Accelerator and Atmospheric Neutrinos Part 1: The Interesting Part

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Outline

1. Neutrino Oscillations
   a. Visualisation
2. Accelerator Neutrinos
   a. Techniques
   b. Key results
   c. Future vision
3. Atmospheric Neutrinos
   a. MSW matter effect
   b. Flux
   c. Key results

There are ***Quizzes*** and ***Homework***!

Great lectures on neutrinos if you want to dive into the subject

- ❑ Steve Boyd, University of Warwick, *Neutrino Physics Lectures*, Warwick Week, 2025

Great text on nuclear, particle, and neutrino physics

1. Mohapatra, R. N., Pal, P. B. (2004). *Massive Neutrinos in Physics and Astrophysics*. India: World Scientific.
2. Giunti, C., Kim, C. W. (2007). *Fundamentals of Neutrino Physics and Astrophysics*. United Kingdom: OUP Oxford.
3. Povh, B., Rith, K., Scholz, C., Zetsche, F., Rodejohann, W. (2015). *Particles and Nuclei: An Introduction to the Physical Concepts*. Germany: Springer Berlin Heidelberg. *7th Ed*.
4. Donnelly, T. W., Formaggio, J. A., Holstein, B. R., Milner, R. G., Surrow, B. (2017). *Foundations of Nuclear and Particle Physics*. United Kingdom: Cambridge University Press.
5. Zuber, K. (2020). *Neutrino Physics*. United Kingdom: CRC Press. *3rd Ed*.
6. Rubbia, A. (2022). *Phenomenology of Particle Physics*. United Kingdom: Cambridge University Press.

Part 1: Neutrino Oscillations

Fundamental matter in our **current world view:**
Standard Model

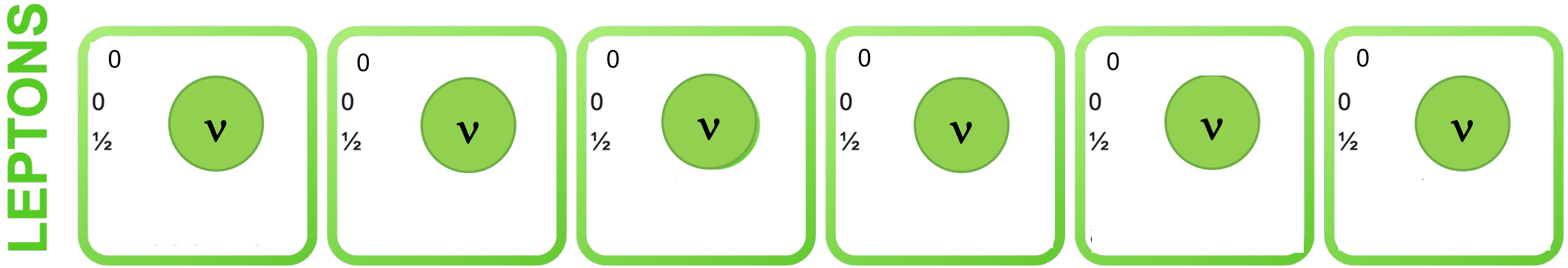
	mass charge spin	I	II	III	I	II	III
QUARKS		≃2.2 MeV/c² ⅔ ½ u **up**	≃1.28 GeV/c² ⅔ ½ c **charm**	≃173.1 GeV/c² ⅔ ½ t **top**	≃2.2 MeV/c² −⅔ ½ ū **antiup**	≃1.28 GeV/c² −⅔ ½ c̄ **anticharm**	≃173.1 GeV/c² −⅔ ½ t̄ **antitop**
QUARKS		≃4.7 MeV/c² −⅓ ½ d **down**	≃96 MeV/c² −⅓ ½ s **strange**	≃4.18 GeV/c² −⅓ ½ b **bottom**	≃4.7 MeV/c² ⅓ ½ d̄ **antidown**	≃96 MeV/c² ⅓ ½ s̄ **antistrange**	≃4.18 GeV/c² ⅓ ½ b̄ **antibottom**
LEPTONS		≃0.511 MeV/c² −1 ½ e **electron**	≃105.66 MeV/c² −1 ½ μ **muon**	≃1.7768 GeV/c² −1 ½ τ **tau**	≃0.511 MeV/c² 1 ½ e⁺ **positron**	≃105.66 MeV/c² 1 ½ μ̄ **antimuon**	≃1.7768 GeV/c² 1 ½ τ̄ **antitau**
LEPTONS		0 0 ½ ν	0 0 ½ ν	0 0 ½ ν	0 0 ½ ν	0 0 ½ ν	0 0 ½ ν

3 generations?!
Symmetric antimatter?

Neutrinos and antineutrinos in Standard Model

1. Charge neutral
2. Massless

❖ How can we tell all 6 of them apart?

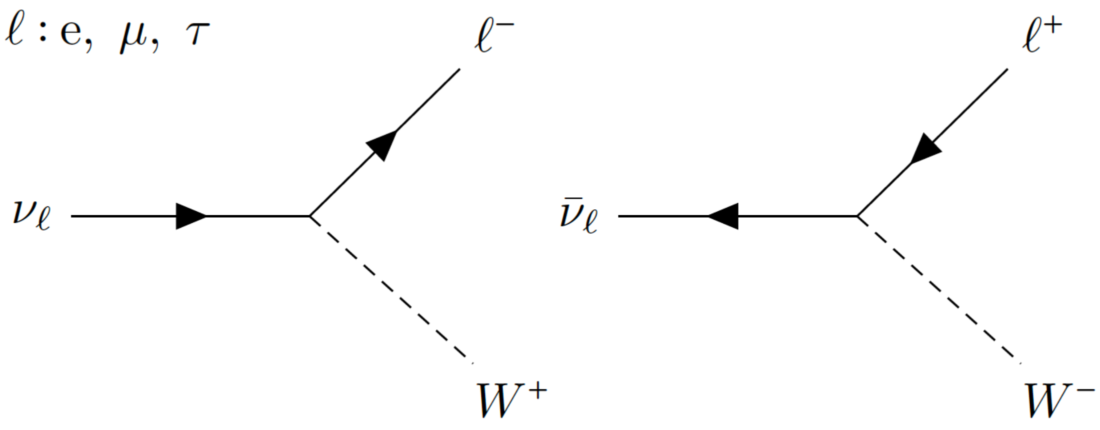


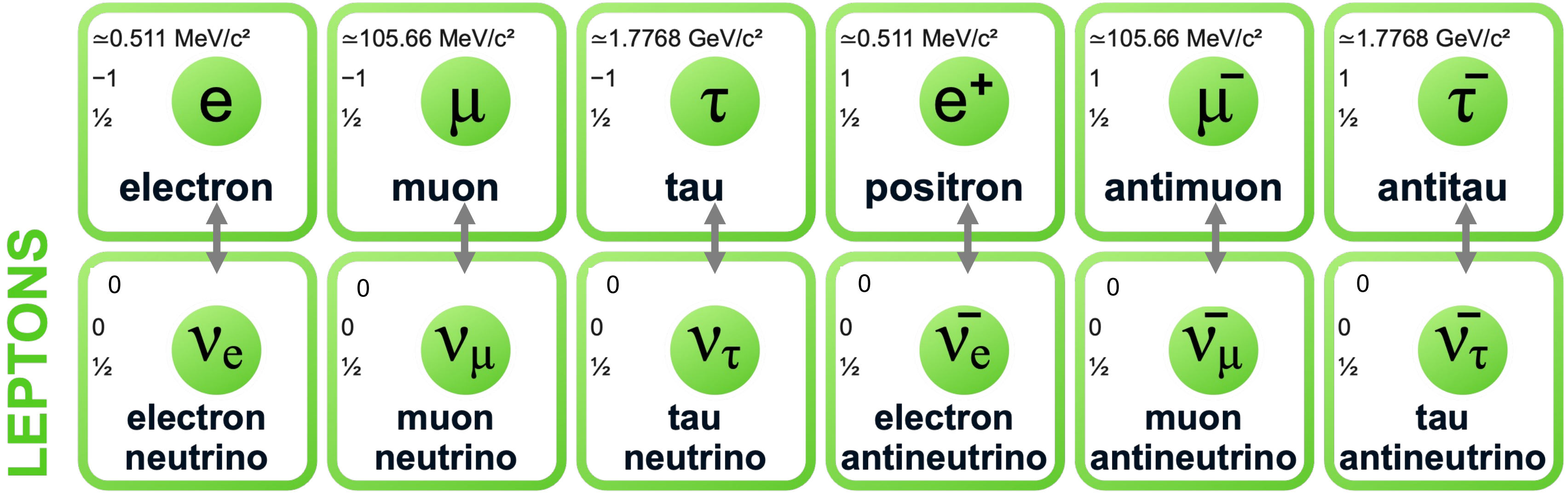
Neutrinos and antineutrinos in Standard Model

1. Charge neutral
2. Massless

❖ How can we tell all 6 of them apart?

3. Flavour, defined by charged-current interactions



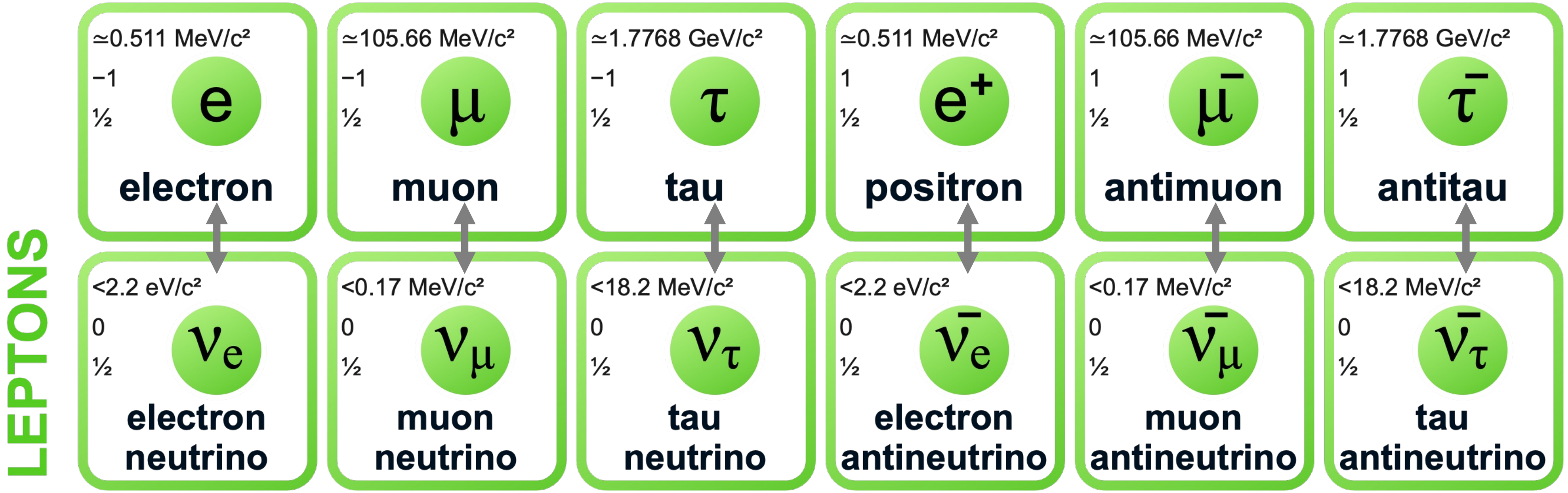


Neutrinos and antineutrinos in Nature

1. Charge neutral
~~2. Massless~~ turns out to be tiny but not zero!

❖ How can we tell all 6 of them apart? *One more way (too many)* to tell the neutrinos apart!

3. Flavour, defined by charged-current interactions

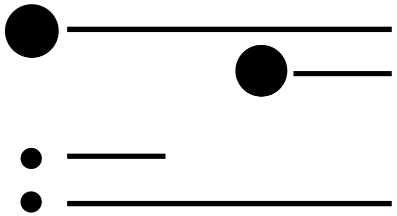


Neutrino Mass and Mixing

Standard Model | Beyond Standard Model

Mass “levels”

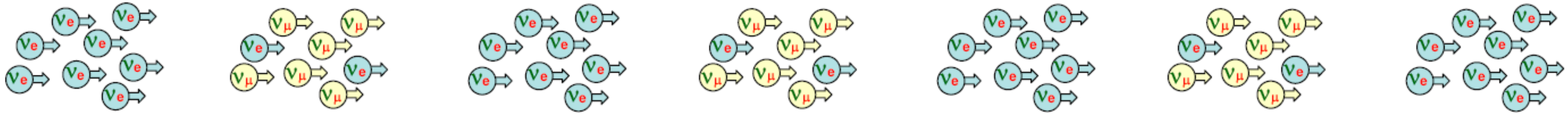
$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} =$ Pontecorvo–Maki–Nakagawa–Sakata **PMNS matrix** $\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$



A problem only when there are more than 2 masses!

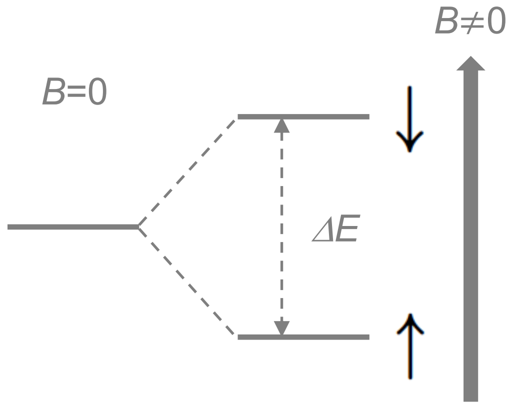
Normal / Inverted Mass Ordering (MO, ~~Hierarchy~~)

Mass gap (Δm^2) ***and*** mixing lead to neutrino flavour oscillations

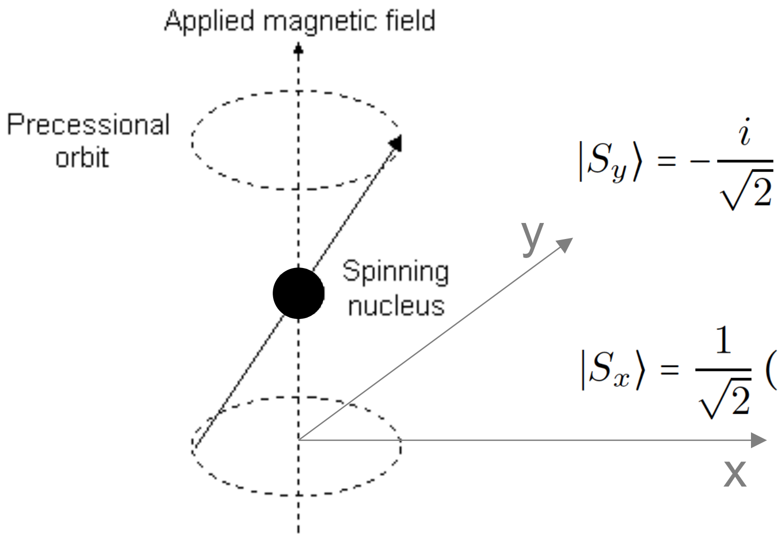


[Mark Thomson, Particle Physics lecture notes]

Analogy: spin rotation in a magnetic field



$|\uparrow\rangle, |\downarrow\rangle$: energy eigenstates



$$|S_y\rangle = -\frac{i}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle)$$

$$|S_x\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$$

Image source: https://teaching.shu.ac.uk/hwb/chemistry/tutorials/molspec/nmr1.htm

Homework: Show that

$$|S_x\rangle_t = \cos\frac{\Delta E}{2}t\,|S_x\rangle_0 - \sin\frac{\Delta E}{2}t\,|S_y\rangle_0$$

Oscillation probability

$$P_{S_x\to S_x}(t) = \cos^2\frac{\Delta E}{2}t$$

$$P_{S_x\to S_y}(t) = \sin^2\frac{\Delta E}{2}t$$

Energy gap

$$\begin{pmatrix}|\uparrow\rangle_t\\|\downarrow\rangle_t\end{pmatrix} = \begin{pmatrix}e^{i\frac{\Delta E}{2}t} & 0\\ 0 & e^{-i\frac{\Delta E}{2}t}\end{pmatrix}\begin{pmatrix}|\uparrow\rangle_0\\|\downarrow\rangle_0\end{pmatrix}$$

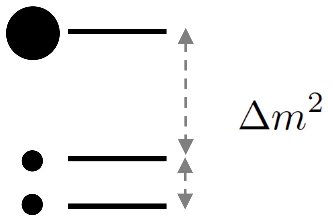
Mixing

$$\begin{pmatrix}|S_x\rangle\\|S_y\rangle\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ -i & i\end{pmatrix}\begin{pmatrix}|\uparrow\rangle\\|\downarrow\rangle\end{pmatrix}$$

Survival $P_{\nu_\mu\to\nu_\mu}\left(\frac{L}{E}\right)$

Appearance $P_{\nu_\mu\to\nu_e}\left(\frac{L}{E}\right)$

$$\begin{pmatrix}\nu_1\\\nu_2\\\nu_3\end{pmatrix}$$



$$\begin{pmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{pmatrix} = \begin{pmatrix} & \text{PMNS} & \end{pmatrix}\begin{pmatrix}\nu_1\\\nu_2\\\nu_3\end{pmatrix}$$

Oscillation Phase: $[E^0]$

- ❑ Δm^2: $[E^2]$
- ❑ L: propagation distance $[E^{-1}]$
- ❑ E: energy [E]

Phase ~ $\Delta m^2 L/E$

The phase that is responsible for oscillation is often written as (with c and $\hbar$ restored)

$$\frac{\Delta_{jk}(mc^2)^2\,L}{4\hbar c\,E} = \frac{\text{GeV fm}}{4\hbar c}\times\frac{\Delta_{jk}m^2}{\text{eV}^2}\frac{L}{\text{km}}\frac{\text{GeV}}{E} \approx 1.27\times\frac{\Delta_{jk}m^2}{\text{eV}^2}\frac{L}{\text{km}}\frac{\text{GeV}}{E}$$

Wiki: https://en.wikipedia.org/wiki/Neutrino_oscillation

PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

Open questions

- ❑ What are the neutrino masses?
  - ❖ Mass gaps (Δm^2_{21}, $|\Delta m^2_{32}|$) and ordering (sgn Δm^2_{32})?
- ❑ What are the mixing parameters?
  - ❖ Mixing angles (θ_{12}, θ_{23} , θ_{13}) and CP-phase (δ_{CP})?

🙅 Not accessible through oscillation measurements:

- ❑ Absolute mass
- ❑ Dirac/Majorana nature

θ_{12}: mixing between ν_1 and ν_2

θ_{23}: mixing between ν_μ and ν_τ

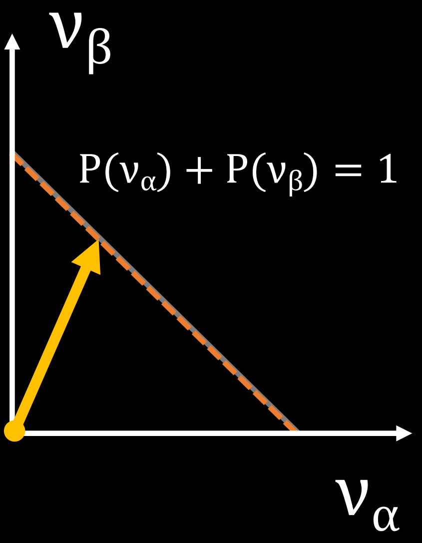
θ_{13}: if 0, effective 2 flavour mixing

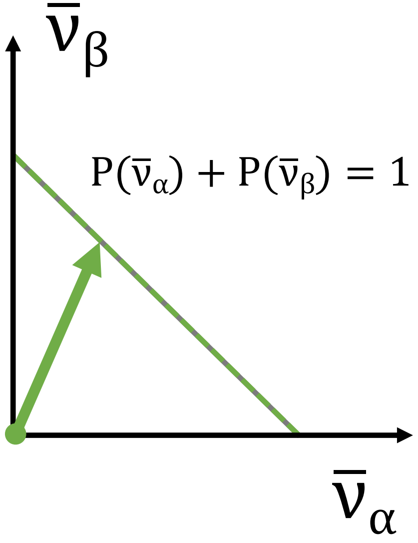
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1'\\ \nu_2'\\ \nu_3\end{pmatrix}$$

$\theta_{13} = 0$

2-flavor oscillation

Antineutrinos

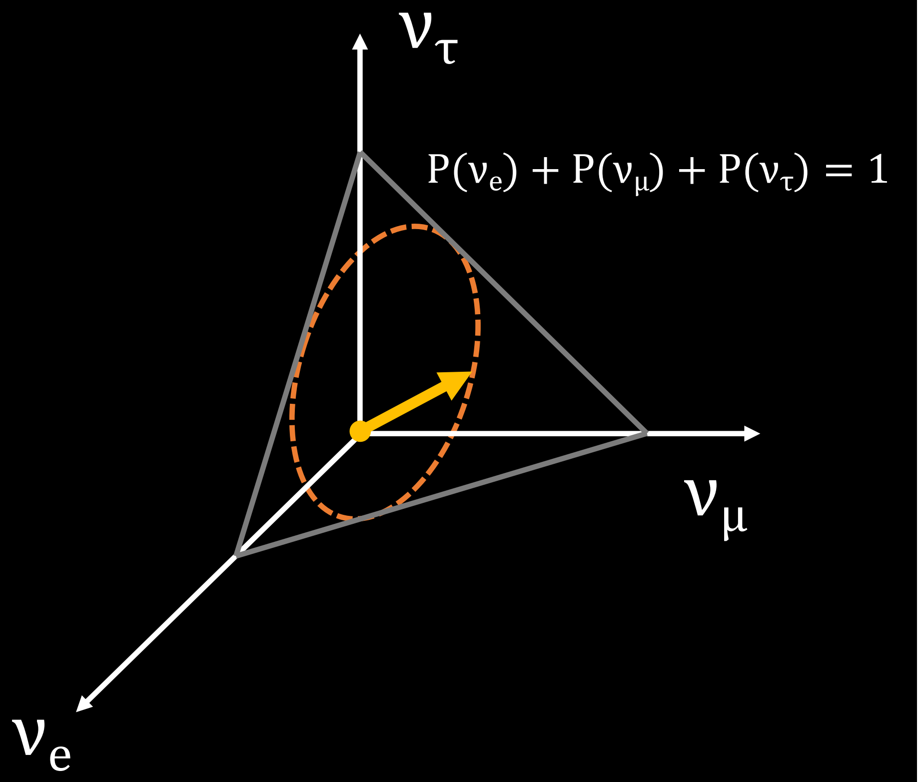




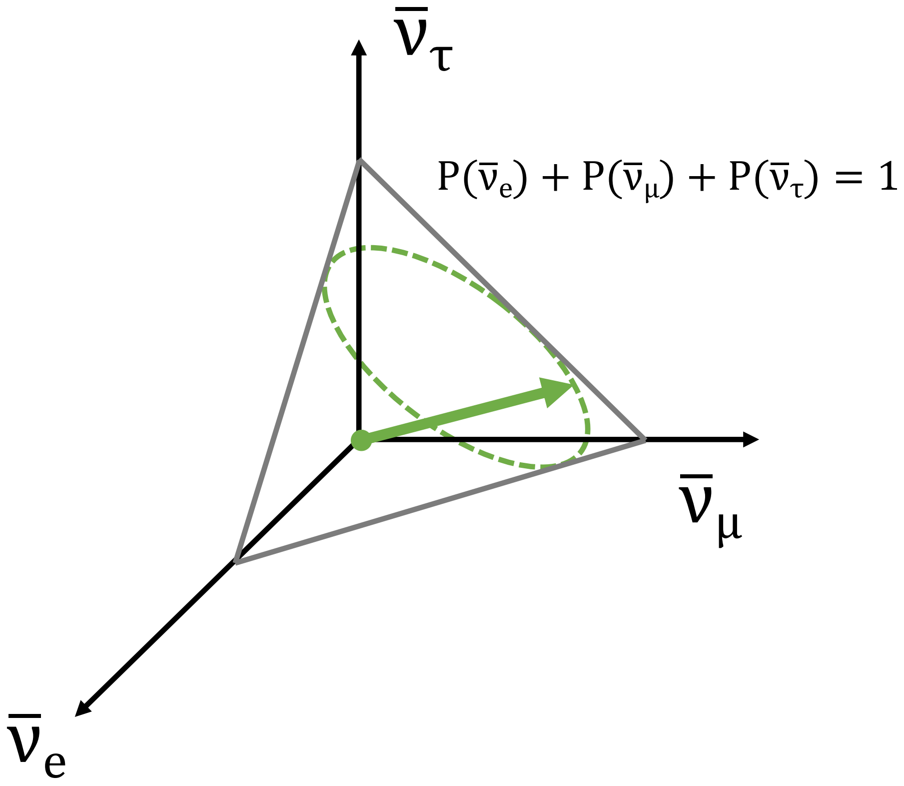
Oscillation as a function of *time*
line-in-**line** → same trivia

$\theta_{13} \neq 0$

3-flavor oscillation



Antineutrinos



Oscillation as a function of *time*
line-in-**plane** → CP-violation possible

PMNS

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Trimaximal mixing
— maximally CP-violating

$$(|U_{i\alpha}|^2) = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix}$$

PMNS

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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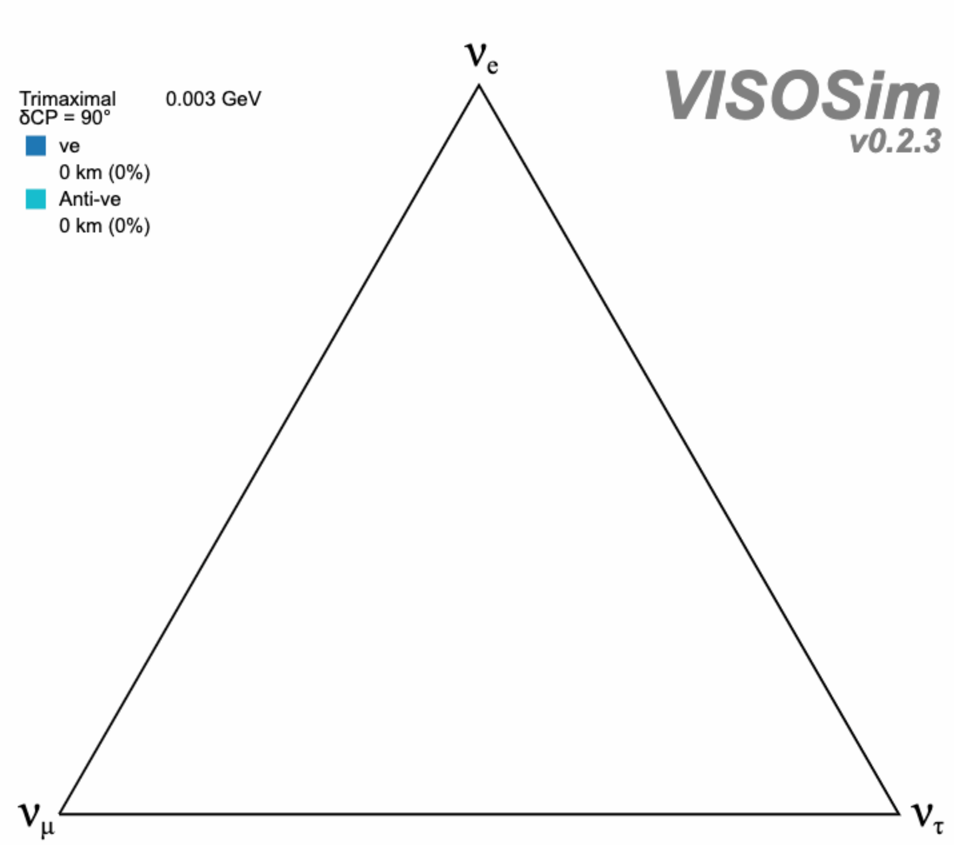


☛ *VISOS*

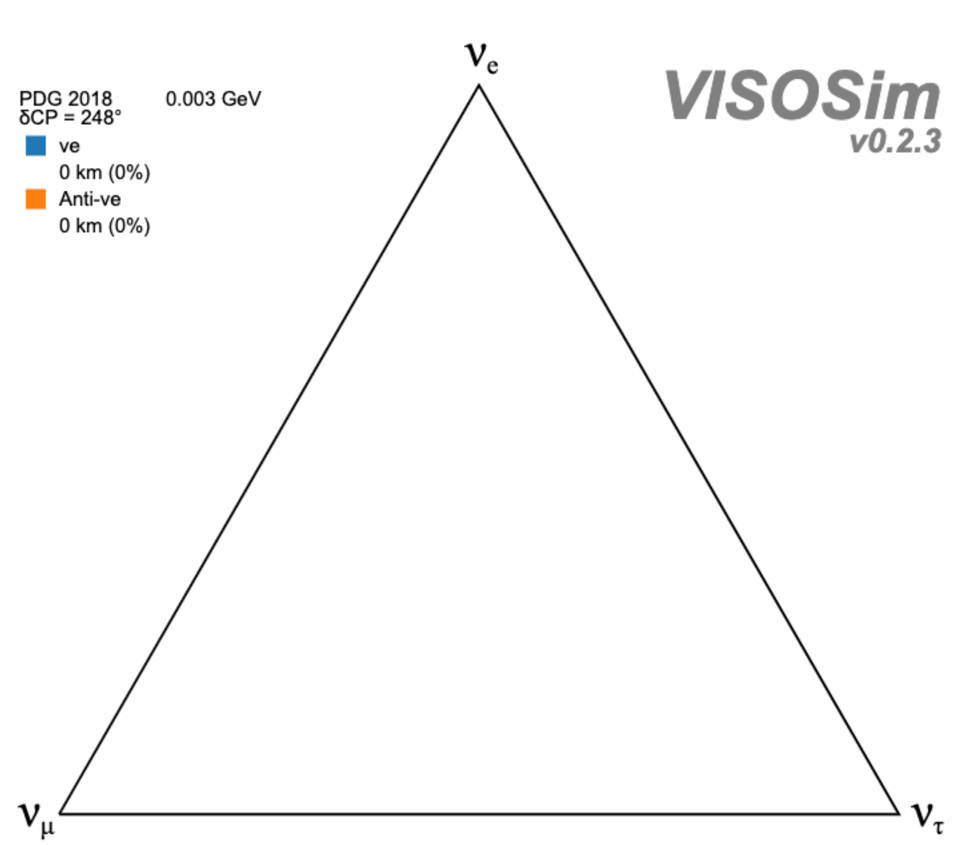
Beautiful but *not* how Nature works ¯_(ツ)_/¯

How Nature might work:

$$\begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix}$$

$$= \begin{bmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.233 \ldots 0.507 & 0.461 \ldots 0.694 & 0.631 \ldots 0.778 \\ 0.261 \ldots 0.526 & 0.471 \ldots 0.701 & 0.611 \ldots 0.761 \end{bmatrix}$$

Quiz: Which experiment has a 50 km baseline observing few-MeV neutrinos?



☛ *VISOS*

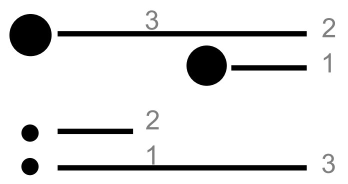
How Nature might work:

$$\begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix}$$

$$= \begin{bmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.233 \ldots 0.507 & 0.461 \ldots 0.694 & 0.631 \ldots 0.778 \\ 0.261 \ldots 0.526 & 0.471 \ldots 0.701 & 0.611 \ldots 0.761 \end{bmatrix}$$

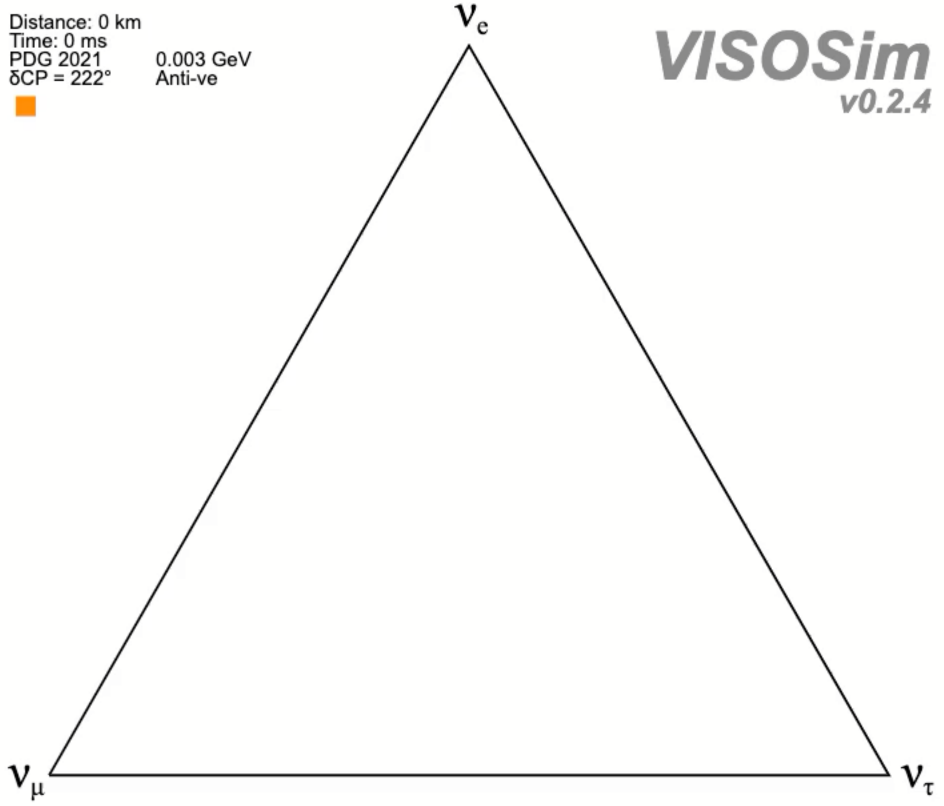
Quiz: Which experiment has a 50 km baseline observing few-MeV neutrinos?

Quiz: Is the oscillation driven by Δm^2_{21} fast or slow? Estimate $|\Delta m^2_{32}|/\Delta m^2_{21}$.



Normal / Inverted MO

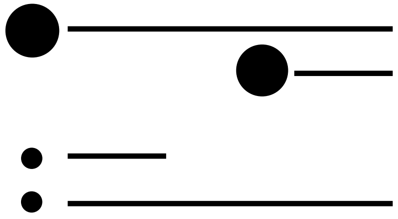
Homework: Estimate Δm^2_{21} and compare your result with PDG.



☛ VISOS

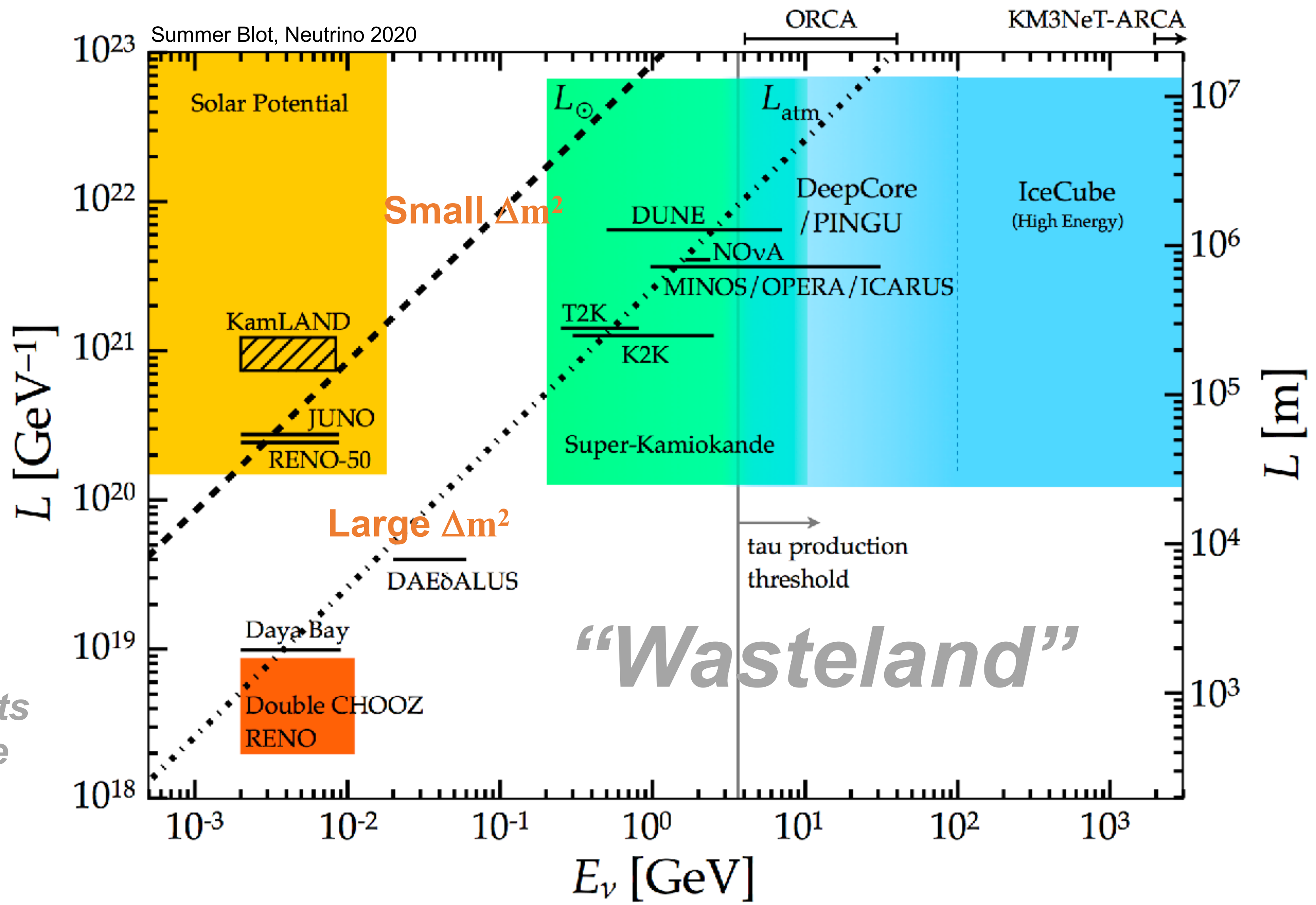
Oscillation Phase ~ $\Delta m^2 L/E$

Only two Δm^2



Normal **Inverted**

Quiz: Name a few experiments in the "wasteland"? What are they for?



Oscillation experiments

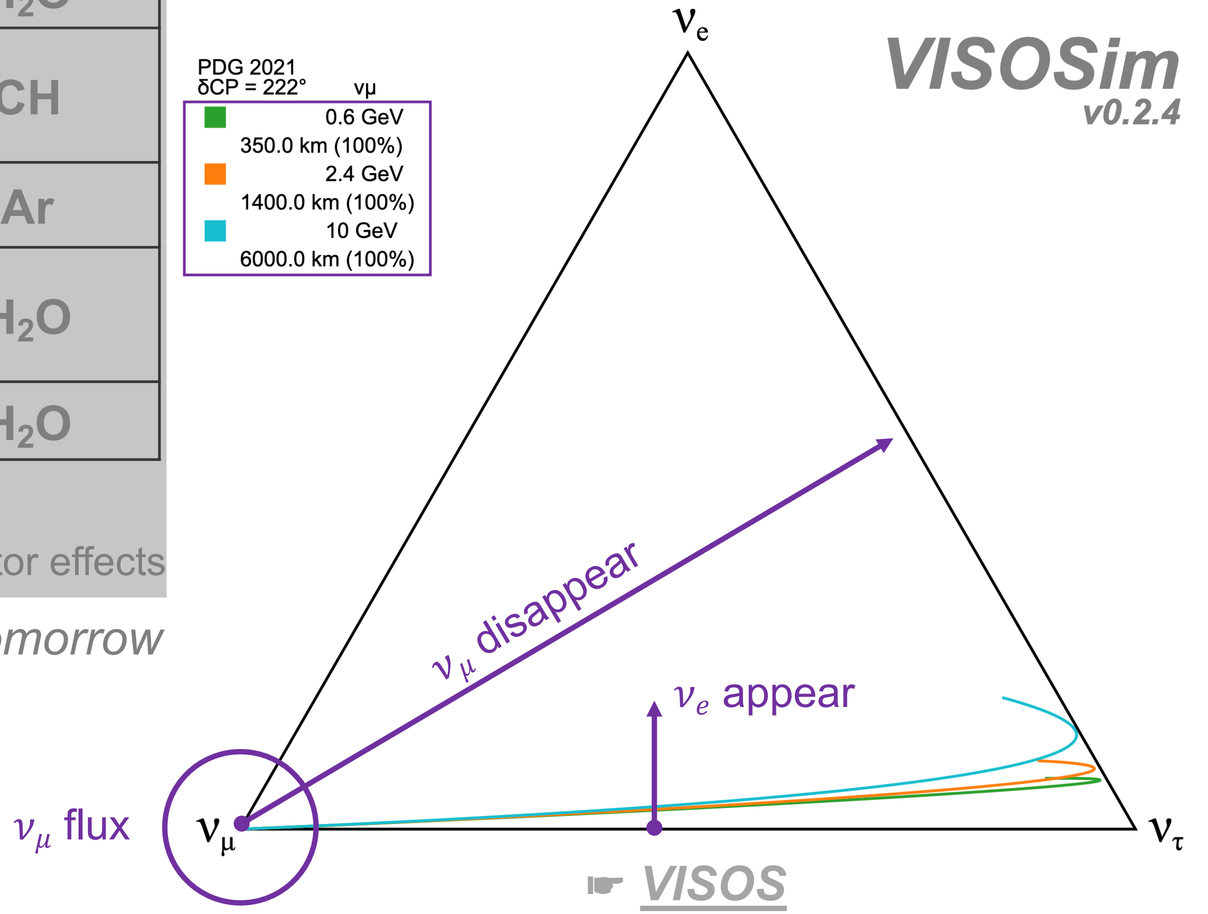
Future Oscillation Experiment	E_ν/GeV @Flux Peak	Detector Technology	Target Nuclei
T2K/HK	**0.6**	**Water Che'**	**H_2O**
NOvA	**2**	**Liquid Scintillator**	**CH**
DUNE	**2.4**	**LAr TPC**	**Ar**
IceCube	**3-10 (NMO sensitive region)**	**Cherenkov in ice**	**H_2O**
SK/KM3NeT		**Water Che'**	**H_2O**

- Flux: ν_μ and $\bar{\nu}_\mu$
- Oscillation
  - ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - **ν_e and $\bar{\nu}_e$ appearance**

Signal = (**Flux** · **Oscillation probability** · Cross section) ⊕ Detector effects

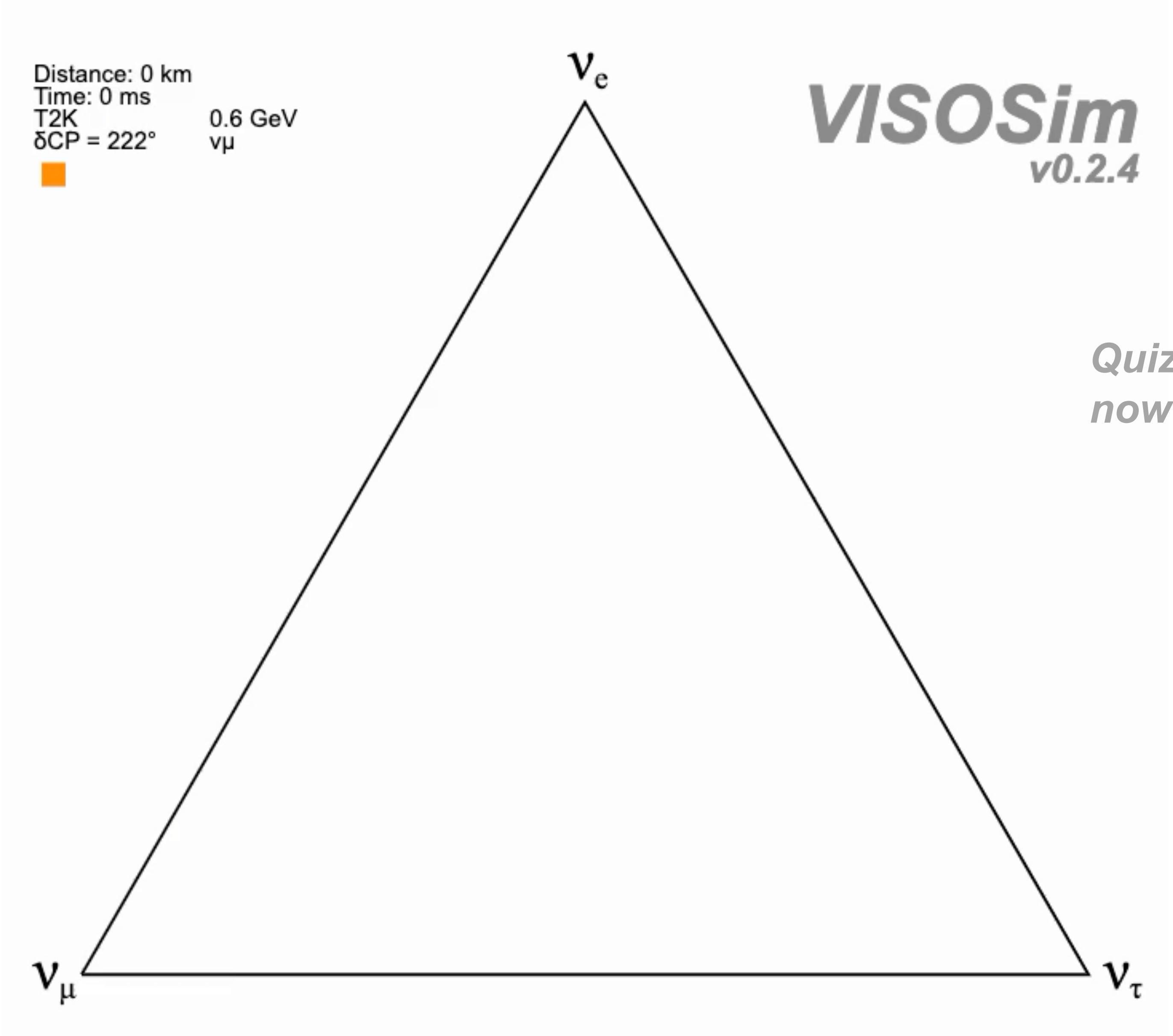
… to discuss tomorrow

Quiz: Is it driven by Δm^2_{21} or Δm^2_{32}?



☛ VISOS

Oscillation experiments



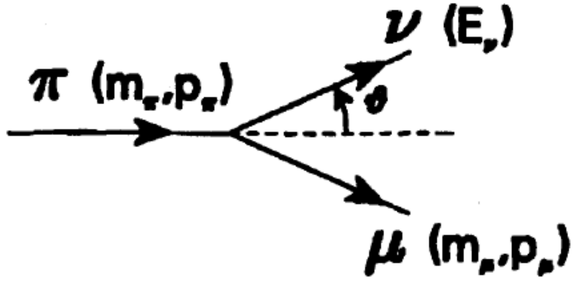
Quiz: What is $|\Delta m^2_{32}|/\Delta m^2_{21}$ now? Is it reasonable?

Part 2: Accelerator Neutrinos

Accelerator Neutrinos

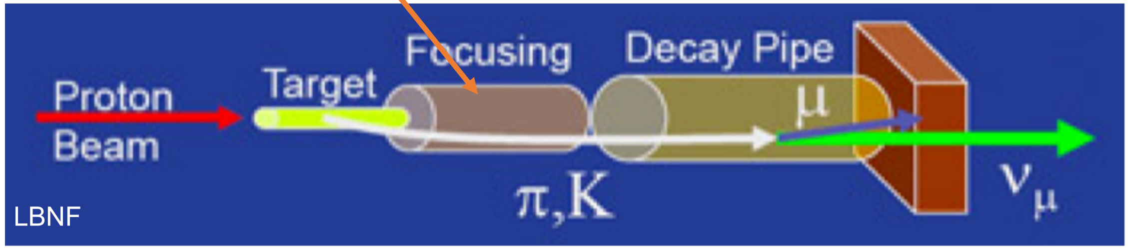
How to obtain a controlled sample of neutrinos?

Let's start from π decays



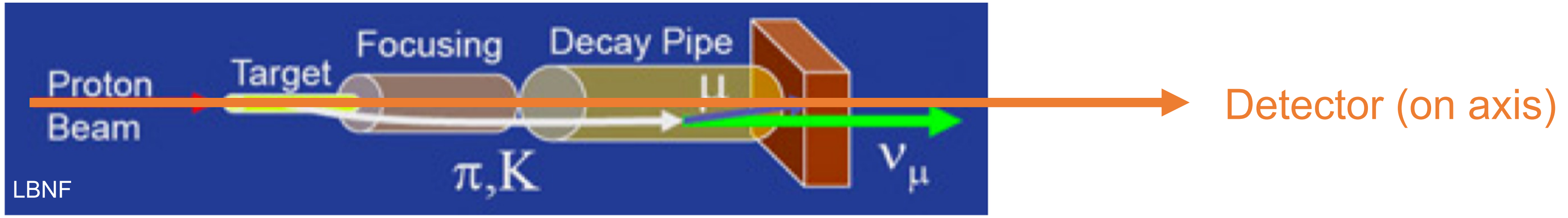
Accelerator Neutrinos

Magnetic "Horn"



Mostly ν_μ from π, few ν_e from K
Proton energy flow and horn → Directional
Horn charge selection on π → High purity ν or $\bar{\nu}$ beams

Accelerator Neutrinos

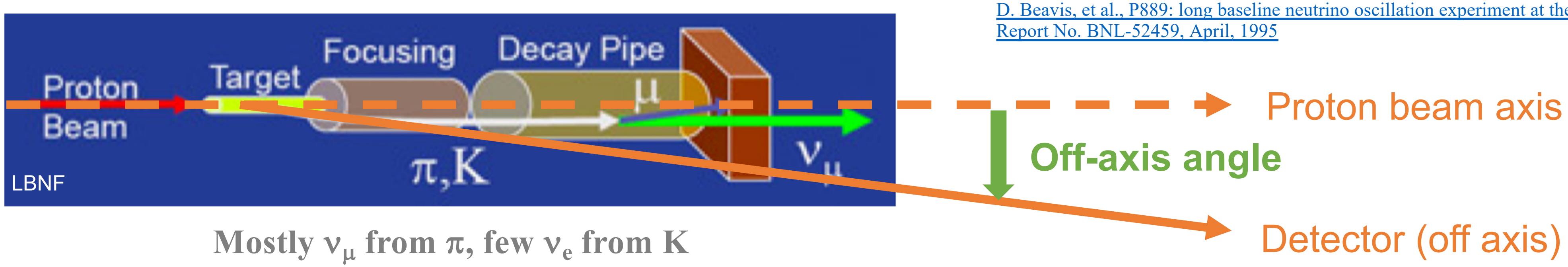


Mostly ν_μ from π, few ν_e from K
Proton energy flow and horn → Directional
Horn charge selection on π → High purity ν or $\bar{\nu}$ beams

Accelerator Neutrinos

Off-axis (OA) technique → Narrow-band beams

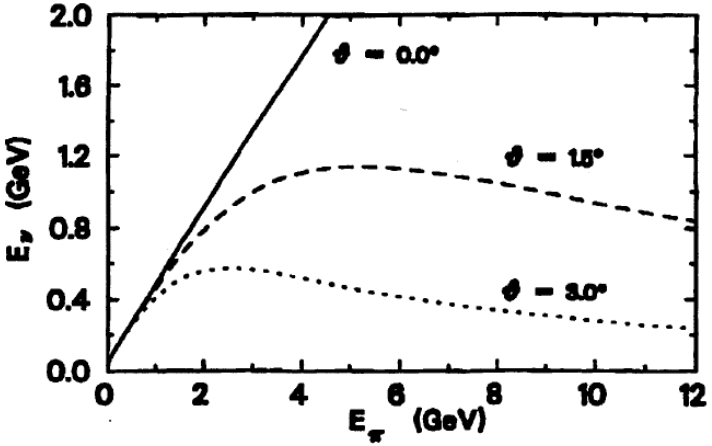
[D. Beavis, et al., P889: long baseline neutrino oscillation experiment at the AGS, Report No. BNL-52459, April, 1995]



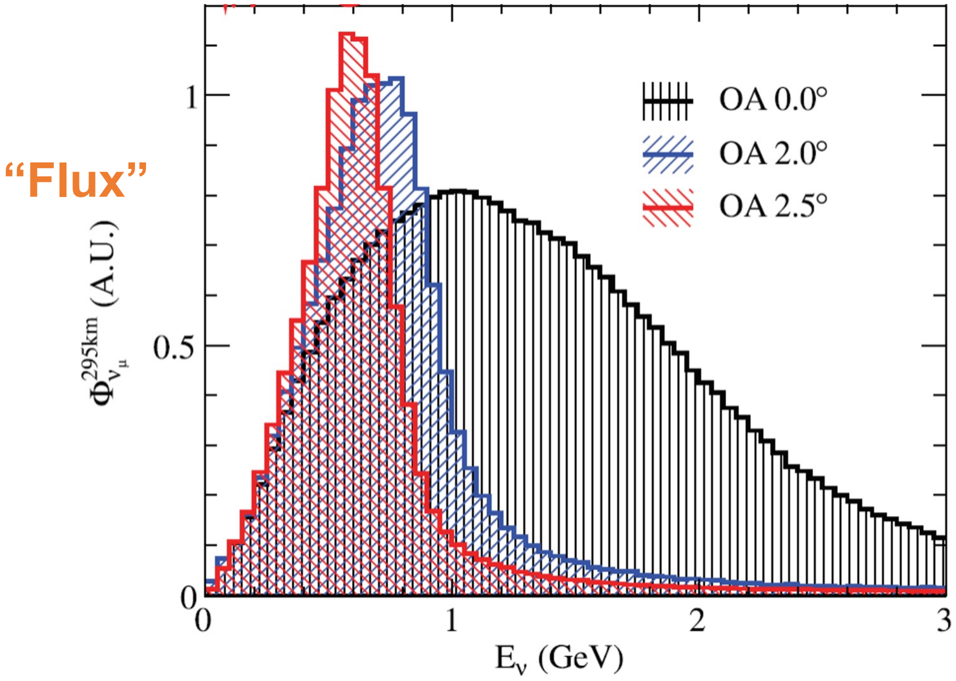
Mostly ν_μ from π, few ν_e from K
Proton energy flow and horn → Directional
Horn charge selection on π → High purity ν or $\bar{\nu}$ beams

From energy, momentum conservation

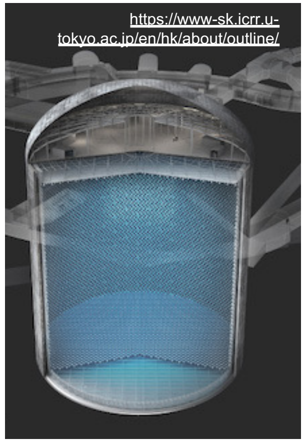
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\vartheta)}$$

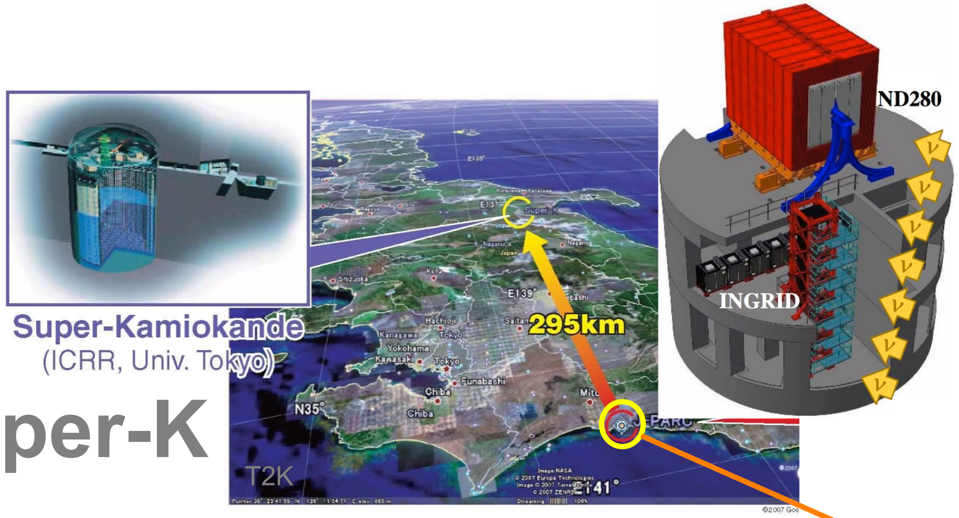


T2K, Phys. Rev. D 87, 012001 (2013)



Accelerator Neutrino Experiments



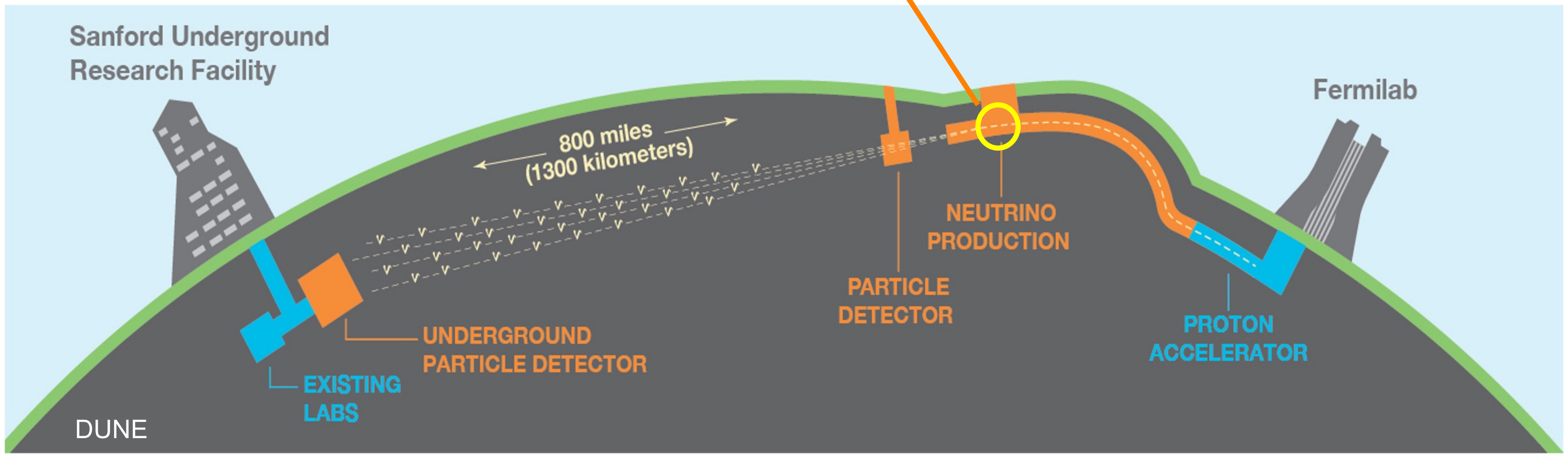


T2K / Hyper-K

NOvA

ν beams via hadron decay

DUNE



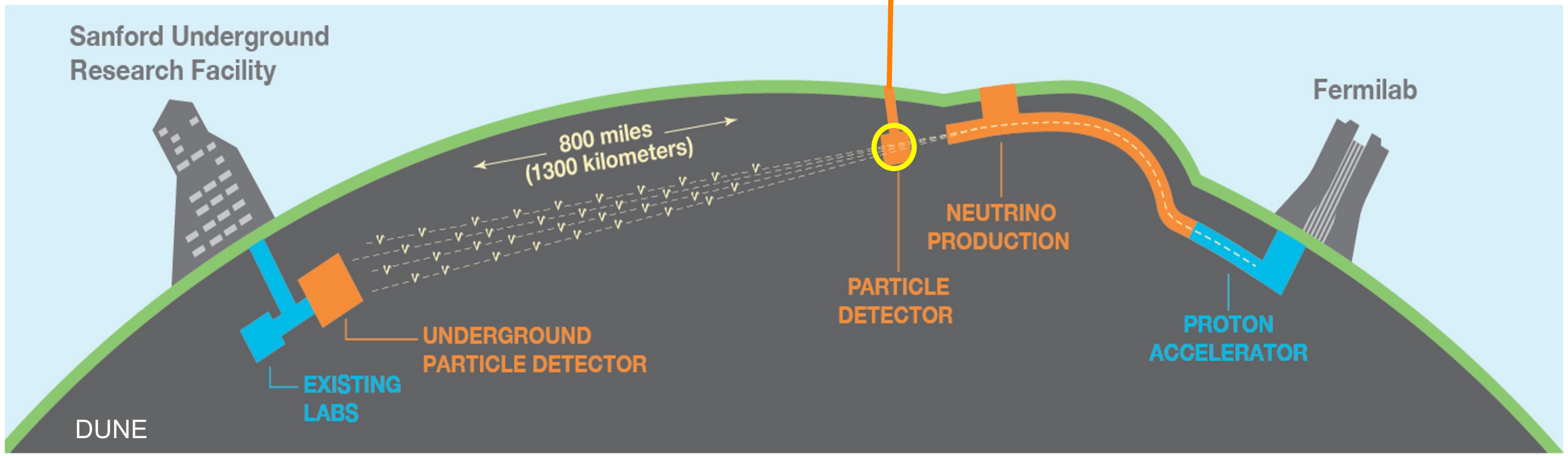
Accelerator Neutrino Experiments

T2K / Hyper-K

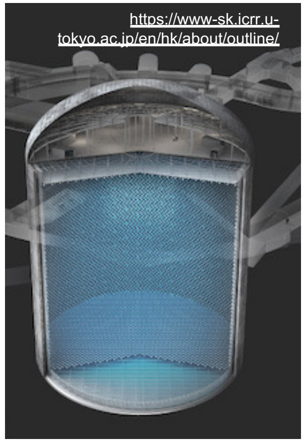
NOvA

Near Detectors (NDs) to constrain ν flux ***and*** cross section ***together*** (no oscillation)

DUNE



Accelerator Neutrino Experiments

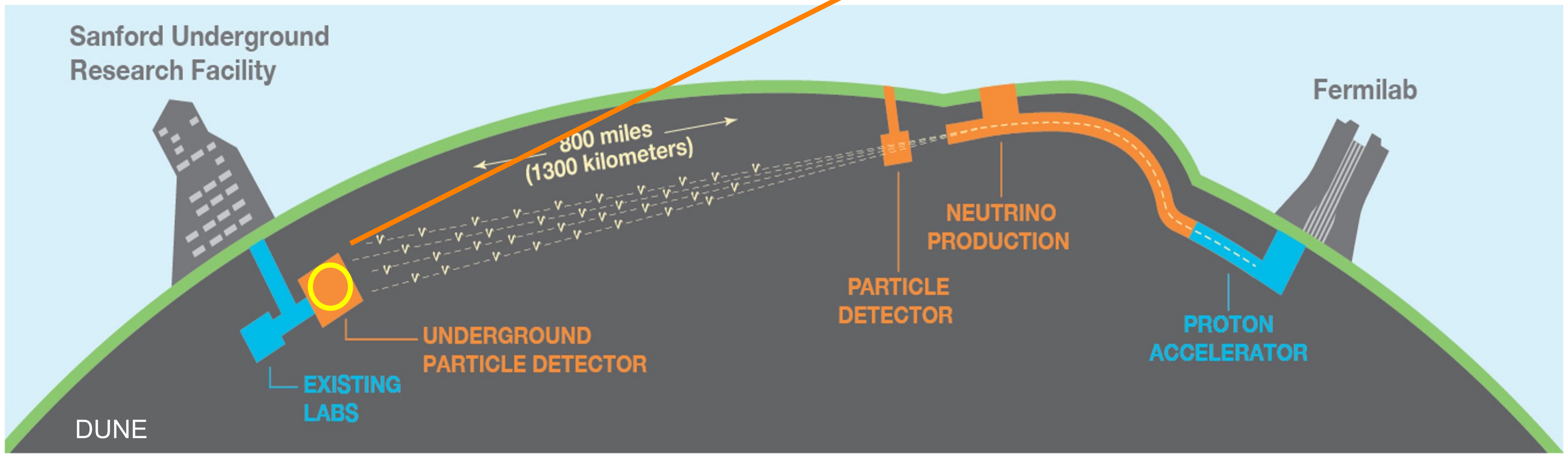


T2K / Hyper-K

NOvA

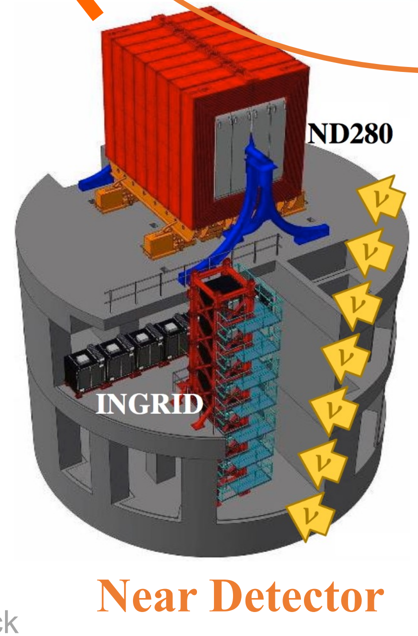
Far Detectors to measure ν oscillation

DUNE



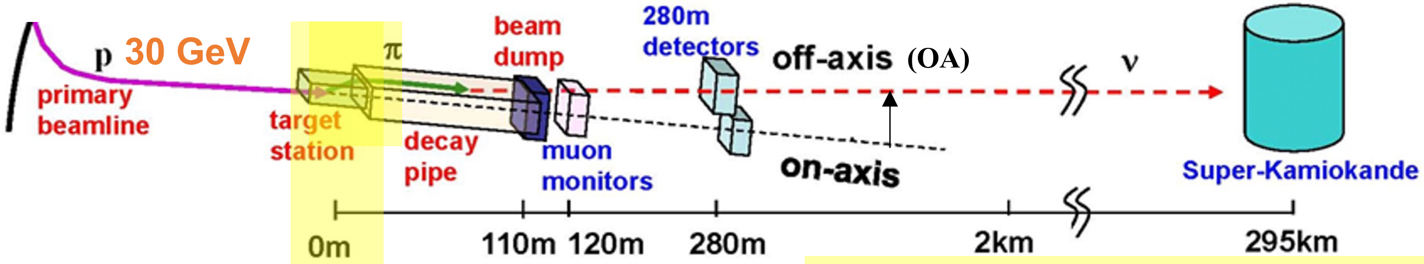
Accelerator Neutrino Experiments

T2K



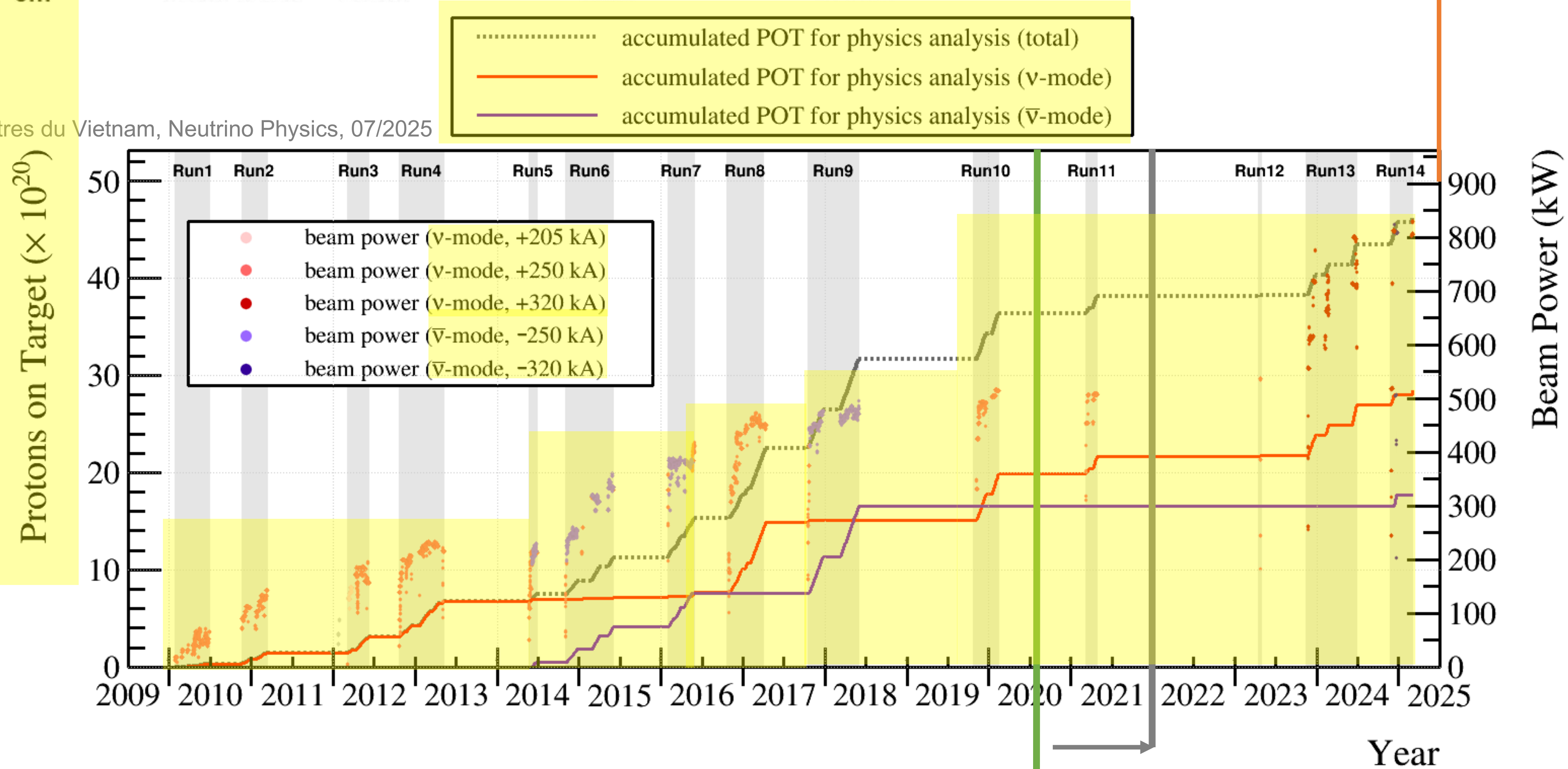
Will check the detectors tomorrow…
… flux and oscillation measurements today

T2K Beams



1.3 MW power near the beginning of the Hyper-Kamiokande data taking [HK, 2505.15019]

T2K, 21st Rencontres du Vietnam, Neutrino Physics, 07/2025



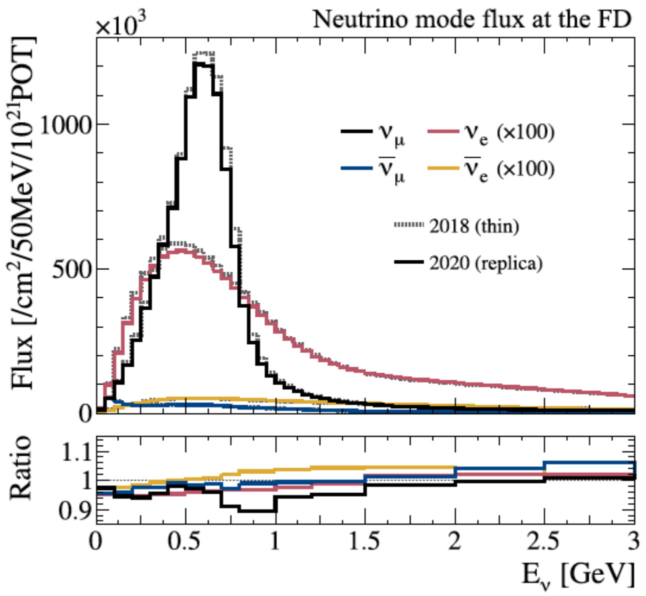
T2K, Eur.Phys.J.C 83, 9, 782 (2023)

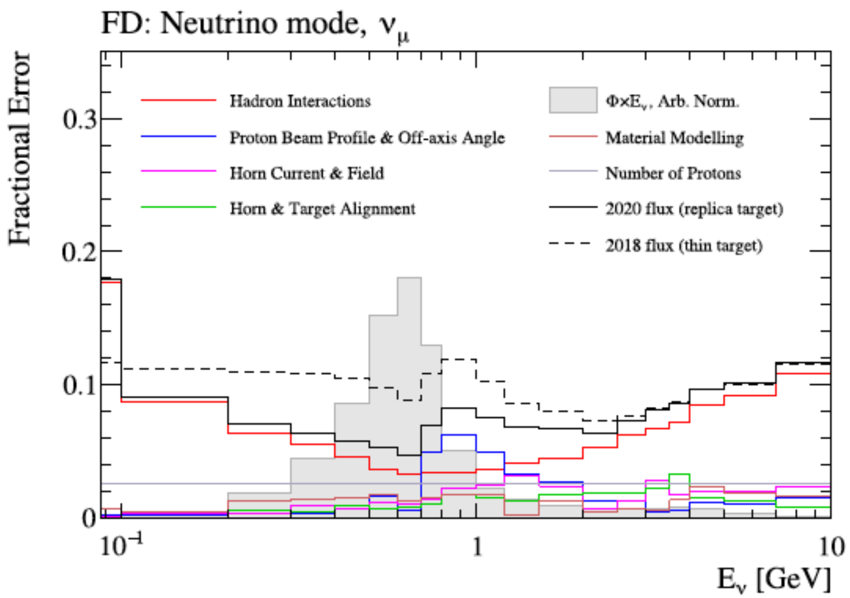
Latest analysis (07/25)

T2K Beams

T2K, Eur.Phys.J.C 83, 9, 782 (2023)

For ν oscillations

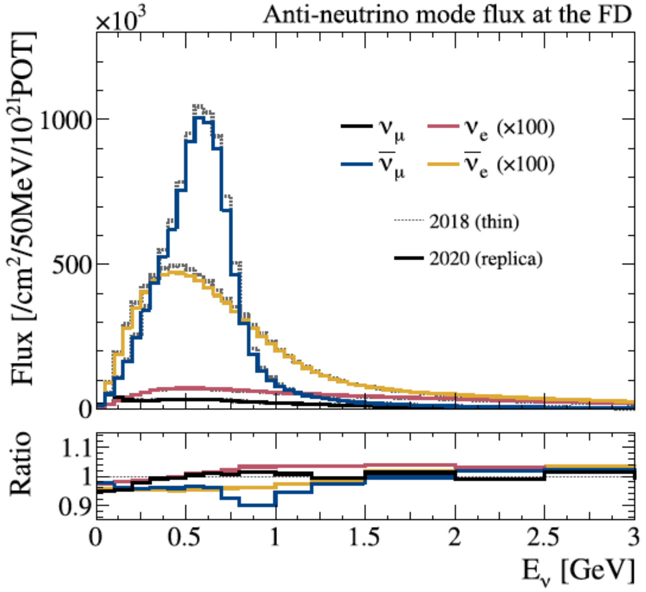


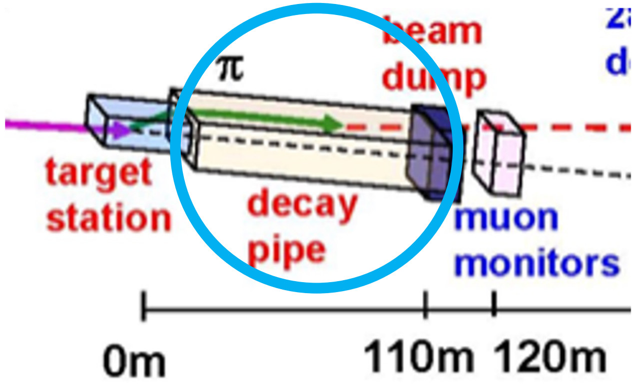


Flux model error 5%+
Extremely hard to get it further down

Bkg from 3 other types
… more on this later

For $\bar{\nu}$ oscillations



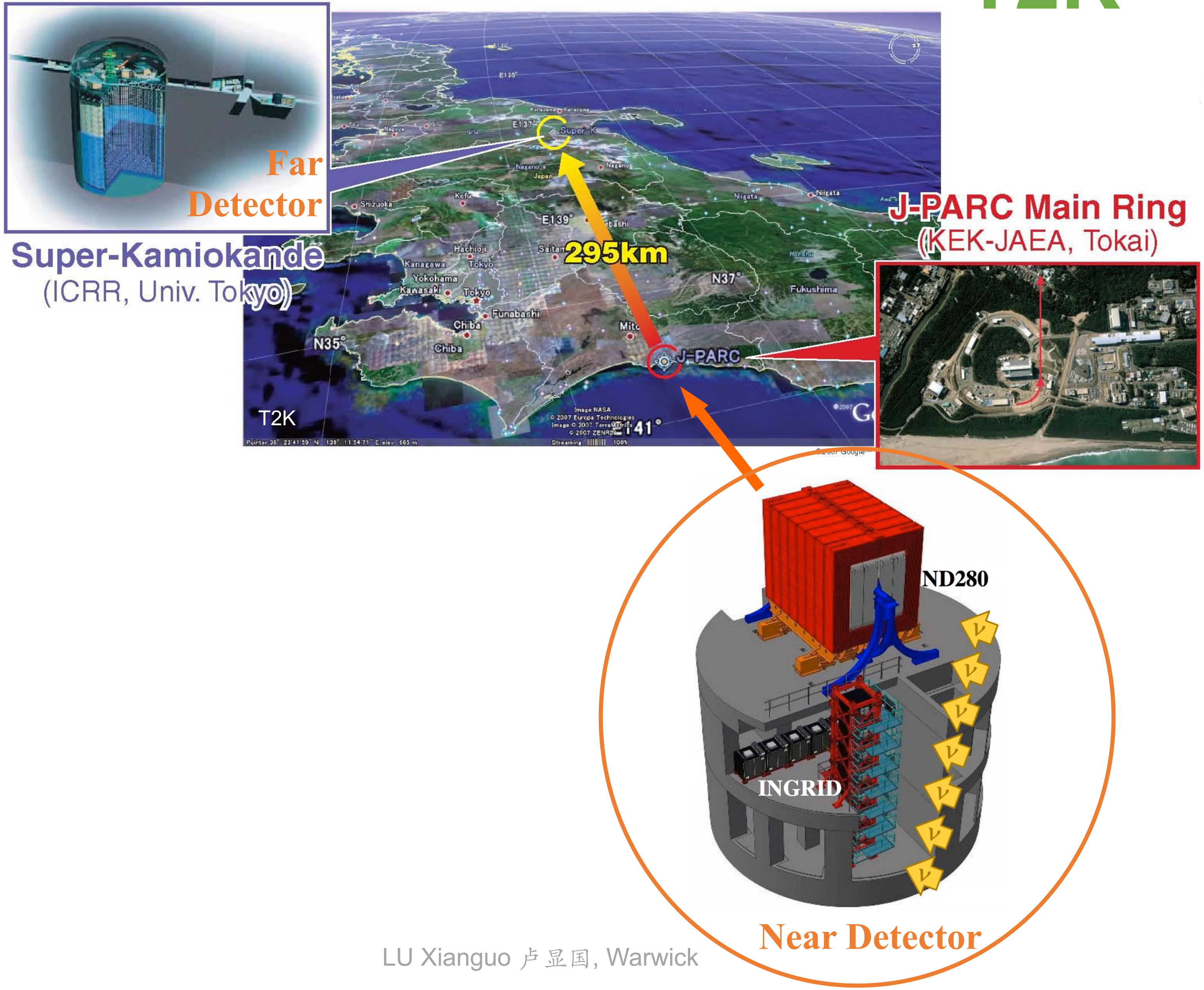


No control over neutrino parents (π, K) after focusing.
Everything relies on the horn.

… more on this later

Accelerator Neutrino Experiments

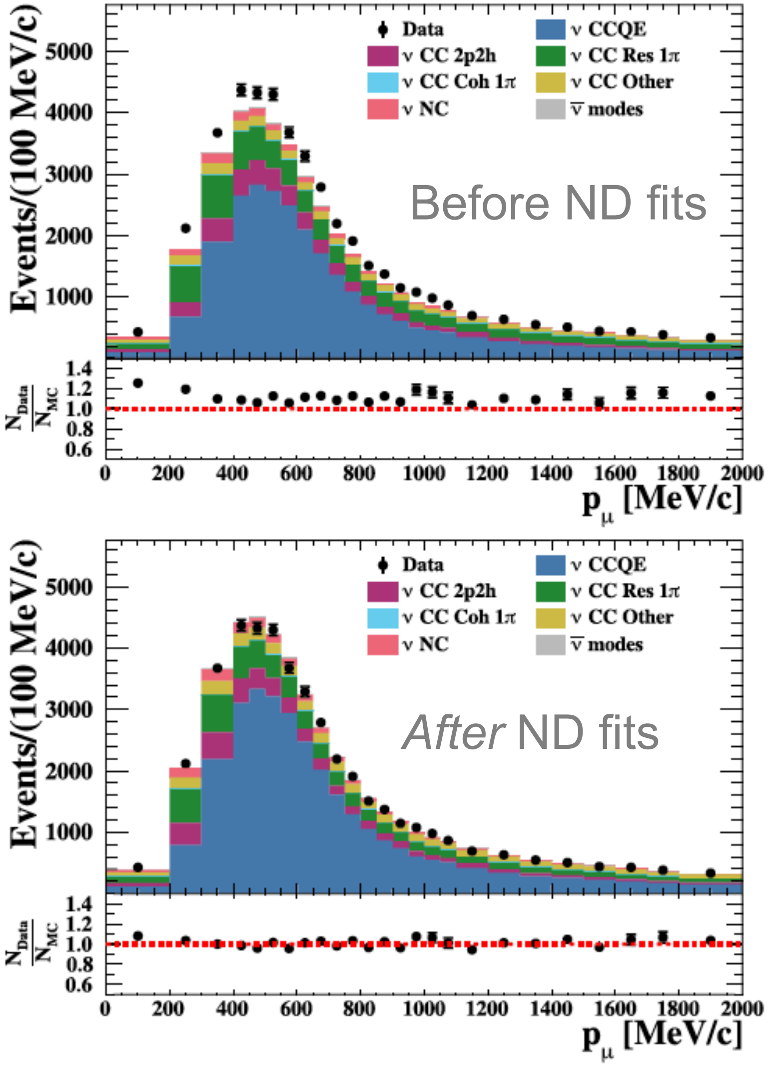
T2K



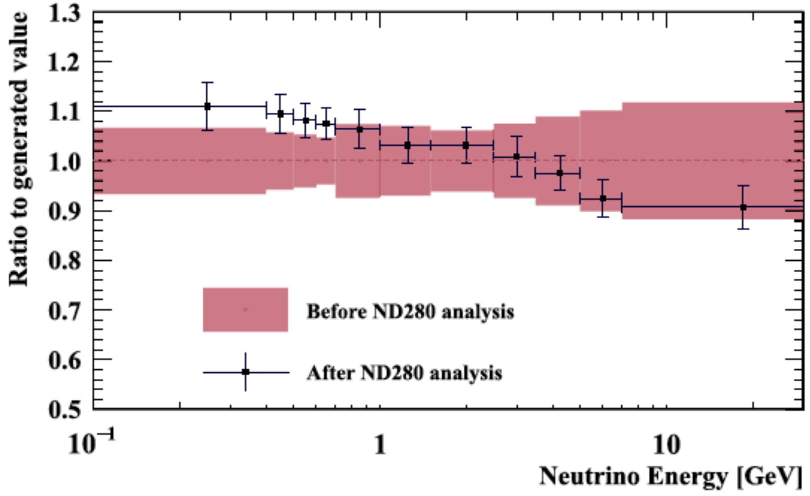
T2K Near Detector (ND) Fits

T2K, Eur.Phys.J.C 83, 9, 782 (2023)

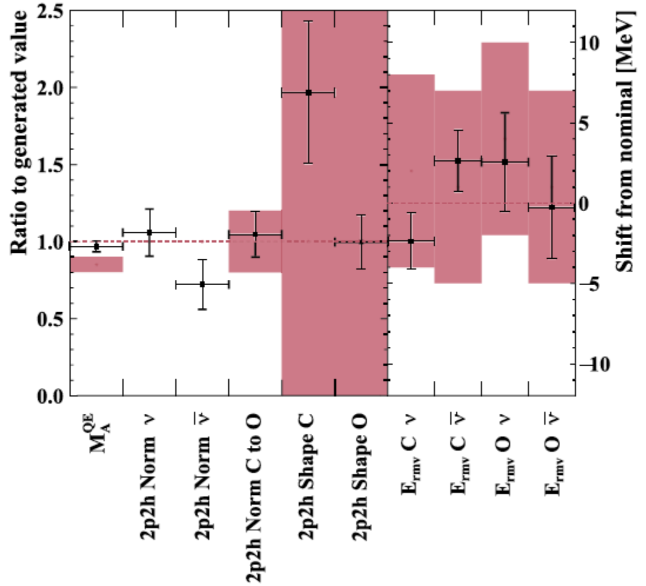
Signal = (**Flux** · ~~Oscillation probability~~ · Cross section) ⊕ Detector effects



(a) FGD1 ν-mode ν_μ CC0π



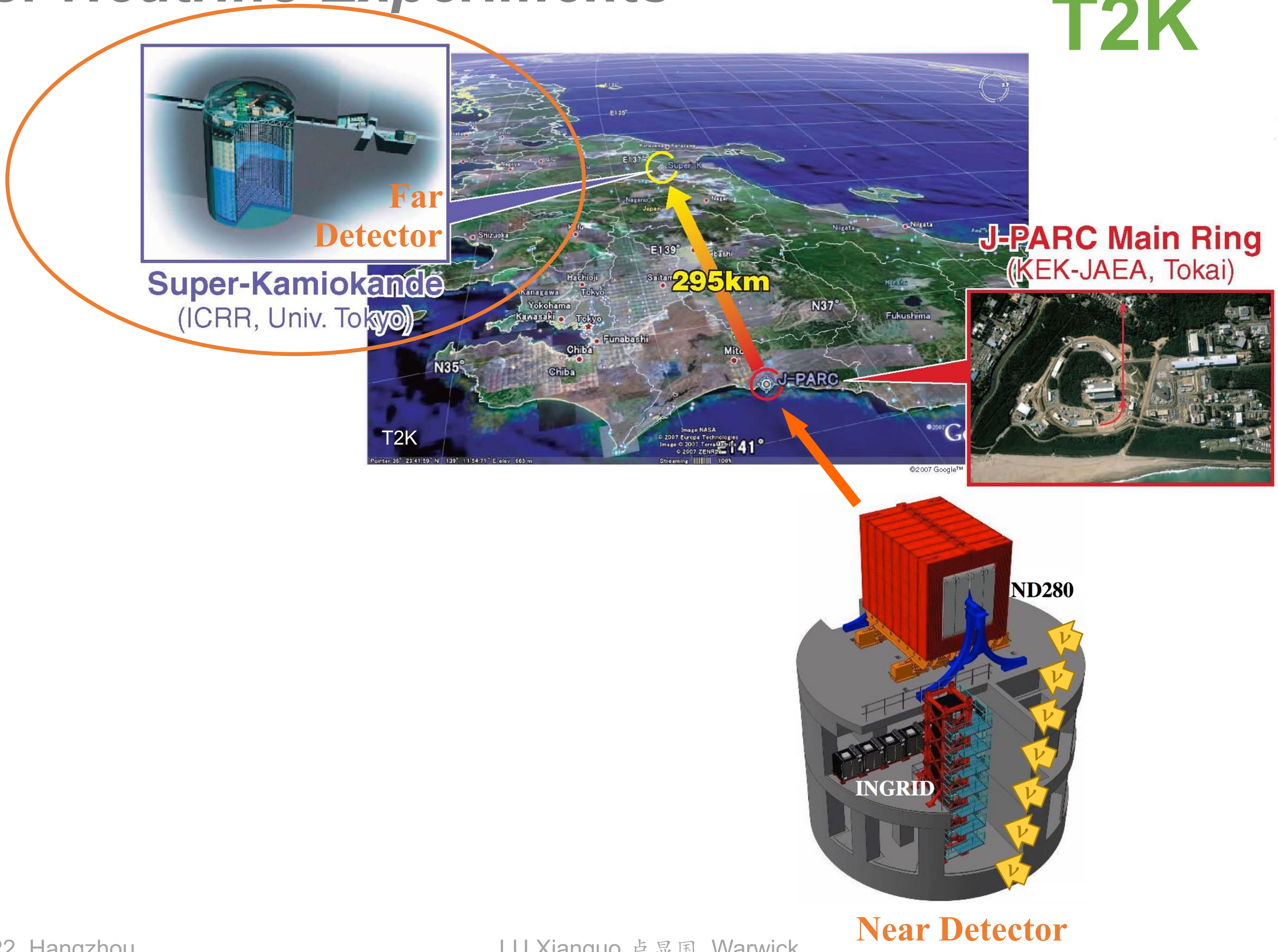
Flux prediction (mean and spread) improved after ND fits



Cross section models *now have* constraints or are better constrained after ND fits

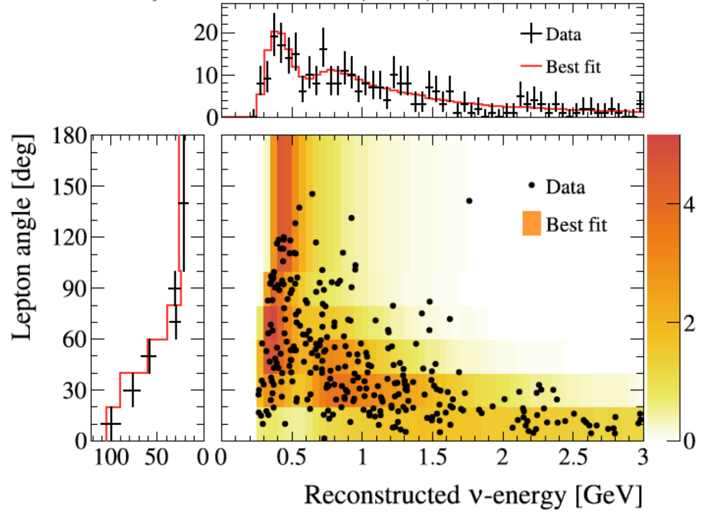
Accelerator Neutrino Experiments

T2K

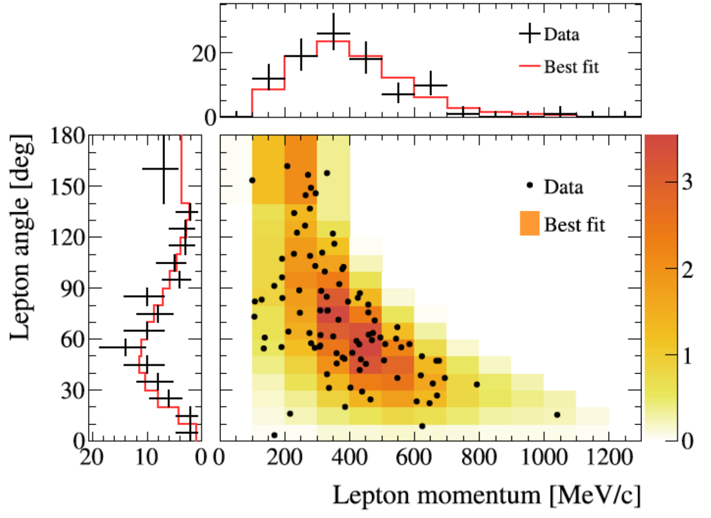


T2K Far Detector Events

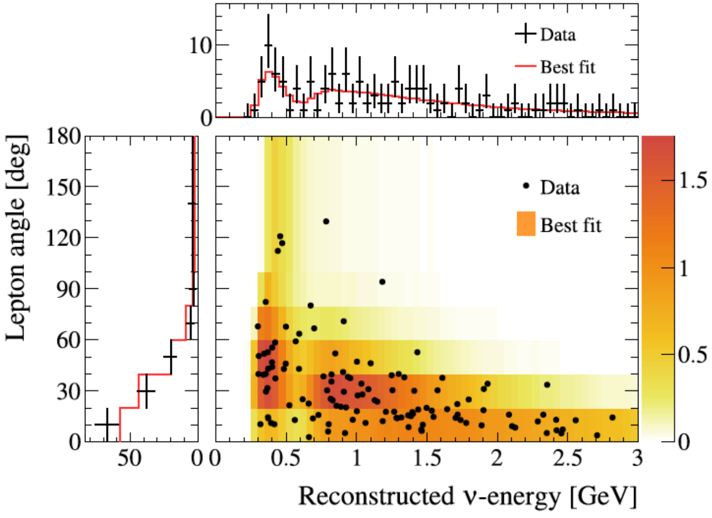
T2K, Eur.Phys.J.C 83, 9, 782 (2023)



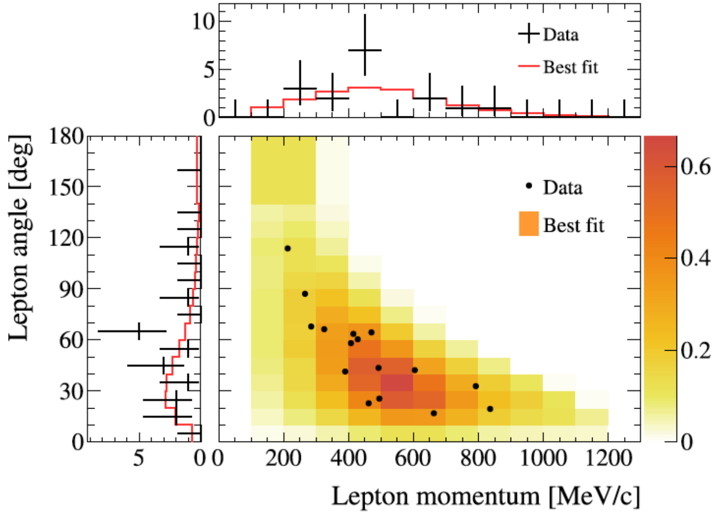
(a) ν-mode 1Rμ



(b) ν-mode 1Re

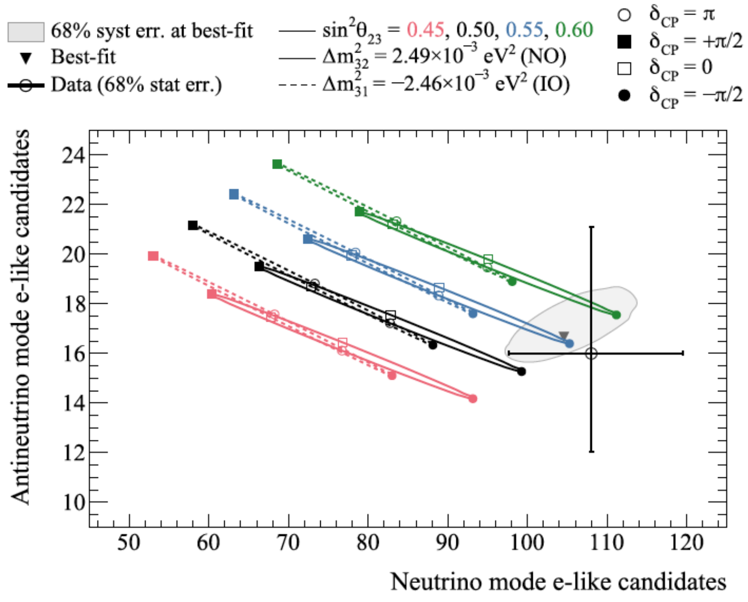


(d) $\bar{\nu}$-mode 1Rμ



(e) $\bar{\nu}$-mode 1Re

- ❑ Flux: ν_μ and $\bar{\nu}_\mu$
- ❑ Oscillation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance, then CP violation**



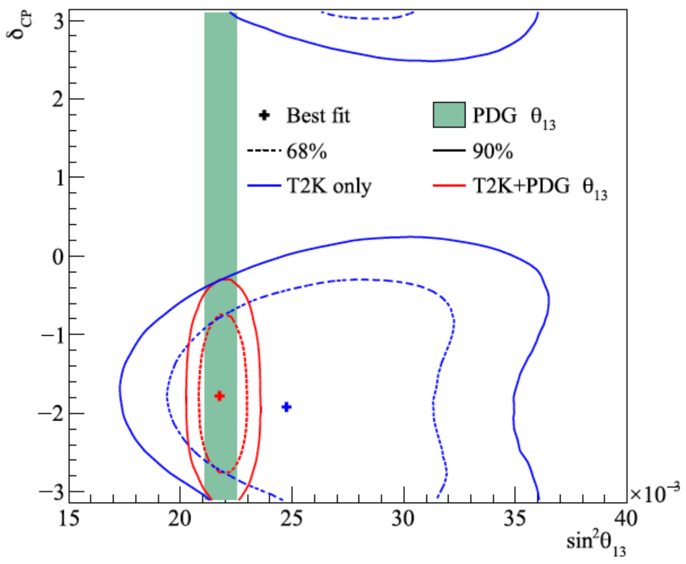
~ Normal ordering, $\delta_{\rm CP} = -\frac{\pi}{2}$

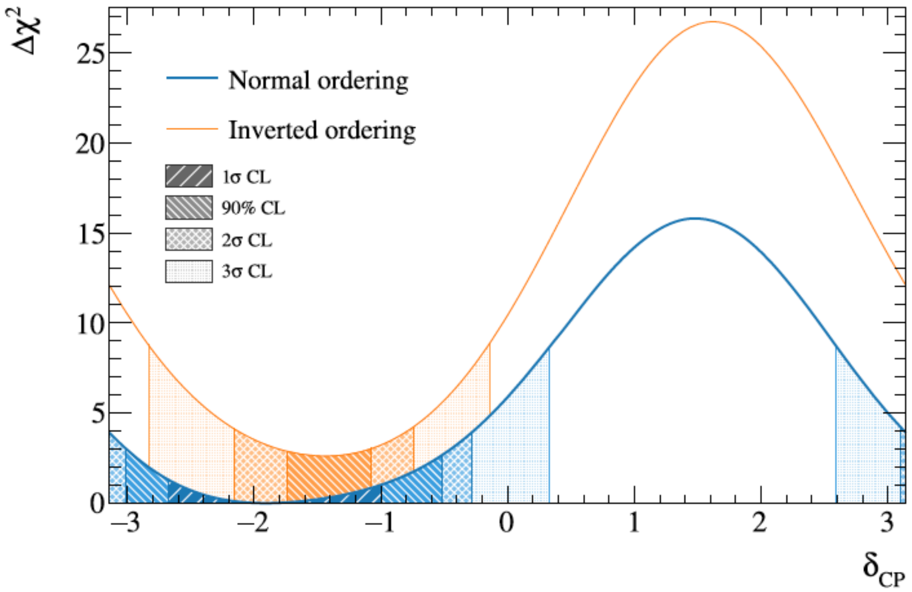
Lucky fluctuations?

… next slide

T2K Oscillation Parameter Results

T2K, Eur.Phys.J.C 83, 9, 782 (2023)





θ_{13} relies on ν_e appearance, statistically very limited

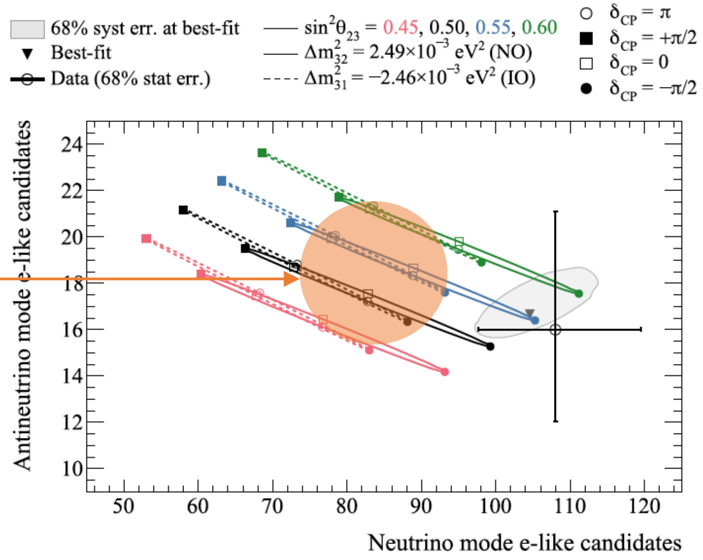
➢ Need reactor constraints

Similar δ_{CP} intervals for both MO

➢ What happens if Nature gives us different event rates here

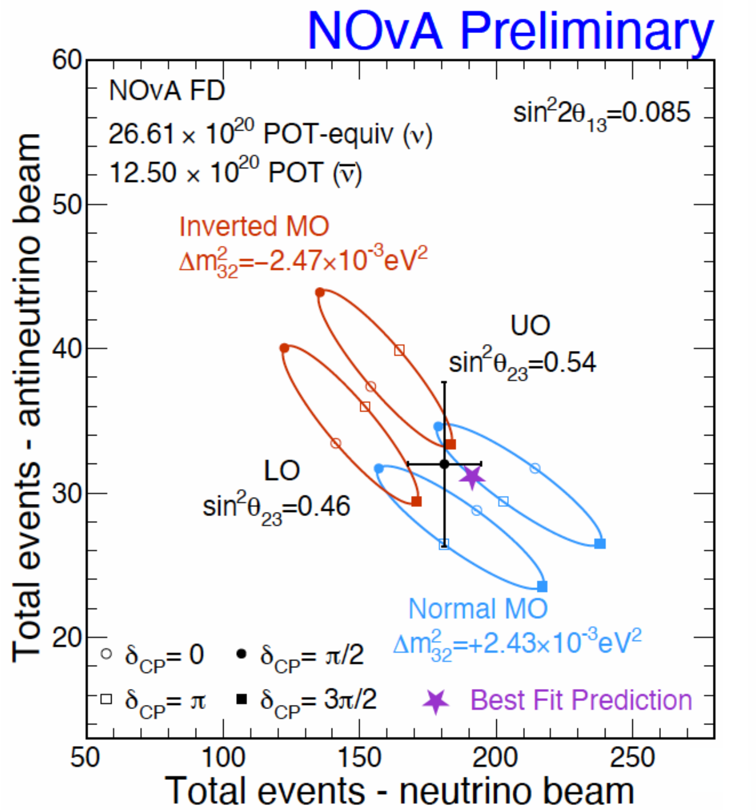
➢ Need external constraints on MO

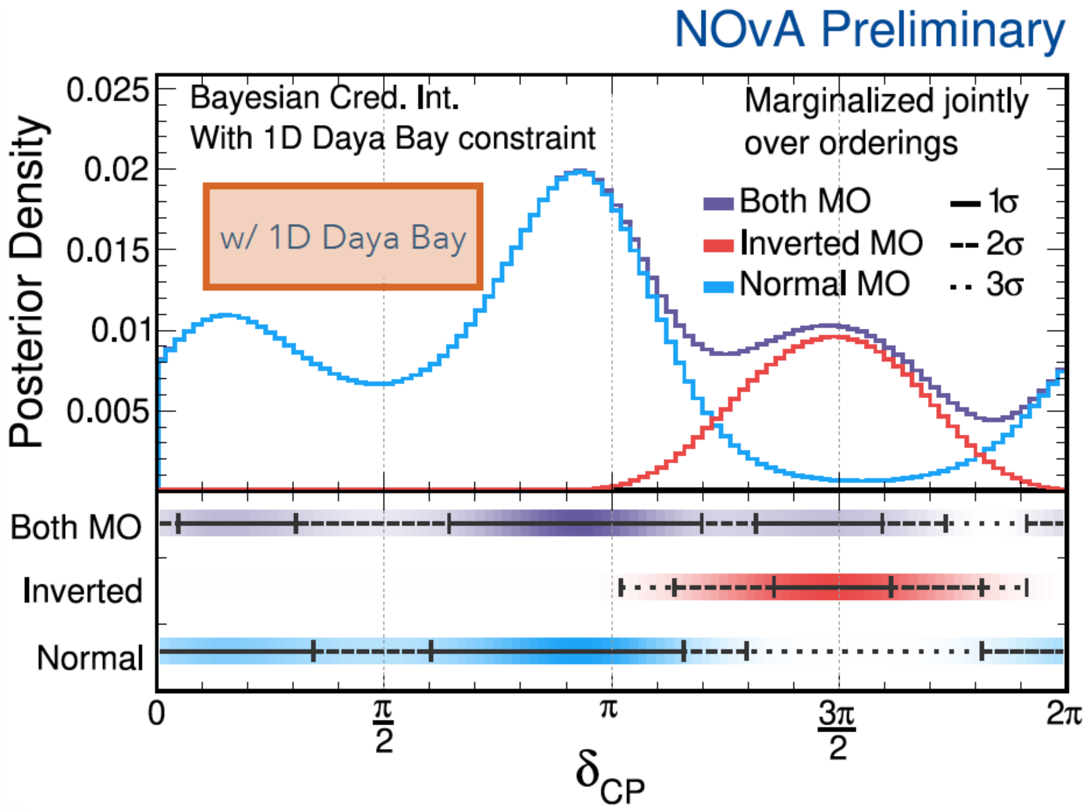
… will come to this later



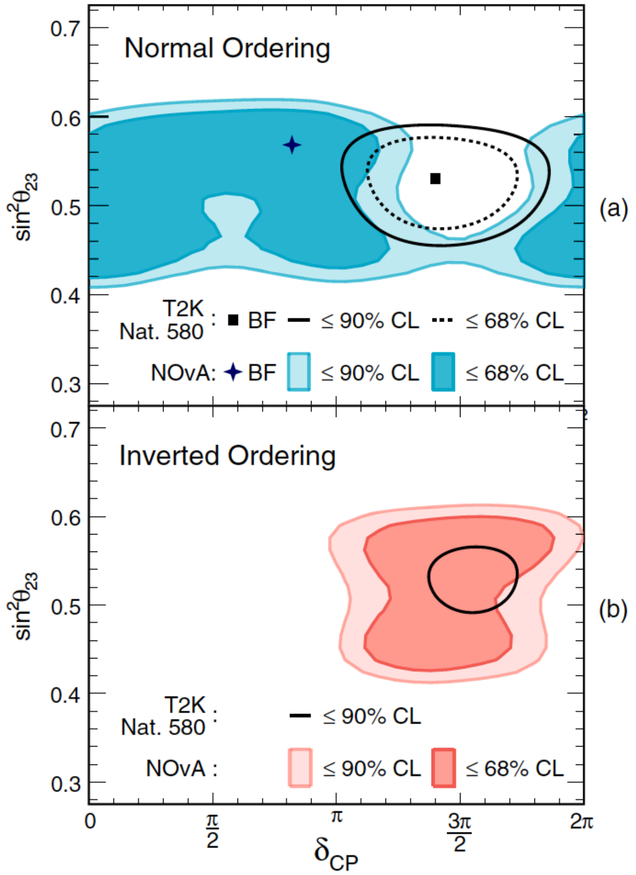
One slide about NOvA

NOvA, 21st Rencontres du Vietnam, Neutrino Physics, 07/2025





NOvA, Phys.Rev.D 106, 032004 (2022)

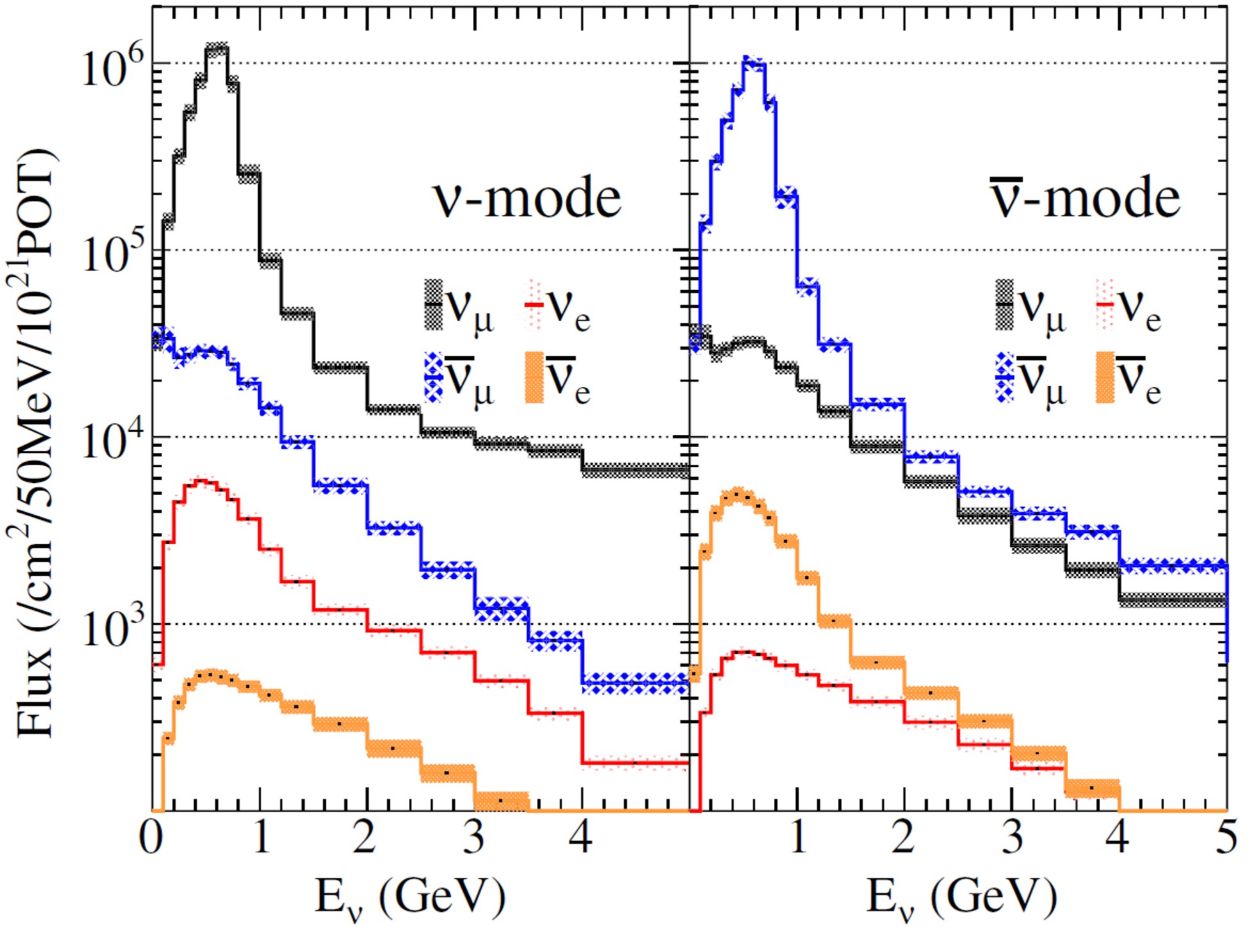


- Not knowing NMO makes it very difficult to determine δ_{CP}
- Already difficult even if NMO known

Coming back to the flux background…

T2K flux

T2K, Phys.Rev.Lett. 116, 181801 (2016)

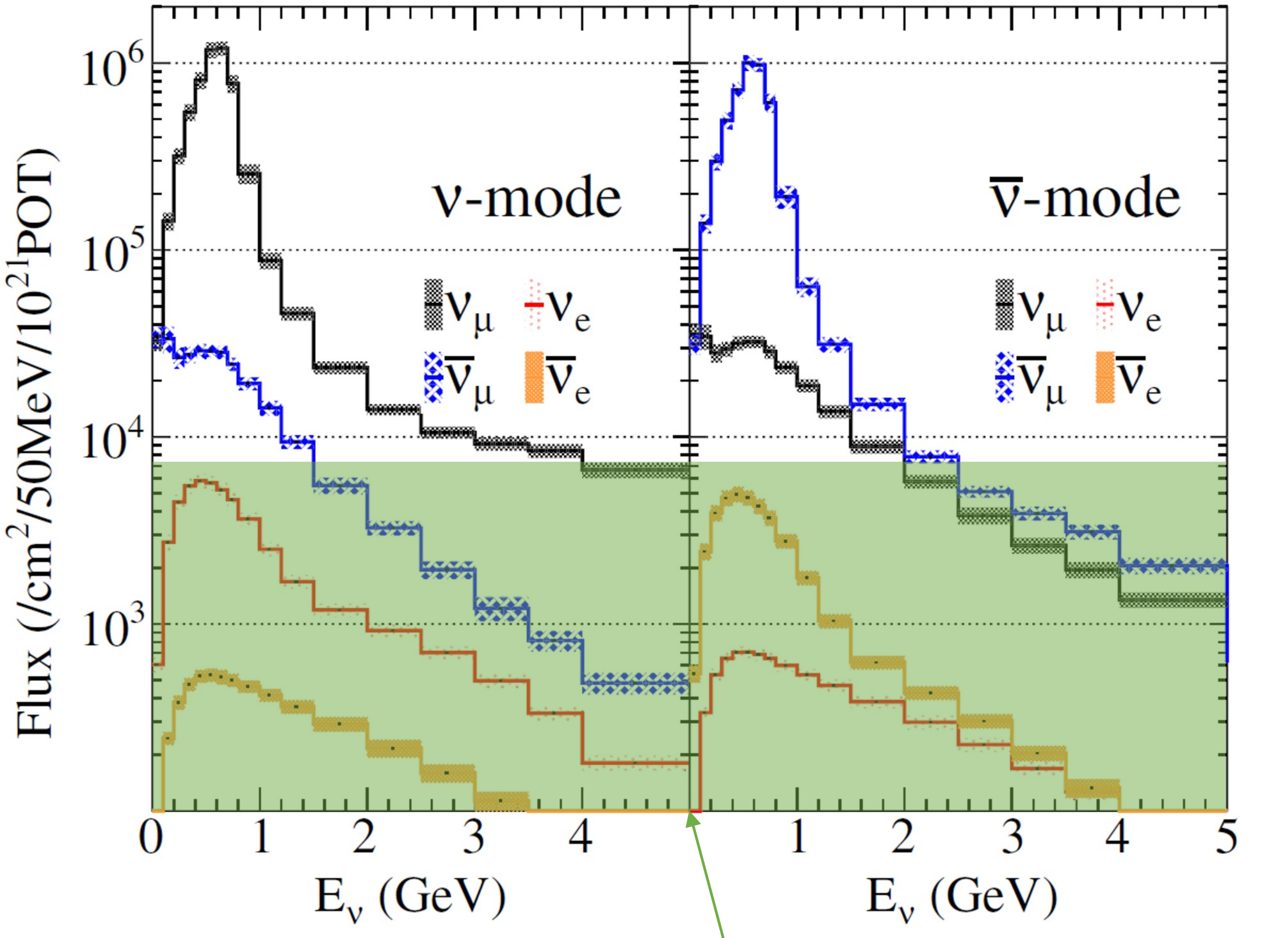


- ❑ Maximise ν_μ and $\bar{\nu}_\mu$ flux

Coming back to the flux background…

T2K flux

T2K, Phys.Rev.Lett. 116, 181801 (2016)



- ❑ Maximise ν_μ and $\bar{\nu}_\mu$ flux
- ❑ **Minimise ν_e and $\bar{\nu}_e$ to observe appearance**
  - ❑ **ν_e and $\bar{\nu}_e$ flux are background**

Call for a GeV ν_e and $\bar{\nu}_e$ Machine

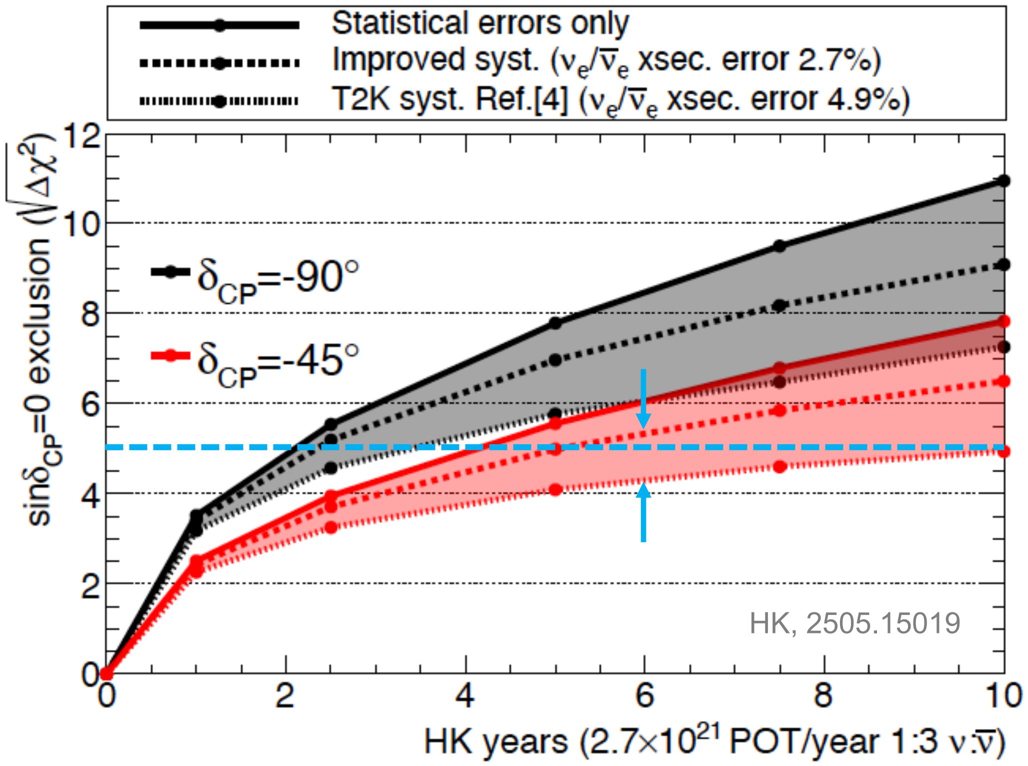
ν_e ($\bar{\nu}_e$) cross sections: major δ_{CP} systematics

- ❑ Very few ν_e scattering data
- ❑ δ_{CP} ~ ν_e appearance ~ no ν_e in beams
  - ❖ No *in situ* ν_e measurements
- ❑ ν_μ for ν_e via lepton universality, but higher precision needed for δ_{CP}

Hyper-K example

Improving error of $\nu_e/\bar{\nu}_e$ xsec ratio 4.9% → 2.7%

- ❑ Improve δ_{CP} sensitivity by ~ 1 σ for 6 year
- ❑ **Significantly shorten running time to reach 5σ**

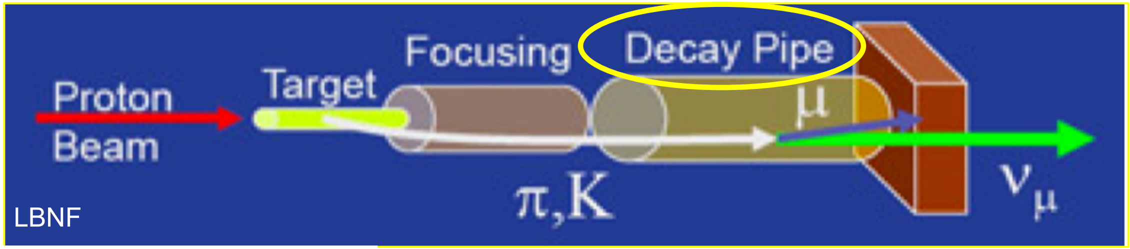


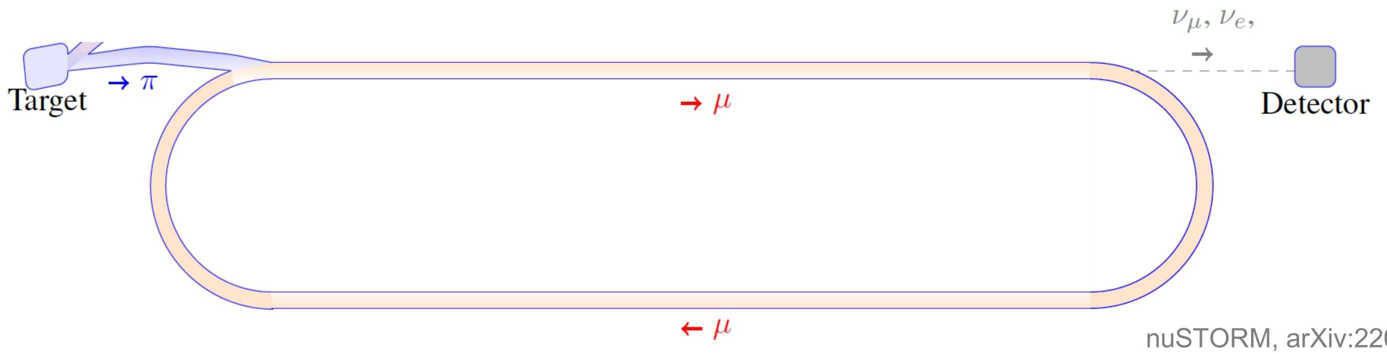
✓ Wishlist

1. **ν_e and $\bar{\nu}_e$ beams with the relevant energy for appearance**
2. **Well-understood fluxes**
3. **High statistics**
4. **Low ν_μ background**

ν from STORed Muons (nuSTORM)

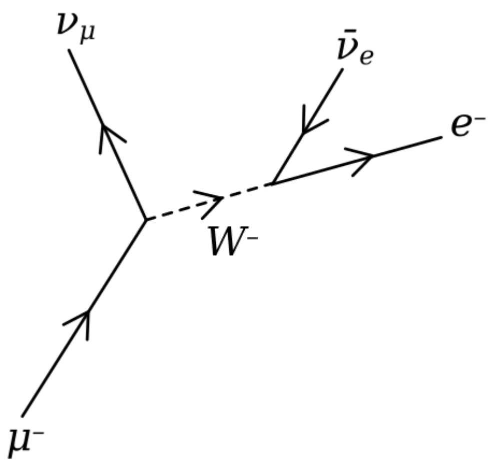
Coming back to the beam control…





nuSTORM, arXiv:2203.07545

- π captured by storage ring → μ → ν, instead of decay pipe → ν
- $\bar{\nu}_\mu$+ν_e and ν_μ+$\bar{\nu}_e$ fluxes from $\mu^{\pm}$ decays
  - **Storage ring: tunable fluxes**
  - **μ decay: perfect understanding of flux shape and normalisation**



Part 3: Atmospheric Neutrinos

More on Neutrino Mass: MSW Matter Effect

Before getting into atmospheric ν …

All neutrinos experience the same NC matter potential in medium.

Additional CC potential for ν_e ("+") and $\bar{\nu}_e$ ("−")

$$V_{\mathrm{CC}} = \pm\sqrt{2}G_{\mathrm{F}}n_{\mathrm{e}}$$

Electron density n_{e}

Fermi constant $\sqrt{2}G_{\mathrm{F}} \simeq 7.63 \times 10^{-14}\frac{\mathrm{eV\ cm^3}}{N_{\mathrm{A}}}$

$A_{\mathrm{CC}} \equiv 2EV_{\mathrm{CC}}$

Homework: Write down the Feynman diagrams of ν_e and $\overline{\nu}_e$ CC interactions with electrons.

Extremely relativistic kinematics

$$E \simeq p + \frac{m^2}{2p},\ p \simeq E$$

As usual, $\Delta m^2 \equiv m_2^2 - m_1^2$

1. No mixing: $\nu_1 = \nu_{\mathrm{e}},\ \nu_2 = \nu_\mu$

   ν_e Hamiltonian in matter

$$H = E + V_{\mathrm{CC}} \equiv E + \frac{m_{\mathrm{M}}^2}{2E}$$

   Effective mass $m_{\mathrm{M}}^2 = m^2 + A_{\mathrm{CC}}$

   (NC induces the same A_{NC} for all neutrino flavours)

   Effective mass gap $\Delta m_{\mathrm{M}}^2 = \Delta m^2 - A_{\mathrm{CC}}$

   - When the matter potential fills up the mass gap

     $A_{\mathrm{CC}} = \Delta m^2$

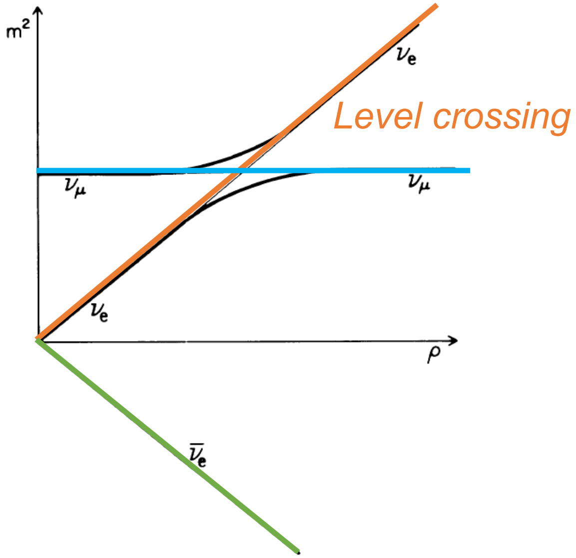
     $$E\,[\mathrm{GeV}]\,n_{\mathrm{e}}\left[\frac{N_{\mathrm{A}}}{\mathrm{cm^3}}\right] = \frac{\Delta m^2\left[10^{-5}\mathrm{eV^2}\right]}{2 \times 7.63 \times 10^{-14}\left[\frac{\mathrm{eV\ cm^3}}{N_{\mathrm{A}}}\right]}$$

     $$En_{\mathrm{e}} \simeq \frac{\Delta m^2}{15},\ E \text{ in GeV}, n_{\mathrm{e}} \text{ in } \frac{N_{\mathrm{A}}}{\mathrm{cm^3}}, \Delta m^2 \text{ in } 10^{-5}\mathrm{eV^2}$$

     Water $n_{\mathrm{e}} = \frac{5}{9}\frac{N_{\mathrm{A}}}{\mathrm{cm^3}}$

     For $\Delta m^2 = 10^{-5}\mathrm{eV^2}$, $E = 0.12$ GeV
   - For $A_{\mathrm{CC}} > \Delta m^2$, $\Delta m_{\mathrm{M}}^2 < 0$
   - For $A_{\mathrm{CC}} \gg \Delta m^2$, $\Delta m_{\mathrm{M}}^2 \simeq -A_{\mathrm{CC}}$

Bethe, Phys.Rev.Lett. 56, 1305 (1986)



More on Neutrino Mass: MSW Matter Effect

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Effective mass $m_M^2 = m^2 + A_{CC}$

(NC induces the same A_{NC} for all neutrino flavours)

Effective mass gap $\Delta m_M^2 = \Delta m^2 - A_{CC}$

- When the matter potential fills up the mass gap

  $A_{CC} = \Delta m^2$

  $$E\,[\text{GeV}]\, n_e \left[\frac{N_A}{\text{cm}^3}\right] = \frac{\Delta m^2\,[10^{-5}\text{eV}^2]}{2\times 7.63\times 10^{-14}\left[\frac{\text{eV cm}^3}{N_A}\right]}$$

  $$E n_e \simeq \frac{\Delta m^2}{15}, E \text{ in GeV}, n_e \text{ in } \frac{N_A}{\text{cm}^3}, \Delta m^2 \text{ in } 10^{-5}\text{eV}^2$$

  Water $n_e = \frac{5}{9}\frac{N_A}{\text{cm}^3}$

  For $\Delta m^2 = 10^{-5}\text{eV}^2$, $E = 0.12$ GeV

- For $A_{CC} > \Delta m^2$, $\Delta m_M^2 < 0$
- For $A_{CC} \gg \Delta m^2$, $\Delta m_M^2 \simeq -A_{CC}$

2. Mixing: Vacuum Hamiltonian in $\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$ basis

$$H \supset \frac{\Delta m^2}{4E}\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}$$

Full Hamiltonian in $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$ basis

$$H' \supset \frac{\Delta m^2}{4E}U\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}U^\dagger + \frac{A_{CC}}{4E}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$
$$\equiv \frac{\Delta m_M^2}{4E}U_M\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}U_M^\dagger,$$

with effective mass gap Δm_M^2 and mixing

$$U_M \equiv \begin{pmatrix}\cos\theta_M & \sin\theta_M\\ -\sin\theta_M & \cos\theta_M\end{pmatrix}$$

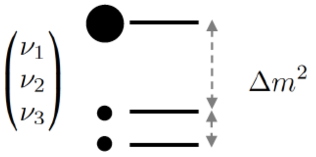
- When $A_{CC} \gg \Delta m^2$, U becomes irrelevant,

$$\frac{A_{CC}}{4E}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix} = \frac{\Delta m_M^2}{4E}U_M\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}U_M^\dagger$$

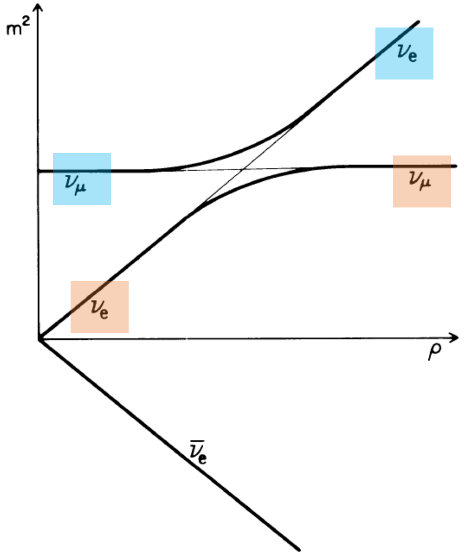
(a) $\Delta m_M^2 = -A_{CC}$, $\theta_M = 0$, falling back to the previous no mixing case, or

(b) $\Delta m_M^2 = A_{CC}$, $\theta_M = \pm\frac{\pi}{2}$, naming $\nu_1 = \nu_\mu$, $\nu_2 = \nu_e$.

$$\begin{pmatrix}|\uparrow\rangle_t\\ |\downarrow\rangle_t\end{pmatrix} = \begin{pmatrix}e^{i\frac{\Delta E}{2}t} & 0\\ 0 & e^{-i\frac{\Delta E}{2}t}\end{pmatrix}\begin{pmatrix}|\uparrow\rangle_0\\ |\downarrow\rangle_0\end{pmatrix}$$



Bethe, Phys.Rev.Lett. 56, 1305 (1986)



Quiz: Is there oscillation when the mixing angle is $\pi/2$?

More on Neutrino Mass: MSW Matter Effect

Extremely relativistic kinematics

$$E \simeq p + \frac{m^2}{2p},\ p \simeq E$$

As usual, $\Delta m^2 \equiv m_2^2 - m_1^2$

1. No mixing: $\nu_1 = \nu_e$, $\nu_2 = \nu_\mu$

   ν_e Hamiltonian in matter

$$H = E + V_{CC} \equiv E + \frac{m_M^2}{2E}$$

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   (NC induces the same A_{NC} for all neutrino flavours)

   Effective mass gap $\Delta m_M^2 = \Delta m^2 - A_{CC}$

   - When the matter potential fills up the mass gap

     $A_{CC} = \Delta m^2$

$$E\,[\text{GeV}]\, n_e \left[\frac{N_A}{\text{cm}^3}\right] = \frac{\Delta m^2\left[10^{-5}\text{eV}^2\right]}{2 \times 7.63 \times 10^{-14}\left[\frac{\text{eV cm}^3}{N_A}\right]}$$

$$E n_e \simeq \frac{\Delta m^2}{15}, E \text{ in GeV}, n_e \text{ in } \frac{N_A}{\text{cm}^3}, \Delta m^2 \text{ in } 10^{-5}\text{eV}^2$$

     Water $n_e = \frac{5}{9}\frac{N_A}{\text{cm}^3}$

     For $\Delta m^2 = 10^{-5}\text{eV}^2$, $E = 0.12$ GeV

   - For $A_{CC} > \Delta m^2$, $\Delta m_M^2 < 0$
   - For $A_{CC} \gg \Delta m^2$, $\Delta m_M^2 \simeq -A_{CC}$

2. Mixing: Vacuum Hamiltonian in $\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$ basis

$$H \supset \frac{\Delta m^2}{4E}\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}$$

   Full Hamiltonian in $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$ basis

$$H' \supset \frac{\Delta m^2}{4E} U \begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix} U^\dagger + \frac{A_{CC}}{4E}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$
$$\equiv \frac{\Delta m_M^2}{4E} U_M \begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix} U_M^\dagger,$$

   with effective mass gap Δm_M^2 and mixing

$$U_M \equiv \begin{pmatrix}\cos\theta_M & \sin\theta_M\\ -\sin\theta_M & \cos\theta_M\end{pmatrix}$$

   - When $A_{CC} \gg \Delta m^2$, U becomes irrelevant,

$$\frac{A_{CC}}{4E}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix} = \frac{\Delta m_M^2}{4E} U_M \begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix} U_M^\dagger$$

     (a) $\Delta m_M^2 = -A_{CC}$, $\theta_M = 0$, falling back to the previous no mixing case, or

     (b) $\Delta m_M^2 = A_{CC}$, $\theta_M = \pm\frac{\pi}{2}$, naming $\nu_1 = \nu_\mu$, $\nu_2 = \nu_e$.

- In general, with

$$U \equiv \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}$$

  The effective mass gap and mixing angle are

$$\Delta m_M^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - A_{CC}\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$
$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \dfrac{A_{CC}}{\Delta m^2 \cos 2\theta}}$$

  e.g. Giunti & Kim (2007)

  Mikheyev-Smirnov-Wolfenstein effect

  Resonance at $A_{CC}^R = \Delta m^2 \cos 2\theta$

  $\theta_M^R = \frac{\pi}{4}$, regardless of θ

  … will come back to this later

Homework: Recover the previous no-mixing and small gap cases with the general effective mass gap and mixing angle.

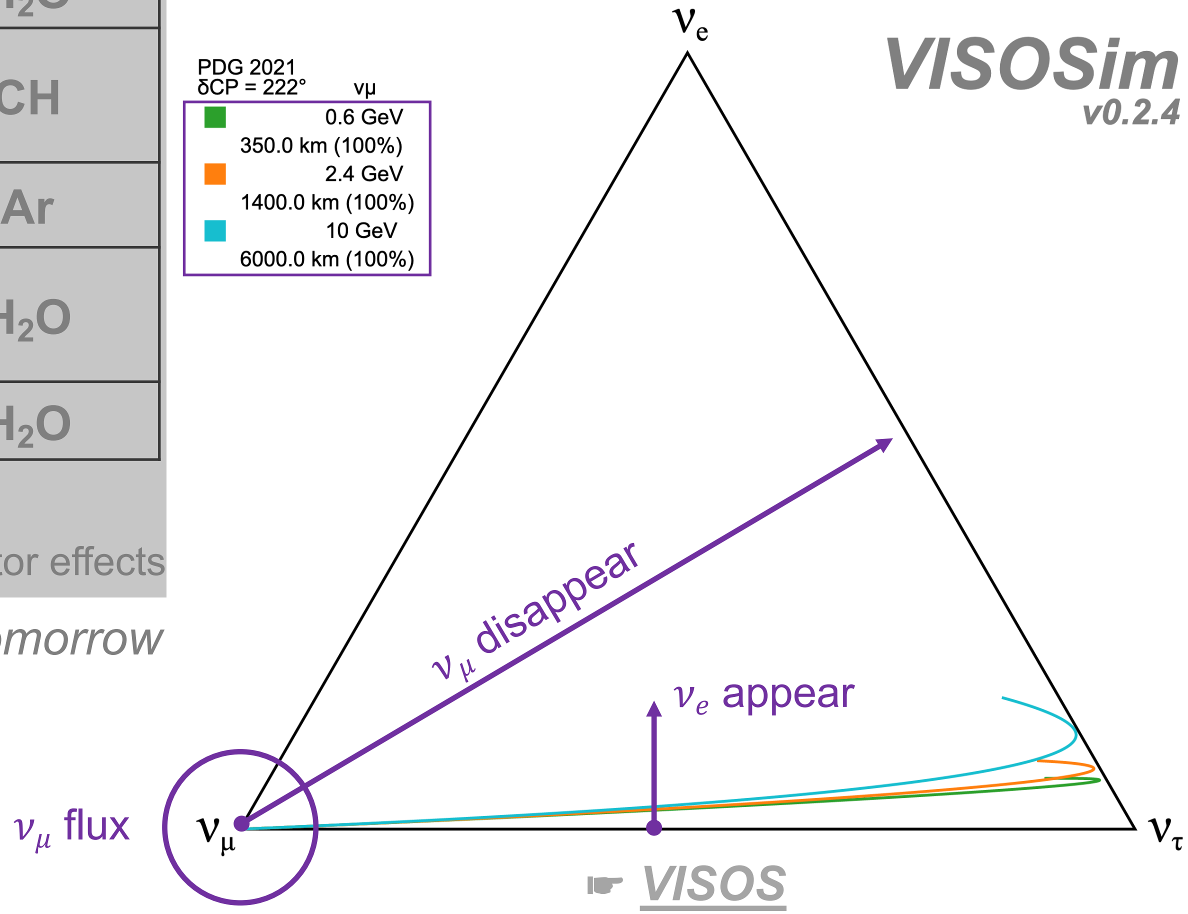
Oscillation experiments

Future Oscillation Experiment	E_ν/GeV @Flux Peak	Detector Technology	Target Nuclei
T2K/HK	0.6	Water Che'	H_2O
NOvA	2	Liquid Scintillator	CH
DUNE	2.4	LAr TPC	Ar
IceCube	3-10 (NMO sensitive region)	Cherenkov in ice	H_2O
SK/KM3NeT		Water Che'	H_2O

Signal = (**Flux** · **Oscillation probability** · Cross section) ⊕ Detector effects

… to discuss tomorrow

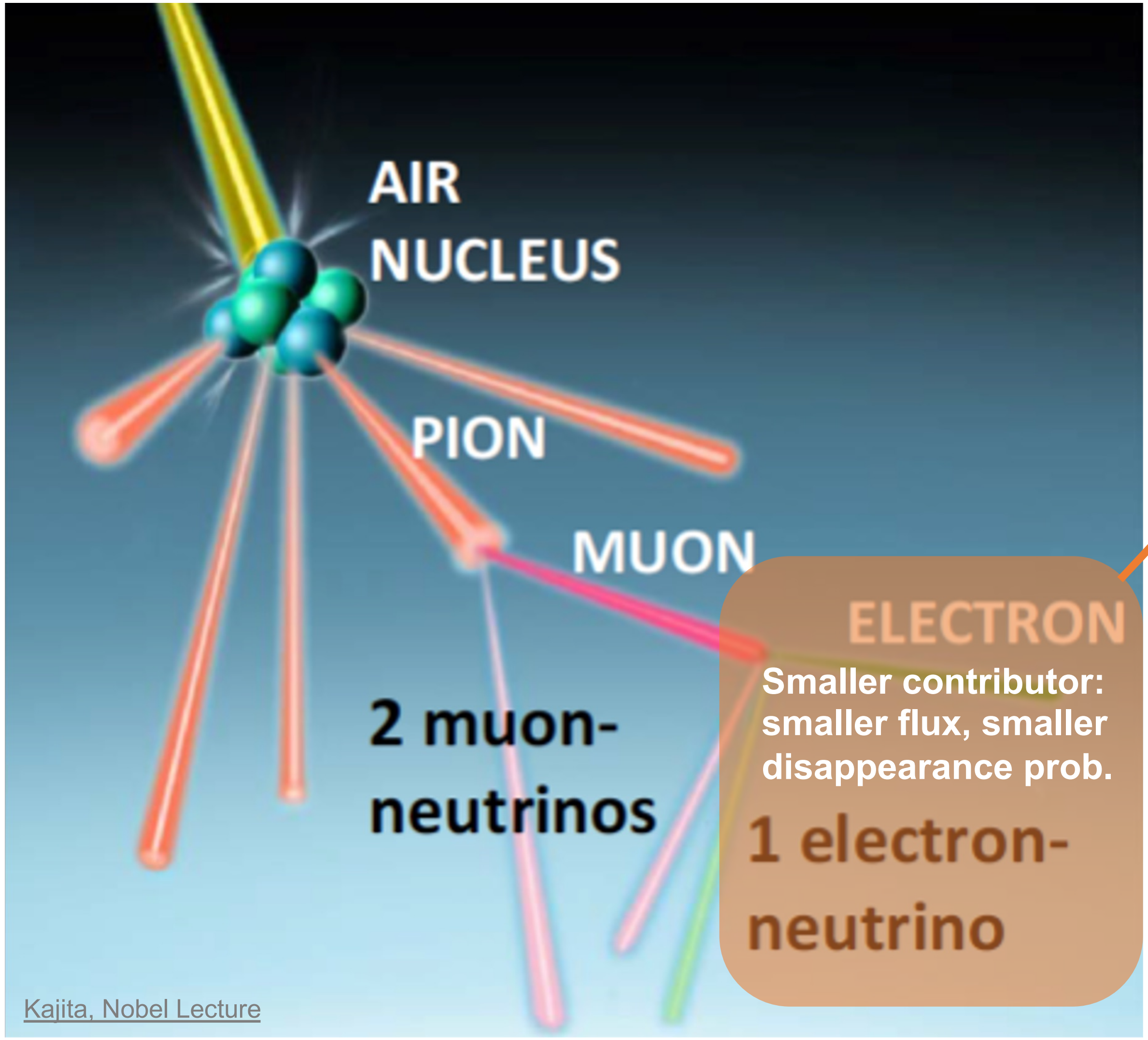
- ❑ Flux: ν_μ and $\bar{\nu}_\mu$
- ❑ Oscillation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance**



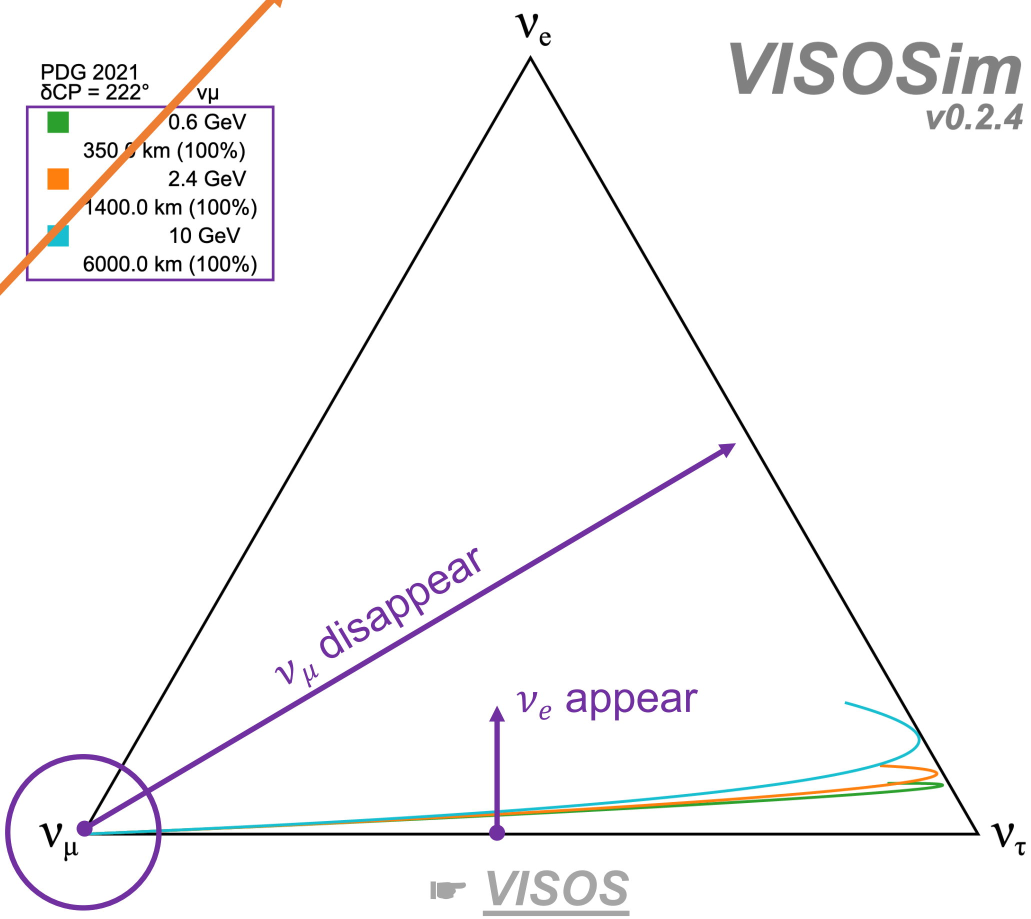
VISOSim v0.2.4

☛ VISOS

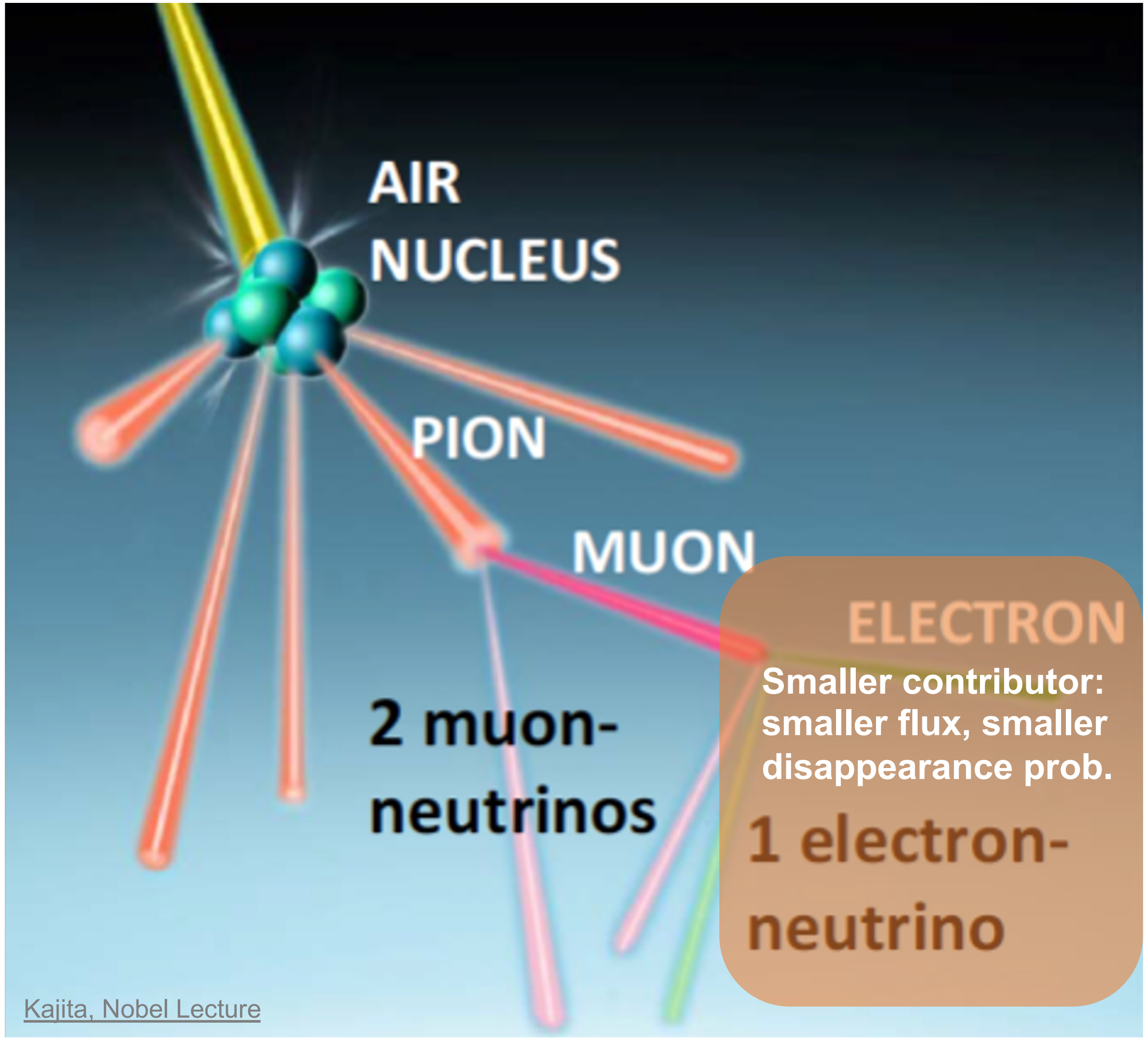
Atmospheric Neutrinos



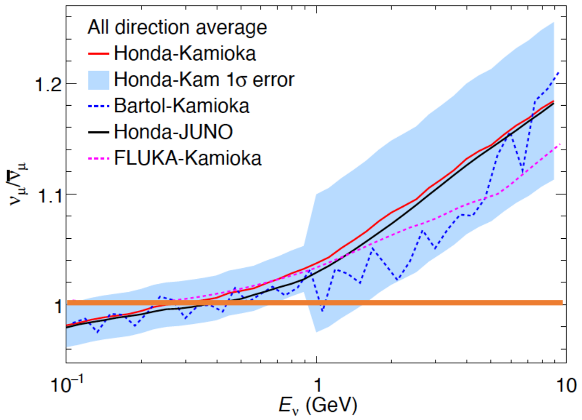
- Flux: ν_μ and $\bar{\nu}_\mu$
- Oscillation
  - ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - **ν_e and $\bar{\nu}_e$ appearance**

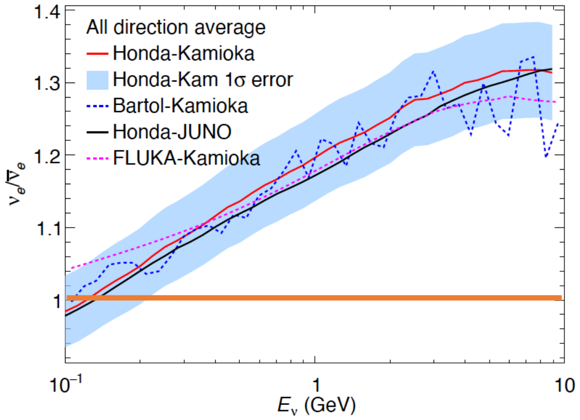


Atmospheric Neutrinos



- ❑ Flux: ν_μ and $\bar{\nu}_\mu$
- ❑ Oslation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance**





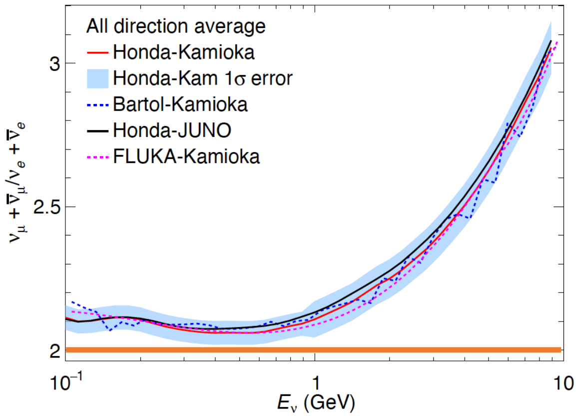


Figure courtesy: Z.-O. He, Warwick

Naïve expectation

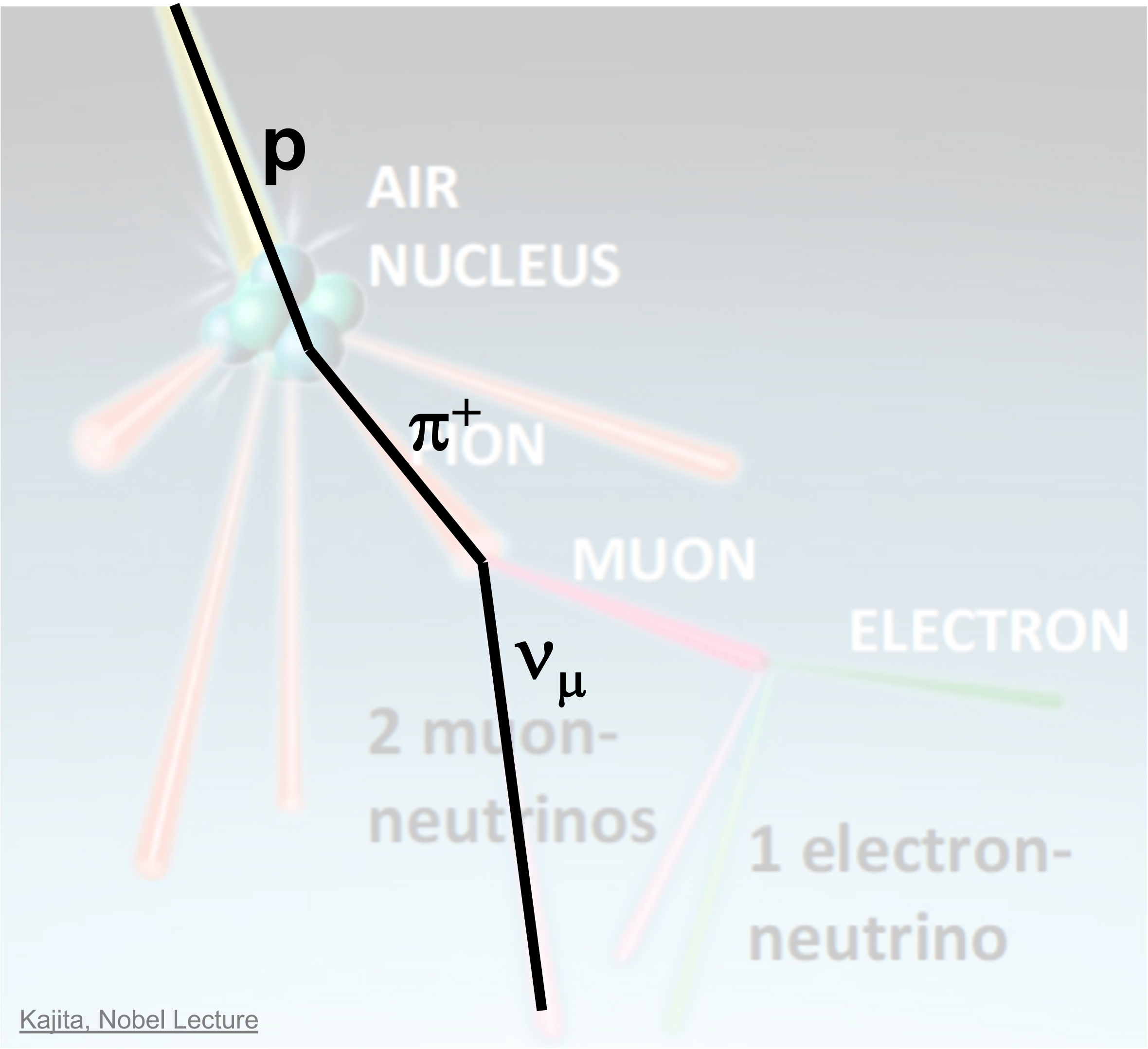
$$\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}=2,\ \frac{\nu}{\bar{\nu}}=1$$

Quiz: What causes $\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}=2$ ***to fail?***

Atmospheric Neutrinos

Fully uncontrolled →

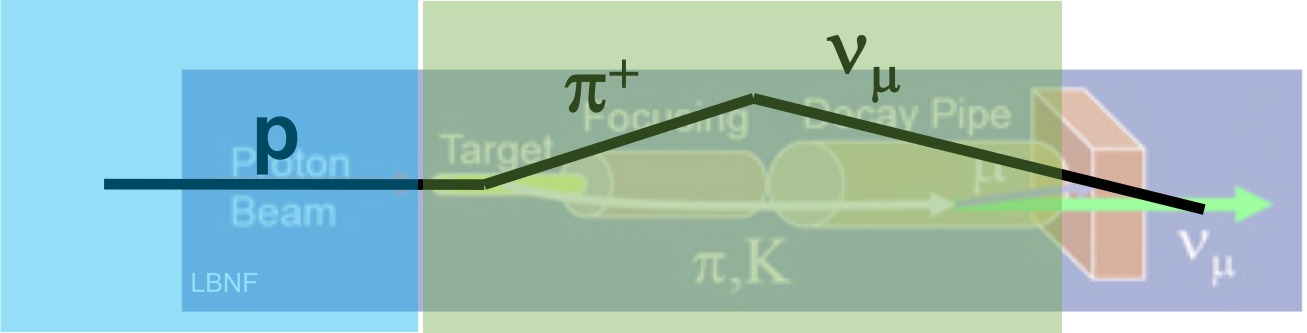
- ❑ Flux: ν_μ and $\bar{\nu}_\mu$
- ❑ Oscillation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance**

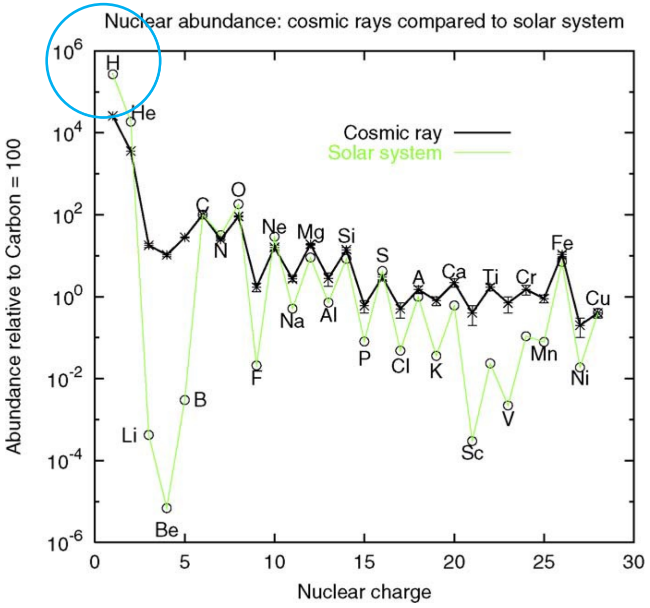


Atmospheric Neutrinos

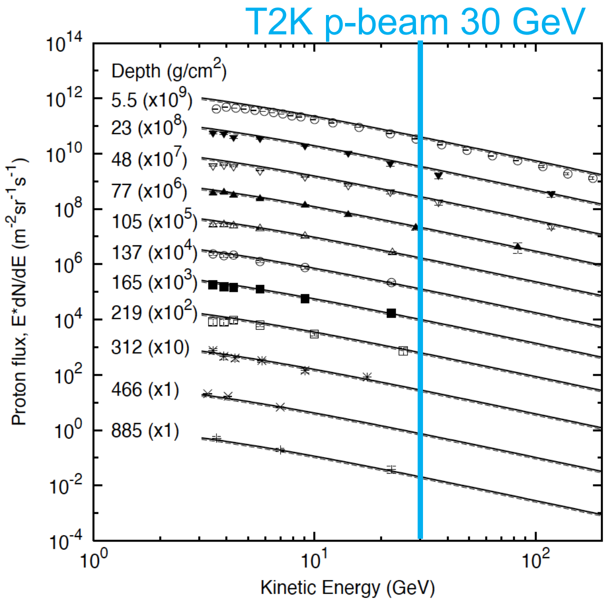
Fully uncontrolled →

- ❑ Flux: ν_μ and $\bar{\nu}_\mu$
- ❑ Oscillation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance**

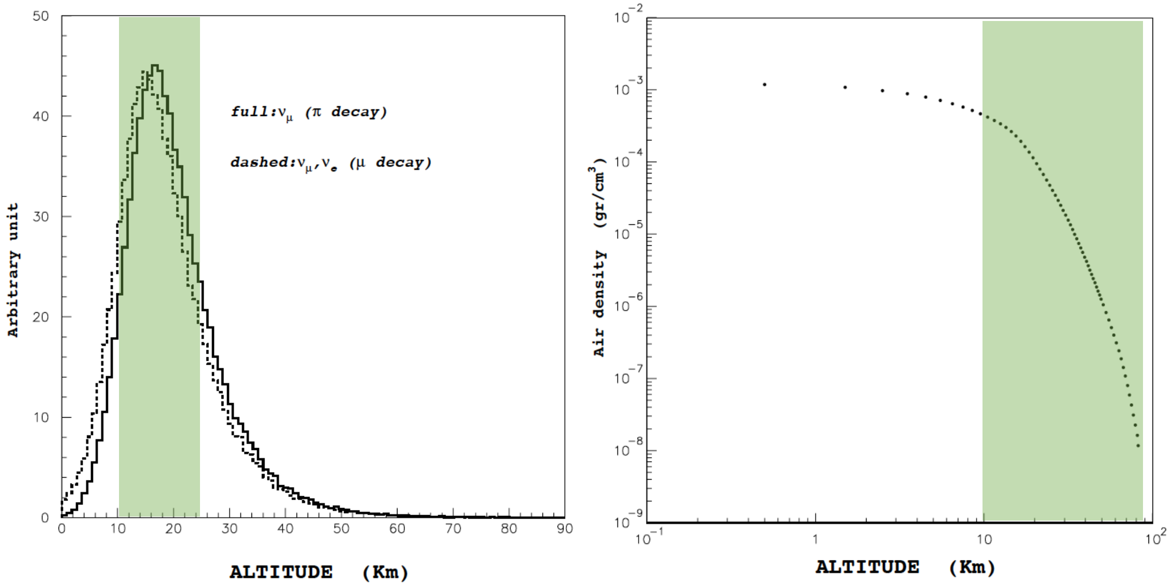




Gaisser and Stanev, Nucl.Phys.A 777, 98 (2006)



Gaisser, astro-ph/0501195



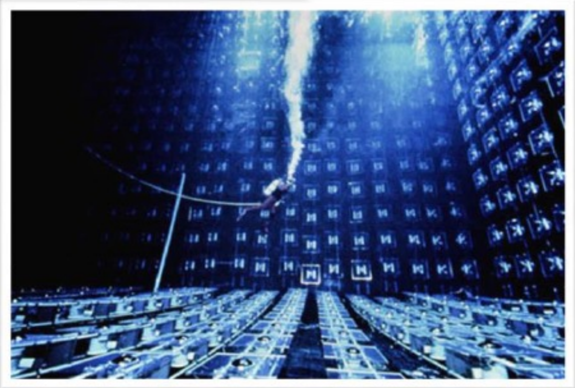
Favier *et al.*, Phys.Rev.D 68, 093006 (2003)

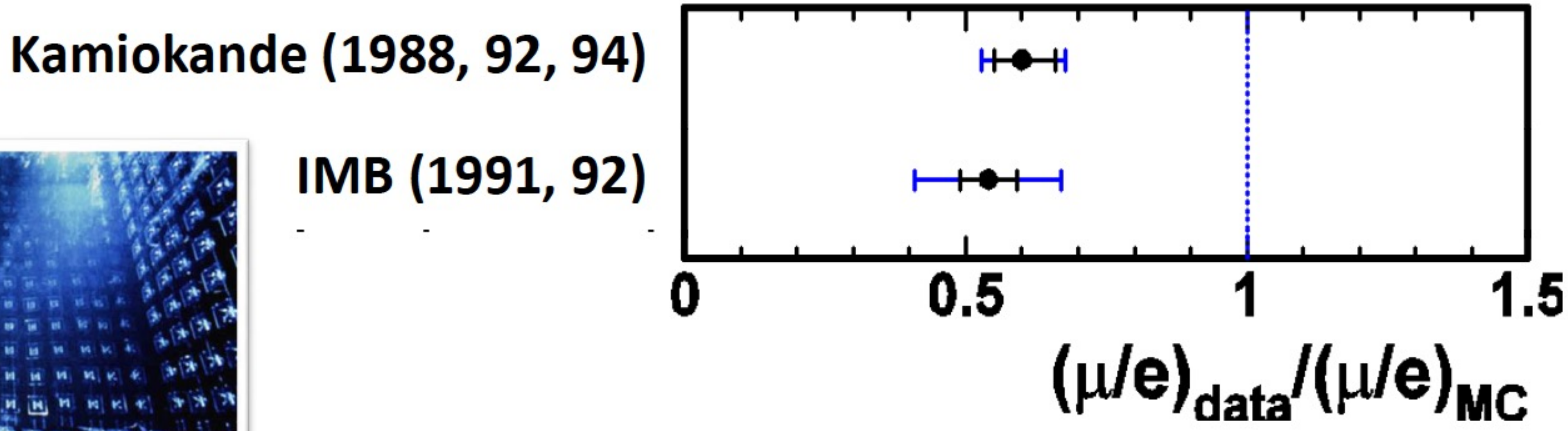
- ❑ Cosmic rays: p + others
- ❑ Not monoenergetic
- ❑ inhomogeneous target, non-localised production

Slide by Kajita, NPB 2024

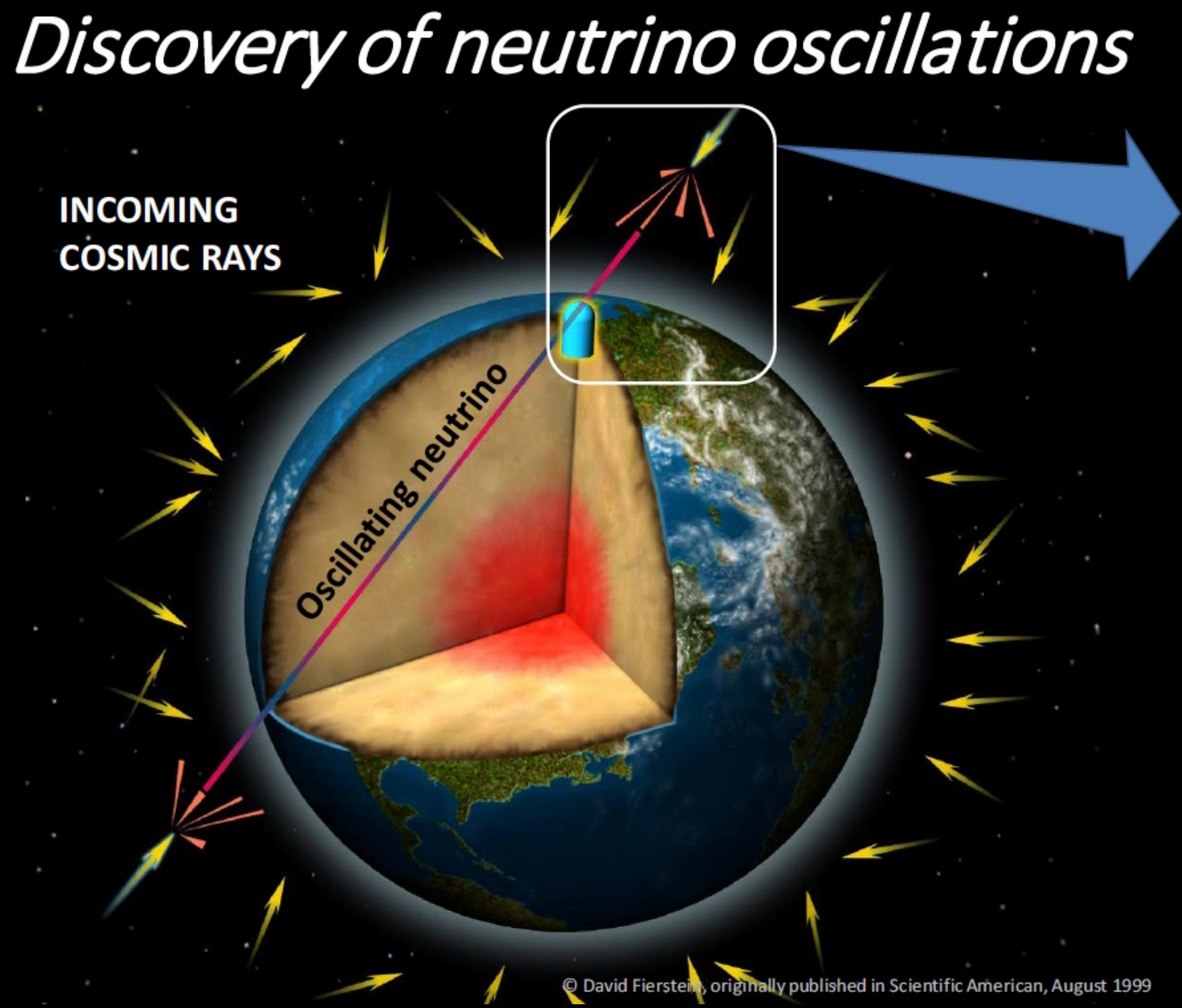
Atmospheric neutrino problem

- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos were the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of the muon-neutrinos events was observed.

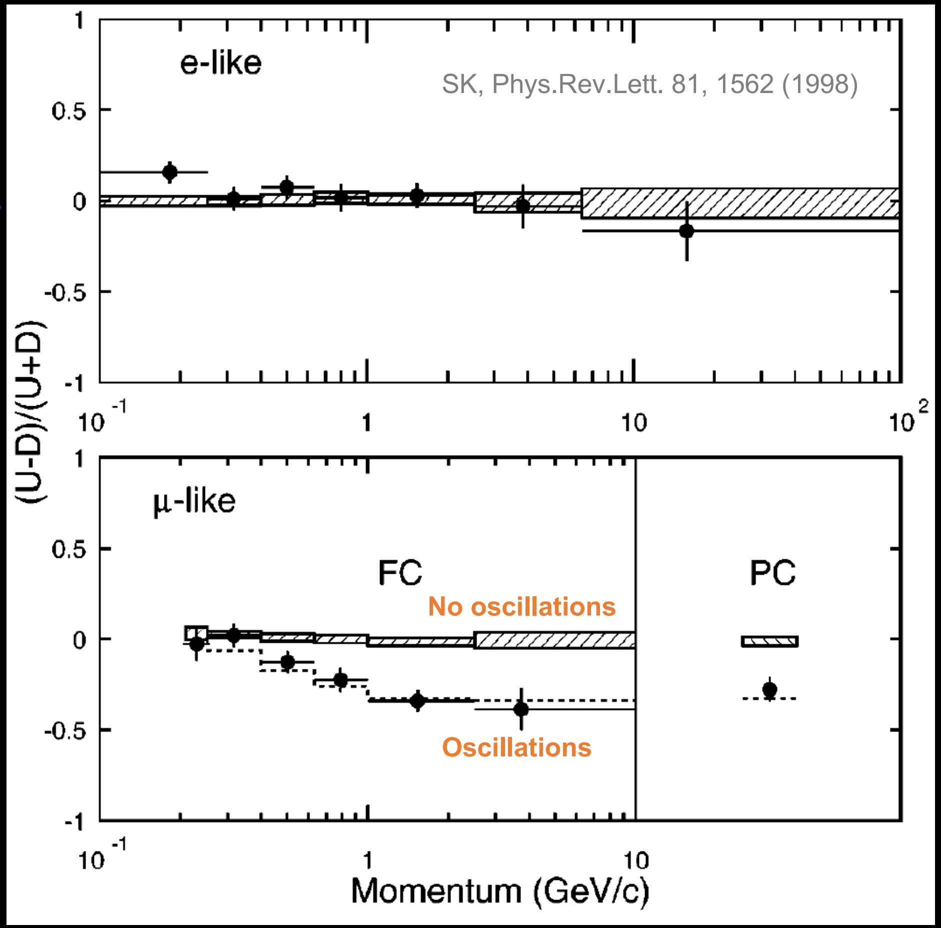




Atmospheric Neutrinos

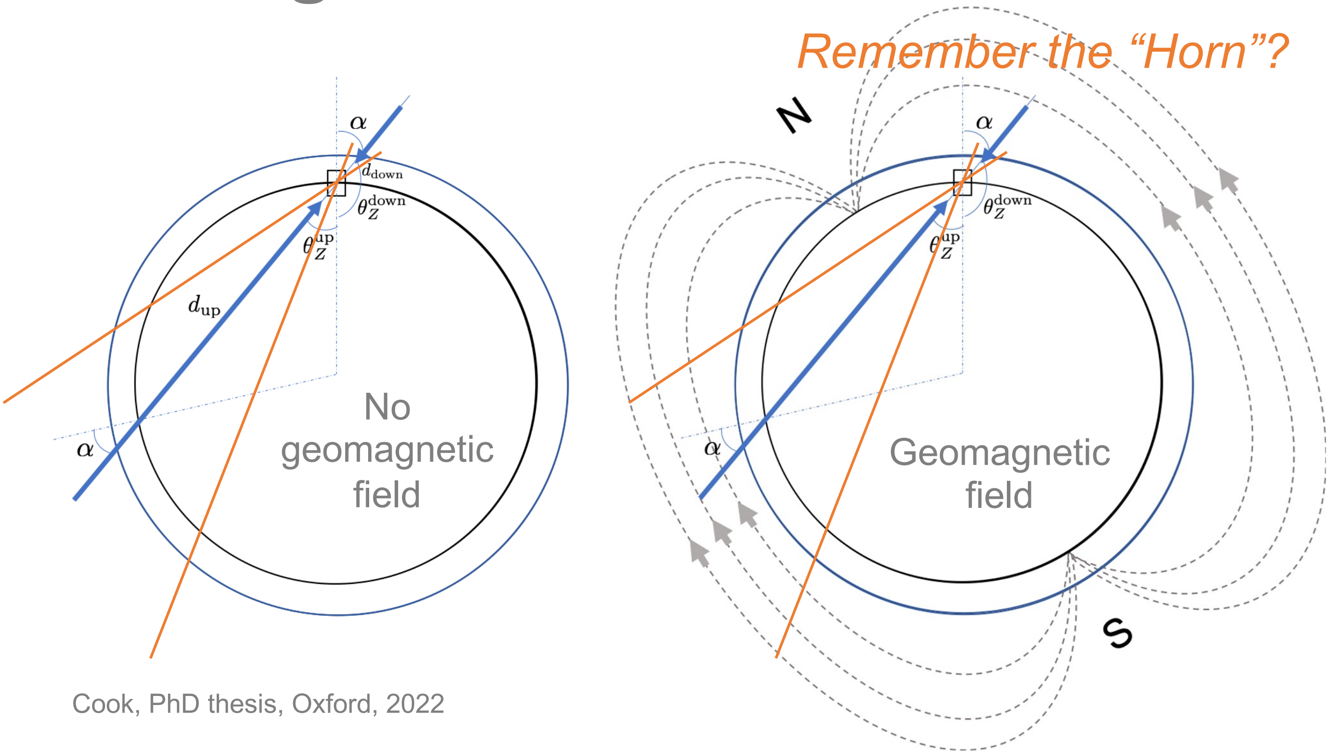


Kajita, Nobel Lecture



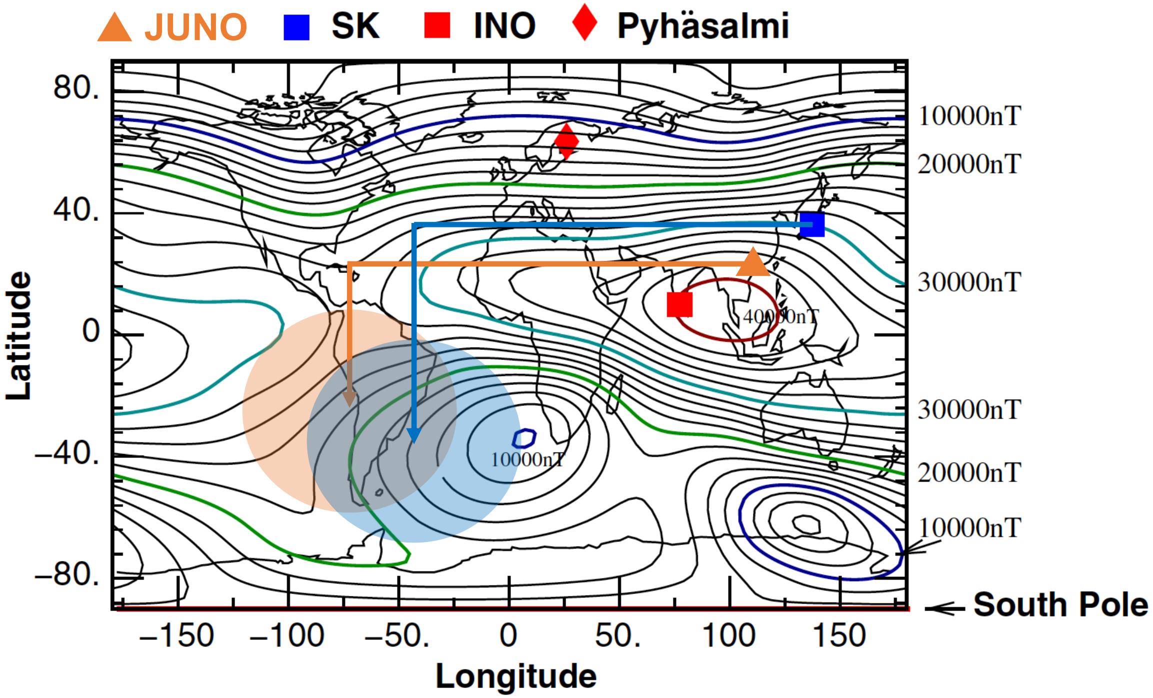
- *L*-dependence: zenith angle variation
- Many systematics cancelled in up-down asymmetry

Geomagnetic effect



Cook, PhD thesis, Oxford, 2022

Honda *et al.*, Phys.Rev.D 92, 023004 (2015)



B (G)	Down (local sky)	Up (over much larger sky region)
SK	0.30	-
JUNO	0.38	-

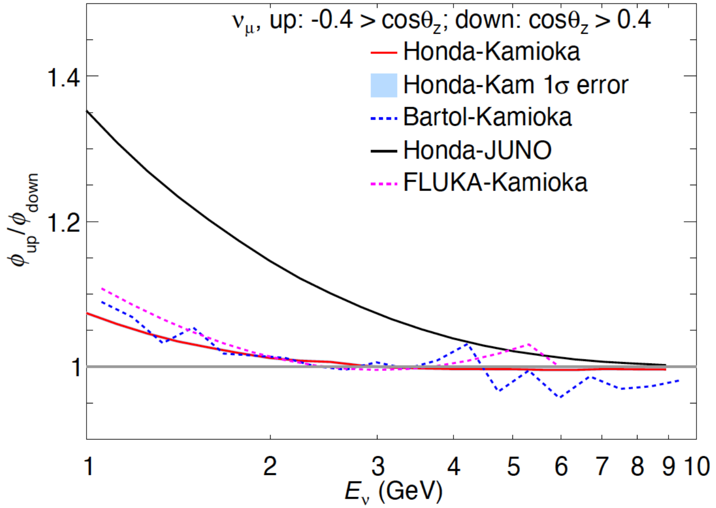


Figure courtesy: Z.-O. He, Warwick

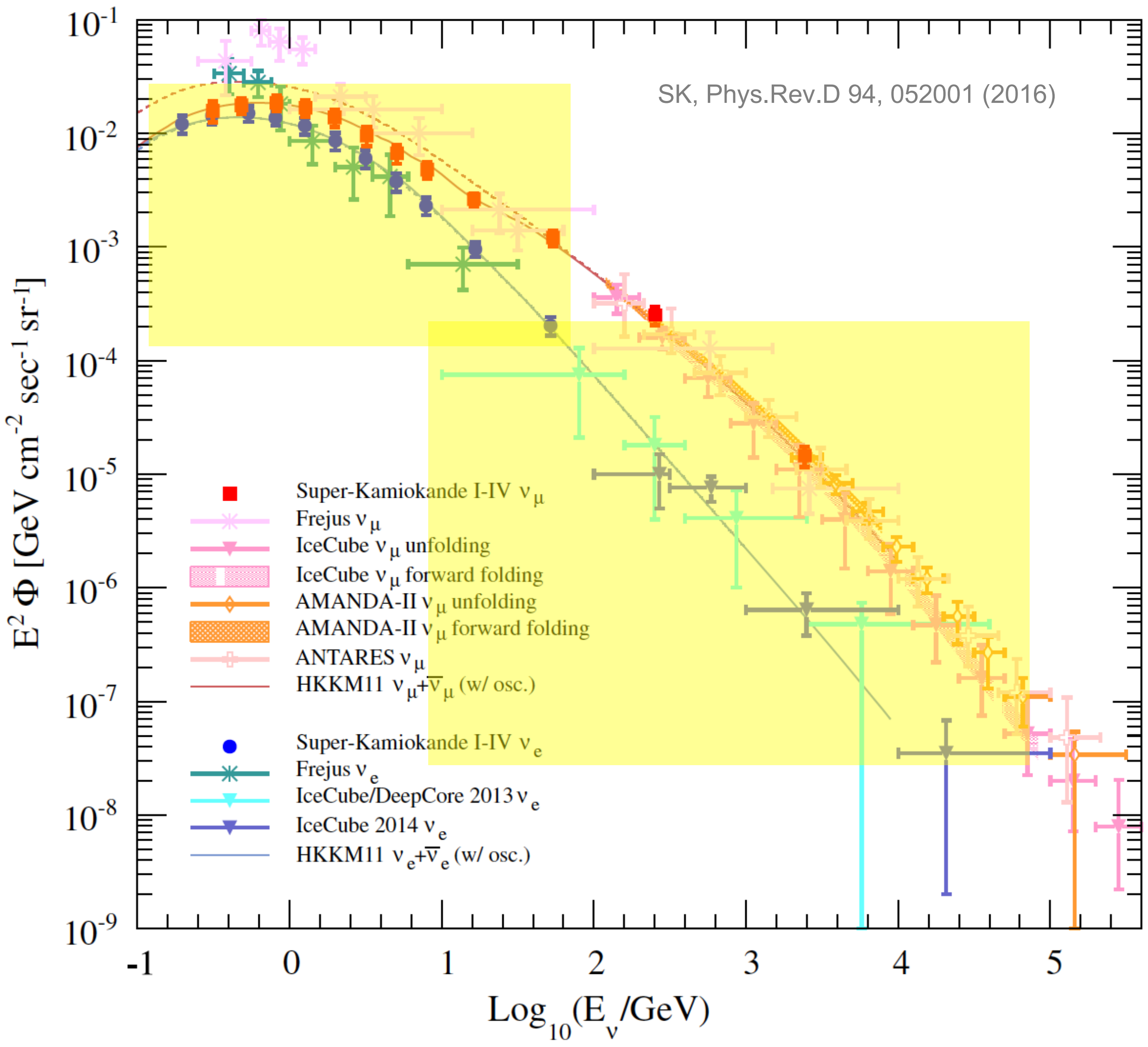
- Intrinsic up-down flux asymmetry can mimic oscillation
  - Local *B* in flux calculation is crucial
  - Worse at low energy

SK flux error in a typical oscillation analysis

Table A1. Systematic error used in this analysis. The second column shows the best-fit value of the systematic error parameter in % and the third column shows the estimated 1σ error size in %. The fit result is within the

Systematic error			Fit value (%)	σ (%)
Flux normalization	$E_\nu < 1$ GeV[1]		7.3	25
	$E_\nu > 1$ GeV[2]		9.6	15
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$	$E_\nu < 1$ GeV		1.3	2
	$1 < E_\nu < 10$ GeV		2.7	3
	$E_\nu > 10$ GeV[3]		6.6	5
$\bar{\nu}_e/\nu_e$	$E_\nu < 1$ GeV		−1.1	5
	$1 < E_\nu < 10$ GeV		−2.7	5
	$E_\nu > 10$ GeV[4]		−0.34	8
$\bar{\nu}_\mu/\nu_\mu$	$E_\nu < 1$ GeV		0.36	2
	$1 < E_\nu < 10$ GeV		3.24	6
	$E_\nu > 10$ GeV[5]		9.2	15
Up/down ratio	< 400 MeV	e-like	0.079	0.1
		μ-like	0.24	0.3
		0-decay μ-like	0.87	1.1
	> 400 MeV	e-like	0.63	0.8
		μ-like	0.40	0.5
		0-decay μ-like	1.34	1.7
	Multi-GeV	e-like	0.55	0.7
		μ-like	0.16	0.2
	Multi-ring sub-GeV	e-like	0.32	0.4
		μ-like	0.16	0.2
	Multi-ring multi-GeV	e-like	0.24	0.3
		μ-like	0.16	0.2
	PC		0.16	0.2

SK Measurement of Atmospheric Neutrino Fluxes

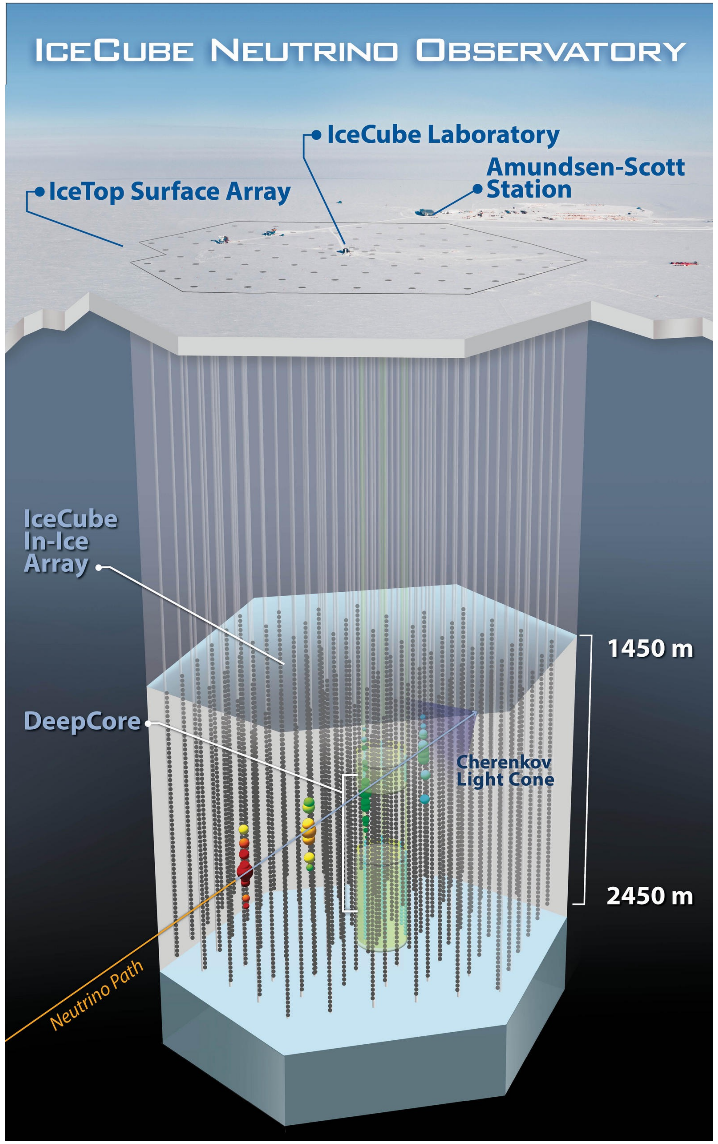


Coming back to IceCube…

SK: low energy
IceCube (DeepCore): high energy

Introducing IceCube

Slide courtesy: Donglian Xu



SK NMO Measurement with Atmospheric Neutrinos

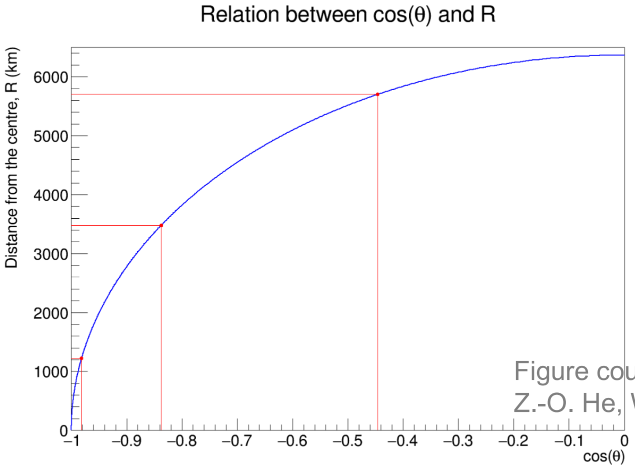
Coming back to the MSW resonance…

Vacuum

$$P(\nu_e \to \nu_e) \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

$$P(\nu_\mu \to \nu_\mu) \cong 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23}) \times \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

$$P(\nu_\mu \leftrightarrow \nu_e) \cong \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$



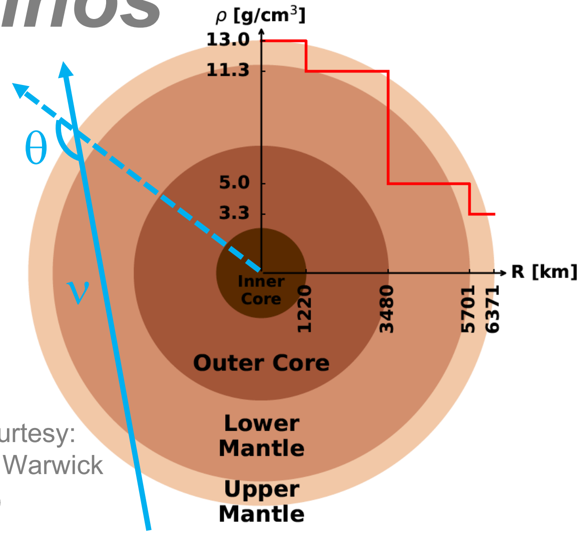


Figure courtesy: Z.-O. He, Warwick

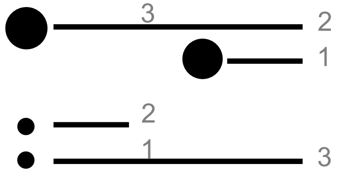
Matter effect seen as probability distortion

Effective mixing and mass gap in matter

$$\sin^2 2\theta_{13,M} = \frac{\sin^2 2\theta_{13}}{(\cos 2\theta_{13} - A_{CC}/\Delta m^2_{32})^2 + \sin^2 2\theta_{13}}$$

$$\Delta m^2_{32,M} = \Delta m^2_{32}\sqrt{(\cos 2\theta_{13} - A_{CC}/\Delta m^2_{32})^2 + \sin^2 2\theta_{13}},$$

e.g. SK, PTEP 053F01 (2019)



Normal / Inverted MO

Small θ_{13}, MSW resonance at $A_{CC} \approx \Delta m^2_{32}$

NO: A_{CC} >0, resonance with ν

IO: A_{CC} <0, resonance with $\bar{\nu}$

$A_{CC} = \Delta m^2$

$E\,[\mathrm{GeV}]\,n_e\left[\frac{N_A}{\mathrm{cm}^3}\right] = \frac{\Delta m^2\,[10^{-5}\mathrm{eV}^2]}{2\times 7.63\times 10^{-14}\left[\frac{\mathrm{eV\,cm}^3}{N_A}\right]}$

$En_e \simeq \frac{\Delta m^2}{15}$, E in GeV, n_e in $\frac{N_A}{\mathrm{cm}^3}$, Δm^2 in $10^{-5}\mathrm{eV}^2$

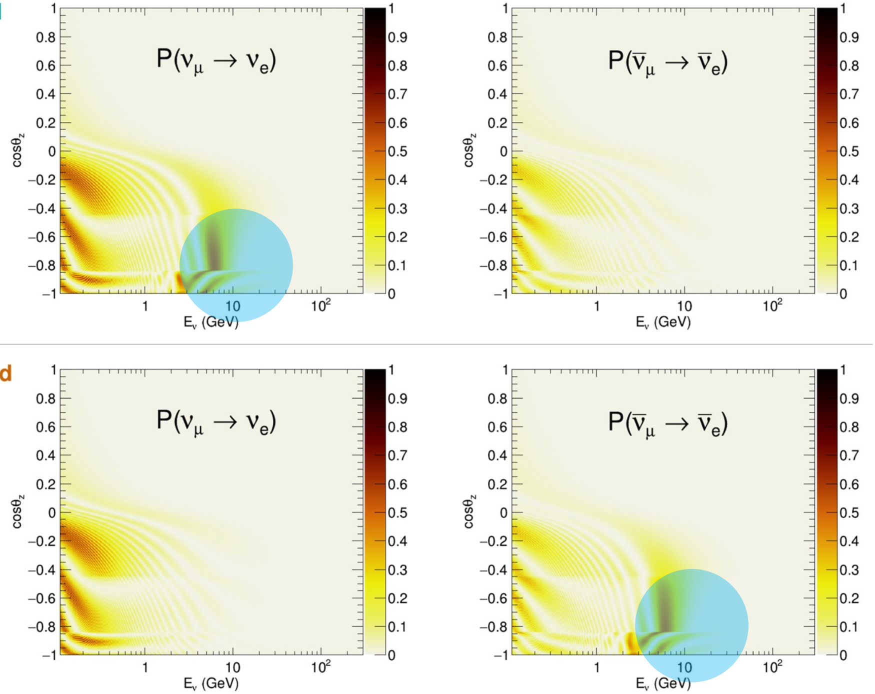
Water $n_e = \frac{5}{9}\frac{N_A}{\mathrm{cm}^3}$

For $\Delta m^2 = 10^{-5}\mathrm{eV}^2$, $E = 0.12$ GeV

For $|\Delta m^2_{23}| = 2\times 10^{-3}\mathrm{eV}^2$, $E = 24$ GeV

Normal

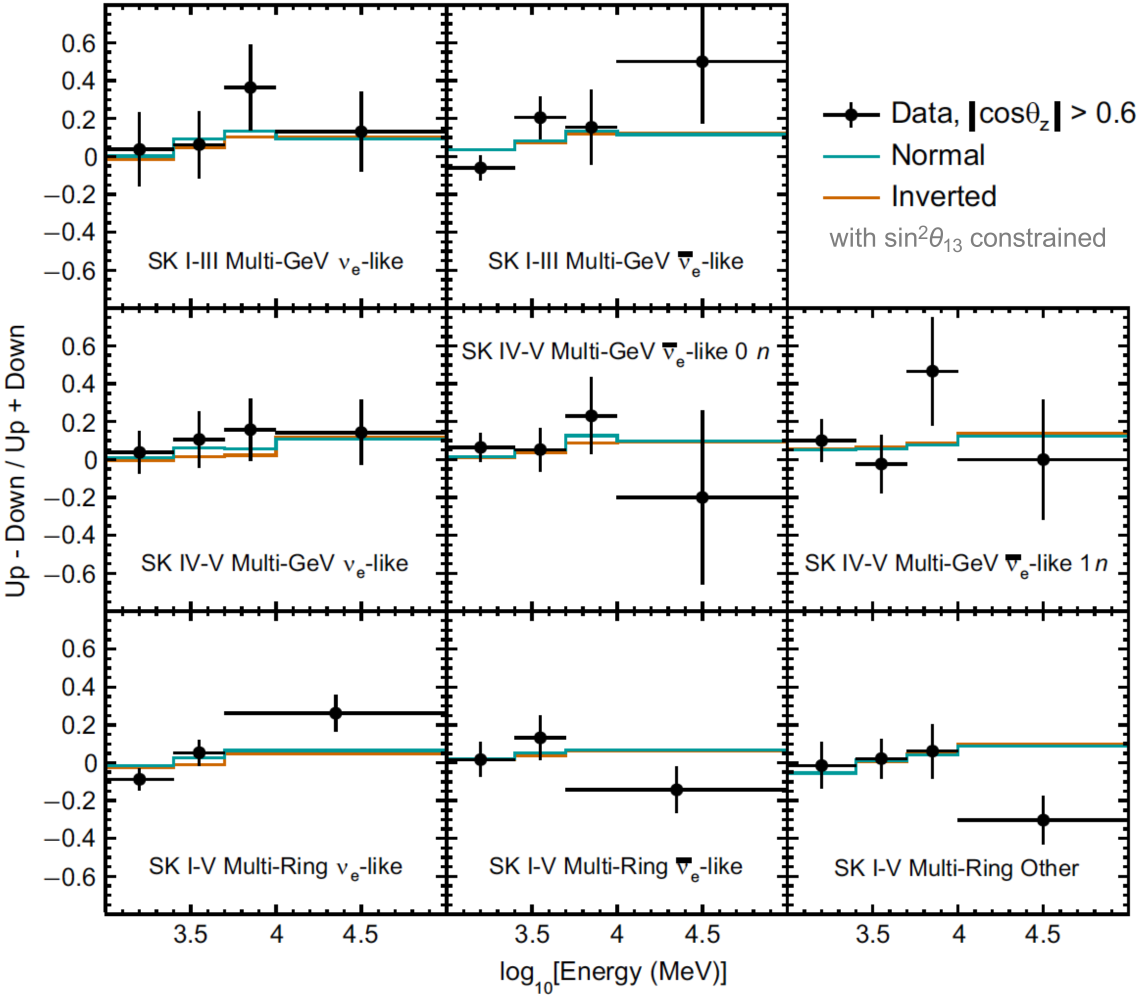
Inverted

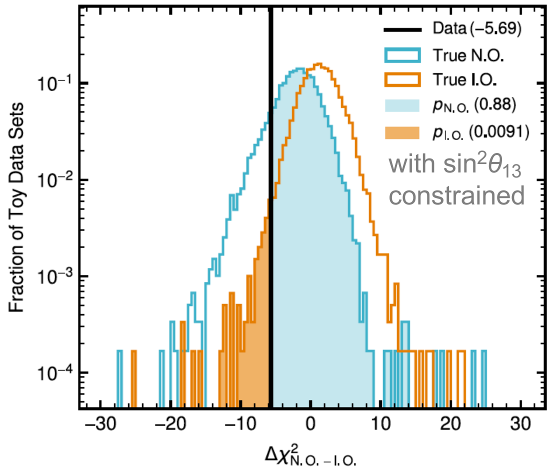


SK, Phys.Rev.D 109, 072014 (2024)

SK NMO Measurement with Atmospheric Neutrinos

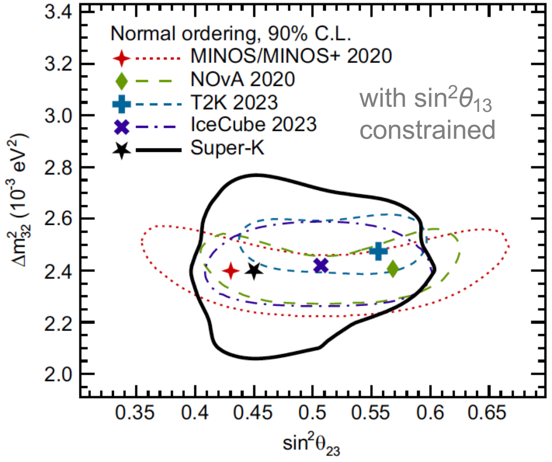
SK, Phys.Rev.D 109, 072014 (2024)





$$\mathrm{CL}_s = \frac{p_{\mathrm{I.O.}}}{1 - p_{\mathrm{N.O.}}}$$ = 0.077, rejecting IO at 92.3% (~ 1.4σ)

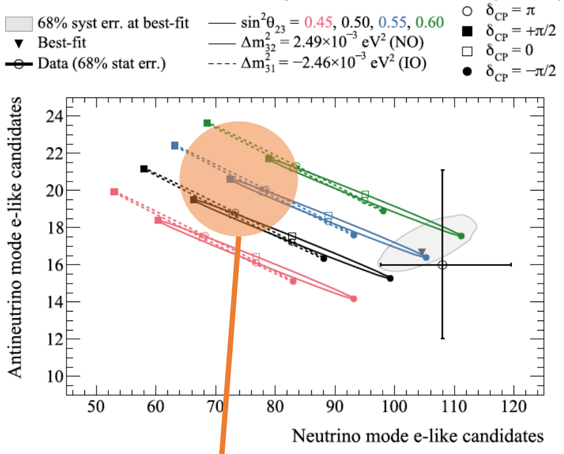
Posiadala-Zezula, NEUTRINO 2024

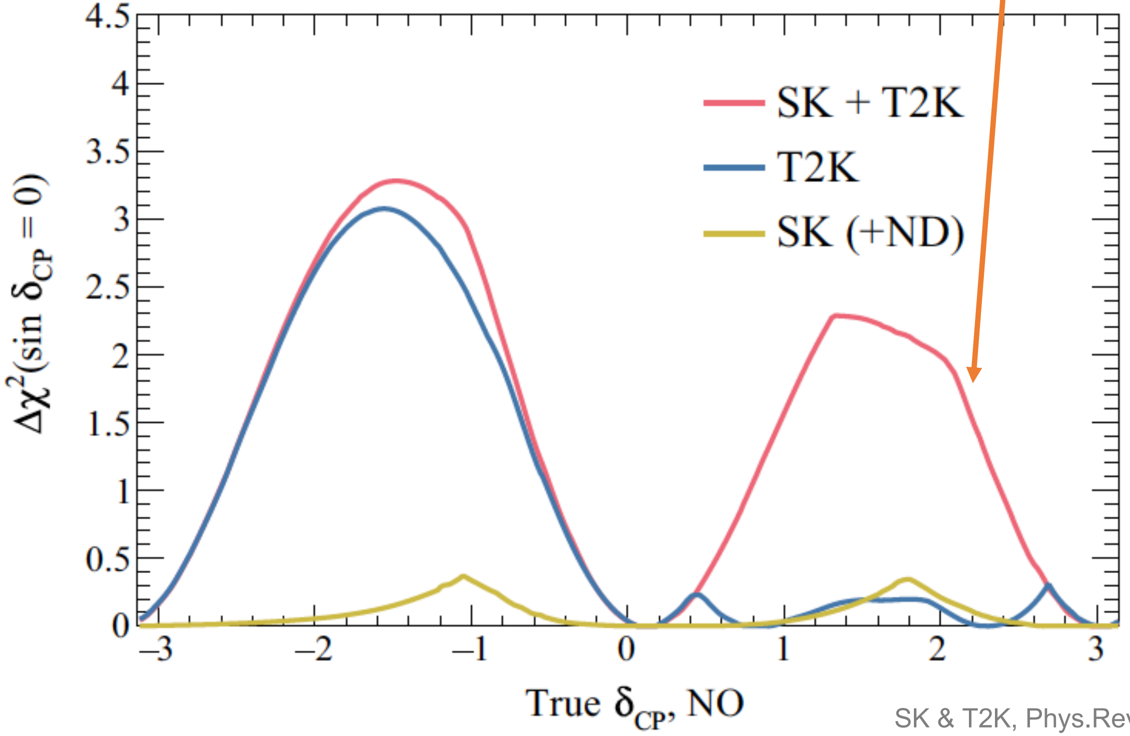


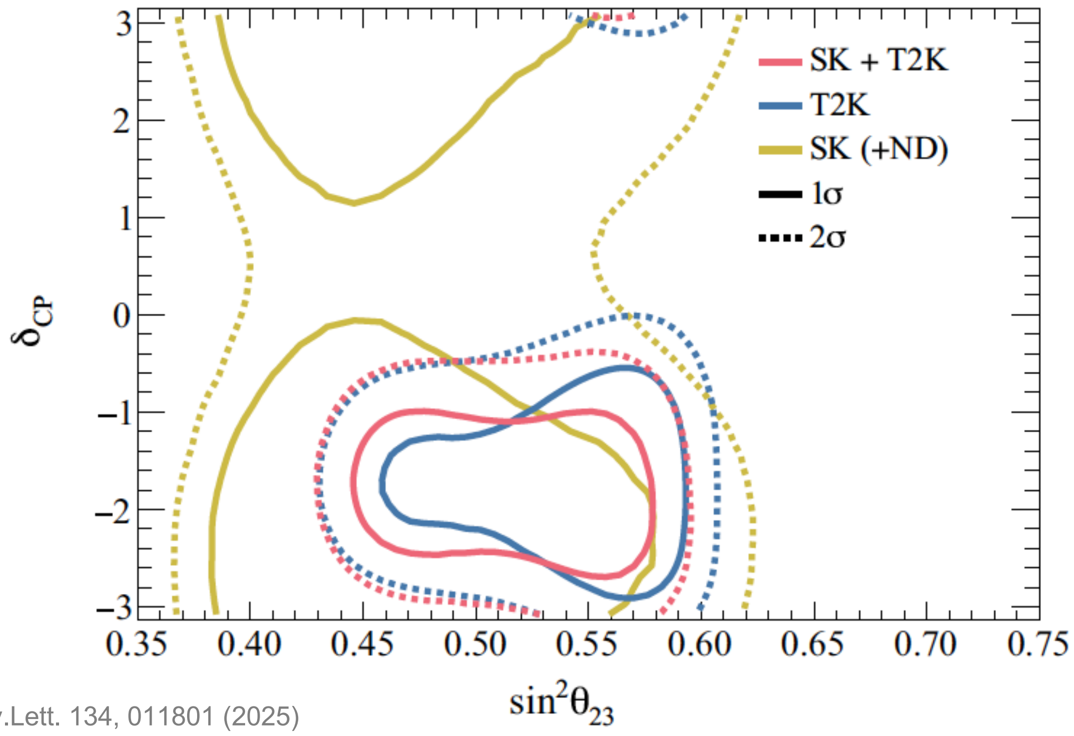
T2K+SK Joint Analysis

Coming back to NMO constraints…

T2K, Eur.Phys.J.C 83, 9, 782 (2023)





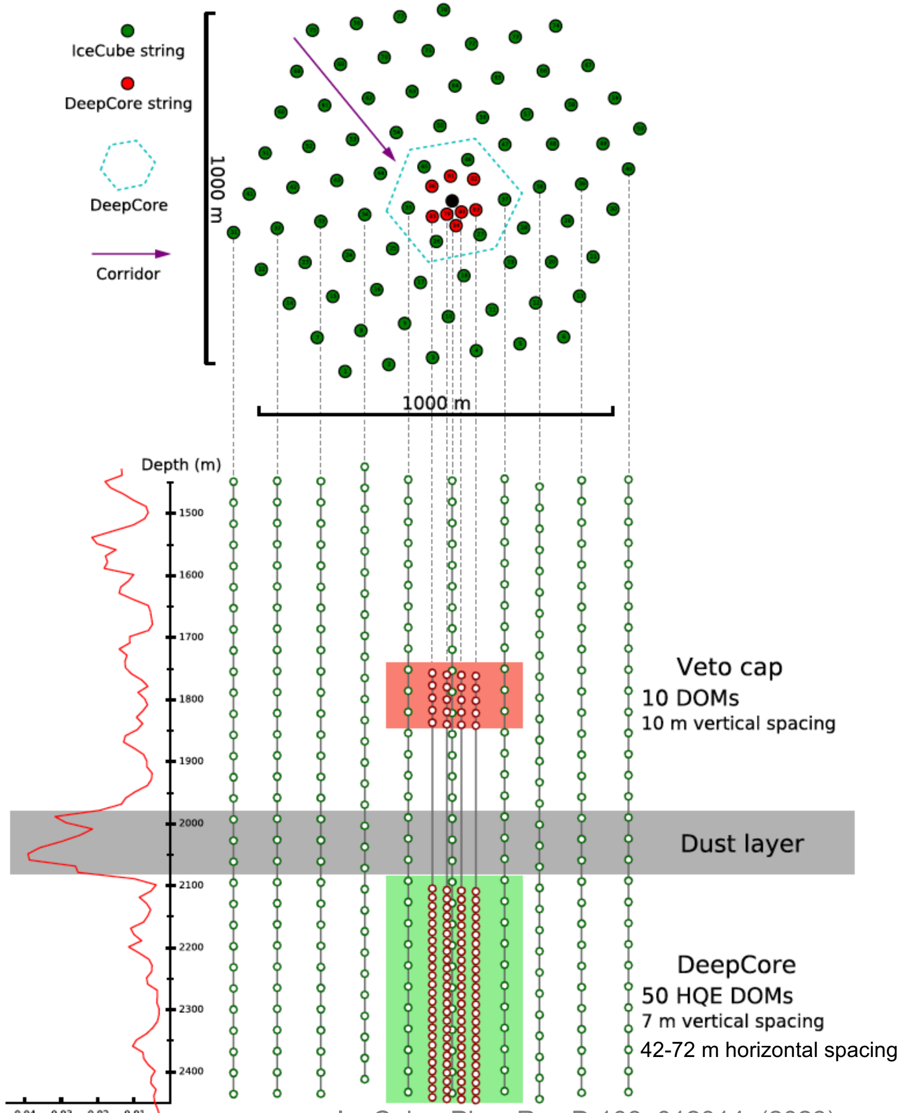


SK & T2K, Phys.Rev.Lett. 134, 011801 (2025)

Sensitivity

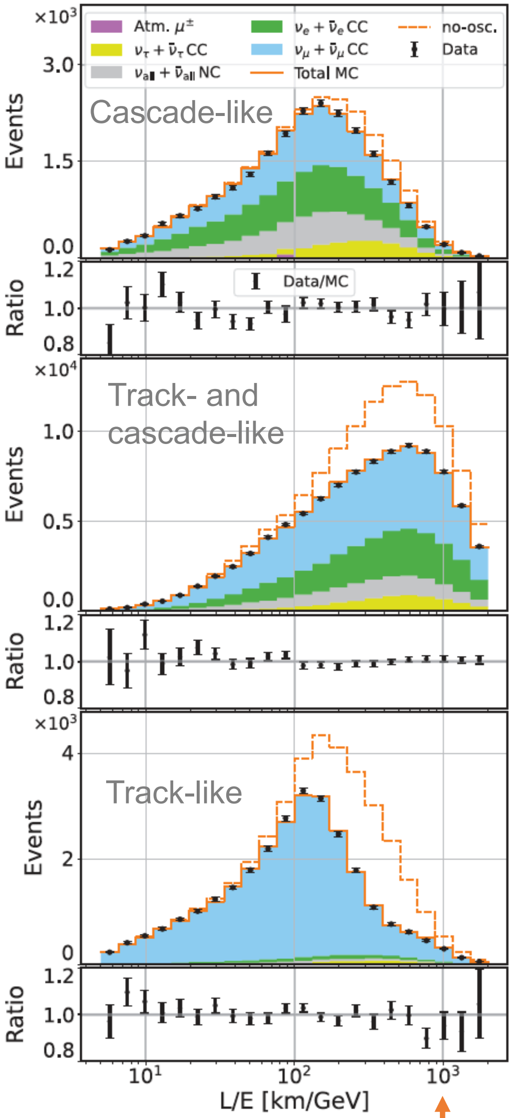
Data results

IceCube DeepCore Atmospheric Oscillation Measurement



IceCube, Phys.Rev.D 108, 012014 (2023)

IceCube, Phys.Rev.Lett. 134, 091801 (2025)

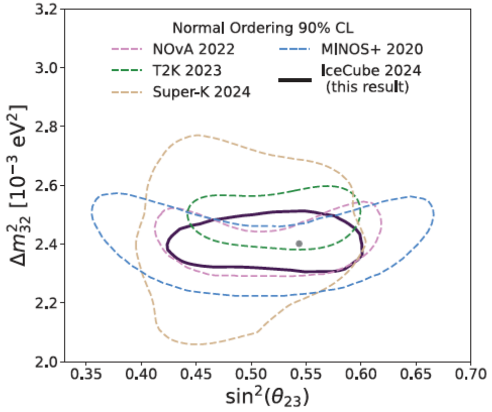


Larger *E* ⟵ ⟶ Larger *L*

10k km/10 GeV

Quiz: What are cascade-like events?

IceCube, Phys.Rev.Lett. 134, 091801 (2025)



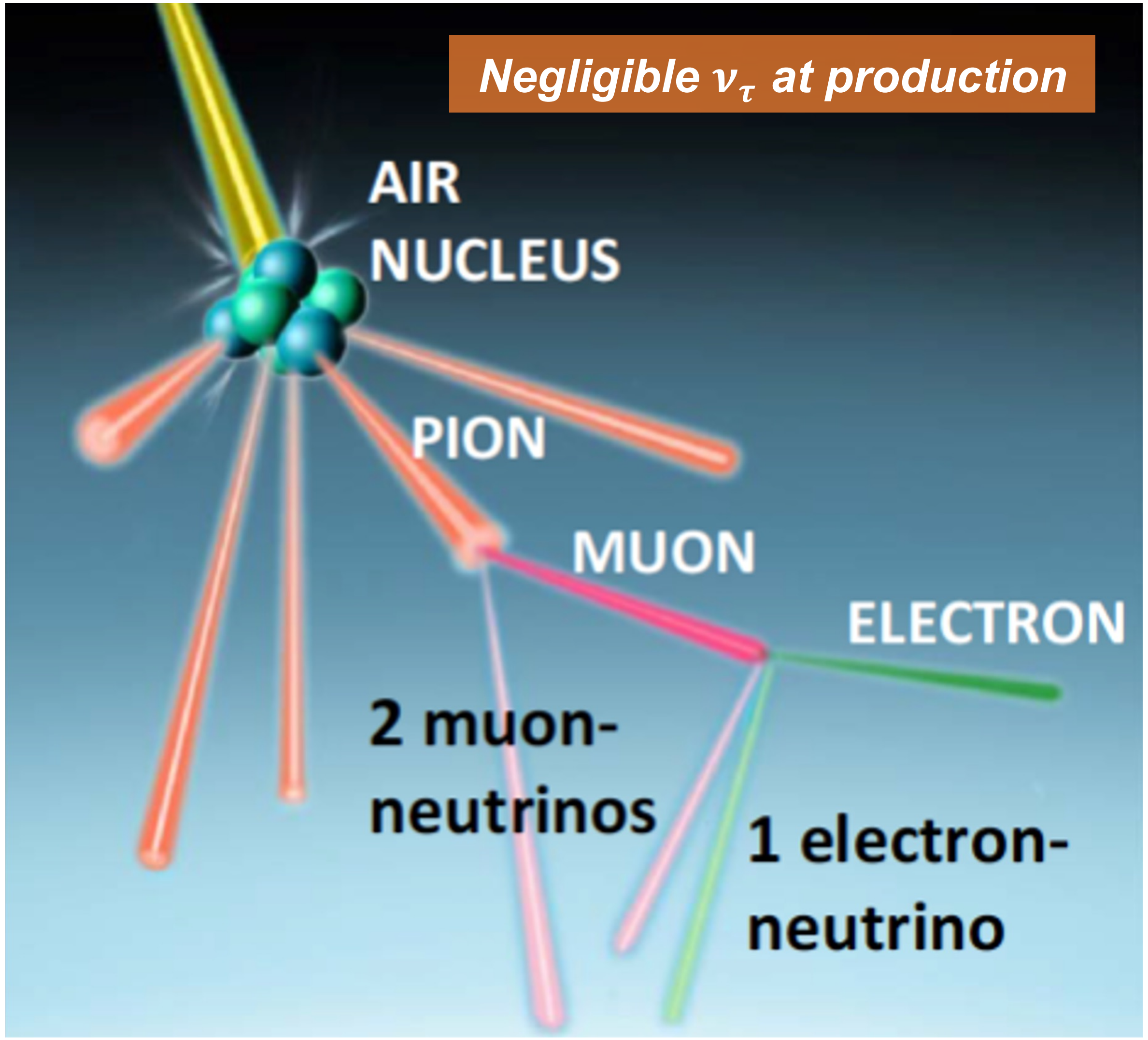
Competitive with other experiments!

1. Huge statistics: km³-scale detector → far more multi-GeV
2. Best L/E coverage: optimised for 5–50 GeV range
3. Lower flux uncertainty: multi-GeV flux is better modelled
4. Cross section uncertainty: multi-GeV xsec dominated by DIS
5. In-situ flux calibration: high-energy unoscillated sample

But not for NMO:

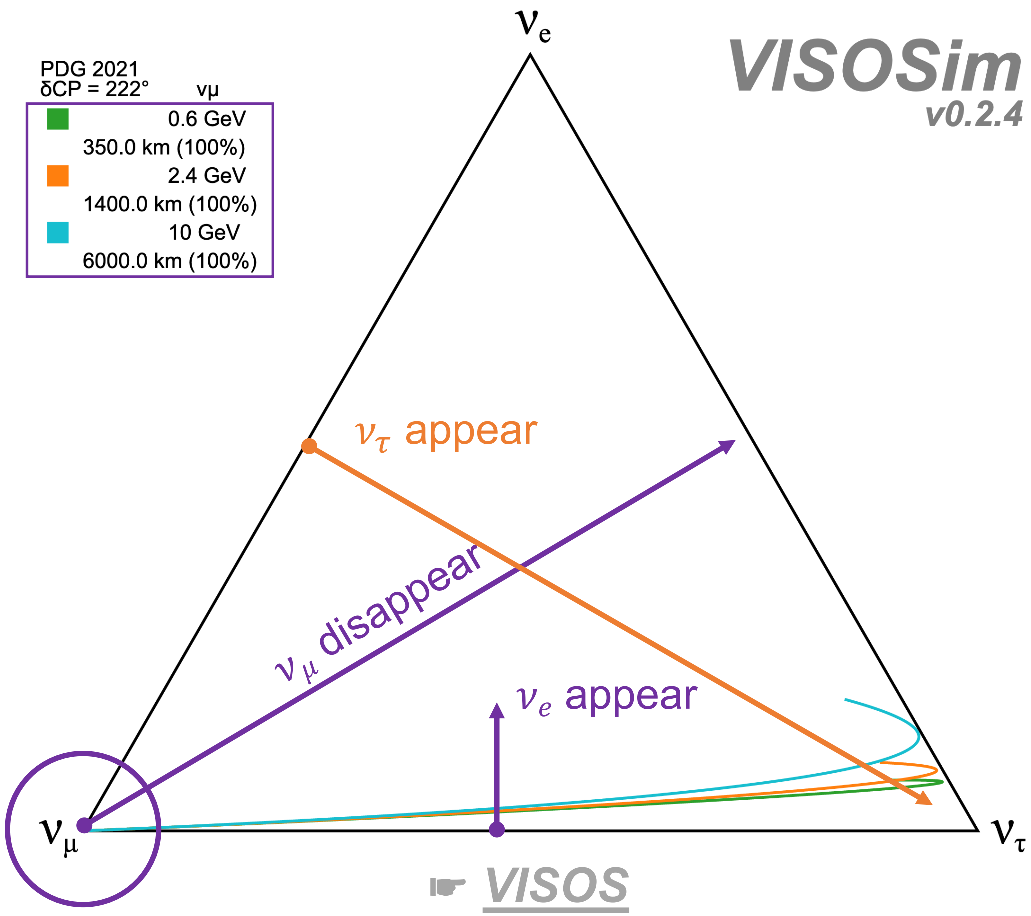
- ***Miss the MSW resonance at lower energy***
- ***PINGU (or ORCA) will lower the energy threshold***
  - ***But then all the low-energy systematics (flux, xsec) are like SK—no way around for NMO***
  - ***One can play with stat. and detector technology.***

ν_τ Appearance with Atmospheric Neutrinos



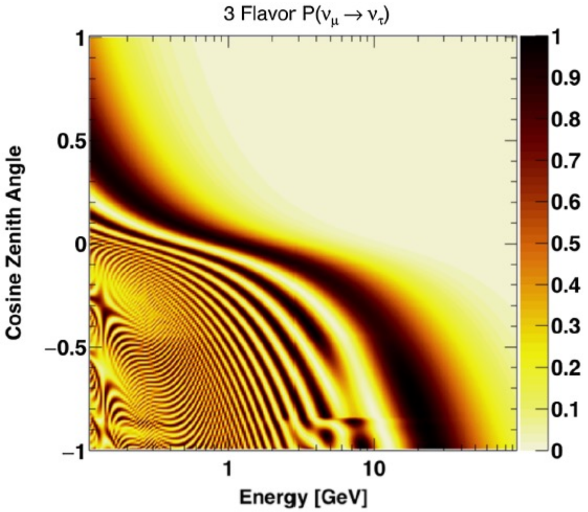
Completing the 3-flavour oscillation picture

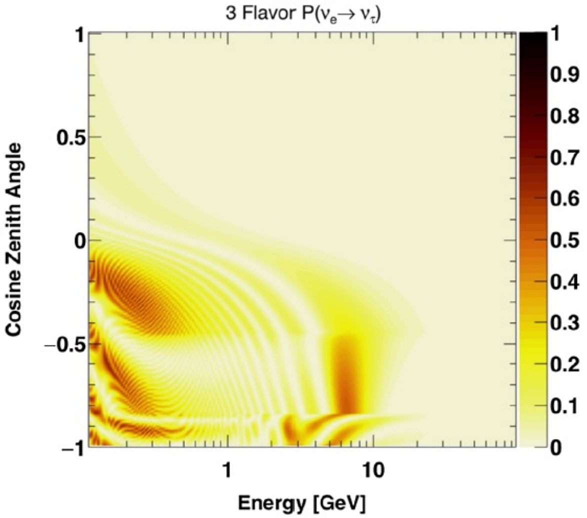
Quiz: Is there matter effect in $\nu_\mu \to \nu_\tau$?



☛ VISOS

Measurements of ν_τ Appearance

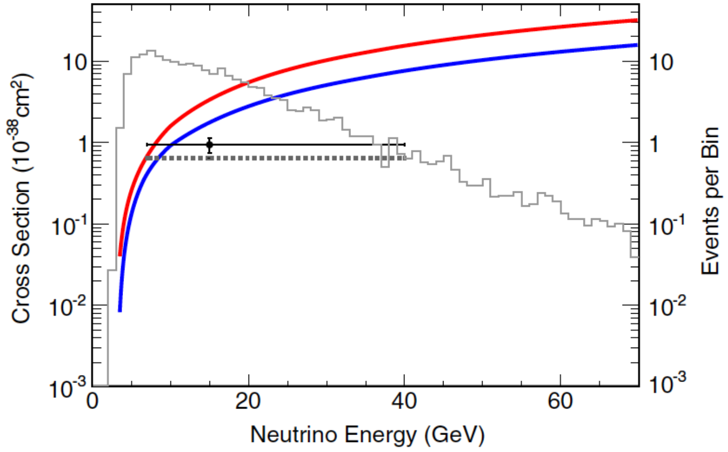


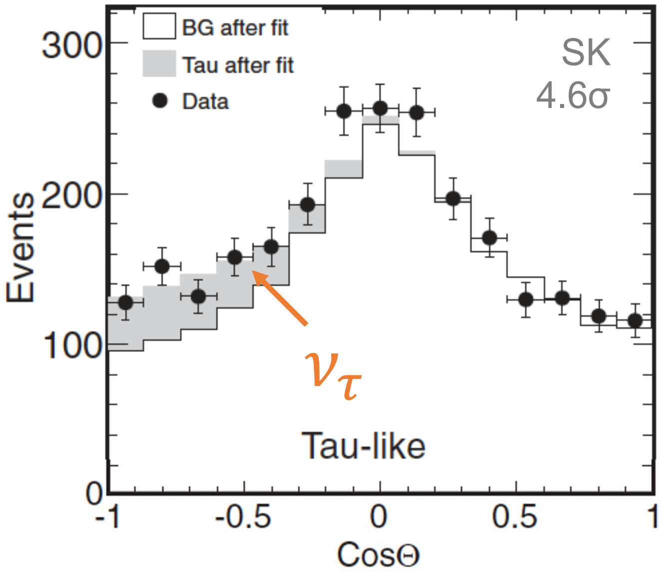


SK, Phys.Rev.D 98, 052006 (2018)

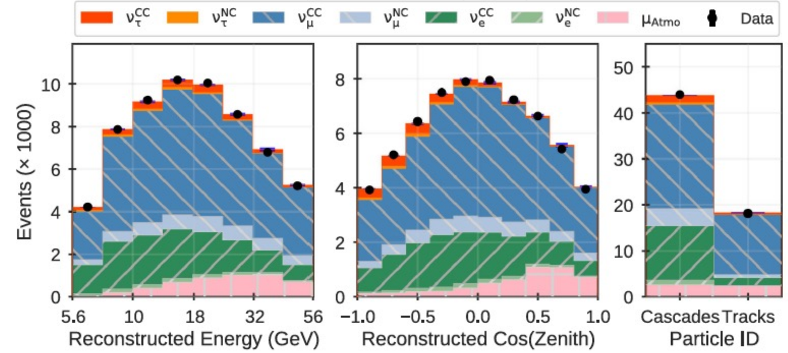
Expected appearance from both ν_μ and ν_e fluxes

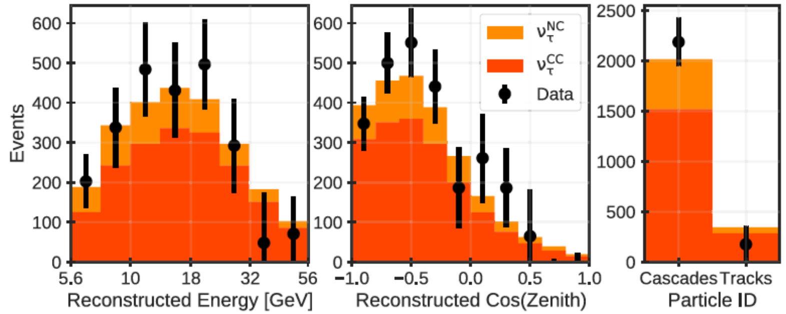
SK, Phys.Rev.D 98, 052006 (2018)

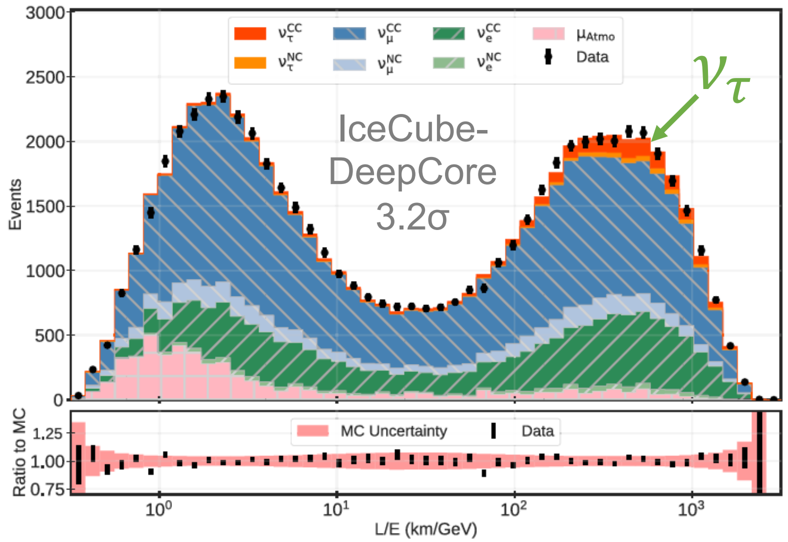




IceCube, Phys.Rev.D 99 (2019) 3, 032007





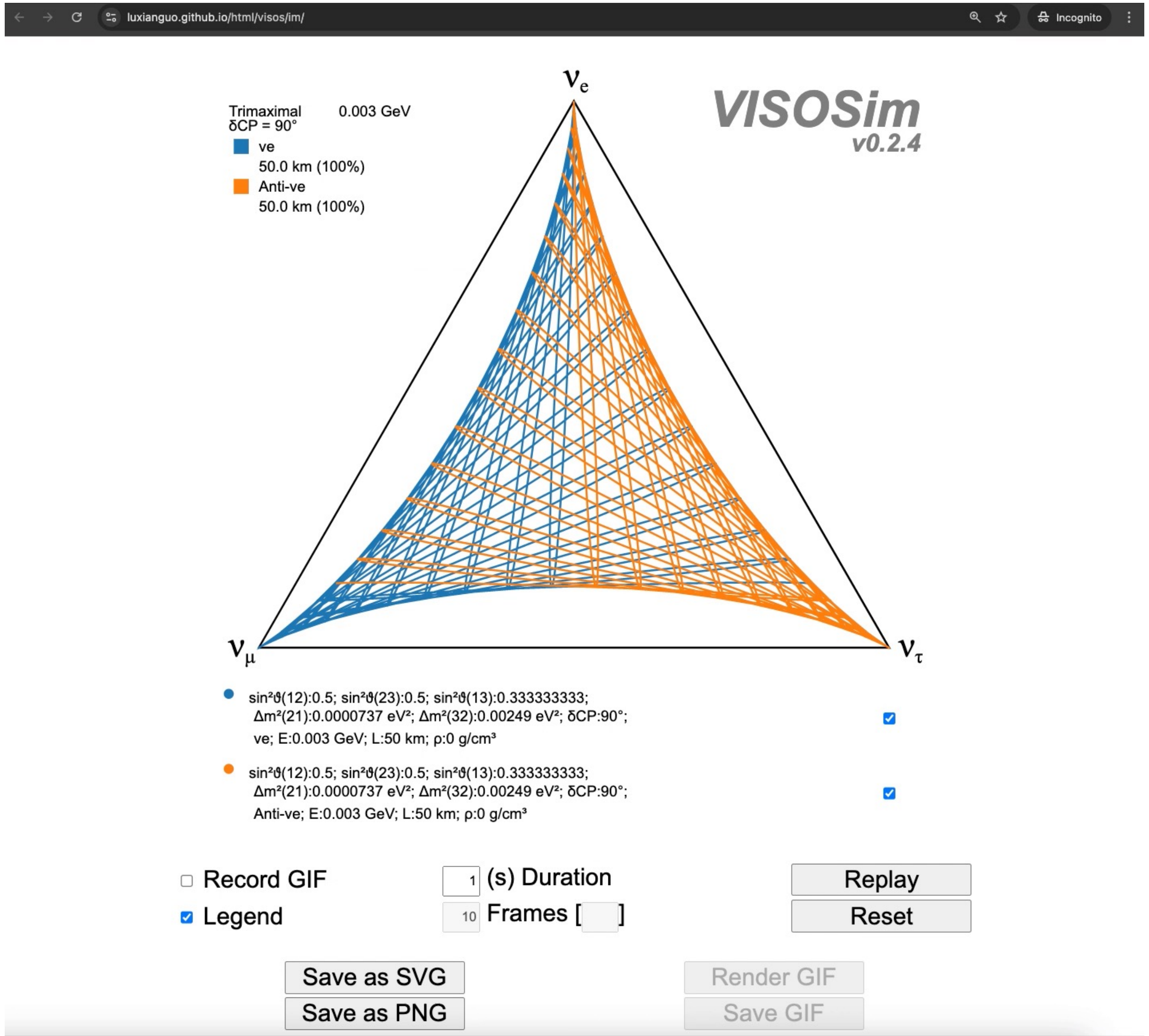


Accelerator and Atmospheric Neutrinos

Neutrino mass gap and mixing → oscillation
***Three* masses → NMO**
***Three*-flavor mixing → δ_{CP}**

1. Neutrino Oscillations
   a. Visualisation: **spin rotation analogy, *VISOSim***
2. Accelerator Neutrinos
   a. Techniques: **hadron decay beams, near-far measurements**
   b. Key results: **T2K and NOvA → δ_{CP} precision needs NMO constraints**
   c. Future vision: **nuSTORM (maybe!)—futuristic, unique ν_e and $\overline{\upsilon}_e$ machine**
3. Atmospheric Neutrinos
   a. MSW matter effect: **start with no mixing / no gap cases**
   b. Flux: **systematics**
   c. Key results: **SK and IceCube → NMO determination still pending**

A Short Demo for VISOSim



Quiz

1. ***Which experiment has a 50 km baseline observing few-MeV neutrinos?***
2. ***Is the oscillation driven by Δm^2_{21} fast or slow? Estimate $|\Delta m^2_{32}|/\Delta m^2_{21}$.***
3. ***Name a few experiments in the "wasteland"? What are they for?***
4. ***Is it driven by Δm^2_{21} or Δm^2_{32}? (What is $|\Delta m^2_{32}|/\Delta m^2_{21}$ now? Is it reasonable?)***
5. ***Is there oscillation when the mixing angle is $\pi/2$?***
6. ***What causes $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = 2$ to fail?***
7. ***What are cascade-like events?***
8. ***Is there matter effect in $\nu_\mu \to \nu_\tau$?***

Homework

1. ***Show that*** $|S_x\rangle_t = \cos\frac{\Delta E}{2}t\,|S_x\rangle_0 - \sin\frac{\Delta E}{2}t\,|S_y\rangle_0$
2. ***Estimate*** Δm_{21}^2 ***and compare your result with PDG.***
3. ***Write down the Feynman diagrams of*** ν_e ***and*** $\overline{\nu}_e$ ***CC interactions with electrons.***
4. ***Recover the previous no-mixing and small gap cases with the general effective mass gap and mixing angle.***

BACKUP

$$P(\nu_\mu(\overline{\nu_\mu}) \to \nu_e(\overline{\nu_e})) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\underline{\sin^2 2\theta_{13}}\left(\frac{\Delta_{13}}{B_{-+}}\right)^2 \sin^2\left(\frac{B_{+-}}{2}L\right)$$

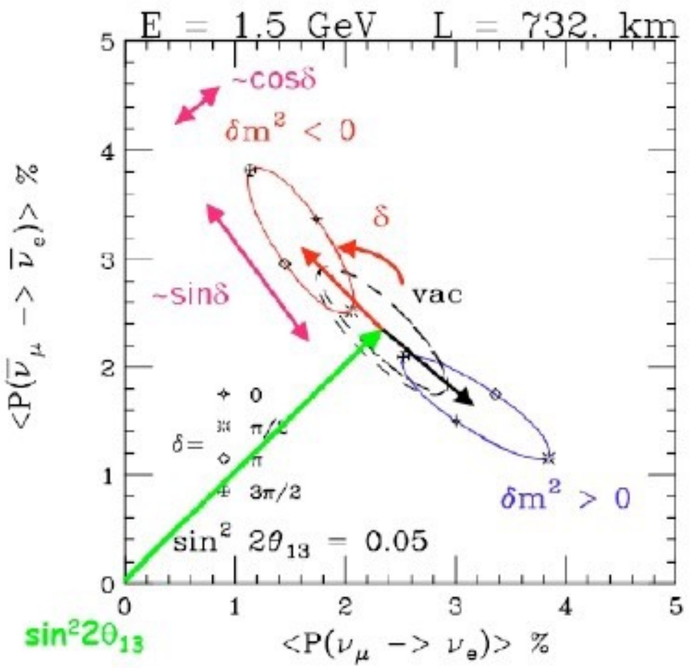
$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A}{2}L\right)$$

$$P_3 = \underline{J}\,\underline{\cos\delta}\,\underline{\cos\left(\frac{\Delta_{23}}{2}L\right)\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_{-+}}\right)}\sin\left(\frac{A}{2}L\right)\sin\left(\frac{B_{-+}}{2}L\right)$$

$$P_4 = \underline{\pm J}\,\underline{\sin\delta}\,\underline{\sin\left(\frac{\Delta_{23}}{2}L\right)\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_{-+}}\right)}\sin\left(\frac{A}{2}L\right)\sin\left(\frac{B_{-+}}{2}L\right)$$

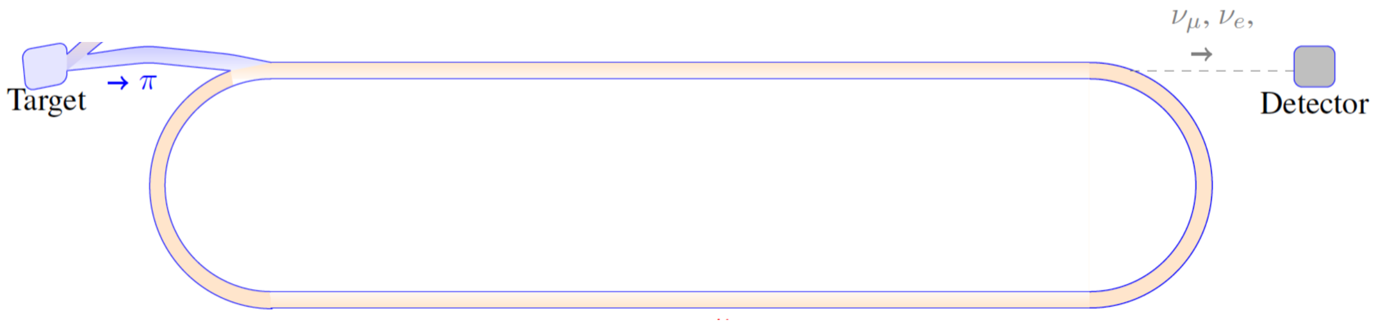
$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E} \qquad A = \sqrt{2}G_F N_e \qquad B_{-+} = |\Delta_{13} \mp A| \qquad J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

- θ_{13}
- $\theta_{23}>45$ or $\theta_{23}<45$
- Sign(Δm_{23}^2)
- δ_{CP}



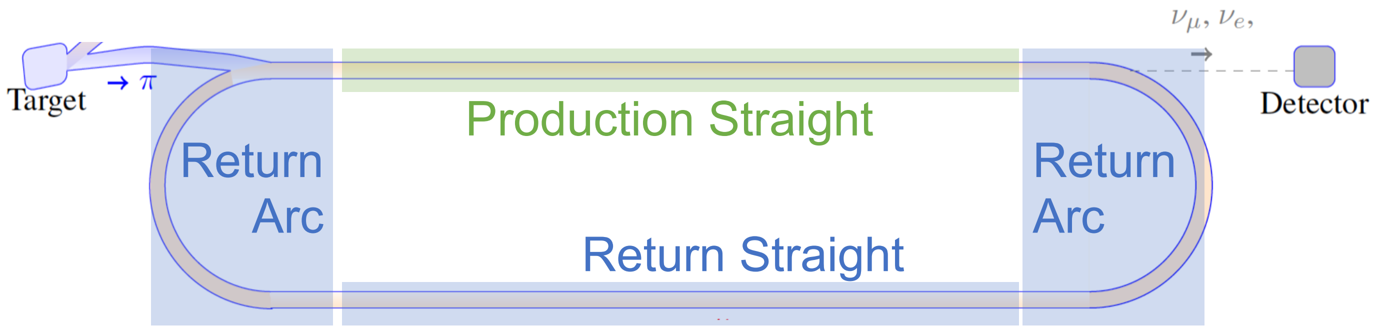
e.g. Boyd, [Warwick Week 2025 lecture]

ν from STORed Muons (nuSTORM)



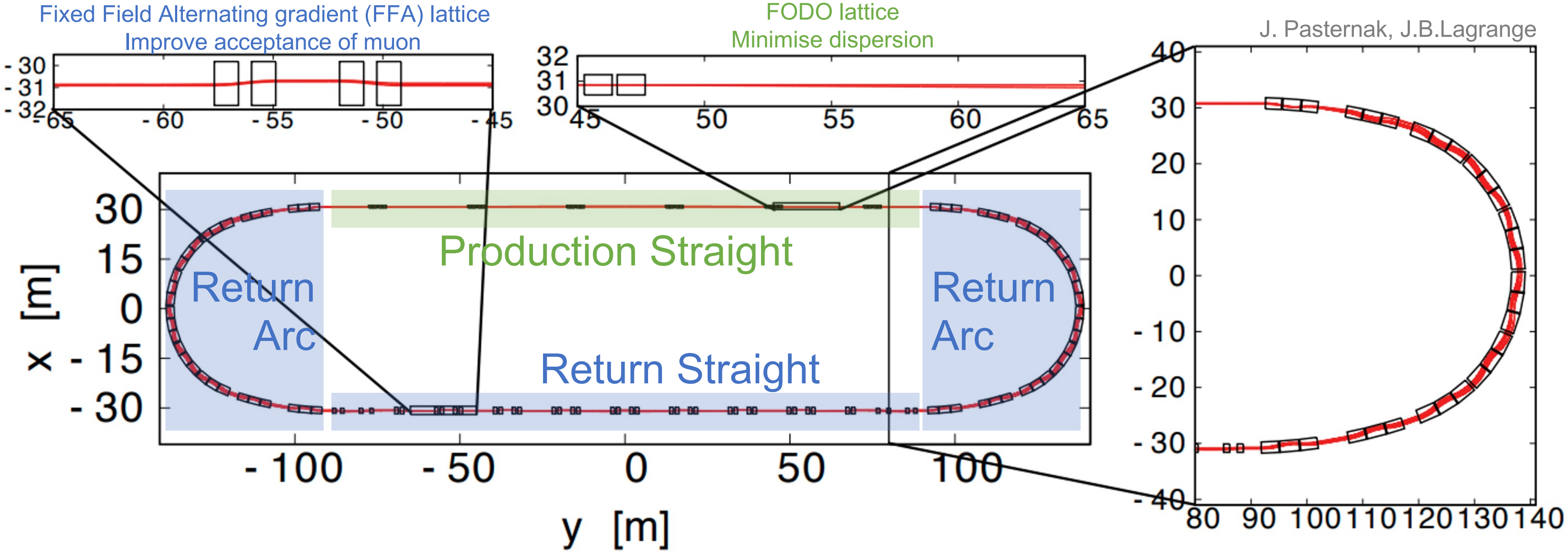
- **1st ν beam facility & highest ever beam power based on stored muons**
- Fine tune neutrino fluxes via μ acceptance

ν from STORed Muons (nuSTORM)



- **1st ν beam facility & highest ever beam power based on stored muons**
- Fine tune neutrino fluxes via μ acceptance

ν from STORed Muons (nuSTORM)

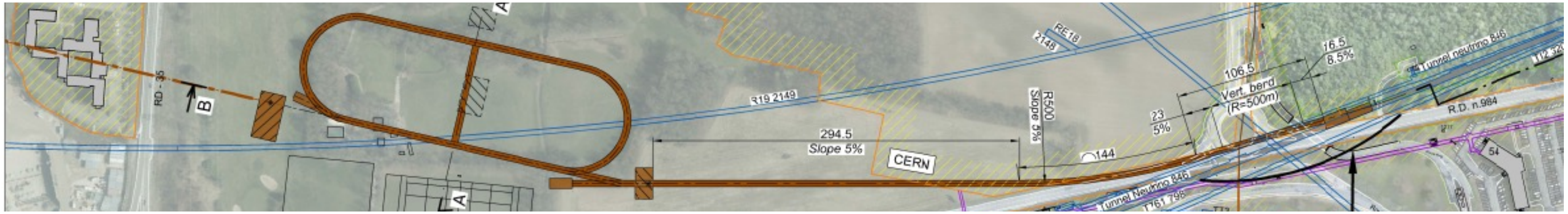


- **1st ν beam facility & highest ever beam power based on stored muons**
- Fine tune neutrino fluxes via μ acceptance

- Production Straight (example w/ π^+ injection)
  - ν_μ flux from $\pi^+ \to \mu^+\nu_\mu$ ("pion flash")
  - $\nu_e + \bar{\nu}_\mu$ flux from $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$
  - Maximise μ capture efficiency
- Return Arcs and Straight
  - p_μ tunable between 1 and 6 GeV/*c*, spread ±16%

A Brief History of nuSTORM

CERN-PBC-REPORT-2019-003
DOI:10.17181/CERN.FQTB.O8QN



2012-13 LoI and Proposal to FNAL PAC [arXiv:1206.0294, arXiv:1308.6822], EoI to CERN [arXiv:1305.1419]

- ➢ Sterile neutrinos
- ➢ Neutrino-nucleus scattering
- ➢ Technology test bed for muon accelerators

2014 Steriles sensitivity [Phys.Rev.D 89, 071301 (2014)]

- ➢ nuSTORM at FNAL

2019 Feasibility of nuSTORM at CERN [CERN-PBC-REPORT-2019-003]

- ➢ SPS 100 GeV proton beam
- ➢ Optimised for neutrino-nucleus scattering, maintaining sensitivity to BSM (steriles + non-unitarity, NSI, Lorentz-invariance/CPT violation)

2022 Snowmass 2021 [arXiv:2203.07545]

- ➢ Advocating synergy with ENUBET and Muon Collider Demonstrator
  - ✓ Muon Collider demonstrator
    - ❖ 6-D cooling
  - ✓ nuSTORM as test bed for muon storage ring
    - ❖ Complete implementation for large acceptance
    - ❖ R&D for very precise determination of stored-muon energy and spread

2025 On-going: European Strategy Update for Particle Physics

- ➢ Submission: https://indico.cern.ch/event/1439855/abstracts/191113/

❑ ***Why do we need nuSTORM?***

- ✓ Wishlist
  1. **ν_e and $\bar{\nu}_e$ beams with the relevant energy for appearance**
  2. **Well-understood fluxes**
  3. **High statistics**
  4. **Low ν_μ background**

❑ ***What other physics can we do with it?***