New Physics in Neutrino Oscillations

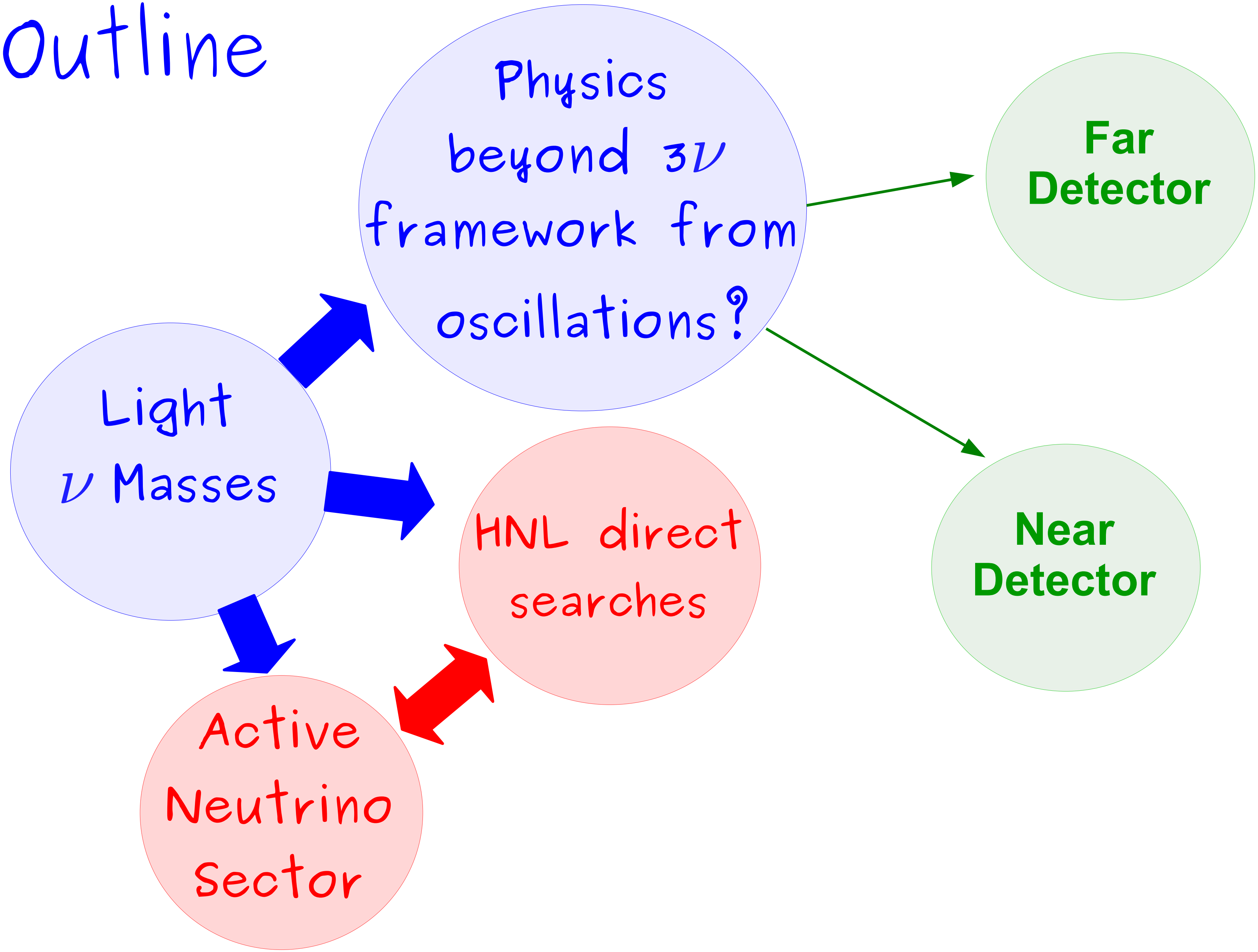
Jacobo López-Pavón

***Workshop on the Standard Model & Beyond* | CORFU**

6 August 2022

CIDEGENT/2018/019

Outline


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

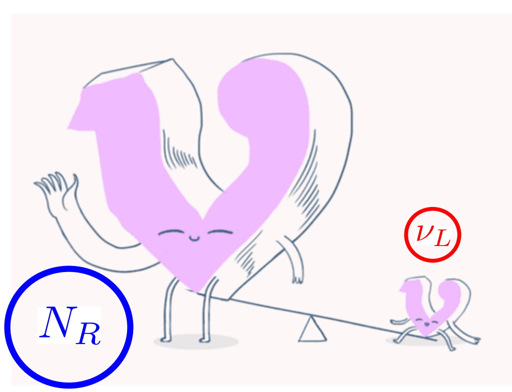
Minimal model: Seesaw Model

- 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

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



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

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:

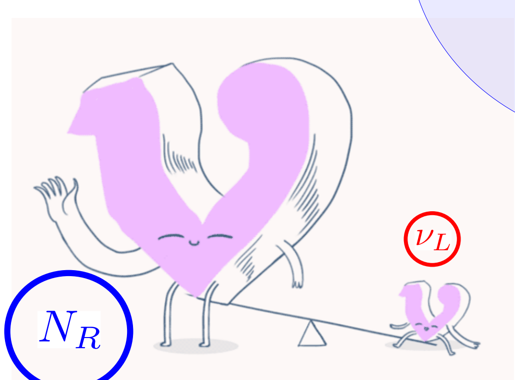
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{K} - \boxed{\frac{1}{2}\overline{N_i^c} M_{ij} N_j} - Y_{i\alpha}\overline{N_i}\widetilde{H}^{\dagger} L_\alpha + h.c.$$

New Physics Scale

Lepton Number Violation

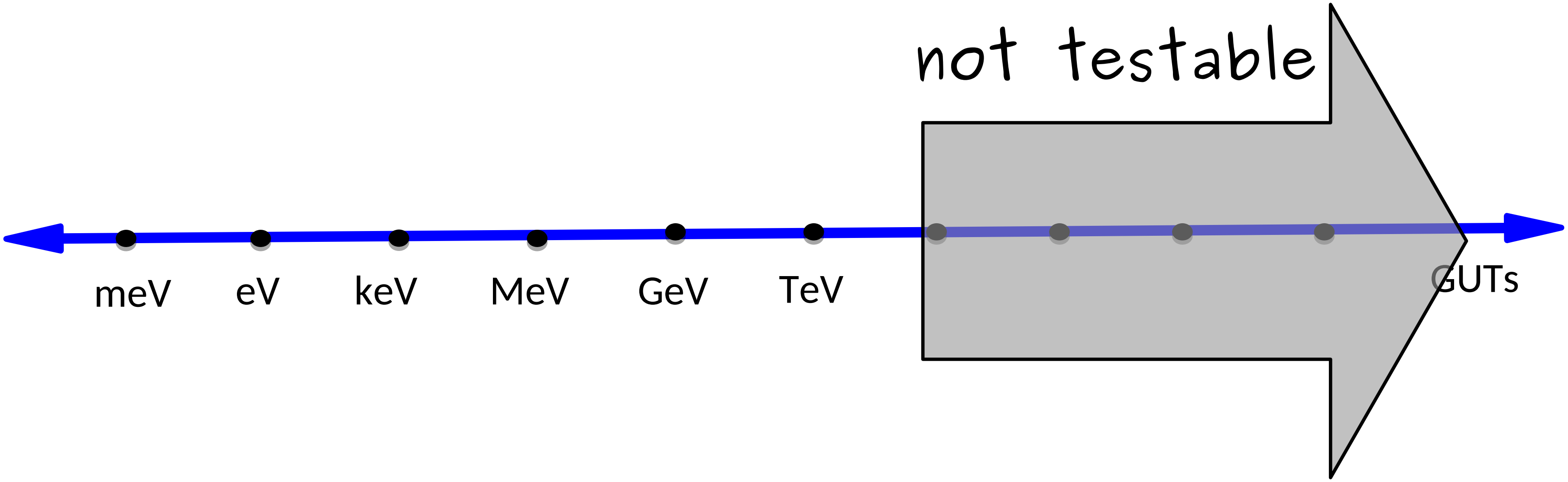
$0\nu\beta\beta$ **decay!**

Leptogenesis!

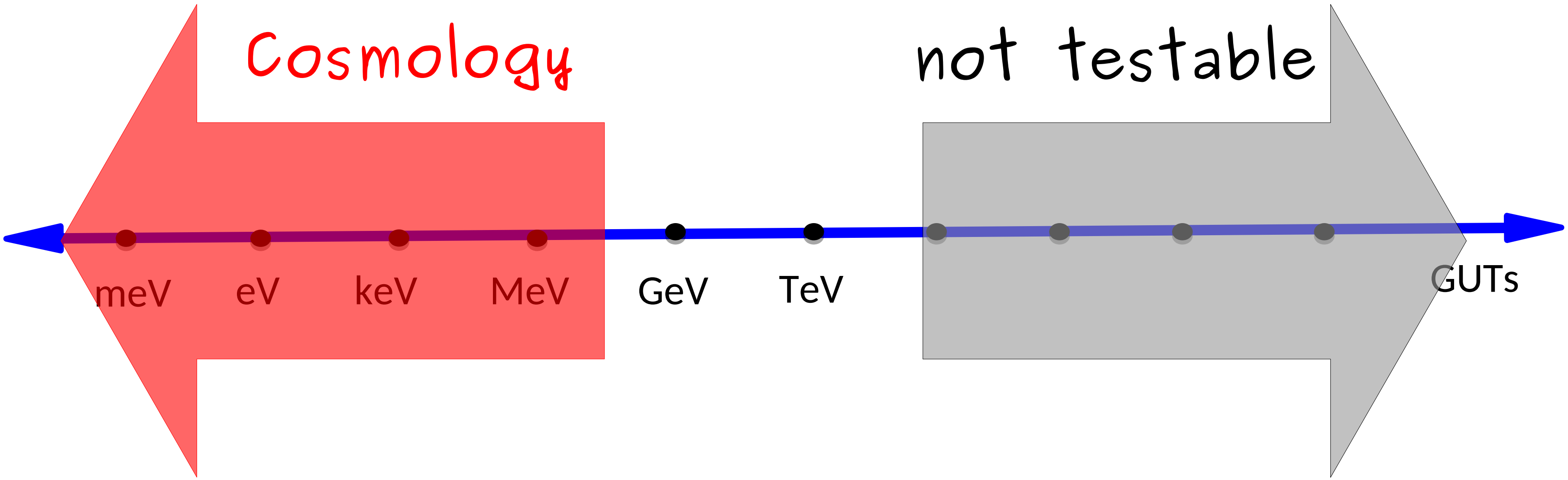


Fukujita, Yanagida 1986

The New Physics Scale

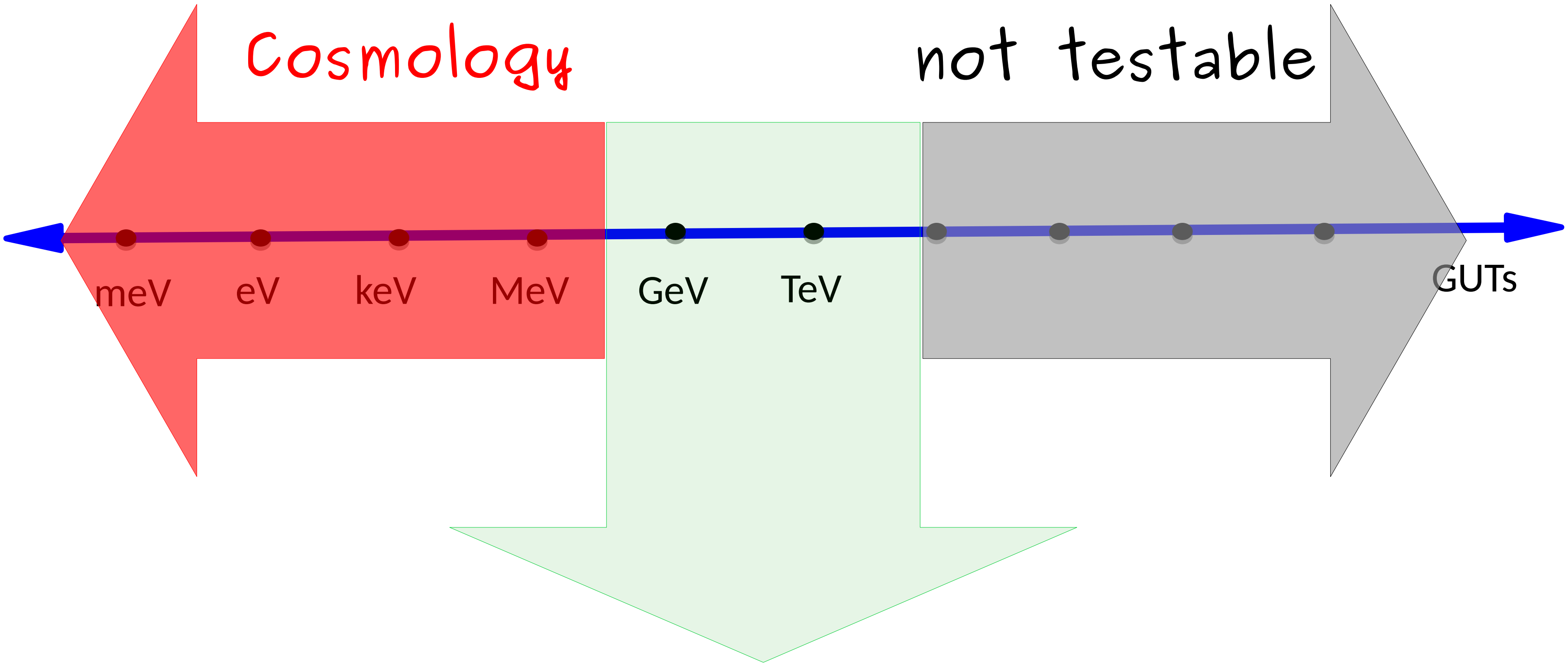


The New Physics Scale



P. Hernandez, M. Kekic, JLP
1311.2614; 1406.2961
Bondarenko, Boyarsky,Klaric,
Mikulenko, Ruchayskiy Syvolap,
Timiryasov 2101.09255

The New Physics Scale



$0\nu\beta\beta$ decay, CLFV, Colliders, Beam-dump...

Are Long Baseline

Neutrino Oscillation experiments

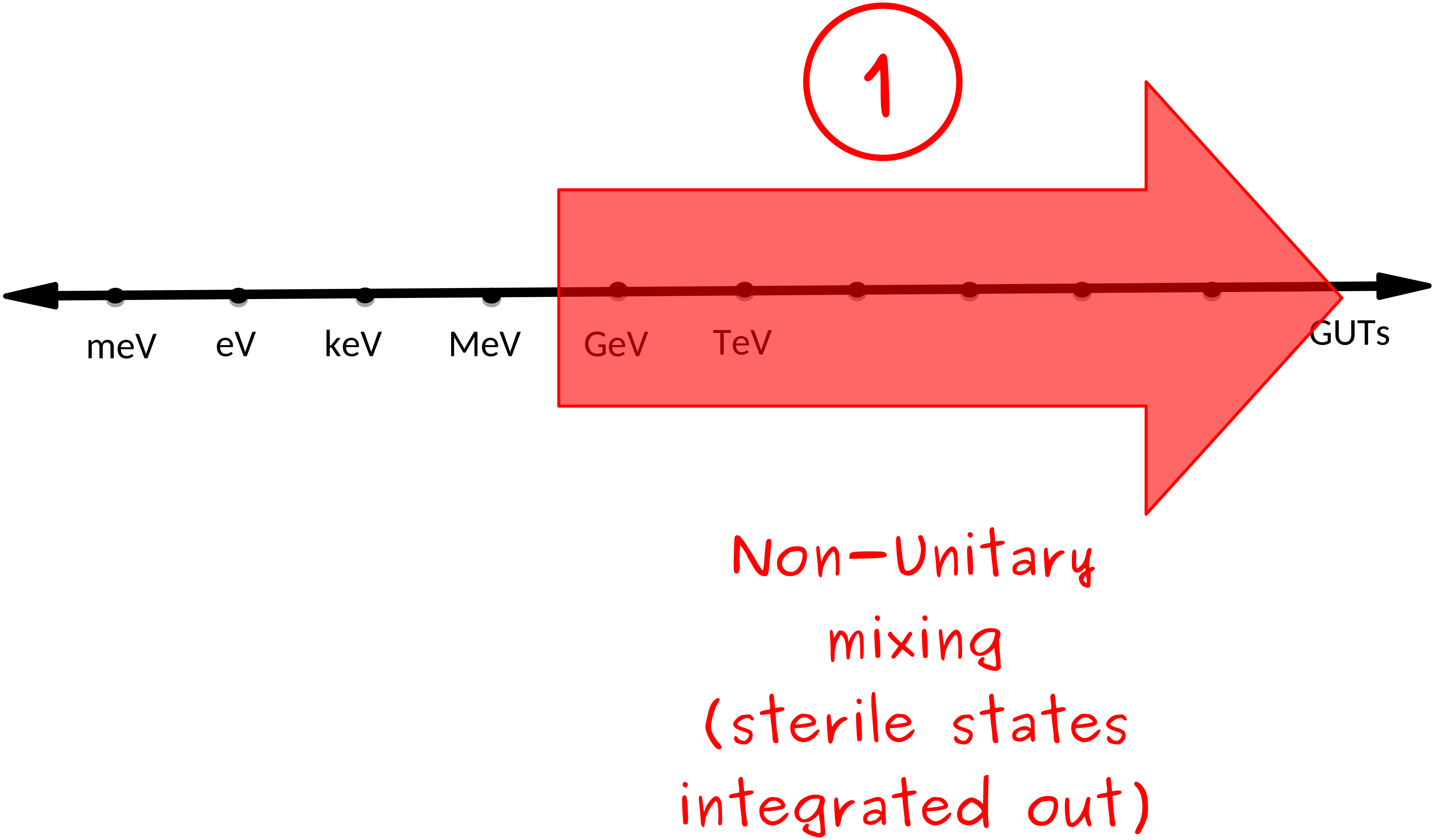
sensitive to

New Physics

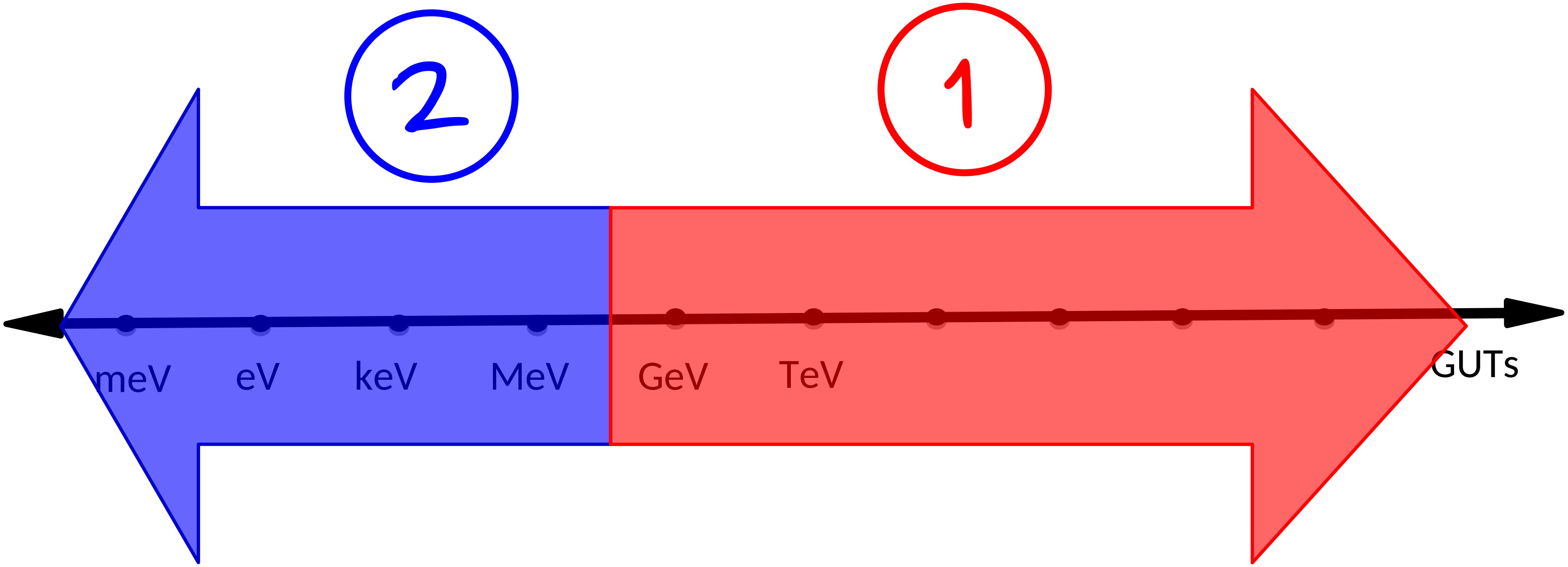
beyond 3ν framework

?

Neutrino Oscillations vs NP scale



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

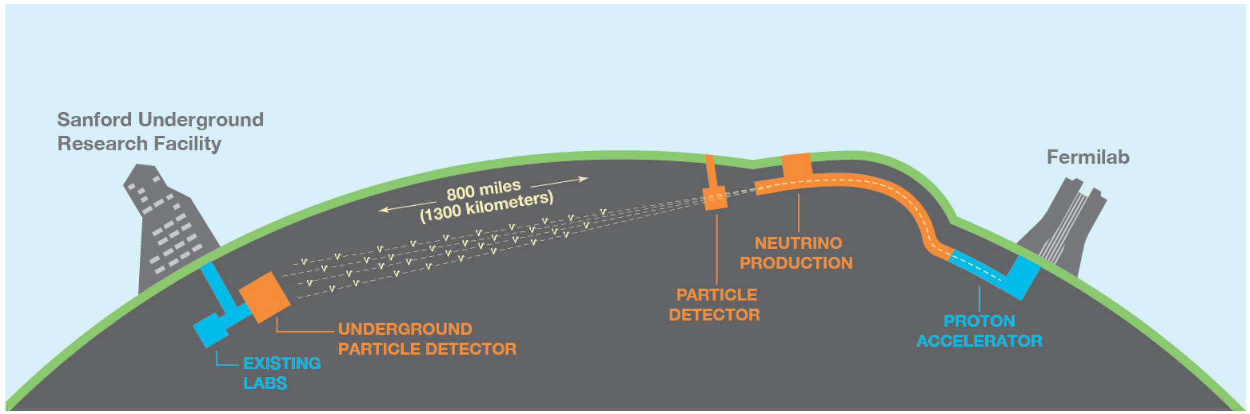
Unitary matrix

(standard unitary PMNS matrix up to small corrections)

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

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

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

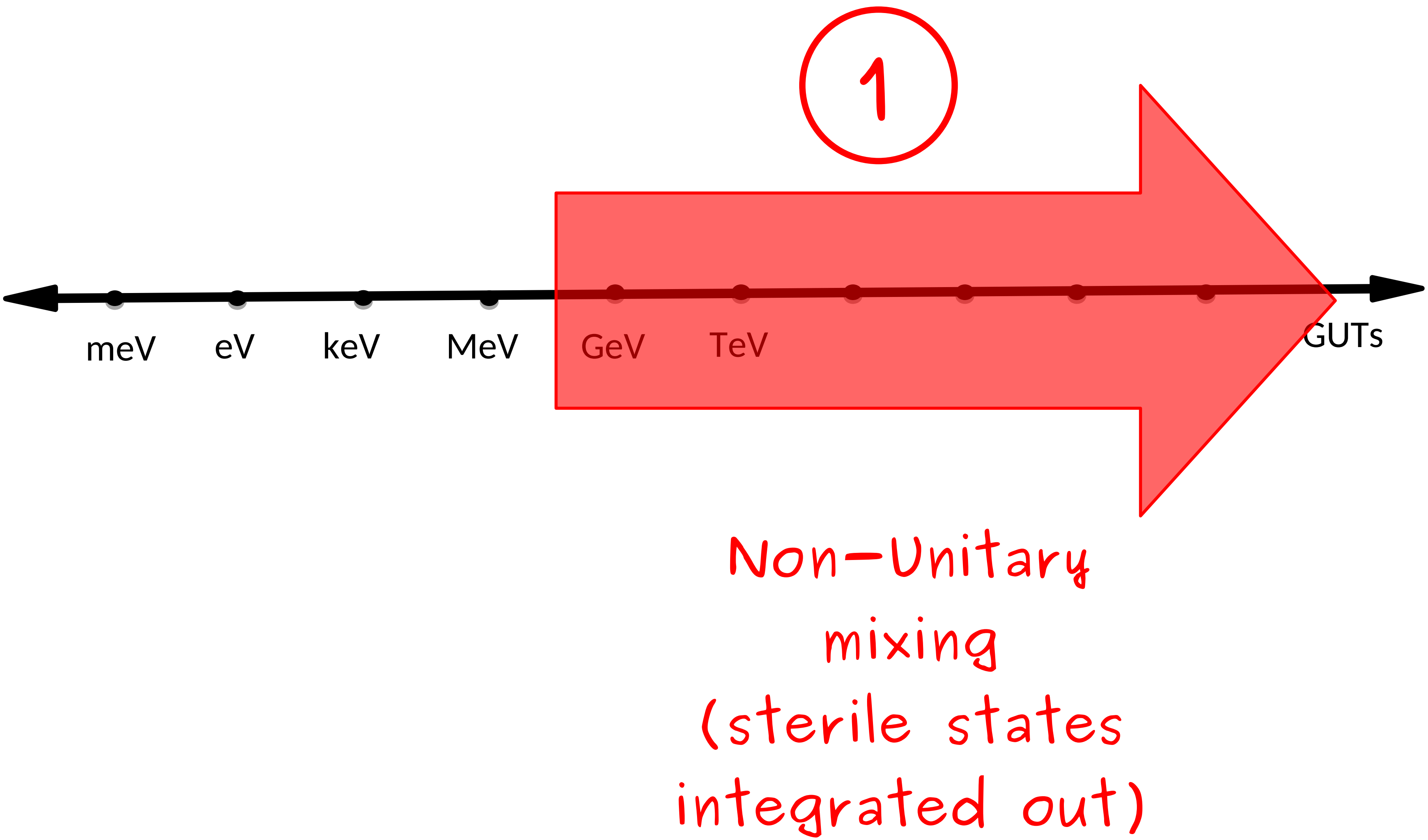
- What is measured in neutrino oscillation experiments

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

Event rate Far Detector

Extrapolation of Near Detector

① Non-Unitary Mixing



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

① Non-Unitary Mixing

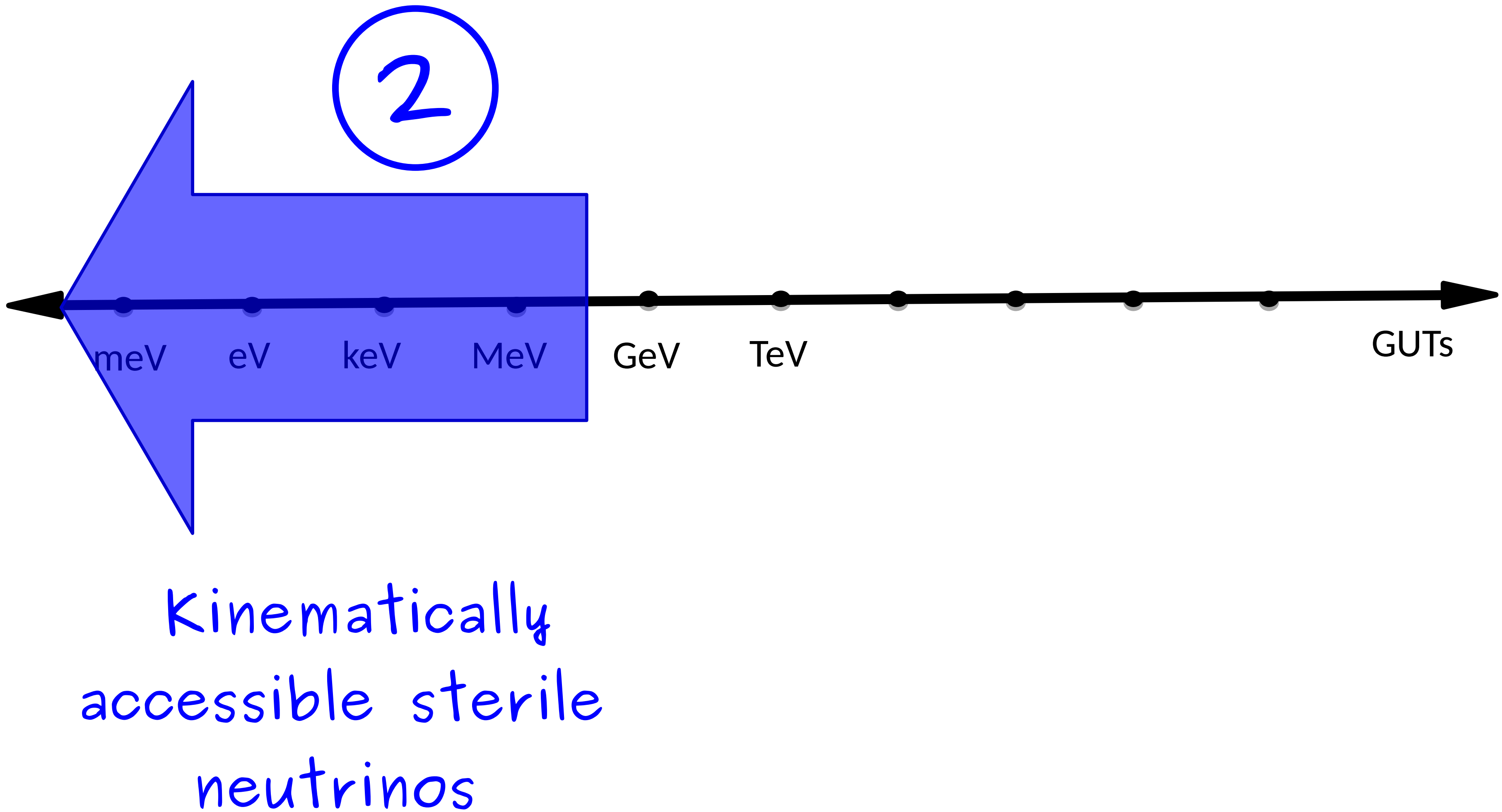
- What is measured in neutrino oscillation experiments

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

- 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



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

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

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

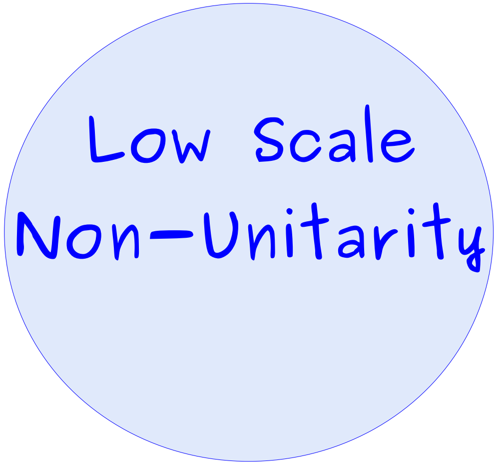
Oscillations could be observed at the near detector

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

② Kinematically accessible Sterile ν

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

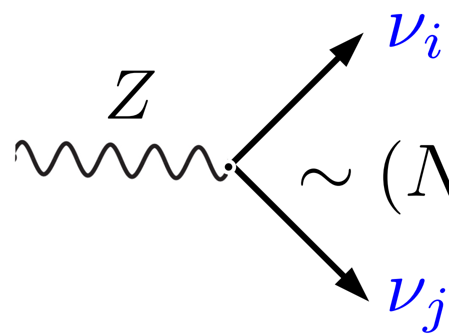
Identical to the heavy non-unitarity case



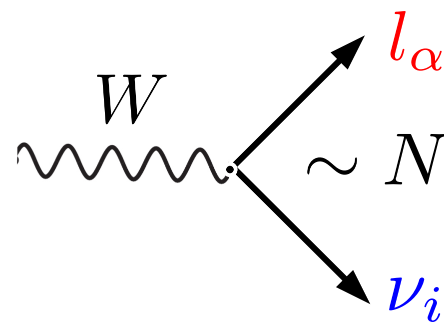
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

Present Bounds

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



$\sim (N^\dagger N)_{ij}$



$\sim N_{\alpha i}$

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

EW & CLFV precision data

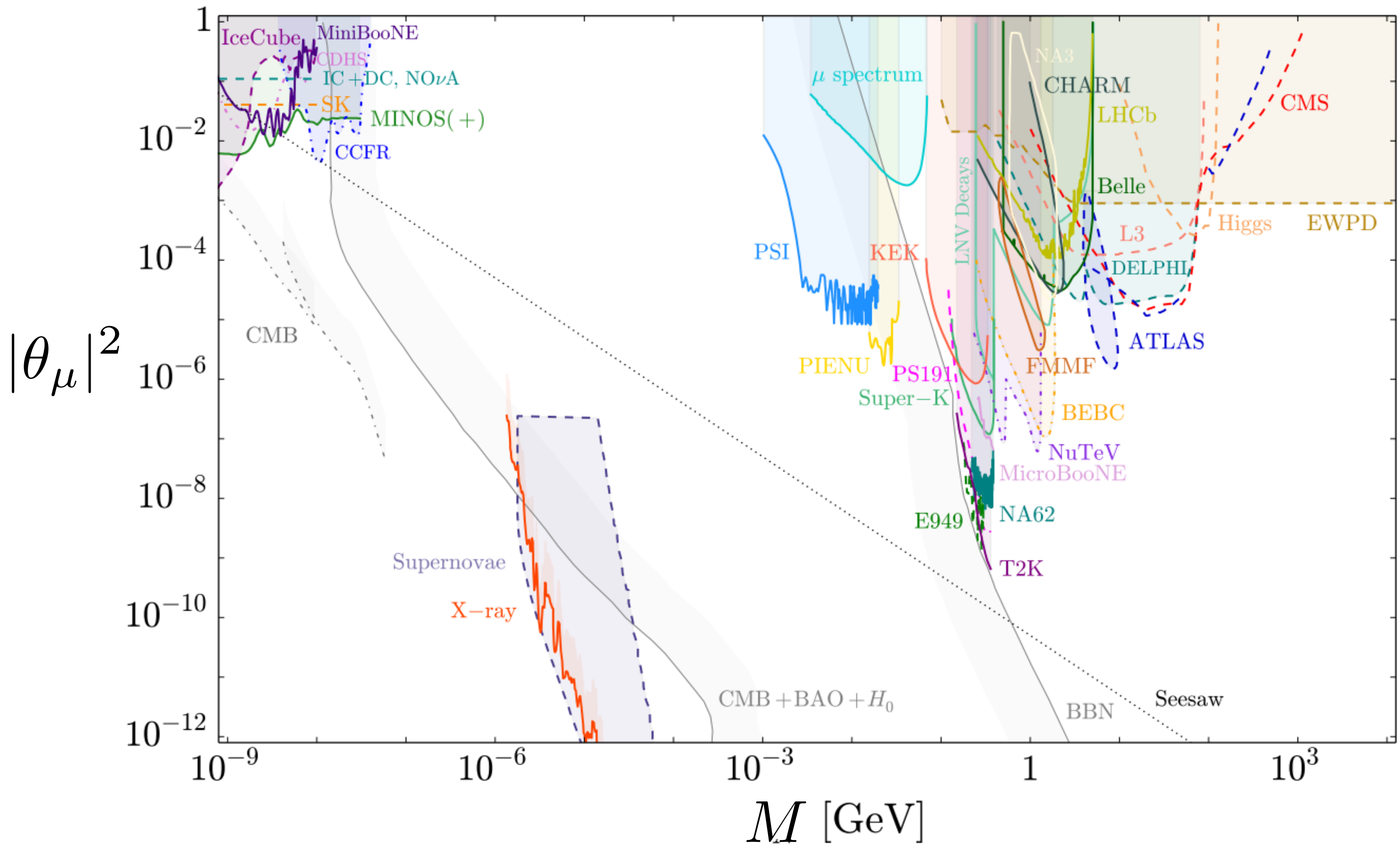
Present Bounds

	Non-Unitarity $(M > \mathrm{EW})$	Non-Unitarity $(M \gtrsim 1\,\mathrm{eV})$	
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	BUGEY
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$	SK
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$	SK
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$	NOMAD
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	NOMAD

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

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

Present Bounds

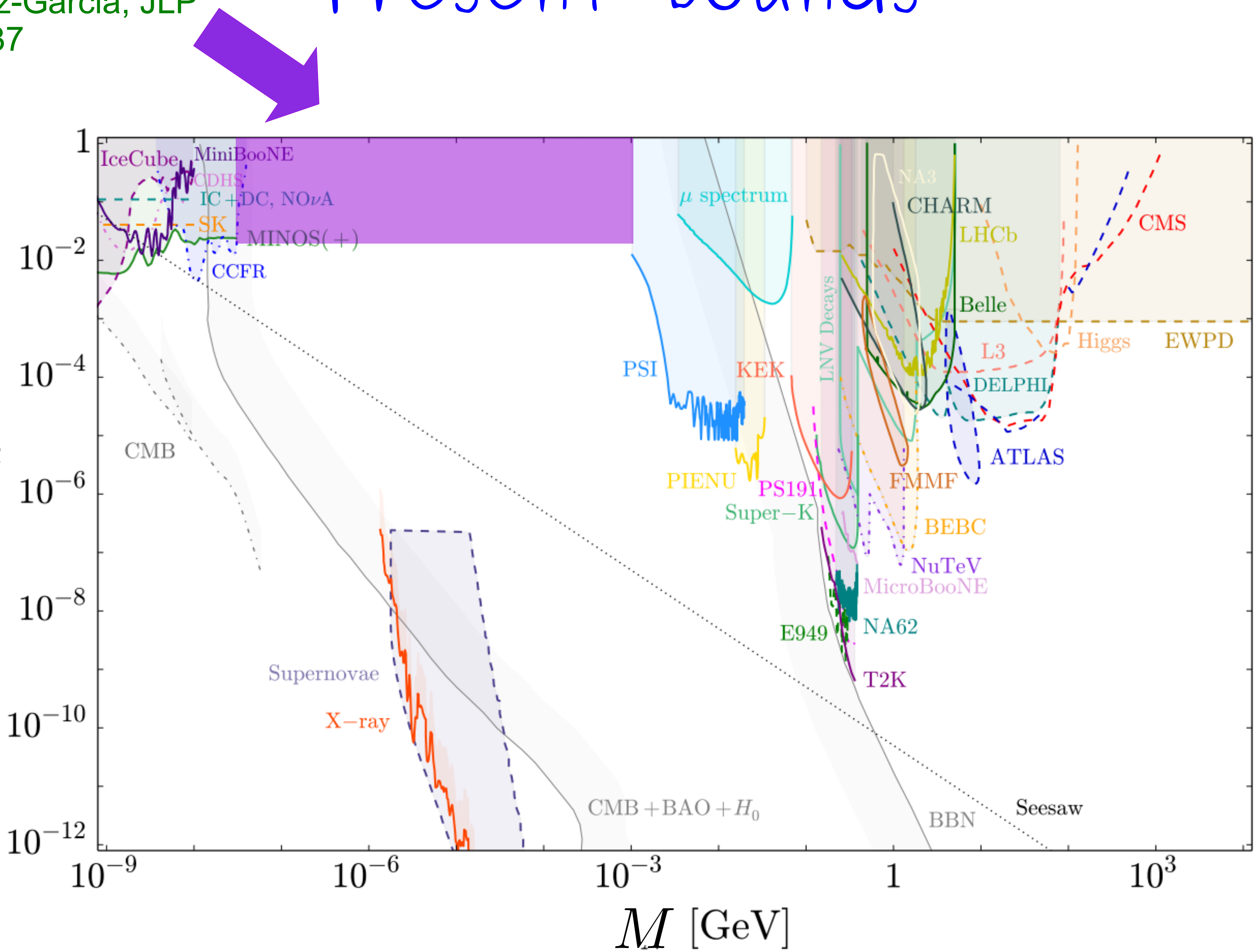


$$|\alpha_{\beta\beta}|^2 = \frac{1}{2}\sum_i |\theta_{\alpha i}|^2$$

Figure from Bolton,Deppisch, Bhupal Dev 1912.03058

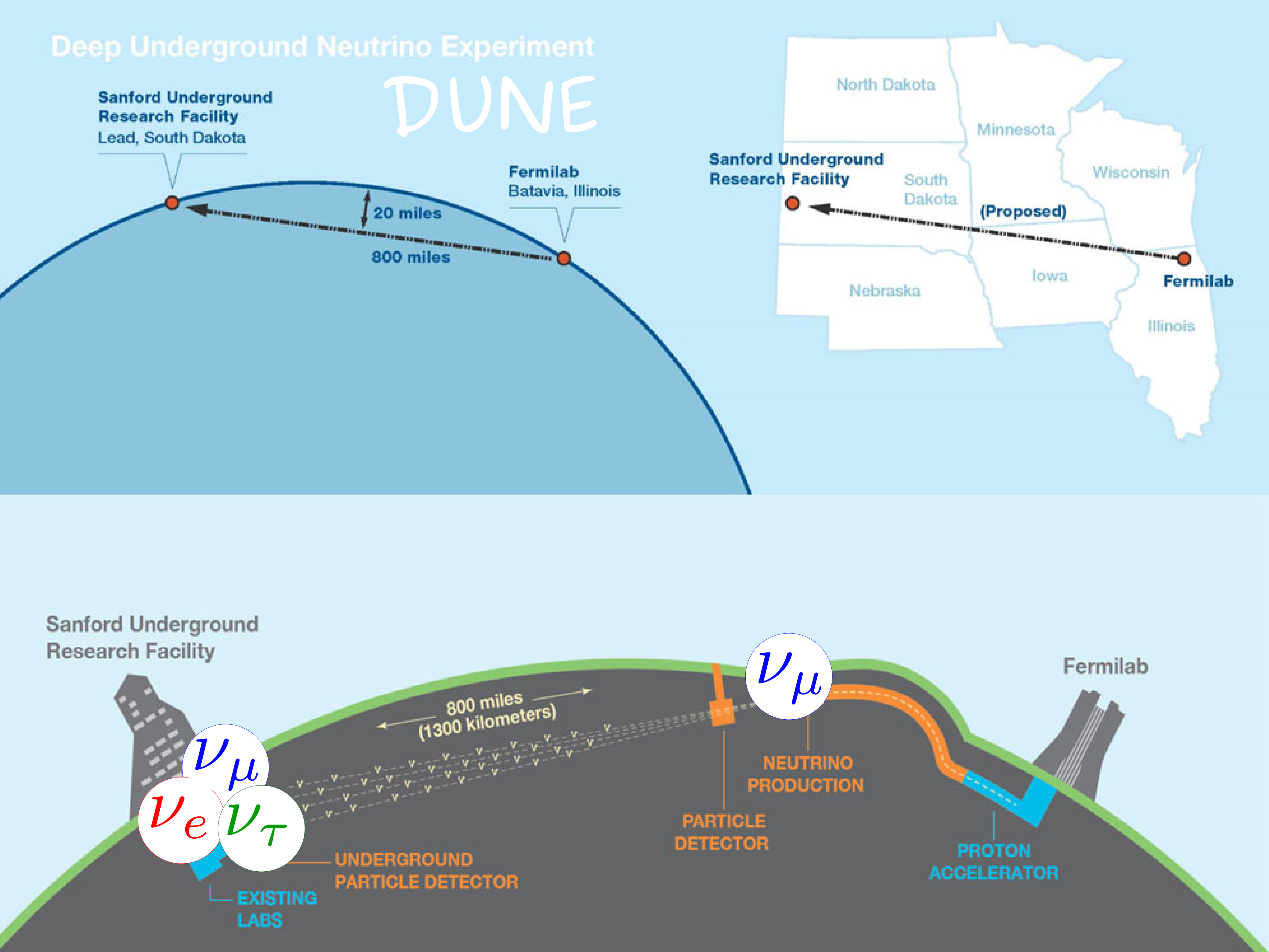
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

Present Bounds



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

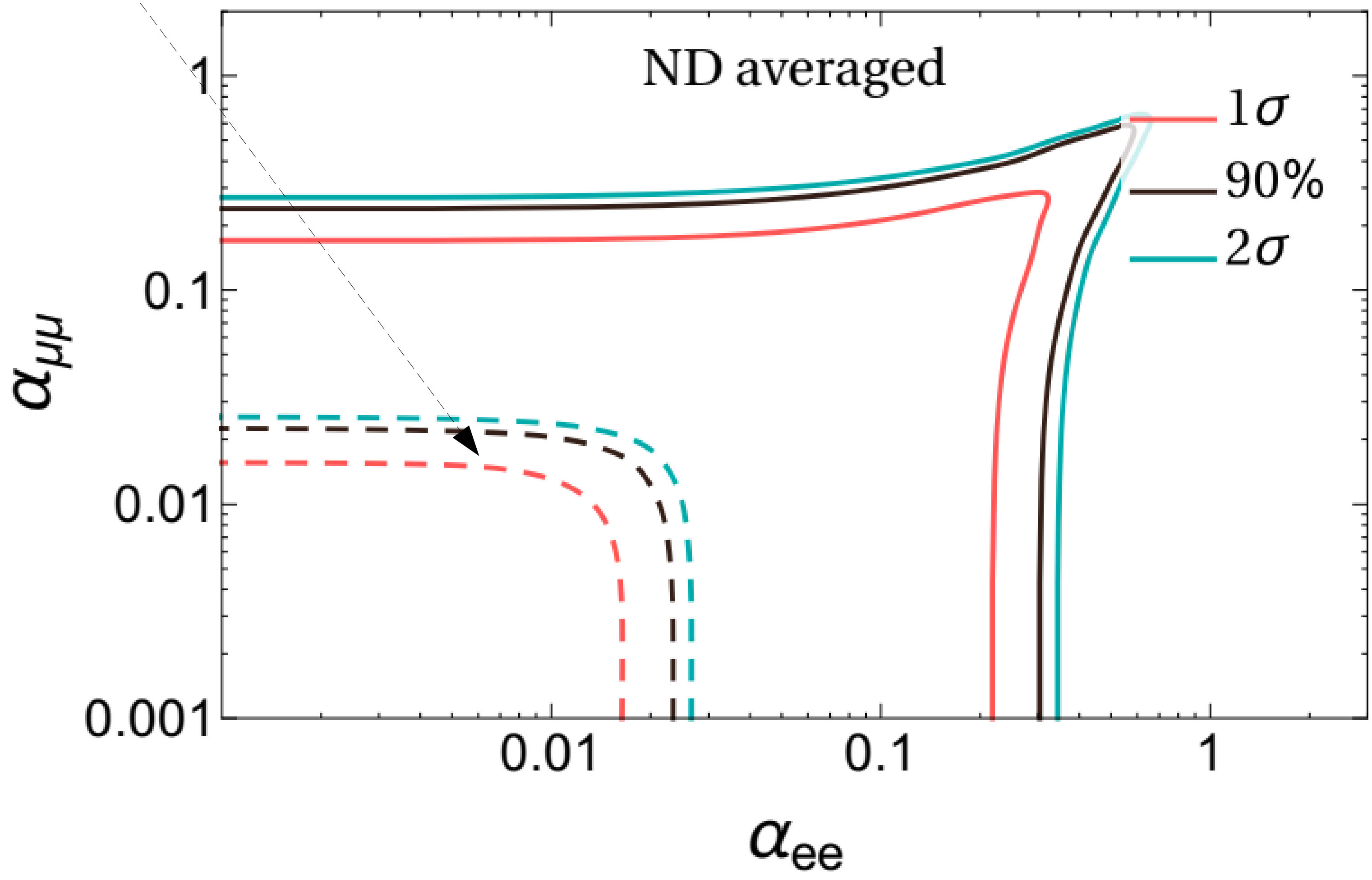
Figure from Bolton,Deppisch, Bhupal Dev 1912.03058



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

Far Detector

Prior
(present bounds)



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

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

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

Averaged-out regime

- What is measured in Near Detector

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

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

zero distance effect!

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

Averaged-out regime

- What is measured in Near Detector

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

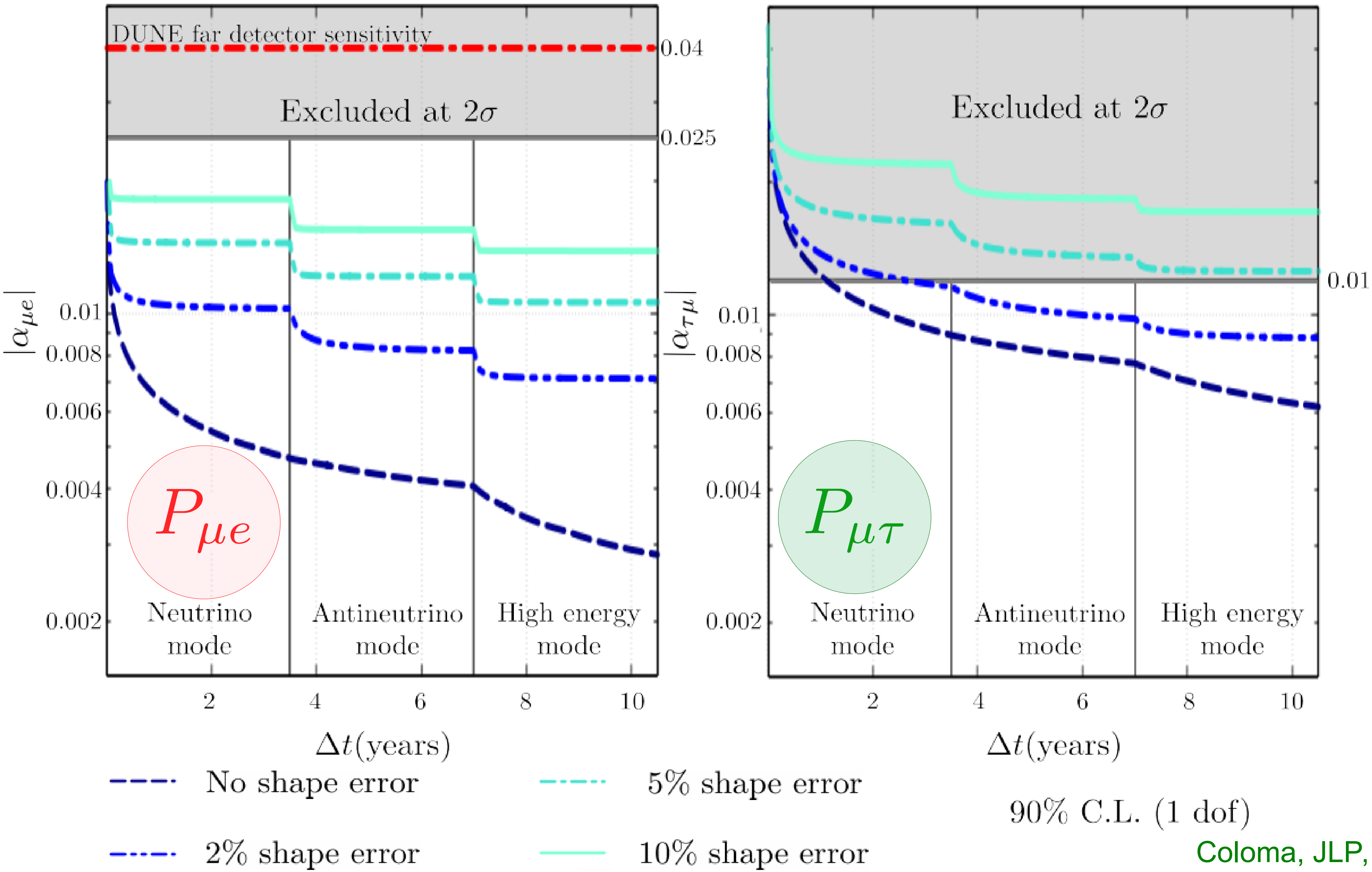
$$\langle \mathcal{P}_{\alpha\beta} \rangle = 2|\alpha_{\alpha\beta}|^2$$

zero distance effect!

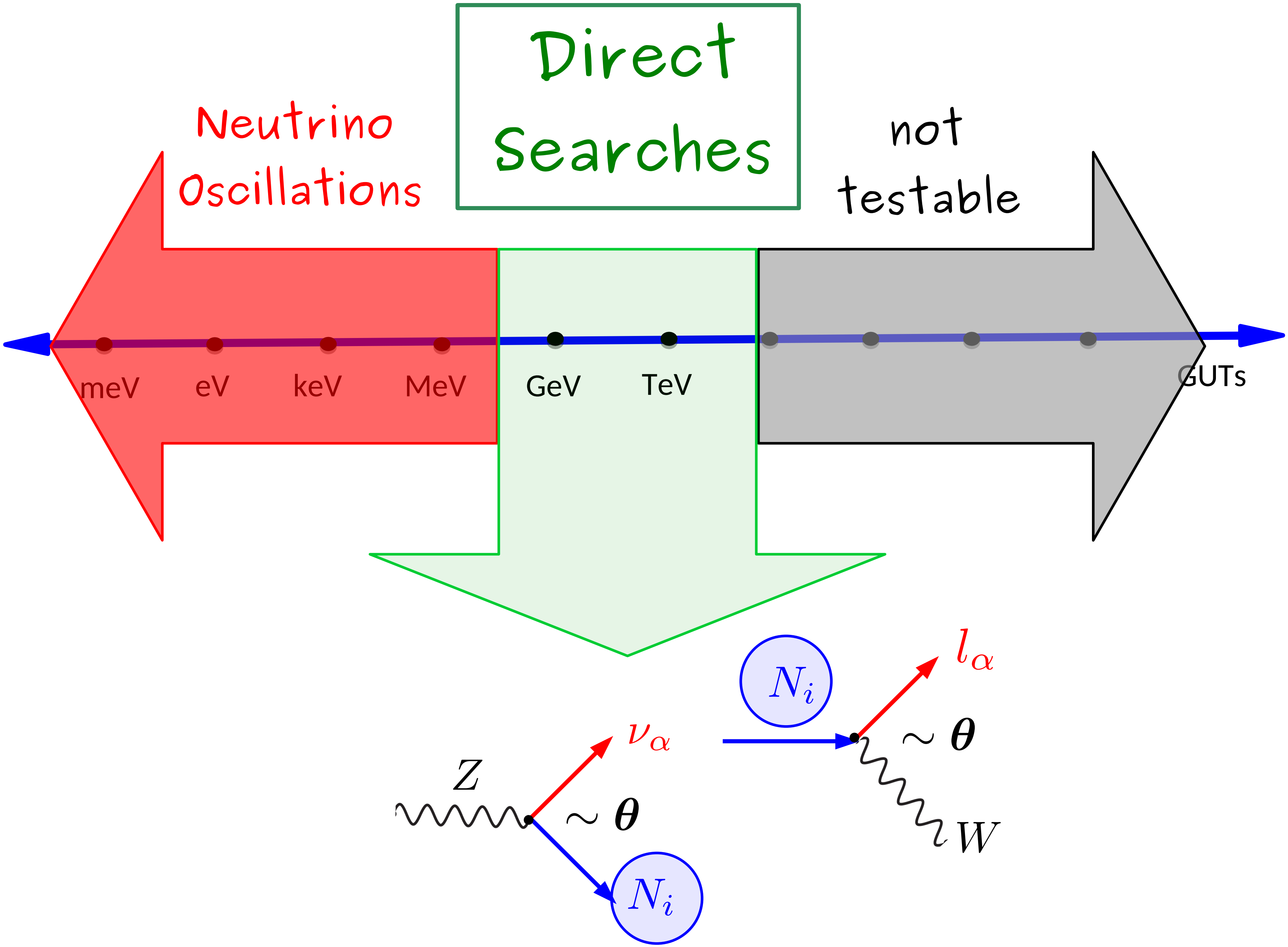
$$\langle \mathcal{P}_{\alpha\alpha} \rangle = 1 - 4|\alpha_{\alpha\alpha}|$$

Low Scale Non-Unitarity

Low Scale Non-Unitarity



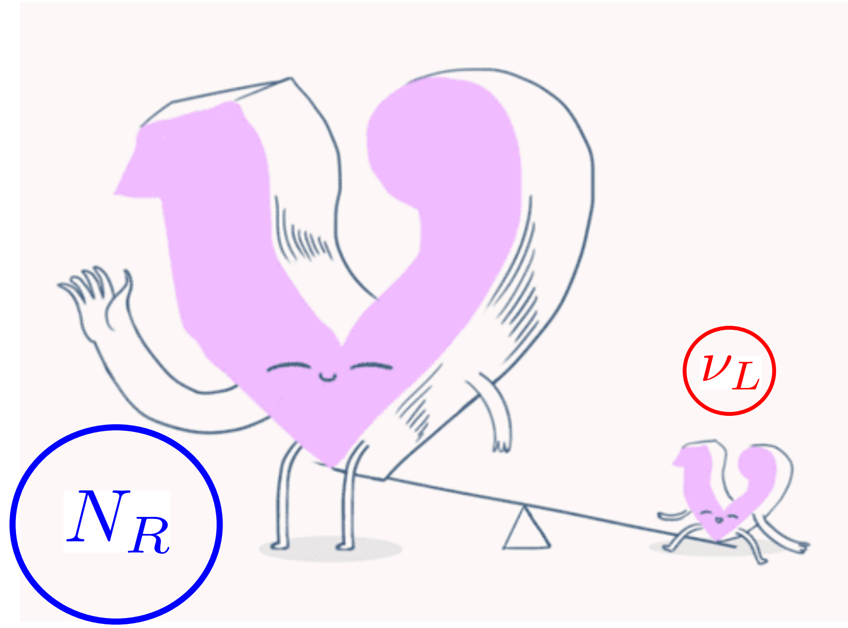
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466



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

Light Neutrino mass generation

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

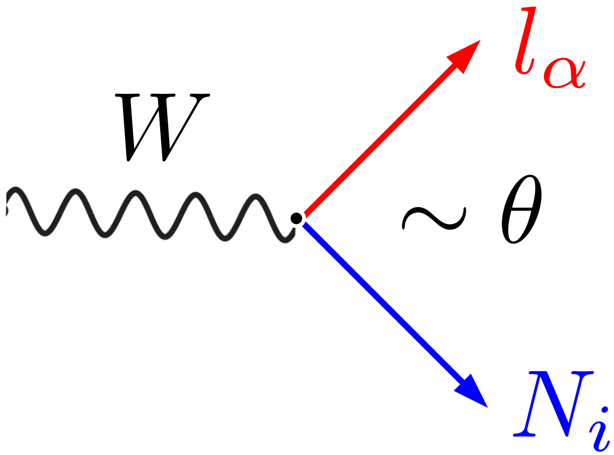


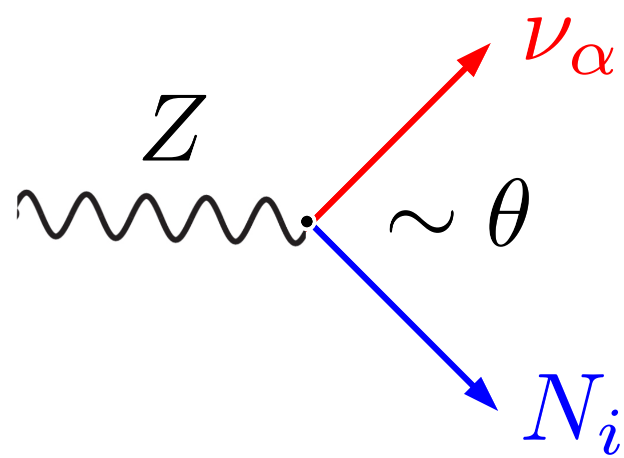
$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y = \theta\, M\, \theta^T = U\, m\, U^T$$

HNL sector

Light-active neutrino sector

Constraint on HNL mixing from active sector





Casas-Ibarra

$$\theta = i U\, m^{1/2}\, R^\dagger M^{-1/2}$$

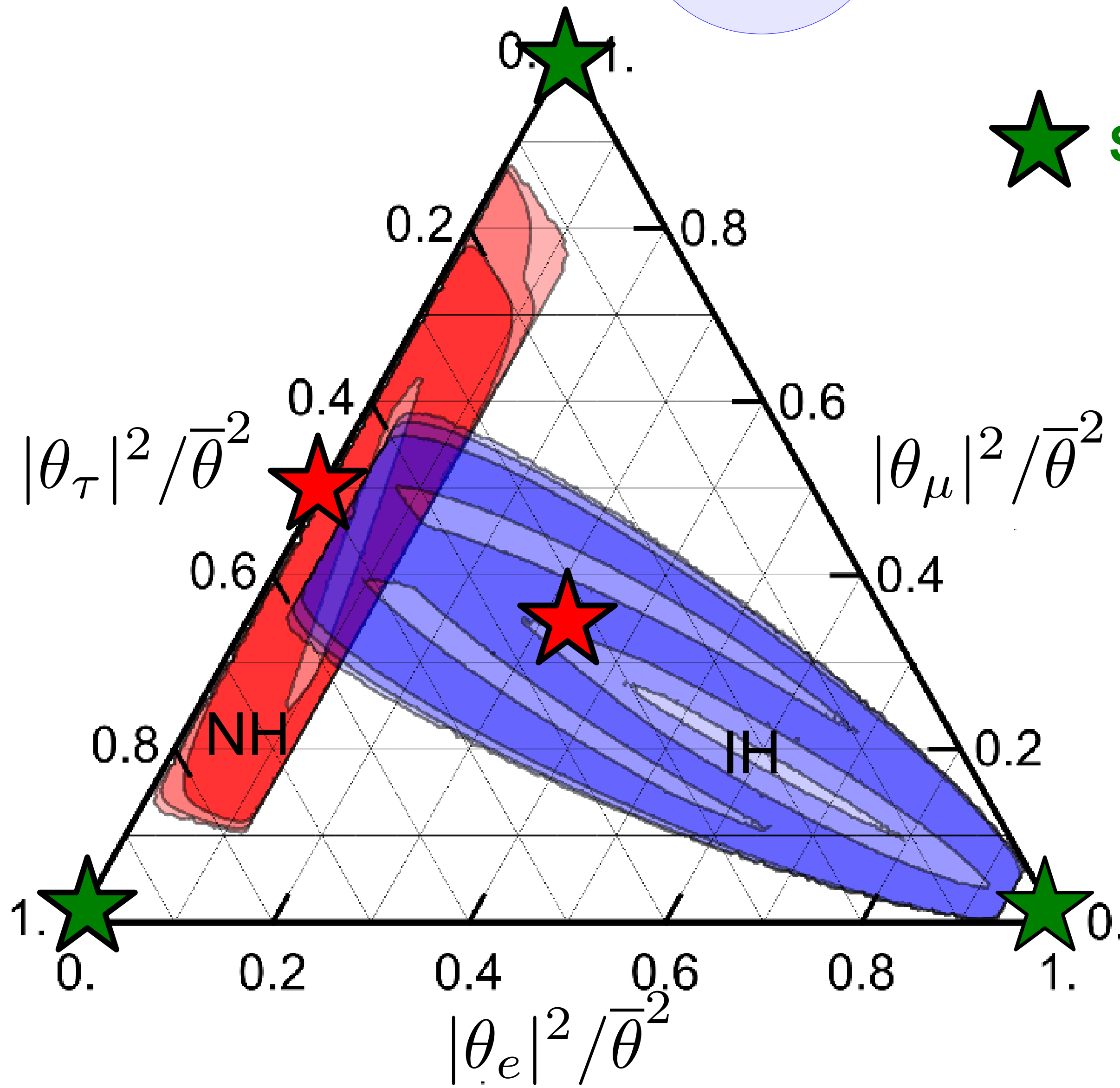
Active Sector

- 3x3 PMNS mixing matrix
- light neutrino masses

HNL Sector

- Complex $3 \times N_R$ orthogonal matrix
- HNL masses

Minimal model $N_R=2$: Flavor Structure

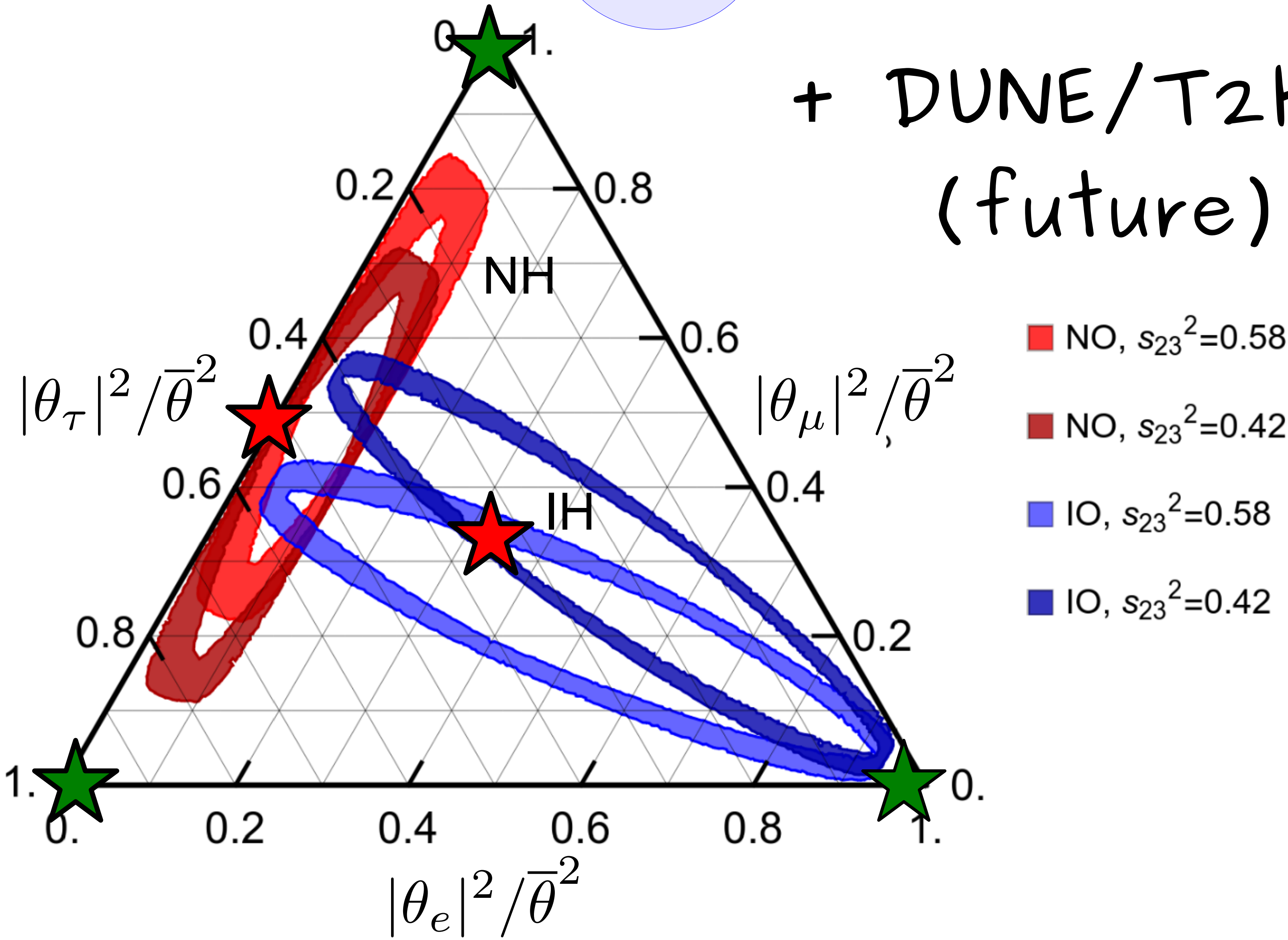


Single flavored benchmarks
(1,0,0), (0,1,0), (0,0,1)

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

Abdullahi et al arXiv:2203.08039
Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

Minimal model $N_R=2$: Flavor Structure

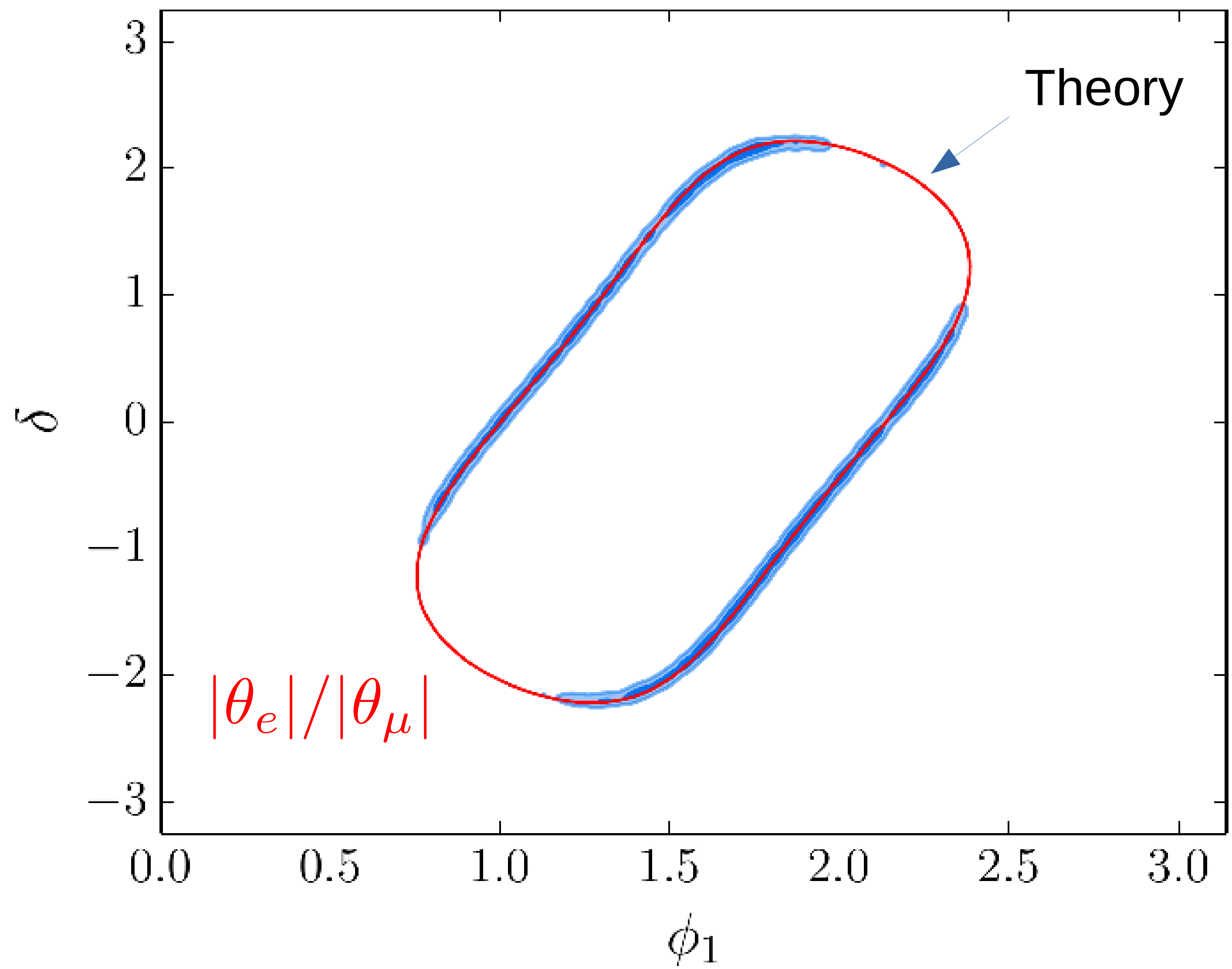


+ DUNE/T2HK...
(future)

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

Abdullahi et al arXiv:2203.08039
Drewes, Klaric, JLP arXiv: 2207.02742

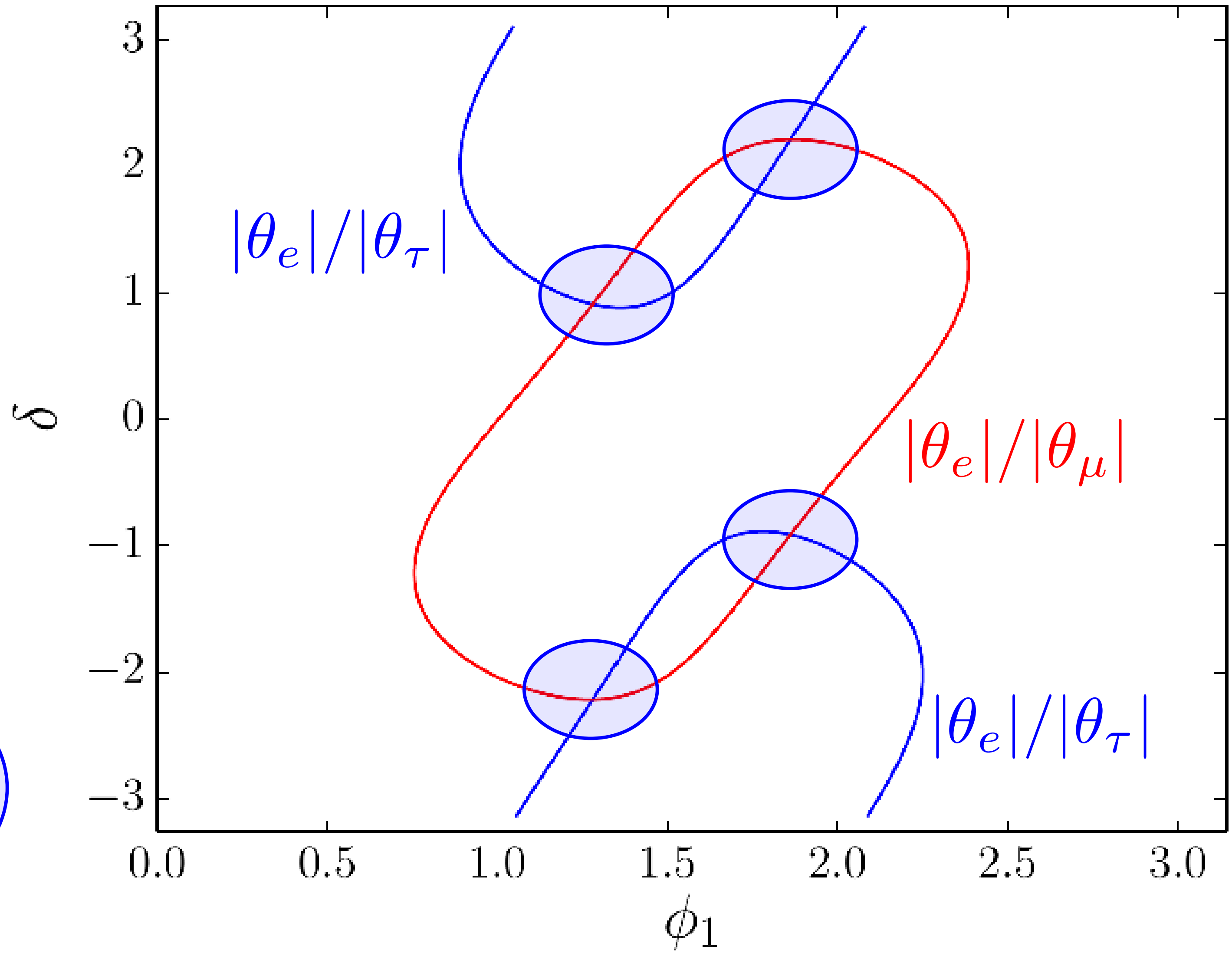
PMNS CP-phases from HNLs searches



$N_R = 2$

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

PMNS CP-phases from HNLs searches

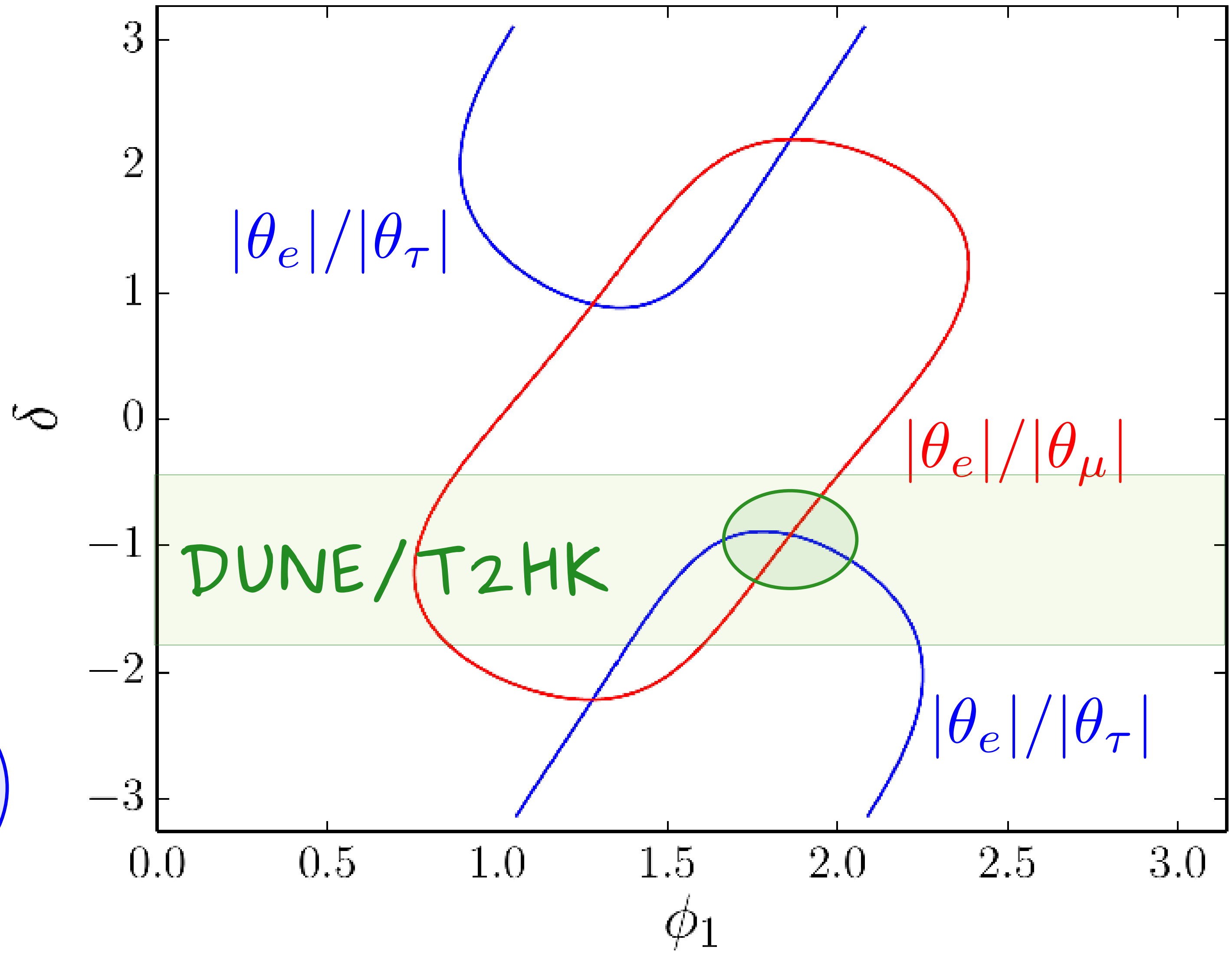


$N_R = 2$

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

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

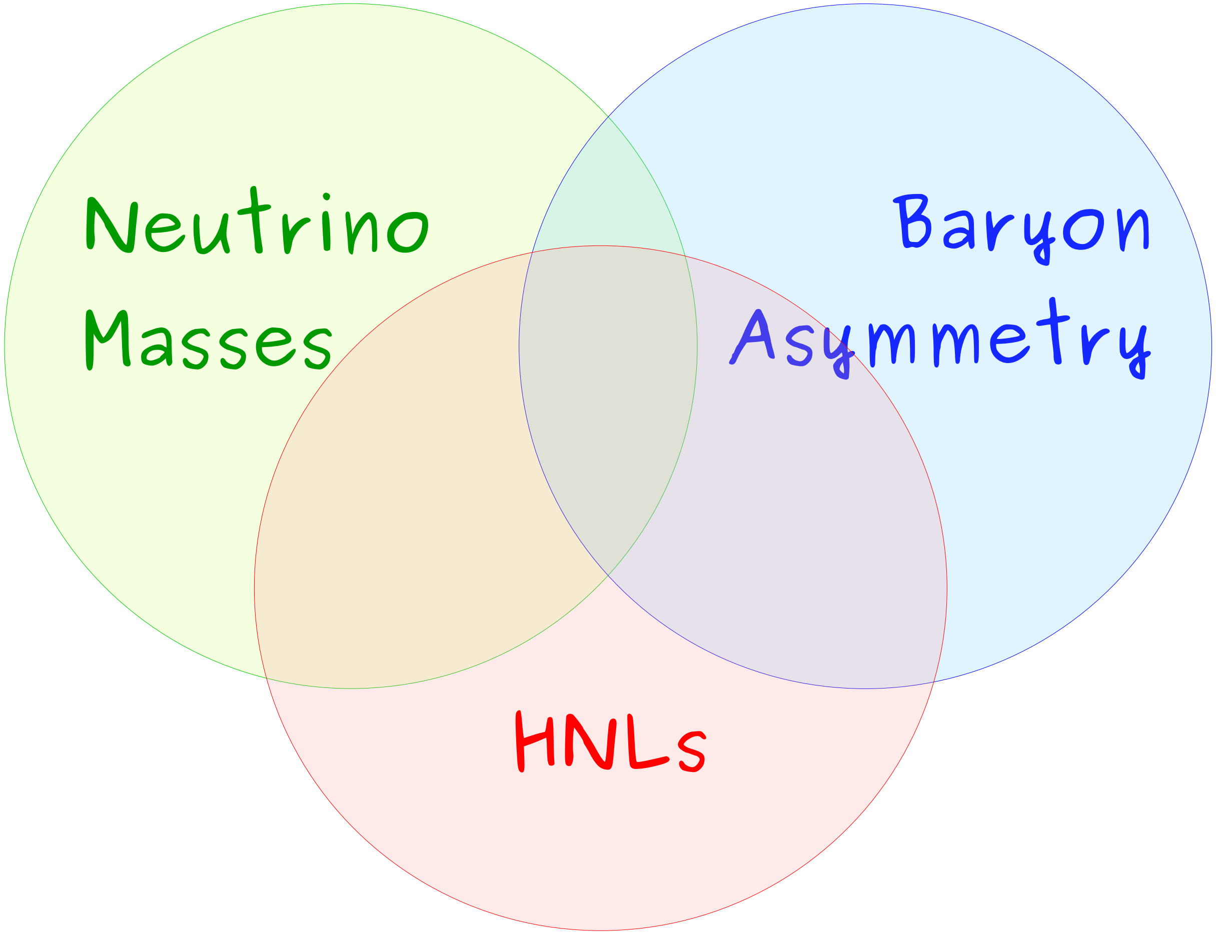
PMNS CP-phases from HNLs searches



$N_R = 2$

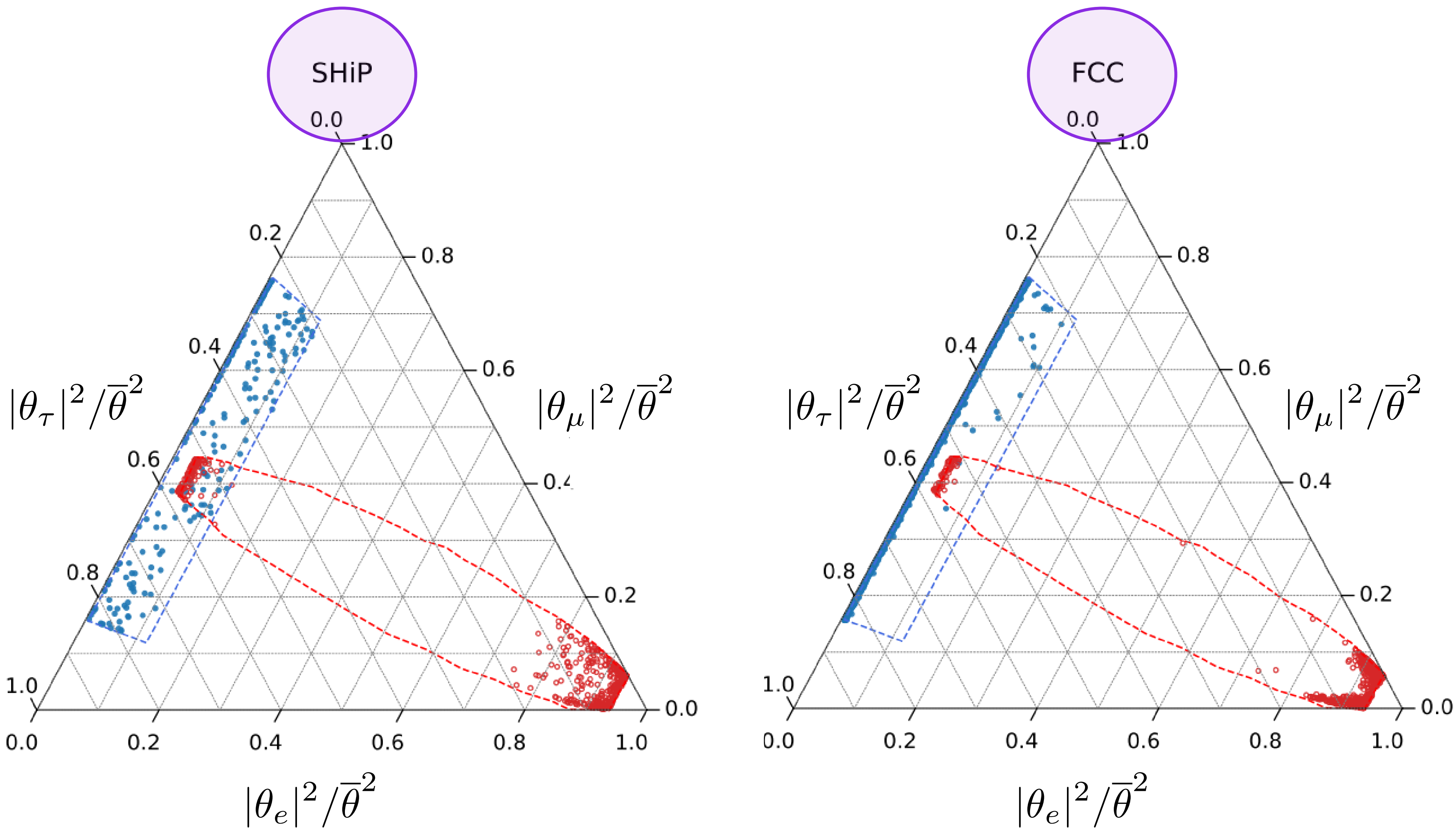
- **Potential determination of the PMNS Majorana phase!**

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



See talk by Apostolos Pilaftsis

Low Scale Leptogenesis: Flavor

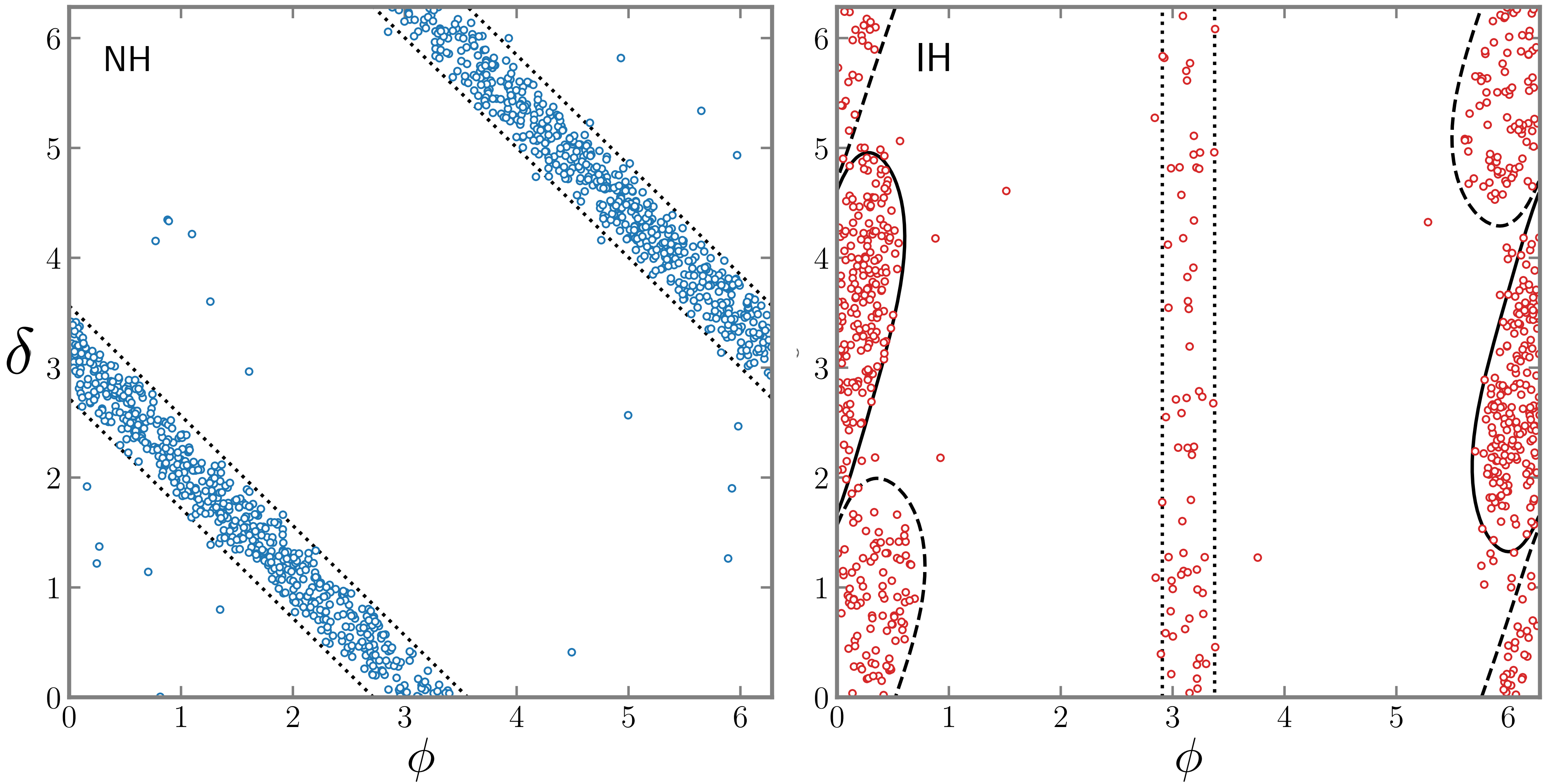


$$\Delta M/M = 10^{-2}$$

$N_R = 2$

Hernandez, JLP, Rius, **Sandner**, arXiv: 2207.01651

Low Scale Leptogenesis: CP phases

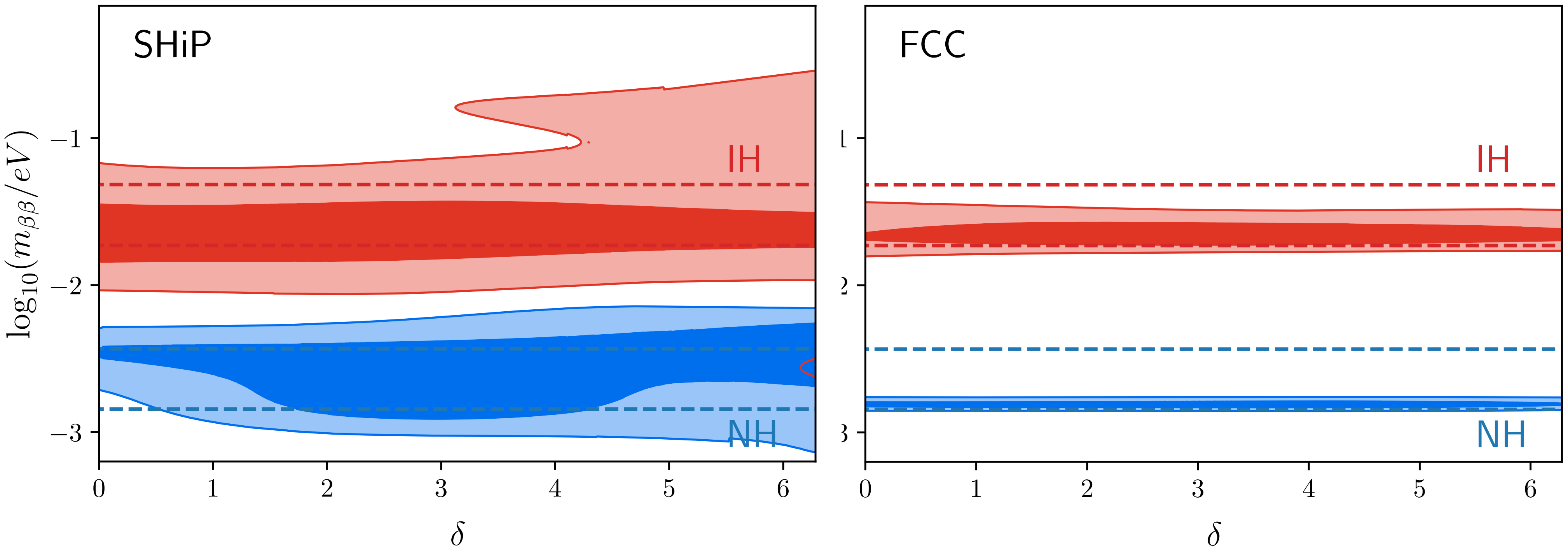


$$\Delta M/M = 10^{-2}$$

$N_R = 2$

Hernandez, JLP, Rius, **Sandner**, arXiv: 2207.01651

Low Scale Leptogenesis: $0\nu\beta\beta$ decay



$$\Delta M/M = 10^{-2}$$

$N_R = 2$

Hernandez, JLP, Rius, **Sandner**, arXiv: 2207.01651

Conclusions

- Near detectors in future neutrino oscillation experiments 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.*

Joint experimental and theoretical effort required to reduce systematics. *Independent measurements of the cross sections would give very relevant information of the energy dependence* (see $\nu\mathrm{STORM}$ proposal)

- Minimal neutrino mass model

measurement of HNLs mass & mixing would allow to **test the mechanisms generating neutrino masses and Baryon asymmetry** *and to indirectly measure the PMNS phases.*

Thank you!


FIPs 2022
Workshop on Feebly-Interacting Particles
17-21 October 2022
CERN
FIPs in colliders
extracted beams / fixed-target experiments
neutrino experiments
astroparticle physics / cosmology
direct and indirect dark matter detectors
axion / ALP experiments
ultra-light particle searches
and beyond
Organizers:
James Beacham
Albert De Roeck
Marco Drewes
Bertrand Echenard
Torben Ferber
Maurizio Giannotti
Gian Francesco Giudice
Stefania Gori
Pilar Hernandez
Igor Irastorza
Joerg Jaeckel
Felix Kahlhoefer
Gaia Lanfranchi
Jacobo Lopez Pavon
Jocelyn Monroe
Silvia Pascoli
Maxim Pospelov
Philip Schuster
Mikhail Shaposhnikov
Jessie Shelton
Yevgeny Stadnik
Stefan Ulmer
indico.cern.ch/e/FIPs2022
CERN

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:

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

Direct searches of HNLs

$N_R = 2$

- Direct detection requires:

$$\theta_{\alpha i} \gg \sqrt{m/M} \Longleftrightarrow \boldsymbol{R_{ij} \gg 1}$$

$$\Longleftrightarrow \theta^2_{\alpha i} \propto e^{-2\theta i} \boxed{e^{2\gamma} f\left(\delta, \phi_1, M_j\right)}$$

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

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

Sensitivity to PMNS CP-phases! δ, ϕ_1

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

LIGHT NEUTRINO
contribution

$$|m_{\beta\beta}|_{IH} \simeq$$

$$\simeq \sqrt{\Delta m^2_{atm}} \left| c^2_{13} \left(c^2_{12} + e^{2i\phi_1} s^2_{12} \left(1 + \frac{r^2}{2} \right) \right) \right.$$

$$\left. - \quad f(A)\, e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 \frac{(0.9\,\mathrm{GeV})^2}{2M_1^2} \frac{\Delta M}{M_1} \right|$$

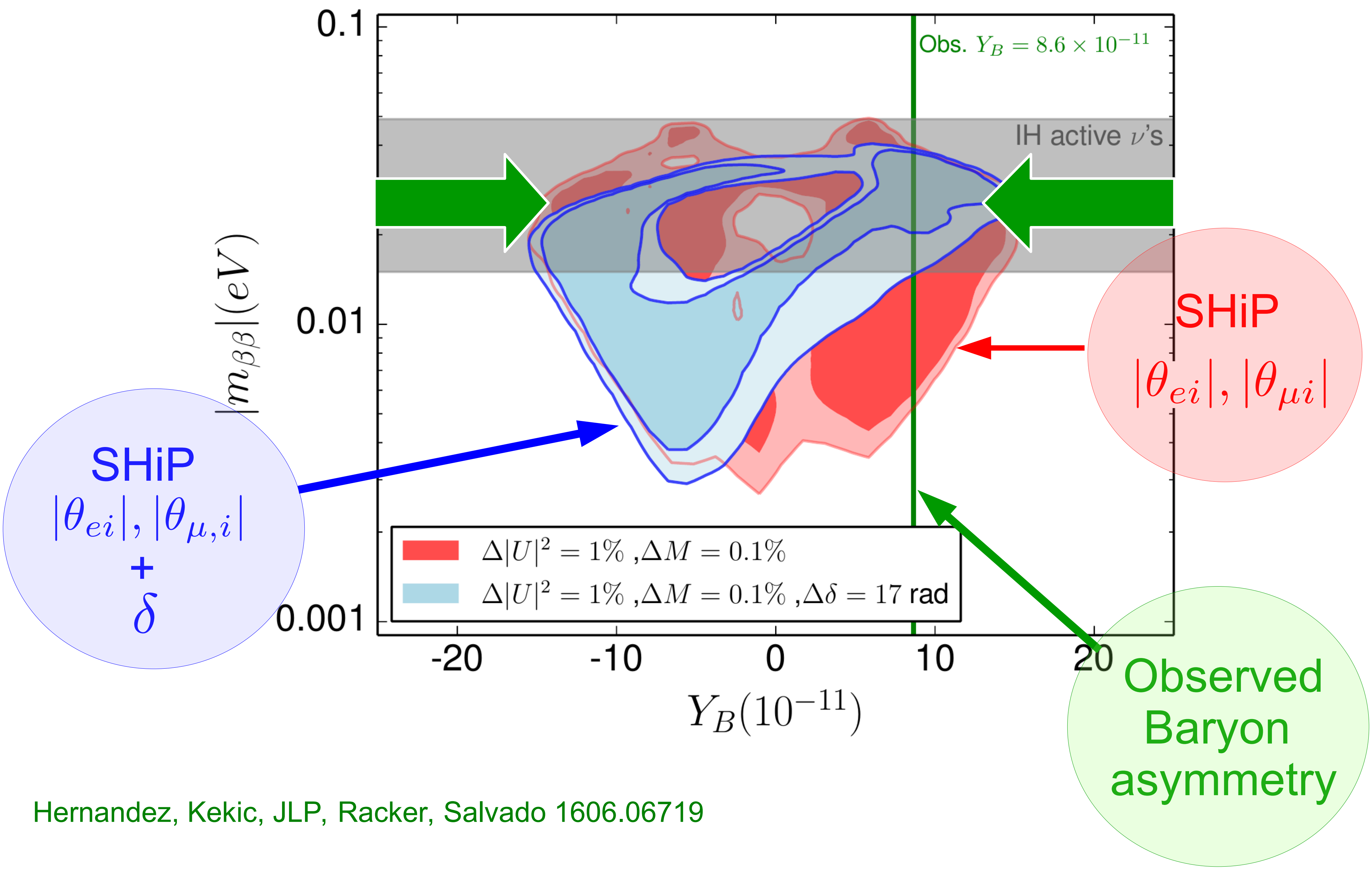
θ

HEAVY NEUTRINO
contribution

- Heavy neutrino contribution can be sizable for $M \sim O\,(GeV)$ ✔

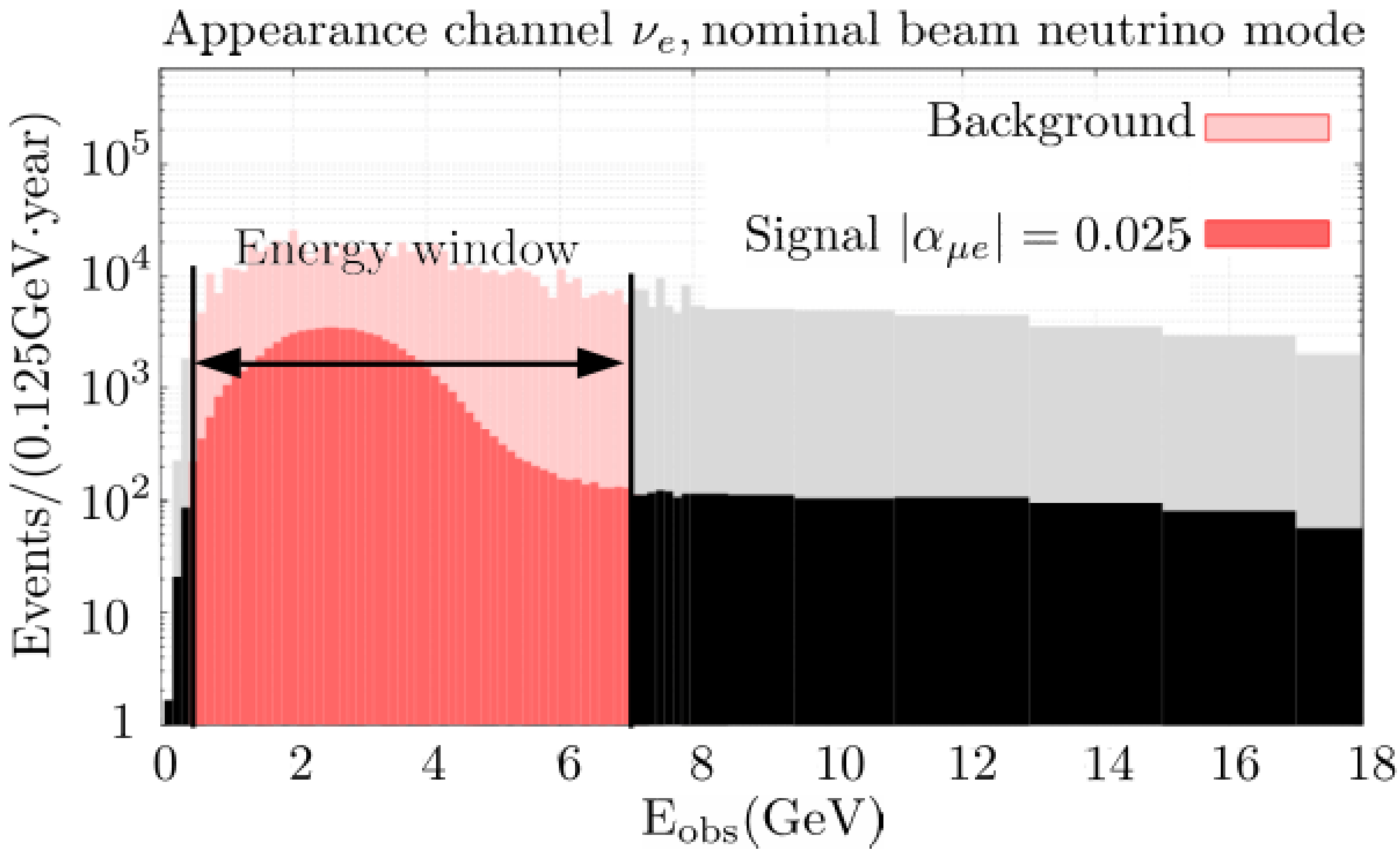
Mitra, Senjanovic, Vissani 2011
JLP, Pascoli, Wong 2012

GeV Scale Leptogeneis $N_R = 2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

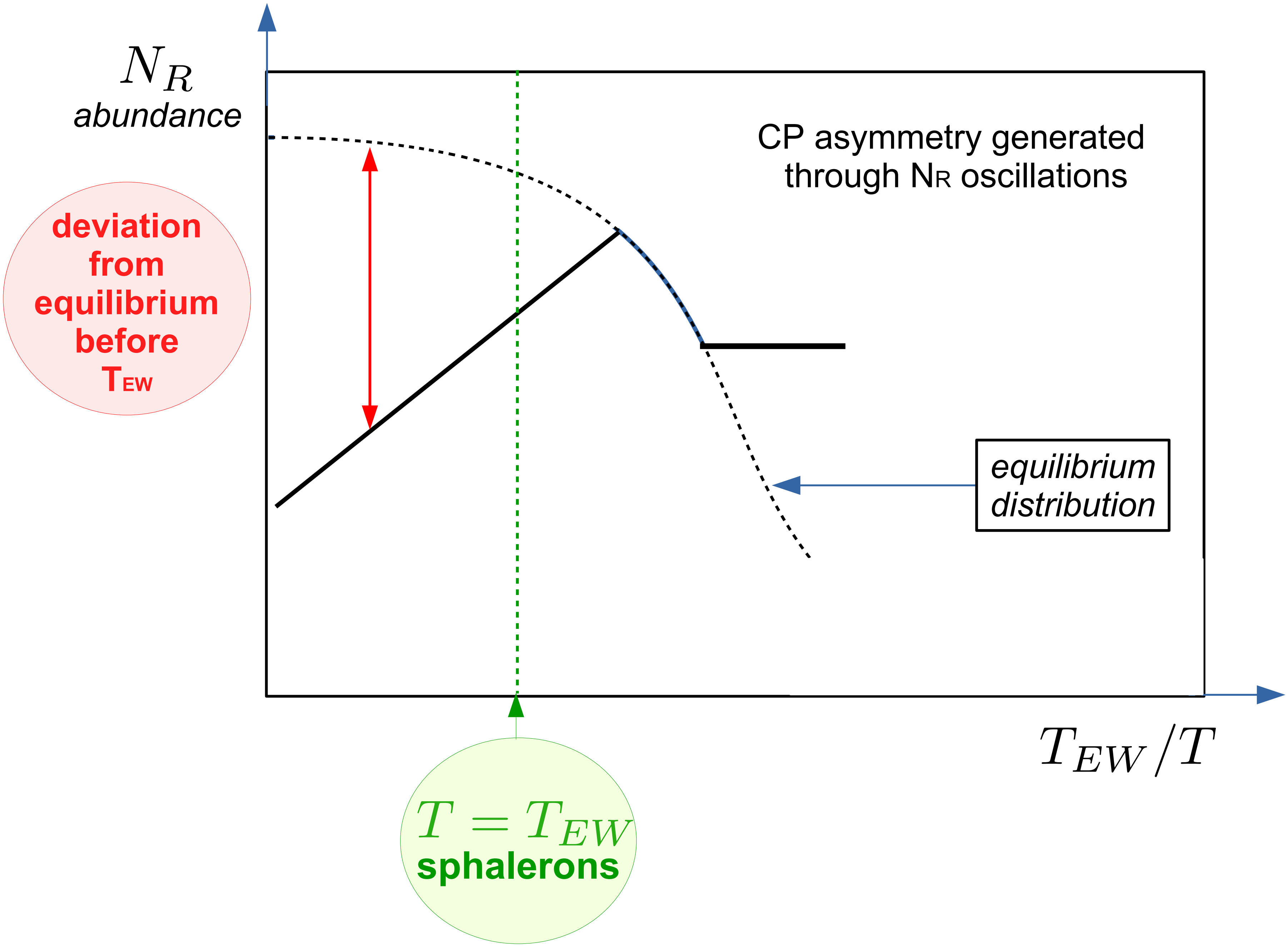
Role of shape uncertainty



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

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

Low Scale Leptogenesis (ARS)



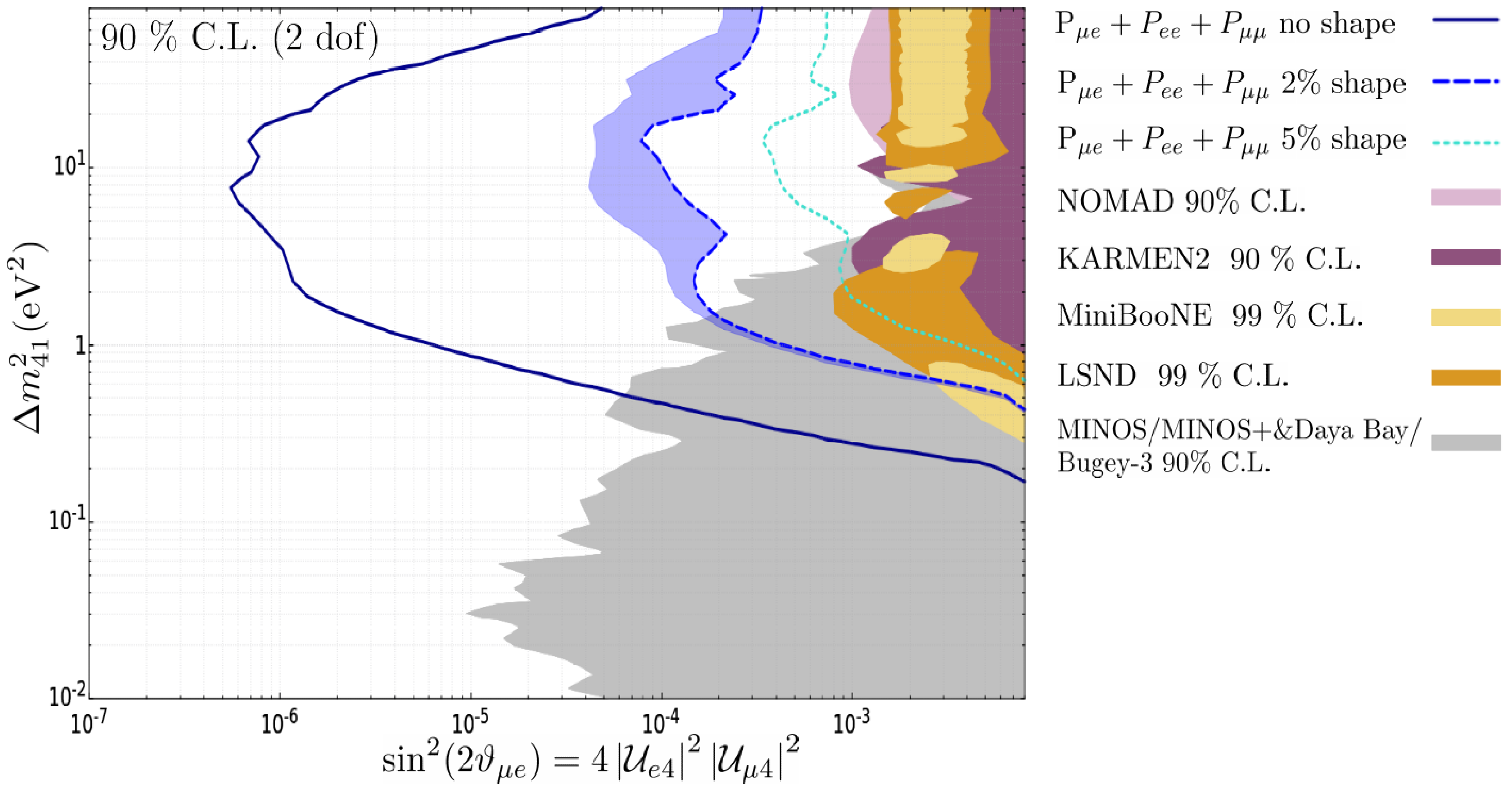
Sterile Neutrinos: 3+1

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

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

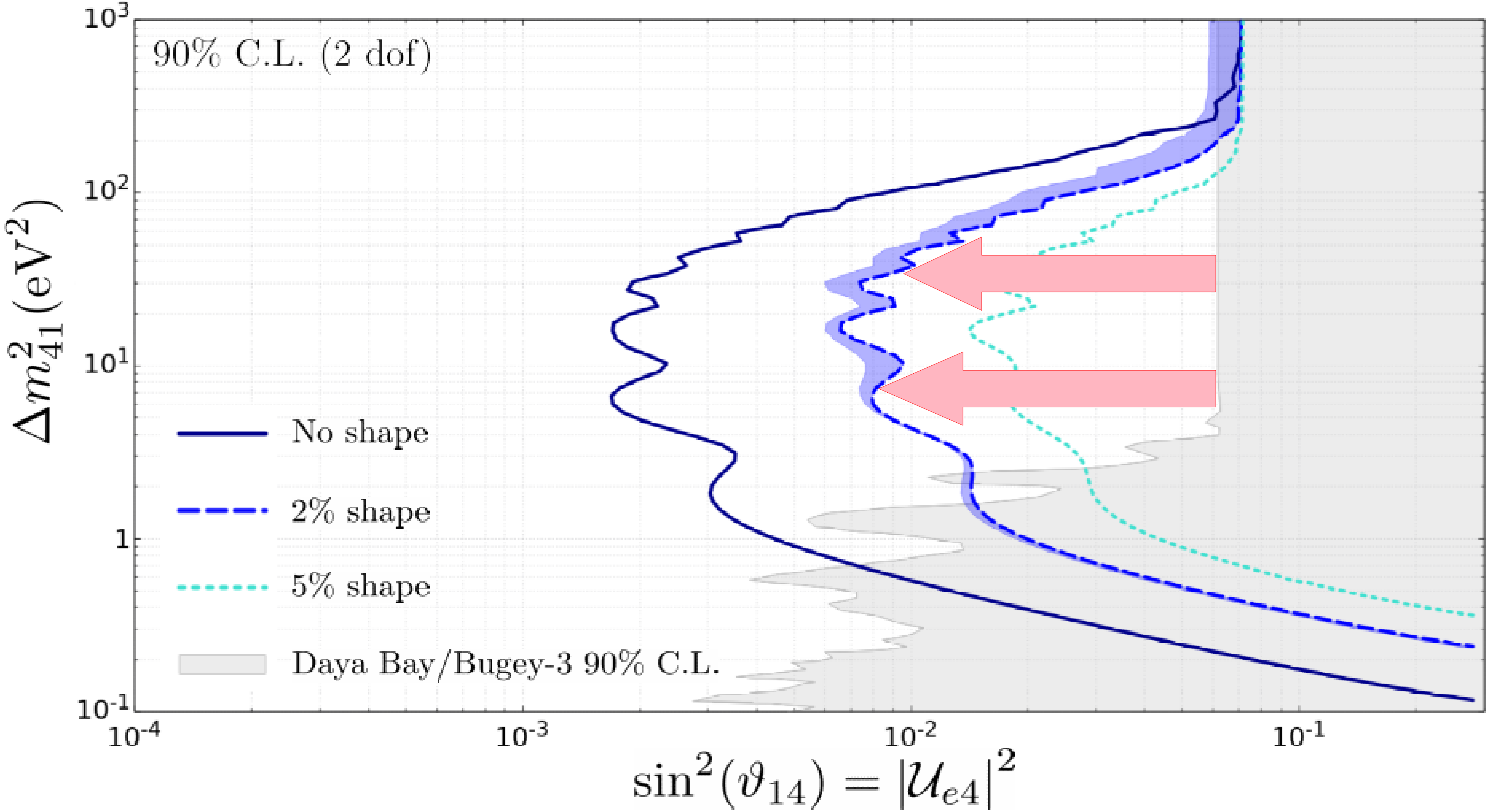
$$\mathcal{P}_{ee} = 1 - 4|U_{e4}|^2 \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

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



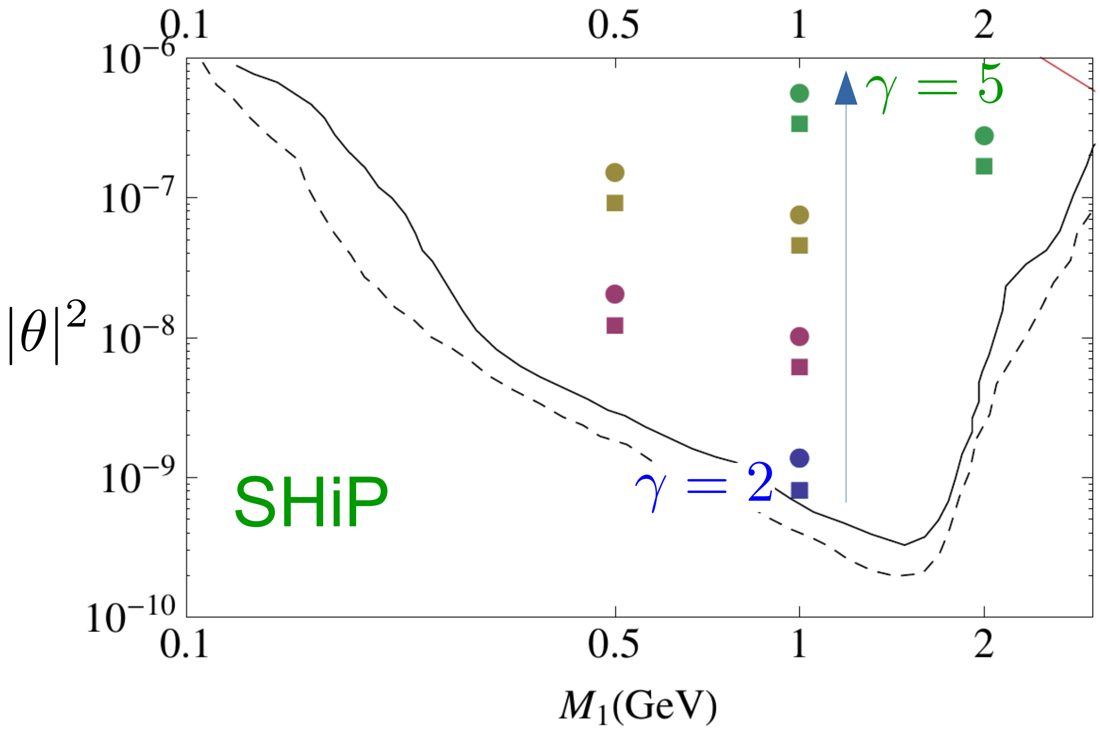
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

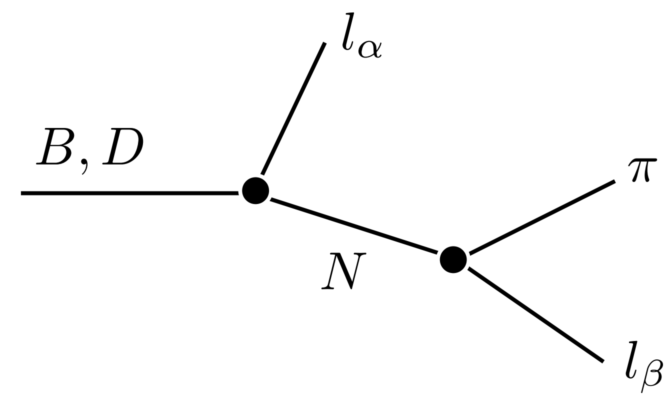
3+1 Sterile Neutrinos: P_{ee}

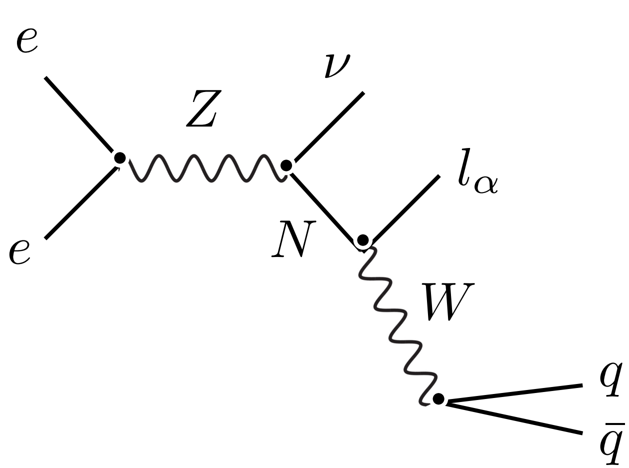


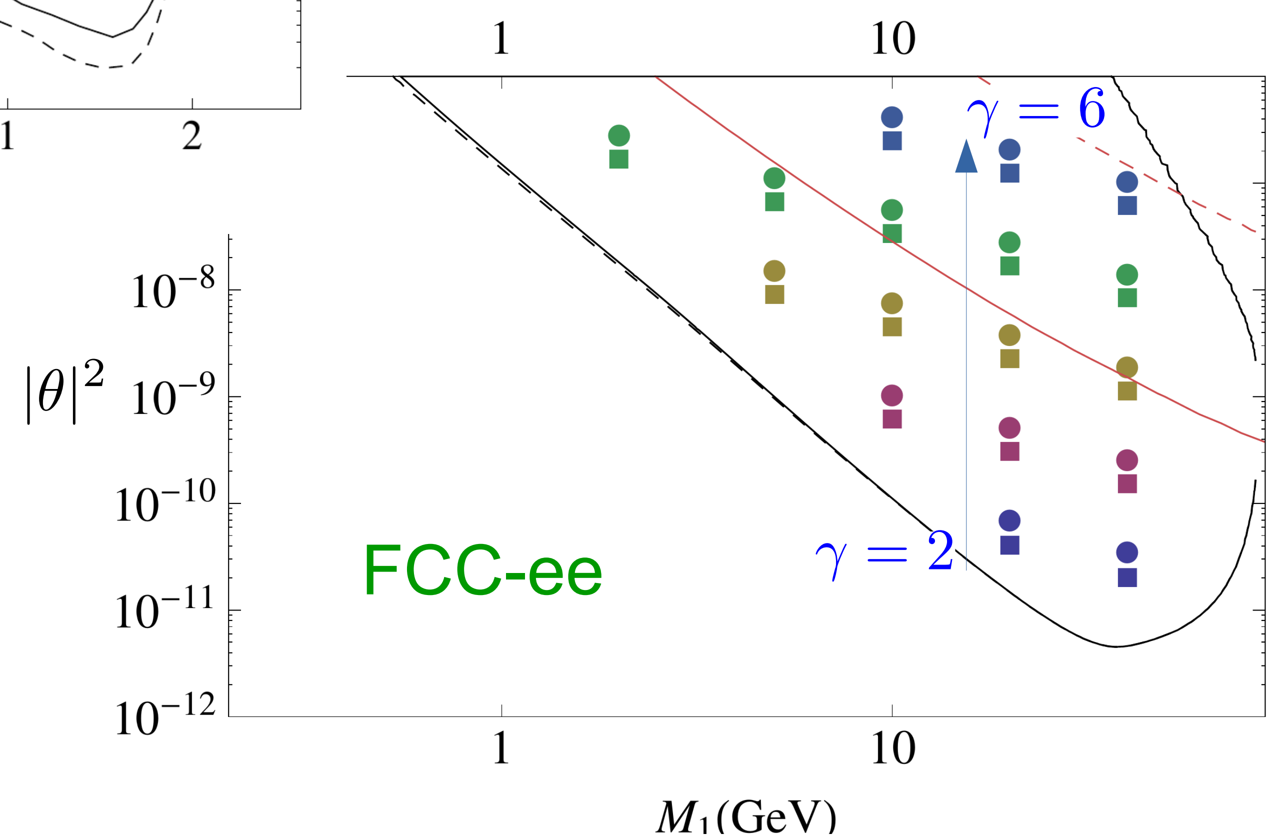
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

For instance…

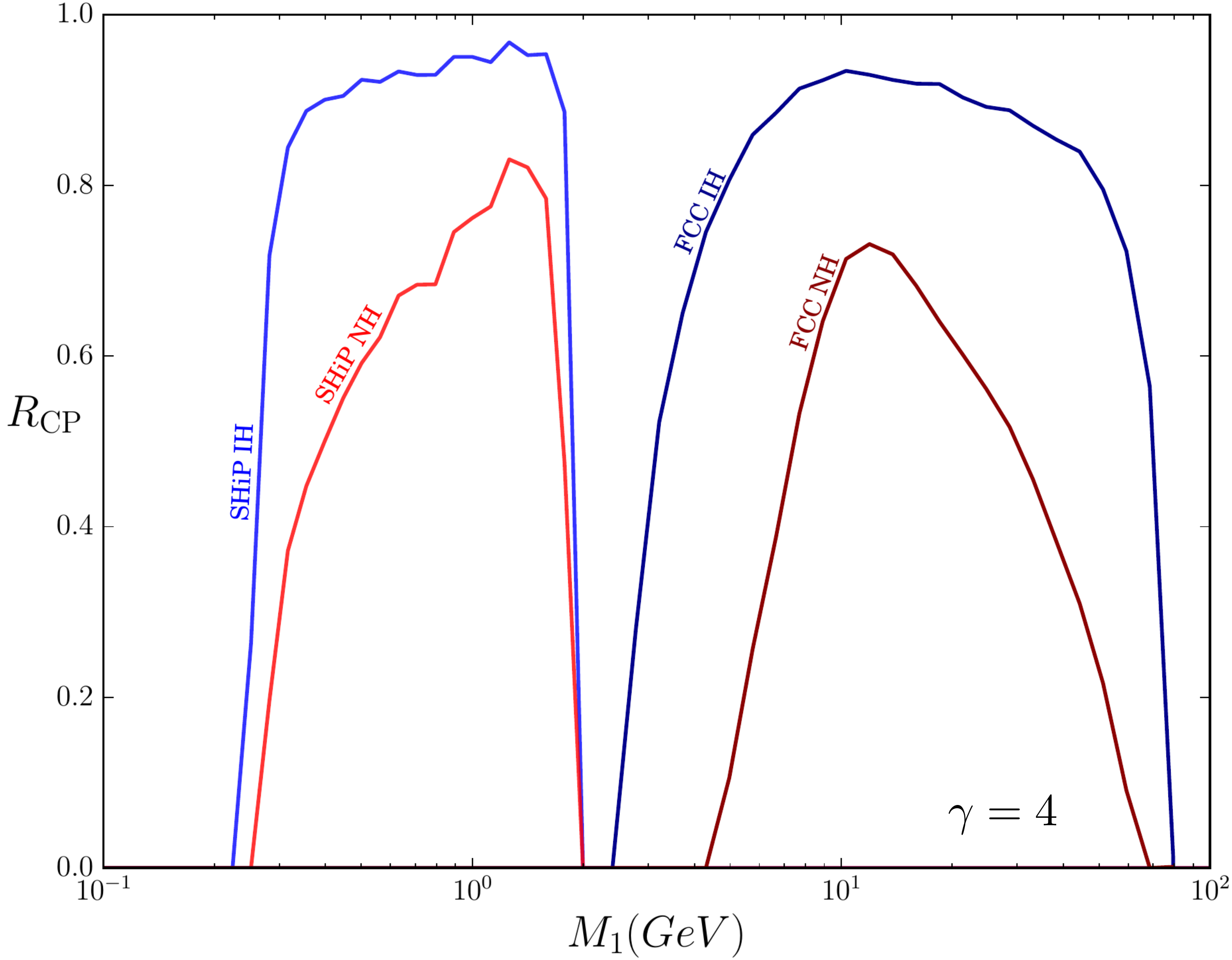






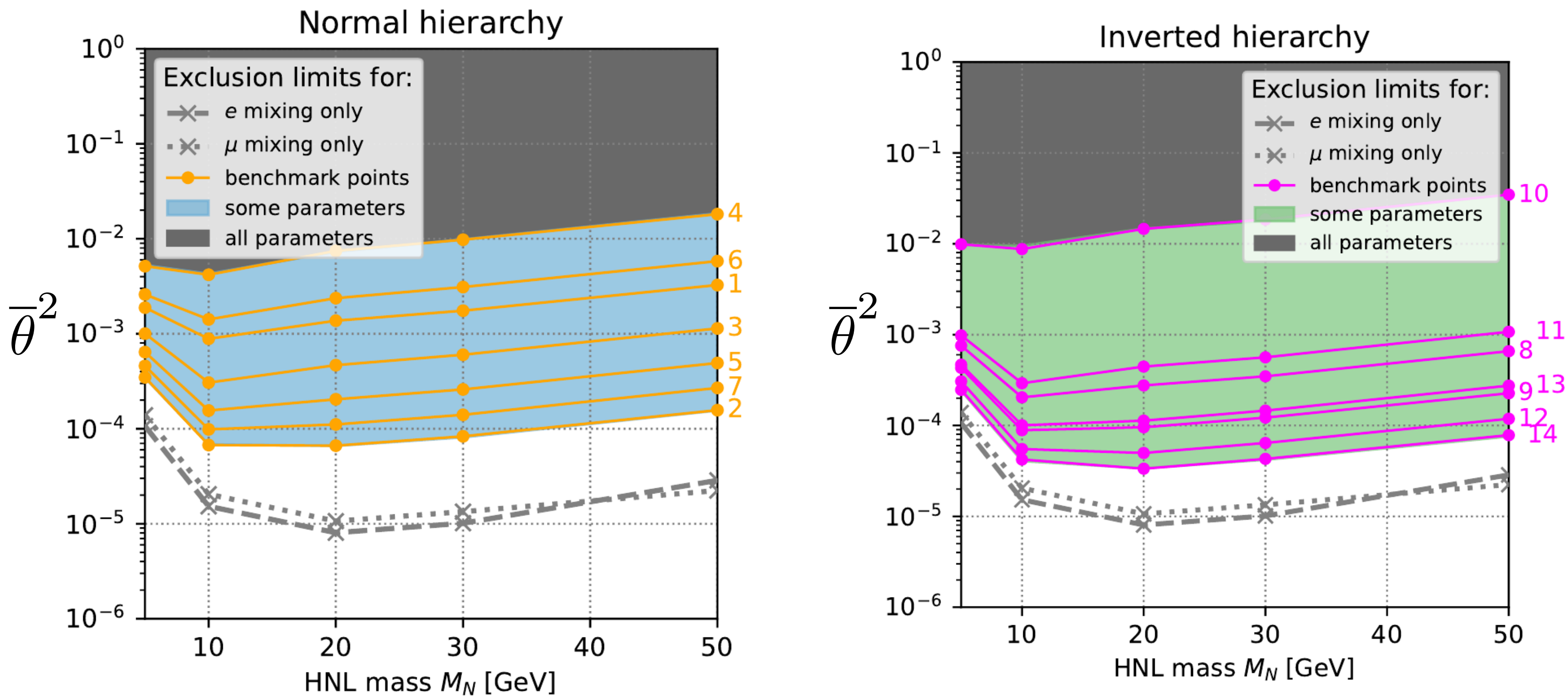


5σ discovery PMNS CP-violation



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

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.

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).

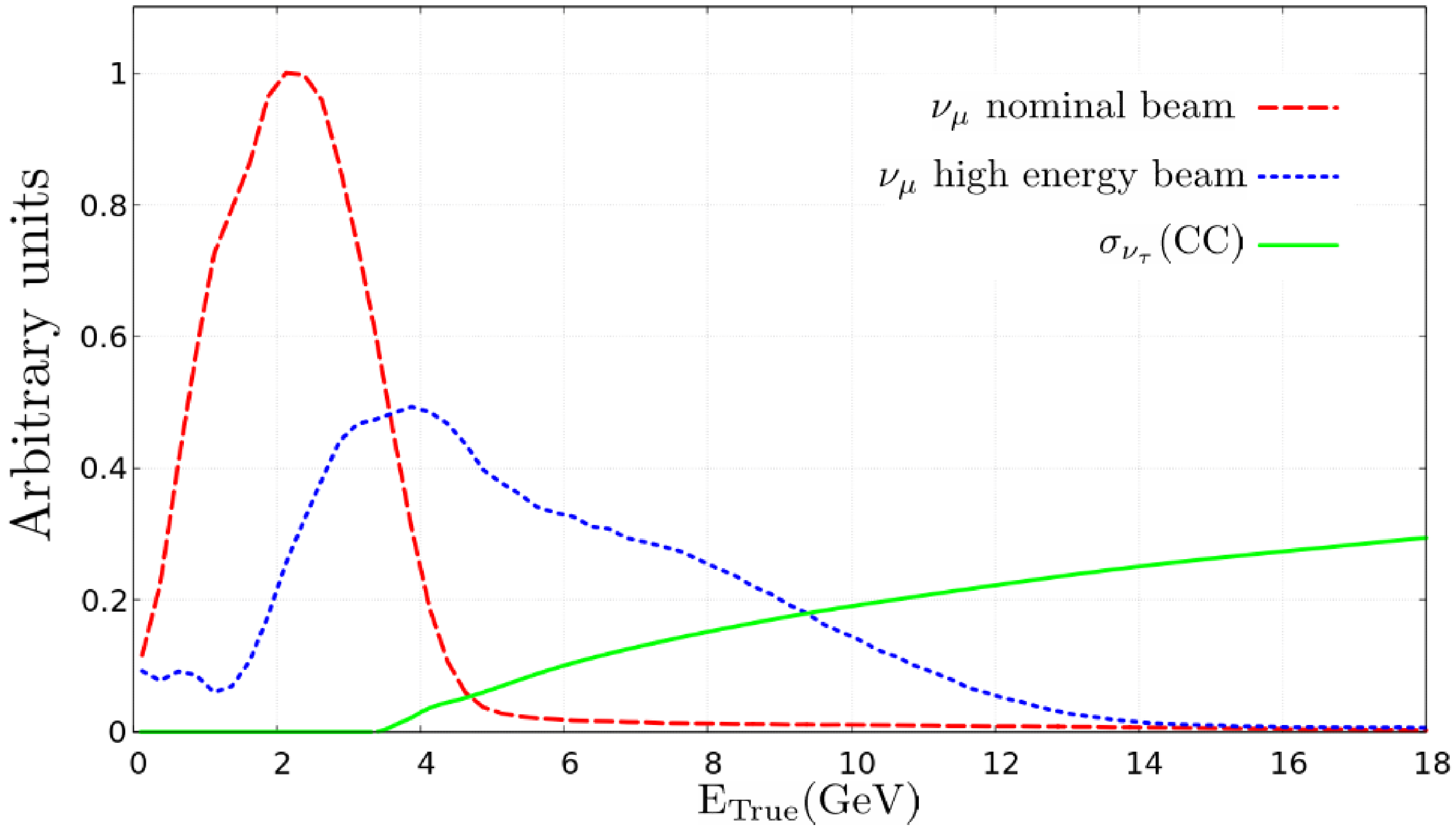
- NC background. We have considered a sample in which 30% of the hadronic events are identified keeping 0.5% of NC background.

de Gouvêa, Kelly, Stenico, Pasquini 1904.07265

See talks by Pedro Machado & Adam Aurisano

ν_τ appearance channel

- Energy threshold of τ production 3.2 GeV.



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

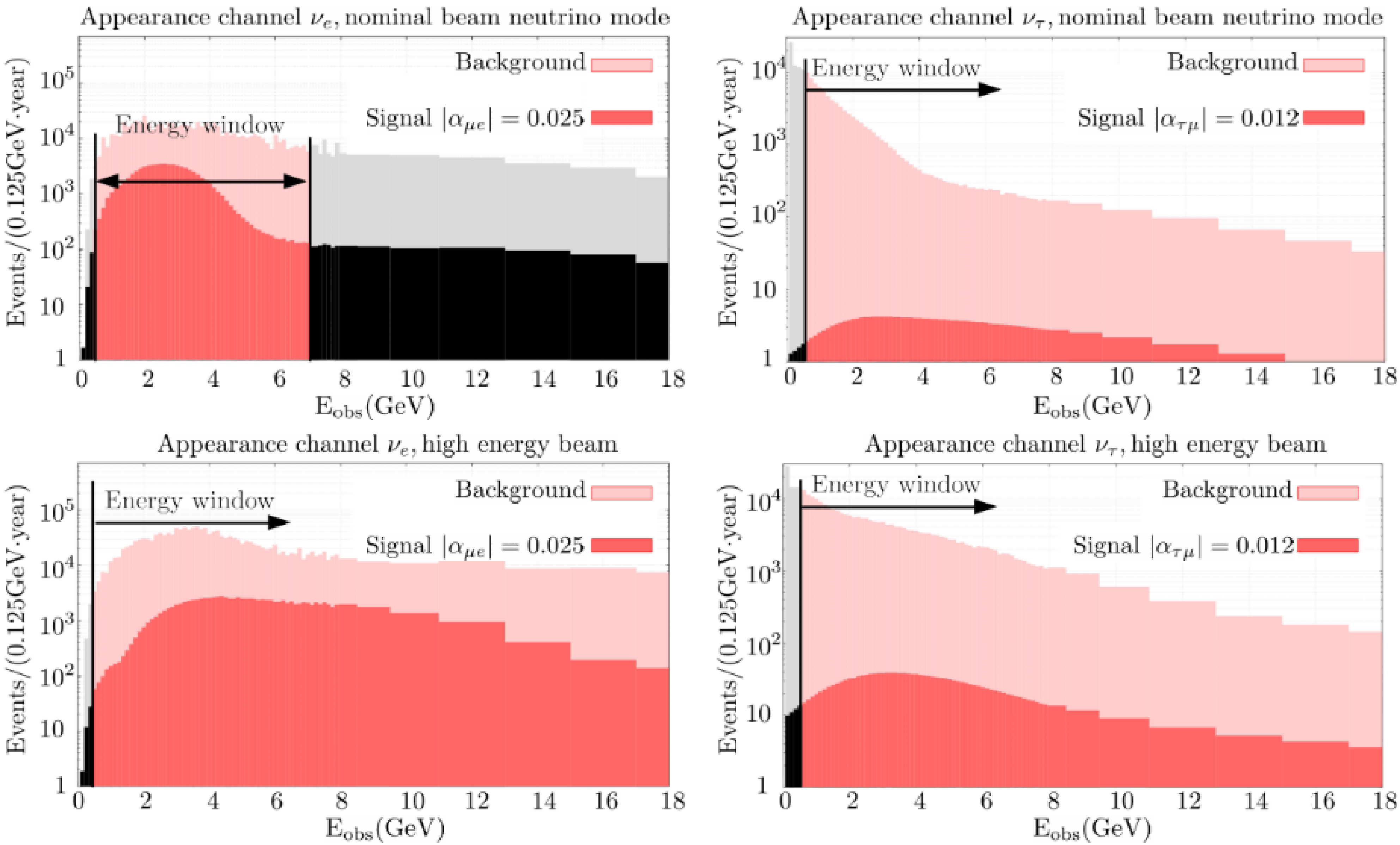
DUNE set up

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)	$M_{\rm det}$
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%

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

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

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

Present Bounds (update)

	2σ Non-Unitarity $(M > \text{EW})$	$90\% C.L.$ Non-Unitarity $(M \gtrsim 1\,\text{eV})$
α_{ee}	$1.3 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$ SOLAR
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$5.0 \cdot 10^{-3}$ MINOS
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$6.5 \cdot 10^{-2}$ ATM
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$9.2 \cdot 10^{-3}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$

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

Fernandez-Martinez, Hernandez-Garcia, JLP 1605.08774
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637
Argüelles et al, 2203.10811