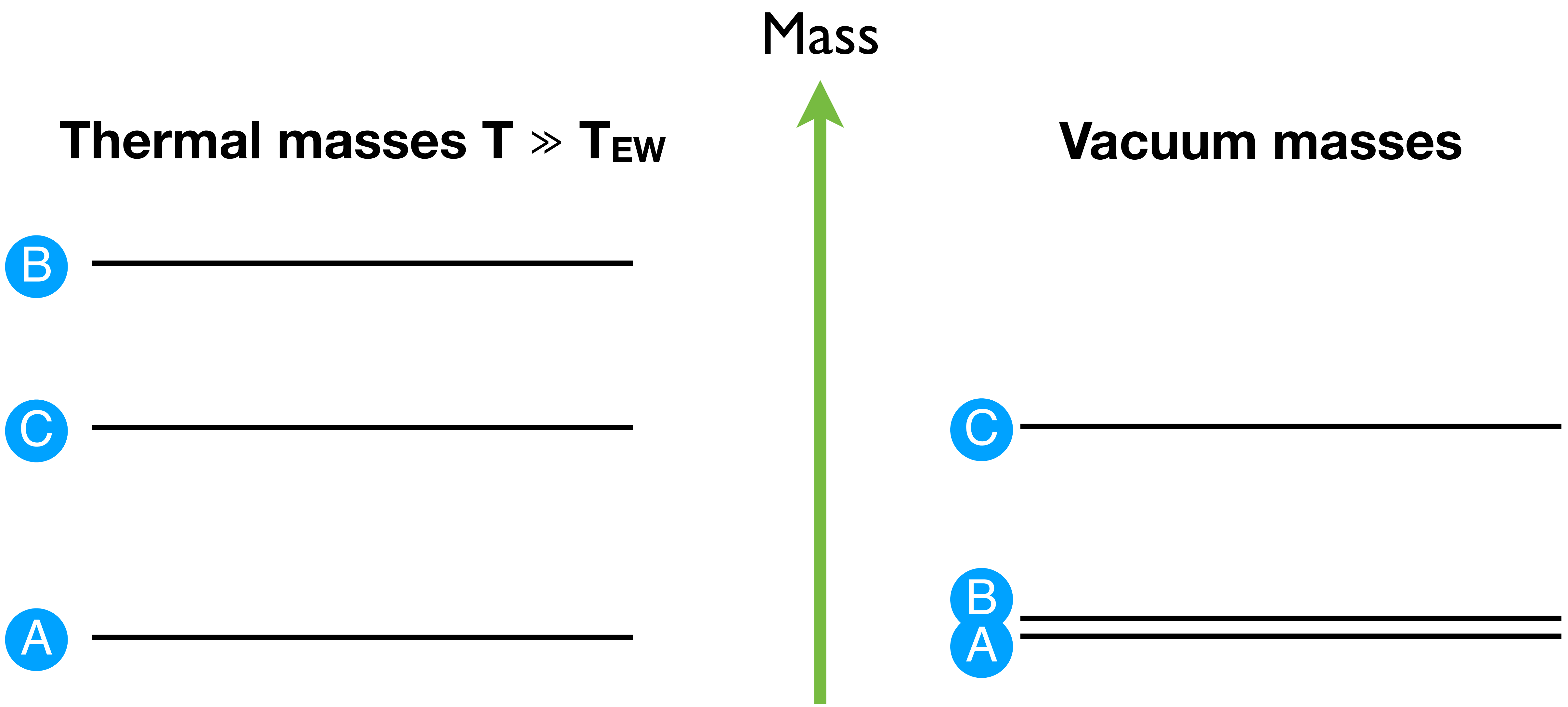


Figure from A. Abada, G. Arcadi, V. Domcke and M. Lucente, arXiv:1507.06215 [hep-ph]

Many studies, e.g. E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255; T. Asaka and M. Shaposhnikov, hep-ph/0505013; M. Shaposhnikov, arXiv:0804.4542 [hep-ph]; T. Asaka and H. Ishida, arXiv:1004.5491 [hep-ph]; T. Asaka, S. Eijima and H. Ishida, arXiv:1112.5565 [hep-ph]; L. Canetti, M. Drewes and M. Shaposhnikov, arXiv:1204.4186 [hep-ph]; L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]; P. Hernández, M. Kekic, J. López-Pavón, J. Racker and N. Rius, arXiv:1508.03676 [hep-ph]…

Low Scale Leptogenesis with 3 RHN

Mass spectrum with 3 right-handed neutrinos and B - L symmetry

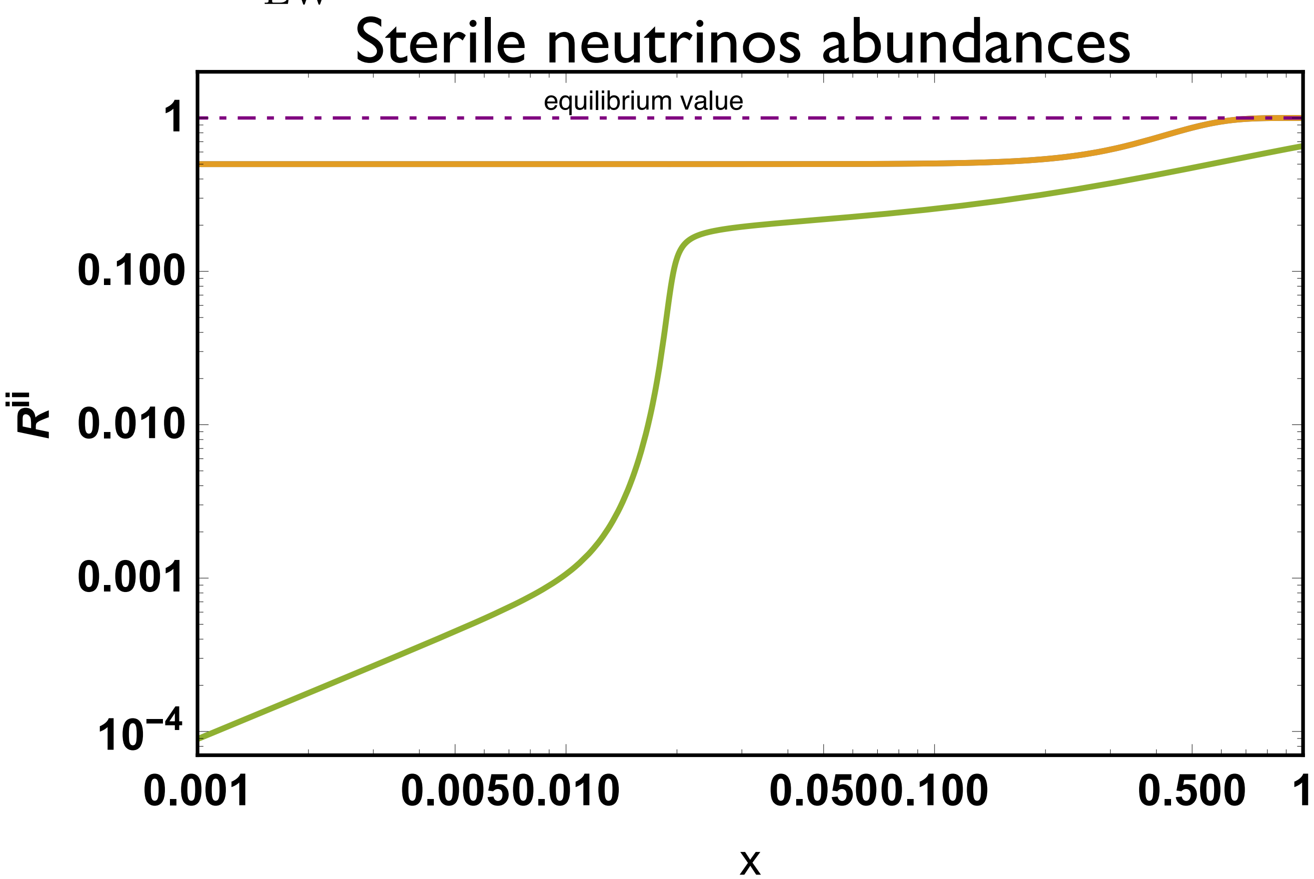


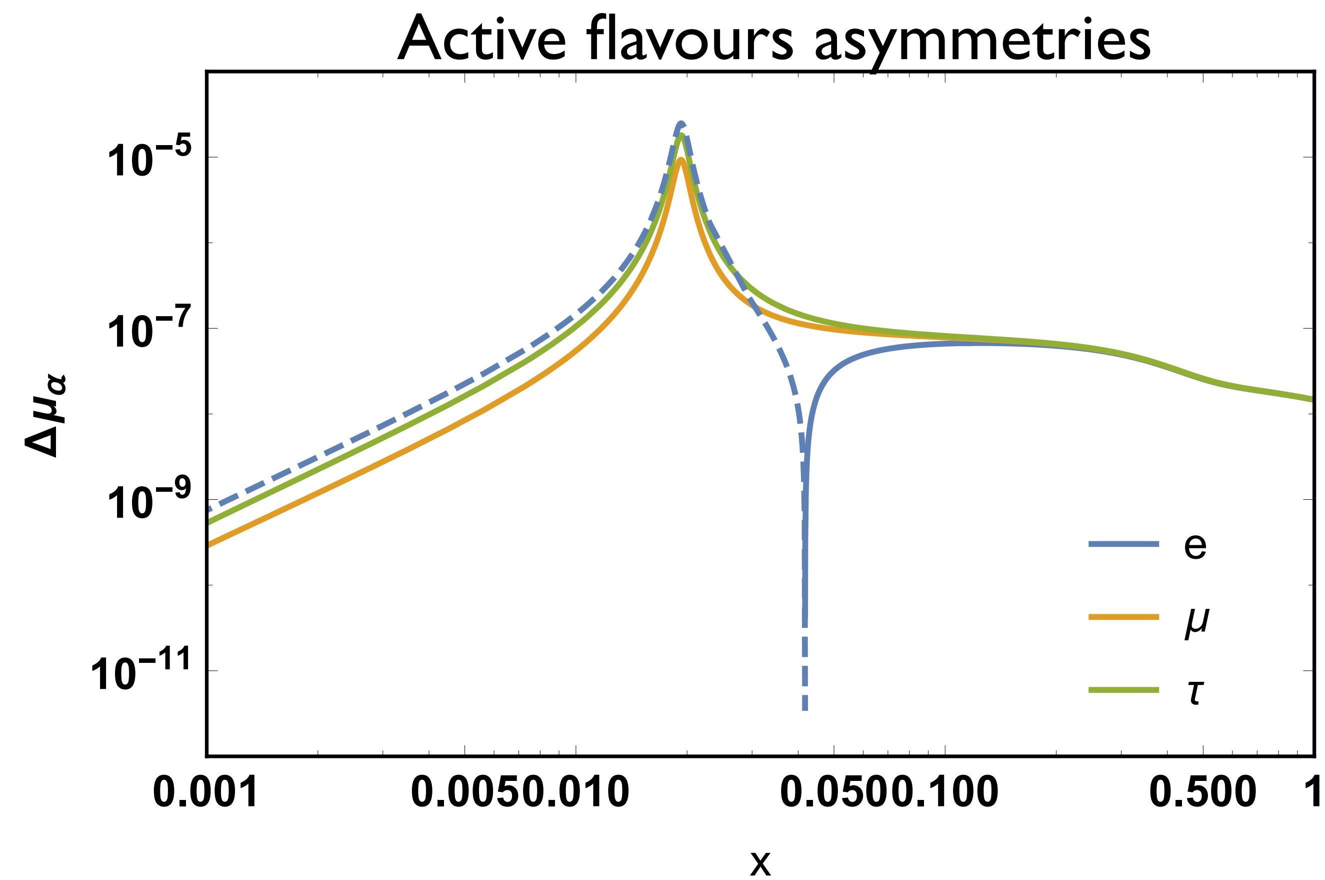
If the vacuum mass of the decoupled state is heavier than the pseudo-Dirac one, there is **necessarily** a level crossing at some finite temperature

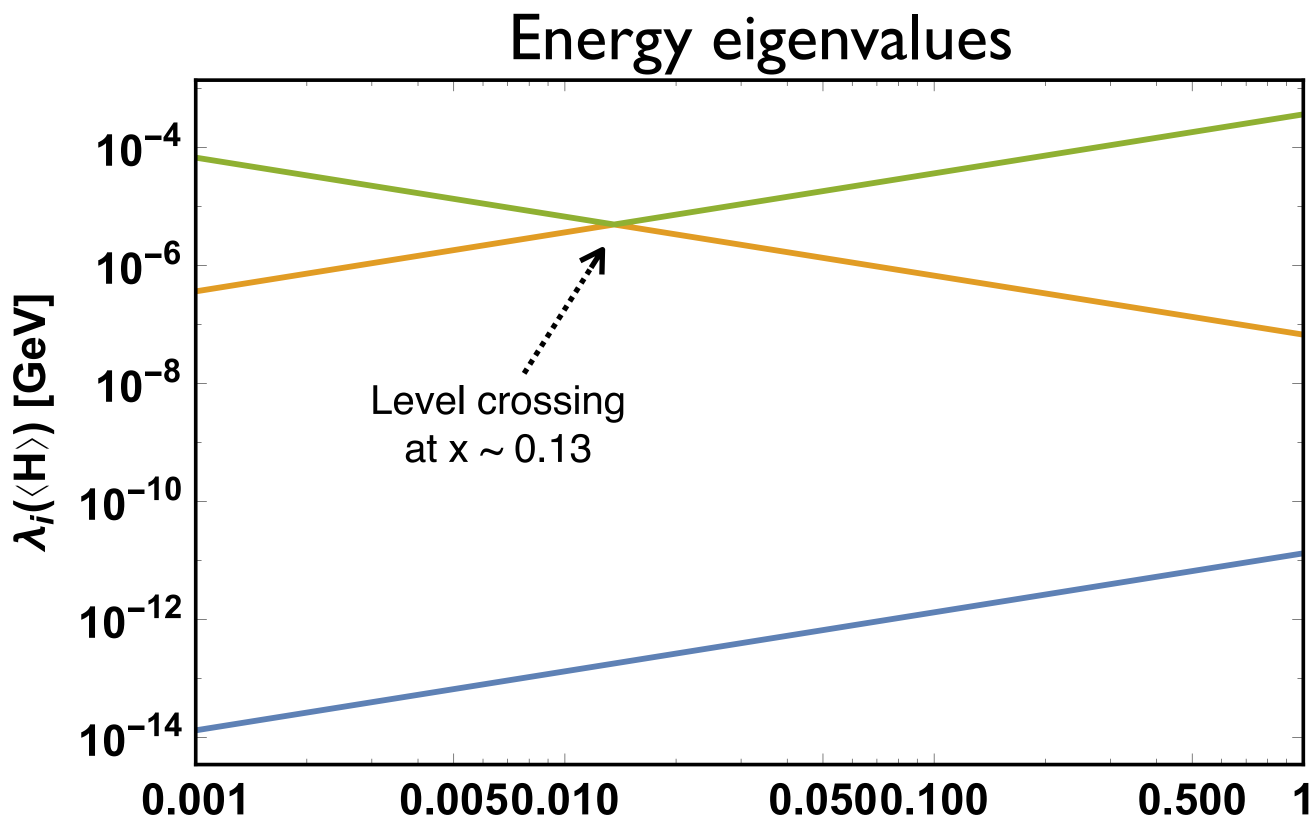
A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M. Lucente, arXiv:1810.12463 [hep-ph]

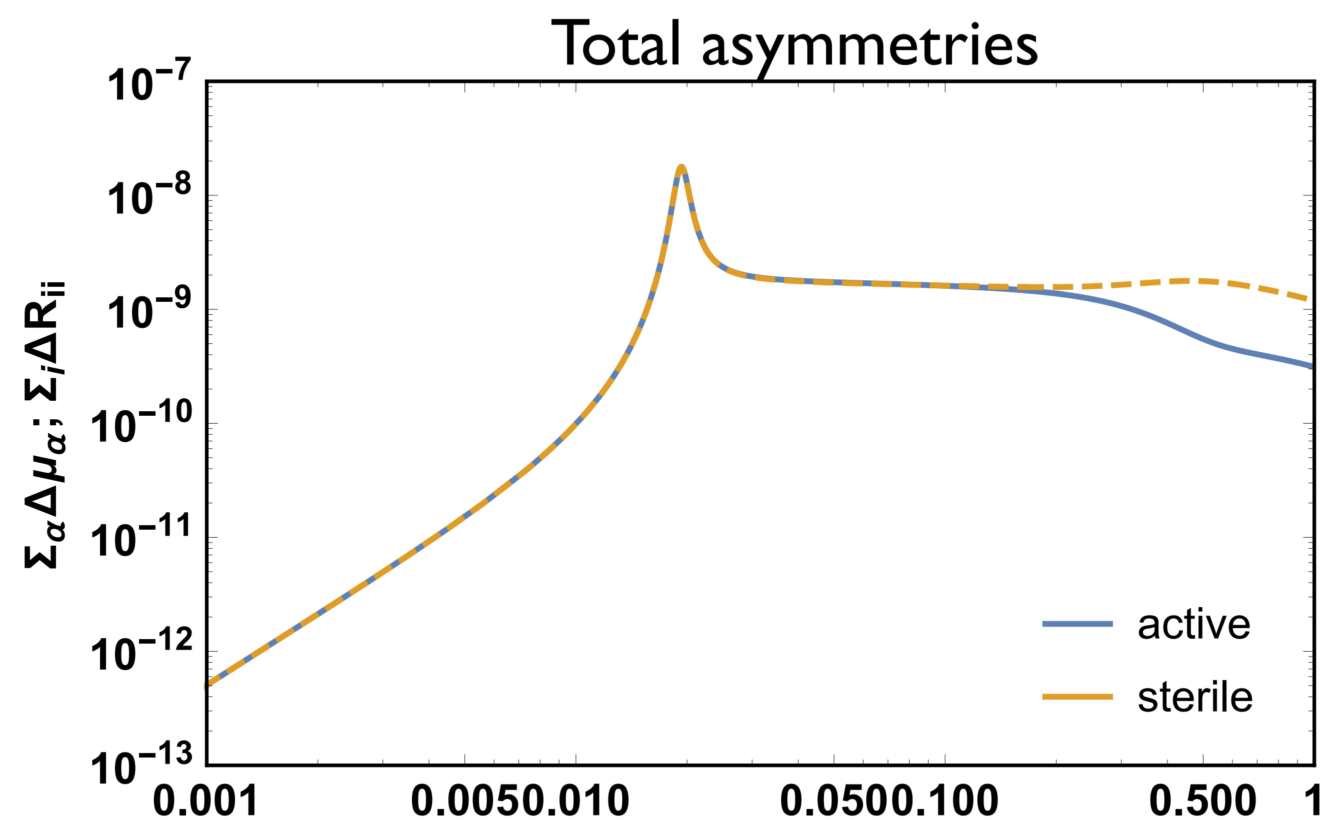
Level crossing: resonant asymmetry production

$x = \frac{T}{T_{\text{EW}}}$ T_{EW} = 140 GeV R : sterile neutrinos density matrix μ_α : active flavours chemical potentials









Conclusion

Lepton number is an accidental symmetry of the SM: test its conservation!

It is violated by non-renormalizable SM operators: EFT generation of ν masses

LNV phenomenology is generally connected with ν mass generation mechanism

LNV rates depend in general on the interference of multiple virtual states

Possible to look for LNV in e.g.
- **neutrinoless 2β decay**
- **meson decay**
- **collider events**

LNV observation could signal the existence of new gauge bosons and/or falsify high-scale leptogenesis

A global B-L symmetry has non-trivial consequences in the early Universe

Backup

Temperature of level crossing

The level crossing temperature in the SM + 3 RHN can be estimated at

$$T_{\text{crossing}} \approx \frac{2\sqrt{2}\bar{M}\sqrt{\mu'^2 - 1}}{\sqrt{\sum_a |F_a|^2}} = 2.8 \times 10^5 \text{ GeV} \left(\frac{\bar{M}}{\text{GeV}}\right) \frac{\sqrt{\mu'^2 - 1}}{\sqrt{\sum_a |(F_a/10^{-5})|^2}}$$

where the Majorana and Yukawa matrices are parameterised as

$$M_M = \bar{M} \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix} \qquad F = \frac{1}{\sqrt{2}} \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}$$

Momentum averaged effective Hamiltonian for the heavy neutrinos

$$\langle H \rangle = \langle H_0 + V_N \rangle = \frac{\pi^2}{36\,\zeta(3)} \left(\frac{\text{diag}(0, M_2^2 - M_1^2, M_3^2 - M_1^2)}{T} + \frac{T}{8} F^\dagger F \right)$$

Quantum kinetic equations for freeze-in leptogenesis

$$
\begin{aligned}
\frac{dR_N}{dt} =& - i\,[\langle H\rangle, R_N] - \frac{1}{2}\langle\gamma^{(0)}\rangle \left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle \left\{F^\dagger \mu F, R_N\right\} + \langle\gamma^{(1a)}\rangle F^\dagger \mu F + \\
& - \frac{1}{2}\langle\widetilde{\gamma}^{(0)}\rangle \left\{M_M F^T F^* M_M, R_N - I\right\} + \frac{1}{2}\langle\widetilde{\gamma}^{(1b)}\rangle \left\{M_M F^T \mu F^* M_M, R_N\right\} + \\
& - \langle\widetilde{\gamma}^{(1a)}\rangle M_M F^T \mu F^* M_M \,,
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\mu_{\Delta a}}{dt} =& - \frac{9\,\zeta(3)}{2N_D\,\pi^2} \Big\{ \langle\gamma^{(0)}\rangle \left(F R_N F^\dagger - F^* R_{\bar N} F^T\right) - 2\langle\gamma^{(1a)}\rangle \mu F F^\dagger + \\
& + \langle\gamma^{(1b)}\rangle \mu \left(F R_N F^\dagger + F^* R_{\bar N} F^T\right) \\
& + \langle\widetilde{\gamma}^{(0)}\rangle \left(F^* M_M R_{\bar N} M_M F^T - F M_M R_N M_M F^\dagger\right) - 2\langle\widetilde{\gamma}^{(1a)}\rangle \mu F^* M_M^2 F^T \\
& + \langle\widetilde{\gamma}^{(1b)}\rangle \mu \left(F^* M_M R_{\bar N} M_M F^T + F M_M R_N M_M F^\dagger\right) \Big\}_{aa} \,,
\end{aligned}
$$

G. Sigl and G. Raffelt, Nucl. Phys. B406 (1993) 423; E. K. Akhmedov, V. A. Rubakov and A. Yu. Smirnov, 9803255; T. Asaka and M. Shaposhnikov, 0505013; L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, 1208.4607; T. Asaka, S. Eijima and H. Ishida, 1112.5565; P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Racker and J. Salvado, 1606.06719; S. Antusch, E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter et al., 1710.03744; A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M. Lucente, 1810.12463

Some SM extensions with L symmetry

Linear seesaw

E. K. Akhmedov, M. Lindner, E. Schnapka and J. W. F. Valle, hep-ph/9507275 and hep-ph/9509255; S. M. Barr, hep-ph/0309152; M. Malinsky, J. C. Romao and J. W. F. Valle, hep-ph/0506296; M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez, arXiv:0906.1461 [hep-ph]

Inverse seesaw

D. Wyler and L. Wolfenstein, Nucl. Phys. B 218 (1983) 205; R. N. Mohapatra, Phys. Rev. Lett. 56 (1986) 561; R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D 34 (1986) 1642; J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez and J. W. F. Valle, Phys. Lett. B 187 (1987) 303; M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. B 216 (1989) 360; F. Deppisch and J. W. F. Valle, hep-ph/0406040; A. Abada and M. Lucente, arXiv:1401.1507 [hep-ph]

Supersymmetry with R-parity violation

J. R. Ellis, G. Gelmini, C. Jarlskog, G. G. Ross and J. W. F. Valle, Phys. Lett. 150B (1985) 142; G. G. Ross and J. W. F. Valle, Phys. Lett. 151B (1985) 375; J. C. Romao, M. A. Diaz, M. Hirsch, W. Porod and J. W. F. Valle, hep-ph/9907499; A. Abada and M. Losada, hep-ph/9908352; M. Hirsch, M. A. Diaz, W. Porod, J. C. Romao and J. W. F. Valle, Phys. Rev. D62 (2000) 113008 [hep-ph/0004115]; A. Abada, S. Davidson and M. Losada, hep-ph/0111332

Scale invariance

V. V. Khoze and G. Ro, arXiv:1307.3764 [hep-ph]

Technicolor-inspired

T. Appelquist and R. Shrock, hep-ph/0204141; T. Appelquist and R. Shrock, hep-ph/0301108

νMSM

M. Shaposhnikov, hep-ph/0605047

Low-scale seesaw realisations

A. Ibarra, E. Molinaro and S. T. Petcov, arXiv:1007.2378 [hep-ph]; A. Ibarra, E. Molinaro and S. T. Petcov, arXiv:1103.6217 [hep-ph]; D. N. Dinh, A. Ibarra, E. Molinaro and S. T. Petcov, arXiv:1205.4671 [hep-ph]