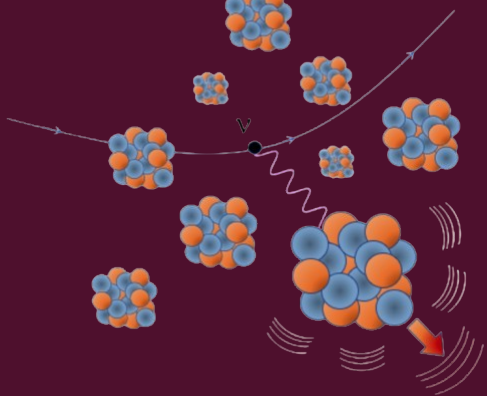




Source and detector NSI at the ESSnuSB+ near detectors

Doris Barčot, Ruđer Bošković Institute, Croatia



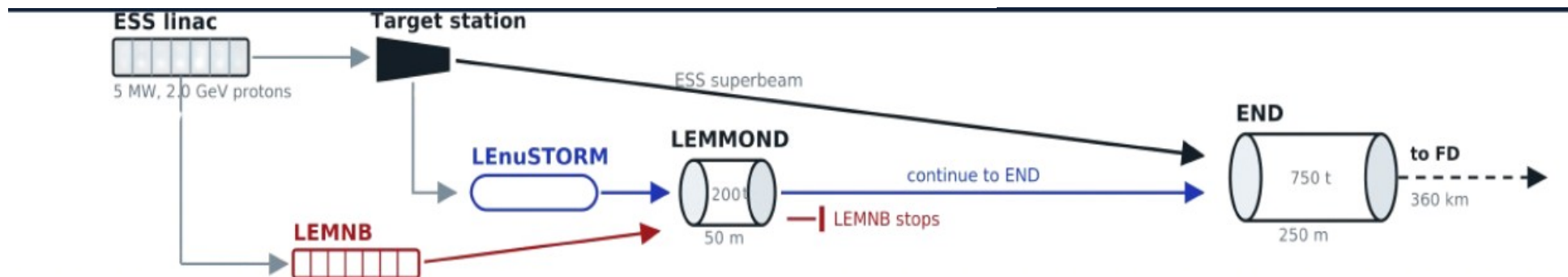
ESSnuSB+ 4th annual collaboration meeting, Sweden, 2026.



What are we trying to probe → **sterile neutrino + NSI @ ND**

Configuration	Flux component	N_0 (interactions)
LEMNB @ LEMMOND	ν_μ	2.3×10^5
ESS @ END	ν_μ (5 MW)	8×10^7
nuSTORM @ LEMMOND	$\bar{\nu}_\mu$	2.5×10^3
	ν_e	6.9×10^3
nuSTORM @ END	$\bar{\nu}_\mu$	2.8×10^2
	ν_e	7.8×10^2

- **LEMNB** flux from WP6
- **LenuSTORM** flux WP4
- **ESS** flux from previous project
- Migration matrices as FD (previous project)
- Mass: **200 t** (LEMMOND), **750 t** (END)



Source and detector NSI

The underlying physics

→ 4-fermion operator:

$$\mathcal{L}_{\text{NSI}} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon_{\alpha\beta}^{f,f',X} [\bar{\nu}_\beta \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 \pm \gamma^5) f]$$

- dimensionless coefficient measure the strength of a new interaction relative to the weak scale
- generally complex, enter neutrino phenomenology in 3 physically distinct places:

SOURCE, PROPAGATION, **DETECTOR**

- CC process that produces a neutrino of flavour α can, in the presence of NSI, emit a state containing admixtures of other flavour

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_\gamma \varepsilon_{\alpha\gamma}^s |\nu_\gamma\rangle$$

- detection interaction that nominally identifies a neutrino as flavour β receives contaminating contributions

$$\langle \nu_\beta^d | = \langle \nu_\beta | + \sum_\gamma \varepsilon_{\gamma\beta}^d \langle \nu_\gamma |$$

$$P_{\alpha\beta} = \left| \langle \nu_\beta^d | e^{-iHL} | \nu_\alpha^s \rangle \right|^2 = \left| [(1 + \varepsilon^d)^T e^{-iHL} (1 + \varepsilon^s)^T]_{\beta\alpha} \right|^2$$

* propagation NSI modifies the effective Hamiltonian, irrelevant for ND

The underlying physics

Why look for source/detector NSI at a near detector?

Standard framework

- ν_μ beam is produced; ν_e/ν_μ interaction is detected
- $L \approx O(10-100 \text{ m})$ standard oscillation phase is negligible

With source/detector NSI

- In production and/or detection, it can create a state with the “wrong” flavour.
→ a flavour-changing event without any oscillation.

$$P_{\alpha\beta} \simeq \left| \left[(1 + \varepsilon^d)^T (1 + \varepsilon^s)^T \right]_{\beta\alpha} \right|^2$$

A clean zero-distance flavour effect — no oscillation pattern to resolve.

* Current bounds are at the $10^{-1}-10^{-2}$ level → expand to second order in ε .

** source and detector contributions are intrinsically degenerate which shapes every result that follows.

The underlying physics

Why look for source/detector NSI at a near detector?

Appearance ($\alpha \neq \beta$)

$$P_{\alpha\beta} = |\varepsilon_{\alpha\beta}^s|^2 + |\varepsilon_{\alpha\beta}^d|^2 + 2 |\varepsilon_{\alpha\beta}^s| |\varepsilon_{\alpha\beta}^d| \cos(\Phi^s - \Phi^d)$$

- No SM term at zero distance $\rightarrow$ signal starts at $\mathcal{O}(\varepsilon^2)$ — intrinsically small.
- Phases enter only as the difference $\Phi^s - \Phi^d$.

Disappearance ($\alpha = \alpha$)

$$P_{\alpha\alpha} \simeq 1 + 2 \operatorname{Re} \varepsilon_{\alpha\alpha}^s + 2 \operatorname{Re} \varepsilon_{\alpha\alpha}^d + \mathcal{O}(\varepsilon^2)$$

- A large SM rate is shifted already at $\mathcal{O}(\varepsilon)$.
- Natural variables $\operatorname{Re}(\varepsilon)$; phases enter as a sum.

Appearance $\rightarrow$ statistics matter

Disappearance $\rightarrow$ systematics matter

Flavour bookkeeping

$$\varepsilon_{\mu e}^s \neq \varepsilon_{e\mu}^s$$

NSI matrix is not symmetric!

Which NSI parameters can ESSnuSB+ reach?

Beam flavour fixes the row of the NSI matrix we can probe

Beam flux	Detection channel	NSI probed	Type
$\nu_\mu / \bar{\nu}_\mu$	$\nu_e / \bar{\nu}_e$ appearance	$\varepsilon_{\mu e}^s, \varepsilon_{\mu e}^d$	off-diagonal
ν_e	ν_μ appearance	$\varepsilon_{e\mu}^s, \varepsilon_{e\mu}^d$	off-diagonal
$\nu_\mu / \bar{\nu}_\mu$	$\nu_\mu / \bar{\nu}_\mu$ survival	$\varepsilon_{\mu\mu}^s, \varepsilon_{\mu\mu}^d$	diagonal
ν_e	ν_e survival	$\varepsilon_{ee}^s, \varepsilon_{ee}^d$	diagonal

Bookkeeping

Appearance → statistics matter

Disappearance → systematics matter

NSI matrix is not symmetric

The central limitation is the event-rate hierarchy!

→ μ -row parameters are reached by intense ν_μ fluxes, dominated by ESS

→ e -row parameters are reached only through the weak nuSTORM ν_e flux

μ -row (ESS ν_μ) $N_0 \sim 8 \times 10^7$ vs e -row (nuSTORM ν_e) $N_0 \sim 7 \times 10^3 \rightarrow \sim 4$ orders of magnitude span

Which NSI parameters can ESSνSB+ reach?

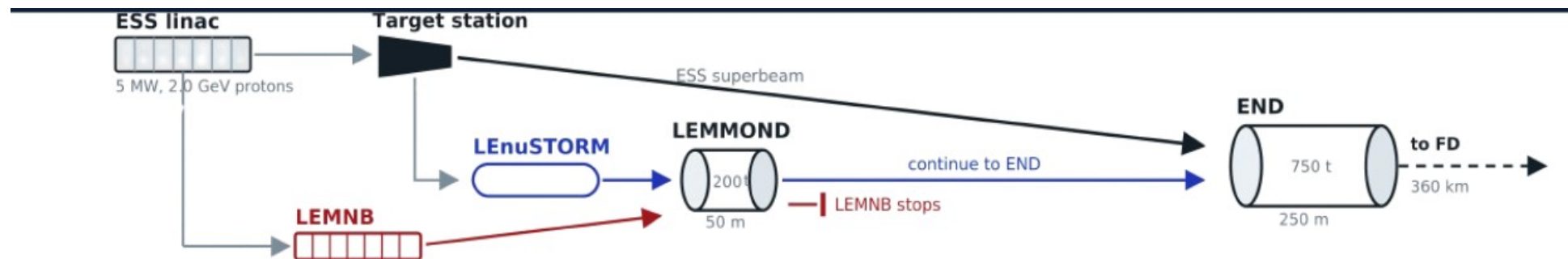
Beam flavour fixes the row of the NSI matrix we can probe

Configuration	Flux component	NSI reachable	N_0 (interactions)
LEMNB @ LEMMOND	ν_μ	$\varepsilon_{\mu e}, \varepsilon_{\mu\mu}$	2.3×10^5
ESS @ END	ν_μ (5 MW)	$\varepsilon_{\mu e}, \varepsilon_{\mu\mu}$	8×10^7
nuSTORM @ LEMMOND	$\bar{\nu}_\mu$	$\varepsilon_{\mu e}, \varepsilon_{\mu\mu}$	2.5×10^3
	ν_e	$\varepsilon_{e\mu}, \varepsilon_{ee}$	6.9×10^3
nuSTORM @ END	$\bar{\nu}_\mu$	$\varepsilon_{\mu e}, \varepsilon_{\mu\mu}$	2.8×10^2
	ν_e	$\varepsilon_{e\mu}, \varepsilon_{ee}$	7.8×10^2

Bookkeeping

Appearance → statistics matter

Disappearance → systematics matter
NSI matrix is not symmetric



Which NSI parameters can ESSnuSB+ reach?

Building the χ^2

→ **pull method** as implemented in *GLOBES*

→ data is generated assuming SM (all NSI true values zero), and for each point in the fit parameter space a χ^2 quantifies the incompatibility with the data

$$\chi^2 = \frac{N_0^2}{\sigma^2} \left[\delta_{\alpha\beta} - P_{\alpha\beta}(\varepsilon_{\text{fit}}^s, \varepsilon_{\text{fit}}^d) \right]^2$$

→ number of events in a channel (/bin): $N = N_0 P_{\alpha\beta}(\varepsilon^s, \varepsilon^d)$, $N_0 = \int dE_\nu \sigma_\beta(E_\nu) \frac{d\phi_\alpha}{dE_\nu}(E_\nu) \epsilon_\beta(E_\nu)$,

→ systematics used: 5% normalization uncertainty on the flux and background (ESS, nuSTORM); 1% LEMNB

Appearance channels

$$\chi^2 = \frac{N_0^2}{\sigma^2} \left[|\varepsilon_{\alpha\beta}^s|^2 + |\varepsilon_{\alpha\beta}^d|^2 + 2|\varepsilon_{\alpha\beta}^s||\varepsilon_{\alpha\beta}^d| \cos \Delta\Phi \right]^2$$

Disappearance channels

$$\chi^2 = \frac{4N_0^2}{\sigma^2} [\text{Re}(\varepsilon_{\alpha\alpha}^s) + \text{Re}(\varepsilon_{\alpha\alpha}^d)]^2$$

Which NSI parameters can ESSnuSB+ reach?

Before the plots: what should the limits do?

Appearance

$$\Delta_{\alpha\beta} \sim \left(\frac{\chi_0^2 \sigma^2}{N_0^2} \right)^{1/4} \propto N_0^{-1/2}$$

statistics-limited — more flux helps.

Disappearance

$$\Delta_{\alpha\alpha} \sim \sqrt{\frac{\chi_0^2}{2}} \sigma_{\text{sys}} \quad (N_0 \text{ cancels})$$

Systematics-limited (mostly) — N_0 cancels.

→ The event-rate table predicts the sensitivity hierarchy.

→ **Neutrinos vs. antineutrinos:**

$$P_{\bar{\alpha}\bar{\beta}} = P_{\alpha\beta}(\Phi \rightarrow -\Phi)$$

cosine is even → antineutrino appearance rate is **identical** to the neutrino one → we're probing the same coefficients → **additional statistics**, no new information

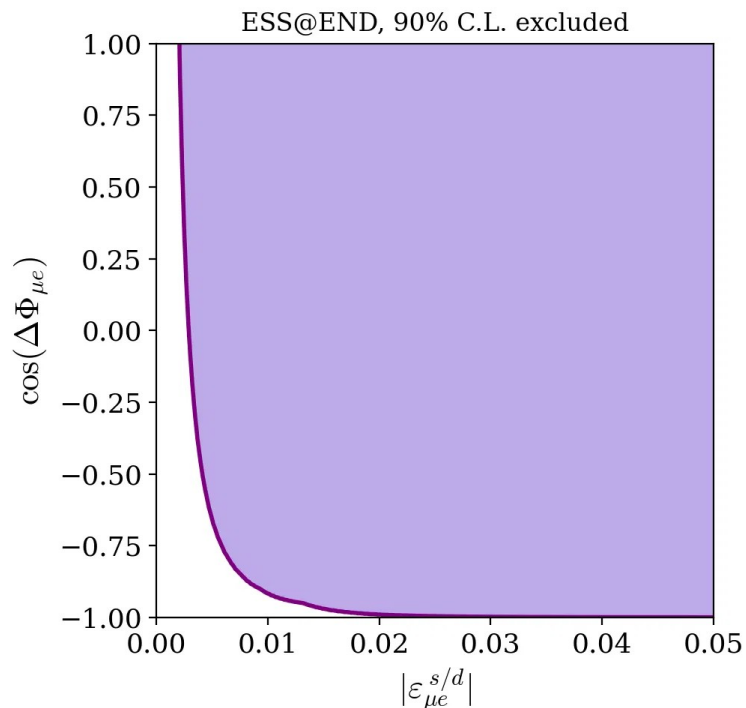
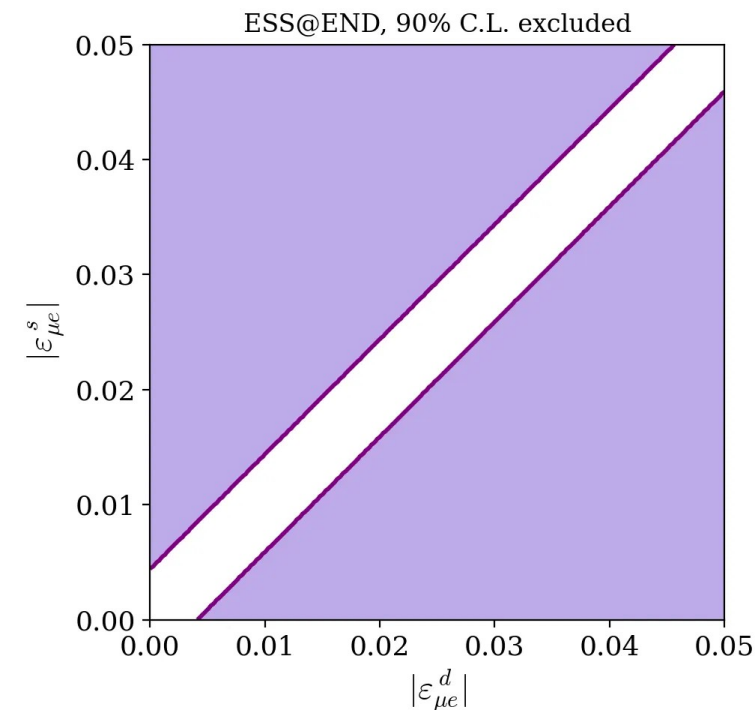
Summary

	Off-diagonal ($\mu e, e\mu$)	Diagonal ($\mu\mu, ee$)
Channel	appearance	disappearance
Leading order in ε	second ($\propto \varepsilon^2$)	first ($\propto \varepsilon$)
Plot variables	$ \varepsilon^s , \varepsilon^d $	$\text{Re}(\varepsilon^s), \text{Re}(\varepsilon^d)$
Phase enters as	difference $\Phi^s - \Phi^d$	sum $\text{Re}(\varepsilon^s) + \text{Re}(\varepsilon^d)$
Allowed region	diagonal band (open)	anticorrelation band
Band half-width	$(4\chi_0^2\sigma^2/N_0^2)^{1/4}$	$\sqrt{\chi_0^2\sigma^2/2N_0^2}$
Limiting factor	statistics ($\propto N_0^{-1/2}$)	systematics (σ_{sys})

*off-diagonal couplings contribute to a diagonal survival probability, but only at second order and only as products of two distinct couplings
→ when **all but one coupling are set to zero**, these terms vanish

Results

Appearance ($\nu_\mu \rightarrow \nu_e$) : the strongest ESSnuSB+ result



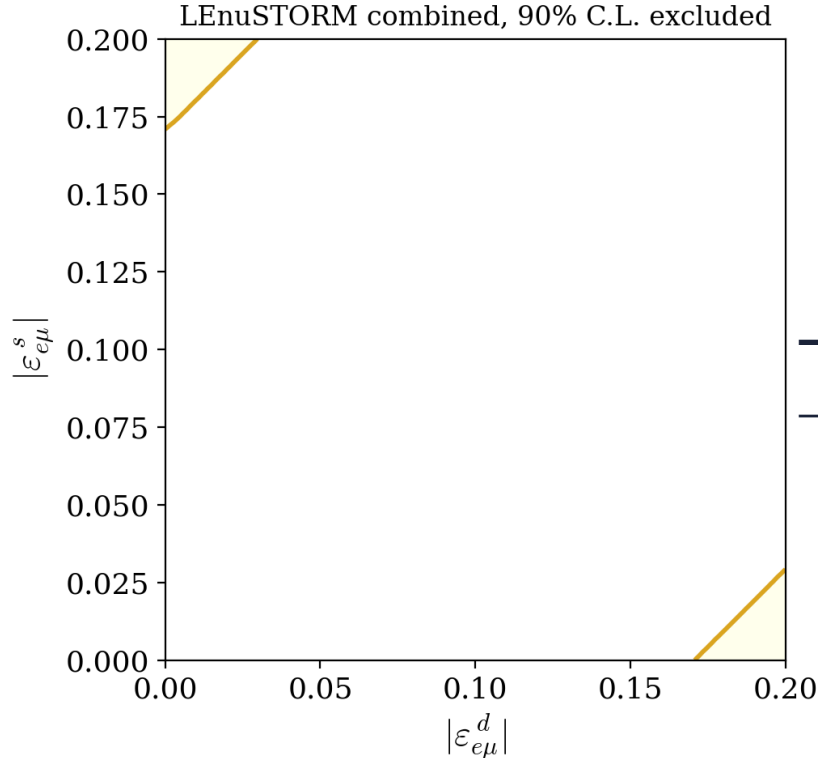
$$|\epsilon_{\mu e}| \approx 0.005$$

* for comparison, LEMNB@LEMMOND is around 0.01

Open diagonal band = source/detector degeneracy ($|\epsilon^s| \approx |\epsilon^d|$ with destructive interference) — one appearance channel cannot separate them.

Results

Appearance ($\nu_e \rightarrow \nu_\mu$) – LEnuSTORM is the only probe



$$|\epsilon_{e\mu}| \approx 0.17$$

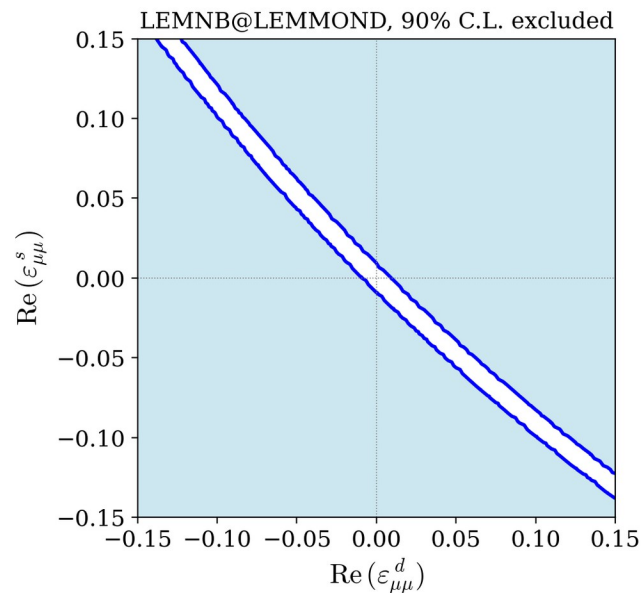
→ Not competitive with existing $O(10^{-2})$ bounds.

→ This is not a failure of the analysis - ν_e flux is intrinsically small

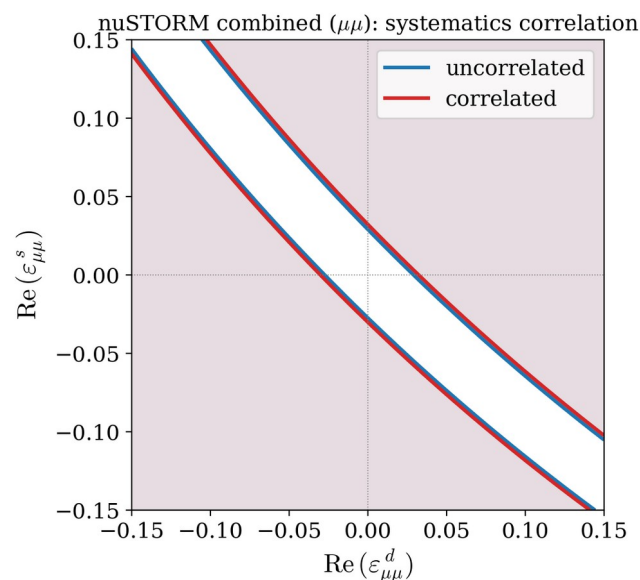
→ nuSTORM gives $N_0 \sim 10^3$, so the $O(\epsilon^2)$ signal is low in statistics

Results

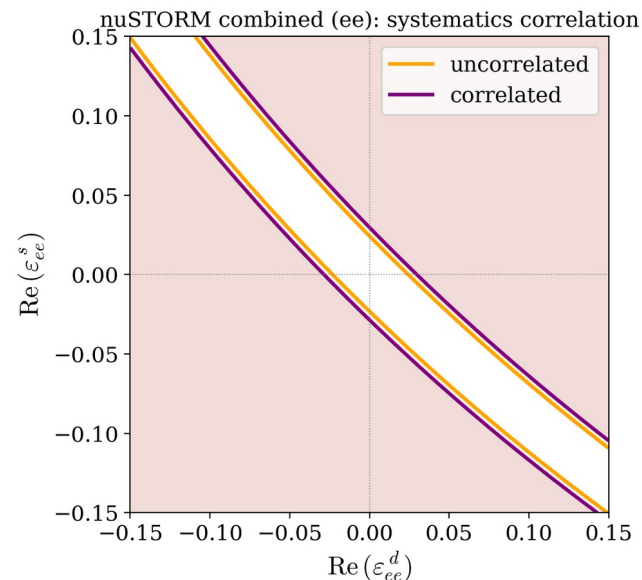
Disappearance: large sensitivity, now systematics-limited (mostly) correlated flux systematics for nuSTORM



$$|\text{Re } \epsilon_{\mu\mu}| \approx 0.009$$



$$|\text{Re } \epsilon_{\mu\mu}| < 0.029 \rightarrow 0.032$$



$$|\text{Re } \epsilon_{ee}| < 0.024 \rightarrow 0.03$$

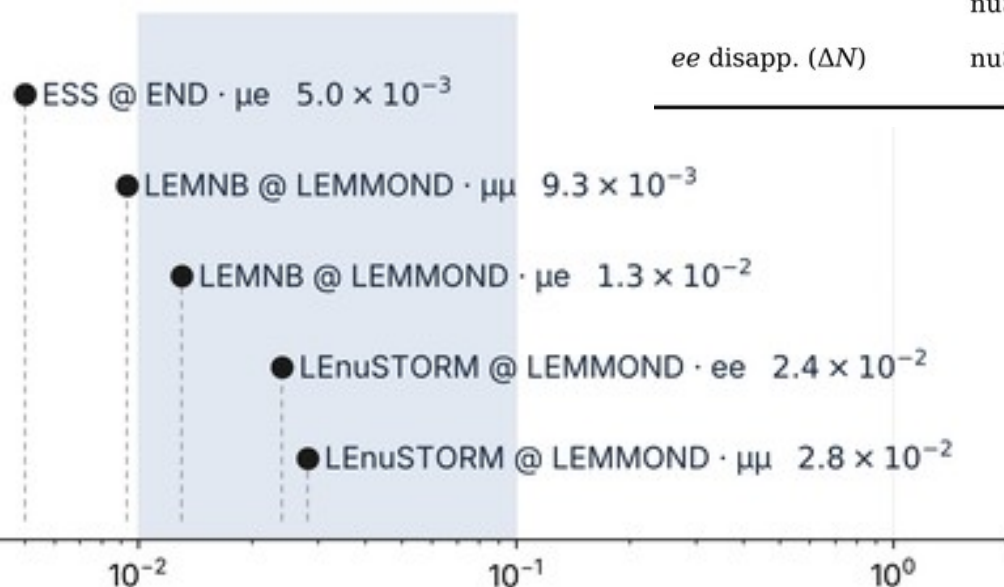
- Anticorrelation band ($\text{Re } \epsilon^s + \text{Re } \epsilon^d$ is what the rate measures); the bound is set by σ_{sys} , not by N_0 .

- Uncorrelated $\rightarrow$ correlated ($\sim 11\%$; less than $\sqrt{2}$ — nuSTORM is not purely systematics-limited)

Results

What is genuinely competitive?

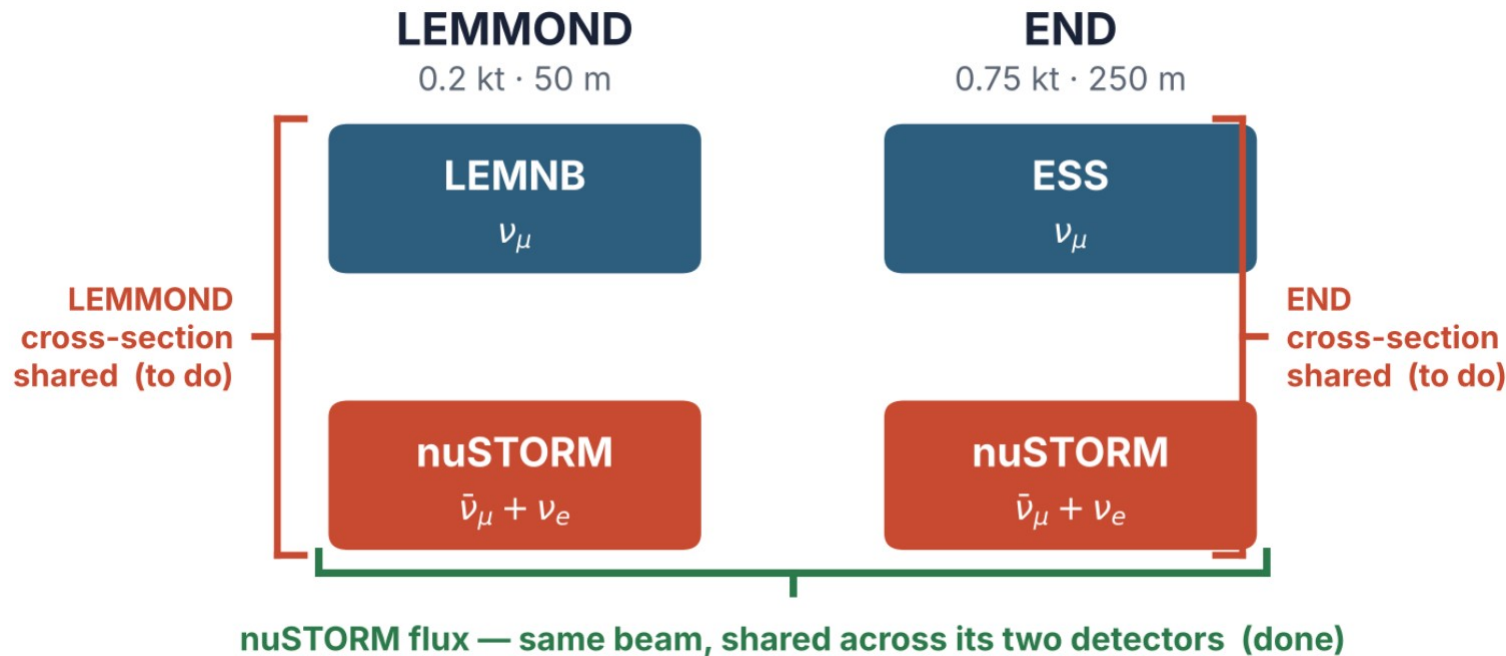
Channel	Configuration	ε	Rate (yr ⁻¹)
μe appearance (S)	ESS @ END	0.005	2133
	LEMNB @ LEMMOND	0.013	~41
$e\mu$ appearance (S)	nuSTORM @ LEMMOND	0.17	~210
$\mu\mu$ disapp. (ΔN)	LEMNB @ LEMMOND	0.009	~280
	nuSTORM @ LEMMOND	0.032	~280
ee disapp. (ΔN)	nuSTORM @ LEMMOND	0.03	~720



* new simulated flux from WP6 could possibly improve LEMNB@LEMMOND bound

** ESS ($\mu\mu$) bound should be strong, but unresolved at the moment

Future prospect: connecting the detectors



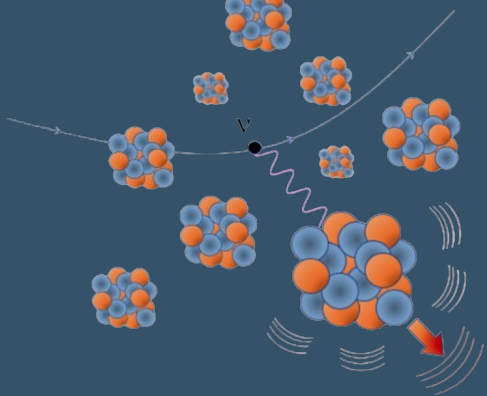
Full correlation structure:

- nuSTORM flux shared across LEMMOND & END — done.
- Detector cross-section shared across beams at one detector (LEMNB+nuSTORM @ LEMMOND; ESS+nuSTORM @ END).
- Exact treatment needs multi-pull chiMultiExp; the honest value lies between uncorrelated and fully correlated.

Work in progress → full combined fit for the publication.

Conclusions

- 1 Near detectors turn “zero distance” into a clean probe of source/detector NSI
- 2 Appearance $O(\epsilon^2)$ vs disappearance $O(\epsilon)$: statistics-limited vs. (mostly) systematics-limited
- 3 ESS’s huge ν_μ statistics make μe the standout: $|\epsilon_{\mu e}| \sim 0.005$
- 4 e-row $(\epsilon_{e\mu}, \epsilon_{ee})$ stays statistics-limited — the beam hierarchy sets what is reachable
- 5 Combined bounds: correlated systematics widen the shared-beam result.



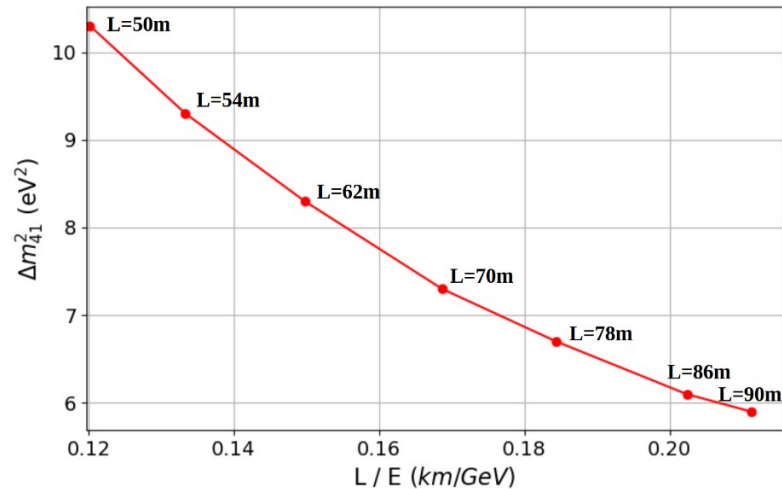
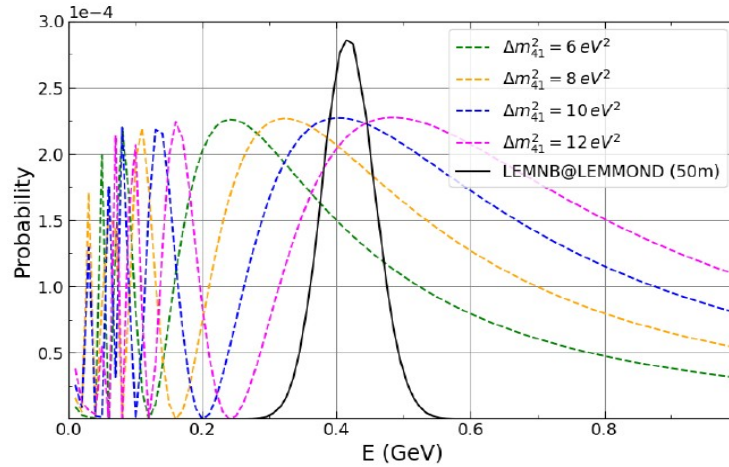
Sterile neutrino at ESSnuSB+

- Effect of decay pipe in 3+1 scenario using LEMNB-LEMMOND setup within ESSnuSB+
- LenuSTORM

Doris Barčot, Ruđer Bošković Institute, Croatia



Narrow beam: baseline picks the Δm^2_{41}



Setup

1 GeV/c pions, $\sim 417 \text{ MeV } \nu_\mu$ peak, 40 m tunnel, 200 t water Cherenkov, $L = 50 \text{ m}$

Mapping

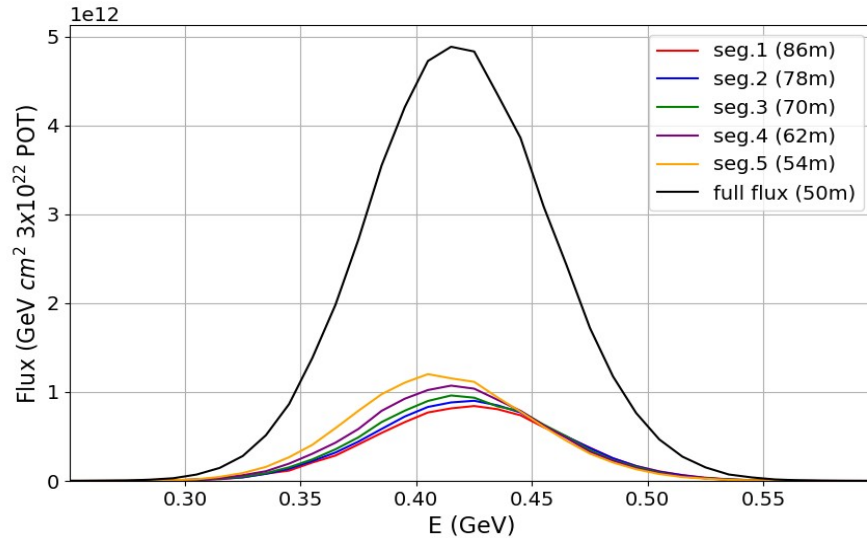
Effective baseline $50 \rightarrow 90 \text{ m}$ moves the first maximum from ~ 10 to $\sim 6 \text{ eV}^2$

Analysis

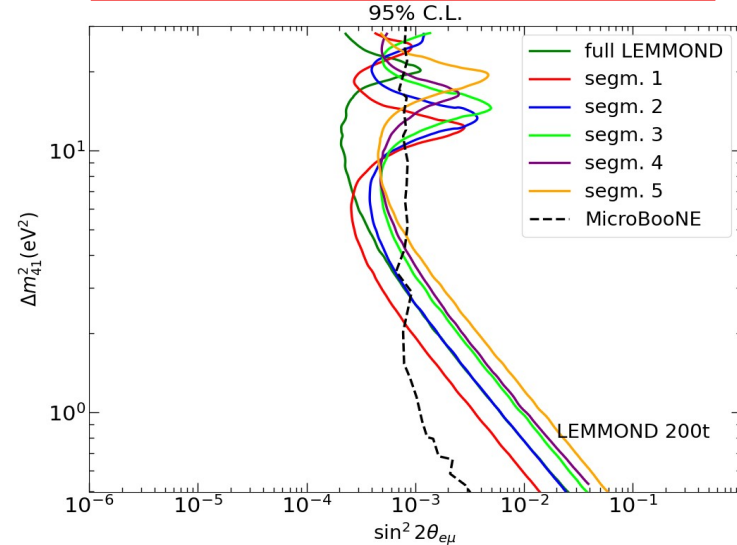
Tunnel split into $5 \times 8 \text{ m}$ segments (54–86 m), GLoBES, 5+5 years $\nu + \bar{\nu}$

$$P_{\mu e} = \sin^2(\theta_{24}) \sin^2(2\theta_{14}) \sin^2\left(1.27 \frac{\Delta m^2_{41} L_i}{E_i}\right)$$

Each segment probes its own Δm^2_{41}

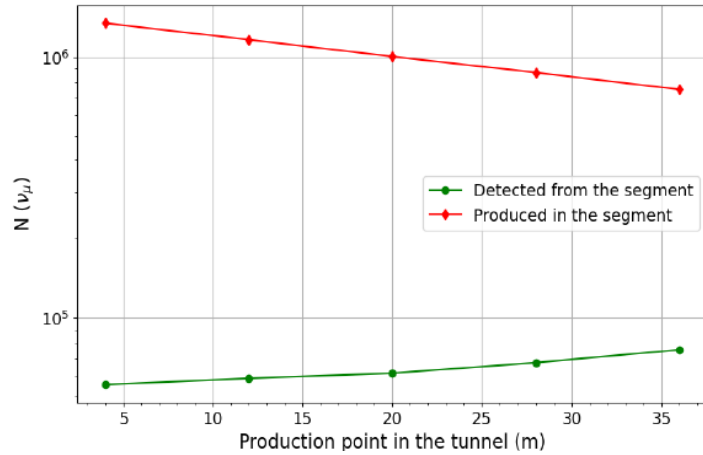


$$\chi^2 = 2 \sum_{i=1}^n \left[N_i^{\text{test}} - N_i^{\text{true}} - N_i^{\text{true}} \log \left(\frac{N_i^{\text{test}}}{N_i^{\text{true}}} \right) \right]$$



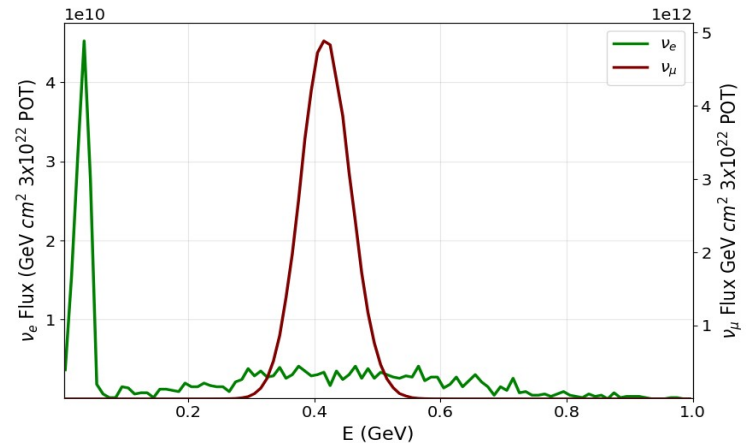
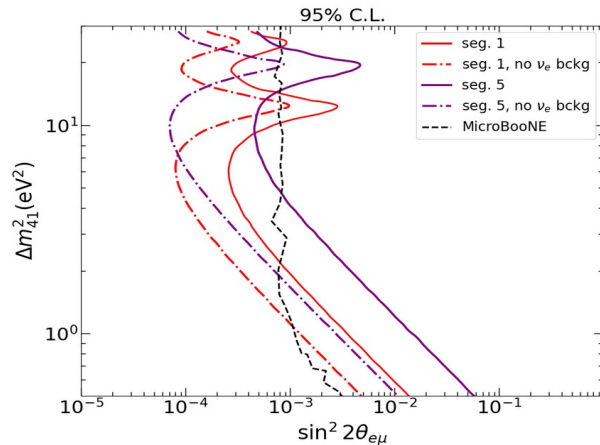
- Detected flux leans to the tunnel exit: early decays are emitted at angles that miss the detector
- Bounds shift with baseline, peak sensitivity ~10 eV² (seg. 5) to ~6 eV² (seg. 1); **seg. 1 gives the strongest bound**

More flux doesn't mean a better bound

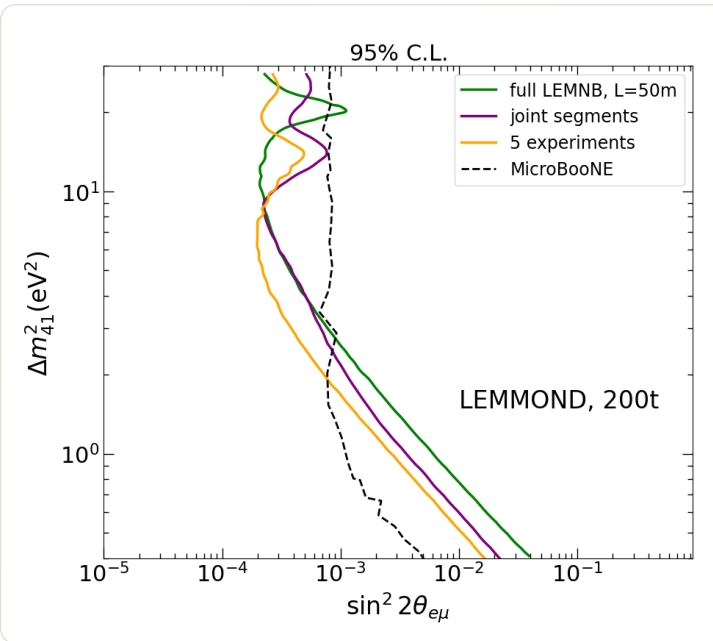


Appearance is limited by the **intrinsic ν_e** of the beam, and it scales with the flux.

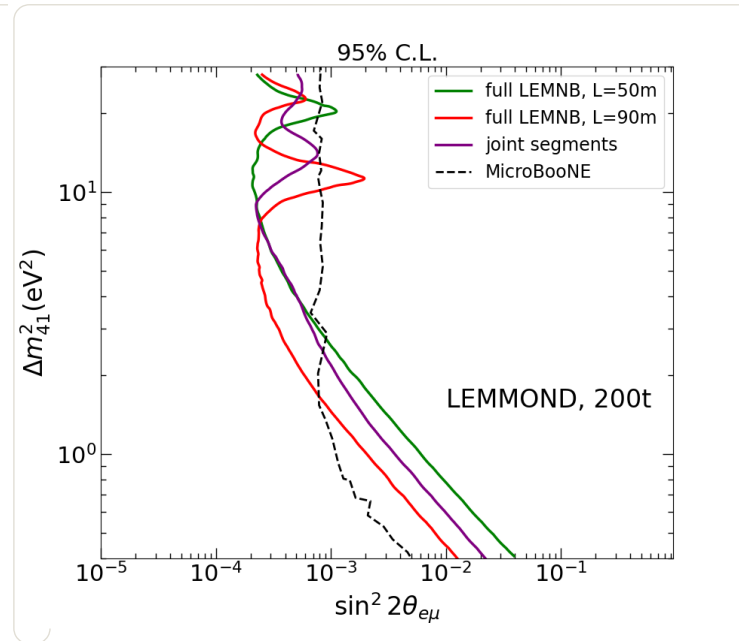
- Segment 5 has the most signal events, but also the most background.
- Seg. 1 has the cleanest signal-to-background.
- Switch the intrinsic ν_e off (dash-dotted) and segment 5 comes out slightly ahead, as statistics would suggest.



All segments together: a reshaped bound



50 m vs joint vs 5 independent

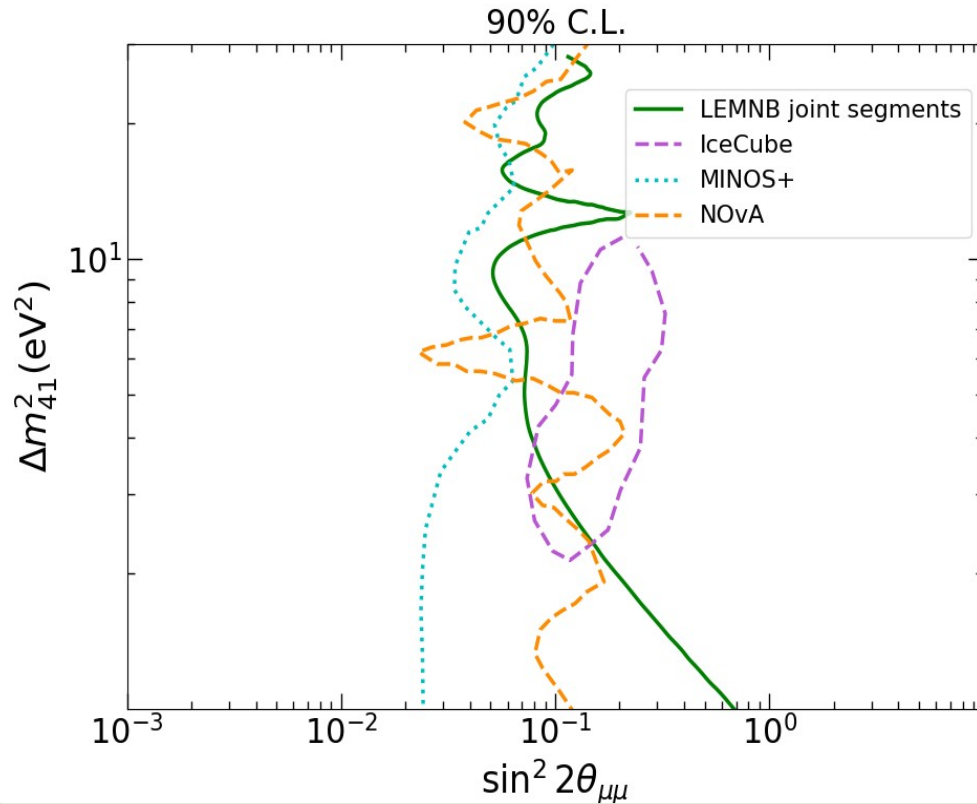


Joint sits between 50 m and 90 m

- **Below ~3 eV²** joint overtakes 50 m: longer baselines oscillate
- **~3–8 eV²** essentially the same
- **Above ~8 eV²** the wiggles move to lower Δm^2_{41}

**Summing five χ^2 over counts.
Combine events first, then one χ^2 .**

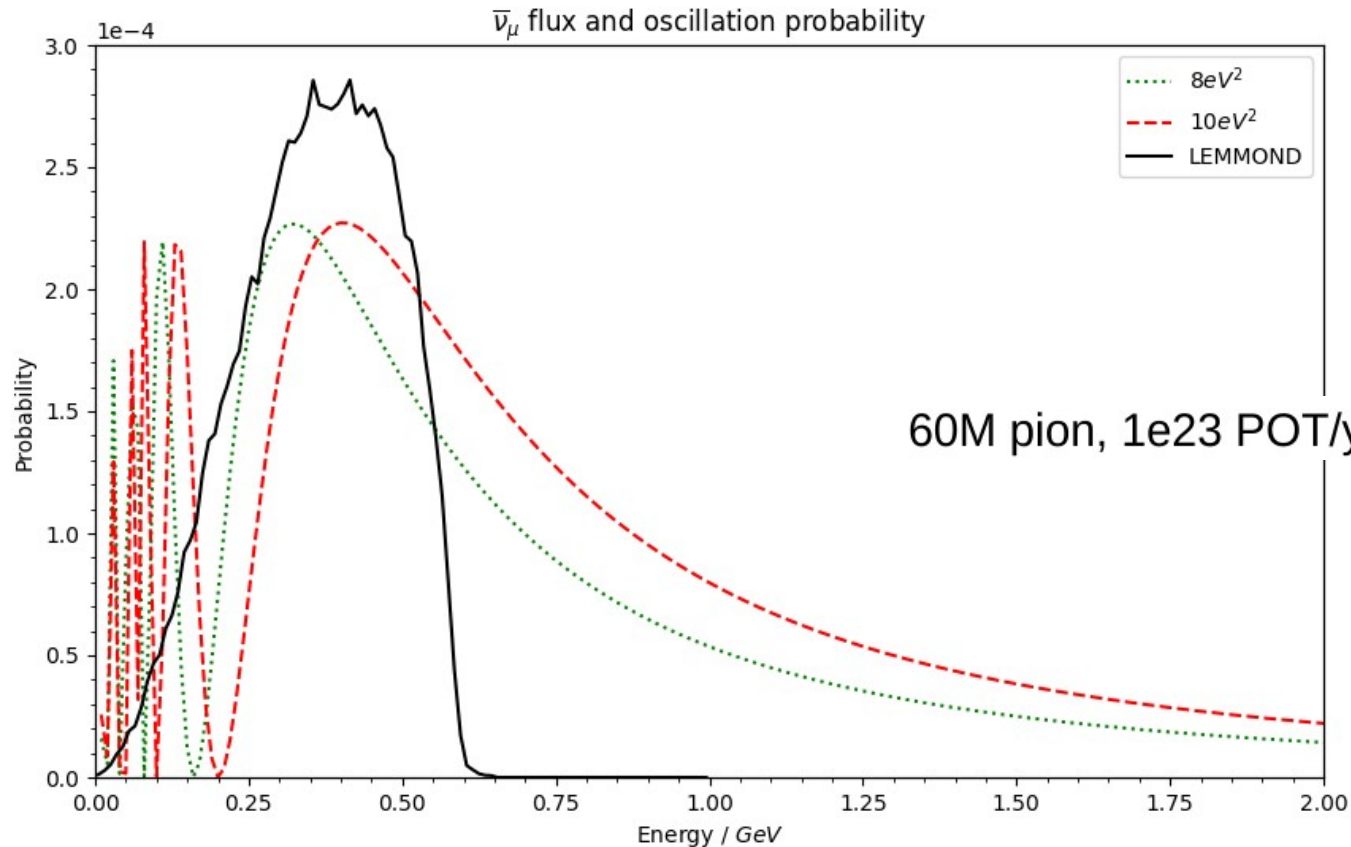
ν_μ disappearance only



- Highest-statistics channels, giving direct access to θ_{24} .
- Strongest around $\Delta m_{41}^2 \sim 10 \text{ eV}^2$.
- Same ballpark as NOvA in this range, weaker than MINOS+.

*Shown at 90% C.L. to match the published bounds

LenuSTORM “situation”



LenuSTORM “situation”

$$\Delta m_{41}^2 = 10 \text{ eV}^2$$

$$L = 50 \text{ m}$$

→ cca **2500** interactions/y

→ cca **20** oscillated events/10y



→ appearance probability at short L has a contribution from sterile mixing of the form

$$\sin^2(2\theta_{\mu e}) \sin^2(\Delta m_{41}^2 L/4E), \text{ where } \sin^2(2\theta_{\mu e}) \equiv \sin^2(2\theta_{14}) \sin^2(\theta_{24})$$

→ we typically display this as an exclusion contour in the $(\sin^2(2\theta_{\mu e}), \Delta m_{41}^2)$ plane.

→ current simulation sample does not have sufficient statistics to produce a proper 2D exclusion contour in the this plane → generating this contour requires scanning a grid of $(\theta_{14}, \theta_{24}, \Delta m_{41}^2)$ values and computing a $\Delta\chi^2$ for each point, which in turn requires enough signal and bkg events in each bin for the χ^2 approx. to be reliable.

Conclusions

- 1 Production point leaves a clear, baseline-driven imprint on the bound, without changing the overall reach
- 2 Best segment is the “cleanest” one: intrinsic ν_e sets the limit
- 3 Combine at event level; independent χ^2 per segment overestimates sensitivity

*Using event-by-event analysis needs a tunnel with timing and vertex reconstruction, so the study shows what such instrumentation could add.

** WP6 made a full flux simulation → our analysis may need an update, depending on the difference in number of interactions (few percent difference at this point)