GeV scale neutrinos: meson interactions and DUNE sensitivity

HIDDeν

Manuel González-López

Results based in Eur. Phys. J. C 81 (2021) 1, 78 [2007.03701]

Pilar Coloma, Enrique Fernández-Martínez, MGL, Josu Hernández-García and Zarko Pavlovic

UNIVERSIDAD AUTONOMA DE MADRID

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Introduction to RHNs

Right-handed neutrinos are key ingredients in many SM extensions.
They constitute the simplest way to account for neutrino masses.

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + \sum_{j=4}^{3+n} U_{\alpha j}N_j$$

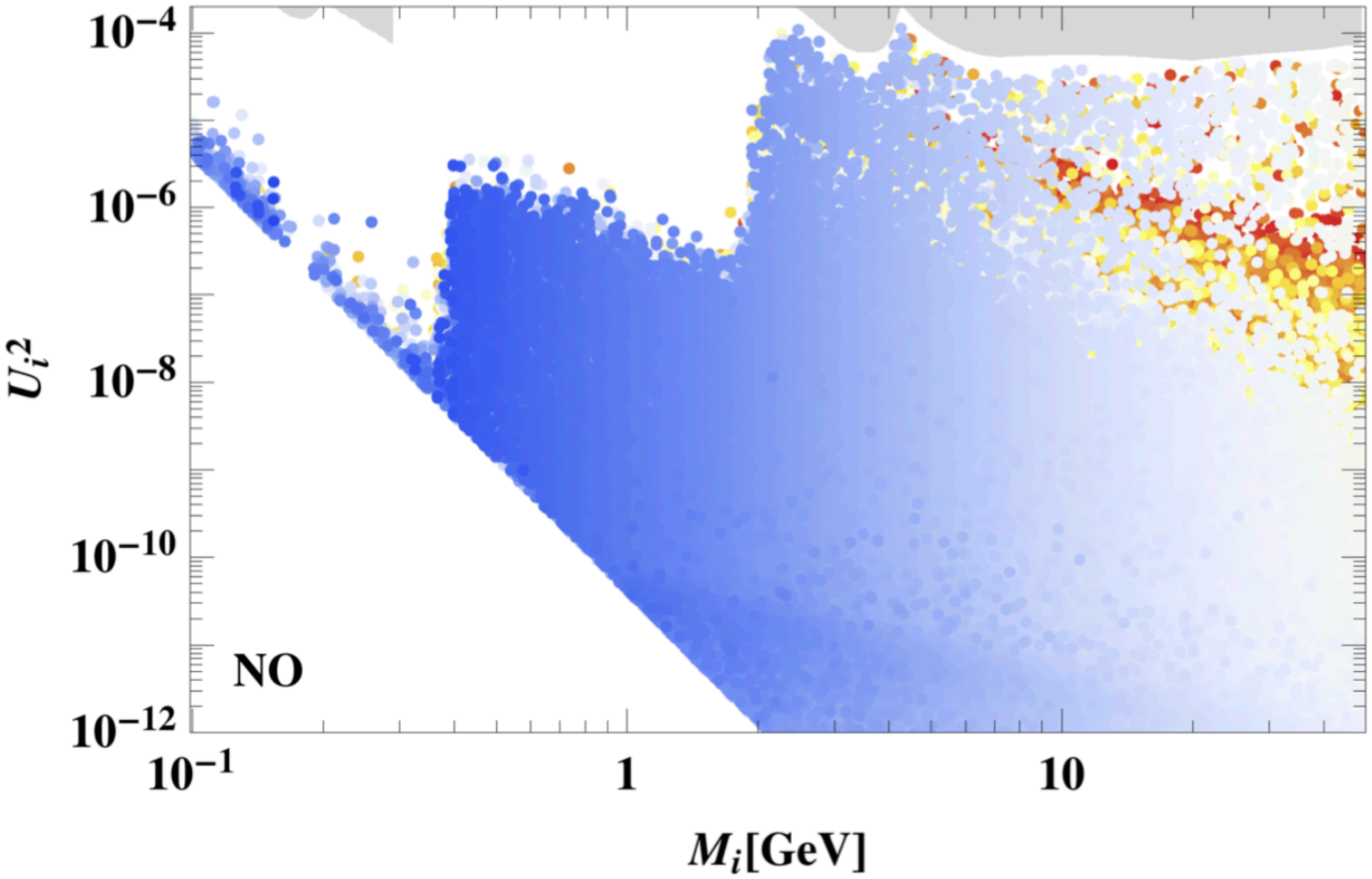
Possible ranges for sterile neutrino masses span many orders of magnitude, from the eV to the GUT scale, giving rise to very different phenomenology.

Minimal extension of the SM

- No extra interactions or symmetry groups. The only new particles are the RH neutrinos, singlets of all gauge groups.
- RHNs only talk to the SM via mixing with active neutrinos. Their interactions are only controlled by their mass and mixings.
- At least 2 RHNs are needed to explain neutrino masses. The pheno can be simplified in a 3 + 1 scenario, determined by 4 parameters.

Neutrinos in the GeV scale

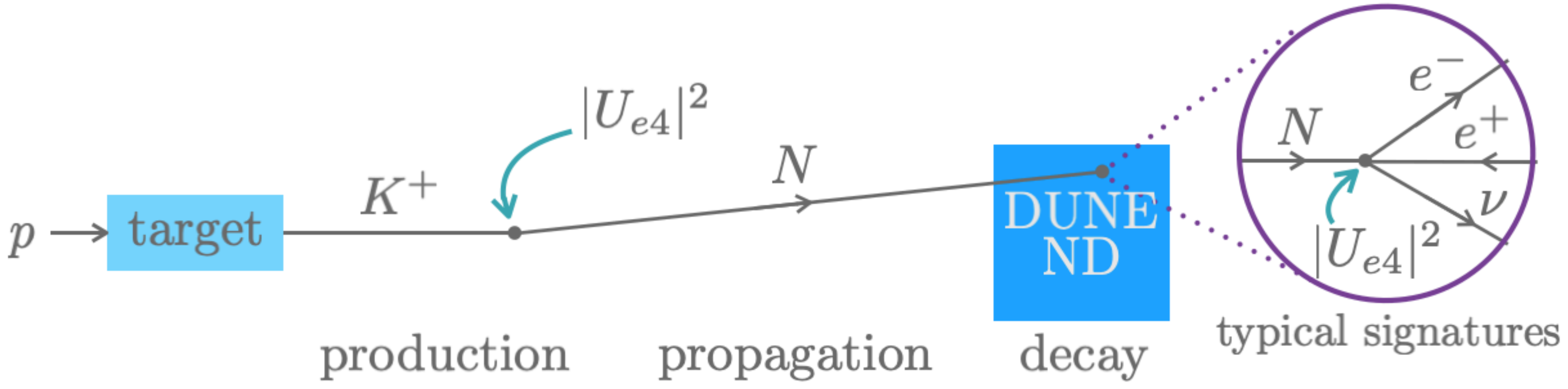
The GeV scale is particularly interesting: no extra hierarchy problem, feasible leptogenesis and accesible at lab experiments.



A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric, *JHEP* 01 (2019) 164 [1810.12463]

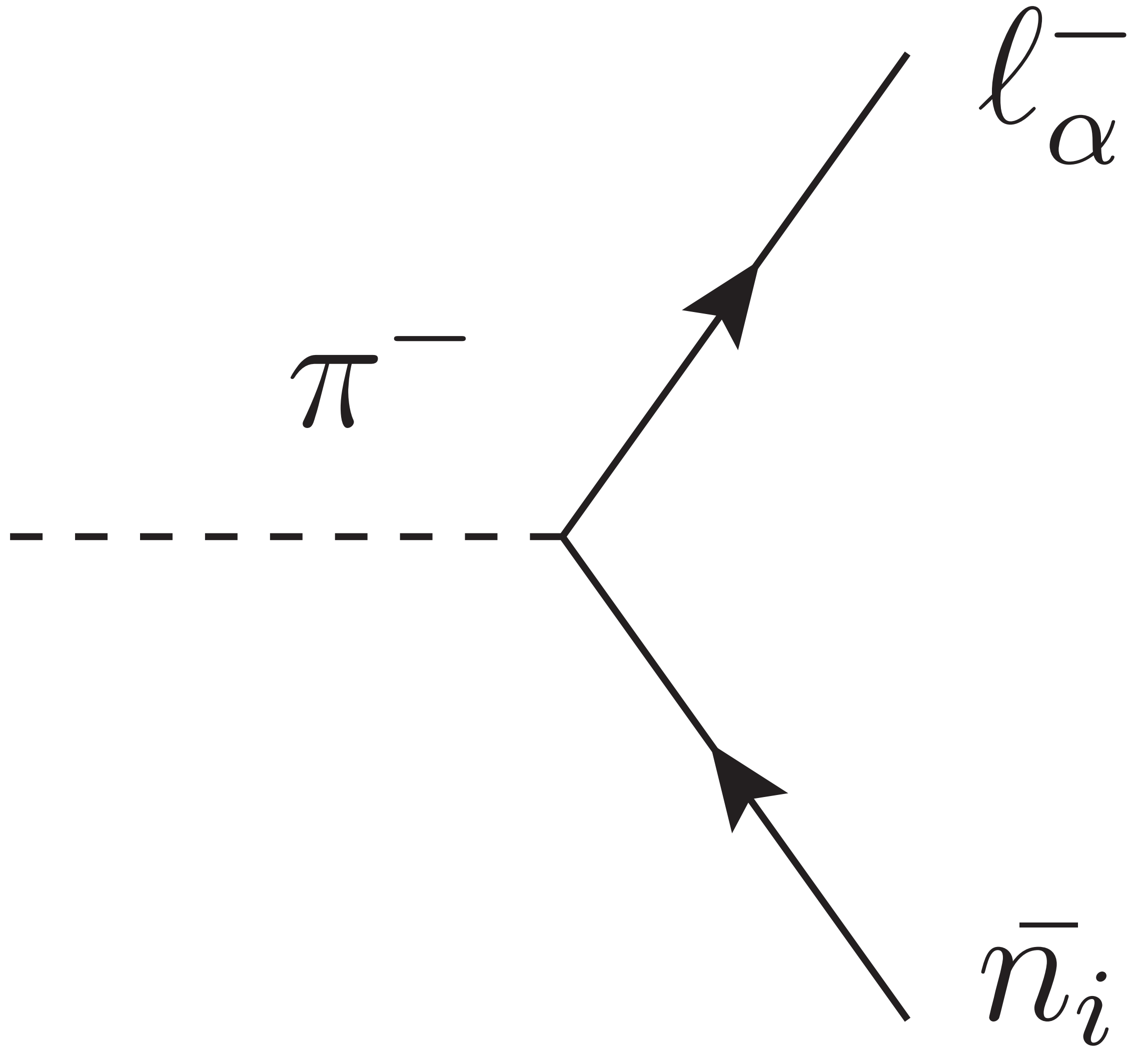
HNLs at beam dump experiments

Heavy neutrinos can be produced at beam dump facilities via meson decays and decay in the near detector into leptons and lighter mesons.



HNL production and decay depend only on their mass and mixing. DUNE ND has a great potential to explore wide regions in the (U^2, M_4) parameter space.

Low energy effective operators



Hadronic matrix element in terms of meson momentum and decay constant.

Meson momentum translated into a derivative acting on the lepton current.

Masses arise from applying Dirac's equation to on-shell fermions.

$$\mathcal{O}_{\pi\ell_\alpha\bar{n}_i} = i\sqrt{2}G_F U_{\alpha i} V_{ud} f_\pi \bar{\ell}_\alpha (m_\alpha P_L - m_i P_R) n_i \pi^-$$

FeynRules implementation

- Enlarged neutrino sector: ν_1, ν_2, ν_3, N_4, controlled by $U_{\alpha i}, M_4$.

Both for Majorana and Dirac neutrinos

- Inclusion of charged and neutral mesons (pseudoscalars and vectors).*

- RHN production and decay via meson interactions and fully leptonic processes.

*Optional switch to restore quarks instead of mesons

Results

90% C.L.
7.7·10^21 PoT

20% signal eff. assumed for full bkg. rejection[1]

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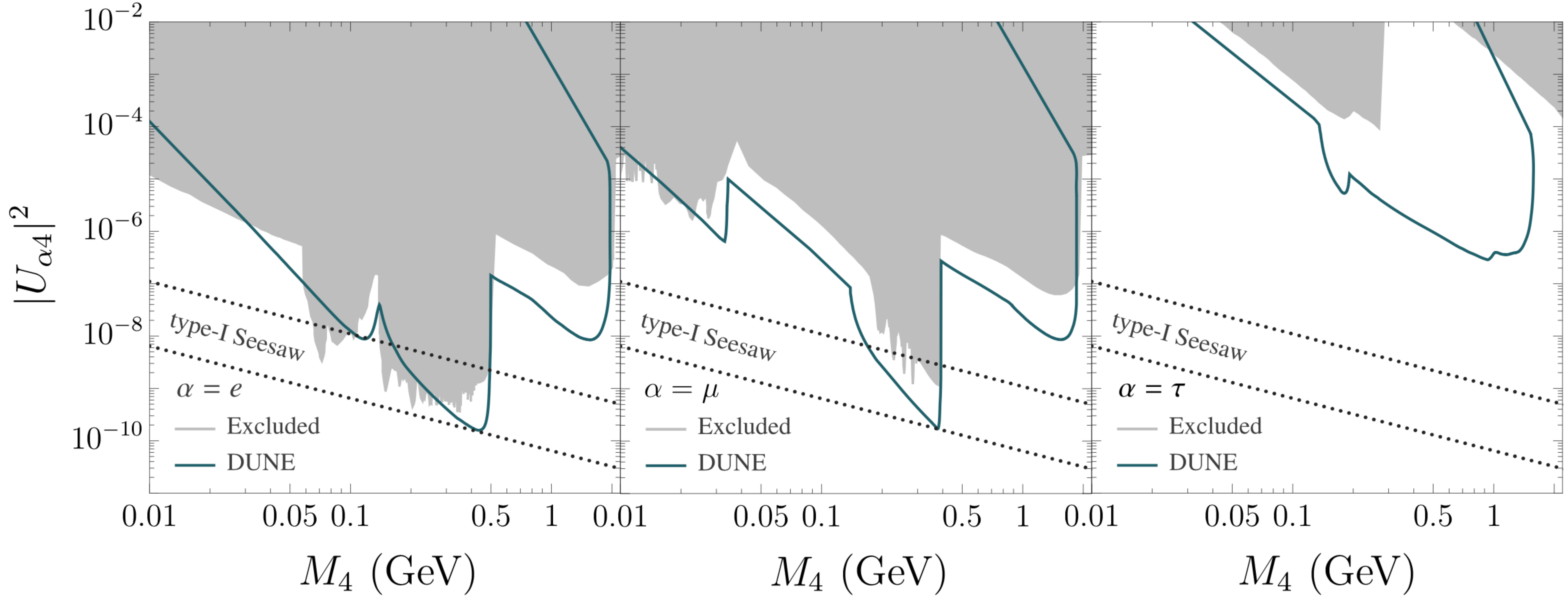
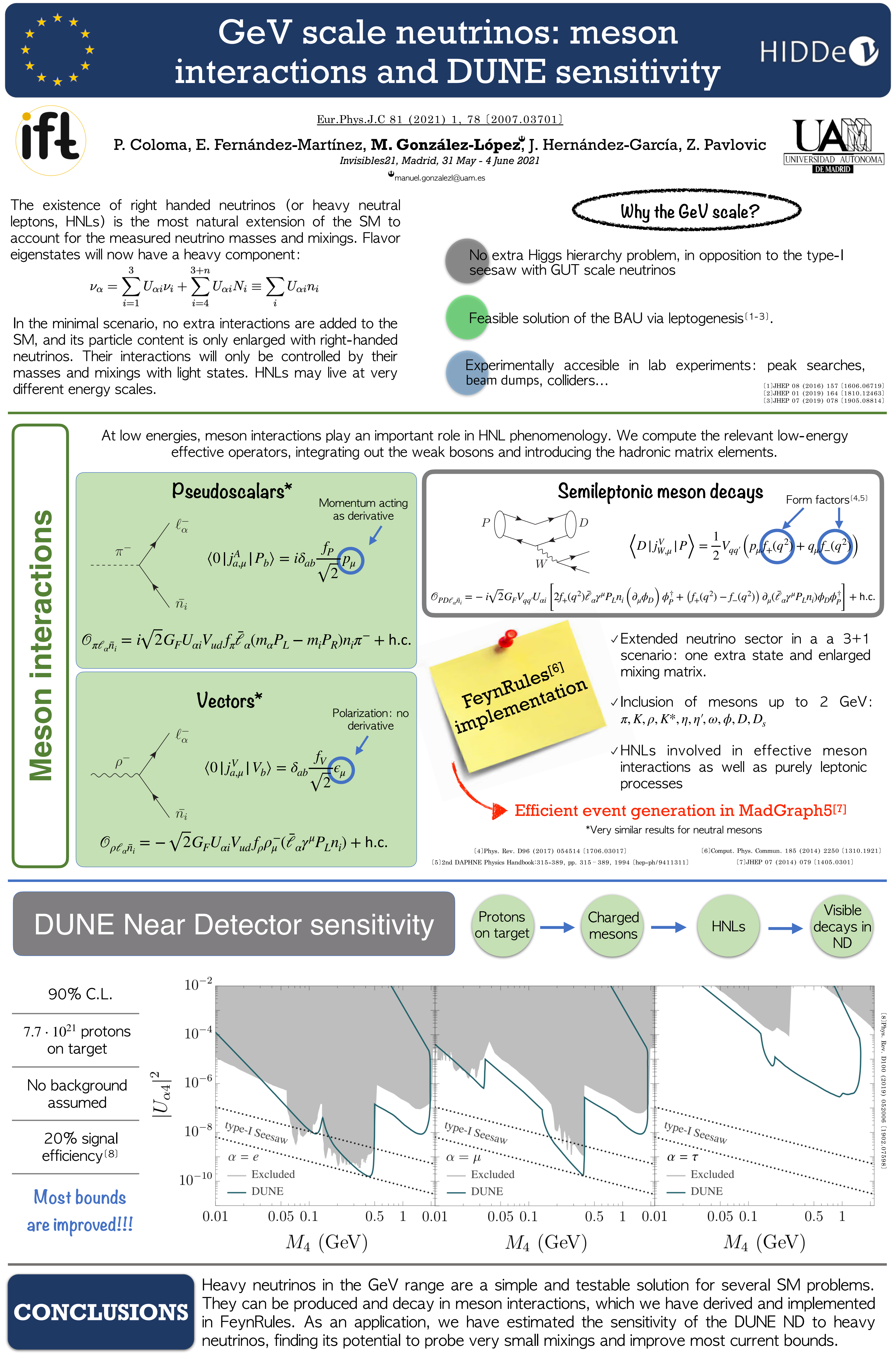


[1]T2K collaboration, K. Abe et al., Phys. Rev. **D100** (2019) 052006 [1902.07598]

Summary

- ✓ **HNLs play an important role in many natural extensions of the SM**
- ✓ **Exciting prospects to probe them through meson interactions**
- ✓ **DUNE ND could explore new regions of the parameter space**

thank you!



Poster @Indico

+ questions @Slack!

Back-up

$$\mathcal{L}_\nu^{\text{mass}} \supset -\sum_{\alpha=e,\mu,\tau}\sum_{j=1}^{n} Y_{\nu,\alpha j}\overline{L}_{L,\alpha}\tilde{\phi}N_{R,j} - \sum_{j=1}^{n} M_j \overline{N}_{L,j}N_{R,j} + \text{h.c.}$$

$$\mathcal{M} = \begin{pmatrix} \mathbf{0}_{3\times3} & Y_\nu v/\sqrt{2} & \mathbf{0}_{3\times n} \\ Y_\nu^t v/\sqrt{2} & \mathbf{0}_{n\times n} & M \\ \mathbf{0}_{n\times 3} & M & \mathbf{0}_{n\times n} \end{pmatrix}$$

Dirac neutrinos

(non self-conjugate neutrino fields)

Different mass matrices → Different mixing matrices

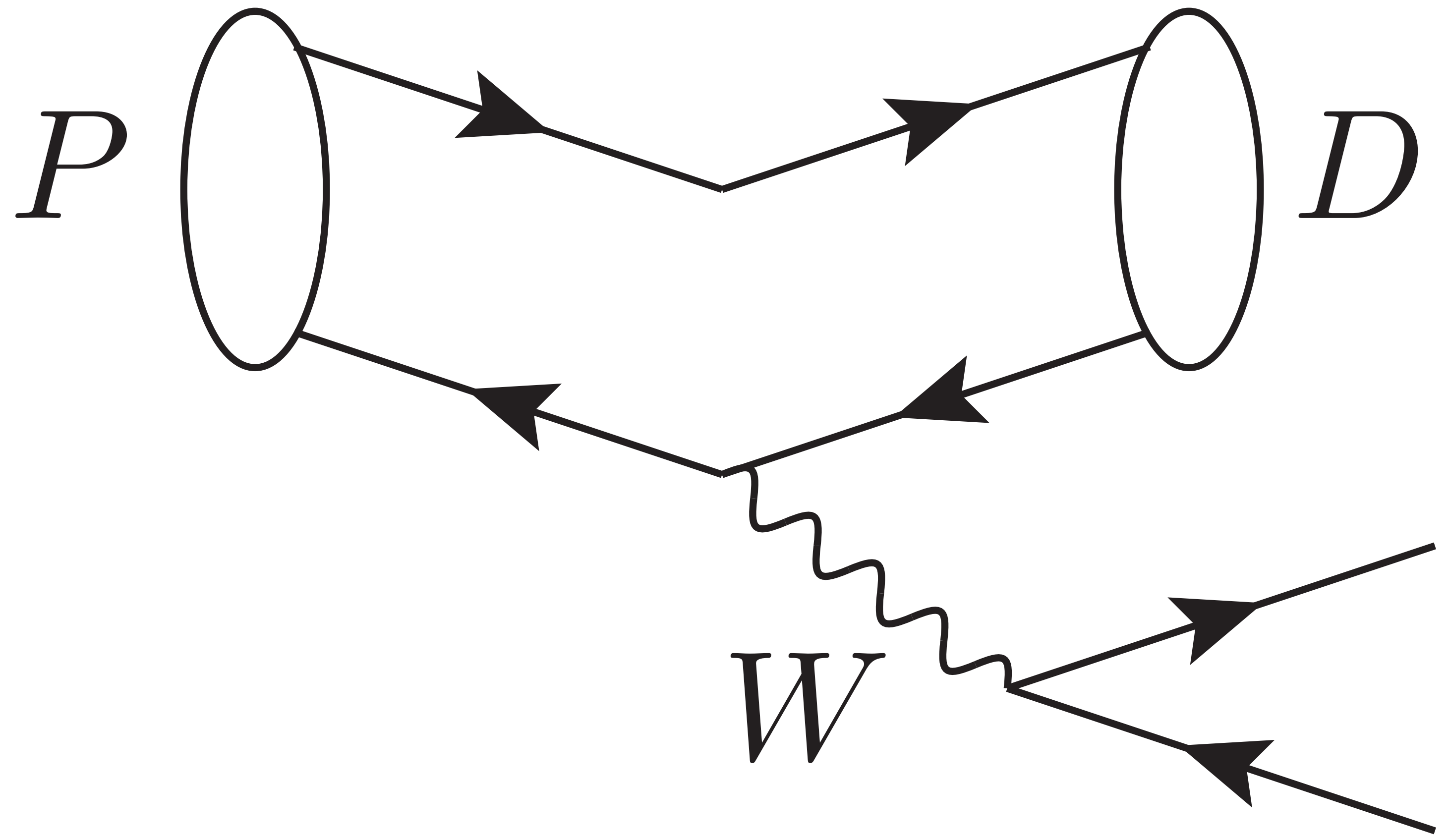
Majorana neutrinos

(self-conjugate neutrino fields)

$$\mathcal{L}_\nu^{\text{mass}} \supset -\sum_{\alpha=e,\mu,\tau}\sum_{j=1}^{n} Y_{\nu,\alpha j}\overline{L}_{L,\alpha}\tilde{\phi}N_{R,j} - \frac{1}{2}\sum_{j=1}^{n} M_j \overline{N}_{R,j}N^c_{R,j} + \text{h.c.}$$

$$\mathcal{M} = \begin{pmatrix} \mathbf{0}_{3\times3} & Y_\nu v/\sqrt{2} \\ Y_\nu^t v/\sqrt{2} & M \end{pmatrix}$$

Semileptonic processes



$$i\mathcal{M}_{PD\ell_\alpha\bar{n}_i} = \frac{ig^2}{2M_W^2} U_{\alpha i}\bar{u}_\alpha \gamma^\mu P_L v_i \left\langle D | j^V_{W,\mu} | P \right\rangle$$

Form factors

$$\left\langle D | j^V_{W,\mu} | P \right\rangle = \frac{1}{2} V_{qq'} \left(p_\mu f_+(q^2) + q_\mu f_-(q^2) \right)$$

Meson momentum sum

Meson momentum transfer

$$\mathcal{O}_{PD\ell_\alpha\bar{n}_i} = \sqrt{2} G_F V_{qq'} U_{\alpha i} \bar{\ell}_\alpha \left[\left(f_+(q^2) - f_-(q^2) \right) (m_\alpha P_L - m_i P_R) \phi_D - 2i f_+(q^2) (\partial_\mu \phi_D) \gamma^\mu P_L \right] n_i \phi_P^\dagger + \text{h.c.}$$

Main discrepancies with literature

1 HNL decays to neutral vectors

$$\Gamma(N_4 \to \nu V^0) = \frac{G_F^2 M_4^3}{32\pi m_V^2} f_V^2 g_V^2 |U|^2 (1 + 2x_V^2)(1 - x_V^2)^2$$

Different g_V and BR in previous works!

	ρ^0	ω	ϕ
This work	$1 - 2s_w^2$	$-\frac{2s_w^2}{3}$	$\sqrt{2}\left(\frac{2s_w^2}{3} - \frac{1}{2}\right)$
[1]	$1 - 2s_w^2$	$\frac{4s_w^2}{3}$	$\frac{4s_w^2}{3} - 1$
[2]	$1 - s_w^2$		

[1]K. Bondarenko, A. Boyarsky, D. Gorbunov and O. Ruchayskiy, JHEP **11** (2018) 032 [1805.08567].
[2]P. Ballett, T. Boschi and S. Pascoli, JHEP **20** (2020) 111 [1905.00284].

Main discrepancies with literature

2 Meson decay constants

- π , K , D and D_s constants are precisely measured.
- η and η' are not eigenstates: effective constants are employed.
- Vector mesons' constants are not easily determined.

Source of disagreement

Meson decay constants

η and η' mesons

These mesons are not interaction eigenstates: a change of basis is needed

$$\begin{pmatrix} f_{\eta,8} & f_{\eta,0} \\ f_{\eta',8} & f_{\eta',0} \end{pmatrix} = \begin{pmatrix} f_8 \cos\theta_8 & -f_0 \sin\theta_0 \\ f_8 \sin\theta_8 & f_0 \cos\theta_0 \end{pmatrix}^{[1]}$$

→ **Effective constants**

$$\begin{cases} f_\eta \equiv \dfrac{\cos\theta_8 f_8}{\sqrt{3}} + \dfrac{\sin\theta_0 f_0}{\sqrt{6}} \\ f_{\eta'} \equiv \dfrac{\sin\theta_8 f_8}{\sqrt{3}} - \dfrac{\cos\theta_0 f_0}{\sqrt{6}} \end{cases}$$

[1] R. Escribano, S. González-Solís, P. Masjuan and P. Sanchez-Puertas, Phys.Rev. D94 (2016) 054033 [1512.07520]

Meson decay constants

Vector mesons

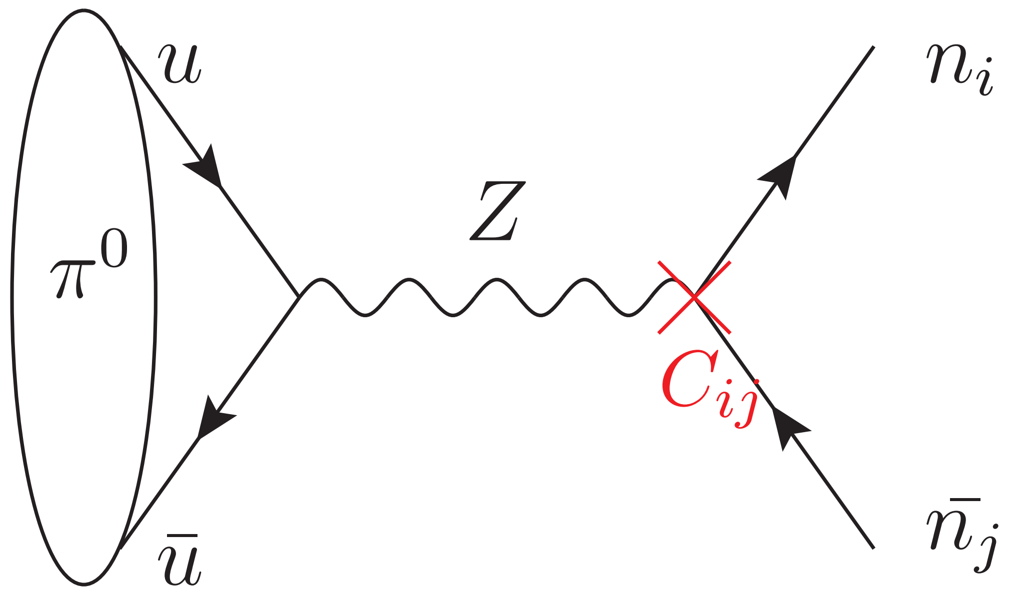
- Matching of $\Gamma(V^0 \to e^+e^-)$ to experimental data and extraction of f_{V^0}
- Negligible electromagnetic effects in $\rho^\pm$ case: $f_{\rho^\pm} \approx f_{\rho^0}$
- Matching of $\Gamma(\tau^- \to K^{*,-}\nu_\tau)$ to experimental data and extraction of f_{K^*}

Charged vectors

$$i\mathcal{M}_{\rho^- \ell_\alpha \bar{n}_i} = \frac{ig^2}{2M_W^2} U_{\alpha i} \bar{u}_\alpha \gamma^\mu P_L v_i \langle 0 | j^V_{W,\mu} | \rho^- \rangle$$

$$\langle 0 | j^V_{a,\mu} | V_b \rangle = \delta_{ab} \frac{f_V}{\sqrt{2}} \epsilon_\mu \,,$$

$$\mathcal{O}_{\rho \ell_\alpha \bar{n}_i} = -\sqrt{2} G_F U_{\alpha i} V_{ud} f_\rho \rho^-_\mu (\bar{\ell}_\alpha \gamma^\mu P_L n_i) + \text{h.c.}$$



$$\mathcal{O}_{\pi^0 n_i \bar{n}_j} = \frac{i}{2} G_F C_{ij} \underbrace{f_\pi^{*}}_{f_{P^0}} \bar{n}_i (m_i P_L - m_j P_R) n_j \pi^0 + \text{h.c.}$$

$$C_{ij} \equiv \sum_\alpha U^*_{\alpha i} U_{\alpha j}$$

Neutral pseudoscalars

Neutral vectors

$$\mathcal{O}_{\rho^0 n_i \bar{n}_j} = -\frac{1}{2} G_F C_{ij} \underbrace{(1 - 2 s_w^2)^{*}}_{g_V} f_\rho \rho^0_\mu (\bar{n}_i \gamma^\mu P_L n_j) + \text{h.c.}$$

*Significant discrepancies in the literature

HNL Branching Ratios

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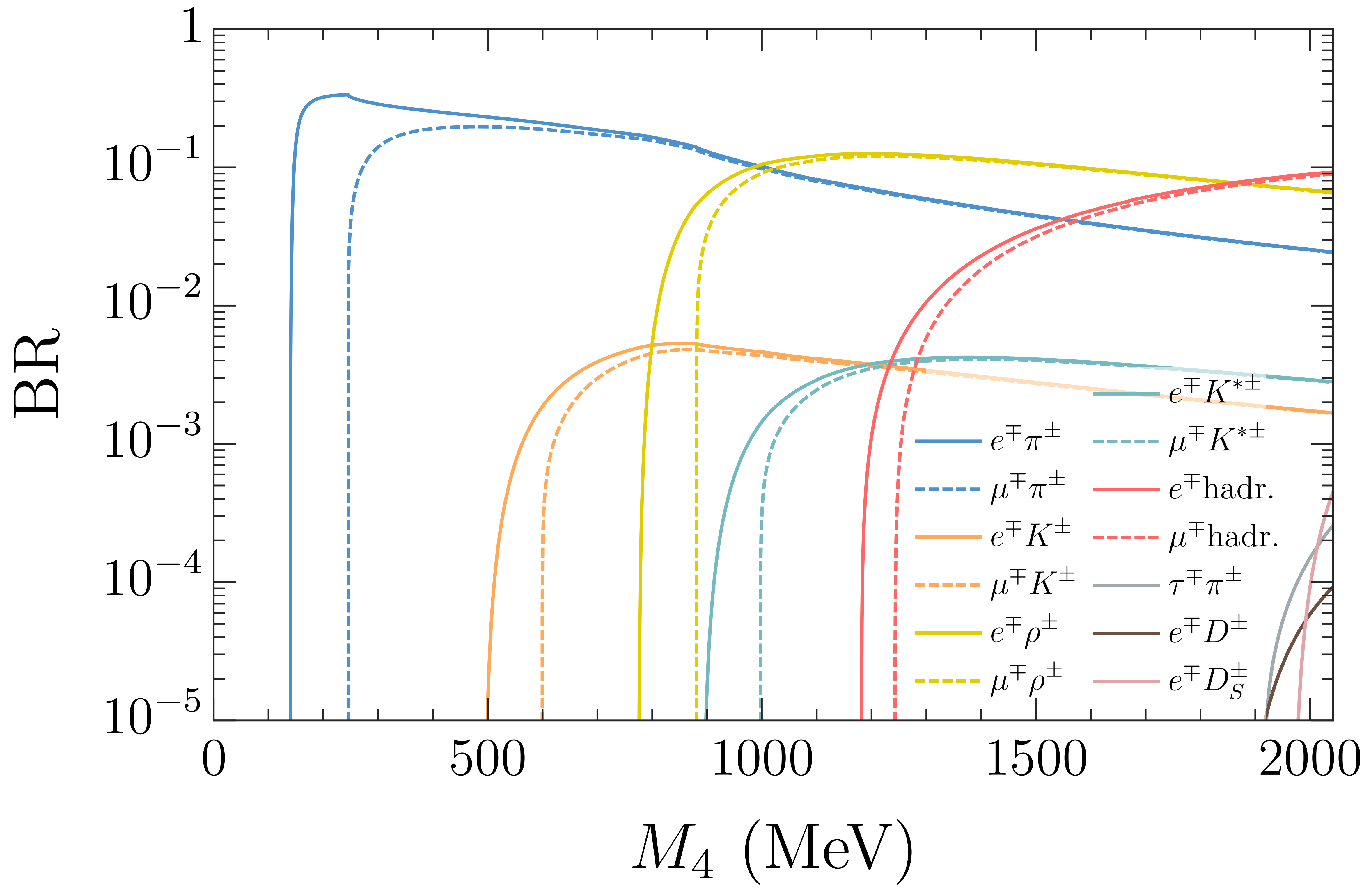

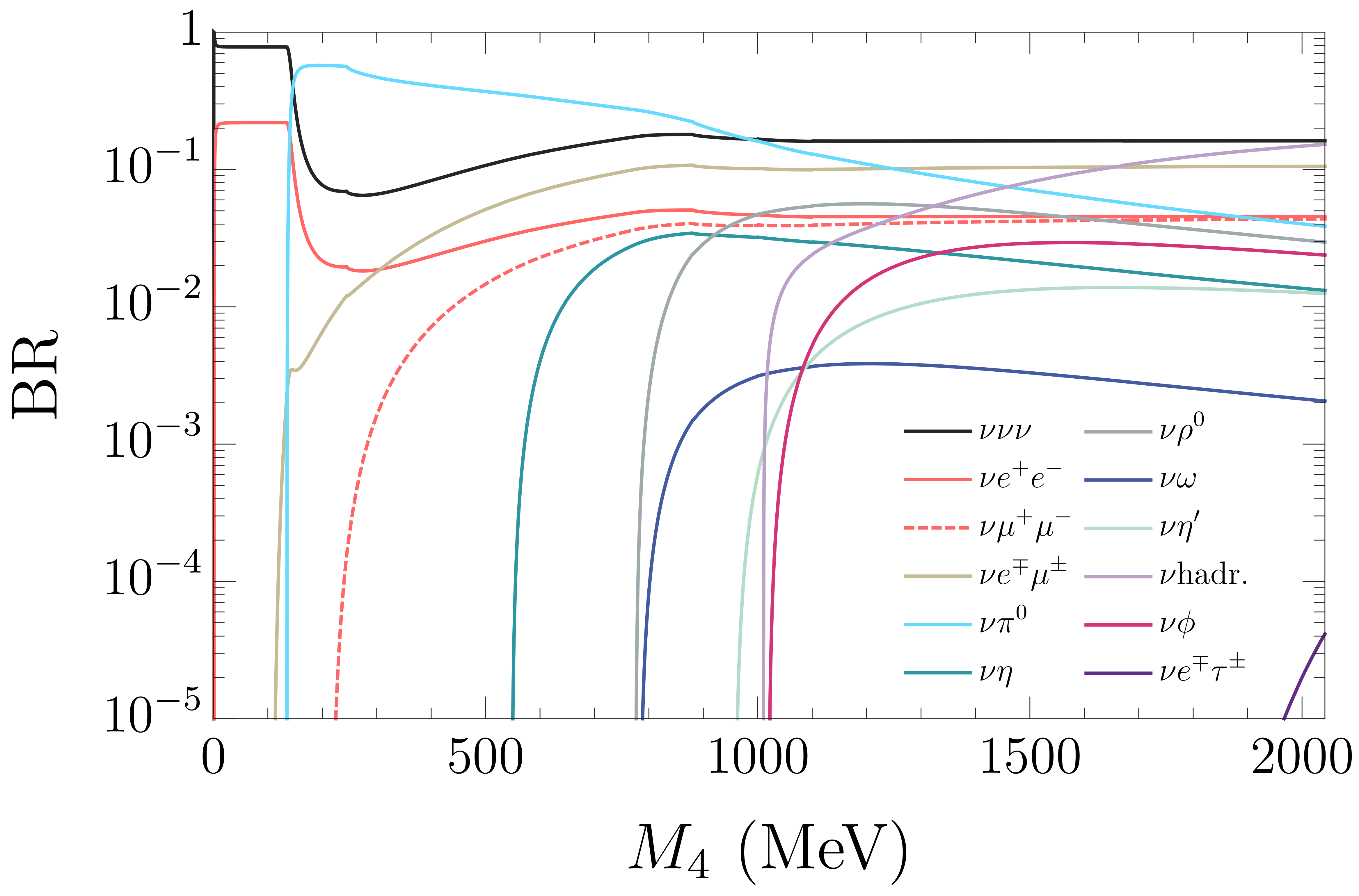

Multimeson decays become relevant in the region $M_4 \gtrsim 1000\,\mathrm{MeV}$

Effect of the lab frame boost

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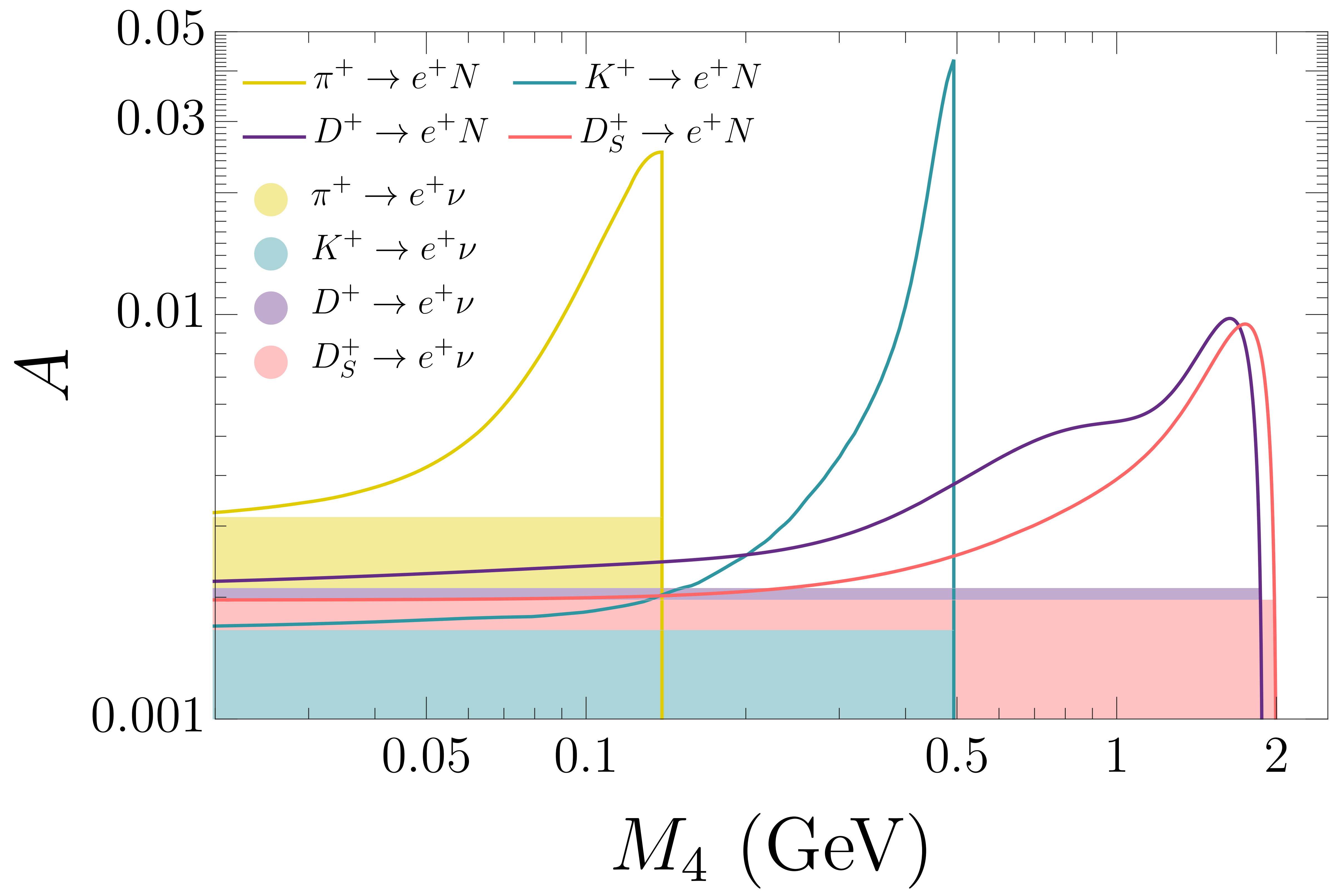

Increased detector acceptance due to HNL mass

HNL multimeson decays

τ leptons exhibit non-negligible BR (~25%) into states with several mesons: analogous case for HNLs

Estimation from quark processes

$$\Gamma\,(N_4 \to \mathrm{hadr}) = (1 + \Delta_{\mathrm{QCD}})\,\Gamma\,(N_4 \to \mathrm{quarks})$$ [1]

$$\Delta_{\mathrm{QCD}} = \frac{\alpha_s}{\pi} + 5.2\frac{\alpha_s^2}{\pi^2} + 26.4\frac{\alpha_s^3}{\pi^3}$$ [2]

[1] K. Bondarenko, A. Boyarsky, D. Gorbunov and O. Ruchayskiy, JHEP **11** (2018) 032 [1805.08567]

[2] S. Gorishnii, A. Kataev and S. Larin, Phys. Lett. B **259** (1991) 144.

This procedure applies separately for different quark flavors. Phase space suppression must be applied in the multi-kaon case:

$$\Gamma\,(N_4 \to \nu K's) = (1 + \Delta_{\mathrm{QCD}})\,\Gamma\,(N_4 \to \nu s\bar{s})\sqrt{1 - 4m_K^2/M_4^2}$$

Sensitivity plots

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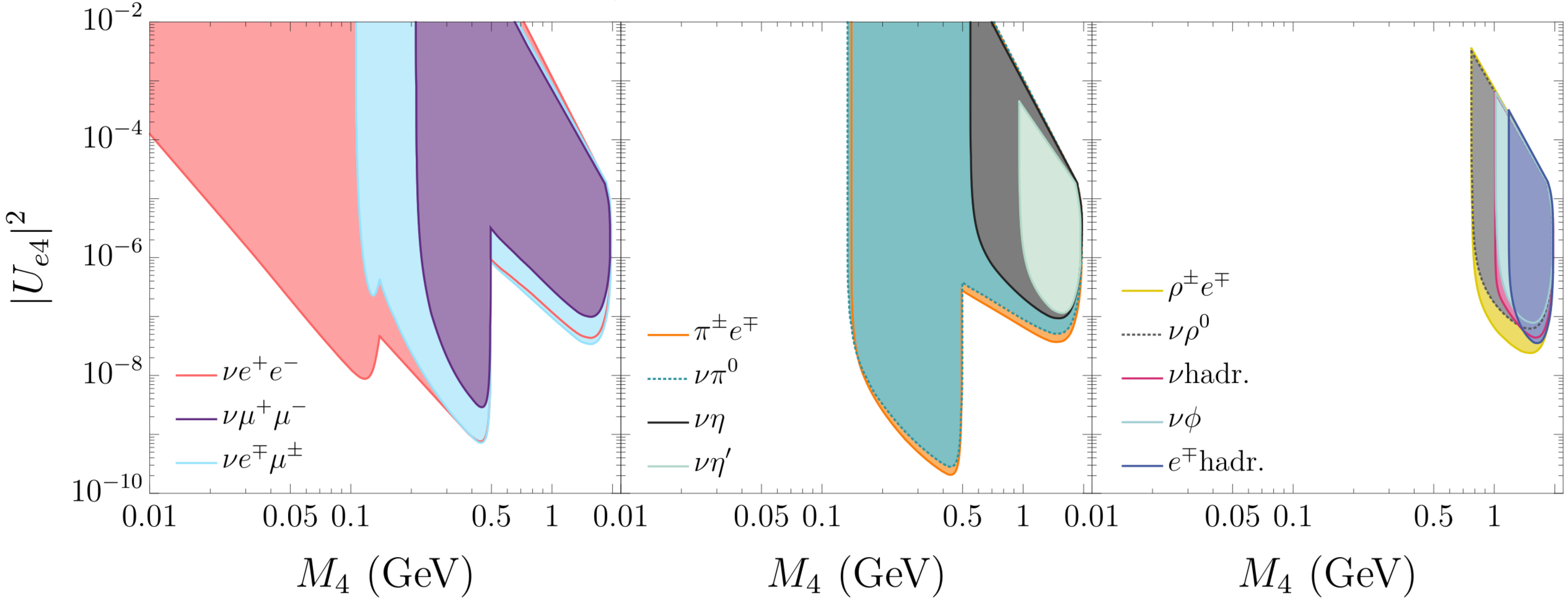

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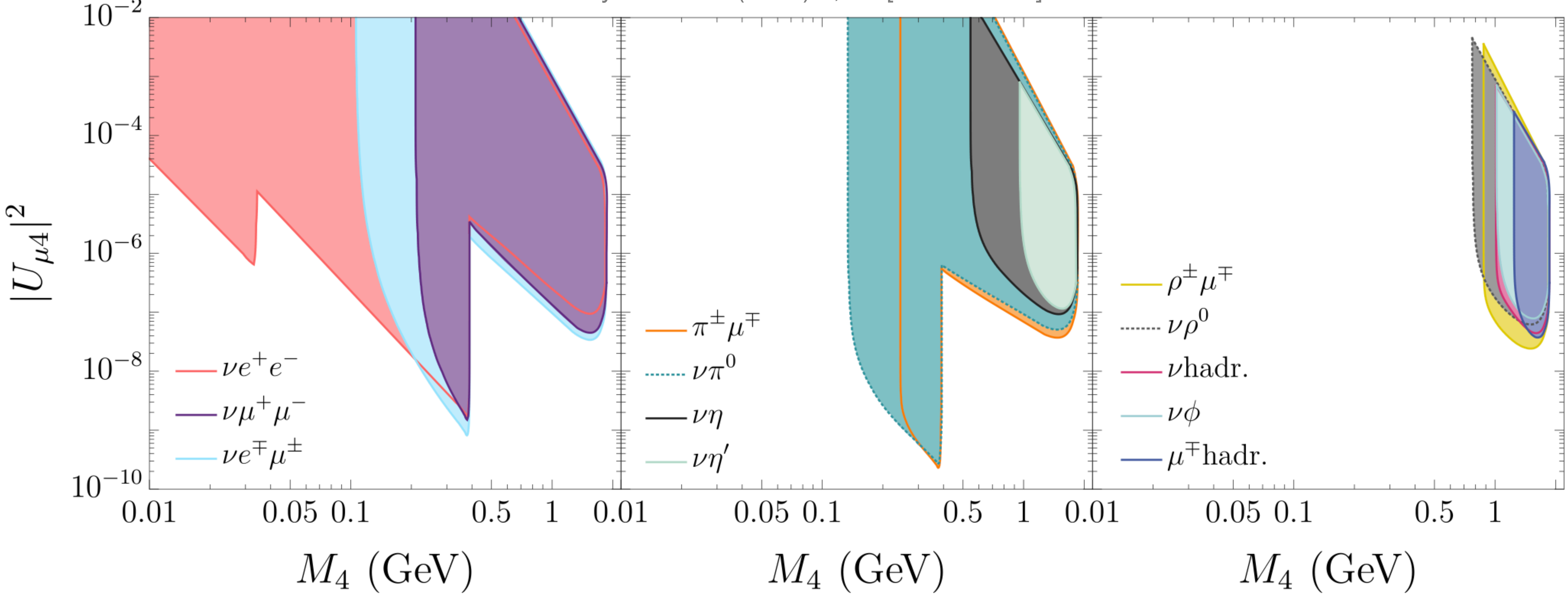

Sensitivity plots

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