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

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.)
arXiv: 1811.05623 (JHEP 1904 (2019) 004.)

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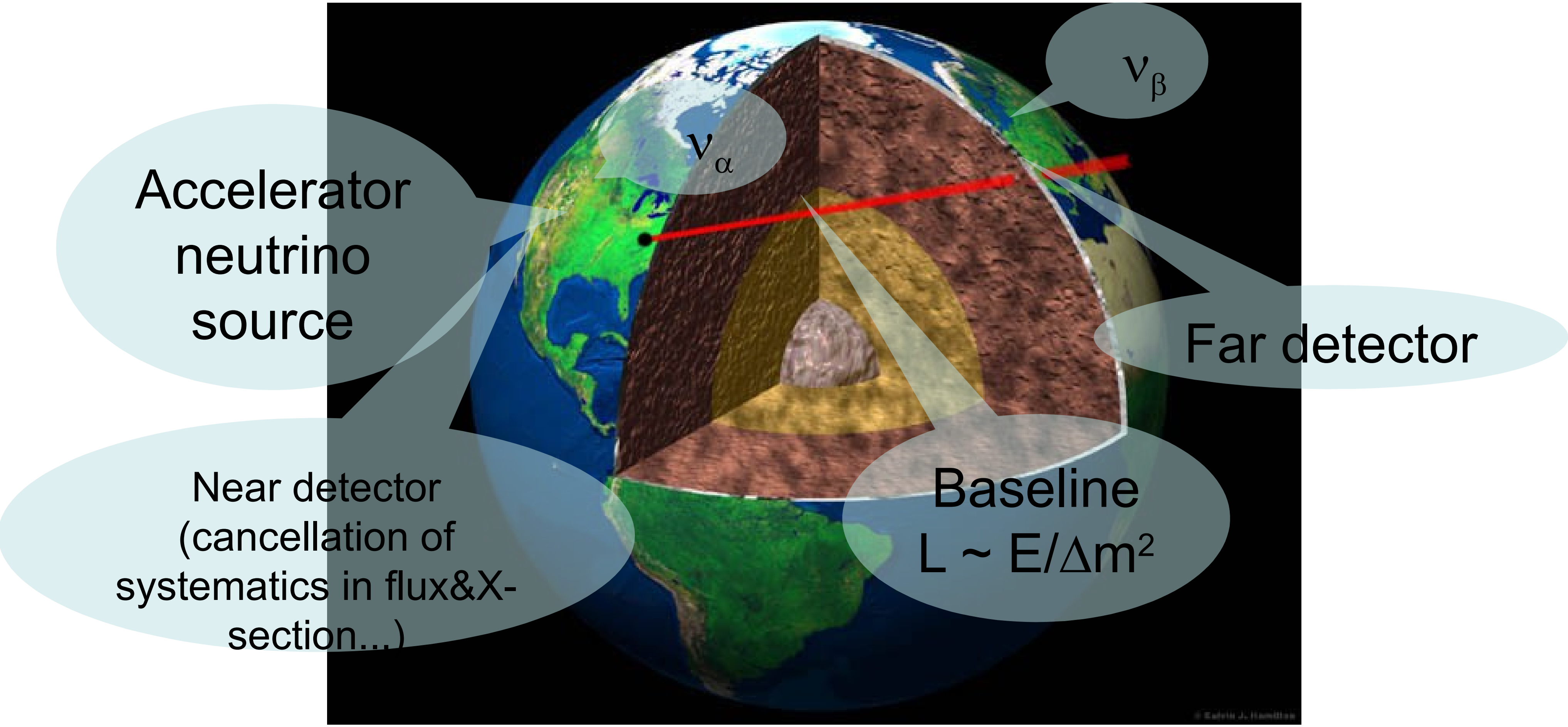
Remarks:

- Neutrinos in the Standard Model (SM) are strictly massless.
- The discovery of neutrino oscillation--> non-zero neutrino masses
- The addition of new degrees of freedom needed!

Principle of accelerator neutrino oscillations



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

Search for CPV at a long-baseline neutrino experiment

- Seek to measure asymmetry of two oscillation modes:

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- Event rates convolution of:

  - Flux, cross sections, detector mass, efficiency, E-scale:

  =>measurements at %-level required.

  - Theoretical description:

  =>initial state momentum, nuclear excitations, final-state effects

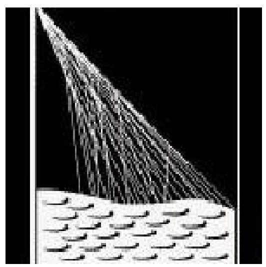
- Lack of knowledge of cross sections leads to:

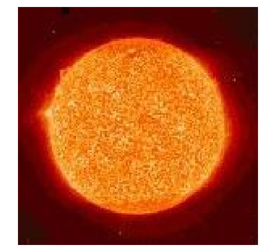
  - Systematic uncertainties

  - Biases

Status of neutrino mixings

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

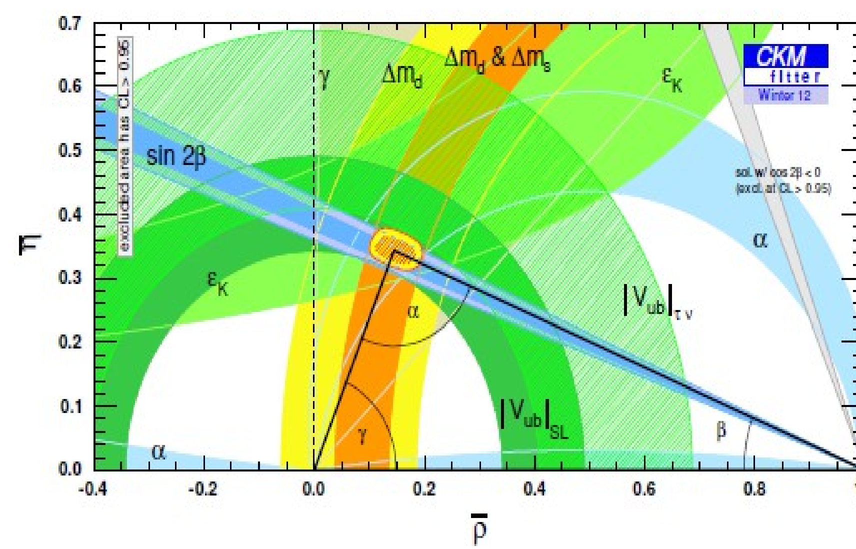
= () x (

) x ()

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

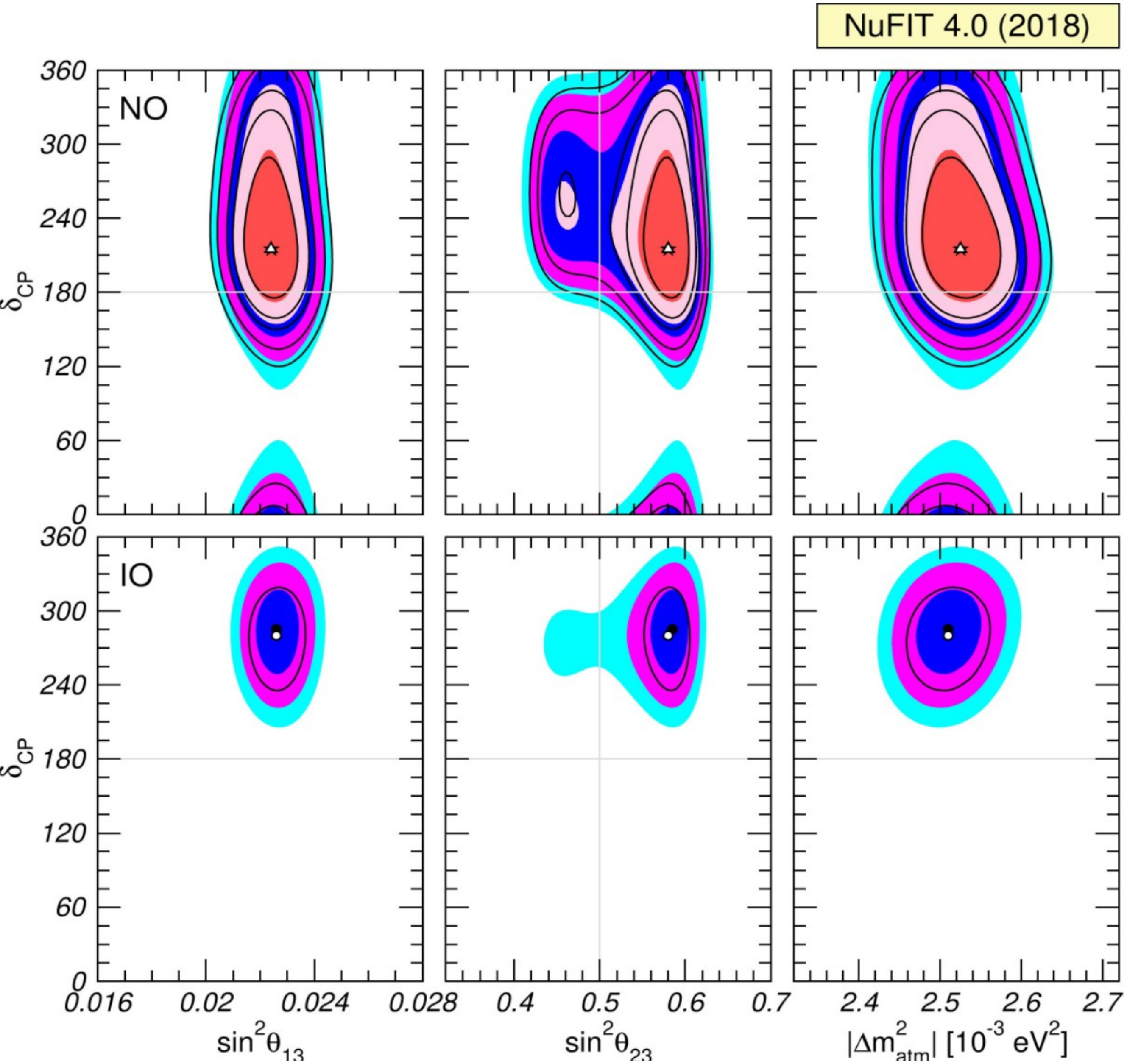
Capozzi et al.
PRD 95, 096014 (2017)

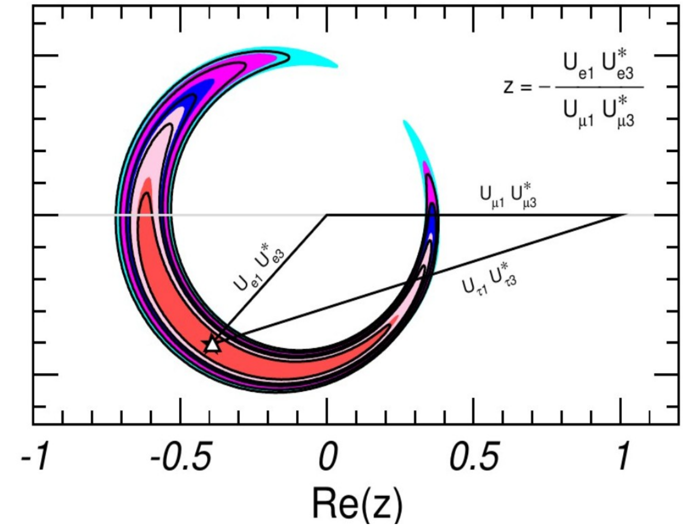
- Not precise enough!
- Can we achieve the level similar to CKM?



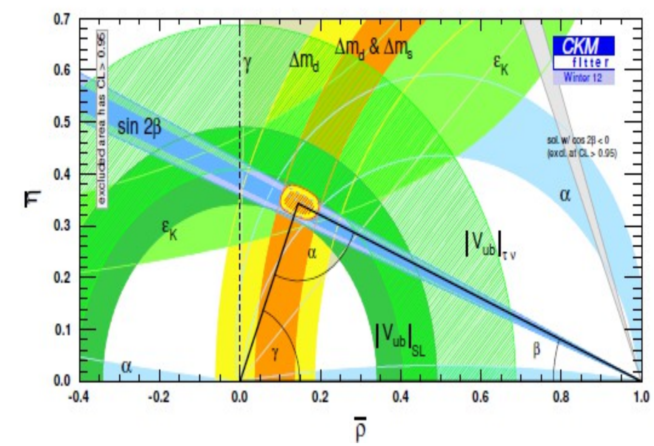
- Sub-percent level in CKM.

Latest results in a global fit



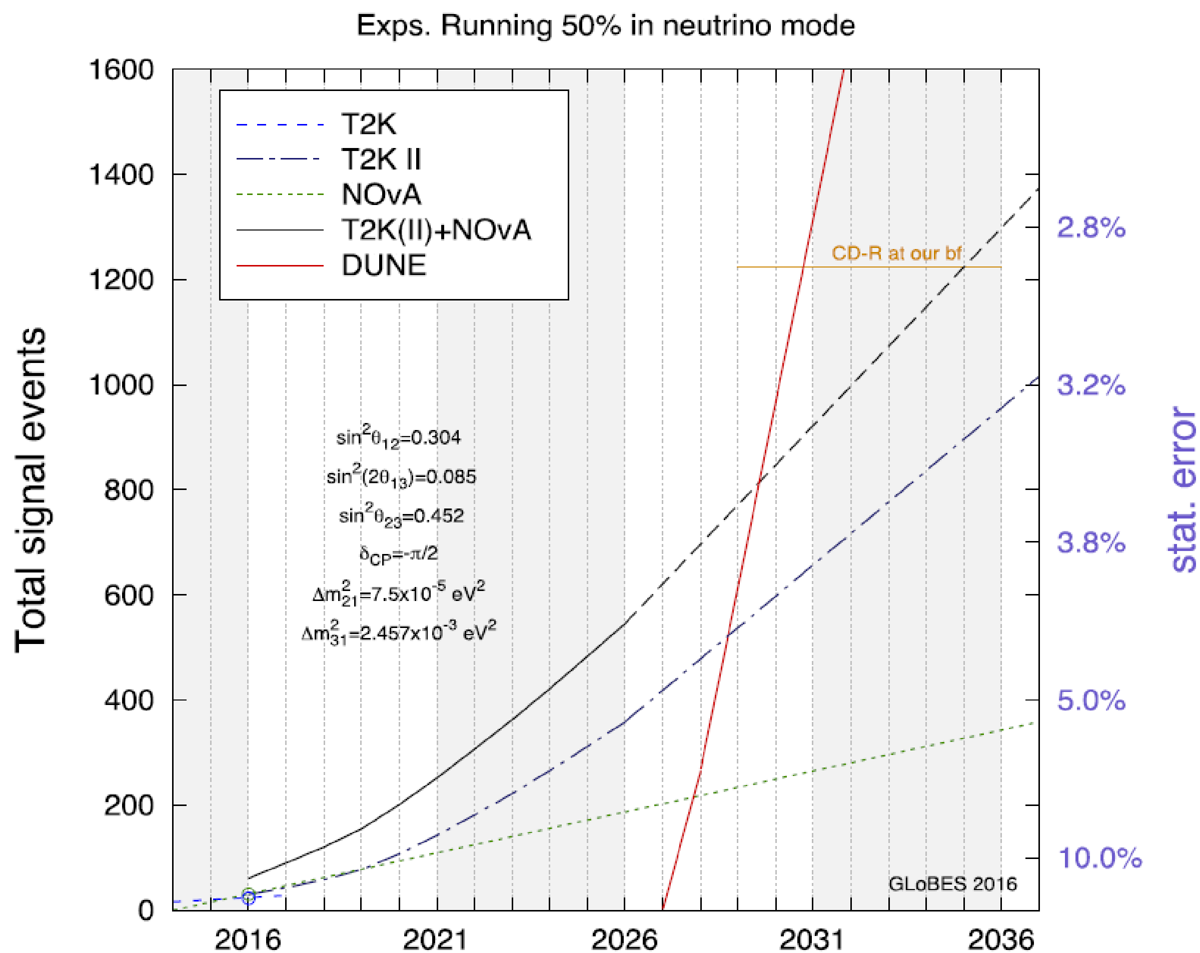


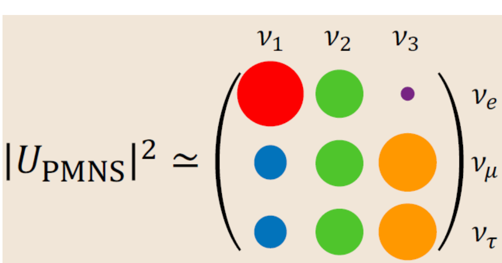
- Not precise enough!
- We currently have no way to directly measure any of sides containing tau-neutrinos.

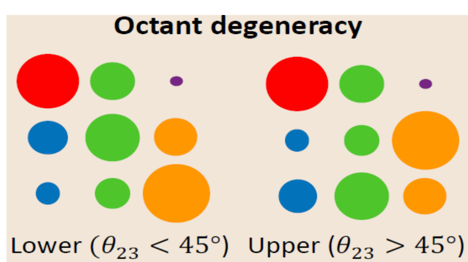


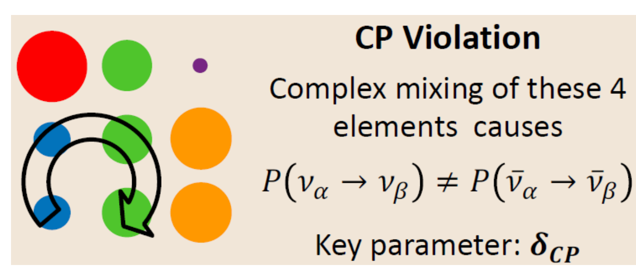
Latest results and expected sensitivities soon

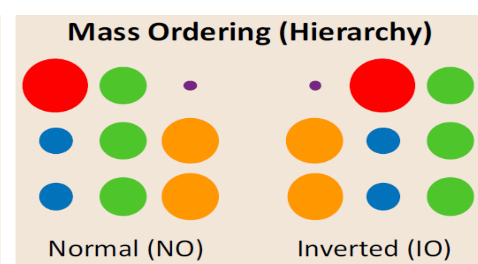
	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$
$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$
$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$
$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$





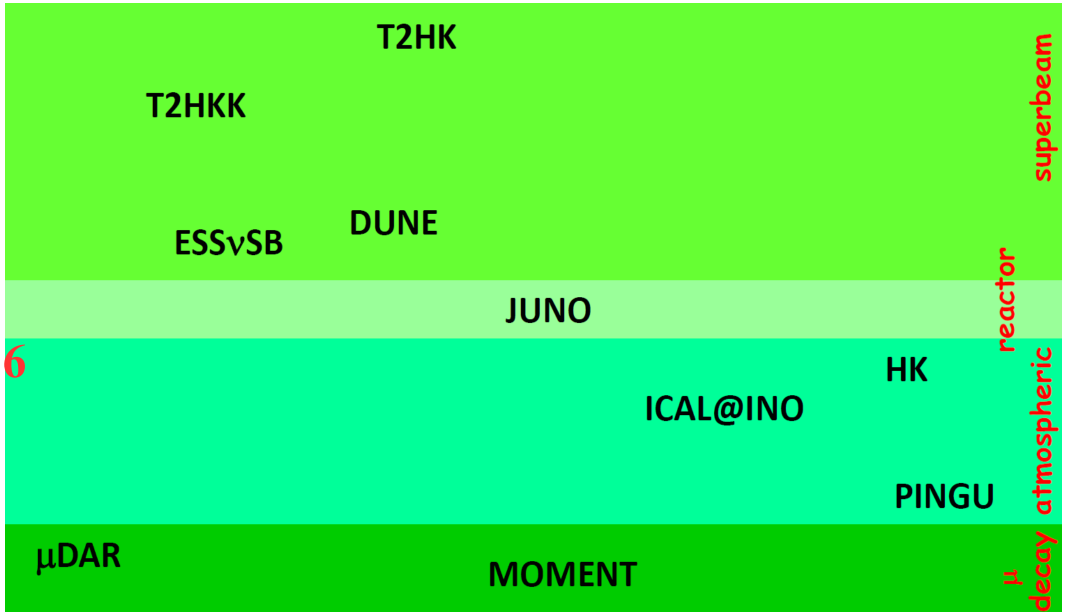






Classification of global neutrino oscillation experiments

Neutrino beams:

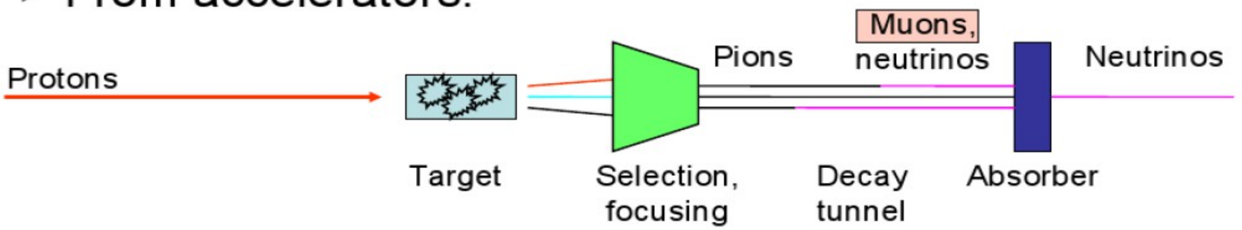


Ref: NuFact2016

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

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

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

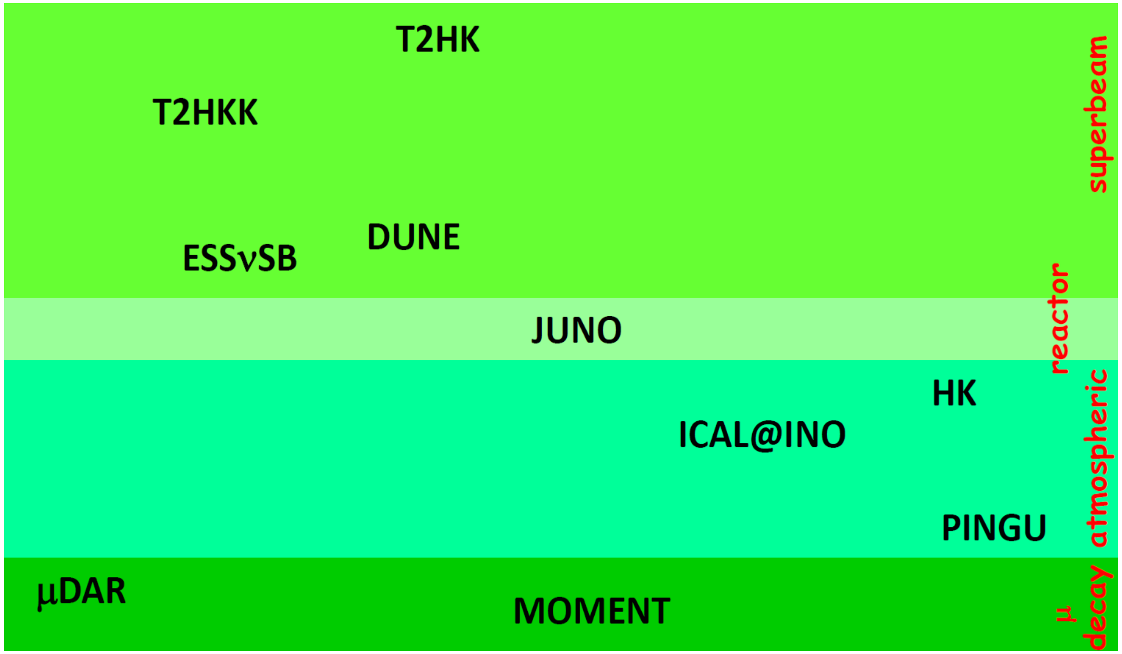


Credit: Walter Winter

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

Classification of global neutrino oscillation experiments

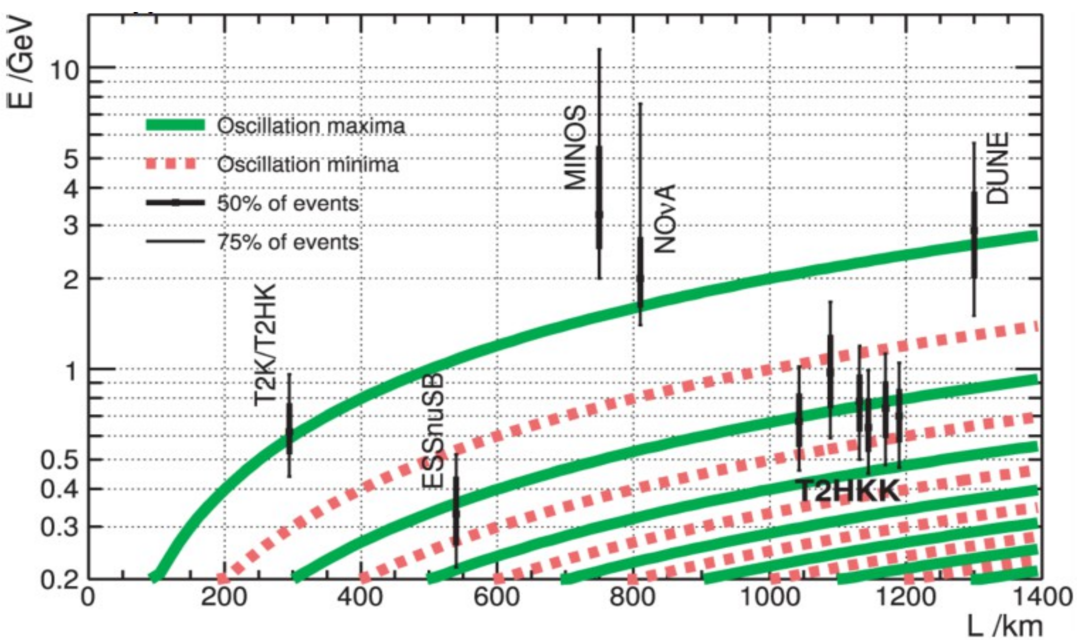
Neutrino beams:



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

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

L/E

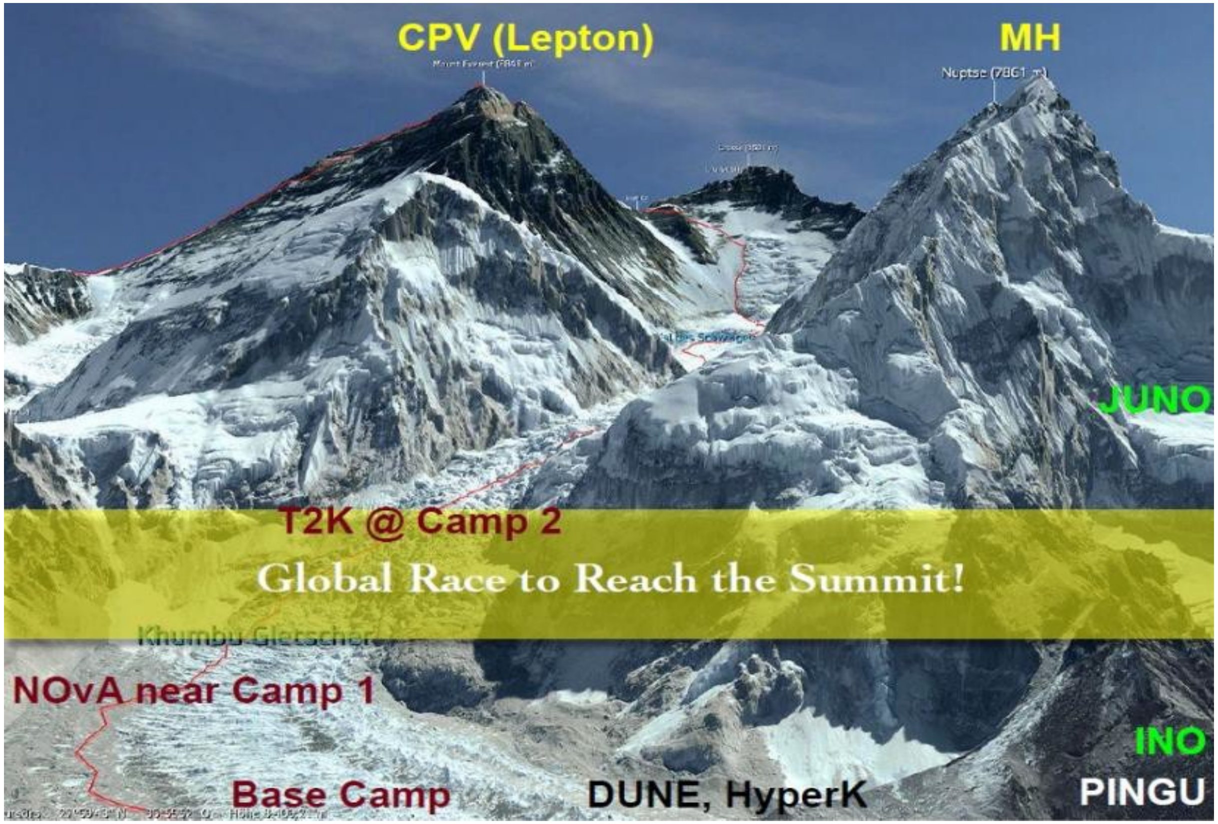


Ref: NuFact2016

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: $\Delta\, m^2_{31} > 0$ 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?



Chung-Kee JUNG
@ NNN2016

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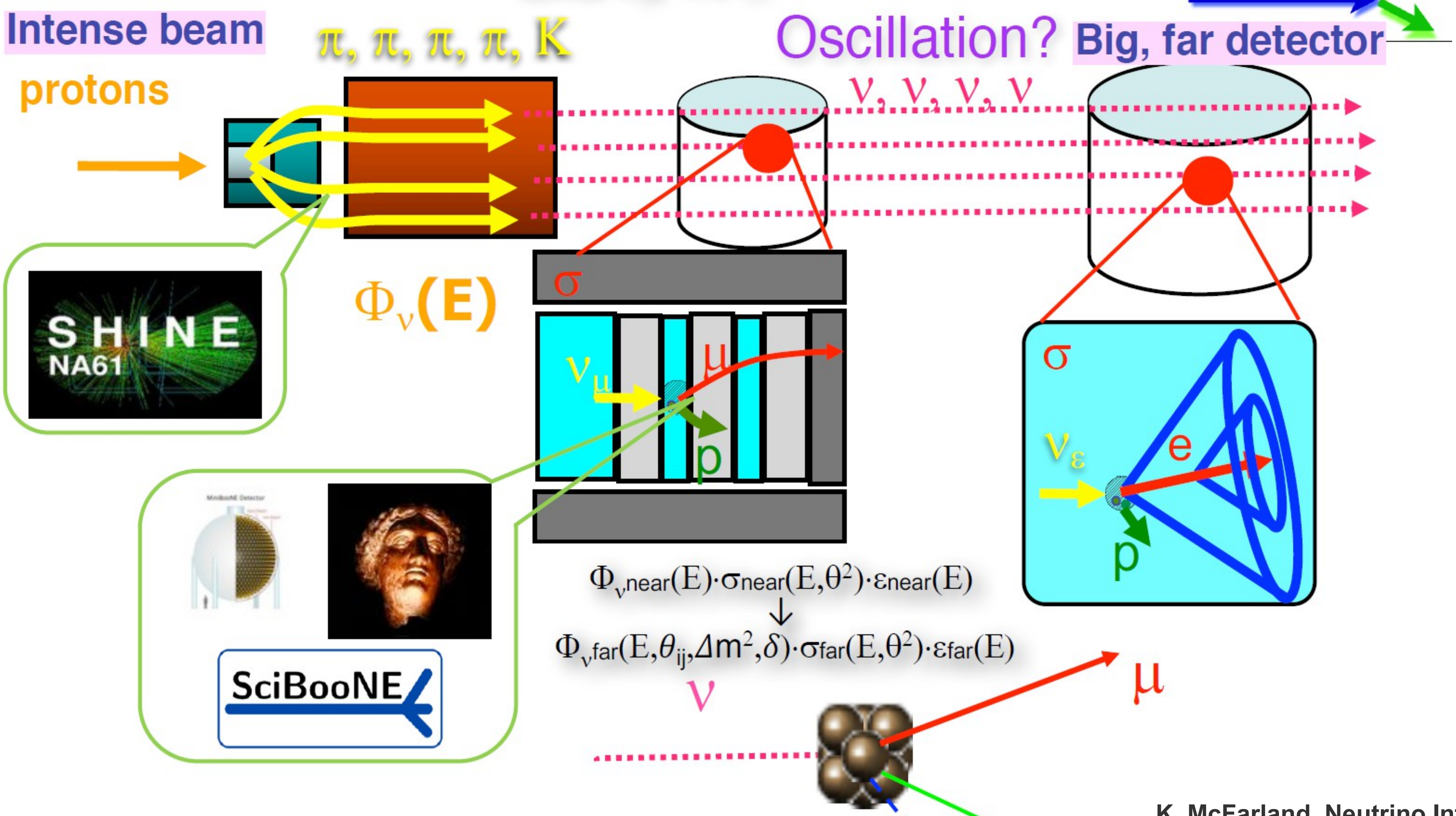
The T2K experiment

$$\pi^+ \to \mu^+ + \nu_\mu$$

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

T2K experimental strategy

Search for CPV by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

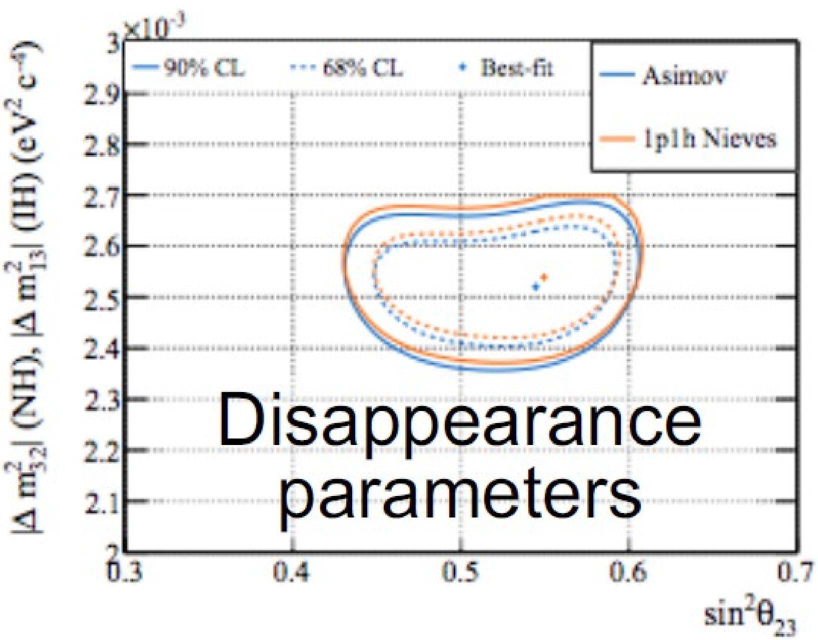


K. McFarland, Neutrino Interaction Uncertainties @ NNN2018

T2K

- **Suffering from uncertainties in cross sections.**

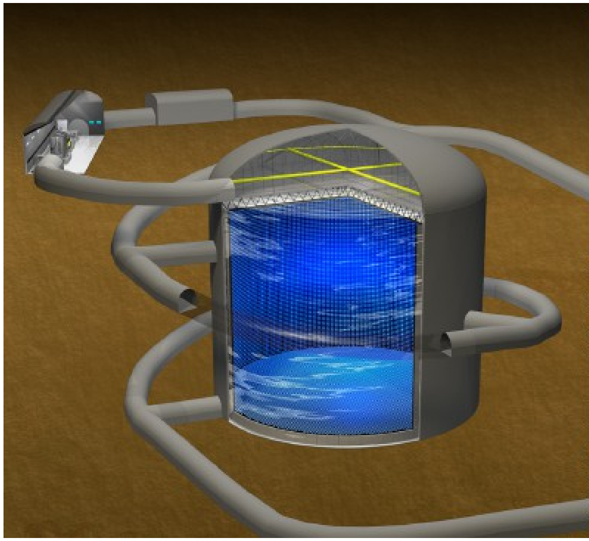
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

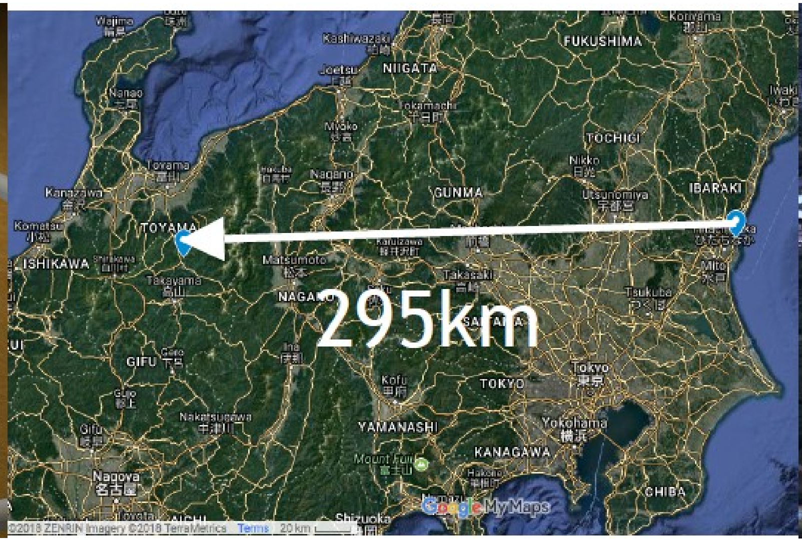


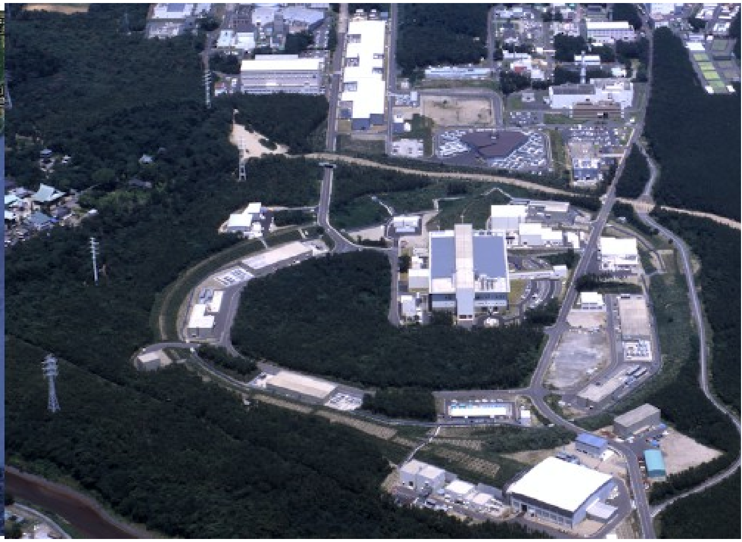
K. McFarland, Neutrino Interaction Uncertainties @ NNN2018

T2HK lead by Japan

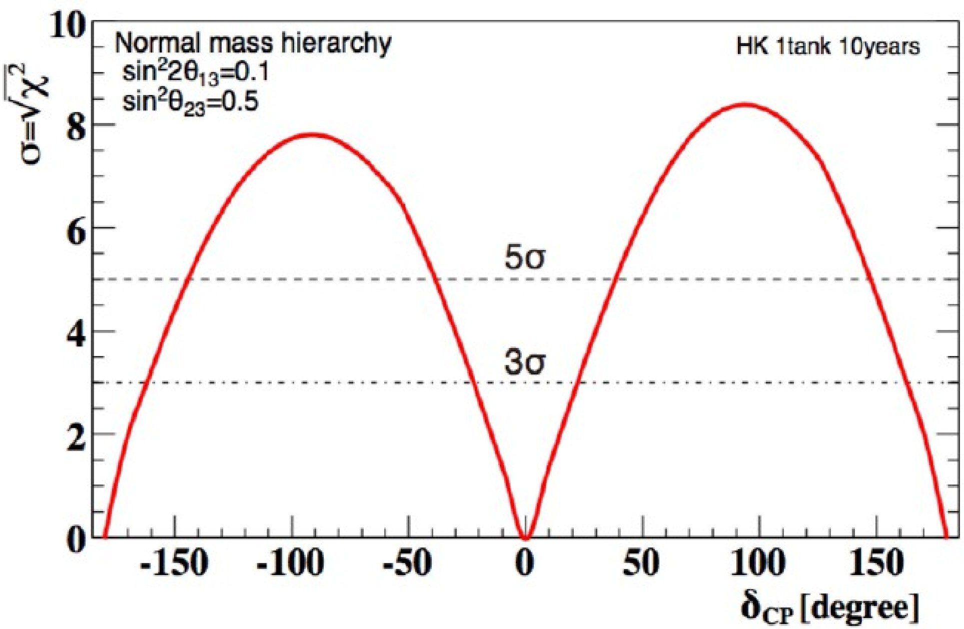
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



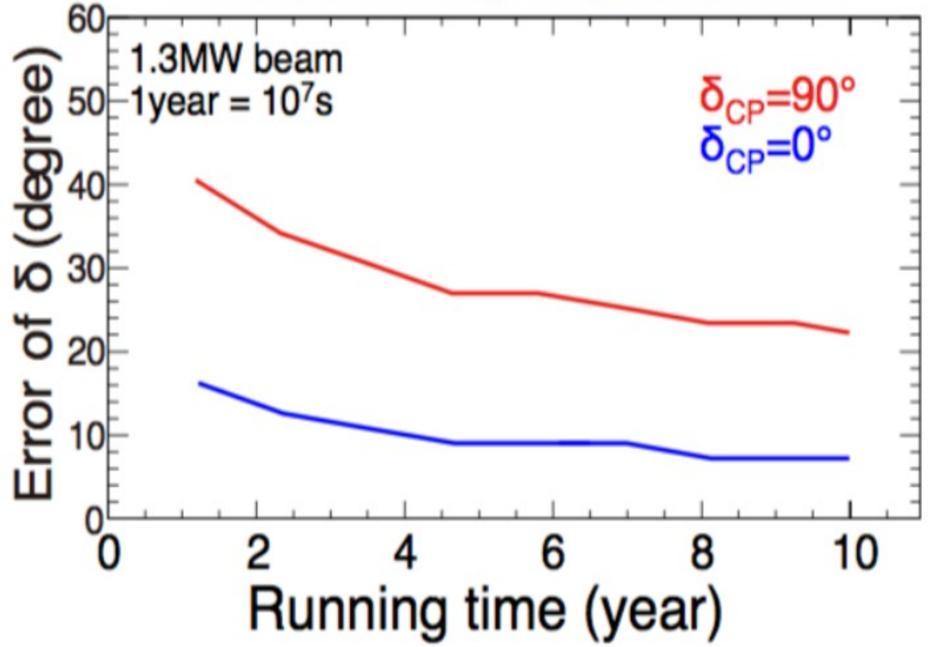




Significance of CP violation measurement

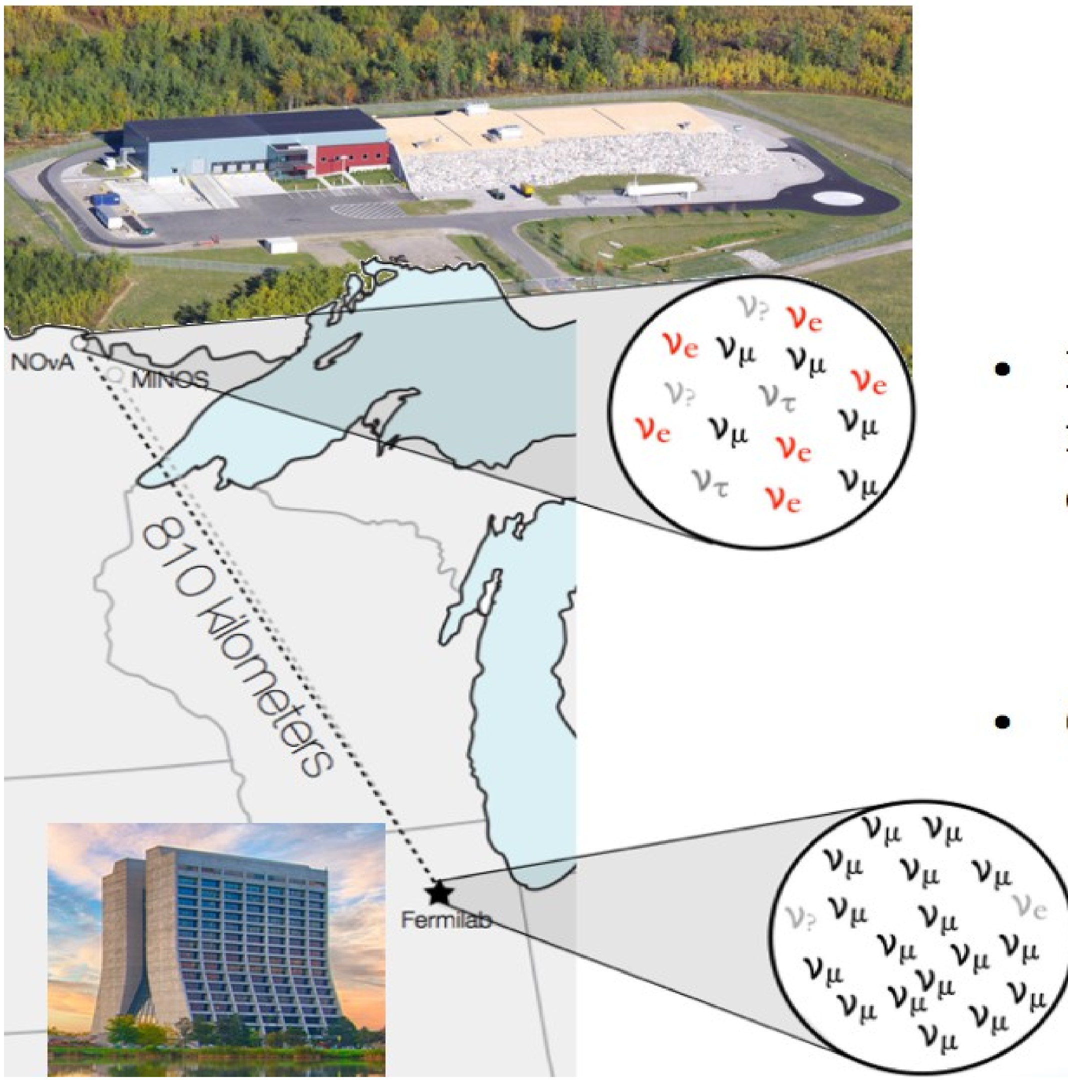


Precision of δ_{CP} measurement



The NOvA experiment

The NOvA Experiment



- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab
  - **Near Detector** to measure the beam before oscillations
  - **Far Detector** measures the oscillated spectrum.
- **Primary goal**: measurement of 3-flavor oscillations via:
  - $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Other goals include:
  - Searches for sterile neutrinos
  - Neutrino cross sections
  - Supernova neutrinos
  - Cosmic ray physics

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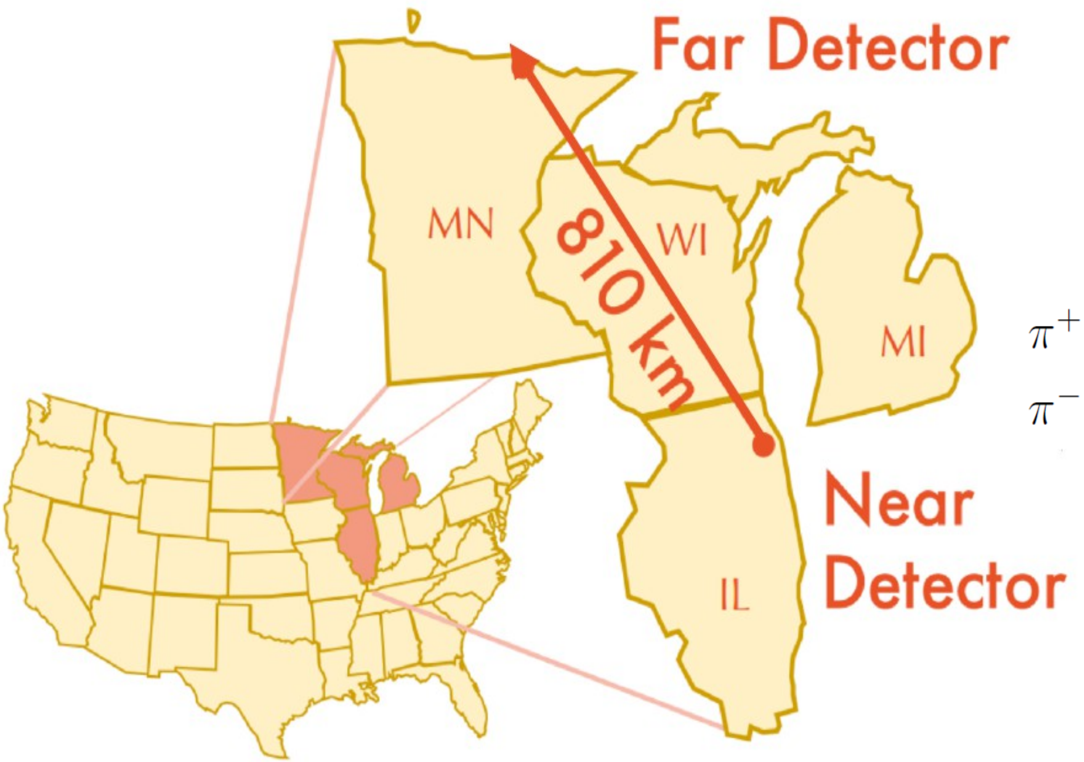
NOvA: Off-axis long-baseline neutrino oscillation experiment

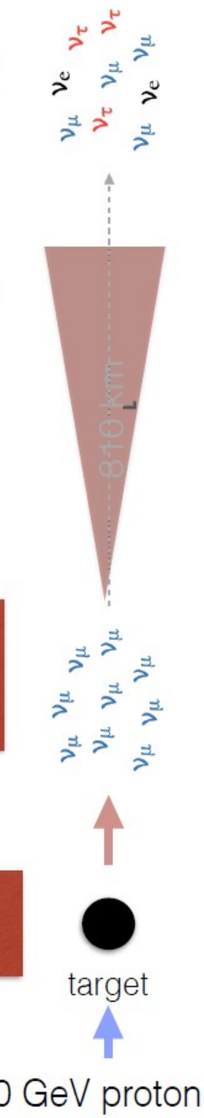


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Measure beam content after oscillation.
Use of a ratio measurement allows for reduction most systematics

Characterize muon-neutrino beam with ND

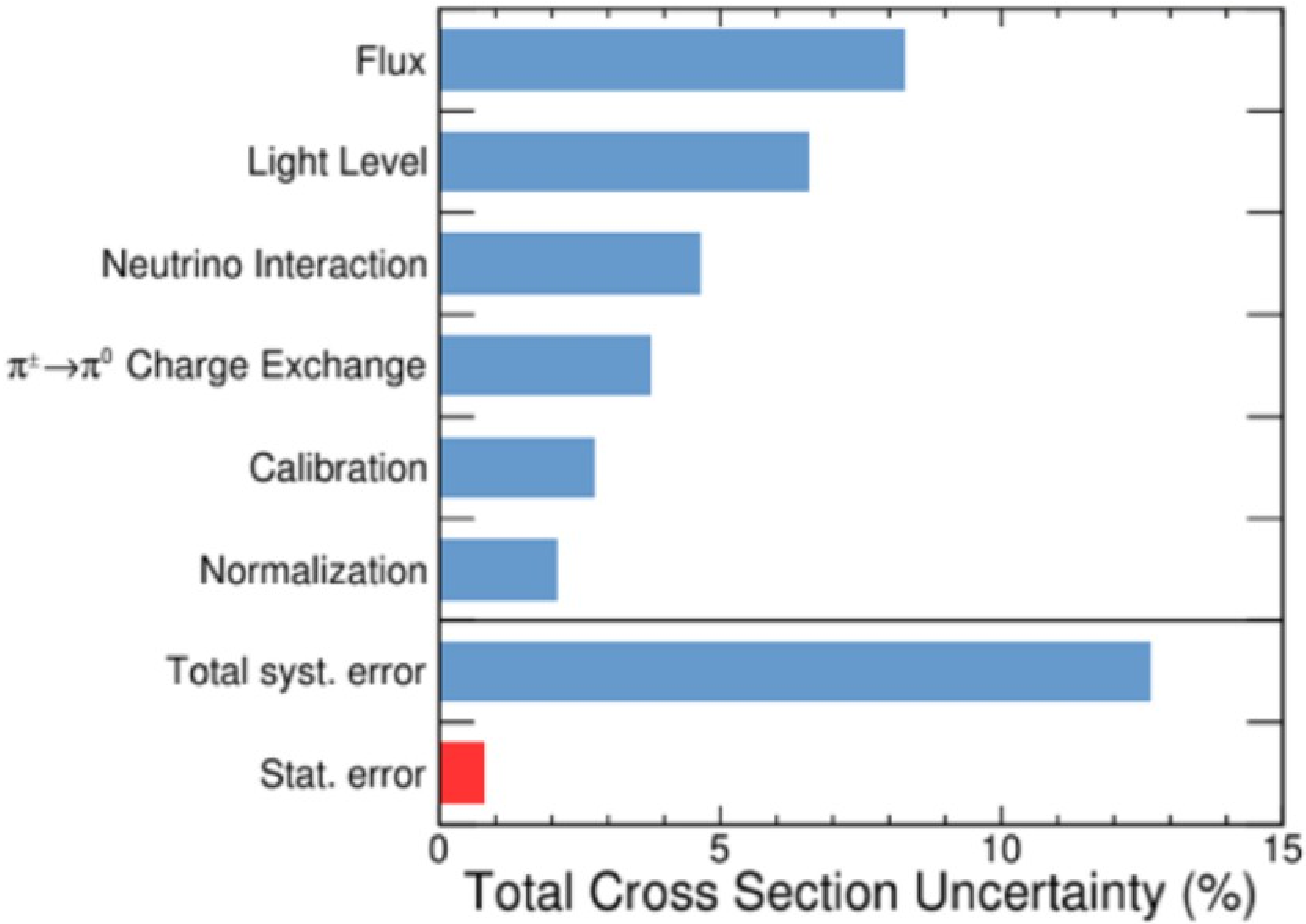
Create ~100% muon-neutrino beam (or anti-neutrino beam)



- Oscillation analysis consists of four samples
  - ν_e appearance ($\nu_\mu \longrightarrow \nu_e$)
  - ν_μ surval ($\nu_\mu \longrightarrow \nu_\mu$)
  - and the anti-neutrino versions of the same

NOvA in US

- **Suffering from uncertainties in cross sections.**



DUNE lead by US

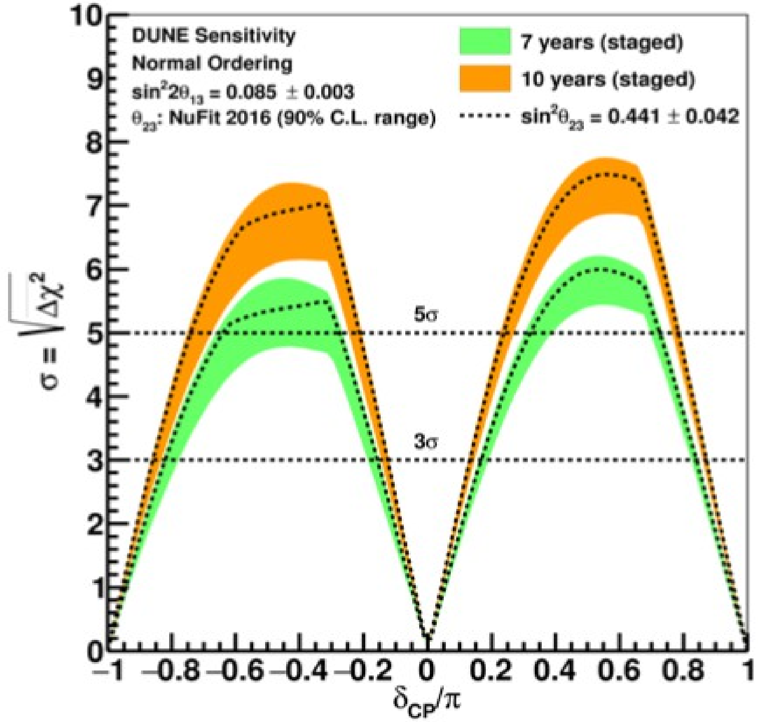
DEEP UNDERGROUND NEUTRINO EXPERIMENT

CP Violation Sensitivity

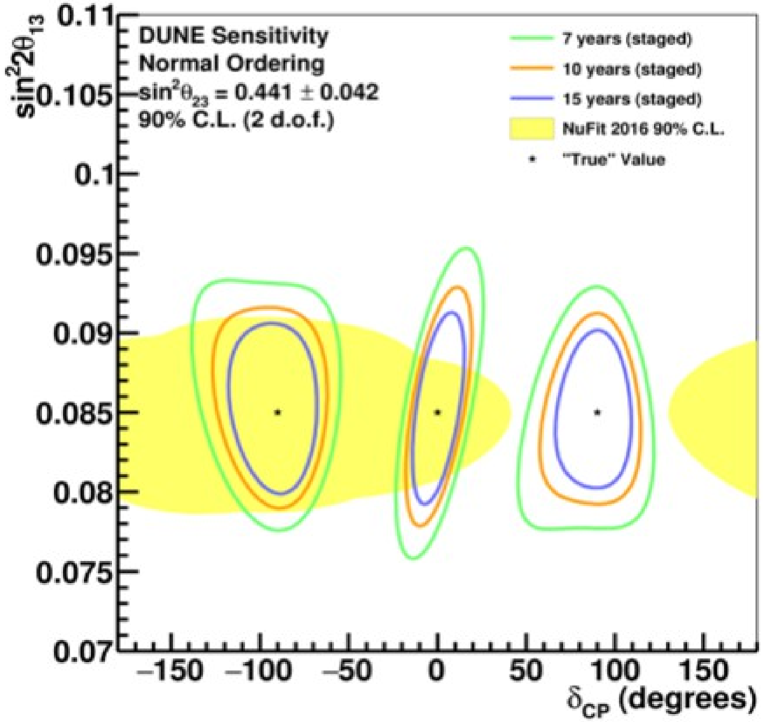
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

DUNE CDR:

CP Violation



Width of band indicates variation in possible central values of θ_{23}

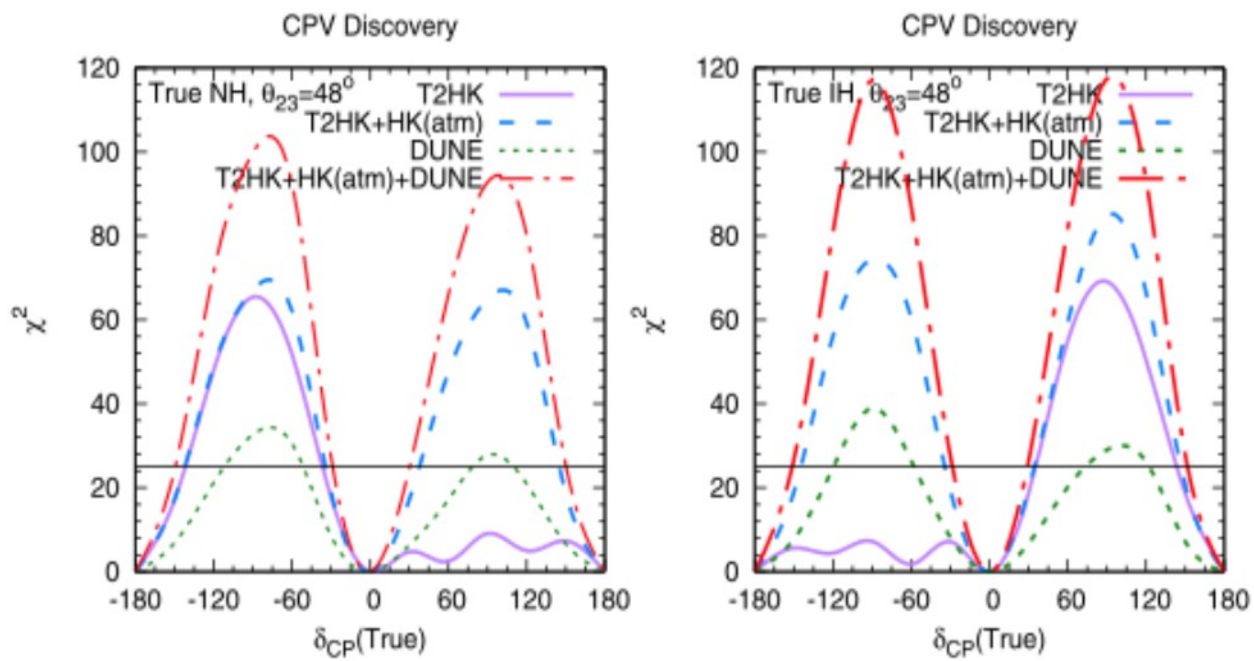


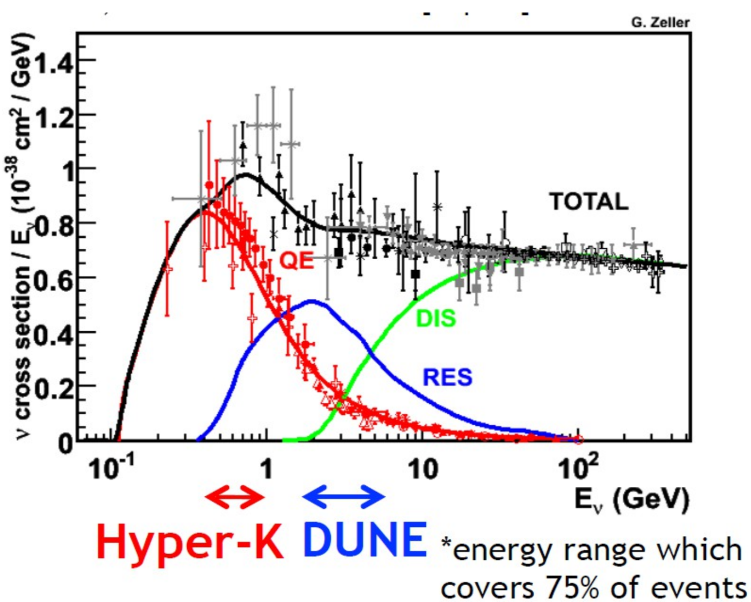
Simultaneous measurement of neutrino mixing angles and δ_{CP}

Comparison/complementarity of T2HK and DUNE

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

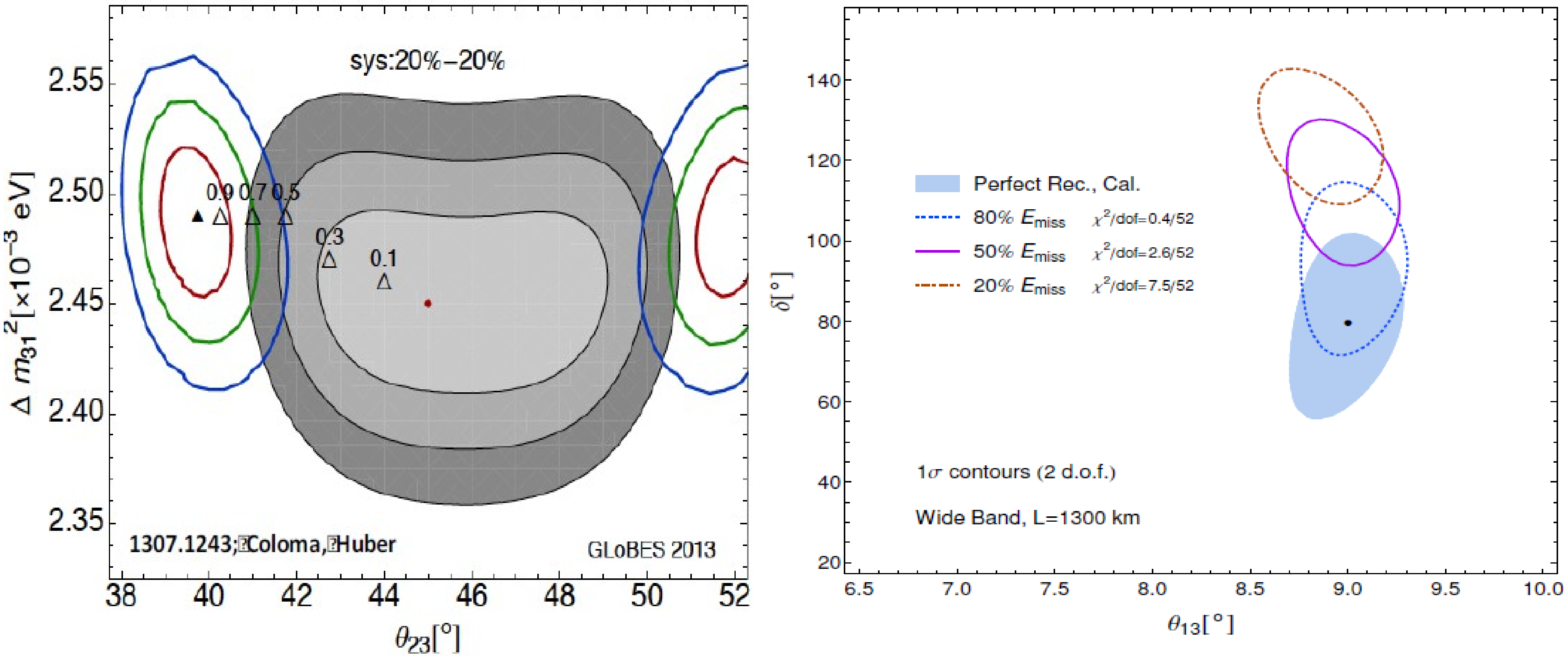
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$





- **The next generation of accelerator-based oscillation experiments will require ~% uncertainties (on far detector event rate and shape predictions)**
- **Neutrino-nucleus interaction modeling is difficult at the GeV scale**
- **Existing models are unlikely to provide sufficient precision for future experiments**

- **Killers hidden in these uncertainties: either in fluxes or in cross sections!**



- **Why not choose the best neutrino sources produced by muon decays?**
- **Measure the cross section of neutrino interactions more precisely!**

Search for new physics beyond CPV?

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05; Doring, Pas, Sicking, Weiler, 18
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 09, 10; Bertuzzo, Jana, Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12; Liao, Marfatia, Whisnant 18

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- Warm up of neutrino oscillation.
- Global efforts: discovery of CPV? Beyond CPV?
- **Progress of Chinese efforts.**
- Summary.

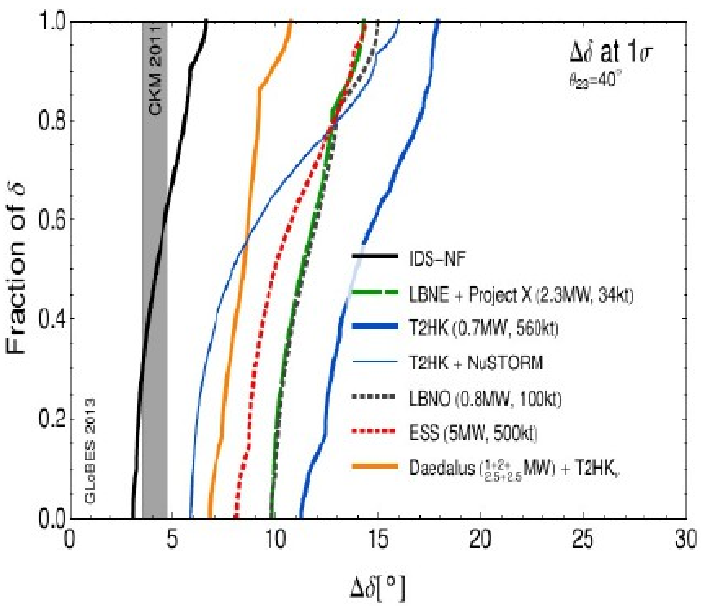
Dreaming machine with well-known fluxes by muon decay beams

- **Muon-decay neutrino beams with well-defined fluxes:**

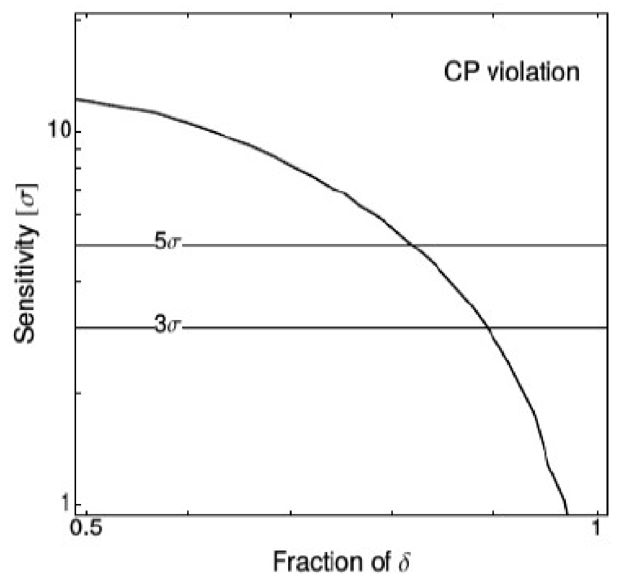
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

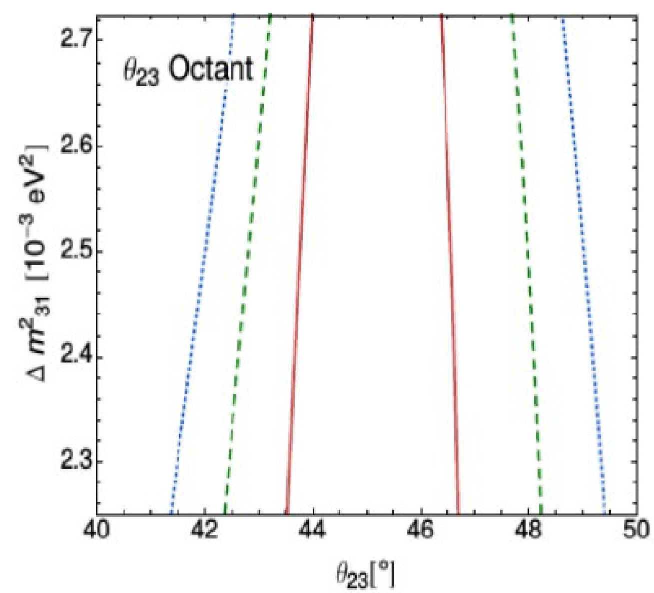
- **Dreaming machine to reach the sub-percent level sensitivity of neutrino mixing parameters.**



Global comparison



Discovery reach of CPV



Octant sensitivity

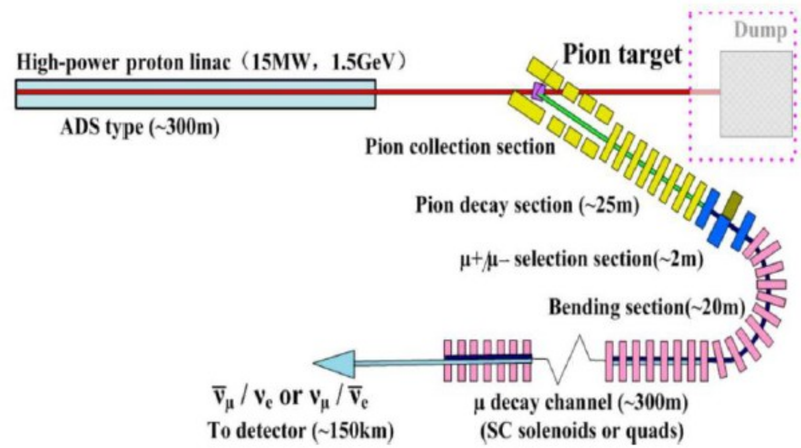
Overview of a Chinese proposed MOMENT

(Muon-decay MEdium baseline NeuTrino beam facility)

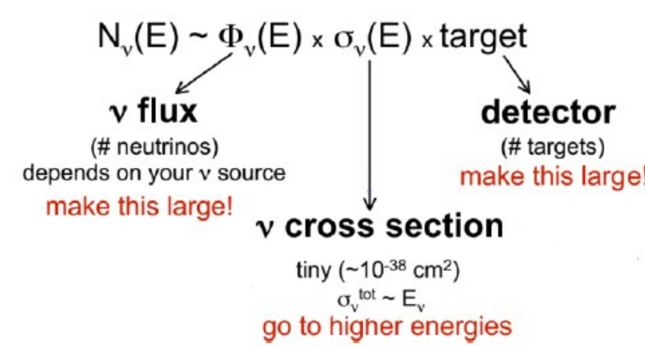
- **MOMENT**: the proposal is still in an early stage ; the details have not been completely fixed.

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

- **Baseline**: L=150 km

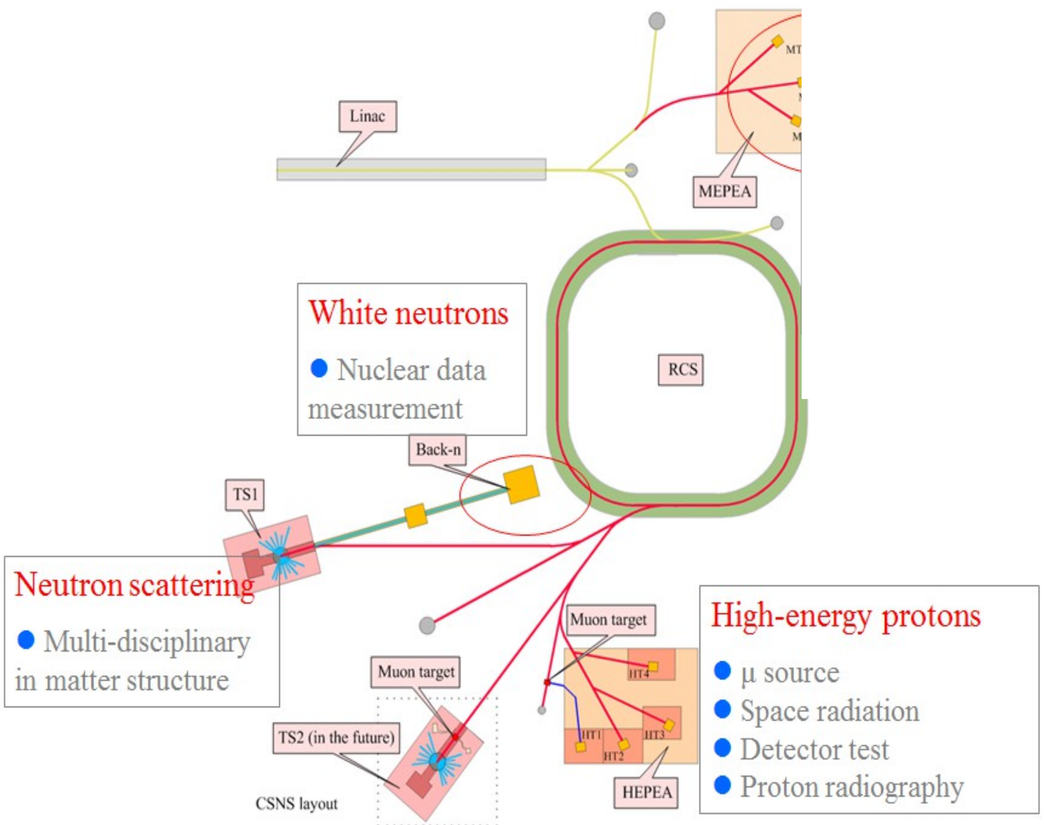


In the MOMENT: the neutrino flux peak at low energies
→ require a very massive detector to compensate the low interaction cross section

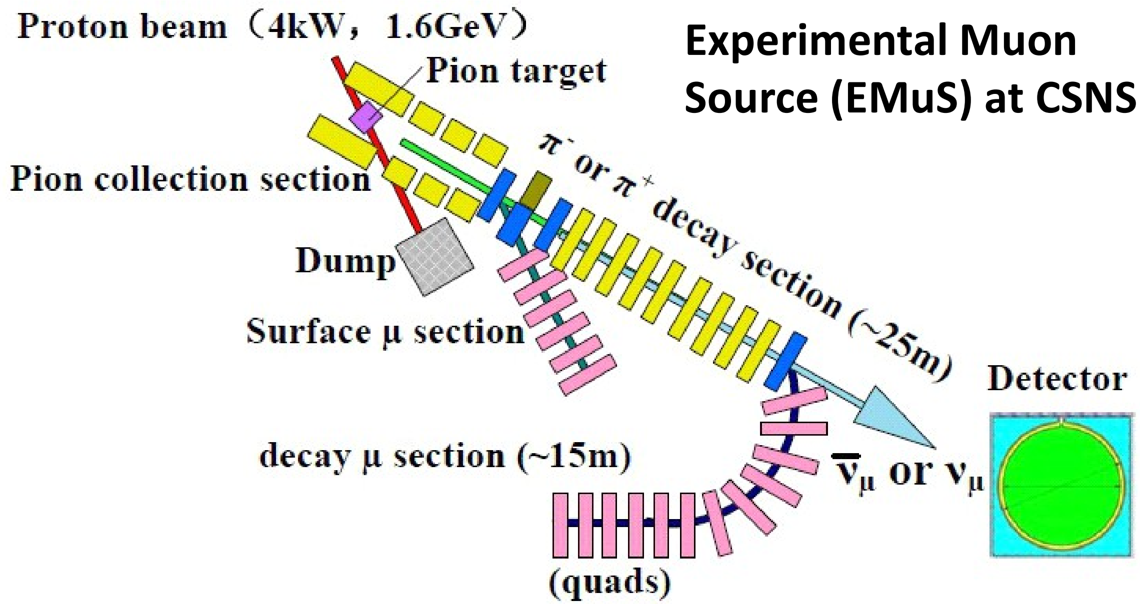


Chinese proton drivers to muon beams

- **CAS-IHEP: pulsed proton beam, 1.6 GeV, 25 Hz @ 100 kW.**



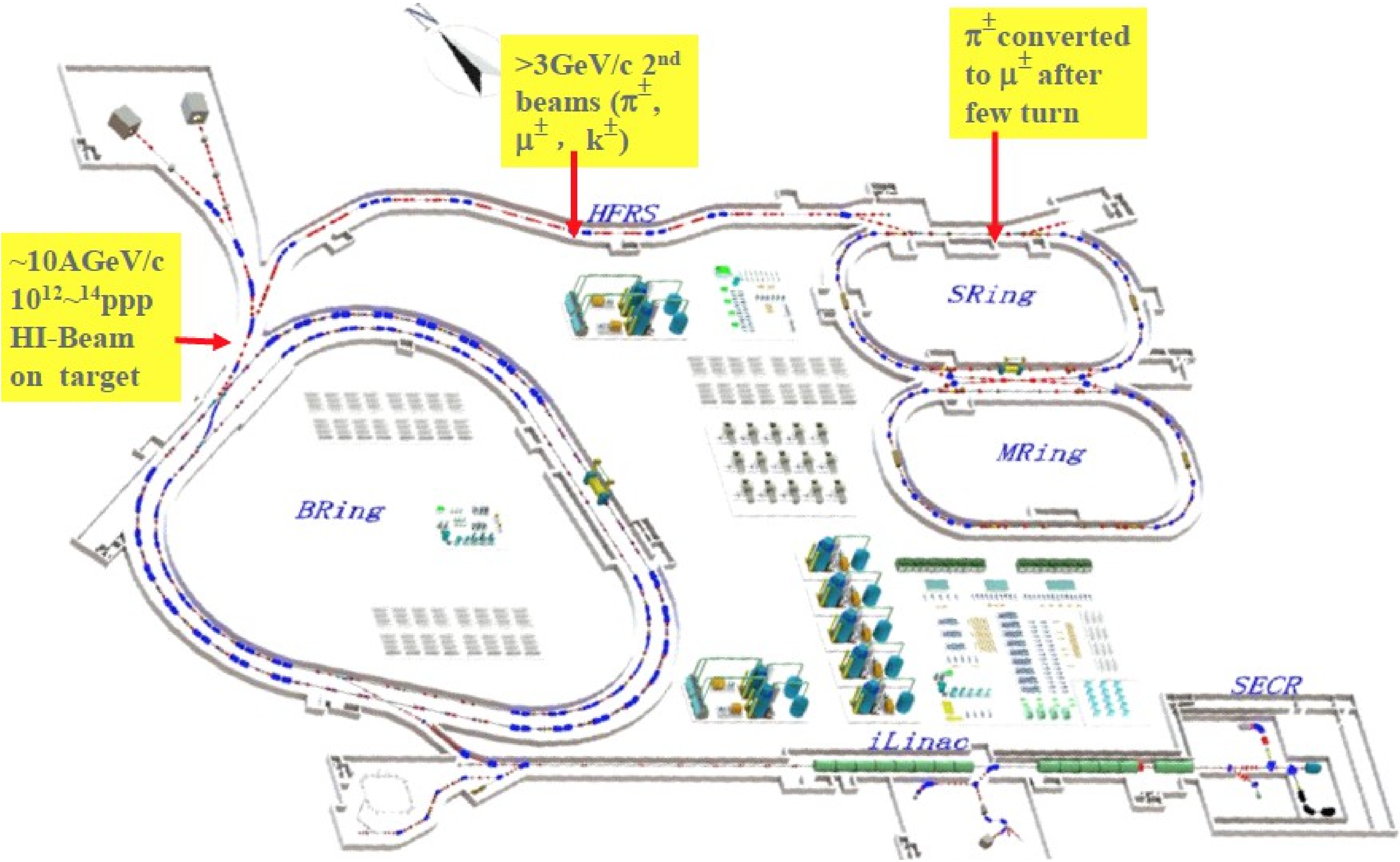
Schematic for CSNS multiple platforms



Experimental Muon Source (EMuS) at CSNS

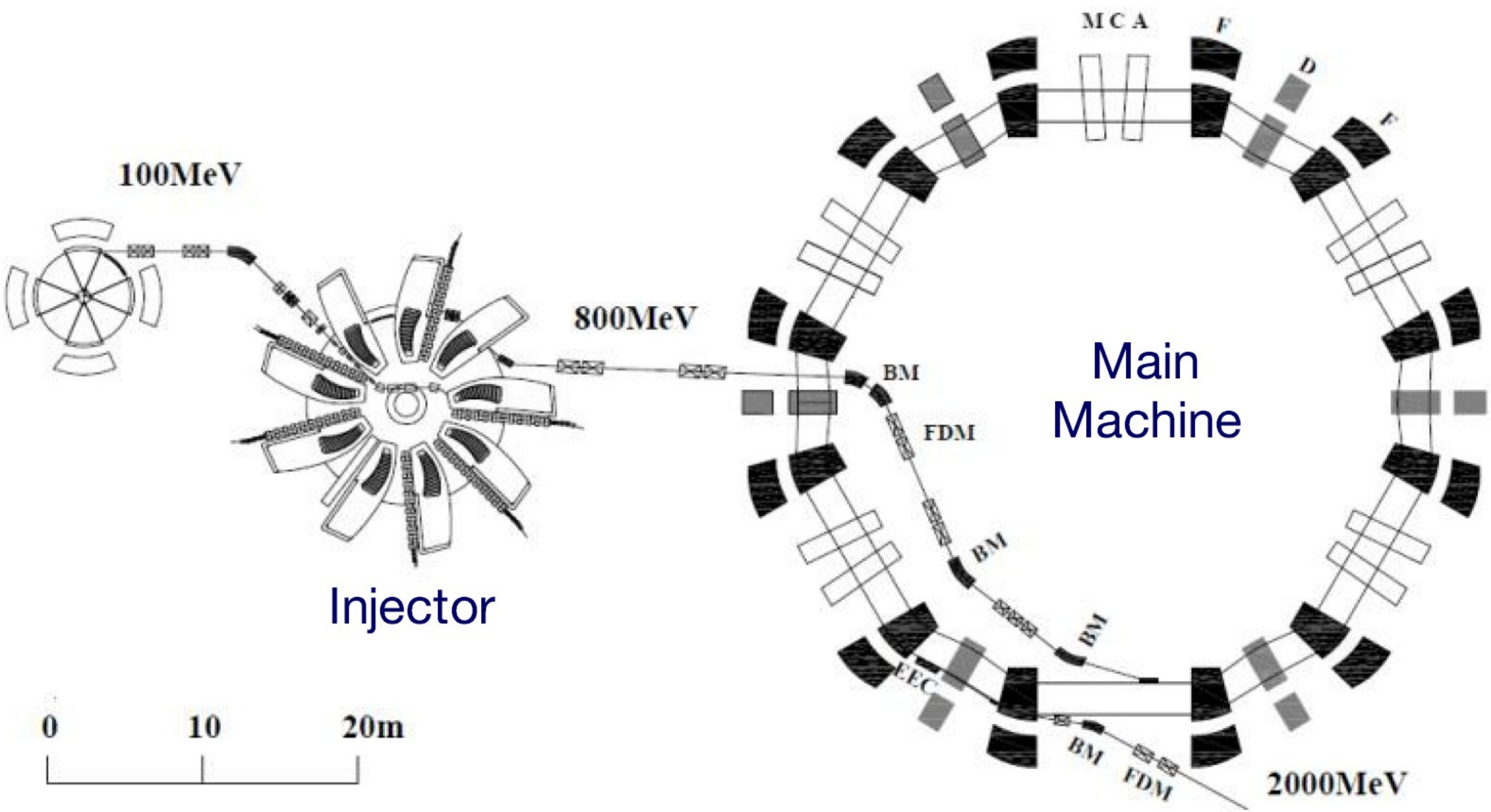
Chinese proton drivers towards muon beams

- **CAS-IMP: continuos proton beam, 500 MeV @ 2.5 MW.**



Chinese proton drivers towards muon beams

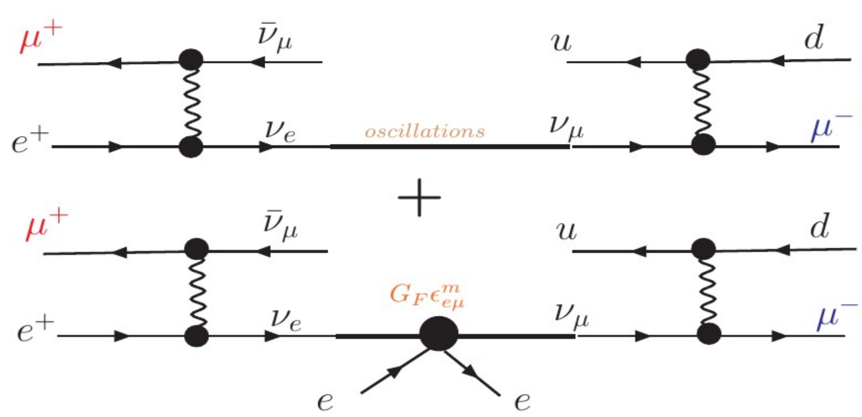
- **CIAE: Continuous proton beam 0.1 GeV → 0.8 GeV → 2 GeV.**



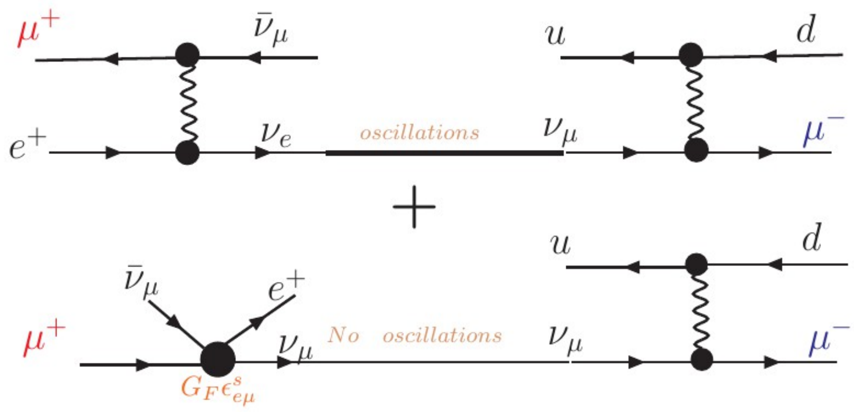
Links between NSIs and neutrino oscillations

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

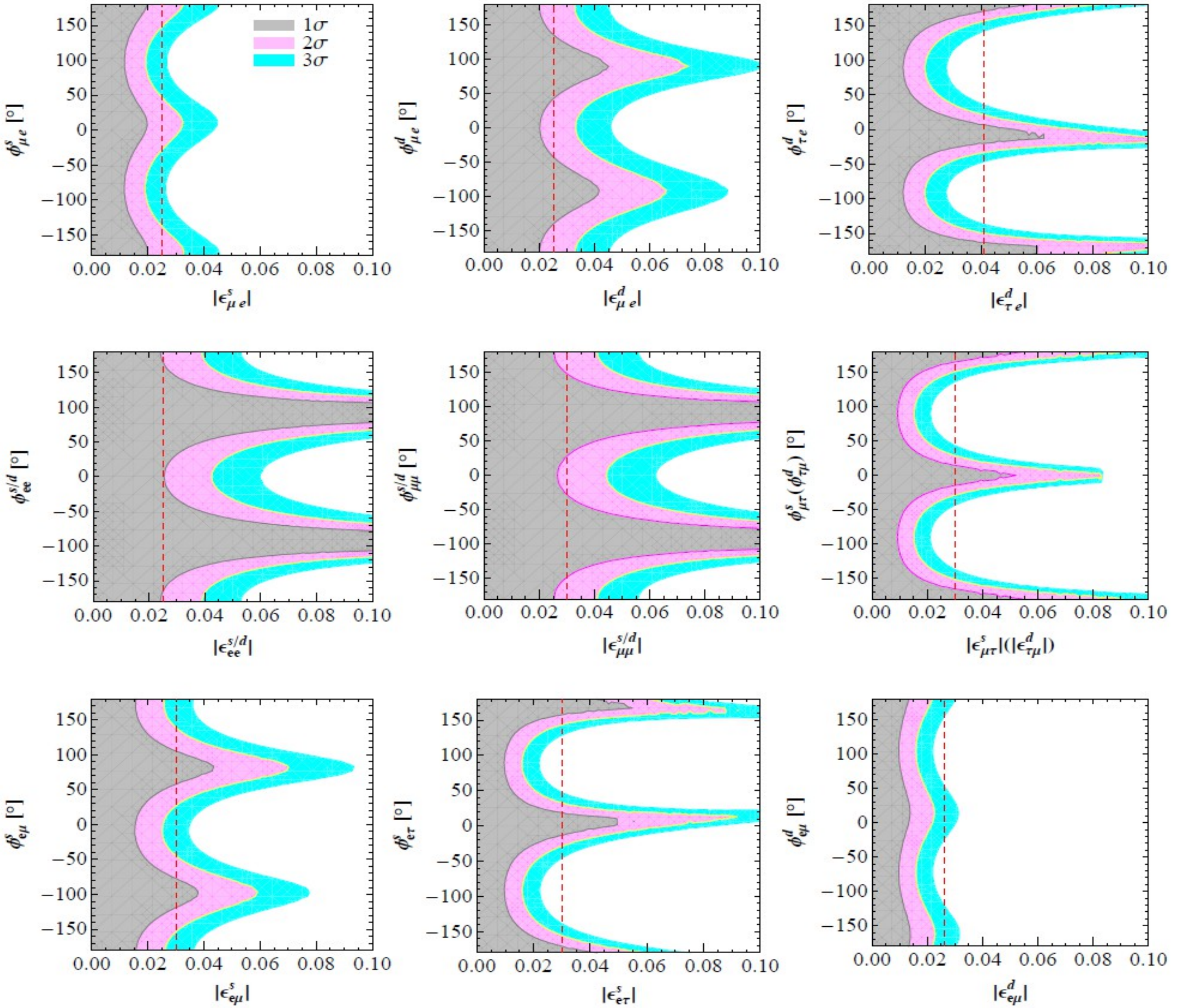


NSI at neutrino productions

Constraints of CC-NSIs 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.**

arXiv:1705.09500

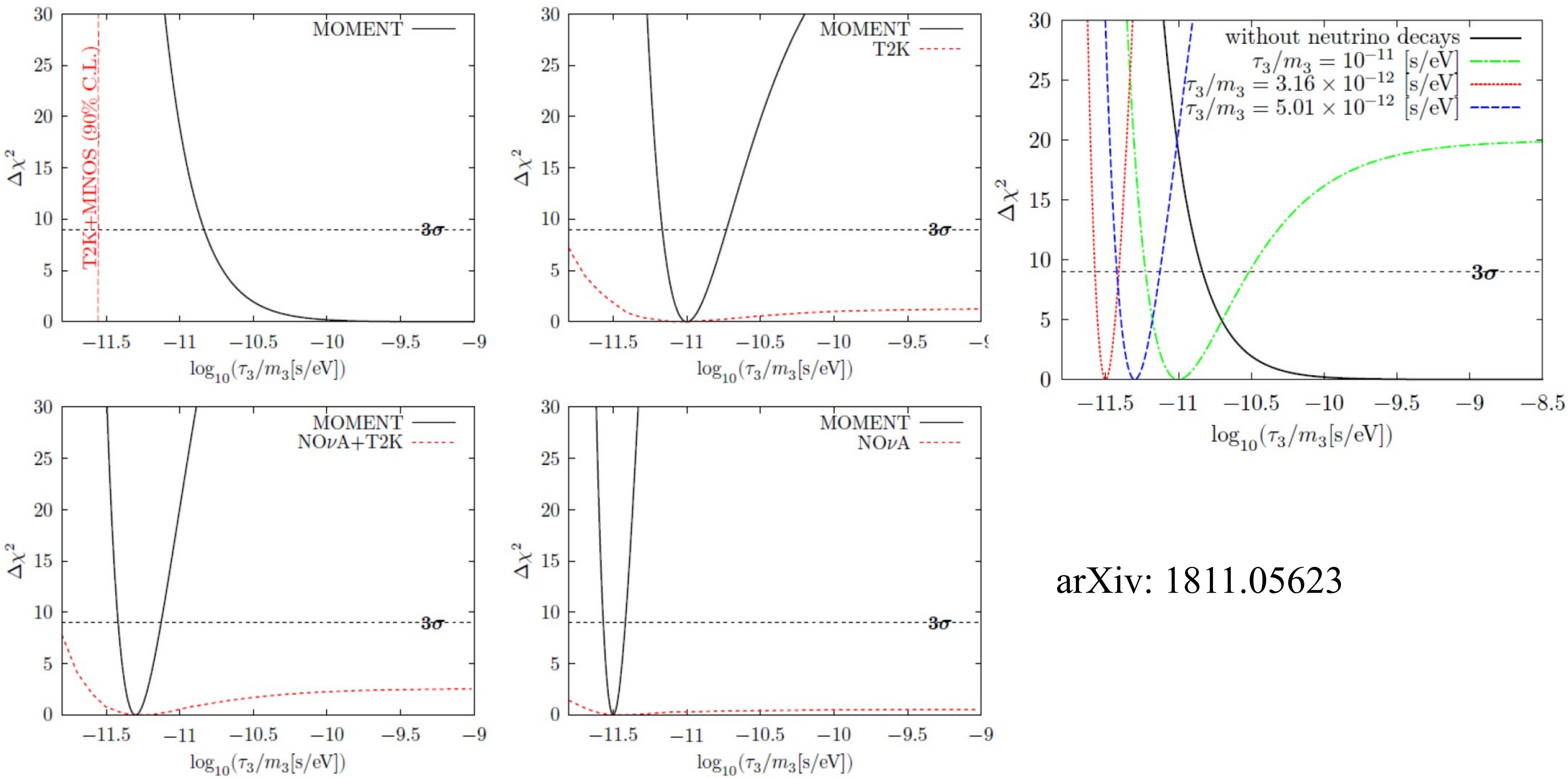


An exercise: neutrino invisible decays at MOMENT

- Hints in the recent discrepancy of NOvA and T2K.

  S. Choubey, D. Dutta and D. Pramanik, JHEP **1808**, 141 (2018)

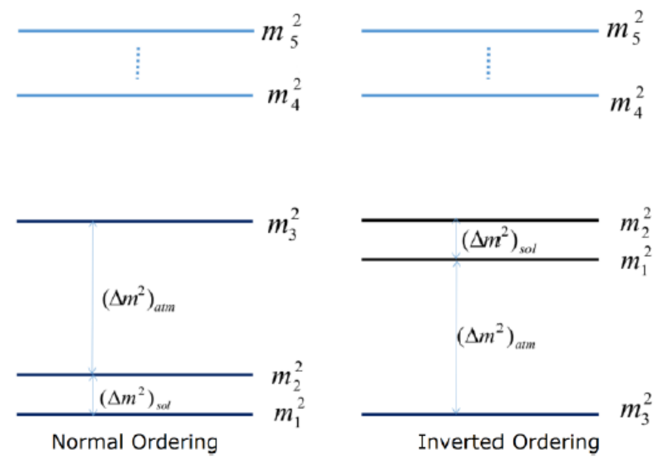
- MOMENT will confirm/resolve the issue with more than 3 sigma C. L.



arXiv: 1811.05623

Tests of unitarity violation

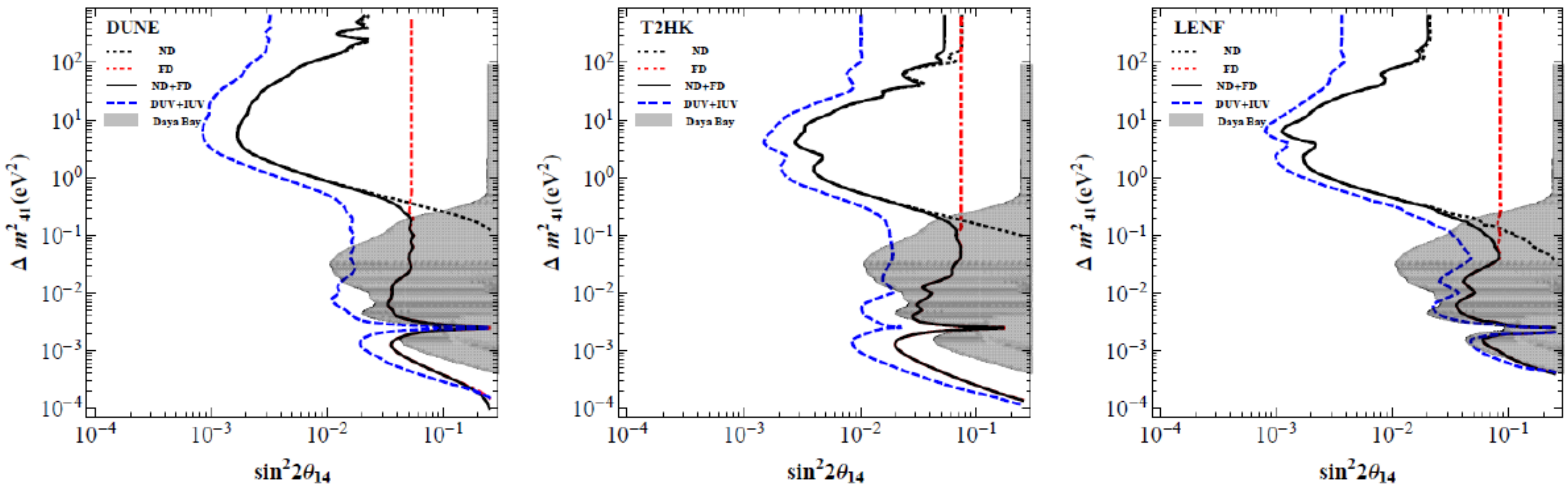
- Light sterile neutrino anomaly (eV scale)
- Heavy sterile neutrinos from see-saw model (GeV scale)
- Dark matter candidate (keV scale)
- IUV (indirect unitary violation) by heavy sterile neutrinos
- DUV (direct unitary violation) by light sterile neutrinos: oscillation with active ones



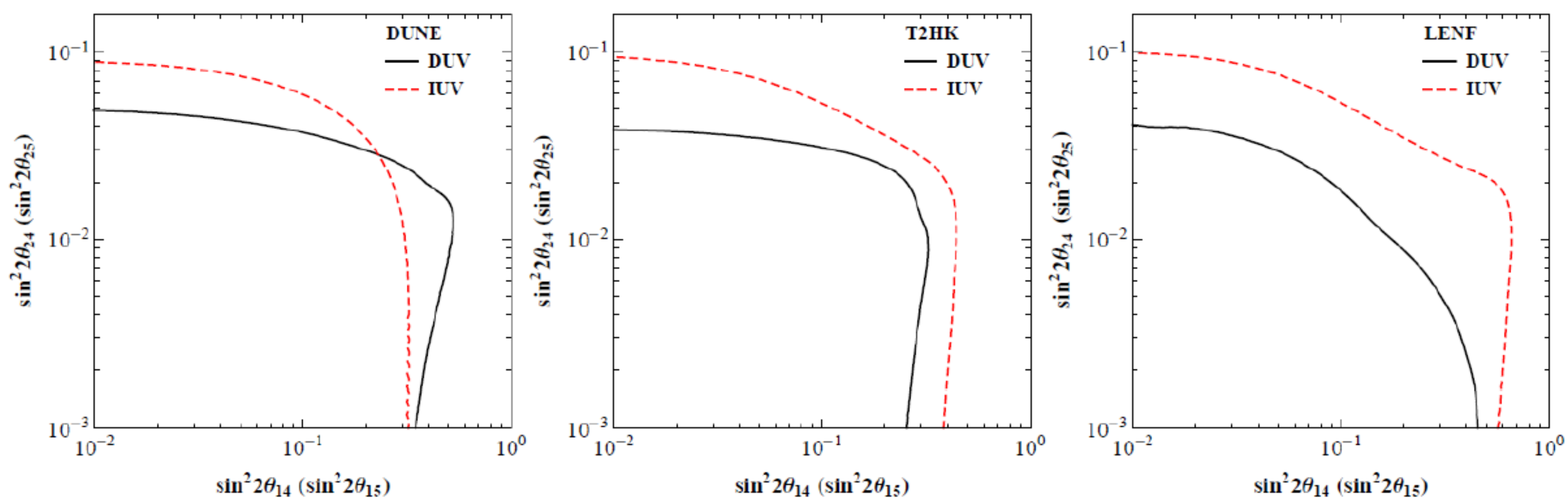
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1}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

- 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 in terms of unitarity violations

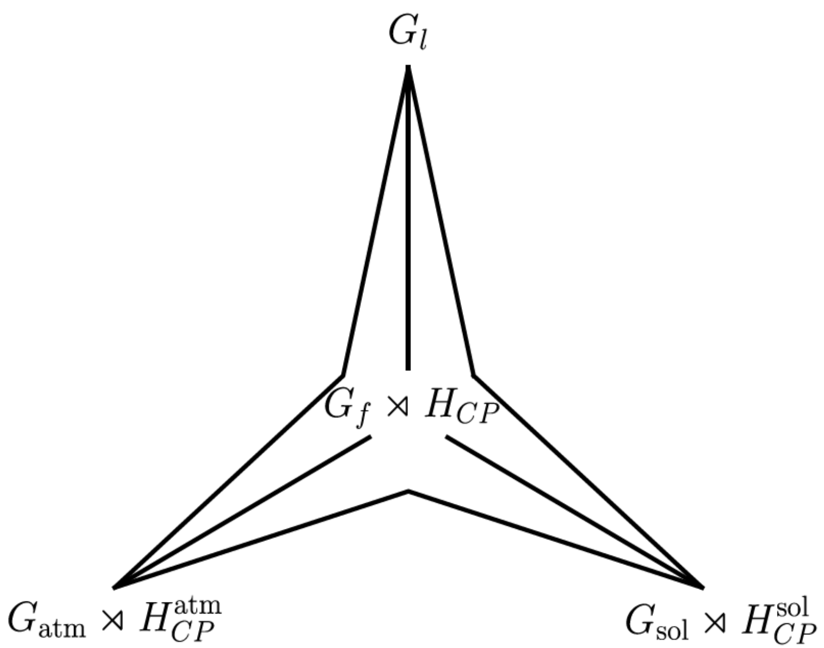


arXiv: 1708.04909



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

- **Take the Tri-direct CP symmetry model as an example.**
- **Reduced degrees of freedom compared with 6 DoFs in PMNS.**

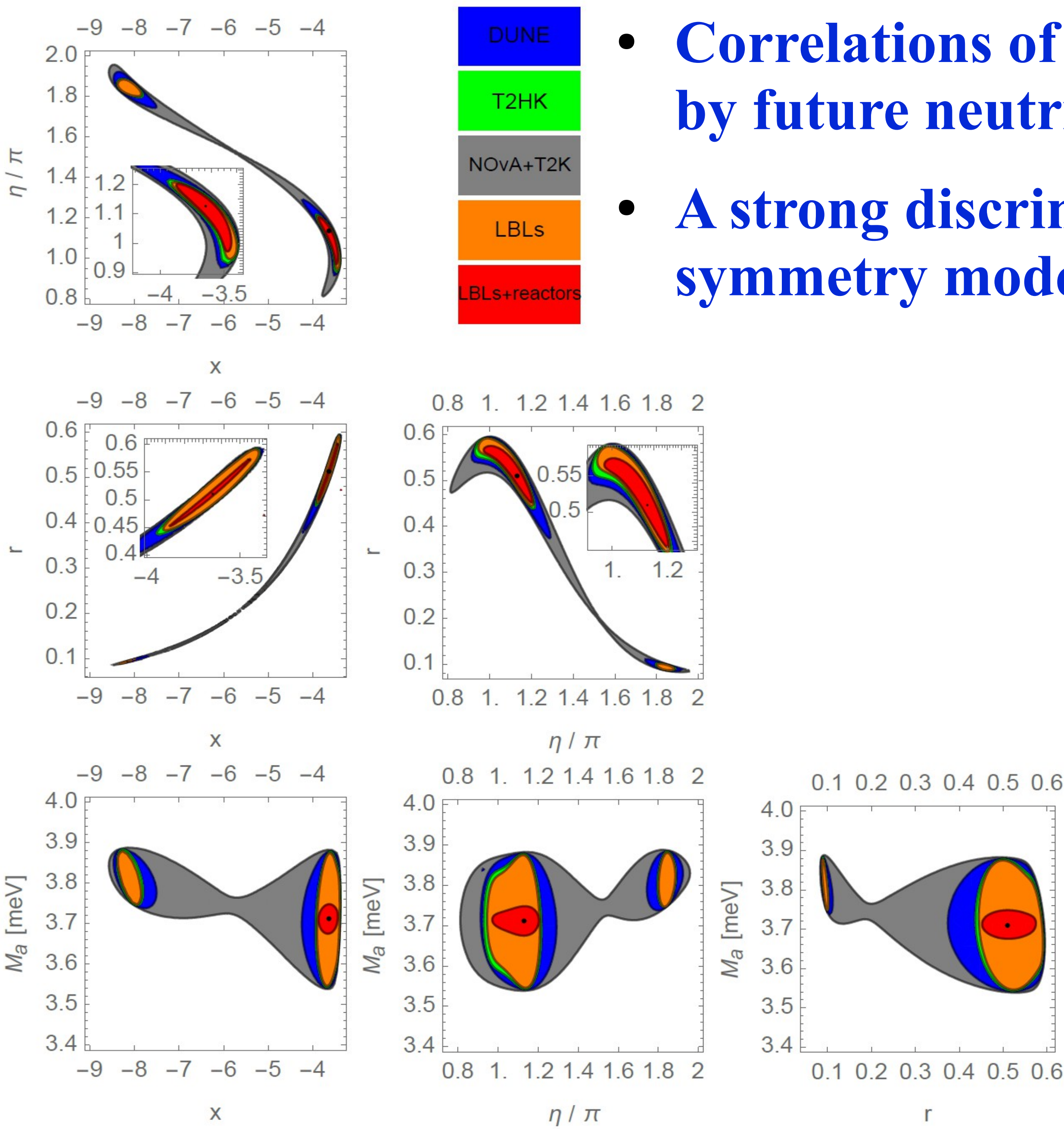


$$m_\nu = m_a \begin{pmatrix} 1 & \omega & \omega^2 \\ \omega & \omega^2 & 1 \\ \omega^2 & 1 & \omega \end{pmatrix} + e^{i\eta} m_s \begin{pmatrix} 1 & x & x \\ x & x^2 & x^2 \\ x & x^2 & x^2 \end{pmatrix}$$

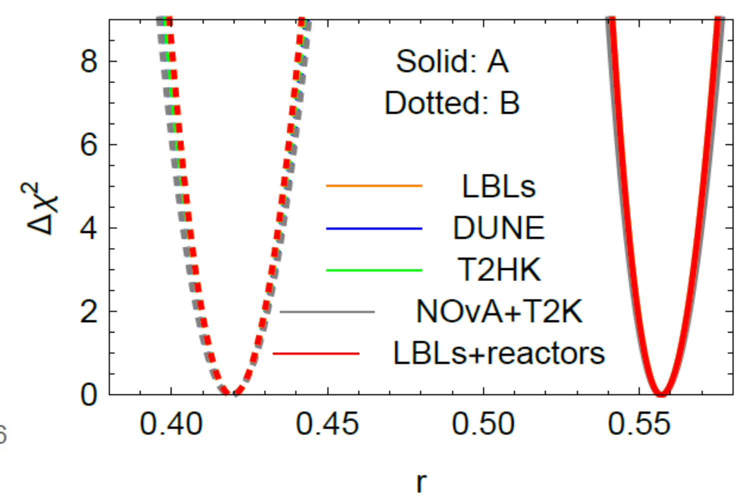
$$\mathcal{L} = -y_l L \phi_l E^c - y_{\rm atm} L \phi_{\rm atm} N_{\rm atm}^c - y_{\rm sol} L \phi_{\rm sol} N_{\rm sol}^c - \frac{1}{2} x_{\rm atm} \xi_{\rm atm} N_{\rm atm}^c N_{\rm atm}^c - \frac{1}{2} x_{\rm sol} \xi_{\rm sol} N_{\rm sol}^c N_{\rm sol}^c + \text{h.c.}$$

G.J. Ding, S. King, C. C. Li, arXiv: 1807.07538.

Test of neutrino models based on flavor symmetries



- **Correlations of new DoFs well constrained by future neutrino experiments.**
- **A strong discrimination of tri-direct CP symmetry models.**



Work in progress
by Ding, Li, Tang, Wang.

Table of Contents

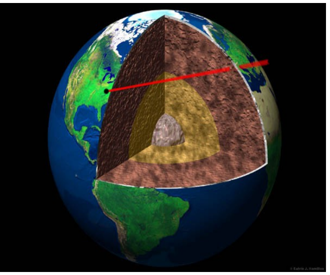
- Warm up of neutrino oscillation business.
- Motivations of neutrino physics.
- Discovery of the leptonic CP violation?
- **Summary**

Summary

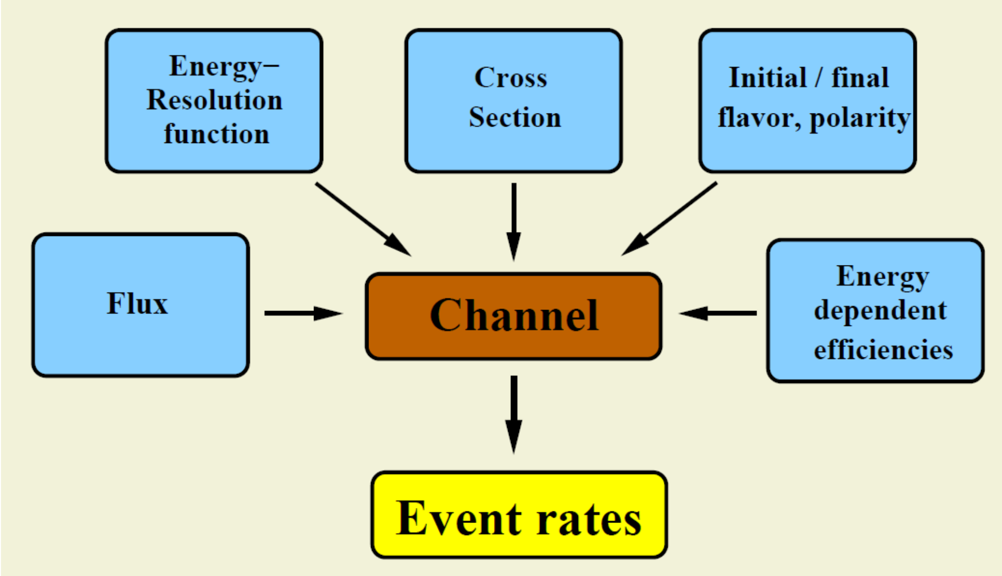
- **Lots of new physics to be done with neutrino oscillation experiments.**
- **T2HK and DUNE are complementary in discovery of CPV.**
- **Apart from CPV, we should do precision measurements and search for new physics.**
- **Chinese efforts are on the way with neutrinos produced by accelerator muon sources.**
- **Welcome to work together on new physics searches with accelerator neutrinos.**

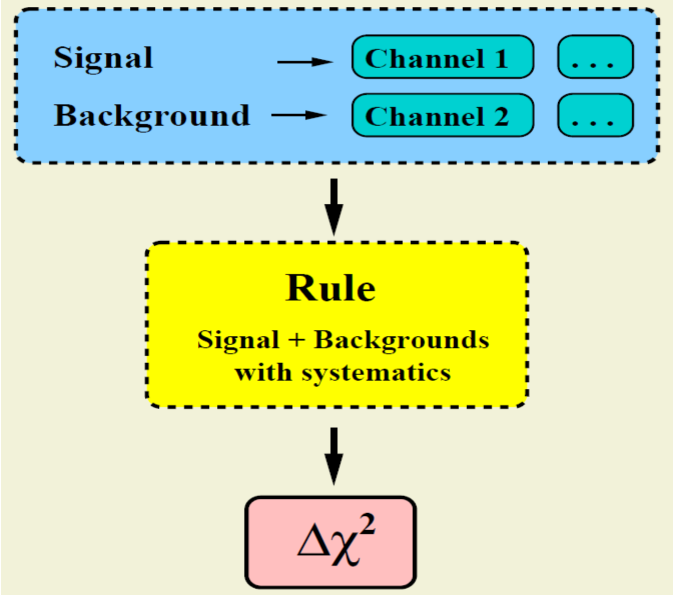
Thanks for your attention!

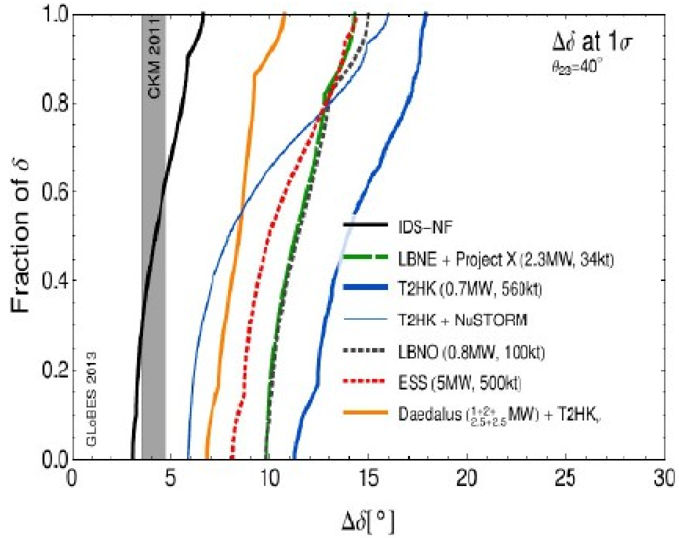
Simulations of neutrino oscillations w/o new physics



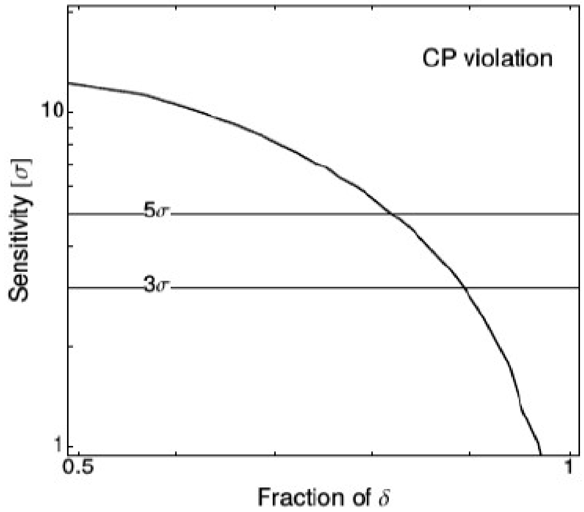
Credits:
J. Kopp



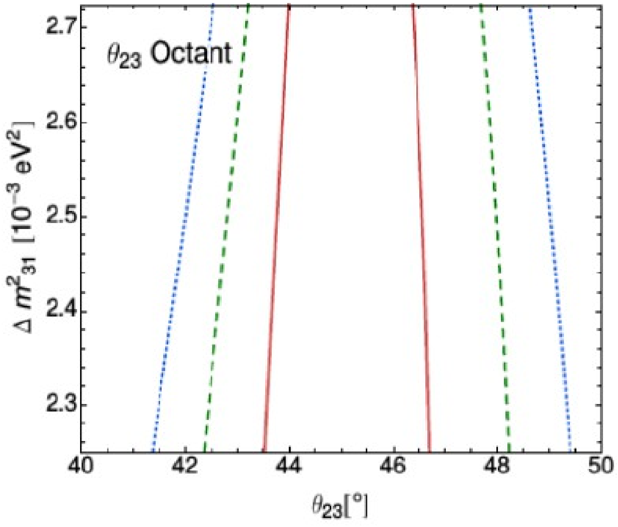




Global comparison

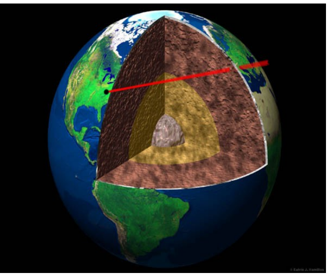


Discovery reach of CPV

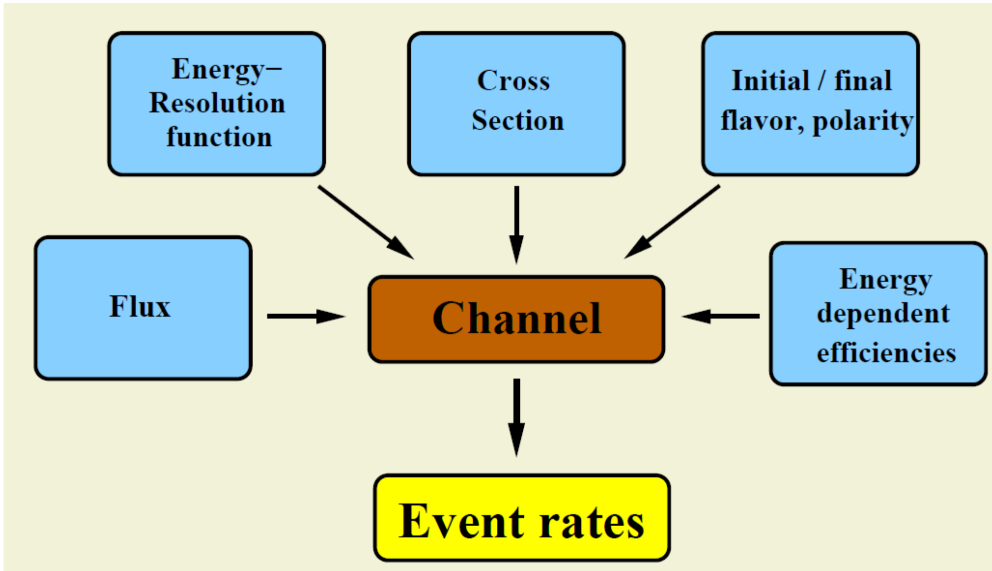


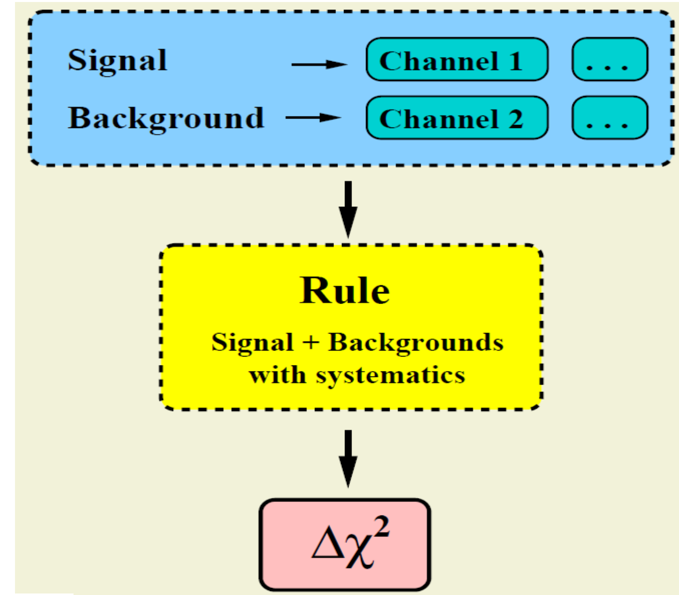
Octant sensitivity

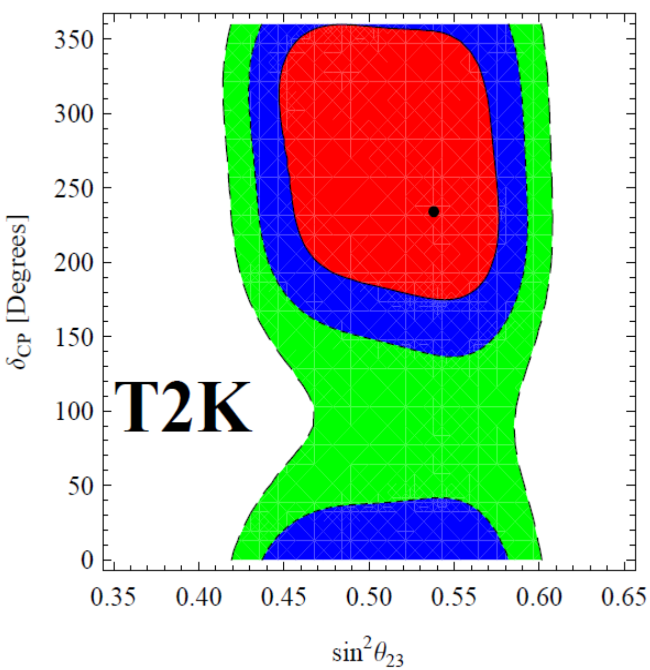
Simulations of neutrino oscillations w/o new physics

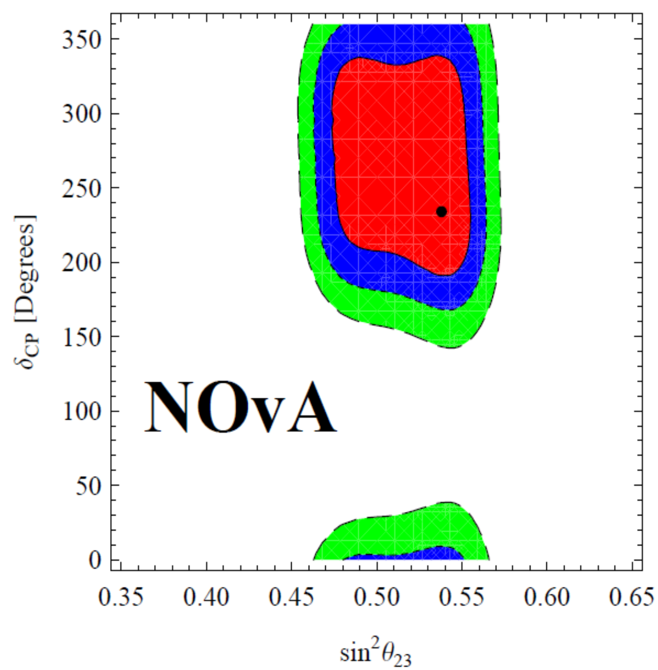


Credits:
J. Kopp









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