(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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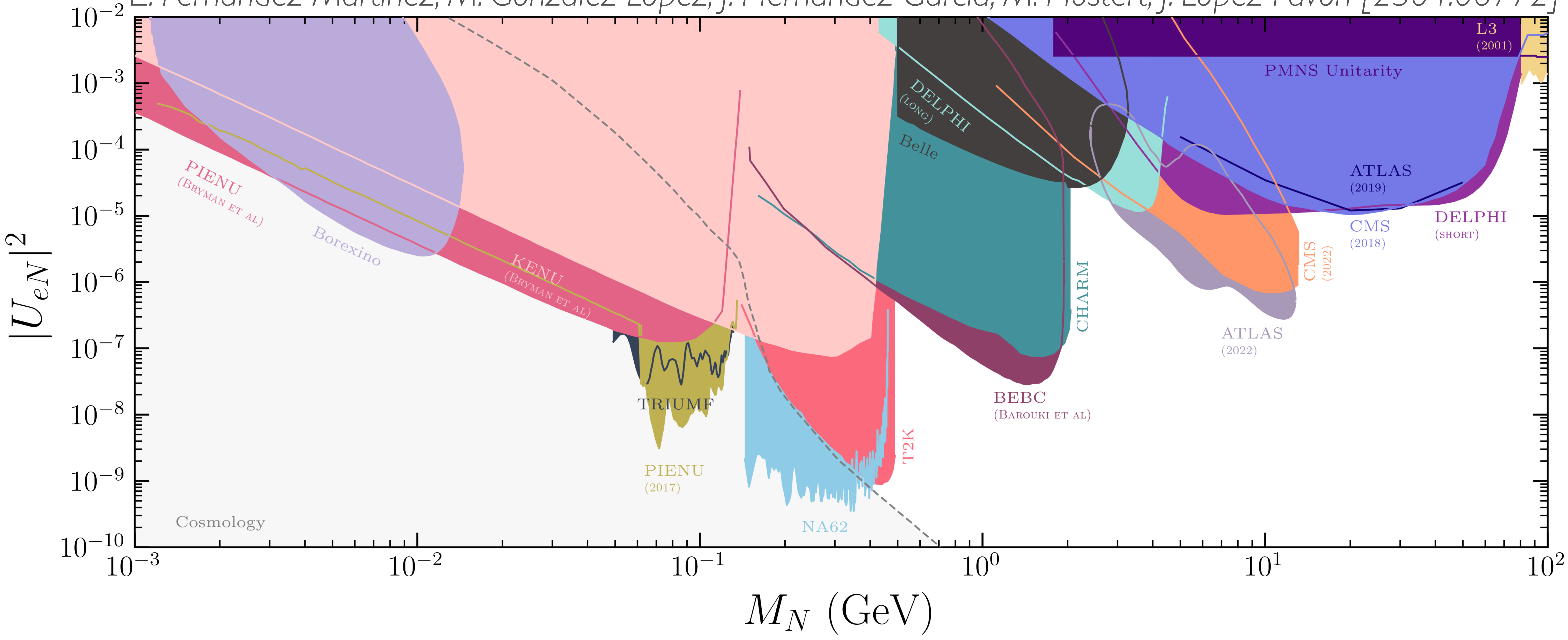
Searches for heavy neutrinos

- Plethora of searches for heavy neutrinos

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



- Above EW scale, precision global bounds dominate

Why update the global fit?

Not included, you can ask me later

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

- Improvement of the analysis:
  - ★ Correlations between observables
  - ★ Better statistics: Bootstrapping

Heavy neutrinos and non-unitarity

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$$-\mathscr{L} \supset Y_\nu \overline{L}_L \tilde{H} N + \frac{1}{2} M_M \overline{N^c} N$$

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$$\underbrace{\eta = \frac{1}{2}\Theta\Theta^\dagger}_{\text{Mass-independent}} \qquad \Theta \equiv \frac{v}{\sqrt{2}} Y_\nu M_M^{-1}$$

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

Observables

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

- We consider the following observables:
  - ★ M_W and s^2_{eff}
  - ★ Z-pole observables
  - ★ LFU ratios
  - ★ $|V_{ud}|$ and $|V_{us}|$ measurements
  - ★ Charged lepton flavor violation (cLFV) constraints

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  - M_W and s^2_{eff}
  - Z-pole observable
  - LFU ratios
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  - Charged lepton flavo

Observable	SM prediction	Experimental value	
$M_W \simeq M_W^{SM}\,(1+0.20\,(\eta_{ee}+\eta_{\mu\mu}))$	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]
$\Gamma_{\mathrm{inv}}^{\mathrm{LHC}} \simeq \Gamma_{\mathrm{inv}}^{\mathrm{SM}}\,(1-0.33\,(\eta_{ee}+\eta_{\mu\mu})-1.33\eta_{\tau\tau})$	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]
$\lvert V^\beta_{ud}\rvert \simeq \sqrt{1-\lvert V_{us}\rvert^2}\,(1+\eta_{\mu\mu})$	$\sqrt{1-\lvert V_{us}\rvert^2}$	0.97373(31)	[76]
$\lvert V^{\tau\to K\nu}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee}+\eta_{\mu\mu}-\eta_{\tau\tau})$	$\lvert V_{us}\rvert$	0.2236(15)	[79]
$\lvert V^{\tau\to K,\pi}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2234(15)	[76]
$\lvert V^{K_L\to\pi e\nu}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2229(6)	[76]
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$\lvert V^{K_S\to\pi e\nu}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2220(13)	[76]
$\lvert V^{K_S\to\pi\mu\nu}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	0.2193(48)	[76]
$\lvert V^{K^\pm\to\pi e\nu}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2239(10)	[76]
$\lvert V^{K^\pm\to\pi\mu\nu}_{us}\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	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]

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

- Restrictive flavor structure + cLFV: tight constraints

Results: 3 heavy neutrino case

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

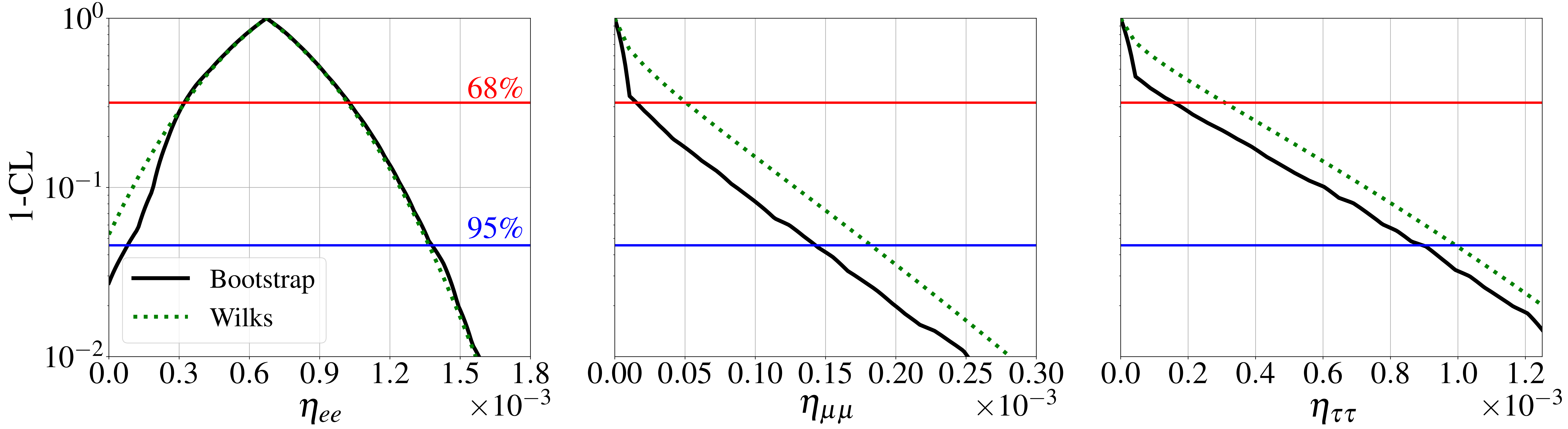
3N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$[0.28, 0.99] \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$[0.31, 1.0] \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-5}$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

- More flexible flavor structure

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

Results: 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

Conclusions

- Precision bounds on heavy neutrinos start dominating above M_W
- First global bounds on 2 neutrino case
- Bounds substantially change between setups (2N-SS, 3N-SS, G-SS)
- Quantified deviations from Wilks' theorem

Thanks for your attention!

Backup

Backup

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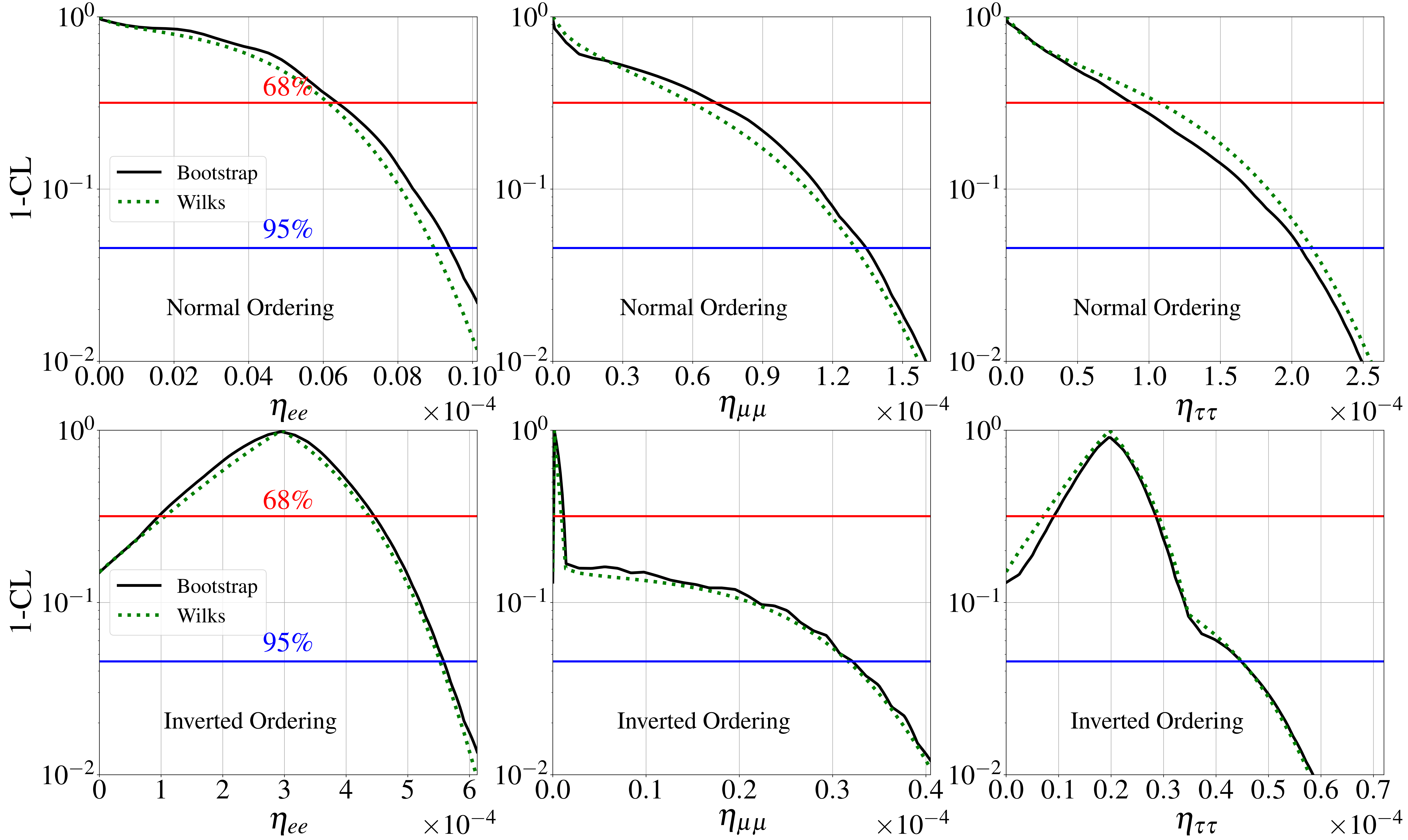
Backup



1-CL
Bootstrap
Wilks
68%
95%
Normal Ordering
Inverted Ordering
η_{ee}
$\eta_{\mu\mu}$
$\eta_{\tau\tau}$
$\times 10^{-4}$
10^{0}
10^{-1}
10^{-2}
0.00 0.02 0.04 0.06 0.08 0.10
0.0 0.3 0.6 0.9 1.2 1.5
0.0 0.5 1.0 1.5 2.0 2.5
0 1 2 3 4 5 6
0.0 0.1 0.2 0.3 0.4
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

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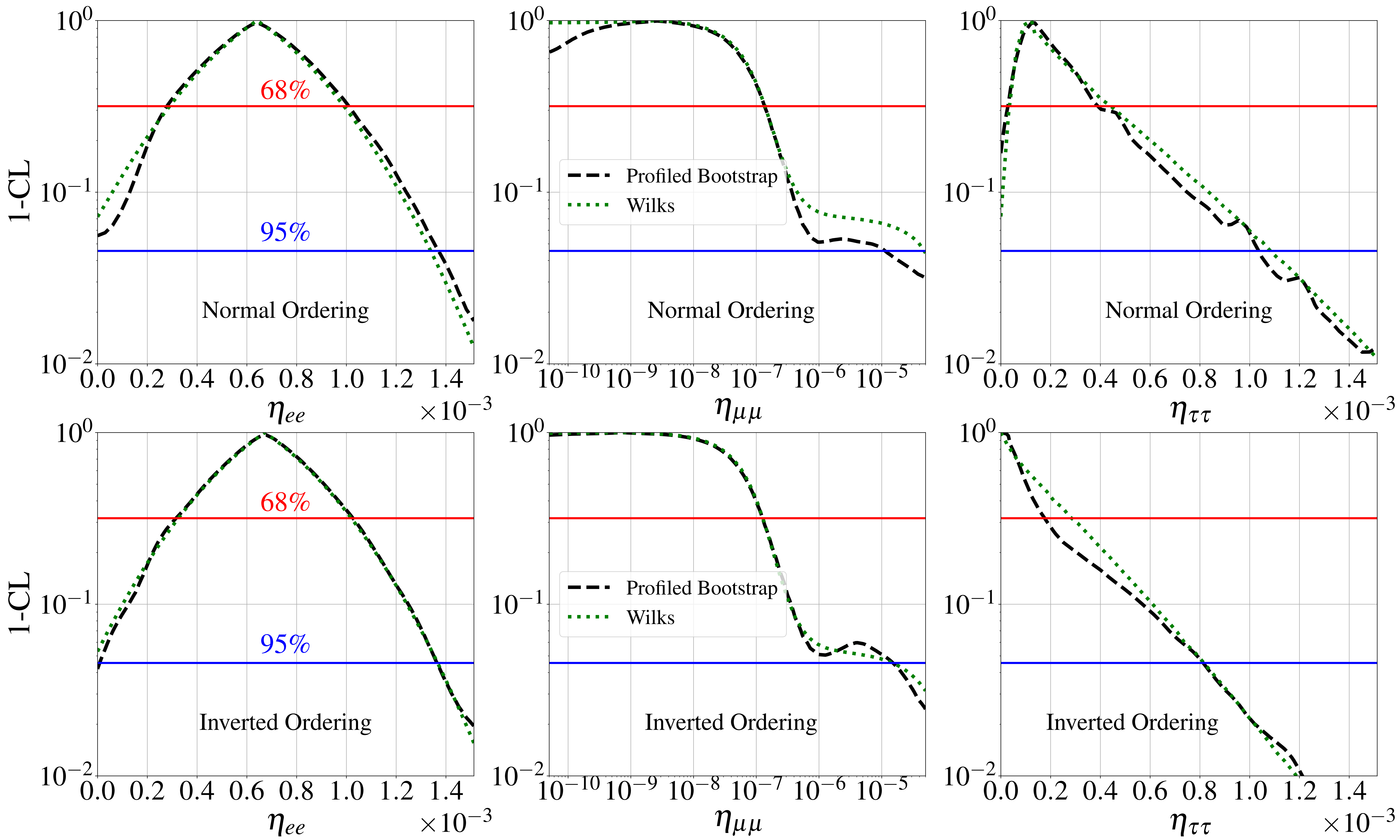
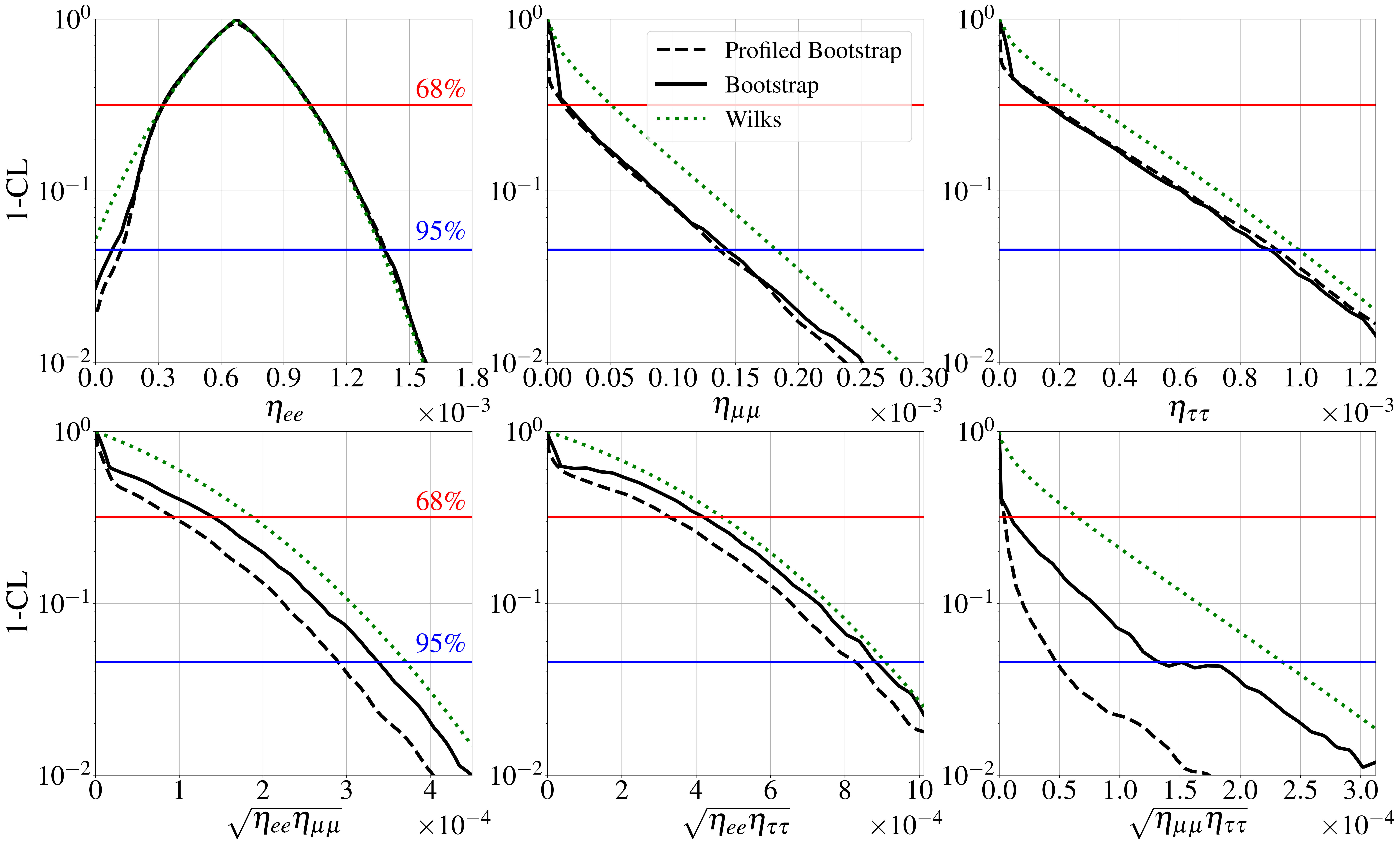

1-CL
68%
95%
Normal Ordering
Inverted Ordering
Profiled Bootstrap
Wilks
η_{ee}
$\eta_{\mu\mu}$
$\eta_{\tau\tau}$
$\times 10^{-3}$

Backup



1-CL
68%
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Profiled Bootstrap
Bootstrap
Wilks
η_{ee}
$\eta_{\mu\mu}$
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$\times 10^{-3}$
$\sqrt{\eta_{ee}\eta_{\mu\mu}}$
$\sqrt{\eta_{ee}\eta_{\tau\tau}}$
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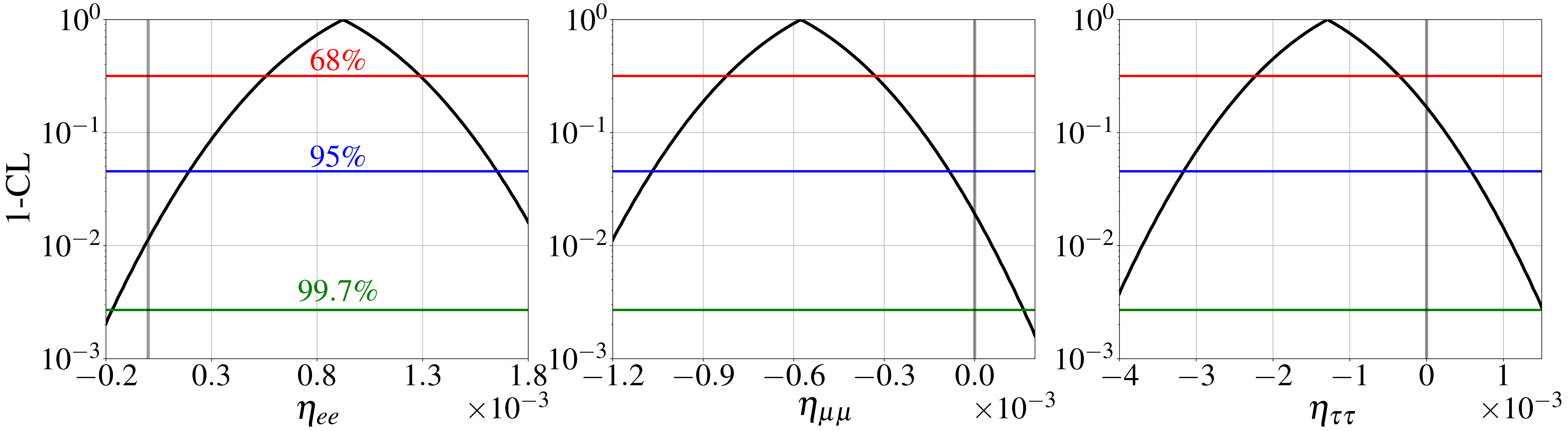
$\times 10^{-4}$

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
$\eta_{\tau\tau}$
$\times 10^{-3}$