Facultad de Ciencias
Universidad Autónoma de Madrid
Instituto de Física Teórica UAM-CSIC

Rencontres de Moriond since 1966

PROBING THE HEAVY NEUTRINO HYPOTHESIS

Xabier Marcano

Funded by the European Union
PheNumenal
EXCELENCIA SEVERO OCHOA

Motivation

ν_e	ν_μ	ν_τ	?
electron neutrino	**muon neutrino**	**tau neutrino**	

ν_e — electron neutrino

ν_μ — muon neutrino

ν_τ — tau neutrino

?

BSM Behind Neutrino Masses

ν_e

electron neutrino

ν_μ

muon neutrino

ν_τ

tau neutrino

ν_s

Heavy neutrino

ν_e

electron neutrino

Curriculum Vitae

Heavy Neutrino

Right-handed/sterile neutrino, heavy neutral lepton (HNL)

ν_s

Spin
1/2

Color
single

Isospin
single

Charge
0

Mass
how dare you!?

Social life
not much

Work experience

- Neutrino masses

Other skills

- Osc. anomalies
- Dark matter
- Baryogenesis
- Cooking

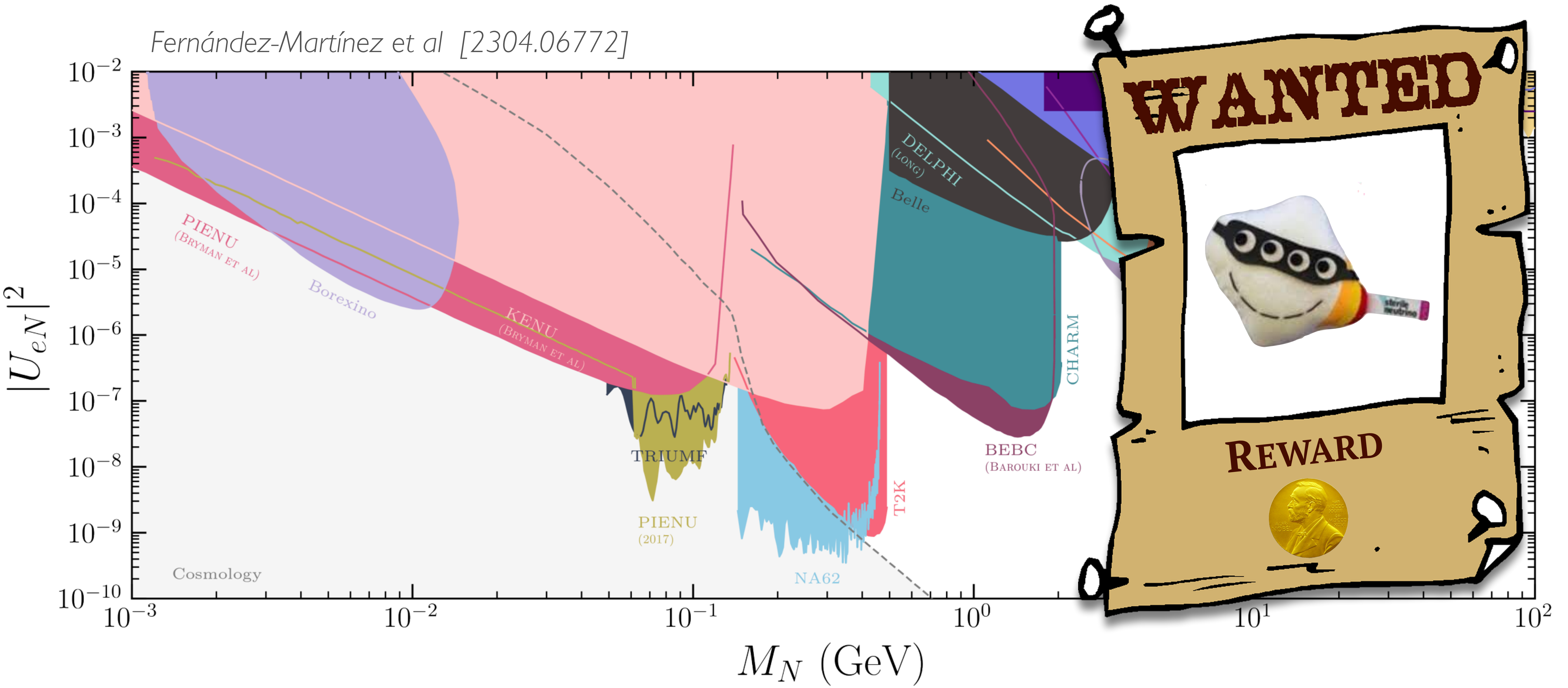
citations

ν_s

Heavy neutrino

Searches for Heavy Neutrinos

Fernández-Martínez et al [2304.06772]

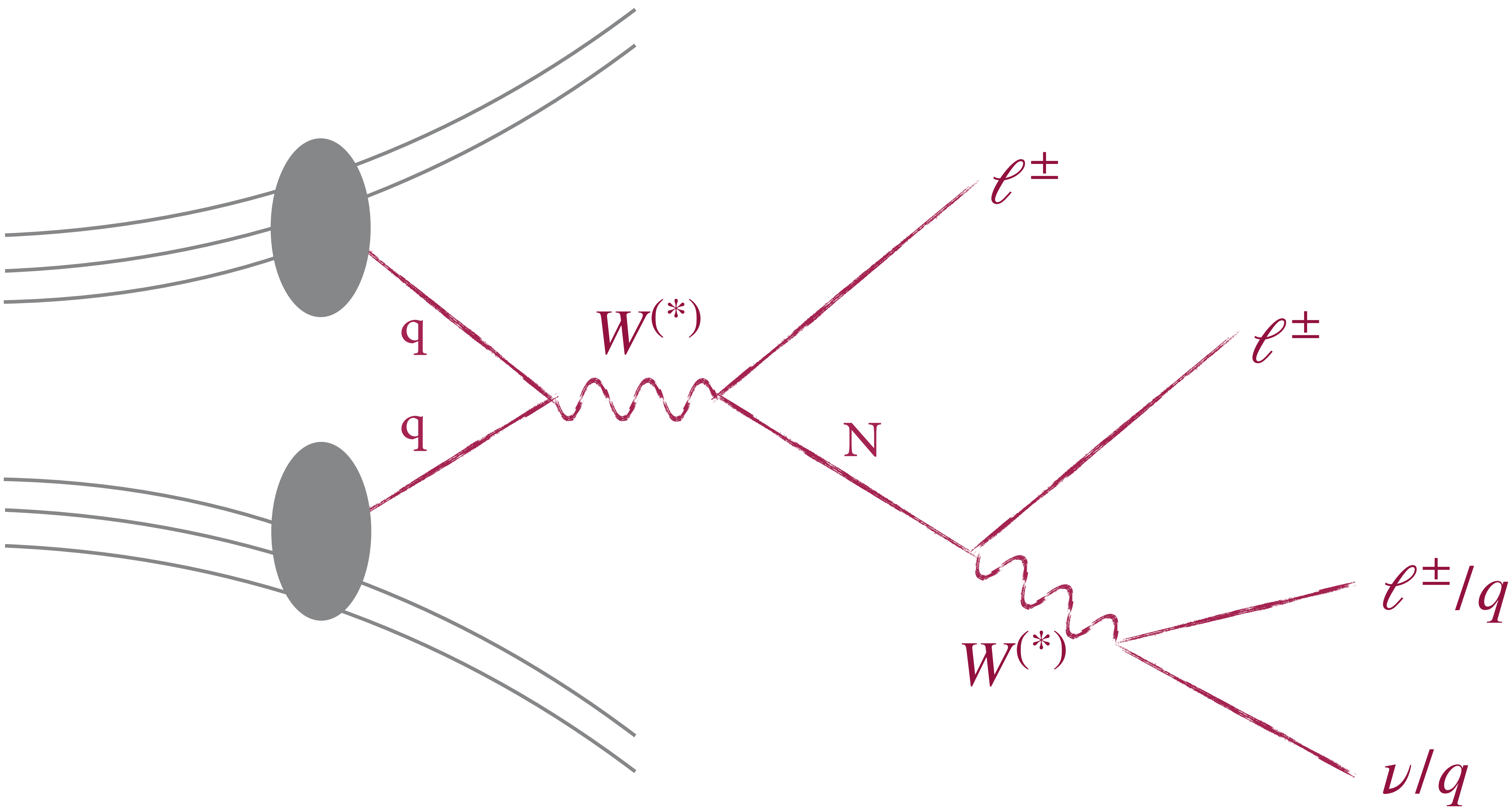


Which track?

Heavy Neutrino (HNL) Searches at LHC

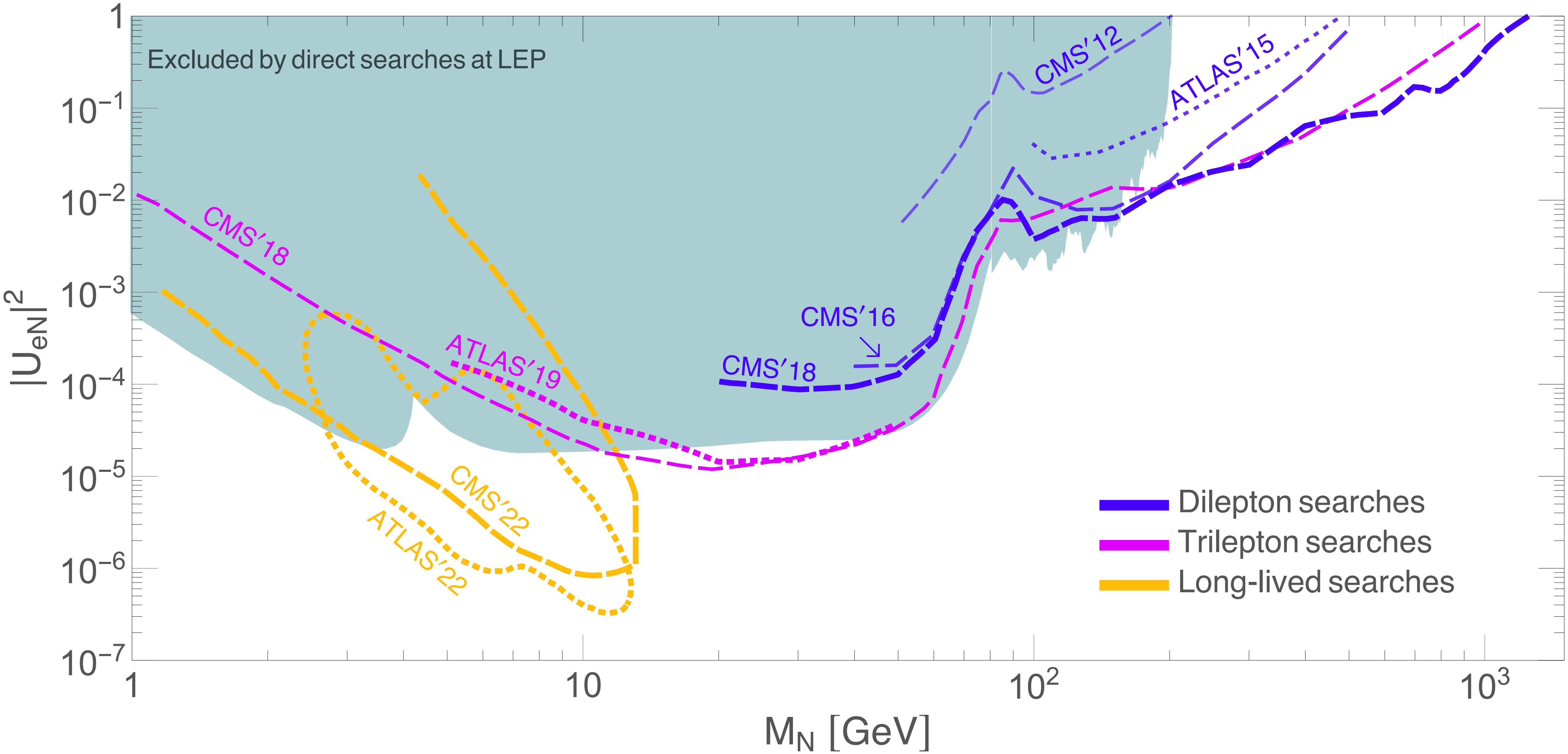
— see talk by Sergio Grancagnolo —

Production and Decay at LHC



Current Status: electron

Abada, Escribano, XM, Piazza [2208.13882]



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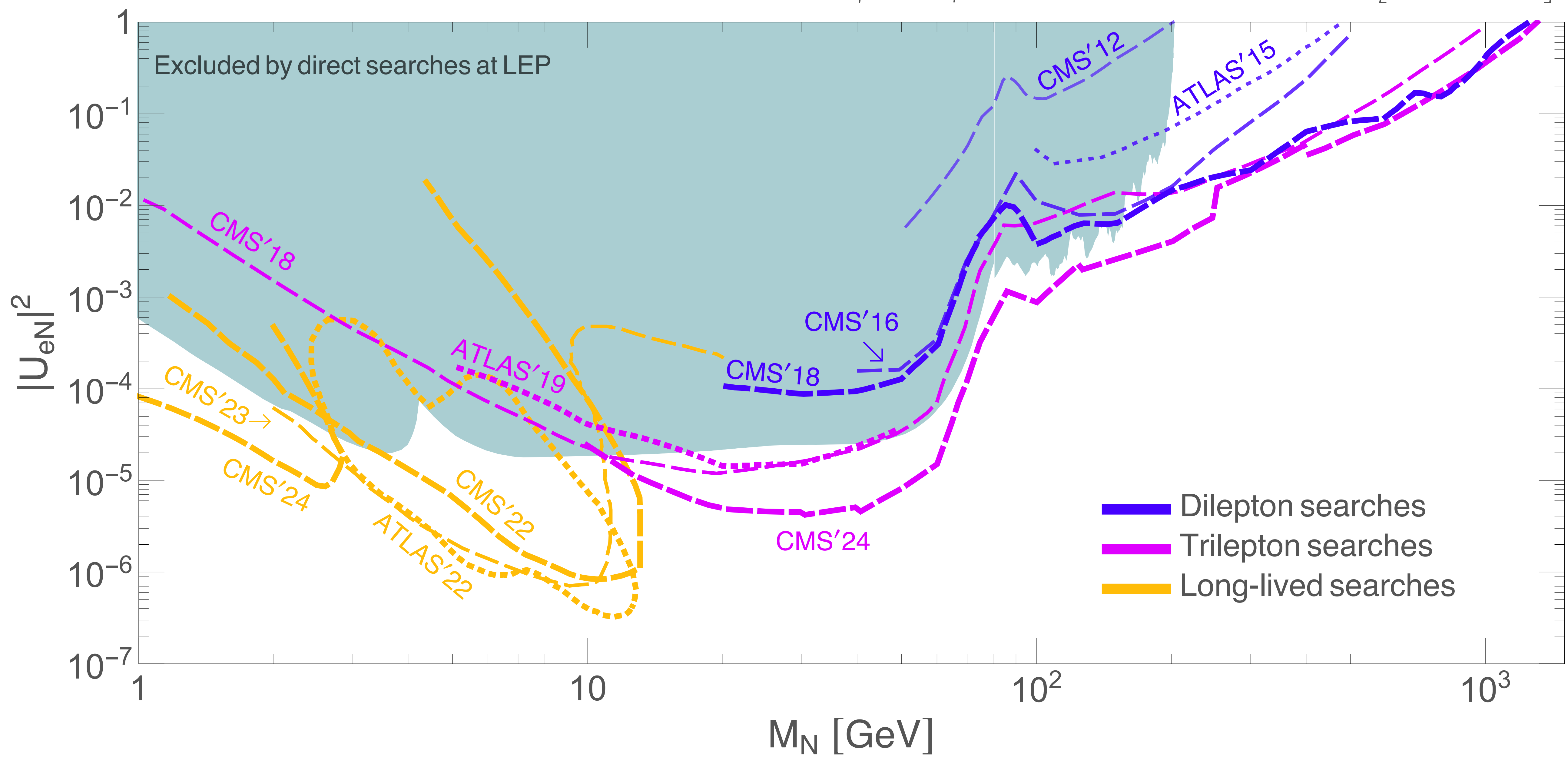
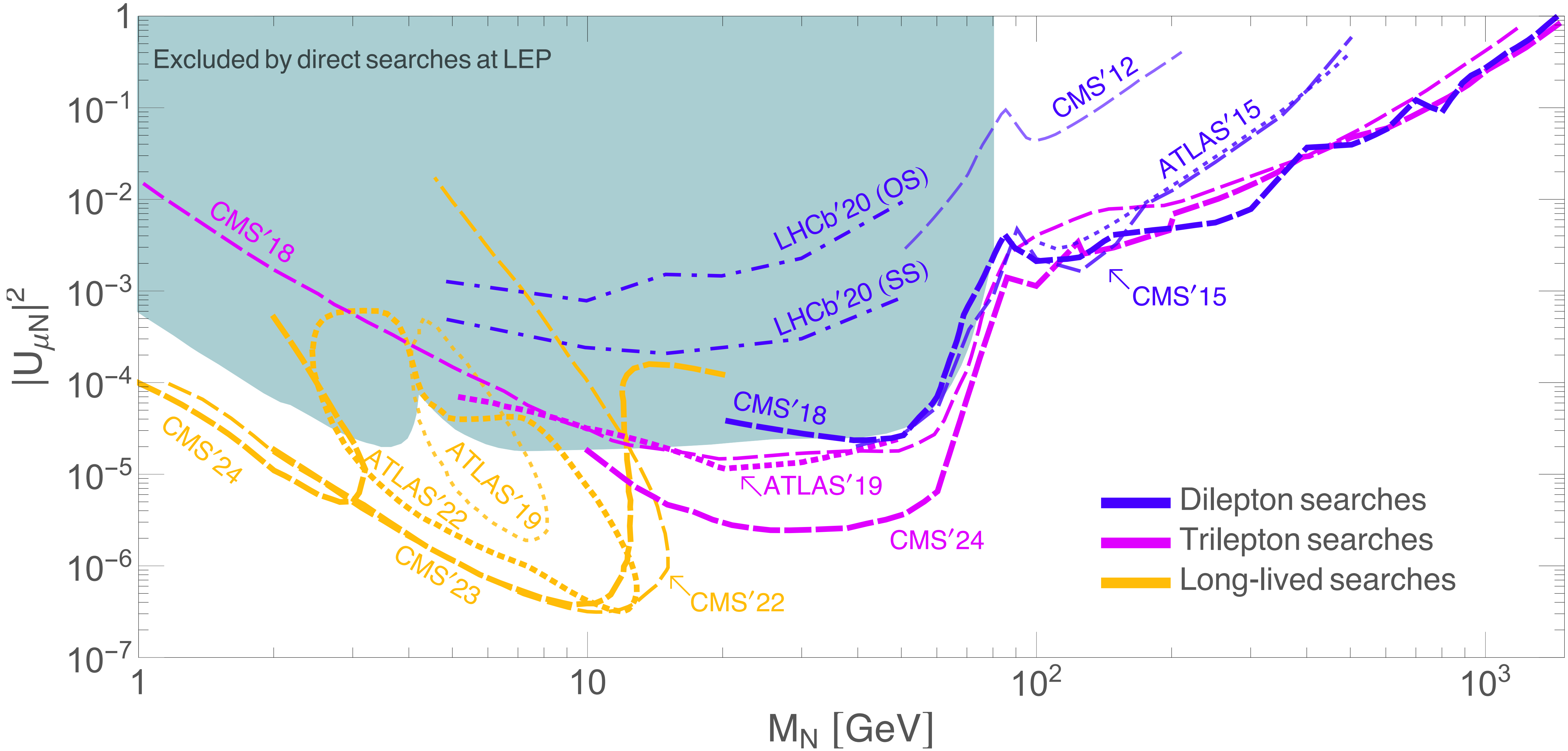
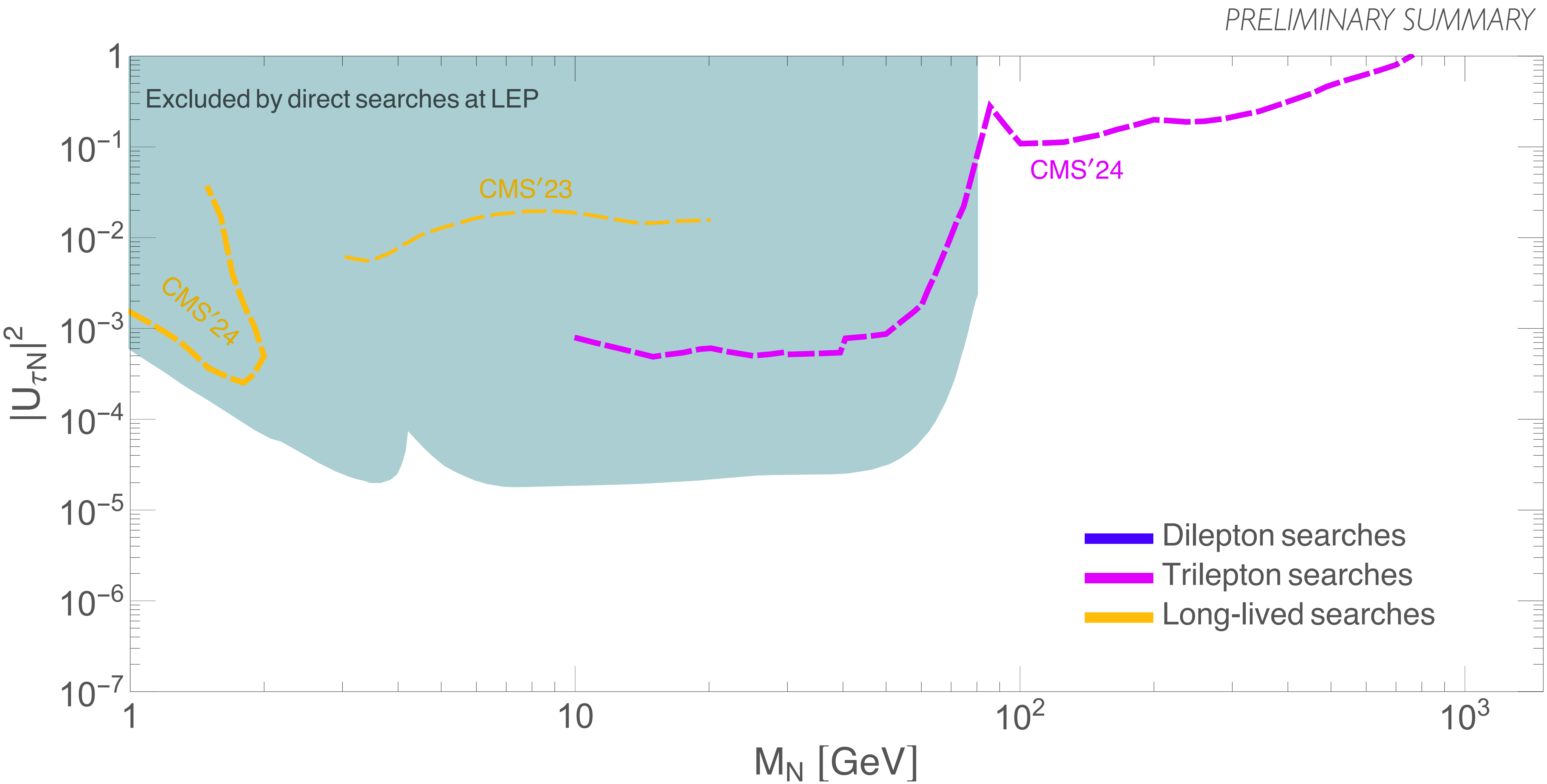


Current Status: muon

updated from Abada, Escribano, XM, Piazza [2208.13882]



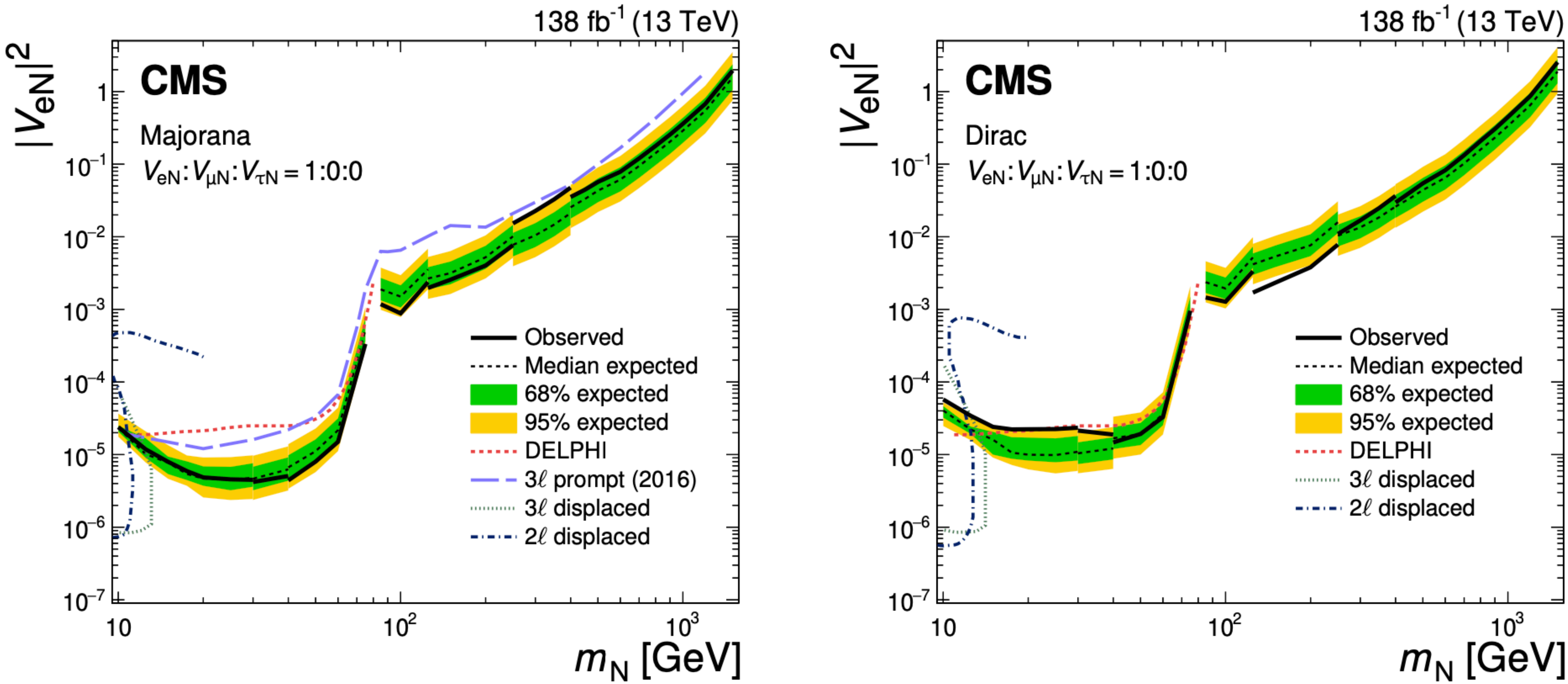
Current Status: tau



Dirac vs Majorana

- *Search for both Dirac (LNV=0) and Majorana (LNV=LNC) hypotheses*

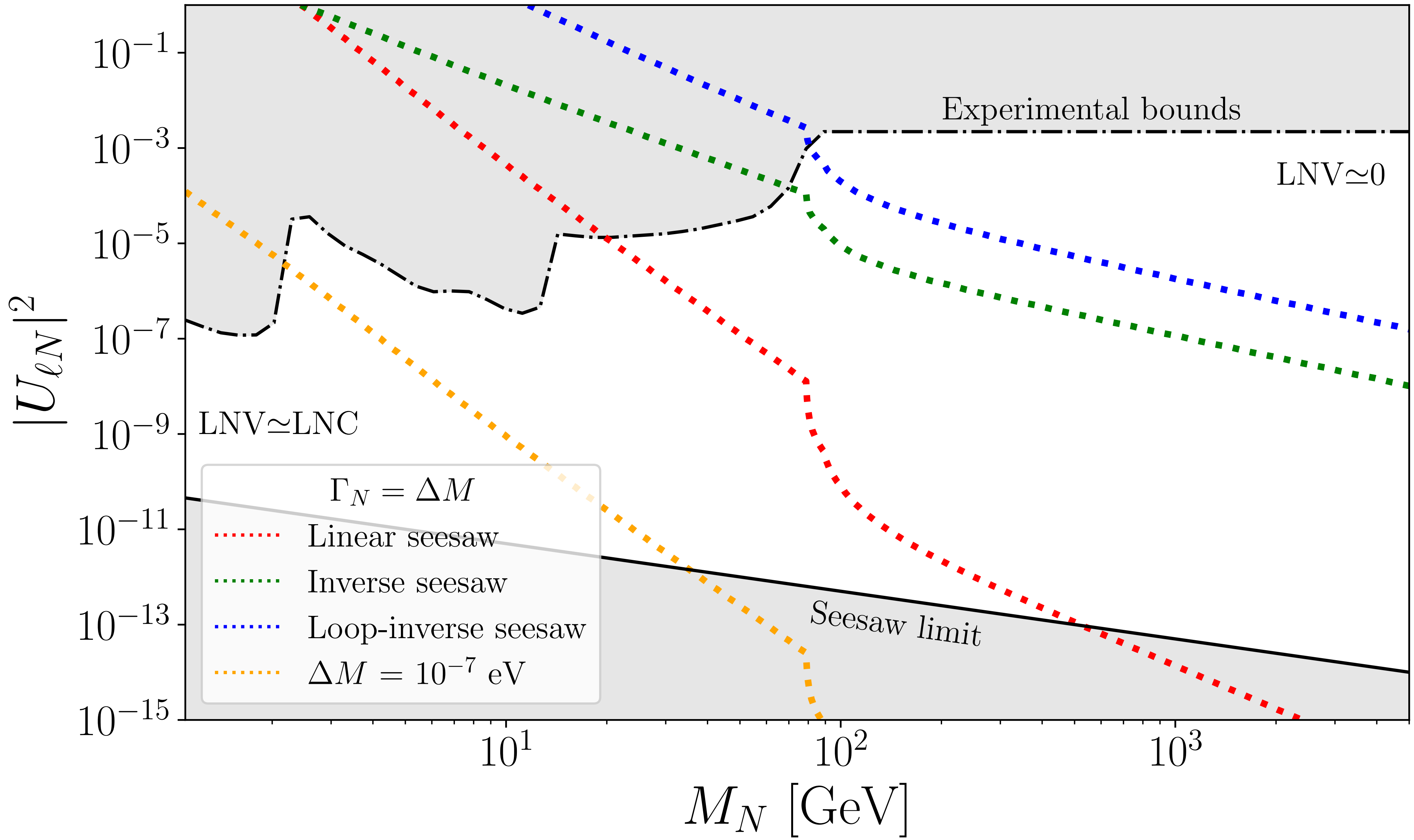
CMS trilepton [2403.00100]



Dirac vs Majorana

- *Search for both Dirac (LNV=0) and Majorana (LNV=LNC) hypotheses*
- *Discriminate between neutrino mass models (low-scale seesaws)*

Fernández-Martínez, XM, Naredo-Tuero [2209.04461]



Going Beyond the Single Mixing

— Realistic Models usually predict mixings to all flavor —

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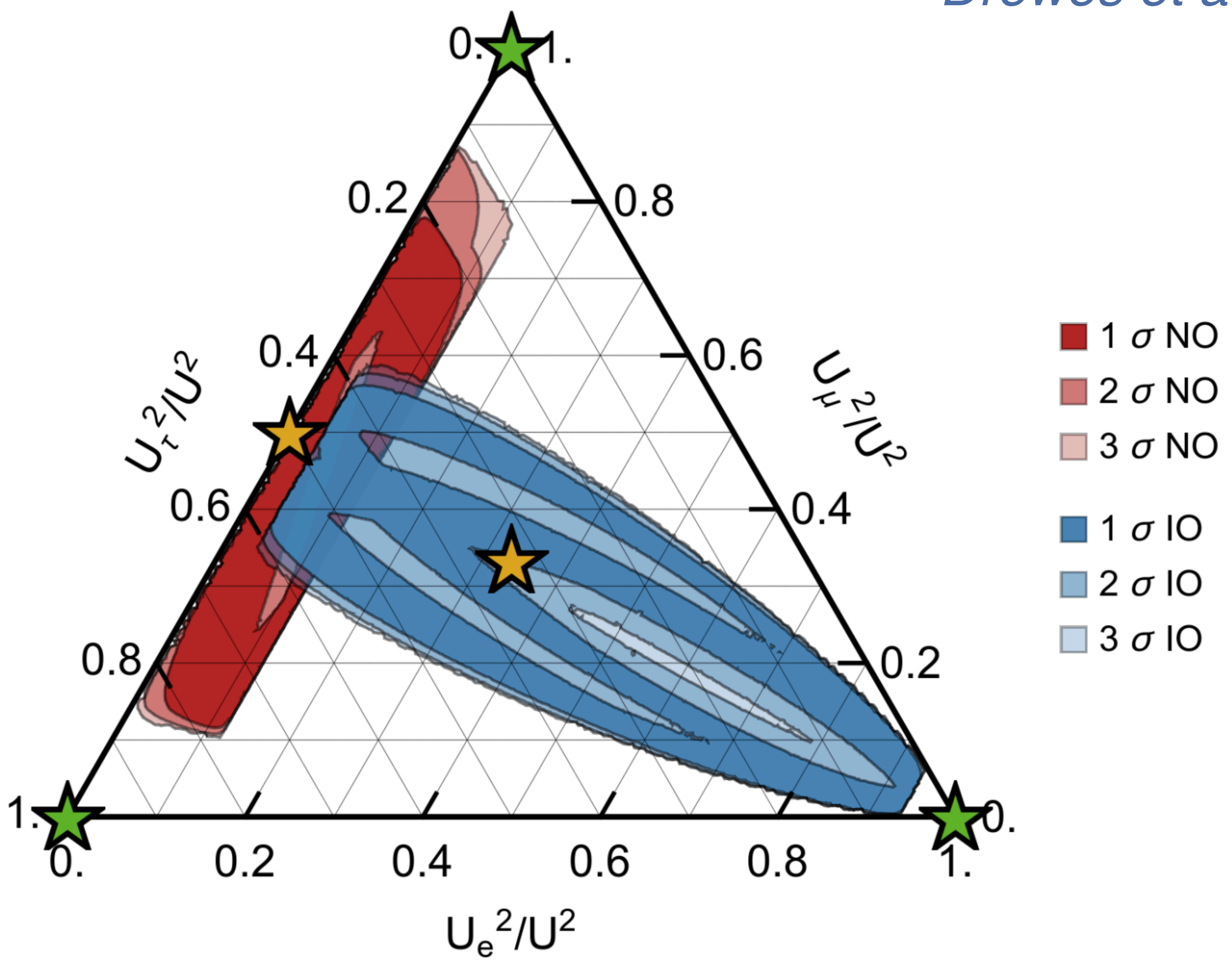
- *Results in the HEPData record* ✓

— Realistic Models usually predict mixings to all flavor —

- *Results in the HEPData record* ✓
- *Use motivated Benchmarks from flavor patterns in minimal models*

— Drewes et al [2207.02742] —



Going Beyond the Single Mixing

— Abada, Escribano, XM, Piazza [2208.13882]—

- *Simple recasting, e.g.* $pp \to \mu\mu jj$

$$\sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu jj)$$

$$\downarrow$$

$$|U_{\mu N}|^2 \, \mathrm{BR}(N \to \mu jj)$$

$$\downarrow$$

$$|U_{\mu N}|^2$$

Going Beyond the Single Mixing

— *Abada, Escribano, XM, Piazza [2208.13882]*—

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hep-ex →

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hep-ph →

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↓ ← *Mixing to a single flavor*

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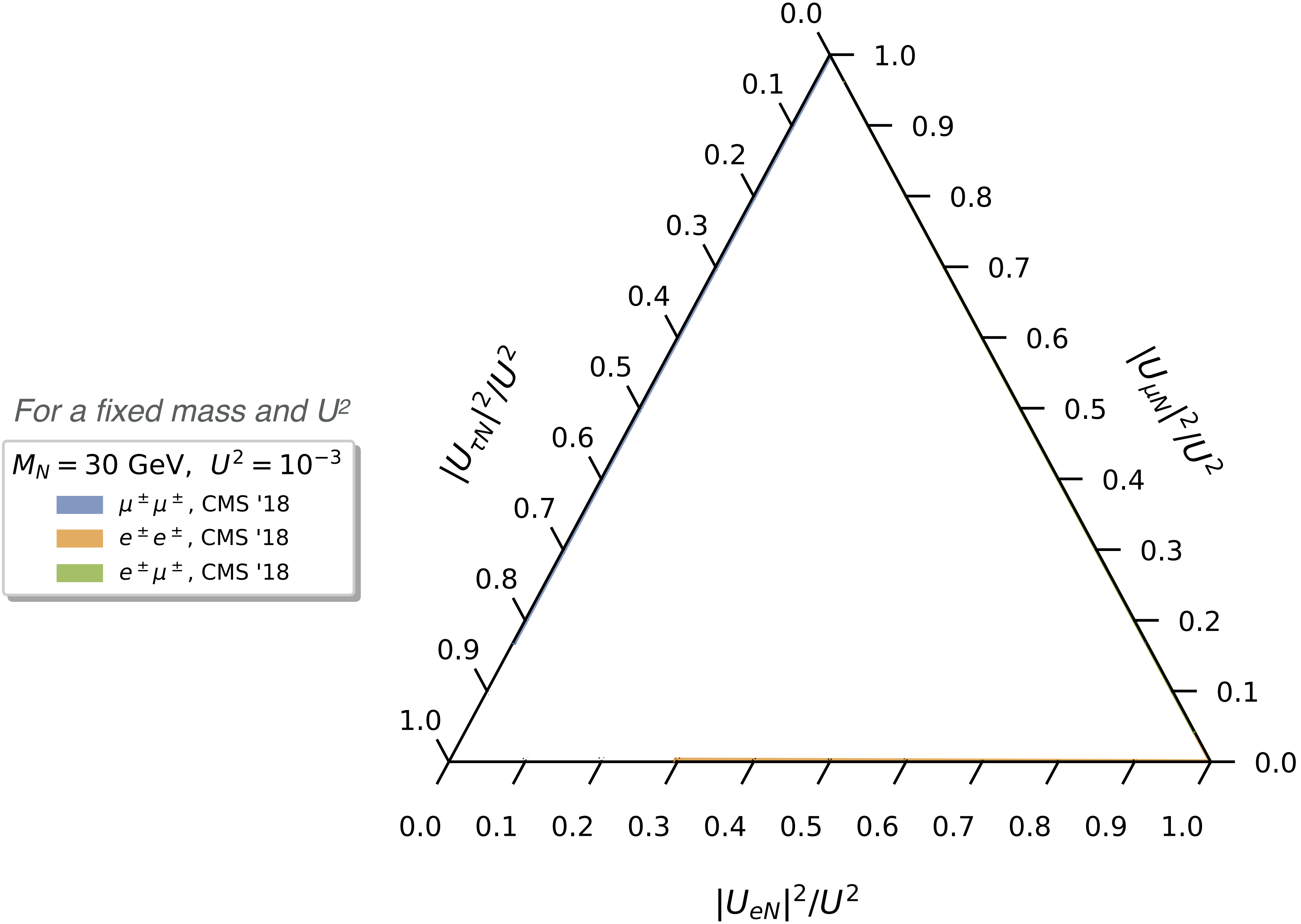
Recast — dileptons

— Abada, Escribano, XM, Piazza [2208.13882]—

For a fixed mass and U^2



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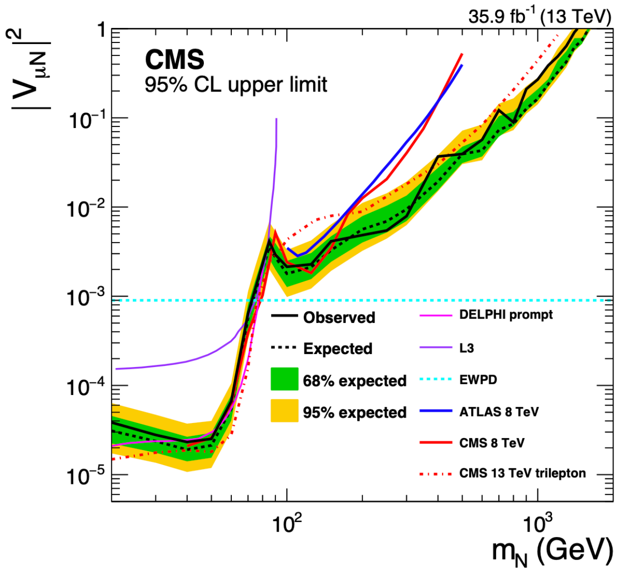

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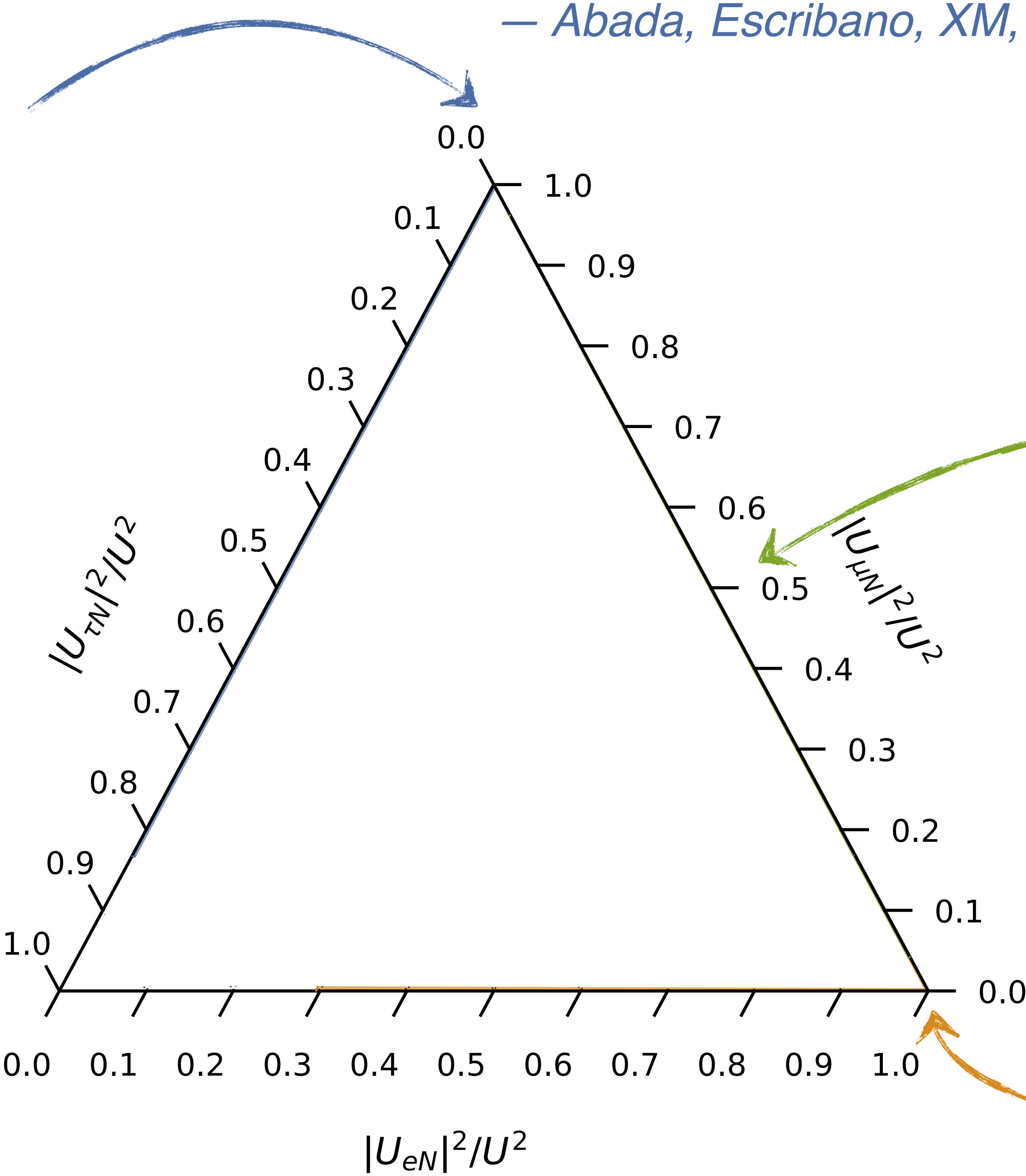
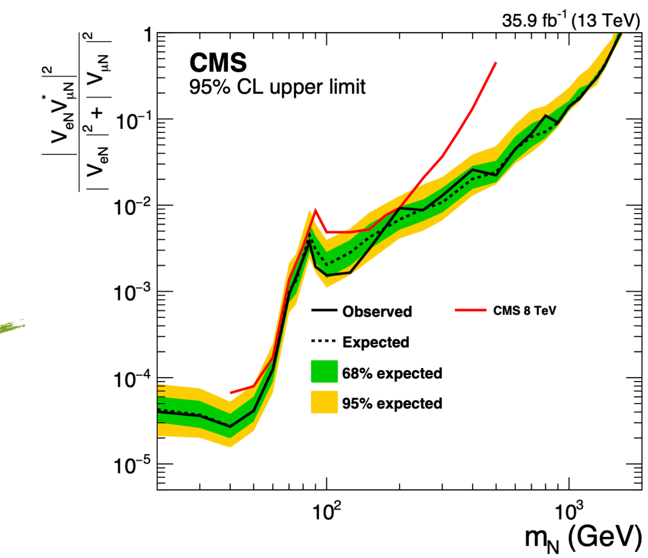
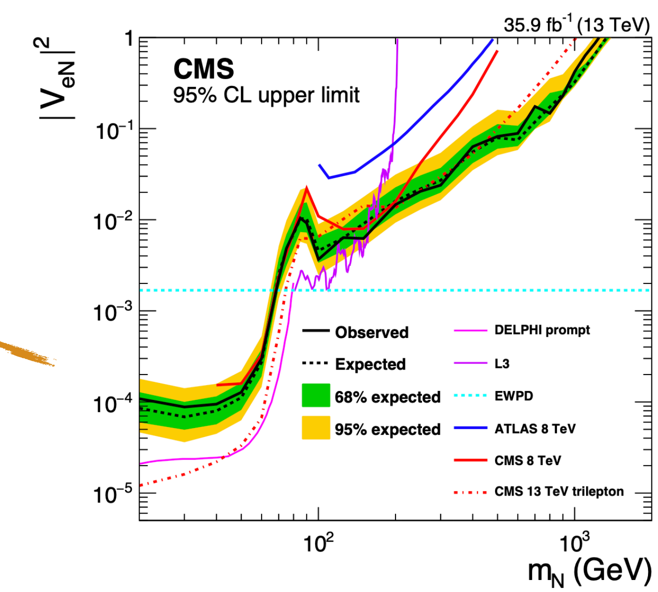
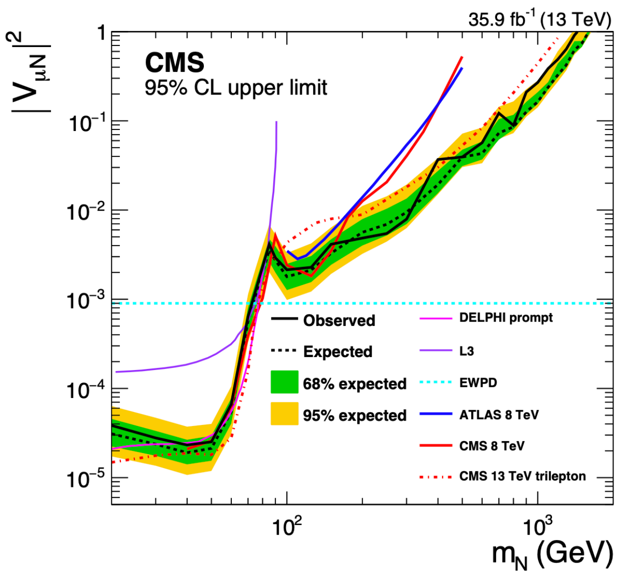






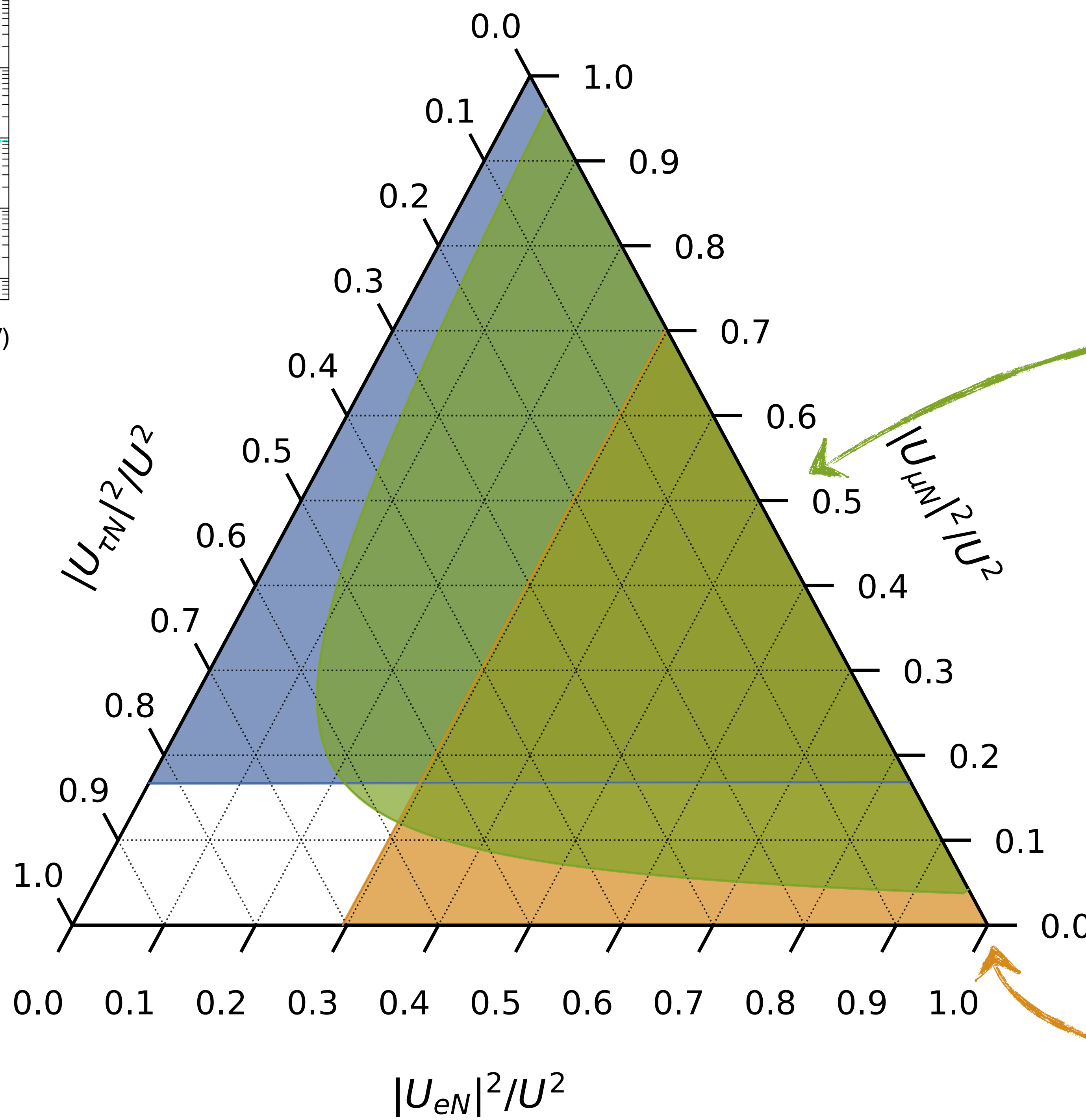
Recast — dileptons

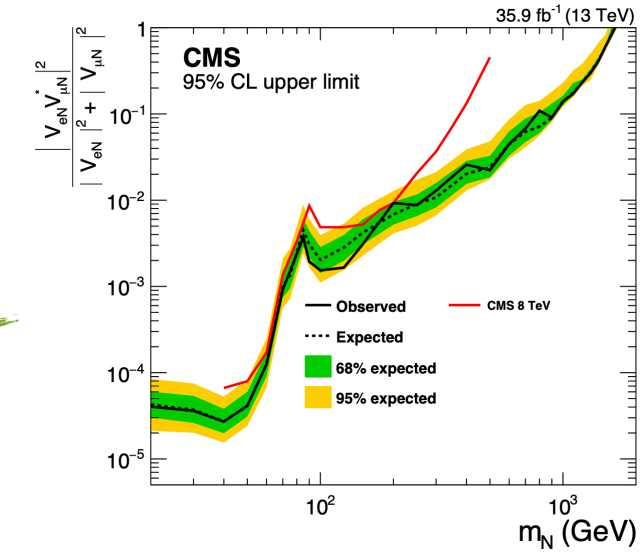
— *Abada, Escribano, XM, Piazza [2208.13882]*—

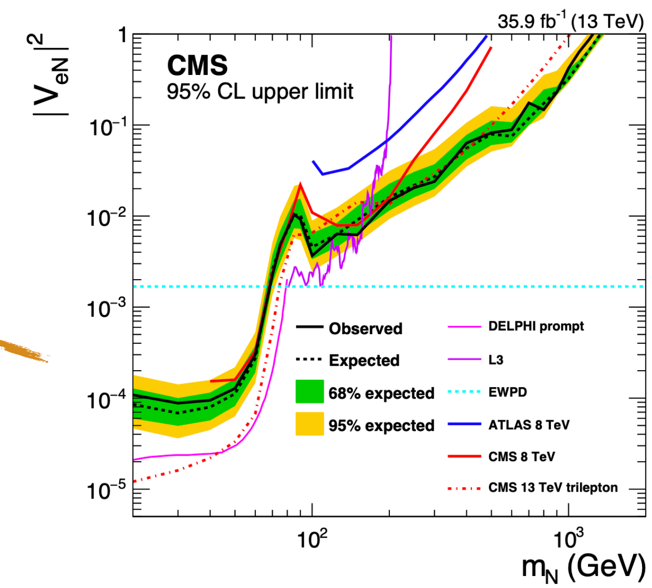


For a fixed mass and U²

$M_N = 30$ GeV, $U^2 = 10^{-3}$
- $\mu^\pm\mu^\pm$, CMS '18
- $e^\pm e^\pm$, CMS '18
- $e^\pm\mu^\pm$, CMS '18







Going Beyond the Single Mixing

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- *Simple recasting, e.g.* $pp \to \mu\mu jj$

hep-ex → $\sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu jj)$

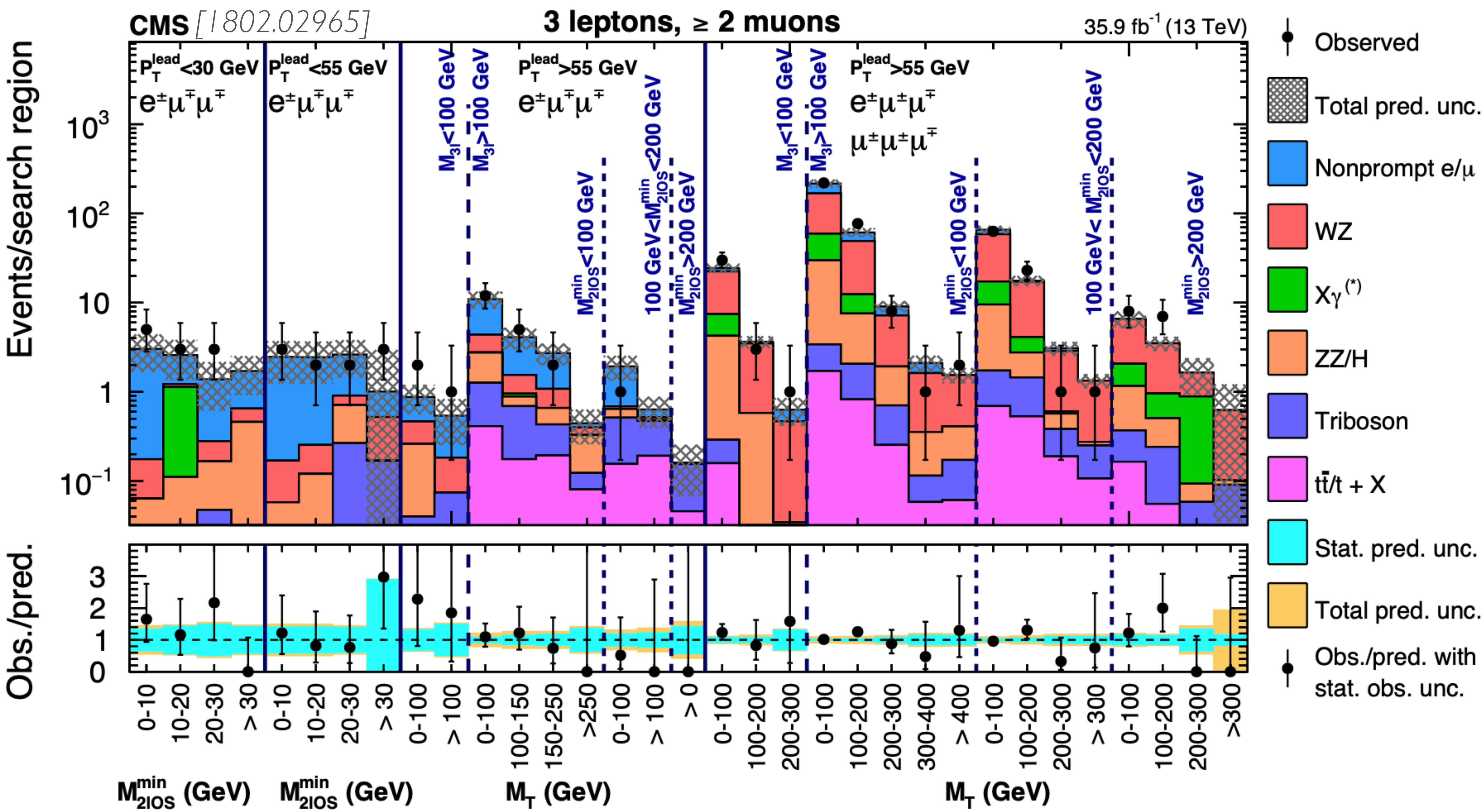
↓

$|U_{\mu N}|^2 \, \mathrm{BR}(N \to \mu jj)$

↓ ← *Mixing to a single flavor*

hep-ph → $|U_{\mu N}|^2$

Recast — Trileptons



- *Simple recasting, e.g.* $pp \to \mu\mu e\nu \oplus \mu\mu\mu\nu$

$$\sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu e \nu) \;\oplus\; \sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu\mu\nu)$$

$$\downarrow \qquad\qquad\qquad \downarrow$$

$$|U_{\mu N}|^2\, \mathrm{BR}(N \to \mu e \nu) \;\oplus\; |U_{\mu N}|^2\, \mathrm{BR}(N \to \mu\mu\nu)$$

$$\searrow \qquad \swarrow$$

$$|U_{\mu N}|^2$$

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*Mixing to a single flavor**

$$|U_{\mu N}|^2 \, \mathrm{BR}(N \to \mu e\nu) \;\oplus\; |U_{\mu N}|^2 \, \mathrm{BR}(N \to \mu\mu\nu)$$

Mixing to a single flavor

$$|U_{\mu N}|^2$$

— *see also Tastet et al [2107.12980] —

Recast – Tril

Dear
~~Santa~~ LHC experimentalists
Please provide sensitivities on $|U_{\alpha N}|^2 \times \mathrm{BR}$
(also) for each flavor channel individually
E.g. in trilepton searches for $U_{\mu N}$:
- Limits only from $\mu\mu\mu$ channel (to-do)
- Limits only from $e\mu\mu$ channel (to-do)
- Combined results (done)
CERN

Low-energy effects in precision physics

*— see talk by **Daniel Naredo**—*

If we integrate out the Heavy Neutrinos…

- dim-5: neutrino masses (Weinberg operator)

$$m_\nu = -\,\Theta M_M \Theta^T$$

active-steriles mixings

heavy mass scale

- dim-6: ***non-unitarity*** of leptonic mixing matrix

$$N = (1-\eta)U \quad \text{with} \quad \eta = \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \cdot & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \cdot & \cdot & \eta_{\tau\tau} \end{pmatrix} = \frac{1}{2}\Theta\Theta^\dagger$$

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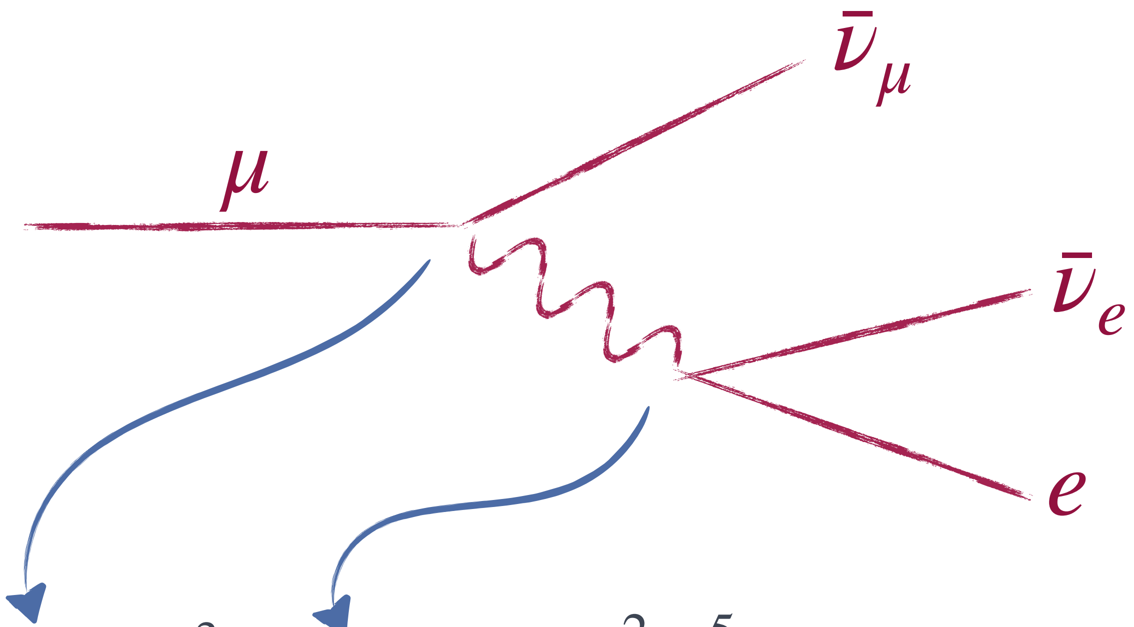
Modifies precision and flavor observables

$$\sum_{i=1}^{3} N_{\alpha i} N^\dagger_{i\beta} = \delta_{\alpha\beta} - 2\eta_{\alpha\beta} + \mathcal{O}\left(\eta^2_{\alpha\beta}\right)$$

- Modifies the muon decay



$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} \sum_{i=1}^{3} \left| N_{\mu i} \right|^2 \sum_{j=1}^{3} \left| N_{ej} \right|^2 \simeq \frac{G_F^2 m_\mu^5}{192\pi^3} \left(1 - 2\eta_{ee} - 2\eta_{\mu\mu} \right) \equiv \frac{G_\mu^2 m_\mu^5}{192\pi^3}$$

$$G_F \simeq G_\mu \left(1 + \eta_{ee} + \eta_{\mu\mu} \right)$$

Modifies all EWPO observables !!!

Non-Unitarity Effects

- Modifies G_F

$$G_F \simeq G_\mu \left(1 + \eta_{ee} + \eta_{\mu\mu}\right)$$

- Modifies M_W and s_W

$$M_W = M_Z \sqrt{\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha\left(1 + \eta_{ee} + \eta_{\mu\mu}\right)}{\sqrt{2} G_\mu M_Z^2 (1 - \Delta r)}}} \qquad s_W^2 = \frac{1}{2}\left(1 - \sqrt{1 - \frac{2\sqrt{2}\pi\alpha\left(1 + \eta_{ee} + \eta_{\mu\mu}\right)}{G_\mu M_Z^2 (1 - \Delta r)}}\right)$$

- Modifies Z invisible decay width

$$\Gamma_{\rm inv} \simeq \frac{G_\mu M_Z^3}{12\sqrt{2}\pi}\left(3 - \left(\eta_{ee} + \eta_{\mu\mu} + 4\eta_{\tau\tau}\right)\right)$$

- See **talk by Daniel Naredo** for more observables and details

Global Fit to Precision and Flavor

— *M. Blennow, E. Fernández Martínez, J. Hernández-García, J. López-Pavón, XM, D. Naredo-Tuero [2306.01040]*—

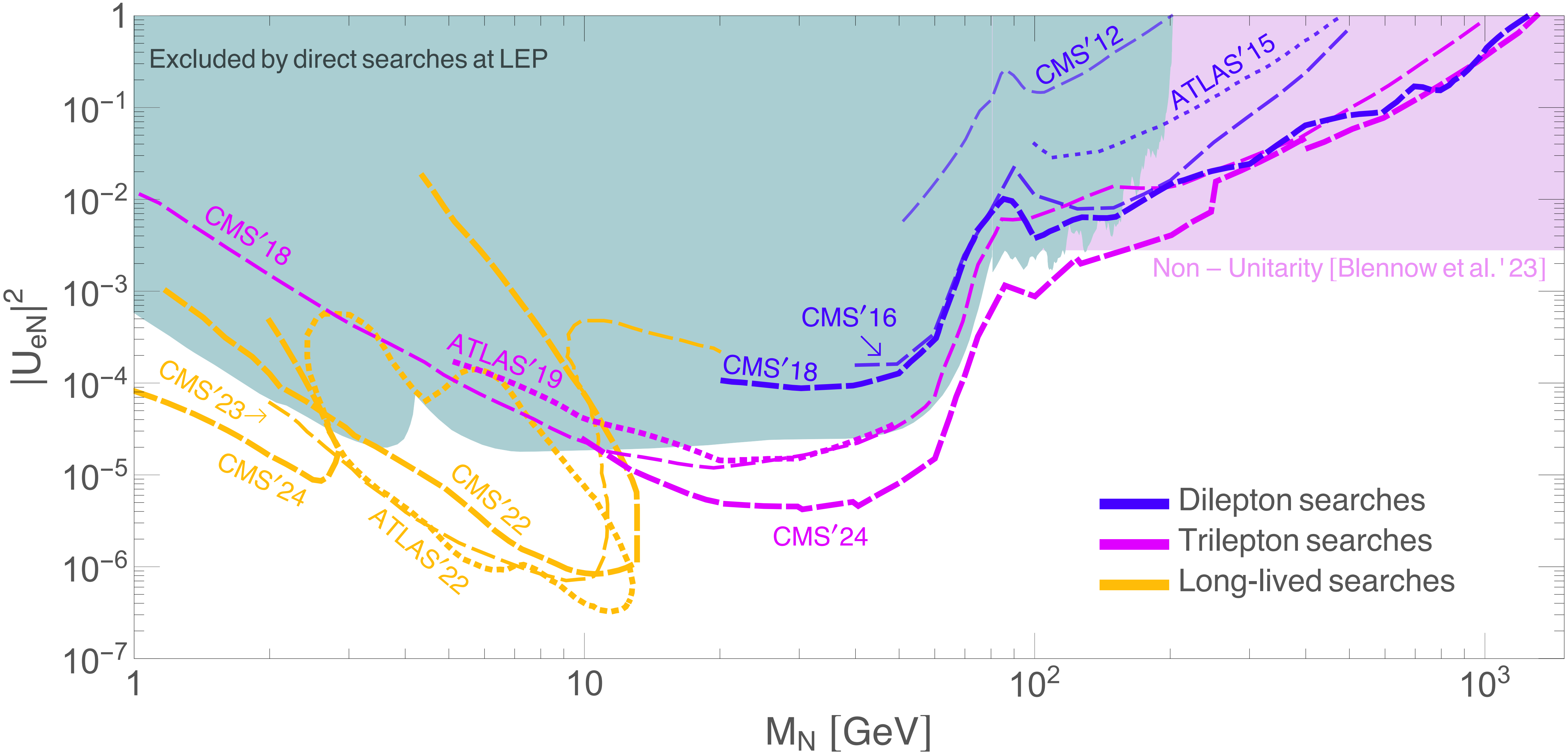
General Seesaw scenario

G-SS	LFC Bound		LFV Bound	
	68%CL	95%CL	68%CL	95%CL
η_{ee}	$[0.33, 1.0] \cdot 10^{-3}$	$[0.081, 1.4] \cdot 10^{-3}$	-	-
$\eta_{\mu\mu}$	$1.5 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	-	-
$\eta_{\tau\tau}$	$1.6 \cdot 10^{-4}$	$8.9 \cdot 10^{-4}$	-	-
$\mathrm{Tr}\,[\eta]$	$[0.28, 1.2] \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	-	-
$\|\eta_{e\mu}\|$	$1.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$	$\mathbf{8.4 \cdot 10^{-6}}$	$\mathbf{1.2 \cdot 10^{-5}}$
$\|\eta_{e\tau}\|$	$\mathbf{4.2 \cdot 10^{-4}}$	$\mathbf{8.8 \cdot 10^{-4}}$	$5.7 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$
$\|\eta_{\mu\tau}\|$	$\mathbf{9.4 \cdot 10^{-6}}$	$\mathbf{1.8 \cdot 10^{-4}}$	$6.6 \cdot 10^{-3}$	$9.4 \cdot 10^{-3}$

— See talk by **Daniel Naredo** for details and more scenarios —

Current Status: electron

updated from Abada, Escribano, XM, Piazza [2208.13882]



Current Status: muon

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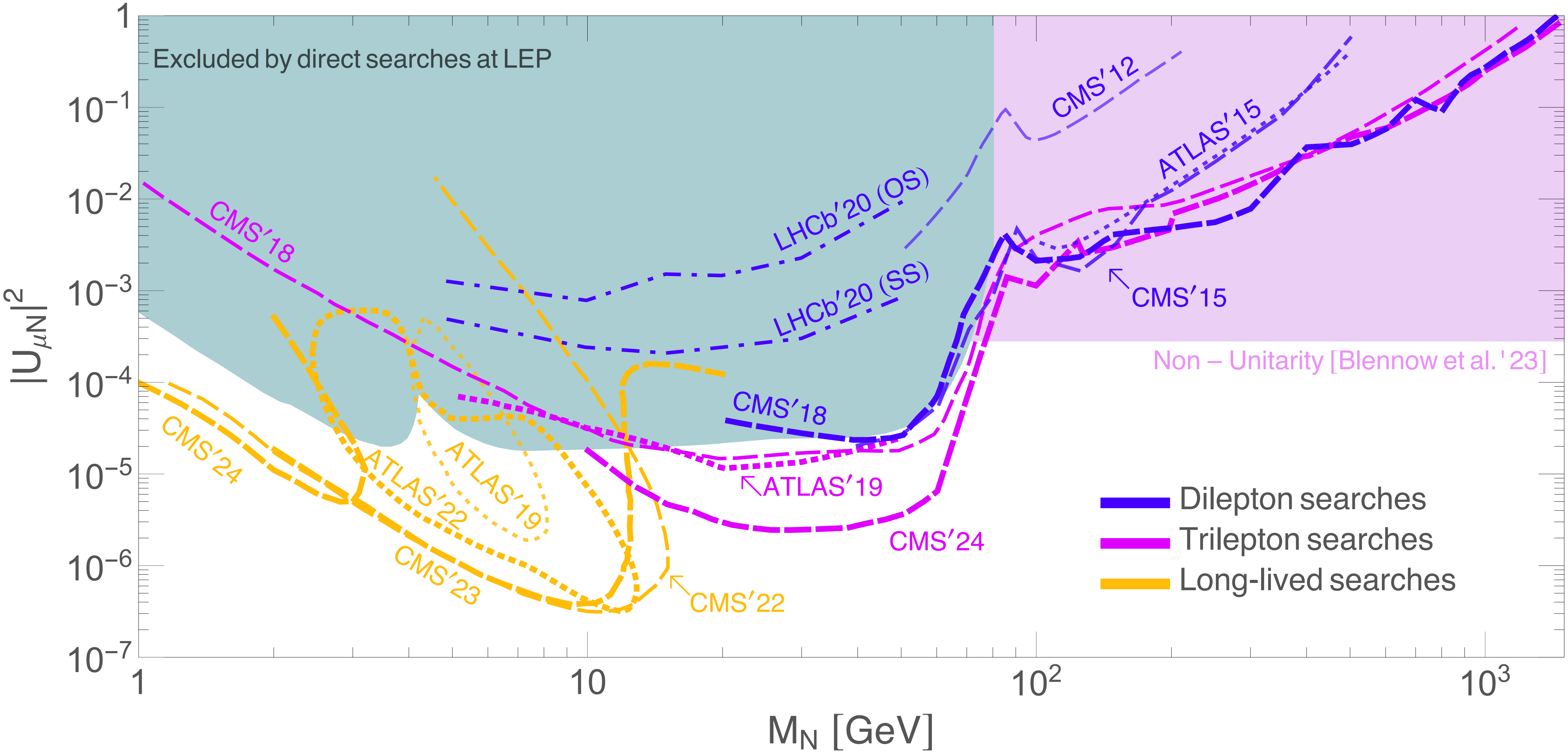
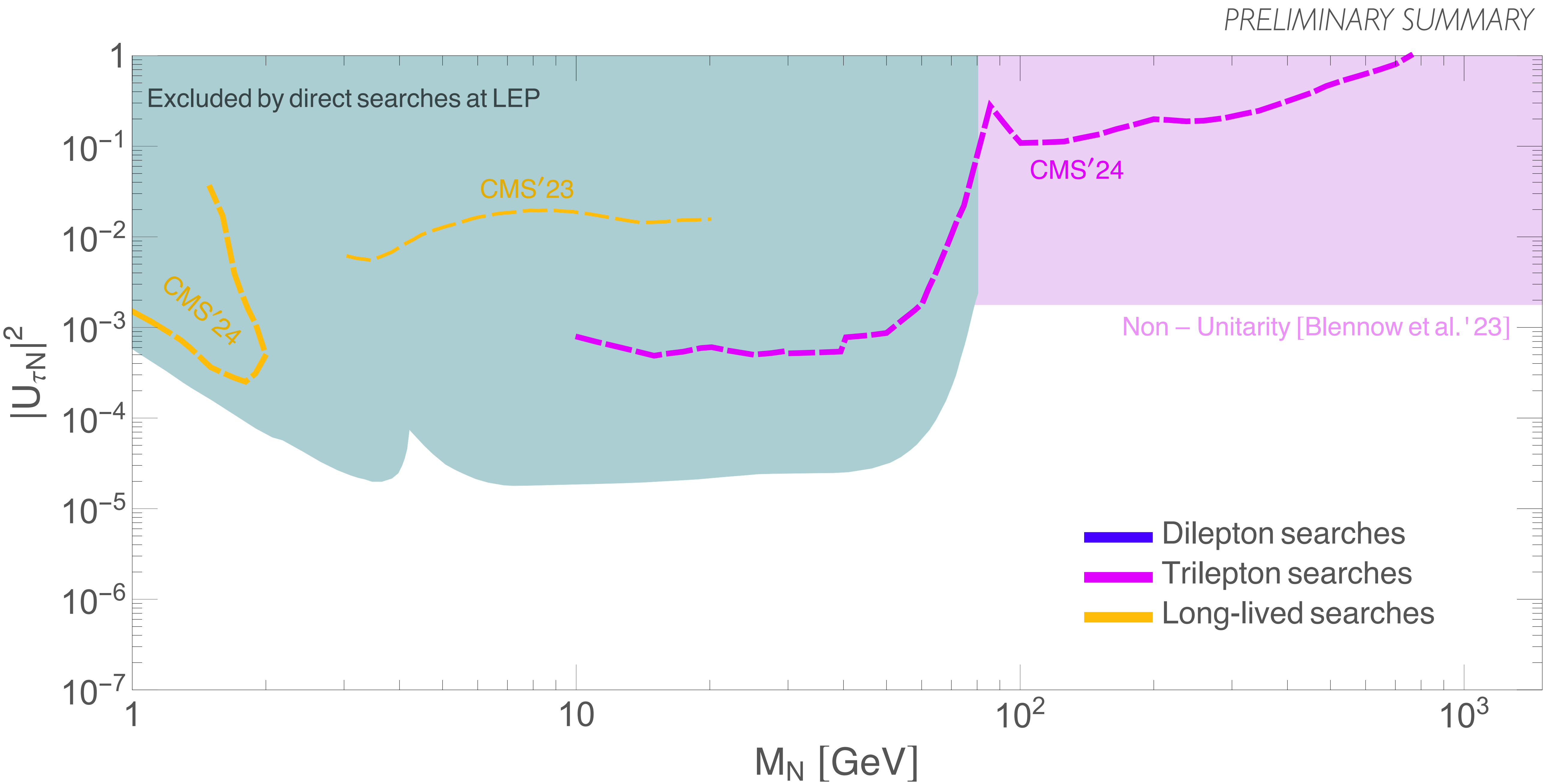


Current Status: tau



Heavy Neutrinos probes at both energy and intensity frontiers

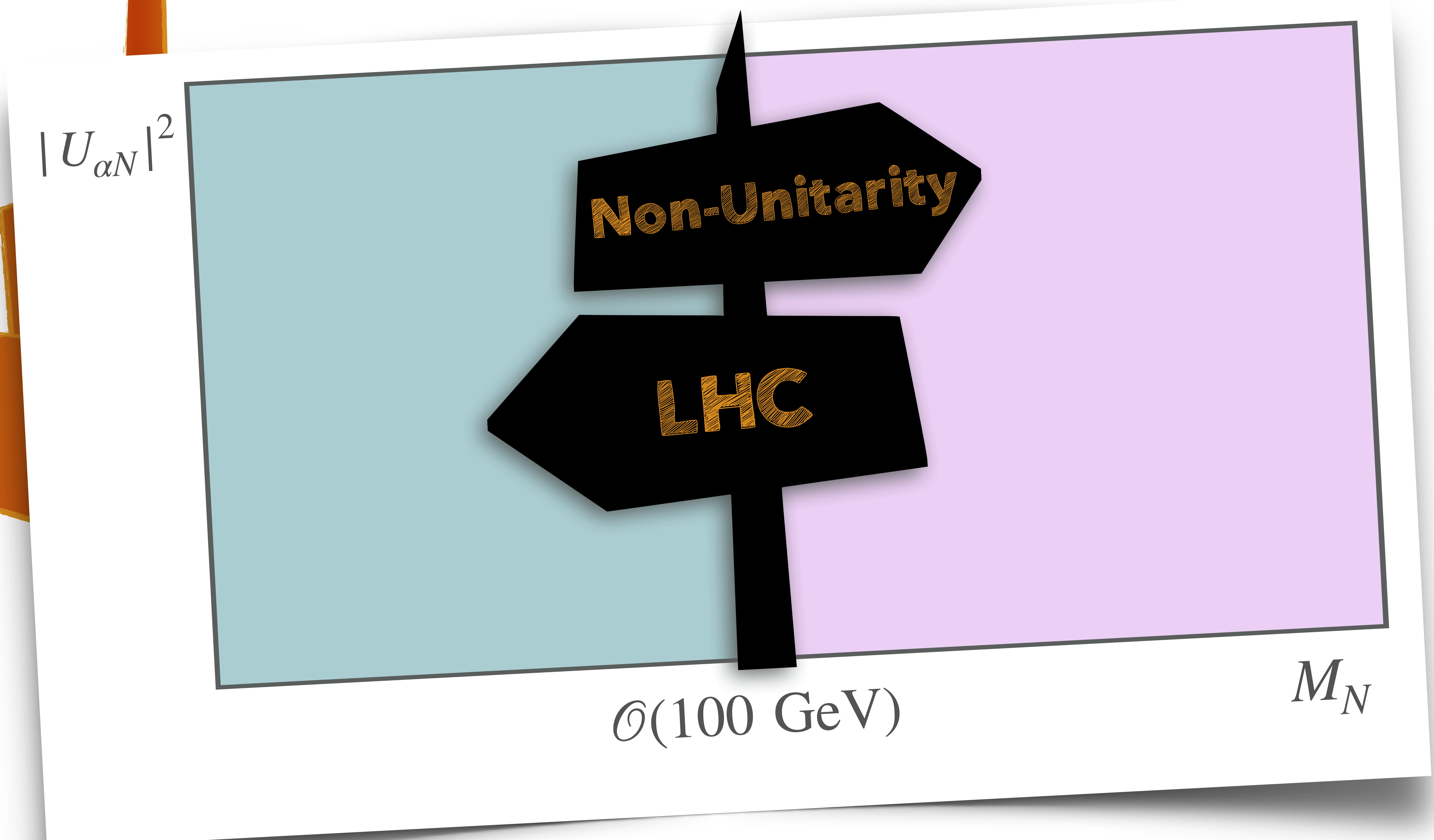
- LHC improved LEP bounds for U_{eN} and $U_{\mu N}$
- LNV vs LNC help selecting neutrino mass models
- Easy recasts w/ individual bounds on $|U_{\alpha N}|^2 \times \mathrm{BR}$

- Heavy Neutrinos induce Non-Unitarity
- New Global bounds from EWPO and flavor

— talk by Daniel Naredo —

- Strongest bounds for heaviest masses

Heavy Neutrinos probes at both energy and intensity frontiers



Thank you!

Funded by the European Union's Horizon Europe Programme under the Marie Skłodowska-Curie grant agreement no. 101066105-PheNUmenal. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

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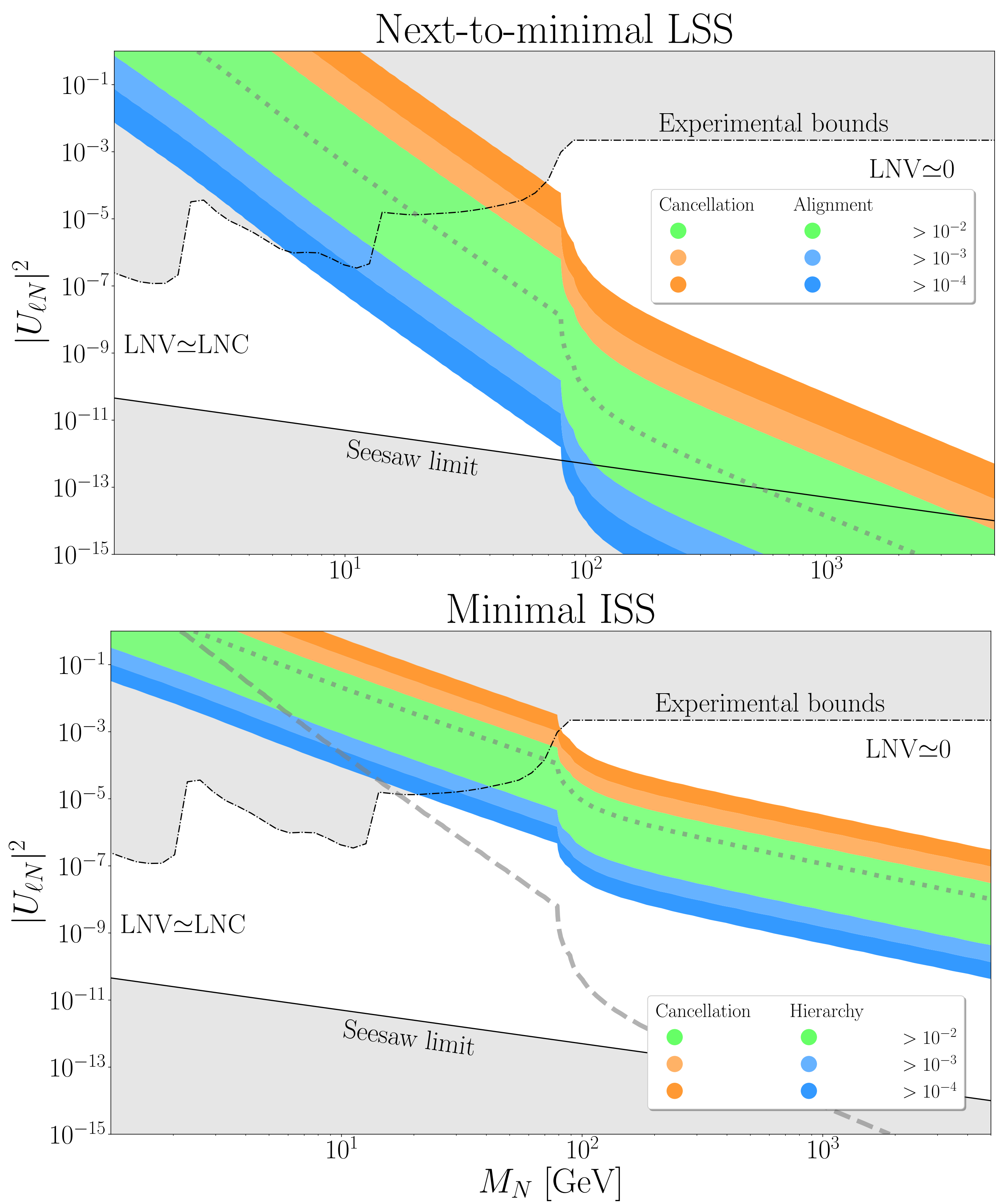
EXCELENCIA SEVERO OCHOA

Back up

Fernández-Martínez, XM, Naredo-Tuero [2209.04461]



About CDF-II

— M. Blennow, E. Fernández Martínez, J. Hernández-García, J. López-Pavón, XM, D. Naredo-Tuero [2306.01040]—

Set of observables	p-g.o.f.	tension	p-value
CDF-II vs $M_W/s^2_{\rm eff}$	$21.75/1$	4.7σ	$3.1 \cdot 10^{-6}$
CDF-II vs Z-pole	$21.48/1$	4.6σ	$3.6 \cdot 10^{-6}$
CDF-II vs $M_W/s^2_{\rm eff}$ and Z-pole	$27.30/1$	5.2σ	$1.7 \cdot 10^{-7}$

- *Non-unitarity could push M_W towards CDF-II* Blennow al [2204.04559]

$$M_W \simeq M_W^{\rm SM}\big(1 + 0.20\,(\eta_{ee} + \eta_{\mu\mu})\big)$$

- *But $\eta_{ee} + \eta_{\mu\mu}$ also modifies s_W and Z-pole obs, which agree with SM*

- ***CDF-II in strong tension, can't be explained just with non-unitarity***

— *not included in our GF* —

Hand-waving estimates

Observables at the per-mille precision

$$\eta \lesssim \mathcal{O}\left(10^{-3}\right)$$

Few non-trivial tendencies:

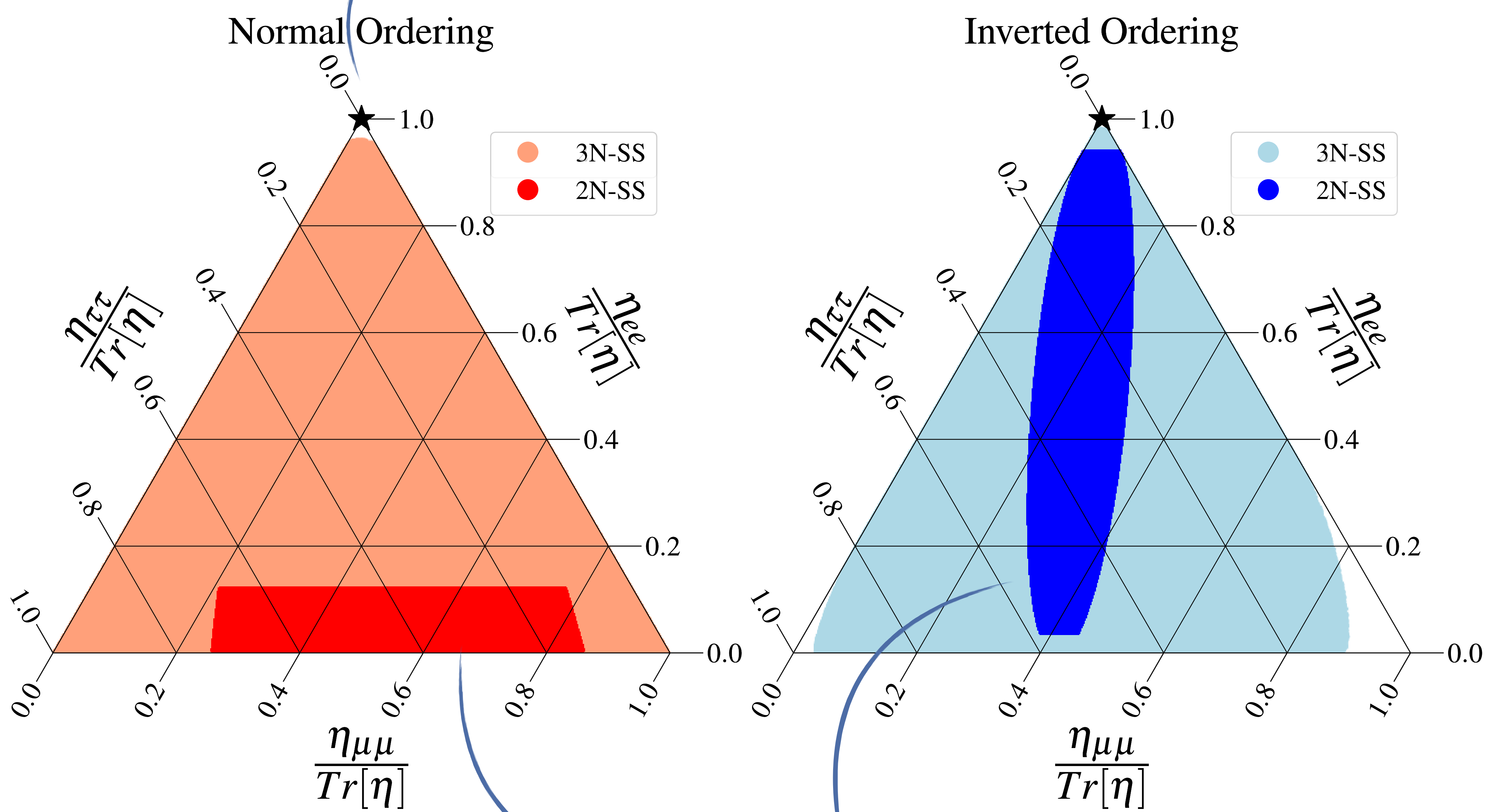
- M_W, s_W → mild preference for $\eta_{ee} + \eta_{\mu\mu} > 0$
- V_{ud} → disfavors $\eta_{\mu\mu} > 0$
- LFU → mild preference for $\eta_{ee} > \eta_{\mu\mu}$
- Others just SM-like

mild preference (1-2σ) for

$$\eta_{ee} > 0\,, \quad \eta_{\mu\mu} = 0\,, \quad \eta_{\tau\tau} = 0$$

Importance of Correlations due to m_ν

Preference of data $(\eta_{ee} > 0,\ \eta_{\mu\mu} = \eta_{\tau\tau} = 0)$



Consistent with oscillation data

— M. Blennow, E. Fernández Martínez, J. Hernández-García, J. López-Pavón, XM, D. Naredo-Tuero [2306.01040]—

Qualitative Results

95%CL, just order of magnitude

	2N-SS		3N-SS		G-SS
	NO	IO	NO	IO	
η_{ee}	10^{-5}	10^{-4}	10^{-3}	10^{-3}	$[0.1,1]\cdot 10^{-3}$
$\eta_{\mu\mu}$	10^{-4}	10^{-5}	10^{-5}	10^{-5}	10^{-4}
$\eta_{\tau\tau}$	10^{-4}	10^{-5}	10^{-3}	10^{-3}	10^{-3}
$\|\eta_{e\mu}\|$	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}
$\|\eta_{e\tau}\|$	10^{-5}	10^{-4}	10^{-3}	10^{-3}	10^{-3}
$\|\eta_{\mu\tau}\|$	10^{-4}	10^{-5}	10^{-5}	10^{-5}	10^{-4}

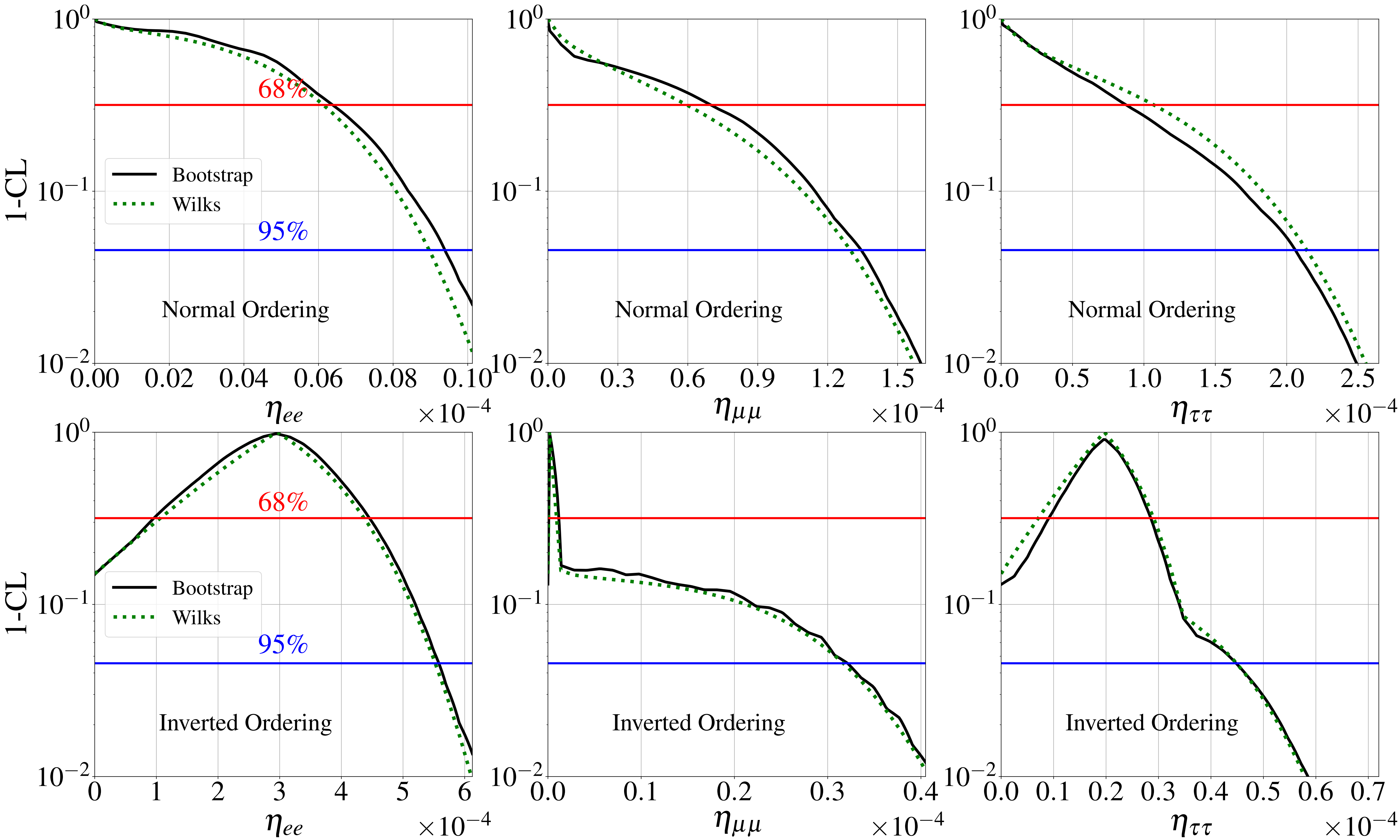
Results for the Minimal Scenario

2N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\|\theta_e\|^2}{2}$	$6.4 \cdot 10^{-6}$	$9.4 \cdot 10^{-6}$	$[0.98, 4.4] \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$
$\eta_{\mu\mu} = \frac{\|\theta_\mu\|^2}{2}$	$6.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.20, 1.0] \cdot 10^{-6}$	$3.2 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\|\theta_\tau\|^2}{2}$	$8.6 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$	$[0.94, 2.8] \cdot 10^{-5}$	$4.5 \cdot 10^{-5}$
$\mathrm{Tr}\,[\eta] = \frac{\|\theta\|^2}{2}$	$1.6 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$[1.1, 4.8] \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$
$\|\eta_{e\mu}\| = \frac{\|\theta_e \theta_\mu^*\|}{2}$	$8.3 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$[0.37, 1.0] \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$
$\|\eta_{e\tau}\| = \frac{\|\theta_e \theta_\tau^*\|}{2}$	$1.5 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	$[0.25, 1.2] \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
$\|\eta_{\mu\tau}\| = \frac{\|\theta_\mu \theta_\tau^*\|}{2}$	$7.2 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.38, 3.0] \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$

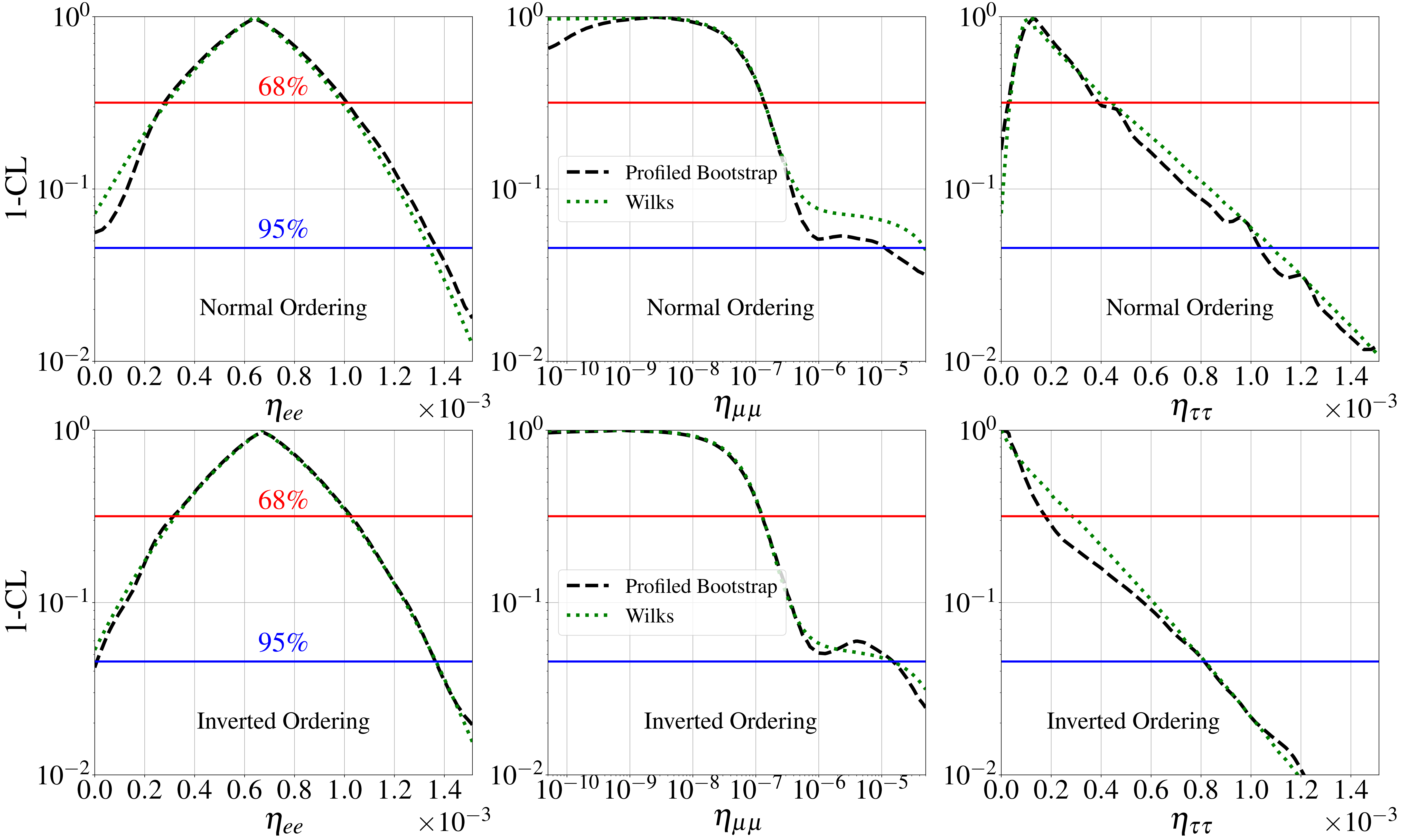
Results for the Next-to-Minimal Scenario

3N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$[0.28, 0.99] \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$[0.31, 1.0] \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\lvert\theta_\tau\rvert^2}{2}$	$[0.3, 3.9] \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$	$1.7 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$
$\mathrm{Tr}\,[\eta] = \frac{\lvert\theta\rvert^2}{2}$	$[0.35, 1.3] \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$[0.33, 1.0] \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
$\lvert\eta_{e\mu}\rvert = \frac{\lvert\theta_e\theta_\mu^*\rvert}{2}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$
$\lvert\eta_{e\tau}\rvert = \frac{\lvert\theta_e\theta_\tau^*\rvert}{2}$	$[1.3, 5.1] \cdot 10^{-4}$	$9.0 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$
$\lvert\eta_{\mu\tau}\rvert = \frac{\lvert\theta_\mu\theta_\tau^*\rvert}{2}$	$5.0 \cdot 10^{-6}$	$5.7 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$

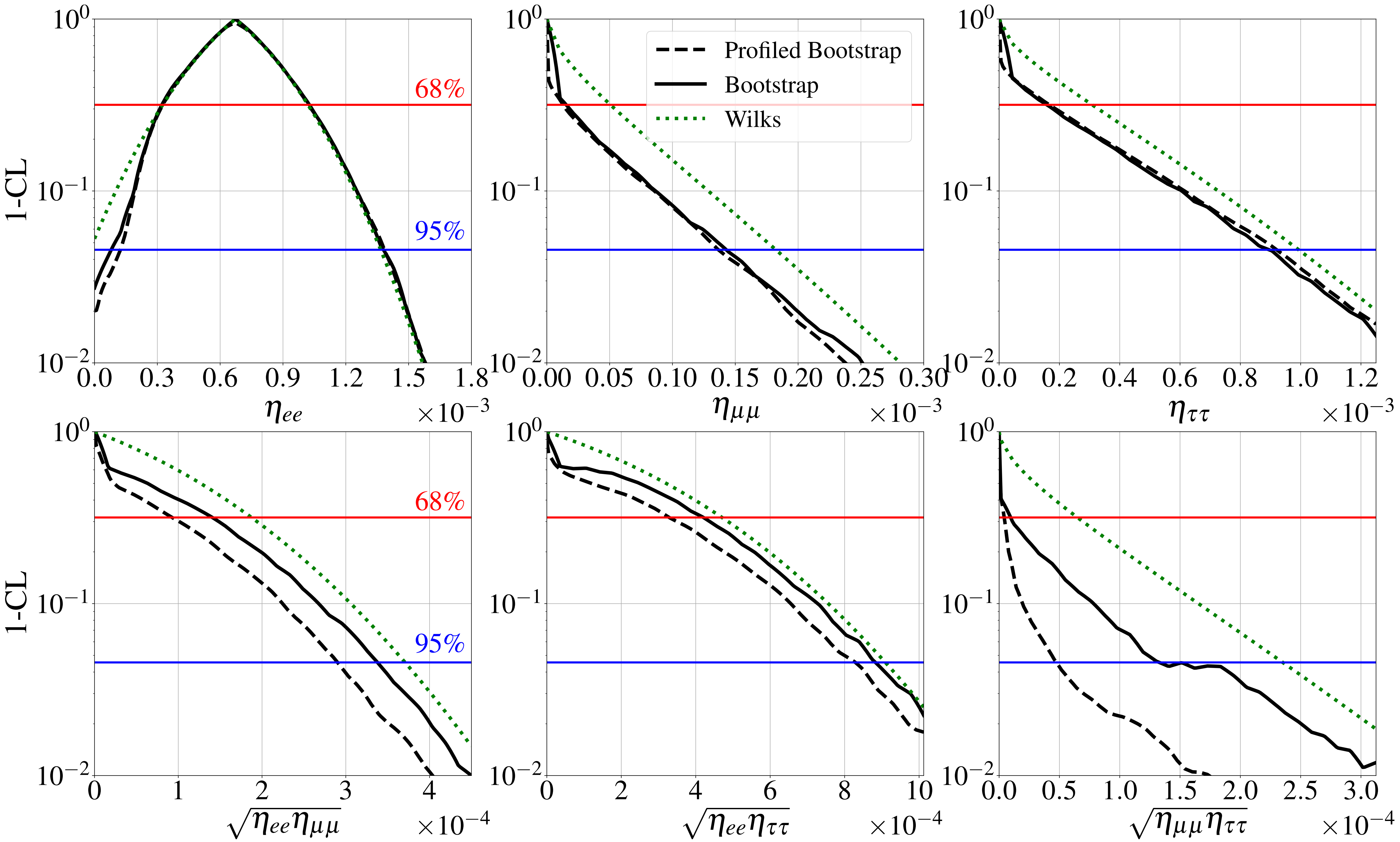
Profiles for the 2N-SS



Profiles for the 3N-SS



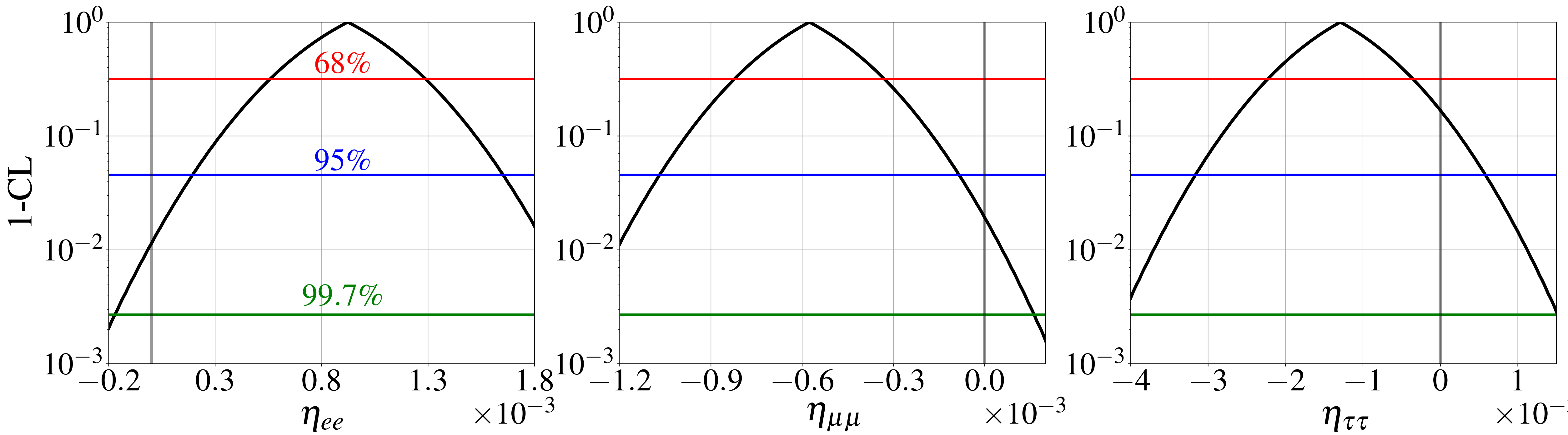
Profiles for the G-SS



Generic Unitarity Violation

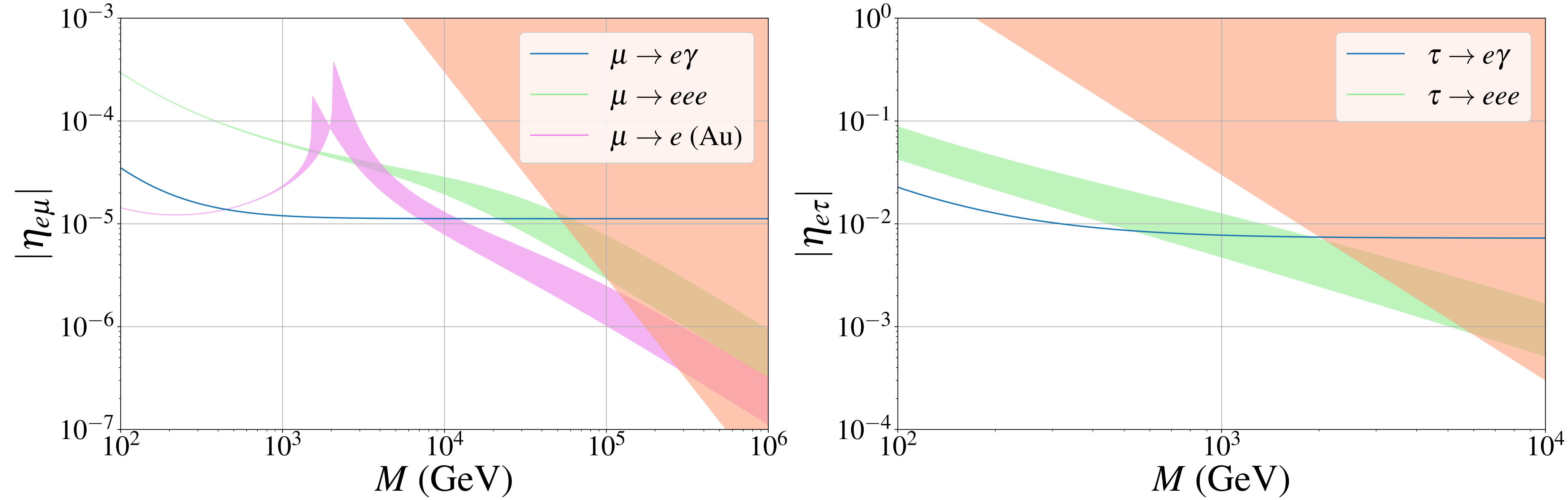
— *M. Blennow, E. Fernández Martínez, J. Hernández-García, J. López-Pavón, XM, D. Naredo-Tuero [2306.01040]*—

- *Not imposing η to be definite positive* ***(beyond just heavy neutrinos)***



GUV	LFC Bound			LFV Bound	
	68%CL	95%CL		68%CL	95%CL
η_{ee}	$[0.56, 1.29] \cdot 10^{-3}$	$[0.20, 1.65] \cdot 10^{-3}$	$\|\eta_{e\mu}\|$	$5.0 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$
$\eta_{\mu\mu}$	$[-8.2, -3.3] \cdot 10^{-4}$	$[-1.1, -0.088] \cdot 10^{-3}$	$\|\eta_{e\tau}\|$	$3.4 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$
$\eta_{\tau\tau}$	$[-2.2, -0.38] \cdot 10^{-3}$	$[-3.1, 0.56] \cdot 10^{-3}$	$\|\eta_{\mu\tau}\|$	$4.0 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$

— M. Blennow, E. Fernández Martínez, J. Hernández-García, J. López-Pavón, XM, D. Naredo-Tuero [2306.01040]—



- *Off-diag η entries induce **charged LFV,** e.g.*

$$\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) \simeq \frac{3\alpha}{2\pi} |\eta_{\alpha\beta}|^2$$

— for M >> M_W —

- *Some cLFV obs have non-trivial mass dependence*

— marginalize over M —

- Non-unitarity effects are also parametrized via the α-parametrization

$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

- Our results are **easily translated,** e.g. in the 2N-SS:

$$\text{NO:} \quad \mathbb{I} - \alpha < \begin{pmatrix} 9.4 \cdot 10^{-6} & 0 & 0 \\ 2.4 \cdot 10^{-5} & 1.3 \cdot 10^{-4} & 0 \\ 4.4 \cdot 10^{-5} & 2.6 \cdot 10^{-4} & 2.1 \cdot 10^{-4} \end{pmatrix}$$

$$\text{IO:} \quad \mathbb{I} - \alpha < \begin{pmatrix} 5.5 \cdot 10^{-4} & 0 & 0 \\ 2.6 \cdot 10^{-5} & 3.2 \cdot 10^{-5} & 0 \\ 2.8 \cdot 10^{-4} & 7.0 \cdot 10^{-5} & 4.5 \cdot 10^{-5} \end{pmatrix}$$

— See [2306.01040] for other scenarios —