New physics searches with near detectors at the Neutrino Factory

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Contents

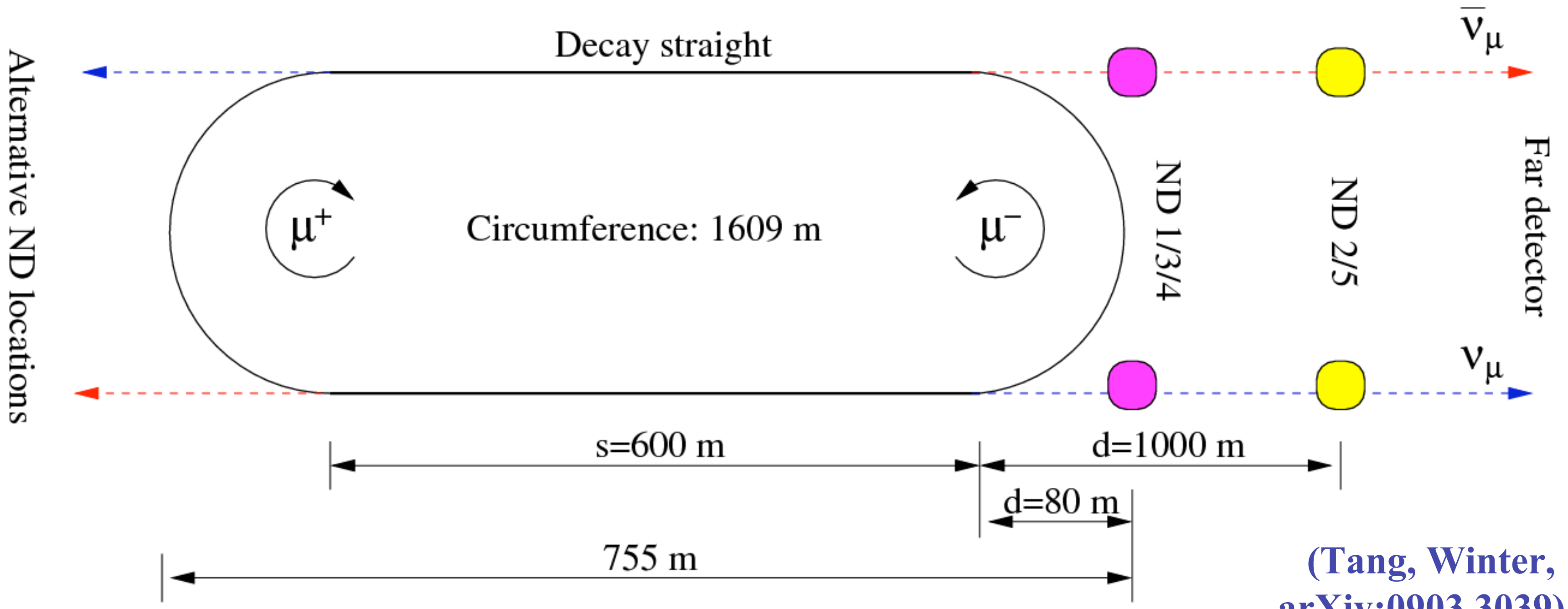
- Introduction:
  Near detectors at the Neutrino Factory
- NuFact versus Superbeam as source
- Physics case for near detectors for new physics searches
- NU versus NSI
- Summary

Near detectors at the Neutrino Factory

Near detectors

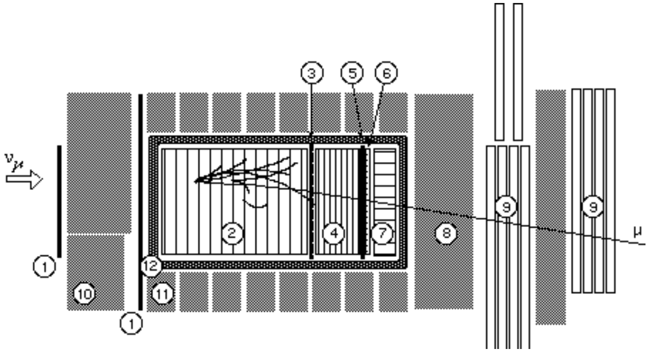
for standard oscillation physics

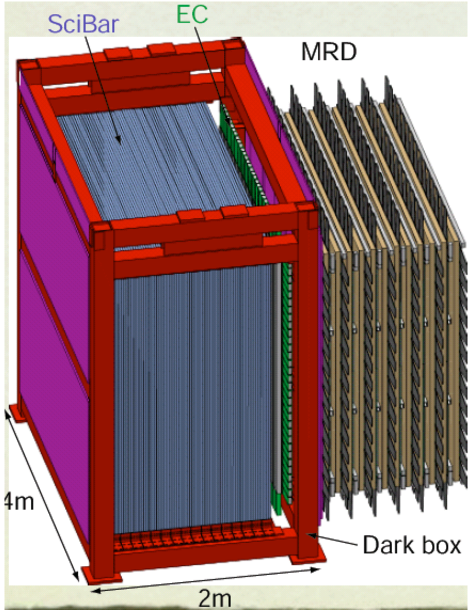
- Need two near detectors, because μ^+/μ^- circulate in different directions
- For X-sec measurement: No CID required, only excellent flavor-ID
- Possible locations:



(Tang, Winter, arXiv:0903.3039)

Geometry of the detectors?





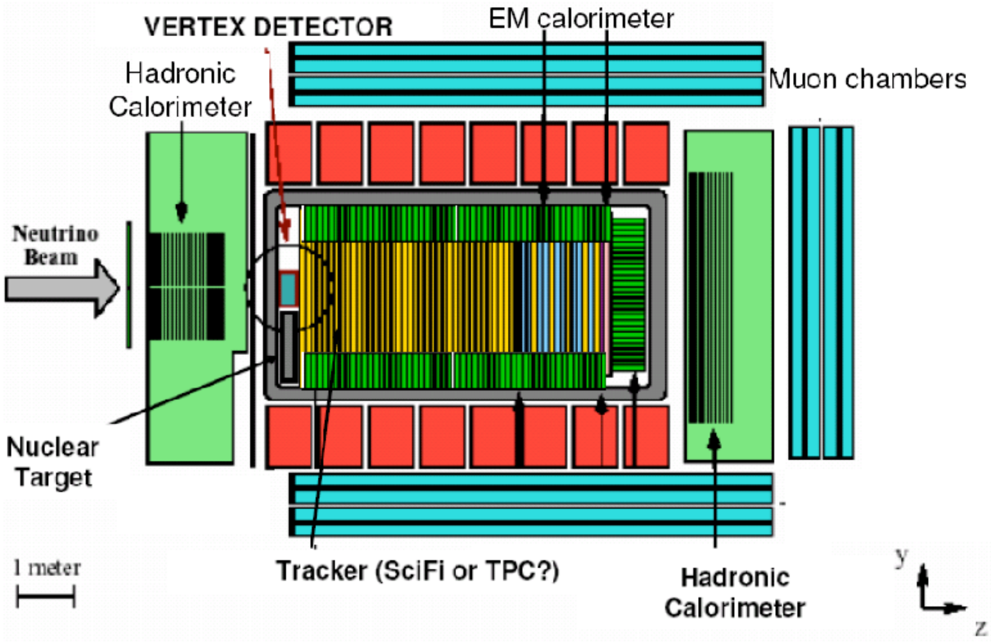


Figure 13: *Possible geometry for a near detector at a neutrino factory.*

(ISS detector WG report)

Requirements

for standard oscillation physics (summary)

- Physics: Muon neutrino+antineutrino inclusive CC event rates needed (other flavors not needed in far detectors for IDS-NF baseline), no ν_e, ν_τ measurement required
- Systematics: QE scattering + inverse muon decay for beam monitoring (flux knowledge)
- Backgrounds: Charge identification to understand backgrounds (but no intrinsic beam contamination)
- At least same characteristics/quality (energy resolution etc.) as far detectors
  (a silicon vertex detector or ECC or liquid argon may do much better …)
- Location and size not really relevant, because extremely large statistics (maybe size relevant for beam monitoring, background extrapolation)

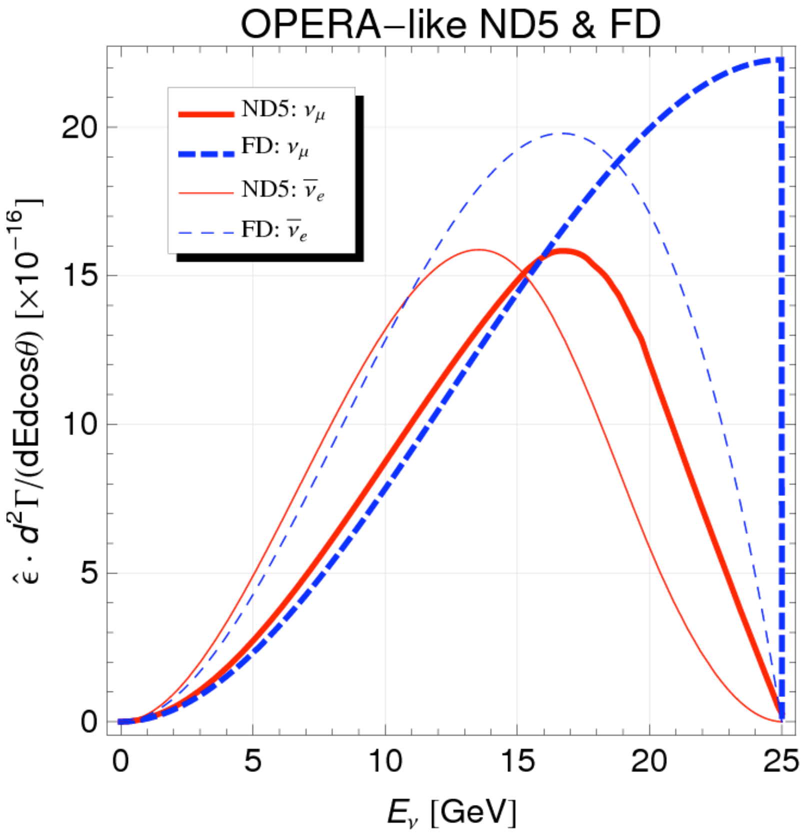
➢ The specifications of the near detectors may actually be driven by **new physics** searches!

**(see ISS detector WG report; Tang, Winter, arXiv:0903.3039;
Talk by P. Soler @ IDS-NF plenary, Mumbai, 2009)**

Beam+straight geometry

- Near detectors described in GLoBES by ε (E)=A_{eff}/A_{det} x on-axis flux **and** $L_{\mathrm{eff}} = \sqrt{d(d+s)}$
- For ε(E) ~ 1: Far detector limit
- Example: OPERA-sized detector at d=1 km: $L_{\mathrm{eff}} = 1265\,\mathrm{m}$

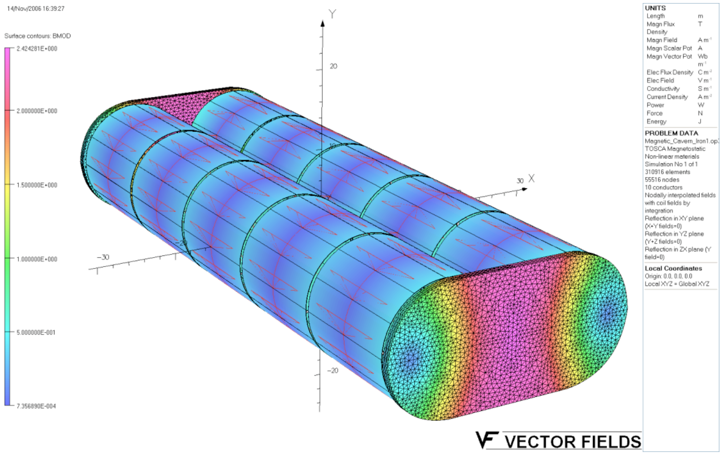
(Tang, Winter, arXiv:0903.3039)

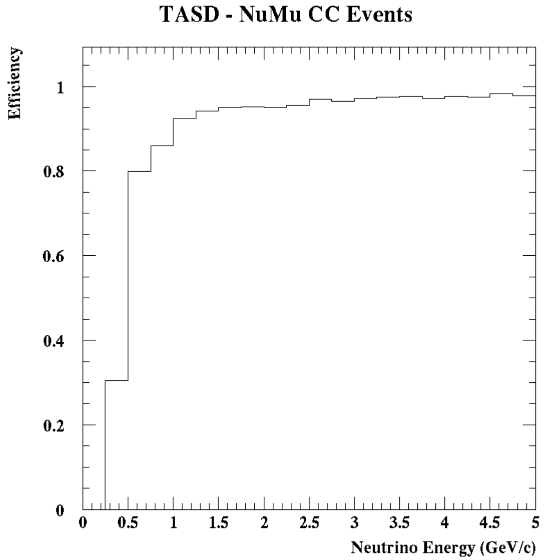


➢ L > ~1 km: GLoBES std. description valid (with L_{eff})

The new player in town: Low energy NuFact

- For large $\sin^2 2\theta_{13} > 0.01$, lower E_μ sufficient for standard oscillation physics
- Magnetized TASD used as detector
- Becomes alternative baseline setup?
- Main issue: τ production threshold
  - What are the consequences for non-standard physics searches at near detectors? Comparison to superbeam-based detector? (very few studies, so far)





(Geer, Mena, Pascoli, hep-ph/0701258; Bross et al, arXiv:0708.3889+arXiv:0911.3776)

NuFact versus Superbeam as source

(Some thoughts)

Superbeam versus NuFact:

Source characteristics

- Superbeam
  - Decay tunnel relatively short (point source?)
  - Only muon neutrinos or antineutrinos $\nu_\mu \longrightarrow \nu_\tau$
  - Intrinsic beam BG (different flavors and polarity)
  - Neutrino production by pion decays
- Neutrino factory
  - Relatively long decay straight (line source)
  - Muon+electron neutrinos/antineutrinos

$$\nu_\mu \longrightarrow \nu_\tau \, , \qquad \bar{\nu}_e \longrightarrow \bar{\nu}_\tau$$

  - Channel discriminated by CID in detector
  - Neutrino production by muon decays

Near detector synergy?

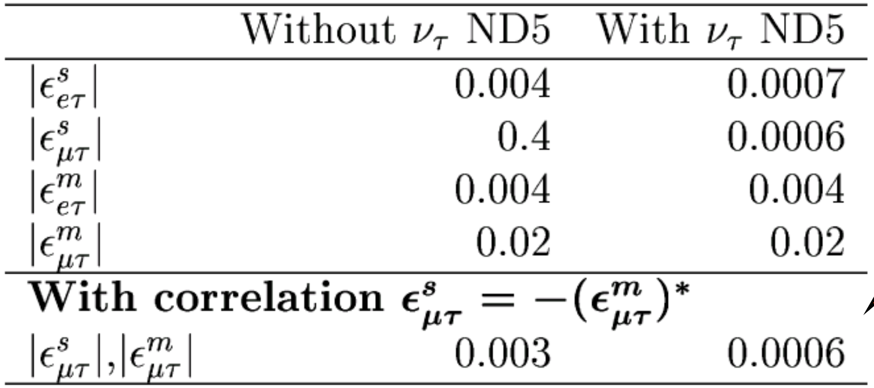
- Complementarity NuFact-SB for effects for which
  - Source has to be be point-like (steriles?)
  - Hadronic versus leptonic production important (NU versus NSI, source NSI, …?)
  - Superbeam can improve the current bounds
- Technological synergy (prototype for NuFact?)
  - ➢ Can even the same detector be used if only $\nu_\tau + \bar{\nu}_\tau$ measured?
  - ➢ Is there a possibility to synergize the MINSIS and NuFact near detector developments?

Near detector for new physics searches

There is a physics case at the neutrino factory!

Source NSI with ν_τ at a NuFact

- Probably most interesting for near detectors: $\varepsilon_{e\tau}^s$, $\varepsilon_{\mu\tau}^s$ (no intrinsic beam BG)
- Near detectors measure zero-distance effect ~ $|\varepsilon^s|^2$
- Helps to resolve correlations



	Without ν_τ ND5	With ν_τ ND5
$\lvert\epsilon^s_{e\tau}\rvert$	0.004	0.0007
$\lvert\epsilon^s_{\mu\tau}\rvert$	0.4	0.0006
$\lvert\epsilon^m_{e\tau}\rvert$	0.004	0.004
$\lvert\epsilon^m_{\mu\tau}\rvert$	0.02	0.02
With correlation $\boldsymbol{\epsilon^s_{\mu\tau} = -(\epsilon^m_{\mu\tau})^*}$		
$\lvert\epsilon^s_{\mu\tau}\rvert, \lvert\epsilon^m_{\mu\tau}\rvert$	0.003	0.0006

ND5: OPERA-like ND at d=1 km, 90% CL

(Tang, Winter, arXiv:0903.3039)

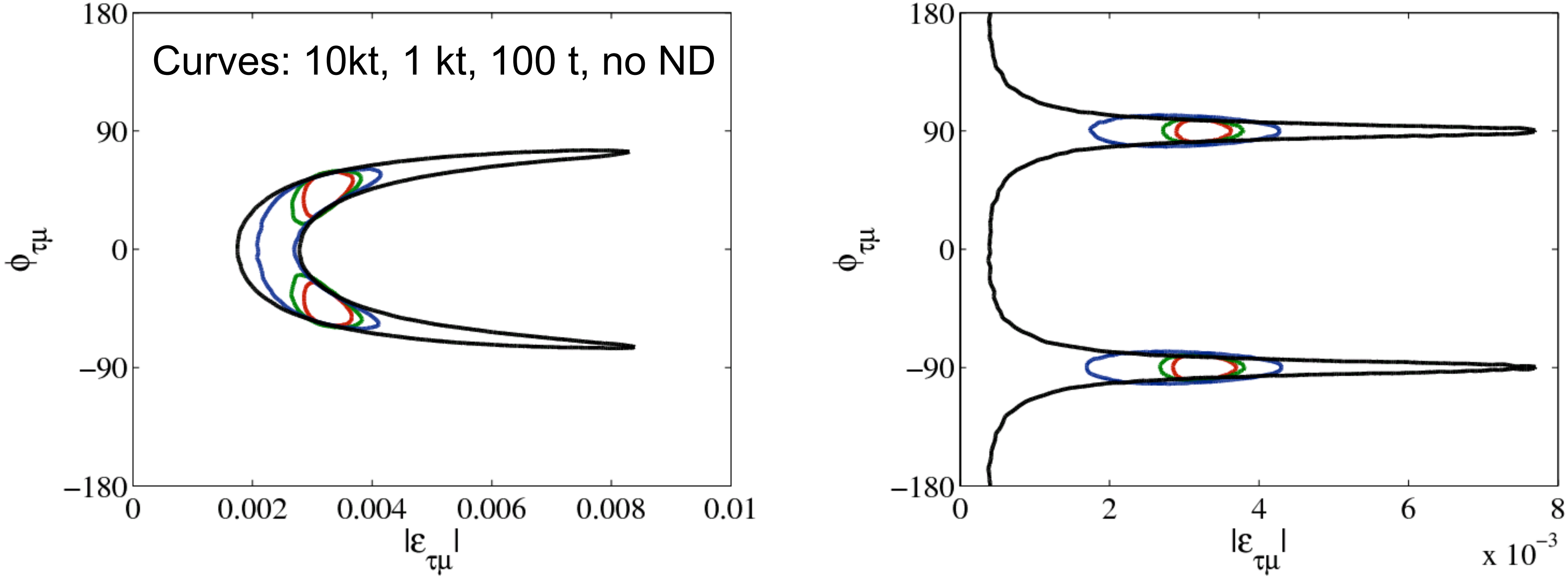
This correlation is always present if:
- NSI from d=6 operators
- No CLFV

(Gavela et al, arXiv:0809.3451; see also Schwetz, Ohlsson, Zhang, arXiv:0909.0455 for a particular model)

Non-unitarity (NU)

- Example:

  (Antusch, Blennow, Fernandez-Martinez, Lopez-Pavon, arXiv:0903.3986)


Curves: 10kt, 1 kt, 100 t, no ND

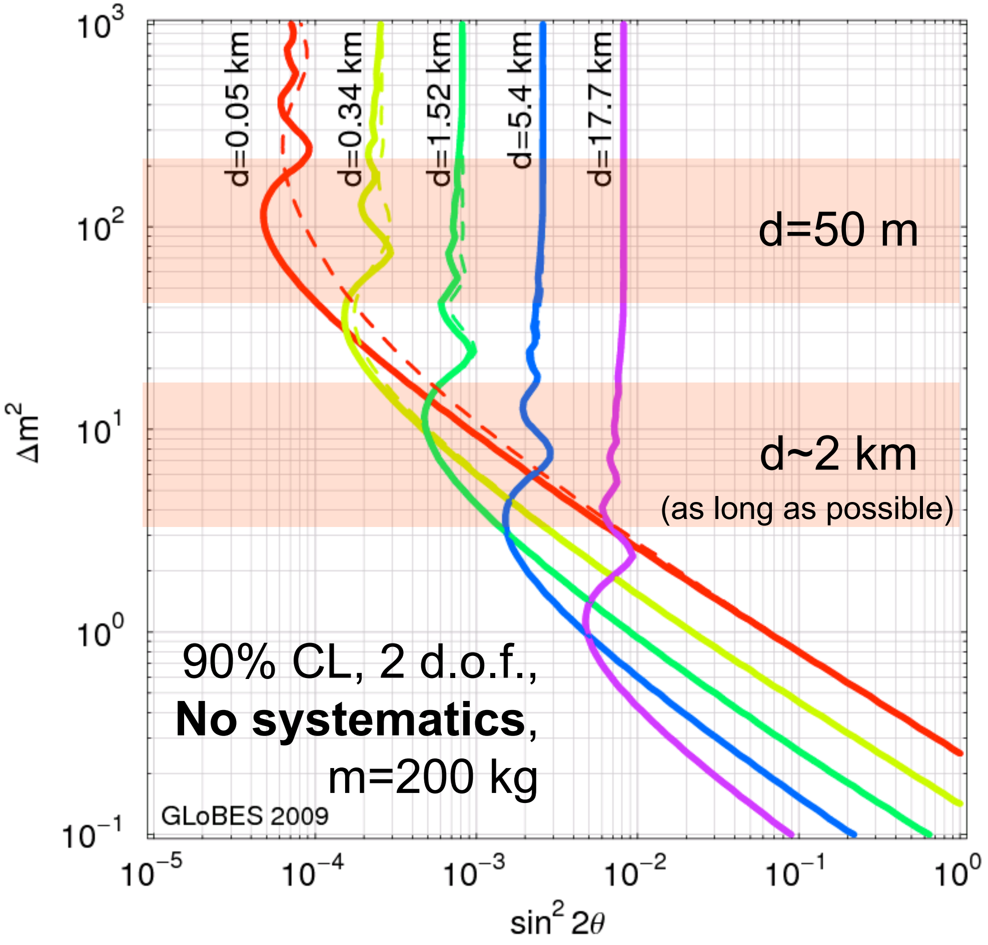
- ν_τ near detector important to detect zero-distance effect
- Magnetization not mandatory (this appl.), size matters

NDs for sterile neutrino searches

Example: SBL ν_e disappearance

- Two flavor short-baseline searches useful to constrain sterile neutrinos etc.
- ν_e disappearance:

$$P_{ee} \quad = \quad 1 - \sin^2(2\theta_\nu)\,\sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right)$$



(Giunti, Laveder, Winter, arXiv:0907.5487)

- Averaging over straight important (dashed versus solid curves)
- Pecularity: Baseline matters, depends on Δm_{31}^2
- Magnetic field if $\nu_e \longrightarrow \bar{\nu}_e\ ,\ \bar{\nu}_\mu$

NU versus NSI

New physics from heavy mediators

- Effective operator picture if mediators integrated out:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \delta\mathscr{L}^{d=5}_{\rm eff} + \delta\mathscr{L}^{d=6}_{\rm eff} + \cdots , \quad \text{with} \quad \delta\mathscr{L}^{d}_{\rm eff} \propto \frac{1}{\Lambda^{d-4}}\mathcal{O}^{d}$$

ν mass

d=6, 8, 10, ...: NSI, NU

Describes additions to the SM in a gauge-inv. way!

- Interesting **leptonic** dimension **six** operators

Fermion-mediated
⇨ Non-unitarity (NU)

$$\delta\mathcal{L}_{\rm eff} = c_{\alpha\beta}\left(\overline{L}_{\alpha}\tilde{\phi}\right) i\partial\!\!\!/\left(\tilde{\phi}^{\dagger}L_{\beta}\right)$$

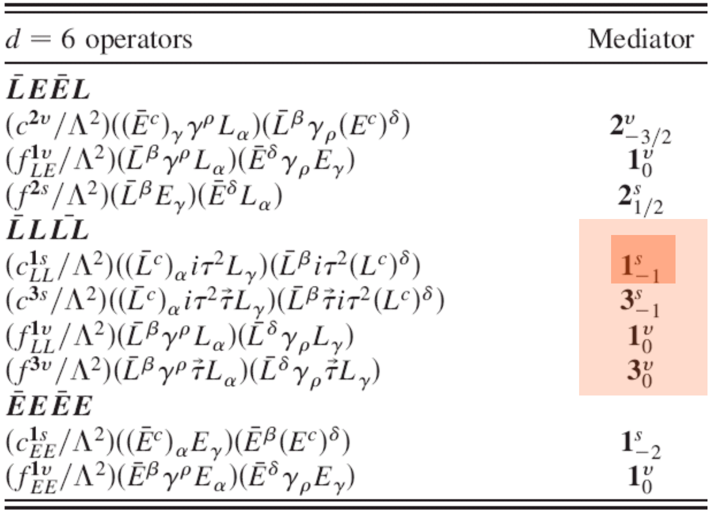
Scalar or vector mediated ⇨ Non-standard int. (NSI)

$$\delta\mathcal{L}_{\rm eff} = 2\sqrt{2}\,G_F\,(\varepsilon^{L/R})^{\alpha\gamma}_{\beta\delta}\;\left(\bar{\nu}^{\beta}\gamma^{\rho}\mathrm{P}_L\nu_{\alpha}\right)\;\left(\bar{\ell}^{\delta}\gamma^{\rho}\mathrm{P}_{L/R}\ell_{\gamma}\right)$$

NU versus NSI at d=6

Distinguish three classes of non-standard effects (NSE):

- **Fermion-mediated leptonic d=6 operator (NU, O^F)**
  - Particular correlation among source, propagation, detection effects
  - Experiment-independent: appear at NuFact + Superbeam!
- **Boson-mediated leptonic d=6 operator (NSI, O^S)**
  - At tree level: d=6 operator only mediated by scalars, vectors (CLFV can also be suppressed by combinations of these) →
  - Leads to source NSI at NuFact (not Superbeam) and matter NSI
- **Other (d>6 NSI, hadronic, etc)**



$d = 6$ operators	Mediator
$\bar{L}E\bar{E}L$	
$(c^{2v}/\Lambda^2)((\bar{E}^c)_\gamma \gamma^\rho L_\alpha)(\bar{L}^\beta \gamma_\rho (E^c)^\delta)$	$\mathbf{2}^v_{-3/2}$
$(f^{1v}_{LE}/\Lambda^2)(\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)$	$\mathbf{1}^v_0$
$(f^{2s}/\Lambda^2)(\bar{L}^\beta E_\gamma)(\bar{E}^\delta L_\alpha)$	$\mathbf{2}^s_{1/2}$
$\bar{L}L\bar{L}L$	
$(c^{1s}_{LL}/\Lambda^2)((\bar{L}^c)_\alpha i\tau^2 L_\gamma)(\bar{L}^\beta i\tau^2 (L^c)^\delta)$	$\mathbf{1}^s_{-1}$
$(c^{3s}/\Lambda^2)((\bar{L}^c)_\alpha i\tau^2 \vec{\tau} L_\gamma)(\bar{L}^\beta \vec{\tau} i\tau^2 (L^c)^\delta)$	$\mathbf{3}^s_{-1}$
$(f^{1v}_{LL}/\Lambda^2)(\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{L}^\delta \gamma_\rho L_\gamma)$	$\mathbf{1}^v_0$
$(f^{3v}/\Lambda^2)(\bar{L}^\beta \gamma^\rho \vec{\tau} L_\alpha)(\bar{L}^\delta \gamma_\rho \vec{\tau} L_\gamma)$	$\mathbf{3}^v_0$
$\bar{E}E\bar{E}E$	
$(c^{1s}_{EE}/\Lambda^2)((\bar{E}^c)_\alpha E_\gamma)(\bar{E}^\beta (E^c)^\delta)$	$\mathbf{1}^s_{-2}$
$(f^{1v}_{EE}/\Lambda^2)(\bar{E}^\beta \gamma^\rho E_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)$	$\mathbf{1}^v_0$

(Gavela, Hernandez, Ota, Winter, 2008)

- ➢ Can one identify these/distinguish these?
- ➢ Theory: Can one distinguish between fermions and bosons (d=6) as heavy mediators?

Correlations

Source – propagation - detection

- O^{F} (for ordinary matter with $N_p = N_n$) $\varepsilon^s_{\alpha\beta} = \varepsilon^d_{\alpha\beta} = \eta_{\alpha\beta}$

$$\varepsilon^m_{ee} = 2\eta_{ee}\,, \quad \varepsilon^m_{\mu\mu} = -\eta_{\mu\mu}\,, \quad \varepsilon^m_{\mu\tau} = -\eta_{\mu\tau}\,, \quad \varepsilon^m_{\tau\tau} = -\eta_{\tau\tau}$$

  Forbidden: $\varepsilon^m_{e\mu}$, $\varepsilon^m_{e\tau}$

  (see e.g. Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, 2007; Antusch, Baumann, Fernandez-Martinez, 2008)

- **O^{S} (without CLFV)**

$$\varepsilon^m_{\mu\mu} = -\varepsilon^{\mathrm{NF}}_{ee} = -\varepsilon^{\mathrm{NF}}_{\mu\mu}$$

$$\varepsilon^m_{\mu\tau} = -\left(\varepsilon^{\mathrm{NF}}_{\mu\tau}\right)^*\,,$$

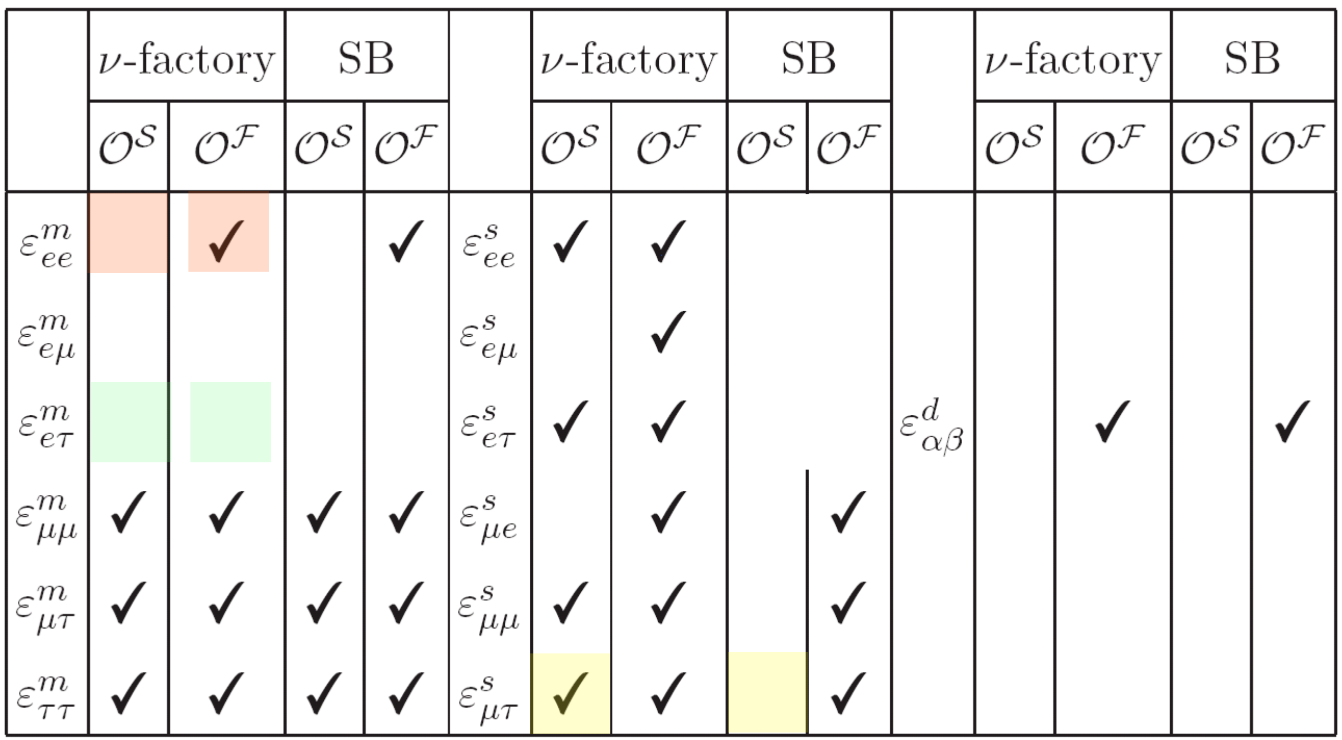
  Forbidden: $\varepsilon^m_{e\alpha}$, $\alpha \in \{e, \mu, \tau\}$, $\varepsilon^{\mathrm{NF}}_{e\mu}$, $\varepsilon^{\mathrm{NF}}_{\mu e}$
  … and no detector effects for leptonic NSI!

  (Gavela, Hernandez, Ota, Winter, 2008)

- Other: No particular correlations, all effects allowed

NuFact versus Superbeam

(Meloni, Ohlsson, Winter, Zhang, to appear)



	ν-factory		SB			ν-factory		SB			ν-factory		SB	
	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$		$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$		$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$
ε^m_{ee}		✓		✓	ε^s_{ee}	✓	✓			$\varepsilon^d_{\alpha\beta}$		✓		✓
$\varepsilon^m_{e\mu}$					$\varepsilon^s_{e\mu}$		✓							
$\varepsilon^m_{e\tau}$					$\varepsilon^s_{e\tau}$	✓	✓							
$\varepsilon^m_{\mu\mu}$	✓	✓	✓	✓	$\varepsilon^s_{\mu e}$		✓		✓					
$\varepsilon^m_{\mu\tau}$	✓	✓	✓	✓	$\varepsilon^s_{\mu\mu}$	✓	✓		✓					
$\varepsilon^m_{\tau\tau}$	✓	✓	✓	✓	$\varepsilon^s_{\mu\tau}$	✓	✓		✓					

- One can exclude by the measurement of certain effects
- Maybe most interesting: $\varepsilon^s_{\mu\tau}$

Example: $\varepsilon_{\mu\tau}$

- Relationships:

  O^F: $\varepsilon^m_{\mu\tau} = -\varepsilon^s_{\mu\tau} = -\varepsilon^d_{\mu\tau}$

  O^S: $\varepsilon^m_{\mu\tau} = -(\varepsilon^{\mathrm{NF}}_{\mu\tau})^* \,, \quad \varepsilon^d_{\mu\tau} = 0 \,, \quad \varepsilon^{\mathrm{SB}}_{\mu\tau} = 0$

- Probability difference:

$$\Delta P_{\mu\mu} \equiv P^{\mathcal{S}}_{\mu\mu} - P^{\mathcal{F}}_{\mu\mu} = \mathrm{Re}\, \varepsilon^s_{\mu\tau} \sin 4\theta_{23} \, \sin^2 \left(\frac{\Delta L}{4E} \right) + \mathrm{Im}\, \varepsilon^s_{\mu\tau} \, \sin 2\theta_{23} \, \sin \left(\frac{\Delta L}{2E} \right)$$

(Kopp, Lindner, Ota, Sato, 2007 vs. Antusch, Blennow, Fernandez-Martinez, Lopez-Pavon, 2009; see Meloni, Ohlsson, Winter, Zhang, to appear)

  - ➢ Consequence: Difference depends on NSI CP-phase

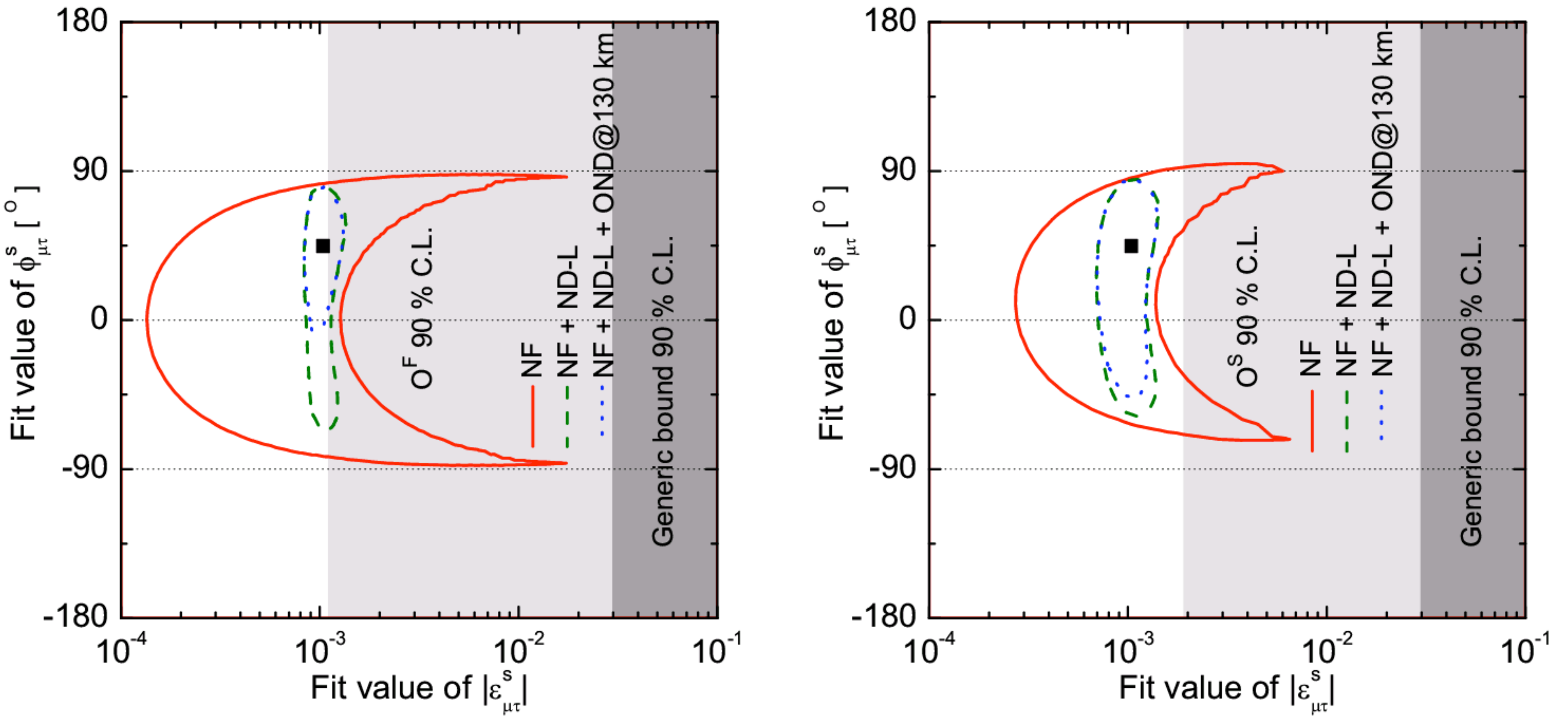
- If ν_τ appearance channel (SBL, NuFact)

$$P^{\mathcal{S}}_{\mu\tau} = \sin^2 2\theta_{23} \left(\frac{\Delta L}{4E} \right)^2 + |\varepsilon^s_{\mu\tau}|^2 + 2\, \mathrm{Im}\, \varepsilon^s_{\mu\tau} \, \sin 2\theta_{23} \left(\frac{\Delta L}{2E} \right)$$

Not in Superbeam

$$P^{\mathcal{F}}_{\mu\tau} = \sin^2 2\theta_{23} \left(\frac{\Delta L}{4E} \right)^2 + 4\, |\varepsilon^s_{\mu\tau}|^2 - 4\, \mathrm{Im}\, \varepsilon^s_{\mu\tau} \, \sin 2\theta_{23} \left(\frac{\Delta L}{2E} \right)$$

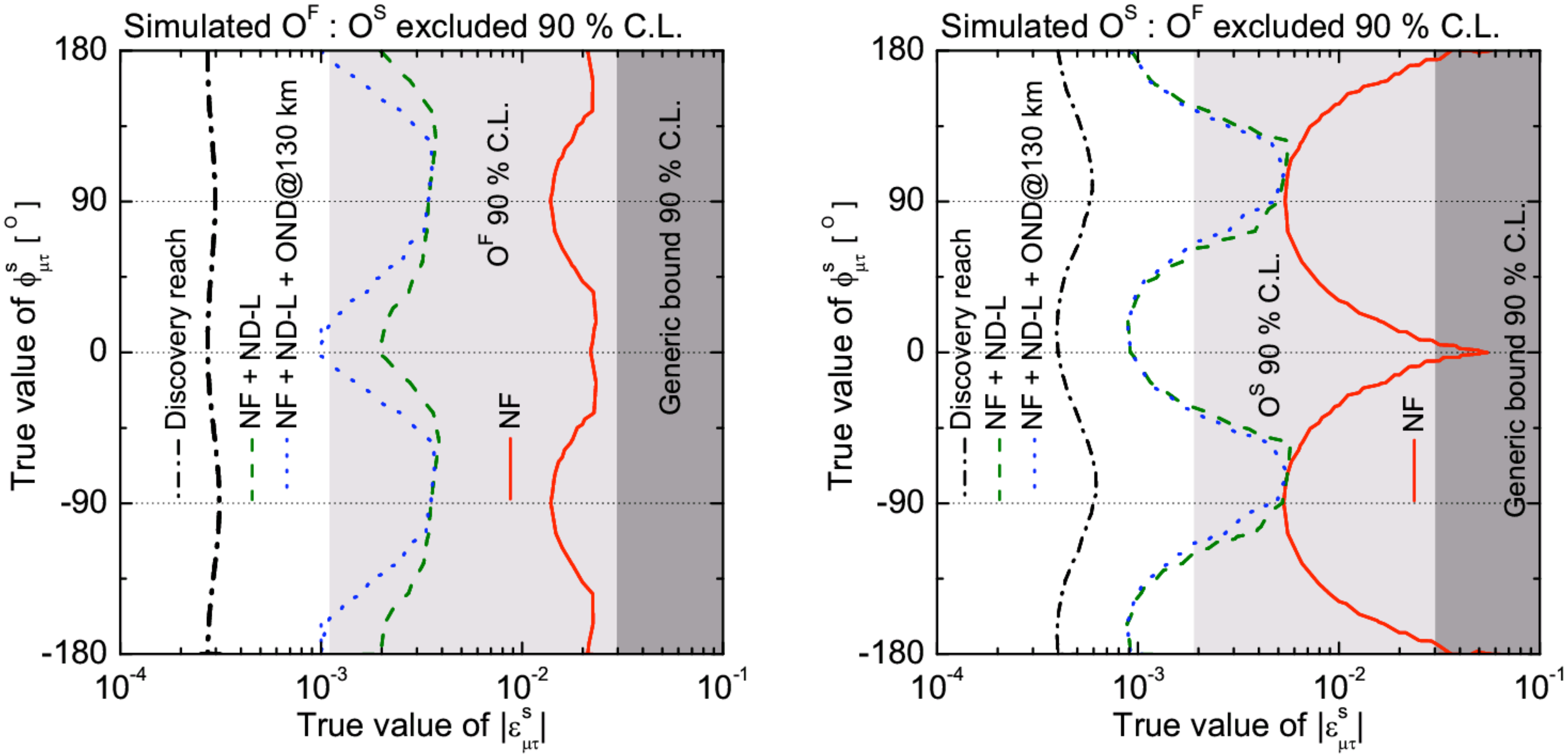
Pheno consequences



- Difficult to disentangle with NuFact alone
  ⇨ Use superbeam?

(Meloni, Ohlsson, Winter, Zhang, to appear)

Distinguishing NSI from NU



- Can hardly distinguish with NuFact alone in region beyond current bounds
- Need Superbeam exp. with sensitivity $\varepsilon_{\mu\tau} \ll 10^{-3}$ (90% CL)

(Meloni, Ohlsson, Winter, Zhang, to appear)

Summary

- There is a physics case for a NuFact ν_τ near detector for NSI, NU, sterile neutrinos
  - ➢ Some of this physics can be done at a superbeam as well, if the sensitivity exceeds the current bounds
- Near detector at NuFact characteristics perhaps driven by new physics searches (size, location, etc.)
- Importance to identify NuFact-SB synergies
  - Physics-wise
  - Technology-wise
- Requirement (NU versus NSI): minimal sensitivity in $|\varepsilon_{\mu\tau}|^2 \sim 10^{-7}$
  Key feature: Source NSI (production) process-dependent, MUV fundamental feature
- Can other channels be used as well?