New Physics in Neutrino Oscillations and role of tau neutrinos

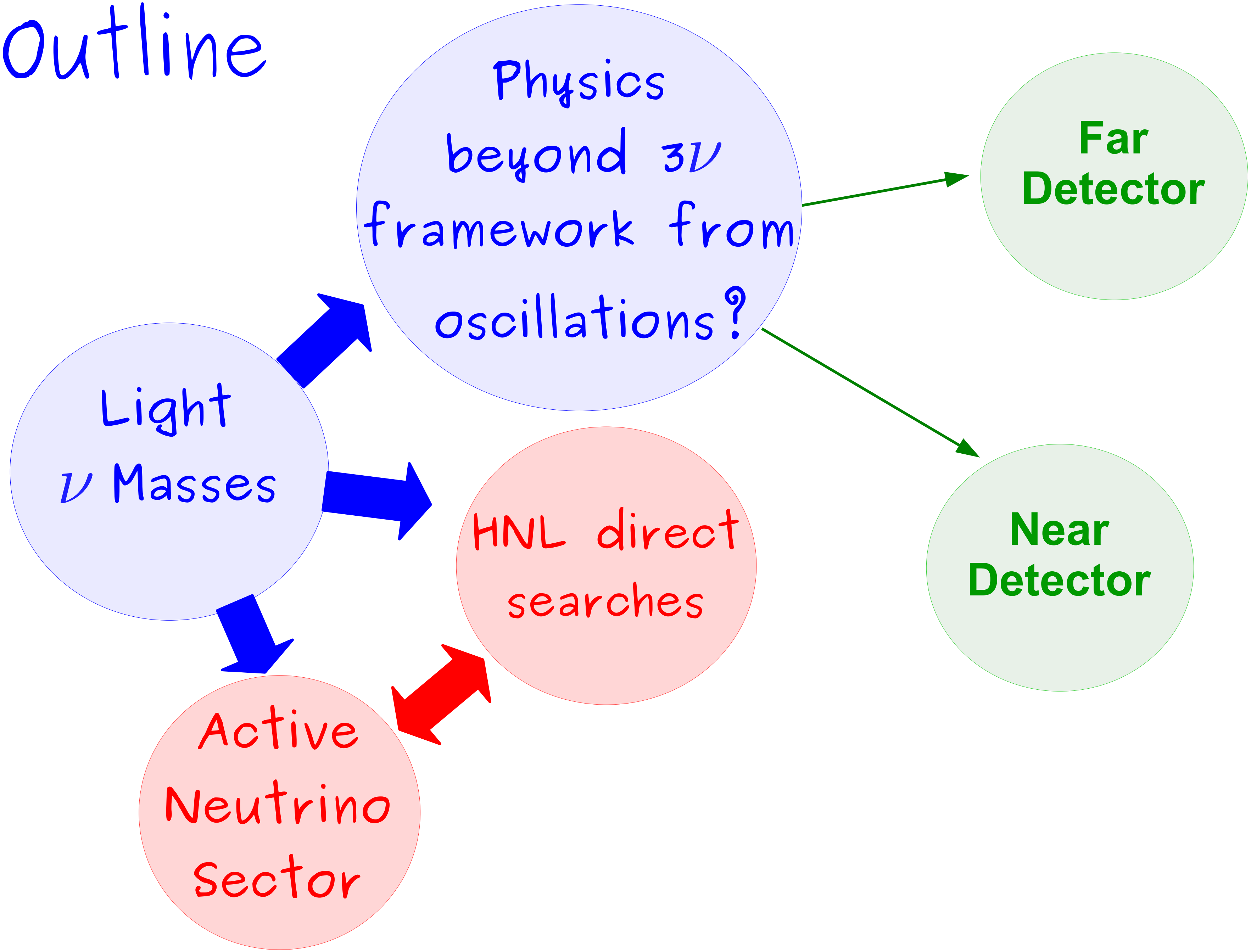
Jacobo López-Pavón

NuTau 2021 *- Tau Neutrinos from GeV to EeV*

28 September 2021

CIDEGENT/2018/019

Outline


Physics beyond 3ν framework from oscillations?
Far Detector
Near Detector
Light ν Masses
HNL direct searches
Active Neutrino Sector

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:

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

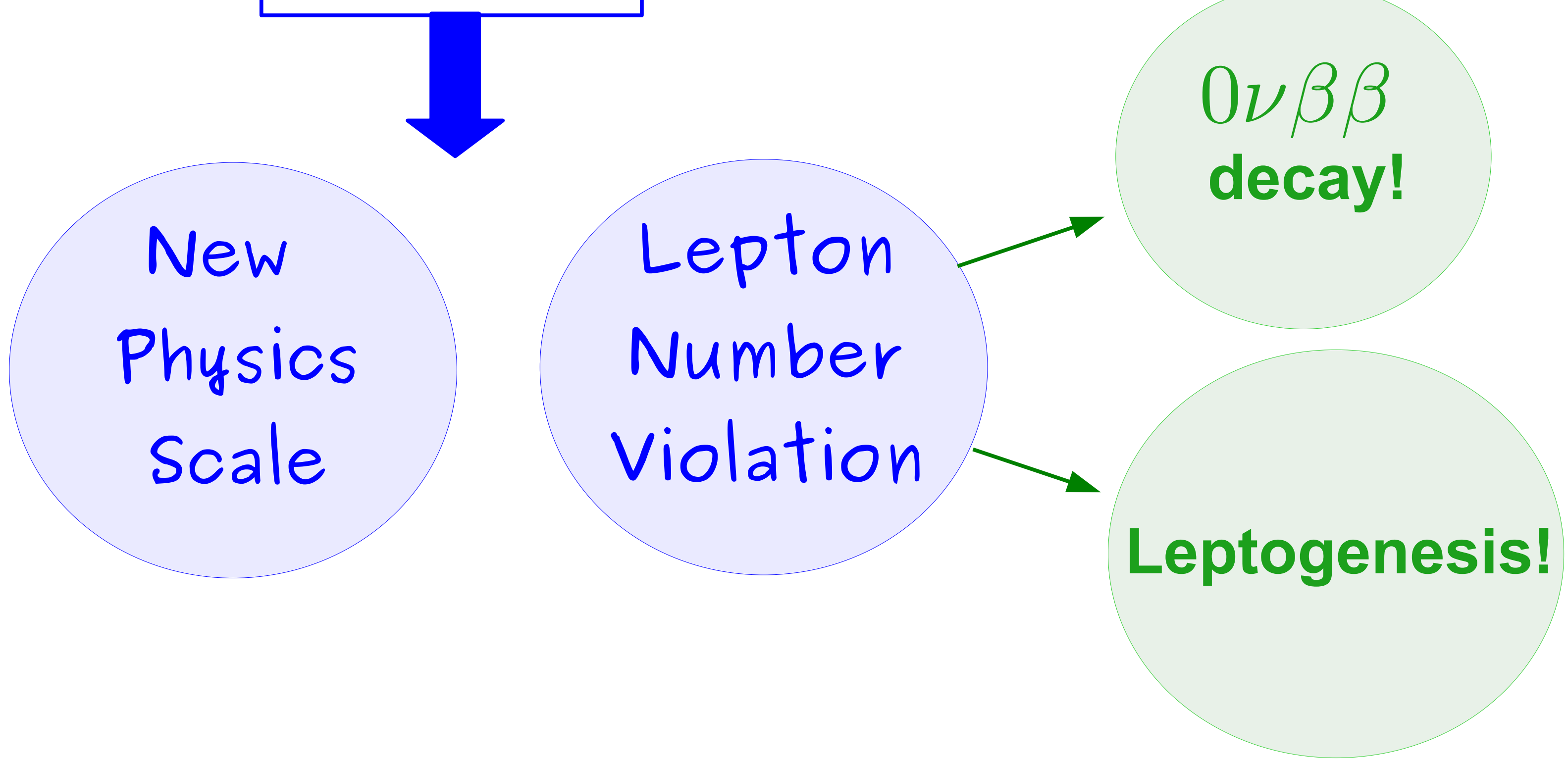
Light Neutrino Masses

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

Minimal model: Seesaw Model

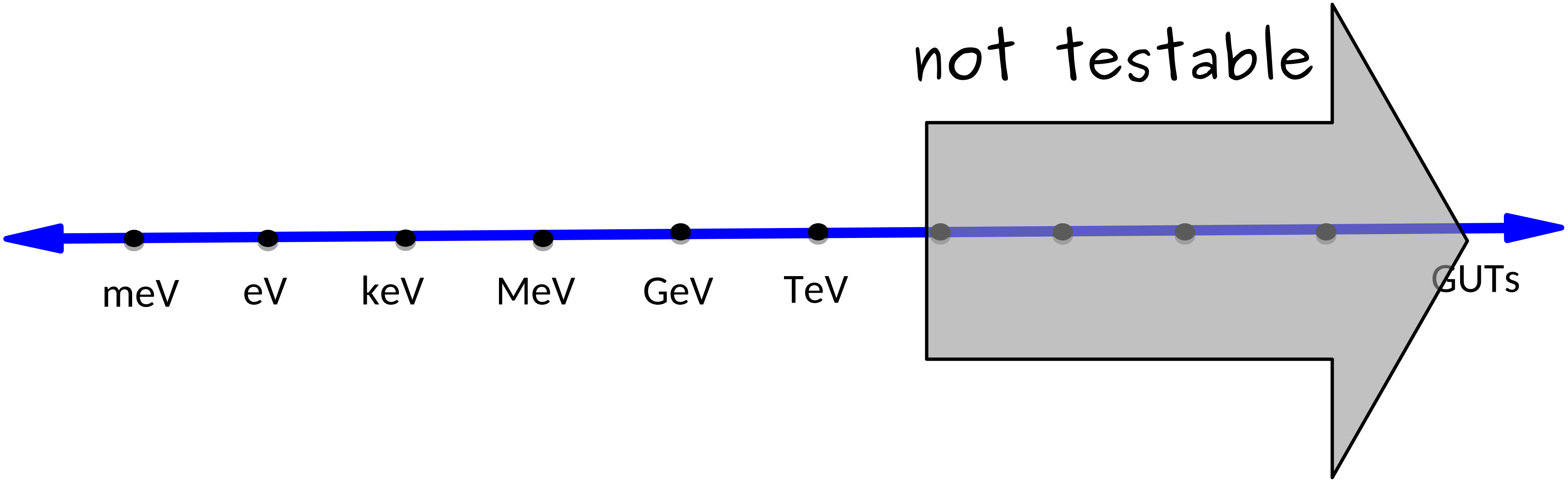
- Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_R) to the SM field content:

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

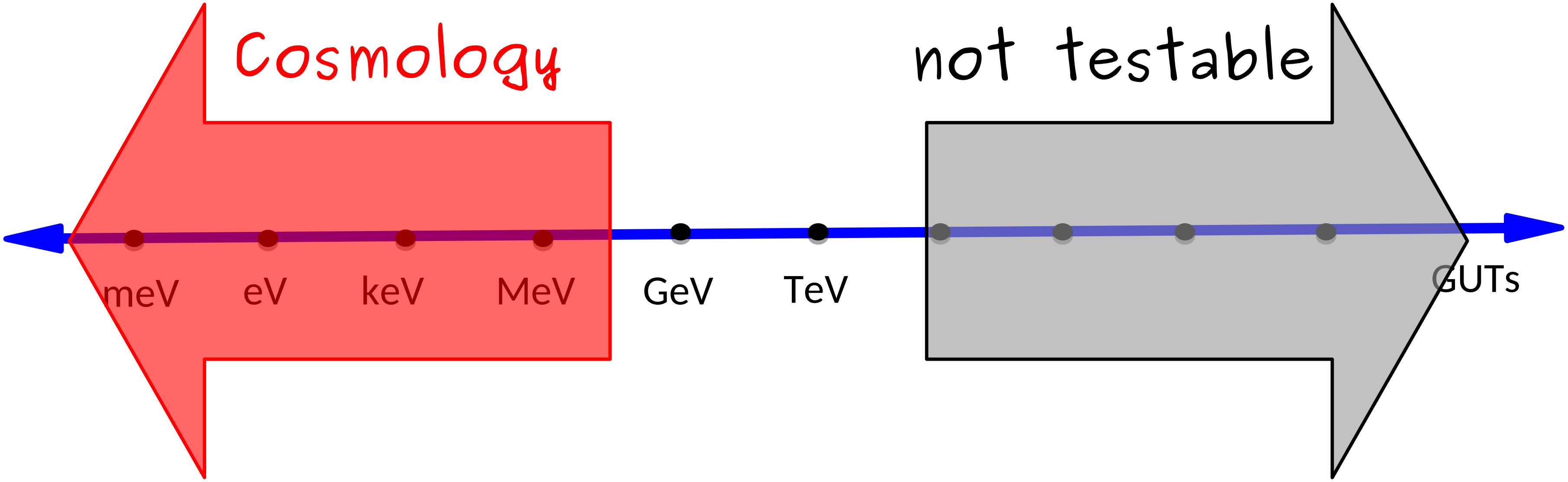


Fukujita, Yanagida 1986

The New Physics Scale

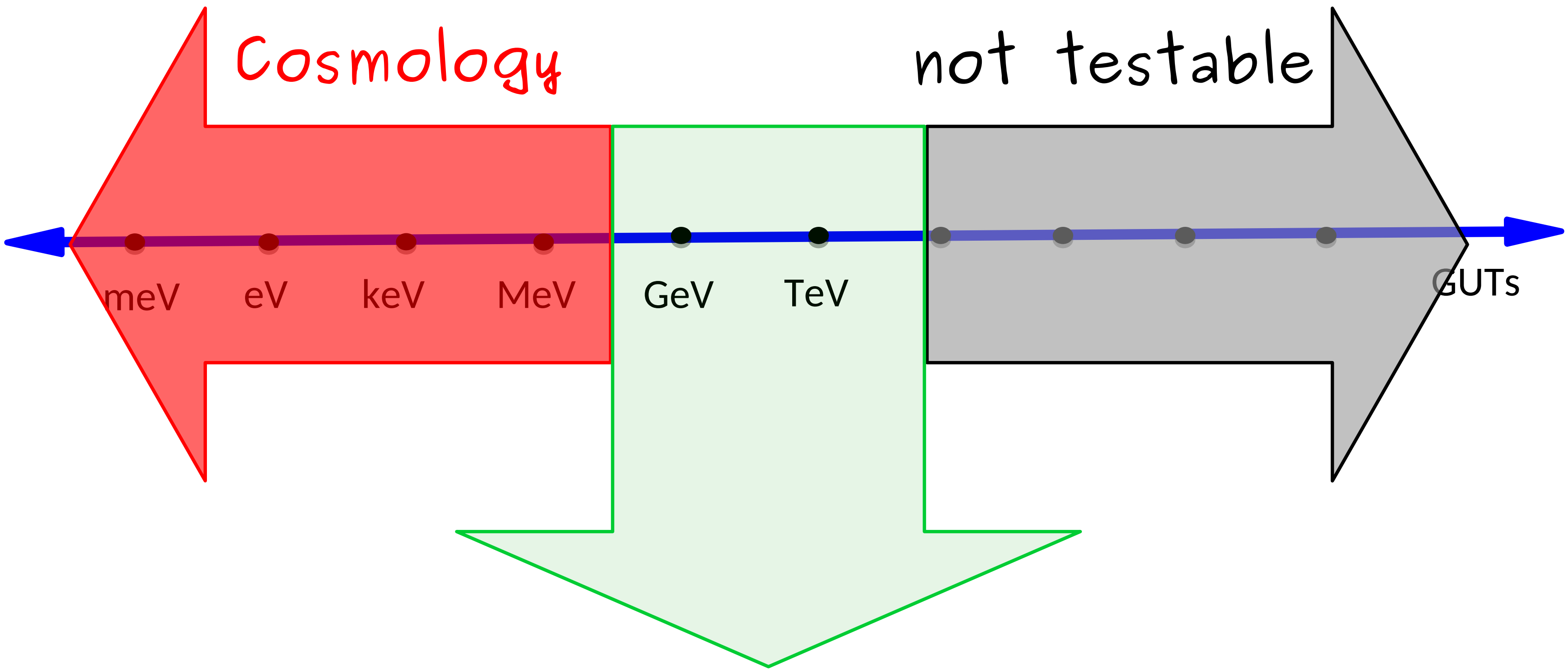


The New Physics Scale



P. Hernandez, M. Kekic, JLP
1311.2614
1406.2961

The New Physics Scale



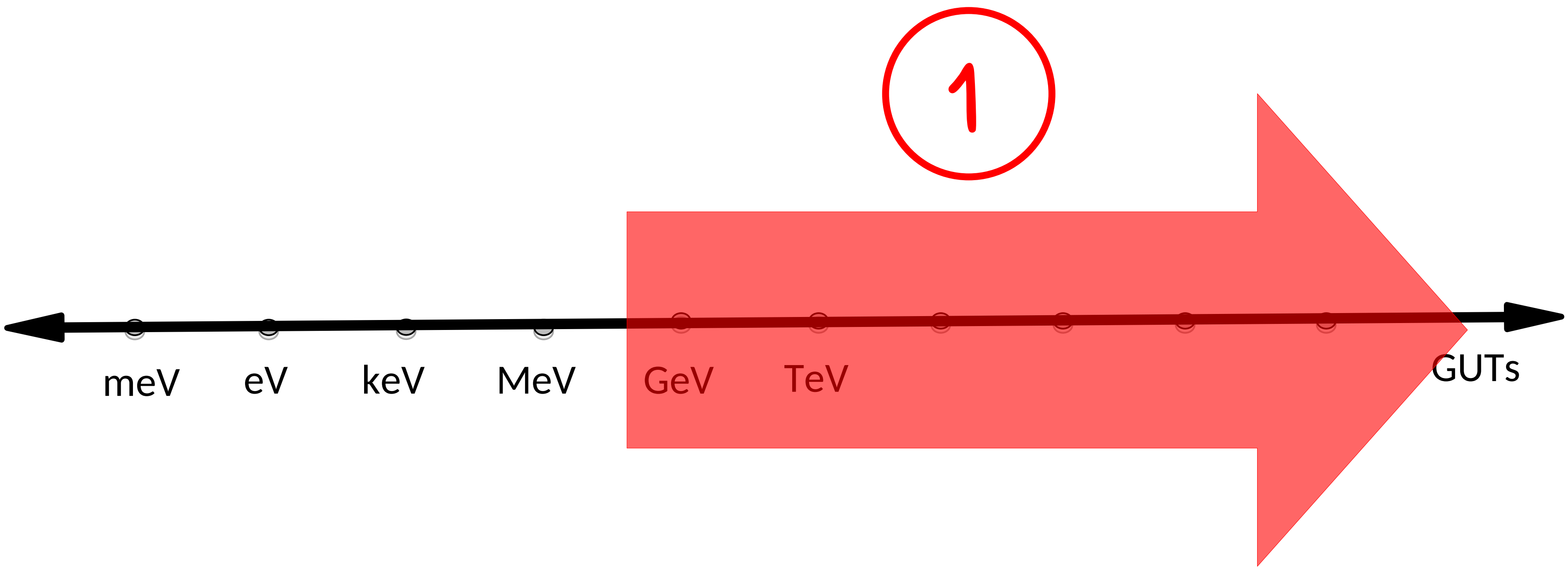
$0\nu\beta\beta$ decay, CLFV, Colliders, direct searches…

See talks by
Laura Field, Vladimir Gligorov, Yuval Grossman,
Felix Kling, Albert De Roeck

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

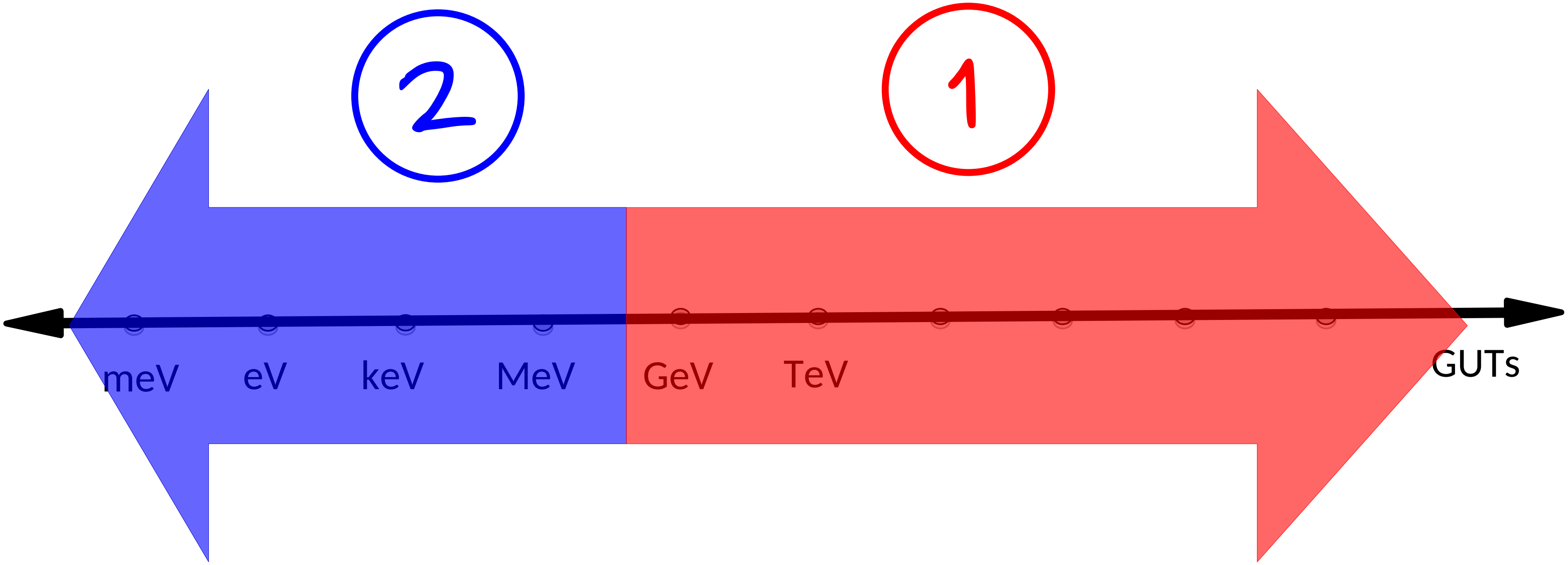
?

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

General Parameterizations

- Triangular parameterization

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

Deviation from unitarity

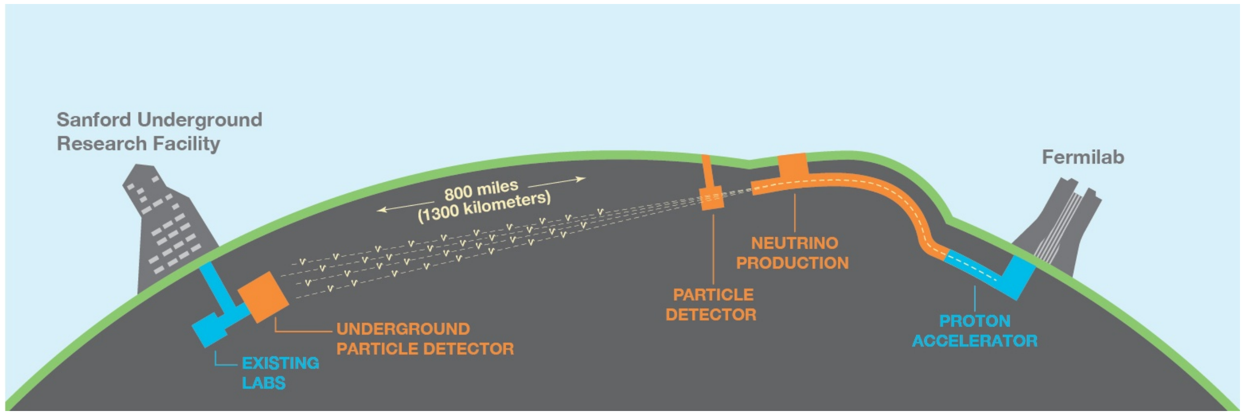
$$T = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

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

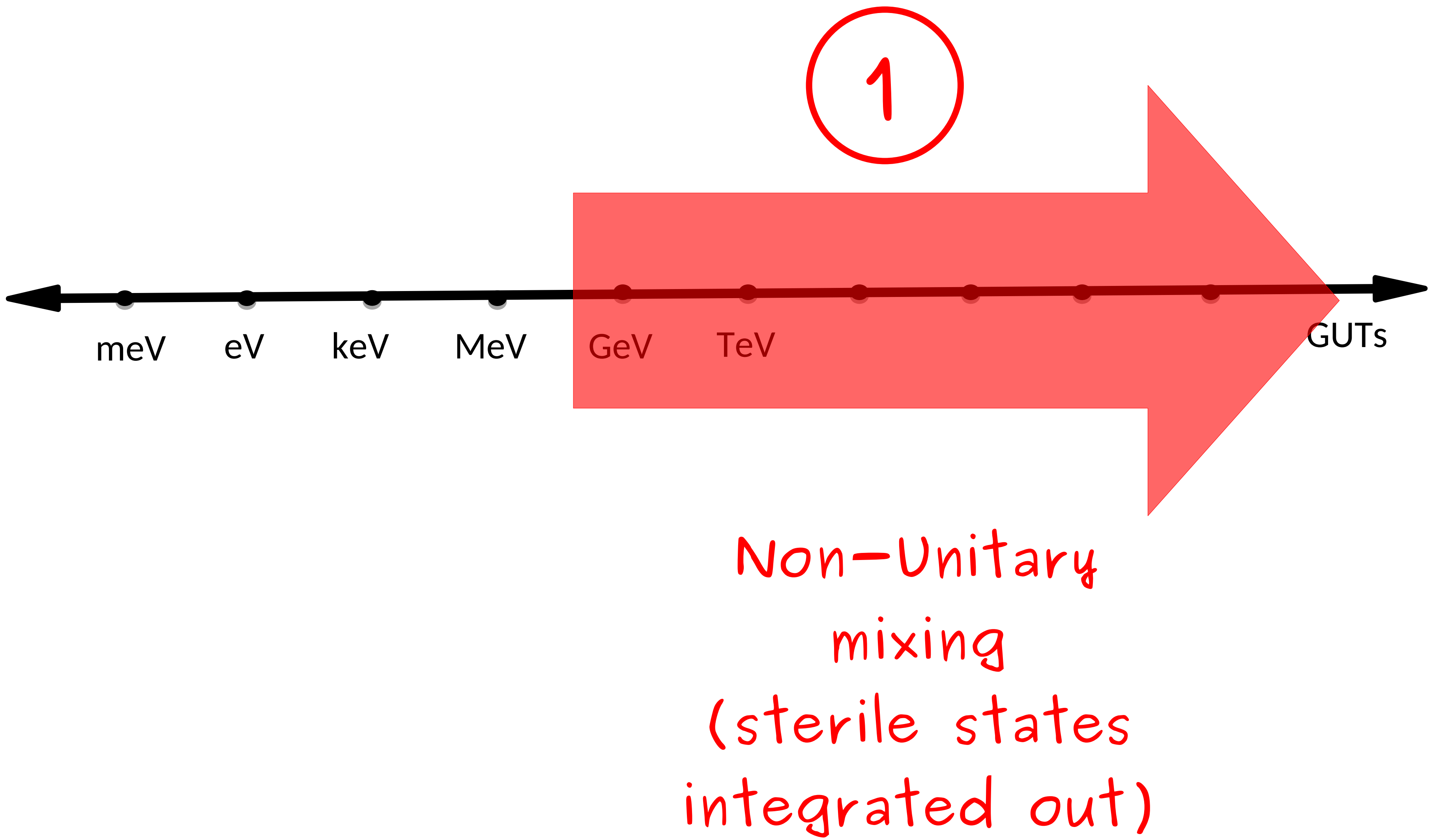
- What is measured in neutrino oscillation experiments

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

Event rate
Far Detector

Extrapolation of
Near Detector

① Non-Unitary Mixing



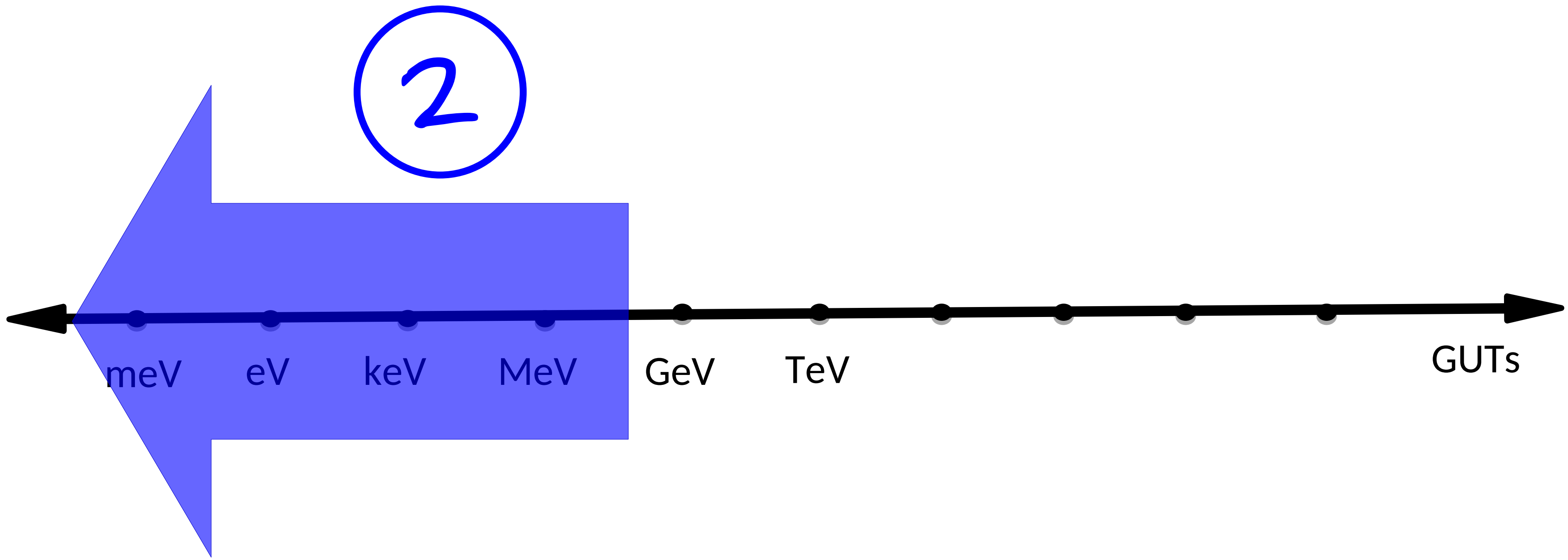
① Non-Unitary Mixing

- 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)

② Kinematically accessible sterile ν



Kinematically accessible sterile neutrinos

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

→ **See also talks by Katarzyna Grzelak, Miriama Rajaoalisoa and Carlos Arguelles**

② Kinematically accessible Sterile ν

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

Identical to the heavy non-unitarity case

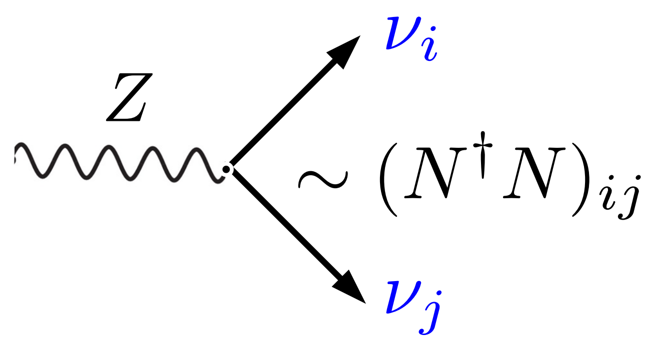
2. The light-heavy oscillations have not yet developed at the near detector.

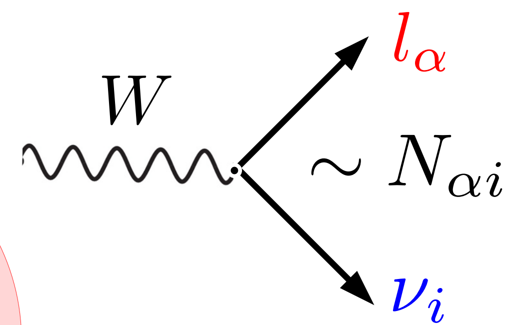
No normalization factor

Low Scale Non-Unitarity

Present Bounds

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





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 ($m > \text{EW}$)	Low-scale Non-Unitarity $\Delta m^2 \gtrsim 100\ \text{eV}^2$		Low-scale Non-Unitarity $\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$	
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
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$	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	$5.3 \cdot 10^{-2}$	

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

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

Present Bounds

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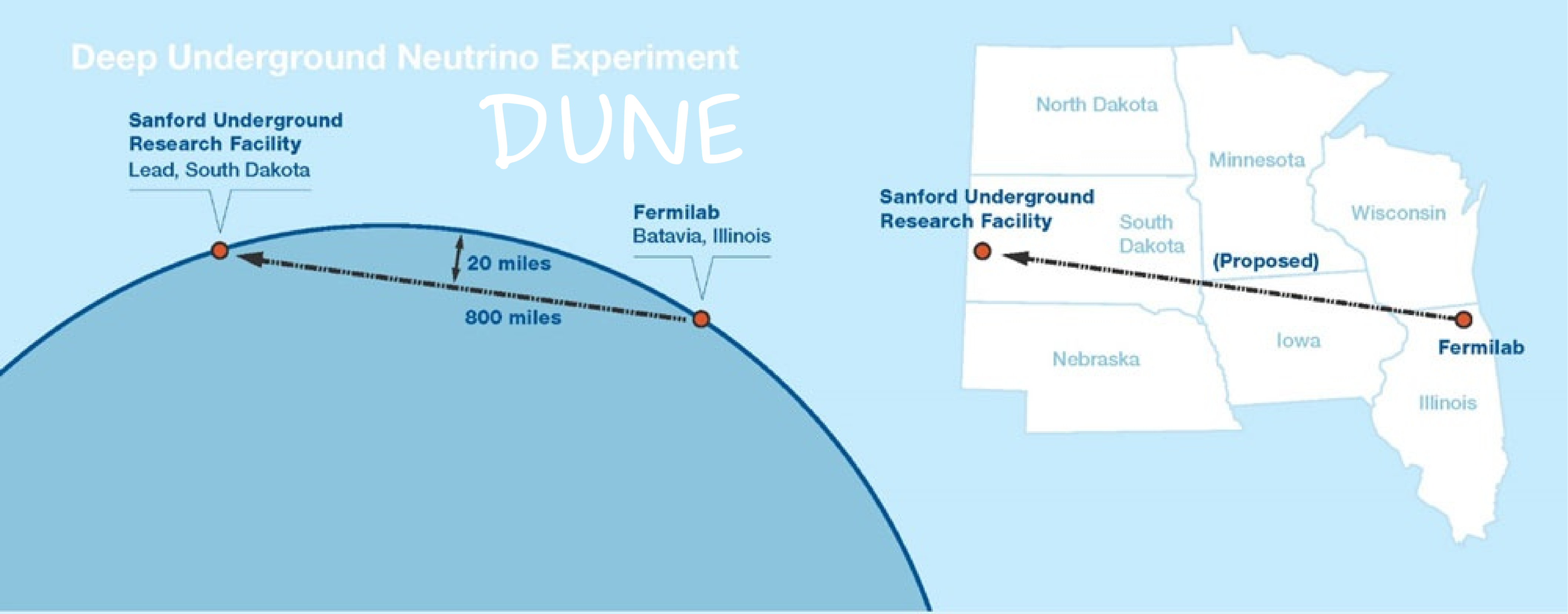
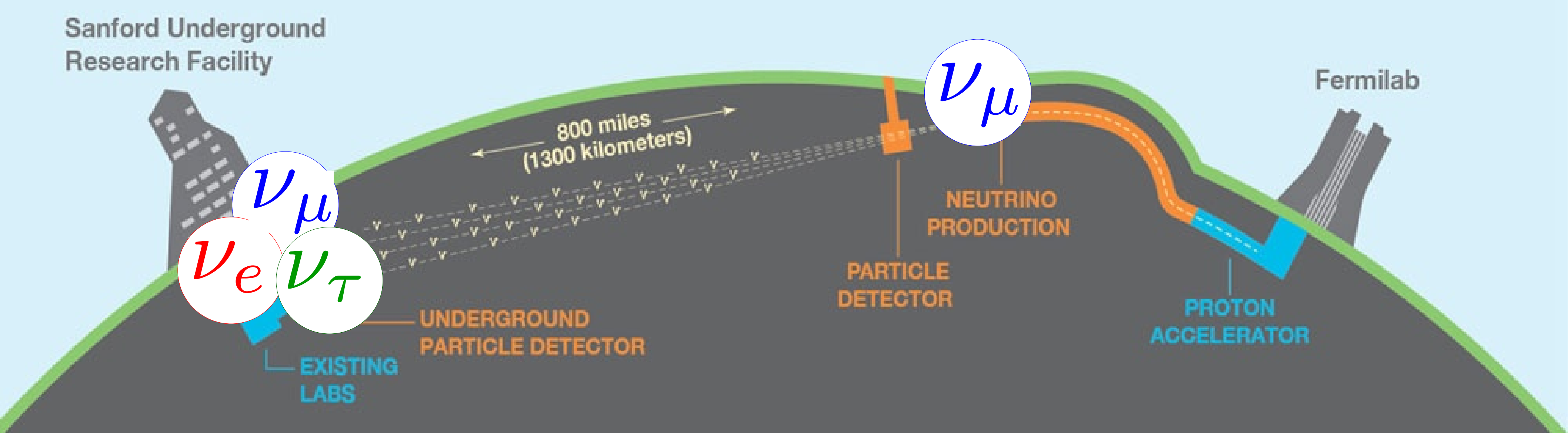
$\|\alpha_{\mu e}\|$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$	NOMAD	$1.7 \cdot 10^{-2}$	
$\|\alpha_{\tau e}\|$	$2.7 \cdot 10^{-3}$	~~$6.9 \cdot 10^{-2}$~~		~~$4.5 \cdot 10^{-2}$~~	
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	NOMAD	~~$5.3 \cdot 10^{-2}$~~	

AGNOSTIC

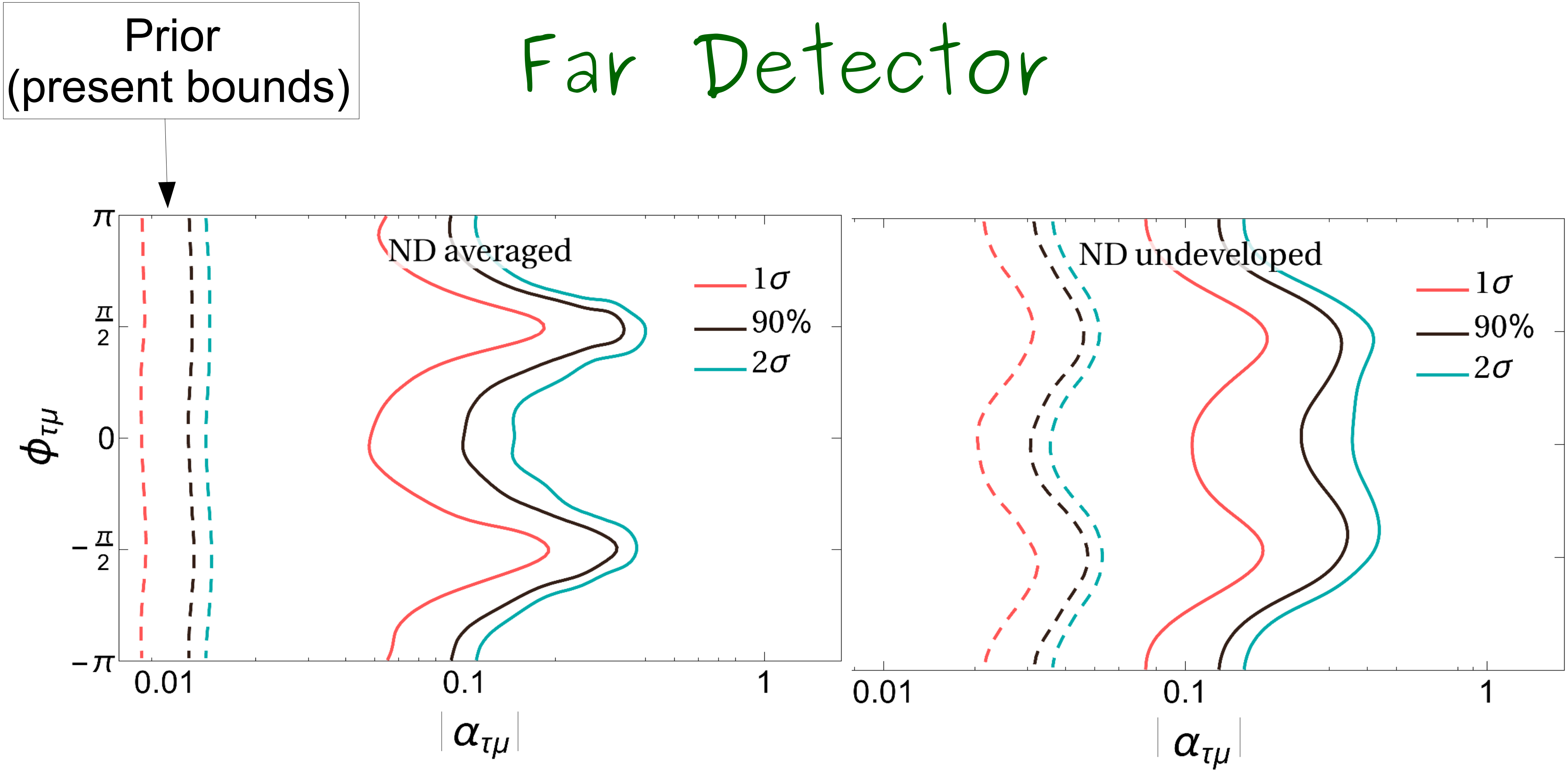
Fernandez-Martinez, Hernandez-Garcia, JLP 1605.08774
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

See also talk by Julia Gehrlein and
Park, Ross-Lonergan 1508.05095
Ellis, Kelly, Weishi Li 2004.13719
Ellis, Kelly, Weishi Li 2008.01088


Deep Underground Neutrino Experiment
DUNE
Sanford Underground Research Facility
Lead, South Dakota
Fermilab
Batavia, Illinois
20 miles
800 miles
North Dakota
Minnesota
Wisconsin
Sanford Underground Research Facility
South Dakota
(Proposed)
Iowa
Nebraska
Fermilab
Illinois


Sanford Underground Research Facility
Fermilab
800 miles (1300 kilometers)
ν_μ
ν_e
ν_τ
NEUTRINO PRODUCTION
PARTICLE DETECTOR
PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS

Far Detector

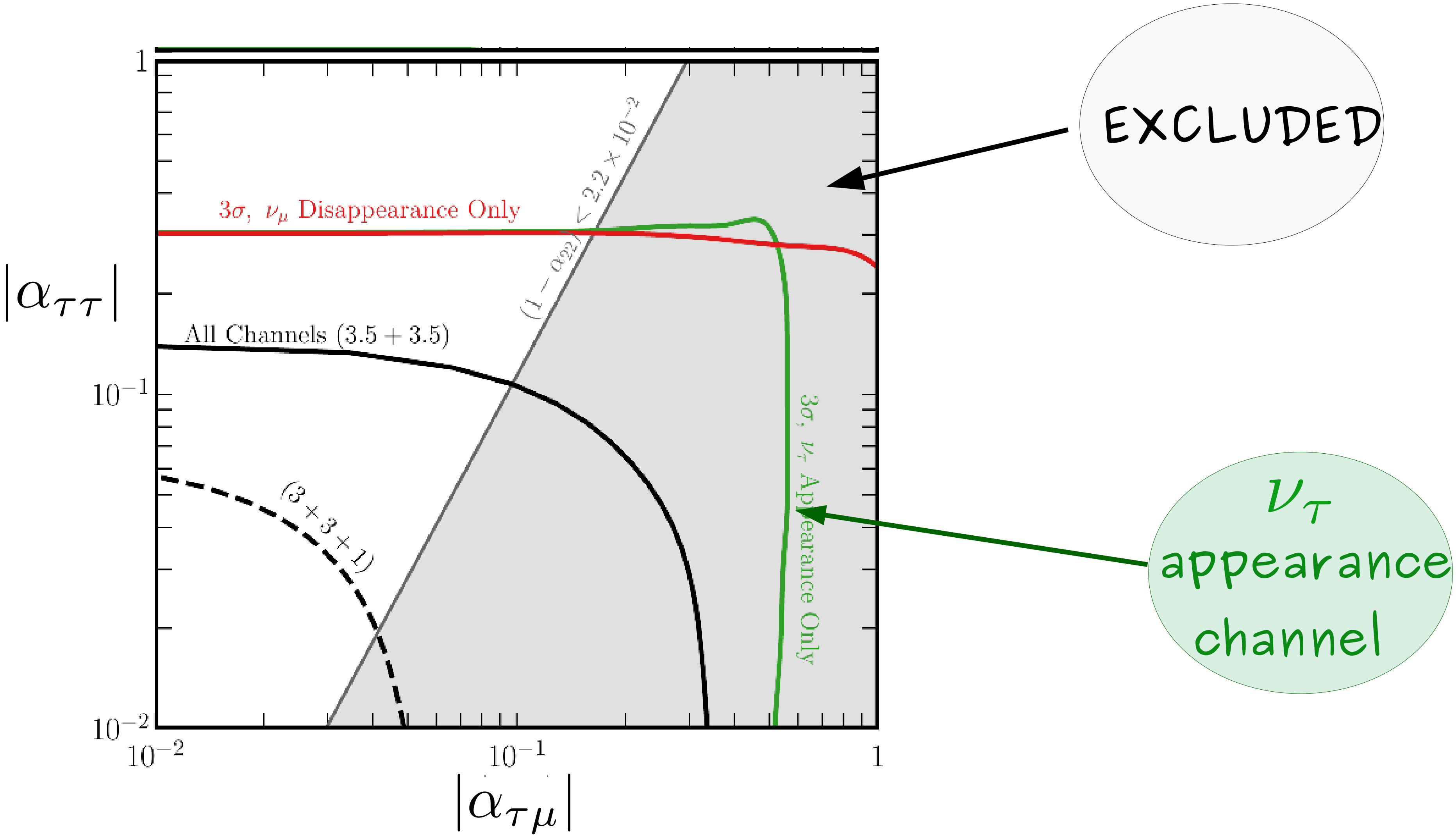


$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{\left[(NN^\dagger)_{\alpha\alpha}\right]^2}$$

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

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

Far Detector



- Including ν_τ appearance channel does not change the picture.

de Gouvêa, Kelly, Steni Pasquini 1904.07265

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 neutrino oscillation experiments

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

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 neutrino oscillation experiments

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

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

Averaged-out regime

- What is measured in neutrino oscillation experiments $\Delta m^2_{41} \gtrsim 100\,\mathrm{eV}^2$

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

zero distance effect!

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

Averaged-out regime

- What is measured in neutrino oscillation experiments $\Delta m^2_{41} \gtrsim 100\,\mathrm{eV}^2$

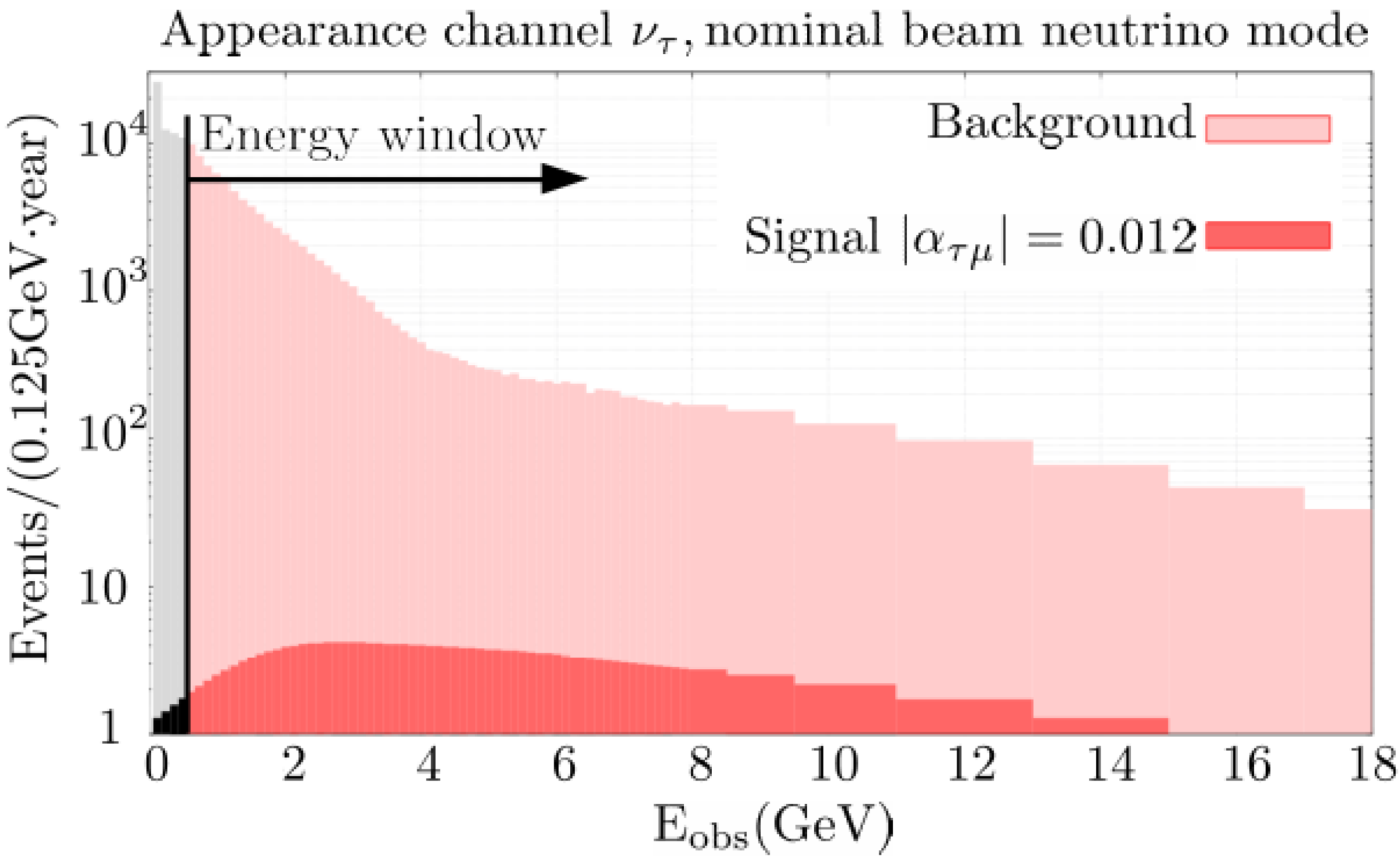
$$\mathcal{P}_{\alpha\beta} = 2|\alpha_{\alpha\beta}|^2$$

zero distance effect!

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

Low Scale Non-Unitarity

Role of shape uncertainty

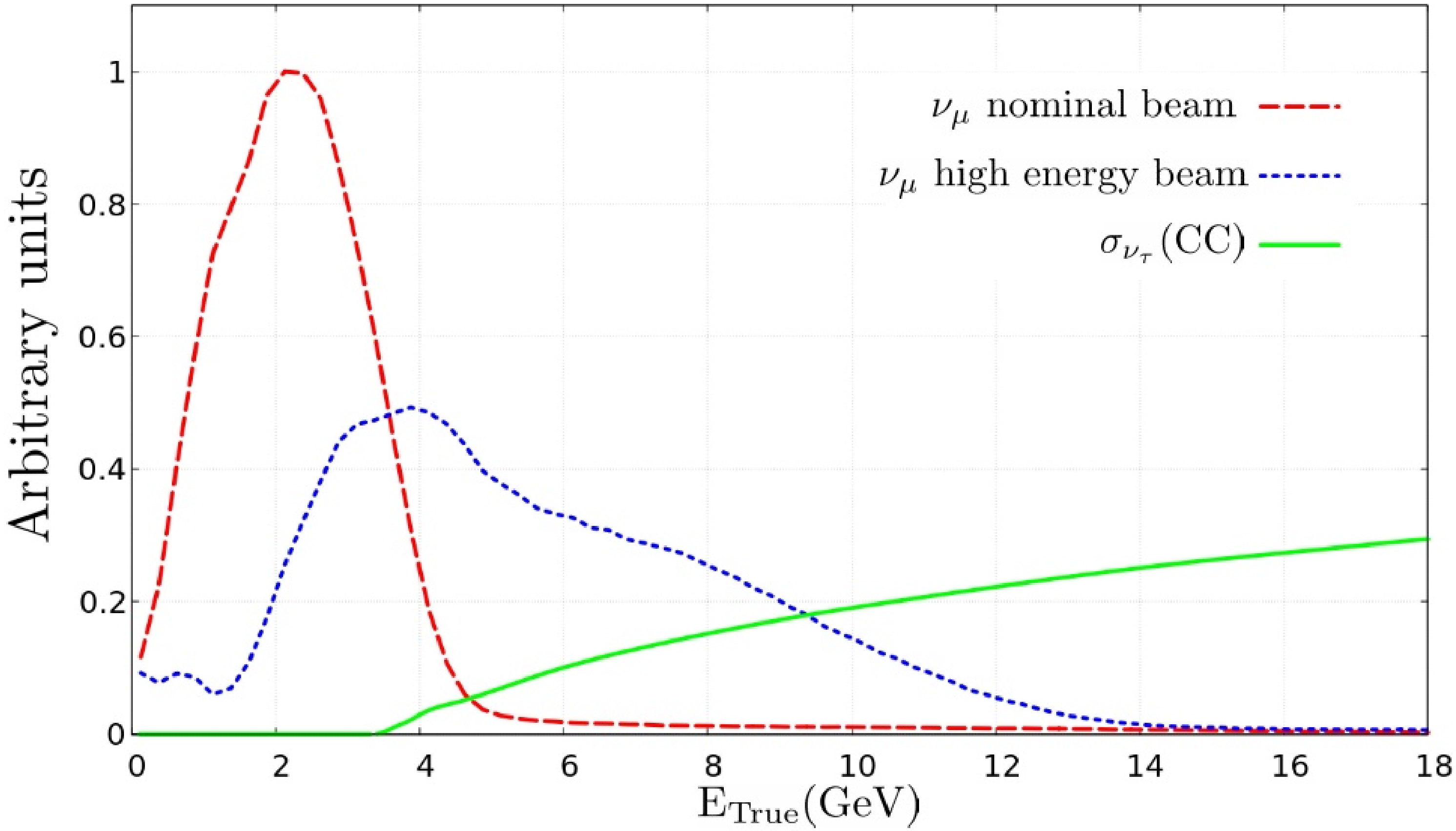


- Sensitivity driven by spectral information.
- Marginal impact of global normalization error.

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

ν_τ appearance channel

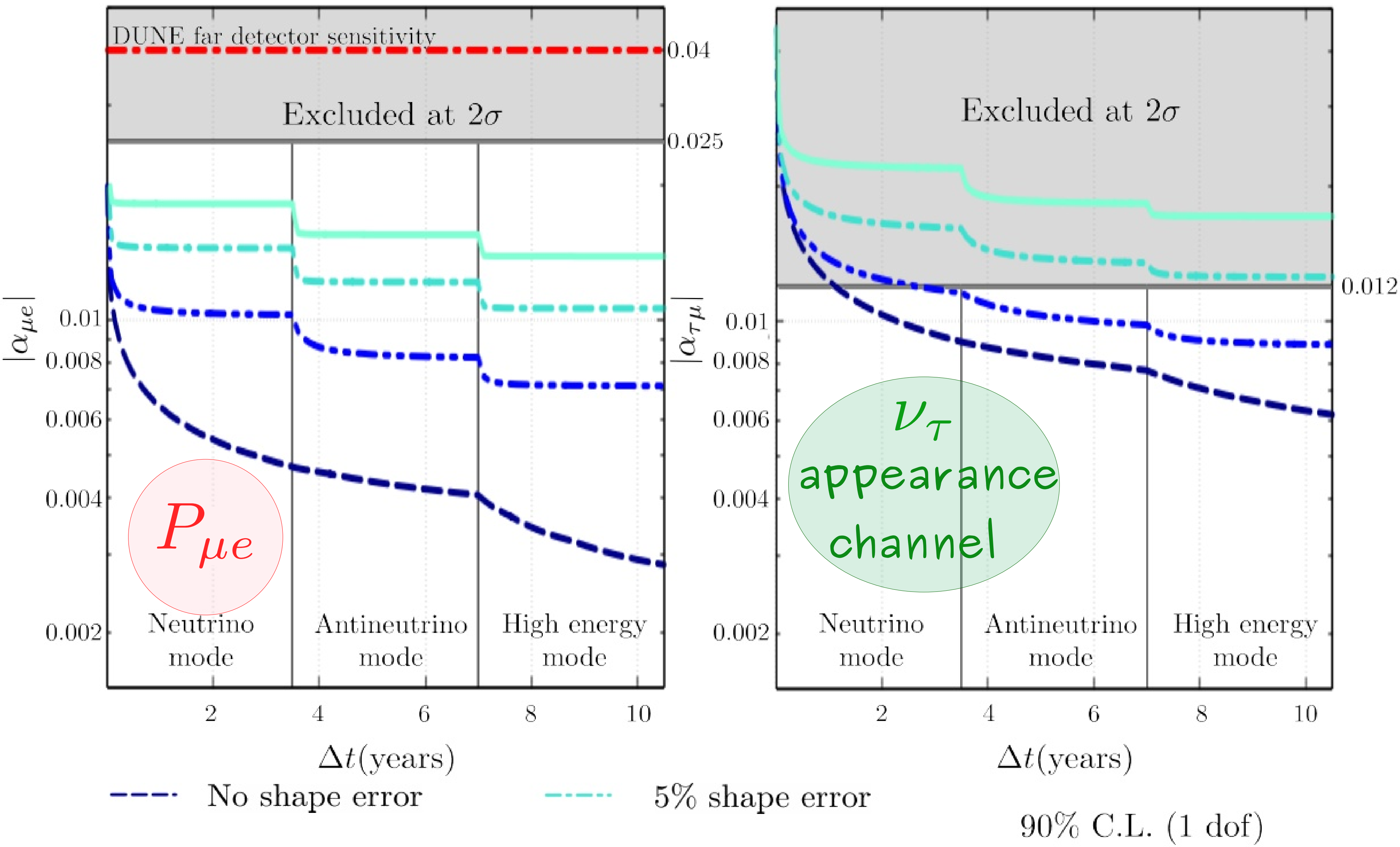
- Energy threshold of τ production 3.2 GeV.



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

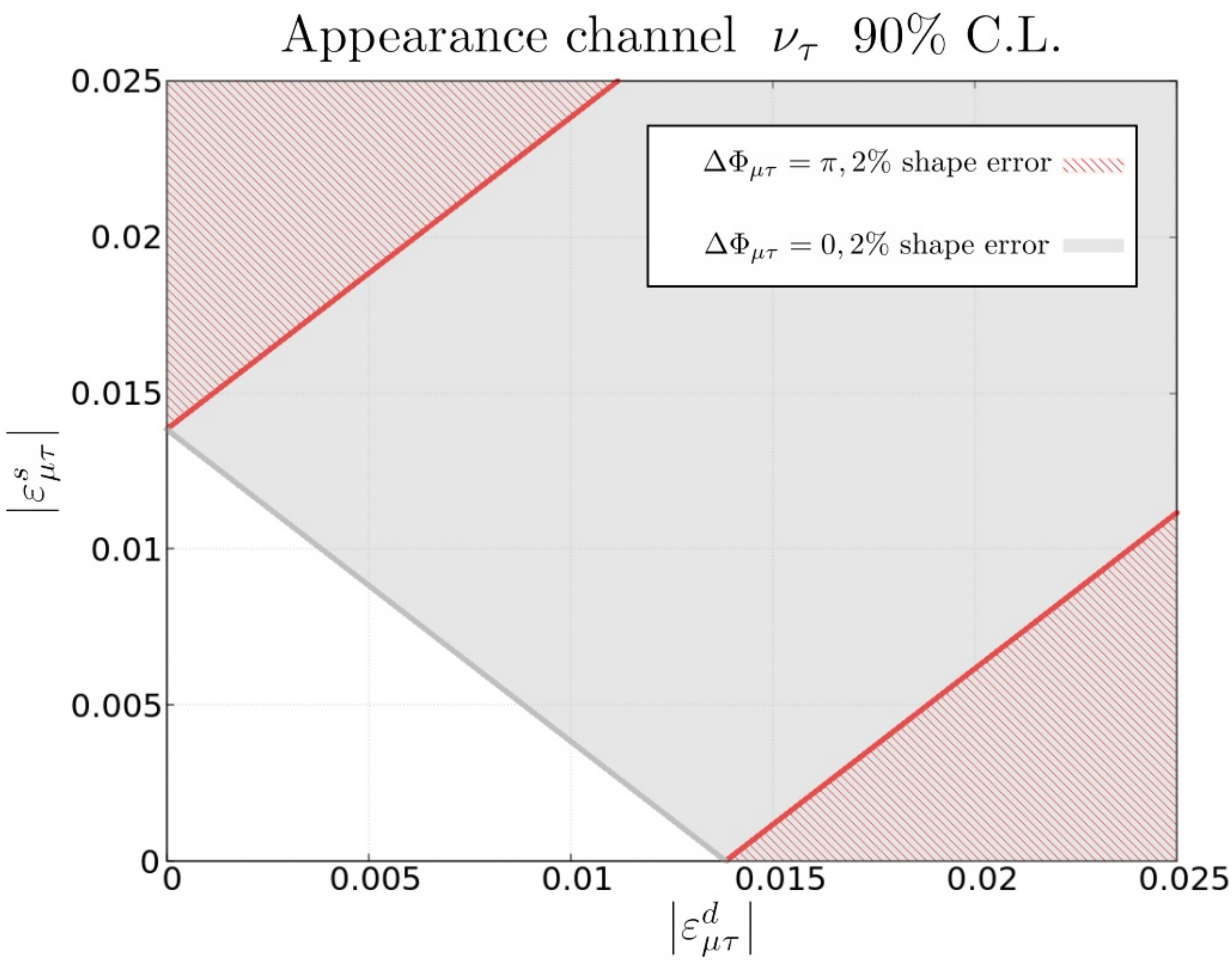
See talks by Pedro Machado, Adam Aurisano, Roger Wendell, Thomas Kosc, Dawn Williams, Dario Autiero, Juliana Stachurska

Low Scale Non-Unitarity



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

NSI in production/detection

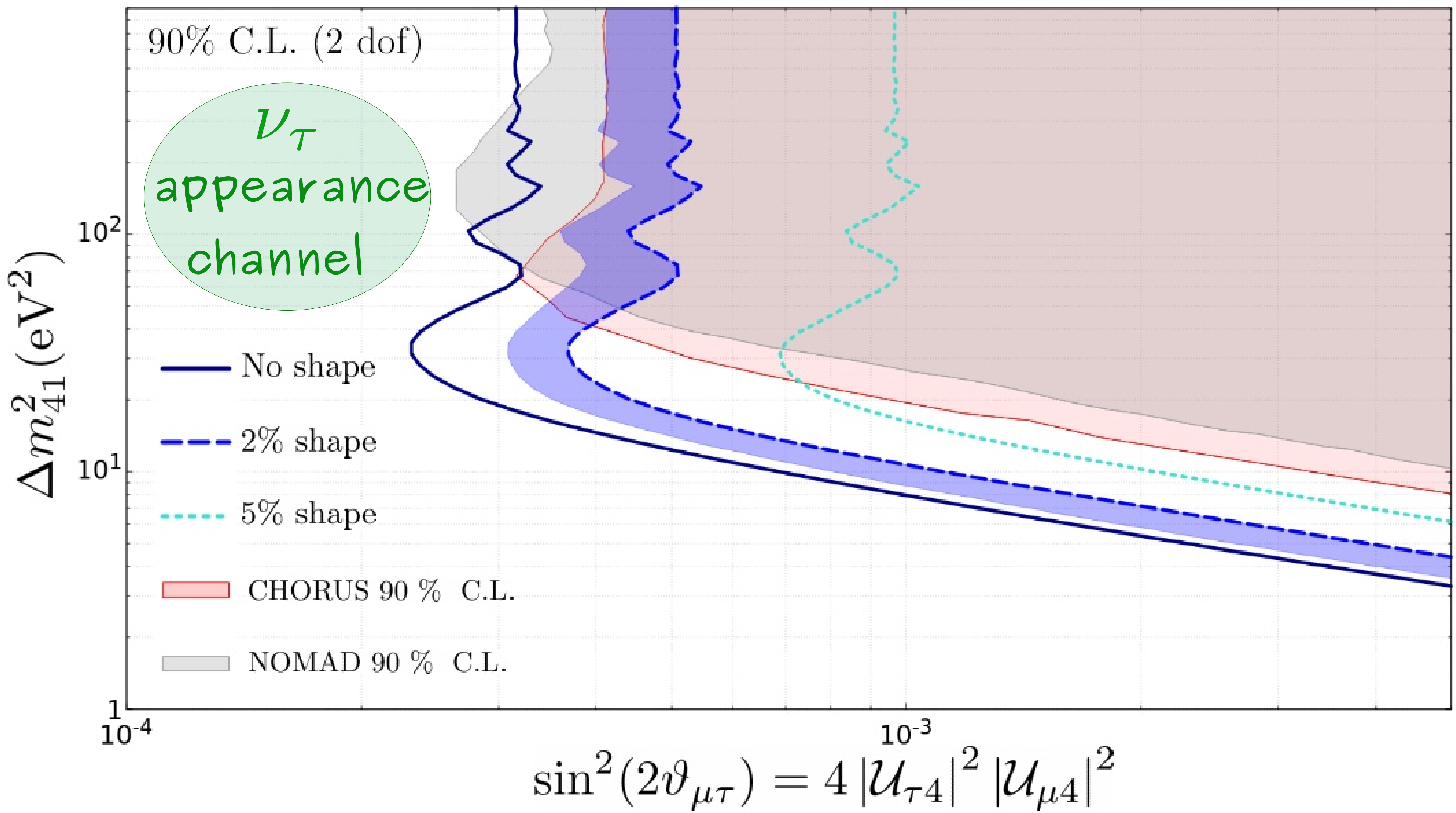


ν_τ appearance channel

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

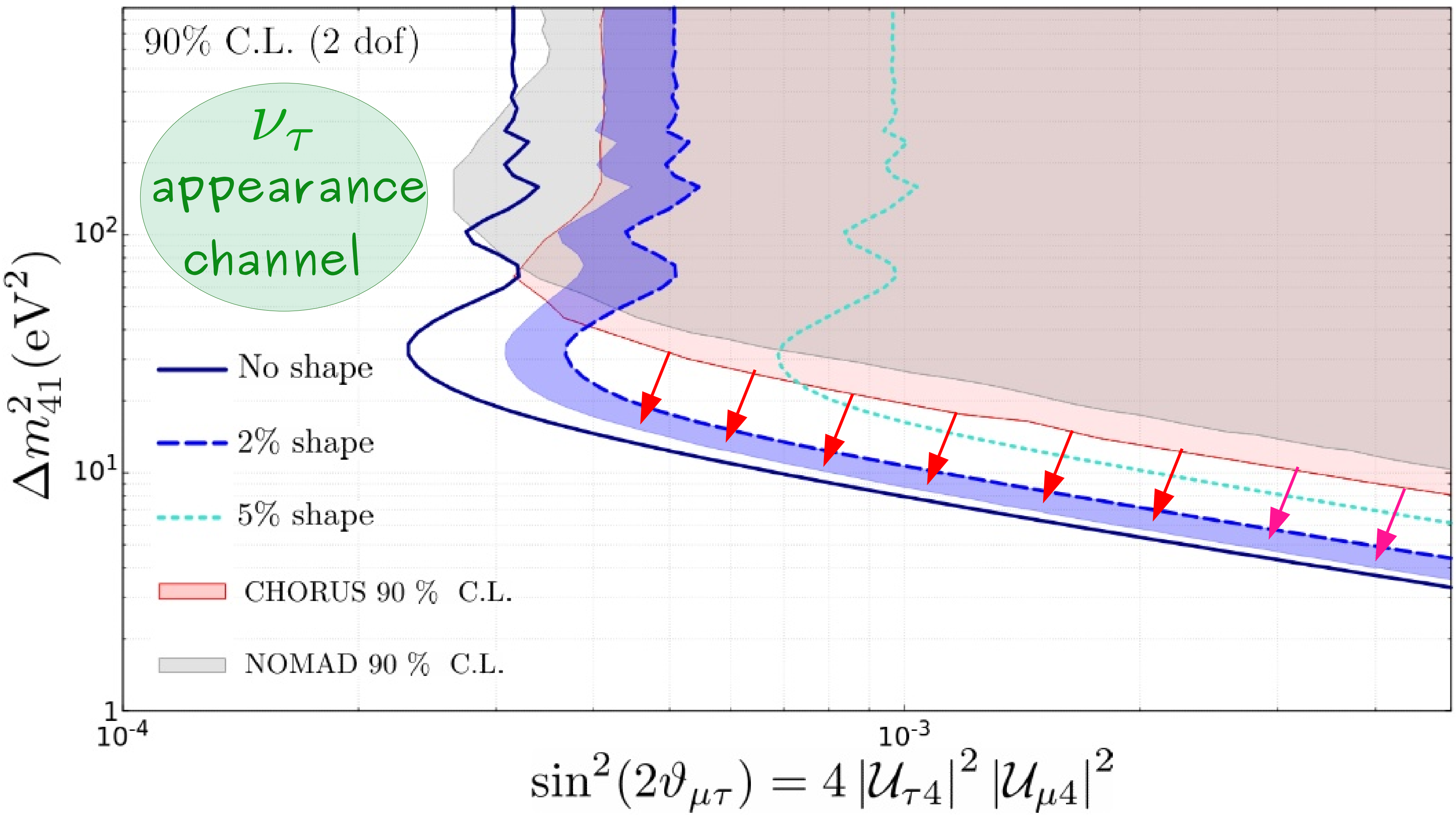
- Mapping: $2|\alpha_{\beta\gamma}|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma})$

3+1 Sterile Neutrinos

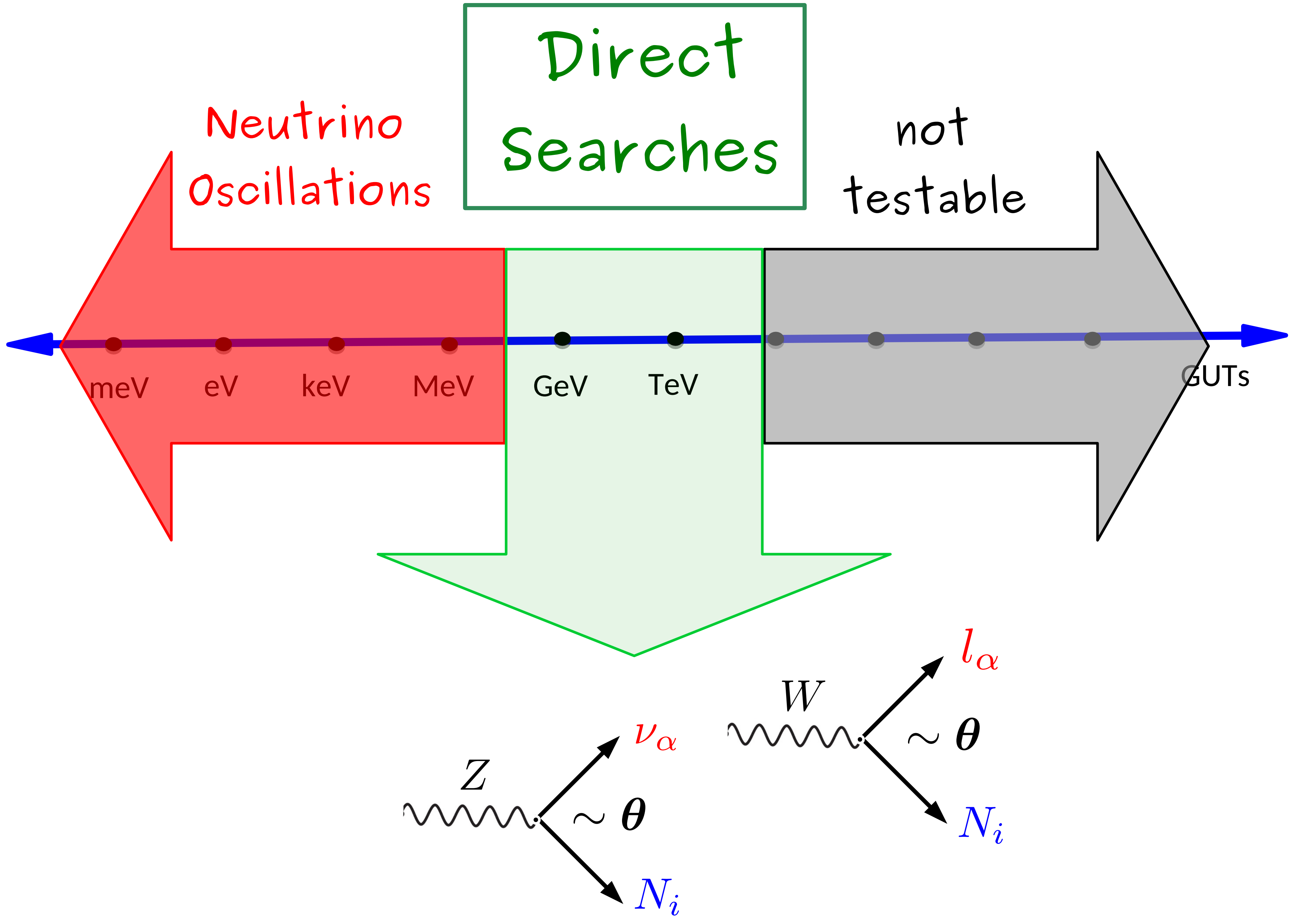


Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

3+1 Sterile Neutrinos



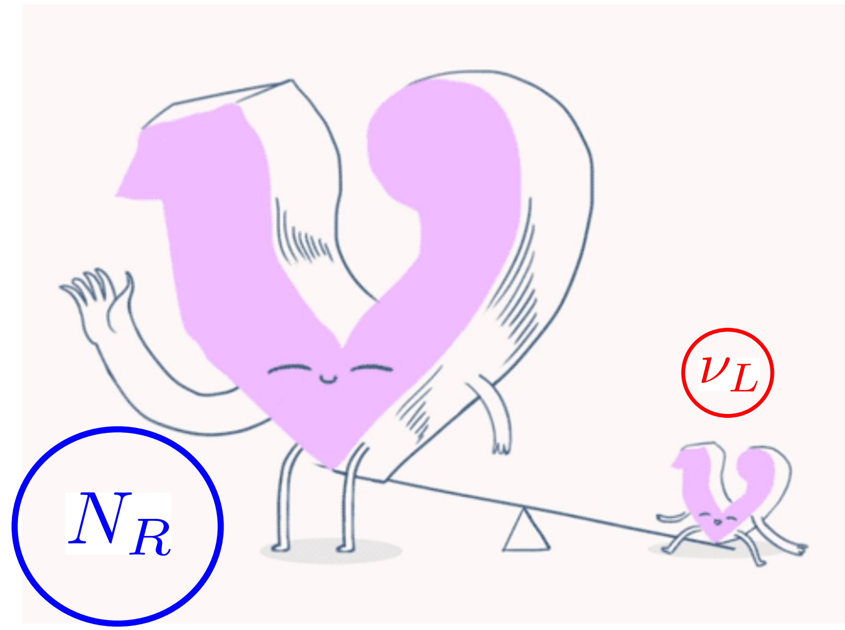
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466



Direct Searches
Neutrino Oscillations
not testable
meV
eV
keV
MeV
GeV
TeV
GUTs
Z
ν_α
$\sim \boldsymbol{\theta}$
N_i
W
l_α
$\sim \boldsymbol{\theta}$
N_i

Light Neutrino mass generation

- Generation of light neutrino masses imposes **constraints on mixing between HNLs and active neutrinos from *light neutrino sector***

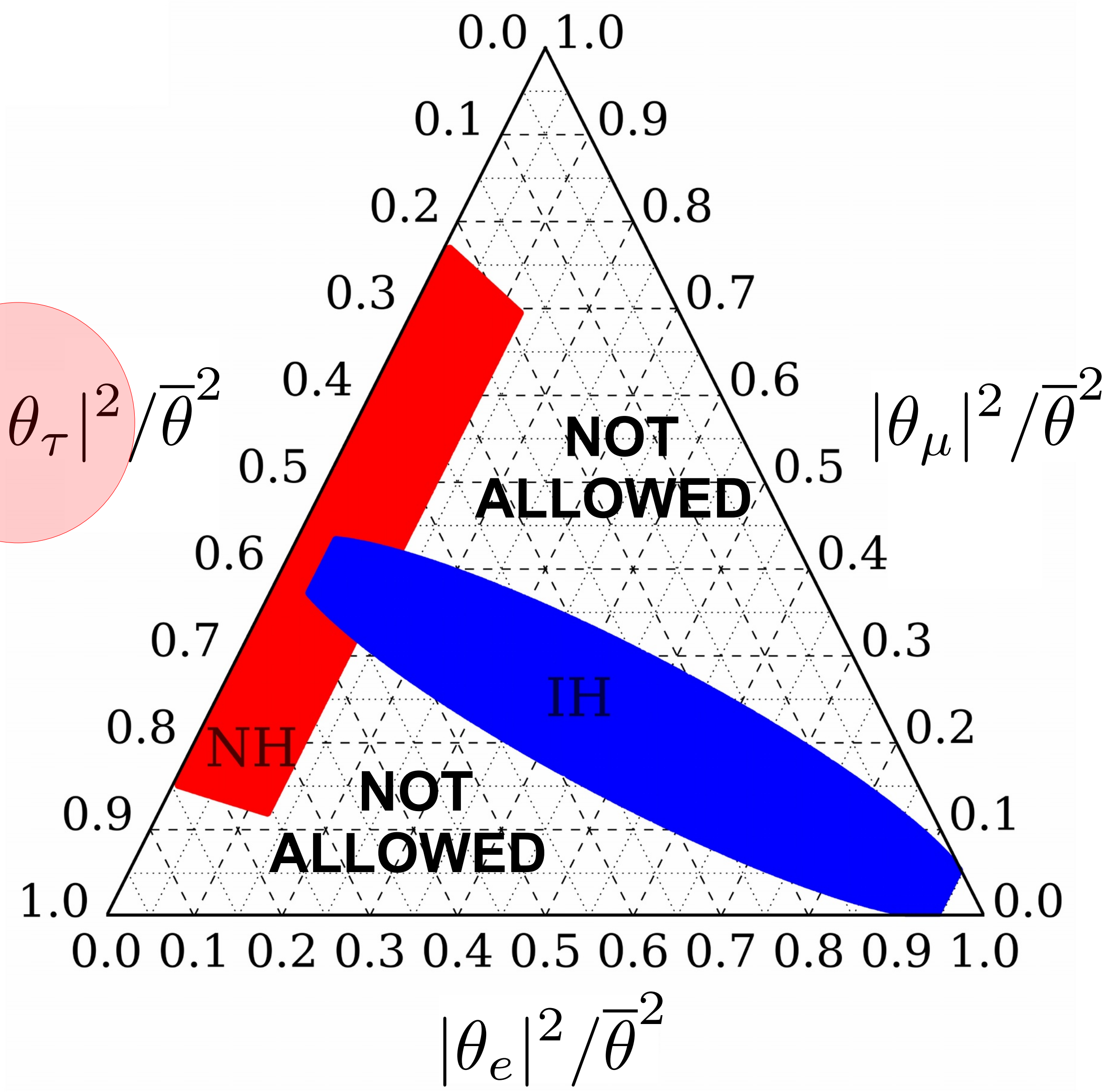


$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y = \theta\, M\, \theta^T = U\, m\, U^T$$

HNL sector

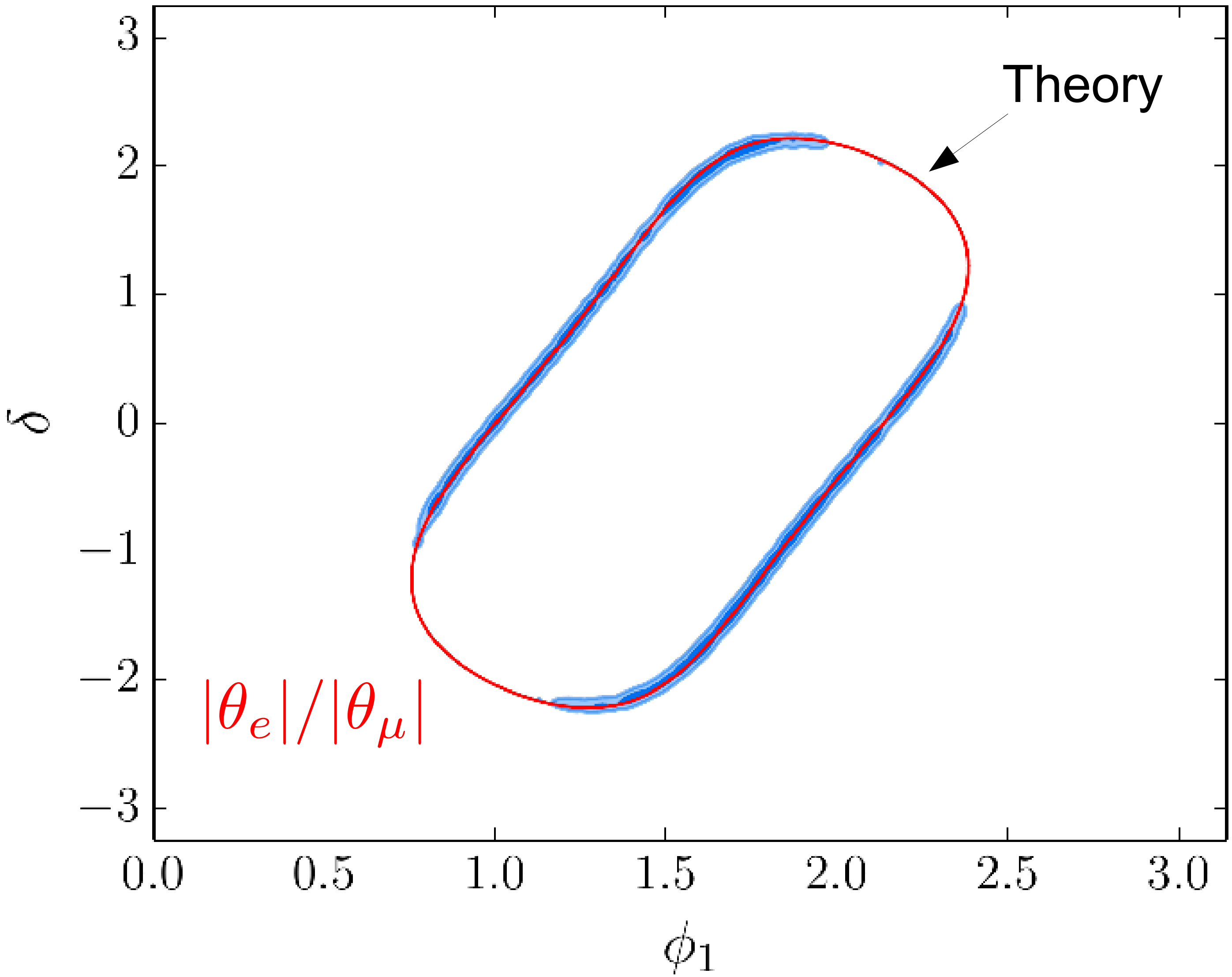
Light-active neutrino sector

Minimal model $N_R=2$: Flavor Structure



Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

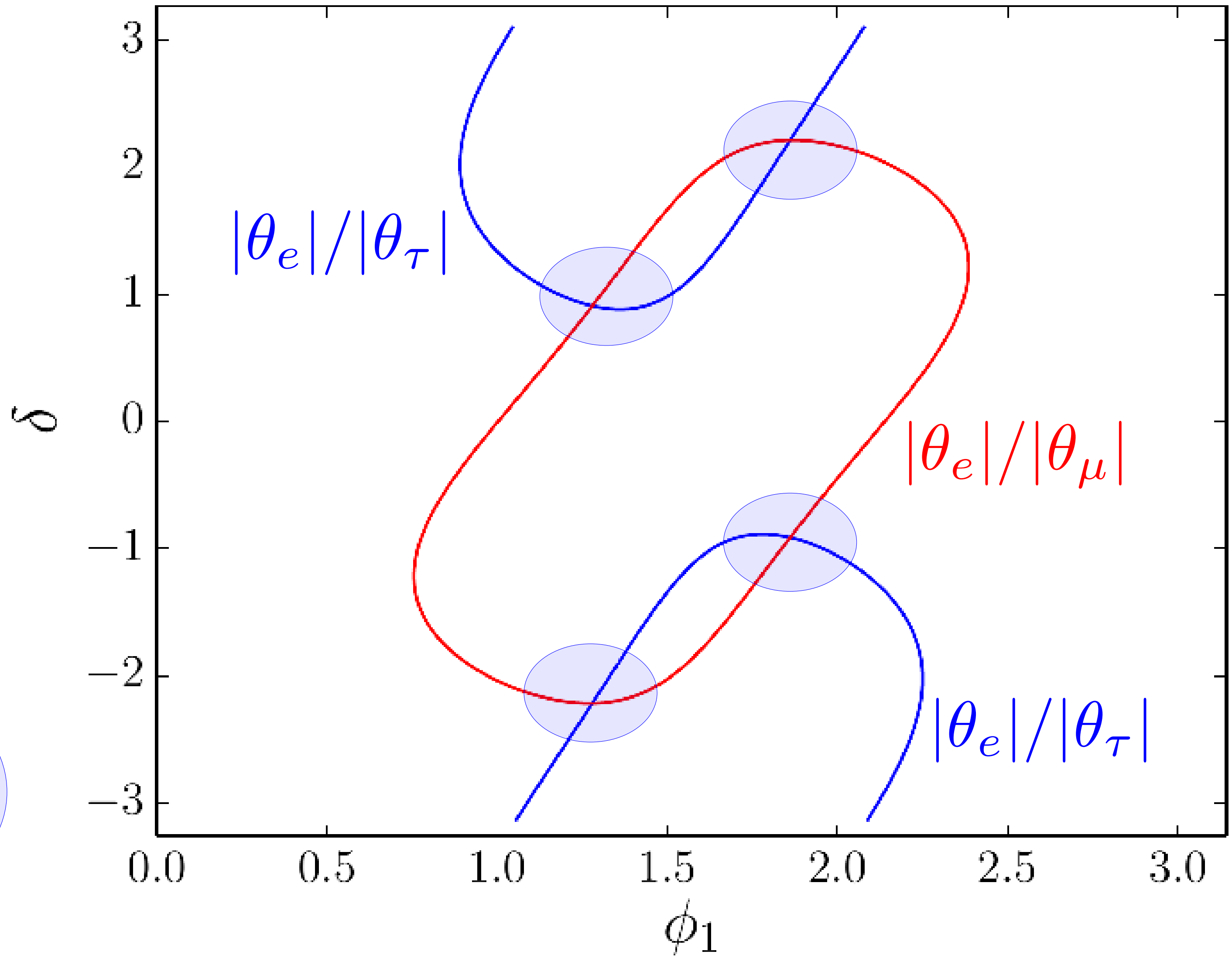
PMNS CP-phases from HNLs searches



$N_R = 2$

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

PMNS CP-phases from HNLs searches

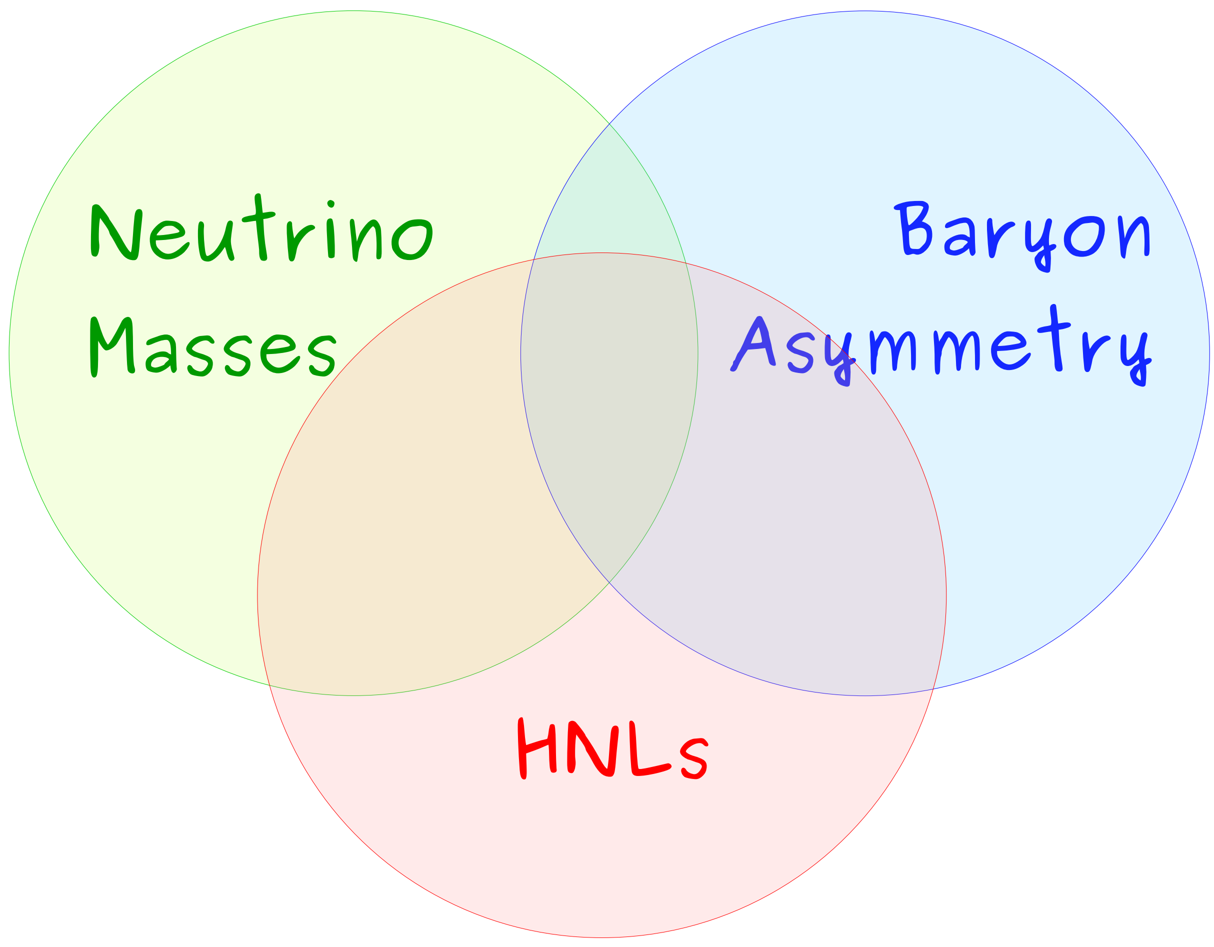


$N_R = 2$

- **Measurement of mixing with tau neutrinos would allow to break degeneracies!**

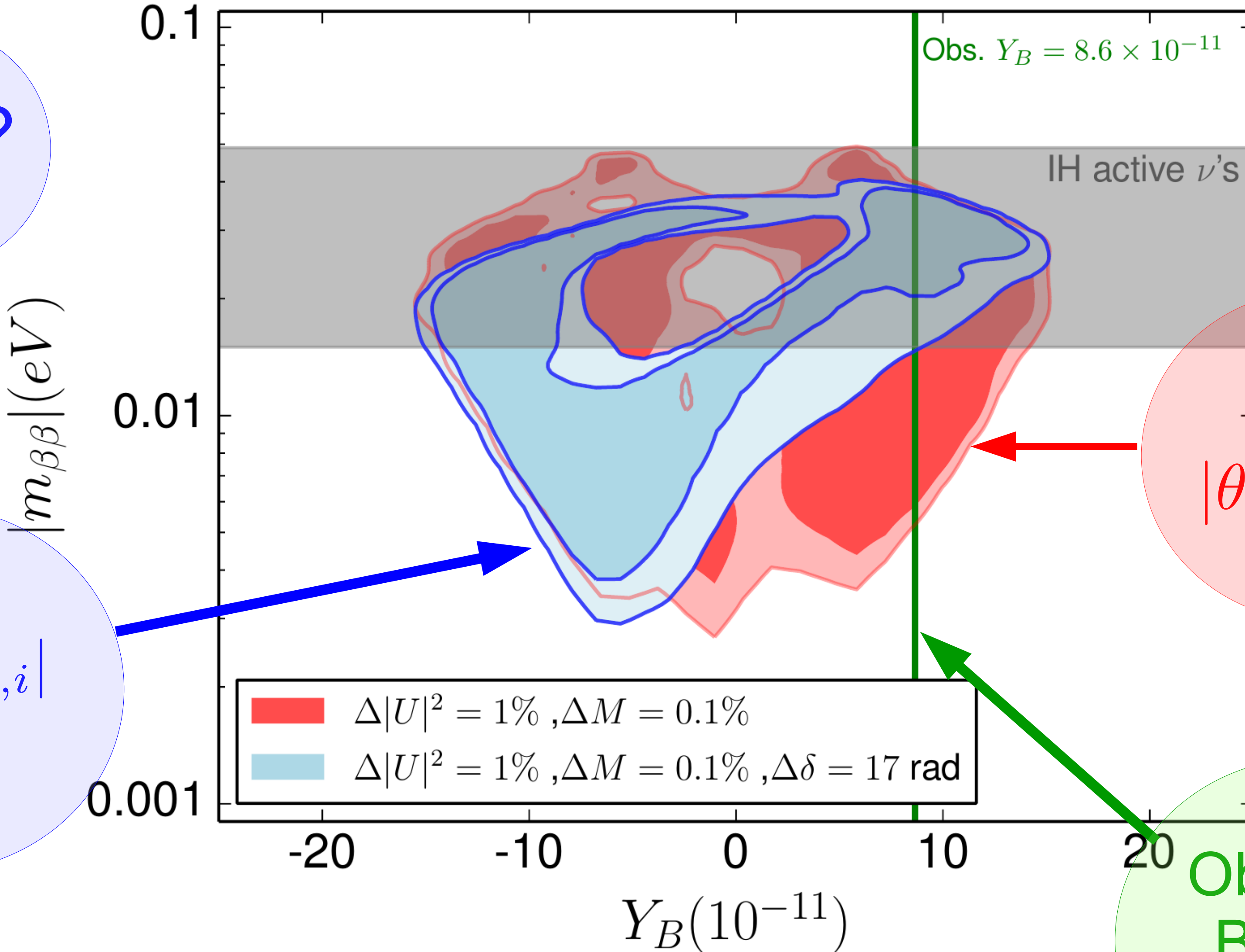
Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Very relevant input to leptogenesis



GeV Scale Leptogeneis $N_R=2$

$|\theta_{\tau i}|$?



SHiP
$|\theta_{ei}|, |\theta_{\mu i}|$

SHiP
$|\theta_{ei}|, |\theta_{\mu,i}|$
+
δ

Observed Baryon asymmetry

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Conclusions

- ν_τ detection can play a relevant role in testing the robustness of the 3-neutrino picture
(low scale Non-Unitarity, sterile neutrino oscillations, NSI…)

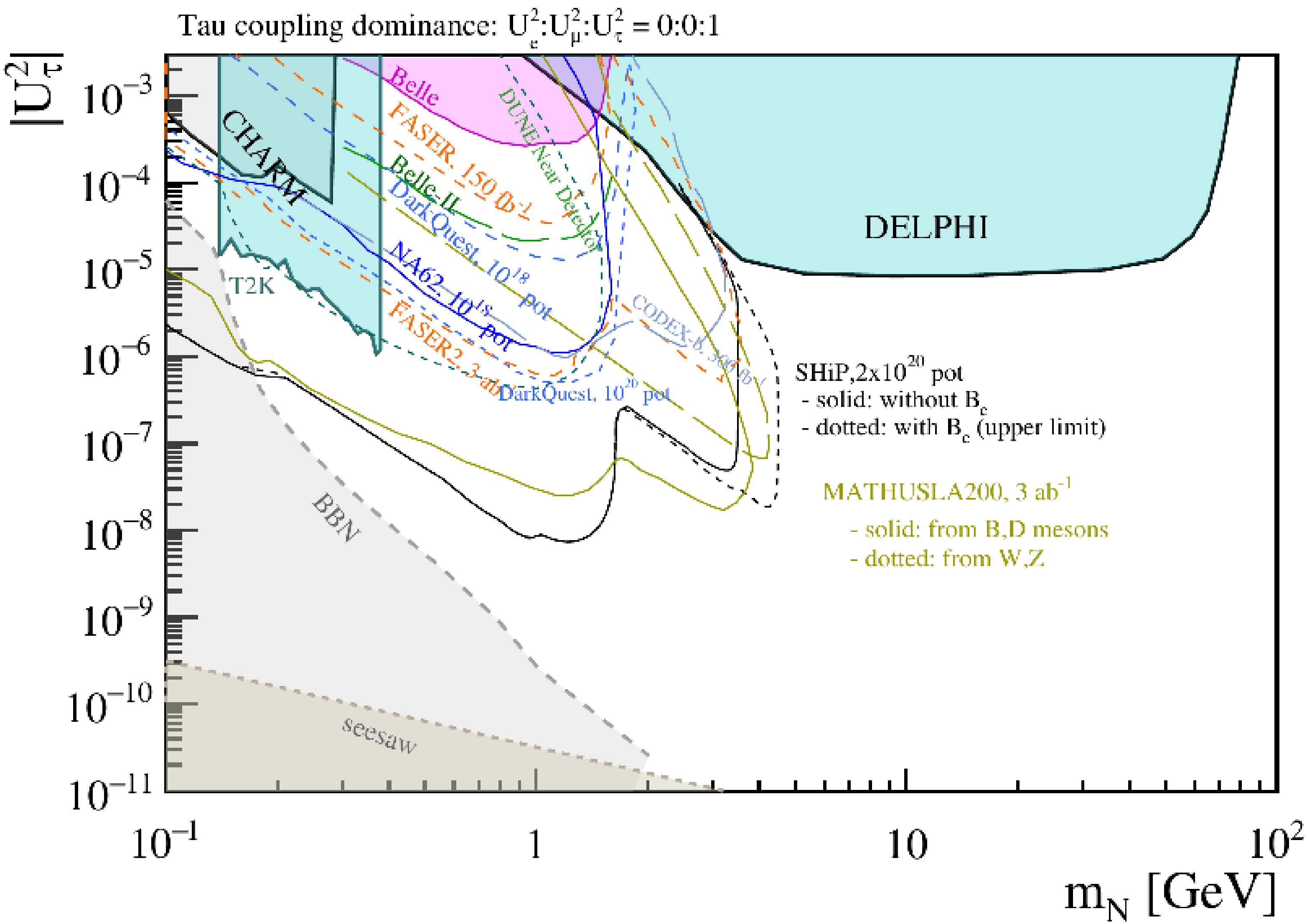
- Measurement of HNL tau mixing would allow to
test low scale minimal neutrino mass model
and to indirectly measure the PMNS phases (including Majorana phase!!) in this framework: very relevant input for testing Leptogenesis!

- More opportunities expected in non minimal scenarios, experiments and observables not considered in this talk.

Stay tuned for the rest of the workshop!

Thank you!

Direct Searches of HNLs



- τ mixing less constrained than mixing with μ, e
- **Window for New Physics signal at GeV scale**

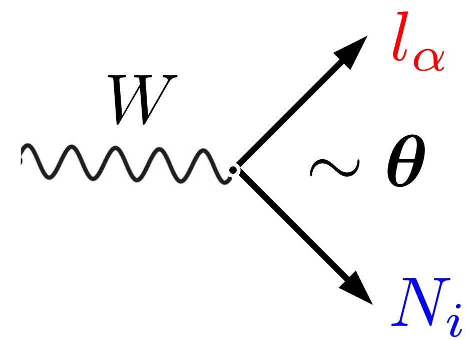
Feebly-Interacting Particles:FIPs 2020 Workshop 2102.12143

Direct searches of HNLs

Casas
Ibarra

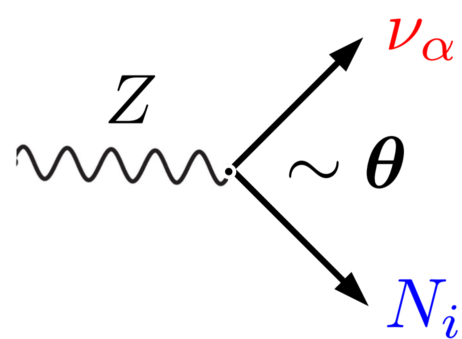
$$\boldsymbol{\theta} = \boxed{i U_{PMNS}\, m^{1/2}}\ \boxed{R^\dagger M^{-1/2}}$$

Light Sector Heavy Sector



- Direct detection requires:

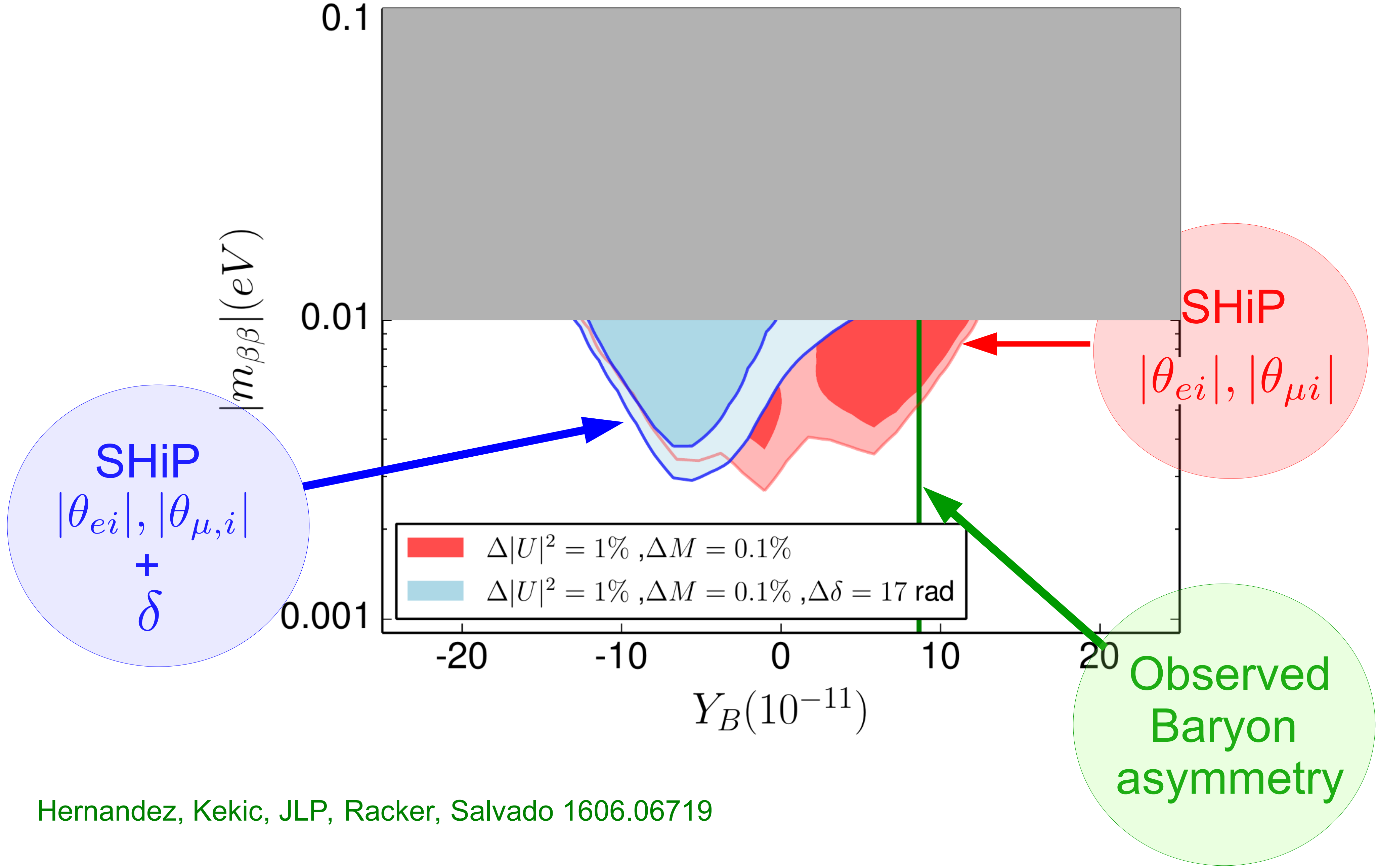
$$\theta \gg \sqrt{m/M} \iff \boldsymbol{R_{ij} \gg 1}$$



- Phenomenological constraint automatically satisfied in inverse and direct seesaw realizations based on a symmetry protected scenario.

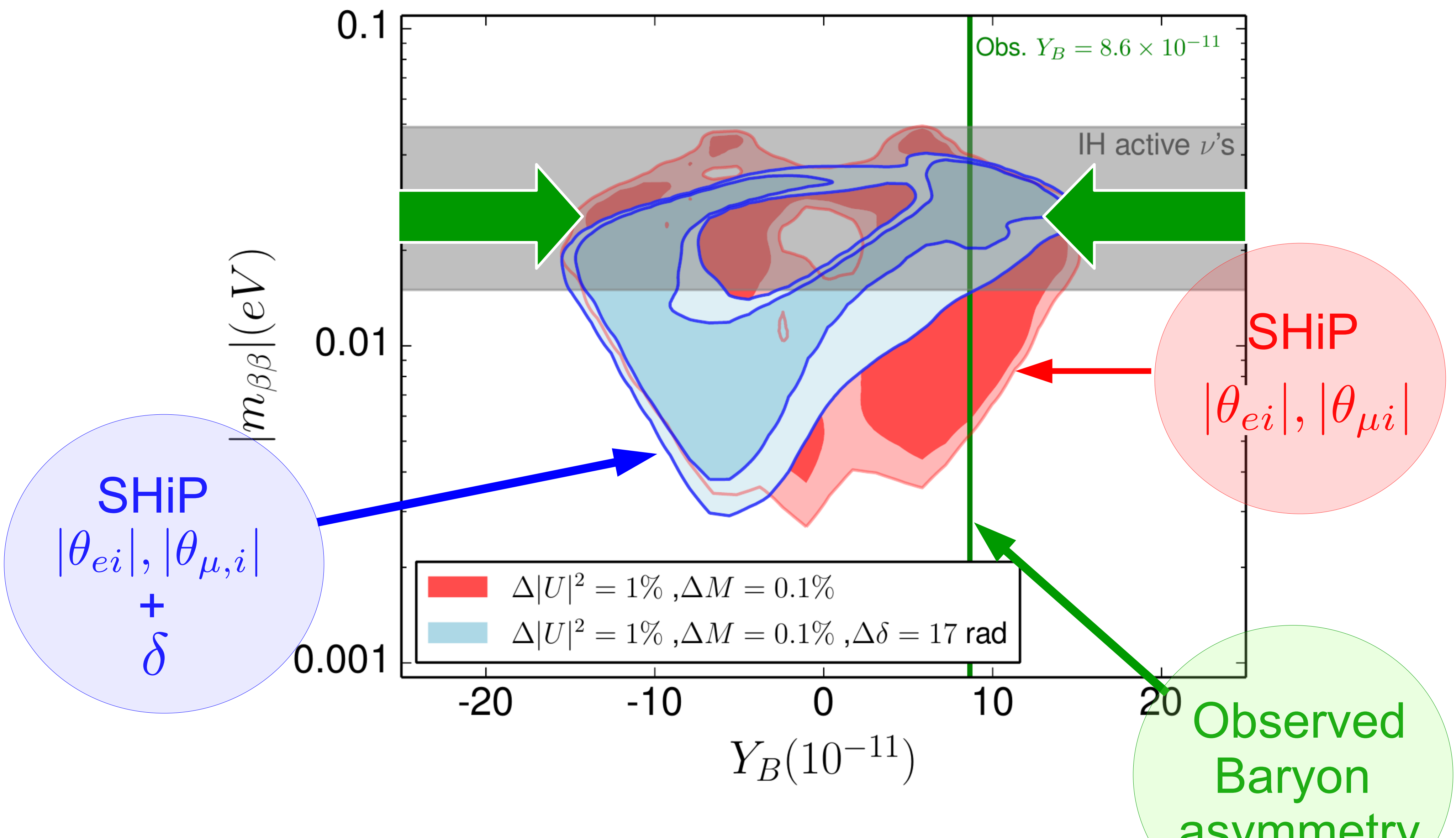
Mohapatra 1986; Mohapatra, Valle 1986; Bernabeu, Santamaria, Vidal, Mendez, Valle 1987; Malinsky, Romao, Valle 2005...

GeV Scale Leptogeneis $N_R = 2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

GeV Scale Leptogeneis $N_R=2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

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

See talks by Pedro Machado & Adam Aurisano

DUNE set up

Globes files

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

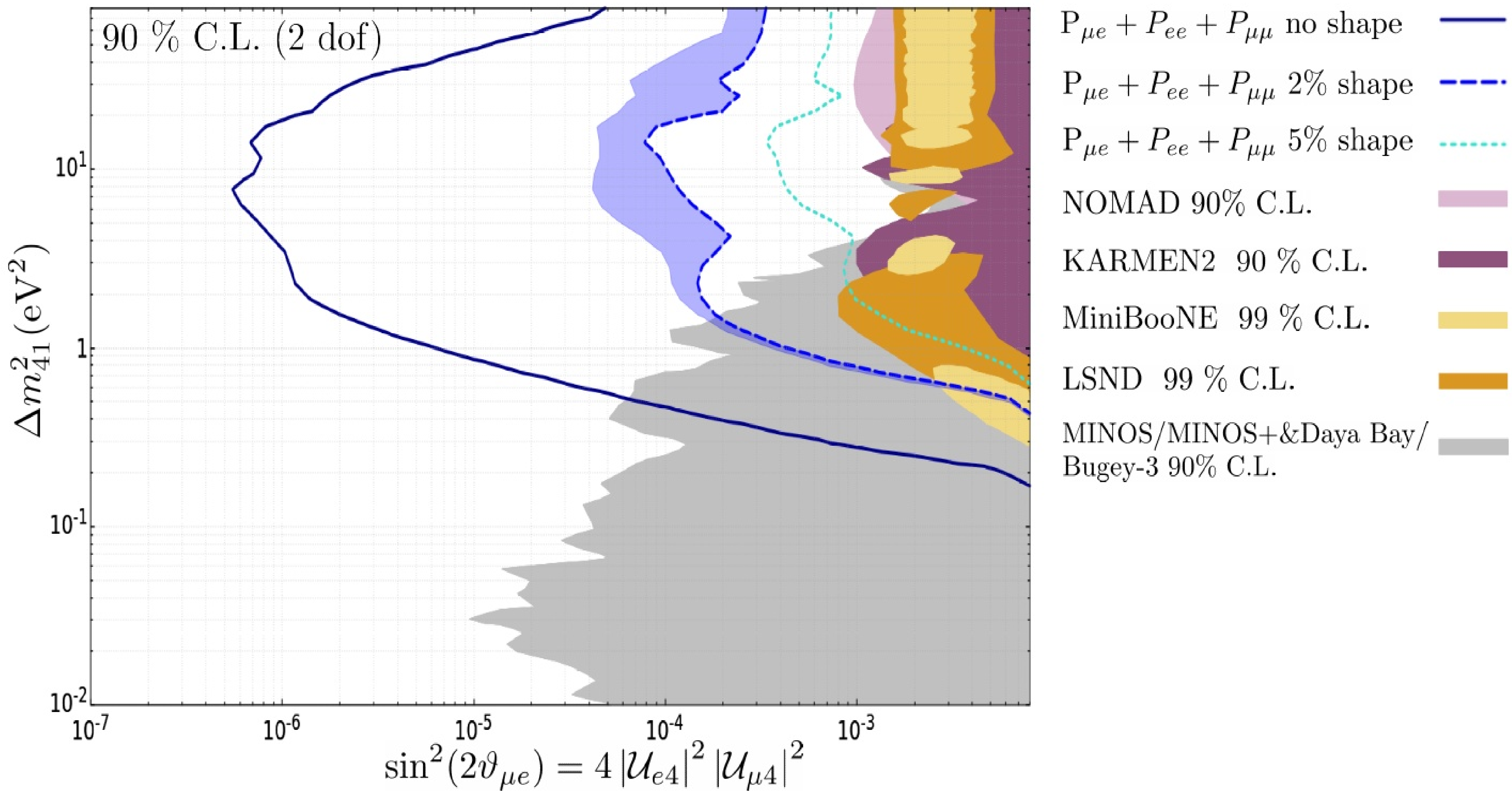
Flux configuration

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

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

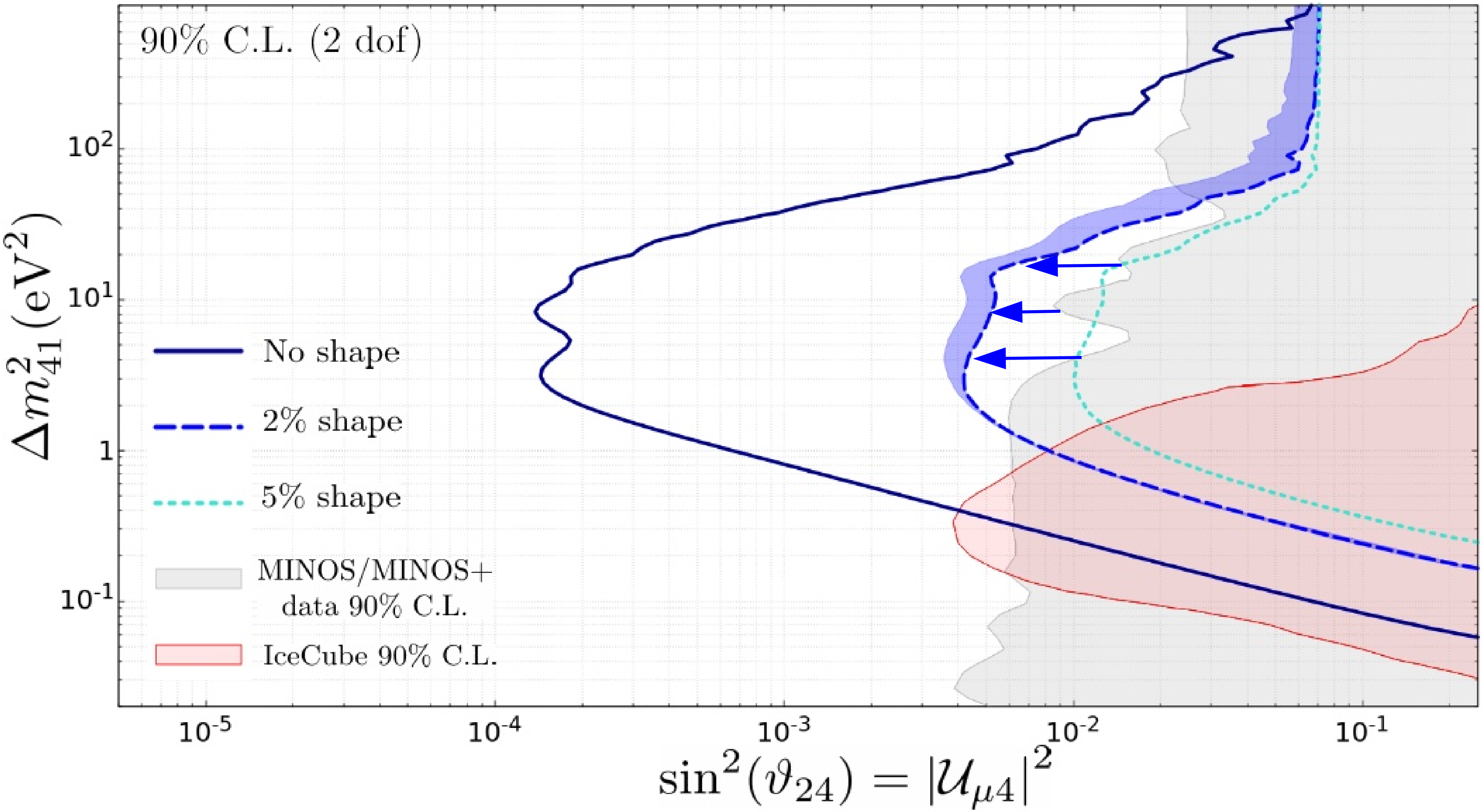
Event sample	Contribution	Benchmark 1		Benchmark 2		Benchmark 3	
		σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}
ν_e-like	Signal	5%	–	5%	–	5%	–
	Intrinsic cont.	10%	–	10%	2%	10%	5%
	Flavor mis-ID	5%	–	5%	2%	5%	5%
	NC	10%	–	10%	2%	10%	5%
ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC (signal)	10%	–	10%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

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



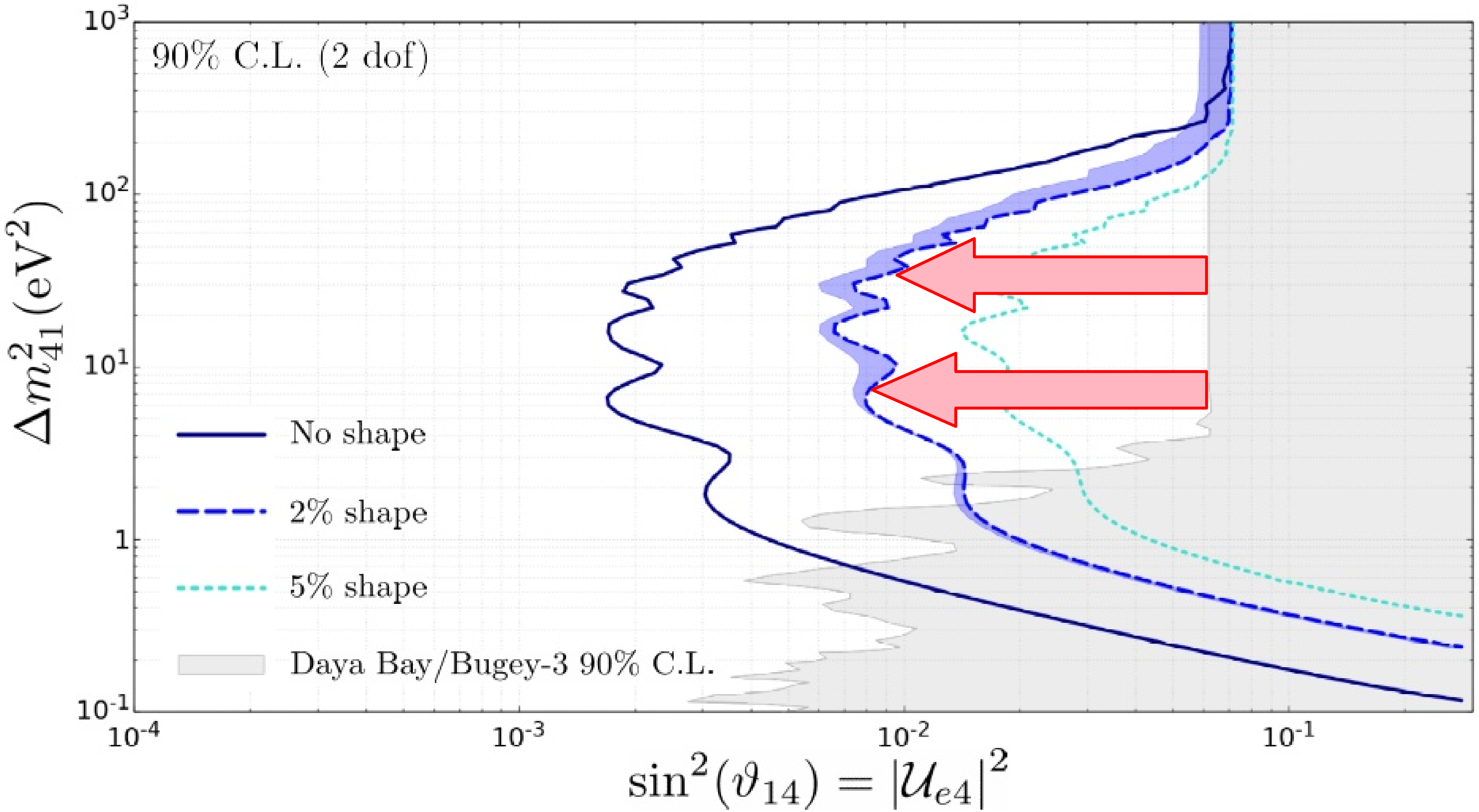
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

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



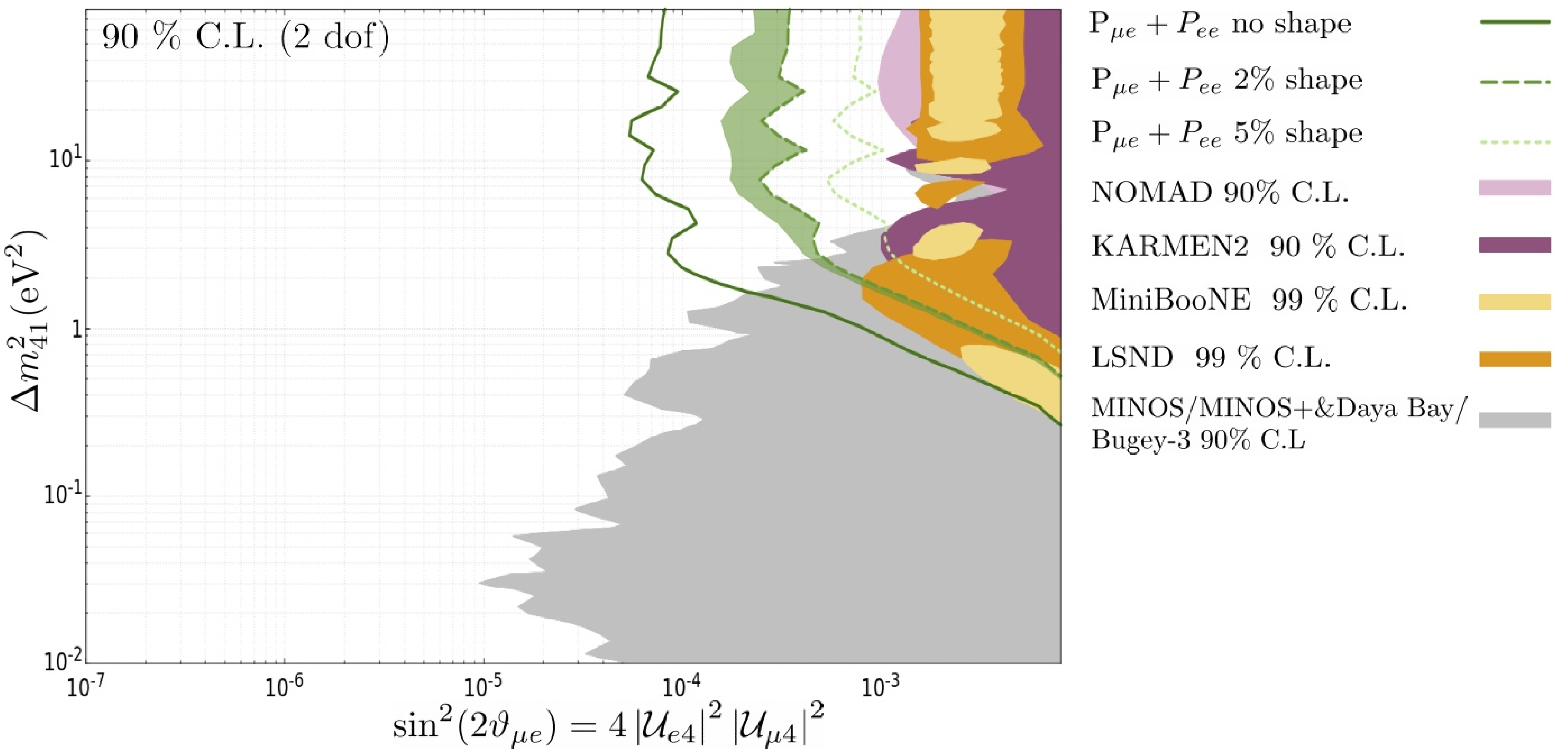
Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

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

PMNS CP-phases from HNLs searches

- For instance, **SHiP and FCC-ee** can measure HNLs parameters:

$$M_1, M_2, |\theta_{ei}|, |\theta_{\mu i}|$$

Sensitivity to PMNS CP-phases! δ, ϕ_1

- $|\theta_{e1}|^2/|\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2/|\theta_{\mu 2}|^2 \simeq$

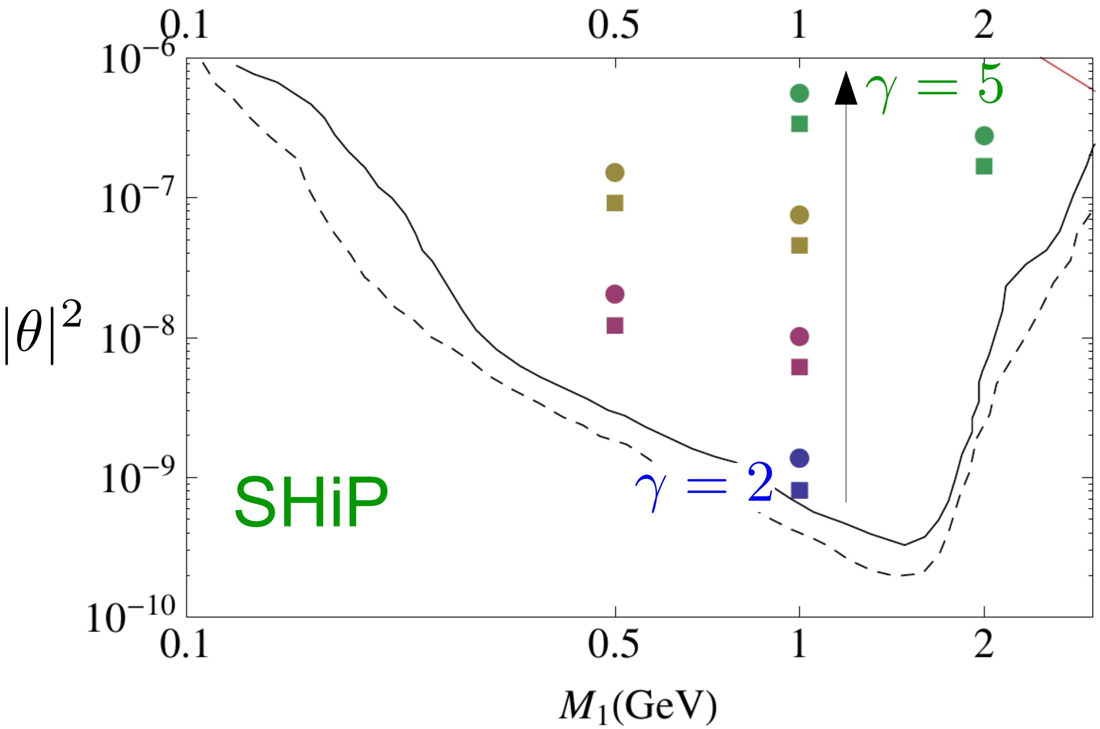
$$\frac{(1 + s_{\phi_1} \sin 2\theta_{12})(1-\theta_{13}^2) + \frac{1}{2} r^2 s_{12}(c_{12} s_{\phi_1} + s_{12})}{\left(1 - \sin 2\theta_{12} s_{\phi_1} \left(1 + \frac{r^2}{4}\right) + \frac{r^2 c_{12}^2}{2}\right) c_{23}^2 + \theta_{13}(c_{\phi_1} s_\delta - \cos 2\theta_{12} s_{\phi_1} c_\delta) \sin 2\theta_{23} + \theta_{13}^2 (1 + \sin 2\theta_{12}) s_{23}^2 s_{\phi_1}}$$

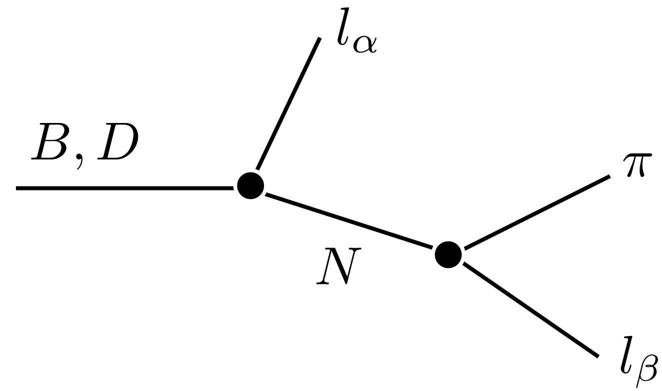
- $|\theta_{ei}|^2, |\theta_{\mu i}|^2 \propto e^{2\gamma}$

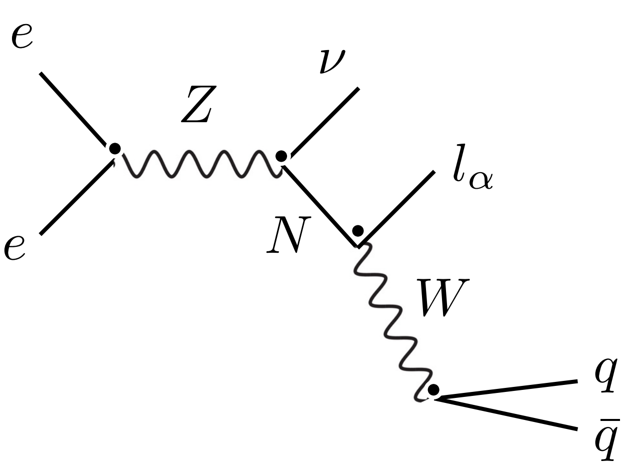
γ parametrizes size of R_{ij} (and thus heavy mixing)

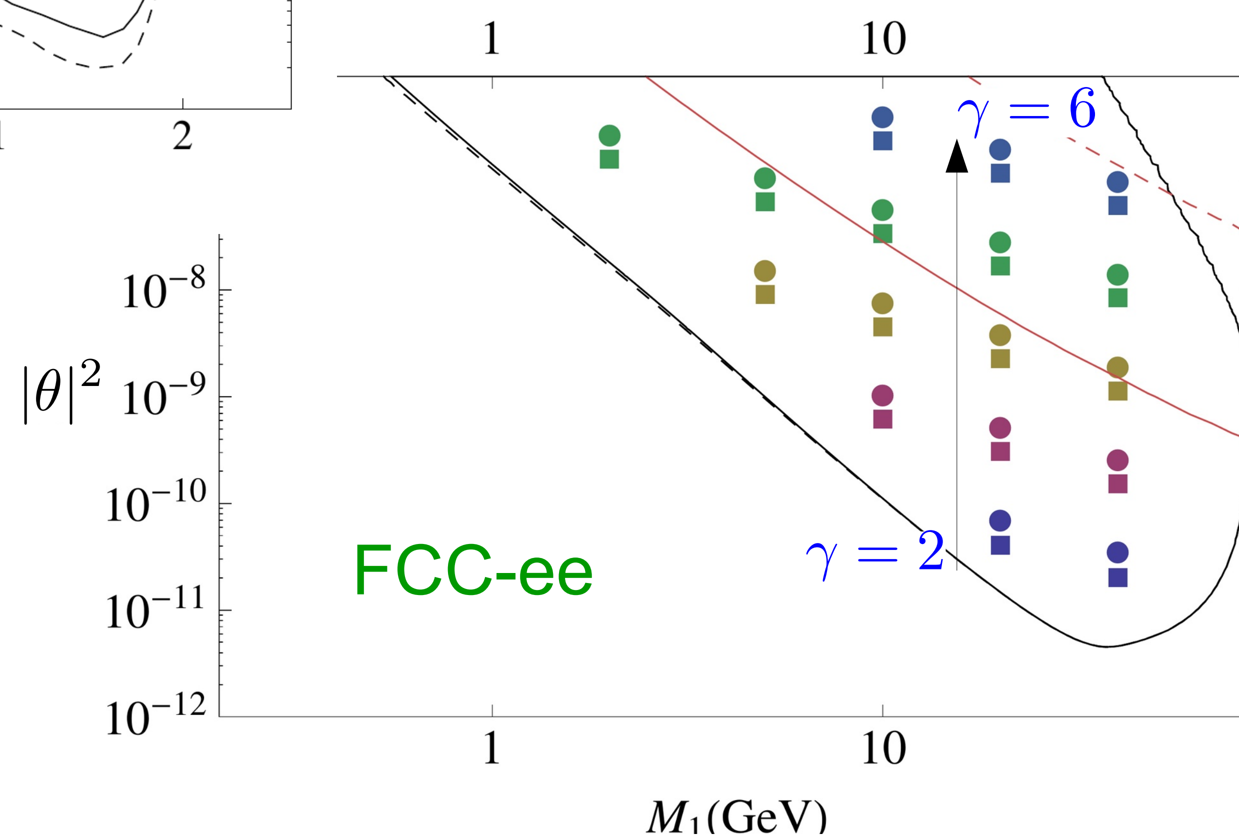
$N_R = 2$

PMNS CP-phases from HNLs searches

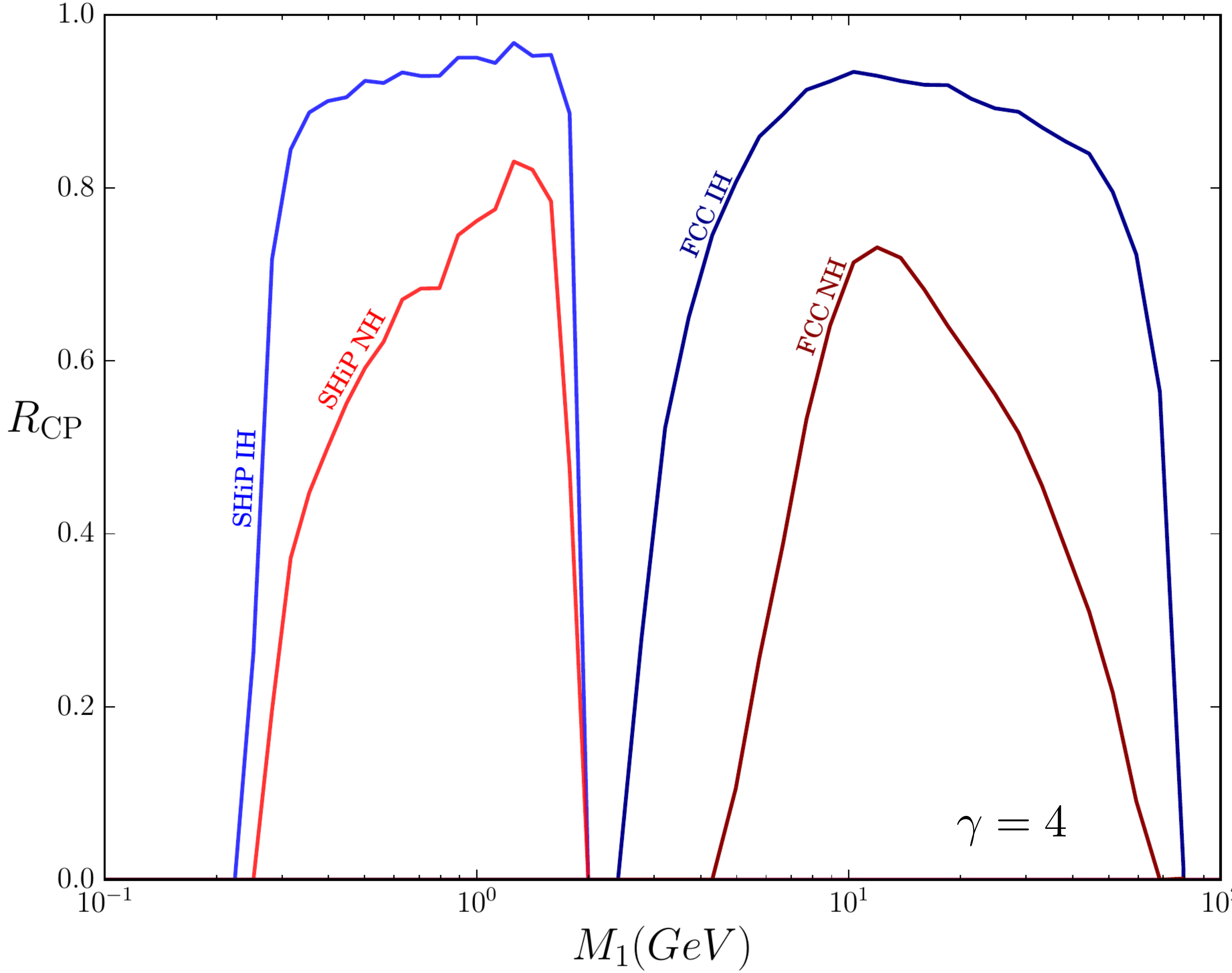








5σ discovery PMNS CP-violation



Caputo, Hernandez, Kekic, JLP, Salvado arXiv:1611.05000

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...).

$$\frac{N_{\nu_\alpha}^{\mathrm{FD}}}{N_{\nu_\alpha}^{\mathrm{ND}}} \sim \frac{L_{\mathrm{ND}}^2}{L_{\mathrm{FD}}^2} \frac{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}{\Phi_\alpha \sigma_\alpha \epsilon_\alpha} P_{\alpha\alpha}$$

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

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

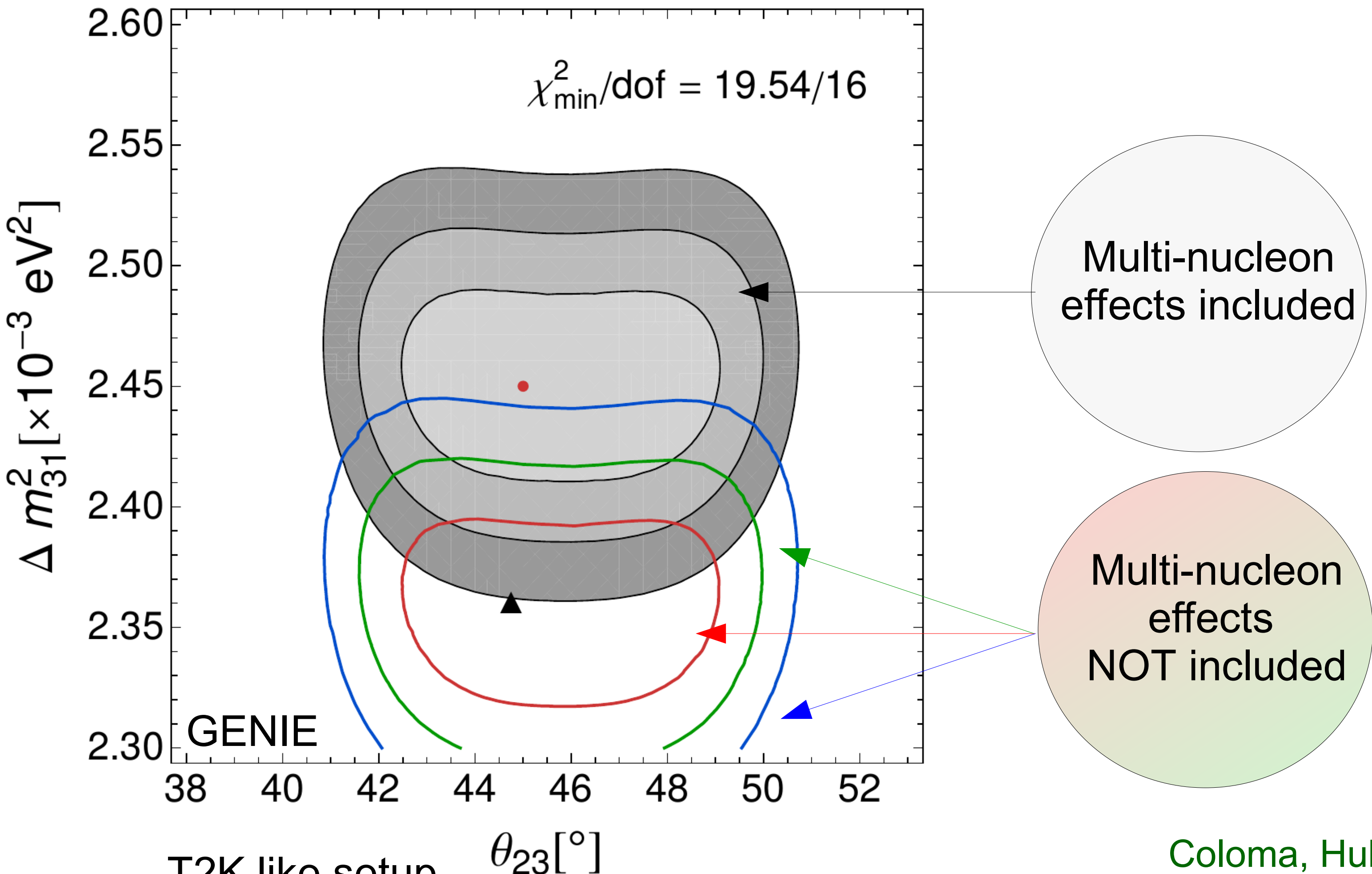
• CP violation requires comparison between neutrino and anti-netrino signals.

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

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.



T2K like setup

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

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

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

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