Jian Tang, Yibing Zhang
Sun Yat-Sen University, Guangzhou
Yu-Feng Li
Institute of High-Energy Physics, CAS
Emilio Ciuffoli, Jarah Evslin, Qiang Fu
Institute of Modern Physics, CAS

Based the following work:
arXiv:1705.09500 (Phys. Rev. D97(2018)035018.)
arXiv:1708.04909 (Phys. Lett. B774 (2017) 217.)
arXiv: 1801.01266 (Phys. Rev. D97(2018)113003.)

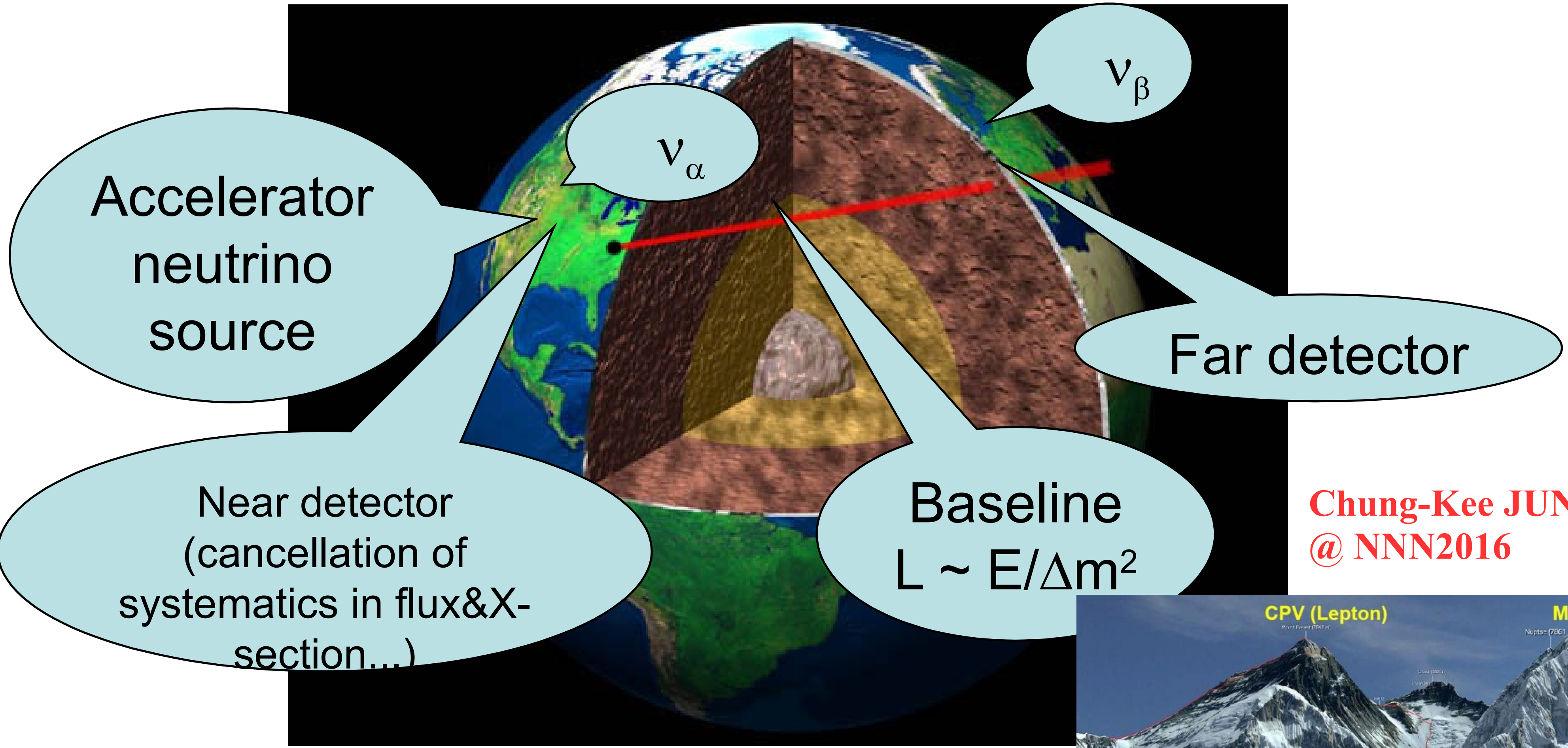
Shanghai, China
June 19th--24th, 2018

Table of Contents

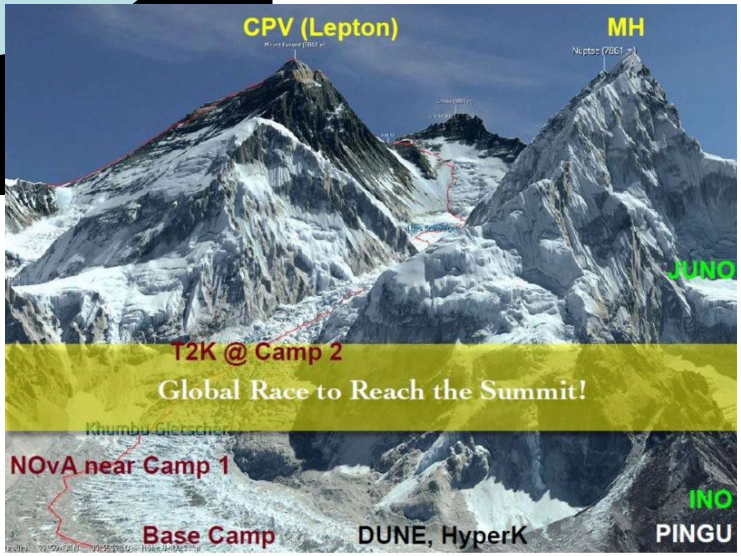
Table of Contents

- **Motivations of accelerator neutrino experiments**
- **CC-NSIs at MOMENT (MuOn decay MEdium-baseline NeuTrino beam facility)**
- **Tests of non-unitarity violation with future's accelerator neutrino facilities**
- **Neutrino Activation Analysis with accelerator neutrinos**
- **Summary**

Simulation of accelerator neutrino oscillations



Chung-Kee JUNG @ NNN2016



Neutrino physics:

1. Are there any sterile neutrinos in Nature?
2. The precise value of angles such as θ_{13} and CP phase $\delta \cdots$
3. The mass hierarchy: $\Delta\, m^2_{31} > 0$ or $\Delta\, m^2_{31} < 0$?
4. Can one determine the matter density in a high precision by neutrino oscillation in matter?
5. The existence of Non-Standard Interactions?

Survey of high-power accelerators around the world

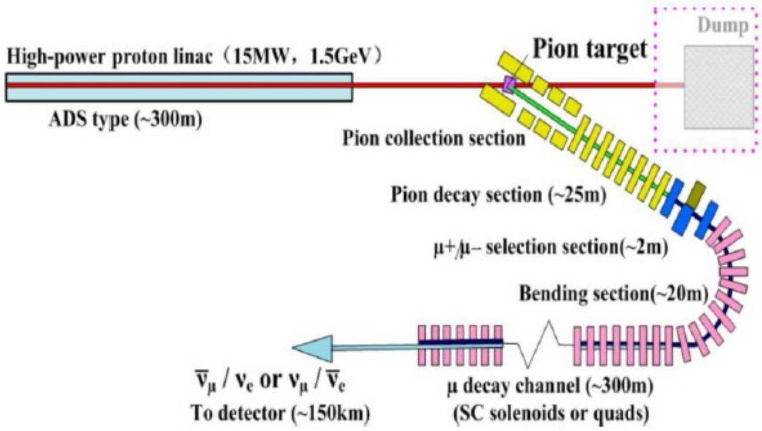
- **High-power proton accelerators are scarce resources and very expensive to construct.**
- **Should benefit as more as possible research fields**
- **Hundred-kW beams mostly available now, energy range from 0.5 to 450 GeV**
- **MW beams:**
  - **two in 1-1.5 MW in operation (PSI, SNS)**
  - **one to reach the design goal 1-MW (J-PARC/RCS)**
  - **one 5 MW under construction (ESS)**
  - **one to start construction soon (CiADS, 2.5 MW)**
  - **two to upgrade: 2.4 MW (FNAL/PIP-II), 1.3 MW (J-PARC/MR)**

Table of Contents

- Motivations of neutrino oscillation experiments
- Physics study at International Study of Neutrino Factory
- **CC-NSIs at MOMENT (MuOn decay MEdium-baseline NeuTrino beam facility)**
- Tests of non-unitarity violation with future's accelerator neutrino facilities
- Neutrino Activation Analysis with accelerator neutrinos
- Summary

(Muon-decay MEdium baseline NeuTrino beam facility)

- MOMENT: the proposal is still in an early stage ; the details have not been completely fixed.



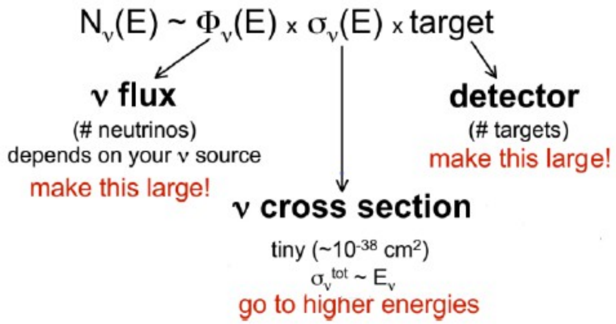
- Peak energy: 200 MeV

  Neutrino energy range: 100MeV—800MeV

  - The lower beam energy at ~ 300 MeV: free from pi0 background

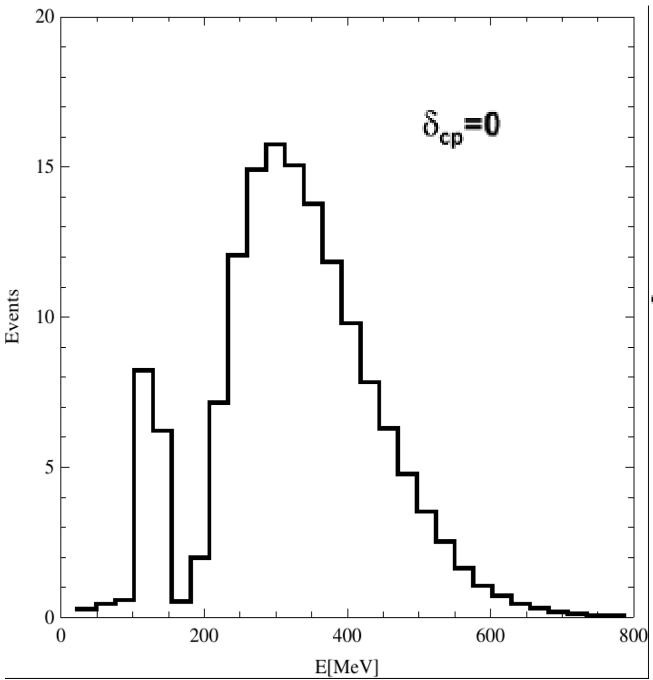
- Baseline: L=150 km

In the MOMENT: the neutrino flux peak at low energies ➡ require a very massive detector to compensate the low interaction cross section

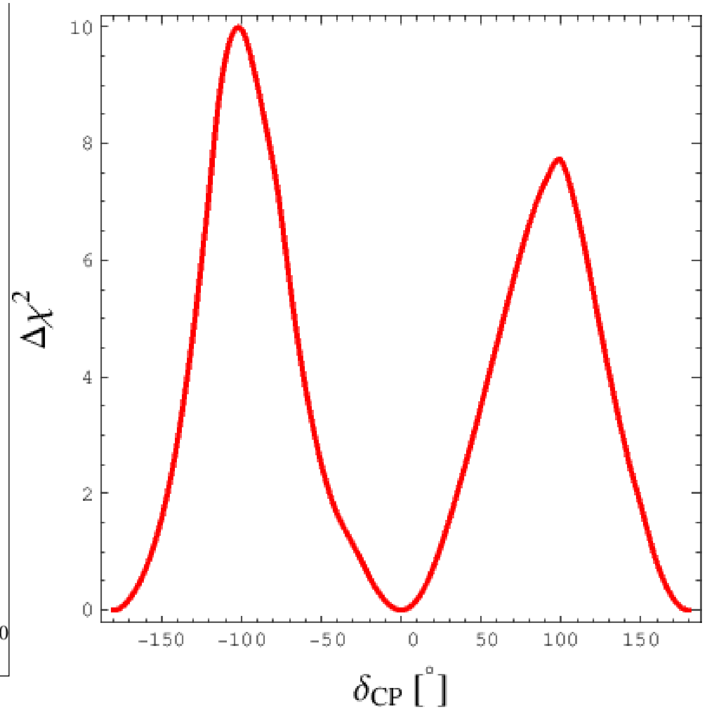


Updates of CPV sensitivity

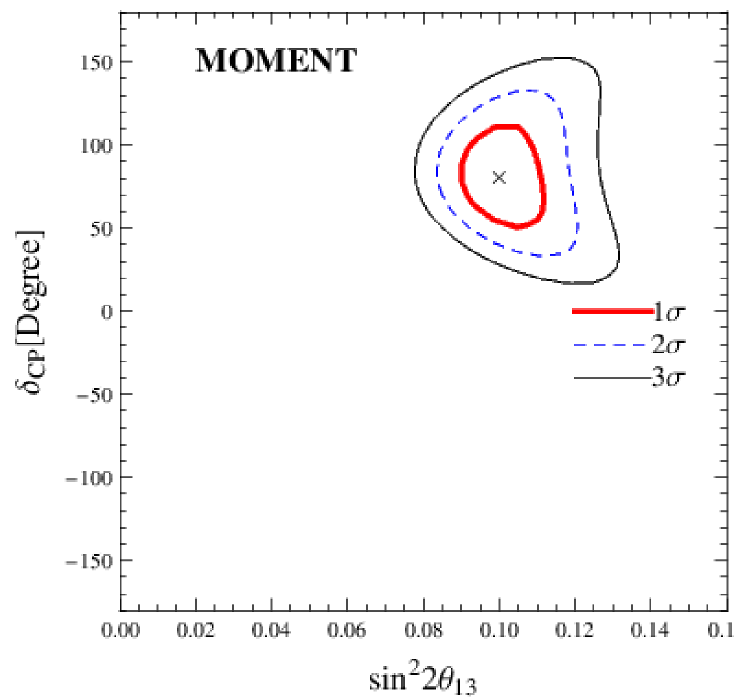
- Neutrino fluxes and detector info inherited from Miao He& Jiashu Lu
- Loss of CPV by a factor of 2 after including both systematic and statistic uncertainties
- All backgrounds highly suppressed, especially atmospheric bckgs!



Detected neutrino spectra



Discovery of CPV

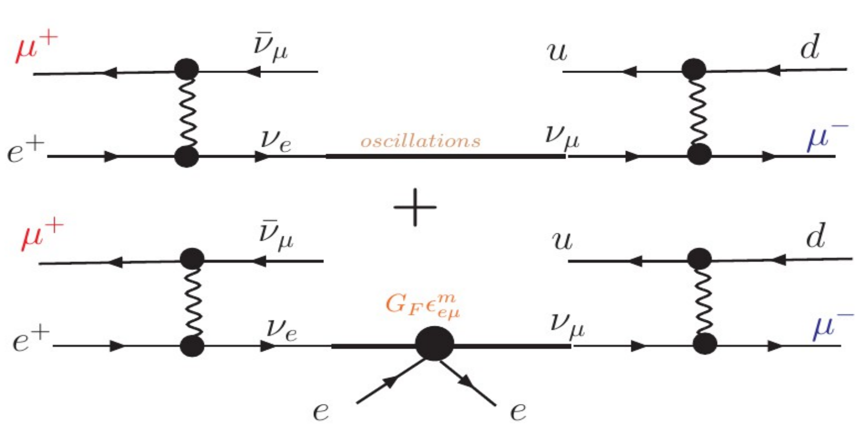


Precision measurements

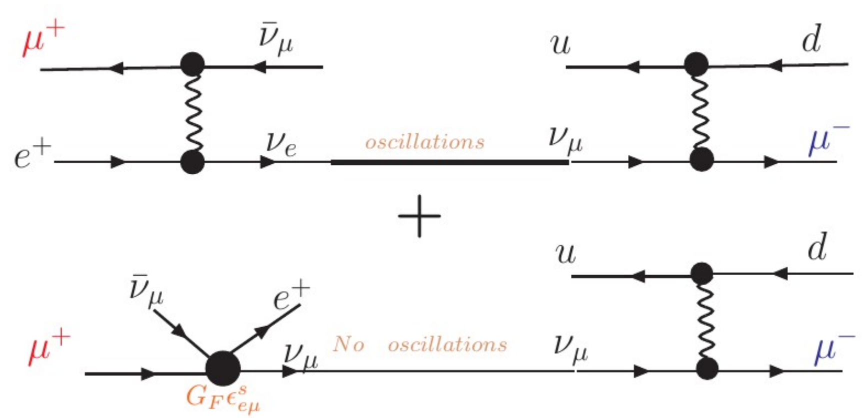
- **First physics study performed by Pilar, Matthias and Erique in arXiv:1511.02859**
- **NC-NSIs in matter considered by Pouya and Yasaman in arXiv: 1602.07099**

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:
  $\mathrm{L_{eff}} = 2\sqrt{2}\, G_F\, (\epsilon^{L/R})^{\alpha\gamma}_{\beta\delta}\ (\bar{\nu}^\beta \gamma^\rho \mathrm{P}_L \nu_\alpha)\ (\bar{\ell}^\delta \gamma^\rho \mathrm{P}_{L/R} \ell_\gamma)$

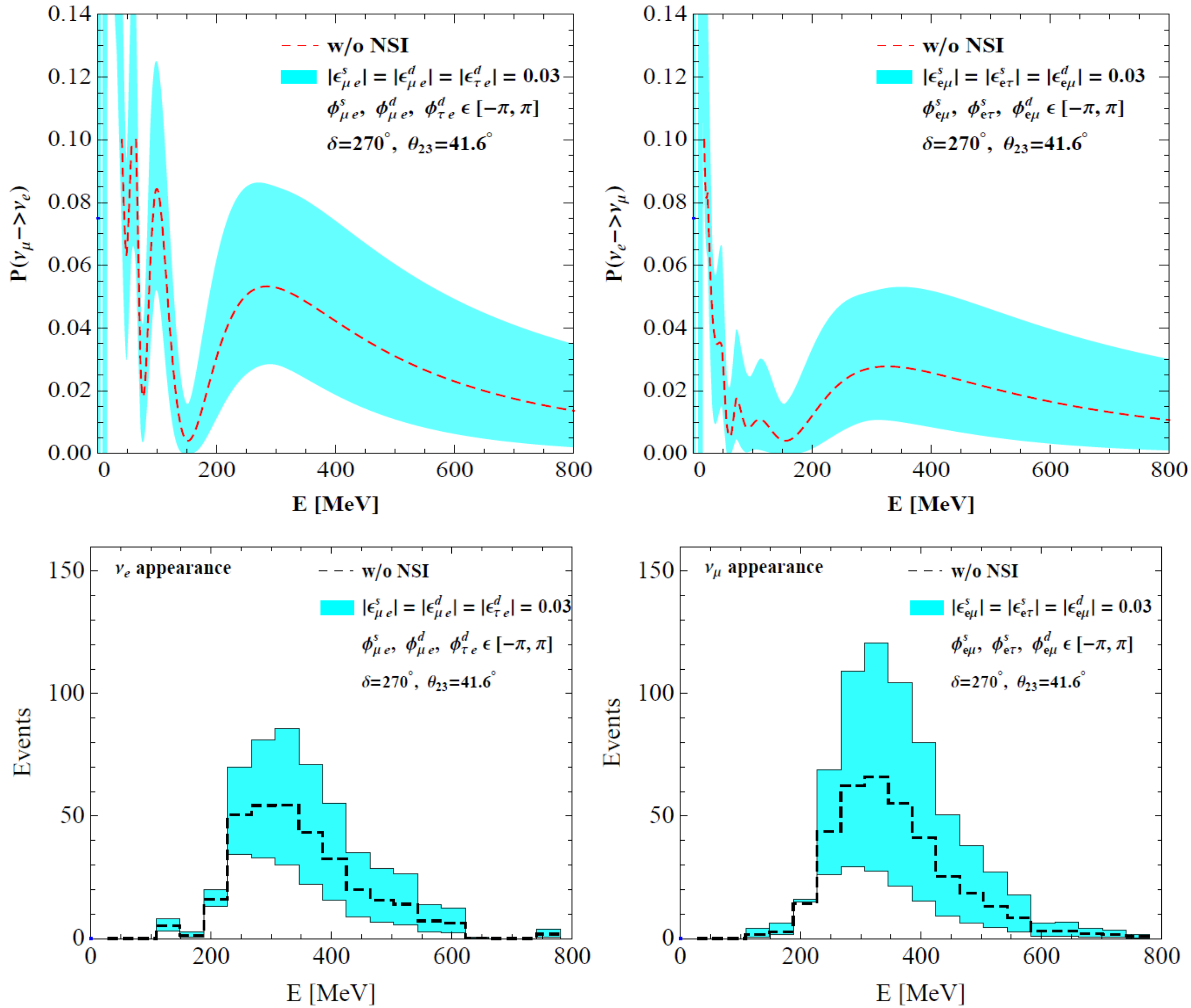


NSI happens to neutrino propagation in matter

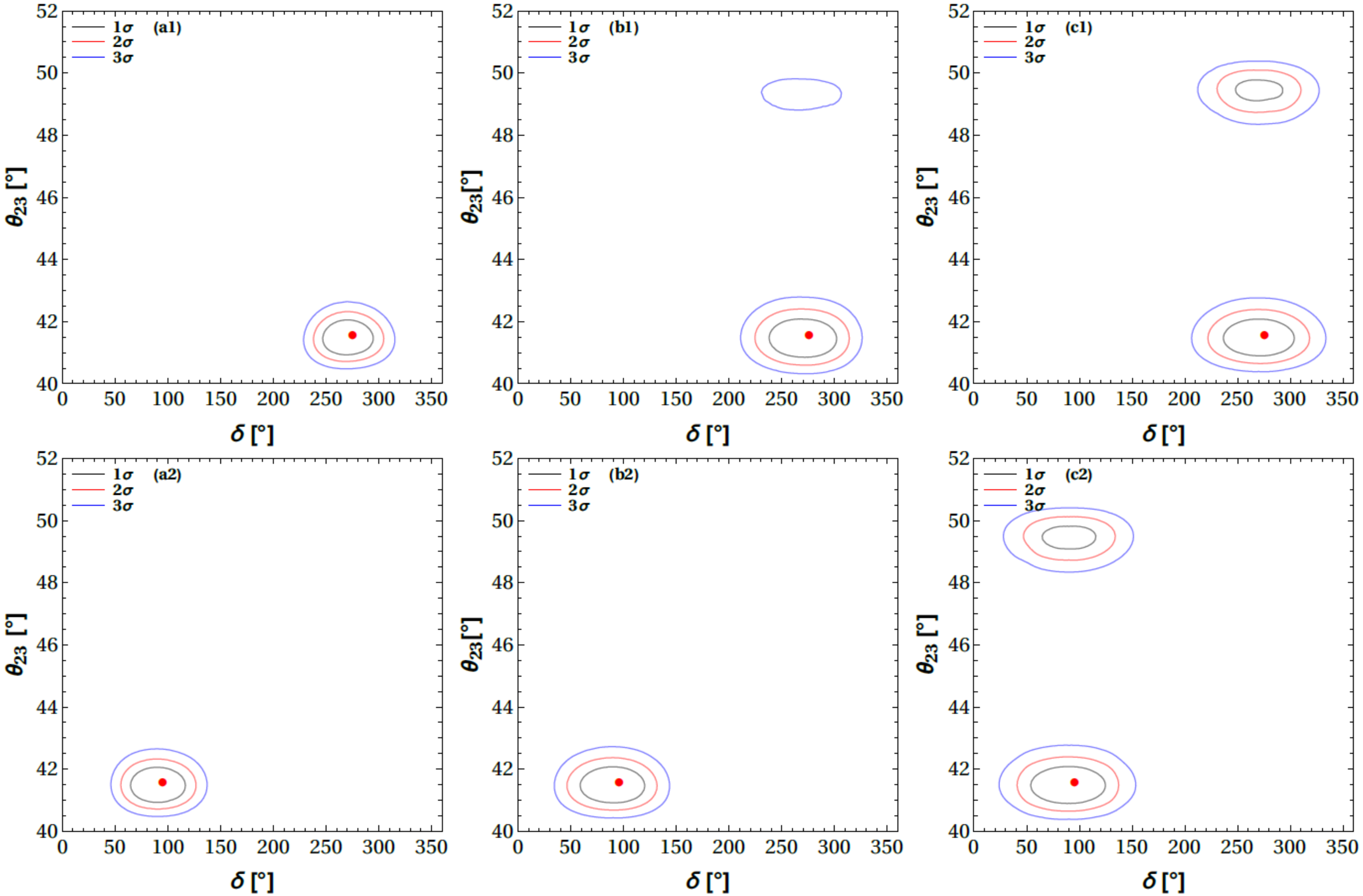


NSI at neutrino productions

Numerical tests of oscillation probabilities and events at MOMENT



Impacts on precision measurements by CC-NSIs



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

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.**

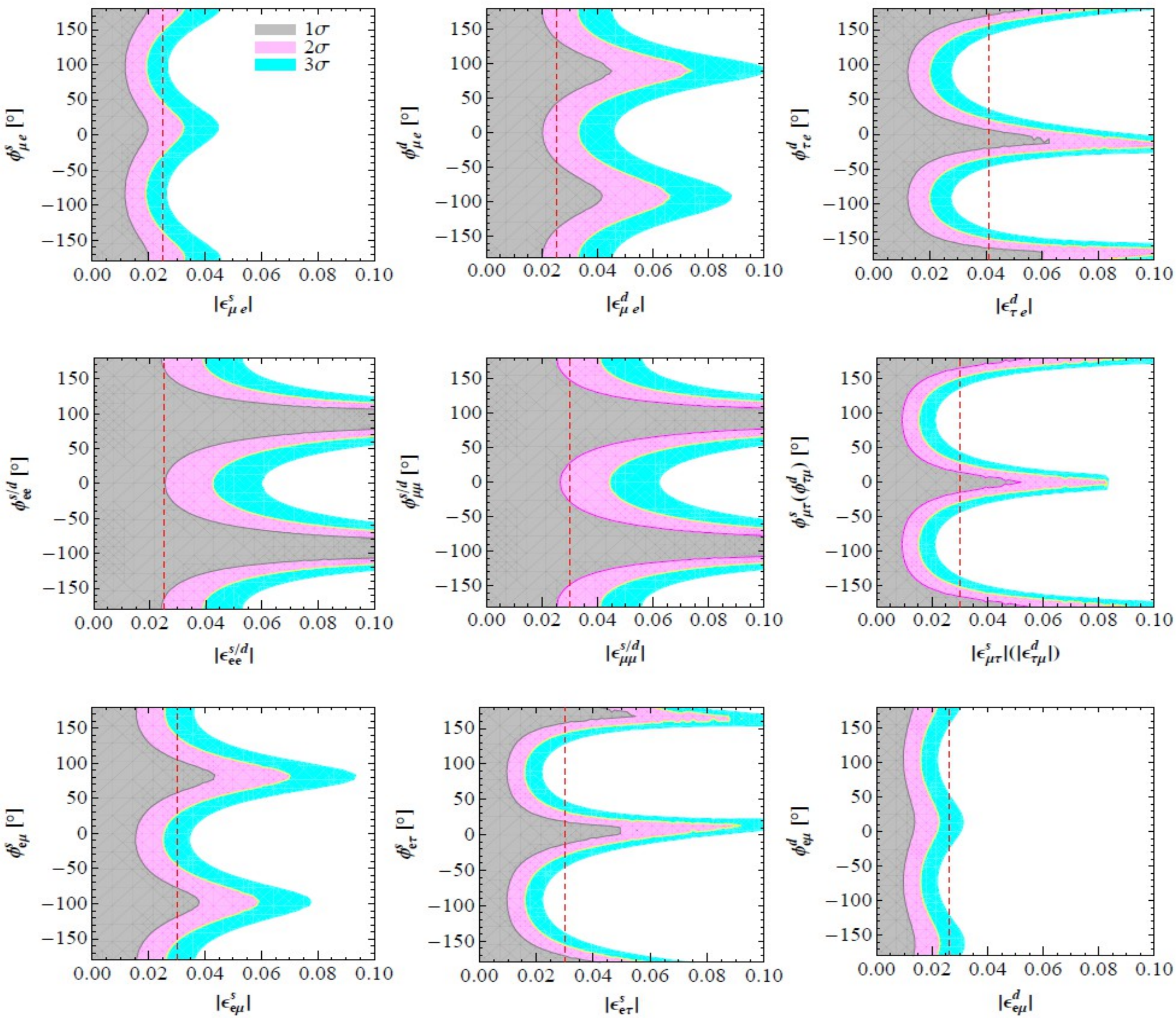
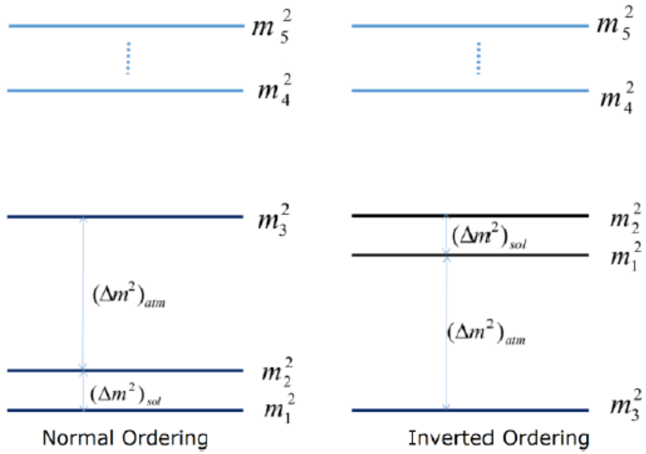


Table of Contents

Tests of unitarity violation

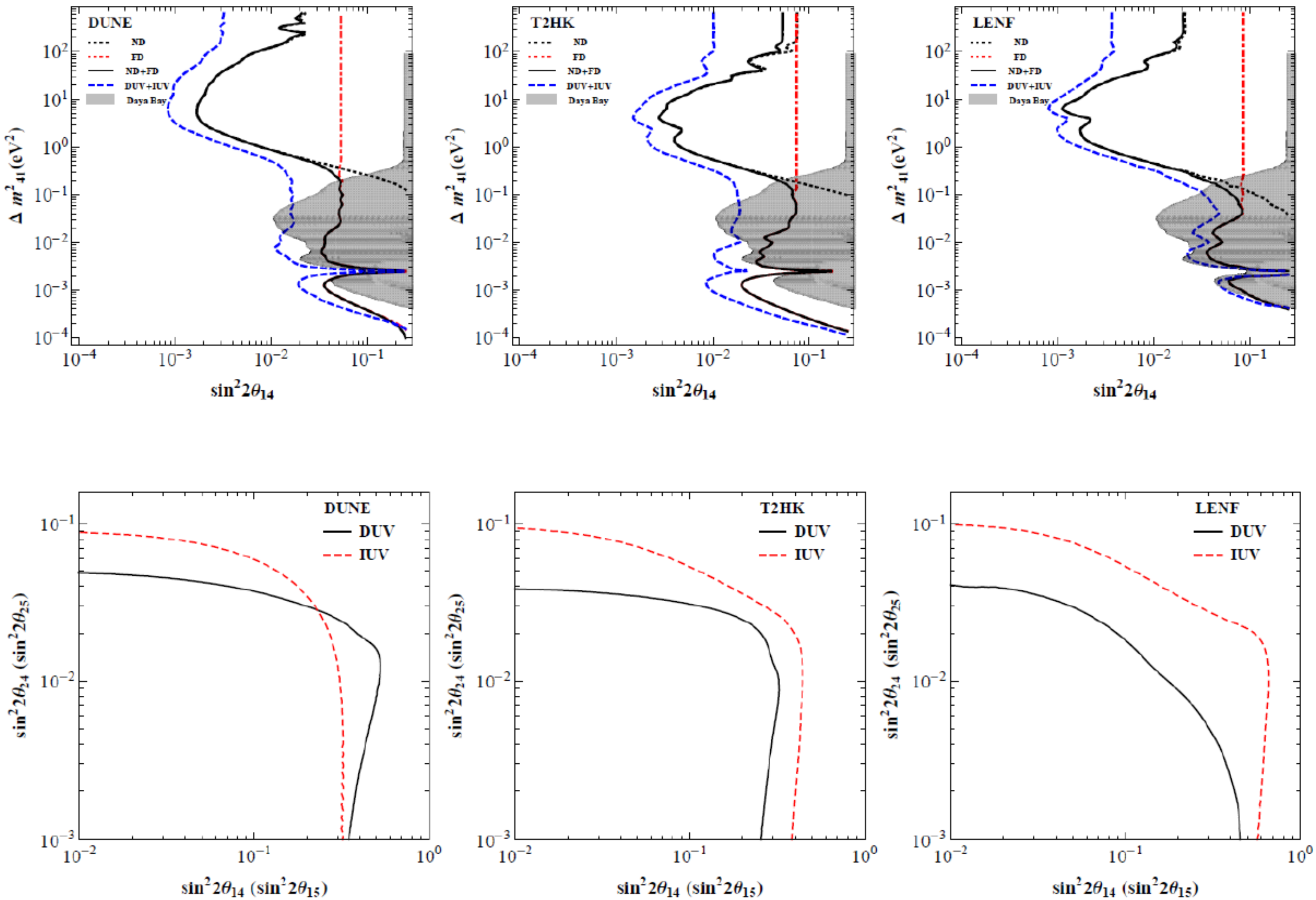
- Light sterile neutrino anomaly (eV scale)
- Heavy sterile neutrinos from see-saw model (GeV scale)
- Dark matter candidate (keV scale)
- IUV (indirect unitary violation) by heavy sterile neutrinos
- DUV (direct unitary violation) by light sterile neutrinos: oscillation with active ones



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- Simplifying the mixing matrix to deal with DUV and IUV, Phys. Lett., B718:1447-1453, 2013
- Pertubation study of oscillation probabilities for DUV and IUV, Phys. Rev., D93(3):033008

Exclusion limits on mixing parameters with non-unitarity



The limits to new paramerters induced by the DUV and IUV effects

Impacts on precision measurements

- IUV can only induce rate correlations to the three neutrino oscillation, but DUV contributes both rate and spectrum signatures to the experimental measurements.

- The DUV generally does not cause degeneracies for theta23.

- The IUV effects would cause degeneracies for theta23 in DUNE and T2HK. Thus we can turn to the most powerful experiment LENF to solve this problem;

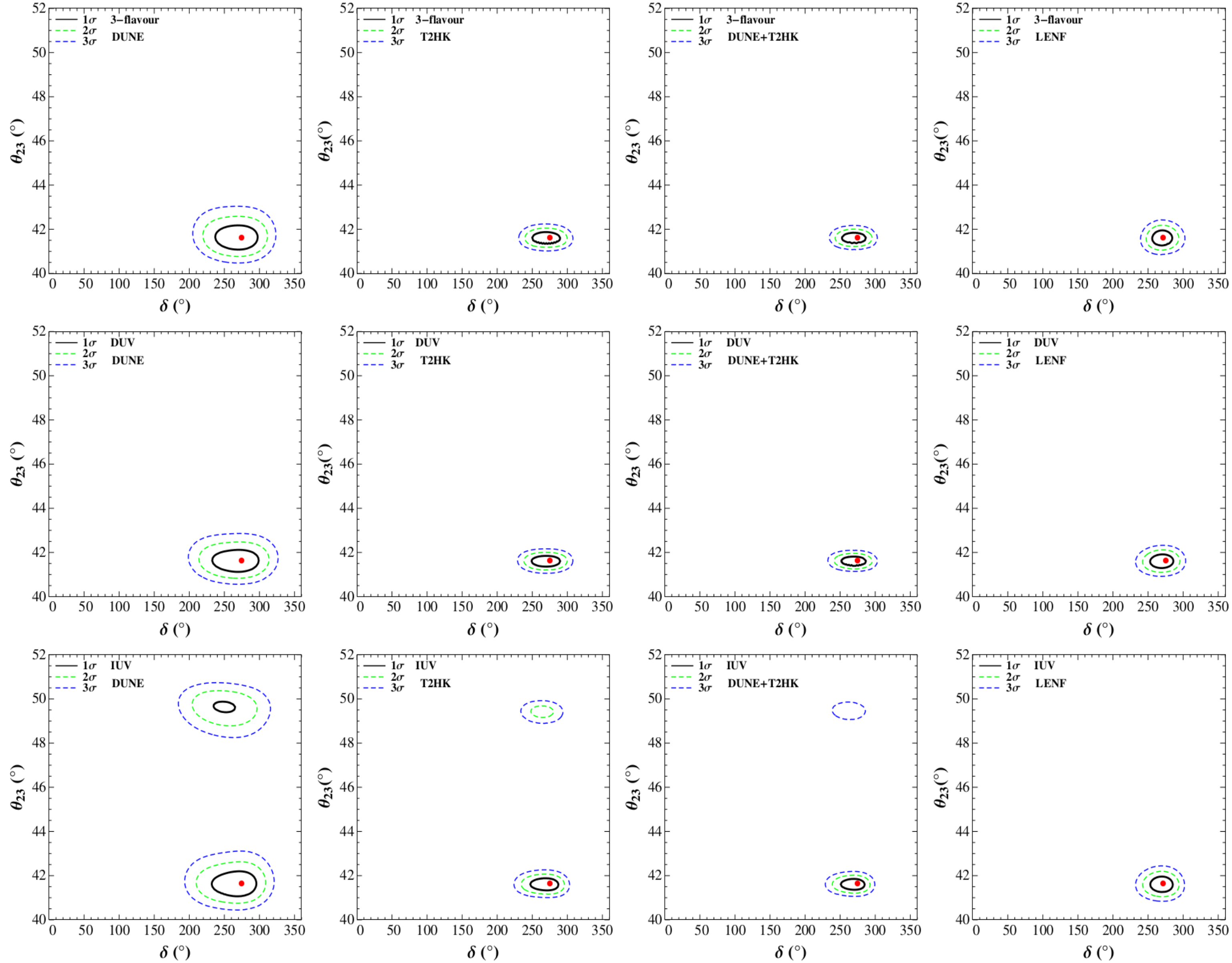


Table of Contents

- Motivations of neutrino oscillation experiments
- Physics study at International Design of Neutrino Factory
- CC-NSIs at MOMENT (MuOn decay MEdium-baseline NeuTrino beam facility)
- Tests of non-unitarity violation with future's accelerator neutrino facilities
- **Neutrino Activation Analysis with accelerator neutrinos**
- Summary

Neutrino-nucleus coherent scatterings

Science

REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

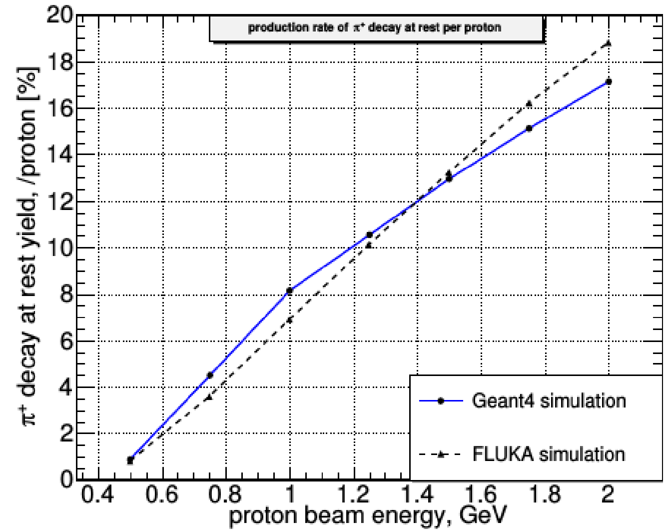
D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

- **Progress of low-threshold DM detectors made it come true.**
- **What else can we do with CEvNS?**

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_F^2[N - (1 - 4\sin^2\theta_w)Z]^2 F^2(Q^2) M^2}{4\pi} \times \frac{1}{M}\left(1 - \frac{E_r}{E_{max}}\right)$$

- **CEvNS is proportional to the number of neutrons in the nucleus.**
- **Nuclear effects are factorized in the form factor: a transformation of the density distribution**

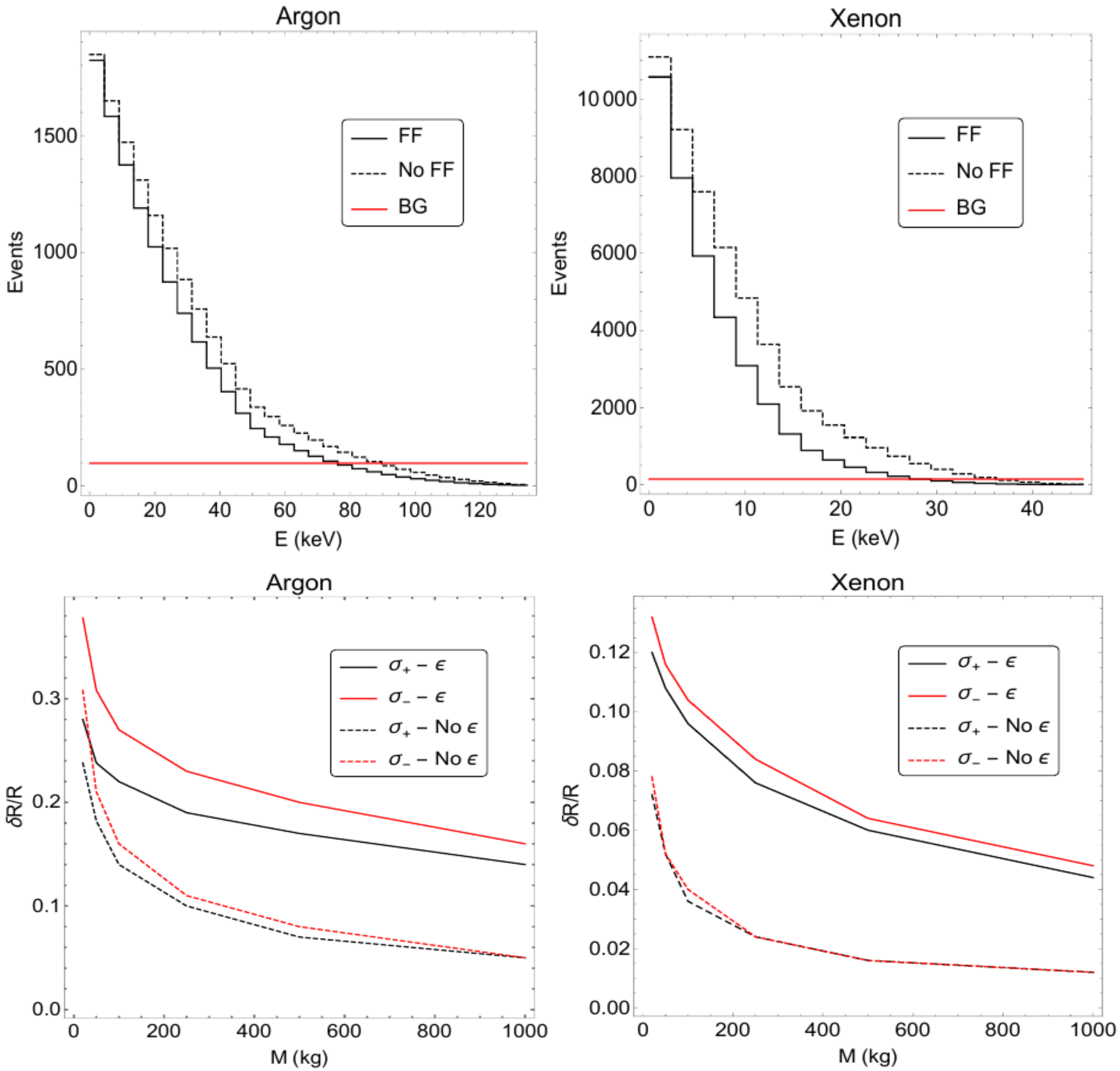
$$F(Q^2) = \frac{1}{Q_w}\int [\rho_n(r) - (1 - 4\sin^2\theta_w)\rho_p(r)] \frac{\sin(Qr)}{Qr} r^2 dr$$



- **Lots of proton accelerators around the world.**
- **Use CEvNS to measure the nuclear structure while it is complementary to CC-scatterings?**
- **Which kind of detector can do the job?**
- **What are requirements to measure the nuclear structure?**

LAr and LXe TPC

- **Learn from DM detection experiments: LAr and LXe TPC.**



- Threshold is the key
- Beam-related backgrounds: timing structures
- Cosmic-induced backgrounds: passive and active vetos

- A ton-scale detector reaches the sub-percent precision of the neutron radius in the nucleus.
- LXe TPC is doing better given the same fiducial mass.
- Good to distinguish nuclear physics models.

Table of Contents

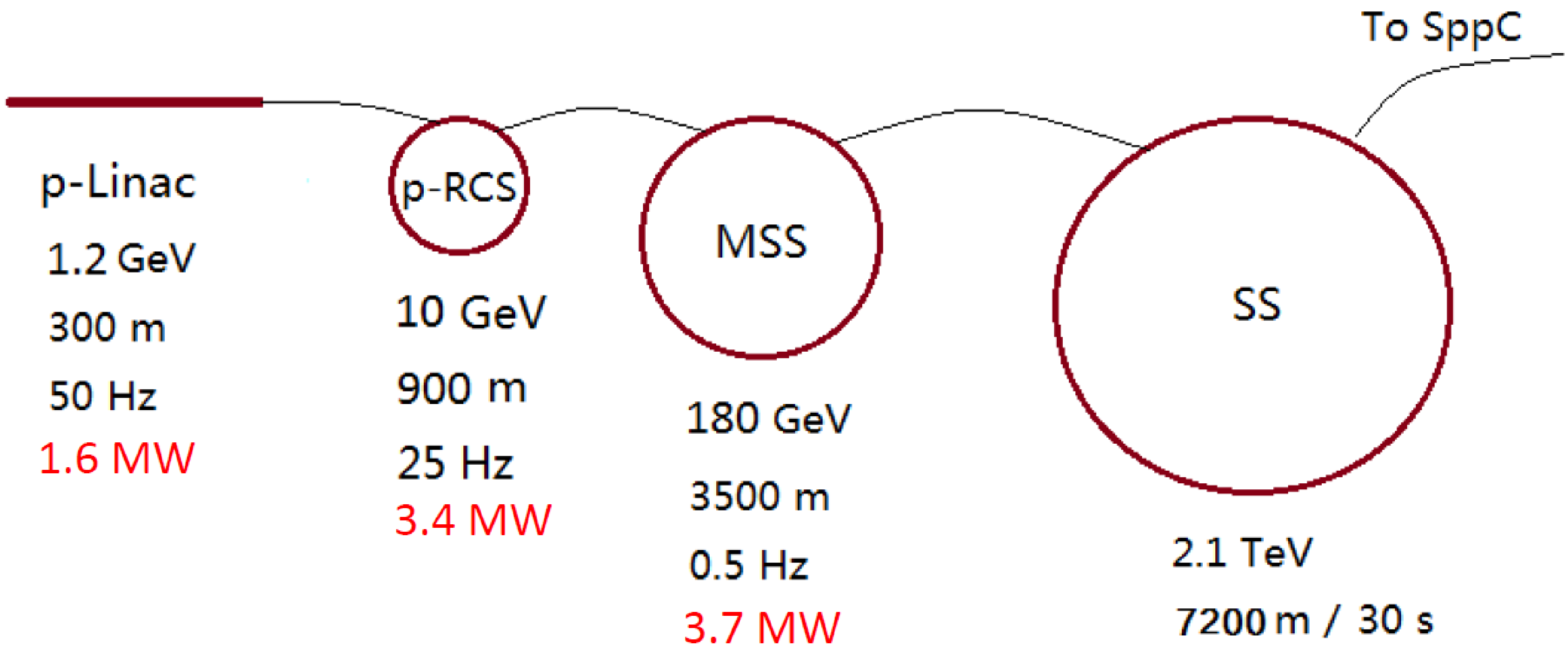
- Motivations of neutrino oscillation experiments
- Physics study at International Study of Neutrino Factory
- CC-NSIs at MOMENT (MuOn decay MEdium-baseline NeuTrino beam facility)
- Tests of non-unitarity violation with future's accelerator neutrino facilities
- New physics related to accelerator neutrinos in progress
- **Summary**

Summary

- **Lots of physics to be done with accelerator neutrinos.**
- **CC-NSI study at MOMENT.**
- **Probe of the direct and indirect unitarity violations at future accelerator neutrino facilities.**
- **Neutrino activation analysis to probe the nuclear structure.**
- **Welcome to work together on new physics searches.**

Thanks for your attention!

SPPC proton driver for neutrino physics



Very powerful injector beams to support rich physics programs including neutrino physics

- Three proton beams in MW level: 1.2 GeV, 10 GeV, 180 GeV