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# Probing Non-Standard Interactions in NOvA with Bayesian MCMC Methods

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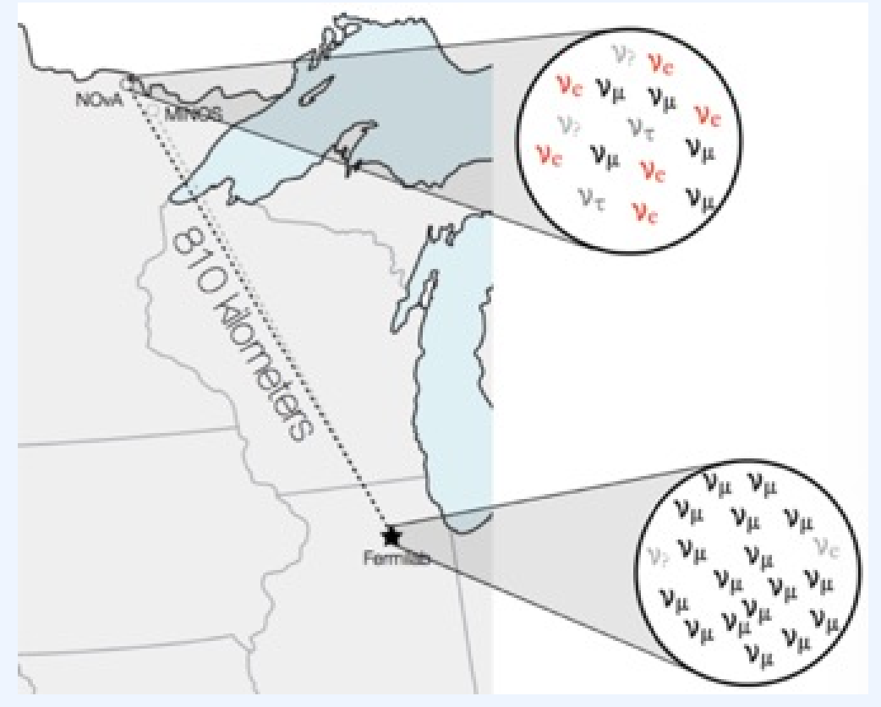
FERMILAB-POSTER-26-0042-PPD

## The NOvA Experiment

- **Long-baseline** $\nu$ oscillation experiment at Fermilab, operational since 2014
- Two liquid-scintillator detectors **810 km** apart: 0.3 kt Near Detector (FNAL) and 14 kt Far Detector (Ash River, MN)
- 14.6 mrad off-axis beam ⇒ narrow peak at **1.8 GeV**
- Long baseline ⇒ large **MSW matter effect**, sensitive to new physics



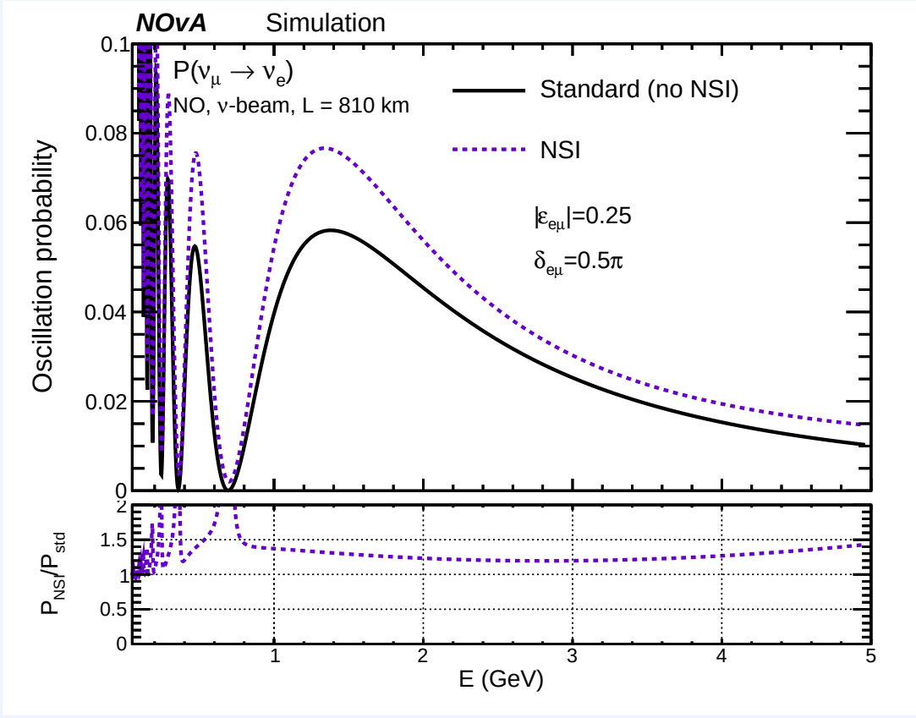
## Non-Standard Interactions (NSI)

NSI add beyond-SM contact interaction terms to the matter Hamiltonian:

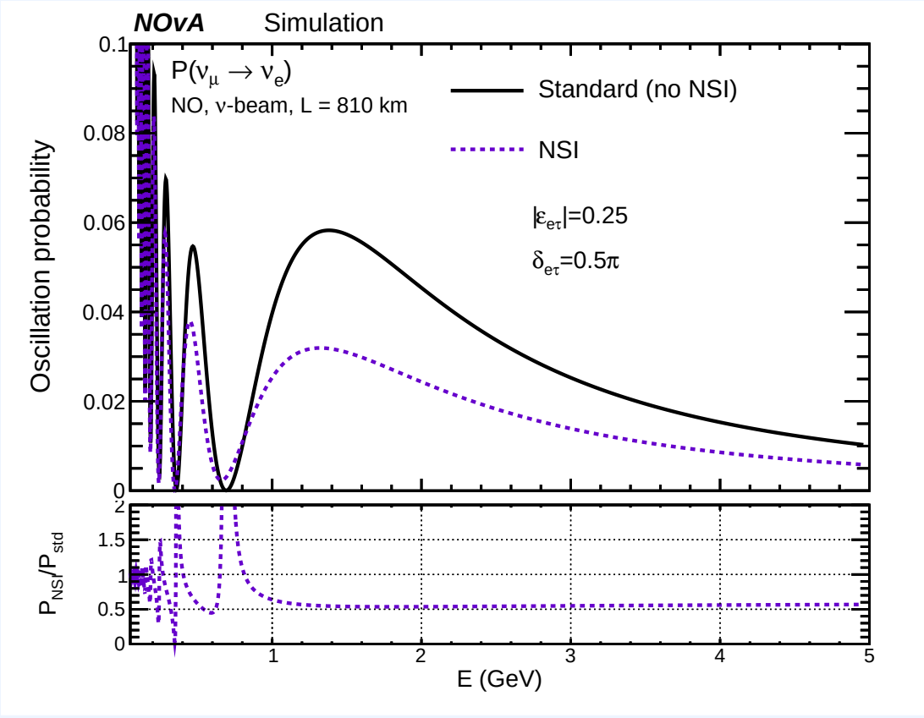
$$\mathcal{H} = U\,\mathrm{diag}(0, \Delta_{21}, \Delta_{31})\,U^\dagger + V_e\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

- Off-diagonal $\varepsilon_{\alpha\beta}$ are **complex**: magnitude $|\varepsilon|$ + CP-violating phase $\delta$; SM limit $\varepsilon_{\alpha\beta} = 0$
- NOvA is sensitive to $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ via $\nu_\mu \to \nu_e$ appearance and the MSW matter effect

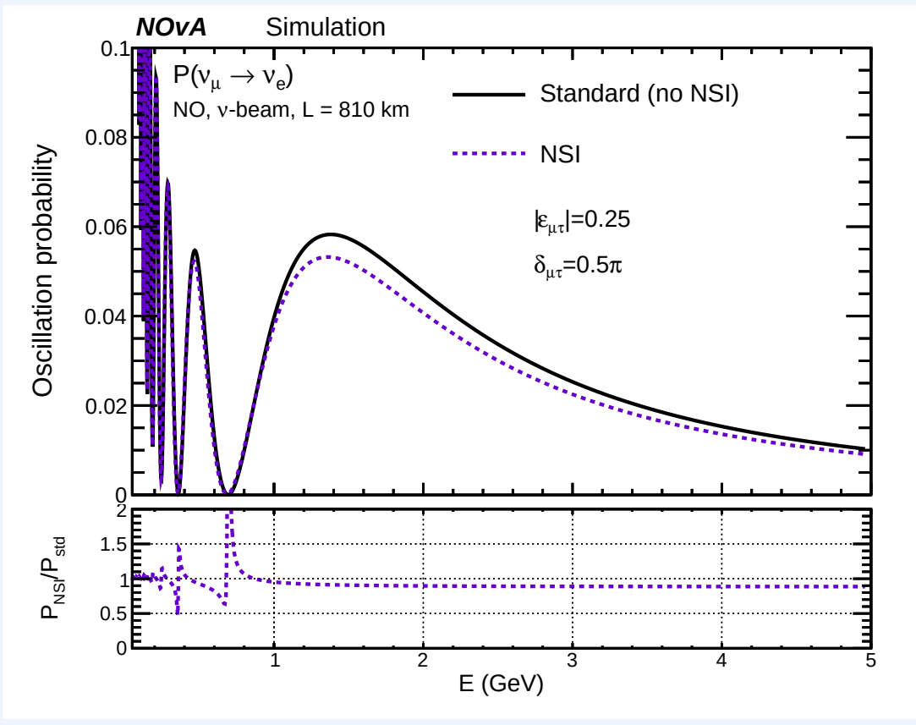
## NSI Effect on $\nu_\mu \to \nu_e$ Appearance



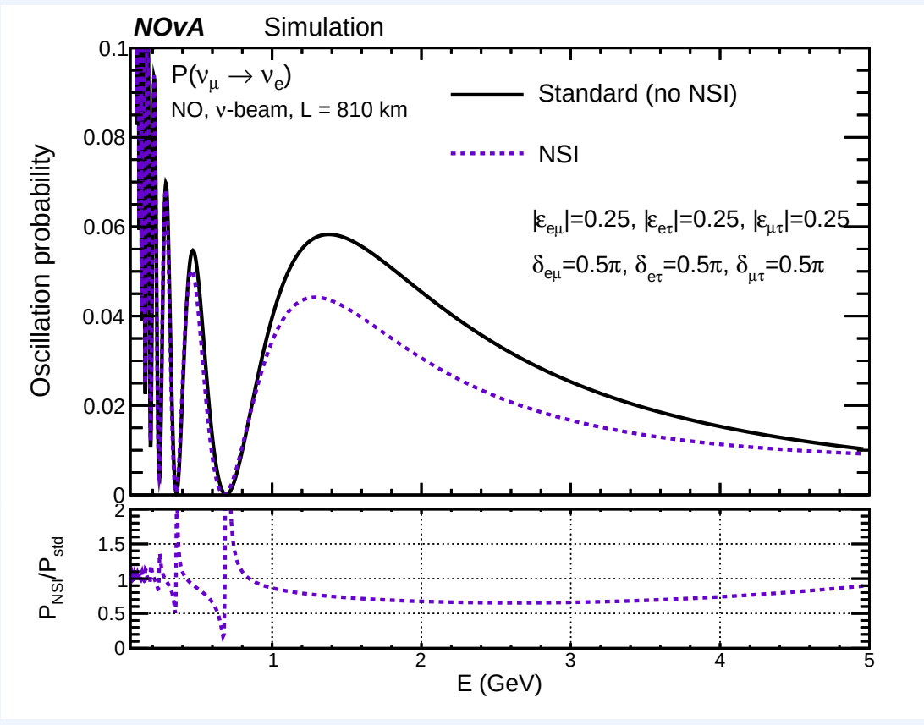
$\varepsilon_{e\mu} = 0.25,\ \delta_{e\mu} = \pi/2$



$\varepsilon_{e\tau} = 0.25,\ \delta_{e\tau} = \pi/2$



$\varepsilon_{\mu\tau} = 0.25,\ \delta_{\mu\tau} = \pi/2$



all $|\varepsilon_{XY}| = 0.25,\ \delta_{XY} = \pi/2$

- Different NSI sectors **could** change oscillation probability in opposing ways
- A frequentist profile-likelihood treats each sector independently; Bayesian MCMC allows **all sectors to vary simultaneously** in a single fit

## Bayesian MCMC: Metropolis-Hastings

$P(\boldsymbol{\theta} \mid \text{data}) \propto \mathcal{L}(\text{data} \mid \boldsymbol{\theta})\,\pi(\boldsymbol{\theta})$, $\mathcal{L} \propto e^{-\frac{1}{2}\chi^2_{\text{NOvA}}}$ (joint $\nu_e+\nu_\mu$, FHC+RHC); NO+IO in one chain; systematics **marginalized**.

**Mechanism:**

**Propose** (Gaussian step, all params) → **Score** $\left(\log\mathcal{L}' = -\frac{1}{2}\chi^2 + \log\pi\right)$ → **Accept** $\left(\alpha = \min(1, e^{\Delta\log\mathcal{L}})\right)$ or stay → ↻

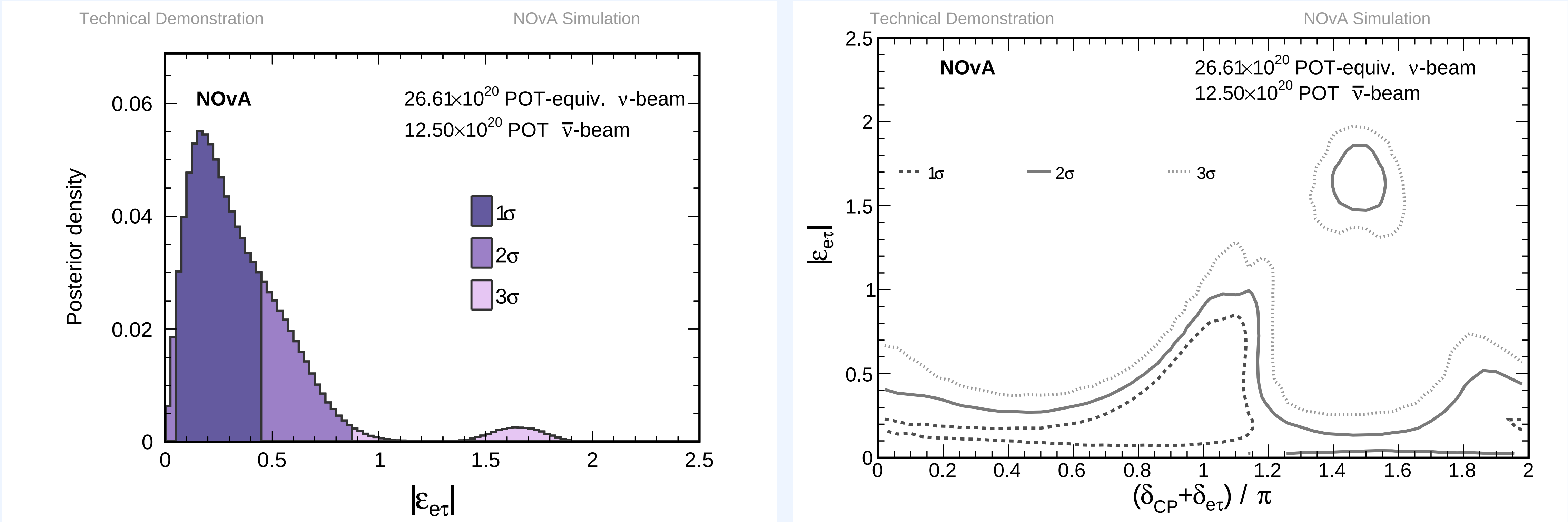
The **prior** $\pi(\boldsymbol{\theta})$ for complex NSI parameters $\varepsilon_{\alpha\beta}$ is non-trivial — see analysis below ↓

## Prior Sensitivity in NSI: Three Approaches ($\varepsilon_{e\tau}$ example)

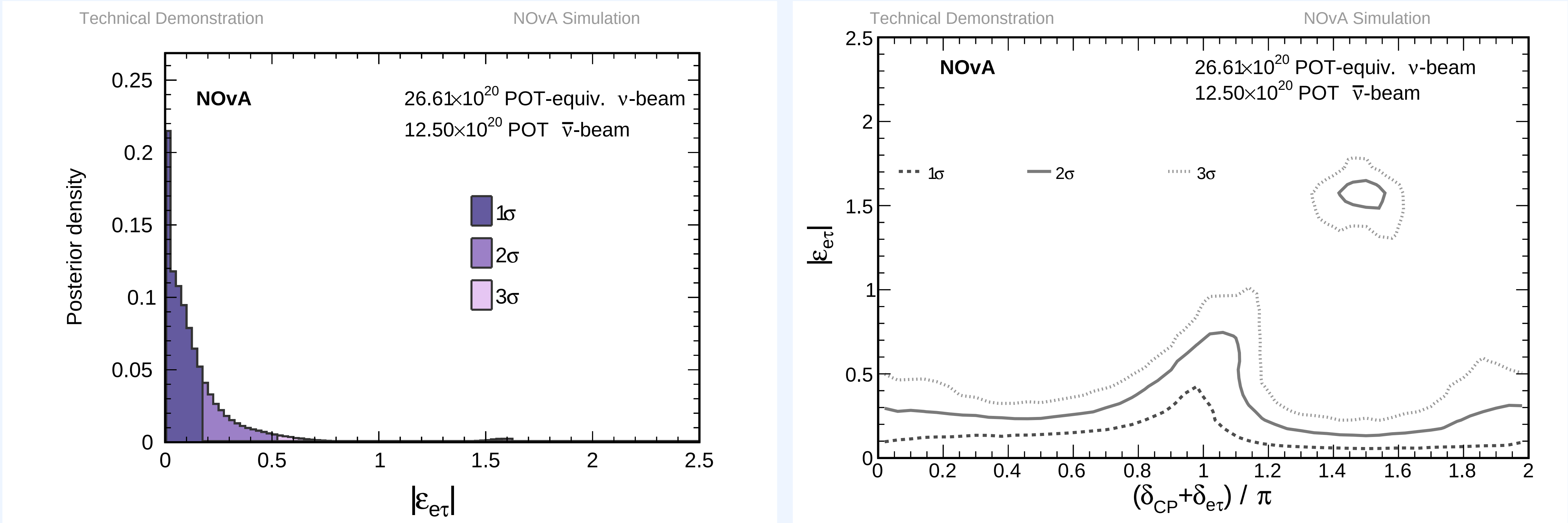
1D posterior, $|\varepsilon_{e\tau}|$ (NO+IO)

2D posterior, $|\varepsilon_{e\tau}|$ vs $\delta_{\text{CP}} + \delta_{e\tau}$

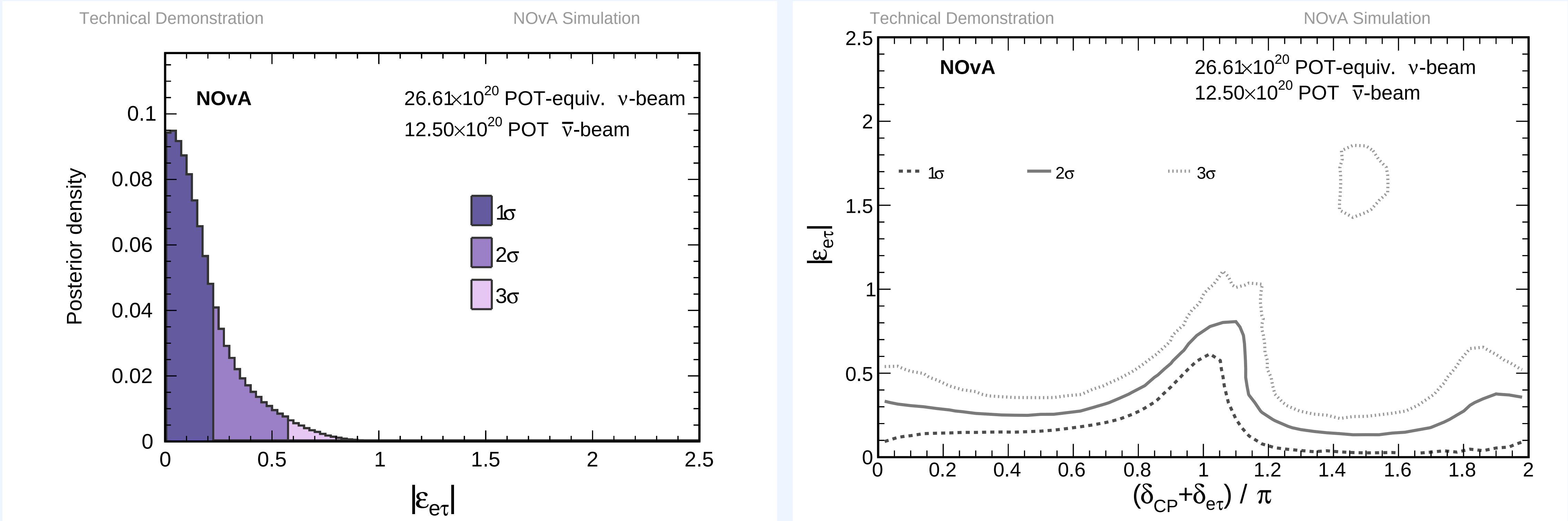
**A: Flat Cartesian** — $\pi(x, y) = \text{const} \;\Rightarrow\; \pi(|\varepsilon|) \propto |\varepsilon|$



**B: Mixture Prior** — $\pi(|\varepsilon|) = 0.1 \cdot \mathcal{HN}(\sigma{=}0.1) + 0.9 \cdot \mathcal{HN}(\sigma{=}1.0)$



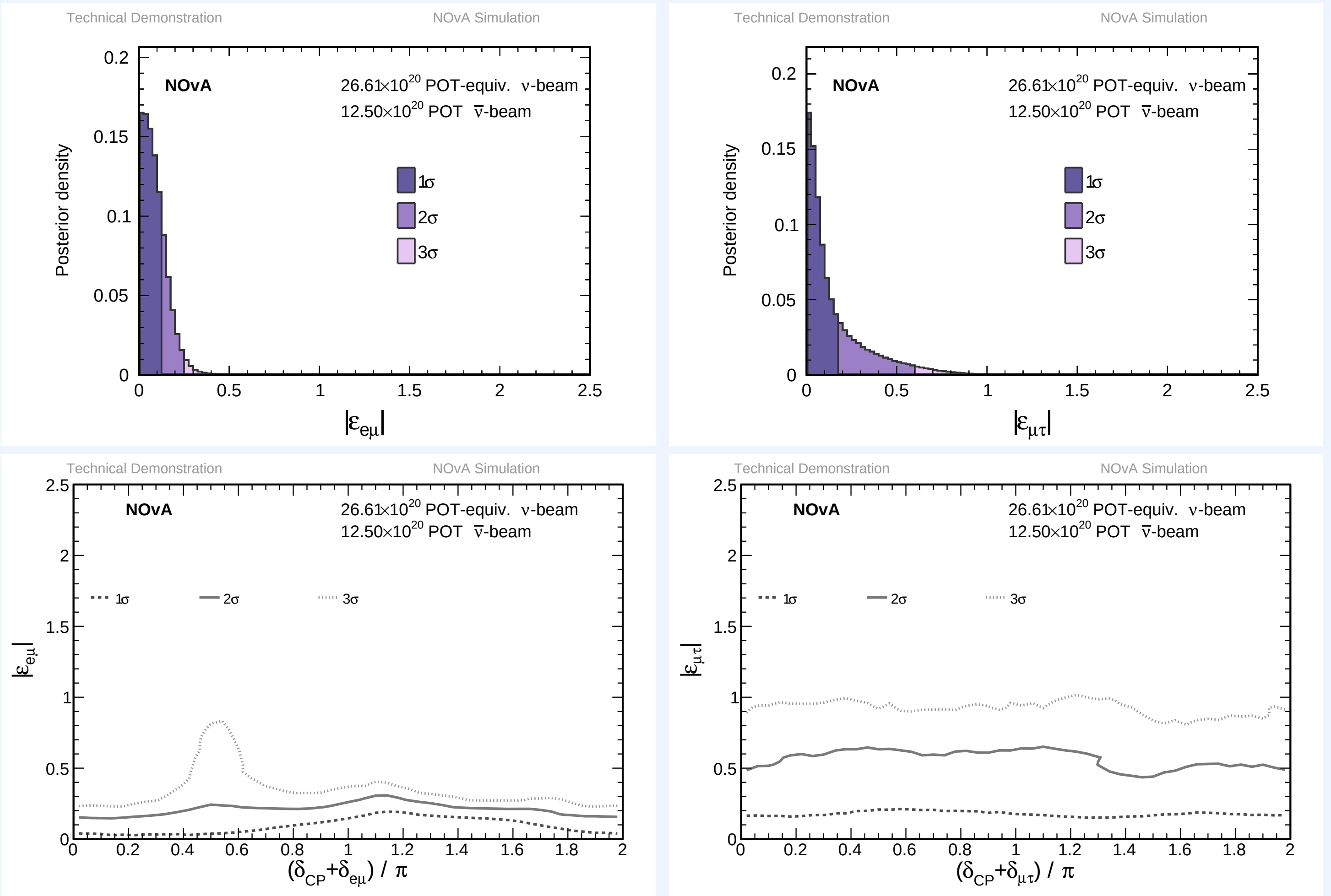
**C: Jacobian Correction ★** — $\log\pi(x, y) = -\log(|\varepsilon| + \varepsilon_{\text{reg}})$, $\varepsilon_{\text{reg}} = 10^{-4}$ **[Preferred]**



## Jacobian Correction Prior for Other NSI Sectors

$\varepsilon_{e\mu}$ sector

$\varepsilon_{\mu\tau}$ sector



## Analysis and Summary of Prior Selections

- **Method A** (flat Cartesian): $\pi(x, y) = \text{const}$ induces $\pi(|\varepsilon|) \propto |\varepsilon|$ via the polar Jacobian — the prior assigns zero probability to $|\varepsilon| = 0$, creating a **dip** at $|\varepsilon| \to 0$ and suppressing the SM limit even when the data have no NSI signal.
- **Method B** (mixture prior): the narrow HN component boosts probability near $|\varepsilon| \approx 0$, but the prior shape dominates the statistics near zero, creating a **spike at** $|\varepsilon| = 0$ — not suitable as a final result.
- **Method C** (Jacobian correction, **recommended**): $-\log(|\varepsilon| + \varepsilon_{\text{reg}})$ added to the log-prior cancels the $|\varepsilon|$ Jacobian, restoring a **flat marginal prior in** $|\varepsilon|$. Dip and spike are both removed; results show good qualitative agreement with the frequentist profile likelihood.

## Conclusions

- Bayesian NSI analysis is a **unique challenge**: complex $\varepsilon_{\alpha\beta}$ makes prior choice non-trivial; **Method C (Jacobian correction)** is the recommended approach
- These results are a **technical demonstration** toward full validation relative to the NOvA frequentist NSI approach

## Acknowledgments & References

This poster was prepared by the NOvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002. Supported by U.S. DOE grant DE-SC0021616 and the University of Mississippi.

[1] M. A. Acero et al. (NOvA Collaboration), *Phys. Rev. D* **110**, 012005 (2024), arXiv:2311.07835.

[2] S. Brooks et al. (eds.), *Handbook of Markov Chain Monte Carlo*, Chapman & Hall/CRC (2011).