New Physics Searches at ESSνSB

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NuFact 2016

Largely based on: **arXiv:1507.02868** and **arXiv:1407.1317**

Outline

1. The ESSνSB
2. Non-Standard Interactions
3. Sterile neutrinos
4. Concluding remarks

How to add a neutrino facility to ESS?

- Increase the linac average power from 5 MW to 10 MW by increasing the linac pulse rate from 14 Hz to 70 Hz, implying that the linac duty cycle increases from 4% to 8%.
- Inject into an accumulator ring (ø 143 m) to compress the 3 ms proton pulse length to 1.5 μs, which is required by the operation of the neutrino horn (fed with 350 kA current pulses). The injection in the ring requires H^- pulses to be accelerated in the linac.
- Add a neutrino target station (studied in EUROν)
- Build near and far neutrino detectors (studied in LAGUNA)
- Boundary condition: the neutron program must not be affected

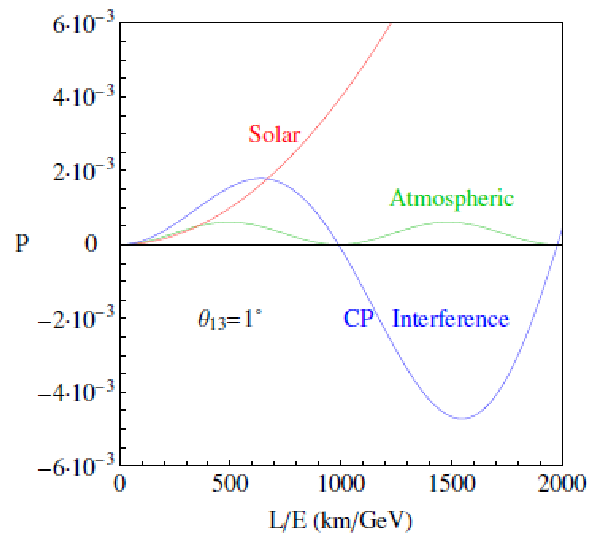
The depth and distance from ESS/ Lund of different mines in Scandinavia

Leptonic CP search with large θ_{13}

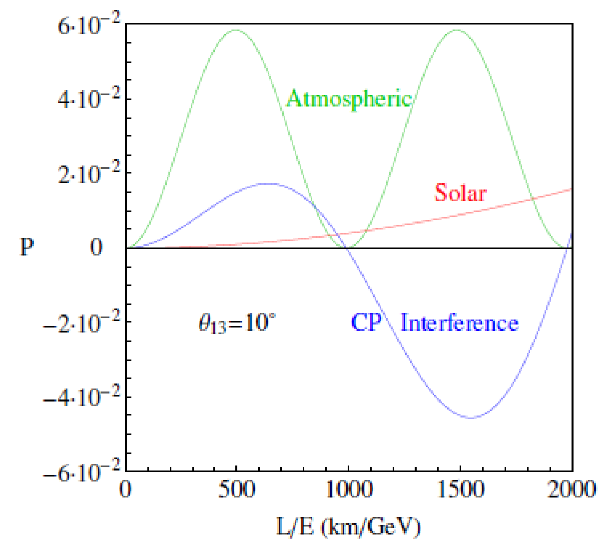
The discovery of θ_{13} opens the avenue for alternative ways of determining leptonic CP violation

At the second oscillation maximum:

- Need enough power
- Less dominated by systematics
- Experiment will continue to improve over time



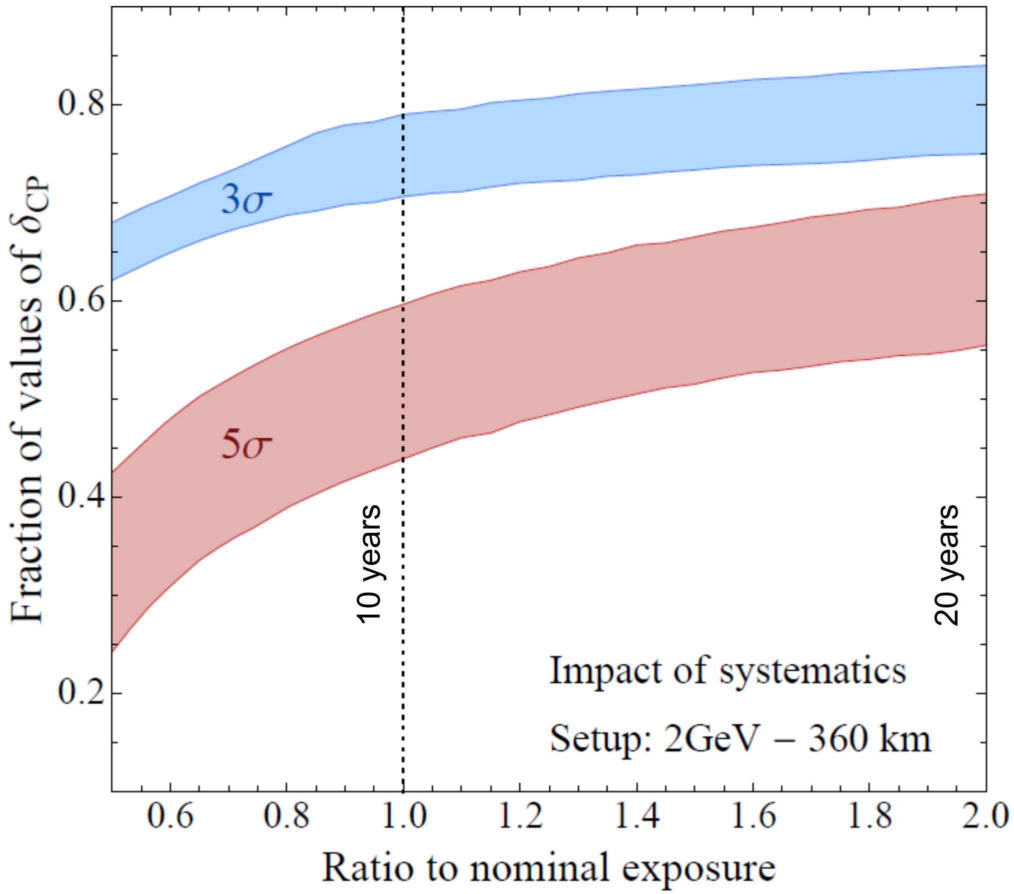
Coloma, Fernandez-Martinez, JHEP 1204 (2012) 089, arXiv:1110.4583



Coloma, Fernandez-Martinez, JHEP 1204 (2012) 089, arXiv:1110.4583

ESSνSB dependence on final exposure

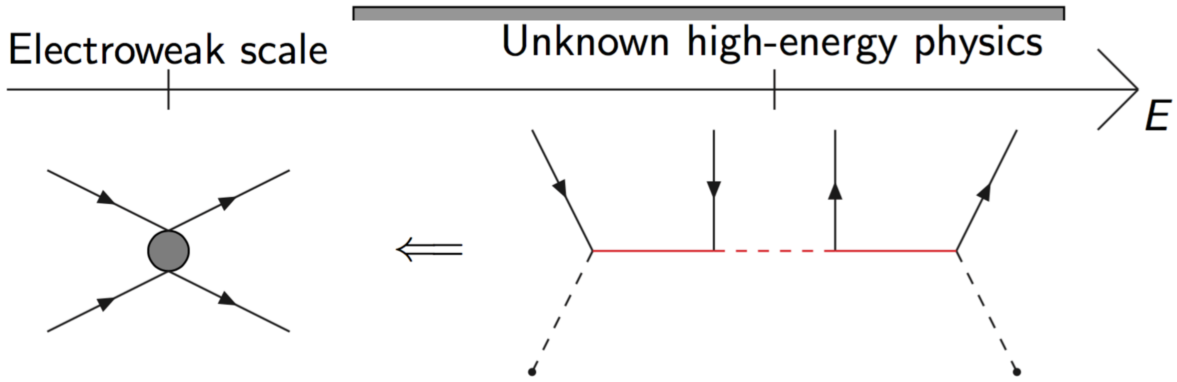
for ESSnuSB systematic errors see 1209.5973 [hep-ph]
(lower limit "default" case, upper limit "optimistic" case)



(courtesy P. Coloma)

Non-Standard Interactions

- Framework based on effective operators parameterizing the effects of states that are integrated out



- Unknown physics at a high energy scale
- Effective four-fermion operators at low scale

CC-like NSI

- Charged current like (CC-like)

$$\mathcal{O}_{\alpha\beta}^{ff'(L,R)} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$

- Alters the produced and detected neutrino states
- “Probabilities” do not necessarily add up to one – also affects cross sections!

NC-like NSI

- Neutral current like (NC-like)

$$\mathcal{O}_{\alpha\beta}^{f(L,R)} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P_{L,R} f) + h.c.$$

- Coherent forward scattering with matter constituents
- Similar to the MSW potential
- Generally results in off-diagonal contributions to the flavor evolution Hamiltonian

Effective description

- Produced and detected states

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\alpha\gamma}^s |\nu_\gamma\rangle$$

$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\gamma\beta}^d \langle\nu_\gamma|$$

- Flavor propagation

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \frac{1}{2E}\left\{U^\dagger\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{bmatrix}U + A\begin{bmatrix}1+\varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m\\ \varepsilon_{\mu e}^m & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m\\ \varepsilon_{\tau e}^m & \varepsilon_{\tau\mu}^m & \varepsilon_{\tau\tau}^m\end{bmatrix}\right\}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

NSI bounds (model independent)

Source

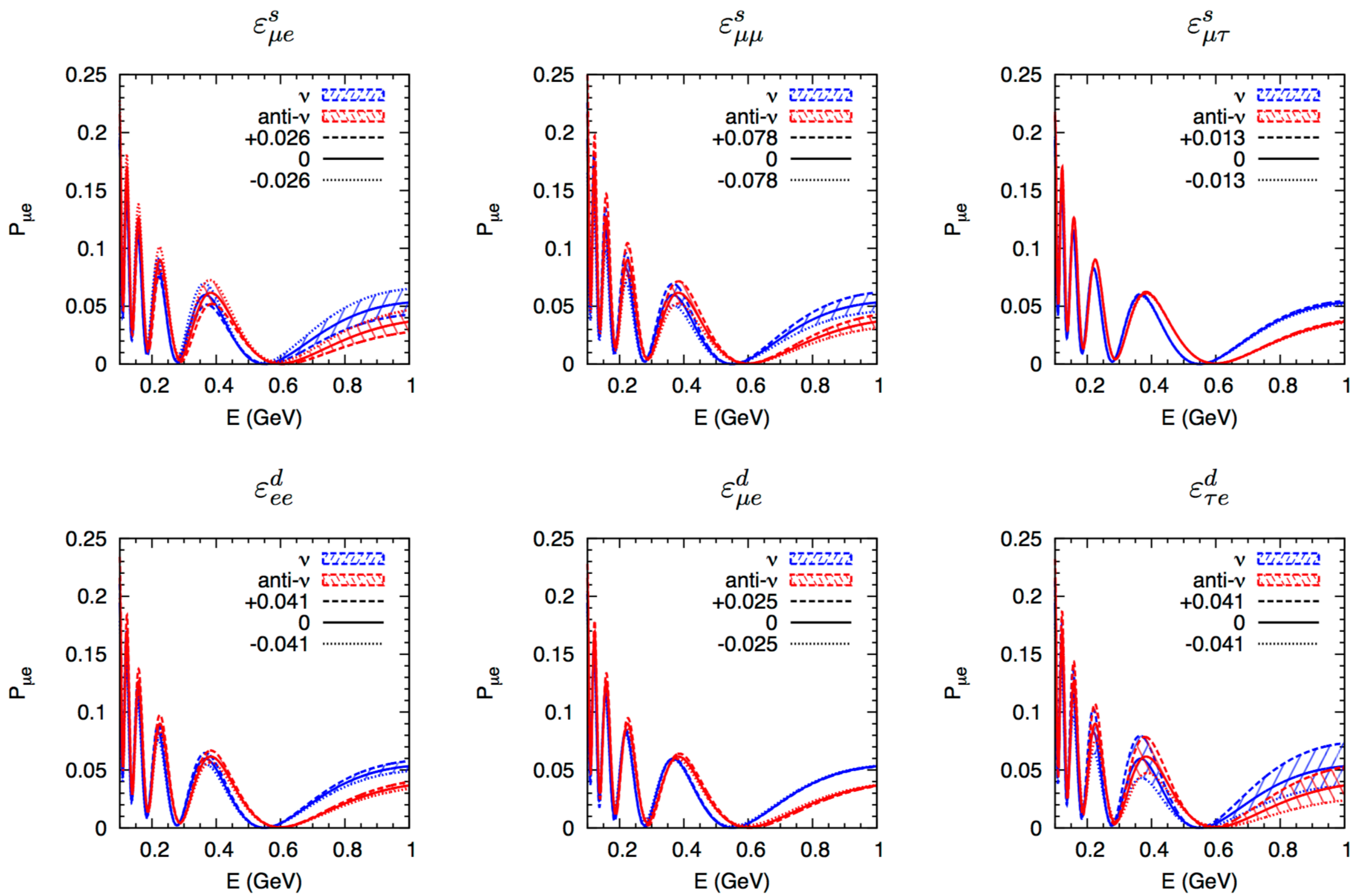
$$|\varepsilon_{\alpha\beta}^{ud}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ \begin{matrix} 1.8 \cdot 10^{-6} \\ 0.026 \end{matrix} & 0.078 & 0.013 \\ \begin{matrix} 0.087 \\ 0.12 \end{matrix} & \begin{matrix} 0.013 \\ 0.018 \end{matrix} & 0.13 \end{pmatrix}$$

Matter (Earth)

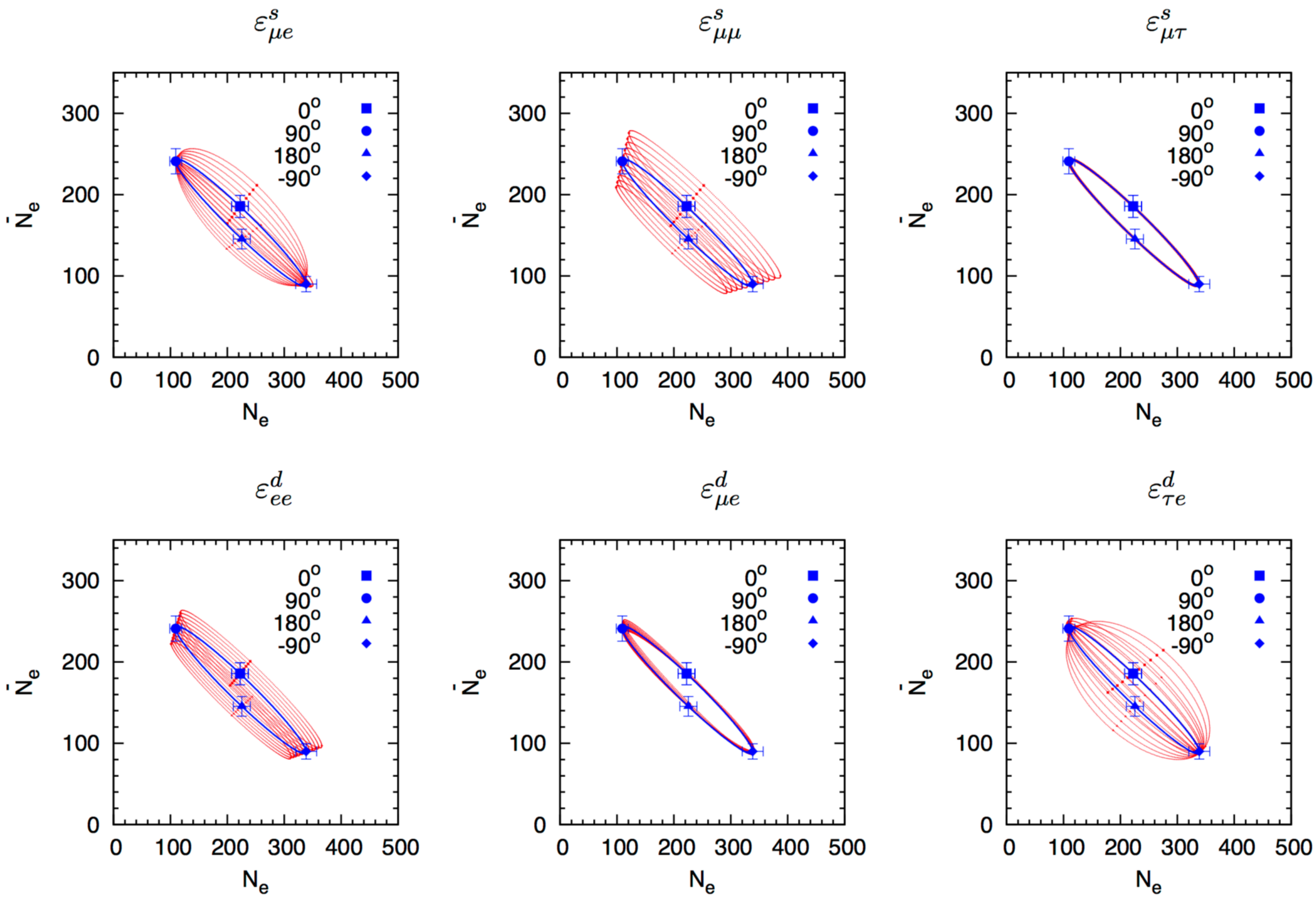
$$|\varepsilon_{\alpha\beta}^{\oplus}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

Blennow, Biggio, Fernandez, **arXiv:0907.0097**

Oscillation probabilities



Bi-event results



In general when considering new physics

Several questions are important when considering the effects of new physics in an experiment:

- What bounds can the experiment put on the new physics?

- How is the performance in terms of standard physics affected?

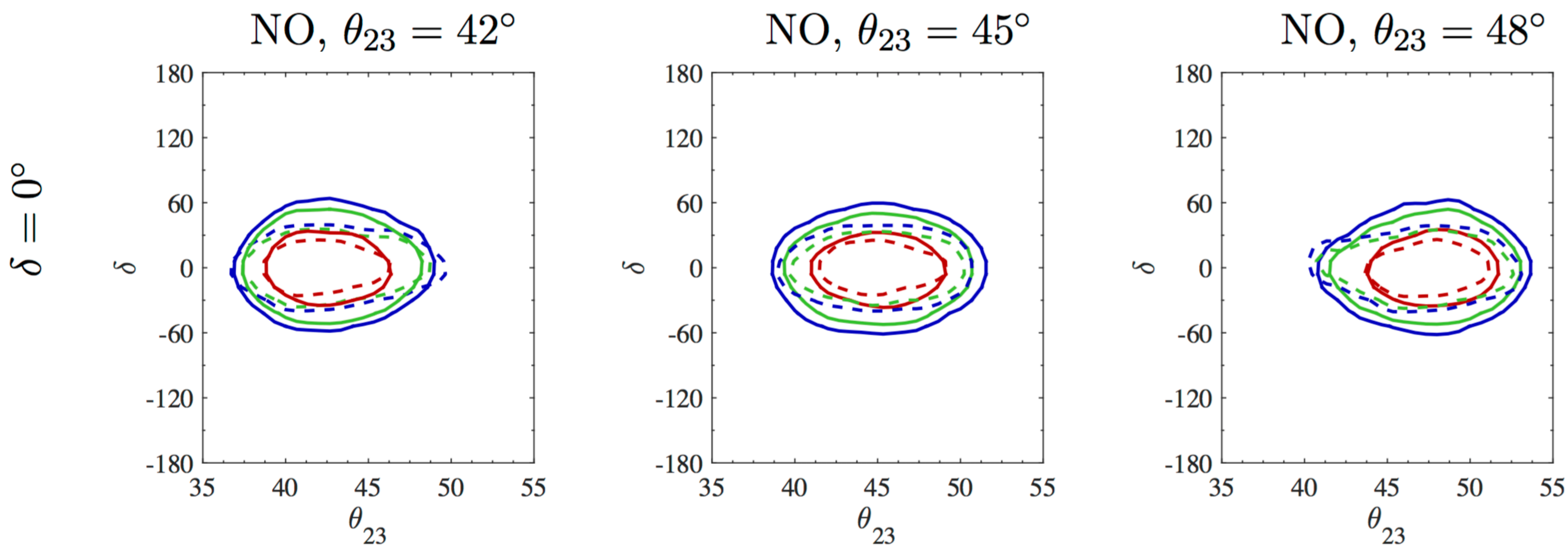
- Could new physics be established?

Sensitivities

Parameter	Limits with all other NSI parameters free	Limits with all other NSI parameters zero	Limits from Ref. [21]
$\lvert\varepsilon^s_{\mu e}\rvert$	0.025	0.014	0.026
$\lvert\varepsilon^s_{\mu\mu}\rvert$	0.27	0.27	0.078
$\lvert\varepsilon^s_{\mu\tau}\rvert$	0.040	0.040	0.013
$\lvert\varepsilon^d_{ee}\rvert$	0.15	0.15	0.041
$\lvert\varepsilon^d_{e\mu}\rvert$	0.087	0.082	0.026
$\lvert\varepsilon^d_{\mu e}\rvert$	0.025	0.014	0.025
$\lvert\varepsilon^d_{\mu\mu}\rvert$	0.28	0.27	0.078
$\lvert\varepsilon^d_{\tau e}\rvert$	0.11	0.12	0.041
$\lvert\varepsilon^d_{\tau\mu}\rvert$	0.040	0.033	0.013

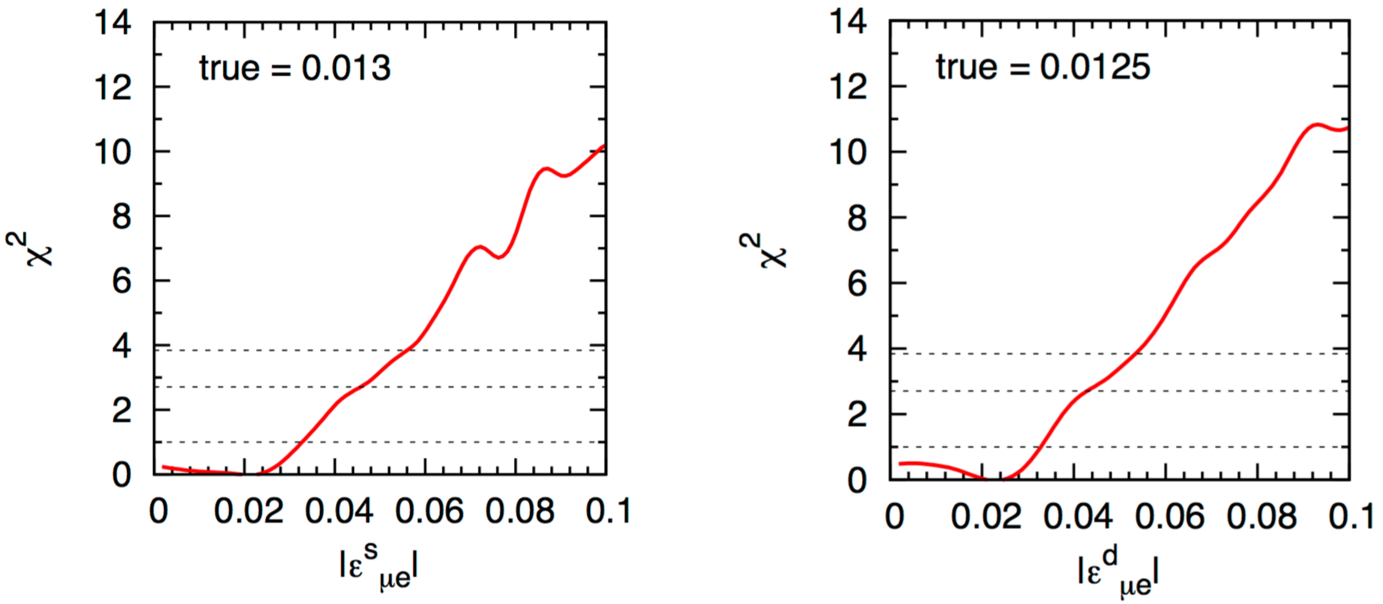
[21] Blennow, Biggio, Fernandez, **arXiv:0907.0097**

Impact on standard oscillations



Dashed lines: Standard parameters only
Solid lines: Including both standard and NSI parameters

Establishing new physics?



True values are taken to be roughly half the current bound
In neither case, the experiment would be able to rule out standard oscillations

Summary NSI at ESSnuSB

- Sensitive mainly to the effects of source and detector effects
  - Not surprising, the matter effects are weak!

- The presence of NSI could possibly affect the measurement of the CP-phase – θ_{23} unaffected

- Difficult to put very strong bounds on NSI in comparison to existing limits

Sterile neutrino oscillations

- Possibility of additional sterile neutrino states
- Mixing matrix extended to (3+n)x(3+n)
- In a 3+1 scenario with other mass squared differences small

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

ESSnuSB and steriles

- A near detector generally required anyway
- Assume a 1 kt water Cherenkov detector placed 1 km from the source
- All sensitivity to steriles comes from the near detector – the far detector is irrelevant for this study

$$\begin{aligned} \text{Case I}: &\quad \text{no active} - \text{sterile mixing} \quad \text{and} \\ \text{Case II}: &\quad \sin^2(2\theta_{\mu e}) = 1.3 \cdot 10^{-2}, \quad \Delta m^2_{41} = 0.42 \text{ eV}^2 \end{aligned}$$

Case II corresponds to the best appearance fit from:

Kopp, Machado, Maltoni, Schwetz, **arXiv:1303.3011**

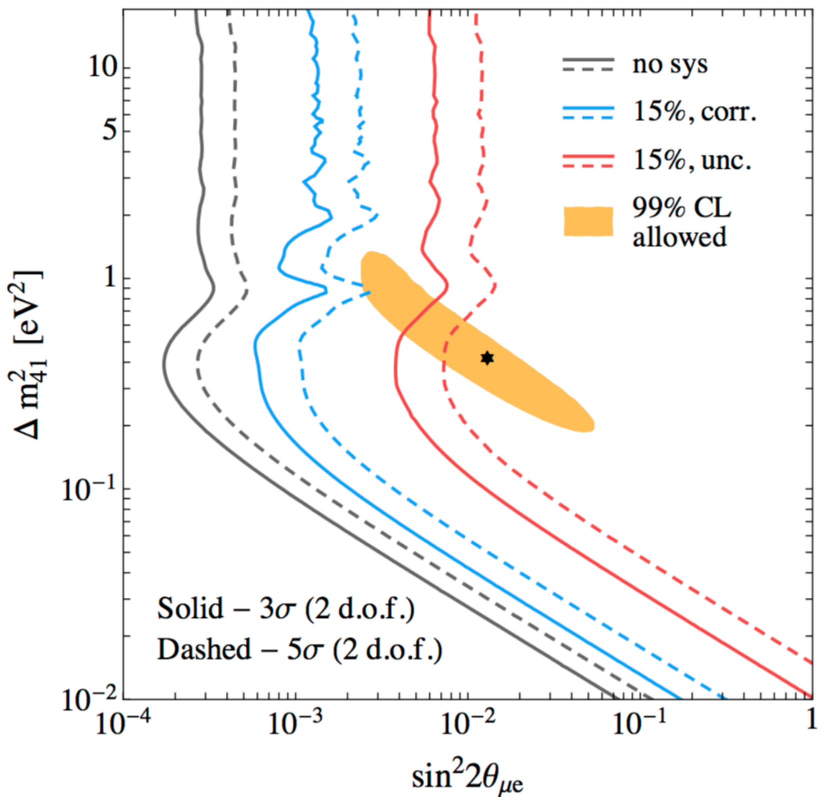
Assumptions on systematic errors

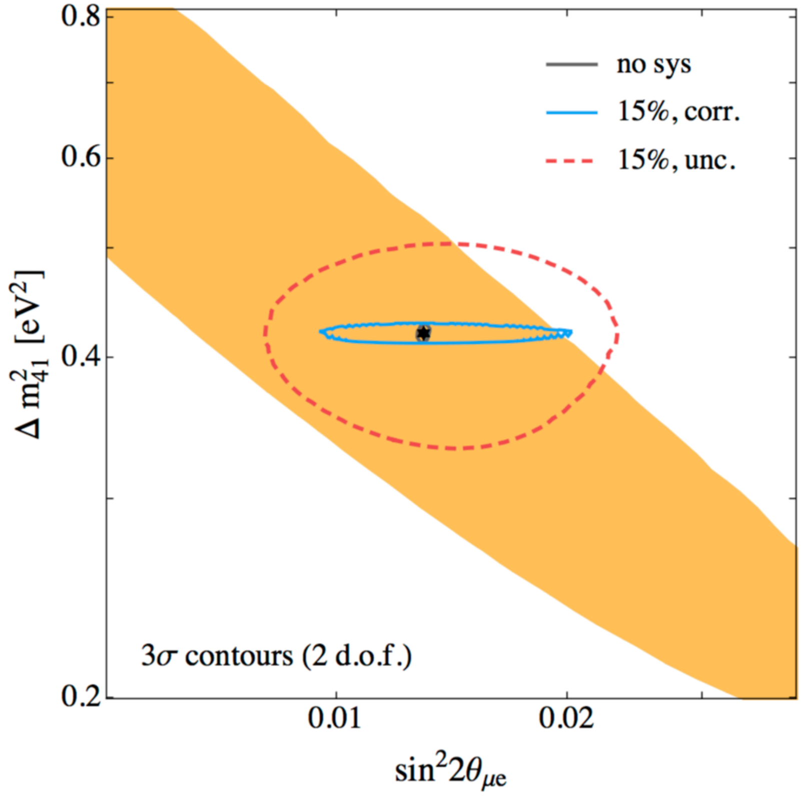
The results will depend heavily on the systematic errors as only one of the detectors (the near one) are relevant. We consider different cases:

- No systematics limit
- 15 % correlated systematics
- 15 % uncorrelated systematics

We assume 2+8 years of running

Sterile neutrino sensitivities





Steriles at ESSnuSB discussion

- A huge number of events in the near detector – statistical errors are small
- Quickly dominated by systematics
- Could easily be competitive with current bounds/hints
- Would rule out current best-fit at high significance
- Other experiments will look for this too – probably not worth doing for this search in itself, but adds to the possible physics potential of the ESSnuSB

Concluding remarks

- New physics at future facilities are important for several reasons
  - Sensitivities for bound
  - Effects on standard physics
  - Possibility of establishing new physics

- NSI
  - ESSnuSB could mainly affect some source/detector bounds
  - Measurement of CP-phase could be somewhat compromised
  - Not enough to establish new physics

Concluding remarks (2)

- Sterile neutrinos
  - A 1 kt near detector at a distance of 1 km would provide a test for sterile neutrino oscillations through the oscillation pattern
  - Would rule out/confirm current best-fit
  - Sensitivity depends strongly on the assumption on systematic errors