Heavy Neutral Lepton Phenomenology

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry
Essential Asymmetries of Nature

ν mass from right-handed neutrinos

Simplest option add ν_R and acquire Dirac masses via Yukawas

$$Y_\nu \bar{\nu}_R \phi \nu_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_\nu v}{\sqrt{2}} \bar{\nu}_R \nu_L \quad m_D = \frac{Y_\nu v}{\sqrt{2}}$$

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Fermion number violation → Baryogenesis via Leptogenesis

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To be searched for at experiments!!

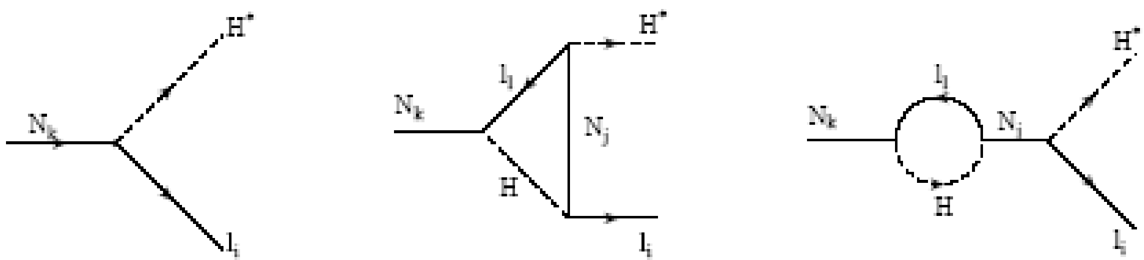
ν mass from right-handed neutrinos

$$m_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \xrightarrow[\text{Seesaw}]{\hspace{3cm}} U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

If $M_N \gg m_D$ then $M \approx M_N$ and $m \approx m_D^t M_N^{-1} m_D \rightarrow$ lightness of ν
small mixing $\Theta \approx m_D^\dagger M_N^{-1}$

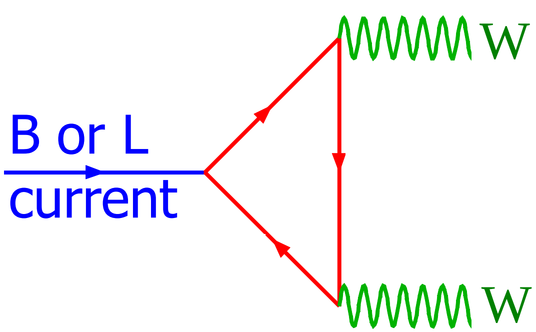
Leptogenesis

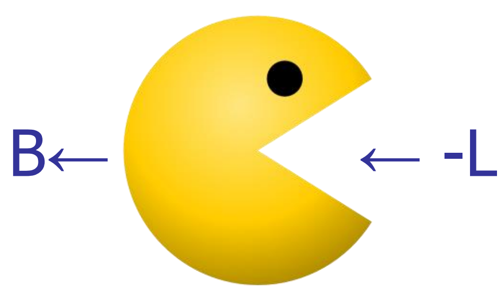
This simplest SM extension may connect to other open problems:



M. Fukugita and T. Yanagida 1986

-L is produced in CP-violating and out-of-quilibrium N decays





and partially converted to B by the SM sphalerons

A new physics scale

But a very high M_N worsens the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

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$$m_D \overline{N}_R \nu_L + M_N \overline{N}_R N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}$$

G. C. Branco, W. Grimus, and L. Lavoura 1988
J. Kersten and A. Y. Smirnov 0705.3221

Low $M \approx M_N$ and large $\Theta \approx m_D^\dagger M_N^{-1}$ even if vanishing $m_\nu = 0$

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$$m_D \bar{N}_R \nu_L + M_N \bar{N}_R N_L + \mu \bar{N}_L^c N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

"inverse Seesaw"

R. Mohapatra and J. Valle 1986

Low $M \approx M_N \pm \frac{\mu}{2}$ and large $\Theta \approx m_D^\dagger M_N^{-1}$ even if small $m_\nu \approx \mu \frac{m_D^2}{M_N^2}$

Links with other open problems: baryogenesis

With lower M_N possible connections with other open problems are easier to probe

ARS leptogenesis possible in the νMSM

E. K. Akhmedov, V. A. Rubakov and A. Yu. Smirnov hep-ph/9803255

T. Asaka and M. Shaposhnikov hep-ph/0505013

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$\bar{N}$

M. Drewes, B. Garbrecht, P. Hernandez, M. Kekic, J. Lopez–Pavon, J. Racker, N. Rius, J. Salvado, D. Teresi 1711.02862

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$$\bar{\nu}_L \xleftrightarrow[\text{oscillations}]{\text{CP violating}} \bar{N}$$

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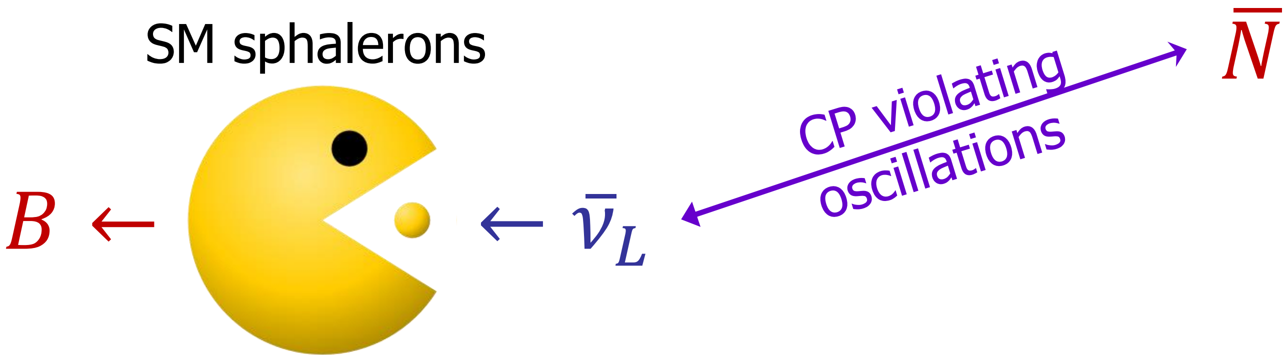

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If the low-E Seesaw mass is also dynamical:

$$Y_\nu \bar{N}_R \widetilde{H}^\dagger L_L + Y_N \bar{N}_R \phi N_L + V(\phi, H) \rightarrow m_D \bar{N}_R \nu_L + M_N \; \bar{N}_R N_L \; + V(\phi, H)$$

New sources of CPV in the Yukawas

and ϕ could induce a 1st order pase transition:

EFM, J. López-Pavón, J. M. No, T. Ota, S. Rosauro-Alcaraz 2007.11008, 2210.16279

P. Hernandez and N. Rius hep-ph/9611227

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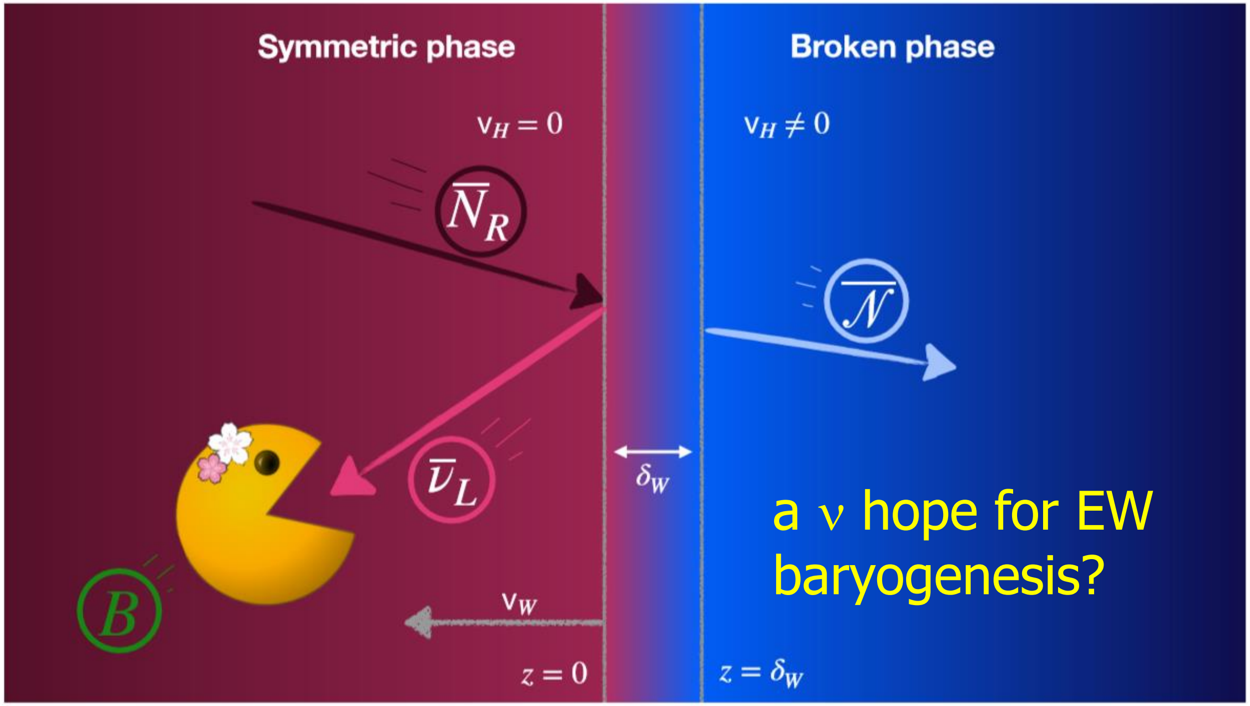

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Production via mixing (Dodelson-Widrow) is ruled out by bounds from X-ray searches

But production could be sufficiently enhanced in presence of large L asymmetry (5-6 orders of magnitude larger than B).

Proof of concept via resonant leptogenesis with extremely degenerate ($\Delta M \sim 10^{-7}$ eV for 2 GeV) neutrinos. Natural??

J. Ghiglieri, M. Laine 1905.08814, 2004.10766

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Also neutrino portals to DM

M. Lindner, A. Merle and V. Niro arXiv:1005.3116

A. Falkowski, J. Juknevich and J. Shelton arXiv:0908.1790.

V. Gonzalez Macias and J. Wudka arXiv:1506.03825

M. Blennow, EFM, A. Olivares-Del Campo,

S. Pascoli, S. Rosauro arXiv:1903.00006

DM interacts with N at renormalizable level

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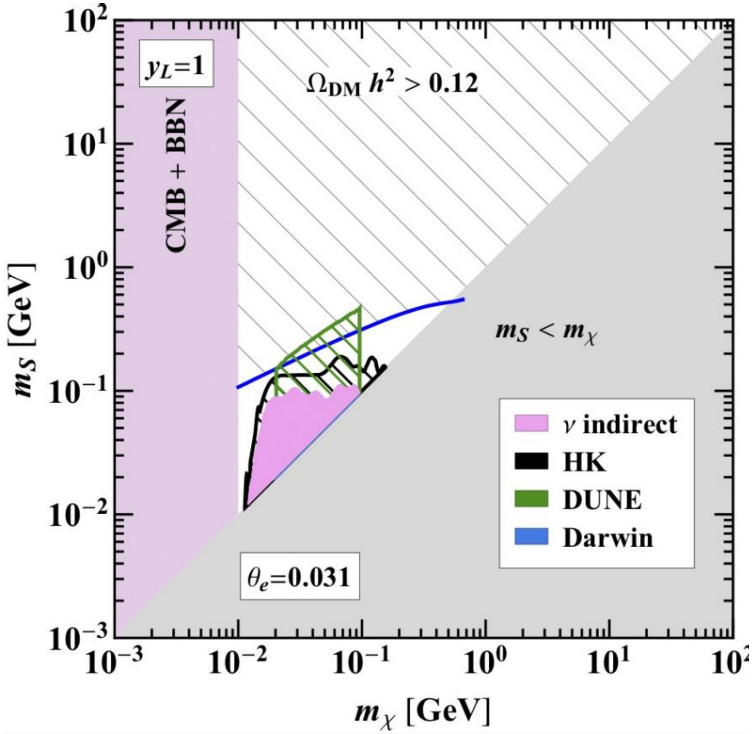
Interactions with the SM ν_L dominate DM production as well as its detection prospects



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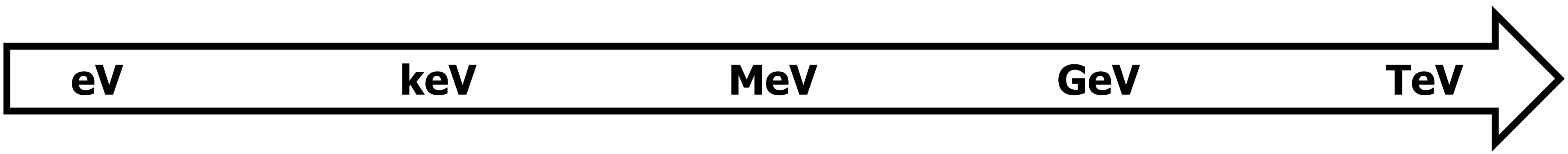

M_N could be anywhere…

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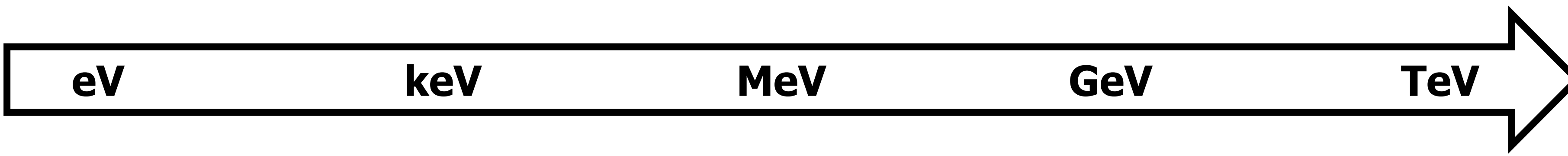

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Very different phenomenology at different scales

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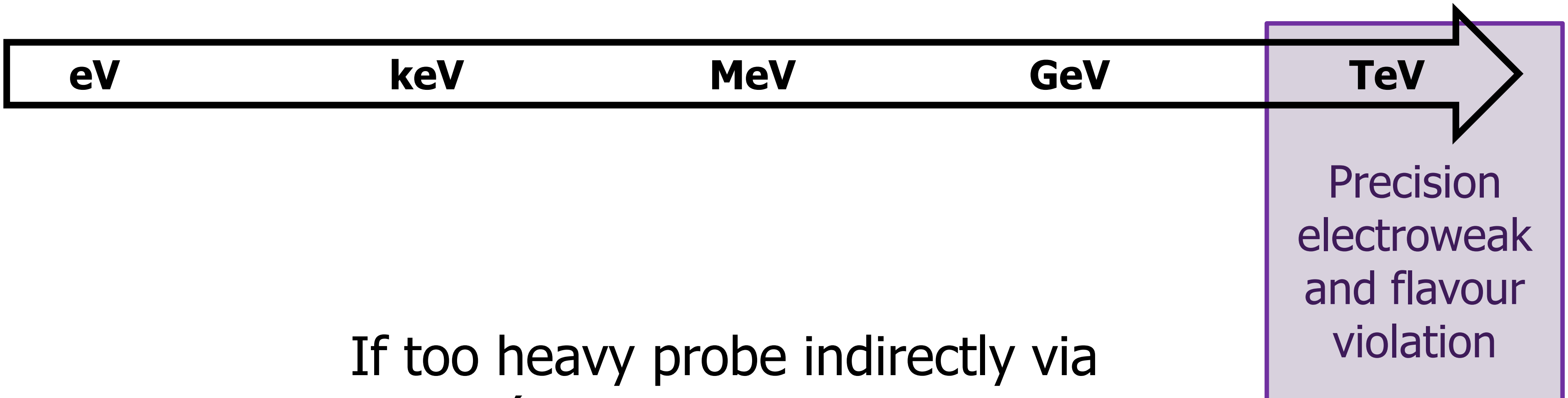
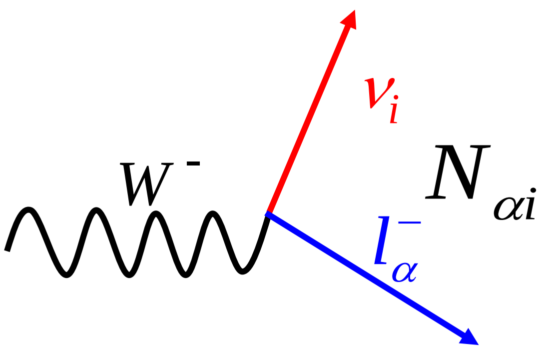


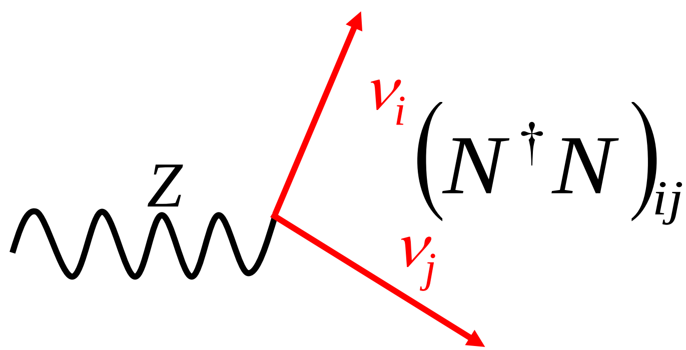
If too heavy probe indirectly via precisión measurements

Looking for N_R: Non-Unitarity

$$U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U \approx \begin{pmatrix} N^t & -\Theta^* \\ \Theta^t & X^t \end{pmatrix} \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix N of active neutrinos will not be unitary





Effects in weak interactions…

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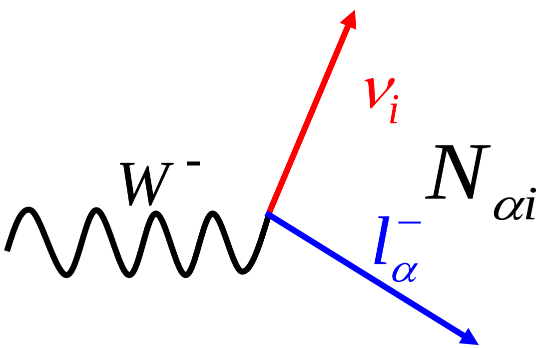
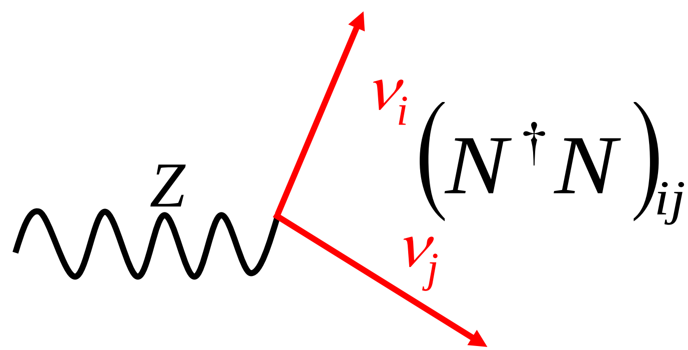




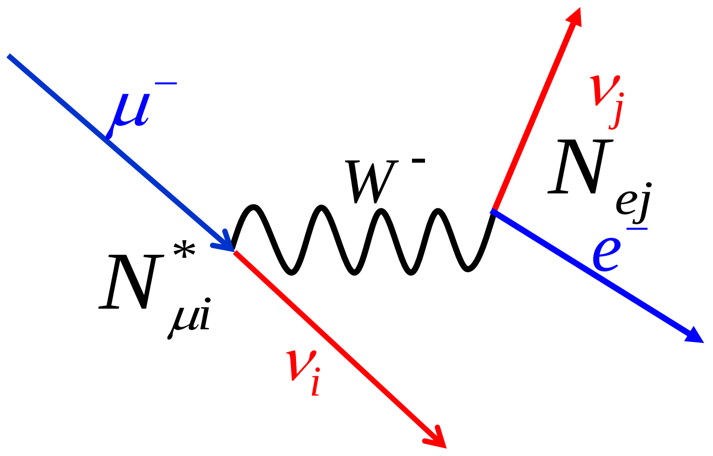
Effects in weak interactions…

When the W and Z are integrated out to obtain the Fermi theory NSI are recovered!

see e.g. M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637 for the dictionary

Looking for N_R: Non-Unitarity

G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

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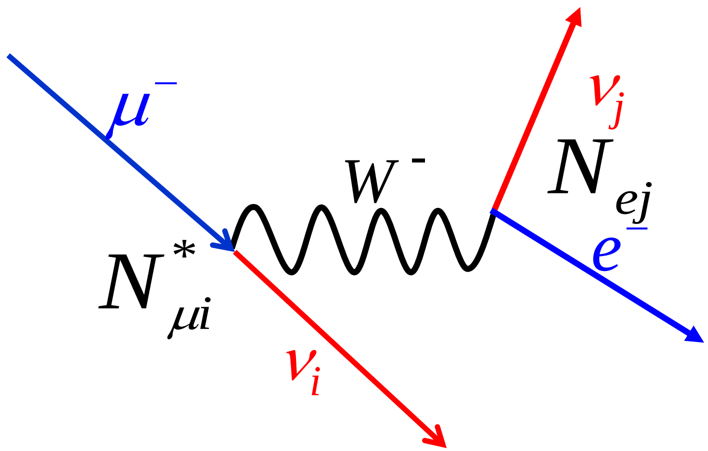

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But this agrees at $\sim 10^{-3}$ with G_F from M_W (modulo CDF), measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and β and K decays

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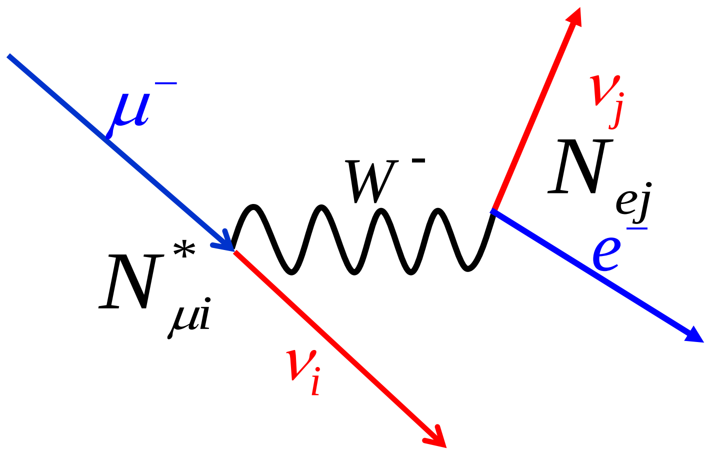

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LFU also strong bounds on ratios:

$$\frac{\left(NN^\dagger\right)_{\alpha\alpha}}{\left(NN^\dagger\right)_{\beta\beta}}$$

From ratios of π, K, and lepton decays

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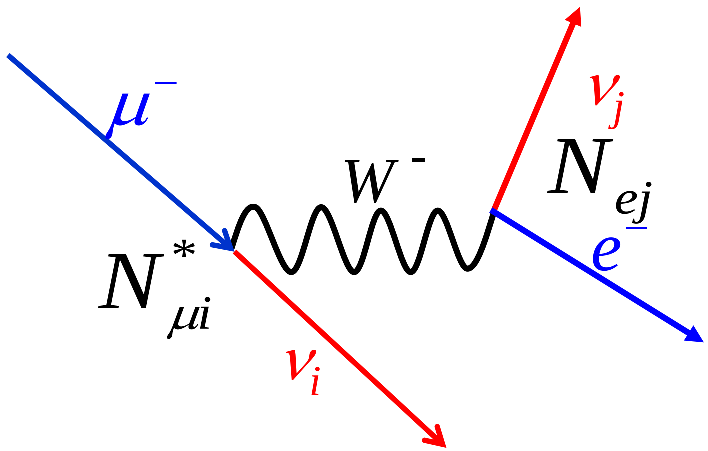

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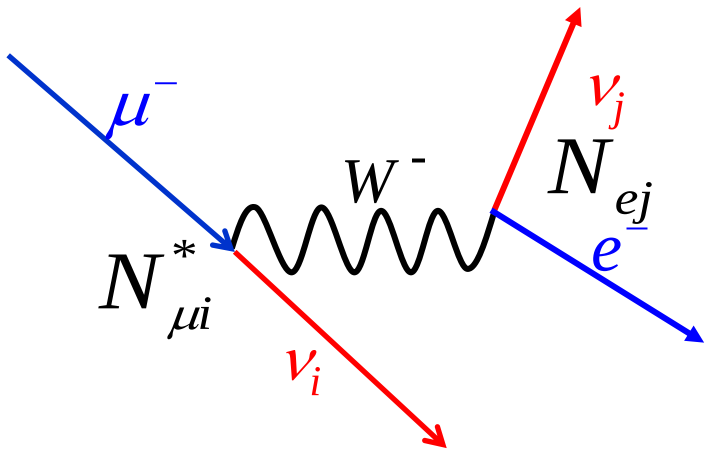

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And LFV processes such as $\mu \to e\,\gamma$ since the GIM cancellation is lost

Looking for N_R: Non-Unitarity

Bounds from a global fit to flavour and Electroweak precision

95% CL	LFC	LFV
$\eta_{ee} = \frac{1}{2}\sum_k \lvert\Theta_{ek}\rvert^2$	$[0.081, 1.4] \cdot 10^{-3}$	-
$\eta_{\mu\mu}$	$1.4 \cdot 10^{-4}$	-
$\eta_{\tau\tau}$	$8.9 \cdot 10^{-4}$	-
$\mathrm{Tr}\,[\eta]$	$2.1 \cdot 10^{-3}$	-
$\lvert\eta_{e\mu}\rvert$	$3.4 \cdot 10^{-4}$	$\mathbf{1.2 \cdot 10^{-5}}$
$\lvert\eta_{e\tau}\rvert$	$\mathbf{8.8 \cdot 10^{-4}}$	$8.1 \cdot 10^{-3}$
$\lvert\eta_{\mu\tau}\rvert$	$\mathbf{1.8 \cdot 10^{-4}}$	$9.4 \cdot 10^{-3}$

$$N = (\mathbb{I} - \eta)U$$

$$\eta = \frac{\Theta\Theta^\dagger}{2} \qquad \Theta \approx m_D^\dagger M_N^{-1}$$

M. Blennow, EFM,
J. Hernandez-Garcia,
J. Lopez-Pavon
X. Marcano and
D. Naredo-Tuero
2306.01040

See also P. Langaker and D. London 1988; S. M. Bilenky and C. Giunti hep-ph/9211269 ; E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228; D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228; S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020; S. Antusch, J. Baumann and EFM 0807.1003; D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009; S. Antusch and O. Fischer 1407.6607; F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774, A. M. Coutinho, A. Crivellin, and C. A. Manzari 1912.08823…

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2 σ preference for mixing with electrons ~0.03

M. Blennow, EFM, J. Hernandez-Garcia, J. Lopez-Pavon X. Marcano and D. Naredo-Tuero 2306.01040

See also P. Langaker and D. London 1988; S. M. Bilenky and C. Giunti hep-ph/9211269 ; E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228; D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228; S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020; S. Antusch, J. Baumann and EFM 0807.1003; D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009; S. Antusch and O. Fischer 1407.6607; F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774, A. M. Coutinho, A. Crivellin, and C. A. Manzari 1912.08823…

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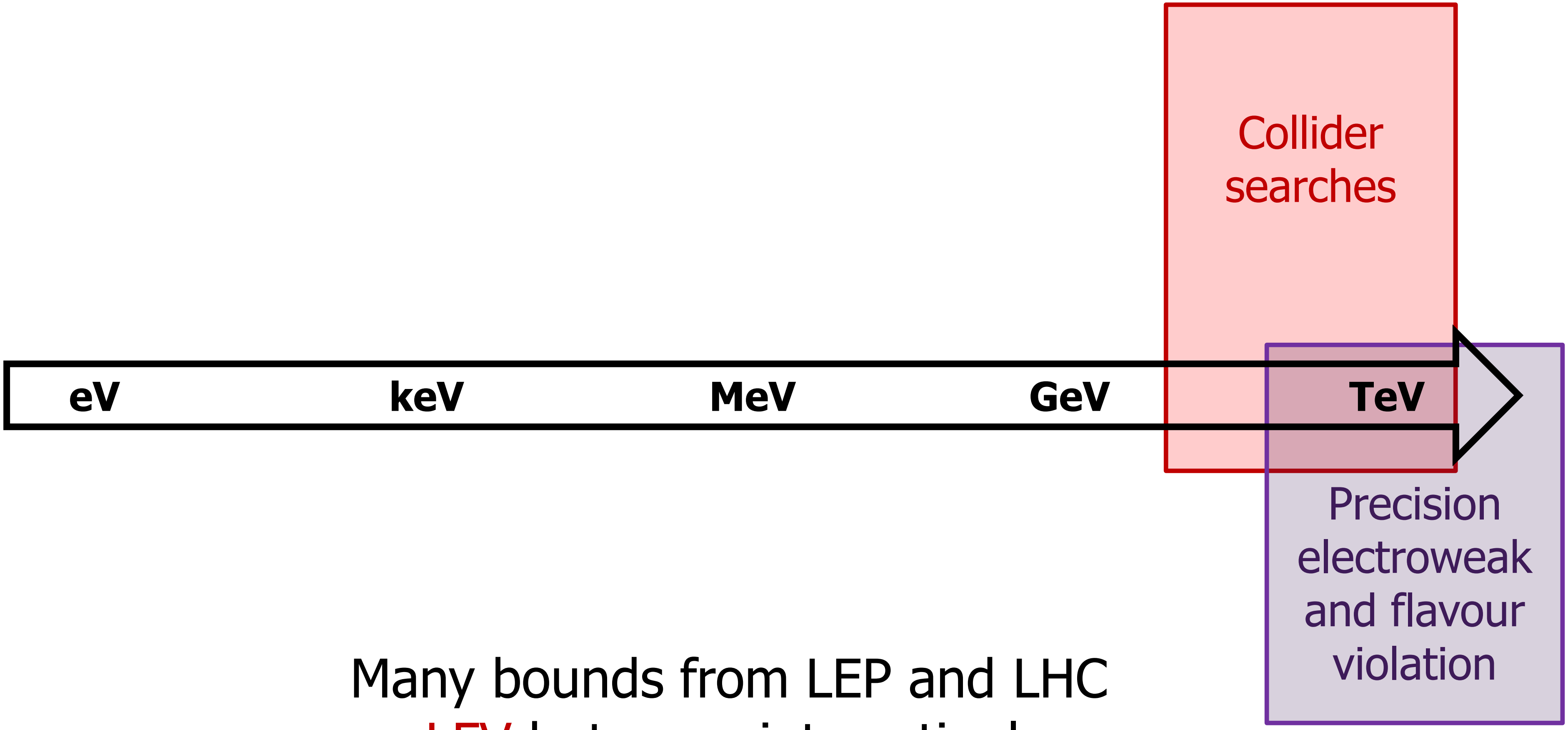

Many bounds from LEP and LHC on LFV but more interestingly LNV signatures

LNV at colliders

If the HNLs are pseudoDirac, LNV signals should be very supressed

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But, if $\Delta M >> \Gamma$ they will oscillate many times between the two states before decaying, breaking the coherence and the supression of LNV
S. Antusch, E. Cazzato, and O. Fischer 1709.03797; M. Drewes, J. Klarić, and P. Klose 1907.13034; J. Gluza and T. Jeliński 1504.05568; P. S. Bhupal Dev and R. N. Mohapatra 1508.02277; G. Anamiati, M. Hirsch, and E. Nardi 1607.05641; A. Das, P. S. B. Dev, and R. N. Mohapatra 1709.06553

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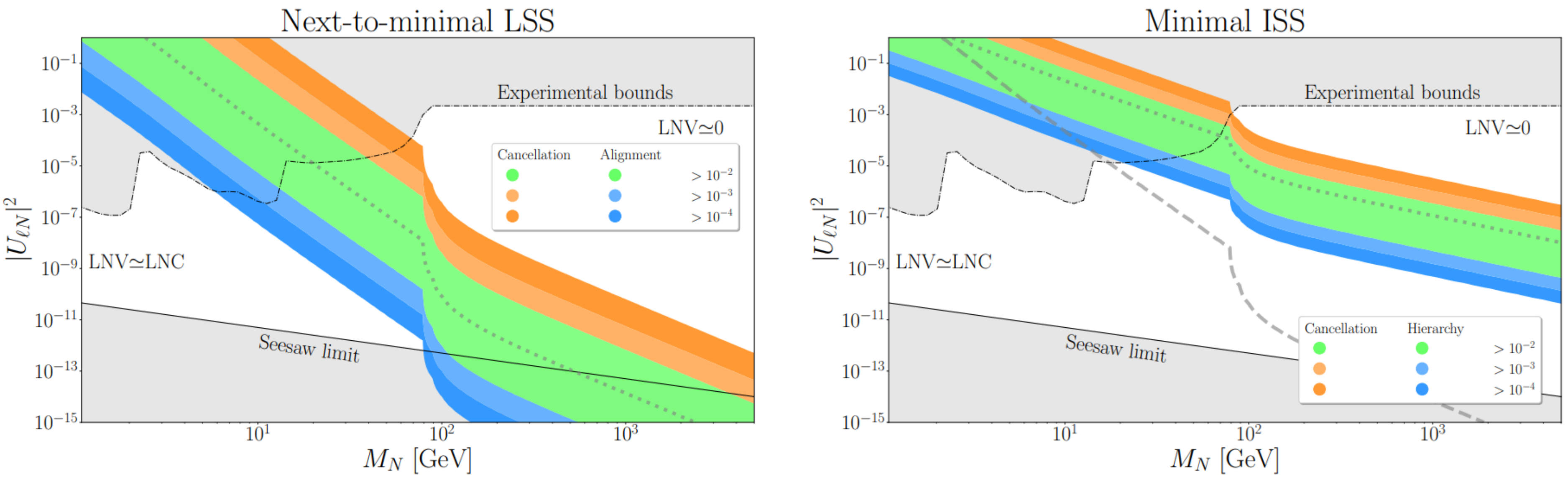


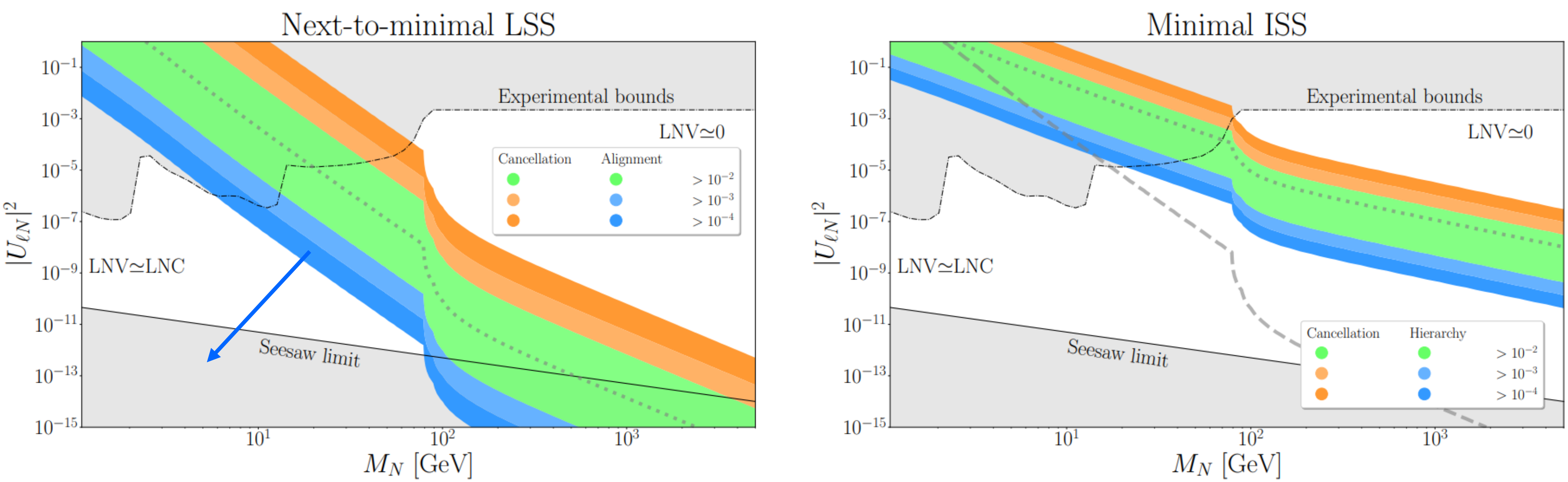
Could allow to distinguish between low scale Seesaw models!

EFM, X. Marcano and D. Naredo-Tuero 2209.04461

LNV at colliders

If the HNLs are pseudoDirac, LNV signals should be very supressed

But, if $\Delta M >> \Gamma$ they will oscillate many times between the two states before decaying, breaking the coherence and the supression of LNV



Very small values of ΔM are related to Yukawas that are almost parallel in the LSS.

Maybe a symmetry can explain the $\Delta M \sim 10^{-7}$eV needed for Shi-Fuller?

EFM, X. Marcano and D. Naredo-Tuero 2209.04461

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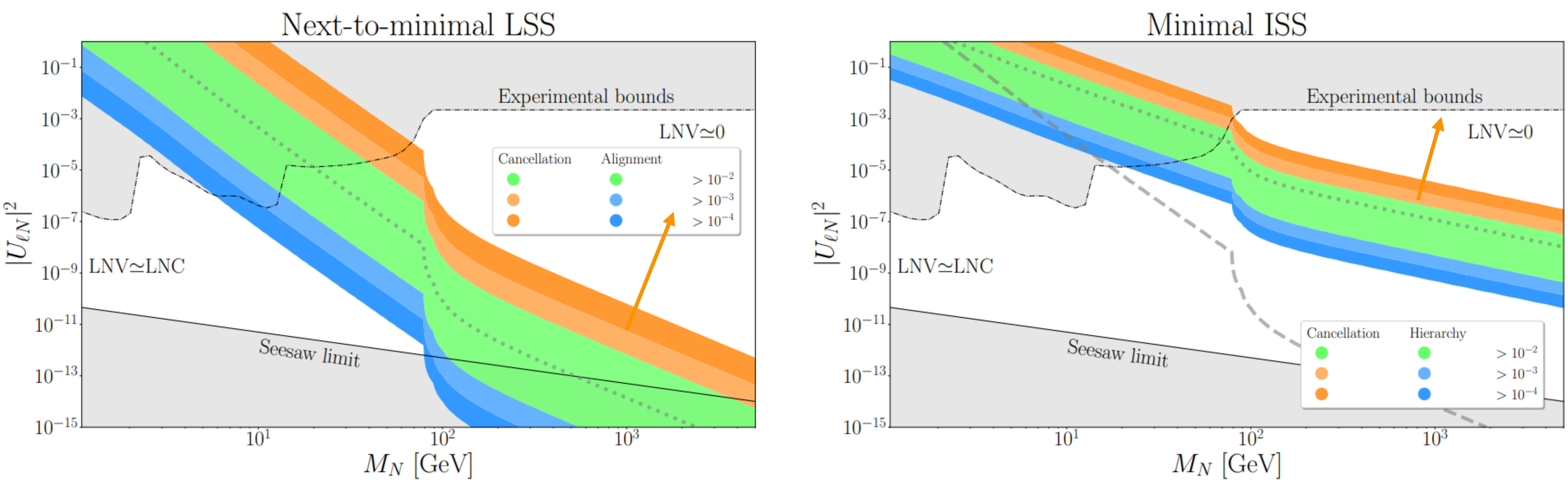
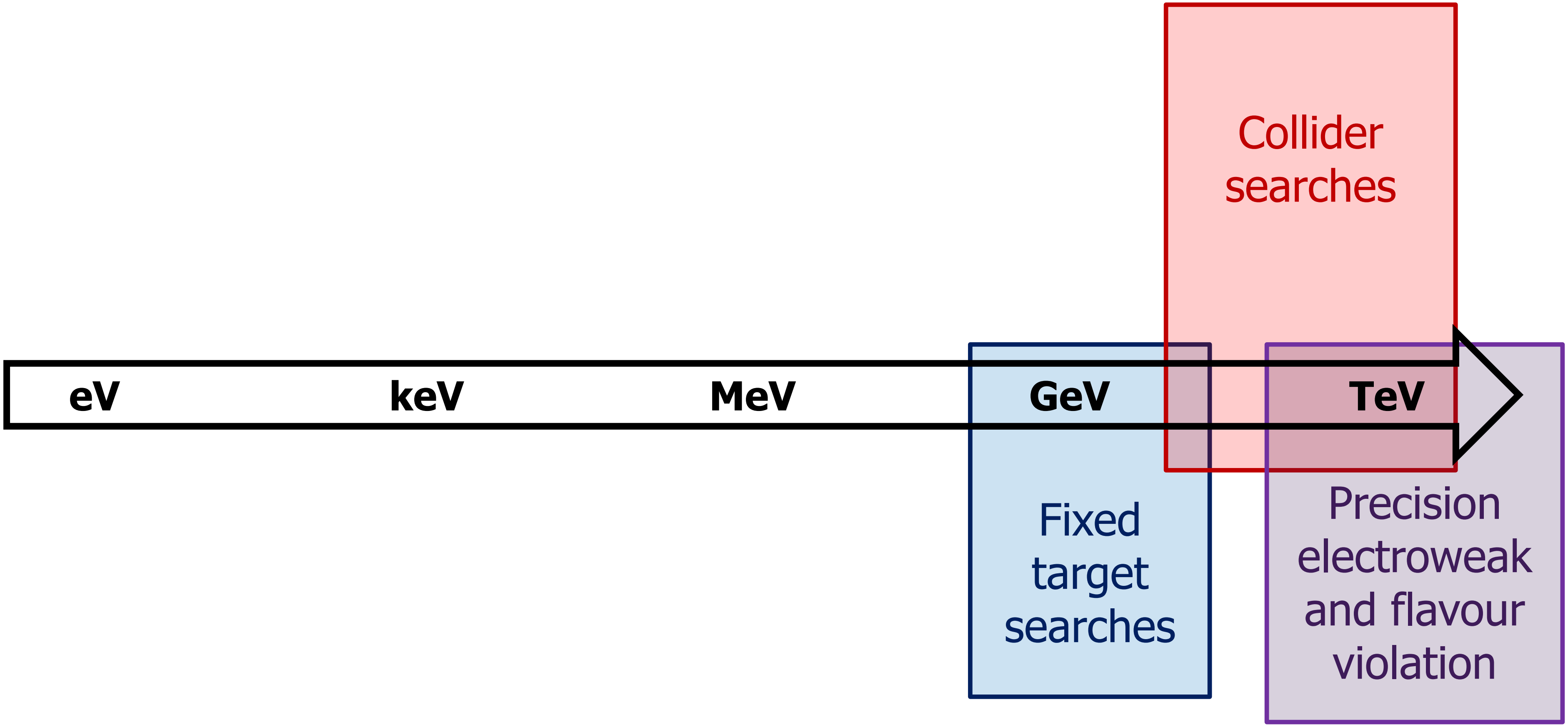


Large values of ΔM need fine tunned cancellations to keep ν mass low.

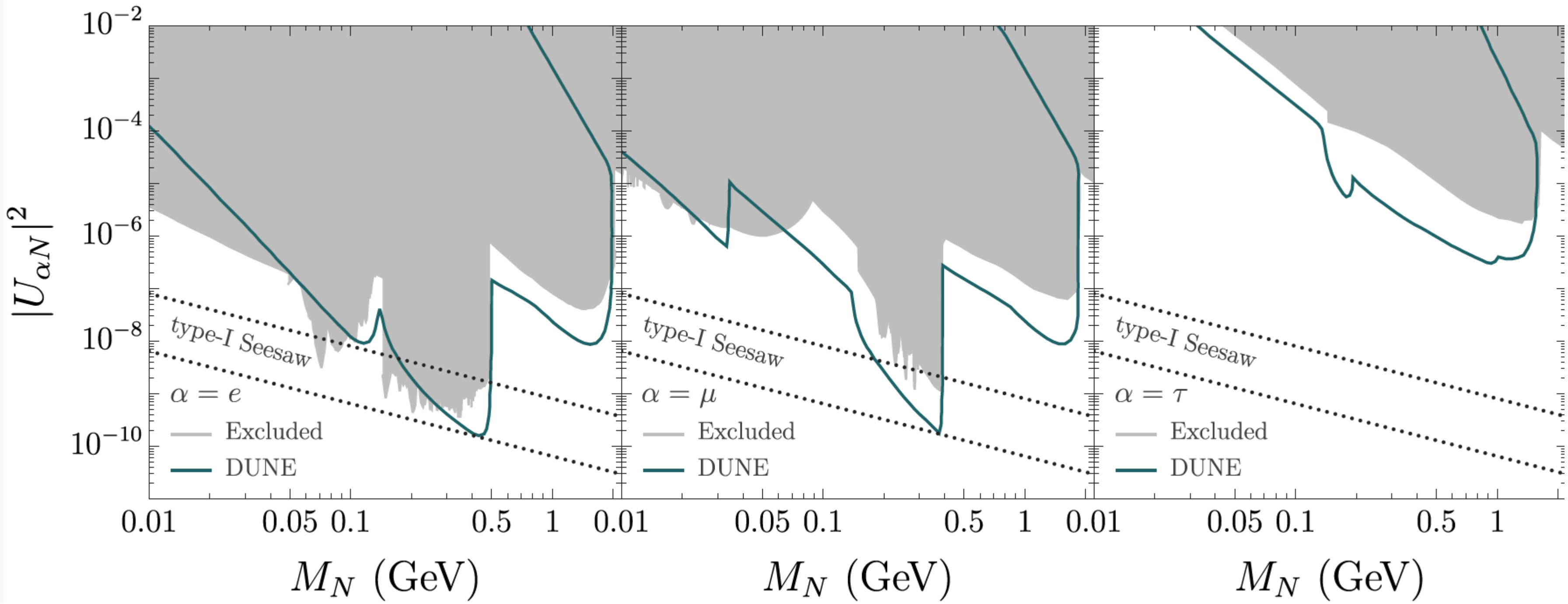
EFM, X. Marcano and D. Naredo-Tuero 2209.04461

A new physics scale



Looking for N_R: Beam Dumps

Sensitivity of DUNE ND to N_R



P. Coloma, EFM, M. González-López, J. Hernández-García arXiv:2007.03701

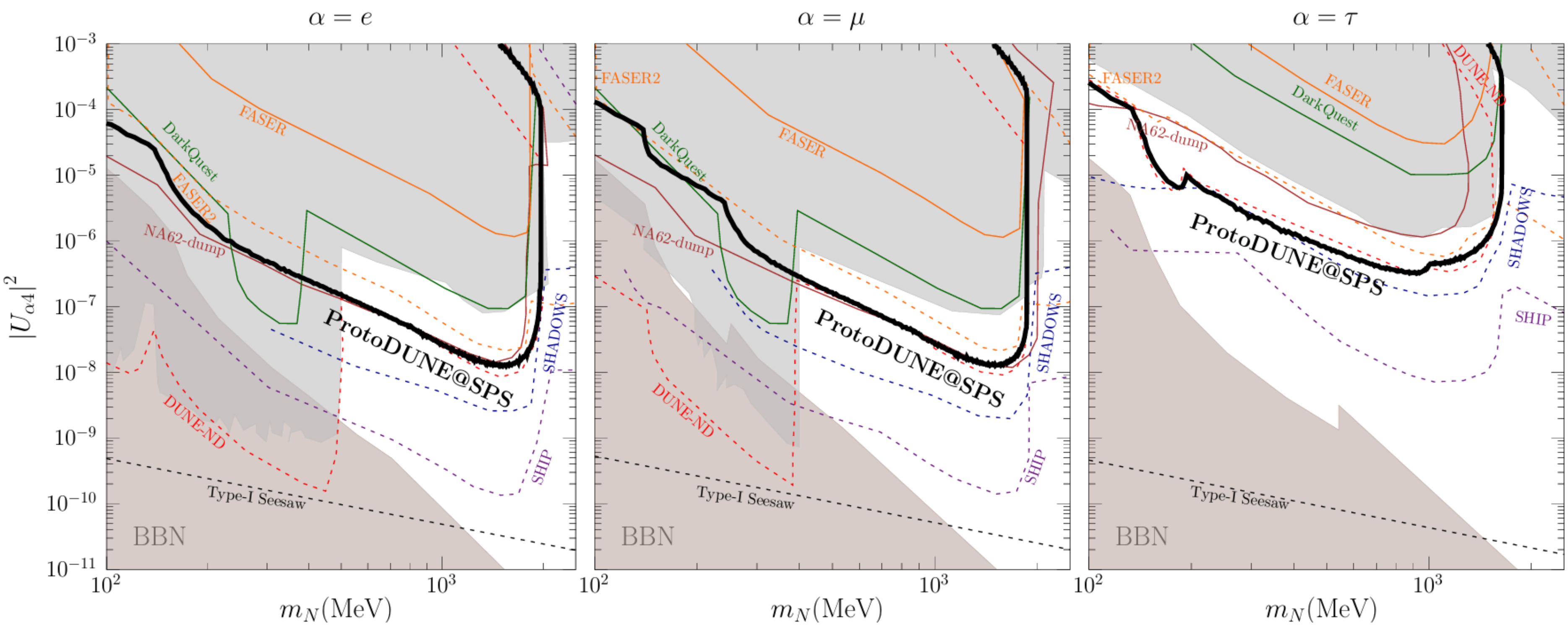
A FeynRules file with interactions between mesons and N_R (HNLs) is provided

See also: P. Ballett, T. Boschi, and S. Pascoli arXiv:1905.00284

J. M. Berryman, A. de Gouvea, P. J. Fox, B. J. Kayser, K. J. Kelly, and J. L. Raaf arXiv:1912.07622

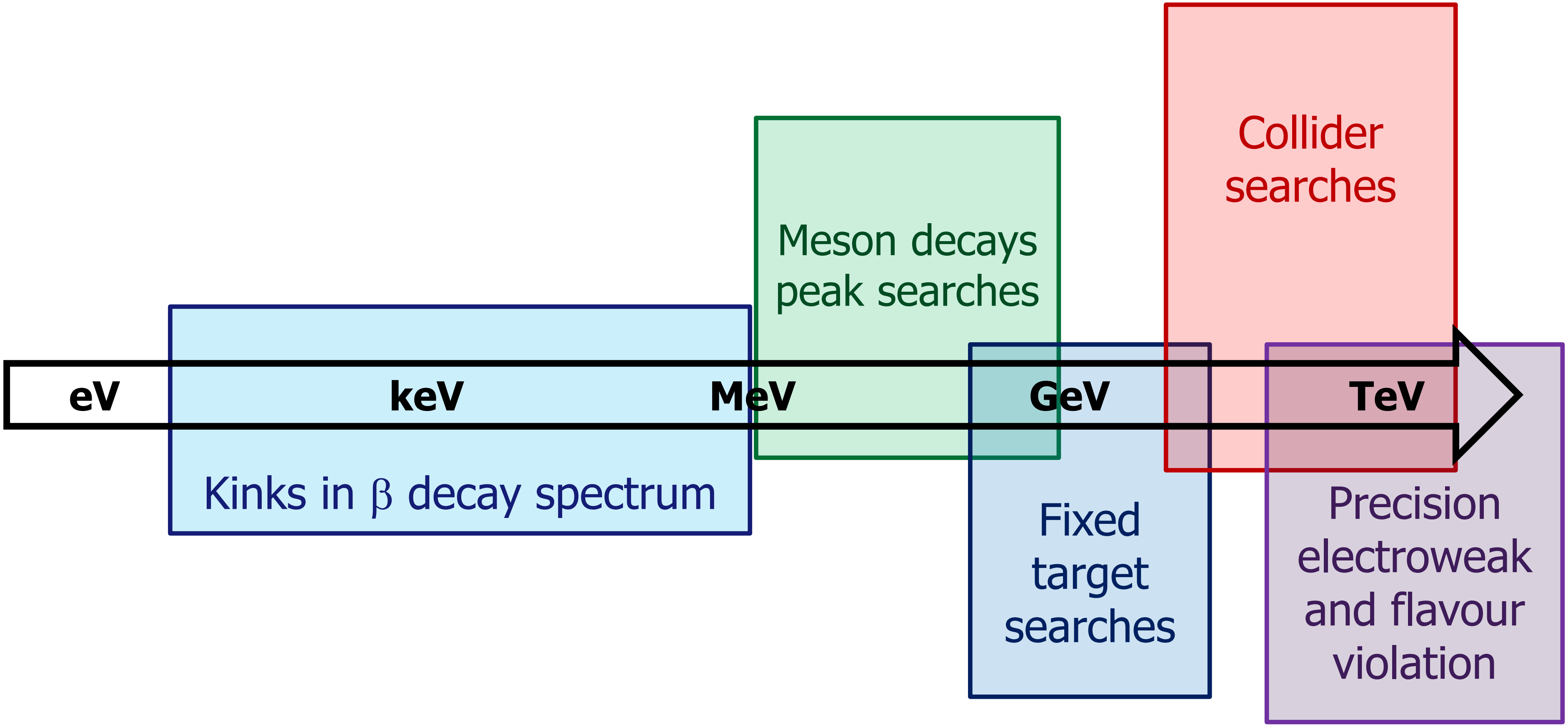
I. Krasnov arXiv:1902.06099; M. Breitbach, L. Buonocore, C. Frugiuele, J Kopp, L. Mittnacht arXiv:2102.03383 ; A. M. Abdullahi, P. Barham Alzas et al. arXiv:2203.08039

Looking for ν_R: Beam Dumps

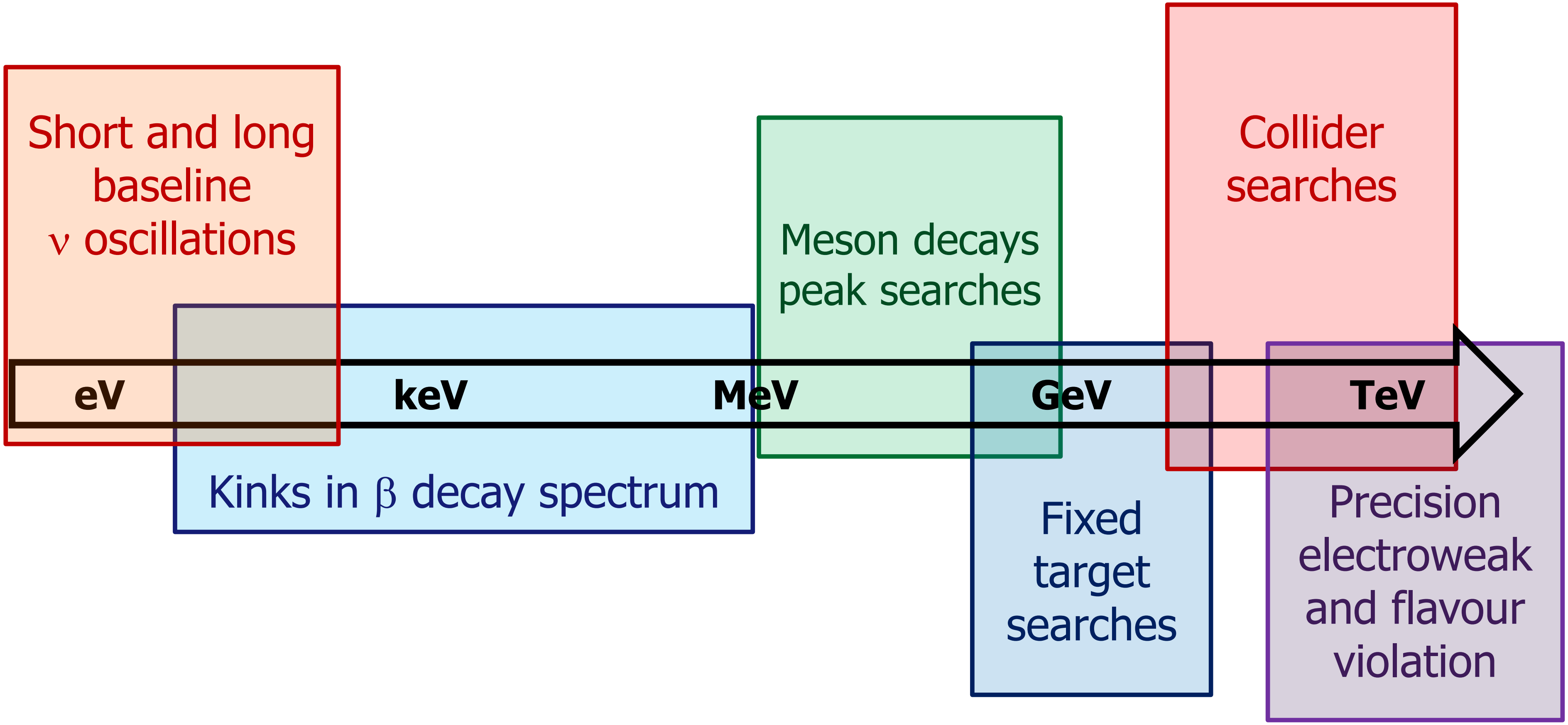


P. Coloma, J. Lopez-Pavon, L. Molina-Bueno and S. Urrea 2304.06765

A new physics scale

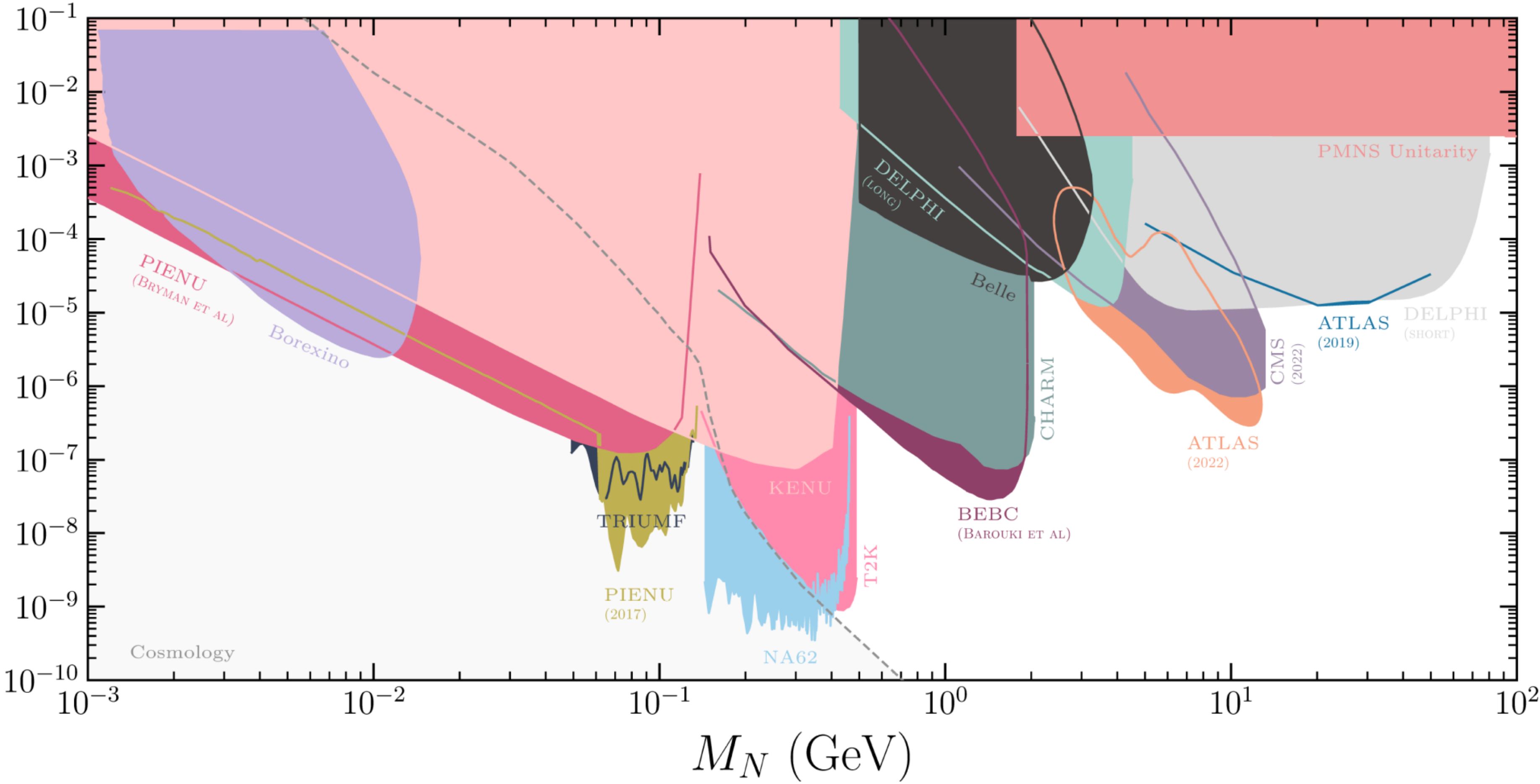


A new physics scale



Looking for N_R

All together:



EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2304.06772
https://github.com/mhostert/Heavy-Neutrino-Limits
See also: P. D. Bolton, F. F. Deppisch and P. S. B. Dev arXiv:1912.03058

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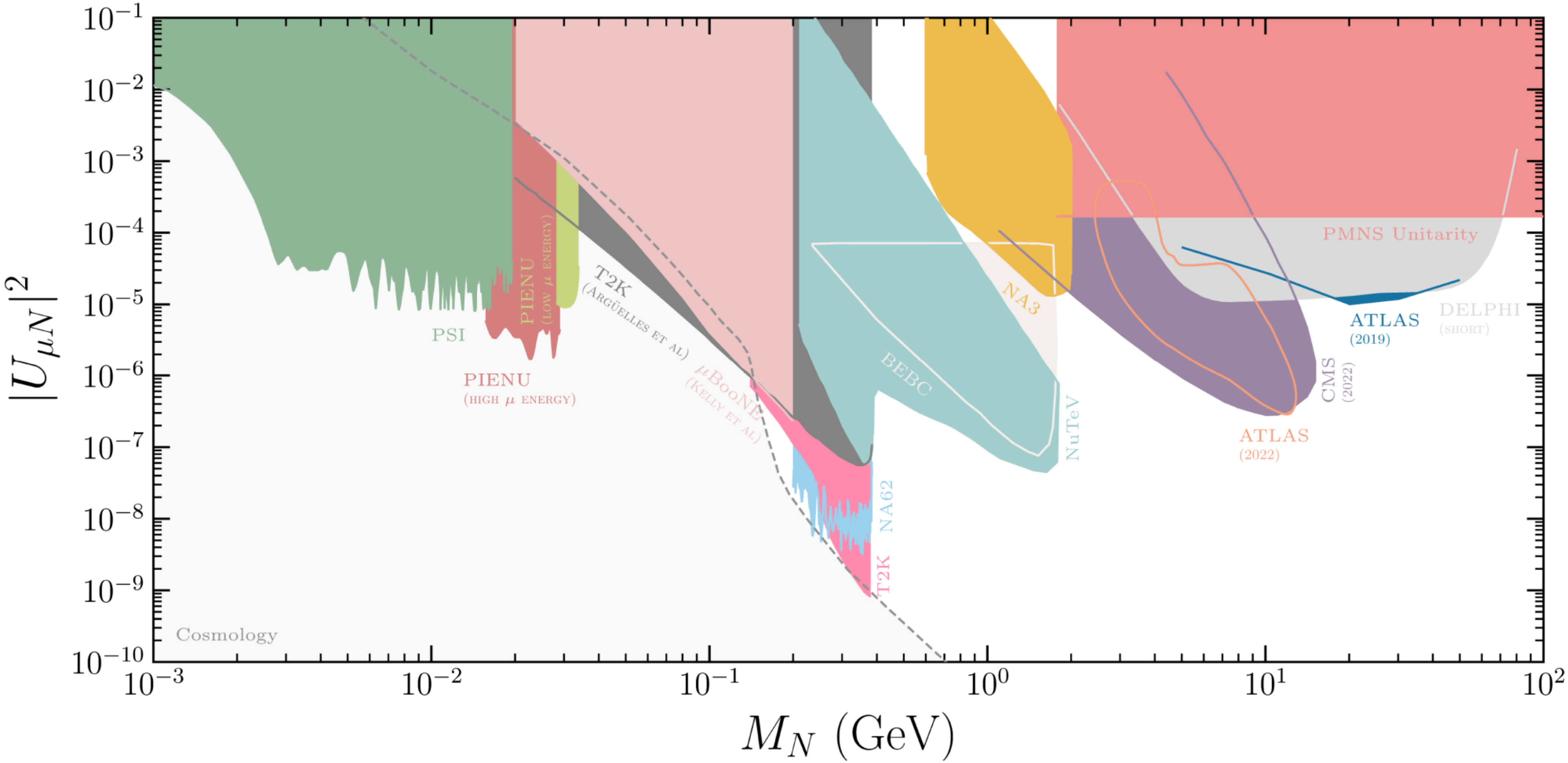

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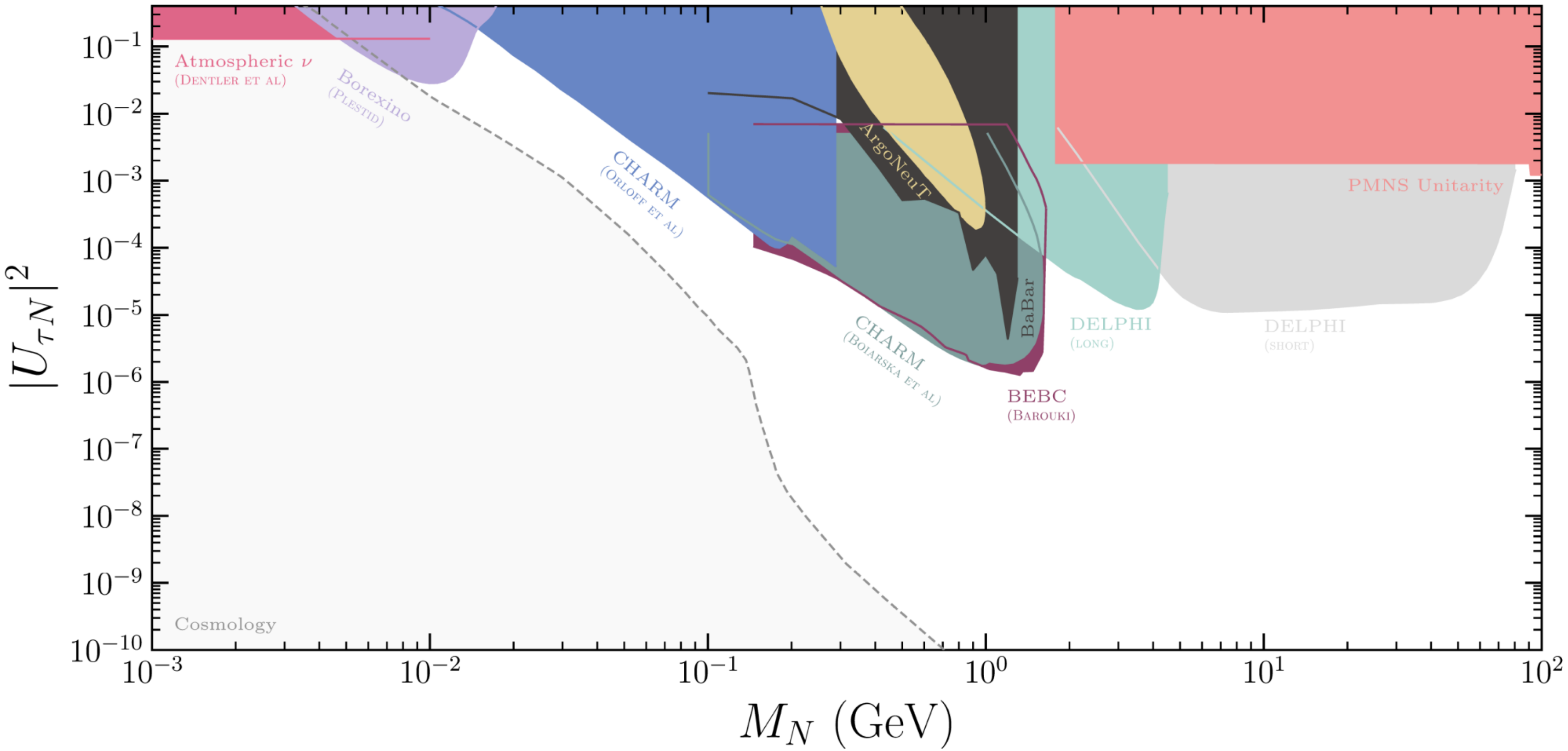

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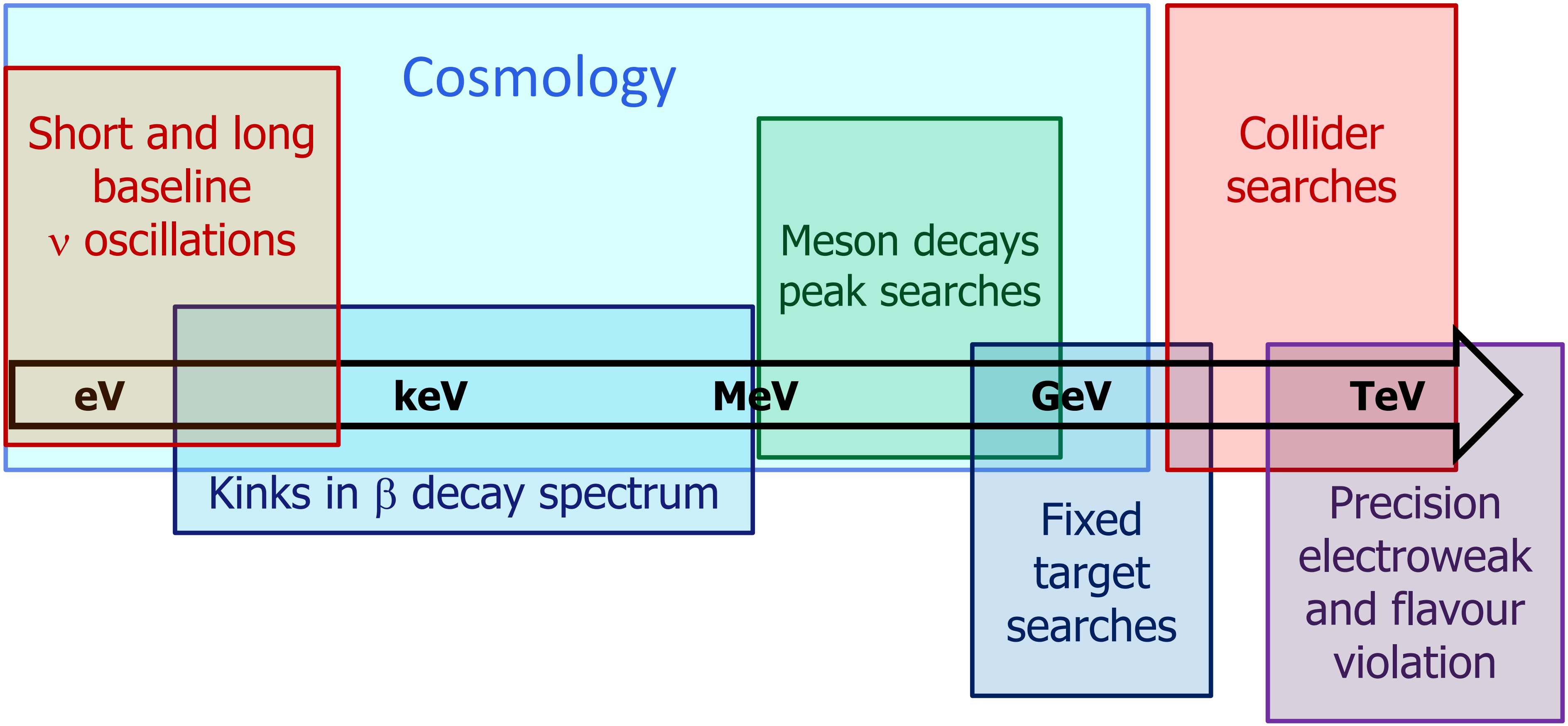
Looking for N_R

And beyond mixing, HNLs interactions through EFT (νSMEFT):

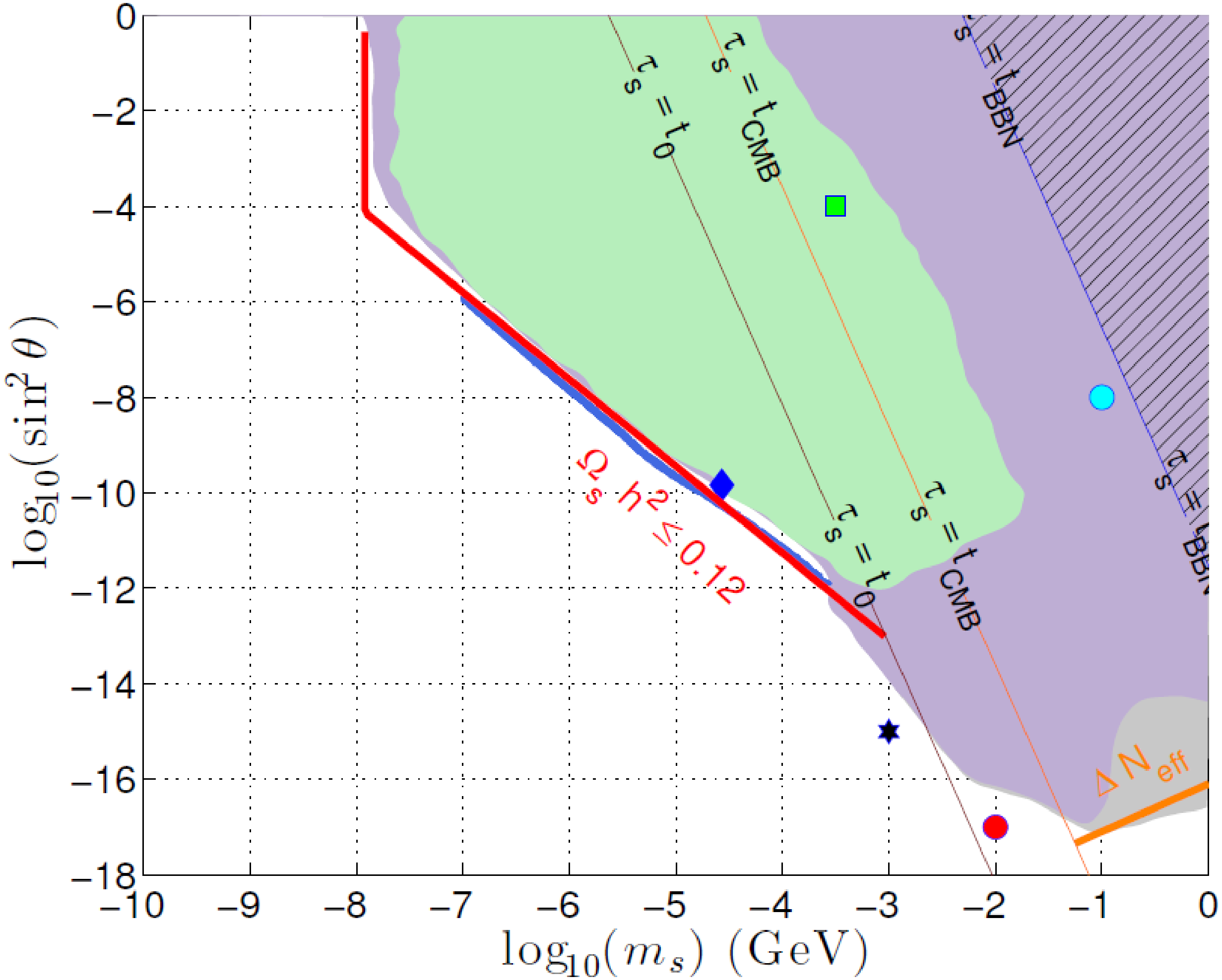
Type	Operator		Leading bounds	Ref.
H-dressed mass	$\mathcal{O}^{d=5}_{\text{Higgs}}$	$\overline{N^c}N\|H\|^2$	Higgs signal strength.	Eq. (3.4)
H-dressed mixing	$\mathcal{O}^{\alpha}_{\text{LNH}}$	$\overline{L_\alpha}\widetilde{H}N(H^\dagger H)$	Standard mixing, invisible H decays.	Fig. 2
Bosonic currents	$\mathcal{O}_{\text{HN}}$	$\overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$	Invisible Z decays, monophoton searches, SN1987A.	Fig. 3
	$\mathcal{O}^{\alpha}_{\text{HN}\ell}$	$\overline{N}\gamma^\mu \ell_\alpha(\widetilde{H}^\dagger i\overleftrightarrow{D}_\mu H)$	Decay-in-flight and peak searches for e and μ. PMNS unitarity and peak searches for τ.	Fig. 4
Moments	$\mathcal{O}^{\alpha}_{\text{NB}}$	$\left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\widetilde{H}B^{\mu\nu}$	Neutrino upscattering, monophoton searches.	Fig. 5
	$\mathcal{O}^{\alpha}_{\text{NW}}$	$\left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\tau^a\widetilde{H}W^{\mu\nu}_a$		Fig. 6
4-fermion NC	$\mathcal{O}_{\text{ff}}$	$(\overline{f}\gamma^\mu f)(\overline{N}\gamma_\mu N)$	Monophoton and monojet searches, SN1987A.	Fig. 7
	$\mathcal{O}^{\alpha}_{\text{LN}}$	$(\overline{L_\alpha}\gamma^\mu L_\alpha)(\overline{N}\gamma_\mu N)$		
	$\mathcal{O}_{\text{QN}}$	$(\overline{Q_i}\gamma^\mu Q_i)(\overline{N}\gamma_\mu N)$		Fig. 8
4-fermion CC	$\mathcal{O}^{\alpha\beta}_{\text{LNL}\ell}$	$(\overline{L_\alpha}N)\epsilon(\overline{L_\alpha}\ell_\beta)$	Monolepton searches, decay-in-flight and peak searches.	Fig. 9
	$\mathcal{O}^{\alpha}_{\text{duN}\ell}$	$\mathcal{Z}^{\text{duN}\ell}_{ij}(\overline{d_i}\gamma^\mu u_j)(\overline{N}\gamma_\mu \ell_\alpha)$		Fig. 10
	$\mathcal{O}^{\alpha}_{\text{LNQd}}$	$\mathcal{Z}^{\text{LNQd}}_{ij}(\overline{L_\alpha}N)\epsilon(\overline{Q_i}d_j)$		Fig. 11
	$\mathcal{O}^{\alpha}_{\text{QuNL}}$	$\mathcal{Z}^{\text{QuNL}}_{ij}(\overline{Q_i}u_j)(\overline{N}L_\alpha)$		Fig. 12

EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2304.06772
https://github.com/mhostert/Heavy-Neutrino-Limits

A new physics scale



Cosmology



A. C Vincent, EFM, P. Hernandez, M. Lattanzi and O. Mena arXiv:1408.1956
See also K. Langhoff, N. J. Outmezguine, and N. L. Rodd arXiv:2209.06216

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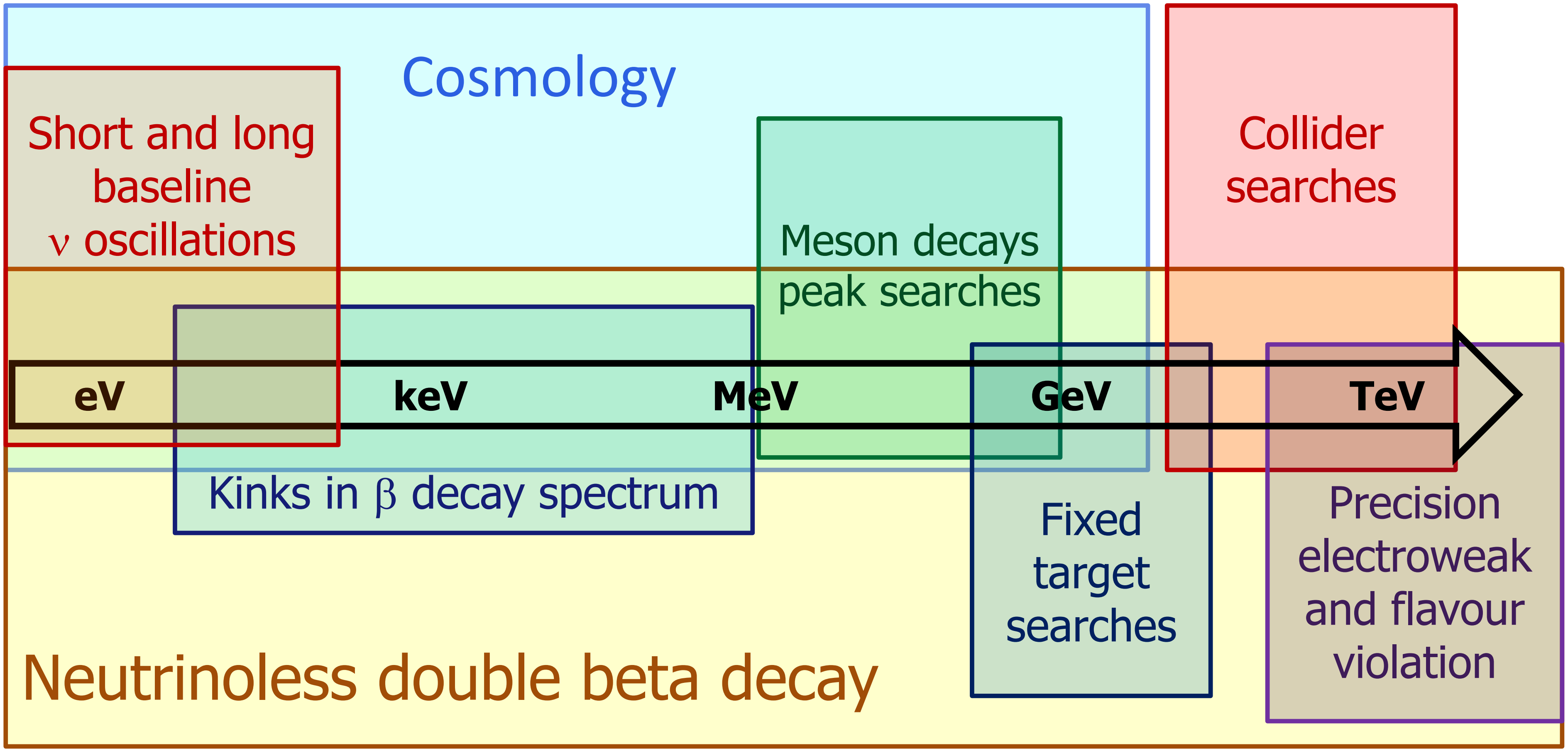
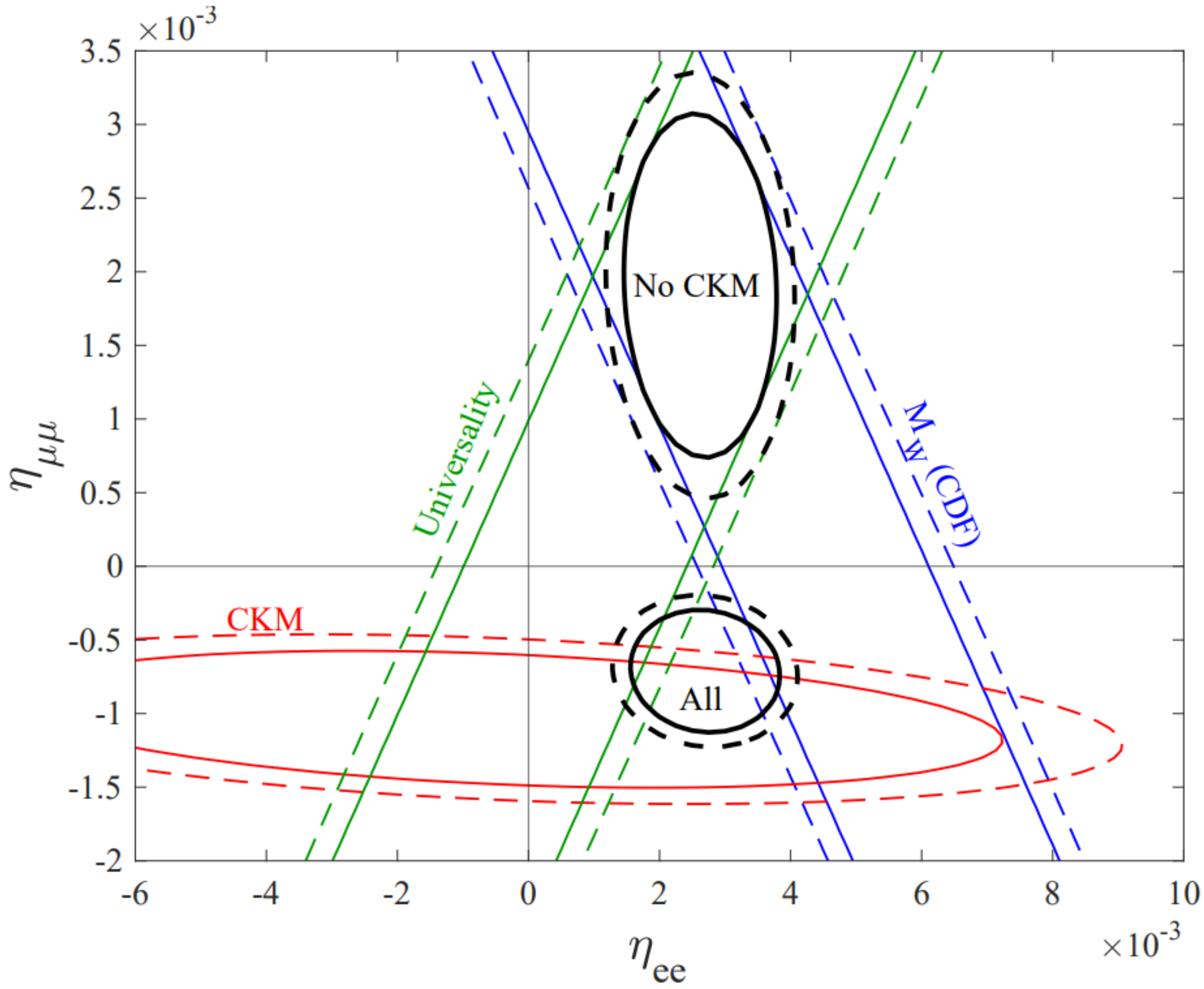


Conclusions

- Neutrino masses and mixings imply new BSM physics
- The simplest extension, right-handed neutrinos, already imply a lot of new phenomenology to search for:
  - Non-unitarity, searches at colliders, beam dumps, oscillations, cosmology, $0\nu\beta\beta$,...
- Also offers conexions to other open problems of the SM
  - Baryogenesis, Dark Matter, Flavour puzzle...

Non-unitarity and M_W from CDF



M. Blennow, P. Coloma, EFM, M-González-Lopez Phys.Rev.D 106 (2022) 7

Leptogenesis

This simplest SM extension may connect to other open problems:

Leptogenesis

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For a dynamical generation of the Baryon asymmetry, we need the 3 Sakharov conditions:

- B Violation
- C and CP Violation
- Deviation from thermal equilibrium

A. Sakharov 1967

Leptogenesis

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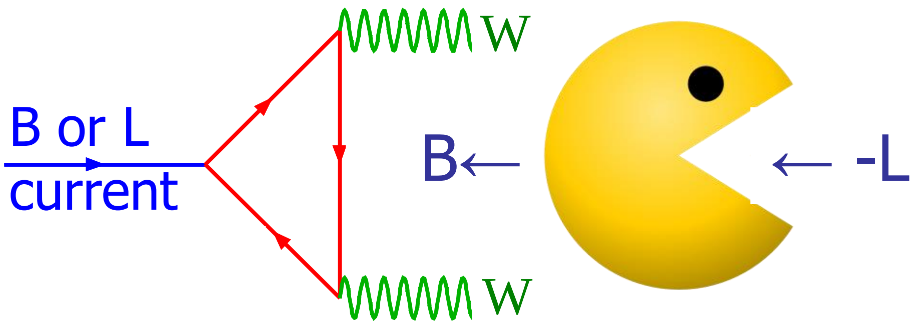

- C and CP Violation: CKM mixing

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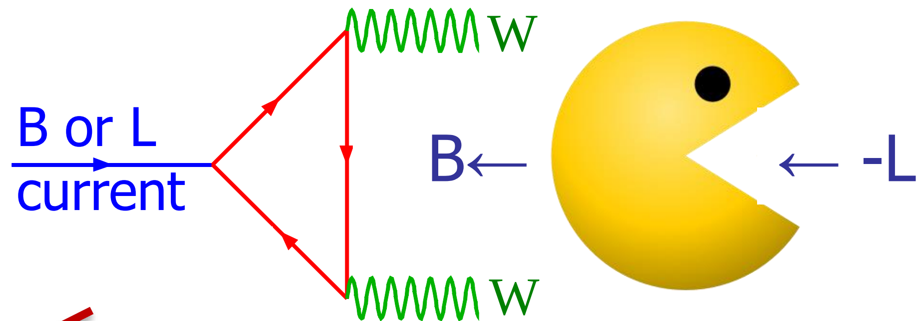

- C and CP Violation: ~~CKM mixing~~ $J = 2.8\cdot 10^{-5}$ too small!

  M. B. Gavela, P. Hernandez, M. Lozano, J. Orloff, O. Pene and C. Quimbay: hep-ph/9312215, 9406288, 9406289

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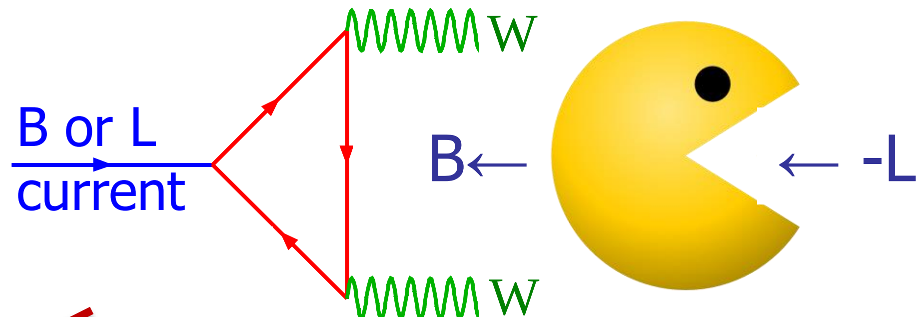

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- Deviation from thermal equilibrium: EW ~~phase transition~~

Not a 1st order pase transition, only crossover

K. Kajantie, M. Laine, K. Rummukainen and M. E. Shaposhnikov hep-ph/9605288

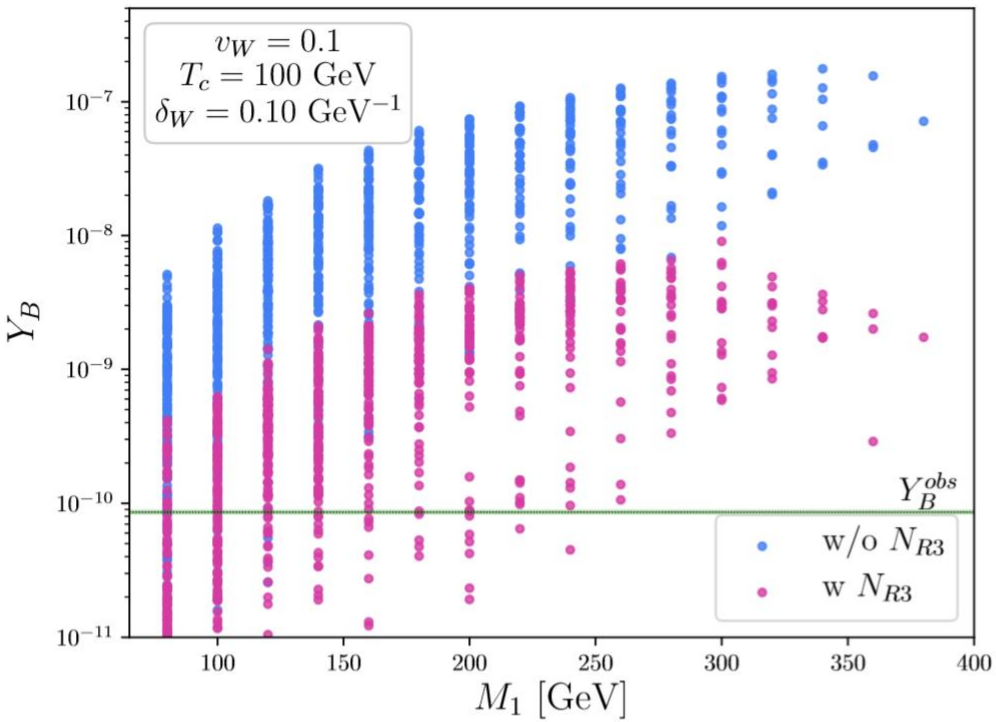
Links with other open problems: baryogenesis

If the low-E Seesaw mass is also dynamical:

$$Y_\nu \overline{N}_R \widetilde{H}^\dagger L_L + Y_N \overline{N}_R \phi N_L + V(\phi, H) \rightarrow m_D \overline{N}_R \nu_L + M_N \, \overline{N}_R N_L \, + V(\phi, H)$$

New sources of CPV in the Yukawas

and ϕ could induce a 1st order pase transition:



Present bounds on the heavy-active mixing allow for enough CPV to generate the Baryon assymmetry if the vev profile during the phase transition is favourable

EFM, J. López-Pavón, T. Ota, S. Rosauro-Alcaraz 2007.11008

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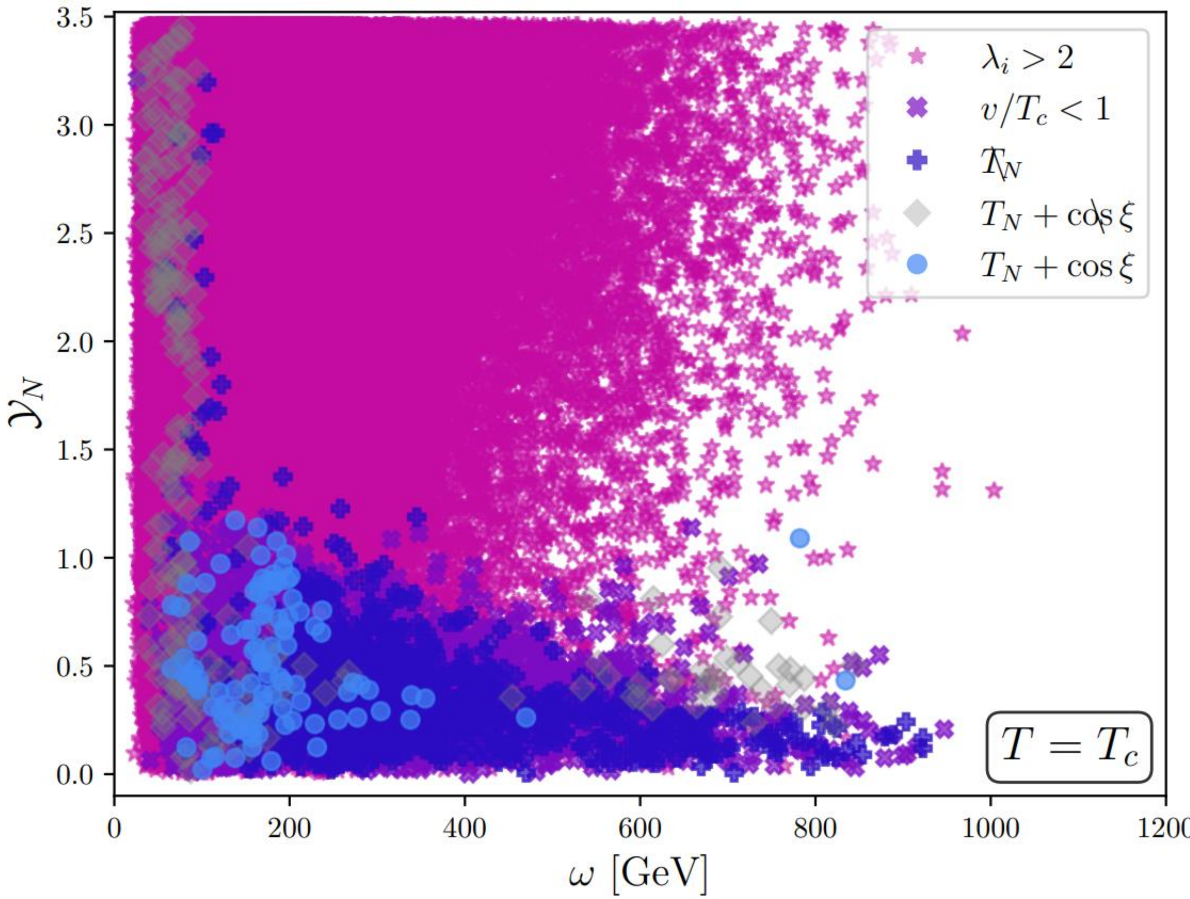

perturbativity
strong EWPT (sphalerons decouple)
nucleation
collider searches
OK

Might be difficult to obtain the necessary vev profiles during the phase transition in agreement with scalar sector bounds.

EFM, J. López-Pavón, J.M. No, T. Ota, S. Rosauro-Alcaraz 2210.16279

Links with other open problems: baryogenesis

EFM, J. López-Pavón, J.M. No, T. Ota, S. Rosauro-Alcaraz 2210.16279

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The return of the baryons?

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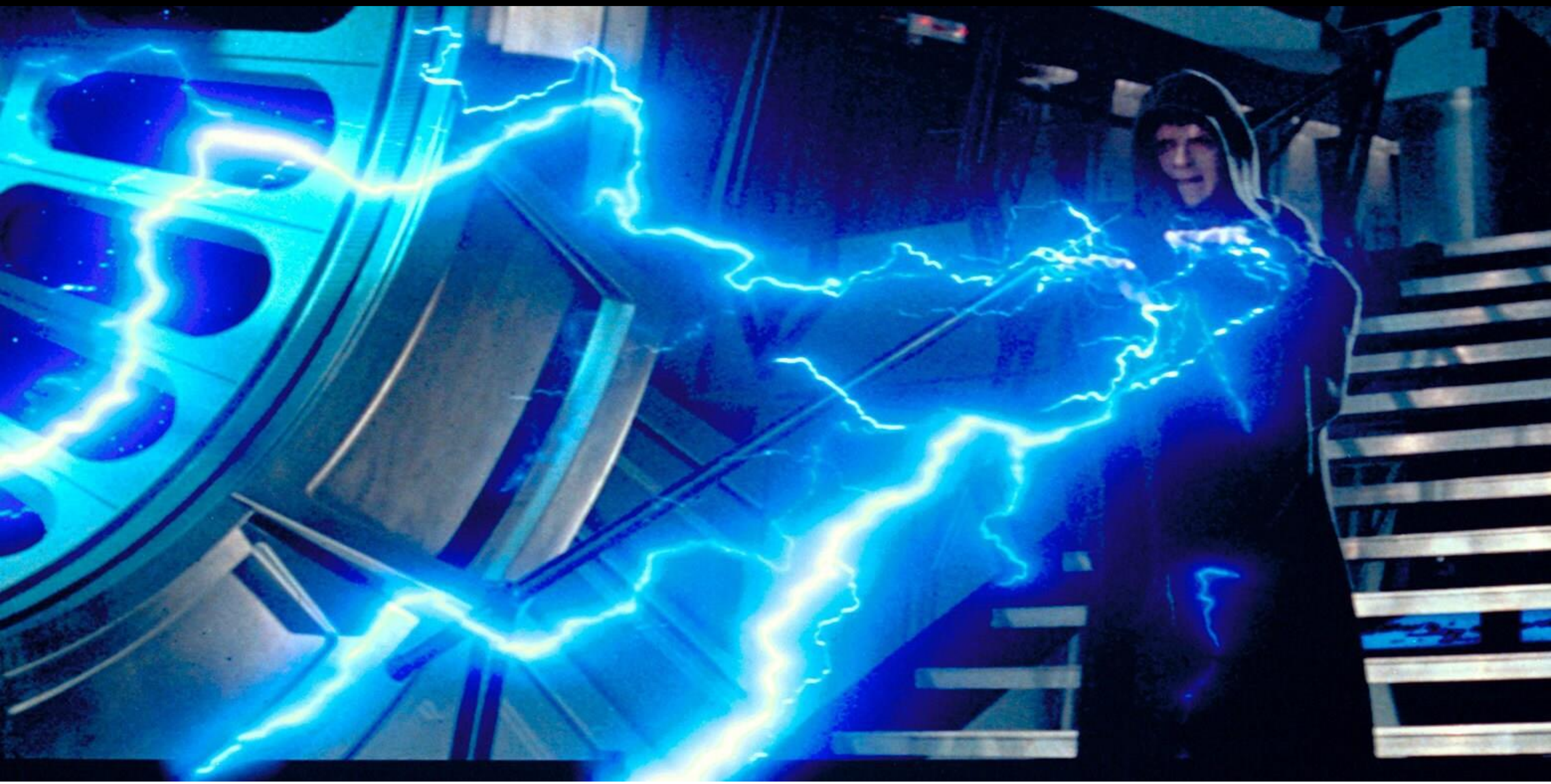

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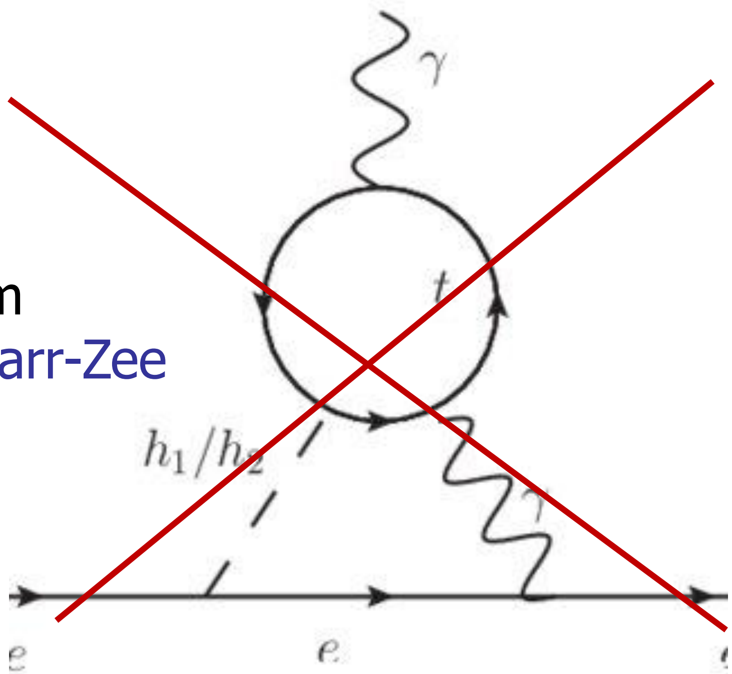
No edm from Barr-Zee



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EFM, J. López-Pavón, T. Ota, S. Rosauro-Alcaraz 2007.11008

Looking for N_R: Non-Unitarity

Or $N=(1-\alpha)\cdot U_{PMNS}$ with $(1-\alpha)=U_{36}U_{26}U_{16}U_{35}U_{25}U_{15}U_{34}U_{24}U_{14}$

$$\alpha \simeq \begin{pmatrix} \frac{1}{2}\left(s_{14}^2+s_{15}^2+s_{16}^2\right) & 0 & 0 \\ \hat{s}_{14}\hat{s}_{24}^*+\hat{s}_{15}\hat{s}_{25}^*+\hat{s}_{16}\hat{s}_{26}^* & \frac{1}{2}\left(s_{24}^2+s_{25}^2+s_{26}^2\right) & 0 \\ \hat{s}_{14}\hat{s}_{34}^*+\hat{s}_{15}\hat{s}_{35}^*+\hat{s}_{16}\hat{s}_{36}^* & \hat{s}_{24}\hat{s}_{34}^*+\hat{s}_{25}\hat{s}_{35}^*+\hat{s}_{26}\hat{s}_{36}^* & \frac{1}{2}\left(s_{34}^2+s_{35}^2+s_{36}^2\right) \end{pmatrix}$$

Triangular structure more convinient for oscillations

Z.-z. Xing 0709.2220 and 1110.0083.
F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1503.08879.

Dictionary

$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \eta_{ee} & 0 & 0 \\ 2\eta_{e\mu}^* & \eta_{\mu\mu} & 0 \\ 2\eta_{e\tau}^* & 2\eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{ee} = -\alpha_{ee} \qquad \epsilon_{\mu\mu} = \alpha_{\mu\mu} \qquad \epsilon_{\tau\tau} = \alpha_{\tau\tau}$$

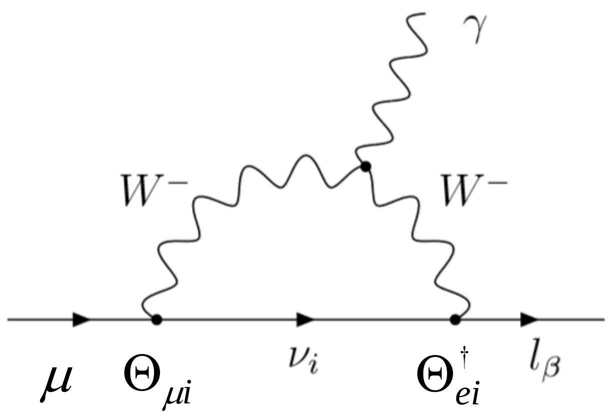
$$\epsilon_{\beta\alpha}^{s*} = \epsilon_{\alpha\beta}^{d} = -\alpha_{\alpha\beta}$$

$$\epsilon_{e\mu} = \frac{1}{2}\alpha_{\mu e}^* \qquad \epsilon_{e\tau} = \frac{1}{2}\alpha_{\tau e}^* \qquad \epsilon_{\mu\tau} = \frac{1}{2}\alpha_{\tau\mu}^*$$

M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637

Probing the Seesaw: Non-Unitarity

All constraints are for the limit of very heavy extra neutrinos
OK for all processes except maybe the loop LFV



Cancellations of these diagrams explored in:
D.V. Forero, S. Morisi,
M. Tortola, J.W.F. Valle 1107.6009

$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\, f\left(\frac{M_i^2}{M_W^2}\right)$$

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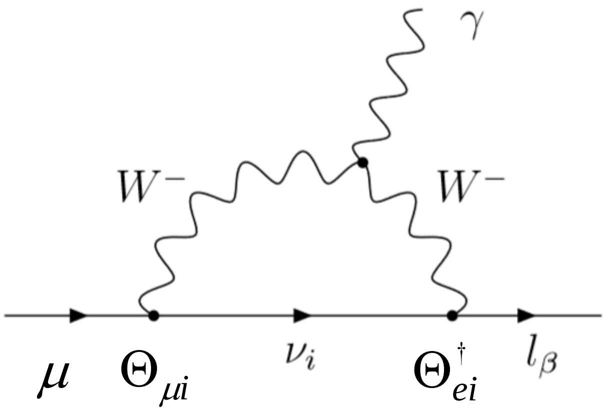

$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\, f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu}\, f(\infty) + \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\left(f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty)\right)$$

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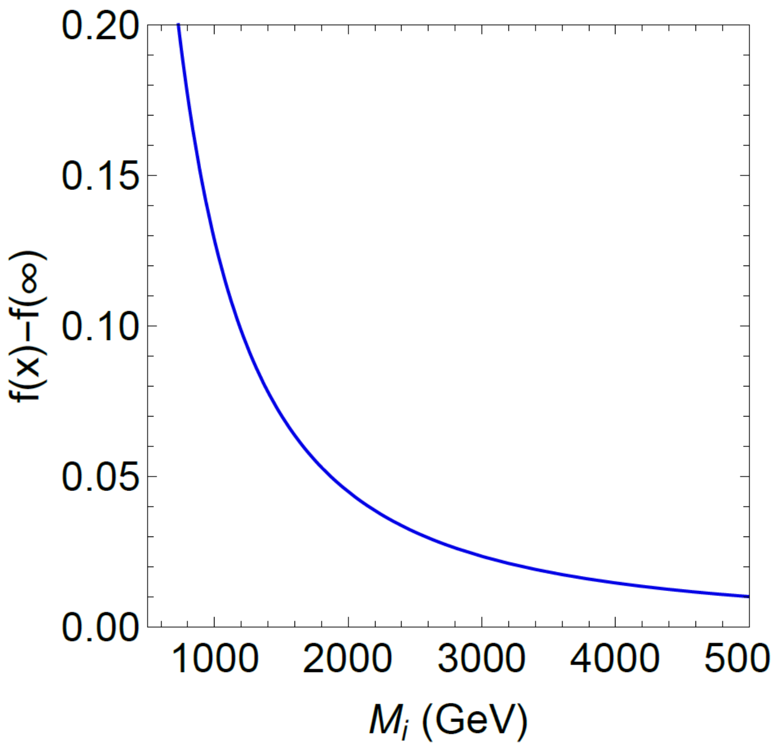

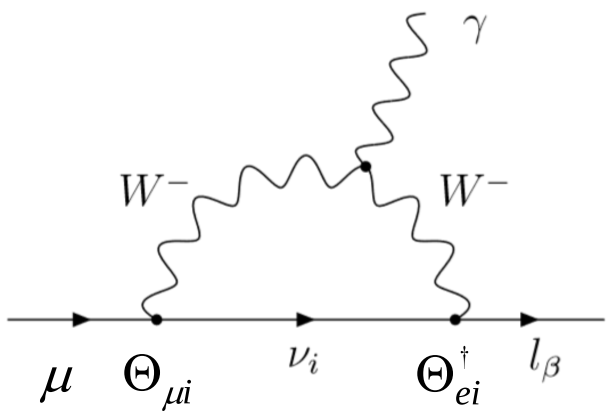

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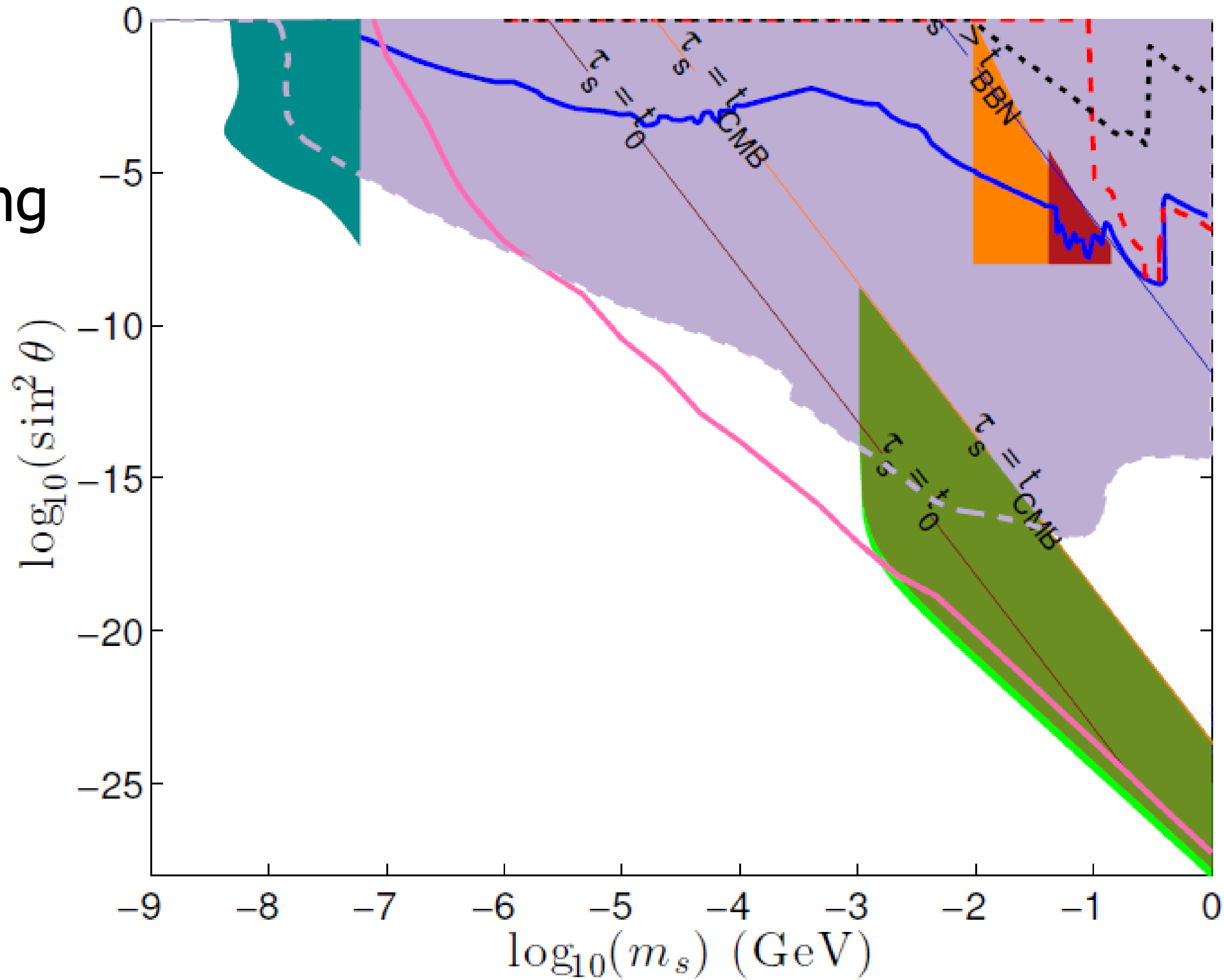
Cosmology and lab constraints

At intermediate scales very strong constraints from direct searches and cosmology



A. C Vincent, EFM, P. Hernandez, M. Lattanzi and O. Mena arXiv:1408.1956

Non-unitarity in oscillations

Just replace U by N

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

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The "zero distance effect" will also be present in the data used to estimate the flux and cross section

Non-unitarity in oscillations

The real observable is the number of events

The measured probability $\hat{P}_{\mu e}(L)$ is the ratio of the events over the prediction from the flux and cross section in absence of oscillations

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For instance, if the prediction for $P_{\mu e}$ comes from near detector data on $P_{\mu\mu}$:

$$\hat{P}_{\mu e}(L) = \frac{P_{\mu e}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{ei} N^*_{\mu i} N_{\mu j} N^*_{ej} e^{\frac{-\Delta m^2_{ij} L}{2E}}}{\left|\left(NN^\dagger\right)_{\mu\mu}\right|^2}$$

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The measured probability $\hat{P}_{\mu e}(L)$ is the ratio of the events over the prediction from the flux and cross section in absence of oscillations

For instance, if the prediction for $P_{\mu e}$ comes from near detector data on $P_{\mu\mu}$:

$$\hat{P}_{\mu e}(L) = \frac{P_{\mu e}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{ei} N^*_{\mu i} N_{\mu j} N^*_{ej} e^{\frac{-\Delta m^2_{ij} L}{2E}}}{\left|\left(NN^\dagger\right)_{\mu\mu}\right|^2}$$

Notice that, in general, this is different to normalizing as

$$|\nu_\alpha\rangle = \frac{N_{\alpha i}|\nu_i\rangle}{\sqrt{\left(NN^\dagger\right)_{\alpha\alpha}}}$$

M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Non-unitarity in oscillations

Also, no zero distance effect in disappearance channles!!

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At most, if the prediction comes from a different channel, one may constrain the ratio

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But these are more efficiently constraint from LFU bounds, from instance π decay ratios, no need to also detect the ν…

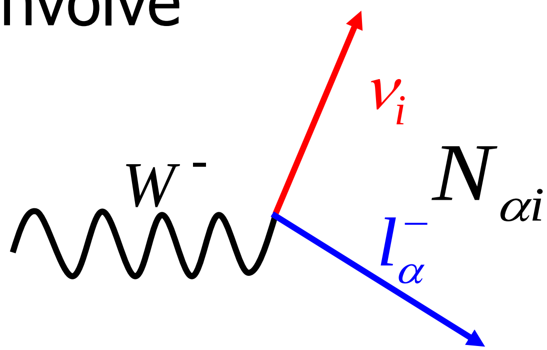
Looking for N_R: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

But they all involve



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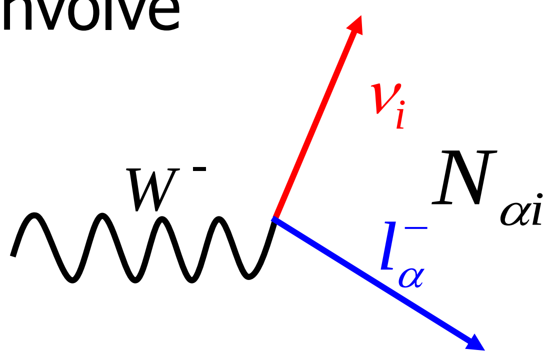

it's where the sensitivity comes from…

So they are all equally "direct" and they all have a neutrino and a charged lepton…

Looking for N_R: Non-Unitarity

Which one is more robust/model-independent?

"Indirect" or "charged leptons"

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"Indirect" or "charged leptons"

G_F from μ decay compared to from M_W, measurements of $\sin\theta_w$ at different energies (Moller, colliders) and β and K decays. Very different physics!

"Direct" or "neutrinos"

Introducing an NSI operator with u and d quarks the zero distance effect could be cancelled
They also come from zero-distance effect…

But in the literature the "neutrino" bounds are assumed to be more robust…

Non-Unitarity vs oscillations

It has become common to call them:

"Indirect" or "charged leptons" "Direct" or "neutrinos"

	"flavor+electroweak" $m >$ EW (2σ limit)	Oscillations (from zero distance effects in disappearance, 90%)
α_{ee}	$1.4 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$ [55]
$\alpha_{\mu\mu}$	$1.4 \cdot 10^{-4}$	$5.0 \cdot 10^{-3}$ [15]
$\alpha_{\tau\tau}$	$8.8 \cdot 10^{-4}$	$6.5 \cdot 10^{-2}$ [56]
$\lvert\alpha_{\mu e}\rvert$	$7.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$9.2 \cdot 10^{-3}$
$\lvert\alpha_{\tau e}\rvert$	$1.8 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$4.8 \cdot 10^{-4}$	$1.1 \cdot 10^{-2}$

From C. Argüelles et al Snowmass Whitepaper arXiv:2203.10811 and M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon in preparation

A new physics scale

Short and long baseline
ν oscillations

eV

keV

MeV

GeV

TeV

Precision electroweak and flavour violation

If light enough the new sterile neutrinos will be produced and participate in oscillation processes.

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637
C. S. Fong, H. Minakata and H. Nunokawa arXiv:1609.08623

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"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}} + \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}} + \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637
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$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}}$$

$$\cancel{+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}}$$

If $\frac{\Delta m^2_{ij} L}{2E} \gg 1$ oscillations too fast to resolve and only see average effect

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637
C. S. Fong, H. Minakata and H. Nunokawa 1609.08623

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$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m_{IJ}^2 L}{2E}}$$

At leading order "heavy" non-unitarity and avergaed-out "light" steriles have the same impact in oscillations

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Non-Unitarity vs oscillations

Bounds from a global fit to flavour and Electroweak precision data

	"flavor+electroweak" $m >$ EW (2σ limit)	Oscillations (from zero distance effects in disappearance, 90%)
α_{ee}	$1.4 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$ [55]
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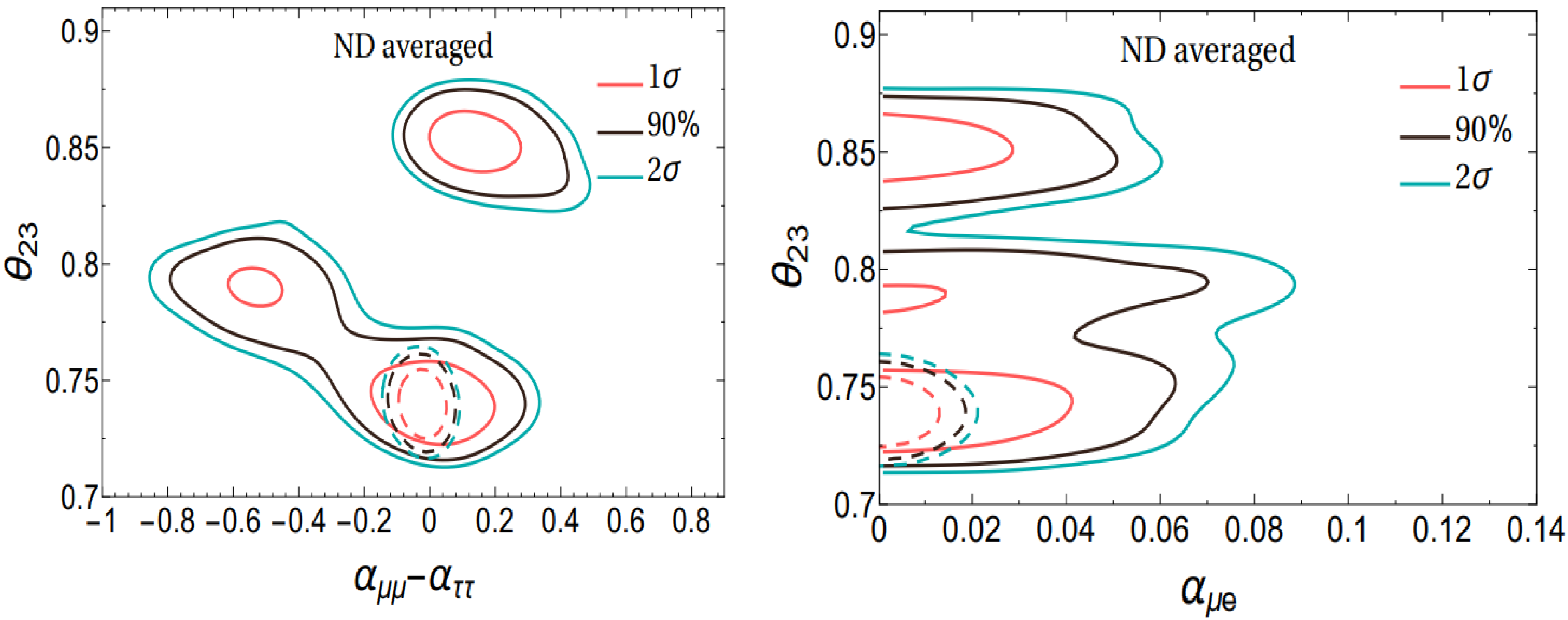
$\lvert\alpha_{\tau e}\rvert$	$1.8 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$3.6 \cdot 10^{-4}$	$1.1 \cdot 10^{-2}$

From C. Argüelles et al Snowmass Whitepaper arXiv:2203.10811 and M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon in preparation

with

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ -\alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ -\alpha_{\tau e} & -\alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U$$

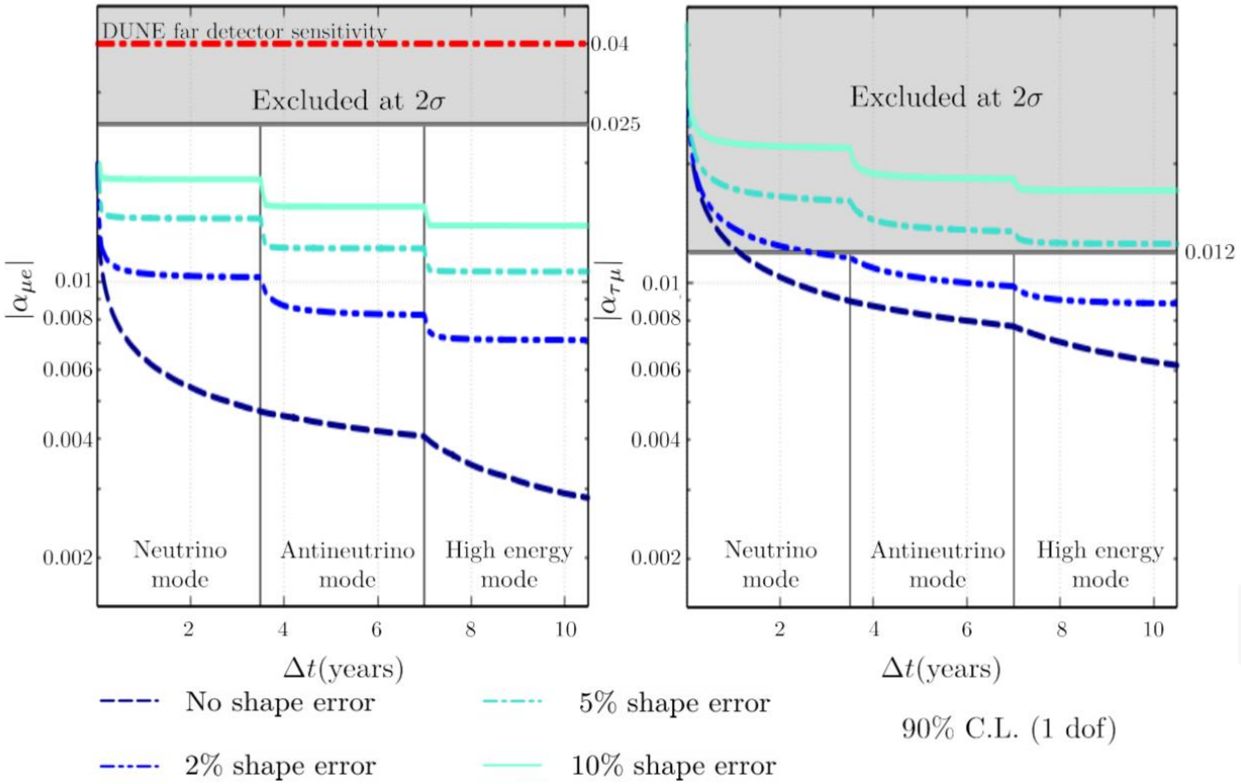
Non-unitarity at DUNE



The far detector would suffer from degeneracies but they are lifted with present bounds

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Non-unitarity at DUNE



The posible improvements by the near detector depend critically on the level of systematic uncertainties, particularly affecting the shape of the spectra

P. Coloma, J. Lopez-Pavon, S. Rosauro-Alcaraz and S. Urrea arXiv:2105.11466

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If $\frac{\Delta m^2_{ij} L}{2E} \ll 1$ at the near detector or in the data to estimate the flux and cross section, the zero distance effect is recovered and bounds apply