New Physics from Oscillations at DUNE Near Detector

Jacobo López-Pavón

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

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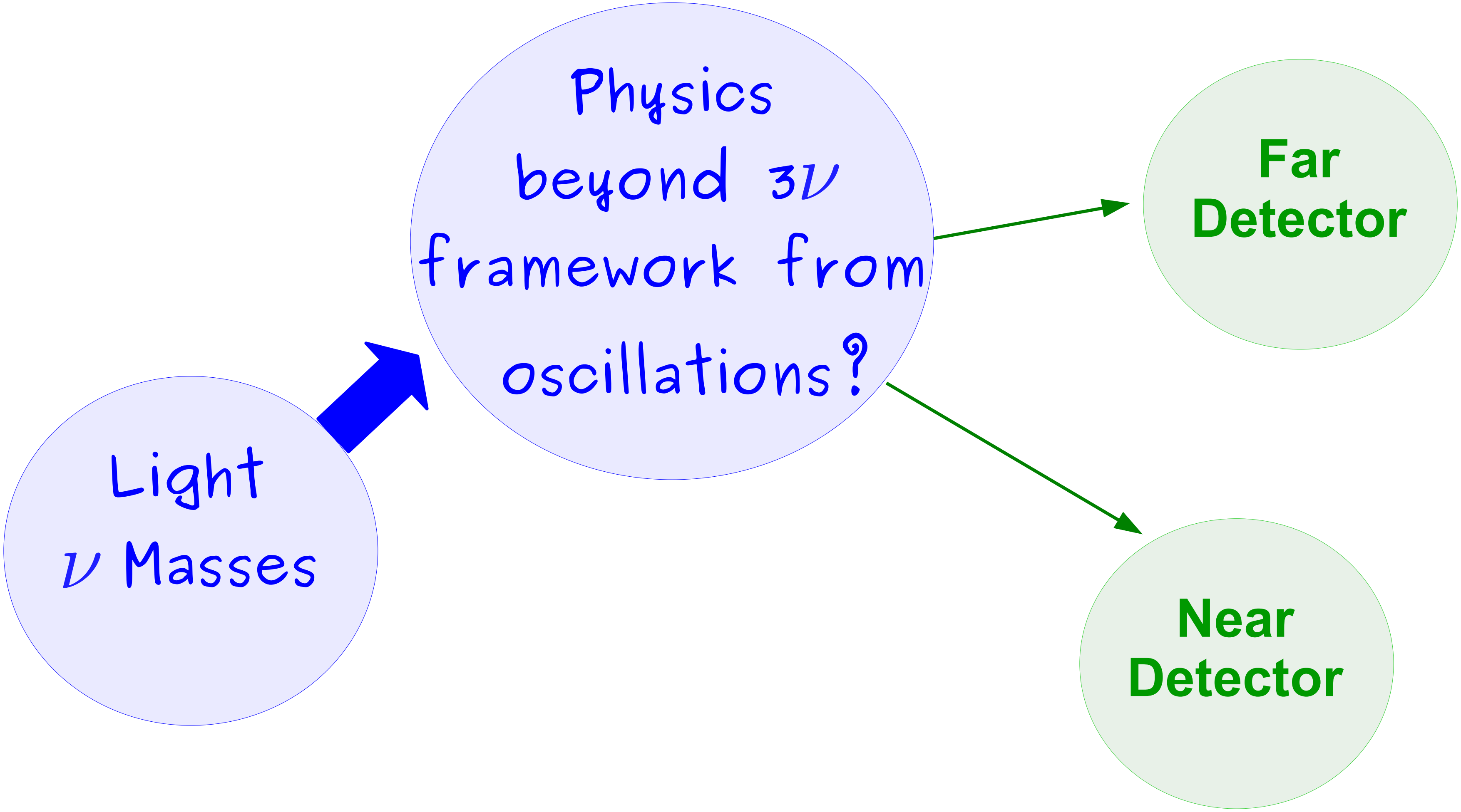
Outline



Physics beyond 3ν framework from oscillations?

Far Detector

Light ν Masses

Near Detector

Minimal model: Seesaw Model

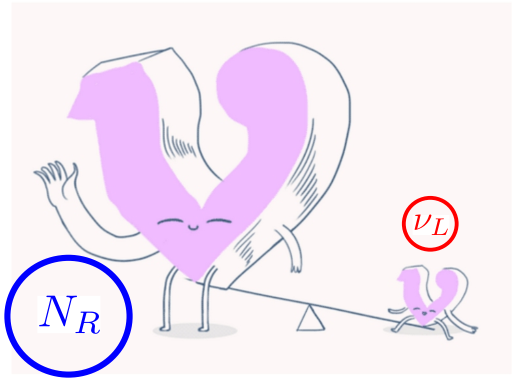
- Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_R) to the SM field content:

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

$$\Downarrow$$

Light Neutrino Masses

$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y$$



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

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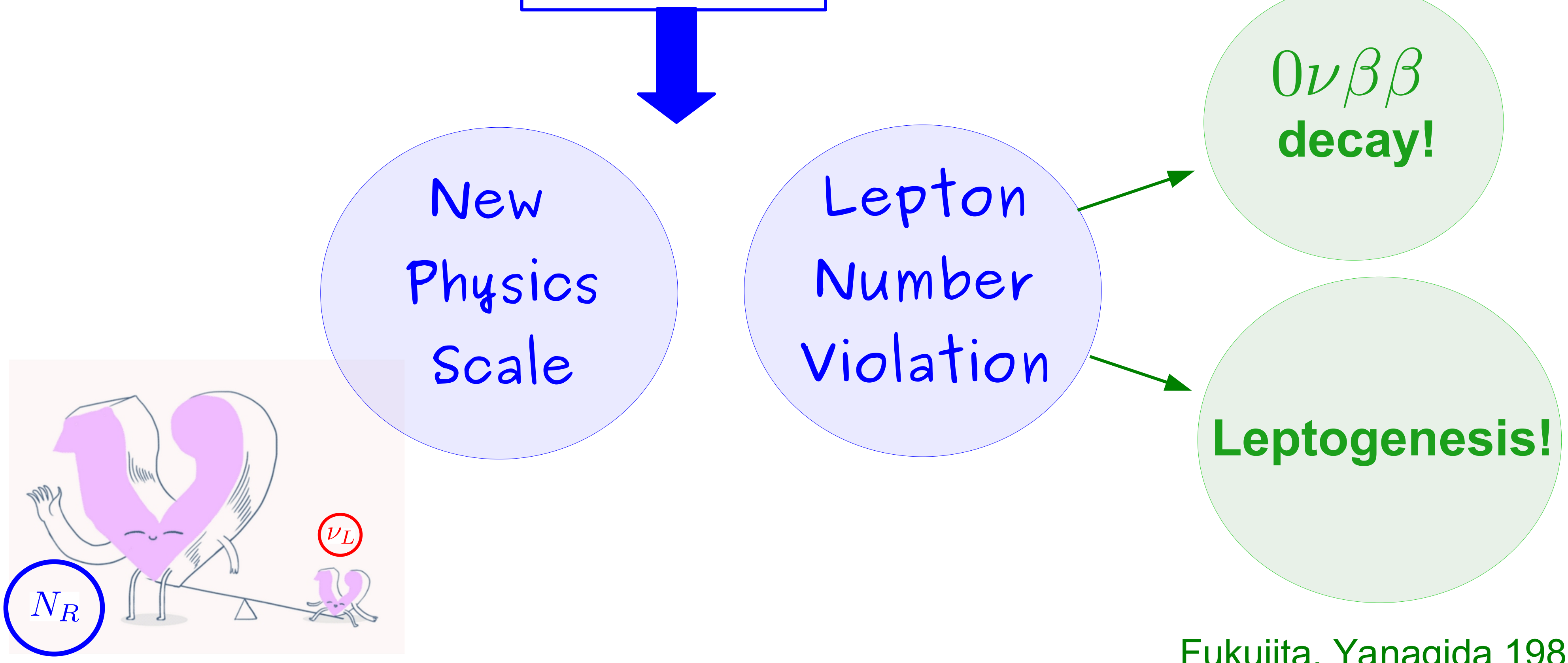


New Physics Scale

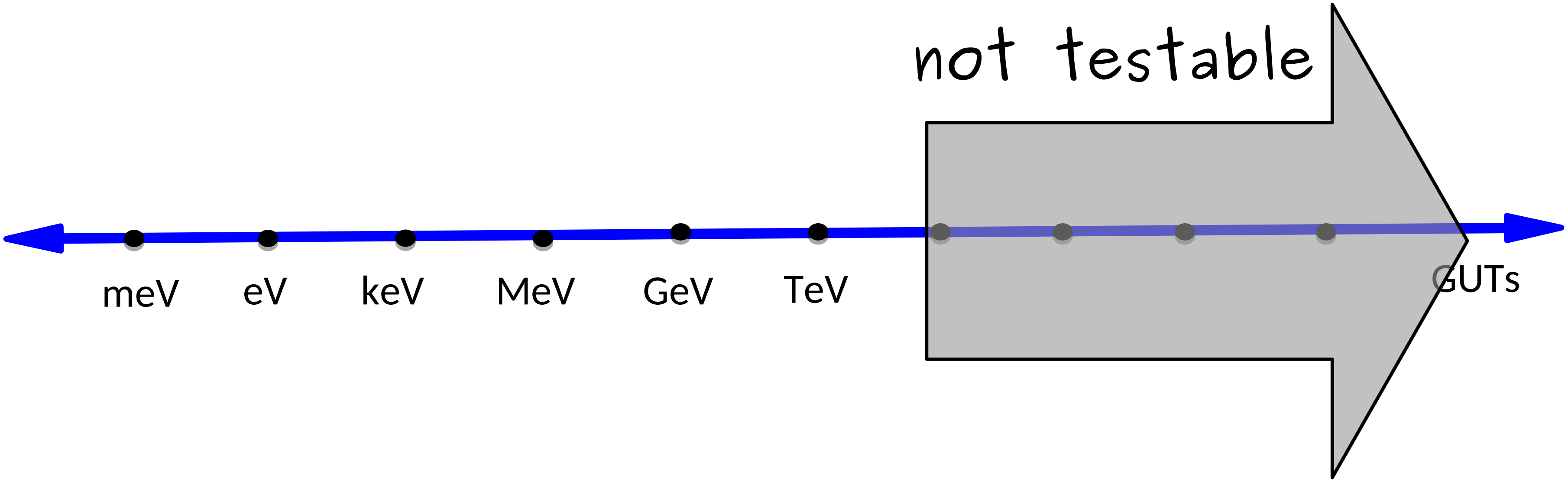
Lepton Number Violation

$0\nu\beta\beta$ **decay!**

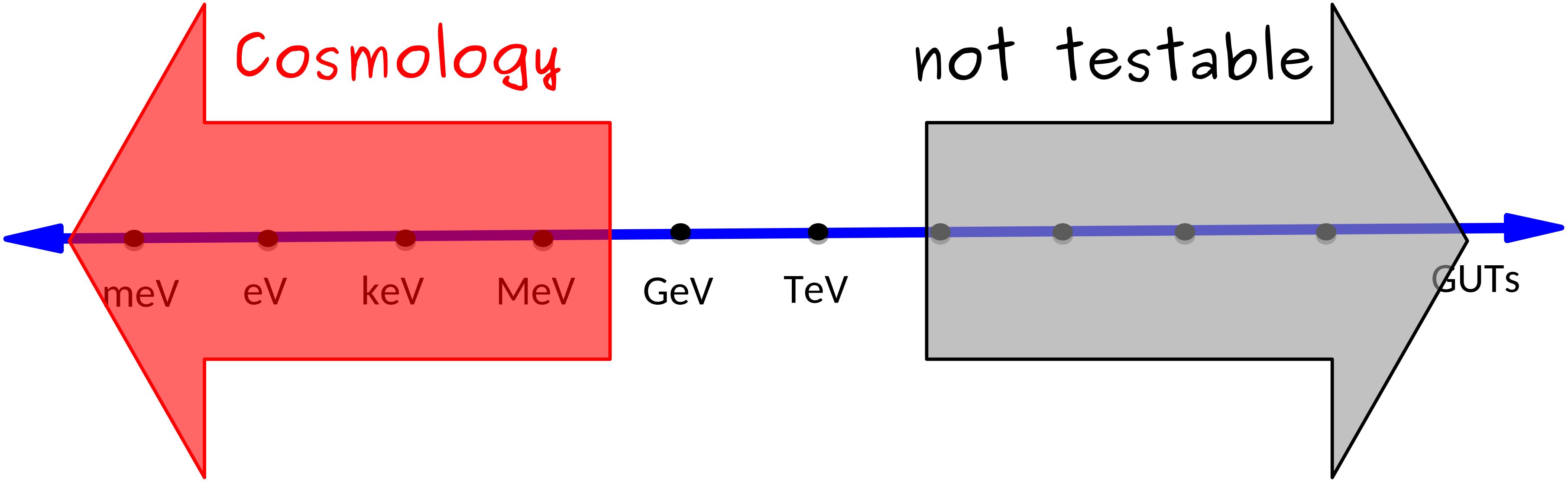
Leptogenesis!

Fukujita, Yanagida 1986

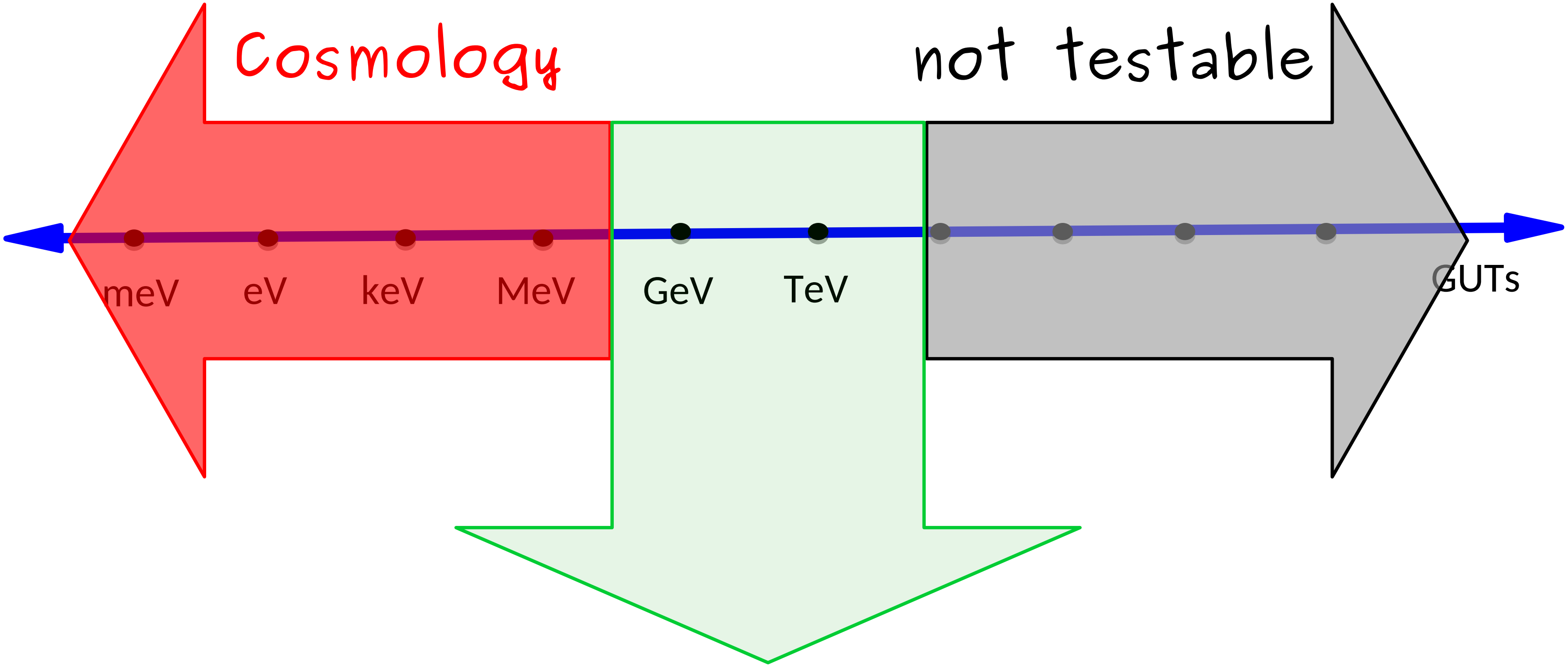
The New Physics Scale



The New Physics Scale



The New Physics Scale

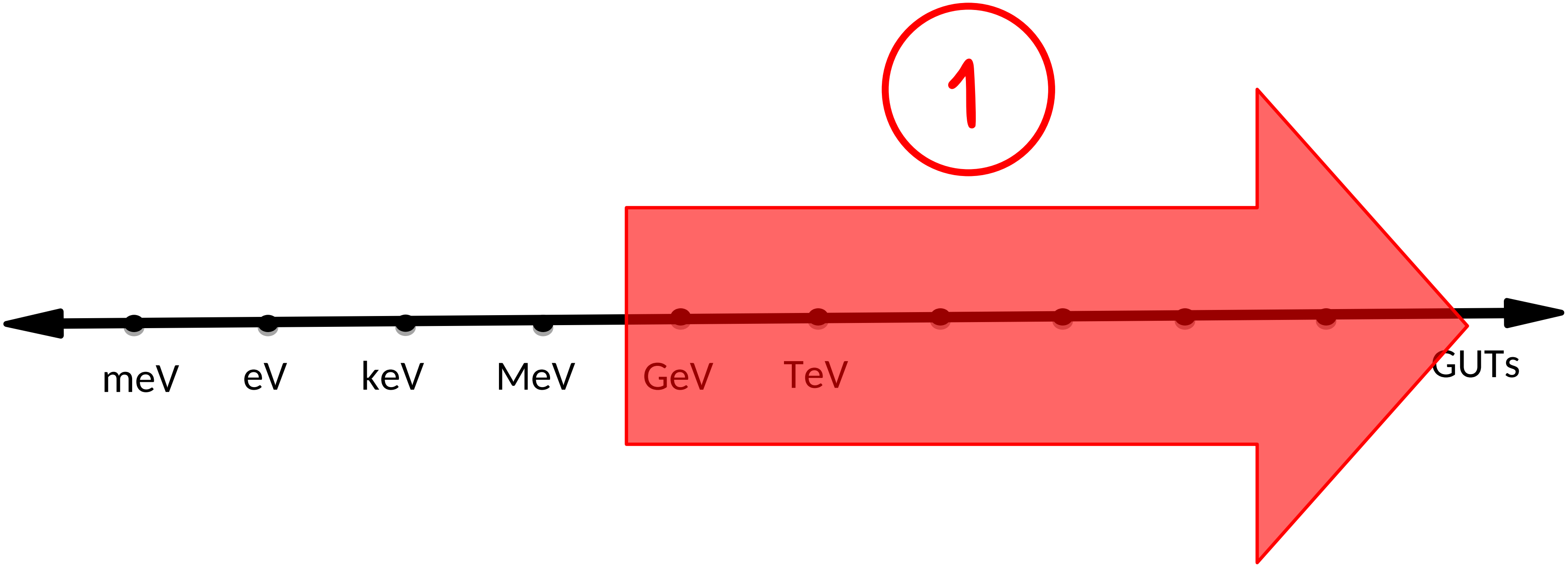


$0\nu\beta\beta$ decay, CLFV, Colliders, direct searches...

Are Long Baseline
Neutrino Oscillation experiments
sensitive to
New Physics
beyond 3ν framework

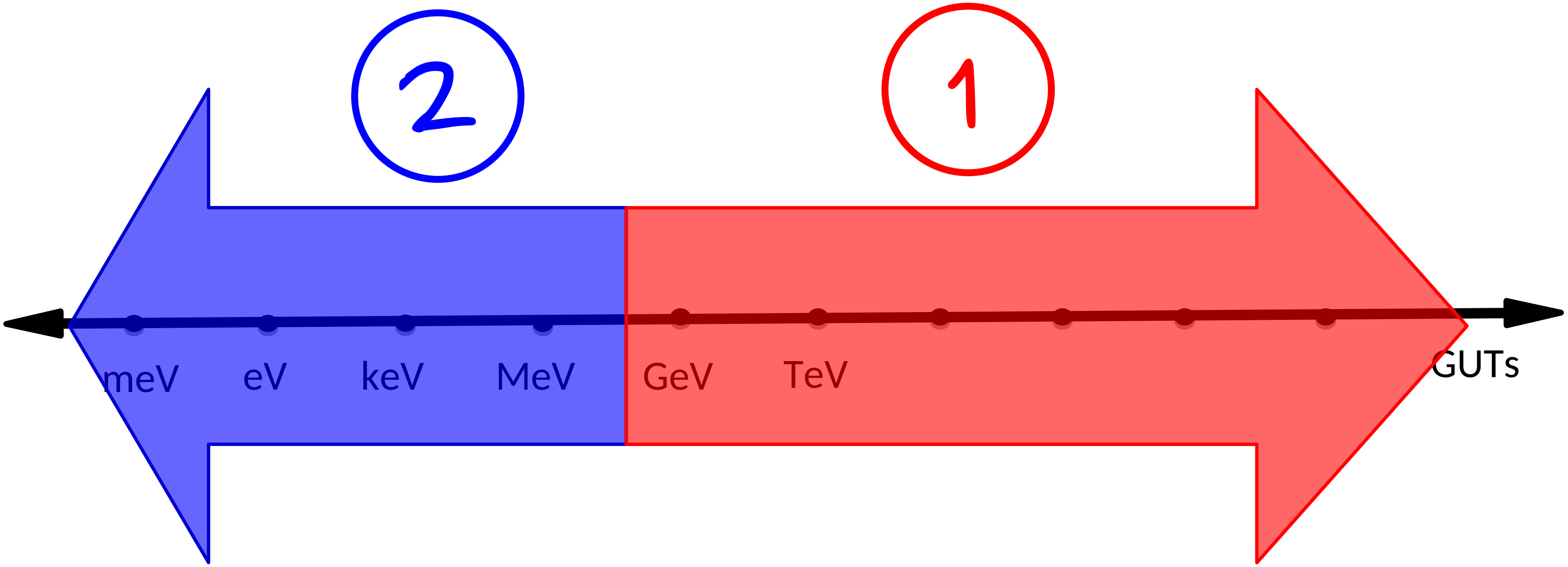
?

Neutrino Oscillations vs NP scale



Non-Unitary mixing
(sterile states integrated out)

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 way

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466.

Model Independent Approach

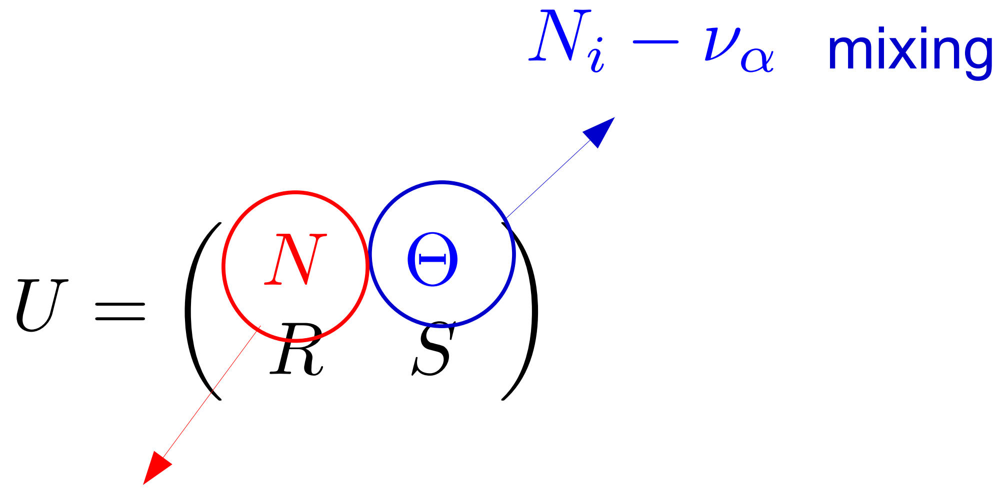
$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Model Independent Approach

$N_i - \nu_\alpha$ mixing

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

Model Independent Approach



$N_i - \nu_\alpha$ mixing

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

Deviation from unitarity of the PMNS matrix

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

General Parameterizations

- Triangular parameterization

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

Deviation from unitarity

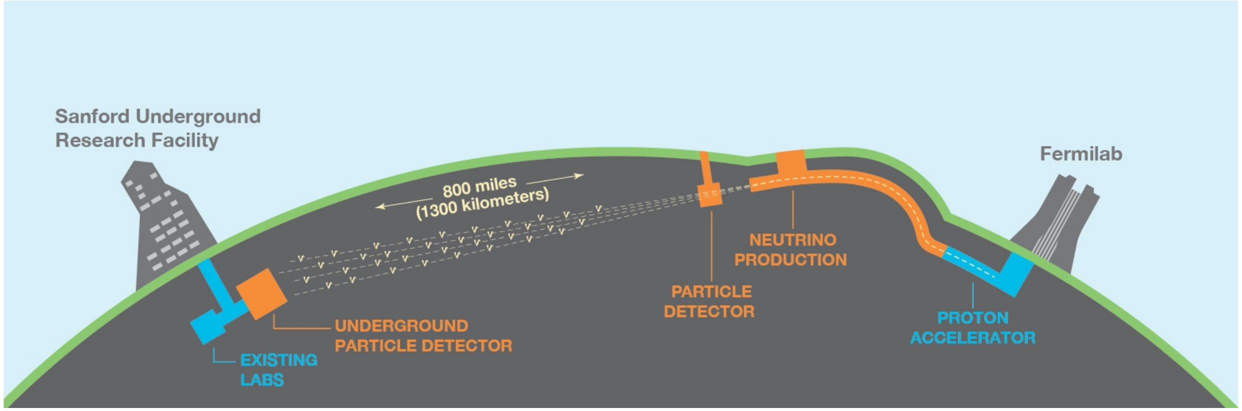
$$T = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Unitary matrix

(standard unitary PMNS matrix
up to small corrections)

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

Far Detector vs Near detector



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

- **Sources of systematics**

  - Cross sections
  - Neutrino flux

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

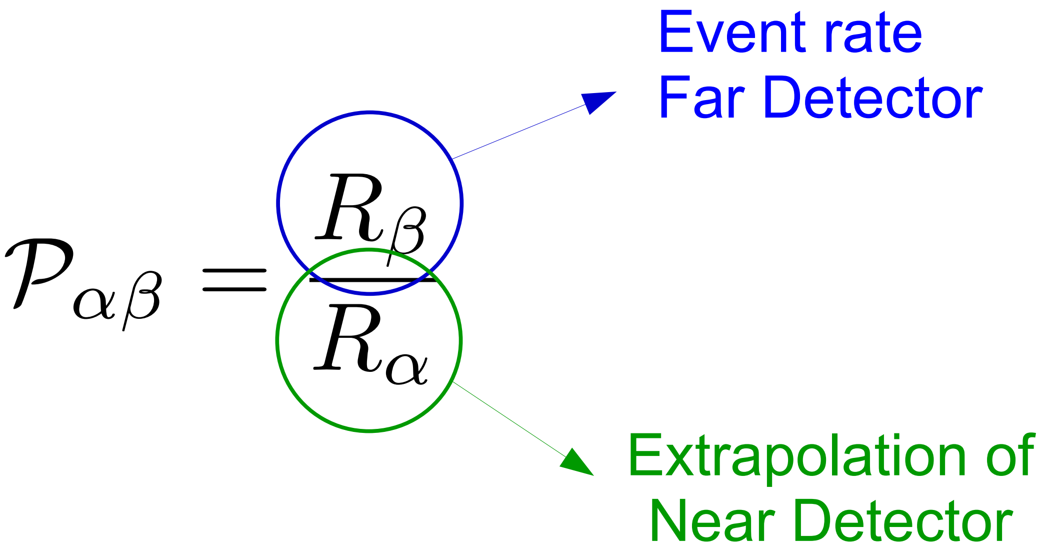
- **New Physics at near detector (strongly affected by systematic uncertainties)**

Far Detector

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

Far Detector

- What is measured in neutrino oscillation experiments

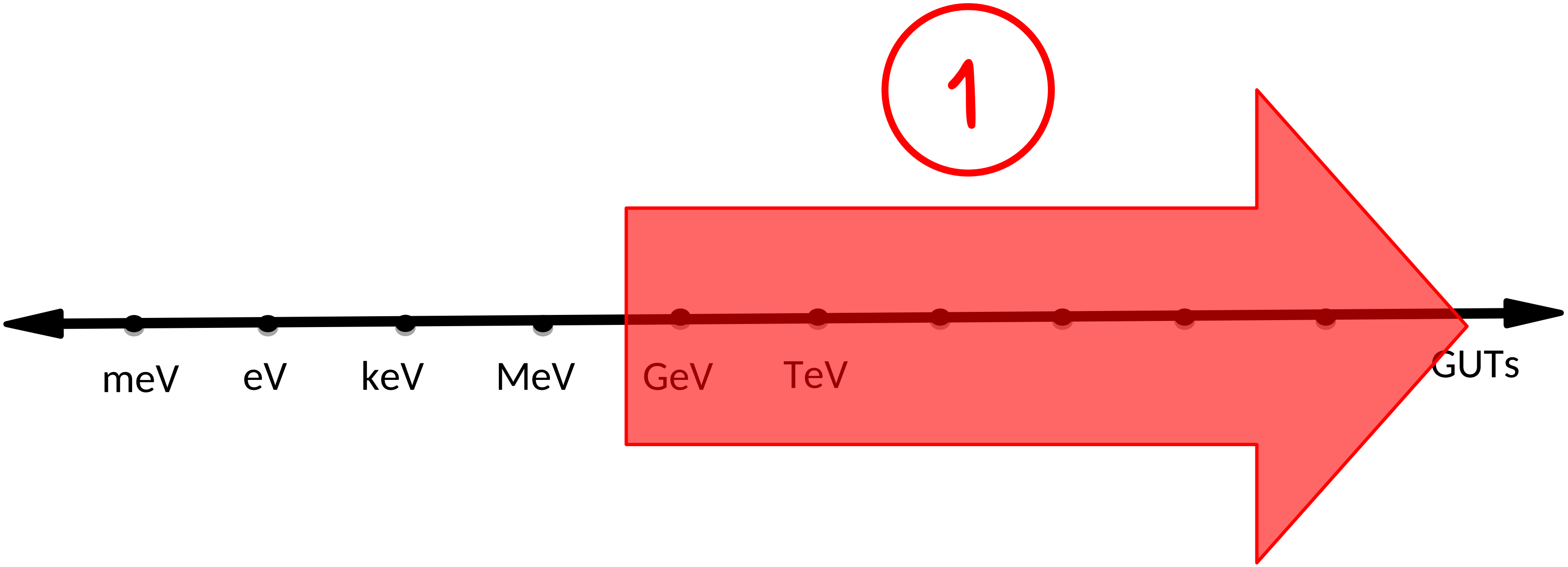


$$\mathcal{P}_{\alpha\beta} = \frac{R_\beta}{R_\alpha}$$

Event rate
Far Detector

Extrapolation of
Near Detector

① Non-Unitary Mixing



Non-Unitary
mixing
(sterile states
integrated out)

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

① Non-Unitary Mixing

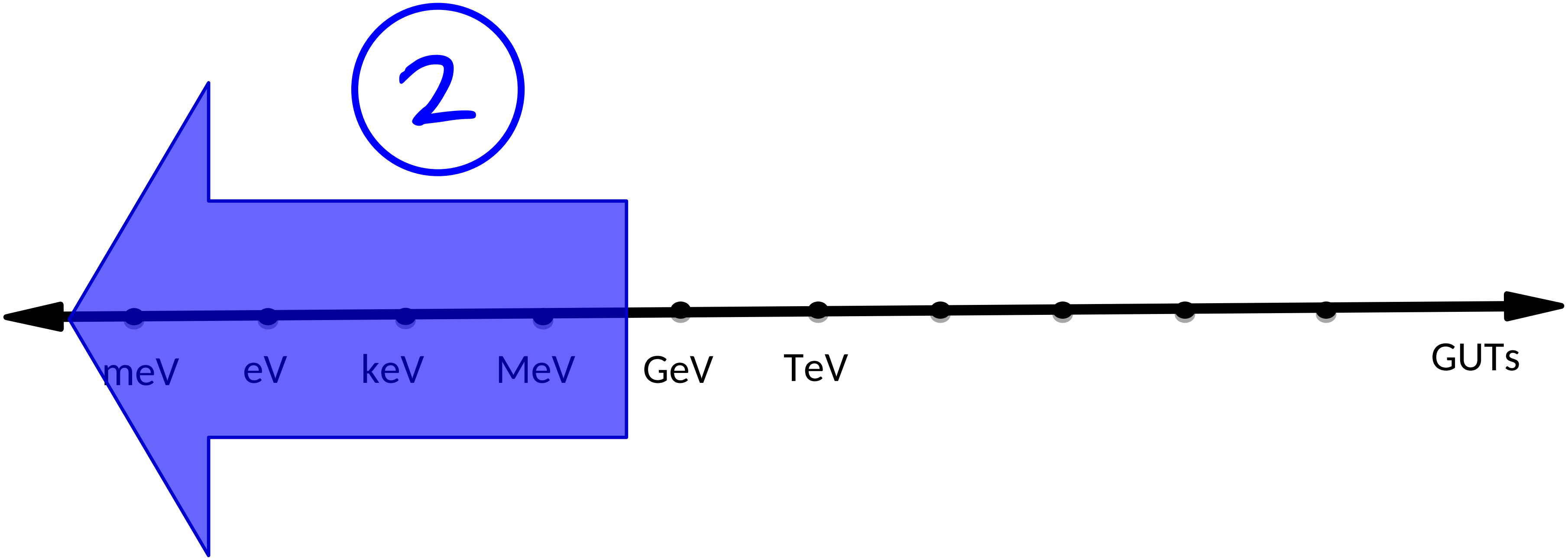
- What is measured in neutrino oscillation experiments

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

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

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

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 detector.

Identical to the heavy non-unitarity case

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

② Kinematically accessible sterile ν

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

Identical to the heavy non-unitarity case

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

No normalization factor

DUNE: $0.1\,\mathrm{eV}^2 \lesssim \Delta m^2 \lesssim 1\,\mathrm{eV}^2$

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

② Kinematically accessible sterile ν

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

Identical to the heavy 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 observed at the near detector

② Kinematically accessible sterile ν

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

Identical to the heavy non-unitarity case

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

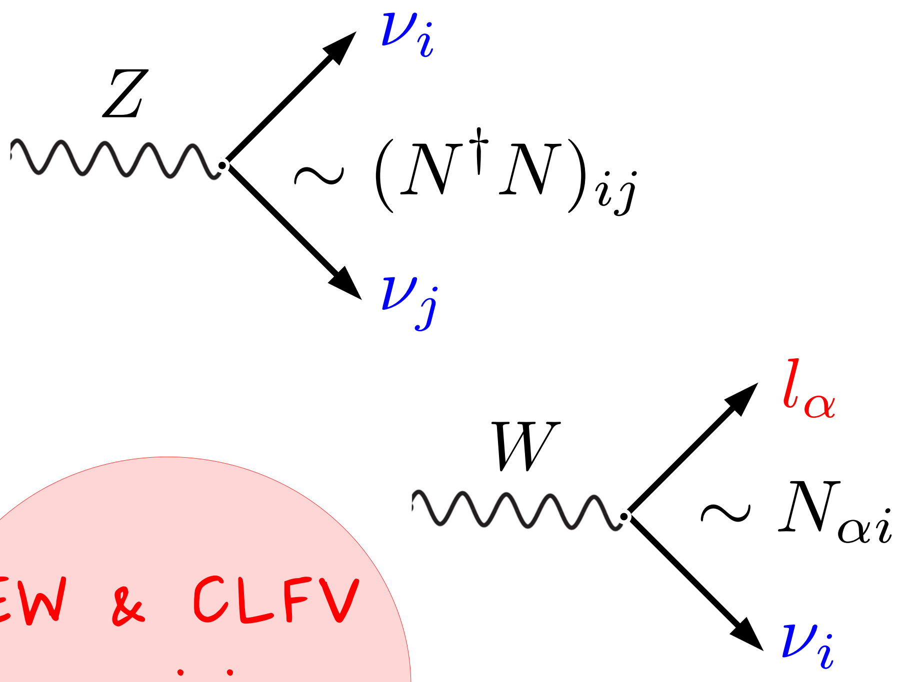
No normalization factor

Low Scale
Non-Unitarity

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

Present Bounds

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



EW & CLFV
precision
data

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

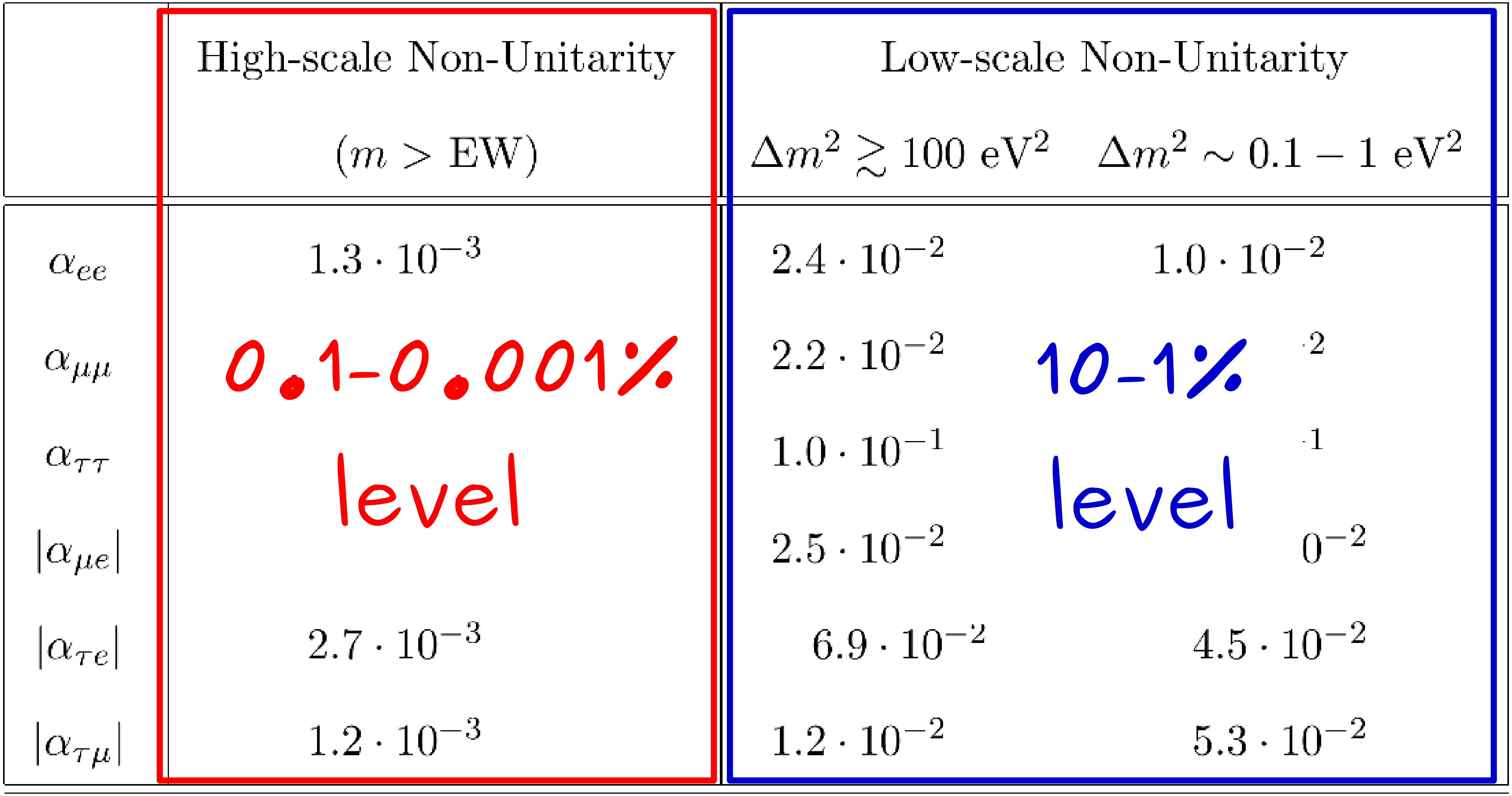
Present Bounds

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

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

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

Present Bounds



	High-scale Non-Unitarity	Low-scale Non-Unitarity	
	$(m > \mathrm{EW})$	$\Delta m^2 \gtrsim 100\ \mathrm{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \mathrm{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
$\alpha_{\mu\mu}$		$2.2 \cdot 10^{-2}$	$\cdot 2$
$\alpha_{\tau\tau}$		$1.0 \cdot 10^{-1}$	$\cdot 1$
$\lvert\alpha_{\mu e}\rvert$		$2.5 \cdot 10^{-2}$	0^{-2}
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$

0.1-0.001% level

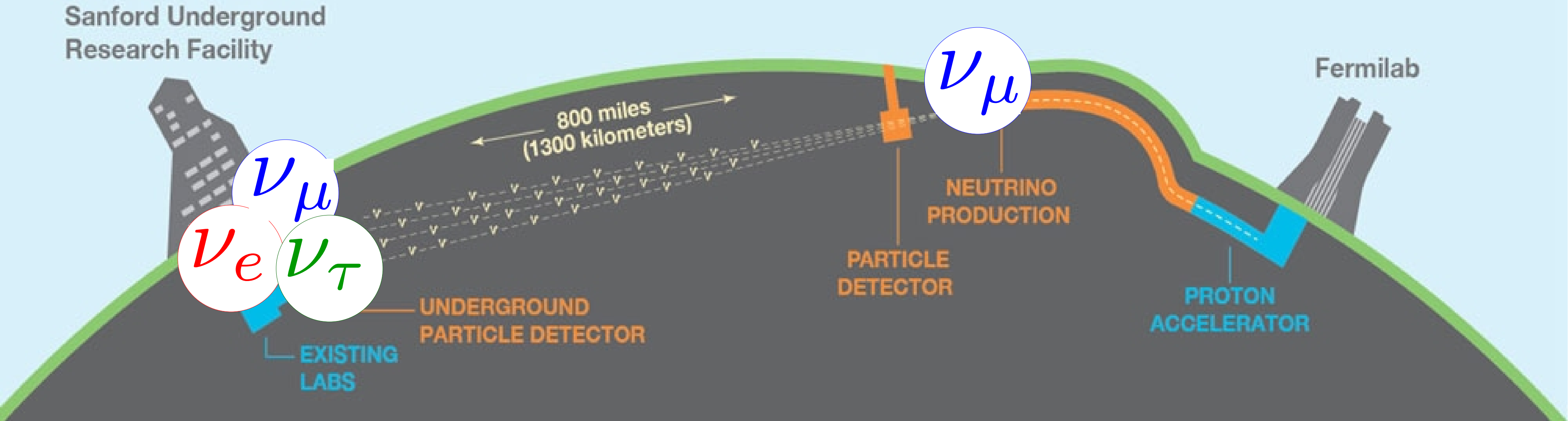
10-1% level

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

See also
Park, Ross-Lonergan 1508.05095
Ellis, Kelly, Weishi Li 2004.13719
Ellis, Kelly, Weishi Li 2008.01088

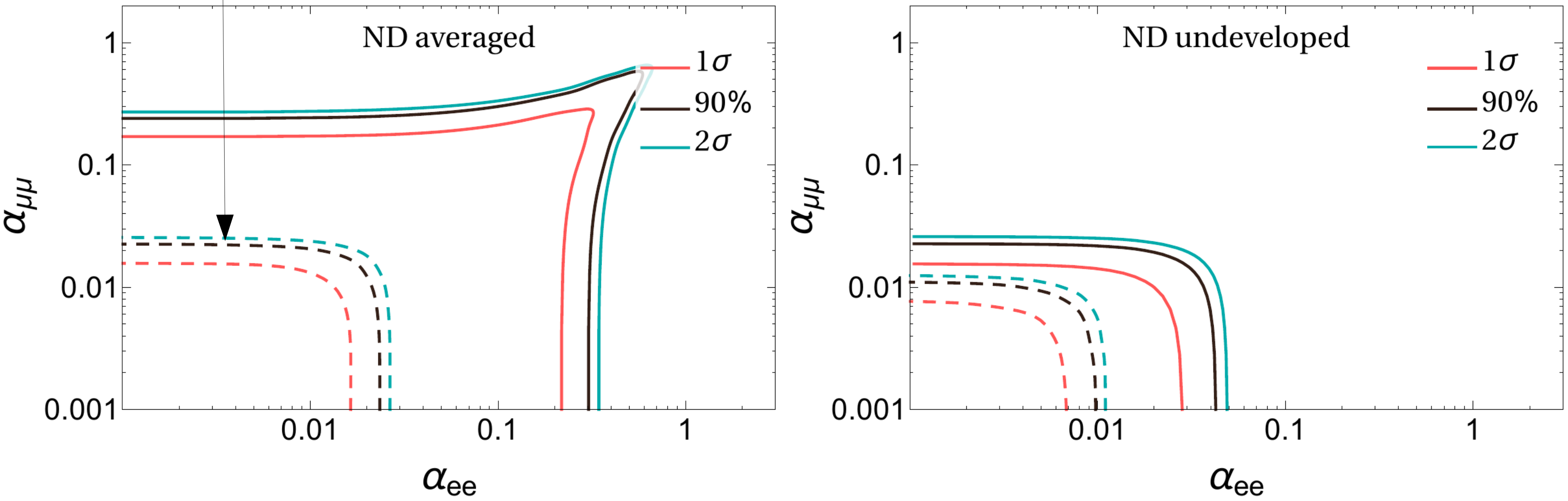
Deep Underground Neutrino Experiment

DUNE



Far Detector

Prior
(present bounds)



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

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

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

Near Detector

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

See also Escrihuela, Forero, Miranda, Tortola, Valle arXiv:1503.08879 for other Near Detector configurations (without including tau detection).

High Scale Non-Unitarity

- What is measured in Near Detector

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

zero
distance
effect!

$$\mathcal{P}_{\alpha\alpha} = \left|(NN^\dagger)_{\alpha\alpha}\right|^2 = 1 - 4\,\alpha_{\alpha\alpha}$$

Sterile Neutrinos: 3+1

- What is measured in Near Detector

$$\mathcal{P}_{\alpha\beta} = 4|U_{\alpha 4}||U_{\beta 4}| \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

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

Averaged-out regime

- What is measured in Near Detector

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

$$\langle \mathcal{P}_{\alpha\beta} \rangle = 2|U_{\alpha 4}||U_{\beta 4}|$$

zero
distance
effect!

$$\langle \mathcal{P}_{\alpha\alpha} \rangle = 1 - 2|U_{\alpha 4}|^2$$

Averaged-out regime

- What is measured in Near Detector

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

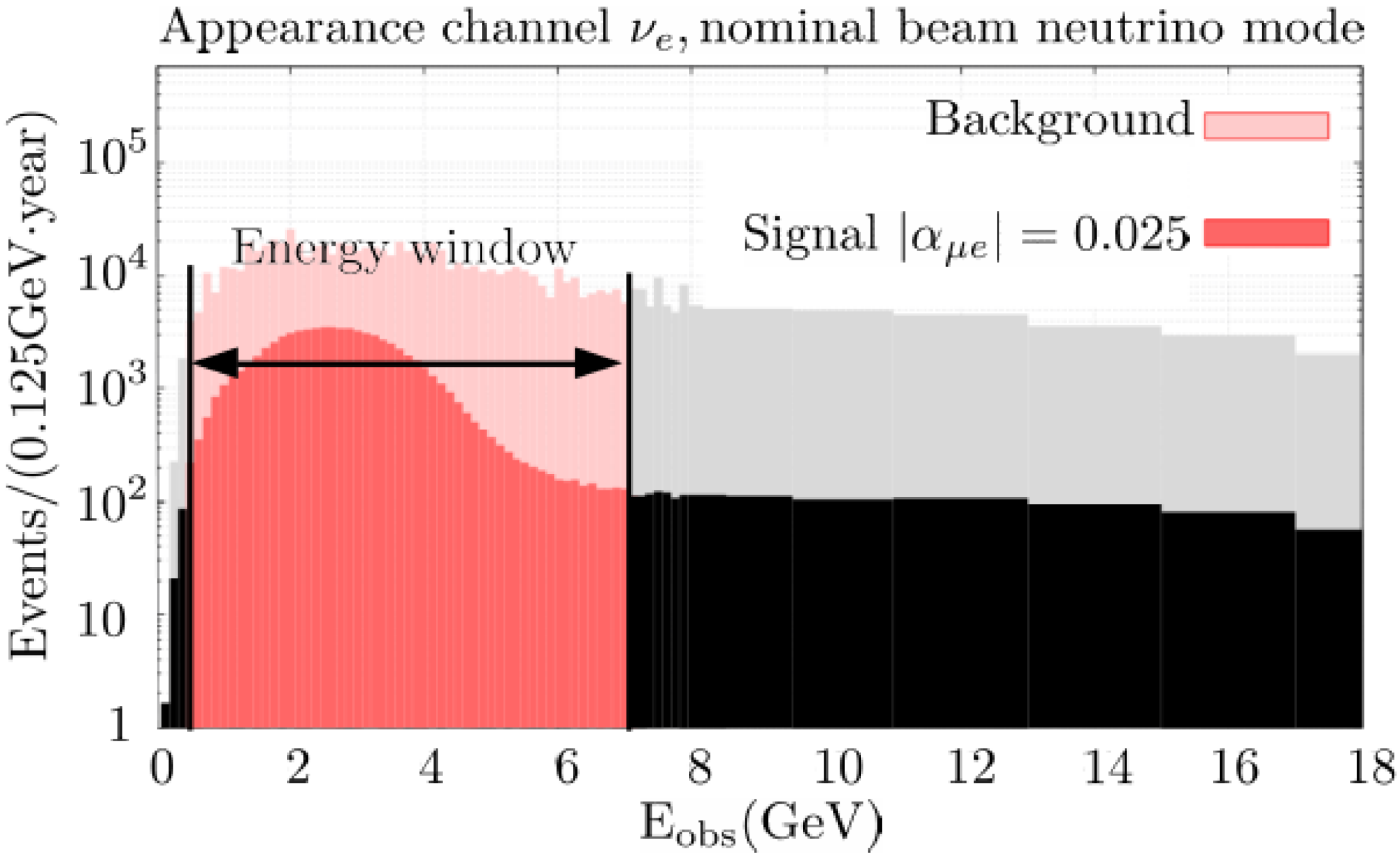
$$\langle \mathcal{P}_{\alpha\beta} \rangle = 2|\alpha_{\alpha\beta}|^2$$

zero
distance
effect!

$$\langle \mathcal{P}_{\alpha\alpha} \rangle = 1 - 4|\alpha_{\alpha\alpha}|^2$$

Low Scale
Non-Unitarity

Role of shape uncertainty

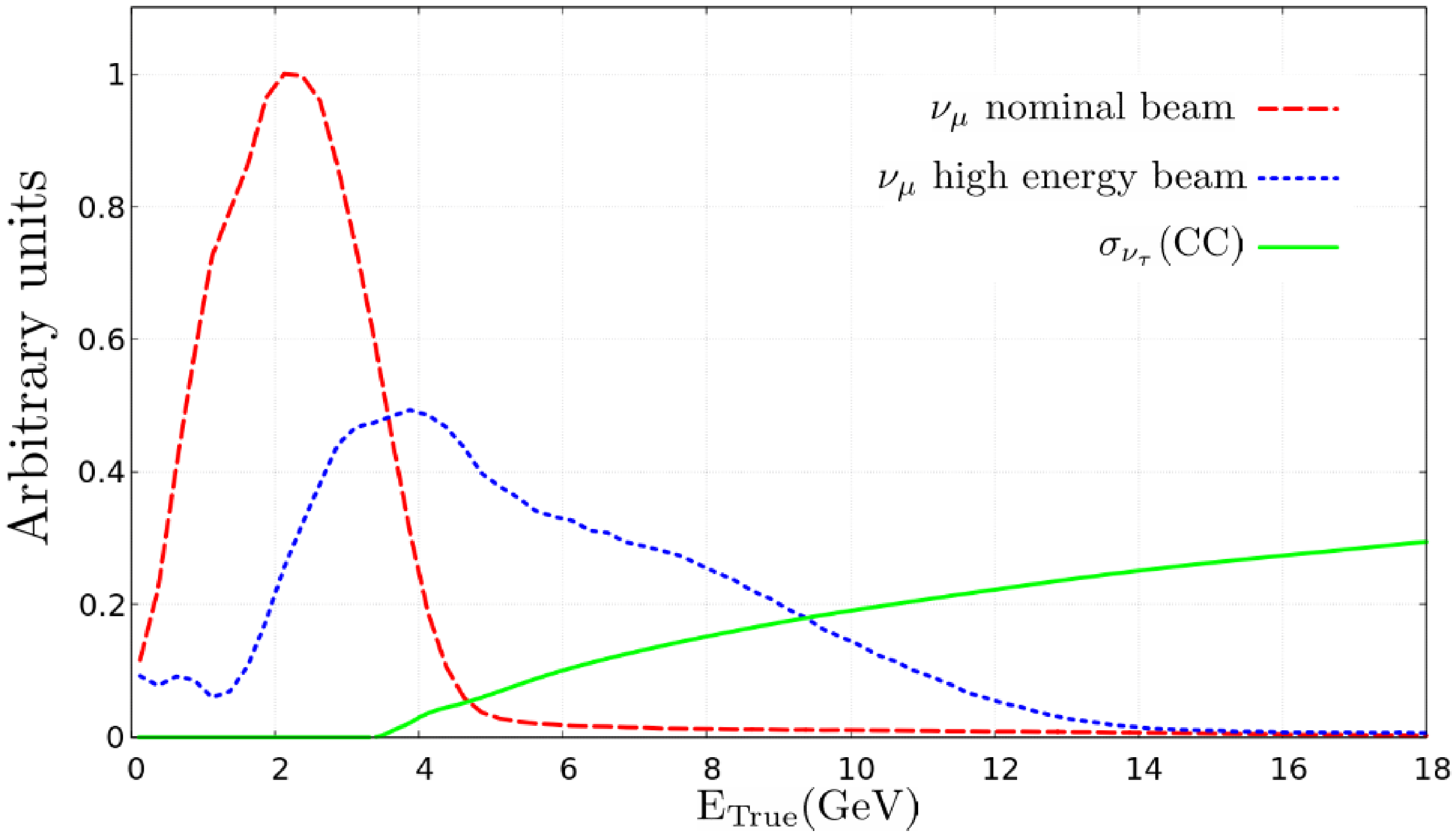


- Sensitivity driven by spectral information.
- Marginal impact of global normalization error.

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

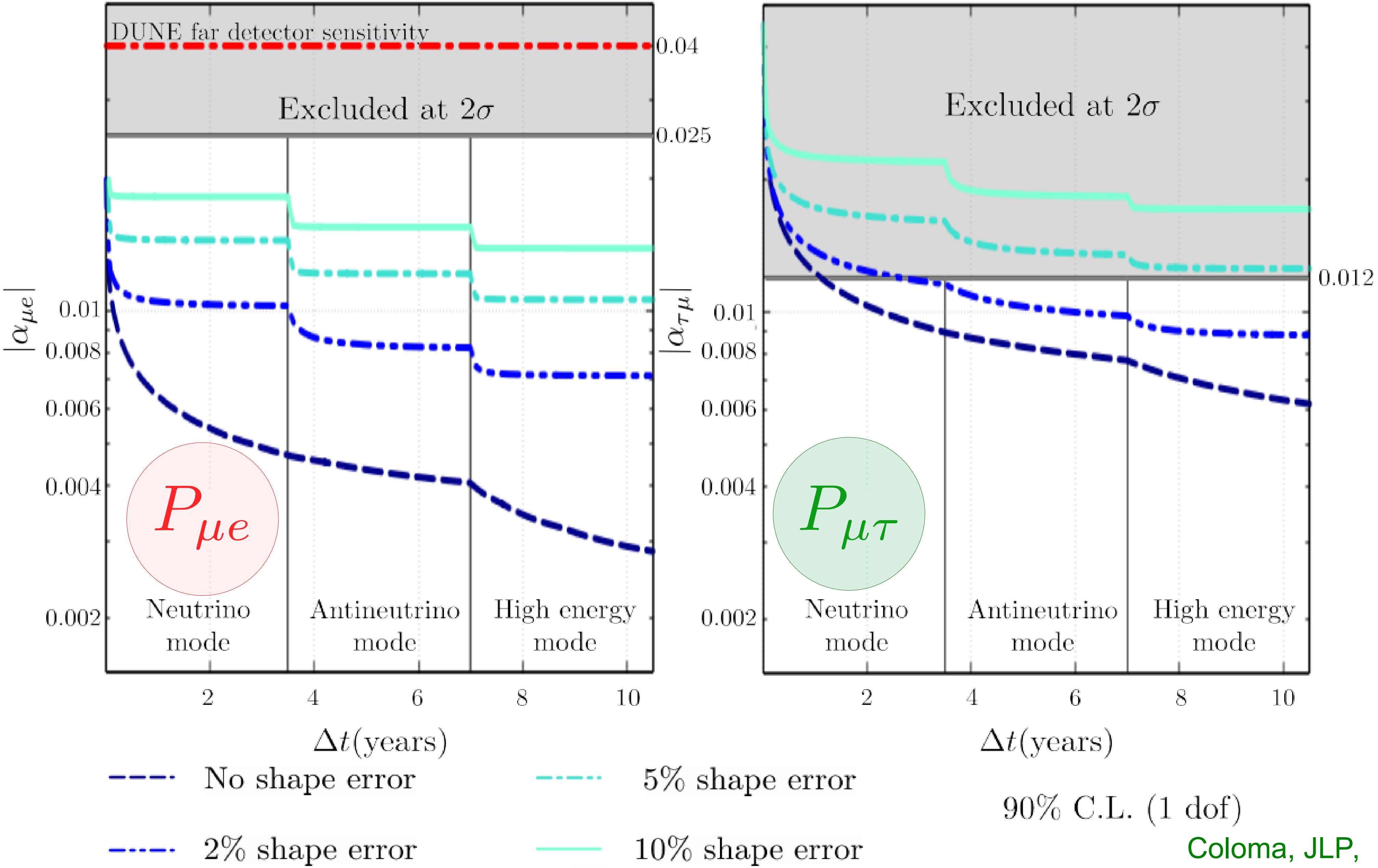
ν_τ appearance channel

- Energy threshold of τ production 3.2 GeV.



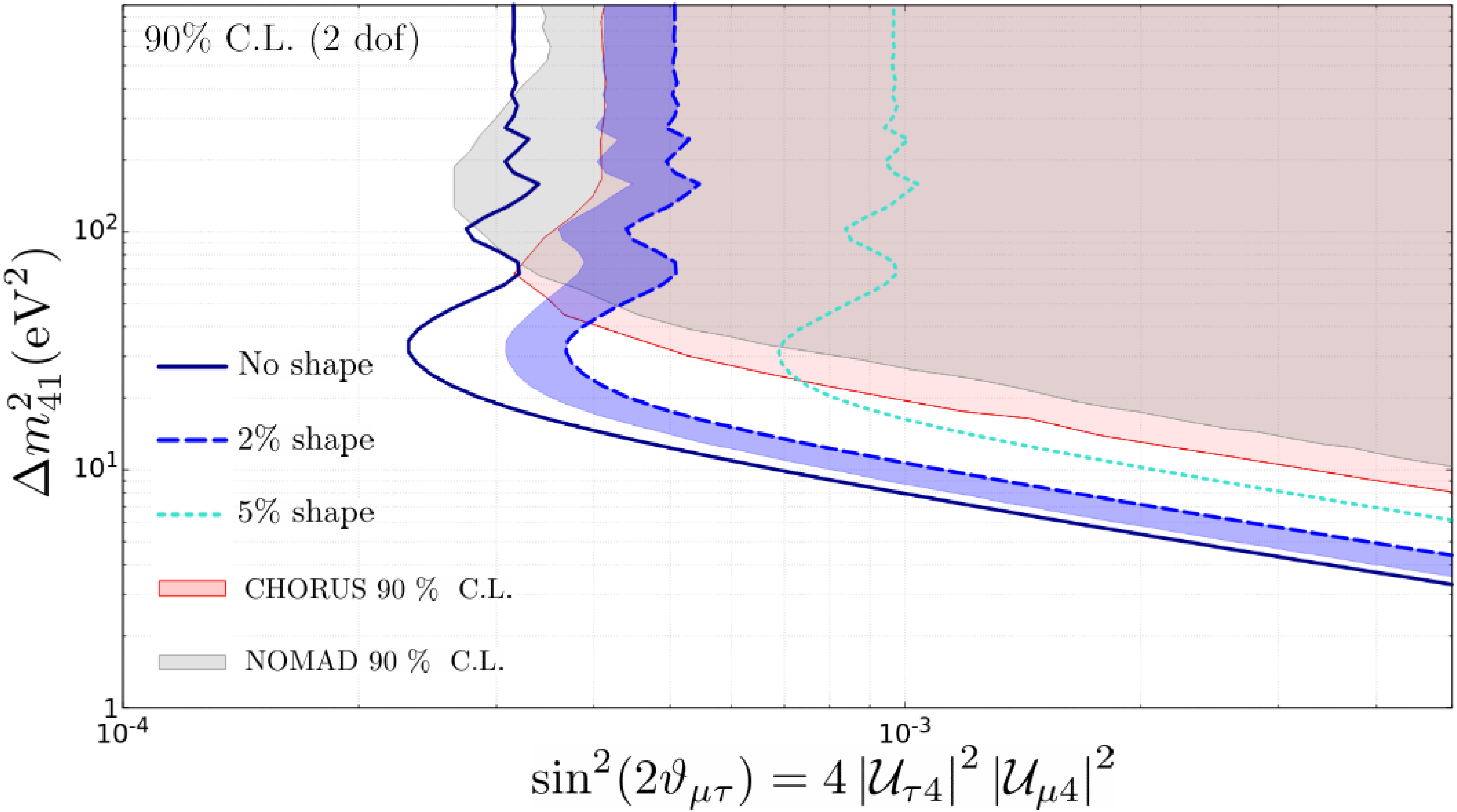
- ν_τ **detection:** we follow de Gouvêa, Kelly, Stenico, Pasquini 1904.07265

Low Scale Non-Unitarity



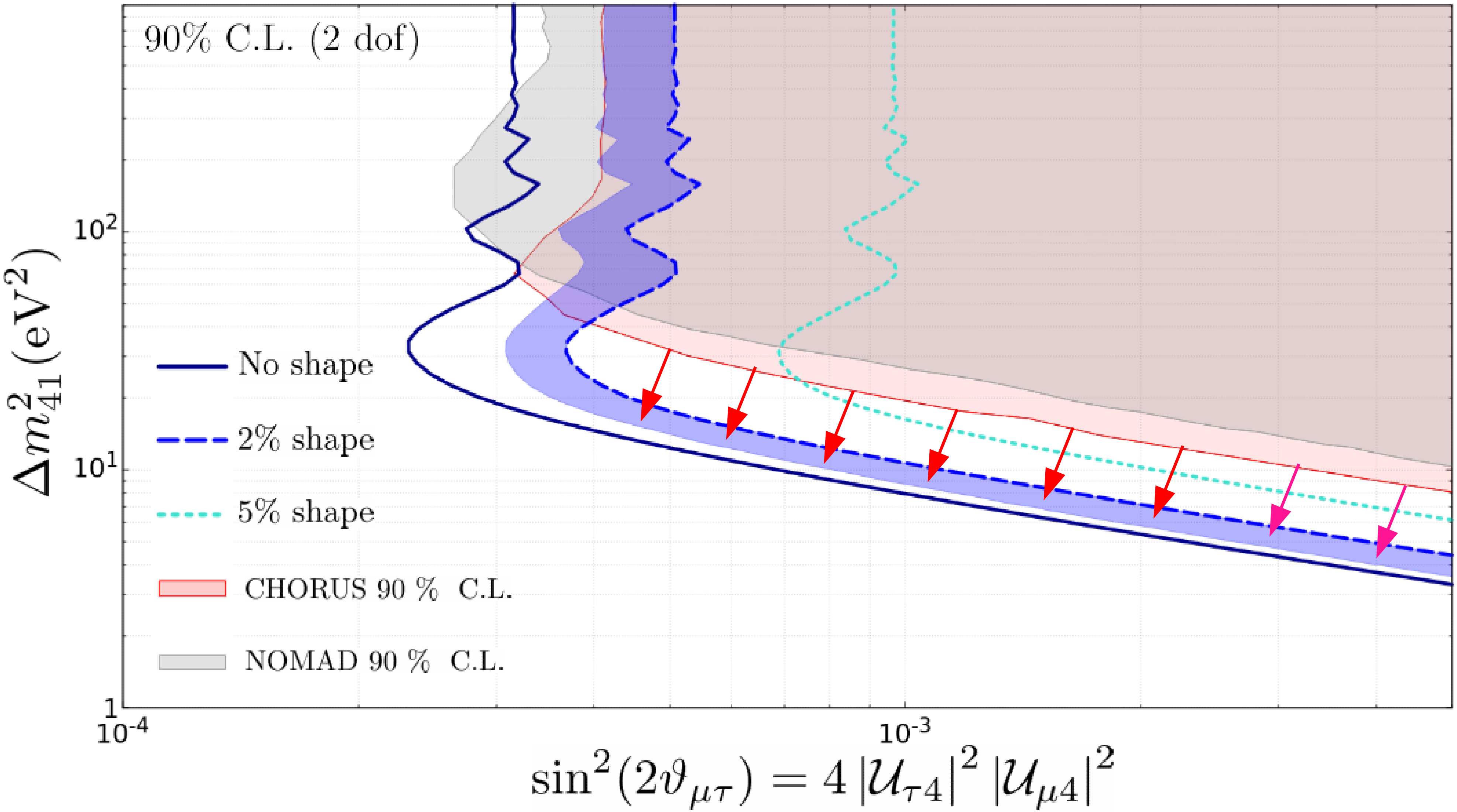
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

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



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

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



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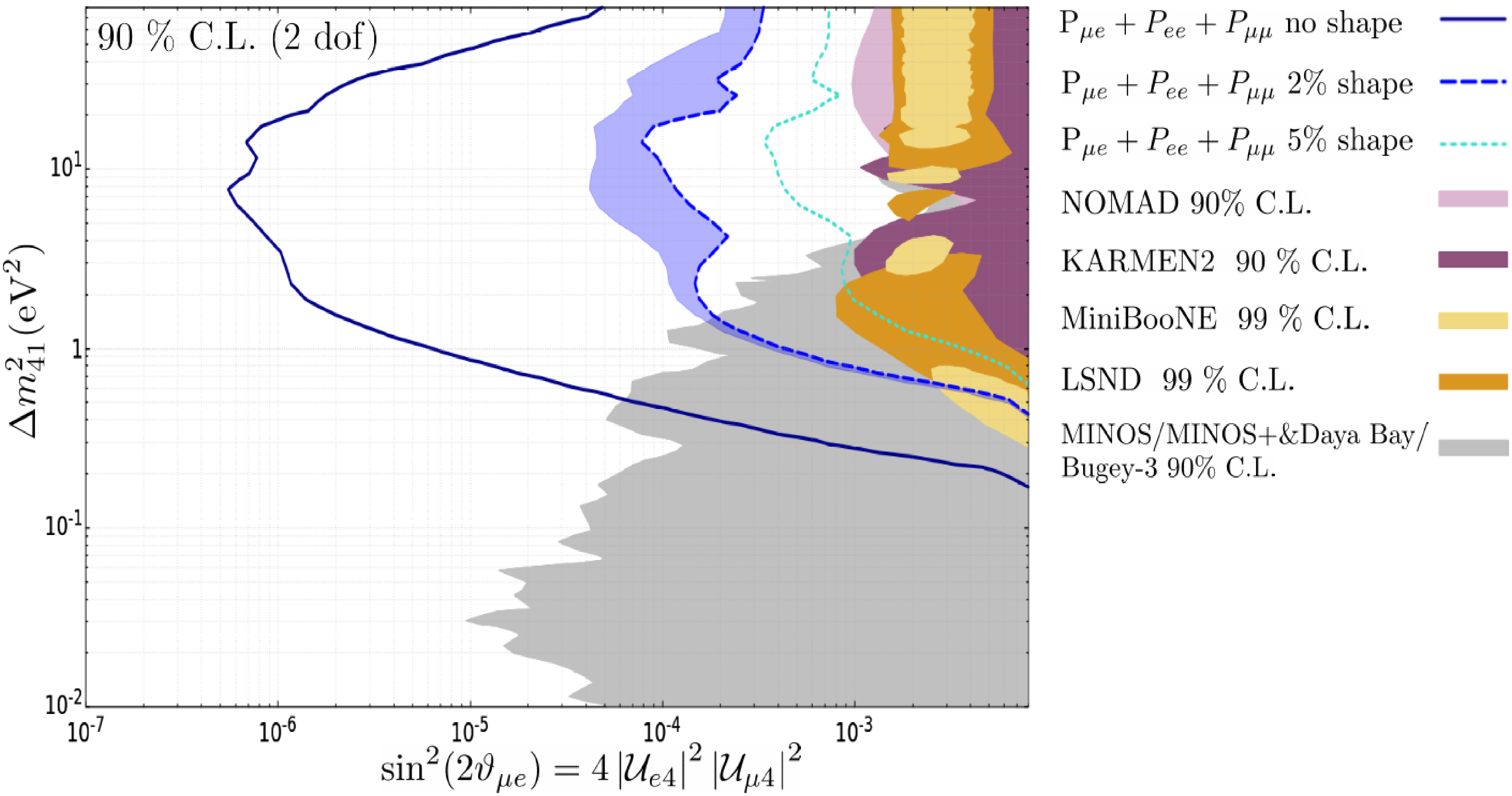
3+1 Sterile Neutrinos: $P_{\mu\mu} + P_{\mu e} + P_{ee}$



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

Conclusions

- Near detectors can play a relevant role in testing the robustness of the 3-neutrino picture

Low scale Non-Unitarity, sterile neutrino oscillations, NSI (Non-Unitarity results can be easily mapped to NSI framework, see 2105.11466)

- **Keeping under control shape uncertainties is a key issue.**

- Sensitivity beyond present bounds only when systematics below 5%

- Joint experimental and theoretical effort required to reduce systematics.

- Independent measurements of the cross sections would give very relevant information regarding the energy dependence.
(see for instance $\nu\mathrm{STORM}$ proposal)

- **Neutrino tau detection opens a complementary New Physics channel.**

Hvala!

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

DUNE set up

Globes files

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

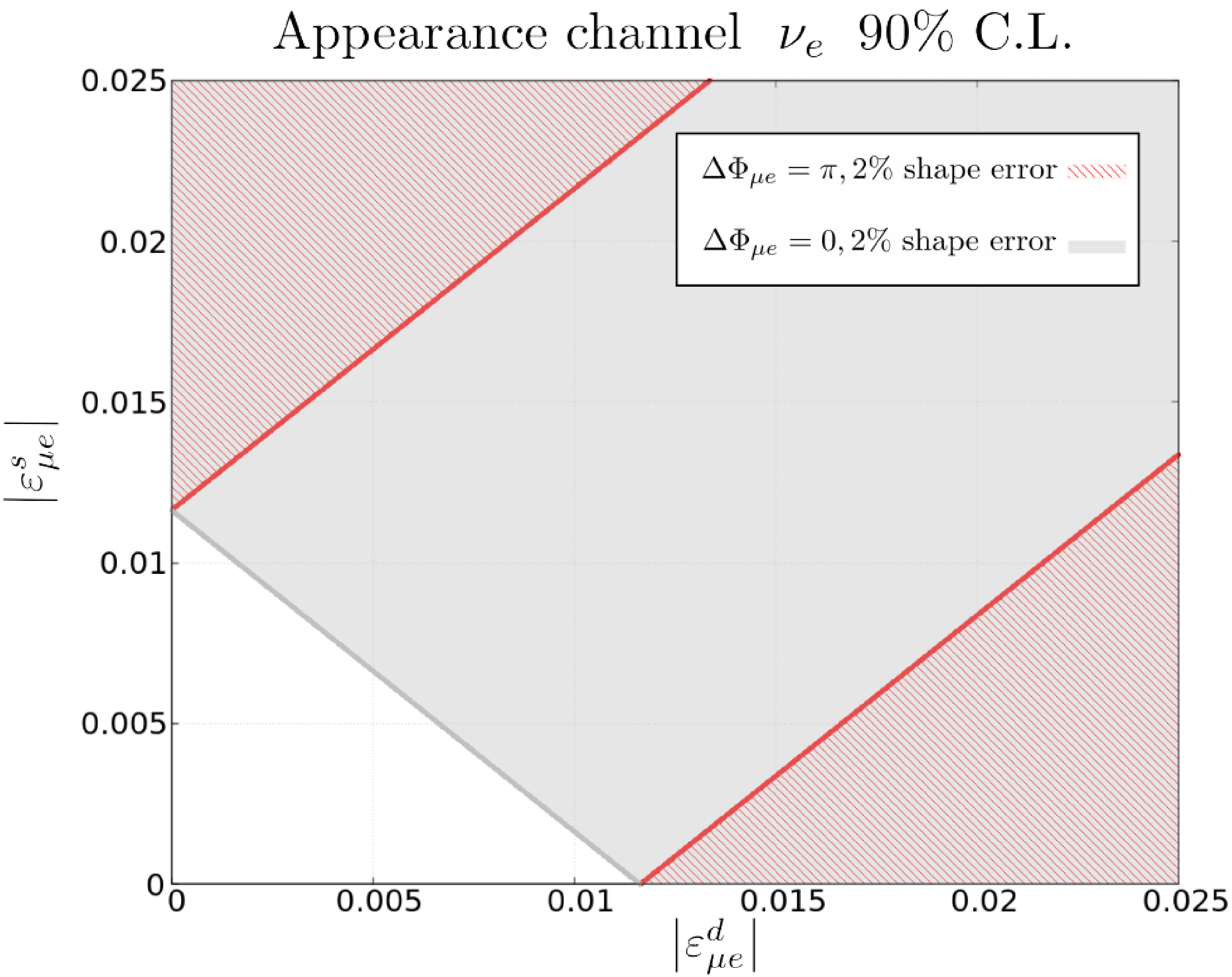
Flux configuration

Beam configuration	Power	E_p	PoT/yr	t_ν (yr)	$t_{\bar{\nu}}$ (yr)	M_{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

Running mode	Sample	Contribution	Event rates ($\times 10^5$)	$E_{\text{obs}}^{\text{max}}$ (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%

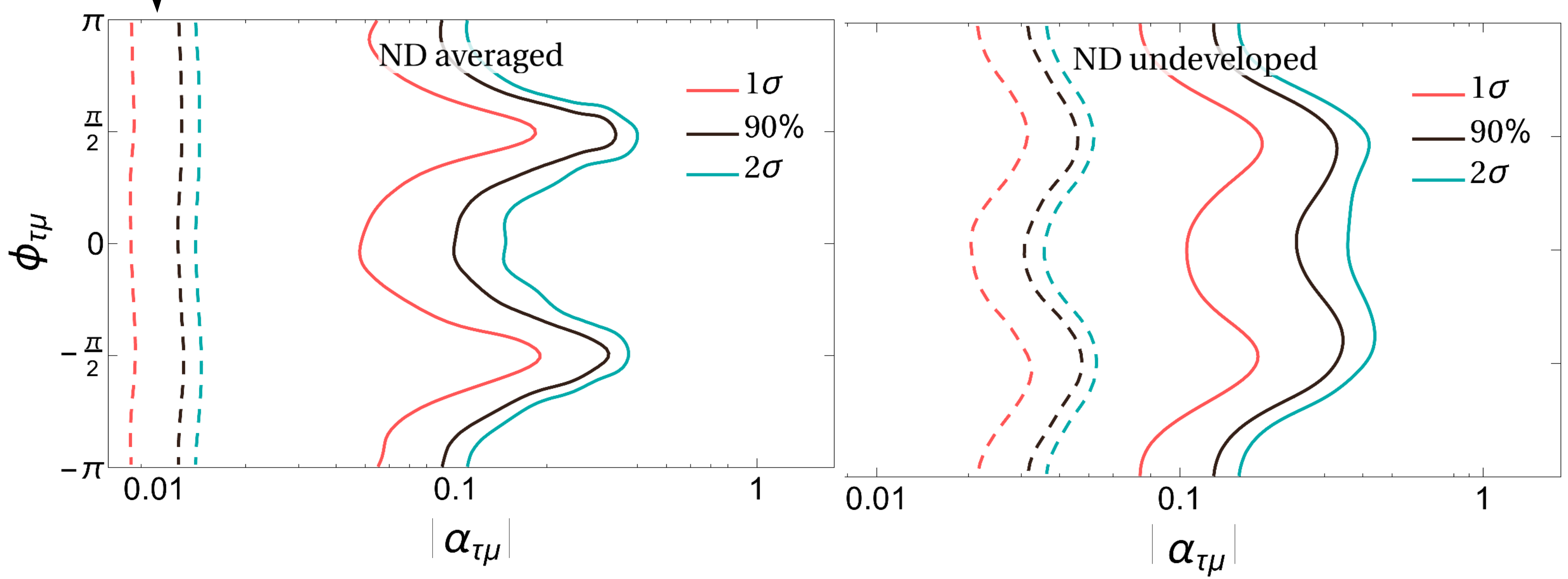
NSI in production/detection: $P_{\mu e}$



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

- Mapping: $2|\alpha_{\beta\gamma}|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma})$

Far Detector



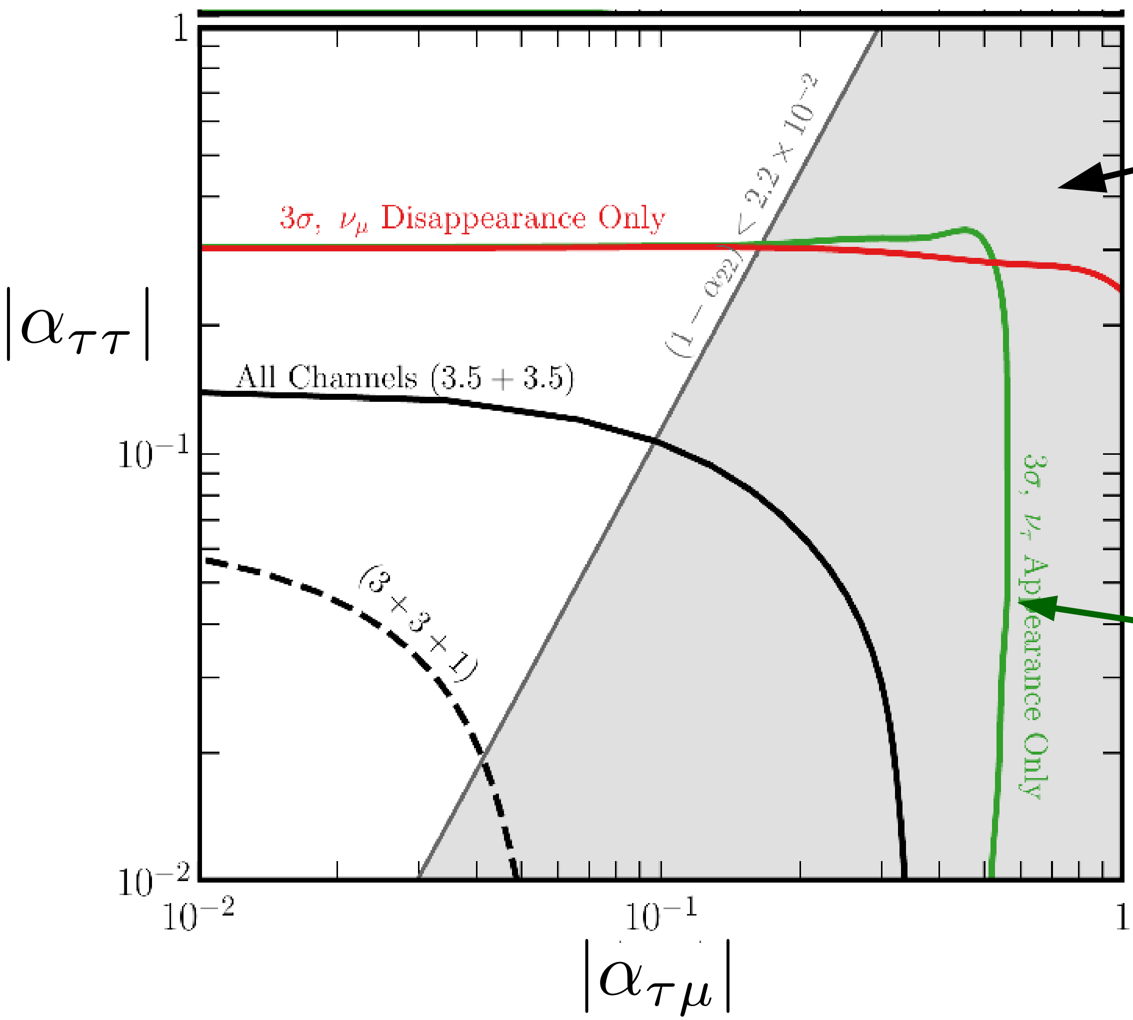
Prior
(present bounds)

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

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

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

Far Detector



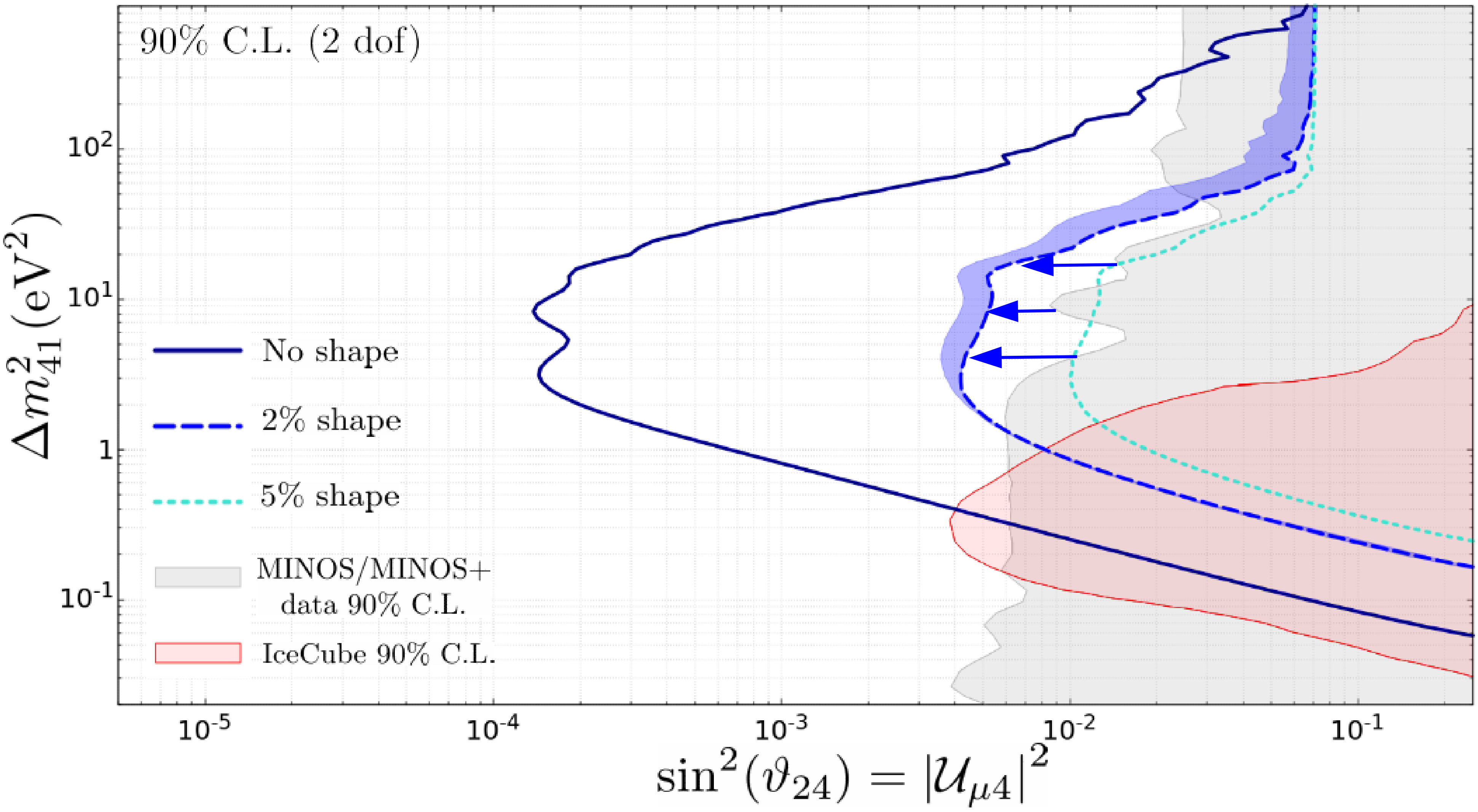
EXCLUDED

ν_τ appearance channel

- Including ν_τ appearance channel does not change the picture.

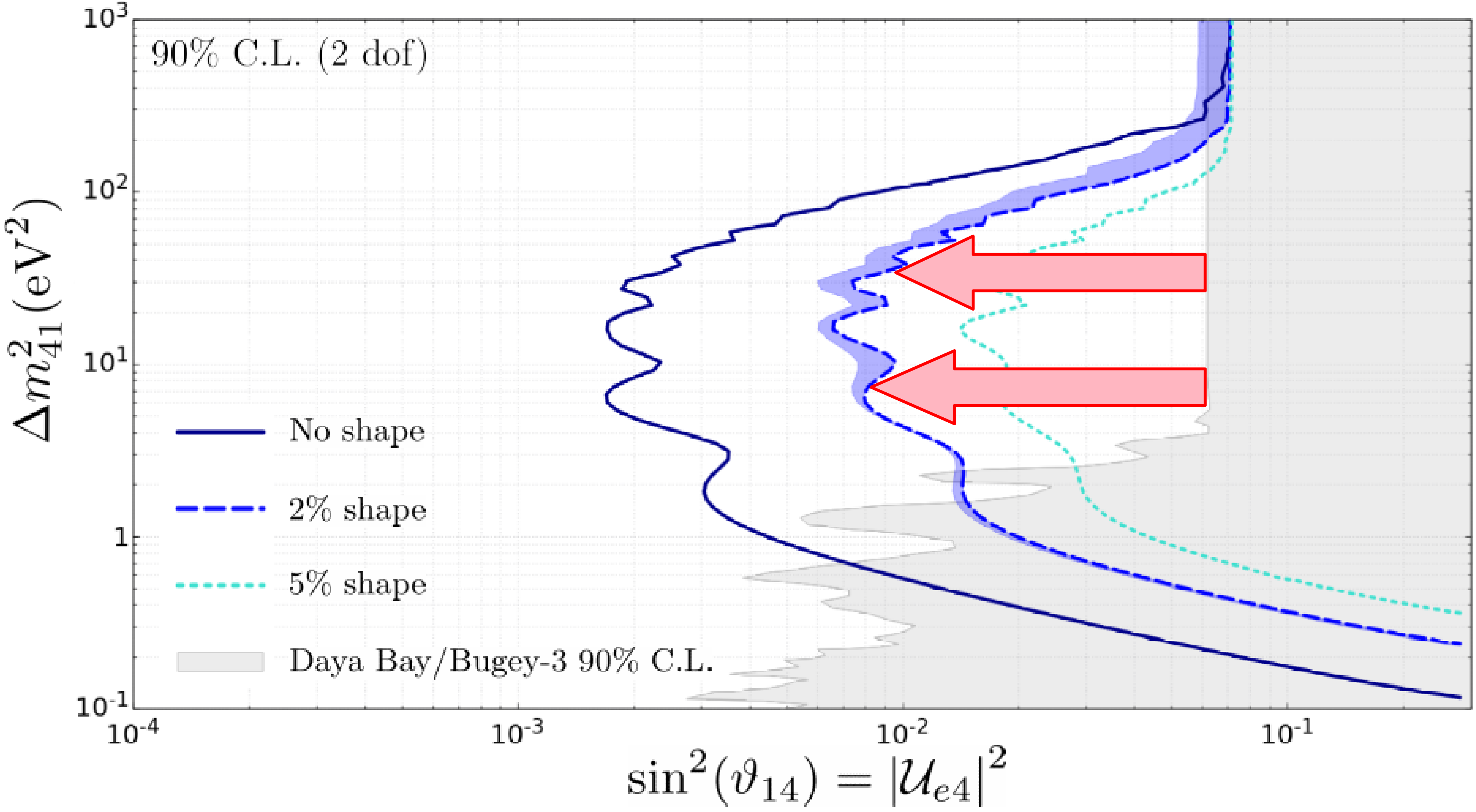
de Gouvêa, Kelly, Steni Pasquini 1904.07265

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



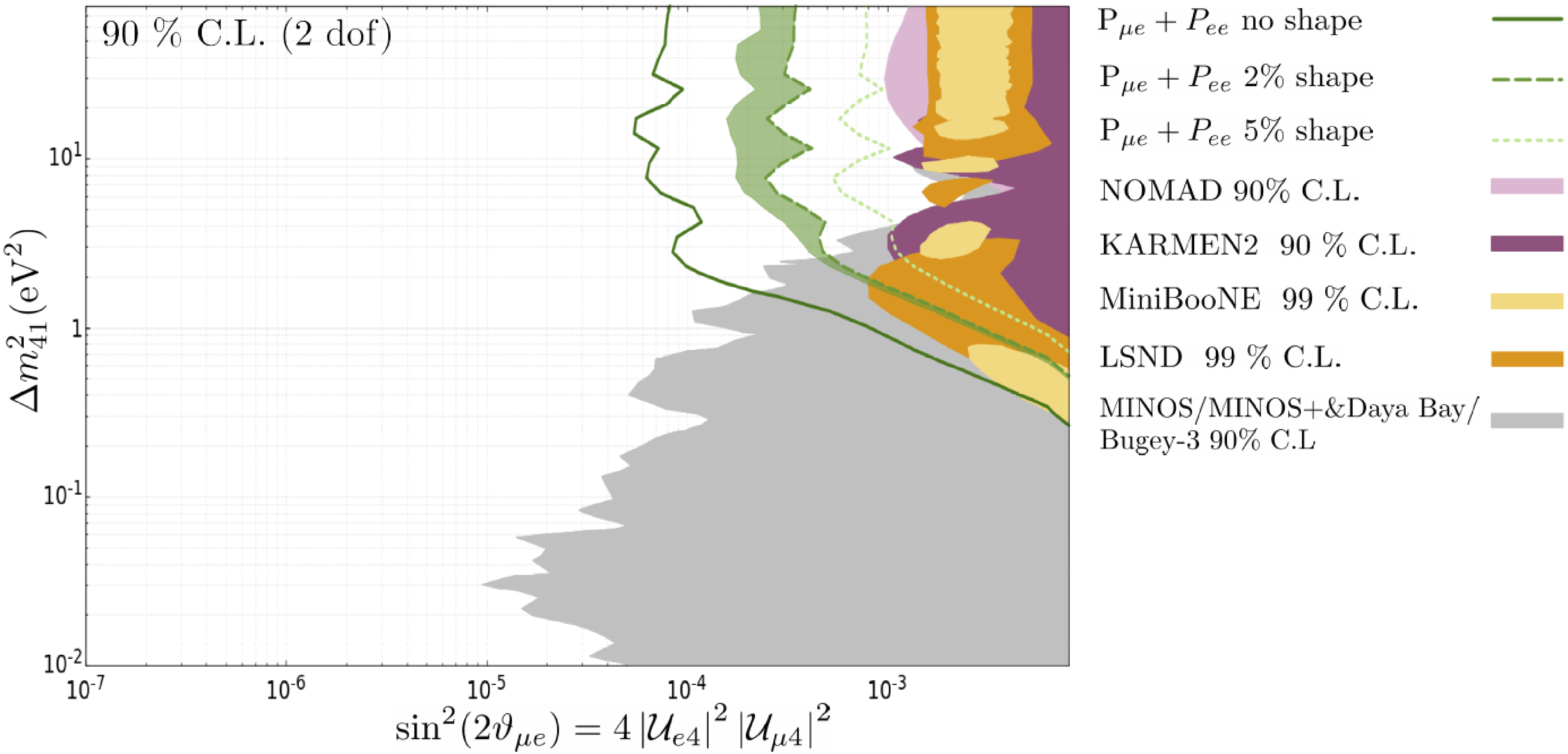
Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

3+1 Sterile Neutrinos: P_{ee}



Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

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



Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

Systematics: Disappearance

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

- Using near detectors is a very effective way of reducing systematics in disappearance experiments (K2K, MINOS, reactors...).

$$\frac{N^{\mathrm{FD}}_{\nu_\alpha}}{N^{\mathrm{ND}}_{\nu_\alpha}} \sim \frac{L^2_{\mathrm{ND}}}{L^2_{\mathrm{FD}}} \xcancel{\frac{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}} P_{\alpha\alpha}$$

Systematics: Appearance (CP violation)

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

- For appearance experiments the situation is more complicated

$$\frac{N_{\nu_e}^{\mathrm{FD}}}{N_{\nu_\mu}^{\mathrm{ND}}} \sim \frac{L_{\mathrm{ND}}^2}{L_{\mathrm{FD}}^2} \frac{\sigma_e \epsilon_e}{\sigma_\mu \epsilon_\mu} P_{\mu e}$$

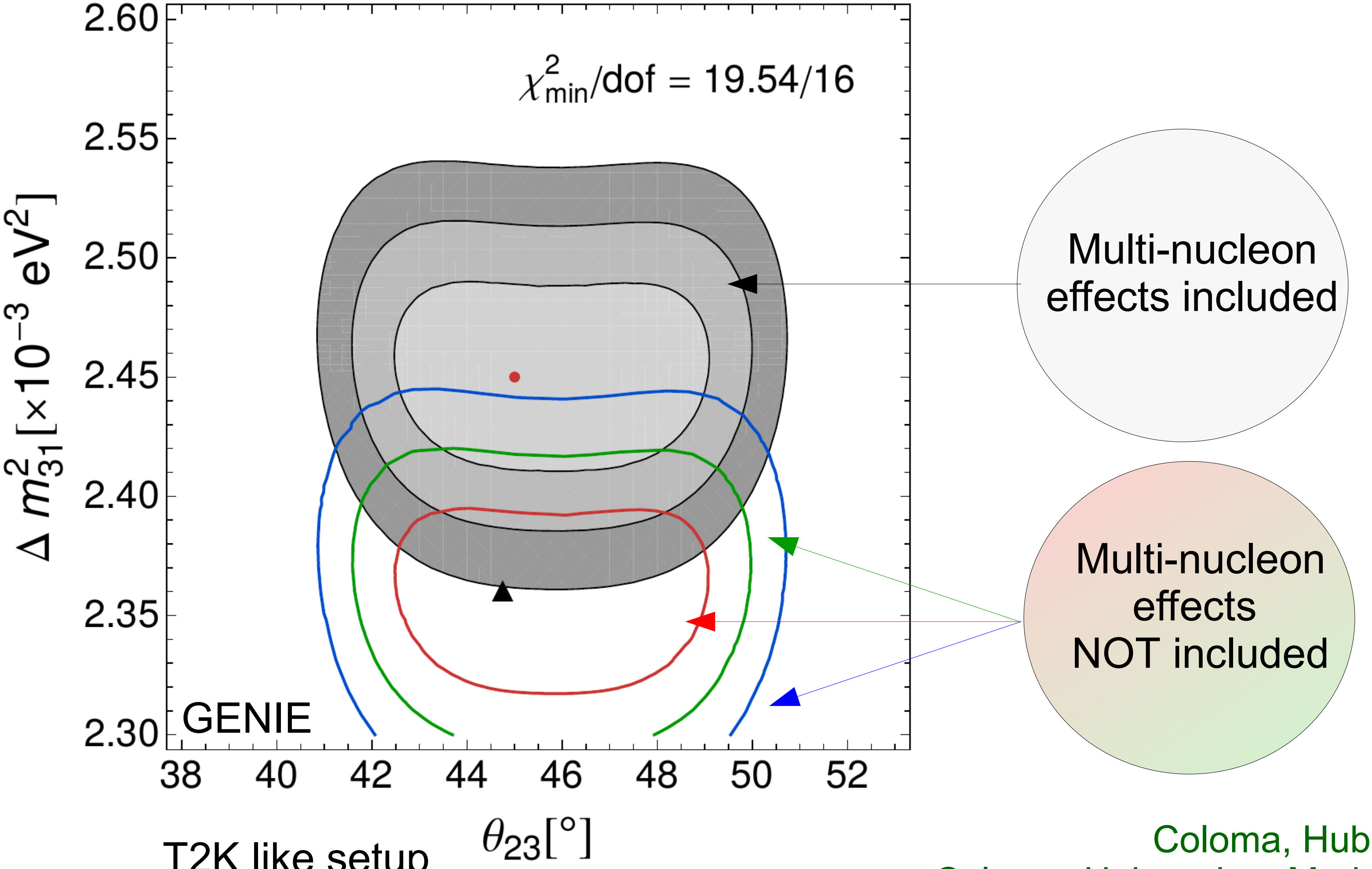
- CP violation requires comparison between neutrino and anti-netrino signals.

$$\frac{N_{\nu_e}^{\mathrm{Far}}}{N_{\bar{\nu}_e}^{\mathrm{Far}}} \sim \frac{N_{\nu_\mu}^{\mathrm{ND}}}{N_{\bar{\nu}_\mu}^{\mathrm{ND}}} \frac{\sigma_e \epsilon_e}{\sigma_\mu \epsilon_\mu} \frac{\sigma_{\bar{\mu}} \epsilon_{\bar{\mu}}}{\sigma_{\bar{e}} \epsilon_{\bar{e}}} \frac{P_{\mu e}}{P_{\bar{\mu}\bar{e}}}$$

Huber, Mezzetto, Schwetz, 0711.2950
Coloma, Huber, Kopp, Winter, 1209.5973

Nuclear Cross sections

- Neutrino-nucleus cross section missmodeling could lead to unacceptably large systematic uncertainties or biased measurements, even after the inclusion of a near detector.



Multi-nucleon effects included

Multi-nucleon effects NOT included

T2K like setup

Coloma, Huber 1307.1243
Coloma, Huber, Jen, Mariani 1311.4506
....

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

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

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

General Parameterizations

- Hermitian parameterization

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

Deviation from unitarity

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

Unitary matrix

(standard unitary PMNS matrix
up to small corrections)

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