Non-Unitarity & Sterile Neutrinos
at neutrino oscillation experiments

Jacobo López-Pavón

Near Detector Physics
at neutrino experiments
CERN, 18- 22 June 2018
Geneve

Outline

- New Physics Scale.
- Neutrino Oscillations vs New Physics
- Parameterizations: Non Unitarity, Sterile neutrinos, NSI.
- Bounds and future sensitivity.
- Conclusions

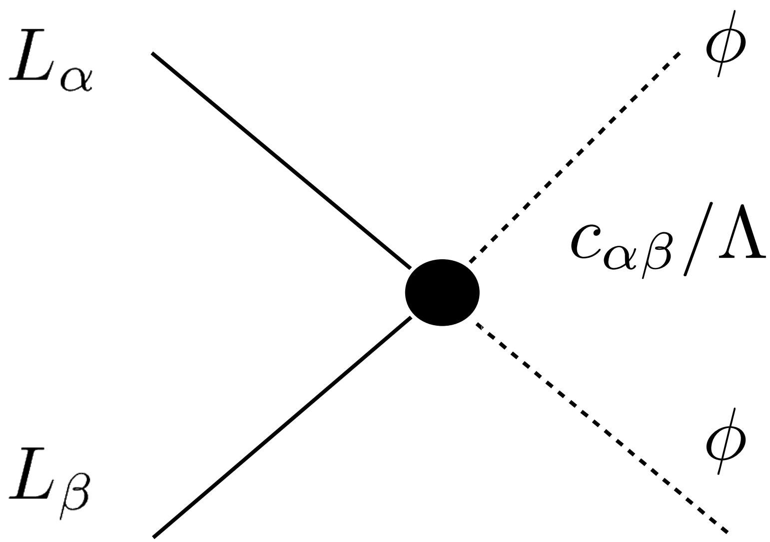
The mechanism responsible for the generation of light neutrino masses

The neutrino mass problem

- Consider SM as a low energy effective theory. With the SM field content, the lowest dimension effective operator is the following (d=5):

$$\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{L^c}_\alpha\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) \xrightarrow{\text{SSB}} \frac{cv^2}{\Lambda}\overline{\nu^c_\alpha}\nu_\alpha$$

Weinberg 76



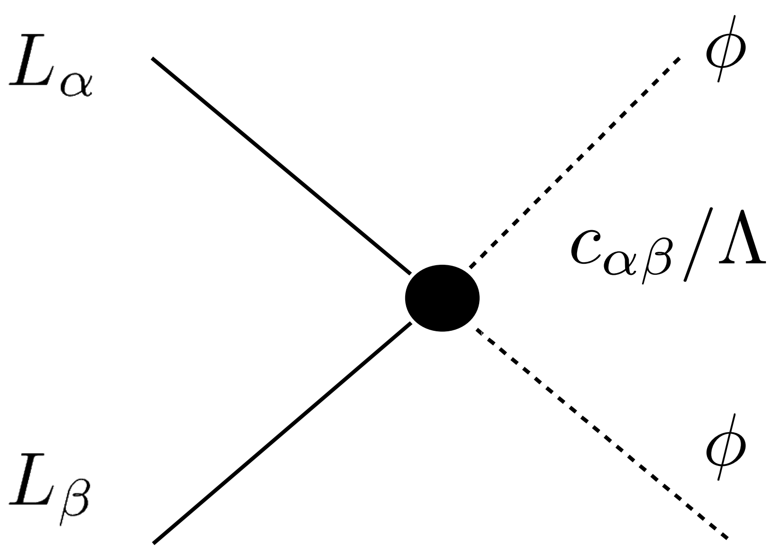
☺ Smallness of neutrino masses can be explained

The neutrino mass problem

- Consider SM as a low energy effective theory. With the SM field content, the lowest dimension effective operator is the following (d=5):

$$\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) \xrightarrow{\text{SSB}} \frac{cv^2}{\Lambda}\overline{\nu^c_\alpha}\nu_\alpha$$

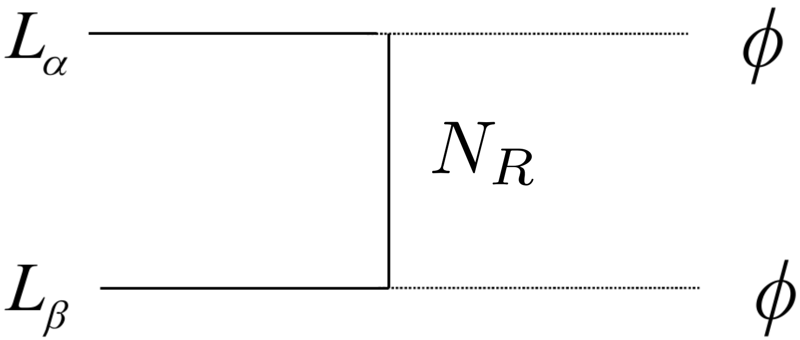
Weinberg 76



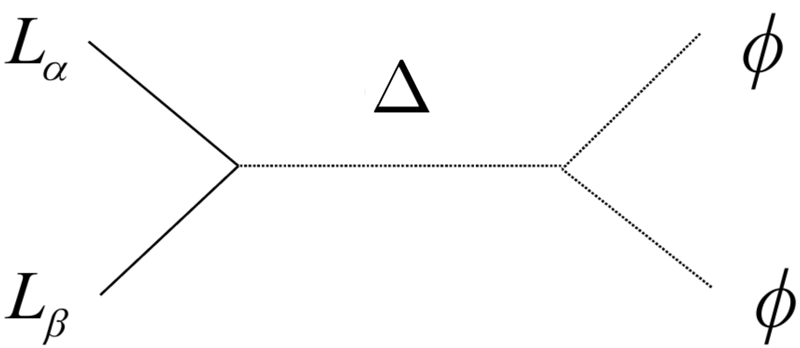
☺ Smallness of neutrino masses can be explained

☺ Majorana masses
Lepton number is violated → $0\nu\beta\beta$ decay

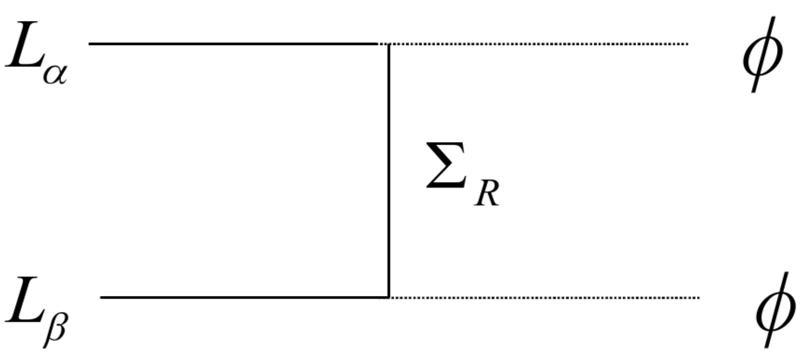
Seesaw Models



Heavy fermion singlet: N_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

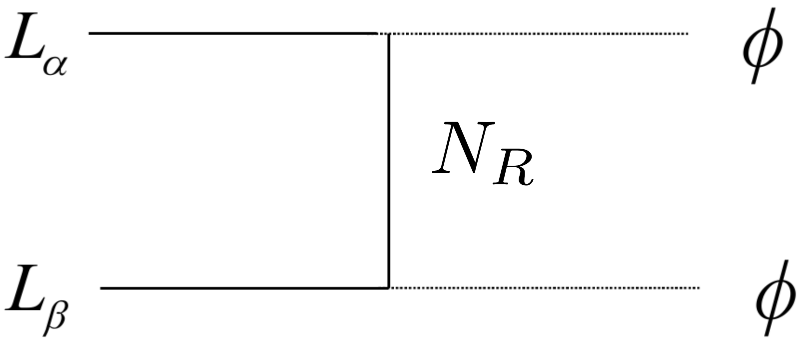


Heavy scalar triplet: Δ. Type II *seesaw.*
Magg, Wetterich 80; Schecter, Valle 80; Lazarides, Shafi, Wetterich 81; Mohapatra, Senjanovic 81.

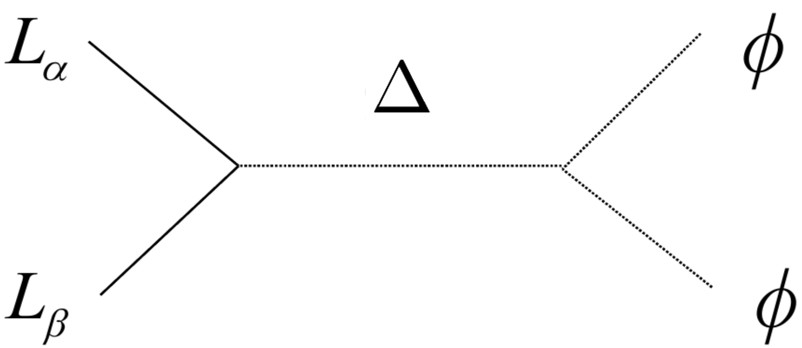


Heavy fermion triplet: Σ
Type III *seesaw.* Foot, Lew, Joshi 89

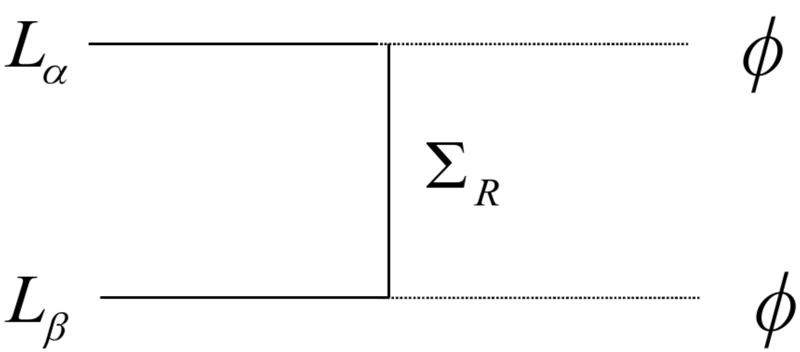
Seesaw Models



Heavy fermion singlet: N_R. Type I *seesaw.* Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.



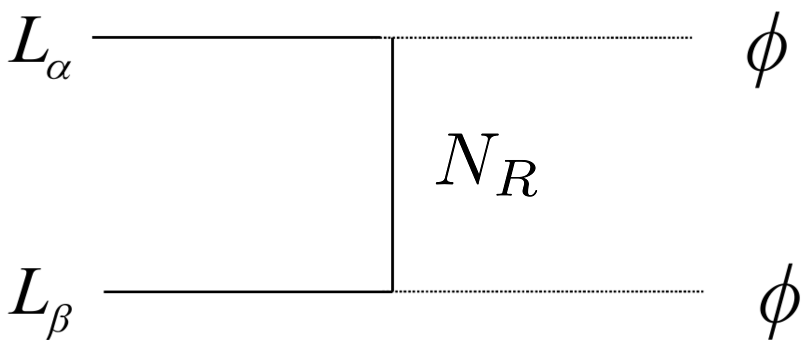
Heavy scalar triplet: Δ. Type II *seesaw.* Magg, Wetterich 80; Schecter, Valle 80; Lazarides, Shafi, Wetterich 81; Mohapatra, Senjanovic 81.



Heavy fermion triplet: Σ

Type III *seesaw.* Foot, Lew, Joshi 89

Minimal Model: Seesaw Model

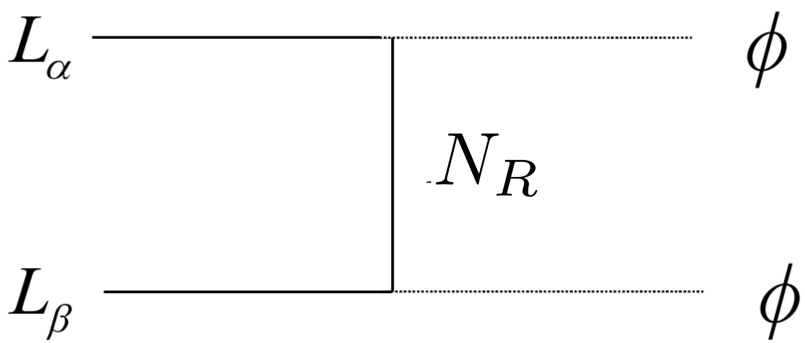


Heavy fermion singlet: N_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

We will focus on the simplest extension of SM able to account for neutrino masses:

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i^c} M_{ij} N_j - Y_{i\alpha}\overline{N_i}\widetilde{\phi}^\dagger L_\alpha + h.c.$$

Minimal Model: Seesaw Model



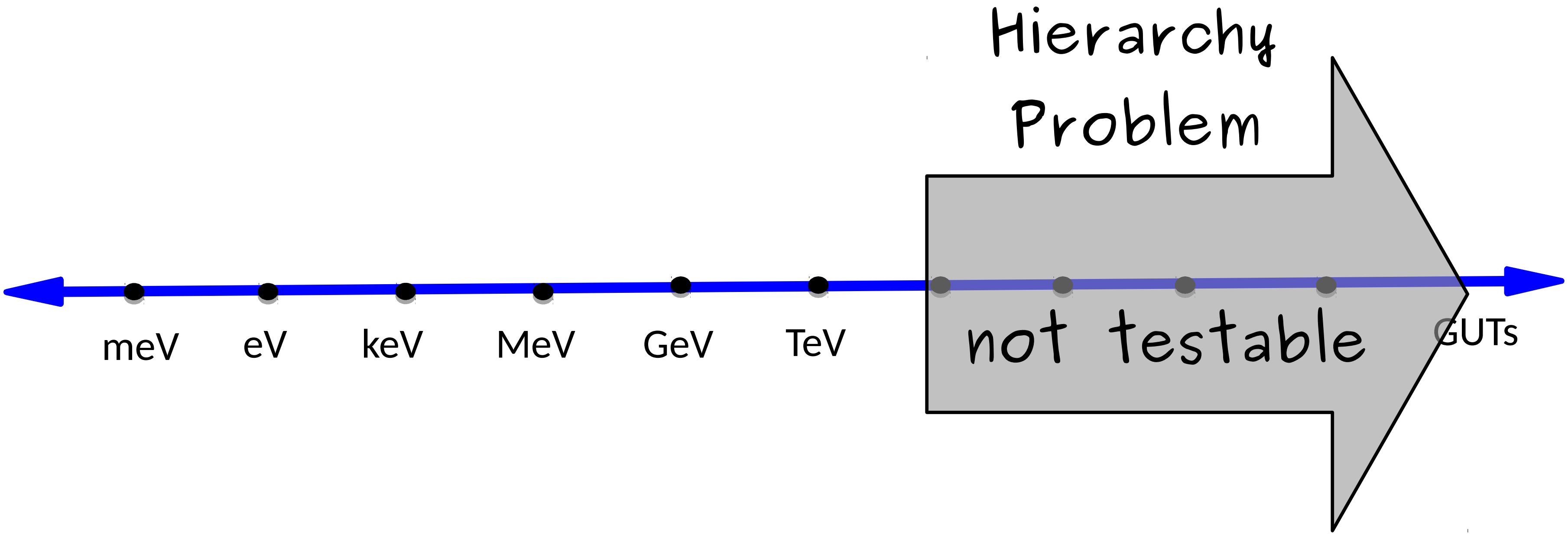
Heavy fermion singlet: N_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

We will focus on the simplest extension of SM able to account for neutrino masses:

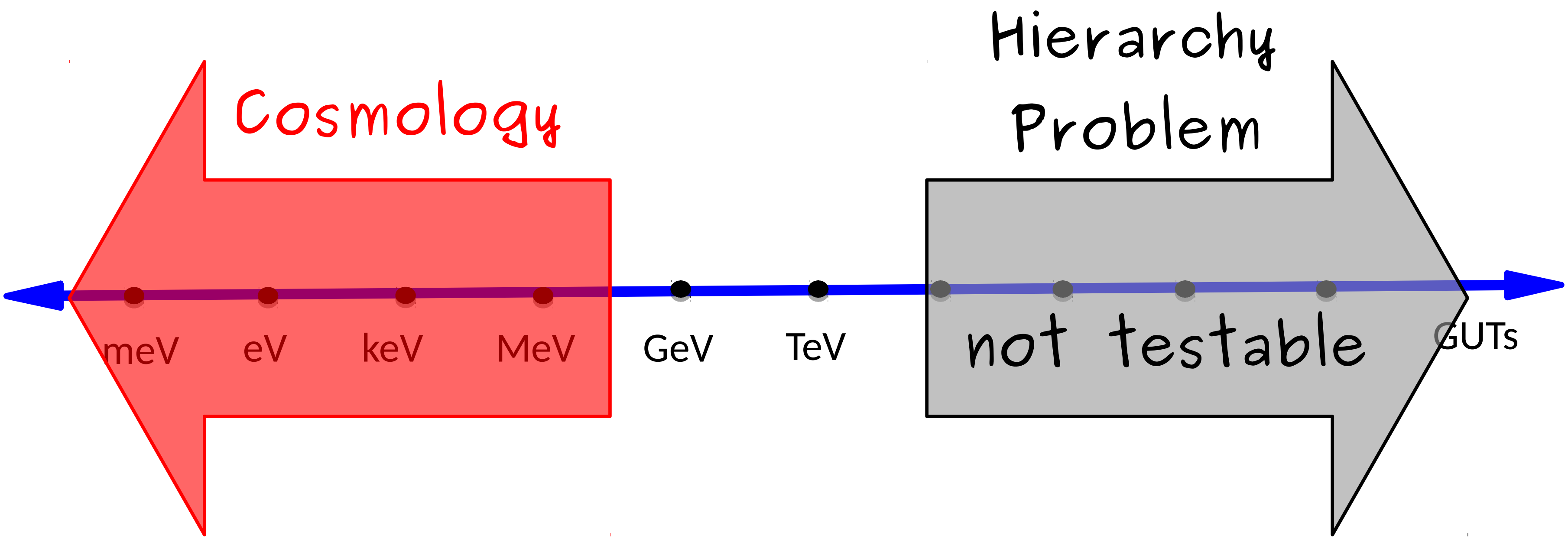
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i^c} M_{ij} N_j - Y_{i\alpha}\overline{N_i}\widetilde{\phi}^\dagger L_\alpha + h.c.$$

New Physics Scale $\quad (m_\nu \sim Y^2 v^2 / M)$

The New Physics Scale

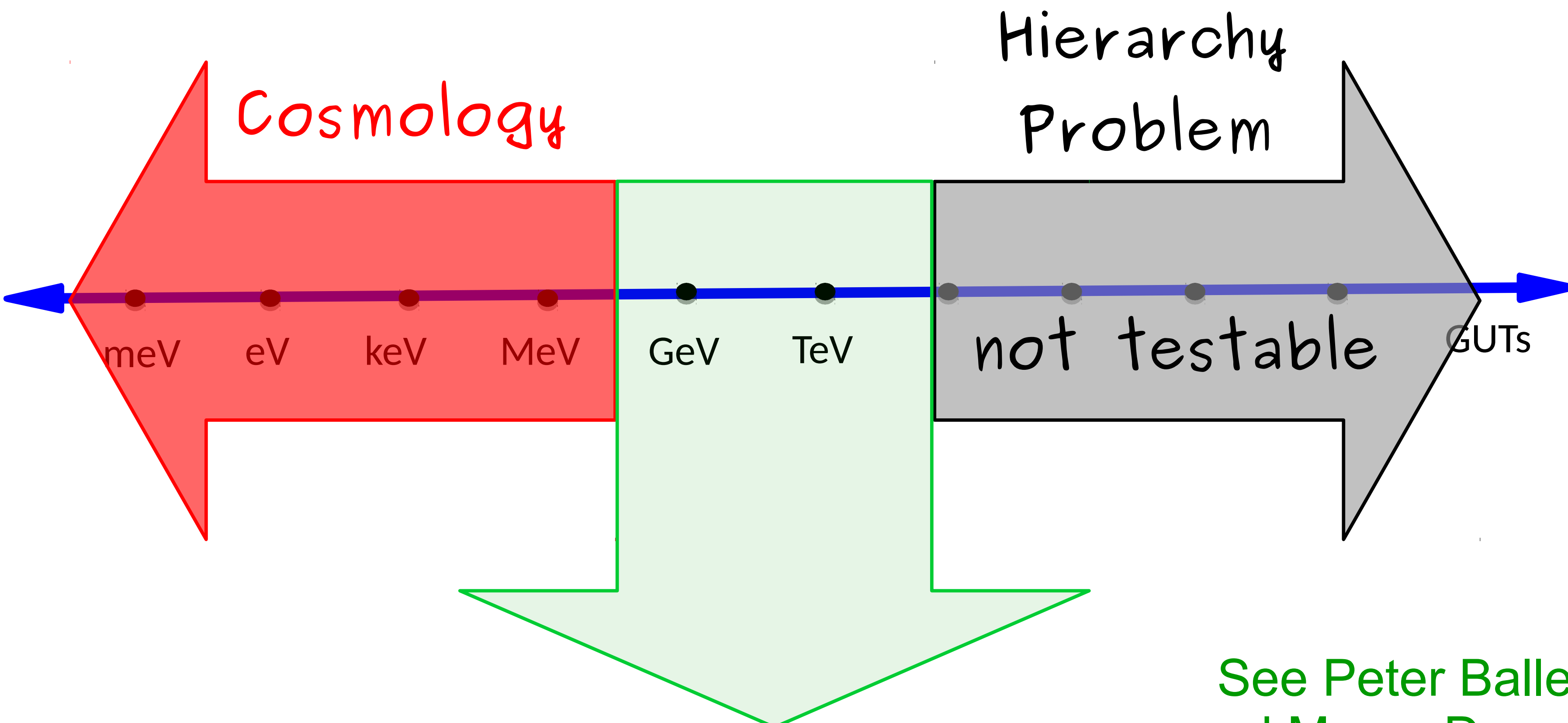


The New Physics Scale



P. Hernandez, M. Kekic, JLP
1311.2614
1406.2961

The New Physics Scale



$0\nu\beta\beta$ decay

LFV, EW precision analysis,

beam dump experiments, LHC, FCC…

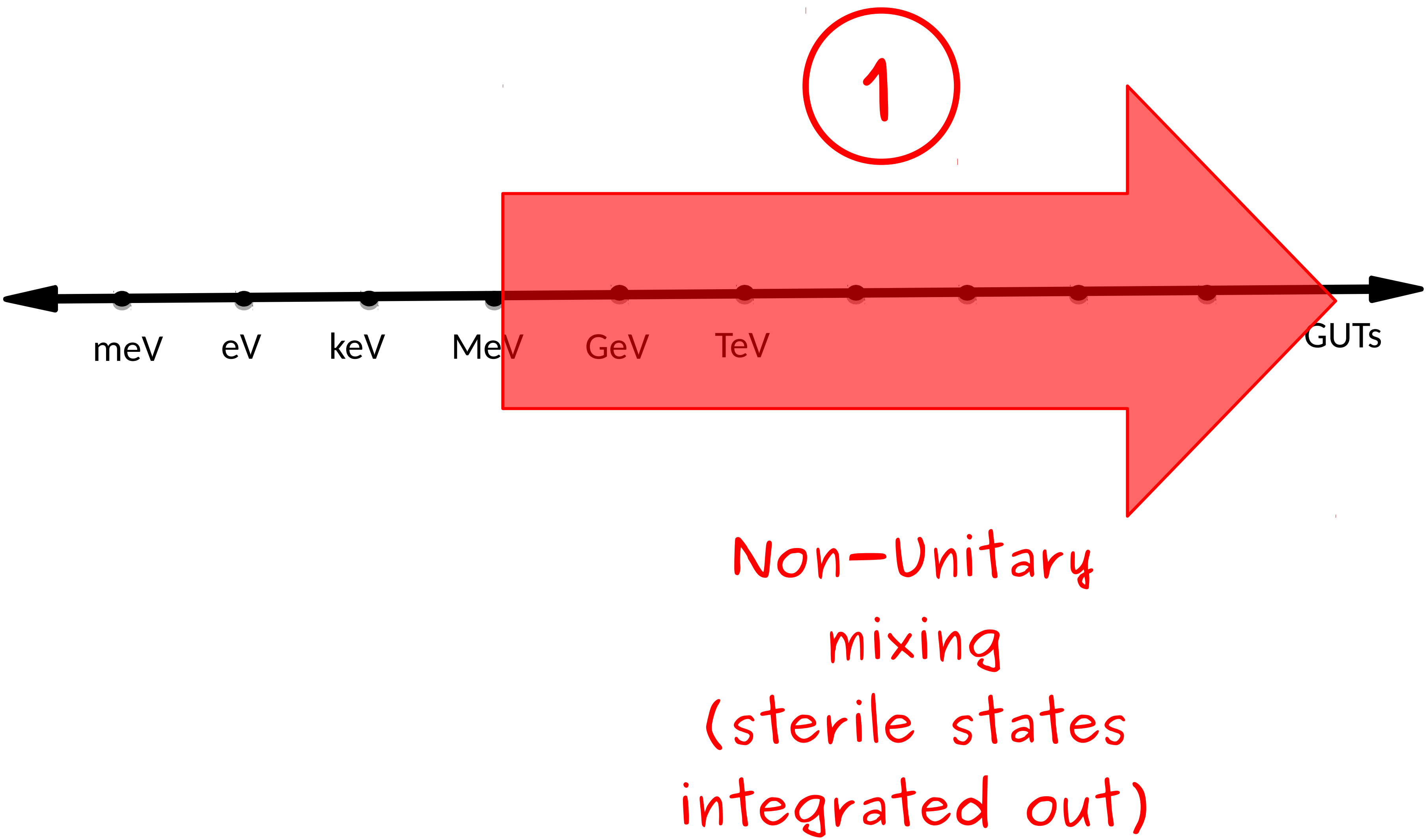
See Peter Ballet and Marco Drewes talks

Are Long Baseline Neutrino Oscillation experiments sensitive to New Physics Beyond 3 neutrino framework

?

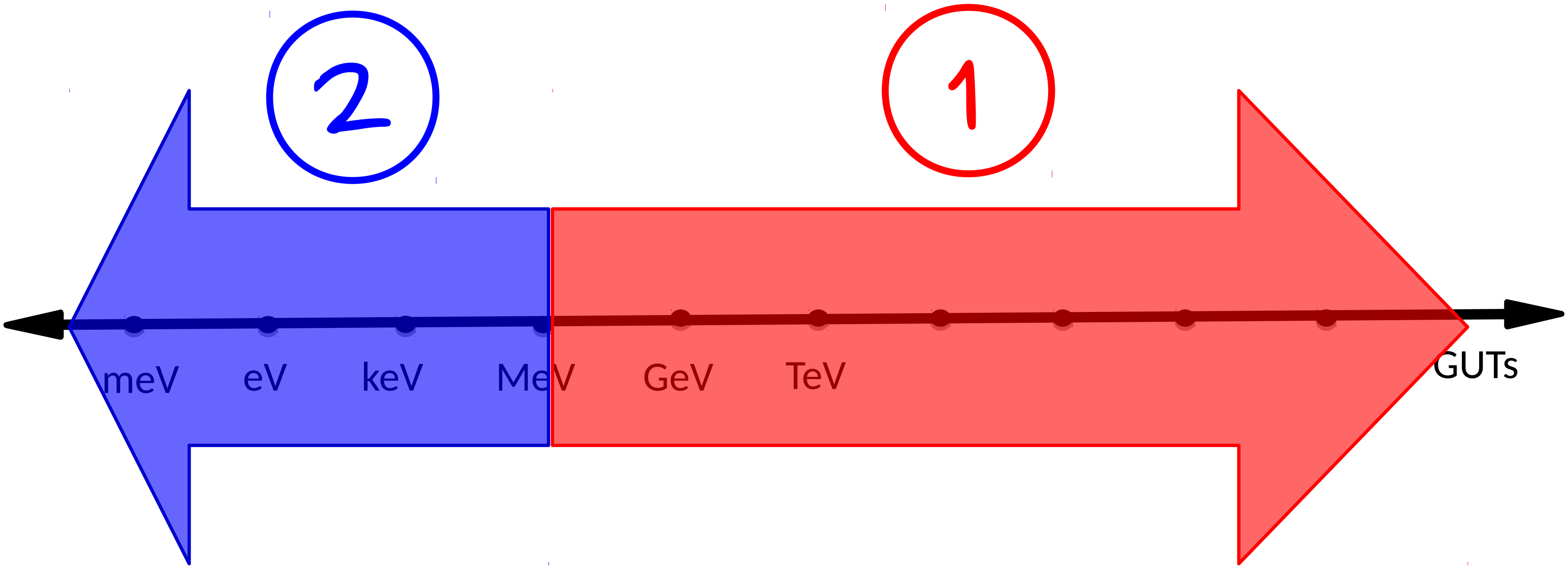
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.

Neutrino Oscillations vs NP scale



Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.
Chee Sheng Fong, Minakata, Nunokawa 1609.08623

Neutrino Oscillations vs NP scale



Kinematically accesible sterile neutrinos

Non-Unitary mixing (sterile states integrated out)

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.
Chee Sheng Fong, Minakata, Nunokawa 1609.08623

Model Independent Approach

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Model Independent Approach

$\nu_s - \nu_\alpha$ mixing

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Model Independent Approach

$\nu_s - \nu_\alpha$ mixing

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Deviation from unitarity of the PMNS matrix

Schechter, Valle 1980
Langacker, London 1988
Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006

General Parameterizations

- Hermitian parameterization

$$N = (I - \eta) U'$$

Deviation from unitarity

$$\eta = \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{e\tau} \end{pmatrix} = \frac{\Theta\Theta^\dagger}{2}$$

Unitarity matrix

(standard unitary PMNS matrix up to small corrections)

Broncano, Gavela, Jenkins 2003
Fernandez-Martinez, Gavela, JLP, Yasuda 2007

General Parameterizations

- Triangular parameterization

$$N = TU = (I - \alpha)U$$

Deviation from unitarity

Unitarity matrix

(standard unitary PMNS matrix
up to small corrections)

$$\alpha = (1 - T) = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Z.-z. Xing 2008, 2012
Escrihuela, Forero, Miranda, Tortola 2015

Mapping

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

$$\theta_{12} - \theta'_{12} = \frac{\mathrm{Re}(s_{23}\eta_{e\tau} - c_{23}\eta_{e\mu})}{c_{13}},$$

$$\theta_{13} - \theta'_{13} = \mathrm{Re}(-s_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\mu} - c_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\tau}),$$

$$\theta_{23} - \theta'_{23} = -\,\mathrm{Re}(\eta_{\mu\tau}) + \tan\theta_{13}\,\mathrm{Re}\left(c_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\mu} - s_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\tau}\right),$$

$$\delta_{\mathrm{CP}} - \delta'_{\mathrm{CP}} = \frac{\cos 2\theta_{12}}{s_{12}c_{12}c_{13}}\,\mathrm{Im}\left(s_{23}\eta_{e\tau} - c_{23}\eta_{e\mu}\right) + \frac{1}{s_{13}c_{13}}\,\mathrm{Im}\left(s_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\mu} + c_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\tau}\right)$$
$$- \frac{\tan\theta_{13}}{s_{23}c_{23}}\,\mathrm{Im}\left(c^3_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\mu} + s^3_{23}e^{i\delta_{\mathrm{CP}}}\eta_{e\tau} + \frac{\eta_{\mu\tau}}{\tan\theta_{13}}\right).$$

$$U = U' + O(\eta)$$

NSI ↔ Non Unitarity & Sterile ν mapping

- NSI in propagation (matter effects)

$$H = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} + V_{\rm CC}\, U^\dagger \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} U,$$

- Mapping

$$\epsilon_{ee} = -\alpha_{ee}, \quad \epsilon_{\mu\mu} = \alpha_{\mu\mu}, \quad \epsilon_{\tau\tau} = \alpha_{\tau\tau}$$

$$\epsilon_{e\mu} = \frac{1}{2}\alpha^*_{\mu e}, \quad \epsilon_{e\tau} = \frac{1}{2}\alpha^*_{\tau e}, \quad \epsilon_{\mu\tau} = \frac{1}{2}\alpha^*_{\tau\mu}$$

NSI ↔ Non Unitarity & Sterile ν mapping

- NSI in production/detection

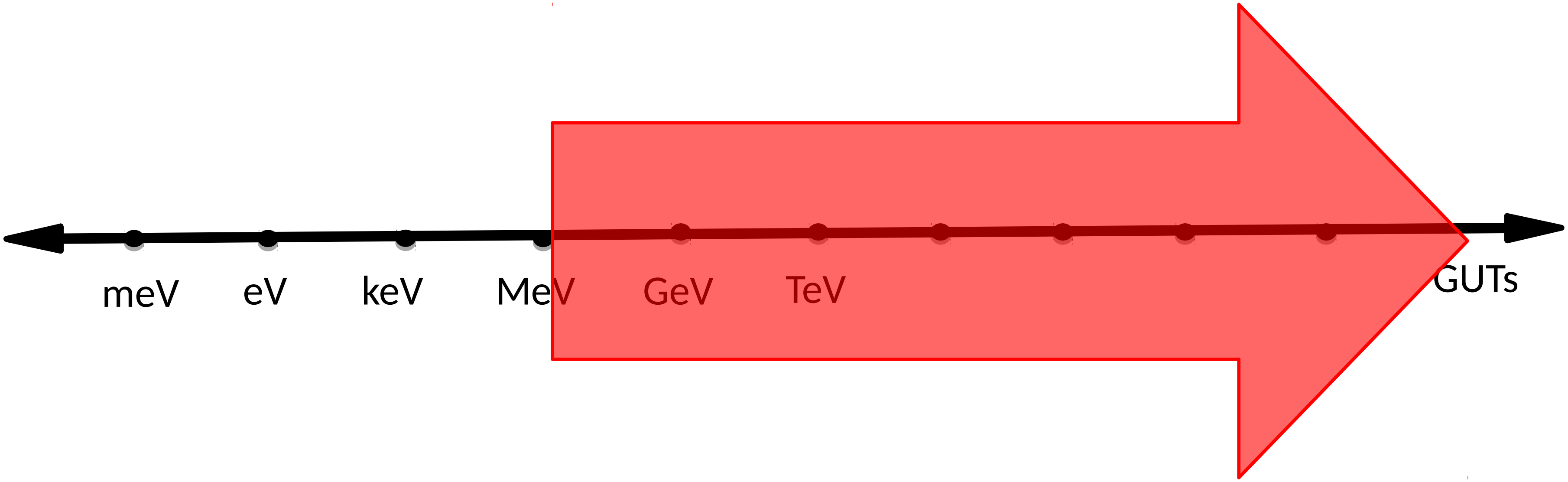
$$P_{\alpha\beta} = |\left[(1+\epsilon^d)US^0U^\dagger(1+\epsilon^s)\right]_{\beta\alpha}|^2$$

- Mapping

$$\epsilon^{s*}_{\beta\alpha} = \epsilon^d_{\alpha\beta} = -\alpha_{\alpha\beta}.$$

Normalization should be considered (ND affected)

① Non-Unitary Mixing



(Extra states integrated out)

① Non-Unitary Mixing

$$H = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} + N^\dagger \begin{pmatrix} V_{\rm CC} + V_{\rm NC} & 0 & 0 \\ 0 & V_{\rm NC} & 0 \\ 0 & 0 & V_{\rm NC} \end{pmatrix} N$$

- Oscillation evolution matrix

$$i\dot{S}^0 = HS^0 \quad \Longrightarrow \quad S^0 = \exp(-iHL)$$

① Non-Unitary Mixing

$$H = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} + N^\dagger \begin{pmatrix} V_{\rm CC} + V_{\rm NC} & 0 & 0 \\ 0 & V_{\rm NC} & 0 \\ 0 & 0 & V_{\rm NC} \end{pmatrix} N$$

- Oscillation evolution matrix

$$i\dot{S}^0 = HS^0 \quad \Rightarrow \quad S^0 = \exp(-iHL)$$

- Theoretical Oscillation Probability

$$P_{\alpha\beta} = |(NS^0N^\dagger)_{\beta\alpha}|^2$$

① Non-Unitary Mixing

$$H = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} + N^\dagger \begin{pmatrix} V_{\rm CC} + V_{\rm NC} & 0 & 0 \\ 0 & V_{\rm NC} & 0 \\ 0 & 0 & V_{\rm NC} \end{pmatrix} N$$

- Oscillation evolution matrix

$$i\dot{S}^0 = HS^0 \quad \Rightarrow \quad S^0 = \exp(-iHL)$$

- Theoretical Oscillation Probability

$$P_{\alpha\beta} = |(N\exp(-iHL)N^\dagger)_{\beta\alpha}|^2$$

Anologous to standard probability just doing $U_{PMNS} \rightarrow N$

1 Non-Unitary Mixing

- What is measured in neutrino oscillation experiments

$$\mathcal{P}_{\alpha\beta} = \frac{R_\beta}{R_\alpha}$$

Event rate
Far Detector

Extrapolation of
Near Detector

① Non-Unitary Mixing

- What is measured in neutrino oscillation experiments

$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{((NN^\dagger)_{\alpha\alpha})^2}.$$

- When $\mathrm{NN}^\dagger = I$ ➡ $\mathcal{P}_{\alpha\beta} = P_{\alpha\beta}$ (SM limit recovered)

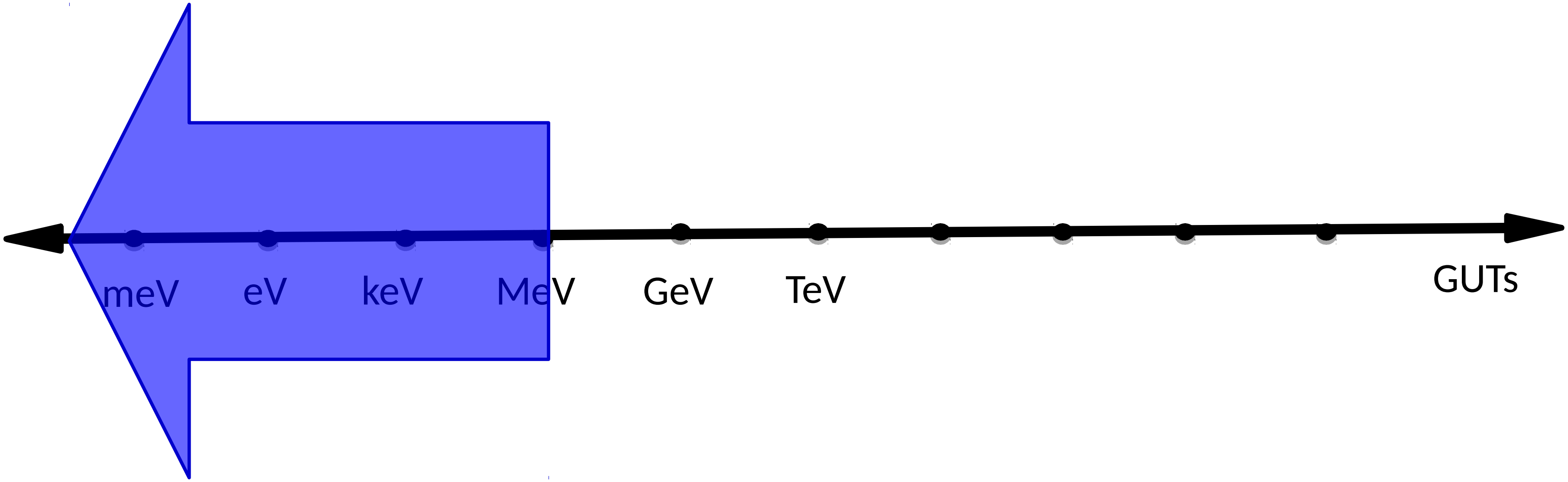
1 Non-Unitary Mixing

- What is measured in neutrino oscillation experiments

$$\mathcal{P}_{\alpha\beta} \approx \left|(NN^{\dagger})_{\beta\alpha}\right|^2 \approx |\alpha_{\alpha\beta}|^2$$

ZERO distance effect!

② Kinematically accessible sterile ν



Kinematically accesible sterile neutrinos

② Kinematically accessible sterile ν

Oscillations in VACUUM

- Oscillation evolution matrix: $\mathcal{S} = \mathcal{U}\mathcal{S}^0\mathcal{U}^\dagger$

complete nxn mixing matrix

Active Block $$S_{\alpha\beta} = \sum_{i\in\text{light}} N_{\alpha i} S^0_{ij} N^*_{\beta j} + \sum_{J\in\text{heavy}} \Theta_{\alpha J}\Theta^*_{\beta J}\Phi_J ,$$

② Kinematically accessible Sterile ν

Oscillations in VACUUM (Average out regime)

- Oscillation evolution matrix: $\mathcal{S} = \mathcal{U}\mathcal{S}^0\mathcal{U}^\dagger$

complete nxn mixing matrix

$\Delta m^2_{iJ} L/E >> 1$

Active Block
$$S_{\alpha\beta} = \sum_{i \in \text{light}} N_{\alpha i} S^0_{ij} N^*_{\beta j} + \sum_{J \in \text{heavy}} \Theta_{\alpha J} \Theta^*_{\beta J} \Phi_J ,$$

(i) Cross terms average to zero

(ii) Sterile oscillation average to constant value, but amplitude subleading

② Kinematically accessible Sterile ν

Oscillations in VACUUM (Average out regime)

- Theoretical Oscillation Probability:

$$\Delta m_{iJ}^2 L/E >> 1$$

$$P_{\beta\alpha} = |S_{\alpha\beta}|^2 = \left| \sum_i N_{\alpha i} S_{ij}^0 N_{\beta j}^* \right|^2 + \mathcal{O}(\Theta^4)$$

- Same expression as in the Non-Unitary case!!

② Kinematically accessible sterile ν

Oscillations in MATTER (Average out regime)

- If matter potential is small in comparison to the light-heavy mass splitting

$$\tilde{\Theta}_{\alpha J} = \Theta_{\alpha J} + \frac{2E}{\Delta m^2_{iJ}} (\delta_{\alpha e} V_{\rm CC} \Theta_{eJ} + \Theta_{\alpha J} V_{\rm NC})$$

$\tilde{\Theta}_{\alpha J}$: light-heavy mixing in matter

$\Theta_{\alpha J}$: light-heavy mixing (vacuum)

② Kinematically accessible Sterile ν

Oscillations in MATTER (Average out regime)

- If matter potential is small in comparison to the light-heavy mass splitting

$$\tilde{\Theta}_{\alpha J} = \Theta_{\alpha J} + \frac{2E}{\Delta m^2_{iJ}} (\delta_{\alpha e} V_{\rm CC} \Theta_{eJ} + \Theta_{\alpha J} V_{\rm NC})$$

$\tilde{\Theta}_{\alpha J}$: light-heavy mixing in matter

$\Theta_{\alpha J}$: light-heavy mixing (vacuum)

$$\Delta m^2_{iJ} L/E >> V_{CC}, V_{NC}$$

② Kinematically accessible Sterile ν

Oscillations in MATTER (Average out regime)

- If matter potential is small in comparison to the light-heavy energy splitting

light-heavy mixing in matter ← $\tilde{\Theta}_{\alpha J} = \Theta_{\alpha J}$ → light-heavy mixing (vacuum)

- Theoretical Oscillation Probability:

$$P_{\beta\alpha} = |S_{\alpha\beta}|^2 = \left| \sum_i N_{\alpha i} S^0_{ij} N^*_{\beta j} \right|^2 + \mathcal{O}(\Theta^4)$$

- Same expression as in the Non-Unitary case!!

② Kinematically accessible sterile ν

- What is measured in neutrino oscillation experiments

$$\mathcal{P}_{\alpha\beta} = \frac{R_\beta}{R_\alpha}$$

Event rate
Far Detector

Extrapolation of
Near Detector

② Kinematically accessible sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the non-unitarity case

② Kinematically accessible sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

No normalization factor

② Kinematically accessible sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

No normalization factor

3. The oscillation frequency dictated by the light-heavy frequency matches the near detector distance.

Oscillations could be seen at the near detector

② Kinematically accessible sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

No normalization factor

3. The oscillation frequency dictated by the light-heavy frequency matches the near detector distance.

Oscillations could be seen at the near detector

See Joachim Kopp's talk yesterday

② Kinematically accessible sterile ν

1. The light-heavy oscillations averaged out at the near detector.

(ND avaraged)

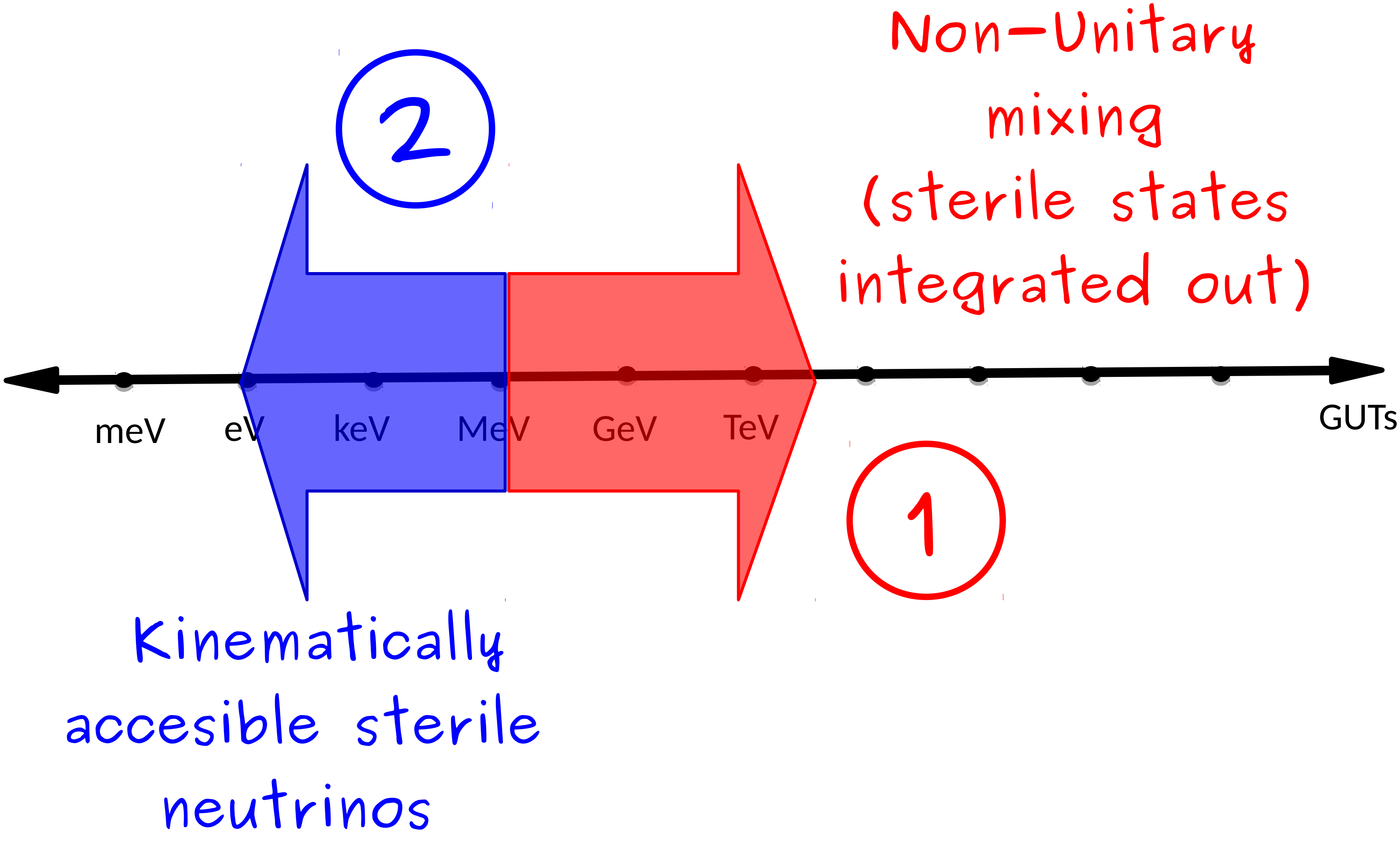
Identical to the non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

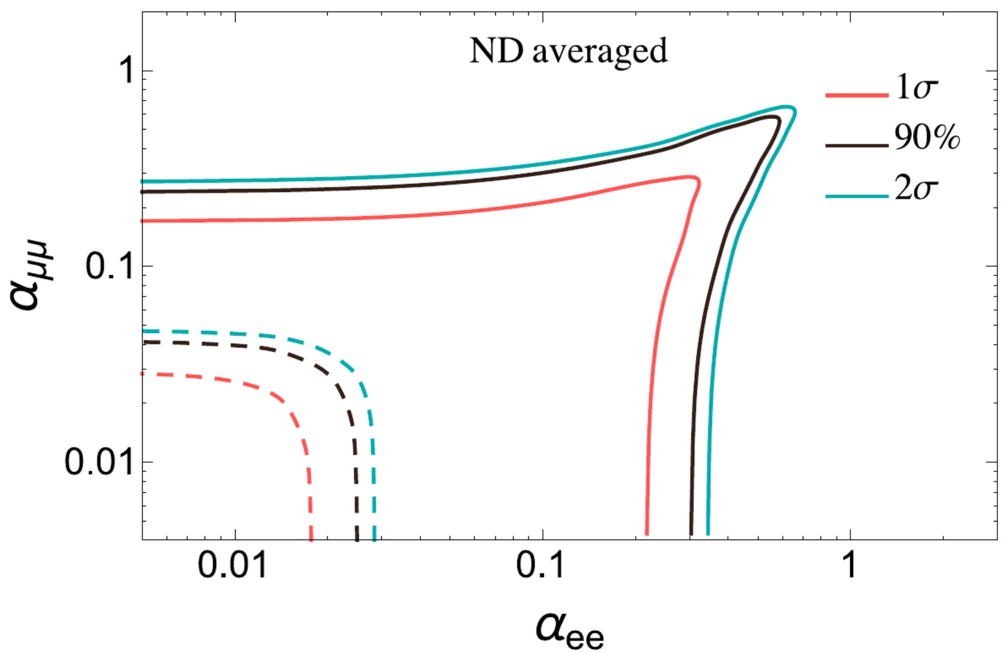
(ND undeveloped)

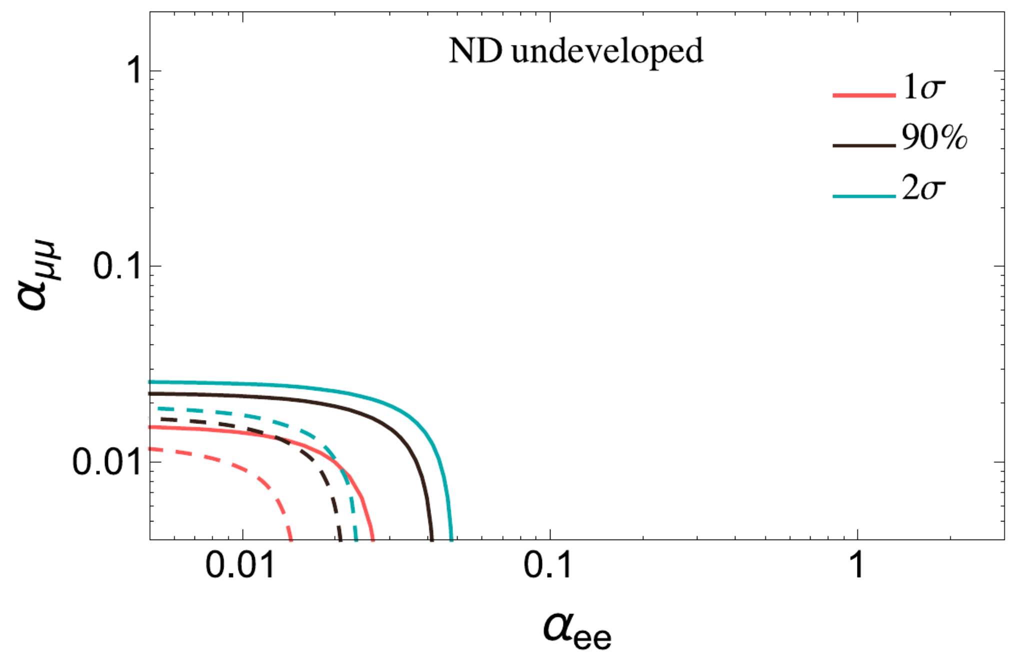
No normalization factor

Both limits can be studied in a unified & model independent way



Dune Sensitivities





$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{((NN^\dagger)_{\alpha\alpha})^2}$$

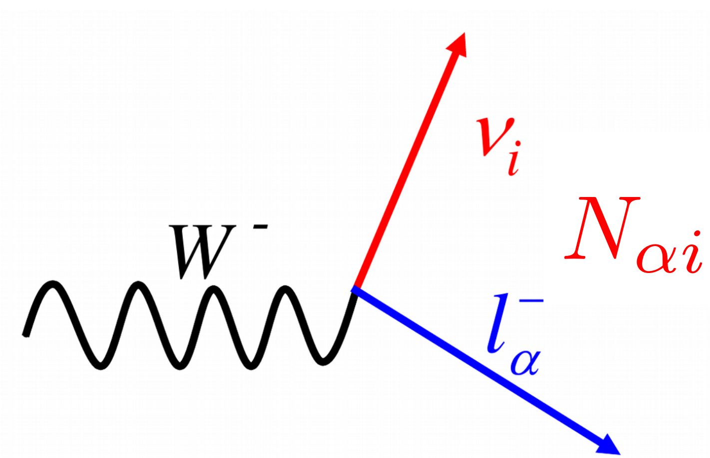
$$\mathcal{P}_{\alpha\beta} = \left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2$$

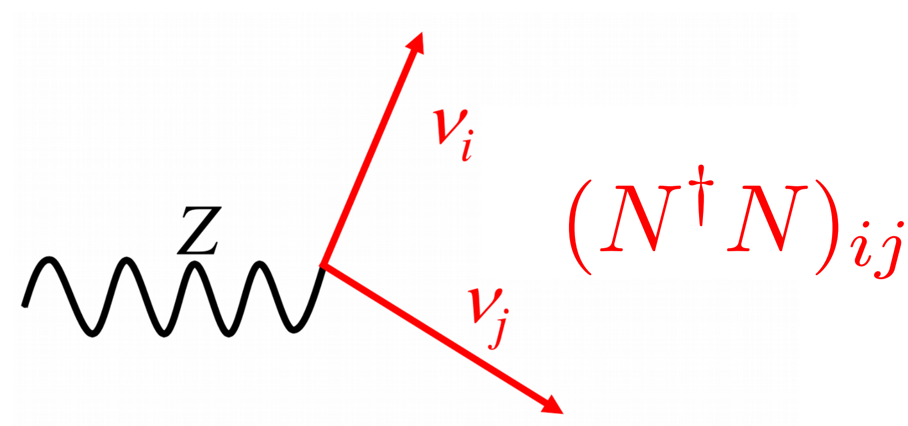
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.
DUNE CDR configuration 1606.09550

Present bounds

Bounds from EW precision data

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$





Non-Unitary mixing (sterile states integrated out)

effects in weak interaccions

Observables

- **28 observables included** in the analysis as a function of α, M_Z and G_μ

- The W boson mass M_W
- The effective weak mixing angle: $s^{2\ \mathrm{lep}}_{\mathrm{W\ eff}}$ and $s^{2\ \mathrm{had}}_{\mathrm{W\ eff}}$
- Four ratios of Z fermionic decays
- The invisible width of the Z
- 8 ratios of weak decays constraining EW universality
- 9 weak decays constraining the CKM unitarity
- 3 radiative LFV decays: $\mu \to e\gamma$, $\tau \to \mu\gamma$ and $\tau \to e\gamma$

Present Bounds

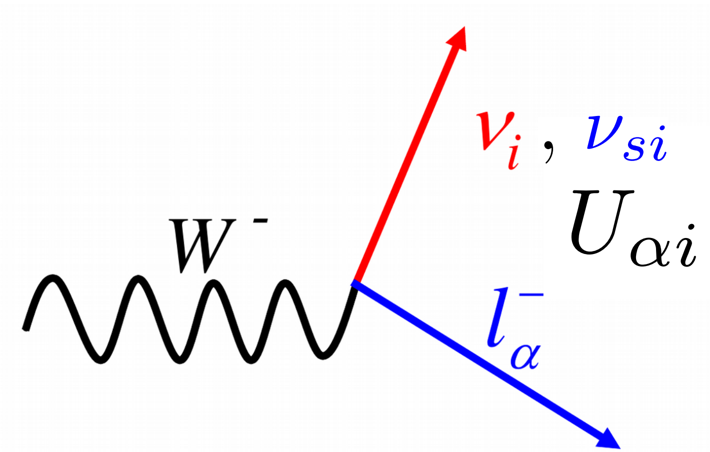
	"Non-Unitarity"	"Light steriles"	
	$(m > \text{EW})$	$\Delta m^2 \gtrsim 100\ \text{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
$\alpha_{\tau\tau}$	$2.8 \cdot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

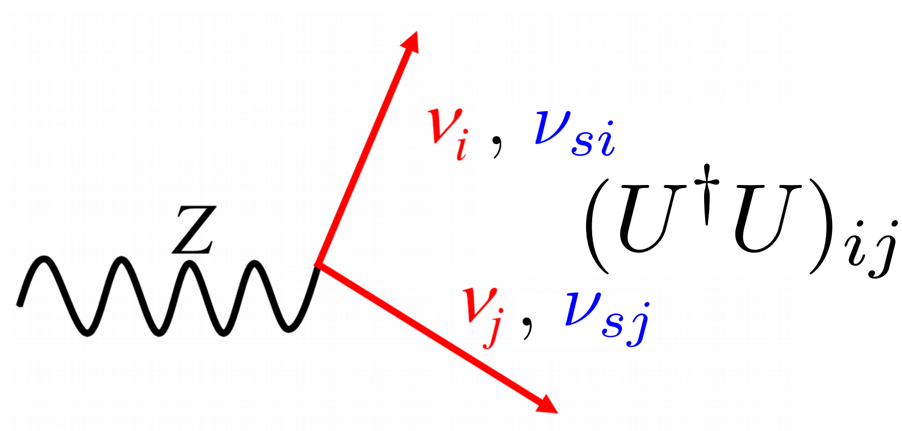
Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Present bounds

Unitarity recovered in EW processes

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$





Kinematically accesible sterile neutrinos

unitarity recovered in weak processes

Present Bounds

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

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Present Bounds

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

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Present Bounds

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

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP
1609.08637

Present Bounds

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

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Present Bounds

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

$$\alpha_{\alpha\beta} \leq 2\sqrt{\alpha_{\alpha\alpha}\alpha_{\beta\beta}}$$

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Present Bounds

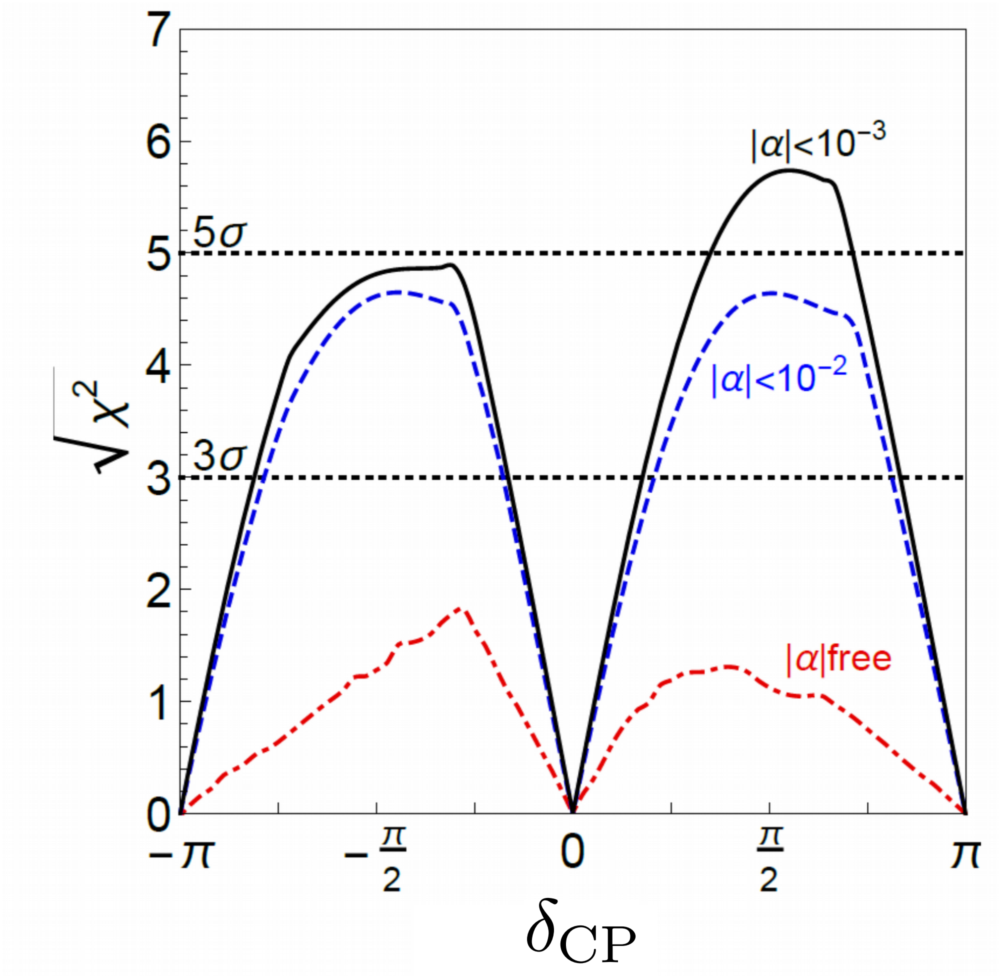
	"Non-Unitarity"	"Light steriles"	
	$(m > \text{EW})$	$\Delta m^2 \gtrsim 100\ \text{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
$\alpha_{\mu\mu}$			
$\alpha_{\tau\tau}$			
$\alpha_{\mu e}$			
$\alpha_{\tau e}$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\alpha_{\tau\mu}$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$

0.1-0.01% level

10-1% level

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Dune Sensitivities

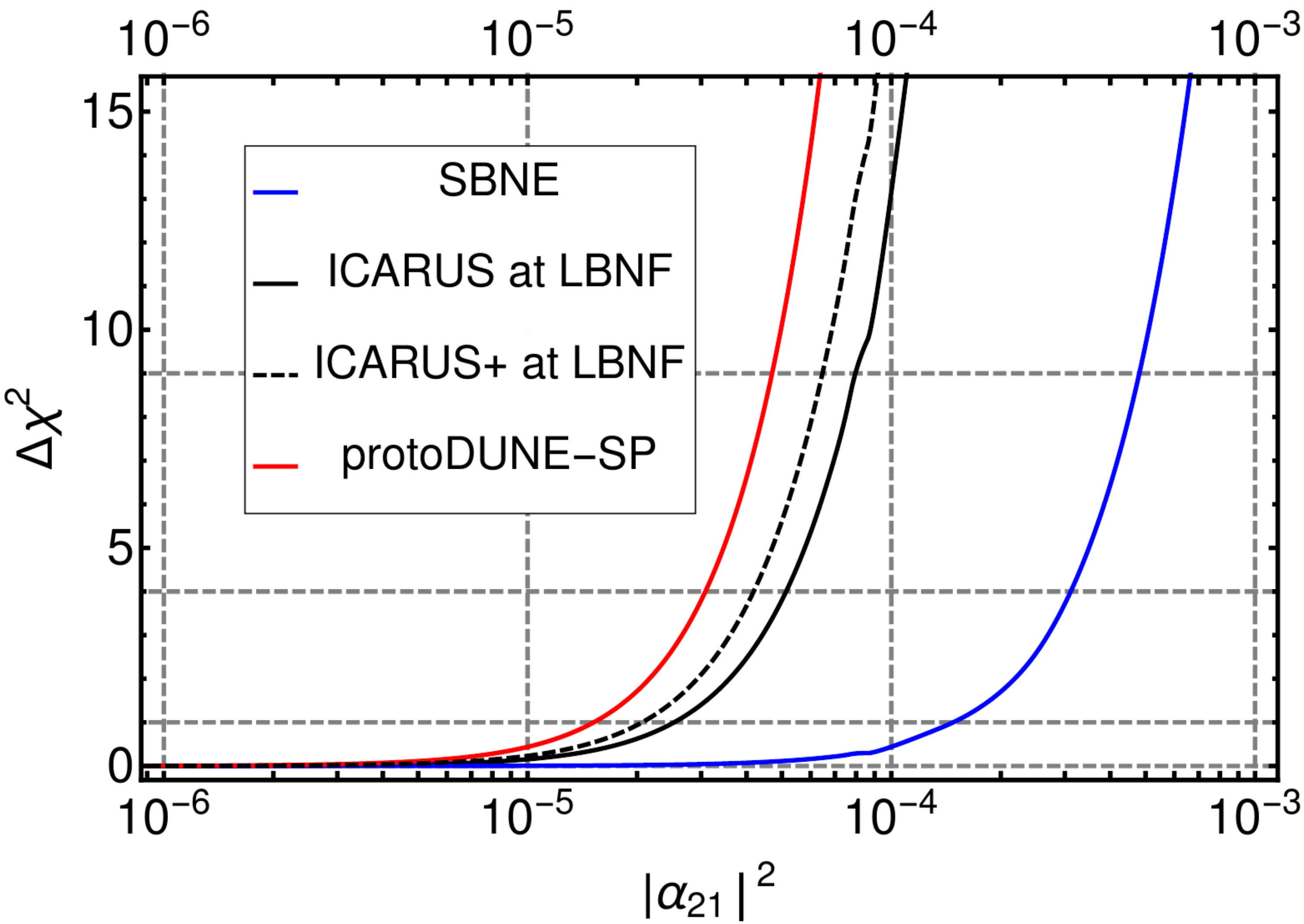


From E. Fernandez-Martinez talk @ Neutrino Platform Week 2018

- With 10^{-3} priors the sensitivity to standard CPV is recovered.

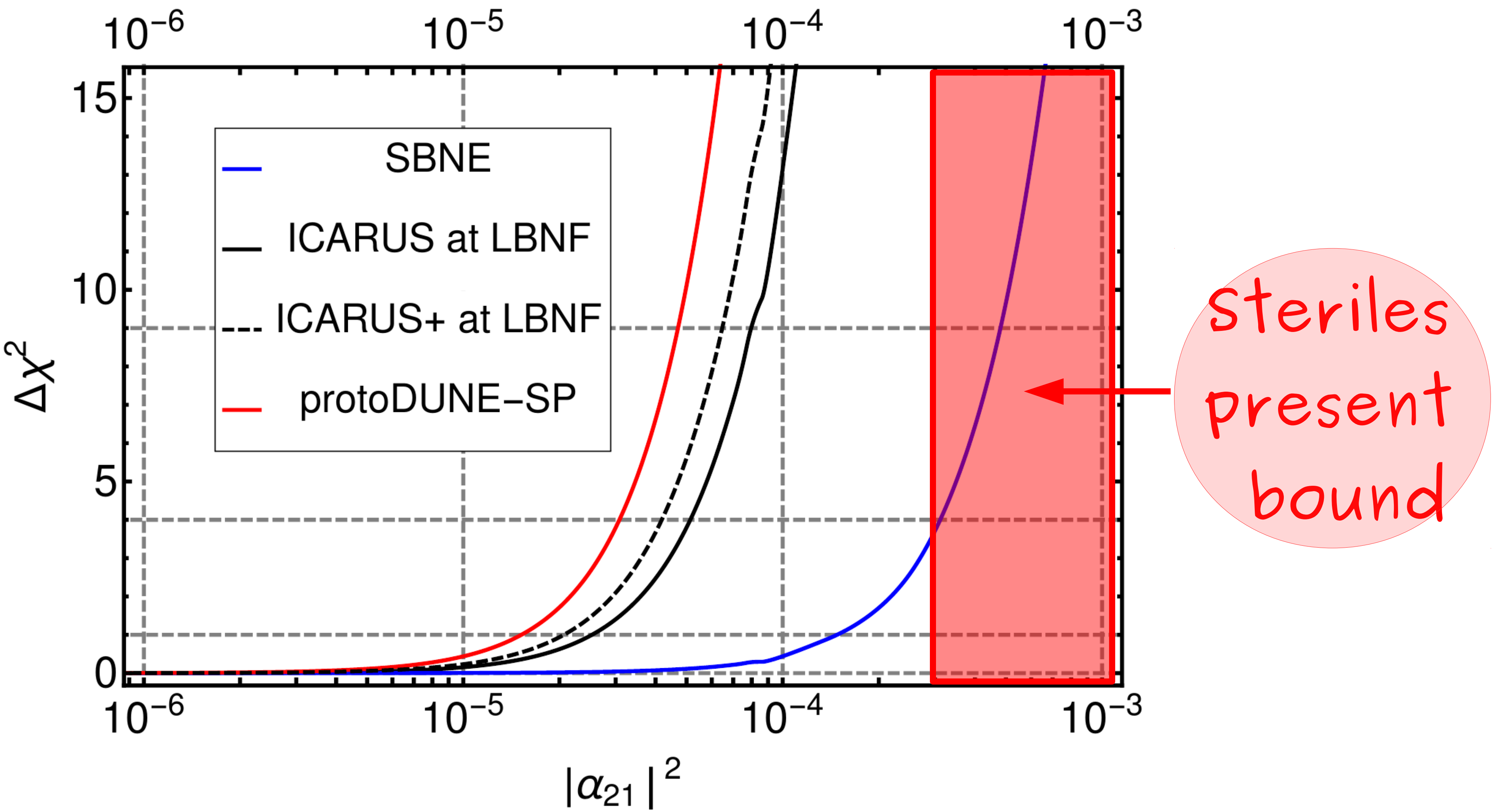
See also: Escrihuela, Forero, Miranda, Tórtola, Valle 1612.07377

Near Detector Sensitivities



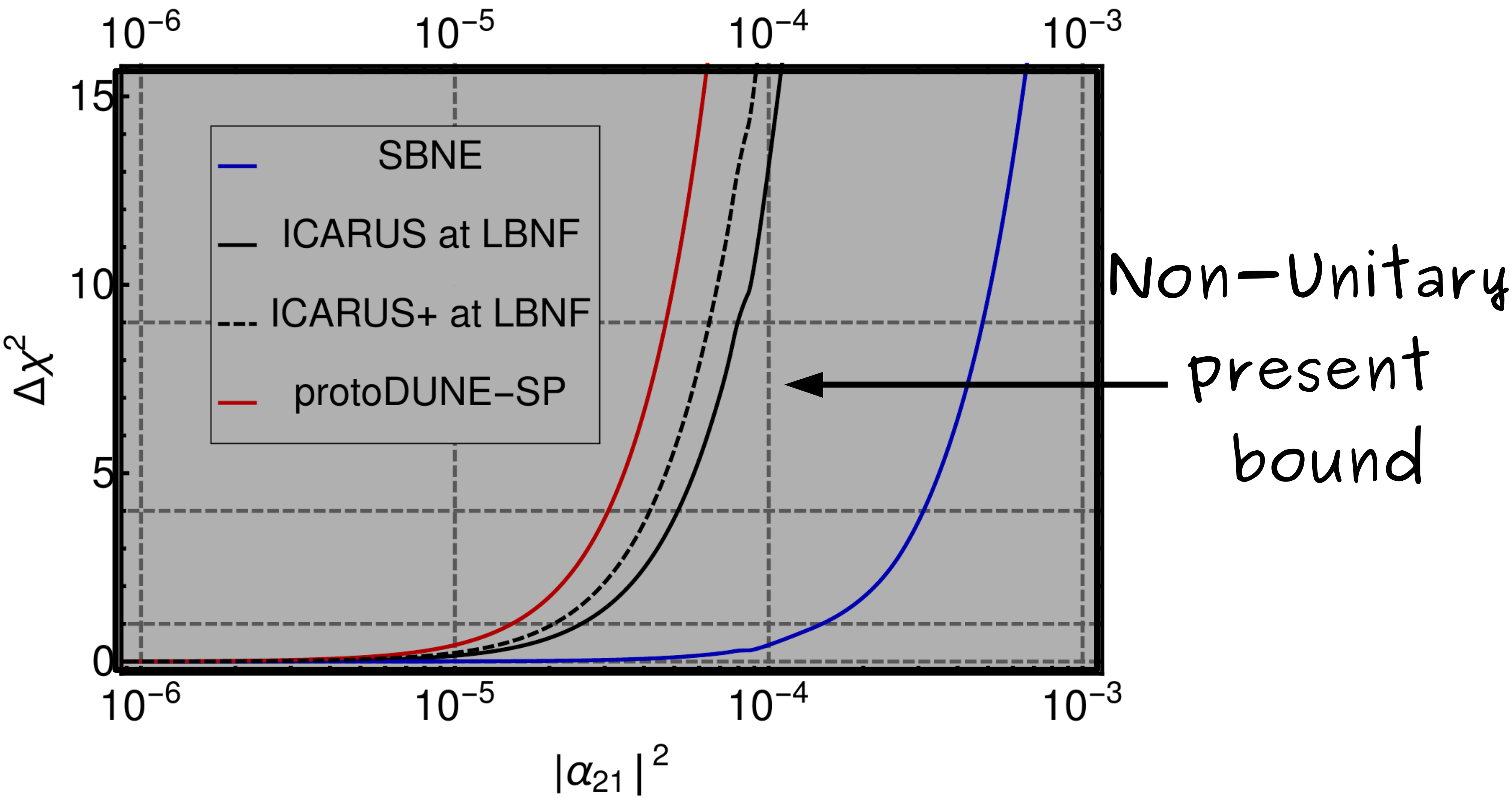
Miranda, Pasquini, Tórtola, Valle 1802.02133

Near Detector Sensitivities



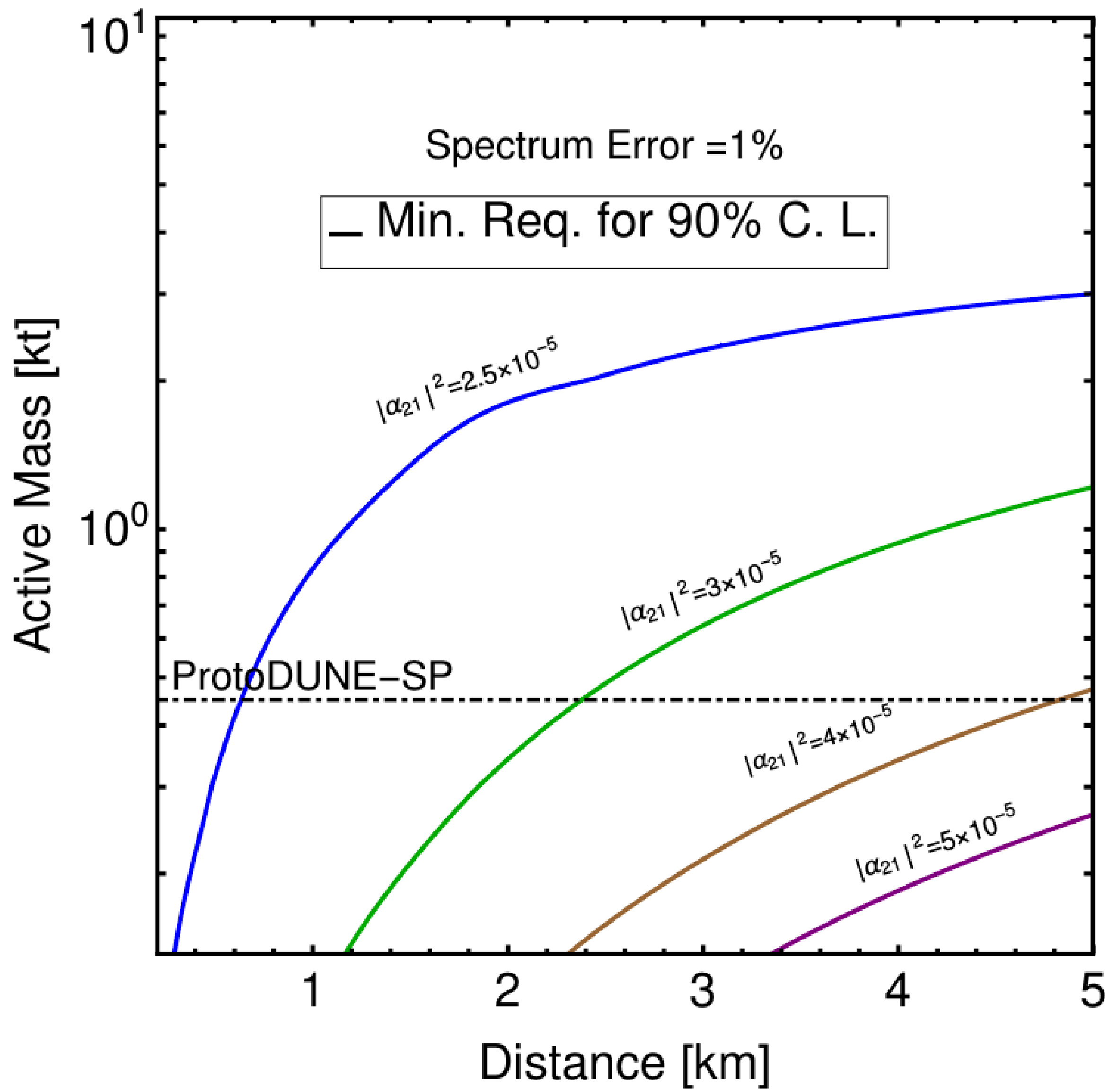
Miranda, Pasquini, Tórtola, Valle 1802.02133

Near Detector Sensitivities



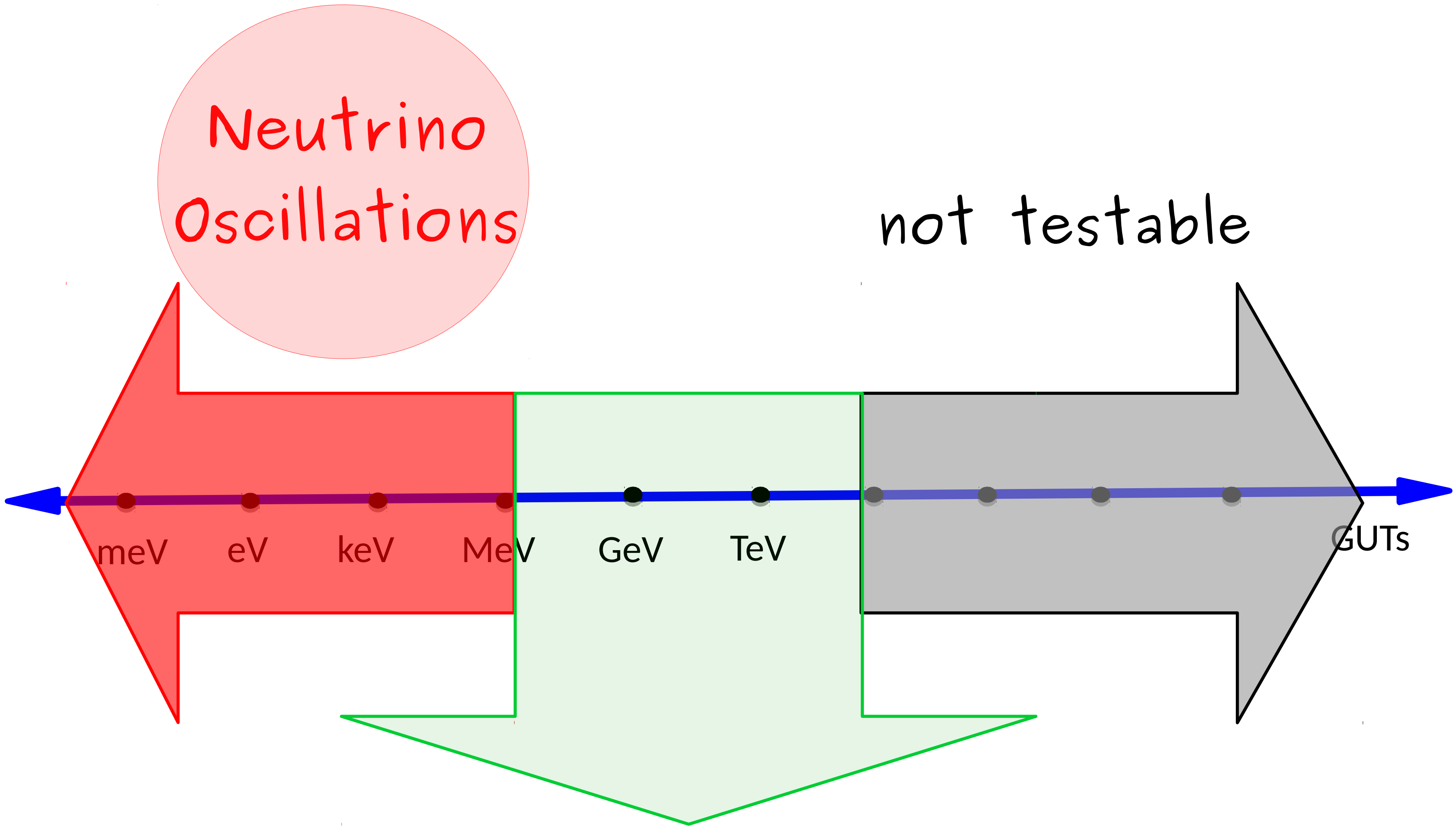
Miranda, Pasquini, Tórtola, Valle 1802.02133

Near Detector Sensitivities



Miranda, Pasquini, Tórtola, Valle 1802.02133

The New Physics Scale



$0\nu\beta\beta$ Decay, LFV, EW precision analysis,
SHiP, LHC, FCC-ee...

Summary and Conclusions

- **Non-unitary mixing** can come from low energy (kinematically accessible sterile neutrinos) or high energy (new states integrated out) New Physics.

- Both limits can be studied in a unified, consistent and model independent way.

- When sterile oscillations are averaged out at the near detector, their effects at the far detector coincide with non-unitarity at leading order, even in presence of a matter potential.

- The role of the near detector is extremely relevant.

- Non-unitarity effects coming from high energy NP are too constrained to impact future neutrino oscillation facilities but sterile neutrinos can play an important role.


Thanks!

Detectors

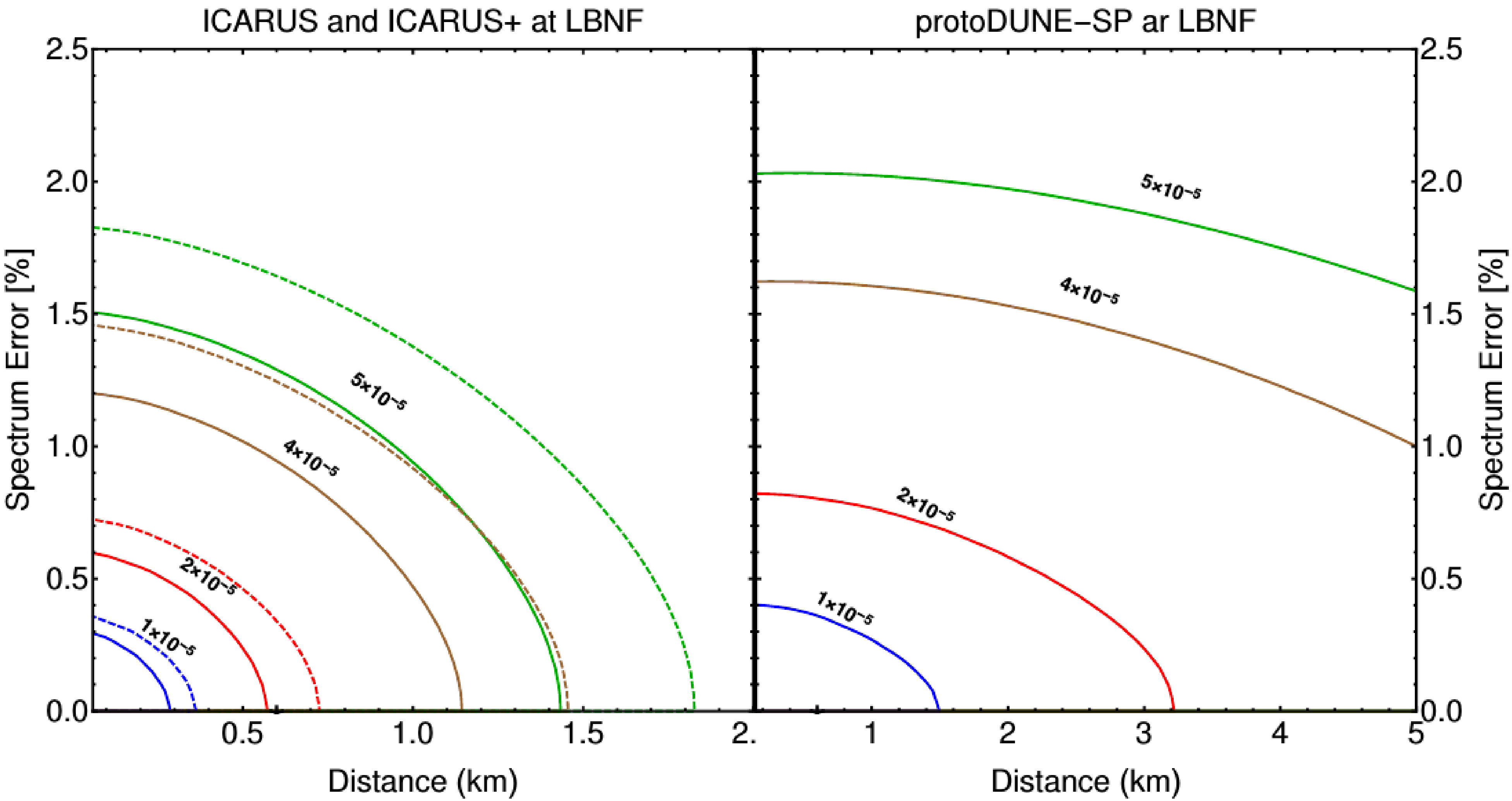
Detector	Active Size	Distance	E range (GeV)	Target
ICARUS	476 t	600 m	0 to 3	Liq. Argon
ICARUS+	476 t	600 m	0 to 5	Liq. Argon
protoDUNE-SP	450 t	600 m	0 to 5	Liq. Argon

TABLE II: Proposals for a second near detector in DUNE.

Detector	Total Size	Active Size	Distance	Target	POT
SBND	220 t	112 t	110 m	Liq. Ar	6.6×10^{20}
MicroBooNE	170 t	89 t	470 m	Liq. Ar	1.32×10^{21}
ICARUS	760 t	476 t	600 m	Liq. Ar	6.6×10^{20}

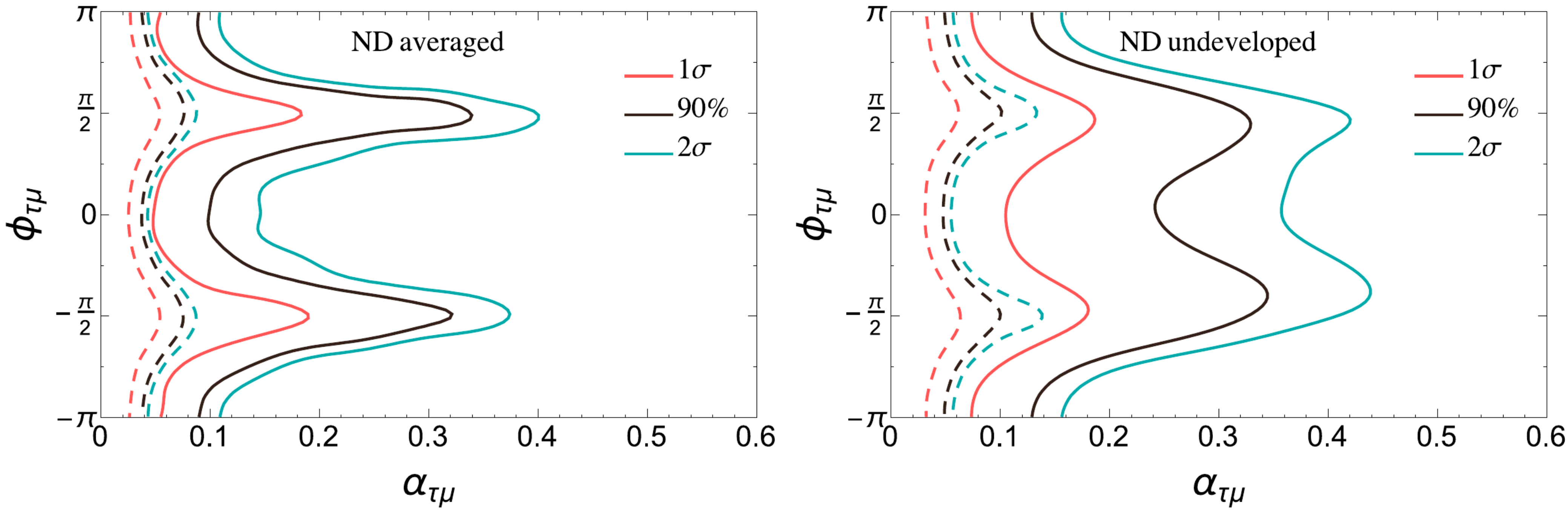
TABLE I: Summary of the main features of the SBNE detectors [5]

Near Detector Sensitivities



Miranda , Pasquini, Tórtola, Valle 1802.02133

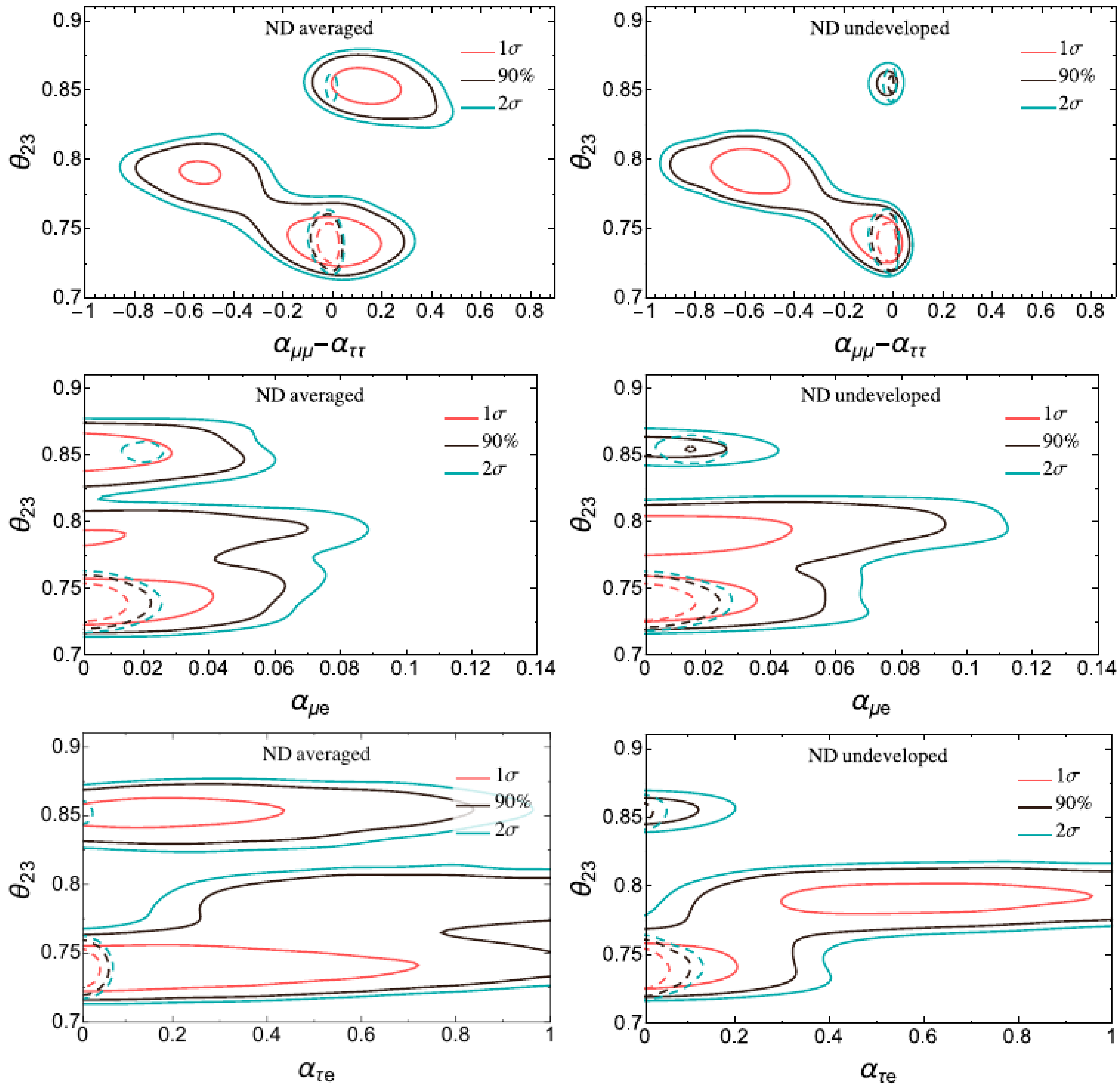
Dune Sensitivities



$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{((NN^\dagger)_{\alpha\alpha})^2}$$

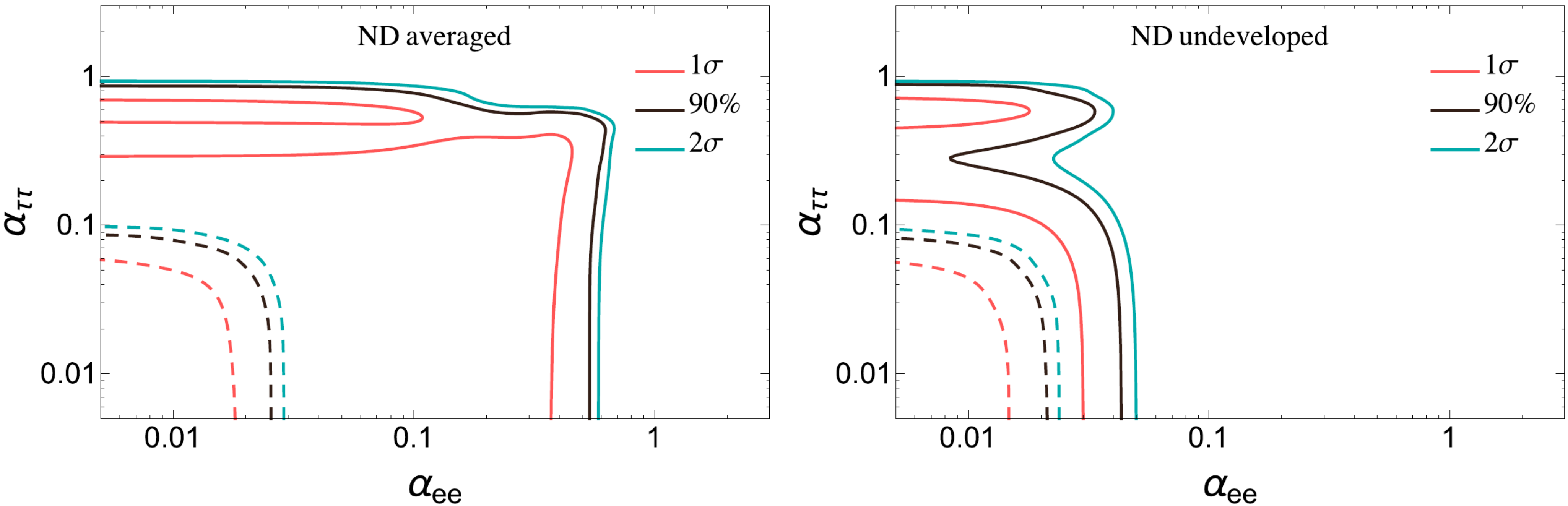
$$\mathcal{P}_{\alpha\beta} = \left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2$$

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.



ND averaged
ND undeveloped
1σ
90%
2σ
θ23
αμμ−αττ
αμe
ατe

Dune Sensitivities

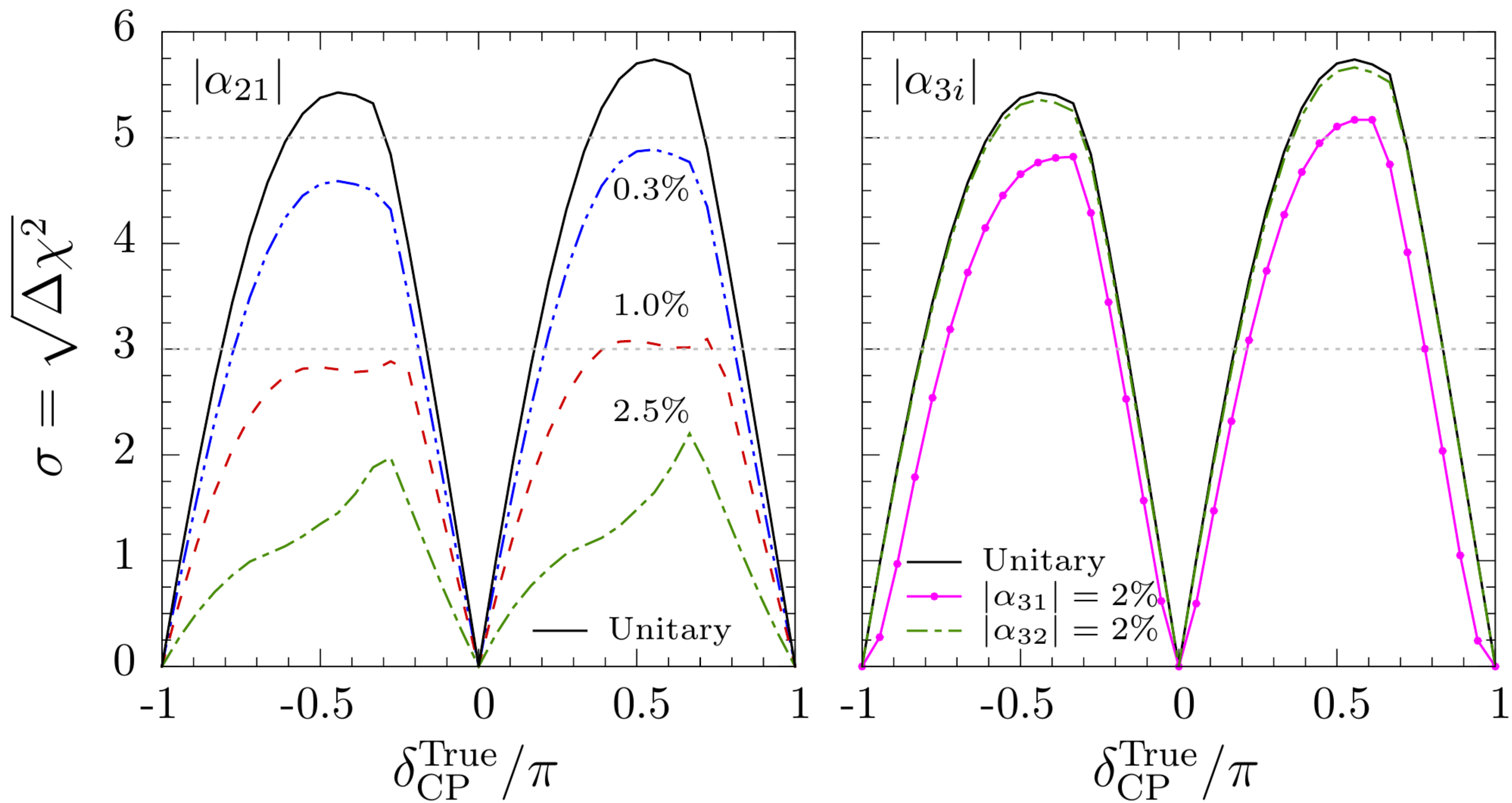


$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{((NN^\dagger)_{\alpha\alpha})^2}$$

$$\mathcal{P}_{\alpha\beta} = \left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2$$

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.

Dune Sensitivities



- With 10^{-3} priors the sensitivity to standard CPV is recovered.

Escrihuela, Forero, Miranda, Tórtola, Valle 1612.07377

General Parameterizations

- Both parameterizations are general

- Identifying U and U' with the standard unitary PMNS matrix...

$$\mathcal{P}^{\eta}_{\mu\mu} = 1 - \left\{\sin^2 2\theta'_{23} - 2\mathrm{Re}[\eta_{\mu\tau}]\sin 4\theta'_{23}\right\}\sin^2\frac{\Delta_{31}}{2}$$

$$\mathcal{P}^{\alpha}_{\mu\mu} = 1 - \sin^2 2\theta_{23}\sin^2\frac{\Delta_{31}}{2}$$

General Parameterizations

- Both parameterizations are general

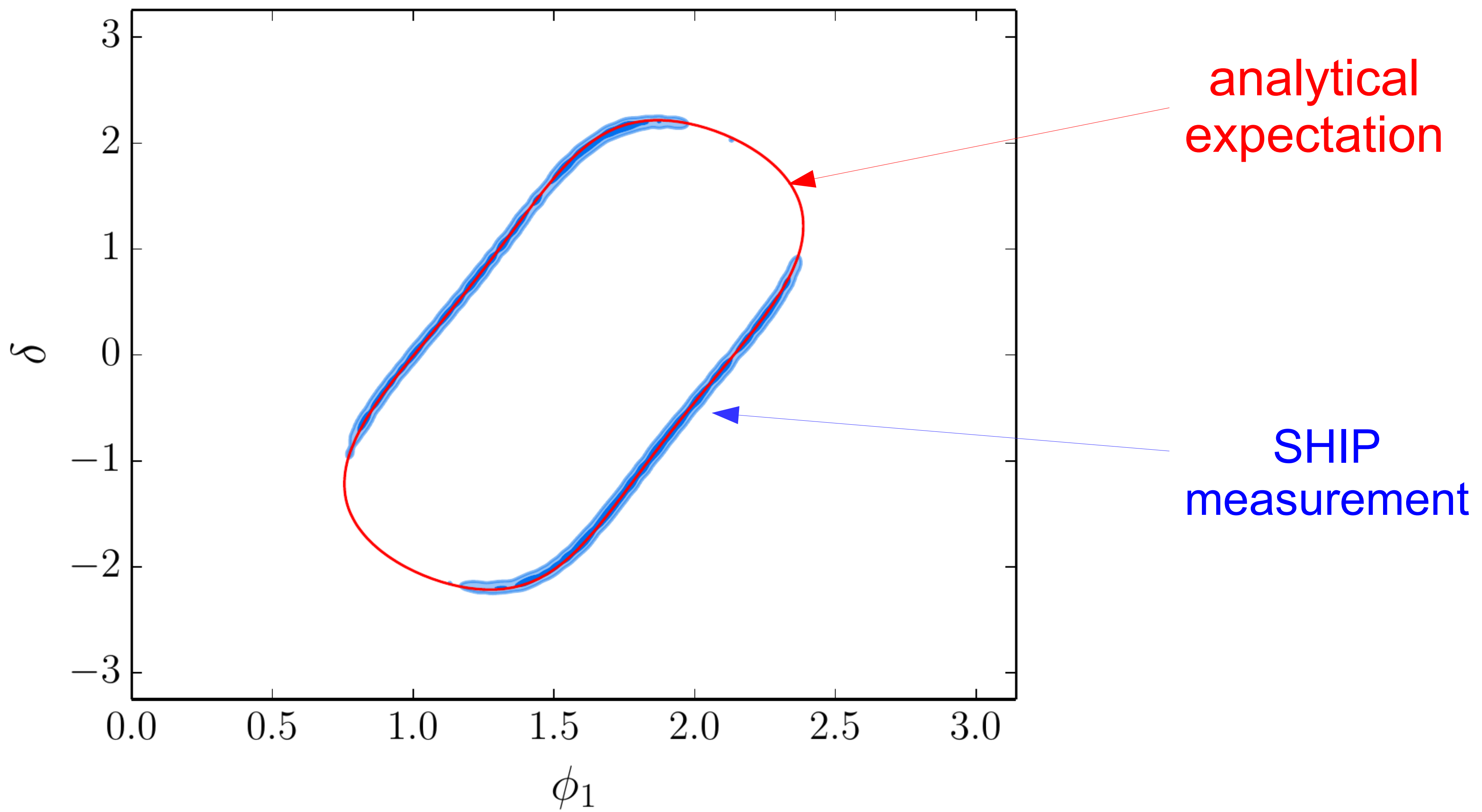
- Identifying U and U' with the standard unitary PMNS matrix...

$$\mathcal{P}^{\eta}_{\mu\mu} = 1 - \left\{\sin^2 2\theta'_{23} - 2\mathrm{Re}[\eta_{\mu\tau}] \sin 4\theta'_{23}\right\} \sin^2 \frac{\Delta_{31}}{2}$$

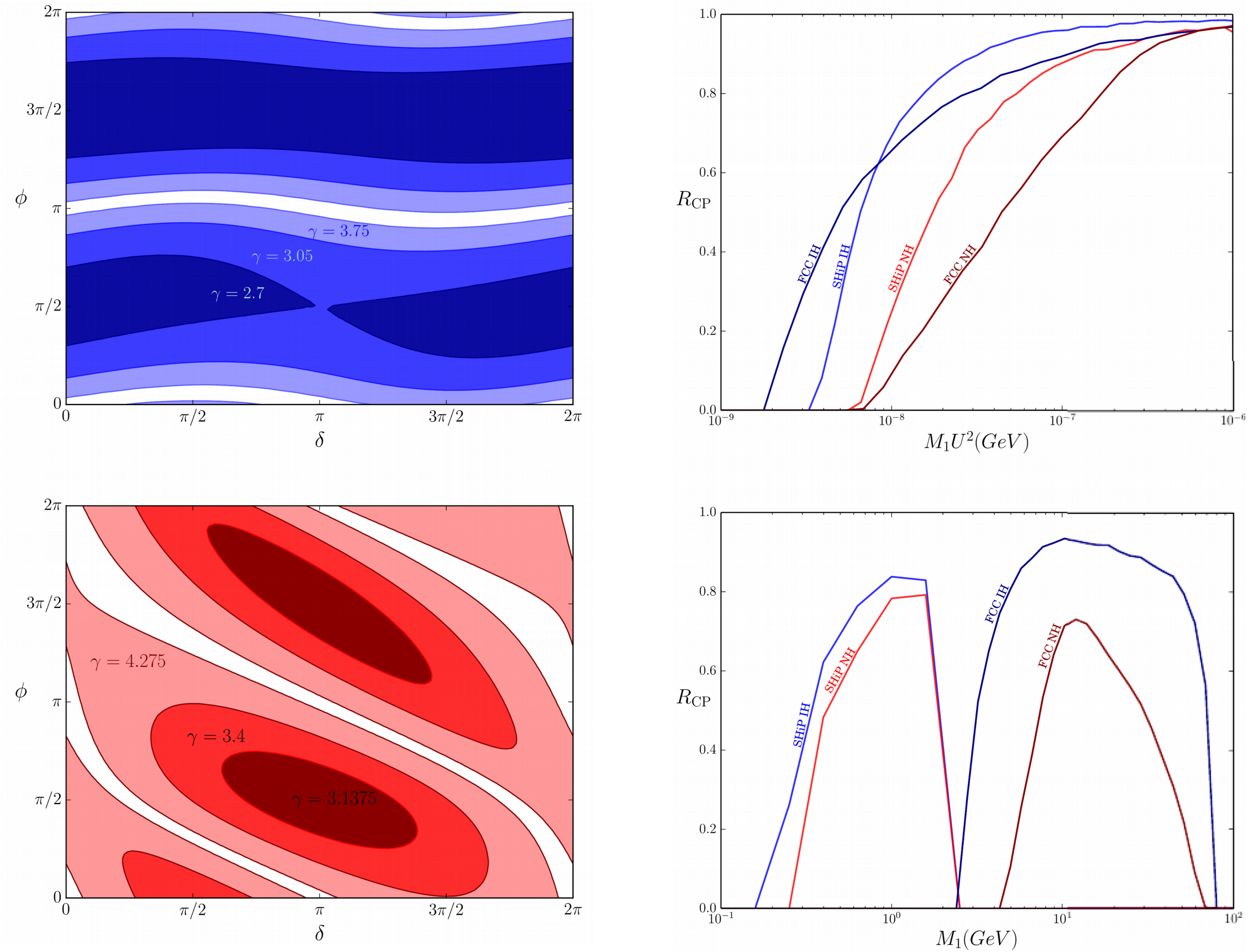
$$\mathcal{P}^{\alpha}_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta_{31}}{2}$$ (Standard Probability)

...different dependence on the non-unitary parameters??

SHIP/FCC sensitive to PMNS CP phases



Recall, neutrino oscillation experiments sensitive to δ



ϕ
δ
0
$\pi/2$
π
$3\pi/2$
2π
$\gamma = 3.75$
$\gamma = 3.05$
$\gamma = 2.7$
$R_{\rm CP}$
$M_1U^2(GeV)$
FCC IH
SHiP IH
SHiP NH
FCC NH
$\gamma = 4.275$
$\gamma = 3.4$
$\gamma = 3.1375$
$M_1(GeV)$

Heavy New Physics scale

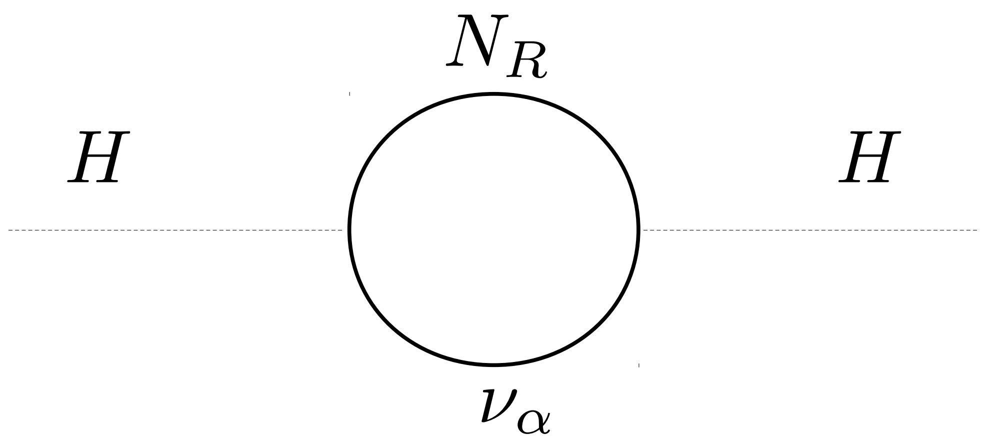
$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T \lesssim \mathcal{O}\,(1\,\mathrm{eV})$$

- $Y \sim 1$ suggests M close to the GUT scale.

- Drawback: New Physics effects at low energies very suppressed by the NP scale M.

Light New Physics scale

- Contrary to the high scale models, a low Majorana scale does not worsen the Higgs mass hierarchy problem.



$$[\delta M_H^2]_{N_R} \propto M^2$$

Vissani 1998

- Drawback: In principle, a small M requires $Y \ll 1$. Suppression of the NP effects controlled by the Yukawa couplings.

$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T \lesssim \mathcal{O}\,(1\,\mathrm{eV})$$

Sizable Phenomenology?

- Sizable New Physics effects require:

(1) $Y \sim \mathcal{O}(1)$

(2) $M \sim \mathcal{O}(\Lambda_{EW})$

$\Rightarrow$ $m_\nu \sim \frac{Y^2 v_{EW}^2}{M} \gg \mathcal{O}(1\,\mathrm{eV})$

Too large neutrino masses!!

Sizable Phenomenology?

• Sizable New Physics effects require:

(1) $Y \sim \mathcal{O}(1)$

(2) $M \sim \mathcal{O}(\Lambda_{EW})$

$$\Rightarrow \quad m_\nu \sim \frac{Y^2 v_{EW}^2}{M} \gg \mathcal{O}(1\,\mathrm{eV})$$

Too large neutrino masses!!

• Way out. Neutrino mass suppression coming from symmetry.

Approximate L conservation.

Inverse and direct seesaw models.
Mohapatra 1986; Mohapatra, Valle 1986; Bernabeu, Santamaria, Vidal, Mendez, Valle 1987; Branco, Grimus, Lavoura 1989; Malinksy, Romao, Valle 2005; Kersten, Smirnov 2007; Gavela, Hambye, D. Hernandez, P. Hernandez 2009;