PHENOMENOLOGICAL FEATURES OF LOW-SCALE SEESAW

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[Cross-Talk] Exploring neutrino see-saw at colliders

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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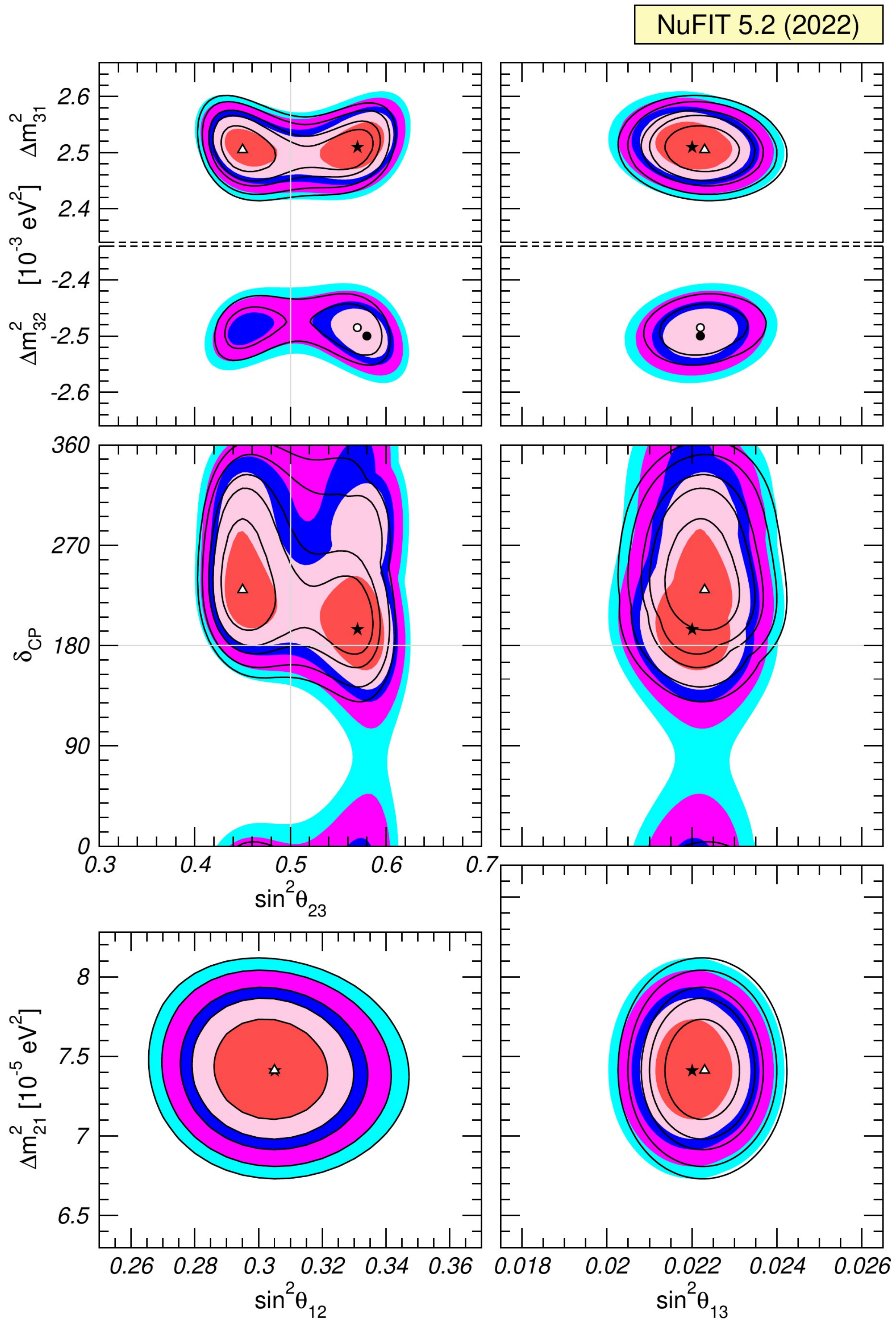
Neutrinos are massive and leptons mix



NuFIT 5.2 (2022)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.142 \to 0.155 \\ 0.233 \to 0.505 & 0.460 \to 0.693 & 0.630 \to 0.779 \\ 0.262 \to 0.525 & 0.473 \to 0.702 & 0.610 \to 0.762 \end{pmatrix}$$

NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

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

Evidence for BSM physics!

The natural (simple) way

Complete the SM field pattern with **right-handed neutrinos**

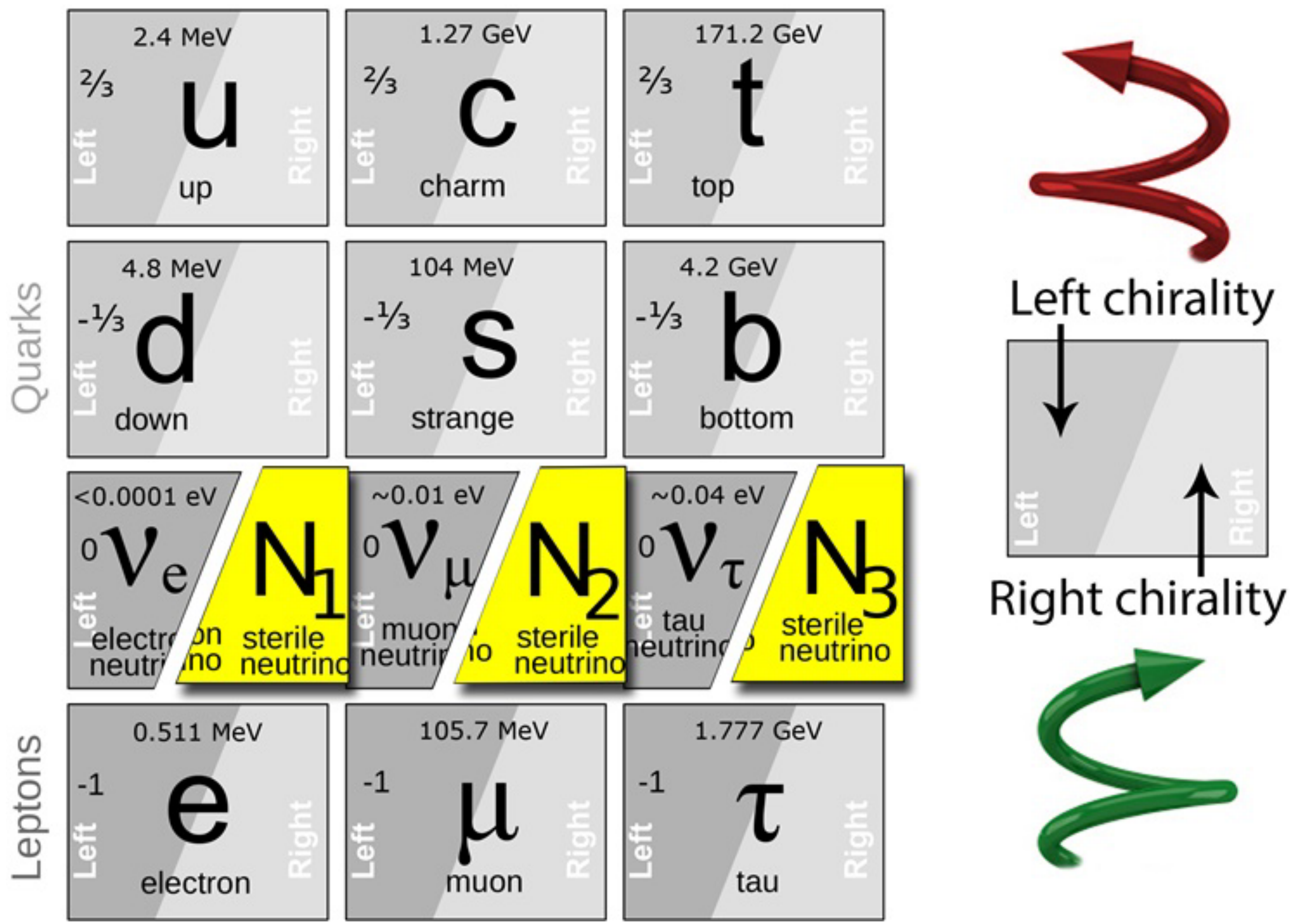


Figure from S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Neutrino masses from sterile singlets

Type-I seesaw mechanism: SM + gauge singlet fermions N_I

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

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

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

m_ν is much smaller than EW scale

Laboratory

$$m_\nu < 1.1\ eV$$

KATRIN collaboration, arXiv:1909.06048 [hep-ex]

Cosmology

$$\sum m_\nu < 0.12\ eV$$

Planck collaboration, arXiv:1807.06209 [astro-ph.CO]

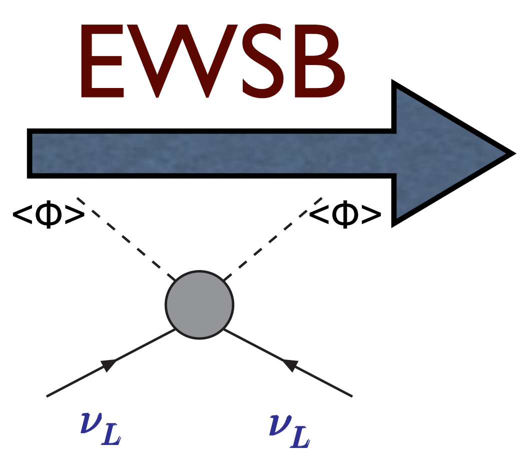
SM as an effective theory

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

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

ΔL = 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

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

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

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

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

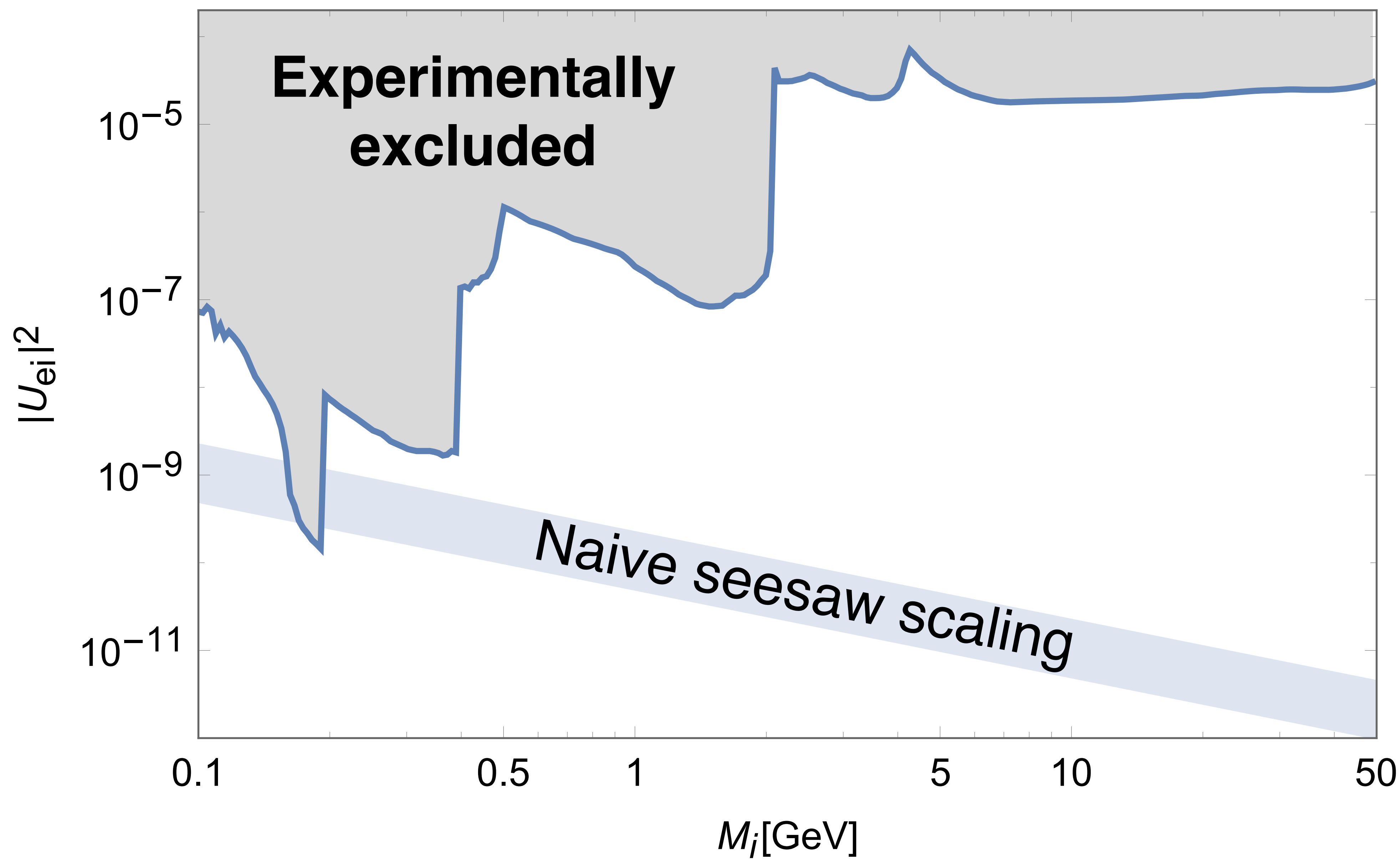
$c_5 \ll 1$

$c_6^i \approx \mathcal{O}(1)$ **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 $|U_{\alpha i}| \lesssim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-5}\sqrt{\frac{\mathrm{GeV}}{M}}$



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)

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

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]

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	$\frac{M_2 - M_1}{M_1 + M_2} \ll 1$ $\mathcal{U}_{\alpha 1} \simeq i\, \mathcal{U}_{\alpha 2}$	$\lvert\mathcal{U}_{\alpha,i}\rvert \ll \lvert\mathcal{U}_{\alpha,j\neq i}\rvert$	$M_i \ll M_{j\neq i}$

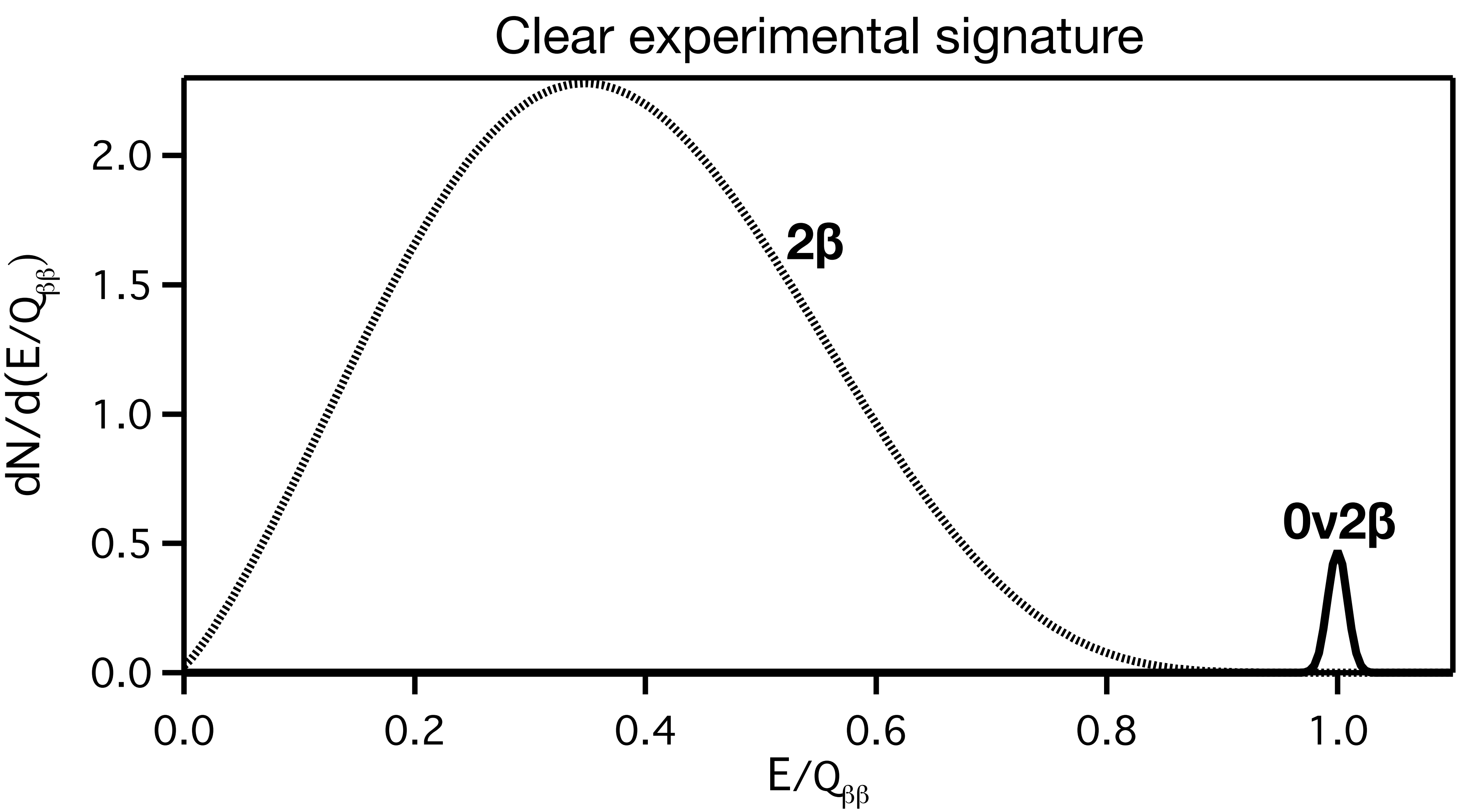
NEUTRINOLESS DOUBLE BETA DECAY

Neutrinoless double beta decay: ΔL = 2

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

If neutrinos are Majorana particles 0ν2β is possible

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



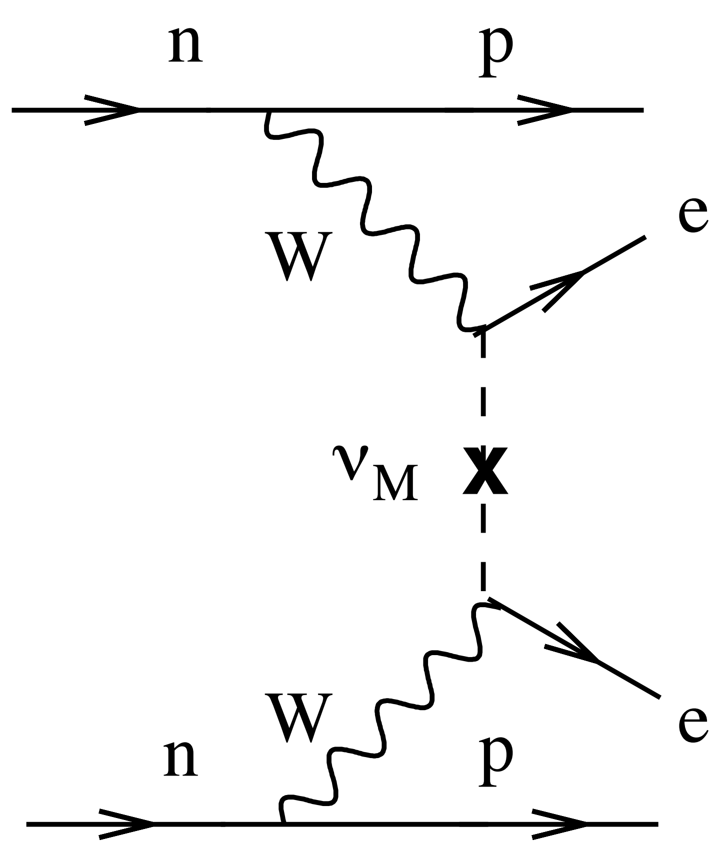


Figure modified from F. T. Avignone III, S. R. Elliott and J. Engel, arXiv:0708.1033 [nucl-ex]

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

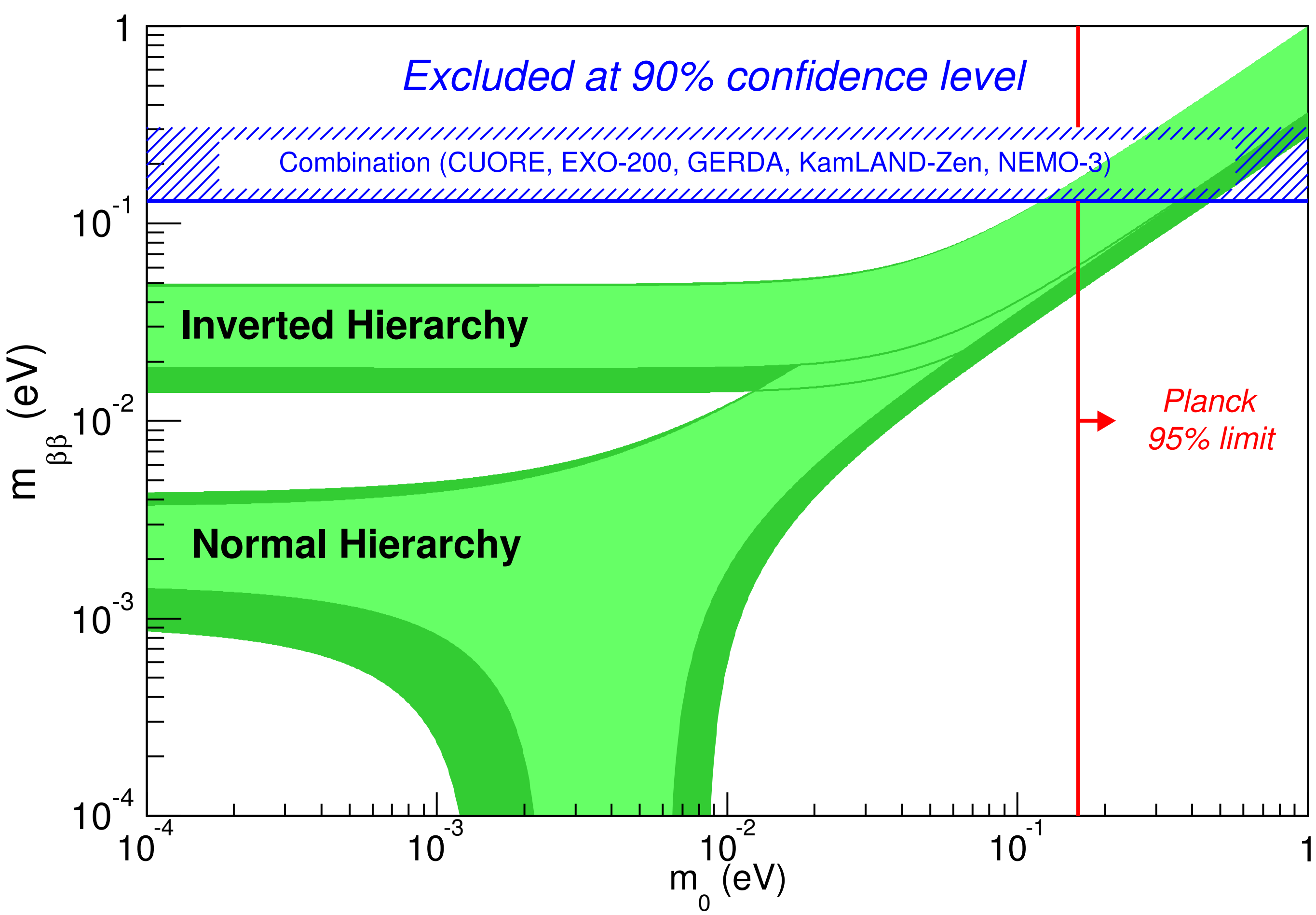


Figure from P. Guzowski, L. Barnes, J. Evans, G. Karagiorgi, N. McCabe and S. Soldner-Rembold, arXiv:1504.03600 [hep-ex]

Current bounds

Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ 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]

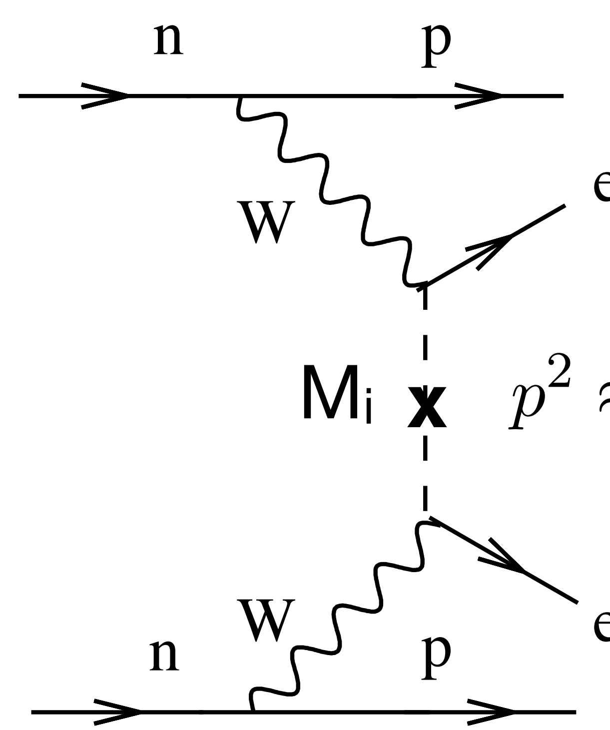
Contribution of heavy neutrinos

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]

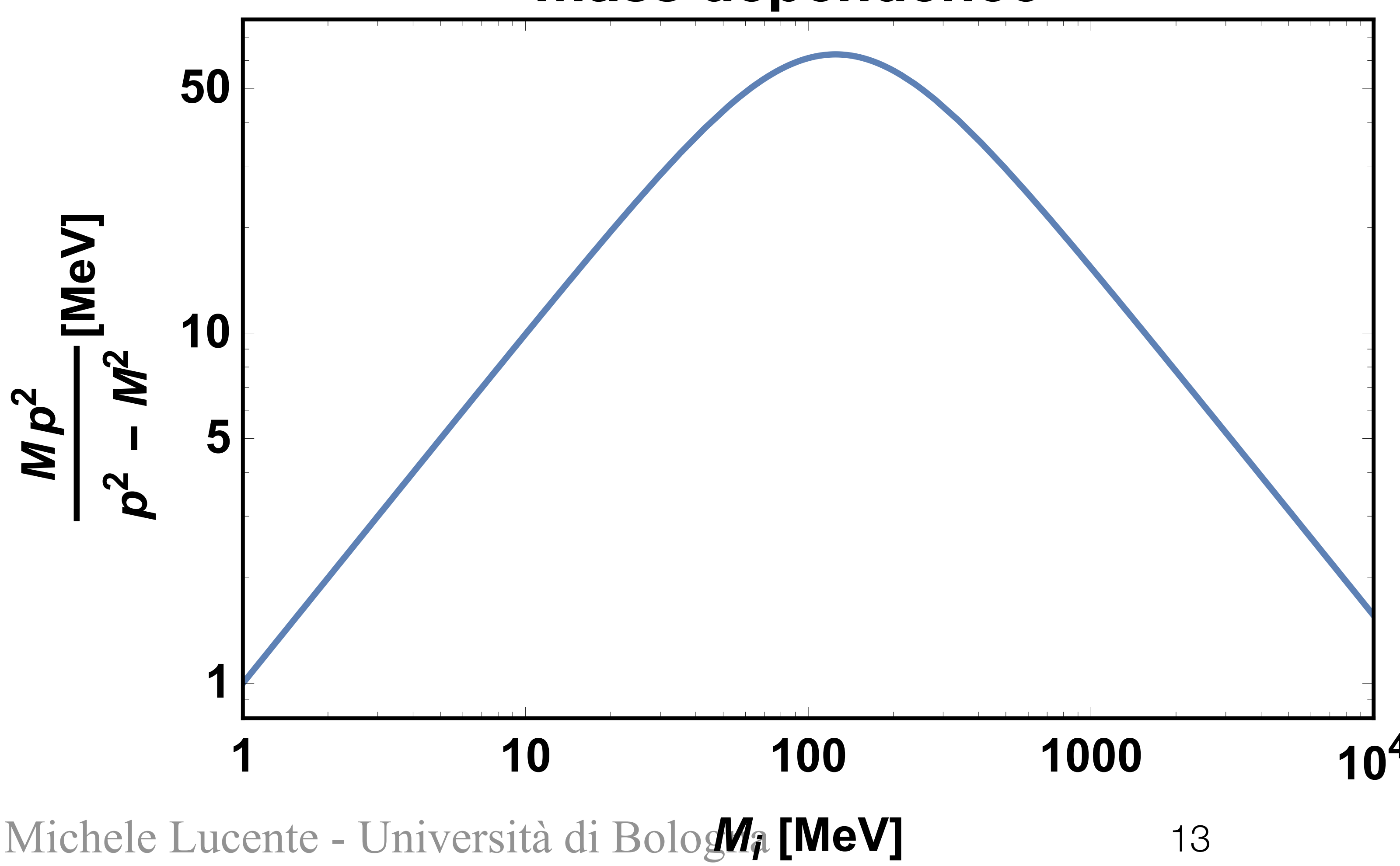
$$\mathcal{A}^{0\nu2\beta} \propto \sum_i M_i\, \mathcal{U}_{ei}^2\; M^{0\nu2\beta}(M_i)$$

$$M^{0\nu2\beta}(M_i) \simeq M^{0\nu2\beta}(0)\frac{p^2}{p^2 - M_i^2}$$



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

Mass dependence



If pseudo-Dirac

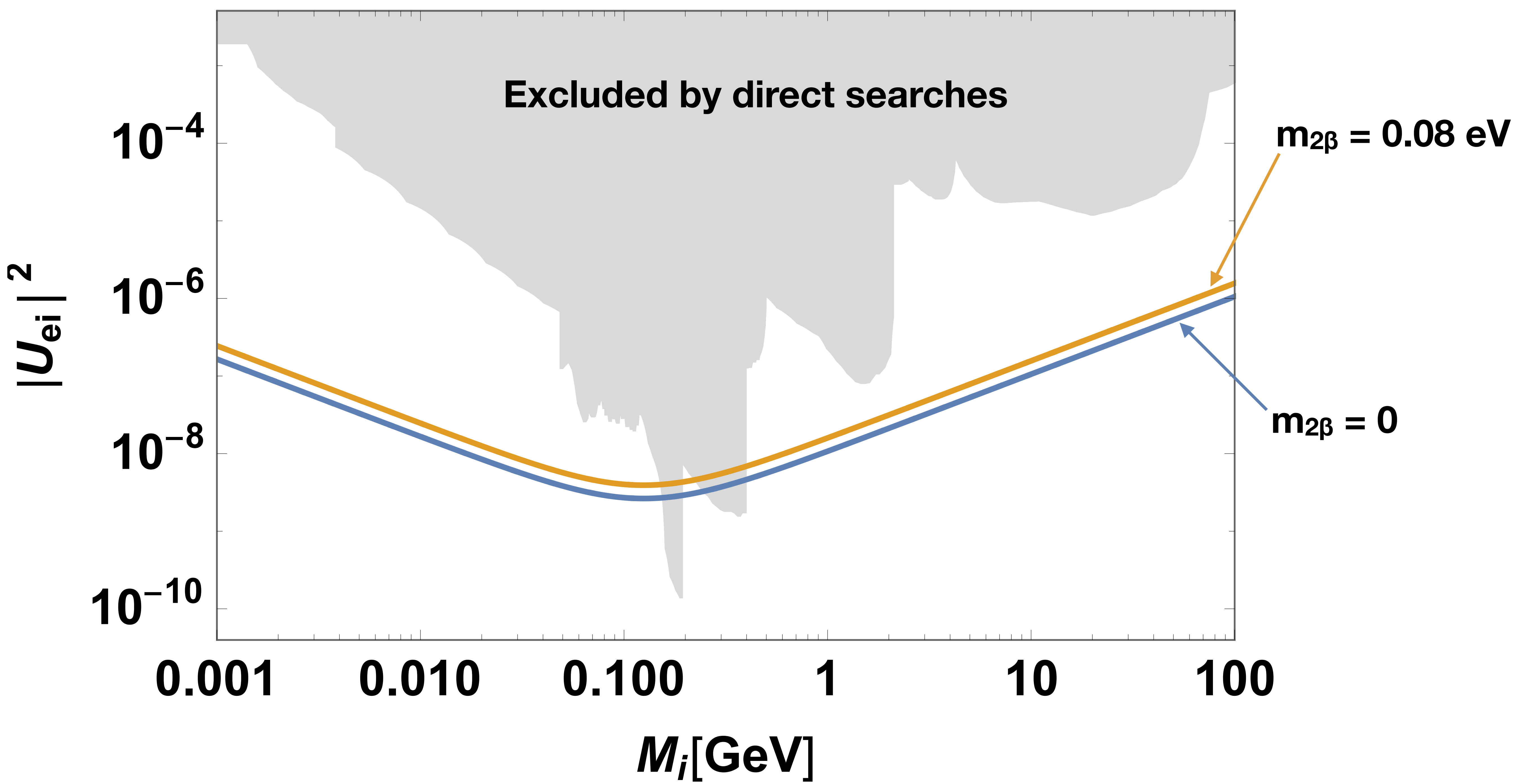
$$M_1 \simeq M_2$$
$$\mathcal{U}_{e1} \simeq i\,\mathcal{U}_{e2}$$

cancellation between contributions of single Majorana states

Extracting contraints on heavy neutrinos

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

0ν2β constraints depend on the full mass spectrum (light + heavy)



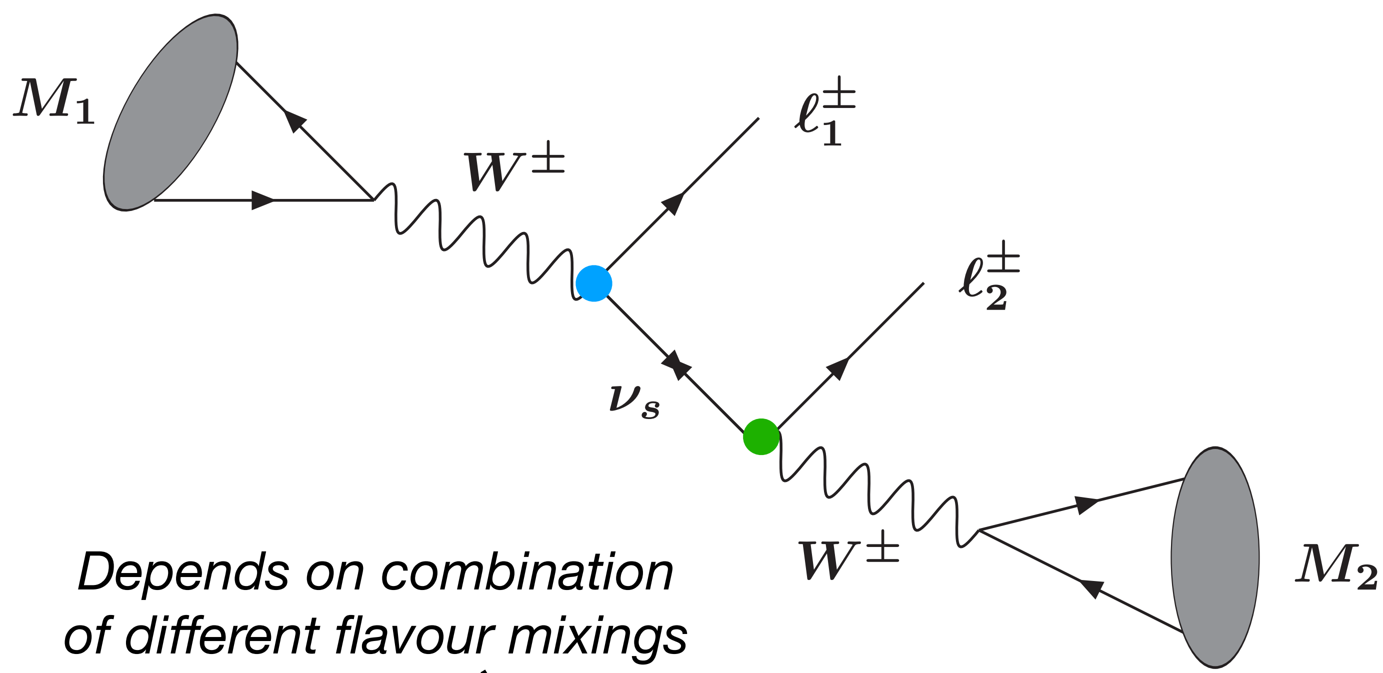
These constraints do not apply to (pseudo-)Dirac particles

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

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



Depends on combination of different flavour mixings

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

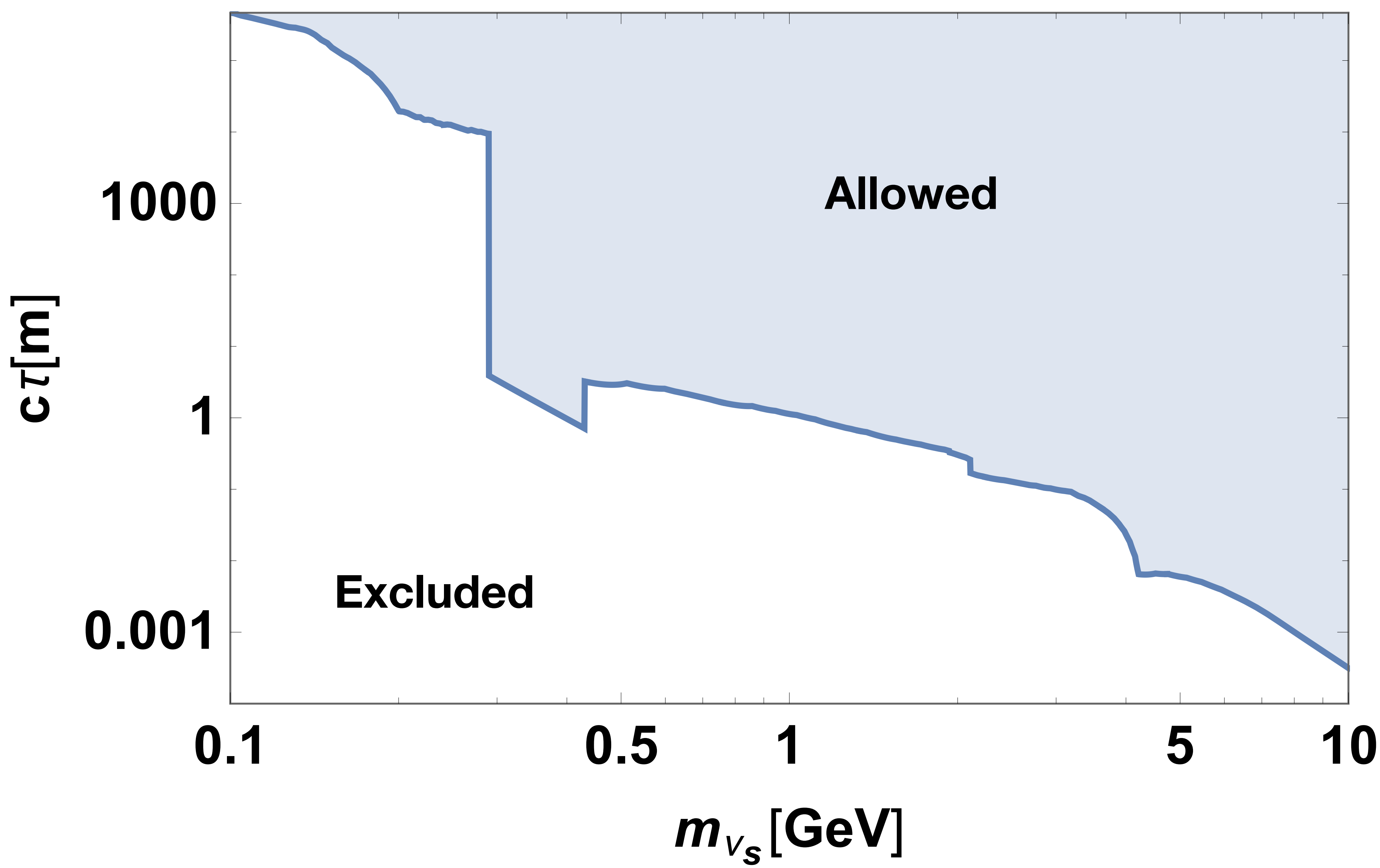
Negligible amplitude unless the intermediate state can go on-shell

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

Lifetime limitations

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

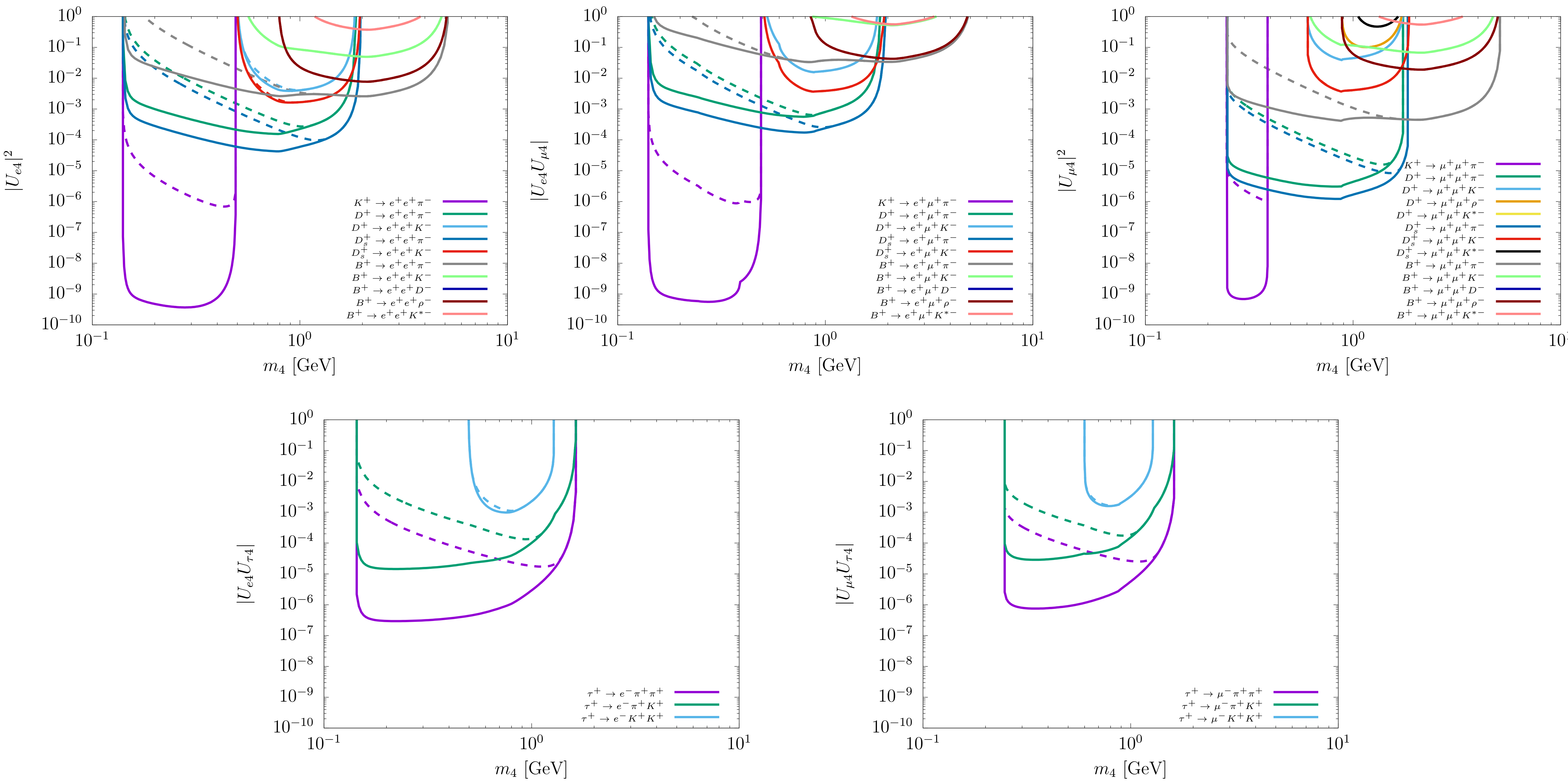
But too long-lived heavy neutrinos decay outside the detector



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

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

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

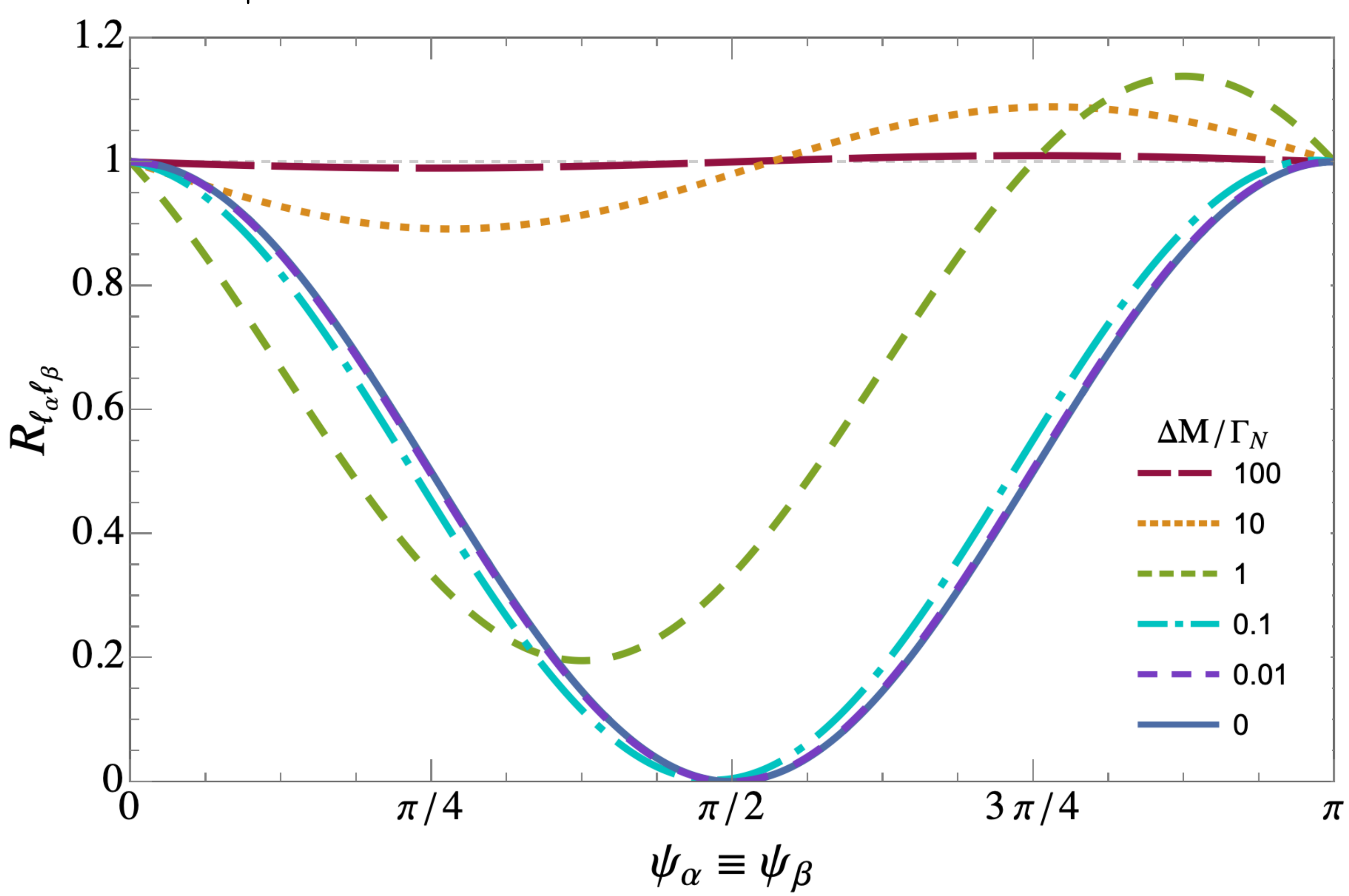
$$\Delta M \ll M \quad \text{and} \quad \Delta M < \Gamma_N$$

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

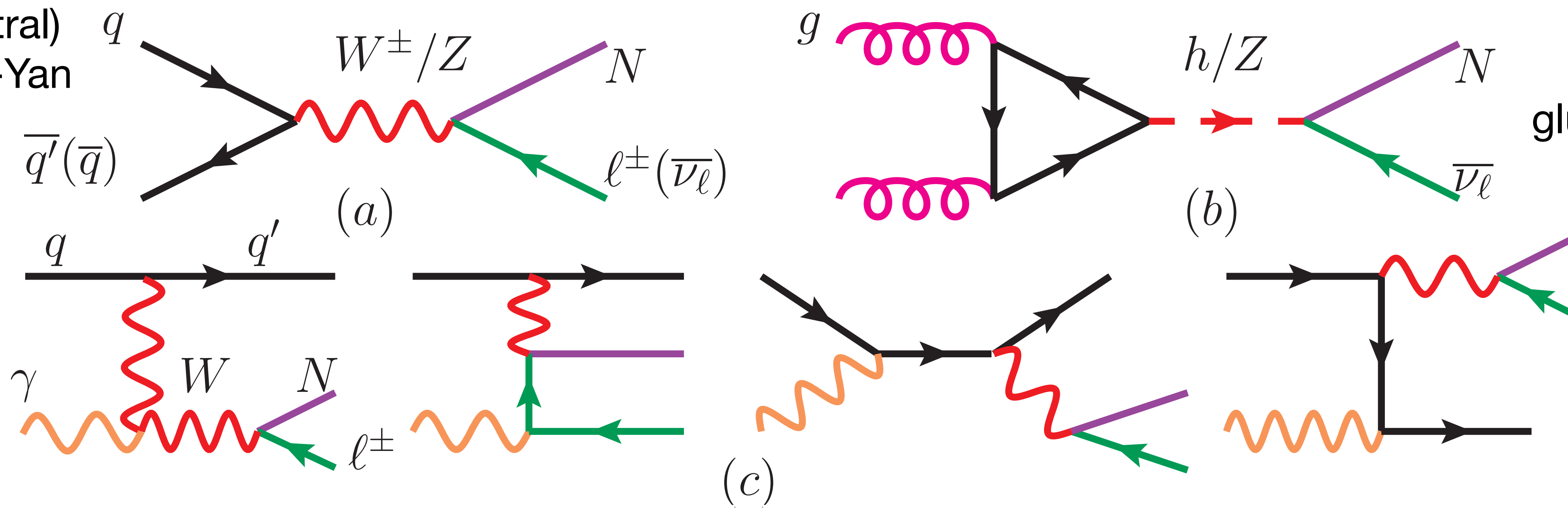


Figure from C. Degrande, O. Mattelaer, R. Ruiz and J. Turner, arXiv:1602.06957 [hep-ph];
see also Y. Cai, T. Han, T. Li and R. Ruiz, arXiv:1711.02180 [hep-ph]

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

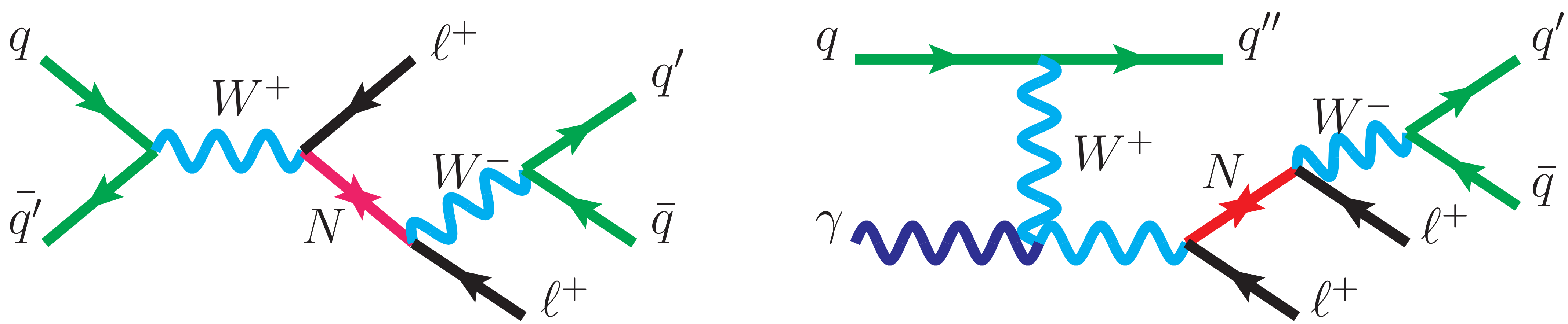
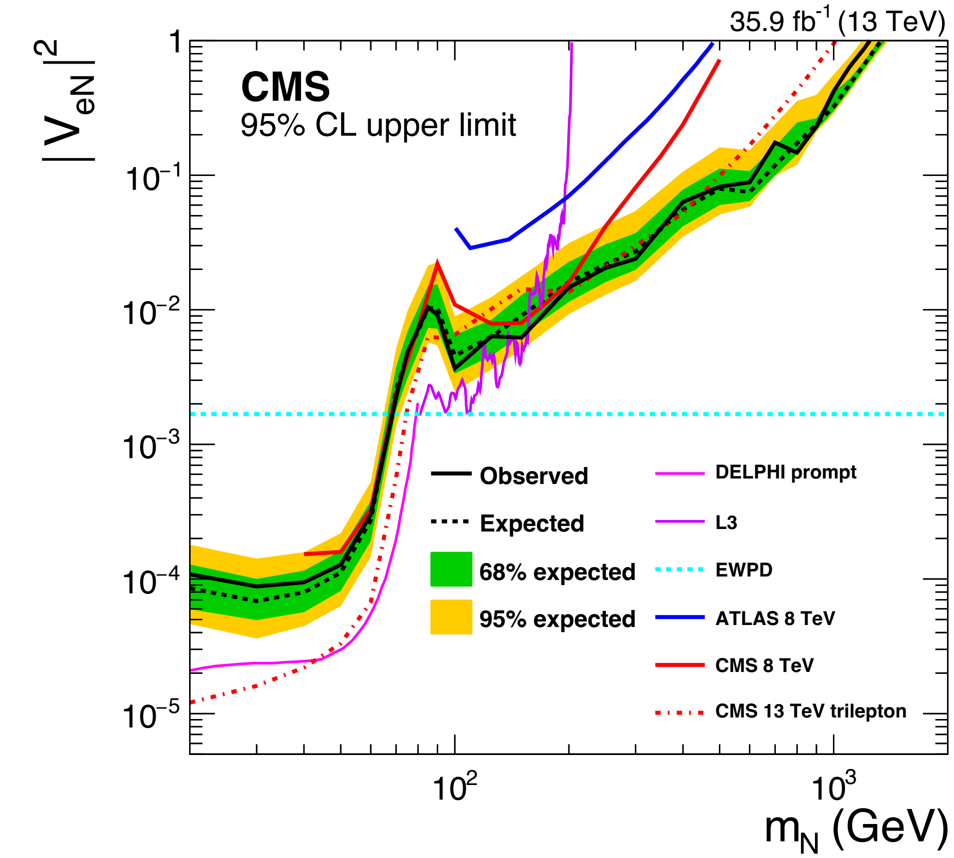
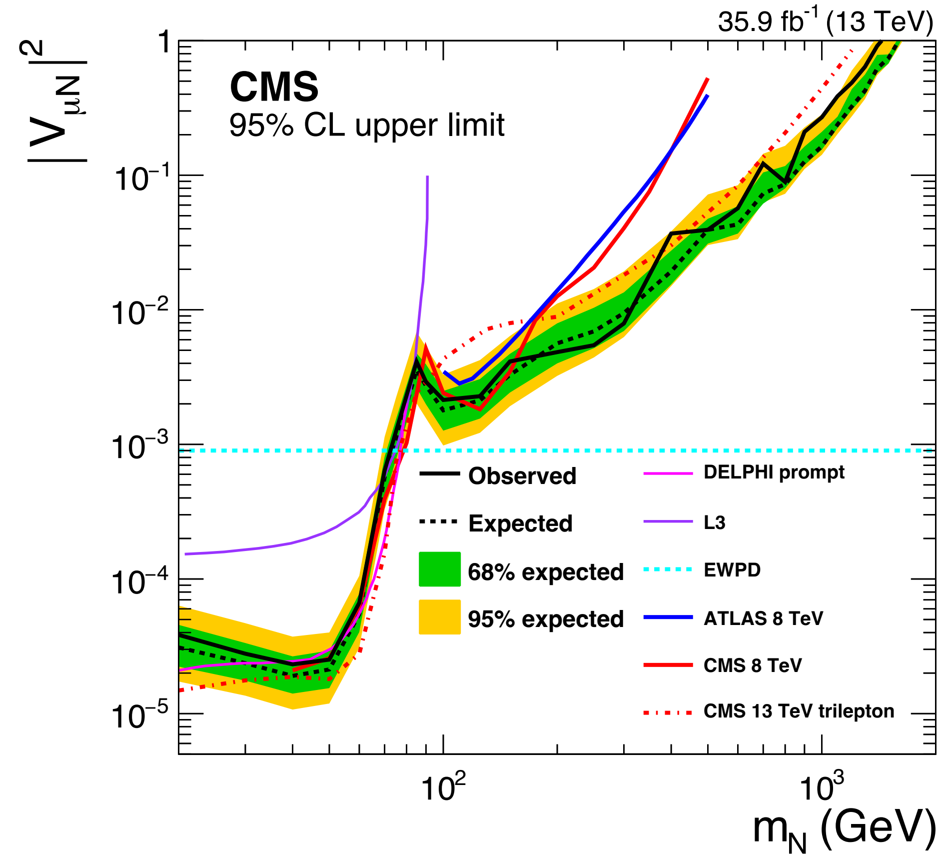


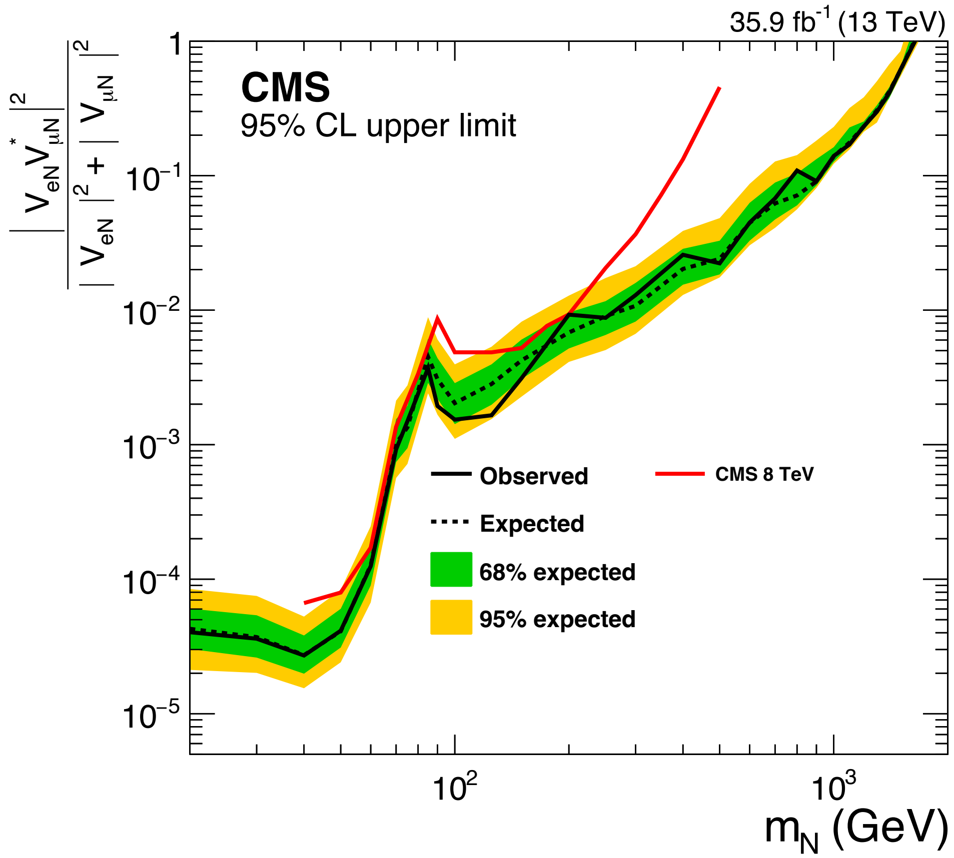
Figure from CMS Collaboration, arXiv:1806.10905 [hep-ex]

Current bounds: single mediator

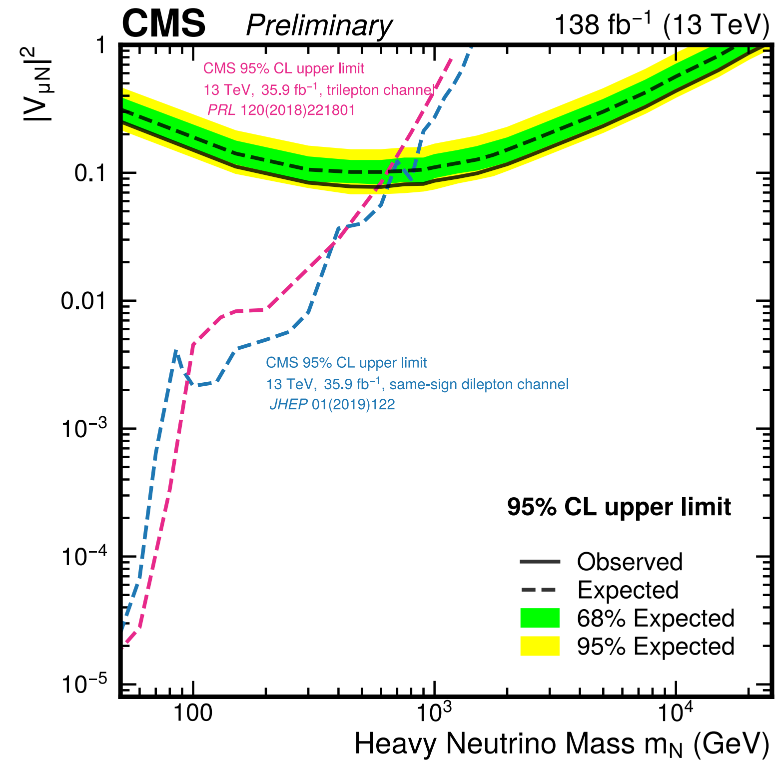
CMS Collaboration, arXiv:1806.10905 [hep-ex]; **see also** ATLAS Collaboration, arXiv:1506.06020 [hep-ex]





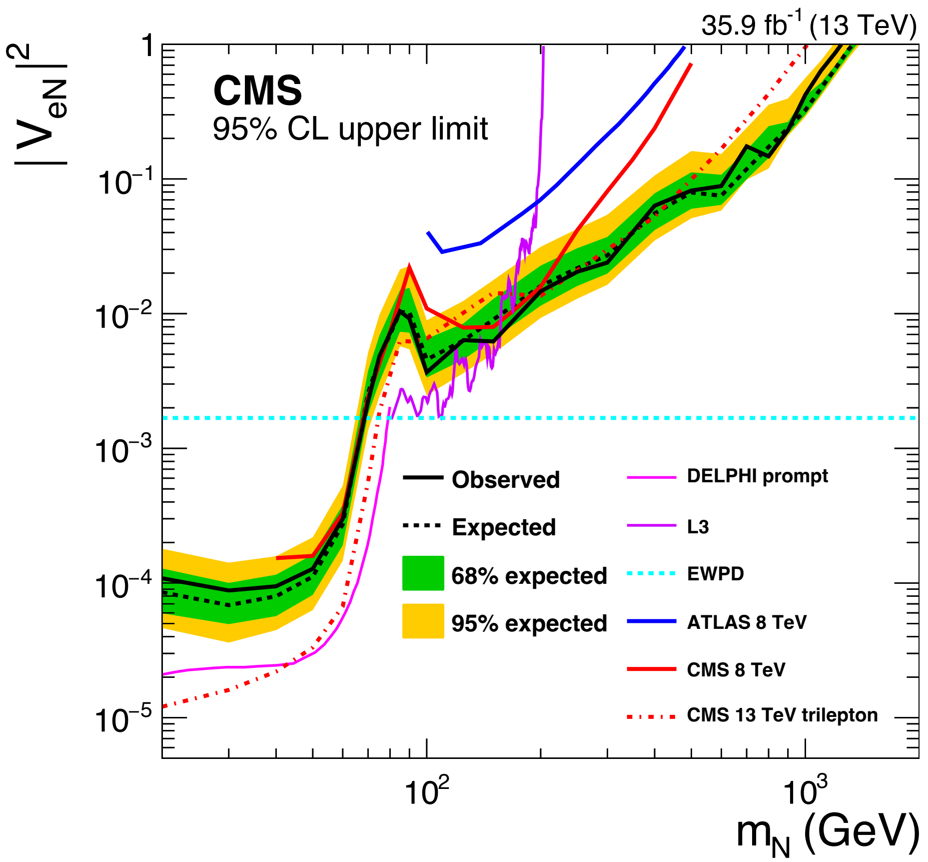


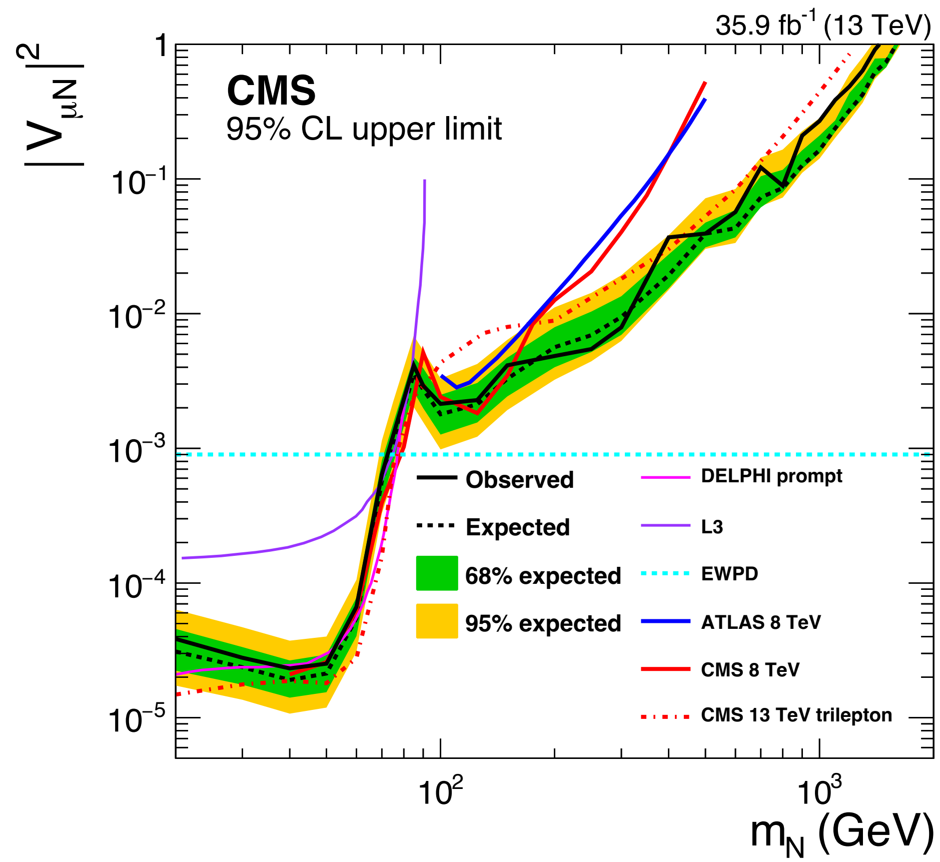
Vector boson fusion

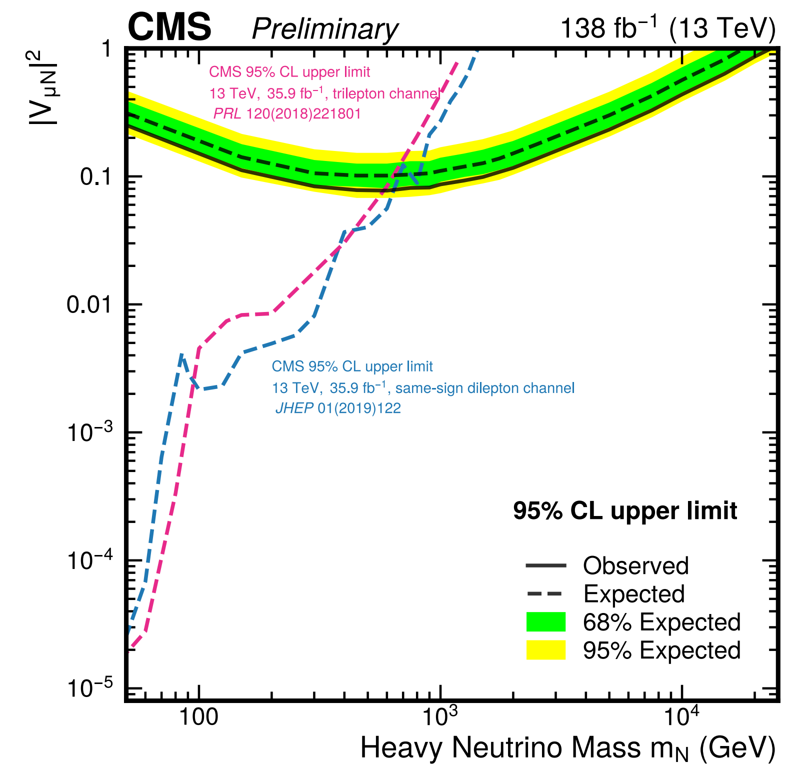


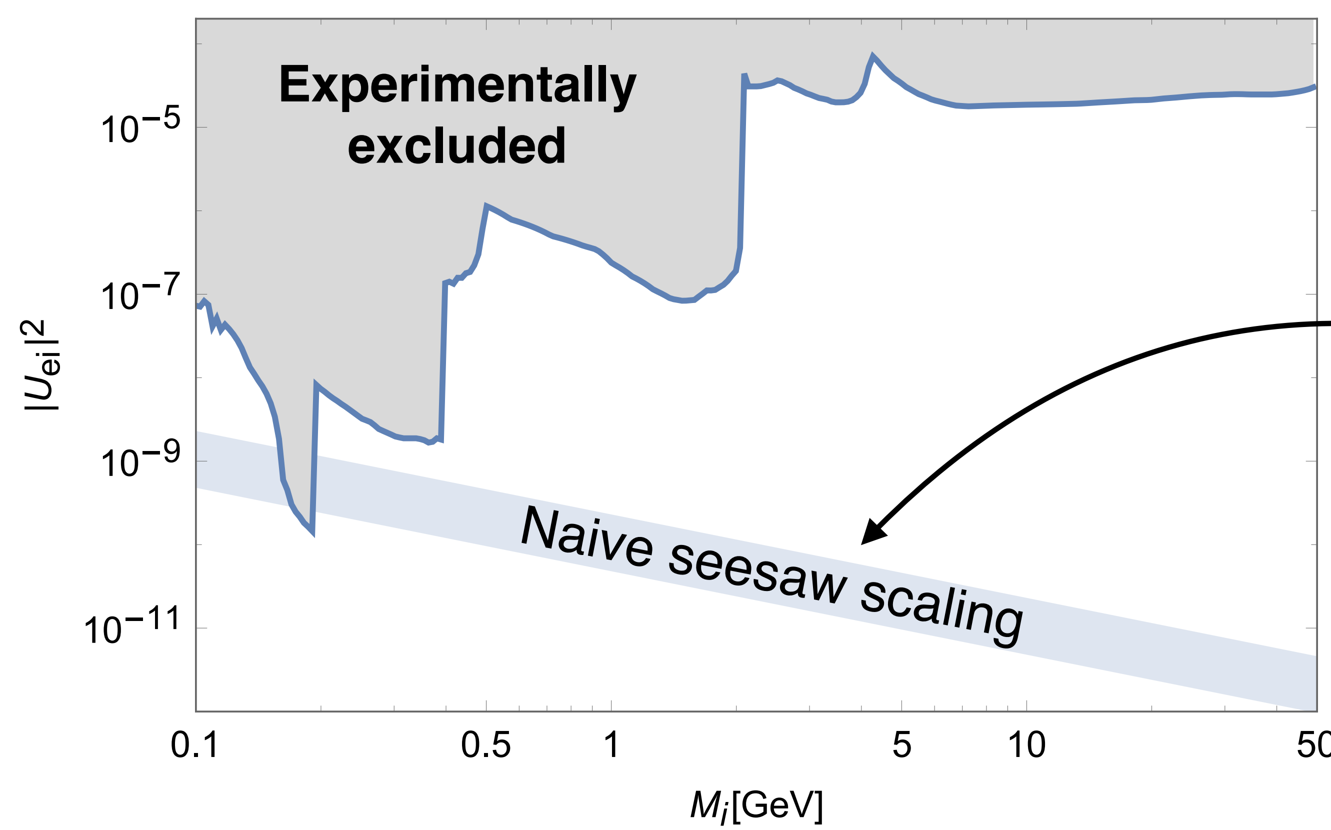
CMS-PAS-EXO-21-003

LNV searches: challenging from model building









Typical LNV coupling size if no accidental cancellations

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

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

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

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

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

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)**

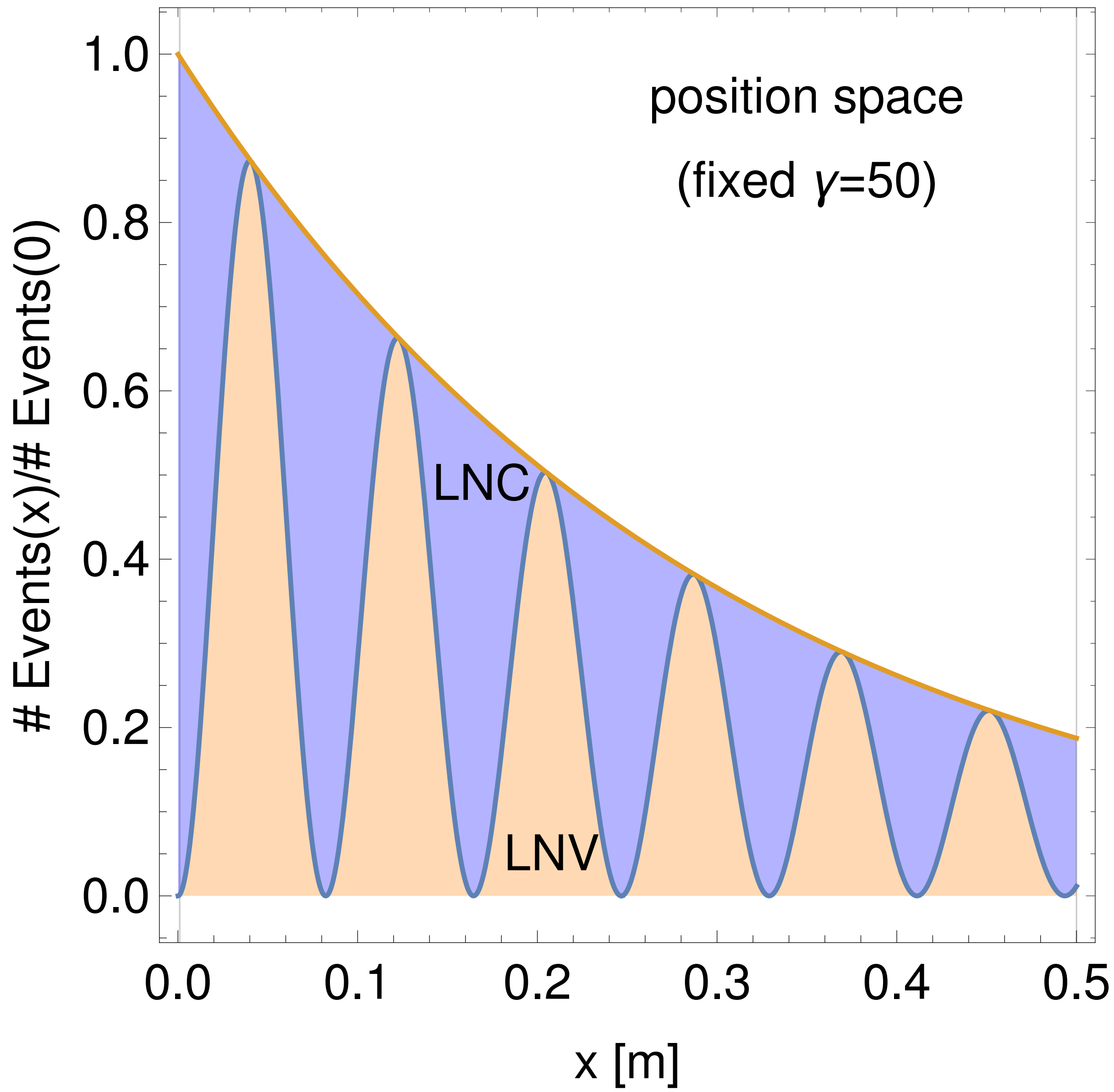
$$R_{\ell\ell}(t_1,t_2) = \frac{\int_{t_1}^{t_2}|g_-(t)|^2dt}{\int_{t_1}^{t_2}|g_+(t)|^2dt} = \frac{\#(\ell^+\ell^+) + \#(\ell^-\ell^-)}{\#(\ell^+\ell^-)}$$

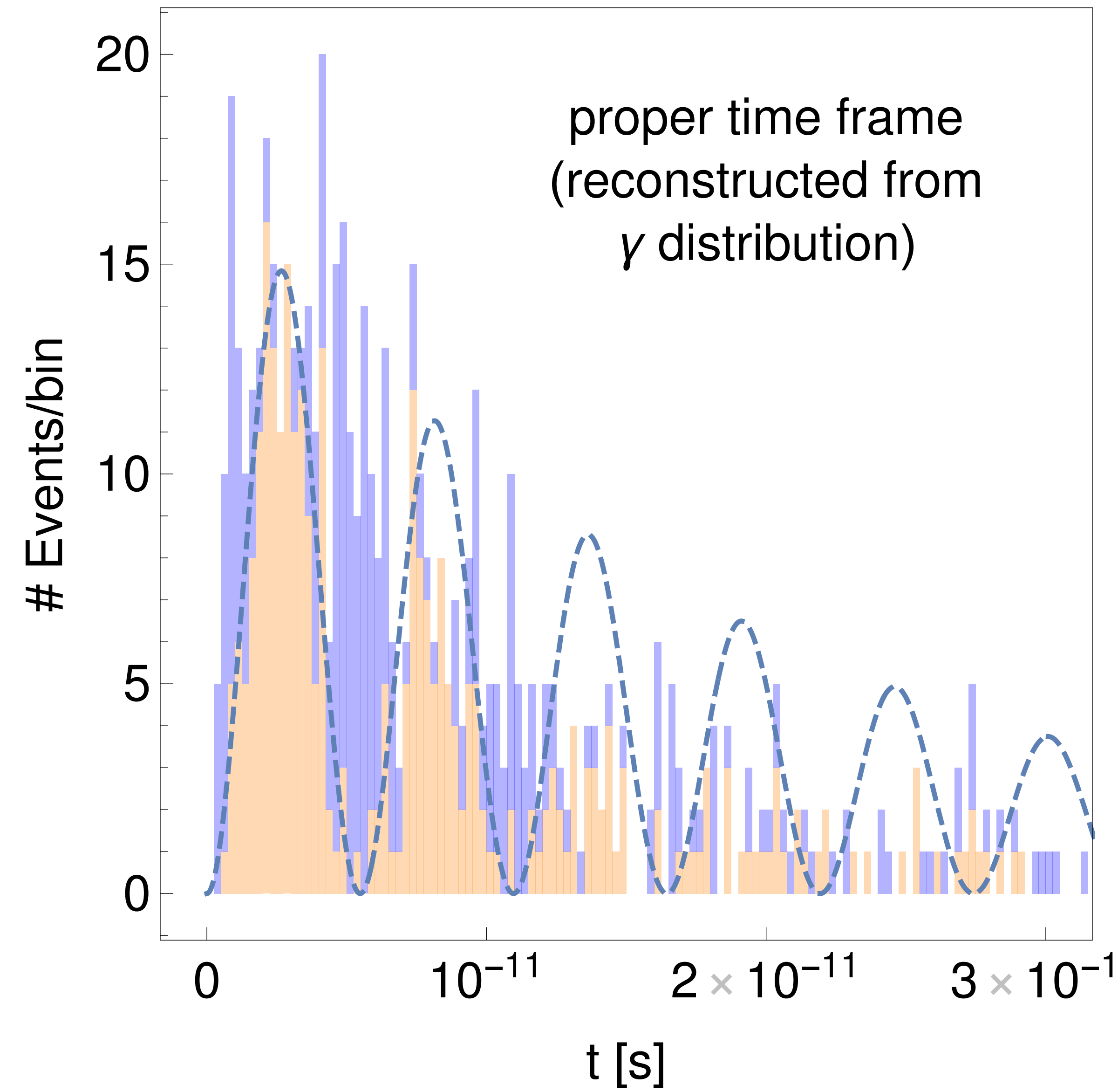
$$R_{ll}(0,\infty) = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

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

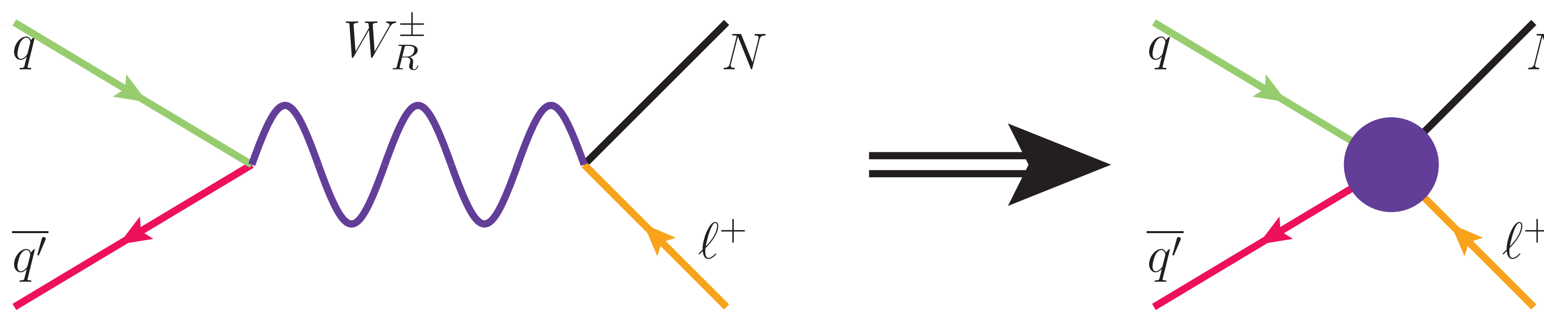
Richard Ruiz, private communication

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

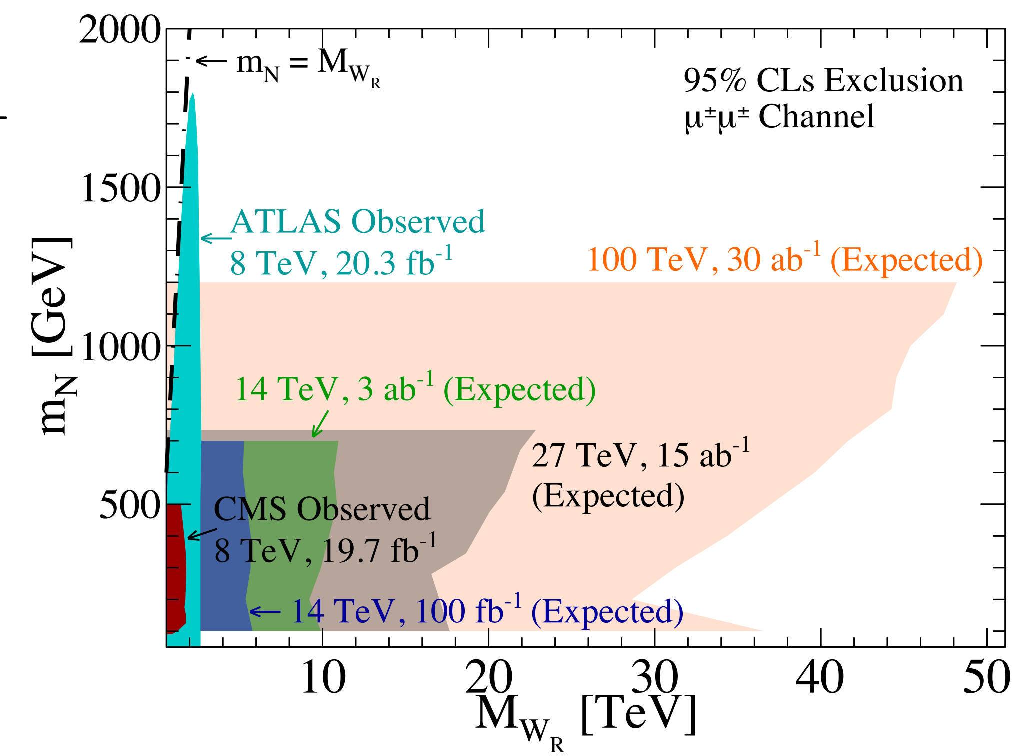
If new gauge mediators are too heavy, light N are still accessible



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]

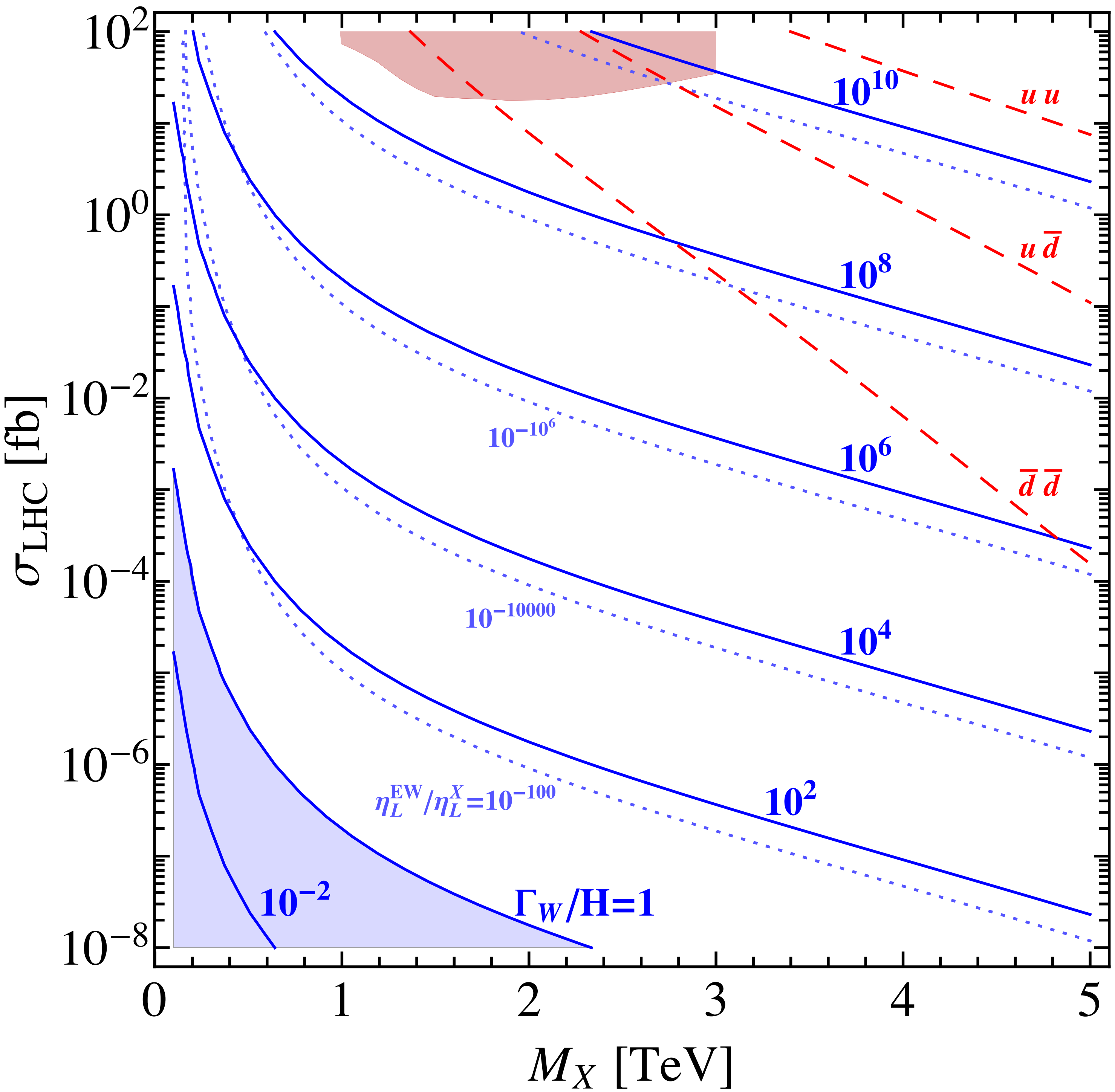
- **Signature:** $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N) +$ no MET
- At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab^{-1}, $M_{W_R} \lesssim 9$ (40) TeV probed
- **DO NOT STOP SEARCHING FOR TYPE I LNV**

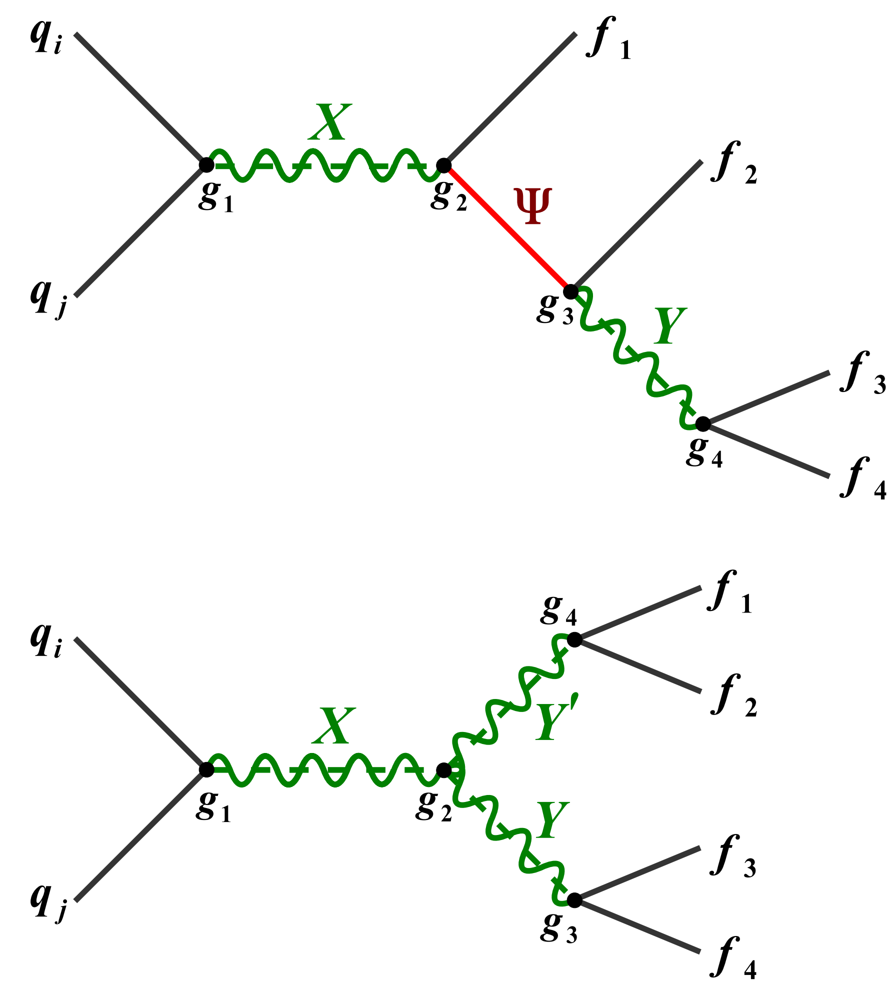


[11] Han, Lewis, **RR**, Si, [1211.6447]; **RR**, [1703.04669]

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

Conclusion

HNL phenomenology is generally connected with ν mass generation mechanism

Lepton number symmetry allows for low scale NP and sizeable couplings

But this symmetry generally suppresses LNV processes

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 physics beyond the simple seesaw and/or falsify high-scale leptogenesis

Backup

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

Fermionic singlet extensions of the SM

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

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

3 x n matrix
Yukawa couplings

n x n matrix
Majorana mass couplings

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

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

(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

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

Unobservable

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

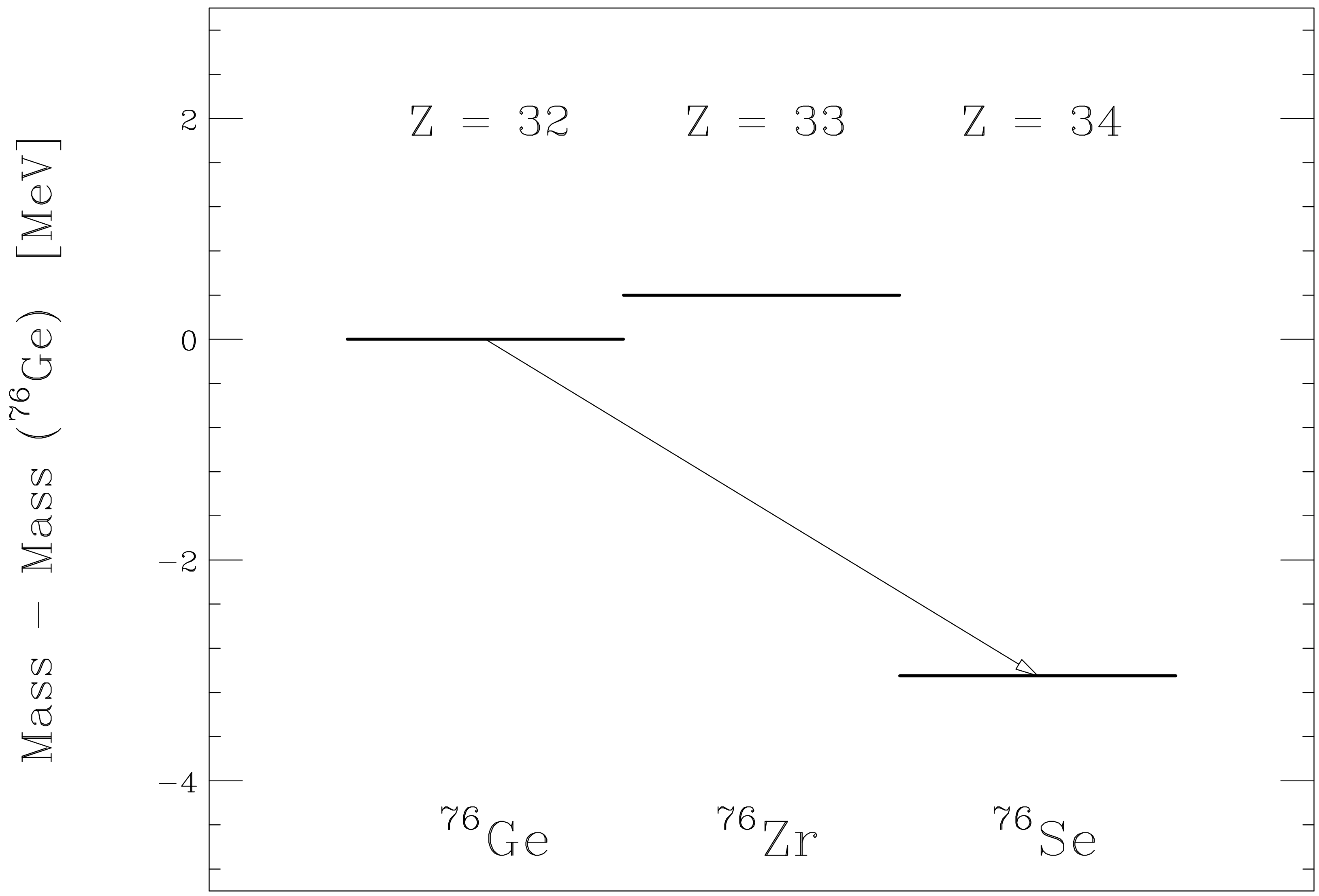
m_i^{tree}
tree-level neutrino mass spectrum

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



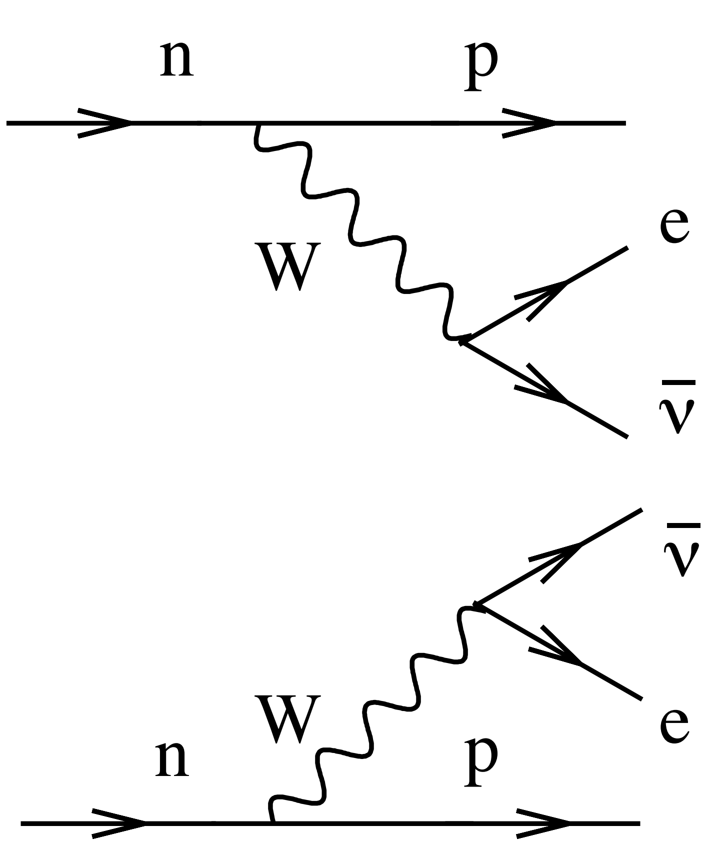


Figure from P. Lipari, Introduction to neutrino physics, in 2001 CERN-CLAF School of high-energy physics

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

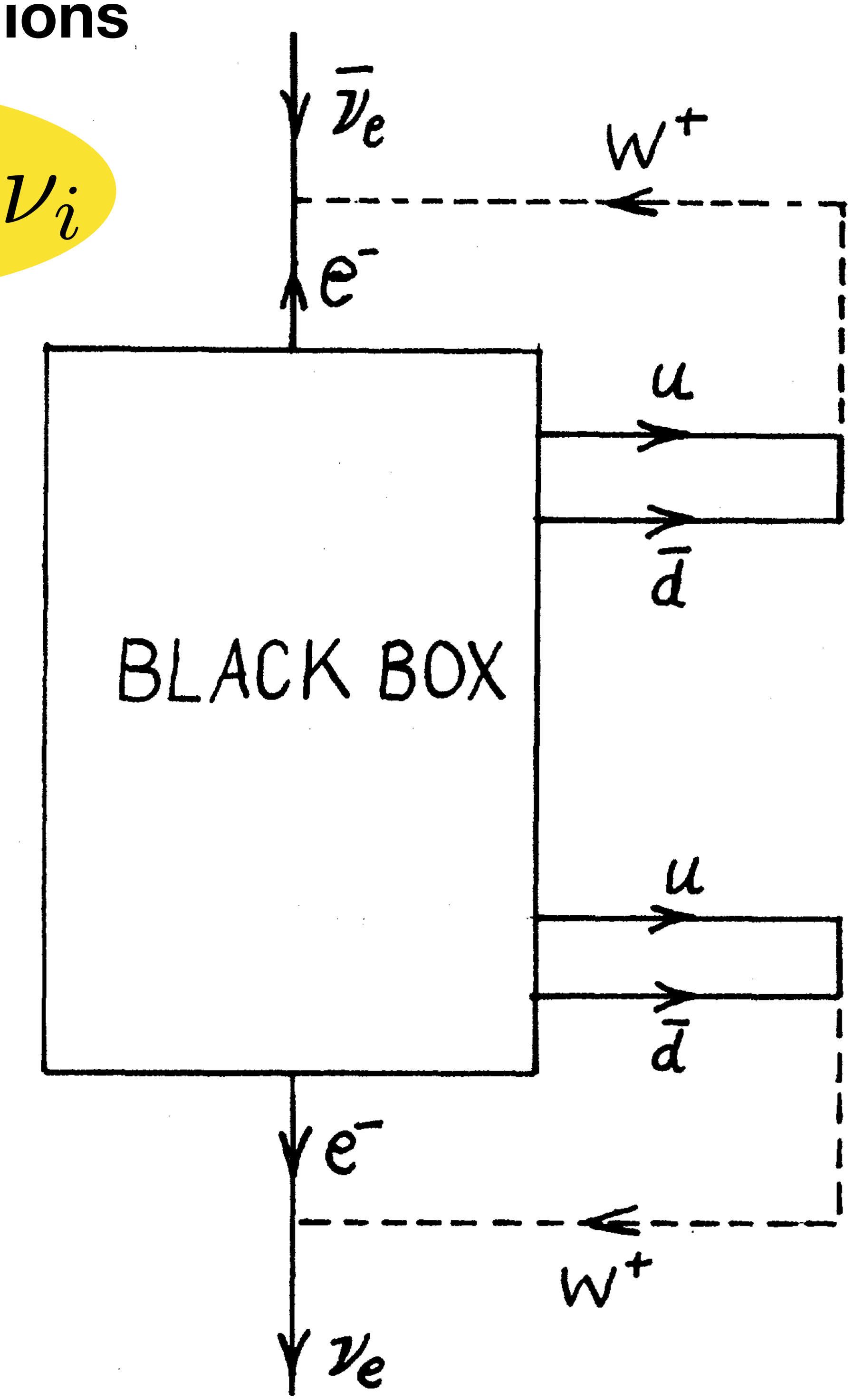
$$\Gamma_{0\nu2\beta} \neq 0$$

↔

Neutrinos are Majorana fermions

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

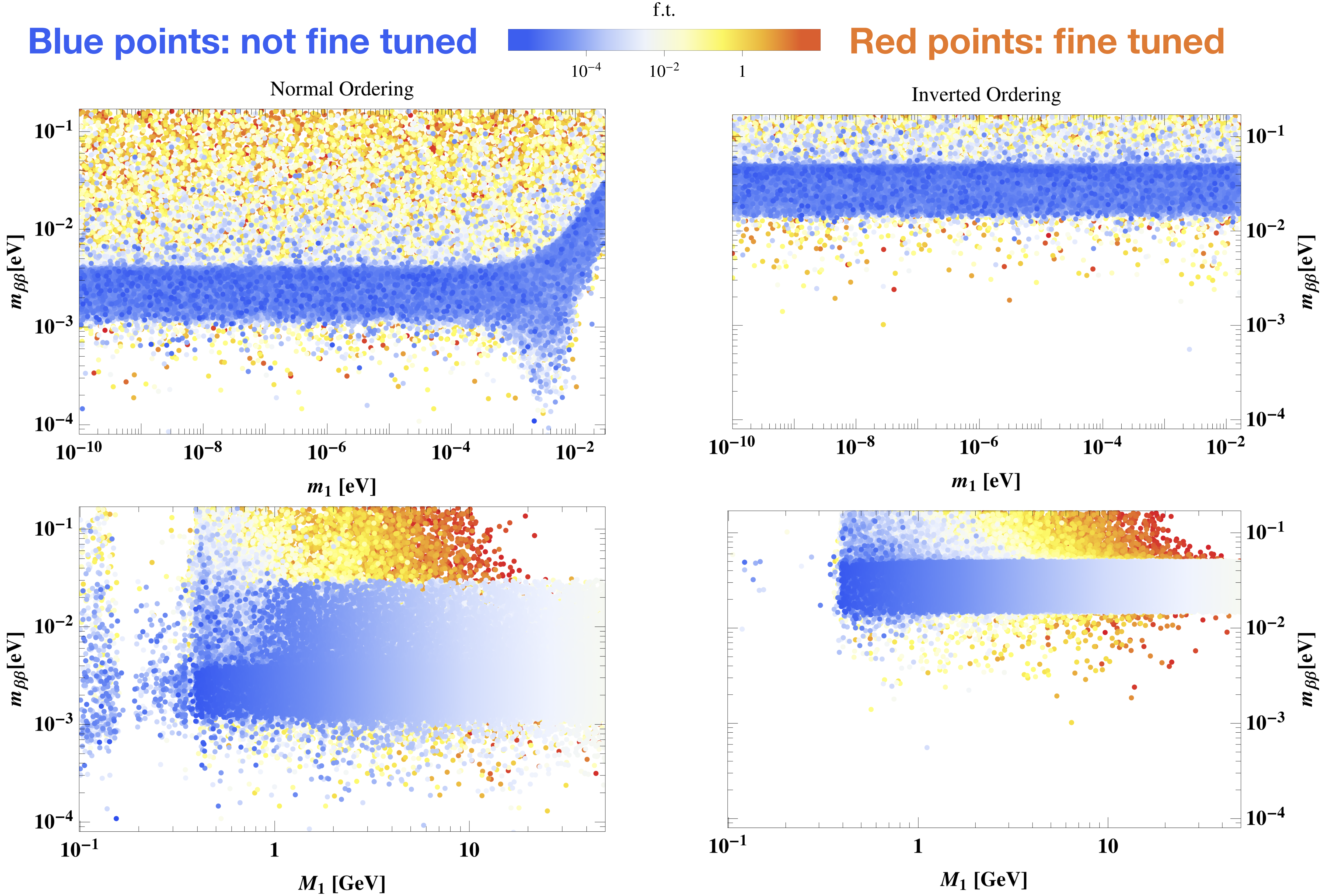
Irrespectively of the underlying mechanism, a non-vanishing 0v2β amplitude generates a Majorana mass term for the SM neutrinos



Heavy neutrinos at GeV scale

Blue points: not fine tuned

Red points: fine tuned



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]

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

Some predictions: single intermediate state

Comprehensive analysis for τ and pseudo-scalar mesons in 1712.03984

(all possible initial and 3-body final states)