Neutrino Oscillations

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University of Manchester

Academic Training Lecture Programme
May 2021

Lecture 2

Reactor measurements of θ_{13} CP violation, and current long-baseline experiments

PMNS Matrix

solar | "reactor" | atmospheric

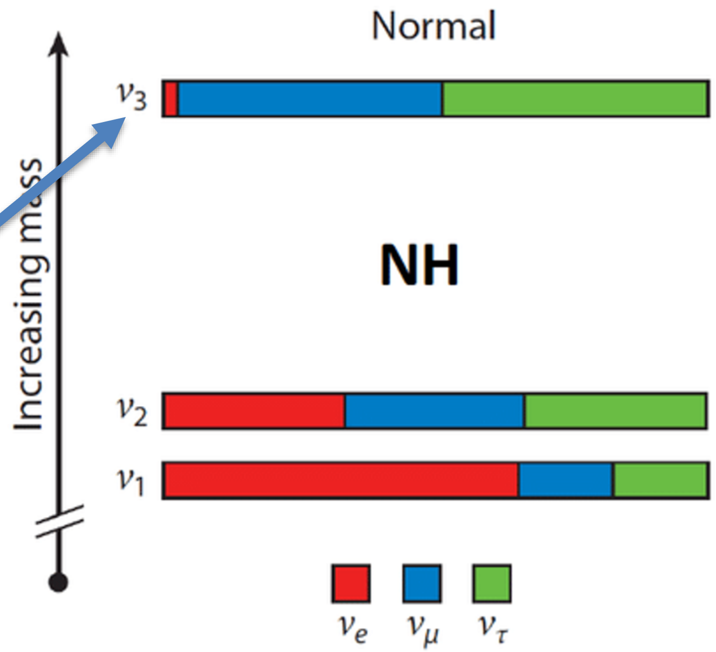
$$U_{\text{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$$\theta_{12} = 33.44^{\circ}{}^{+0.78^{\circ}}_{-0.75^{\circ}}$$

$$\theta_{23} = 49.0^{\circ}{}^{+1.1^{\circ}}_{-1.4^{\circ}}$$

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

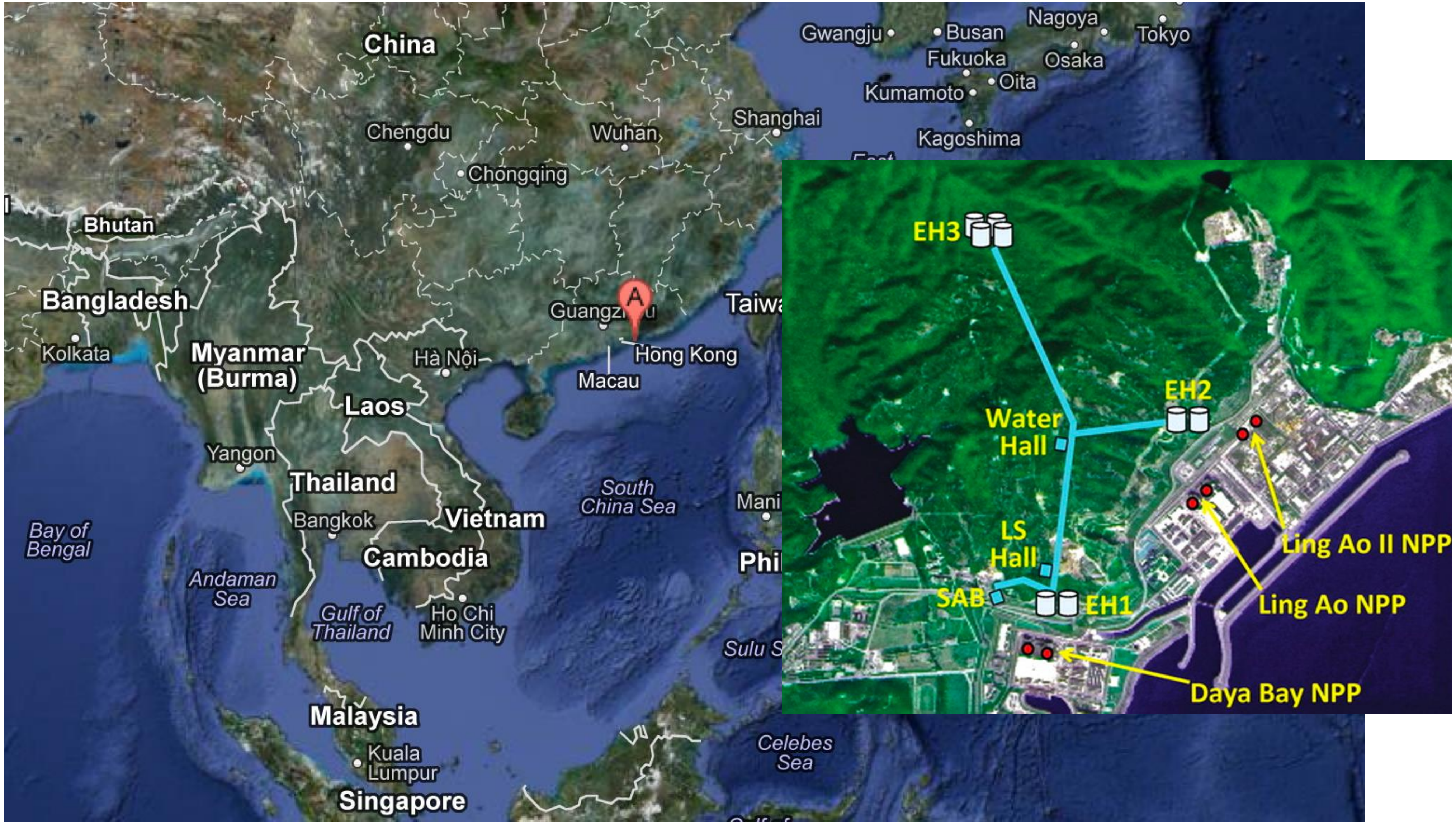
- Θ_{12} and θ_{23} are large ("maximal" mixing)
- Angle θ_{13} is small and mixes ν_e with ν_3
- CPV term (δ) $\propto \theta_{13}$
- Look for ν_e mixing driven by Δm^2_{32}



$$\Delta m^2_{32} = 2.4 \times 10^{-3}\,\text{eV}^2$$

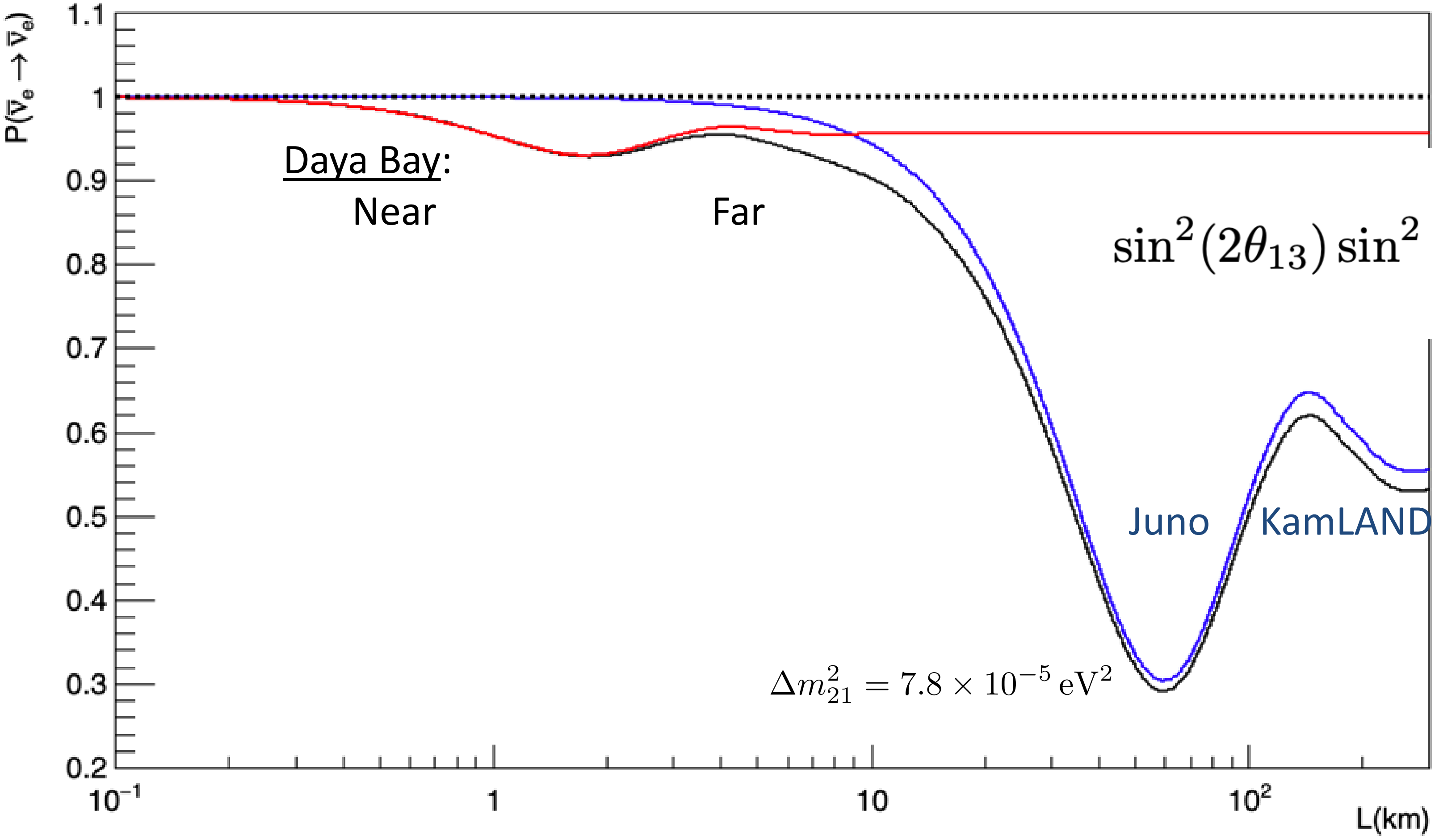
$$\Delta m^2_{21} = 7.8 \times 10^{-5}\,\text{eV}^2$$

Daya Bay reactor



“Reactor” Oscillations

“Survival probability” for anti-ν_e from the reactor ($E \approx 3$ MeV)

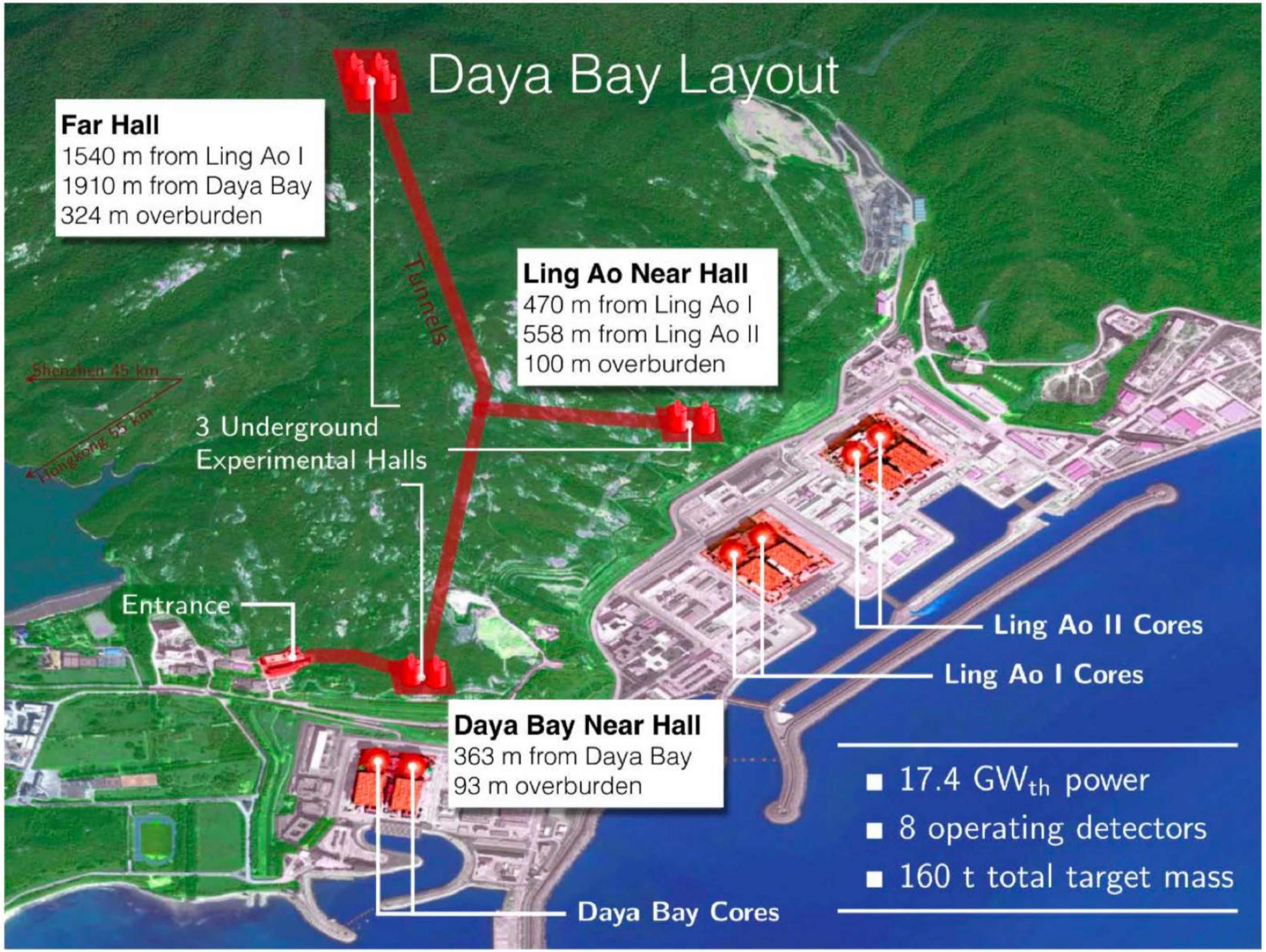


$$\Delta m^2_{32} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{32}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

J. Ling, Neutrino 2020

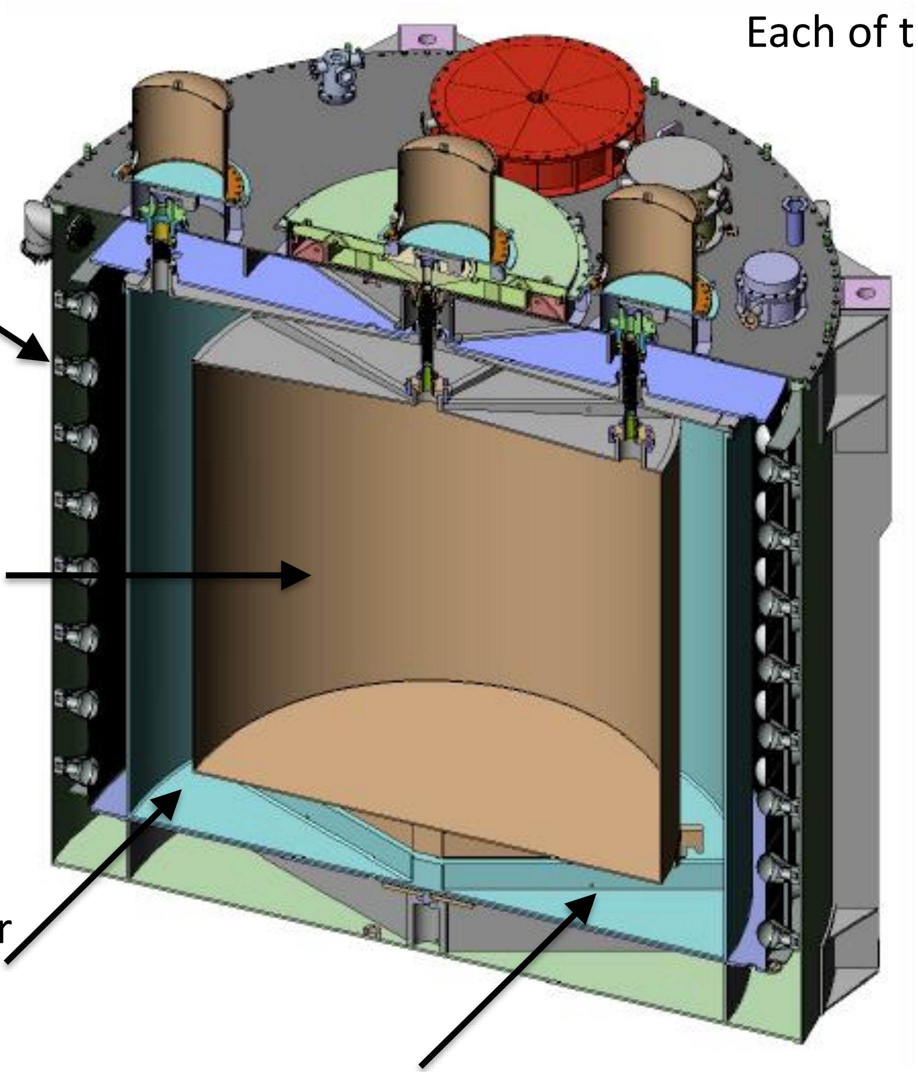
Daya Bay Layout



Daya Bay detectors

Each of the 8 detector is 20 tons.

Photomultiplier tubes

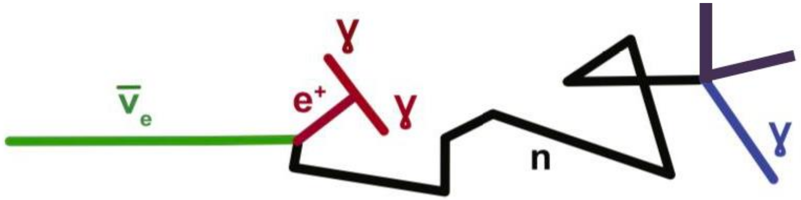


Scintillator, loaded with gadolinium (high neutron capture cross section)

Scintillator buffer (no gadolinium)

Inner acrylic tank

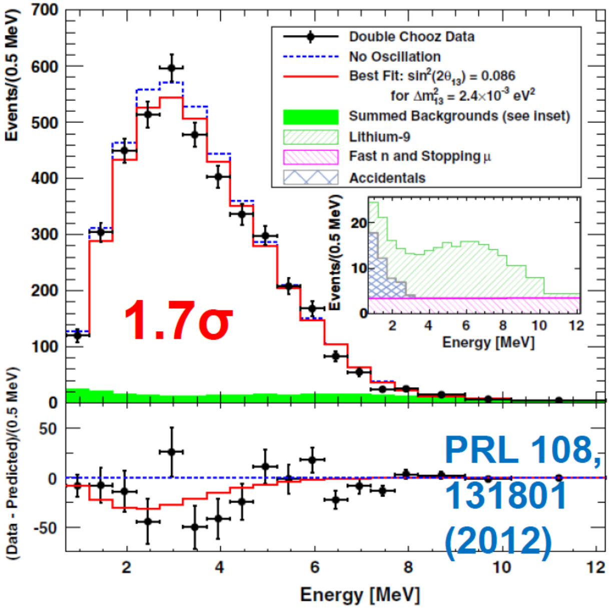
Inverse β decay



$$\bar{\nu}_e + p \rightarrow n + e^+$$

Original θ_{13} measurements (Far/Near)

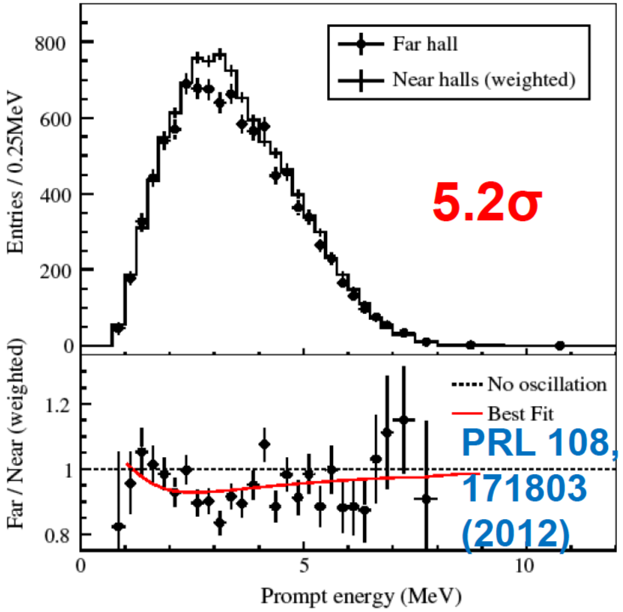
Double Chooz
with only a far detector
(Nov. 2011)



Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$$

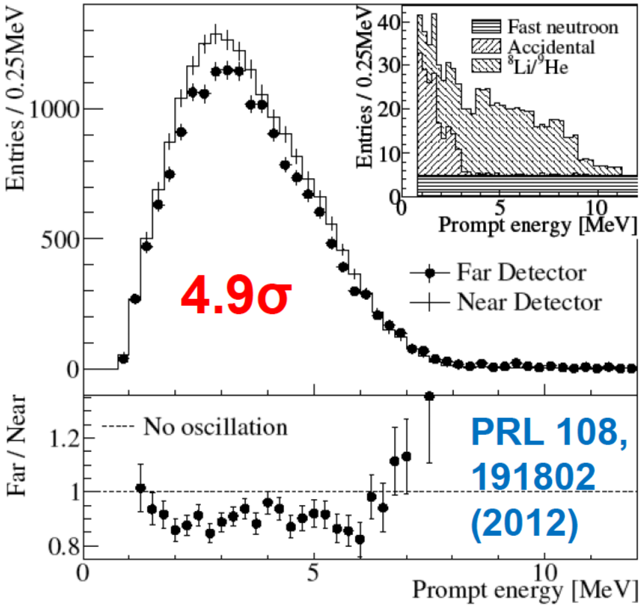
Daya Bay
(March 2012)



Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

RENO
(April 2012)

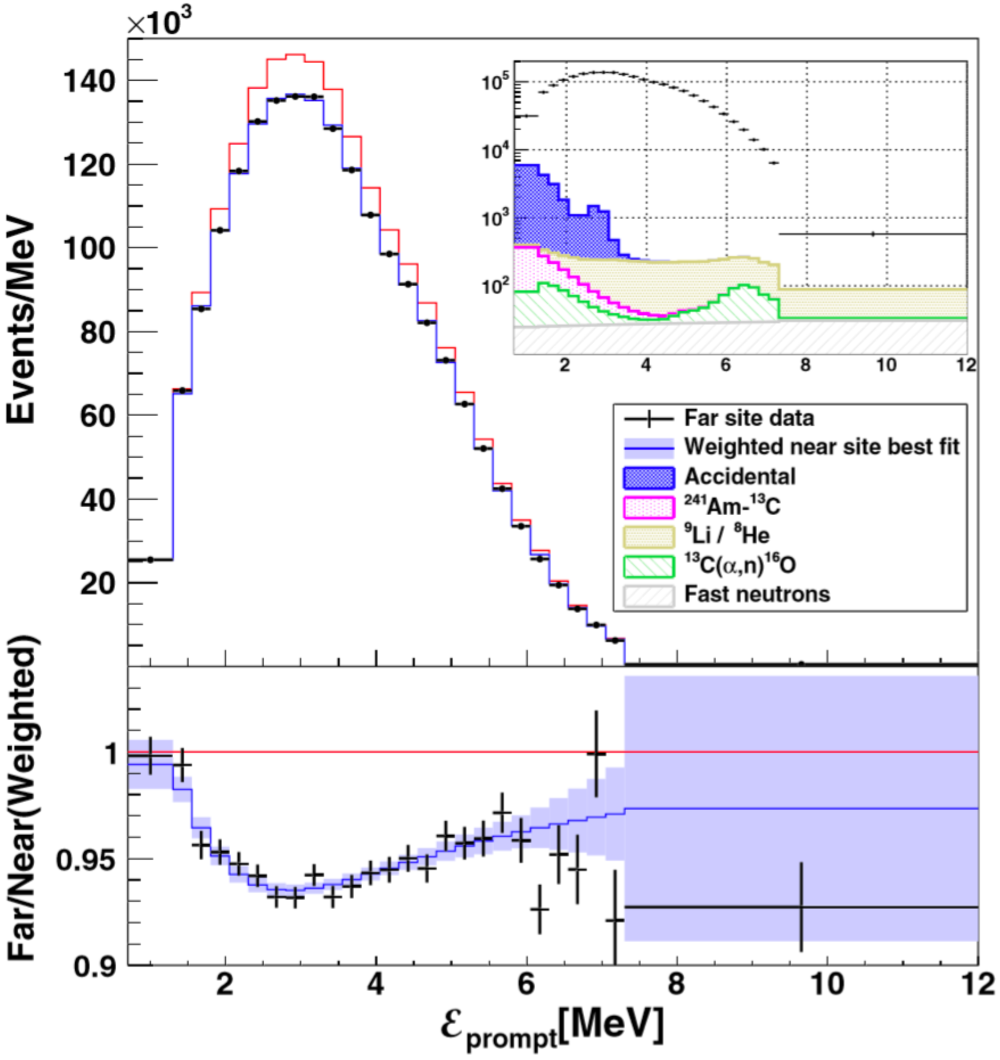


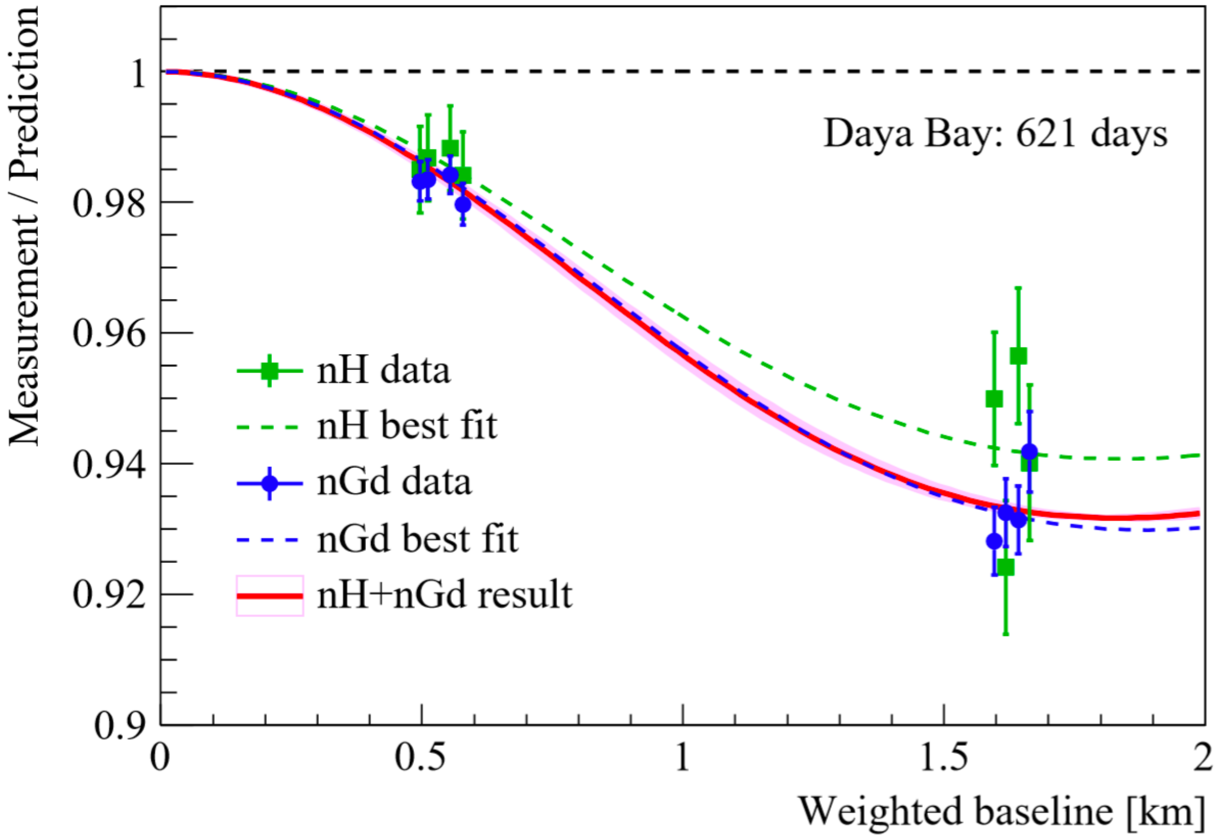
Rate only

$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

M.He, NNN

θ_{13} measurement (Daya Bay)





$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

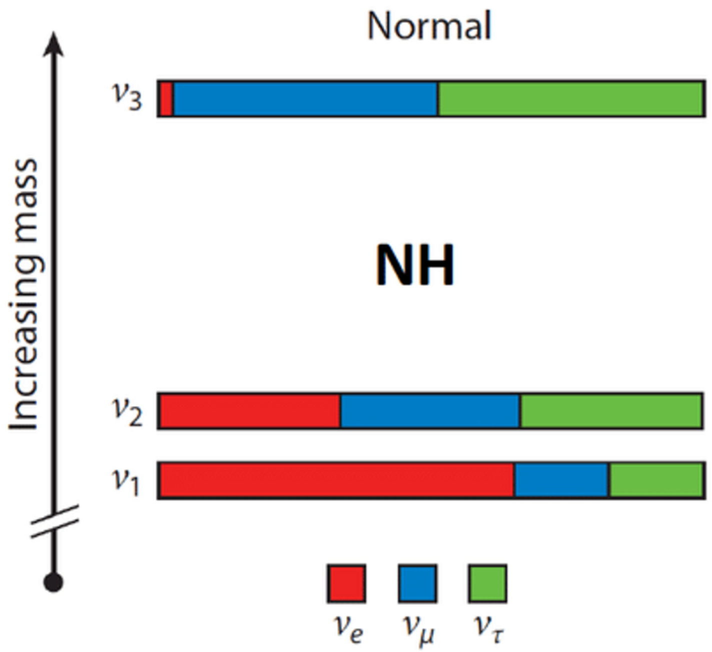
PMNS Matrix

$$
\begin{array}{cccc}
 & \text{solar} & \text{reactor} & \text{atmospheric} \\
U_{\mathrm{PMNS}} = & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}
\end{array}
$$

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

$$\theta_{12} = 33.44^{\circ}{}^{+0.78^{\circ}}_{-0.75^{\circ}}$$

$$\theta_{23} = 49.0^{\circ}{}^{+1.1^{\circ}}_{-1.4^{\circ}}$$



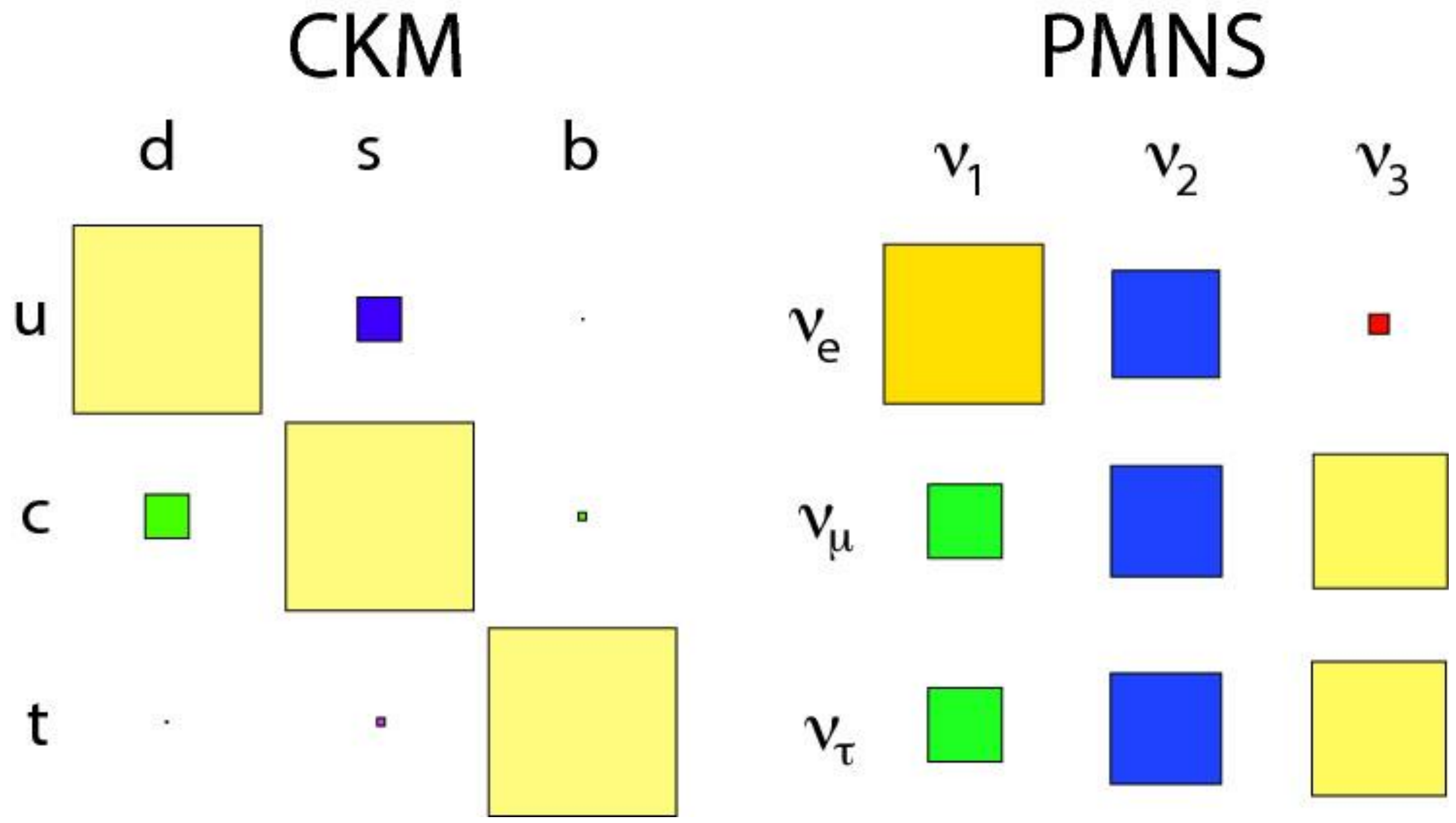
$$\Delta m^2_{32} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{21} = 7.8 \times 10^{-5}\,\mathrm{eV}^2$$

- Small angle θ_{13} mixes ν_e with ν_3
- Look for ν_e mixing driven by Δm^2_{32}
- Reactor: anti-ν_e disappearance
- Accelerator: ν_e appearance in ν_μ beam

  → sensitive to θ_{13} and δ

CKM vs PMNS

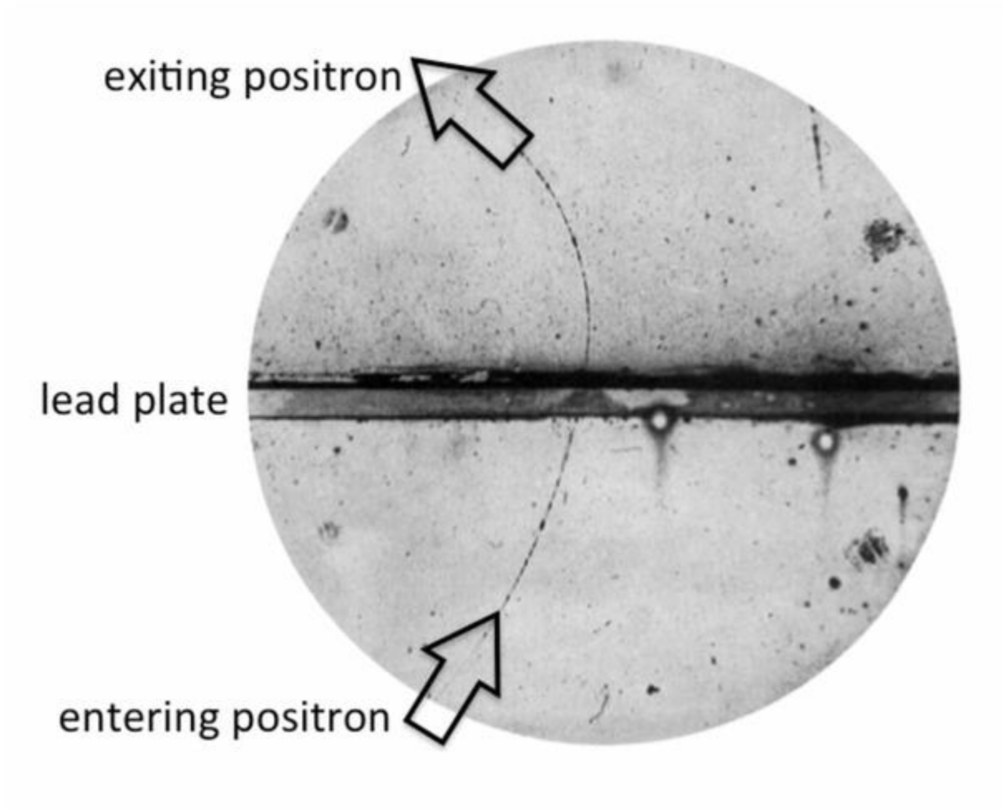


The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Matter and Anti-matter

Paul Dirac

$$\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k \, c\right) \psi(\mathbf{x},t) = i\hbar \frac{\partial \psi(\mathbf{x},t)}{\partial t}$$

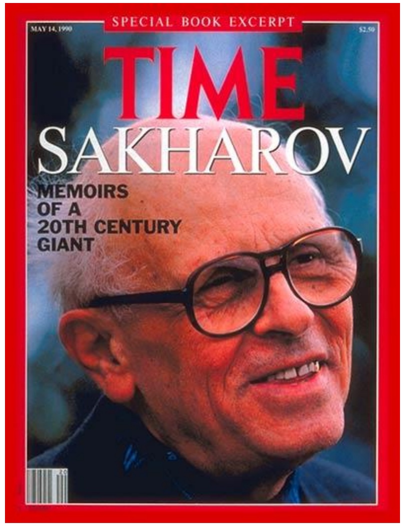


Dirac equation predicts anti-particle states (1928)

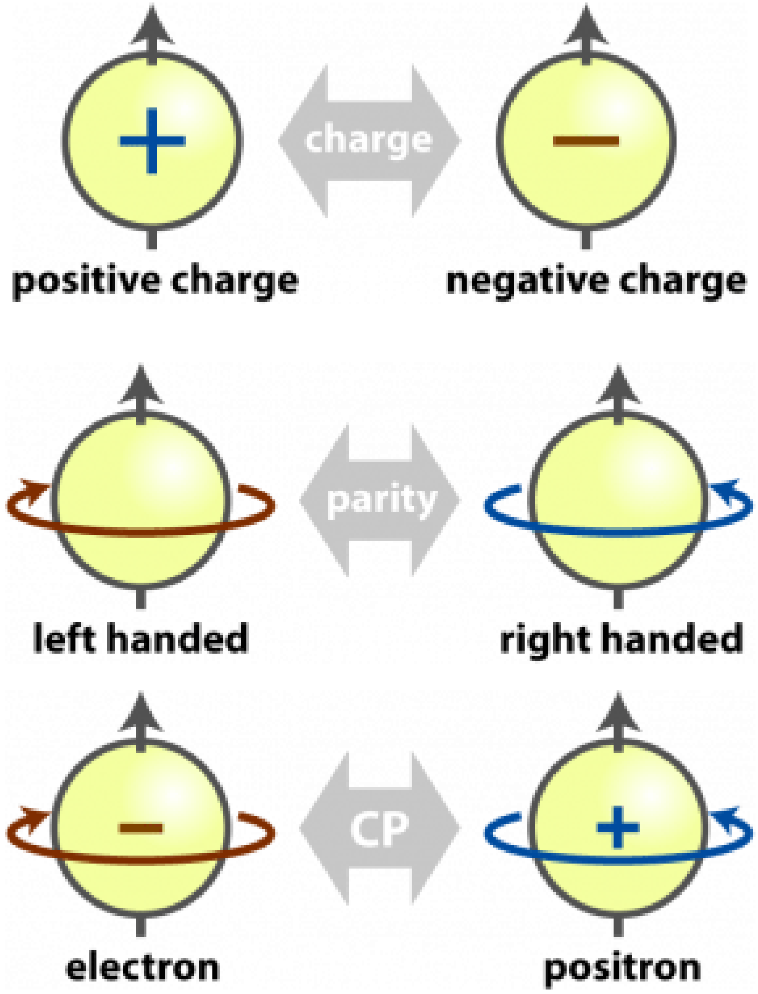
Positron discovered by C.D. Anderson in 1932

Matter-antimatter asymmetry (“CP violation”)

- A tiny ($\approx 10^{-10}$) asymmetry between particle and anti-particles led to our matter dominated universe
- One of the conditions for this asymmetry is violation of *CP symmetry*
- The observation of *CP violation* involving neutrinos could provide support for a theory called *Leptogenesis*



1. Baryon number violation
2. CP violation
3. Departure from thermal equilibrium



Born: 21 May 1921, Moscow, Russia

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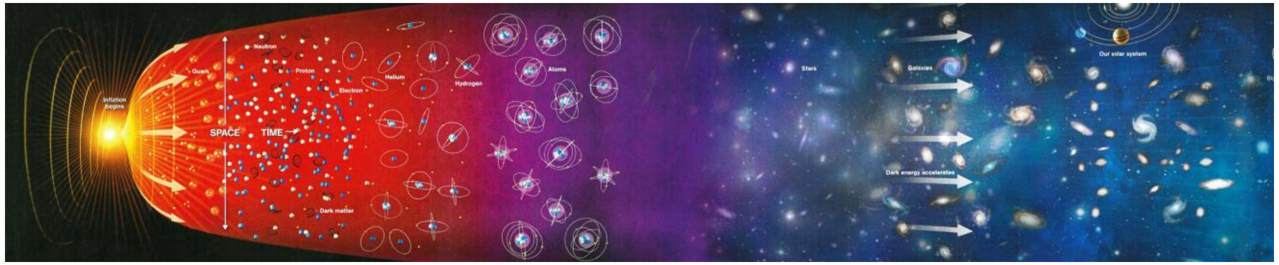
CP violation

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

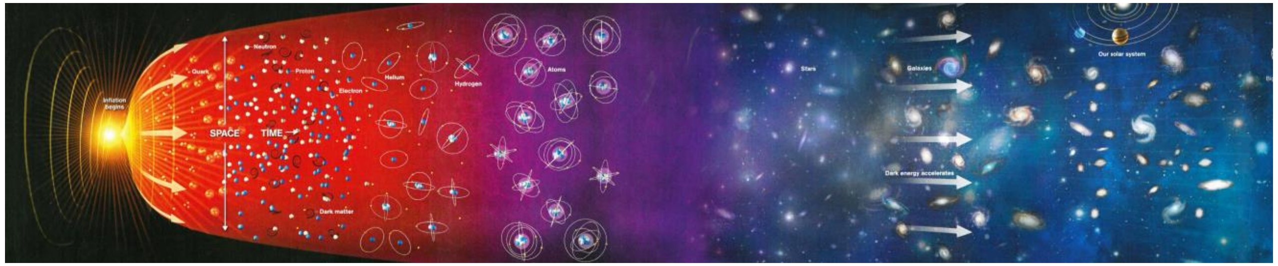
$$c_{ij} = \cos\theta_{ij}; s_{ij} = \sin\theta_{ij}$$

- A 2x2 ”rotation” matrix is real, whereas a 3x3 rotation matrix is imaginary (phase δ).
- CP violation (the difference between a process and its CP conjugate) is only possible when the matrix is imaginary (3 generations!).



CP violation

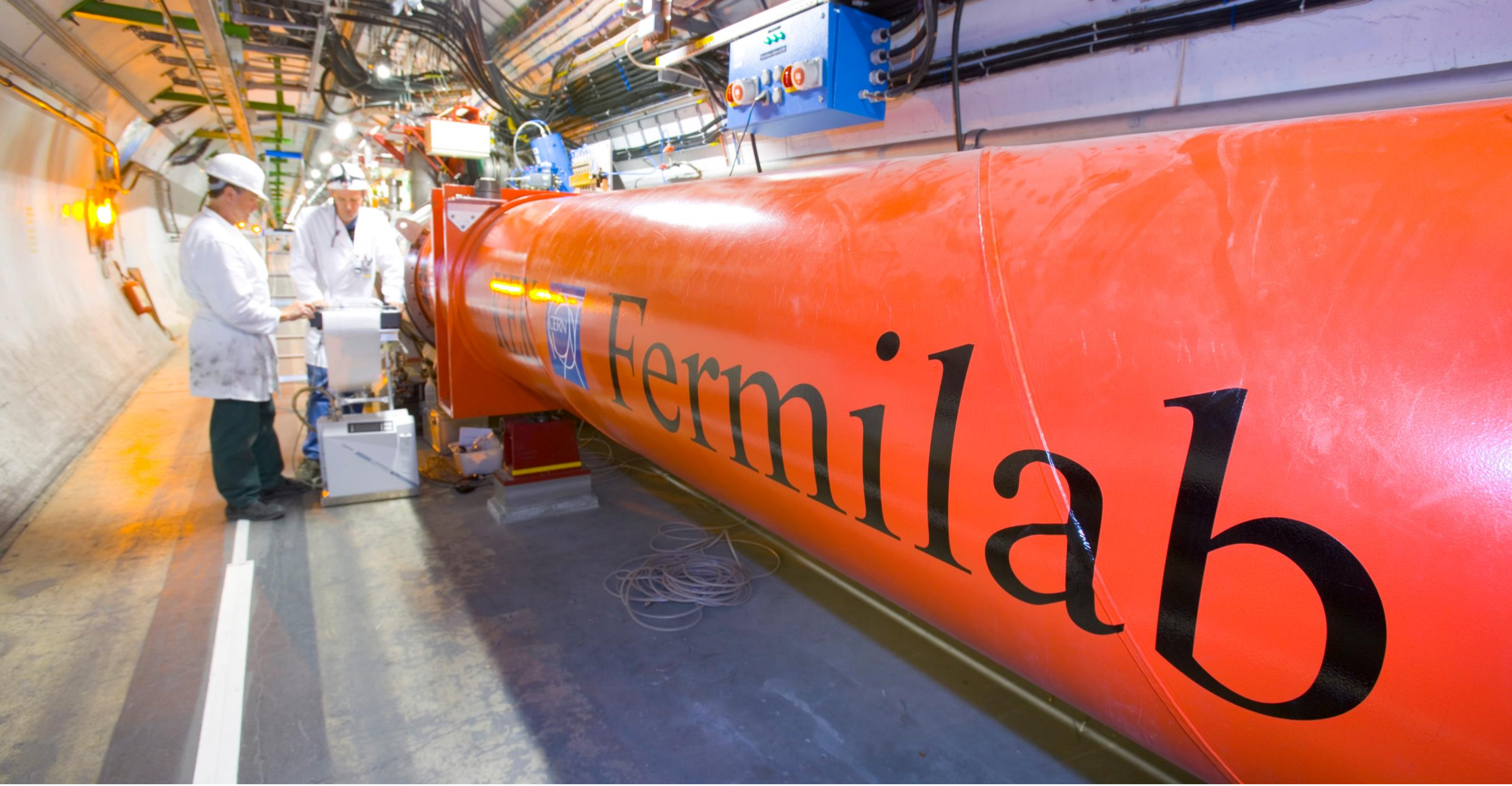
- The same is true for the CKM matrix, where CP violation has been observed for quark processes.
- CP violation in the quark sector is too small to describe the matter dominance in the Universe.
- Discovery of CP violation with neutrinos would lend support to the Leptogenesis model – Leptogenesis would happen at large scales, e.g. through a heavy right-handed neutrino N_R (see-saw mechanism).



CKM vs PMNS – an aside

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

- Neutrinos differ from quarks (Dirac particles), as they can be their own anti-particles (Majorana particles).
- This gives rise to additional complex phases in the PMNS matrix.
- These complex phases appear on the diagonal of the matrix so they have no impact on neutrino oscillations.



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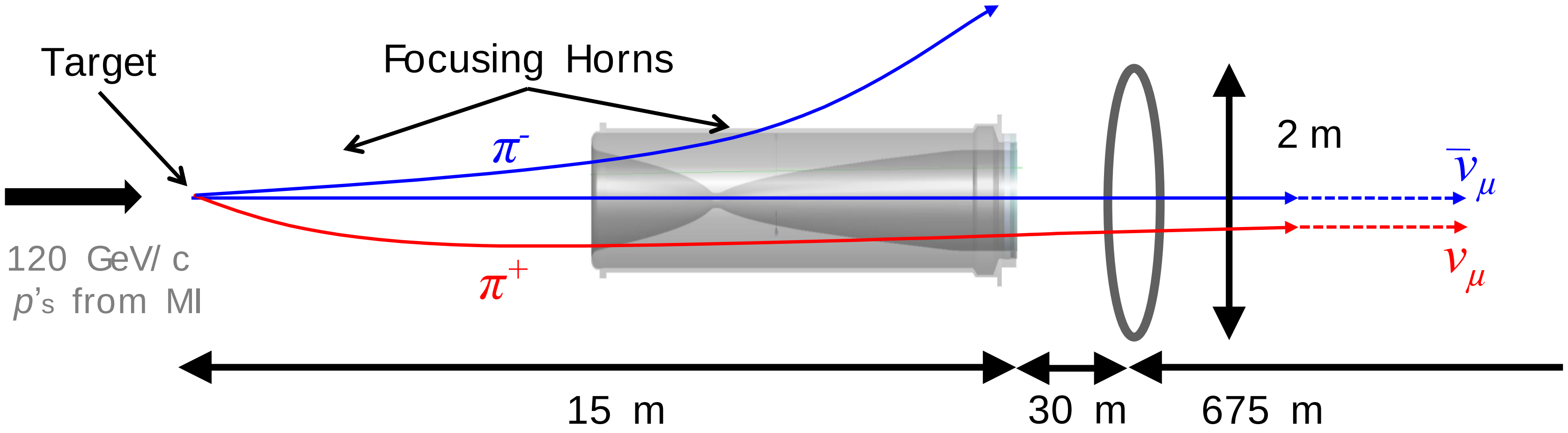
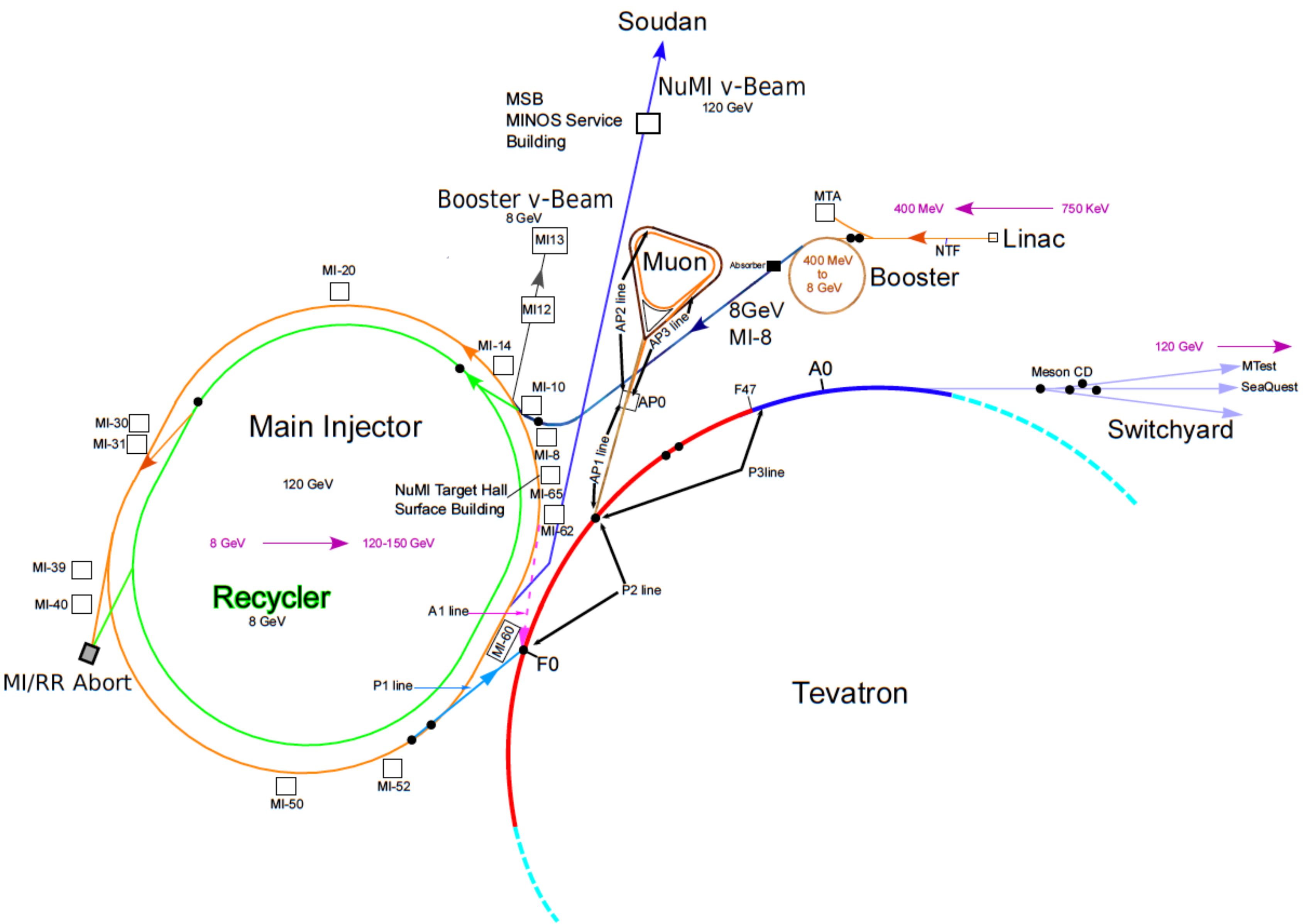
Making a neutrino beam



- As neutrinos are neutral, they cannot be focused, and a magnetic horn is thus used to focus the pions.
- Invented by Simon van der Meer at CERN

Fermilab NuMI beam



Making a neutrino beam

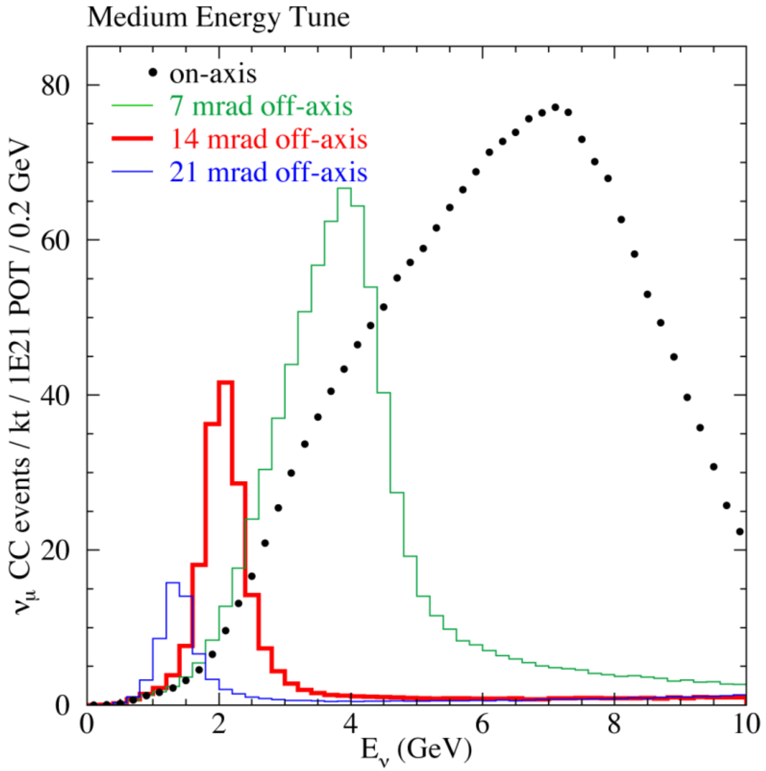
Pion decay at rest:

$$\overline{\nu}_l \leftarrow \pi^+ \rightarrow l^+$$

$$\boxed{E_\nu^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.8\,\mathrm{MeV}}$$

Boost into lab system:

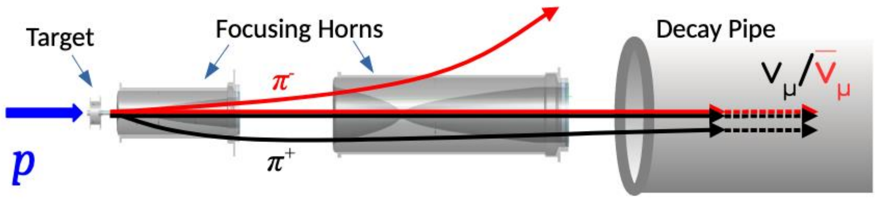
$$\boxed{\begin{aligned} E_\nu &= \frac{m_\pi E_\nu^*}{E_\pi - p_\pi \cos\theta} \\ &= \frac{E_\nu^*}{\gamma_\pi(1-\beta_\pi\cos\theta)} \end{aligned}}$$

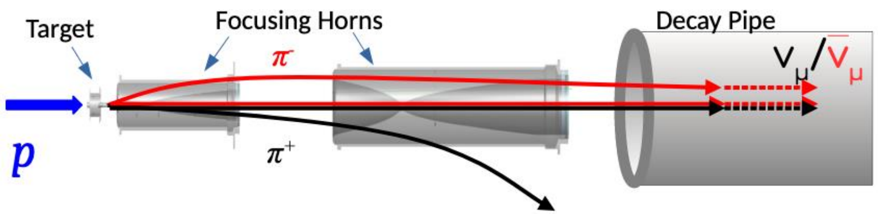


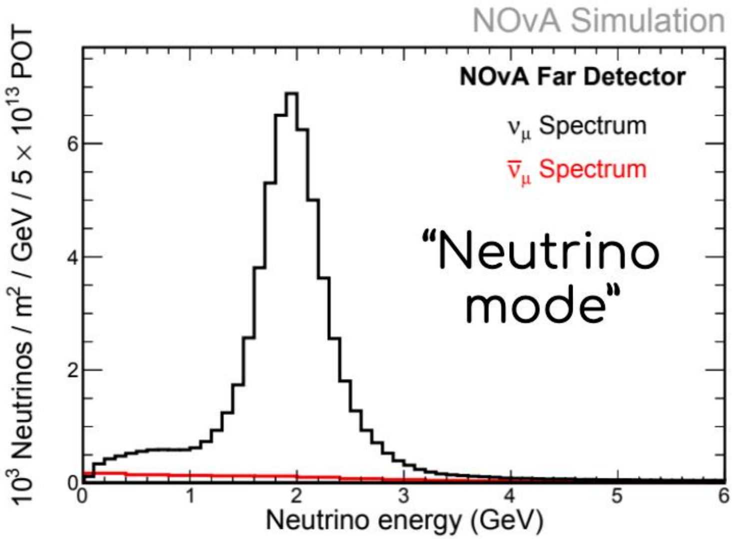
$$E_\pi = 9\ \mathrm{GeV\ at}\ \theta = 0:$$

$$\gamma_\pi = 64.5 \implies E_\nu = 3.8\,\mathrm{GeV}$$

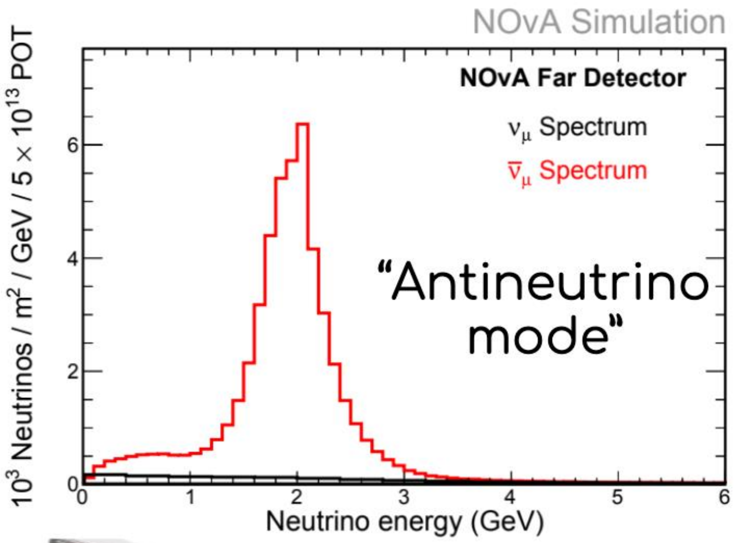
Forward/Reverse Horn Current

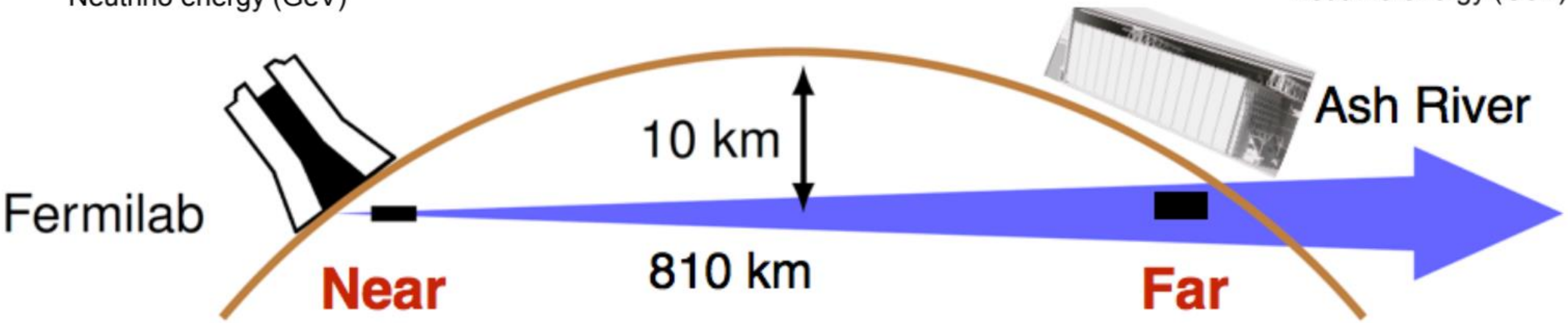




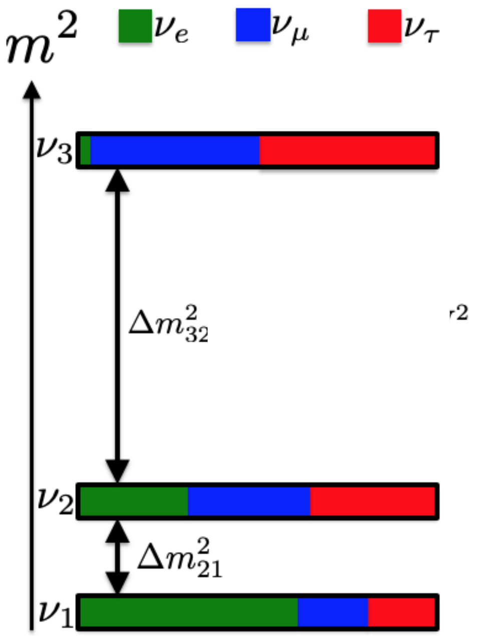


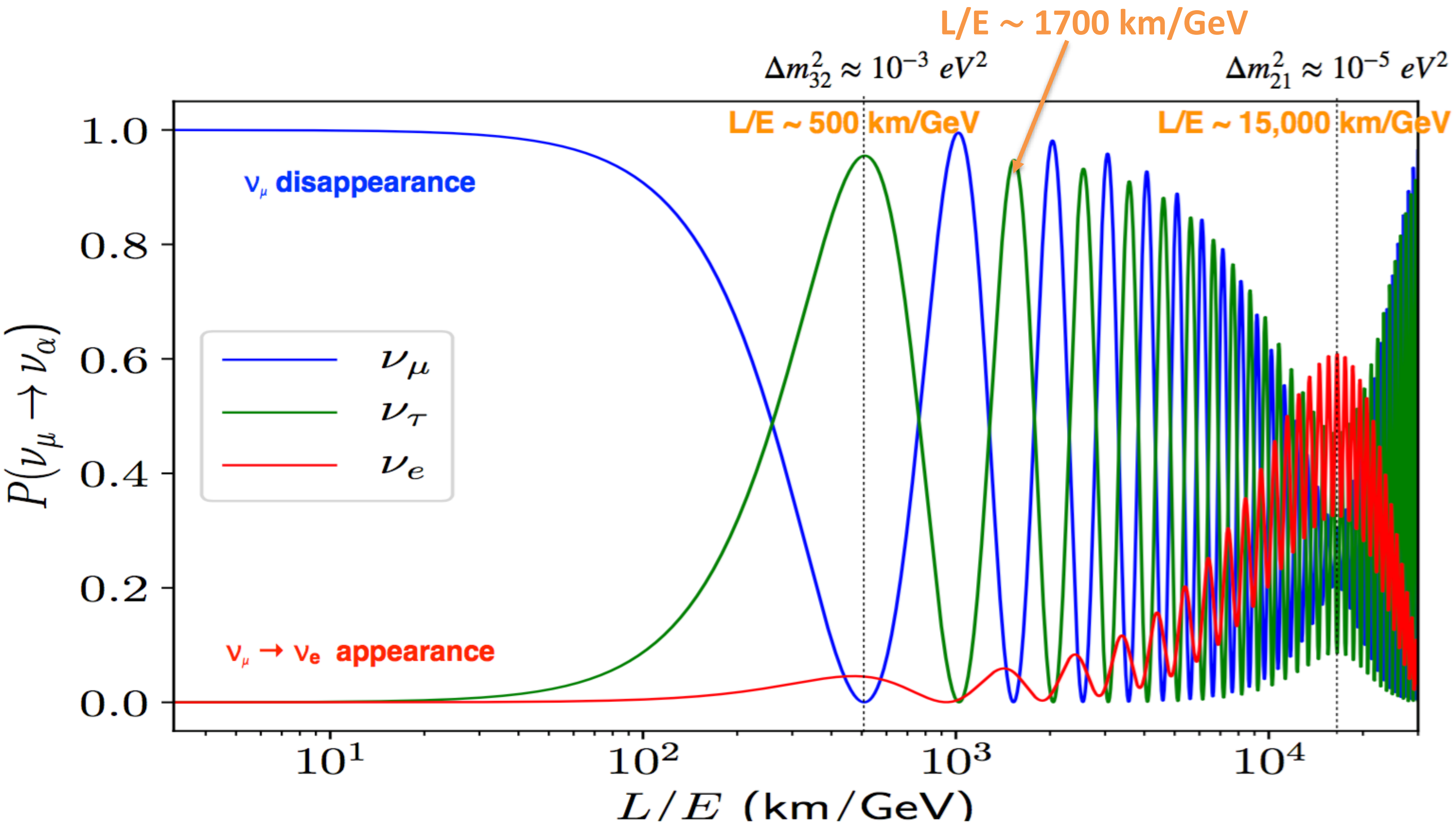
Neutrinos from NuMI beam





Finding the oscillation maximum





Typical neutrino beam energy is around 2.5 GeV

Baseline/Neutrino energy

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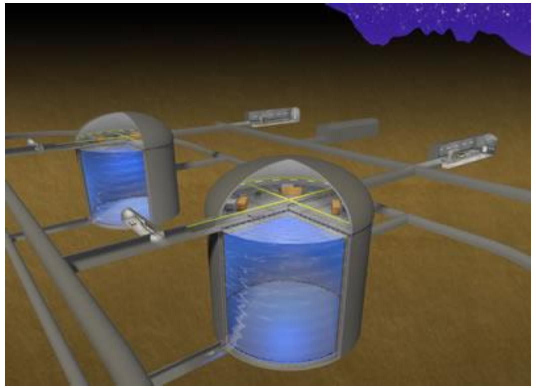
Optimizing L/E for neutrino oscillations

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

L ≈ 300 km

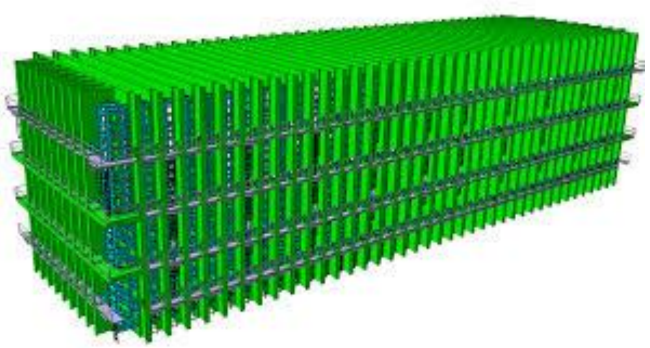
- L/E = 300 km /0.6 GeV = 500 km/GeV
- no matter effects; first oscillation maximum.
- use narrow width neutrino beam (off axis) with E < 1 GeV



Water Cherenkov (T2K,HK)

L = 1300 km

- L/E = 1300 km/2.5 GeV = 500 km/GeV (1^{st} max),
- L/E = 1300 km/0.8 GeV = 1700 km/GeV (2^{nd} max)
- matter effects; first <u>and</u> second oscillation maximum.
- use broad-band neutrino beam (on axis).



Liquid argon (DUNE)

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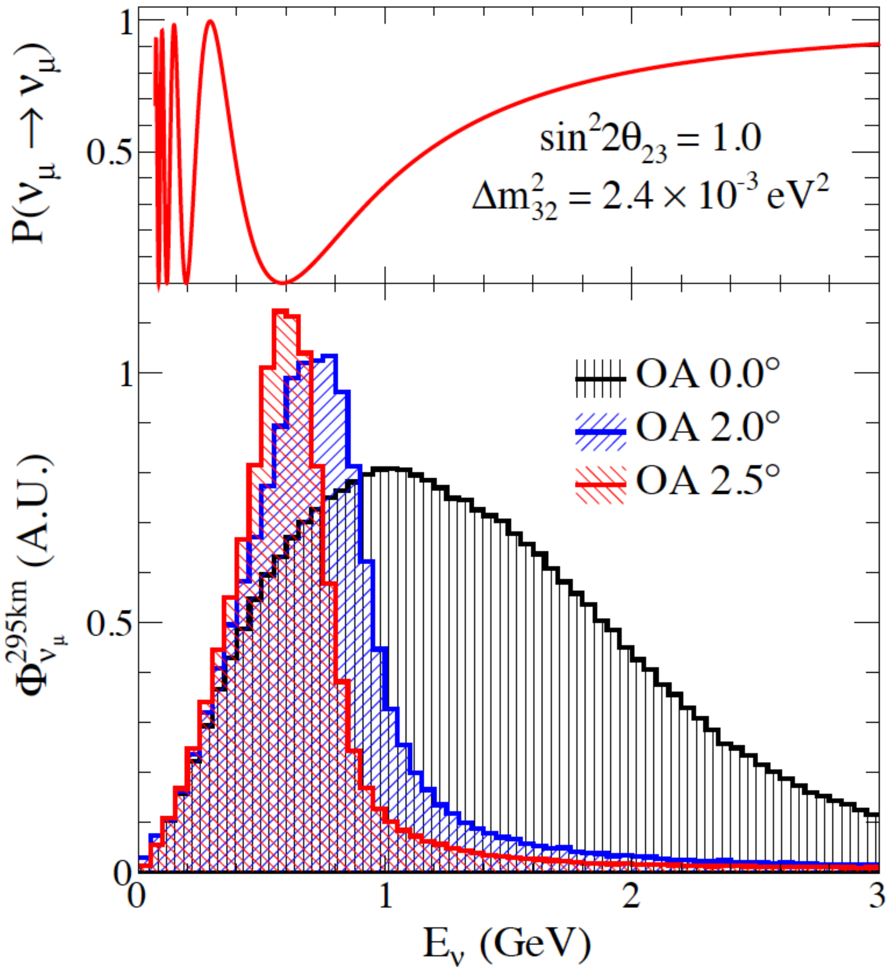
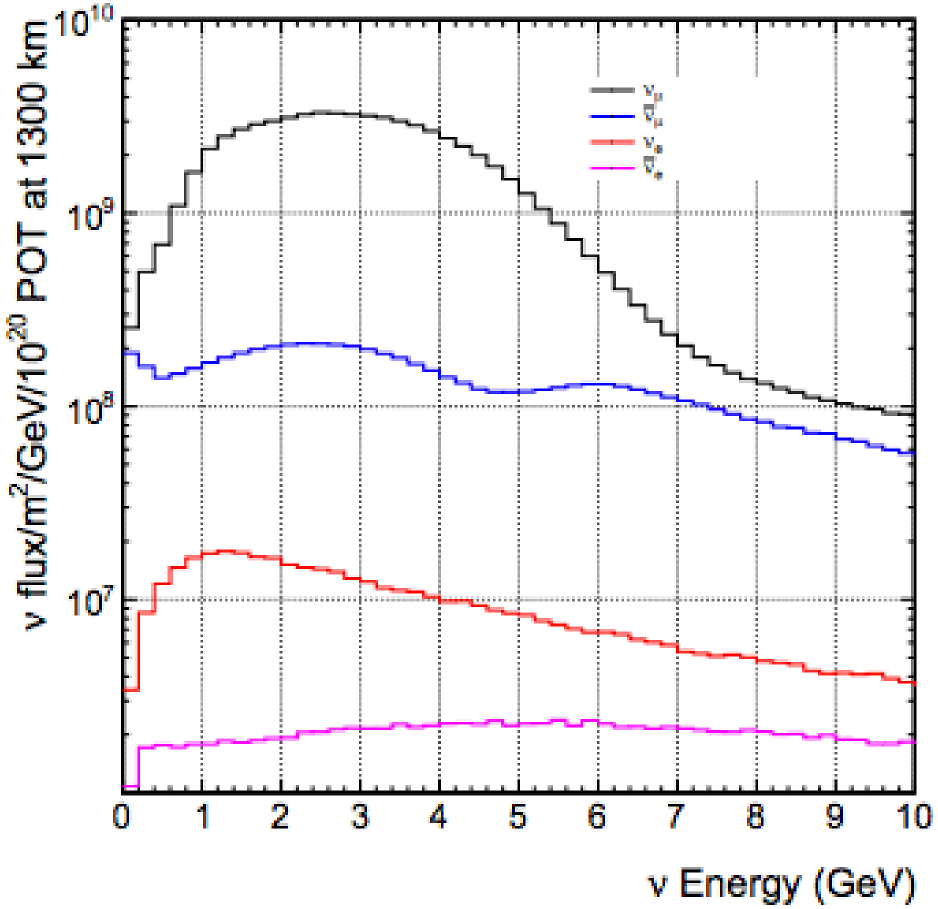
Off-axis vs on-axis beams

T2K at 2.5 degrees

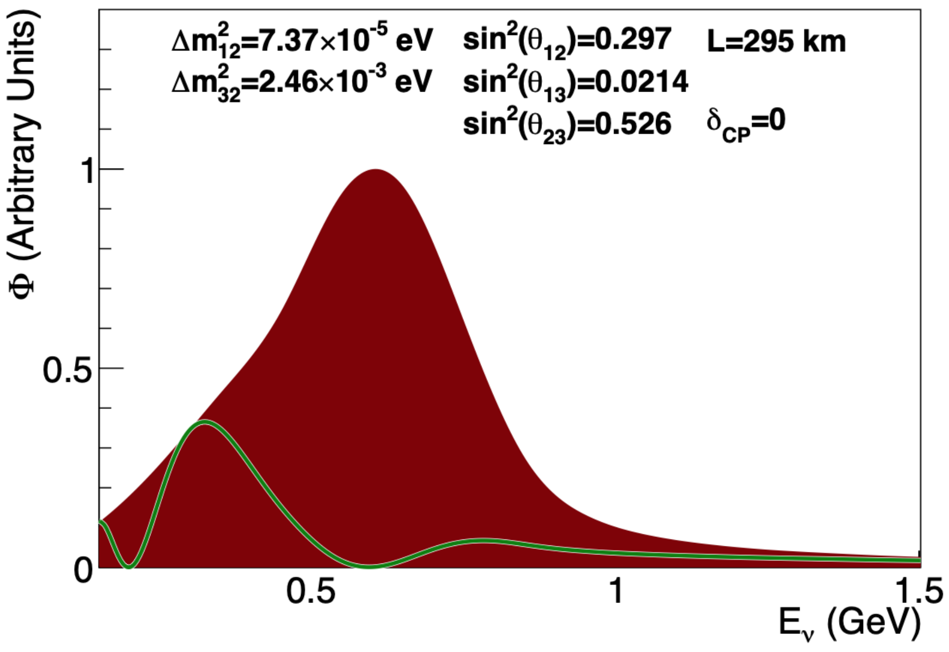


DUNE on-axis beam

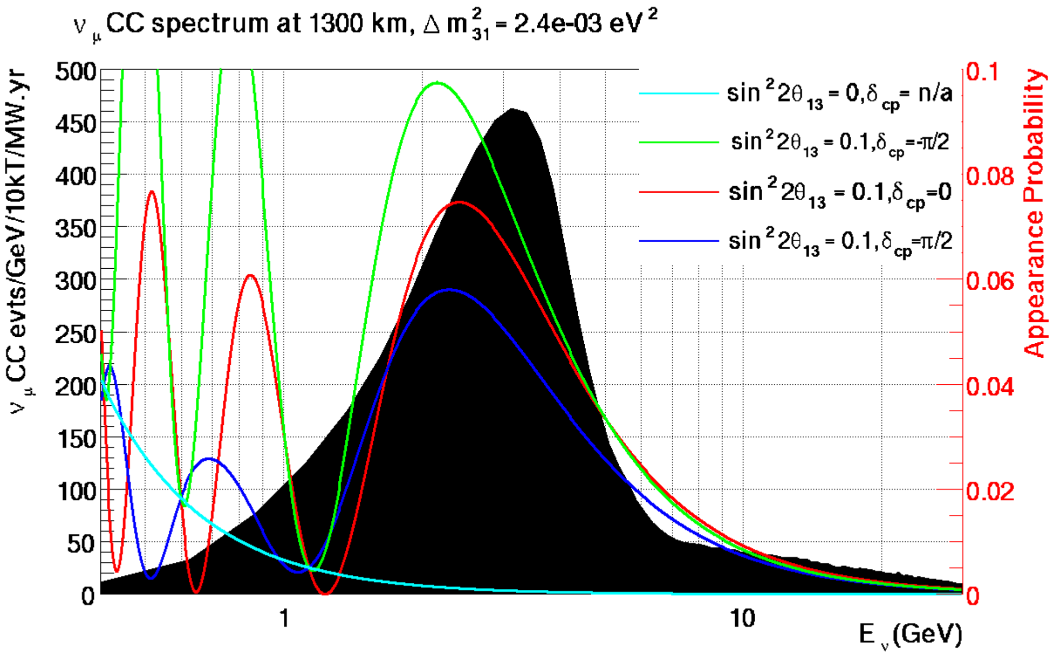


Off-axis vs on-axis beams

T2K at 2.5 degrees



DUNE on-axis beam



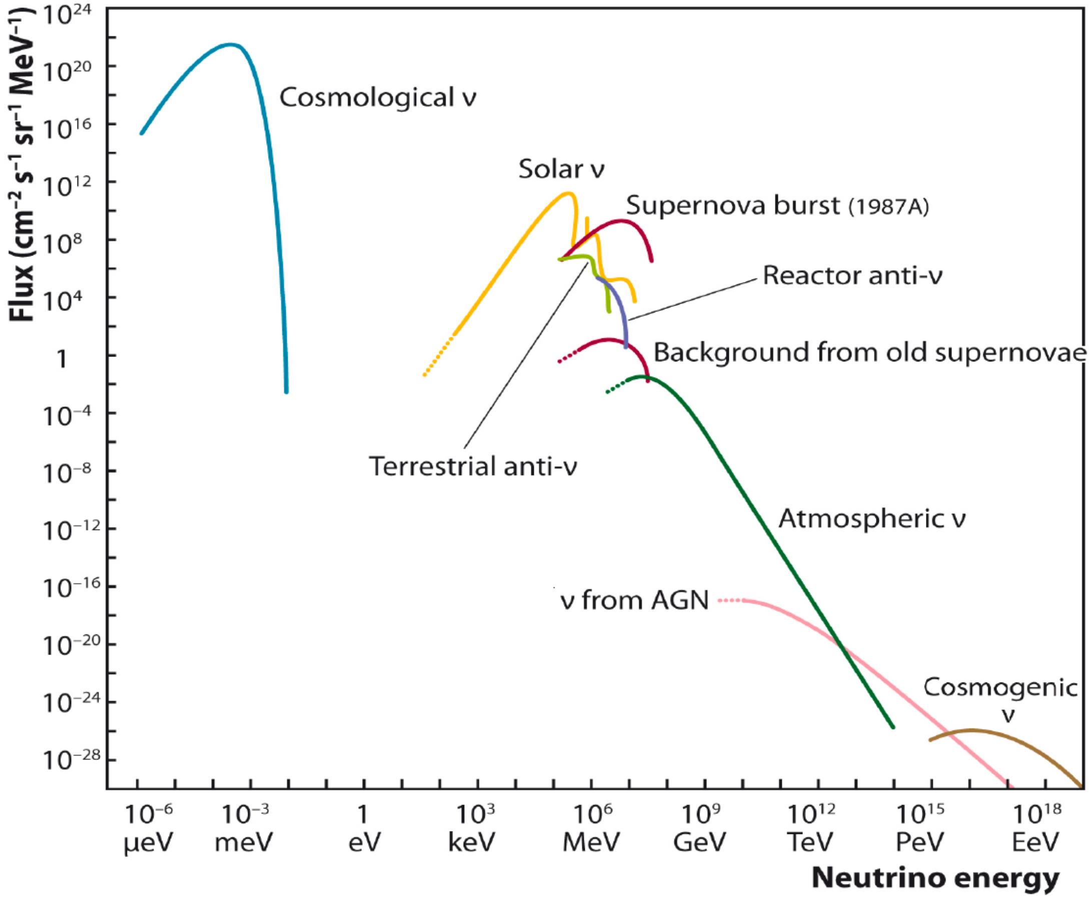
How to measure LBL neutrino oscillations

- Measure flavour change as a function of energy over a long distance.
- Starting with a muon-neutrino beam, we observe muon-neutrino disappearance and electron-neutrino appearance.
- We measure event rates and not the flux directly.
- Measurement is a convolution of the oscillation probabilities *P*, the neutrino flux Φ, the cross sections σ, and the detector response *T*.

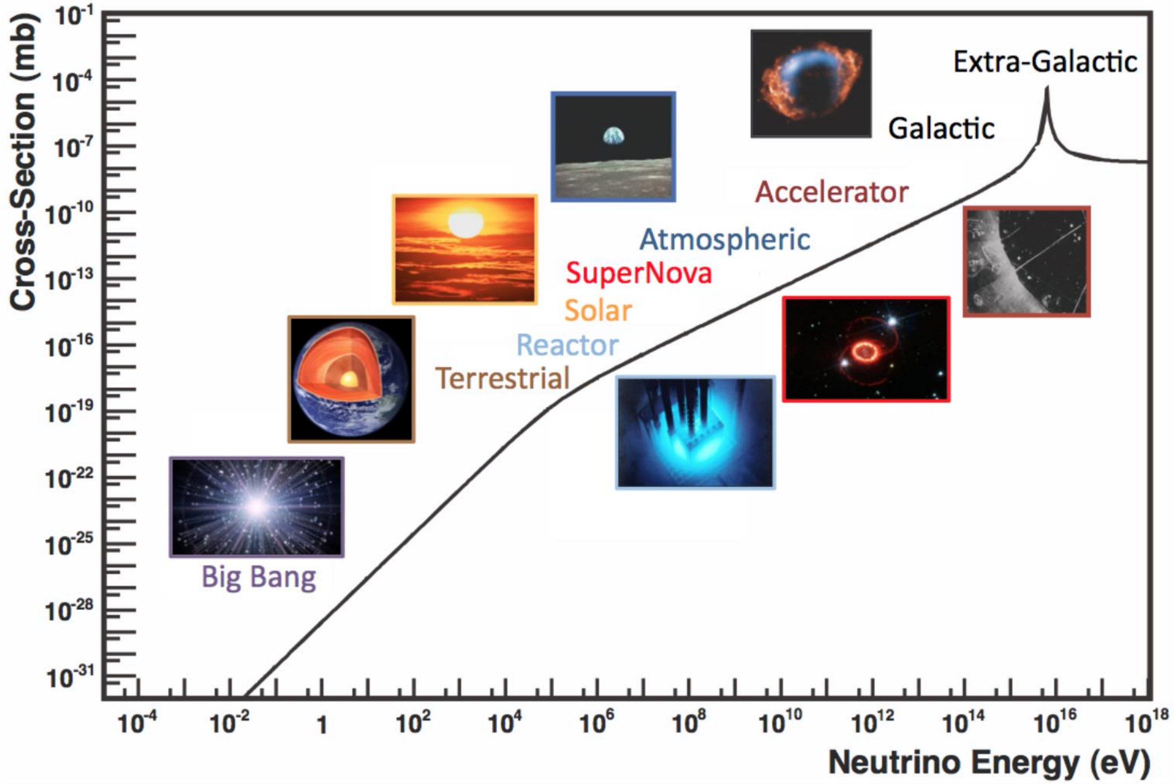
$$\frac{N^{FD}_{\nu_\mu}}{N^{ND}_{\nu_\mu}}(E_{rec}) = \frac{\int \Phi^{FD}_{\nu_\mu}(E_\nu) \cdot P_{\nu_\mu \to \nu_x}(E_\nu) \cdot \sigma^{Ar}_{\nu_x} \cdot T^{FD}_{\nu_x}(E_\nu, E_{rec})\, dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma^{X}_{\nu_\mu} \cdot T^{ND}_{\nu_\mu}(E_\nu, E_{rec})\, dE_\nu}$$

Neutrino sources, flux, and cross sections

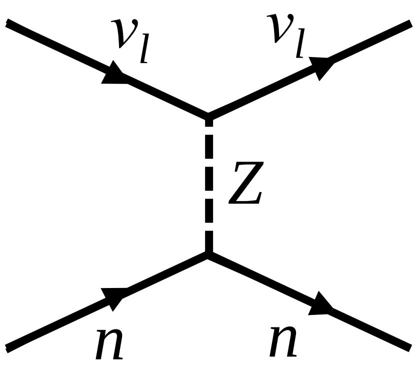
C. Spiering, arXiv:1207.4952



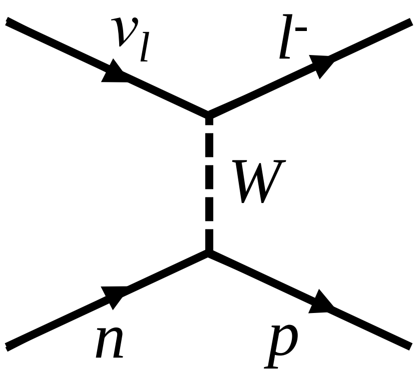
J. Formaggio, G.P. Zeller, arXiv:1305.7513



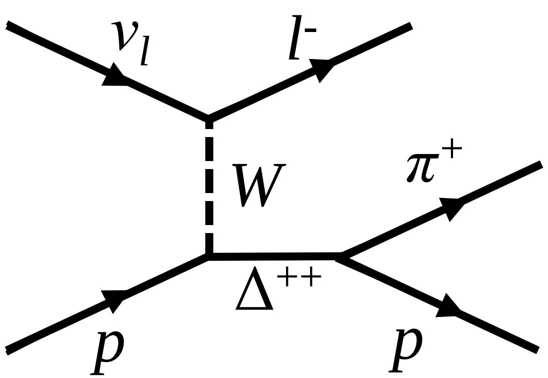
Neutrino-nucleon interaction



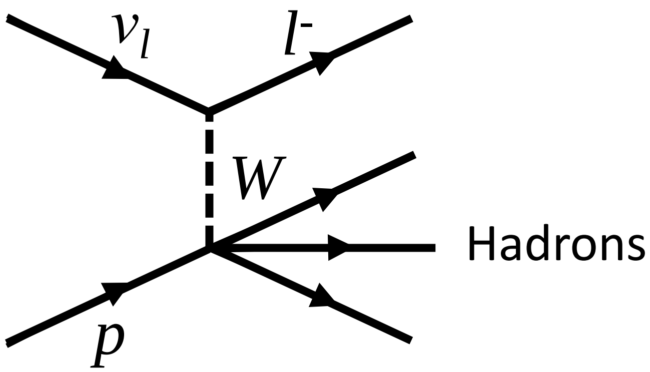
Elastic scattering



Quasi-elastic scattering
(lowest energies)



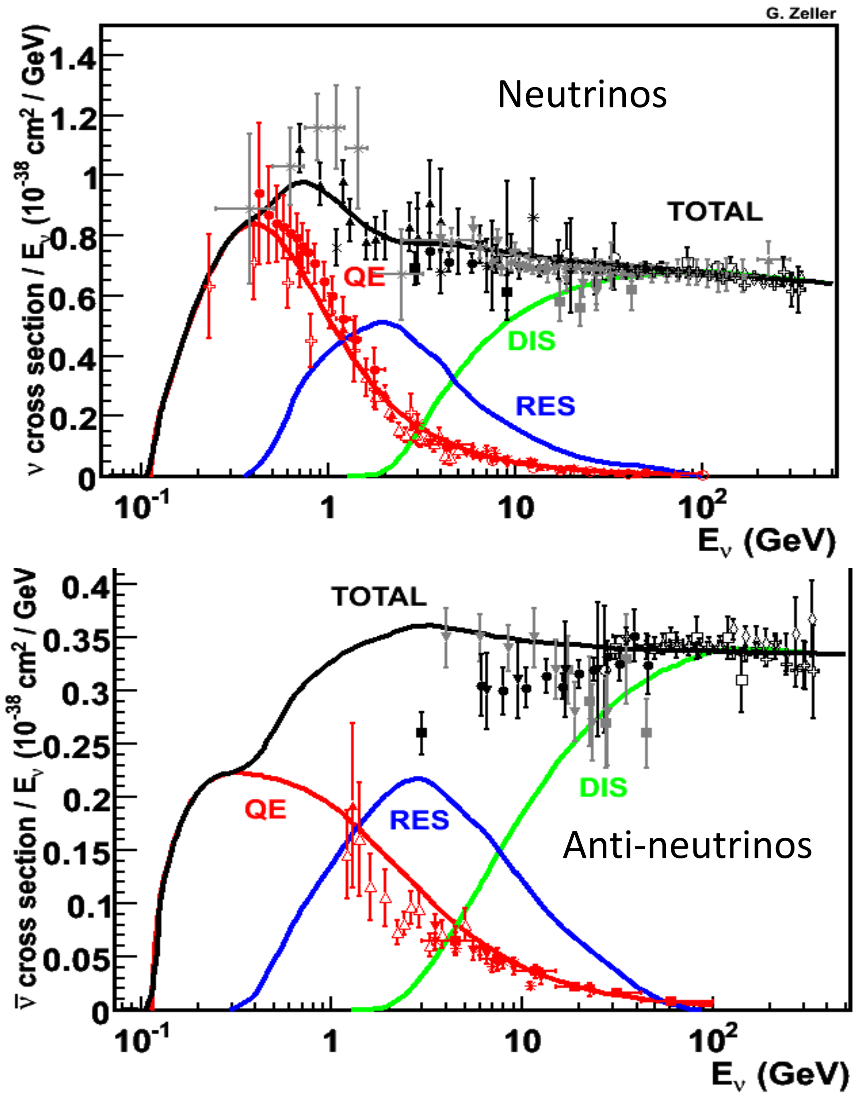
Resonance
(Energies ~1 GeV)



Deep inelastic scattering
Highest energies (>1 GeV)

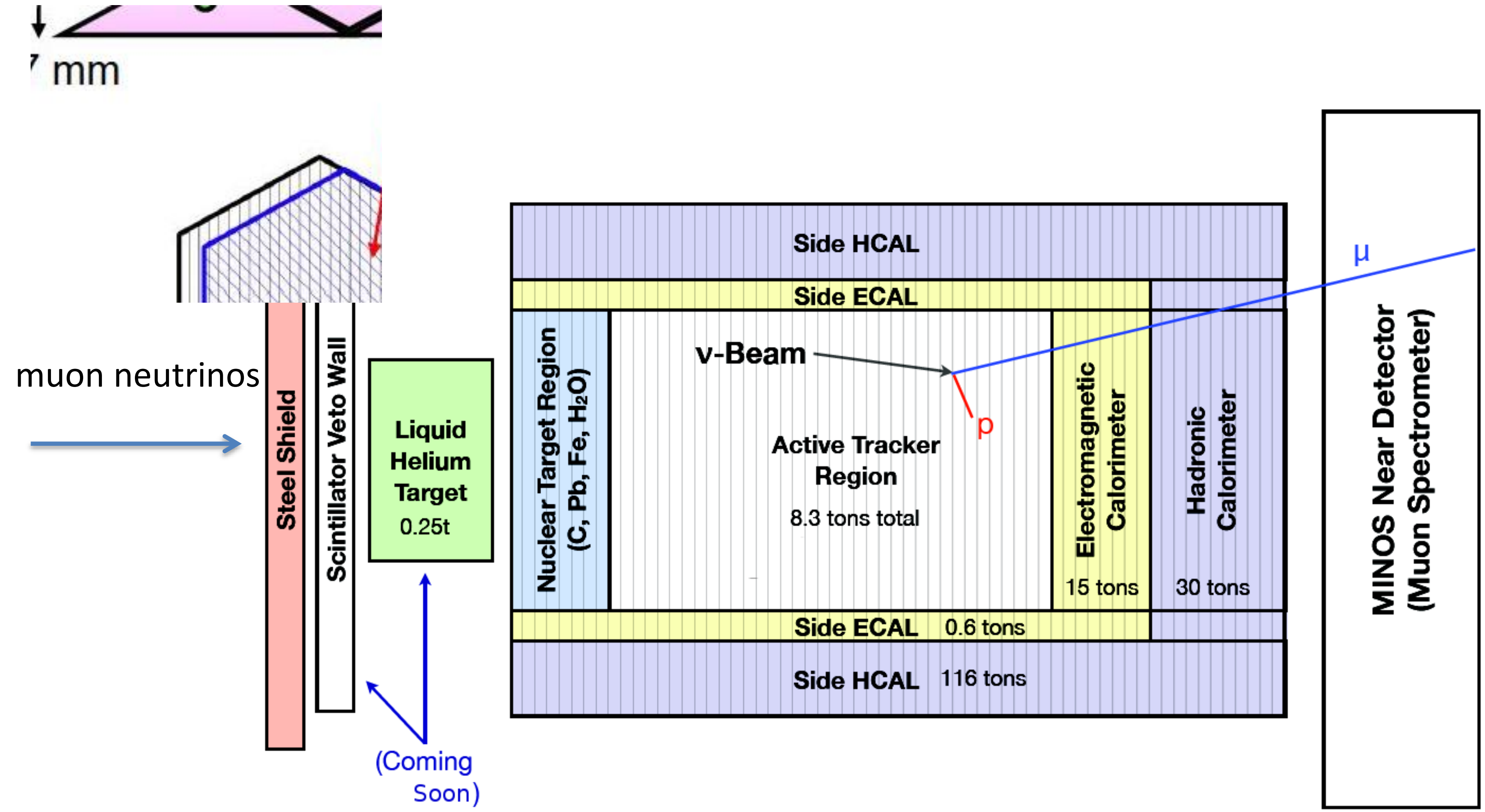
Neutrino-nucleon interactions and cross sections

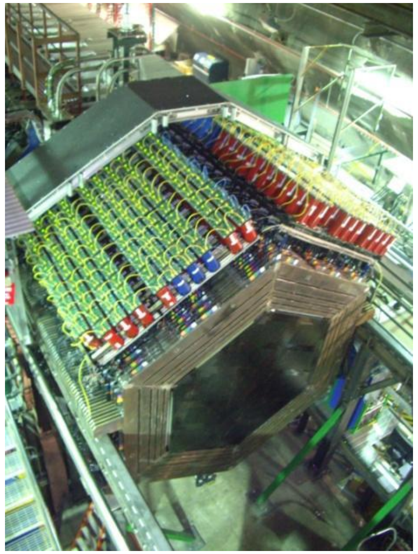
Muon neutrino data



- At lower energies, quasi-elastic dominates.
- At higher energies, resonance production and deep-inelastic scattering
- An important systematic limitation for long-baseline neutrino experiments
- Interaction modelling will affect energy reconstruction.

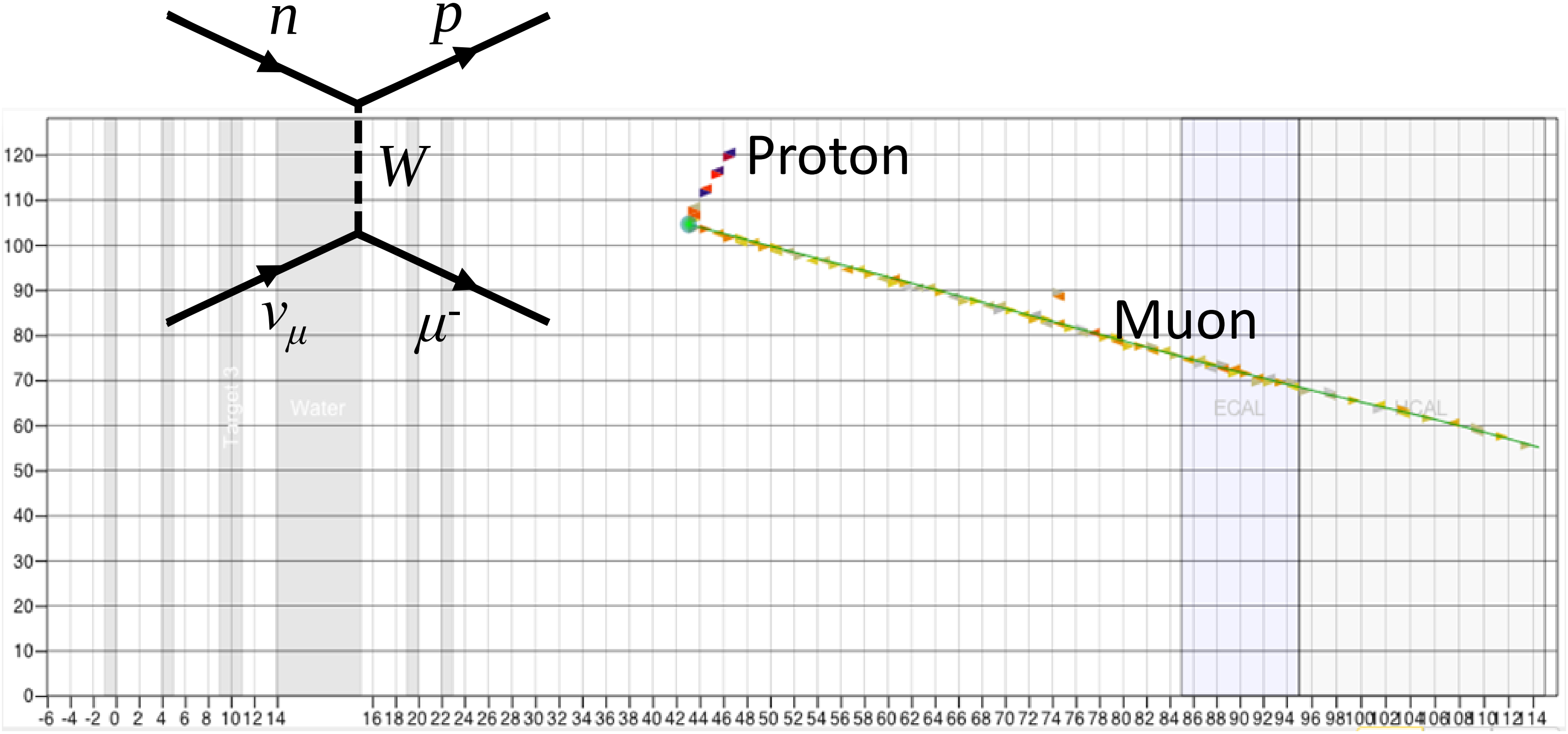
Measuring neutrino cross sections with MINERνA





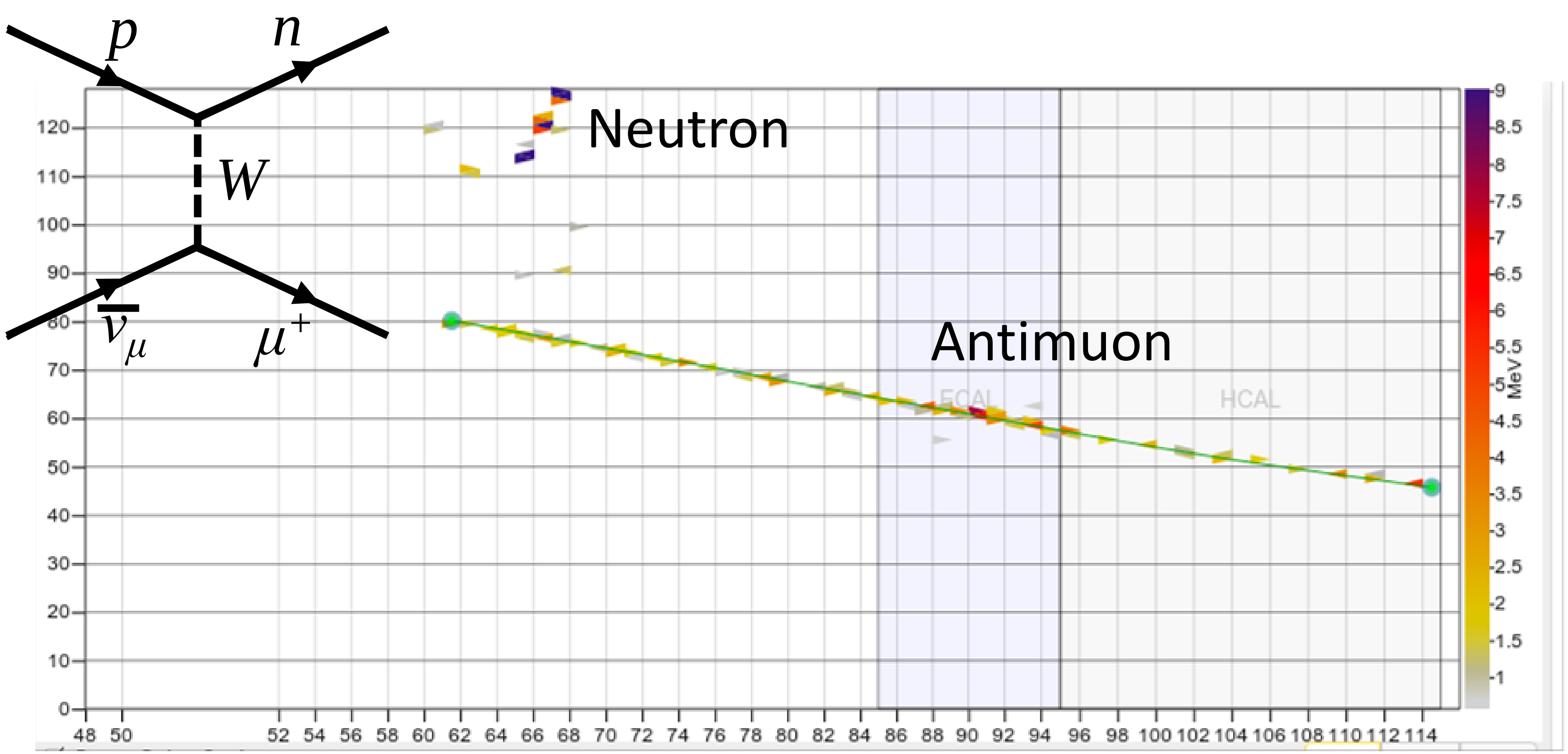
MINERνA ν_μ quasi-elastic interaction

Quasielastic scattering

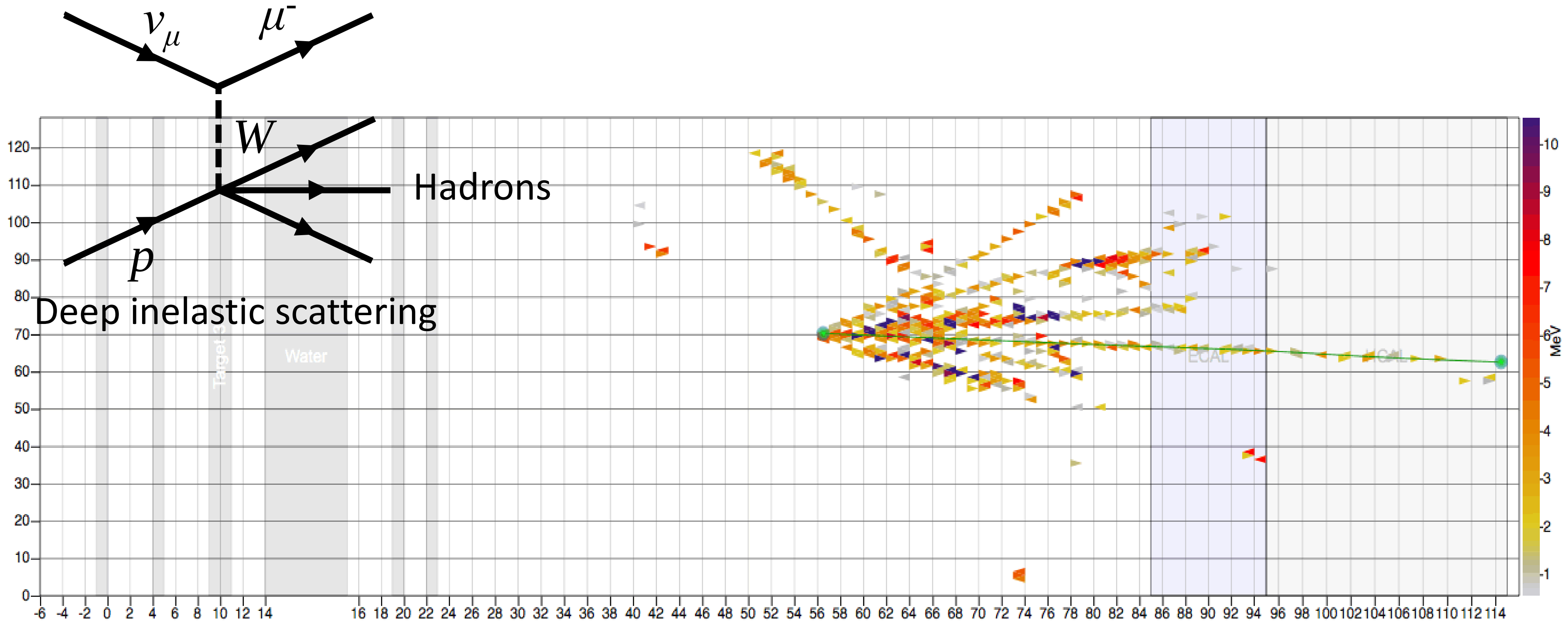


MINERνA $\bar{\nu}_\mu$ quasi-elastic interaction

Quasielastic scattering

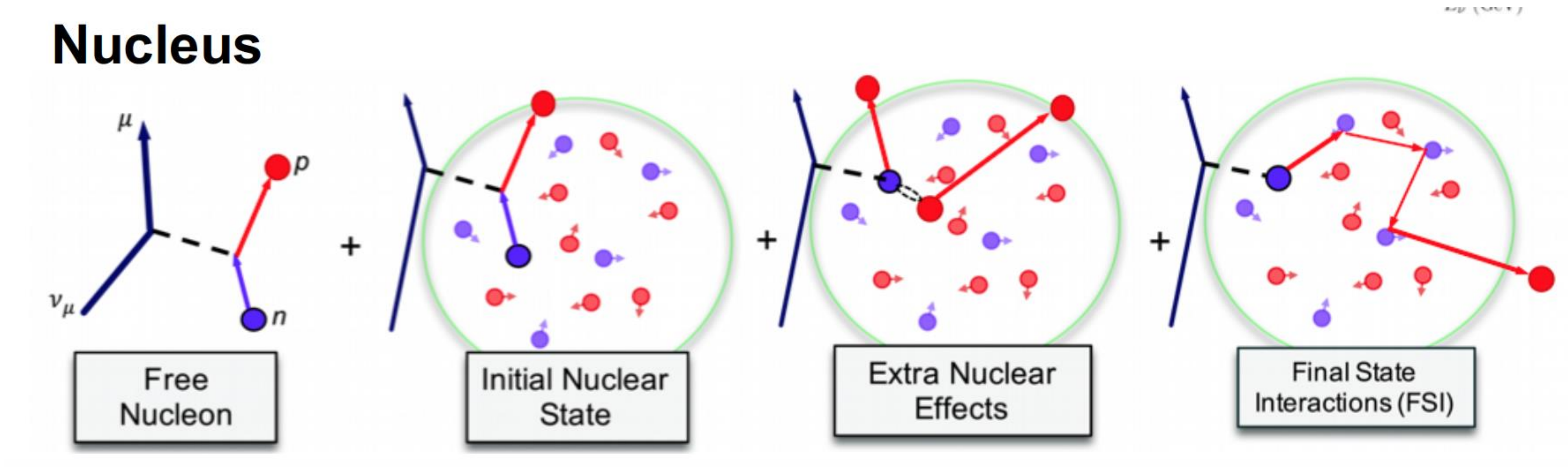


MINERνA deep inelastic scattering event



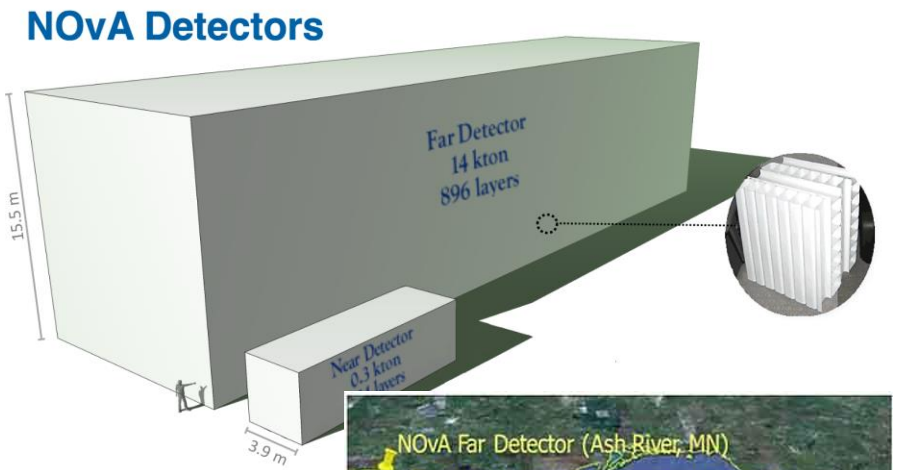
Another Complication

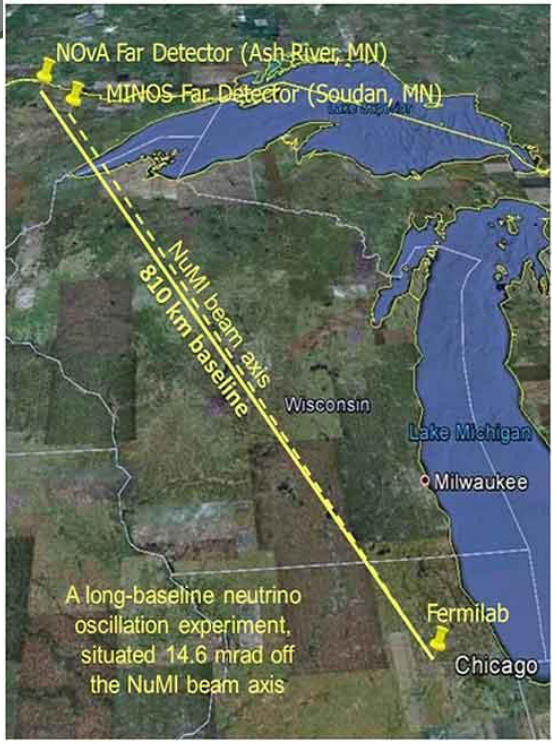
Need to understand nuclear effects – which are messy!



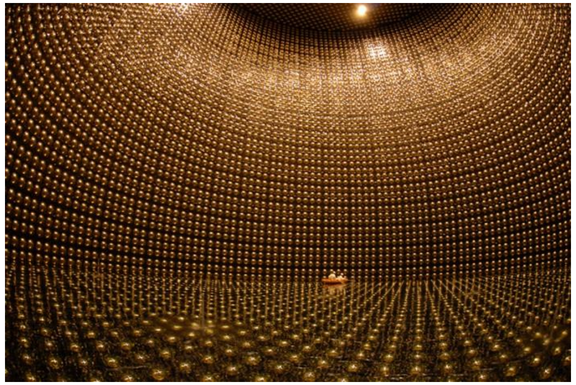
Some effects can be mitigated by use of same nuclear targets

Operating Long-baseline experiments

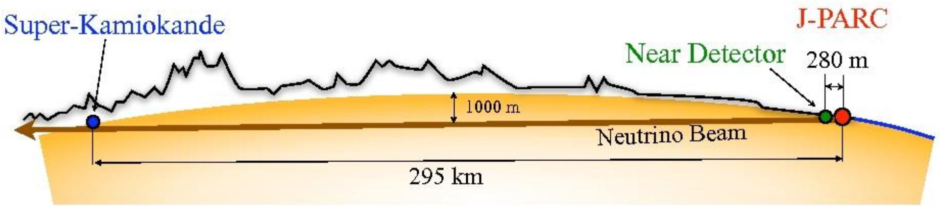


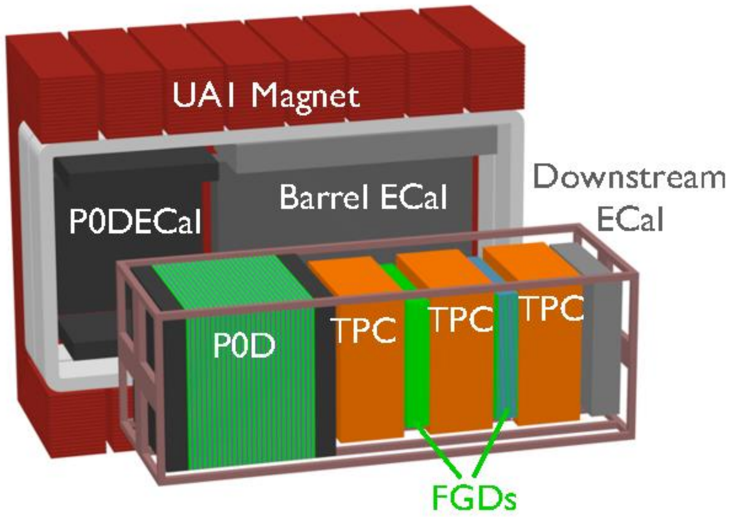


NOvA baseline:
810 km



T2K baseline:
295 km





T2K Experiment

P. Dunne,
Neutrino 2020

- Muon (anti) neutrino beam generated at J-PARC
- Beam travels 295 km to large SK far detector to be measured after oscillations
- Near detector complex, ND280 constrains beam flux and interaction cross-section before oscillation
- Important to constrain non-oscillation parts of model to avoid bias

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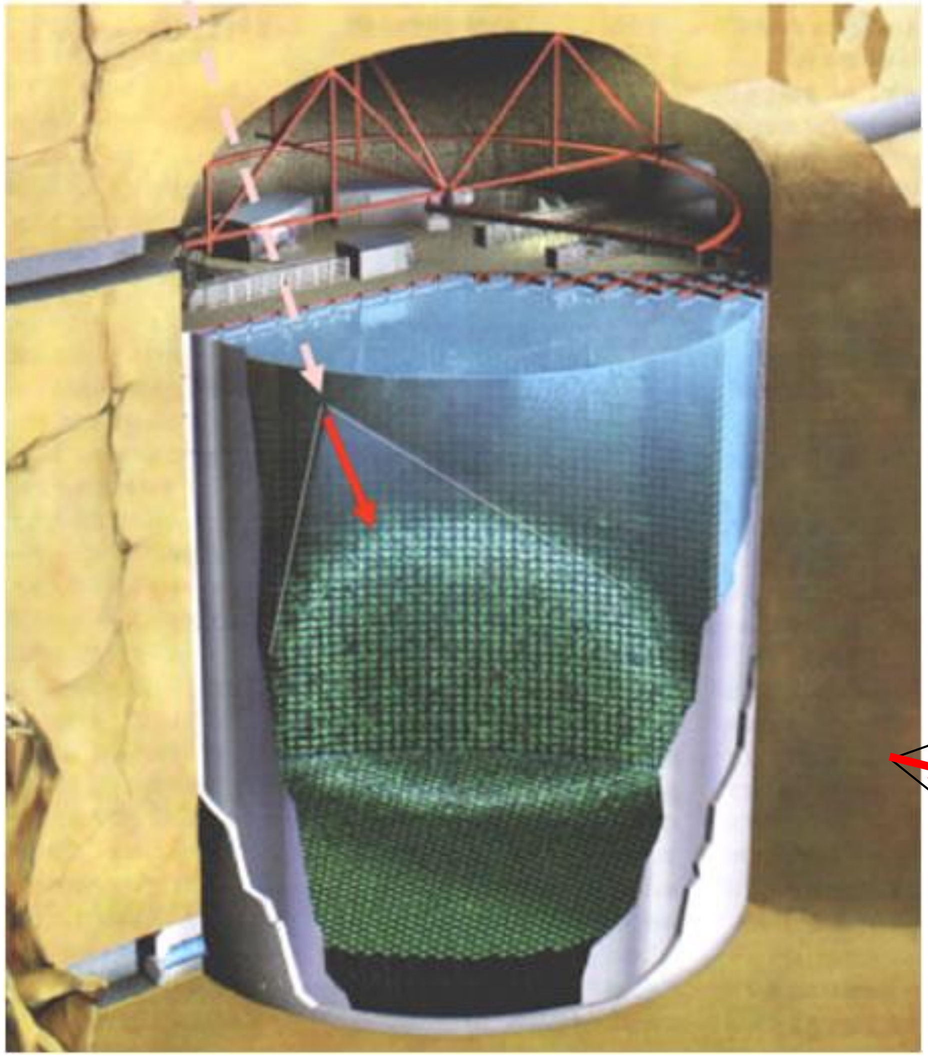
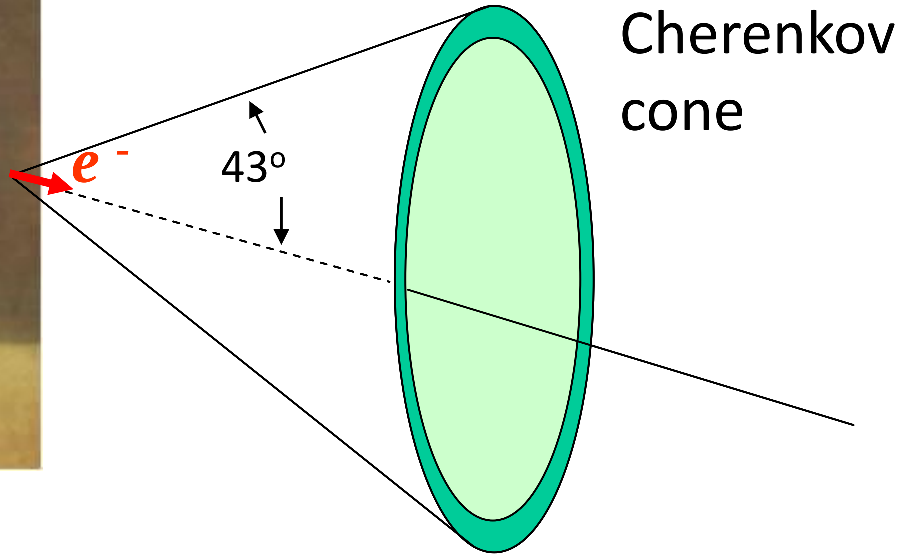
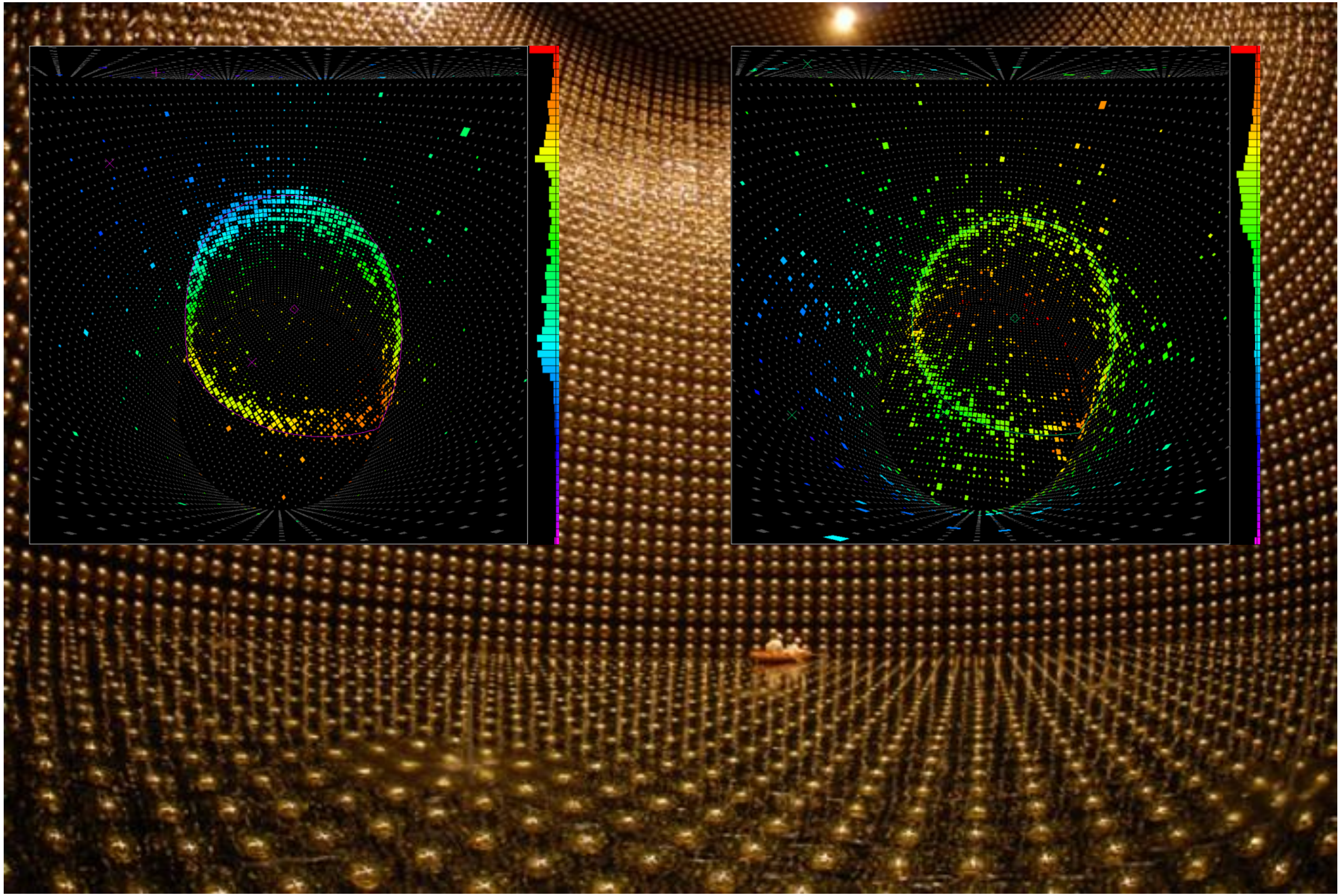
Super-Kamiokande



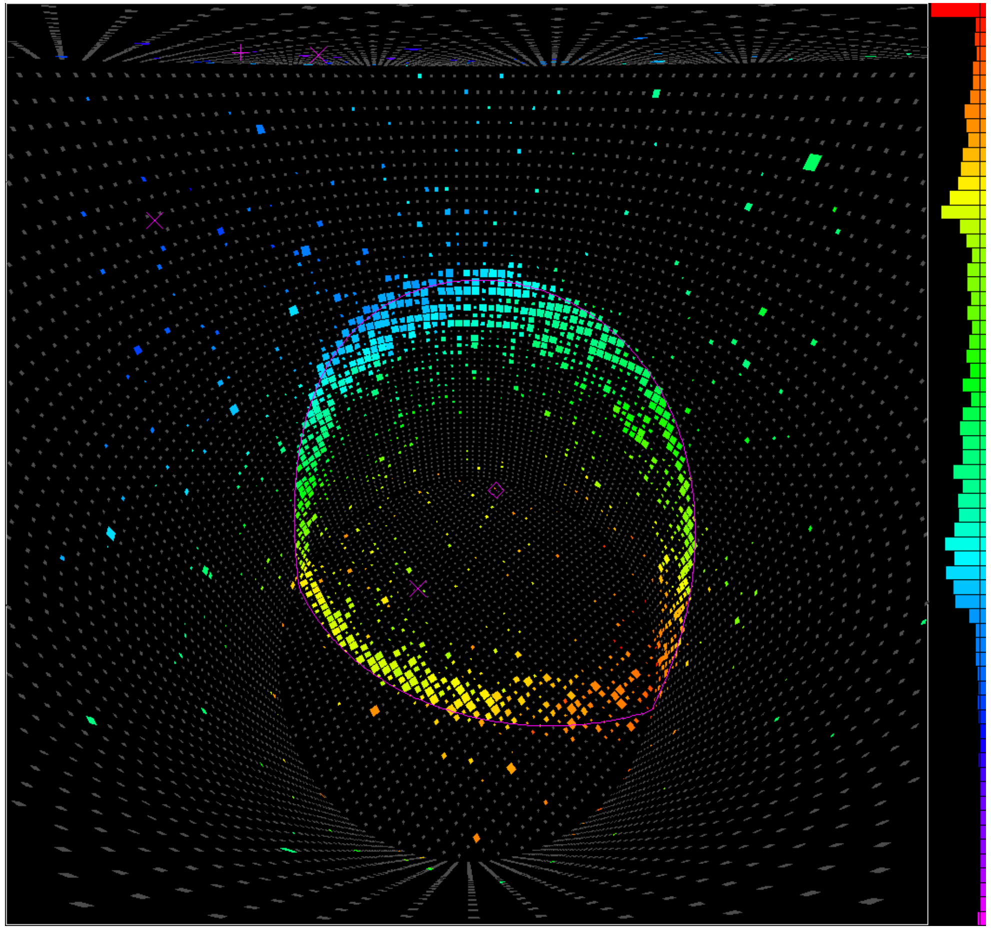
- 50,000 tons of water surrounded by 11,000 PMTs (20 inch).
- 1 km rock overburden
- 39.3m in diameter and 41.4m in height

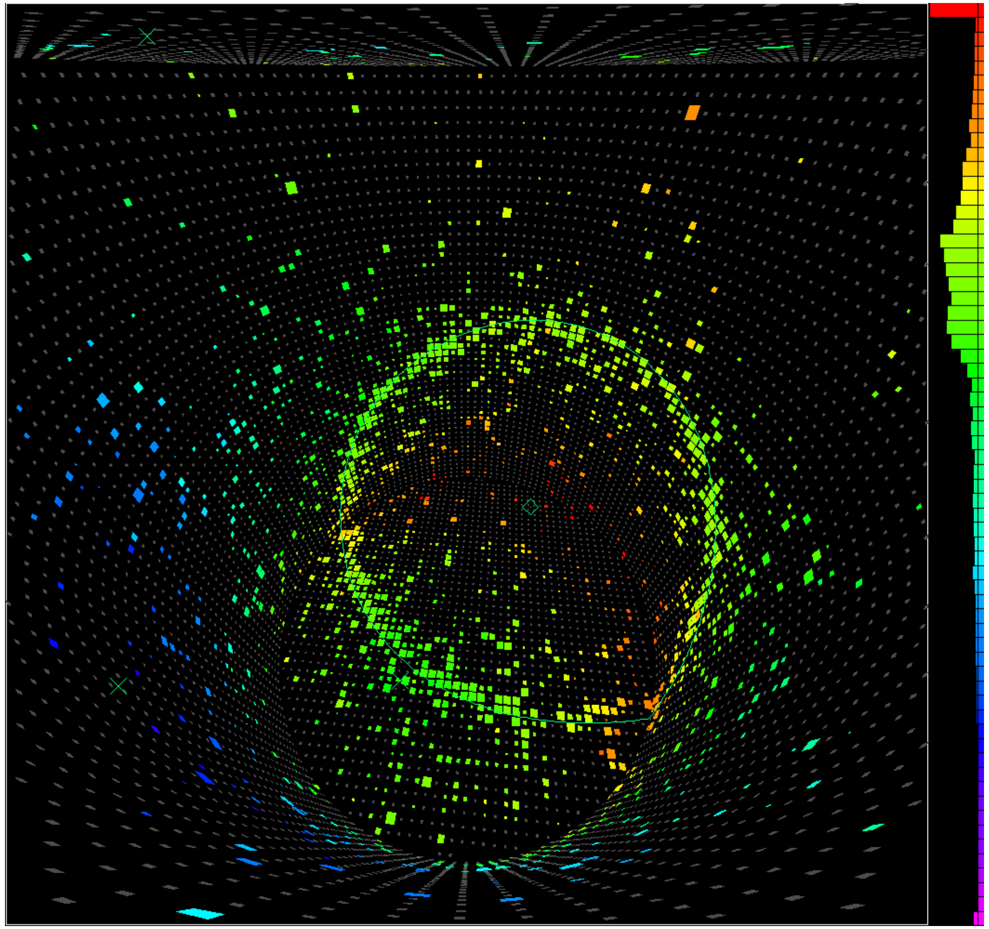


Super-Kamiokande – electron or muon ring?



Super-Kamiokande – electron or muon ring?



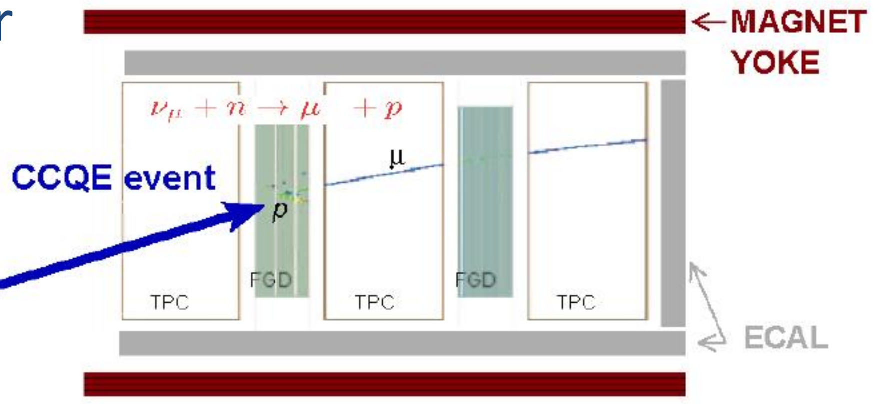


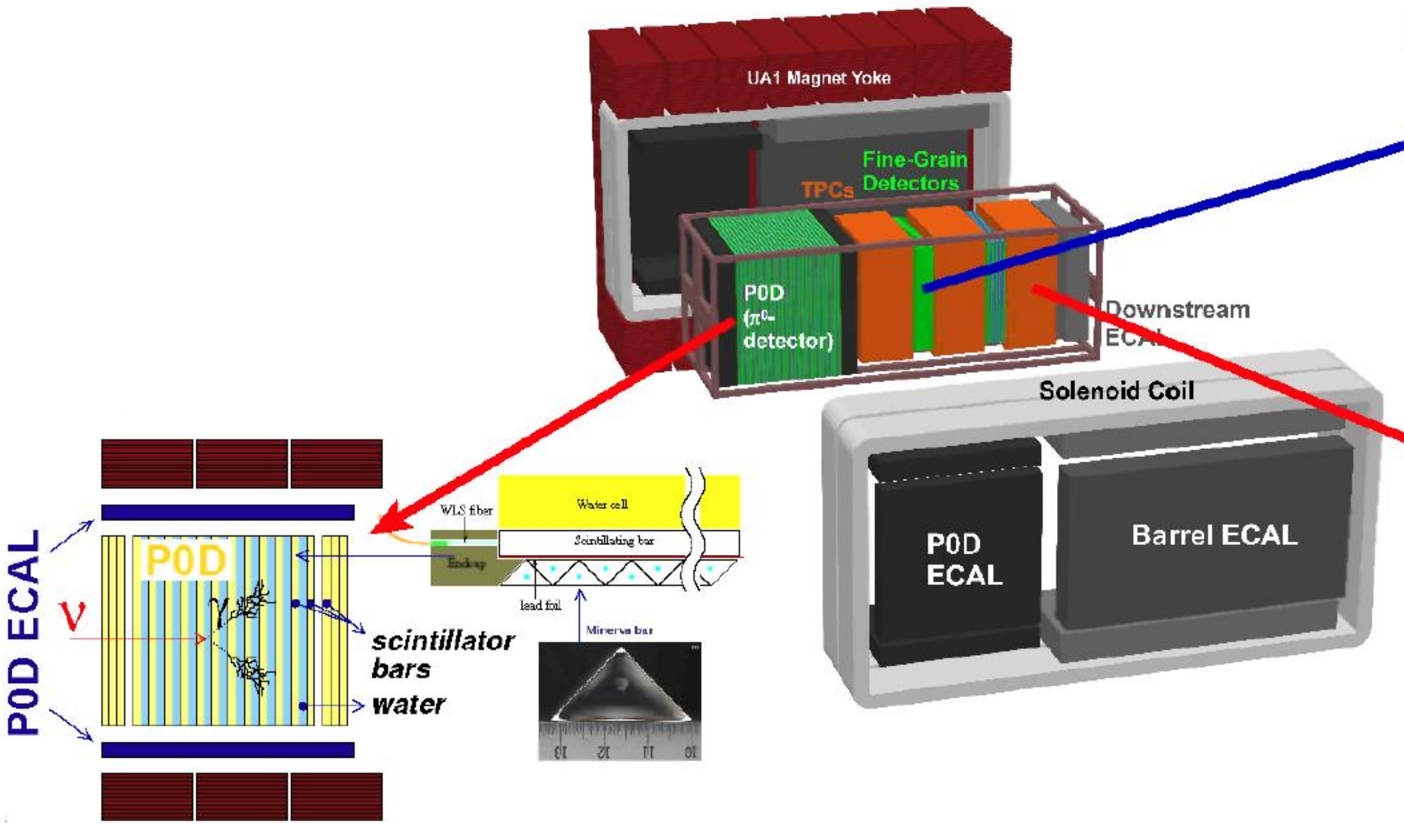
$$\nu_\mu + X \to \mu^- + X'$$

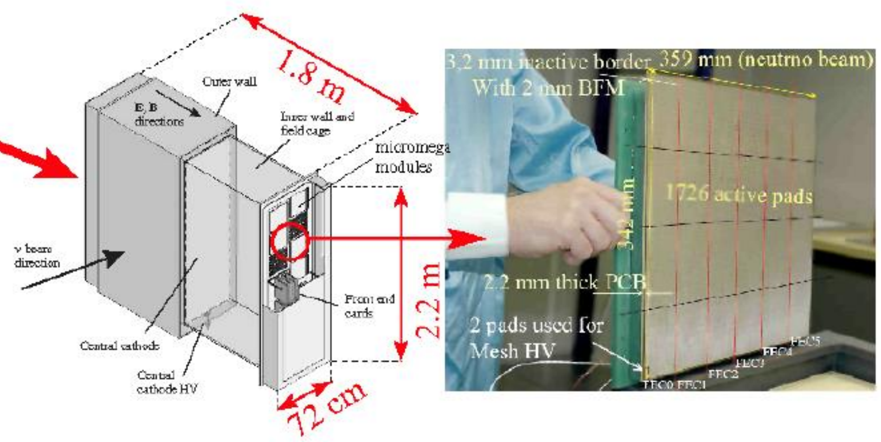
$$\nu_e + X \to e^- + X'$$

The T2K Near Detector (ND280)

Different technology/target for near and far detector







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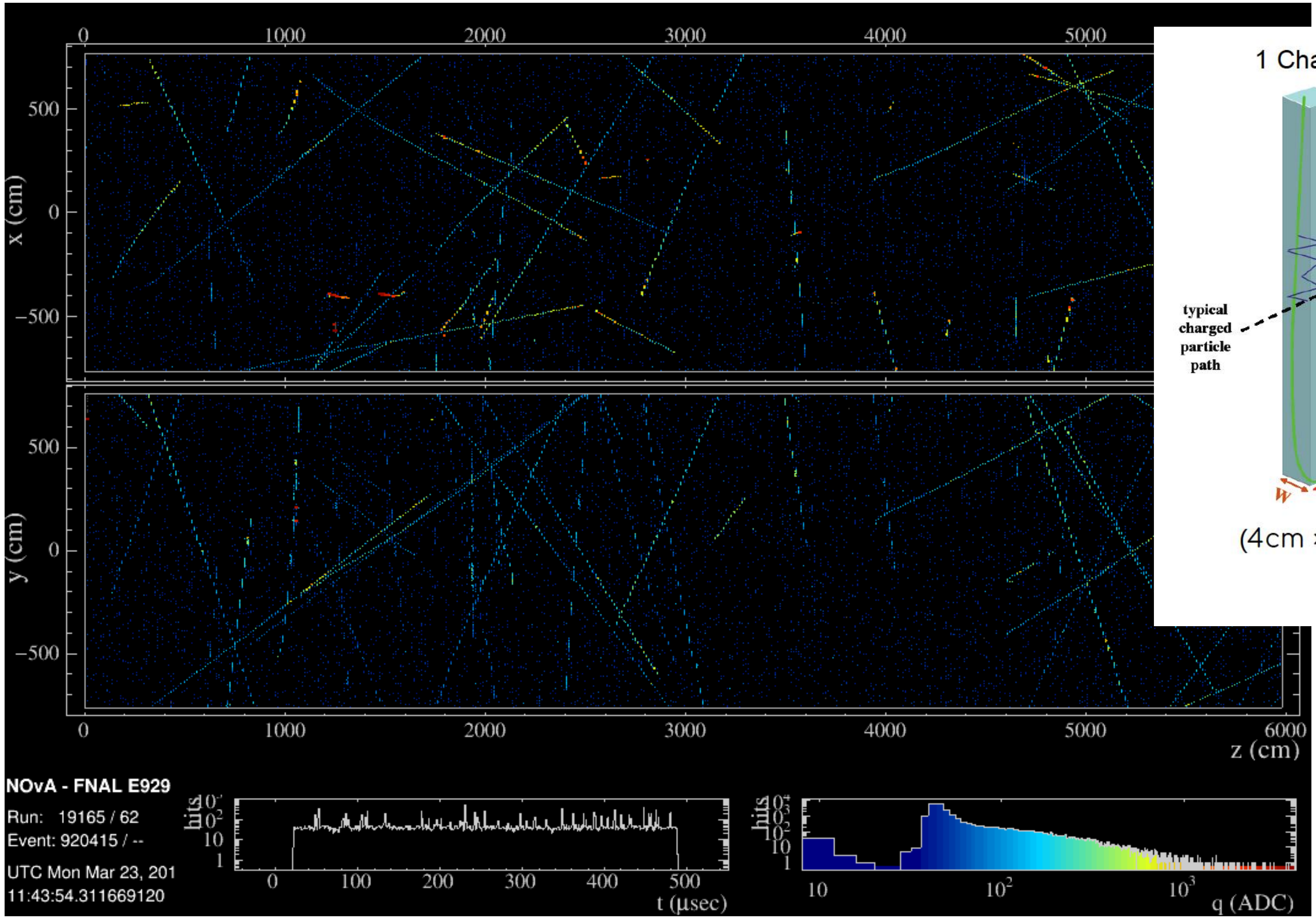
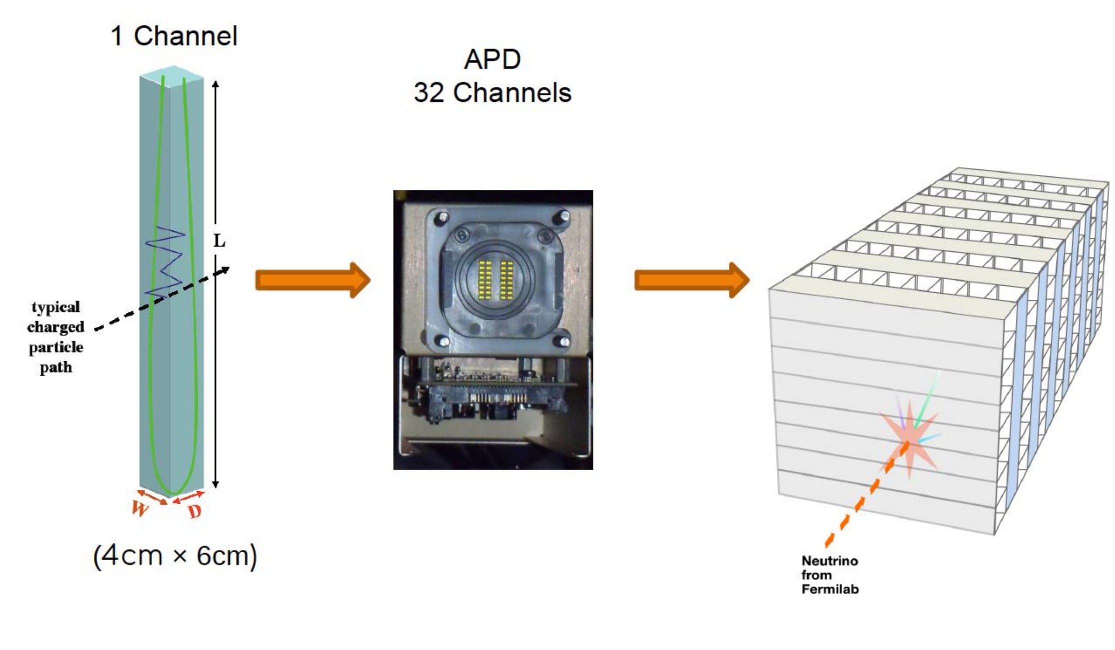
NOvA Experiment

- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

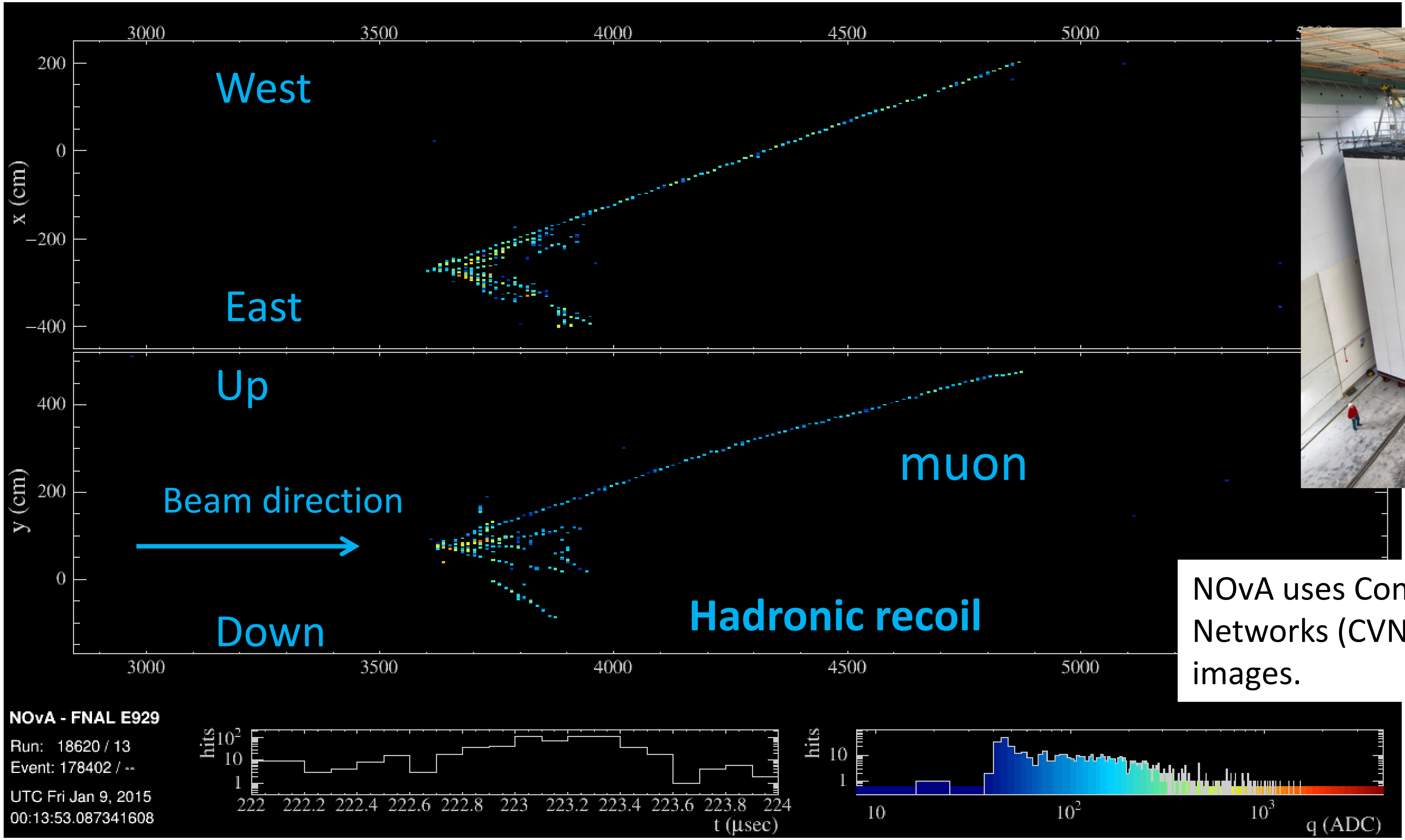
NOvA is on the surface..





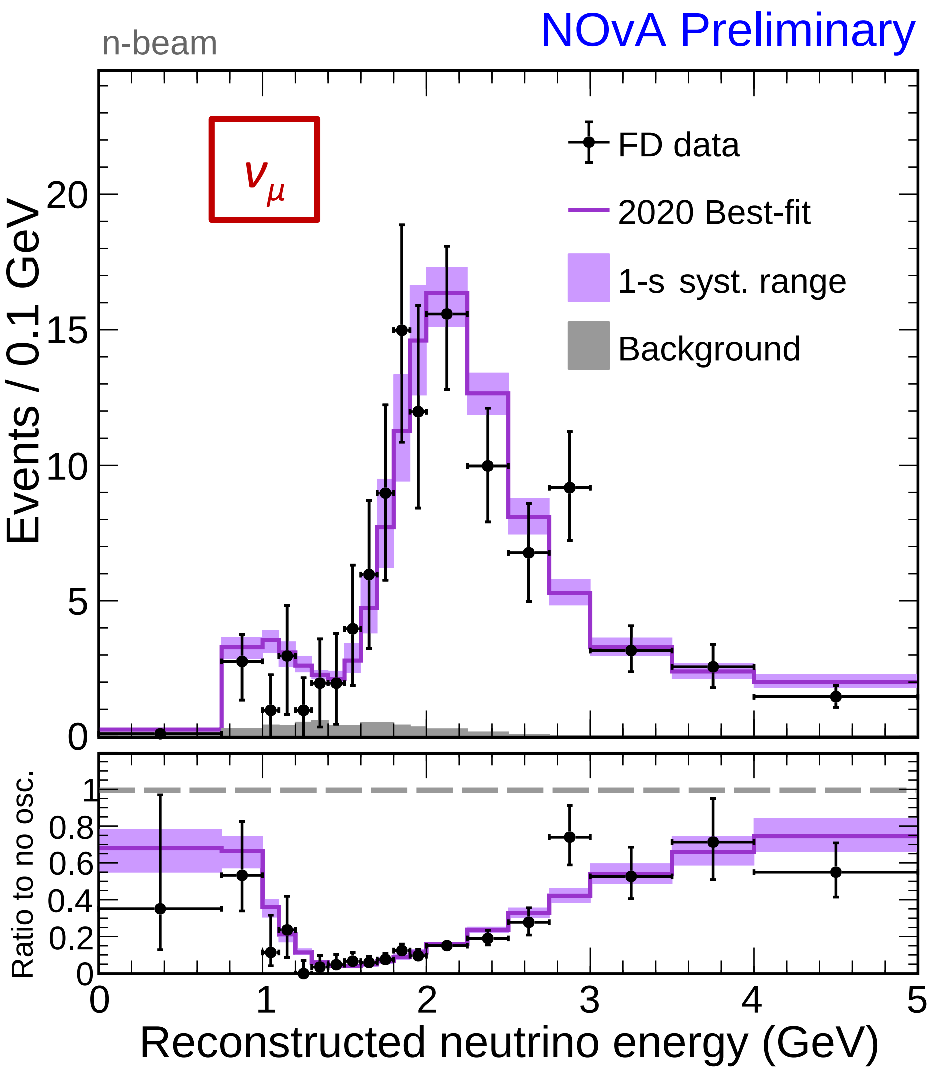
- 14 kt Far Detector
- Equivalent Near Detector
- Liquid scintillator (oil)
- Readout by APDs

NOvA Detector

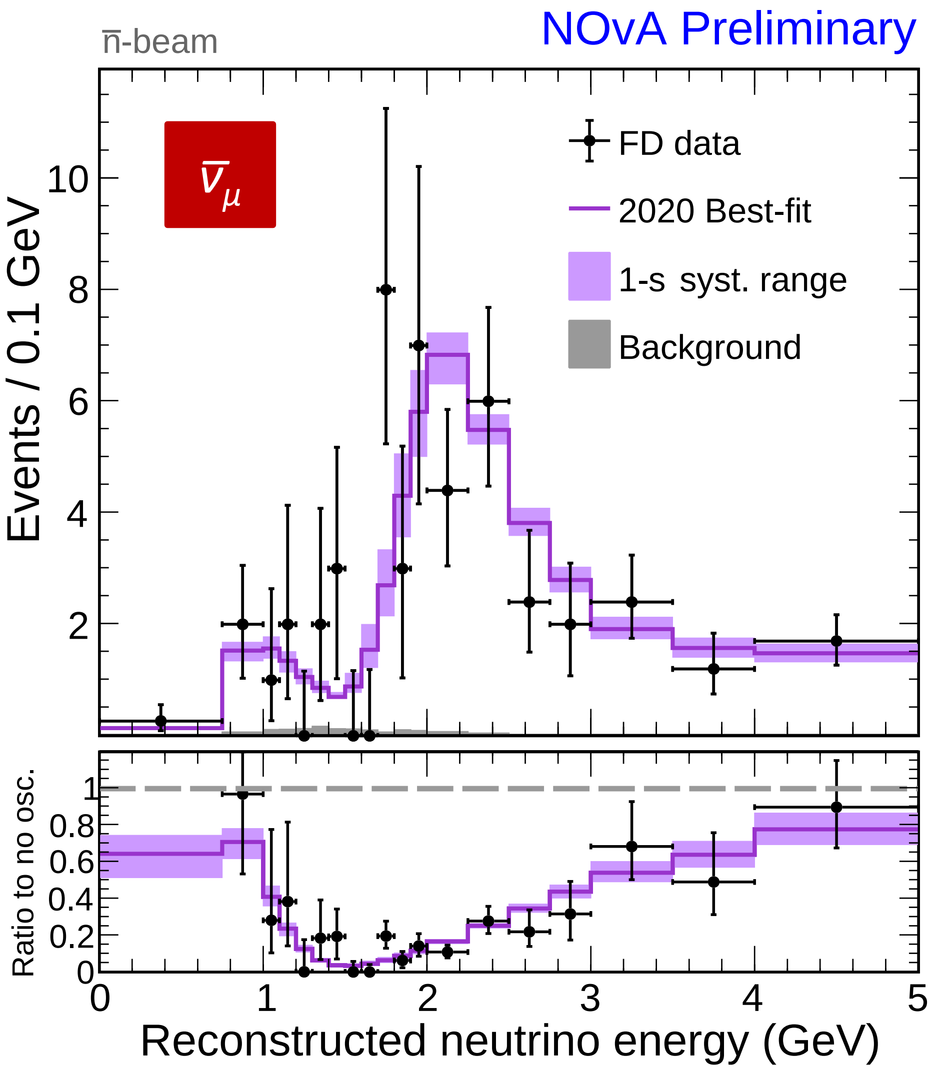


NOvA uses Convolutional Neural Networks (CVNs) to reconstruct images.

ν_μ and $\bar{\nu}_\mu$ disappearance at the NOvA Far Detector



211 events, 8.2 background



105 events, 2.1 background

Alex Himmel, Neutrino 2020

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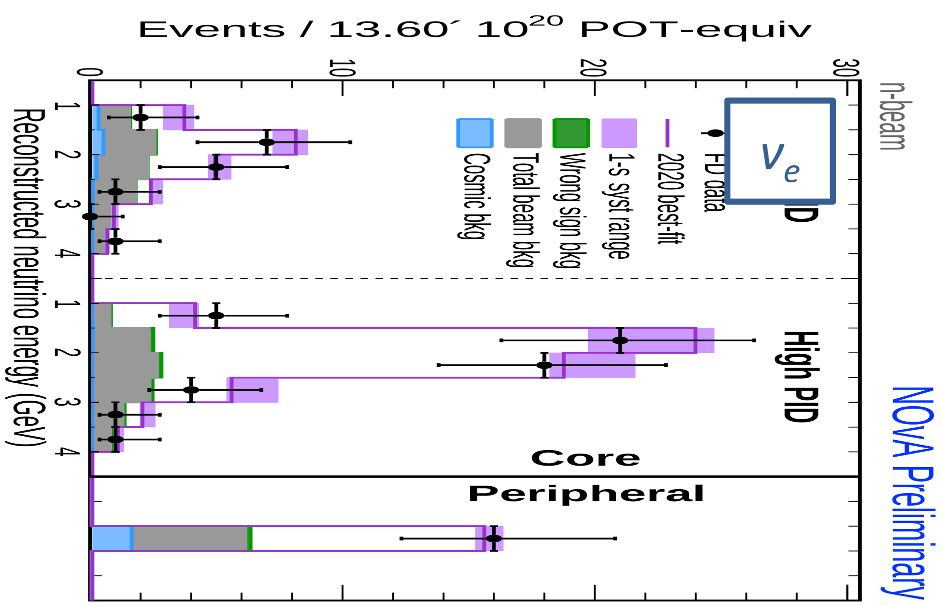
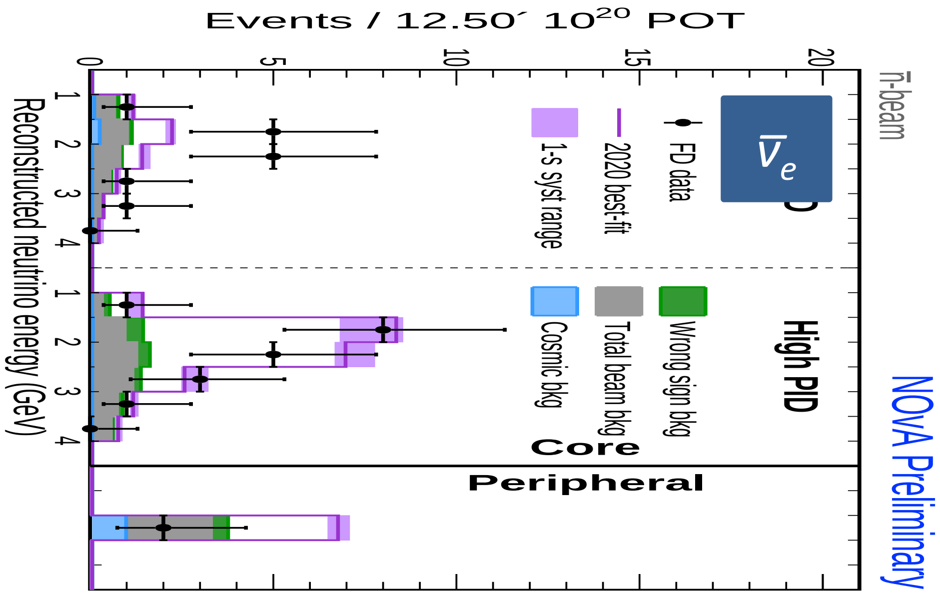
ν_e and $\bar{\nu}_e$ appearance at the NOvA Far Detector





Total Observed	82	Range
Total Prediction	85.8	52-110
Total Bkgd.	26.8	26-28

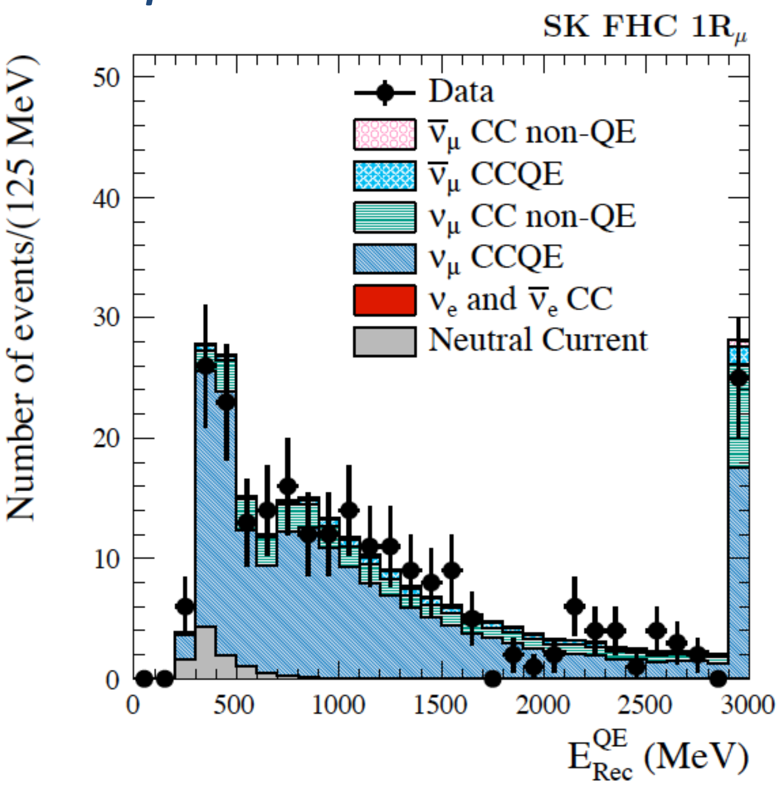
Total Observed	33	Range
Total Prediction	33.2	25-45
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance

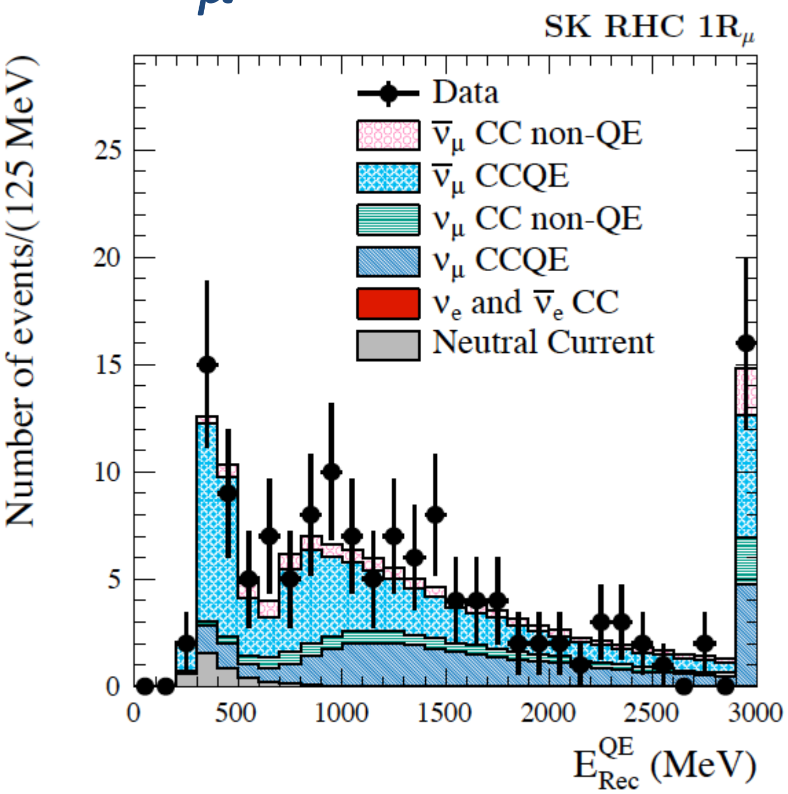
Alex Himmel,
Neutrino 2020

ν_μ and $\bar{\nu}_\mu$ disappearance at the T2K Far Detector (SK)

ν_μ



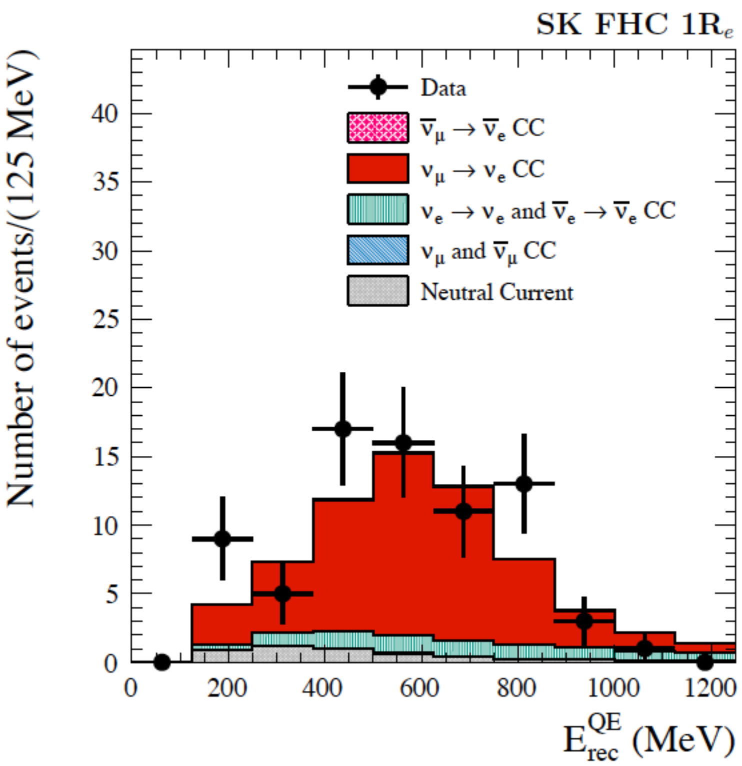
$\bar{\nu}_\mu$



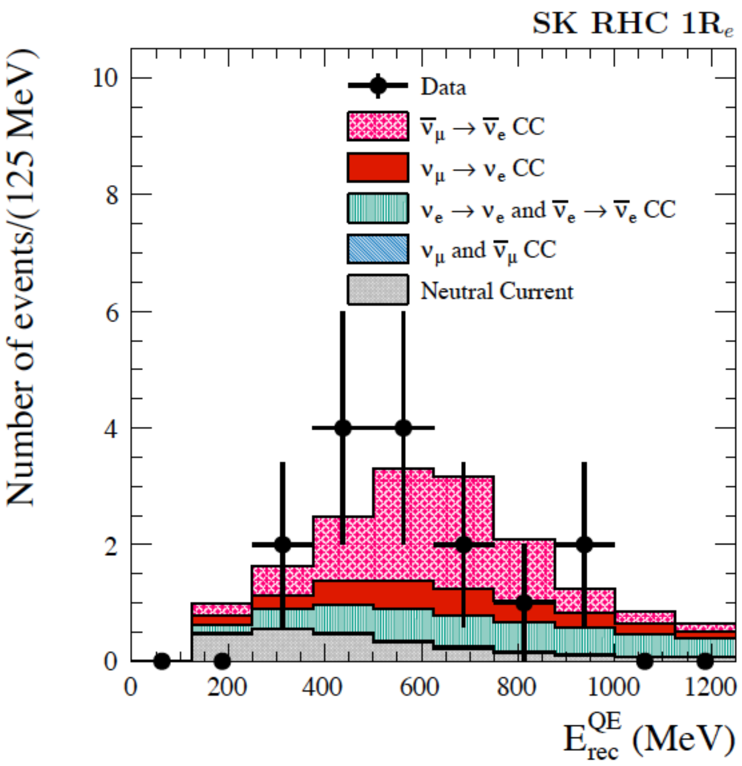
Muon-like rings

ν_e and $\bar{\nu}_e$ appearance at the T2K Far Detector (SK)

ν_e



$\bar{\nu}_e$



electron-like rings (0 π^0)

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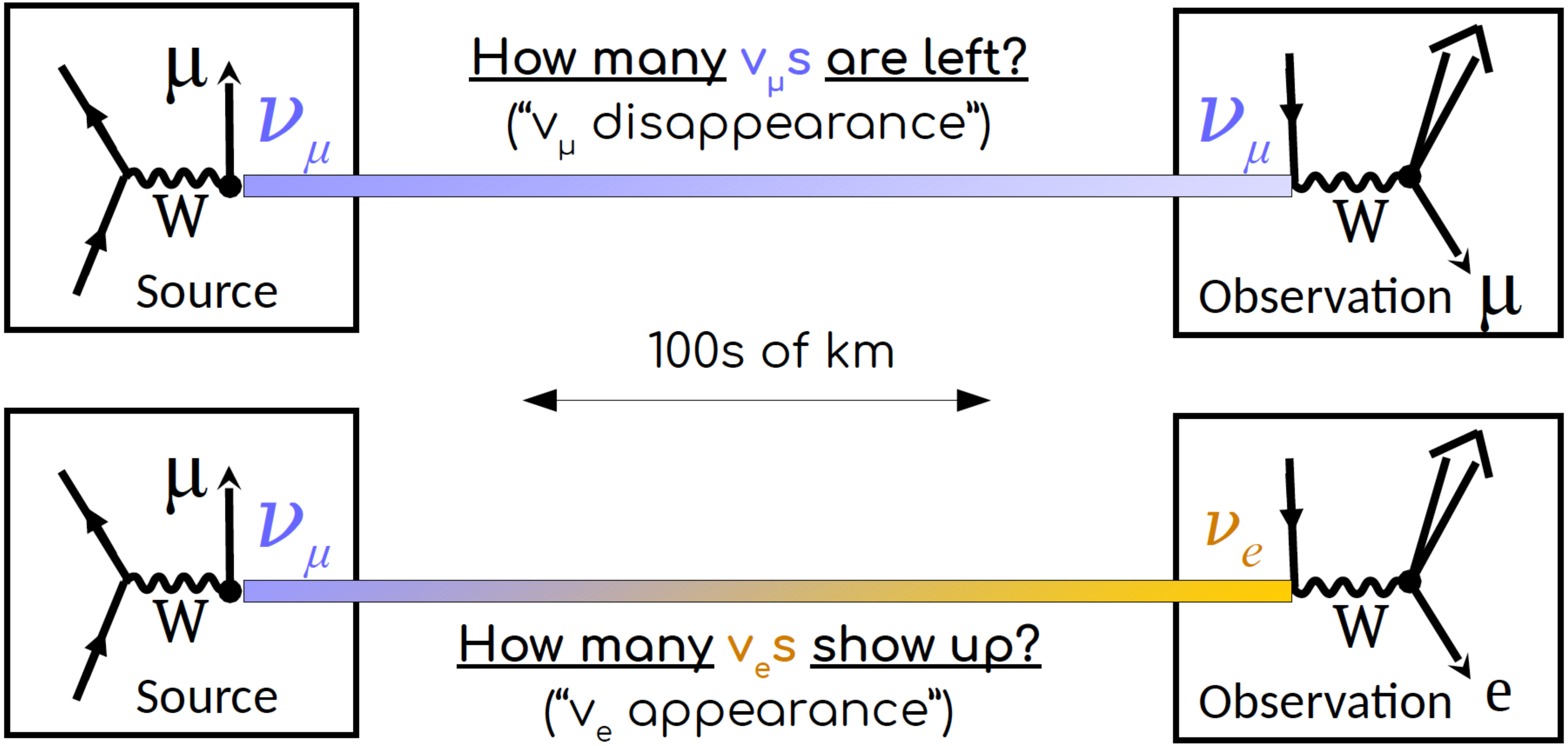
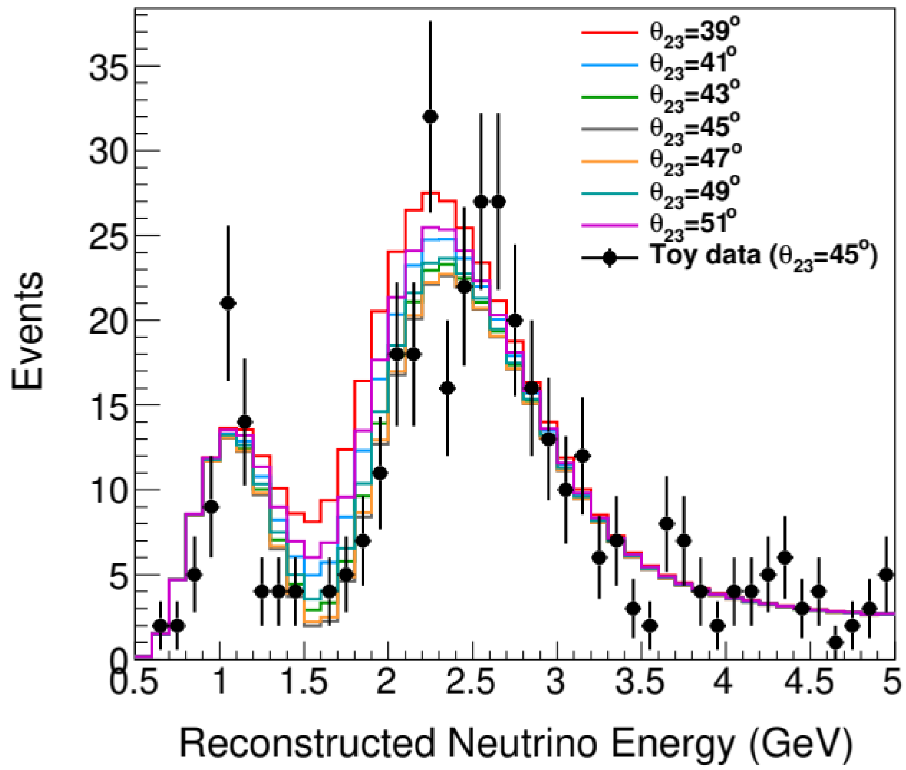
Extracting the Information



J. Wolcott

Extracting the Information



Simultaneous fits of

- Data samples in Near and Far Detector
- Flux model, incl. beam monitor and hadron production (NA61-SHINE)
- Cross section models
- Detector models for Near and Far Detector
- Error correlation matrix
- Oscillations Parameters

J. Wolcott

To give you a “flavour”

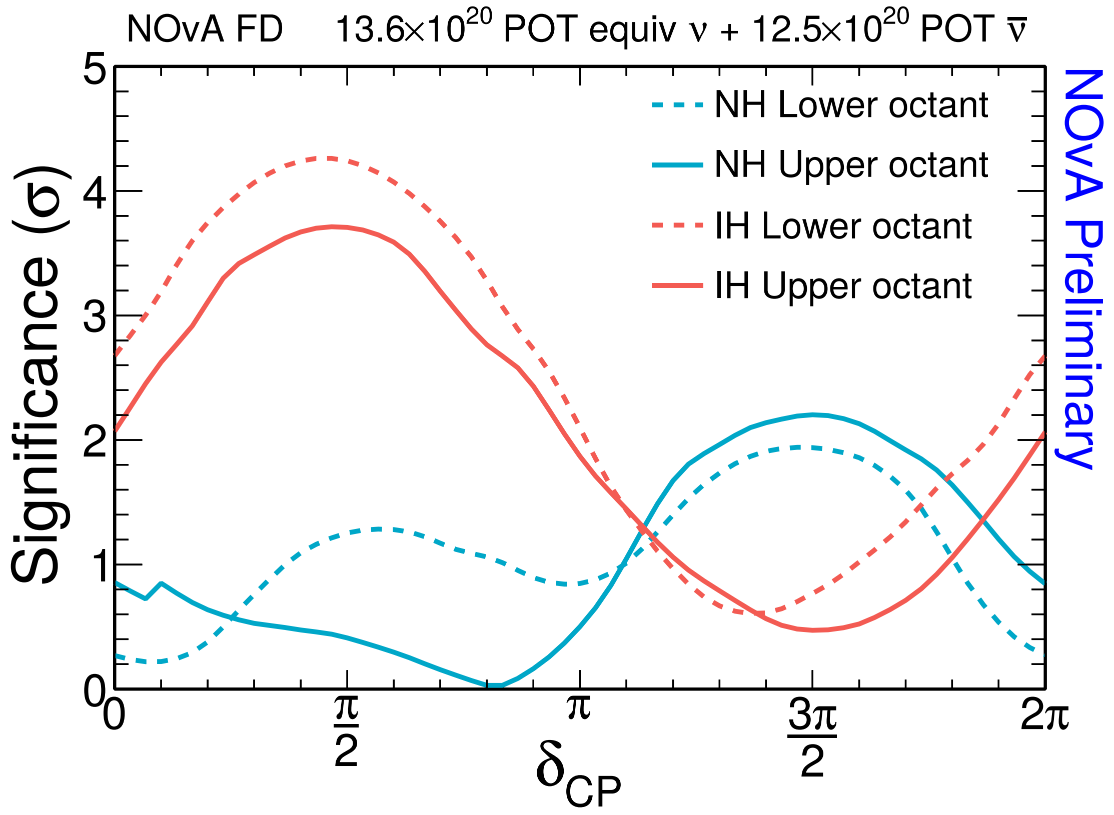
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31} - \boxed{\delta})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}^2$$

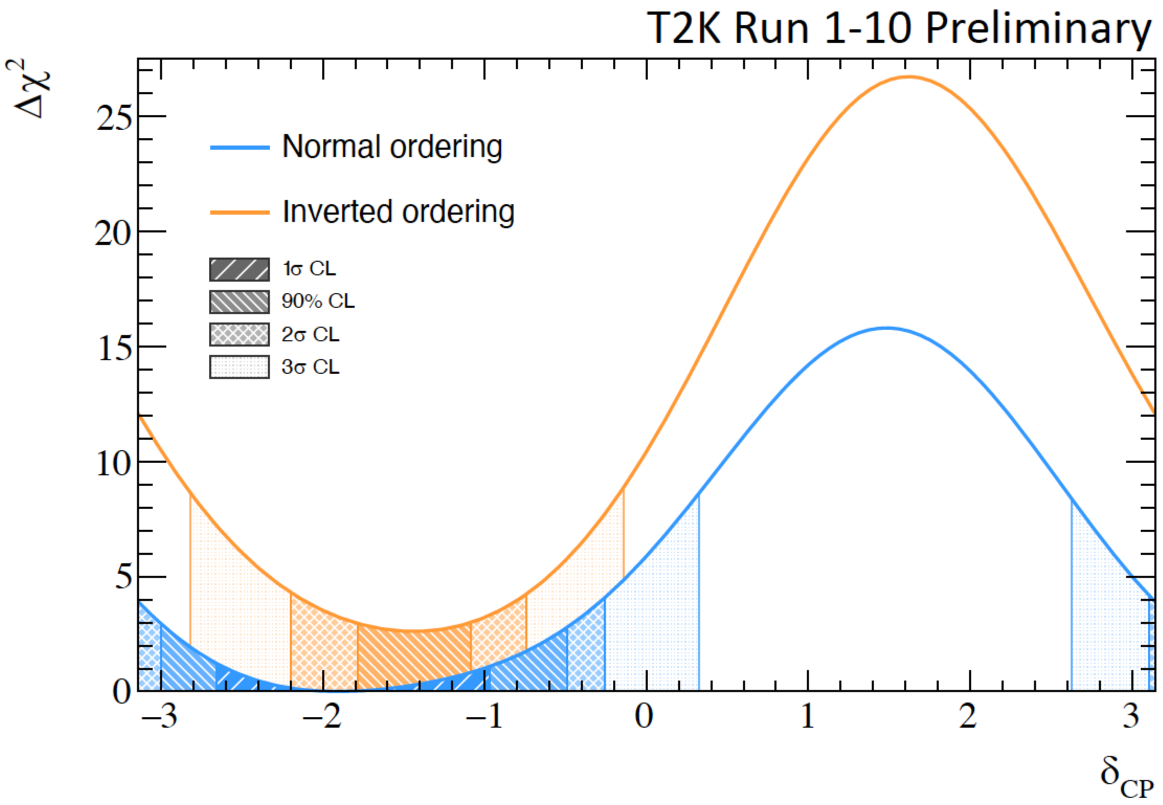
$$a = \frac{G_F N_e}{\sqrt{2}}$$

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

- Electron-neutrino appearance is sensitive to the CP phase.
- Mass ordering effect depends on electron density N_e.
- Simultaneous determination of mass ordering and CP phase only possible with long-baselines by fitting the energy dependence of the flux modulation (unless we add atmospheric data).

CP Violation Phase

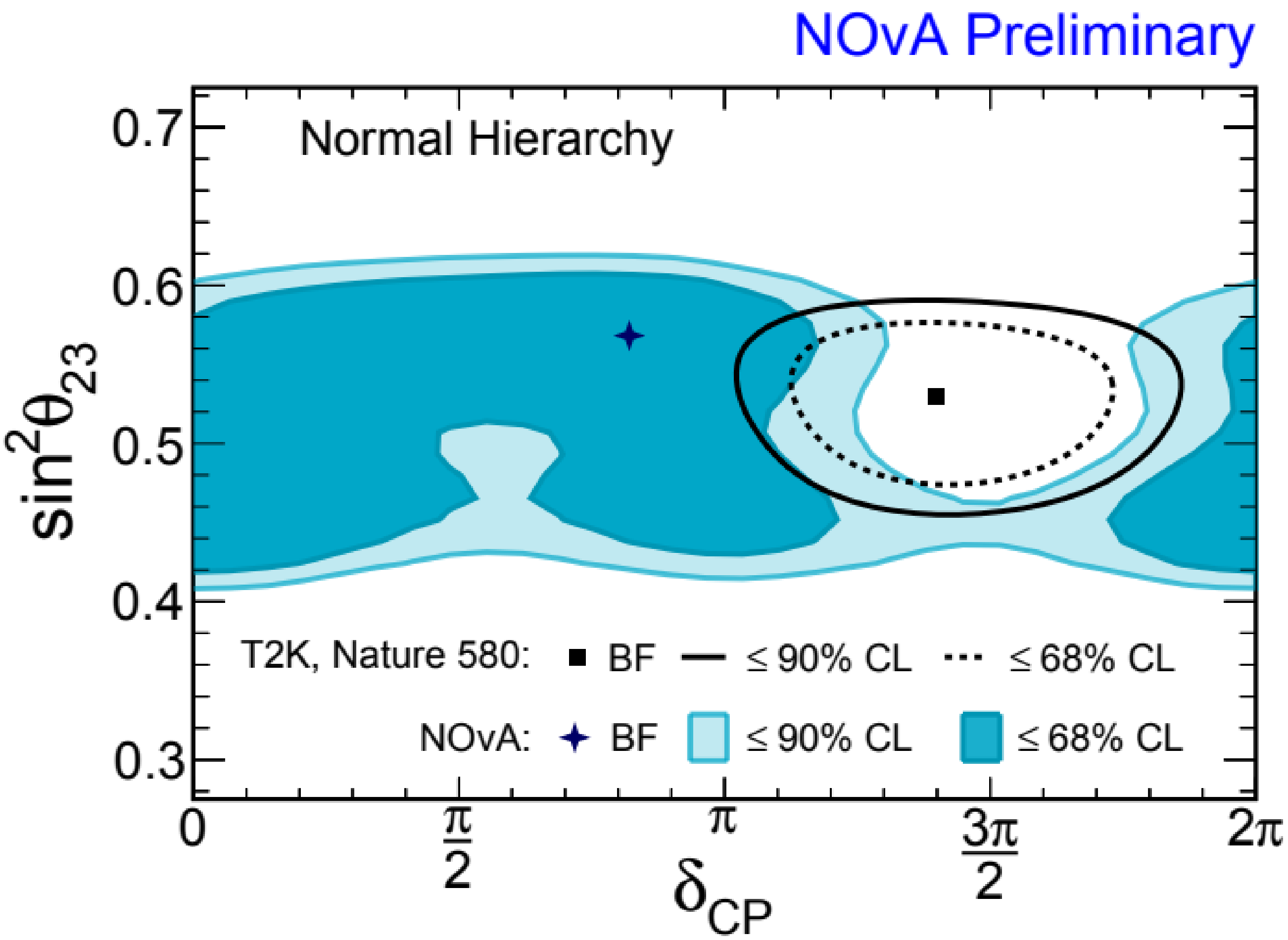




- Sensitivity to combination of CP phase and mass ordering.
- Normal ordering slightly preferred (1σ)
- Exclude IO, $\delta = \pi/2$ at > 3σ
- Disfavour NO, $\delta = 3\pi/2$ at ~2σ

- CP conversation $(0,\pi)$ excluded at 90% confidence level
- Normal ordering preferred

The Status Quo



- Current data are inconclusive – expect some improvements with further running
- Need next-generation experiments to discover CPV and resolve mass ordering