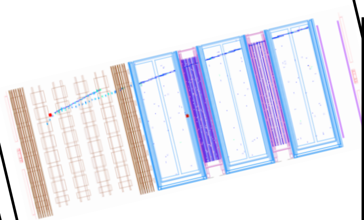
Snapshots of neutrino oscillation physics today and a preview of tomorrow

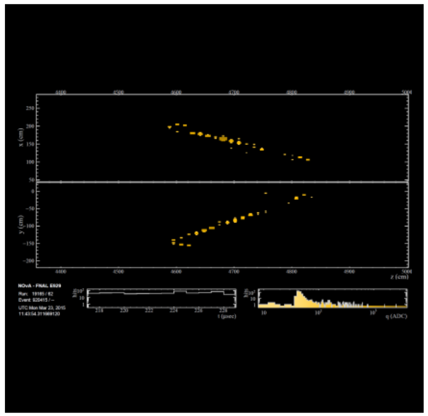
Steve Manly
University of Rochester

Representing the T2K collaboration

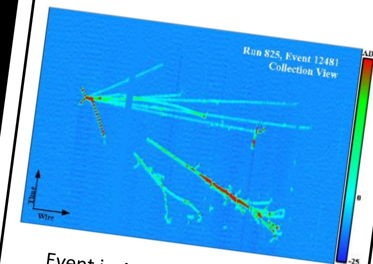
6th International Conference on New Frontiers in Physics (ICNFP2017)
Crete, August 2017



CC ν_μ event in T2K's ND280 detector

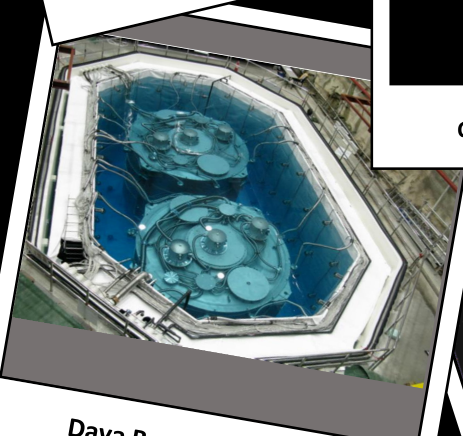


CC ν_e event in NOvA detector

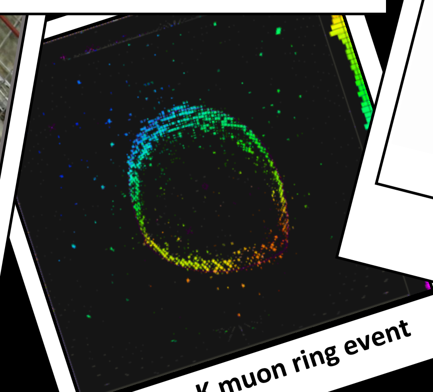


Event in Argoneut LArTPC

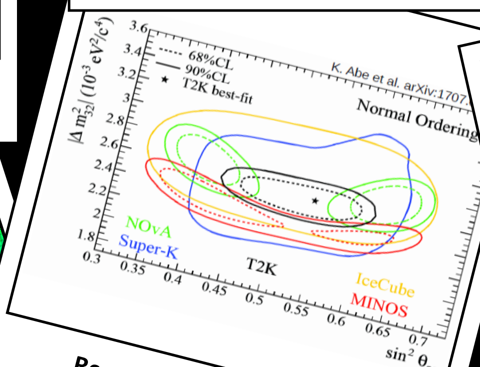
LArTPC's –short baseline program and DUNE long baseline experiment



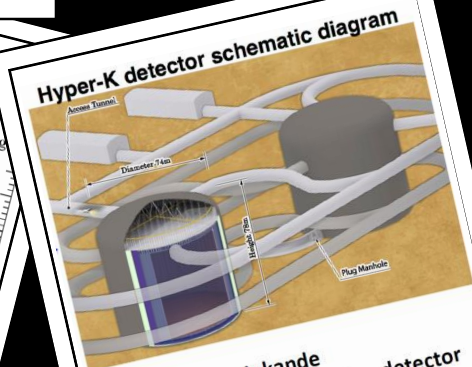
Daya Bay detectors



Super-K muon ring event



Recent disappearance results



Hyper-Kamiokande project

Rich landscape of neutrino physics

Supernova neutrinos

Cosmic neutrino background

Atmospheric oscillations

Solar neutrino oscillations

Area explored in this talk

Neutrino interactions and cross sections

Reactor neutrino oscillations

A few selected results/experiments. Not a systematic survey.

Accelerator long-baseline neutrino oscillations

Sterile neutrinos

Accelerator short-baseline neutrino oscillations

Double beta decay

Neutrino mass from beta decay endpoint

Geo-neutrinos

Two-flavor oscillation formalism

Flavor states interact in nature

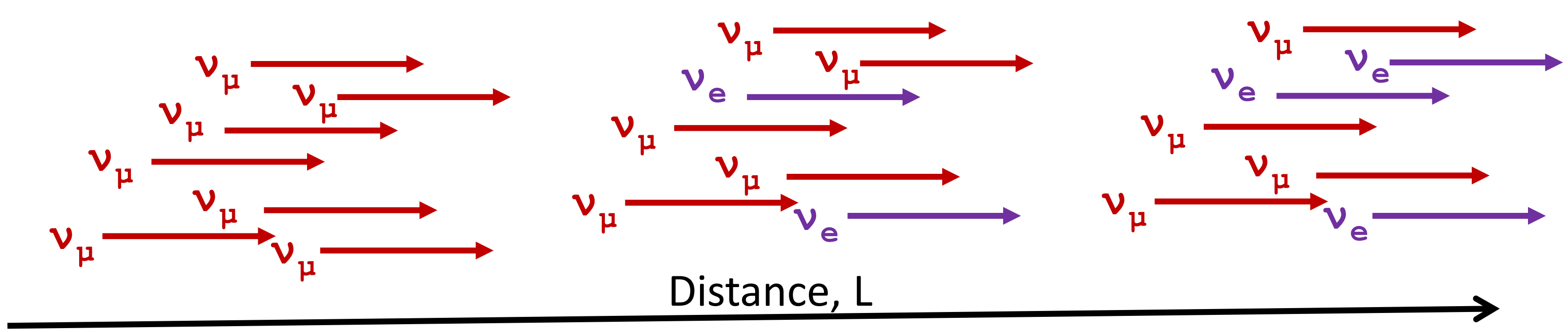
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Mass states propagate
Admixture of states 1 and 2 evolves, i.e., the flavor changes

Probability that neutrino created as one type is detected as different type

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

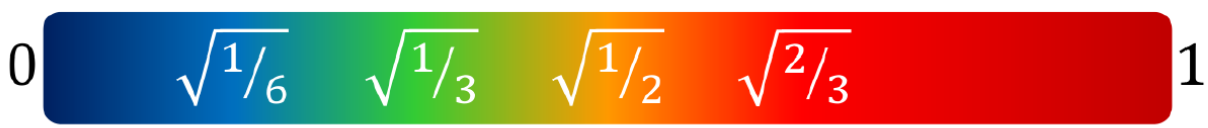


- *At given distance, observe number oscillated neutrinos as function of energy, E*
- *Extract oscillation parameters, Θ and Δm^2*
- *Can measure "appearance" or "disappearance"*

Nature's not quite so simple!
Three-flavor oscillations

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

Observed matrix element sizes



PMNS matrix: Pontecorvo-Maki-Nakagawa-Sakata

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

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$\delta = \delta_{CP}$

Atmospheric /Beam	Beam /Reactor	Reactor /Solar
$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$	$\nu_e \to \nu_e$
$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$	$\nu_e \to \nu_\mu + \nu_\tau$

Appearance probability in the three-flavor scenario

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$

Leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CPV

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$

matter

$$a = 2\sqrt{2} G_F n_e E_\nu$$ (matter parameter)

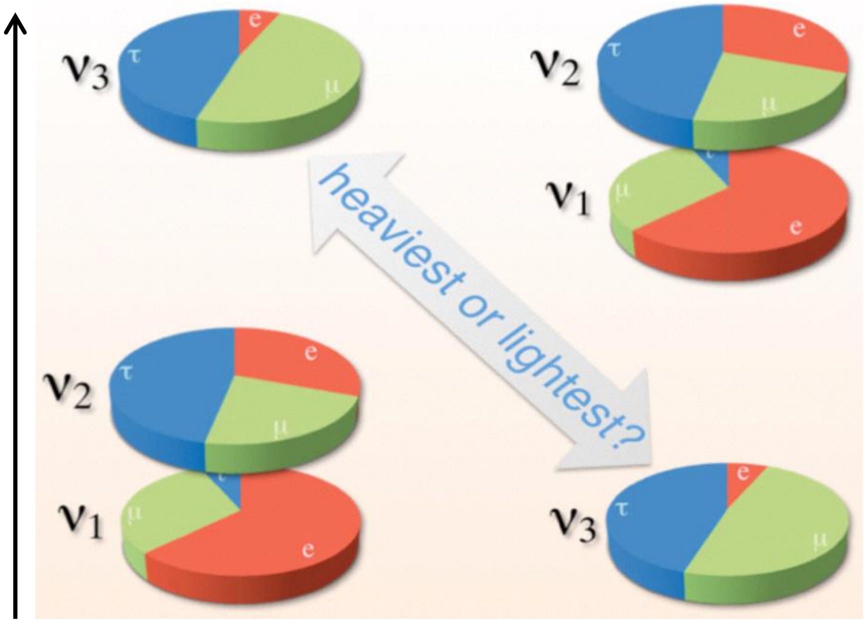
For anti neutrinos,

-Y. Hayato

$a \to -a, \delta \to -\delta$

$$\Delta_{ij} = m_j^2 - m_i^2$$

Some of the open questions



- What is the mass ordering?
- Is there leptonic CP violation? What is δ_{cp}?
- Is θ_{23} maximal (45°)? (If so, ν_μ and ν_τ content of mass eigenstate 3 are equal.)
- If θ_{23} not maximal, which quadrant? ($\theta_{23}>\pi/4$ or $< \pi/4$)

Interesting! But not discussed here (much).

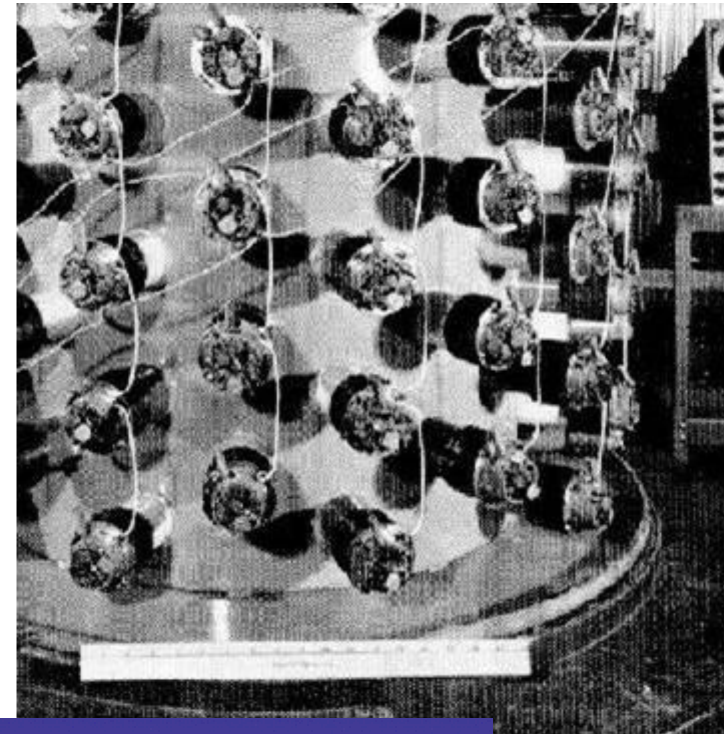
- Are there sterile neutrinos?
- Are neutrinos majorana particles?
- Can (does) CP violation in the lepton sector play a role in the matter-antimatter asymmetry in the universe?

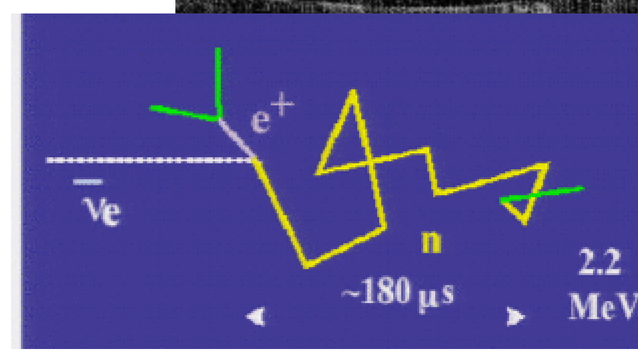
Discovery of the neutrino by inverse beta decay

- Reines and Cowan (1955)
  - Nobel Prize 1995
  - 1 ton detector
  - Neutrinos from a nuclear reactor

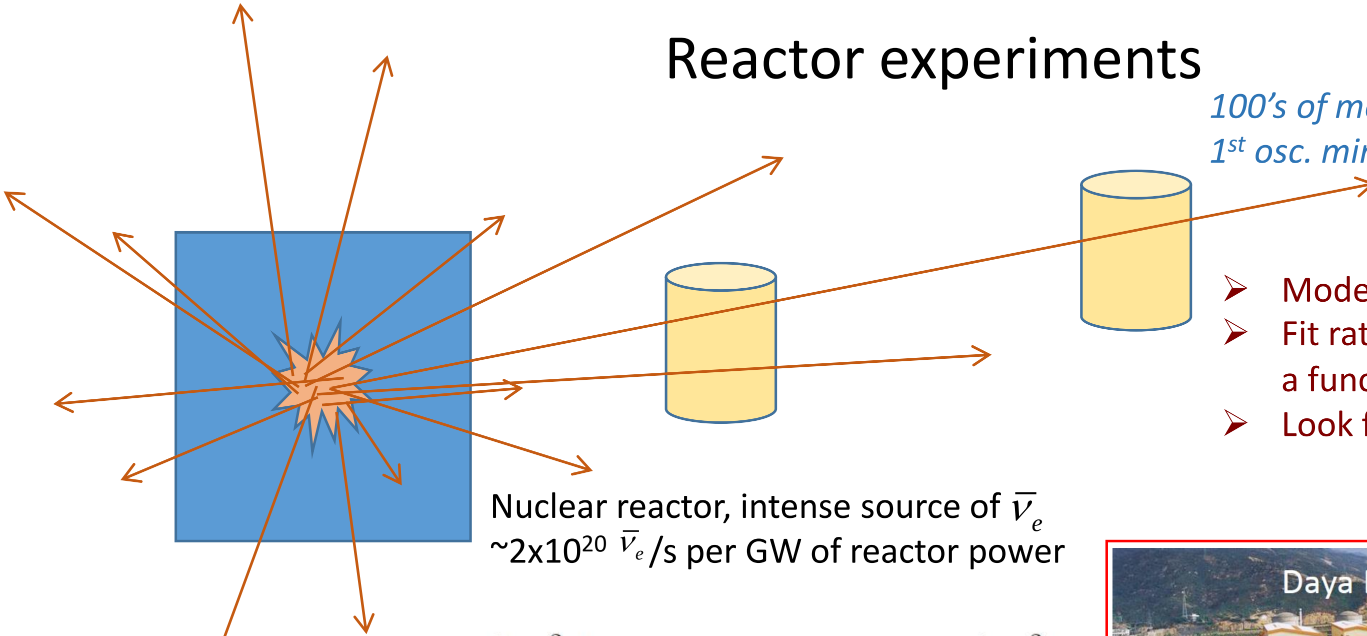
Reines and Cowan at Savannah River

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





Reactor experiments



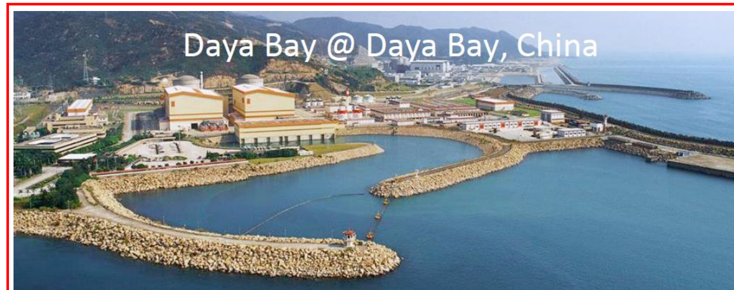
100's of meters from reactor
1st osc. minimum at 1.6 km for E=4 MeV

- Model neutrino flux from reactor
- Fit rate of $\overline{\nu}_e$ survival probability as a function of L/E
- Look for deviation from $1/r^2$

Nuclear reactor, intense source of $\overline{\nu}_e$
~2×10^{20} $\overline{\nu}_e$/s per GW of reactor power

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ee} L}{4E} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

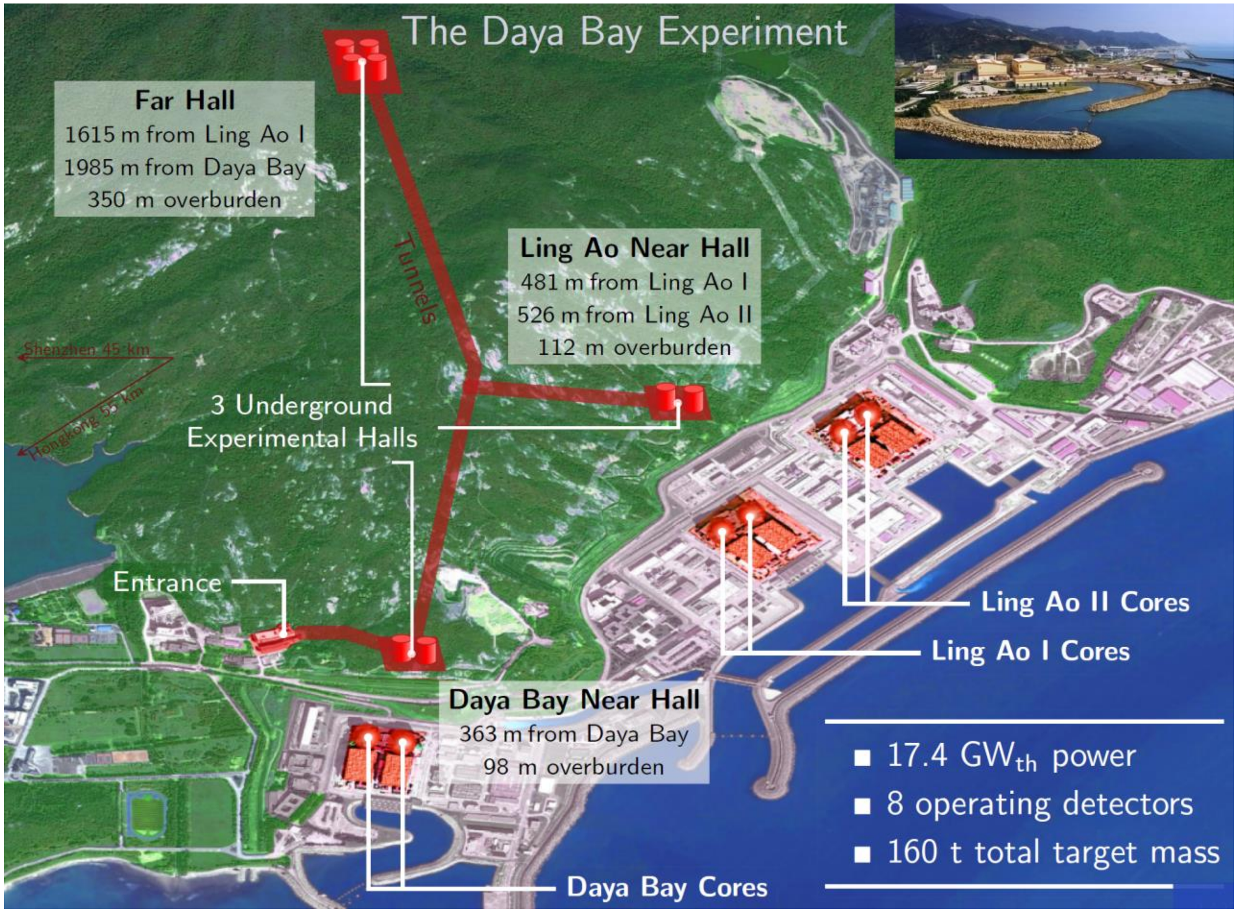
$$|\Delta m^2_{ee}| = \cos^2\theta_{12} |\Delta m^2_{31}| + \sin^2\theta_{12} |\Delta m^2_{32}|$$

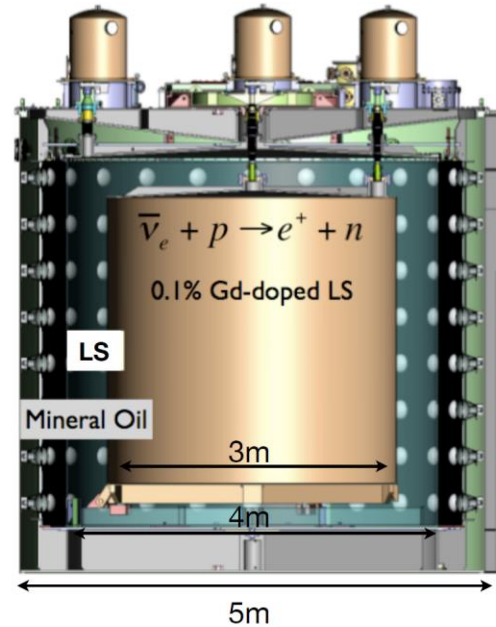


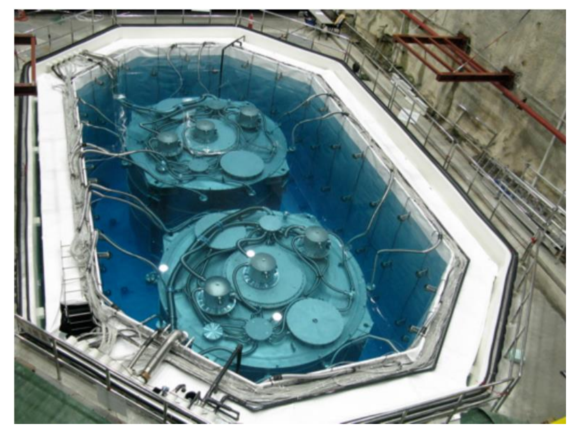
(Discussed in yesterday morning session by Denise Hellwig)

JUNO

Daya Bay experiment



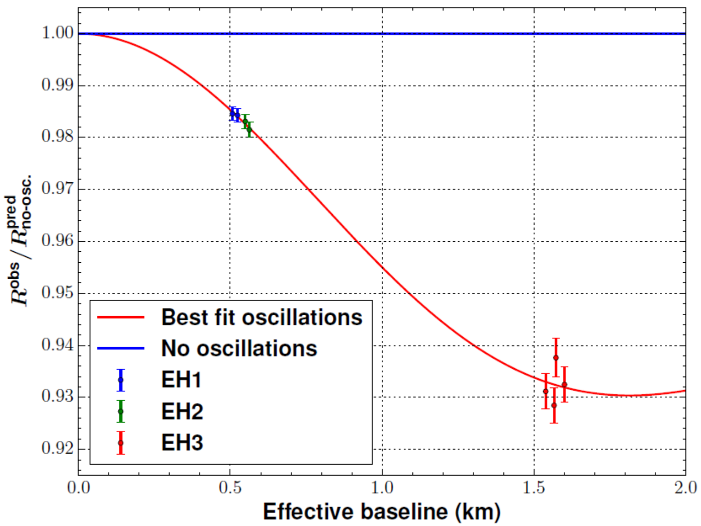


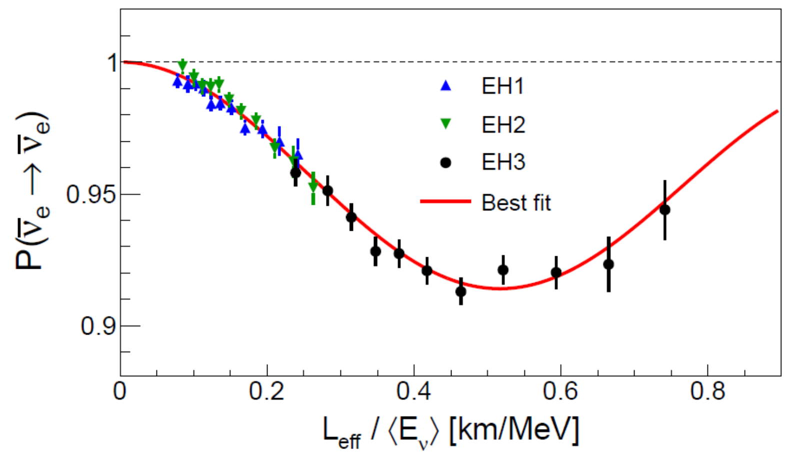


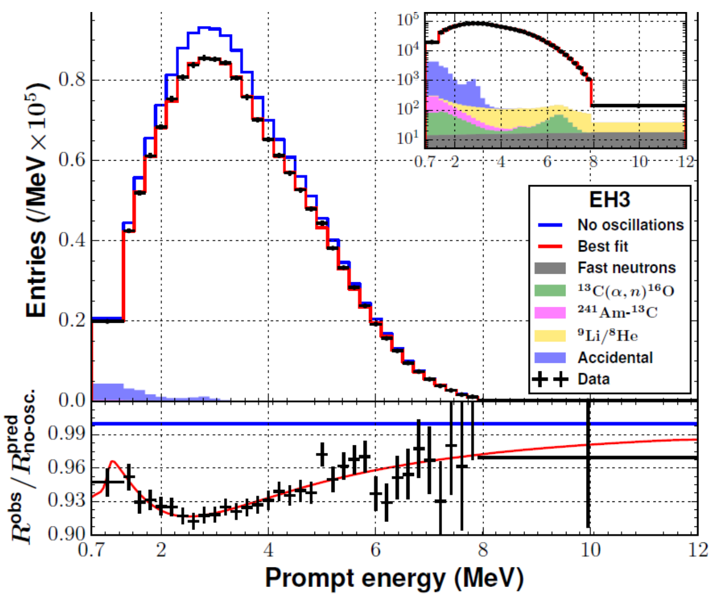
Chao Zhang, Daya Bay collaboration, Neutrino 2014

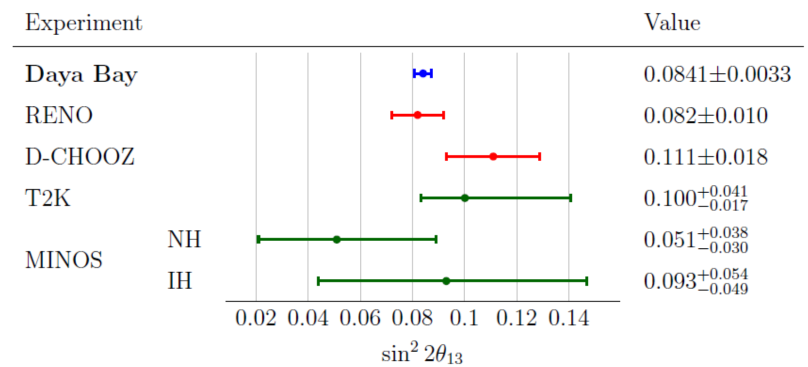
Daya Bay results

PRD **95**, 072006 (2017)









- Very precise measurement of $\sin^2 2\theta_{13}$
- Can be used by other experiments to gain sensitivity in extraction of other oscillation parameters

Accelerator long-baseline neutrino oscillations

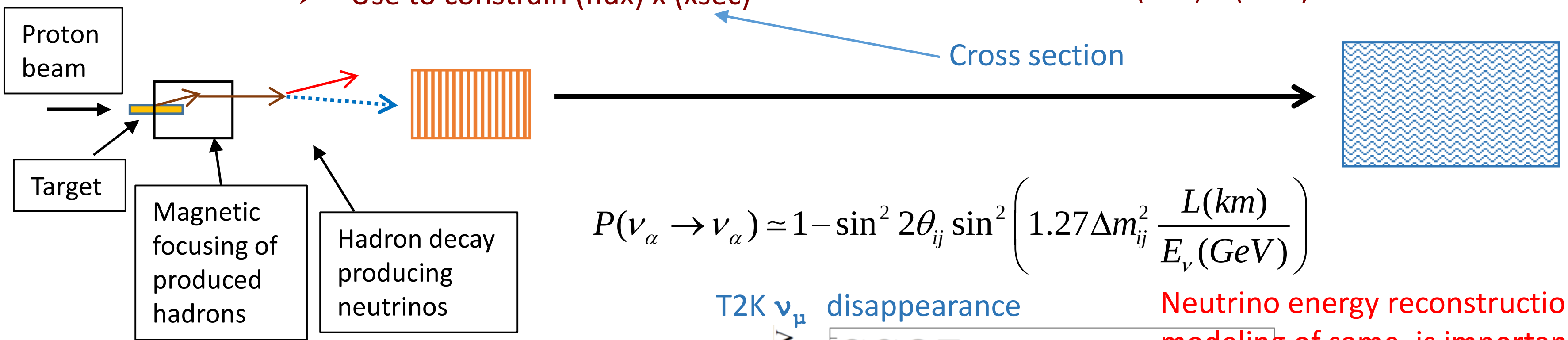
Basic method

Far detector (FD):

- Measure neutrino spectra as function of E_ν
- Extract oscillation parameters by comparing observation with expectation given (flux) x (xsec) at FD

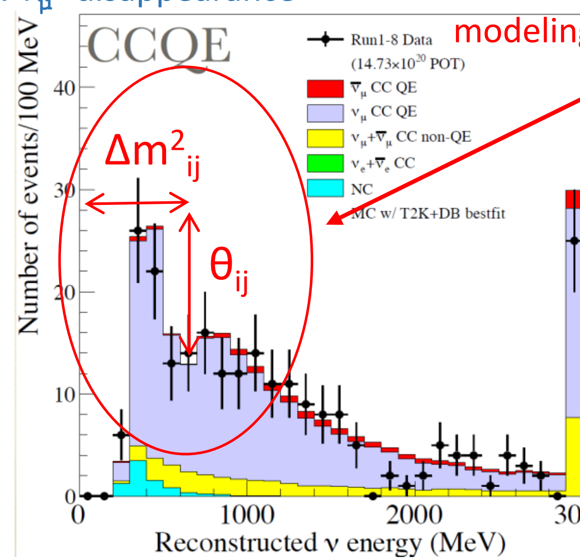
Near detector (ND):

- Close enough so no oscillations yet
- Use to constrain (flux) x (xsec)



$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - \sin^2 2\theta_{ij} \sin^2\left(1.27\Delta m^2_{ij} \frac{L(km)}{E_\nu(GeV)}\right)$$

T2K ν_μ disappearance



Neutrino energy reconstruction, and modeling of same, is important!

Beam:

- Production of hadrons
- Focusing effects
- Can achieve 10-15% errors in flux prediction with external hadron production measurements (i.e., NA61)

MINOS
MINOS+
T2K
NOvA
DUNE
T2HK

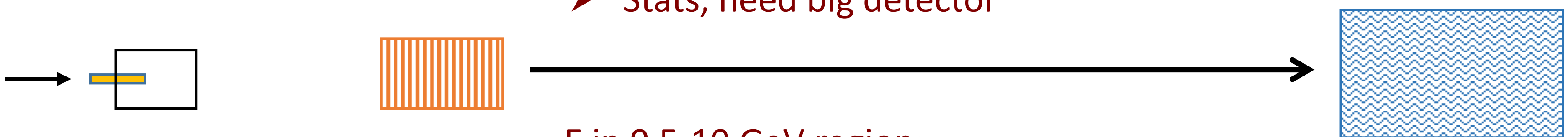
Future

Accelerator long-baseline neutrino oscillations

Some of the issues

L/E dependence:

- L big, ~300-1300 km
- Stats, need big detector

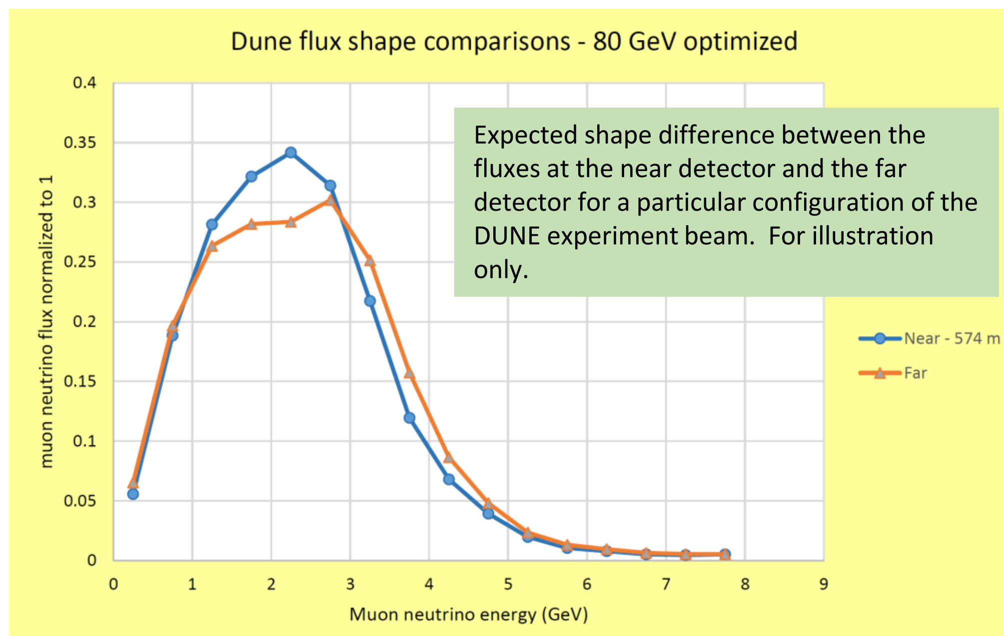


E in 0.5-10 GeV region:

- Mix of processes – CCQE, resonant, deep inelastic
- nuclear effects
- Xsec and modeling uncertainties

Charged-current quasi-elastic

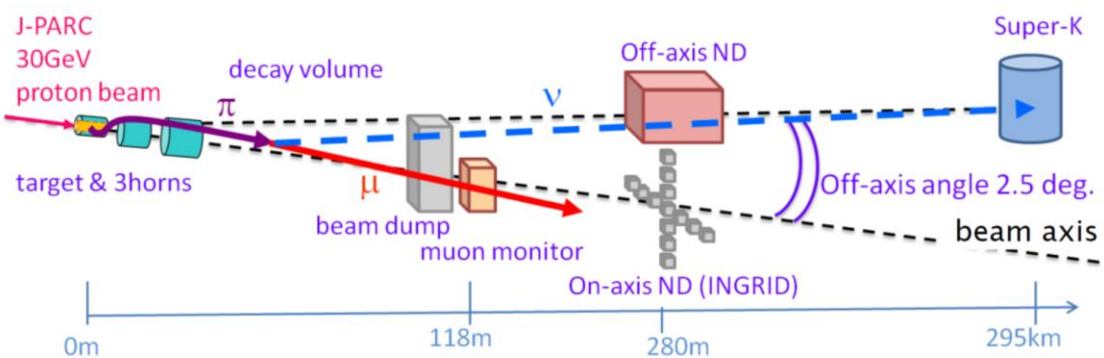
- ND and FD not identical
  - Nuclear target differences
  - acceptance and efficiency differences
- fluxes different at ND and FD
- Reconstructed energy depends on process



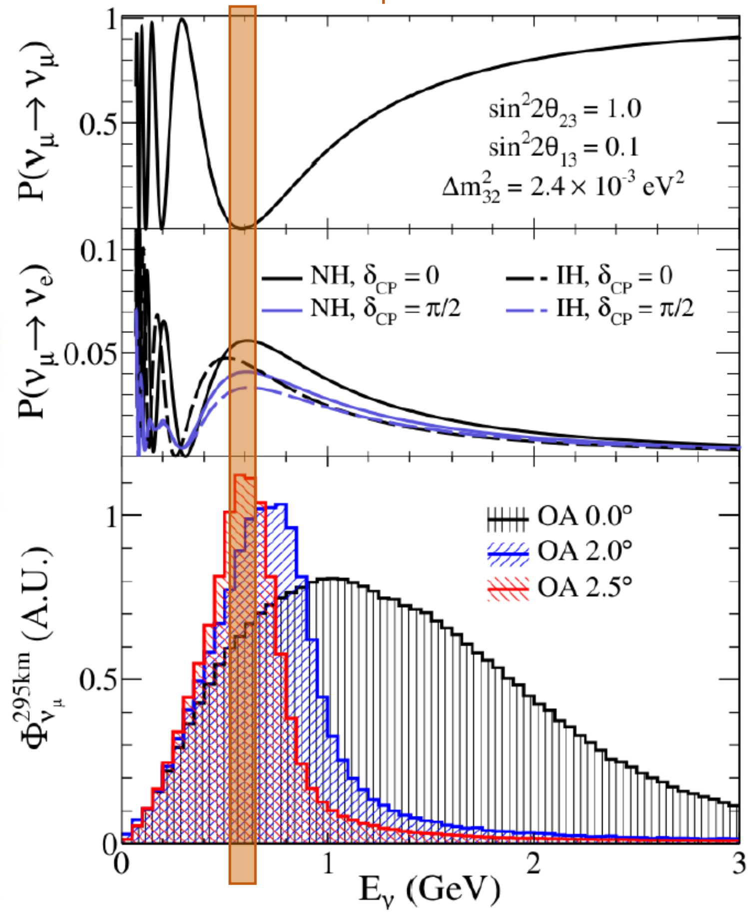
Accelerator long-baseline neutrino oscillations

Tokai to Kamiokande (T2K) experiment

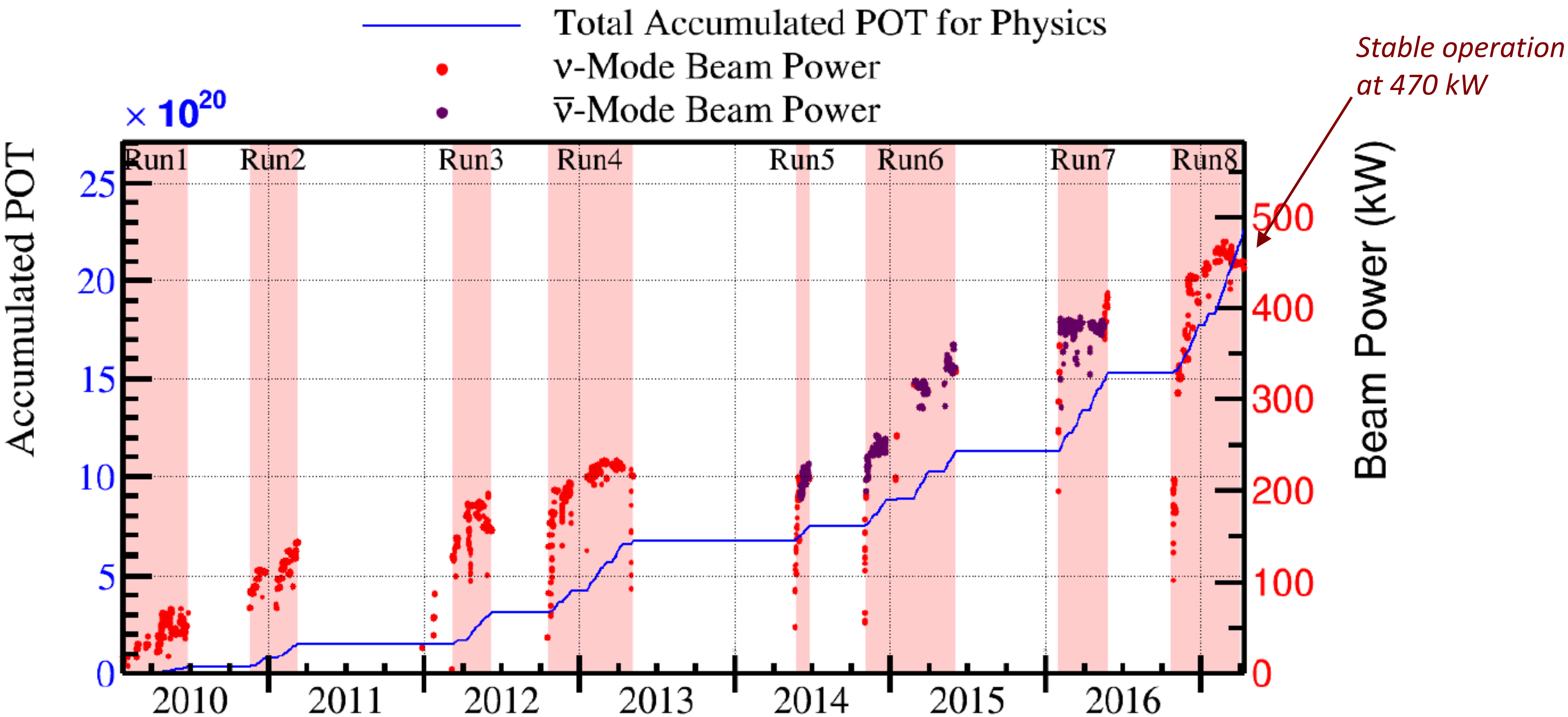
(Discussed in more detail by A. Bravar 8/26 in this meeting)



Peak of spectrum at energy where appearance and disappearance due to oscillations expected to be maximal



T2K data



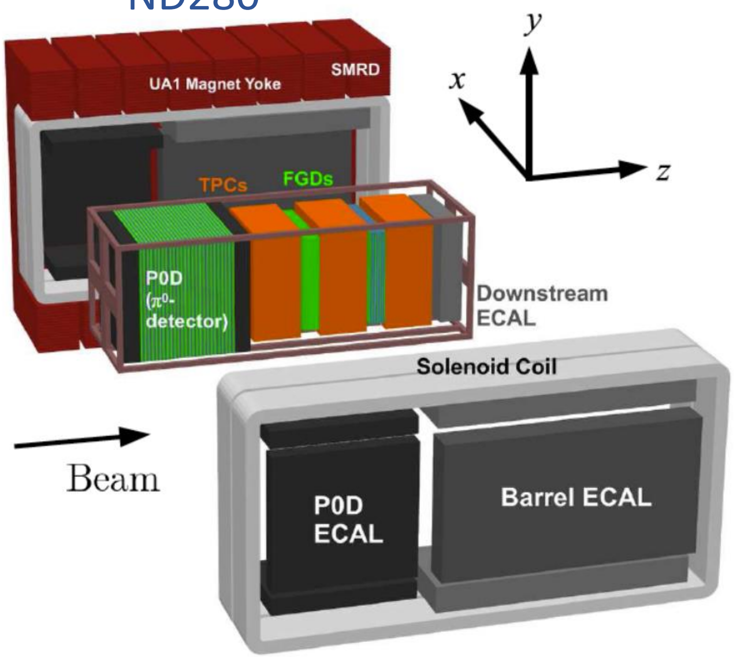
- 14.7x10^{20} protons-on-target (POT) in neutrino mode
- 7.6x10^{20} POT in antineutrino mode
- 29% of the approved T2K POT

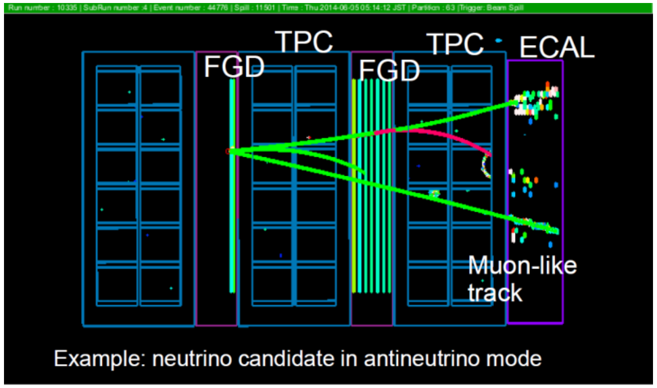
Results through Run 7 data published:
PRL **118**, 151801 (2017)
More detail in arXiv:1707.01048

Some results shown here include Run 8 data

T2K detectors

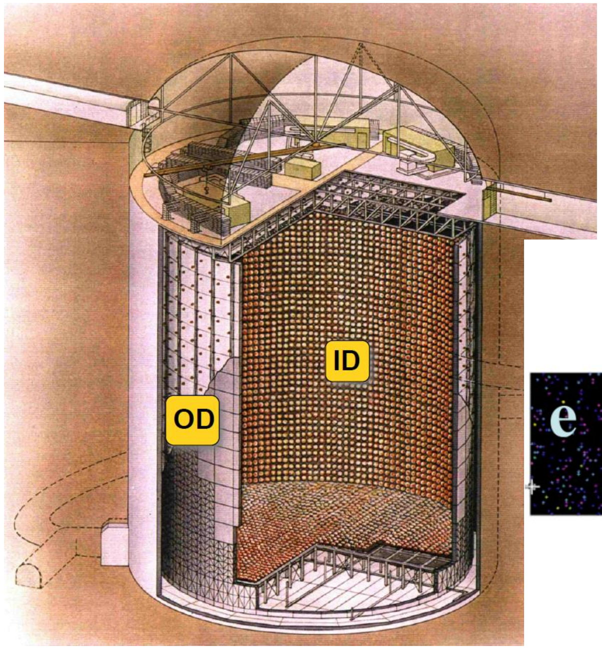
ND280



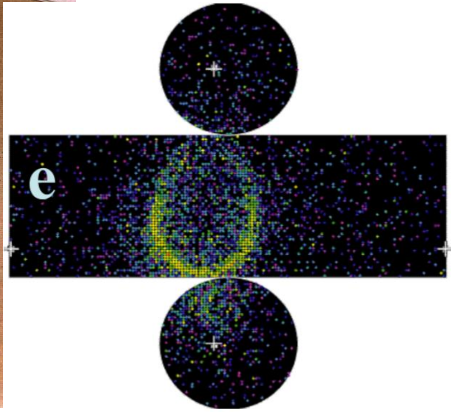


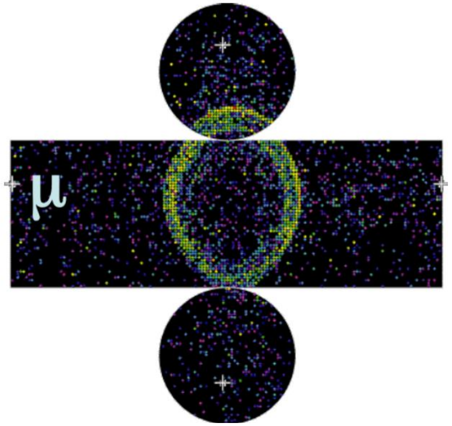
- Fine-grained detectors (FGD)
  - Scintillator bars (water targets in FGD2)
- Time projection chambers (TPC)
- Pizero detector (P0D)
  - Scintillator bars and water targets, lead radiators

Super-Kamiokande



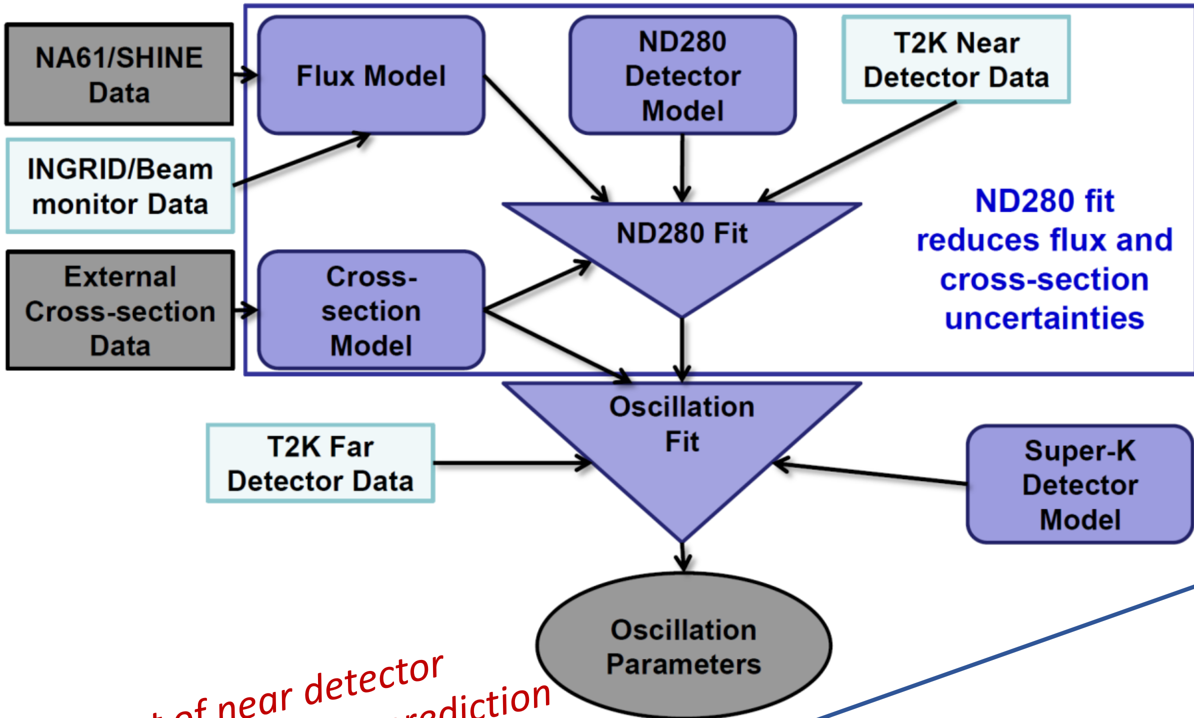
- 50 kton water-Cherenkov detector
- 13,000 PMT's





Analysis overview

-A. Bravar

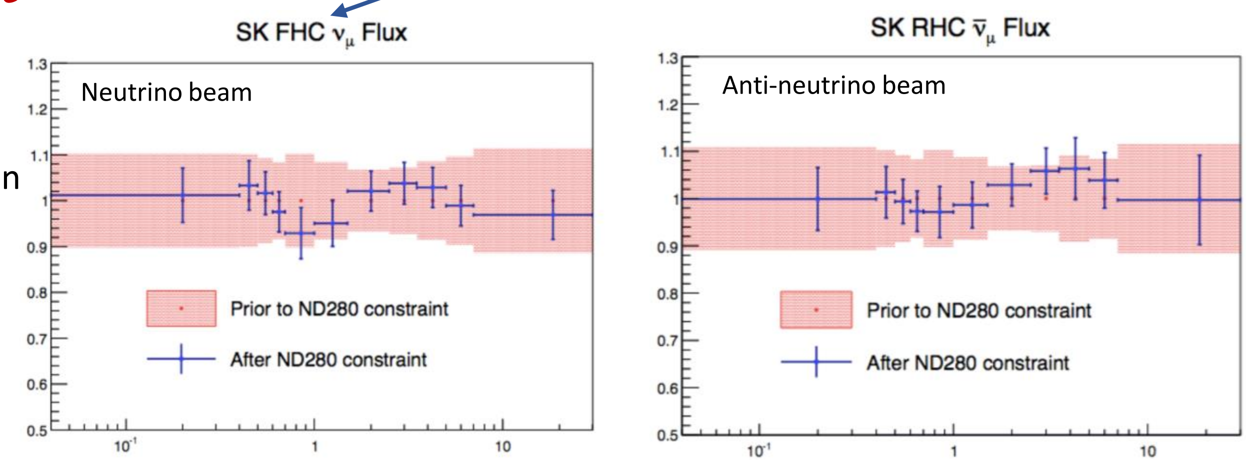


Throughout talk:

- FHC = forward horn current (selects primarily neutrinos)
- RHC = reverse horn current (selects primarily antineutrinos)

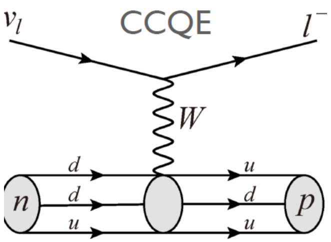
Effect of near detector constraint on flux prediction

Flux prediction relative to central value

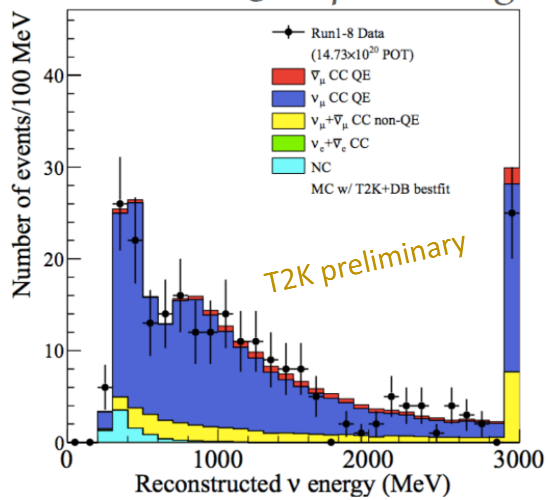


Neutrino energy in GeV

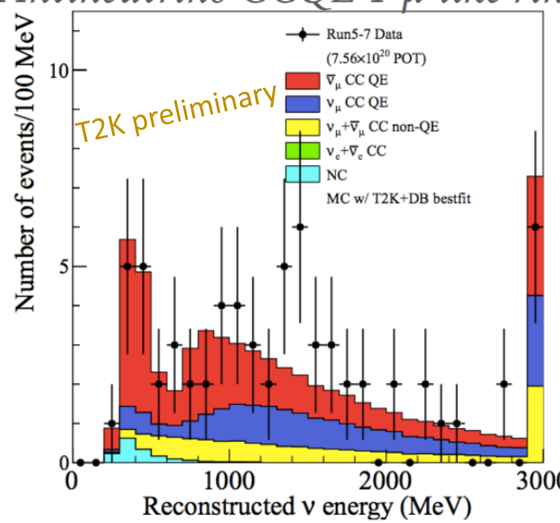
Observed spectra

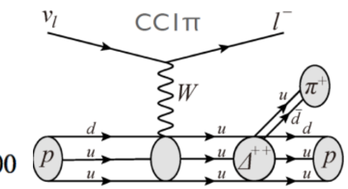


Neutrino CCQE 1 μ-like ring

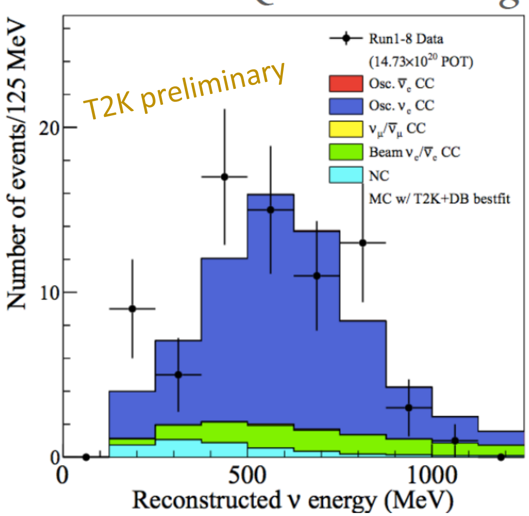


Antineutrino CCQE 1 μ-like ring

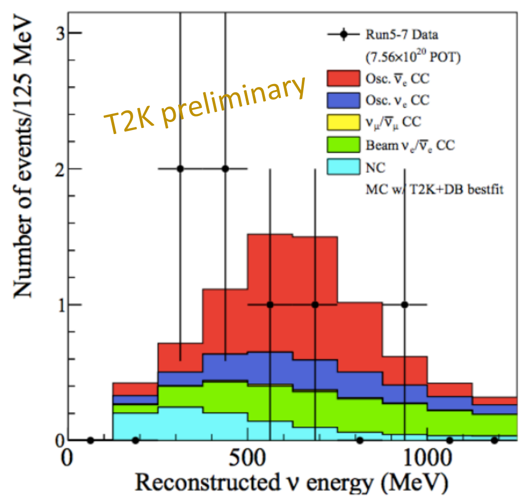




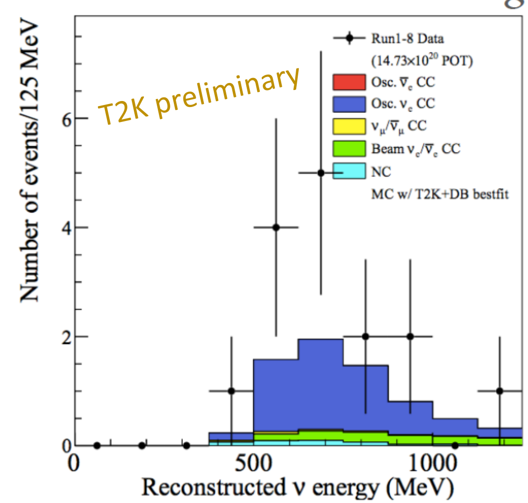
Neutrino CCQE 1 e-like ring



Antineutrino CCQE 1e-like ring



Neutrino CC1π 1e-like ring



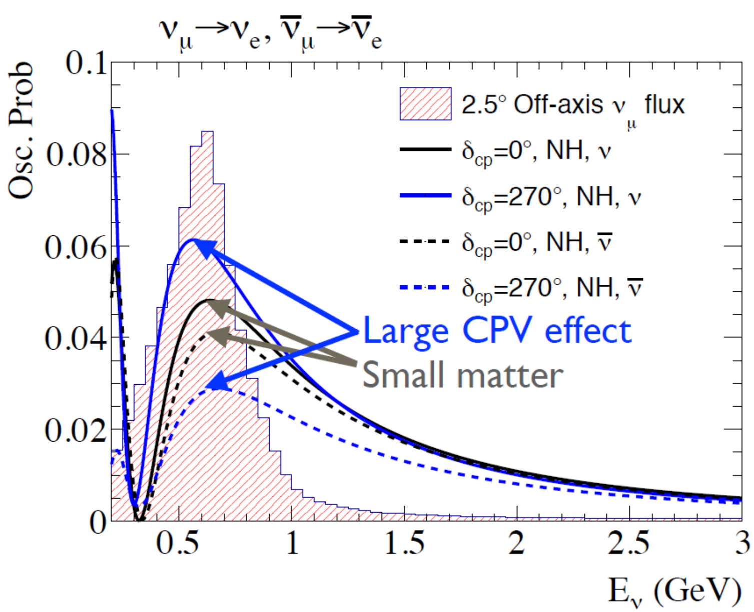
Numbers and CPV

	δ=-0.5π	δ=0	δ=0.5π	δ=π	observed
FHC CCQE 1ring e-like	73.5	61.5	49.9	62.0	**74**
FHC CC1π 1ring e-like	6.92	6.01	4.87	5.78	**15**
RHC CCQE 1ring e-like	*7.93*	*9.04*	*10.04*	*8.93*	***7***
FHC CCQE 1ring μ-like	267.8	267.4	267.7	268.2	**240**
RHC CCQE 1ring μ-like	*63.1*	*62.9*	*63.1*	*63.1*	***68***

Probability for electron appearance is enhanced in neutrino beam

Probability for electron appearance is suppressed in antineutrino beam
Note: big neutrino contribution

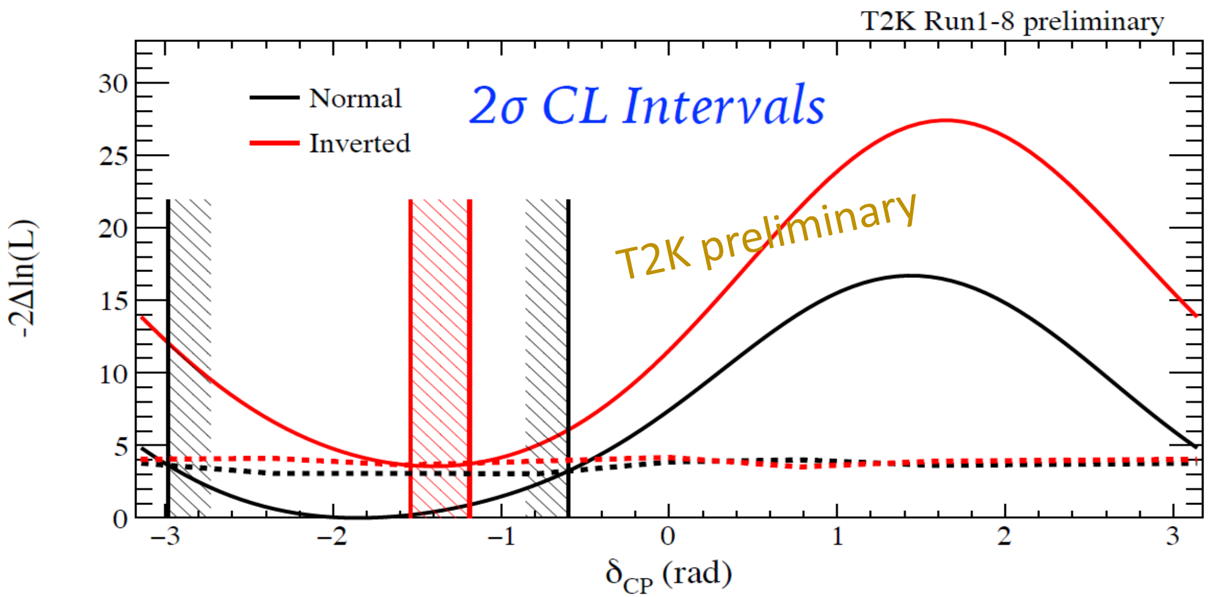
-M. Smy



CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

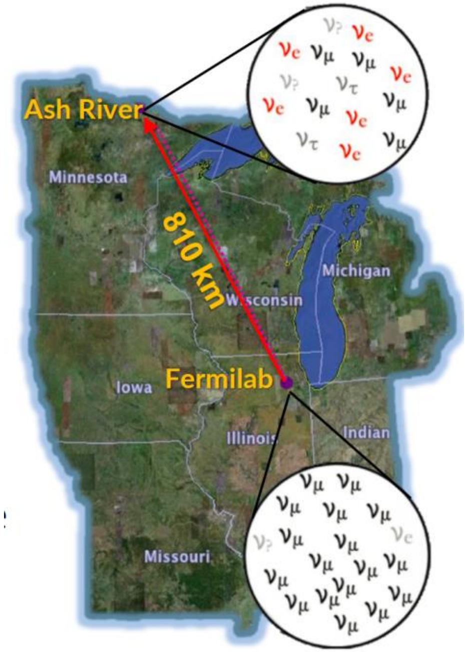
-A. Izmaylov

Constraints on δ_{CP}



- Do fits determining 1 or 2 parameters and marginalizing over the others
- Here T2K used (and marginalized over) the reactor measurement of $\sin^2\theta_{13}$.
- Plot change in $-2\ln(L_{marg})$ relative to global minimum in two hierarchies
- CP conserving values $(0,\pi)$ are outside 2σ intervals

NOVA: NuMI Off-axis ν_e Appearance Experiment



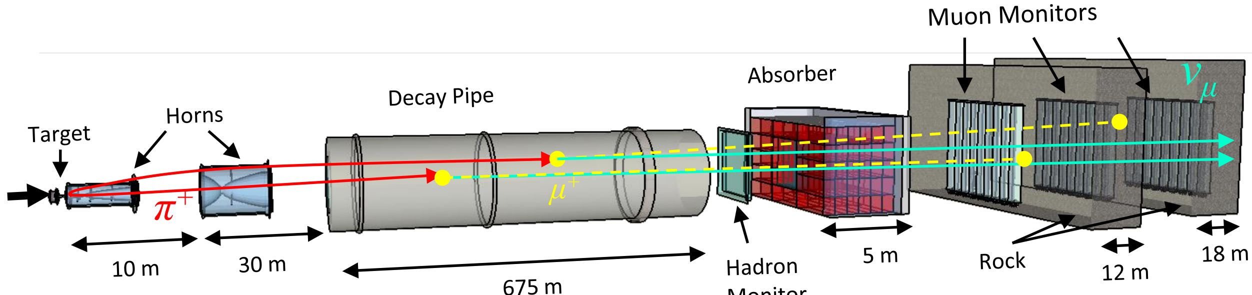
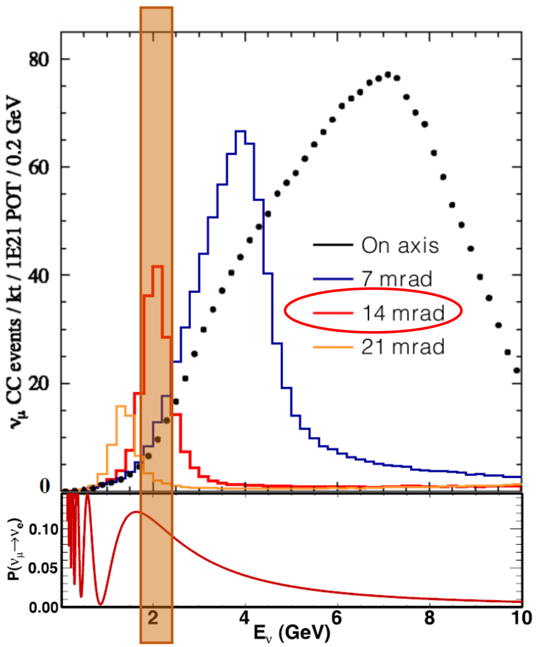
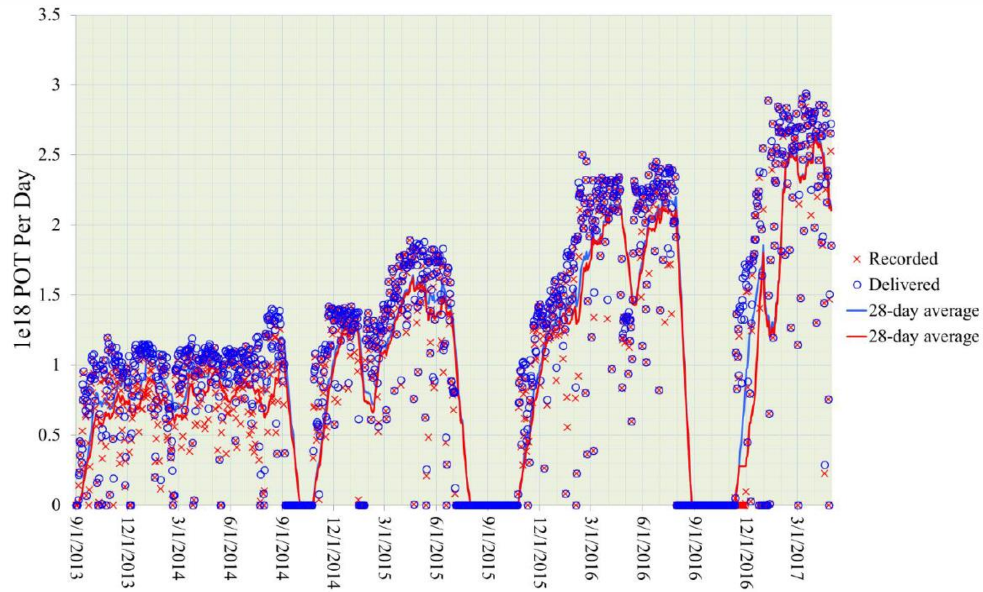


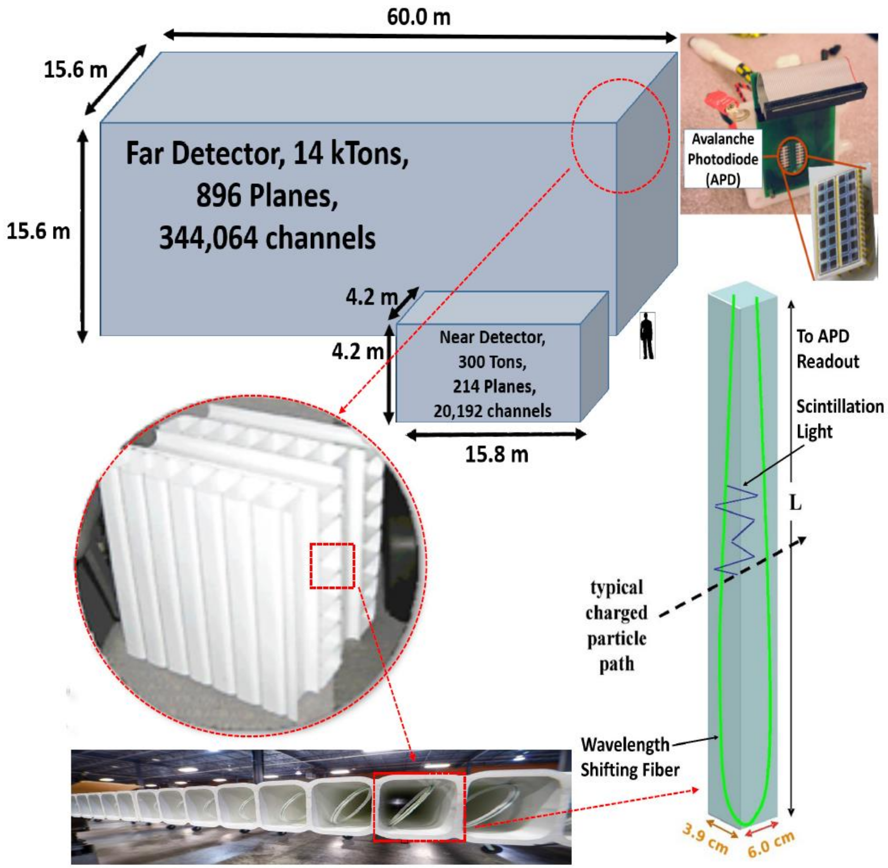
figure courtesy Ž. Pavlović

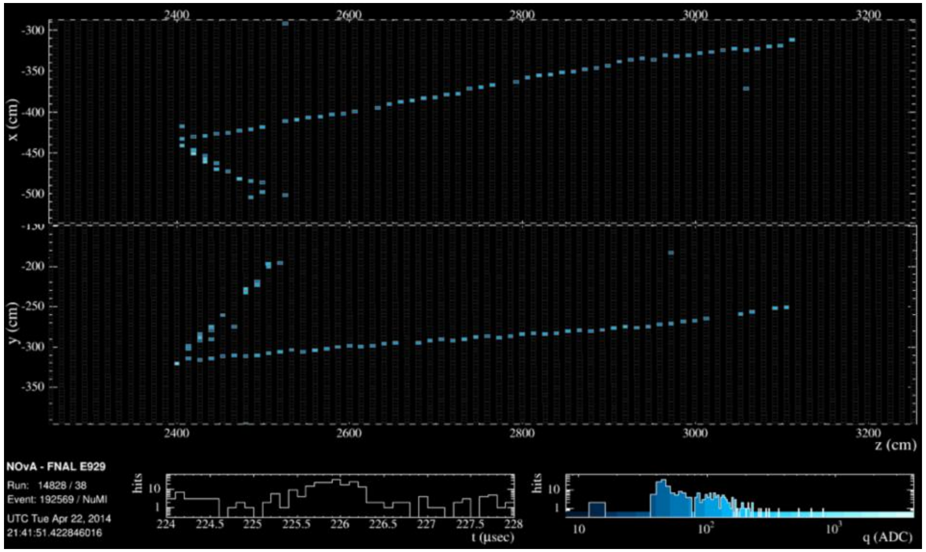


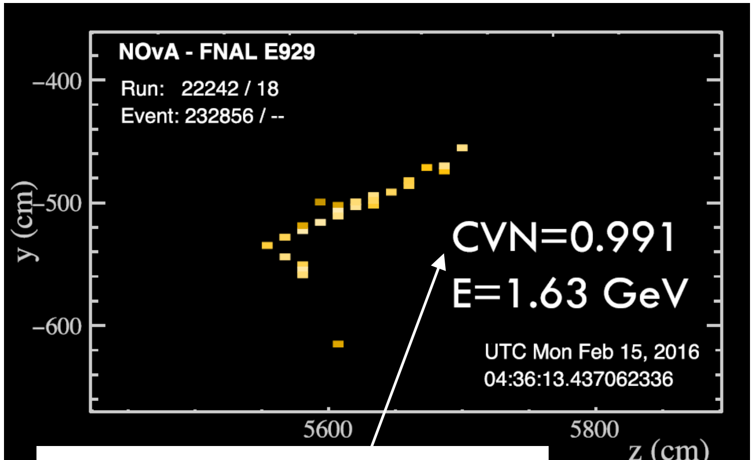


- Achieved 700 kW design goal (750 kW)
- Neutrino beam Feb. 2014-May 2016, antineutrinos since then
- Low Z, 65% active, tracking calorimeter

NOvA experiment



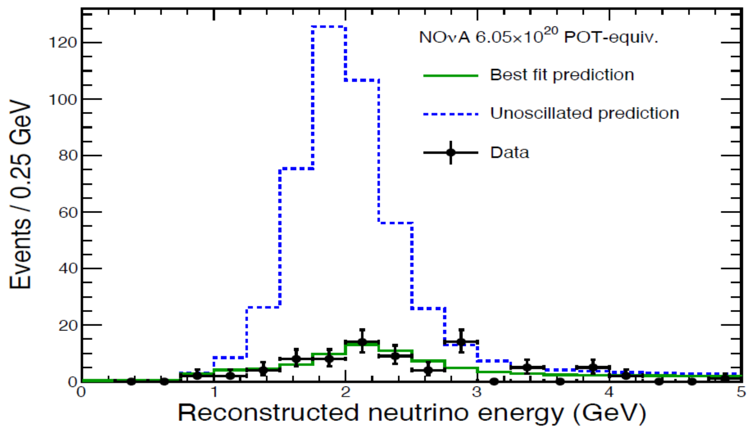


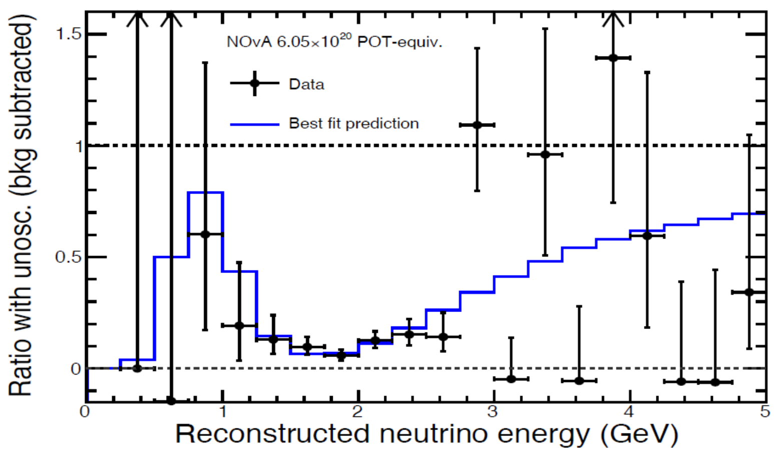


Convolutional neural network acting on “image” of hits in detector – convolutional visual network

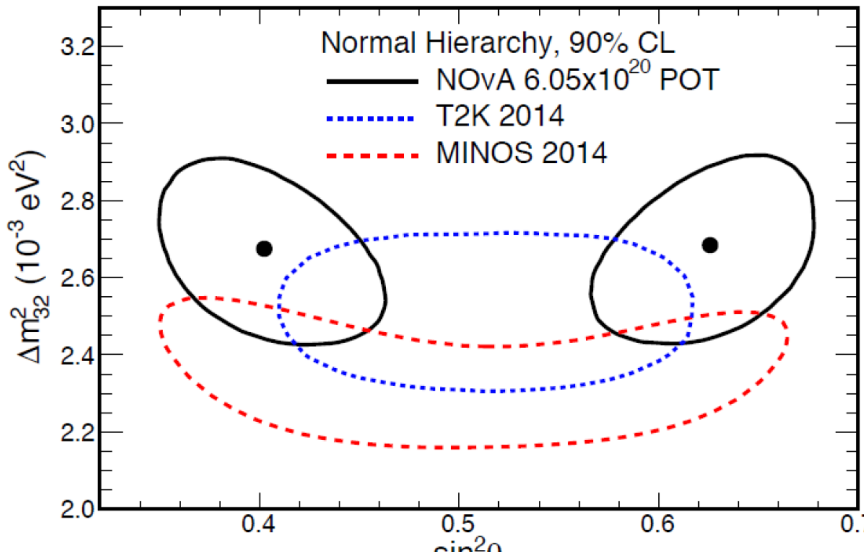
- ND and FD “identical”
- Plastic cells filled with liquid scintillator
- Low Z, 65% active, tracking calorimeter

Constraints on “atmospheric” parameters





-P. Singh

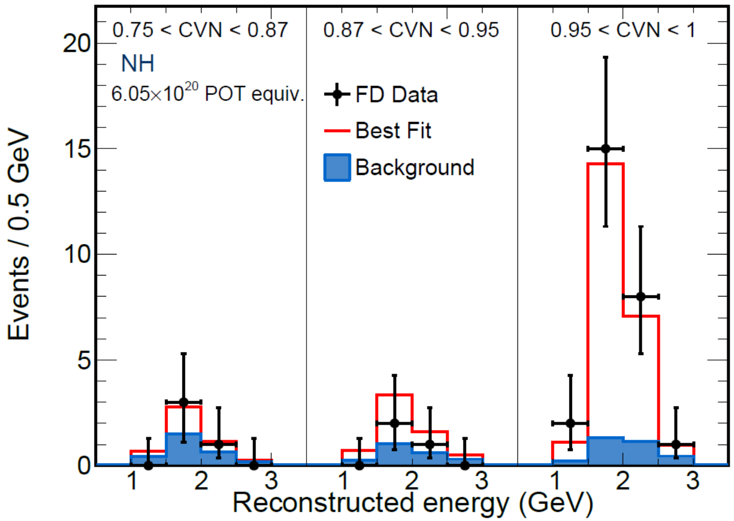


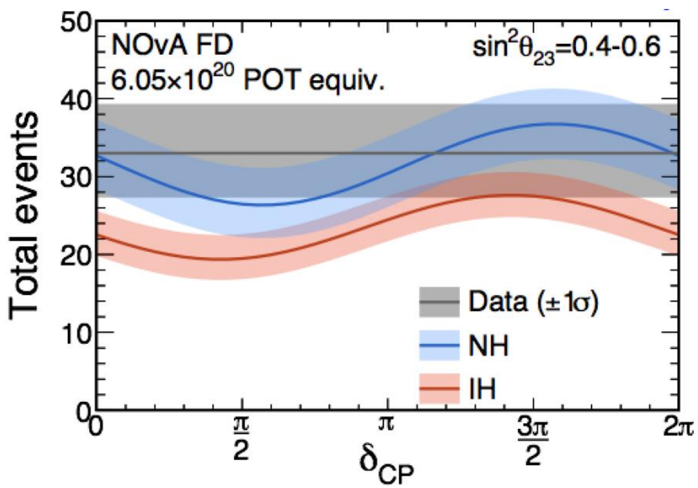
-F. Jediny

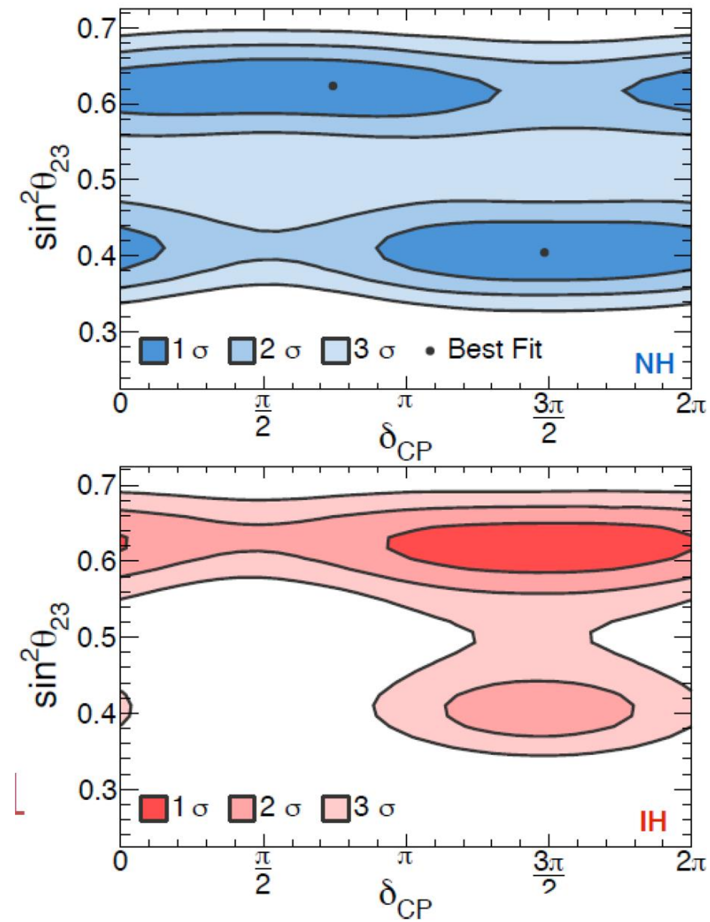
- 78 ν_μ events observed (expect 473 without oscillations)
- Maximal mixing disfavored at 2.6 σ

Constraints on δ_{CP}

ν_e appearance spectra





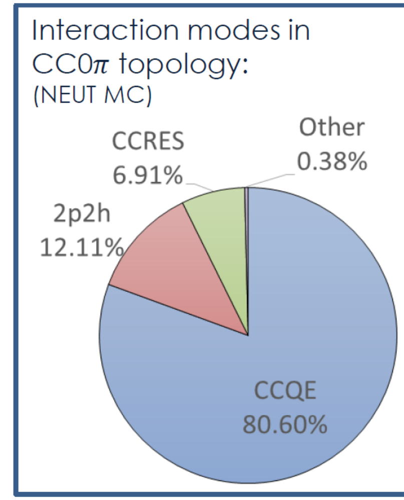


PRL **118**, 231801 (2017)

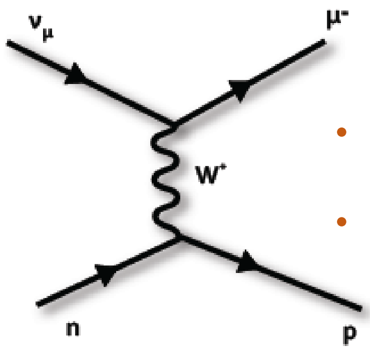
- Fit ν_e spectrum simultaneously with ν_μ spectrum, taking θ_{13} constraint from reactor experiments.
- Fit for $\sin^2\theta_{23}$, δ_{CP} and Δm^2_{32}
- IH, lower octant for θ_{23} rejected at 93% CL.

Into the weeds! Neutrino interaction physics

- Interesting physics
- Critically important for high precision neutrino oscillation physics
  - Reconstruction of neutrino energy
  - Modeling: extrapolation to FD, acceptance, backgrounds, energy bias and resolution, determining systematic errors
  - Expansion of signal into additional channels for increased statistics

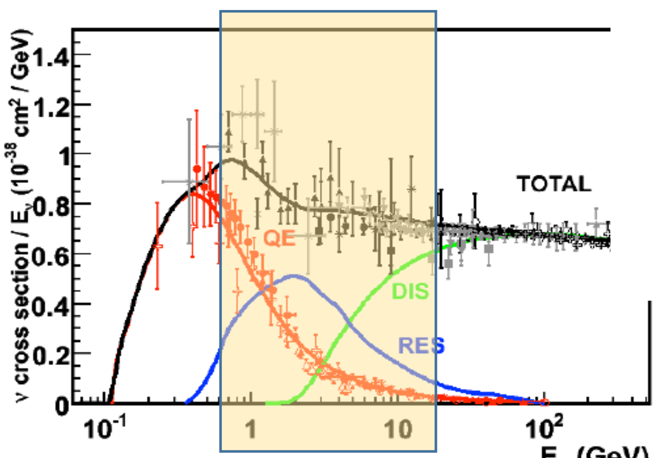


-S.Dolan

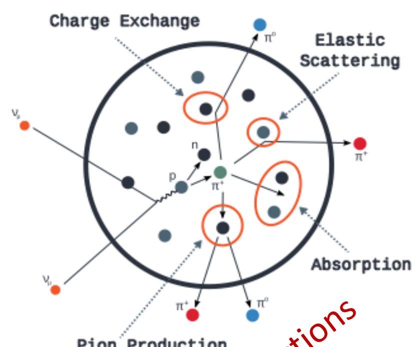


- Assumes free nucleon at rest and no nuclear effects
- Can reconstruct neutrino energy from lepton alone

CCQE: charged current quasielastic

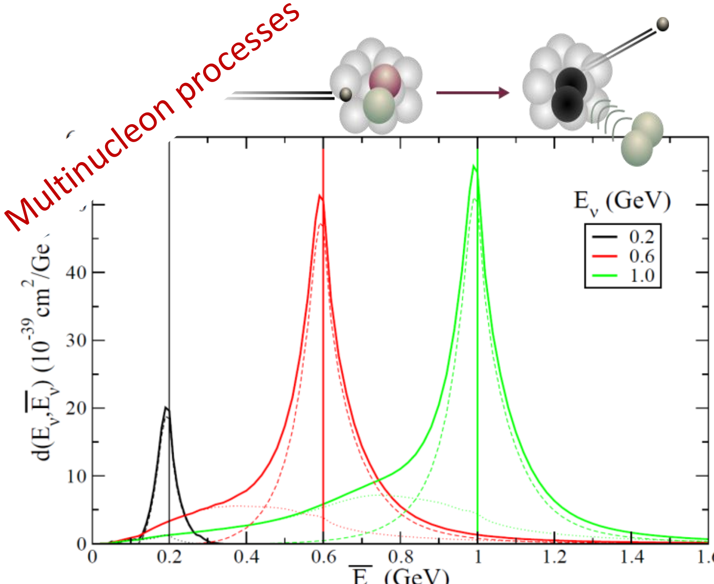


Formaggio, Zeller, Rev. Mod. Phys. 84, 1307, 2012



Final state interactions

Multinucleon processes



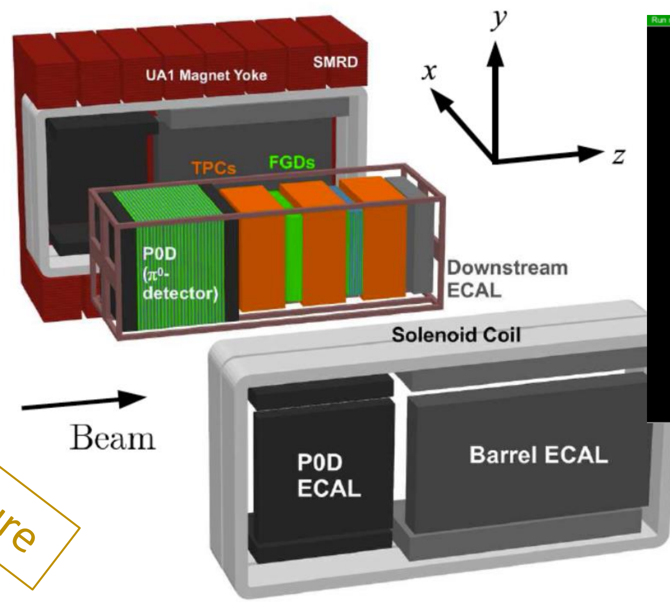
Martini, Ericson, Chanfray, Phys. Rev. D87, 013009, 2013

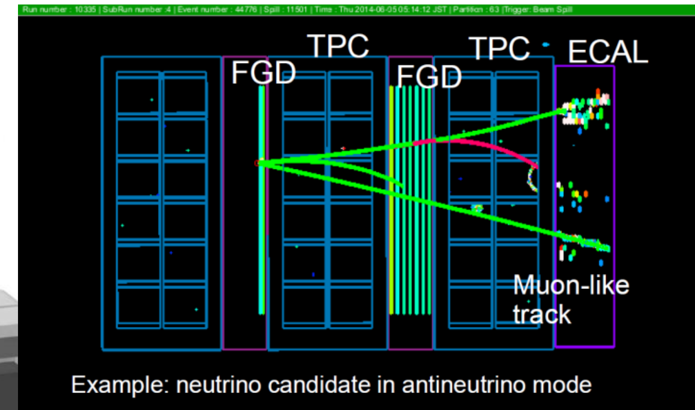
Neutrino interactions: T2K

- ANL, BNL, FNAL, CERN bubble chambers
- NOMAD
- MiniBooNE
- MINERvA
- T2K
- ARGONEUT
- MicroBooNE
- ICARUS (at FNAL)
- SBND
- DUNE

Future

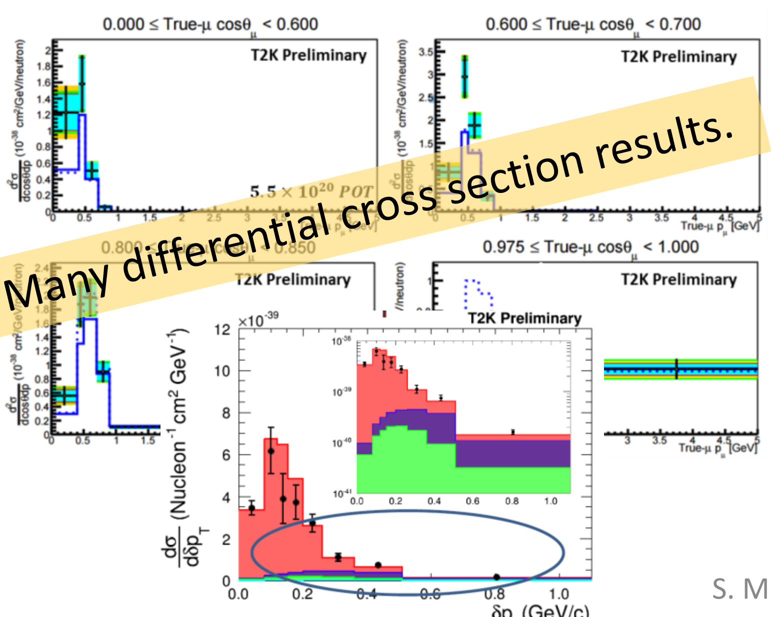
ND280





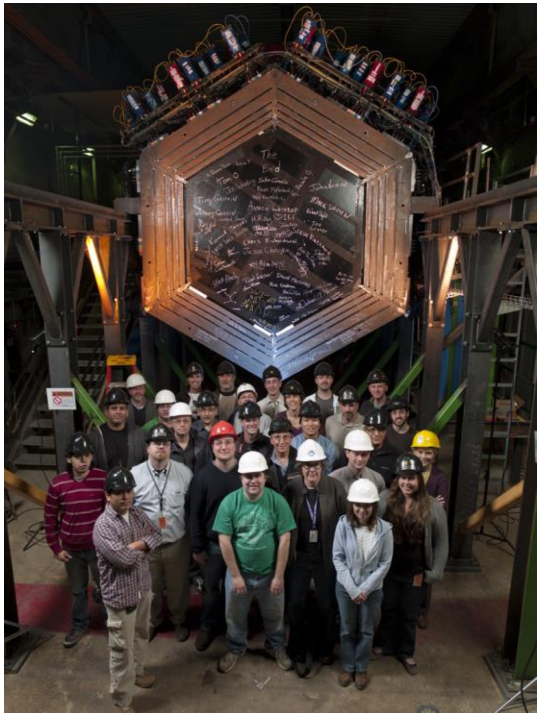
CC = charged current
NC = neutral current

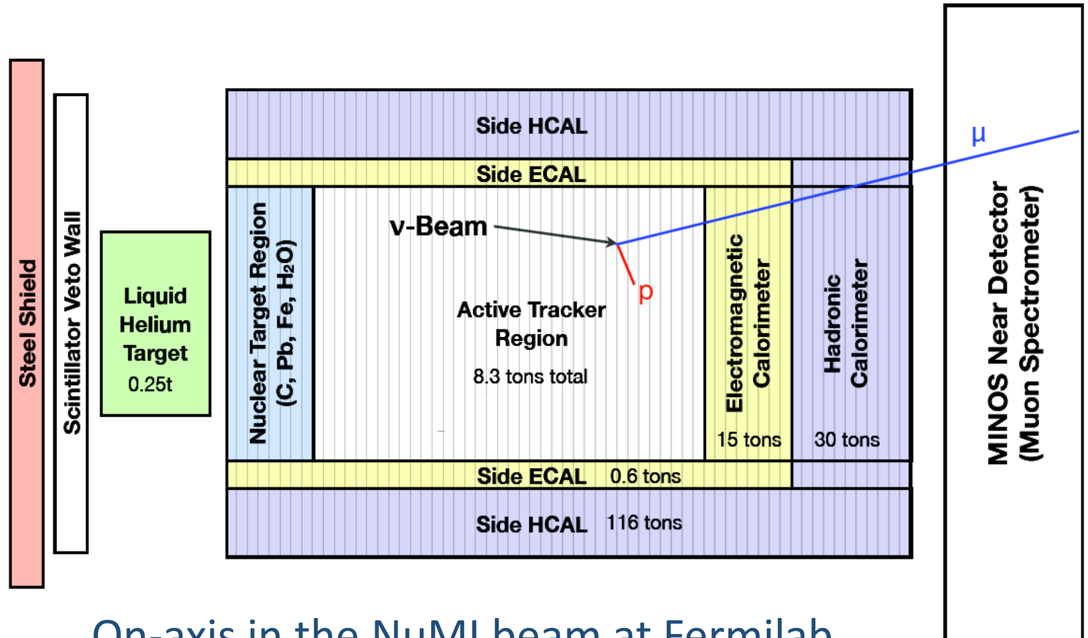
- Water and carbon targets
- Many different recent and soon-to-come results in neutrino xsec physics
- ν_μ, CC and NC, muon and proton variables, pion production
- ν_e CC measurements
- Recent progress on using transverse momentum balance variables to enhance sensitivity to nuclear and FSI effects



Many differential cross section results.

Neutrino interactions: MINERvA

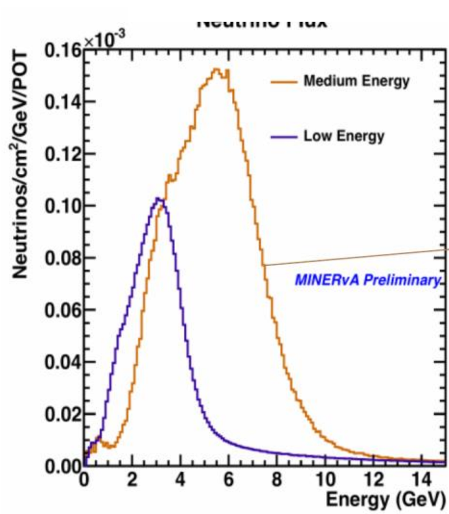


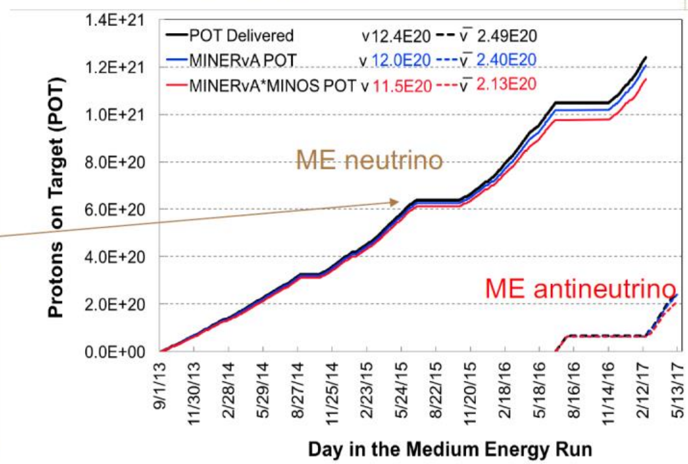


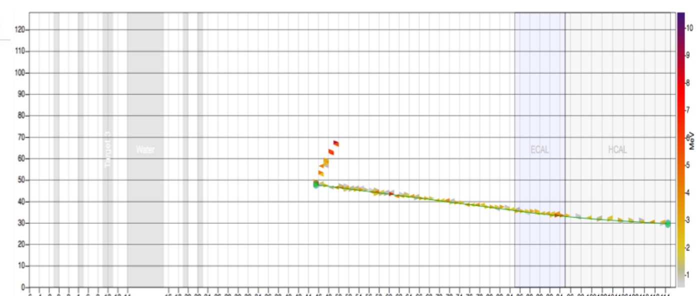
On-axis in the NuMI beam at Fermilab

Beam Power: LE ≈ 250kW.

Beam Power: ME ≈ 650kW.

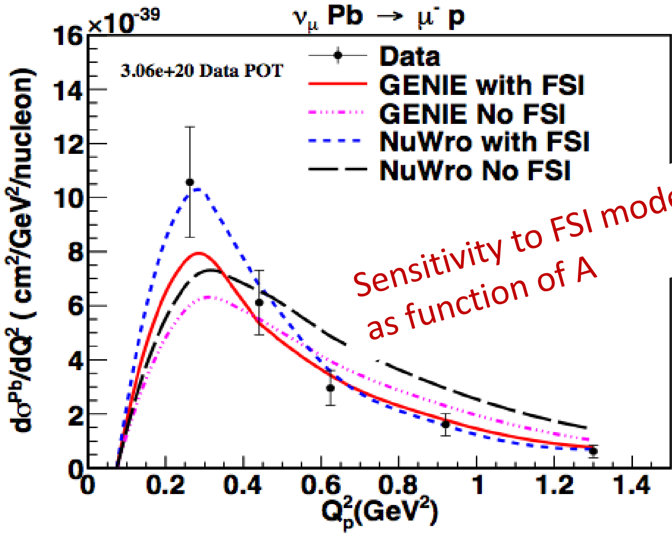




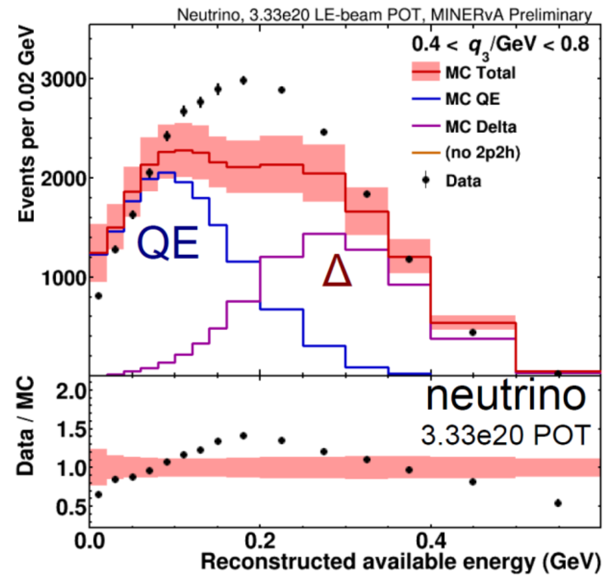


Neutrino interactions: MINERvA

(a couple of NUINT 2017 results)

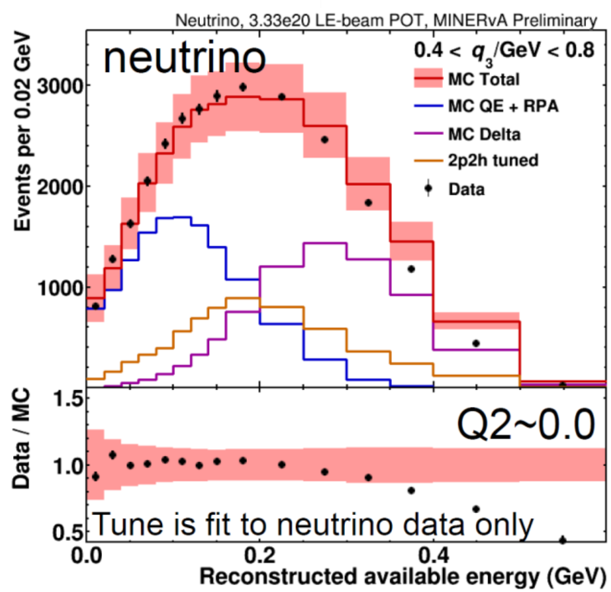


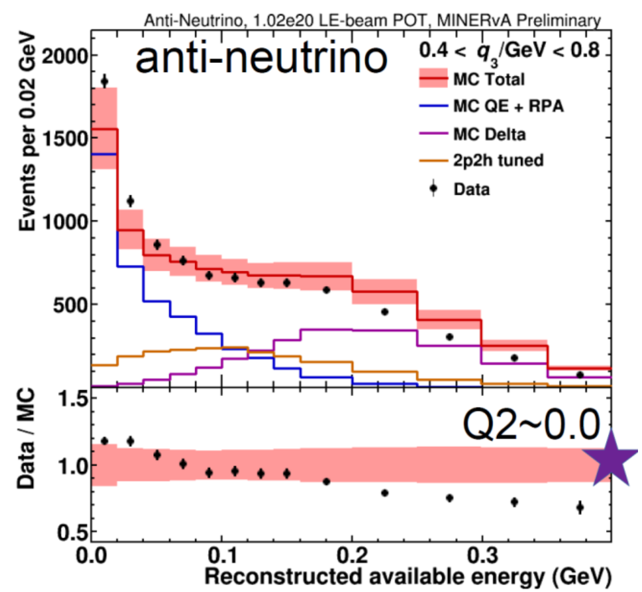
Sensitivity to FSI model as function of A



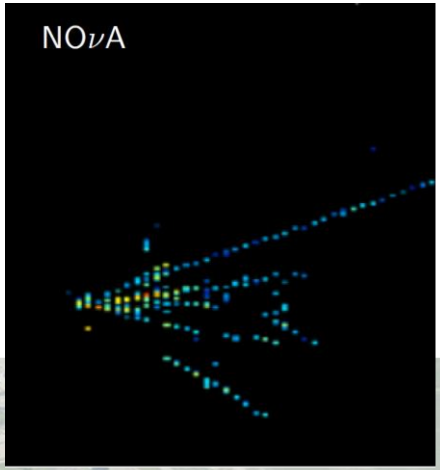
Model agrees with data much better with added multinucleon process.

Tune model on neutrinos and seems to fit antineutrinos well!

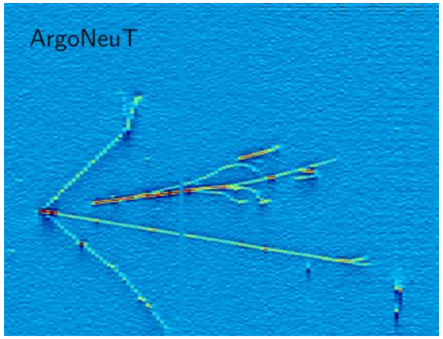




Neutrino interactions: near future



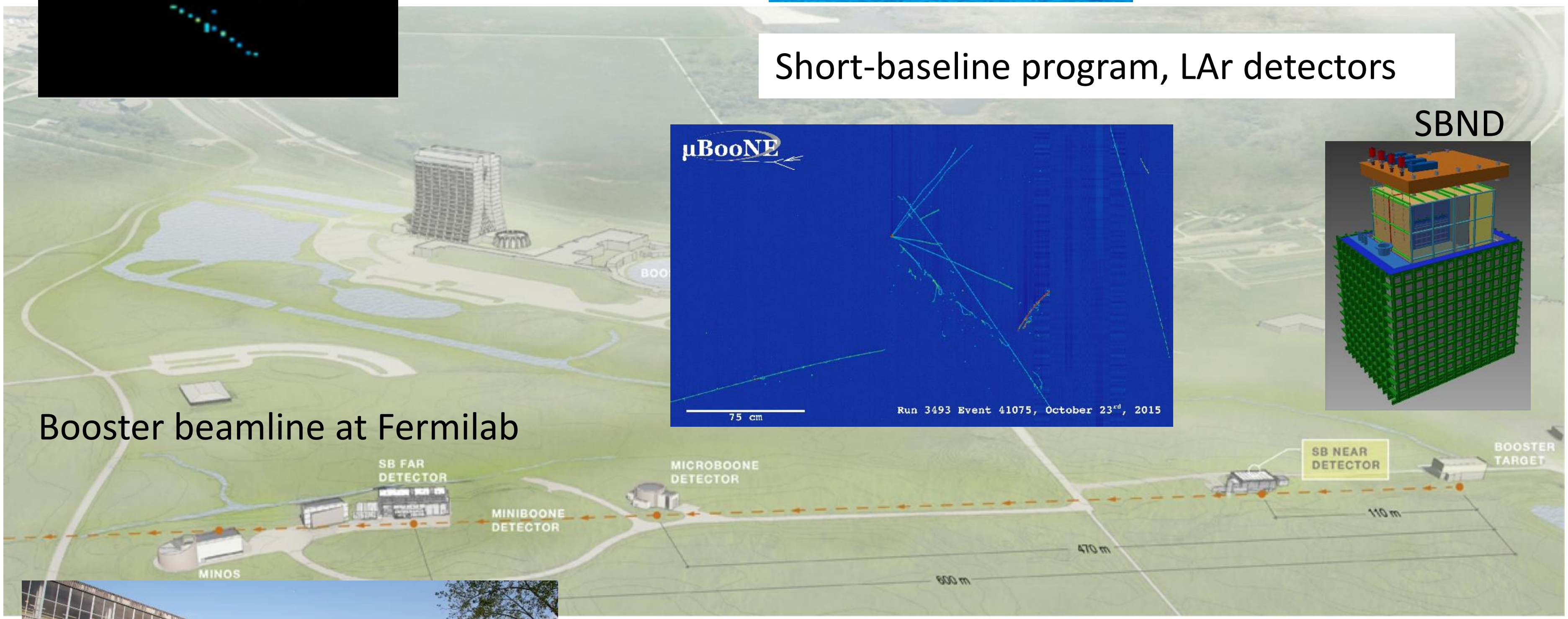
Data in hand, xsec program underway



Small, some interesting results, heralds the LAr era!

Short-baseline program, LAr detectors

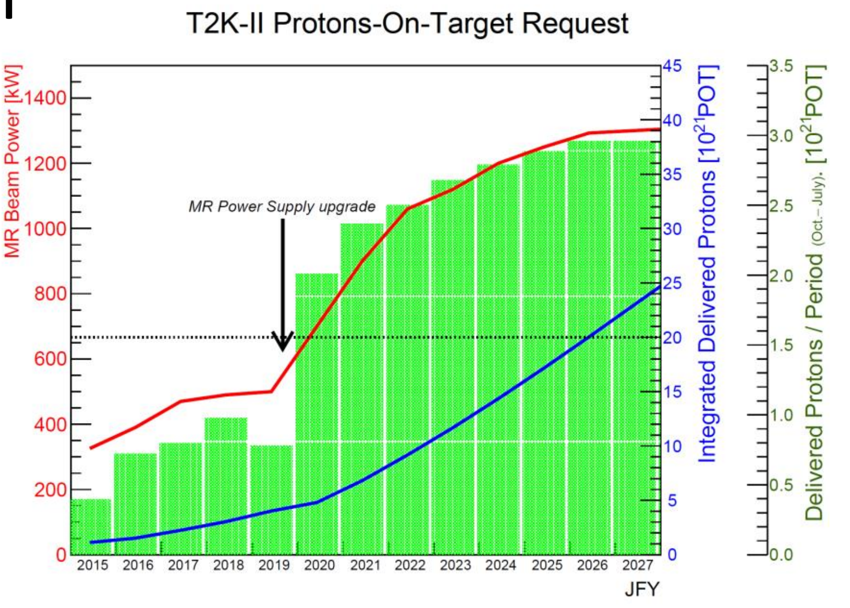
SBND



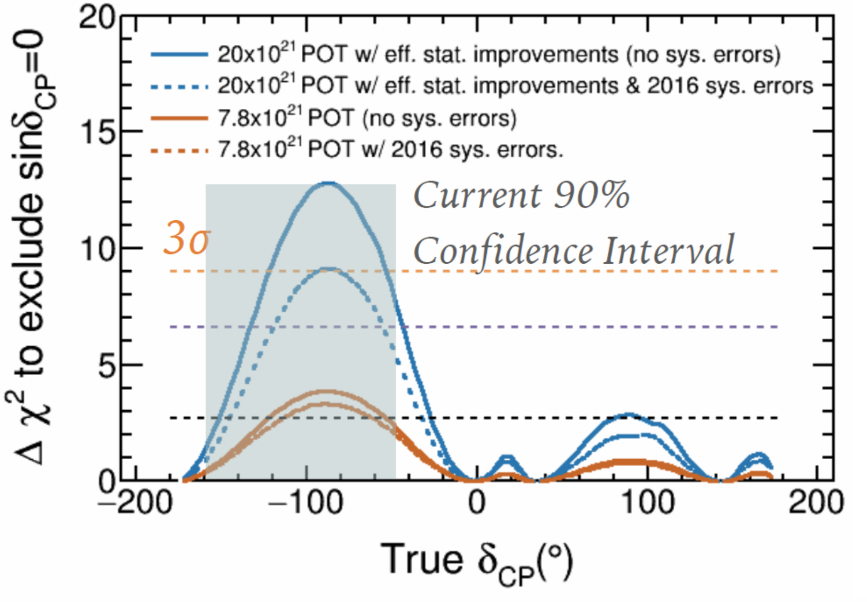
Booster beamline at Fermilab

ICARUS now moved to Fermilab

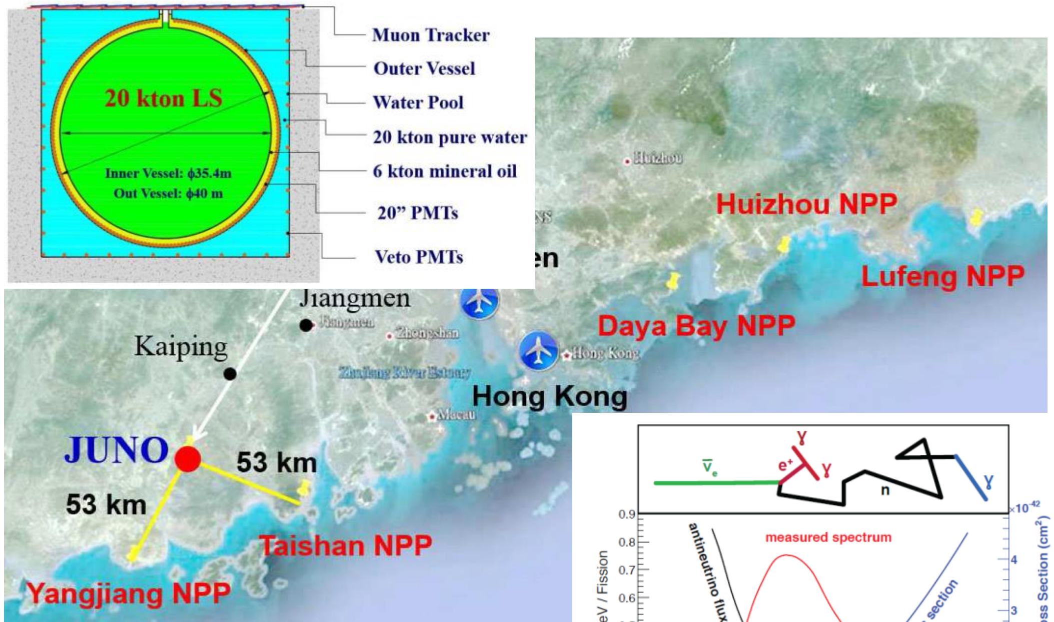
T2K-II

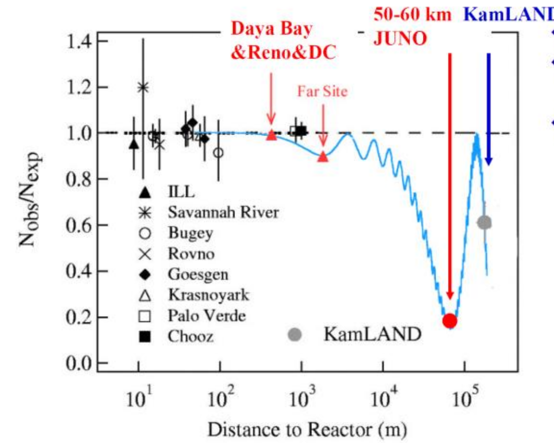


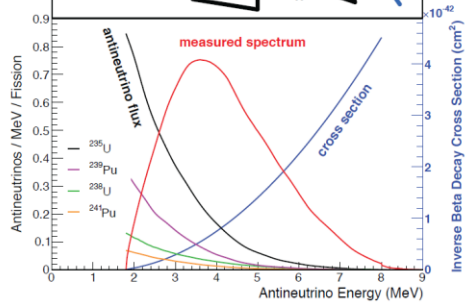
- T2K originally approved for 7.8×10^{21} POT (~3.4 x current data)
- Proposal to extend T2K operation to 2026 and collect 20.0×10^{21} POT
- Factor of 9 over current data
- Analysis and detector and operations upgrades give a 50% improvement in experimental sensitivity

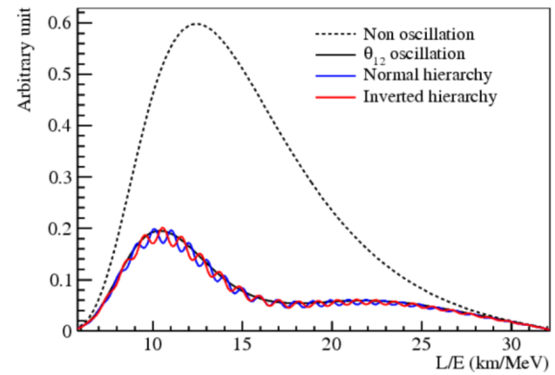


JUNO

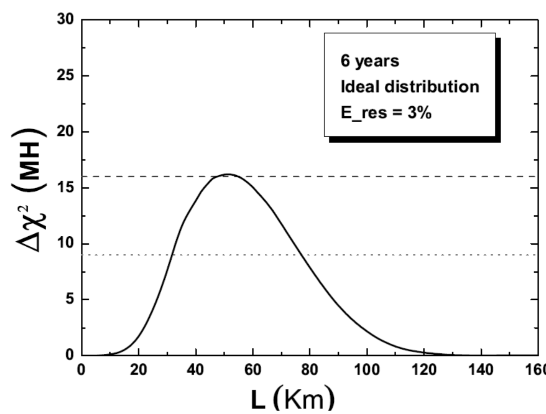


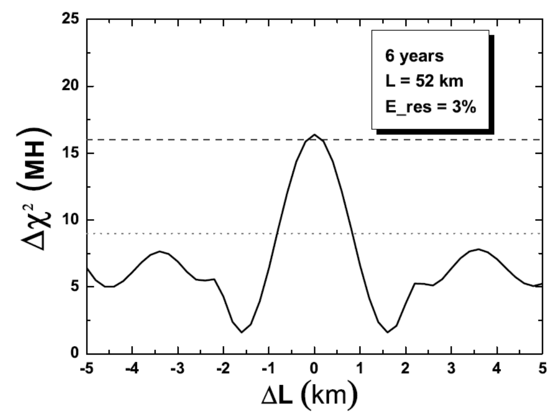






Mass Hierarchy discrimination as function of baseline and baseline difference between two reactors



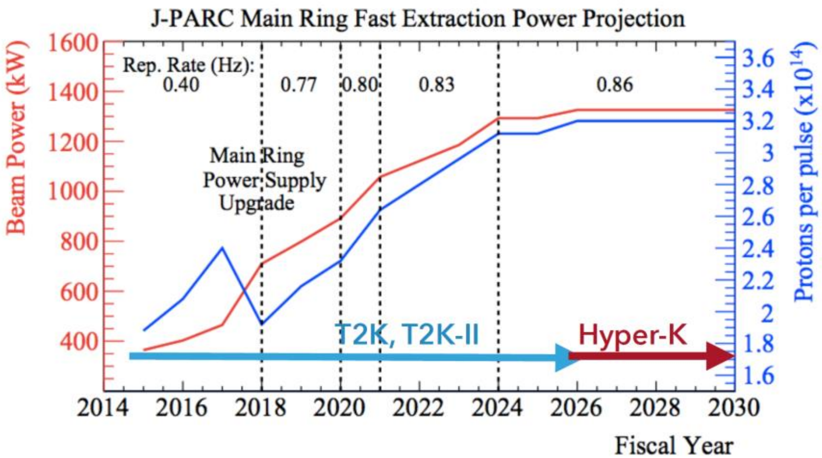


arXiv:1507.05613

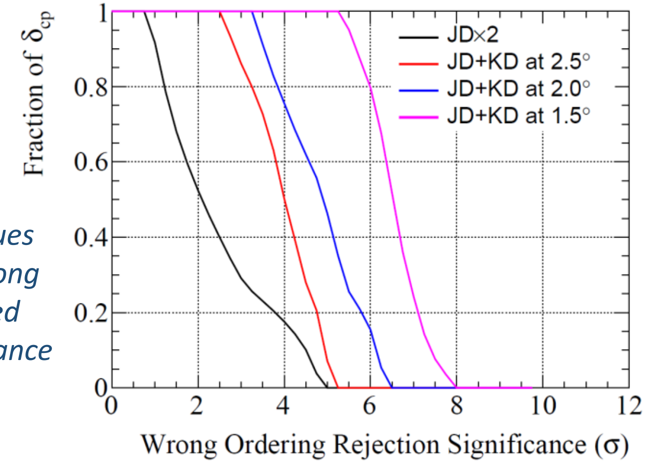
Hyper-Kamiokande

(Discussed in more detail by A. Bravar 8/26 in this meeting)

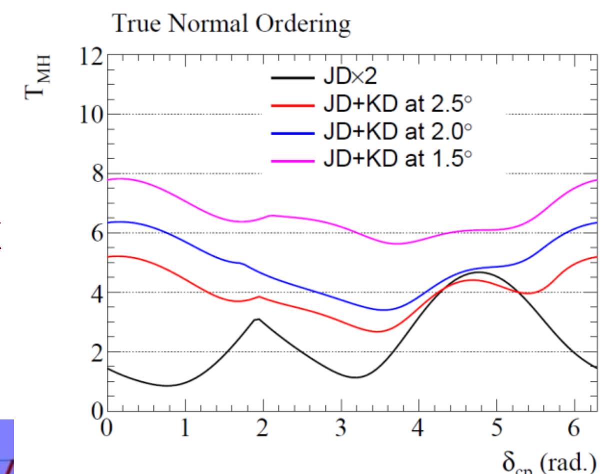
- Long-baseline neutrino oscillations
- Low energy neutrinos
- Proton decay



-M. Hartz, NUFACT 2016

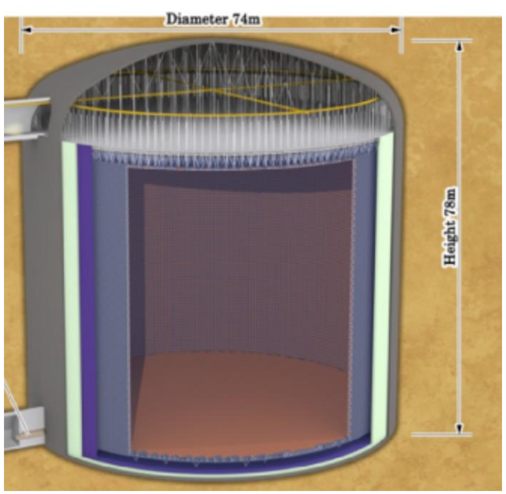


Fraction of δ_{CP} values over which the wrong hierarchy is rejected with given significance

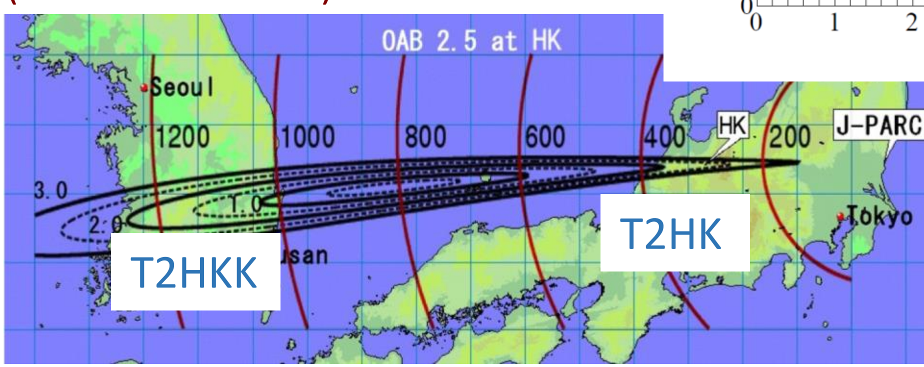


Significance with which CP conservation can be rejected

1 tank is ~8 x SuperK fiducial volume

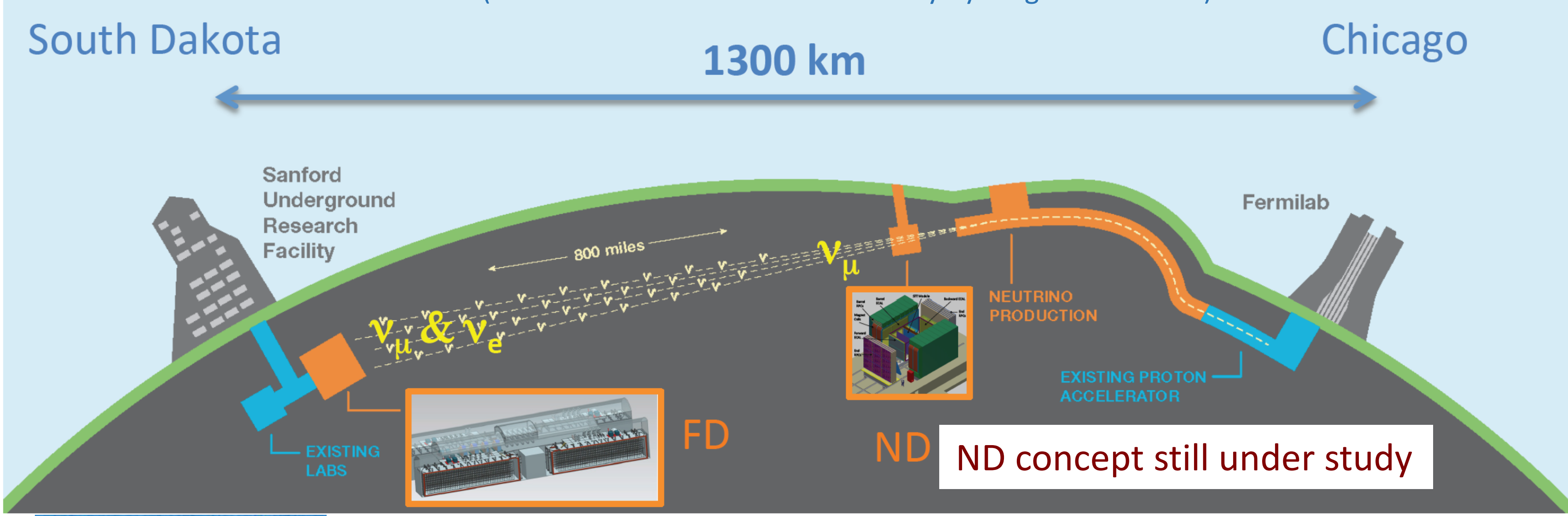


Best sensitivity with one tank near SK (295 km) and one in Korea (1000-1300 km) to improve sensitivity (arXiv:1611.06118)

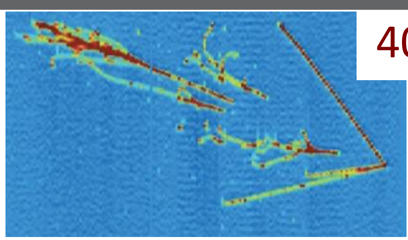


DUNE: Deep Underground Neutrino Experiment

(Discussed in more detail later today by Sergio Bertolucci)



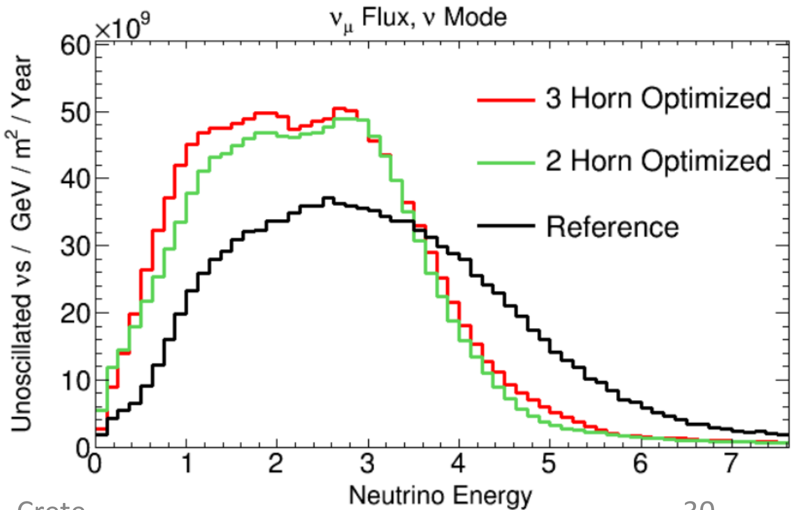
ND concept still under study



40 kt liquid argon TPC (4x10 kt) far detector

- Long-baseline neutrino oscillations
- Supernova neutrinos
- Proton decay

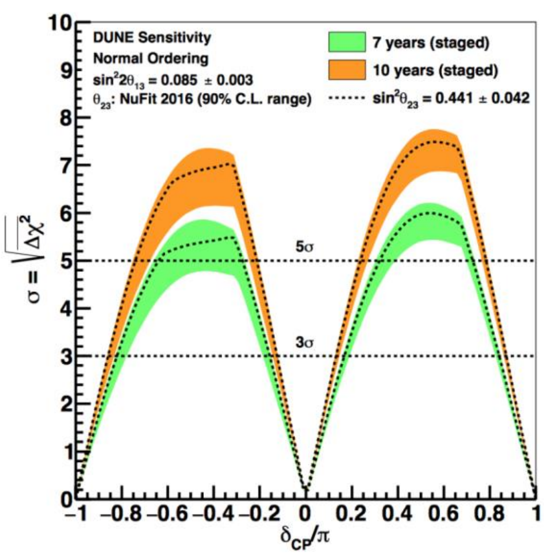
Intense wideband beam

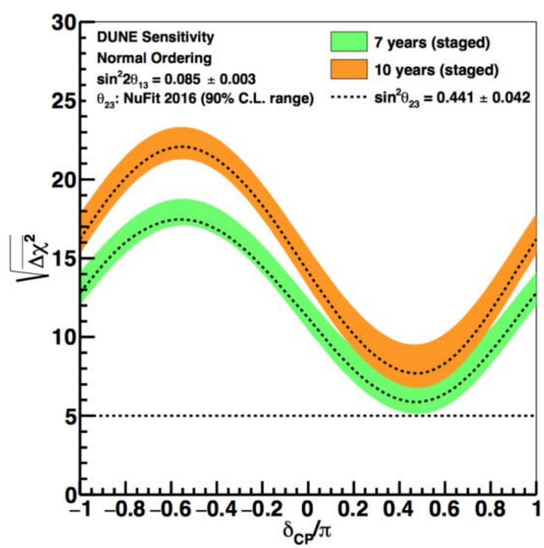


DUNE is happening

Recent groundbreaking at facility in S. Dakota

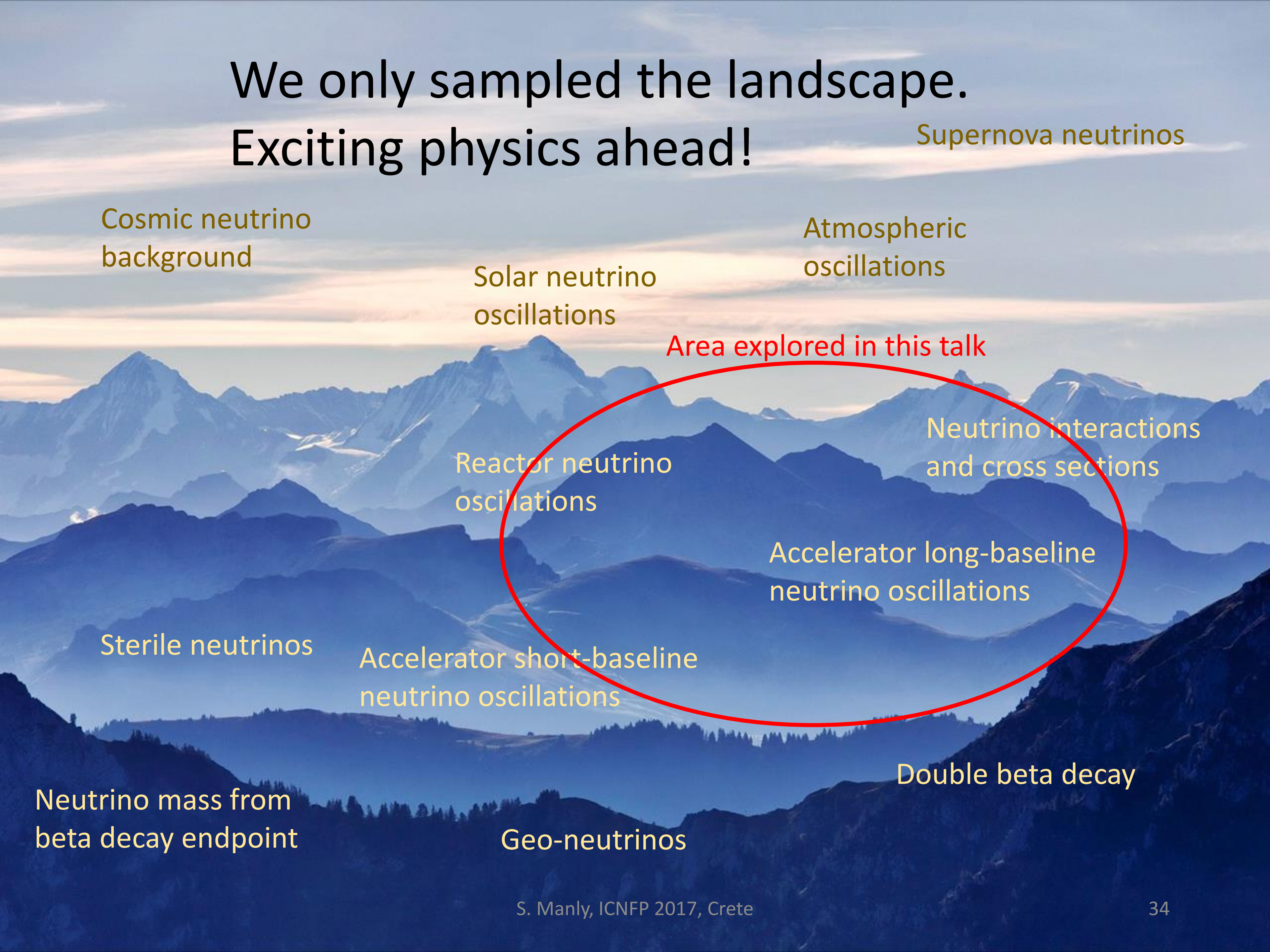
Big LArTPC prototypes under construction at CERN





Planning for first accelerator neutrino data in 2026

We only sampled the landscape. Exciting physics ahead!



We only sampled the landscape. Exciting physics ahead!

Supernova neutrinos

Cosmic neutrino background

Solar neutrino oscillations

Atmospheric oscillations

Area explored in this talk

- T2K continues taking data and upgrading near detector and accelerator
- NOvA to release new results next year
- Strong hints of CP violation observed
- Interesting tension on maximal atmospheric parameter mixing
- Short baseline program beginning to produce results soon
- Continued work on neutrino interaction physics and modeling
- DUNE, T2HK, JUNO pushing to start operation mid-2020's

Neutrino interactions and cross sections

Reactor neutrino oscillations

Accelerator long baseline neutrino oscillations

Sterile neutrinos

Accelerator short baseline neutrino oscillations

Double beta decay

Neutrino mass from beta decay endpoint

Geo-neutrinos