Search for new physics with accelerator neutrino oscillations

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The messages want to be conveyed today

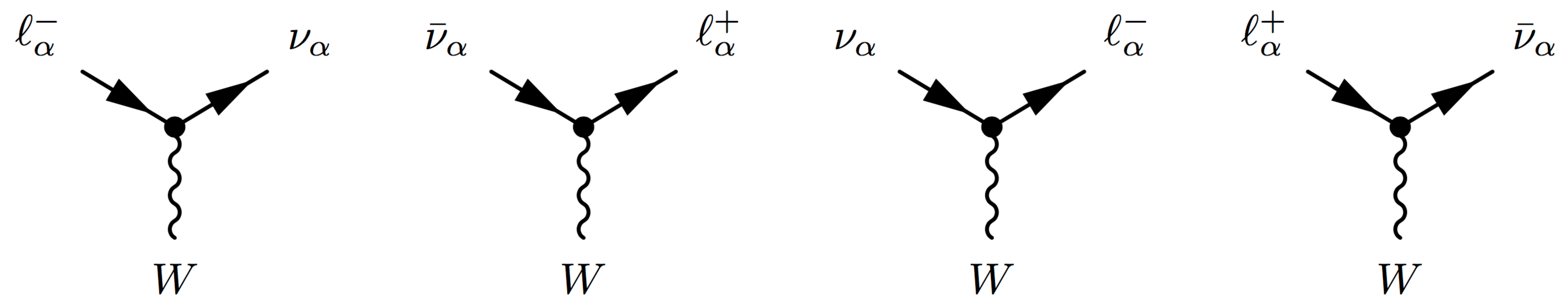
1. Neutrino oscillations are the only evidence for the physics beyond the standard model (BSM) by far.
2. Neutrino physicists want to know more about neutrino oscillations.
3. Particle physicists want to know if there is any other BSM phenomenology.
4. To achieve the above, we need accelerator neutrino facilities.

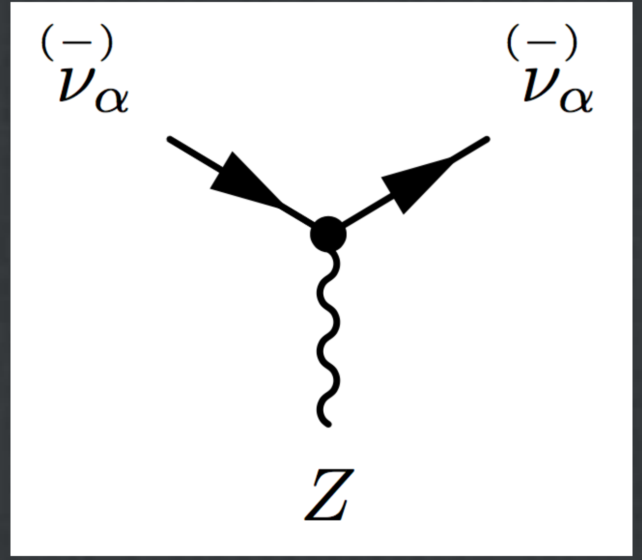
Neutrinos in the standard model

- Its existence was proposed by Pauli in 1930, and was confirmed in 1956.

- They are predicted to be
  1. massless
  2. only weak interactions
  3. three flavours- electron neutrinos, muon neutrinos, and talon neutrinos.

$$\mathscr{L}_{H,\mathrm{L}} = - \sum_{\alpha,\beta=e,\mu,\tau} Y'^{\ell}_{\alpha\beta} \, \overline{L'_{\alpha L}} \, \Phi \, \ell'_{\beta R} + \mathrm{H.c.}$$





Current understanding on neutrino oscillations

neutrino mass-square differences

$$P_{\nu_\alpha\to\nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j}\boxed{\Re\left[U^*_{\alpha k}\,U_{\beta k}\,U_{\alpha j}\,U^*_{\beta j}\right]}\,\boxed{\sin^2\left(\frac{\Delta m^2_{kj}L}{4E}\right)}$$
$$+\,2\sum_{k>j}\boxed{\Im\left[U^*_{\alpha k}\,U_{\beta k}\,U_{\alpha j}\,U^*_{\beta j}\right]}\,\boxed{\sin\left(\frac{\Delta m^2_{kj}L}{2E}\right)}.$$

neutrino mixing

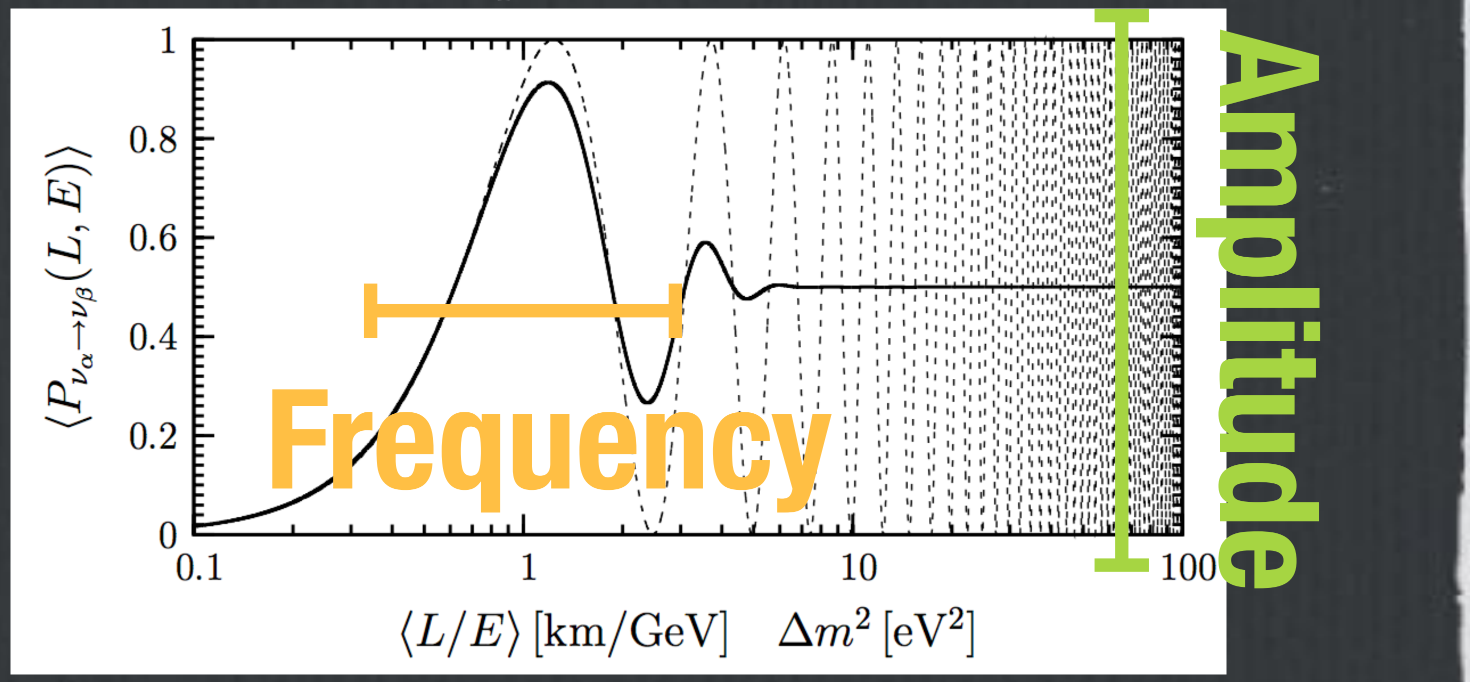
$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu, \tau)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathcal{P}$$

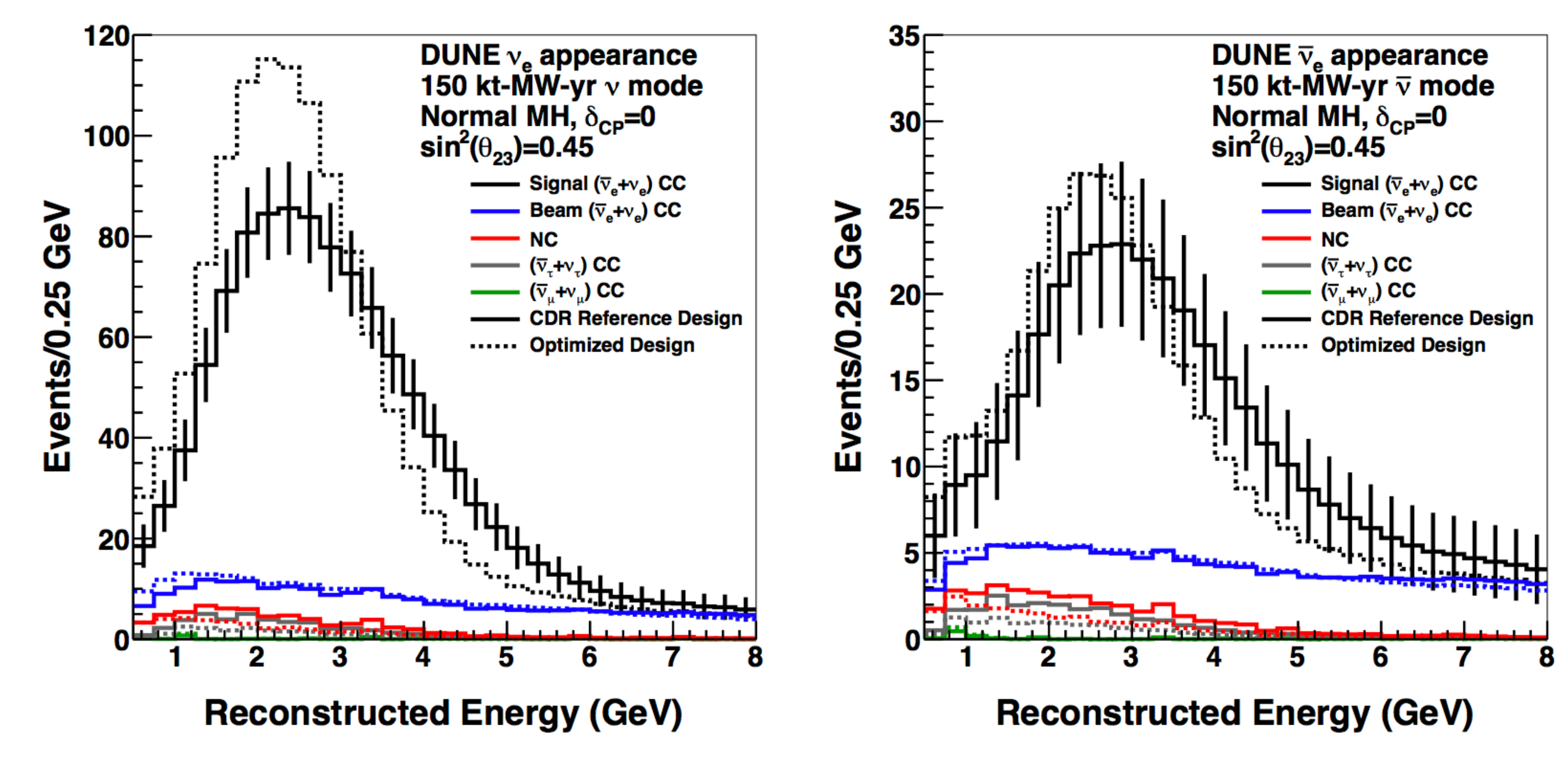
$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

$\mathcal{P} = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$

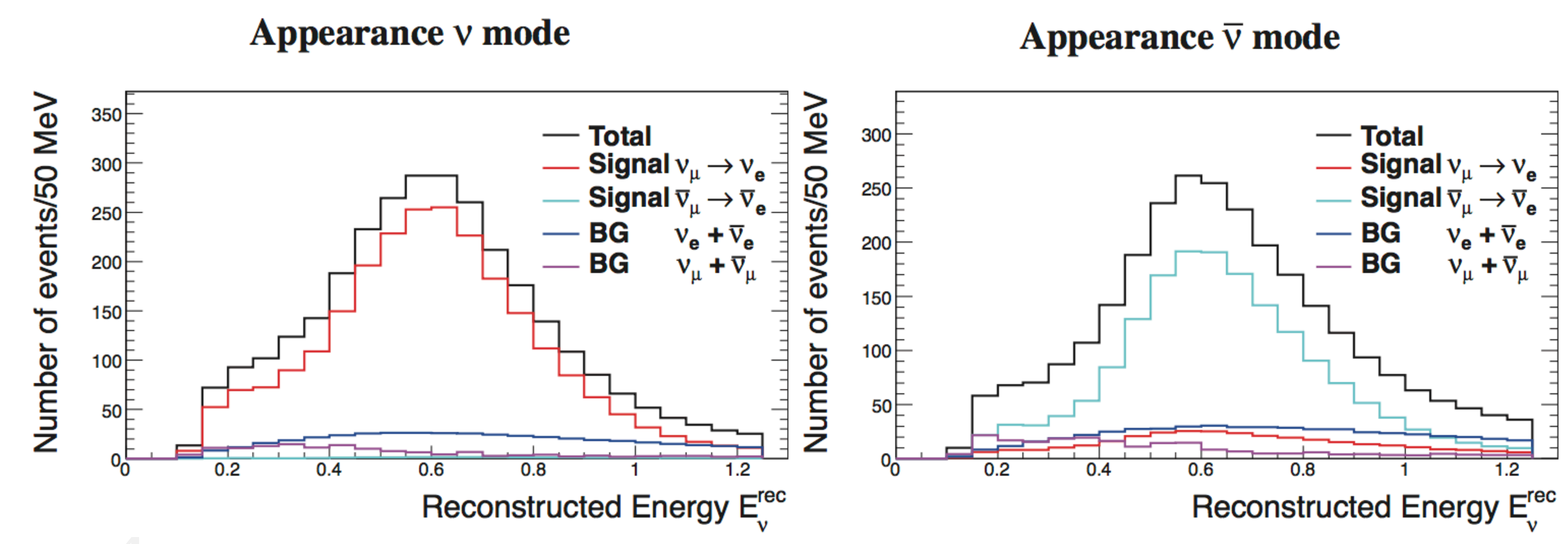
a 2ν *example with* $\sin^2 2\theta = 1.$



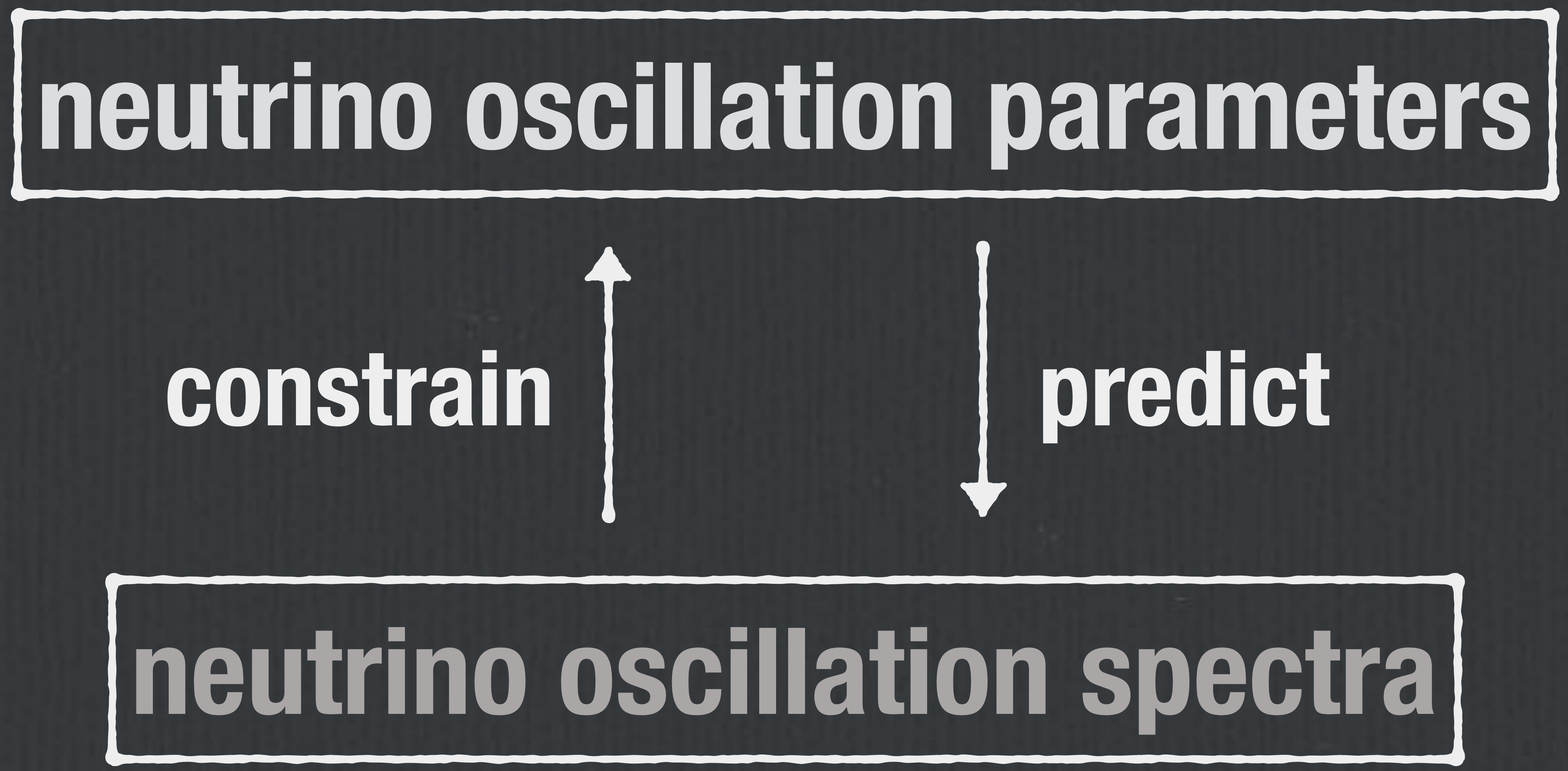
DUNE $\nu_\mu \to \nu_e$



T2HK $\nu_\mu \to \nu_e$



Oscillation parameters vs. neutrino oscillations



neutrino oscillation parameters

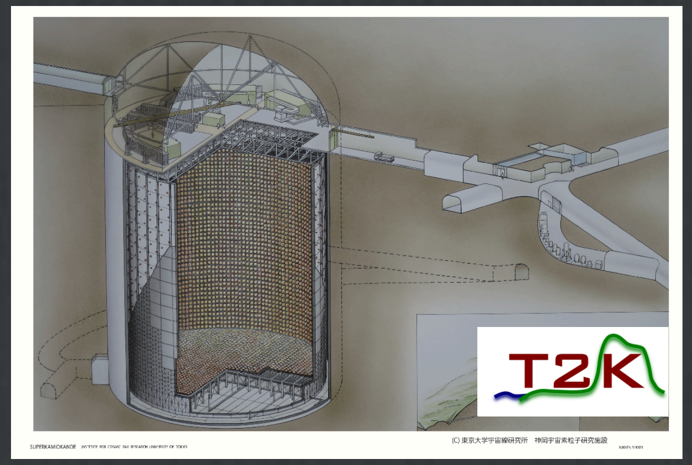
constrain

predict

neutrino oscillation spectra

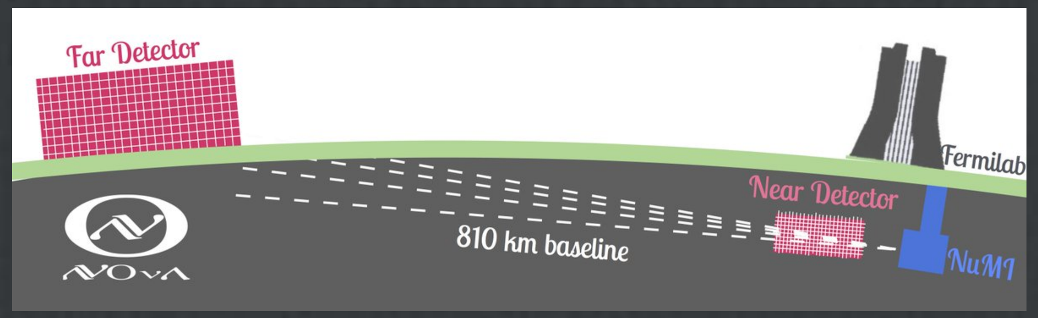
Current, future, and proposed neutrino Oscillation Experiments

Current running



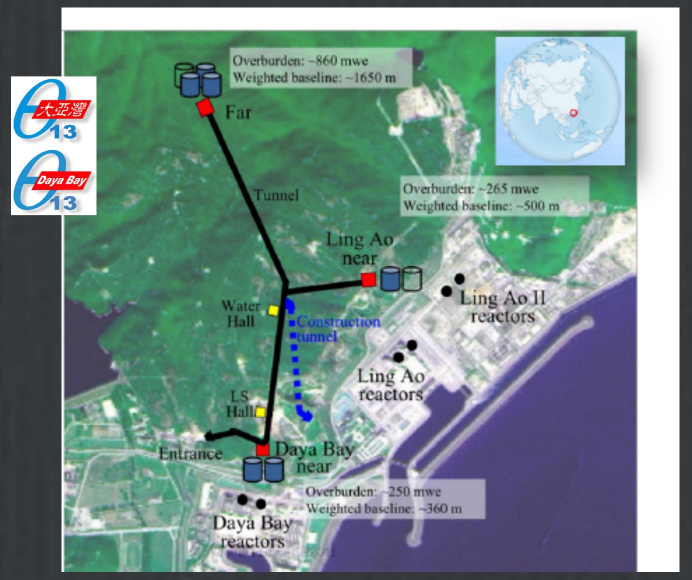
T2K

$\sin\theta_{13}$
$\sin\theta_{23}$
$\sin\delta$



NOvA

$\sin\theta_{23}$
$\sin\delta$
Δm^2_{31}



Daya bay

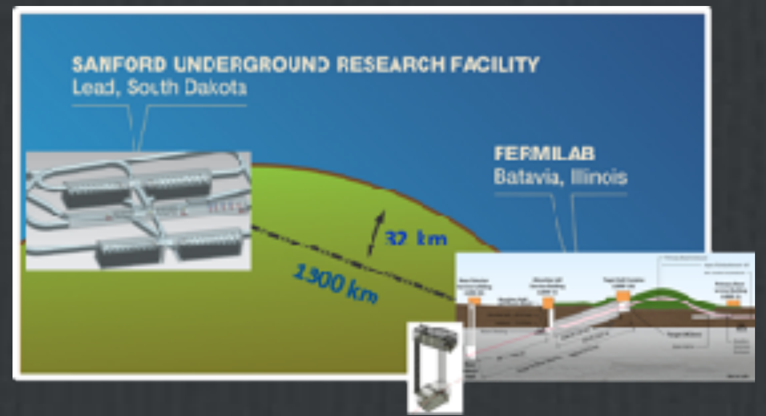
$\sin\theta_{13}$

$|\Delta m^2_{31}|$

Upcoming

T2HK

$\sin\theta_{13}$
$\sin\theta_{23}$
$\sin\delta$



DUNE

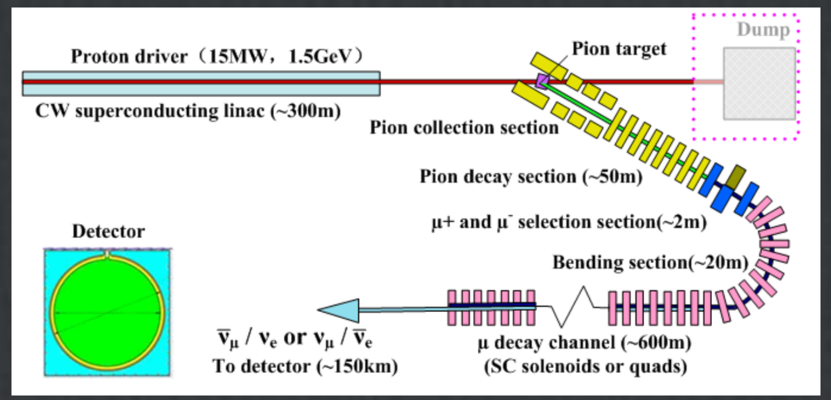
$\sin\theta_{13}$
$\sin\theta_{23}$
$\sin\delta$
Δm^2_{31}

JUNO

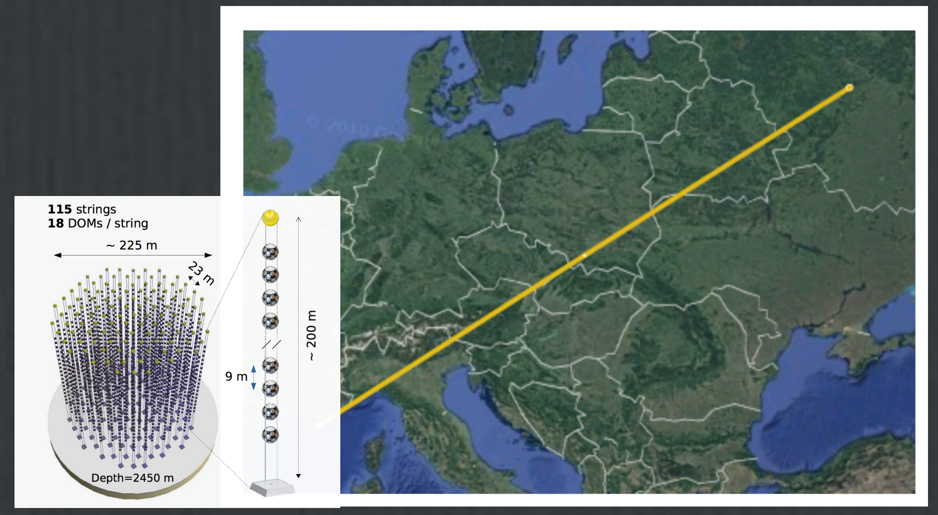
$\sin\theta_{12}$
Δm^2_{21}
Δm^2_{31}

Proposed

NuStorm



MOMENT

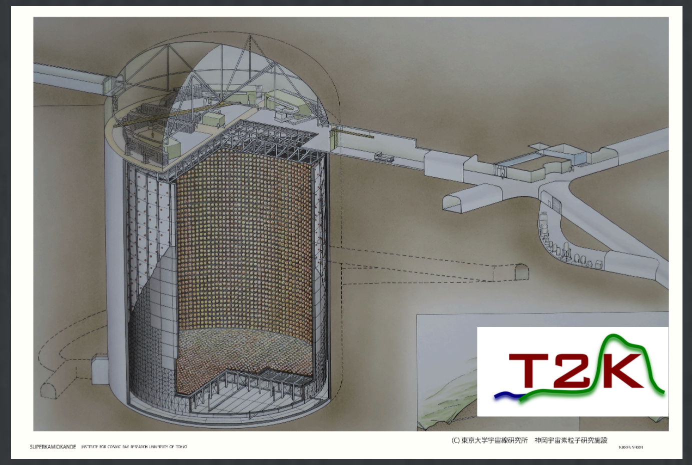


P2O

Current, future, and proposed neutrino Oscillation Experiments

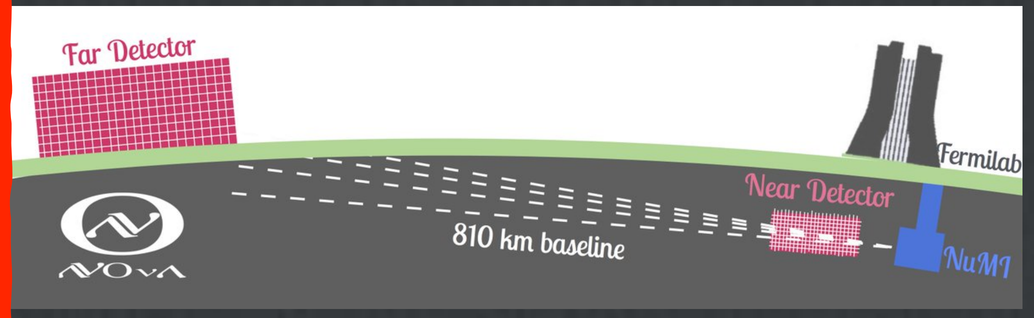
Accelerator Neutrino Projects

Current running



T2K

$\sin\theta_{13}$
$\sin\theta_{23}$
$\sin\delta$



NOvA

$\sin\theta_{23}$
$\sin\delta$
Δm^2_{31}

Daya bay

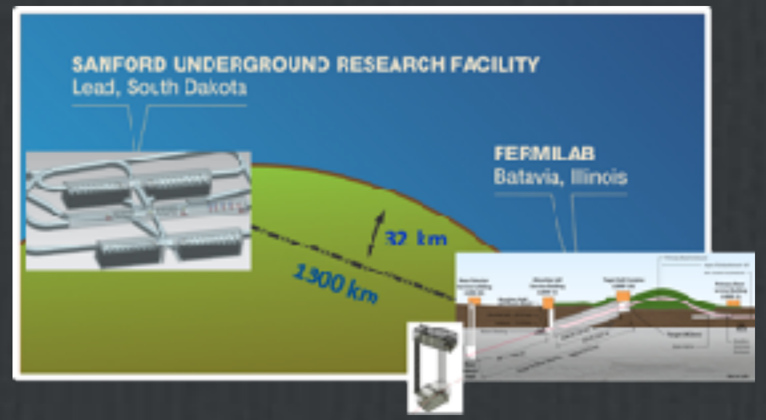
$\sin\theta_{13}$

$|\Delta m^2_{31}|$

Upcoming

T2HK

$\sin\theta_{13}$
$\sin\theta_{23}$
$\sin\delta$



DUNE

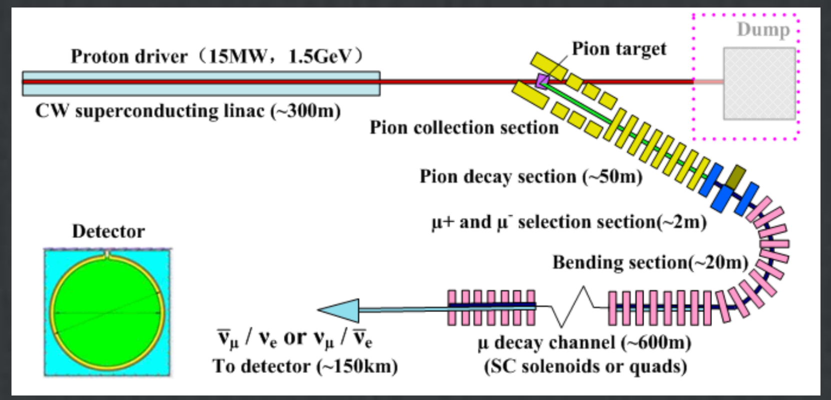
$\sin\theta_{13}$
$\sin\theta_{23}$
$\sin\delta$
Δm^2_{31}

JUNO

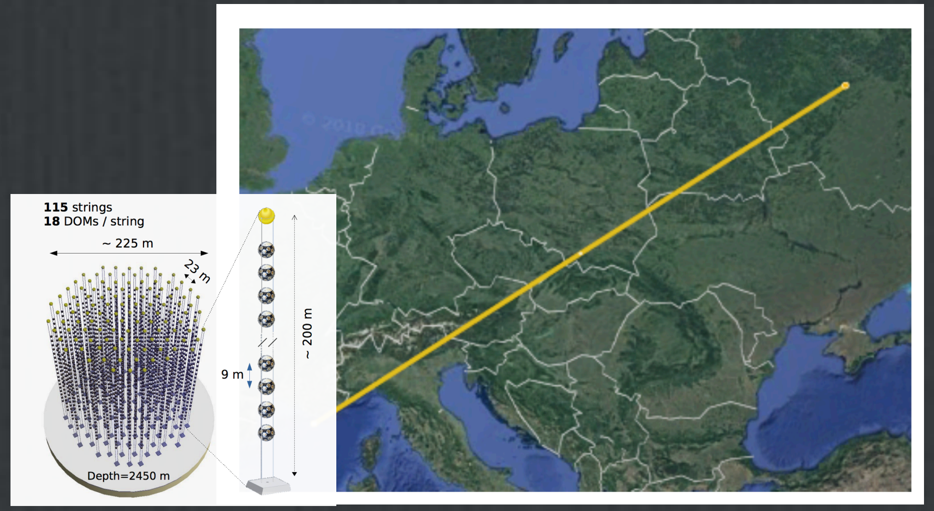
$\sin\theta_{12}$
Δm^2_{21}
Δm^2_{31}

Proposed

NuStorm



MOMENT



P2O

Current understanding on neutrino oscillations

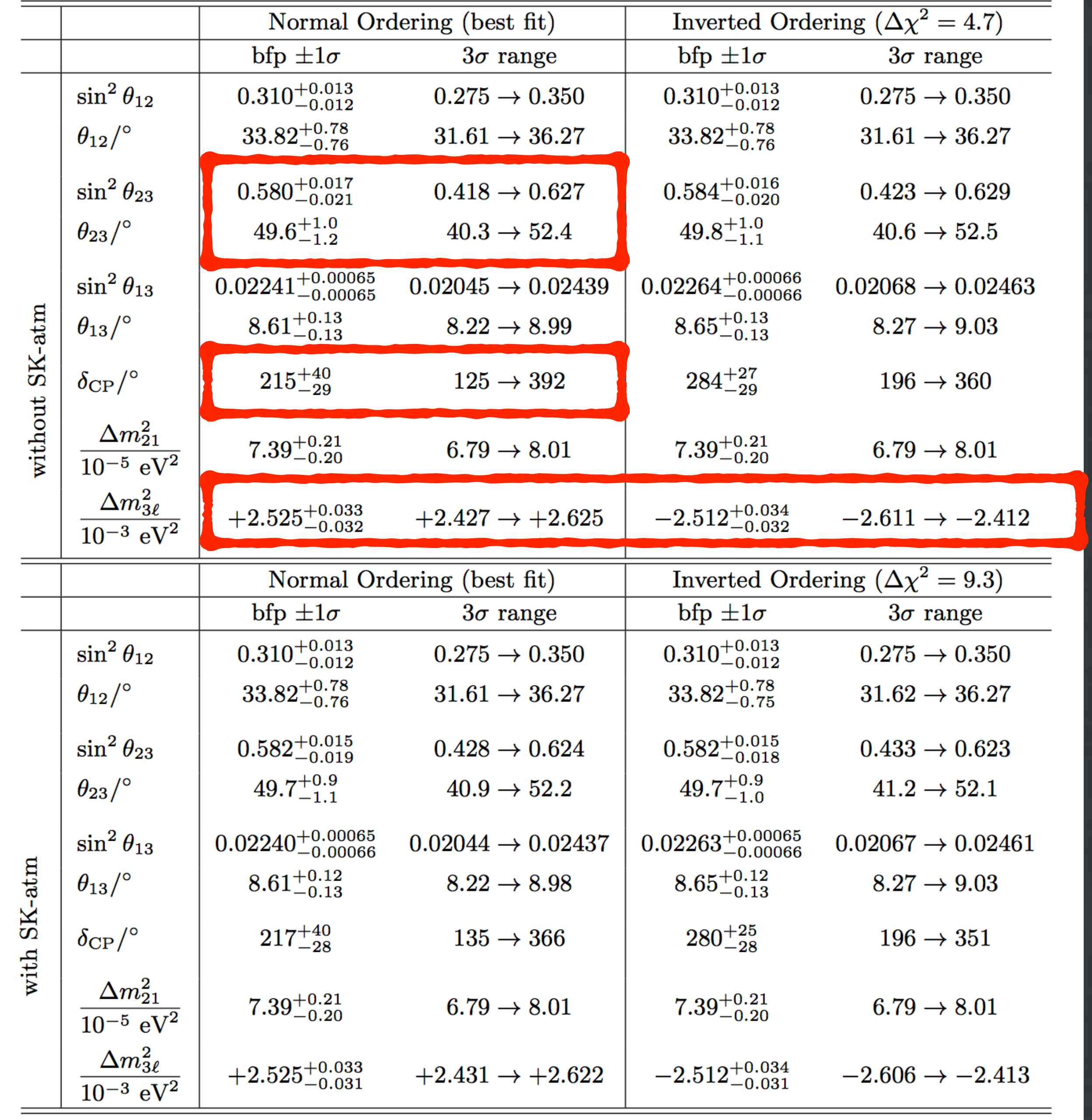
$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2 \sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right).$$

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle \qquad (\alpha = e, \mu, \tau)$$

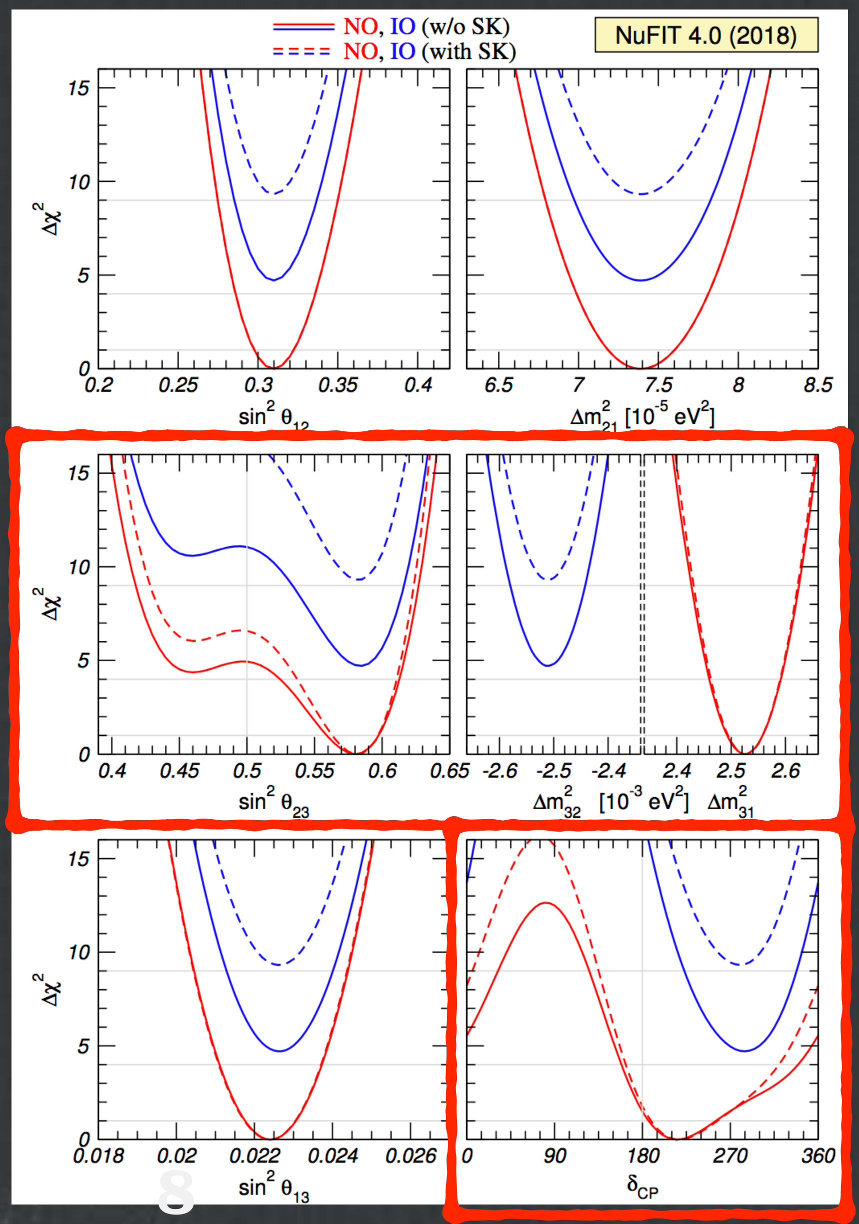
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathcal{P}$$

$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

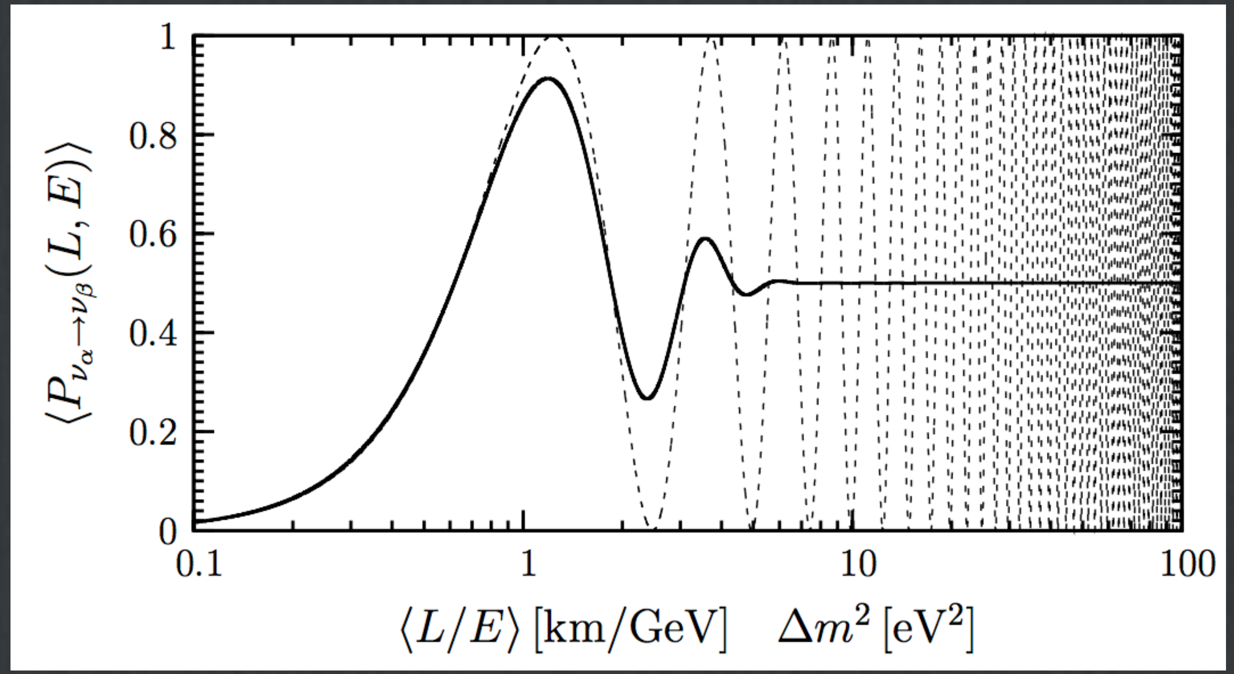
$\mathcal{P} = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\rm CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\rm CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$



a 2ν example with $\sin^2 2\theta = 1$.



Rest of unknowns

if $\mathrm{sign}(\Delta m^2_{31}) >$ or < 0 ?

if $\theta_{23} >$ or $< 45^\circ$?

if $\delta = \pm\pi/2$?

$\delta =$?

Current understanding on neutrino oscillations

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right]\, \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2\sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right]\, \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right).$$

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu, \tau)$$

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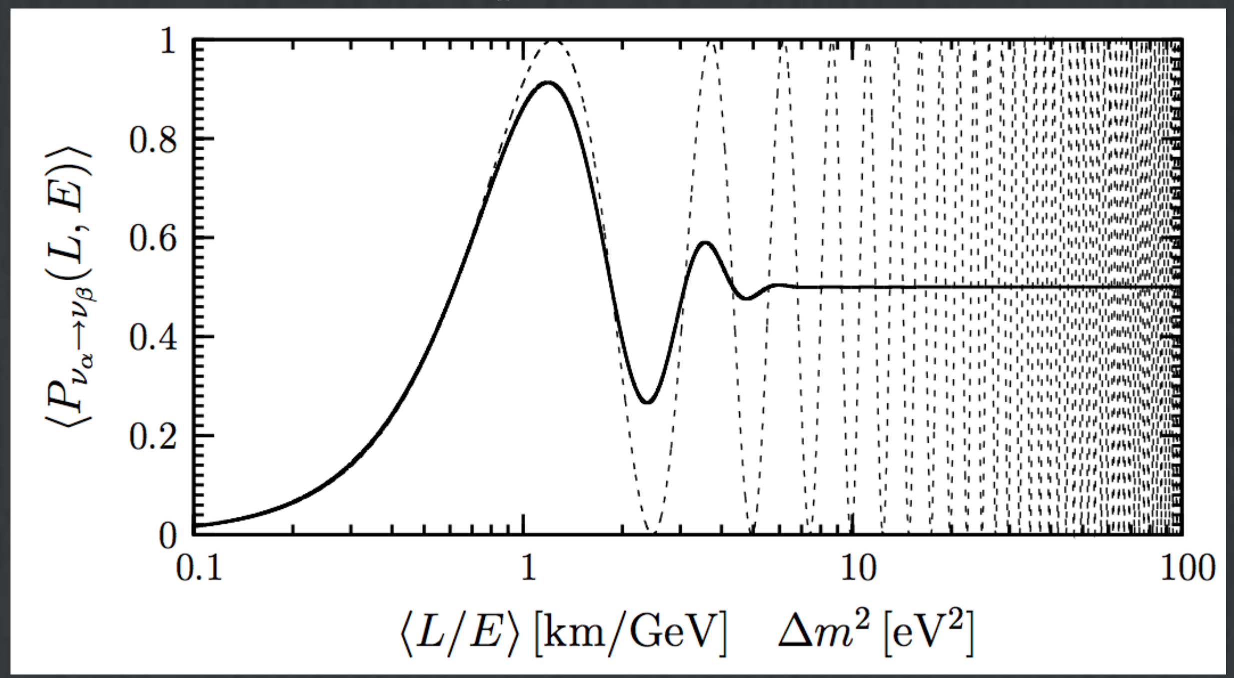
$\mathcal{P} = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$

a 2ν *example with* $\sin^2 2\theta = 1.$



Rest of unknowns

if $\mathrm{sign}(\Delta m^2_{31}) >$ or < 0 ?

if $\theta_{23} >$ or $< 45^\circ$?

if $\delta = \pm\pi/2$?

$\delta =$?

←

We want to resolve it by measuring the appearance channel $P(\nu_\mu \to \nu_e)$, which needs the accelerator neutrino facilities, because of the neutrino flavour and the high neutrino energy.

The messages want to be conveyed today

✓

1. Neutrino oscillations are the only evidence for the physics beyond the standard model (BSM) by far.
2. Neutrino physicists want to know more about neutrino oscillations. if $\mathrm{sign}(\Delta m^2_{31}) >$ or < 0? if $\theta_{23} >$ or $< 45^\circ$? if $\delta = \pm \pi/2$? $\delta =$?
3. Particle physicists want to know if there is any other BSM phenomenology.
4. To achieve the above, we need accelerator neutrino facilities.

We measure $P(\nu_\mu \to \nu_e)$ to resolve some of these problems.

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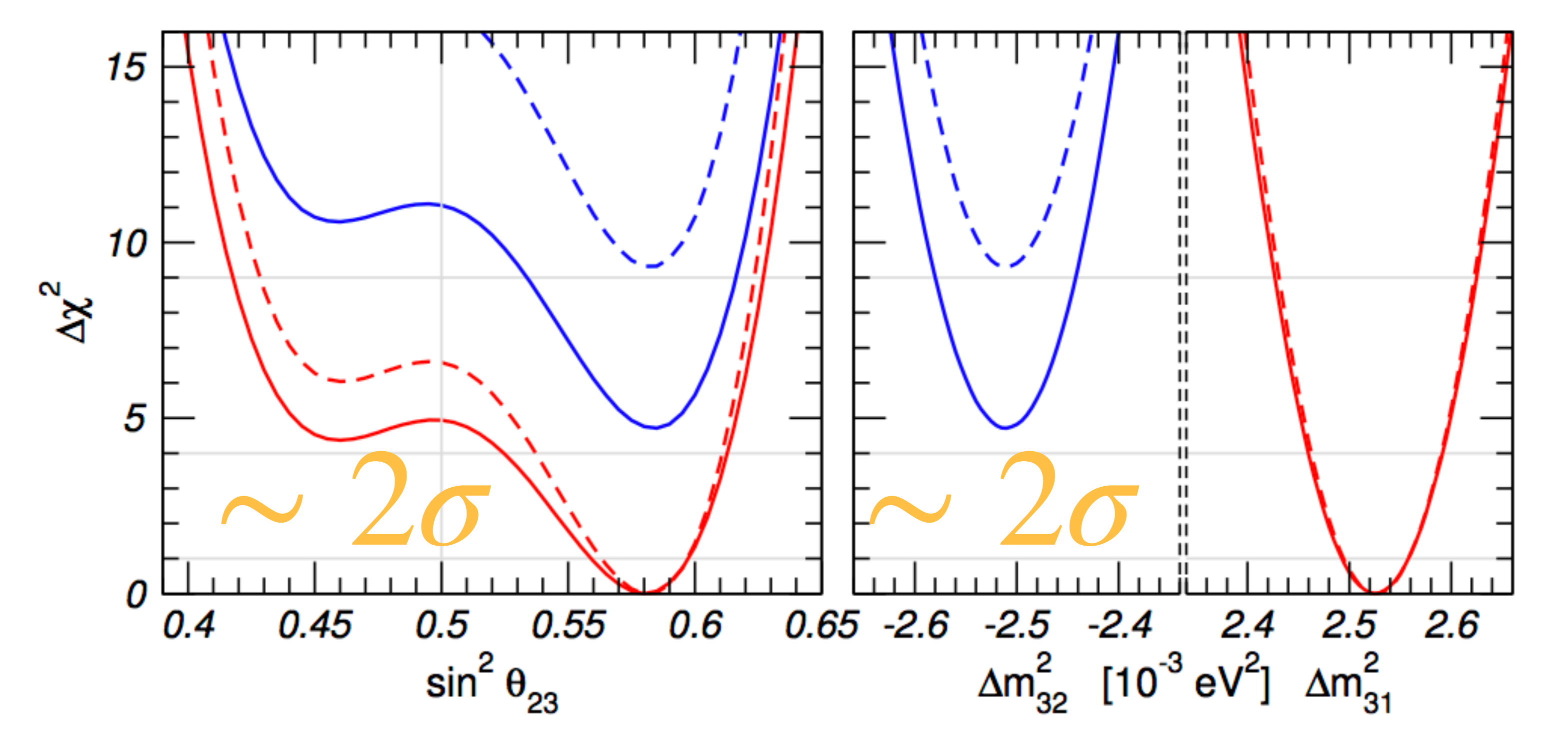
We measure $P(\nu_\mu \to \nu_e)$ to resolve some of these problems.

HOW?

Mass ordering and Octant degeneracies vs. DUNE and T2HK

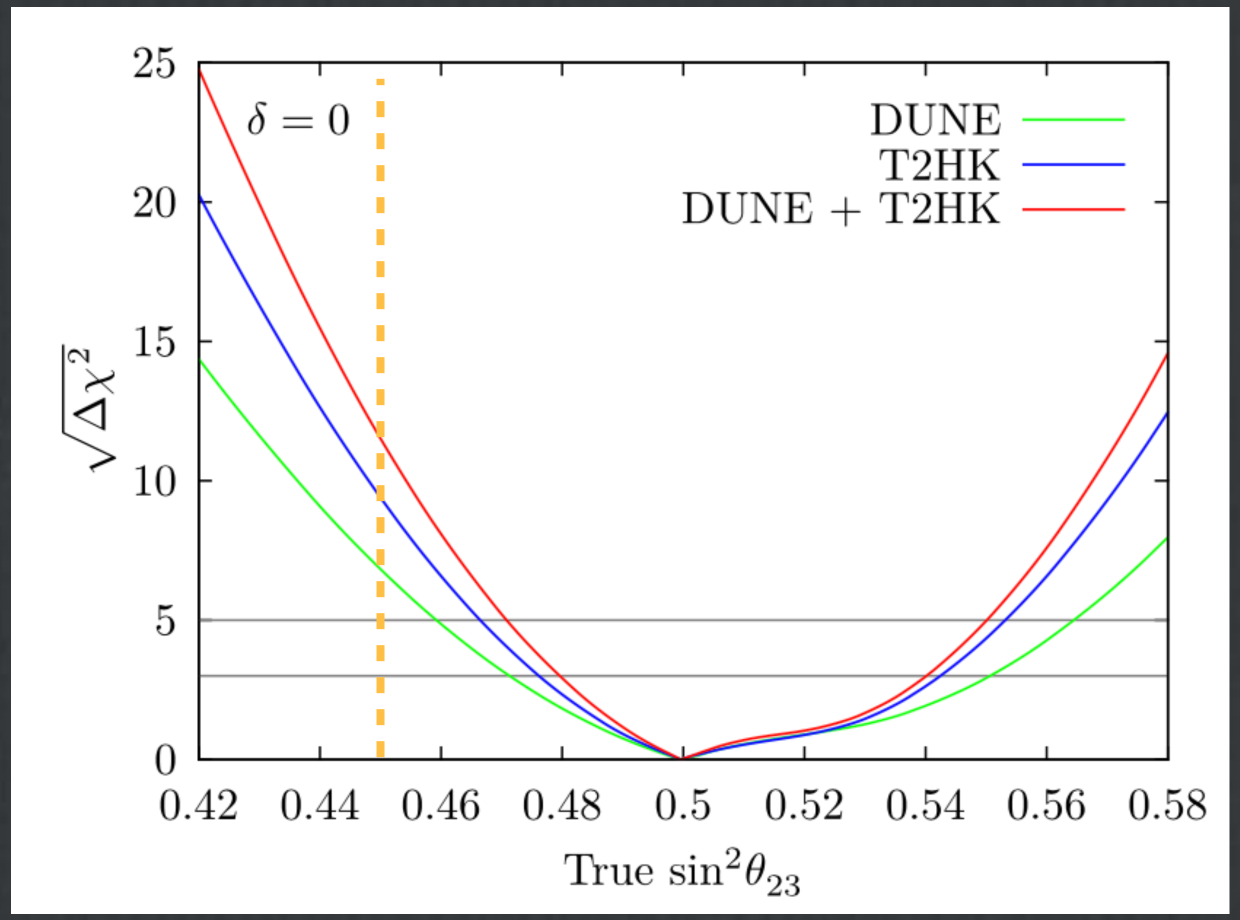
arXiv:1612.07275

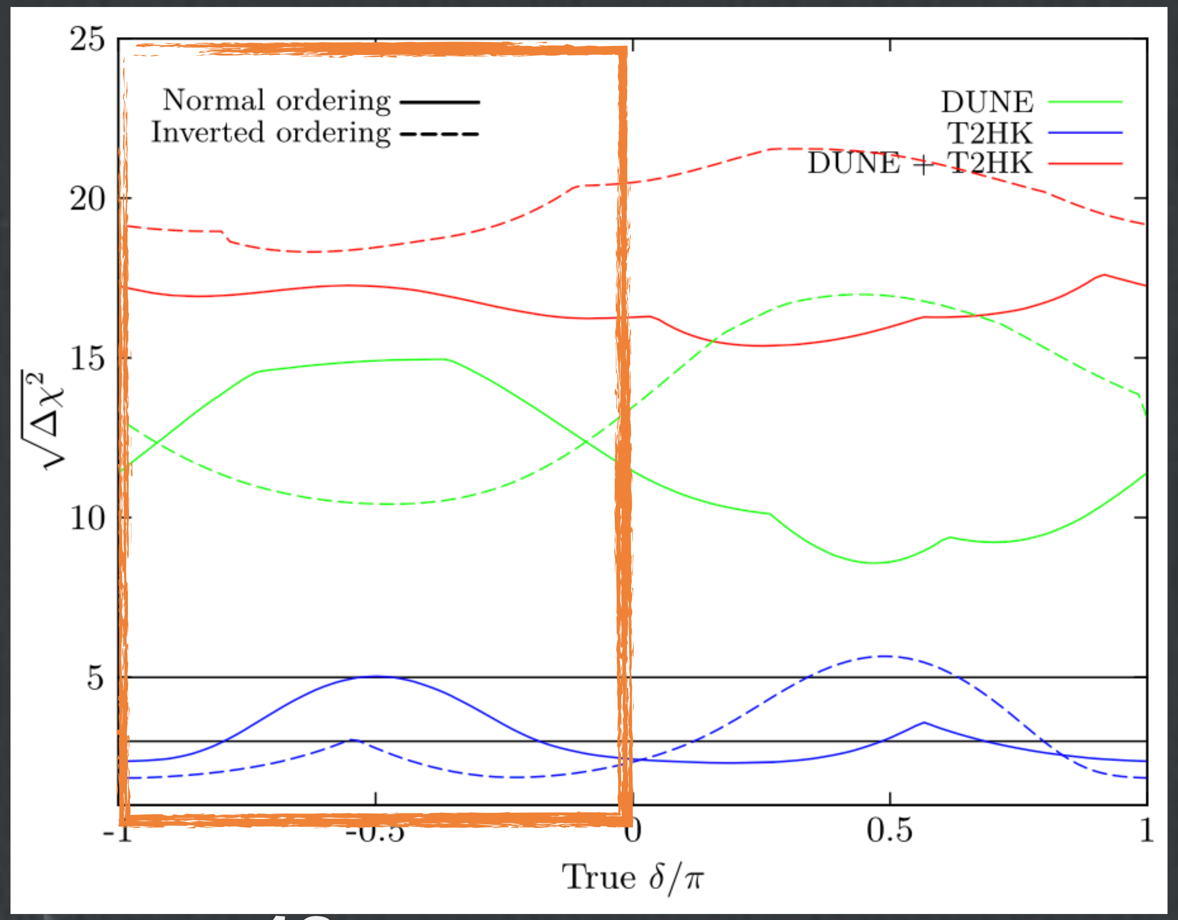
Current global fit



- **High sensitivity for mass ordering and octant degeneracies Is expected.**
- **Mass Ordering and octant degeneracies can be resolved after DUNE and T2HK.**

DUNE and T2HK





DUNE: 5+5 yr

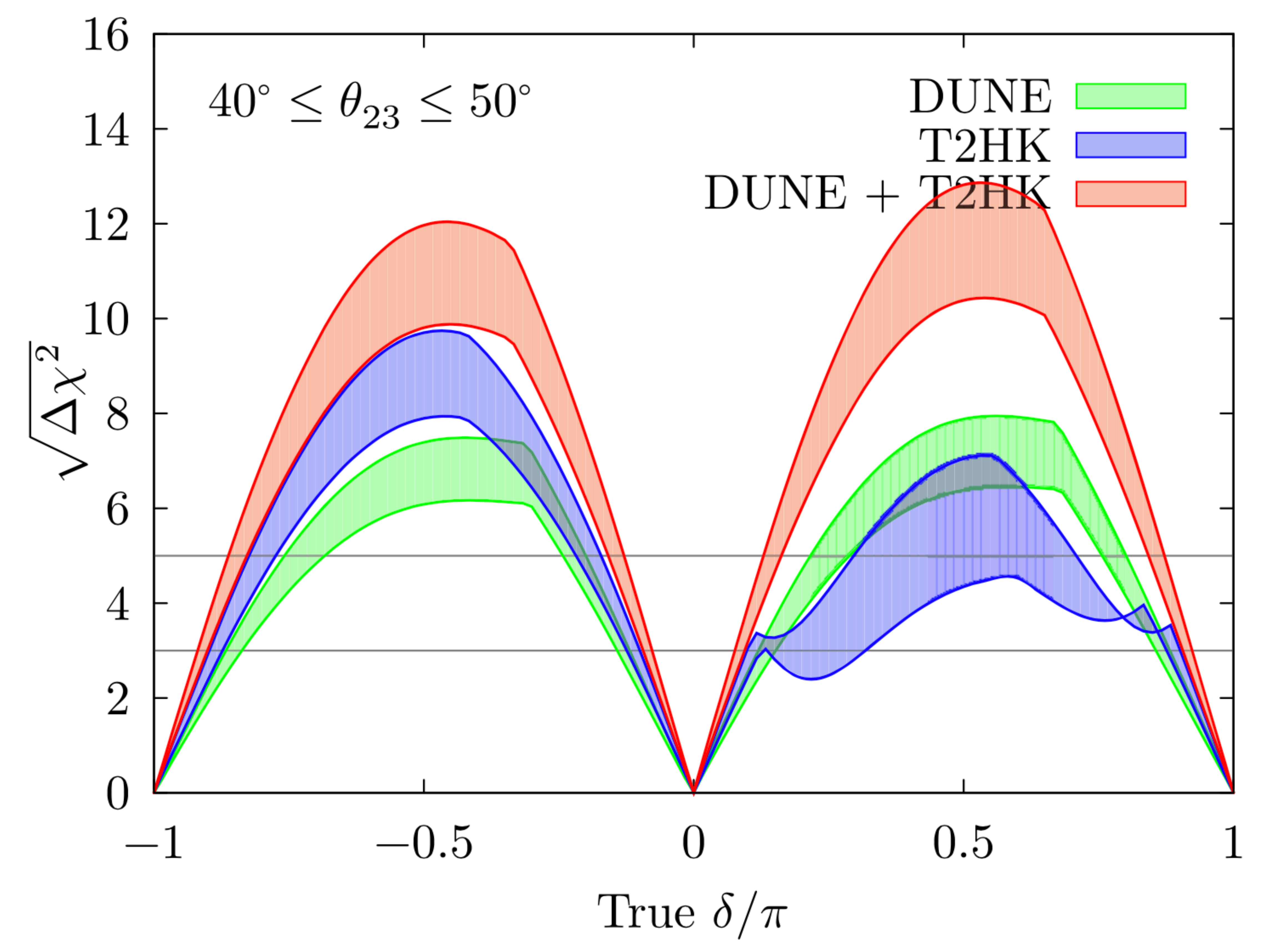
T2HK: 2.5+7.5 yr

CP violation vs. DUNE and T2HK

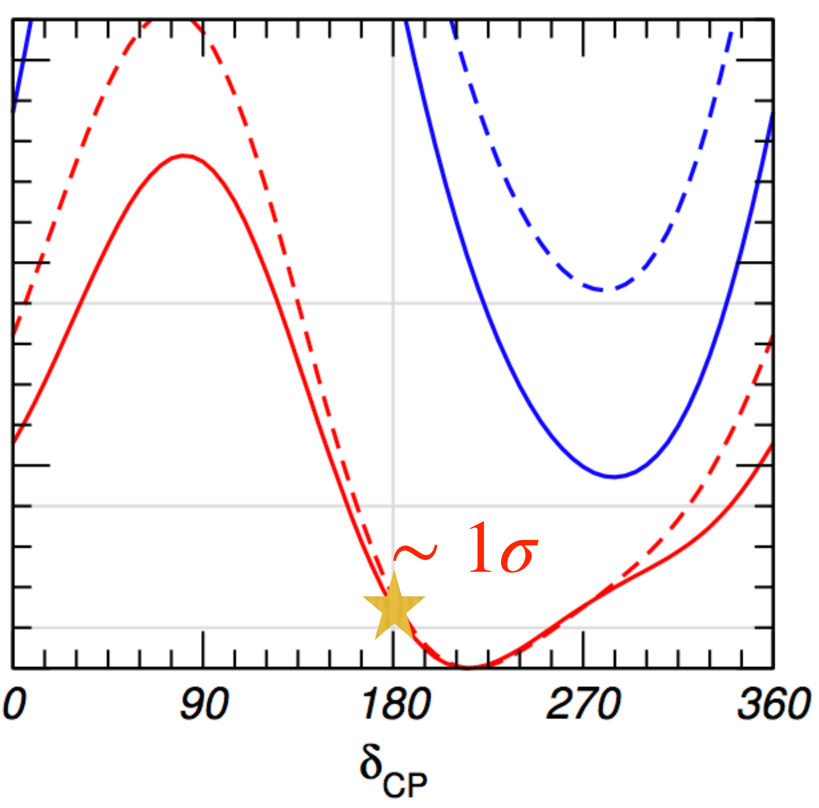
arXiv:1612.07275

$$\Delta\chi^2_{CP} = \min_{\delta\in\{0,\pi\}} \Delta\chi^2(\delta),$$

How good we can exclude the CP conserved scenarios.



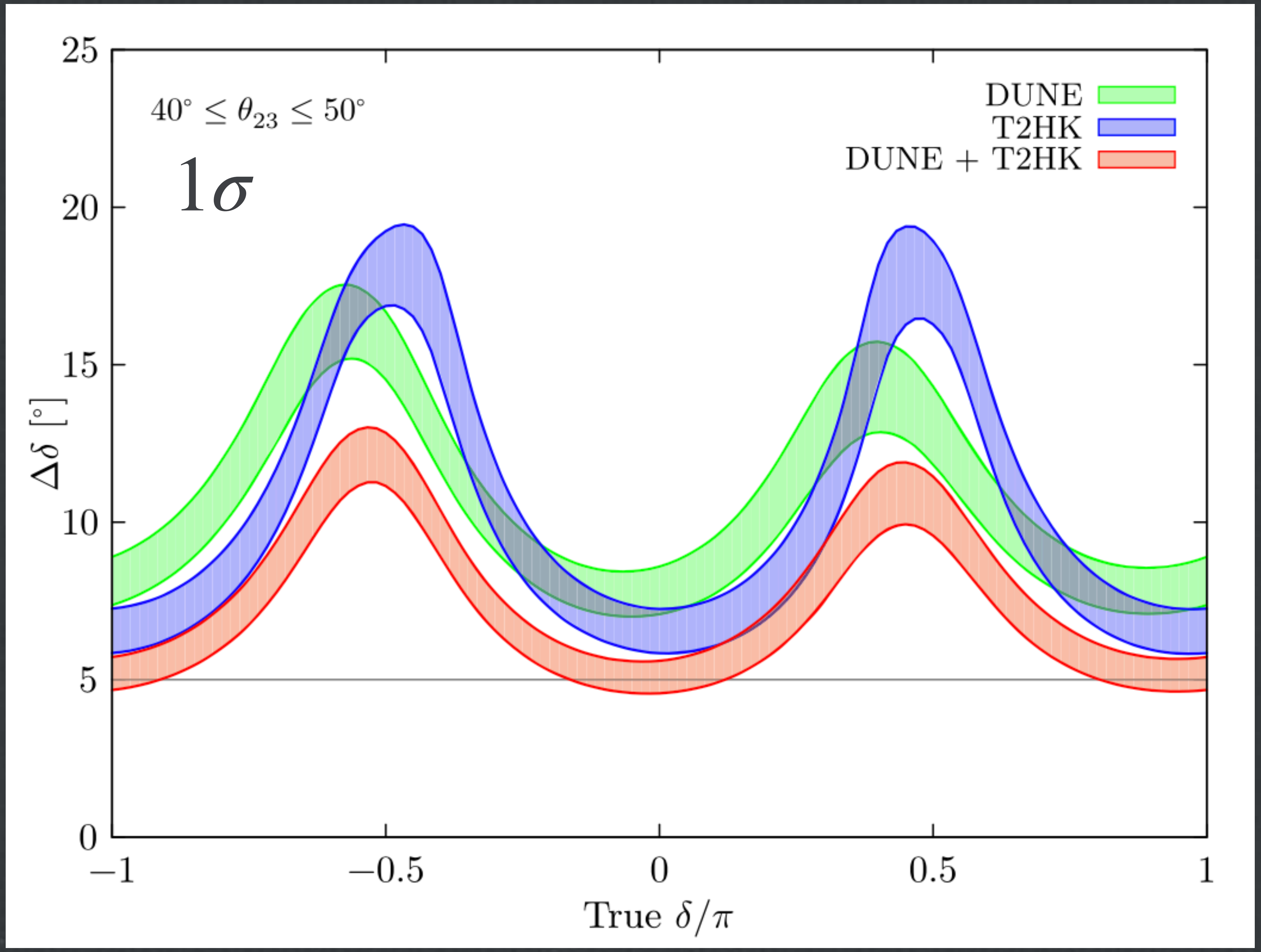
DUNE: 5+5 yr
T2HK: 2.5+7.5 yr



The precision of CP phase with DUNE and T2HK

arXiv:1612.07275

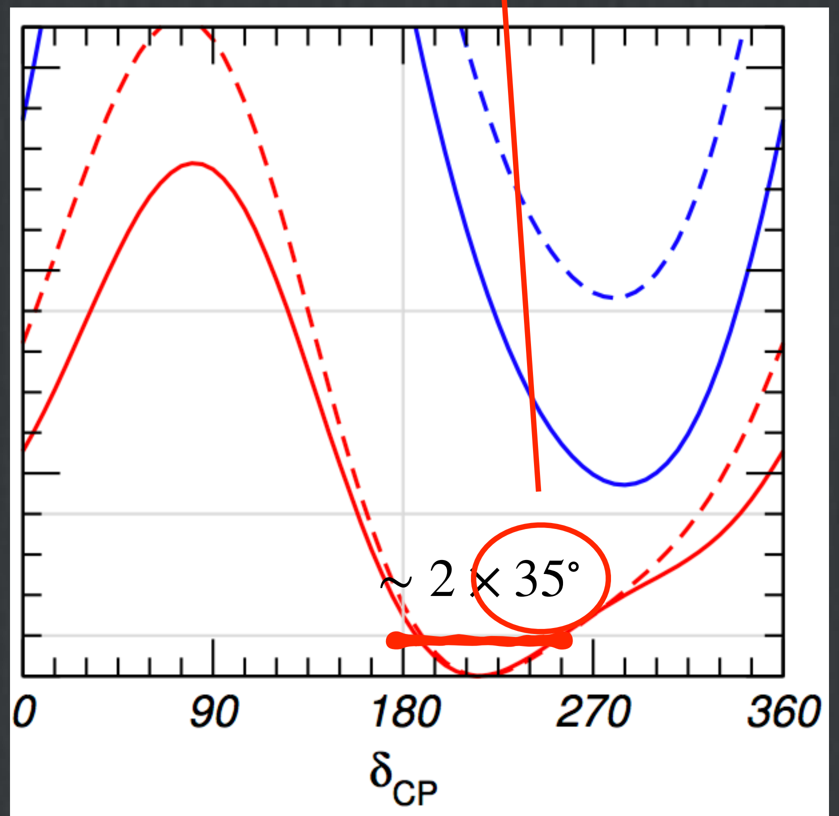
DUNE: 5+5 yr
T2HK: 2.5+7.5 yr



For $\delta = \pm\frac{\pi}{2}$, DUNE is better.

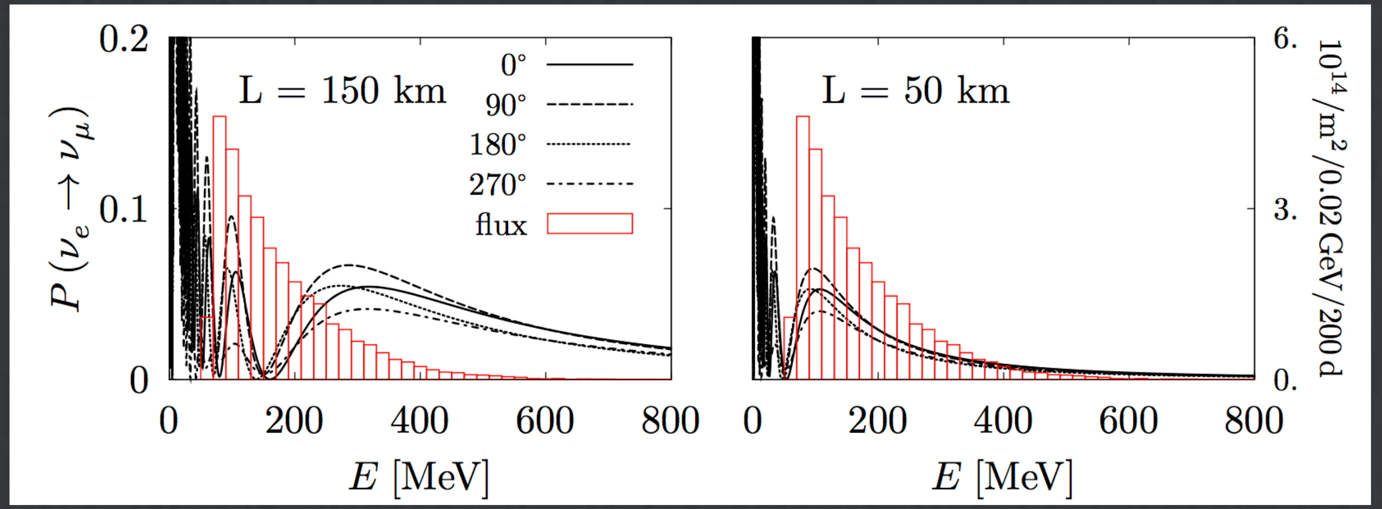
For $\delta = \pm\pi$, T2HK is better.

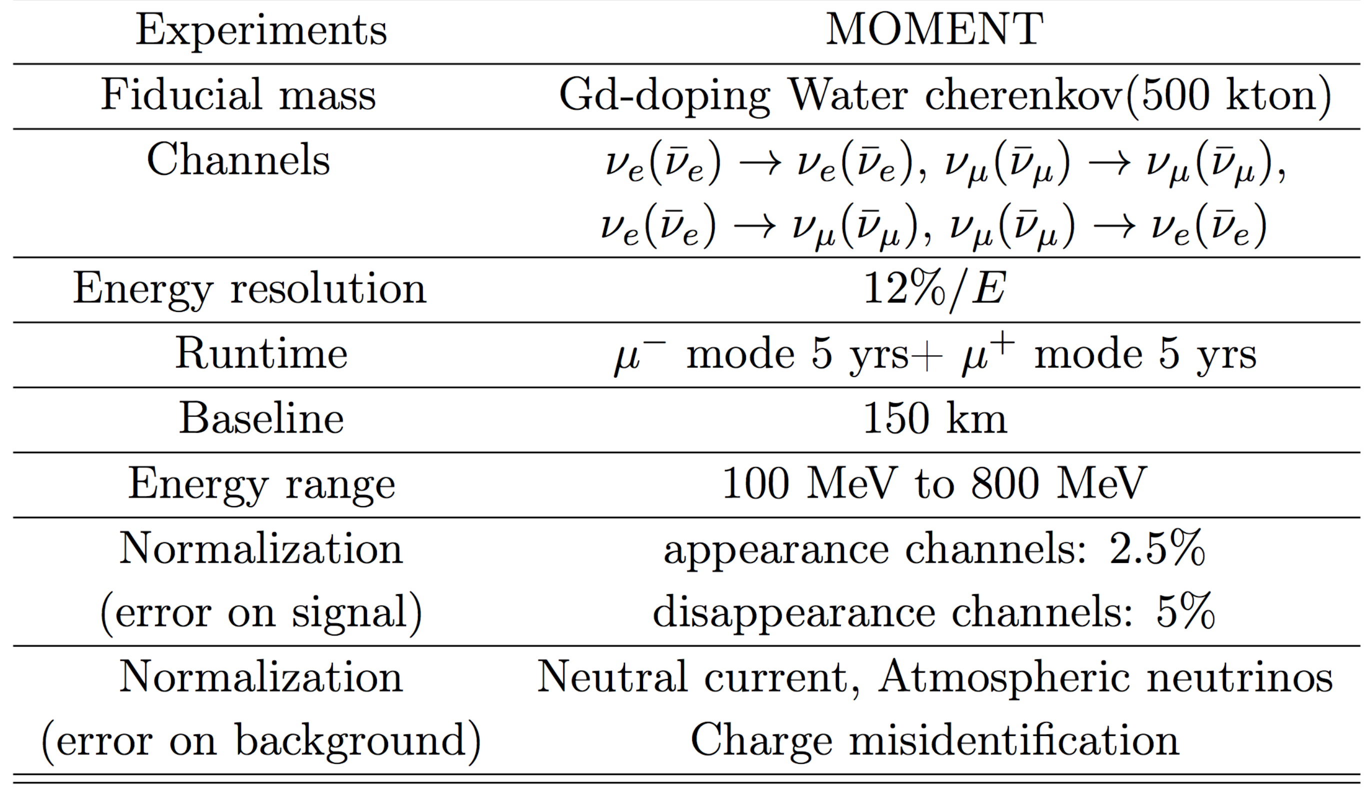
The synergy can reach the precision $< 13^\circ$.



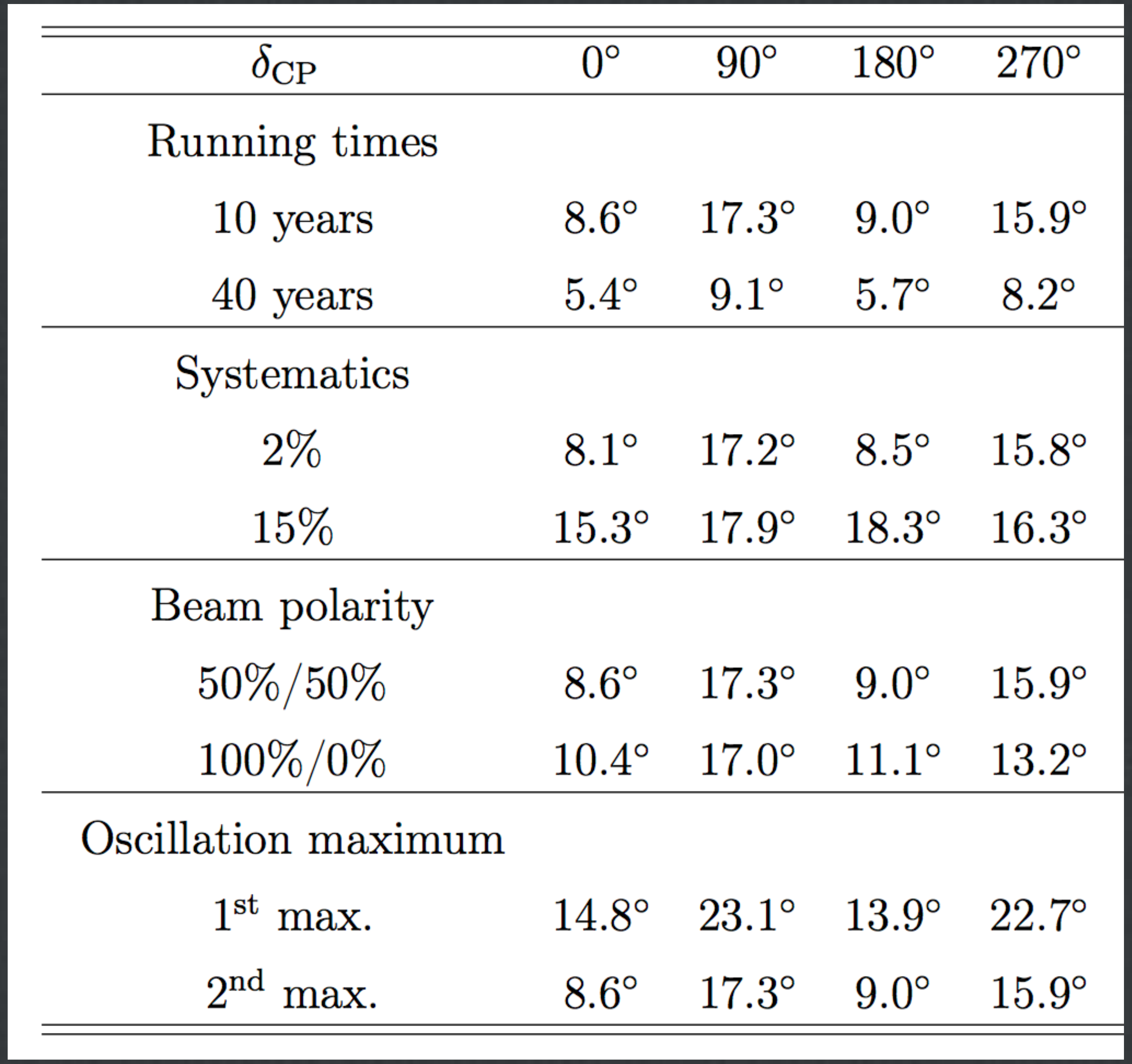
CP phase measurement in MOMENT

arXiv:1909.01548



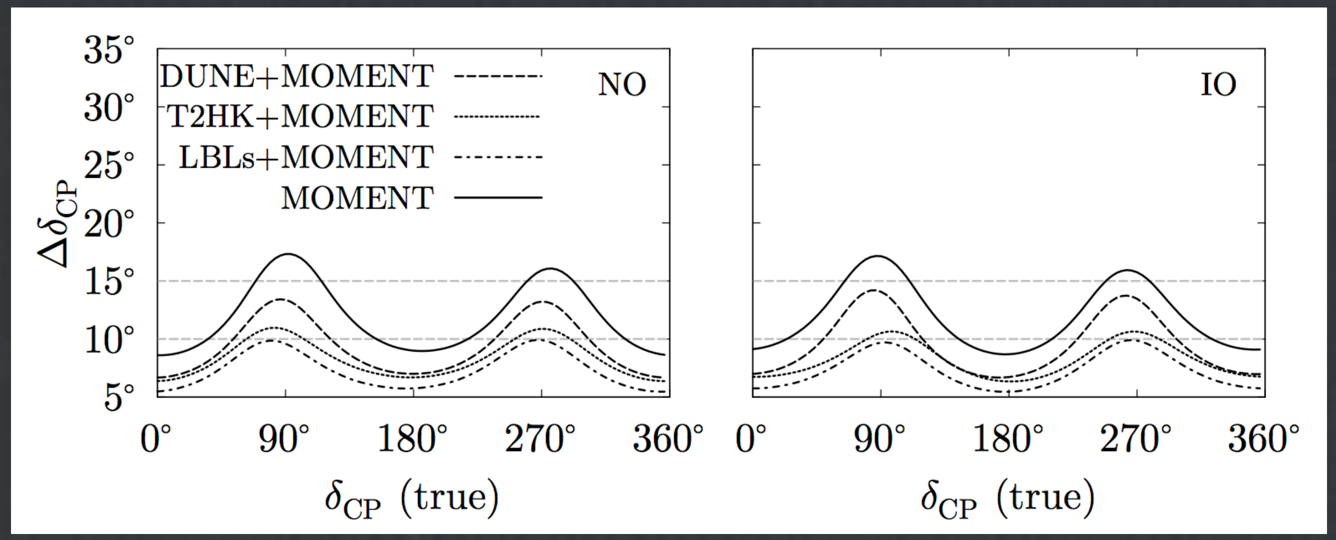


Experiments	MOMENT
Fiducial mass	Gd-doping Water cherenkov(500 kton)
Channels	$\nu_e(\bar{\nu}_e) \to \nu_e(\bar{\nu}_e)$, $\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$, $\nu_e(\bar{\nu}_e) \to \nu_\mu(\bar{\nu}_\mu)$, $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$
Energy resolution	$12\%/E$
Runtime	μ^- mode 5 yrs+ μ^+ mode 5 yrs
Baseline	150 km
Energy range	100 MeV to 800 MeV
Normalization (error on signal)	appearance channels: 2.5% disappearance channels: 5%
Normalization (error on background)	Neutral current, Atmospheric neutrinos Charge misidentification



δ_{CP}	0°	90°	180°	270°
Running times				
10 years	8.6°	17.3°	9.0°	15.9°
40 years	5.4°	9.1°	5.7°	8.2°
Systematics				
2%	8.1°	17.2°	8.5°	15.8°
15%	15.3°	17.9°	18.3°	16.3°
Beam polarity				
50%/50%	8.6°	17.3°	9.0°	15.9°
100%/0%	10.4°	17.0°	11.1°	13.2°
Oscillation maximum				
1^{st} max.	14.8°	23.1°	13.9°	22.7°
2^{nd} max.	8.6°	17.3°	9.0°	15.9°

- **MOMENT is compatible to T2HK in the delta measurement.**
- **Systematics is an advantage for MOEMENT for CP conserved values.**
- **Statistical uncertainty is important for CPV values.**



The messages want to be conveyed today

✓ 1. Neutrino oscillations are the only evidence for the physics beyond the standard model (BSM) by far.

✓ 2. Neutrino physicists want to know more about neutrino oscillations. if $\mathrm{sign}(\Delta m^2_{31}) >$ or < 0 ? if $\theta_{23} >$ or $< 45^\circ$?
if $\delta = \pm\pi/2$? $\delta =$?

We measure $P(\nu_\mu \to \nu_e)$ to resolve some of these problems.

3. Particle physicists want to know if there is any other BSM phenomenology.

4. To achieve the above, we need accelerator neutrino facilities.

Precision measurements offer an opportunity for searching for the new BSM physics.

Neutrino physics in neutrino oscillations

- Flavour symmetry: high-energy symmetries
- Nonstandard interactions: new mediators
- Nonunitarity, neutrino decays, and sterile-active mixing: new fermions

Neutrino physics in neutrino oscillations

☐ Flavour symmetry: high-energy symmetries

☐ Nonstandard interactions: new mediators

☐ Nonunitarity, neutrino decays, and sterile-active mixing: new fermions

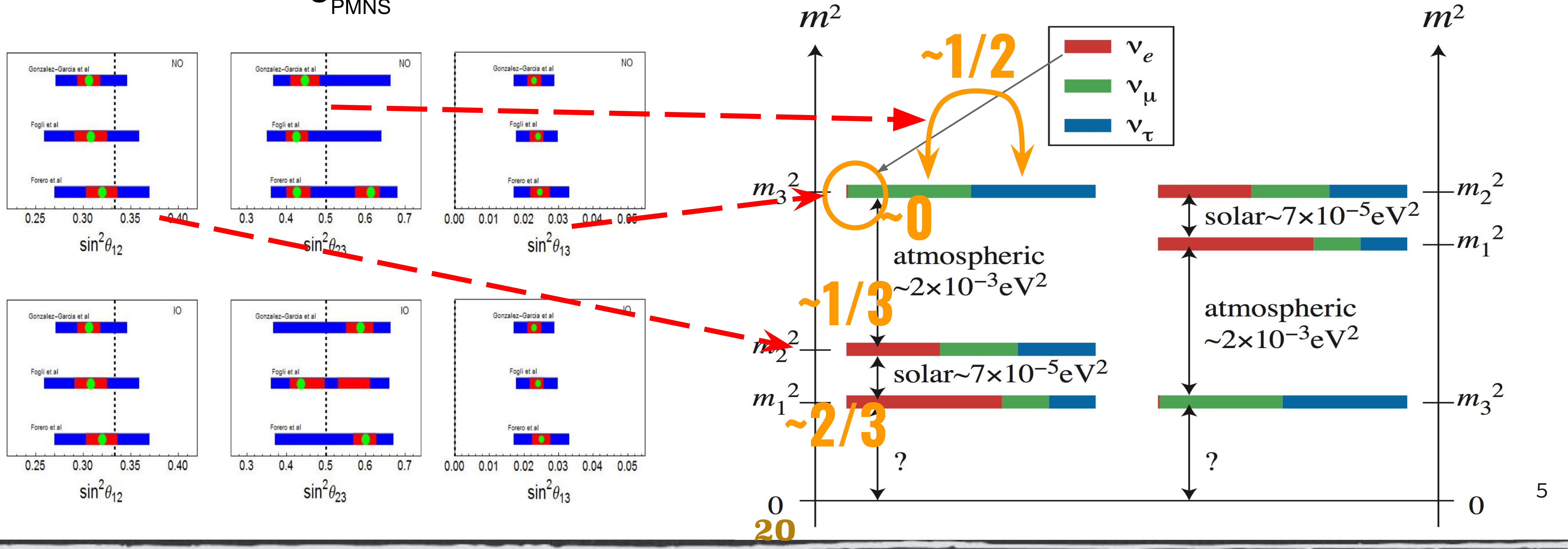
Motivation of flavour symmetry

Observe the pattern of neutrino mixing

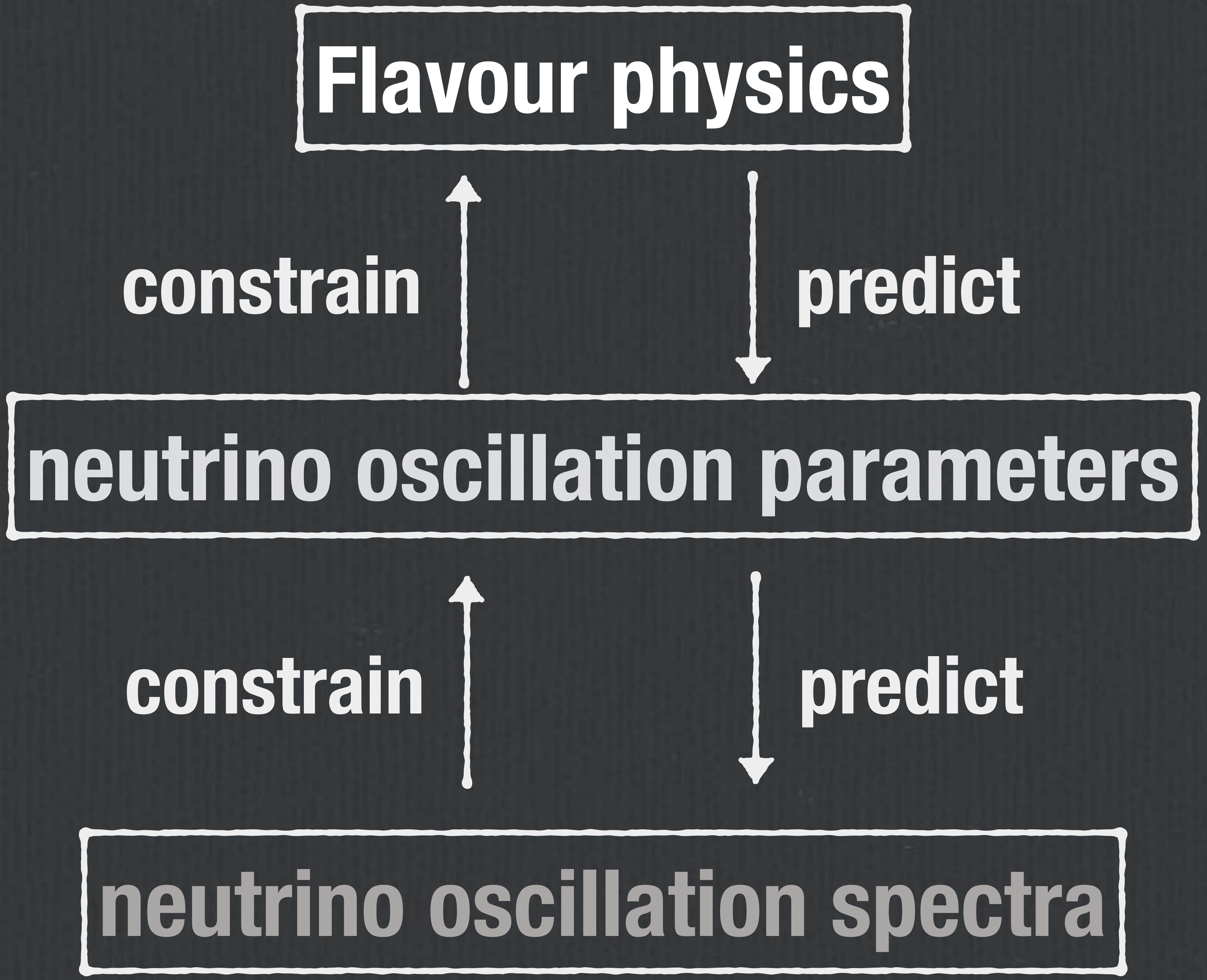
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}_{\text{U}_{\text{PMNS}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{\rm PMNS} = U_{23}U_{13}U_{12}P,$$

$$= \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}e^{i\alpha_1} & 0 & 0\\ 0 & e^{i\alpha_2} & 0\\ 0 & 0 & 1\end{pmatrix}$$



flavour physics in neutrino oscillations



Flavour physics

constrain

predict

neutrino oscillation parameters

constrain

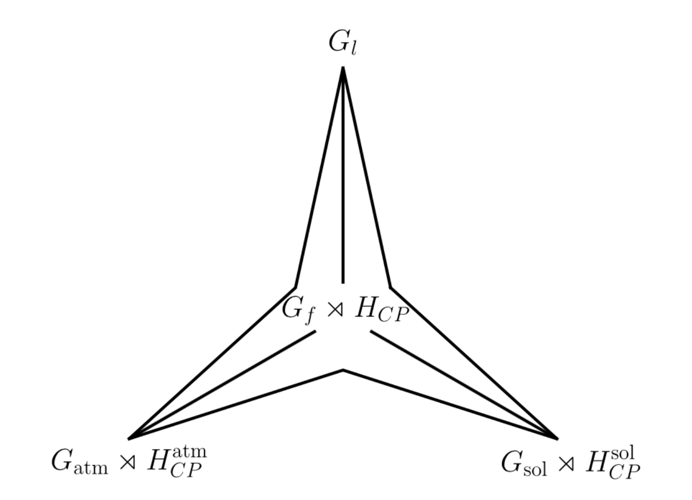
predict

neutrino oscillation spectra

Tri-direct littlest seesaw

arXiv:1807.07538, arXiv:1811.12340.

- Two sterile neutrinos: for atmospheric and solar masses.
- Normal mass ordering and $m_1=0$ are predicted.
- 6 oscillation parameters -> 4 model parameters.
- Explain current neutrino mixing and mass.



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

$e^{i2\pi/3}$

$r \equiv m_s/m_a$

Nufit 4.0

		Normal Ordering (best fit)	
		bfp $\pm1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
	$\delta_{\rm CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$

JUNO *LBLs* *JUNO* *LBLs*

$\Delta\chi^2$	x	η/π	r	$m_a/$ meV	$\theta_{12}/^\circ$	$\theta_{13}/^\circ$	$\theta_{23}/^\circ$	$\delta/^\circ$	$\Delta m^2_{21}/10^{-5}{\rm eV}^2$	$\Delta m^2_{31}/10^{-3}{\rm eV}^2$
~ 6.98	~ -3.65	~ 1.13	~ 0.511	~ 3.71	~ 35.25	~ 8.63	~ 46.98	~ 278.96	~ 7.39	~ 2.525

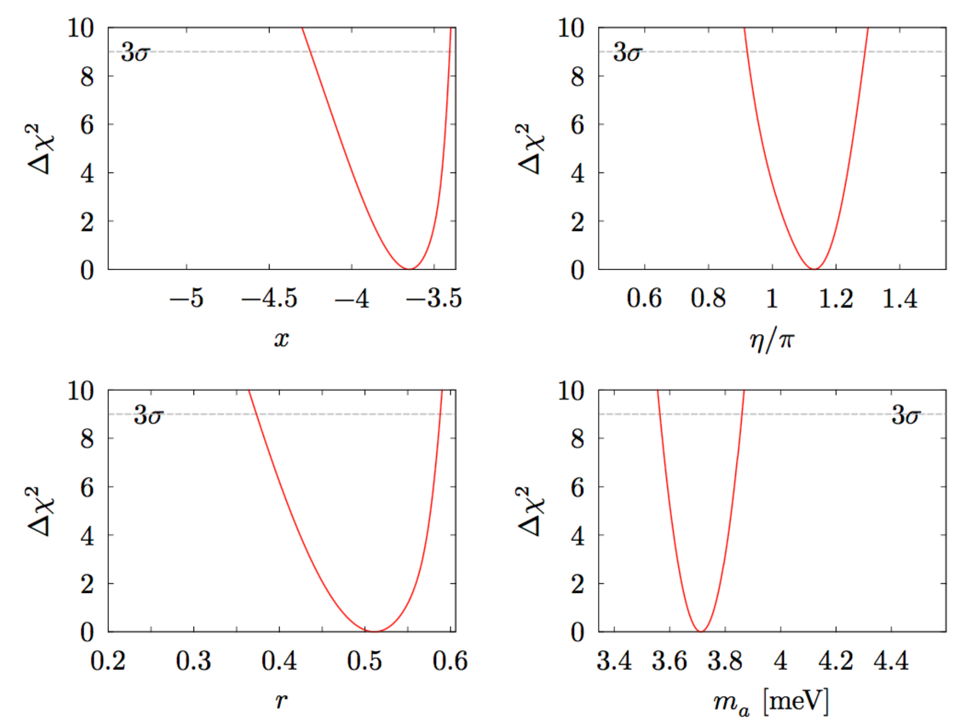
3σ allowed range:

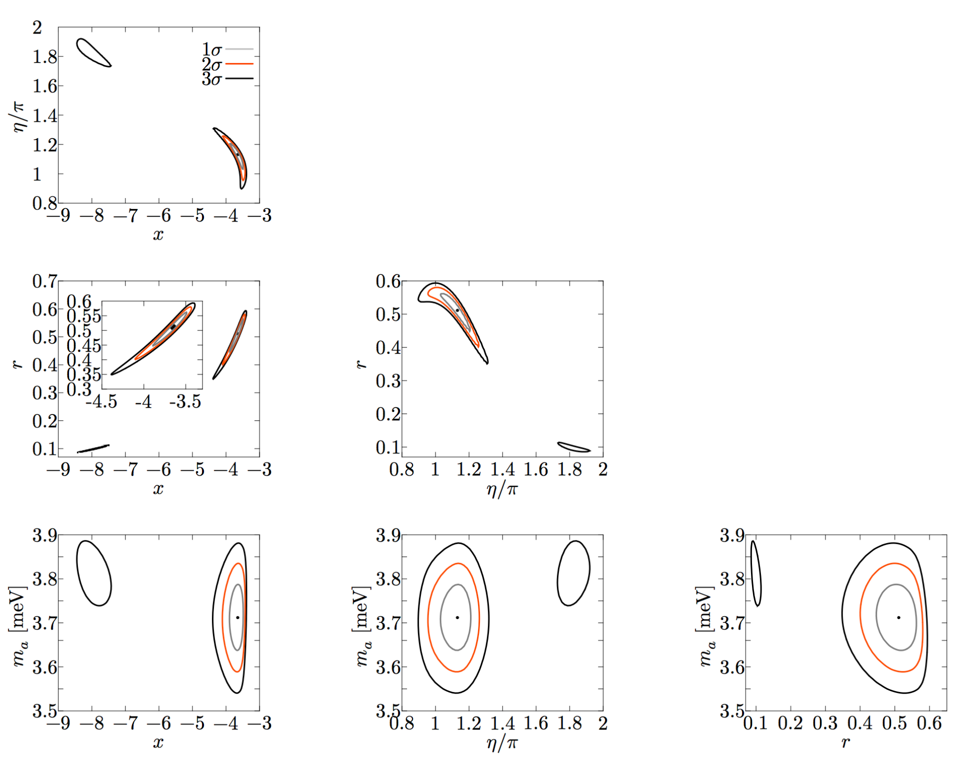
$$-5.475 < x < -3.37,\ 0.455 < \eta/\pi < 1.545,$$
$$0.204 < r < 0.606,\ 3.343 < m_a/{\rm meV} < 4.597.$$

Testing flavour symmetry models with MOMENT

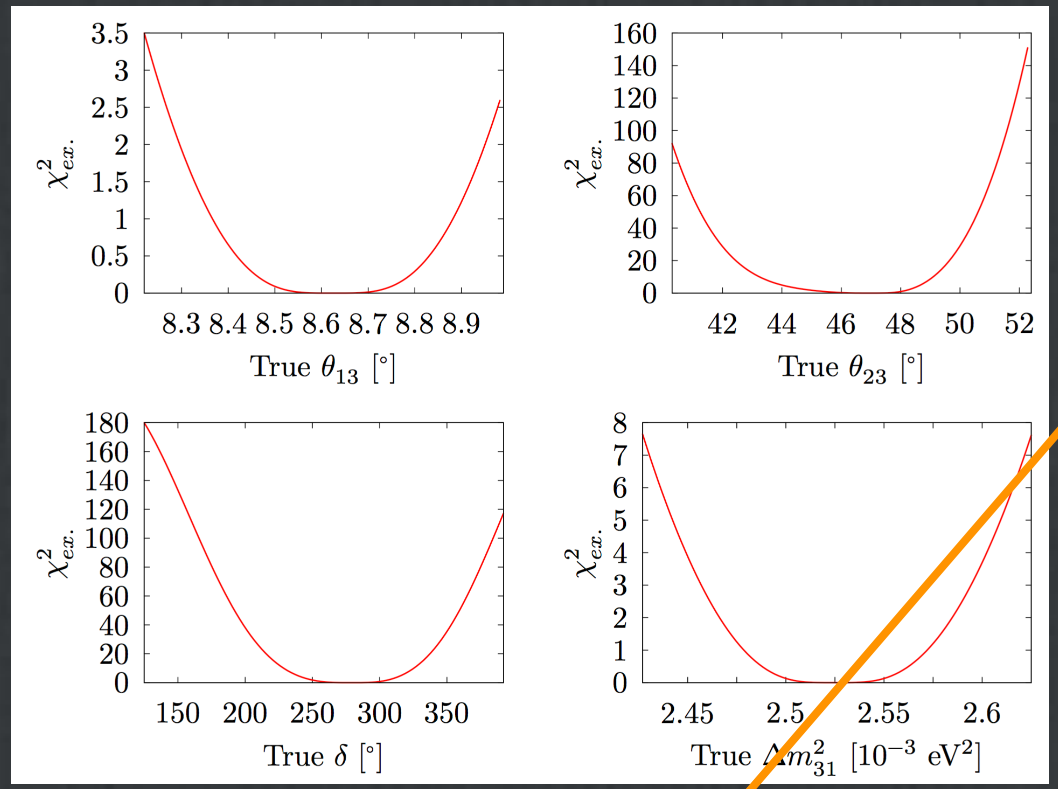
arXiv:1907.01371

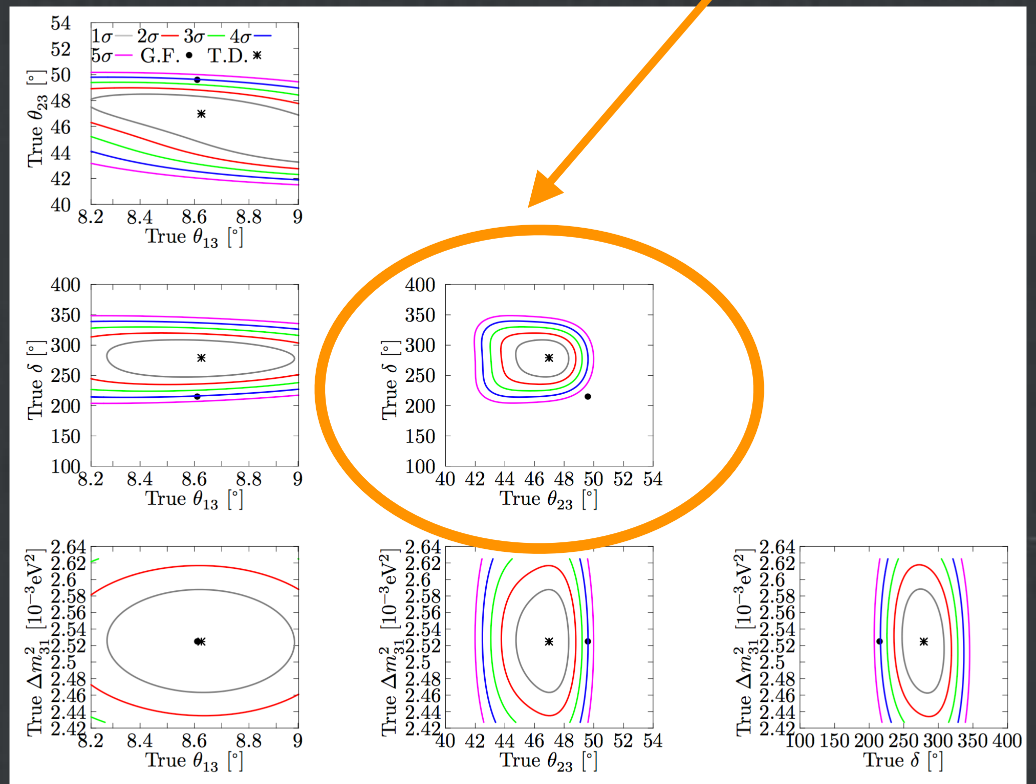
Constraints



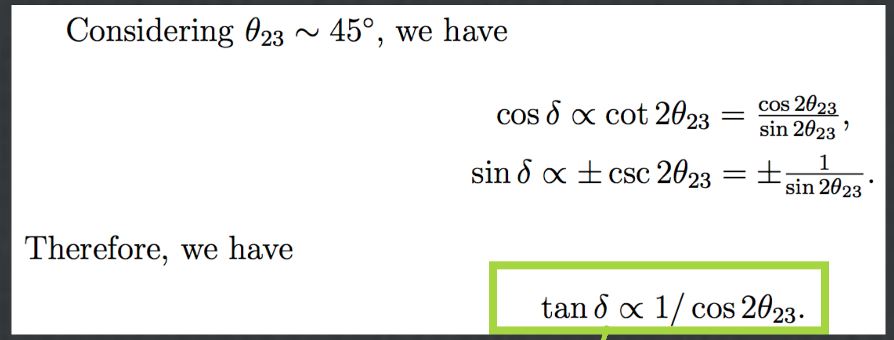


Model exclusion





- The predicted constraint is similar to DUNE.
- The degeneracy is seen.
- Can exclude this model >5 sigma.
- Good θ_{23} and δ measurements are useful to confirm the sum rule, and need accelerator neutrino facilities.

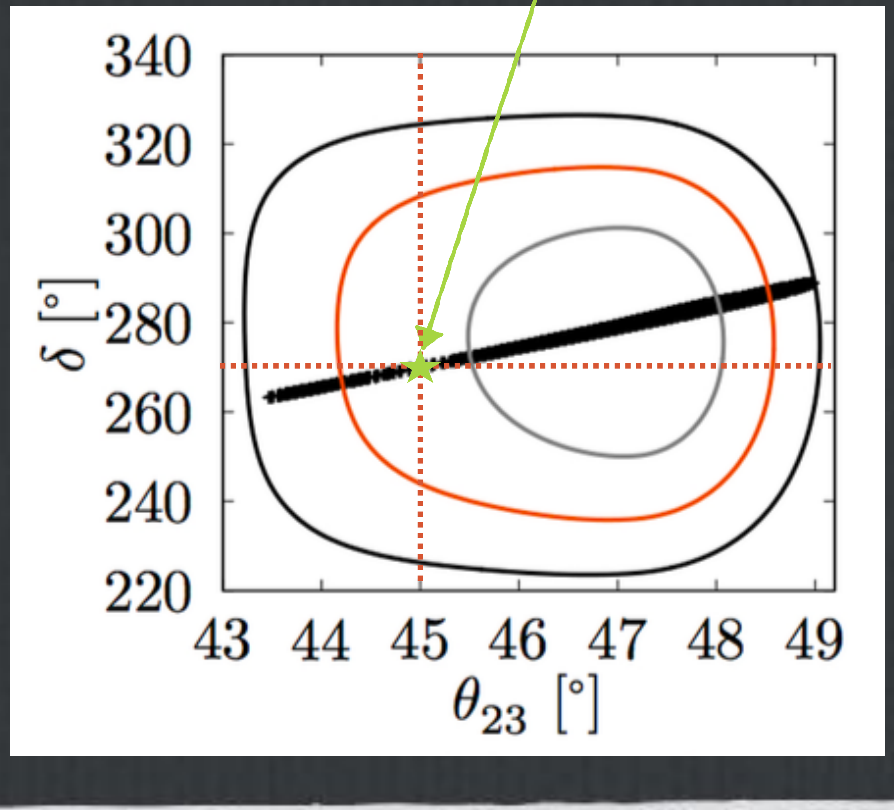


Considering $\theta_{23} \sim 45^\circ$, we have

$$\cos\delta \propto \cot 2\theta_{23} = \frac{\cos 2\theta_{23}}{\sin 2\theta_{23}},$$
$$\sin\delta \propto \pm\csc 2\theta_{23} = \pm\frac{1}{\sin 2\theta_{23}}.$$

Therefore, we have

$$\boxed{\tan\delta \propto 1/\cos 2\theta_{23}.}$$



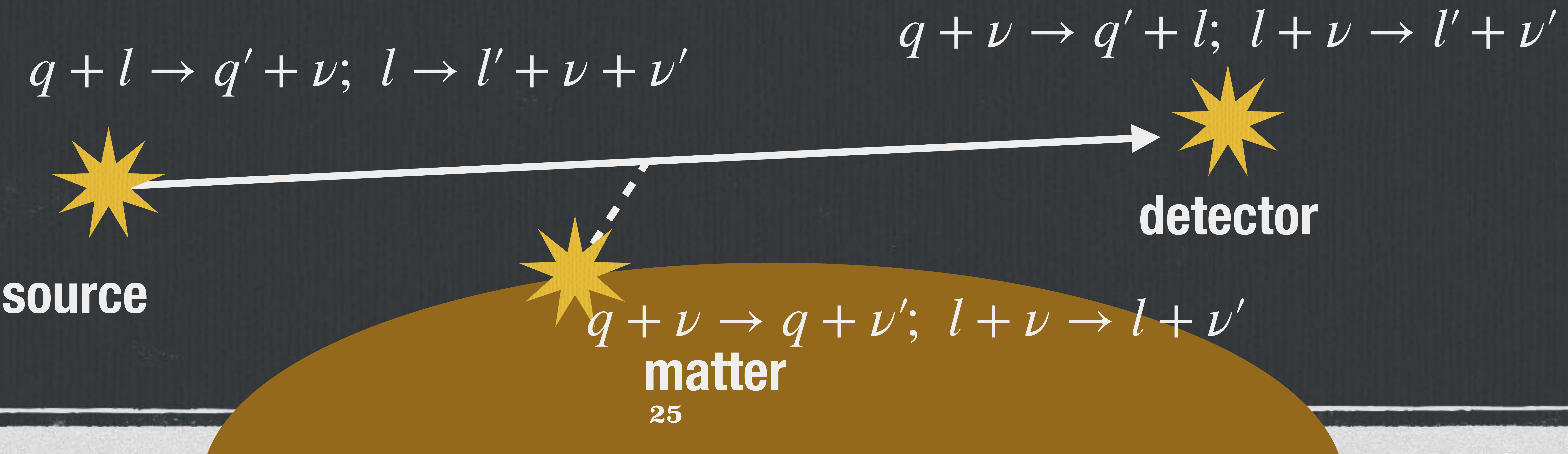
Neutrino physics in neutrino oscillations

- ☐ Flavour symmetry: high-energy symmetries
- ☐ Nonstandard interactions: new mediators
- ☐ Nonunitarity and neutrino decays: new fermions

Nonstandard Interactions

☐ The interactions involve at-least one neutrinos and SM fermions via a BSM mediator, eg. Z'…

☐ It may take place at the source, at the detector, and in matter of neutrino oscillations.



$q + l \to q' + \nu;\ l \to l' + \nu + \nu'$

$q + \nu \to q' + l;\ l + \nu \to l' + \nu'$

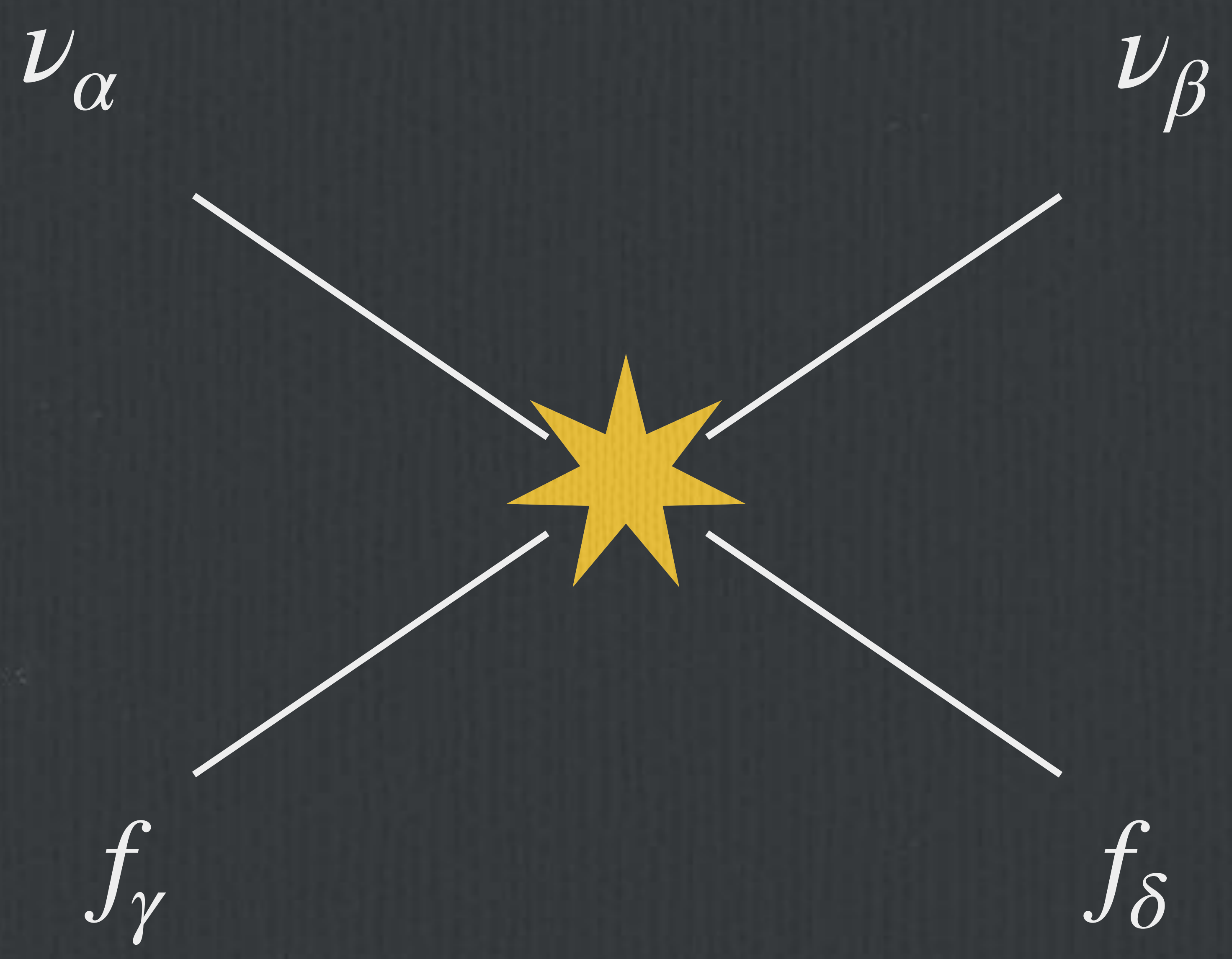
$q + \nu \to q + \nu';\ l + \nu \to l + \nu'$

source

detector

matter

NSIs in matter



Standard matter effects

$$H = \frac{1}{2E}\left\{\boxed{U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}}U^\dagger + \boxed{A\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}} + \boxed{A\begin{pmatrix}\epsilon^{\mathrm{m}}_{ee} & \epsilon^{\mathrm{m}}_{e\mu} & \epsilon^{\mathrm{m}}_{e\tau}\\ \epsilon^{\mathrm{m}}_{\mu e} & \epsilon^{\mathrm{m}}_{\mu\mu} & \epsilon^{\mathrm{m}}_{\mu\tau}\\ \epsilon^{\mathrm{m}}_{\tau e} & \epsilon^{\mathrm{m}}_{\tau\mu} & \epsilon^{\mathrm{m}}_{\tau\tau}\end{pmatrix}}\right\}$$

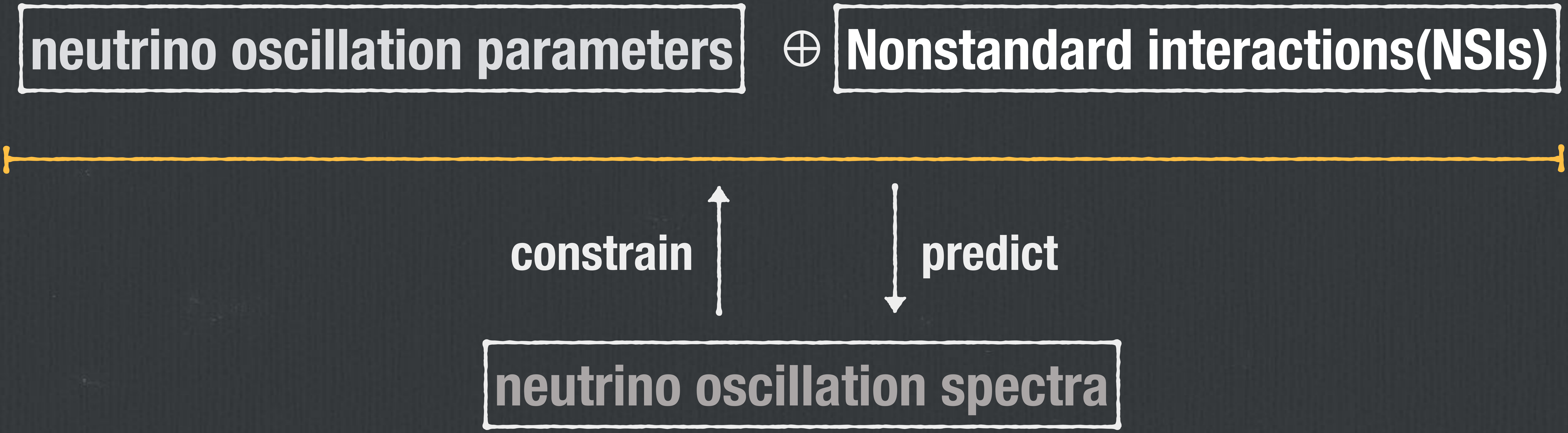
Oscillation in vacuum

NSIs in matter

$\epsilon_{\alpha\beta}$: the ratio between the stregth of NSIs to the Fermi constant.
A : matter potential.

We need accelerator neutrino facilities for at least two reasons: 1) the higher intensity; 2) the higher energy

New particles in neutrino oscillations



neutrino oscillation parameters ⊕ **Nonstandard interactions(NSIs)**

constrain ↑ ↓ predict

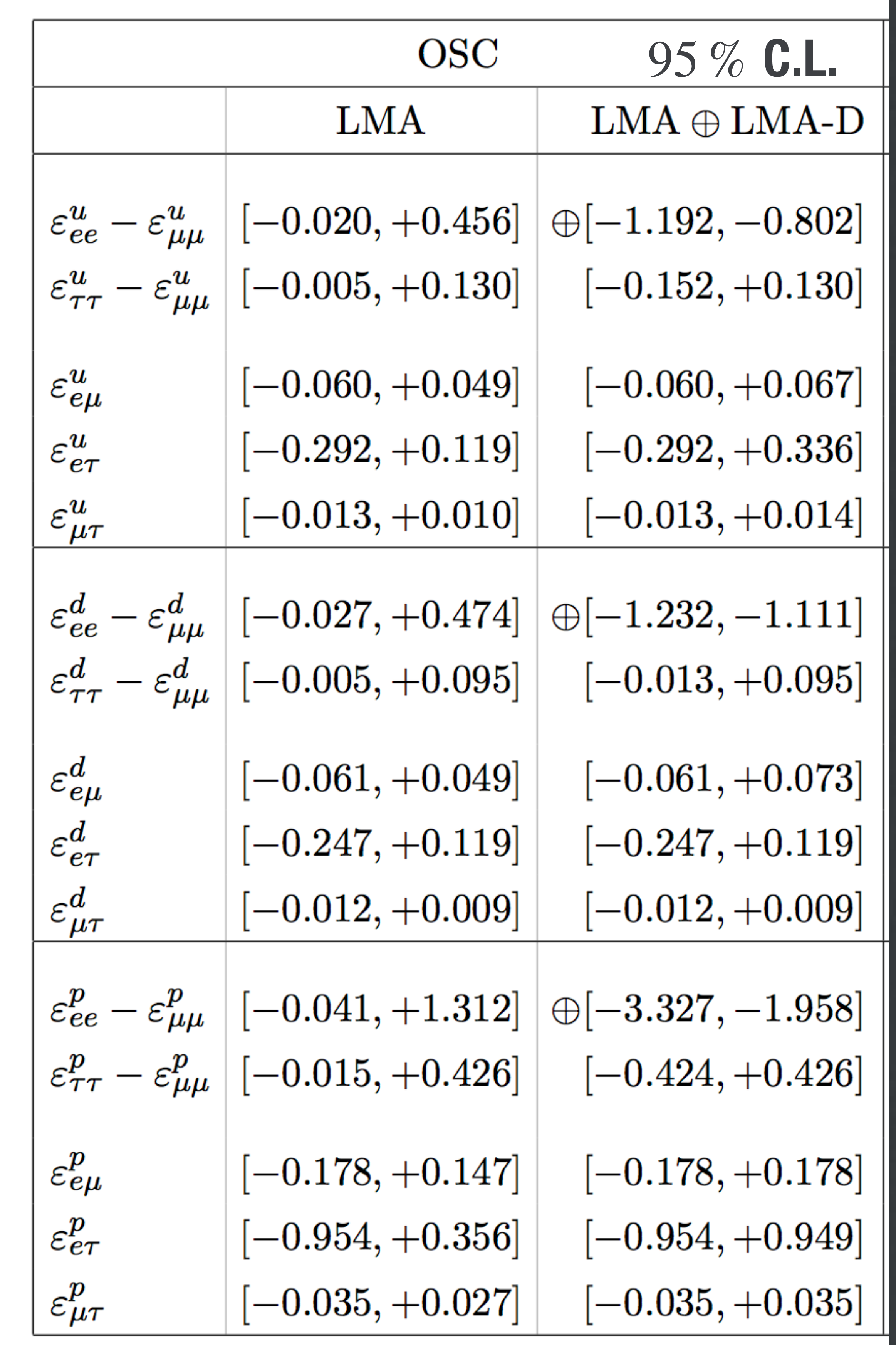
neutrino oscillation spectra

Last understanding of NSIs in matter

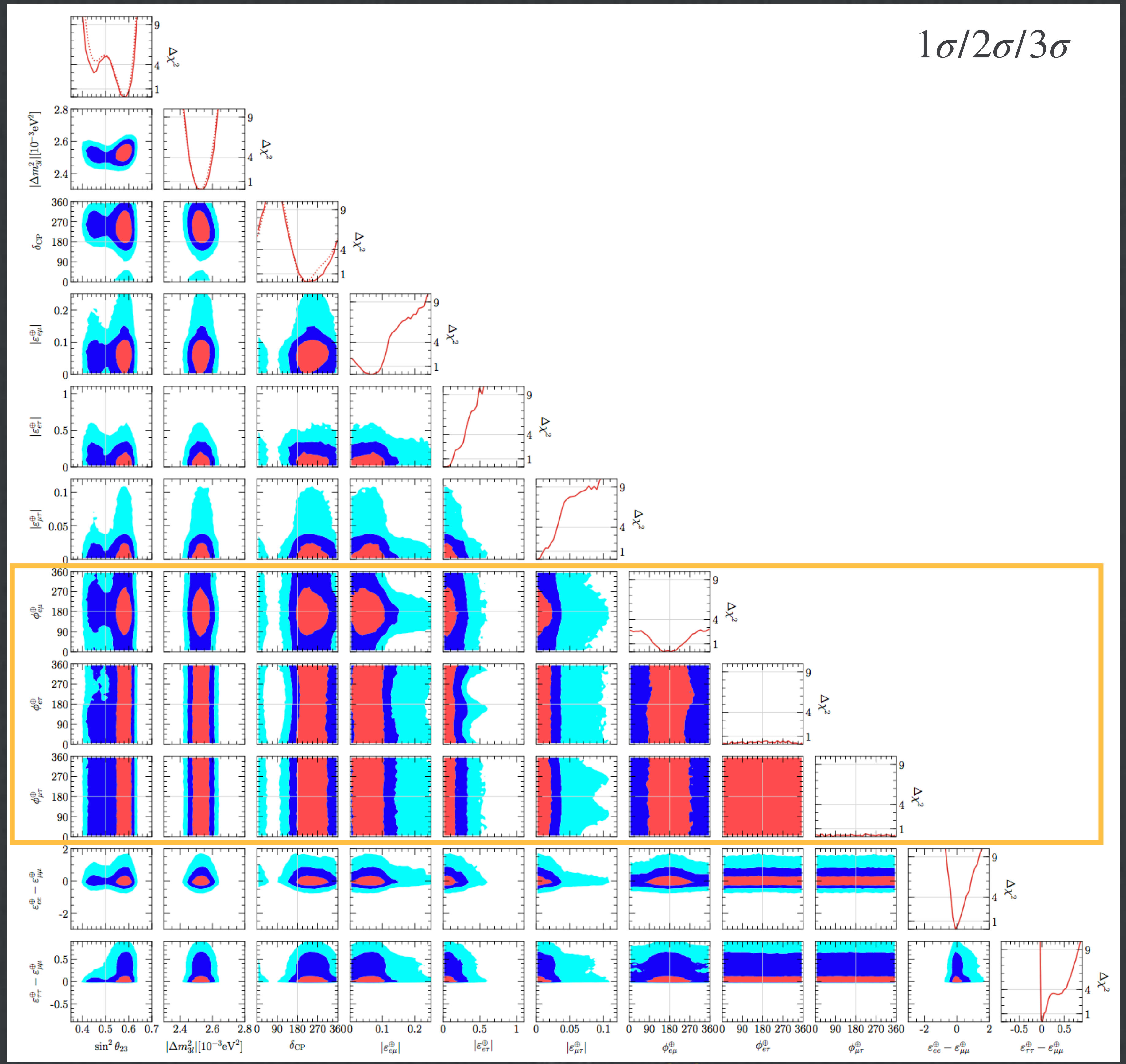
arXiv:1805.04530

arXiv:1905.05203

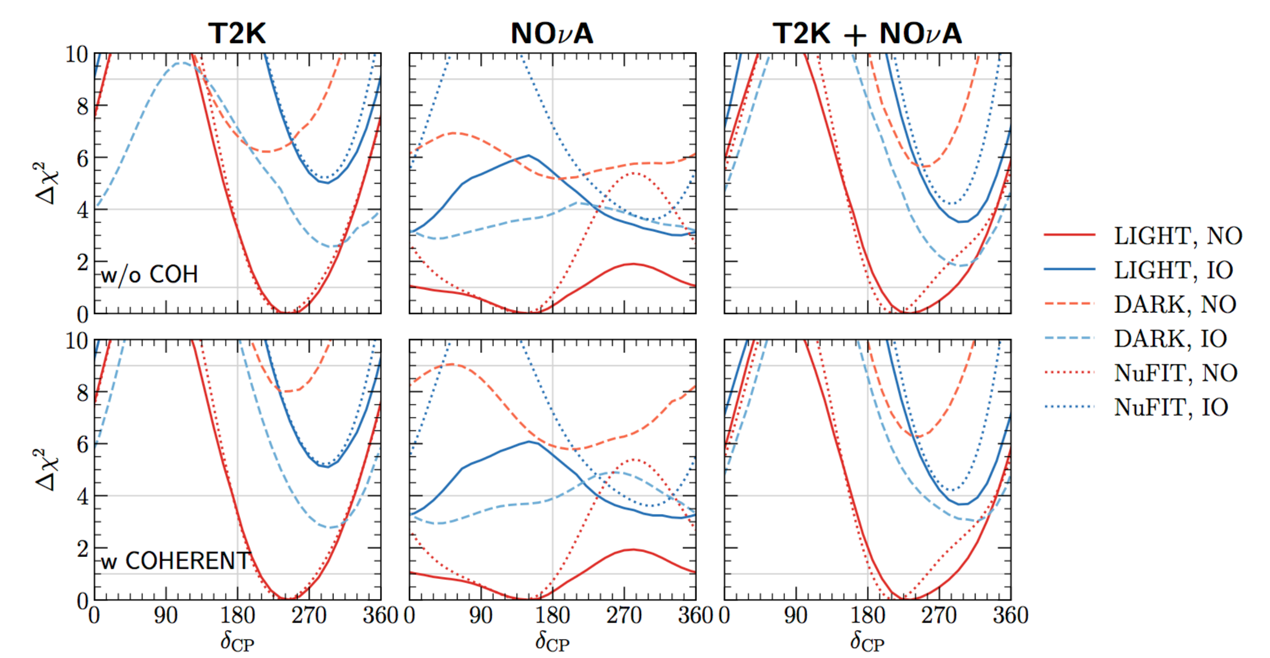
x 3 is about the NSIs in matter

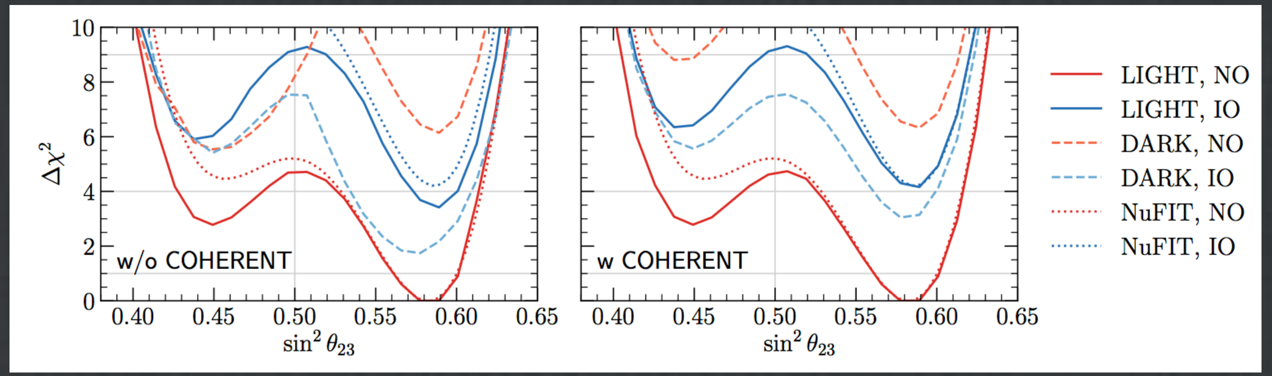


	OSC	95 % **C.L.**
	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.327, -1.958]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$
$\varepsilon^p_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$
$\varepsilon^p_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$
$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$



- NSI parameters are not be constrained very well by oscillation data.
- These new parameters affect the measurement of octant, mass ordering and CPV.

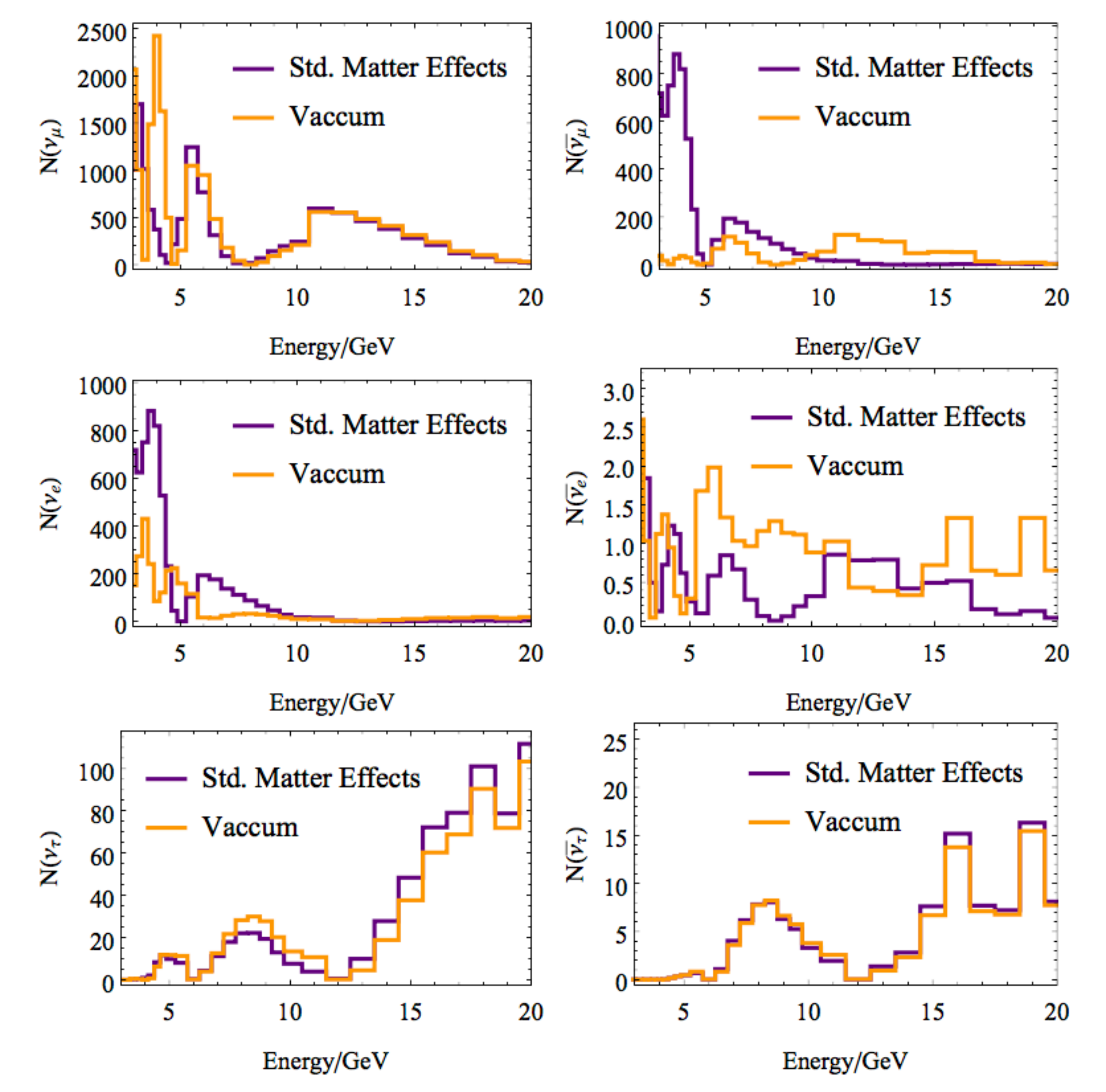


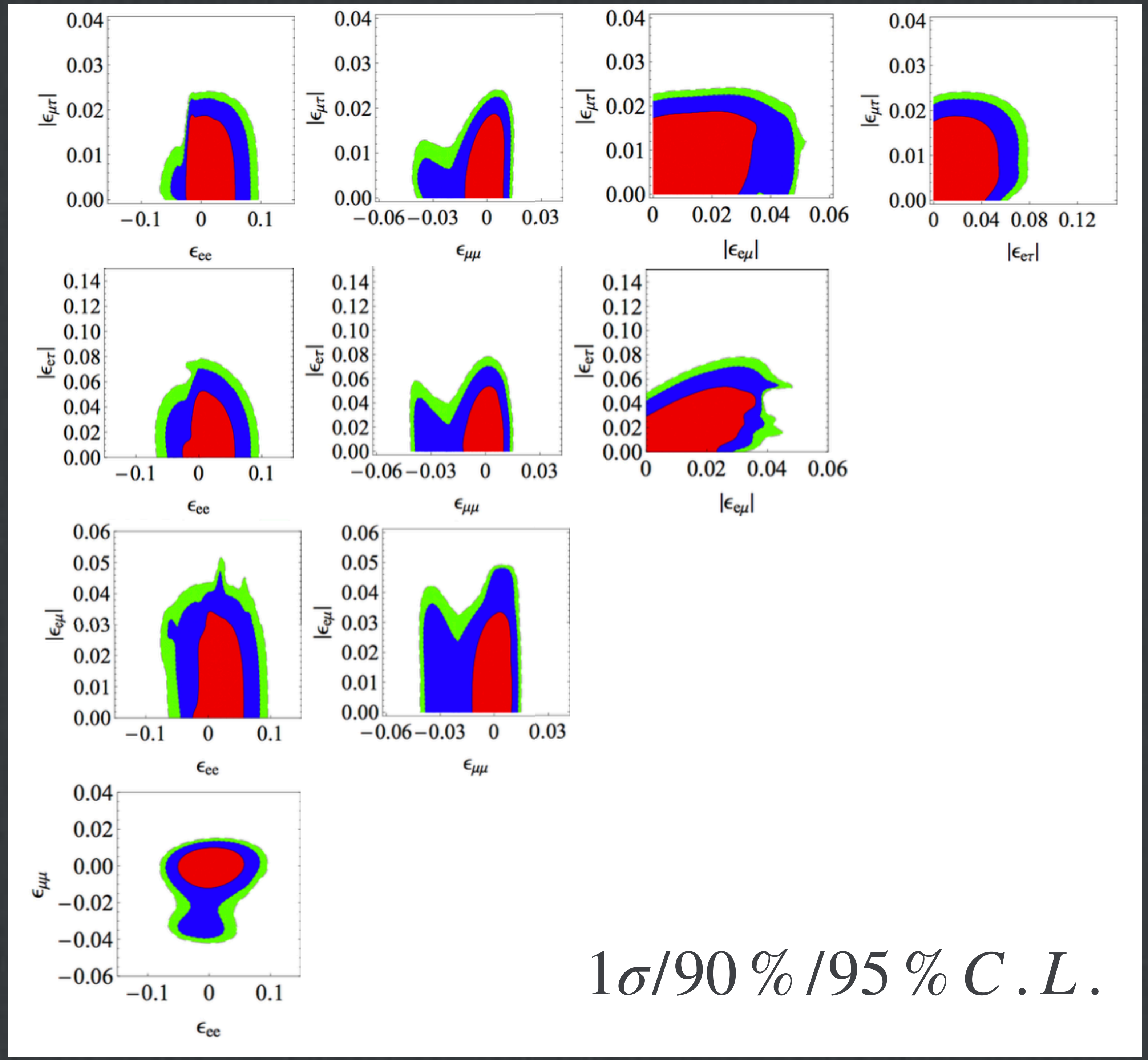


CERN-PINGU configuration (planet-scale nu oscillations)

arXiv:1909.12674

Shooting a neutrino beam from CERN to PINGU
baseline~10000km; large matter effects

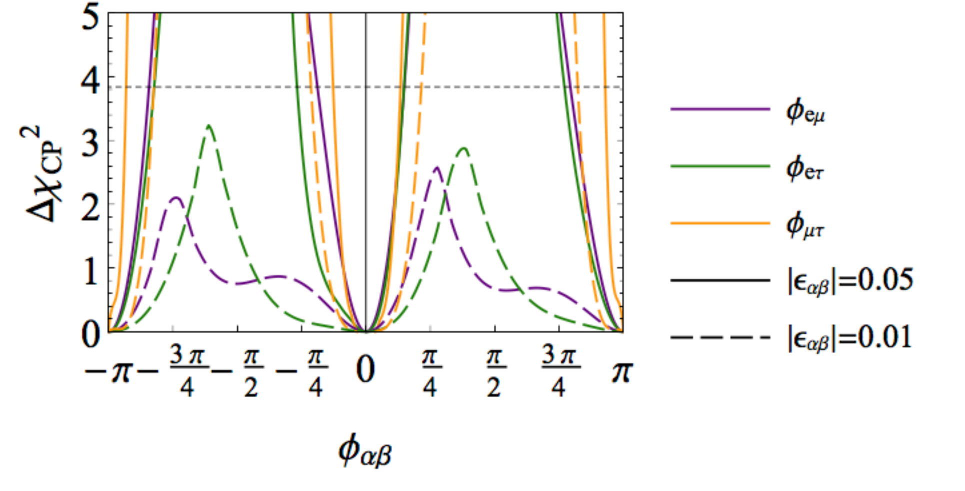




$1\sigma/90\%/95\%\,C.L.$

- Good measurements are expected.
- Most of degeneracies are resolved.
- It can be used for searching for CPV in NSIs.

$$\Delta\chi^2_{CP}(\phi^{true}_{\alpha\beta}) \equiv \min\{\Delta\chi^2(\phi_{\alpha\beta}=0), \Delta\chi^2(\phi_{\alpha\beta}=\pi)\},$$



Neutrino physics in neutrino oscillations

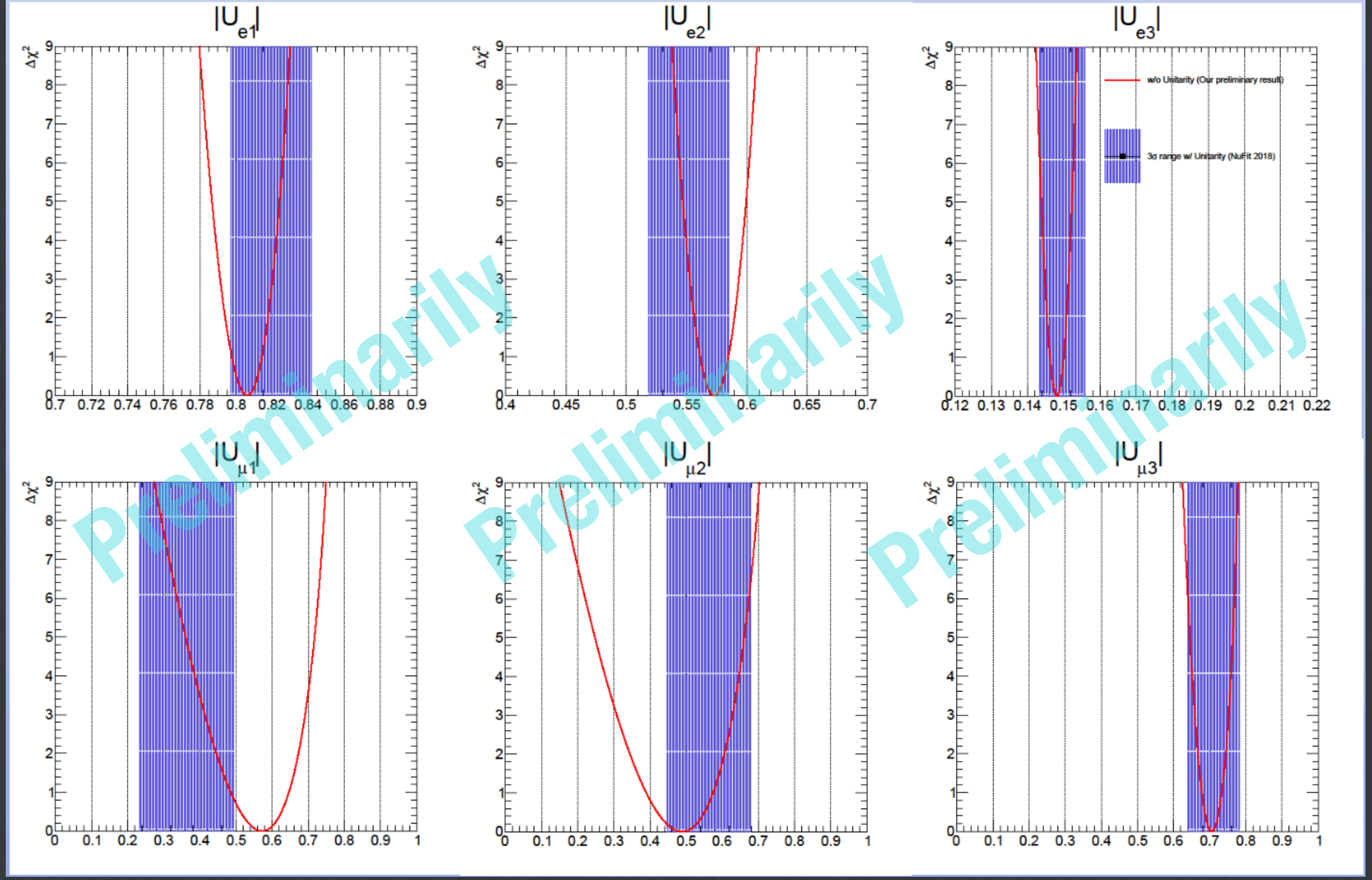
- ☐ Flavour symmetry: high-energy symmetries
- ☐ Nonstandard interactions: new mediators
- ☐ Nonunitarity, neutrino decays, and sterile-active mixing: new fermions

3-neutrino unitarity

$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\rm PMNS}^{3\rm x3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

Experiment type	Experiment	L/E (Δm^2)	Leading Order Function	Unitary Condition
Short baseline reactor experiments ($\bar{\nu}_e$->$\bar{\nu}_e$)	Daya Bay; RENO; Double Chooz	~10^2-10^3 eV^{-2} (Δm^2_{31})	$2\vert U_{e3}\vert^2(\vert U_{e1}\vert^2+\vert U_{e2}\vert^2)$	1st row normalisation
Long baseline reactor experiments ($\bar{\nu}_e$->$\bar{\nu}_e$)	KamLAND	~10^4 eV^{-2} (Δm^2_{21})	$2\vert U_{e1}\vert^2\vert U_{e2}\vert^2$	1st row normalisation
Solar neutrino experiments (ν_e->ν_e)	SNO	N/A (diurnal distance v.s. ~10 MeV)	$\vert U_{e2}\vert^2(\vert U_{e1}\vert^2+\vert U_{e2}\vert^2)$ $+\vert U_{e3}\vert^2$	1st row normalisation
Accelerator experiments (ν_μ->ν_μ)	T2K; NOvA; MINOS	~10^2-10^3 eV^{-2} (Δm^2_{31})	$2\vert U_{\mu 3}\vert^2(\vert U_{\mu 1}\vert^2+\vert U_{\mu 2}\vert^2)$	2st row normalisation
Accelerator experiments (ν_μ->ν_e)	T2K; NOvA	~10^2-10^3 eV^{-2} (Δm^2_{31})	$2{\rm Re}[U_{e3}{}^*U_{\mu 3}(U_{e1}{}^*U_{\mu 1}$ $+U_{e2}{}^*U_{\mu 2})]$	1st &2nd row orthgonality
Accelerator experiments (ν_μ->ν_τ)	OPERAR	~10^3 eV^{-2} (Δm^2_{31})	$2{\rm Re}[U_{\tau 3}{}^*U_{\mu 3}(U_{\tau 1}{}^*U_{\mu 1}$ $+U_{\tau 2}{}^*U_{\mu 2})]$	3rd &2nd row orthgonality

Only 5 events by far



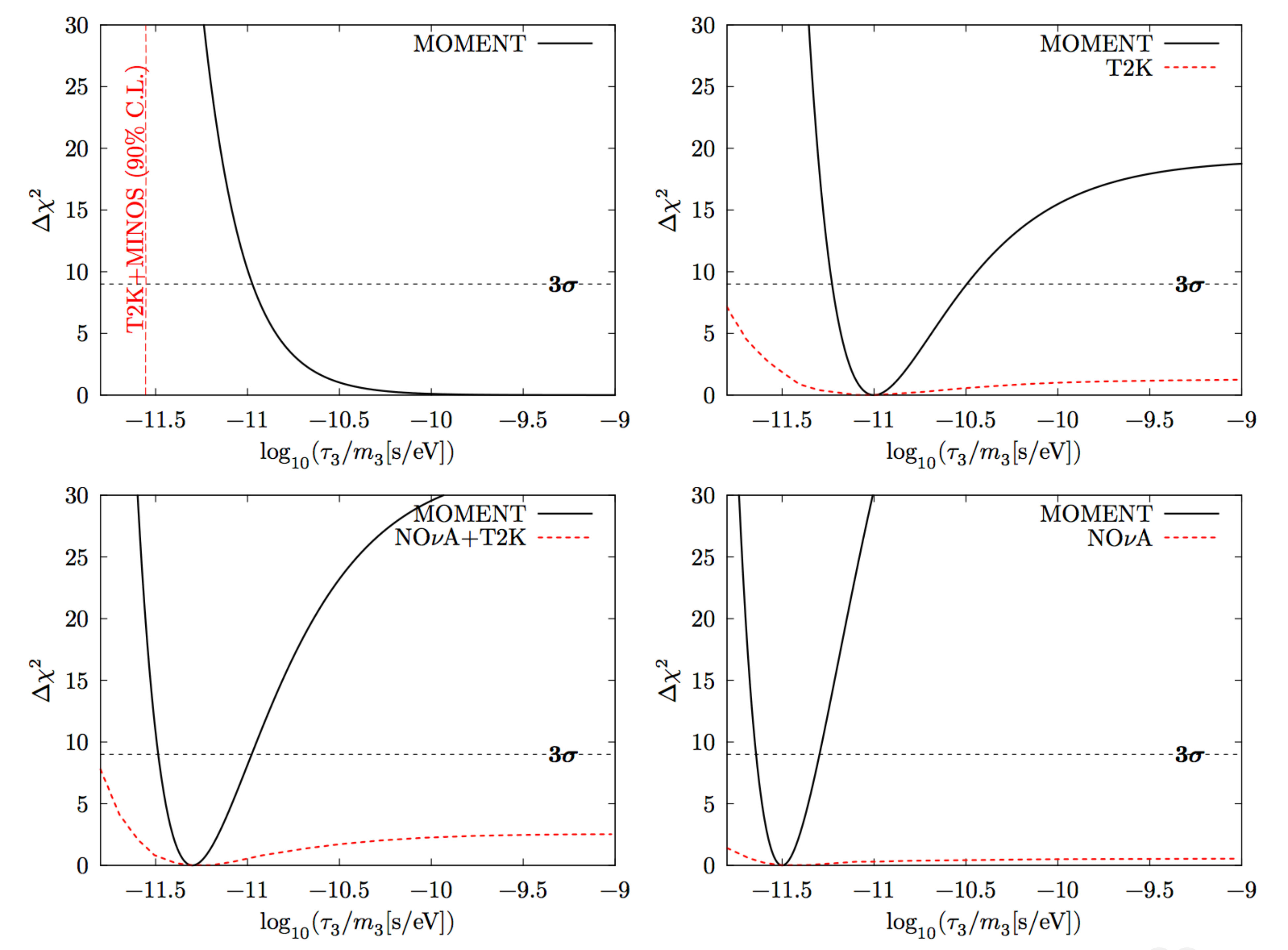
We have good measurement for the "e" row. For "mu" and "tau" rows, we need accelerator facilities.

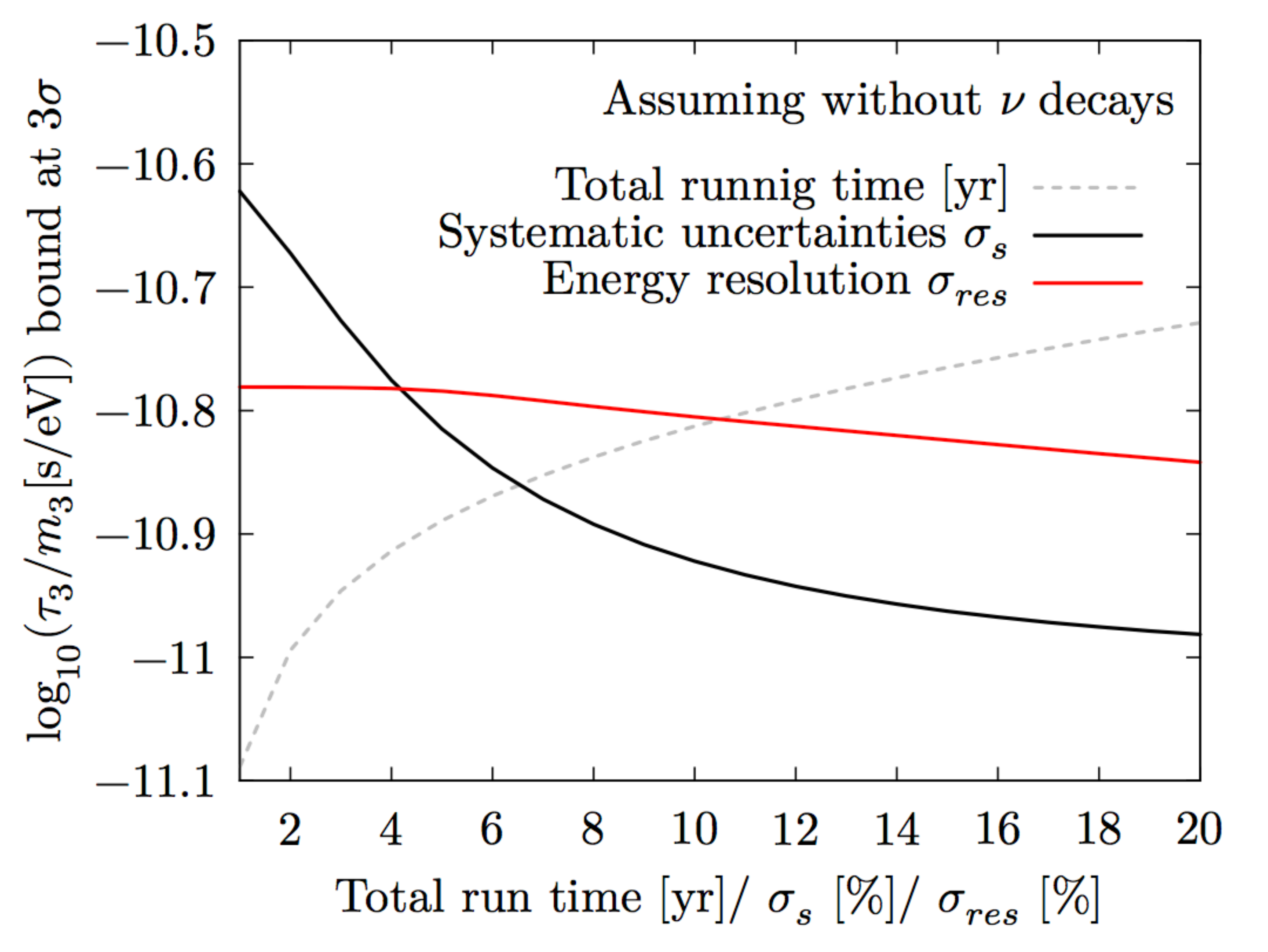
Invisible neutrino decays in MOMENT

arXiv:1811.05623

$$H = U\left\{\frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix} - i\frac{m_3}{2E\tau_3}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{pmatrix}\right\}U^\dagger + \begin{pmatrix}2\sqrt{2}G_F N_e E & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

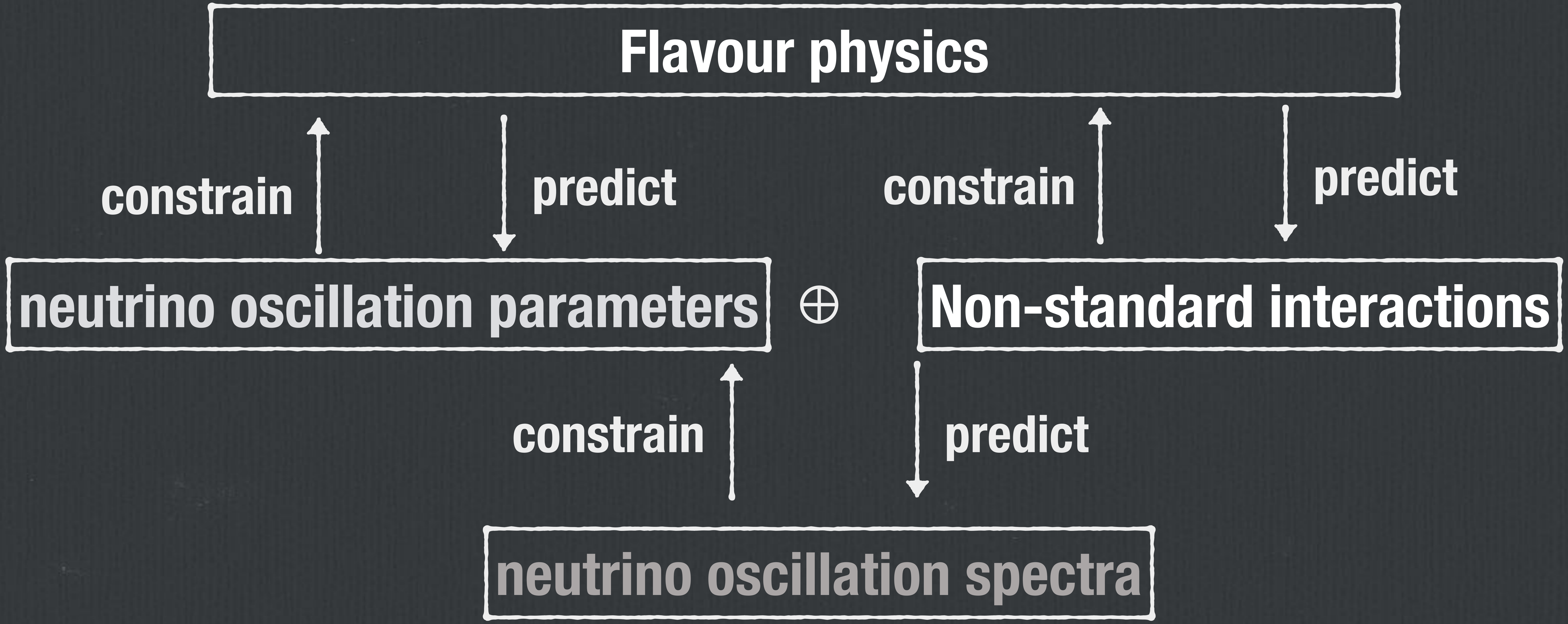
- The baseline of MOMENT is proper to constrain tau_3.
- It can greatly improve the current knowledge of inversive neutrino decays from NOvA and T2K.
- The systemtic error is more important than other factors.





New strategy for flavour symmetry

New strategy for flavour symmetry



Flavour physics

constrain

predict

constrain

predict

neutrino oscillation parameters ⊕ Non-standard interactions

constrain

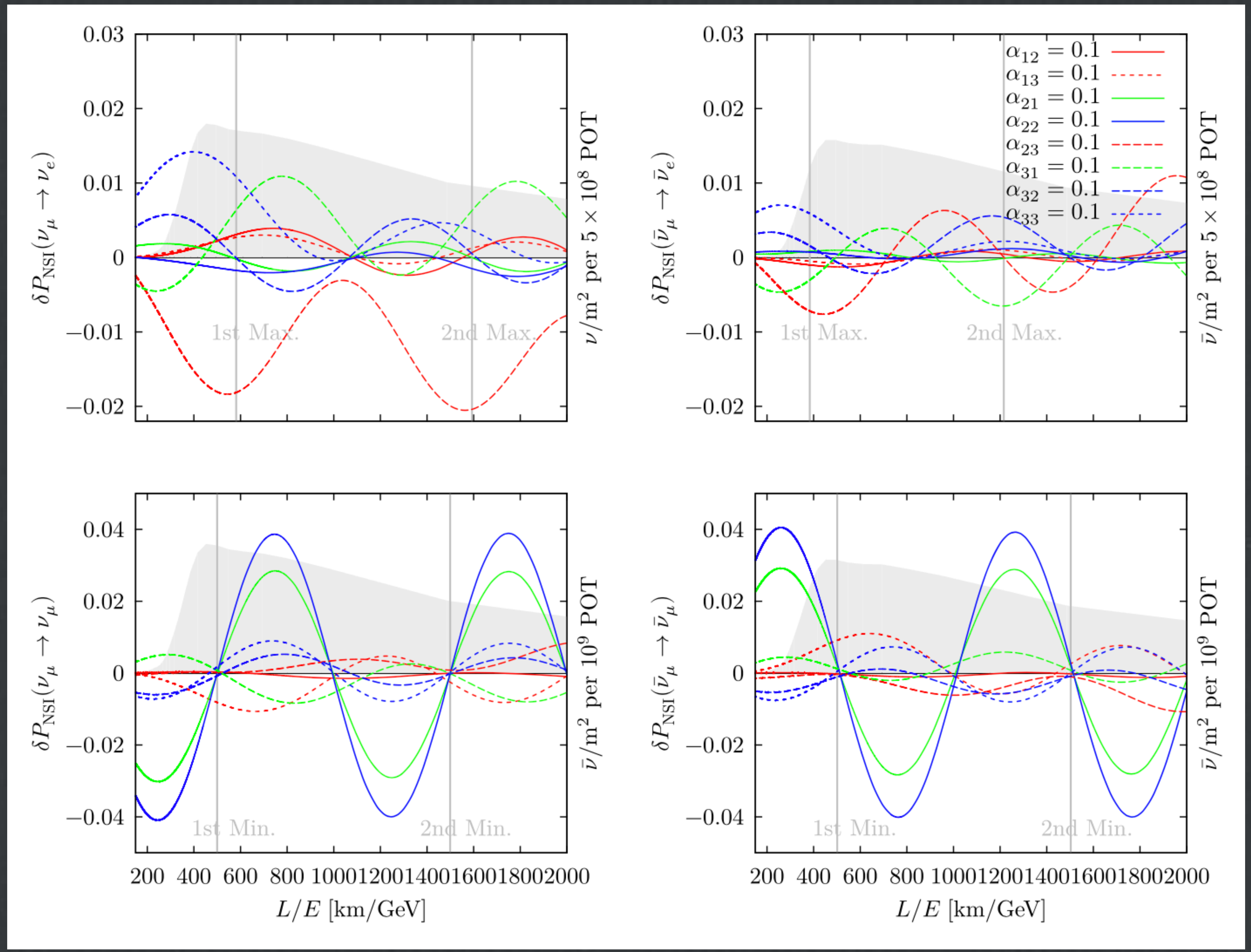
predict

neutrino oscillation spectra

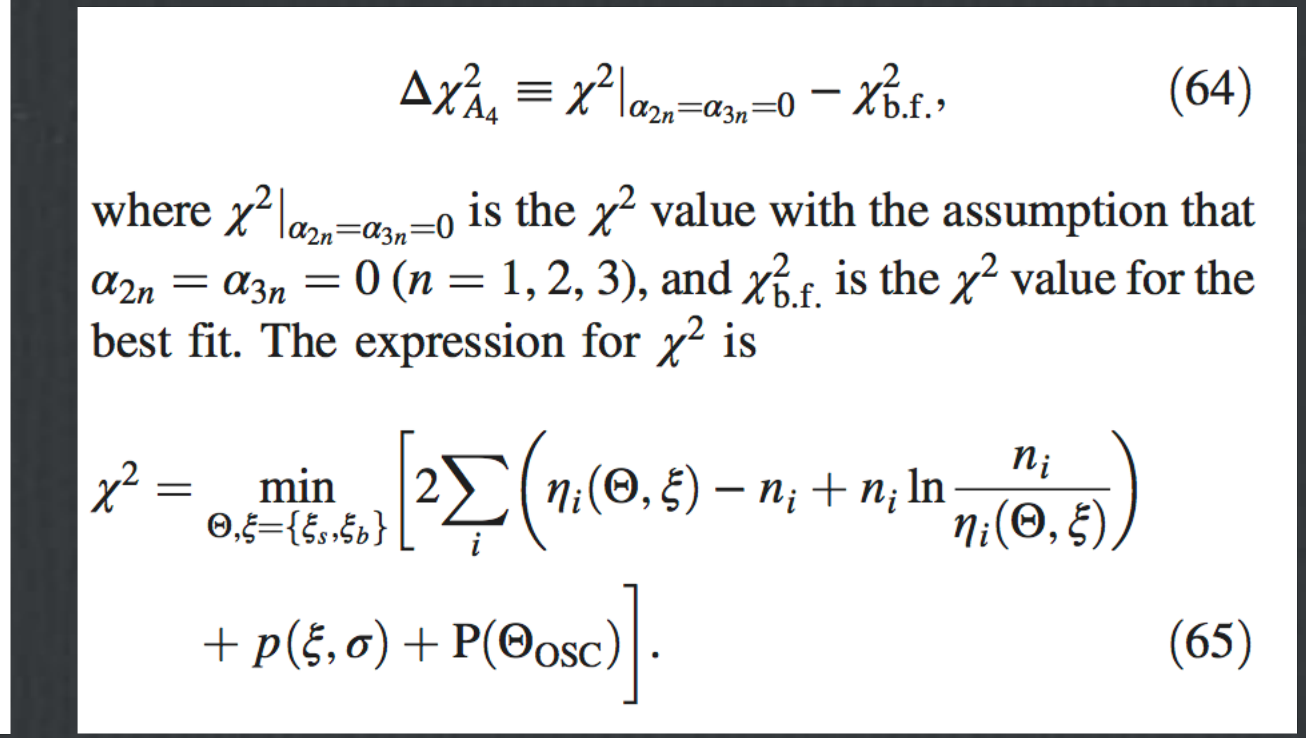
Testing A4 symmetry at high energy for DUN

arXiv:1801.05656

- High precision to test A4 at NSIs are expected.
- A4 conserved at NSI can explain null-NSI measurement in DUNE.



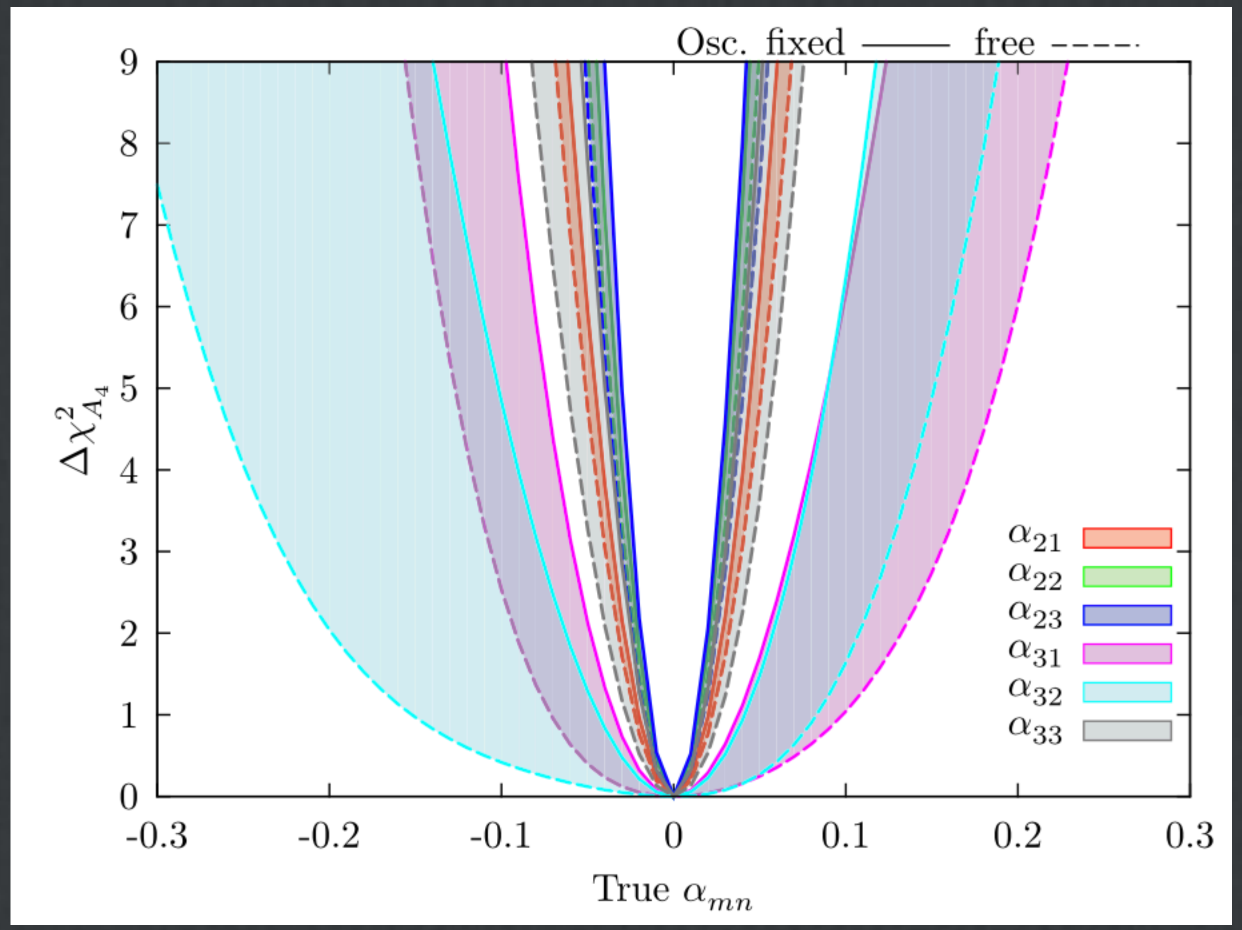
A4 symmetry forbids the flavour-transition NSIs.

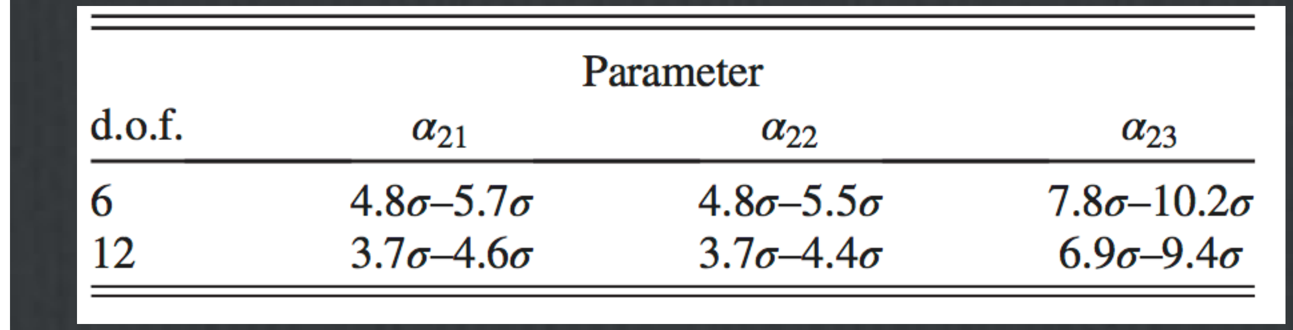


$$\Delta\chi^2_{A_4} \equiv \chi^2|_{\alpha_{2n}=\alpha_{3n}=0} - \chi^2_{\rm b.f.}, \qquad (64)$$

where $\chi^2|_{\alpha_{2n}=\alpha_{3n}=0}$ is the χ^2 value with the assumption that $\alpha_{2n}=\alpha_{3n}=0$ $(n=1,2,3)$, and $\chi^2_{\rm b.f.}$ is the χ^2 value for the best fit. The expression for χ^2 is

$$\chi^2 = \min_{\Theta,\xi=\{\xi_s,\xi_b\}}\left[2\sum_i\left(\eta_i(\Theta,\xi) - n_i + n_i \ln\frac{n_i}{\eta_i(\Theta,\xi)}\right) + p(\xi,\sigma) + {\rm P}(\Theta_{\rm OSC})\right]. \qquad (65)$$





	Parameter		
d.o.f.	α_{21}	α_{22}	α_{23}
6	4.8σ–5.7σ	4.8σ–5.5σ	7.8σ–10.2σ
12	3.7σ–4.6σ	3.7σ–4.4σ	6.9σ–9.4σ

The messages want to be conveyed today

---

1. ✓ Neutrino oscillations are the only evidence for the physics beyond the standard model (BSM) by far.
2. ✓ Neutrino physicists want to know more about neutrino oscillations. if sign$(\Delta m^2_{31}) >$ or < 0? if $\theta_{23} >$ or $< 45^\circ$?
   if $\delta = \pm \pi/2$? $\delta =$?

   We measure $P(\nu_\mu \rightarrow \nu_e)$ to resolve some of these problems.
3. ✓ Particle physicists want to know if there is any other BSM phenomenology.

   Flavour symmetry/ New mediator searching/ New fermion probing
4. To achieve the above, we need accelerator neutrino facilities.

Conclusions

The messages want to be conveyed today

1. Neutrino oscillations are the only evidence for the physics beyond the standard model (BSM) by far.

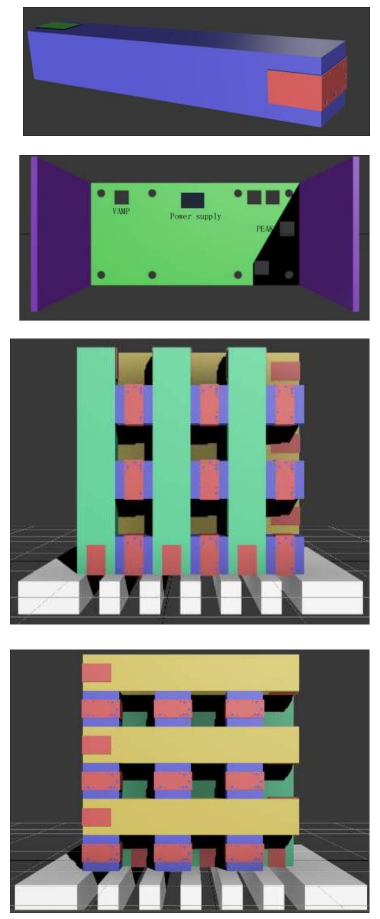
2. Neutrino physicists want to know more about neutrino oscillations.

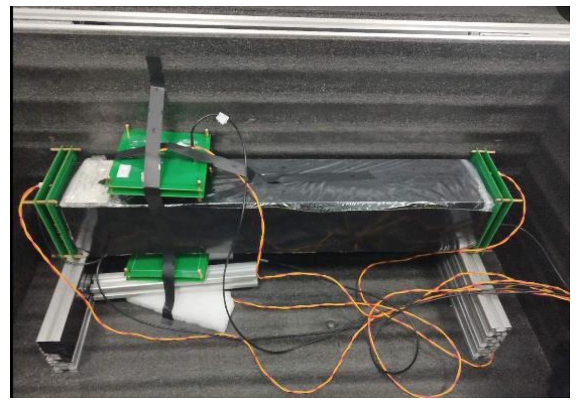
3. Particle physicists want to know if there is any other BSM phenomenology.

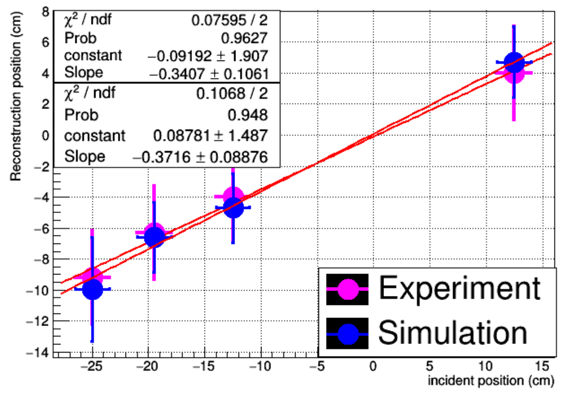
4. To achieve the above, we need accelerator neutrino facilities.

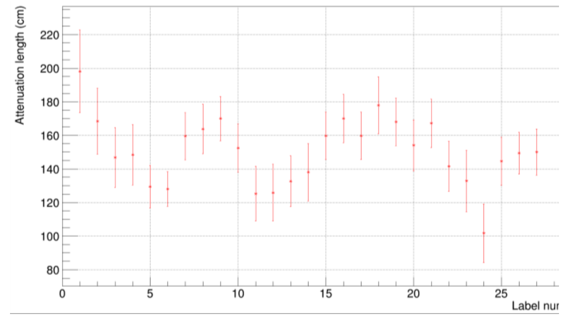
Thank you for your attention

R&D of a muon tracking detector





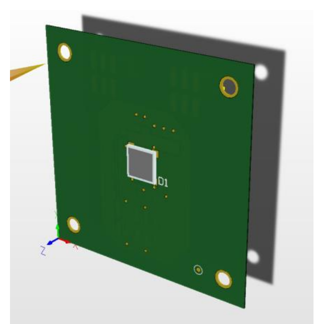




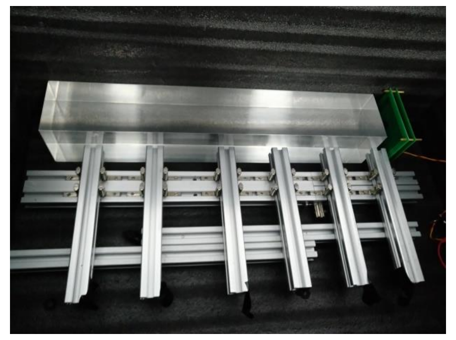
Attenuation length of
each plastic scintillator

探测器prototype

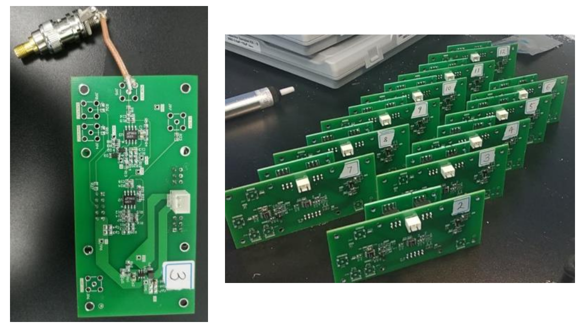
SiPM

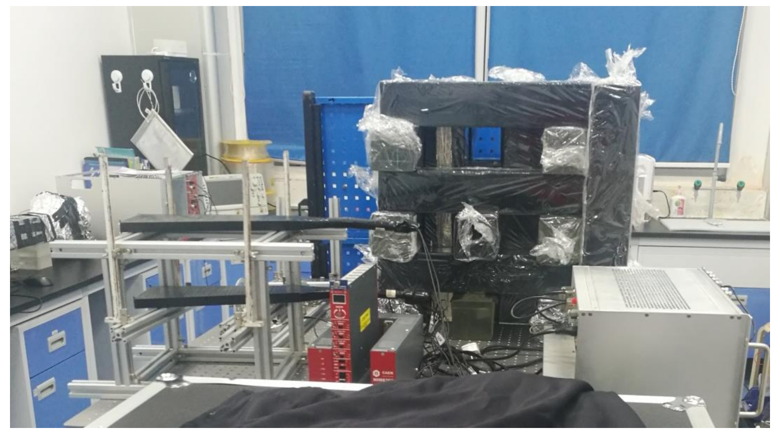


Plastic scintillator



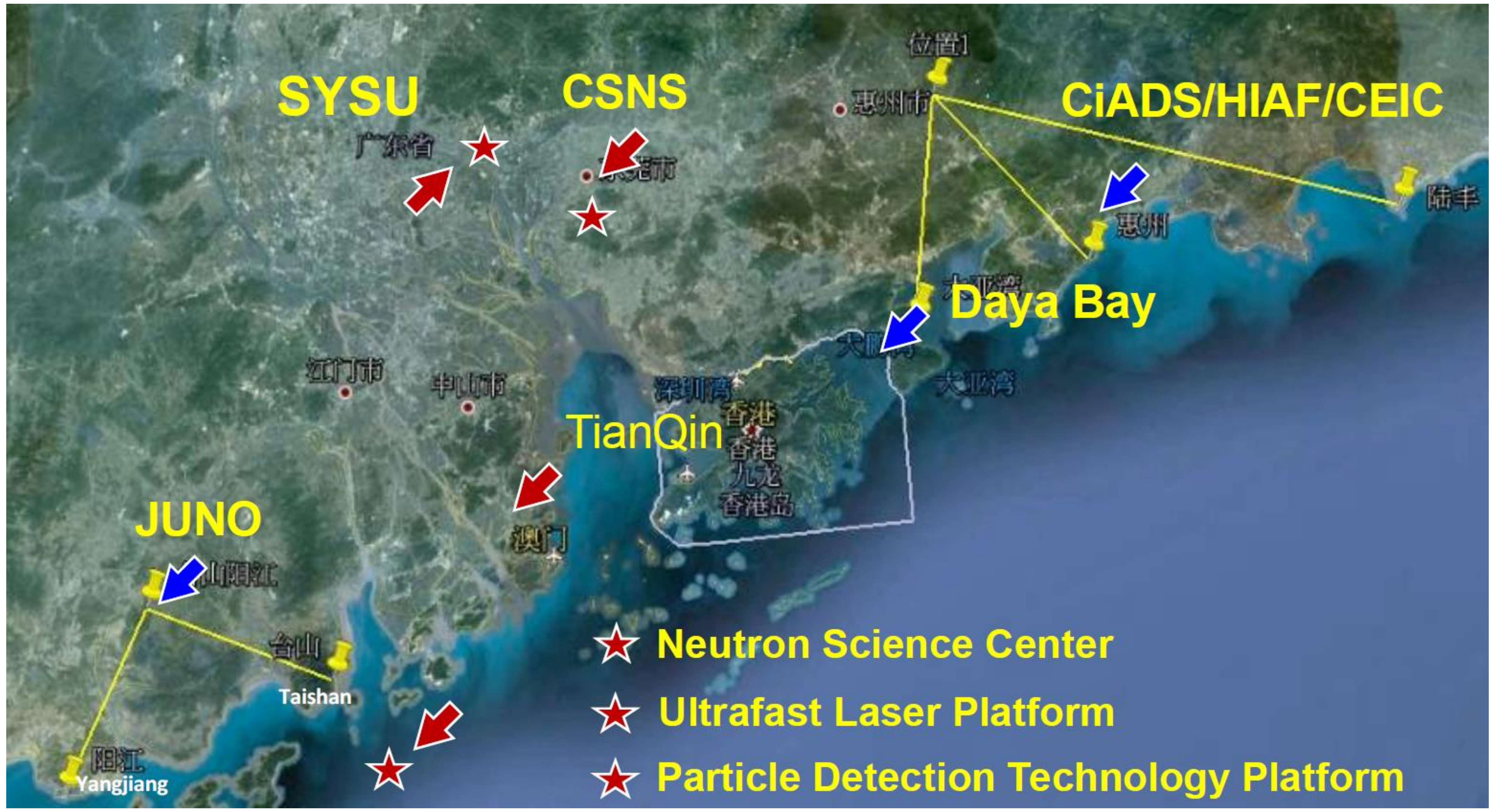
Electronics readout





Pre-assembly

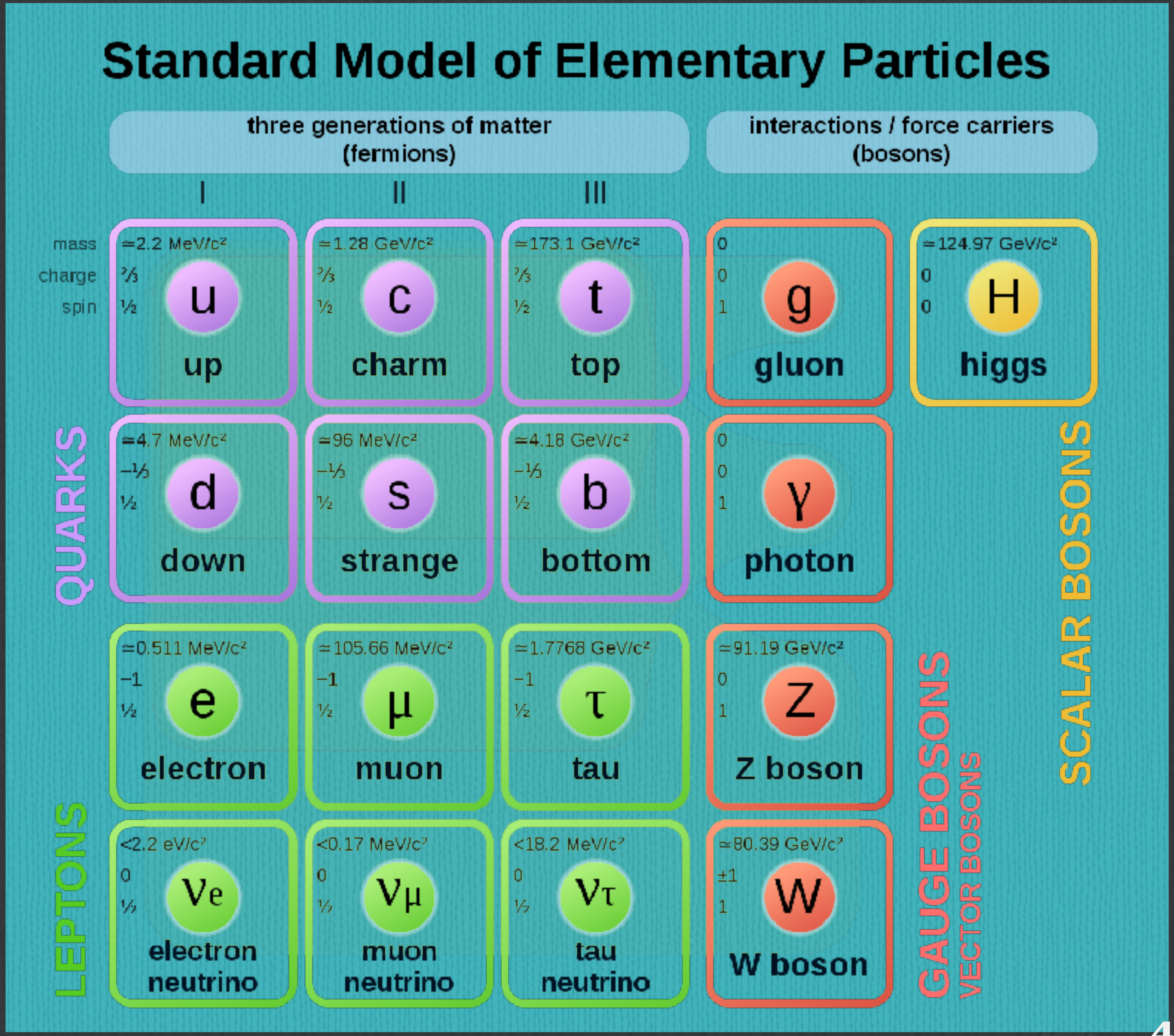
PostDoc advertisement in SYSU



Postdoc openings in our group: **~2K euros/month + bonus + on-campus housing + Postdoc funding** supported by local province**.**
Email: tangjian5@mail.sysu.edu.cn

Back-up

The Standard Model



$$su(2)_L \times u(1)_Y$$

gauge interactions

$$\mathscr{L} = i \sum_{\alpha=e,\mu,\tau} \overline{L'_{\alpha L}} \not{D} L'_{\alpha L} + i \sum_{\alpha=1,2,3} \overline{Q'_{\alpha L}} \not{D} Q'_{\alpha L} + i \sum_{\alpha=e,\mu,\tau} \overline{\ell'_{\alpha R}} \not{D} \ell'_{\alpha R} + i \sum_{\alpha=d,s,b} \overline{q'^{D}_{\alpha R}} \not{D} q'^{D}_{\alpha R} + i \sum_{\alpha=u,c,t} \overline{q'^{U}_{\alpha R}} \not{D} q'^{U}_{\alpha R}$$

$$- \frac{1}{4} \underline{A}_{\mu\nu} \underline{A}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

self-interaction

$$+ (D_\rho \Phi)^\dagger (D^\rho \Phi) - \mu^2 \, \Phi^\dagger \Phi - \lambda \, (\Phi^\dagger \Phi)^2$$

Higgs potential

$$- \sum_{\alpha,\beta=e,\mu,\tau} \left(Y'^{\ell}_{\alpha\beta} \, \overline{L'_{\alpha L}} \, \Phi \, \ell'_{\beta R} + Y'^{\ell *}_{\alpha\beta} \, \overline{\ell'_{\beta R}} \, \Phi^\dagger \, L'_{\alpha L} \right)$$

$$- \sum_{\alpha=1,2,3} \sum_{\beta=d,s,b} \left(Y'^{D}_{\alpha\beta} \, \overline{Q'_{\alpha L}} \, \Phi \, q'^{D}_{\beta R} + Y'^{D *}_{\alpha\beta} \, \overline{q'^{D}_{\beta R}} \, \Phi^\dagger \, Q'_{\alpha L} \right)$$

$$- \sum_{\alpha=1,2,3} \sum_{\beta=u,c,t} \left(Y'^{U}_{\alpha\beta} \, \overline{Q'_{\alpha L}} \, \widetilde{\Phi} \, q'^{U}_{\beta R} + Y'^{U *}_{\alpha\beta} \, \overline{q'^{U}_{\beta R}} \, \widetilde{\Phi}^\dagger \, Q'_{\alpha L} \right).$$

mass term of fermions

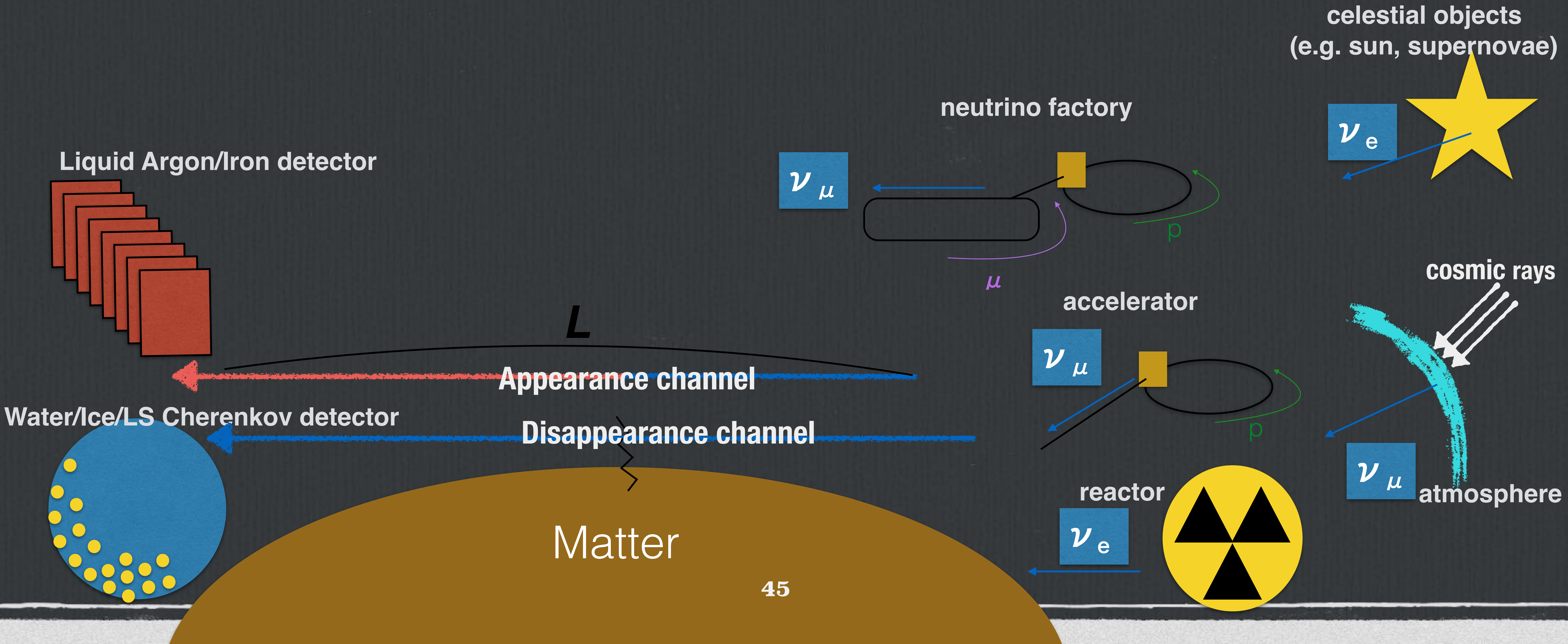
BEYOND The standard model of particle physics

- The neutrino oscillation: neutrinos are massive!
- The dark matter: dark sector is predicted!
- The dark energy: it is inconsistent with Higgs vacuum!

BEHIND neutrino oscillations

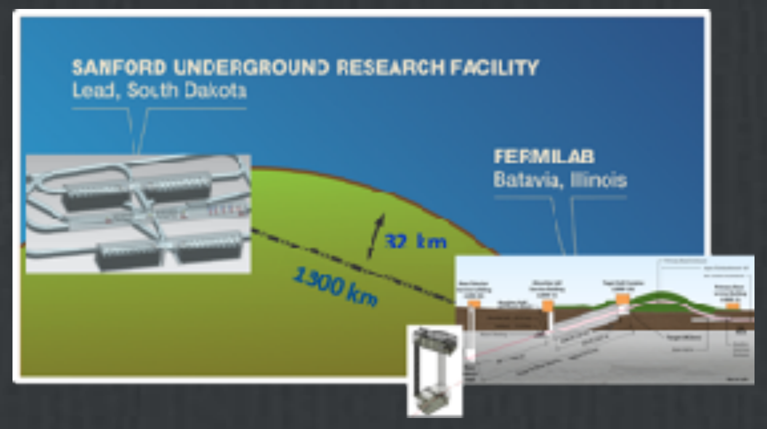
- Neutrino oscillations are the effects caused by the neutrino mass differences and neutrino mixing.
- The neutrino oscillation: neutrinos have mass.
  Time dilation does not apply. Otherwise, any variation of neutrino would not be allowed.
- Neutrino mixing is allowed in SM.

Neutrino Oscillation Experiments



Upcoming LBL accelerator Experiments

- Deep Underground Neutrino Experiment (DUNE):
  1. 1300 km
  2. 40 kton LArTPC
  3. non-negligible matter effects
  4. Superbeam facility



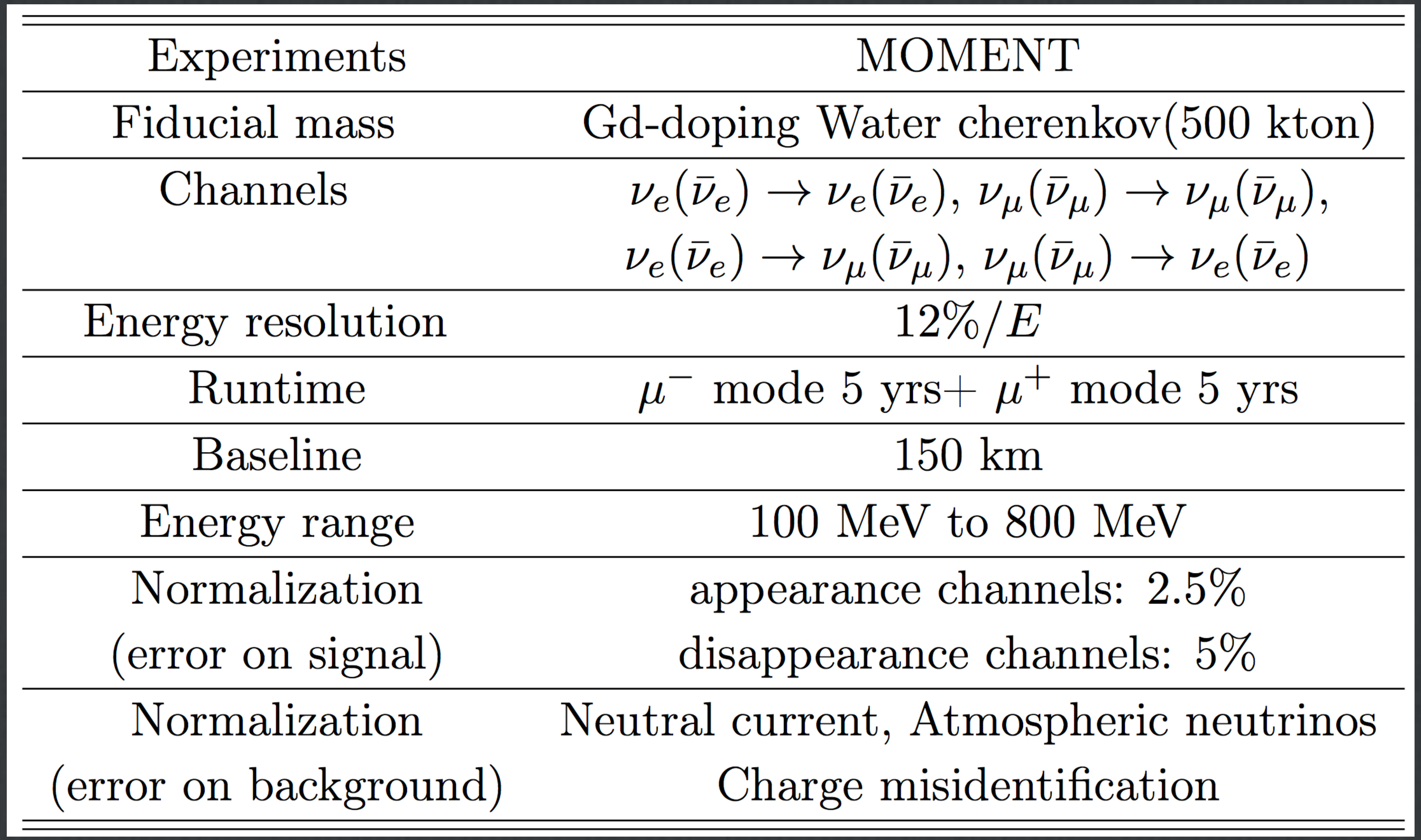
$$\nu_\mu \to \nu_\mu/\nu_e$$

$$\bar{\nu}_\mu \to \bar{\nu}_\mu/\bar{\nu}_e$$

- Tokai to Hyper-Kamiokanda(T2HK):
  1. 295 km
  2. 500 kton Water Cherenkov detector
  3. almost no matter effects
  4. Superbeam facility

MOMENT

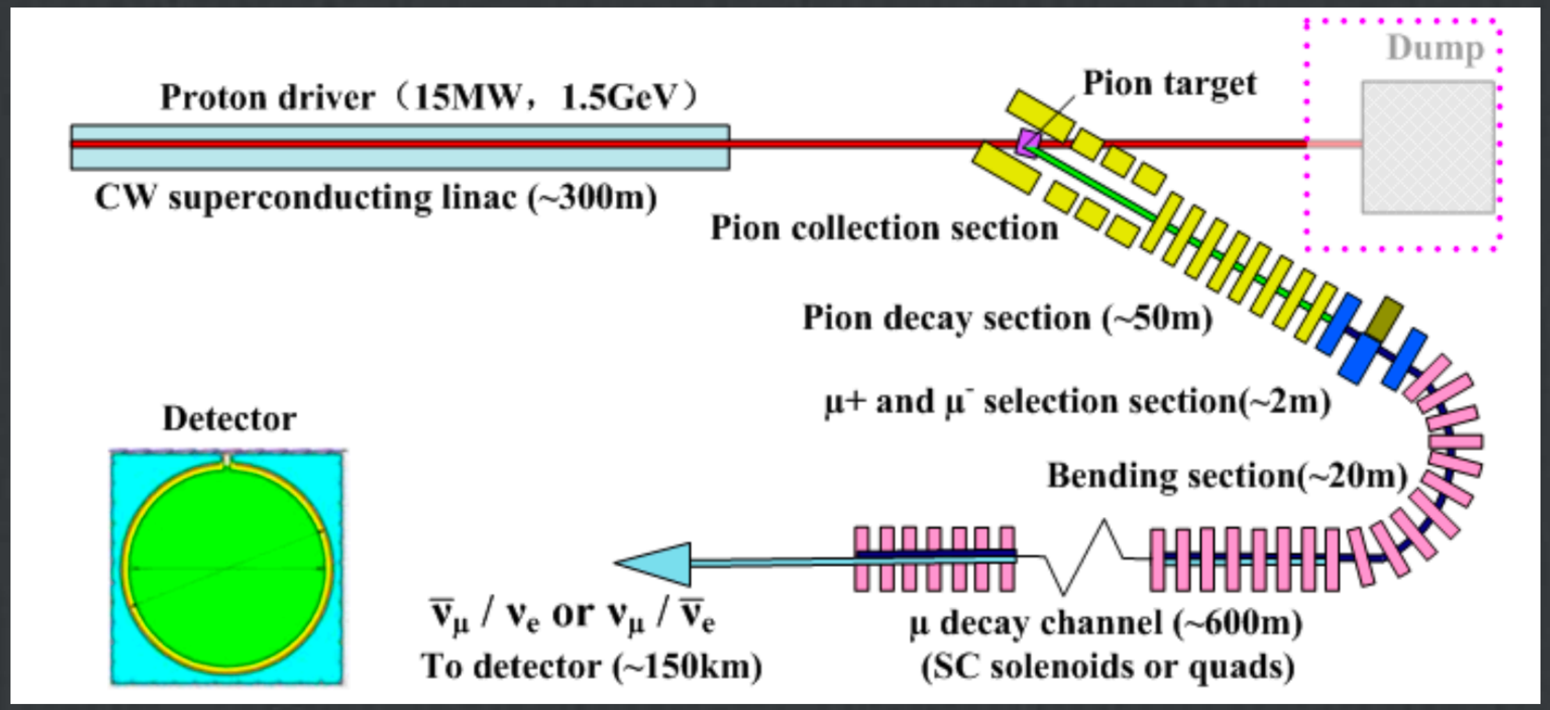
arXiv:1401.8125



Experiments	MOMENT
Fiducial mass	Gd-doping Water cherenkov(500 kton)
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	$12\%/E$
Runtime	μ^- mode 5 yrs+ μ^+ mode 5 yrs
Baseline	150 km
Energy range	100 MeV to 800 MeV
Normalization (error on signal)	appearance channels: 2.5% disappearance channels: 5%
Normalization (error on background)	Neutral current, Atmospheric neutrinos Charge misidentification

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

- **Using muon-decay neutrinos**
- **clean neutrino beam are expected.**
  —> low systematic errors from beam
  —> low background



Precision measurement of the CP phase

$\pi/2$ **for the 1st max.**

$$P(\nu_\mu \to \nu_e; E, L) = P_1 + P_{3/2} + \mathcal{O}(\epsilon^2)$$

$$P_1 = \frac{4}{(1-r_A)^2}\sin^2\theta_{23}\sin^2\theta_{13}\sin^2\left(\frac{(1-r_A)\Delta L}{2}\right)$$

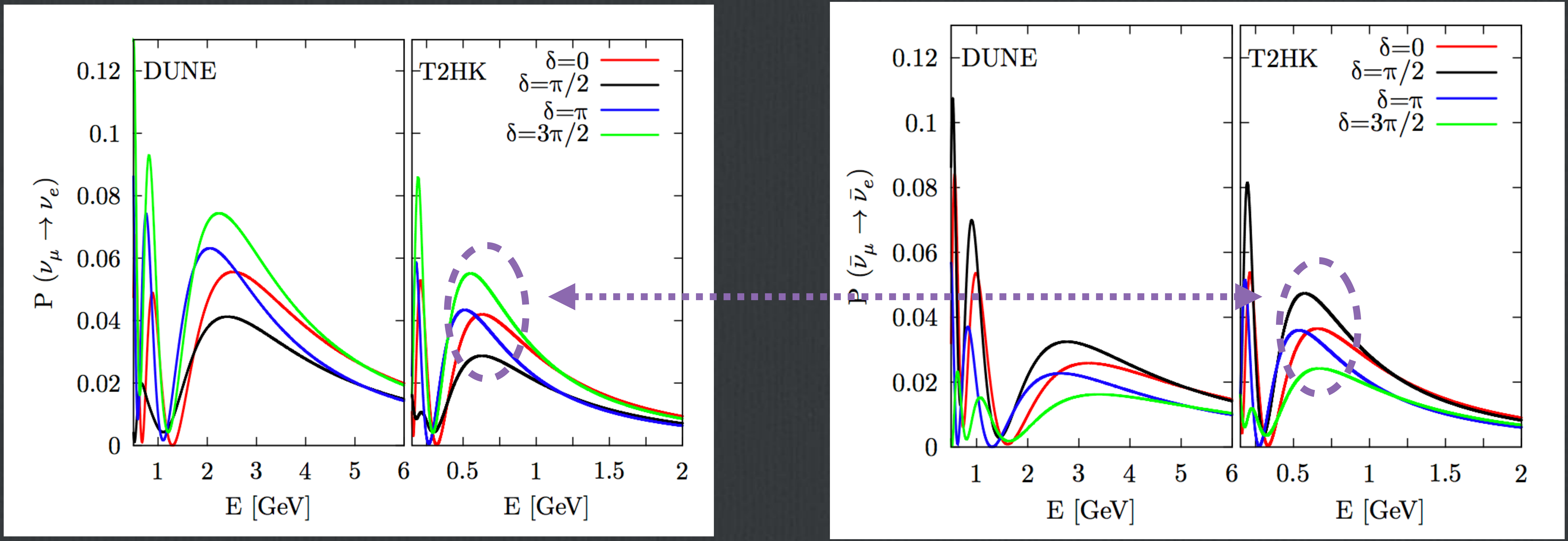
$$P_{3/2} = 8J_r\frac{\epsilon}{r_A(1-r_A)}\underbrace{\boxed{\cos\left(\delta + \frac{\Delta L}{2}\right)}}_{= \sin\delta}\sin\left(\frac{r_A\Delta L}{2}\right)\times\sin\left(\frac{(1-r_A)\Delta L}{2}\right)$$

$$J_r = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\sin\theta_{13}$$

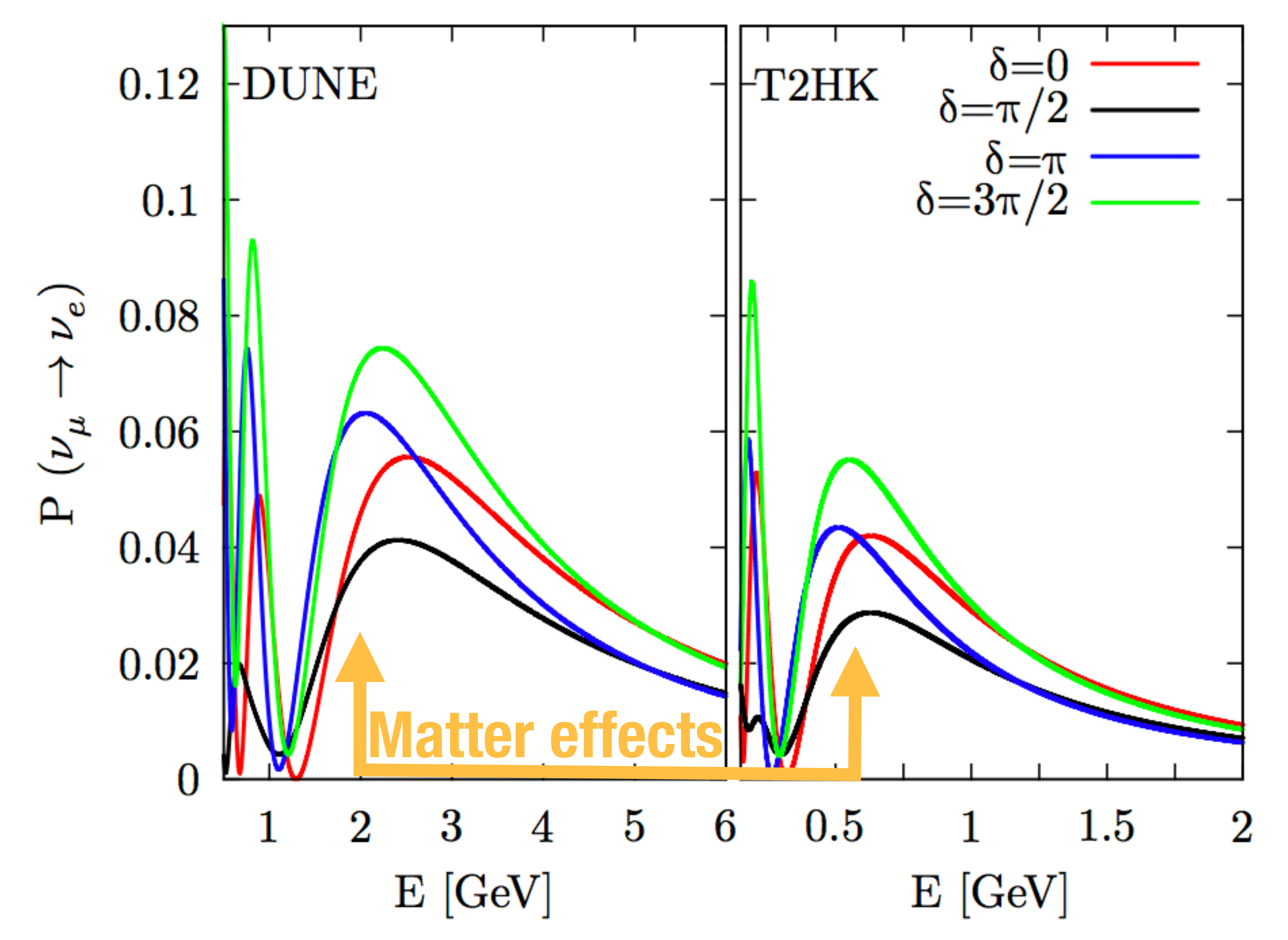
$$r_A = 2\sqrt{2}G_F N_e E/\Delta m^2_{31}; \qquad \Delta = \Delta m^2_{31}/2E$$

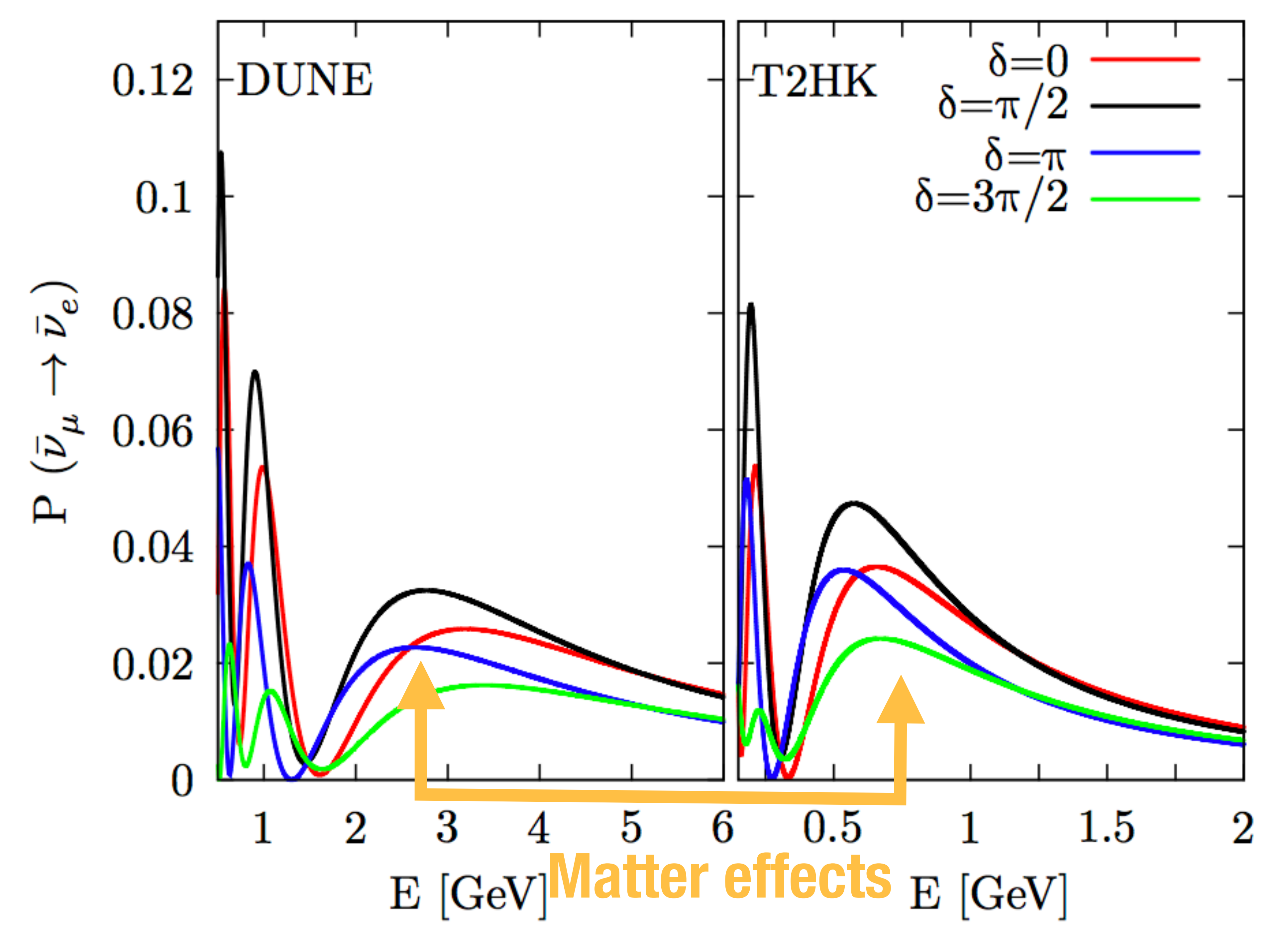
Oscillation for DUNE and T2HK with different CP phases

Normal ordering



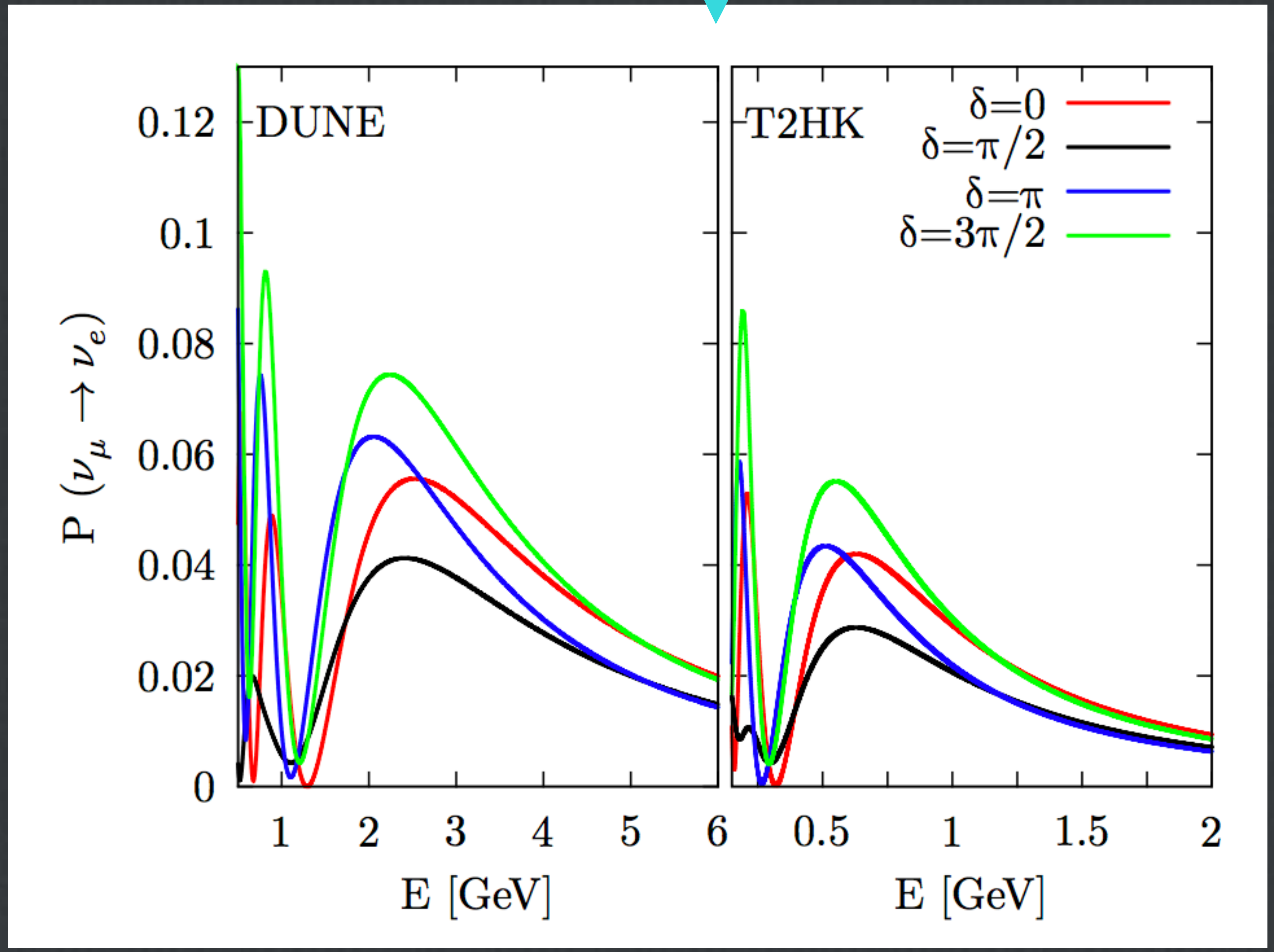
Oscillation for DUNE and T2HK with different CP phases

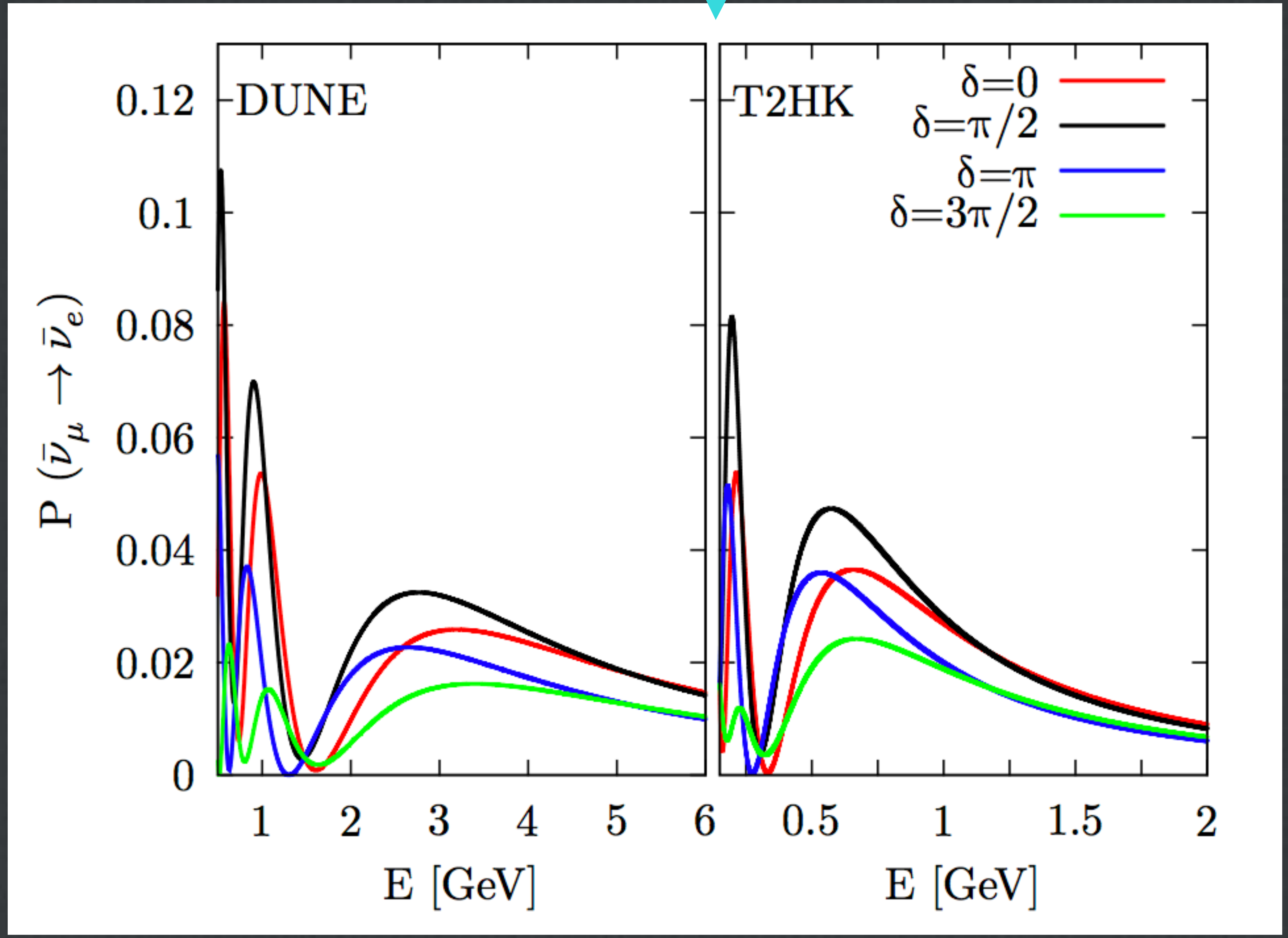




Oscillation for DUNE and T2HK with different CP phases

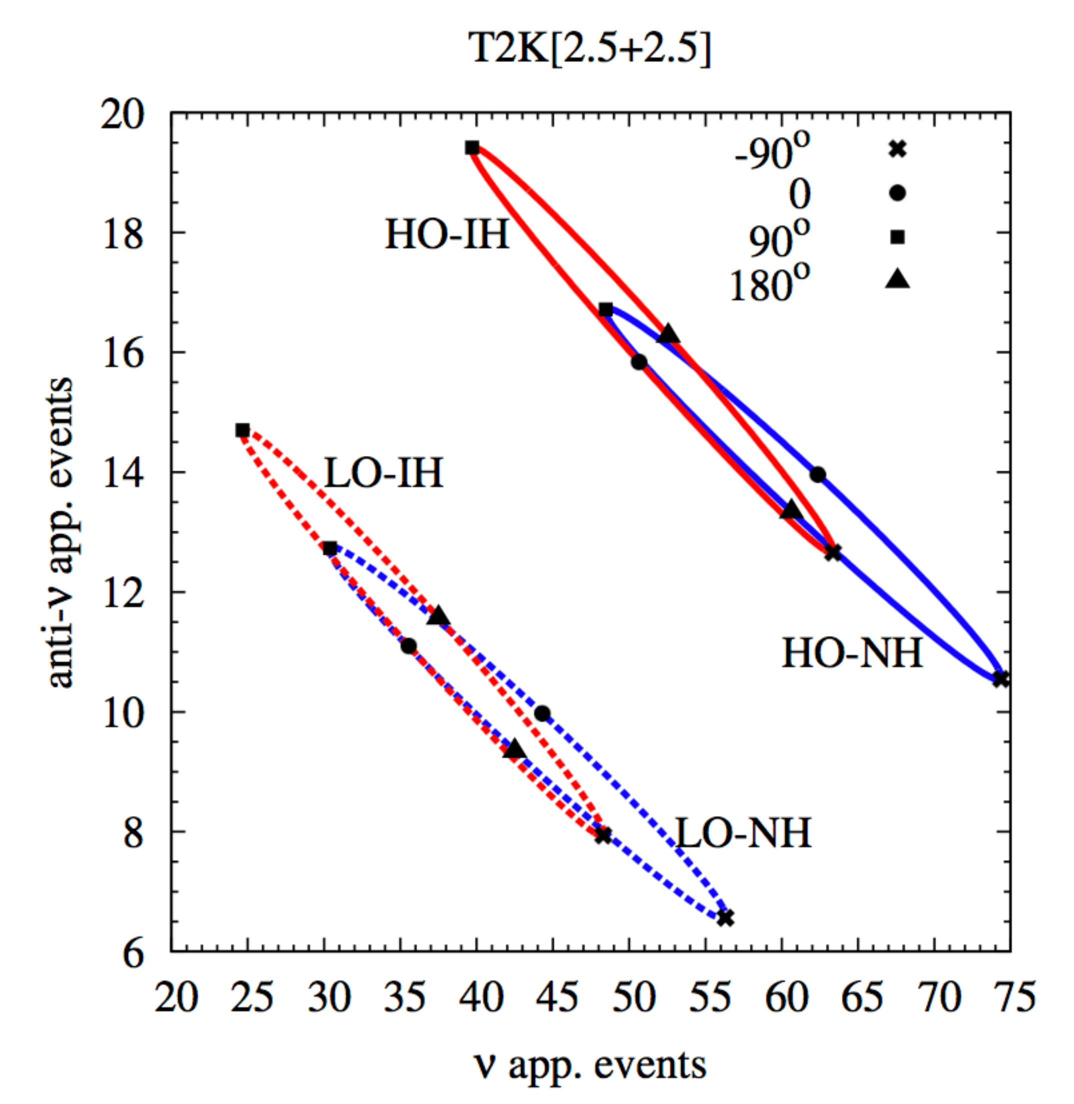
Mass ordering



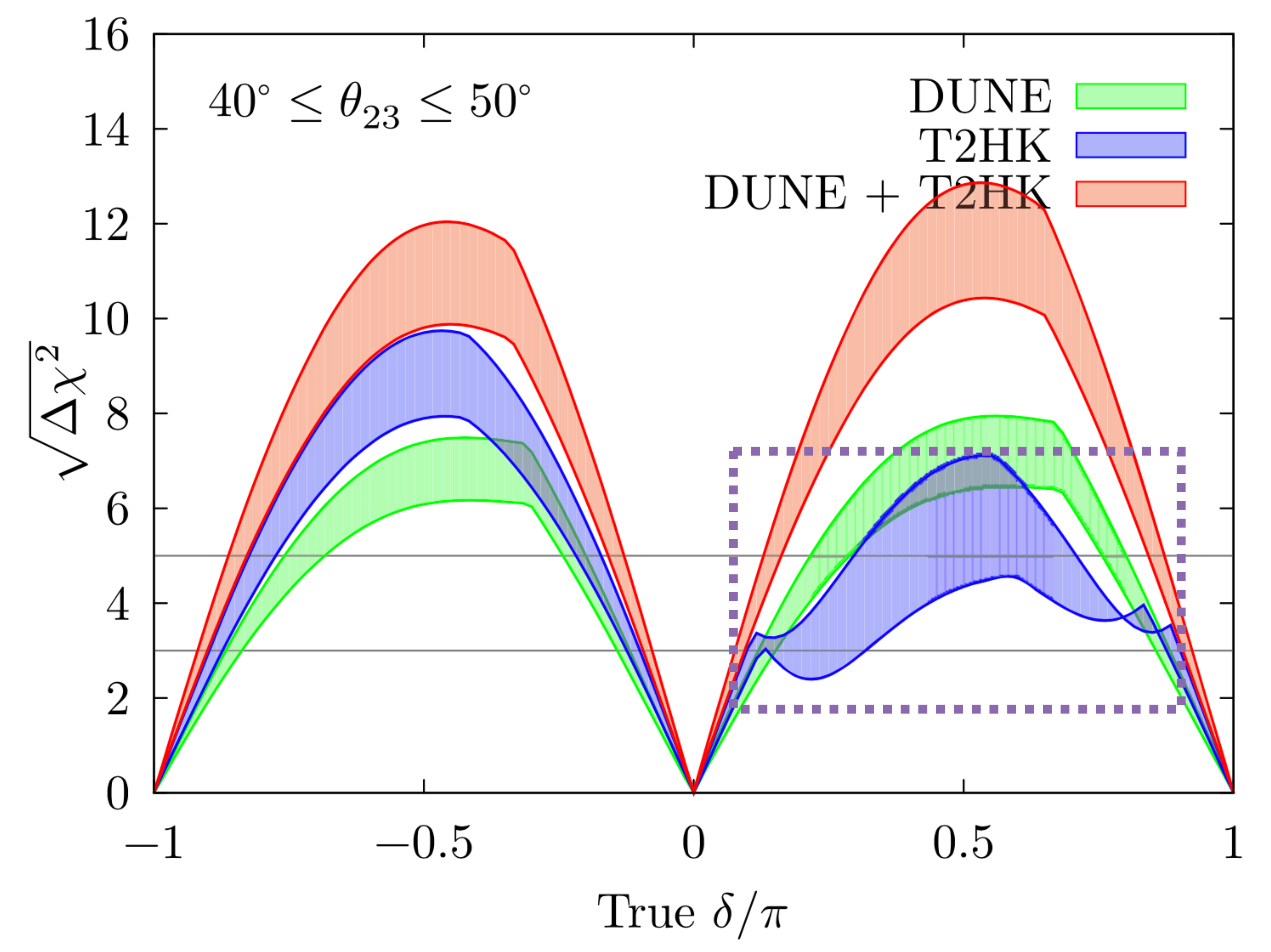


Matter effects resolve the degeneracy

arXiv:1612.07275



The degeneracy between delta and MO



DUNE: 5+5 yr

T2HK: 2.5+7.5 yr

- High sensitivity is predicted.
- The degeneracy in T2HK can be resolved by including DUNE data.

CSD Littlest Seesaw

arXiv:1612.01999

- Two sterile neutrinos: for atmospheric and solar masses.
- Normal mass ordering and m_1=0 are predicted.
- 6 oscillation parameters -> 3 model parameters.
- Explain current neutrino mixing and mass.

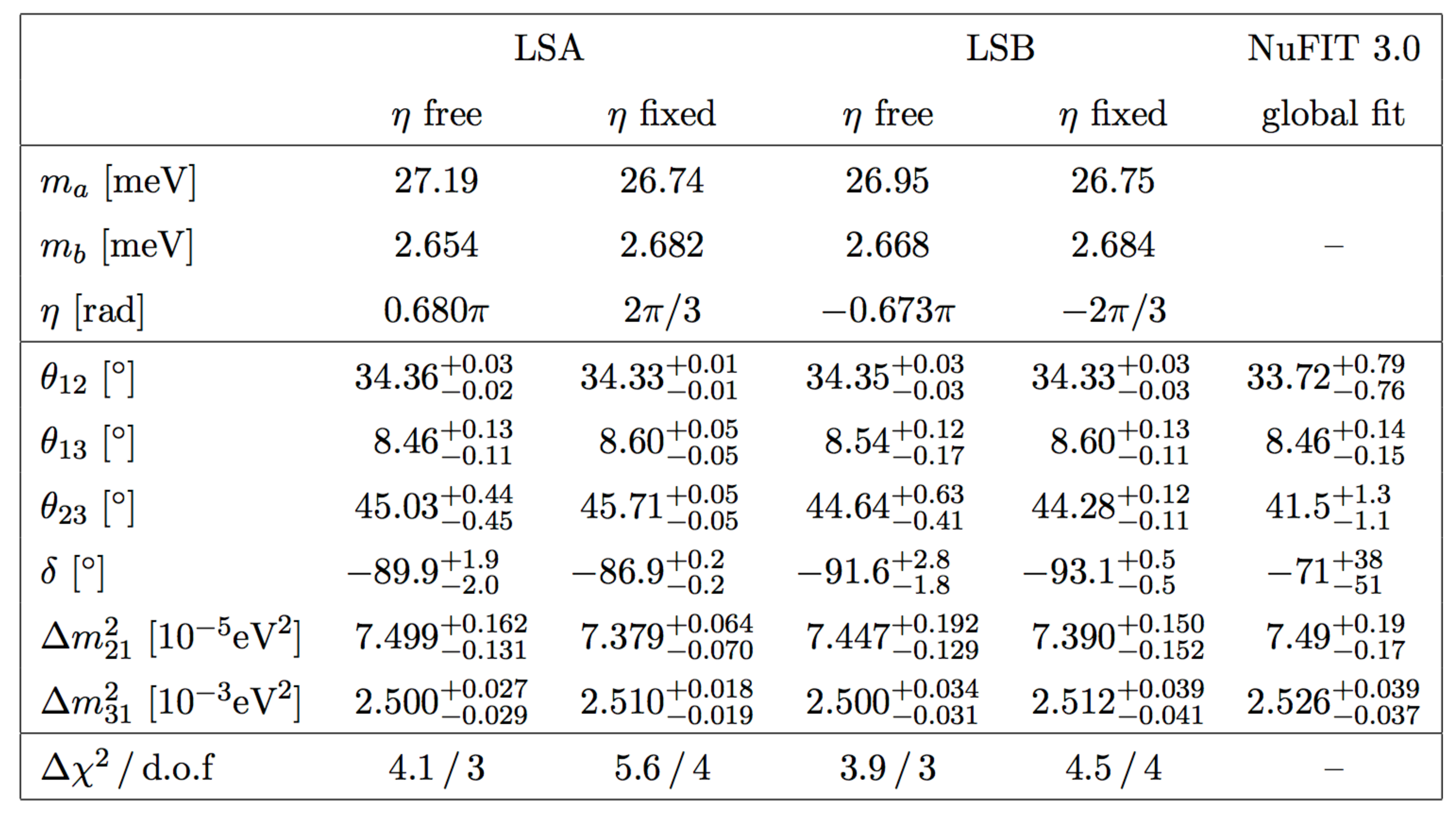
$\theta_{13} \sim (n-1)\frac{\sqrt{2}}{3}\frac{m_2}{m_3}$

$\propto (1,n,n-2)^T$

$$m^\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & n & (n-2) \\ n & n^2 & n(n-2) \\ (n-2) & n(n-2) & (n-2)^2 \end{pmatrix}$$

$$m^\nu_{\rm LSA} = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix},$$

$$m^\nu_{\rm LSB} = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & 1 & 3 \\ 1 & 1 & 3 \\ 3 & 3 & 9 \end{pmatrix}.$$

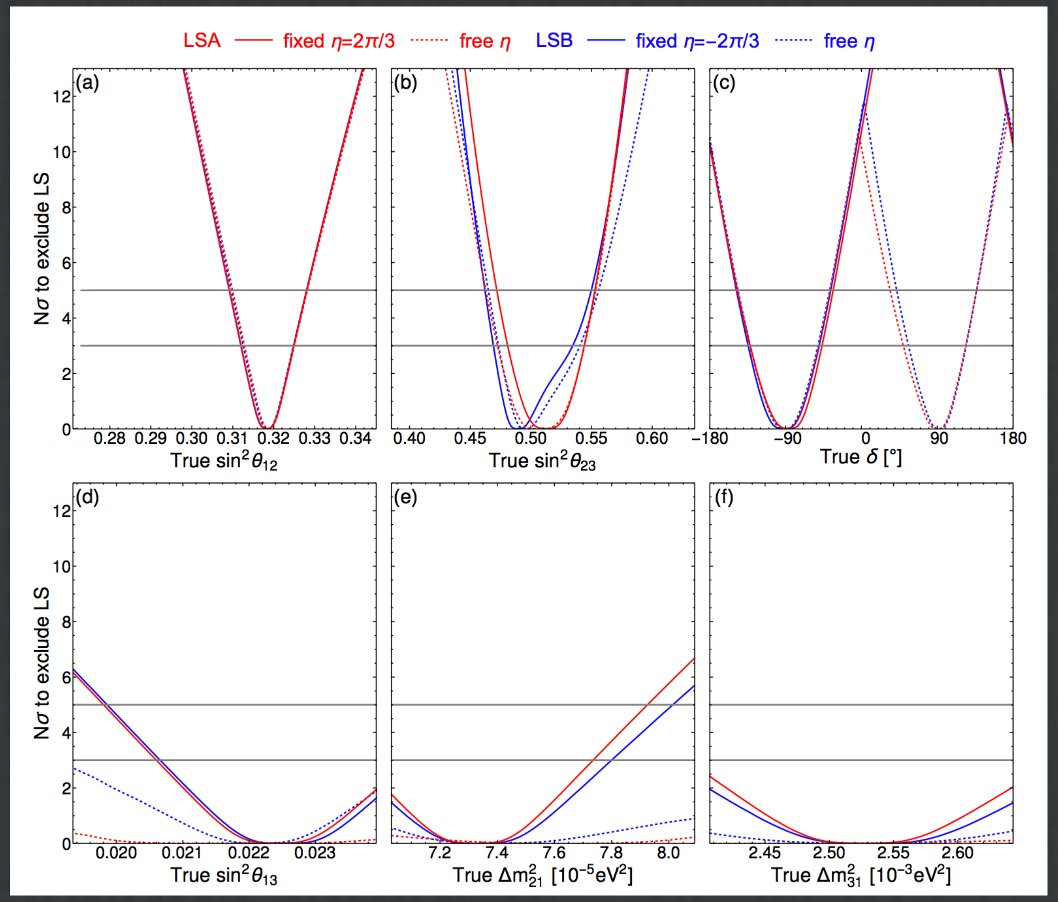


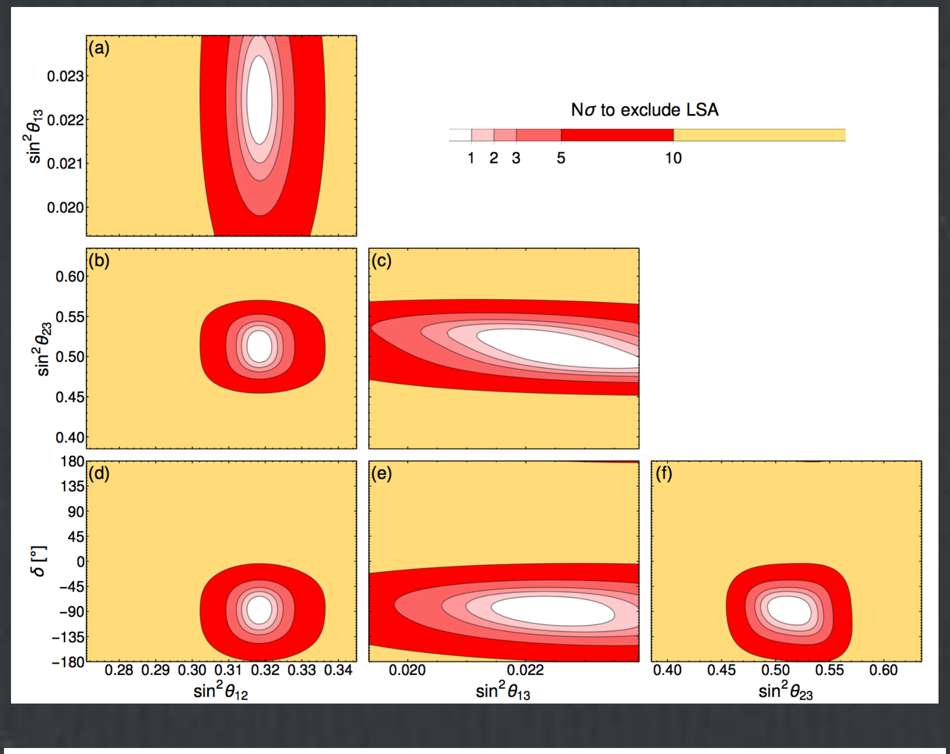
	LSA		LSB		NuFIT 3.0
	η free	η fixed	η free	η fixed	global fit
m_a [meV]	27.19	26.74	26.95	26.75	
m_b [meV]	2.654	2.682	2.668	2.684	–
η [rad]	0.680π	$2\pi/3$	-0.673π	$-2\pi/3$	
θ_{12} [°]	$34.36^{+0.03}_{-0.02}$	$34.33^{+0.01}_{-0.01}$	$34.35^{+0.03}_{-0.03}$	$34.33^{+0.03}_{-0.03}$	$33.72^{+0.79}_{-0.76}$
θ_{13} [°]	$8.46^{+0.13}_{-0.11}$	$8.60^{+0.05}_{-0.05}$	$8.54^{+0.12}_{-0.17}$	$8.60^{+0.13}_{-0.11}$	$8.46^{+0.14}_{-0.15}$
θ_{23} [°]	$45.03^{+0.44}_{-0.45}$	$45.71^{+0.05}_{-0.05}$	$44.64^{+0.63}_{-0.41}$	$44.28^{+0.12}_{-0.11}$	$41.5^{+1.3}_{-1.1}$
δ [°]	$-89.9^{+1.9}_{-2.0}$	$-86.9^{+0.2}_{-0.2}$	$-91.6^{+2.8}_{-1.8}$	$-93.1^{+0.5}_{-0.5}$	-71^{+38}_{-51}
Δm^2_{21} [10^{-5}eV^2]	$7.499^{+0.162}_{-0.131}$	$7.379^{+0.064}_{-0.070}$	$7.447^{+0.192}_{-0.129}$	$7.390^{+0.150}_{-0.152}$	$7.49^{+0.19}_{-0.17}$
Δm^2_{31} [10^{-3}eV^2]	$2.500^{+0.027}_{-0.029}$	$2.510^{+0.018}_{-0.019}$	$2.500^{+0.034}_{-0.031}$	$2.512^{+0.039}_{-0.041}$	$2.526^{+0.039}_{-0.037}$
$\Delta\chi^2$ / d.o.f	4.1 / 3	5.6 / 4	3.9 / 3	4.5 / 4	–

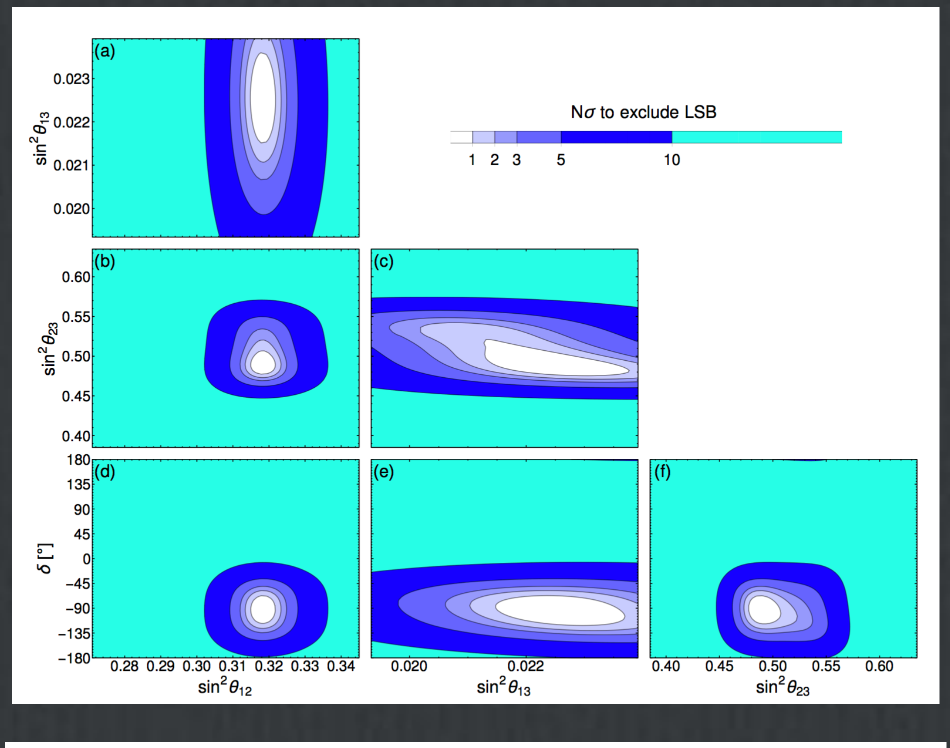
CSD Littlest Seesaw with future accelerator and reactor exps.

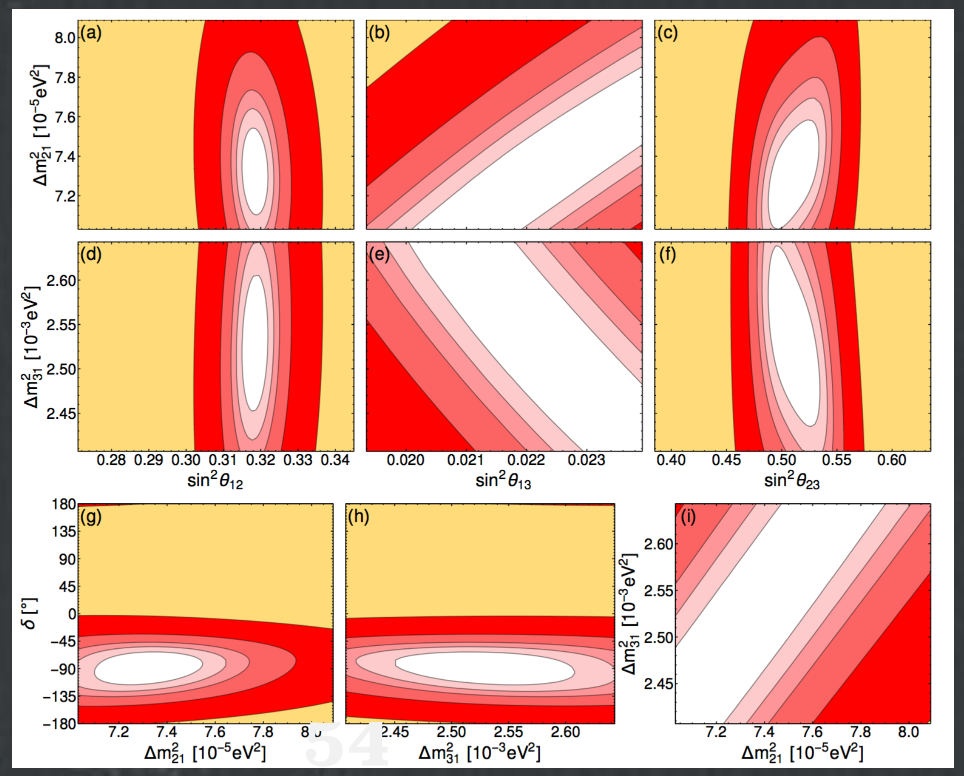
arXiv:1612.01999

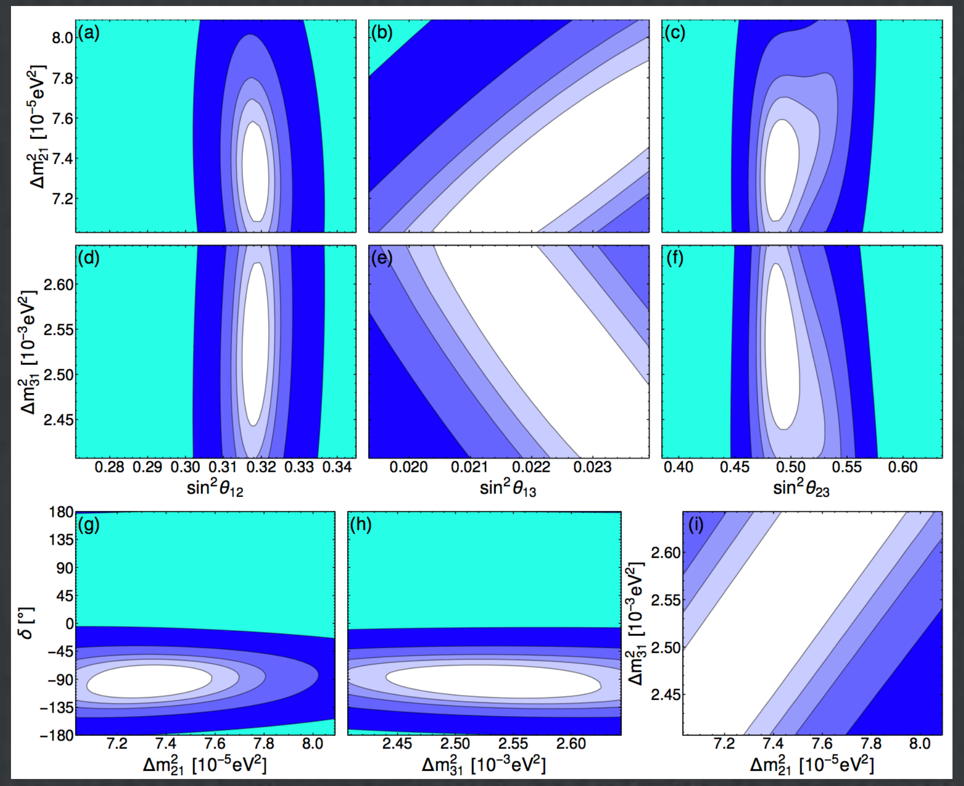
- ☐ High exclusion ability for DUNE + T2HK + JUNO + RENO-50





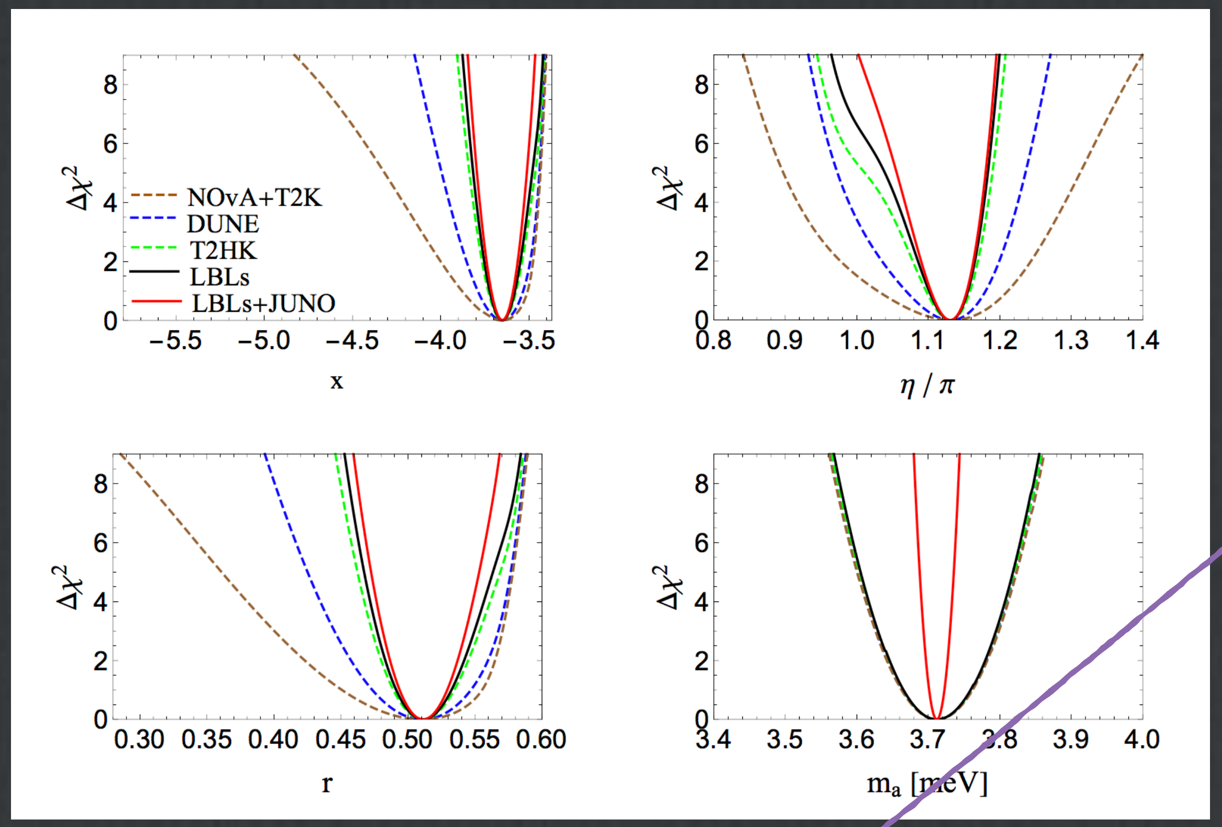


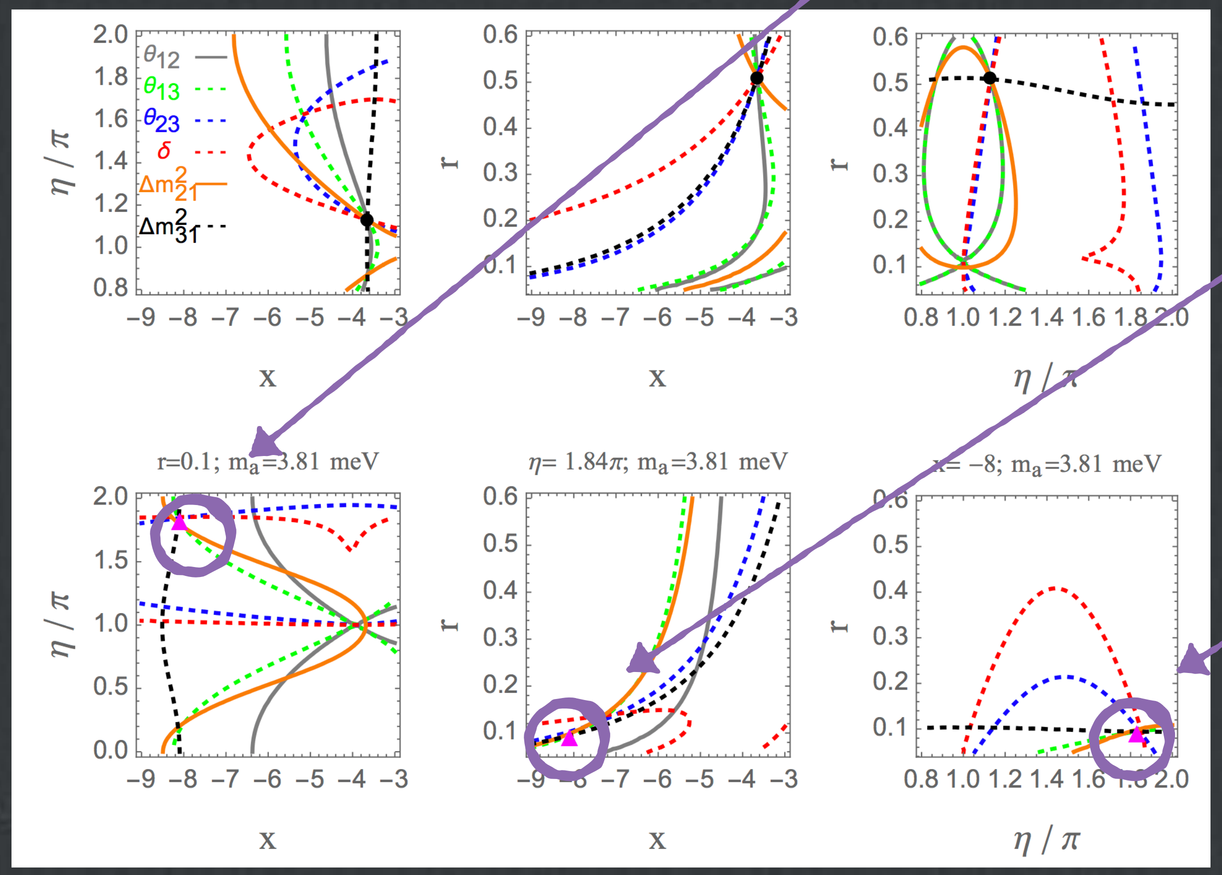


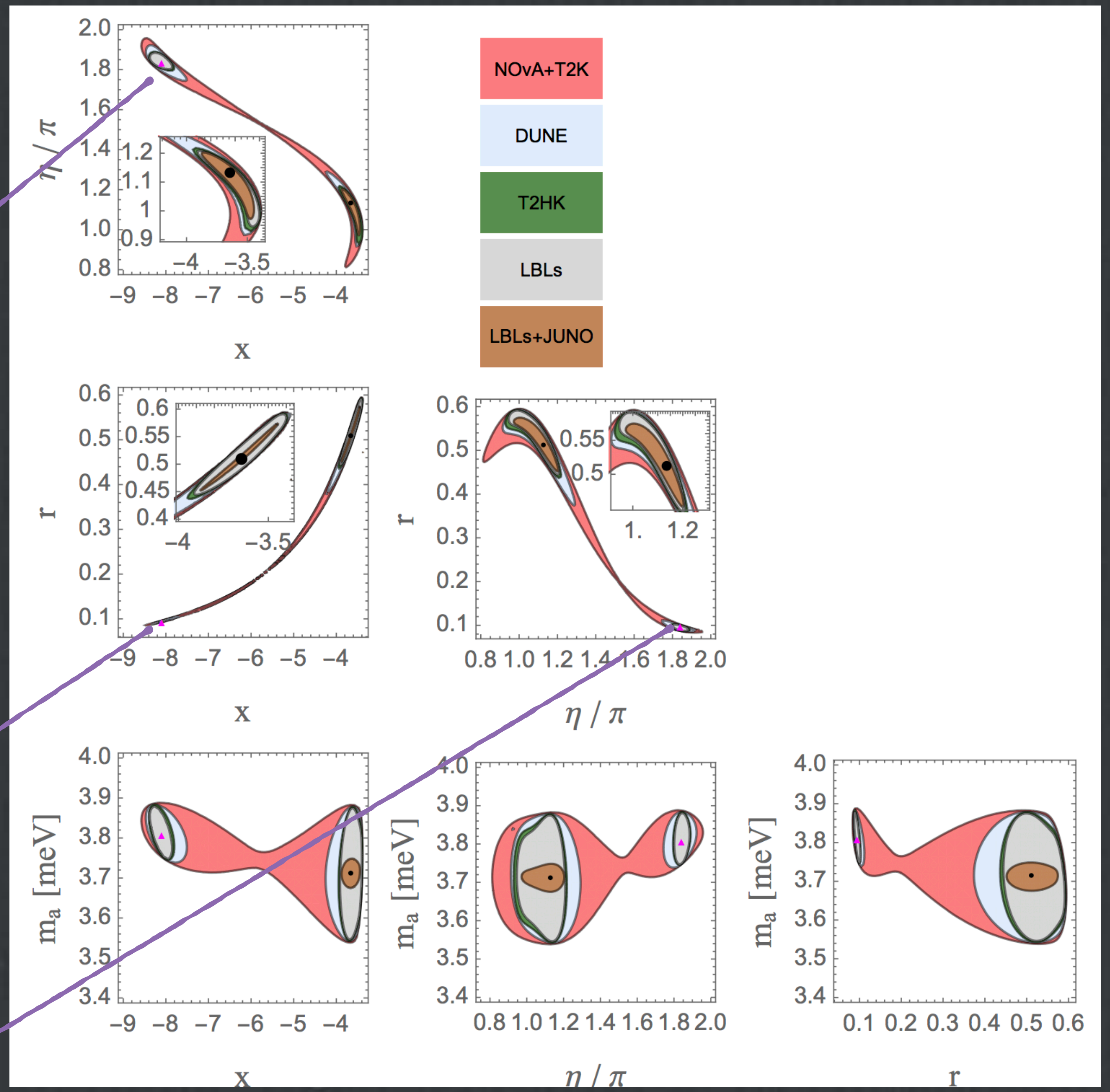


tri-direct littlest seesaw vs. future experiments

arXiv:1905.12939







- The understanding for this model will be improved.
- With the improvement of sensitivity, more degeneracies appear.
- Degeneracies can be resolved by combining different measurements.

Flavour symmetry predicts the neutrino mixing

Higher-energy Symmetry, e.g. A_4 or S_4…etc

Break the symmetry by flavoron

Seesaw I

Seesaw II

Seesaw III

The possible form for mass matrix, i.e. mixing matrix (e.g. TBM…etc) and mass-square splittings.

Depend on how it breaks, we have direct approach,…etc. Currently, tri-direct approach is proposed.

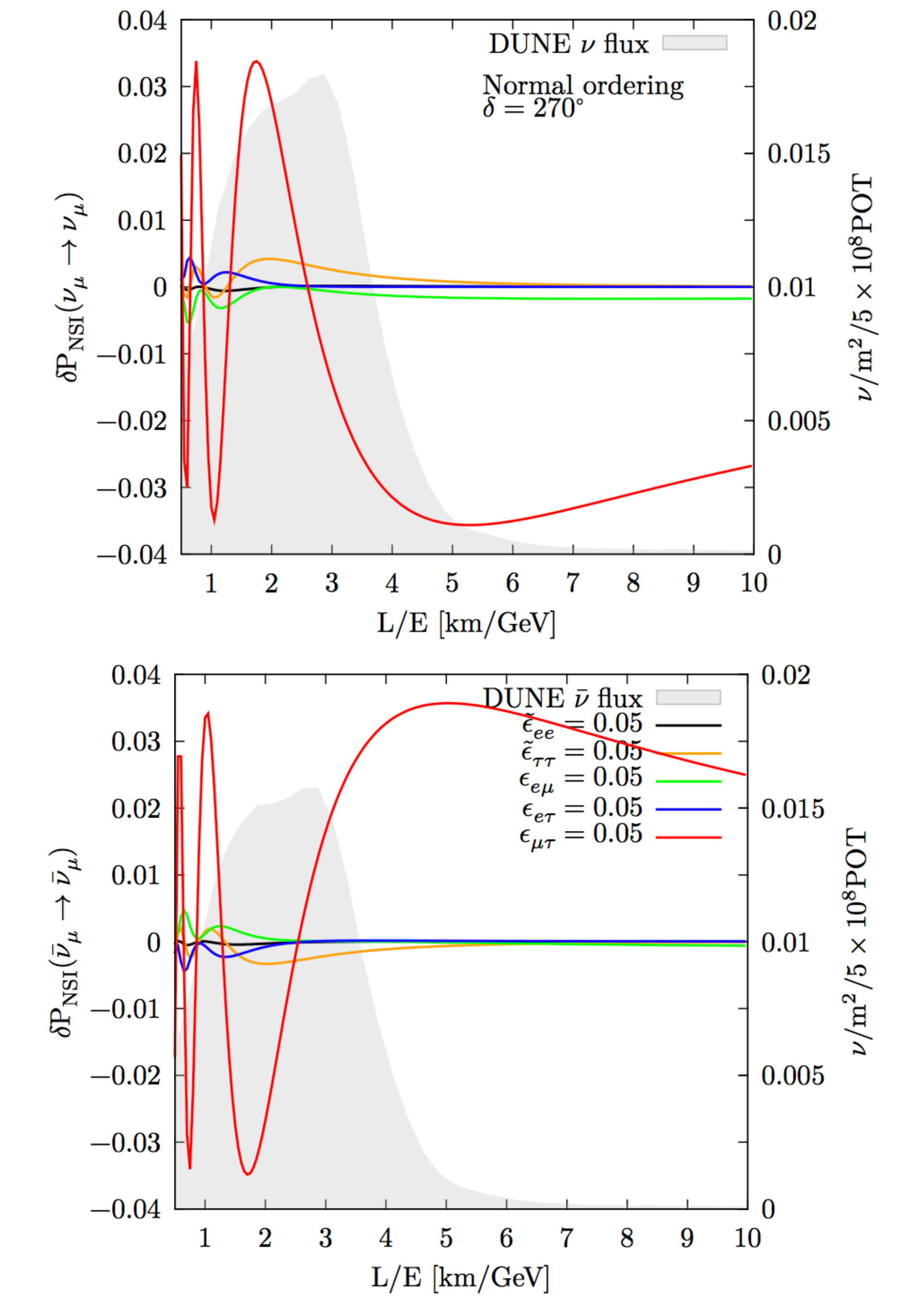
$$U_{\rm TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

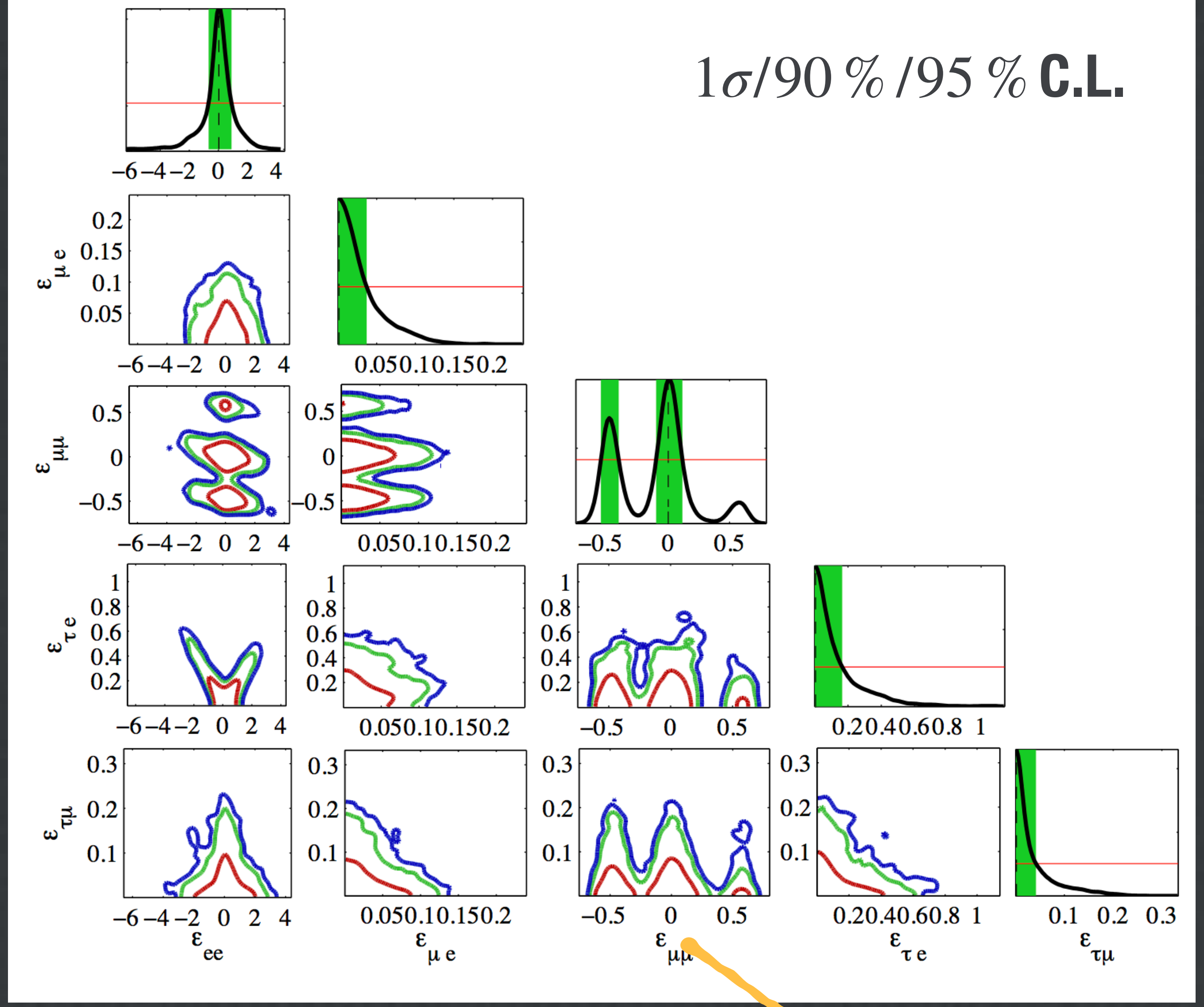
Other new physics

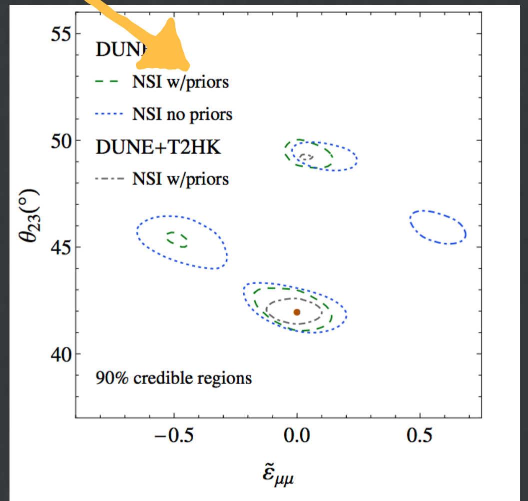
- **Neutrino decays** arXiv:1603.08696; arXiv:1705.03599; arXiv:1805.01848, etc
- **Nonunitarity of neutrino mixing** arXiv:1508.05095; arXiv:1609.08637, etc
- **Sterile-active neutrino mixing** arXiv:1609.08637; arXiv: 1906.00045, etc
- **etc…**

NSIs in matter for DUNE

arXiv:1511.06375,
& TC's PhD thesis

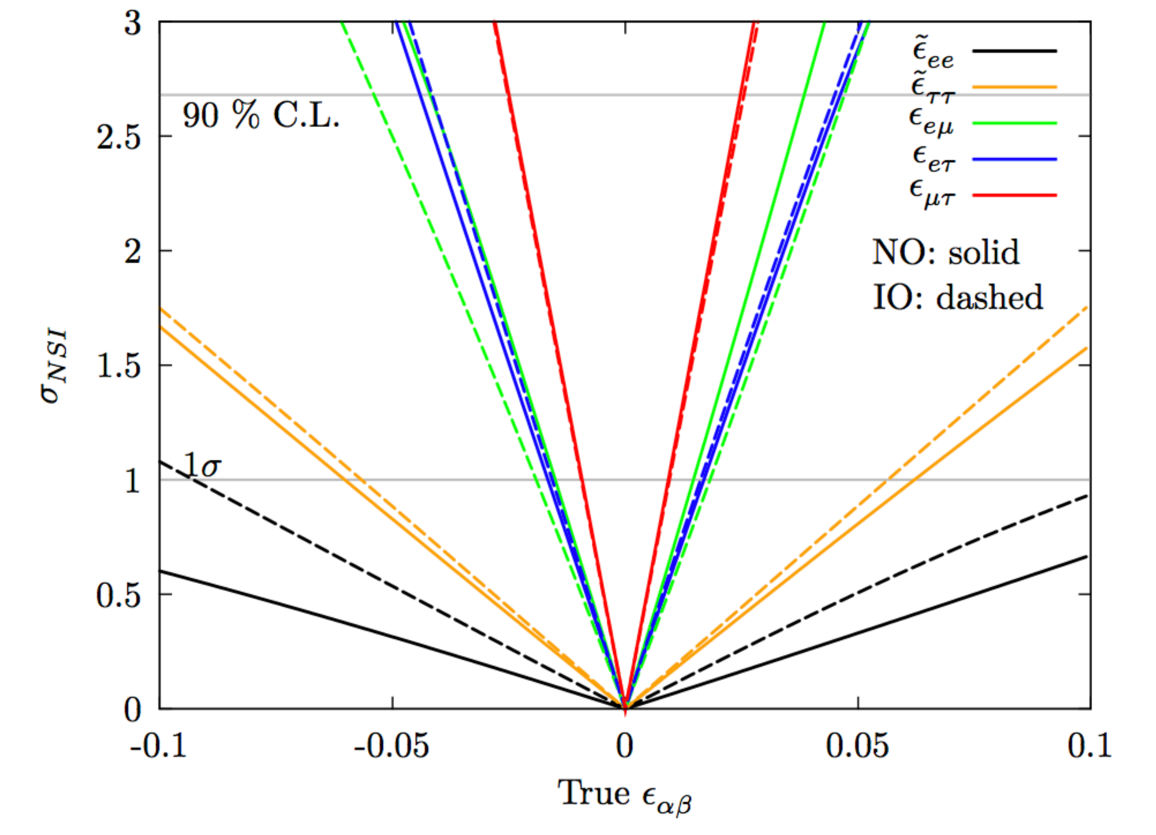






- **DUNE can detect the effect of NSIs well, but needs improvement for measuring it because of the degenercies.**

$$\sigma^2_{\textbf{NSI}} \equiv \min_{\Theta_{PMNS}} \left\{ \chi^2|_{\epsilon_{\alpha\beta}=0} - \chi^2_{\textbf{b.f.}} \right\}$$

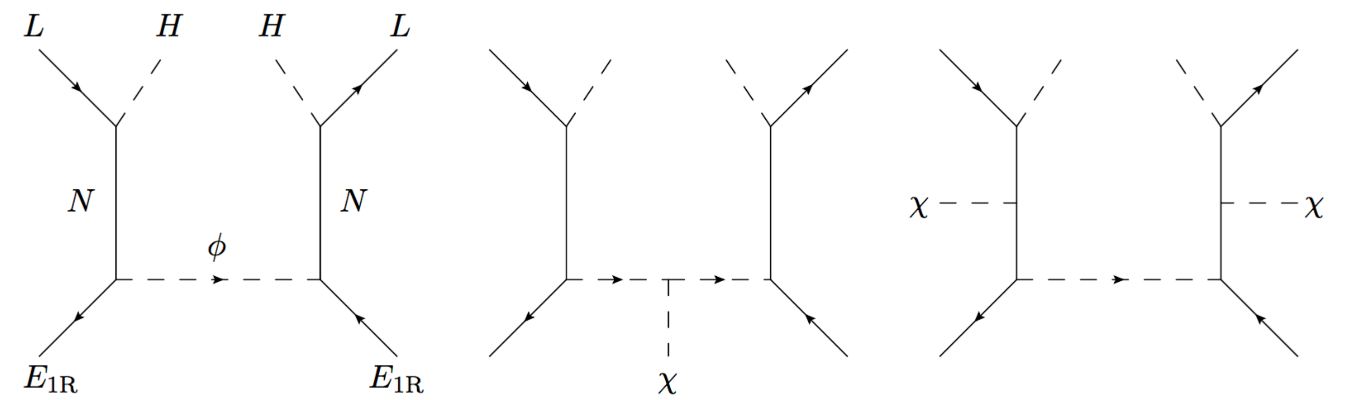


Predict NSIs with flavour symmetry

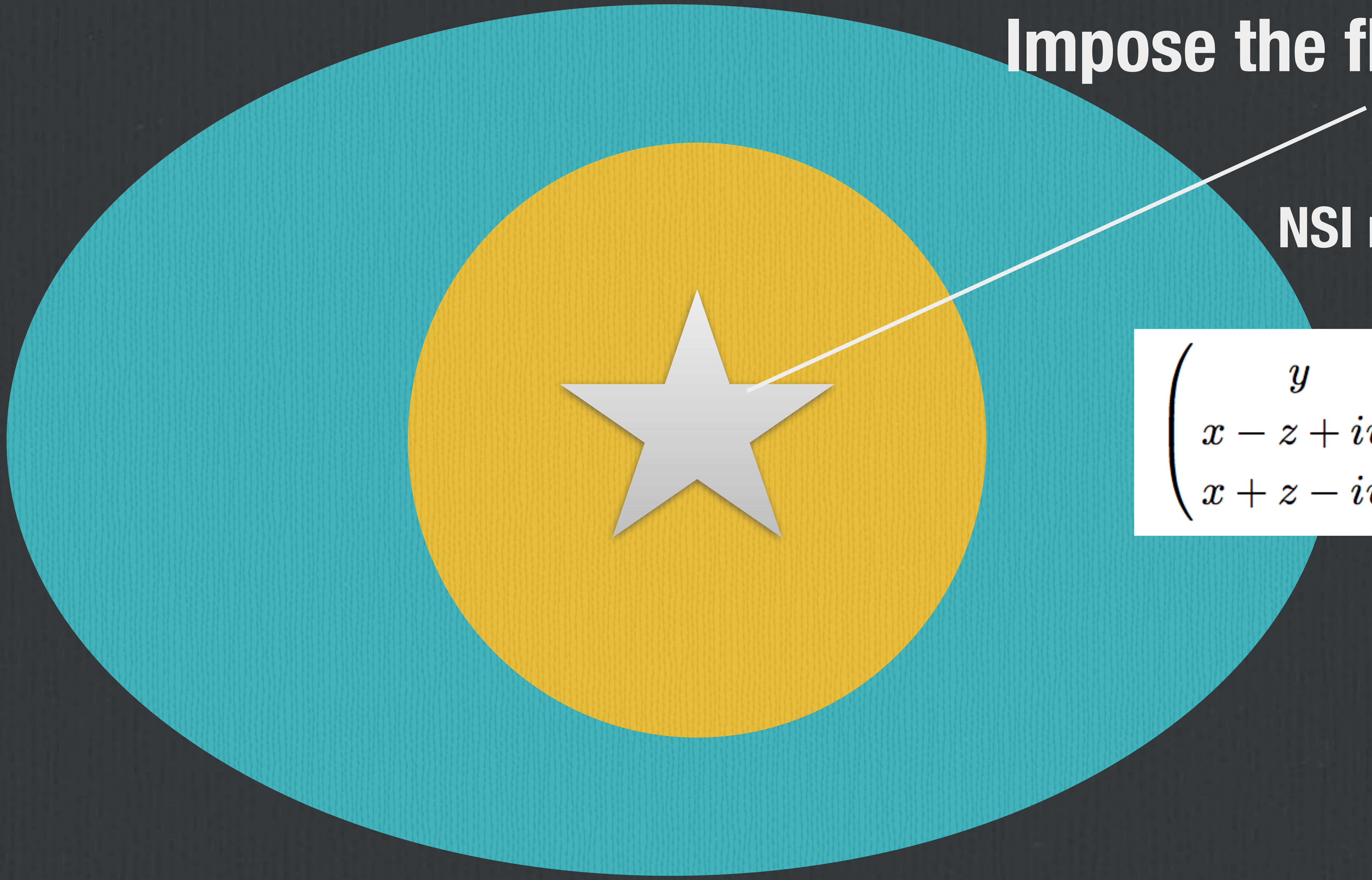
UV complete model for sizeable NSIs

Include a new charged scalar and right-handed neutrinos

$$\mathcal{L} = (D_\mu\phi)^\dagger(D^\mu\phi) - (M_\phi^2)_{\alpha\beta}\phi_\alpha^*\phi_\beta + \overline{N}i\partial\!\!\!/N - M_{N\alpha\beta}\overline{N_{\alpha\mathrm{R}}}N_{\beta\mathrm{L}}$$
$$-\kappa_{\alpha\beta\gamma}\overline{E_{\alpha\mathrm{R}}}N_{\beta\mathrm{L}}\phi_\gamma^* - y_{\alpha\beta}\overline{L_\alpha}\tilde{H}N_{\beta\mathrm{R}} + \mathrm{h.c.}\,,$$



Predict NSIs with flavour symmetry



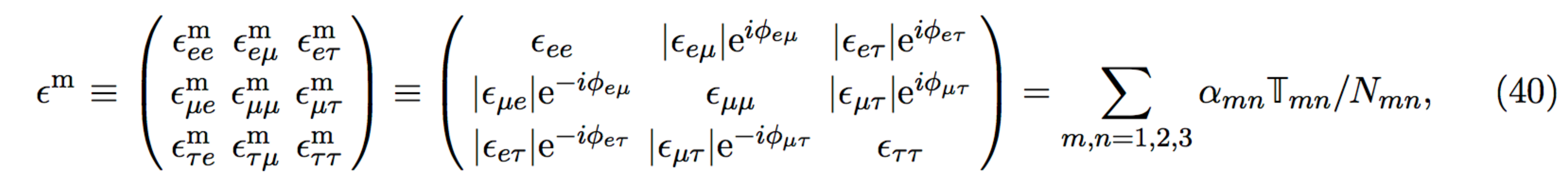
Impose the flavour symmetry

NSI matrix is predicted in the form of

$$\begin{pmatrix} y & x-z-iw & x+z+iw \\ x-z+iw & x+z & y-iw \\ x+z-iw & y+iw & x-z \end{pmatrix}$$

Predict NSIs with A4/Z2 flavour symmetries

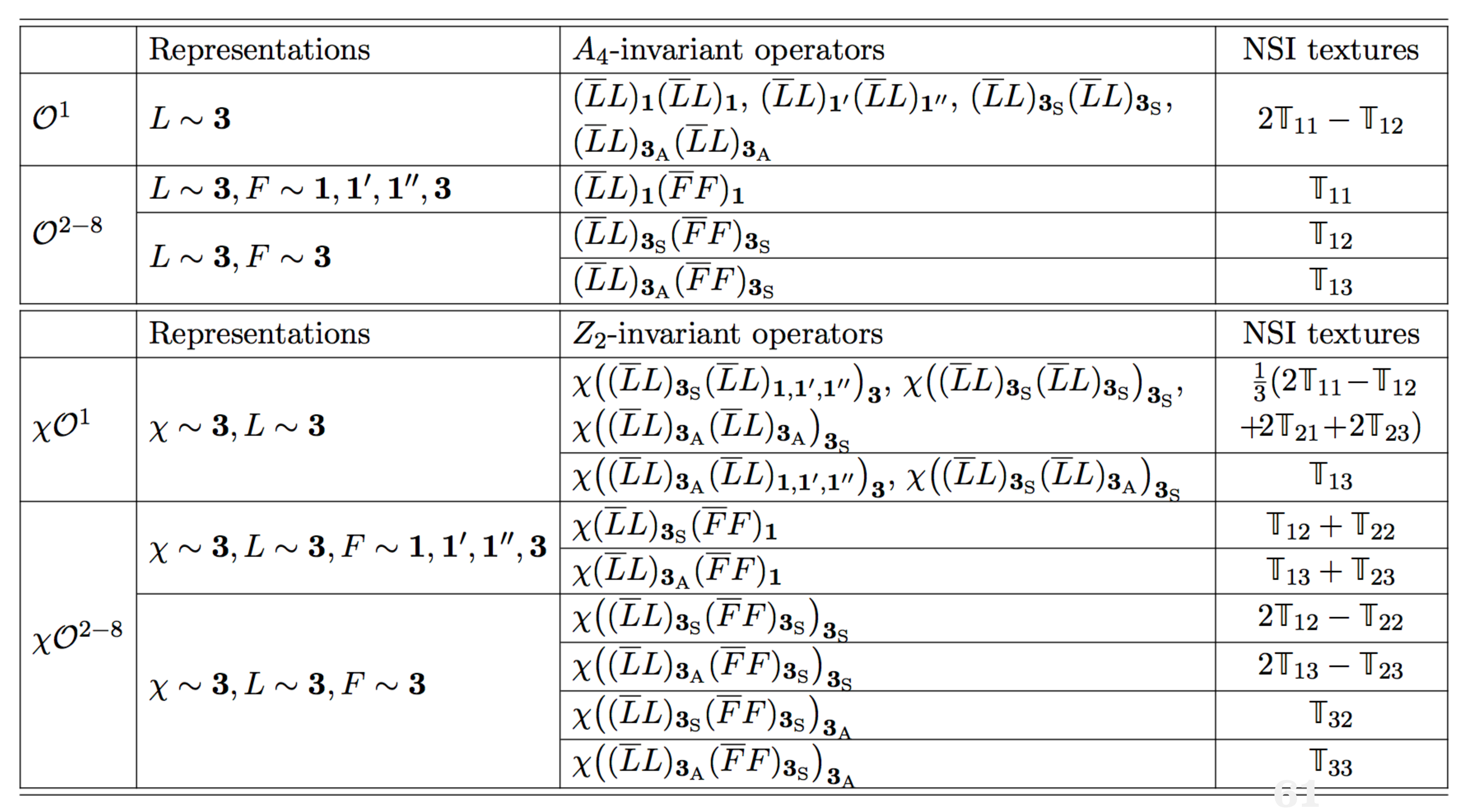
arXiv:1801.05656



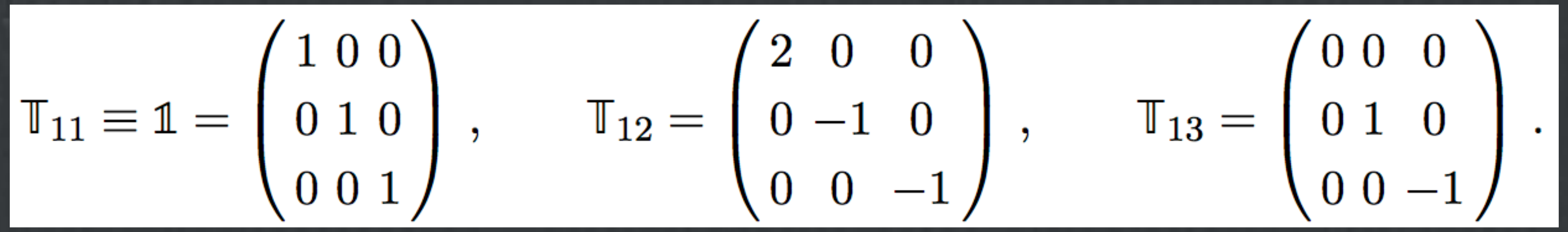
$$\epsilon^{\mathrm{m}} \equiv \begin{pmatrix} \epsilon^{\mathrm{m}}_{ee} & \epsilon^{\mathrm{m}}_{e\mu} & \epsilon^{\mathrm{m}}_{e\tau} \\ \epsilon^{\mathrm{m}}_{\mu e} & \epsilon^{\mathrm{m}}_{\mu\mu} & \epsilon^{\mathrm{m}}_{\mu\tau} \\ \epsilon^{\mathrm{m}}_{\tau e} & \epsilon^{\mathrm{m}}_{\tau\mu} & \epsilon^{\mathrm{m}}_{\tau\tau} \end{pmatrix} \equiv \begin{pmatrix} \epsilon_{ee} & |\epsilon_{e\mu}|\mathrm{e}^{i\phi_{e\mu}} & |\epsilon_{e\tau}|\mathrm{e}^{i\phi_{e\tau}} \\ |\epsilon_{\mu e}|\mathrm{e}^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|\mathrm{e}^{i\phi_{\mu\tau}} \\ |\epsilon_{e\tau}|\mathrm{e}^{-i\phi_{e\tau}} & |\epsilon_{\mu\tau}|\mathrm{e}^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix} = \sum_{m,n=1,2,3} \alpha_{mn} \mathbb{T}_{mn}/N_{mn}, \qquad (40)$$

N_{mn} is the normalisation factor.

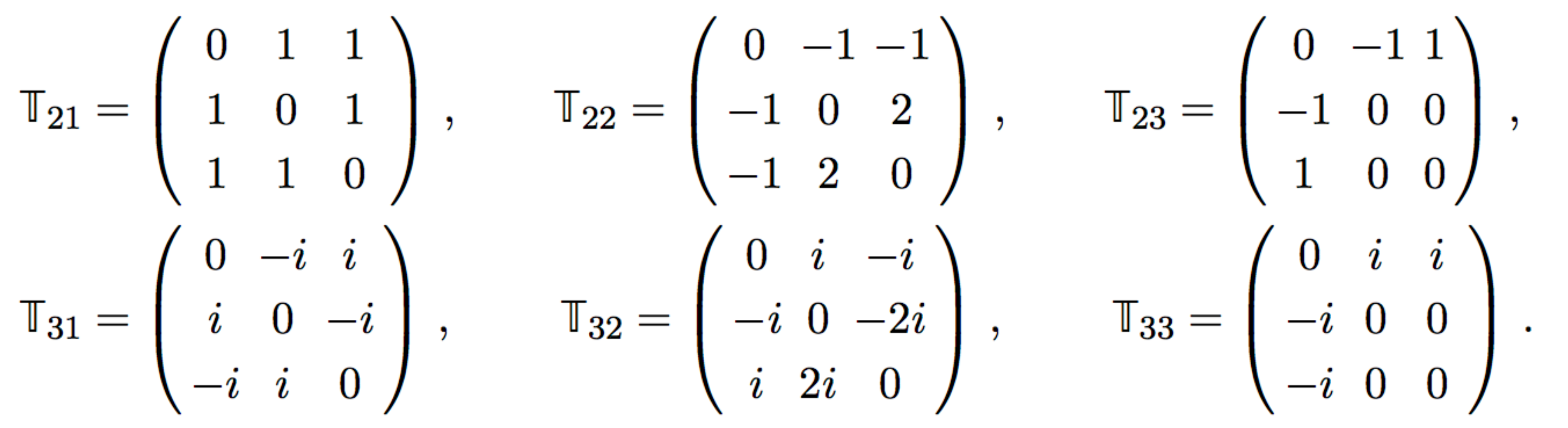
- Preserving A4 at NSIs, flavour-transition NSIs are forbidden.



	Representations	A_4-invariant operators	NSI textures
$\mathcal{O}^1$	$L \sim \mathbf{3}$	$(\overline{L}L)_{\mathbf{1}}(\overline{L}L)_{\mathbf{1}}$, $(\overline{L}L)_{\mathbf{1}'}(\overline{L}L)_{\mathbf{1}''}$, $(\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{L}L)_{\mathbf{3}_\mathrm{S}}$, $(\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{L}L)_{\mathbf{3}_\mathrm{A}}$	$2\mathbb{T}_{11} - \mathbb{T}_{12}$
$\mathcal{O}^{2-8}$	$L \sim \mathbf{3}, F \sim \mathbf{1}, \mathbf{1}', \mathbf{1}'', \mathbf{3}$	$(\overline{L}L)_{\mathbf{1}}(\overline{F}F)_{\mathbf{1}}$	$\mathbb{T}_{11}$
	$L \sim \mathbf{3}, F \sim \mathbf{3}$	$(\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{F}F)_{\mathbf{3}_\mathrm{S}}$	$\mathbb{T}_{12}$
		$(\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{F}F)_{\mathbf{3}_\mathrm{S}}$	$\mathbb{T}_{13}$
	Representations	Z_2-invariant operators	NSI textures
$\chi\mathcal{O}^1$	$\chi \sim \mathbf{3}, L \sim \mathbf{3}$	$\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{L}L)_{\mathbf{1},\mathbf{1}',\mathbf{1}''}\big)_{\mathbf{3}}$, $\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{L}L)_{\mathbf{3}_\mathrm{S}}\big)_{\mathbf{3}_\mathrm{S}}$, $\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{L}L)_{\mathbf{3}_\mathrm{A}}\big)_{\mathbf{3}_\mathrm{S}}$	$\frac{1}{3}(2\mathbb{T}_{11}-\mathbb{T}_{12}$ $+2\mathbb{T}_{21}+2\mathbb{T}_{23})$
		$\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{L}L)_{\mathbf{1},\mathbf{1}',\mathbf{1}''}\big)_{\mathbf{3}}$, $\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{L}L)_{\mathbf{3}_\mathrm{A}}\big)_{\mathbf{3}_\mathrm{S}}$	$\mathbb{T}_{13}$
$\chi\mathcal{O}^{2-8}$	$\chi \sim \mathbf{3}, L \sim \mathbf{3}, F \sim \mathbf{1}, \mathbf{1}', \mathbf{1}'', \mathbf{3}$	$\chi(\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{F}F)_{\mathbf{1}}$	$\mathbb{T}_{12} + \mathbb{T}_{22}$
		$\chi(\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{F}F)_{\mathbf{1}}$	$\mathbb{T}_{13} + \mathbb{T}_{23}$
	$\chi \sim \mathbf{3}, L \sim \mathbf{3}, F \sim \mathbf{3}$	$\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{F}F)_{\mathbf{3}_\mathrm{S}}\big)_{\mathbf{3}_\mathrm{S}}$	$2\mathbb{T}_{12} - \mathbb{T}_{22}$
		$\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{F}F)_{\mathbf{3}_\mathrm{S}}\big)_{\mathbf{3}_\mathrm{S}}$	$2\mathbb{T}_{13} - \mathbb{T}_{23}$
		$\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{S}}(\overline{F}F)_{\mathbf{3}_\mathrm{S}}\big)_{\mathbf{3}_\mathrm{A}}$	$\mathbb{T}_{32}$
		$\chi\big((\overline{L}L)_{\mathbf{3}_\mathrm{A}}(\overline{F}F)_{\mathbf{3}_\mathrm{S}}\big)_{\mathbf{3}_\mathrm{A}}$	$\mathbb{T}_{33}$



$$\mathbb{T}_{11} \equiv \mathbb{1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathbb{T}_{12} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad \mathbb{T}_{13} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$



$$\mathbb{T}_{21} = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}, \quad \mathbb{T}_{22} = \begin{pmatrix} 0 & -1 & -1 \\ -1 & 0 & 2 \\ -1 & 2 & 0 \end{pmatrix}, \quad \mathbb{T}_{23} = \begin{pmatrix} 0 & -1 & 1 \\ -1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

$$\mathbb{T}_{31} = \begin{pmatrix} 0 & -i & i \\ i & 0 & -i \\ -i & i & 0 \end{pmatrix}, \quad \mathbb{T}_{32} = \begin{pmatrix} 0 & i & -i \\ -i & 0 & -2i \\ i & 2i & 0 \end{pmatrix}, \quad \mathbb{T}_{33} = \begin{pmatrix} 0 & i & i \\ -i & 0 & 0 \\ -i & 0 & 0 \end{pmatrix}.$$

Testing Z2 symmetry

arXiv:1801.05656

- NSI matrix is greatly simplified, and its predictivity is enhanced.

$$\begin{pmatrix} y & x-z-iw & x+z+iw \\ x-z+iw & x+z & y-iw \\ x+z-iw & y+iw & x-z \end{pmatrix}$$

Current constraints

1σ bounds of global fit results			
$\tilde{\epsilon}^u_{ee}$	[0.188, 0.376]	$\tilde{\epsilon}^d_{ee}$	[0.203, 0.384]
$\tilde{\epsilon}^u_{\tau\tau}$	$[-0.003, 0.012]$	$\tilde{\epsilon}^d_{\tau\tau}$	$[-0.003, 0.012]$
$\epsilon^u_{e\mu}$	$[-0.046, 0.002]$	$\epsilon^d_{e\mu}$	$[-0.048, 0]$
$\epsilon^u_{e\tau}$	$[-0.038, 0.065]$	$\epsilon^d_{e\tau}$	$[-0.036, 0.066]$
$\epsilon^u_{\mu\tau}$	$[-0.004, 0.003]$	$\epsilon^d_{\mu\tau}$	$[-0.004, 0.003]$

Global Fit		Global Fit		DUNE sensitivity	
w^u	–	w^d	–	w	$[-0.013, 0.025]$
x^u	$[-0.034, 0.013]$	x^d	$[-0.035, 0.012]$	x	$[-0.1, 0.1]$
y^u	$[-0.004, 0.003]$	y^d	$[-0.004, 0.003]$	y	$[-0.01, 0.01]$
z^u	$[-0.002, 0.005]$	z^d	$[-0.002, 0.005]$	z	$[-0.007, 0.017]$

Current constraints predict the form

$$\epsilon = \begin{pmatrix} 0 & x & x \\ x & x & 0 \\ x & 0 & x \end{pmatrix}.$$

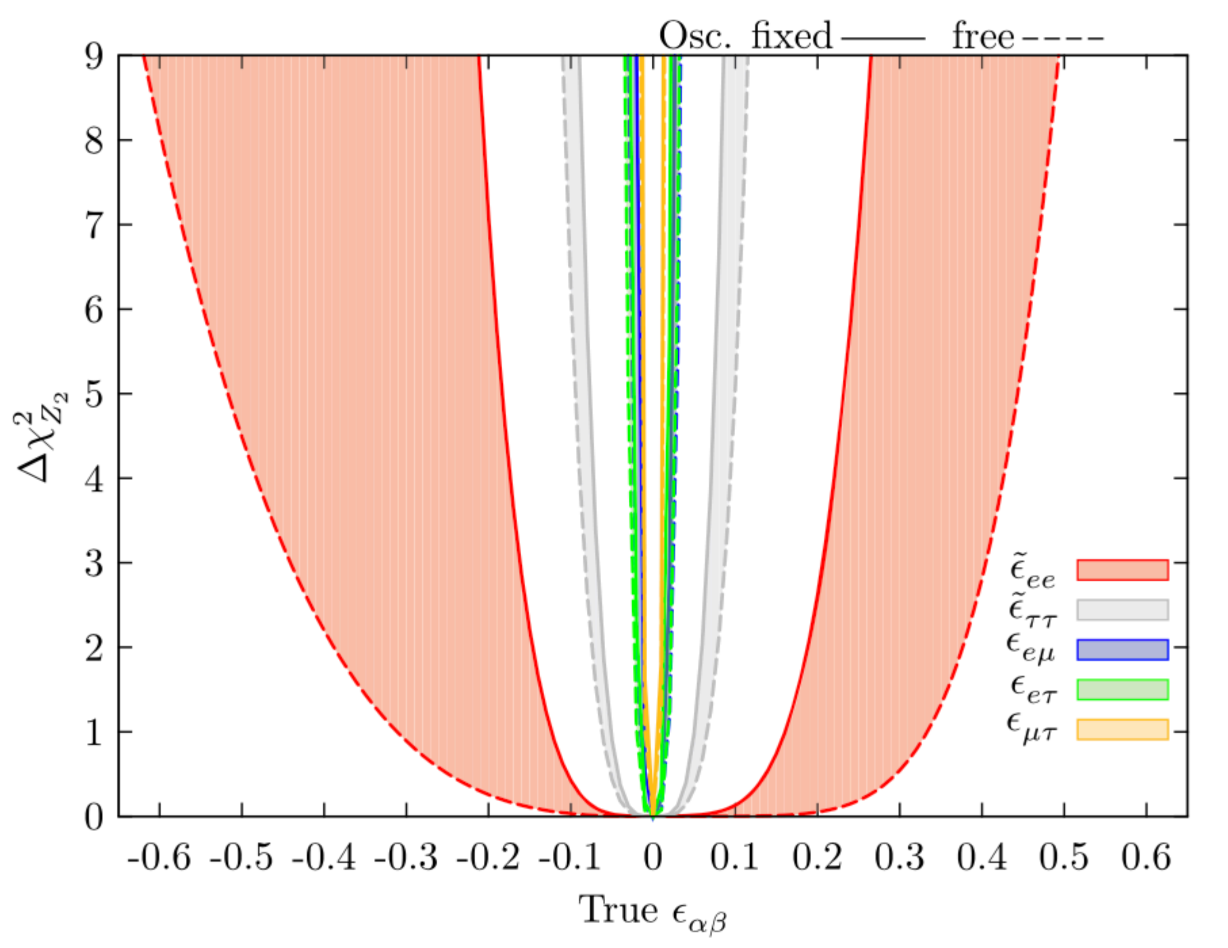
$$\epsilon_{e\mu} = \epsilon_{e\tau} = -\tilde{\epsilon}_{ee},$$

$$\epsilon_{\mu\tau} = \tilde{\epsilon}_{\tau\tau} = 0.$$

Testing Z₂ for DUNE

$$\Delta\chi^2_{Z_2} \equiv \chi^2|_x - \chi^2_{\mathrm{b.f.}},$$

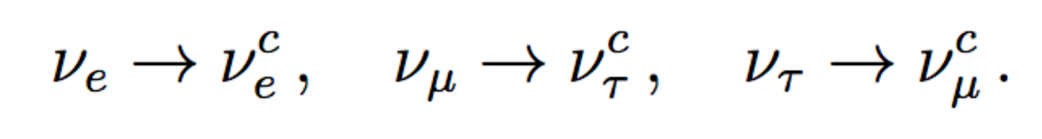
	Parameter				
d.o.f.	$\tilde{\epsilon}_{ee}$	$\tilde{\epsilon}_{\tau\tau}$	$\epsilon_{e\mu}$	$\epsilon_{e\tau}$	$\epsilon_{\mu\tau}$
7	2.2σ–4.7σ	~0	3.1σ–6.1σ	5.7σ–9.4σ	~0
13	1.1σ–3.7σ	~0	2σ–5.1σ	4.7σ–8.6σ	~0



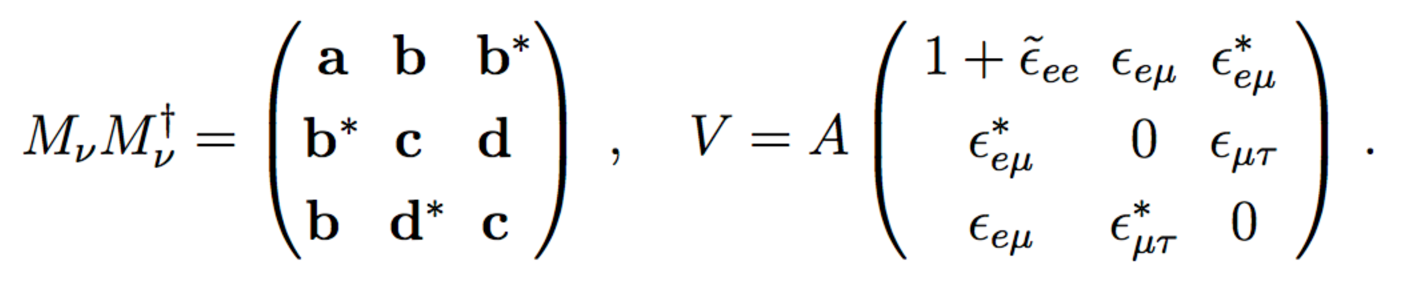
Low energy mu-tau reflection symmetry

arXiv:1911.00213

mu-tau reflection symmetry

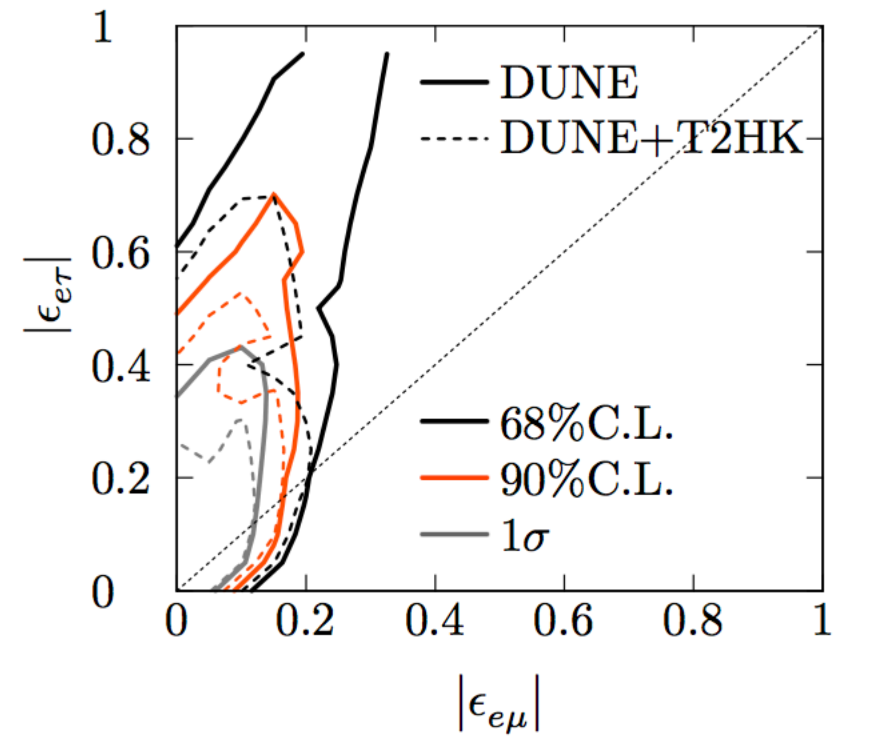


$$\nu_e \to \nu_e^c\,, \quad \nu_\mu \to \nu_\tau^c\,, \quad \nu_\tau \to \nu_\mu^c\,.$$



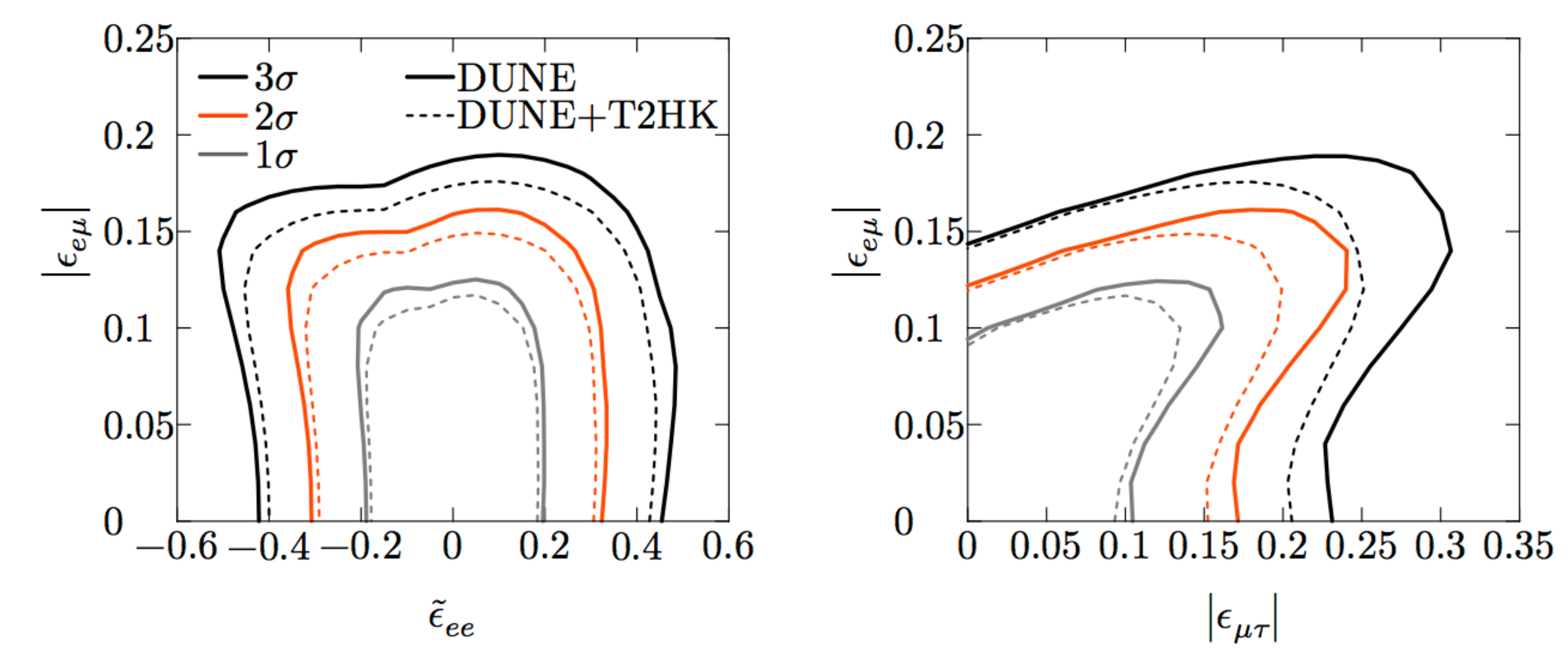
$$M_\nu M_\nu^\dagger = \begin{pmatrix} \mathbf{a} & \mathbf{b} & \mathbf{b}^* \\ \mathbf{b}^* & \mathbf{c} & \mathbf{d} \\ \mathbf{b} & \mathbf{d}^* & \mathbf{c} \end{pmatrix}\,, \quad V = A \begin{pmatrix} 1+\tilde{\epsilon}_{ee} & \epsilon_{e\mu} & \epsilon_{e\mu}^* \\ \epsilon_{e\mu}^* & 0 & \epsilon_{\mu\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\tau}^* & 0 \end{pmatrix}\,.$$

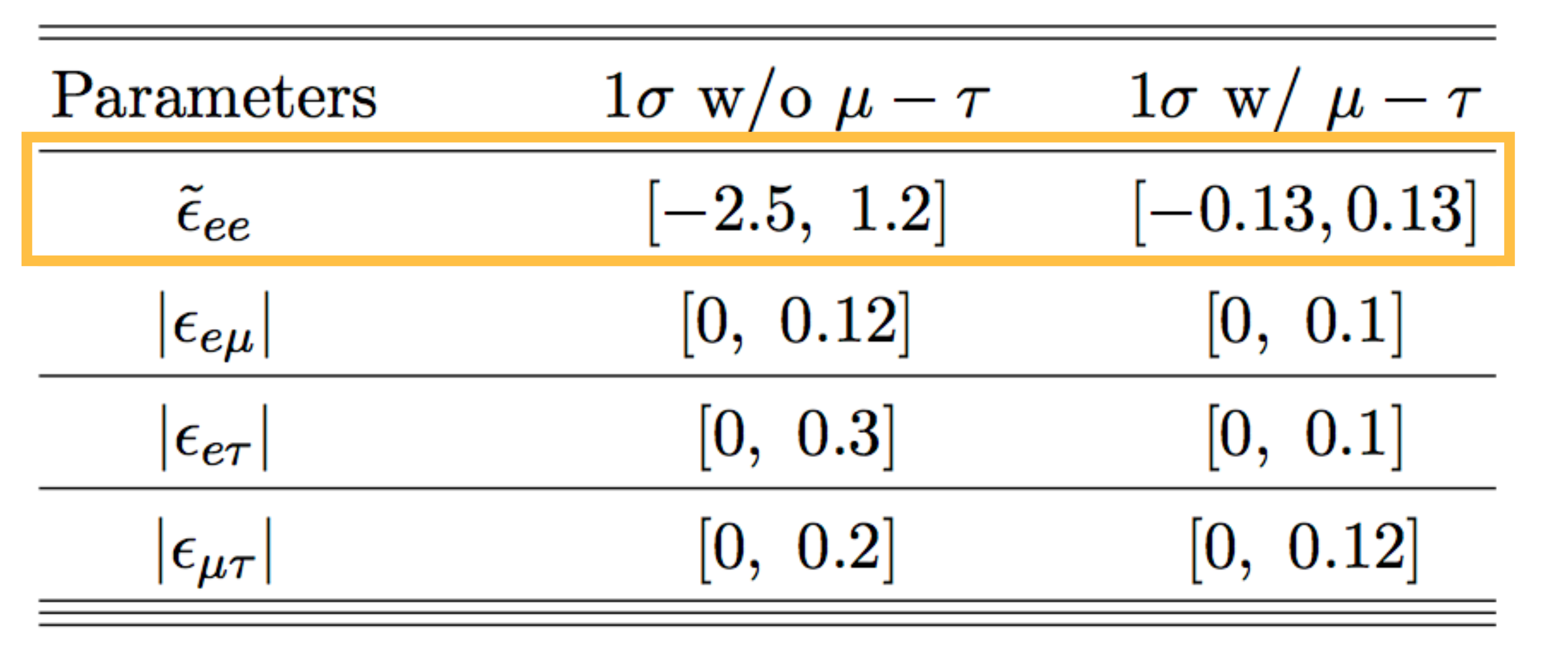
Constraints w/o mu-tau



Constraints w/ mu-tau

- The parameter space becomes smaller, because of the reduction of number of d.o.f and the smaller allowed region for the e-tau component.





Parameters	1σ w/o $\mu-\tau$	1σ w/ $\mu-\tau$
$\tilde{\epsilon}_{ee}$	$[-2.5,\ 1.2]$	$[-0.13, 0.13]$
$\lvert\epsilon_{e\mu}\rvert$	$[0,\ 0.12]$	$[0,\ 0.1]$
$\lvert\epsilon_{e\tau}\rvert$	$[0,\ 0.3]$	$[0,\ 0.1]$
$\lvert\epsilon_{\mu\tau}\rvert$	$[0,\ 0.2]$	$[0,\ 0.12]$