NEUTRINOS AND BEYOND THE STANDARD MODEL SEARCHES

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UNIVERSITÀ DI BOLOGNA

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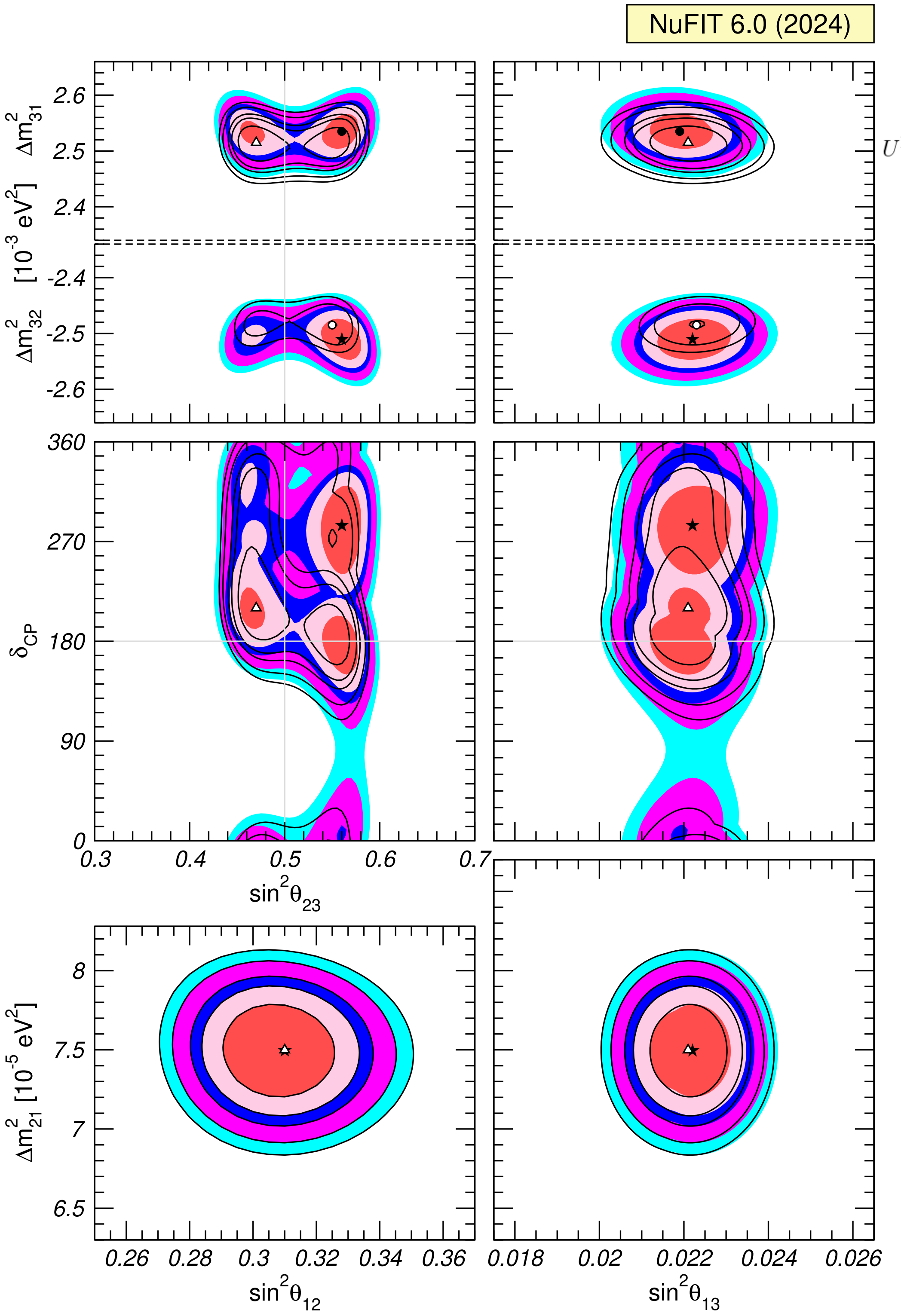
Neutrinos are massive and leptons mix



I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro and T. Schwetz, arXiv:2410.05380 [hep-ph]

$$U^{\rm NO} = \begin{pmatrix} 0.7838 \to 0.8442 & 0.5135 \to 0.6004 & (-0.1568 \to 0.1489) + i(-0.1182 \to 0.1520) \\ (-0.4831 \to -0.2394) + i(-0.0749 \to 0.0962) & (0.4636 \to 0.6749) + i(-0.0521 \to 0.0668) & 0.6499 \to 0.7719 \\ (0.3068 \to 0.5391) + i(-0.0643 \to 0.0933) & (-0.6897 \to -0.4821) + i(-0.0446 \to 0.0644) & 0.6161 \to 0.7434 \end{pmatrix}$$

P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola and J. W. F. Valle,arXiv:2006.11237 [hep-ph]

Evidence for BSM physics!

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91 – 3.17	2.77 – 3.31	2.64 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475 – 2.515	2.454 – 2.536	2.433 – 2.558	0.8
	IO	2.465	2.444 – 2.485	2.423 – 2.506	2.403 – 2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.27	2.11 – 2.33	2.06 – 2.38	2.4
	IO	2.23	2.19 – 2.30	2.14 – 2.35	2.08 – 2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60 – 4.96	4.47 – 5.68	4.37 – 5.81	5.1
	IO	5.45	5.28 – 5.60	4.58 – 5.73	4.43 – 5.83	4.3
δ/π	NO	1.20	1.07 – 1.37	0.88 – 1.81	0.73 – 2.03	18
	IO	1.48	1.36 – 1.61	1.24 – 1.72	1.12 – 1.83	8
$\Delta\chi^2_{\rm IO-NO}$	IO−NO	+5.0				

F. Capozzi, W. Giarè, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo, arXiv:2503.07752 [hep-ph]

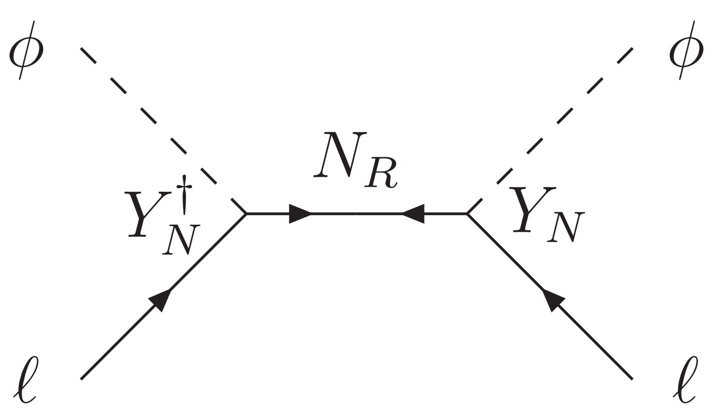
Naturally small neutrino masses

There are only 3 tree-level realisations of neutrino masses in the minimal SM

E. Ma, arXiv:hep-ph/9805219 [hep-ph]
A. Abada, C. Biggio, F. Bonnet, M. B. Gavela and T. Hambye, arXiv:0707.4058 [hep-ph]

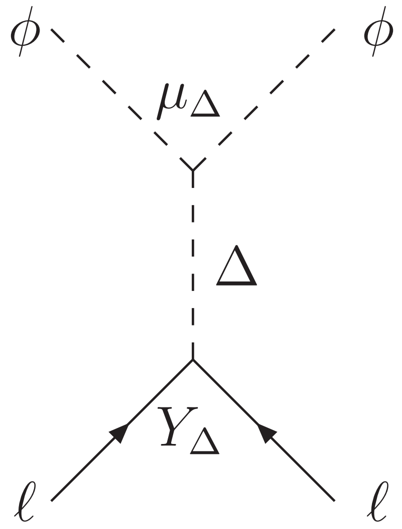
Generate $\frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{l^c_{L\alpha}}\,\widetilde{\Phi}^*\right)\left(\widetilde{\Phi}^\dagger l^\beta_L\right)+h.c.$ from seesaw mechanism

Type-I



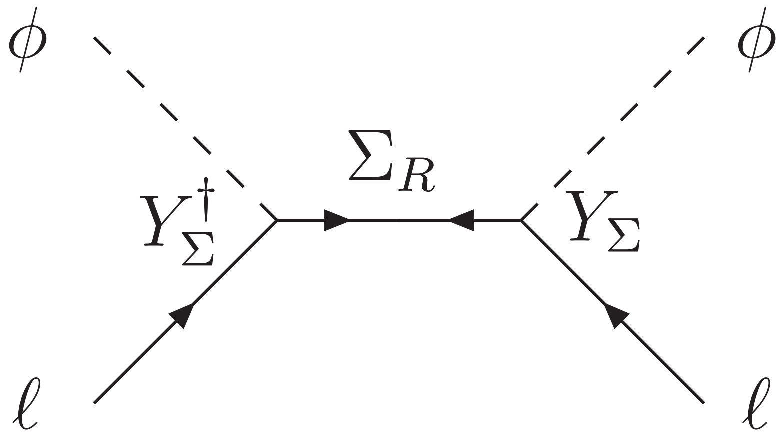
P. Minkowski, Phys. Lett. B 67 (1977), 421-428; M. Gell-Mann, P. Ramond and R. Slansky, arXiv:1306.4669 [hep-th]; T. Yanagida in Proceedings of the Workshop on the Unified Theories and the Baryon Number in the Universe (1979); R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980), 912

Type-II



M. Magg and C. Wetterich, Phys. Lett. B 94 (1980), 61-64; J. Schechter and J. W. F. Valle, Phys. Rev. D 22 (1980), 2227; C. Wetterich, Nucl. Phys. B 187 (1981), 343-375; G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B 181 (1981), 287-300; R. N. Mohapatra and G. Senjanovic, Phys. Rev. D 23 (1981), 165

Type-III



R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C 44 (1989), 441; E. Ma and D. P. Roy, arXiv:hep-ph/0206150 [hep-ph]; T. Hambye, Y. Lin, A. Notari, M. Papucci and A. Strumia, arXiv:hep-ph/0312203 [hep-ph]; B. Bajc and G. Senjanovic, arXiv:hep-ph/0612029 [hep-ph]; B. Bajc, M. Nemevsek and G. Senjanovic, arXiv:hep-ph/0703080 [hep-ph]; I. Dorsner and P. Fileviez Perez, arXiv:hep-ph/0612216 [hep-ph]; P. Fileviez Perez, arXiv:hep-ph/0702287 [hep-ph]; P. Fileviez Perez, arXiv:0705.3589 [hep-ph]

Type-I seesaw mechanism

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

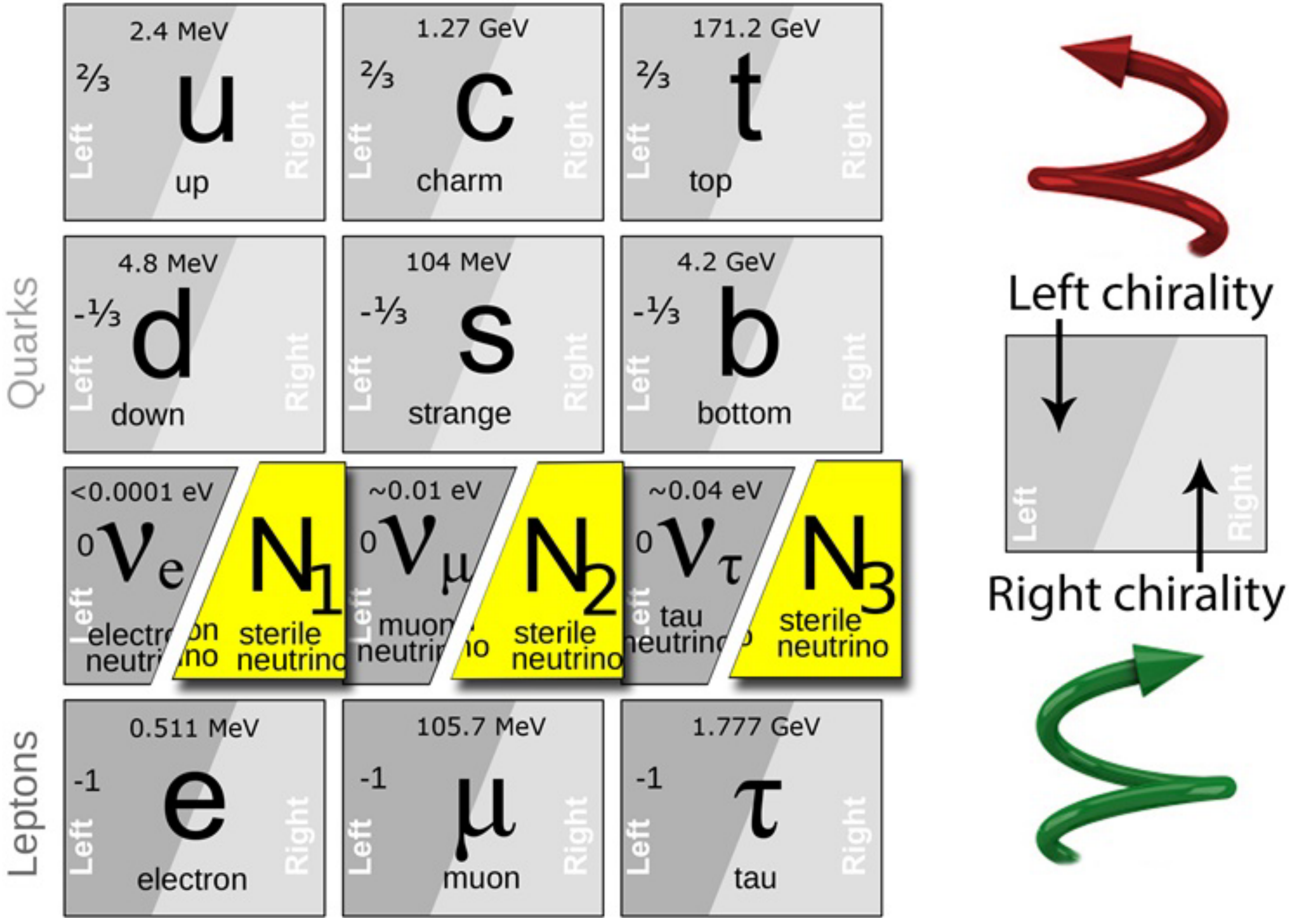


Figure from S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

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]

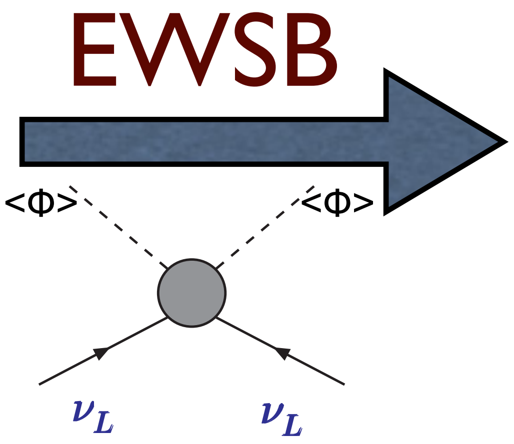
SM as an effective theory

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

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

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

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

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

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

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

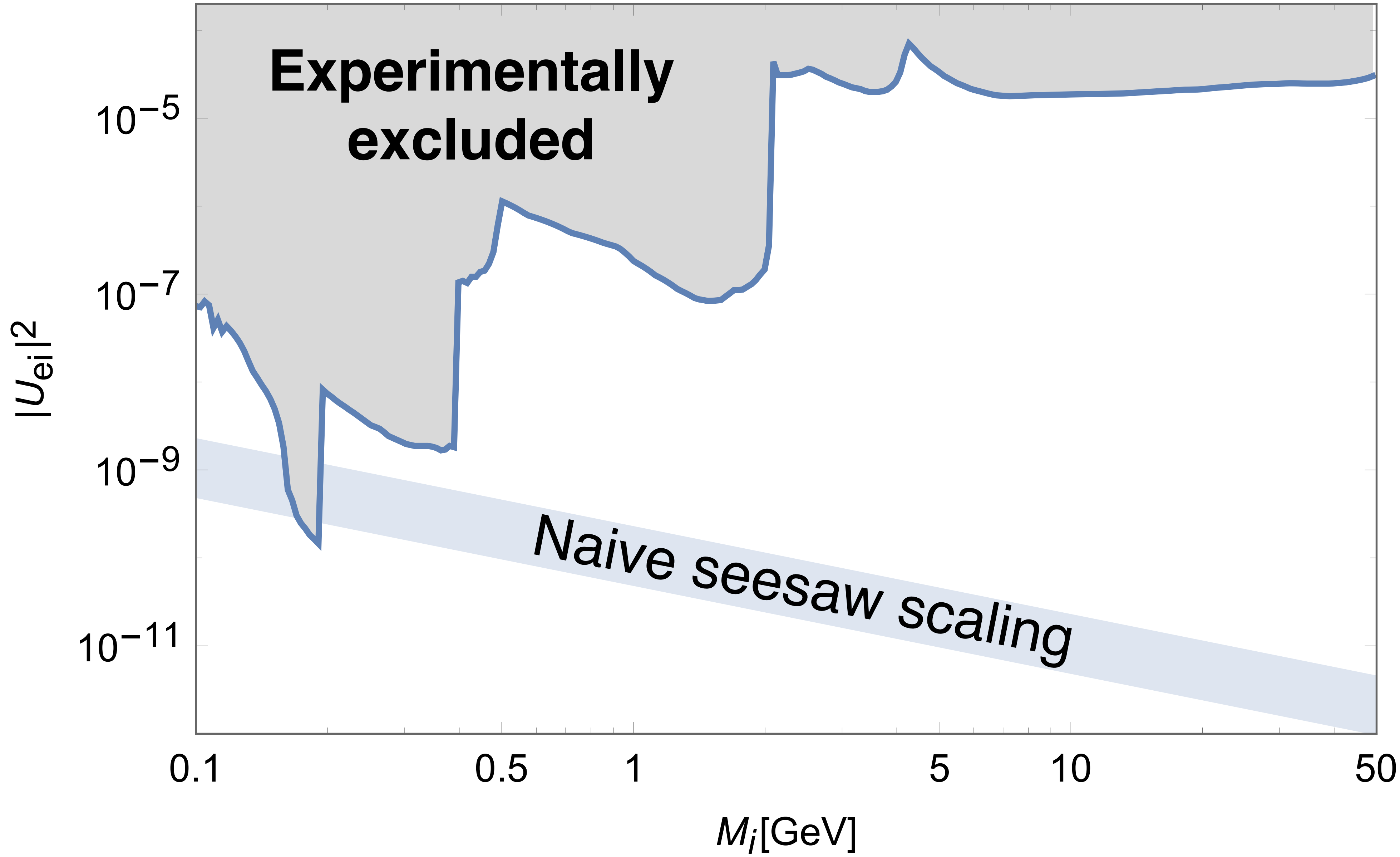
$c_5 \ll 1$

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



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]

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

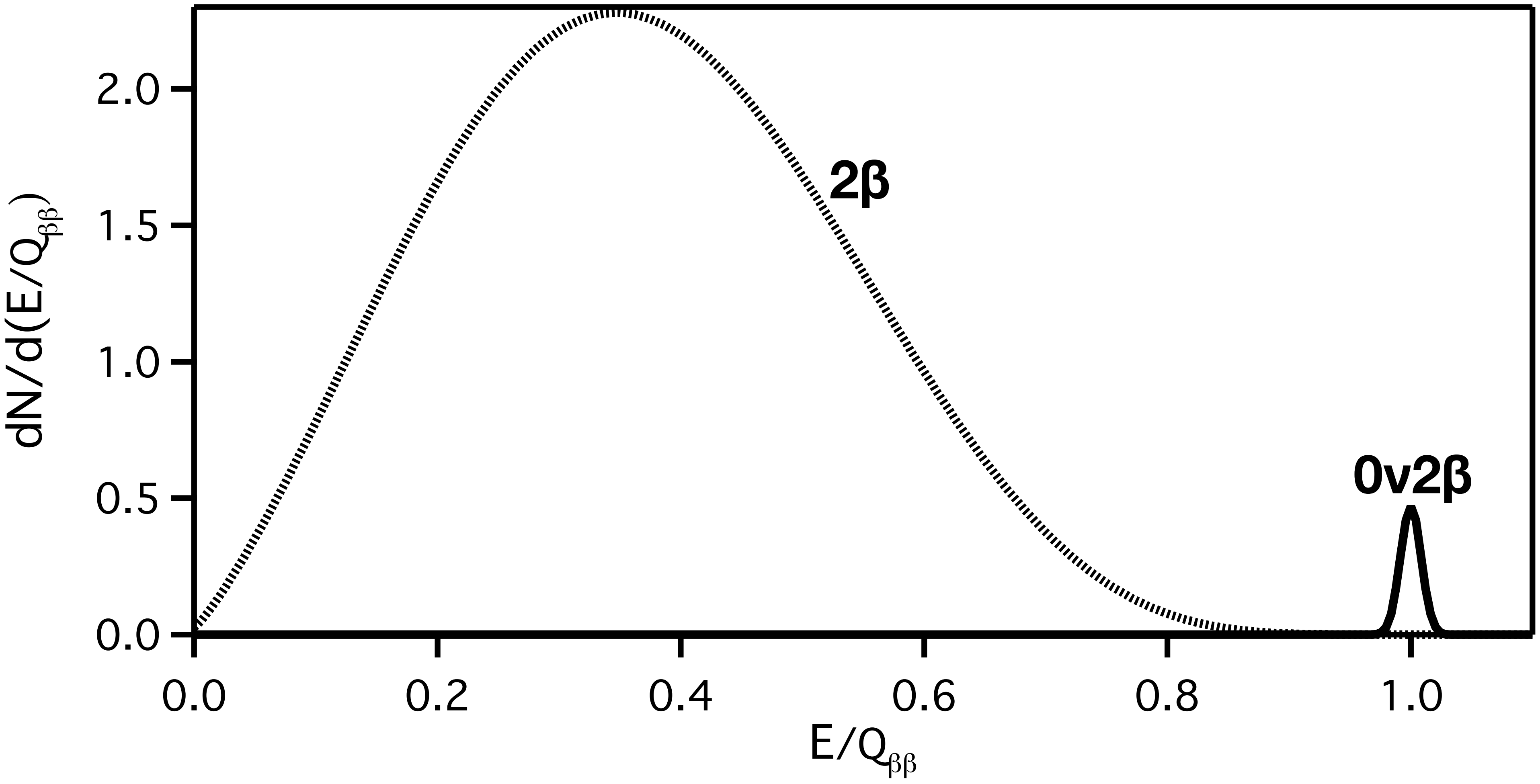
Neutrinoless double beta decay: ΔL = 2

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

If neutrinos are Majorana particles 0ν2β is possible

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

Clear experimental signature



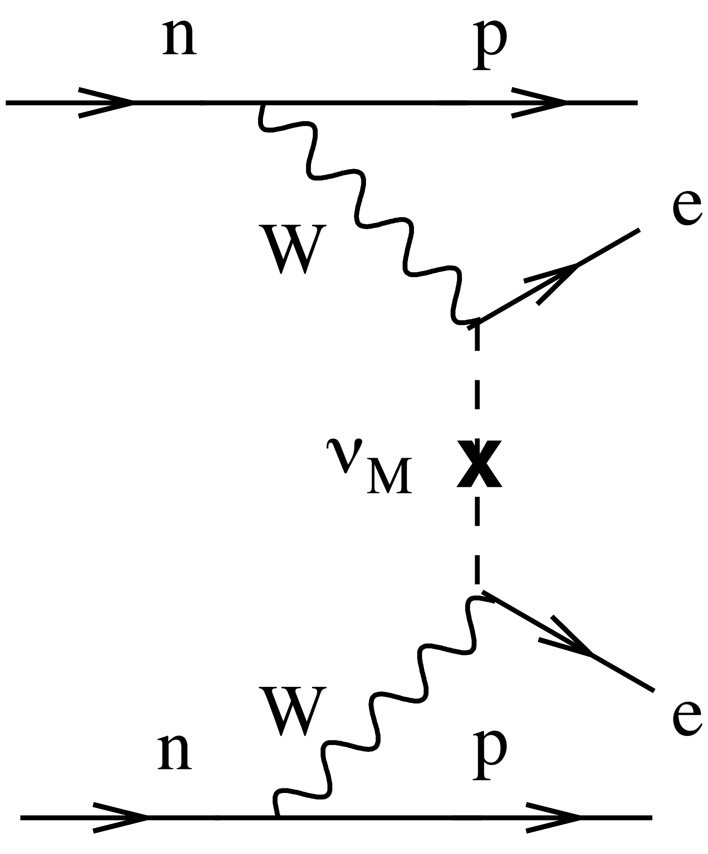
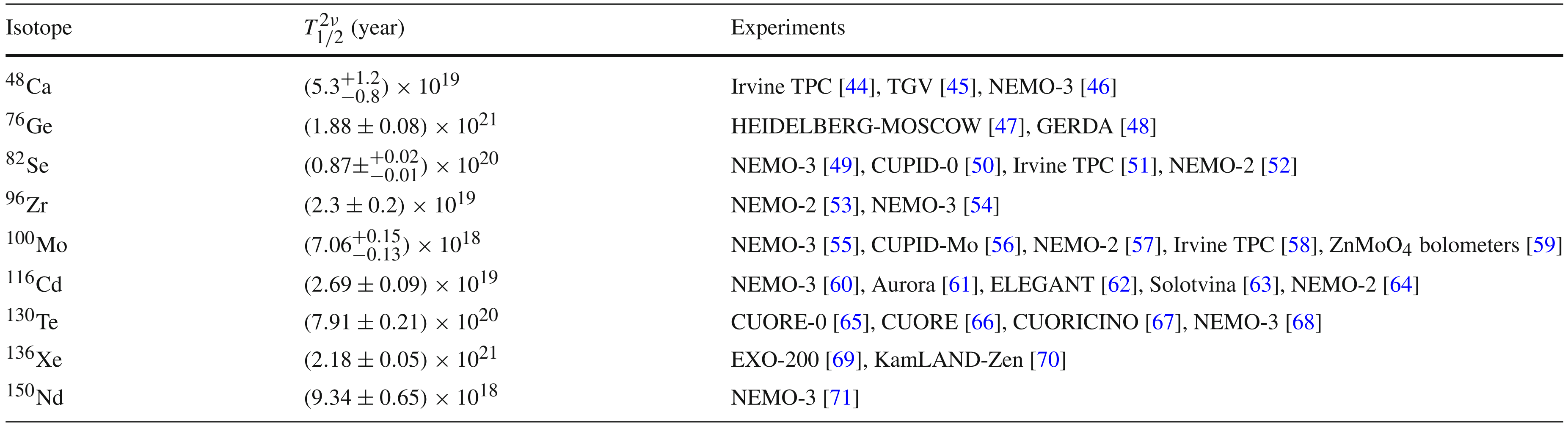


Figure modified from F. T. Avignone III, S. R. Elliott and J. Engel, arXiv:0708.1033 [nucl-ex]

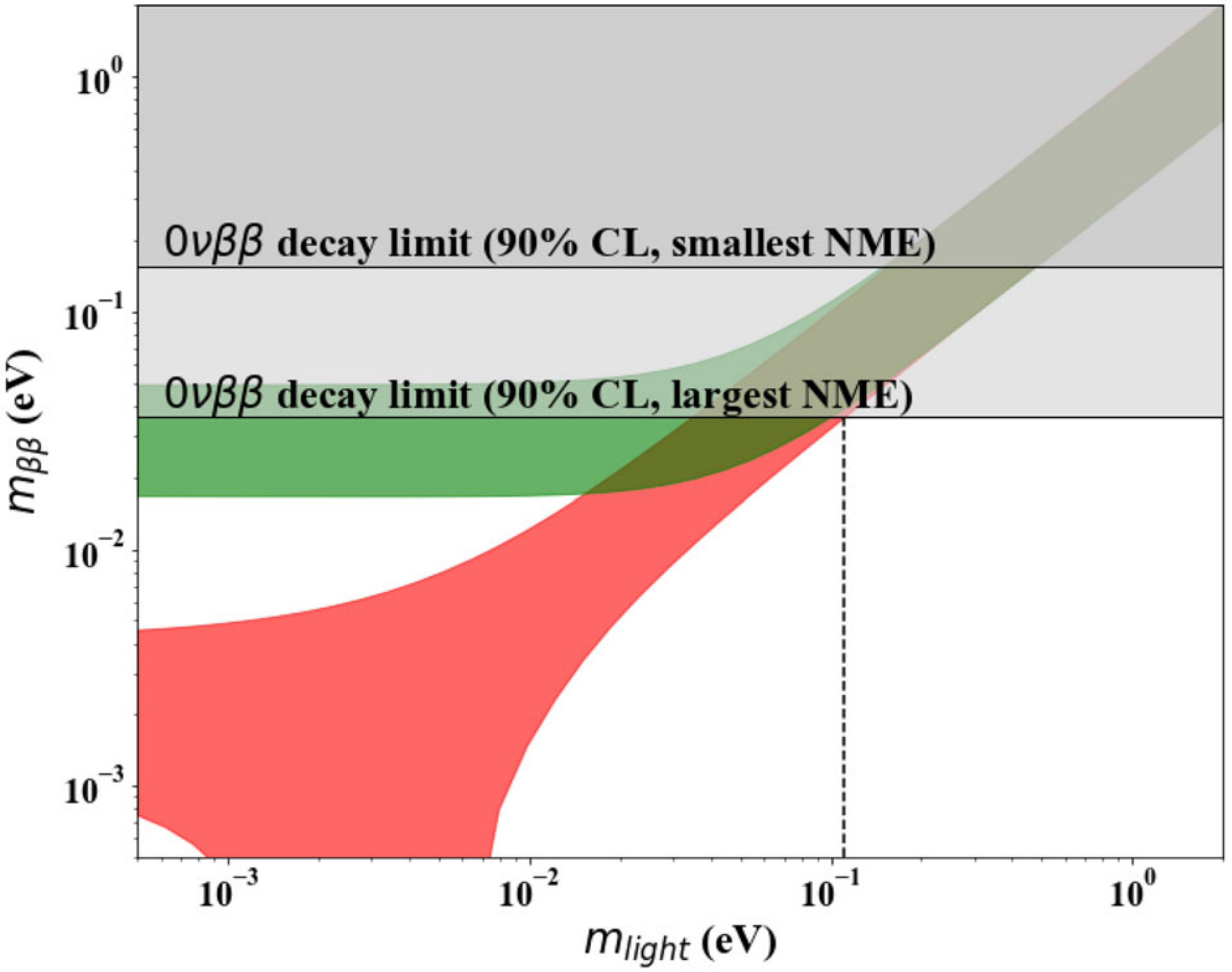
Experimental status: minimal SM

The amplitude for light neutrino exchange is proportional to

$$m_{2\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$



Isotope	$T_{1/2}^{2\nu}$ (year)	Experiments
^{48}Ca	$(5.3^{+1.2}_{-0.8}) \times 10^{19}$	Irvine TPC [44], TGV [45], NEMO-3 [46]
^{76}Ge	$(1.88 \pm 0.08) \times 10^{21}$	HEIDELBERG-MOSCOW [47], GERDA [48]
^{82}Se	$(0.87 \pm^{+0.02}_{-0.01}) \times 10^{20}$	NEMO-3 [49], CUPID-0 [50], Irvine TPC [51], NEMO-2 [52]
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	NEMO-2 [53], NEMO-3 [54]
^{100}Mo	$(7.06^{+0.15}_{-0.13}) \times 10^{18}$	NEMO-3 [55], CUPID-Mo [56], NEMO-2 [57], Irvine TPC [58], ZnMoO$_4$ bolometers [59]
^{116}Cd	$(2.69 \pm 0.09) \times 10^{19}$	NEMO-3 [60], Aurora [61], ELEGANT [62], Solotvina [63], NEMO-2 [64]
^{130}Te	$(7.91 \pm 0.21) \times 10^{20}$	CUORE-0 [65], CUORE [66], CUORICINO [67], NEMO-3 [68]
^{136}Xe	$(2.18 \pm 0.05) \times 10^{21}$	EXO-200 [69], KamLAND-Zen [70]
^{150}Nd	$(9.34 \pm 0.65) \times 10^{18}$	NEMO-3 [71]



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

J. J. Gómez-Cadenas, J. Martín-Albo, J. Menéndez, M. Mezzetto, F. Monrabal and M. Sorel, Riv. Nuovo Cim. 46 (2023) no.10, 619-692

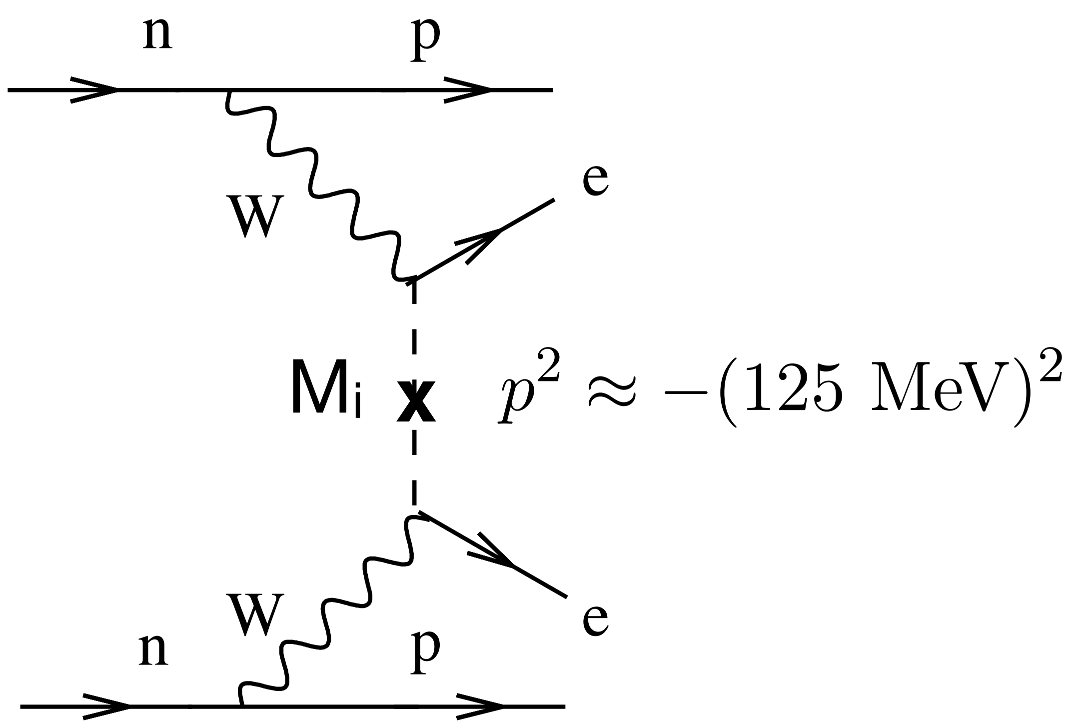
Contribution of heavy neutrinos

Heavy Majorana neutrinos contribute as well to 0ν2β amplitude

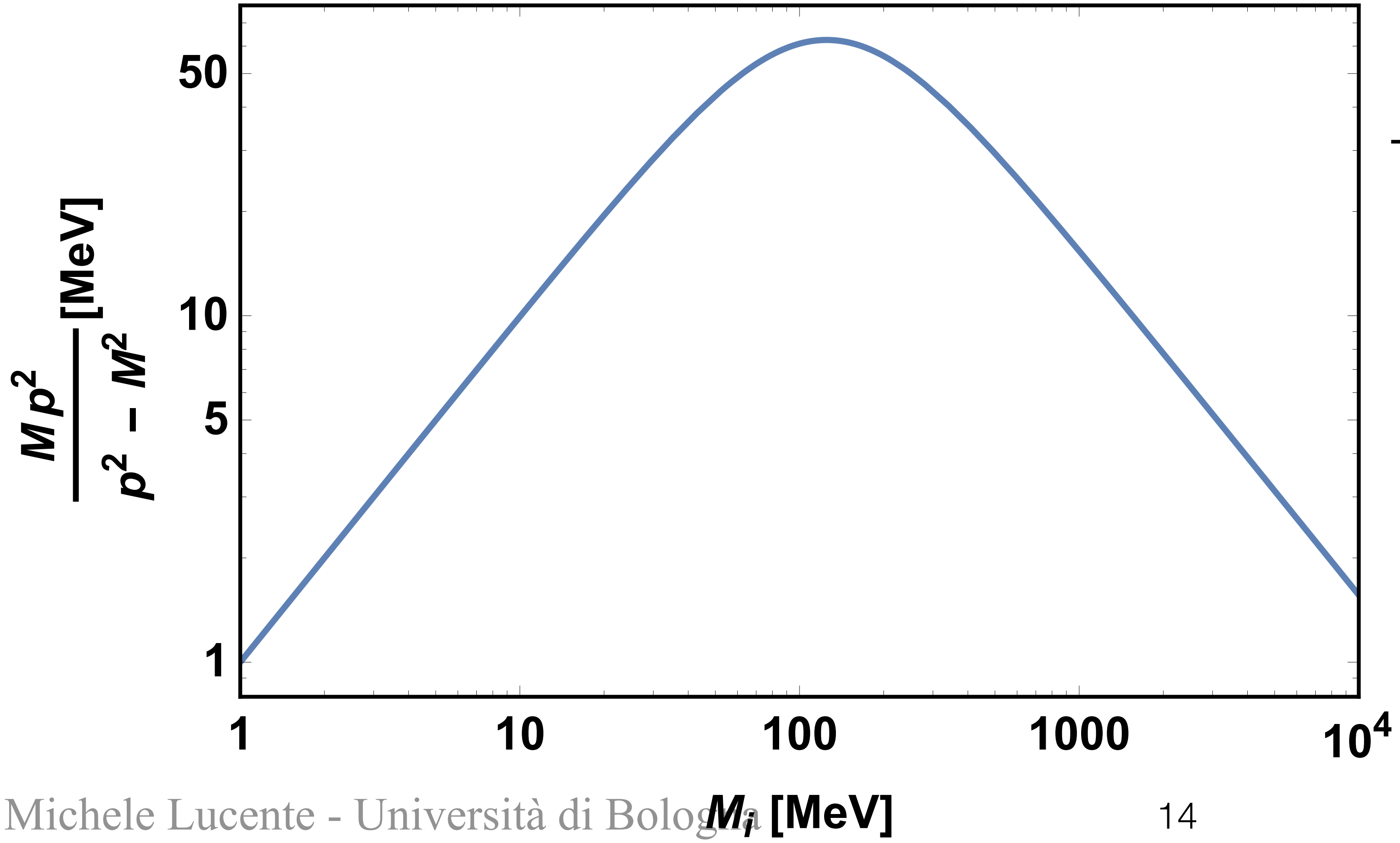
F. L. Bezrukov, hep-ph/0505247; M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon and J. Menendez, arXiv:1005.3240 [hep-ph]; A. Abada and M.L., arXiv:1401.1507 [hep-ph]; A. Faessler, M. González, S. Kovalenko and F. Šimkovic, arXiv:1408.6077 [hep-ph]; A. Abada, V. De Romeri, M.L., A. M. Teixeira and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

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

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



Mass dependence



If pseudo-Dirac

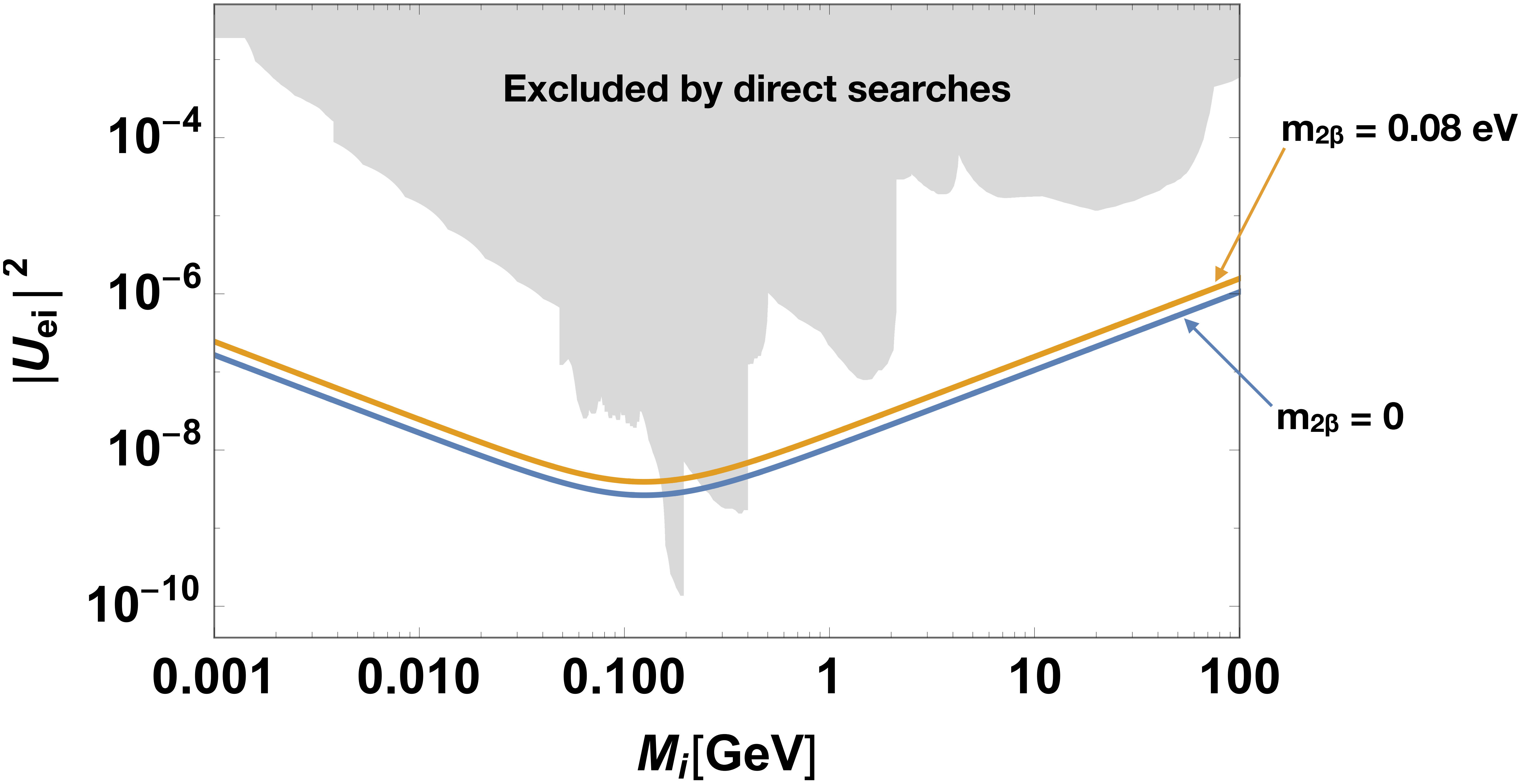
$$M_1 \simeq M_2$$
$$\mathcal{U}_{e1} \simeq i\,\mathcal{U}_{e2}$$

cancellation between contributions of single Majorana states

Extracting contraints on heavy neutrinos

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

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



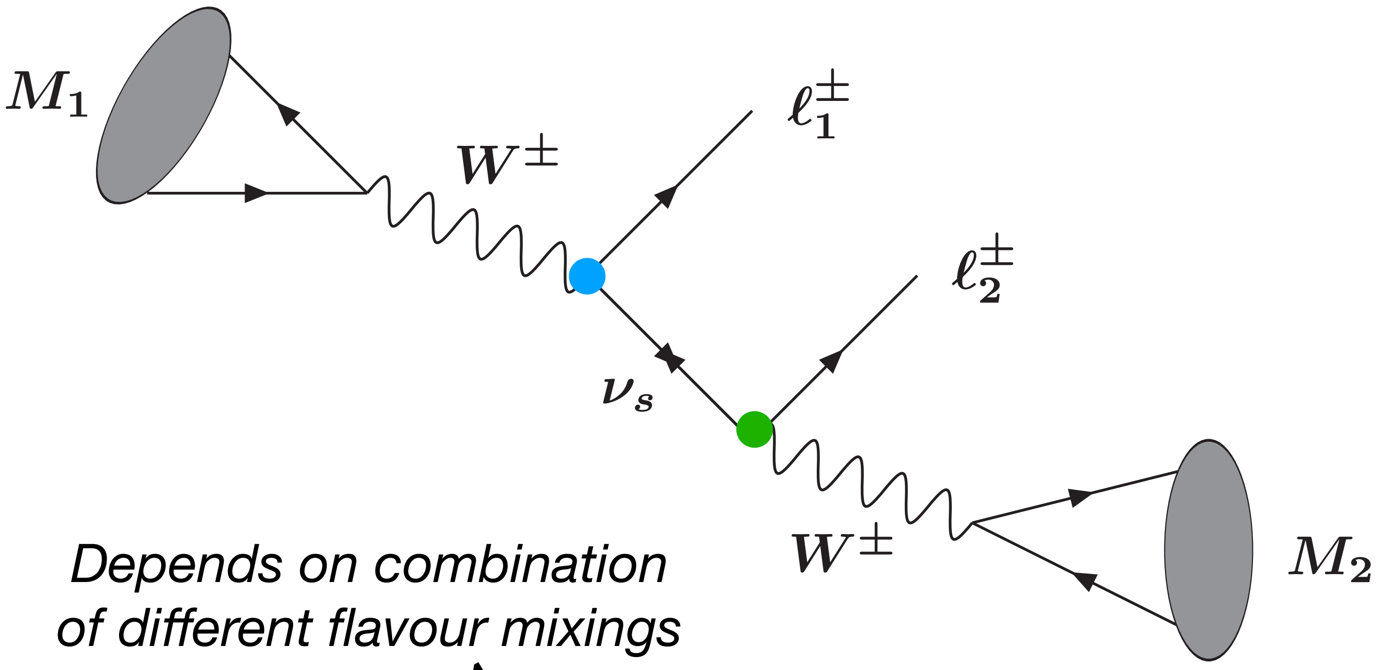
These constraints do not apply to (pseudo-)Dirac particles

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

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



Depends on combination of different flavour mixings

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

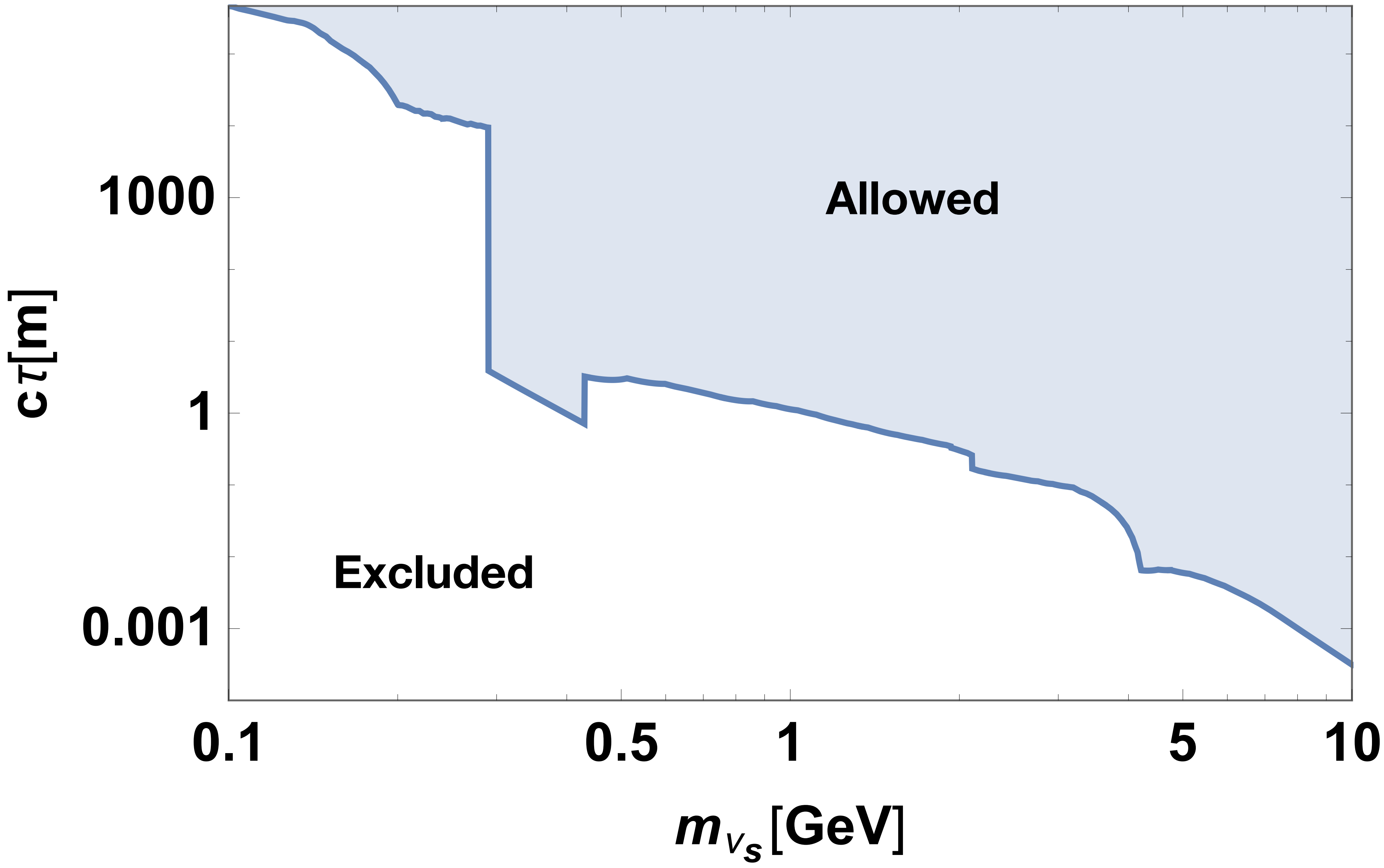
Negligible amplitude unless the intermediate state can go on-shell

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

Lifetime limitations

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

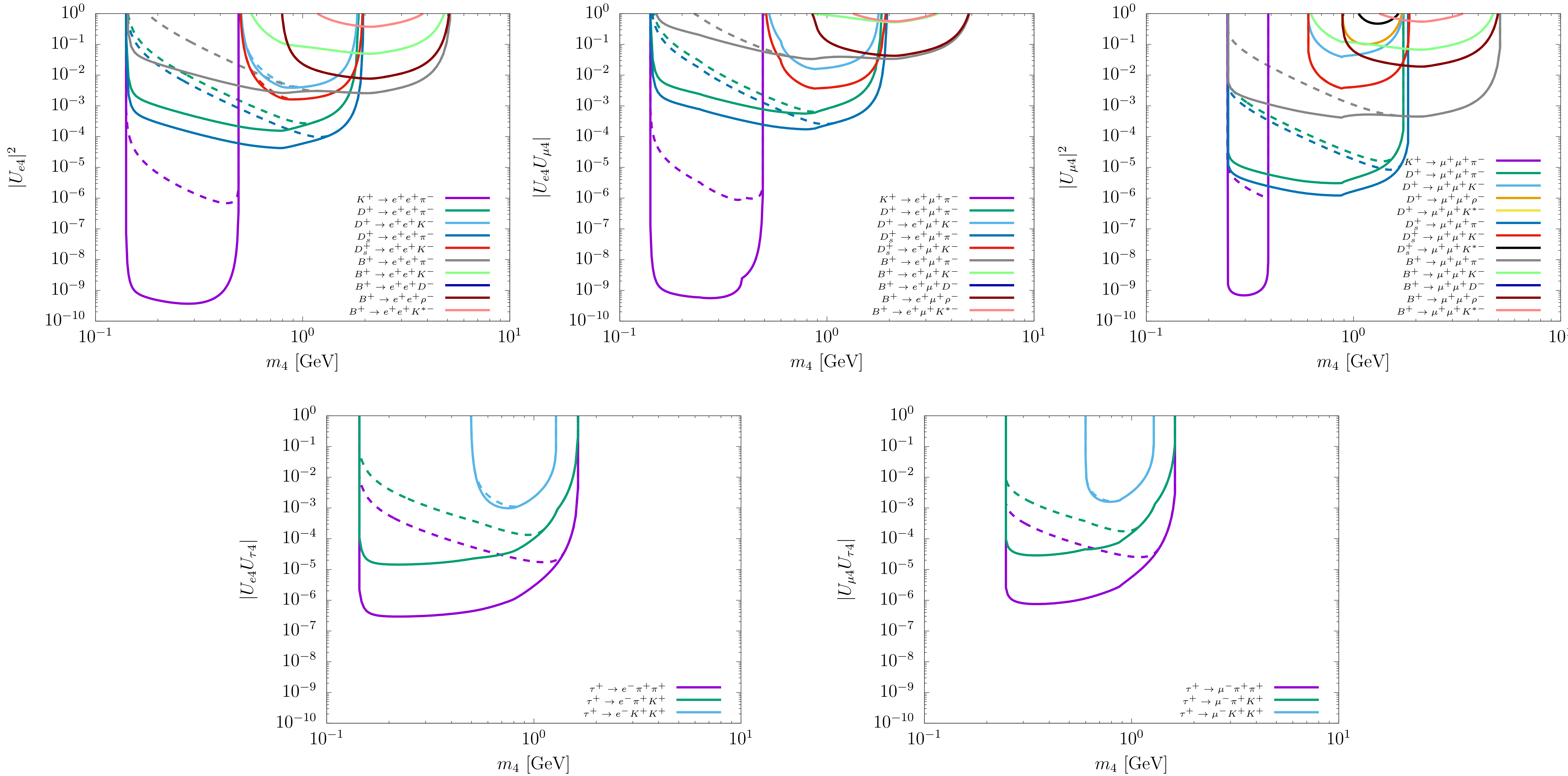
But too long-lived heavy neutrinos decay outside the detector



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

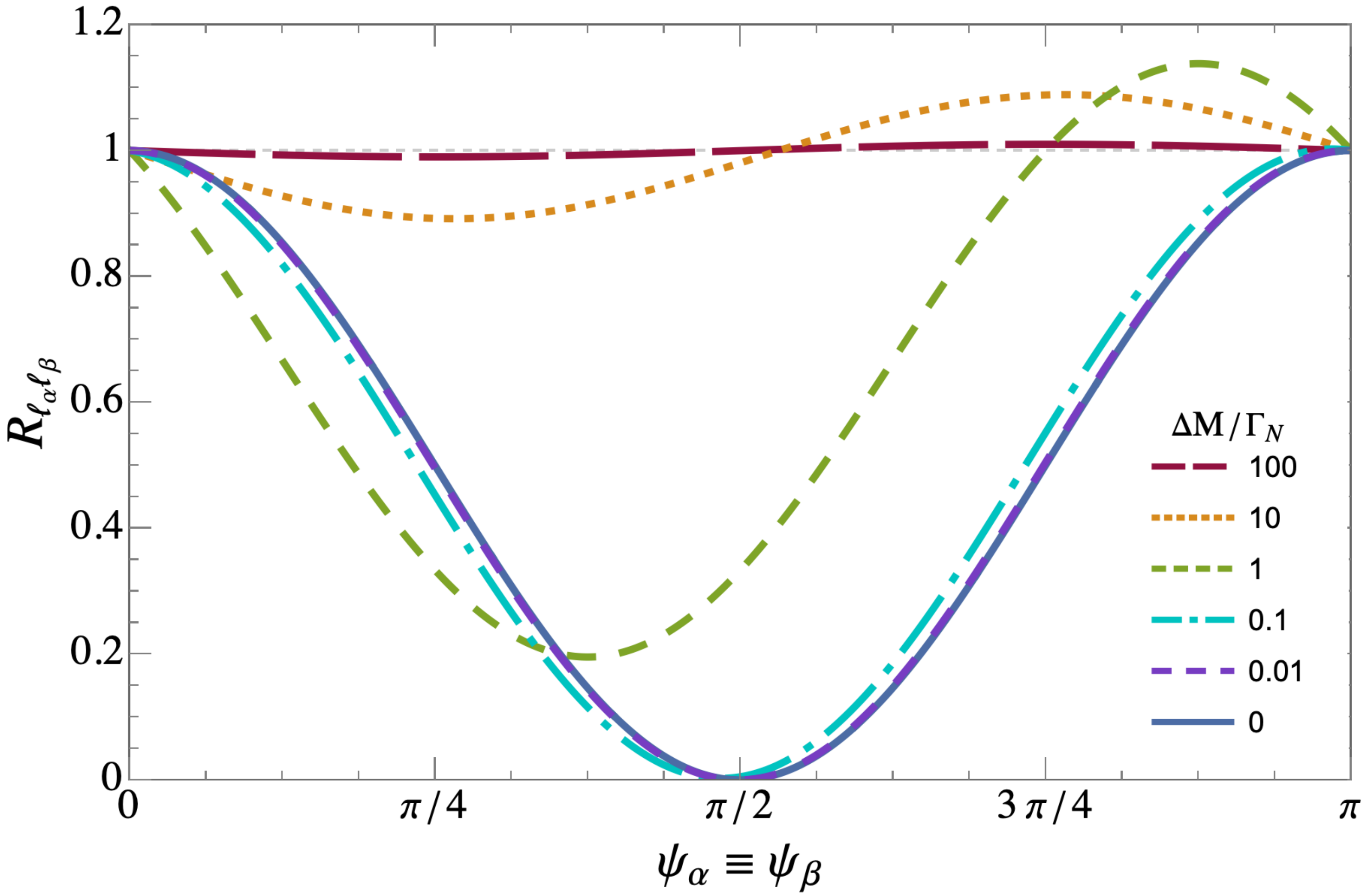
$$\Delta M \ll M \quad \text{and} \quad \Delta M < \Gamma_N$$

interference effects arise due to the CP-violating phases

$$\left|\mathcal{A}^{\text{LNC}}_{M\to M'\ell^+_\alpha\ell^-_\beta}\right|^2 \propto \left|U_{\alpha4}U^*_{\beta4}g(m_4) + U_{\alpha5}U^*_{\beta5}g(m_5)\right|^2,$$

$$\left|\mathcal{A}^{\text{LNV}}_{M\to M'\ell^+_\alpha\ell^+_\beta}\right|^2 \propto \left|U_{\alpha4}U_{\beta4}f(m_4) + U_{\alpha5}U_{\beta5}f(m_5)\right|^2,$$

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



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

$$\psi_\alpha \equiv \phi_{\alpha5} - \phi_{\alpha4}$$

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

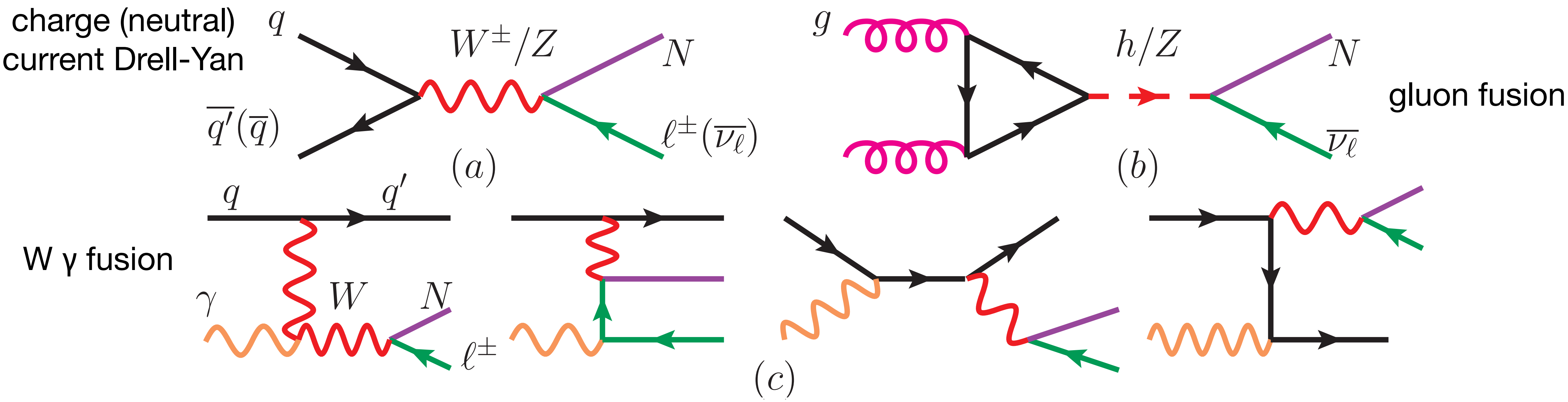


Figure from C. Degrande, O. Mattelaer, R. Ruiz and J. Turner, arXiv:1602.06957 [hep-ph];
see also Y. Cai, T. Han, T. Li and R. Ruiz, arXiv:1711.02180 [hep-ph]

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

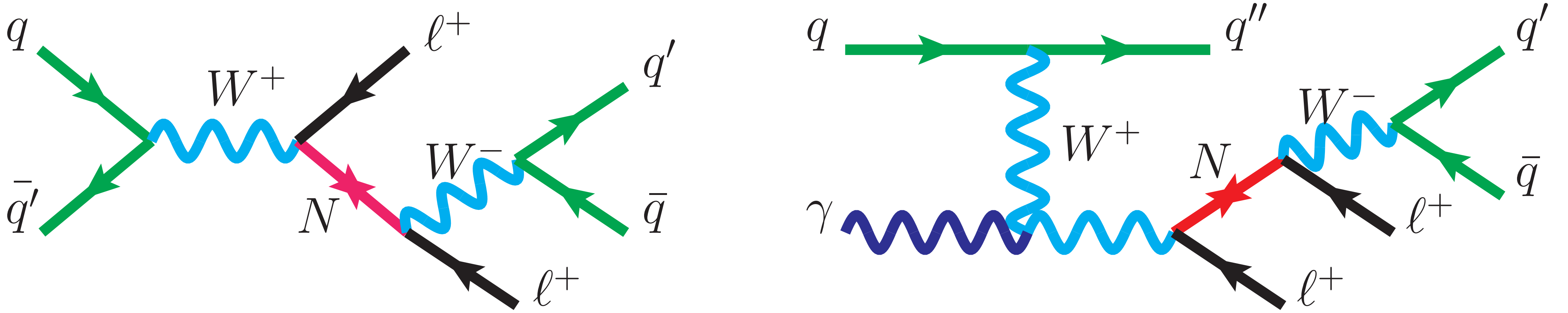


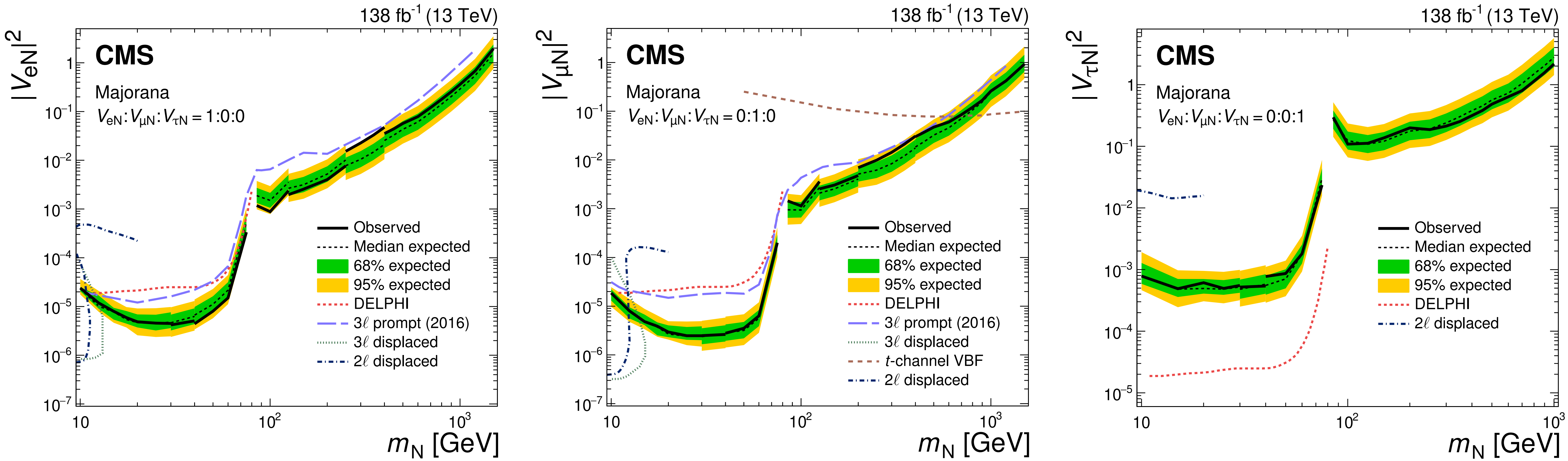
Figure from CMS Collaboration, arXiv:1806.10905 [hep-ex]

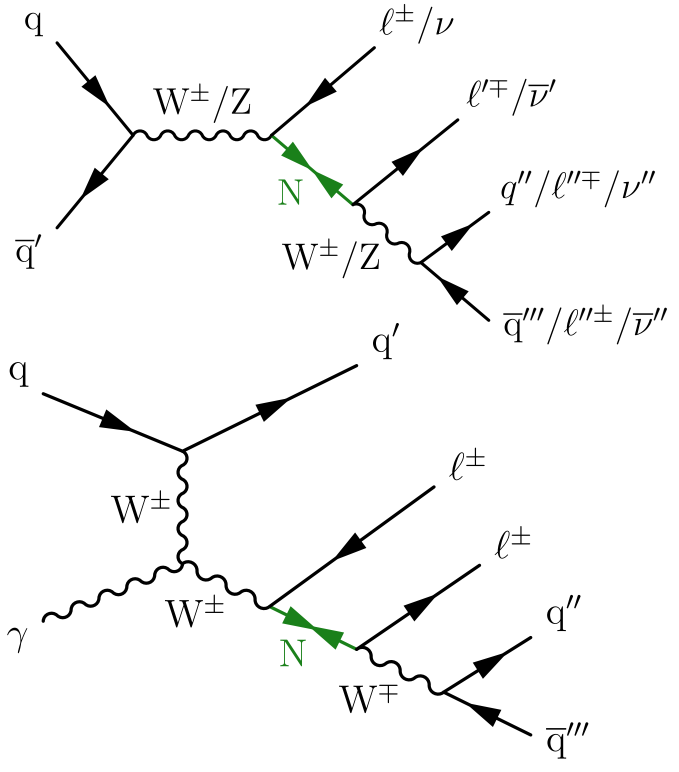
Prompt decays @ CMS

CMS collaboration, arXiv:2405.17605 [hep-ex]

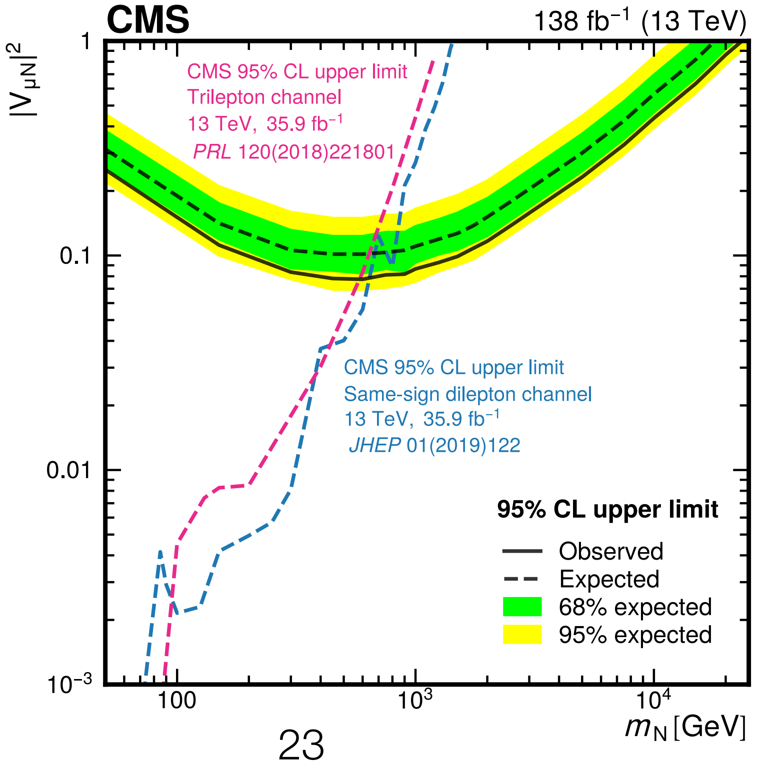
Prompt decays

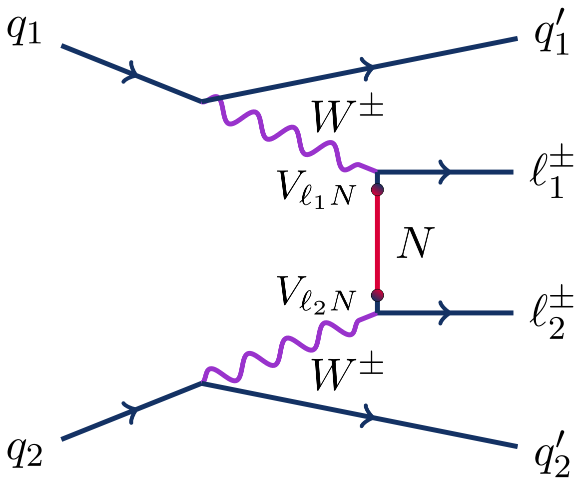
arXiv:2403.00100 [hep-ex]





Vector boson fusion

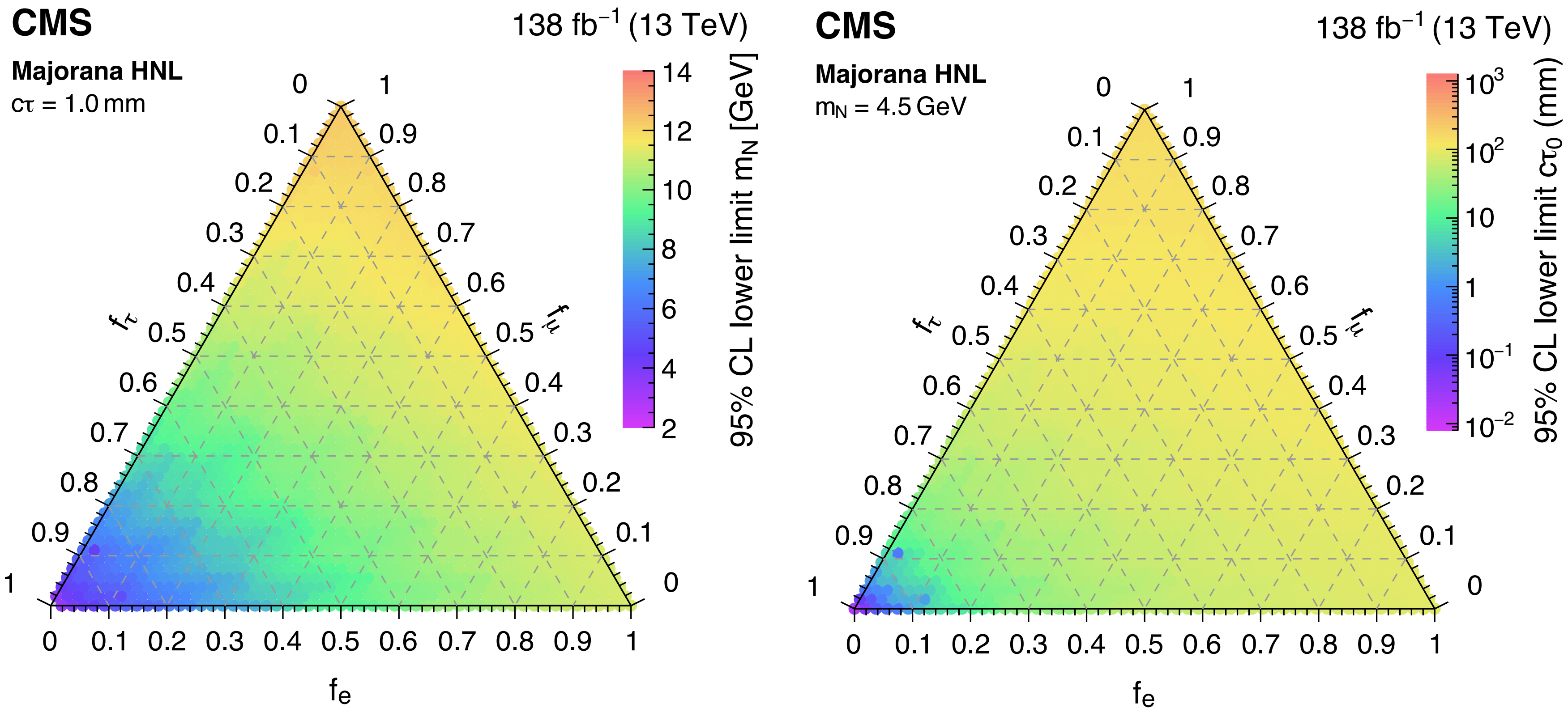




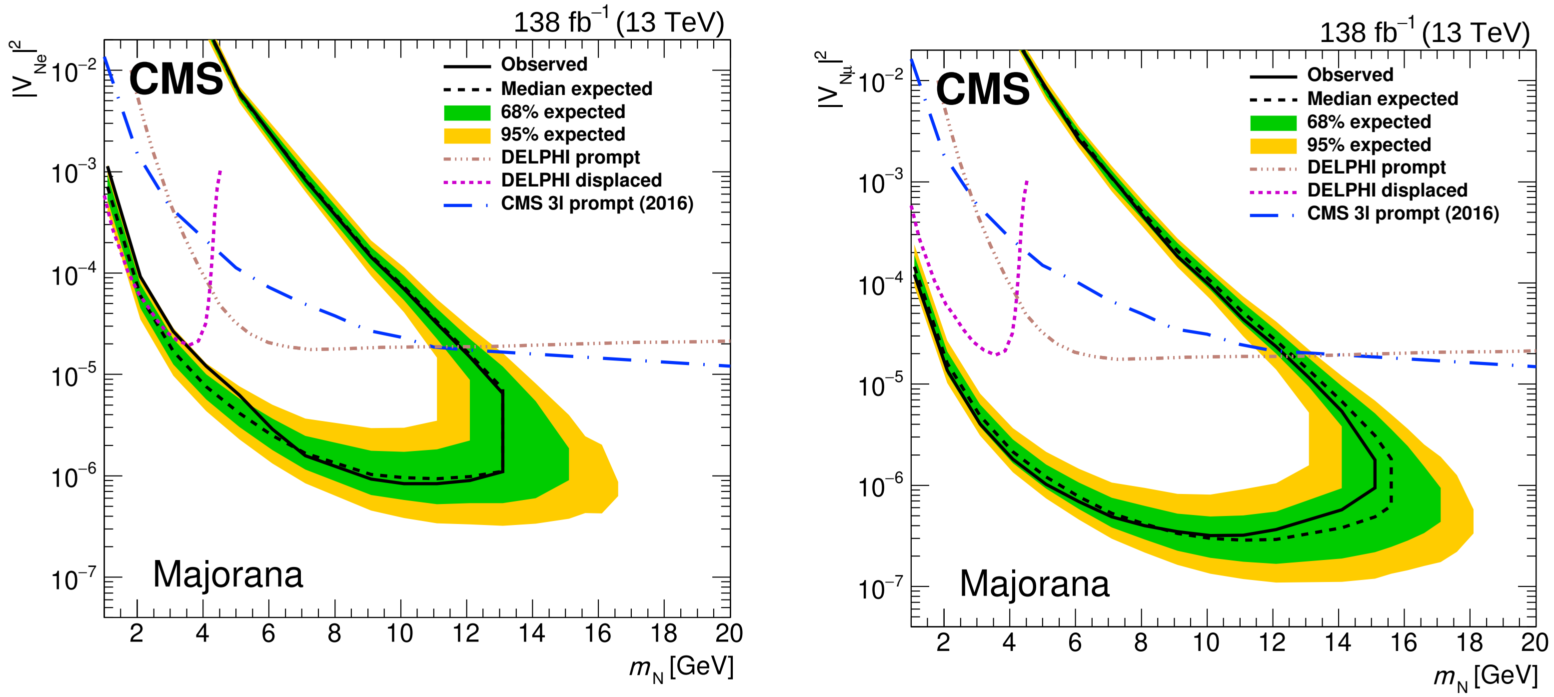
arXiv:2206.08956 [hep-ex]

Long-lived HNL @ CMS

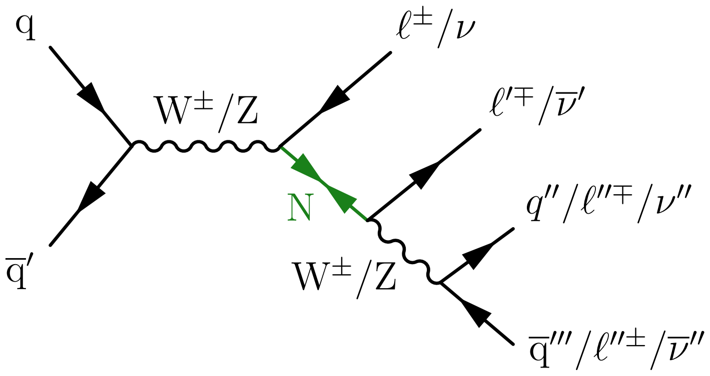
CMS collaboration, arXiv:2405.17605 [hep-ex]



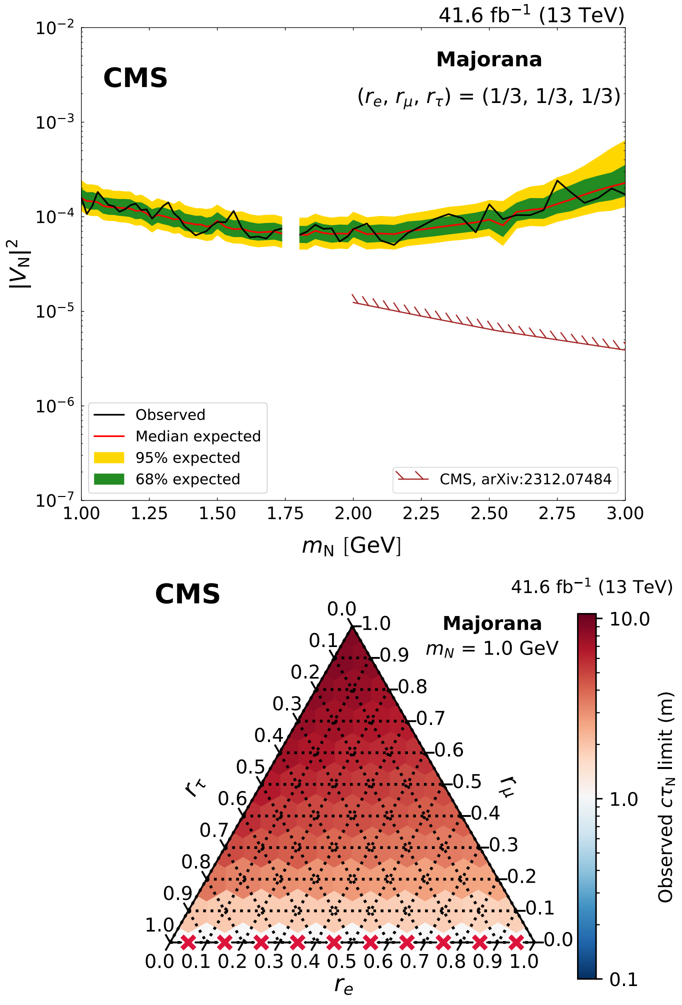
arXiv:2312.07484 [hep-ex]



arXiv:2201.05578 [hep-ex]

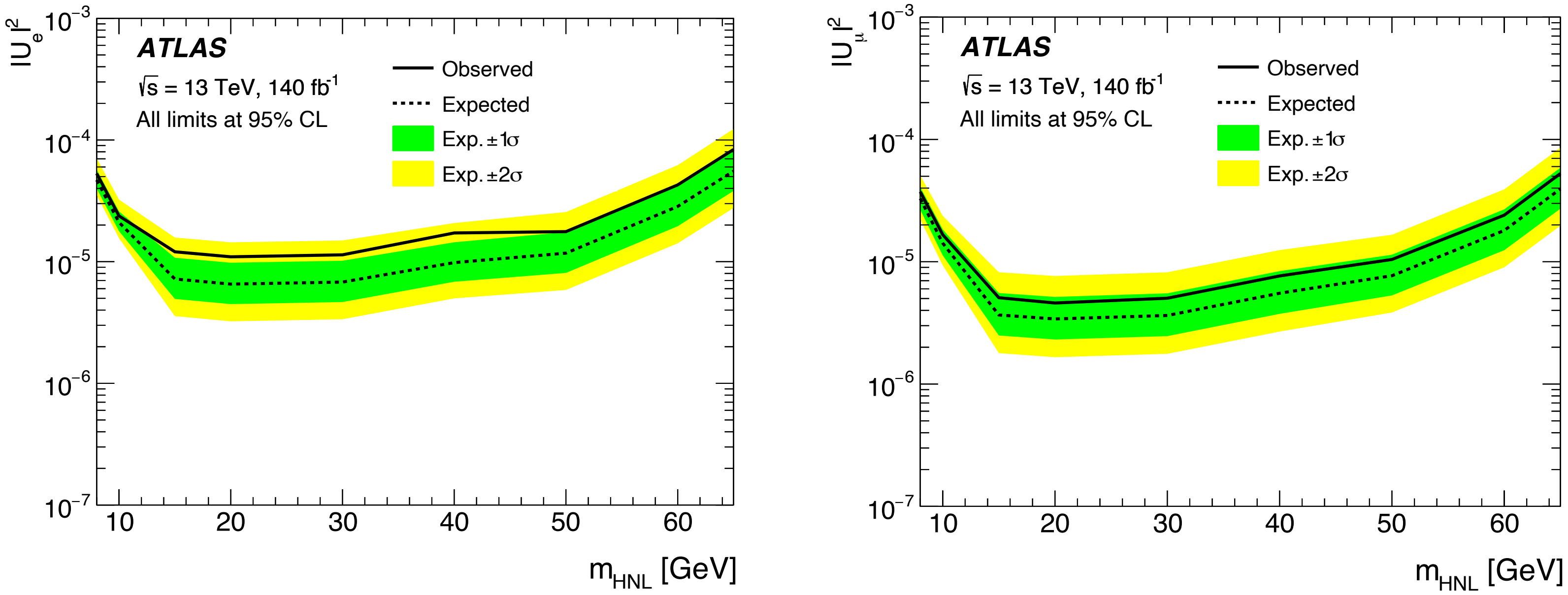


B meson decay

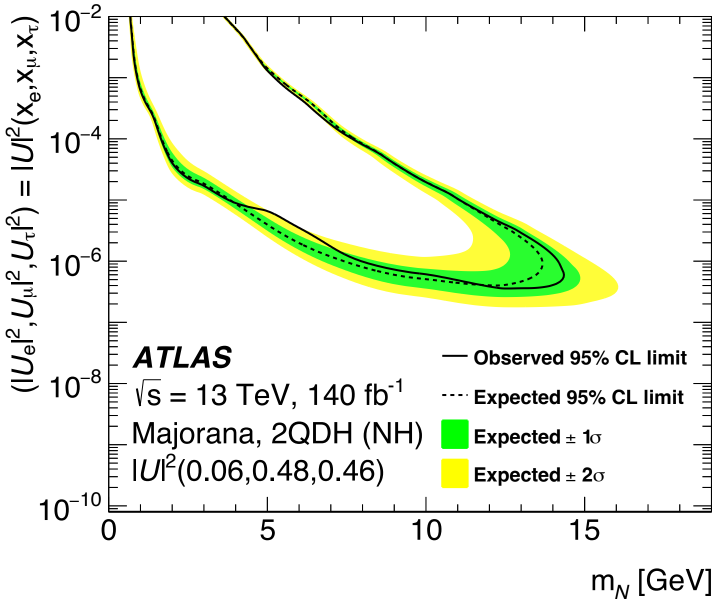


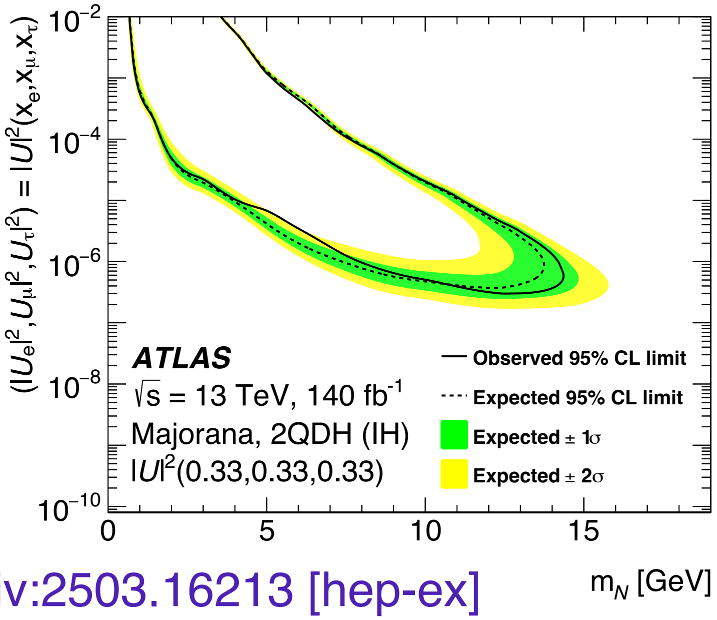
arXiv:2403.04584 [hep-ex]

HNL ATLAS searches

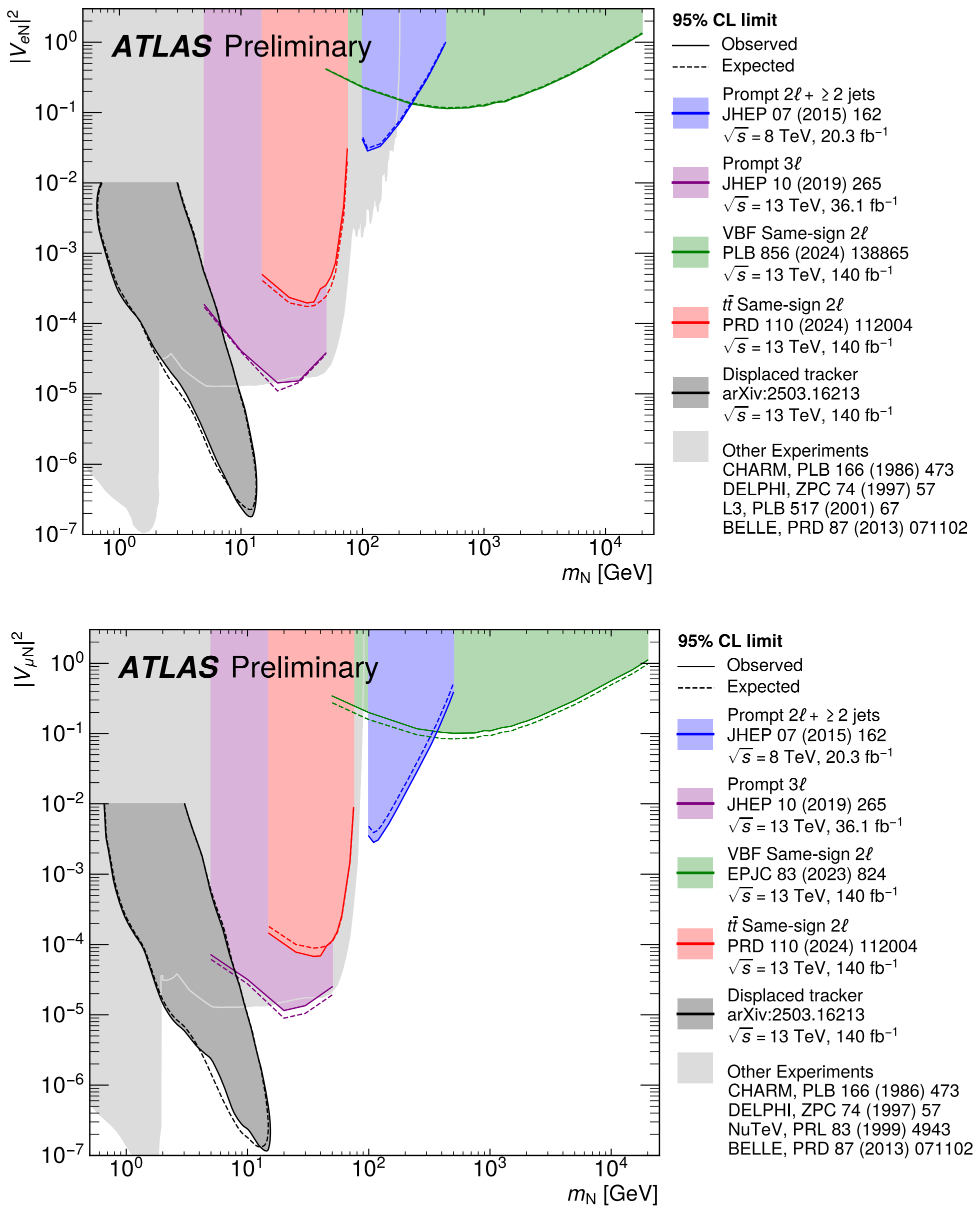


arXiv:2508.20929 [hep-ex]





arXiv:2503.16213 [hep-ex]



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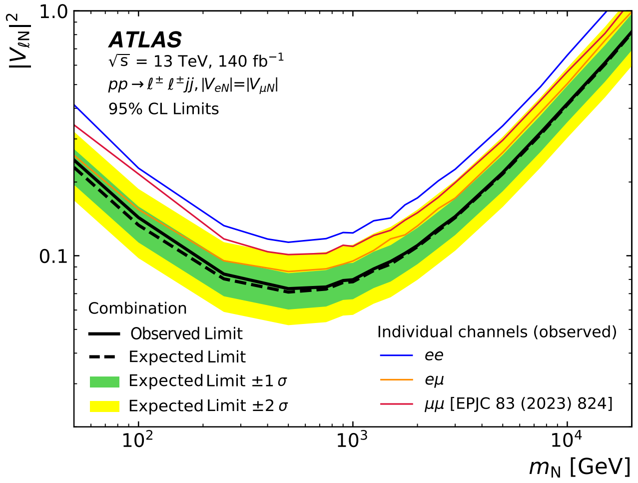


PoS LHCP2024 (2025), 032

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

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

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

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

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

Timescales

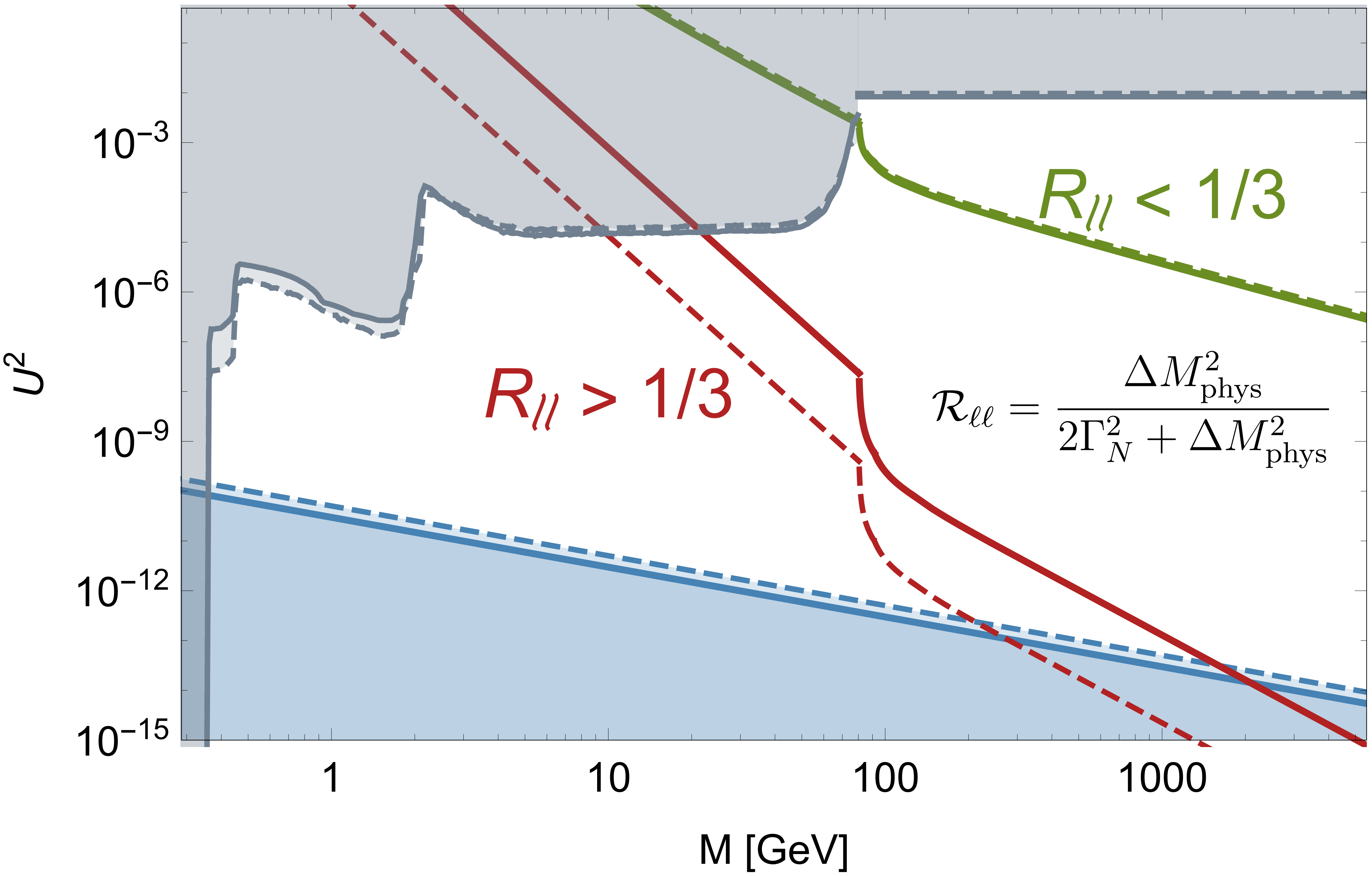
$\Delta M \gg \Gamma$	**decay after decoherence (Majorana limit)**
$\Delta M \approx \Gamma$	**oscillations**
$\Delta M \ll \Gamma$	**oscillations do not develop (Dirac limit)**

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

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

LNV observability at colliders

Type-I seesaw with n = 2 RHN reproducing neutrino oscillation data



M. Drewes, J. Klarić and P. Klose, arXiv:1907.13034 [hep-ph]

ADDITIONAL SEARCHES

A wealth of opportunities

Neutrino Masses and Mixing: Current Status and Open Questions *Yufeng Li*
14:30 - 14:55

Long-Baseline Neutrino Experiments: A Journey from Discovery to Precision and Beyond *Lucio Ludovici*
09:00 - 09:25

Neutrinos in the Multi-Messenger Era *Piera Sapienza*
15:45 - 16:10

Status of the Hyper-Kamiokande experiment *Jan Kisiel*
14:55 - 15:20

The DUNE Experiment: Status and Outlook *Jianming Bian et al.*
15:20 - 15:45

JUNO status and prospects *Jie ZHAO*
10:15 - 10:40

FASERv2, FLArE and other future nu exp. at collider *Wenjie Wu*
15:45 - 16:10

LFV/LFU theory *Marco Ardu*
16:40 - 17:05

Muon LFV/LFU measurements at JPARC, PSI, FNAL *Yusuke Uchiyama*
17:05 - 17:30

Tau LFV/LFU measurements *Fabian Becherer*
17:30 - 17:55

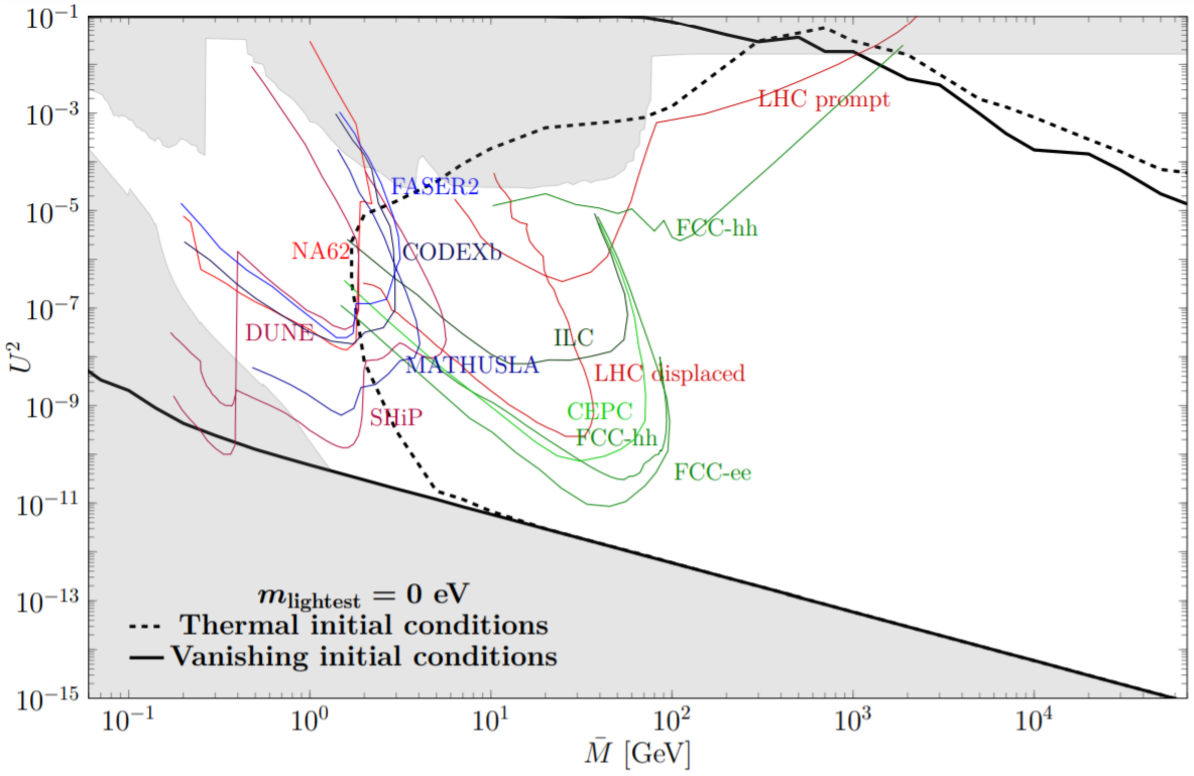
CONNECTION TO FURTHER BSM QUESTIONS

One stone, three birds

Other than ν masses, HNL can provide a solution to other SM observational issues

New source of CP violation

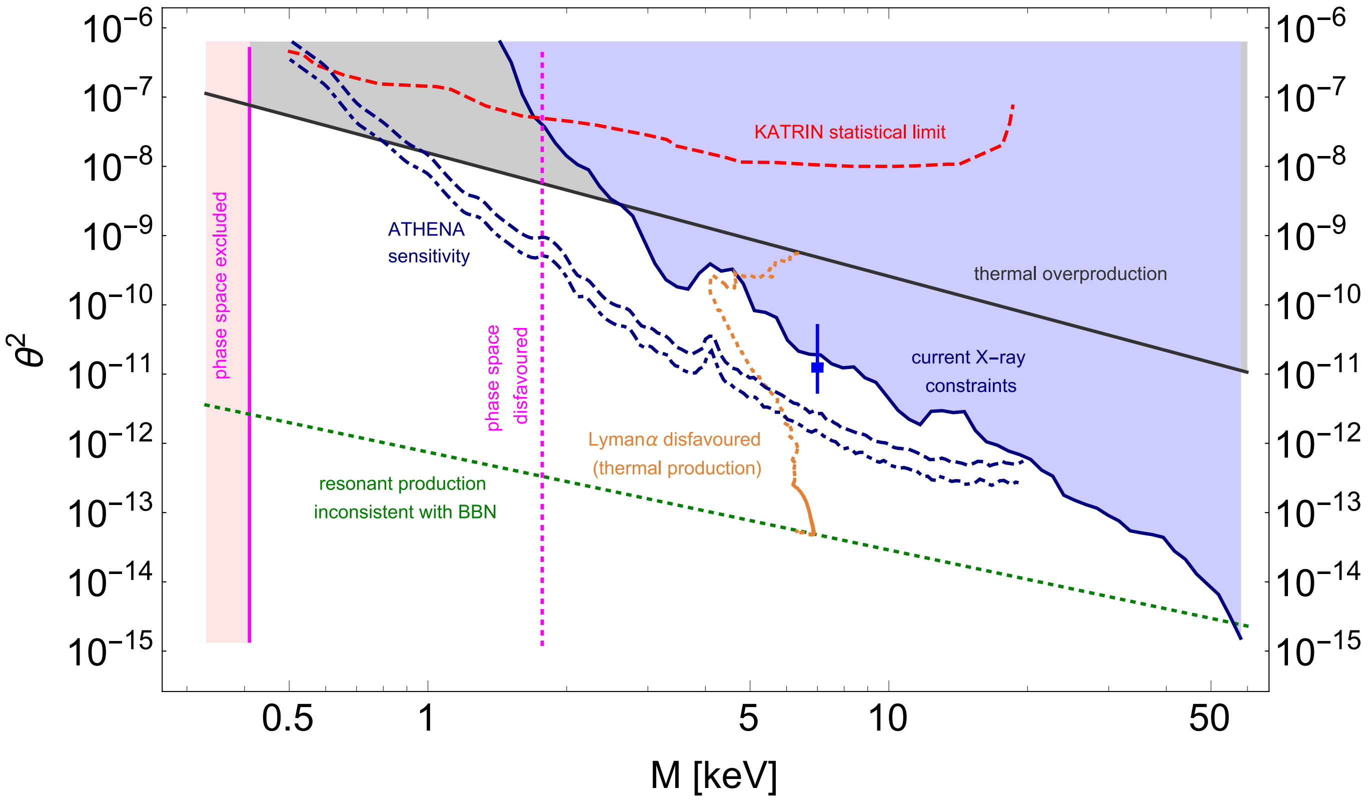
Leptogenesis



M. Drewes, Y. Georis and J. Klarić, arXiv:2106.16226 [hep-ph]

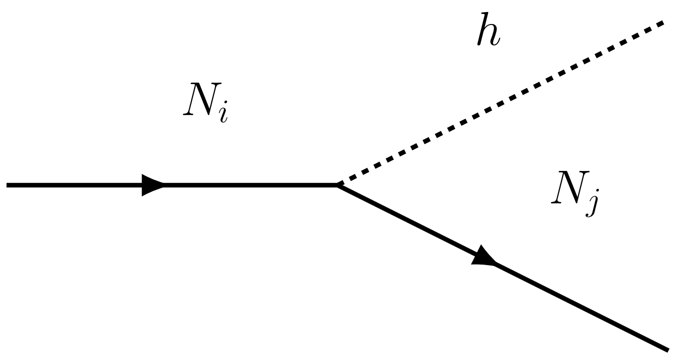
Long-lived particles

Dark matter



A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens and O. Ruchayskiy, arXiv:1807.07938 [hep-ph]

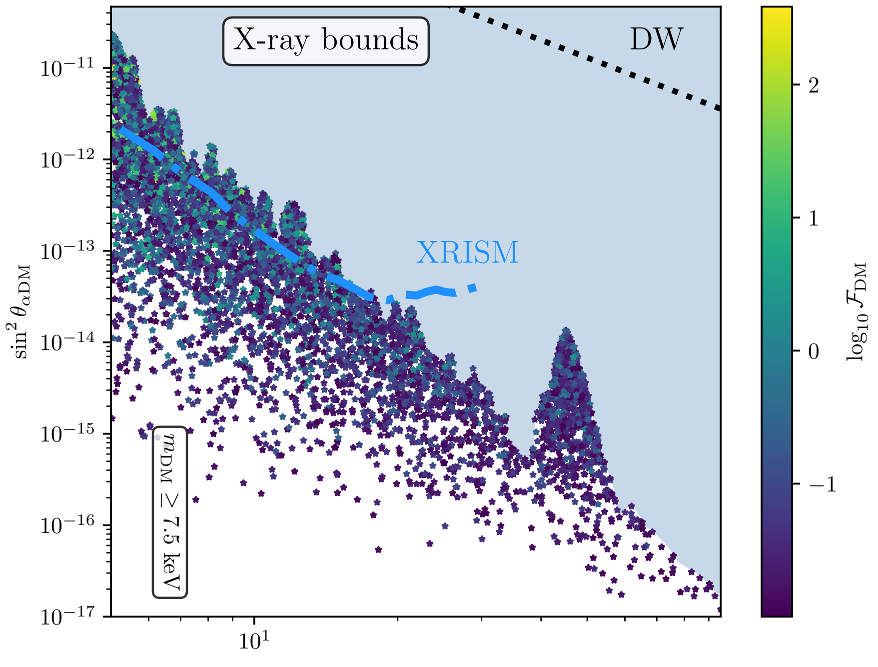
A new testable dark matter solution



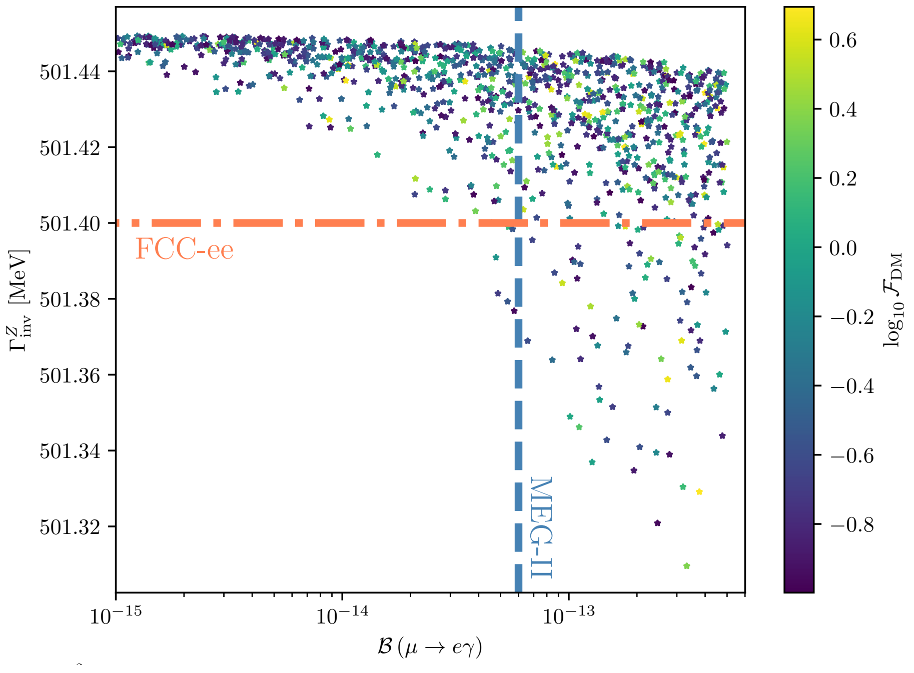
We computed the thermal correction in the production of DM from the decay of heavy states

The DM solutions exist and are testable by different experimental searches

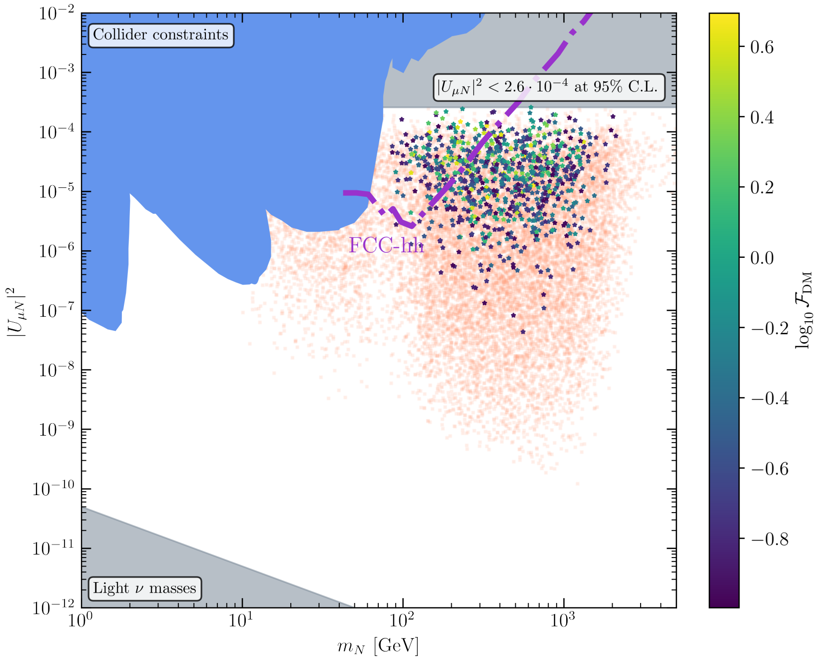
Indirect



Precision



Collider



A. Abada, G. Arcadi, M. Lucente and S. Rosauro-Alcaraz, arXiv:2503.20017 [hep-ph]; A. Abada, G. Arcadi, M. Lucente, G. Piazza and S. Rosauro-Alcaraz, arXiv:2308.01341 [hep-ph]; M. Lucente, arXiv:2103.03253 [hep-ph]

Conclusion

Massive neutrinos call for BSM physics

Multiple possibilities, we focus on the simple RHN extension

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

Multiple testability opportunities $\left\{ \right.$

- **neutrinoless 2β decay**
- **meson and tau decay**
- **collider and fixed target**
- **LFV/LNV and precision**
- **neutrino telescopes**
- **…**

HNL can also provide simultaneous solution to the BAU and DM problems

Backup

Accidental symmetries of the SM

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

B

Baryon number

(Individual quark flavour numbers are violated by CKM mixing)

L$_\alpha$

Flavour numbers
$\alpha = e, \mu, \tau$

L

Lepton number
$L = \Sigma_\alpha L_\alpha$

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)

$\cancel{L_\alpha}$

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*

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

3 x n matrix
Yukawa couplings

n x n matrix
Majorana mass
couplings

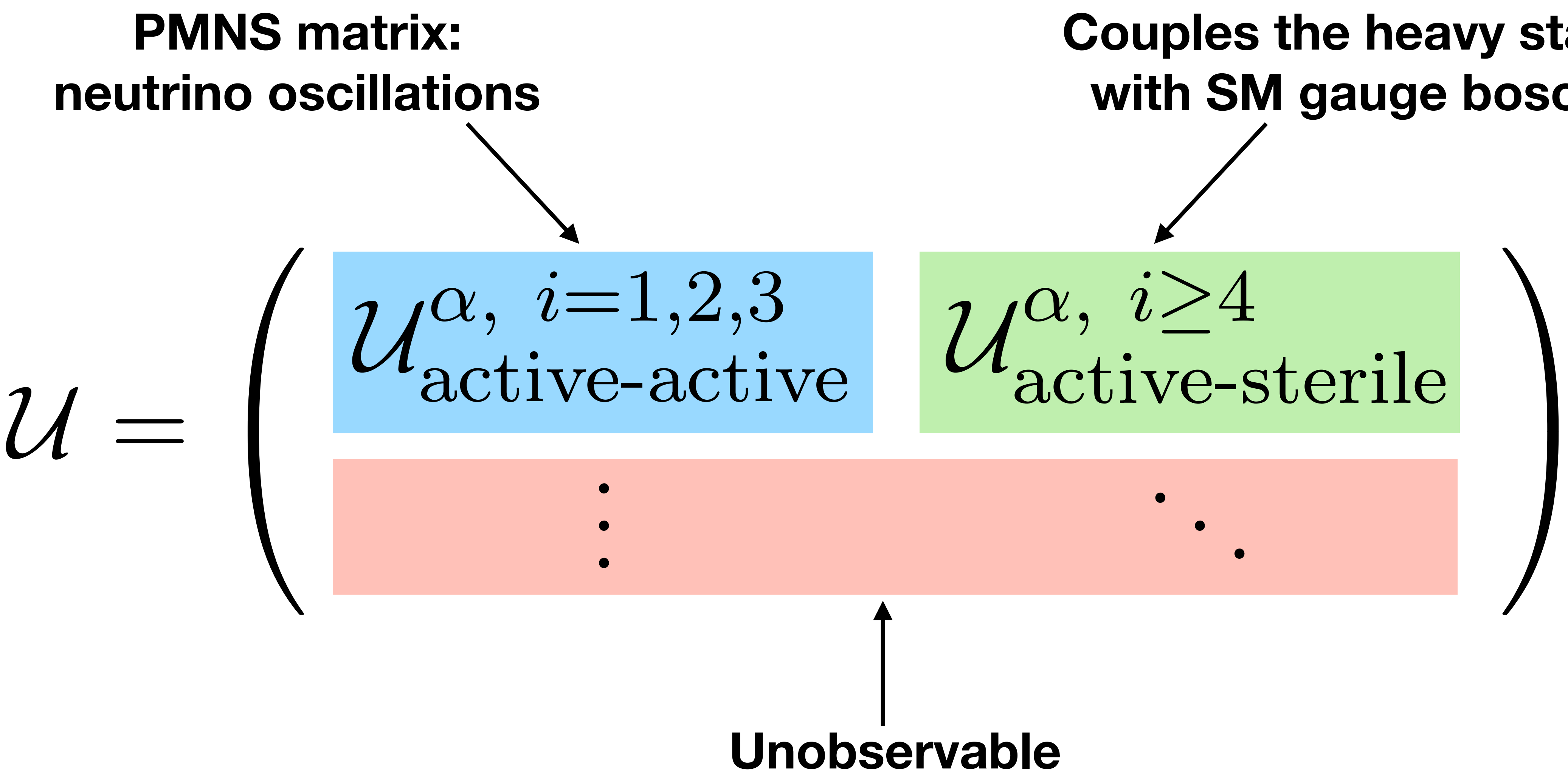
After electroweak phase transition < Φ > = v ≃ 174 GeV

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

(3+n) dimensional
mass matrix

Phenomenology of fermionic singlets

$$\mathcal{U}^T \mathcal{M}\, \mathcal{U} = \hat{\mathcal{M}}_{\text{diag}} \quad \Rightarrow \quad \begin{cases} \text{3 light (mostly active) states} \\ n \text{ heavy (mostly sterile) states} \end{cases}$$



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

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

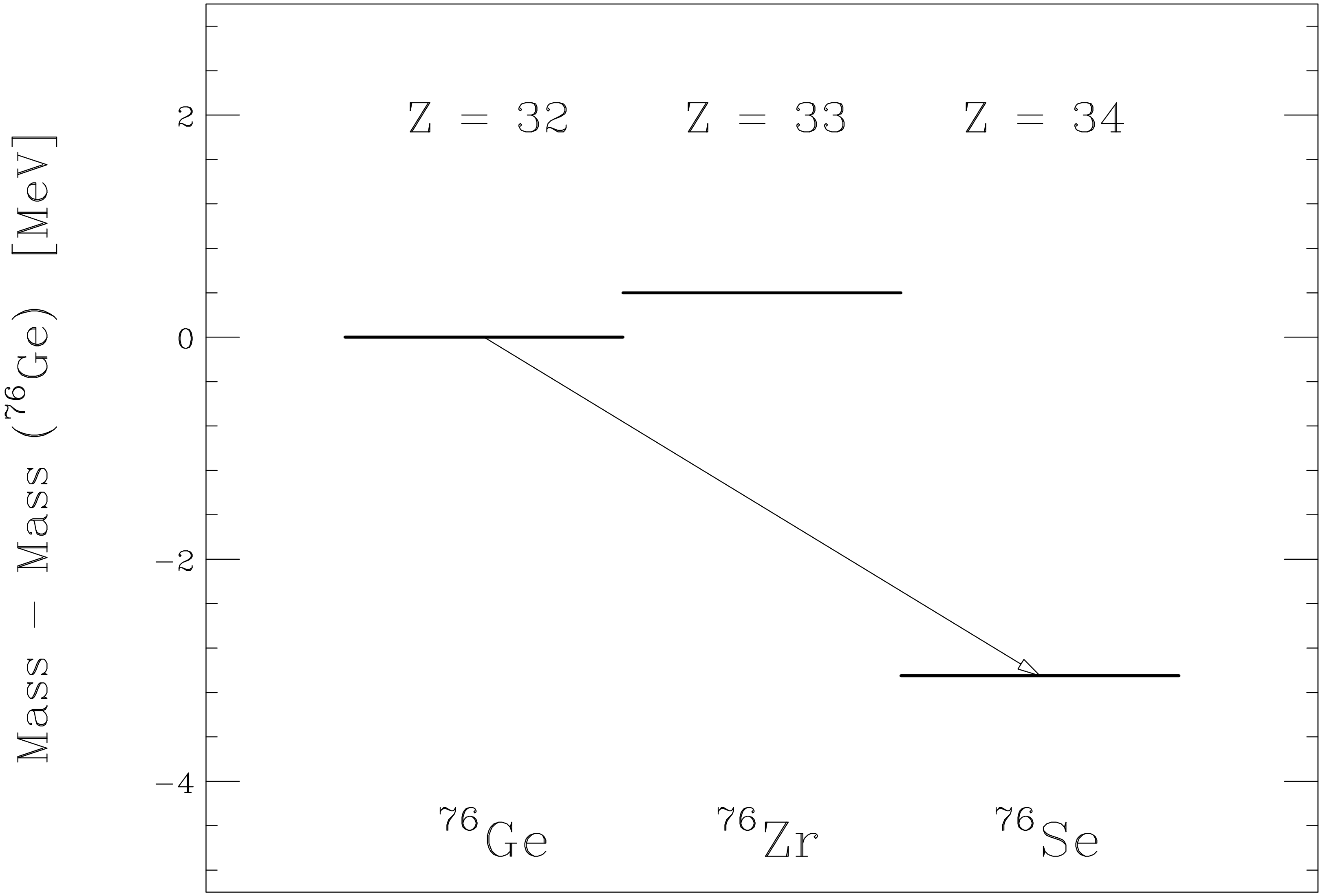
$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left(\frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

m_i^{loop}	m_i^{tree}
1-loop neutrino mass spectrum	tree-level neutrino mass spectrum

Double beta decay

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

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



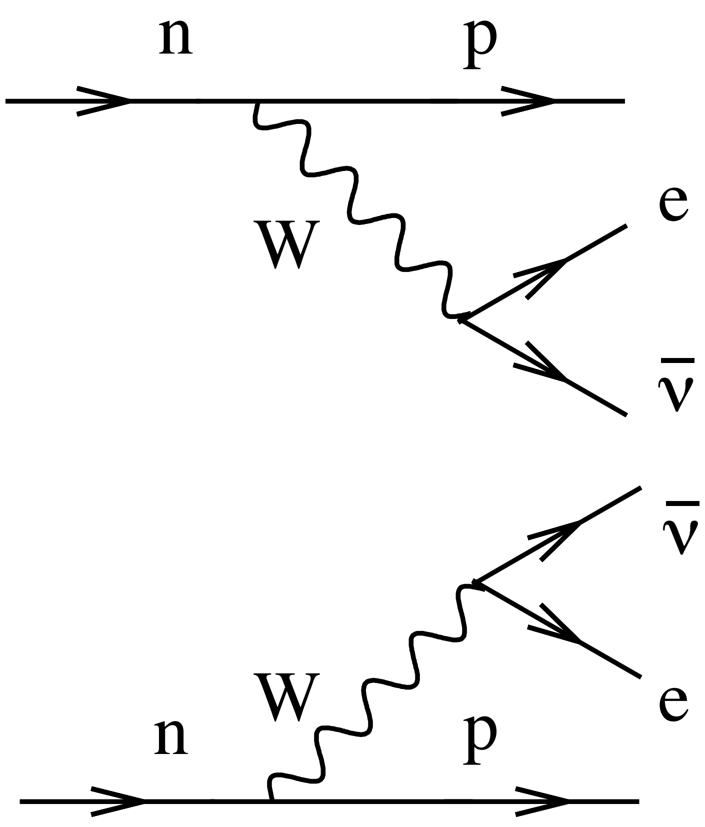


Figure from P. Lipari, Introduction to neutrino physics, in 2001 CERN-CLAF School of high-energy physics

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]

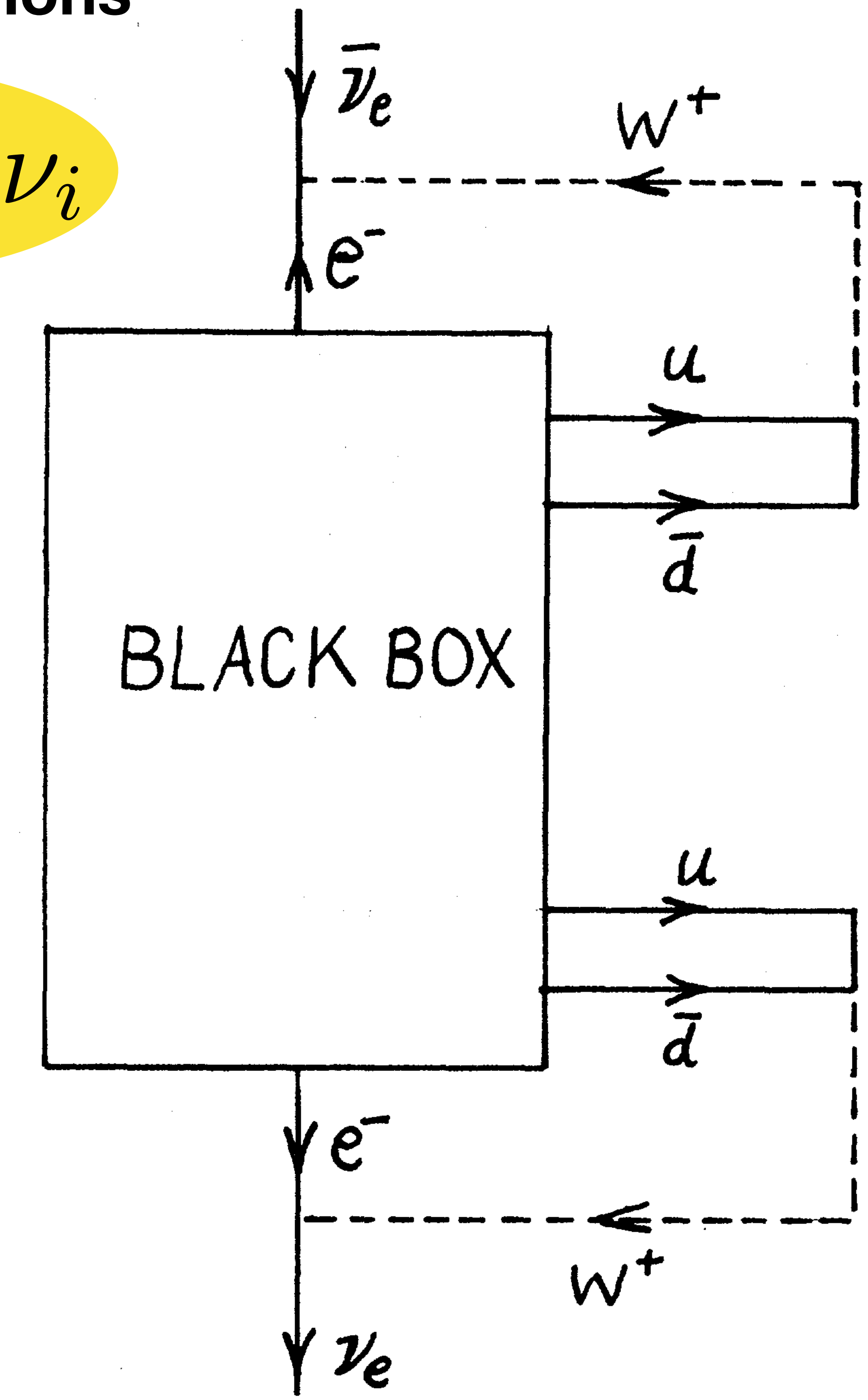
Non-vanishing 0ν2β amplitude

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

$$\Longleftrightarrow$$

Neutrinos are Majorana fermions

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

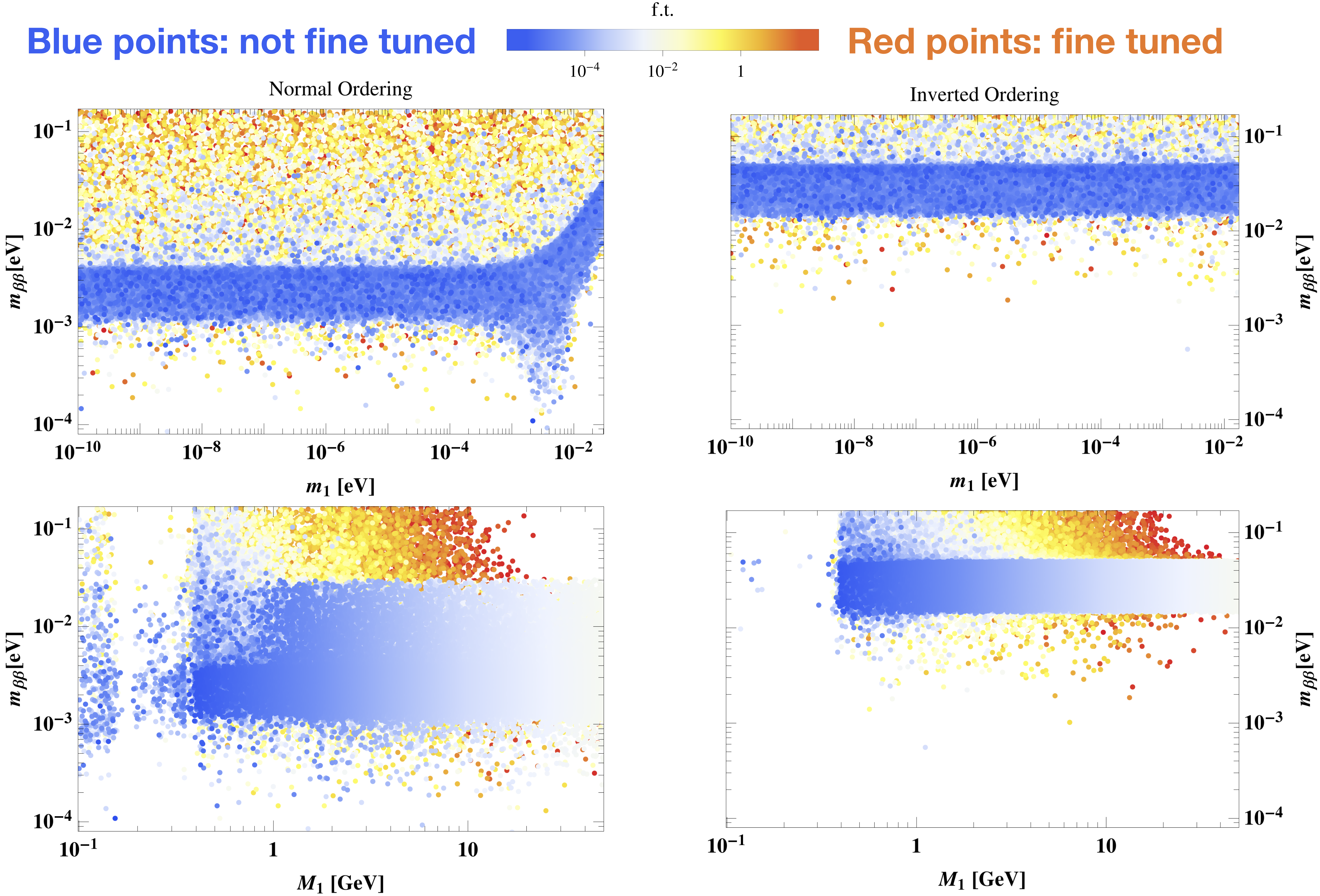


Irrespectively of the underlying mechanism, a non-vanishing 0ν2β amplitude generates a Majorana mass term for the SM neutrinos

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]

Meson and tau LNV: 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

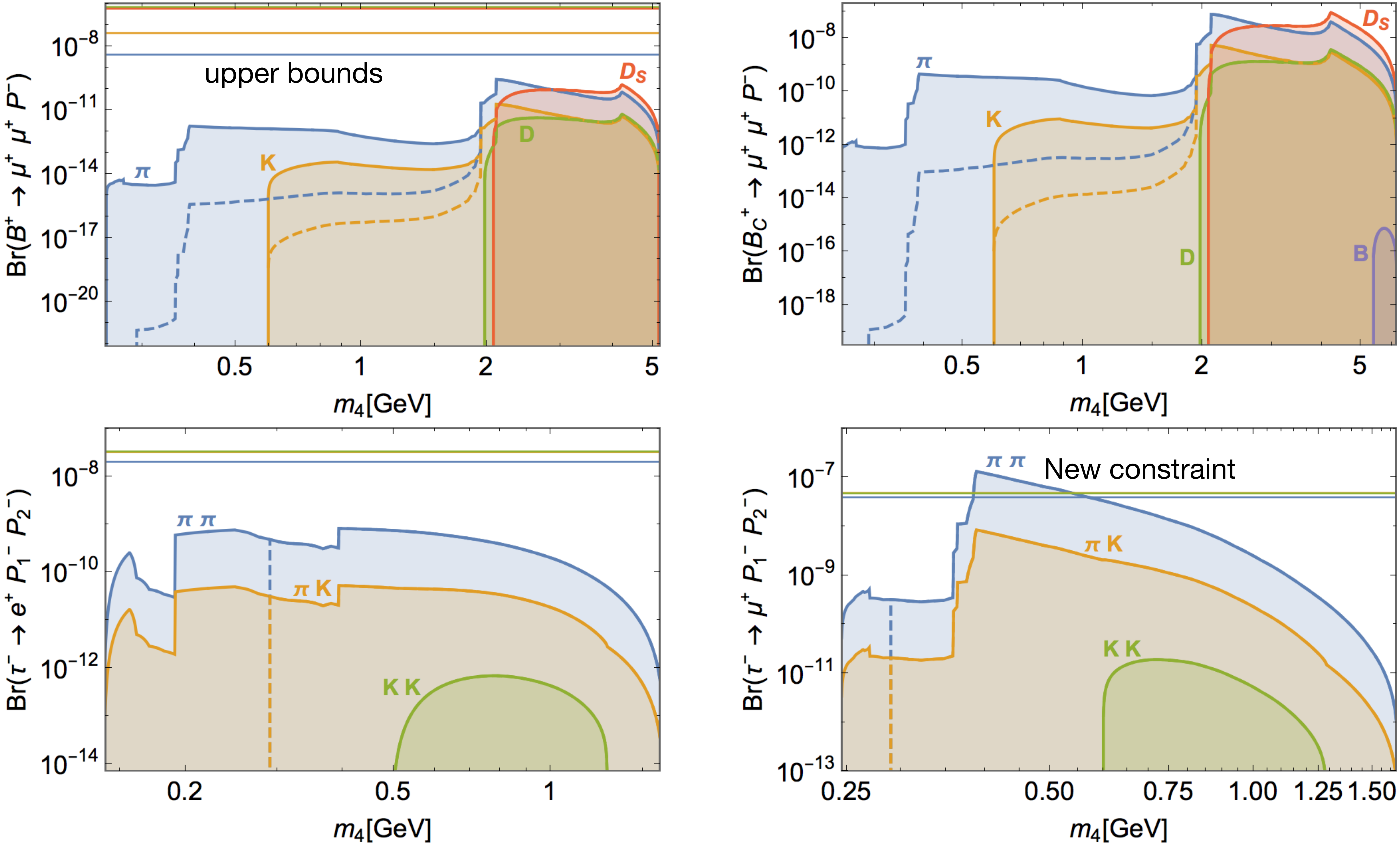
LNV decay	Current bound	
	$\ell = e$	$\ell = \mu$
$\tau^- \to \ell^+ \pi^- \pi^-$	2.0×10^{-8}	3.9×10^{-8}
$\tau^- \to \ell^+ \pi^- K^-$	3.2×10^{-8}	4.8×10^{-8}
$\tau^- \to \ell^+ K^- K^-$	3.3×10^{-8}	4.7×10^{-8}
LNV matrix m_ν	$m_\nu^{e\tau}$	$m_\nu^{\mu\tau}$

upper bounds from the Belle

Some predictions: single intermediate state

Comprehensive analysis for τ and pseudo-scalar mesons in 1712.03984

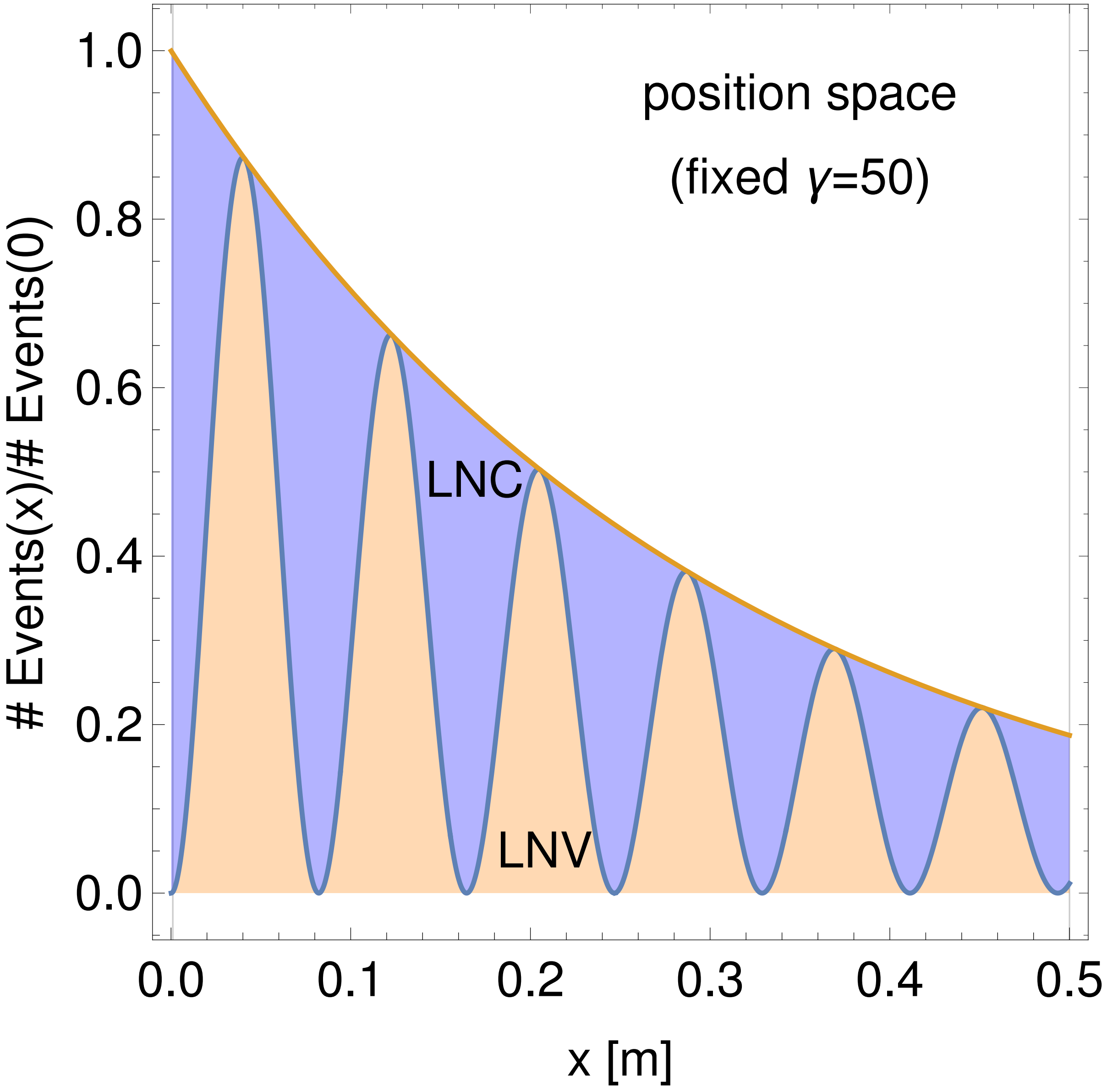
(all possible initial and 3-body final states)

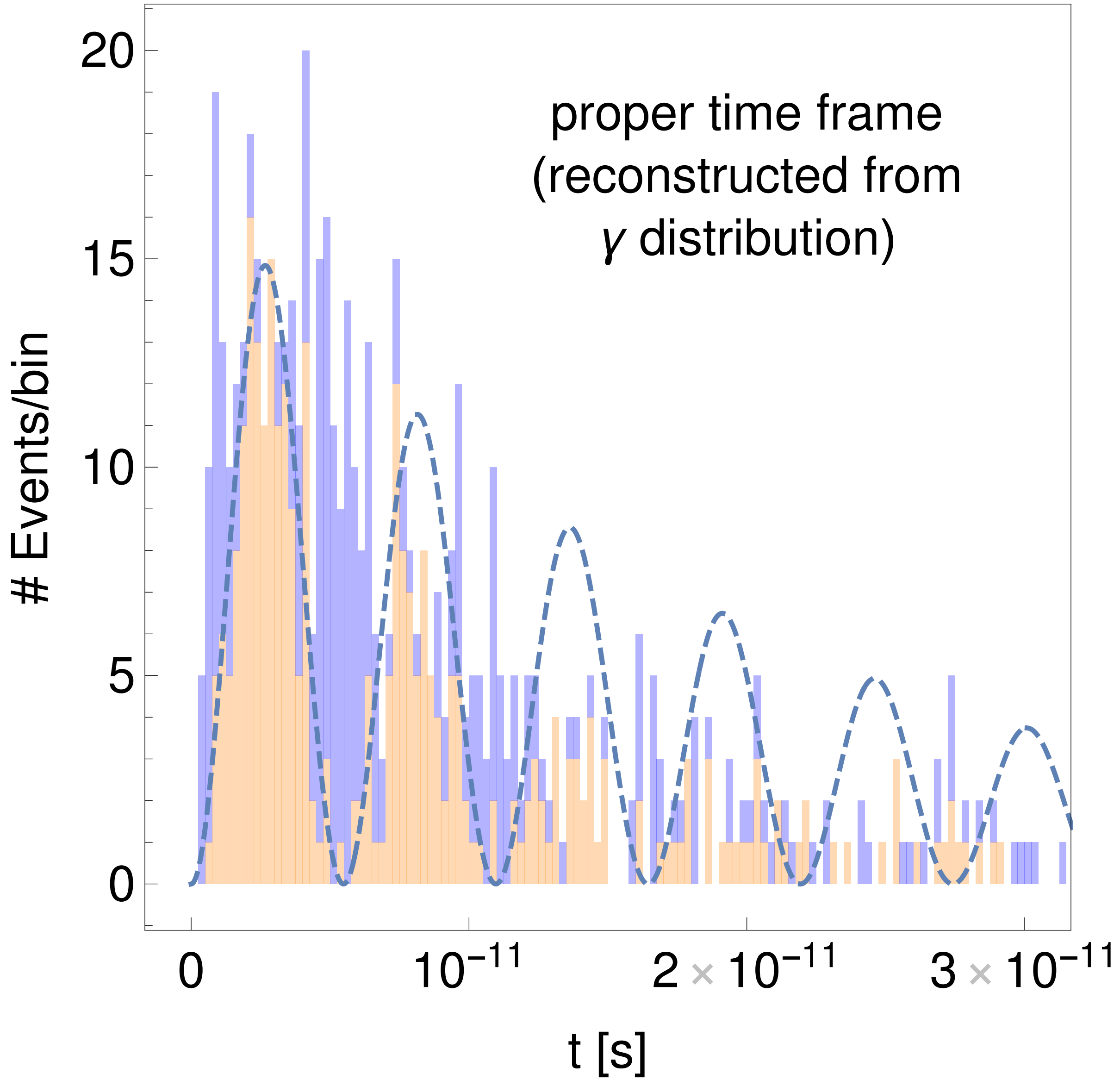


HNL oscillations at colliders

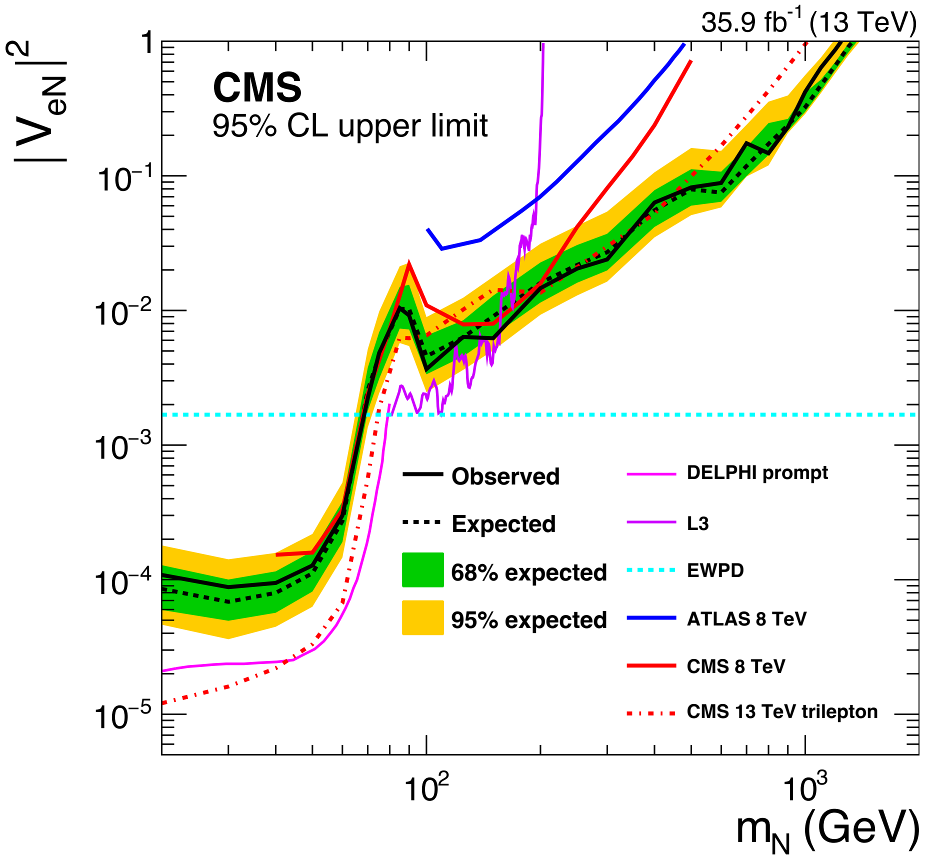
S. Antusch, E. Cazzato and O. Fischer, arXiv:1709.03797 [hep-ph]

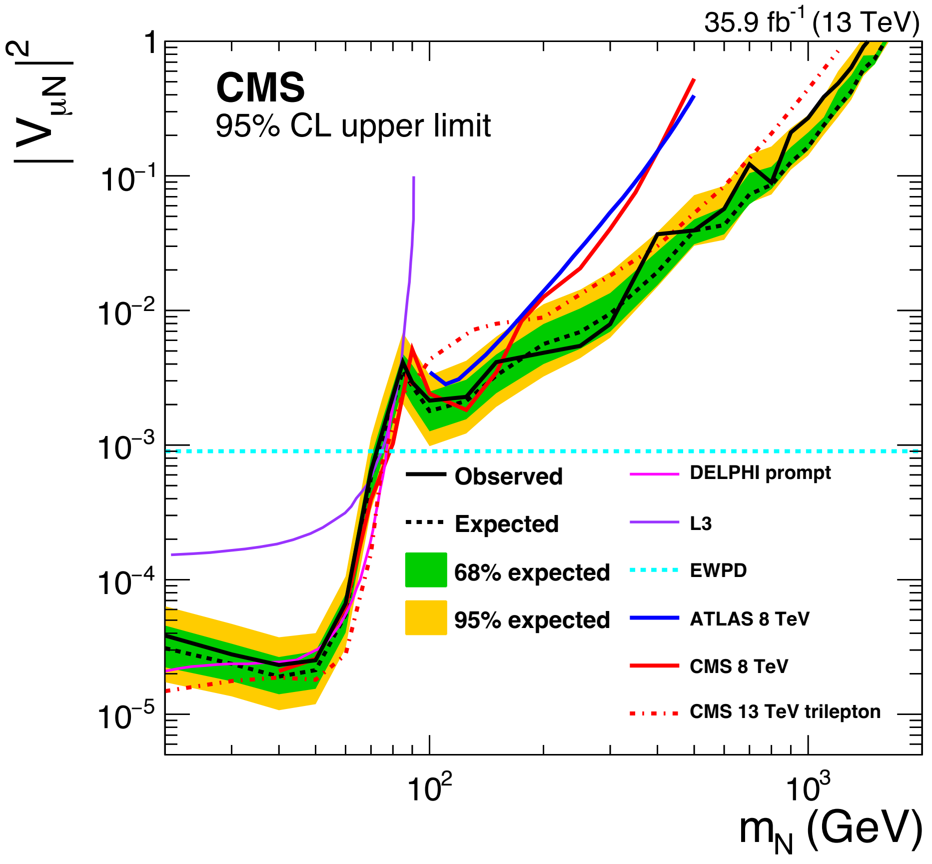
E.g. LHCb experiment for Linear Seesaw with M = 7 GeV, $U^2 = 10^{-5}$, Inverted Ordering

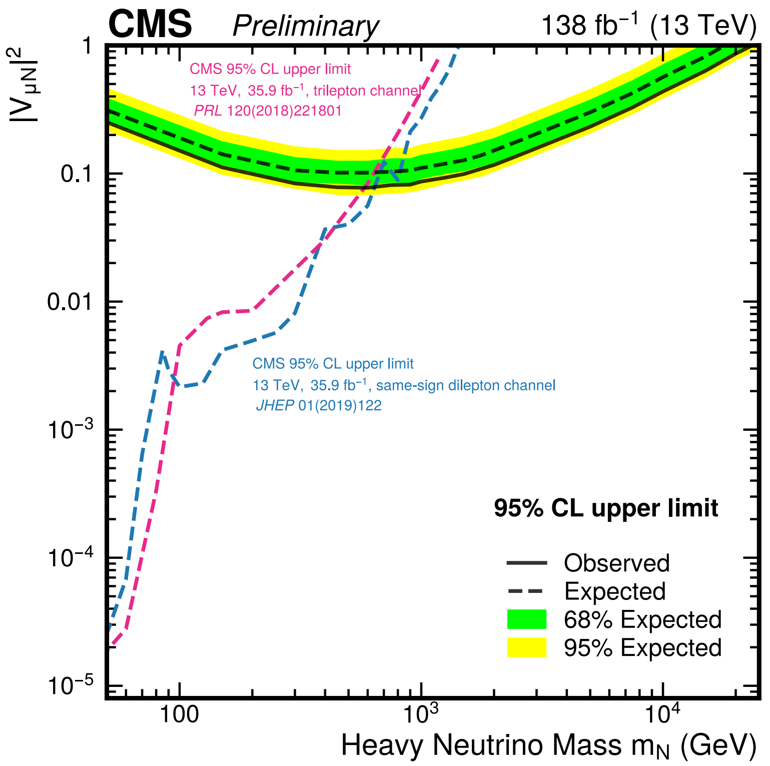


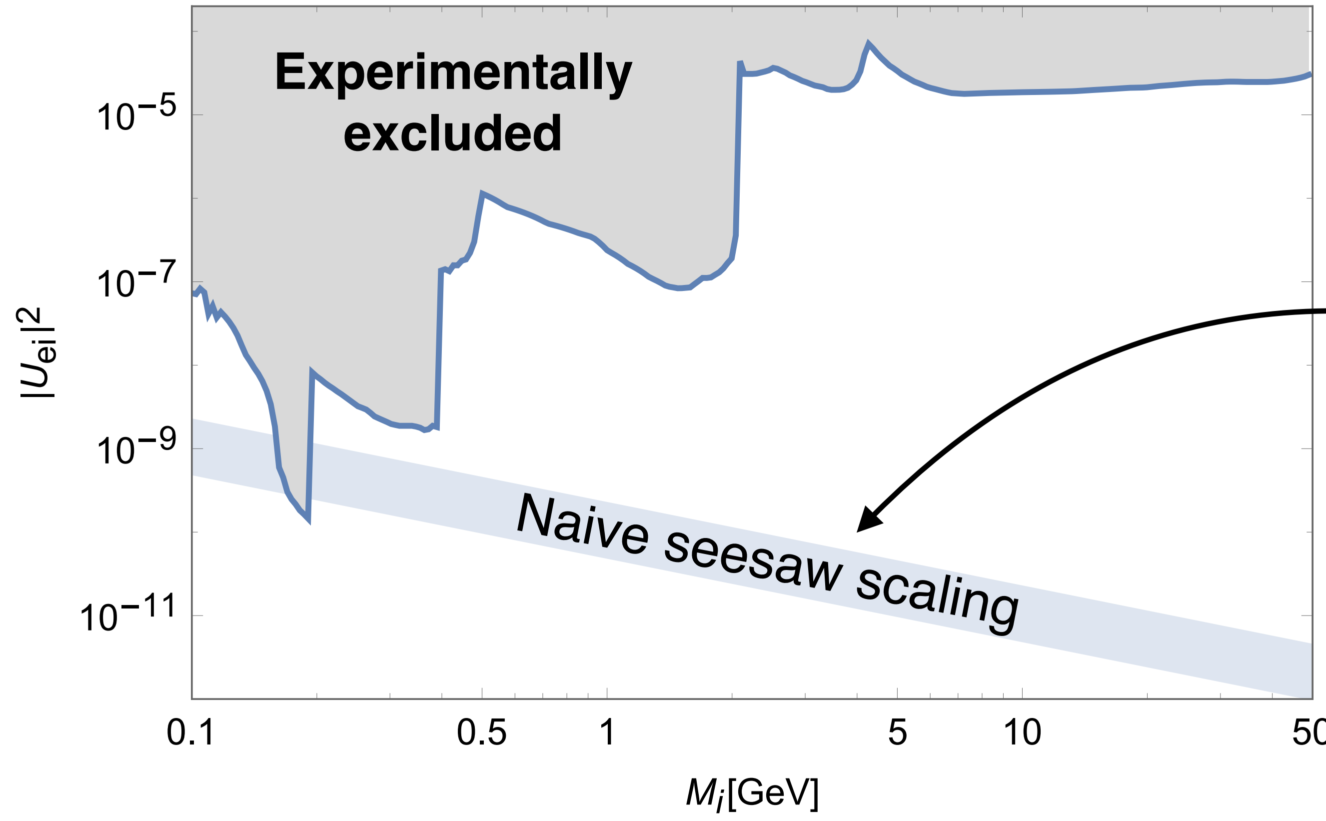


LNV searches: challenging from model building







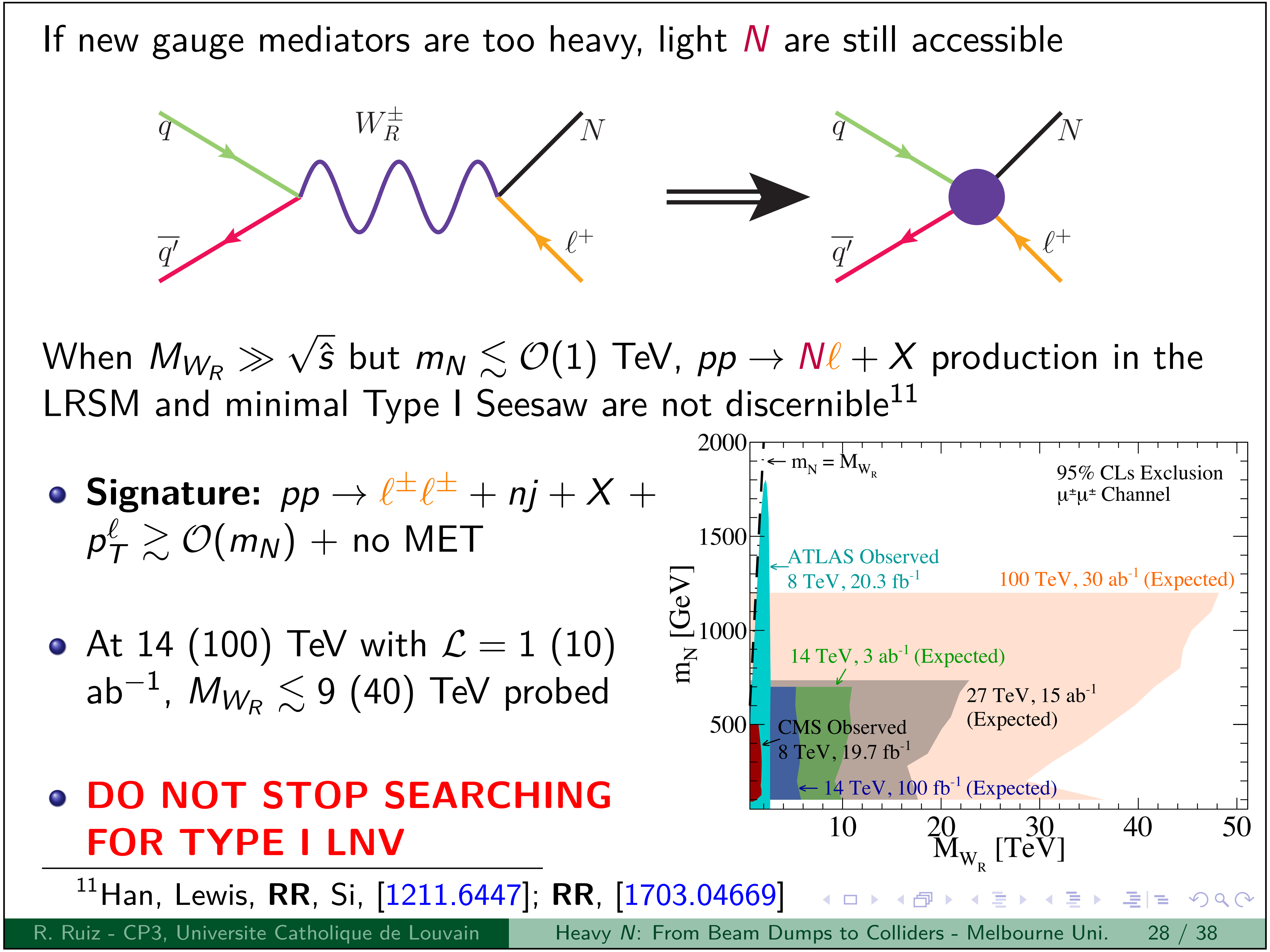


Typical LNV coupling size if no accidental cancellations

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

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**

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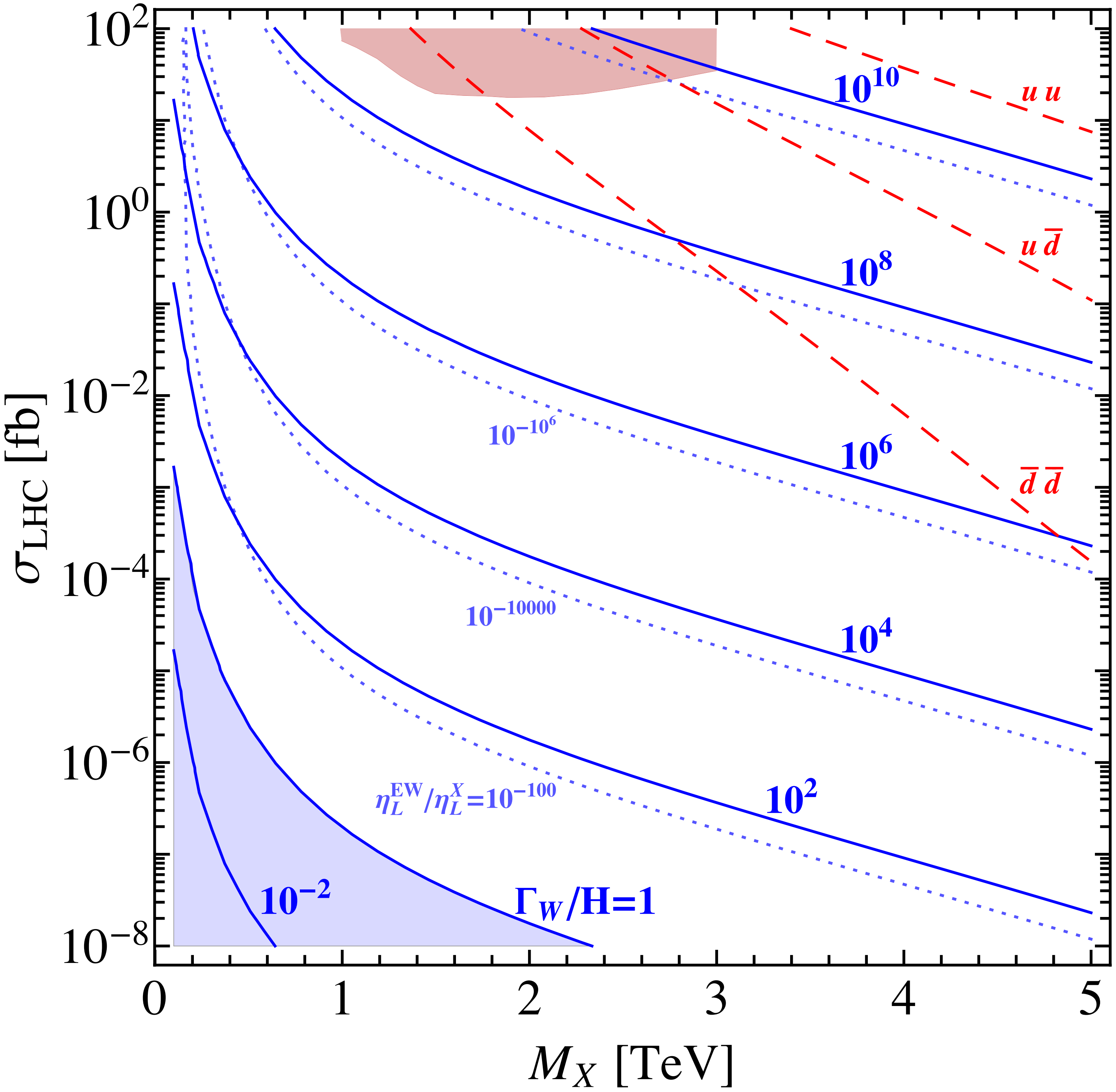
[11] Han, Lewis, **RR**, Si, [1211.6447]; **RR**, [1703.04669]

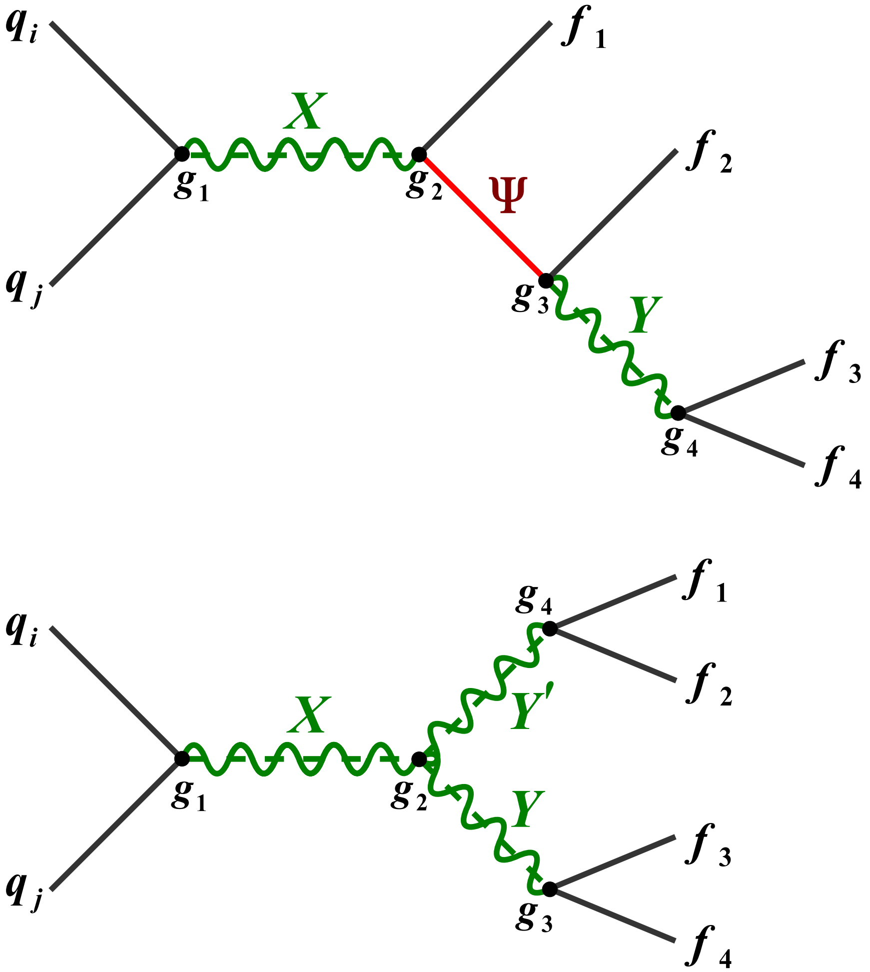
R. Ruiz - CP3, Universite Catholique de Louvain | Heavy N: From Beam Dumps to Colliders - Melbourne Uni. 28 / 38

Courtesy of Richard Ruiz

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