(Updated) Global bounds on heavy neutrino mixing

Based on:
M. Blennow, E. Fernández Martínez, J. Hernández-García, J. López-Pavón, X. Marcano, DN [2306.01040]

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SUSY2023 - Daniel Naredo - 19/07/2023

Motivation

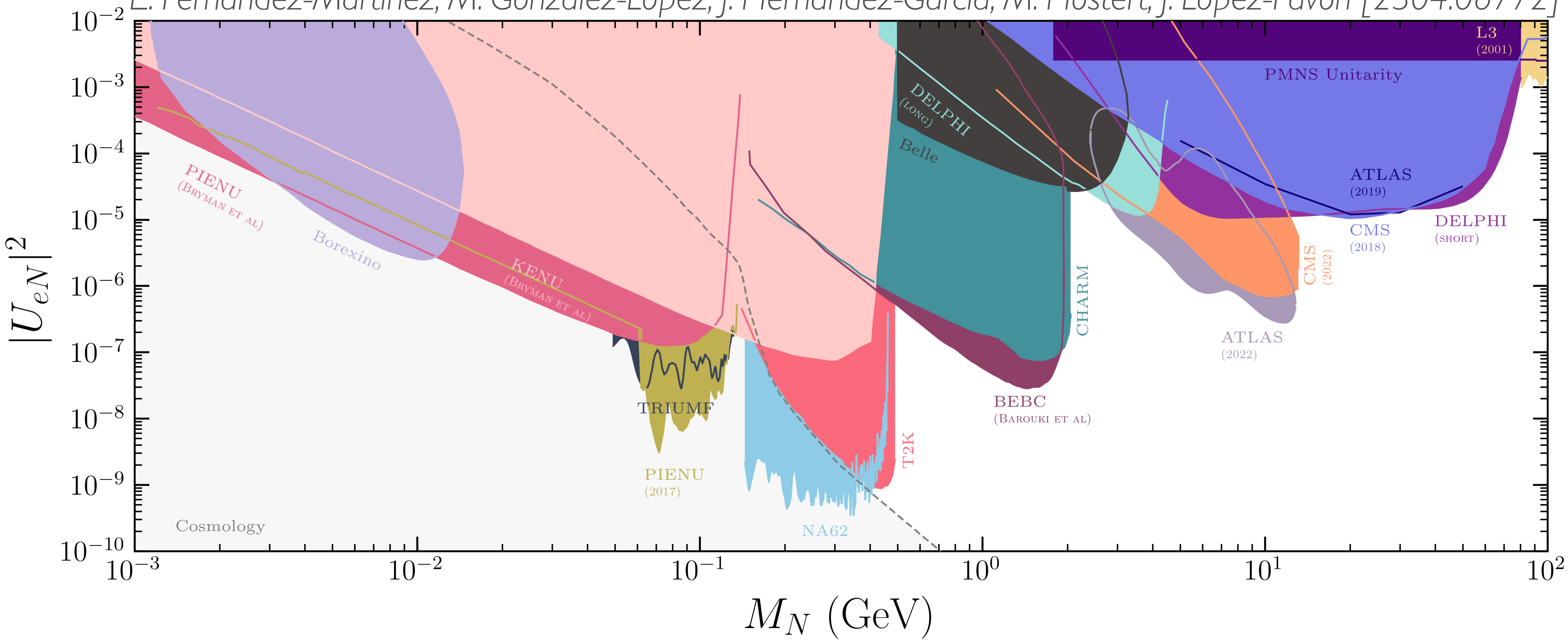
- Neutrinos are massive ⟶ need a mechanism to generate their (tiny) masses

- Seesaw mechanism via heavy neutrinos

Searches for heavy neutrinos

- Plethora of searches for heavy neutrinos

E. Fernández-Martínez, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón [2304.06772]



- However, experimental bounds die off for $M_N > M_W$

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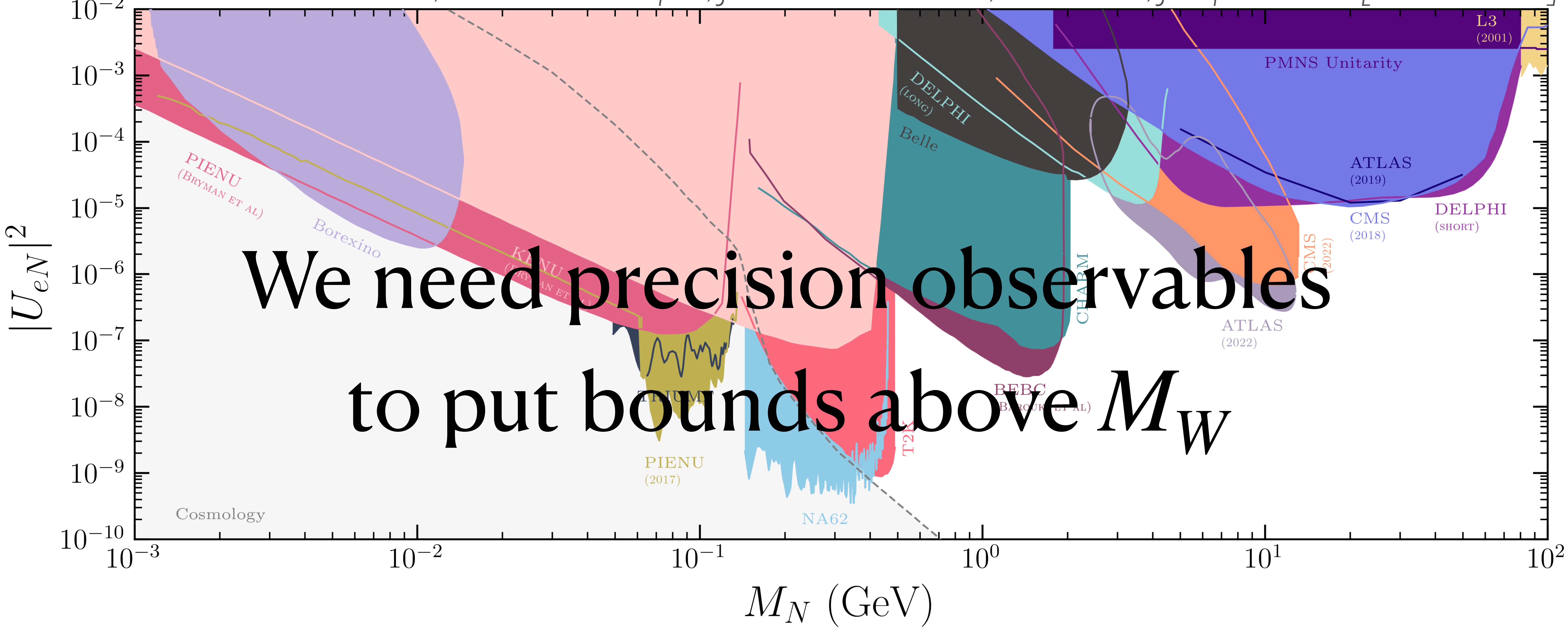

We need precision observables to put bounds above M_W

- However, experimental bounds die off for $M_N > M_W$

Why update the global fit?

- Updates on key observables:
  - ★ New measurements of M_W (CDF-II, ATLAS)
  - ★ Anomaly ($\sim 2-3\sigma$) in the extraction of CKM elements $|V_{ud}|$ and $|V_{us}|$
  - ★ LEP anomaly ($\sim 2\sigma$) in N_ν is now gone

- Improvement of the analysis:
  - ★ Correlations
  - ★ Deviations from Wilks' theorem: Bootstrapping

Non-unitarity in general

- Precision observables are modified by leptonic non-unitarity

- In general: $$N = \left(1-\eta\right) \underbrace{U}_{\text{Diagonalises } m_\nu}, \qquad \eta^\dagger = \eta$$

- Convenient: η has flavor indices

- Generally, mass eigenstates are summed over:

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

Heavy neutrinos and non-unitarity

- In general: $$N = \left(1-\eta\right) \underbrace{U}_{\text{Diagonalises } m_\nu}, \qquad \eta^\dagger = \eta$$

- In the context of heavy neutrinos $N \sim (1,1,0)$: $$-\mathscr{L} \supset Y_\nu \overline{L}_L \tilde{H} N + \frac{1}{2} M_M \overline{N^c} N$$

$$\mathscr{M} = \begin{pmatrix} 0 & Y_\nu v/\sqrt{2} \\ Y_\nu^T v/\sqrt{2} & M_M \end{pmatrix}$$

Diagonalised by:

$$\Theta \equiv \frac{v}{\sqrt{2}} Y_\nu M_M^{-1}$$

$$V = \begin{pmatrix} 1-\frac{1}{2}\Theta\Theta^\dagger & \Theta \\ -\Theta^\dagger & 1-\frac{1}{2}\Theta^\dagger\Theta \end{pmatrix} \begin{pmatrix} U & 0 \\ 0 & U' \end{pmatrix}$$

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Heavy neutrinos and non-unitarity

- In the Type-I seesaw:

$$N = \left(1 - \frac{1}{2}\Theta\Theta^\dagger\right) U, \qquad \underbrace{\eta = \frac{1}{2}\Theta\Theta^\dagger}_{\text{Mass-independent}}$$

- η is positive-definite $\begin{cases} \eta_{\alpha\alpha} \geq 0 \\ |\eta_{\alpha\beta}| \leq \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}} \ \text{(Schwarz inequality)} \end{cases}$

- Additionally: $m_\nu \simeq -\Theta M_M \Theta^T$ can impose correlations within η

Precision observables and non-unitarity

- SM inputs $\begin{cases} \alpha \\ M_Z \\ G_F \end{cases}$

- G_F is extracted from μ-decay $\longrightarrow$ Modified by lepton non-unitarity

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

$$G_F \simeq G_\mu \left(1 + \eta_{ee} + \eta_{\mu\mu} \right) \longrightarrow \text{Modifies all EWPO}$$

M_W and s^2_{eff}

- We consider only tree-level η-dependence and loop-level SM corrections

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

- Similarly with s^2_{eff}

Z-pole observables

- Z-boson partial widths also modified

- $\Gamma\left(Z \to f\bar{f}\right)$ modified by G_F and s^2_{eff}

- Γ_{inv} modified by G_F and by $Z \to \nu\nu$ vertex

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LEP precision measurements also constrain η

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LEP precision measurements
also constrain η

Z-pole observables
are in strong tension with
CDF-II M_W measurement

Lepton Flavor Universality (LFU)

- $W \to l\nu$ vertex modified by η

$$\sum_{i=1}^{3} |N_{\alpha i}|^2 = 1 - 2\eta_{\alpha\alpha}$$

- Weak interactions are no longer flavor universal

- Ratios of π, K and τ decays constrain the universality of weak interactions

CKM unitarity

- The CKM matrix remains unitary:

$$1 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\,, \qquad |V_{ud}| = \sqrt{1 - \underbrace{|V_{us}|^2}_{\text{Nuisance parameter (minimized over)}}}\,,$$

- But the extraction of $|V_{ud}|$ and $|V_{us}|$ is affected

- $|V_{ud}|$ extracted from superallowed β-decays

$$|V_{ud}^{\beta}| = |V_{ud}| \underbrace{\left(1 + \eta_{ee} + \eta_{\mu\mu}\right)}_{G_F} \underbrace{\left(1 - \eta_{ee}\right)}_{W \to e\nu \text{ vertex}} \simeq \sqrt{1 - |V_{us}|^2}\left(1 + \eta_{\mu\mu}\right)$$

CKM unitarity

- $|V_{us}|$ extracted from K and τ semileptonic decays

- Cabibbo anomaly: $|V_{ud}| < \sqrt{1 - |V_{us}|^2}$ at $2 - 3\sigma$ level

- Only worsened in presence of $\eta_{\mu\mu} > 0$

Charged Lepton Flavor Violation (cLFV)

- Previous observables are LFC: depend on $\eta_{\alpha\alpha}$

- The off-diagonal elements $\eta_{\alpha\beta}$ induces LFV processes $\begin{cases} l_\alpha \to l_\beta \gamma \\ l_\alpha \to l_\beta l_\beta l_\beta \\ \mu - e \end{cases}$

For example: $$BR\left(l_\alpha \to l_\beta \gamma\right) \simeq \frac{3\alpha}{2\pi} |\eta_{\alpha\beta}|^2, \quad \text{for} \quad M_N \gg M_W$$

- The off-diagonal elements alternatively constrained via the Schwarz inequality:

$$|\eta_{\alpha\beta}| \leq \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$$

The preference of the data

- M_W, s^2_{eff} showcase $\sim 1-2\sigma$ preference for $\eta_{ee}+\eta_{\mu\mu}>0$

- LFU prefers $\eta_{ee}>\eta_{\mu\mu}$ at $\sim 1\sigma$

- Cabibbo anomaly disfavors $\eta_{\mu\mu}>0$

- Observables constraining $\eta_{\tau\tau}$ show good agreement with SM

- Summing up: data prefers $\eta_{ee}>0\,, \eta_{\mu\mu}=0\,, \eta_{\tau\tau}=0$

Cases under study

- Minimal scenario with 2 heavy neutrinos: 2N-SS
  (Previously missing in the literature)

- Next-to-minimal scenario with 3 heavy neutrinos: 3N-SS

- General scenario with arbitrary number of heavy neutrinos: G-SS

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★ Correlations from m_ν

★ $|\eta_{\alpha\beta}| = \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$

★ LFV with LFC

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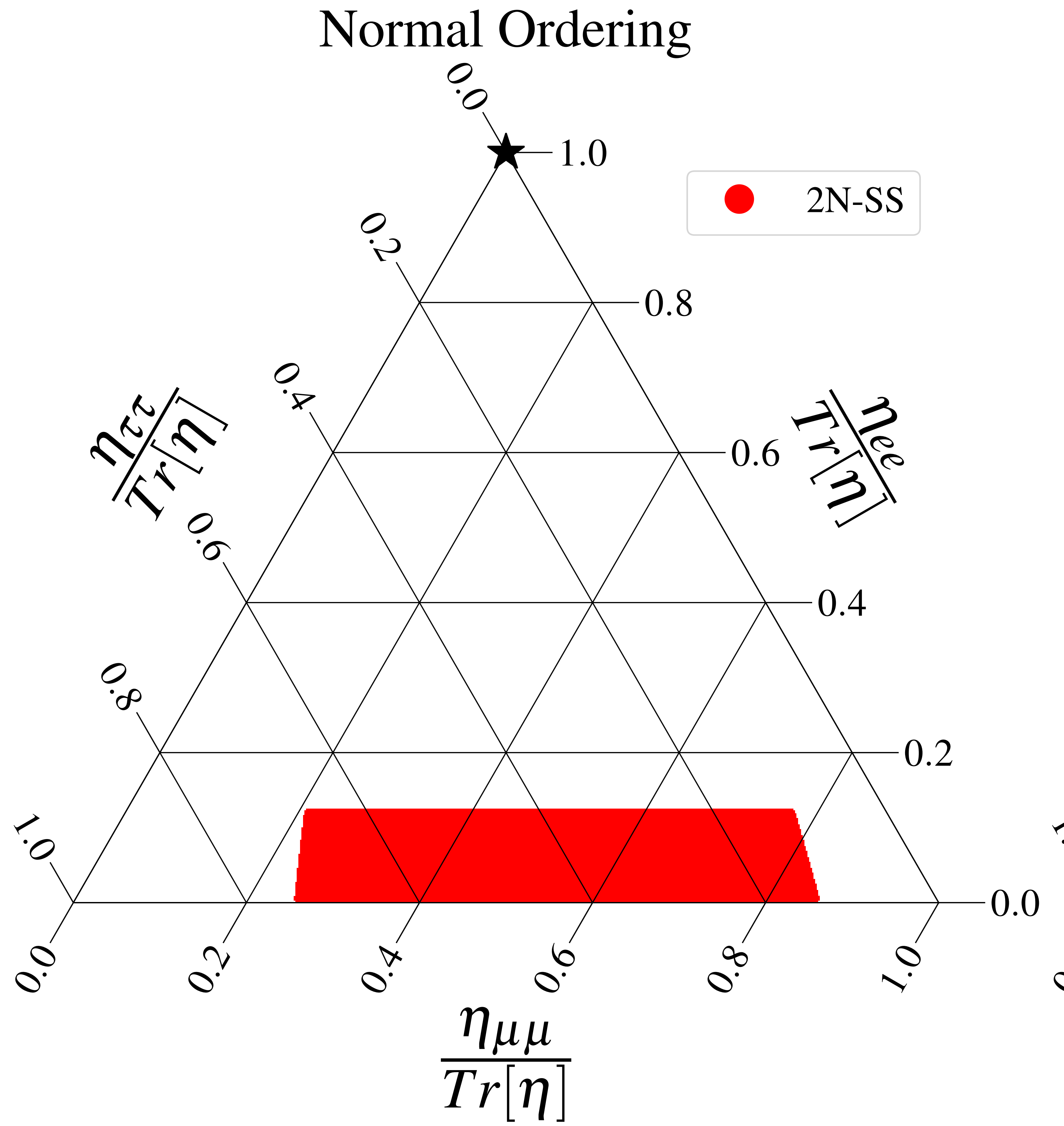
★ $|\eta_{\alpha\beta}| = \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$
★ LFV with LFC

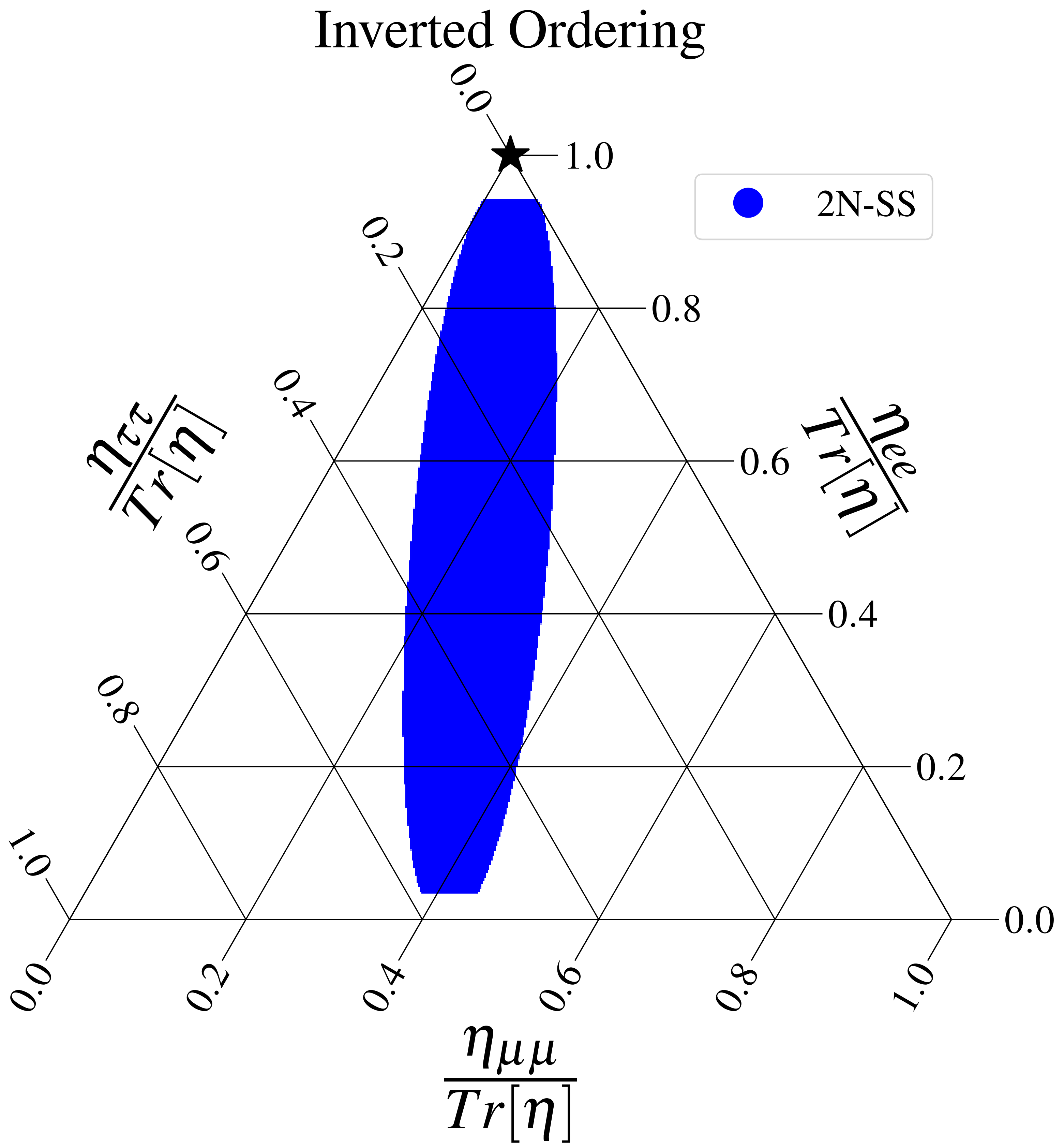
- General scenario with arbitrary number of heavy neutrinos: G-SS

★ η_{ee}, $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ independent
★ $|\eta_{\alpha\beta}| \leq \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$
★ LFV decoupled from LFC

Results for the 2 heavy neutrino case

- Very restrictive flavor structure





- cLFV bounds play a very important role

Results for the 2 heavy neutrino case

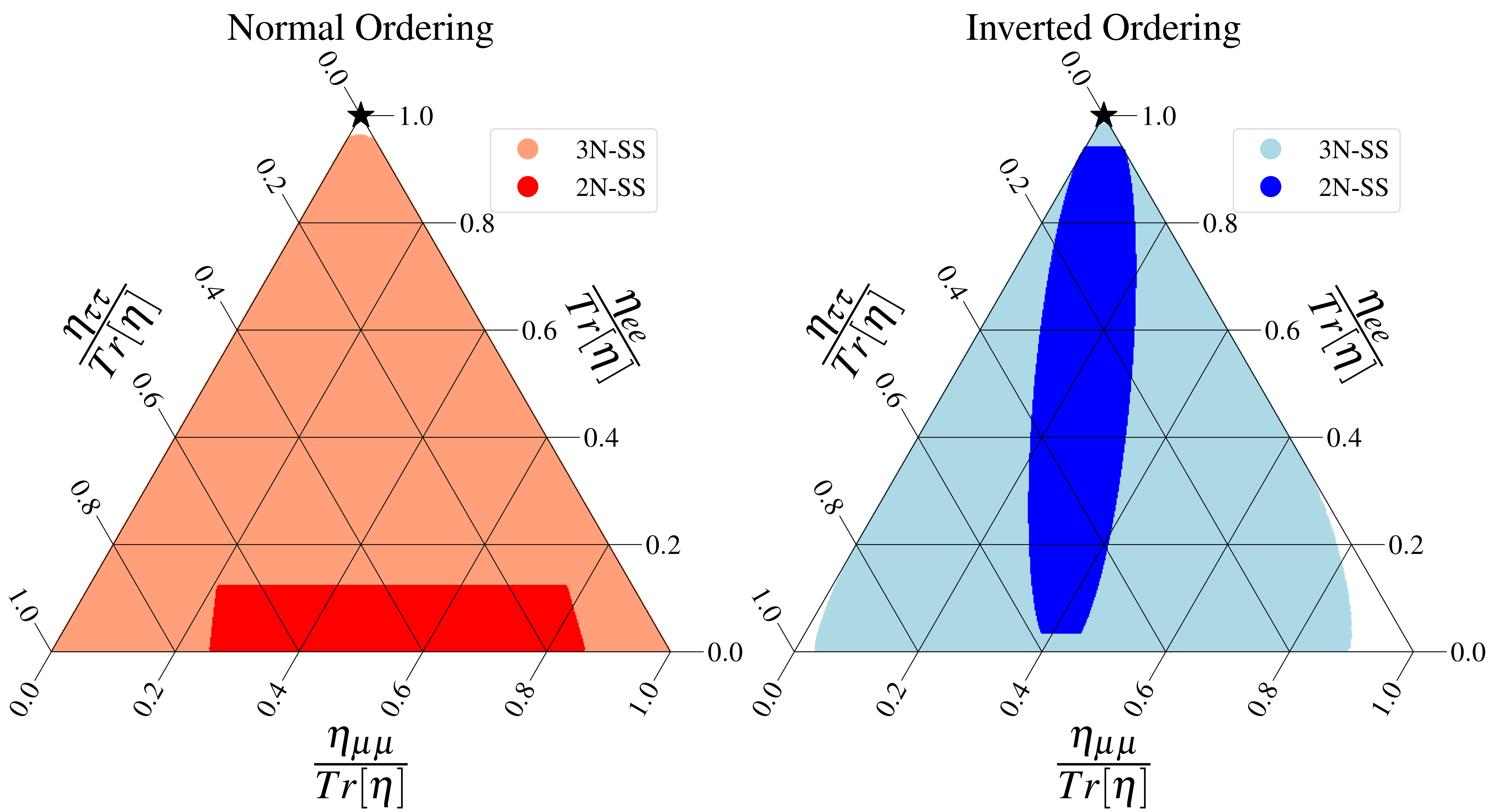
- Stringent bounds $\sim 10^{-5} - 10^{-4}$

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

- Non-zero best-fit for IO, unlike NO

Results for the 3 heavy neutrino case

- More flexible flavor structure



- Easier to accommodate data and survive cLFV bounds

Results for the 3 heavy neutrino case

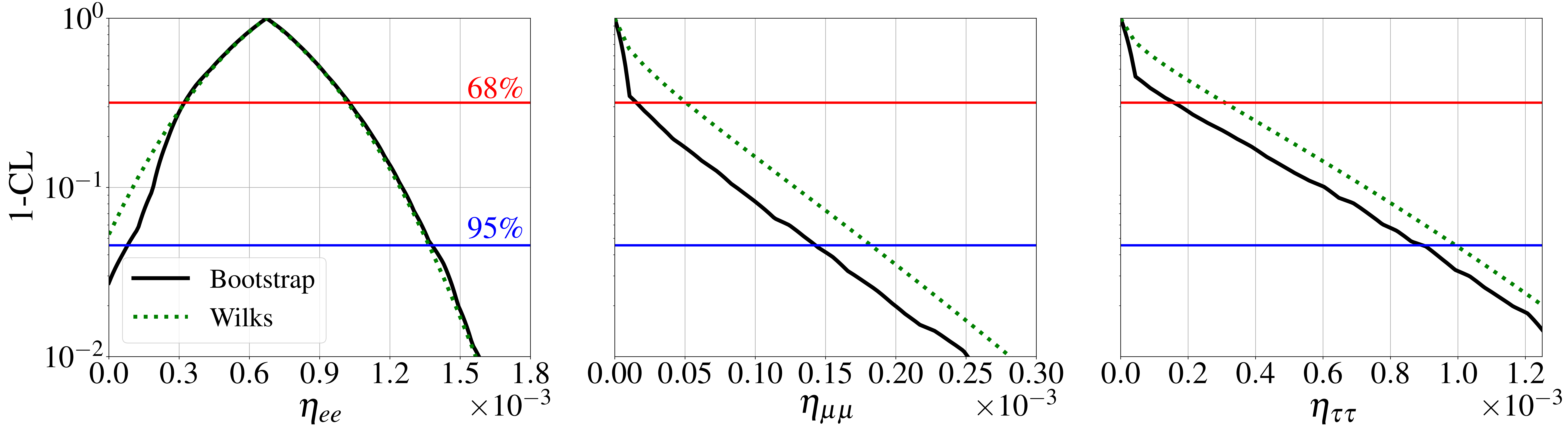
- $\sim 10^{-3}$ bounds on $\eta_{ee}, \eta_{\tau\tau}$ and $\sim 10^{-5}$ bound on $\eta_{\mu\mu}$

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

- cLFV in $\mu - e$ sector strongly constrains $\eta_{\mu\mu}$

Results for arbitrary number of heavies

- $\sim 10^{-3}$ bounds on $\eta_{ee}, \eta_{\tau\tau}$ and $\sim 10^{-4}$ bound on $\eta_{\mu\mu}$



- Physical boundary $\eta_{\alpha\alpha} \geq 0$ induces deviations from Wilks' theorem

Results for arbitrary number of heavies

- LFC bounds on $|\eta_{e\tau}|$ and $|\eta_{\mu\tau}|$ much stronger than the LFV ones

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

Conclusions

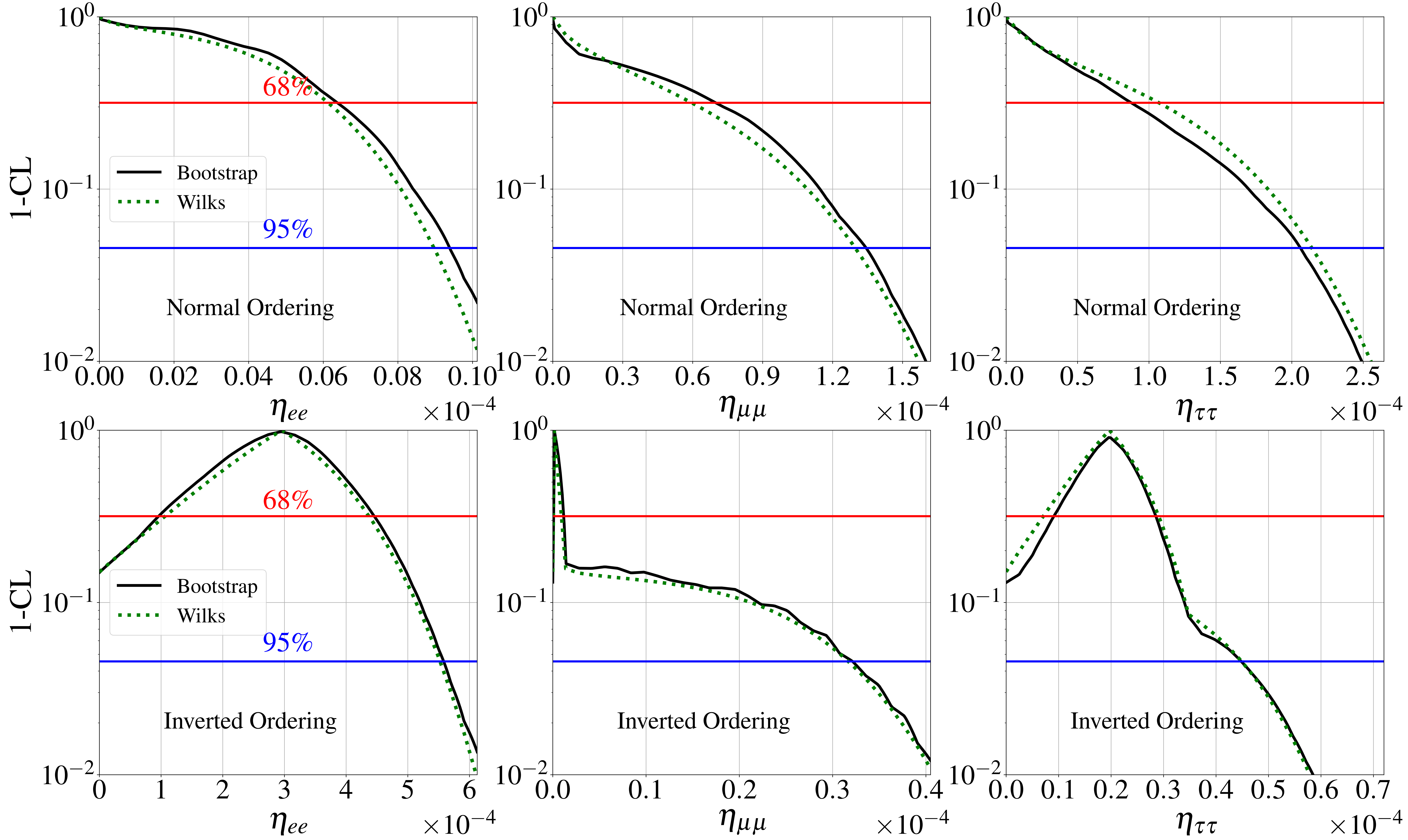
- (Updated) Bounds obtained for different setups (2N-SS, 3N-SS, G-SS)
- Bounds substantially change between setups
- Quantified tension between CDF-II M_W and other observables: irreconcilable
- Quantified deviations from Wilks' theorem

Thanks for your attention!

Backup

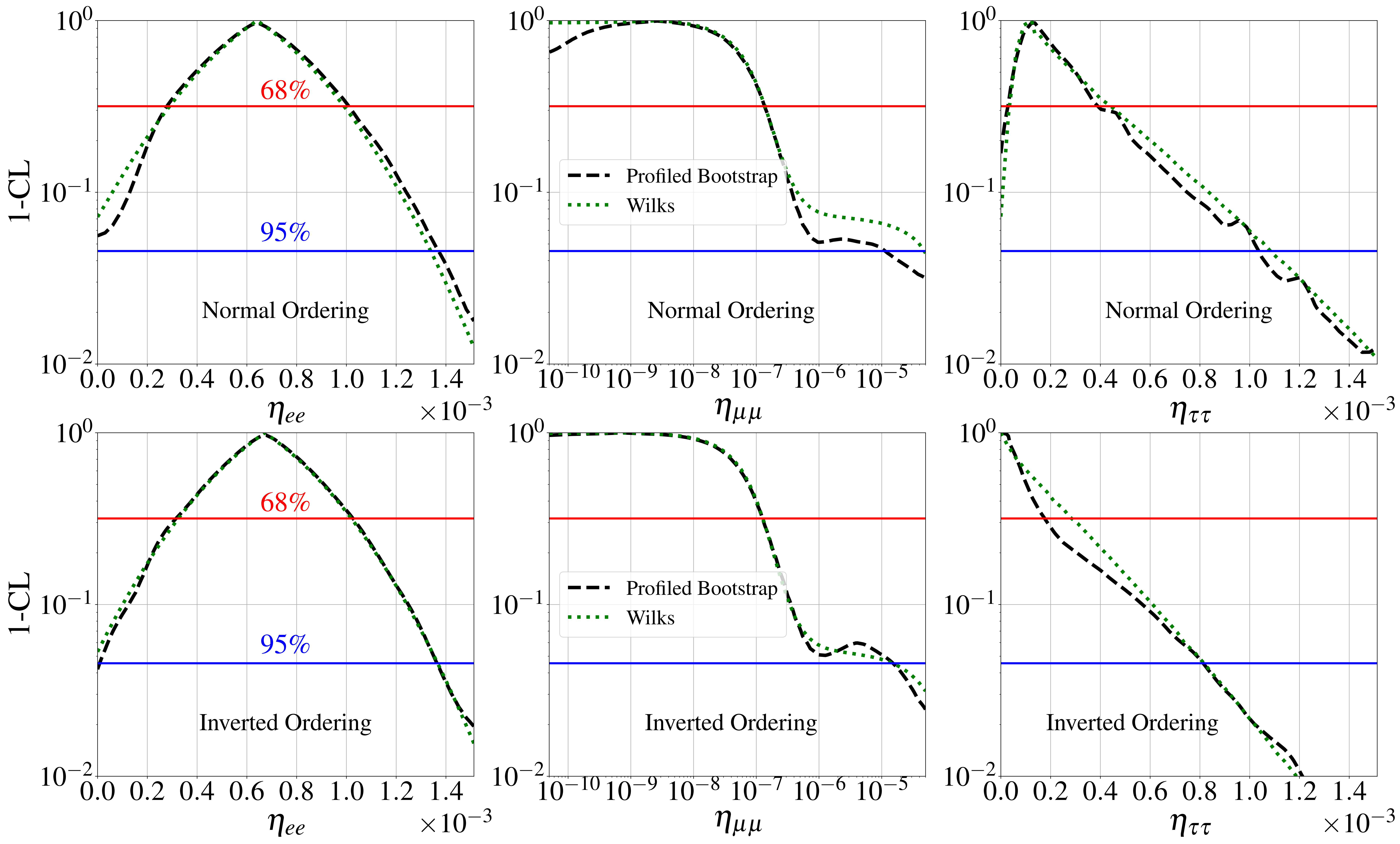
Observable	SM prediction	Experimental value	
$M_W \simeq M_W^{\mathrm{SM}}\,(1+0.20\,(\eta_{ee}+\eta_{\mu\mu}))$	80.356(6) GeV	80.373(11) GeV	-
$s^{2\ \mathrm{Tev}}_{\mathrm{eff}} \simeq s^{2\ \mathrm{SM}}_{\mathrm{eff}}\,(1-1.40\,(\eta_{ee}+\eta_{\mu\mu}))$	0.23154(4)	0.23148(33)	[76]
$s^{2\ \mathrm{LHC}}_{\mathrm{eff}} \simeq s^{2\ \mathrm{SM}}_{\mathrm{eff}}\,(1-1.40\,(\eta_{ee}+\eta_{\mu\mu}))$	0.23154(4)	0.23129(33)	[76]
$\Gamma^{\mathrm{LHC}}_{\mathrm{inv}} \simeq \Gamma^{\mathrm{SM}}_{\mathrm{inv}}\,(1-0.33\,(\eta_{ee}+\eta_{\mu\mu})-1.33\eta_{\tau\tau})$	0.50145(5) GeV	0.523(16) GeV	[77]
$\Gamma_Z \simeq \Gamma_Z^{\mathrm{SM}}\,(1+1.08\,(\eta_{ee}+\eta_{\mu\mu})-0.27\eta_{\tau\tau})$	2.4939(9) GeV	2.4955(23) GeV	[76]
$\sigma^0_{\mathrm{had}} \simeq \sigma^{0\ \mathrm{SM}}_{\mathrm{had}}\,(1+0.50\,(\eta_{ee}+\eta_{\mu\mu})+0.53\eta_{\tau\tau})$	41.485(8) nb	41.481(33) nb	[76]
$R_e \simeq R_e^{\mathrm{SM}}\,(1+0.27\,(\eta_{ee}+\eta_{\mu\mu}))$	20.733(10)	20.804(50)	[76]
$R_\mu \simeq R_\mu^{\mathrm{SM}}\,(1+0.27\,(\eta_{ee}+\eta_{\mu\mu}))$	20.733(10)	20.784(34)	[76]
$R_\tau \simeq R_\tau^{\mathrm{SM}}\,(1+0.27\,(\eta_{ee}+\eta_{\mu\mu}))$	20.780(10)	20.764(45)	[76]
$R^\pi_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	1.0010(9)	[78]
$R^\pi_{\tau\mu} \simeq (1-(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	0.9964(38)	[78]
$R^K_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	0.9978(18)	[78]
$R^\tau_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	1.0018(14)	[78]
$R^\tau_{\tau\mu} \simeq (1-(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	1.0010(14)	[78]
$\left\lvert V^\beta_{ud}\right\rvert \simeq \sqrt{1-\lvert V_{us}\rvert^2}\,(1+\eta_{\mu\mu})$	$\sqrt{1-\lvert V_{us}\rvert^2}$	0.97373(31)	[76]
$\left\lvert V^{\tau\to K\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee}+\eta_{\mu\mu}-\eta_{\tau\tau})$	$\lvert V_{us}\rvert$	0.2236(15)	[79]
$\left\lvert V^{\tau\to K,\pi}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2234(15)	[76]
$\left\lvert V^{K_L\to\pi e\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2229(6)	[76]
$\left\lvert V^{K_L\to\pi\mu\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	0.2234(7)	[76]
$\left\lvert V^{K_S\to\pi e\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2220(13)	[76]
$\left\lvert V^{K_S\to\pi\mu\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	0.2193(48)	[76]
$\left\lvert V^{K^\pm\to\pi e\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2239(10)	[76]
$\left\lvert V^{K^\pm\to\pi\mu\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	0.2238(12)	[76]
$\left\lvert \frac{V_{us}}{V_{ud}}\right\rvert^{K,\pi\to\mu\nu} \simeq \frac{\lvert V_{us}\rvert}{\sqrt{1-\lvert V_{us}\rvert^2}}$	$\frac{\lvert V_{us}\rvert}{\sqrt{1-\lvert V_{us}\rvert^2}}$	0.23131(53)	[76]

Backup



1-CL
Bootstrap
Wilks
68%
95%
Normal Ordering
Inverted Ordering
η_{ee}
$\eta_{\mu\mu}$
$\eta_{\tau\tau}$
$\times 10^{-4}$

Backup



1-CL
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Normal Ordering
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Wilks
η_{ee}
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$\times10^{-3}$
10^{0}
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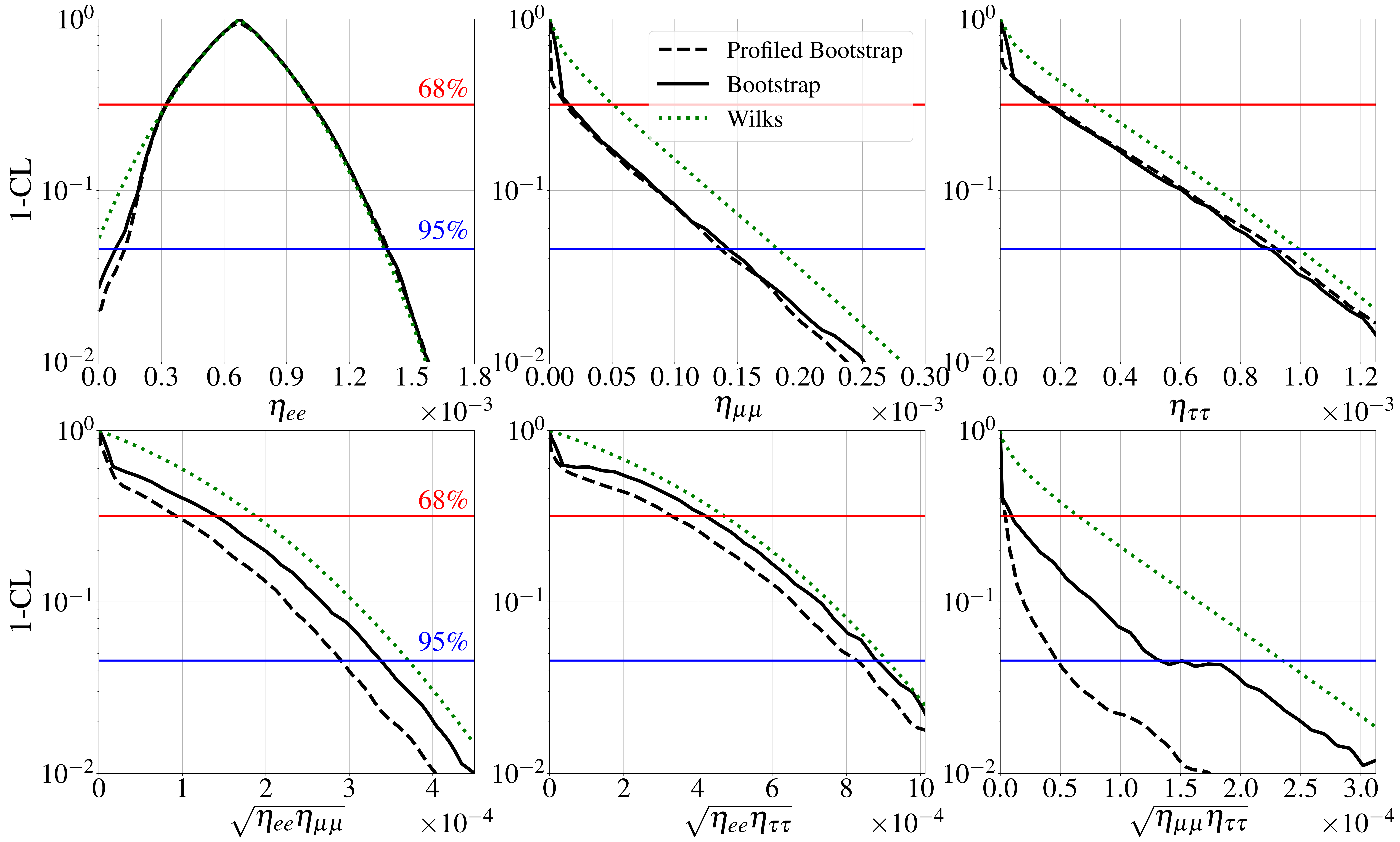
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}

Backup



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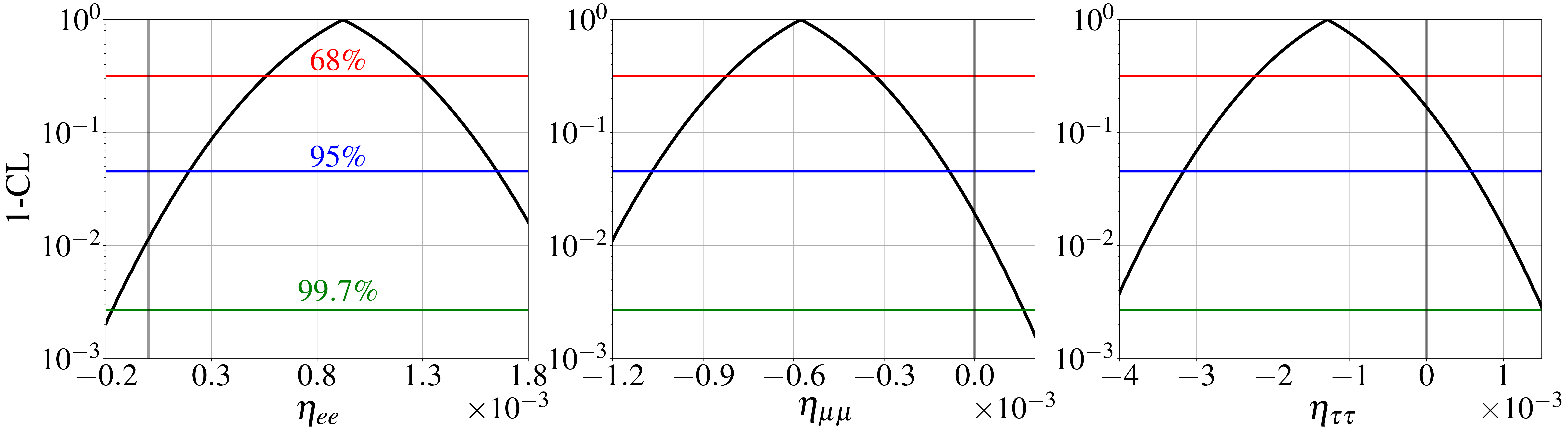
Backup


1-CL
10^0
10^{-1}
10^{-2}
10^{-3}
68%
95%
99.7%
−0.2
0.3
0.8
1.3
1.8
η_{ee}
$\times 10^{-3}$
−1.2
−0.9
−0.6
−0.3
0.0
$\eta_{\mu\mu}$
$\times 10^{-3}$
−4
−3
−2
−1
0
1
$\eta_{\tau\tau}$
$\times 10^{-3}$