Neutrino oscillation
NOvA + T2K

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Outline

- Neutrino oscillation basics
- Design principles
- T2K and NOvA

Neutrino oscillation basics

Neutrinos interact weakly and have mass

Mass eigenstates are not the same as flavor eigenstates

Neutrinos are produced in weak eigenstates, but evolve as mass eigenstates

Non-zero probability of observing other weak eigenstates at future times (distances)

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

$$|\nu_i(t)\rangle \sim e^{-ip\cdot x}\,|\nu_i(0)\rangle$$

$$|\nu_i(L)\rangle \sim e^{-im_i^2 L/2E}\,|\nu_i(0)\rangle$$

Neutrino oscillation basics

PMNS mixing matrix:

- 3x3 unitary matrix -> 9 dof
- Split into 3 Euler angles, and 6 complex phases
- At least 3 of these phases can be absorbed into the definitions of the neutrino states and are not physical
- If neutrinos are Dirac particles -> 2 more phases can be absorbed
- In total, it is commonly expressed as…

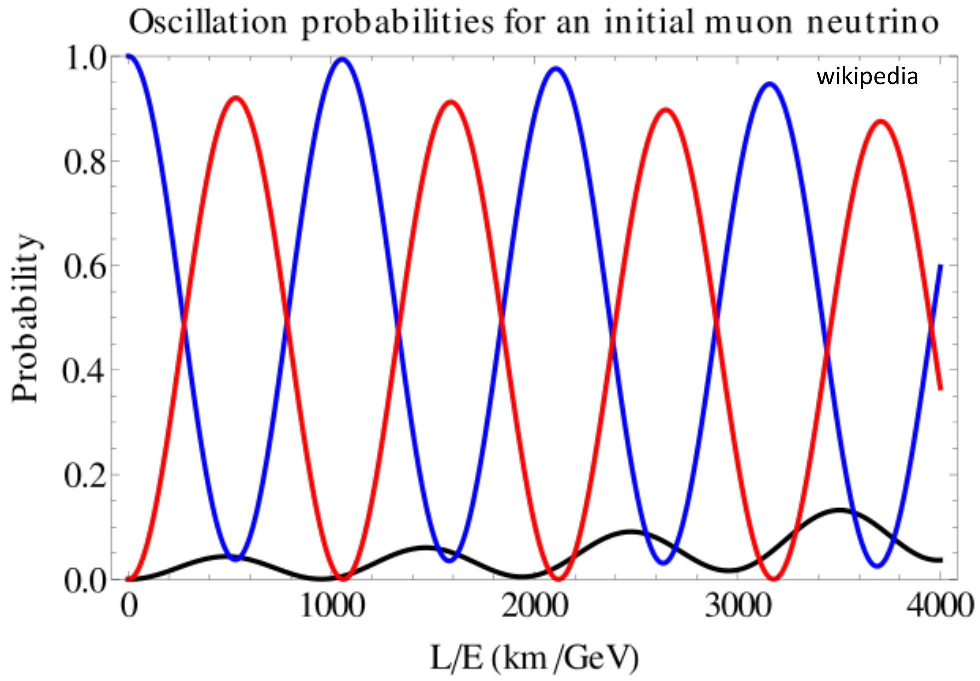
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Neutrino oscillation basics

Oscillation probability can be found by taking the square of the inner product

$$\langle \nu_\beta(L) | \nu_\alpha(0) \rangle$$

- Probability depends on L/E, mixing angles, mass splitting, and complex phases



$$P_{\alpha\to\beta}(L) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\delta m^2_{ij}L/4E) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\delta m^2_{ij}L/2E)$$

Requirements

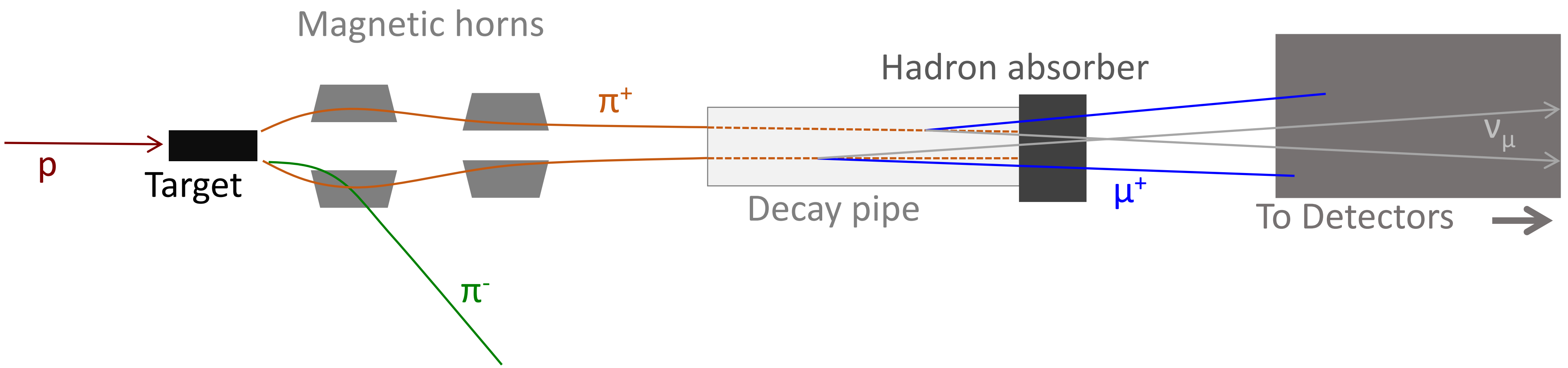
What goes into making a good oscillation measurement?

- Distinguish between flavors
- Large target to improve statistics
- Well understood energy spectrum (L/E dependence)
- Low backgrounds

Focus on accelerator-produced muon neutrinos (T2K + NOvA)

General design: Beam

Beam production

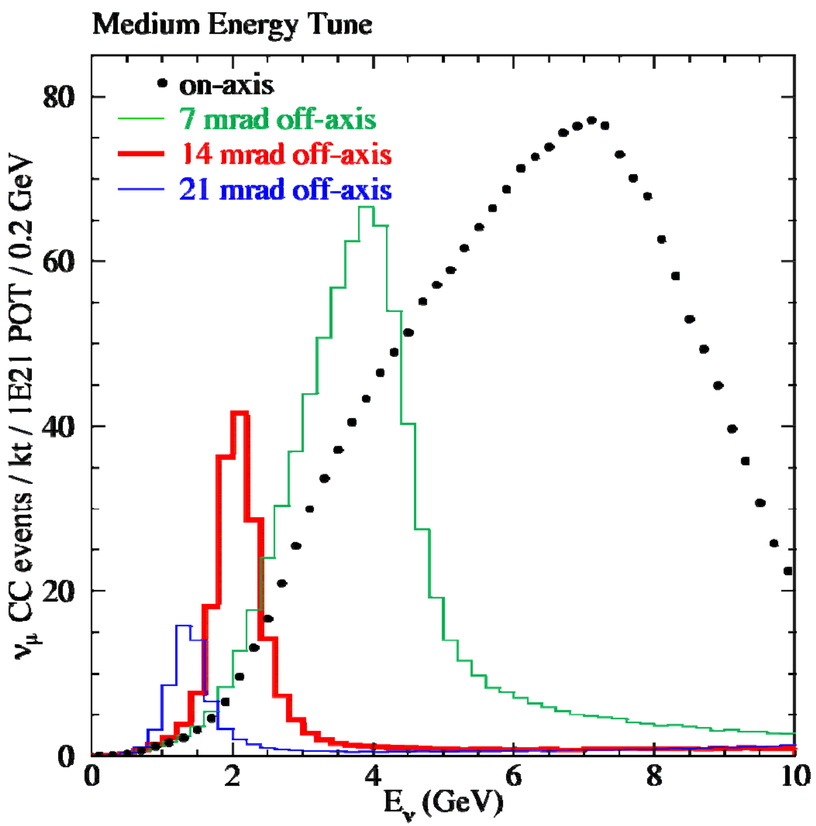


General design: Beam

Off-axis beam

2-body decay in flight kinematics produce a strong relationship between parent energy and neutrino energy

- produces an enhanced neutrino energy peak at off-axis angles
- peak energy depends on off-axis angle



$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

General design: Detector technology

Specific requirements for neutrinos (compared to Atlas / etc.)

- Target / detector combo
- High mass = scalability, must be cheap!

~kton scale is required

muon / electron id

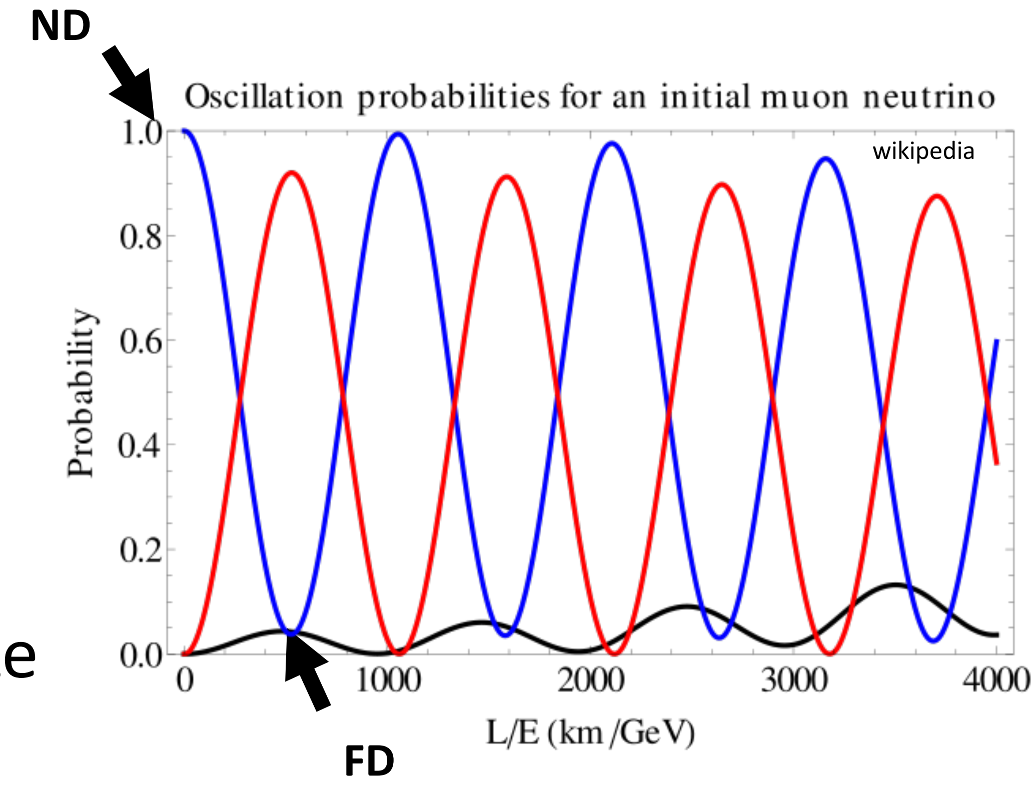
General design: Near / far detector

Near / far detector goals:

- Measure flavor content of beam
- Measure energy spectrum of beam
- Constrain backgrounds

First oscillation maximum

- Build near / far detector to maximize expected signal



The two experiments

T2K

NOvA

recent neutrino experiments with goals of

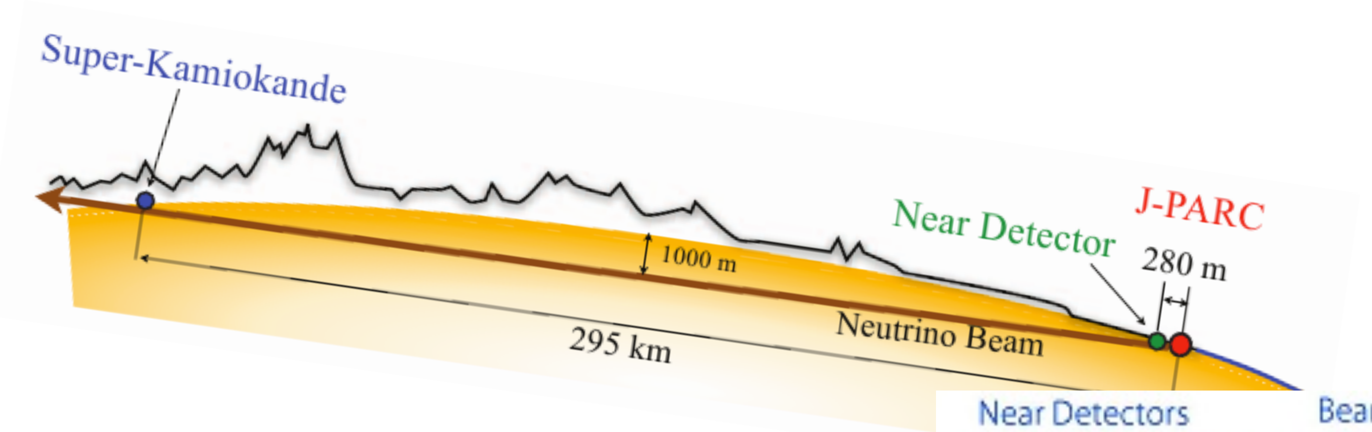
- measuring theta23 octant (precision of ~0.01)
- measurement of deltam^232 (precision of ~10^-4eV^2)
- search for sterile oscillations

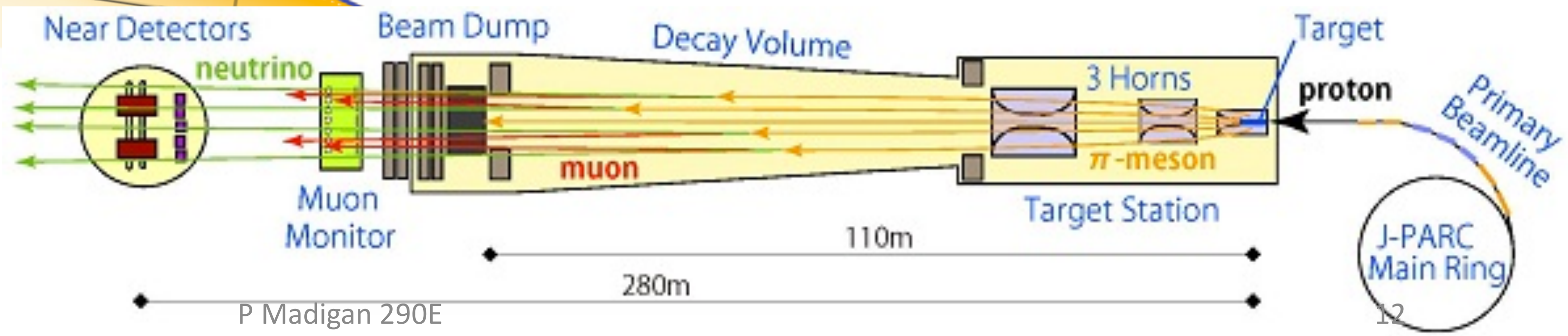
T2K beam

J-PARC beam in Tokai, Japan to SuperK in Kamioka

50GeV proton beam, off-axis by 43mrad = peak neutrino energy of 0.6GeV

Beamline of 295km





T2K detectors

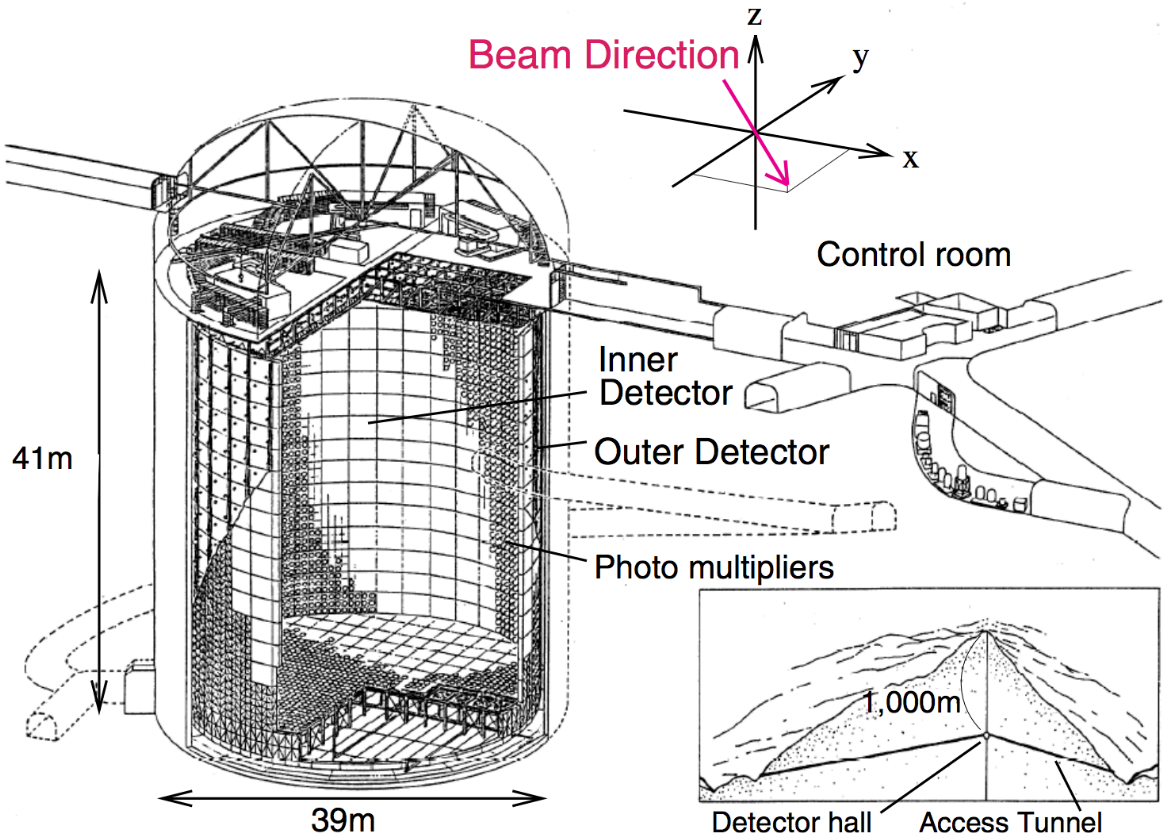
Super Kamiokande – 1km underground

22.5kt water cherenkov detector

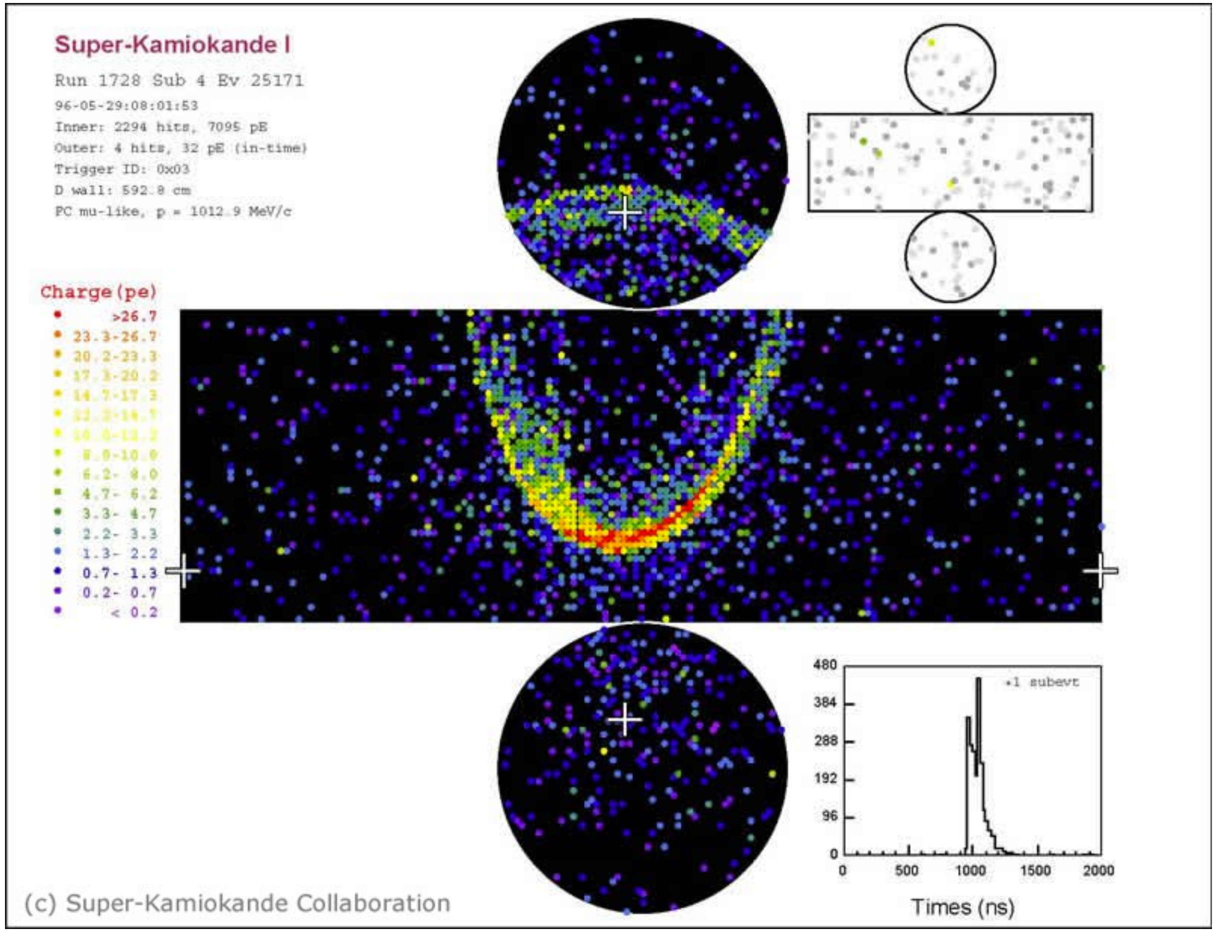
ID 10k PMTs

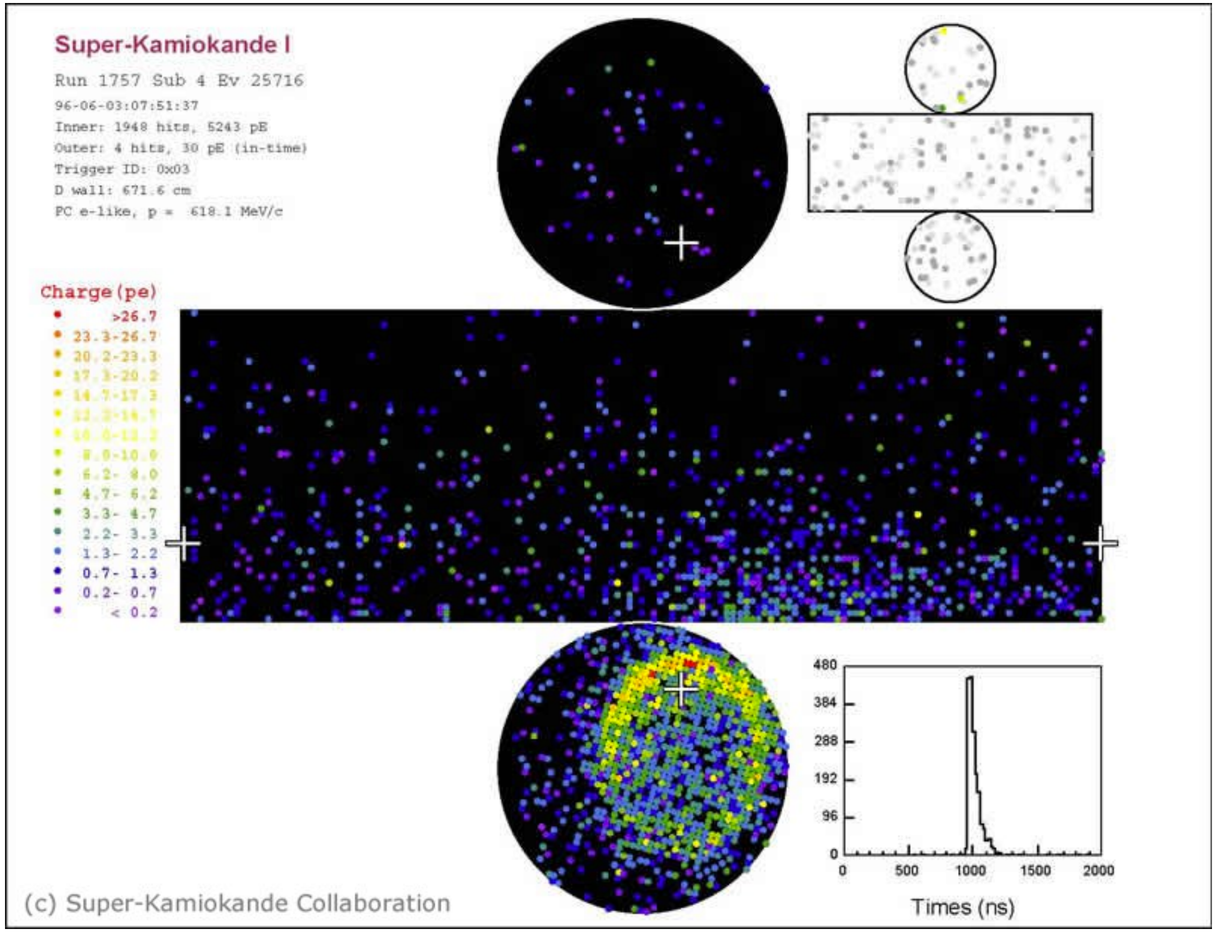
OD 1800 PMTs

Reconstruction via ring imaging, intensity, and timing



T2K detectors

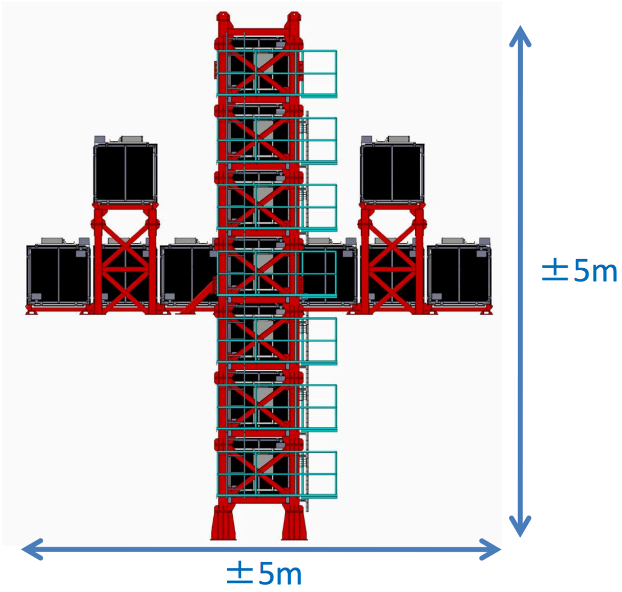


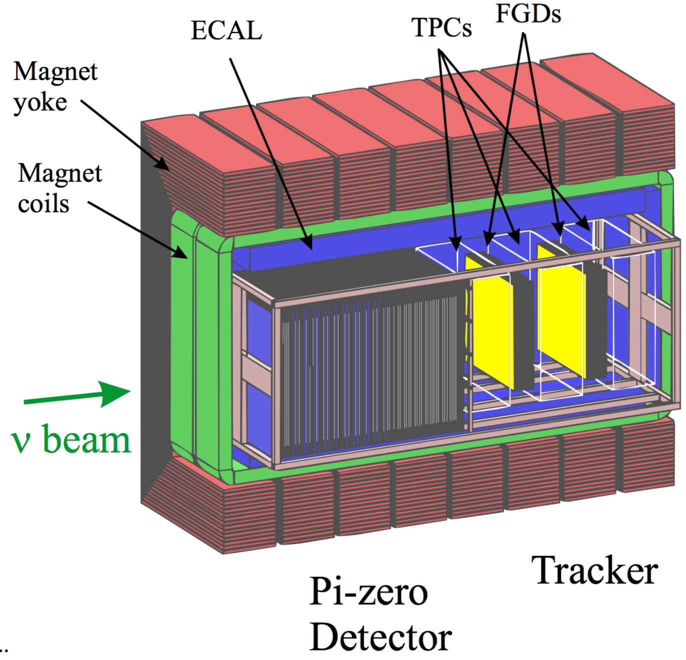


T2K detectors

Near detector system consists of 2 main detectors

- INGRID (on axis)
- ND280 (off axis)





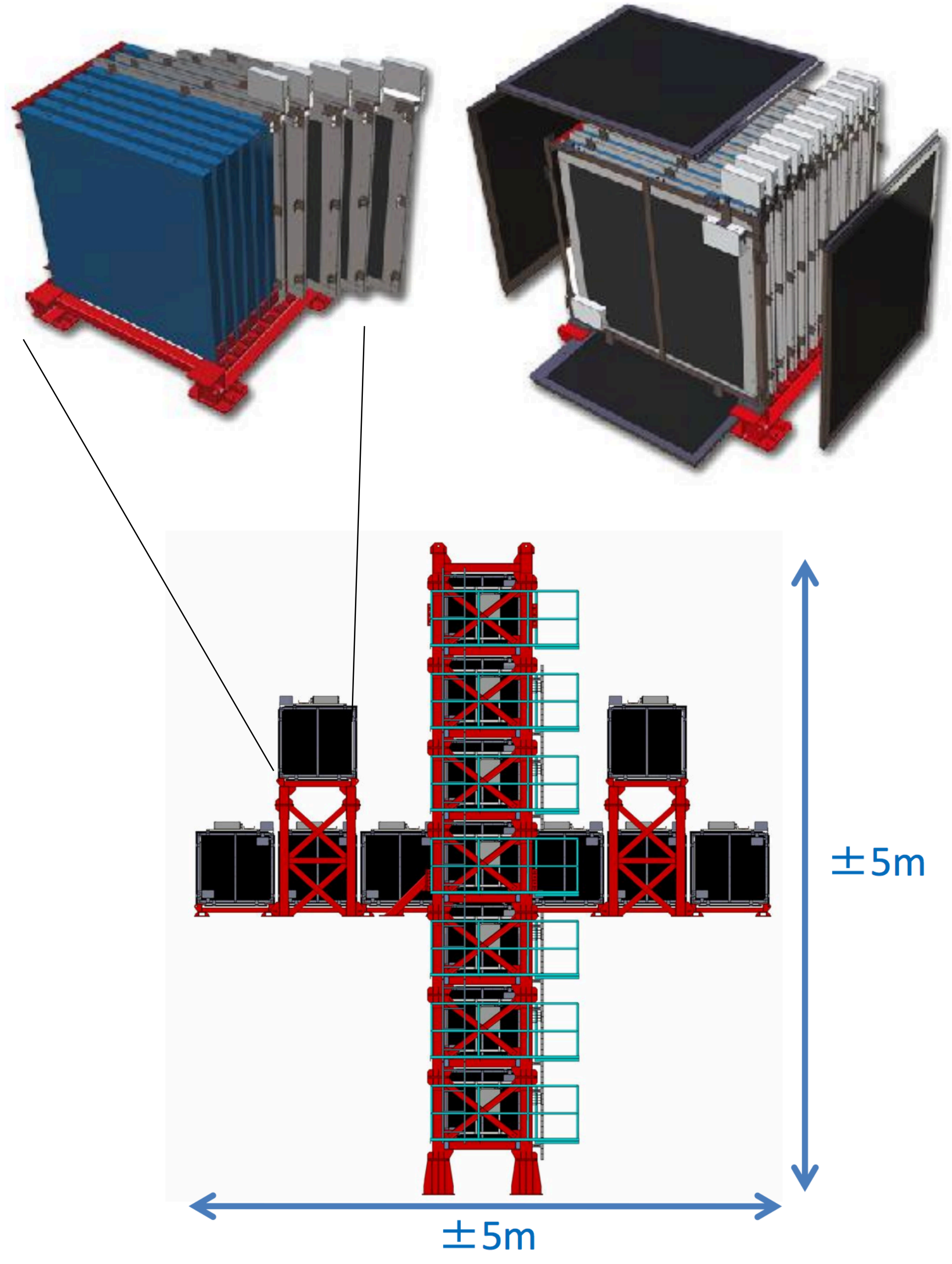
T2K detectors

INGRID

280m downstream of absorber

Directly measures neutrino beam profile and direction

Provides a better monitor of the neutrino beam direction than muon monitors

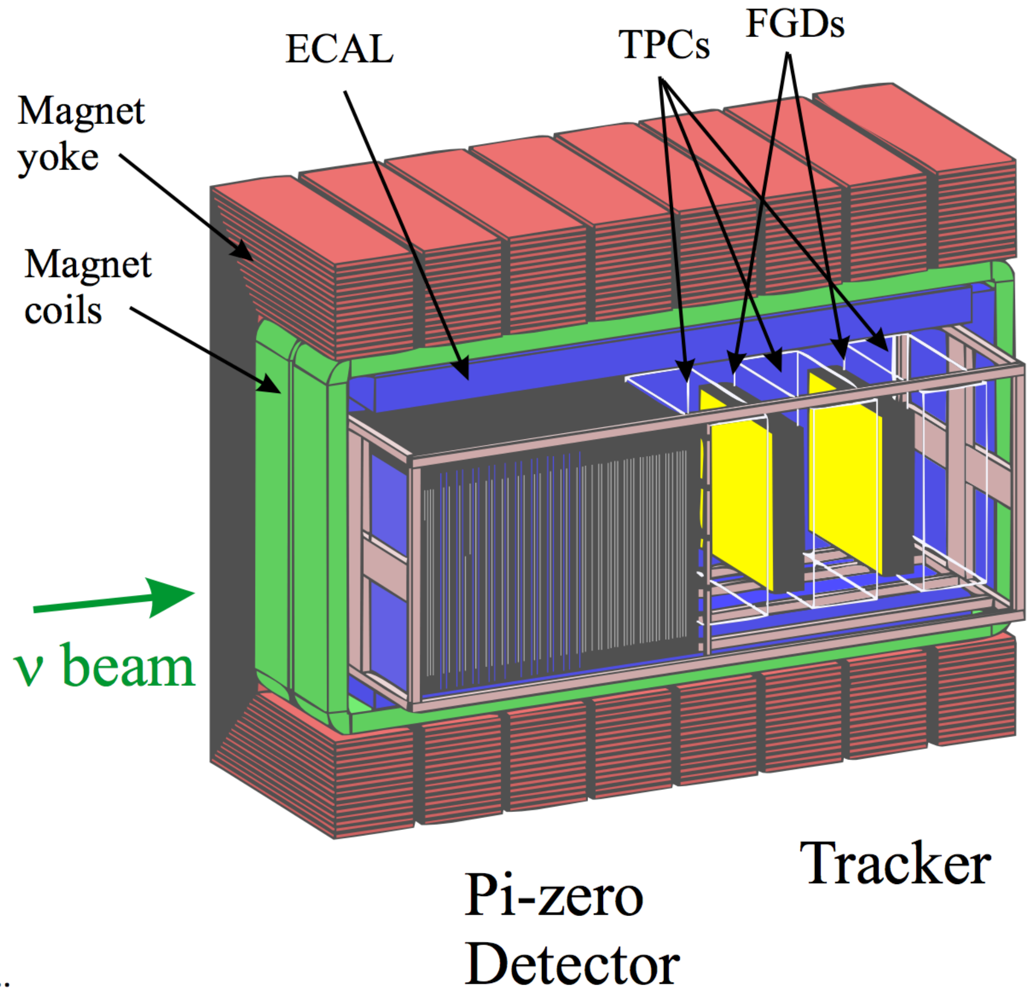


T2K detectors

ND280 – 280m off axis by 43mrad

5 submodules:

- POD: specialized pi0 detector
- TPCs: muon momentum and PID
- 1t FGDs: neutrino target mass
- Ecals: pi0 decays
- SMRD: energy of escaping muons and cosmic ray trigger

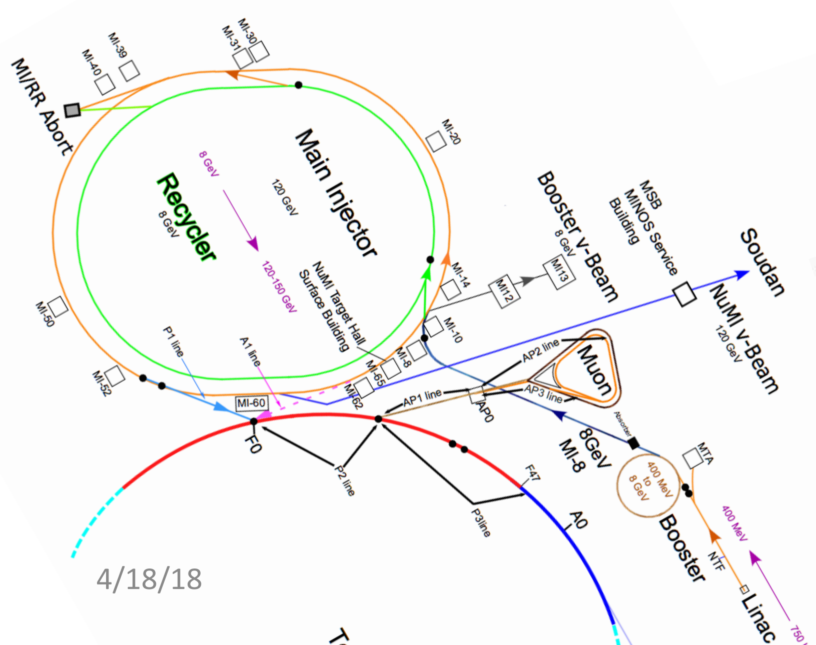


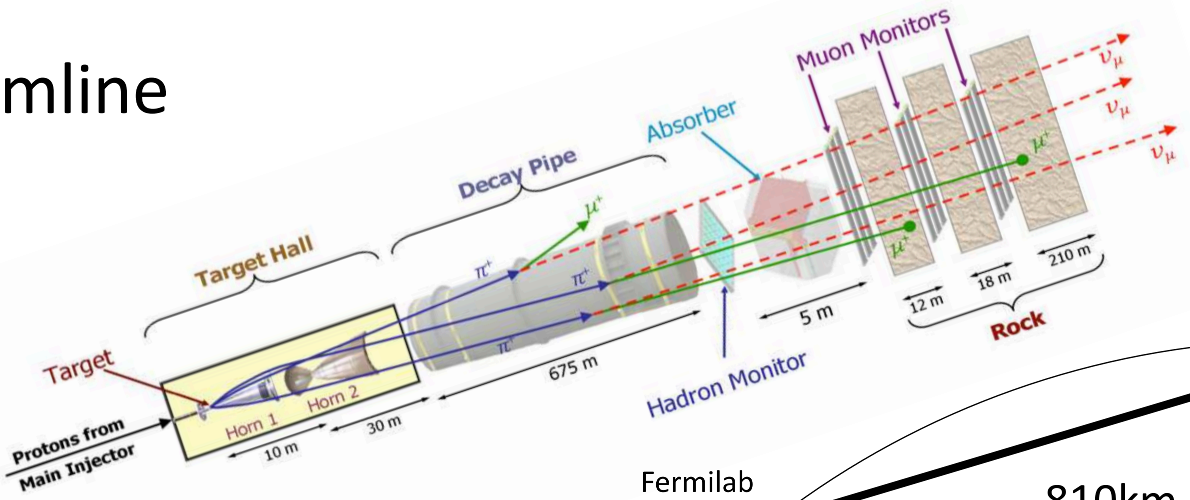
NOvA beam

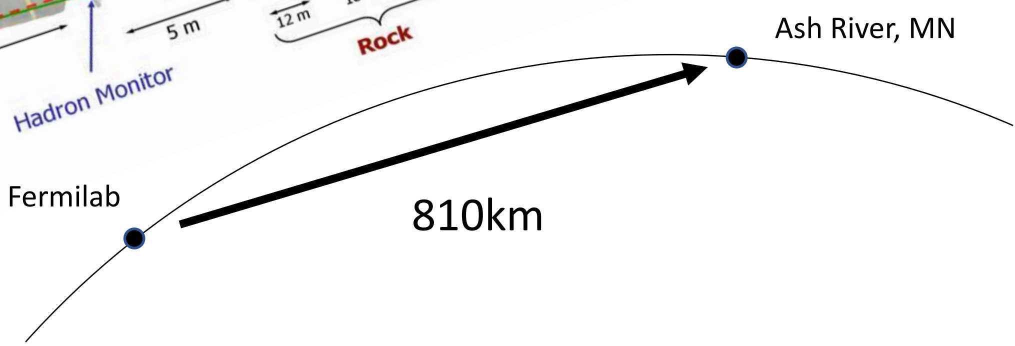
Fermilab NuMI beam

120GeV proton beam of 120GeV, off-axis by 14.6mrad = neutrino peak at 2GeV

Beamline of 810km beamline



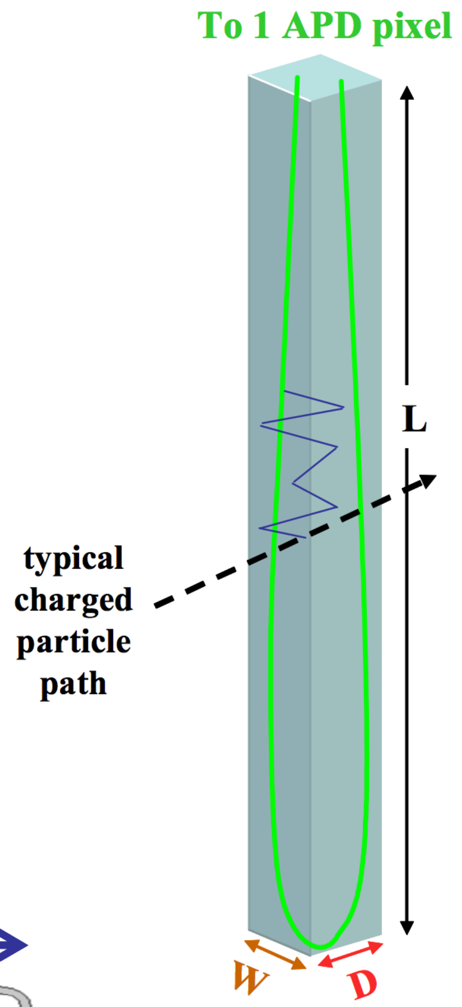


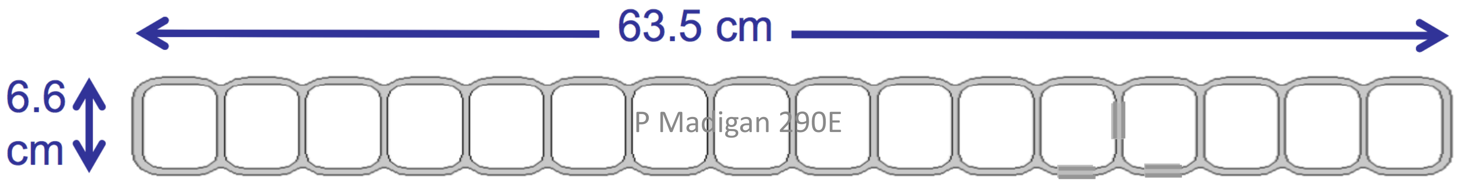


NOvA detectors

NOvA basic building block

- Liquid scintillator bars with wavelength shifting (WLS) fibers
- Extruded plastic cells 4cm x 6cm x 15.5m sized for 54-foot trucks
- Scintillator produces in 360-390nm range
  - Additives downshift to 400-450nm
  - WLS downshifts to 490-550nm for higher PMT efficiency
- 13000km of fiber, layered to provide total internal reflection of light

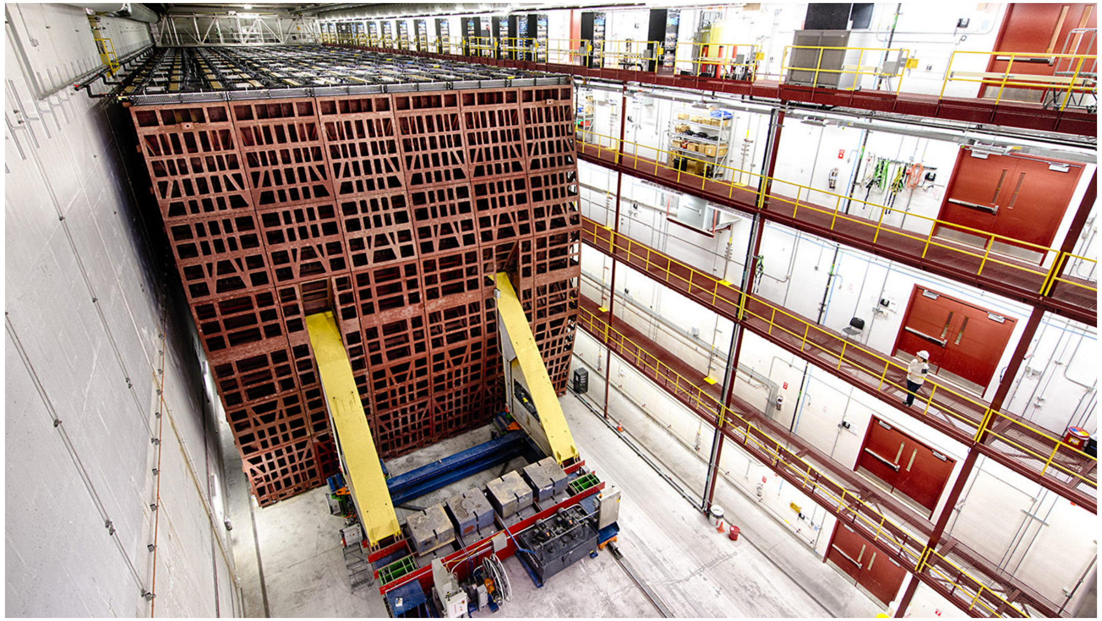


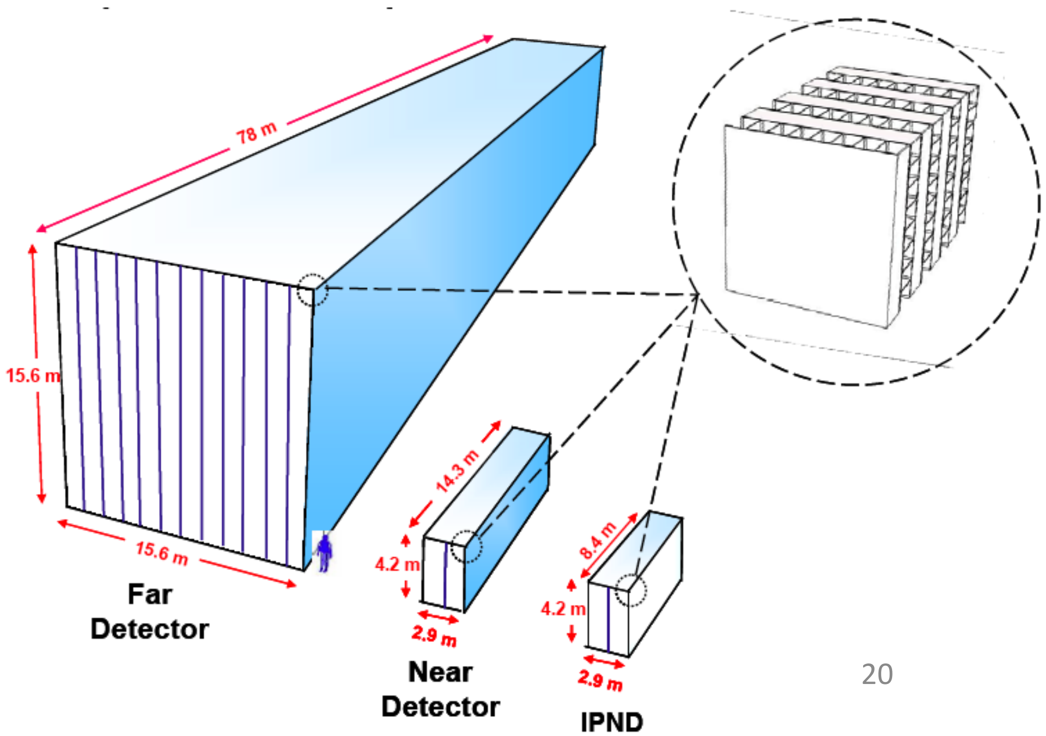


NOvA detectors

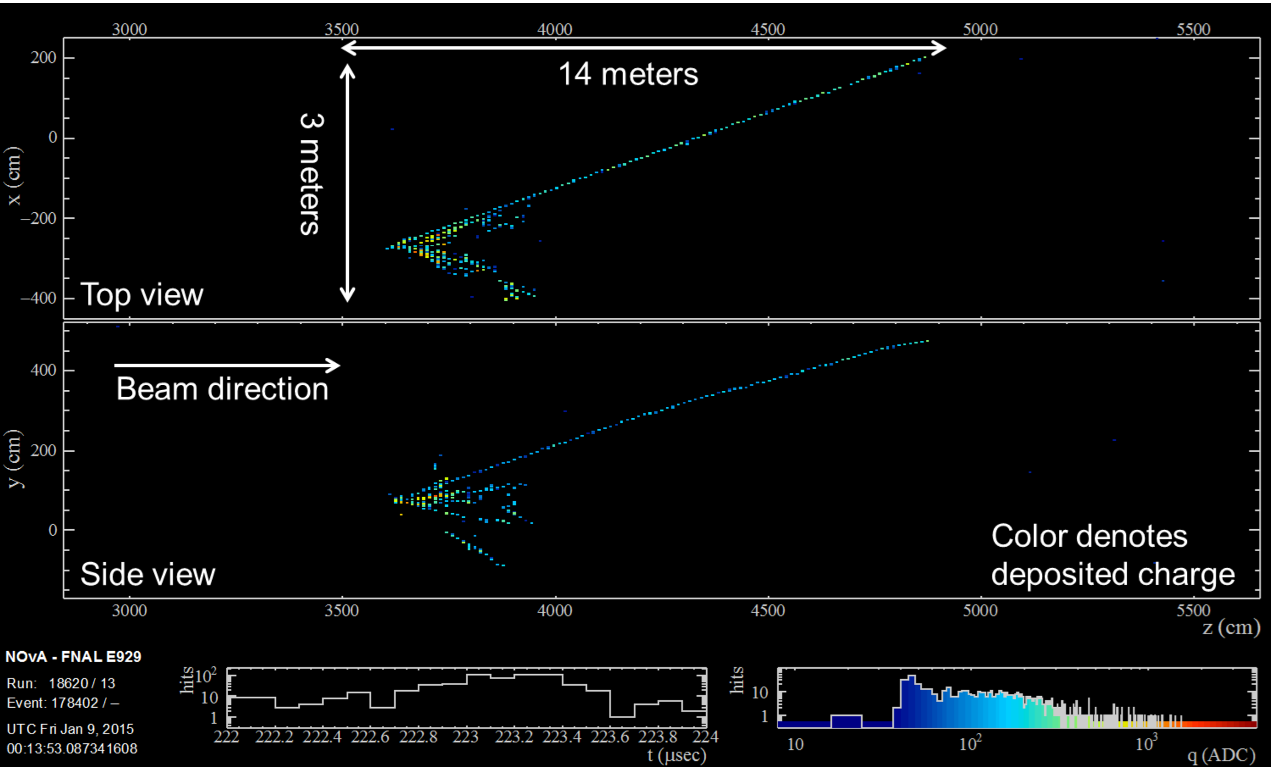
Far Detector

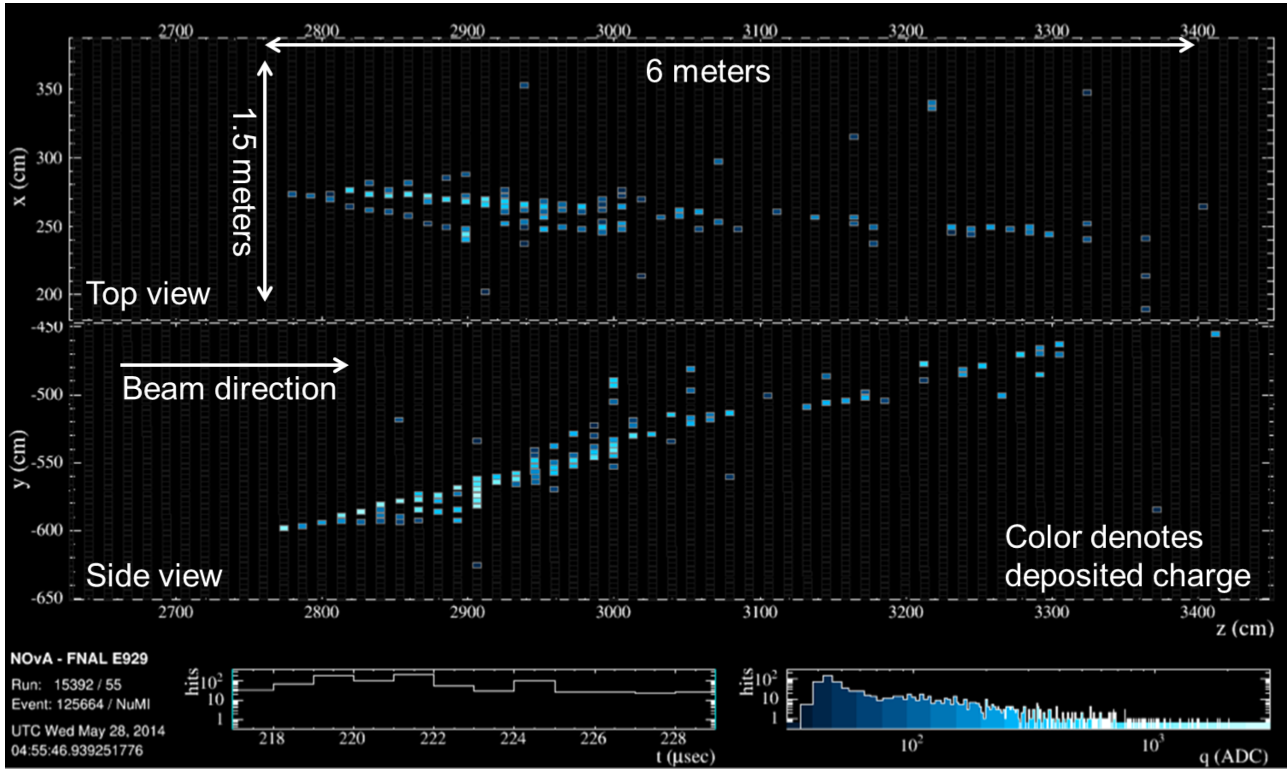
- Surface detector, 810km beamline, 15kt, 10kt active
- 385,000 scintillator cells
- flavor id via track topology (muon-like or electron-like)





NOvA detectors

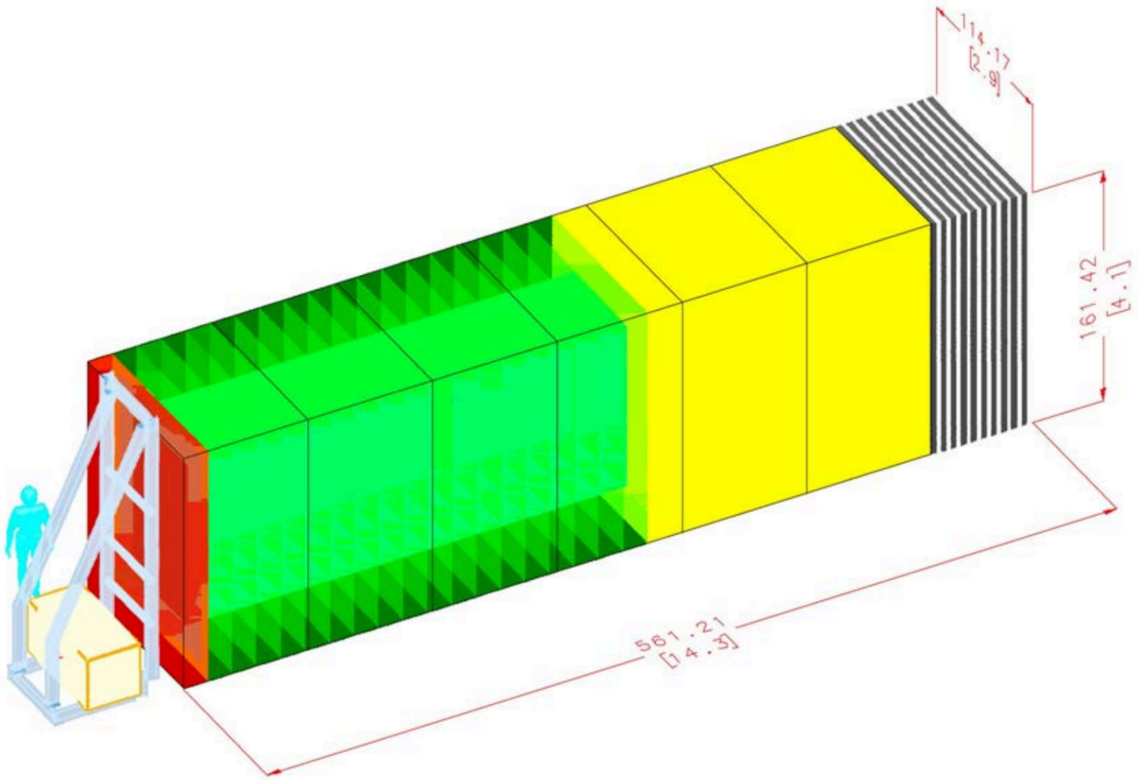




NOvA detectors

Near Detector

- Similar design as FD – scintillator cells
- Consists of an upstream veto, fiducial + containment, and a muon catcher
- Muon catcher is steel interspersed with active scintillator



Analysis

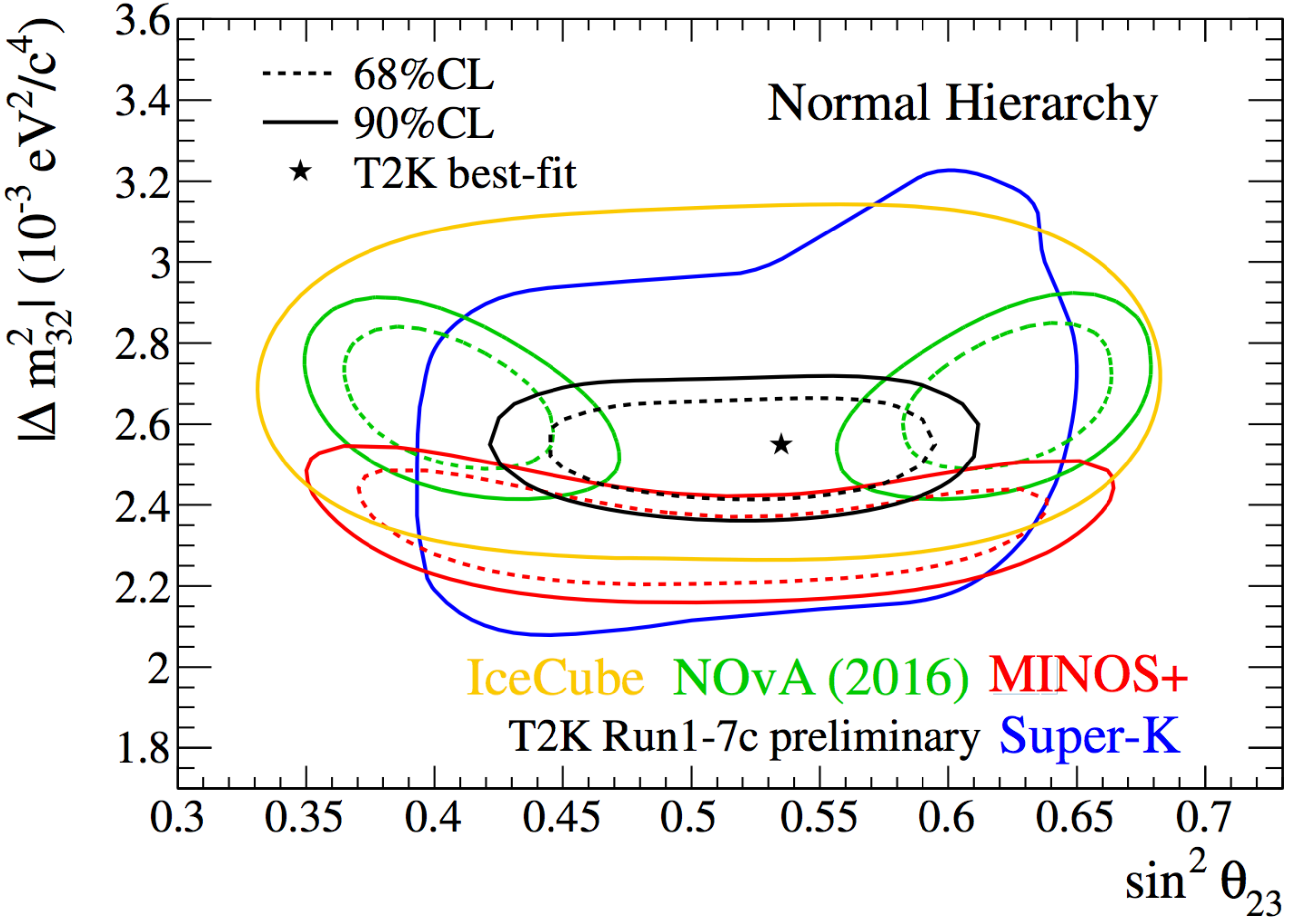
Generally, analysis is performed by comparing the expected far detector flux (as predicted by near detector) to the observed far detector flux

Use extensive detector and beam modelling to determine the translation from near detector to far detector

- NOvA: FLUKA + Geant4 + GENIE
- T2K: Constrained FLUKA + Geant3 based models (NA61/SHINE)

Results

Tension!



Summary

General qualities for oscillation experiments

- Large-mass active-target detectors
- Well-understood neutrino spectra

T2K and NOvA

- Two oscillation experiments observing muon neutrino disappearance and electron neutrino appearance
- Tension between the two experiments

References

- T2K TDR + NIM papers on submodules
- NOvA TDR
- arXiv:hep-ex/1409.7469
- arXiv:hep-ex/1701.00432

Neutrino oscillation

circa 2012

Parameter	best-fit ($\pm 1\sigma$)	3σ
$\Delta m^2_{\odot}$ [10^{-5} eV ^{2}]	$7.58^{+0.22}_{-0.26}$	$6.99 - 8.18$
$\lvert\Delta m^2_A\rvert$ [10^{-3} eV ^{2}]	$2.35^{+0.12}_{-0.09}$	$2.06 - 2.67$
$\sin^2\theta_{12}$	$0.306\ (0.312)^{+0.018}_{-0.015}$	$0.259\ (0.265) - 0.359\ (0.364)$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$	$0.34 - 0.64$
$\sin^2\theta_{13}$ [140]	$0.021\ (0.025)^{+0.007}_{-0.008}$	$0.001\ (0.005) - 0.044\ (0.050)$
$\sin^2\theta_{13}$ [142]	0.0251 ± 0.0034	$0.015 - 0.036$