Unitarity of the leptonic mixing matrix

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Non-Unitarity (NU)

- **Relation among flavor** neutrino states **and** neutrino **mass eigenstates is given by Non Unitary matrix**. The following relation among neutrino fields holds:

$$\nu_\alpha = N_{\alpha i}\,\nu_i$$

- Thus *CC and NC neutrino interactions are modified*

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\left(W_\mu^- \bar{\ell}_\alpha \gamma_\mu P_L N_{\alpha i} \nu_i + \text{ h.c.}\right) - \frac{g}{2\cos\theta_W} Z_\mu \bar{\nu}_i \gamma^\mu P_L \left(N^\dagger N\right)_{ij} \nu_j$$

- This is **generated adding only this d=6 effective** *operator* to the SM

$$\delta\mathcal{L}^{\mathrm{d}=6} = \frac{4\eta_{\alpha\beta}}{v^2}\left(\overline{L}_\alpha \tilde{H}\right) i\vec{\partial}\left(\tilde{H}^\dagger L_\beta\right)$$

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006

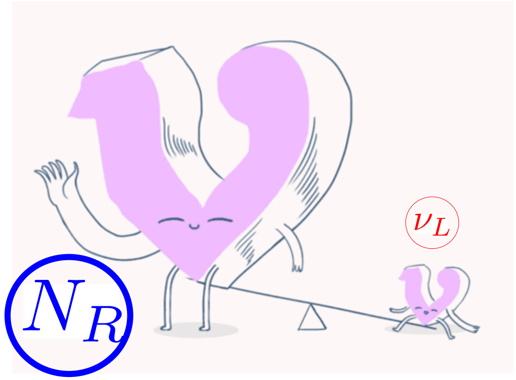
Non-Unitarity (NU)

• *Several theories accounting for neutrino masses generate NU*. Typically extensions involving heavy fermions as type-I and type-III seesaws, some extra-dimensional constructions or Left-Right symmetric models.

• However, **when the SM is extended exclusively with fermionic singlets all the new physics effects are encoded in** a **NU** leptonic mixing matrix.

• Other extensions as type-III seesaw induce additional new physics effects leading to a more constrained scenario.

See for instance Biggio, Fernandez-Martinez, Filaci, J. Hernandez-Garcia, JLP 1911.11790



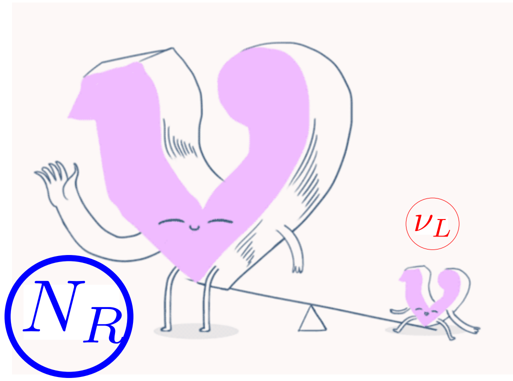
Minimal model: Mass Matrix

$$
M_\nu = \begin{array}{c c l}
 & \begin{array}{cc} \overline{\nu^c} & \quad\overline{N} \end{array} & \\
 & \begin{pmatrix} 0 & Y^T v/\sqrt{2} \\ Y v/\sqrt{2} & M \end{pmatrix} & \begin{array}{l} \nu \\ N^c \end{array}
\end{array}
$$

$$\Downarrow$$

Light
Neutrino
Masses

$$
\begin{pmatrix} \boxed{\frac{v^2}{2} Y^T M^{-1} Y} & 0 \\ 0 & M \end{pmatrix}
$$



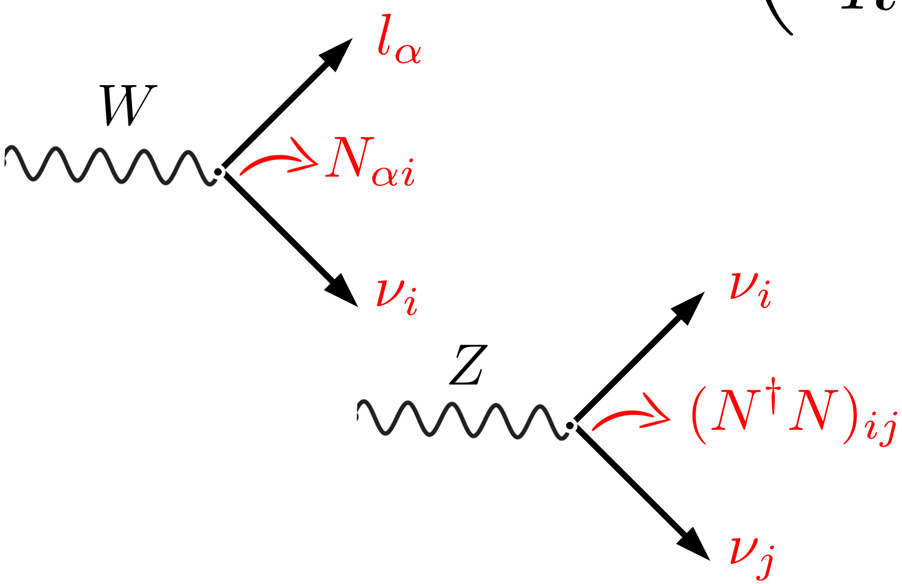
Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80

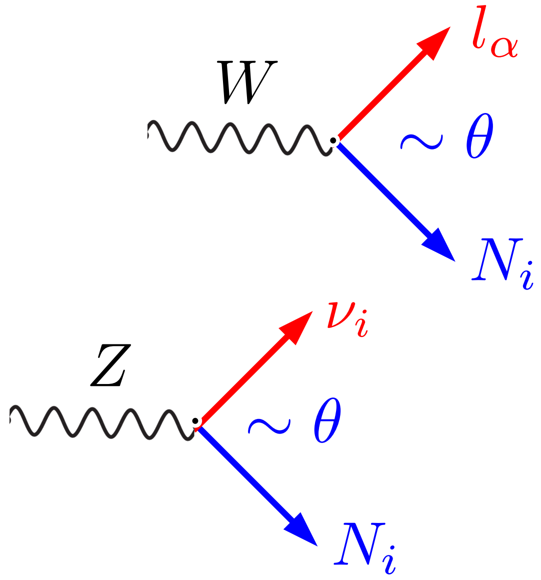
Mixing

$\nu_i - \nu_\alpha$
mixing

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

$N_i - \nu_\alpha$
mixing





Non unitary PMNS matrix

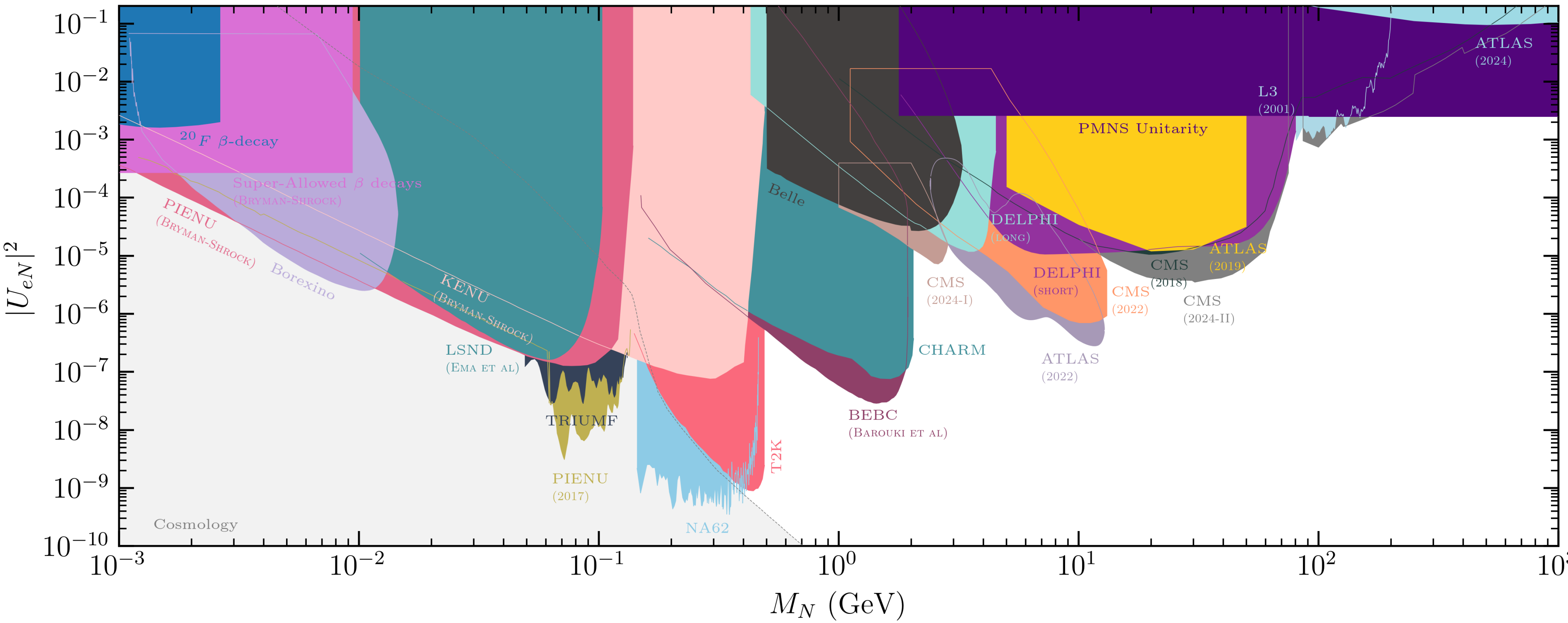
- Constraints from *EW and CLFV precision data*

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006
Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

"Direct" Searches

- *Sterile neutrino oscillations, kinks in beta decays & peak searches in semileptonic meson decays, beam-dump experiments, colliders...*

The New Physics (NP) Scale



kinks in beta decays
peak searches in semileptonic

beam-dump experiments

colliders

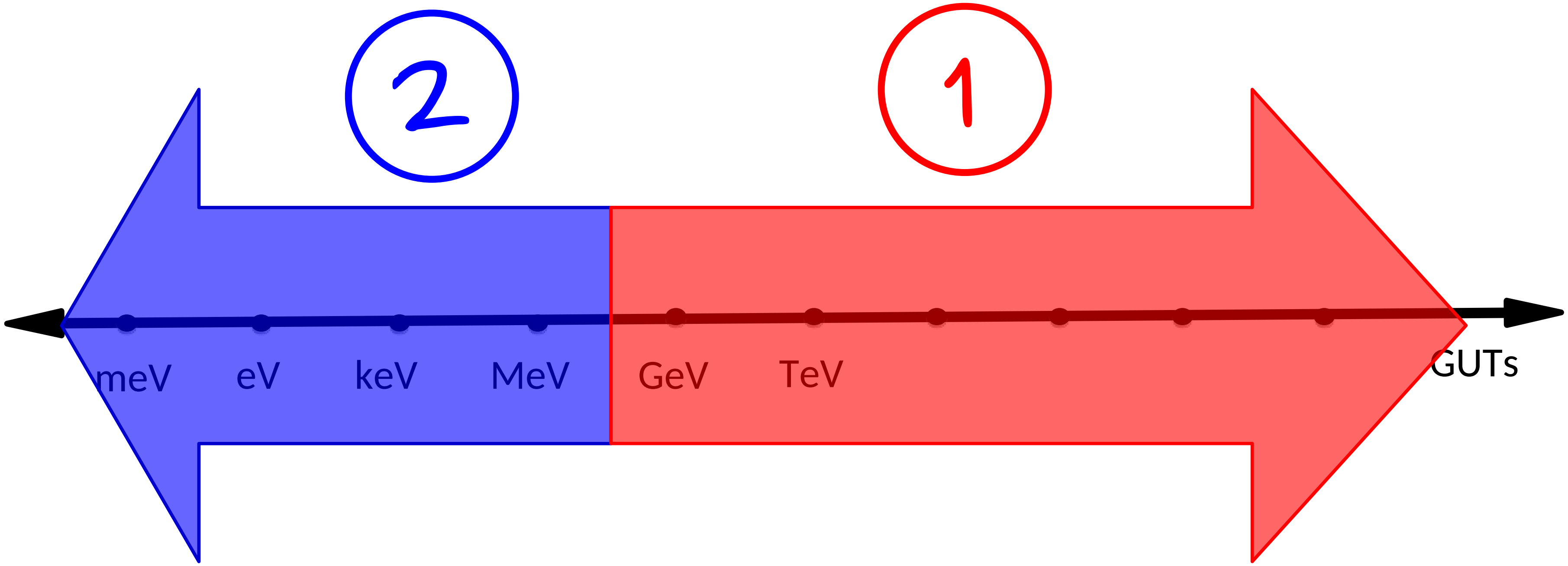
EW & CLFV
precision data

https://github.com/mhostert/Heavy-Neutrino-Limits
Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

Are Long Baseline Neutrino Oscillation experiments sensitive to Non Unitarity effects?

?

Neutrino Oscillations vs NP scale



Kinematically accessible sterile neutrinos

Non-Unitary mixing (sterile states integrated out)

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

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

$N_i - \nu_\alpha$ mixing

Deviation from unitarity of the PMNS matrix

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637
Blennow, Fernandez-Martinez, Hernandez-Garcia, JLP, Marcano, Naredo-Tuero, Urrea 2502.19480

General Parameterizations

- Triangular parameterization

$$N = (I - T)U$$

Deviation from unitarity

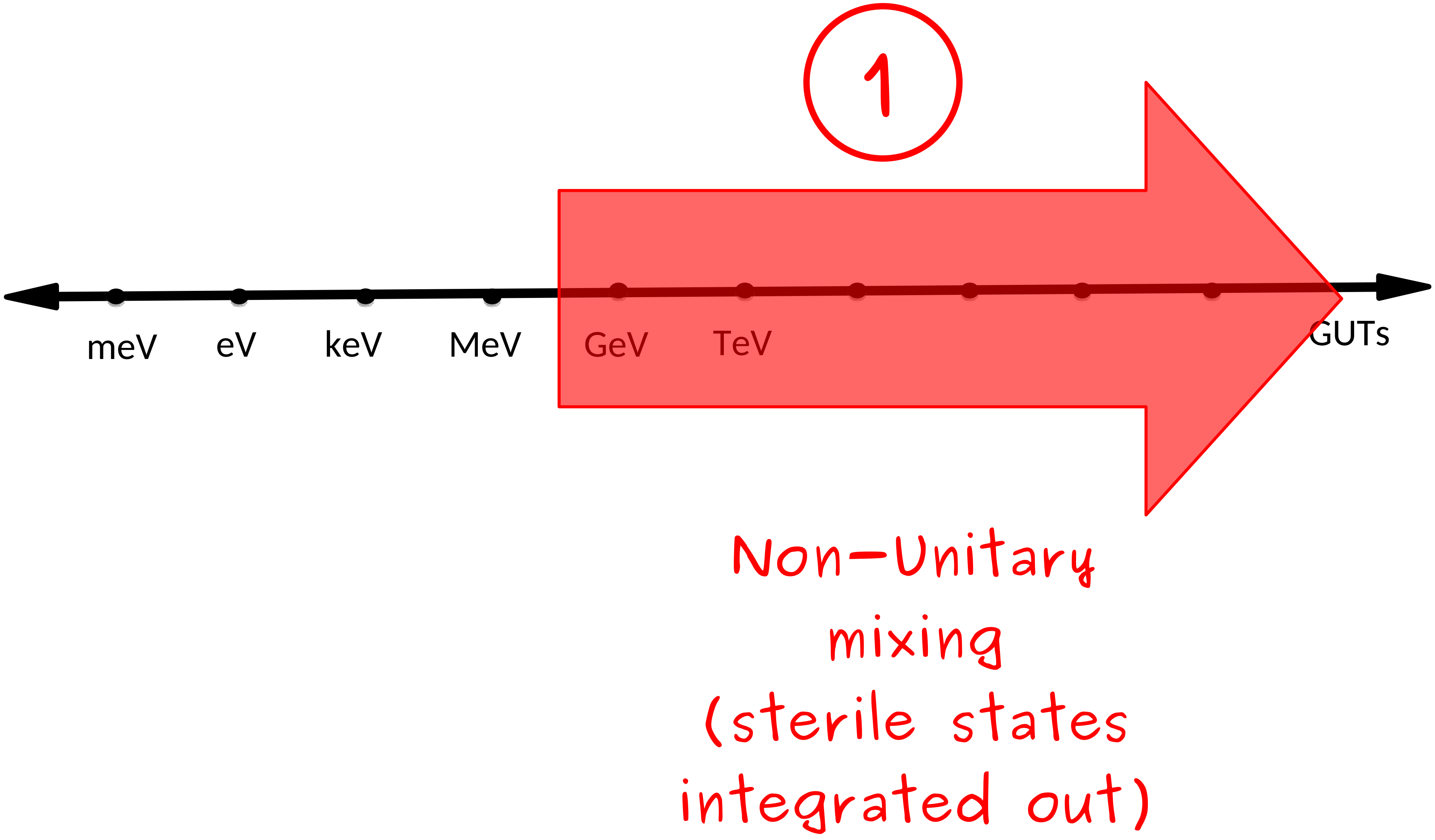
$$T = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Unitary matrix

(standard unitary PMNS matrix
up to small corrections)

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

1 Non-Unitary Mixing



1 Non-Unitary Mixing

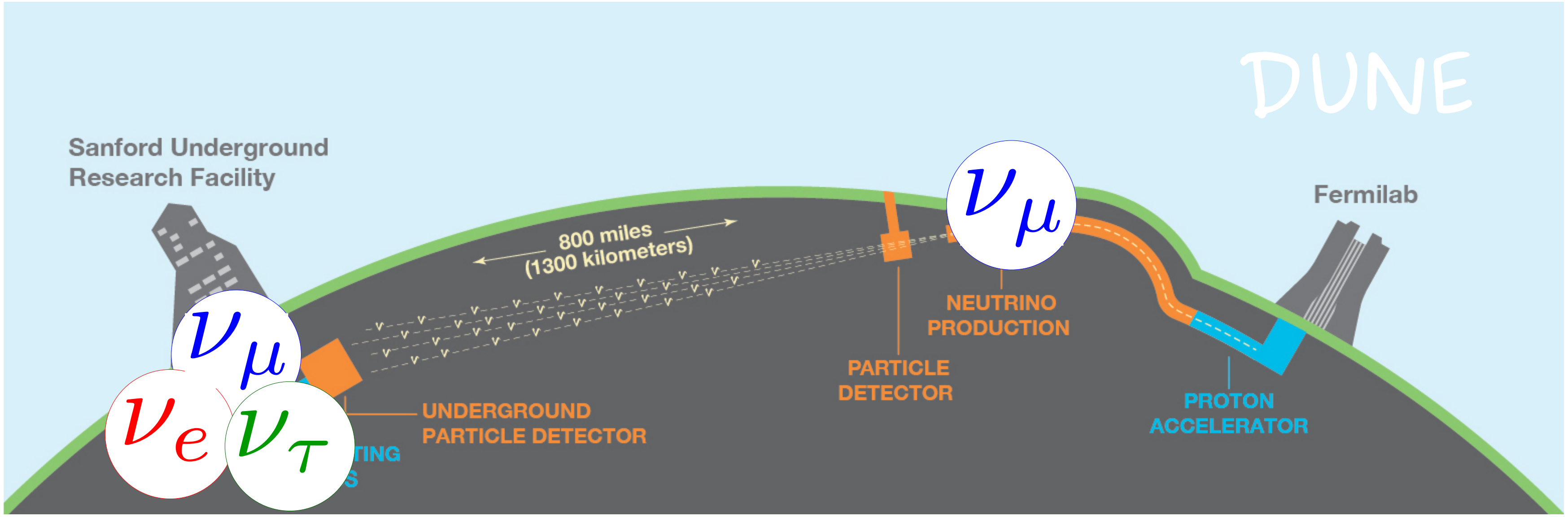
- What is measured in neutrino oscillation experiments

$$\tilde{P}_{\nu_\alpha \to \nu_\beta}(L) = \frac{\frac{dR_{\alpha\to\beta}}{dE}}{\mathcal{N}_{\rm tgt}\,\varepsilon\,\phi_\alpha \frac{d\sigma_\beta}{dE}} = \frac{\left|\sum_i N^*_{\alpha i}\, e^{-im_i^2 L/2E} N_{\beta i}\right|^2}{\sum_i |N_{\alpha i}|^2 \sum_j |N_{\beta j}|^2}$$

- When $\mathrm{NN}^\dagger = I$ ➡ Standard three family probability recovered

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.0863
Coloma, Fernández-Martínez, JLP, Marcano, Naredo-Tuero, Urrea 2411.00090
Blennow, Fernandez-Martinez, Hernandez-Garcia, JLP, Marcano, Naredo-Tuero, Urrea 2502.19480

Far Detector vs Near detector



$$\frac{dR_{\alpha\to\beta}}{dE} \sim \frac{\Phi_\alpha(E)}{L^2} P_{\alpha\beta}(L/E) \frac{d\sigma_\beta}{dE} \epsilon_\beta(E)$$

- **Sources of systematics**

  - Cross sections
  - Neutrino flux

- ***Near detector*** *measurements* ***reduce far detector systematic uncertainties***

- **New Physics at near detector (strongly affected by systematic uncertainties)**

Far Detector using ND data

- What is measured in neutrino oscillation experiments

Event rate
Far Detector

$$\tilde{P}_{\nu_\alpha \to \nu_\beta}(L) = \frac{R_\beta}{R_\alpha} = \frac{\left| \sum_i N^*_{\alpha i}\, e^{-i m_i^2 L/2E} N_{\beta i} \right|^2}{\sum_i |N_{\alpha i}|^2 \sum_j |N_{\alpha j}|^2}$$

Extrapolation of Near Detector: flux and cross section are from measurements of same flavor at ND

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Near Detector

- What is measured at Near Detector

$$\tilde{P}_{\nu_\alpha \to \nu_\beta}(0) = |\alpha_{\alpha\beta}|^2$$

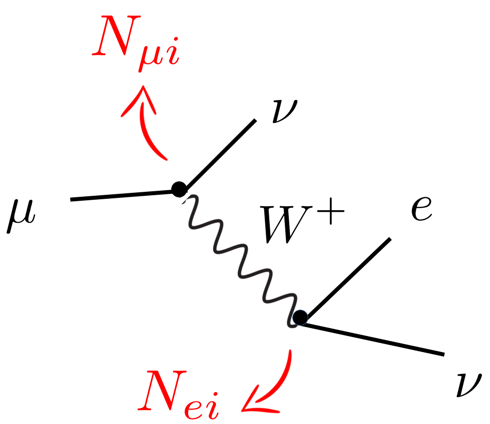
zero distance effect!

Matter effects

- Effective potential in the mass basis

$$H^m_{\mathrm{mat},\oplus} = \sqrt{2} G_F n_e U^t \begin{pmatrix} 1-\alpha_{ee}-\alpha_{\mu\mu} & \alpha_{\mu e}/2 & \alpha_{\tau e}/2 \\ \alpha^*_{\mu e}/2 & 0 & \alpha_{\tau\mu}/2 \\ \alpha^*_{\tau e}/2 & \alpha^*_{\tau\mu}/2 & \alpha_{\tau\tau}-\alpha_{\mu\mu} \end{pmatrix} U^* \; .$$

- But Fermi constant aslso include NU corrections



$$G_F \simeq G_\mu (1 + \alpha_{ee} + \alpha_{\mu\mu})$$

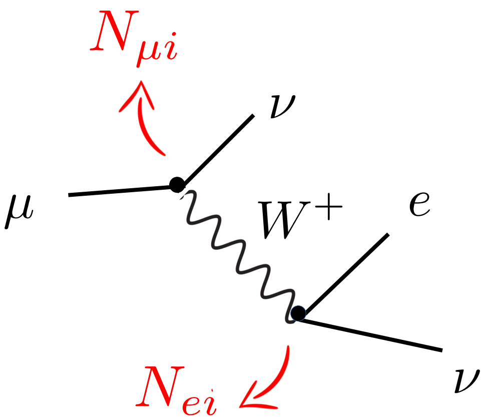
Matter effects

- Effective potential in the mass basis

$$H^{m}_{\mathrm{mat},\oplus} = \sqrt{2}G_\mu n_e U^t \begin{pmatrix} 1 & \alpha_{\mu e}/2 & \alpha_{\tau e}/2 \\ \alpha^*_{\mu e}/2 & 0 & \alpha_{\tau\mu}/2 \\ \alpha^*_{\tau e}/2 & \alpha^*_{\tau\mu}/2 & \alpha_{\tau\tau} - \alpha_{\mu\mu} \end{pmatrix} U^*$$

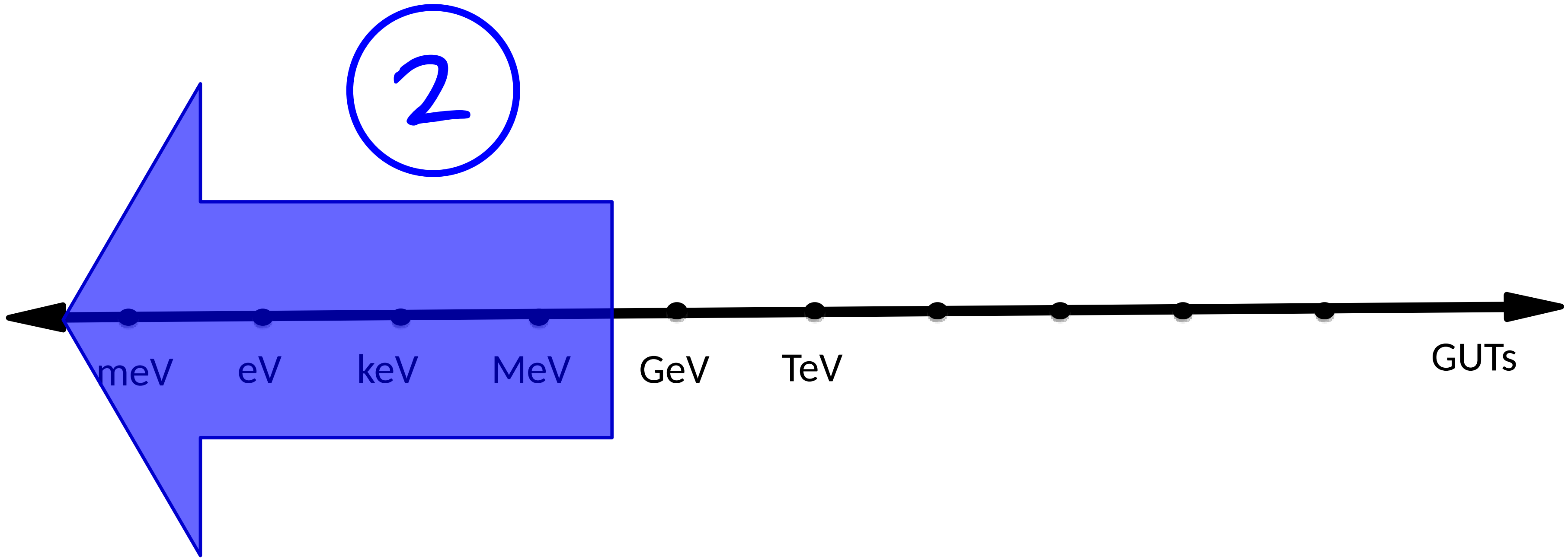
Aloni, Dery 2211.09638

- But Fermi constant also includes NU corrections



$$G_F \simeq G_\mu(1 + \alpha_{ee} + \alpha_{\mu\mu})$$

② Kinematically accessible Sterile ν



Kinematically
accessible sterile
neutrinos

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

② Kinematically accessible Sterile ν

1. The light-heavy oscillations averaged out at the near and far detectors.

Identical to NU case at leading order

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

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

Oscillations could be observed at the near detector

See talks by Erin Yandel, Matteo Tenti, Daeun Jung, Nikita Mashin and Jiyoung Choi

Sterile Neutrinos: 3+1

- What is measured at Near Detector

$$\tilde{P}_{\nu_\alpha \to \nu_\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$\tilde{P}_{\nu_\alpha \to \nu_\alpha} = 1 - 4|U_{\alpha 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Averaged-out regime

- What is measured at Near Detector

$\Delta m^2_{41} \gtrsim 100\,\mathrm{eV}^2$

$$\left\langle \tilde{P}_{\nu_\alpha \to \nu_\beta} \right\rangle = 2|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

zero distance effect!

$$\left\langle \tilde{P}_{\nu_\alpha \to \nu_\alpha} \right\rangle = 1 - 2|U_{\alpha 4}|^2$$

Averaged-out regime

- What is measured at Near Detector

$\Delta m^2_{41} \gtrsim 100\,\mathrm{eV}^2$

$$\left\langle \tilde{P}_{\nu_\alpha \to \nu_\beta} \right\rangle = 2|\alpha_{\alpha\beta}|^2$$

zero distance effect!

$$\left\langle \tilde{P}_{\nu_\alpha \to \nu_\alpha} \right\rangle = 1 - 4|\alpha_{\alpha\alpha}|$$

Low Scale Non-Unitarity

② Kinematically accessible Sterile ν

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

Identical to NU case at leading order

Low Scale Non-Unitarity

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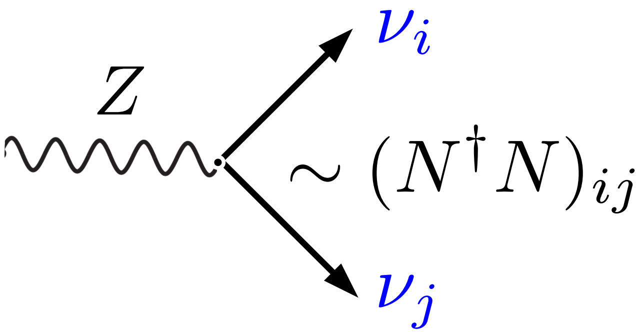
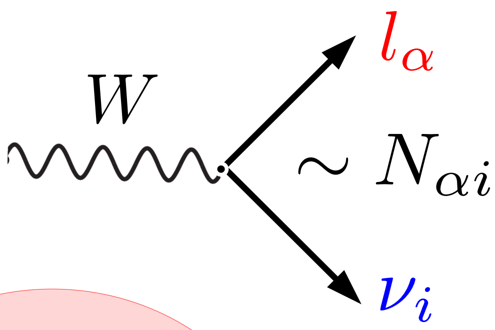
Present Bounds





90% CL	Flavour & EWPO $\mathbf{m > M_Z}$	
	Direct	**Schwarz**
α_{ee}	1.2×10^{-3}	$\alpha_{\alpha\beta} \leq 2\sqrt{\alpha_{\alpha\alpha}\alpha_{\beta\beta}}$
$\alpha_{\mu\mu}$	8.6×10^{-5}	-
$\alpha_{\tau\tau}$	6.0×10^{-4}	-
$\lvert\alpha_{\mu e}\rvert$	1.9×10^{-5}	5.4×10^{-4}
$\lvert\alpha_{\tau e}\rvert$	6.2×10^{-3}	1.5×10^{-3}
$\lvert\alpha_{\tau\mu}\rvert$	6.9×10^{-3}	1.5×10^{-4}

EW & CLFV precision data

Blennow, Fernandez-Martinez, Hernandez-Garcia, JLP, Marcano, **Naredo-Tuero** 2306.01040
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Present Bounds

90% CL	**Averaged ν Oscillations** $\mathbf{m > 10}$ **eV**		**Flavour & EWPO** $\mathbf{m > M_Z}$	
	Direct	**Schwarz**	**Direct**	**Schwarz**
α_{ee}	8.4×10^{-3} Solar	-	1.2×10^{-3}	- EW+CLFV
$\alpha_{\mu\mu}$	1.2×10^{-2} MINOS+	Oscillations -	8.6×10^{-5}	precision
$\alpha_{\tau\tau}$	2.9×10^{-2} IceCUBE	-	6.0×10^{-4}	data
$\lvert\alpha_{\mu e}\rvert$	1.8×10^{-2}	1.4×10^{-2}	1.9×10^{-5}	5.4×10^{-4}
$\lvert\alpha_{\tau e}\rvert$	6.1×10^{-2} NOMAD	2.2×10^{-2}	6.2×10^{-3}	1.5×10^{-3}
$\lvert\alpha_{\tau\mu}\rvert$	9.1×10^{-3}	2.6×10^{-2}	6.9×10^{-3}	1.5×10^{-4}

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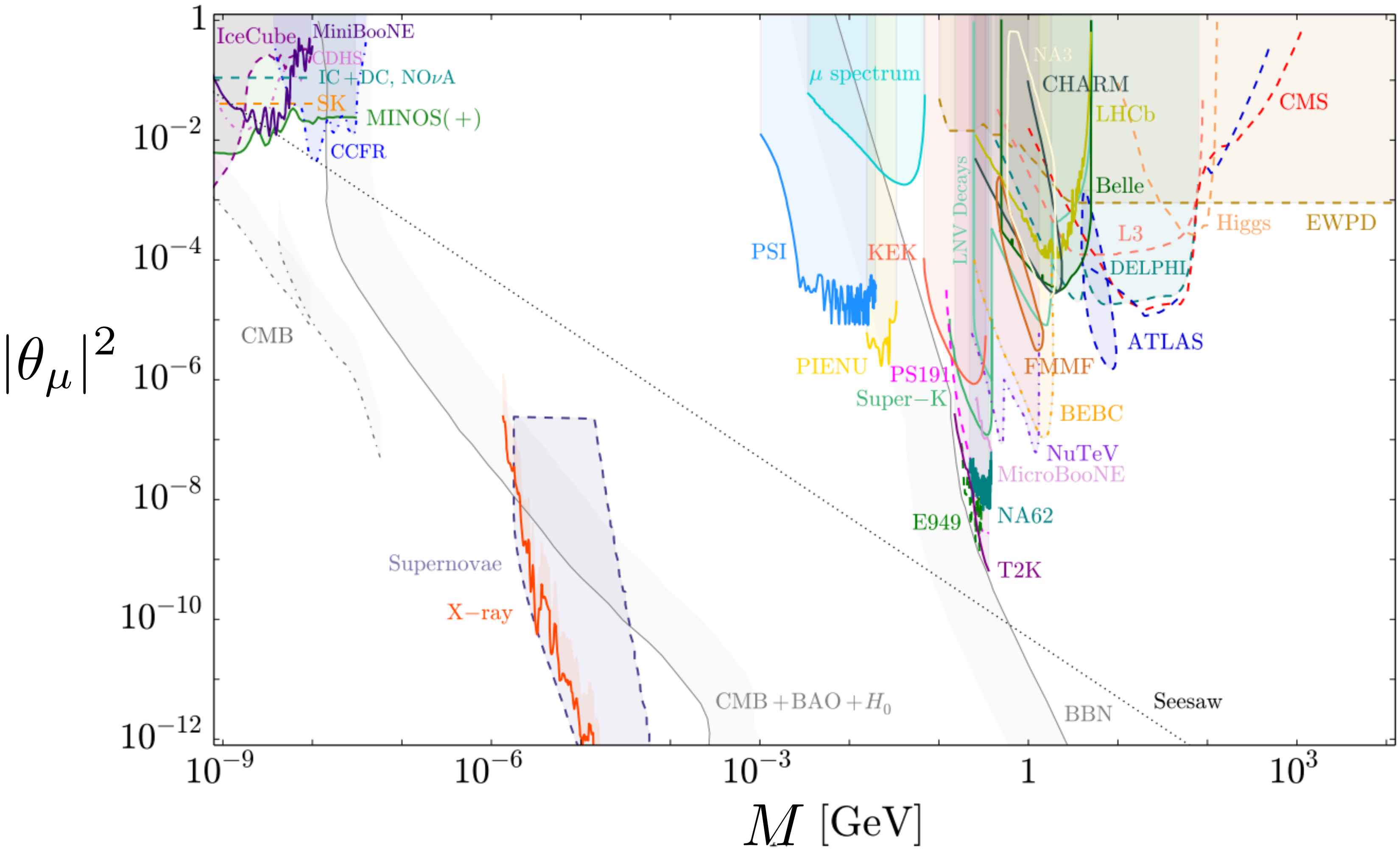
Present Bounds



$$|\alpha_{\beta\beta}|^2 = \frac{1}{2}\sum_i |\theta_{\alpha i}|^2$$

Figure from Bolton,Deppisch, Bhupal Dev 1912.03058

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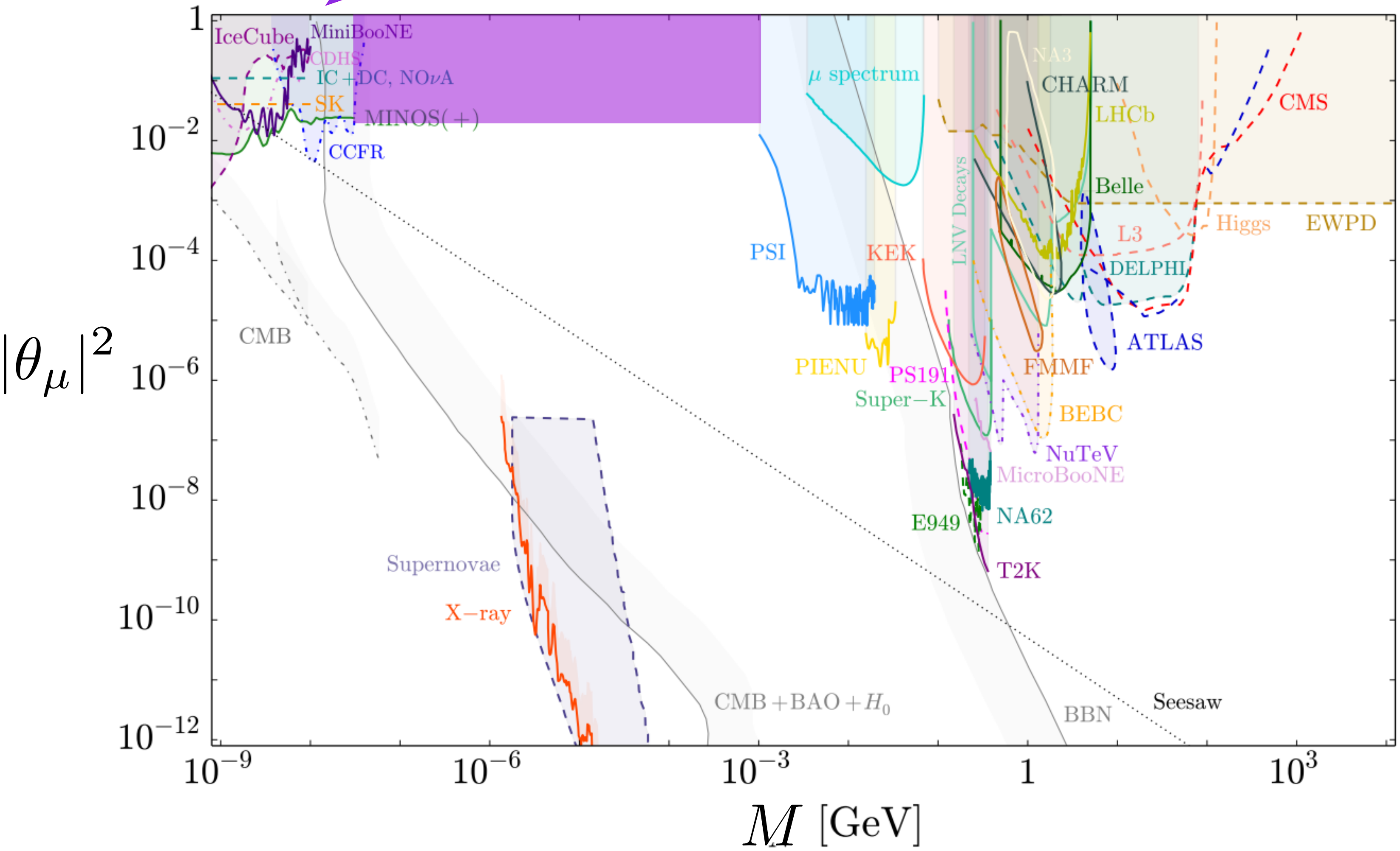
Present Bounds



$$|\alpha_{\beta\beta}|^2 = \frac{1}{2}\sum_i |\theta_{\alpha i}|^2$$

Figure from Bolton,Deppisch, Bhupal Dev 1912.03058

Why is there confusion in literature?

- Potentially interesting alternative: *to avoid parameterizing deviations from unitarity*

  Parke, Ross-Lonergan,1508.05095; Ellis, Kelly, Li, 2004.13719; Ellis, Kelly, Li, 2008.01088

- Unitarity triangles in the quark sector are successful unitarity test: independent measurements of the individual V_{ab}^{CKM} compared to test unitarity conditions.

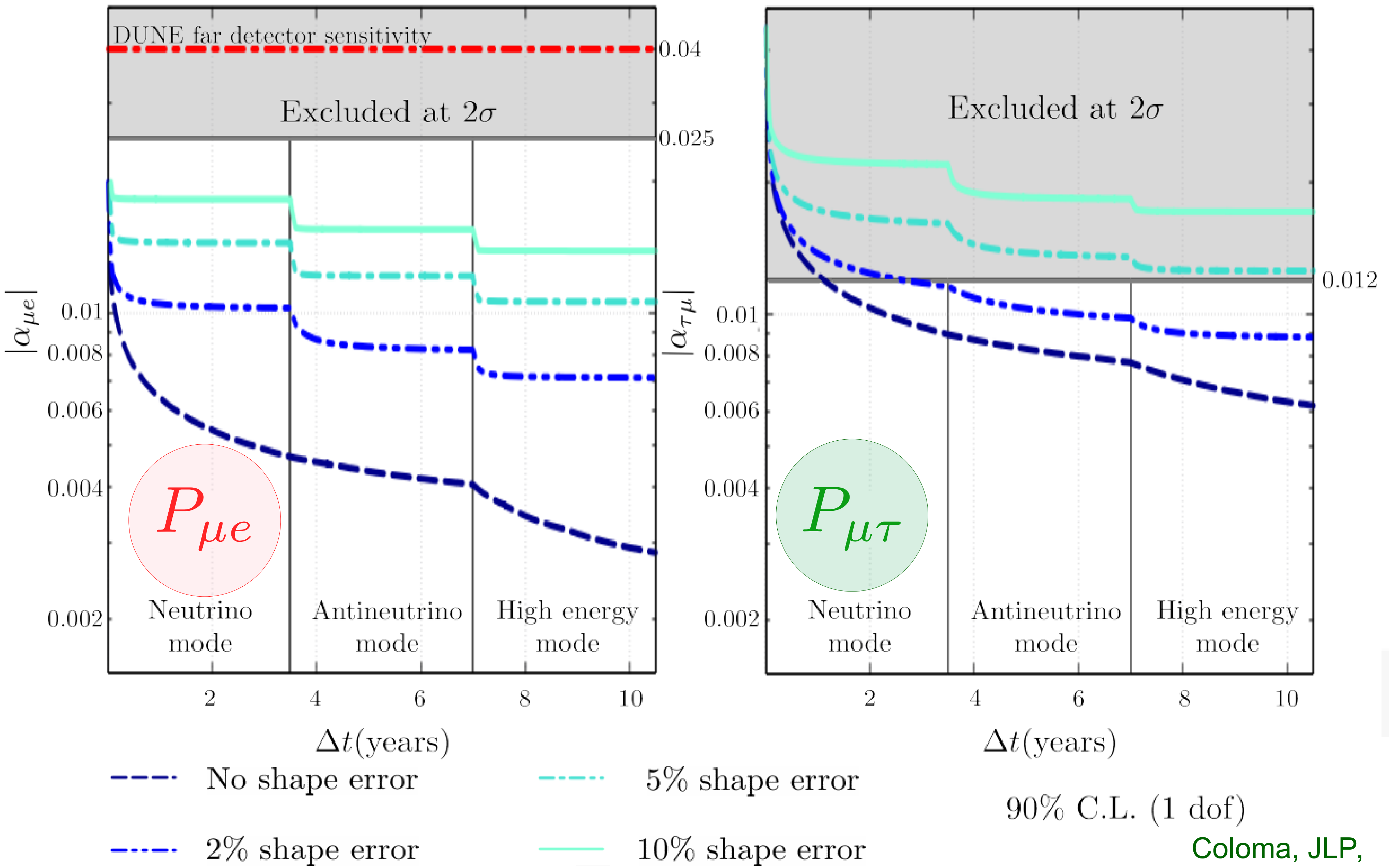
- This is not efficient in the lepton sector because, contrary to the quark sector, only charged leptons are detected and thus a direct measurement of $N_{\alpha i}$ is not directly possible!

- *Avoiding using a convenient parameterization might lead to wrong conclusions*.

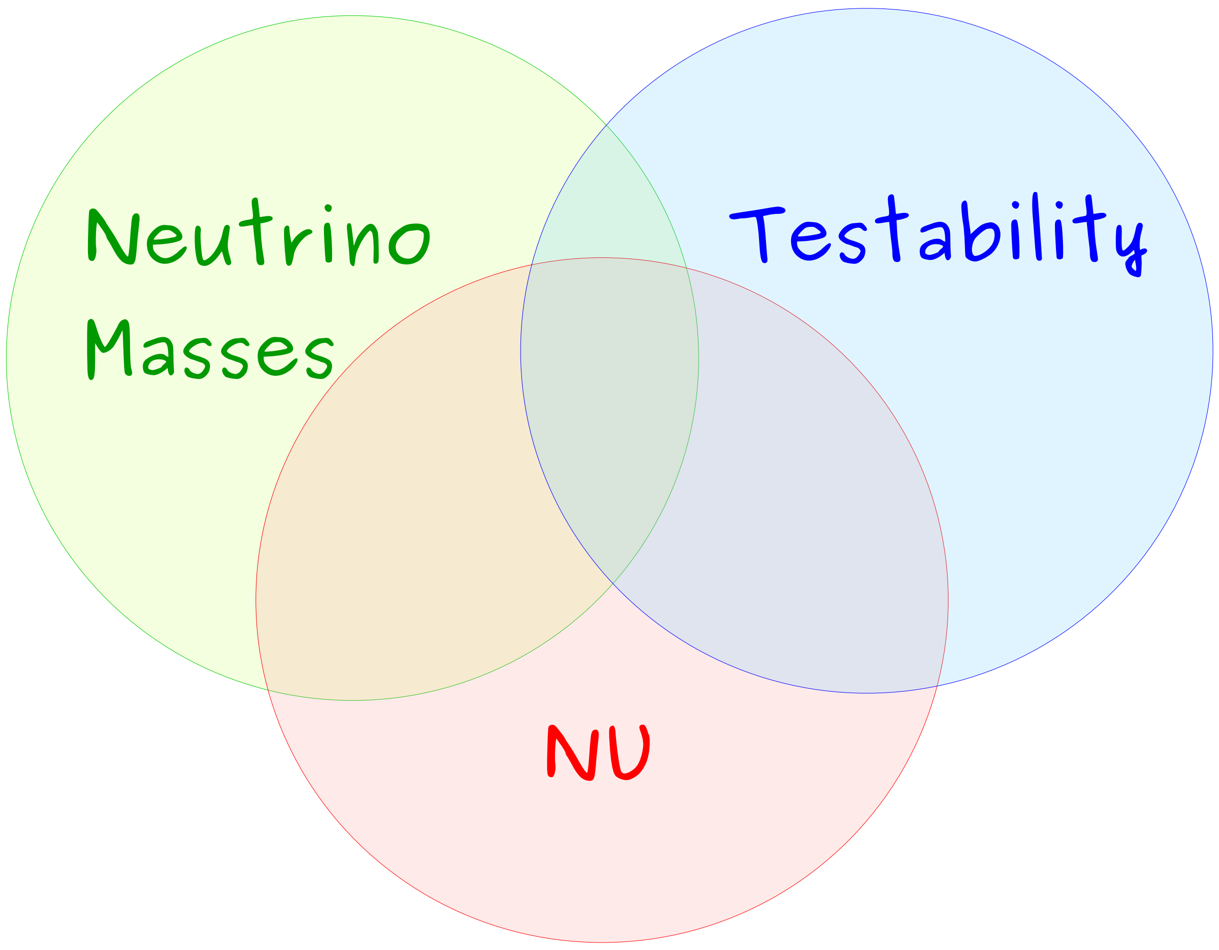
- Zero distance and matter effects are directly sensitive to α. **Our current knowledge of the lepton mixing matrix is that it is close to unitary with higher accuracy than the uncertainty we have in its individual entries.**

$$(NN^\dagger)_{\beta\gamma} \approx \delta_{\beta\gamma} - \alpha_{\beta\gamma} - \alpha^*_{\gamma\beta}$$

Low Scale Non-Unitarity (DUNE ND)

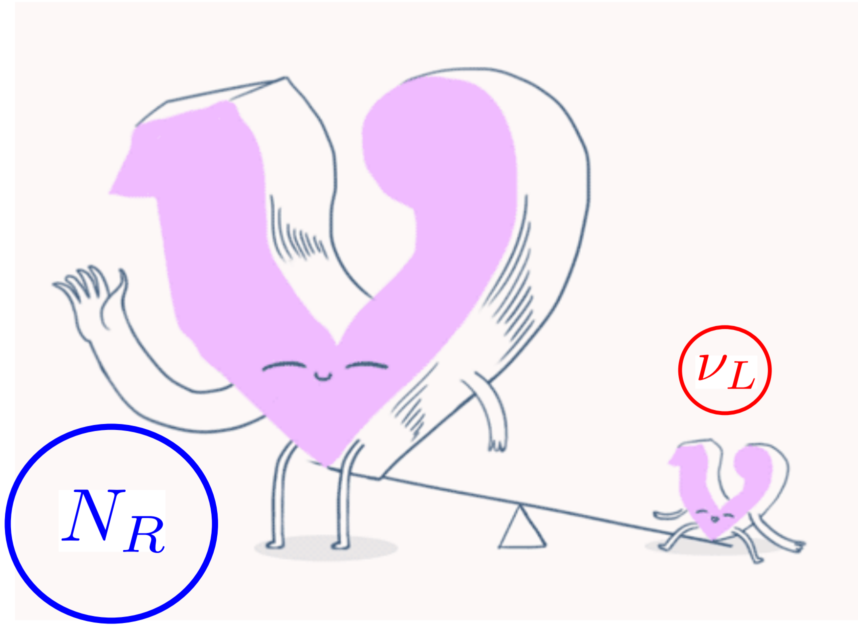


Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466


Neutrino
Masses
Testability
NU

Constraints from neutrino mass mechanism

- Generation of light neutrino masses imposes **constraints on HNL mixing and thus on NU parameters**

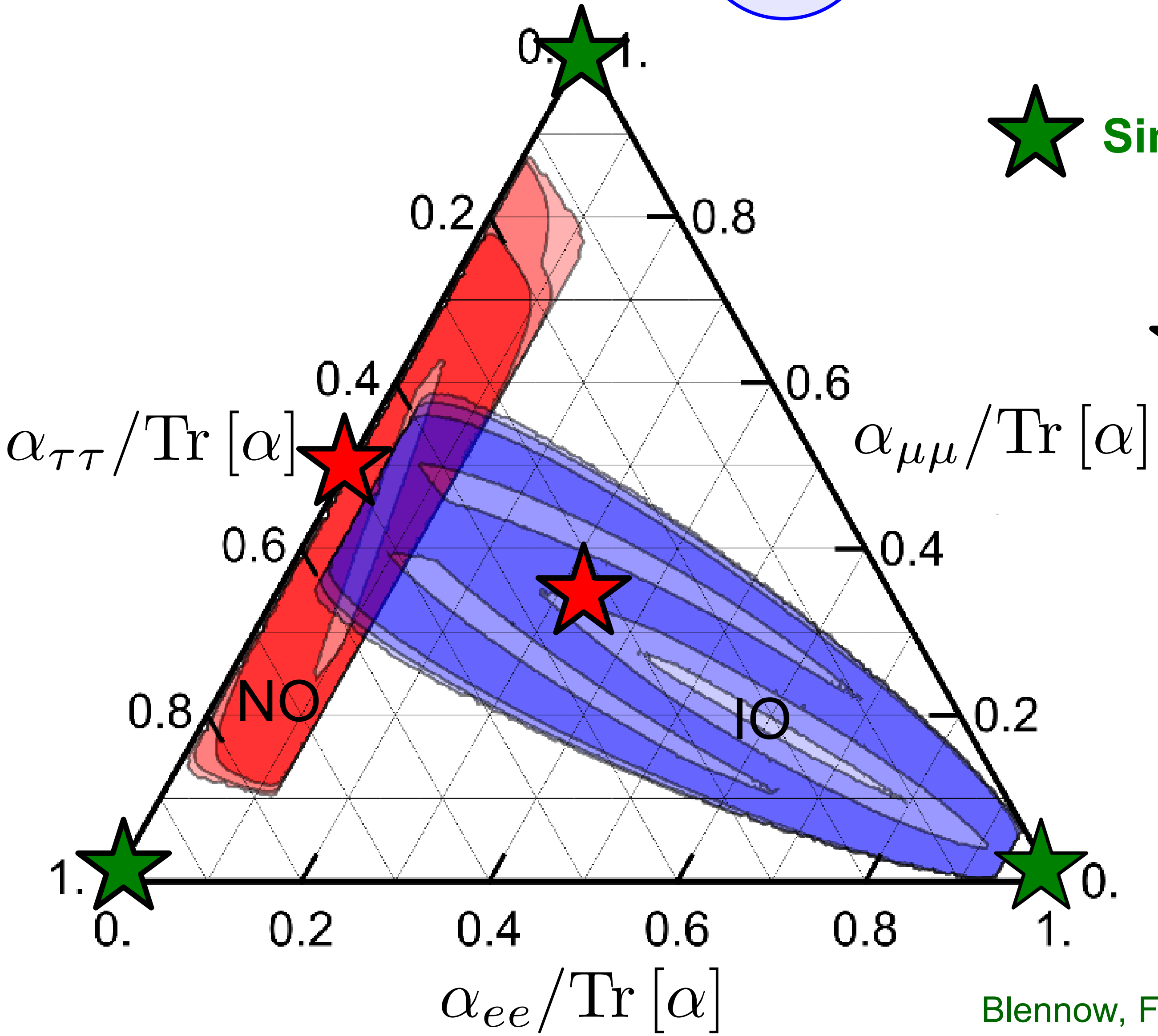


$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y = \boxed{\theta\, M\, \theta^T} = \boxed{U\, m\, U^T}$$

HNL sector

Light-active neutrino sector

Minimal model ($n_R=2$): Flavor Structure



Single flavored benchmarks
(1,0,0), (0,1,0), (0,0,1)

NEW 2021
(0, 1/2, 1/2)
(1/3, 1/3, 1/3)

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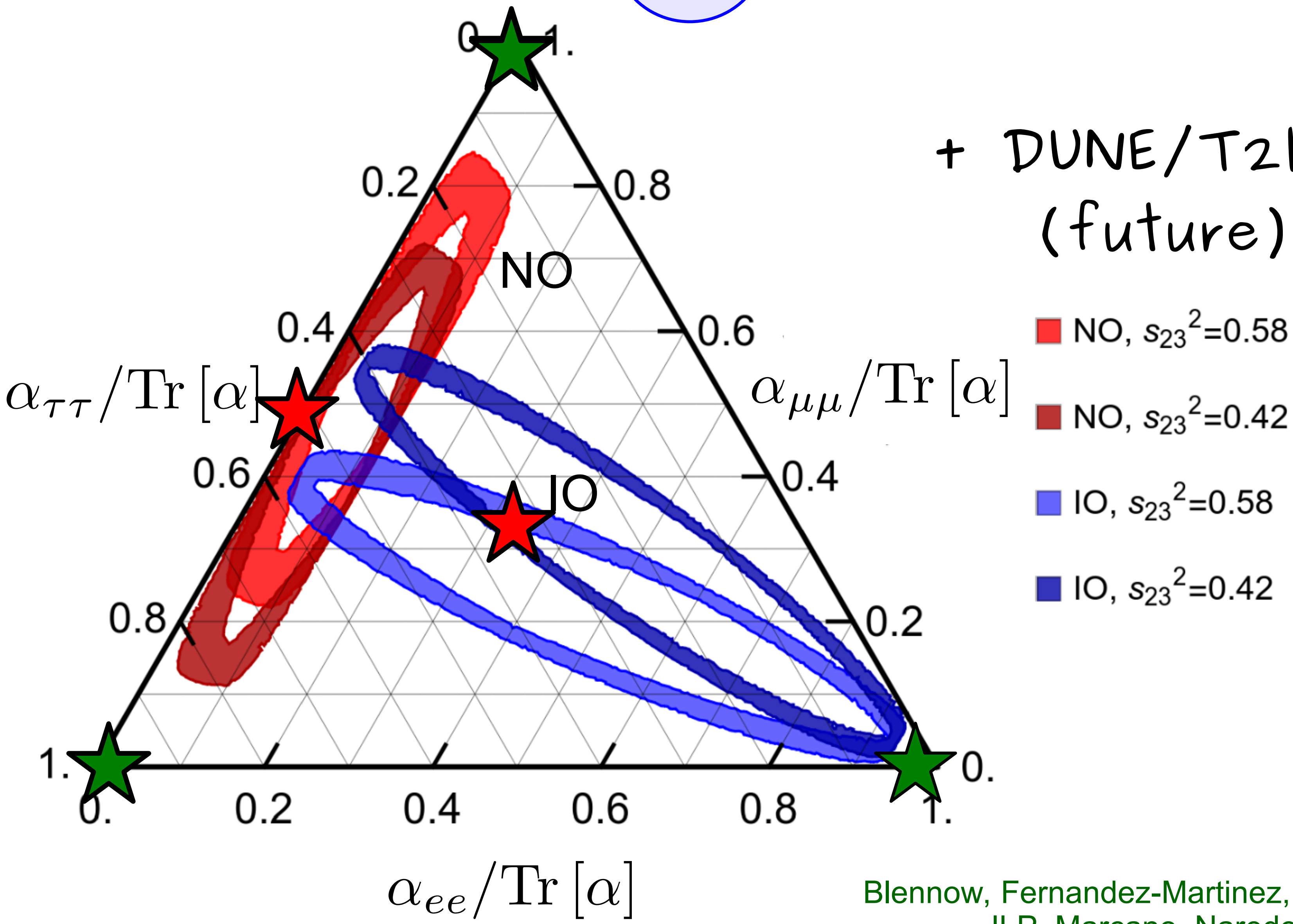
JLP, Marcano, Naredo-Tuero 2306.01040
Abdullahi et al 2203.08039
Drewes, Klaric, JLP 2207.02742
Caputo, Hernandez, JLP, Salvado, 1704.08721

Minimal model ($n_R=2$): Flavor Structure



+ DUNE/T2HK...
(future)

DUNE forecast assuming $\delta = -\pi/2$

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Abdullahi et al 2203.08039
Drewes, Klaric, JLP 2207.02742
Caputo, Hernandez, JLP, Salvado, 1704.08721

Conclusions

- Current onstraints on NU from EW and CLFV precision data well beyond sensitivity of oscillation experiments.
  Best chance: Future CLFV experiments and FCC-ee EW precision data.

- For kinematically accessible sterile neutrino the EW and CLFV bounds do not apply and NU-like effects generated in the averaged out regime. *Still stringent constraints from short baseline oscillation experiments and experiments strongly sensitive to matter effects.*

- Near detectors at future oscillation experiments are probably the best option to test robustness of standard 3 neutrino picture.

- *Keeping under control shape uncertainties is a key issue.* PRISM might help! (we are currently analyzing this possibility). Independent measurements of the cross sections would give very relevant information of the energy dependence (see talk by Kenneth Long: $\nu\mathrm{STORM}$ proposal)

Thank you!

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Event Rate and Normalization

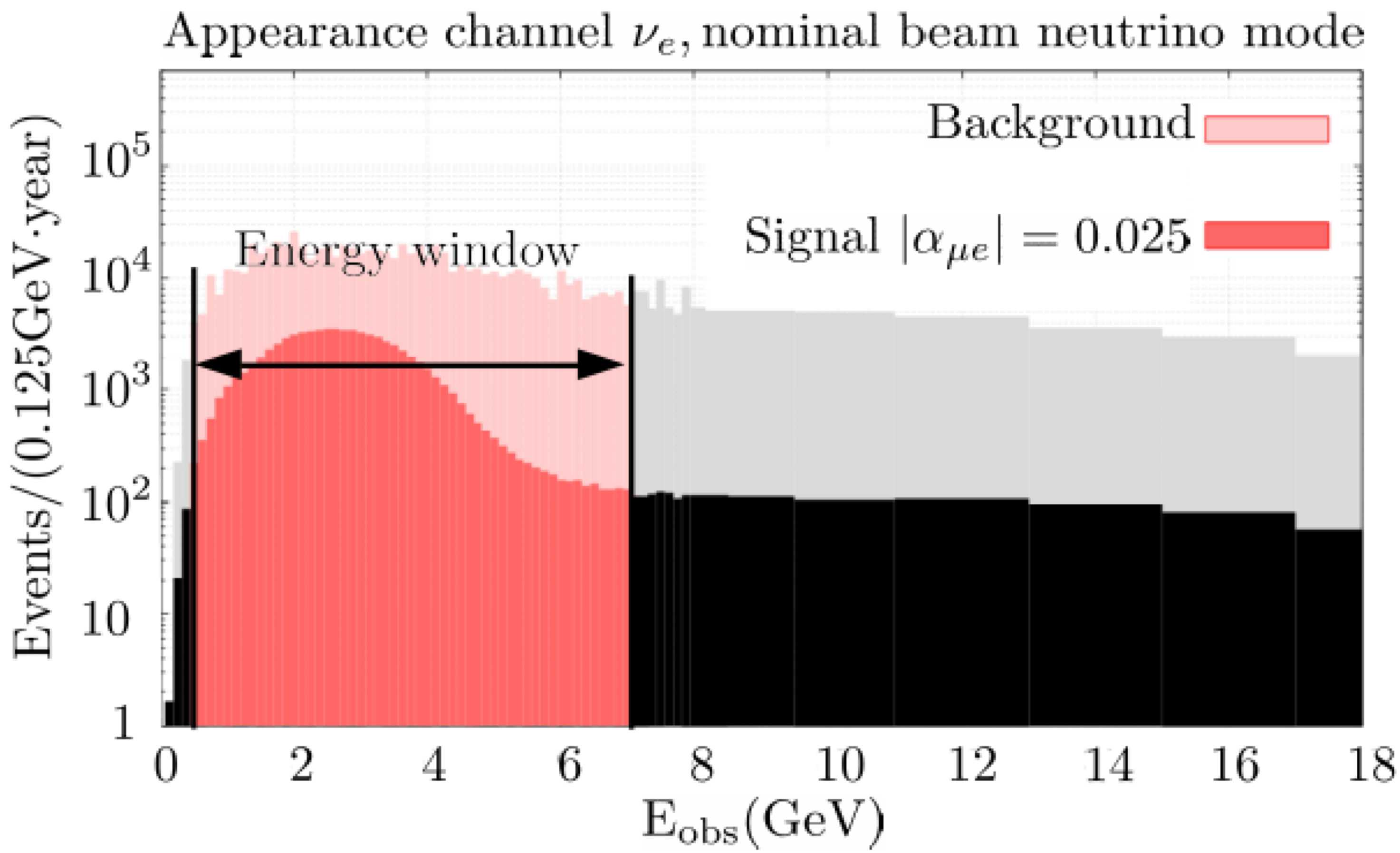
$$R_{\alpha}^{\mathrm{CC},\beta}(L) = \frac{N_S N_T}{32\pi L^2 E_S m_T E_\nu} \sum_{k,l} e^{-i\frac{\Delta m_{kl}^2 L}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}_{\alpha k}^{P} \overline{\mathcal{M}}_{\alpha l}^{P} \int d\Pi_D \mathcal{M}_{\beta k}^{D} \overline{\mathcal{M}}_{\beta l}^{D}$$

QFT

$$\left.\begin{aligned} R_{\alpha}^{\mathrm{CC},\beta}(L) &= N_T \Phi_\alpha P_{\alpha\beta}(L) \frac{d\sigma_\beta}{dE_\nu} \\ P_{\alpha\beta}(L) &= \frac{R_{\alpha}^{\mathrm{CC},\beta}(L)}{N_T \Phi_\alpha^{\mathrm{est}} \frac{d\sigma_\beta^{\mathrm{est}}}{dE_\nu}} \end{aligned}\right\}$$

Experiments

Role of shape uncertainty



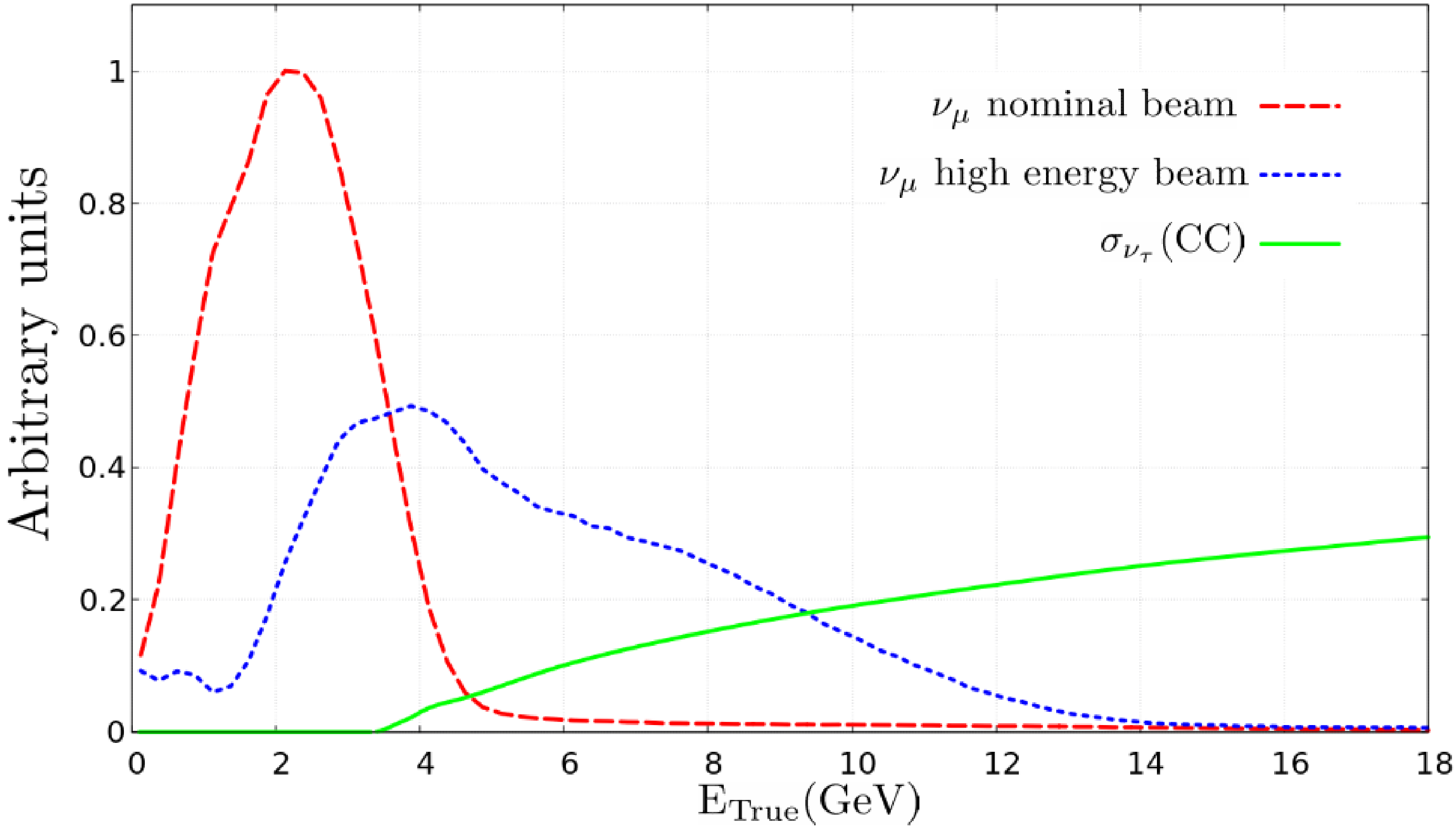
- Sensitivity driven by spectral information.

- Marginal impact of global normalization error.

Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

ν_τ appearance channel

- Energy threshold of τ production 3.2 GeV.



- ν_τ **detection:** we follow de Gouvêa, Kelly, Stenico, Pasquini 1904.07265

ν_τ appearance channel

ν_τ detection:

- Energy threshold of τ production 3.2 GeV.

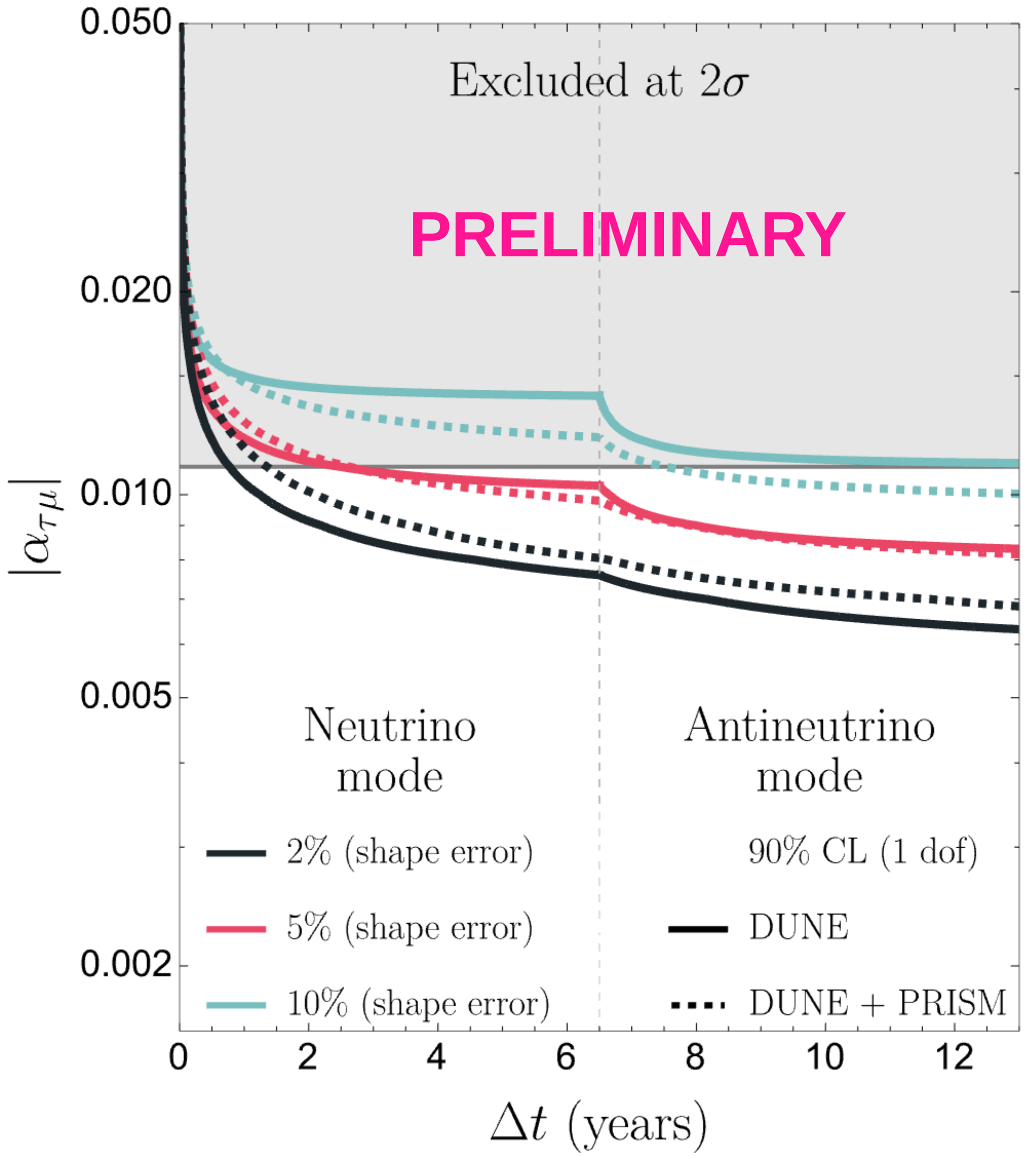
- Short lifetime of τ, indirect measurement via hadronic decays (~ 65% branching ratio).

- NC background. We have considered a sample in which 30% of the hadronic events are identified keeping 0.5% of NC background.

de Gouvêa, Kelly, Stenico, Pasquini 1904.07265

Low Scale Non-Unitarity (PRISM)

$P_{\mu\tau}$



3 on axis + 0.5 x 7 different off axis

Hernandez-Garcia, JLP, Urrea

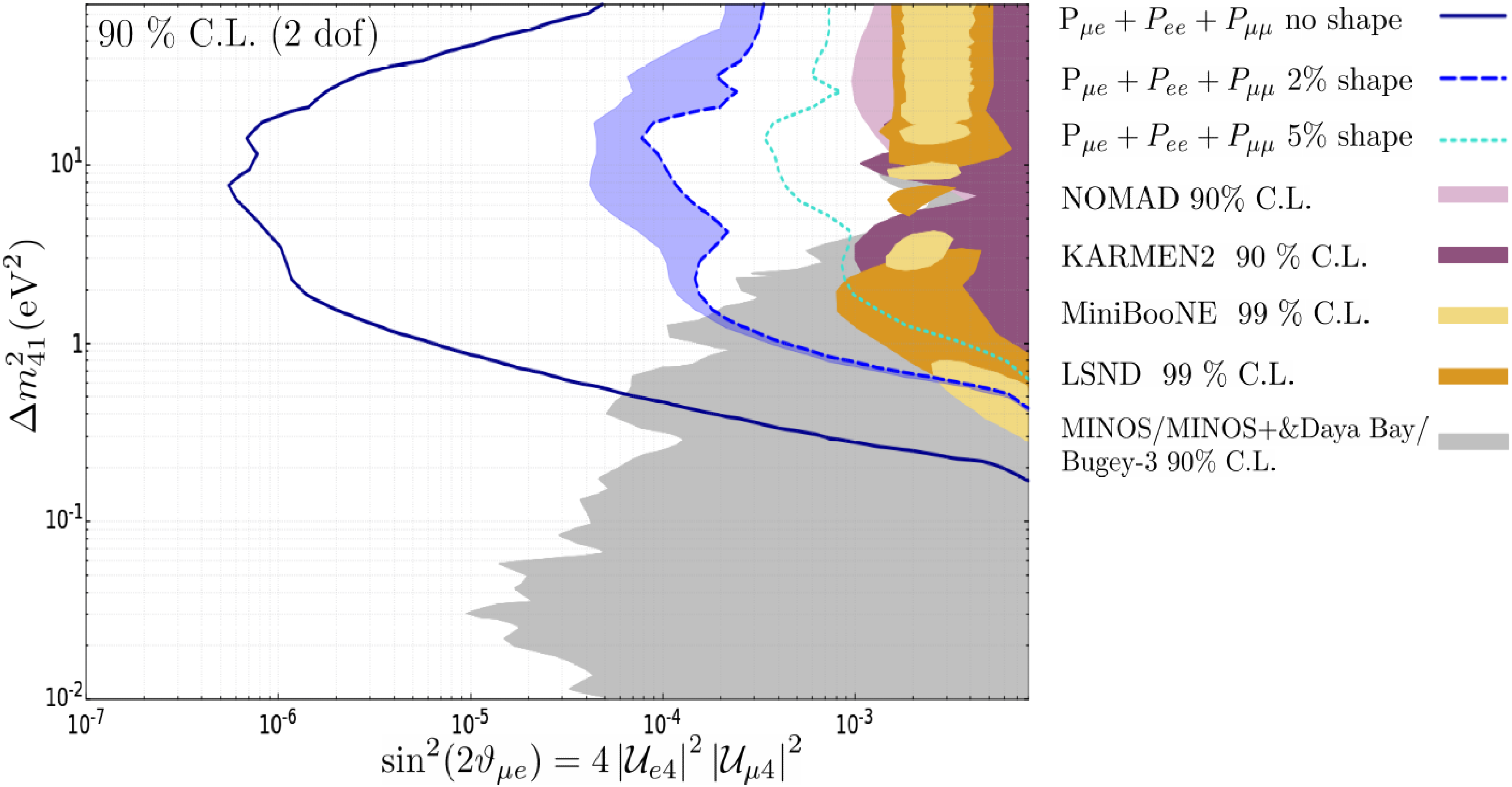
Sterile Neutrinos: 3+1

$$\mathcal{P}_{\mu e} = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$\mathcal{P}_{\mu\mu} = 1 - 4|U_{\mu 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

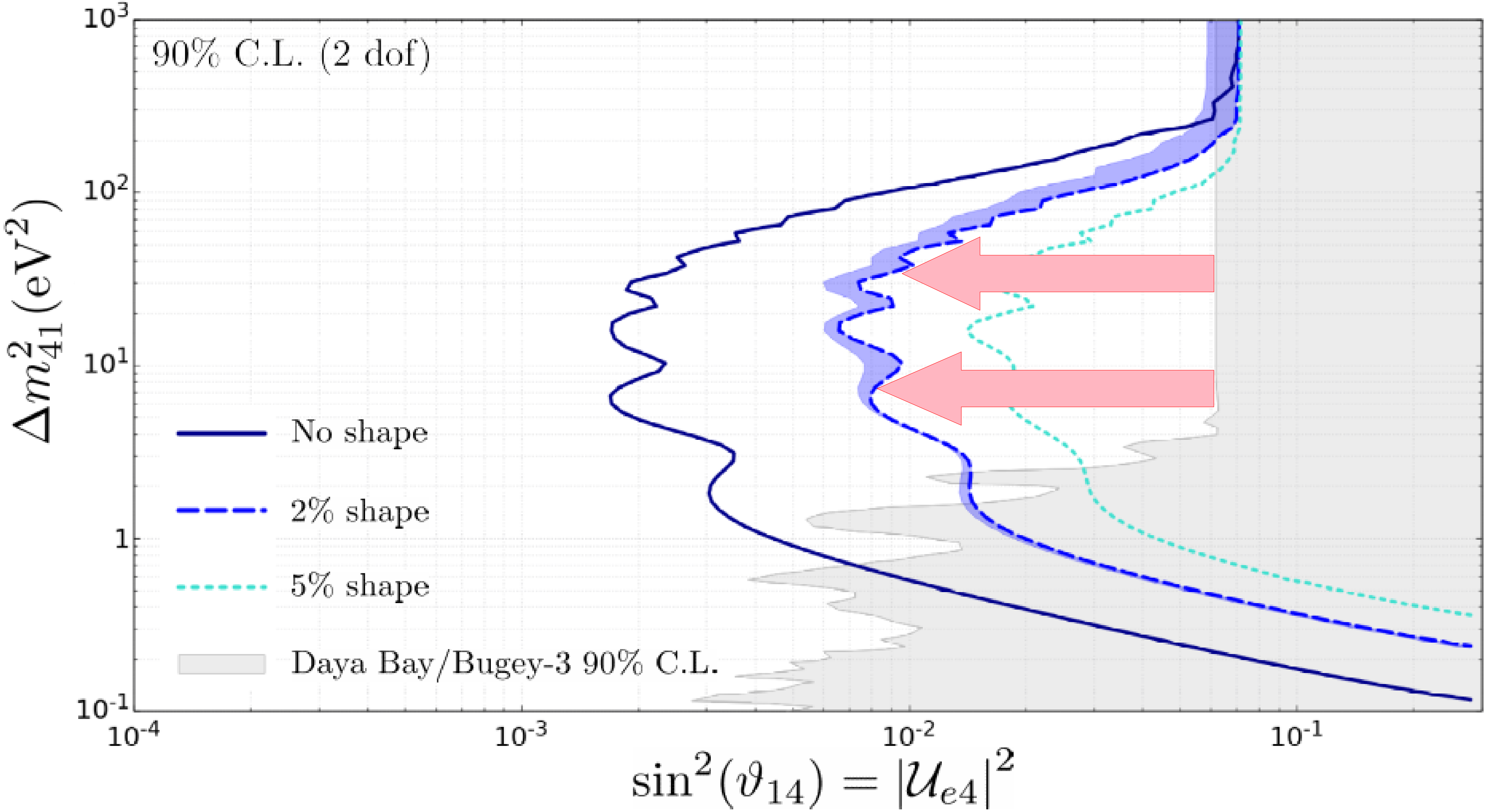
$$\mathcal{P}_{ee} = 1 - 4|U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

3+1 Sterile Neutrinos: $P_{\mu\mu} + P_{\mu e} + P_{ee}$



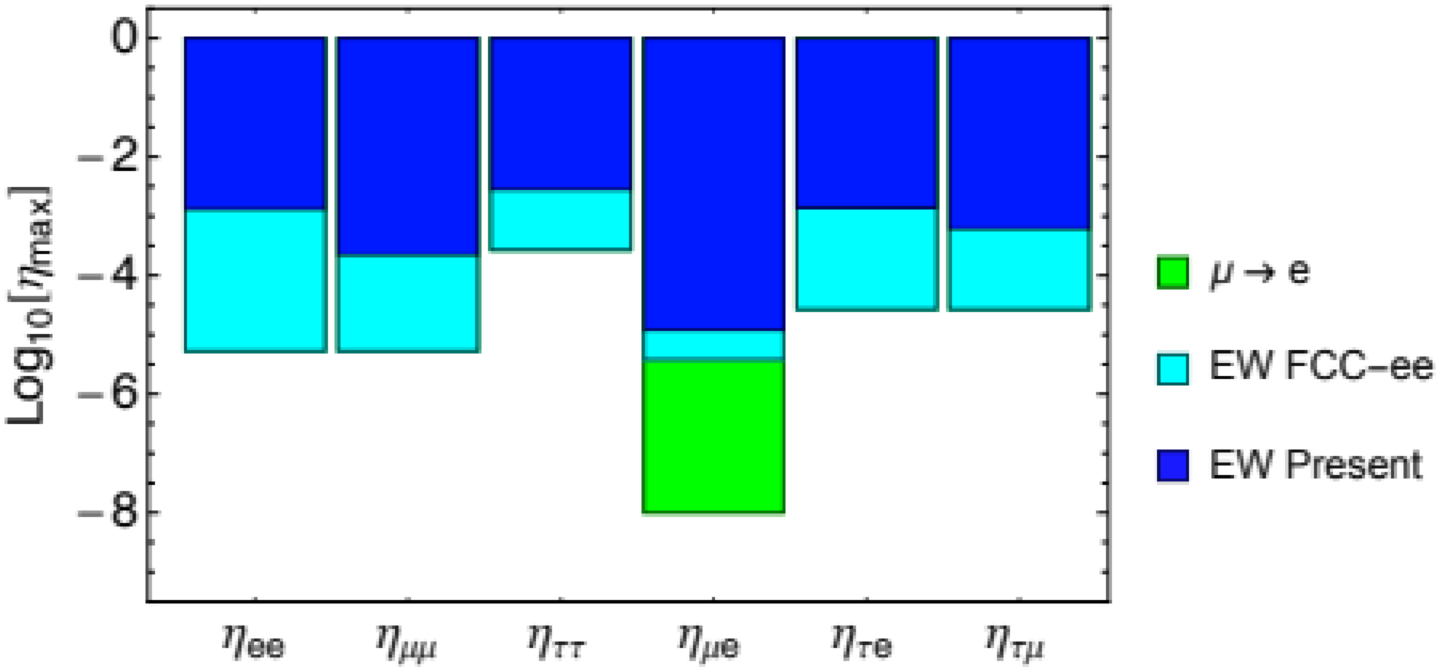
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

3+1 Sterile Neutrinos: P_{ee}



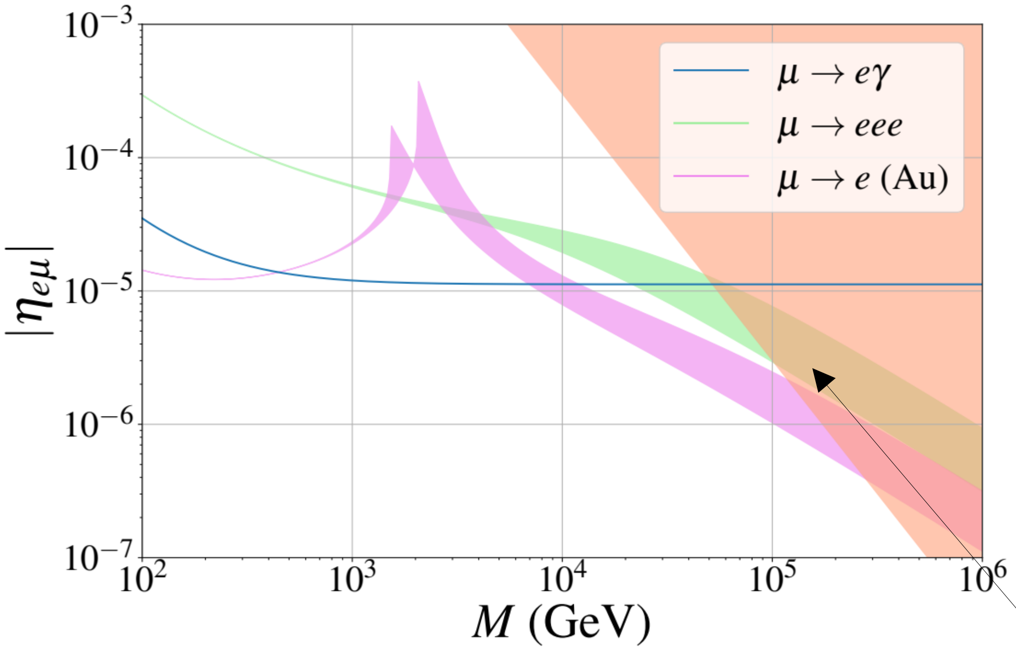
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

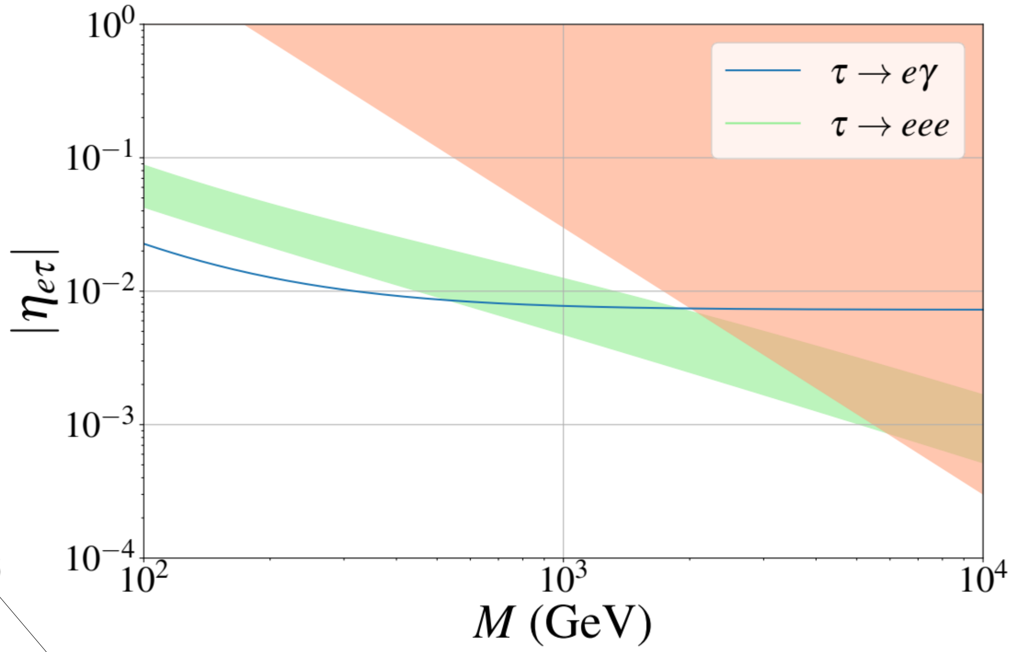
Future Sensitivity CLFV and FCC-ee



- Not updated. Future sensitivity extracted from Antusch, Fischer 1502.05915

LFV transitions (minimal model)

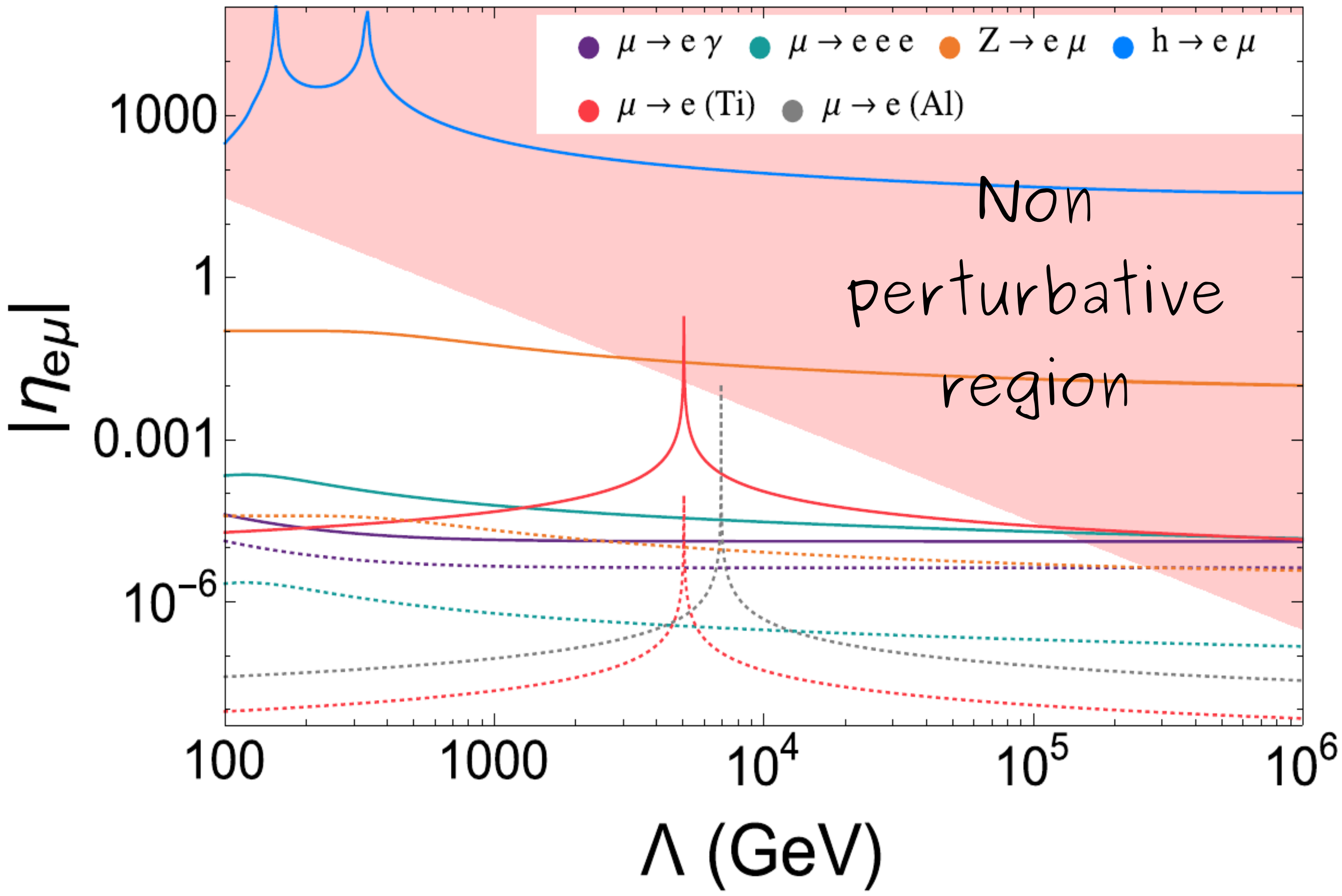




See also Urquia-Calderon, Timiryasov, Ruchayskiy 2206.04540

Blennow, Fernandez-Martinez, Hernandez-Garcia, JLP, Marcano, Naredo-Tuero 2306.01040

LFV transitions (minimal model)



Fernandez-Martinez, Hernandez-Garcia, JLP 1605.08774

Approximated LNC

$$\begin{array}{cccc} \overline{\nu^c} & \overline{N}_1 & \overline{N}_2 & \\ 1 & -1 & 1 & L \end{array}$$

$$M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & \Lambda \\ \epsilon Y_2 v/\sqrt{2} & \Lambda & \mu \end{pmatrix} \begin{array}{cc} 1 & \nu \\ -1 & N_1^c \\ 1 & N_2^c \end{array}$$

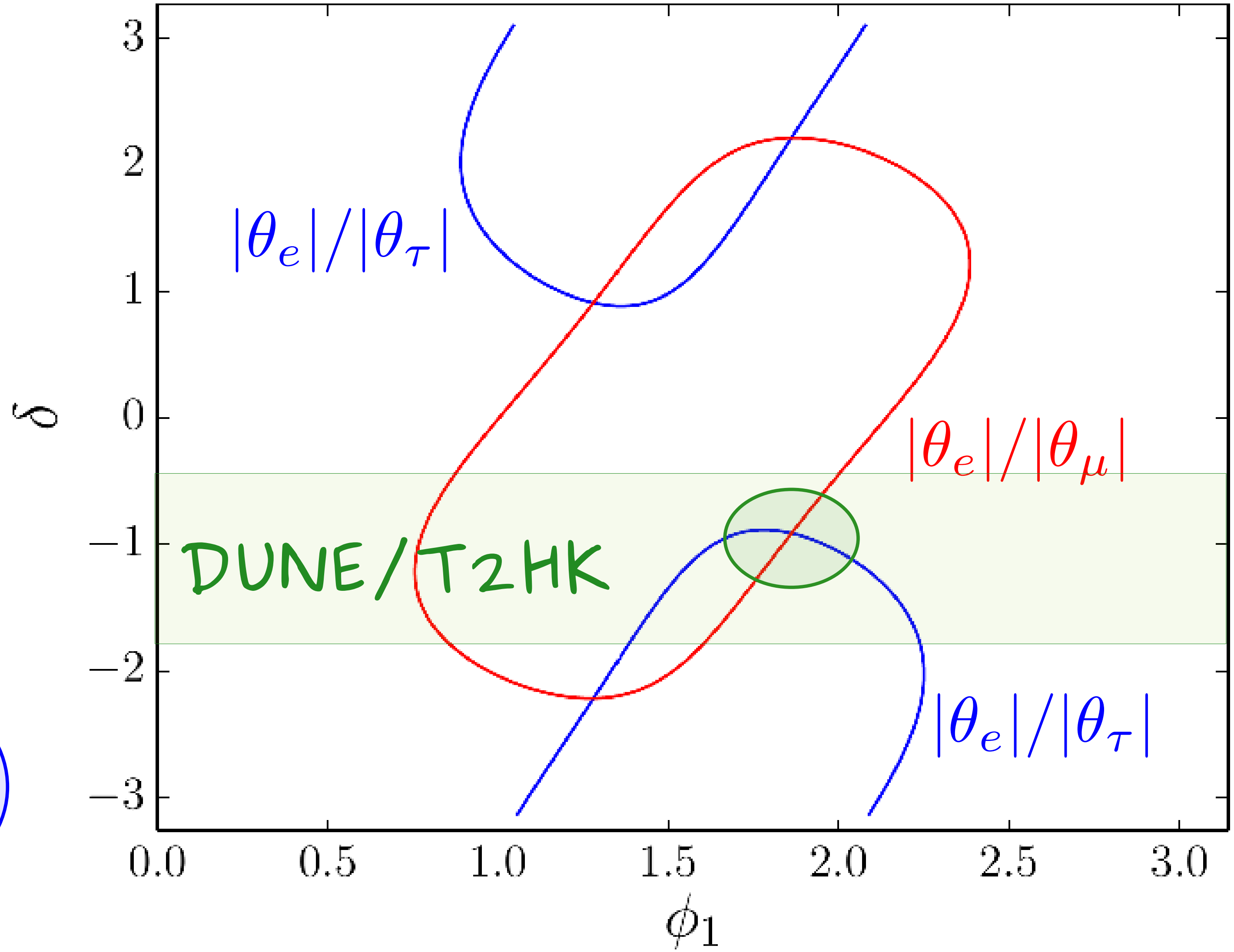
- Light nu masses suppressed with LNV parameters

$$m_\nu = \mu \frac{v^2}{2\Lambda^2} Y_1^T Y_1 + \frac{v^2}{2\Lambda} \epsilon Y_2^T Y_1 + \frac{v^2}{2\Lambda} Y_1^T \epsilon Y_2$$

- Quasi-Dirac heavy neutrinos with large mixings:

$$M_2 \approx M_1 \approx \Lambda \qquad \Delta M \approx \mu' + \mu \qquad \theta \sim Y_1 v/\Lambda$$

PMNS CP-phases from HNLs searches



$N_R = 2$

- **Potential determination of the PMNS Majorana phase!**

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719
Caputo, Hernandez, Kekic, JLP, Salvado 1611.05000

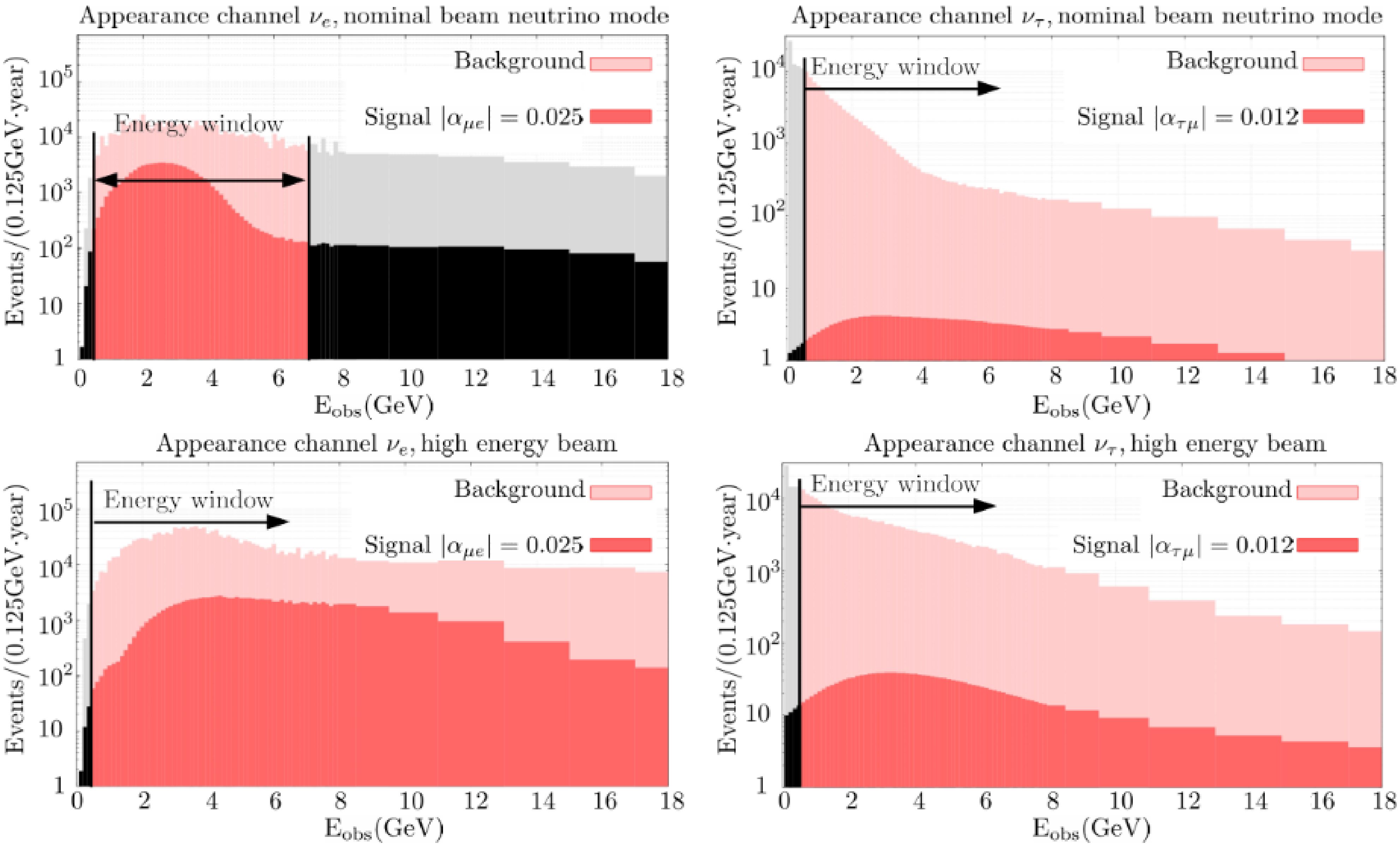
DUNE set up

Globes files

DUNE Collaboration, arXiv:2103.04797 [hep] 8 Mar 2021.

Flux configuration

Beam configuration	Power	E_p	PoT/yr	t_ν (yr)	$t_{\bar{\nu}}$ (yr)	$M_{\rm det}$
Nominal	1.2 MW	120 GeV	1.1×10^{21}	3.5	3.5	67.2 tons
High-Energy	1.2 MW	120 GeV	1.1×10^{21}	3.5	–	67.2 tons



Appearance channel ν_e, nominal beam neutrino mode
Background
Signal $|\alpha_{\mu e}| = 0.025$
Energy window
Events/(0.125GeV·year)
E_{obs}(GeV)
Appearance channel ν_τ, nominal beam neutrino mode
Background
Signal $|\alpha_{\tau\mu}| = 0.012$
Energy window
Events/(0.125GeV·year)
E_{obs}(GeV)
Appearance channel ν_e, high energy beam
Background
Signal $|\alpha_{\mu e}| = 0.025$
Energy window
Events/(0.125GeV·year)
E_{obs}(GeV)
Appearance channel ν_τ, high energy beam
Background
Signal $|\alpha_{\tau\mu}| = 0.012$
Energy window
Events/(0.125GeV·year)
E_{obs}(GeV)

Running mode	Sample	Contribution	Event rates ($\times 10^5$)	$E_{\rm obs}^{\rm max}$ (GeV)
ν mode (nominal)	ν_e-like	Intrinsic cont.	20.18	7.125
		Flavor mis-ID	4.61	
		NC	6.77	
	ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	2,235.72	7.125
		NC	17.35	
	ν_τ-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	39.33	18
		NC	3.23	
$\bar{\nu}$ mode (nominal)	$\bar{\nu}_e$-like	Intrinsic cont.	11.18	7.125
		Flavor mis-ID	1.07	
		NC	3.89	
	$\bar{\nu}_\mu$-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	1,013.42	7.125
		NC	9.76	
	$\bar{\nu}_\tau$-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	27.75	18
		NC	1.80	
ν mode (HE)	ν_e-like	Intrinsic cont.	38.10	18
		Flavor mis-ID	12.98	
		NC	30.51	
	ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	5,784.30	18
		NC	72.15	
	ν_τ-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	259.67	18
		NC	9.42	

Event sample	Contribution	Benchmark 1		Benchmark 2		Benchmark 3	
		σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}
ν_e-like	Signal	5%	–	5%	–	5%	–
	Intrinsic cont.	10%	–	10%	2%	10%	5%
	Flavor mis-ID	5%	–	5%	2%	5%	5%
	NC	10%	–	10%	2%	10%	5%
ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC (signal)	10%	–	10%	2%	10%	5%
	NC	10%	–	10%	2%	10%	5%
ν_τ-like	Signal	20%	–	20%	–	20%	–
	NC	10%	–	10%	2%	10%	5%

$$\chi^2_{\min}(\{\Theta\}) = \min_{\{\xi,\zeta\}}\left[\chi^2_{\rm stat}(\{\Theta,\xi,\zeta\}) + \sum_s \left(\frac{\zeta_s}{\sigma_{{\rm norm},s}}\right)^2 + \sum_b \left(\frac{\zeta_b}{\sigma_{{\rm norm},b}}\right)^2 \right.$$
$$\left. + \sum_i \left(\frac{\xi_i^{\rm sig}}{\sigma_{\rm shape,sig}}\right)^2 + \sum_i \left(\frac{\xi_i^{\rm bg}}{\sigma_{\rm shape,bg}}\right)^2 \right] ,$$

$$\chi^2_{\rm stat}(\{\Theta,\xi,\zeta\}) = \sum_i 2\left(N_i(\{\Theta,\xi,\zeta\}) - O_i + O_i \ln\frac{O_i}{N_i(\{\Theta,\xi,\zeta\})}\right)$$

$$N_i(\{\Theta,\xi,\zeta\}) = \sum_s (1+\xi_i^{\rm sig}+\zeta_s)\, s_i(\{\Theta\}) + \sum_b (1+\xi_i^{\rm bg}+\zeta_b)\, b_i(\{\Theta\})$$

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

Mapping

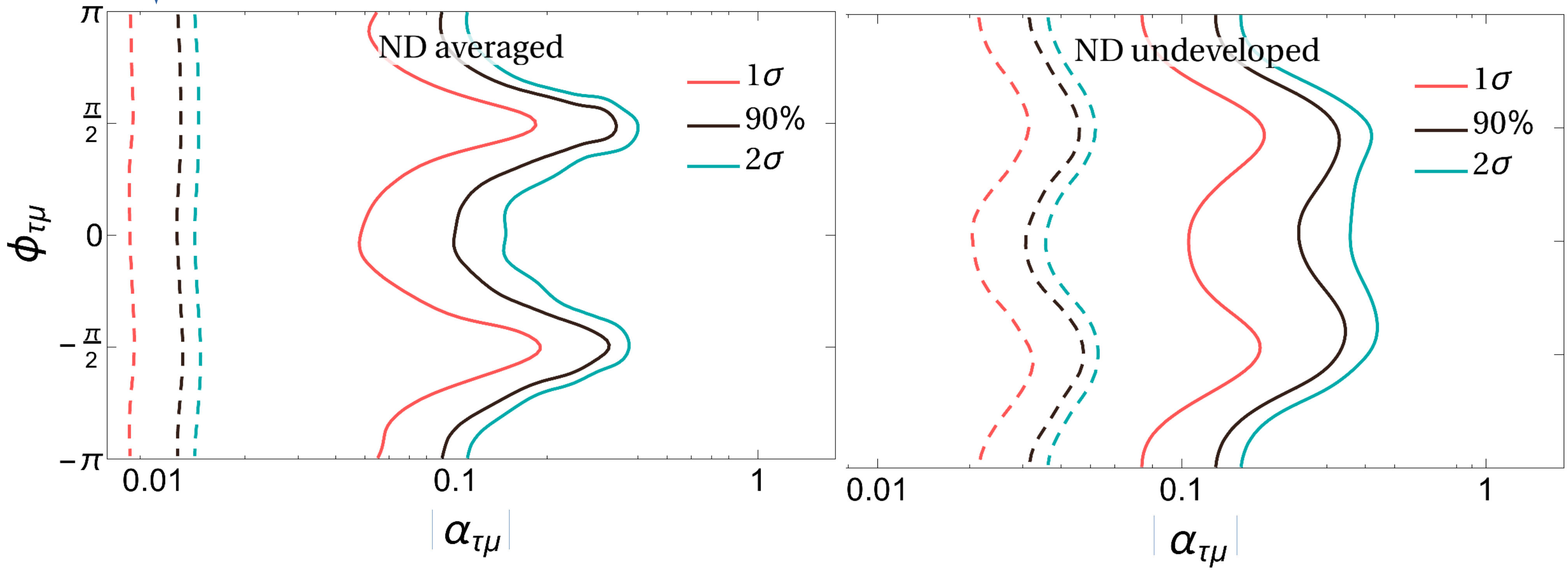
$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \eta_{ee} & 0 & 0 \\ 2\eta^*_{e\mu} & \eta_{\mu\mu} & 0 \\ 2\eta^*_{e\tau} & 2\eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

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

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

Prior
(present bounds)

Far Detector



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

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

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

② Kinematically accessible Sterile ν

Oscillations in VACUUM (Average out regime)

complete nxn mixing matrix

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

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

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

(i) Cross terms average to zero

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

2 Kinematically accessible Sterile ν

Oscillations in VACUUM (Average out regime)

- Theoretical Oscillation Probability:

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

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

- Same expression as in the Non-Unitary case up to normalization factors.

② Kinematically accessible Sterile ν

Oscillations in MATTER (Average out regime)

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

light-heavy mixing in matter

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

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

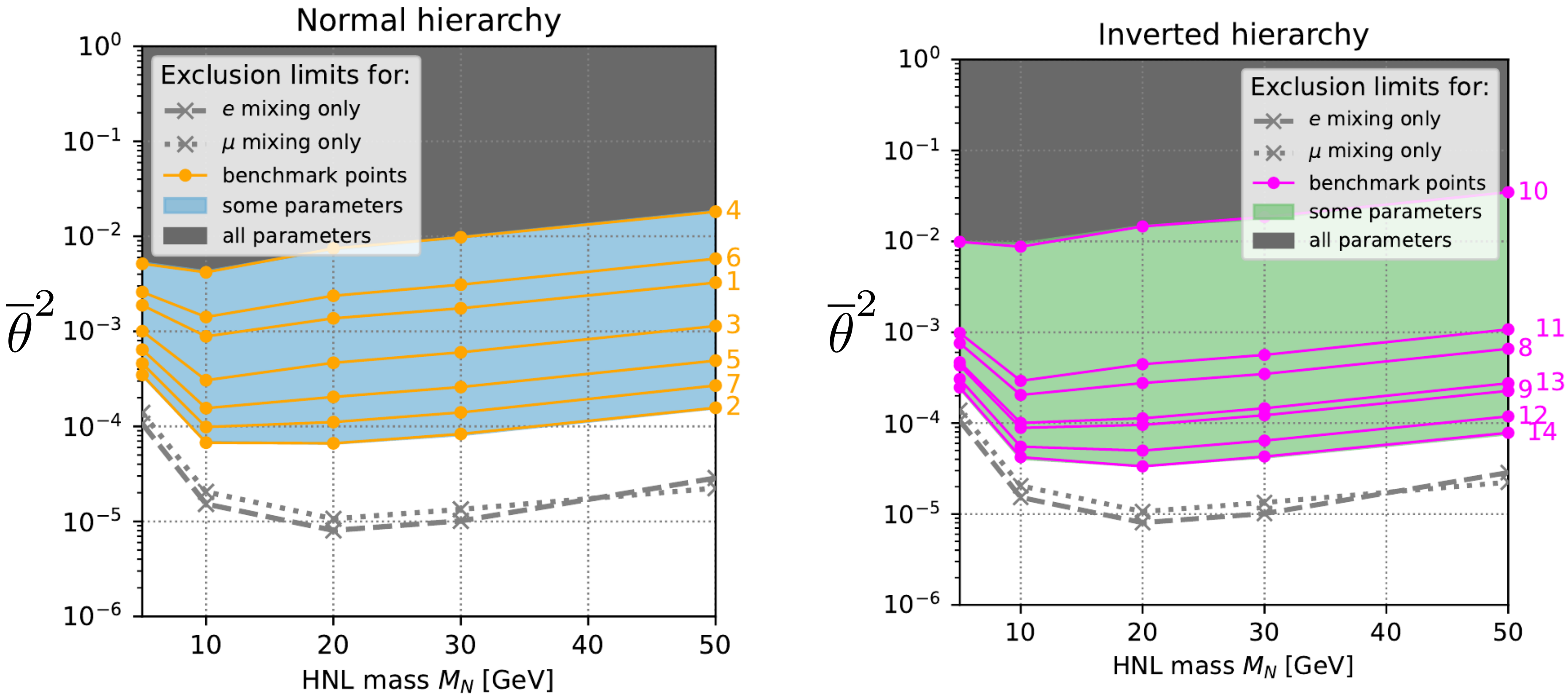
light-heavy mixing in matter ← $\tilde{\Theta}_{\alpha J} = \Theta_{\alpha J}$ → light-heavy mixing (vacuum)

- 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 up to normalization factors.

Flavor pattern vs sensitivity

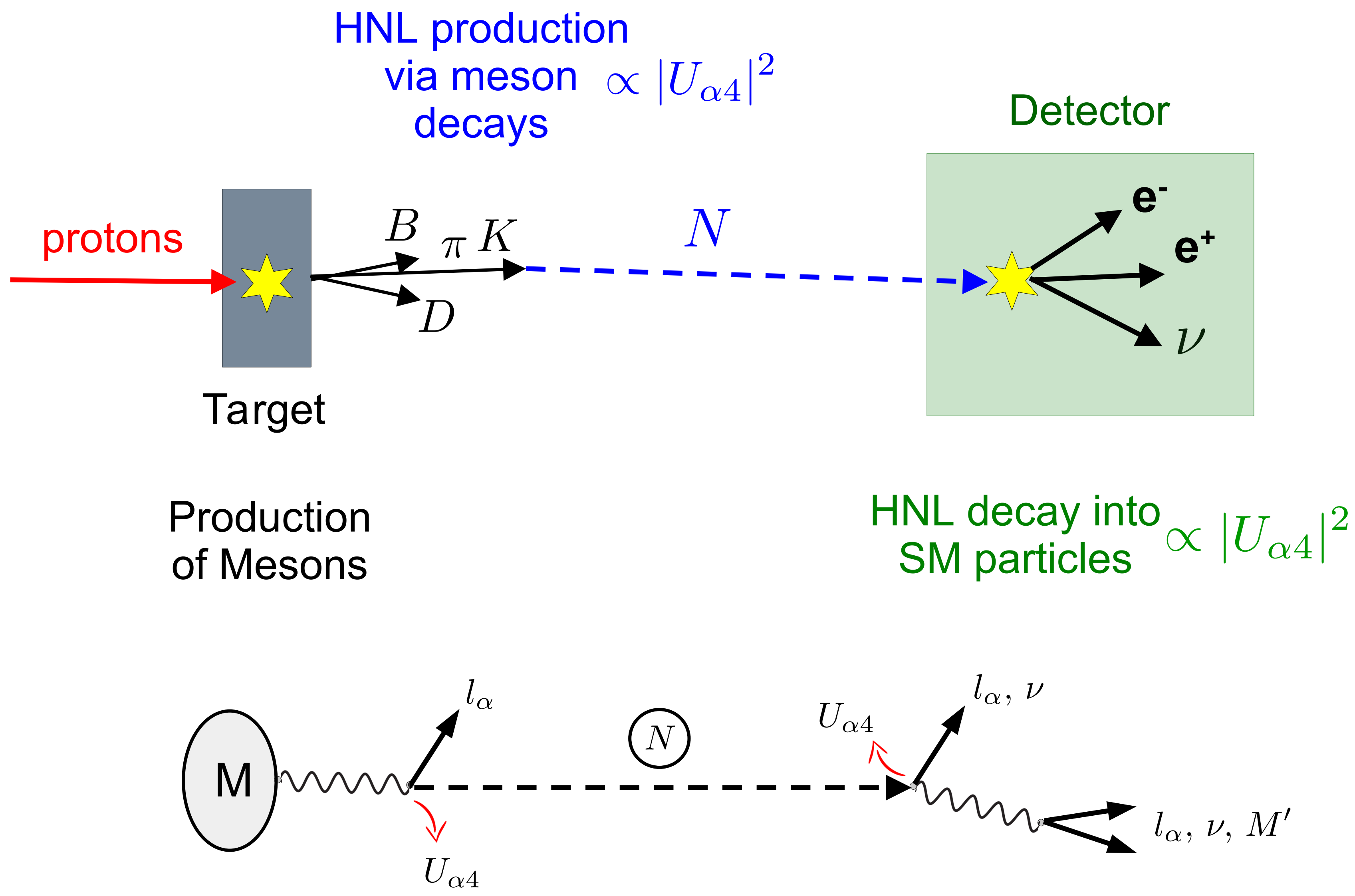


- Interpretation of ATLAS data depends on assumptions about "flavor mixing pattern"   Tastet, Ruchayskiya, Timiryasov 2107.12980

See talks by Tastet and Xabier Marcano

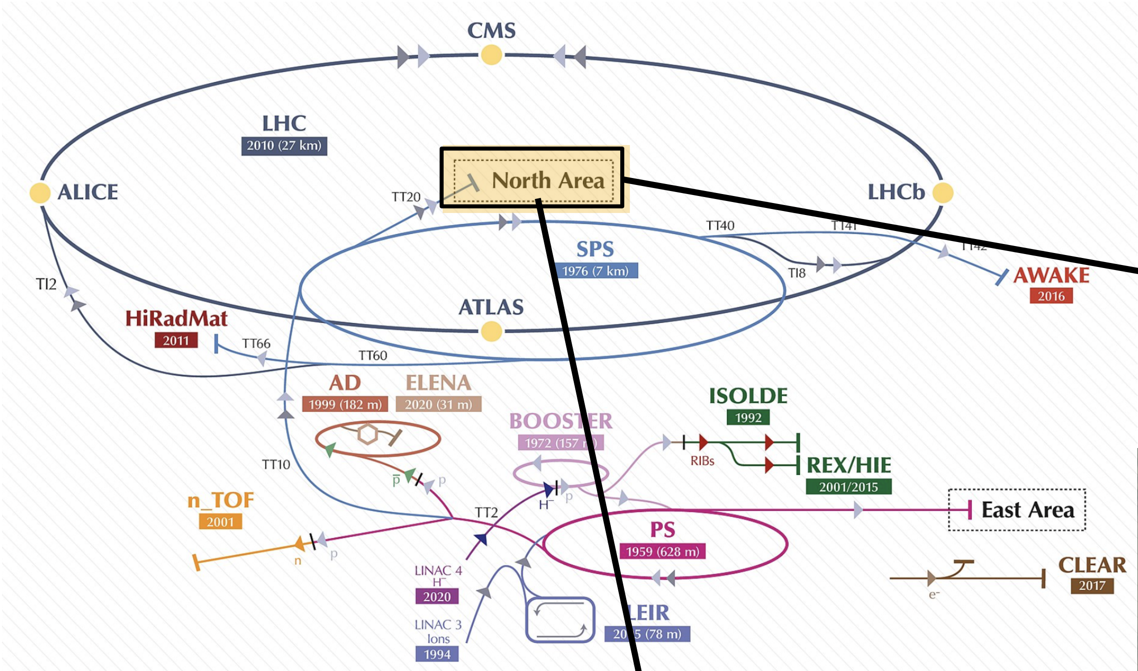
- Same conclusion applies to other experimental searches.

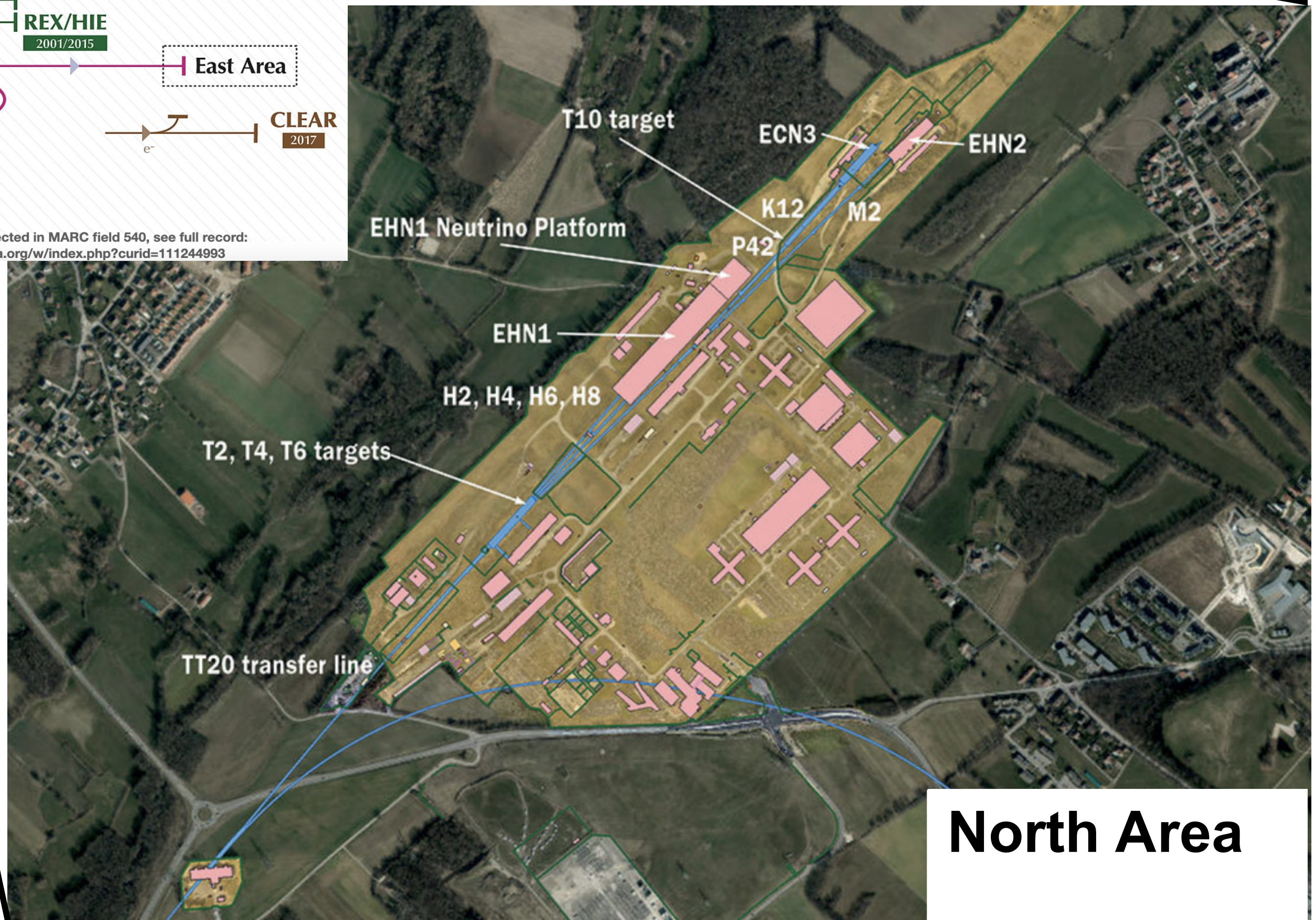
ProtoDUNE in beam dump configuration?



See talk by Jelle Groot for other beam dump searches

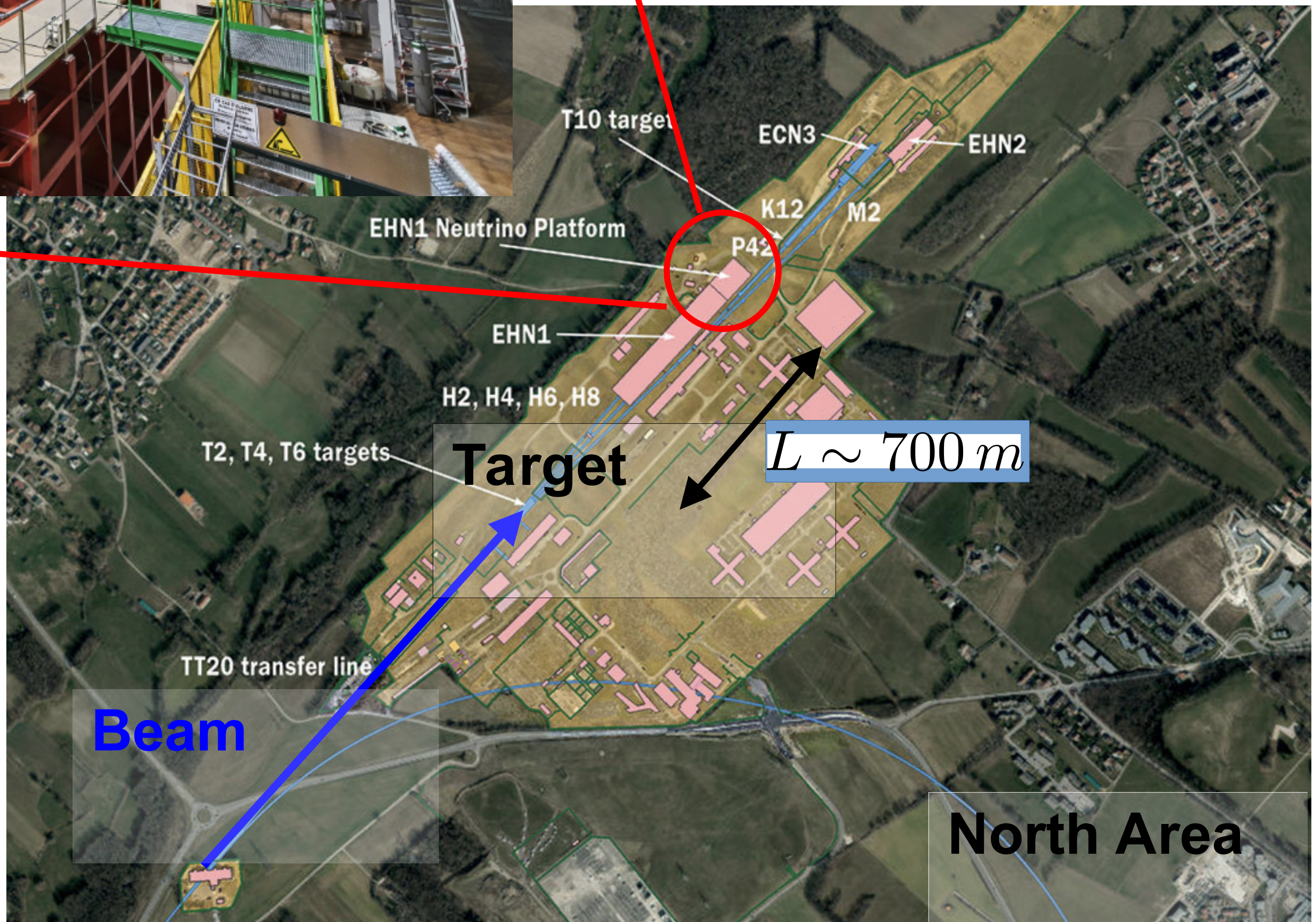
North Area & SPS accelerator @CERN





North Area & SPS accelerator @CERN

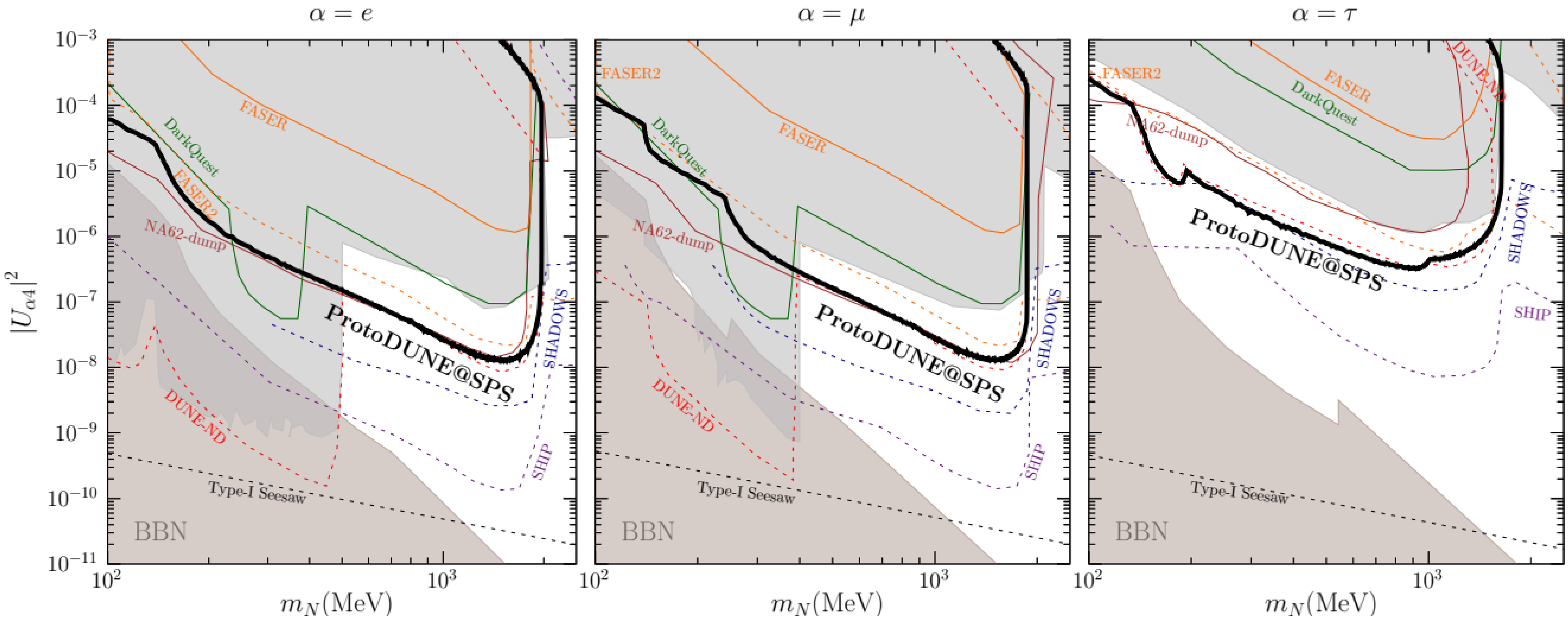
CERN Neutrino Platform
(**ProtoDUNE** detectors)



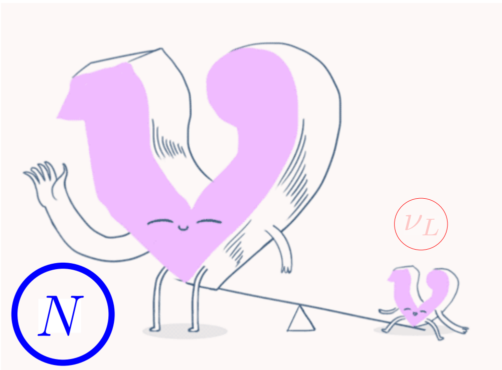
ProtoDUNE detectors (already located at CERN)

Two kiloton-scale liquid Argon Time Projection Chambers (LArTPCs) constructed to prototype and consolidate the technology of the DUNE Far Detector.

ProtoDUNE in beam dump configuration?



Coloma, JLP, Molina-Bueno, Urrea 2304.06765



DUNE collaboration, JINST 15 (2020) no.12, P12004