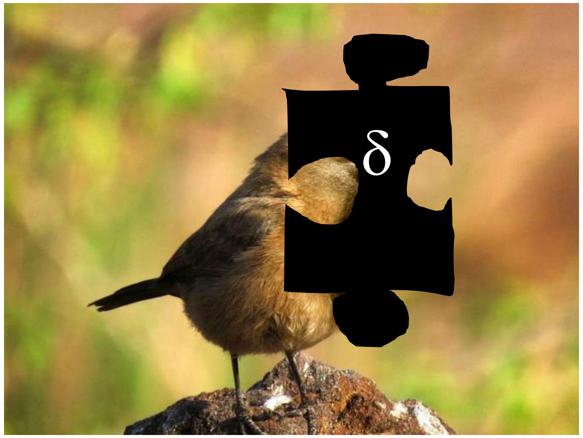
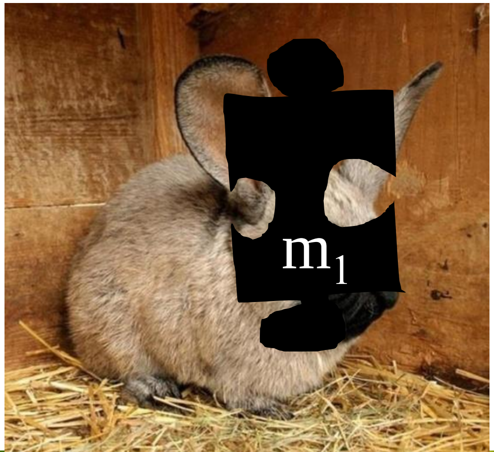
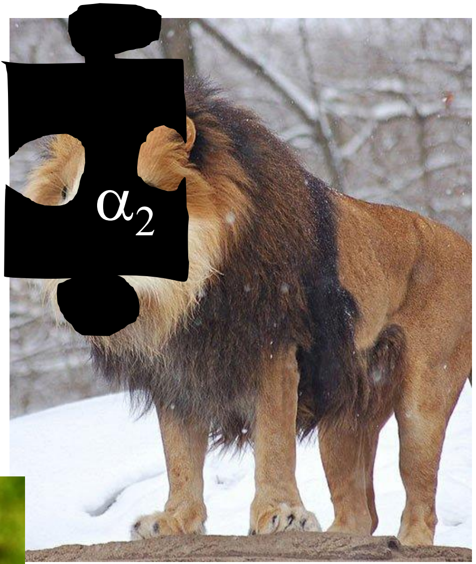
ν mass origin and its testability

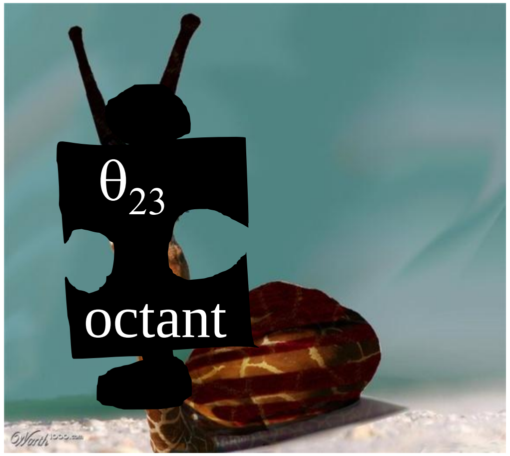
Enrique Fernández Martínez

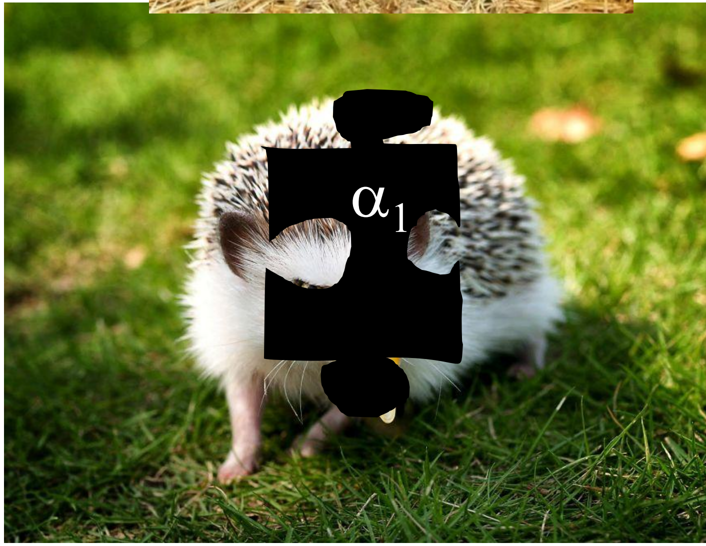
Neutrino physics missing pieces

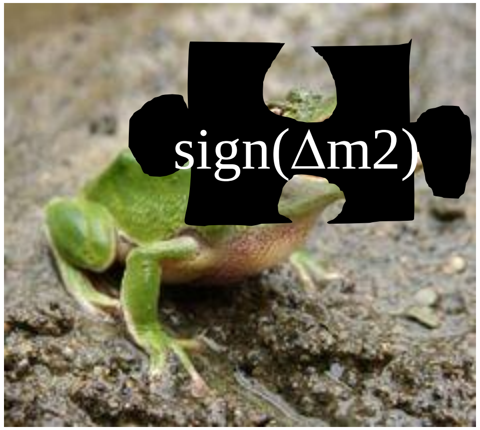












Neutrino physics missing pieces

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

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→ To be sought for at experiments!!

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Seesaw

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eV **keV** **MeV** **GeV** **TeV**

M_N could be anywhere…

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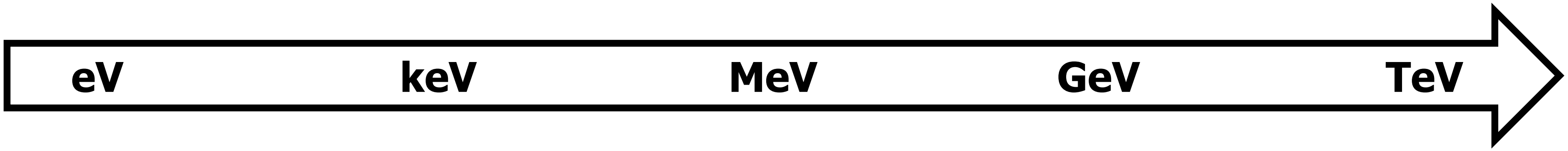
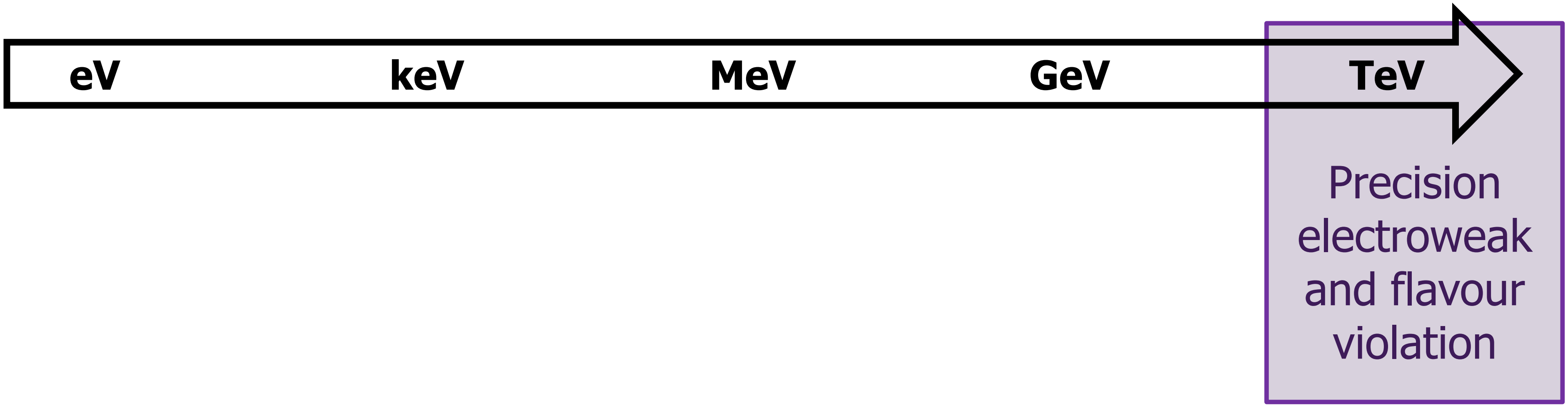


eV **keV** **MeV** **GeV** **TeV**

M_N could be anywhere…

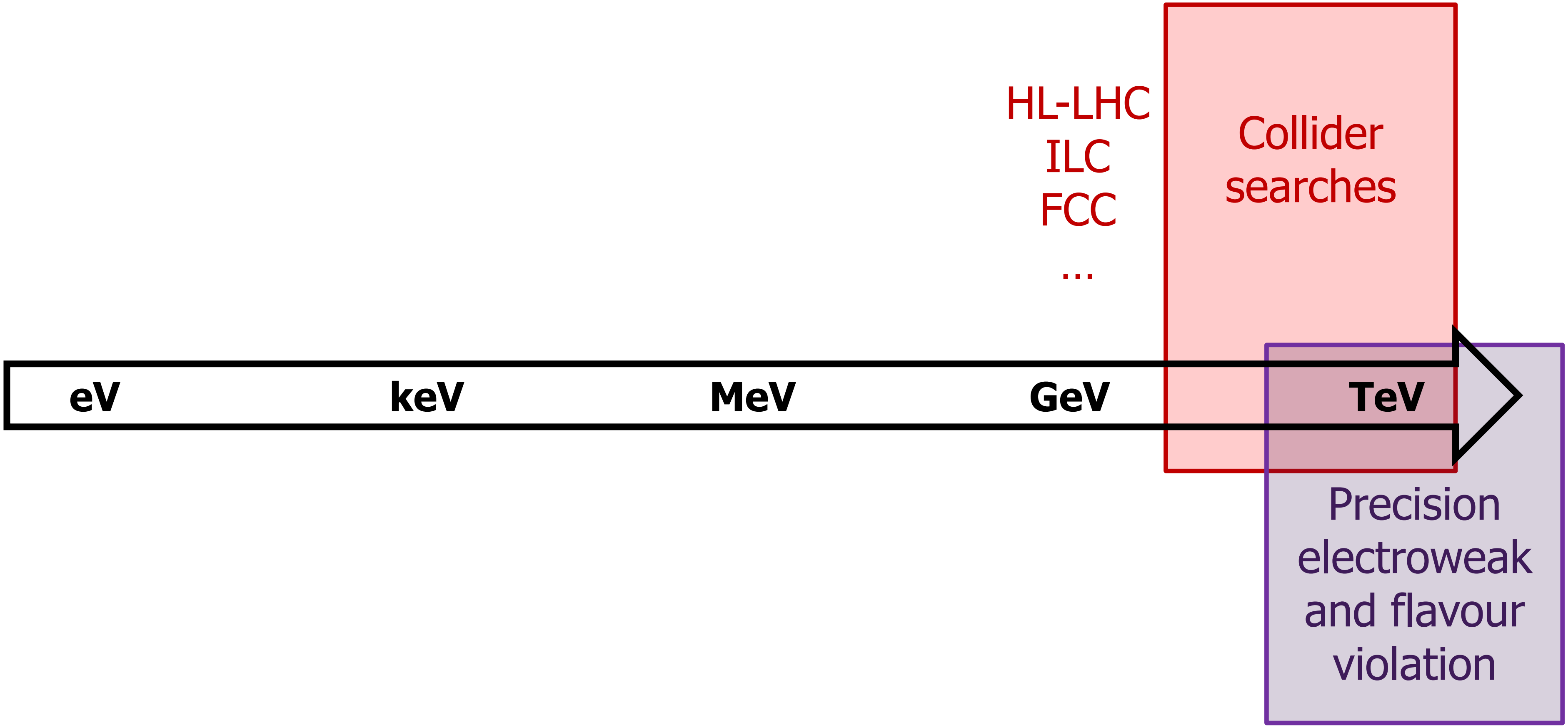
Very different phenomenology at different scales

A new physics scale



Precision electroweak and flavour violation

A new physics scale



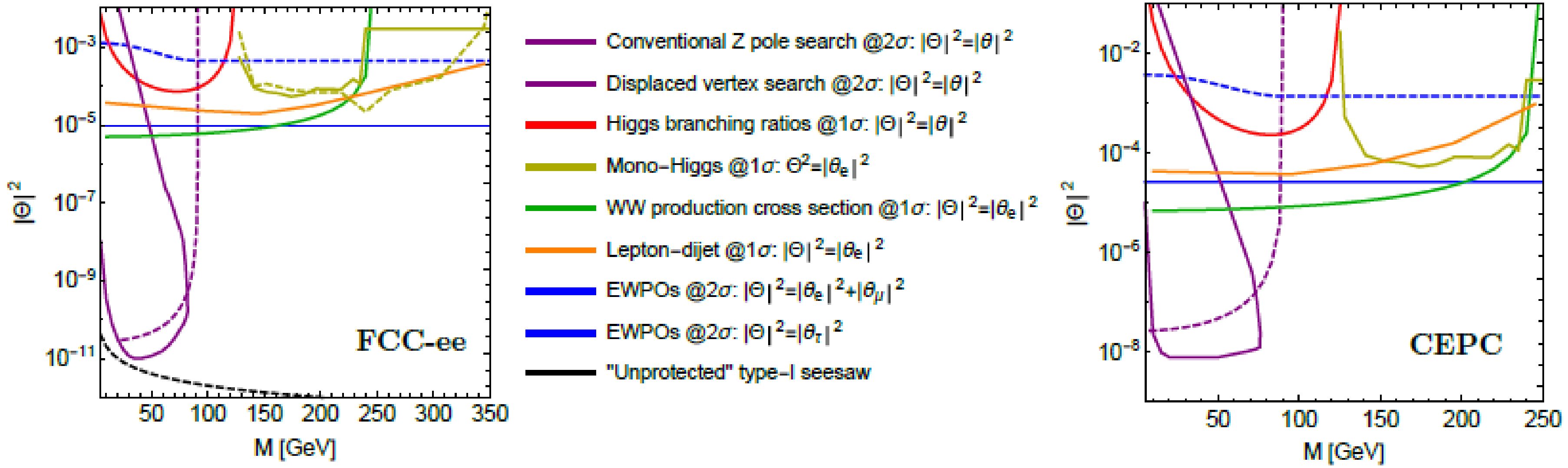
HL-LHC
ILC
FCC
…

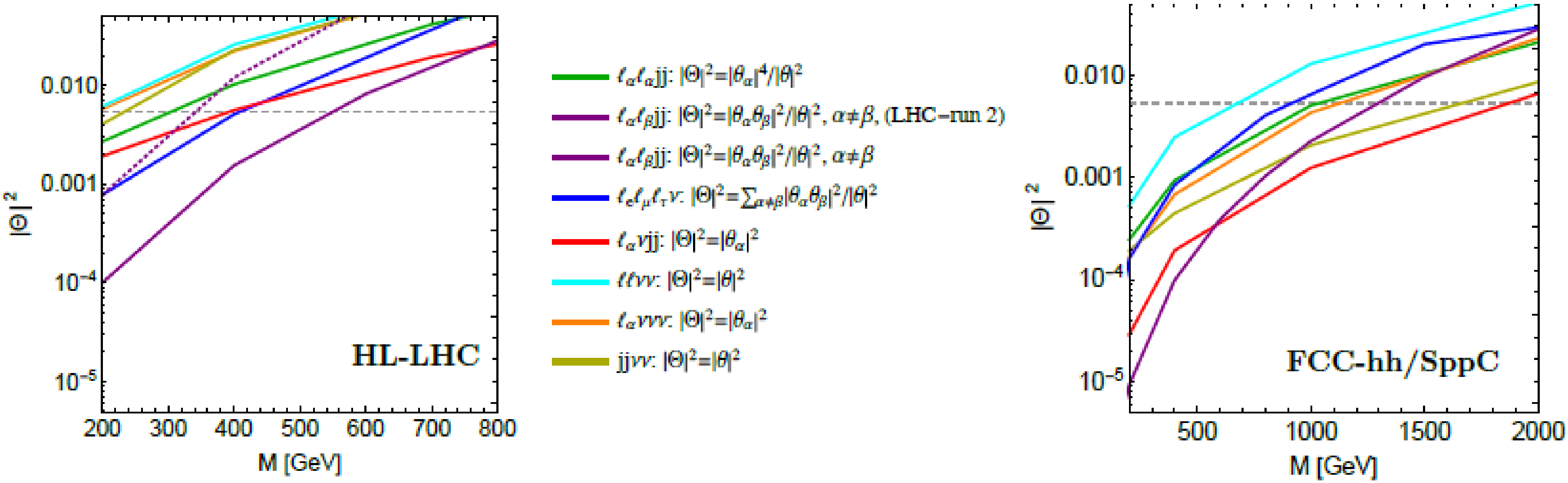
Collider searches

eV keV MeV GeV TeV

Precision electroweak and flavour violation

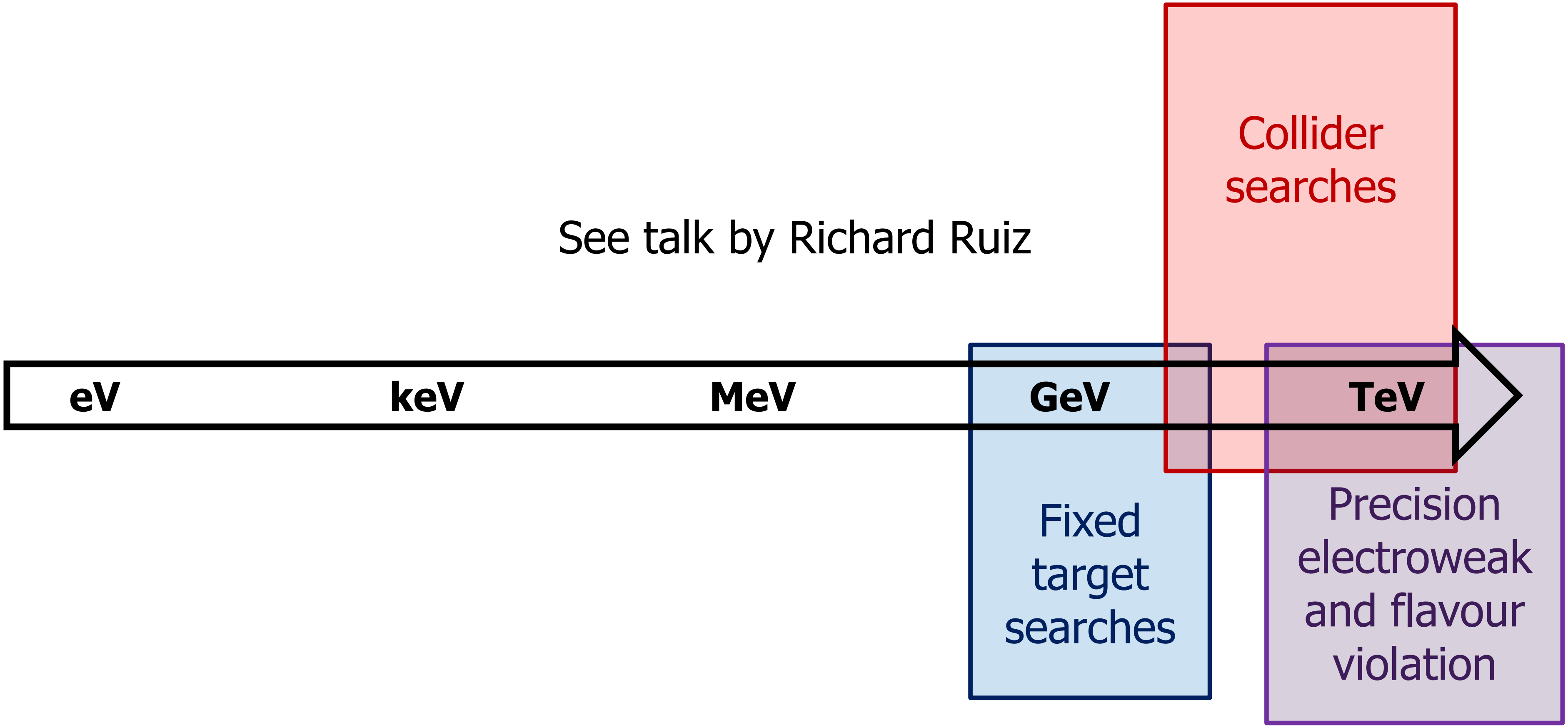
Collider searches





S. Antusch, E. Cazzato and O. Fischer arXiv:1612.02728

A new physics scale



Collider searches

See talk by Richard Ruiz

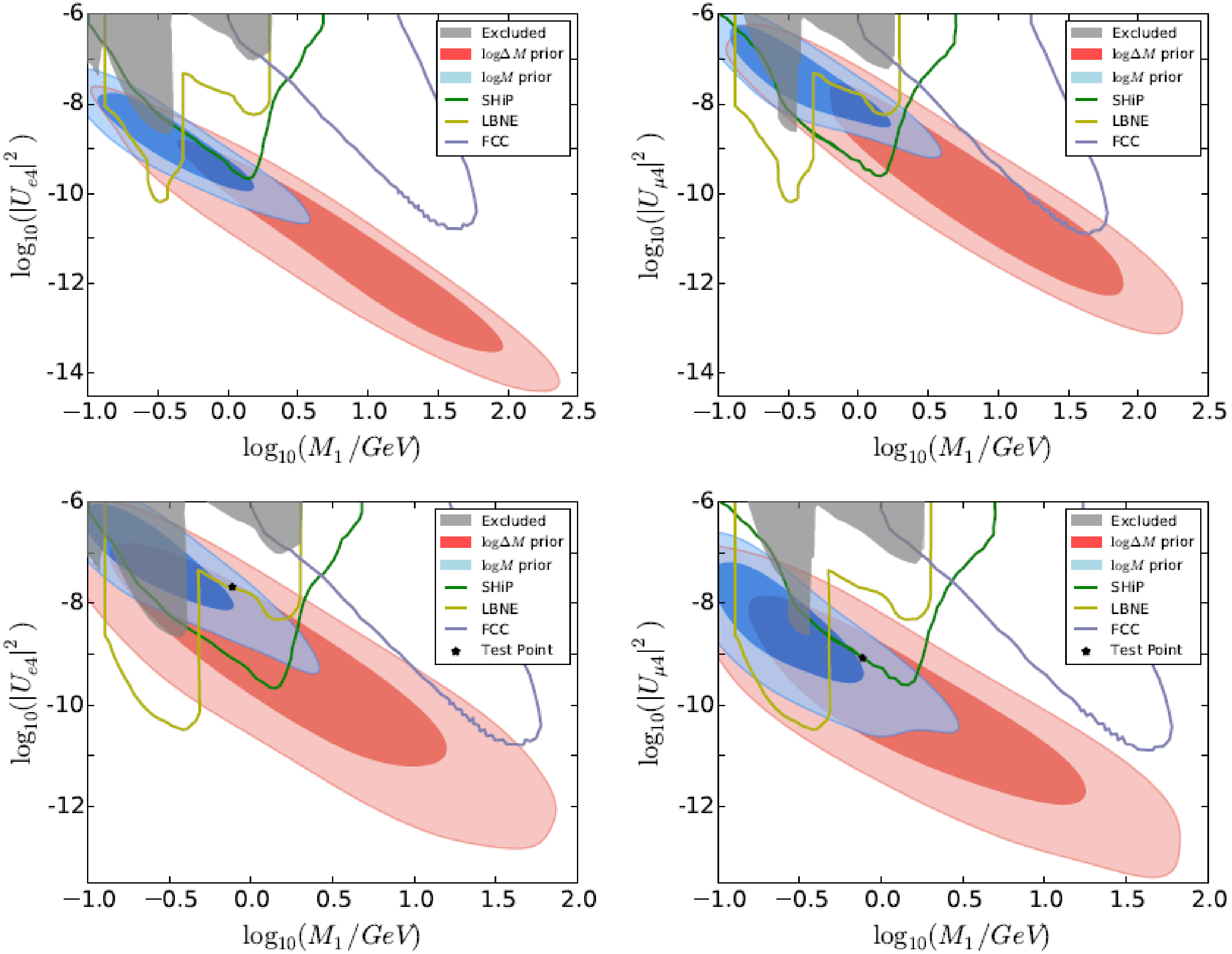
eV **keV** **MeV** **GeV** **TeV**

Fixed target searches

Precision electroweak and flavour violation

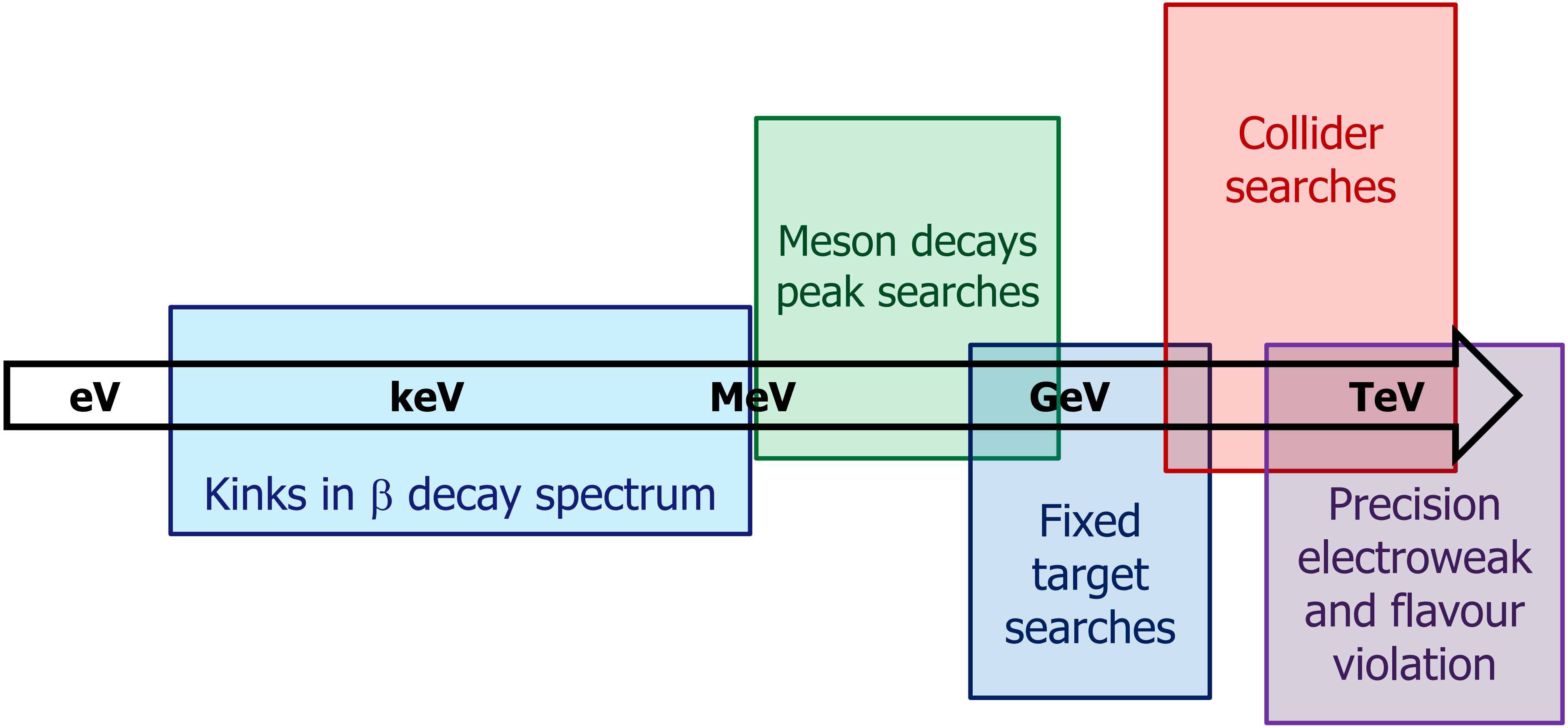
ν near detectors
SHIP
MATHUSLA …

Fixed Target searches vs leptogenesis



P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Racker and J. Salvado arXiv:1606.06719

A new physics scale



Collider searches

Meson decays peak searches

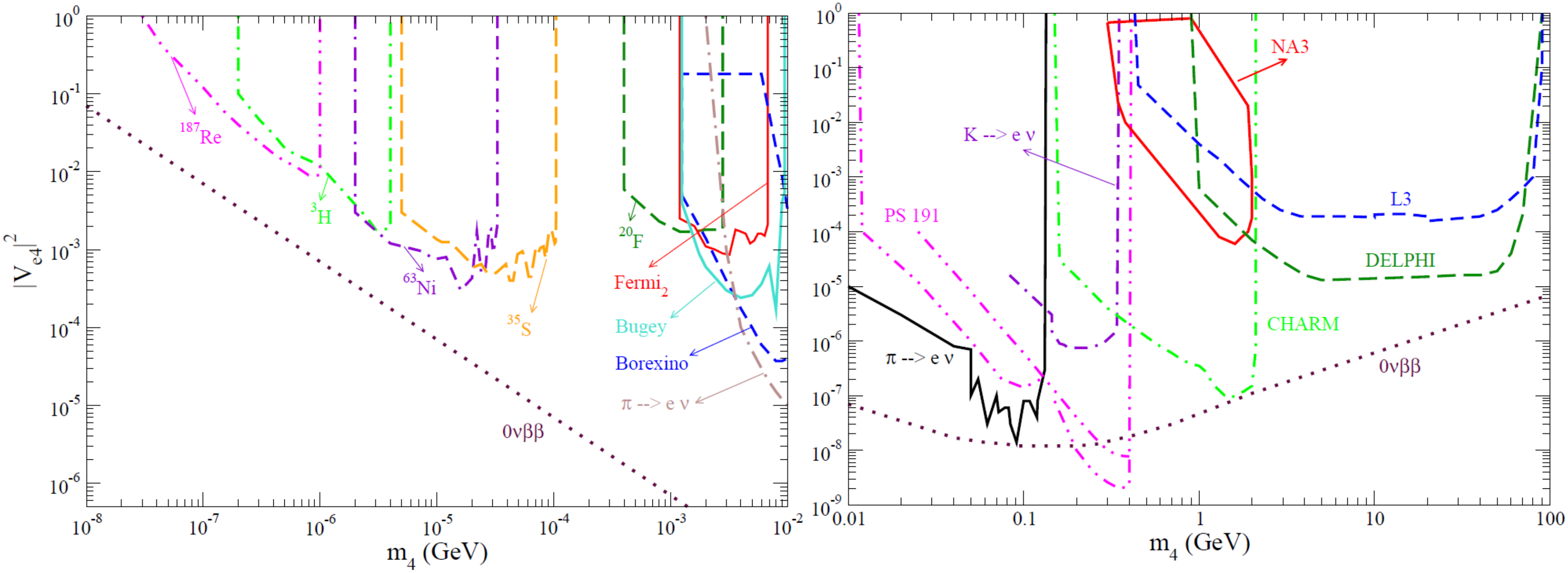
eV **keV** **MeV** **GeV** **TeV**

Kinks in β decay spectrum

Fixed target searches

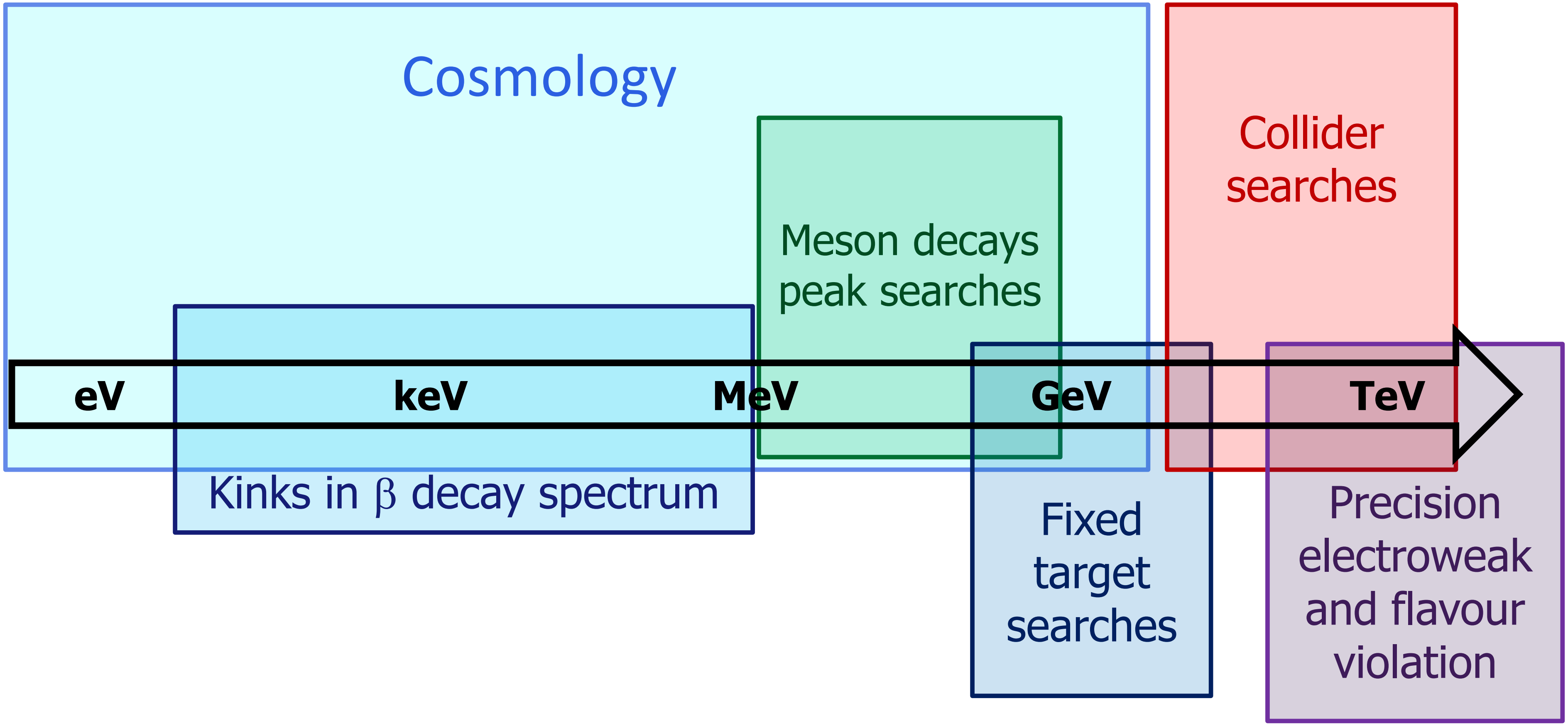
Precision electroweak and flavour violation

Meson, β decay + other searches



A. Atre, T. Han, S. Pascoli and B. Zhang arXiv:0901.3589

A new physics scale



Cosmology

Collider searches

Meson decays peak searches

eV keV MeV GeV TeV

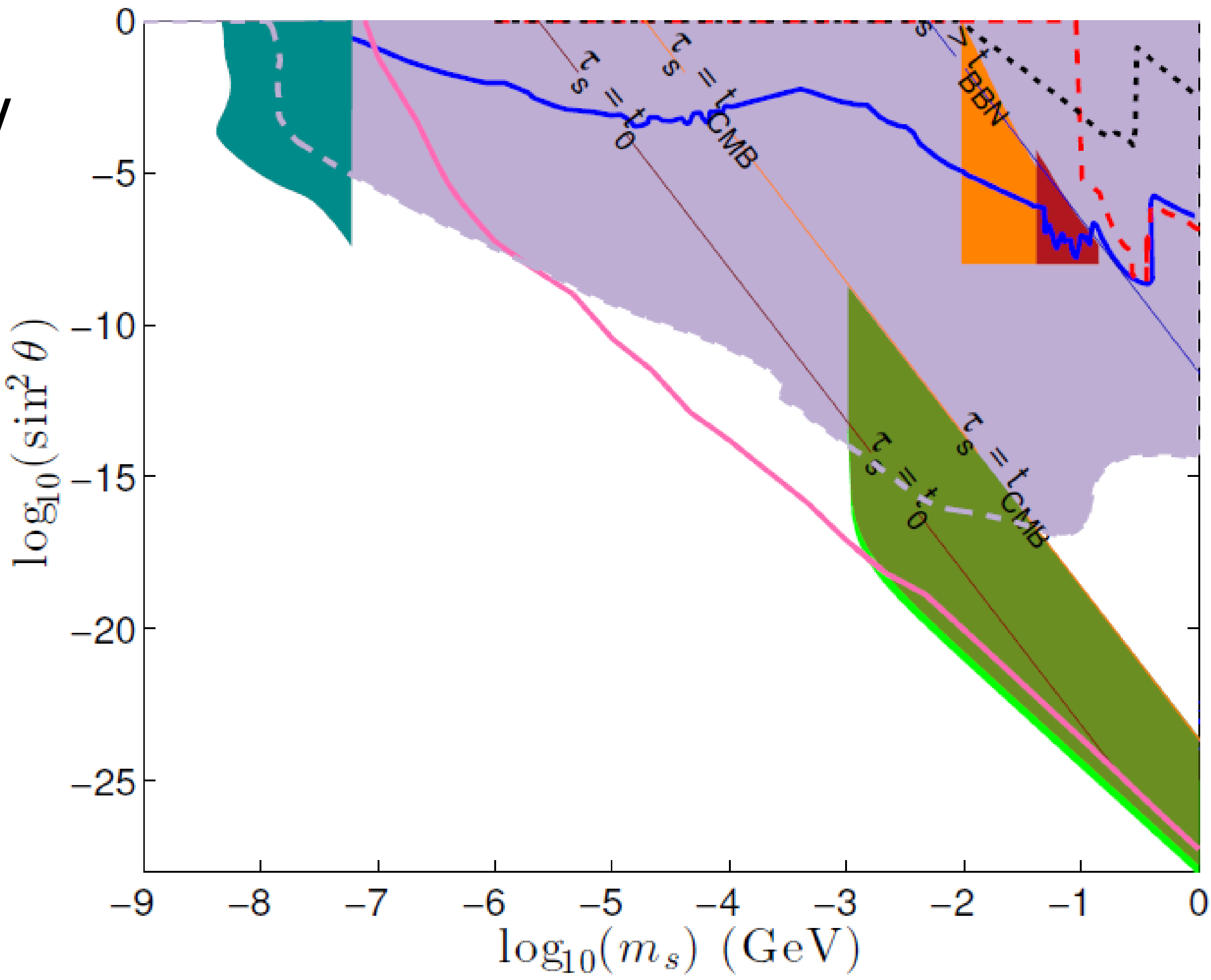
Kinks in β decay spectrum

Fixed target searches

Precision electroweak and flavour violation

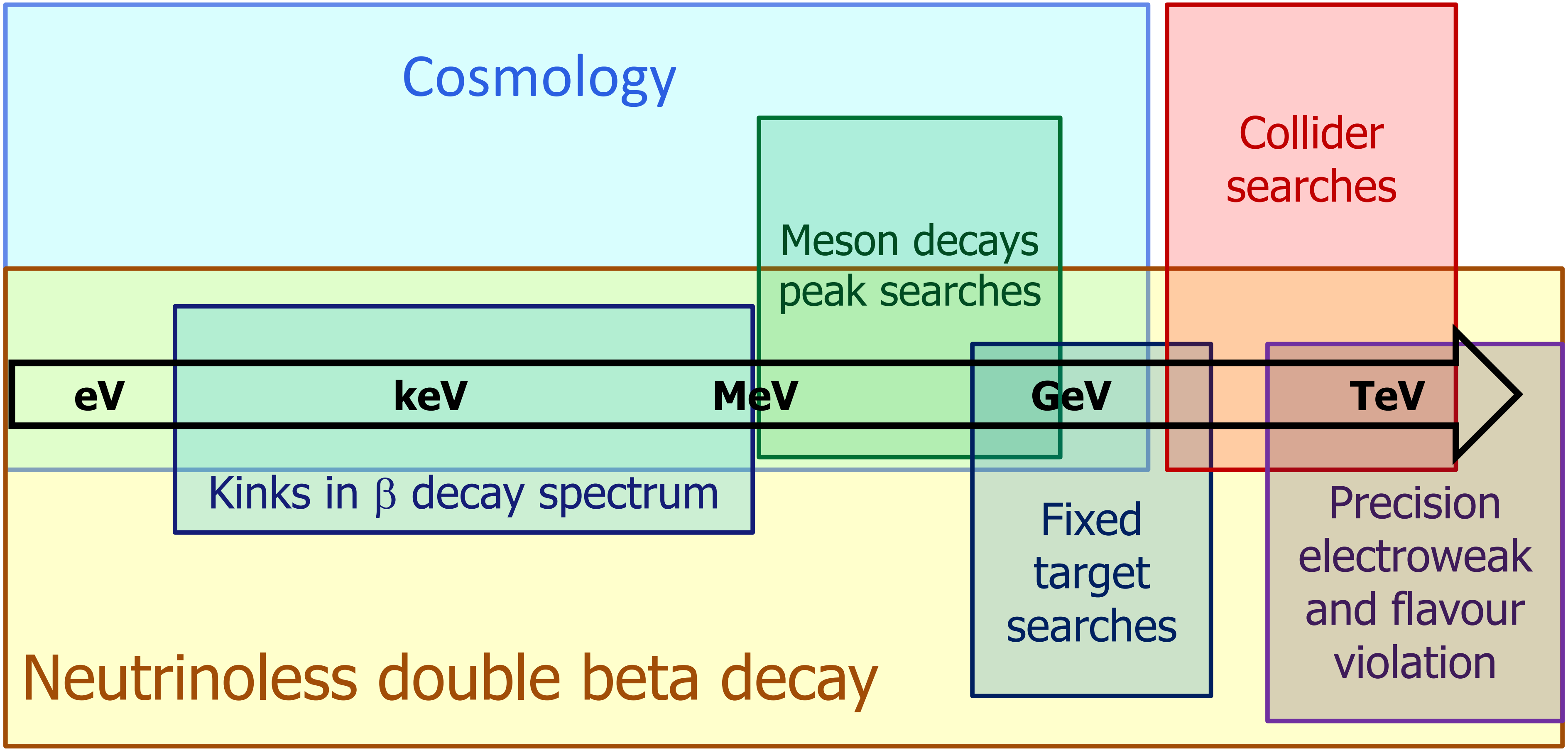
Cosmology constraints

Below ~100 GeV very strong constraints from cosmology



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

A new physics scale



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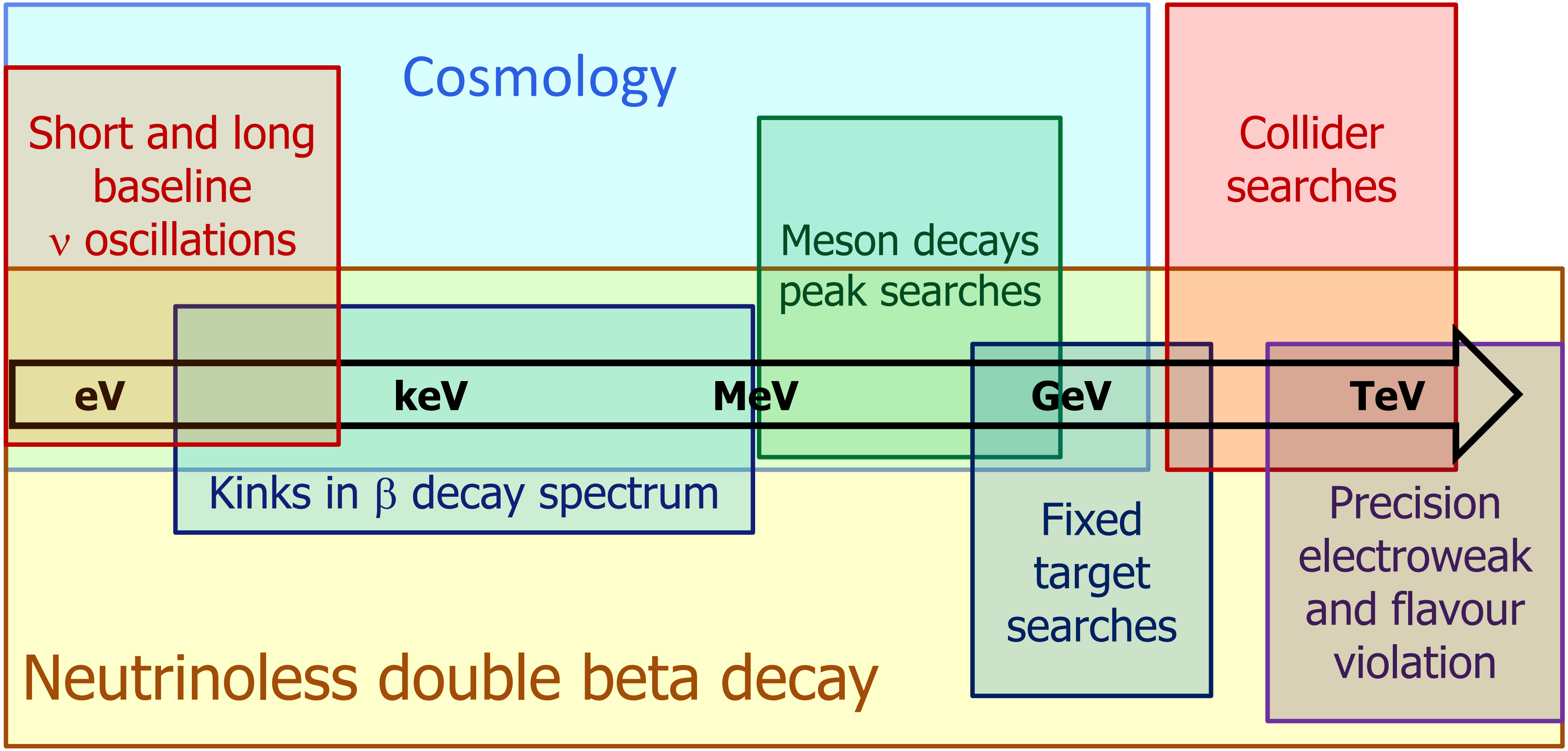

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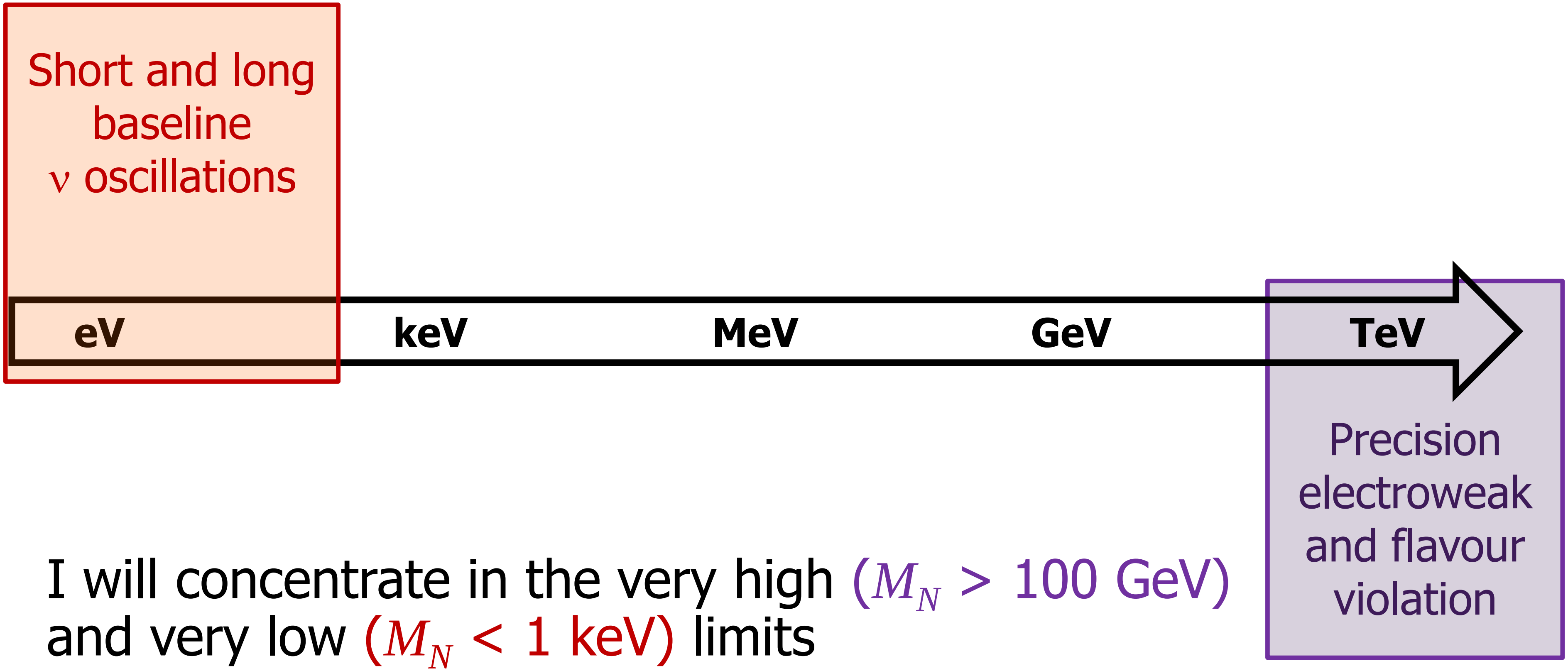


Short and long baseline
ν oscillations

eV **keV** **MeV** **GeV** **TeV**

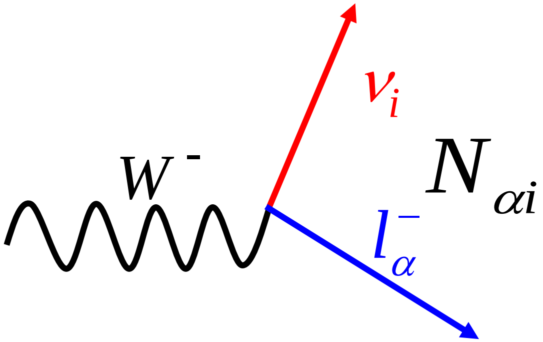
Precision electroweak and flavour violation

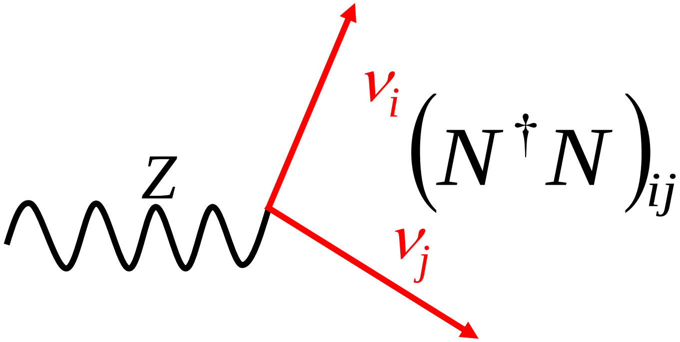
I will concentrate in the very high (M_N > 100 GeV) and very low (M_N < 1 keV) limits

Probing the Seesaw: Non-Unitarity

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

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





Effects in weak interactions…

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

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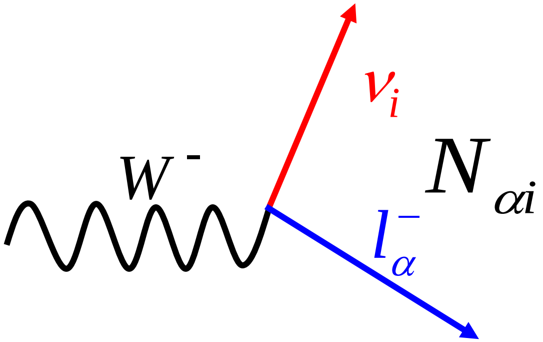

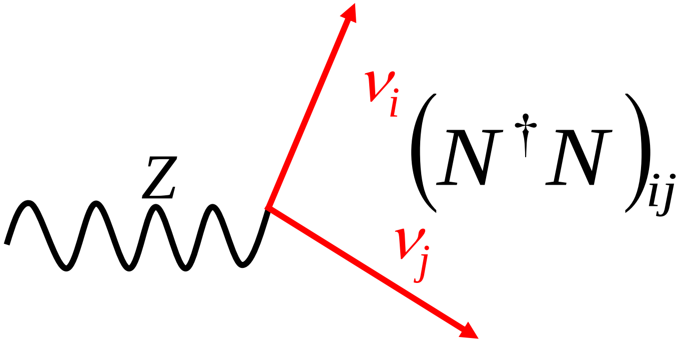

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… and oscillation probabilities…

$$\left|\nu_\alpha\right\rangle \approx \sum_i N_{\alpha i}^* \left|\nu_i\right\rangle$$

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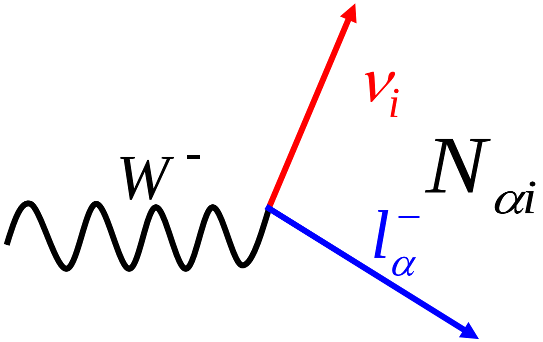

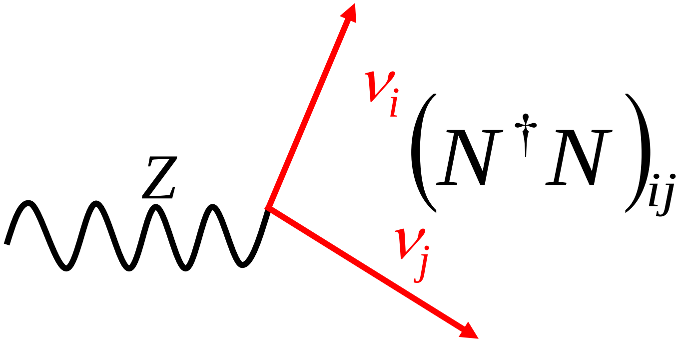

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Zero-distance effect:

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

Probing the Seesaw: Non-Unitarity

In general $N=(1-\alpha)\cdot U$ with α lower triangular and U Unitary

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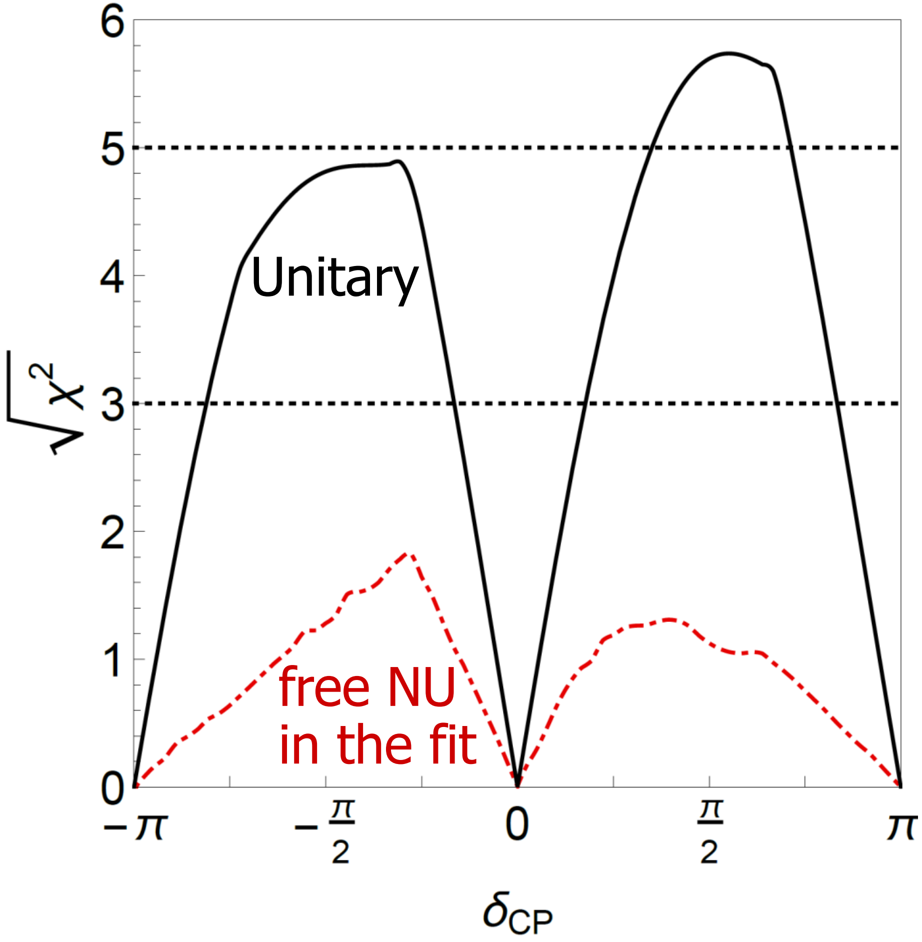


The new phases in α imply new sources of CP violation that could be confused with the standard

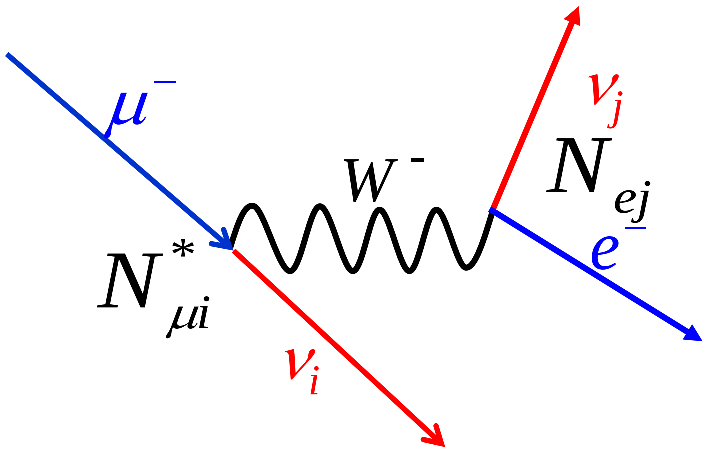
If uncosntrained and allowed in the fit they destroy the CPV discovery potential of DUNE

See also: F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1612.07377.

Probing the Seesaw: Non-Unitarity

In general $N = (1-\alpha)\cdot U$ with α lower triangular and U Unitary

G_F from μ decay is affected!



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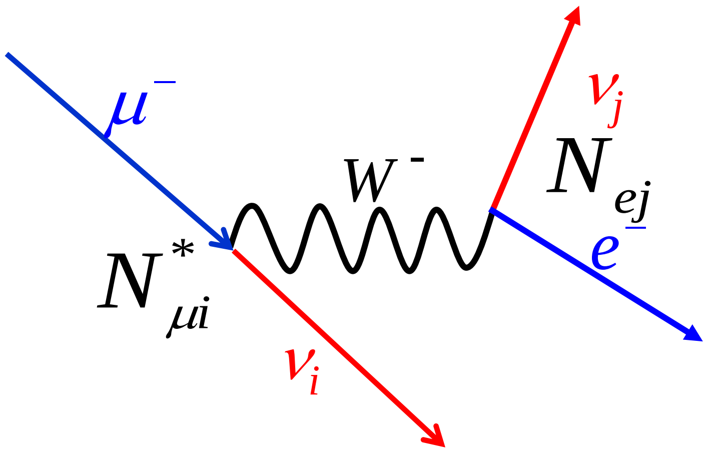

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Agree at the ~per mille level

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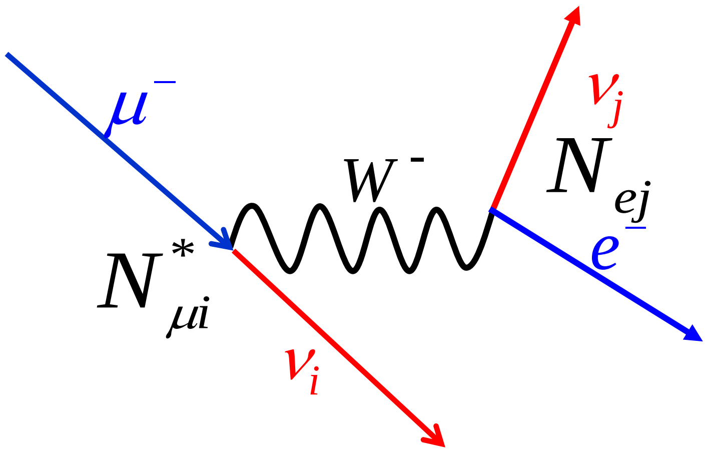

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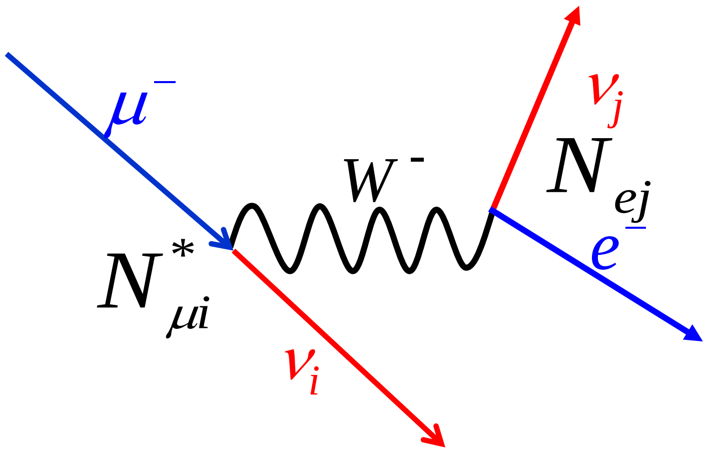

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Measurements of s_W^2 or tests of CKM unitarity from β and K decay also constrain G_F

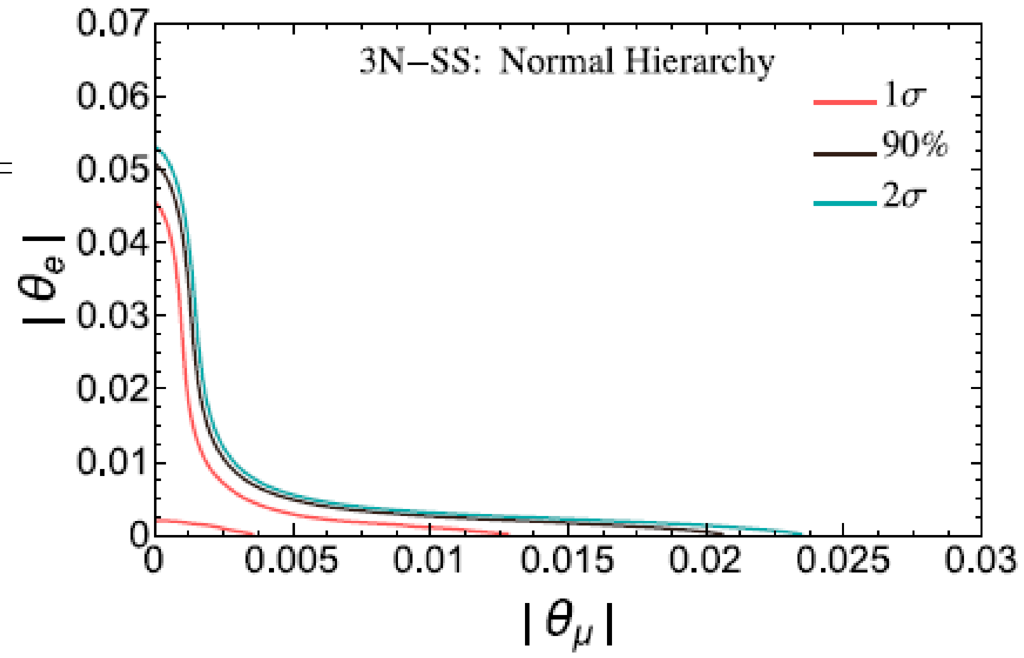
Lepton weak universality from π, K and τ decay ratios

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)

	“Non-Unitarity” $(m > \mathrm{EW})$
α_{ee}	$1.3 \cdot 10^{-3}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}\ (2.4 \cdot 10^{-5})$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$



EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1605.08774

See also: S. Antusch and O. Fischer arxiv: 1407.6607

Probing the Seesaw: Non-Unitarity

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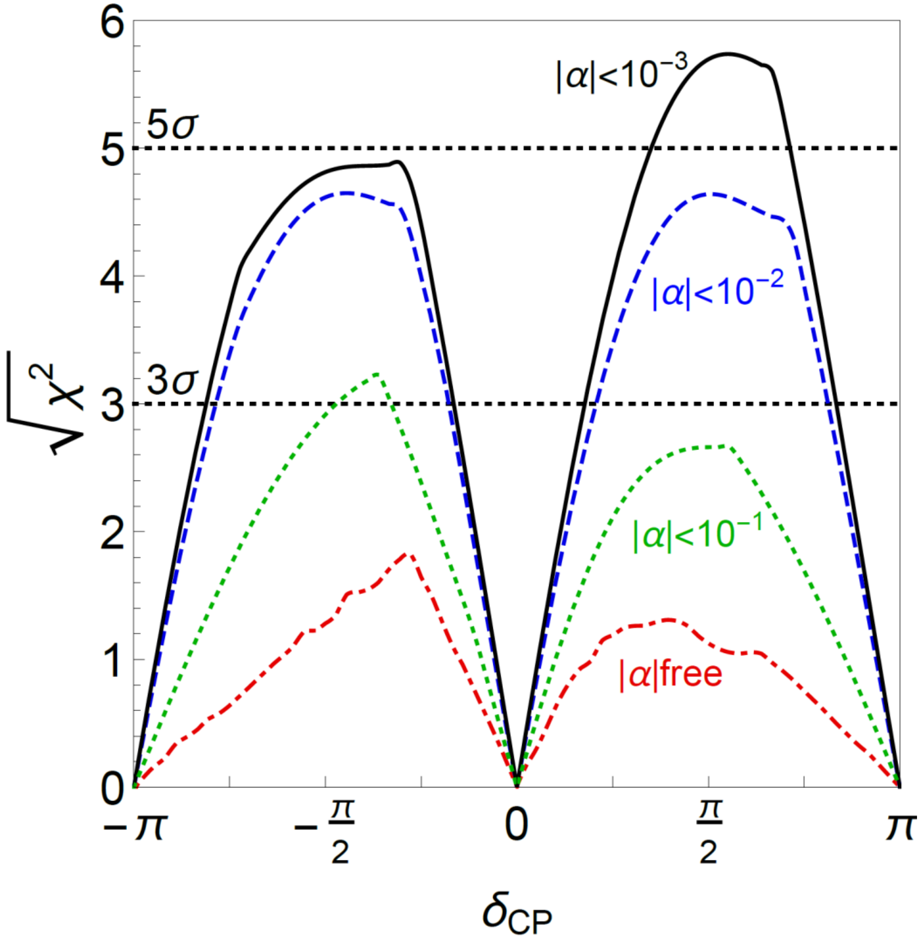


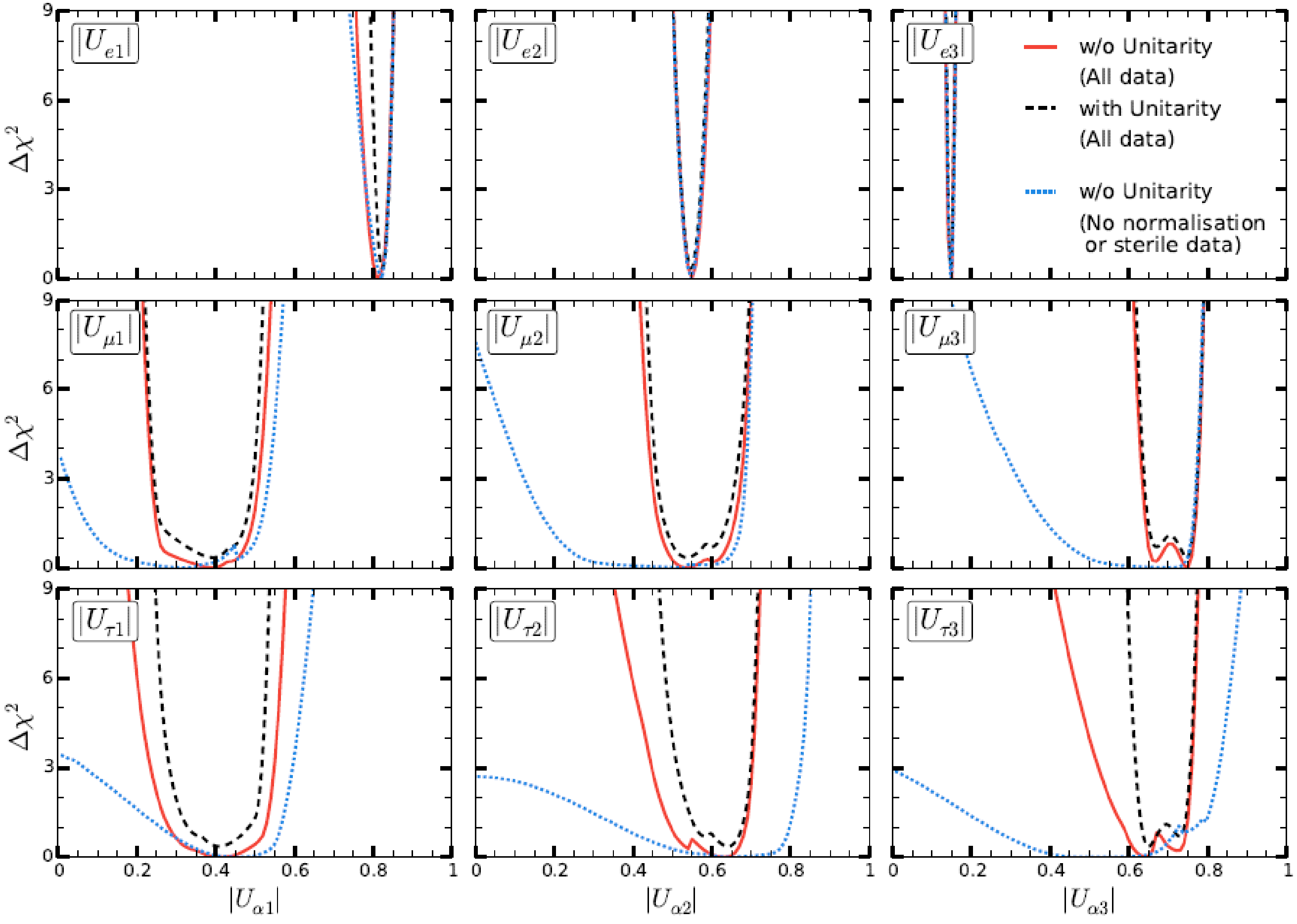
The new phases in α imply new sources of CP violation that could be confused with the standard

With ~10^{-3} priors on NU, the CPV discovery potential of DUNE is recovered

See also: F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1612.07377.

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

Steriles vs NU

	"Non-Unitarity"	"Light steriles"	
	$(m > \mathrm{EW})$	$\Delta m^2 \gtrsim 100\ \mathrm{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \mathrm{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}\ (2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$

EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774

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

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 1609.08637
C. S. Fong, H. Minakata and H. Nunokawa 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 1609.08637
C. S. Fong, H. Minakata and H. Nunokawa 1609.08623

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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 1609.08637
C. S. Fong, H. Minakata and H. Nunokawa 1609.08623

Steriles vs NU

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

“Heavy ν” Non-Unitarity

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

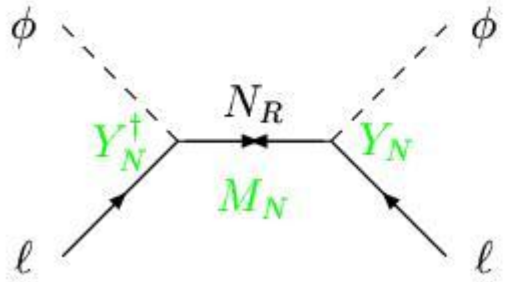
“Light ν” Steriles

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

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

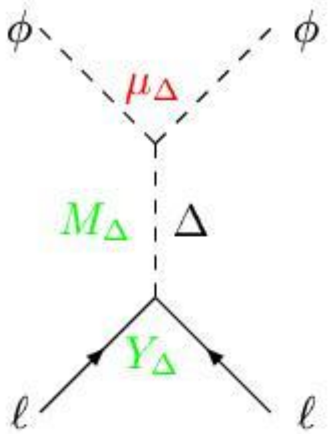
M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Other mechanisms for neutrino masses



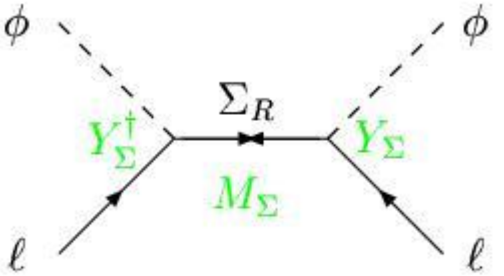
Type I seesaw

N_R fermionic singlet



Type II seesaw

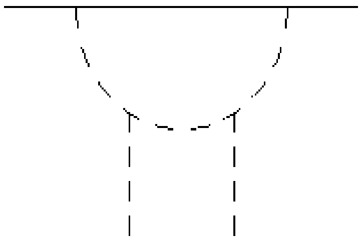
Δ scalar triplet

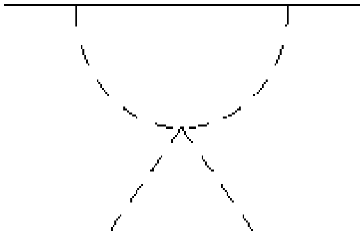


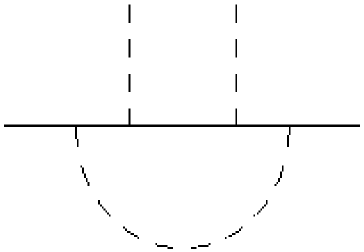
Type III seesaw

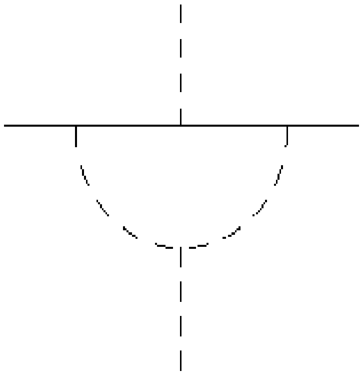
Σ_R fermionic triplet

Loop level realizations







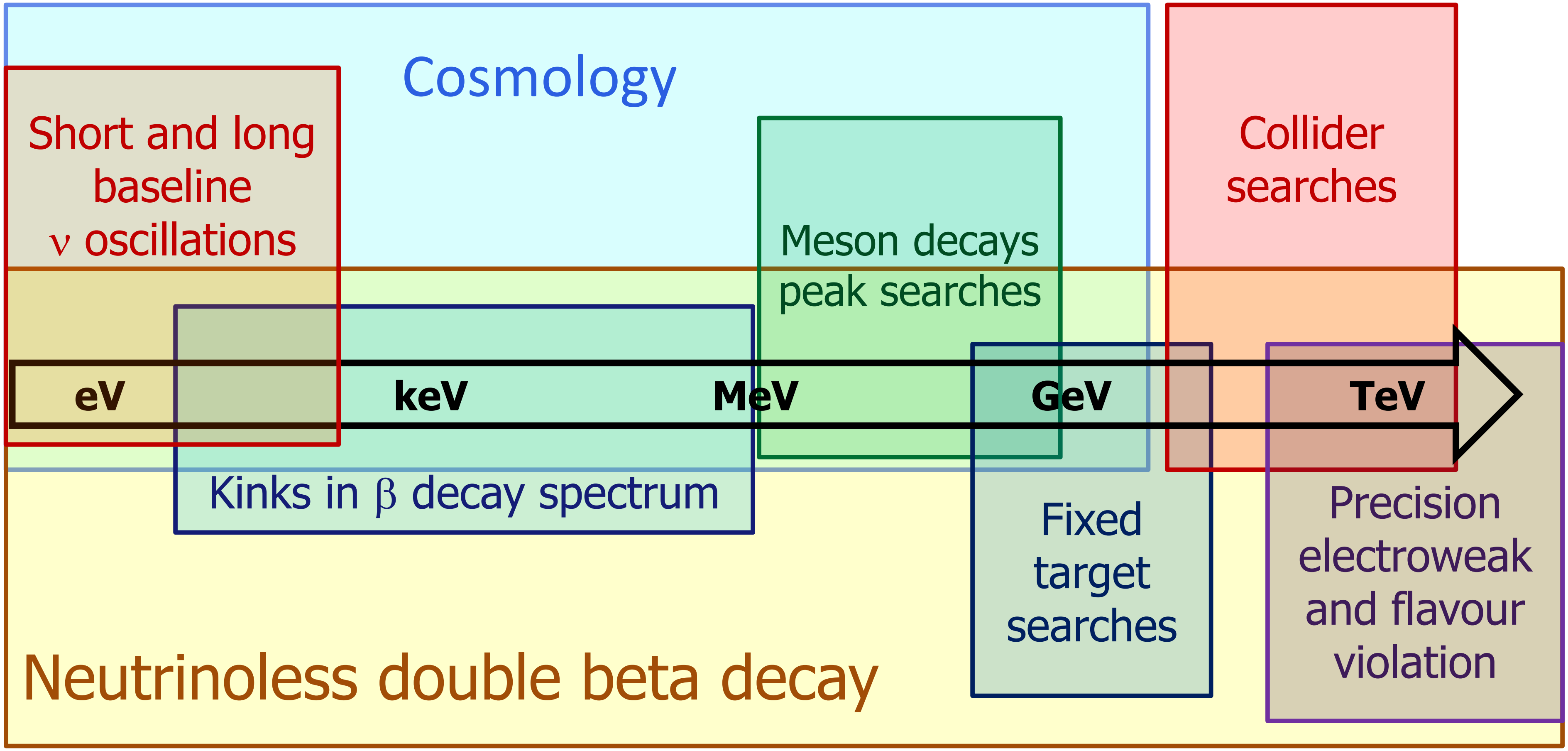


...

Neutrino mass mechanisms different from the type-I Seesaw involve charged particles → Collider and precission searches

Conclusions

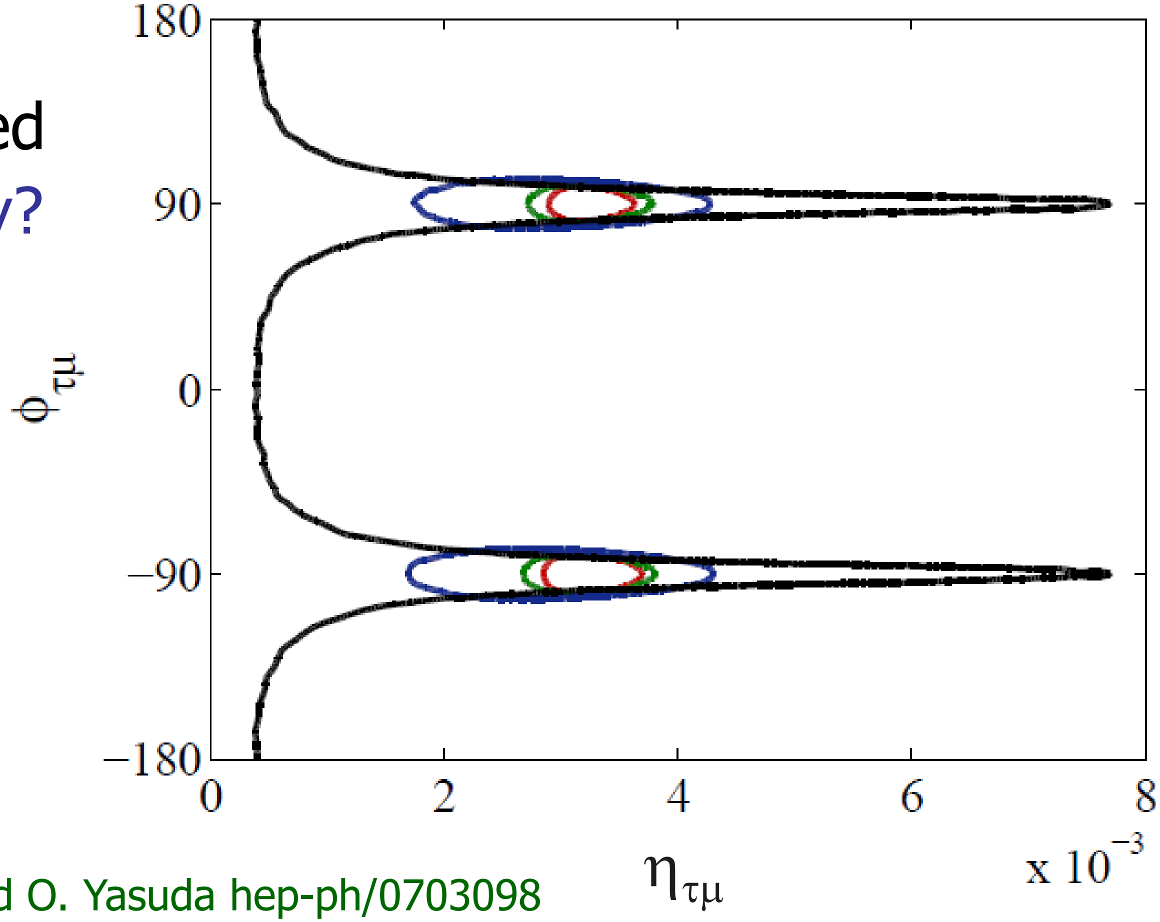
- Neutrino masses and mixings point to a new physics scale where Lepton number is broken
- Different phenomenology depending on the scale



Probing the Seesaw: Non-Unitarity

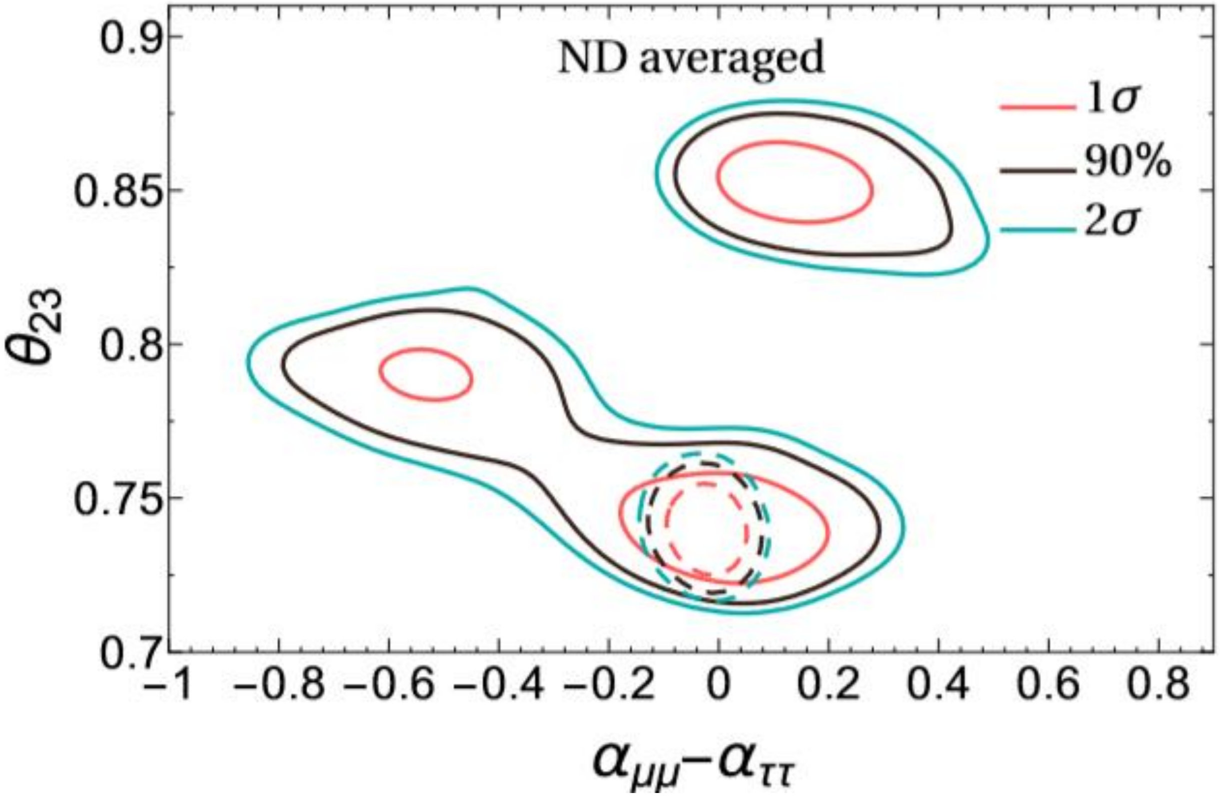
Non-unitarity from heavy ν mixing is beyond the reach of present and near future facilities (given the 10^{-3}-10^{-4} bounds)

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

Averaged out steriles at DUNE



If uncosntrained they can also hinder DUNE's hability to determine the octant or maximality of θ_{23} but with present bounds they are not a problem

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