



GeV scale neutrinos: meson interactions and DUNE sensitivity

HIDDe 

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



Invisibles21 Workshop, Madrid, 31st May - 4th June 2021

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



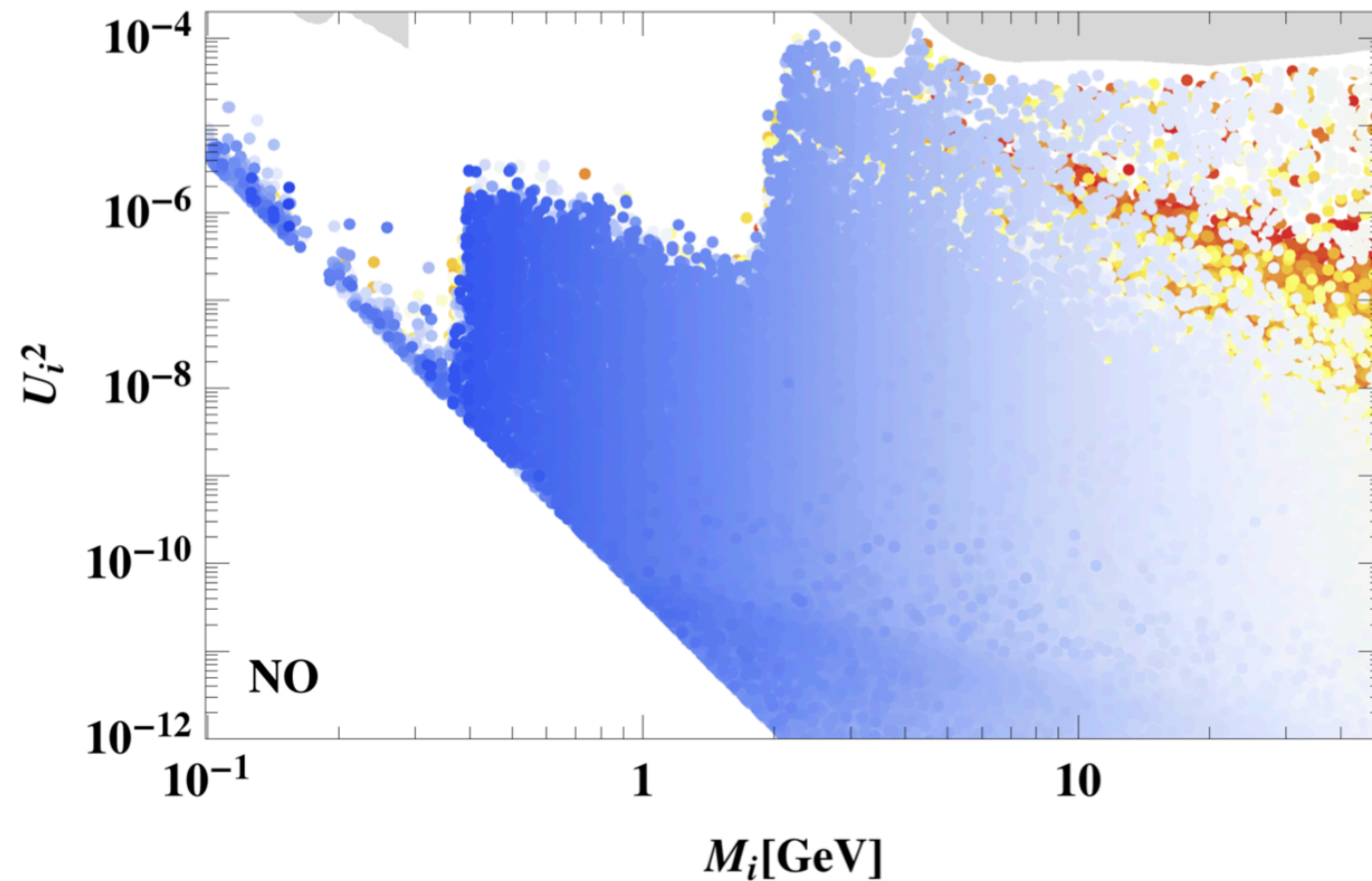
No extra interactions or symmetry groups. The only new particles are the RH neutrinos, singlets of all gauge groups.

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.

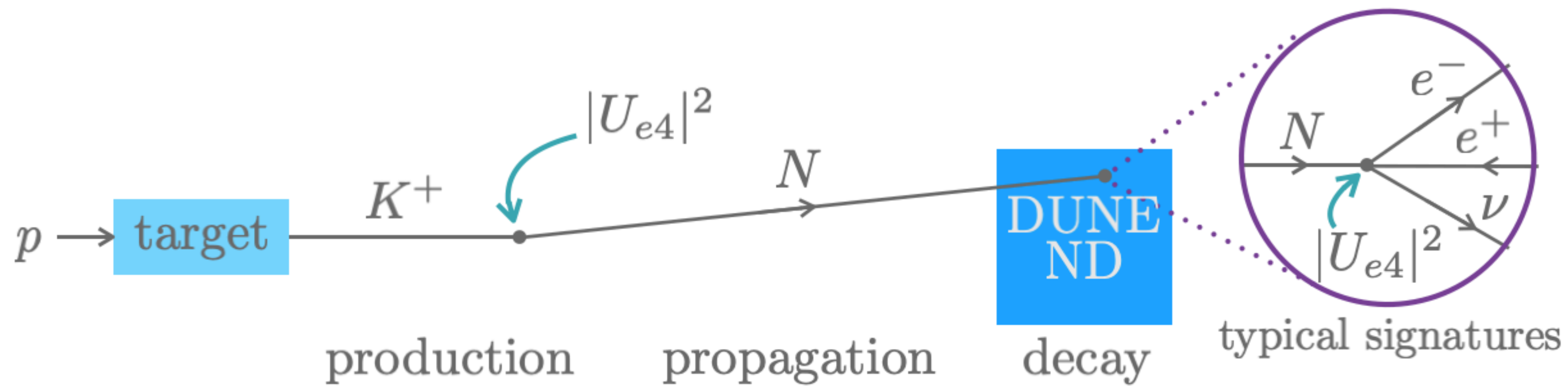
Neutrinos in the GeV scale

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



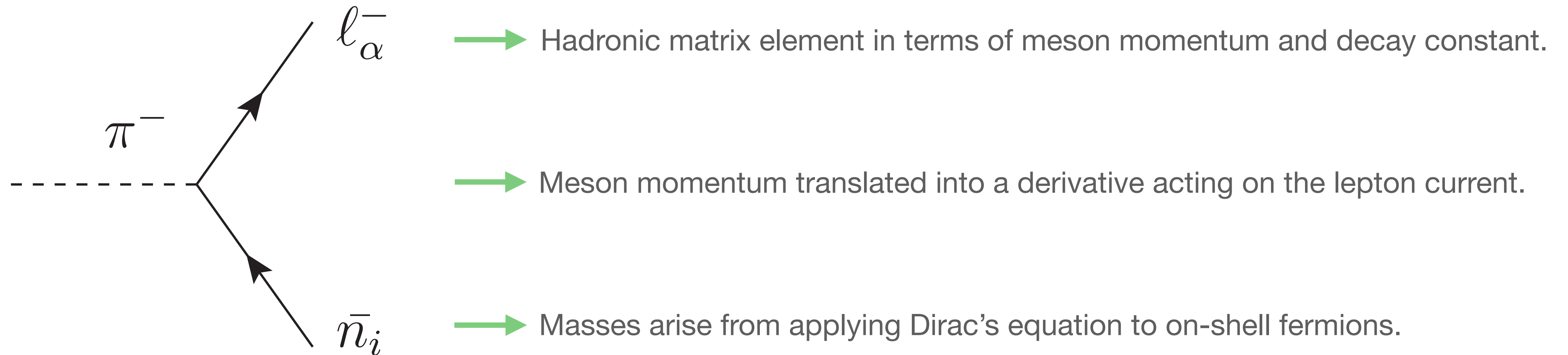
HNLs at beam dump experiments

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



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

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.

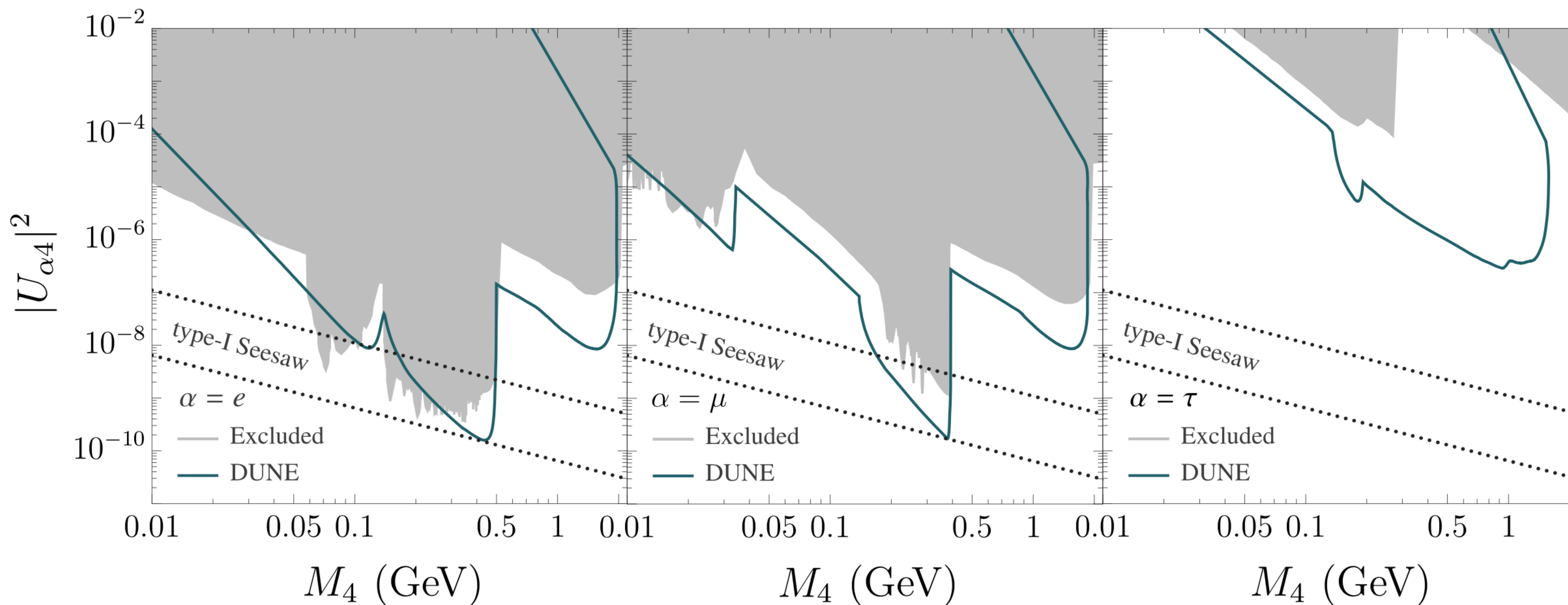
*Optional switch to restore quarks instead of mesons

Results

90% C.L.
7.7 · 10²¹
PoT

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

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



^[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!

The existence of right handed neutrinos (or heavy neutral leptons, HNLs) is the most natural extension of the SM to account for the measured neutrino masses and mixings. Flavor eigenstates will now have a heavy component:

$$\nu_\alpha = \sum_{i=1}^3 U_{\alpha i} \nu_i + \sum_{i=4}^{3+n} U_{\alpha i} N_i \equiv \sum_i U_{\alpha i} n_i$$

In the minimal scenario, no extra interactions are added to the SM, and its particle content is only enlarged with right-handed neutrinos. Their interactions will only be controlled by their masses and mixings with light states. HNLs may live at very different energy scales.

Why the GeV scale?

- No extra Higgs hierarchy problem, in opposition to the type-I seesaw with GUT scale neutrinos
- Feasible solution of the BAU via leptogenesis⁽¹⁻³⁾.
- Experimentally accessible in lab experiments: peak searches, beam dumps, colliders...

Meson interactions

At low energies, meson interactions play an important role in HNL phenomenology. We compute the relevant low-energy effective operators, integrating out the weak bosons and introducing the hadronic matrix elements.

Pseudoscalars*

Momentum acting as derivative

$$\langle 0 | j_{a,\mu}^A | P_b \rangle = i \delta_{ab} \frac{f_P}{\sqrt{2}} p_\mu$$

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

Vectors*

Polarization: no derivative

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

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

Semileptonic meson decays

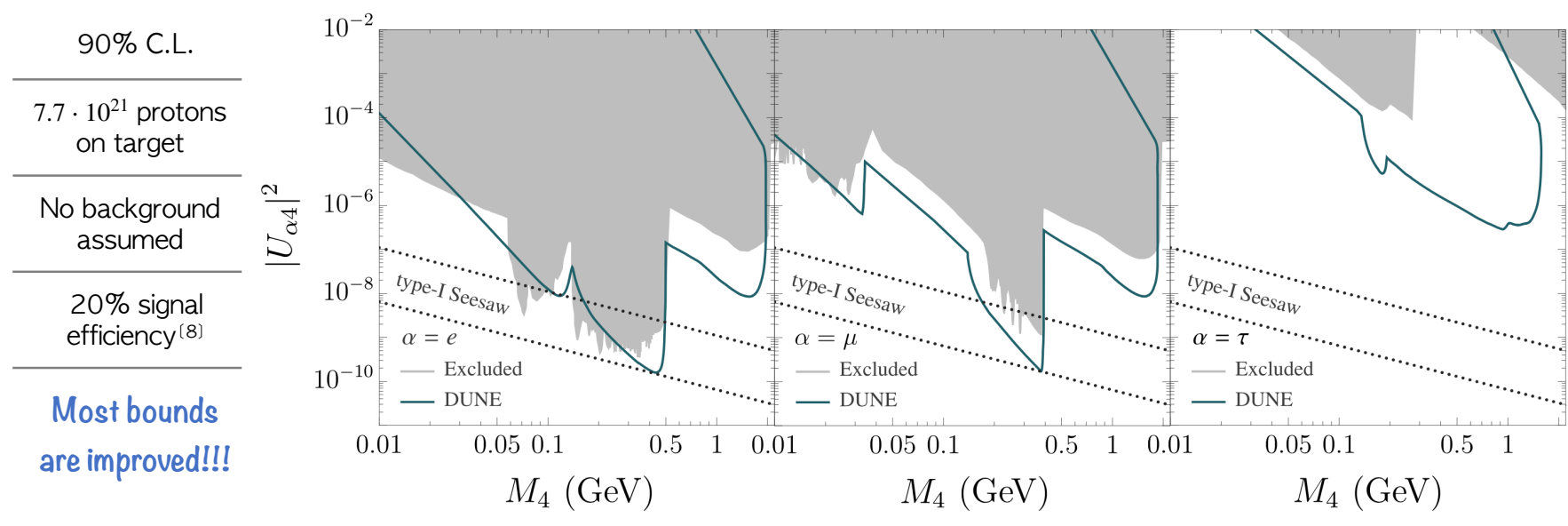
Form factors^(4,5)

$$\langle D | j_{W,\mu}^V | P \rangle = \frac{1}{2} V_{qq'} (p_\mu F_V(q^2) + q_\mu F_S(q^2))$$

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


- ✓ Extended neutrino sector in a 3+1 scenario: one extra state and enlarged mixing matrix.
 - ✓ Inclusion of mesons up to 2 GeV: $\pi, K, \rho, K^*, \eta, \eta', \omega, \phi, D, D_s$
 - ✓ HNLs involved in effective meson interactions as well as purely leptonic processes
- Efficient event generation in MadGraph5⁽⁷⁾**
- *Very similar results for neutral mesons

[4] Phys. Rev. D96 (2017) 054514 [1706.03017] [6] Comput. Phys. Commun. 185 (2014) 2250 [1310.1921]
 [5] 2nd DAPHNE Physics Handbook:315-389, pp. 315-389, 1994 (hep-ph/9411311) [7] JHEP 07 (2014) 079 [1405.0301]



CONCLUSIONS Heavy neutrinos in the GeV range are a simple and testable solution for several SM problems. They can be produced and decay in meson interactions, which we have derived and implemented in FeynRules. As an application, we have estimated the sensitivity of the DUNE ND to heavy neutrinos, finding its potential to probe very small mixings and improve most current bounds.

Back-up

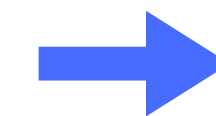
$$\mathcal{L}_\nu^{\text{mass}} \supset - \sum_{\alpha=e,\mu,\tau} \sum_{j=1}^n Y_{\nu,\alpha j} \bar{L}_{L,\alpha} \tilde{\phi} N_{R,j} - \sum_{j=1}^n M_j \bar{N}_{L,j} N_{R,j} + \text{h.c.}$$

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

Dirac neutrinos

(non self-conjugate neutrino fields)

Different
mass
matrices



Different
mixing
matrices

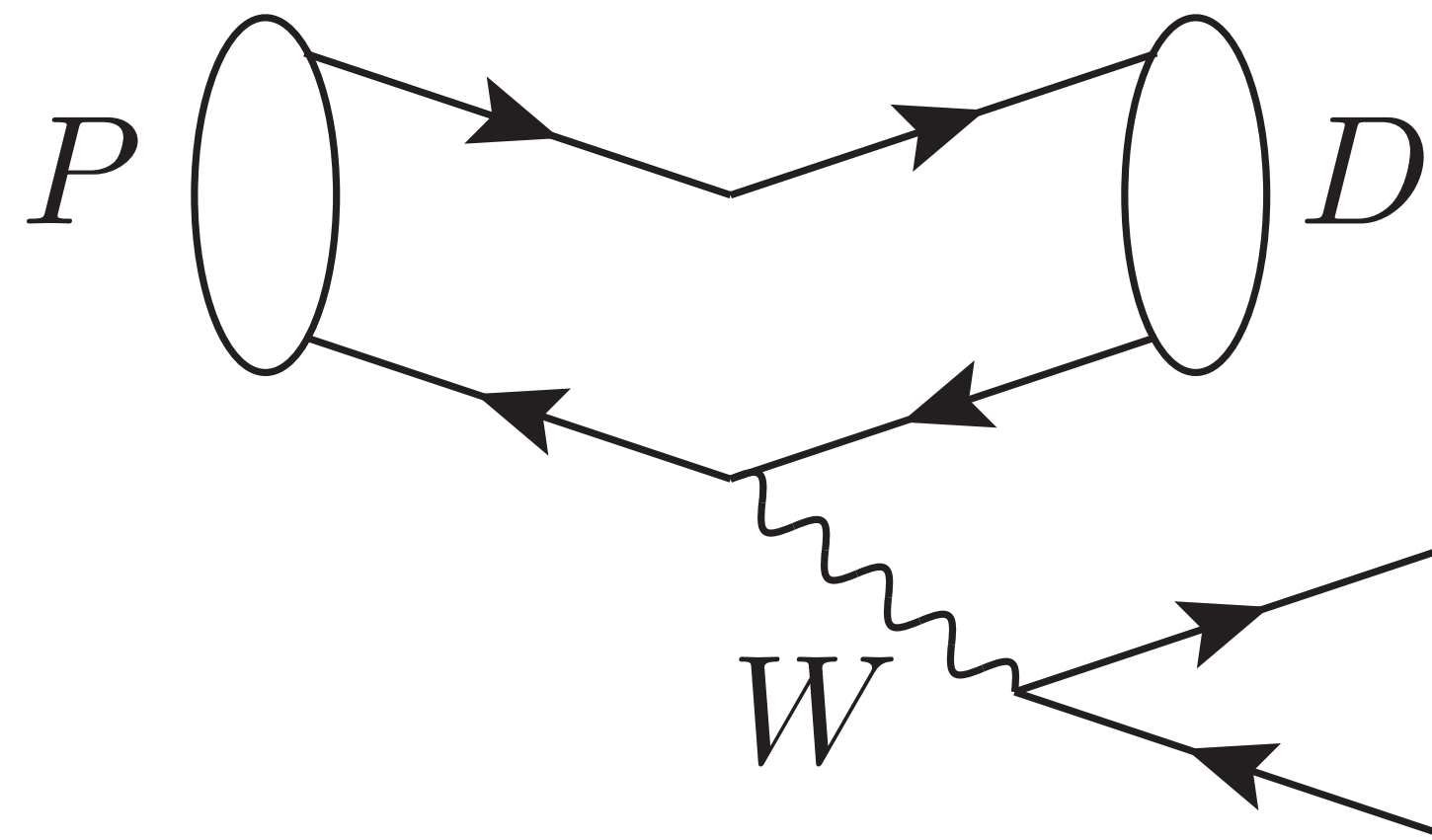
Majorana neutrinos

(self-conjugate neutrino fields)

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

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

Semileptonic processes



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

Form factors

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

Meson momentum
sum

Meson momentum
transfer

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

Main discrepancies with literature

1 HNL decays to neutral vectors

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

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

$$\begin{pmatrix} f_{\eta,8} & f_{\eta,0} \\ f_{\eta',8} & f_{\eta',0} \end{pmatrix} = \begin{pmatrix} f_8 \cos \theta_8 & -f_0 \sin \theta_0 \\ f_8 \sin \theta_8 & f_0 \cos \theta_0 \end{pmatrix} \xrightarrow{\text{[1]}} \text{Effective constants} \begin{cases} f_{\eta} \equiv \frac{\cos \theta_8 f_8}{\sqrt{3}} + \frac{\sin \theta_0 f_0}{\sqrt{6}} \\ f_{\eta'} \equiv \frac{\sin \theta_8 f_8}{\sqrt{3}} - \frac{\cos \theta_0 f_0}{\sqrt{6}} \end{cases}$$

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

Meson decay constants

Vector mesons

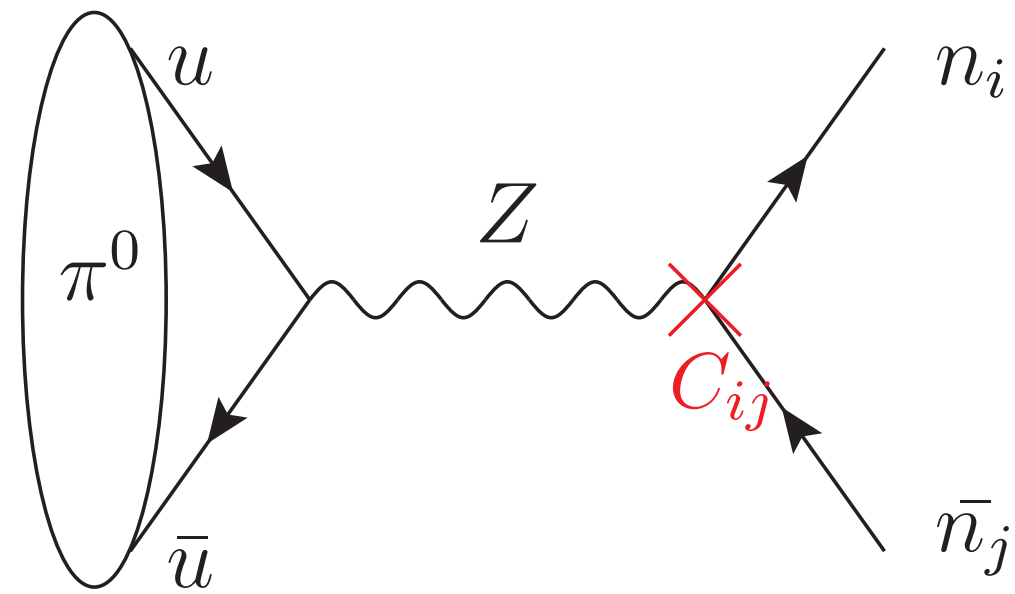
- Matching of $\Gamma(V^0 \rightarrow e^+e^-)$ to experimental data and extraction of f_{V^0}
- Negligible electromagnetic effects in ρ^\pm case: $f_{\rho^\pm} \approx f_{\rho^0}$
- Matching of $\Gamma(\tau^- \rightarrow K^{*,-} \nu_\tau)$ to experimental data and extraction of f_{K^*}

Charged vectors

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

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

$$\left. \begin{array}{l} i\mathcal{M}_{\rho^- \ell_\alpha \bar{n}_i} = \frac{ig^2}{2M_W^2} U_{\alpha i} \bar{u}_\alpha \gamma^\mu P_L v_i \langle 0 | j_{W,\mu}^V | \rho^- \rangle \\ \langle 0 | j_{a,\mu}^V | V_b \rangle = \delta_{ab} \frac{f_V}{\sqrt{2}} \epsilon_\mu, \end{array} \right\} \mathcal{O}_{\rho \ell_\alpha \bar{n}_i} = -\sqrt{2} G_F U_{\alpha i} V_{ud} f_\rho \rho_\mu^- (\bar{\ell}_\alpha \gamma^\mu P_L n_i) + \text{h.c.}$$



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

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

Neutral pseudoscalars

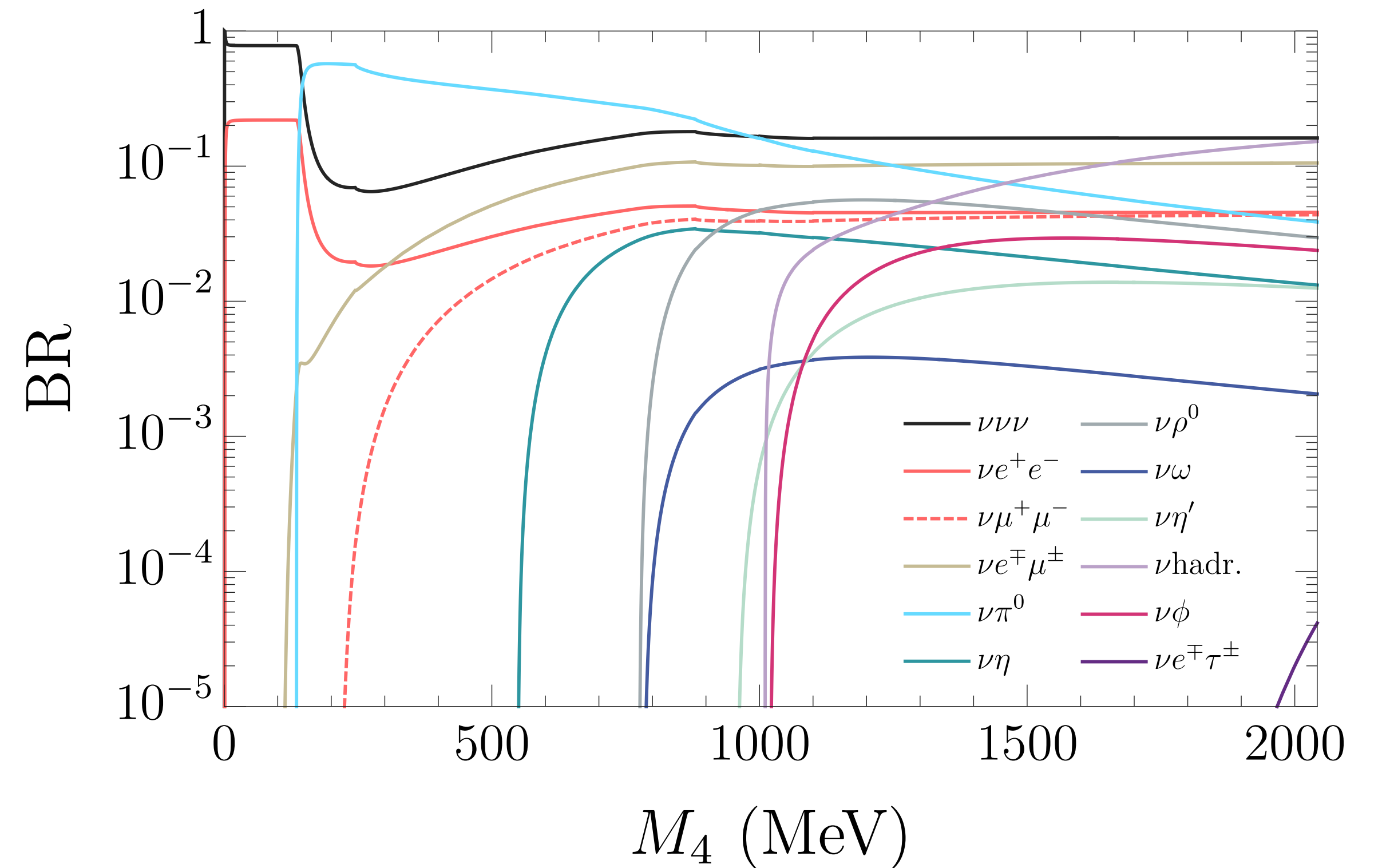
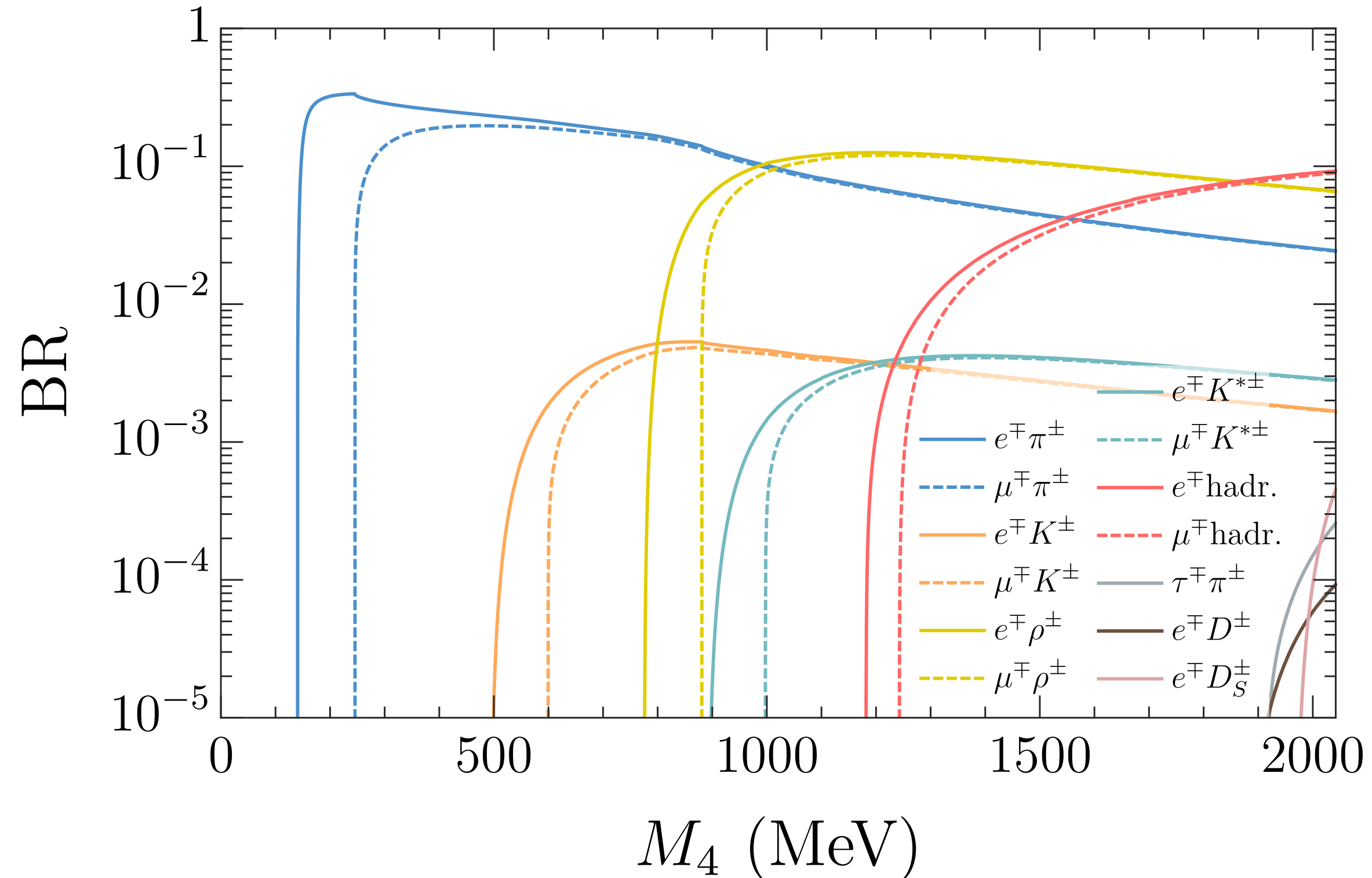
Neutral vectors

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

*Significant discrepancies in the literature

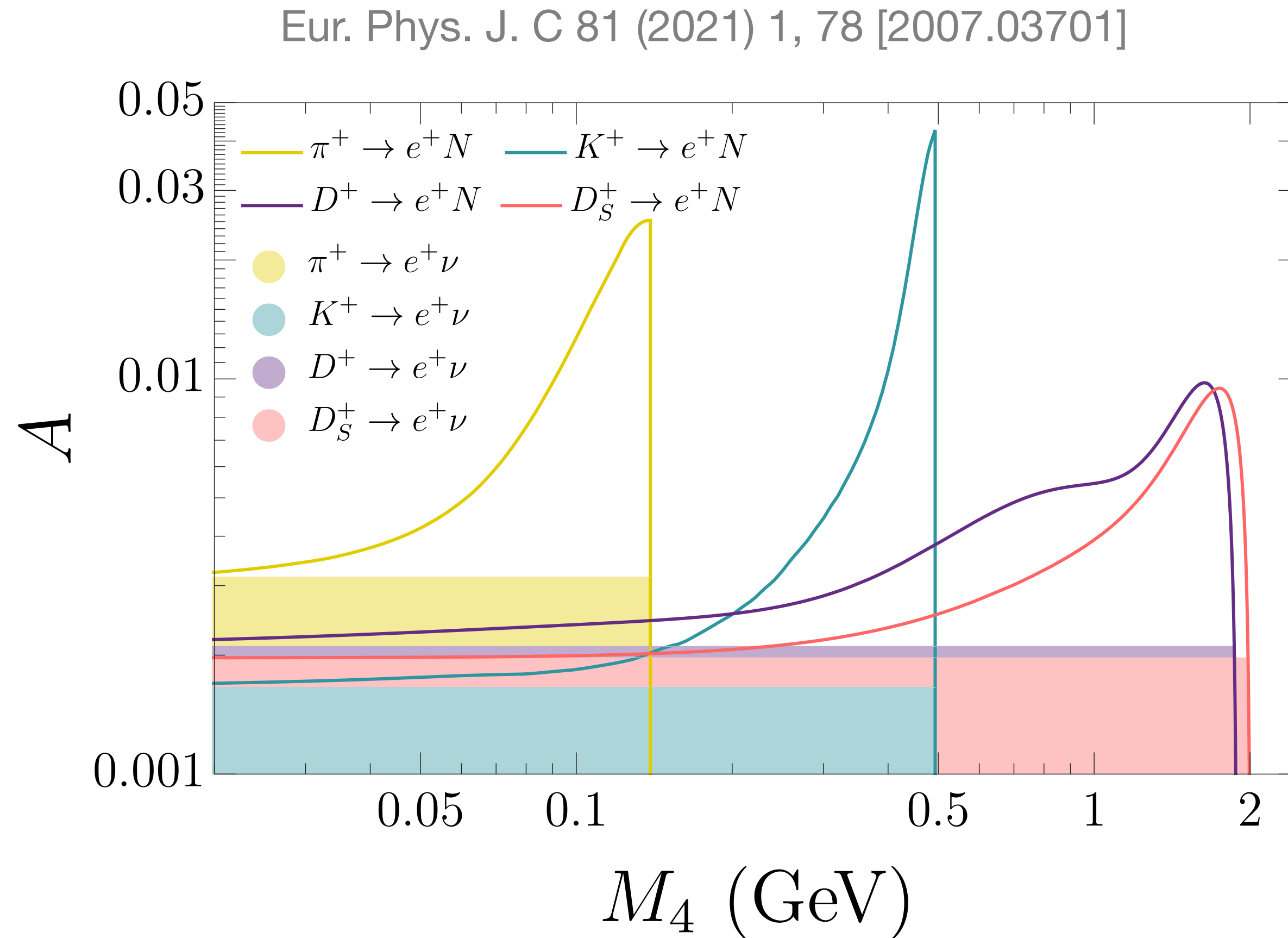
HNL Branching Ratios

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



Multimeson decays become relevant in the region $M_4 \gtrsim 1000$ MeV

Effect of the lab frame boost



Increased detector acceptance due to HNL mass

HNL multimeson decays

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

Estimation
from quark
processes

$$\Gamma(N_4 \rightarrow \text{hadr}) = (1 + \Delta_{\text{QCD}}) \Gamma(N_4 \rightarrow \text{quarks})^{[1]}$$

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

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

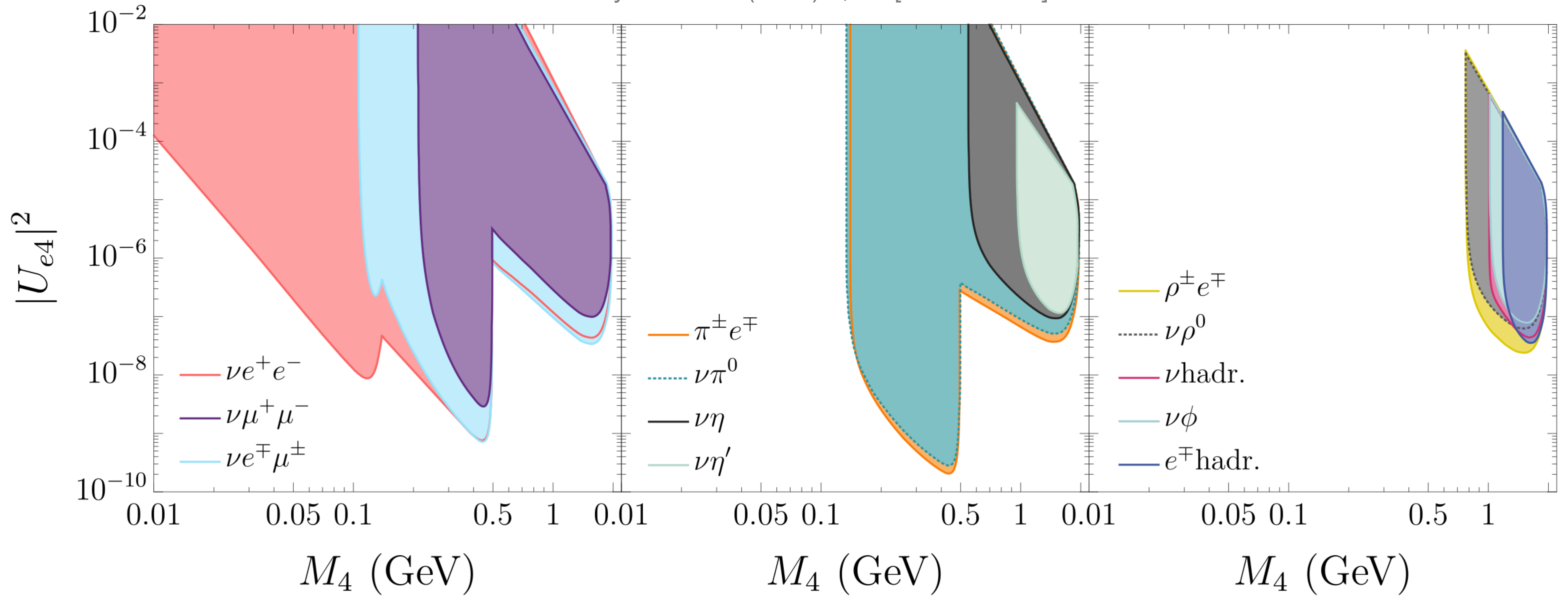
[2]S. Gorishnii, A. Kataev and S. Larin, Phys. Lett. B **259** (1991) 144.

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

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

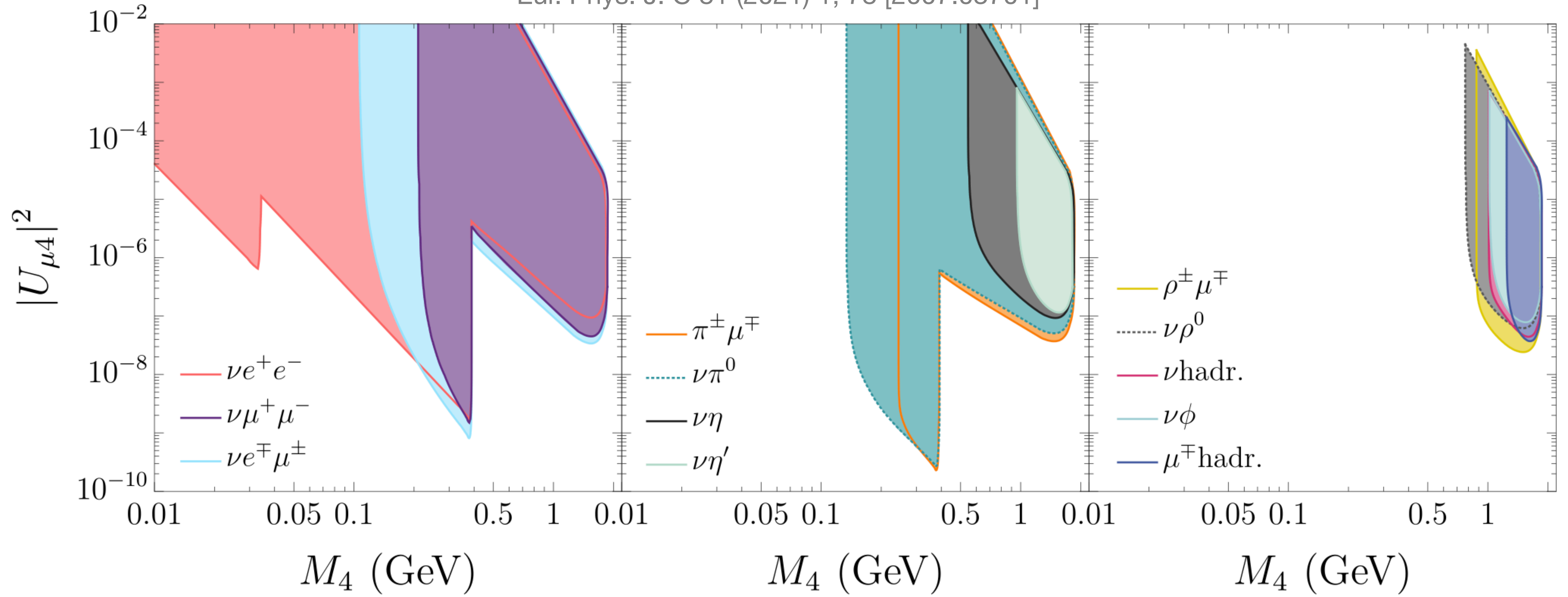
Sensitivity plots

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



Sensitivity plots

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



Sensitivity plots

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

