Searching for New Physics in LBL

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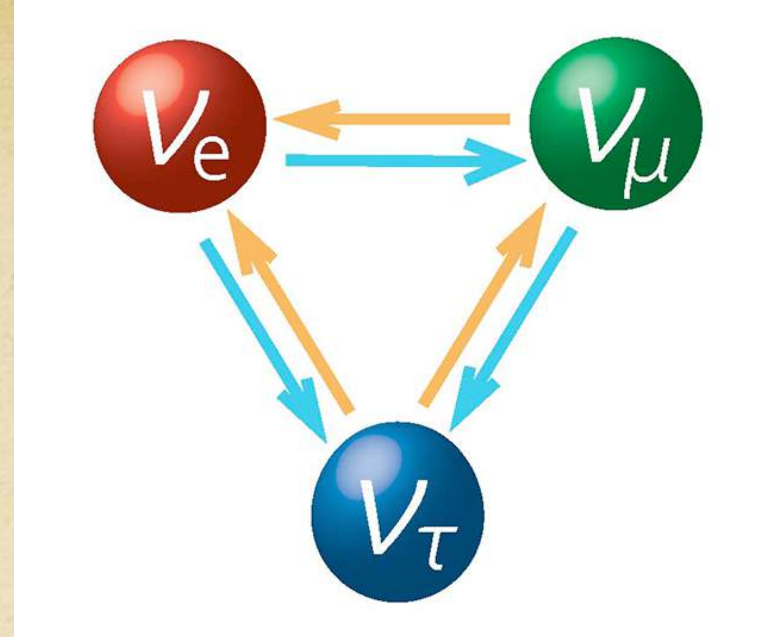
Neutrino Oscillations



Nus are produced and detected by weak CC interactions

For example: $\pi^+ \to \mu^+ + \nu_\mu$ **flavor eigenstates**

Their propagation is defined in terms of **mass eigenstate**

The flavor eigenstates can be written as a linear combination of the mass eigenstates

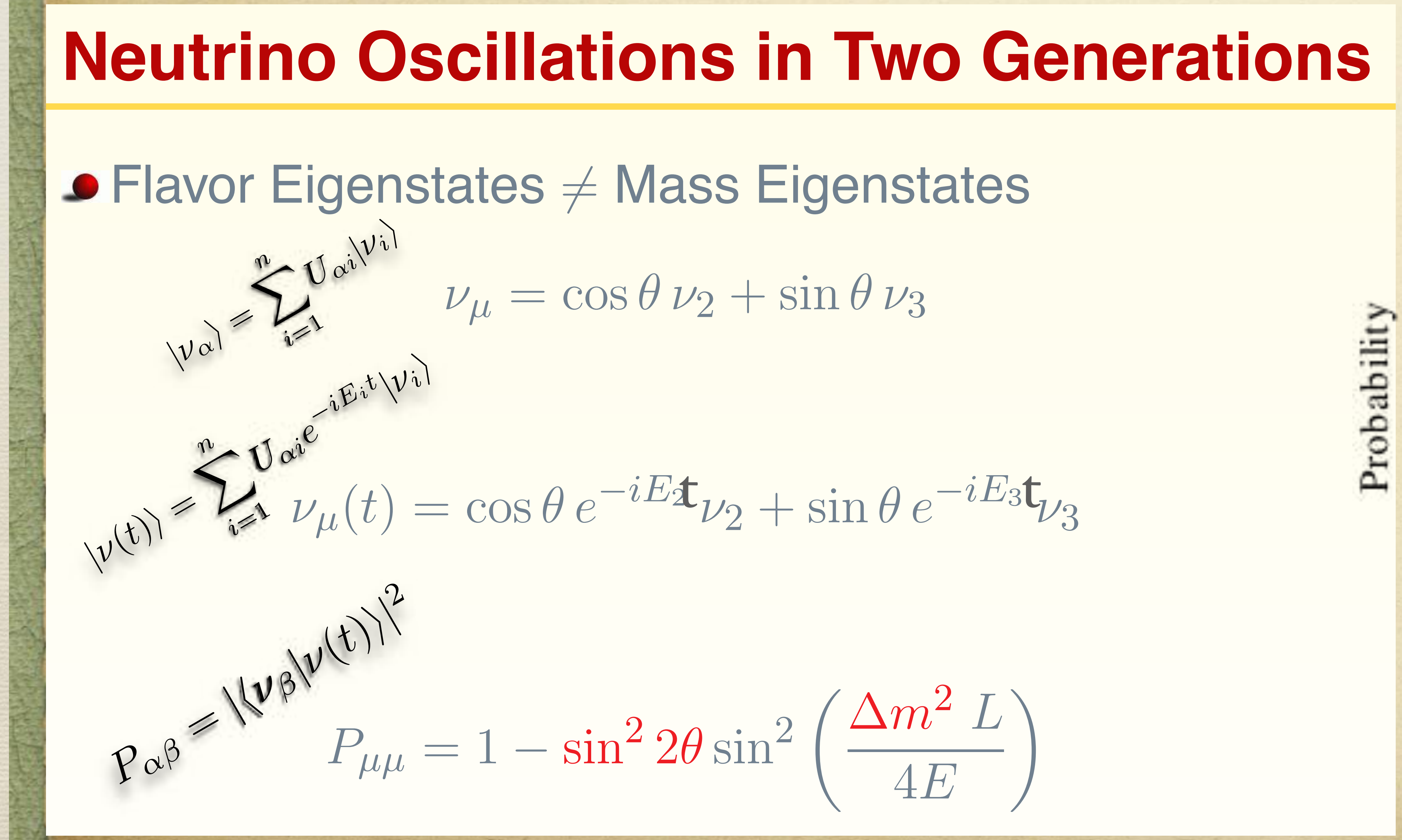
$$\boxed{|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}|\nu_i\rangle} \xrightarrow{\text{after time } t} \boxed{|\nu(t)\rangle = \sum_{i=1}^{n} U_{\alpha i} e^{-iE_i t}|\nu_i\rangle}$$

$$\boxed{P_{\alpha\beta} = |\langle \nu_\beta | \nu(t)\rangle|^2}$$

Neutrino Oscillations

Assume that there are two generations of massive neutrinos

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad 0 \leq \theta \leq \frac{\pi}{2}$$



Neutrino Oscillations in Two Generations

- Flavor Eigenstates $\neq$ Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}|\nu_i\rangle$$

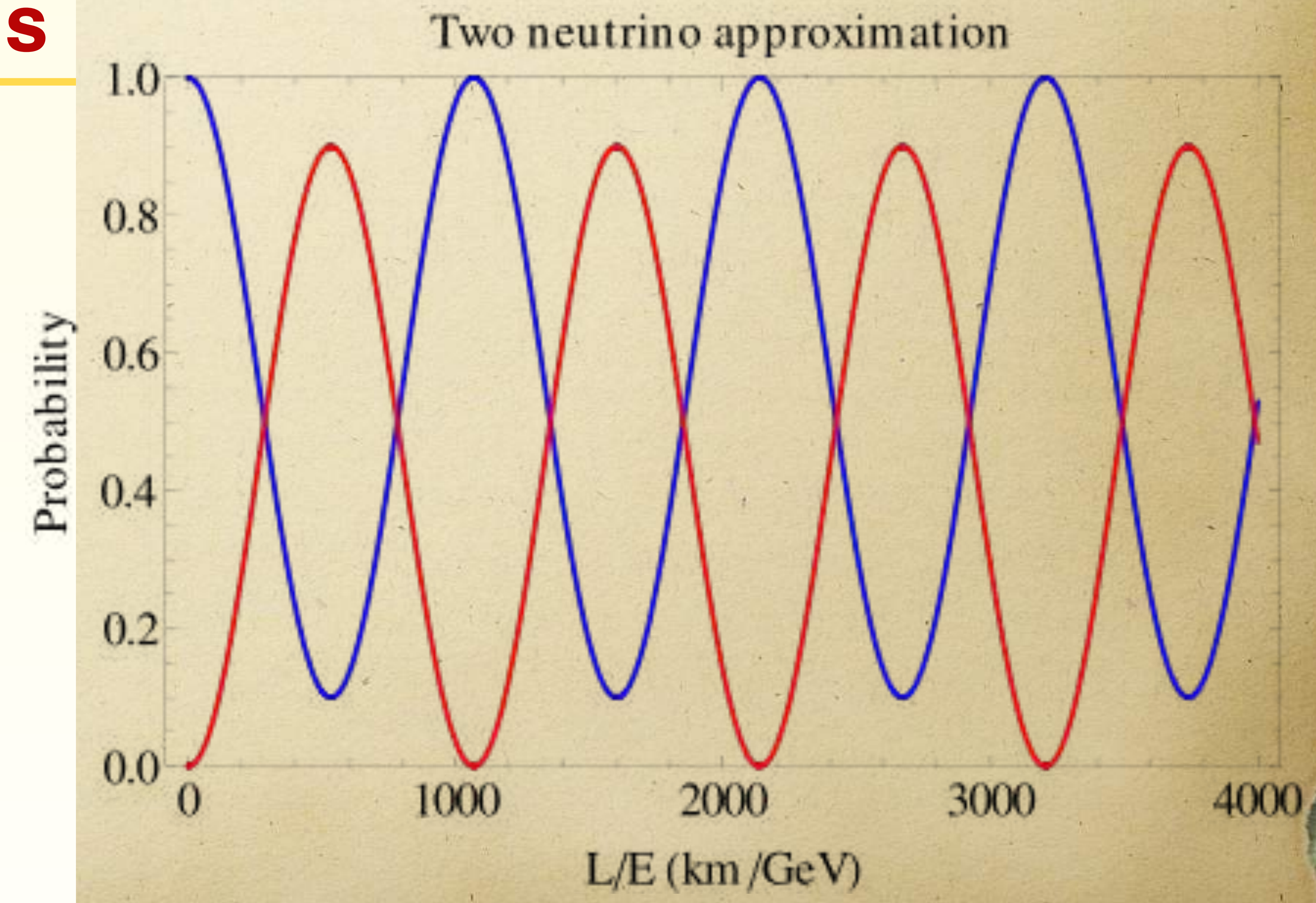
$$\nu_\mu = \cos\theta\,\nu_2 + \sin\theta\,\nu_3$$

$$|\nu(t)\rangle = \sum_{i=1}^{n} U_{\alpha i} e^{-iE_i t}|\nu_i\rangle$$

$$\nu_\mu(t) = \cos\theta\, e^{-iE_2 t}\nu_2 + \sin\theta\, e^{-iE_3 t}\nu_3$$

$$P_{\alpha\beta} = |\langle\nu_\beta|\nu(t)\rangle|^2$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2\ L}{4E}\right)$$



Three Flavor Oscillations in Vacuum

- Flavor Eigenstates $\neq$ Mass Eigenstates
- $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$P_{\beta\gamma}(L) = \delta_{\beta\gamma} \quad -4\sum_{j>1} Re\left(U_{\beta i}U^\star_{\gamma i}U^\star_{\beta j}U_{\gamma j}\right)\frac{\sin^2 \Delta m^2_{ij} L}{4E}$$

$$\pm 2\sum_{j>1} Im\left(U_{\beta i}U^\star_{\gamma i}U^\star_{\beta j}U_{\gamma j}\right)\frac{\sin \Delta m^2_{ij} L}{2E}.$$

3 mixing angles

1 CP Phase

2 mass-squared diff

Next on the agenda

- Confirmation of CP violation in neutrino oscillations
- Measurement of the CP phase
- Determination of neutrino mass ordering
- Determining the "octant" of theta23
- Looking for new physics in neutrino oscillations
- Dirac or Majorana

Neutrino-less double beta decay

- Supernova neutrinos - Galactic SN / Diffuse SN neutrino background

Gd loaded SK

- Multi-messenger astronomy with UHE neutrinos at Neutrino Telescopes

Forthcoming Experiments

- Long-baseline experiments - T2HK, DUNE, ESSnuSB
- Atmospheric neutrino experiments - INO, PINGU, ORCA, HK, ESSnuSB
- LBL Reactor antineutrino experiments - JUNO
- SBL Reactor antineutrino experiments - SBN, JSNS2…..
- Neutrino-less double beta decay - nEXO,….

CP Violation

- Why bother?

Important parameter in the neutrino mixing matrix

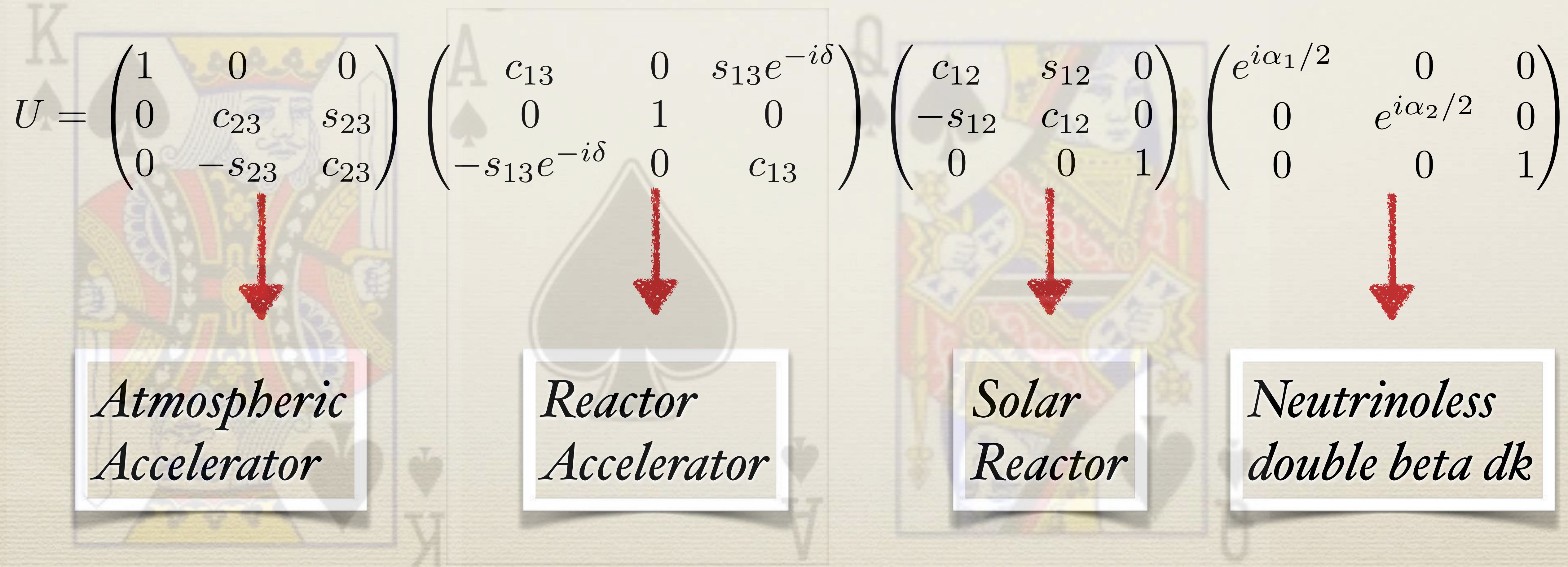
Key player in model of neutrino mass - pointer at the correct BSM theory

Pointer to leptogenesis

-

CP Violation

- If we observe a difference between flavor oscillations of neutrinos and antineutrino → CP violation
- CP dependence in neutrino oscillations comes from the phase δ_{CP} in the neutrino mixing matrix … this phase is mostly referred to as the “Dirac CP phase”



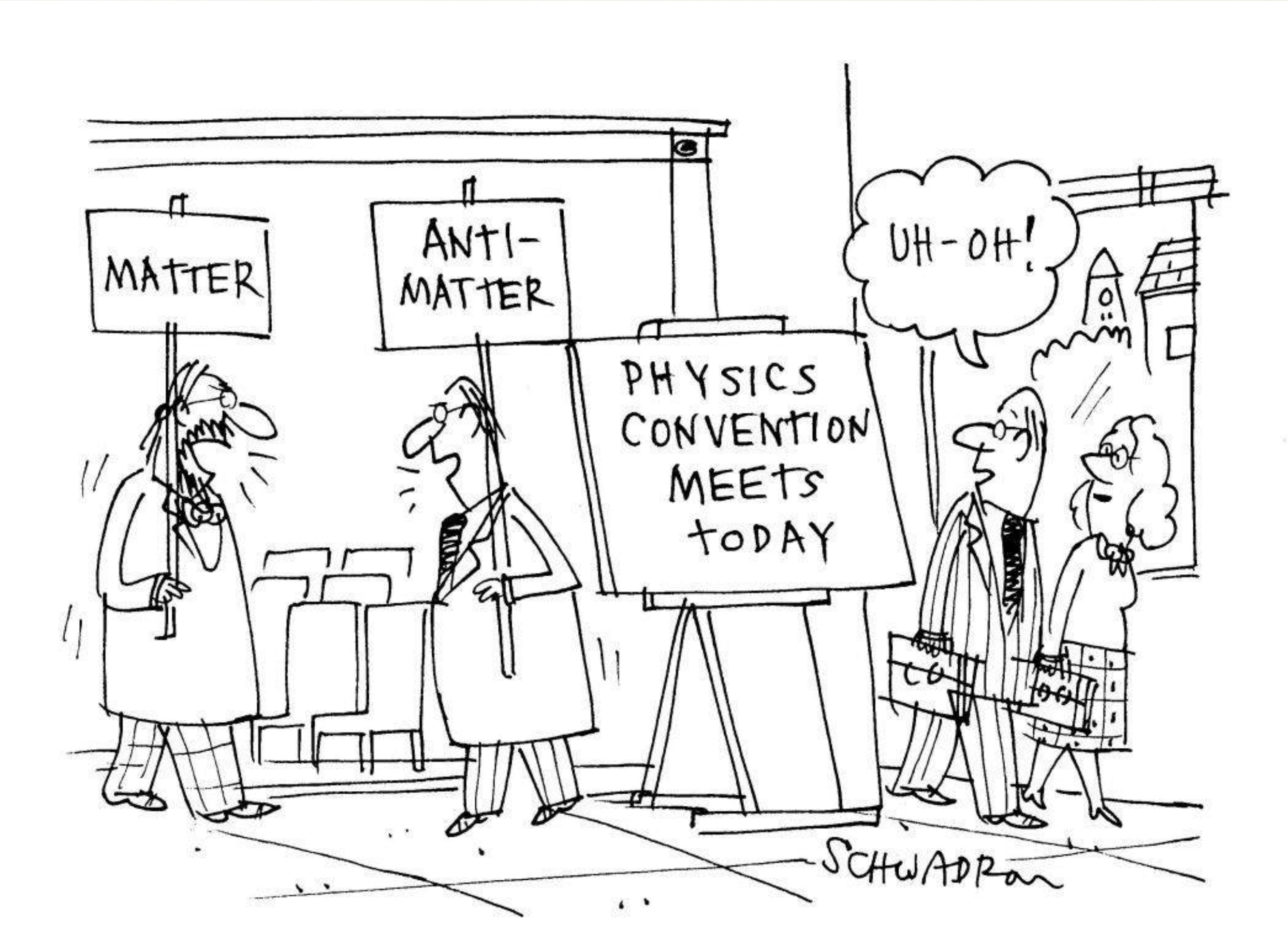
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Accelerator

Reactor Accelerator

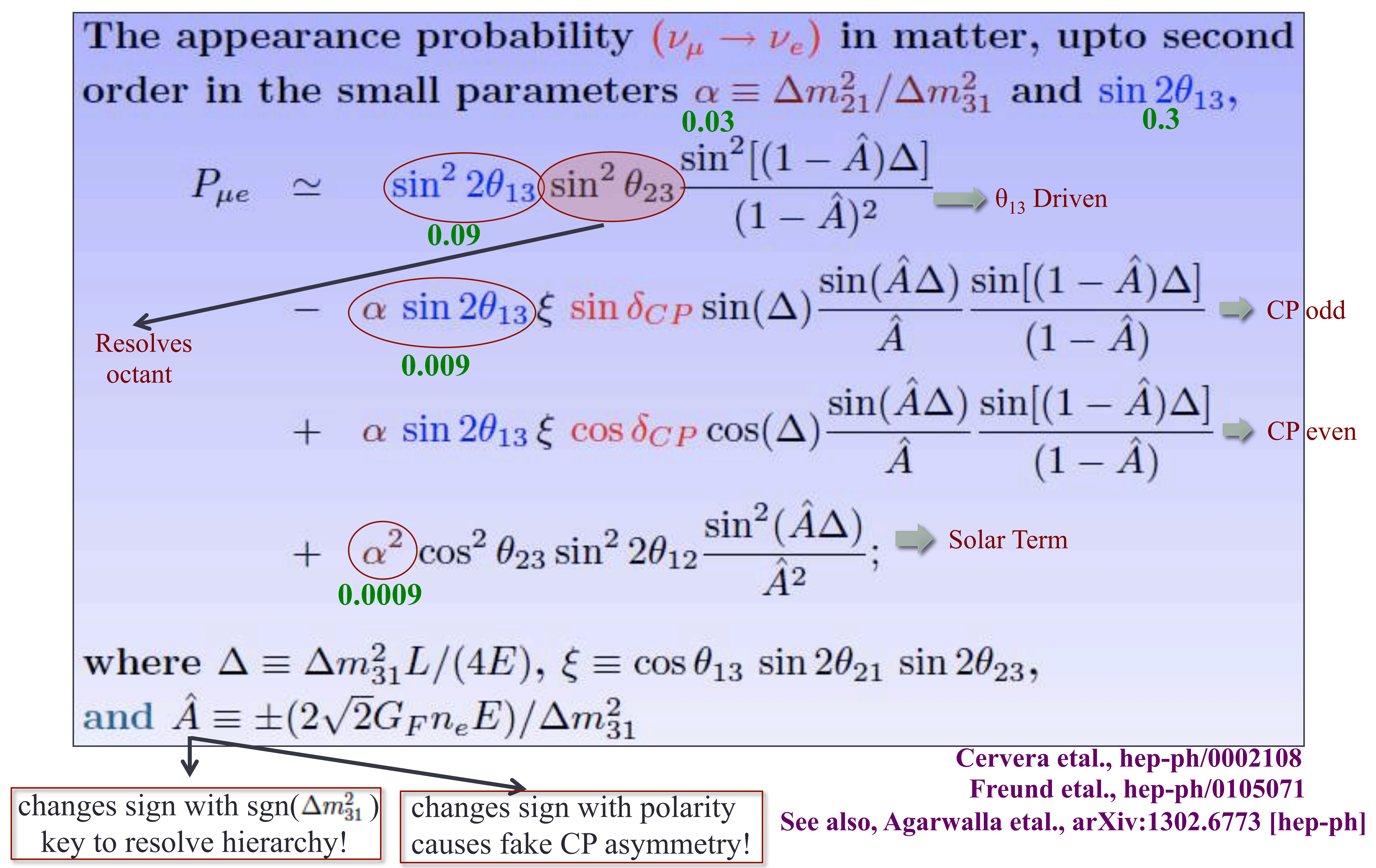
Solar Reactor

Neutrinoless double beta dk



CP Violation

The best method to see CP violation is to measure the oscillation probability



The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\underset{0.03}{\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}}$ and $\underset{0.3}{\sin 2\theta_{13}}$,

$$P_{\mu e} \simeq \underset{0.09}{\sin^2 2\theta_{13}} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \rightarrow \theta_{13} \text{ Driven}$$

$$- \underset{0.009}{\alpha \sin 2\theta_{13}} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \rightarrow \text{CP odd}$$

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \rightarrow \text{CP even}$$

$$+ \underset{0.0009}{\alpha^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}; \rightarrow \text{Solar Term}$$

Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

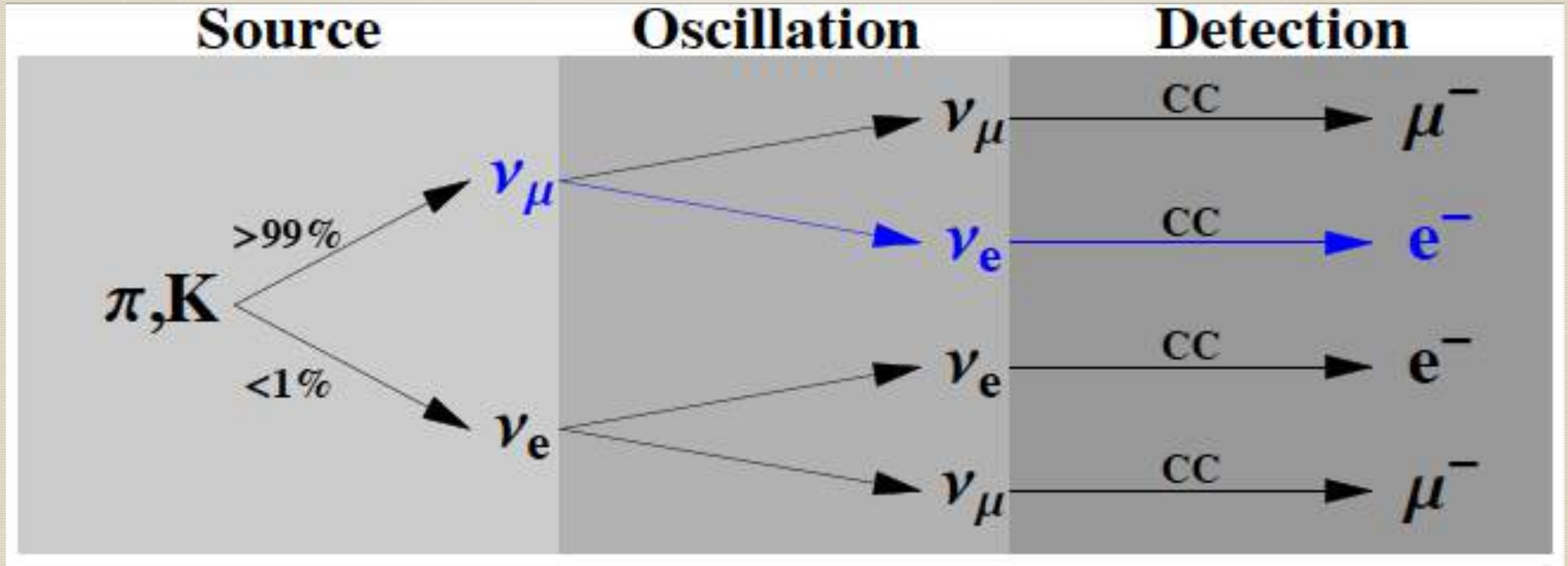
changes sign with sgn(Δm^2_{31})
key to resolve hierarchy!

changes sign with polarity
causes fake CP asymmetry!

Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracy! How can we break them?

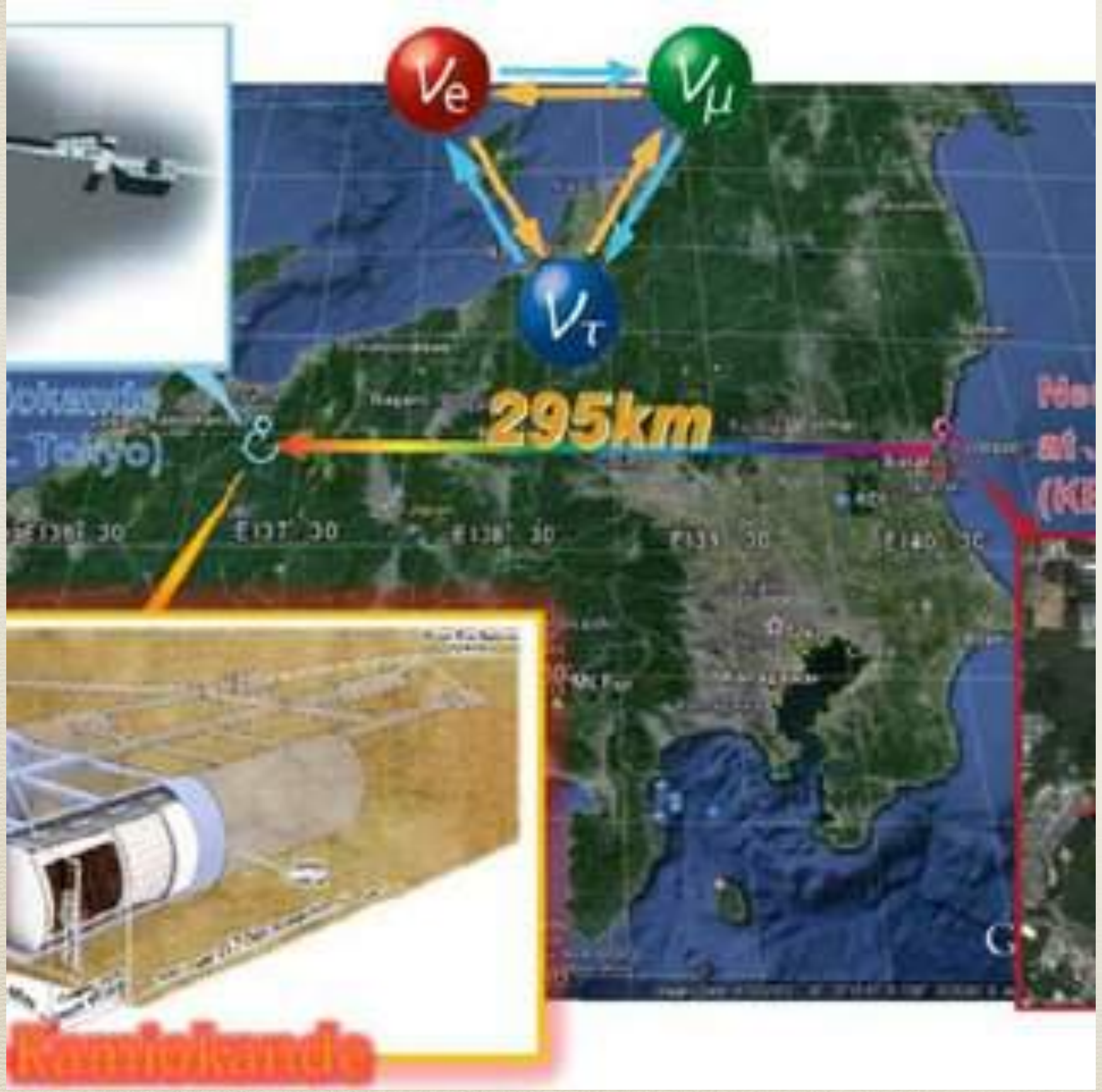
Using Accelerator Beams

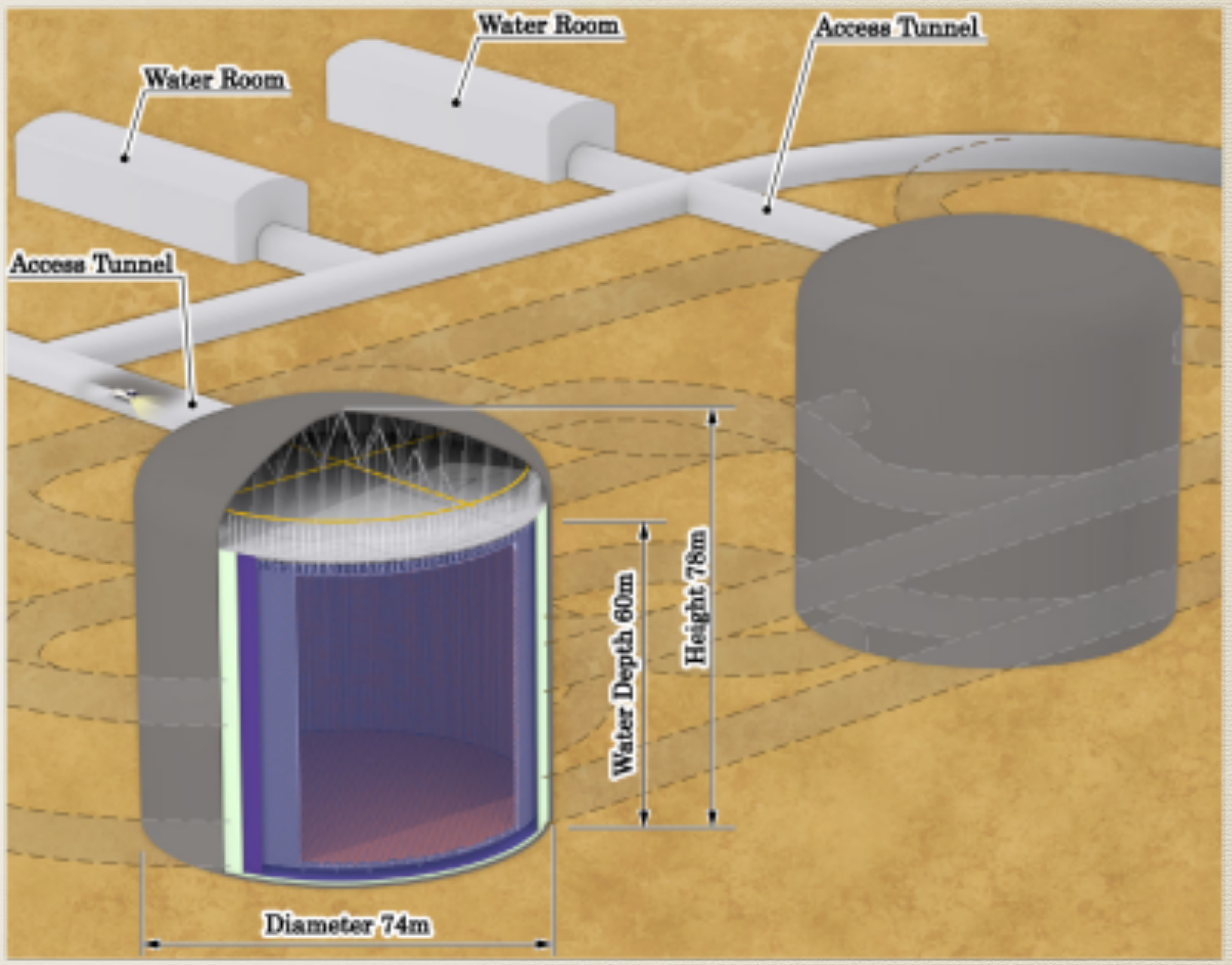


Requirements

- Intense beam
- Big Detector
- Low systematic uncertainty
- Good energy resolution
- Good particle ID
- Low backgrounds

Candidate Experiments - **T2HK**





T2HK

The Hyper-Kamiokande (HK) project is officially approved

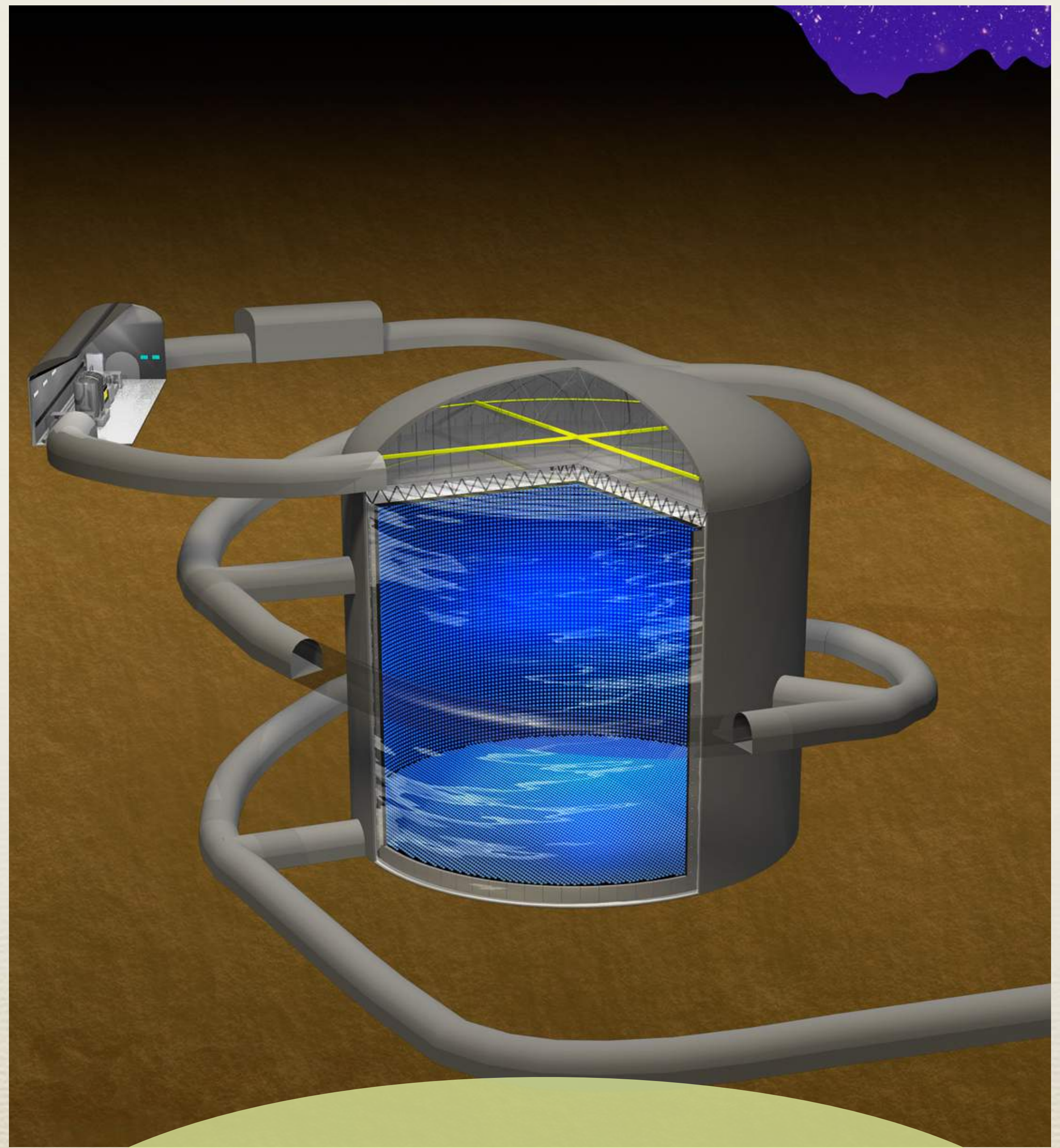
HK is under construction and operations are scheduled to start in 2027

KEK will upgrade the JPARC accelerator beam for a high intensity nu beam

DM Indirect Detection

Solar Neutrinos

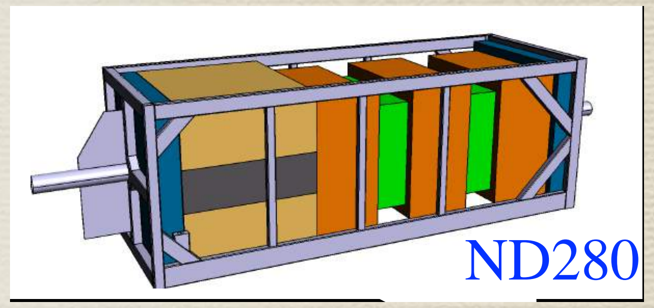
Atm Neutrinos

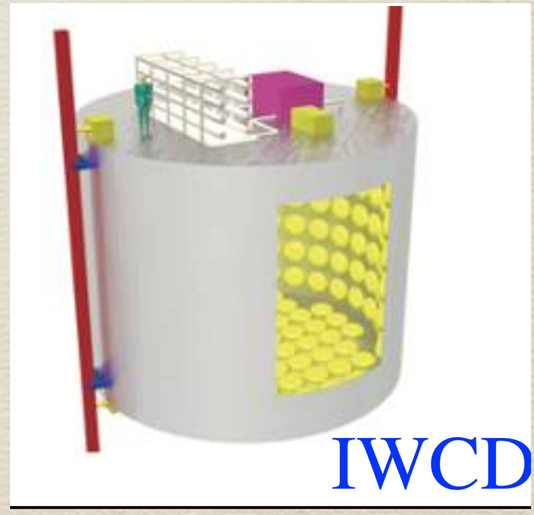


JPARC neutrinos

Proton decay

SN neutrinos

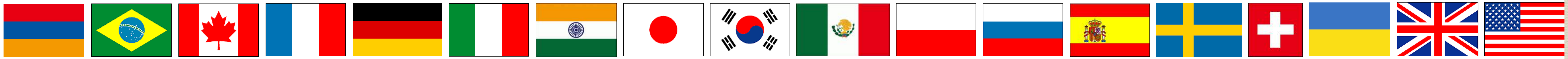




	Super-K	Hyper-K
Overburden	1000 m	650 m
Number of ID PMT	11,000	40,000
Photo-coverage	40%	40% (×2 sensitivity)
Total/Fiducial vol.	50 / 22.5 kton	260 / 188 kton

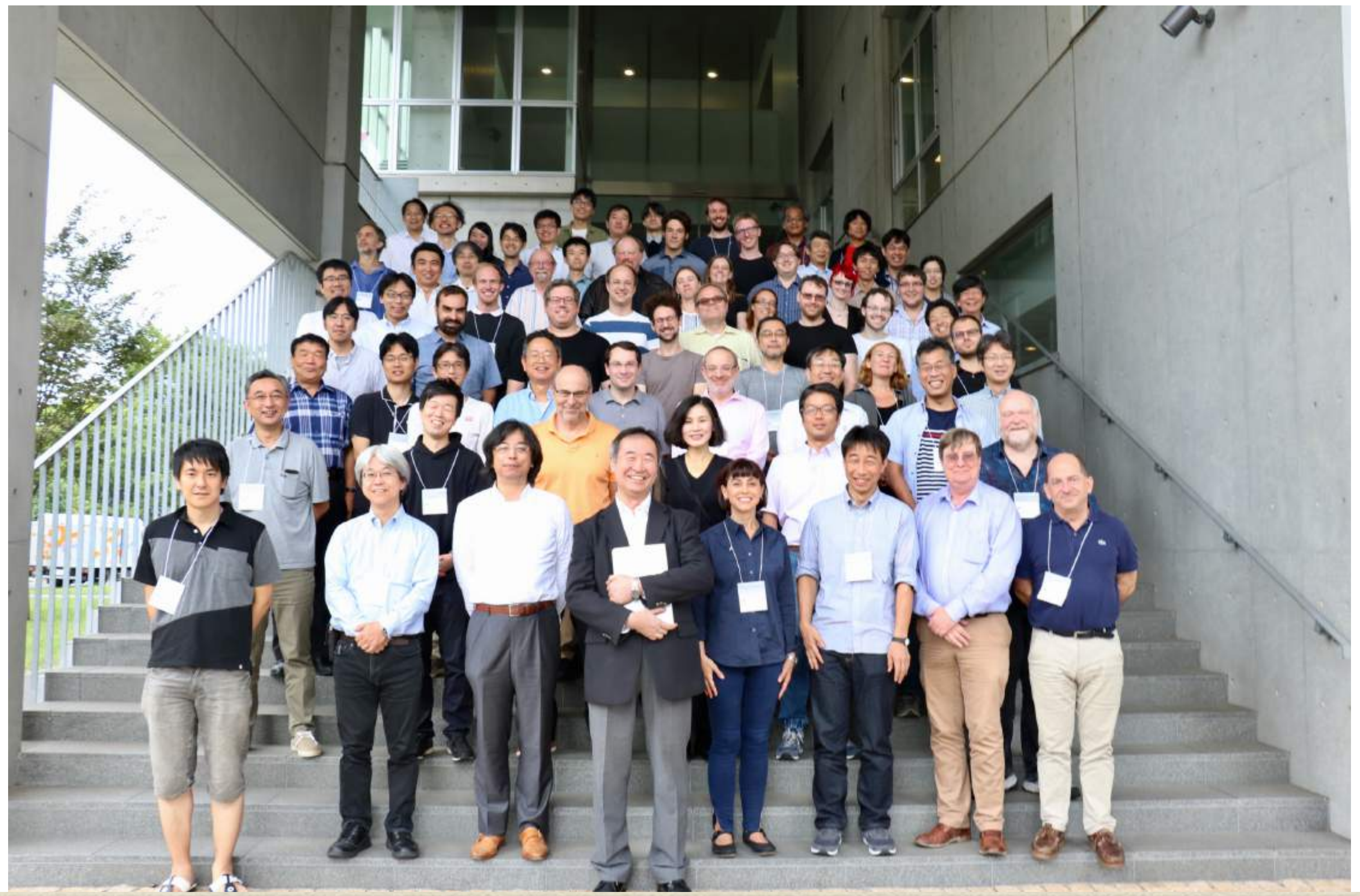
T2HK

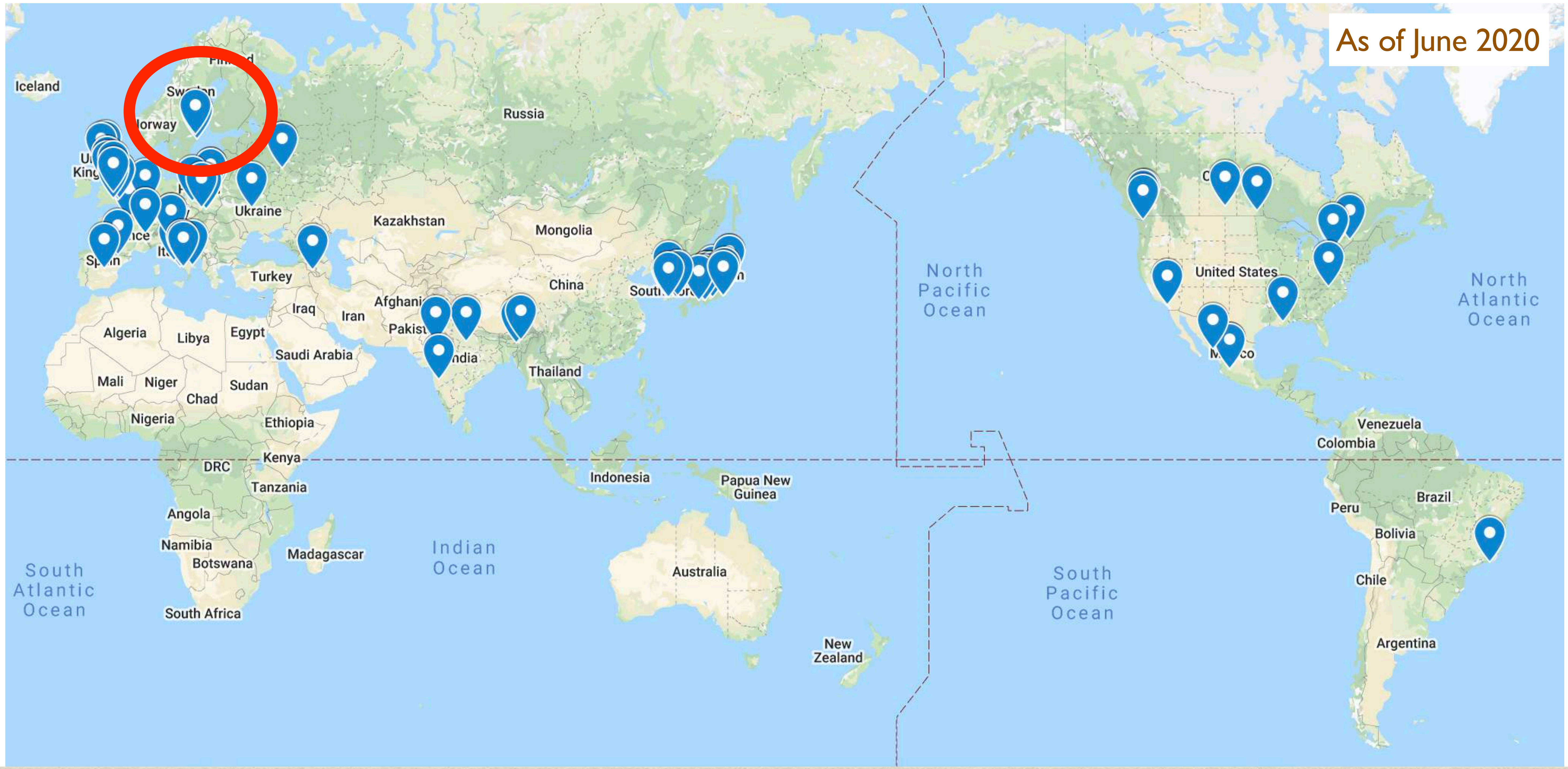
Hyper-Kamiokande Proto-Collaboration



18 countries, 82 institutes, ~390 people

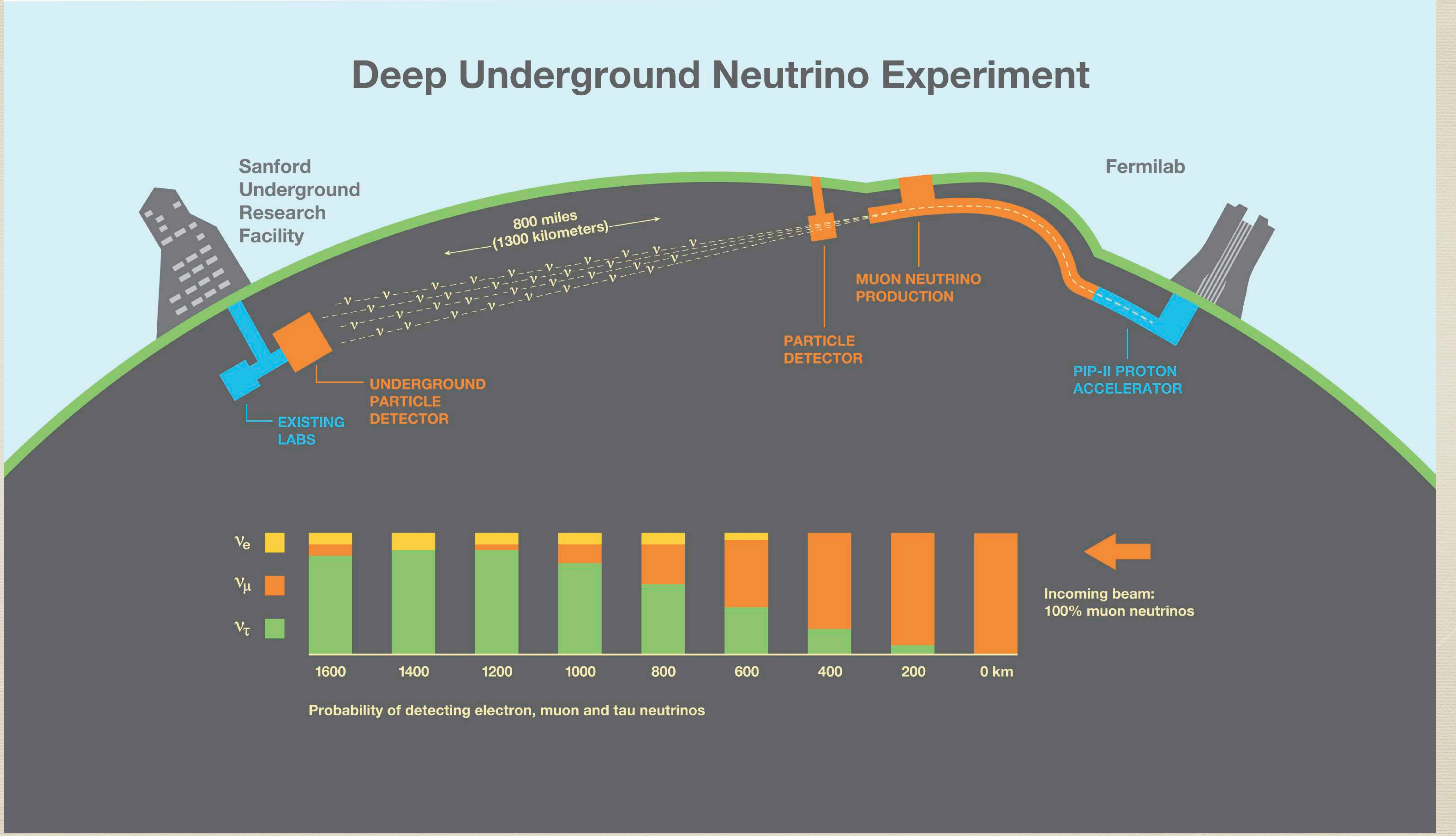
Hyper-Kamiokande



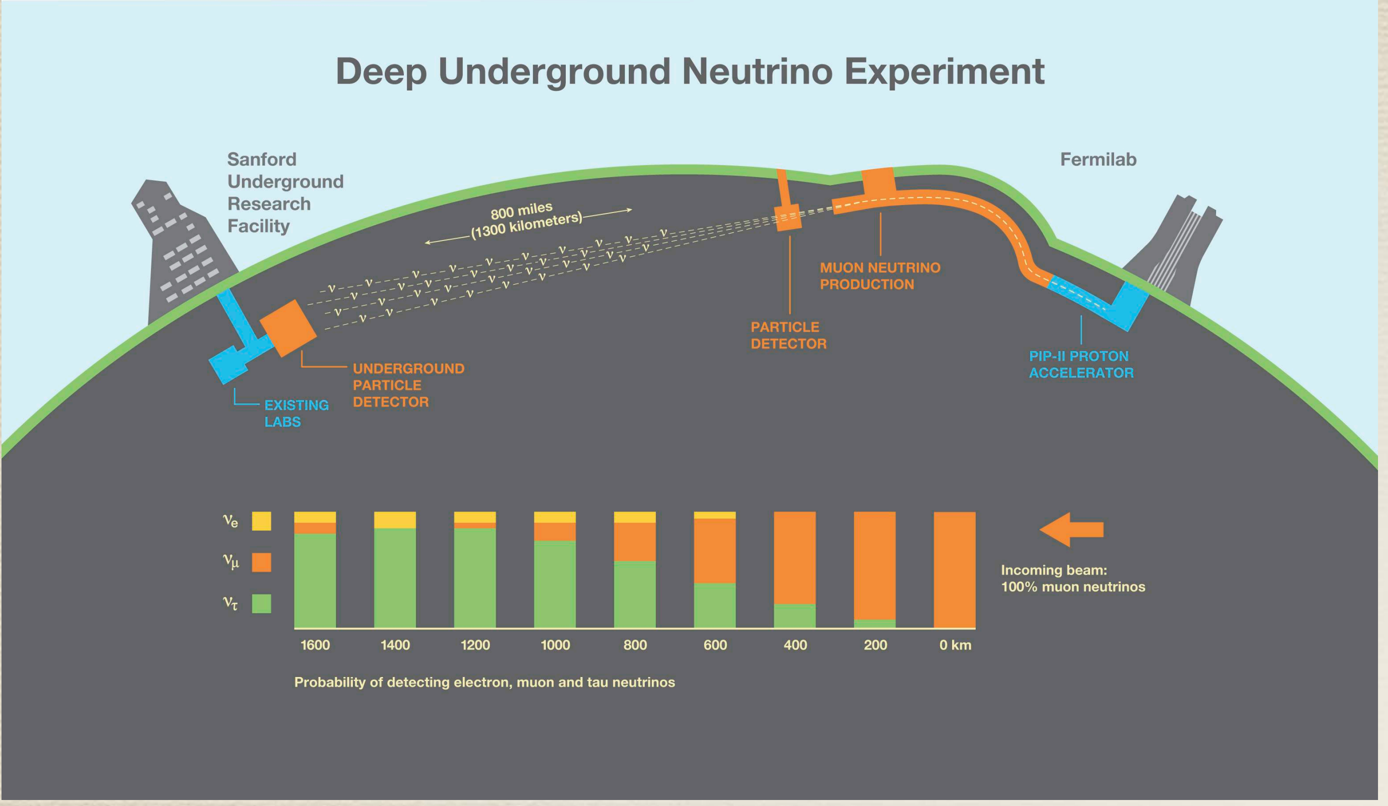


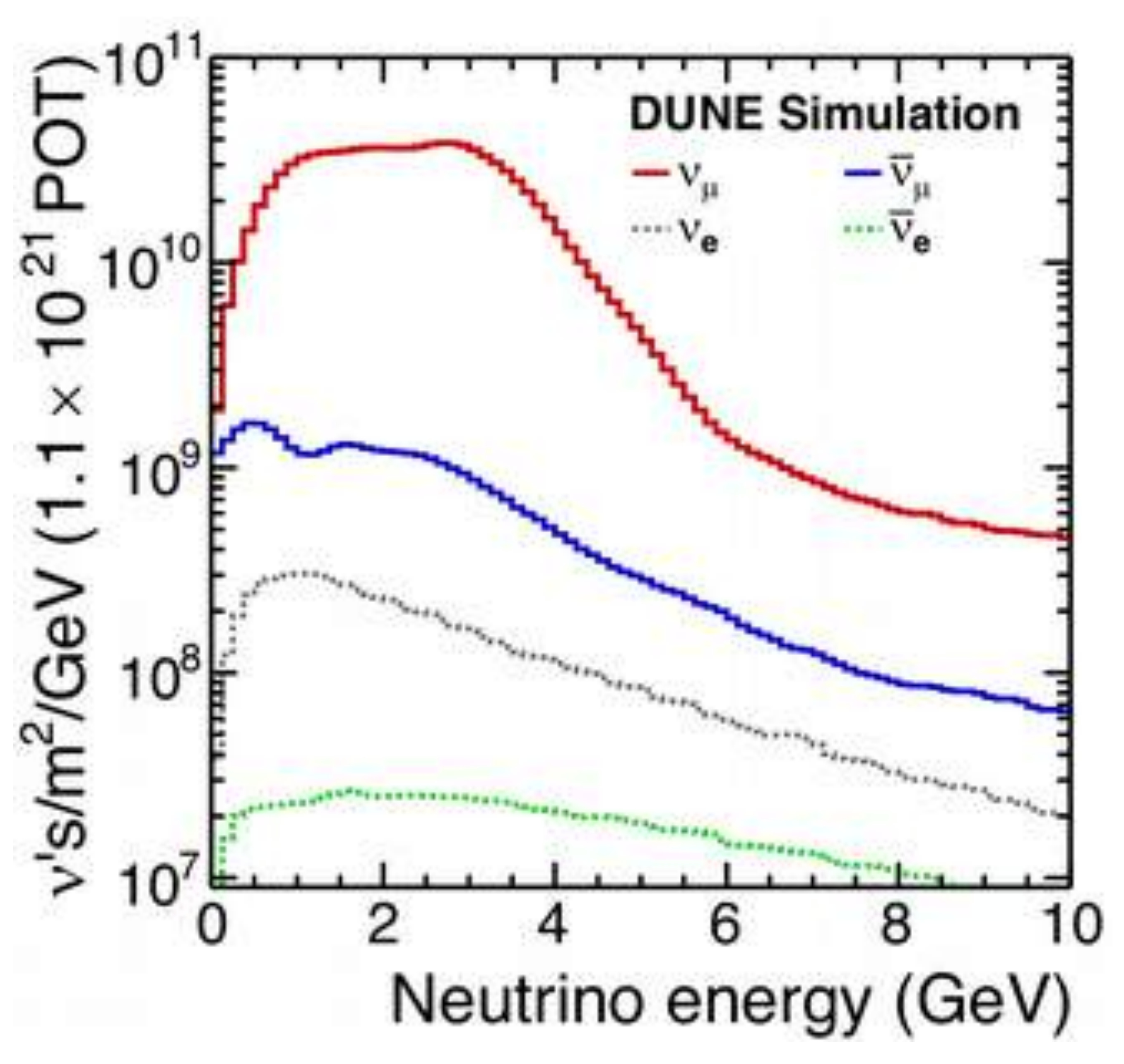
As of June 2020

Candidate Experiments - DUNE

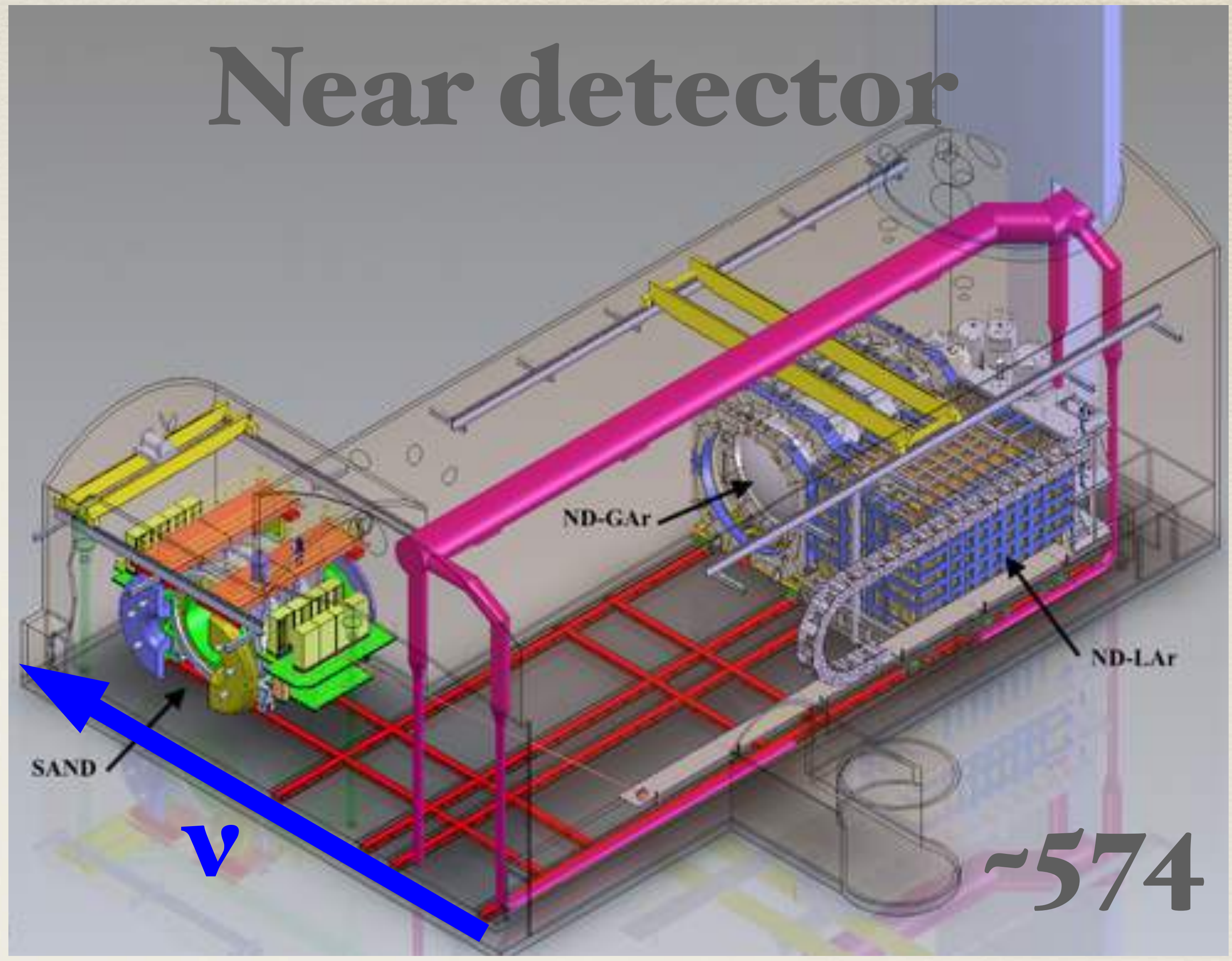


DUNE



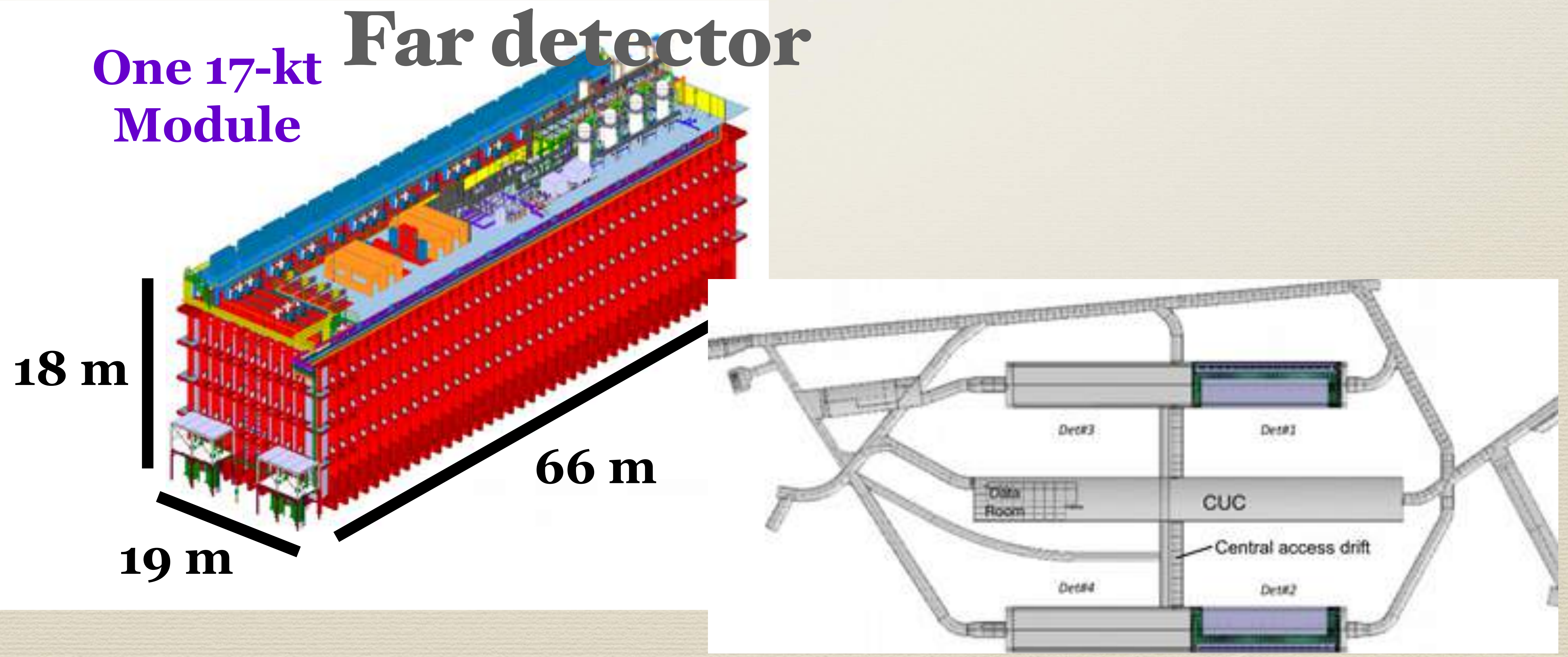


Near detector



~574 m from target

Far detector

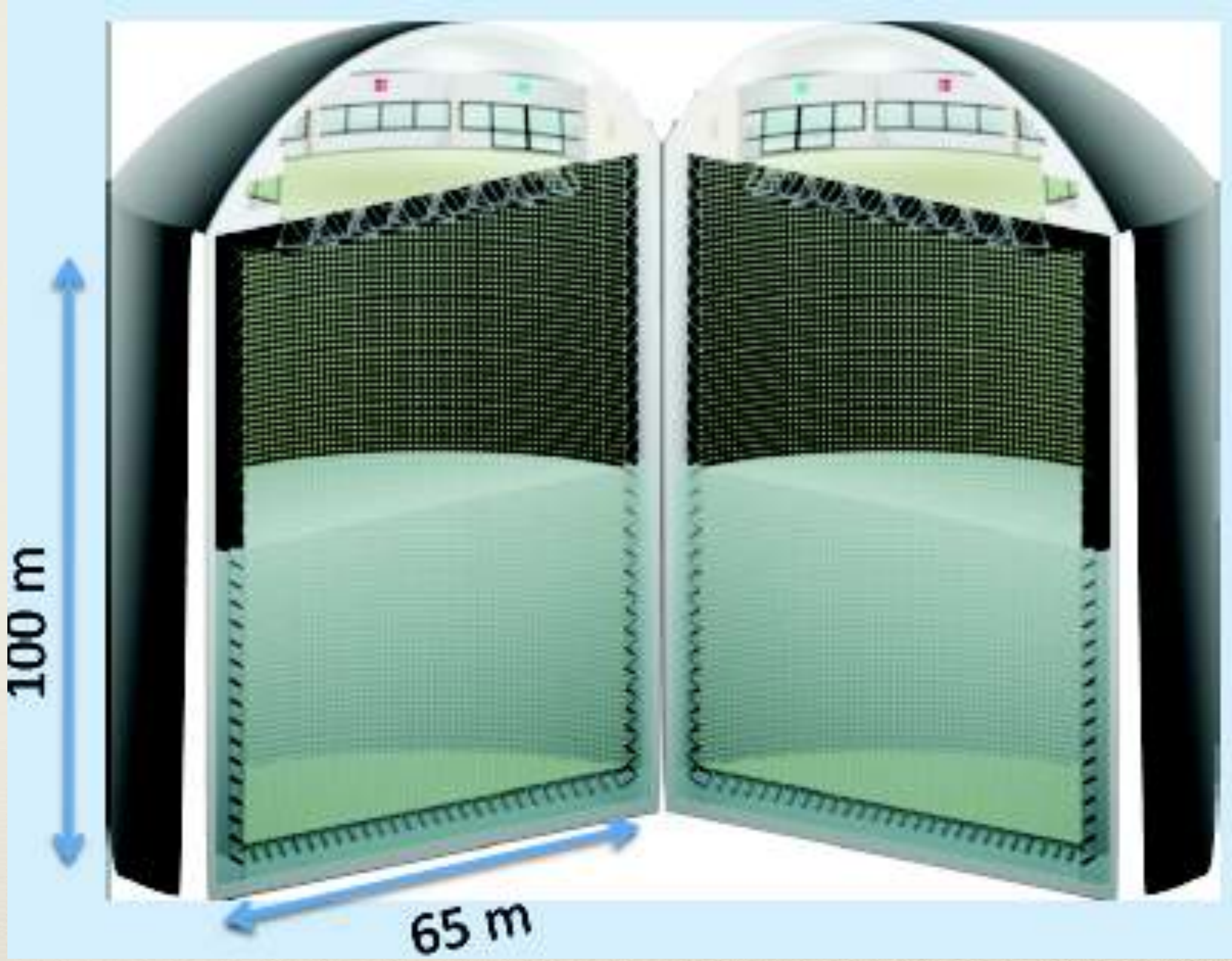


DUNE

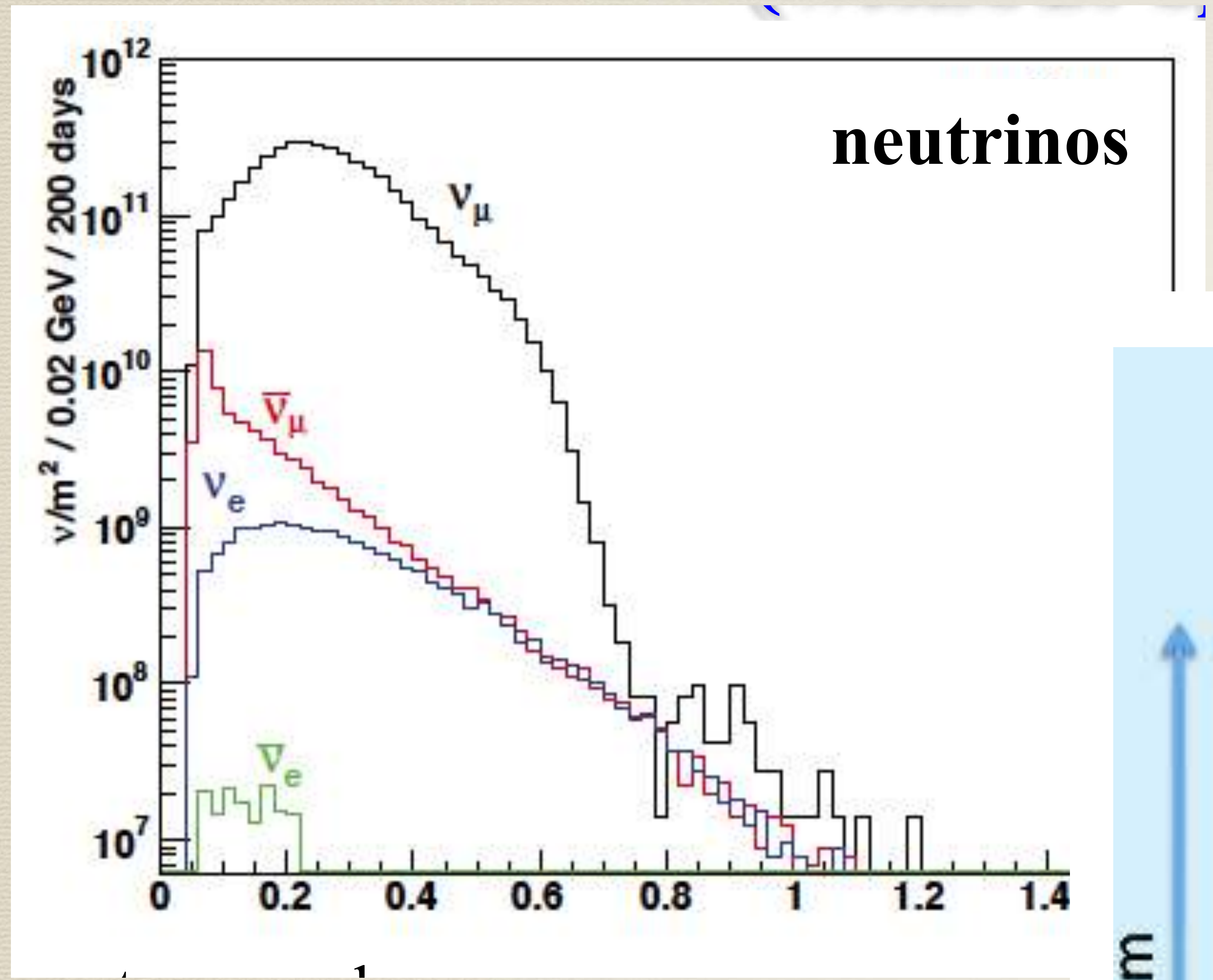
- **1157 collaborators** from 197 institutions in 33 countries (w/ CERN)!

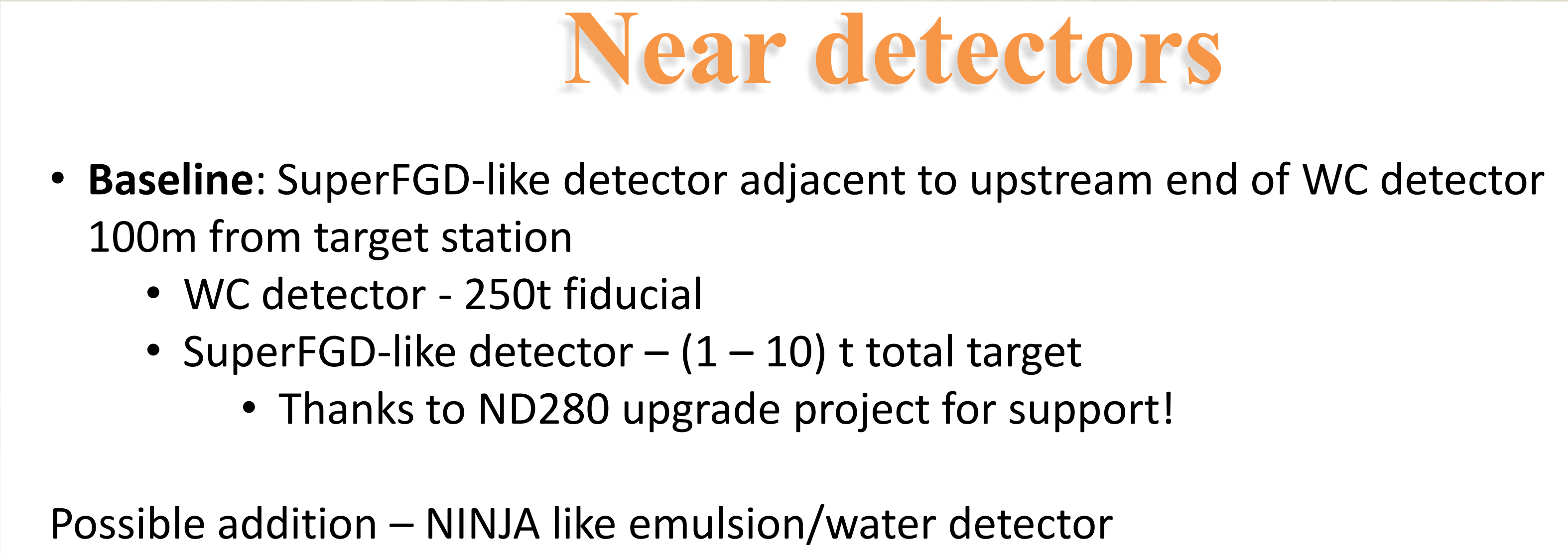
Candidate Experiments

ESSnuSB



ESSnuSB

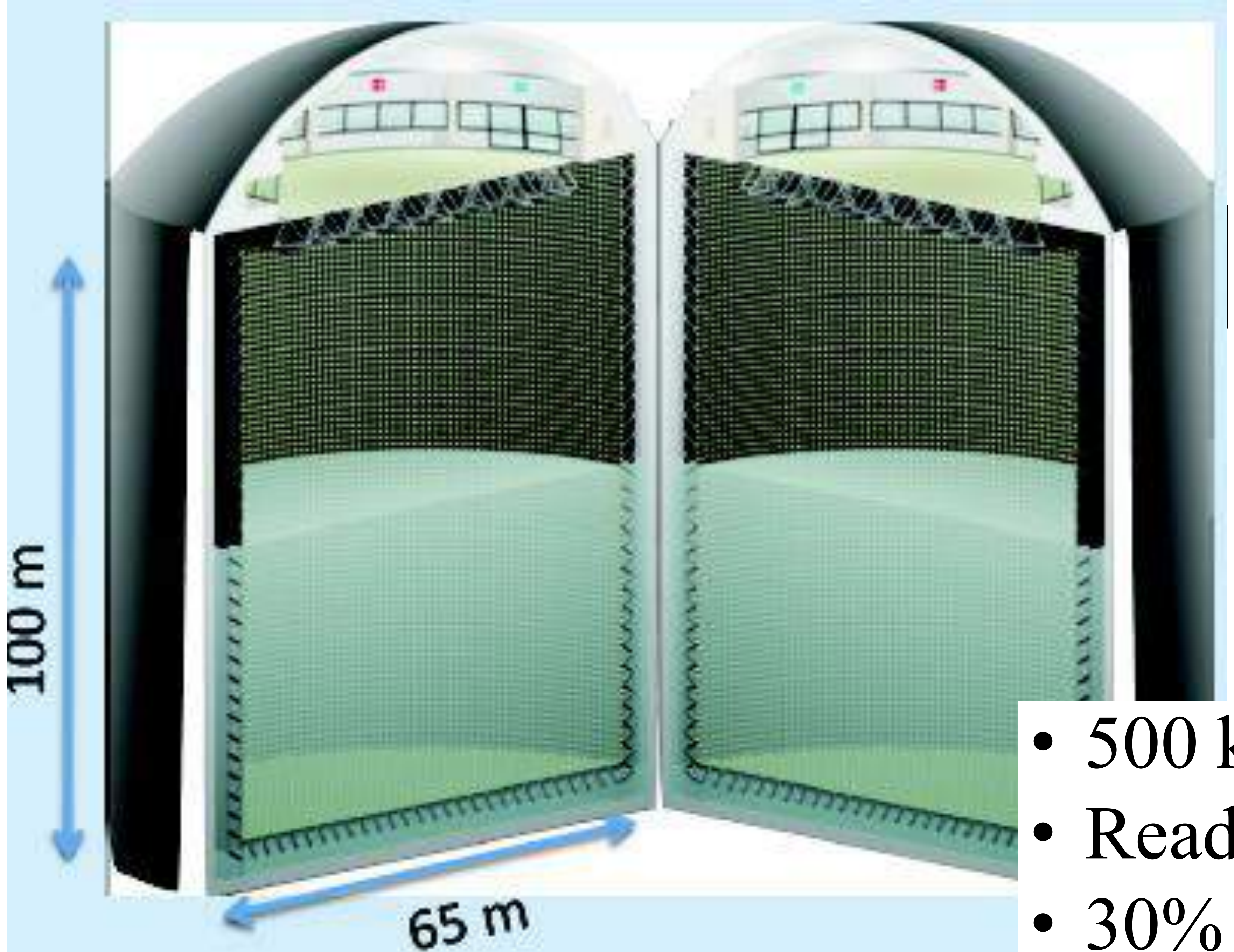




Near detectors

- **Baseline**: SuperFGD-like detector adjacent to upstream end of WC detector 100m from target station
  - WC detector - 250t fiducial
  - SuperFGD-like detector – (1 – 10) t total target
    - Thanks to ND280 upgrade project for support!

Possible addition – NINJA like emulsion/water detector



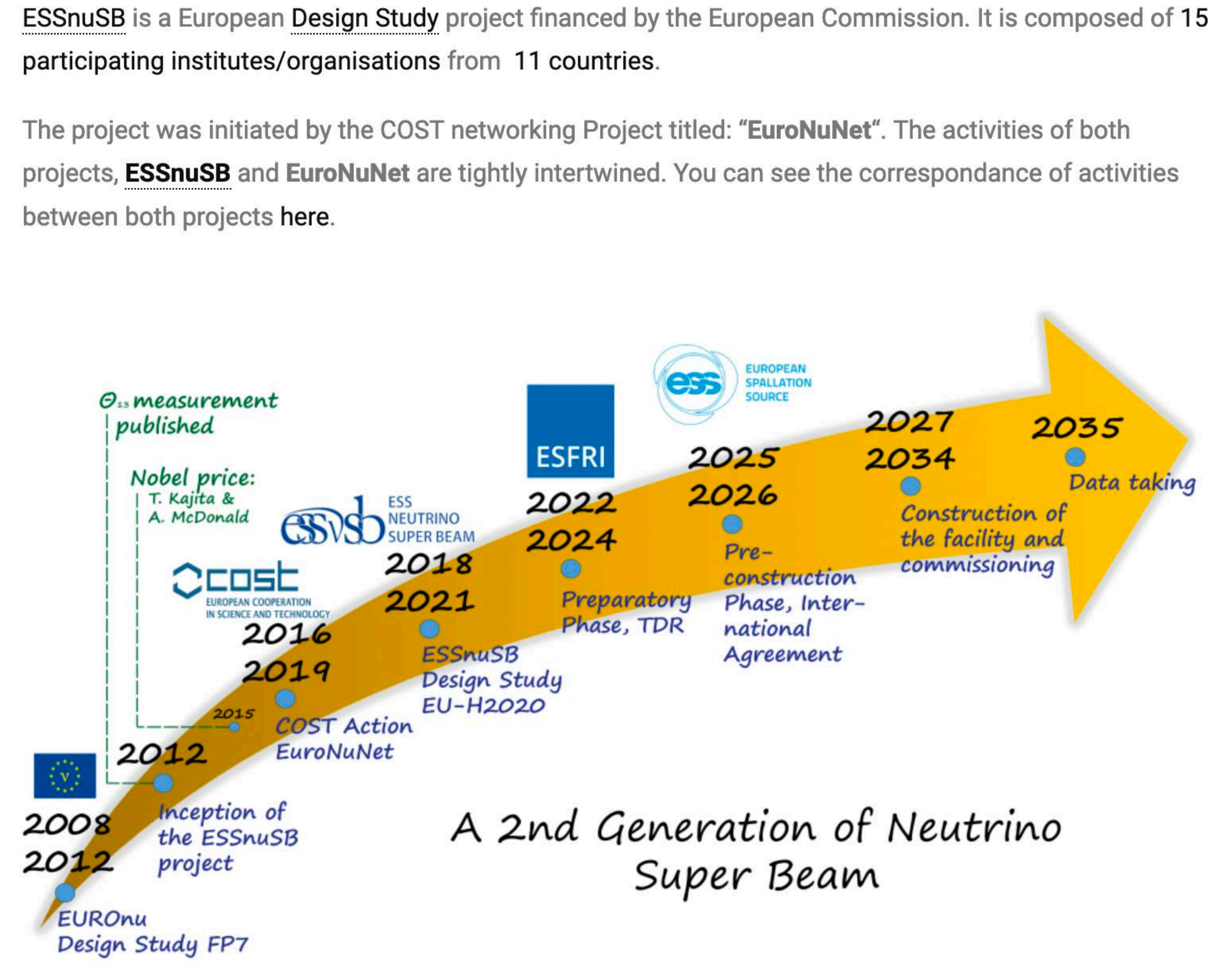
Far detector

The novelty of this exp is that it will be the first neutrino experiment operating on the second oscillation maxima

Also T2HKK

- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage

ESSnuSB

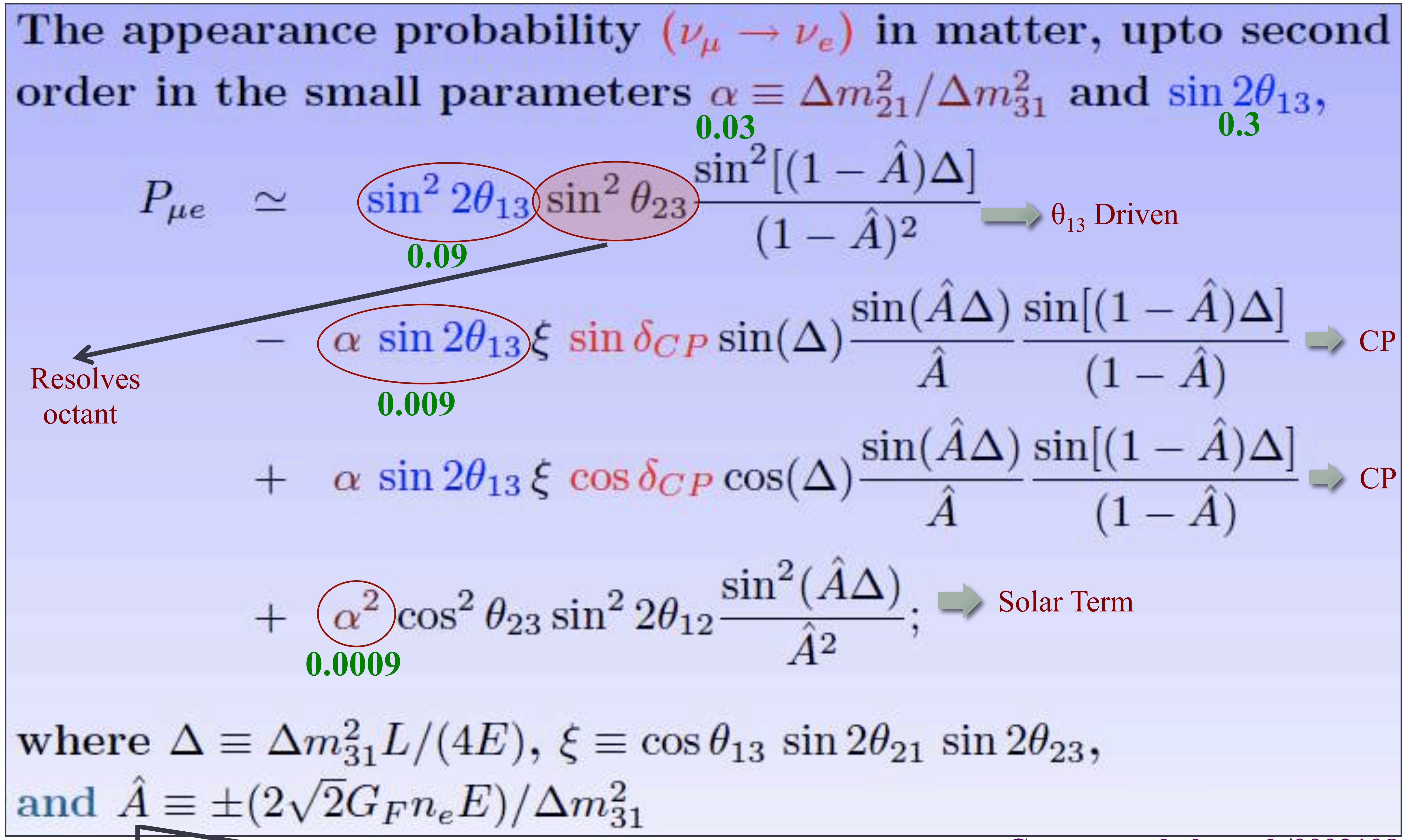


ESSnuSB is a European Design Study project financed by the European Commission. It is composed of 15 participating institutes/organisations from 11 countries.

The project was initiated by the COST networking Project titled: "**EuroNuNet**". The activities of both projects, **ESSnuSB** and **EuroNuNet** are tightly intertwined. You can see the correspondance of activities between both projects here.

CP Violation

The best method to see CP violation is to measure the oscillation probability



The appearance probability $(\nu_\mu \rightarrow \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$,

0.03 **0.3**

$$P_{\mu e} \simeq \underset{0.09}{\sin^2 2\theta_{13}} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \Rightarrow \theta_{13} \text{ Driven}$$

$$- \underset{0.009}{\alpha \sin 2\theta_{13}} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \Rightarrow \text{CP odd}$$

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \Rightarrow \text{CP even}$$

$$+ \underset{0.0009}{\alpha^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}; \Rightarrow \text{Solar Term}$$

Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,

and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

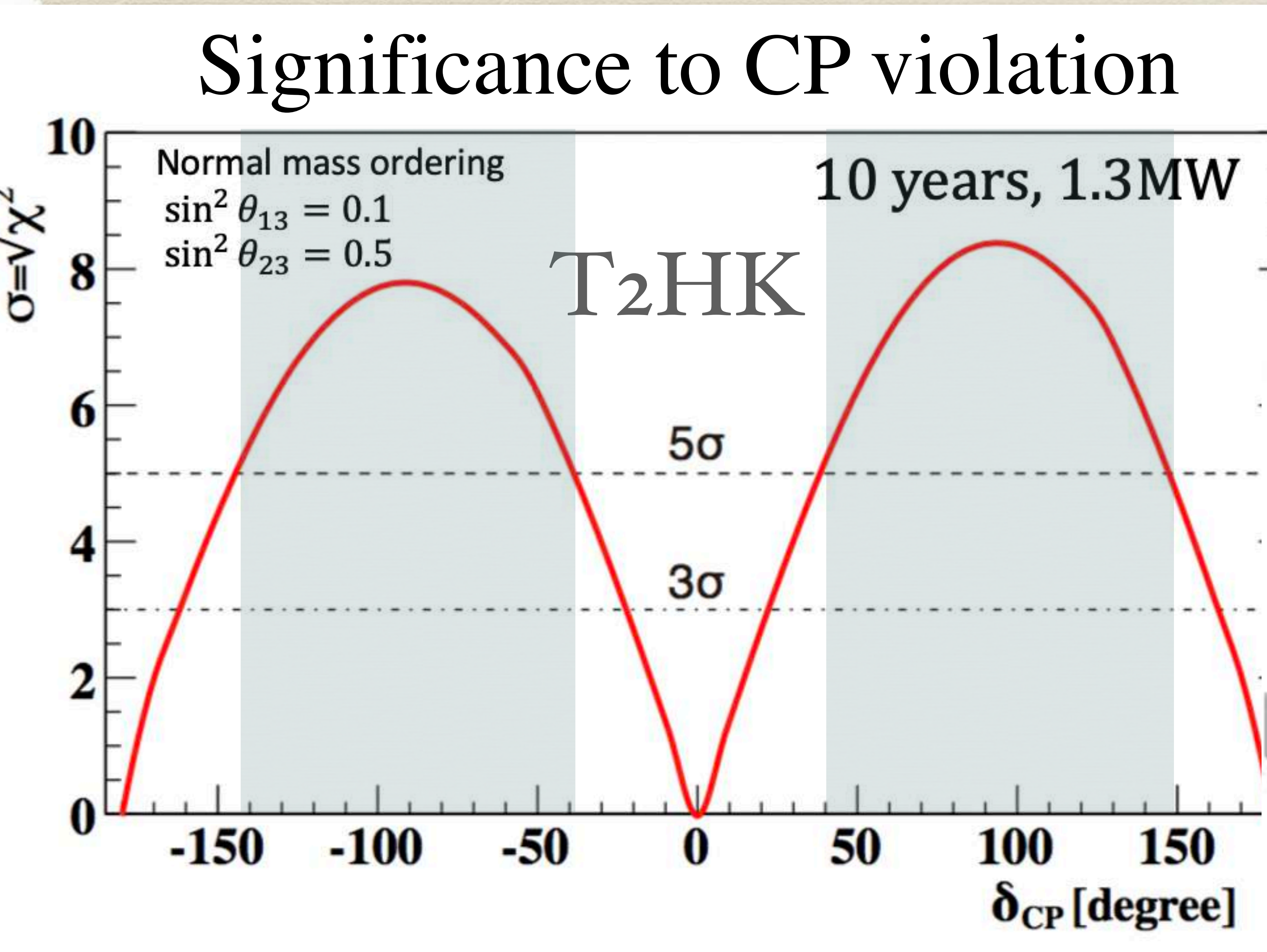
changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

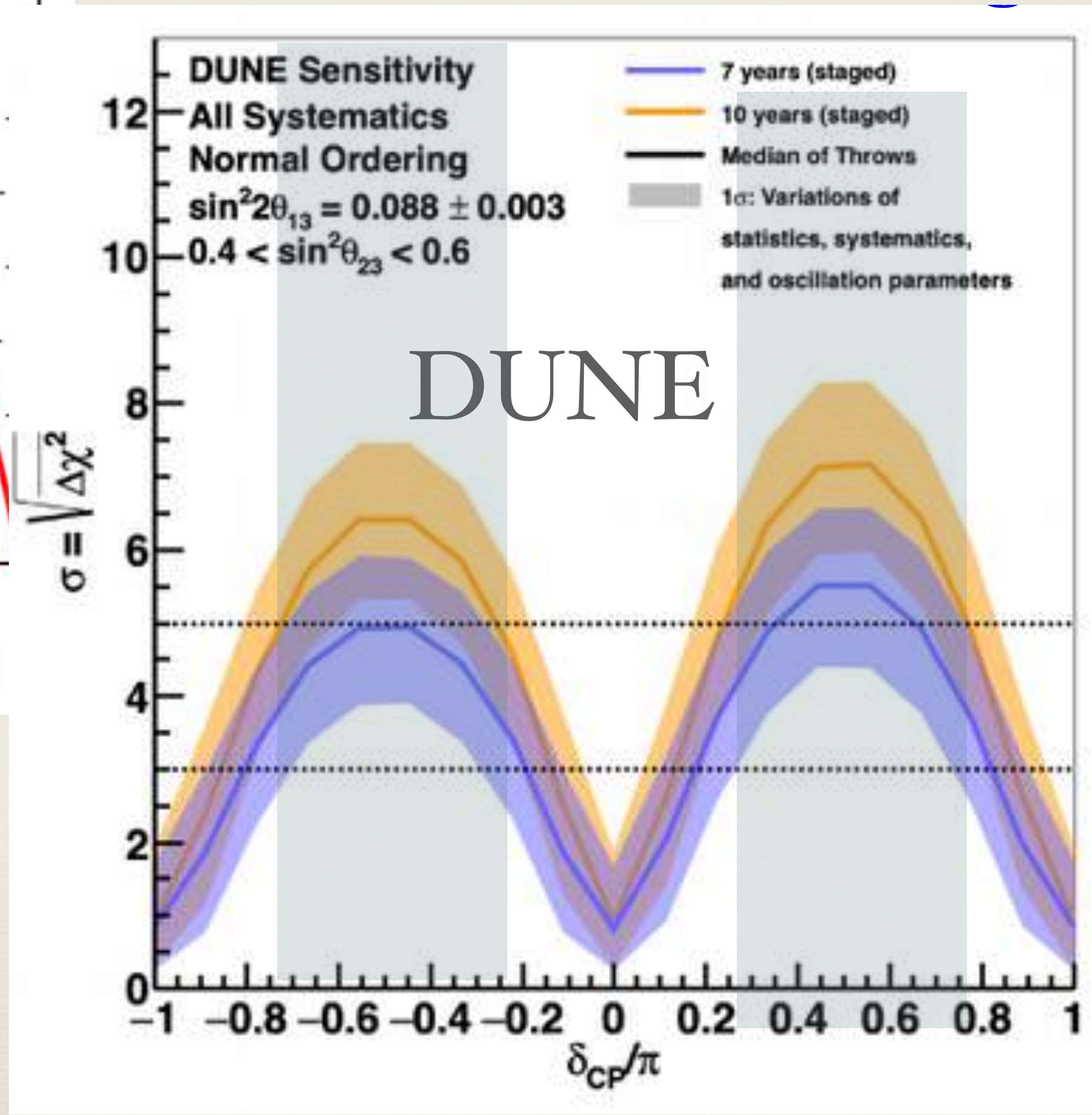
changes sign with polarity causes fake CP asymmetry!

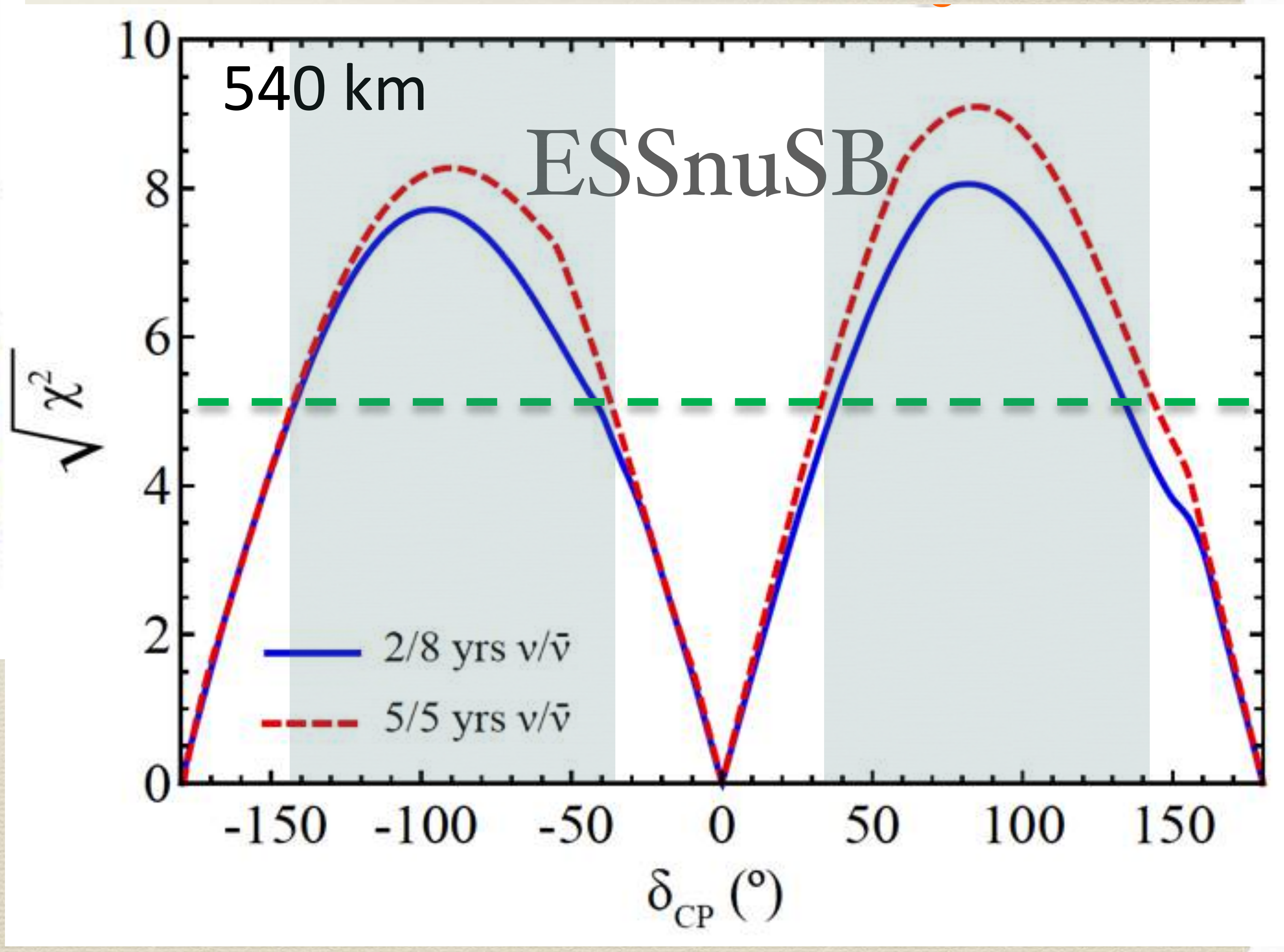
Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracy! How can we break them?

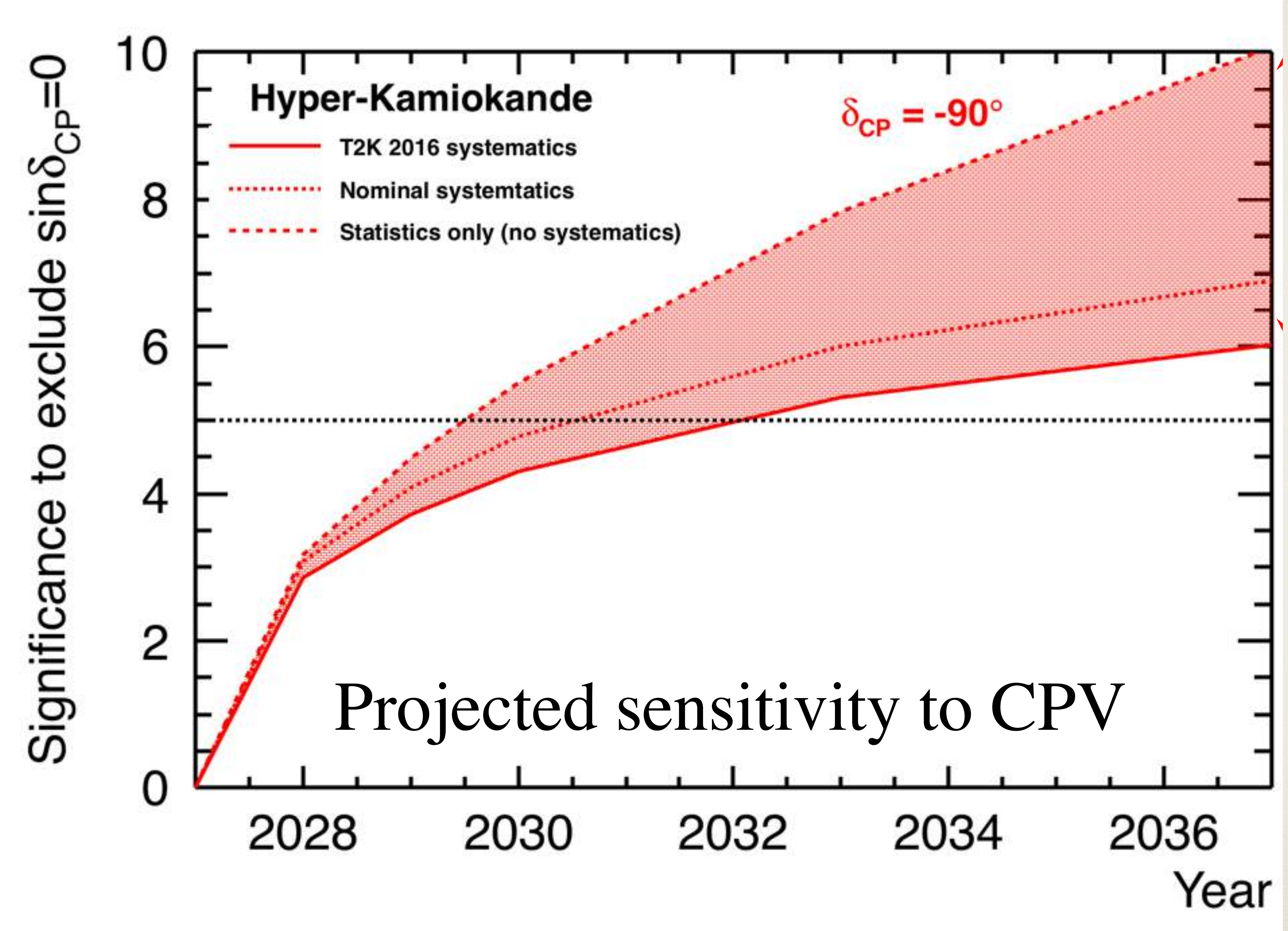
Sensitivity to CP Violation


Significance to CP violation

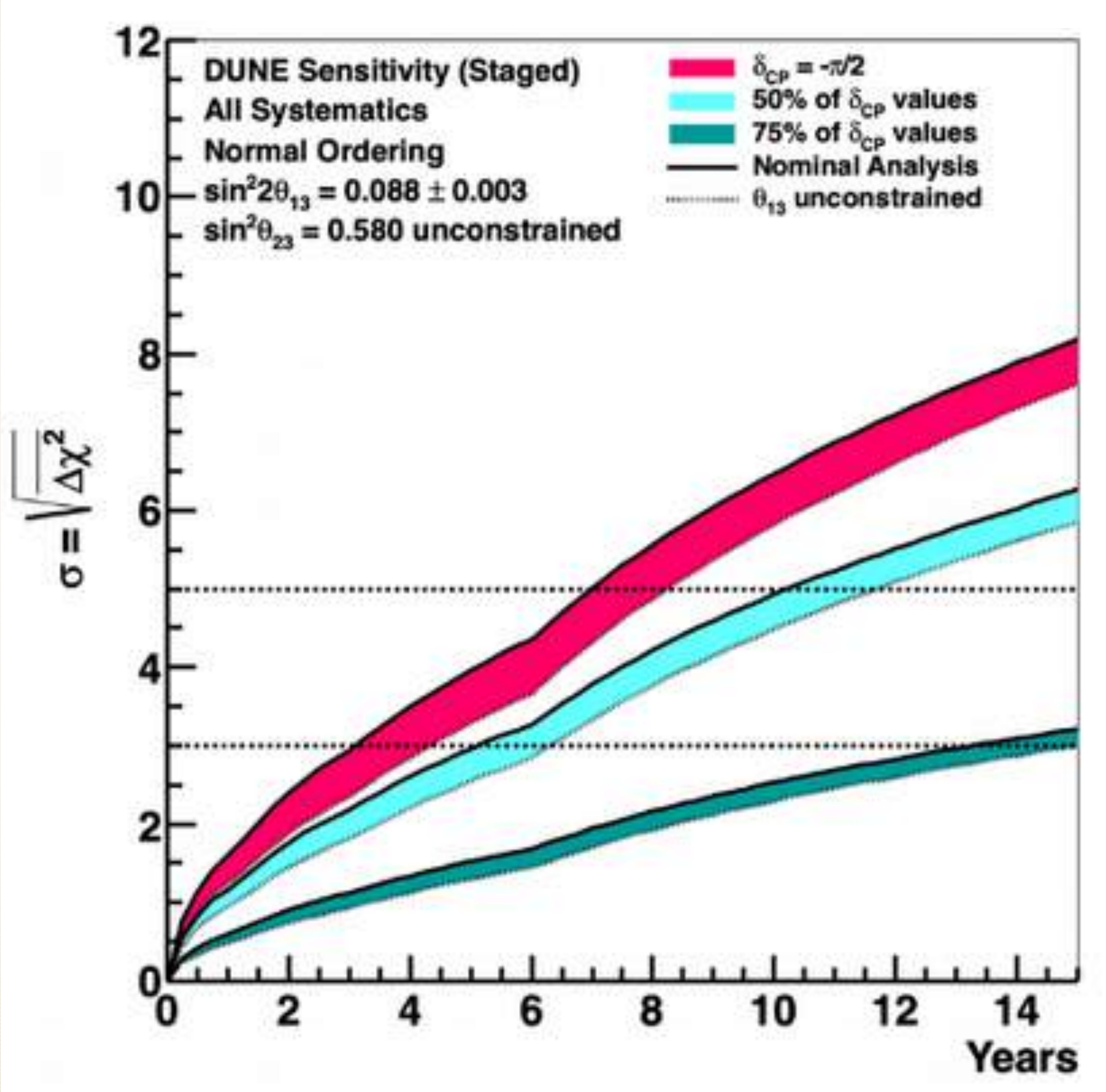




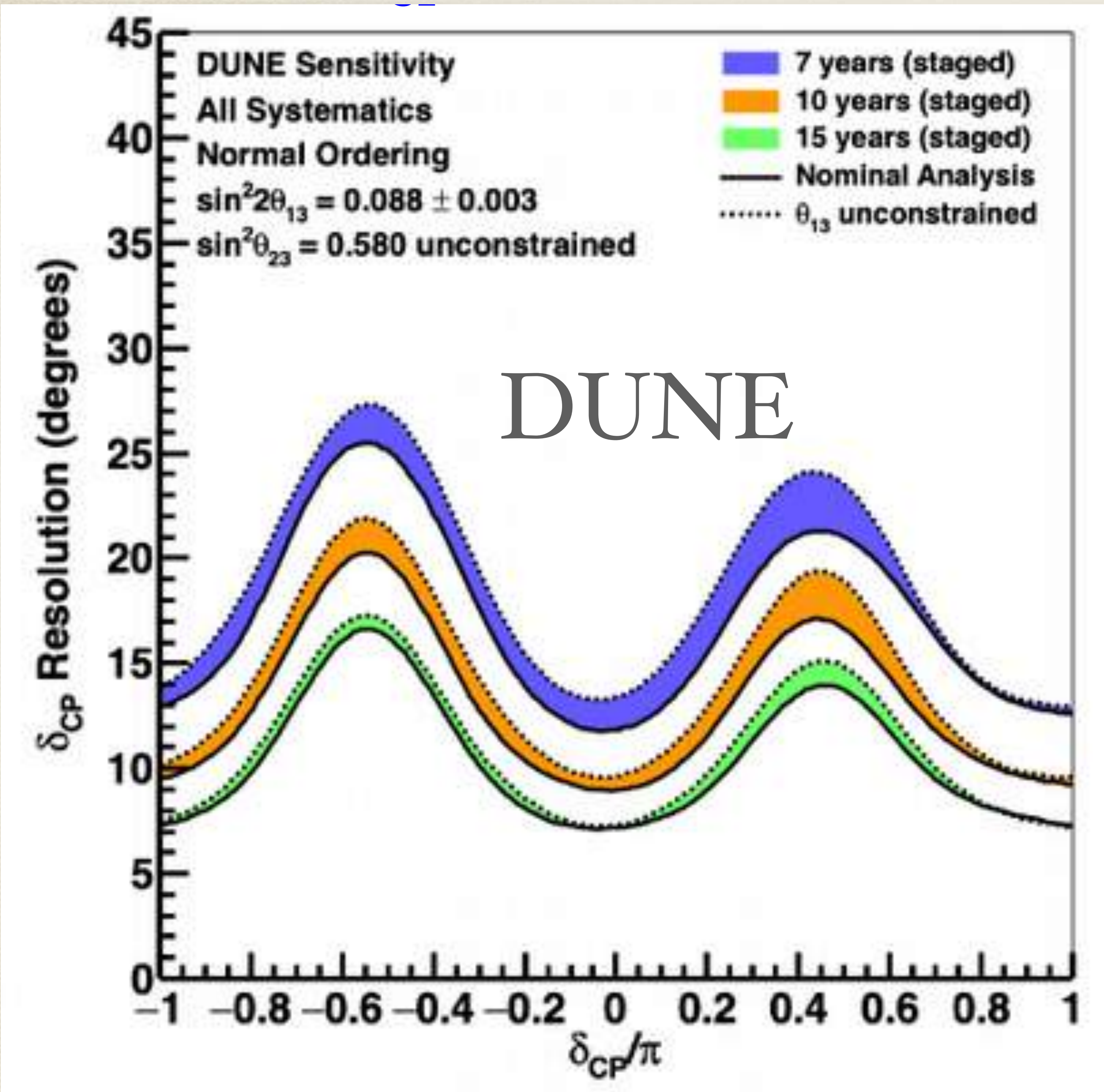
CP Violation - Challenges

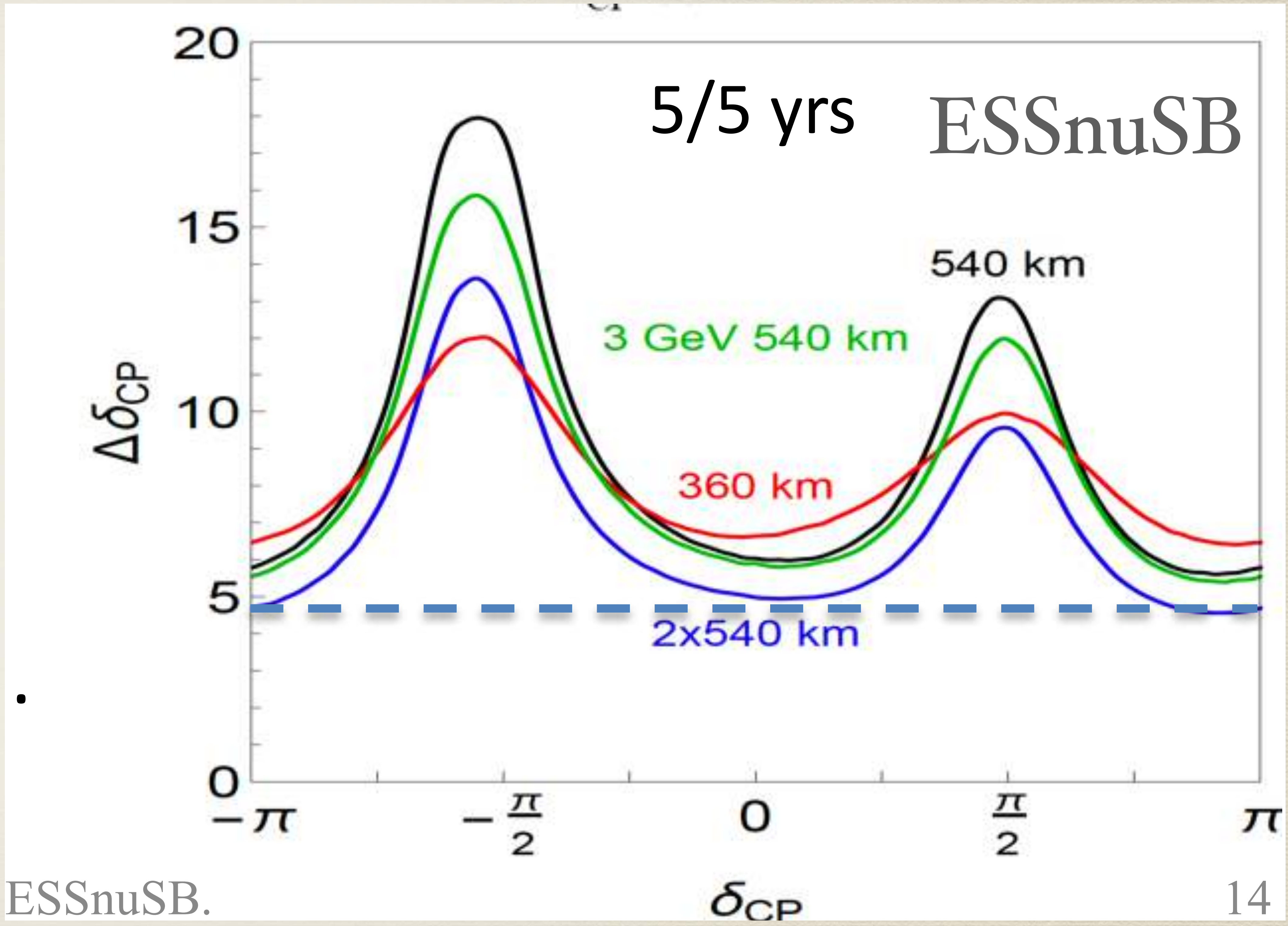


Projected sensitivity to CPV



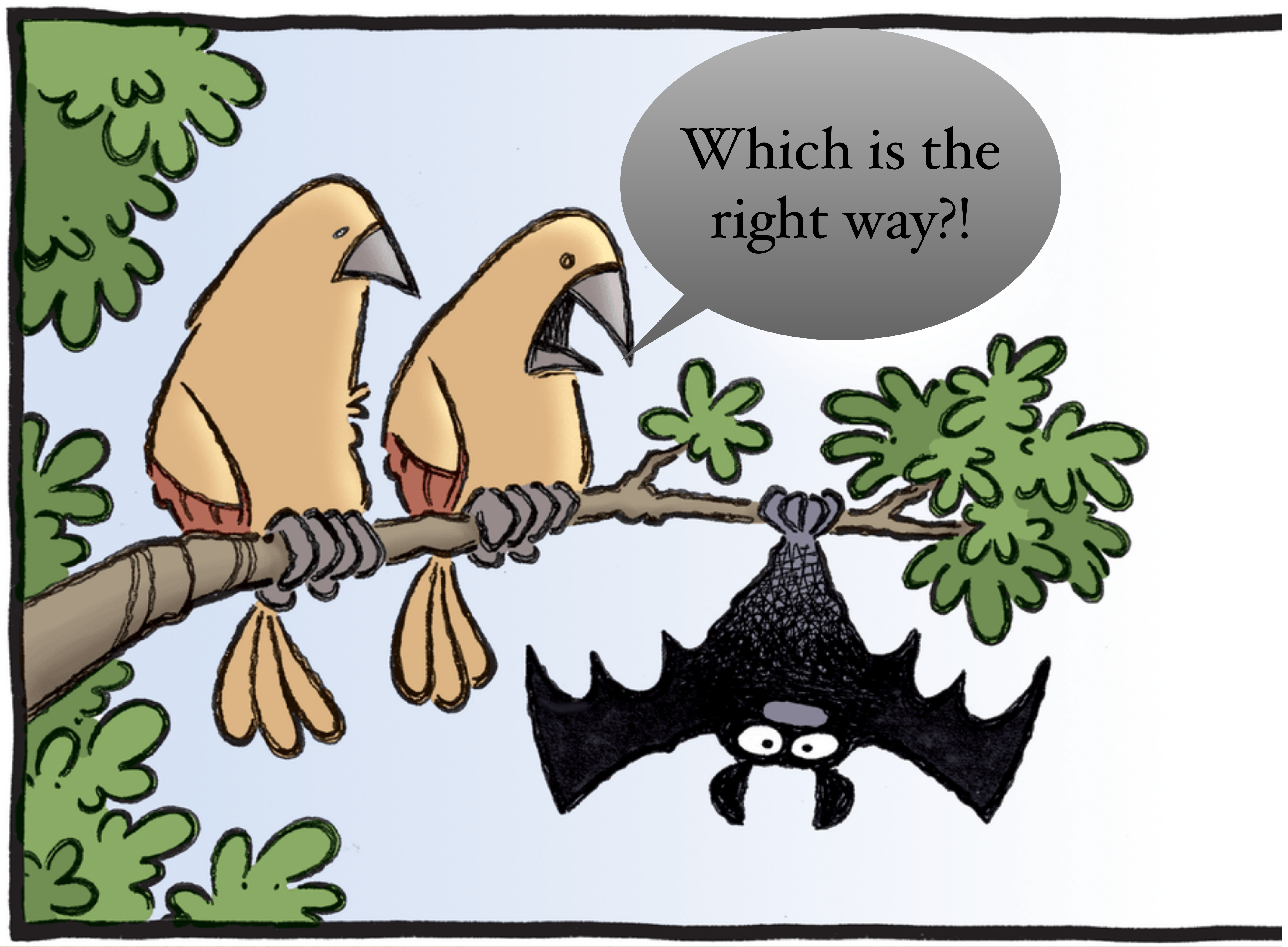
Measurement of the CP phase

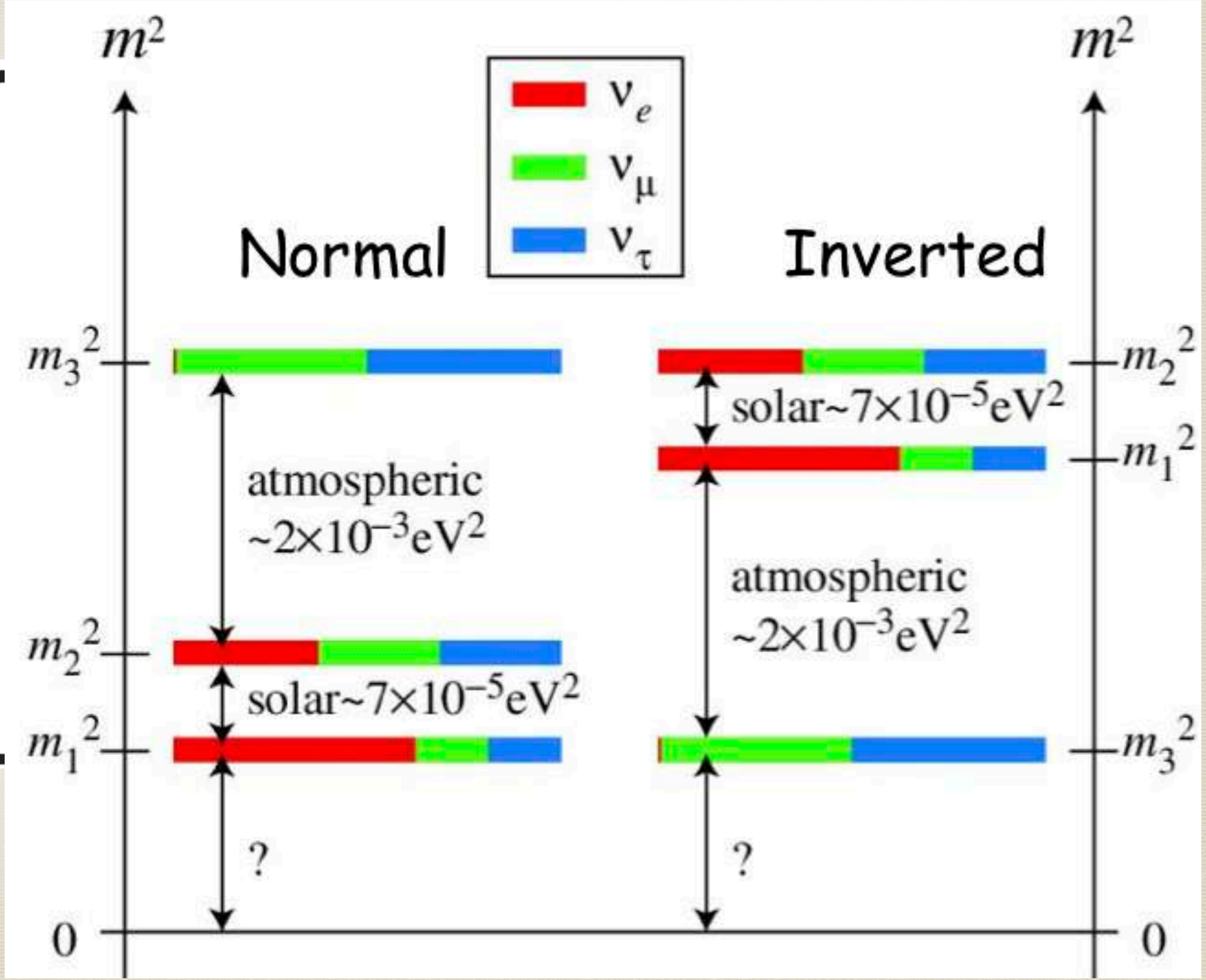




ESSnuSB.

Neutrino Mass Ordering





Sign of Δm^2_{21} is known

Sign of Δm^2_{31} is unknown

What depends on sign of Δm^2_{31}

- Neutrino oscillation probabilities could depend on the sign of Δm^2_{31}

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

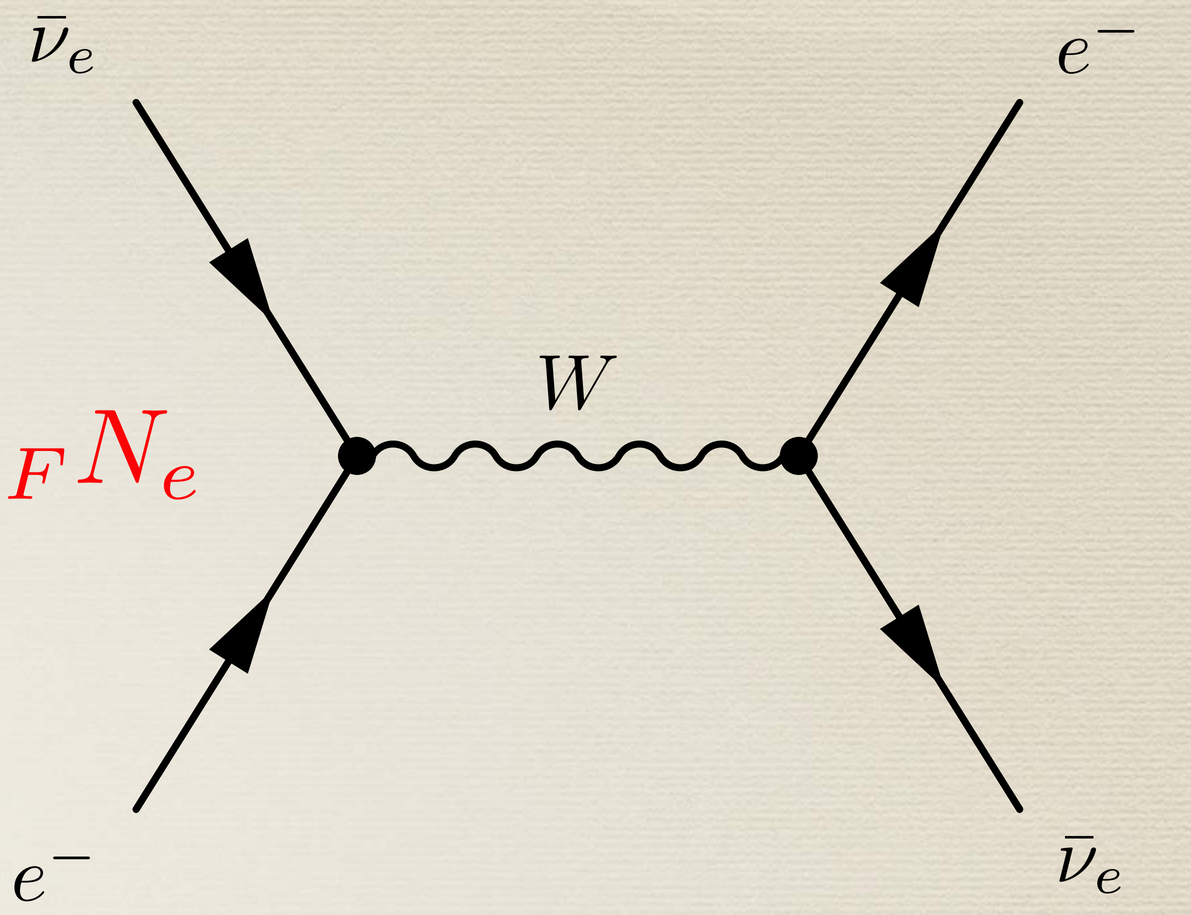
- However, this is not an effective way of determining the sign of Δm^2_{kj} due to the presence of "degeneracies"

Matter Effects

Forward scattering of ν_e and $\bar{\nu}_e$ with electrons in matter

Effective potential

$\sqrt{2}G_F N_e$



This effective potential modifies the neutrino mass and mixing in matter

$$(\Delta m^2)^m = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2)^2 \sin^2 2\theta}$$

$$\sin^2 2\theta_m = \frac{(\Delta m^2)^2 \sin^2 2\theta}{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2)^2 \sin^2 2\theta}$$

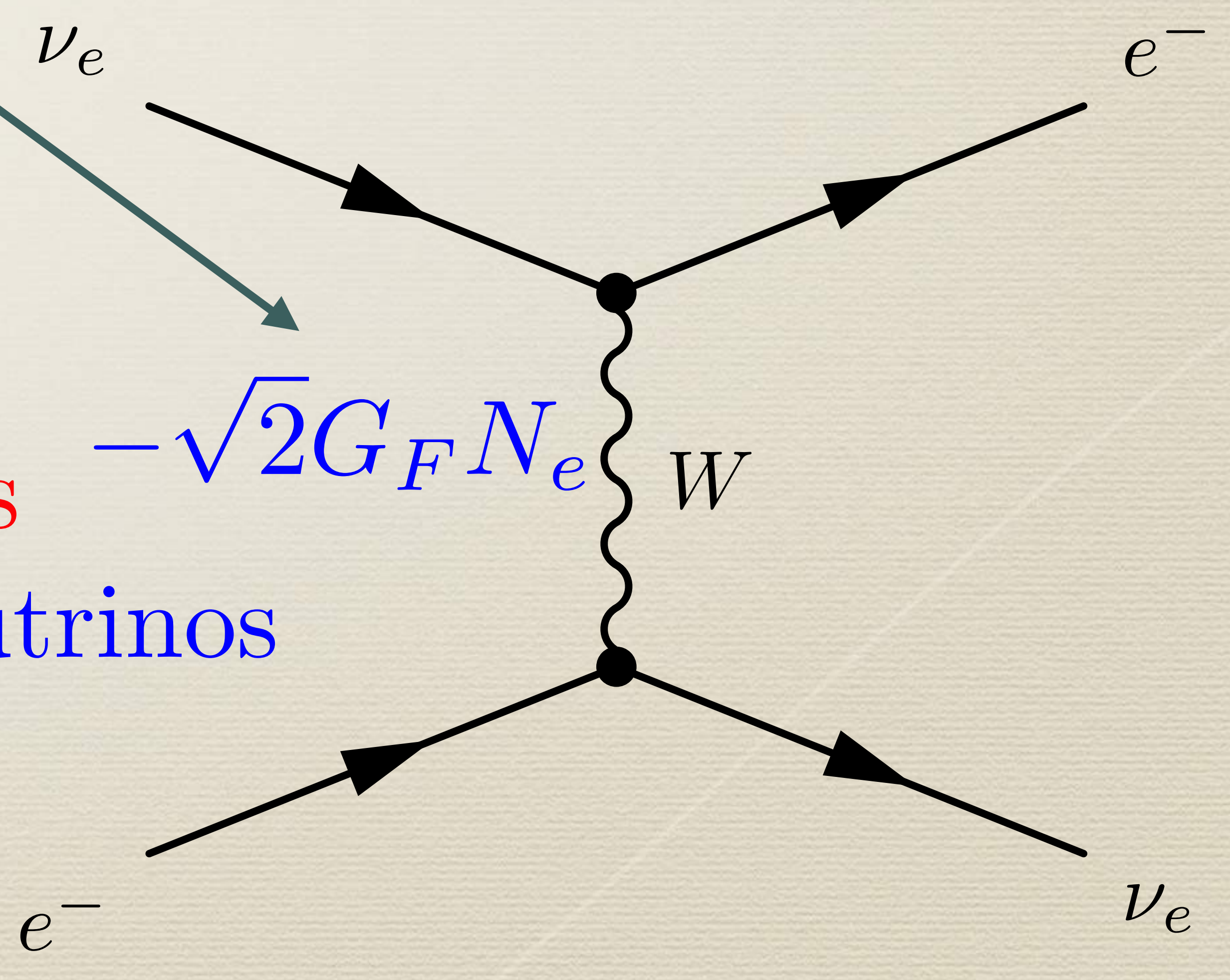
Relative sign

$A = 2E * (\text{effective potential})$

$A = 2\sqrt{2}G_F N_e E$ for neutrinos

$A = -2\sqrt{2}G_F N_e E$ for antineutrinos

$-\sqrt{2}G_F N_e$

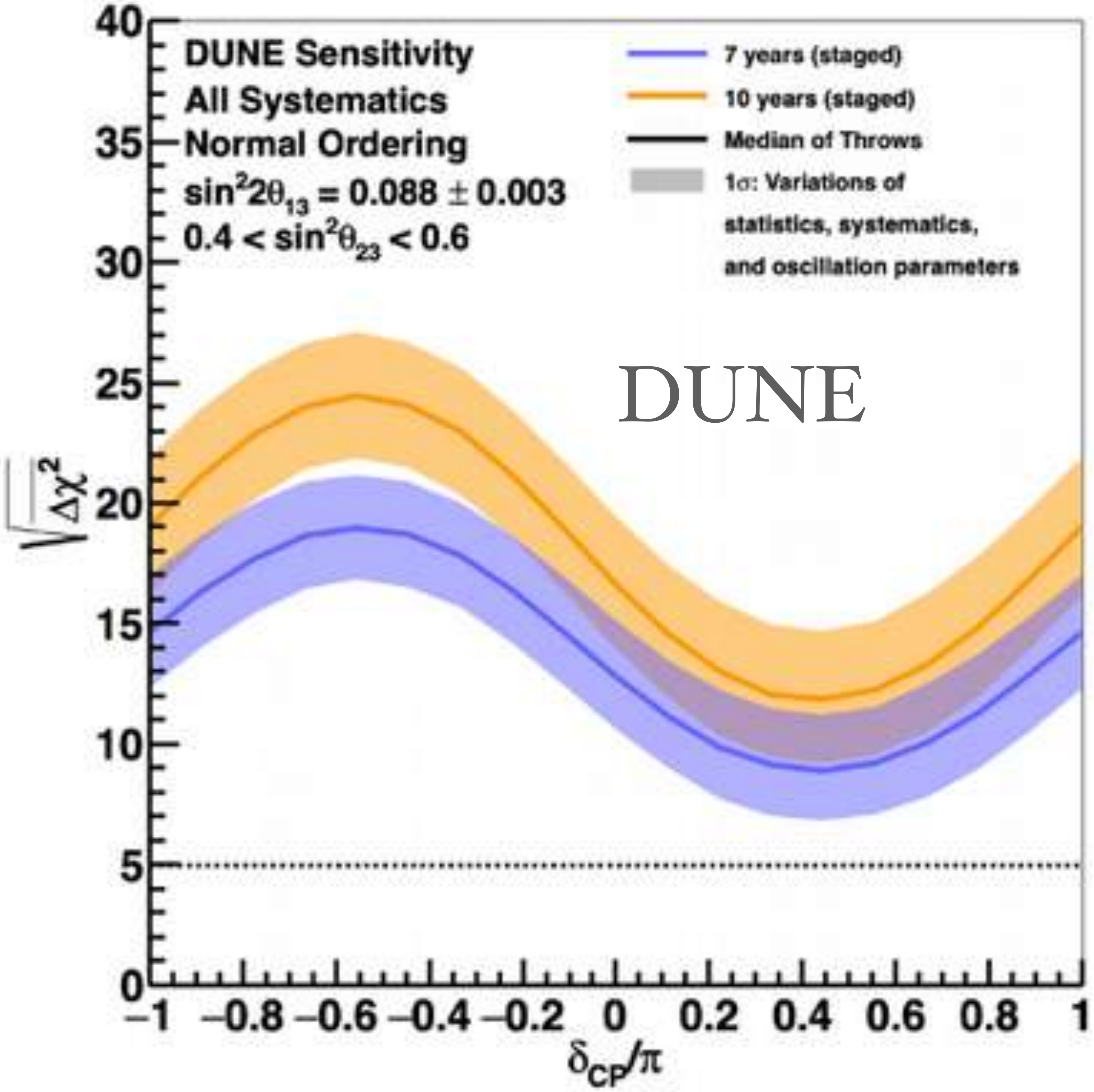


Normal ordering → matter effects for neutrinos

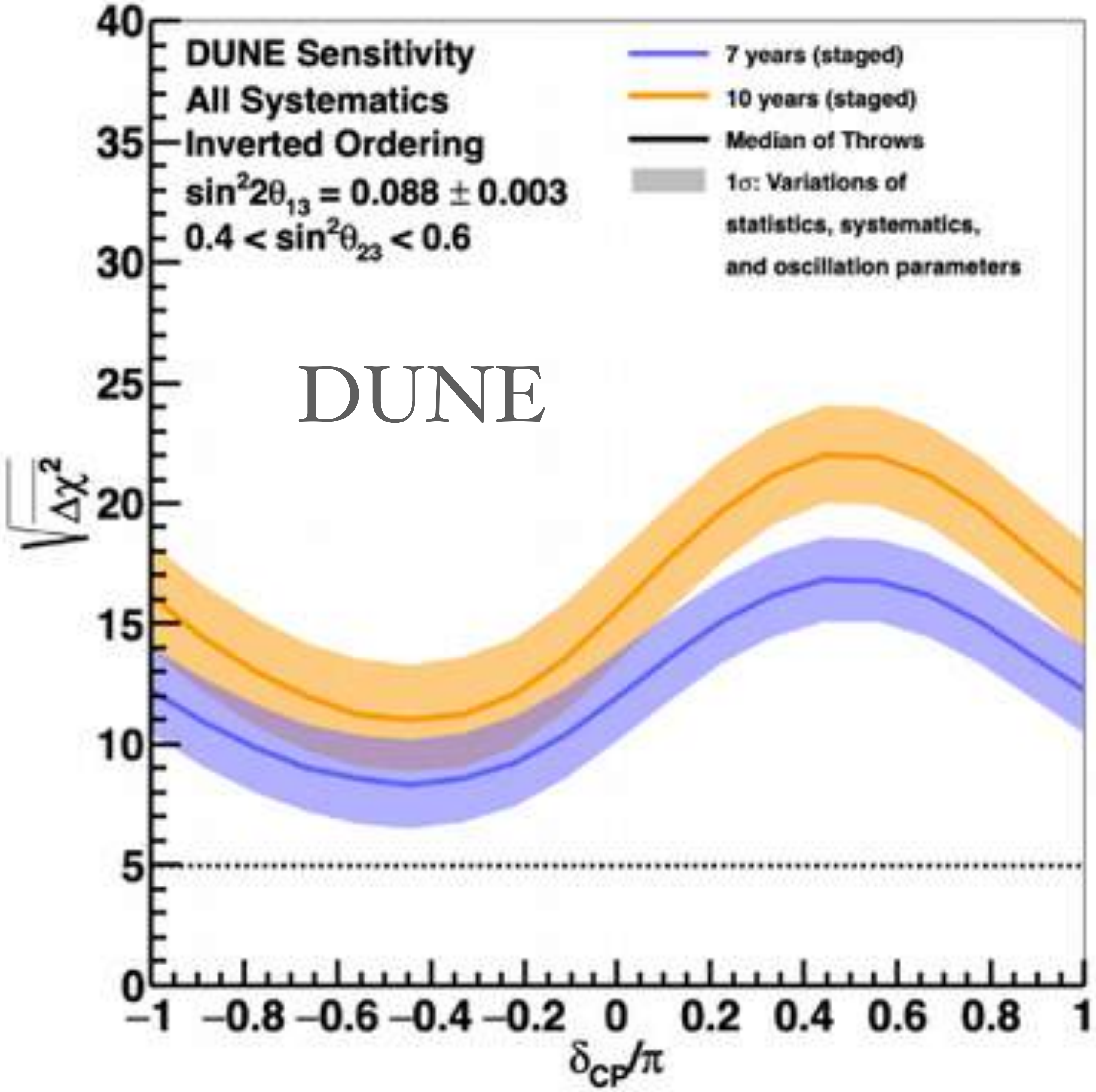
Inverted ordering → matter effects for antineutrinos

Neutrino Mass Ordering using Accelerator Beams

True Normal Ordering



True Inverted Ordering



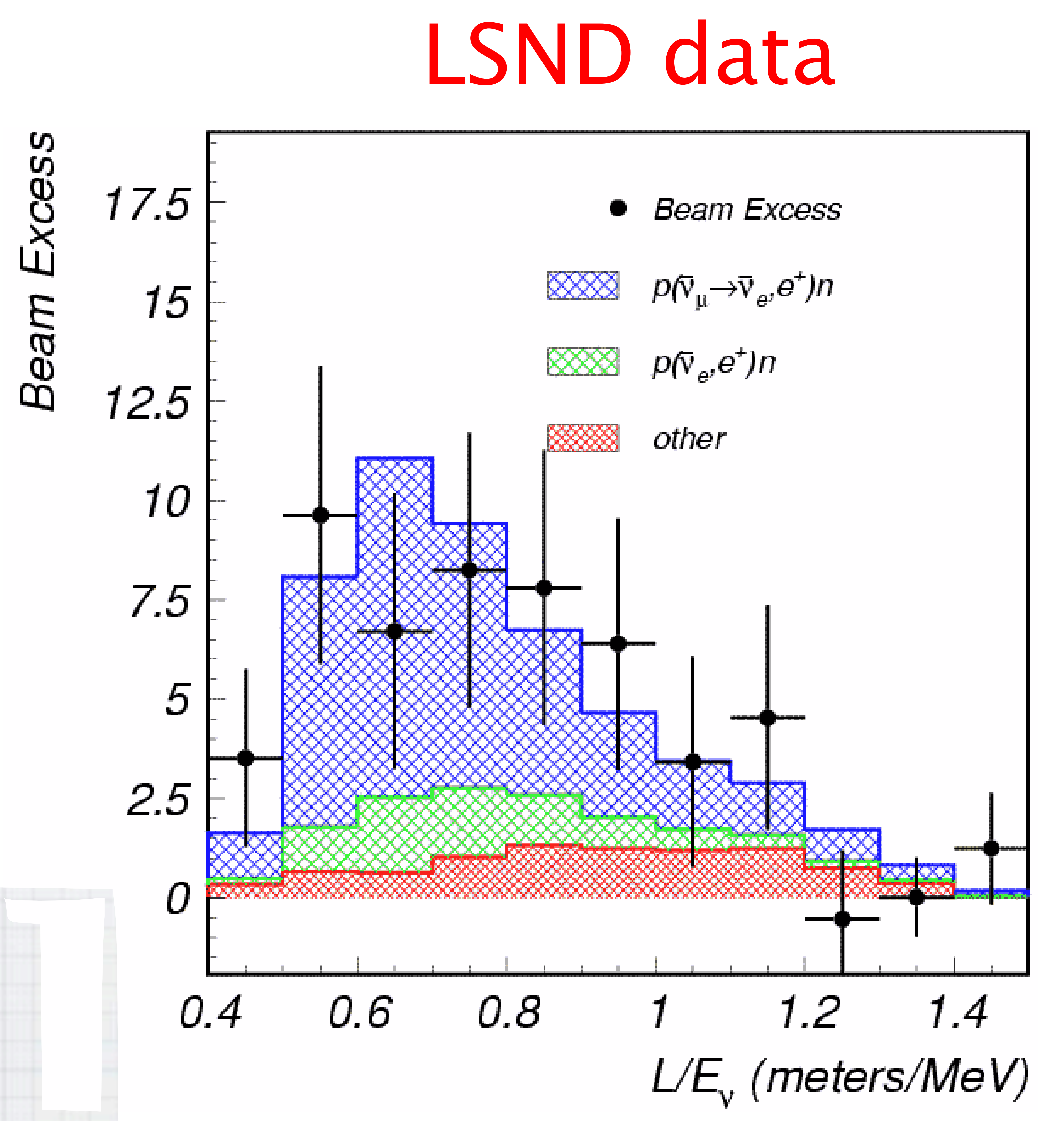
New Physics in Neutrino Oscillations

New Physics

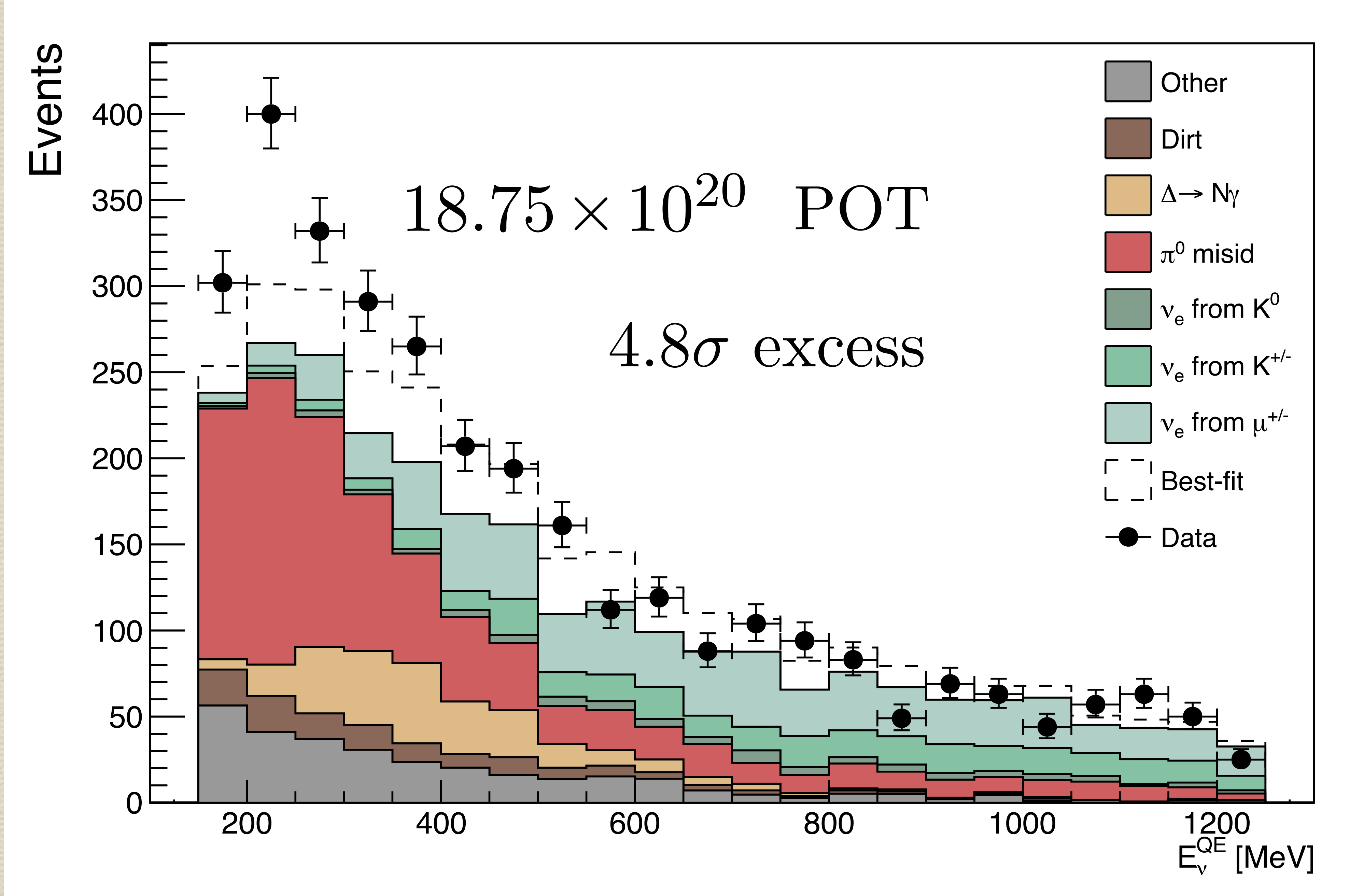
- Sterile neutrinos
- Non-standard neutrino interactions
- Neutrino decay
- Non-Unitarity
- Lorentz invariance violation
- ...
- .....

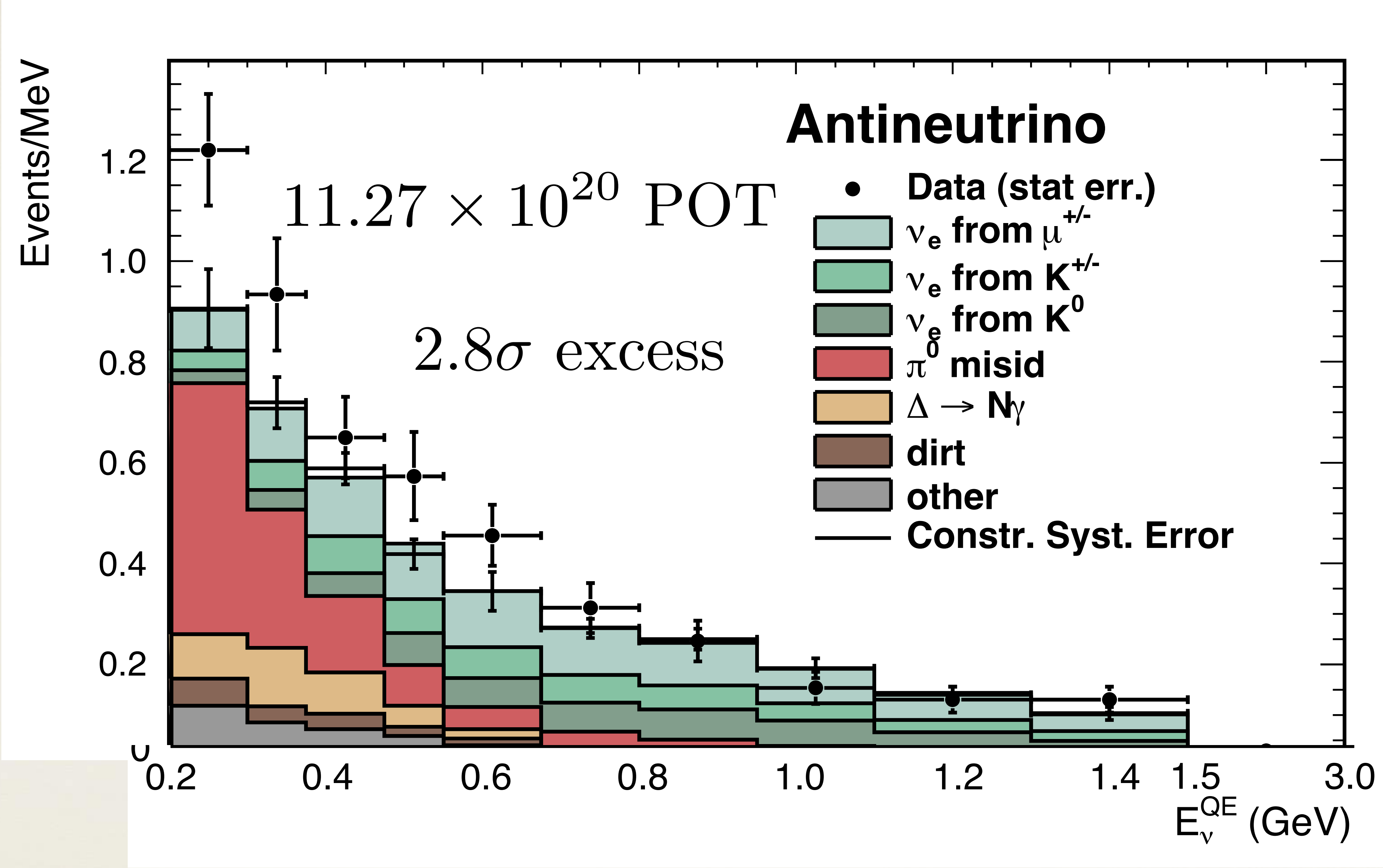
Sterile Neutrinos
LSND

- 3.8σ excess in antineutrinos at $L/E \approx 0.4$-1.2 m/MeV
- requires presence of sterile neutrino states with $\Delta m^2 = 1$ eV^2


LSND data

MiniBooNE

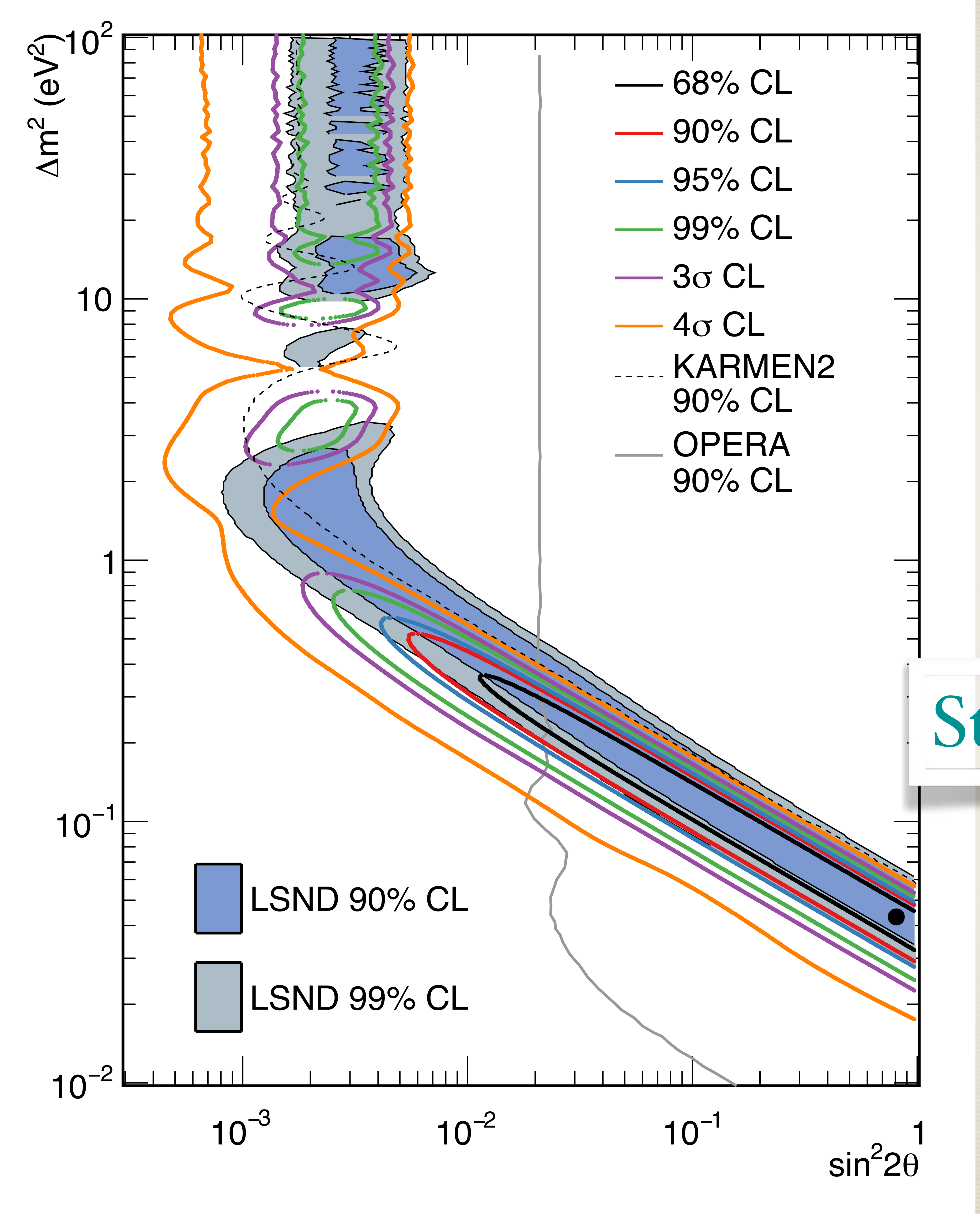


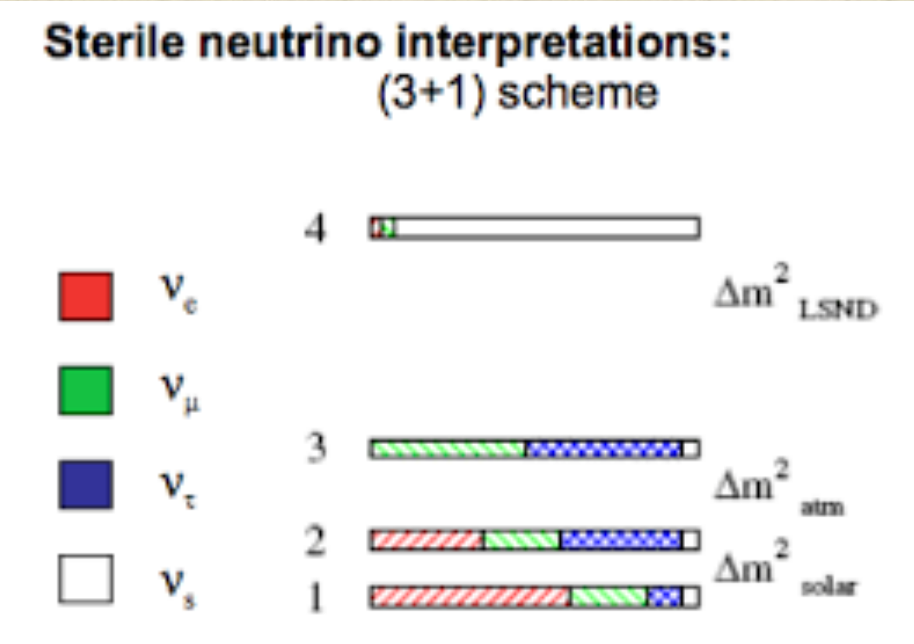


MiniBooNE is consistent with LSND

Combined with LSND this is a greater than 6 sigma excess

Sterile Neutrinos





Additional neutrino is needed

3+1scheme *S. Goswami (1995)*

3+2 scheme *Karagiorgi et al (2006)*

1+3+1 scheme *Choubey,Haries,Ross(2006)*

Sterile neutrinos are severely constrained in cosmology

Tension between LSND/MB and data from:

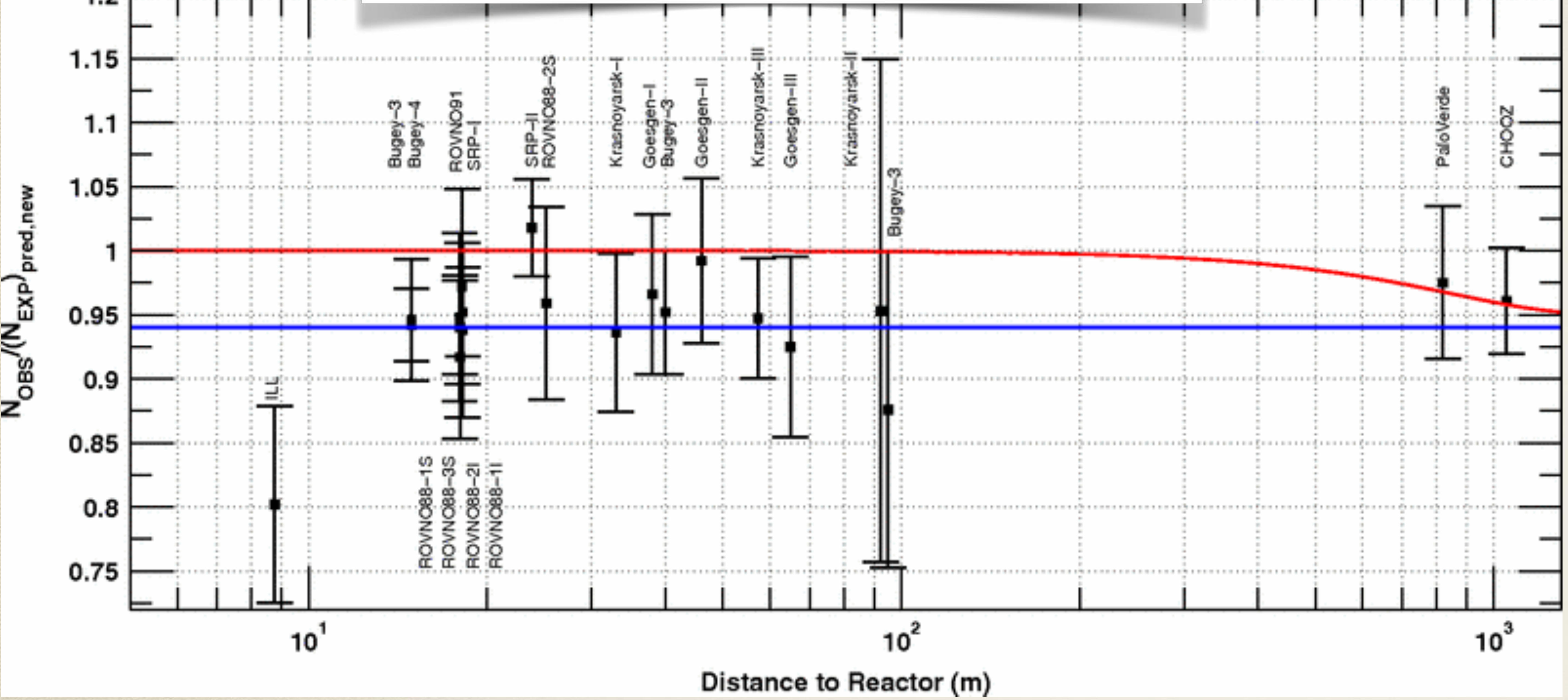
Karmen, NOMAD, E776, ICARUS, OPERA, MINOS, CDHS, NOvA, IceCube, SK, DeepCore

Short-Baseline Neutrino Program - FNAL,US

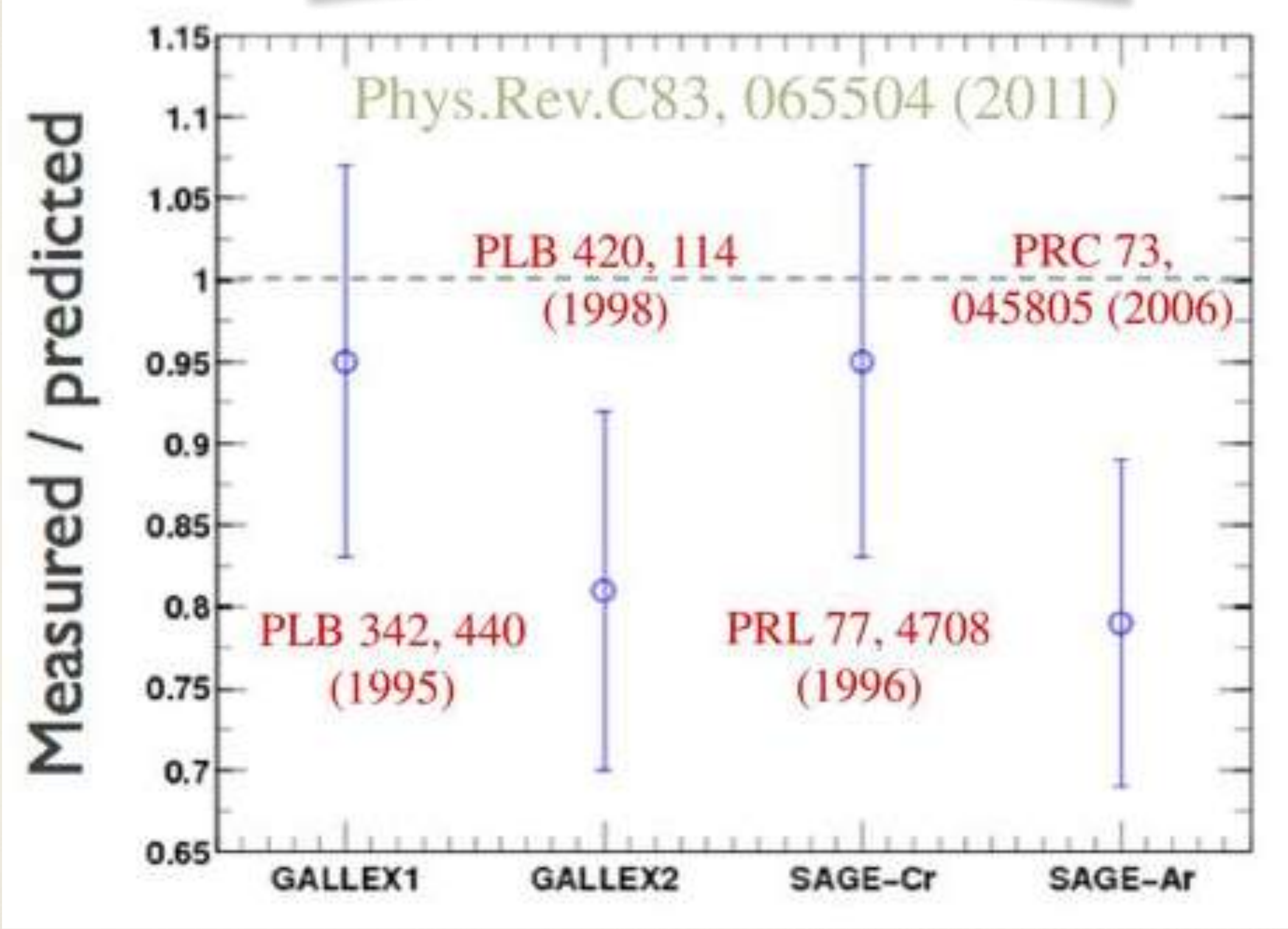
JSNS2 proposal at JPARC, Japan

Sterile Neutrinos

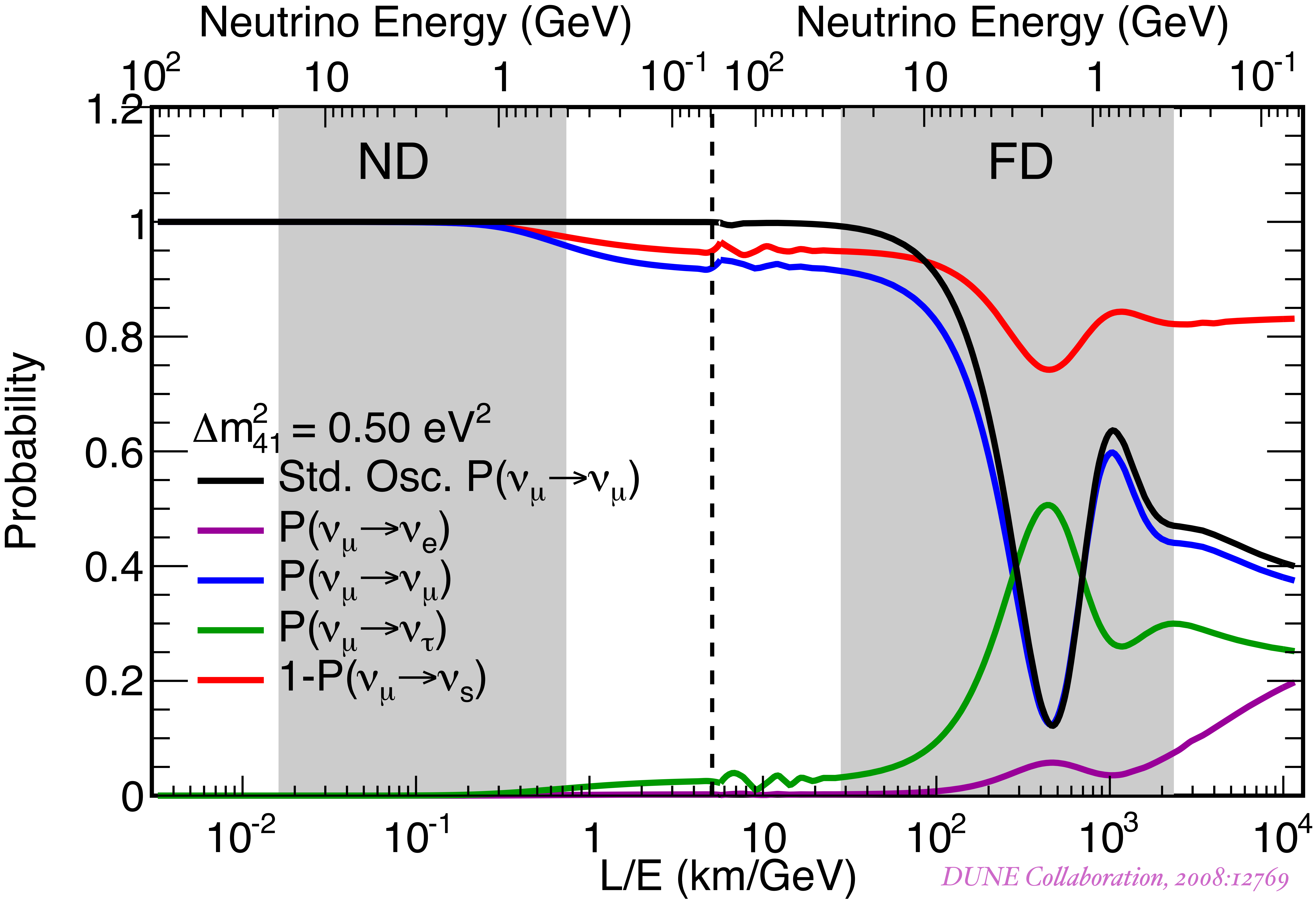
Reactor Flux Anomaly



Gallium Anomaly



DayaBay, NEOS, DANSS, Neutrino-4, Prospect, Stereo



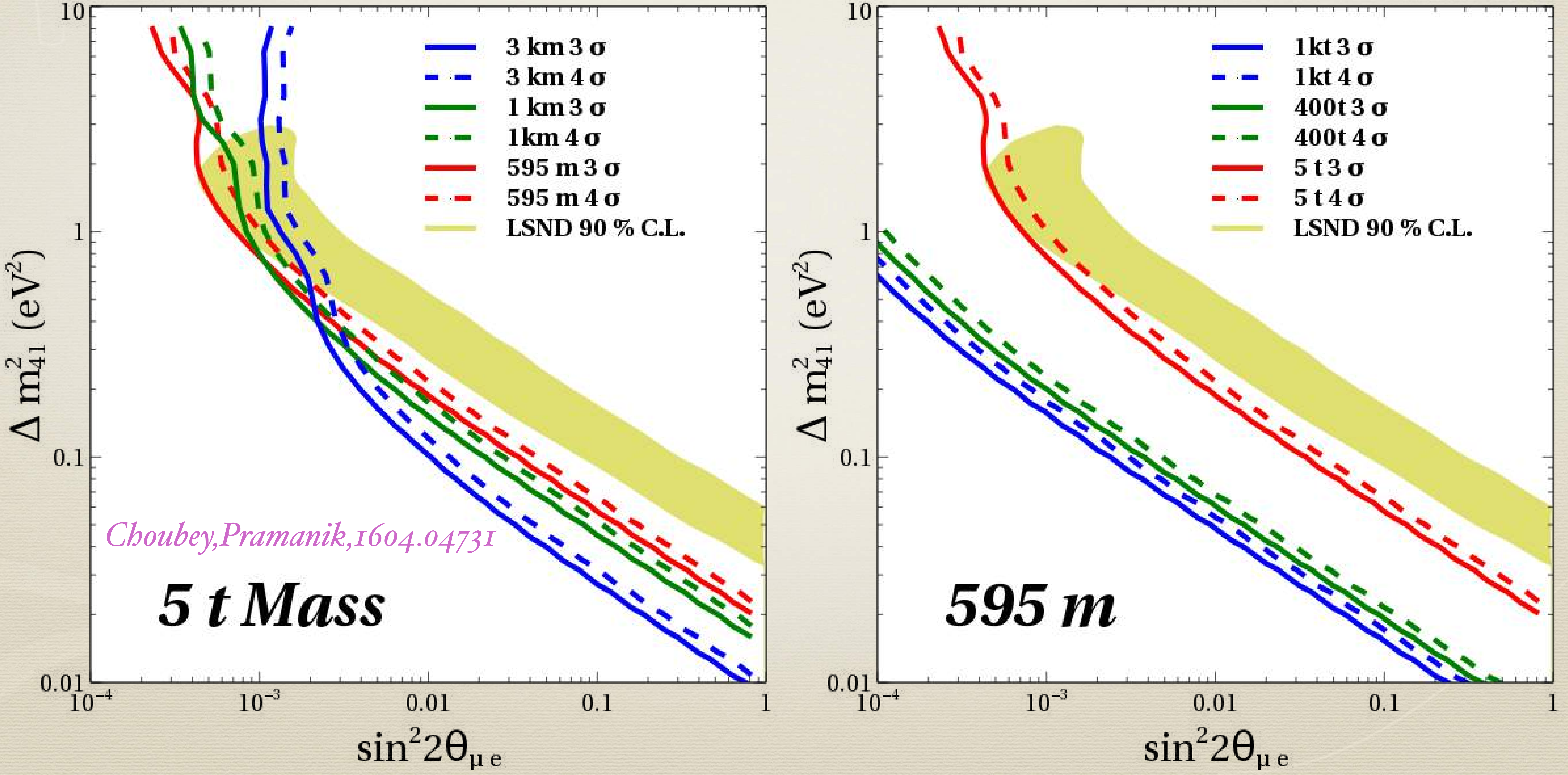
DUNE Collaboration, 2008:12769

Probing LSND with LBL Experiments

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{\mu e} \sin^2(\frac{\Delta m^2 L}{4E})$$

DUNE Near Detector

See Blennow,Coloma,Fernandez-Martinez,1407.1317 for ESSnuSB



Choubey,Pramanik,1604.04731

Neutrino Oscillations in 3+1 At Long Baseline

$$P_{\mu e}^{4\nu} = P_1 + P_2(\delta_{13}) + P_3(\delta_{24}) + P_4(\delta_{13}+\delta_{24})$$

$$\begin{aligned}
P_1 \;&=\; \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} \\
&+\; \Big(a^2\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu}\Big)\big(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\big) \\
&+\; \Big(b^2a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu}\Big)\sin^2\Delta_{21}\,,
\end{aligned}$$

$$\begin{aligned}
P_2(\delta_{13}) \;&=\; ba^2\sin 2\theta_{\mu e}^{3\nu}\Big[\cos(\delta_{13})\big(\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\big) \\
&\quad -\; \frac{1}{2}\sin(\delta_{13})\big(\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\big)\Big]\,,
\end{aligned}$$

$$\begin{aligned}
P_3(\delta_{24}) \;&=\; ba\sin 2\theta_{\mu e}^{4\nu}\Big[\cos(\delta_{24})\big(\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\big) \\
&\quad +\; \frac{1}{2}\sin(\delta_{24})\big(\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\big)\Big]\,,
\end{aligned}$$

$$\begin{aligned}
P_4(\delta_{13}+\delta_{24}) \;&=\; a\sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[\cos(\delta_{13}+\delta_{24})\Big(-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} \\
&\quad +\; \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\Big) \\
&\quad +\; \frac{1}{2}\sin(\delta_{13}+\delta_{24})\big(\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\big)\Big]\,,
\end{aligned}$$

$$\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$$

$$b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$$

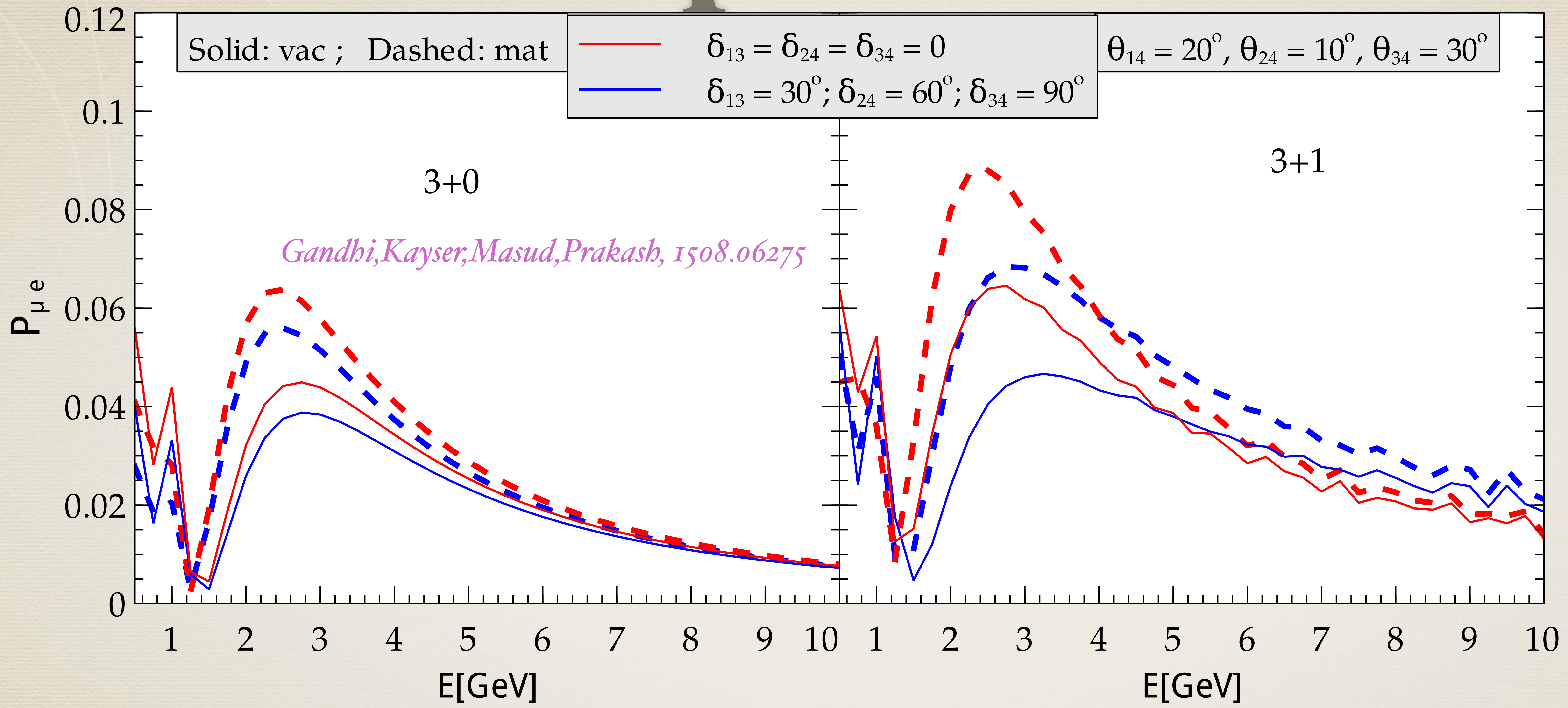
$$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$$

$$a = \cos\theta_{14}\cos\theta_{24}.$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Additional CP Violation

Probing LSND with LBL Experiments

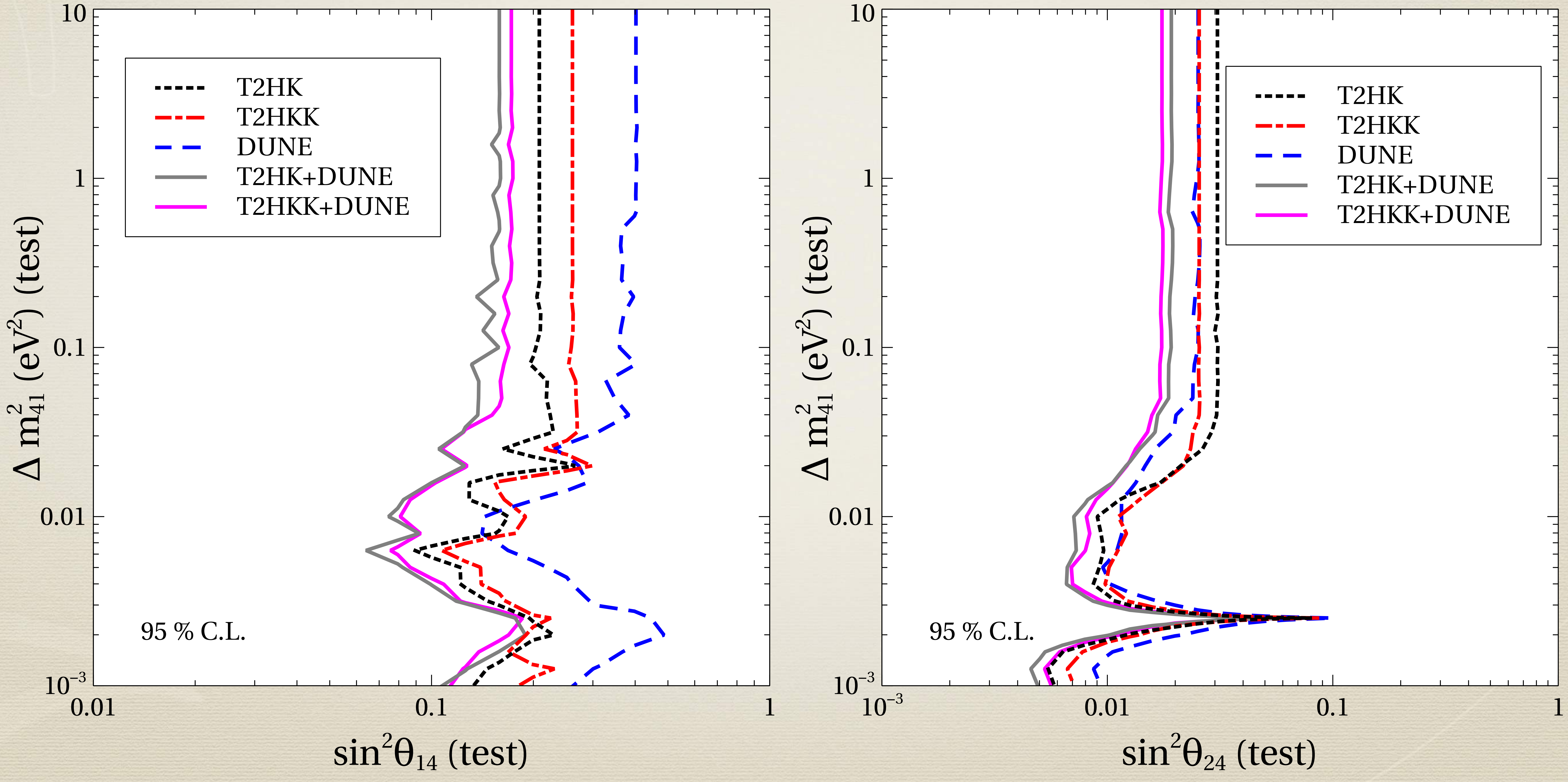


Neutrino oscillation probabilities differ for 3+0 and 3+1 schemes even for the far detector of the long-baseline experiments

Very rich body of literature

This dependence has phenomenological implications such as:

Measuring sterile neutrino paramaters at the LBL expts



Choubey,Dutta,Pramanik, 1711.07464

This dependence has phenomenological implications such as:

Modifying the sensitivity of the experiment to standard oscillation params

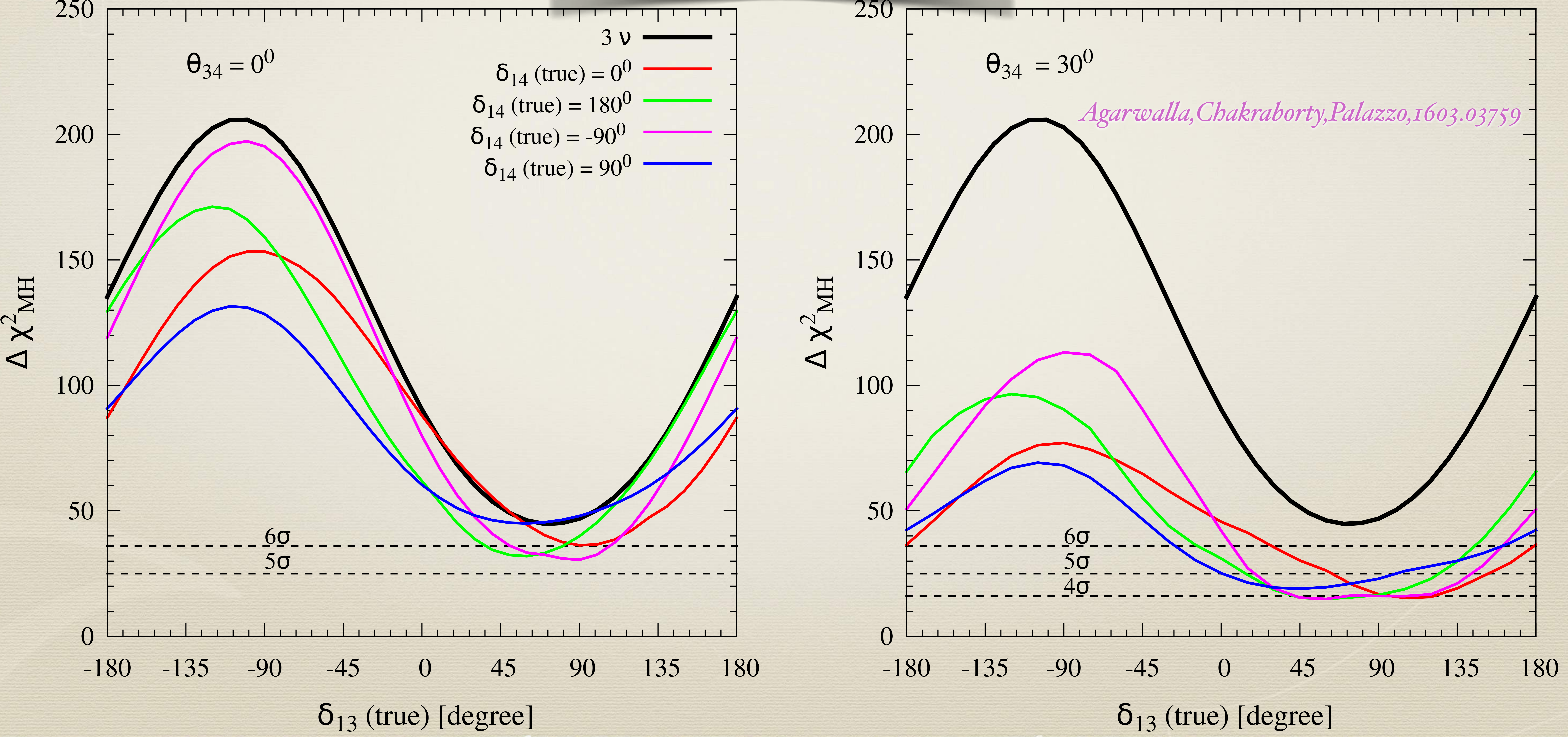
CP Violation

Choubey,Dutta,Pramanik, 1704.07269

This dependence has phenomenological implications such as:

Modifying the sensitivity of the experiment to standard oscillation params

Mass Hierarchy

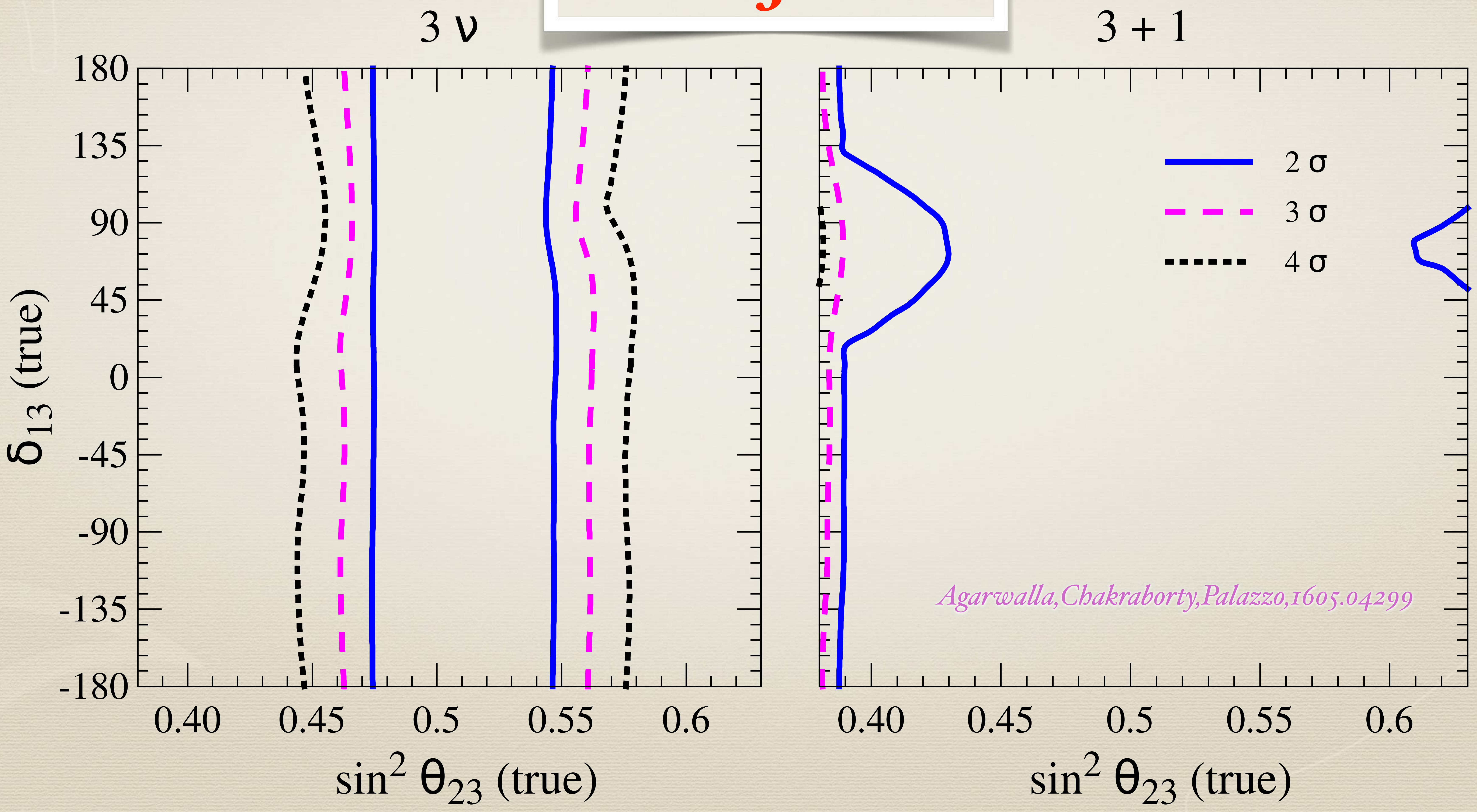


Agarwalla,Chakraborty,Palazzo,1603.03759

This dependence has phenomenological implications such as:

Modifying the sensitivity of the experiment to standard oscillation params

Theta23 Octant

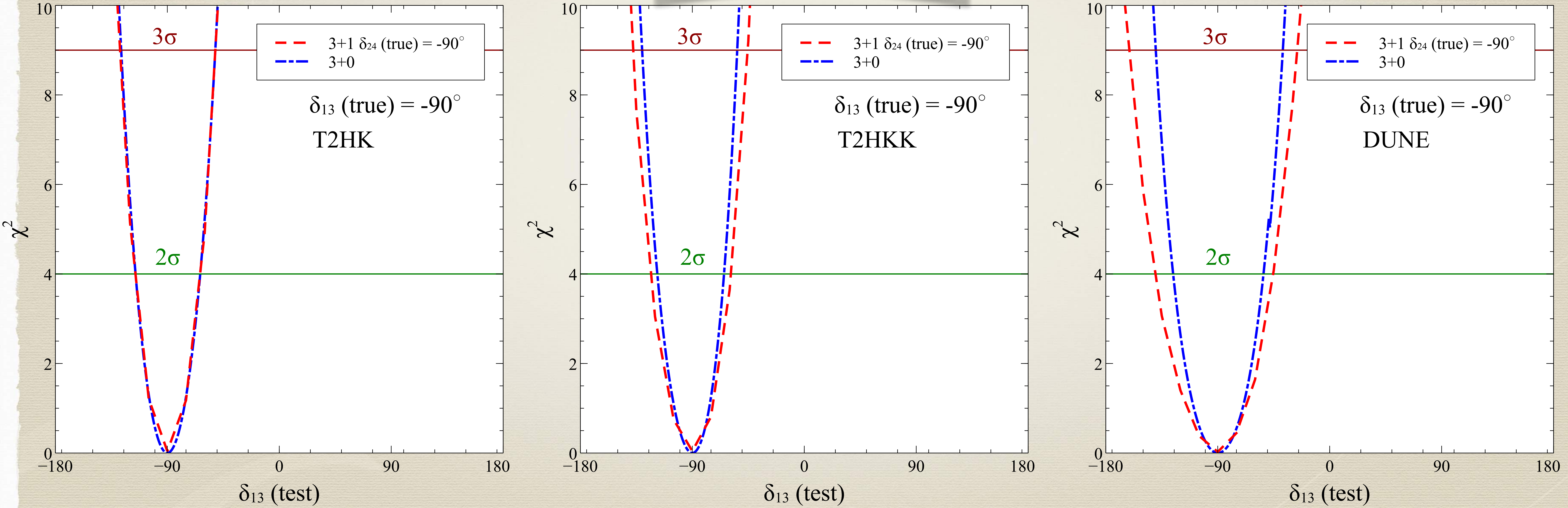


Agarwalla,Chakraborty,Palazzo,1605.04299

This dependence has phenomenological implications such as:

Affecting the measurement of CP phase δ_{13}

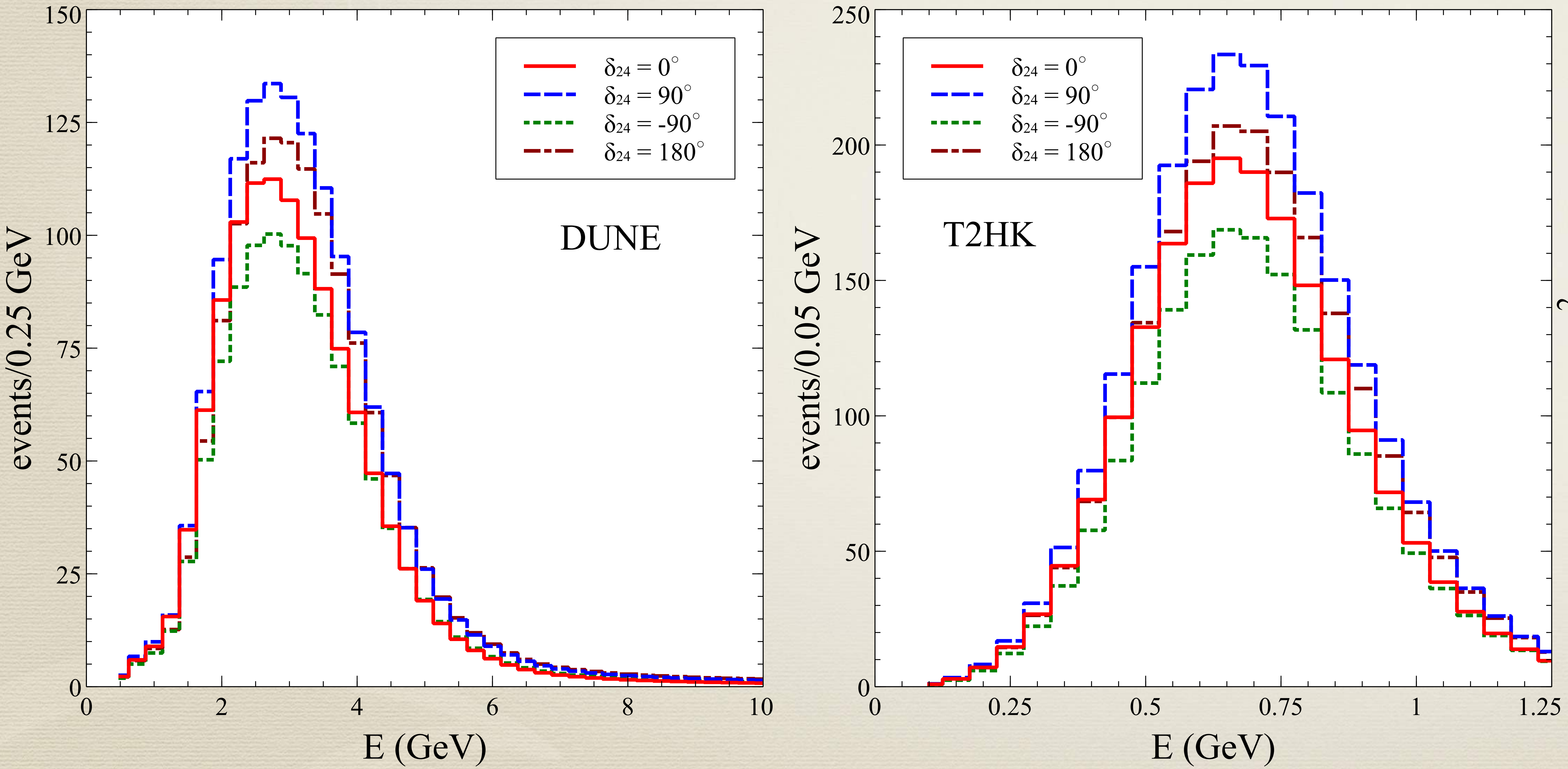
δ_{13} Precision

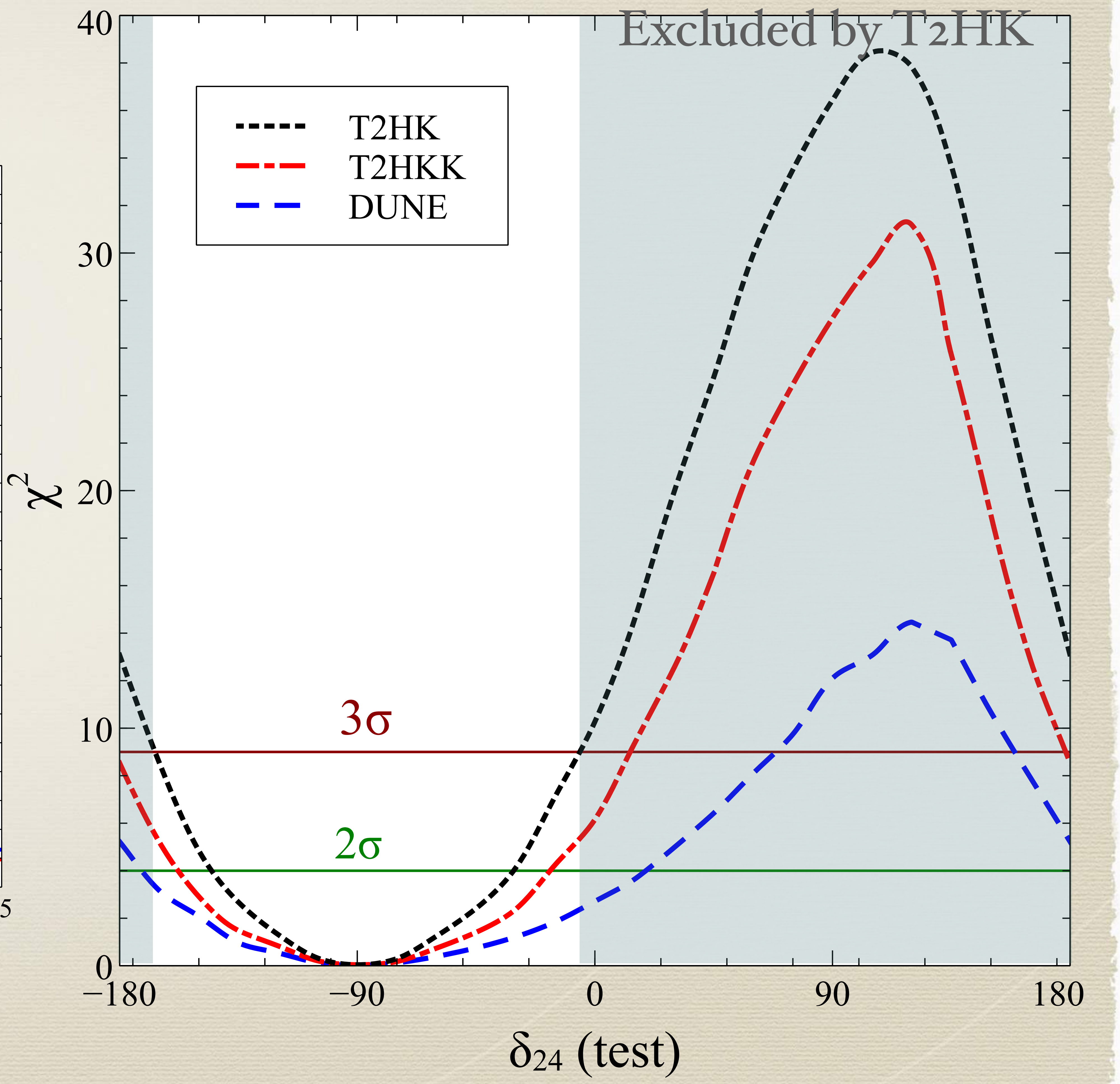


Choubey,Dutta,Pramanik, 1711.07464

This dependence has phenomenological implications such as:

Measuring the sterile CP phase





Choubey,Dutta,Pramanik, 1711.07464

Non-Standard Interactions

If there exist effective operators of the form

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'C}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

then they will modify neutrino evolution inside matter

$$\hat{H} = \frac{1}{2E}\left[U\mathrm{diag}(m_1^2, m_2^2, m_3^2)U^\dagger + \mathrm{diag}(A, 0, 0) + A\varepsilon^m\right]$$

These epsilon parameters are called matter NSIs

The corresponding epsilon parameters in an effective charged current operator are called source/detector NSIs

Long-Range Force

Impact of Matter NSIs

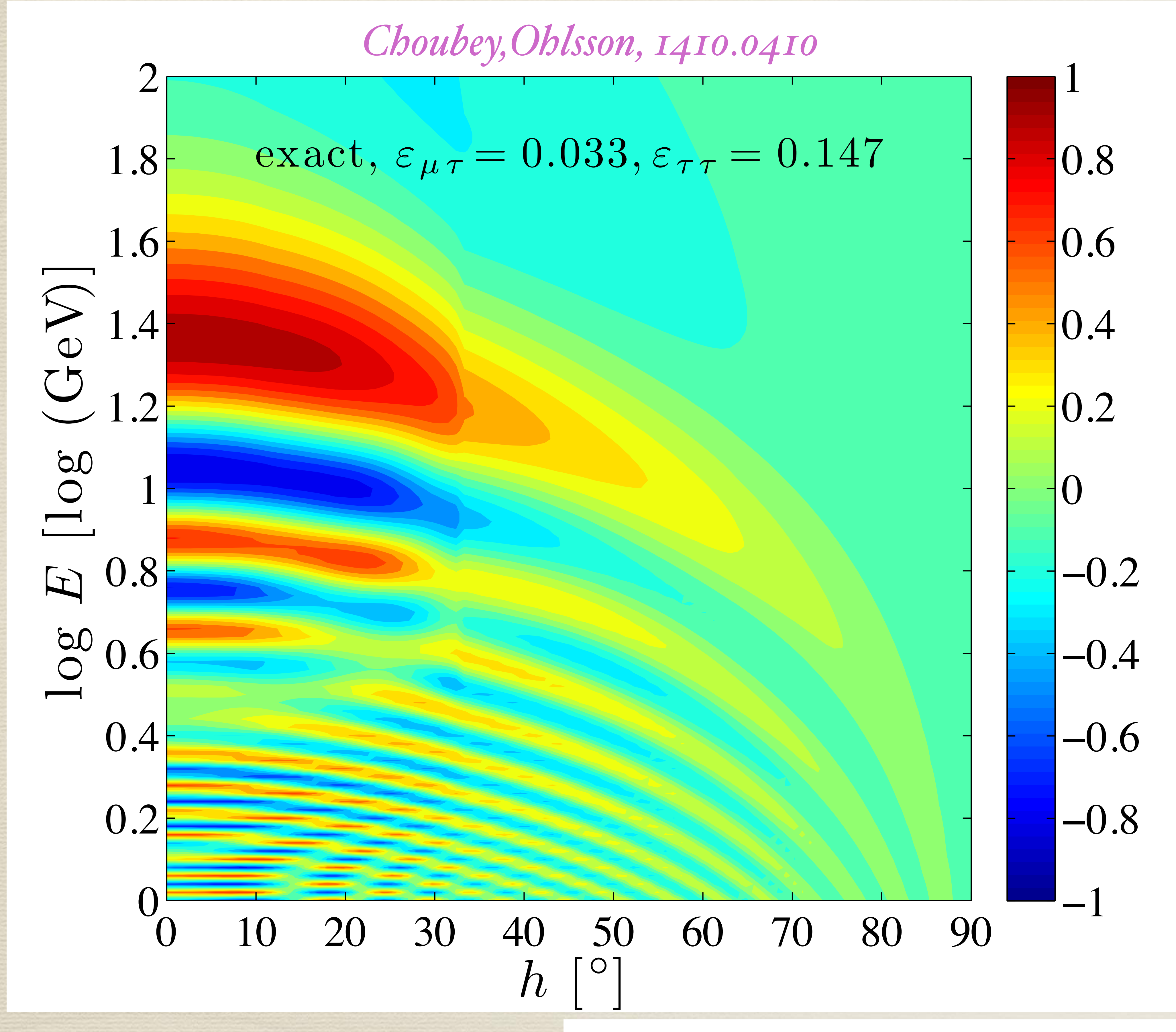
$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \frac{1}{2E}\left\{U^\dagger\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{bmatrix}U + A\begin{bmatrix}1+\varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m\\ \varepsilon_{\mu e}^m & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m\\ \varepsilon_{\tau e}^m & \varepsilon_{\tau\mu}^m & \varepsilon_{\tau\tau}^m\end{bmatrix}\right\}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

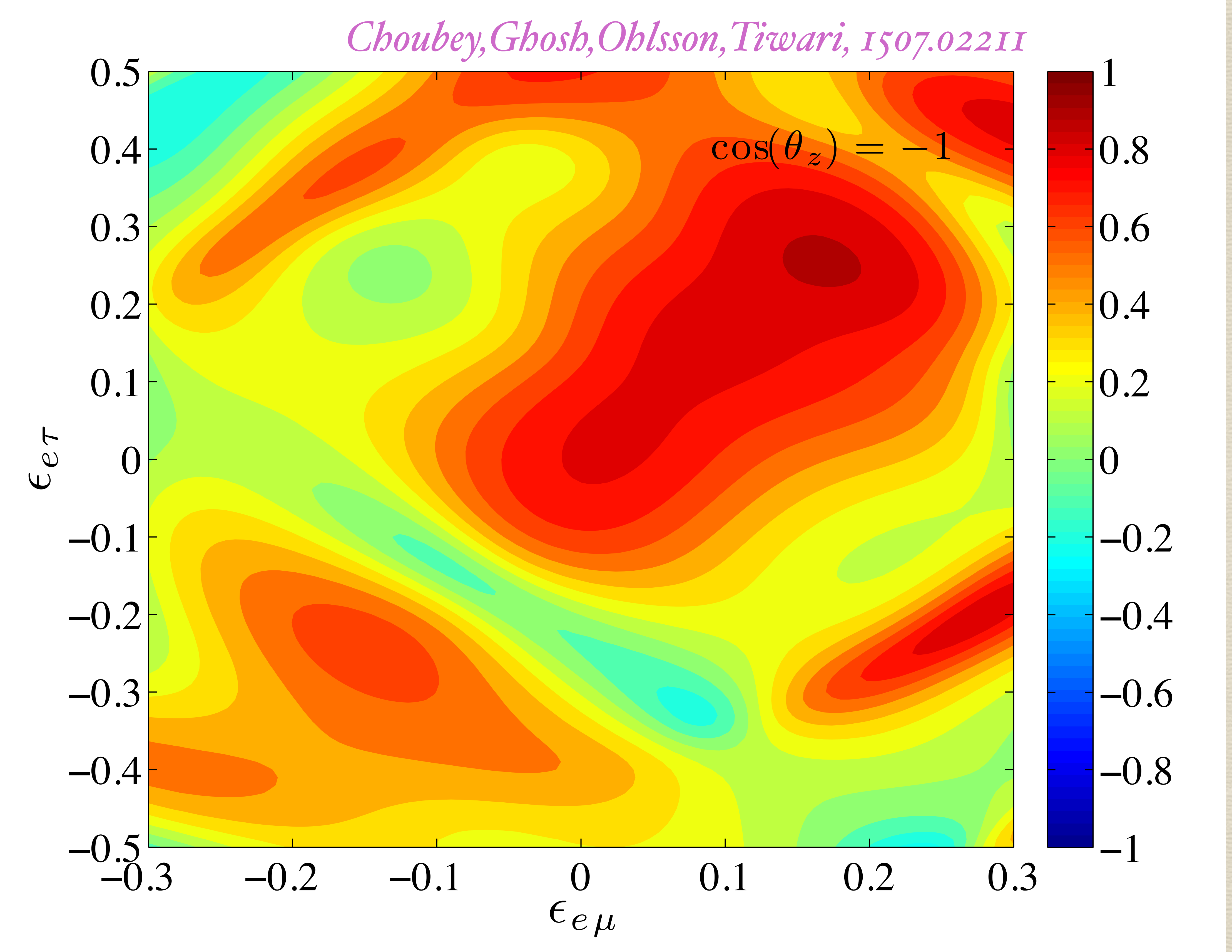
$$|\varepsilon_{\alpha\beta}^m| < \begin{bmatrix}4.2 & 0.3 & 3.0\\ 0.3 & - & 0.04\\ 3.0 & 0.04 & 0.15\end{bmatrix}$$

Biggio, blennow,Fernandez-Martinez, 0907.0097

Additional Matter Effect

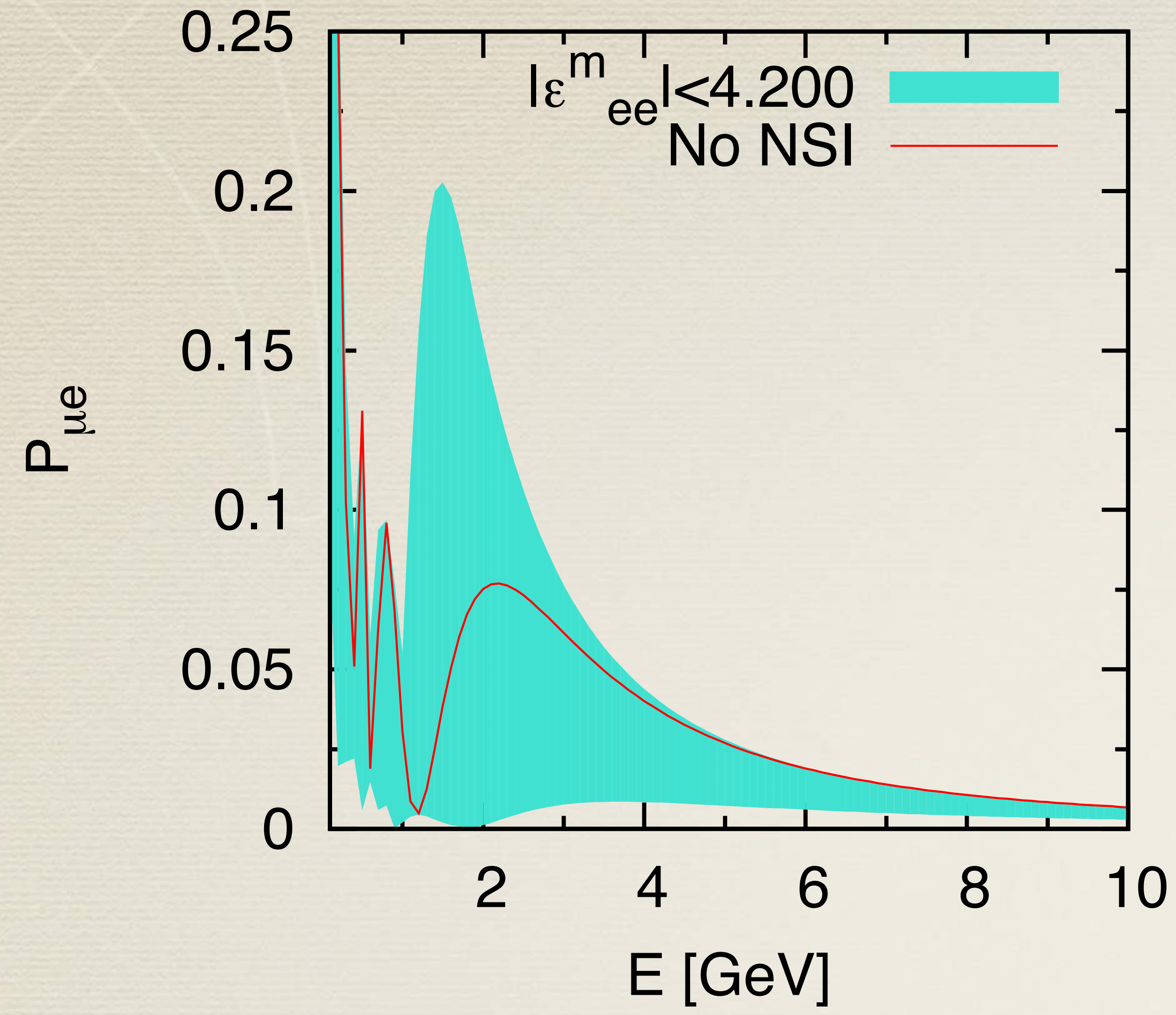
Impact of Matter NSIs

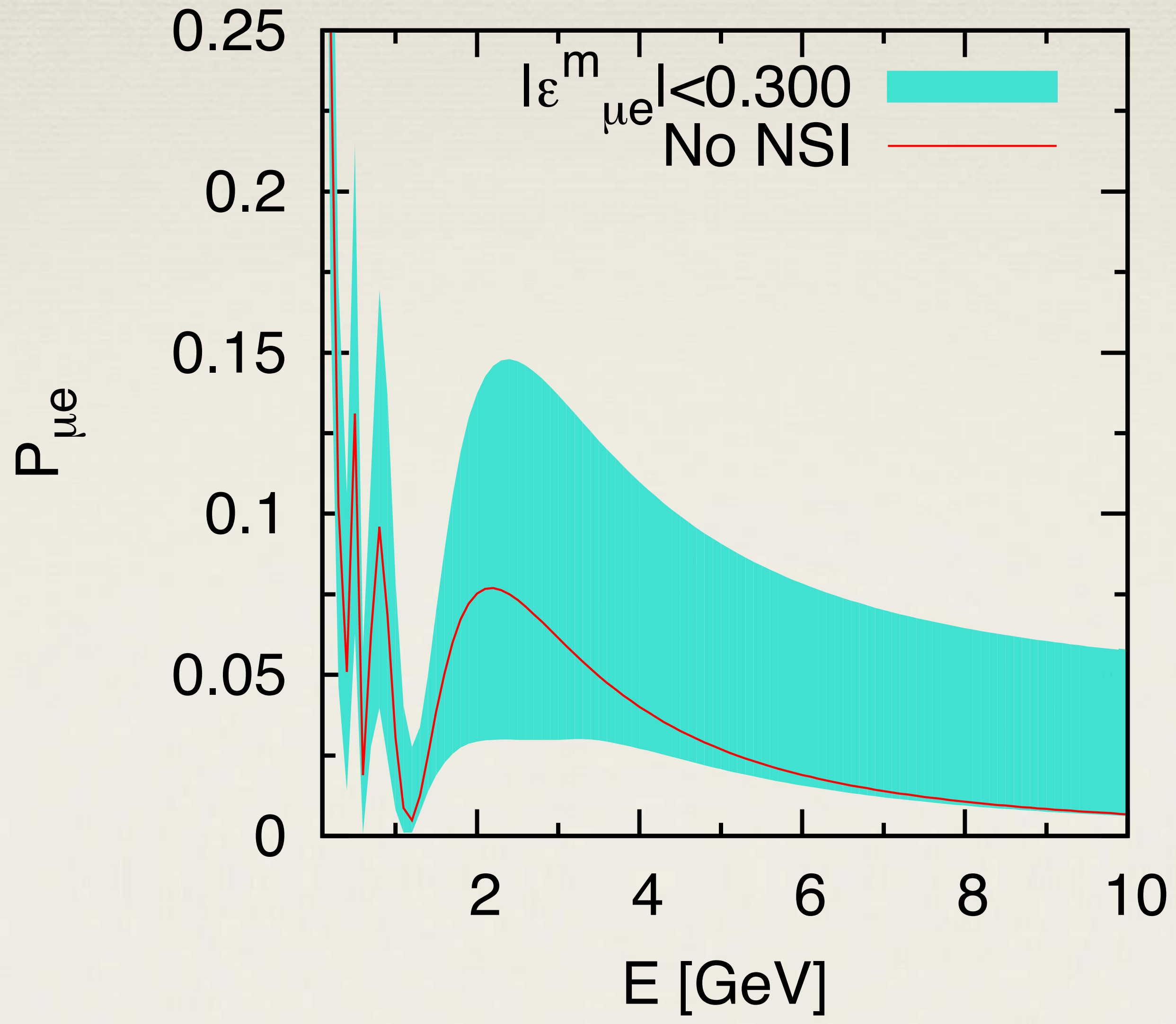

Choubey,Ohlsson, 1410.0410

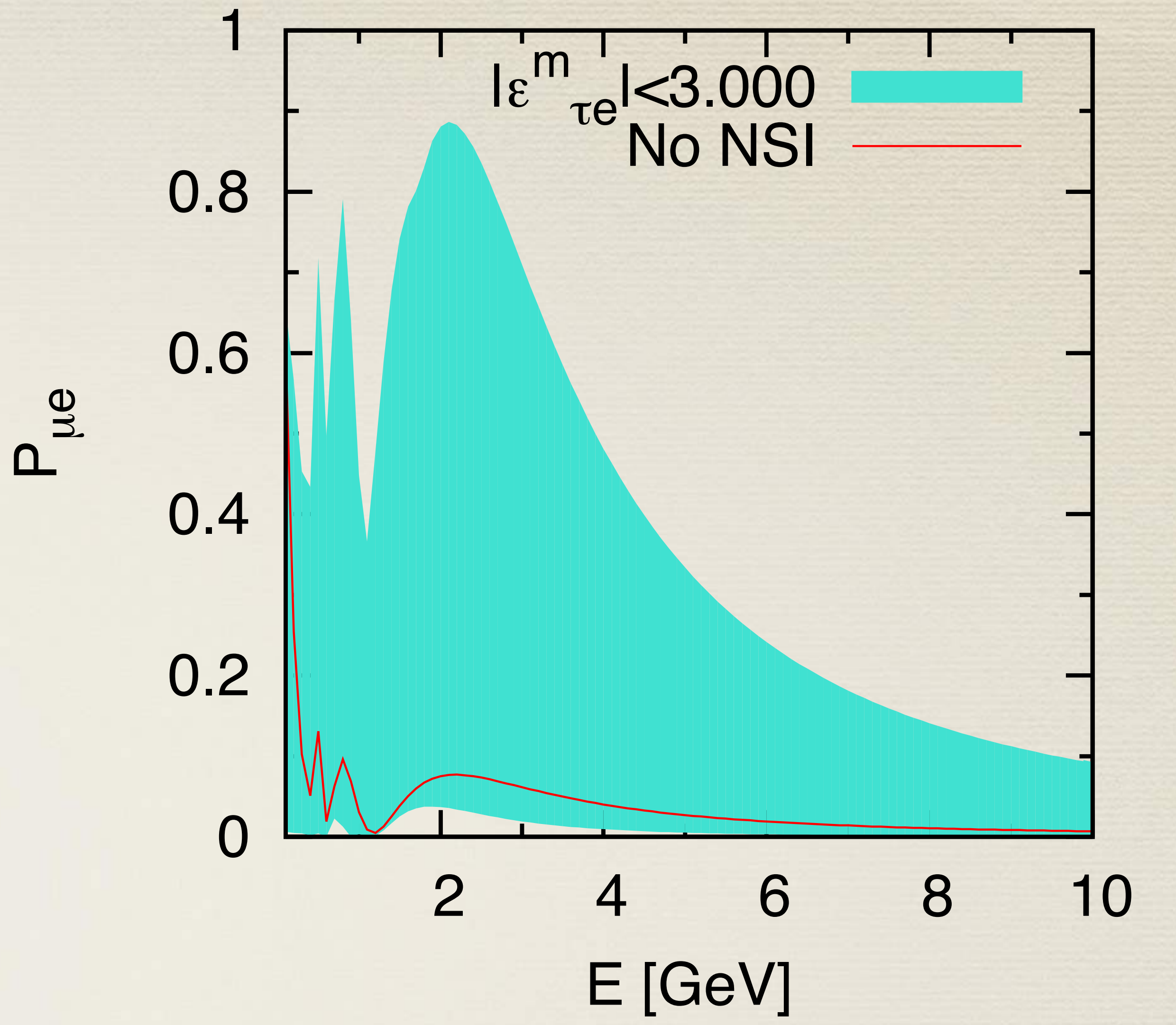

Choubey,Ghosh,Ohlsson,Tiwari, 1507.02211

NSI can change the probabilities, can lead to degeneracies and can change the sensitivity of the experiments

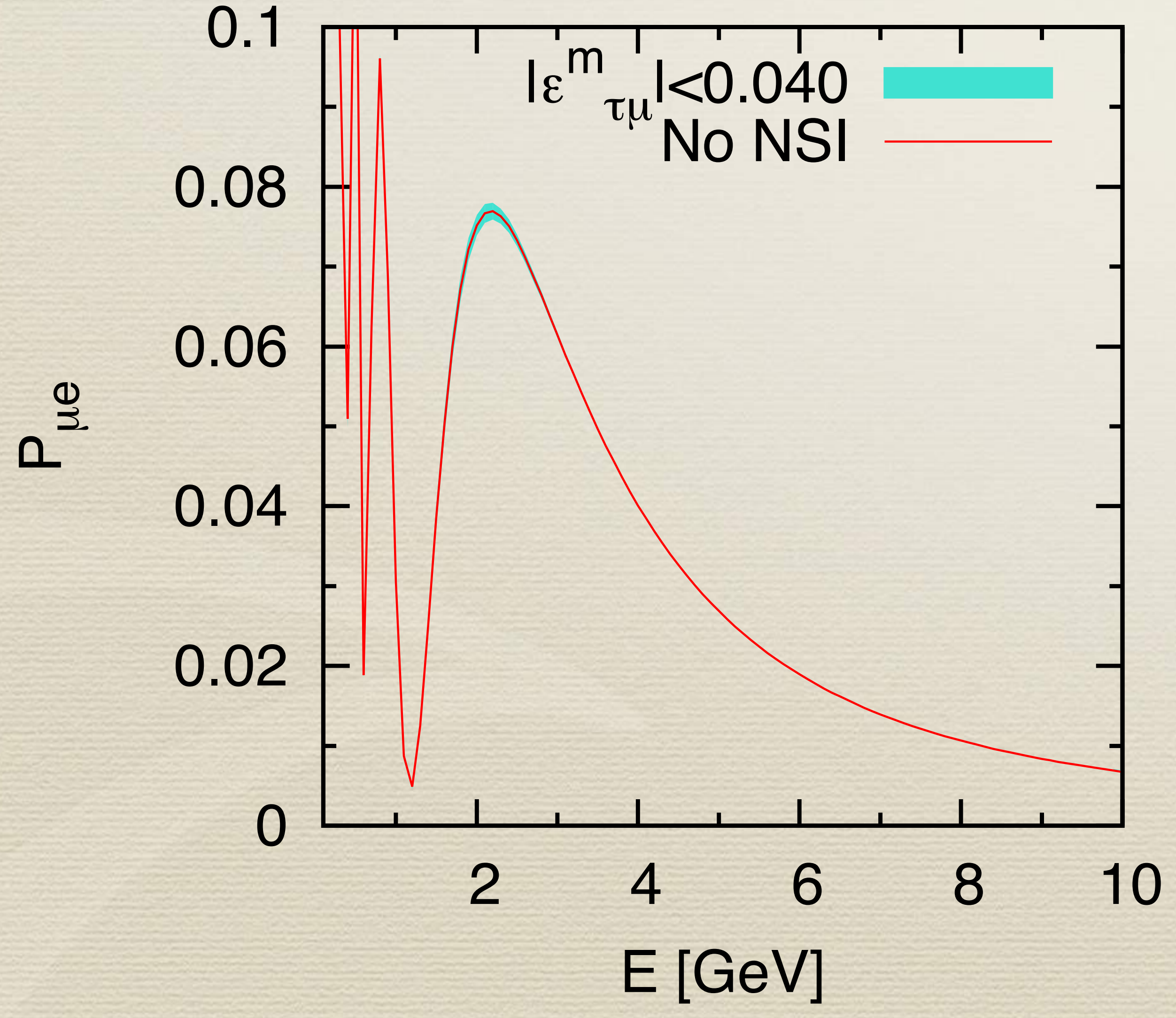
Impact of Matter NSIs on DUNE

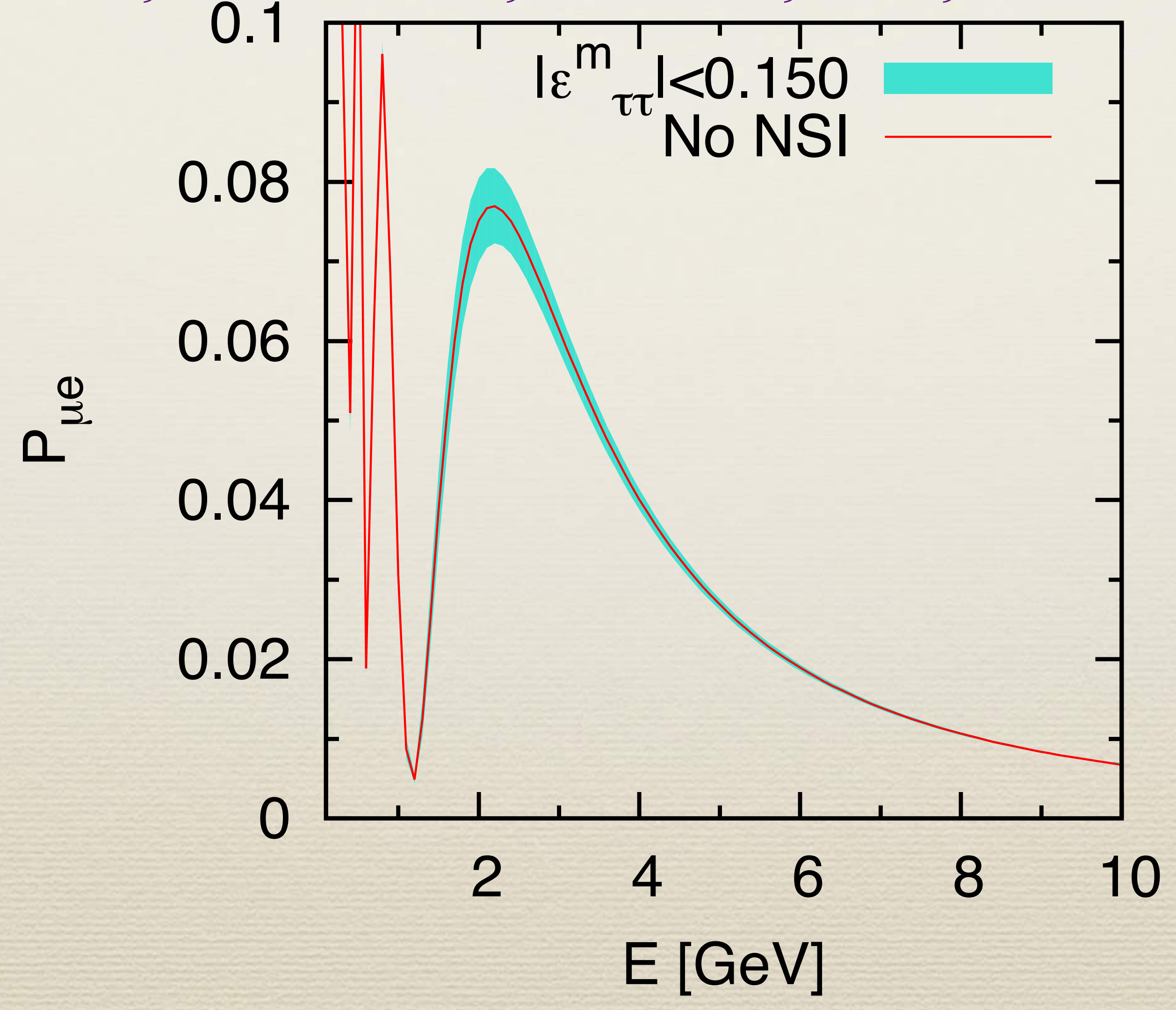




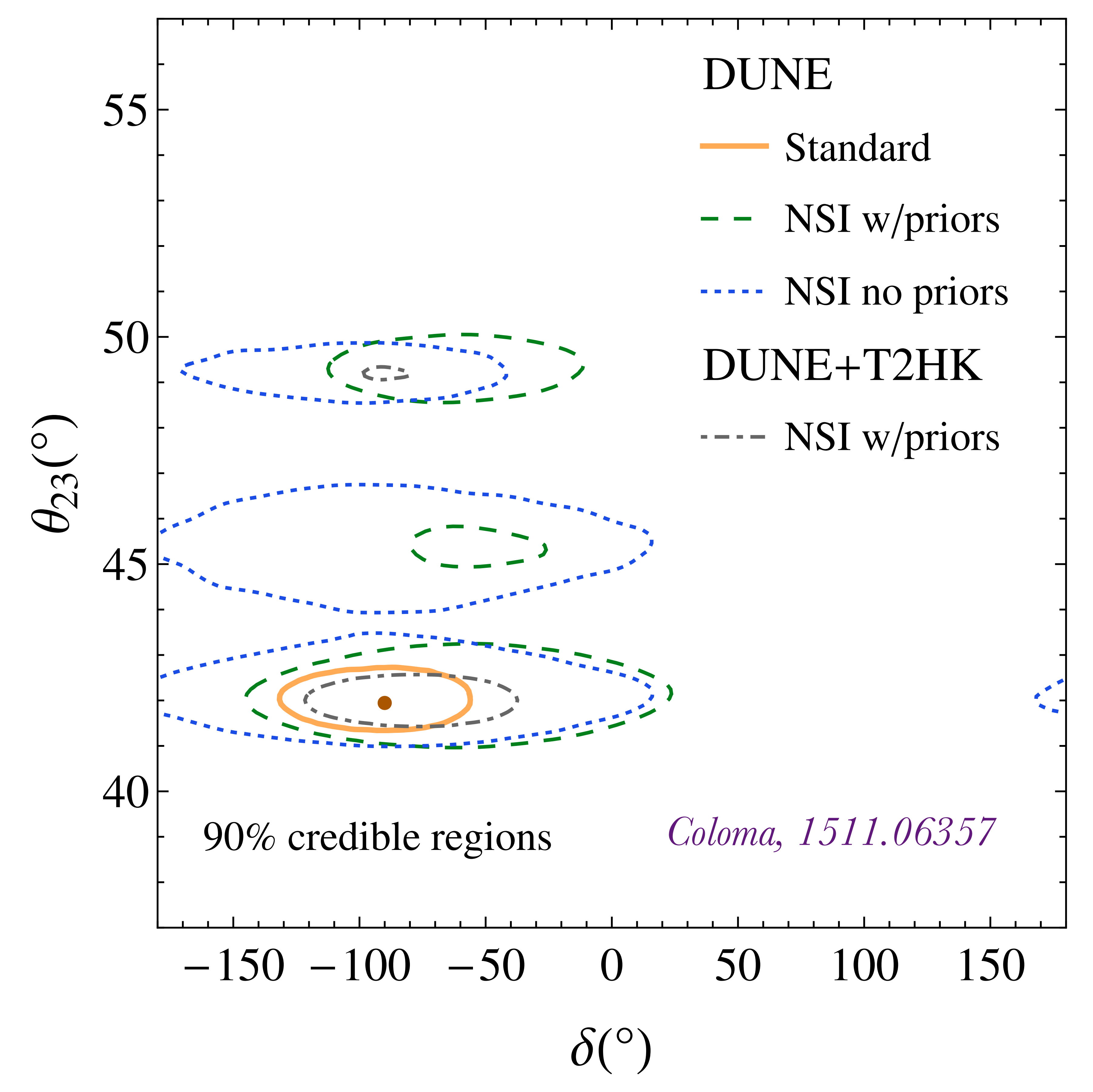


Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851



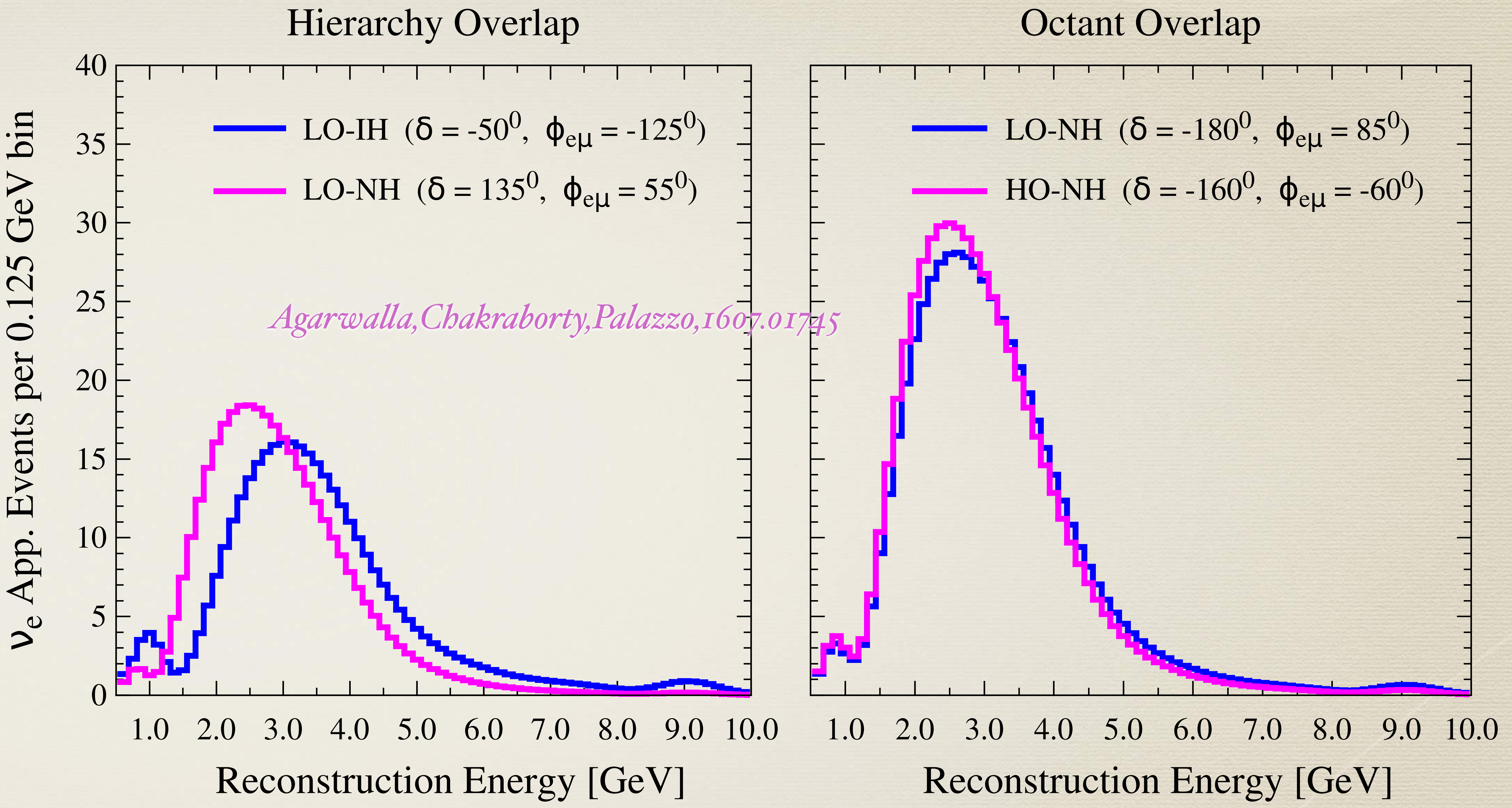


Impact of Matter NSIs on DUNE



90% credible regions

Coloma, 1511.06357



Hierarchy Overlap

Octant Overlap

Agarwalla,Chakraborty,Palazzo,1607.01745

- *Reduced sensitivity in delta*
- *New degenerate solutions in theta23*

Impact of Source/Detector NSIs

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon^s_{\alpha\gamma}|\nu_\gamma\rangle$$

$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \varepsilon^d_{\gamma\beta}\langle\nu_\gamma|$$

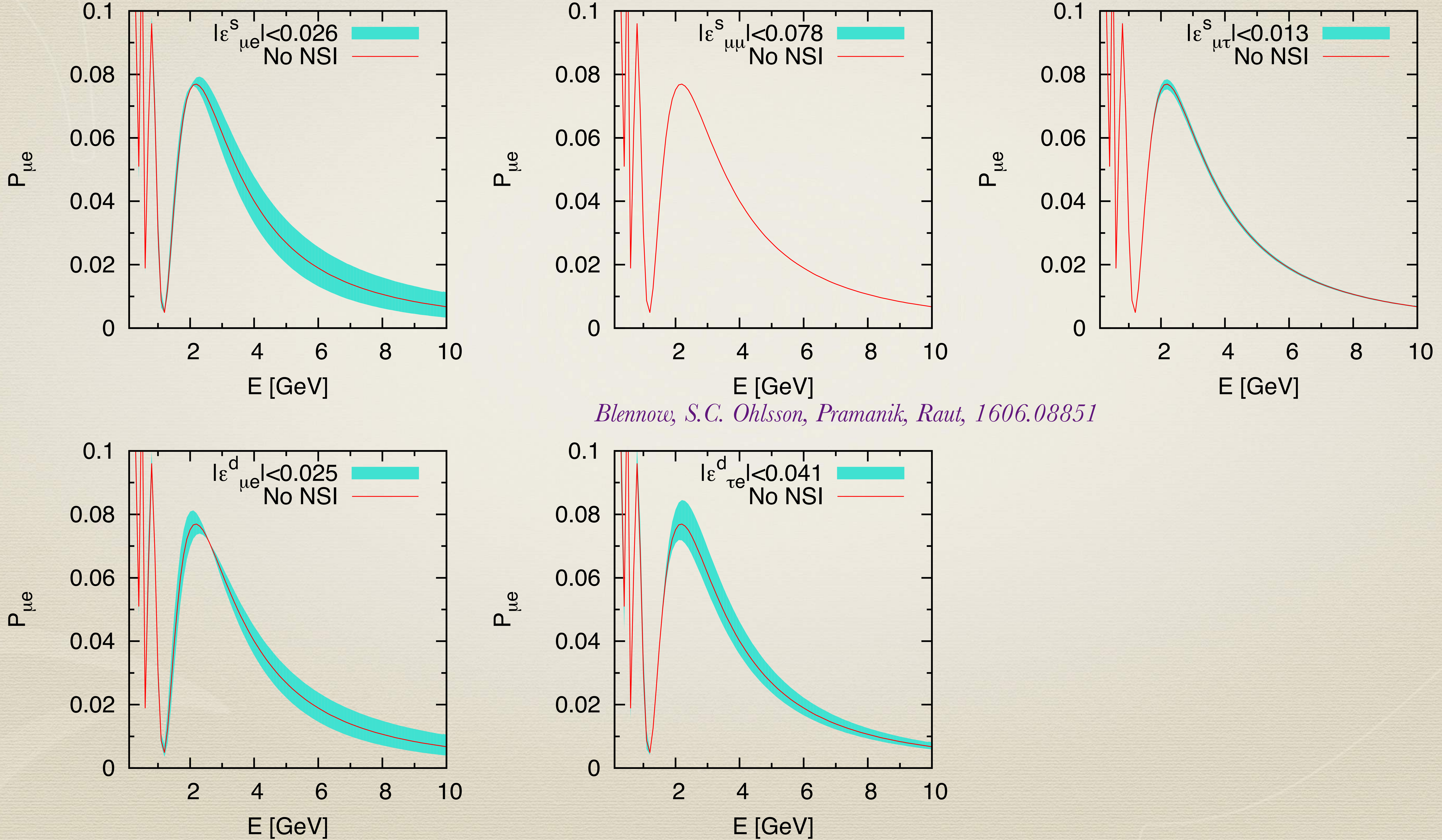
The matrices ε^s and ε^d that represent the source and the detector NSIs, repectively, are in general complex matrices with 18 real parameters each. These are the nine amplitudes $|\varepsilon^{s/d}_{\alpha\beta}|$ and nine phases $\varphi^{s/d}_{\alpha\beta}$.

$$|\varepsilon^{s/d}_{\alpha\beta}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}$$

Biggio, blennow,Fernandez-Martinez, 0907.0097

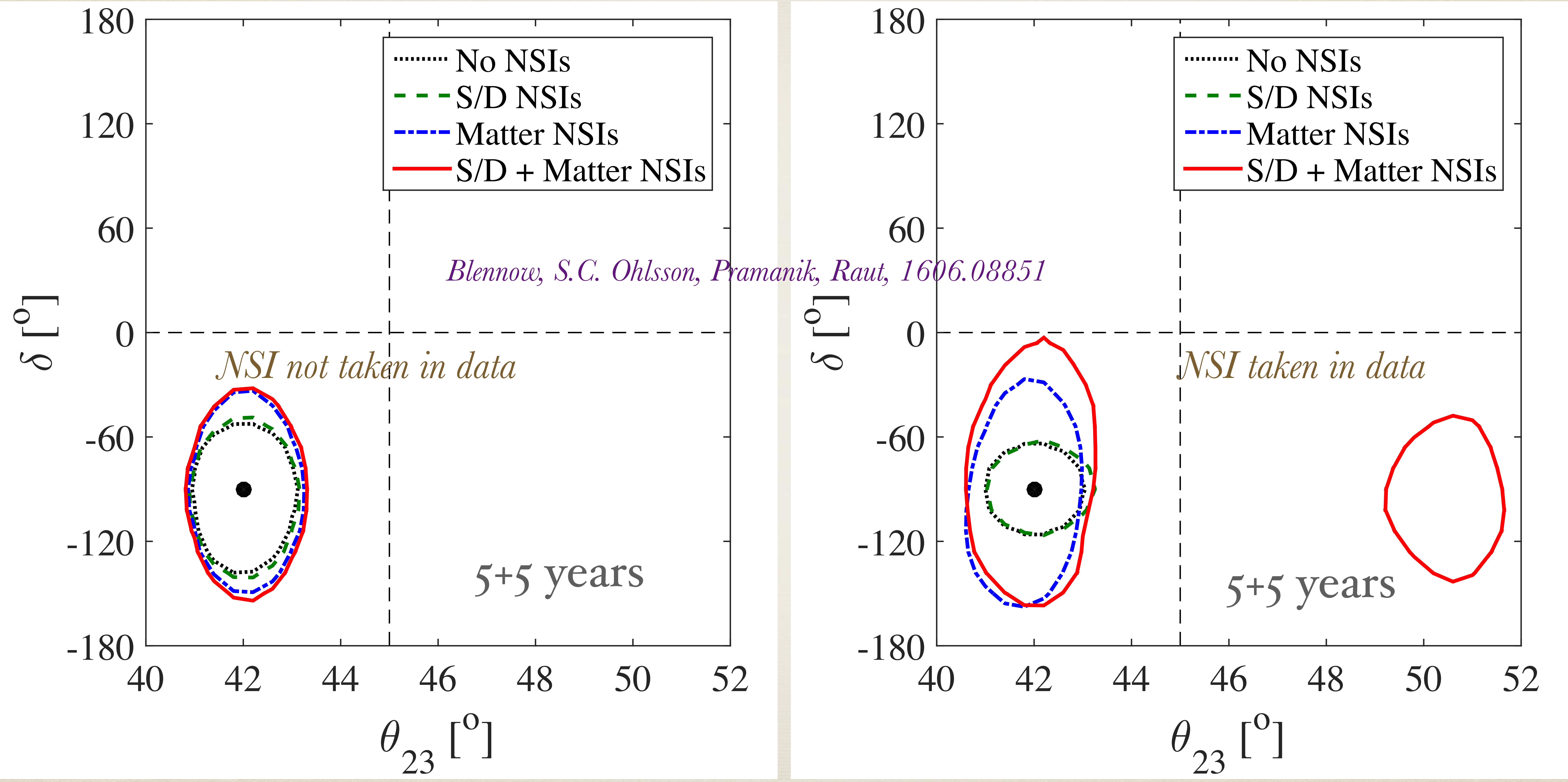
Apparent Non-Unitarity

Impact of Source/Detector NSIs



Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851

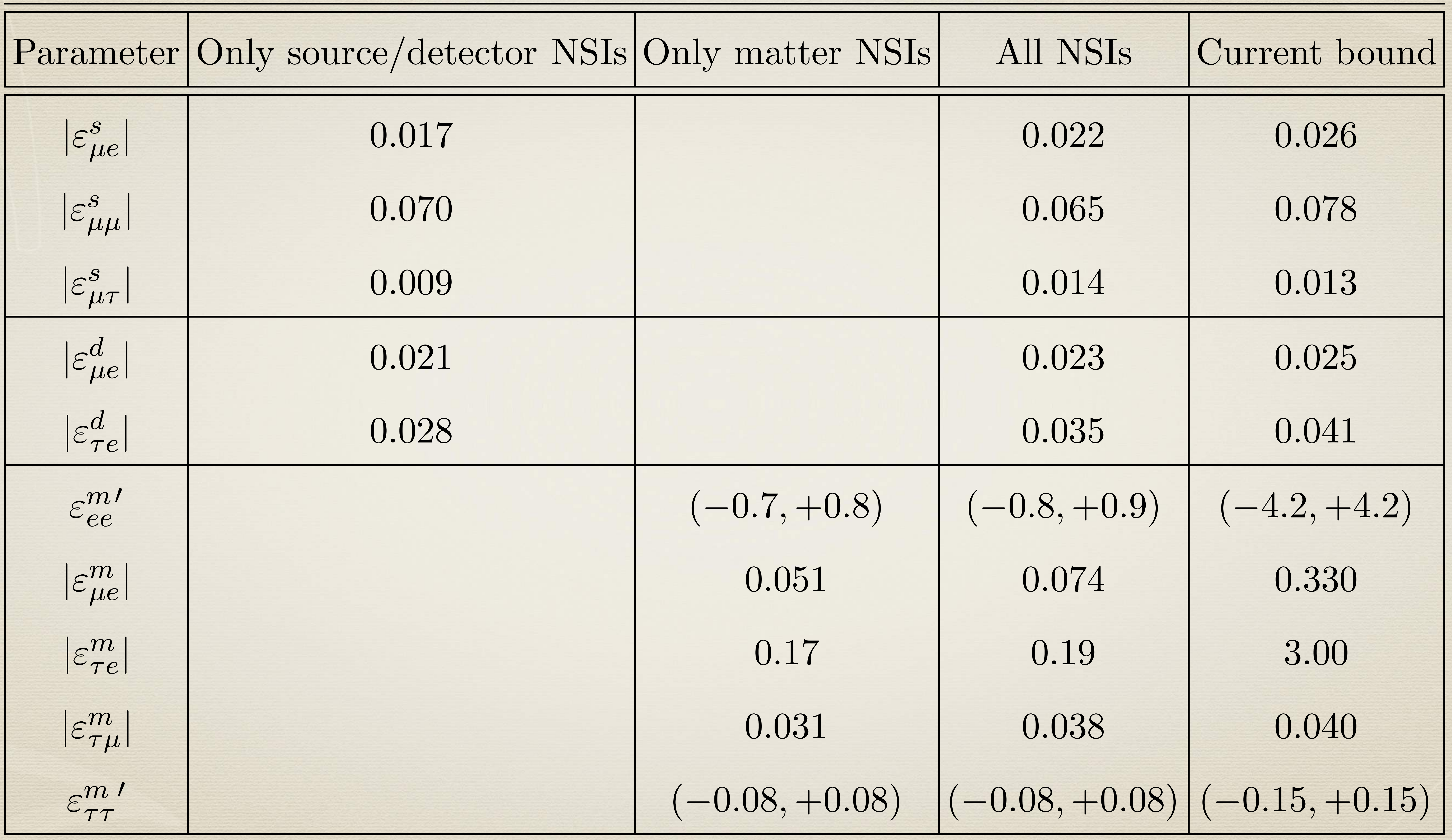
Impact of S/D + Matter NSIs



Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851

Correlations between matter and S/D NSIs lead to a new degenerate solution in theta23

Constraining NSIs with DUNE



Parameter	Only source/detector NSIs	Only matter NSIs	All NSIs	Current bound
$\lvert\varepsilon^{s}_{\mu e}\rvert$	0.017		0.022	0.026
$\lvert\varepsilon^{s}_{\mu\mu}\rvert$	0.070		0.065	0.078
$\lvert\varepsilon^{s}_{\mu\tau}\rvert$	0.009		0.014	0.013
$\lvert\varepsilon^{d}_{\mu e}\rvert$	0.021		0.023	0.025
$\lvert\varepsilon^{d}_{\tau e}\rvert$	0.028		0.035	0.041
$\varepsilon^{m\,\prime}_{ee}$		$(-0.7, +0.8)$	$(-0.8, +0.9)$	$(-4.2, +4.2)$
$\lvert\varepsilon^{m}_{\mu e}\rvert$		0.051	0.074	0.330
$\lvert\varepsilon^{m}_{\tau e}\rvert$		0.17	0.19	3.00
$\lvert\varepsilon^{m}_{\tau\mu}\rvert$		0.031	0.038	0.040
$\varepsilon^{m\,\prime}_{\tau\tau}$		$(-0.08, +0.08)$	$(-0.08, +0.08)$	$(-0.15, +0.15)$

Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851

TABLE I. Expected 90 % credible regions on NSI parameters from DUNE.

Neutrino Decay

Allow for $\nu_i \to \nu' + J$

Chikashige, Mohapatra, Peccei, PLB 98, (1981)
Gelmini, Roncadelli, PLB 99 (1981)
Gelmini, Valle, PLB 142 (1984)

$$\tau_i = \frac{16\pi}{g_{dk}^2} \frac{m_d^3}{\Delta m^2 (m_i + m_d)^2}$$

Acker, Pakvasa, Pantaleone, PRD 45 (1992)

Neutrino Decay

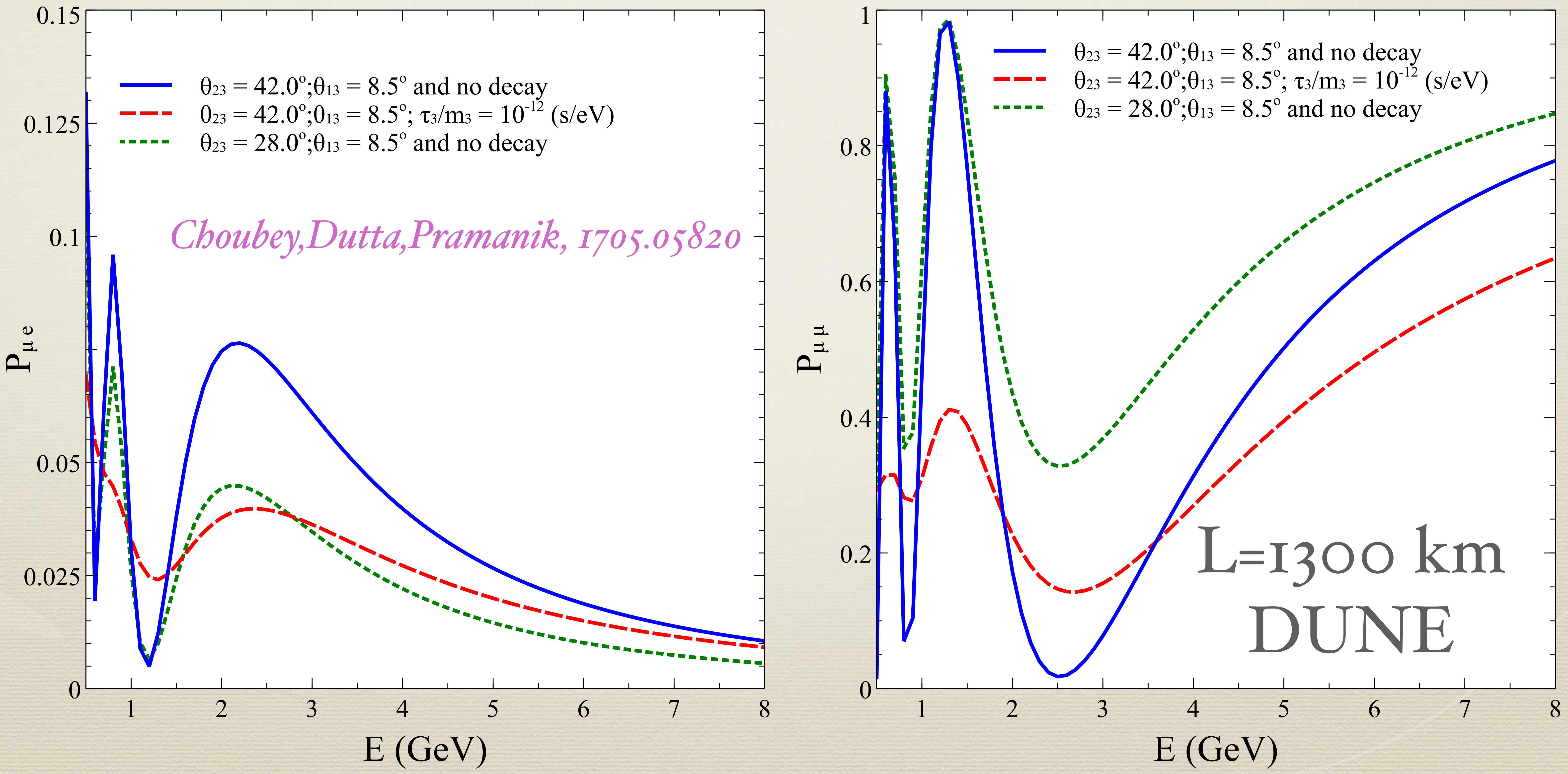
Acker, Pakvasa, Pantaleone, PRD 45 (1992)

Allow for $\nu_i \to \nu' + J$

Chikashige, Mohapatra, Peccei, PLB 98, (1981)
Gelmini, Roncadelli, PLB 99 (1981)
Gelmini, Valle, PLB 142 (1984)

$$\tau_i = \frac{16\pi}{g_{dk}^2} \frac{m_d^3}{\Delta m^2 (m_i + m_d)^2}$$

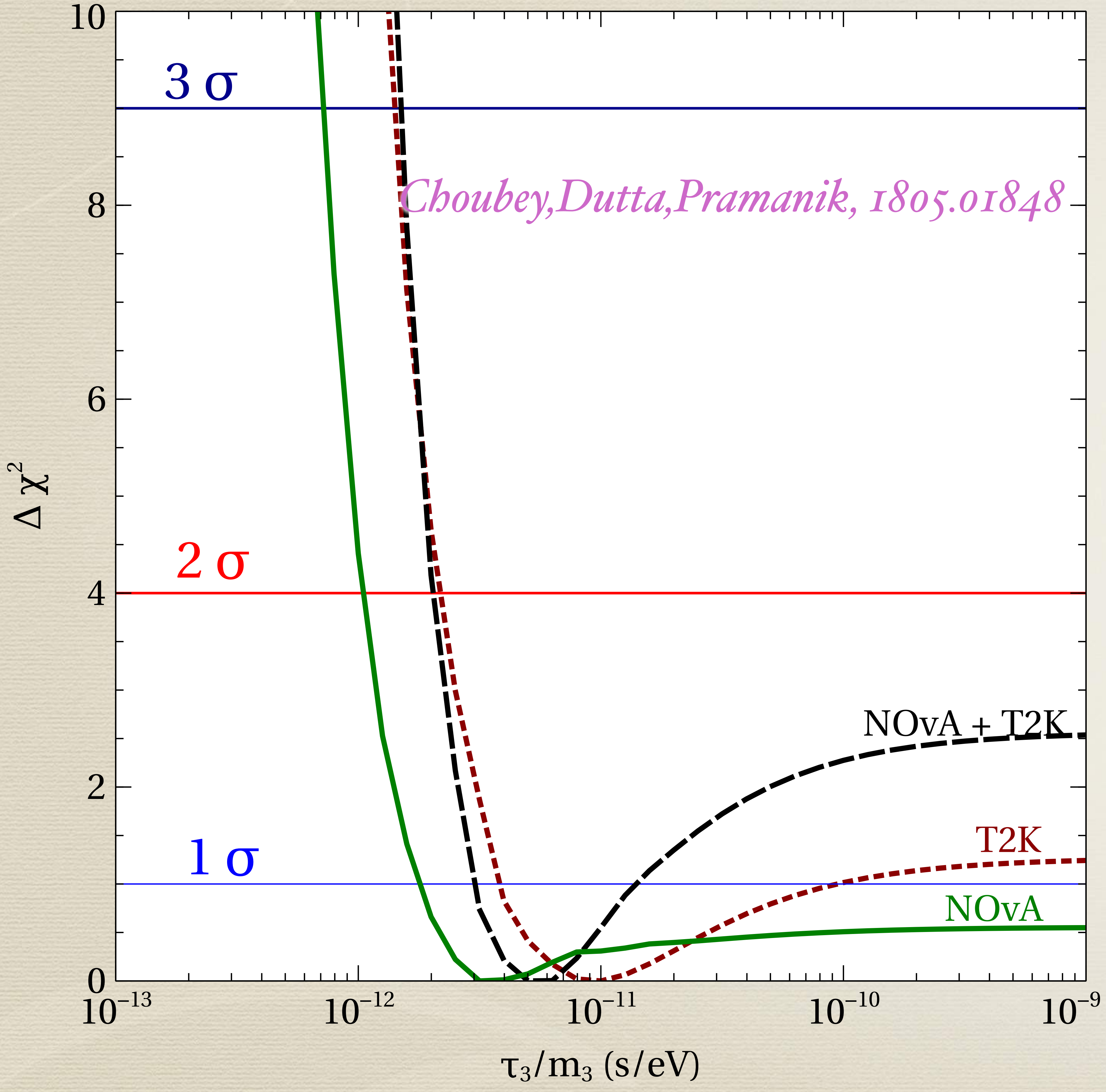
$$P_{\mu\mu}^{2G} = \left[\cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{m_3 L}{\tau_3 E}}\right]^2 - \sin^2 2\theta_{23} e^{-\frac{m_3 L}{2\tau_3 E}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$



Choubey,Dutta,Pramanik, 1705.05820

L=1300 km
DUNE

Neutrino Decay



Choubey,Dutta,Pramanik, 1805.01848

Choubey,Ghosh,Kempe,Ohlsson, 2010.16334

Experiment	90 % C.L. (3σ) bound on τ_3/m_3 [s/eV]
T2K + NOνA	$2.3\ (1.5) \times 10^{-12}$
T2K + MINOS	$2.8\ (1.8) \times 10^{-12}$
SK + MINOS	$2.9\ (0.54) \times 10^{-10}$
MOMENT	$2.8\ (1.6) \times 10^{-11}$
ESSnuSB (540 km)	$4.22\ (1.68) \times 10^{-11}$
DUNE	$4.50\ (2.38) \times 10^{-11}$
ESSnuSB (360 km)	$4.95\ (2.64) \times 10^{-11}$
JUNO	$9.3\ (4.7) \times 10^{-11}$
INO	$1.51\ (0.566) \times 10^{-10}$
KM3NeT-ORCA	$2.5\ (1.4) \times 10^{-10}$
T2HK	$-\ (2.7) \times 10^{-11}$

Conclusion

- CP violation is expected to be discovered at more than 5 sigma significance
- This has far-reaching implications for theoretical models of neutrino mass and leptogenesis
- Neutrino mass ordering should be discovered at high significance in DUNE and atmospheric neutrino experiments
- Octant of theta23 is important for model building and will be probed
- New Physics can affect the measurement of all of above and needs to be kept in mind
- New physics itself can be studied at neutrino facilities