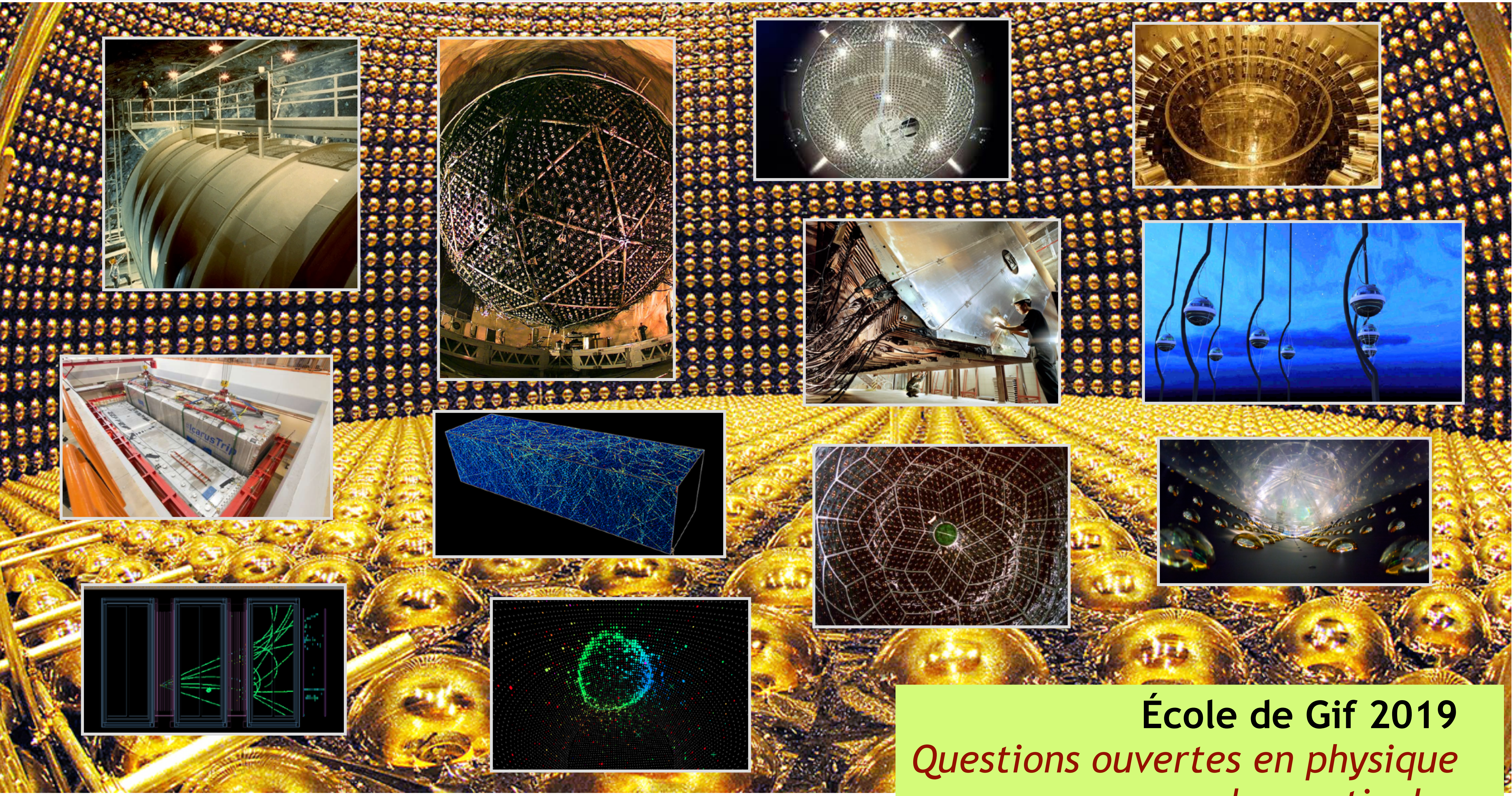
Les expériences du futur : potentiel de physique

Physique des neutrinos



École de Gif 2019

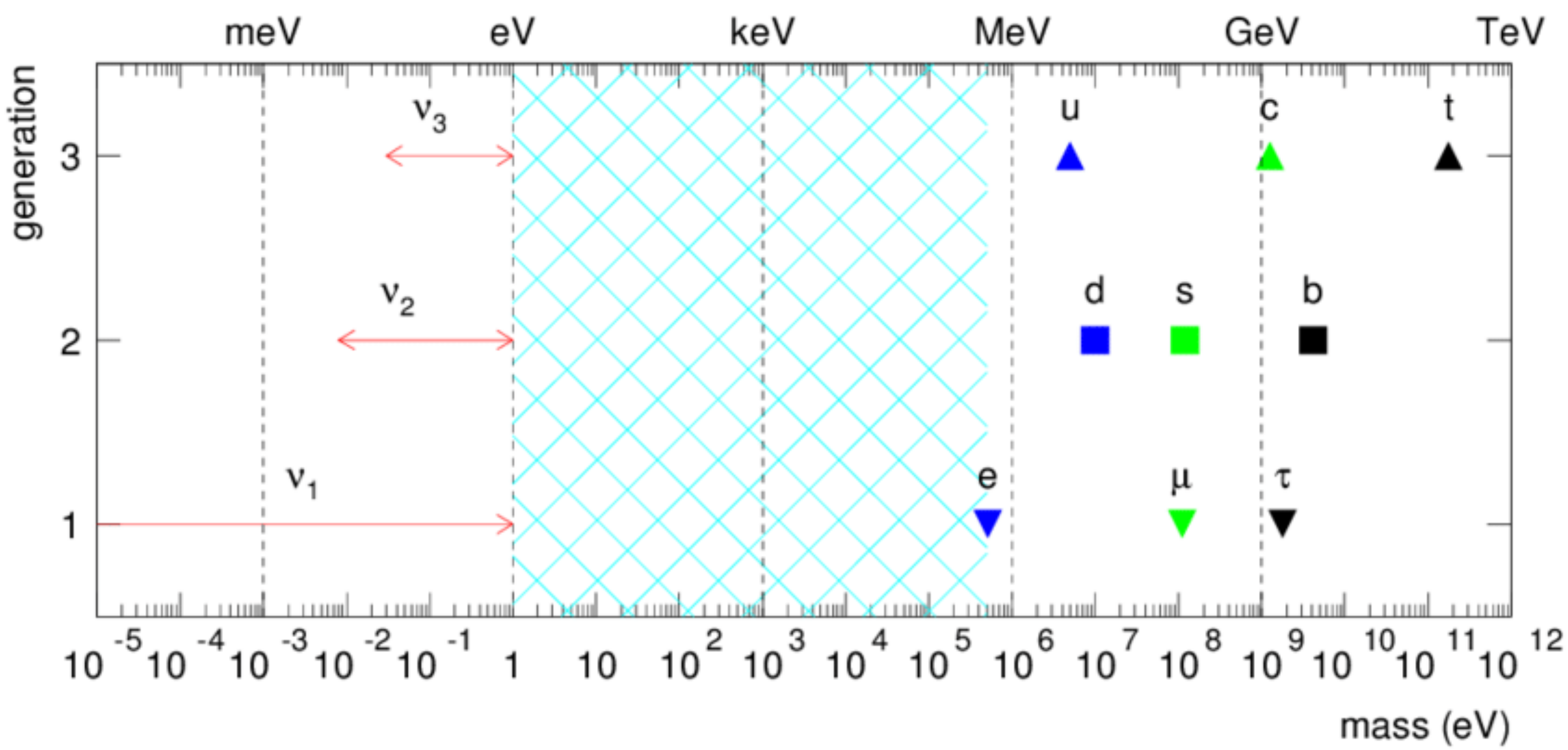
Questions ouvertes en physique des particules

2-6 septembre 2019

École polytechnique, Palaiseau

Gautier Hamel de Monchenault

What's so Special with Neutrinos?



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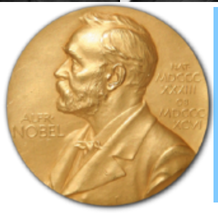
- ✓ they're super light!
- ✓ they might be Majorana particles
- ✓ neutrinos are massive: the SM is incomplete!
- ✓ the neutrino mass spectrum is not hierarchical
- ✓ the flavour states are not even close to be mass eigenstates
- ✓ large flavour mixing angles can potentially lead to large CP violation
- ✓ the origin of neutrino masses might be different from that of quarks and leptons (still involving the Higgs field or not)
- ✓ they might be related to the mechanism of baryogenesis
- ✓ etc.

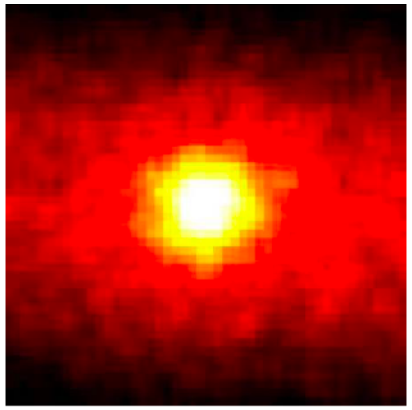


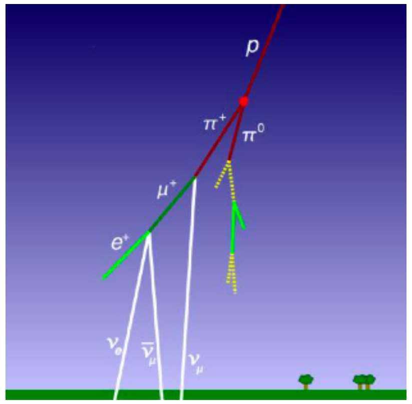
1995 Reines
2000 Davis, Koshiba
2015 Kajita McDonald

Neutrino Sources

Neutrinos can been seen as flavour states: ν_e, ν_μ, ν_τ (and $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$)

Neutrino sources
- natural: Sun, Earth, cosmic rays, SN, …
- artificial: reactors, accelerators





reactor

KamLand
Double-Chooz
Daya Bay
Reno…

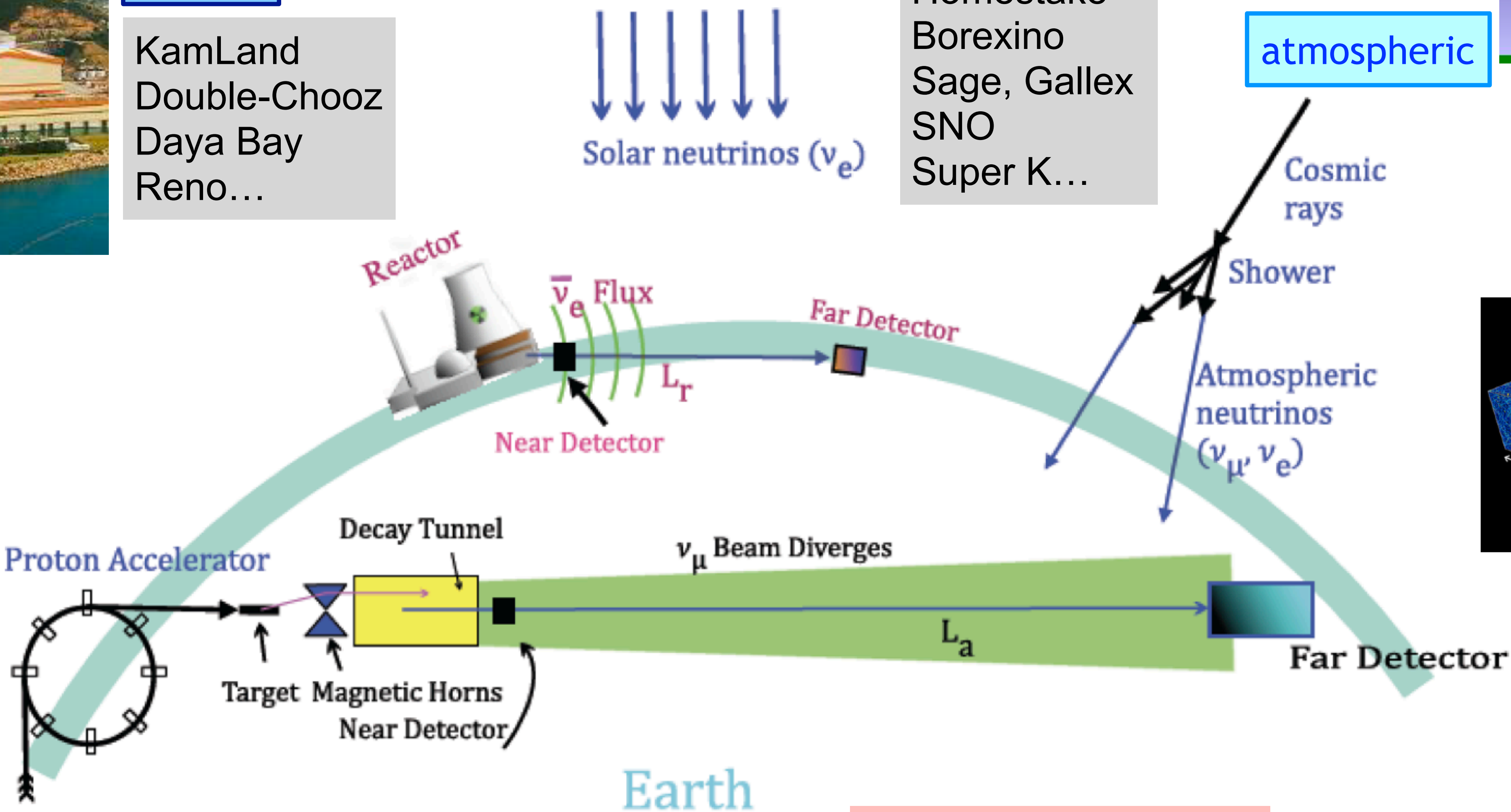
solar

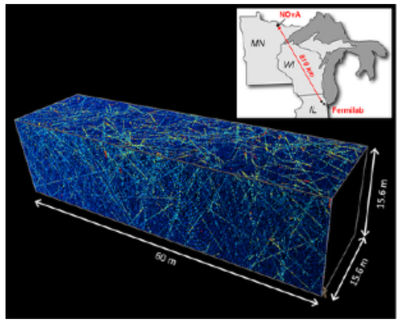
Homestake
Borexino
Sage, Gallex
SNO
Super K…

Super K
Minos
IceCube…

atmospheric

Accelerator LBL



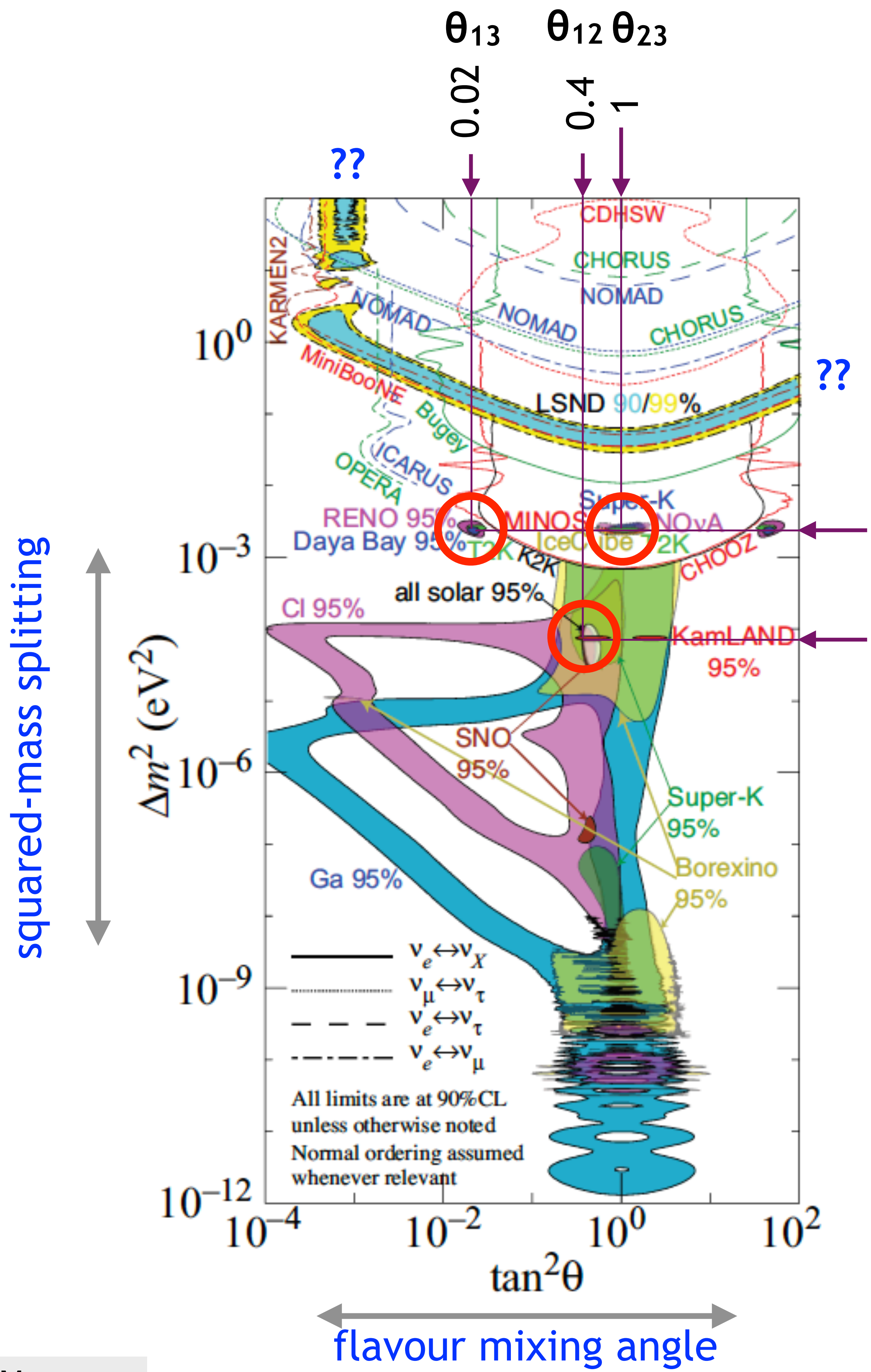


K2K, T2K
Minos, NOvA
Opera…

One hundred billion solar neutrinos per cm^2 per sec

Detection: 1 kilo-ton of water → one solar neutrino per day

Decades of Neutrino Oscillation Experiments



$\theta_{12} = \theta_\odot \simeq 34^\circ$

$\theta_{23} = \theta_{atm} \simeq 45^\circ$

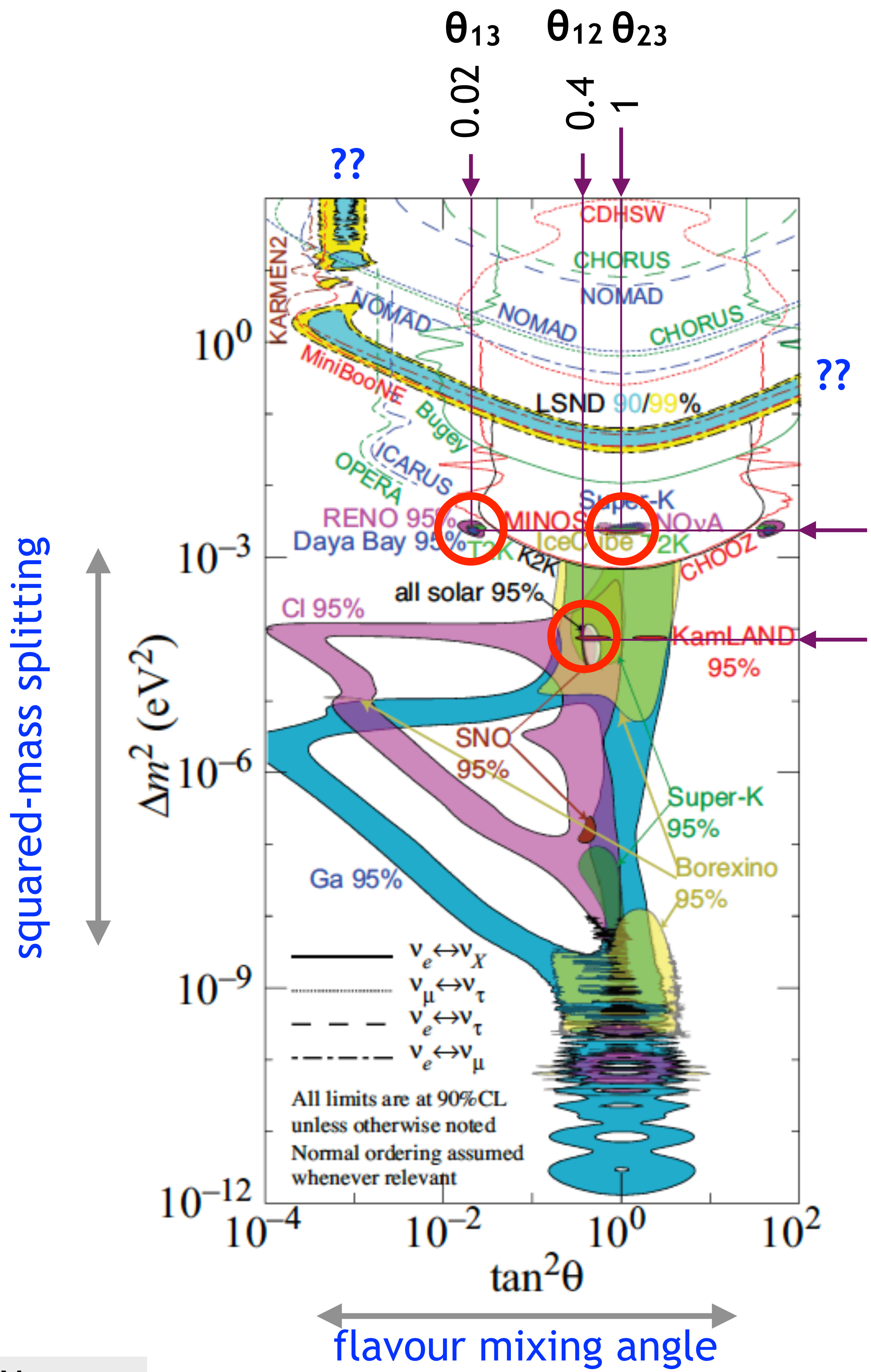
$\theta_{13} \simeq 8^\circ$

$2.5\ 10^{-3}\ eV^2$ $\quad \Delta m^2 = \Delta m^2_{atm}$

$7.3\ 10^{-5}\ eV^2$ $\quad \delta m^2 = \Delta m^2_\odot$

Neutrino flavour oscillations (SK/SNO 1998) prove that neutrinos have non-zero distinct masses and establish the paradigm with three neutrinos ν_1, ν_2, ν_3 (mass states)

favoured 95% CL : solid regions
excluded 90% CL : open regions



2.5 10^{-3} eV^2 Δm^2

7.3 10^{-5} eV^2 δm^2

$\theta_{12} = \theta_\odot \simeq 34^o$

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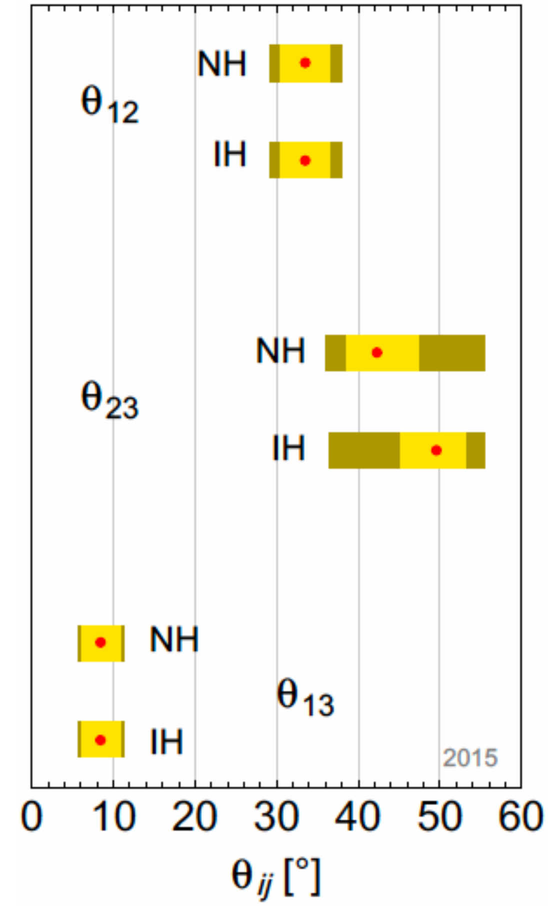

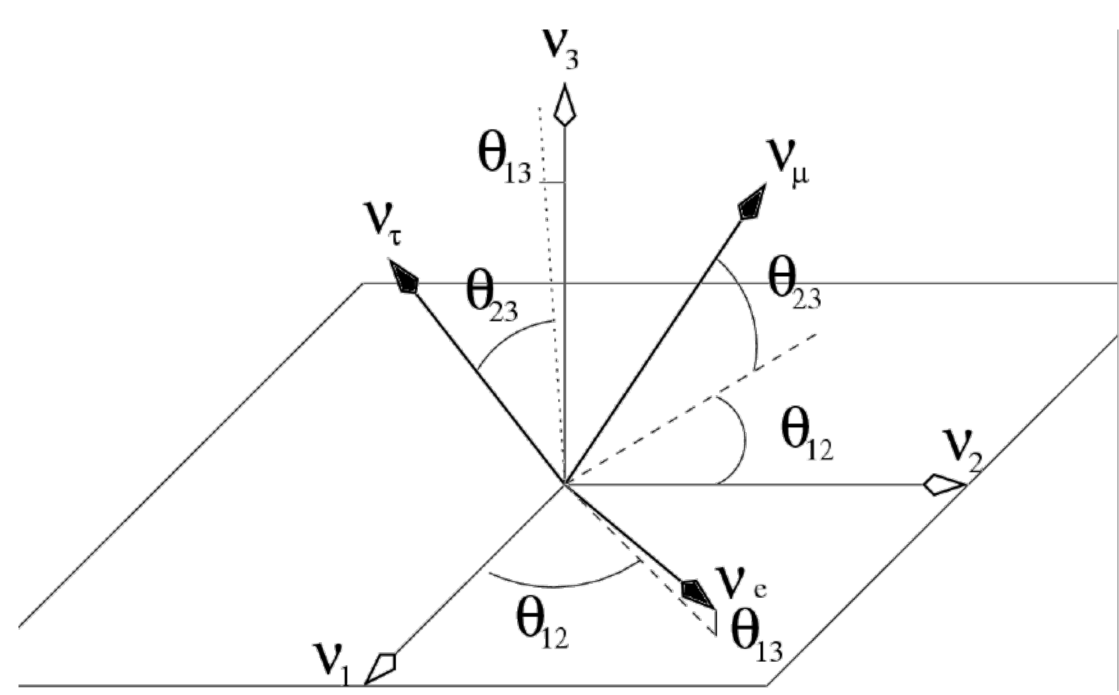

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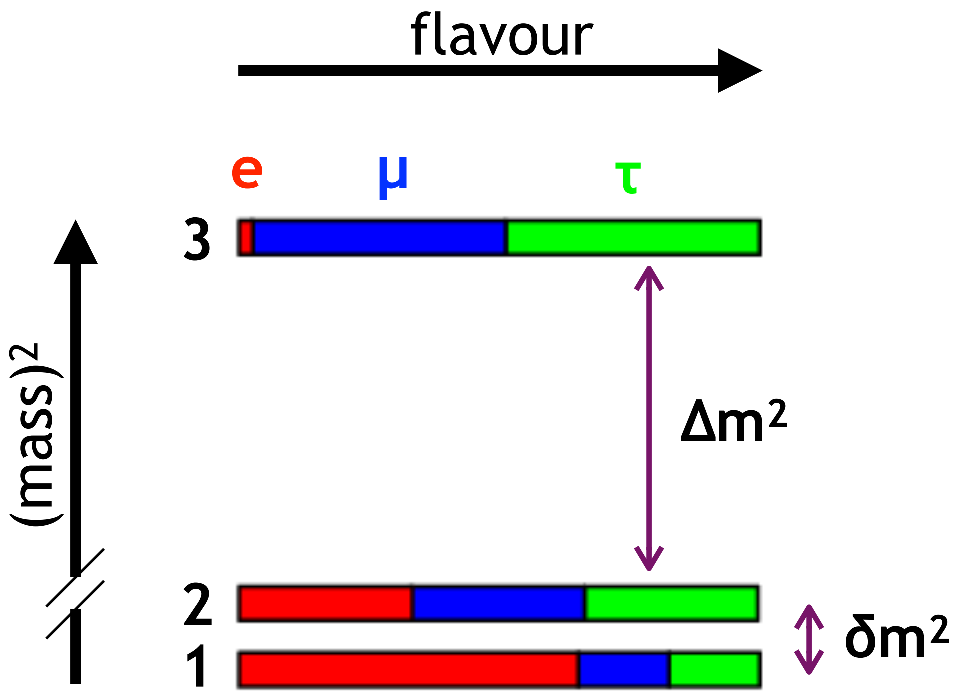
3-Neutrino Paradigm Flavour Structure

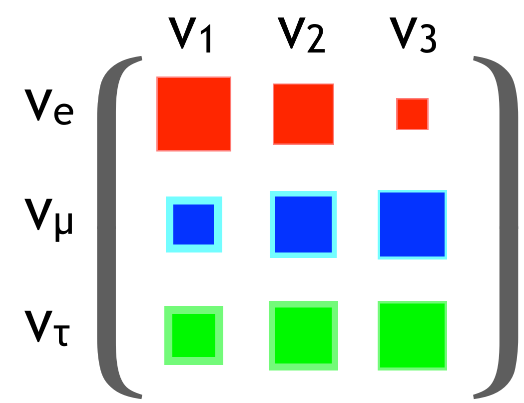


☞ PMNS flavour mixing matrix
(Pontecorvo, Maki-Nakagawa-Sakata)

flavour PMNS mass

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle \qquad \alpha = \mathrm{e},\ \mu,\ \tau$$

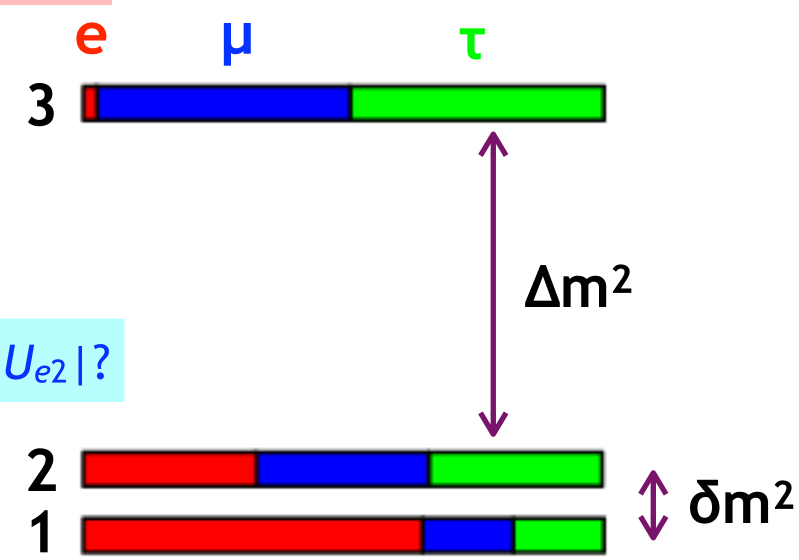
U_{PMNS} =



3-Neutrino Paradigm Flavour Structure

$|U_{e3}| \neq 0$
(recently discovered)

$|U_{\tau 3}| = |U_{\mu 3}|$?
("maximal μ-τ mixing")



$|U_{\tau 2}| = |U_{\mu 2}| = |U_{e2}|$?

$\nu_e \simeq$ 68% of ν_1, 30% of ν_2, 2% of ν_3

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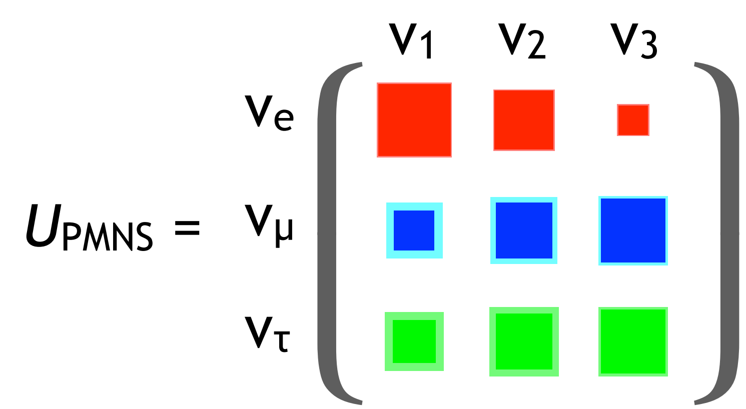
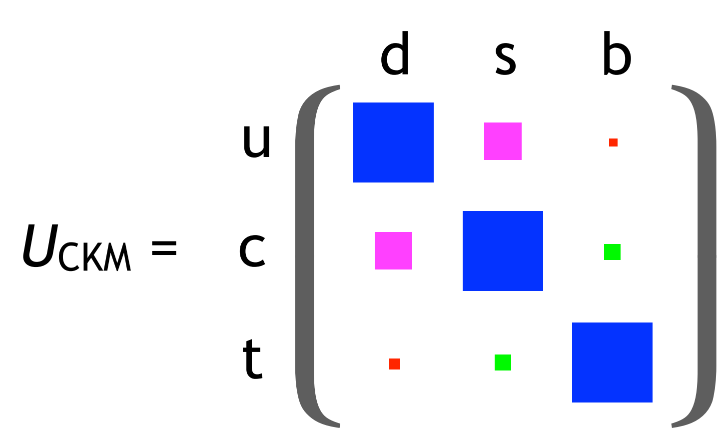


The flavour structure is the leptonic sector
is radically different than in the quark sector:



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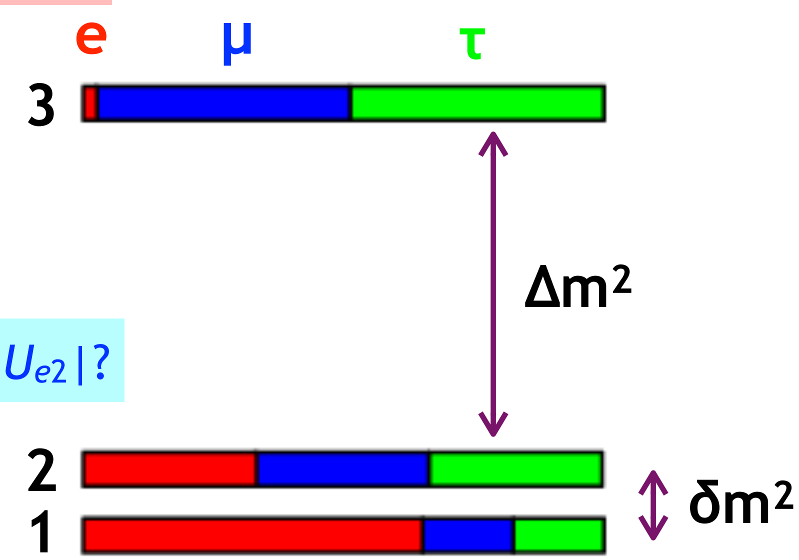
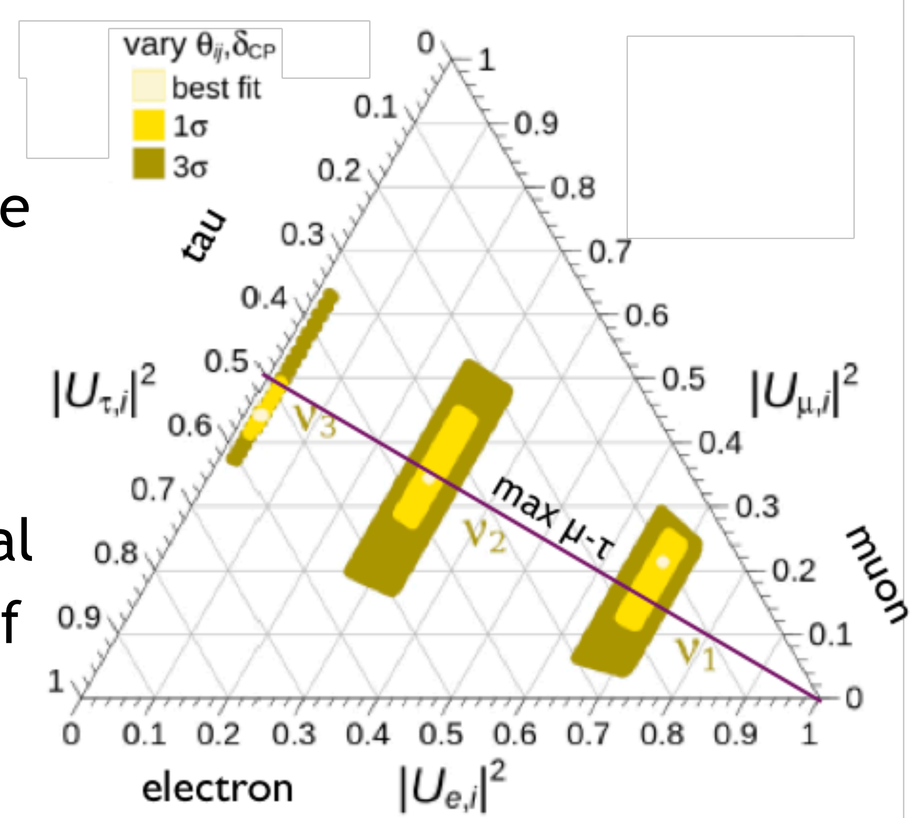


$|U_{\tau2}| = |U_{\mu2}| = |U_{e2}|$?

$\nu_e \simeq$ 68% of ν_1, 30% of ν_2, 2% of ν_3

What *flavour* symmetry can produce this pattern of flavour mixing?

- if yes, how is that symmetry broken?
- more broadly, is there a dynamical origin to the mixing and masses of neutrinos?



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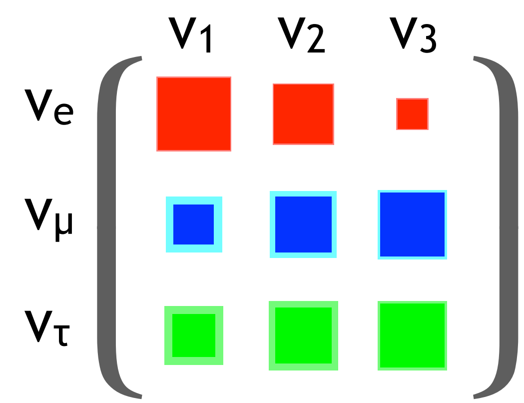
U_{PMNS} =

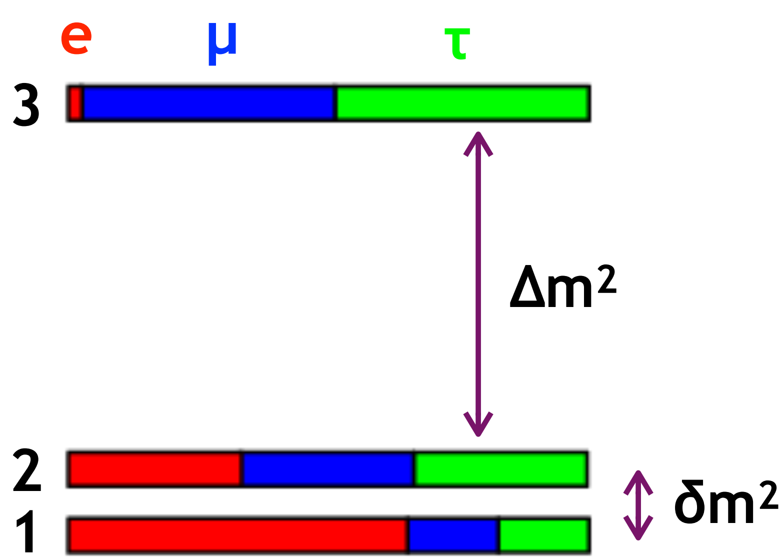


?

e.g., tribimaximal

$$\begin{array}{c|ccc} & \nu_1 & \nu_2 & \nu_3 \\ \hline \nu_e & \sqrt{2/3} & \sqrt{1/3} & 0 \\ \nu_\mu & \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \nu_\tau & \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{array}$$

PMNS Parameterisation



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flavour PMNS mass

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle \qquad \alpha = \mathrm{e},\ \mu,\ \tau$$

Neutrino oscillations depend on

- 2 squared-mass differences:
  Δm^2_{21} and Δm^2_{32}
- 3 mixing angles: θ_{12}, θ_{13}, and θ_{23}
- 1 phase: δ_{CP}

Usual parameterisation of the PMNS mixing matrix:

flavour | PMNS | mass

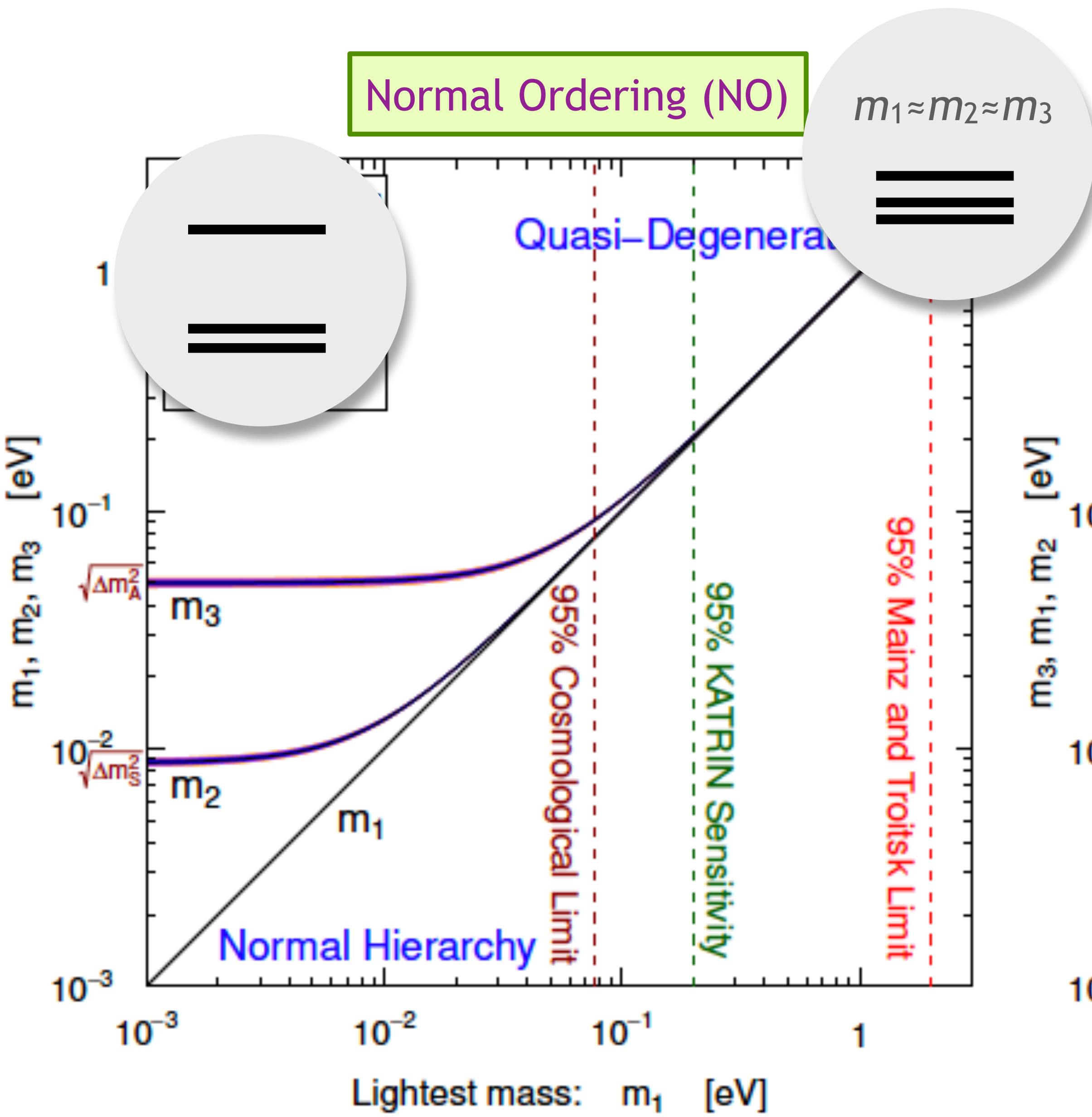
$$\begin{pmatrix}\nu_\mathrm{e}\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

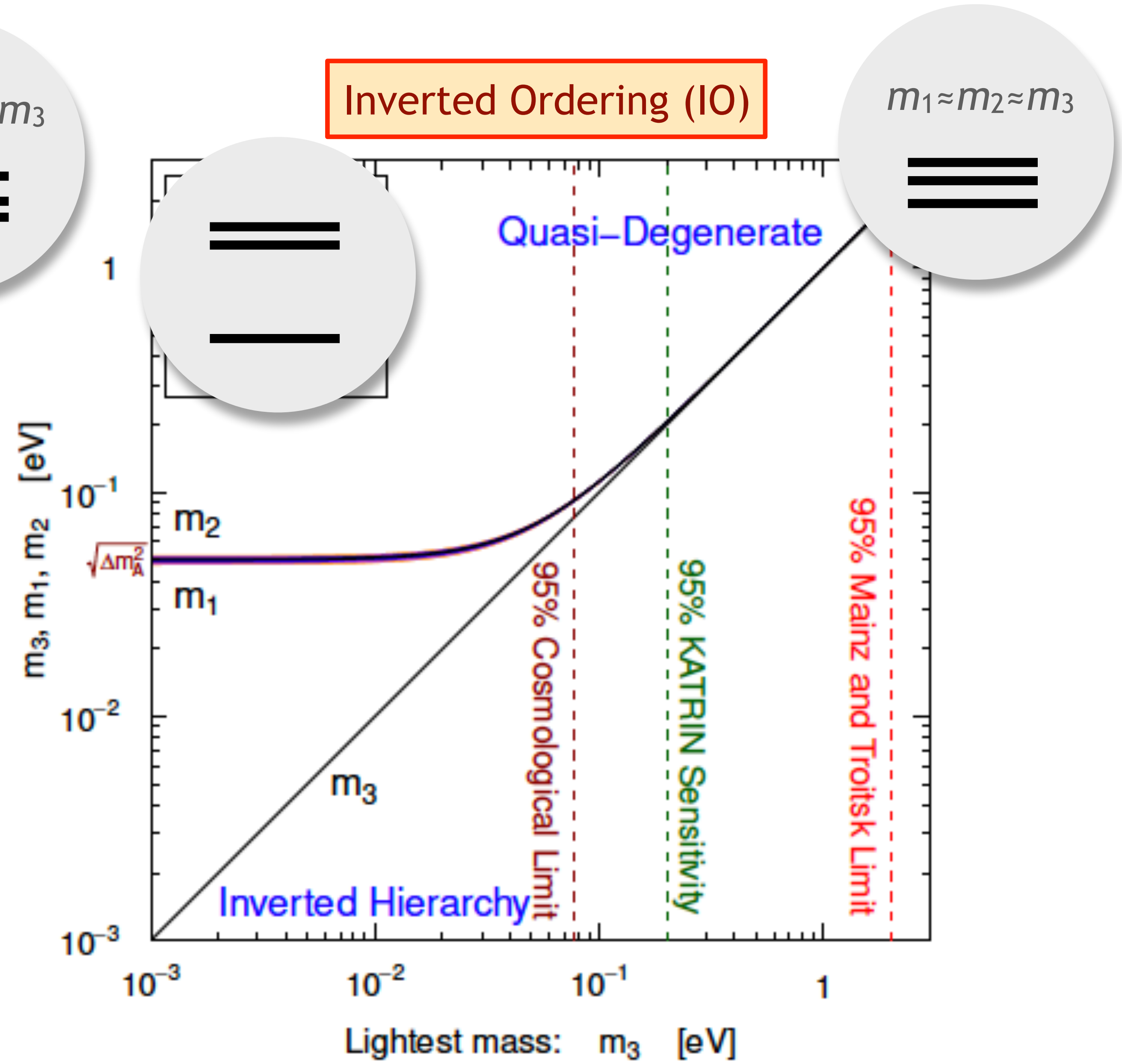
atmospheric | accelerator/reactor | solar

(oscillations do not depend on 2 possible Majorana phases α_1 and α_2)

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

Ordering or Hierarchy?





$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

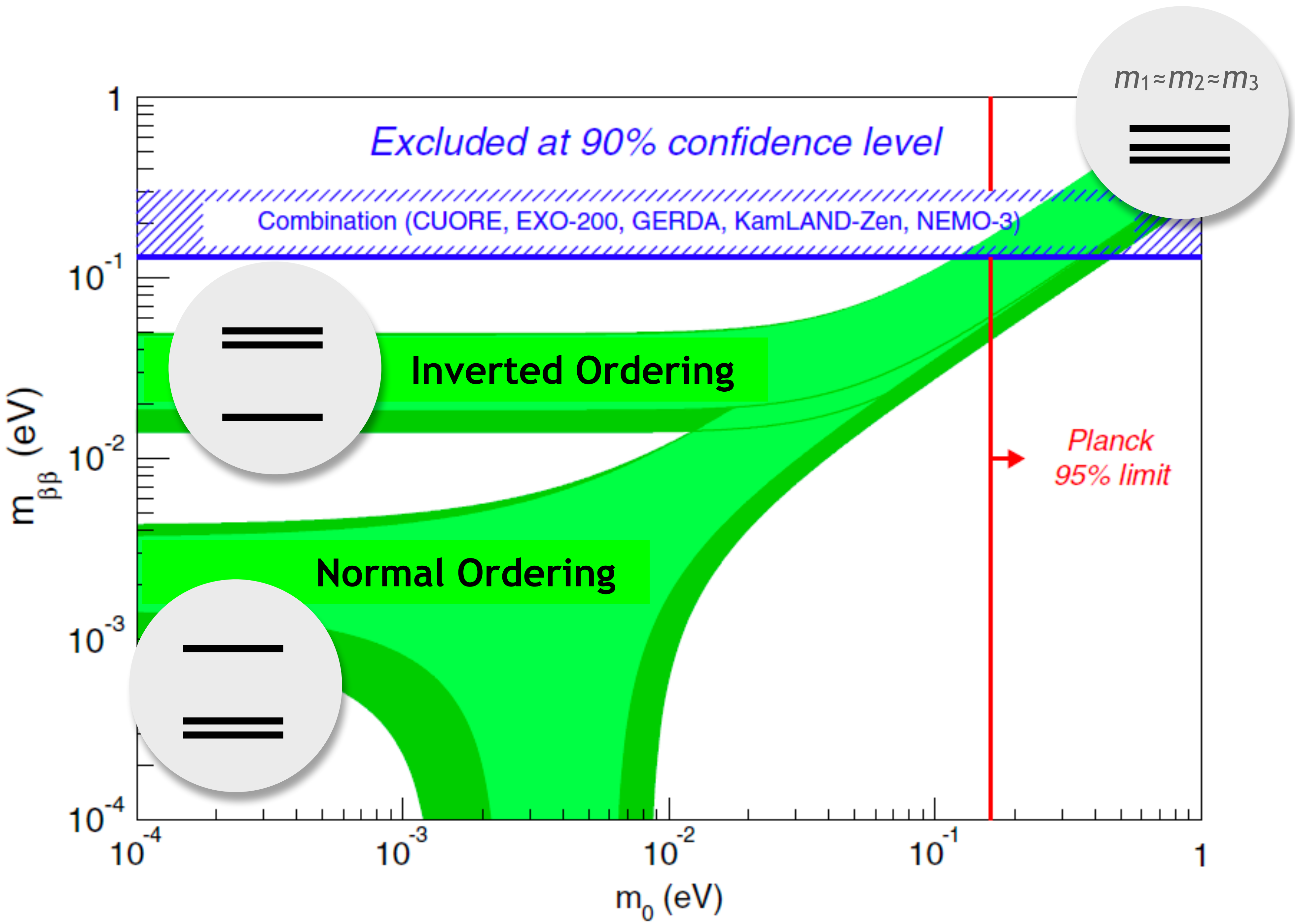
$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

➠ quasi degenerate for $m_{lightest} > \sqrt{\Delta m^2} \approx 50$ meV

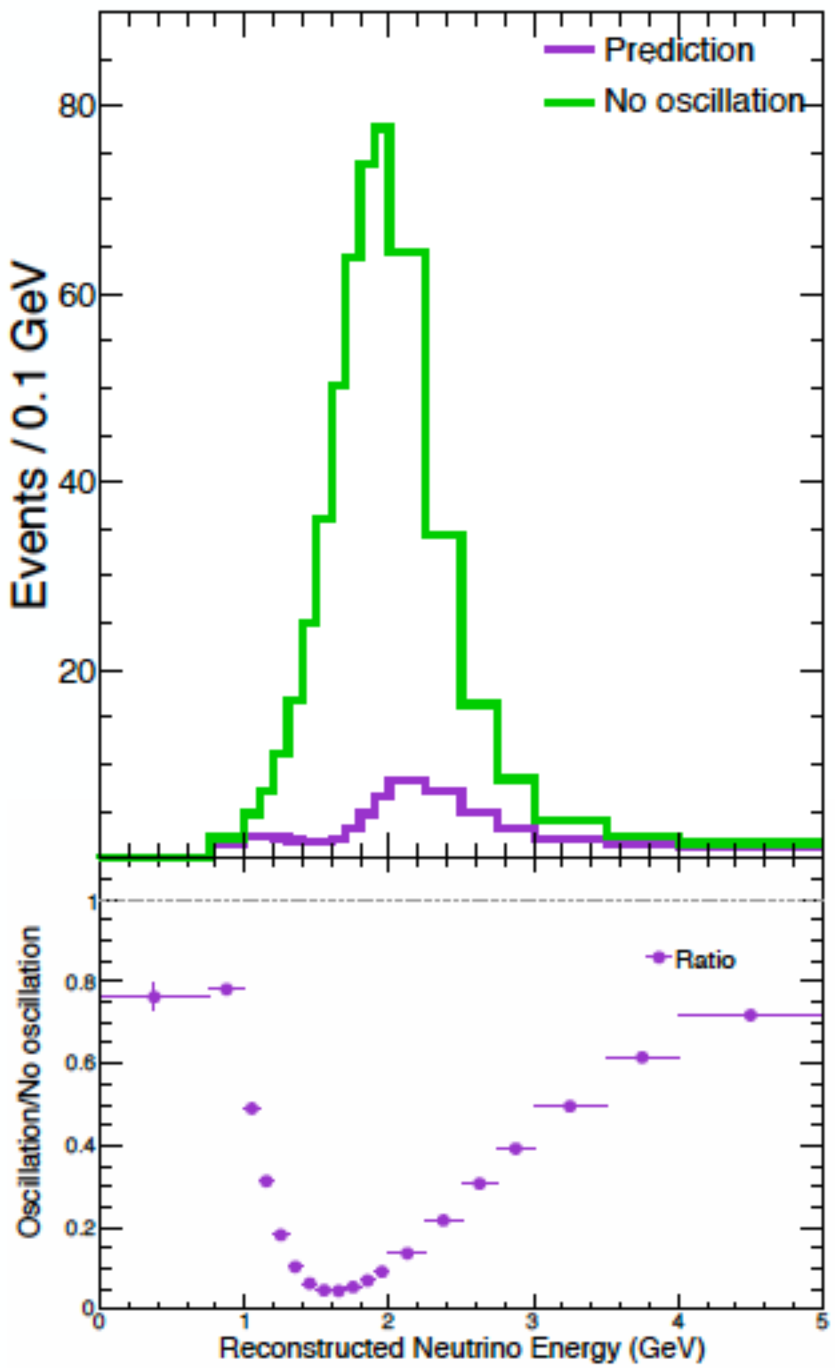
best limits from cosmology (Planck + BAO)

see lecture by Ch. Yèche

Neutrinoless Double Beta Decay



2-Neutrino Transition Probabilities



2-Neutrino Transition probability

$$P_{\nu_\alpha \to \nu_\beta} = P_{\nu_\beta \to \nu_\alpha} = \sin^2 2\theta \, \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

Survival probability

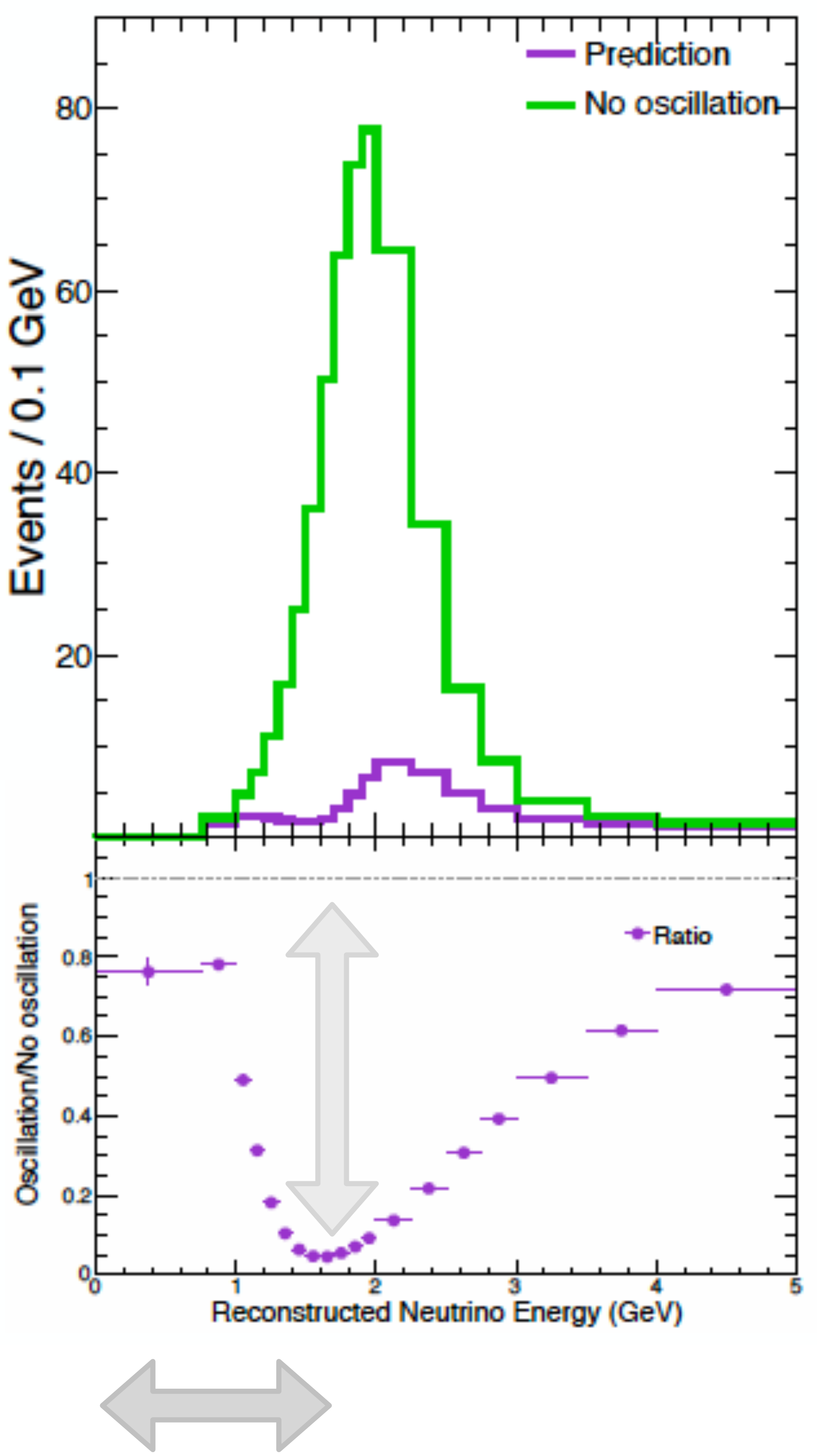
$$P_{\nu_\alpha \to \nu_\alpha} = P_{\nu_\beta \to \nu_\beta} = 1 - P_{\nu_\alpha \to \nu_\beta}$$

to be integrated over energy and distance, and convoluted with cross section, resolution, efficiency, etc.

An example: disappearance at NOvA

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \, \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right)$$

Transition Probabilities



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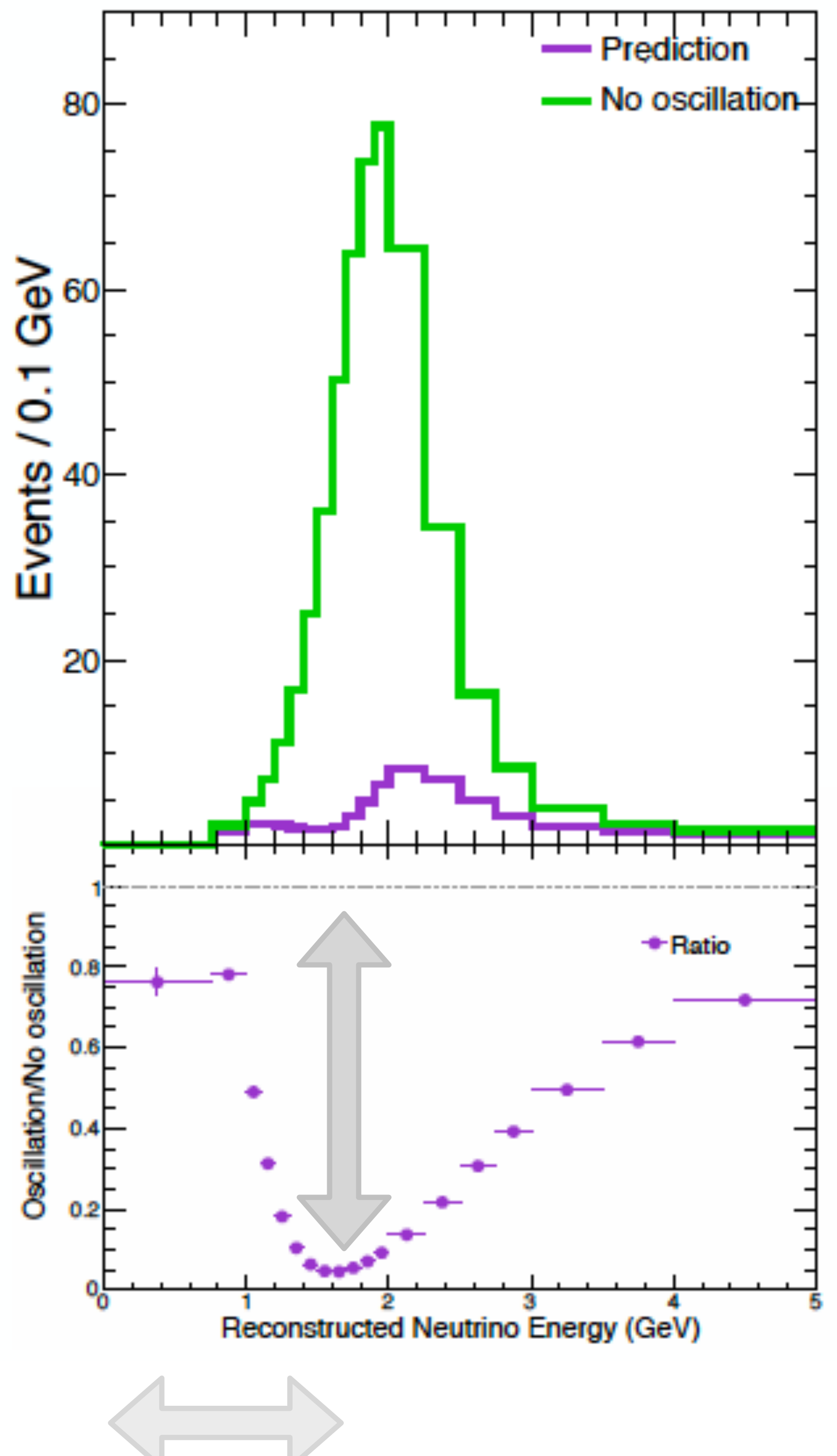
to be integrated over energy and distance, and convoluted with cross section, resolution, efficiency, etc.

frequency

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \, \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right)$$

Transition Probabilities



Transition probability

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to be integrated over energy and distance, and convoluted with cross section, resolution, efficiency, etc.

amplitude

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \, \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right)$$

Neutrino Flavour Transition in Vacuum

Transition probability:

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} \; - 4\sum_{i<j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ji}\,\frac{L}{4E}\right)$$

CP conserving

$$\mp\, 2\sum_{i<j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \;\sin\left(\Delta m^2_{ji}\,\frac{L}{2E}\right)$$

CP violating

$$\alpha, \beta = \mathrm{e}, \mu, \tau$$

$$\Delta m^2_{ji} \equiv m^2_j - m^2_i$$

time dependence on

- mass squared differences
- L(=baseline)/E(=energy) ratio

Jarlskog rephasing invariant:

$$J_{\mathrm{CP}} = -\sum_{i<j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \; = \pm J$$

with $J = c_{12}s_{12}c_{23}s_{23}c^2_{13}s_{13}\sin\delta_{\mathrm{CP}}$

CP Violation in Vacuum

$$A^{\rm CP}_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$

$$= -16 J_{\rm CP} \sin\left(\Delta m^2_{21}\frac{L}{4E}\right) \sin\left(\Delta m^2_{31}\frac{L}{4E}\right) \sin\left(\Delta m^2_{32}\frac{L}{4E}\right)$$

Necessary conditions for study of CP violation

- sensitivity to all three mixing angles
- sensitivity to atmospheric and solar oscillations

Jarlskog rephasing invariant:

$$J_{\rm CP} = -\sum_{i<j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \quad = \pm J$$

all CP violation effects are proportional to *J*

with $\quad J = c_{12} s_{12} c_{23} s_{23} c^2_{13} s_{13} \sin\delta_{\rm CP}$

$$J^{\rm max}_{\rm CP} = 0.033 \pm 0.001$$

Despite the large value of the phase, γ = (71 ± 5)°, CP violation effects are small in CKM due to small mixing angles

to be compared with the Jarlskog invariant of the CKM matrix

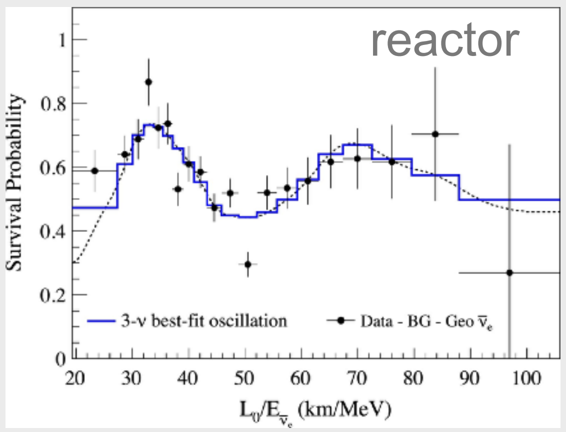
$$J^{\rm CKM}_{\rm CP} = (3.0 \pm 0.2) \times 10^{-5}$$

In the neutrino sector, CP violating effects can be much larger, depending on $\delta_{\rm CP}$

From 2- to 3-Neutrino Effects

disappearance and...

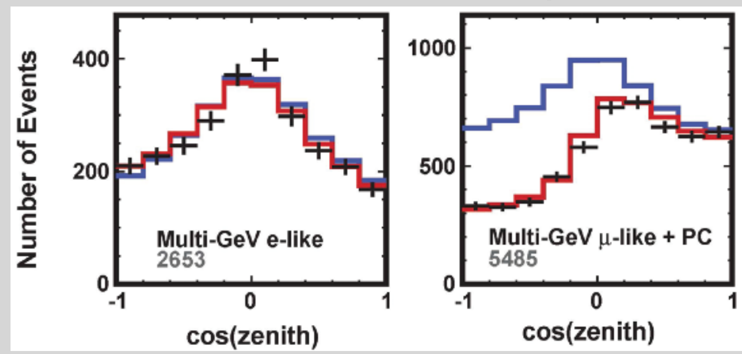
e → e δm^2 θ_{12}



KamLand

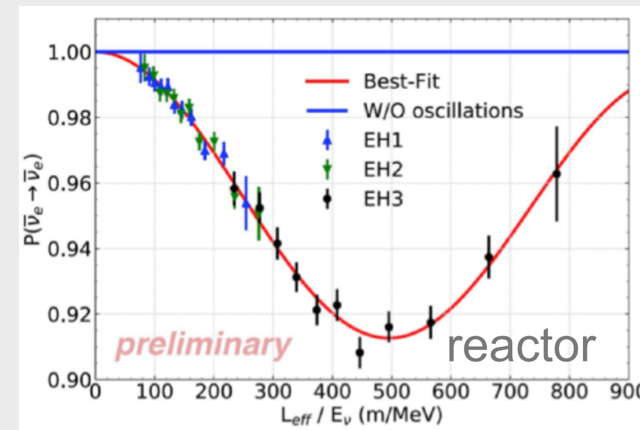
μ → μ Δm^2 θ_{23}

atmospheric



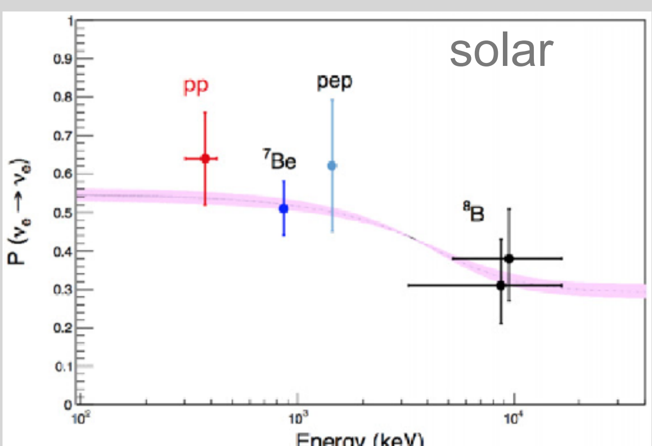
Super K

e → e Δm^2 θ_{13} θ_{23}



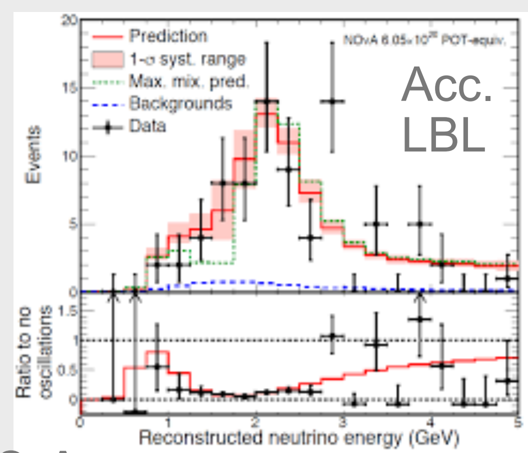
Daya Bay

e → e δm^2 θ_{12}



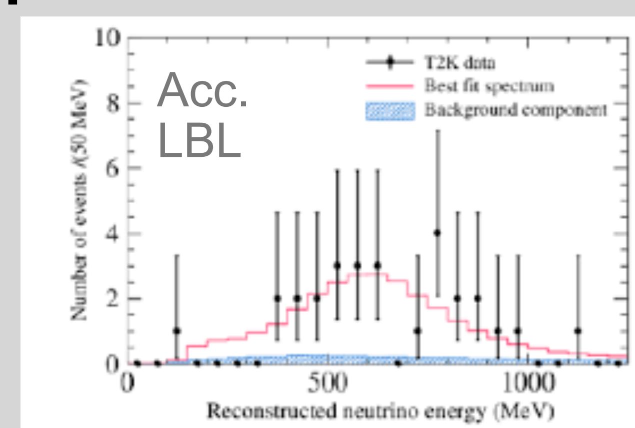
Borexino

μ → μ Δm^2 θ_{23}



NOvA

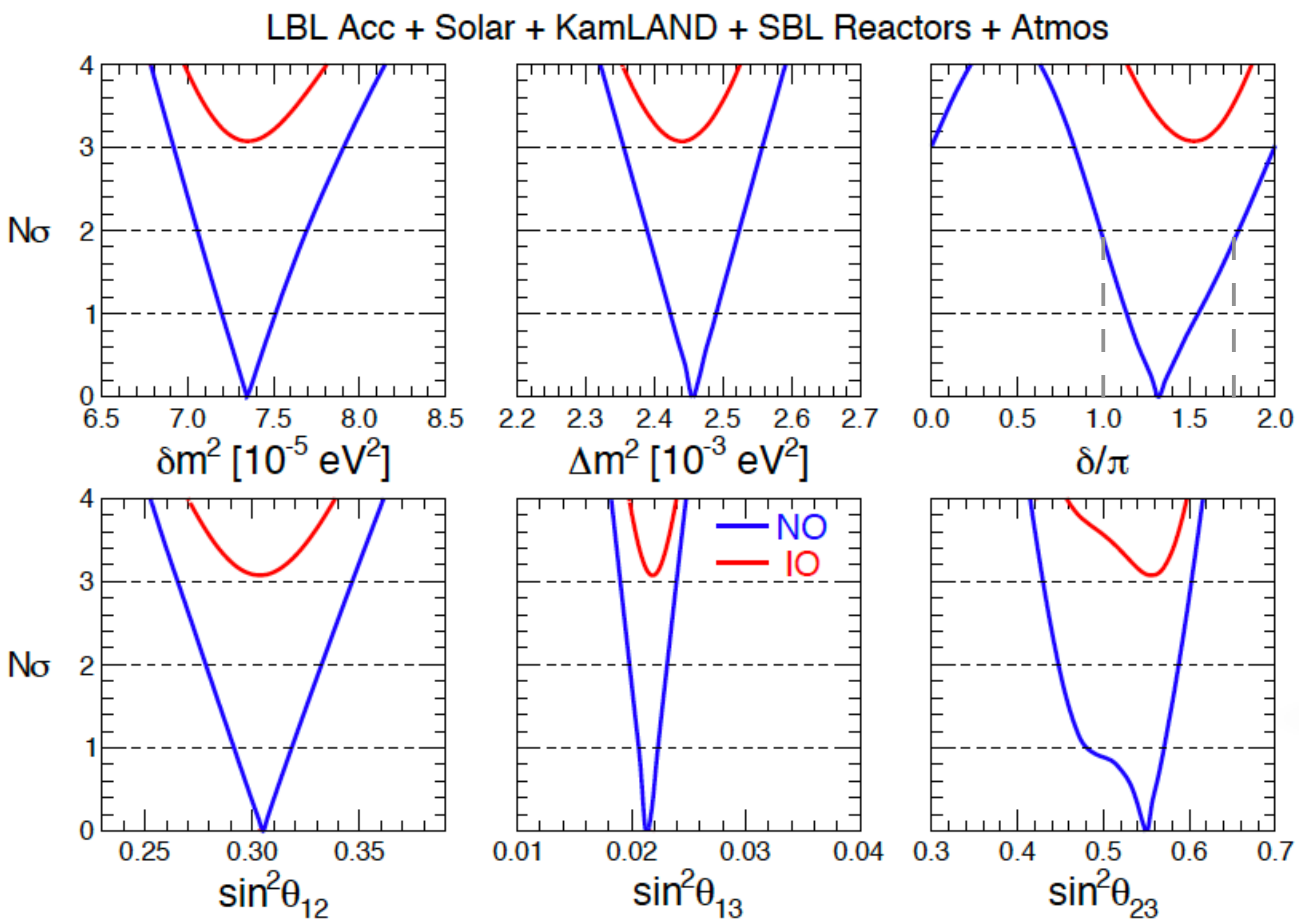
μ → e Δm^2 θ_{13} θ_{23}

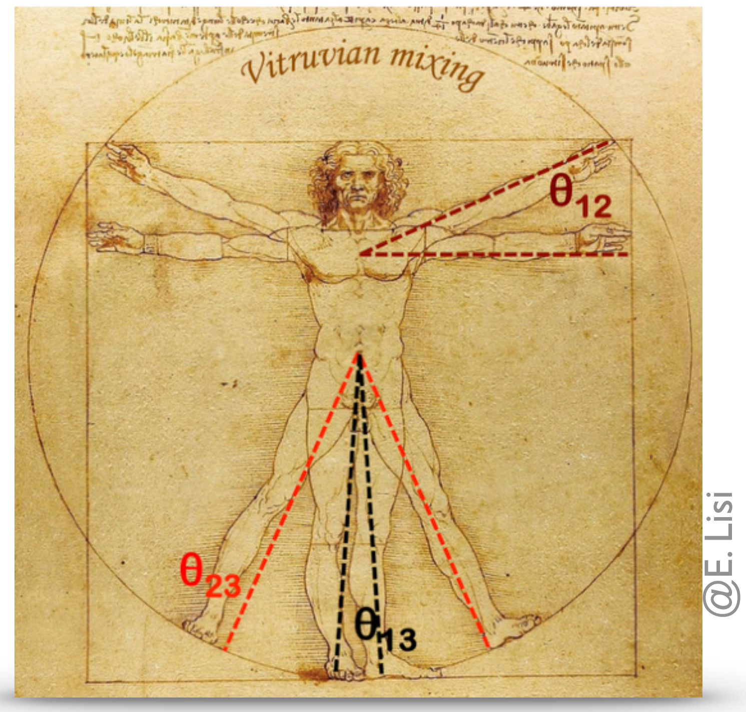


T2K

appearance

Present Knowledge of PMNS





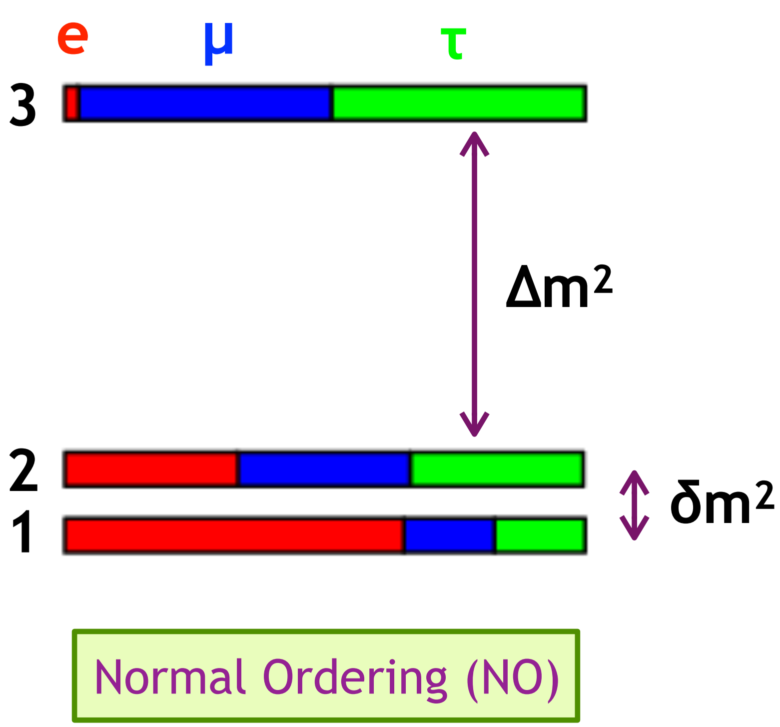
- the Normal Ordering (NO) hypothesis is favoured (at the 3σ level)
- the CP conservation hypothesis is disfavoured (at the more then 2σ level)
- the data are compatible with maximal CP violation ($\delta_{CP} = -\pi/2$)

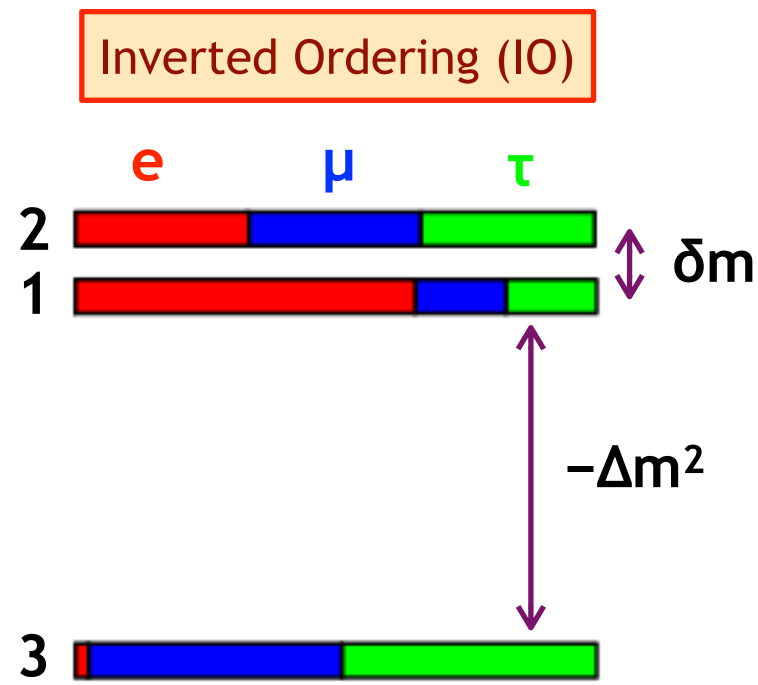
Mass Ordering

2-neutrino oscillations do not depend on the absolute mass scale:

$$m_{min} = m_1 \text{ (NO) or } m_3 \text{ (IO)}$$

➠ the sign of Δm^2 is not known



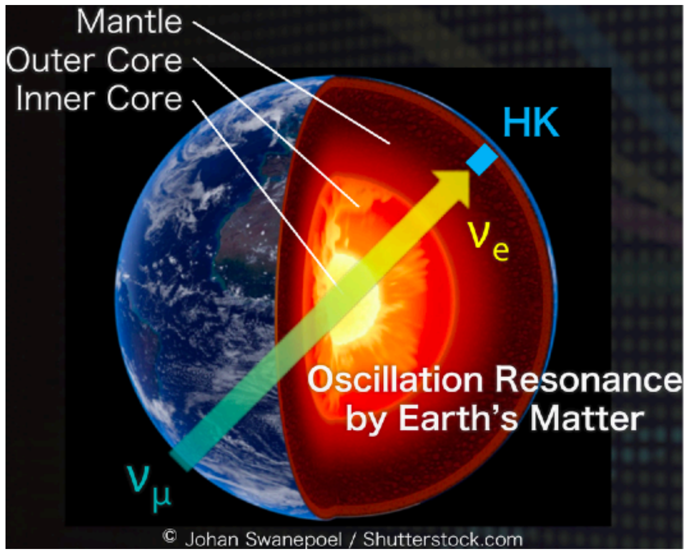


The Mass Ordering comes into play in several ways:

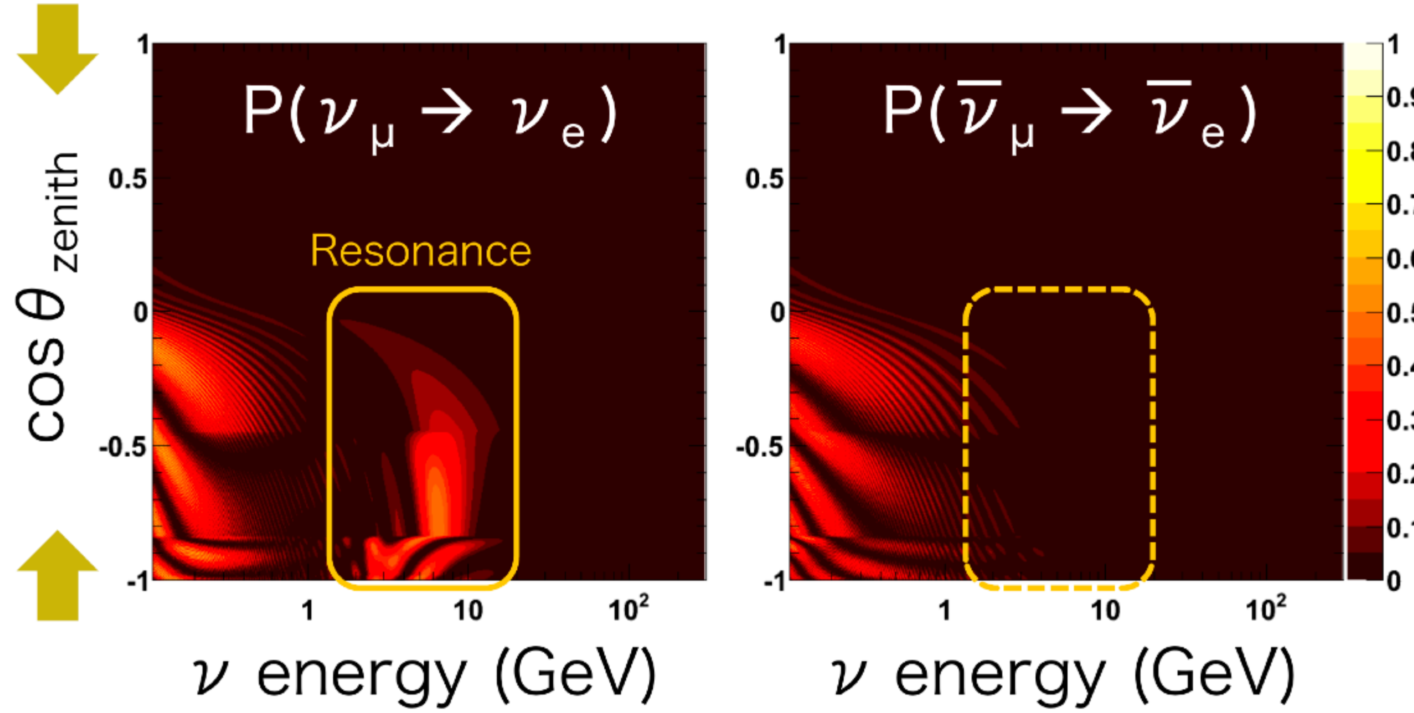
- matter effects (NSW) in the Earth
  ➠ SK/HK, IceCube/PINGU, KM3NET/ORCA
- 3-ν interference effects due to the small difference (3%) in Δm^2_{13} and Δm^2_{32}
  ➠ JUNO
- matter effects in long baseline experiments

Mass Hierarchy with Atmospheric νs

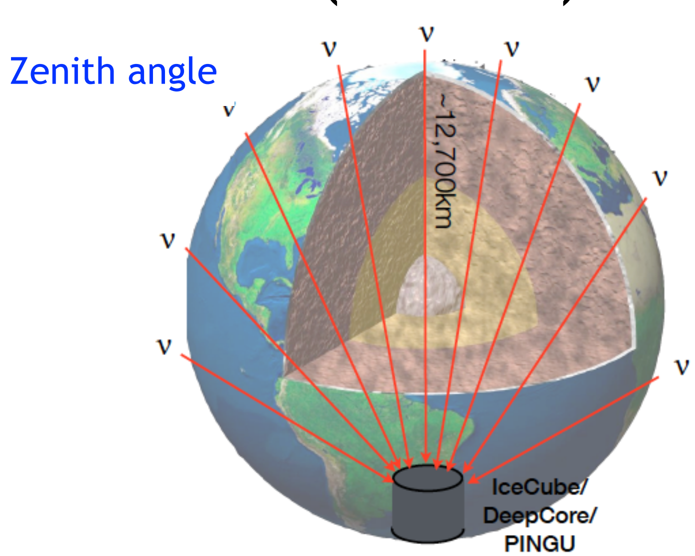
Hyper-Kamiokande



Normal Hierarchy case



PINGU (IceCube)



Mass hierarchy accessible through MSW effect in upward-going multi-GeV ν_e sample

- Normal Ordering : enhancement of $\nu_\mu \rightarrow \nu_e$
- Inverted Ordering : enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Potential to determine mass ordering (> 3σ) by 2030

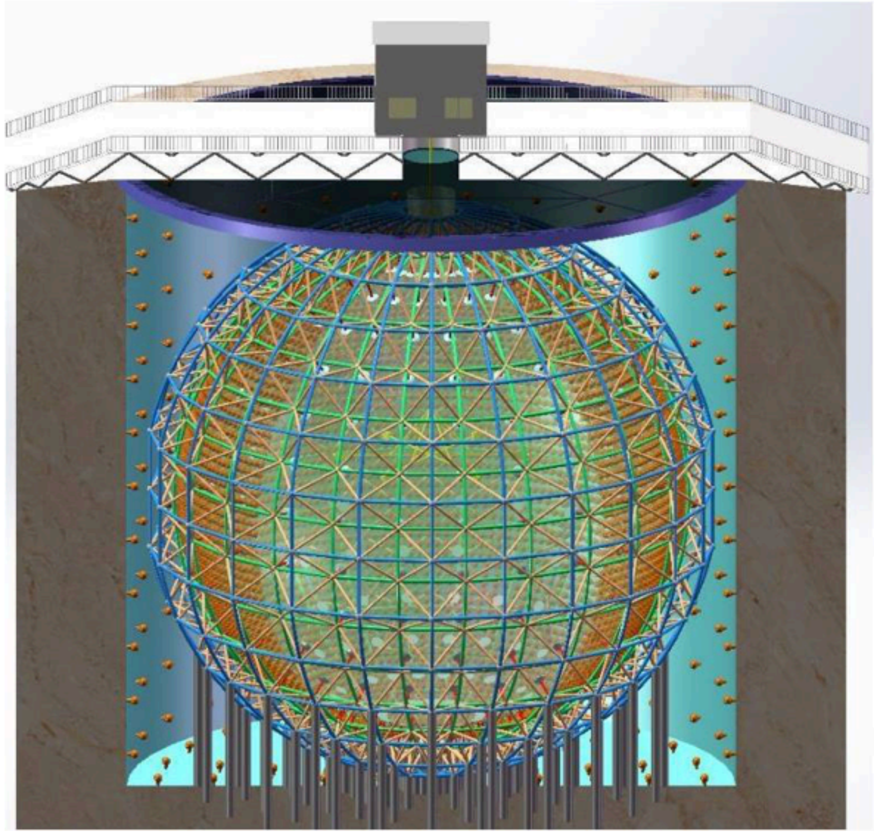
$$\sin^2 2\theta_{13}^{\mathrm{M}} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} \pm (\cos 2\theta_{13} + \sqrt{2}G_{\mathrm{F}}N_{\mathrm{e}}/\Delta m^2_{31})}$$

(mostly) $\nu/\bar{\nu}$

mass ordering

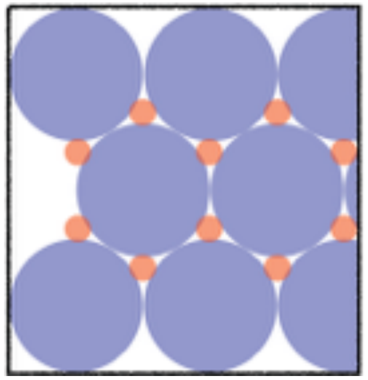
JUNO

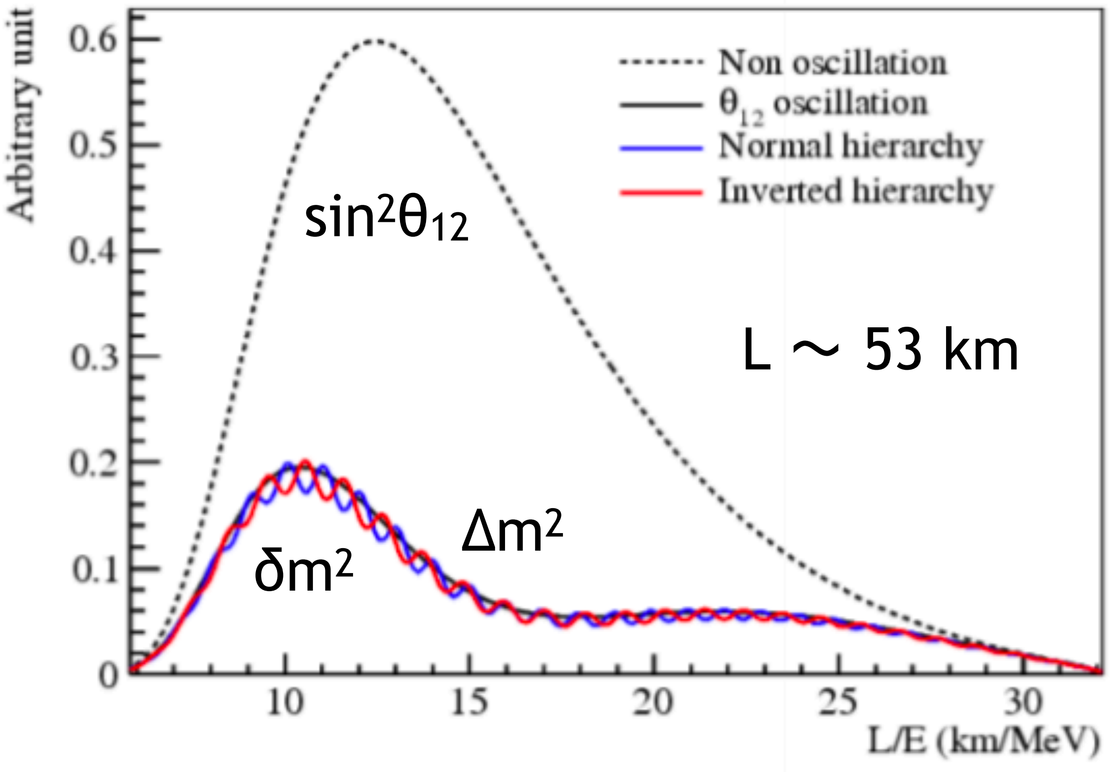
Reactor experiment in China
- 50 km baseline (2 reactors)
- 20 kt liquid scintillator detector
- 3% energy resolution @ 1 MeV



~2021

PMT coverage > 75%

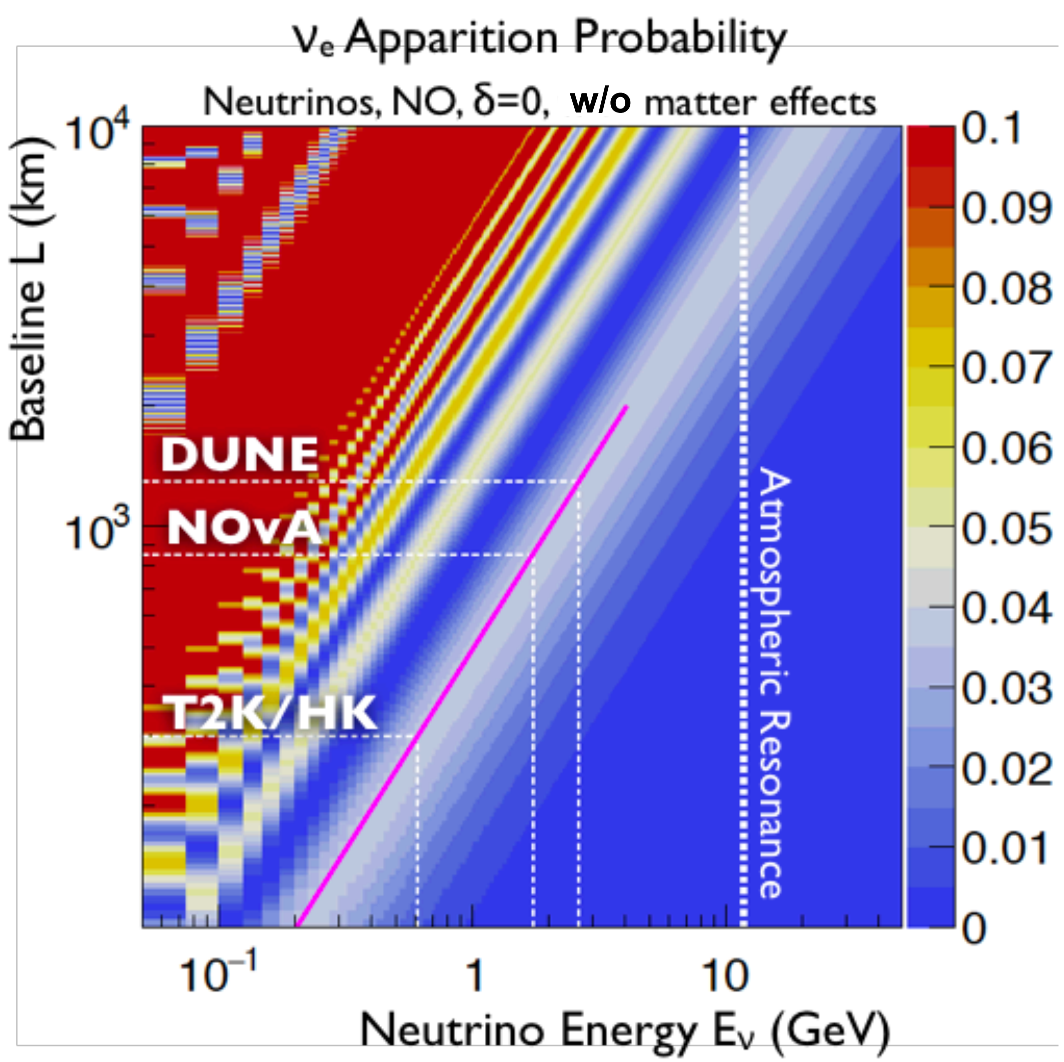




$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\Delta m_{21}^2 L/4E\right) - c_{12}^2 \sin^2 2\theta_{13} \sin^2\left(\Delta m_{31}^2 L/4E\right) - s_{12}^2 \sin^2 2\theta_{13} \sin^2\left(\Delta m_{32}^2 L/4E\right)$$

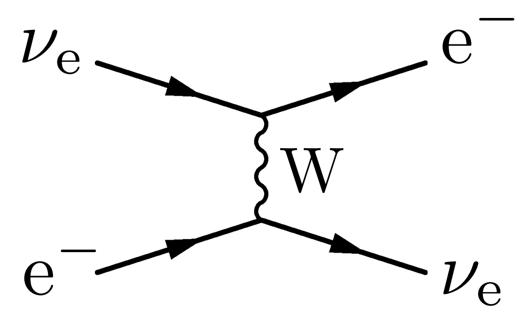
- MO at 4σ in 6 years
- percent level measurements of $\sin^2\theta_{12}$, δm^2 and Δm^2

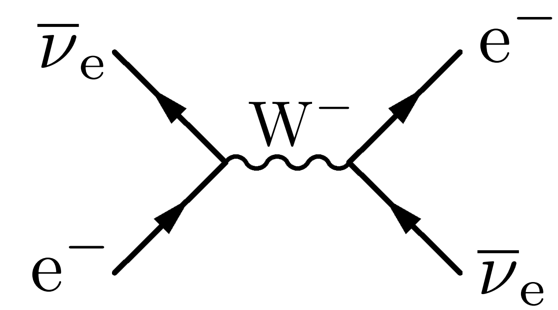
Matter Effects in LBL Experiments



Neutrinos and antineutrinos travel through matter not antimatter

- electron density in matter causes an asymmetry via CC coherent forward elastic scattering





- this effectively modifies the flavour mixing angles (larger effect between ν_1 and ν_3)

$$\tan 2\theta_{13}^{M} =$$

$$\tan 2\theta_{13}/(1 - 2EV_{CC}/\Delta m_{13}^2 \cos 2\theta_{13})$$

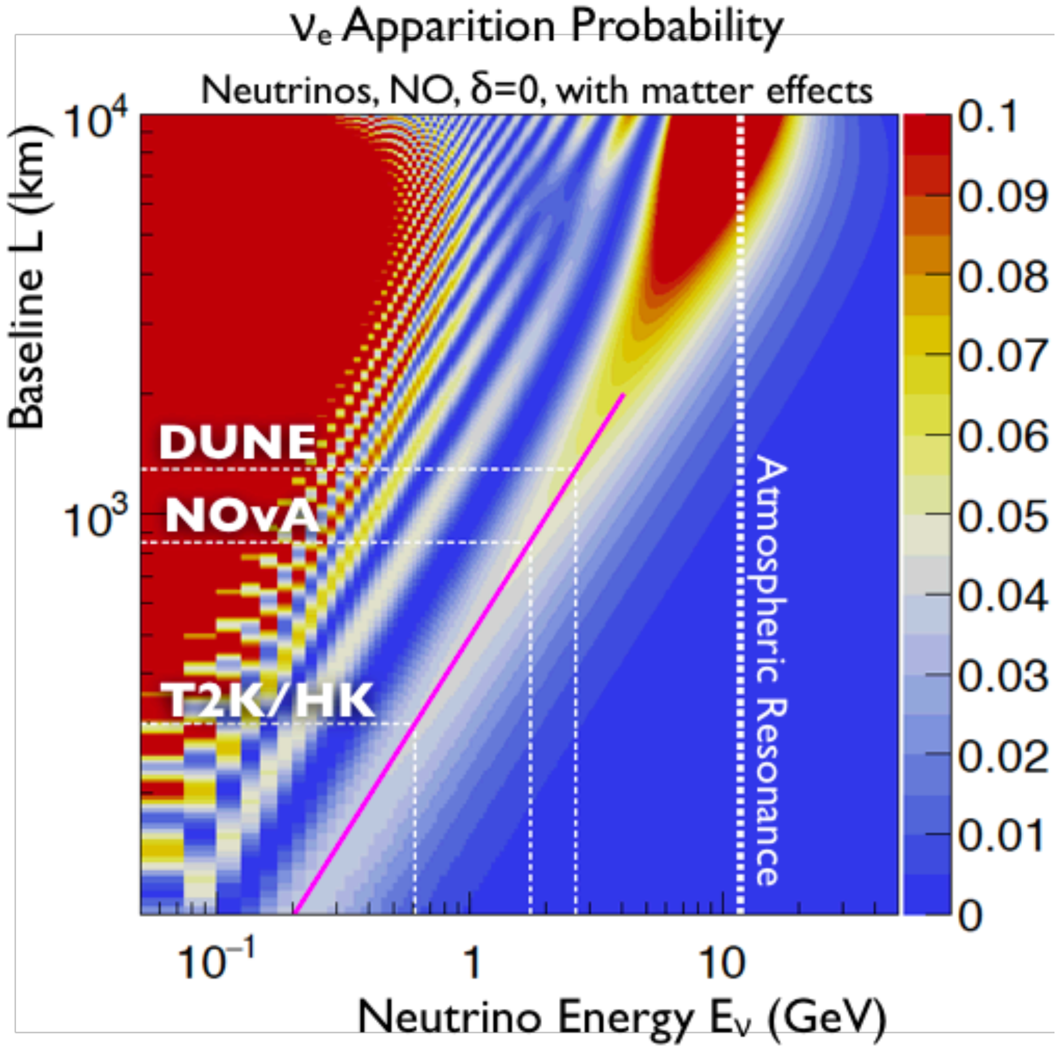
where

$$V_{CC} = \sqrt{2} G_F N_e$$

potential due to coherent forward scattering

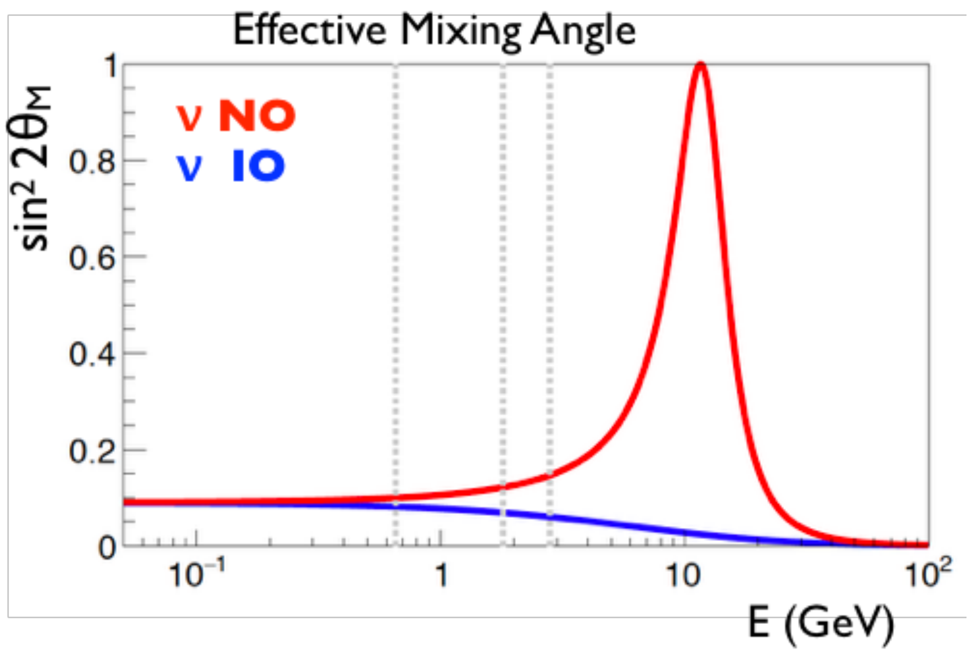
- this depends on the electron density N_e and on the Mass Ordering (sign of Δm^2_{13})
- for antineutrinos $V_{cc} \rightarrow -V_{cc}$

Matter Effects in LBL Experiments



A MSW resonance situation occurs for

- neutrinos in Normal Ordering
- antineutrinos in Inverse Ordering



$$E_{\rm res} = |\Delta m^2_{31}| \cos 2\theta_{13} / 2\sqrt{2} G_{\rm F} N_{\rm e}$$

$$\frac{\Delta m^2 L}{4E} = 1.27 \frac{\Delta m^2 [\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

For Earth mantle density ρ = 2.6 g/cm³,

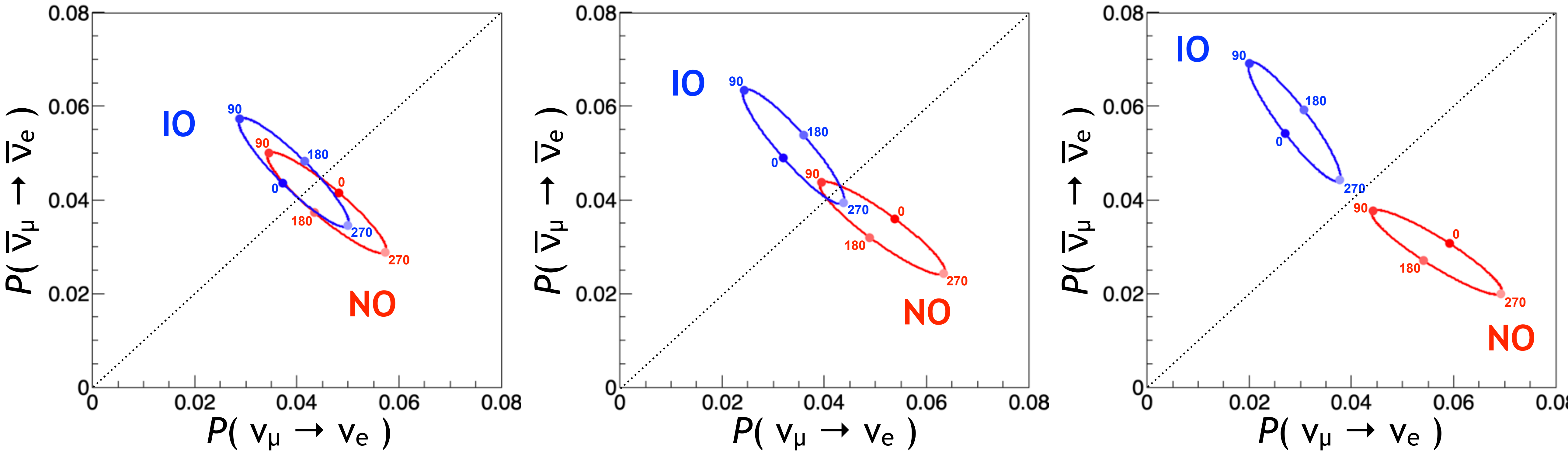
E_{res} ≈ 10 GeV

➠ for a given *L*/*E*, matter effects are larger for longer baselines

CP Violation vs Matter Effects

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs $P(\nu_\mu \to \nu_e)$ Fixed L/E = 450 km/GeV

T2K/HK L = 295 km **NoVA** L = 800 km **DUNE** L = 1 300 km



E = 660 MeV

E = 1.8 GeV

E = 2.9 GeV

At given L/E, **larger baseline** means **higher energy**, hence **bigger matter effect**, hence **more fake CP violation**

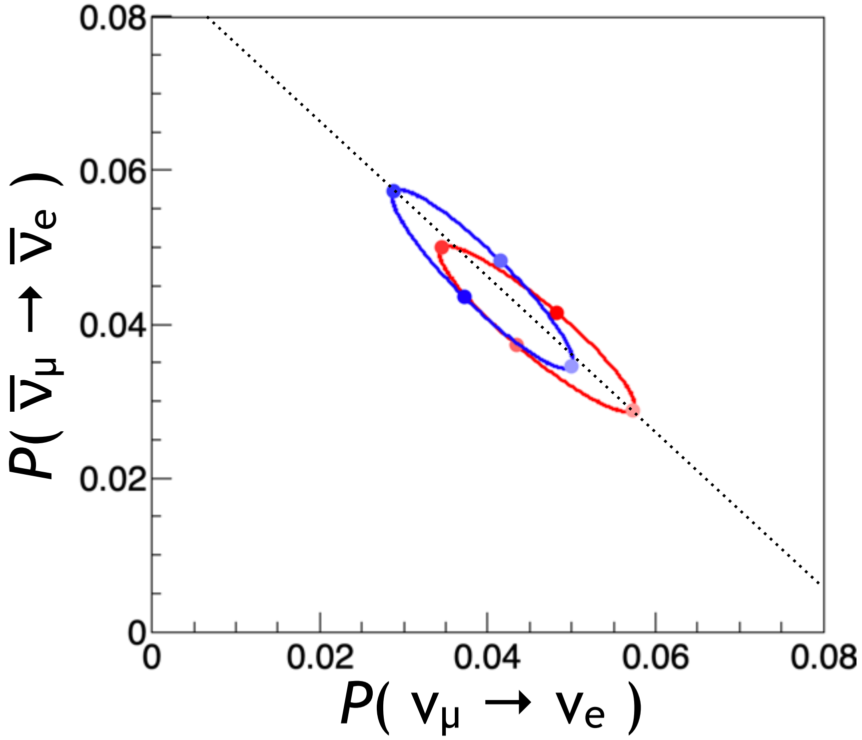
$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{13} = 0.022$

CP Violation vs Matter Effects

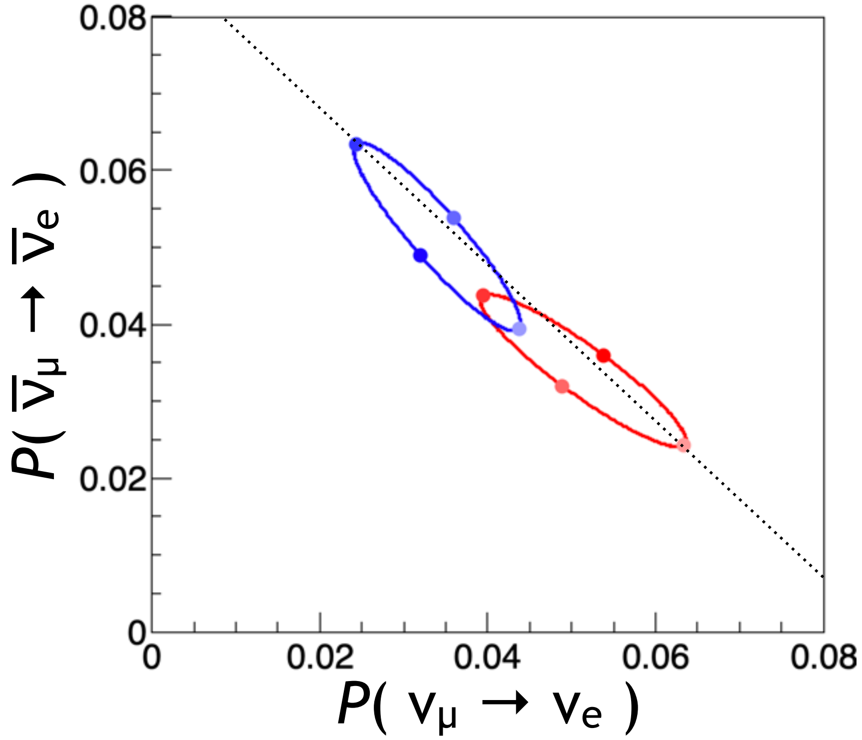
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $P(\nu_\mu \rightarrow \nu_e)$ Fixed L/E = 450 km/GeV

T2K/HK L = 295 km



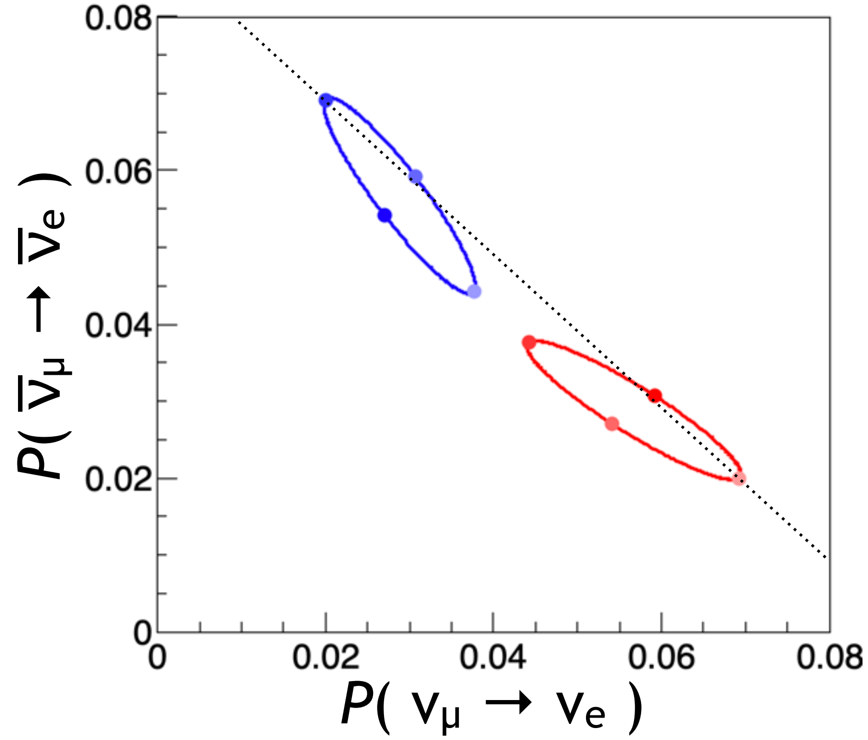
E = 660 MeV

NoVA L = 800 km



E = 1.8 GeV

DUNE L = 1 300 km



E = 2.9 GeV

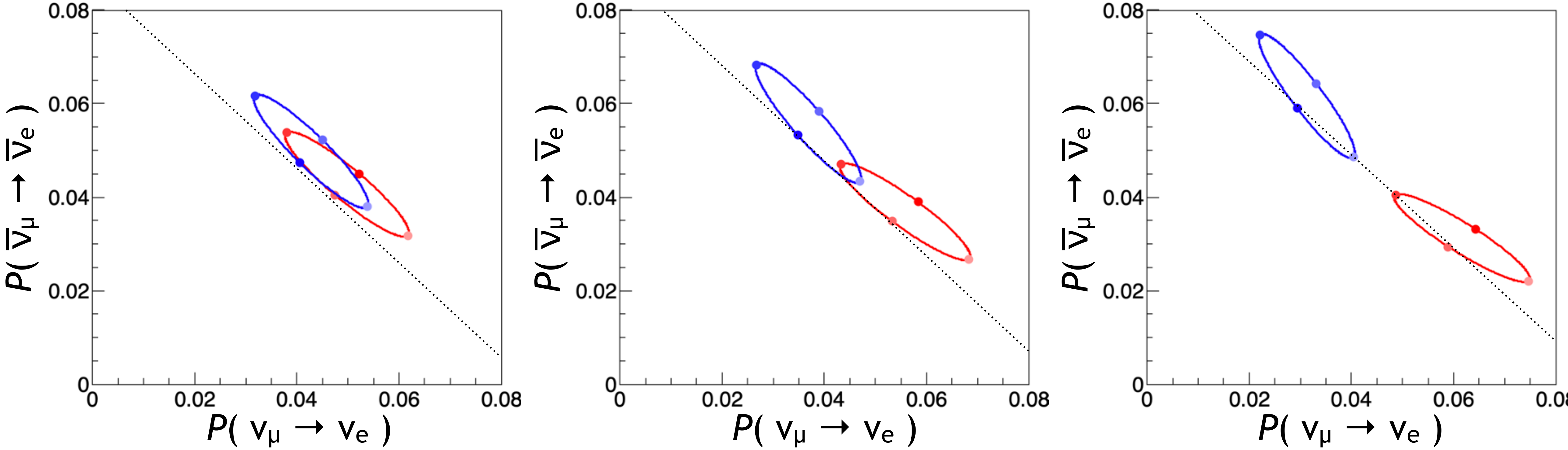
$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{13} = 0.022$

CP Violation vs Matter Effects

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $P(\nu_\mu \rightarrow \nu_e)$ Fixed L/E = 450 km/GeV

T2K/HK L = 295 km   **NoVA** L = 800 km   **DUNE** L = 1 300 km



E = 660 MeV   E = 1.8 GeV   E = 2.9 GeV

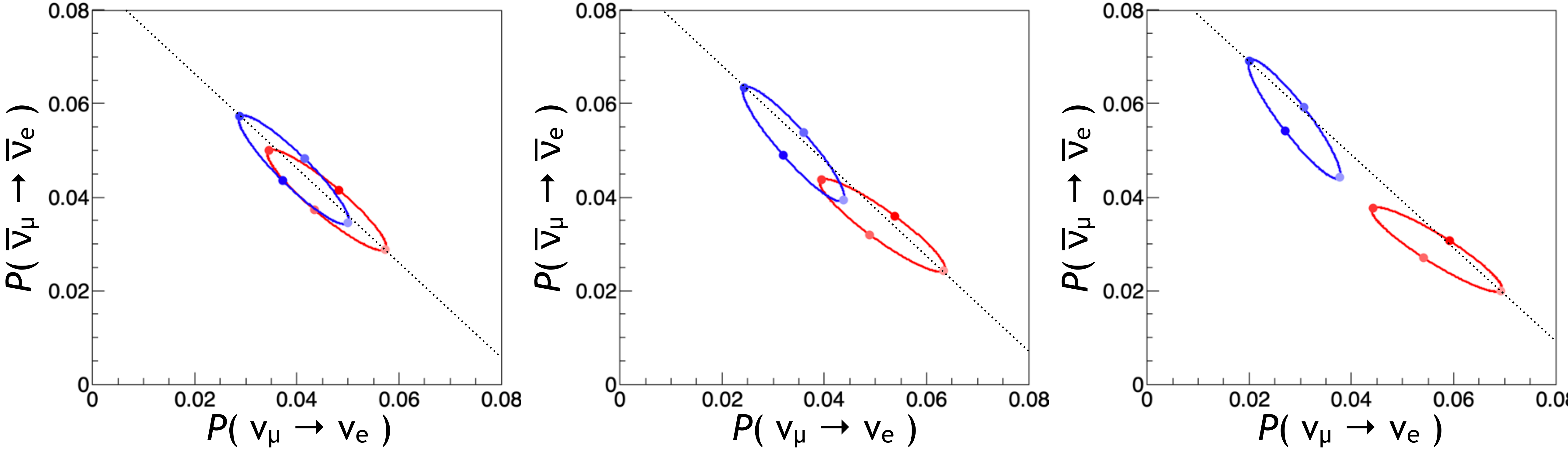
$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{13} = 0.024$

CP Violation vs Matter Effects

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs $P(\nu_\mu \to \nu_e)$ Fixed L/E = 450 km/GeV

T2K/HK L = 295 km | **NoVA** L = 800 km | **DUNE** L = 1 300 km



E = 660 MeV | E = 1.8 GeV | E = 2.9 GeV

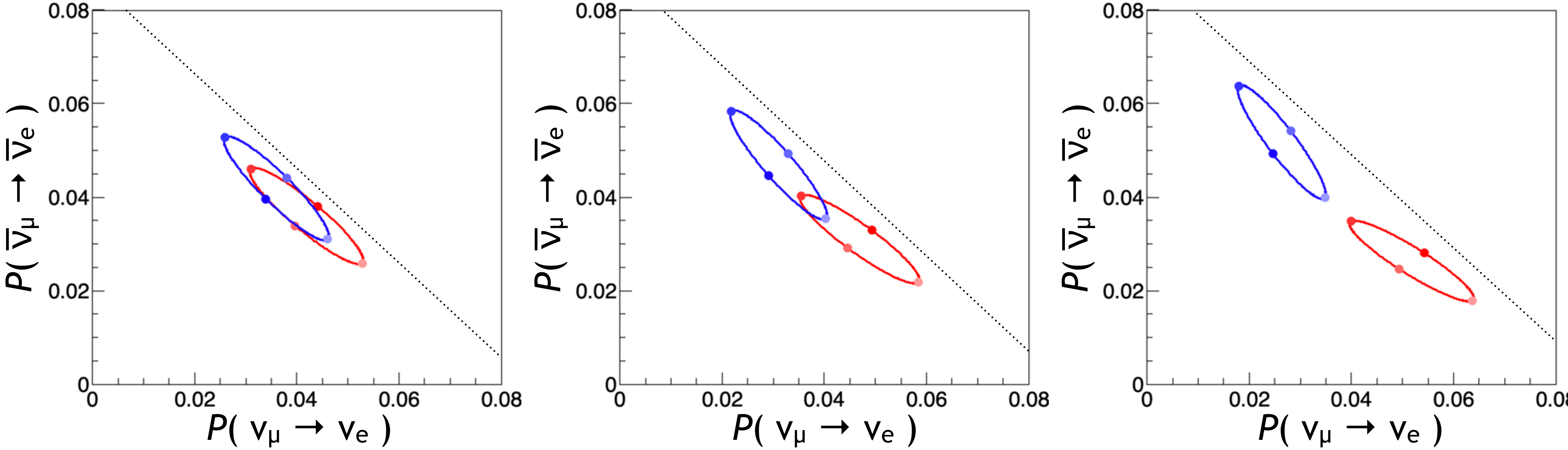
$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{13} = 0.022$

CP Violation vs Matter Effects

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $P(\nu_\mu \rightarrow \nu_e)$ Fixed L/E = 450 km/GeV

T2K/HK L = 295 km | **NoVA** L = 800 km | **DUNE** L = 1 300 km



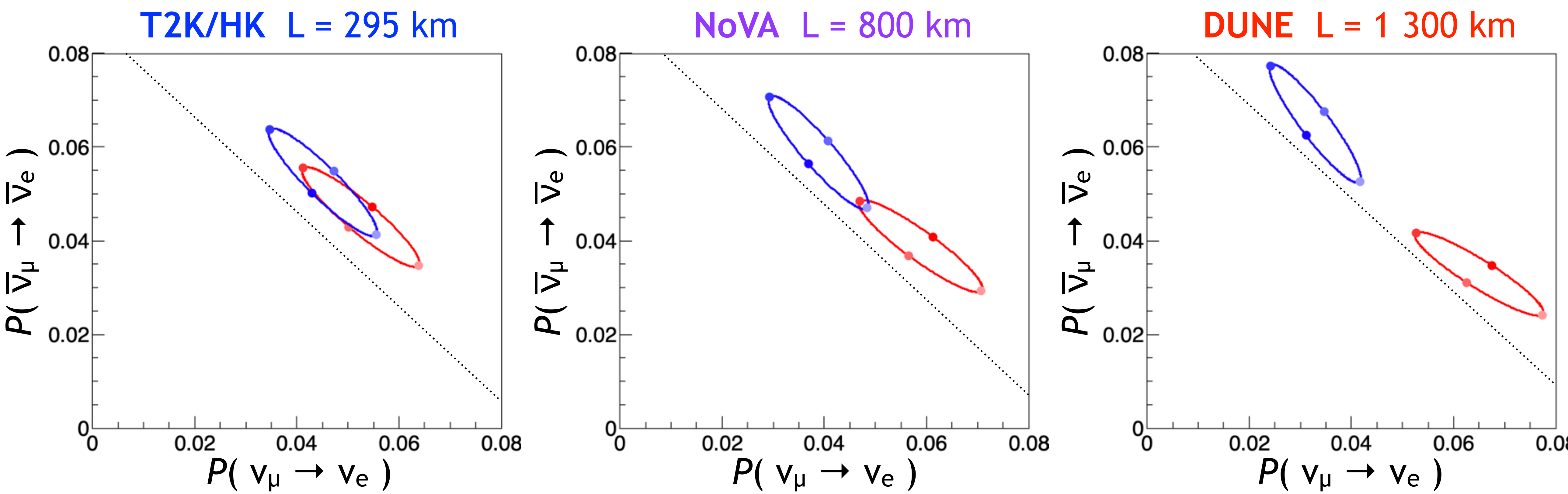
E = 660 MeV | E = 1.8 GeV | E = 2.9 GeV

$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{13} = 0.020$

CP Violation vs Matter Effects

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $P(\nu_\mu \rightarrow \nu_e)$ Fixed L/E = 450 km/GeV



E = 660 MeV

E = 1.8 GeV

E = 2.9 GeV

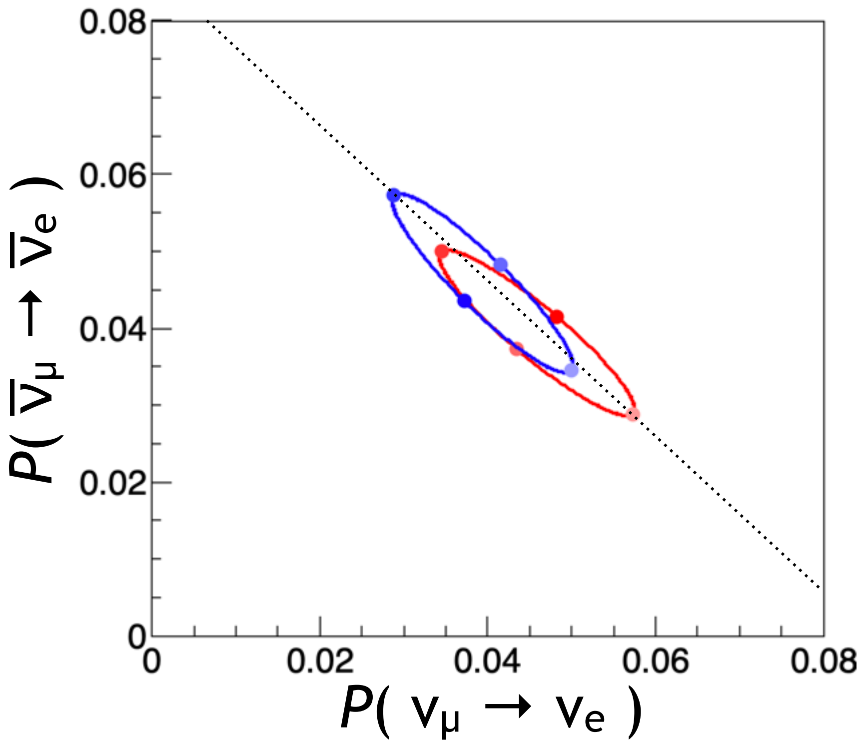
$\sin^2\theta_{23} = 0.575$

$\sin^2\theta_{13} = 0.022$

CP Violation vs Matter Effects

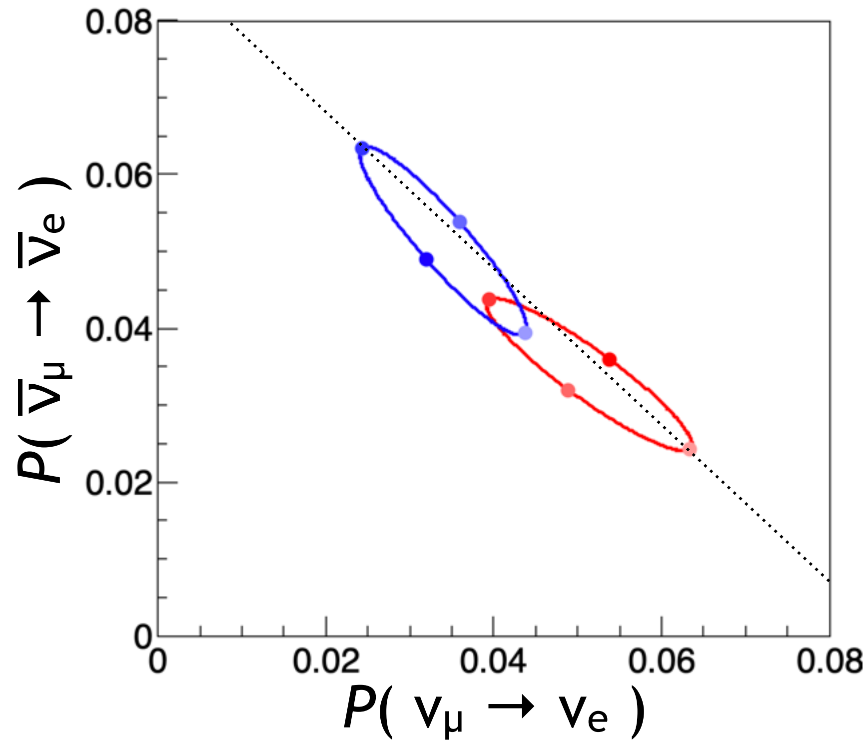
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs $P(\nu_\mu \to \nu_e)$ Fixed L/E = 450 km/GeV

T2K/HK L = 295 km



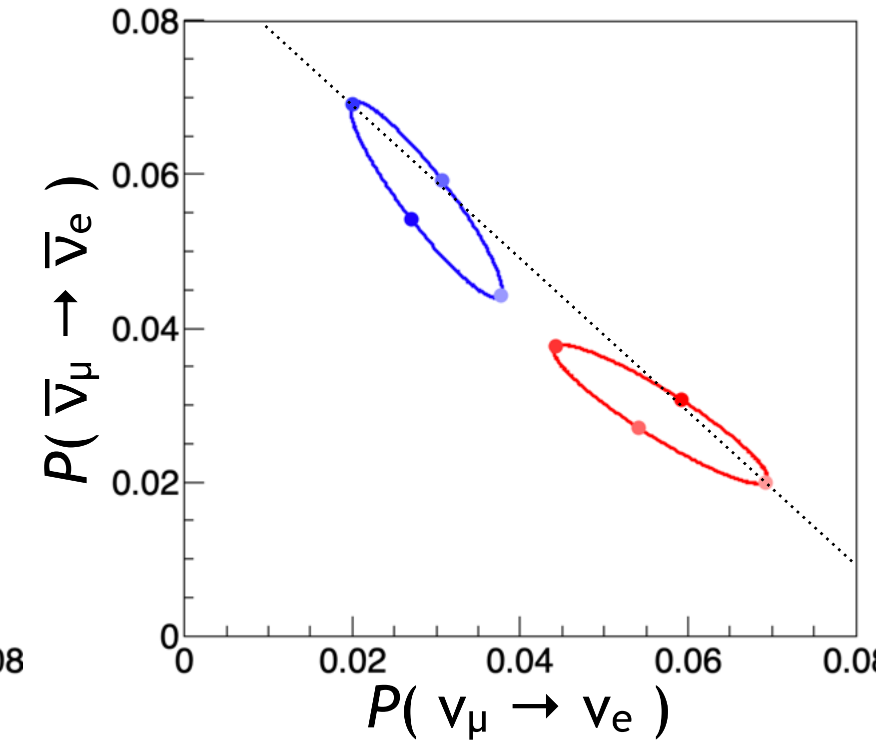
E = 660 MeV

NoVA L = 800 km



E = 1.8 GeV

DUNE L = 1 300 km

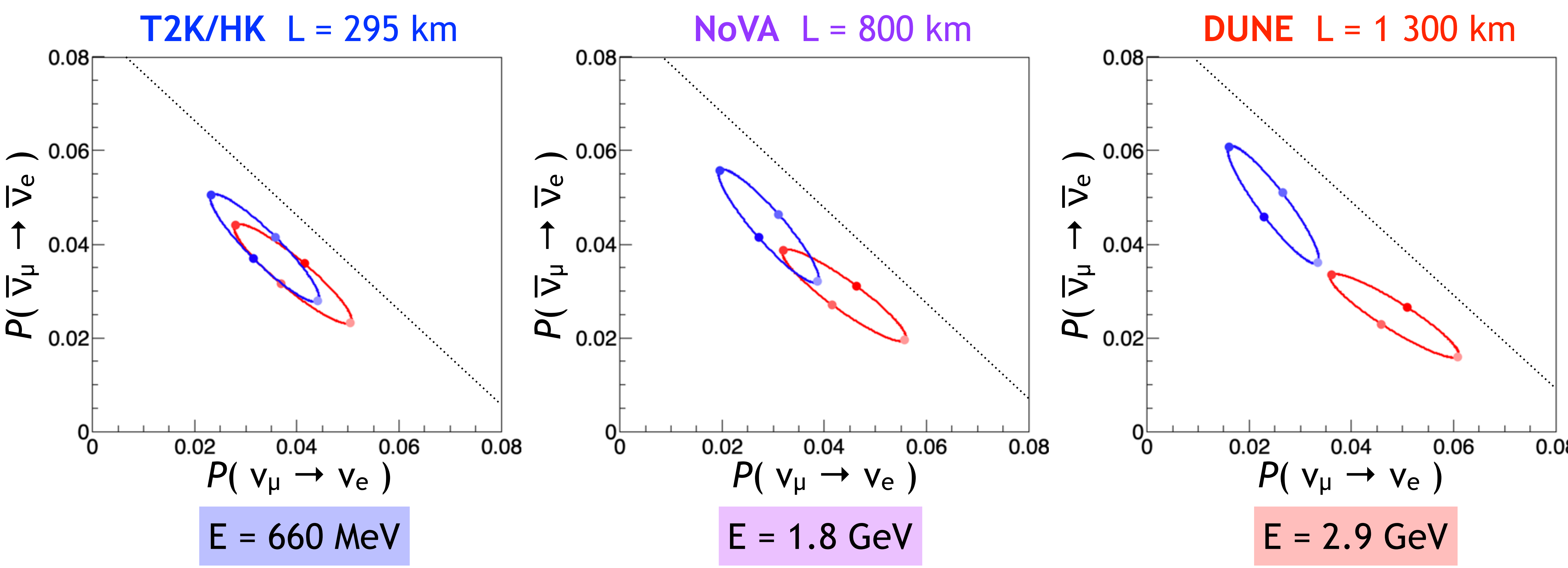


E = 2.9 GeV

$\sin^2\theta_{23} = 0.5$
$\sin^2\theta_{13} = 0.022$

CP Violation vs Matter Effects

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs $P(\nu_\mu \to \nu_e)$ Fixed L/E = 450 km/GeV

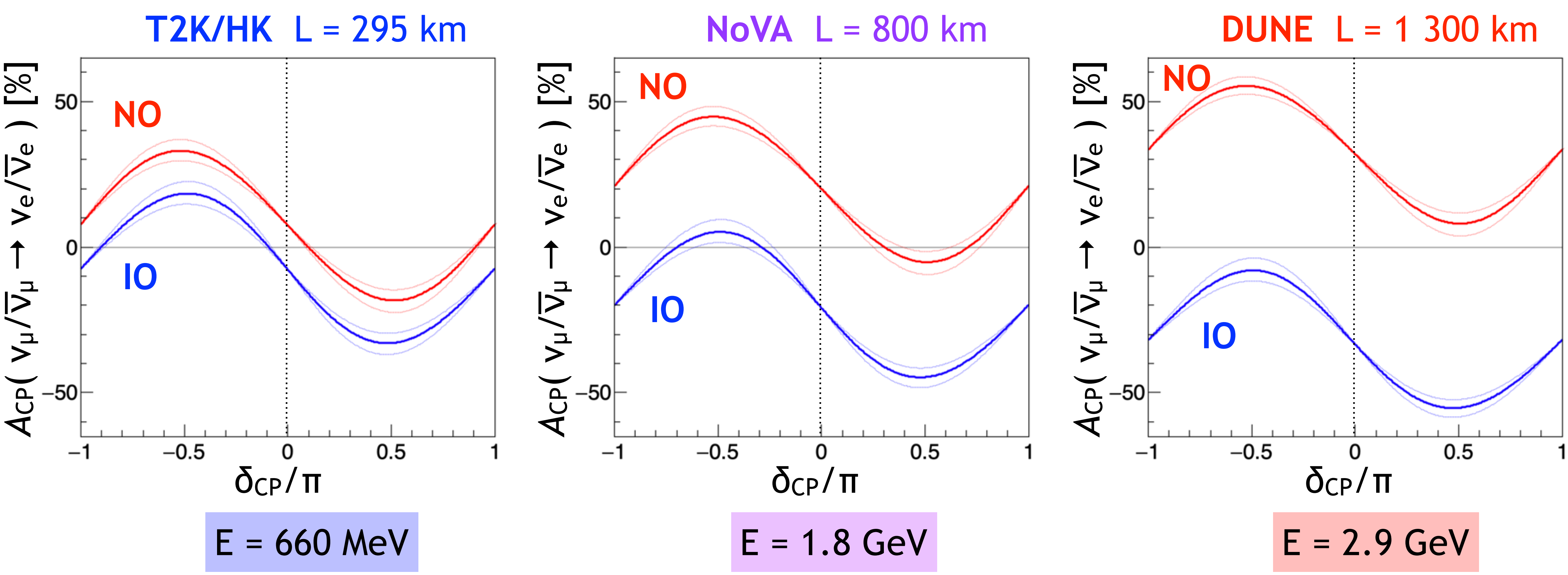


$\sin^2\theta_{23} = 0.425$
$\sin^2\theta_{13} = 0.022$

CP Asymmetries

$A_{CP}(\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e)$ [%]

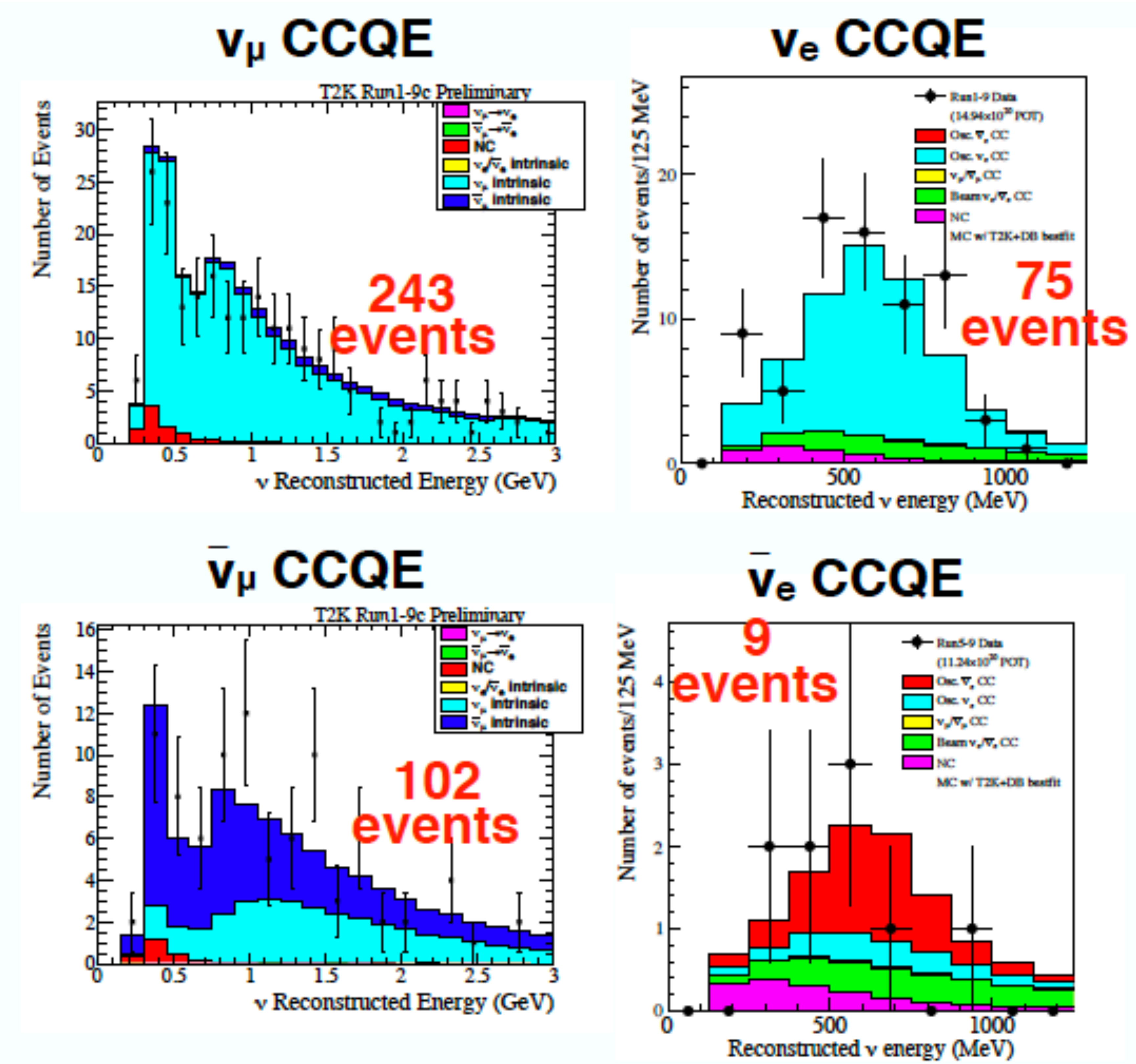
Fixed L/E = 450 km/GeV



$\sin^2\theta_{23}$ = 0.425-**0.5**-0.575

$\sin^2\theta_{13}$ = 0.022

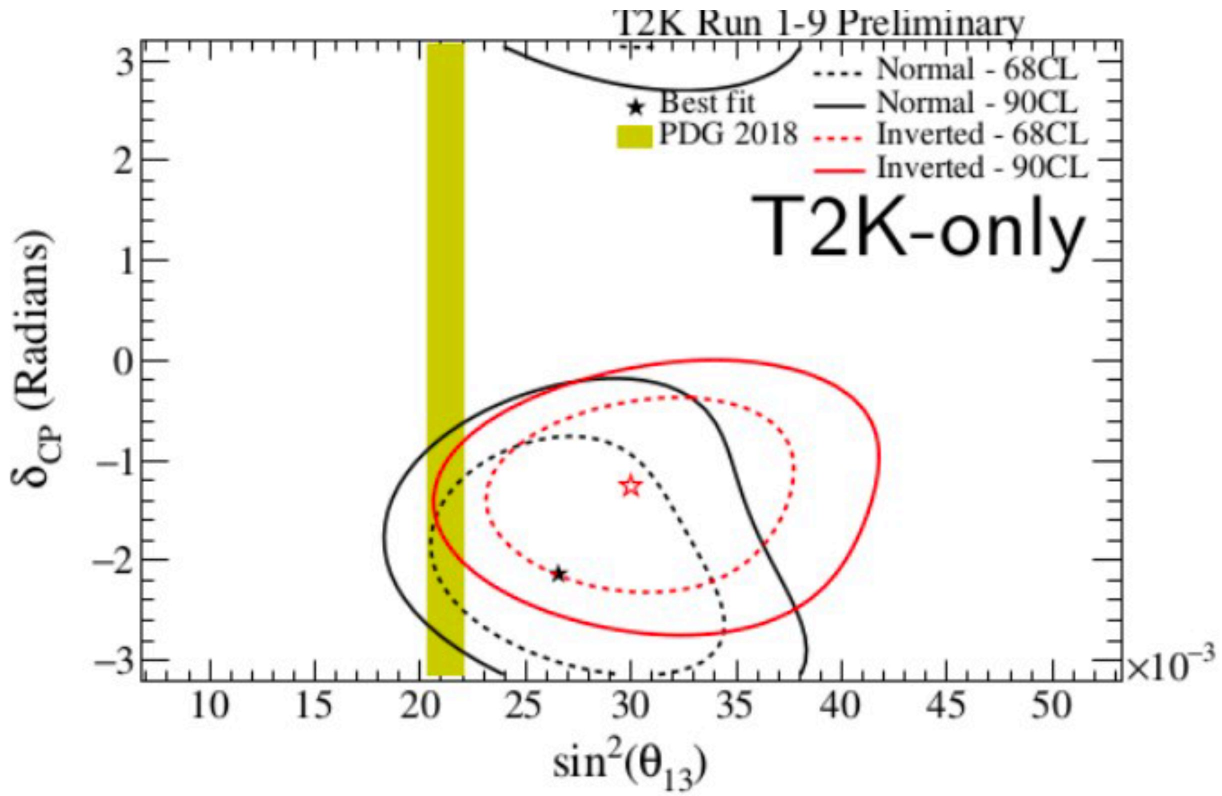
T2K: Far Detector Sample

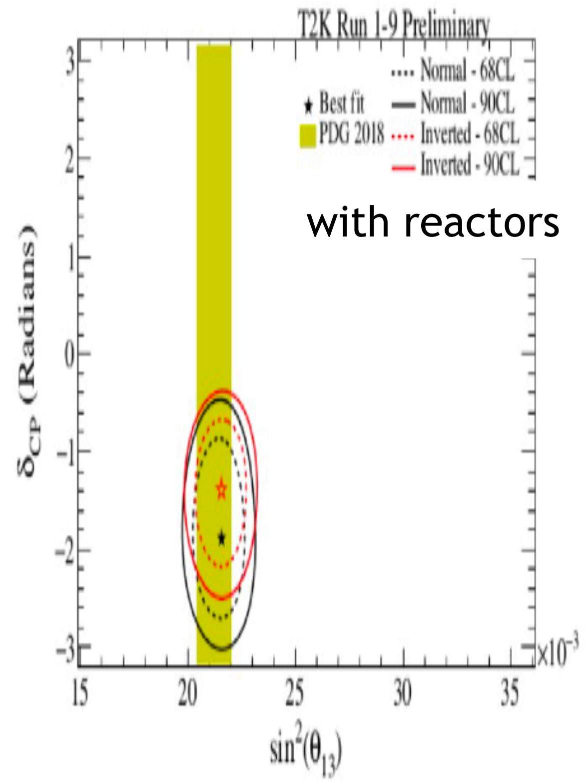


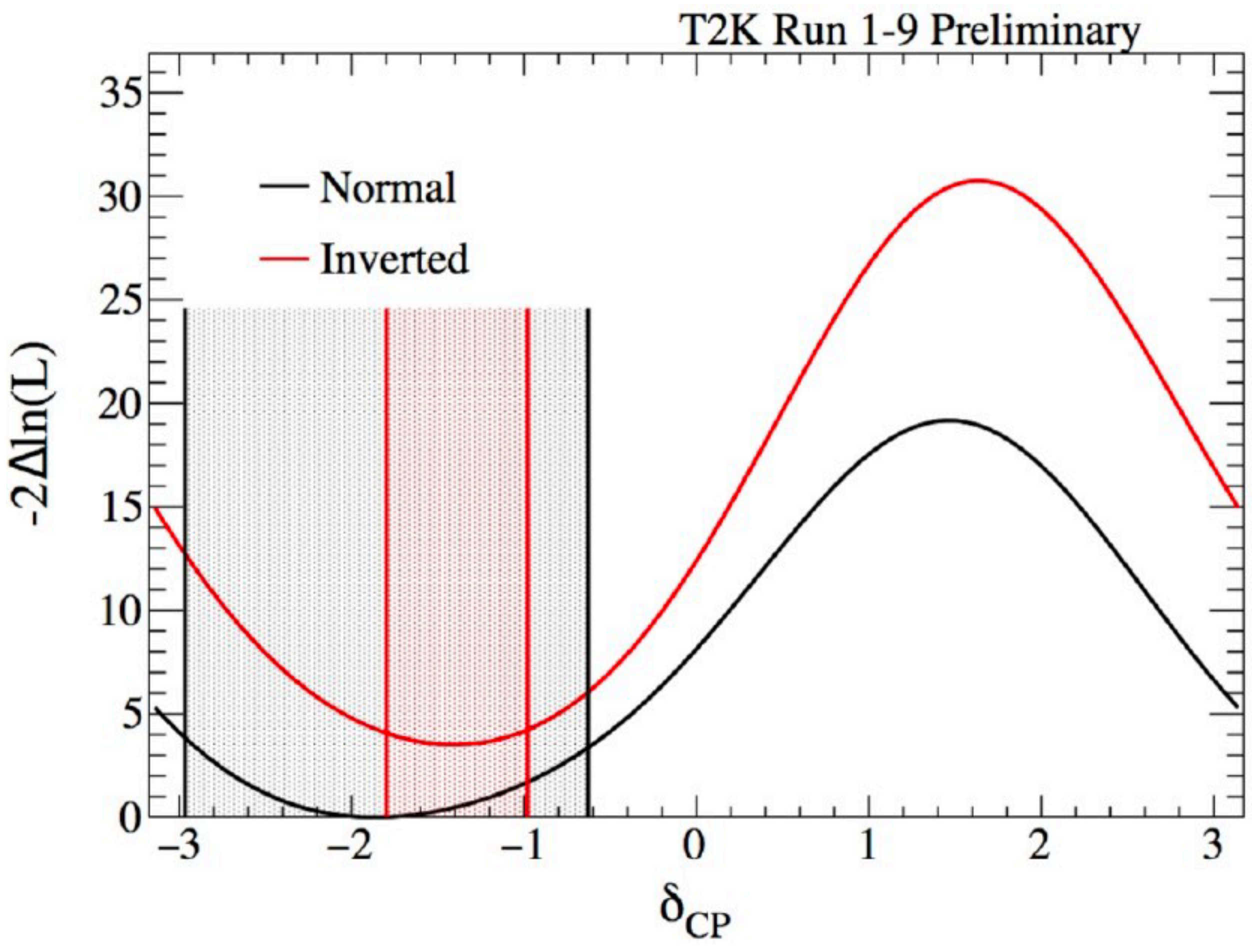
data:
3×10^{21} POT (50/50 ν and $\bar{\nu}$)

ν_μ CCQE → 243 events
$\bar{\nu}_\mu$ CCQE → 102 events
ν_e CCQE → 75 events
$\bar{\nu}_e$ CCQE → 9 events
ν_e CC1π → 15 events

T2K CP Analysis

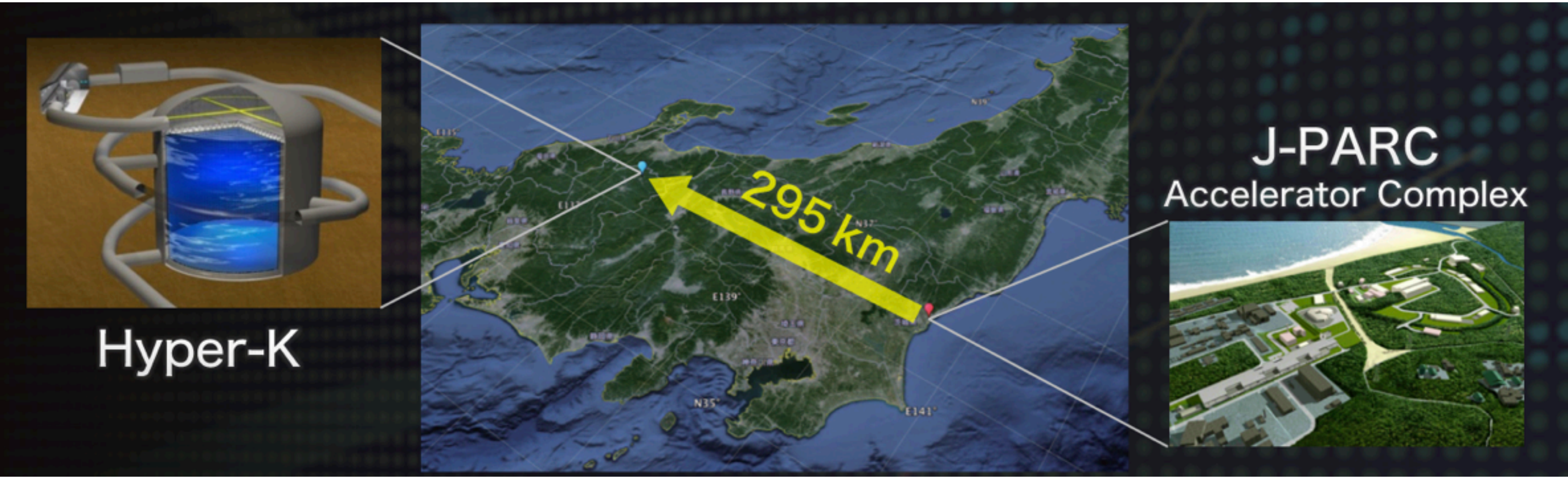




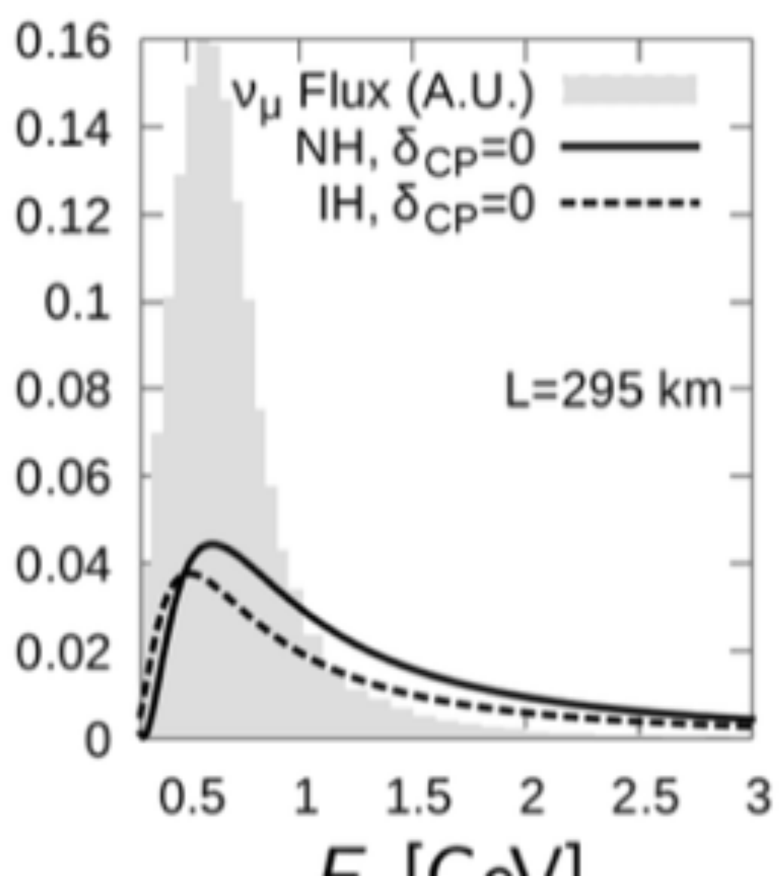


CP-conserving values (0, π) are outside the 2σ intervals for both mass ordering

JPARC/T2HK

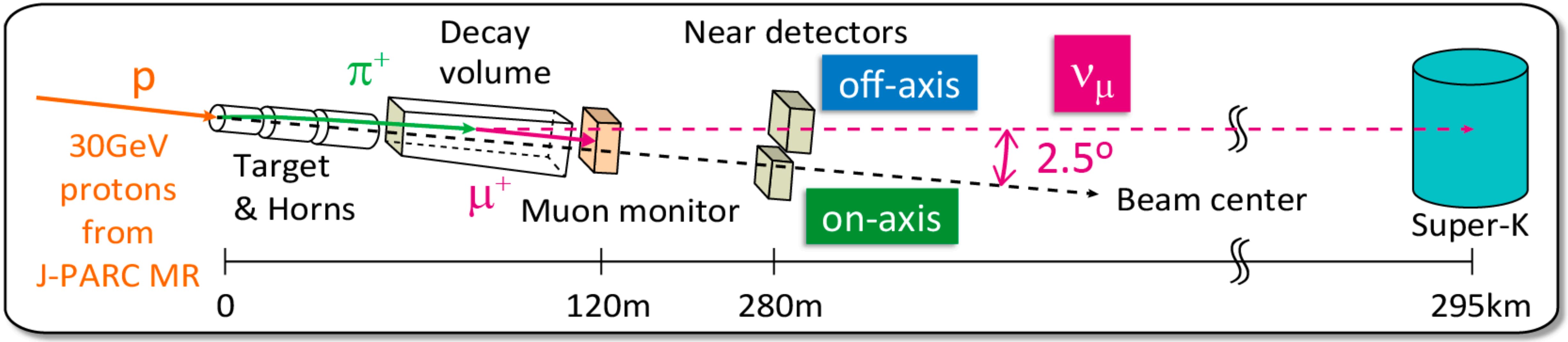


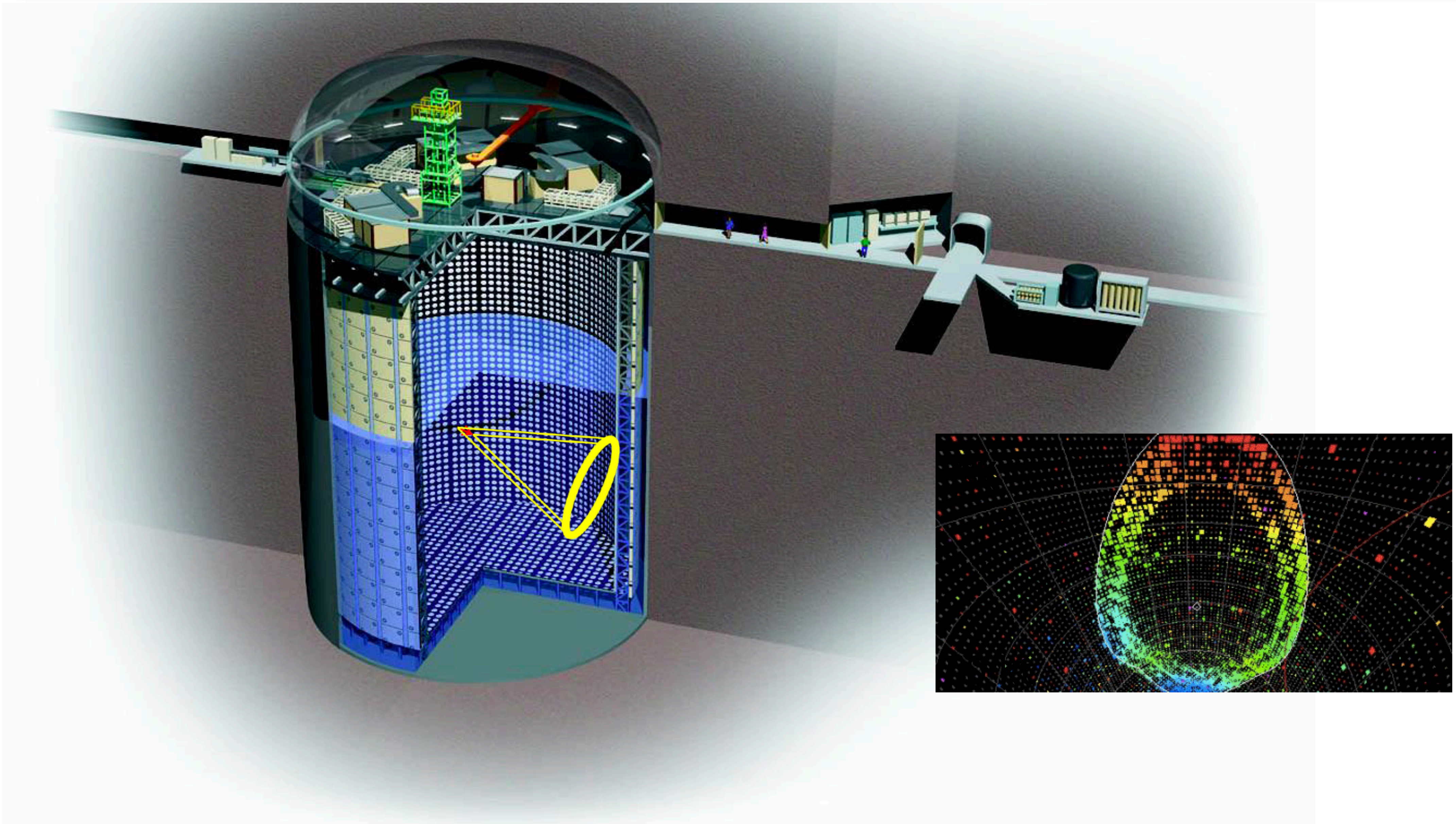
180 kt Water Cherenkov



- LBL = 295 km
- off-axis (2.5°)
- narrow beam
- <E_ν> = 600 MeV
- first maximum of oscillations

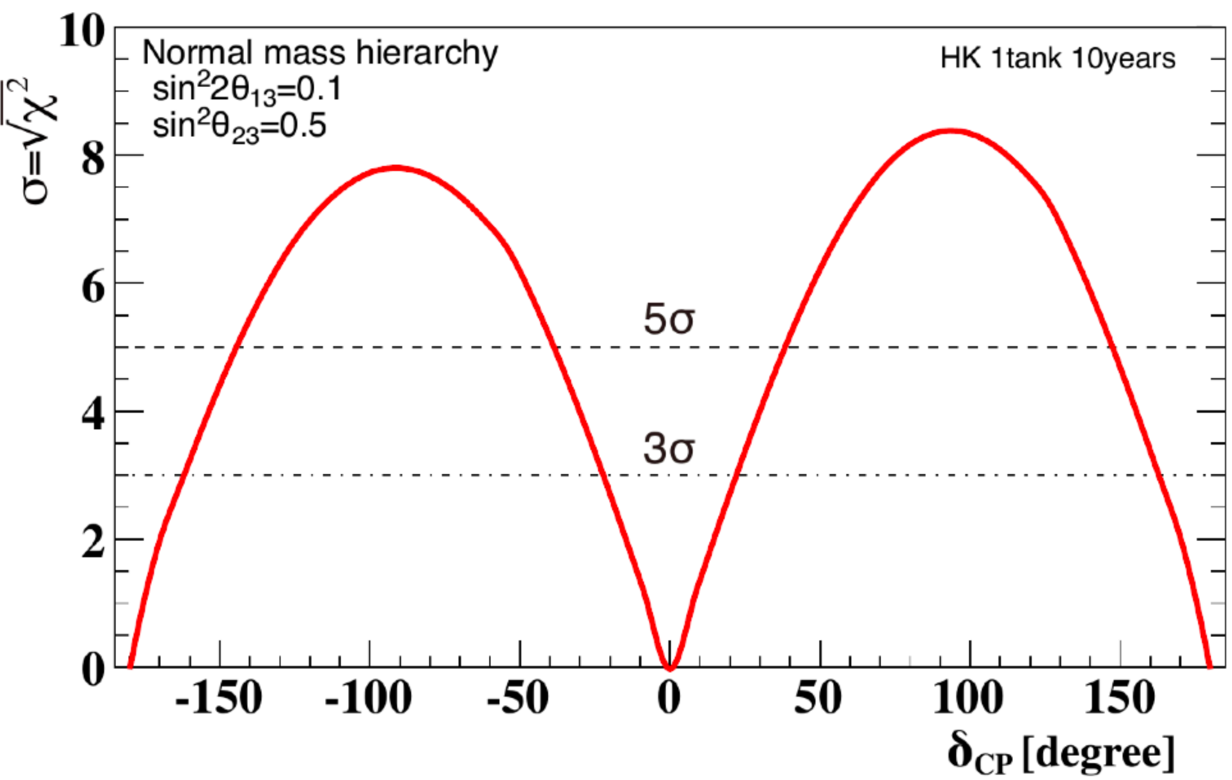
From JPARC to SuperK





HK Sensitivities

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—



☛ Schedule

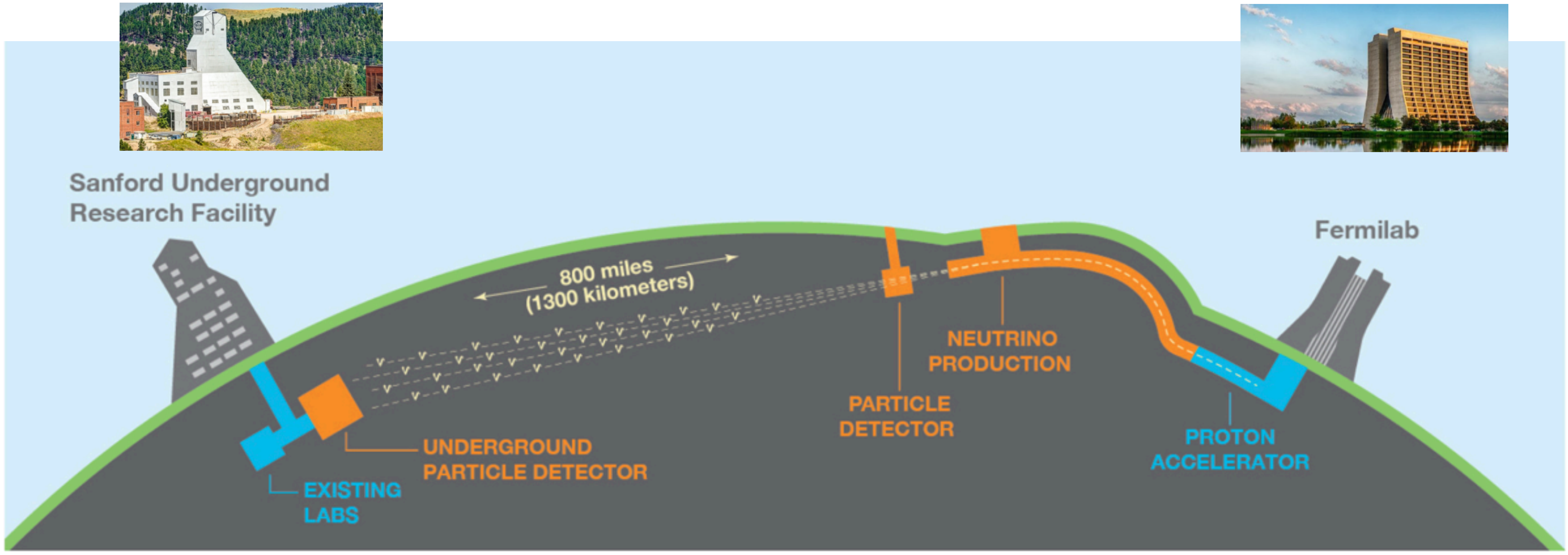
- 1.3 MW × 186 kton for 10 yr

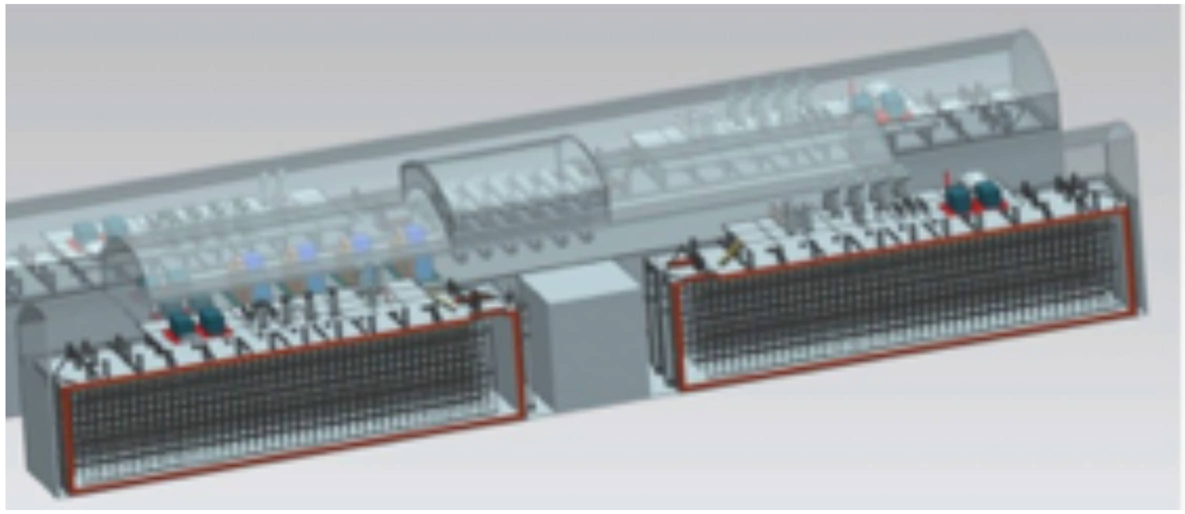
☛ ν/ν̄ running = 1:3

☛ operations up-time as SK

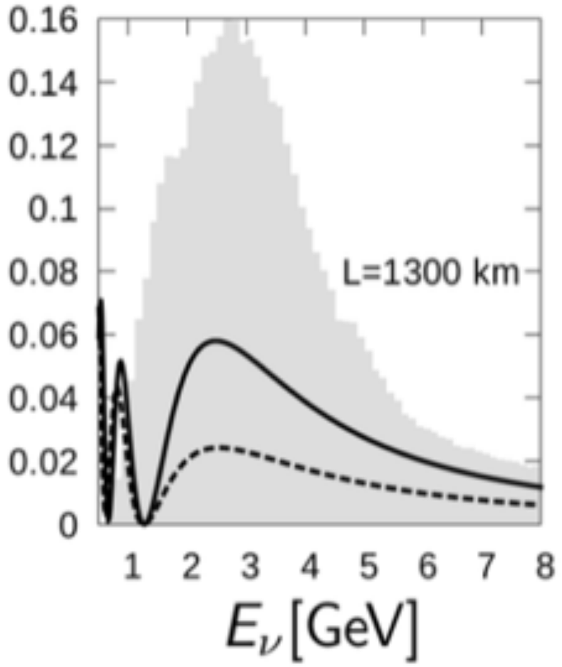
- 60% of phase space with >5σ sensitivity in 10yr
- 5σ sensitivity in 2 yrs for maximal CPV

LBNF/DUNE



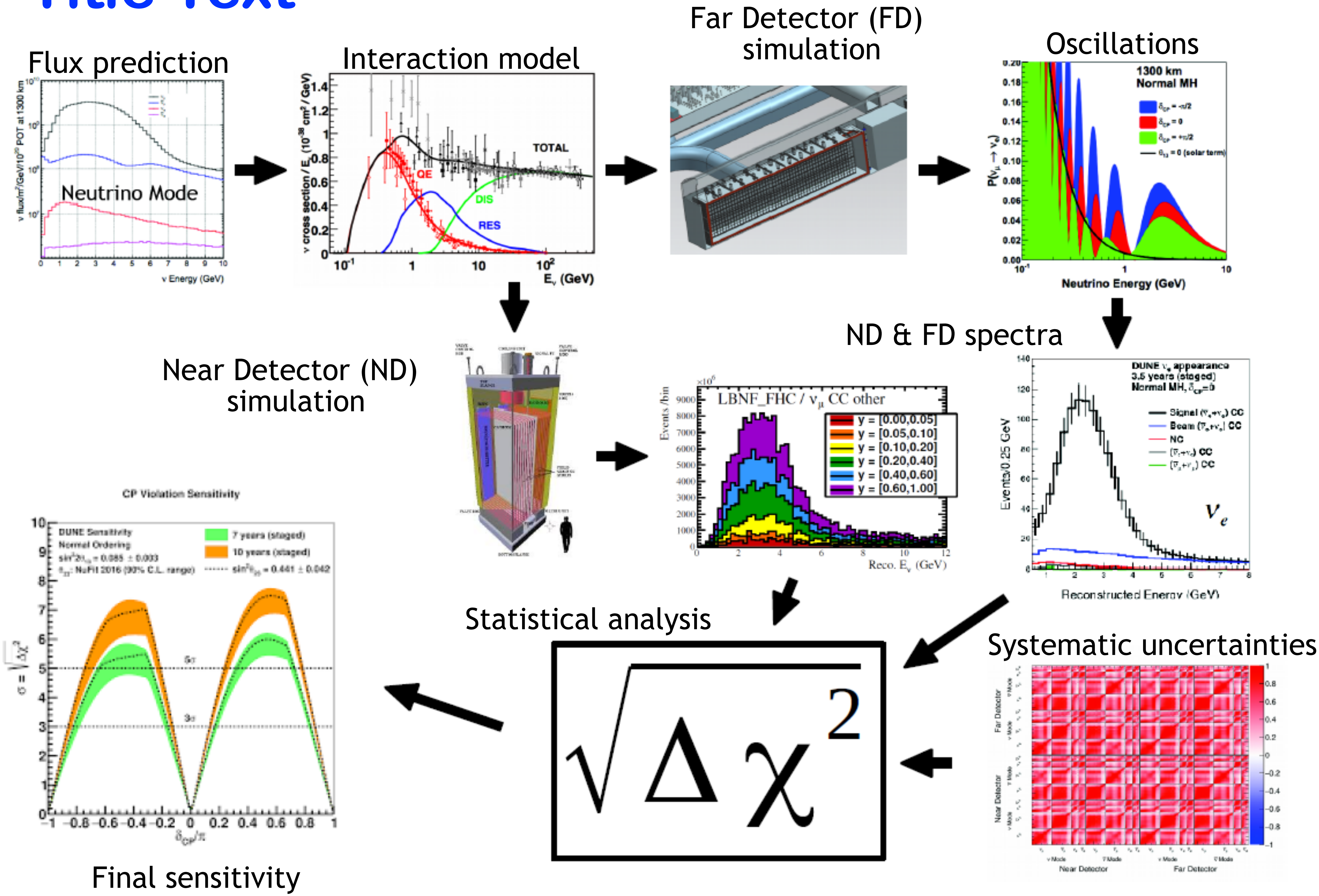


4 × 10 kt Liquid Argon



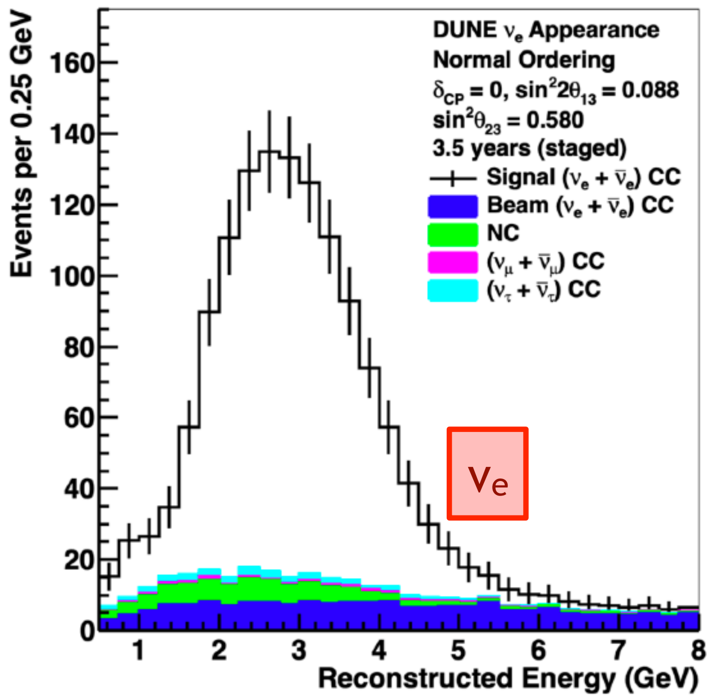
- LBL = 1 300 km
- on-axis
- **wide beam**
- $\langle E_\nu \rangle$ = 3 GeV
- first maximum of oscillations
- also second maximum

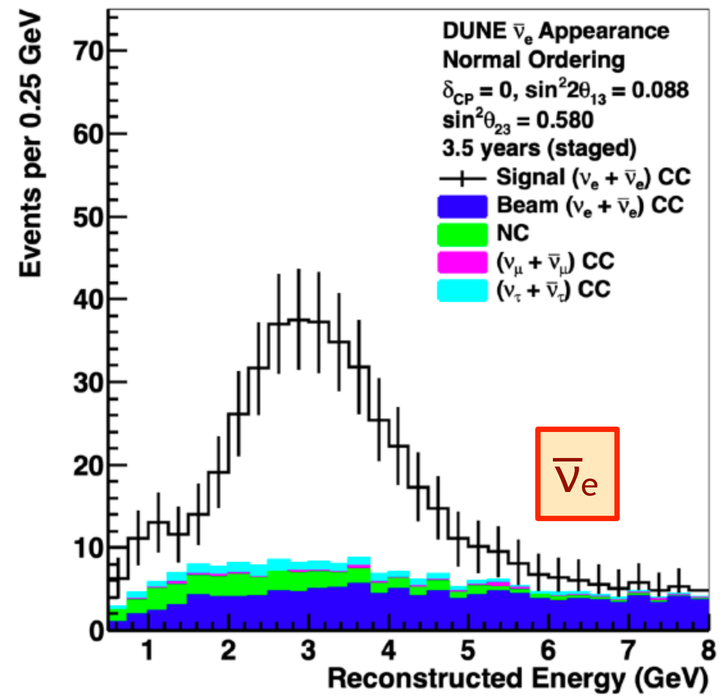
Title Text



Flux prediction
Neutrino Mode
ν Energy (GeV)
Interaction model
TOTAL
QE
DIS
RES
E_ν (GeV)
Far Detector (FD) simulation
Oscillations
1300 km
Normal MH
Neutrino Energy (GeV)
Near Detector (ND) simulation
ND & FD spectra
LBNF_FHC / ν_μ CC other
y = [0.00,0.05]
y = [0.05,0.10]
y = [0.10,0.20]
y = [0.20,0.40]
y = [0.40,0.60]
y = [0.60,1.00]
Reco. E_ν (GeV)
Events/bin
Reconstructed Energy (GeV)
ν_e
CP Violation Sensitivity
DUNE Sensitivity
Normal Ordering
7 years (staged)
10 years (staged)
δ_{CP}/π
Statistical analysis
$\sqrt{\Delta\chi^2}$
Systematic uncertainties
Near Detector
Far Detector
Final sensitivity

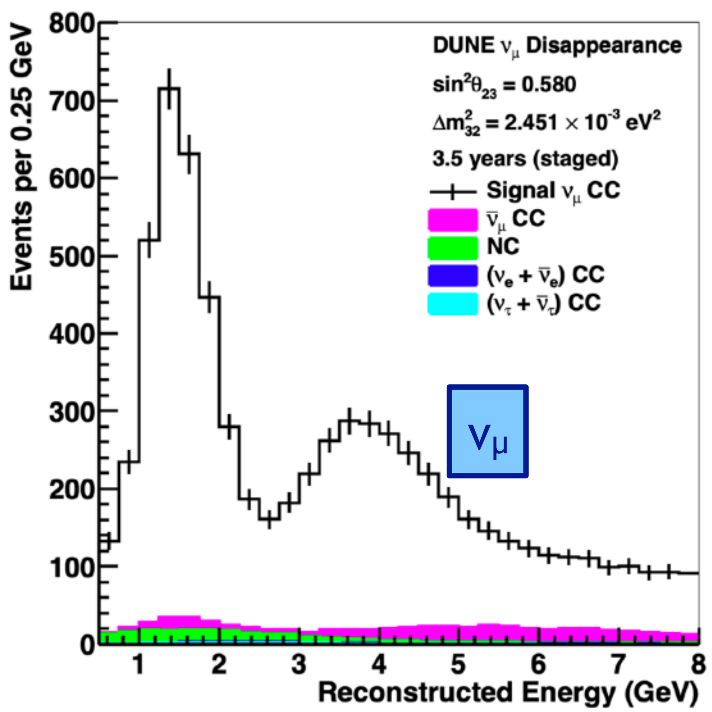
DUNE Far Detector Samples (7 years)

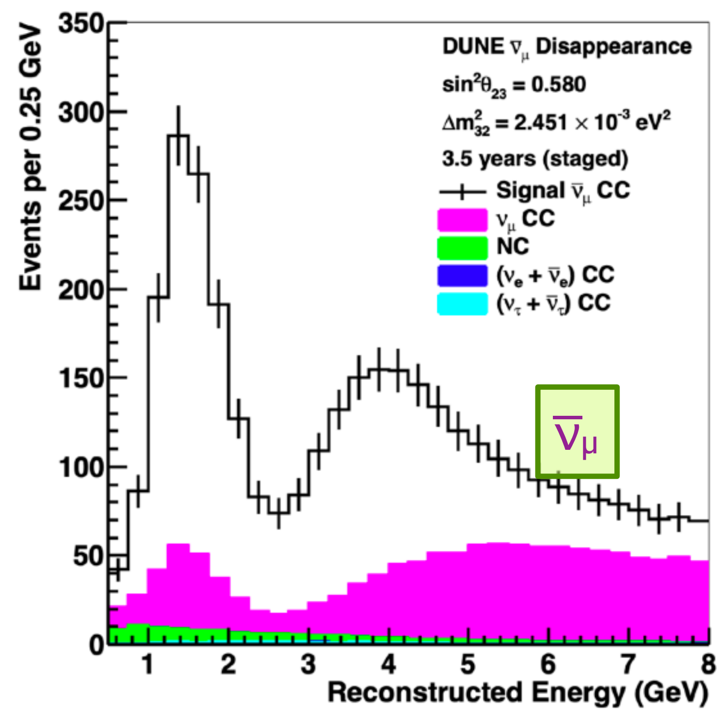




ν_e, $\bar{\nu}_e$ appearance:

1 000 events

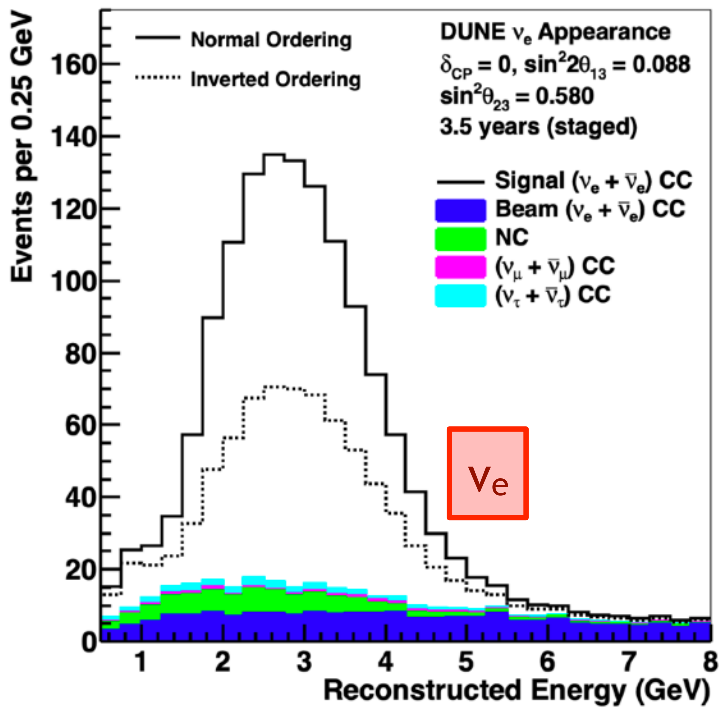


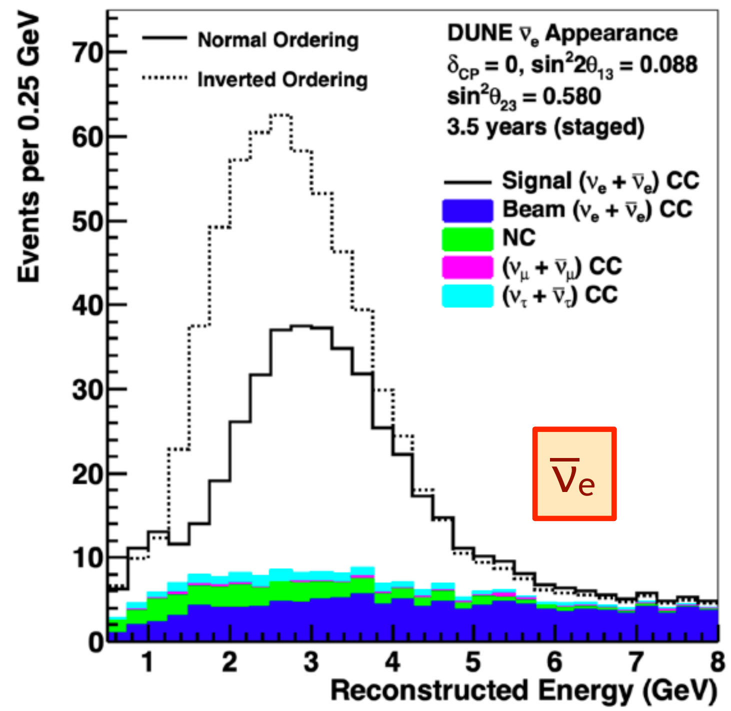


ν_μ, $\bar{\nu}_\mu$, disappearance

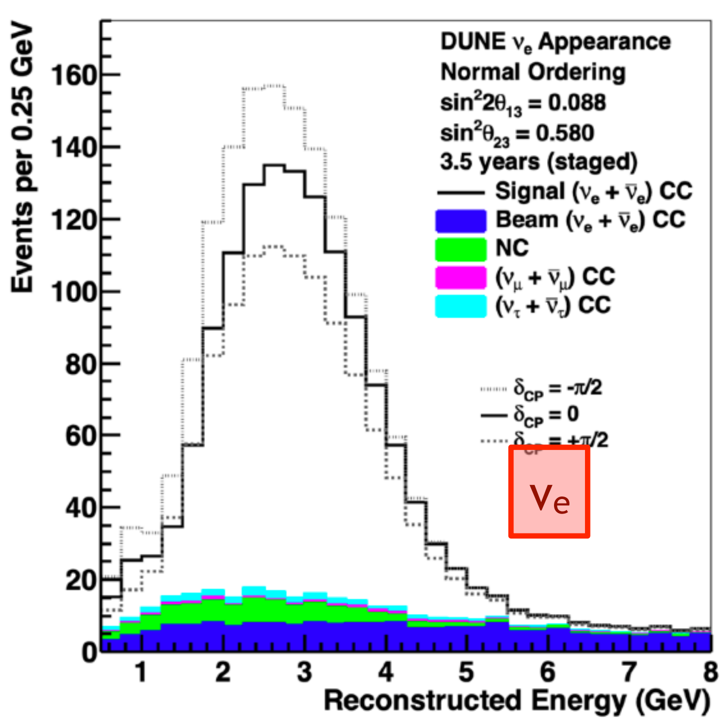
10 000 events

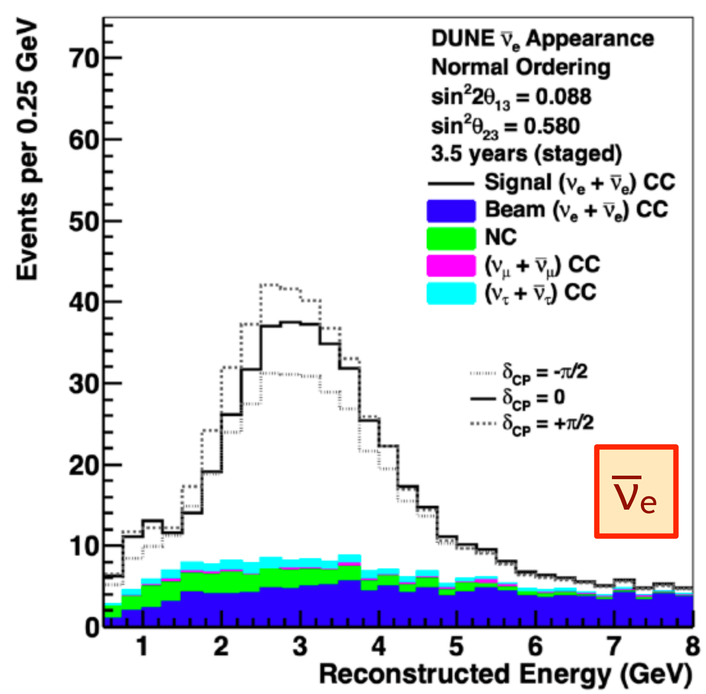
DUNE Far Detector Samples (7 years)





Variation with mass ordering

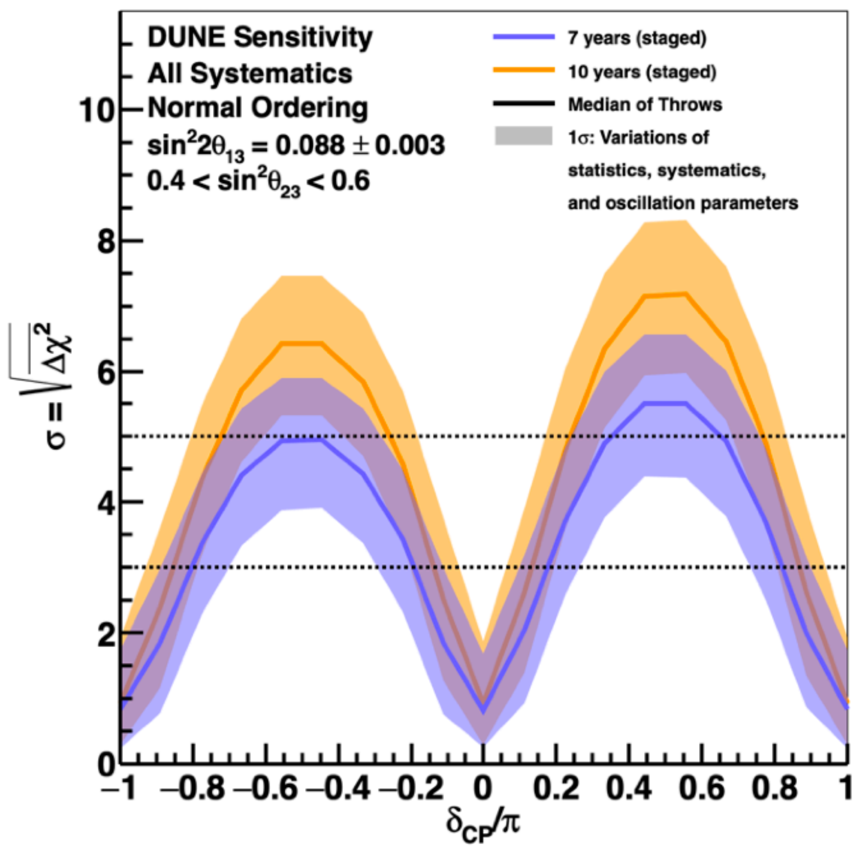




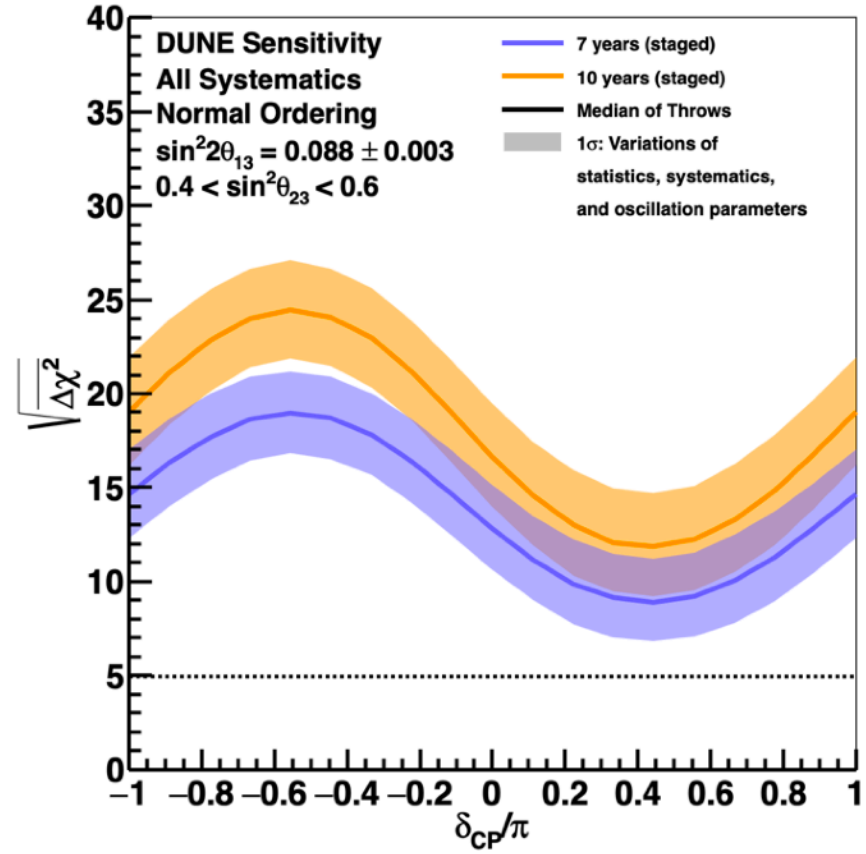
Variation with δ_{CP}

DUNE Sensitivities

CP Violation



Mass Ordering



☛ Staged schedule

- 1.2 MW × 20 kton at start
- 1.2 MW × 30 kton after 1 yr
- 1.2 MW × 40 kton after 3 yr
- 2.4 MW × 40 kton after 6 yr

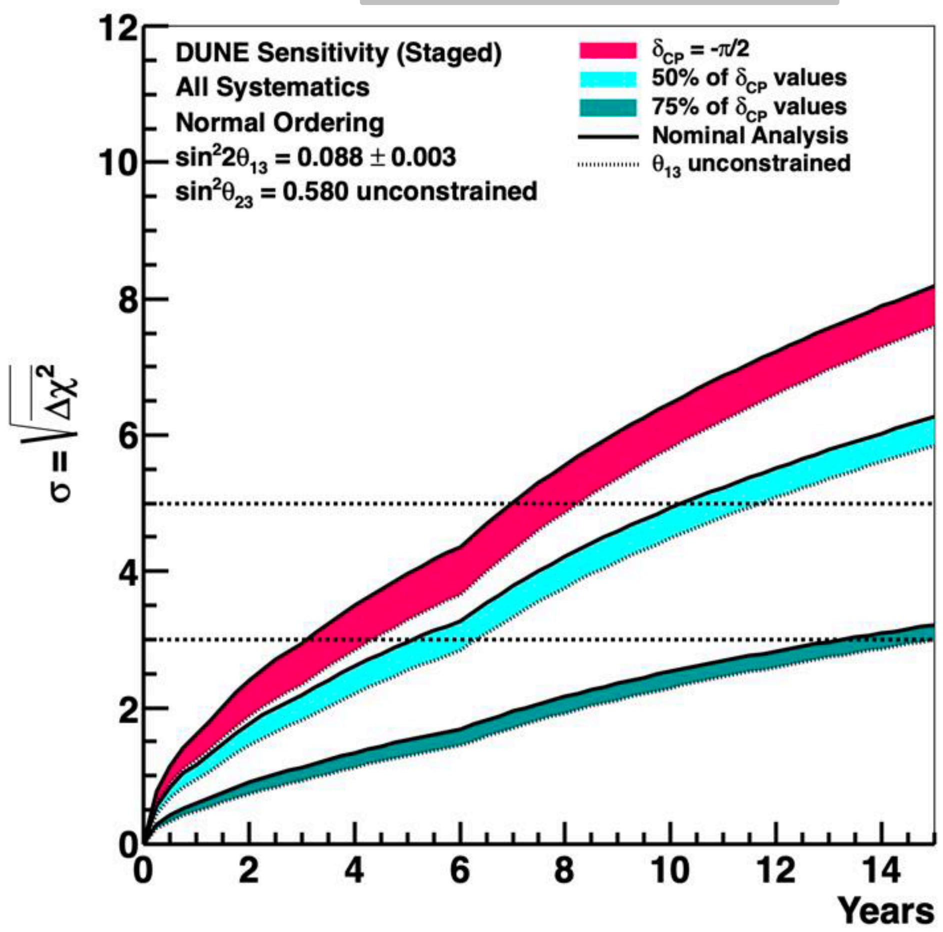
☛ equal ν/ν̄ running

☛ 56% operations up-time

simultaneous fit of ND and FD data

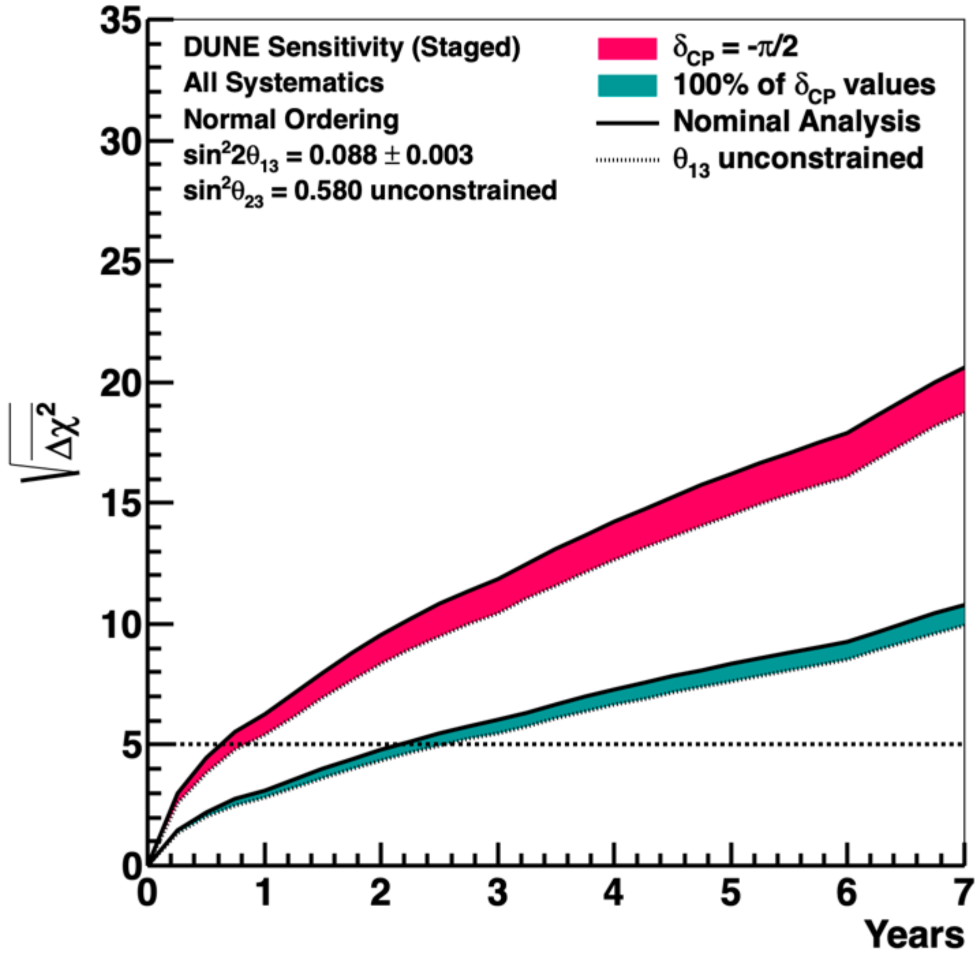
DUNE Sensitivities with Time

CP Violation



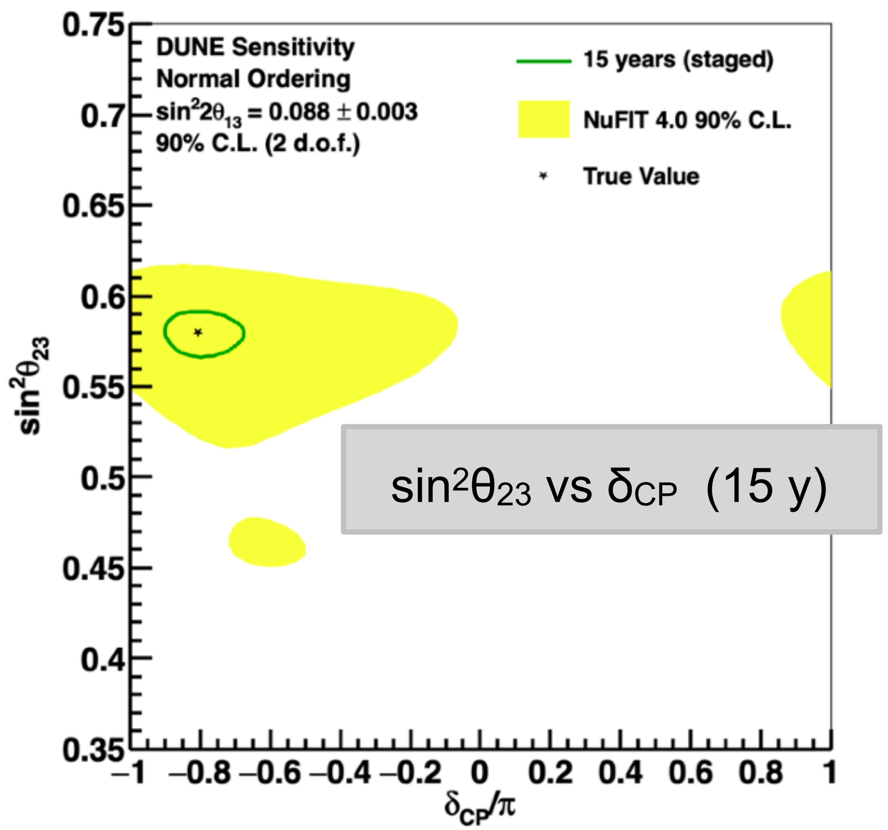
5σ for 50% of δ_{CP} values in 10 years

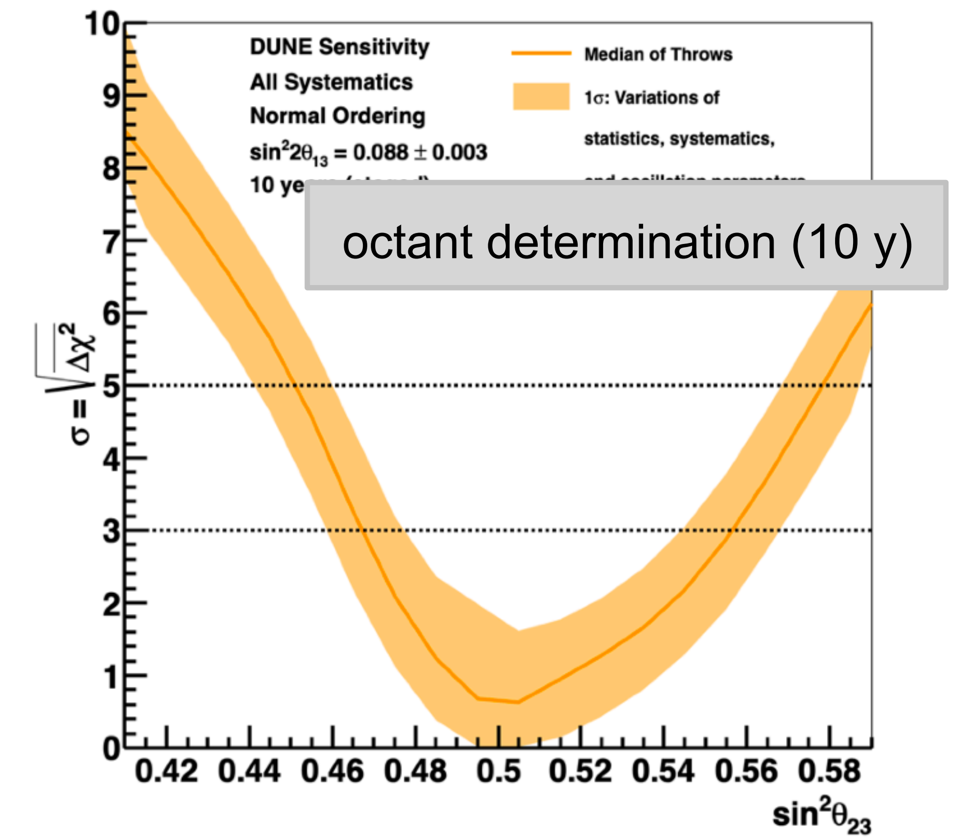
Mass Ordering

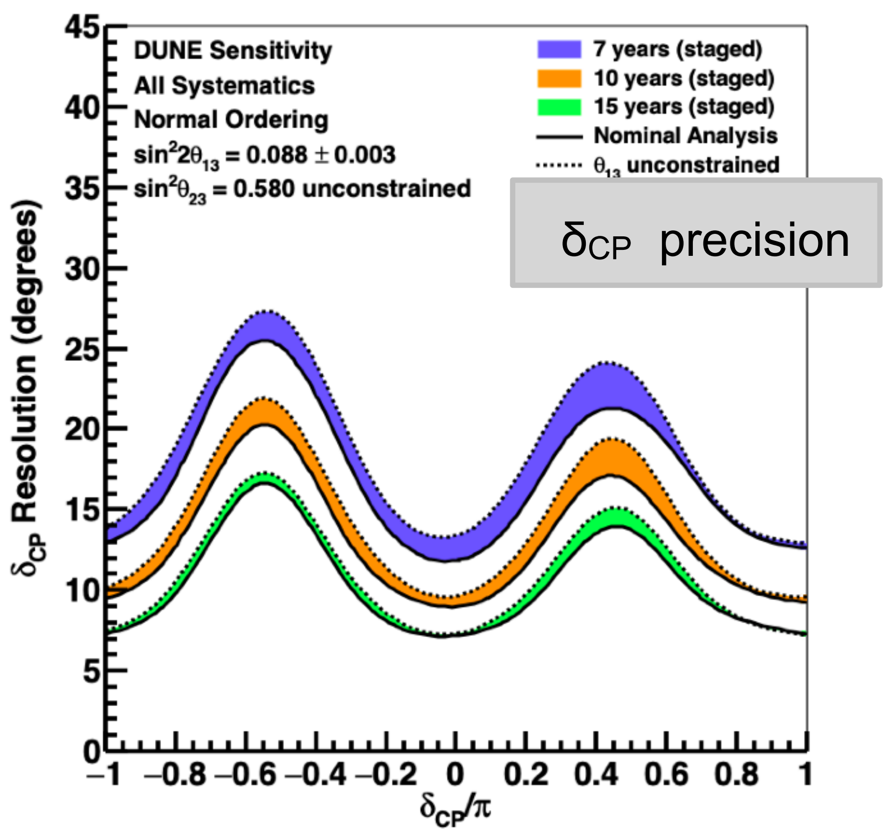


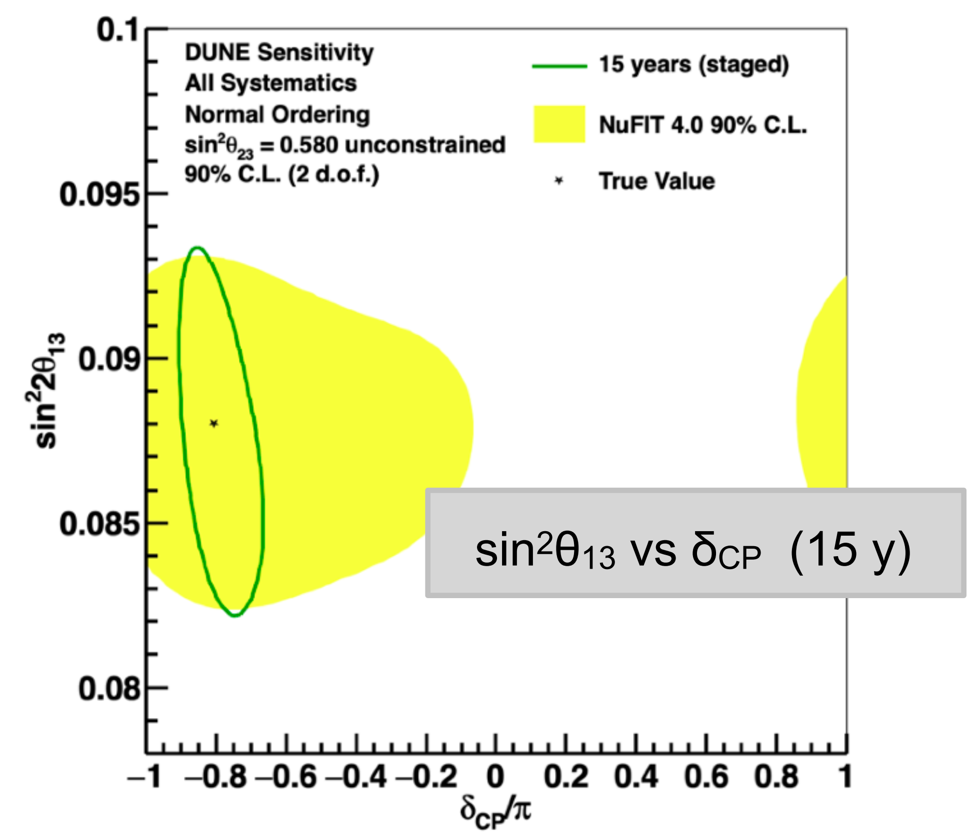
mass ordering at 5σ in at most 2 years

DUNE Summary of Expected Performance

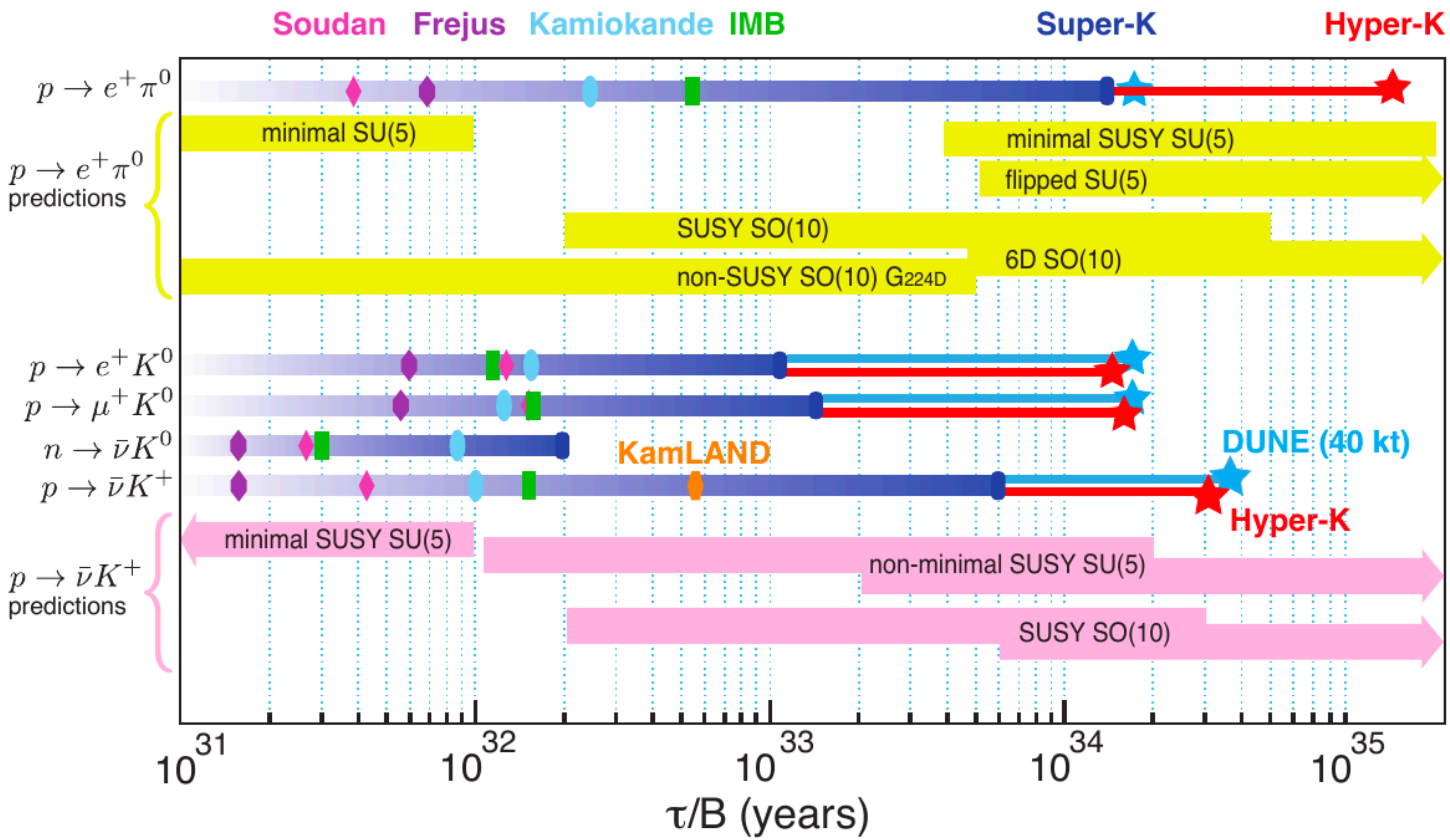




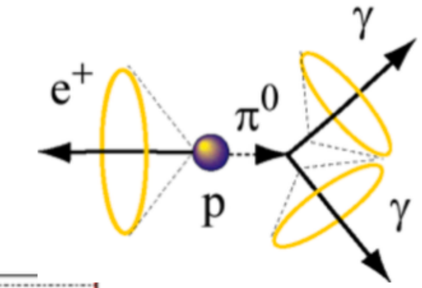


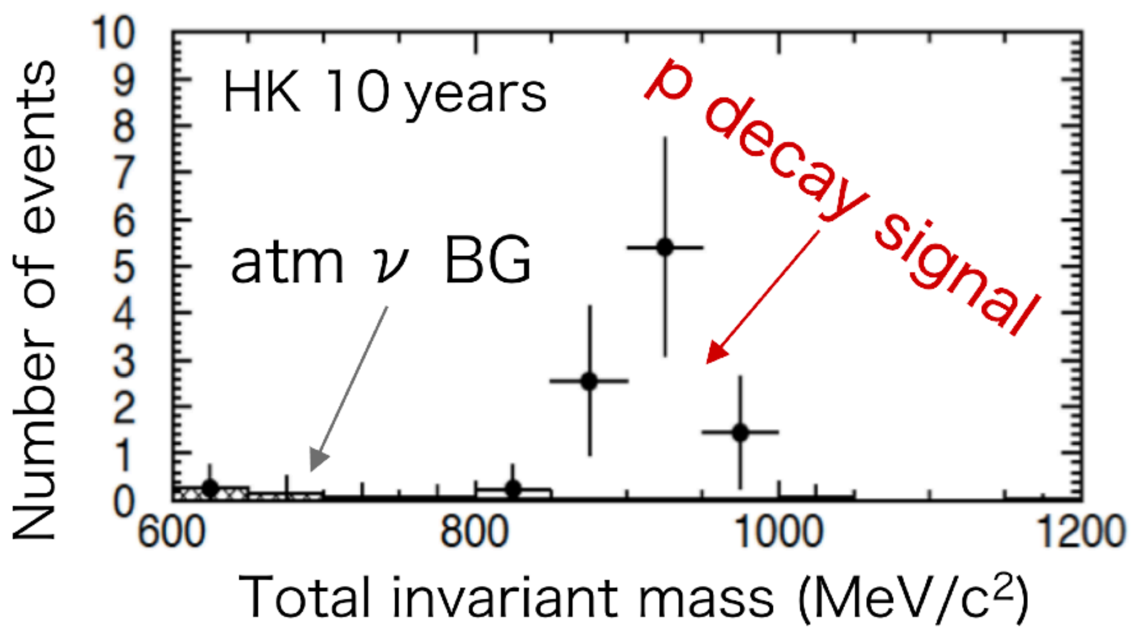


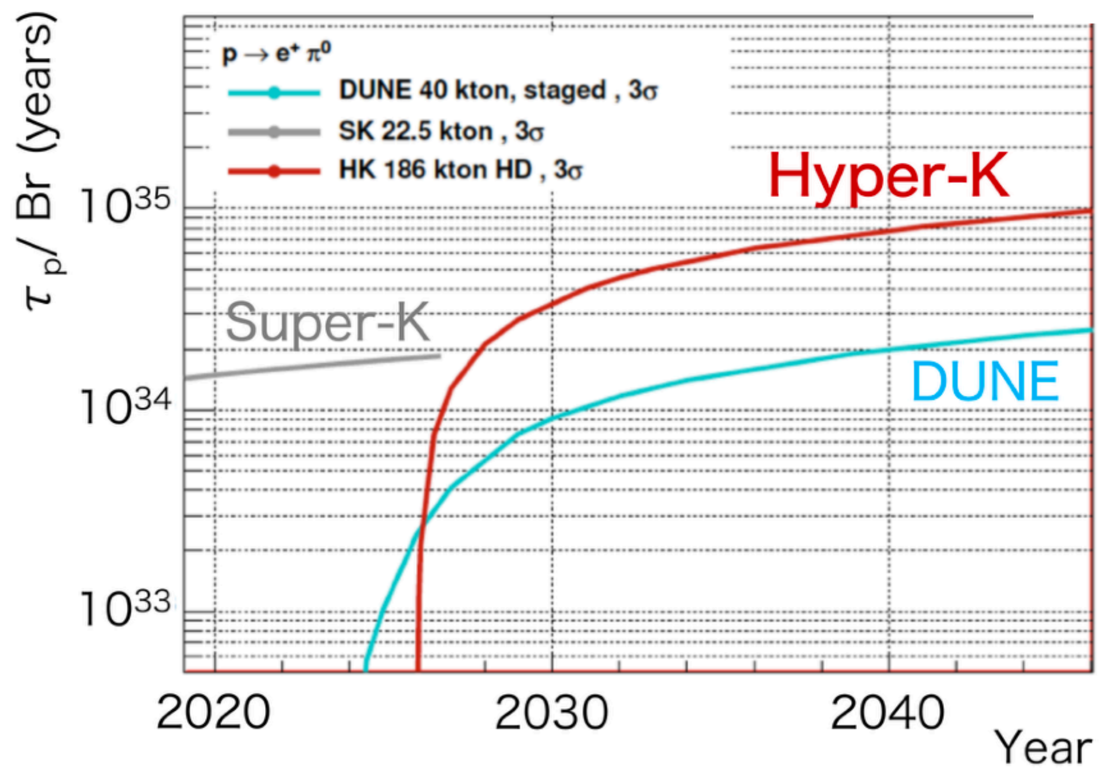
Proton Decay and GUT



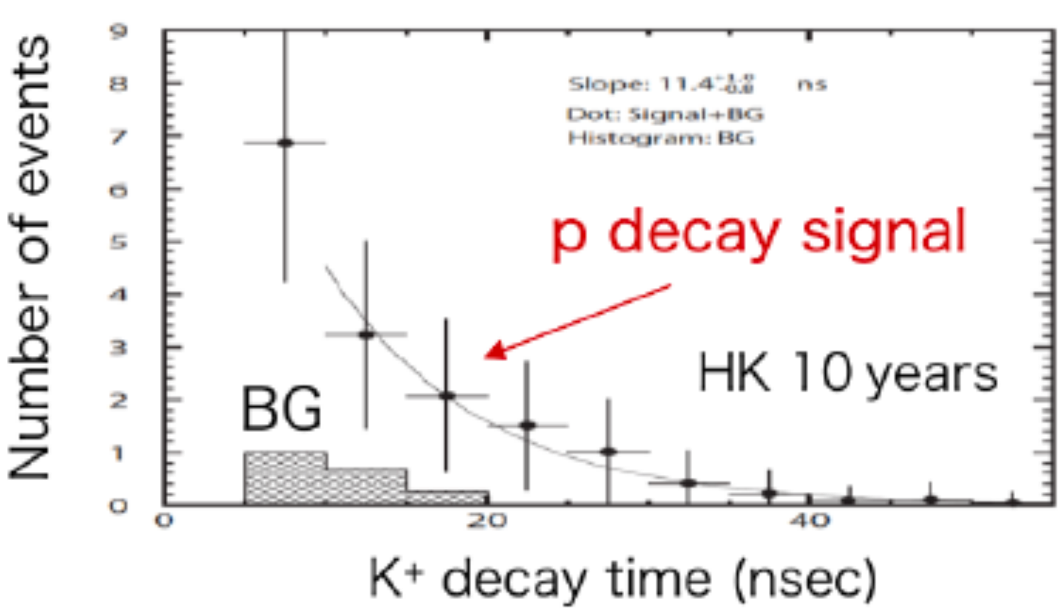
Proton Decay in HK

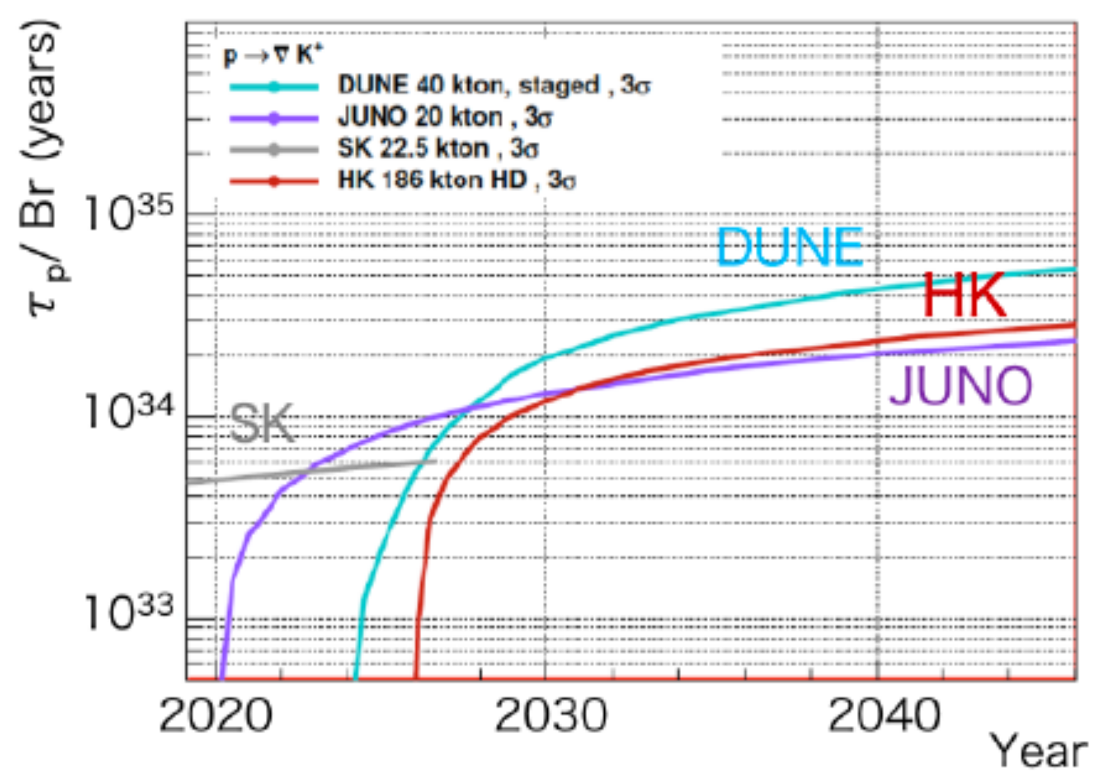






ultimate 3σ sensitivity to $\tau_p/BR = 10^{35}$ yr

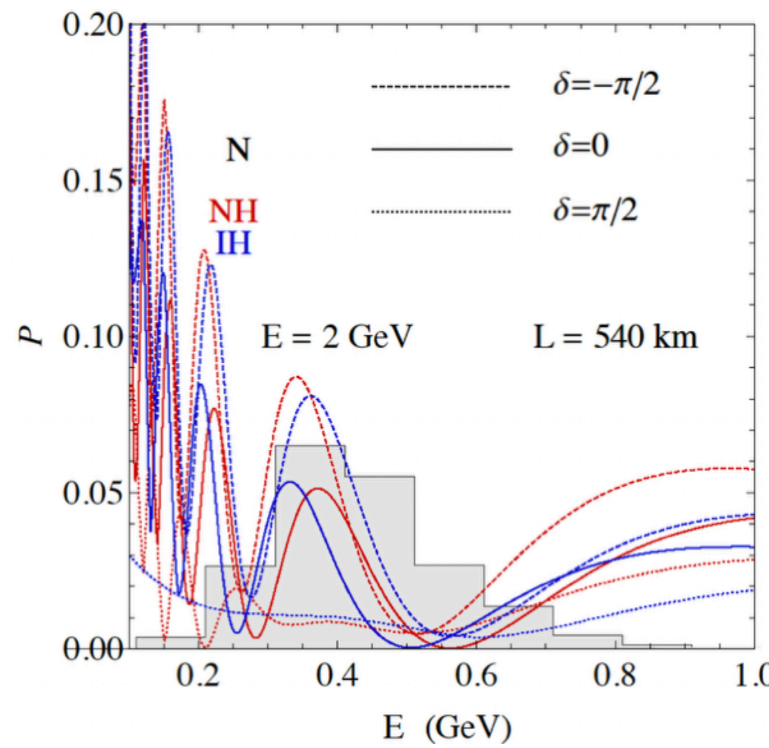




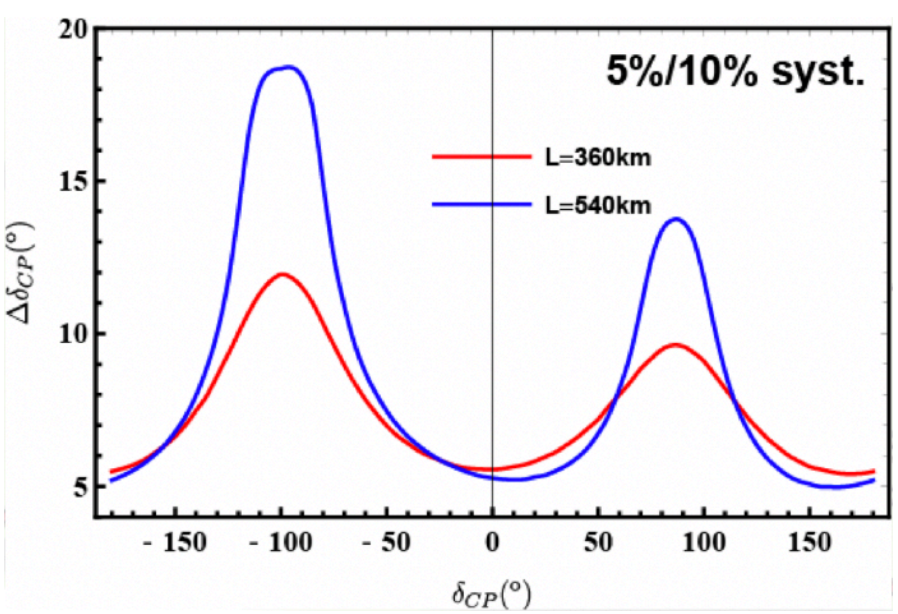
ultimate 3σ sensitivity to $\tau_p/BR = 3 \times 10^{33}$ yr

Longer Term: ESSnuSB?

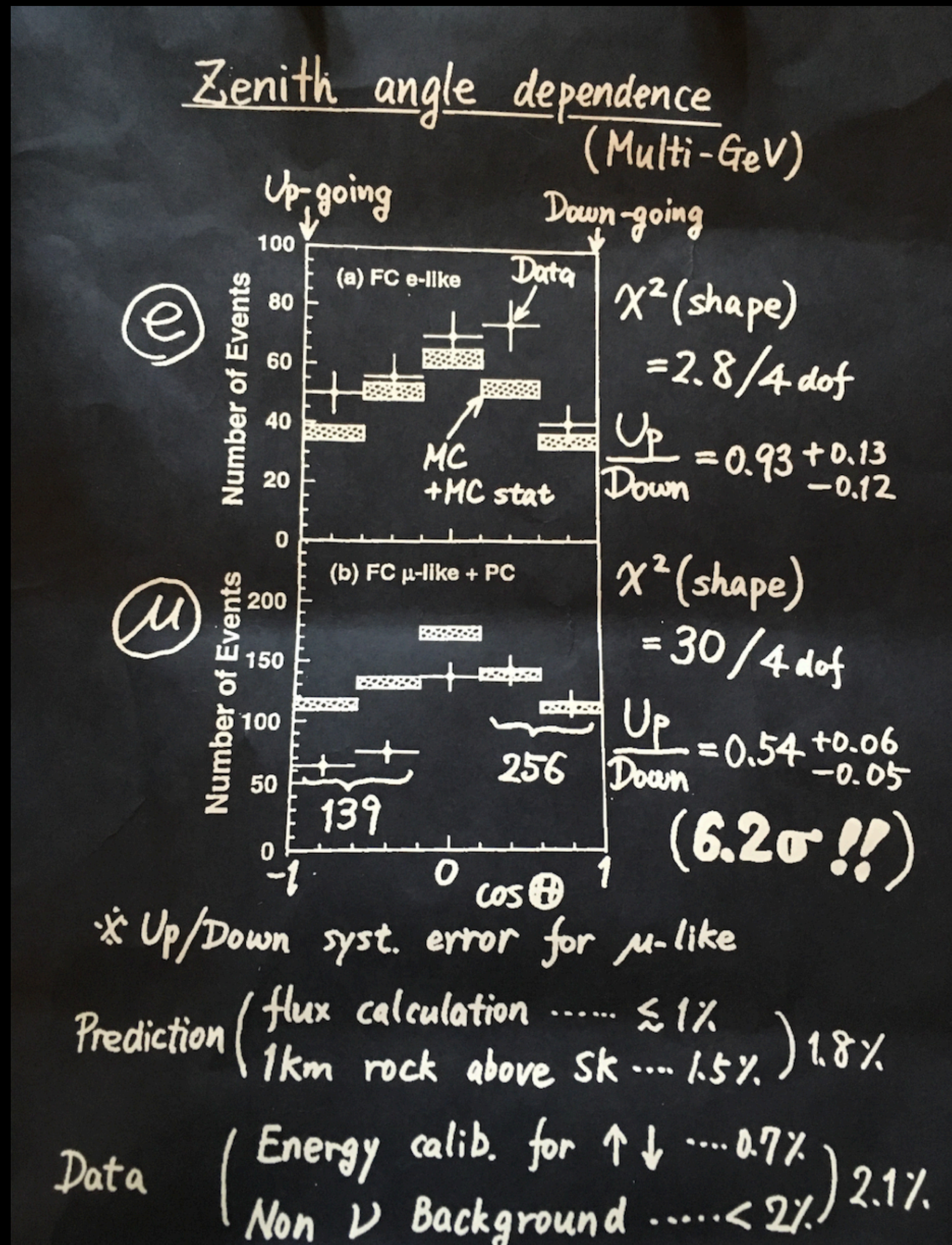
- ESSnuSB (European Spallation Source Neutrino Super Beam)
  - ESS neutron source under construction in Lund (Sweden)
  - far mega-ton class water Cherenkov detector?
  - two candidate sites: Garpenberg (L = 540 km) and Zinkgruven (L = 360 km)



Excellent coverage of the second maximum



- more sensitivity on δ_{CP}
- less influence from systematic uncertainties



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