Study of CC-NSIs at the MOMENT experiment

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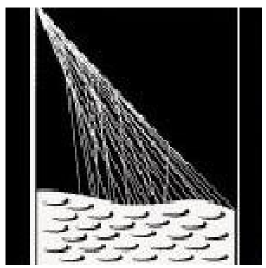
Based on the work with Yibing Zhang
arXiv: 1705.09500

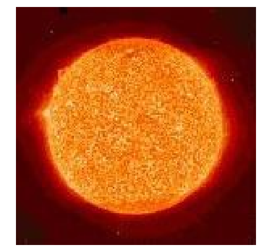
Table of Contents

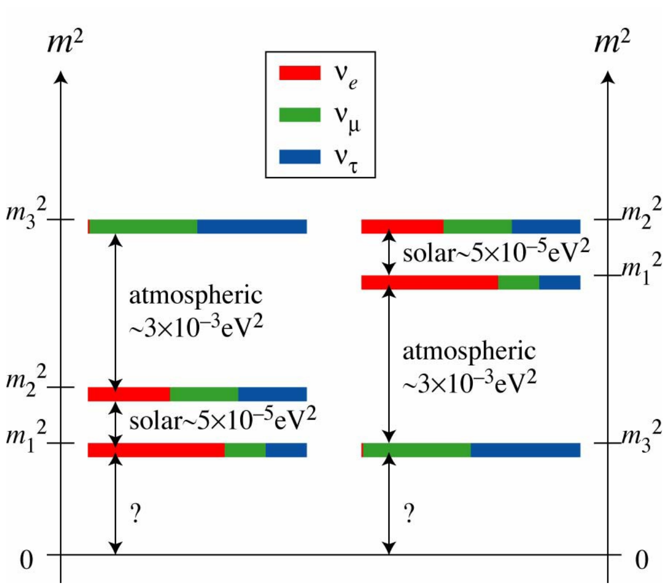
- **Motivation:**
  - **Puzzles in neutrino physics**
  - **Links between NSIs and neutrino oscillation**
  - **Status of the MOMENT proposal**
- **Remarks on neutrino oscillation channels with CC-NSIs**
- **Impact on precision measurements from CC-NSIs**
- **Correlations and constraints of CC-NSIs**
- **Summary**

Puzzles in neutrino physics

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

= () x (

) x ()

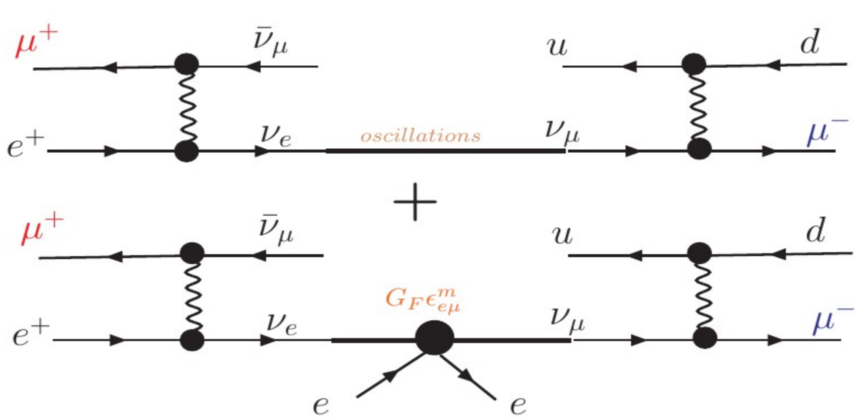


- **Absolute neutrino mass scale?**
- **Neutrino: Dirac or Majorana fermion?**
- **Mass hierarchy: m3>m1 v.s m3<m1**
- **Leptonic CP violation?**
- **Sterile neutrinos?**
- **Non-standard neutrino interactions?**
- **Non-unitary neutrino mixing?**

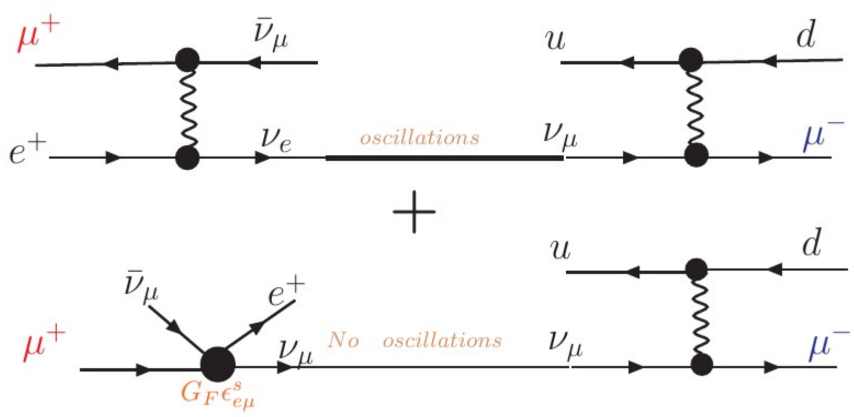
Links between NSIs and neutrino oscillations

New physics beyond SM: new particles, new couplings, new phenomenon...

- Flavor violating interactions with neutrinos:
  $\nu_\alpha f \to \nu_\beta f, l_\alpha^- \to \nu_\beta e^- \bar{\nu}_e \cdots$
- 4-fermion vertices:
  $\mathrm{L_{eff}} = 2\sqrt{2}\, G_F\, (\epsilon^{L/R})^{\alpha\gamma}_{\beta\delta}\ (\bar{\nu}^\beta \gamma^\rho \mathrm{P}_L \nu_\alpha)\ (\bar{\ell}^\delta \gamma^\rho \mathrm{P}_{L/R} \ell_\gamma)$



NSI happens to neutrino propagation in matter



NSI at neutrino productions

Current bounds on NSIs

Constraints by experiments with neutrinos and charged leptons (Davidson et al., 2003):

$$\begin{bmatrix} -0.9 < \varepsilon_{ee} < 0.75 & |\varepsilon_{e\mu}| \lesssim 3.8 \times 10^{-4} & |\varepsilon_{e\tau}| \lesssim 0.25 \\ & -0.05 < \varepsilon_{\mu\mu} < 0.08 & |\varepsilon_{\mu\tau}| \lesssim 0.25 \\ & & |\varepsilon_{\tau\tau}| \lesssim 0.4 \end{bmatrix}$$

Constraints including loops (Biggio, Blennow, Fernández-Martínez, 2009):

Model independent bound for $\varepsilon_{e\mu}$ *increases* by a factor of 10^3!

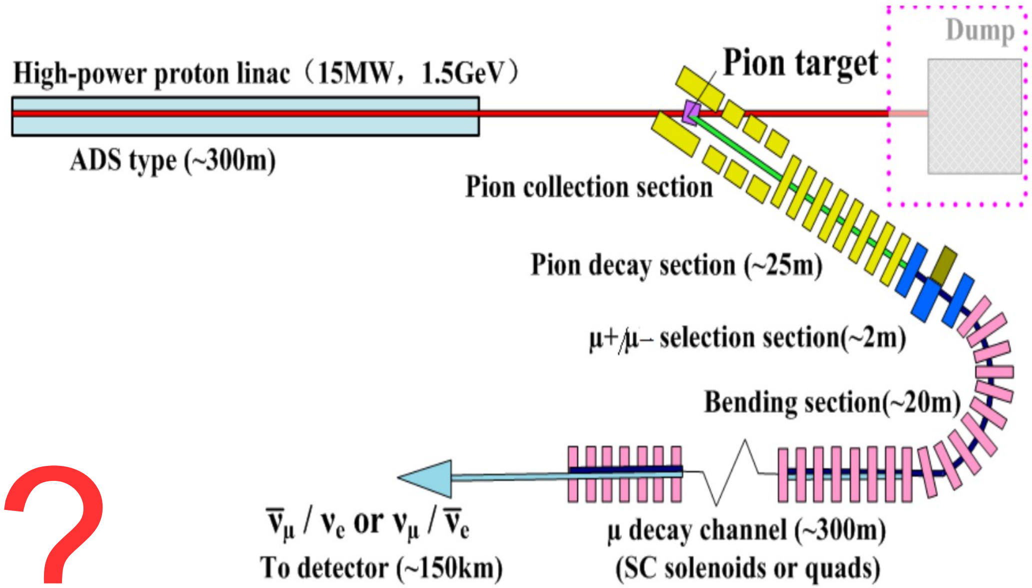
$$|\epsilon^{\mu e}| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix} \quad 90\%\mathrm{C.L.} \qquad |\epsilon^{ud}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.013 & 0.13 \end{pmatrix} \quad 90\%\mathrm{C.L.}$$

Chinese proposal: MuOn-decay Medium baseline NeuTrino beam experiment (MOMENT)

- **Neutrino flux: 200-300 MeV**
- **Baseline: 150 km**
- **Proton beam: 1.5-2.0 GeV**
- **Intensity of proton beam: 10 mA**
- **POT/y: 1.1*e+24**
- **Neutrino flavors:**

$$+ \;:\; \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$- \;:\; \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



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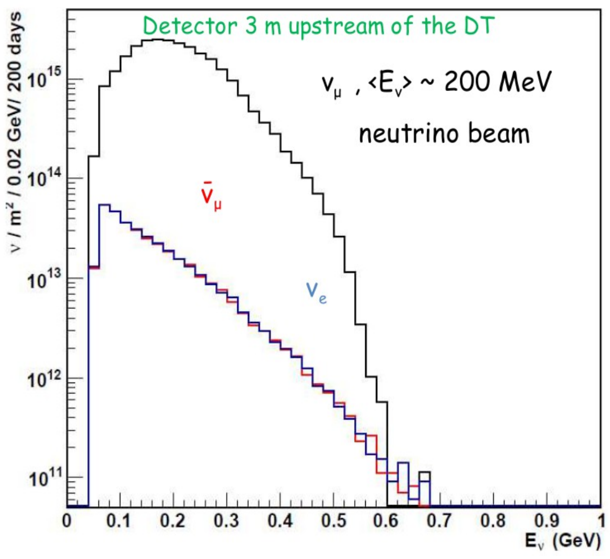
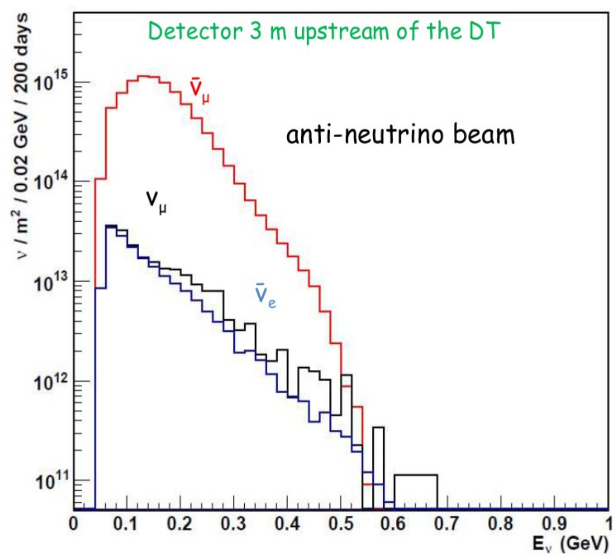
The proposal sells the design of accelerators with plenty of room for imagination of detectors.

- Which type of detector?
- What kind of physics can we do?





Proposal of neutrino detectors for MOMENT

- **In MOMENT, neutrino flux peaked at low energies → require a massive detector to compensate for the small cross section.**
- **Good flavor and charge identifications are needed!**

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

make this large!

detector

(# targets)

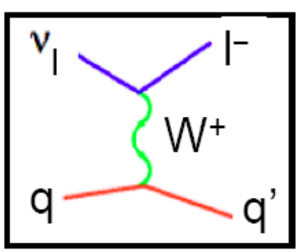
make this large!

ν cross section

tiny (~10^{-38} cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

go to higher energies



Charged Current (CC)

- neutrino in
- charged lepton out

this is how we detected neutrinos in the first place

$\nu_e \to e^-$ $\bar{\nu}_e \to e^+$

$\nu_\mu \to \mu^-$ $\bar{\nu}_\mu \to \mu^+$

$\nu_\tau \to \tau^-$ $\bar{\nu}_\tau \to \tau^+$

- flavor of outgoing lepton "tags" flavor of incoming neutrino
- charge of outgoing lepton determines whether ν or anti-ν

- **In MOMENT, neutrino flux peaked at low energies → require a massive detector to compensate for the small cross section.**
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ν flux
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depends on your ν source
make this large!

ν cross section
tiny (~10^{-38} cm^2)
$\sigma_\nu^{tot} \sim E_\nu$
go to higher energies

detector
(# targets)
make this large!

$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$\nu_\mu + n \rightarrow p + \mu^-$$

- **Choose the Water Cherenkov detector due to its excellent flavor identifications and high efficiencies at the low-energy range.**
- **Distinguishing neutrinos and anti-neutrinos solved by doping the water with Gd (at the 0.1-0.2% level)**

Ref: hep-ph/0309300

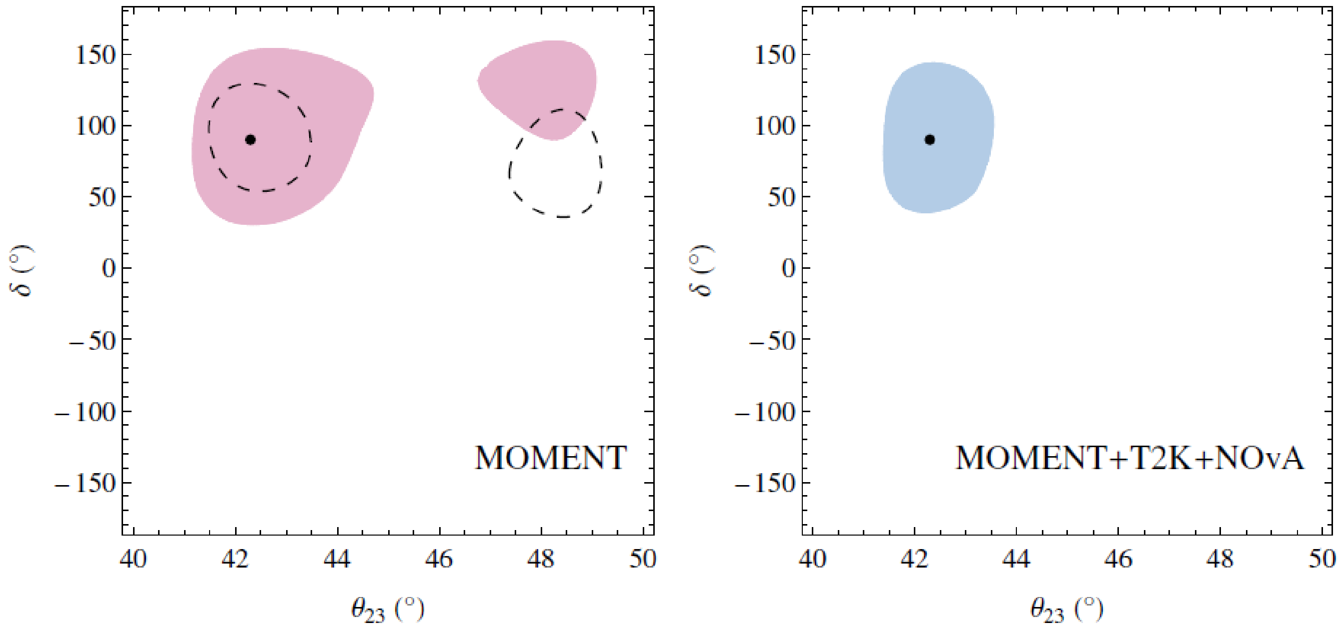
Overview of physics study at MOMENT

- **First standard neutrino oscillation physics study performed by Pilar, Matthias and Erique in arXiv:1511.02859**

  → CP discovery reach in a complementarity with T2K&NOvA.

- **NC-NSIs in matter considered by Pouya and Yasaman in arXiv: 1602.07099**

  → Degeneracy induced by NSIs and measurements of CPV.



Ref:

arXiv:1511.02859

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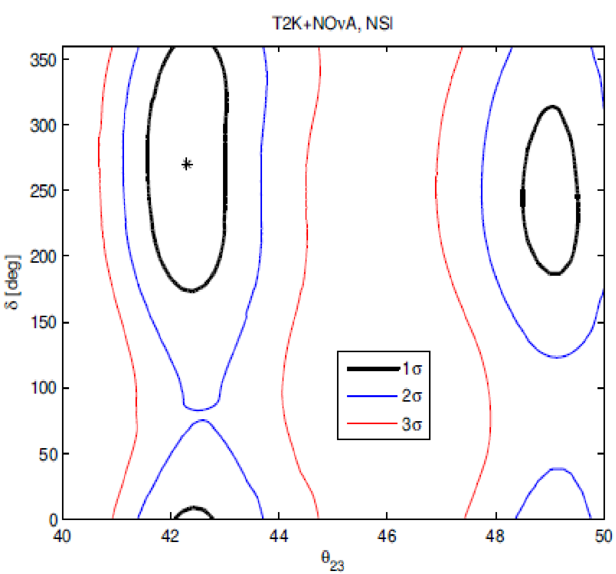

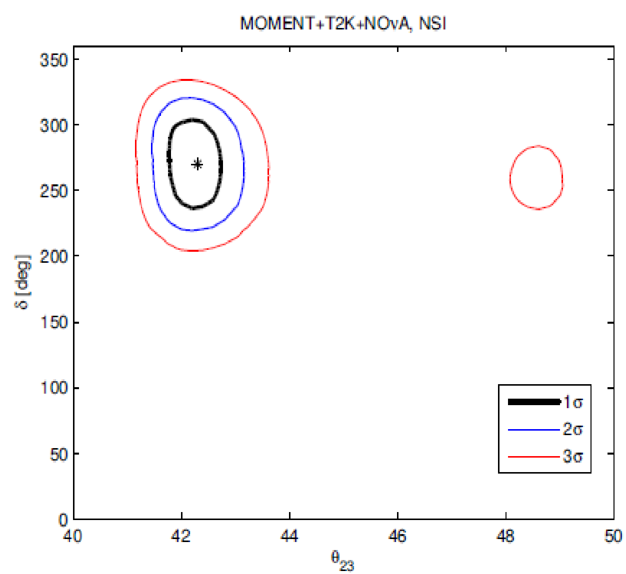

Ref:

arXiv:1511.02859

But, baseline of ~150 km is relatively short.

What about CC-NSIs?

Table of Contents

- Motivation:
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- Impact on precision measurements from CC-NSIs
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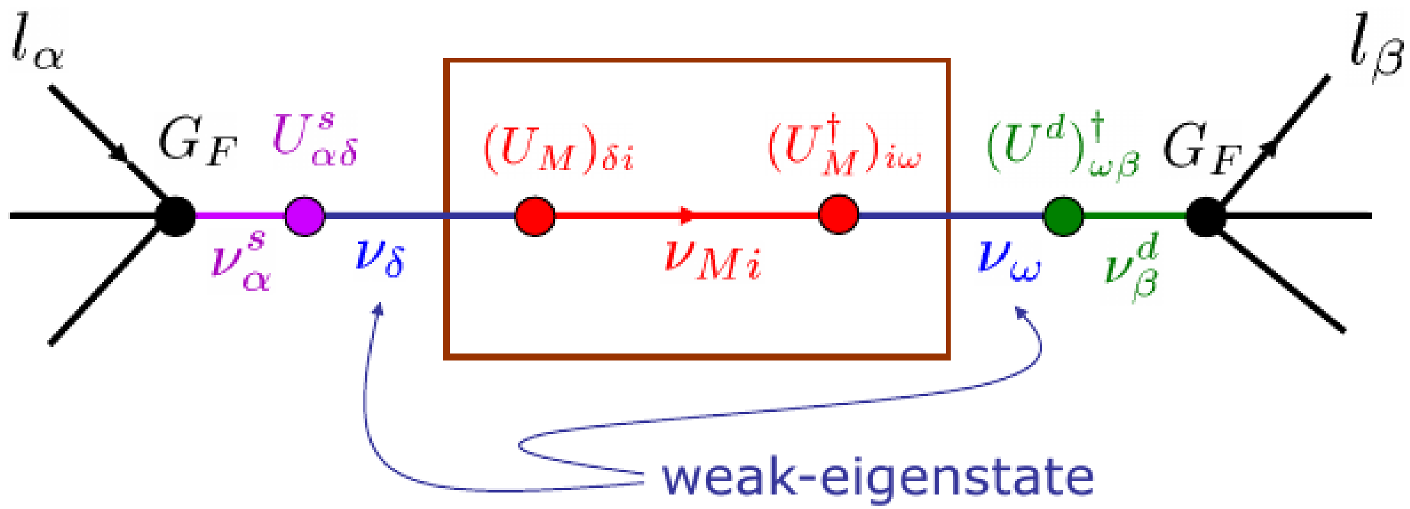
- Summary

Formalism of neutrino oscillation with NSIs

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i [U^s U_M]_{\alpha i} \exp\left(i \frac{(\Delta m_M^2)_{i1} L}{4E} \right) [U^d U_M]^\dagger_{i\beta} \right|^2$$



Zero-distance effects: 2-flavor case

$$\frac{\Delta m^2 L}{4E} \to 0 \Rightarrow P(\nu_e \to \nu_\mu) \to \left(\epsilon^s_{e\mu} - \epsilon^d_{e\mu}\right)^2$$

Ref: Slides borrowed from Tommy Ohlsson

Neutrino oscillation channels at a near detector

Follow the same strategy and extend to 3 flavors + CC-NSIs:

$$P^{ND}_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \approx 1 + 2|\epsilon^s_{ee}| \cos\phi^s_{ee} + 2|\epsilon^d_{ee}| \cos\phi^d_{ee}$$

$$P^{ND}_{\bar{\nu}^s_\mu \to \bar{\nu}^d_\mu} \approx 1 + 2|\epsilon^s_{\mu\mu}| \cos\phi^s_{\mu\mu} + 2|\epsilon^d_{\mu\mu}| \cos\phi^d_{\mu\mu}$$

$$P^{ND}_{\nu^s_\mu \to \nu^d_e} \approx |\epsilon^s_{\mu e}|^2 + |\epsilon^d_{\mu e}|^2 + 2|\epsilon^s_{\mu e}||\epsilon^d_{\mu e}| \cos(\phi^s_{\mu e} - \phi^d_{\mu e})$$

$$P^{ND}_{\nu^s_e \to \nu^d_\mu} \approx |\epsilon^s_{e\mu}|^2 + |\epsilon^d_{e\mu}|^2 + 2|\epsilon^s_{e\mu}||\epsilon^d_{e\mu}| \cos(\phi^s_{e\mu} - \phi^d_{e\mu})$$

- **Zero-distance effects show up for CC-NSIs at the near detector**
- **It is important for a near detector to discover New physics**

Neutrino oscillation channels at a far detector

$$
\begin{aligned}
P^{vac}_{\nu_\mu\to\nu_e} = {} & s^2_{2\times13}s^2_{23}\sin^2\Delta_{31} \\
& +\alpha\Delta_{31}s_{2\times12}s_{2\times23}s_{13}[\sin(2\Delta_{31})\cos\delta - 2\sin\delta\sin^2\Delta_{31} \\
& +\alpha^2\Delta^2_{31}c^2_{23}s^2_{2\times12} \\
& -|\epsilon^s_{\mu e}|s_{2\times13}s_{23}\sin(\delta+\phi^s_{\mu e})\sin(2\Delta_{31}) \\
& -2|\epsilon^s_{\mu e}|s_{2\times13}s_{23}\cos(\delta+\phi^s_{\mu e})\sin^2\Delta_{31} \\
& -|\epsilon^d_{\mu e}|s_{2\times13}s_{23}\sin(\delta+\phi^d_{\mu e})\sin(2\Delta_{31}) \\
& -2|\epsilon^d_{\mu e}|s_{2\times13}s_{23}c_{2\times23}\cos(\delta+\phi^d_{\mu e})\sin^2\Delta_{31} \\
& +4|\epsilon^d_{\tau e}|c_{23}s_{2\times13}s^2_{23}\cos(\delta+\phi^d_{\tau e})\sin^2\Delta_{31} \\
& -2\alpha\Delta_{31}|\epsilon^s_{\mu e}|c_{13}s_{2\times12}c_{23}\sin\phi^s_{\mu e} \\
& +2\alpha\Delta_{31}|\epsilon^d_{\mu e}|s_{2\times12}c_{13}c_{23}s^2_{23}\cos\phi^d_{\mu e}\sin(2\Delta_{31}) \\
& -2\alpha\Delta_{31}|\epsilon^d_{\mu e}|s_{2\times12}c_{13}c_{23}\sin\phi^d_{\mu e}(1-2s^2_{23}\sin^2\Delta_{31}) \\
& +4\alpha\Delta_{31}|\epsilon^d_{\tau e}|c_{13}c^2_{23}s_{2\times12}s_{23}\sin\phi^d_{\tau e}\sin^2\Delta_{31} \\
& +2\alpha\Delta_{31}|\epsilon^d_{\tau e}|c_{13}c^2_{23}s_{2\times12}s_{23}\cos\phi^d_{\tau e}\sin(2\Delta_{31}) \\
& +O(\alpha^3)+O(\alpha^2 s_{13})+O(\alpha s^2_{13})+O(s^3_{13}) \\
& +O(\epsilon\alpha^2)+O(\epsilon s^2_{13})+O(\epsilon^2)
\end{aligned}
$$

$$
\begin{aligned}
P^{vac}_{\nu_e\to\nu_\mu} = {} & s^2_{2\times13}s^2_{23}\sin^2\Delta_{31} \\
& +\alpha\Delta_{31}s_{2\times12}s_{2\times23}s_{13}[\sin(2\Delta_{31})\cos\delta + 2\sin\delta\sin^2\Delta_{31}] \\
& +\alpha^2\Delta^2_{31}c^2_{23}s^2_{2\times12} \\
& +|\epsilon^s_{e\mu}|s_{2\times13}s_{23}\sin(\delta-\phi^s_{e\mu})\sin(2\Delta_{31}) \\
& -4|\epsilon^s_{e\mu}|s_{2\times13}s_{23}c_{2\times23}\cos(\delta-\phi^s_{e\mu})\sin^2\Delta_{31} \\
& +4|\epsilon^s_{e\tau}|c_{23}s_{2\times13}s^2_{23}\cos(\delta-\phi^s_{e\tau})\sin^2\Delta_{31} \\
& +|\epsilon^d_{e\mu}|s_{2\times13}s_{23}\sin(\delta-\phi^d_{e\mu})\sin(2\Delta_{31}) \\
& -2|\epsilon^d_{e\mu}|s_{2\times13}s_{23}\cos(\delta-\phi^d_{e\mu})\sin^2\Delta_{31} \\
& +2\alpha\Delta_{31}|\epsilon^s_{e\mu}|s_{2\times12}c_{13}c_{23}s^2_{23}\cos\phi^s_{e\mu}\sin(2\Delta_{31}) \\
& -2\alpha\Delta_{31}|\epsilon^s_{e\mu}|s_{2\times12}c_{13}c_{23}\sin\phi^s_{e\mu}(1-2s^2_{23}\sin^2\Delta_{31}) \\
& +2\alpha\Delta_{31}|\epsilon^s_{e\tau}|c_{13}c^2_{23}s_{2\times12}s_{23}\cos\phi^s_{e\tau}\sin(2\Delta_{31}) \\
& +4\alpha\Delta_{31}|\epsilon^s_{e\tau}|c_{13}c^2_{23}s_{2\times12}s_{23}\sin\phi^s_{e\tau}\sin^2\Delta_{31} \\
& -2\alpha\Delta_{31}|\epsilon^d_{e\mu}|c_{13}s_{2\times12}c_{23}\sin(\phi^d_{e\mu}) \\
& +O(\alpha^3)+O(\alpha^2 s_{13})+O(\alpha s^2_{13})+O(s^3_{13}) \\
& +O(\epsilon\alpha^2)+O(\epsilon s^2_{13})+O(\epsilon^2)
\end{aligned}
$$

- **Selections of proper CC-NSI parameters to be studied in simulation**
- **Understand correlations of CC-NSI and standard parameters**

Neutrino oscillation channels at a far detector

$$
\begin{aligned}
P^{vac}_{\nu_\mu\to\nu_e} = {} & s^2_{2\times13}s^2_{23}\sin^2\Delta_{31} \\
& +\alpha\Delta_{31}s_{2\times12}s_{2\times23}s_{13}[\sin(2\Delta_{31})\cos\delta - 2\sin\delta\sin^2\Delta_{31}] \\
& +\alpha^2\Delta^2_{31}c^2_{23}s^2_{2\times12} \\
& -|\epsilon^s_{\mu e}|s_{2\times13}s_{23}\sin(\delta+\phi^s_{\mu e})\sin(2\Delta_{31}) \\
& -2|\epsilon^s_{\mu e}|s_{2\times13}s_{23}\cos(\delta+\phi^s_{\mu e})\sin^2\Delta_{31} \\
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& -2|\epsilon^d_{\mu e}|s_{2\times13}s_{23}c_{2\times23}\cos(\delta+\phi^d_{\mu e})\sin^2\Delta_{31} \\
& +4|\epsilon^d_{\tau e}|c_{23}s_{2\times13}s^2_{23}\cos(\delta+\phi^d_{\tau e})\sin^2\Delta_{31} \\
& -2\alpha\Delta_{31}|\epsilon^s_{\mu e}|c_{13}s_{2\times12}c_{23}\sin\phi^s_{\mu e} \\
& +2\alpha\Delta_{31}|\epsilon^d_{\mu e}|s_{2\times12}c_{13}c_{23}s^2_{23}\cos\phi^d_{\mu e}\sin(2\Delta_{31}) \\
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& +2\alpha\Delta_{31}|\epsilon^d_{\tau e}|c_{13}c^2_{23}s_{2\times12}s_{23}\cos\phi^d_{\tau e}\sin(2\Delta_{31}) \\
& +O(\alpha^3)+O(\alpha^2 s_{13})+O(\alpha s^2_{13})+O(s^3_{13}) \\
& +O(\epsilon\alpha^2)+O(\epsilon s^2_{13})+O(\epsilon^2)
\end{aligned}
$$

Correlations and adjust the location of maximum

Vanishing for maximal mu-tau symmetry

Correlations and change the amplitude of peak

$$
\begin{aligned}
P^{vac}_{\nu_e\to\nu_\mu} = {} & s^2_{2\times13}s^2_{23}\sin^2\Delta_{31} \\
& +\alpha\Delta_{31}s_{2\times12}s_{2\times23}s_{13}[\sin(2\Delta_{31})\cos\delta + 2\sin\delta\sin^2\Delta_{31}] \\
& +\alpha^2\Delta^2_{31}c^2_{23}s^2_{2\times12} \\
& +|\epsilon^s_{e\mu}|s_{2\times13}s_{23}\sin(\delta-\phi^s_{e\mu})\sin(2\Delta_{31}) \\
& -4|\epsilon^s_{e\mu}|s_{2\times13}s_{23}c_{2\times23}\cos(\delta-\phi^s_{e\mu})\sin^2\Delta_{31} \\
& +4|\epsilon^s_{e\tau}|c_{23}s_{2\times13}s^2_{23}\cos(\delta-\phi^s_{e\tau})\sin^2\Delta_{31} \\
& +|\epsilon^d_{e\mu}|s_{2\times13}s_{23}\sin(\delta-\phi^d_{e\mu})\sin(2\Delta_{31}) \\
& -2|\epsilon^d_{e\mu}|s_{2\times13}s_{23}\cos(\delta-\phi^d_{e\mu})\sin^2\Delta_{31} \\
& +2\alpha\Delta_{31}|\epsilon^s_{e\mu}|s_{2\times12}c_{13}c_{23}s^2_{23}\cos\phi^s_{e\mu}\sin(2\Delta_{31}) \\
& -2\alpha\Delta_{31}|\epsilon^s_{e\mu}|s_{2\times12}c_{13}c_{23}\sin\phi^s_{e\mu}(1-2s^2_{23}\sin^2\Delta_{31}) \\
& +2\alpha\Delta_{31}|\epsilon^s_{e\tau}|c_{13}c^2_{23}s_{2\times12}s_{23}\cos\phi^s_{e\tau}\sin(2\Delta_{31}) \\
& +4\alpha\Delta_{31}|\epsilon^s_{e\tau}|c_{13}c^2_{23}s_{2\times12}s_{23}\sin\phi^s_{e\tau}\sin^2\Delta_{31} \\
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& +O(\epsilon\alpha^2)+O(\epsilon s^2_{13})+O(\epsilon^2)
\end{aligned}
$$

- **Selections of proper CC-NSI parameters to be studied in simulation**
- **Understand correlations of CC-NSI and standard parameters**

Numerical tests of oscillation probabilities/events

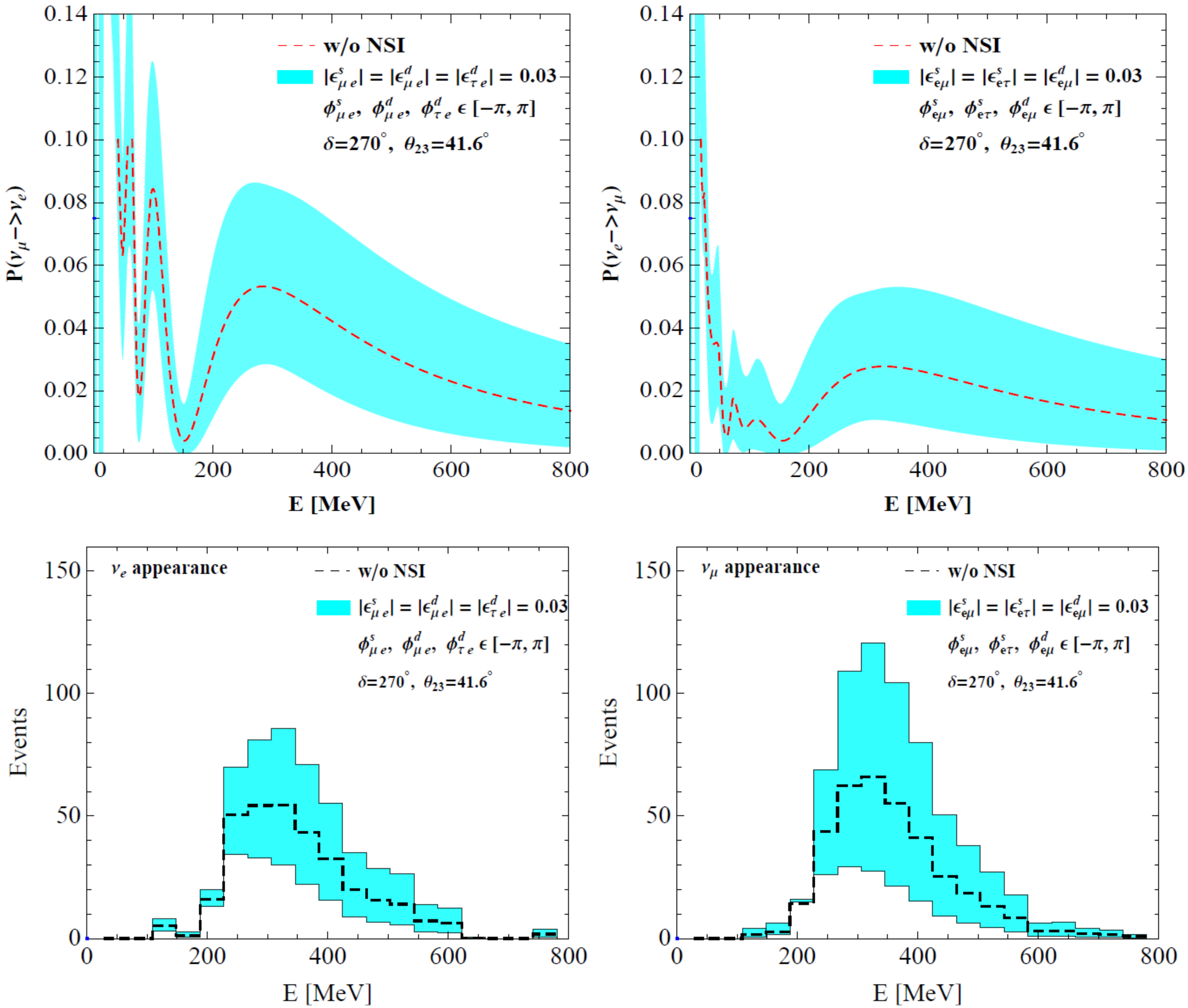
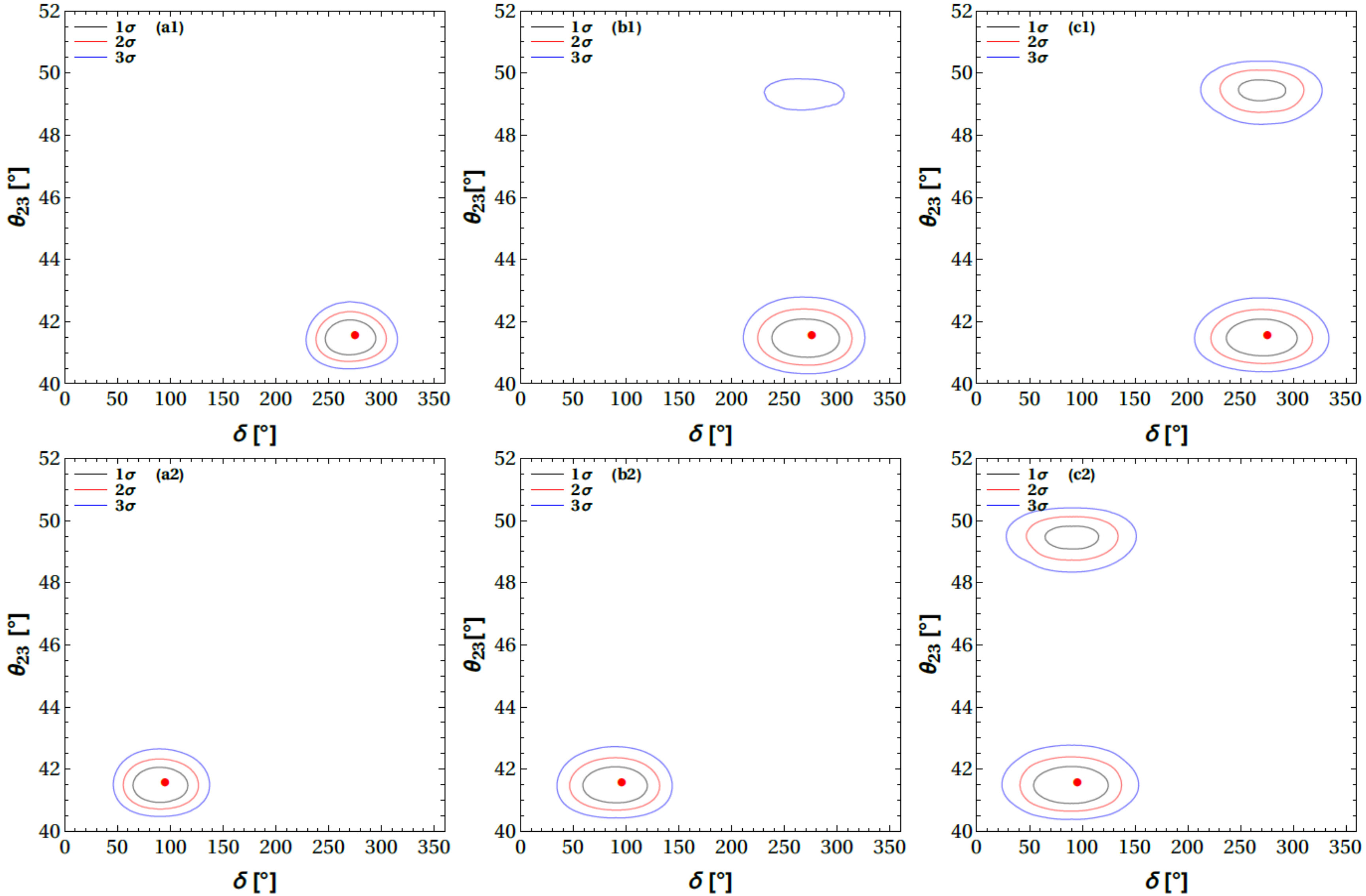


Table of Contents

Impacts on precision measurements by CC-NSIs

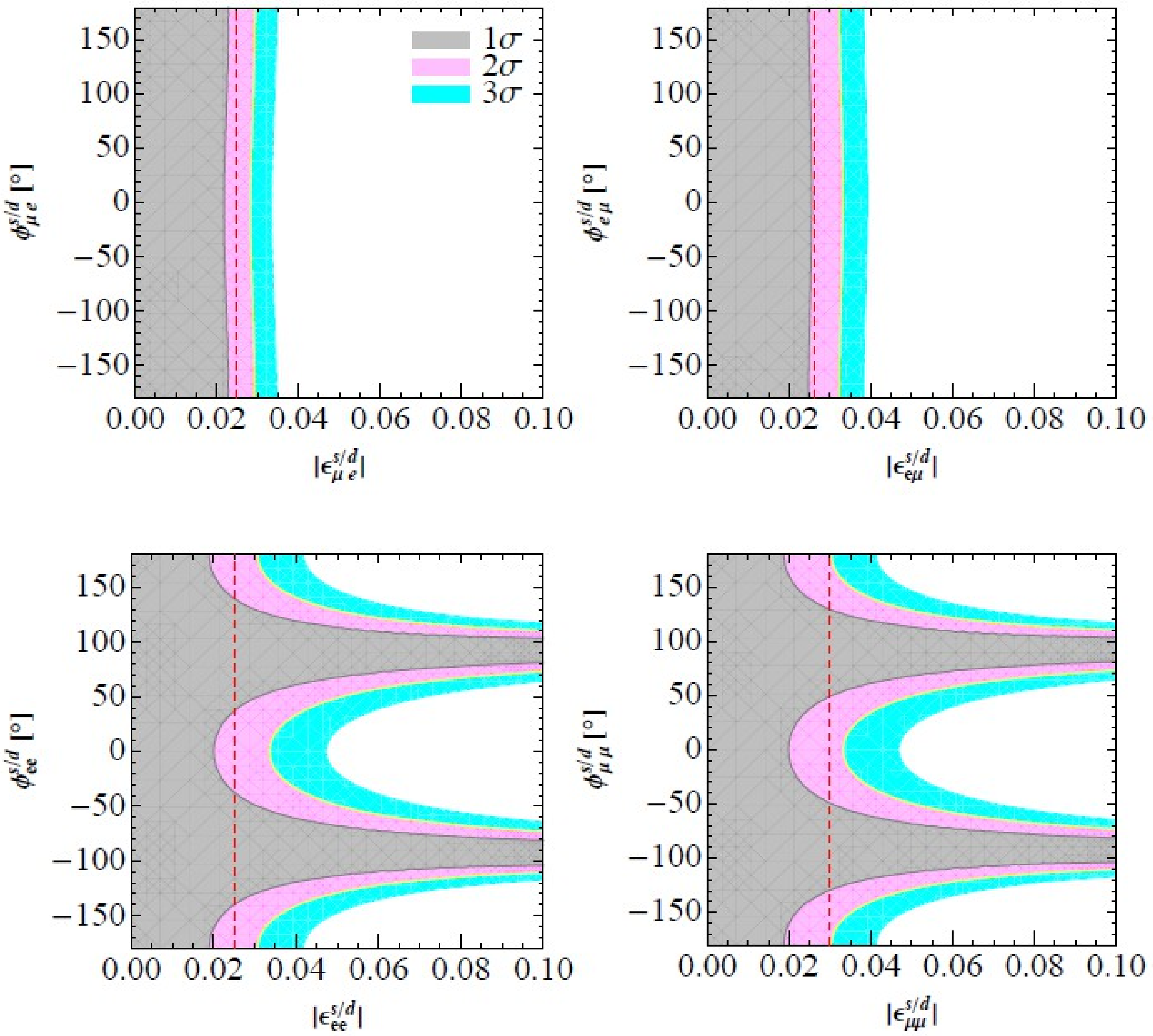


Degeneracy shows up after an introduction of CC-NSIs at some parameter space.

Table of Contents

Constraints of CC-NSIs with a near detector at MOMENT

- **Colorful regions are allowed after running a near detector at MOMENT.**
- **Appearance channels can well constrain the magnitude of related NSI parameters while have no impacts on their phases.**
- **Disappearance channels can exclude a large region allowed in current bounds.**
- **A strong correlation between the magnitude and phase of NSIs.**



Constraints of CC-NSIs with a far detector at MOMENT

- **Colorful regions are allowed after running a far detector at MOMENT.**
- **The e-mu sector of NSI are the best constrained**
- **Almost all NSI-induced CP phases change the exclusion limits severely except the e-mu sector.**
- **Limits from other sectors are not as good as those from the e-mu sector of NSI.**

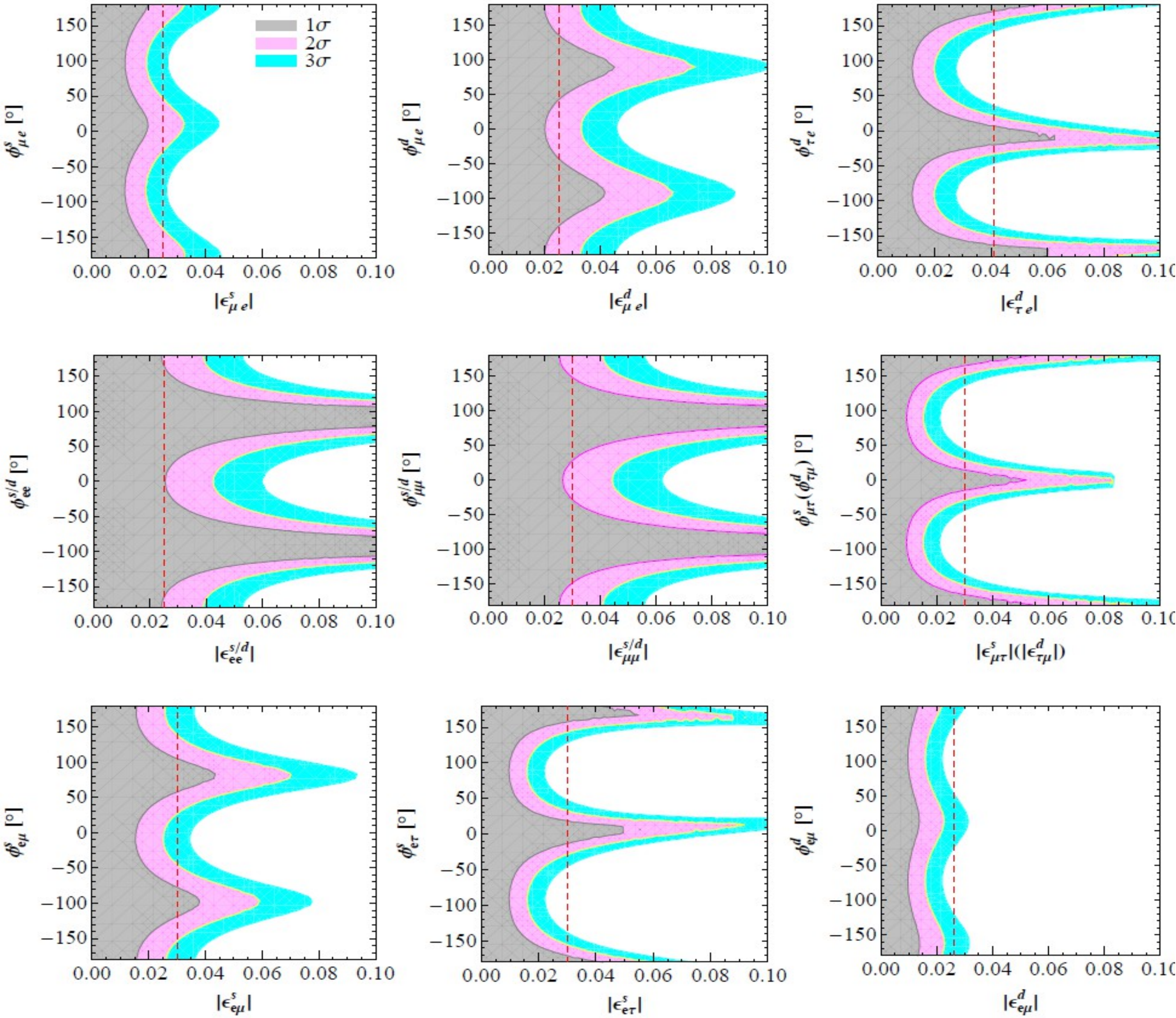


Table of Contents

Summary

- **We have studied CC-NSI effects with ND+FD at MOMENT.**
- **We have found some improvements of bounds on CC-NSIs at MOMENT.**
- **NSIs destroy the precision measurements of standard mixing parameters.**
- **Degeneracies between NSI and standard mixing parameters deserve further study.**

Parameter	ND constraints	FD constraints	ND+FD constraints	Current bounds
$\lvert\epsilon^s_{ee}\rvert$	0.027	0.028	0.018	0.025
$\lvert\epsilon^s_{e\mu}\rvert$	0.023	0.018	0.014	0.03
$\lvert\epsilon^s_{e\tau}\rvert$	n/a	0.065	0.065	0.03
$\lvert\epsilon^s_{\mu e}\rvert$	0.025	0.021	0.015	0.025
$\lvert\epsilon^s_{\mu\mu}\rvert$	0.028	0.029	0.019	0.03
$\lvert\epsilon^s_{\mu\tau}\rvert$	n/a	0.054	0.054	0.03
$\lvert\epsilon^d_{ee}\rvert$	0.027	0.028	0.027	0.041
$\lvert\epsilon^d_{e\mu}\rvert$	0.023	0.015	0.013	0.026
$\lvert\epsilon^d_{\mu e}\rvert$	0.025	0.022	0.025	0.025
$\lvert\epsilon^d_{\mu\mu}\rvert$	0.028	0.03	0.028	0.078
$\lvert\epsilon^d_{\tau e}\rvert$	n/a	0.065	0.065	0.041
$\lvert\epsilon^d_{\tau\mu}\rvert$	n/a	0.054	0.054	0.013

Thank you for your attention!

Backup: Detector implementation in simulation

- **Near and far detectors are needed.**

Fiducial mass (ND/FD)	Gd-doping Water cherenkov (100 t/500 kton)
Baseline (ND/FD)	500 m/150 km
Channels	$\nu_e(\bar{\nu}_e) \to \nu_e(\bar{\nu}_e)$, $\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$ $\nu_e(\bar{\nu}_e) \to \nu_\mu(\bar{\nu}_\mu)$, $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$
Energy resolution	$8.5\%/\sqrt{E}$
Runtime	μ^- mode 5 yrs+ μ^+ mode 5 yrs
Energy range	100 MeV to 800 MeV
Efficiency	ν_μ ($\bar{\nu}_\mu$) seclection: 50% ν_e ($\bar{\nu}_e$) selection: 40%
Normalization error on signal	appearance channels: 2.5% disappearance channels: 5%
Normalization error on backgroud	5% (all channels)
Backgound sources	Neutral current charge misidentifications atmospheric neutrinos

Backup: Oscillation channels faked by CC-NSIs

$$\mu^+ \to \nu_e \xrightarrow{\text{Osc.}} \nu_\mu \to \mu^- \tag{1}$$

$$\mu^+ \to \nu_e \xrightarrow{\text{Osc.}} \nu_e \to e^- \tag{2}$$

$$\mu^+ \to \bar{\nu}_\mu \xrightarrow{\text{Osc.}} \bar{\nu}_\mu \to \mu^+ \tag{3}$$

$$\mu^+ \to \bar{\nu}_\mu \xrightarrow{\text{Osc.}} \bar{\nu}_e \to e^+ \tag{4}$$

With CC-NSIs at the source, things are changed:

$$\mu^+ \xrightarrow{\text{NSI}} \nu_\mu \xrightarrow{\text{No osc.}} \nu_\mu \to \mu^-, \tag{5}$$

$$\mu^+ \xrightarrow{\text{NSI}} \bar{\nu}_e \xrightarrow{\text{No osc.}} \bar{\nu}_e \to e^+, \tag{6}$$

Similarly, we obtain the processes including CC-NSIs at the detector:

$$\mu^+ \to \nu_e \xrightarrow{\text{No osc.}} \nu_e \xrightarrow{\text{NSI}} \mu^-. \tag{7}$$

$$\mu^+ \to \bar{\nu}_\mu \xrightarrow{\text{No osc.}} \bar{\nu}_\mu \xrightarrow{\text{NSI}} e^+. \tag{8}$$

Chirality discussions about NSI effective Lagrangian

$$\mathcal{L}^{s,d}_{\text{CC-NSI}} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon^{CC}_{\alpha\beta} [\bar{\nu}_\alpha \gamma^\mu (1 \mp \gamma^5) \ell_\beta][\bar{f} \gamma_\mu (1 \mp \gamma^5) f'] + h.c.$$

	source		detector	
	superbeam	muon-decay beam	superbeam	muon-decay beam
f	d	μ/e	d	d
f'	u	ν_μ/ν_e	u	u
ν_α	ν_e,ν_μ,ν_τ	ν_e,ν_μ,ν_τ	ν_e,ν_μ,ν_τ	ν_e,ν_μ,ν_τ
ℓ_β	e/μ	e/μ	e,μ	e, μ

$$\begin{aligned}
\mathcal{L}_{\text{CC-NSI}} = & \frac{G_F}{\sqrt{2}} (\epsilon^{\mu\mp}_{e\mu})^s \{\bar{\nu}_\mu \gamma^\rho (1-\gamma^5) \nu_\mu\} \{\bar{\mu} \gamma_\rho (1 \mp \gamma^5) e\} \\
& + \frac{G_F}{\sqrt{2}} (\epsilon^{e\mp}_{e\mu})^s \{\bar{\nu}_e \gamma^\rho (1-\gamma^5) \nu_e\} \{\bar{\mu} \gamma_\rho (1 \mp \gamma^5) e\} \\
& + \frac{G_F}{\sqrt{2}} (\epsilon^{\mu\mp}_{e\mu})^d \{\bar{\mu} \gamma^\rho (1-\gamma^5) \nu_e\} \{\bar{u} \gamma_\rho (1 \mp \gamma^5) d\} \\
& + \frac{G_F}{\sqrt{2}} (\epsilon^{e\mp}_{e\mu})^d \{\bar{\nu}_\mu \gamma^\rho (1-\gamma^5) e\} \{\bar{u} \gamma_\rho (1 \mp \gamma^5) d\} + \text{h.c.}
\end{aligned}$$

$$|\nu_e^{(s)}\rangle = |\nu_e\rangle + \left\{ (\epsilon^{\mu-}_{e\mu})^s + (\epsilon^{\mu+}_{e\mu})^s \times \mathcal{O}\left(\frac{m_\mu m_e}{E_\mu E_e}\right) \right\} |\nu_\mu\rangle.$$

$$|\bar{\nu}_\mu^{(s)}\rangle = |\bar{\nu}_\mu\rangle + \left\{ (\epsilon^{e-}_{e\mu})^s + (\epsilon^{e+}_{e\mu})^s \times \mathcal{O}\left(\frac{m_\mu m_e}{E_\mu E_e}\right) \right\} |\bar{\nu}_e\rangle.$$

$$\langle \nu_\mu^{(d)}| = \langle \nu_\mu| + \left\{ (\epsilon^{\mu-}_{e\mu})^d + (\epsilon^{\mu+}_{e\mu})^d \times \mathcal{O}\left(\frac{m_u m_d}{E_u E_d}\right) \right\} \langle \nu_e|$$

$$\langle \bar{\nu}_e^{(d)}| = \langle \bar{\nu}_e| + \left\{ (\epsilon^{e-}_{e\mu})^d + (\epsilon^{e+}_{e\mu})^d \times \mathcal{O}\left(\frac{m_u m_d}{E_u E_d}\right) \right\} \langle \bar{\nu}_\mu|$$

(V-A)(V+A) NSIs suppressed by

the helicity factors $\mathcal{O}\left(\frac{m_\mu m_e}{E_\mu E_e}\right)$ and $\mathcal{O}\left(\frac{m_u m_d}{E_u E_d}\right)$