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Many thanks to my collaborators:
Yibing Zhang, Tse-Chun Wang(SYSU),
Yu-Feng Li(IHEP, China), Gui-Jun Ding(USTC),
Emilio Ciuffoli, Jarah Evslin, Qiang Fu(IMP, China)

Mostly based on 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)

Jinan University, Shandong province, China
Sep. 14th--16th, 2018

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- **Motivations of accelerator neutrino experiments**
- **CC-NSIs at MOMENT**
- **Tests of non-unitarity violation with future's accelerator neutrino facilities**
- **Neutrino Activation Analysis with accelerator neutrinos**
- **Summary**

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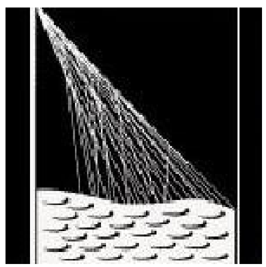
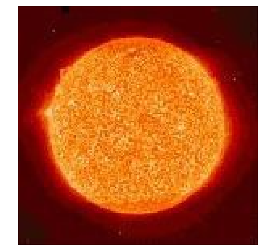
Status of neutrino mixings

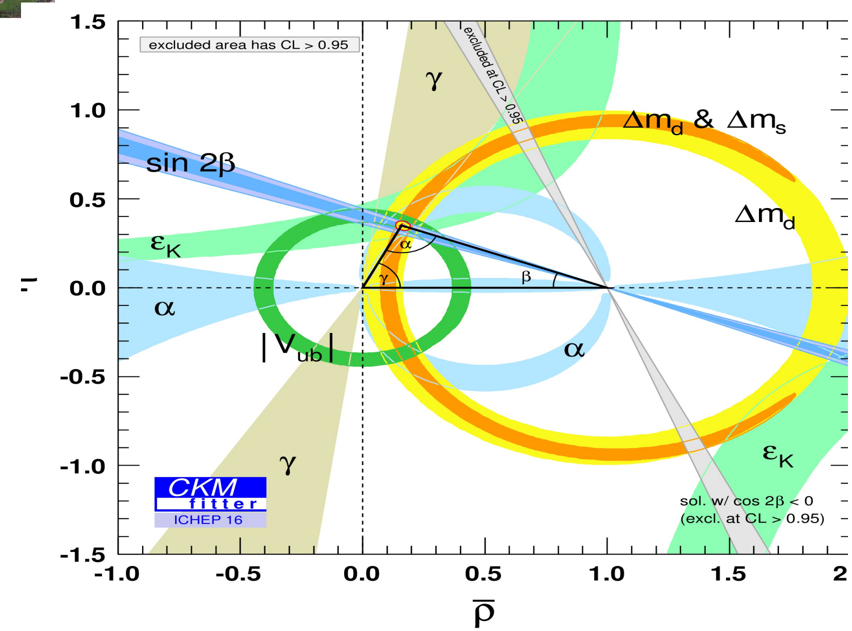
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

= () x (

) x ()

Parameter	Value	Precision (%)
Δm^2_{21}	$7.37\ 10^{-5}$ eV^2	2.3
θ_{12}	34°	5.8
Δm^2_{32}	$2.52\ 10^{-3}$ eV^2	1.6
θ_{23}	42°	~9
θ_{13}	8.4°	4

Capozzi et al. PRD 95, 096014 (2017)



- Not precise enough!
- Can we achieve the level similar to CKM?

- Sub-percent level in CKM.

Oscillation probability in a perturbative expansion

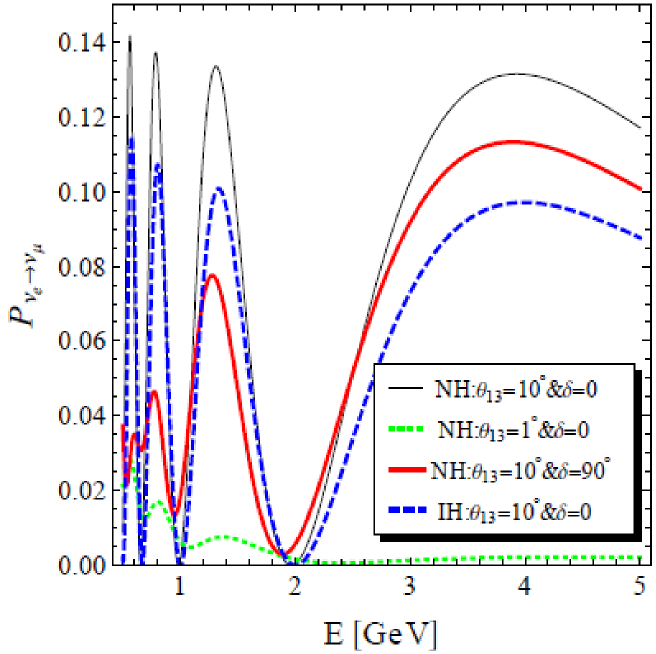
$$\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}\,, \quad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E}\,, \quad A \equiv \frac{VL}{2\Delta}$$

$$P_{\nu_e \to \nu_\mu} =$$

$$+\,4\, s_{13}^2 s_{23}^2 \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

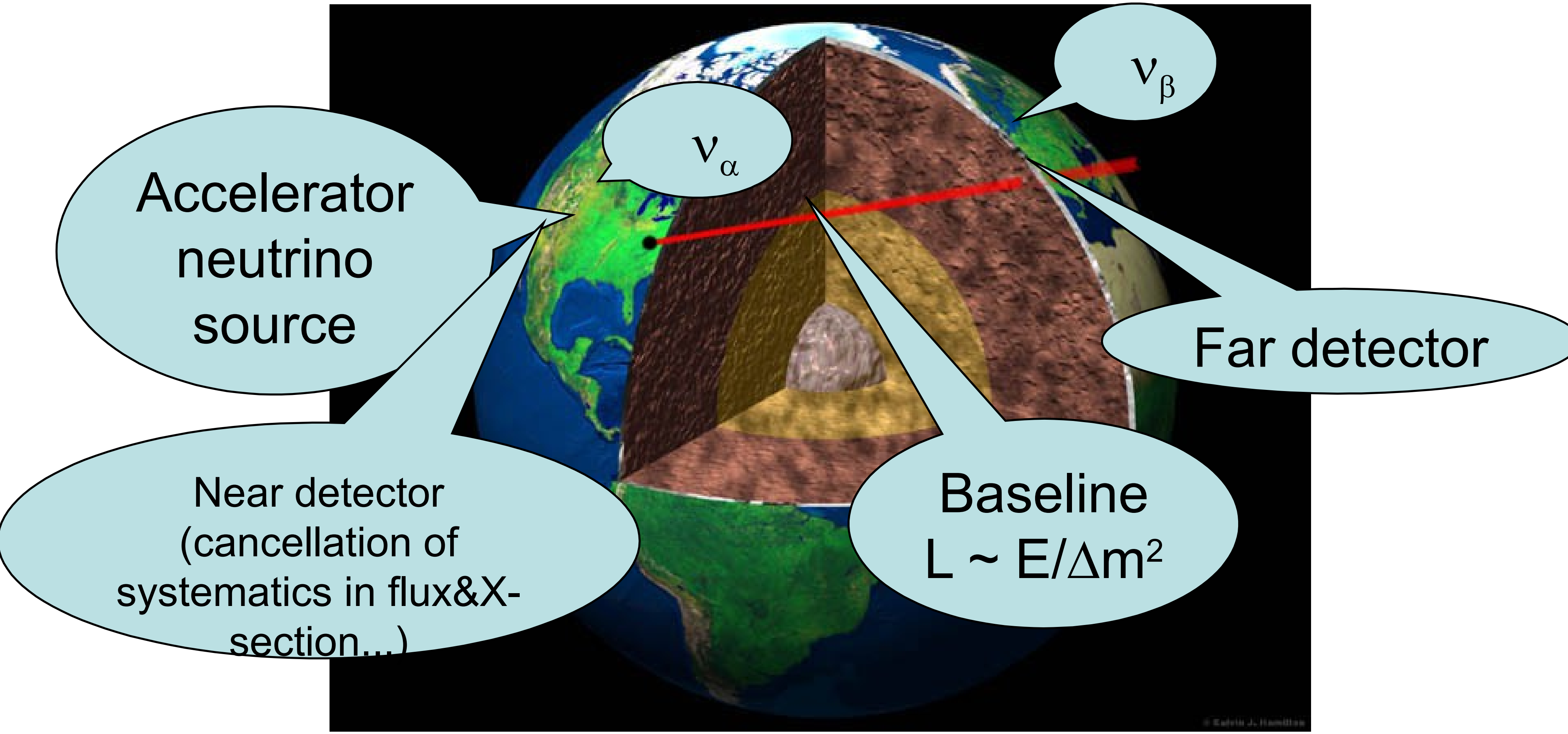
$$+\,\alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta - \delta_{\rm CP}) \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1}$$

$$+\,\alpha^2 \sin^2 2\theta_{12}\, c_{23}^2 \frac{\sin^2 A\Delta}{A^2}$$



- θ_{13} controls the amplitude.
- $\delta_{\rm CP}$ is a low energy effect.
- MH is determined in the high energy part.
- Degeneracies could appear due to the property of trigonometric functions.

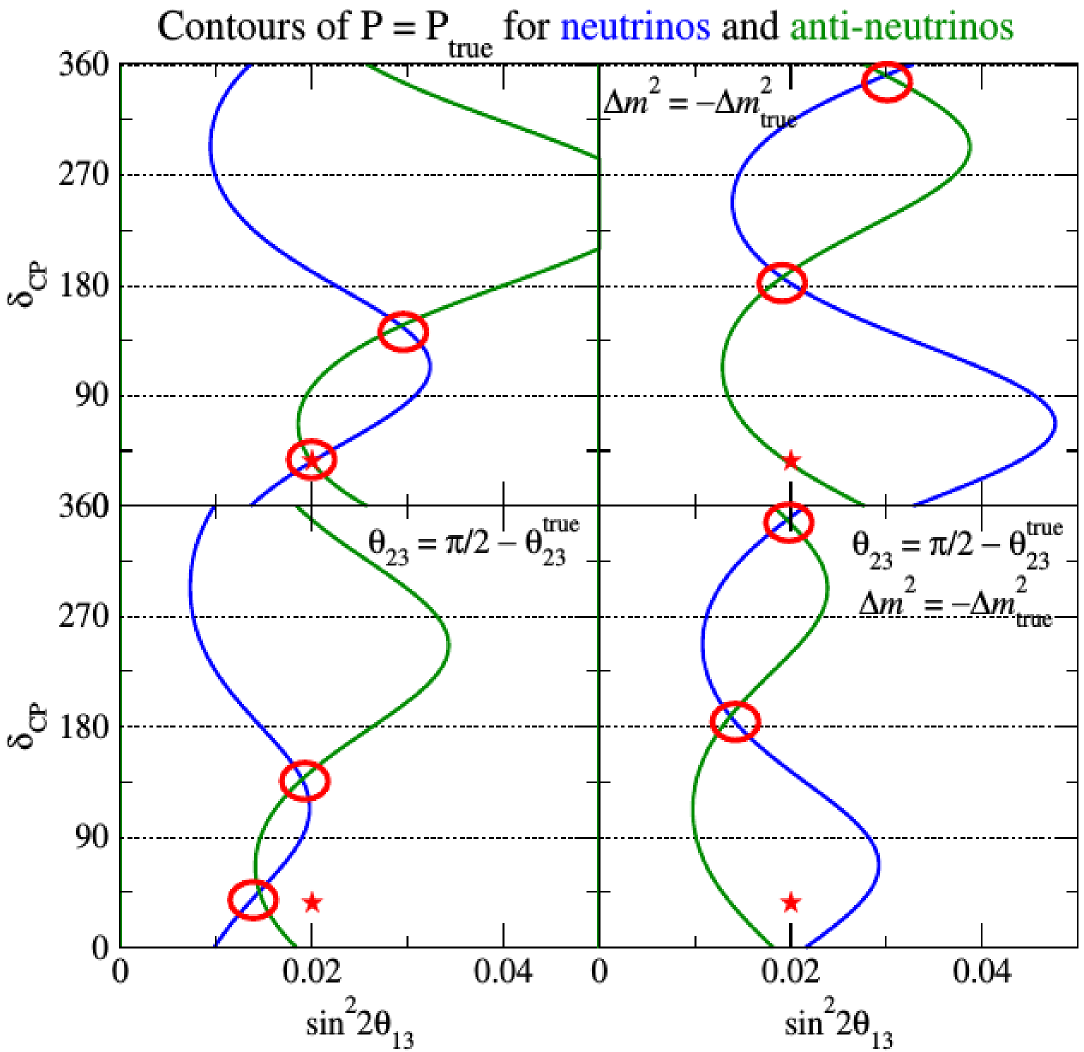
Principle of accelerator neutrino oscillations



- Source types and spectra
- Matter density profiles
- Cross sections
- Detector properties: efficiencies, resolutions, backgrounds ...
- Systematical uncertainties

The eight-fold degeneracy Barger, Marfatia, Whisnant, PRD 02

$$P(\bar{\theta}_{13},\bar{\delta},|\Delta m^2_{31}|,\theta_{23}) = P(\theta_{13},\delta,|\Delta m^2_{31}|,\theta_{23})$$
$$P(\bar{\theta}_{13},\bar{\delta},-|\Delta m^2_{31}|,\theta_{23}) = P(\theta_{13},\delta,|\Delta m^2_{31}|,\theta_{23})$$
$$P(\bar{\theta}_{13},\bar{\delta},|\Delta m^2_{31}|,\pi/2-\theta_{23}) = P(\theta_{13},\delta,|\Delta m^2_{31}|,\theta_{23})$$
$$P(\bar{\theta}_{13},\bar{\delta},-|\Delta m^2_{31}|,\pi/2-\theta_{23}) = P(\theta_{13},\delta,|\Delta m^2_{31}|,\theta_{23})$$



- ambiguities in determination of θ_{13} and δ_{CP}
- can involve an ambiguity between CP conserving and CP violating values of δ_{CP}
- sign(Δm^2_{31}) is not determined (neutrino mass ordering)
- the octant of θ_{23} is not determined

- Suppose a given experiment divides the range of observation into N bins. The outcome is reported in number of observed events in each bin n_i.

  (Expect Poisson distribution for the number of events in each bin.)

- For given oscillation parameters

$$\boldsymbol{\theta} = (\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\rm CP}, \Delta m^2_{21}, \Delta m^2_{31}) \qquad (P = 6)$$

  we can predict the expected number of events per bin $\mu_i(\boldsymbol{\theta})$.

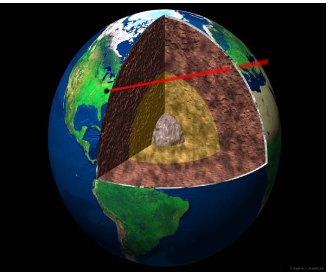
- Build a χ^2, e.g.

$$\chi^2(\boldsymbol{\theta}) = \sum_{i=1}^{N} \left[\frac{\mu_i(\boldsymbol{\theta}) - n_i}{\sigma_i} \right]^2$$

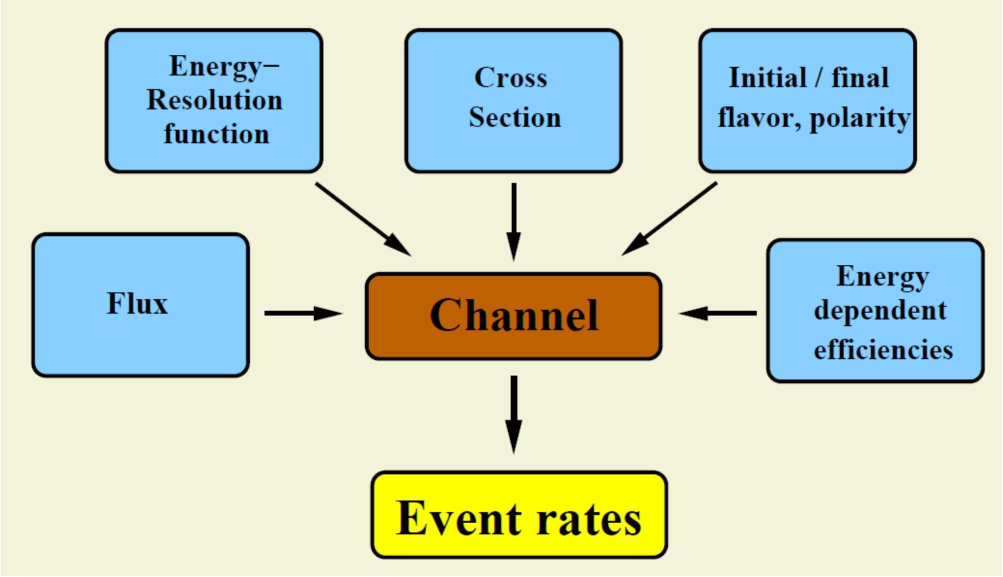
- Use $\chi^2(\boldsymbol{\theta})$ to perform a statistical analysis

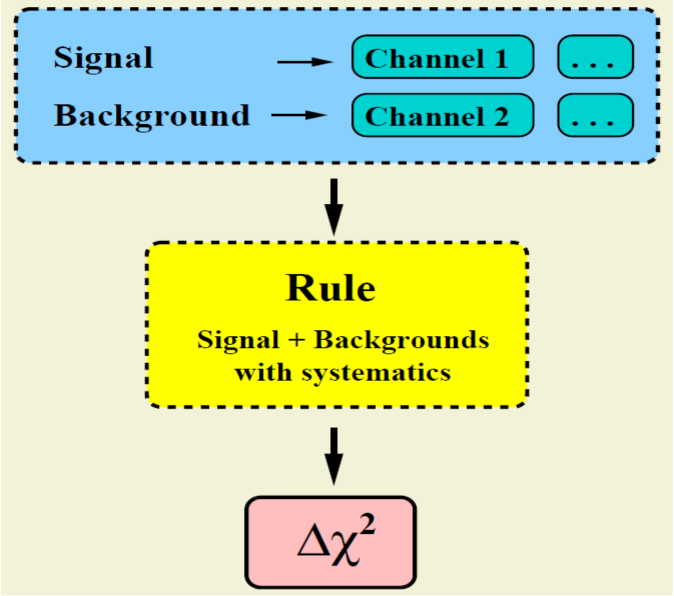
Ref: lectures given by T. Schwetz

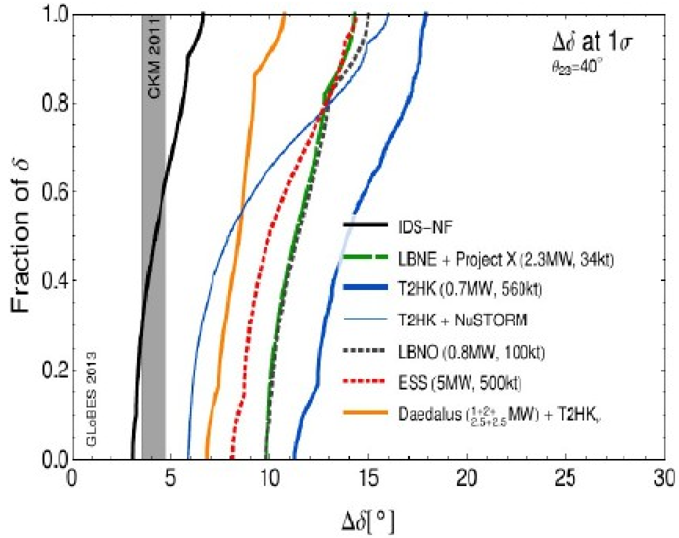
Simulations of neutrino oscillations w/o new physics



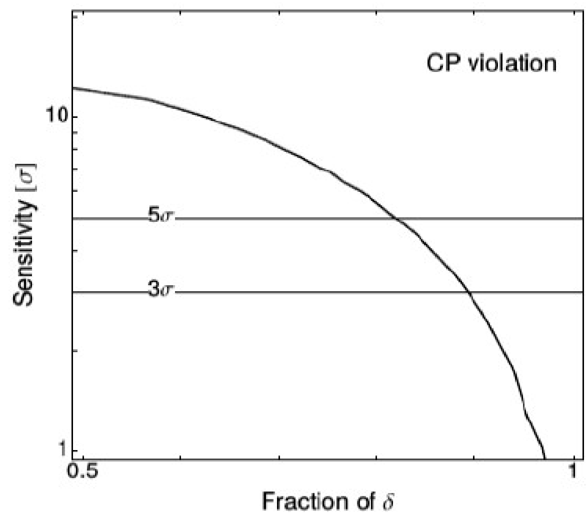
Credits:
J. Kopp



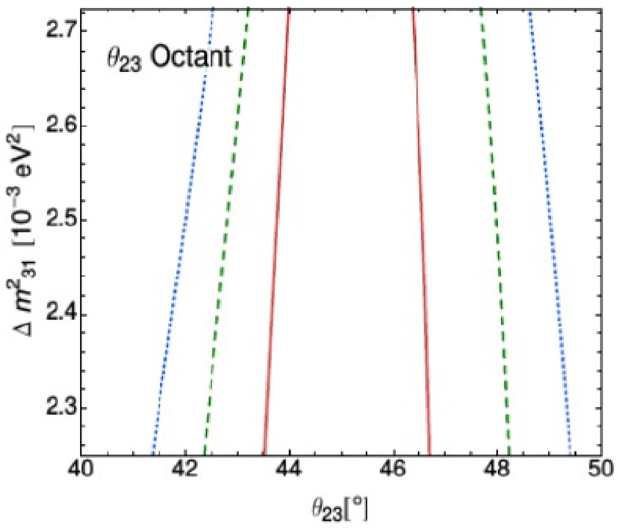




Global comparison

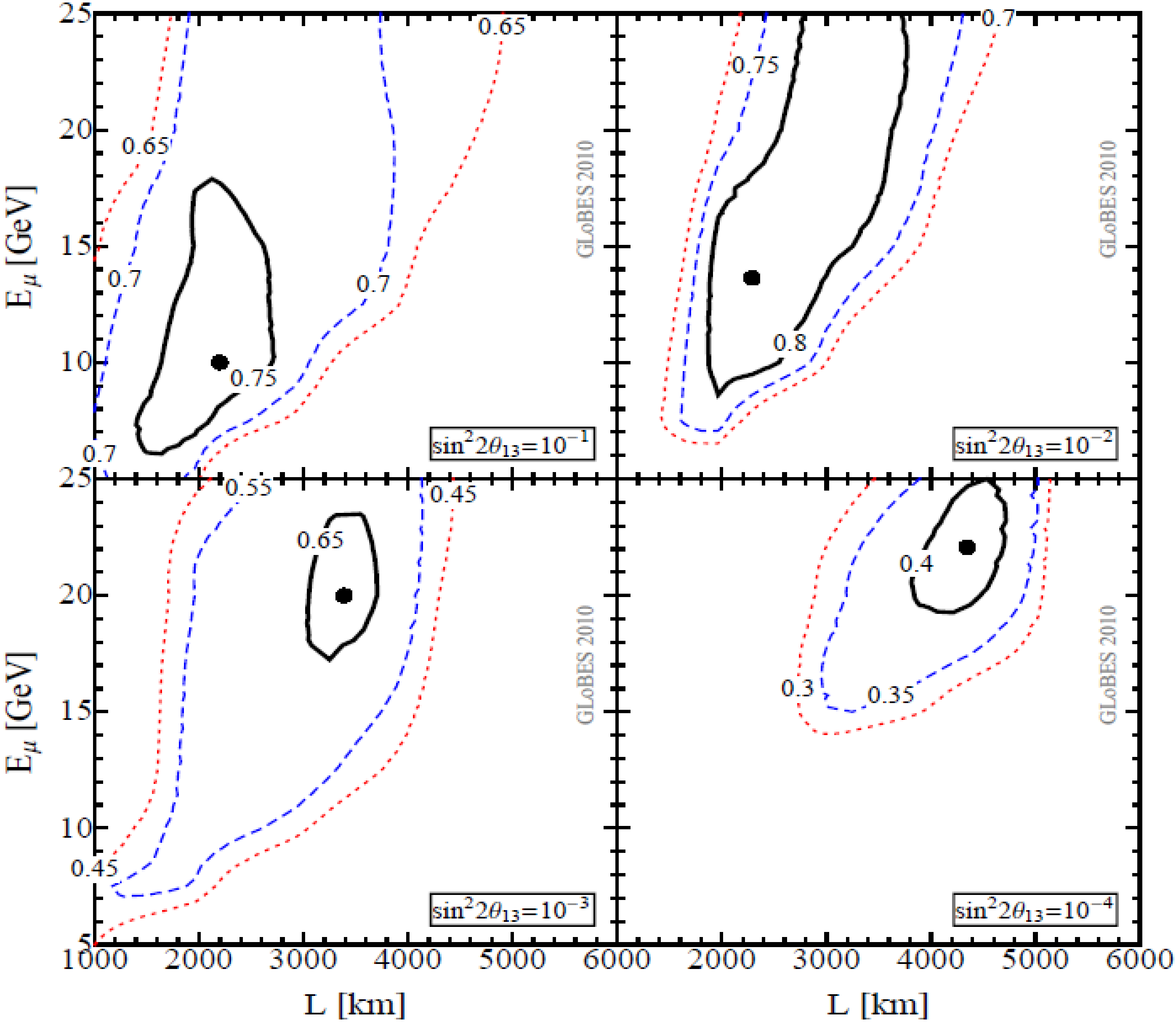


Discovery reach of CPV



Octant sensitivity

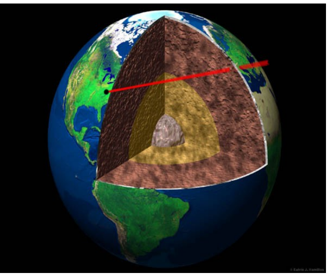
Optimization of the beam energy and baseline



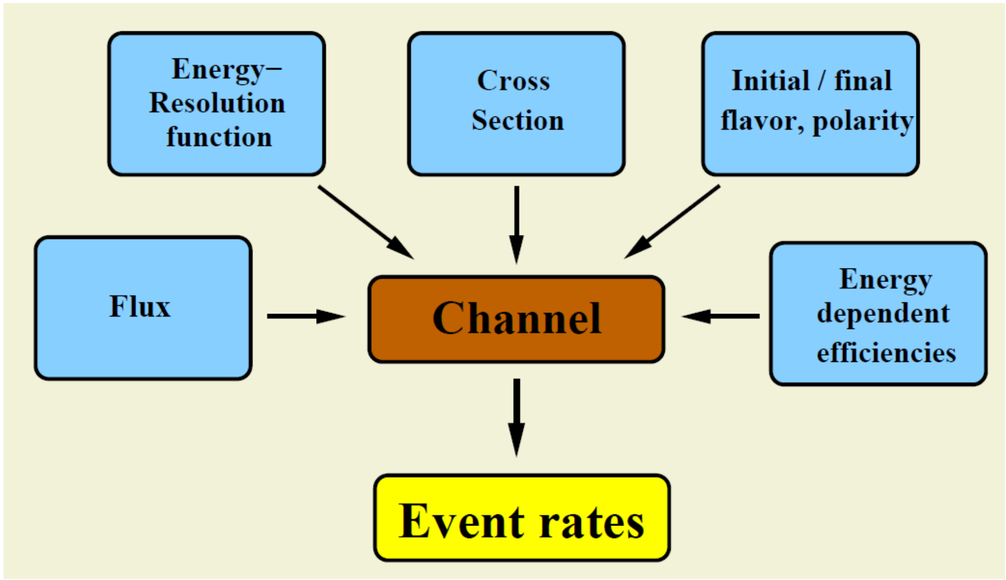
Main physics performance indicator: CPV at 3 sigma

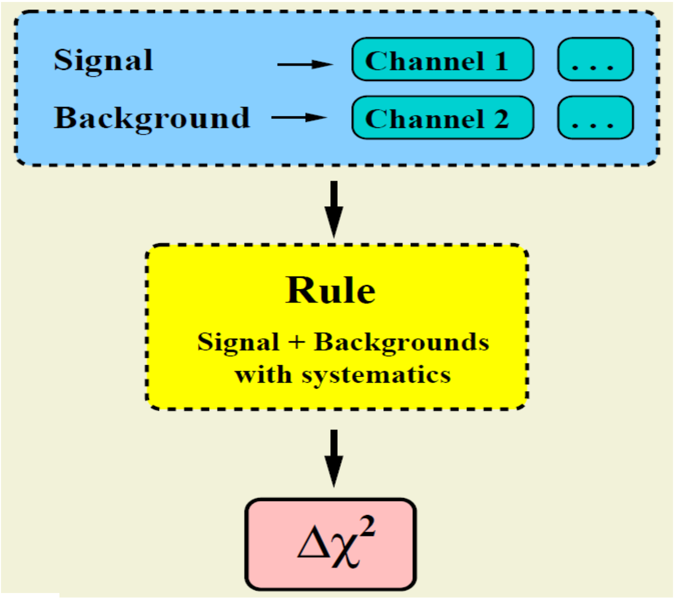
Ref: SA, PH, JT, WW
JHEP 1101 (2011) 120

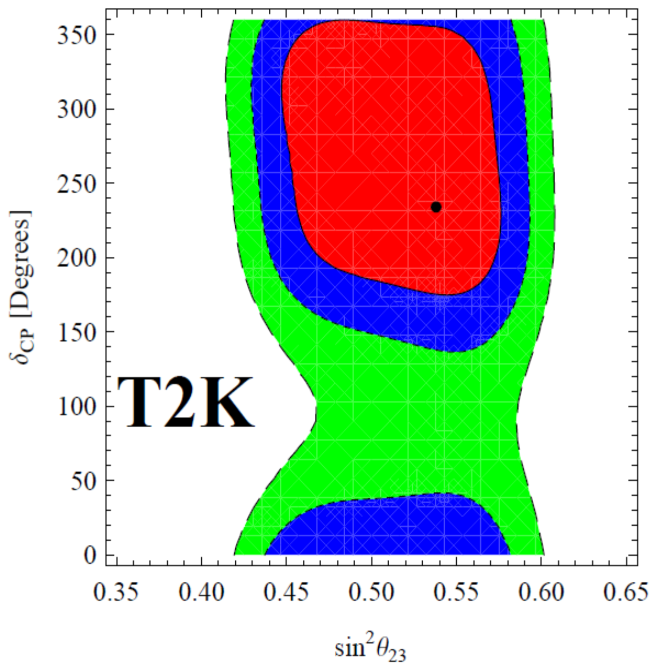
Simulations of neutrino oscillations w/o new physics

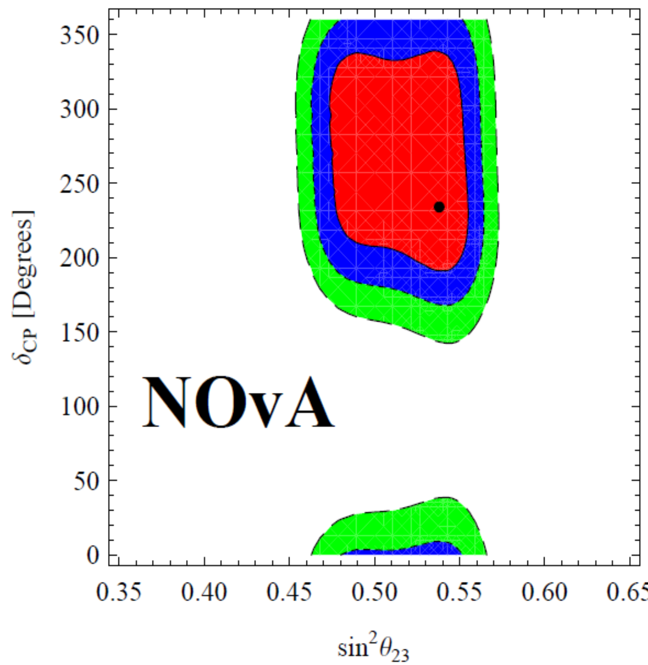


Credits:
J. Kopp







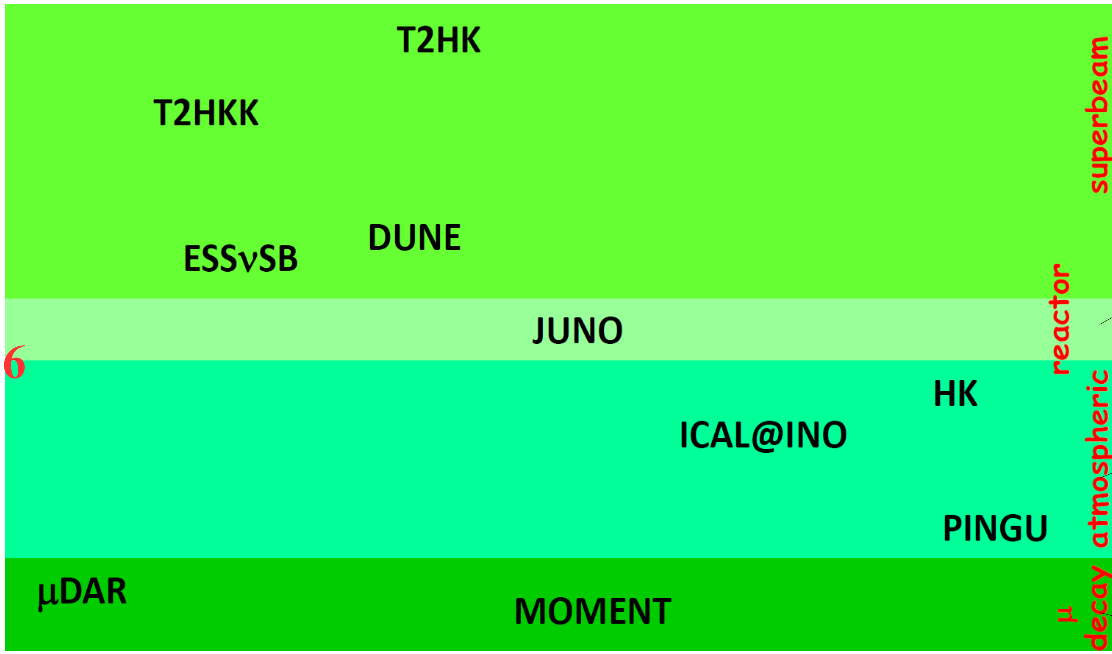


Taken from work in progress with Ding, Li, Tang, Wang.

Classification of global neutrino oscillation experiments

Neutrino beams:

Ref: NuFact2016



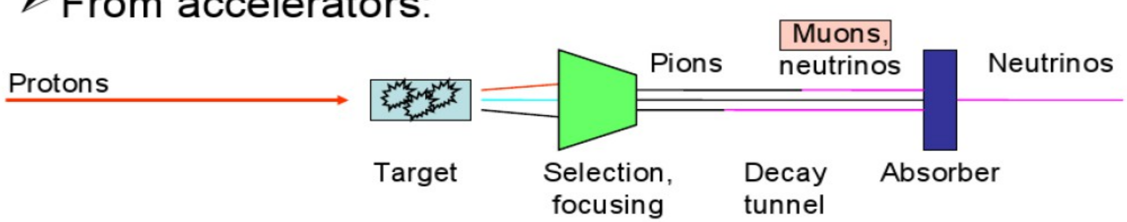
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

Beta decays

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

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

- Beta decay: $n \to p + e^- + \bar{\nu}_e$
  - Example: Nuclear reactors, beta beams
- Pion decay: $\pi^- \to \mu^- + \bar{\nu}_\mu$ → Superbeam
  - From accelerators:

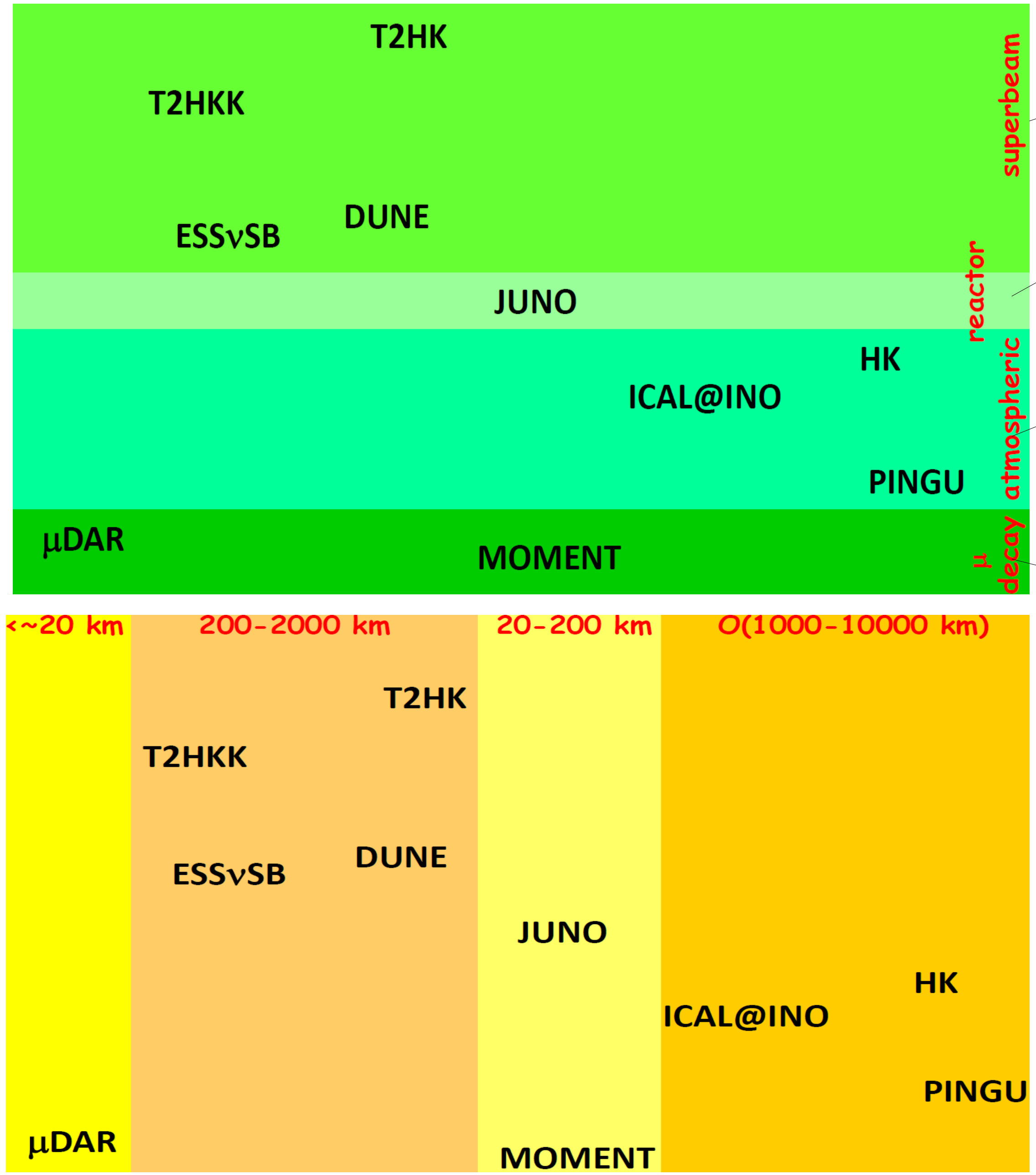


Credit: Walter Winter

- Muon decay: $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$
  - Muons produced by pion decays! Neutrino Factory

Classification of global neutrino oscillation experiments

Neutrino beams:



Baseline:

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

Beta decays

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

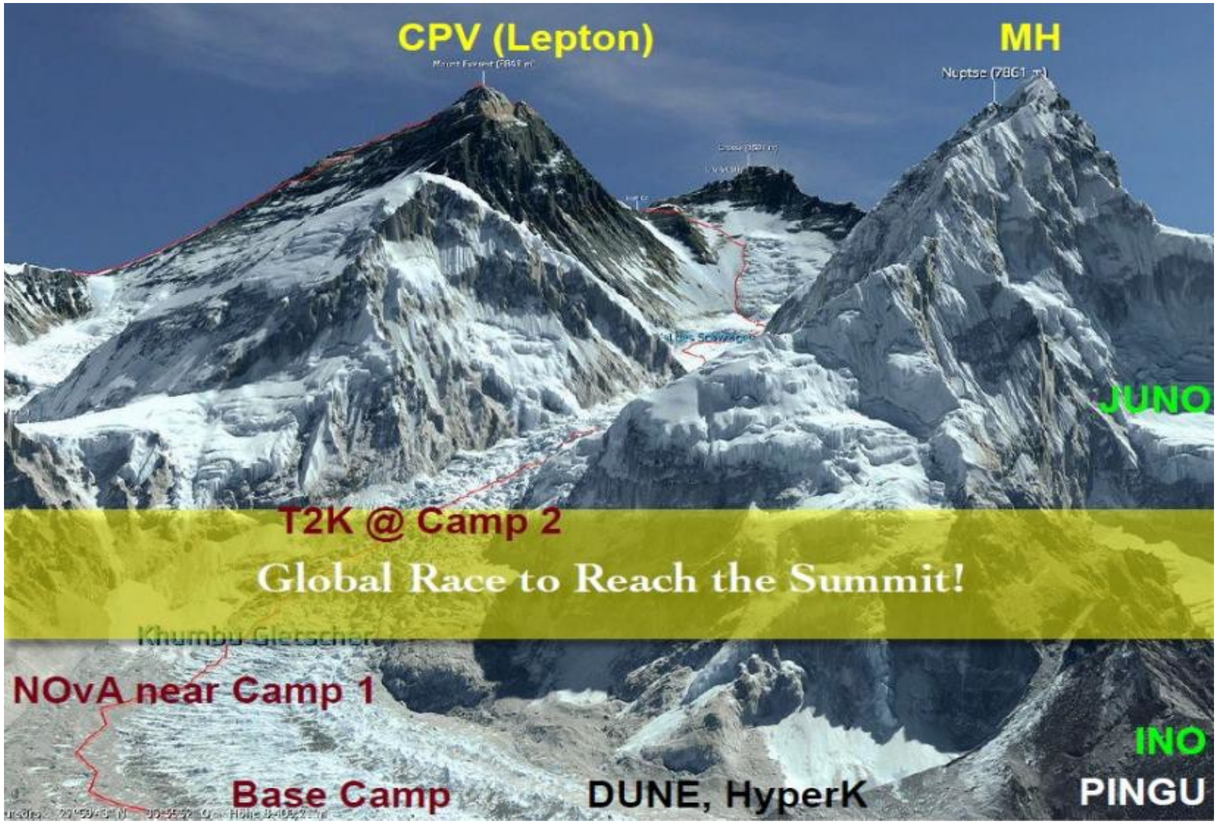
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Ref: NuFact2016

What are precision measurements and new physics?

Neutrino physics topics:

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: Δ m$^2_{31} > 0$ or Δ 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?

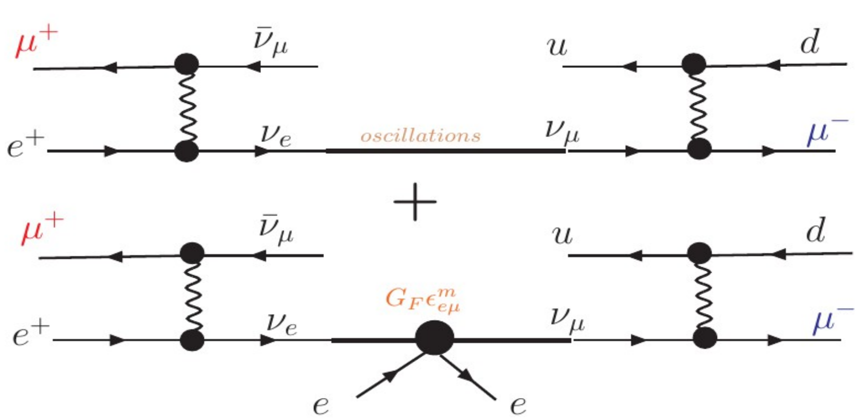


Chung-Kee JUNG
@ NNN2016

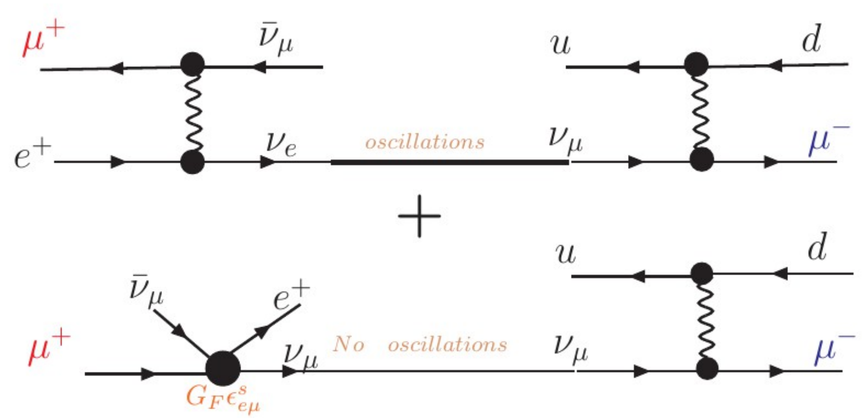
Links between NSIs and neutrino oscillations

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

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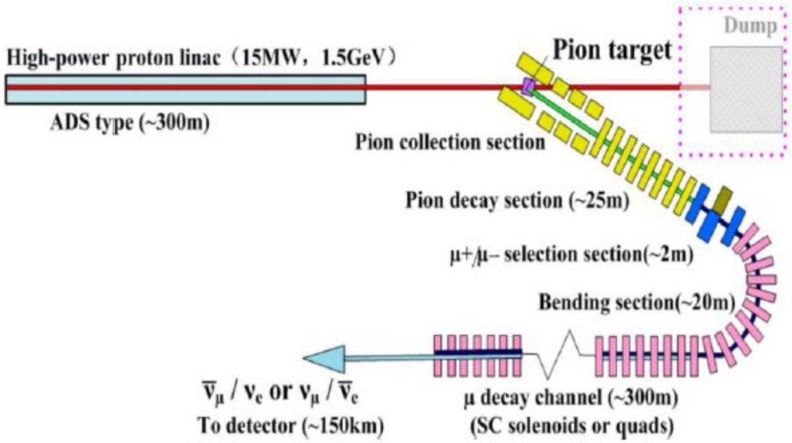
- Motivations of neutrino oscillation experiments
- Physics study at International Study of Neutrino Factory
- **CC-NSIs at MOMENT (MuOn decay MEdium-baseline NeuTrino beam facility)**
- Tests of non-unitarity violation with future's accelerator neutrino facilities
- Neutrino Activation Analysis with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

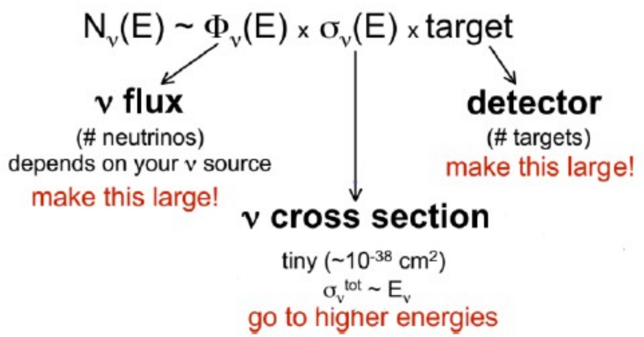


- Peak energy: 200 MeV
  Neutrino energy range: 100MeV—800MeV
  - The lower beam energy at ~ 300 MeV: free from pi0 background

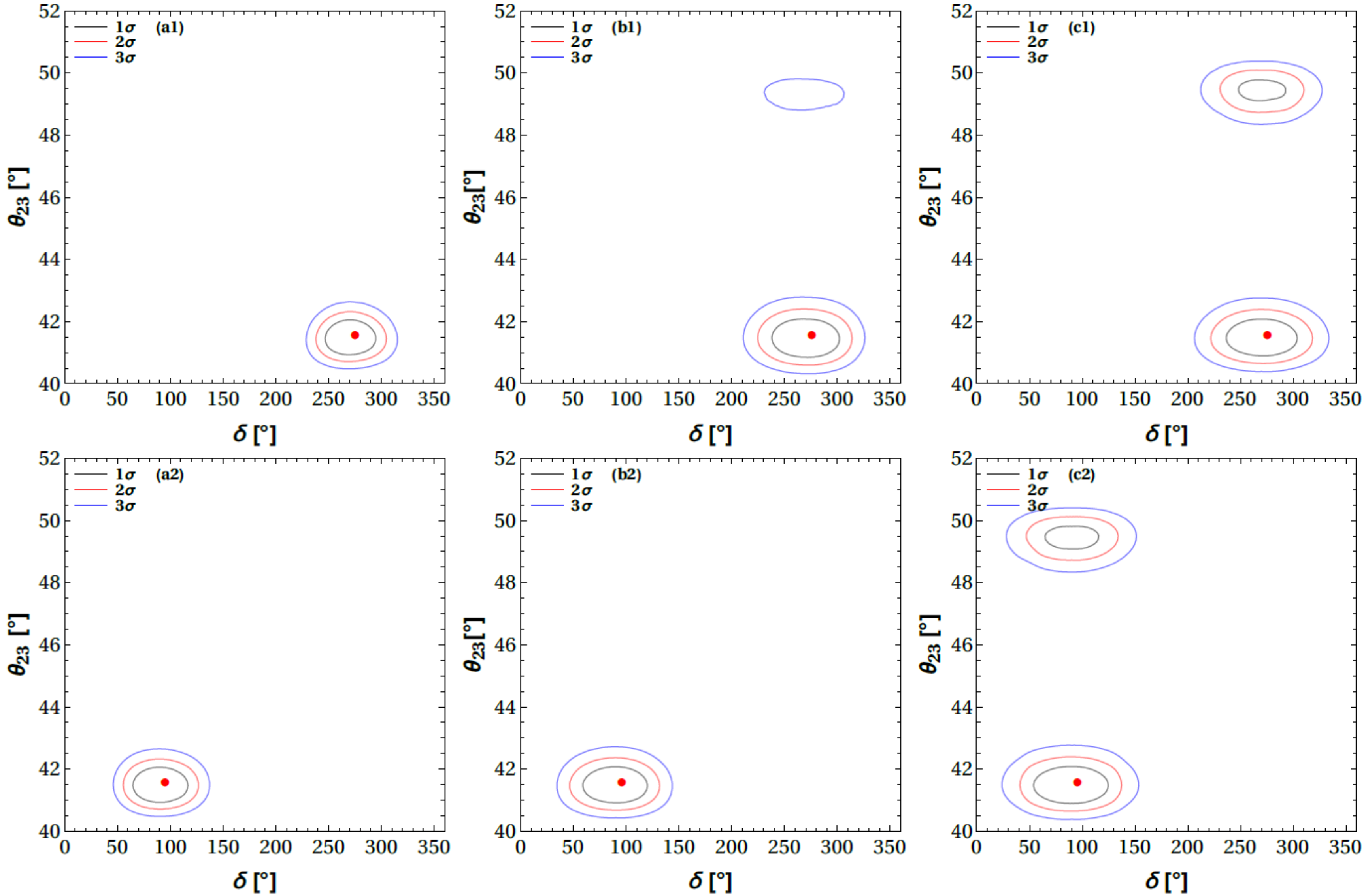
- Baseline: L=150 km

In the MOMENT: the neutrino flux peak at low energies

require a very massive detector to compensate the low interaction cross section



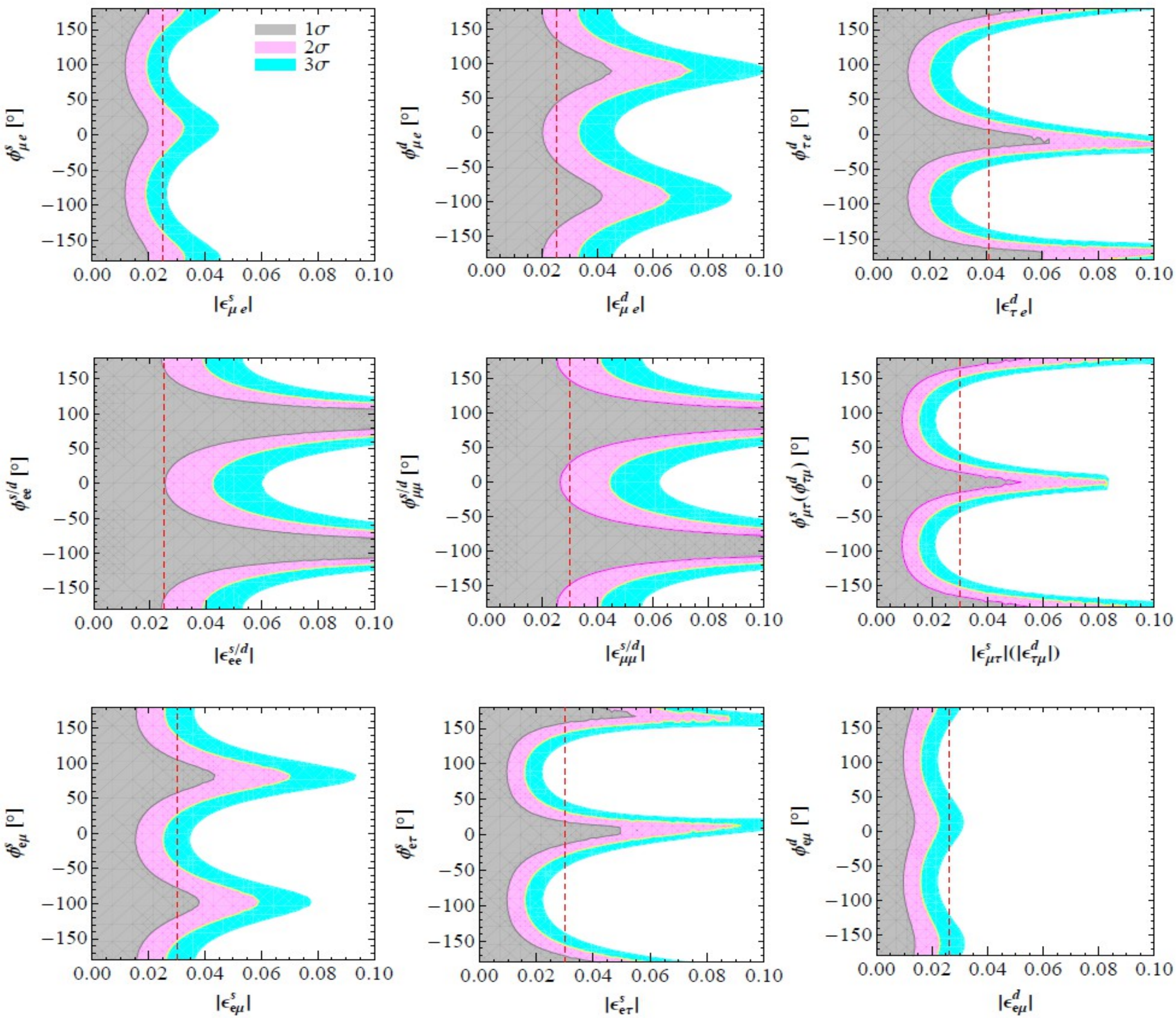
Impacts on precision measurements by CC-NSIs



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.**



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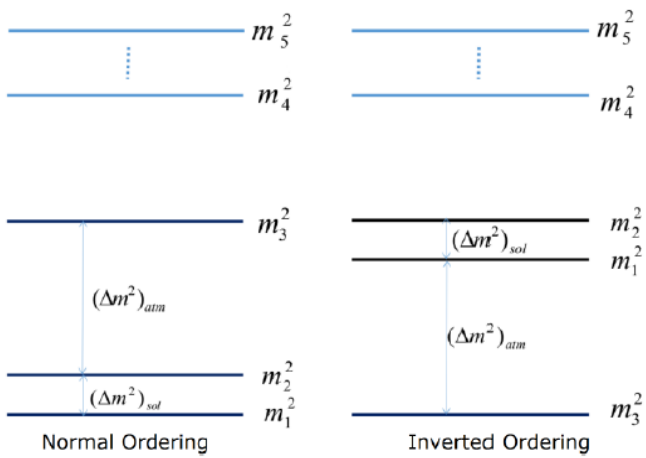
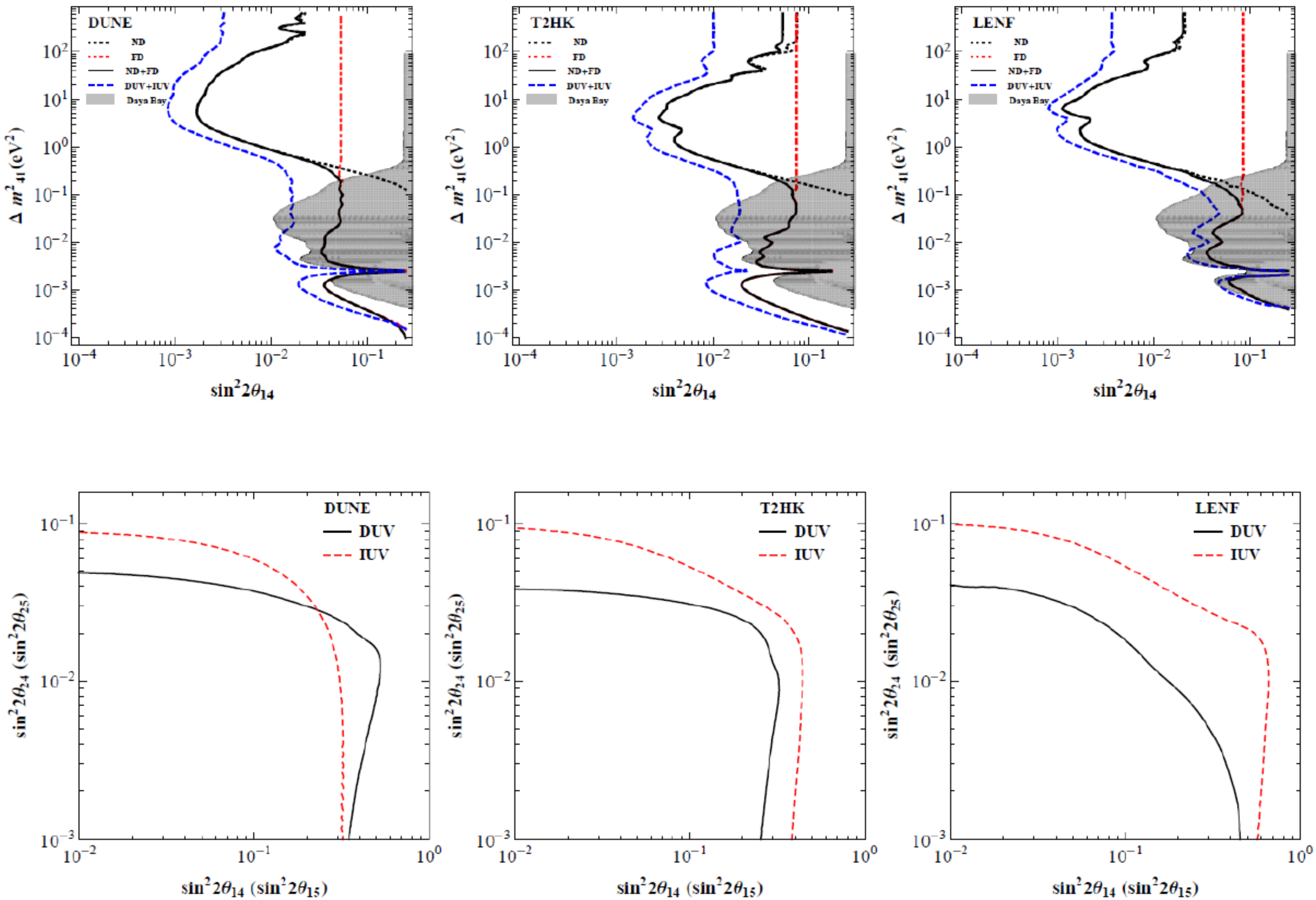
- Light sterile neutrino anomaly (eV scale)
- Heavy sterile neutrinos from see-saw model (GeV scale)
- Dark matter candidate (keV scale)
- IUV (indirect unitary violation) by heavy sterile neutrinos
- DUV (direct unitary violation) by light sterile neutrinos: oscillation with active ones



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

- 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



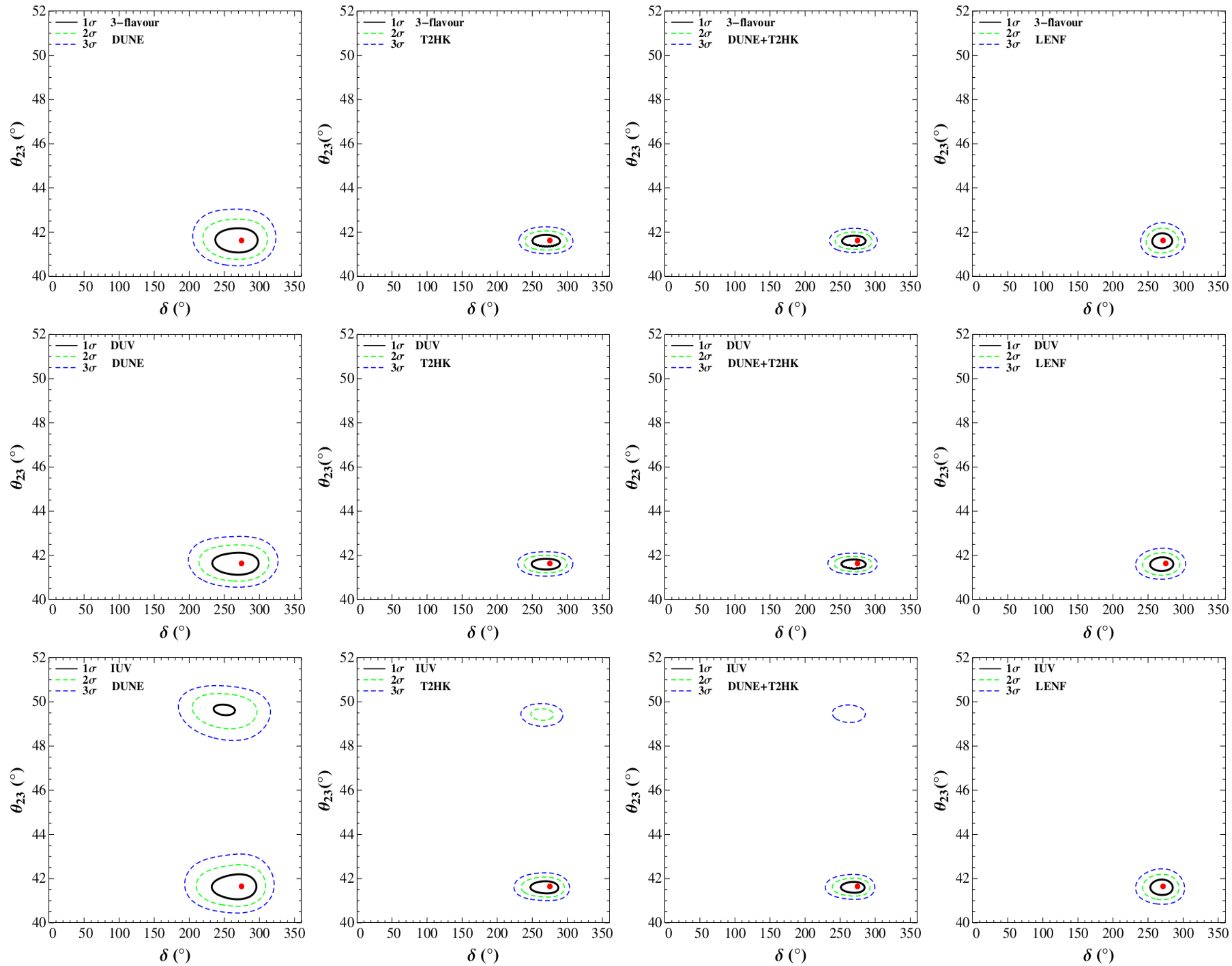
The limits to new paramerters induced by the DUV and IUV effects

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;



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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#

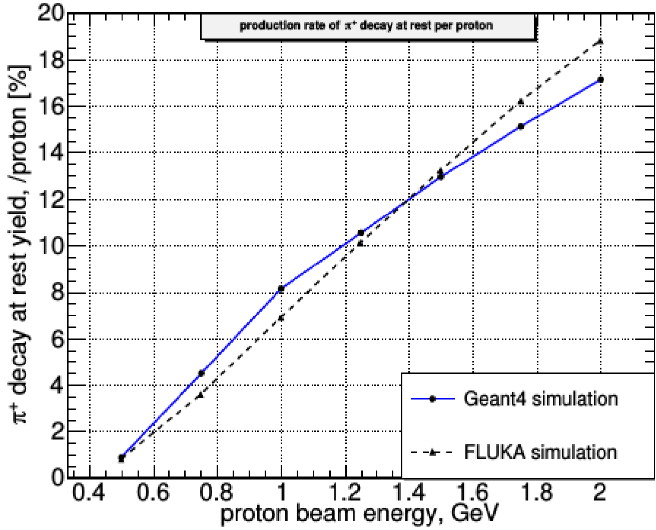
- **Progress of low-threshold DM detectors made it come true.**
- **What else can we do with CEvNS?**

Neutrino Activation Analysis

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

- **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**

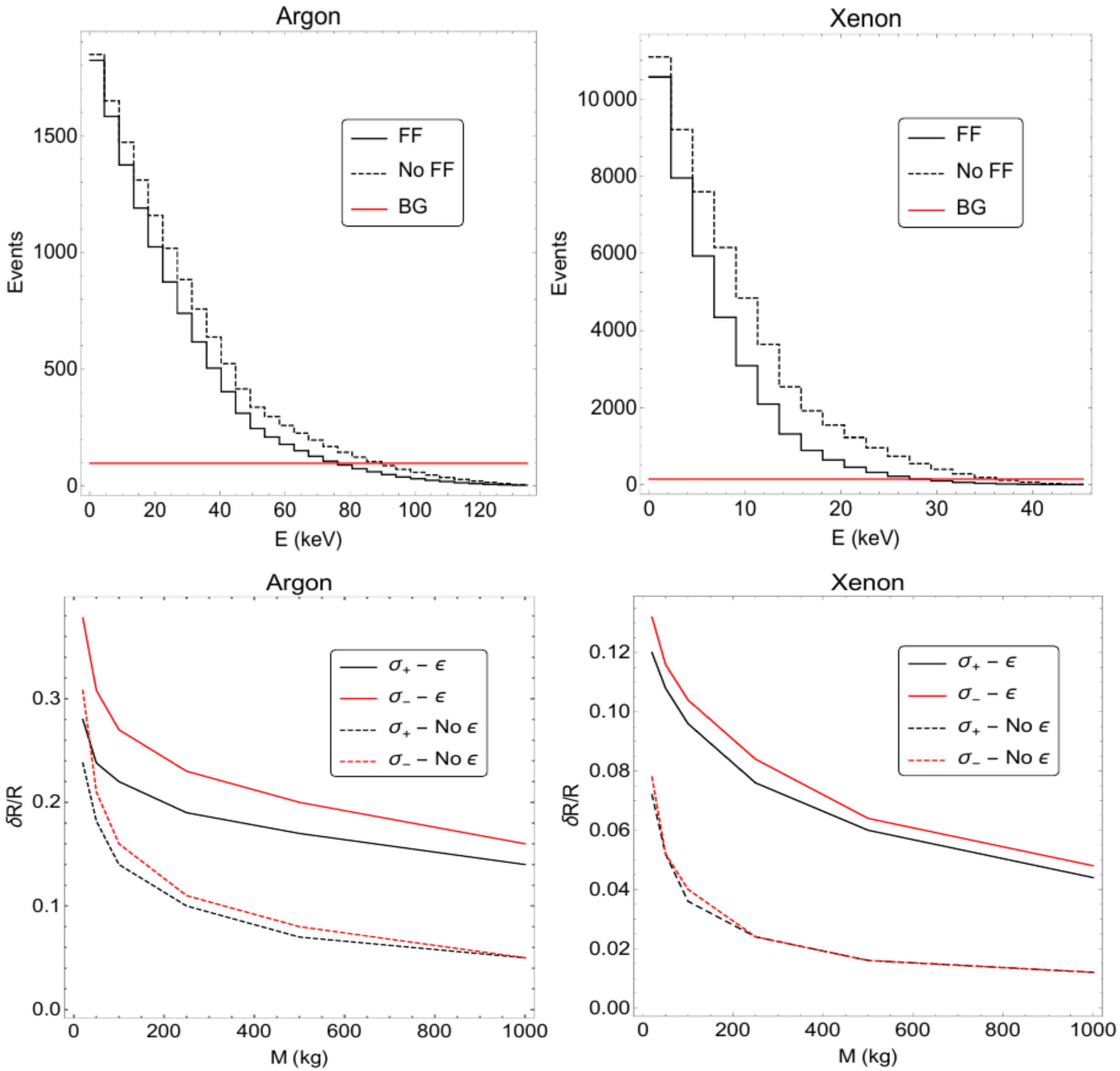
$$F(Q^2) = \frac{1}{Q_w}\int [\rho_n(r) - (1-4\sin^2\theta_w)\rho_p(r)]\frac{\sin(Qr)}{Qr}r^2dr$$



- **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.

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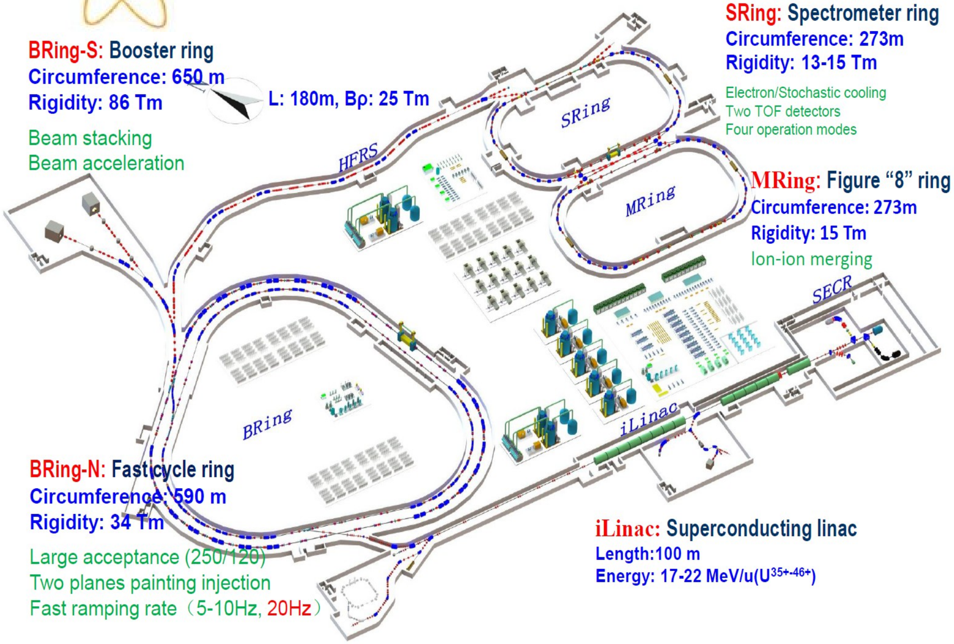
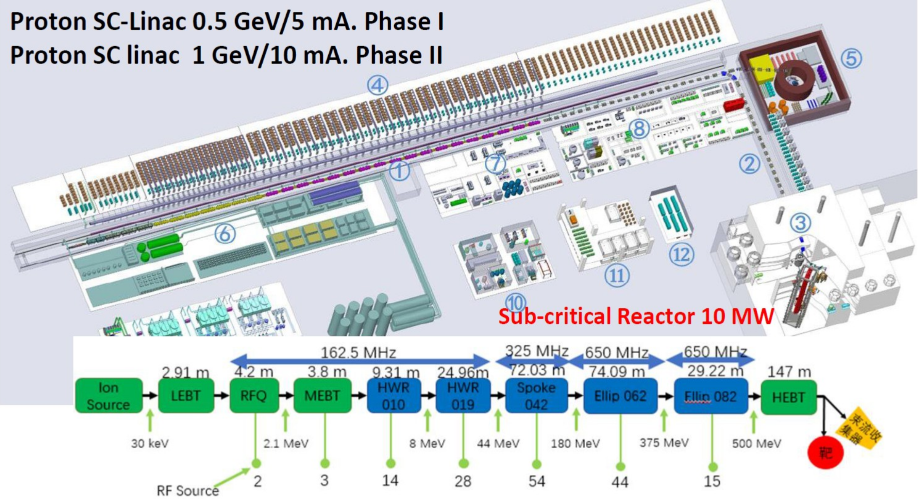
- New physics related to accelerator neutrinos in progress
- **Summary**

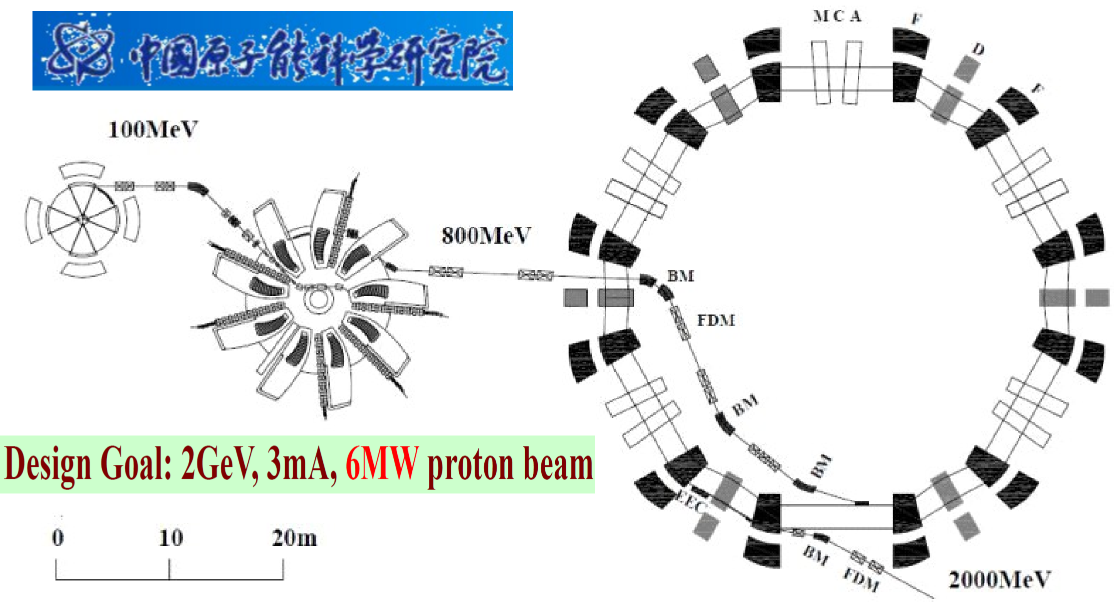
Ambitions of accelerator R&Ds in China

HIAF & CIADS in Huizhou





2 GeV High Power Circular Accelerator Complex



CSNS in Dongguan: 1.6 GeV 100 kW->500kW

Summary

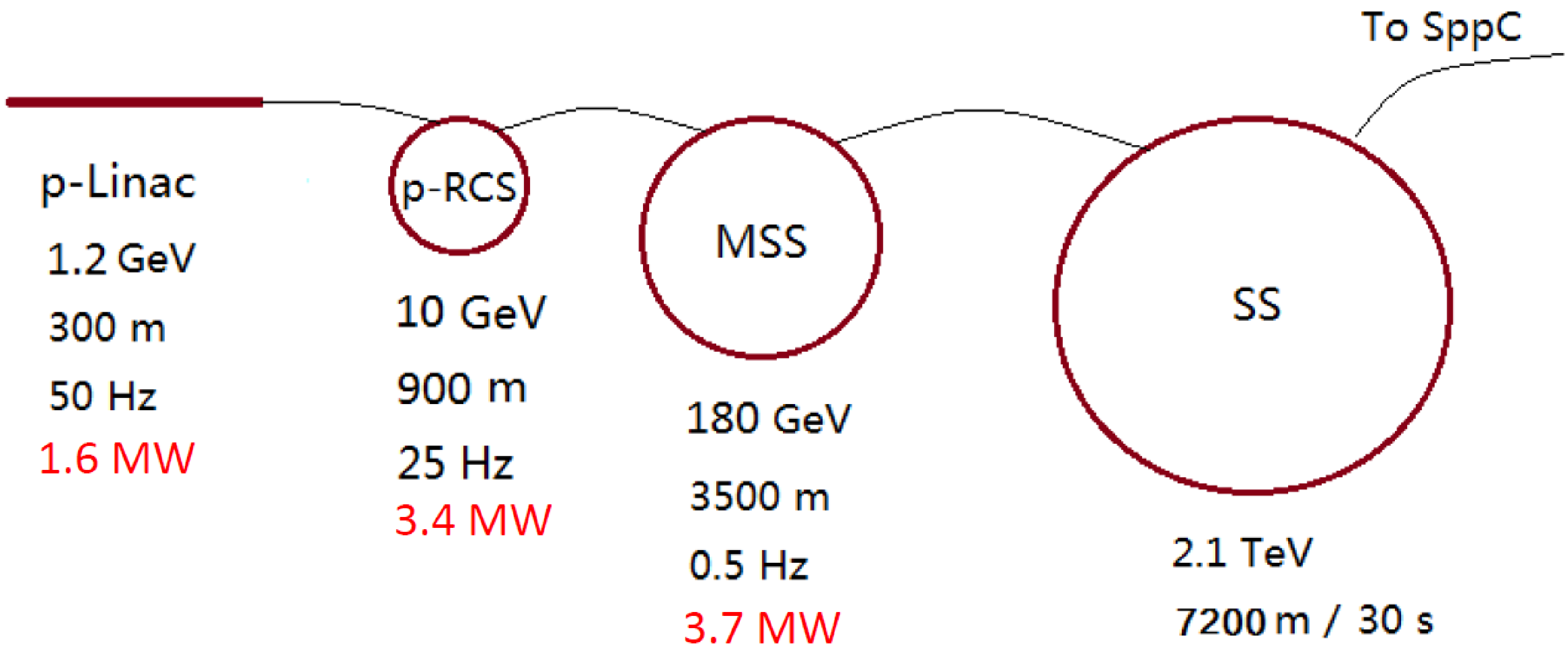
- **Lots of physics to be done with accelerator neutrinos.**
- **Optimize the baseline and beam energy first.**
- **Show a comparison of physics performance to stand out!**
- **Apart from CPV, we should do precision measurements and search for new physics.**
  - **Probe of unitarity violations, NSIs, neutrino decays, long-range forces, CPT violations.**
  - **Neutrinos in the DM wind, flavor-symmetry models......**
  - **Neutrino scatterings to probe the nuclear structure...**
- **Welcome to work together on precision measurements and new physics searches with accelerator neutrinos.**

Thanks for your invitation and attention!

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)**

SPPC proton driver for neutrino physics

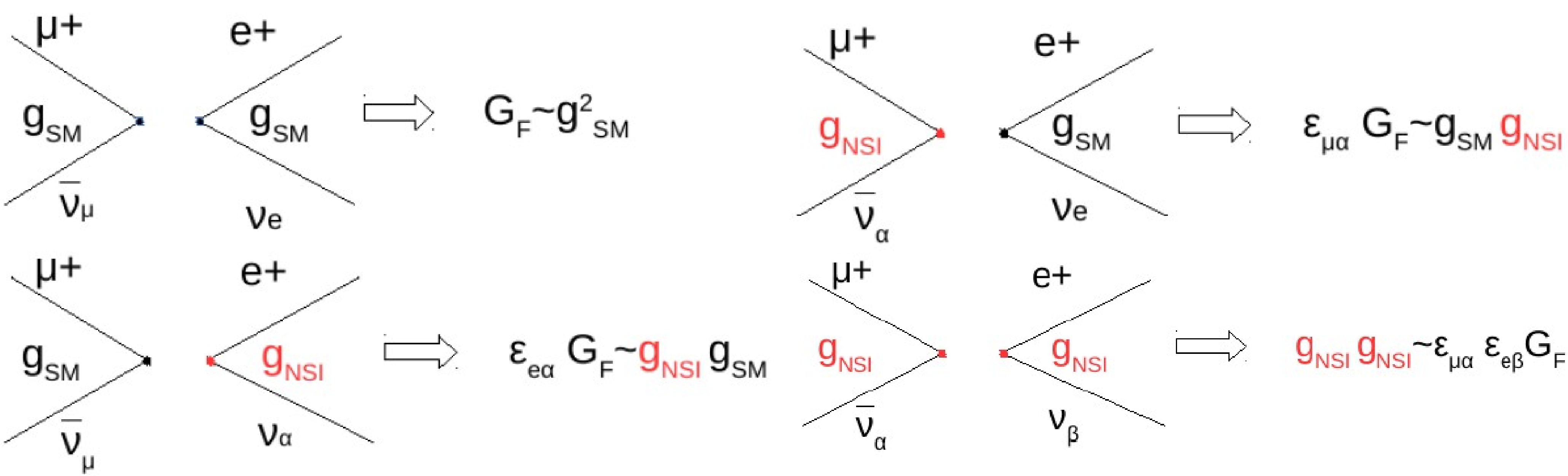


Very powerful injector beams to support rich physics programs including neutrino physics

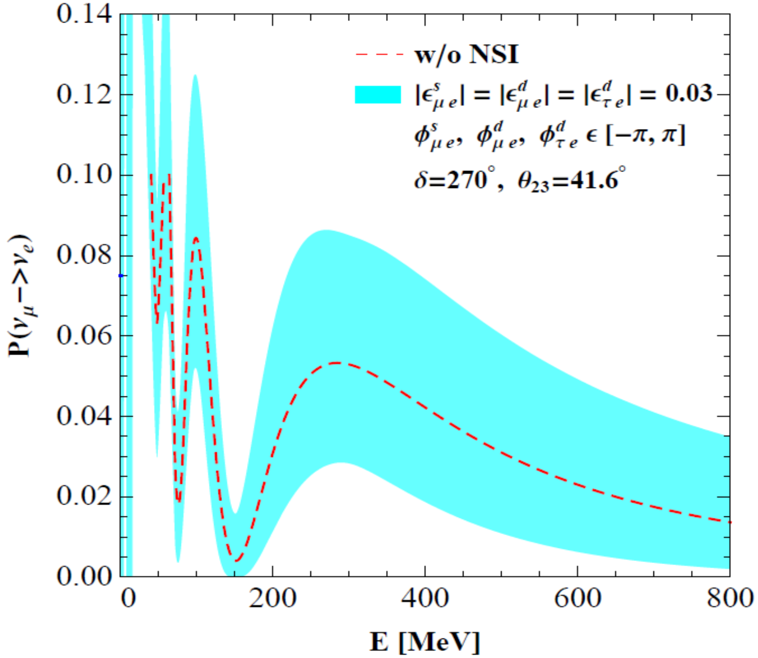
- Three proton beams in MW level: 1.2 GeV, 10 GeV, 180 GeV

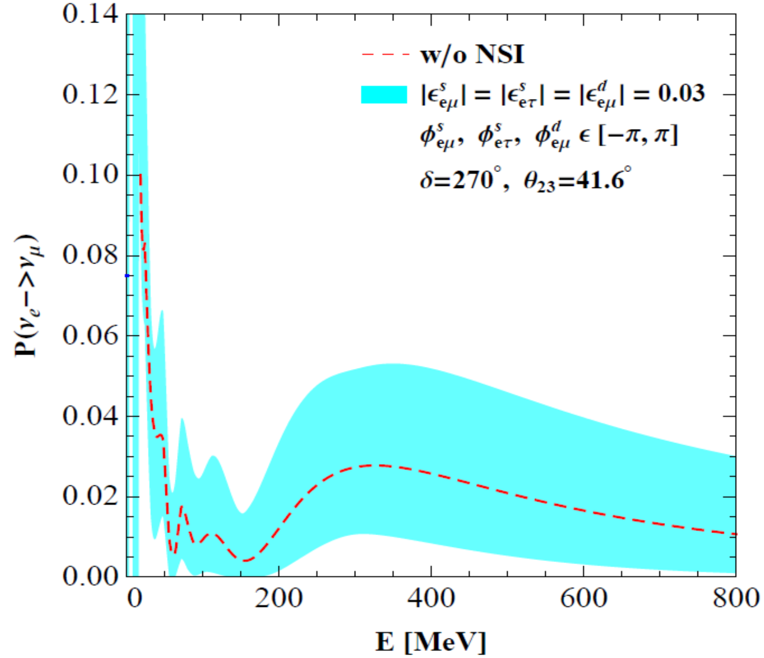
Coherent v.s incoherent processes

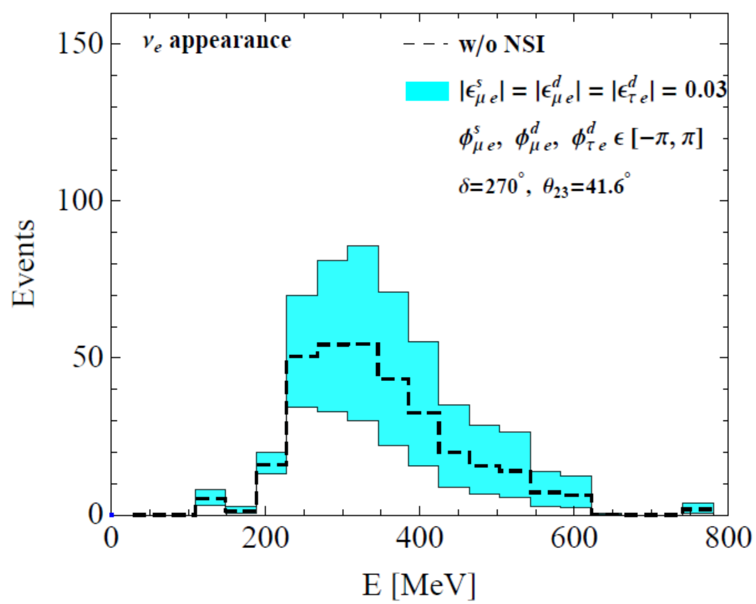
- **Coherent processes:** $\mu^+ \longrightarrow e^+ + \nu_\alpha + \bar{\nu}_\mu \;\; \mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\alpha$
- **Incoherent processes:** $\mu^+ \longrightarrow e^+ + \nu_\beta + \bar{\nu}_\alpha$
- **Why shall we consider the coherent processes only?**

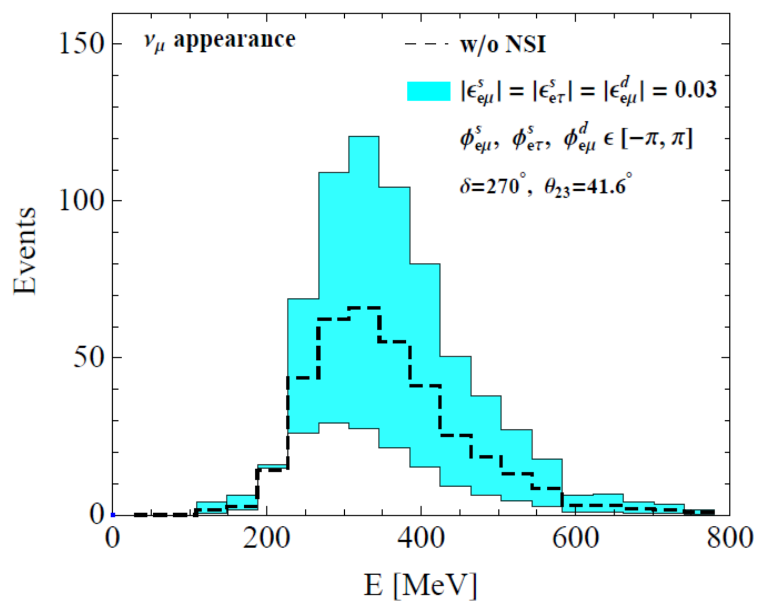


Numerical tests of oscillation probabilities and events at MOMENT



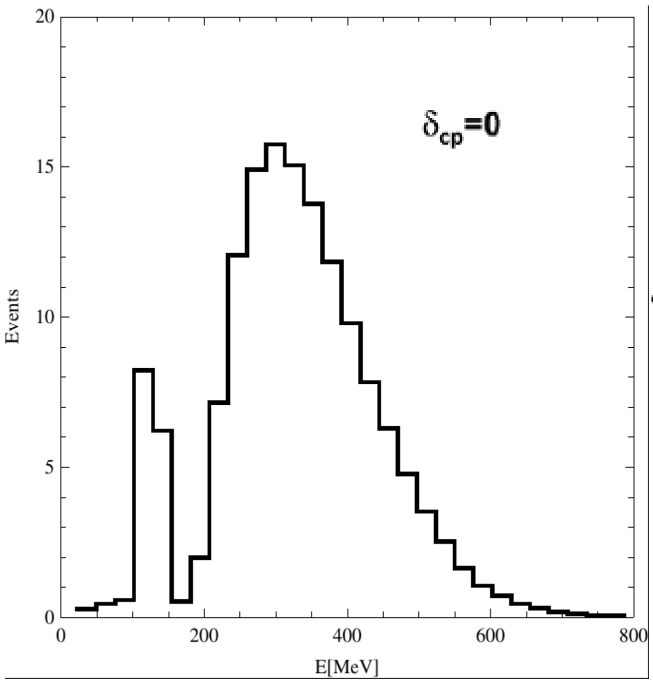




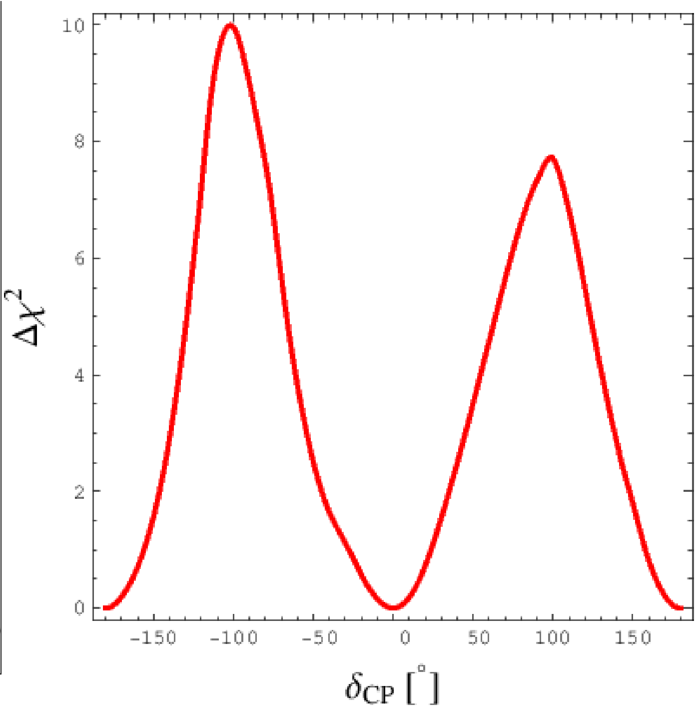


Updates of CPV sensitivity

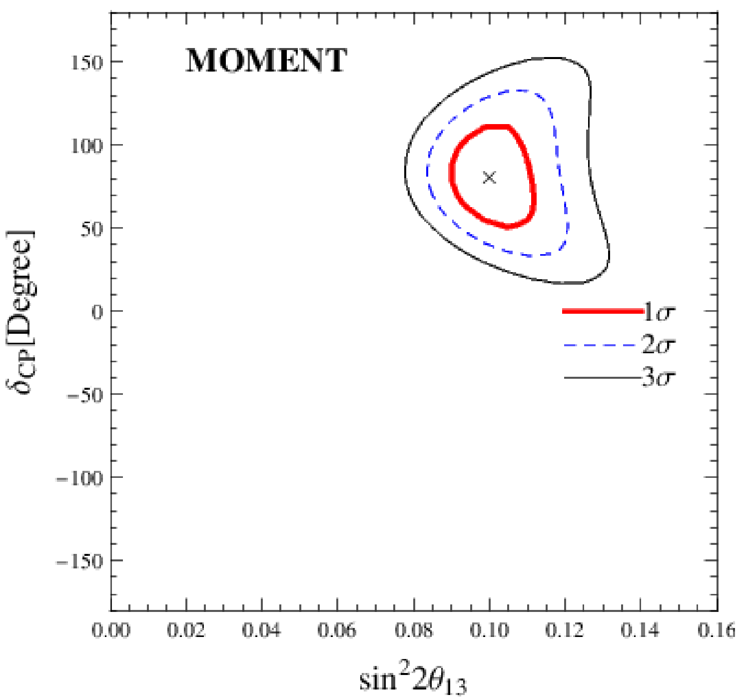
- Neutrino fluxes and detector info inherited from Miao He& Jiashu Lu
- Loss of CPV by a factor of 2 after including both systematic and statistic uncertainties
- All backgrounds highly suppressed, especially atmospheric bckgs!



Detected neutrino spectra



Discovery of CPV



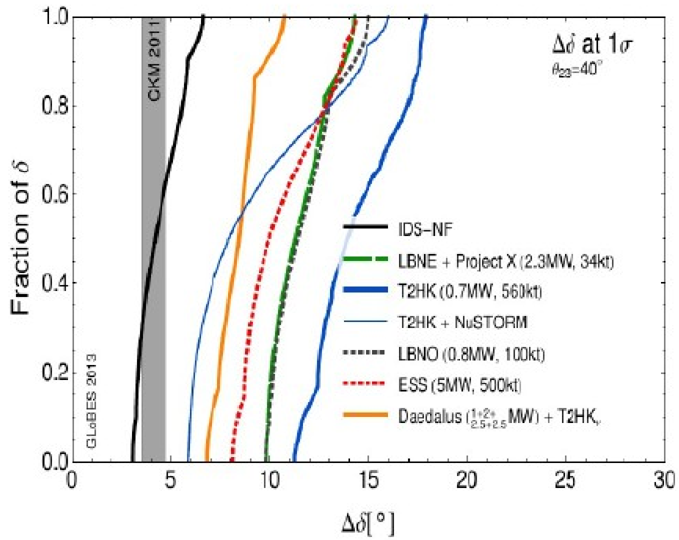
Precision measurements

- **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**

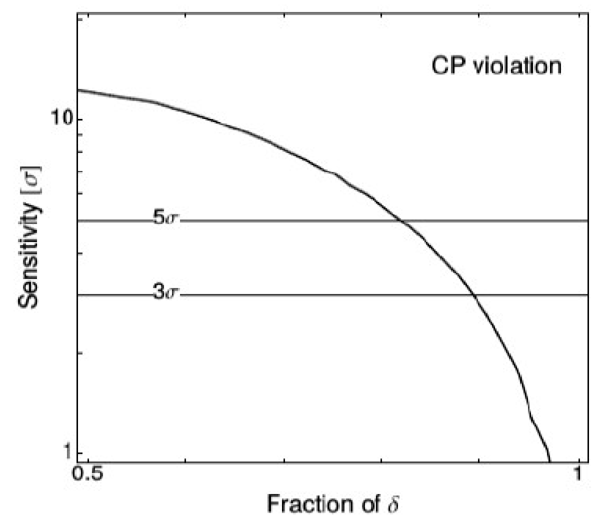
Setups in the reference design report for NF

	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Neutrino Detectors	
Distance to long-baseline neutrino detector	1 500–2 500 km
Long-baseline Magnetised Iron Detector (MIND)	100 kT
Near detectors, magnetised, high-resolution spectrometers	2

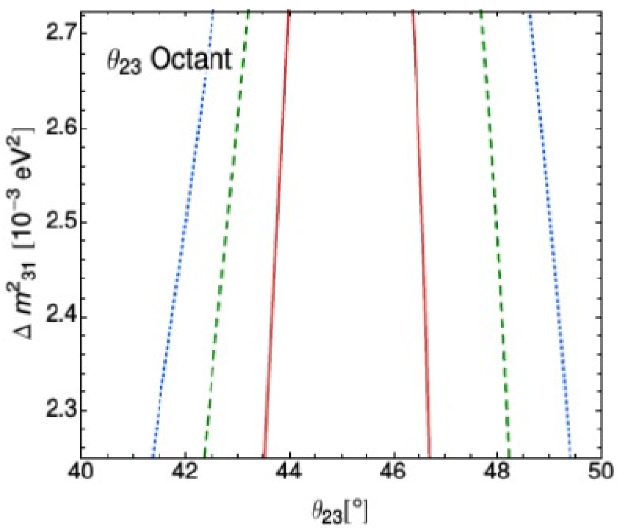
Source	Uncertainty
Normalization	1.3 %
Flux	0.1%
$\nu_{e,\mu}$ interaction rate	0.5%
ν_τ interaction rate	40%
NC background	9.5%
Charge mis-ID bg.	15%



Global comparison



Discovery reach of CPV



Octant sensitivity