Seesaw mechanism in ν oscillations

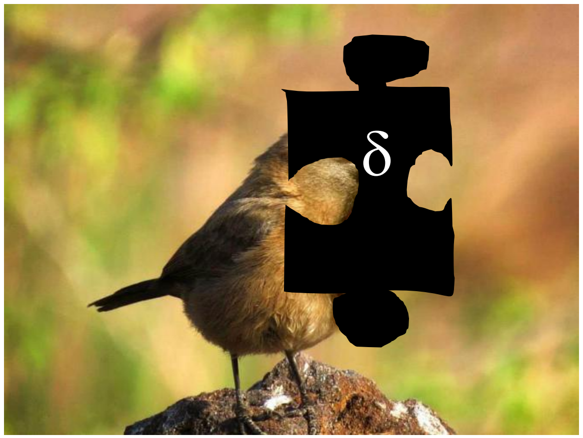
Enrique Fernández Martínez

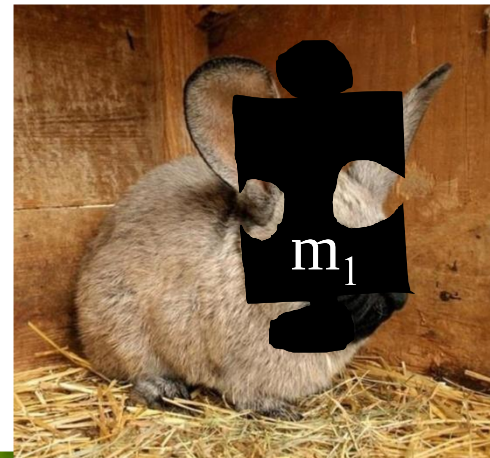
UNIVERSIDAD AUTONOMA DE MADRID

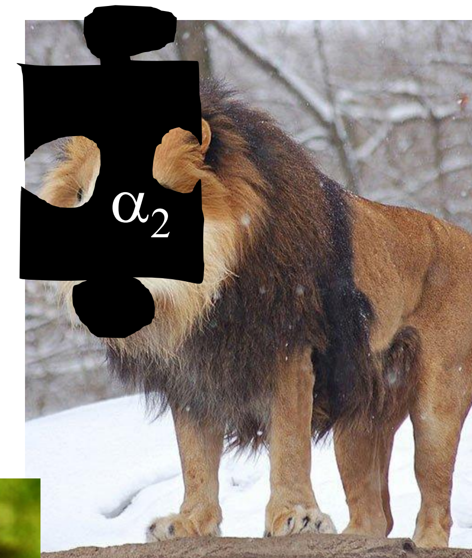
νProbes

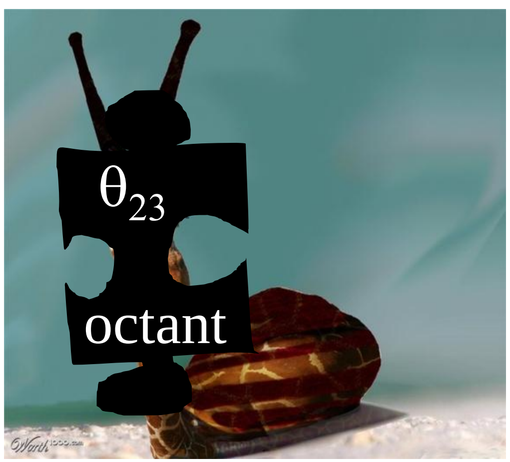
invisiblesPlus elusives

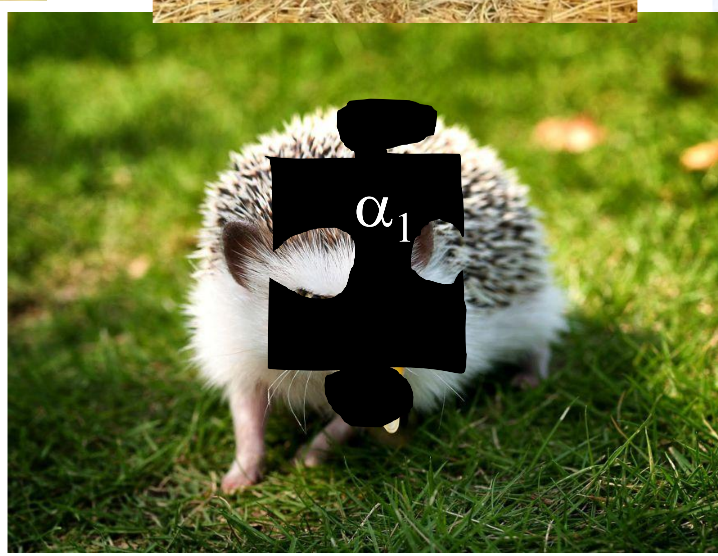
Neutrino physics missing pieces

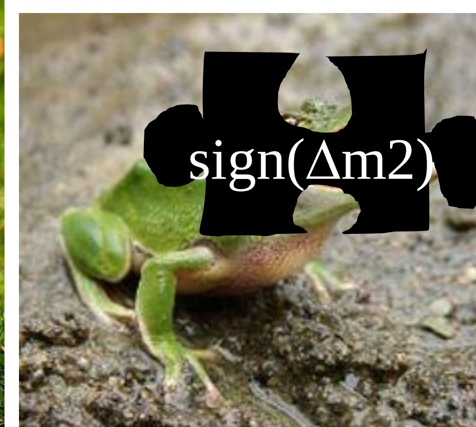












Neutrino physics missing pieces

Neutrino masses beyond the SM

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \, \overline{f_L} \phi f_R$$

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Simplest option add N_R: a Majorana mass is also allowed

$$M_N \overline{N}_R^C N_R$$

A new physics scale

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→ To be sought for at experiments!!

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

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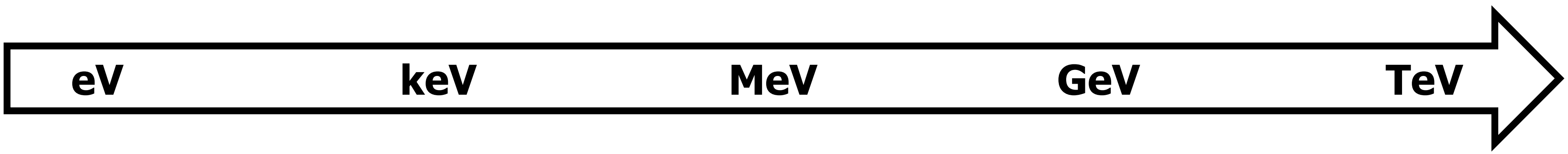

M_N could be anywhere…

A new physics scale

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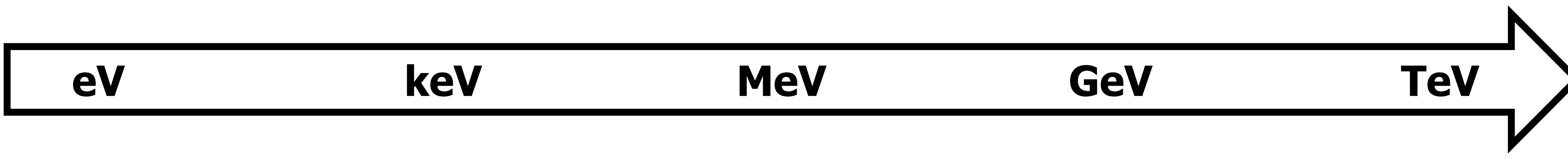
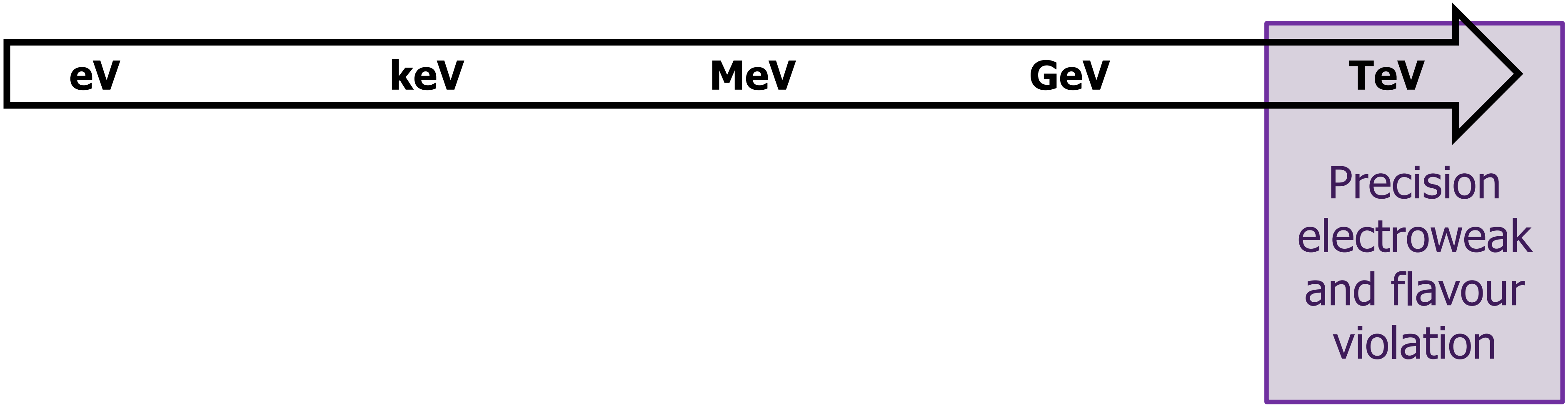


M_N could be anywhere…

Very different phenomenology at different scales

A new physics scale

See talk by Asmaa Abada



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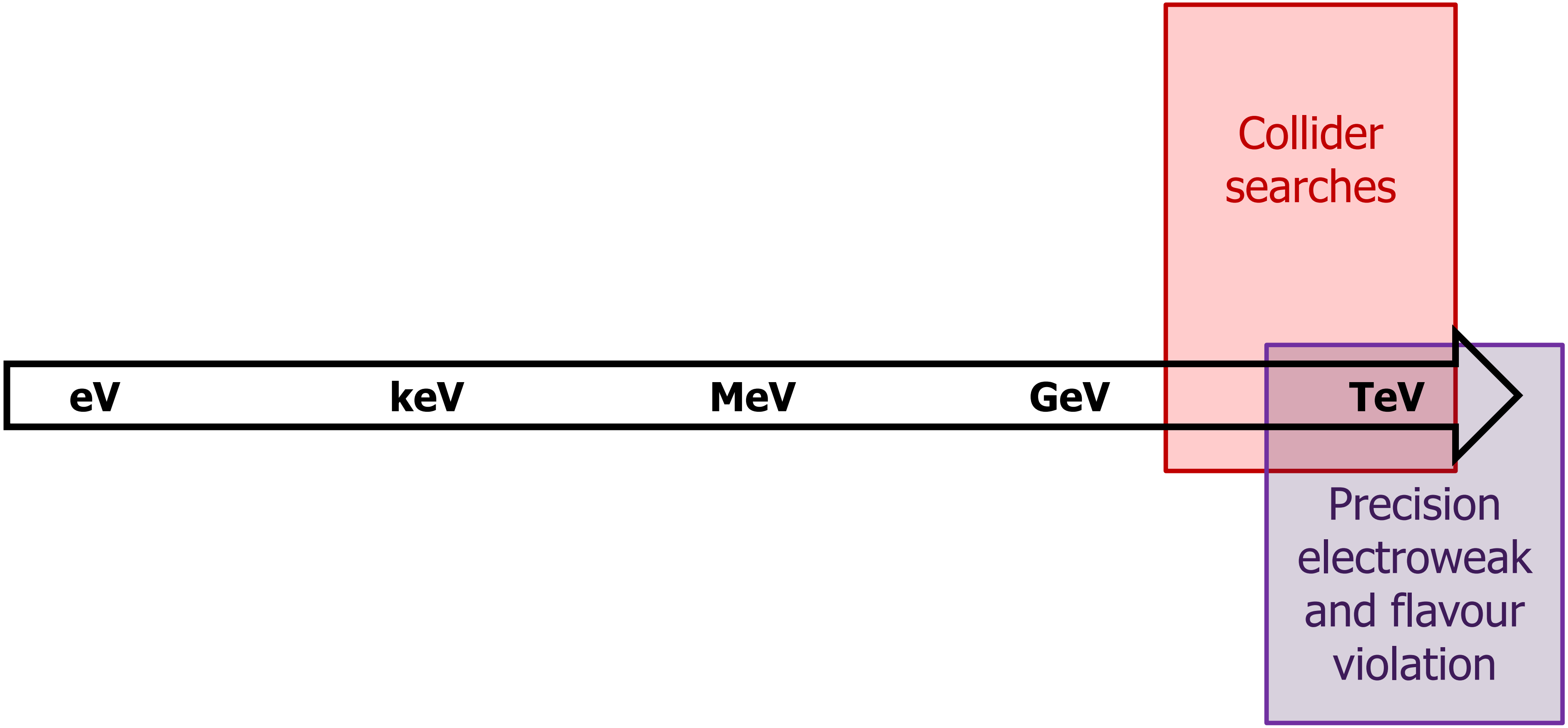

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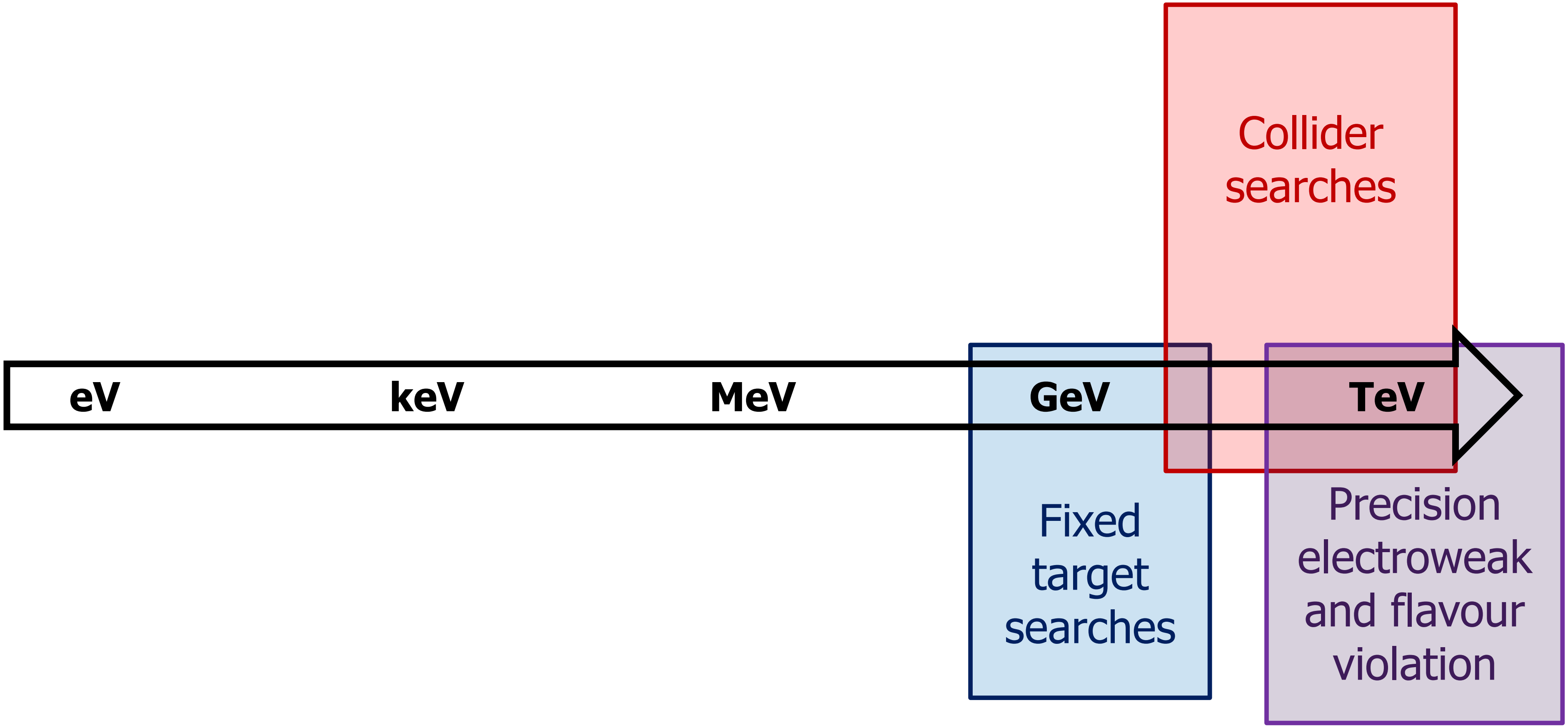

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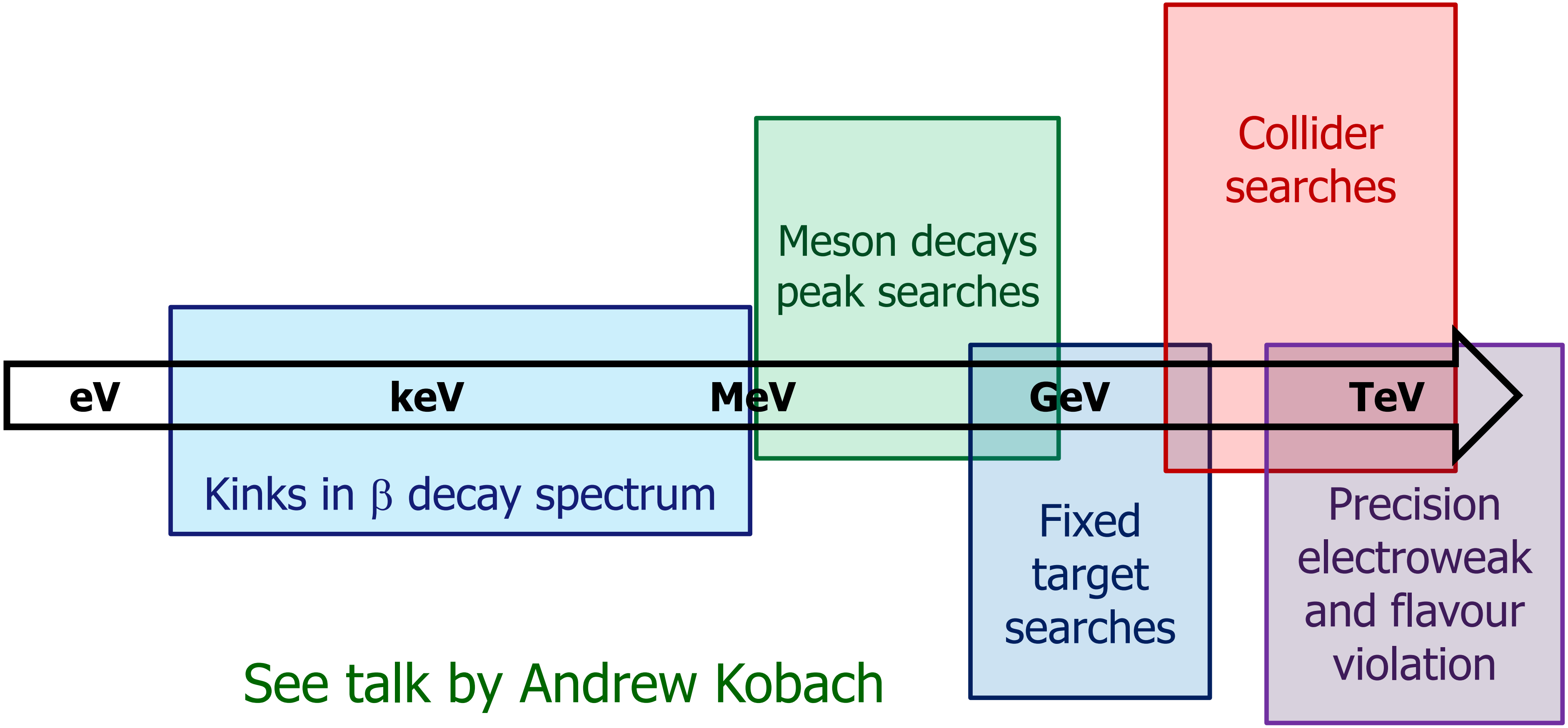

See talk by Andrew Kobach

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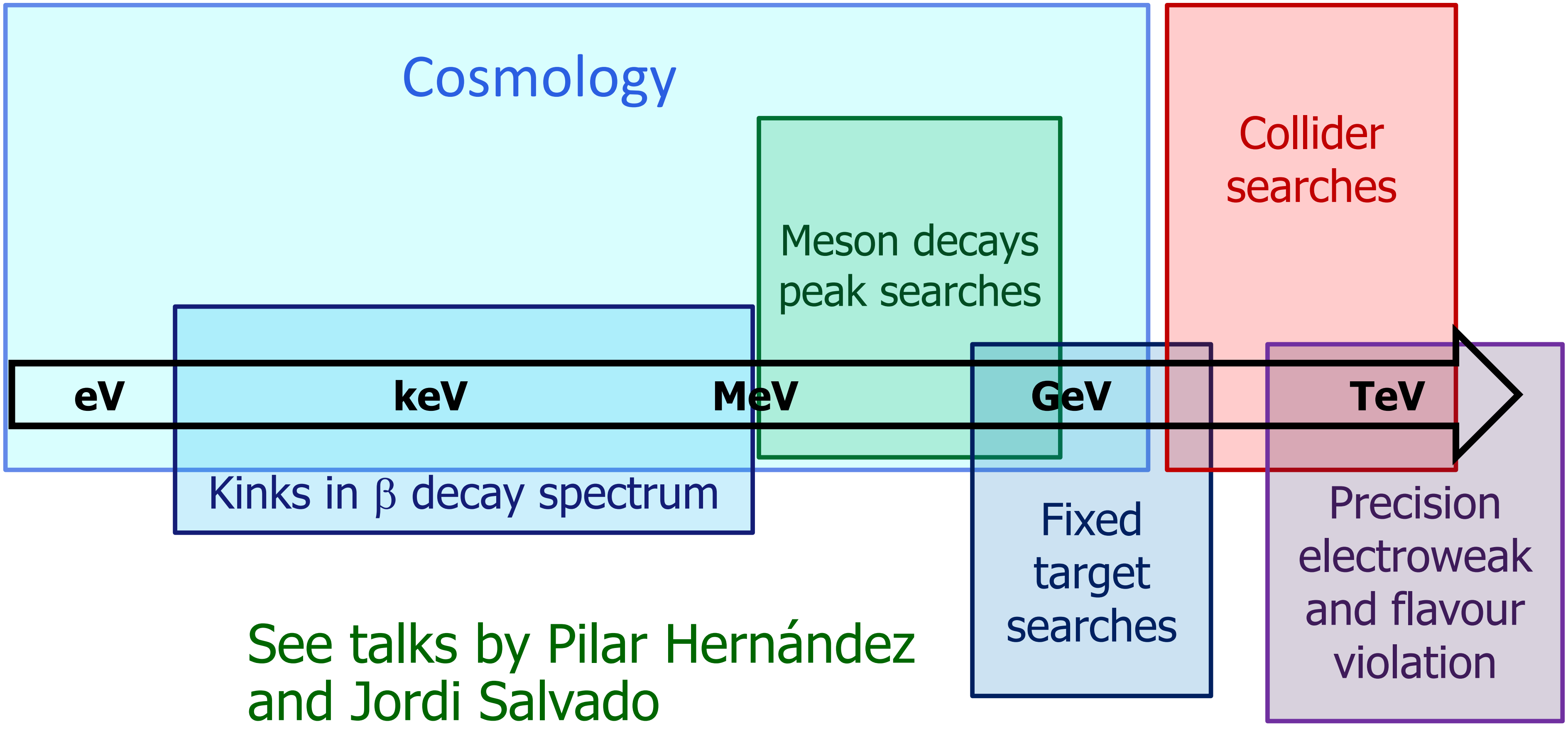
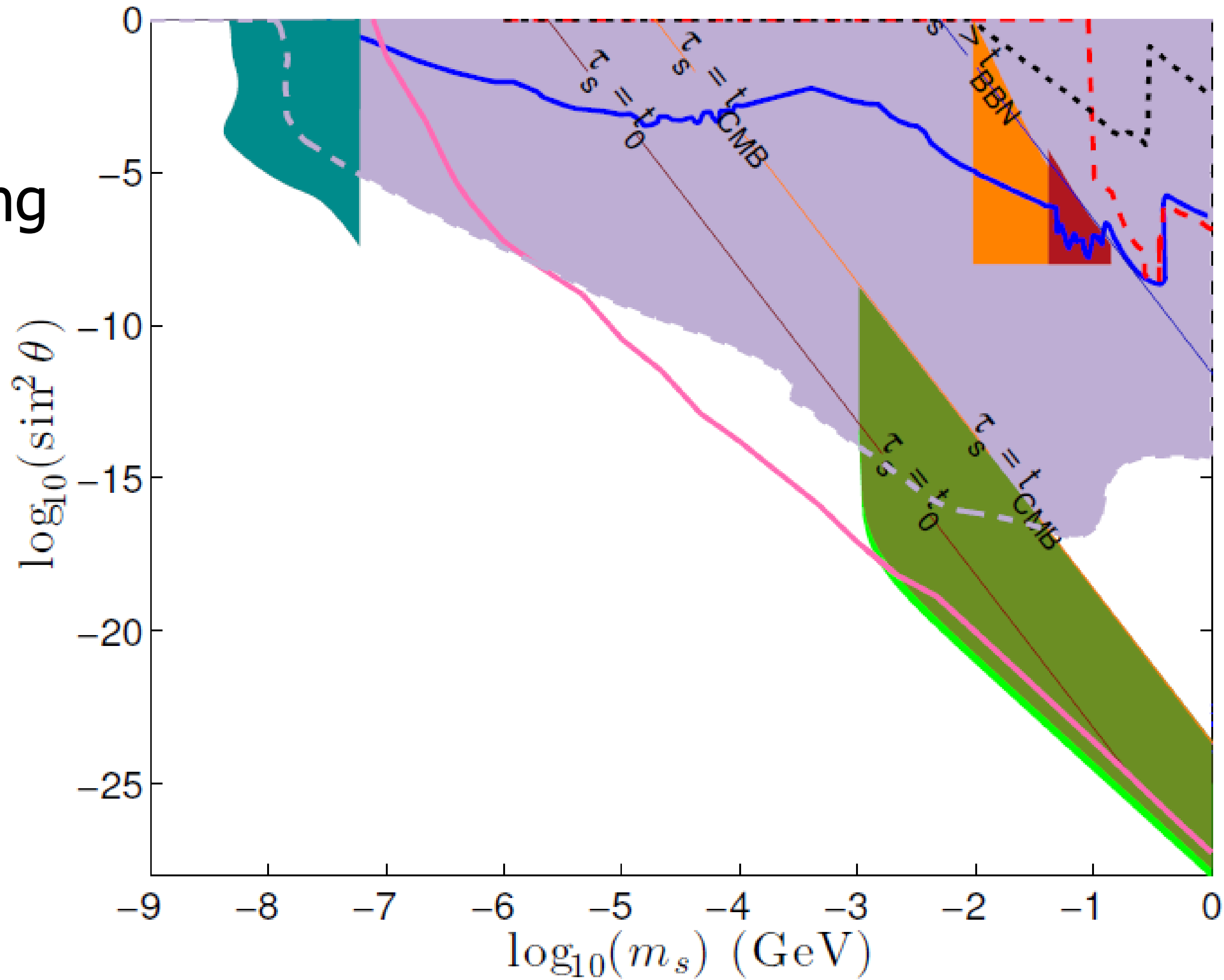


See talks by Pilar Hernández and Jordi Salvado

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

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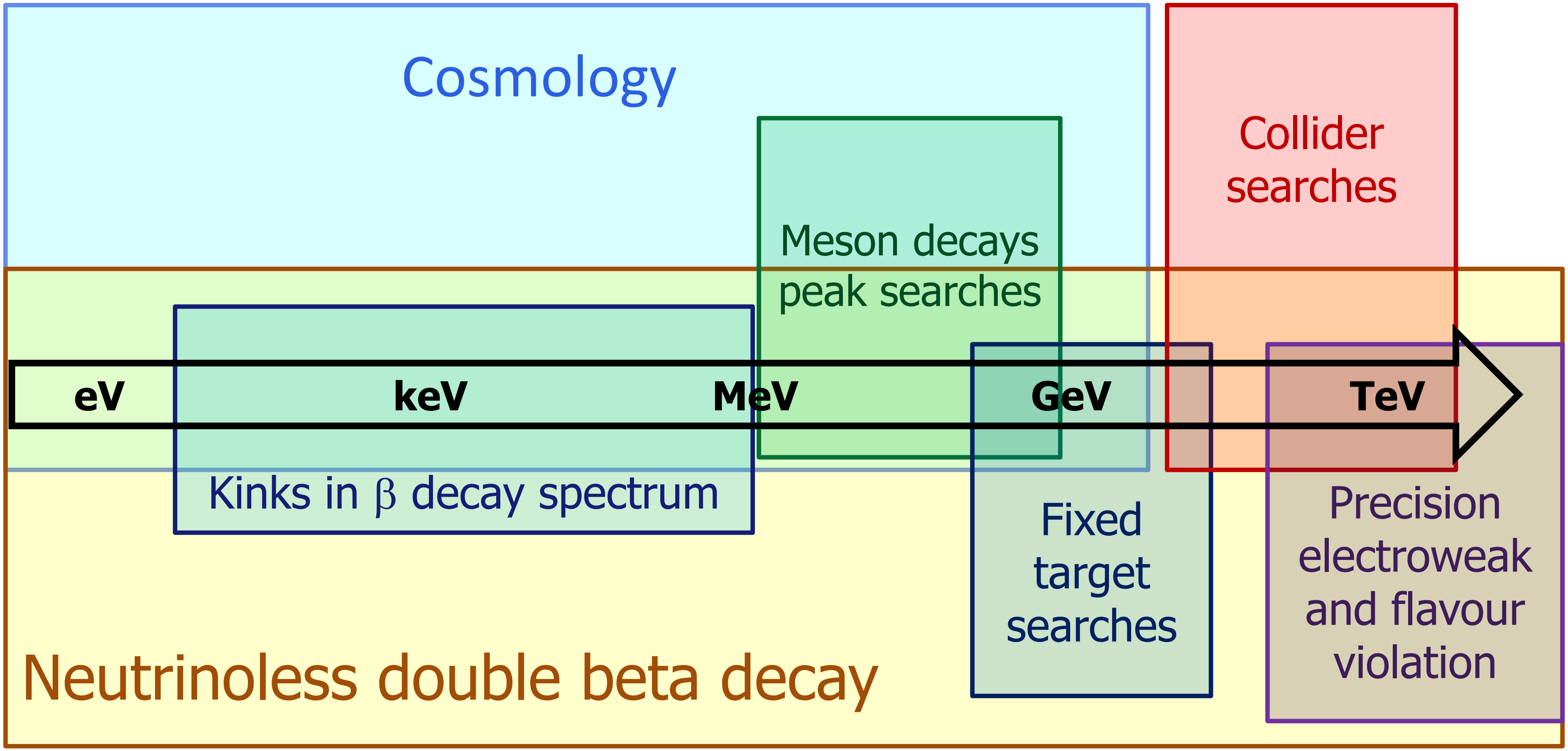

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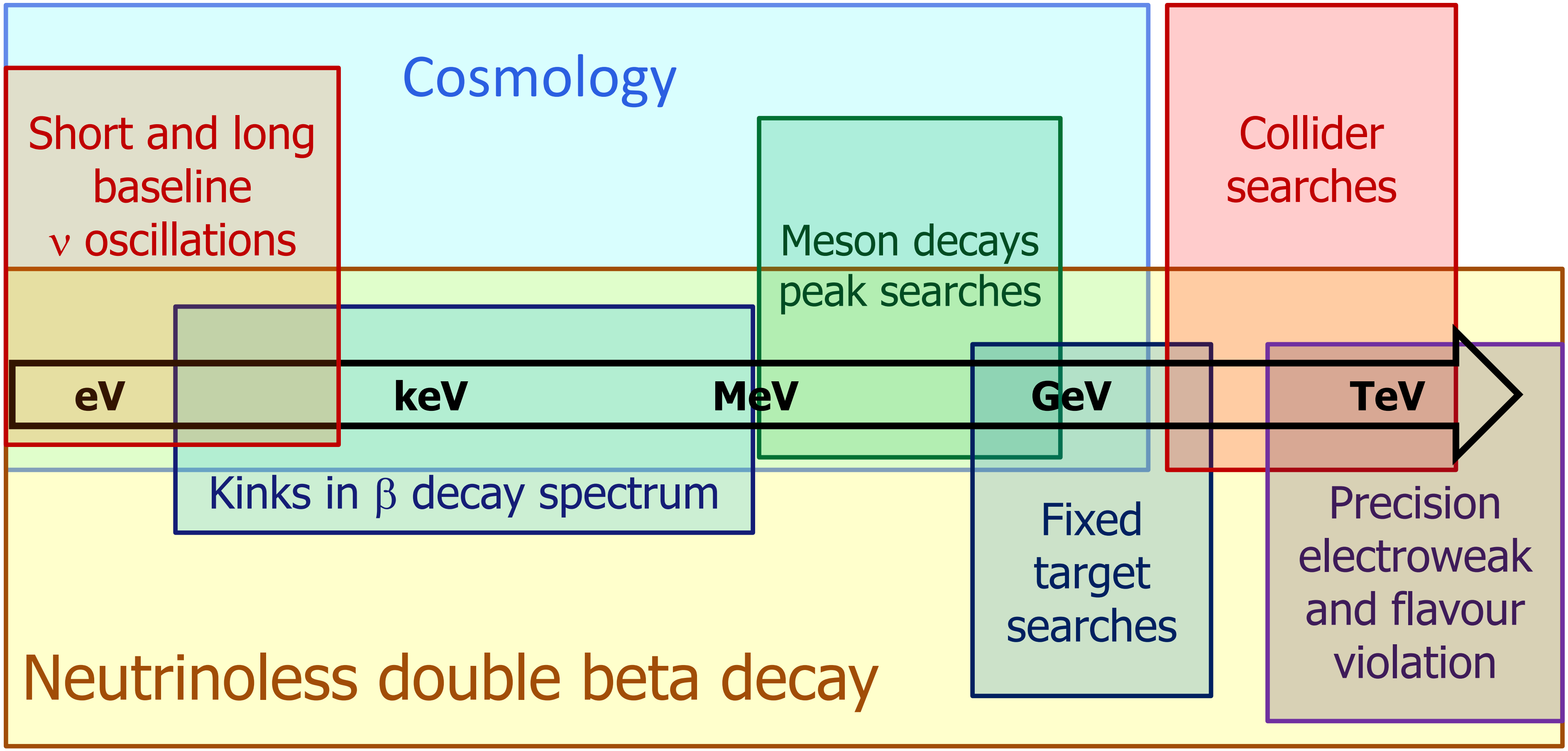

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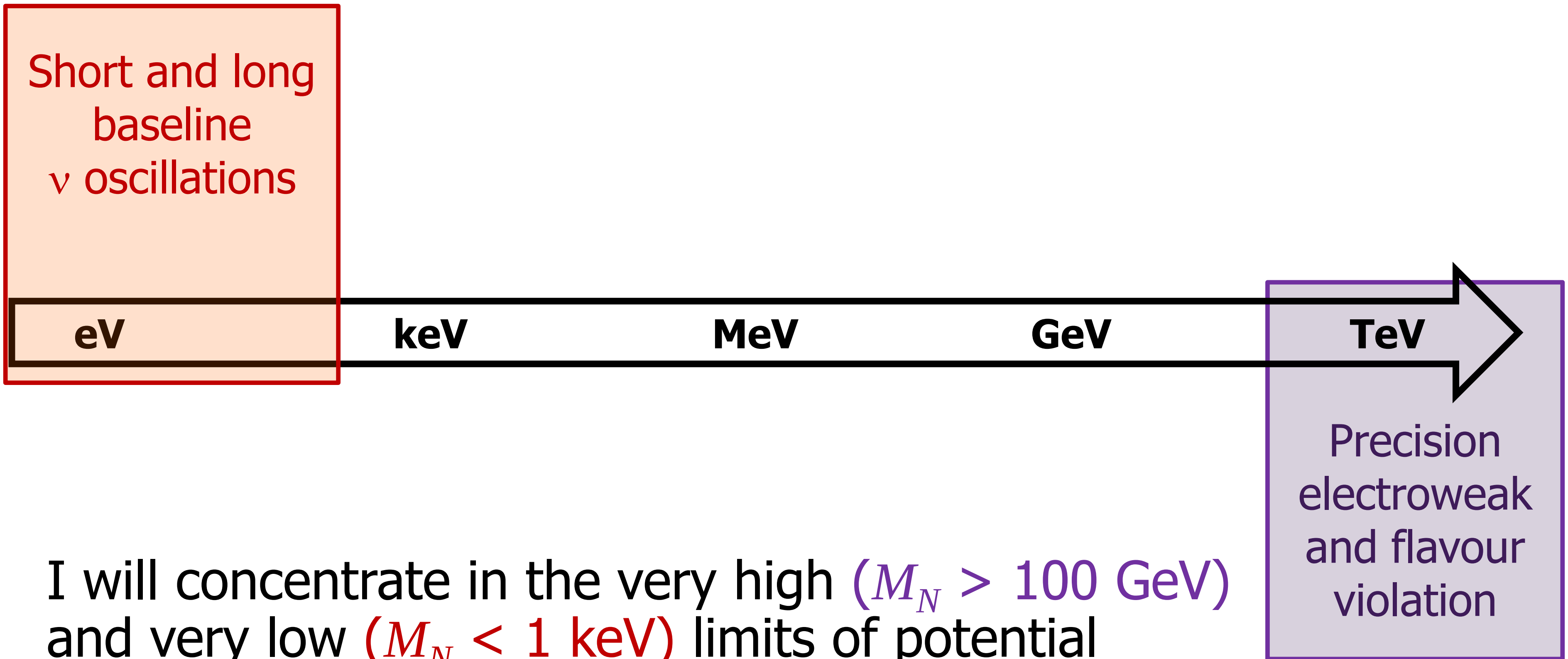

I will concentrate in the very high $(M_N > 100\ \mathrm{GeV})$ and very low $(M_N < 1\ \mathrm{keV})$ limits of potential interest for ν oscillations

Neutrino Oscillations

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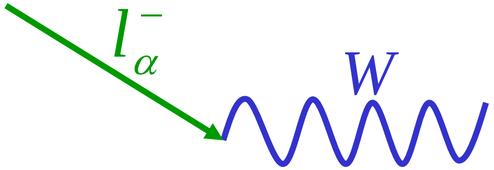

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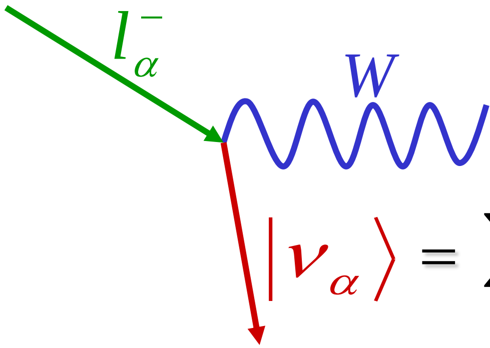

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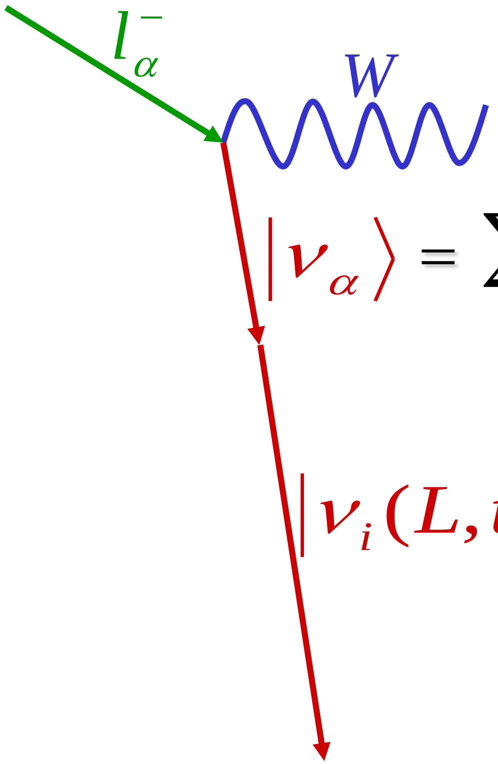

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$$|\nu_i(L,t)\rangle = e^{-i(E_i t - p_i L)} |\nu_i\rangle$$

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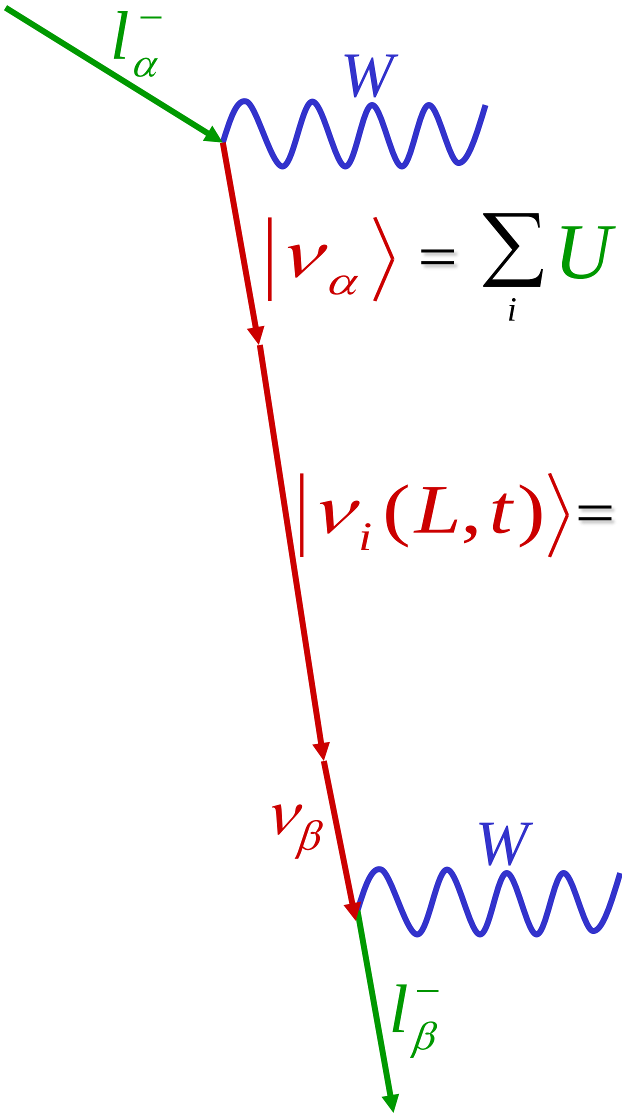

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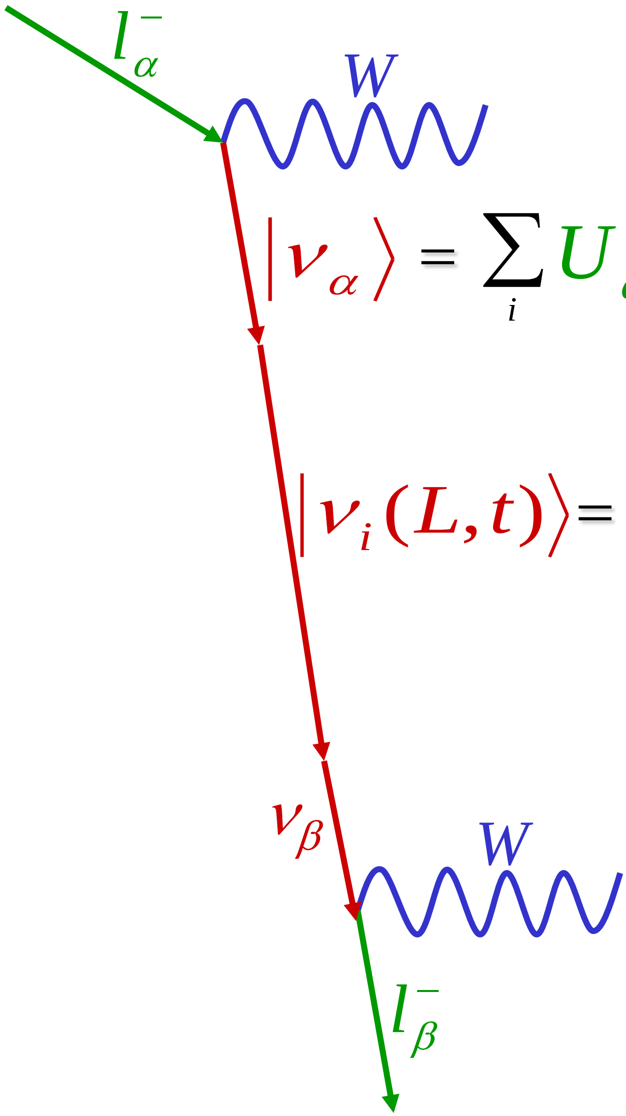

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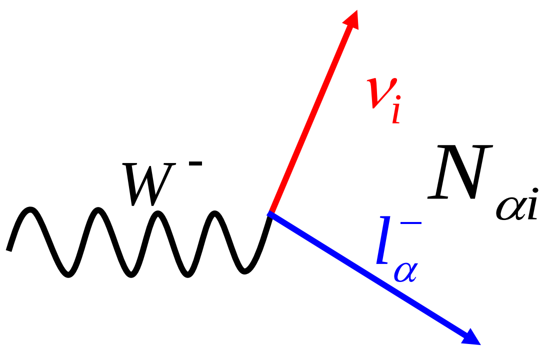
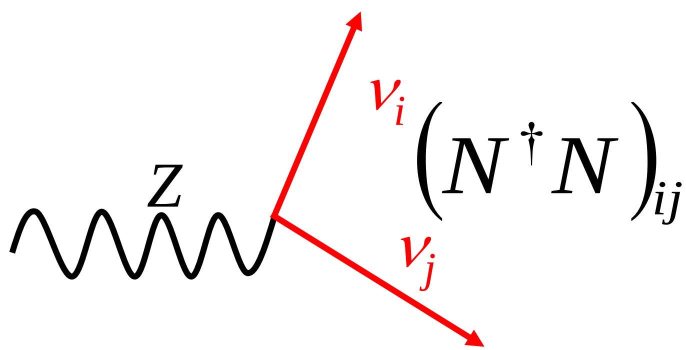
Probing the Seesaw: Non-Unitarity

$$U^T \begin{pmatrix} 0 & m_D \\ m_D^t & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

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





Effects in weak interactions…

$$\Gamma = \Gamma_{SM} \sum_i \left|N_{\alpha i}\right|^2 = \Gamma_{SM} \left(NN^\dagger\right)_{\alpha\alpha}$$

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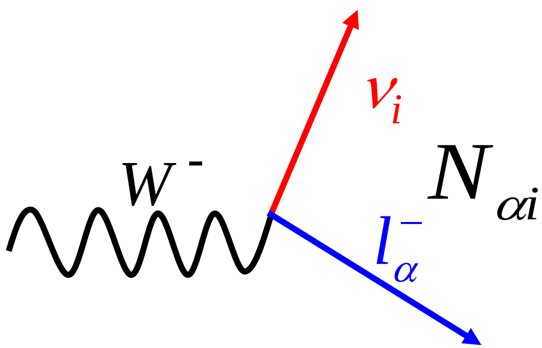

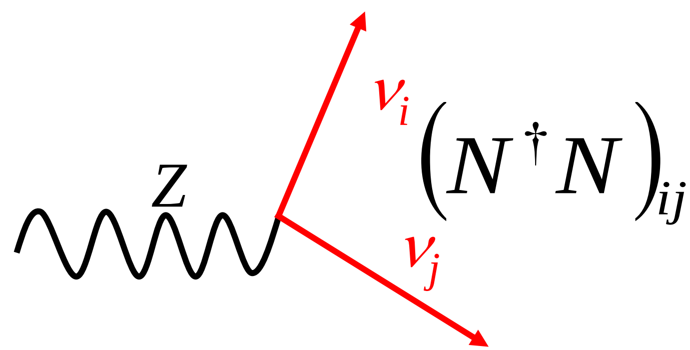

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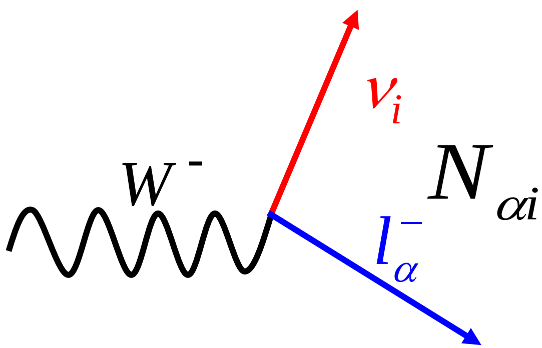

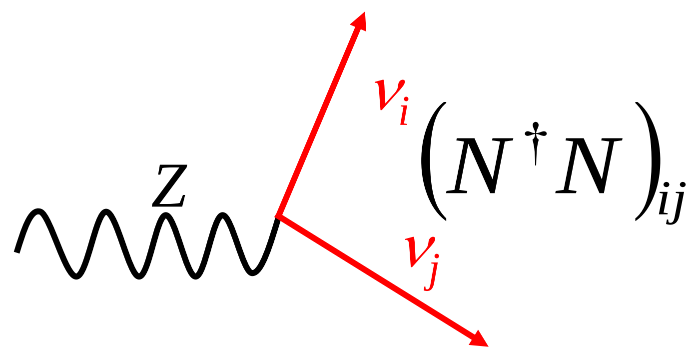

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Zero-distance effect:

$$P\left(\nu_\alpha \to \nu_\beta; 0\right) \propto \left|\sum_i N_{\alpha i}^* N_{\beta i}\right|^2 \neq \delta_{\alpha\beta}$$

Probing the Seesaw: Non-Unitarity

In general $N = (1-\eta)\cdot U$ with η Hermitian and U Unitary

For a Seesaw $\eta = \dfrac{\Theta\Theta^{\dagger}}{2}$ with $\Theta \approx m_{\mathrm{D}}^{\dagger} M_N^{-1}$ the heavy-active mixing

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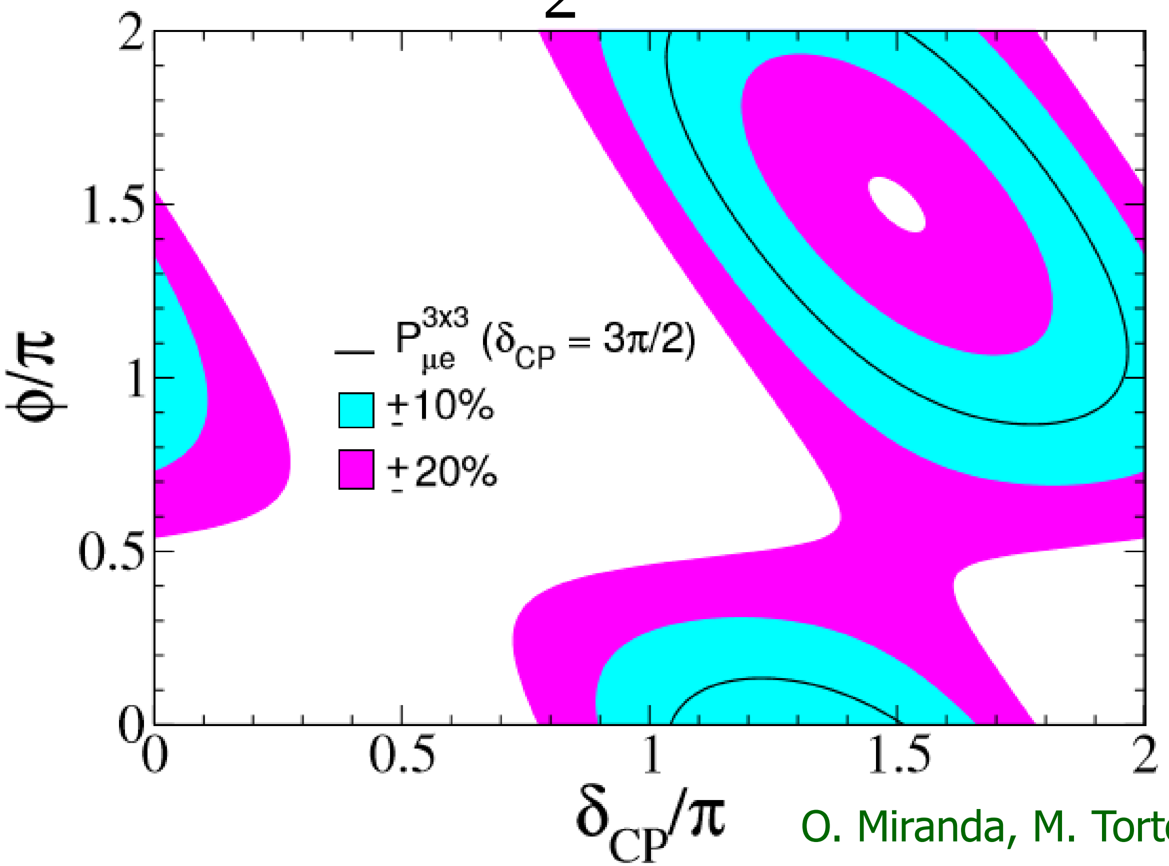

The new phases in η imply new sources of CP violation that could be confused with the standard if similar in magnitude

For $\eta_{e\mu} = 0.01\, e^{i\phi}$

O. Miranda, M. Tortola and J. Valle arXiv:1604.05690

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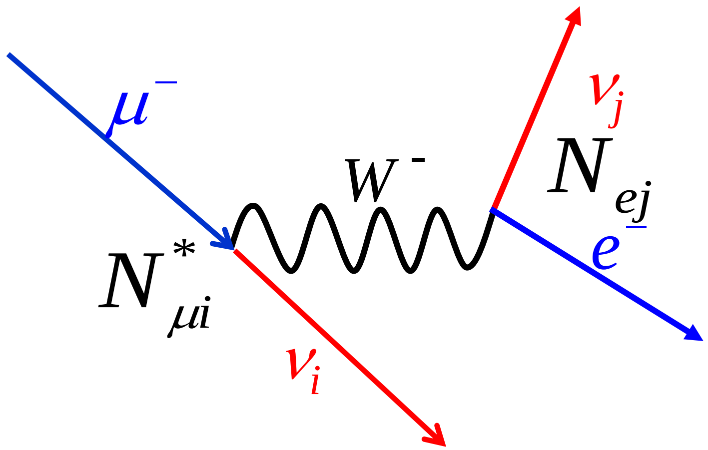
G_F from μ decay is affected!



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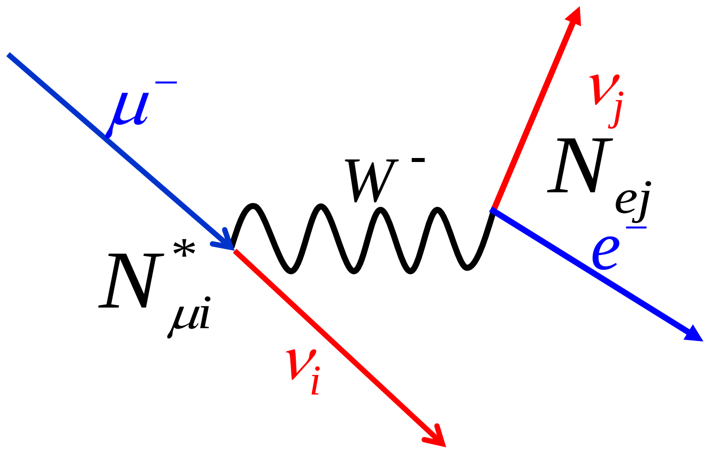

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But $G_F = \dfrac{\alpha\pi M_Z^2}{\sqrt{2}M_W^2\left(M_Z^2 - M_W^2\right)}$

Agree at the ~per mille level

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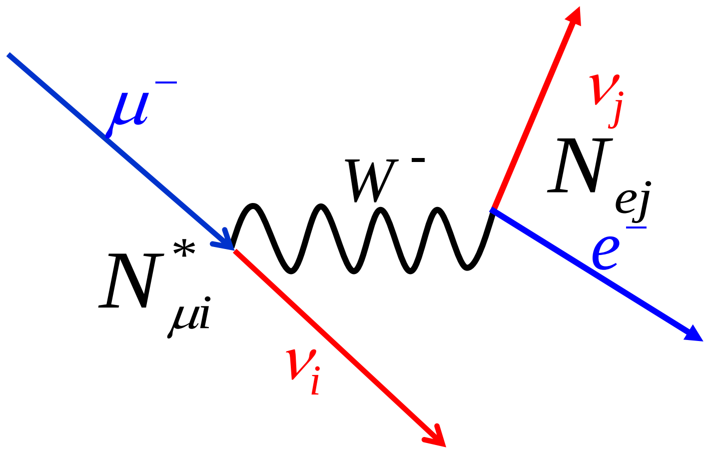

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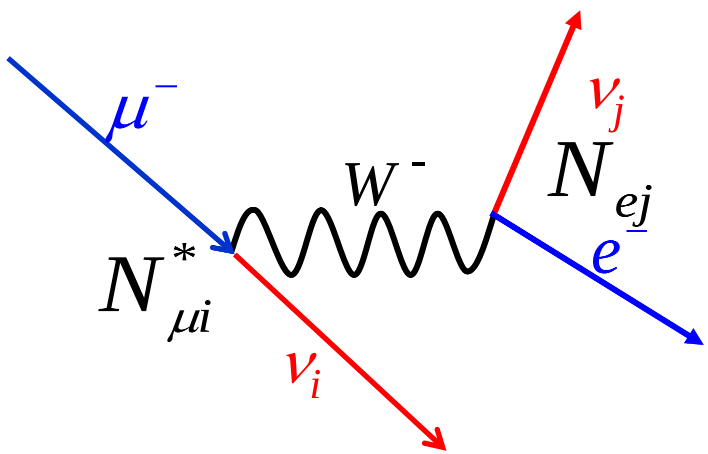

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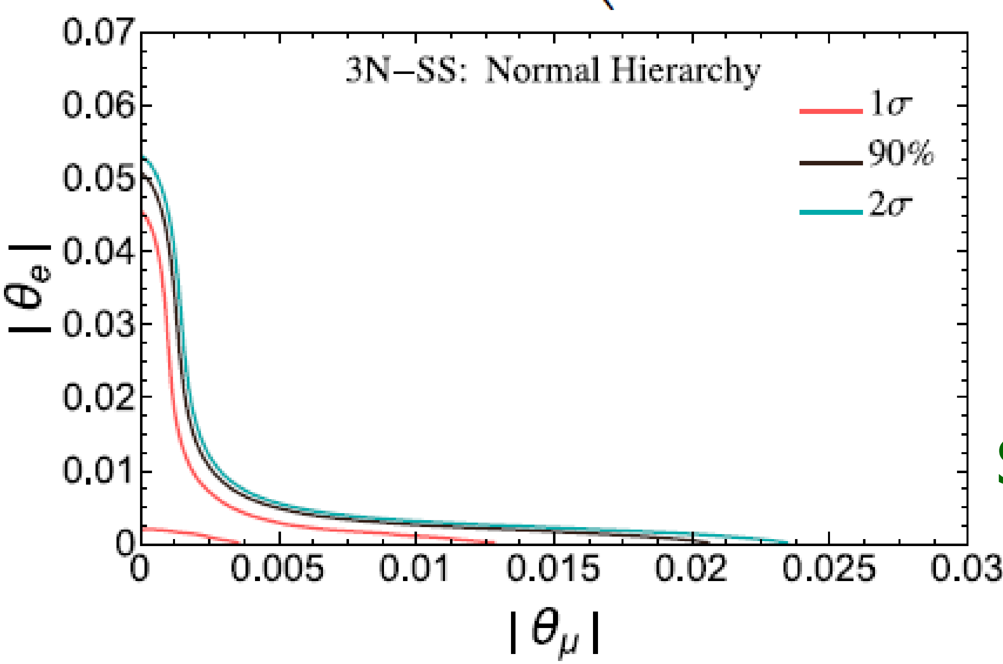
Lepton weak universality from π, K and τ decay ratios

LVF processes from the loss of the GIM cancellation...

Probing the Seesaw: Non-Unitarity

Recent bounds from a global fit to flavour and Electroweak precision data (28 observables considered) EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1605.08774

$$|\eta_{\alpha\beta}| \leq \begin{pmatrix} 1.3 \cdot 10^{-3} & 1.2 \cdot 10^{-5} & 1.4 \cdot 10^{-3} \\ 1.2 \cdot 10^{-5} & 2.0 \cdot 10^{-4} & 6.0 \cdot 10^{-4} \\ 1.4 \cdot 10^{-3} & 6.0 \cdot 10^{-4} & 2.8 \cdot 10^{-3} \end{pmatrix}$$



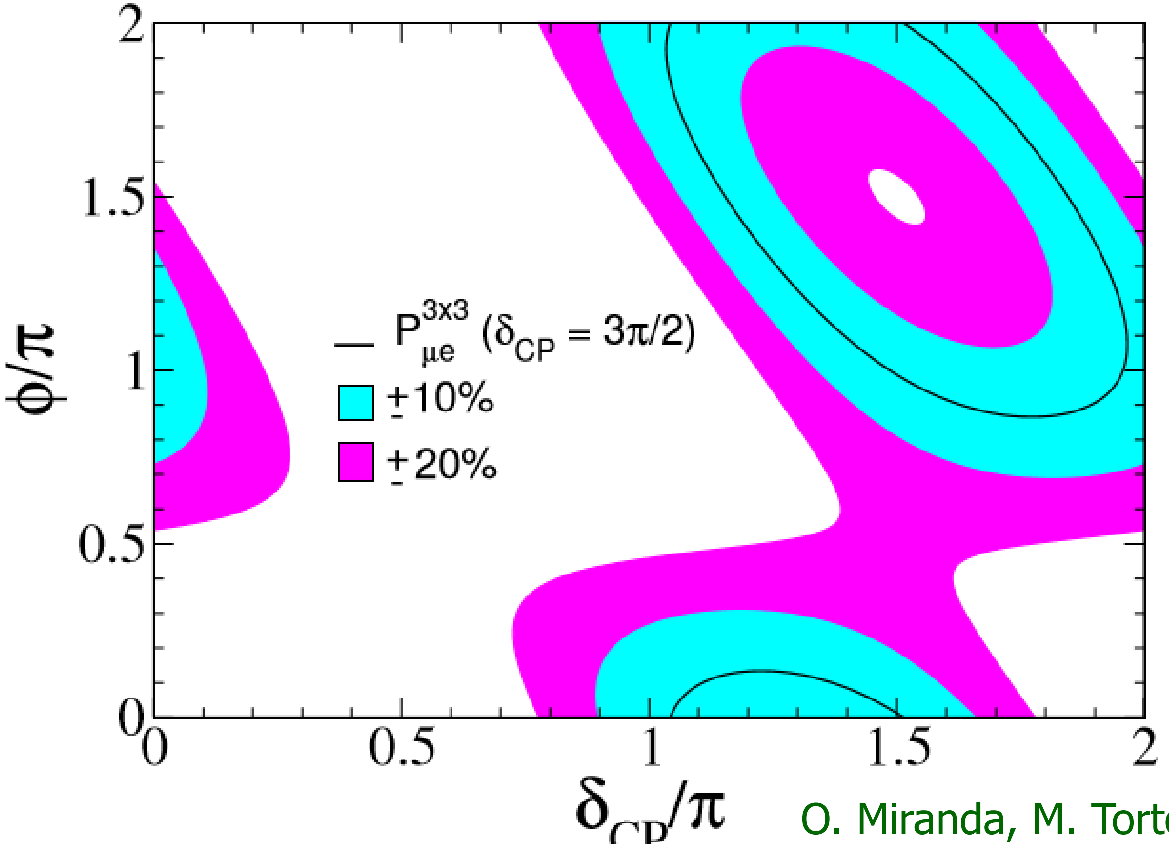
$$N = (1-\eta) U_{PMNS} \qquad \eta = \frac{\Theta\Theta^\dagger}{2}$$

$$\Theta = m_D M_N^{-1}$$

See poster by Josu Hernandez

Probing the Seesaw: Non-Unitarity

Despite some confusion in present literature non-unitarity from heavy ν mixing is beyond the reach of present and near future facilities (given the 10^{-3}-10^{-4} bounds)



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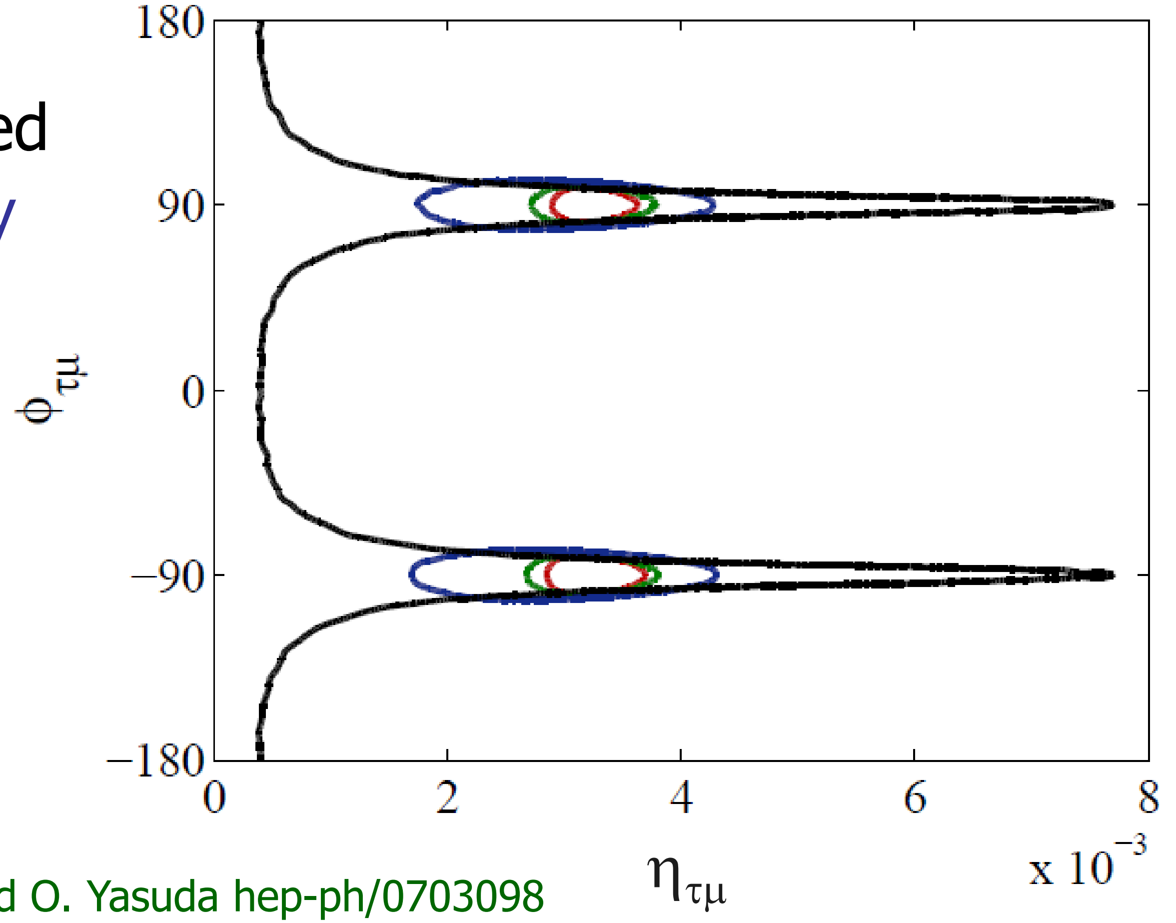
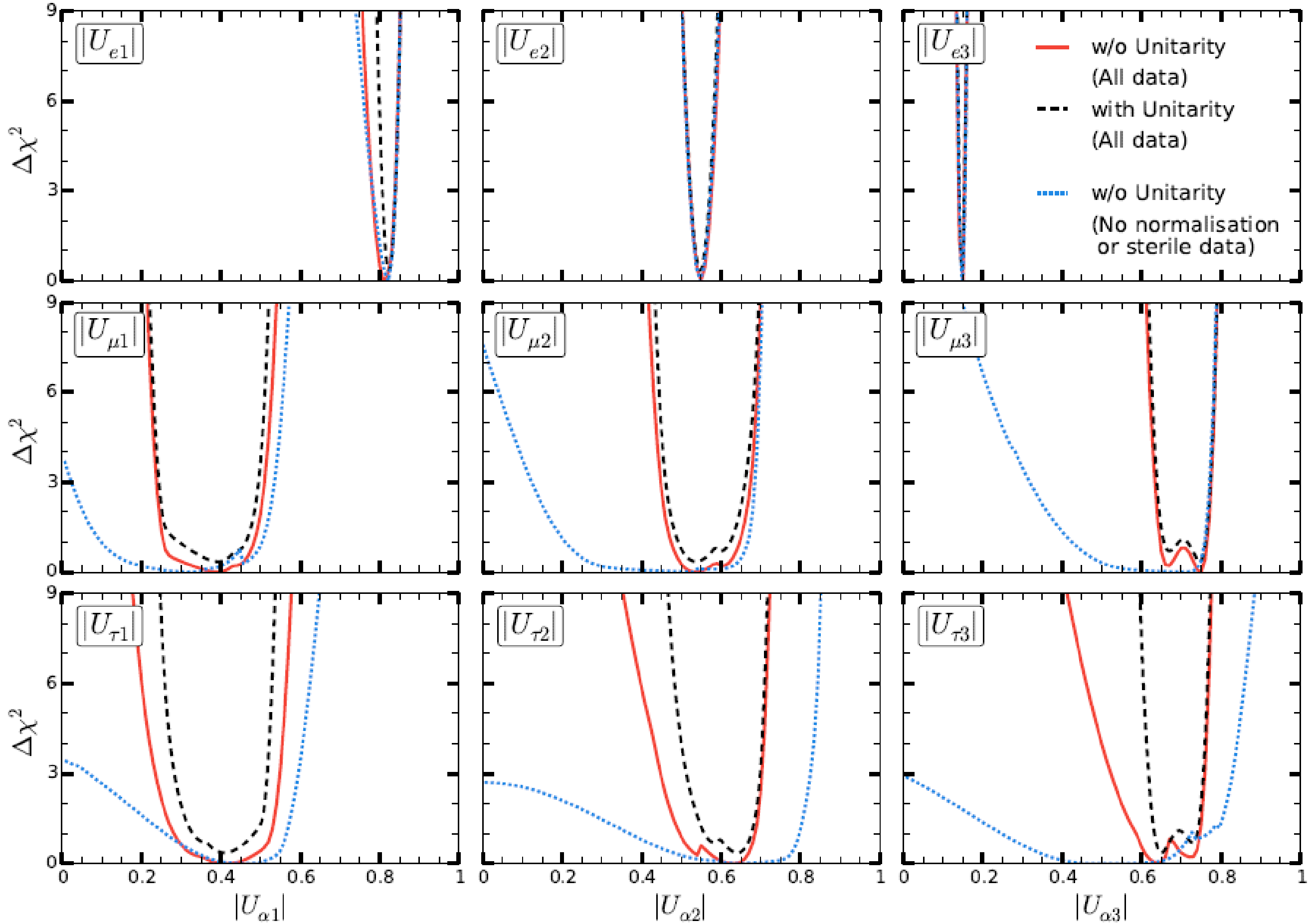
But it could be probed at a Neutrino Factory



EFM, B. Gavela, J. Lopez-Pavon and O. Yasuda hep-ph/0703098
S. Antusch, M. Blennow, EFM and J. Lopez-Pavon arXiv:0903.3986

Probing the Seesaw: Steriles

For very light (< keV) extra neutrinos these strong constraints are lost and ν oscillations are our best probe of this scale.



S. Parke and M. Ross-Lonergan arXiv:1508.05095

Probing the Seesaw: Steriles vs NU

Non-unitarity (from heavy ν mixing) constraints from precision EW and flavour observables

$$|\eta_{\alpha\beta}| \leq \begin{pmatrix} 1.3 \cdot 10^{-3} & 1.2 \cdot 10^{-5} & 1.4 \cdot 10^{-3} \\ 1.2 \cdot 10^{-5} & 2.0 \cdot 10^{-4} & 6.0 \cdot 10^{-4} \\ 1.4 \cdot 10^{-3} & 6.0 \cdot 10^{-4} & 2.8 \cdot 10^{-3} \end{pmatrix}$$

$$N = (1-\eta)U_{PMNS} \qquad \eta = \frac{\Theta\Theta^{\dagger}}{2} \qquad \Theta = m_D M_N^{-1}$$

@ 95% CL

$$|\eta_{\alpha\beta}| \leq \begin{pmatrix} 2.6 \cdot 10^{-2} & 2.4 \cdot 10^{-2} & 3.6 \cdot 10^{-2} \\ 2.4 \cdot 10^{-2} & 4.5 \cdot 10^{-2} & 4.8 \cdot 10^{-2} \\ 3.6 \cdot 10^{-2} & 4.8 \cdot 10^{-2} & 0.10 \end{pmatrix}$$

Non-unitarity (from light ν mixing) constraints from oscillation searches

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.XXXXX

Probing the Seesaw: Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix}$$

"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.XXXXX

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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.XXXXX

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

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.XXXXX

Probing the Seesaw: Steriles vs NU

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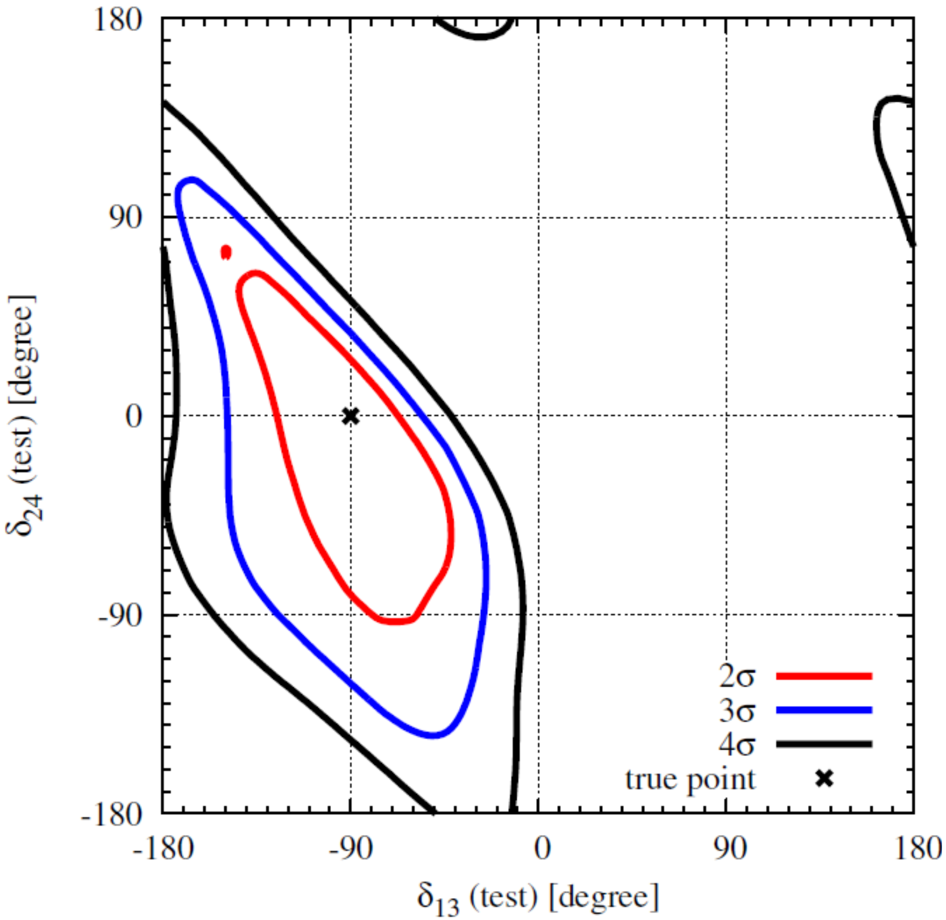
"Light ν" Steriles

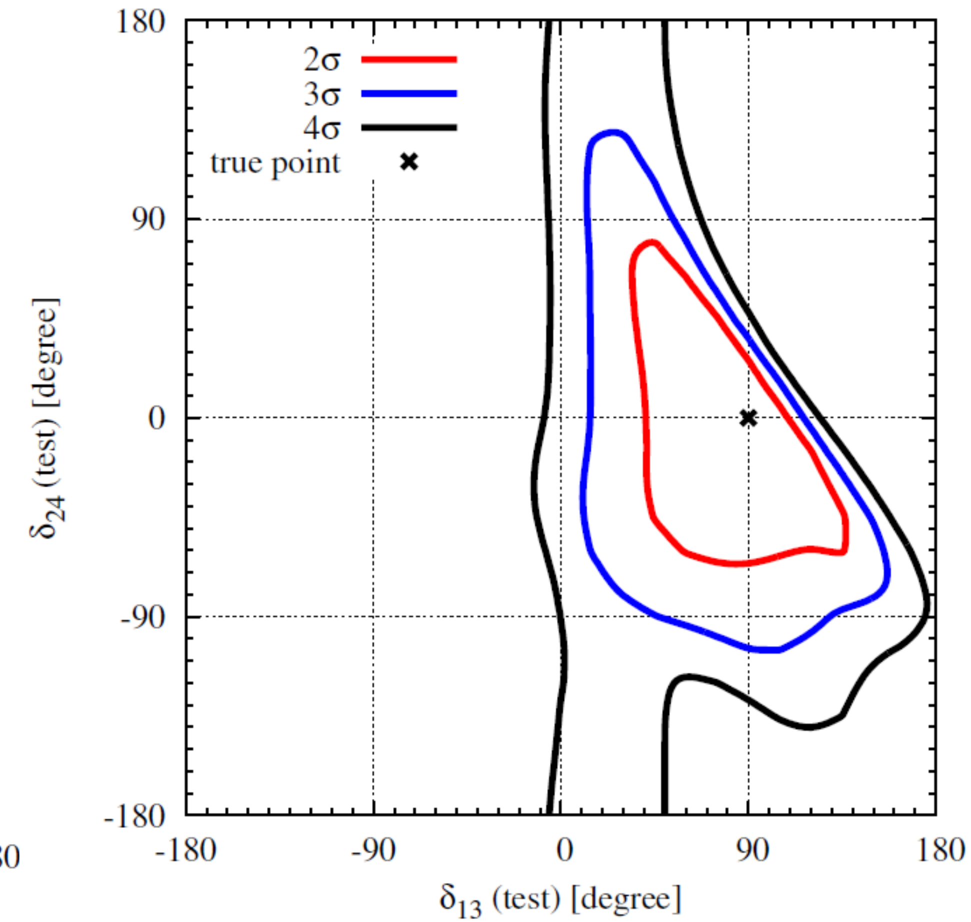
$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}} + \cancel{\sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}}}$$

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.XXXXX

Steriles and CPV at DUNE far detector

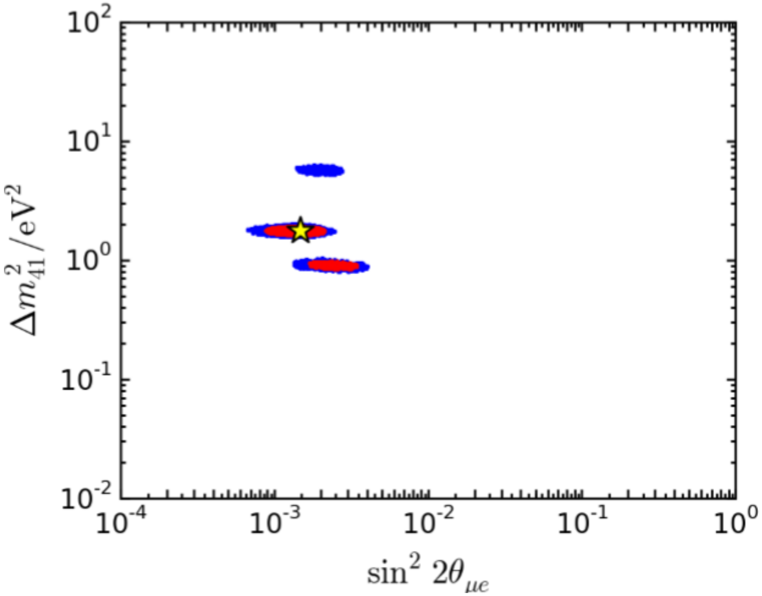


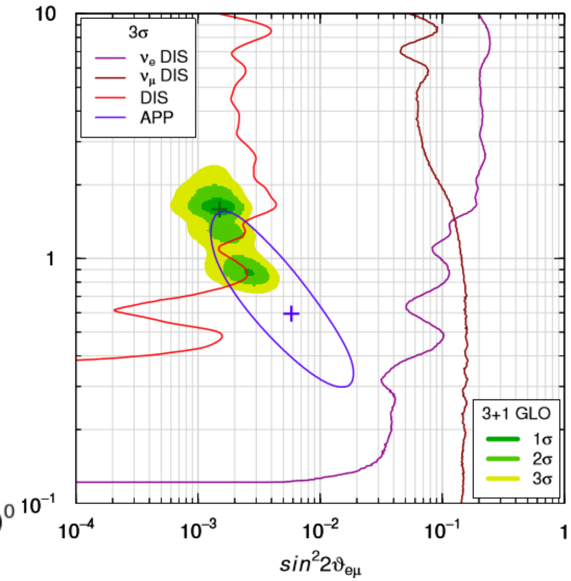


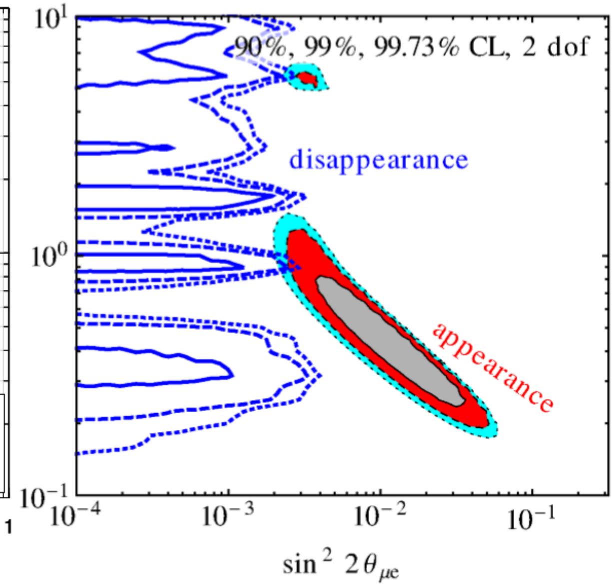
D. Dutta et al arXiv:1607.02152

Probing the Seesaw: Steriles

Present sterile neutrino anomalies







G. H. Collin et al arXiv:1602.00671; S. Gariazzo et al arXiv:1507.08204; J. Kopp et al arXiv:1303.3011

Can also be interpretetd in a (really) low scale Seesaw context

A. de Gouvea hep-ph/0501039; A. Donini et al 1106.0064; M. Blennow and EFM 1107.3992
J. Fan and P. Langacker 1201.6662; A. Donini et al 1205.5230

Conclusions

- Neutrino masses and mixings point to a new physics scale where Lepton number is broken
- Different phenomenology depending on the scale
- Only the Neutrino Factory could explore the very high scale scenario (PMNS non-unitarity)
- But present and near-future ν oscillation facilities can probe the very low scale (sterile ν) limit
- If sterile ν oscillations are "averaged out" the two limits give the same pheno at leading order