

# Non-Standard Neutrino Interactions and PMNS Non-Unitarity

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Enrique Fernández-Martínez



in**Vi**siblesPlus elus**i**ves

# Searching for matter NSI

As Mariam discussed NSI can have a huge impact in neutrino oscillation facilities:

$$2\sqrt{2}G_F \epsilon_{\alpha\beta}^{f,V} (\bar{\nu}_\beta \gamma^\mu P_L \nu_\alpha) (\bar{f} \gamma_\mu f)$$

P. Coloma,  
M.C. Gonzalez-Garcia,  
M. Maltoni and  
T. Schwetz 1708.02899

	$f = u$	$f = d$
$\epsilon_{ee}^{f,V}$	[0.028, 0.60]	[0.030, 0.55]
$\epsilon_{\mu\mu}^{f,V}$	[-0.088, 0.37]	[-0.075, 0.33]
$\epsilon_{\tau\tau}^{f,V}$	[-0.090, 0.38]	[-0.075, 0.33]
$\epsilon_{e\mu}^{f,V}$	[-0.073, 0.044]	[-0.07, 0.04]
$\epsilon_{e\tau}^{f,V}$	[-0.15, 0.13]	[-0.13, 0.12]
$\epsilon_{\mu\tau}^{f,V}$	[-0.01, 0.009]	[-0.009, 0.008]

Bounds mainly driven by oscillation data (+COHERENT)...  
...can they be saturated avoiding additional constraints?

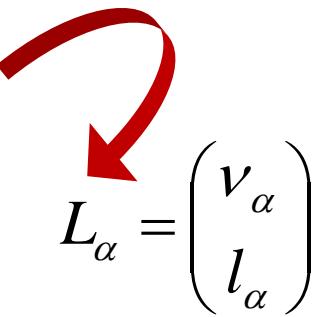
See also Y. Farzan and M. Tortola 1710.09360 for a review

# Gauge invariance

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However

$$2\sqrt{2}G_F \epsilon_{\alpha\beta}^m (\bar{\nu}_\beta \gamma^\mu P_L \nu_\alpha) (\bar{f} \gamma_\mu P_{L,R} f)$$

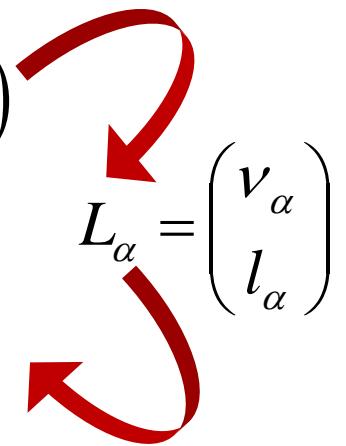
$$L_\alpha = \begin{pmatrix} \nu_\alpha \\ l_\alpha \end{pmatrix}$$


# Gauge invariance

However  $2\sqrt{2}G_F \epsilon_{\alpha\beta}^m (\bar{\nu}_\beta \gamma^\mu P_L \nu_\alpha) (\bar{f} \gamma_\mu P_{L,R} f)$

is related to  $2\sqrt{2}G_F \epsilon_{\alpha\beta}^m (\bar{l}_\beta \gamma^\mu P_L l_\alpha) (\bar{f} \gamma_\mu P_{L,R} f)$

by gauge invariance and very strong bounds exist



$$\epsilon_{e\mu}^m < \sim 10^{-6}$$

$\mu \rightarrow e \gamma$

$$\epsilon_{e\tau}^m < \sim 10^{-4}$$

$\mu \rightarrow e$  in nuclei

$$\epsilon_{\mu\tau}^m < \sim 10^{-4}$$

$\tau$  decays

S. Bergmann et al. hep-ph/0004049

Z. Berezhiani and A. Rossi hep-ph/0111147

S. Antusch, M. Blennow, EFM and T. Ota, 1005.0756

# Large NSI?

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Search for gauge invariant **SM** extensions satisfying:

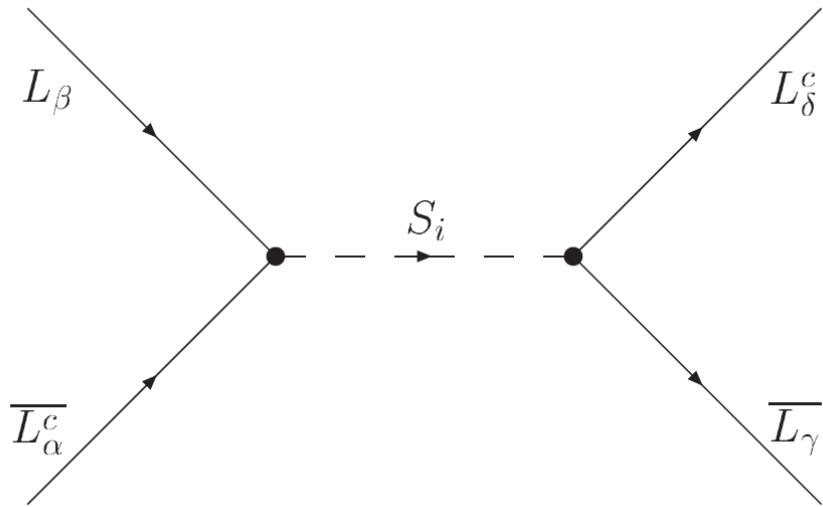
- Matter **NSI** are generated at tree level by integrating out heavy fields
- 4-charged fermion ops not generated at the same level
- No cancellations between diagrams with **different** messenger particles to avoid constraints
- The Higgs Mechanism is responsible for **EWSB**

S. Antusch, J. Baumann and EFM 0807.1003

B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

# Large NSI?

At d=6 only one direct possibility: charged scalar singlet



Present in Zee model or  
R-parity violating SUSY

$$\mathcal{L}_{int}^S = -\lambda_{\alpha\beta}^i \overline{L}_\alpha^c i\sigma_2 L_\beta S_i + \text{H.c.} = \lambda_{\alpha\beta}^i S_i (\overline{\ell}_\alpha^c P_L \nu_\beta - \overline{\ell}_\beta^c P_L \nu_\alpha) + \text{H.c.}$$

$$\mathcal{L}_{NSI}^{d=6,as} = c_{\alpha\beta\gamma\delta}^{d=6,as} (\overline{L}_\alpha^c i\sigma_2 L_\beta) (\overline{L}_\gamma i\sigma_2 L_\delta^c) \quad \varepsilon_{\alpha\beta}^{m,e_L} = \sum_i \frac{\lambda_{e\beta}^i \lambda_{e\alpha}^{i*}}{\sqrt{2} G_F m_{S_i}^2}$$

# Large NSI?

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Since  $\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$  only  $\varepsilon_{\mu\mu}$ ,  $\varepsilon_{\mu\tau}$  and  $\varepsilon_{\tau\tau} \neq 0$

Very constrained:

$$|\varepsilon_{\mu\mu}^{m,e_L}| < 8.2 \cdot 10^{-4}$$

$$|\varepsilon_{\tau\tau}^{m,e_L}| < 8.4 \cdot 10^{-3}$$

$$|\varepsilon_{\mu\tau}^{m,e_L}| < 1.9 \cdot 10^{-3}$$

$\mu \rightarrow e \gamma$

$\mu$  decays

$\tau$  decays

CKM unitarity

F. Cuypers and S. Davidson hep-ph/9310302  
S. Antusch, J. Baumann and EFM 0807.1003

# NSI from right-handed neutrinos

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All **SM** fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_L \phi f_R \xrightarrow{\substack{\text{SSB} \\ \langle \phi \rangle = \frac{v}{\sqrt{2}}}} \frac{Y_f v}{\sqrt{2}} \bar{f}_L f_R \quad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add  $N_R$ : a Majorana mass is also allowed

$$M_{_N} \bar{N}_{_R}^C N_{_R}$$

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To be searched for at experiments!!

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

If  $M_N \gg m_D$  then  $M \approx M_N$  and  $m \approx m_D^T M_N^{-1} m_D \rightarrow$  smallness of  $v$  masses

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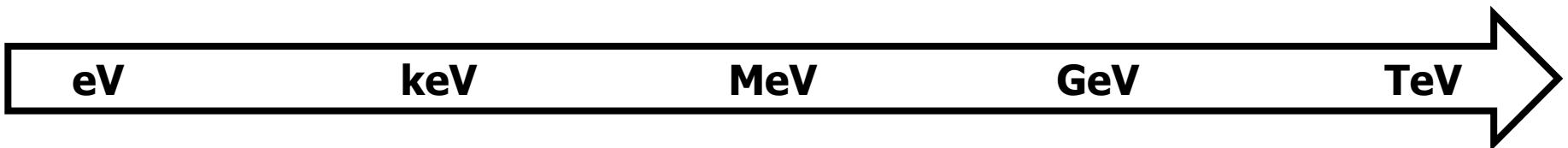
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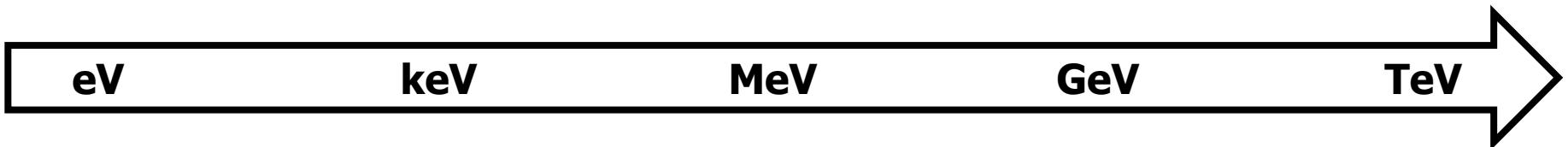


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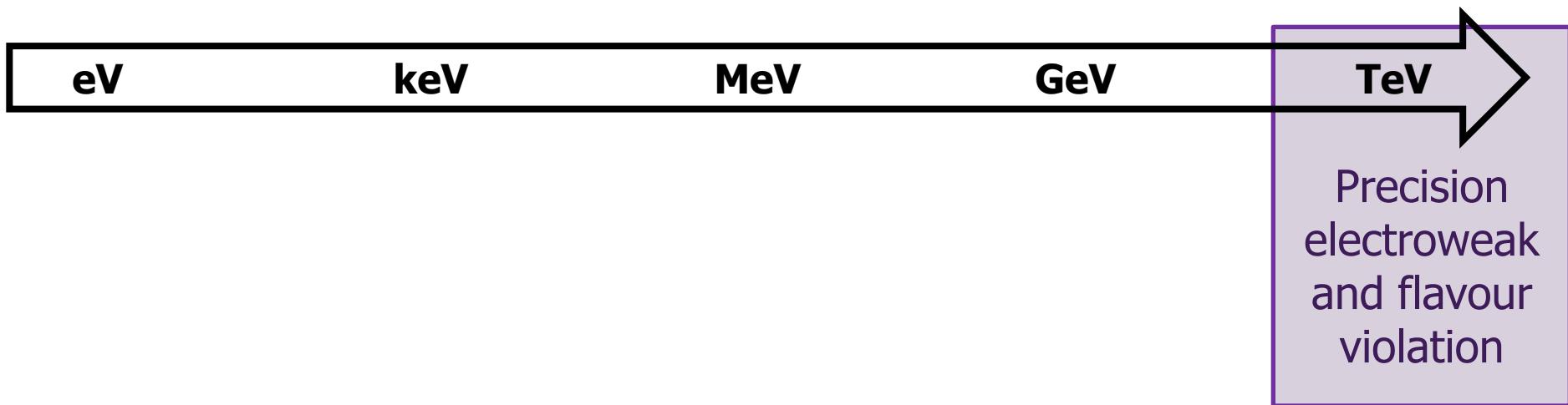
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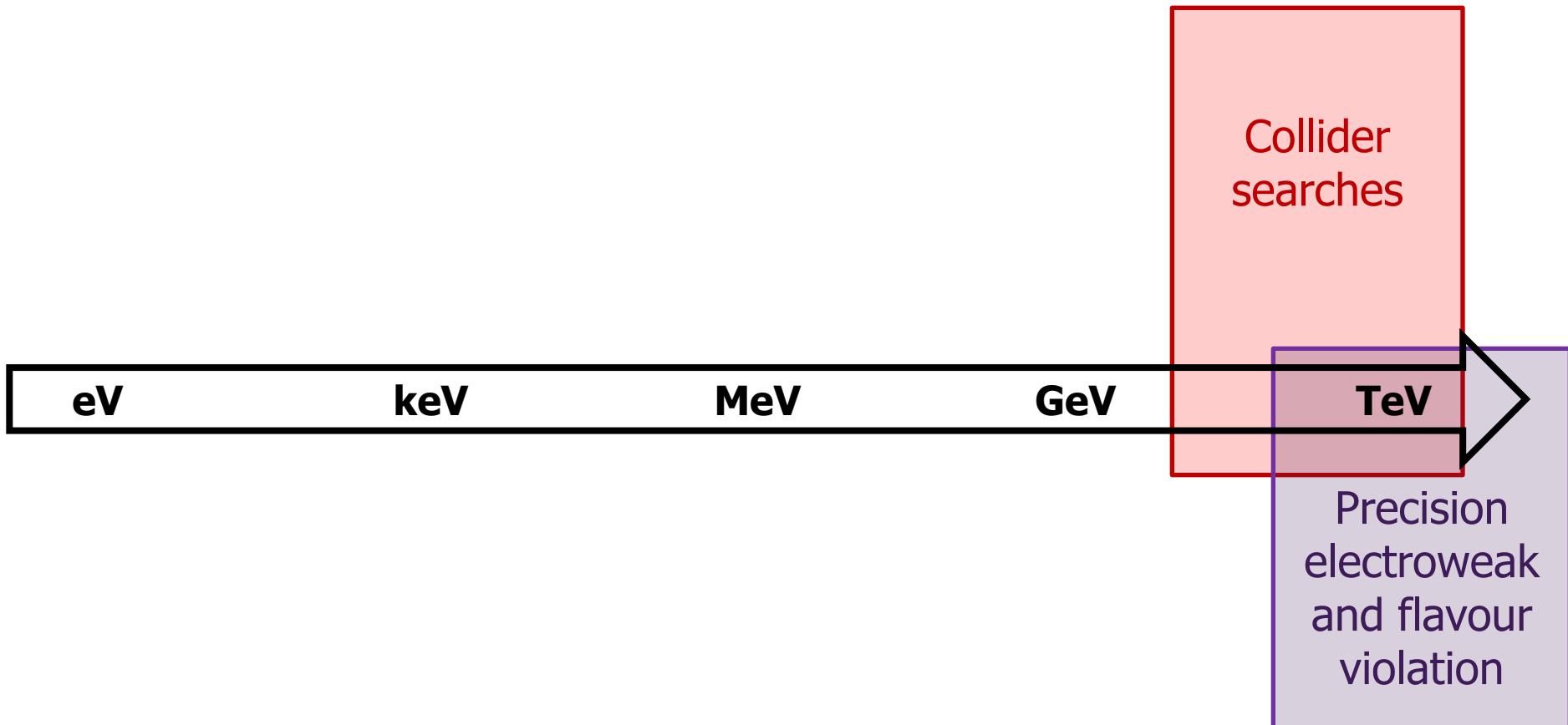
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Very different phenomenology at different scales

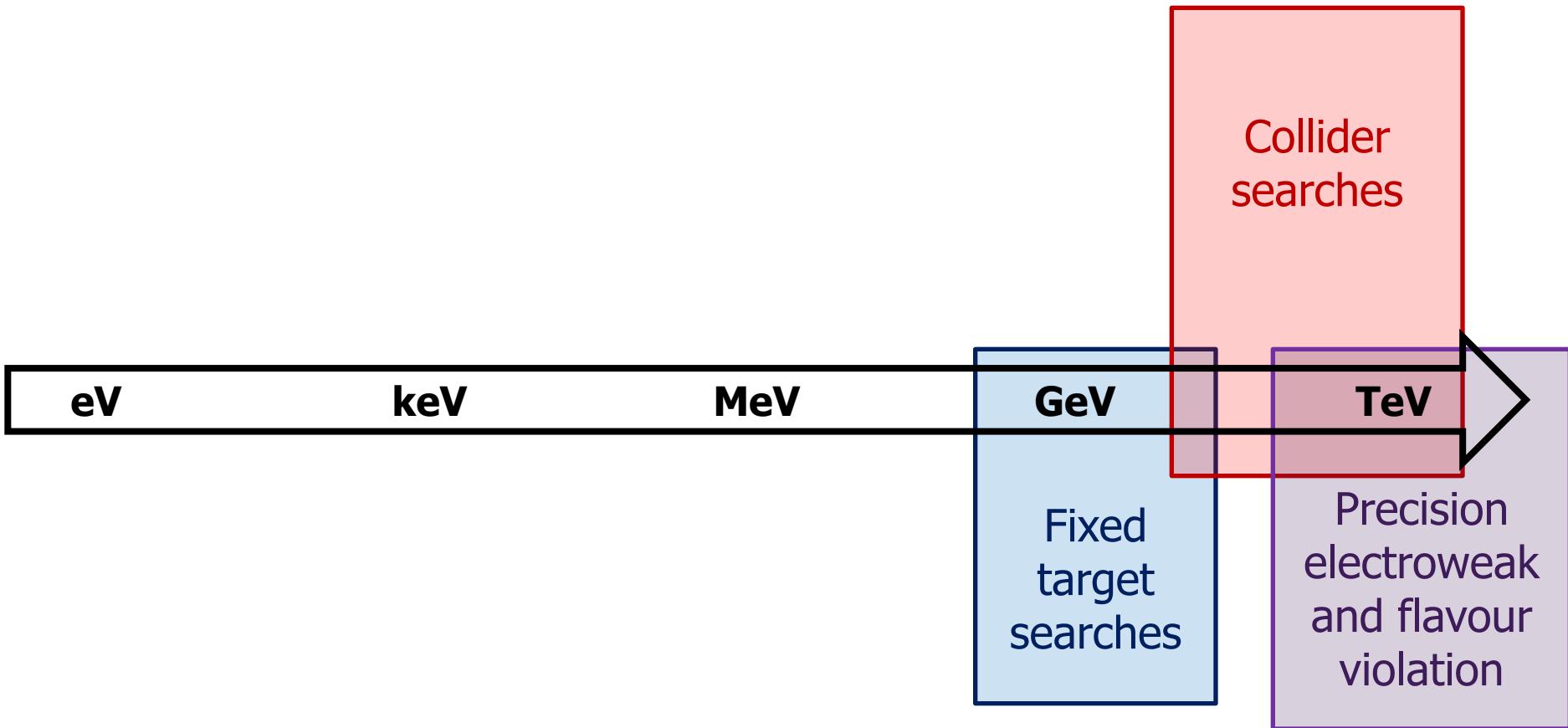
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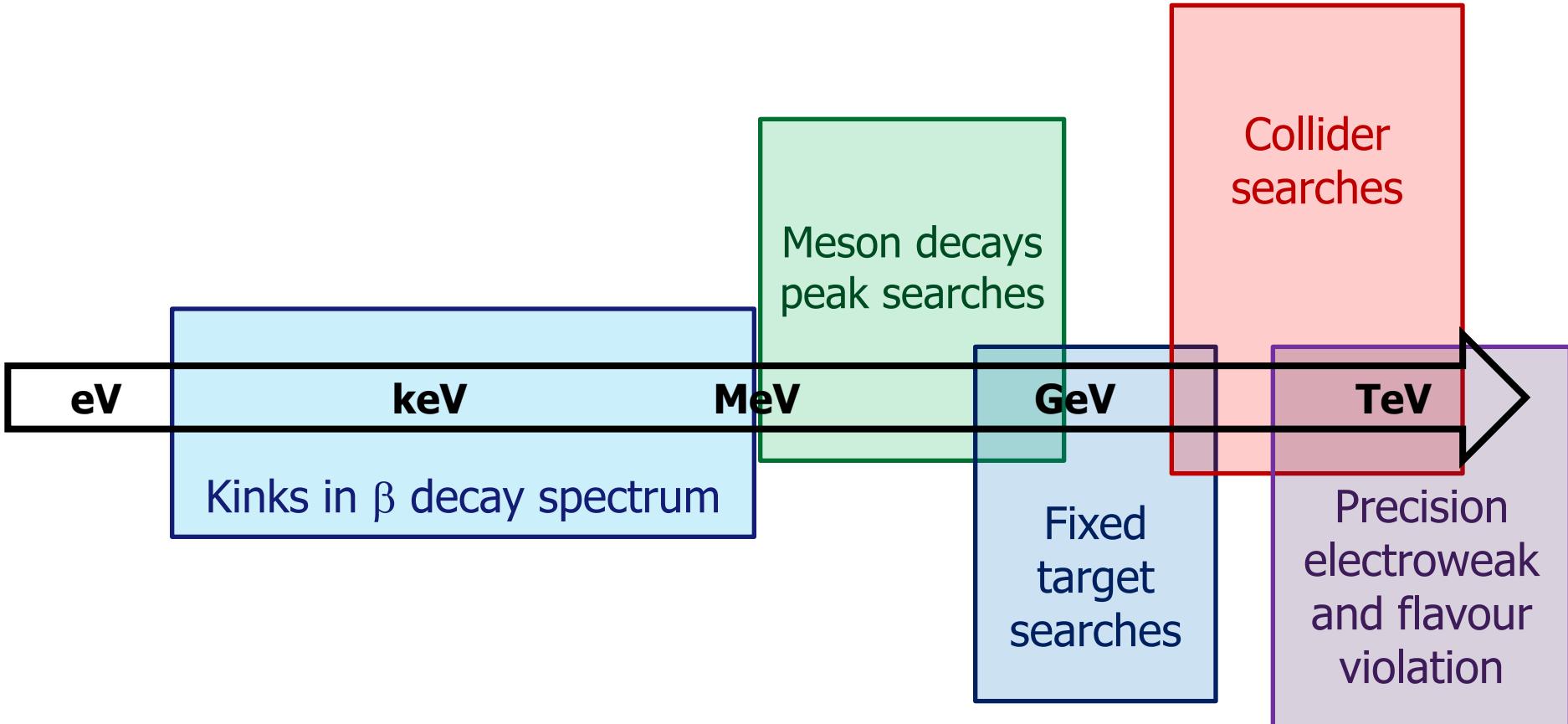
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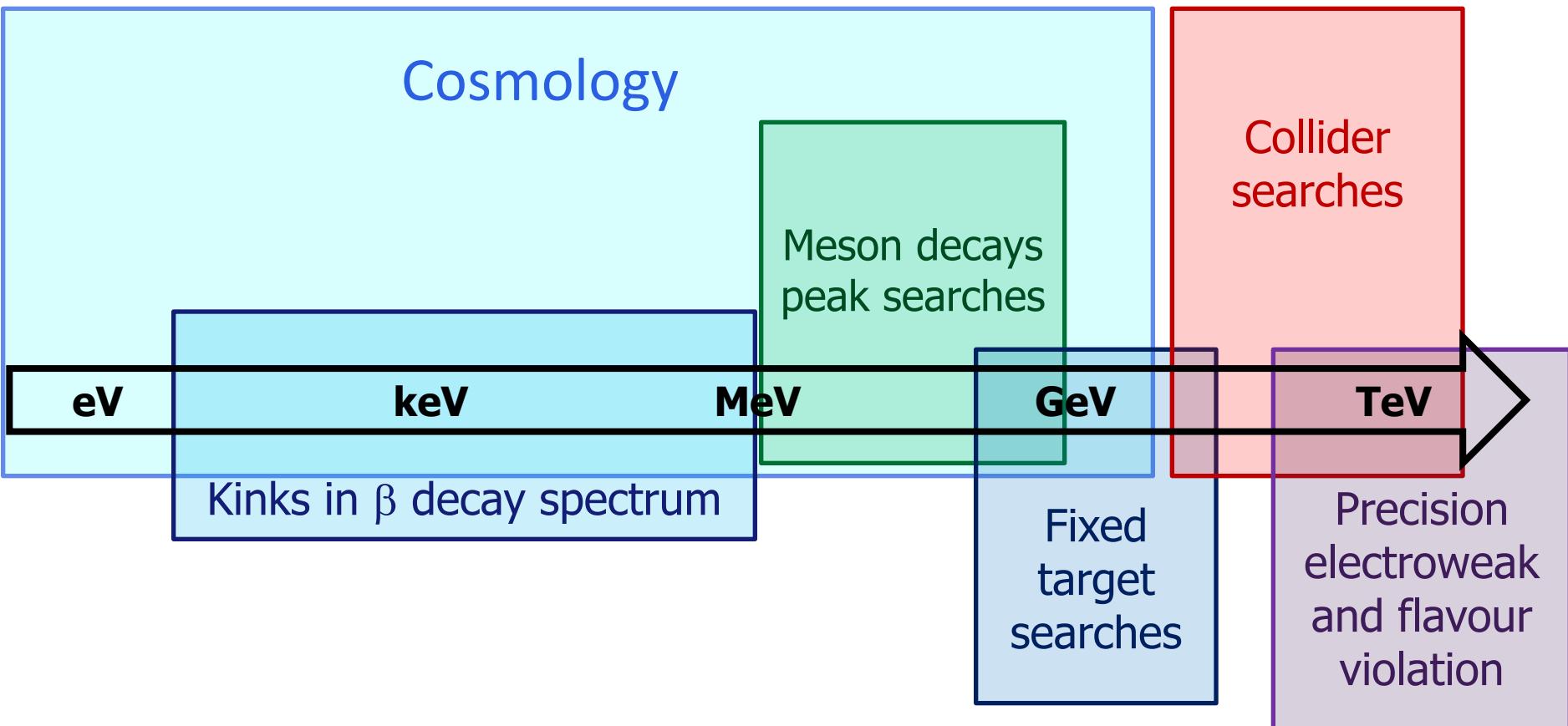
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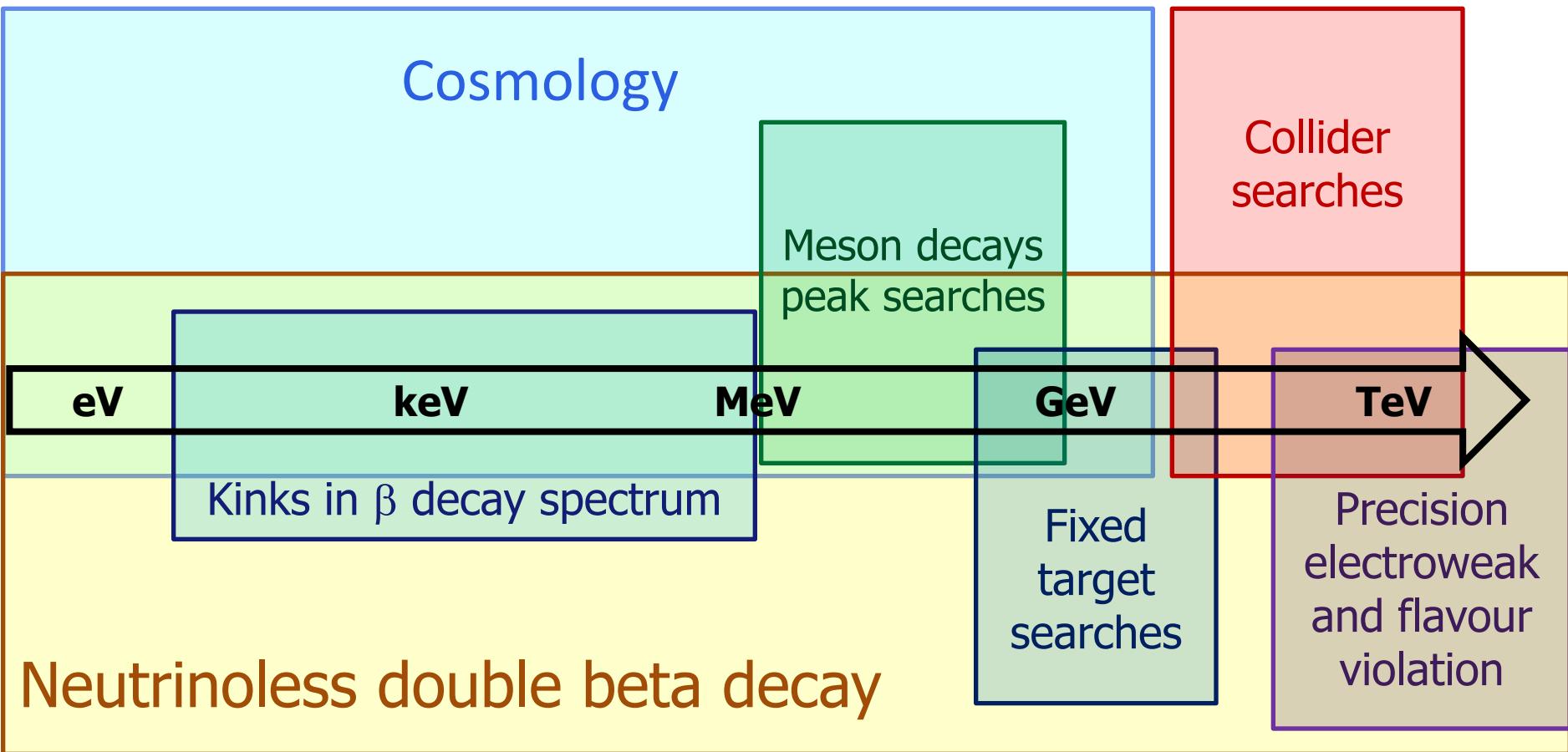
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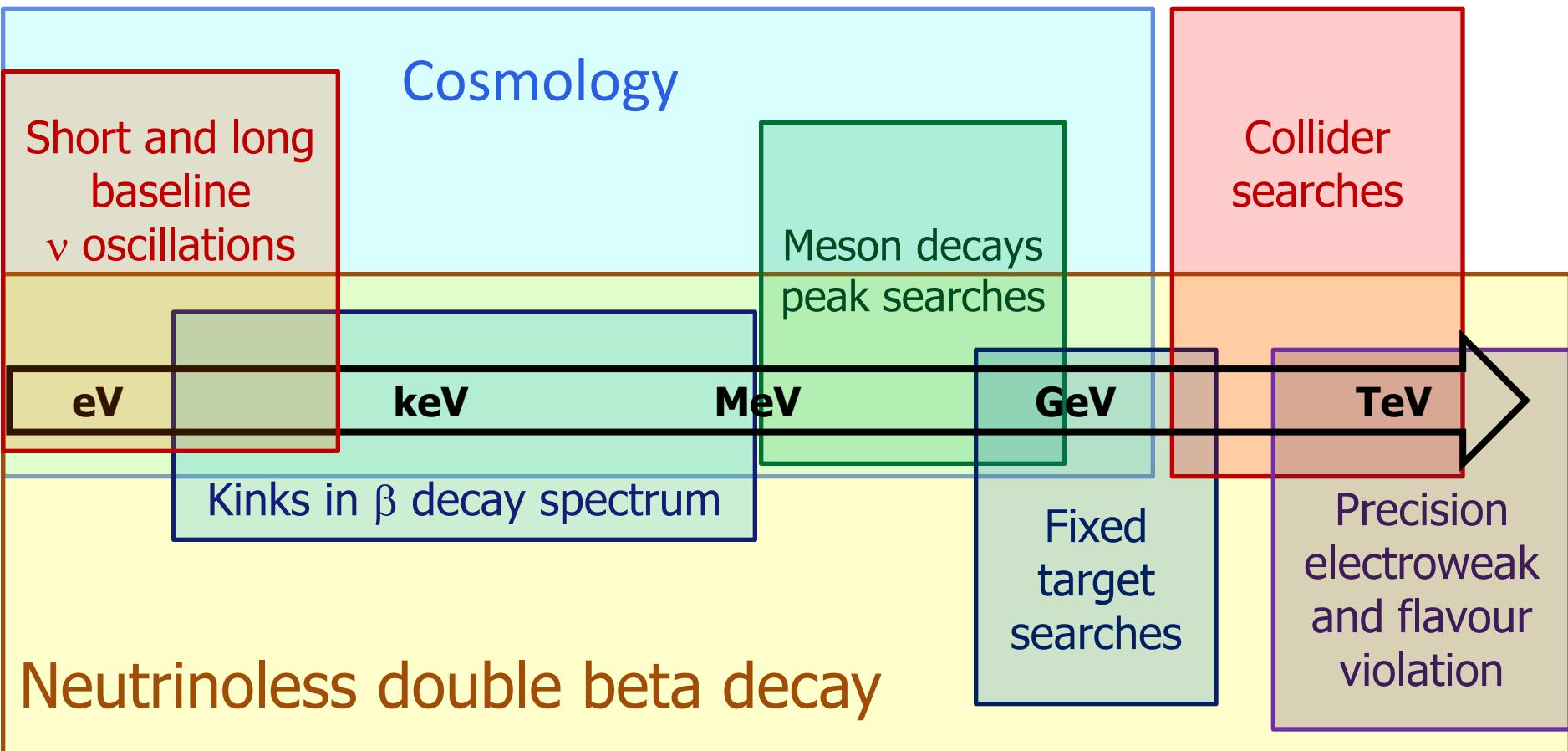
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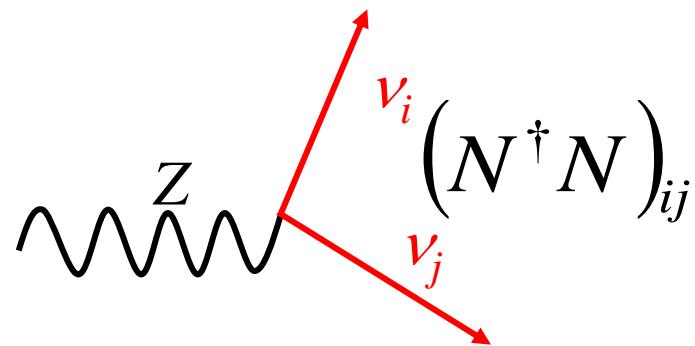
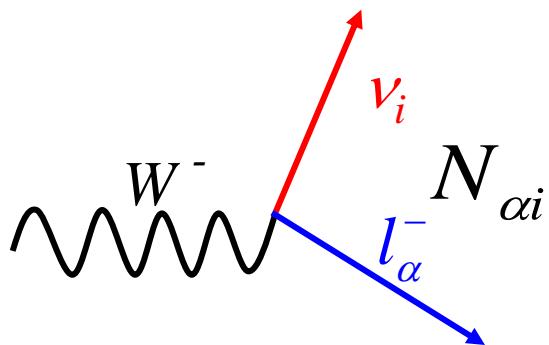
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# Probing the Seesaw: Non-Unitarity

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

The  $3 \times 3$  submatrix  $N$  of active neutrinos will not be unitary

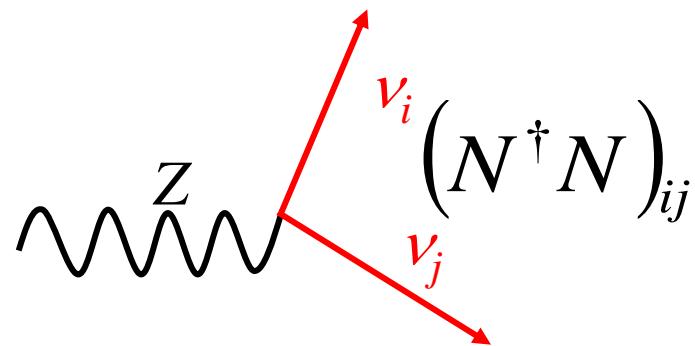
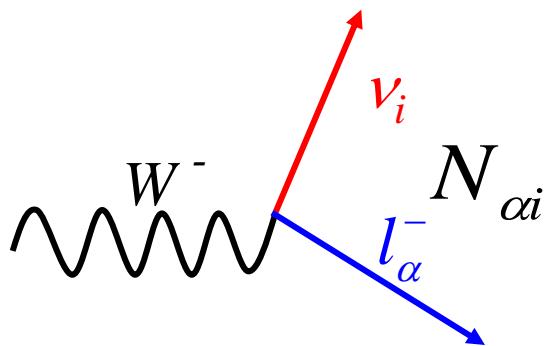


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Effects in weak interactions...

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

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

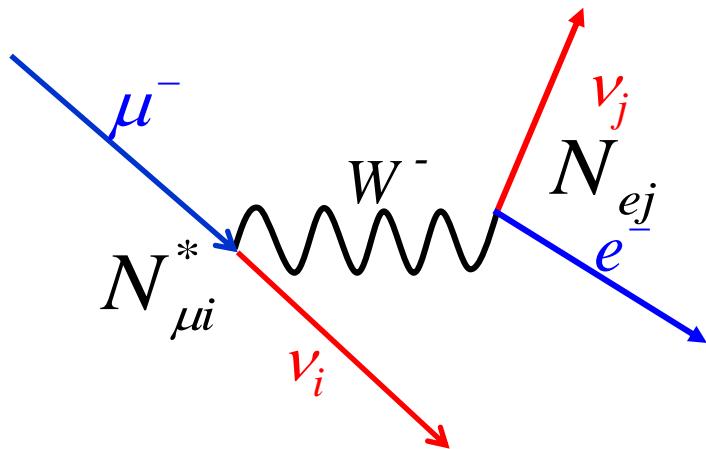
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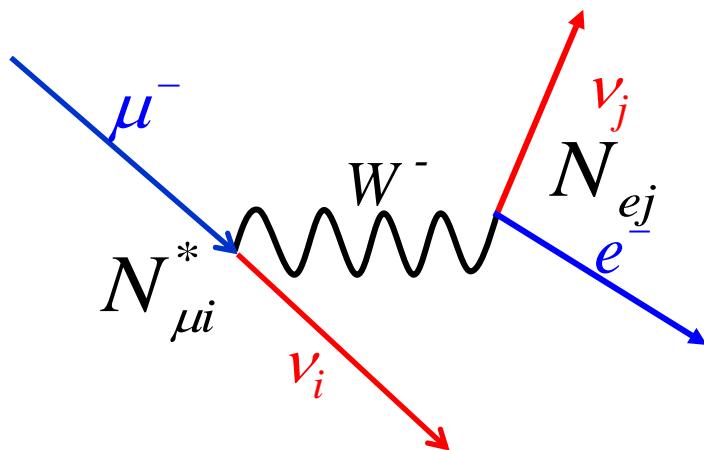
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$$\text{But } G_F = \frac{\alpha\pi M_Z^2}{\sqrt{2}M_W^2(M_Z^2 - M_W^2)}$$

Agree at the ~per mille level

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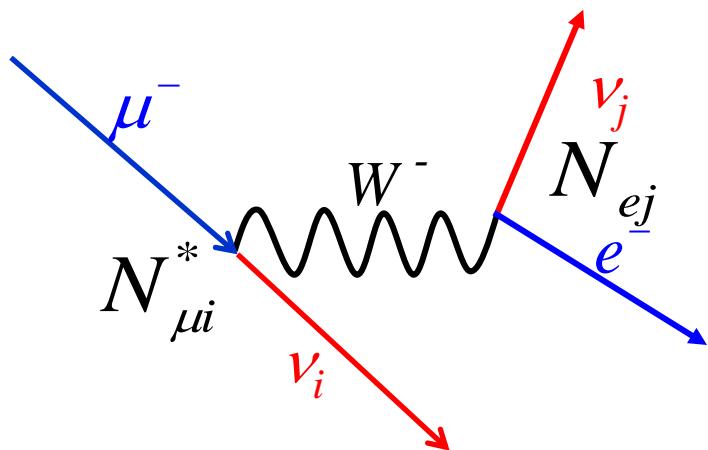
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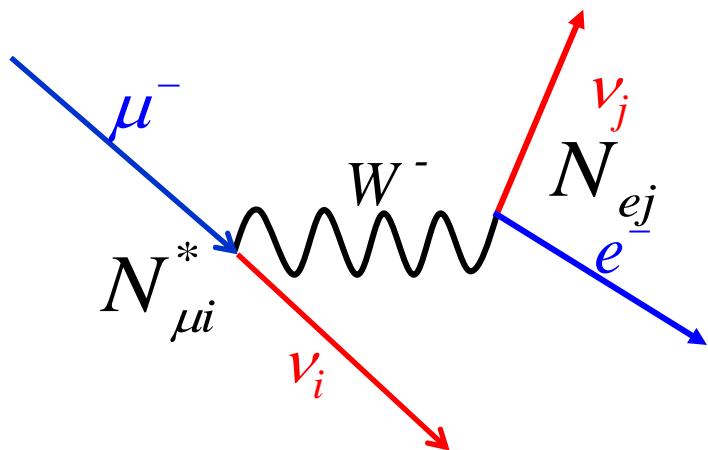
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Lepton weak universality from  $\pi$ ,  $K$  and  $\tau$  decay ratios

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

# Probing the Seesaw: Non-Unitarity

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Recent bounds from a **global fit** to **flavour** and **Electroweak** precision data (28 observables considered)

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

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

See also (incomplete list!) 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

# Probing the Seesaw: Non-Unitarity

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

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

Triangular structure more convenient 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.

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F. J. Escrivuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1503.08879.

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

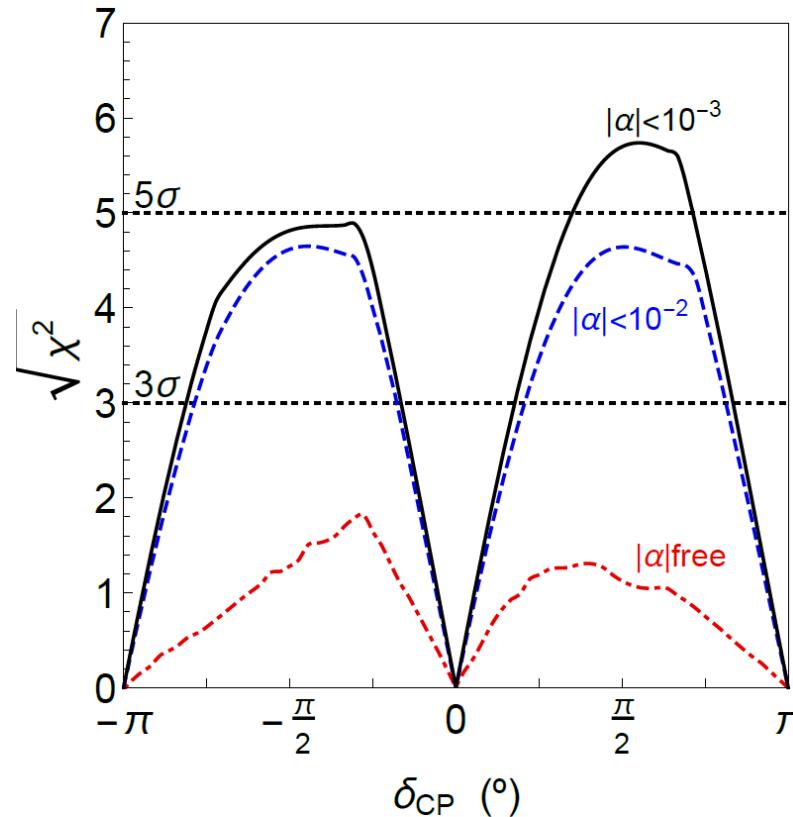
**Dictionary**

$$\epsilon_{\beta\alpha}^{s*} = \epsilon_{\alpha\beta}^d = -\alpha_{\alpha\beta} \quad \epsilon_{ee} = -\alpha_{ee} \quad \epsilon_{\mu\mu} = \alpha_{\mu\mu} \quad \epsilon_{\tau\tau} = \alpha_{\tau\tau}$$

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

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

# Effects in oscillations



If unconstrained, just allowing for them in the fit destroys the sensitivity to CPV of DUNE but with priors of  $10^{-3}$  the standard sensitivity is recovered

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

# A new physics scale

Short and long  
baseline  
 $\nu$  oscillations

eV

keV

MeV

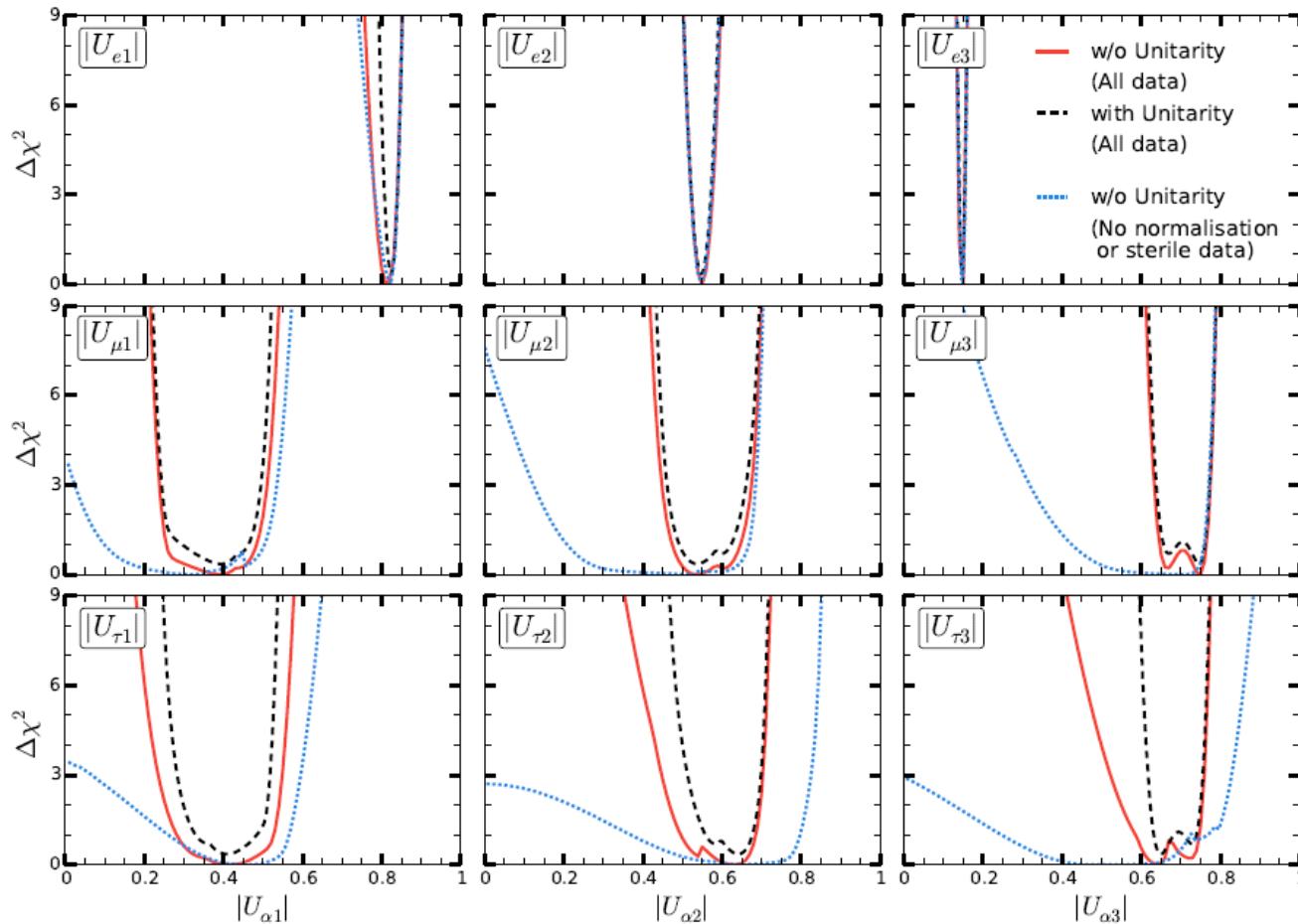
GeV

TeV

Precision  
electroweak  
and flavour  
violation

# A different possibility: lighter Steriles

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



# Steriles vs NU

	“Non-Unitarity” $(m > \text{EW})$	“Light steriles”	
		$\Delta m^2 \gtrsim 100 \text{ eV}^2$	$\Delta m^2 \sim 0.1 - 1 \text{ eV}^2$
$\alpha_{ee}$	$1.3 \cdot 10^{-3}$ [44]	$2.4 \cdot 10^{-2}$ [46]	$1.0 \cdot 10^{-2}$ [46]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [44]	$2.2 \cdot 10^{-2}$ [47]	$1.4 \cdot 10^{-2}$ [48]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [44]	$1.0 \cdot 10^{-1}$ [47]	$1.0 \cdot 10^{-1}$ [47]
$ \alpha_{\mu e} $	$6.8 \cdot 10^{-4} (2.4 \cdot 10^{-5})$ [44]	$2.5 \cdot 10^{-2}$ [49]	$1.7 \cdot 10^{-2}$
$ \alpha_{\tau e} $	$2.7 \cdot 10^{-3}$ [44]	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$ \alpha_{\tau\mu} $	$1.2 \cdot 10^{-3}$ [44]	$1.2 \cdot 10^{-2}$ [50]	$5.3 \cdot 10^{-2}$

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

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

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

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

$$+ \sum_{i,J} N_{\beta i} N_{\alpha i}^* \Theta_{\alpha J} \Theta_{\beta J}^* e^{\frac{-i\Delta m_{iJ}^2 L}{2E}}$$

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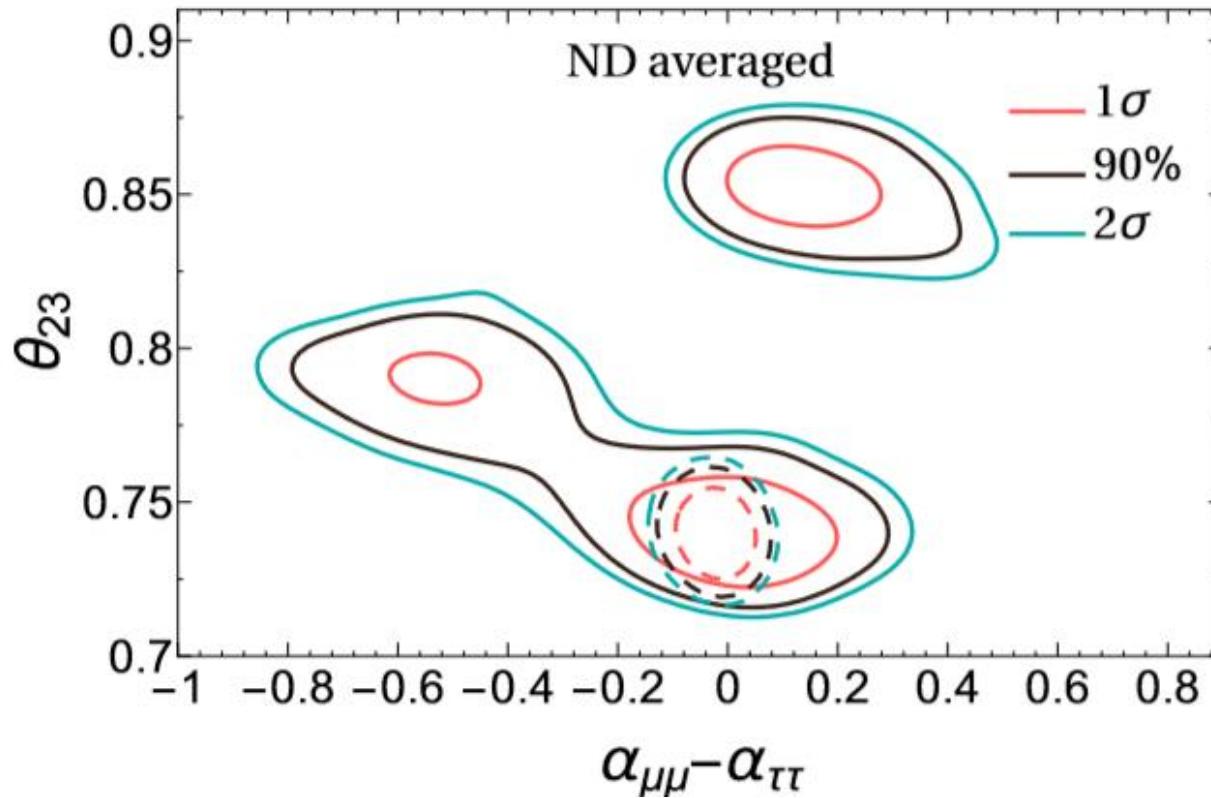
$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N_{\alpha i}^* N_{\alpha j} N_{\beta j}^* e^{\frac{-i\Delta m_{ij}^2 L}{2E}}$$

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

# Averaged out steriles at DUNE



If unconstrained they can also hinder DUNE's ability to determine the octant or maximality of  $\theta_{23}$  but with present bounds they are not a problem

# Conclusions

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- Gauge invariance applied to **NSI** implies very **strong bounds**. Possible ways out:
  - EFT not applicable (**light mediators**)
  - **Cancellation** between **different NSI mediators** (**finetuning**)
- Non-Unitarity a type of **NSI**, very motivated by **Seesaw!** But **strong constraints** from flavour and EW precision. Ways out:
  - Low energy non-Unitarity (averaged out **steriles!**)
  - With present constraints standard searches not affected.
- Other ideas?

# Can we escape these bounds?

In F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377  
bounds from charged lepton flavour and precision EW tests are quoted separately from short baseline oscillation searches.

Neutrinos + charged leptons		
$\alpha_{11} >$	0.9974	0.9963
$\alpha_{22} >$	0.9994	0.9991
$\alpha_{33} >$	0.9988	0.9976
$ \alpha_{21}  <$	$1.7 \times 10^{-3}$	$2.5 \times 10^{-3}$
$ \alpha_{31}  <$	$2.0 \times 10^{-3}$	$4.4 \times 10^{-3}$
$ \alpha_{32}  <$	$1.1 \times 10^{-3}$	$2.0 \times 10^{-3}$

Neutrinos only		
$\alpha_{11} >$	0.98	0.95
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**Interesting suggestion:** there might be a cancellation with some other source of new physics in the first set not present in the second.

The first set is more model-dependent and the second more robust??

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Not possible? Main bounds from first set come from  $\mu$ ,  $\pi$ ,  $\beta$ ,  $K$  and  $\tau$  decays. These are the same processes to produce and detect  $\nu$ . If they are cancelled by new physics, prod and det NSI cancelling the NU effects also in oscillations should be induced.

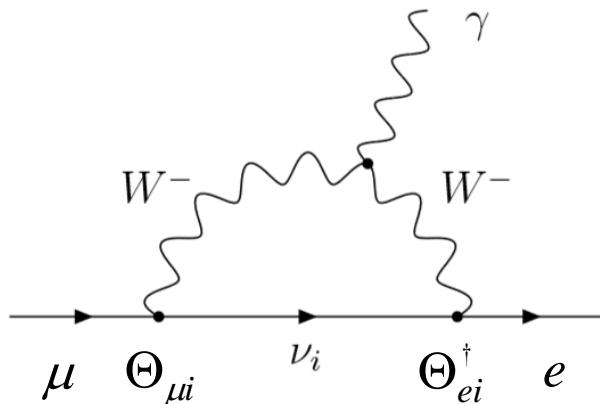
Ideas for discussion?

# Probing the Seesaw: Non-Unitarity

Recent bounds from a **global fit** to **flavour** and **Electroweak** precision data (28 observables considered)

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

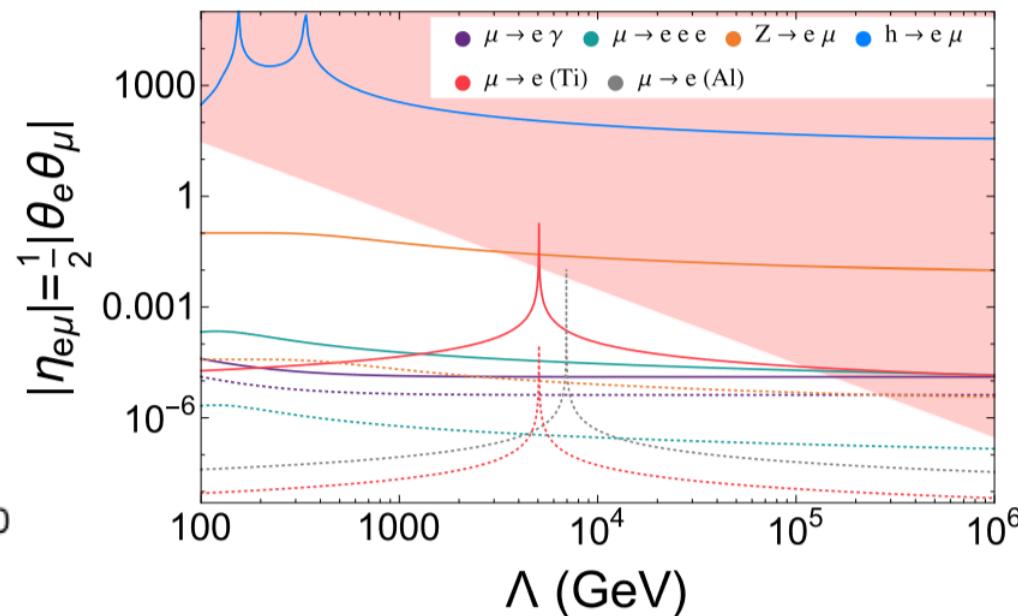
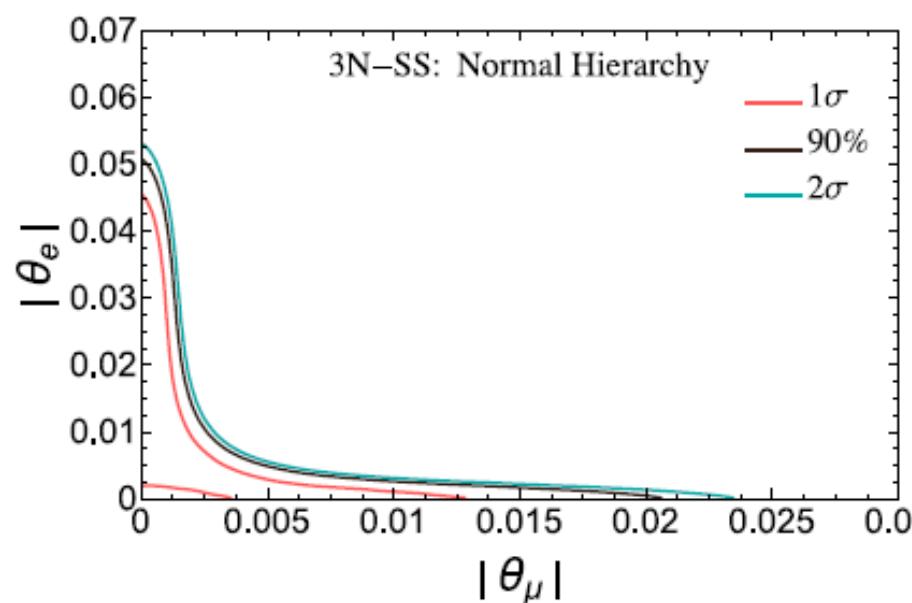
All constraints are for the limit of **very heavy** extra neutrinos  
OK for all processes except maybe the **loop LFV**



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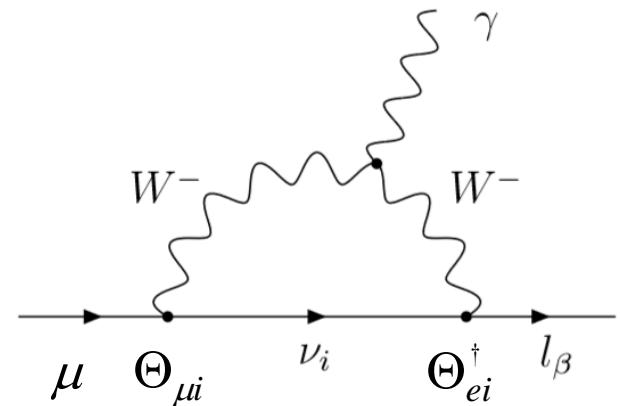


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Cancellations of these diagrams explored in:

D.V. Forero, S. Morisi,  
M. Tortola, J.W.F. Valle 1107.6009



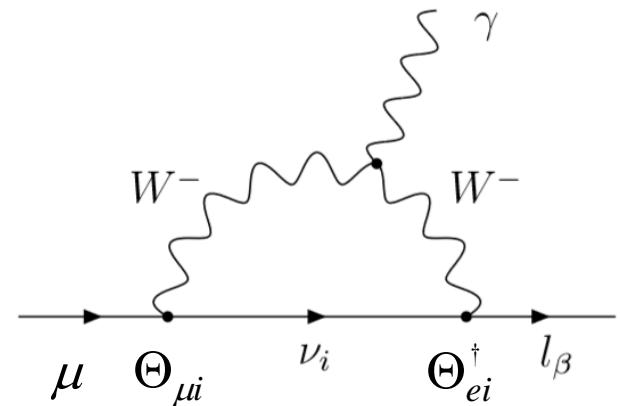
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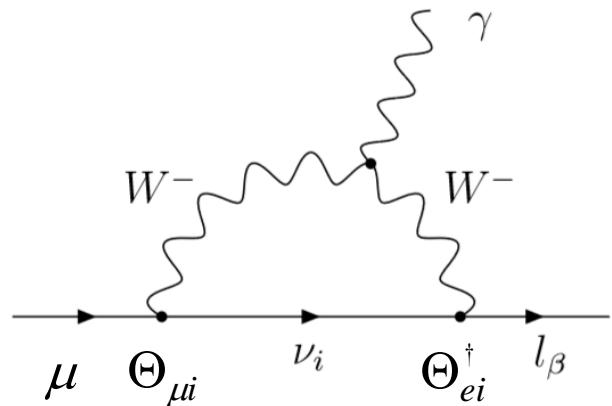
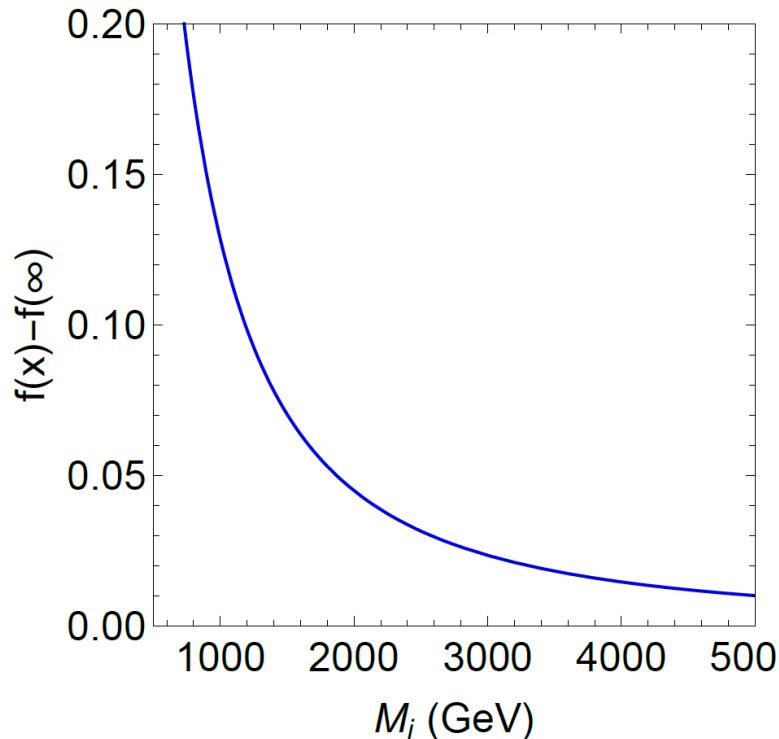
D.V. Forero, S. Morisi,  
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$$\Gamma \propto \sum_i \Theta_{\mu i} \Theta_{ei}^\dagger f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu} f(\infty) + \sum_i \Theta_{\mu i} \Theta_{ei}^\dagger \left( f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty) \right)$$

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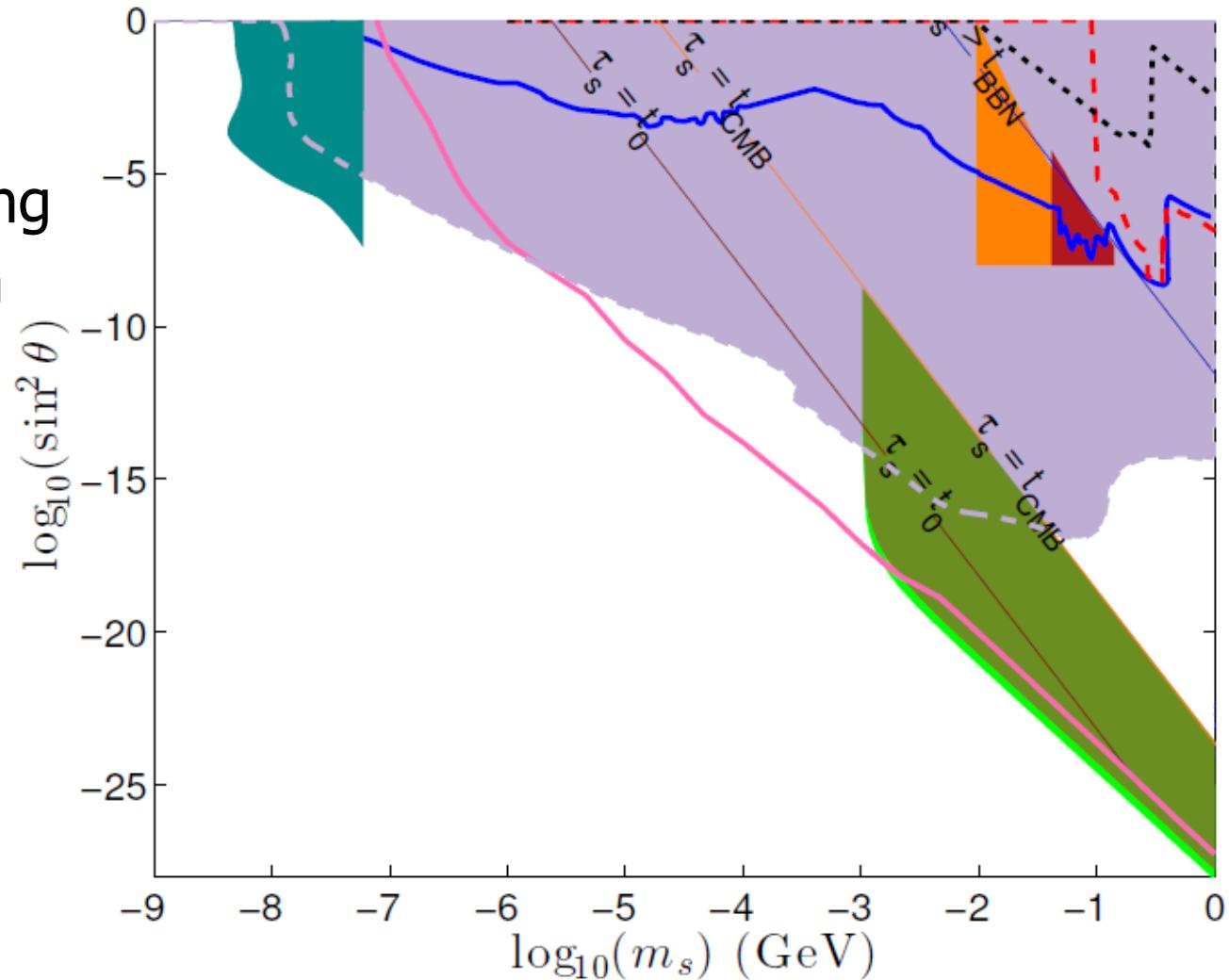
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Without the loop processes

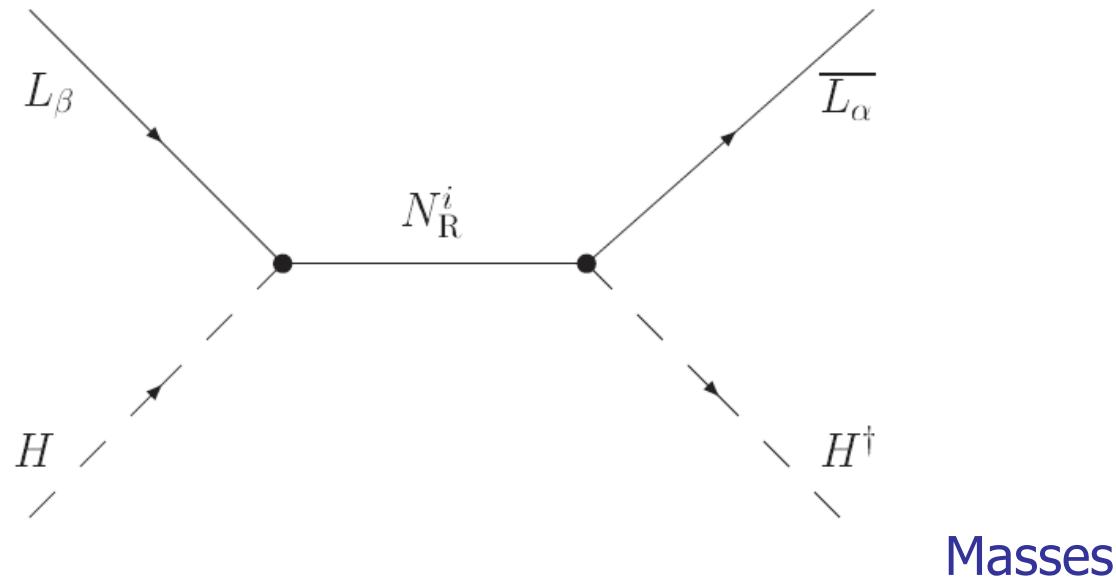
# Cosmology and lab constraints

At intermediate scales very strong constraints from direct searches and cosmology



# Large NSI?

At d=6 indirect way: fermion singlets



$$Y_N^t \frac{1}{M_N} Y_N (\bar{L}_\beta^c i\sigma_2 H) (H^t i\sigma_2 L_\alpha) \xrightarrow{\text{SSB}} \langle H \rangle = \frac{v}{\sqrt{2}} \quad m_\nu = Y_N^t \frac{v^2}{2M_N} Y_N$$

Weinberg 1979

# Large NSI?

At d=6 indirect way: fermion singlets

$$Y_N^\dagger \frac{1}{M_N^2} Y_N (\bar{L}_\beta i\sigma_2 H^*) i\partial (H^t i\sigma_2 L_\alpha) \xrightarrow{\text{SSB}} \eta \bar{\nu}_\beta i\partial \nu_\alpha$$
$$\langle H \rangle = \frac{v}{\sqrt{2}}$$
$$\eta = Y_N^t \frac{v^2}{2M_N^2} Y_N$$

Mixing