Neutrino Oscillation Experiments

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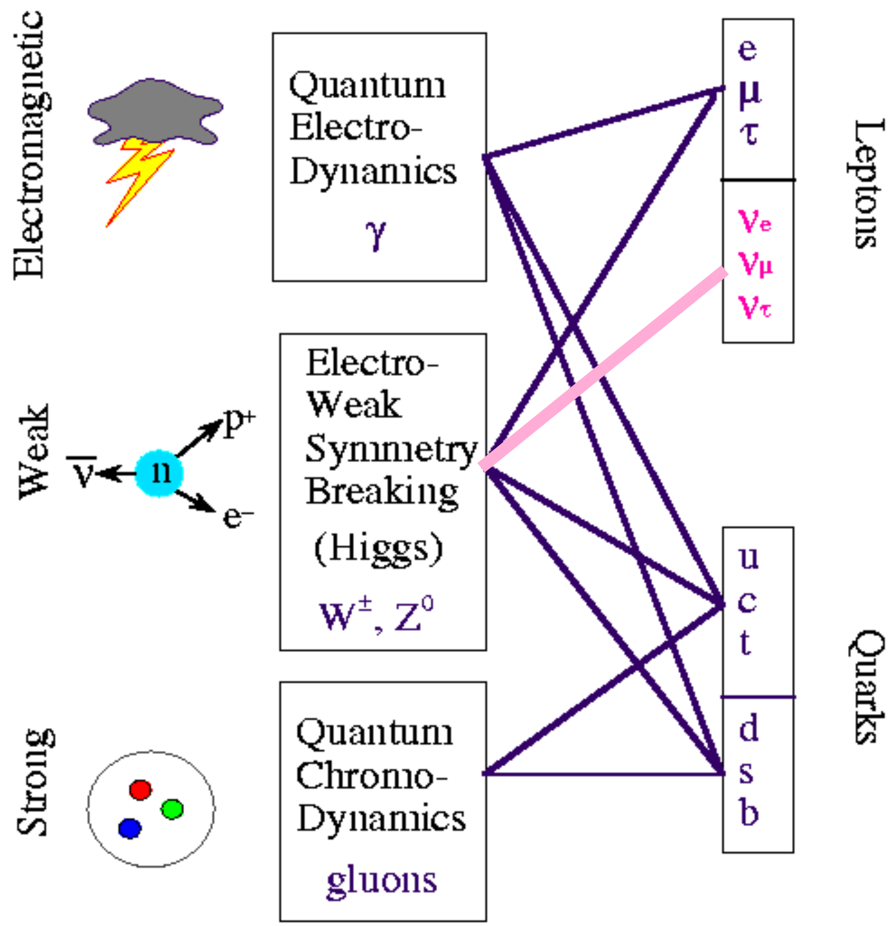
Talk Outline

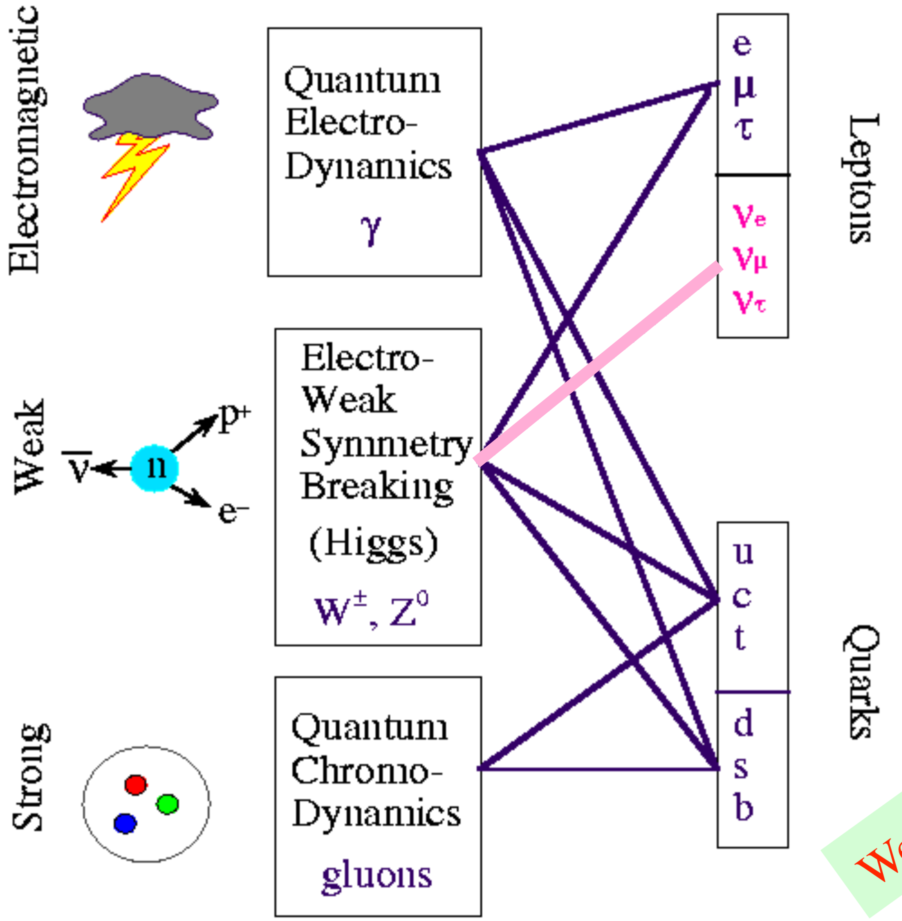
- Introduction to Standard Model and Neutrinos
- Neutrino Oscillations
- Neutrino Oscillation Experiments and Results
- Recent Measurement Mixing Angle Theta-13
- Current Accelerator Neutrino Experiments
- Future Measurements
- Summary

Standard Model of Particle Physics



- Neutrinos are the only fundamental fermions with no electric charge
- Neutrinos only interact through the "weak force"
- Neutrinos are massless
- Neutrino interaction through W and Z bosons is (V-A)
  - Neutrinos are left-handed (Antineutrinos are right-handed)
- Neutrinos have three types
  - Electron $\nu_e \rightarrow e$
  - Muon $\nu_\mu \rightarrow \mu$
  - Tau $\nu_\tau \rightarrow \tau$

Standard Model of Particle Physics



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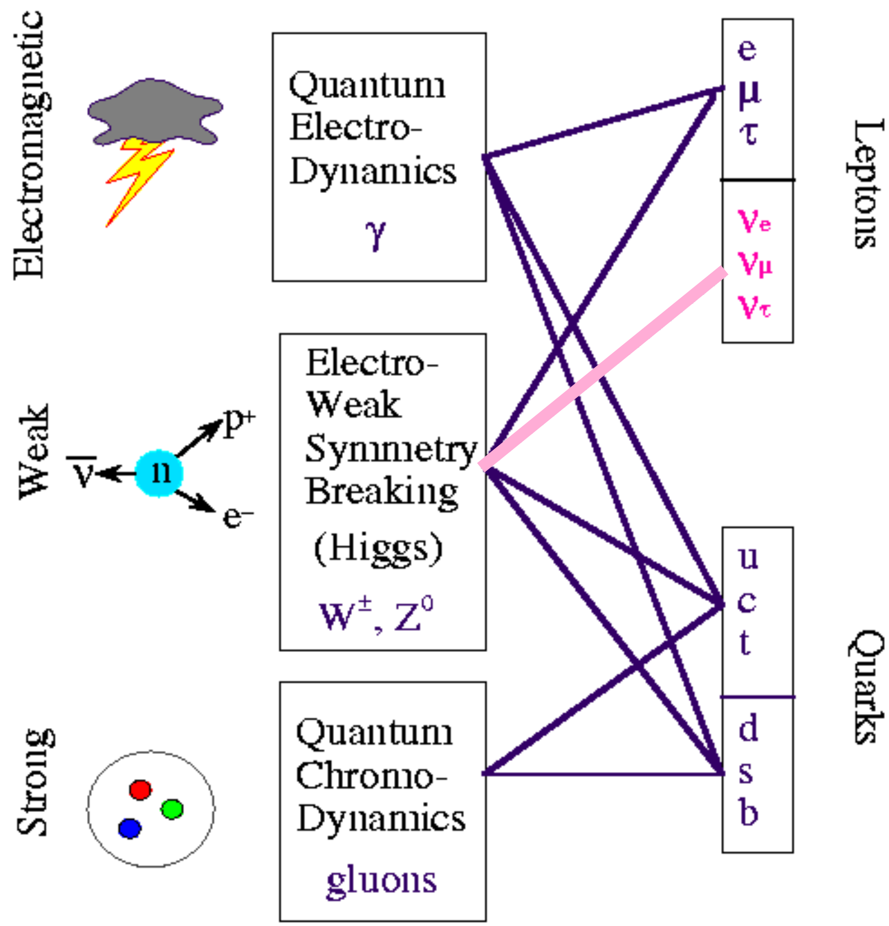
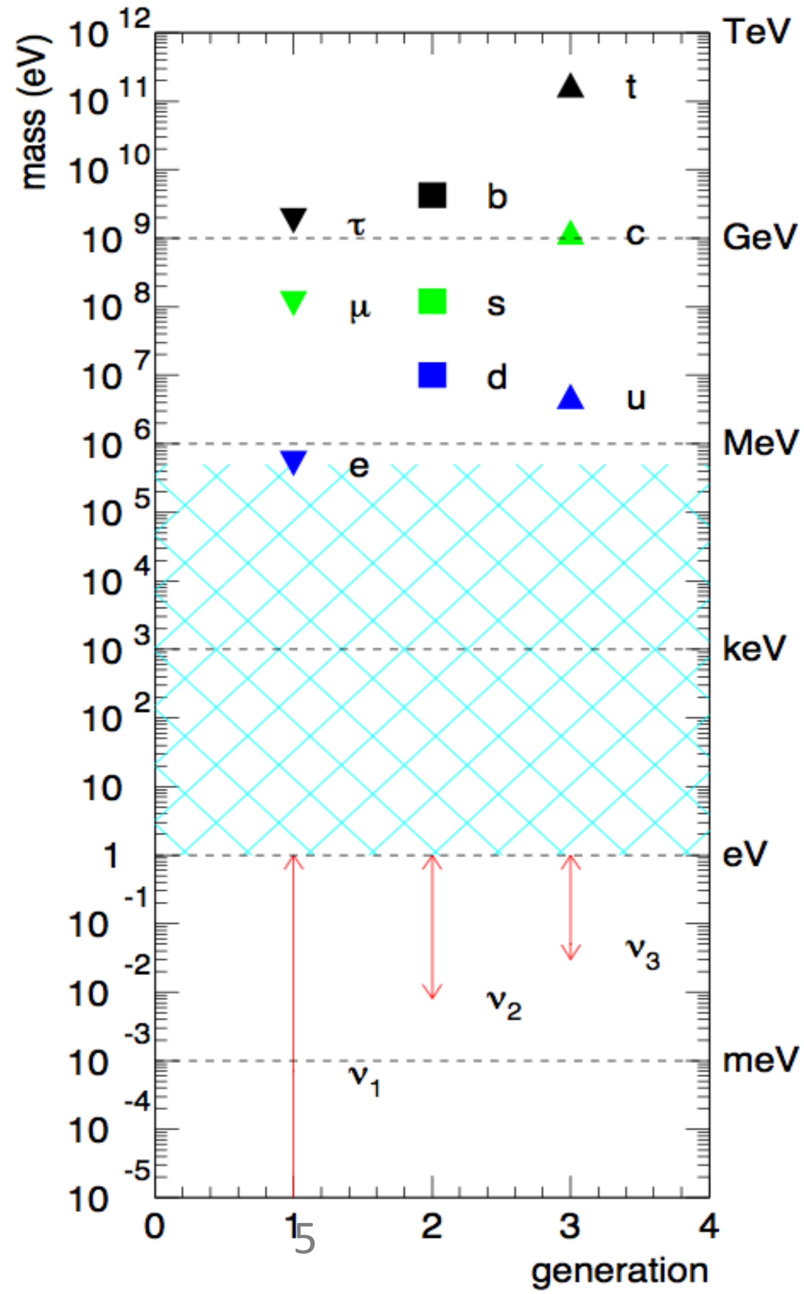
We have learned that neutrino are not massless particles!

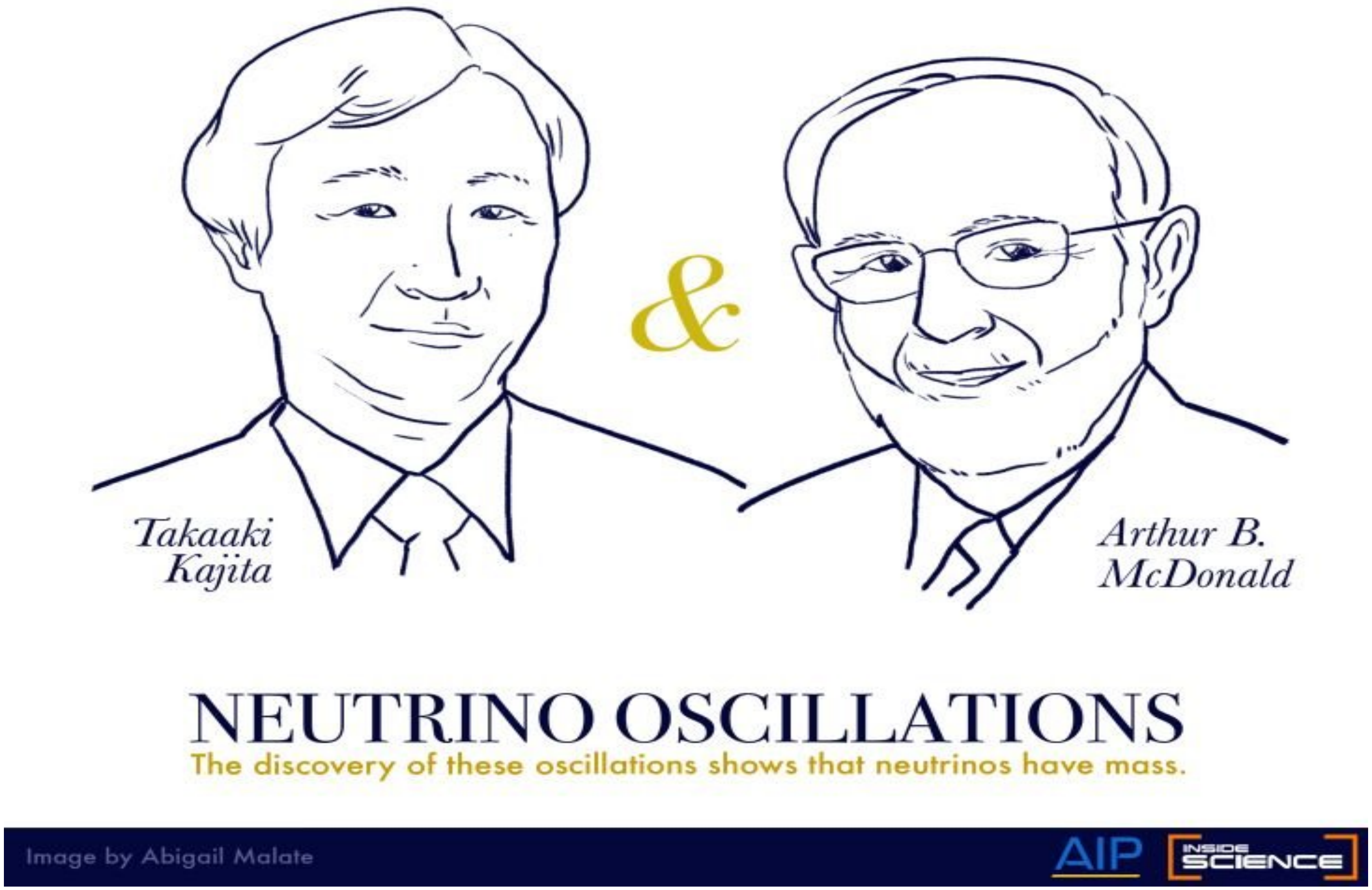
Standard Model of Particle Physics





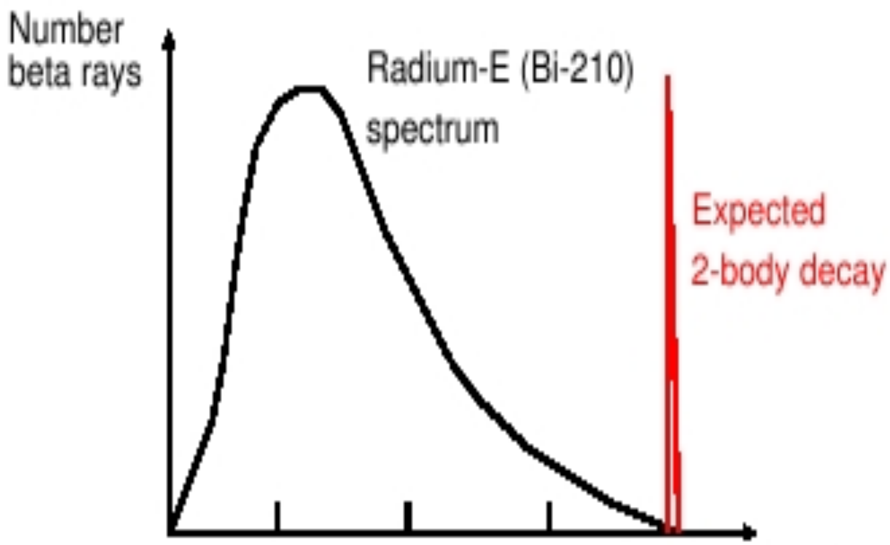
-Unlike the mass of a quark or charged lepton, neutrino mass is unlikely to be coming from a linear coupling between the particle and the Higgs boson field.

2015 Nobel Prize in Physics



- The Nobel Prize awarded to T. Kajita and A. McDonald for **"the discovery of neutrino oscillations, which shows that neutrinos have mass**" was a result of more than fifty years efforts of many experimental and theoretical physicists.

How we started with neutrinos?



- Continuous beta spectrum was the first hint that there is an extra particle in the beta decay reaction:

$n \rightarrow p + e^{-} + ?$

- W. Pauli explained:

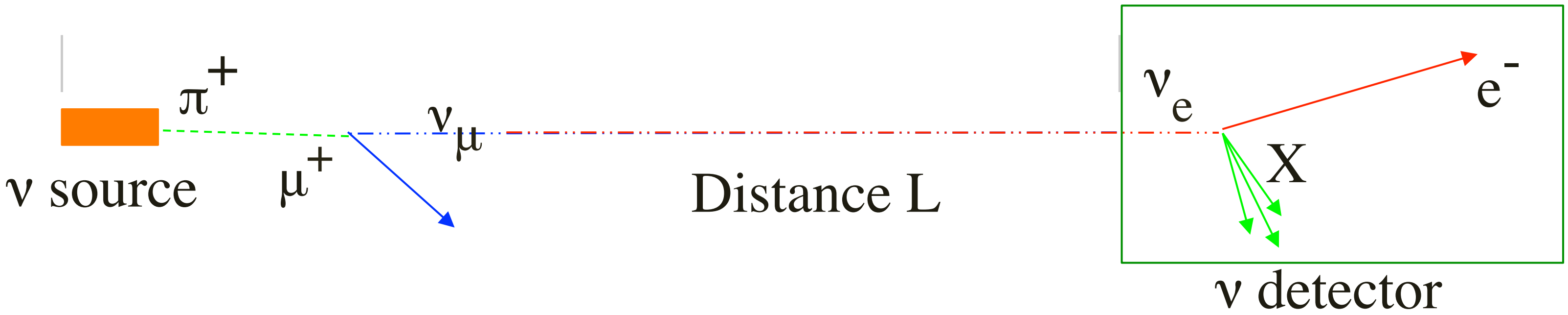
4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^{6} nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Neutrino Oscillations

-It has been observed that neutrinos change a flavor when travelling over a distance.



-Such behavior may be explained by quantum mechanics, if the flavor states (ν_e , ν_μ , ν_τ) are a linear combinations of the mass states (ν_1 , ν_2 , ν_3).

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k}|\nu_k\rangle \quad (\alpha = e,\mu,\tau)$$

Production of neutrino flavors: example $\pi^+ \rightarrow \mu^+\nu_\mu$

$$|\nu_\mu> = U_{\mu 1}\ |\nu_1> + U_{\mu 2}\ |\nu_2> + U_{\mu 3}\ |\nu_3>$$

Need to choose parametrization for mixing elements U_{ij}

Propagation of neutrino over distance (ie time) in mass states depends on energy

$$|\nu_\mu(t)> = U_{\mu 1}\ |\nu_1>\ e^{(iE1t)} + U_{\mu 2}\ |\nu_2>\ e^{(iE2t)} + U_{\mu 3}\ |\nu_3>\ e^{(iE3t)}$$

Probability of neutrino transformation in L/E (proper time)

$$P(\nu_\mu \rightarrow \nu_e) = |<\nu_e|\nu_\mu(t)>|^2$$

Detection of neutrino through corresponding lepton

$\nu_\mu N \rightarrow \mu^- X$

$\nu_e N \rightarrow e^- X$

$\nu_\tau N \rightarrow \tau^- X$

Neutrino Oscillations

Simplified Model: only two neutrino mix

Weak state — Mass state

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

Oscillation Probability

$|\nu_\mu(t)\rangle = -\sin\theta\, |\nu_1\rangle + \cos\theta\, |\nu_2\rangle$

e^{-iE1t} e^{-iE2t}

Δm^2 is the mass squared difference between the two neutrino states

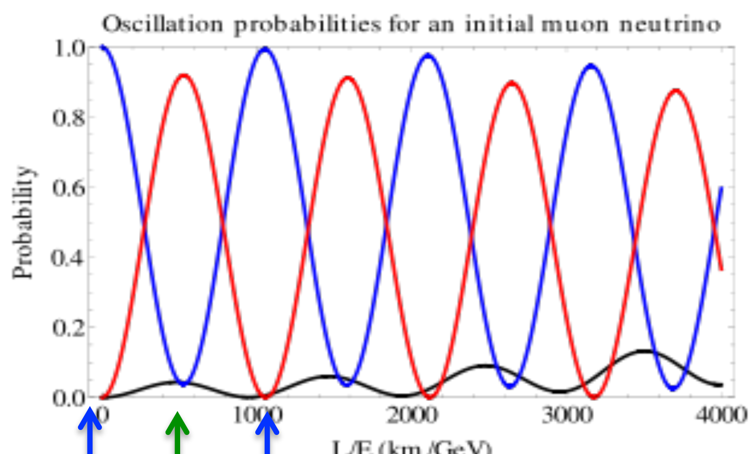
Distance from point of creation of neutrino beam to detection point

$$P_{osc} = |\langle \nu_e | \nu_\mu(t)\rangle|^2 = \sin^2 2\theta \; \sin^2 1.27 \left[\frac{\Delta m^2 L}{E}\right]$$

θ Is the mixing angle

E is the energy of the neutrino beam

Spontaneous change of neutrino flavor is what we call a neutrino oscillation.



100% ν_μ 100% ν_μ

100-x% ν_μ, x% (ν_e + ν_τ)

$\Delta m^2_{32} = m^2_3 - m^2_2$

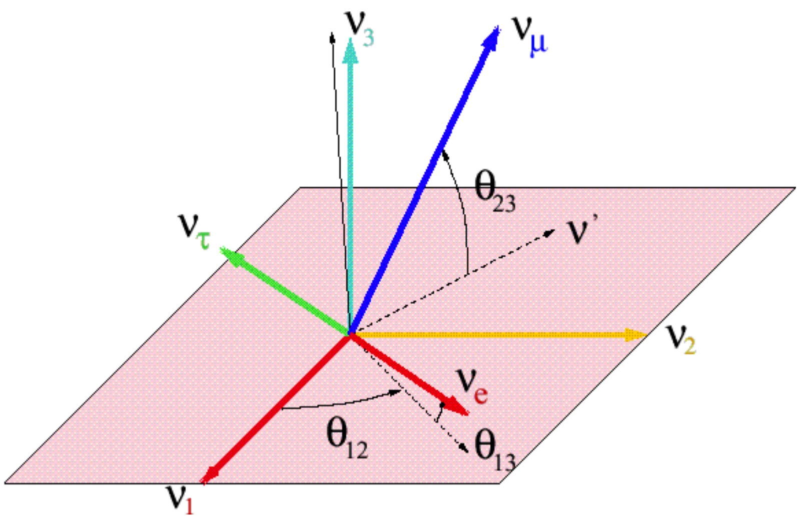
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m_{23}^{\;2} L}{E_\nu}\right)$$

-As a consequence there is a non-zero probability to observe the original neutrino as a different flavor when detected over the distance L.

-**Such experimental observation implies that neutrinos have mass, and that neutrinos mix.**

Neutrino Oscillations

-We know there are at least three neutrinos out there.
-With three known neutrinos the mixing of flavor and mass eigenstates is written in a form of so-called PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix:



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

-Parametrized matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Neutrino Oscillations

- The three neutrino mixing:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

θ_{12} measured from $P(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_x)$ by reactor $\bar{\nu}_e$ and solar ν_e.

θ_{13} measured from $P(\bar{\nu}_e \to \bar{\nu}_e)$ by reactor $\bar{\nu}_e$.
θ_{13} and δ measured from $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e)$ by accelerator ν_μ.

θ_{23} measured from $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu)$ by atmospheric ν_μ and accelerator ν_μ.

- Neutrino oscillation parameters:

PMNS matrix: 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
1 phase: δ => CP-violation in ν-sector

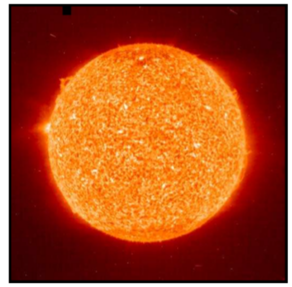
Mass differences: 2 mass difference scales: Δm^2_{12}, Δm^2_{23}.

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Neutrino Sources

- Neutrinos come from "everywhere"

Nuclear Reactors

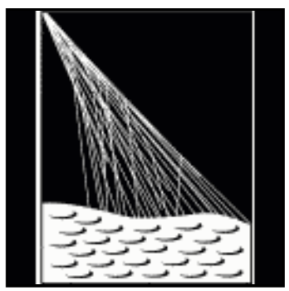


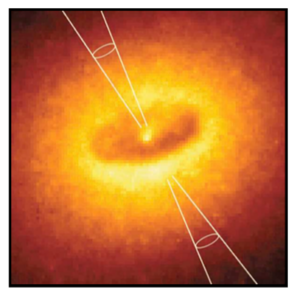
Sun

Particle Accelerators

Supernovae
(star collapse)

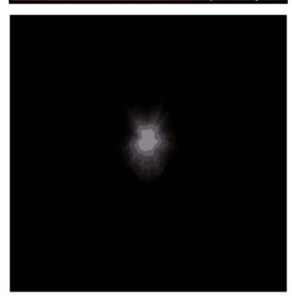
Earth's Atmosphere
(Cosmic Rays)





Astrophysical Sources

Earth's Crust
(Natural
Radioactivity)



Big Bang
(330 ν/cm^3)

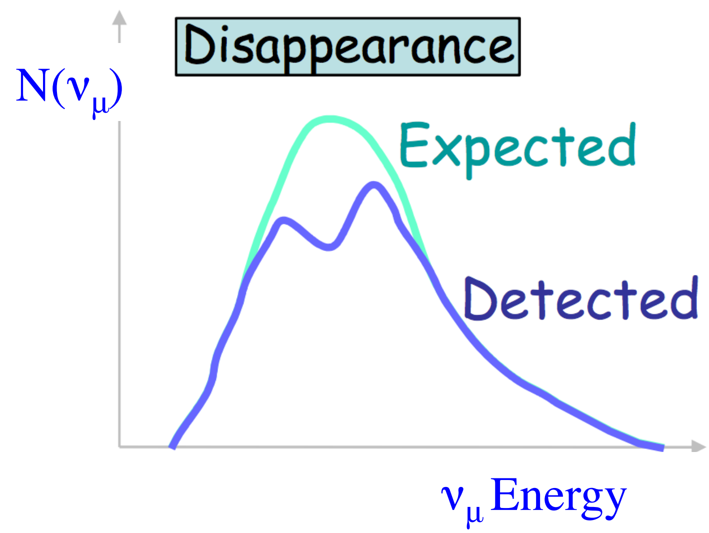
Detecting Neutrino Oscillation

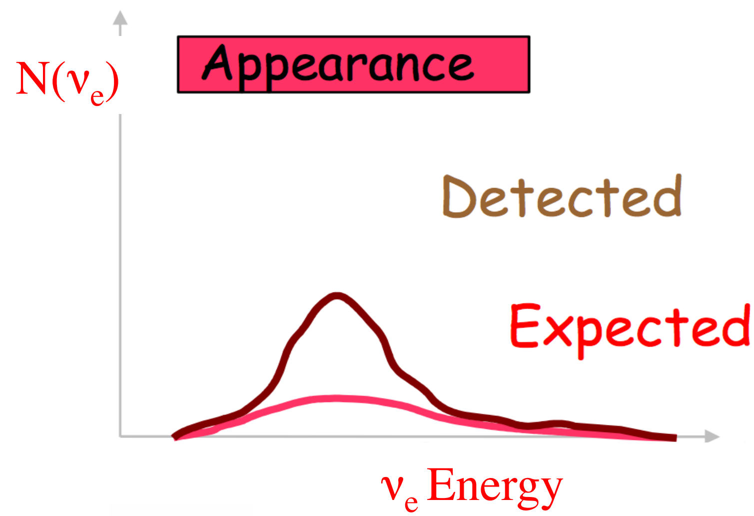
- Appearance vs disappearance experiments
  Example: consider searching for $\nu_\mu \rightarrow \nu_e$ oscillation

- Disappearance:
  -Detect fewer ν_μ events than expected.
  -Should have a characteristic energy signature – oscillation probability depends on E.

- Appearance:
  -Detect more ν_e events than expected.
  -Oscillation depends on E: the events that disappeared in the blue plot are related to those appearing in the red plot.

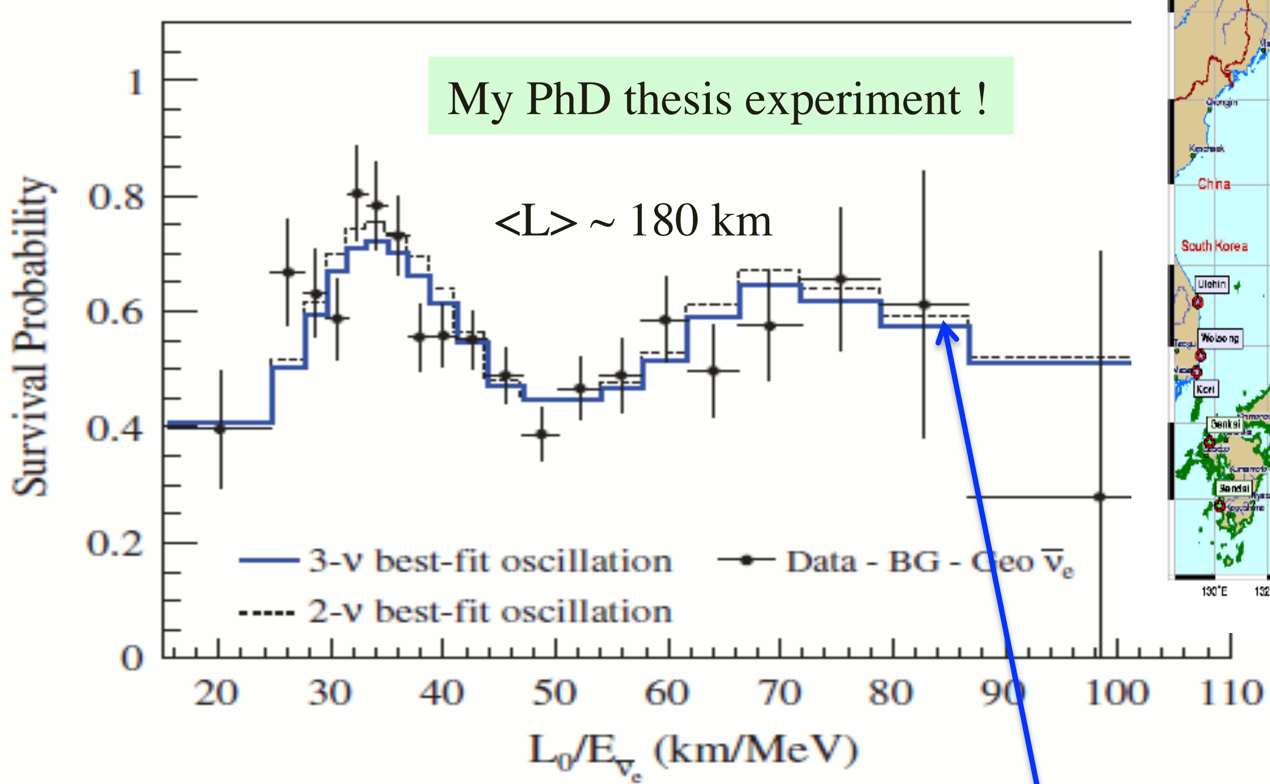
- Goal: Determine Δm^2, θ



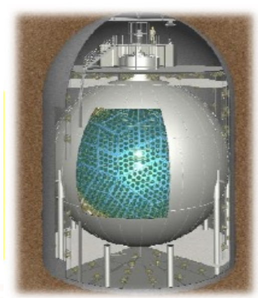


Example of Neutrino Experiment

- KamLAND experiment: reactor anti-neutrino disappearance experiment
  -demonstrated neutrino mixing and provided the most-precise measurement of Δm_{21}^2 up-to-date.



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



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\ \sin^2 2\theta_{12}\ \sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\ \sin^2\Delta_{31} + \sin^2\theta_{12}\ \sin^2\Delta_{32})$$

(becomes 2-ν oscillation if $\theta_{13} = 0$!)

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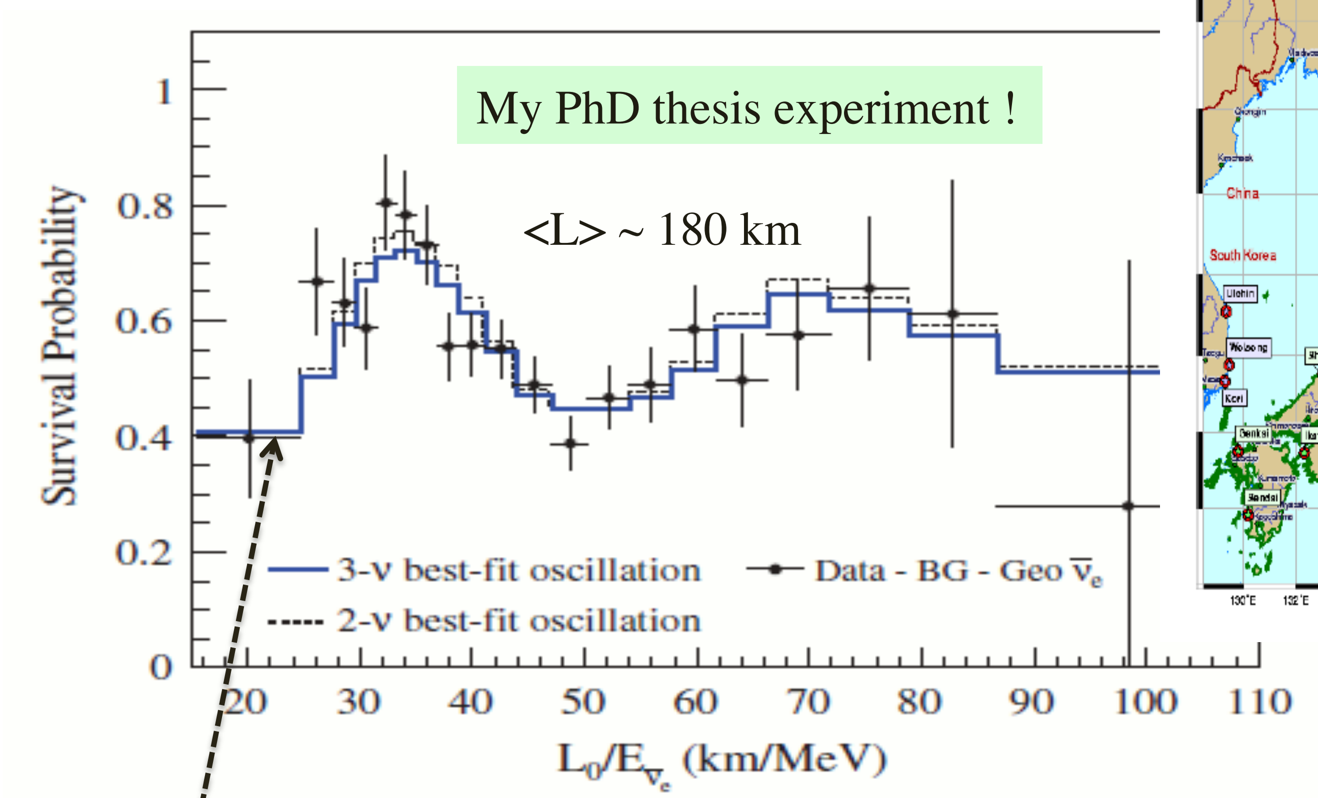
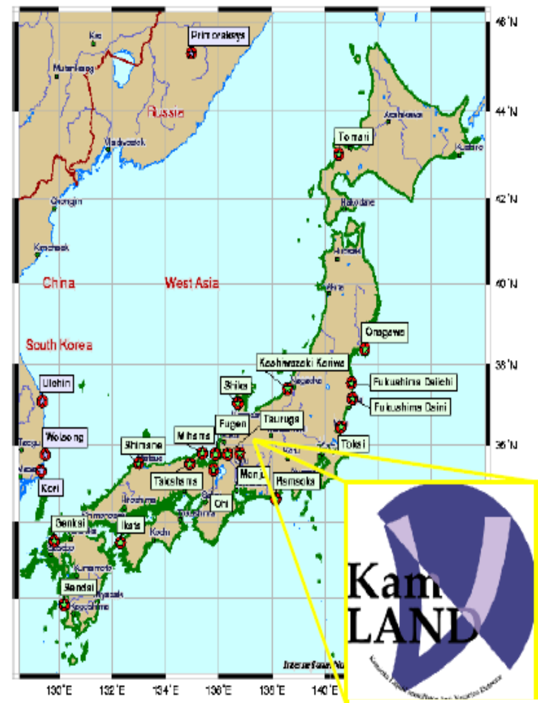
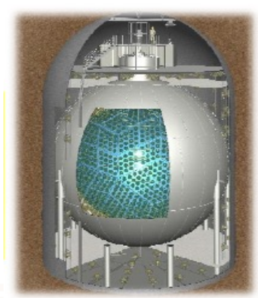




$$\bar{\nu}_e + p \rightarrow e^+ + n$$



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\ \sin^2(1.27\Delta m_{21}^2 L[m]/E_\nu[MeV])$$

(if $\theta_{13} = 0$)

Neutrino Oscillation Results

- Current understanding

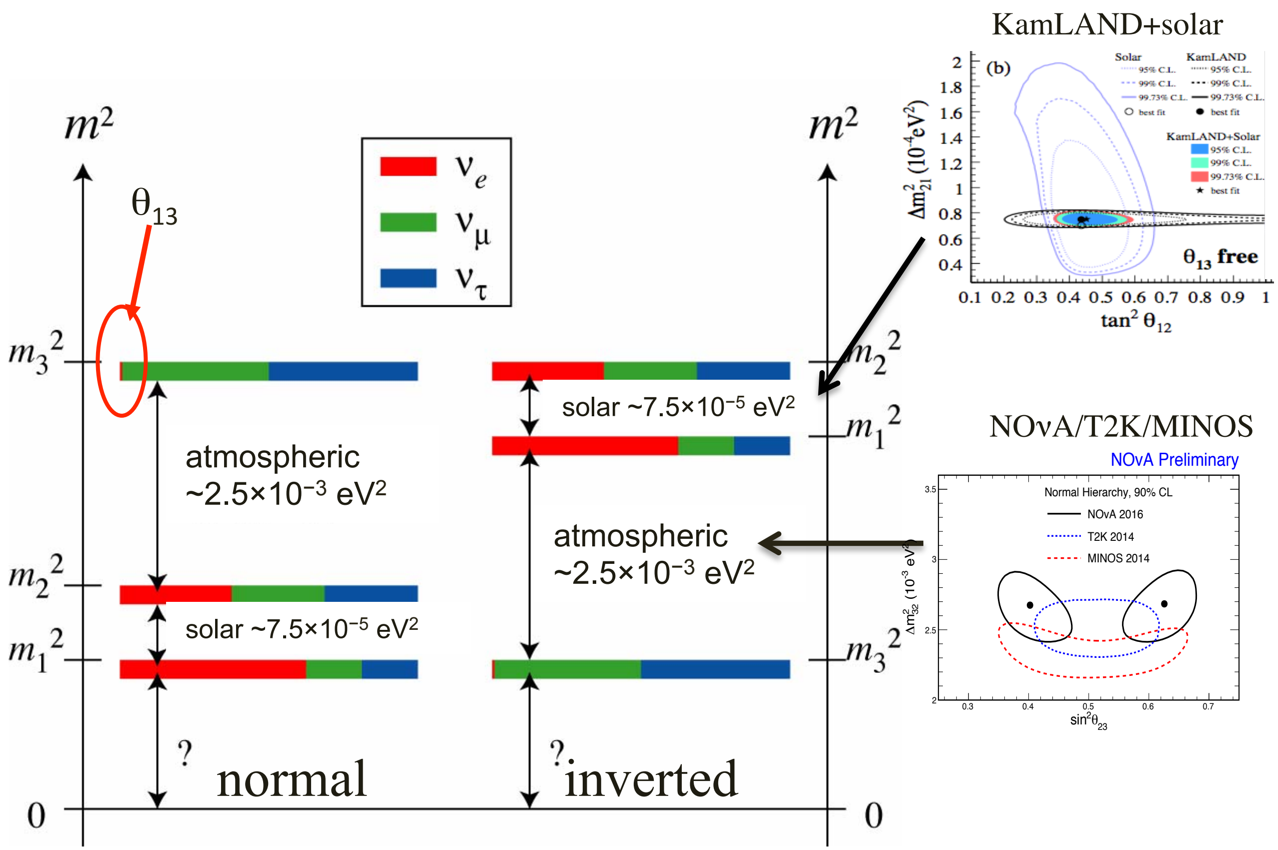
-Mass squared differences:

$\Delta m^2_{21} \approx 7.5 \text{ x } 10^{-5} eV^2$
$|\Delta m^2_{32}| \approx 2.5 \text{ x } 10^{-3} eV^2$

-Mixing angles:

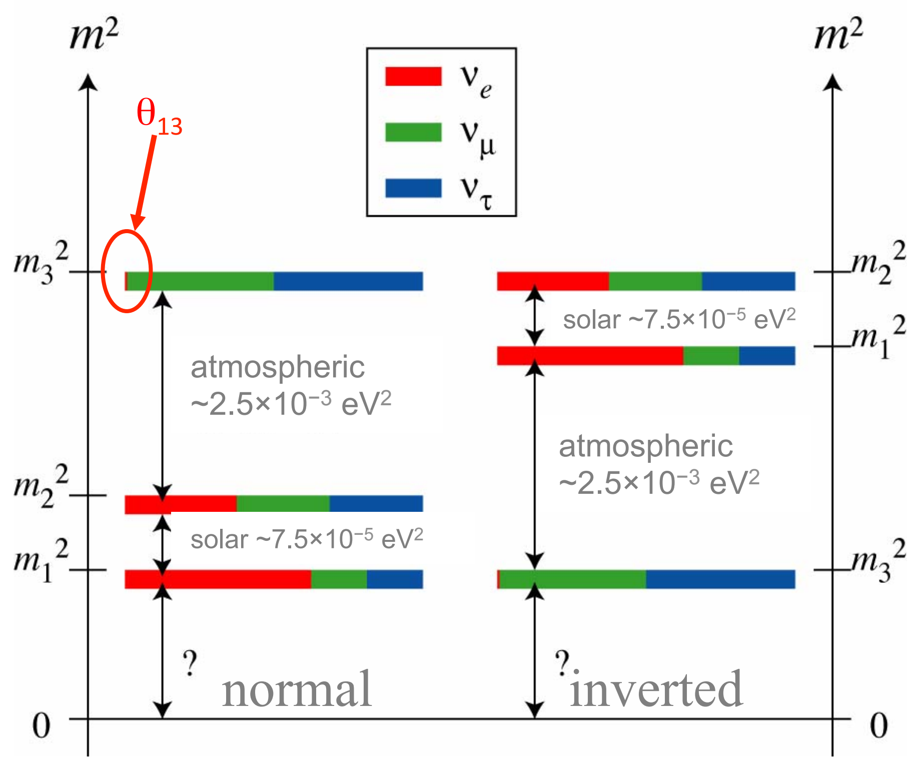
$\sin^2\theta_{12} \approx 0.31$
$\sin^2\theta_{23} \approx 0.45 - 0.55$
$\sin^2\theta_{13} \approx 0.02$ (measured recently)

-Absolute mass scale is unknown.



Neutrino Oscillation Questions

Recently measured what is ν_e component in the ν_3 mass eigenstate, i.e. θ_{13}.



Missing information in 3x3 mixing scheme:

1. Is the μ - τ mixing maximal?
   -Only know $\sin^2\theta_{23} \approx 0.45 - 0.55$

2. What is the mass hierarchy?
   -Normal or inverted?

3. Do neutrinos exhibit CP violation, i.e. is $\delta_{CP} \neq 0$?

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{13}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

4. Why are quark and neutrino mixing matrices so different?

$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \quad \text{vs.} \quad V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

Different neutrino experiments

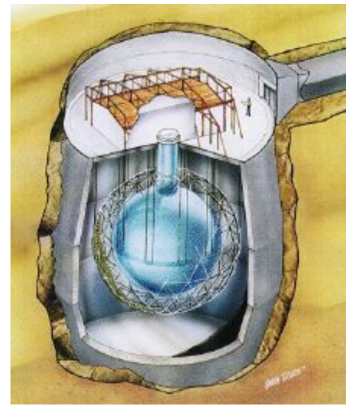
Solar: BOREXINO, SNO…

Atmospheric: Super-K…

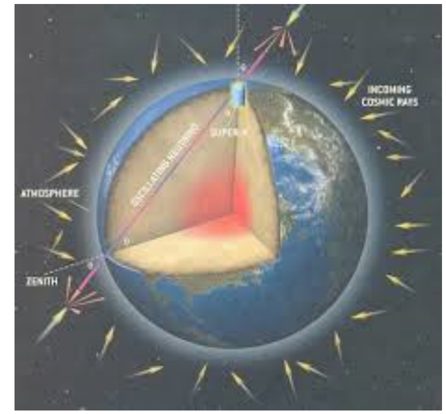
Accelerator: MINOS, NOνA, T2K...

Reactor: Daya Bay, Double Chooz, RENO, KamLAND...

Cosmic: IceCube …

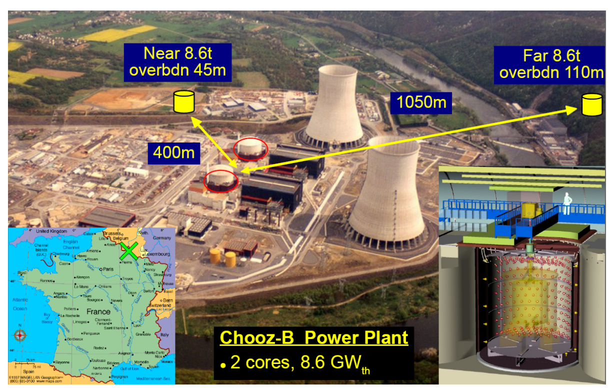


SNO ($\nu_e \rightarrow \nu_{\mu,\tau}$)

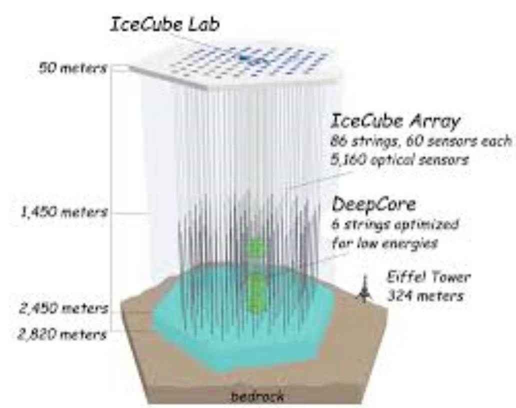


Super-K($\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_{\mu,\tau}$)

NOνA



Double Chooz ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)

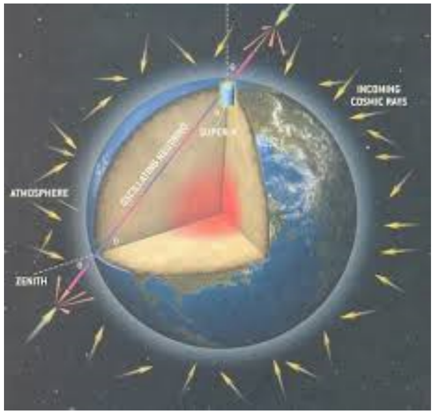


Ice Cube

Different neutrino experiments

- First ideas of neutrino oscillations were pioneered in 1957-58 by Bruno Pontecorvo

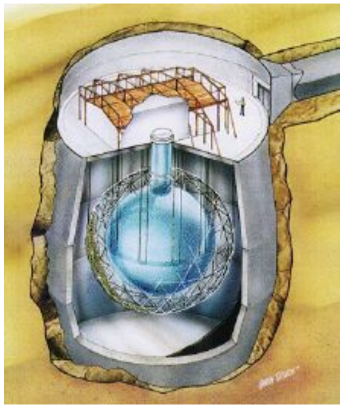
- First model independent evidence in favor of disappearance of atmospheric ν_μ’s was obtained in 1998 by Super-Kamiokande collaboration
  -but there was model-dependent evidence comes from multiple Solar- neutrino experiments



Super-K($\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_{\mu,\tau}$)

- First model independent evidence of the disappearance of solar ν_e’s was obtained by the SNO collaboration in 2001

- First model independent evidence of the disappearance of reactor $\bar{\nu}_e$’s was obtained by the KamLAND collaboration in 2002



SNO ($\nu_e \rightarrow \nu_{\mu,\tau}$)

- The discovery of neutrino oscillations was confirmed by many experiments(K2K, MINOS, T2K, DayaBay, RENO, Double Chooz, NOνA)

Experimental Methods to measure θ_{13}

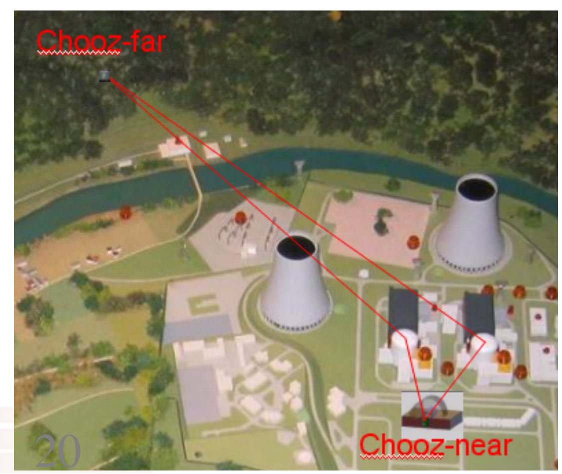
- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

NOvA:
$\langle E_\nu \rangle \approx 2$ GeV
L = 810 km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for a change in ν_e flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
L = 1100 m



Long Baseline Accelerator Appearance Experiments

-θ_{13} probed by measuring electron neutrino appearance from accelerator produced muon neutrinos:

$$\begin{aligned} P(\nu_\mu \to \nu_e) \; = \; & \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\ & + \cos\delta \sin 2\theta_{23} \sin 2\theta_{12} \; \sin 2\theta_{13} \; \cos\Delta_{32} \Big(\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}\Big) \Big(\frac{\sin(aL)}{(aL)} \Delta_{21}\Big) \\ & - \sin\delta \sin 2\theta_{23} \sin 2\theta_{12} \; \sin 2\theta_{13} \; \sin\Delta_{32} \Big(\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}\Big) \Big(\frac{\sin(aL)}{(aL)} \Delta_{21}\Big) \\ & + \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2, \end{aligned}$$

-The oscillation probability is complicated and dependent not only on θ_{13} but also on

CP-violation parameter (δ_{CP}),
Mass hierarchy (sign of Δm^2_{31}),
Size of $\sin^2\theta_{23}$.

-Therefore any attempt to measure CP-violation and the mass hierarchy would be greatly simplified if θ_{13} was measured independently.

Reactor Disappearance Experiments

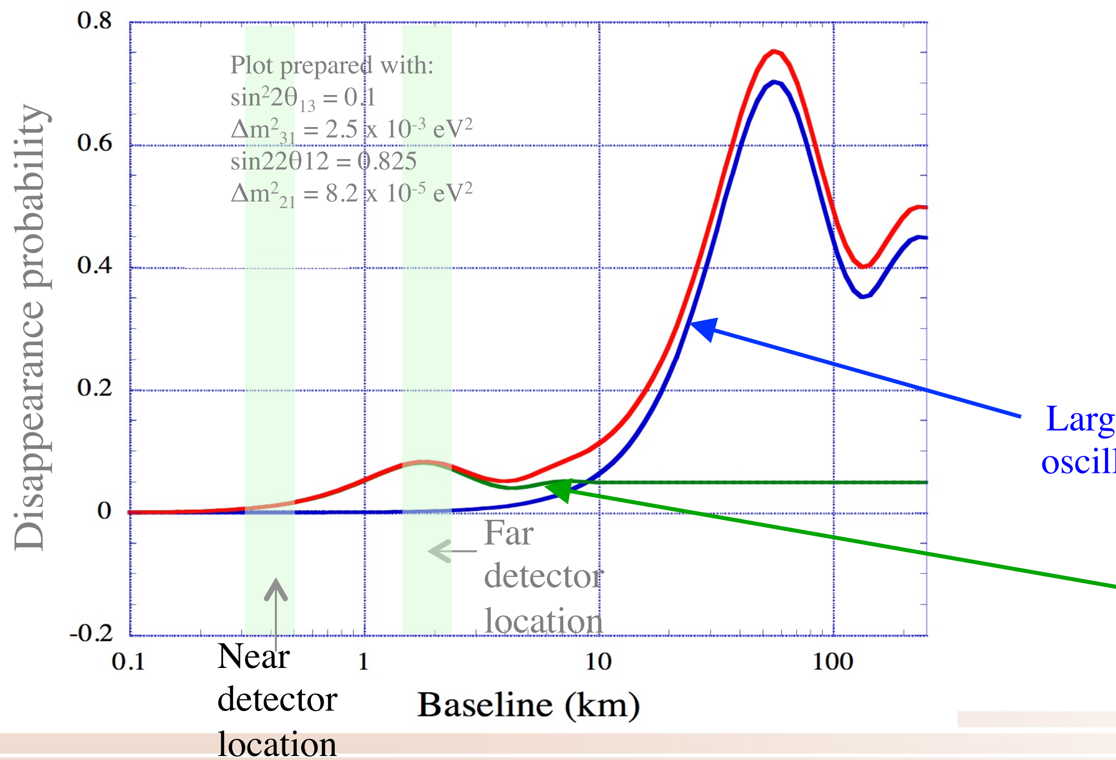
-A clean measurement of θ_{13} can be performed by observing the disappearance of electron antineutrinos.

-In general, the electron antineutrino survival probability is given by

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\ \sin^2 2\theta_{12}\ \sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\ \sin^2\Delta_{31} + \sin^2\theta_{12}\ \sin^2\Delta_{32})$$

-At distances 1-2 km from a reactor source this further simplifies to:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\ \sin^2\frac{\Delta m^2_{31}L}{4E}$$



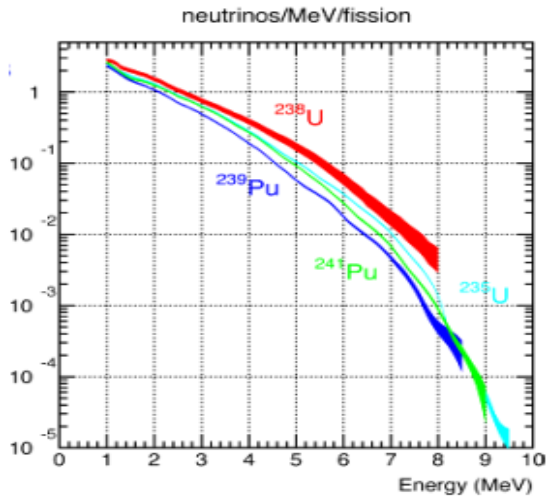
-No dependence on:

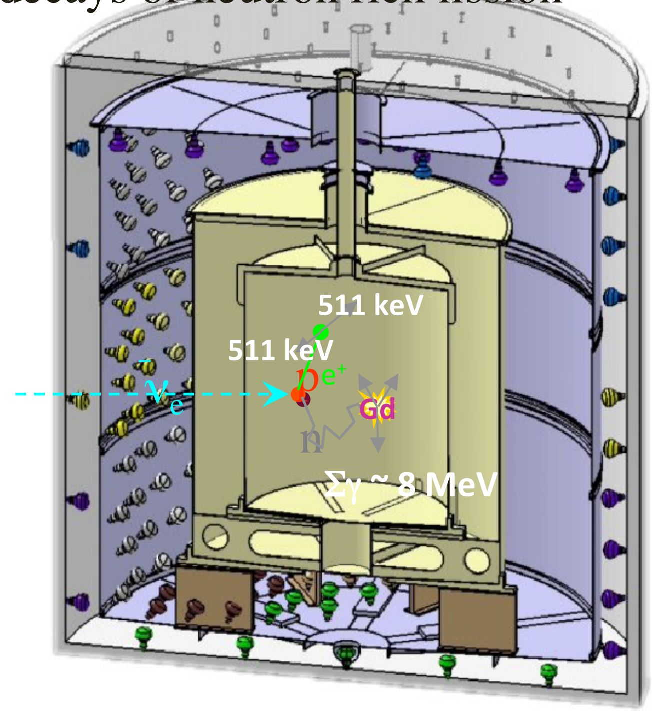
CP-violation parameter (δ_{CP}),
Mass hierarchy (sign of Δm^2_{31}),
Size of $\sin^2\theta_{23}$.

Reactor Disappearance Experiments

Neutrino Source and Detector

- Nuclear reactor is a pure source of $\bar{\nu}_e$: $\bar{\nu}_e$ originate from β-decays of neutron rich fission products of U, Pu.





-A modern nuclear power reactor may have a thermal power of P_{therm} = 3.8 GW.

>99.9% of ν_e produced by fissions of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu.

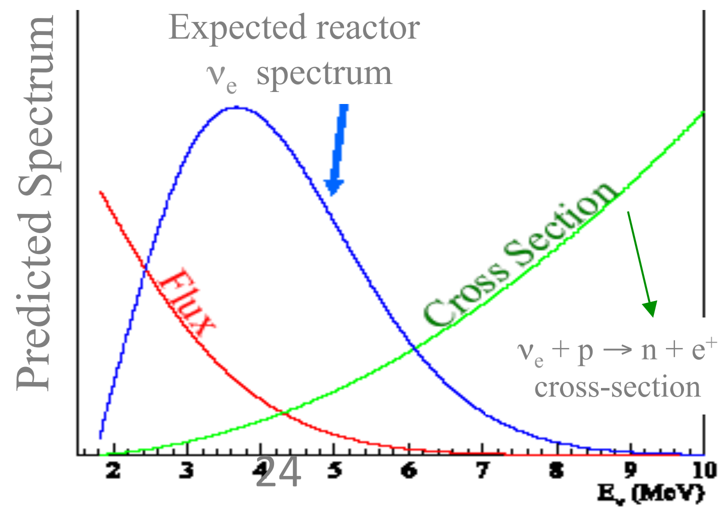
-Flux is know to at a few percent level.

-About 200 MeV / fission of energy is released in fission of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu.

-The resulting fission rate, f, is thus: $f = 1.2 \times 10^{20}$ fissions/s

-At $6\nu_e$ / fission the resulting yield is: 7.1×10^{20} ν_e / s.

Signal = Positron signal + Neutron Signal (within a few capture times)



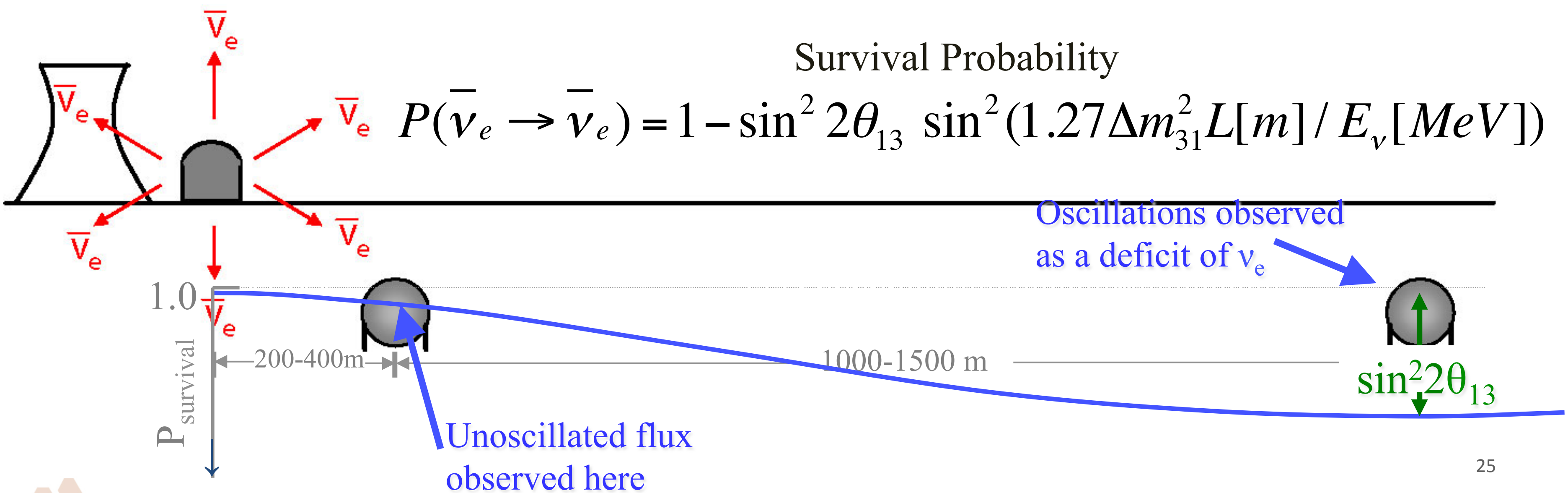
-Mean energy of $\bar{\nu}_e$ is ~3.5 MeV: only $\bar{\nu}_e$ disappearance experiments are possible.

Experimental Technique to measure θ_{13}

-Add an identical near detector →eliminate dependence on reactor flux.
-Optimize baseline →near detector close to reactors, far detector at oscillation maximum.
-Use large detectors with reduced systematics uncertainties →large data statistics, minimize systematics.
High power reactor sites →improved statistics.
Reduce backgrounds →go deeper and use active veto systems.
Stable scintillator →eliminate potential aging effects.

Survival Probability

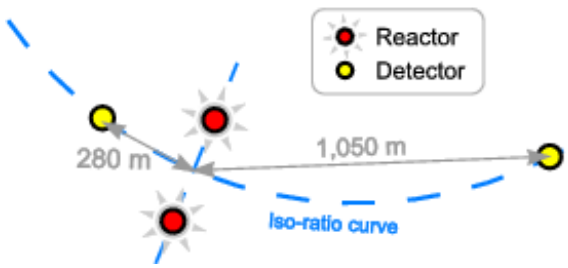
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\ \sin^2(1.27\Delta m^2_{31} L[m] / E_\nu[MeV])$$

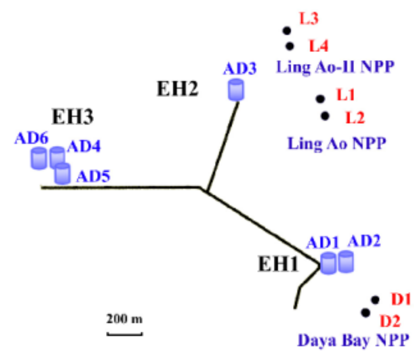


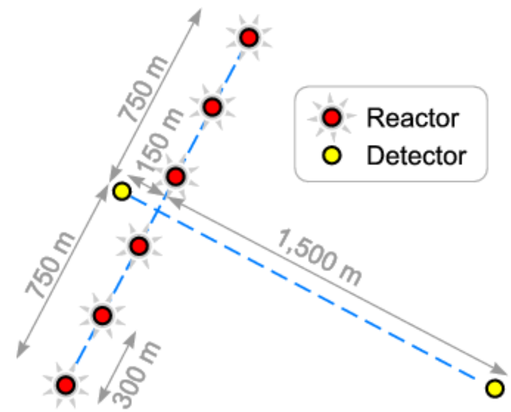
Three current θ_{13} reactor measurements

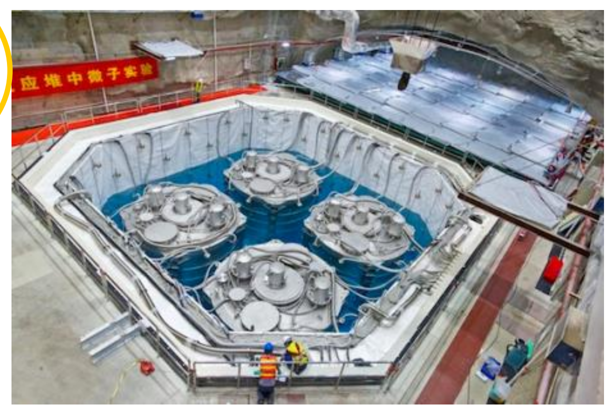
-Three recent θ_{13} reactor measurements from three experiments

Double Chooz (France) | Daya Bay (China) | RENO (S. Korea)









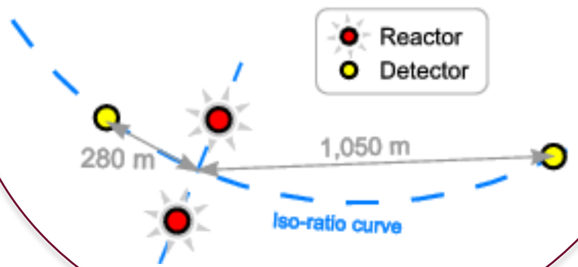
"The Big Bang Theory" wrt first Double Chooz θ_{13} Results

Three current θ_{13} reactor measurements

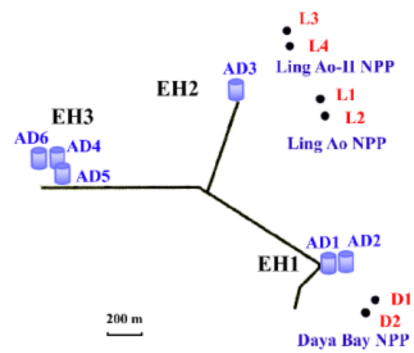
-Three recent θ_{13} reactor measurements from three experiments

Will describe Double Chooz
✔ My experiment

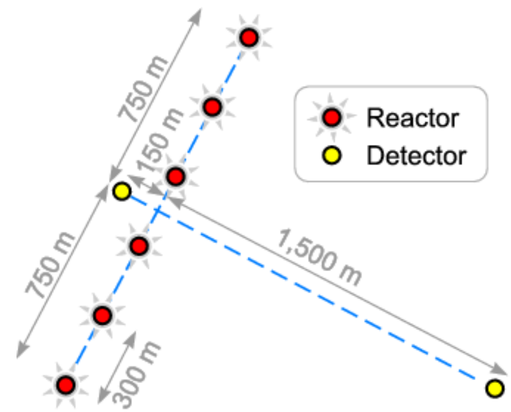
Double Chooz (France)

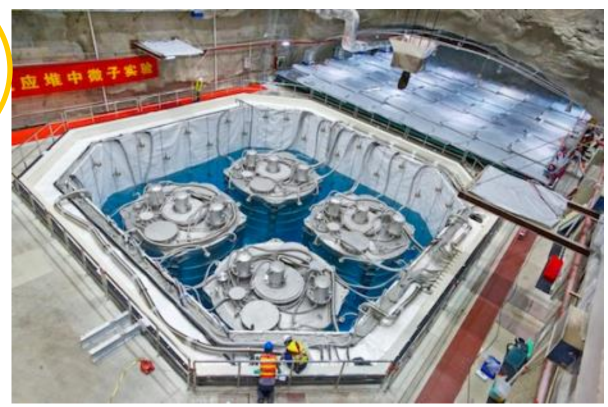


Daya Bay (China)



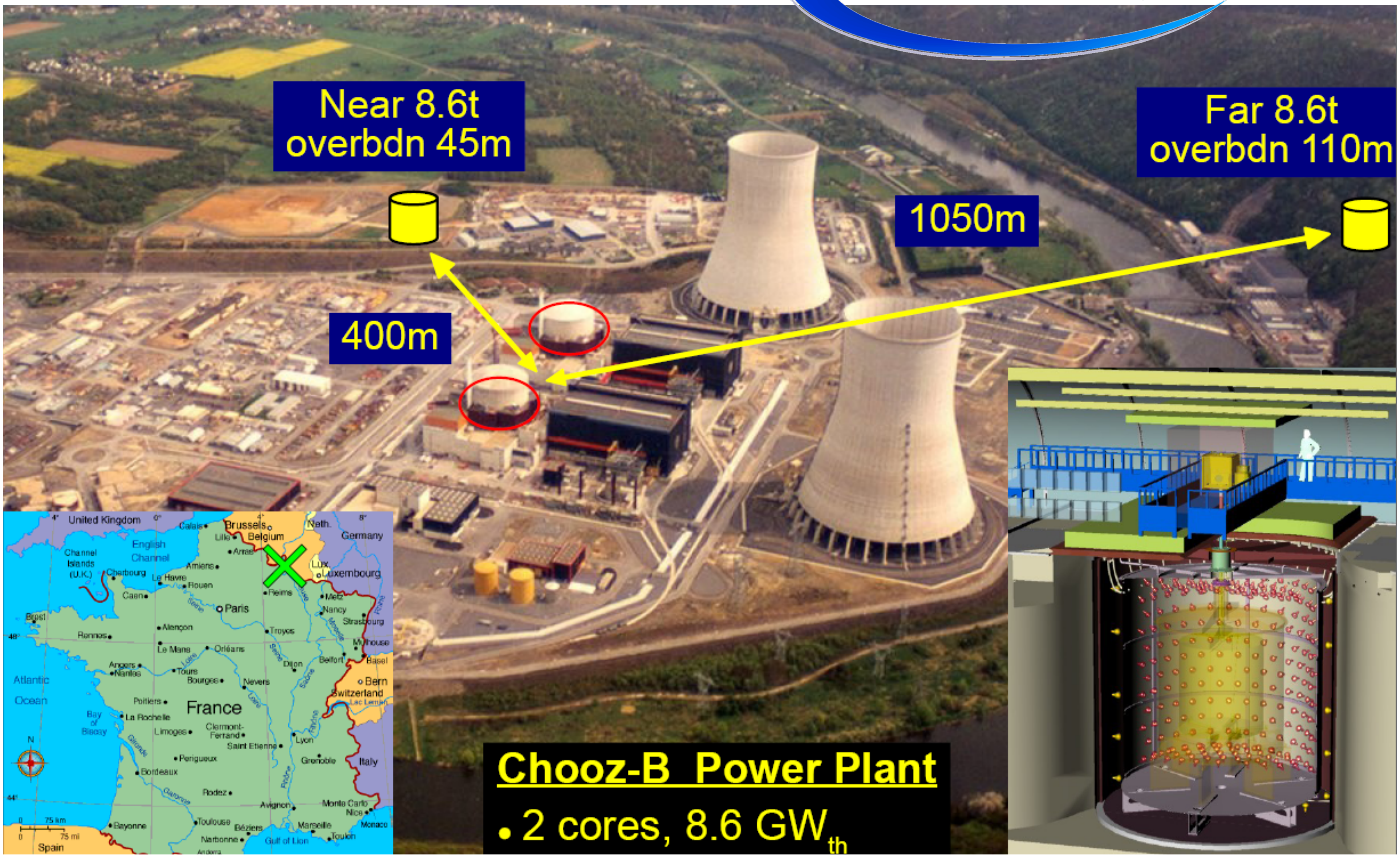
RENO (S. Korea)





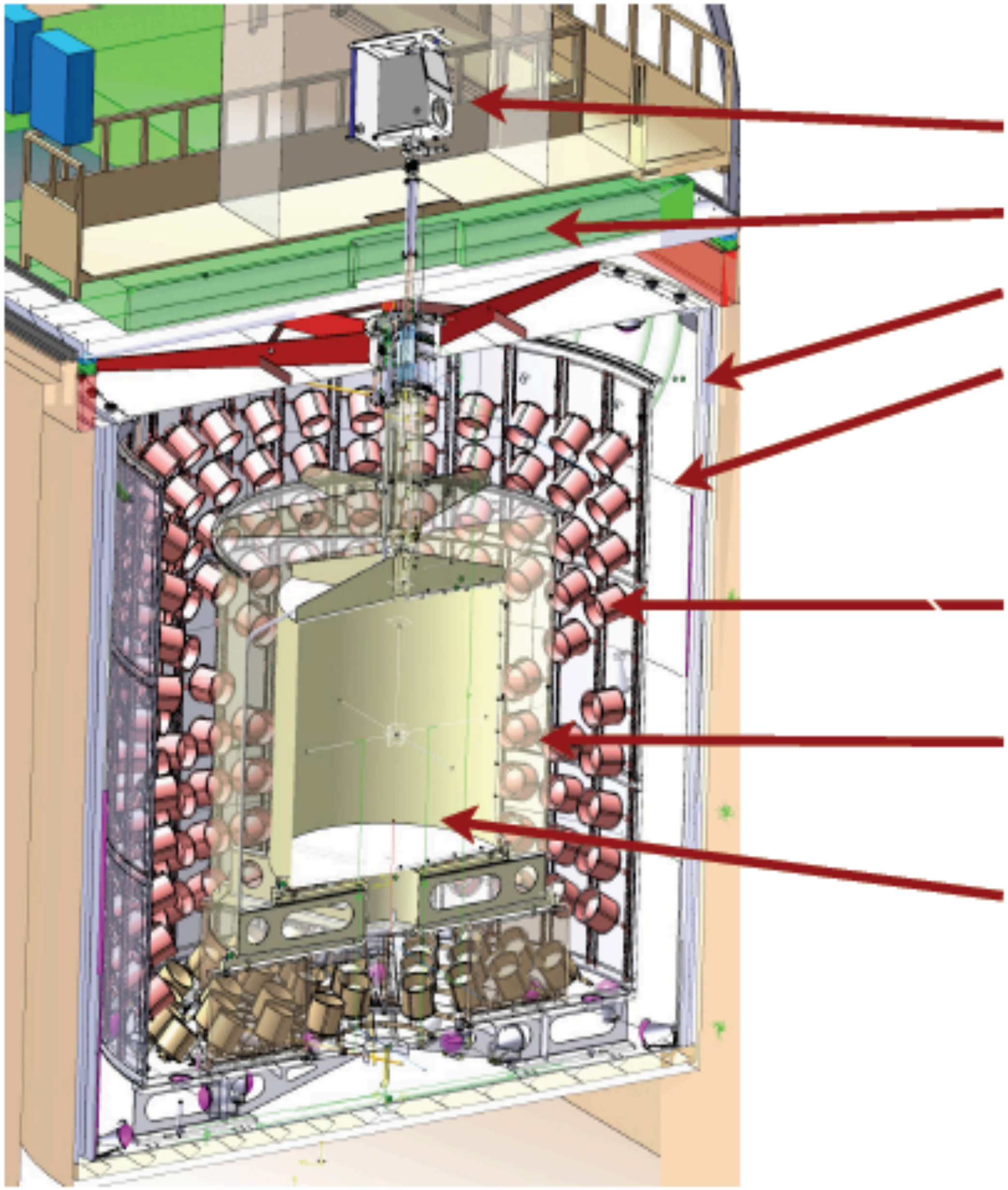
"The Big Bang Theory" wrt first Double Chooz θ_{13} Results

Double Chooz Experiment



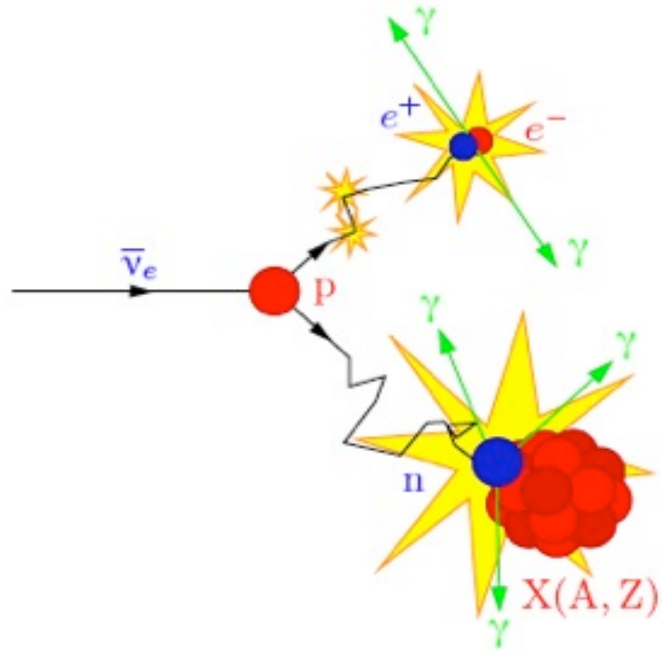
Double Chooz Detector Design

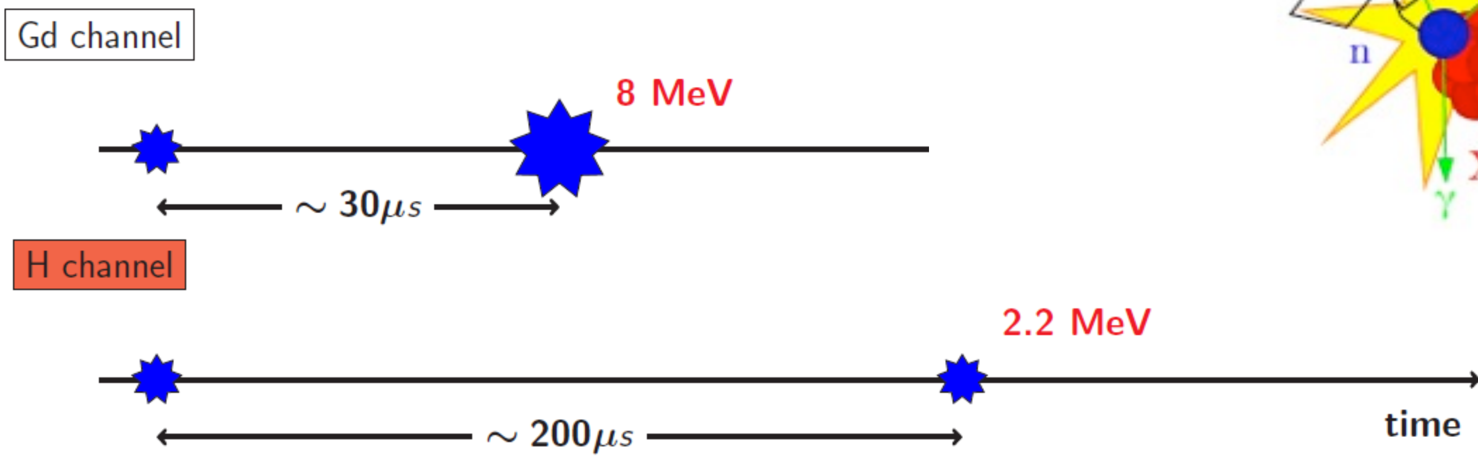
- Two identical detectors called “Far” detector and “Near” detector



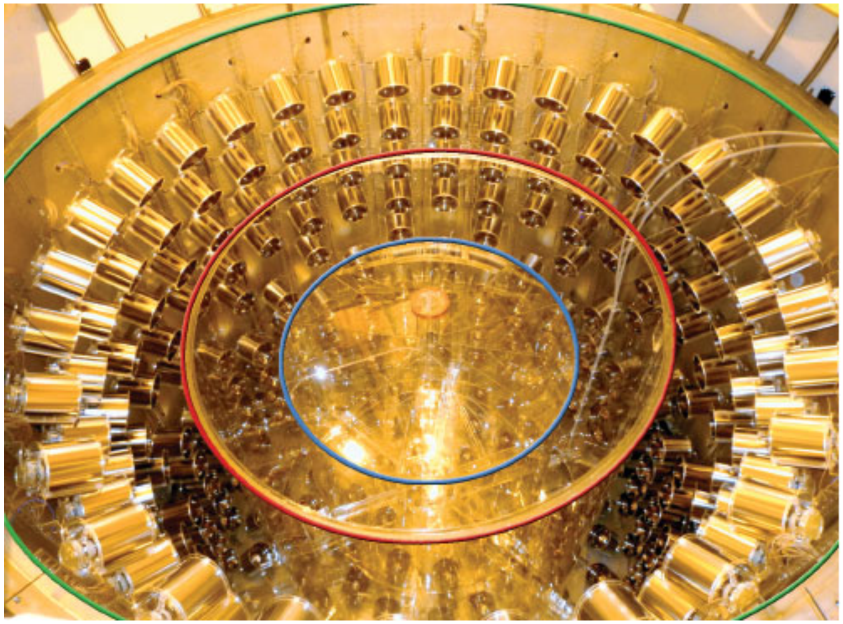
Anti-Neutrino Detection

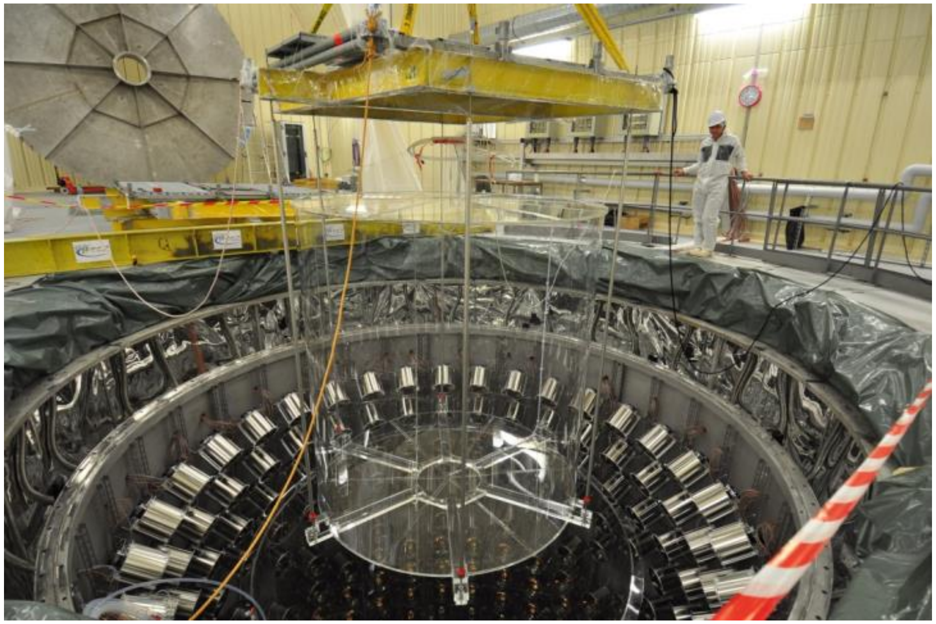
- **Inverse Beta Decay (IBD)**:
  - $\overline{\nu}_e + p \rightarrow n + e^+$
- **Prompt signal**: positron energy + annihilation γ's ($1 \sim 9$ MeV)
- **Delayed signal**: γ's from neutron capture on Gd or H
- **Delayed coincidence**





Double Chooz Timeline

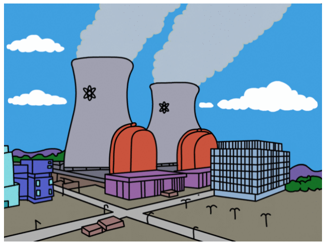




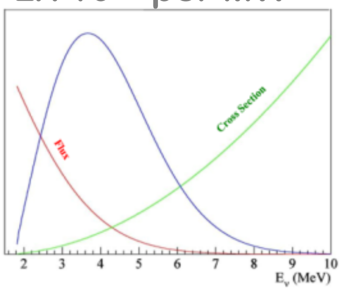
- 2010: Constructed and filled the single Far detector.
- April 2011: Far detector started data taking.
- November 2011: First data analysis complete
- 2014: Constructed and filled the Near detector.
- Jan. 2015: Near detector started data taking.
- March 2016: First two detector oscillation results.
- September 2016: Updated two detector oscillation results.

Data Analysis Process

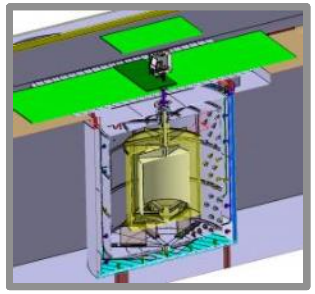
- Data flow and analysis chain

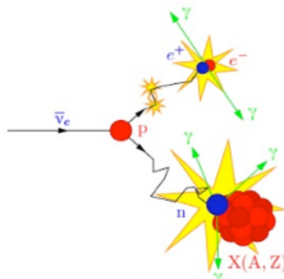


2X 10^{17} per MW

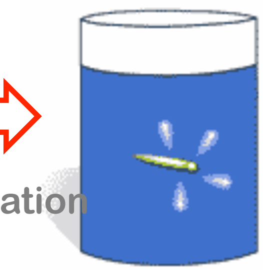


IBD

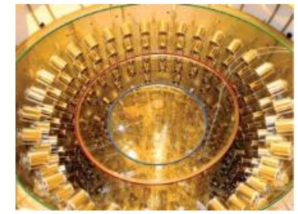


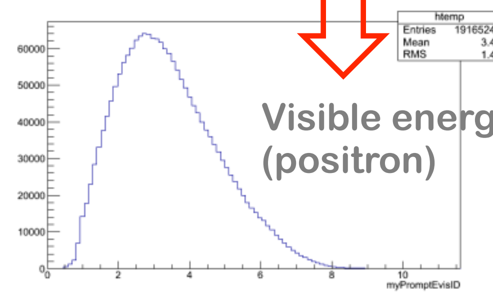


Scintillation



PMT





Visible energy (positron)

- At the Far Detector there is difference between the prediction and collected data due to the neutrino oscillation, proportional to the size of θ_{13}.

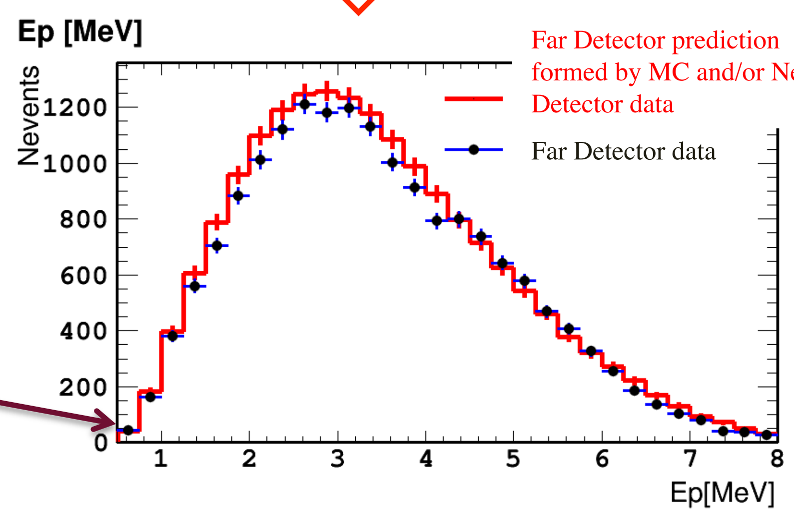
Input from long-baseline Accelerator neutrino exps.

Fixed in Double Chooz

$$P = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E_\nu}\right)$$

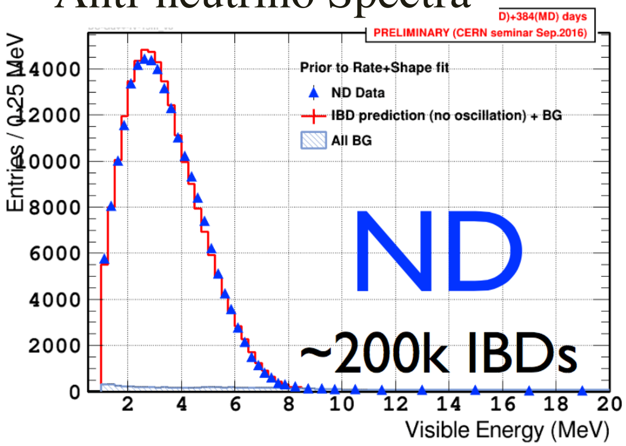
Anti-neutrino oscillation survival probability measured by ratio of Data/Prediction as a function of E

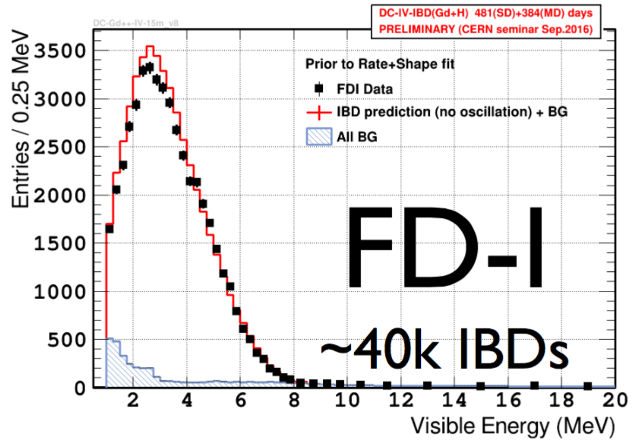
?

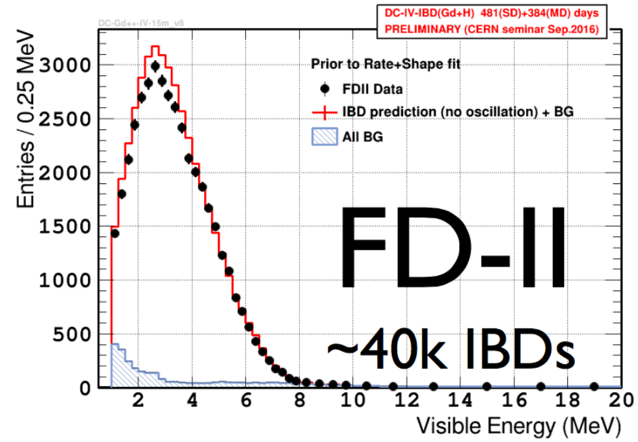


Double Chooz θ_{13} Results

Anti-neutrino Spectra



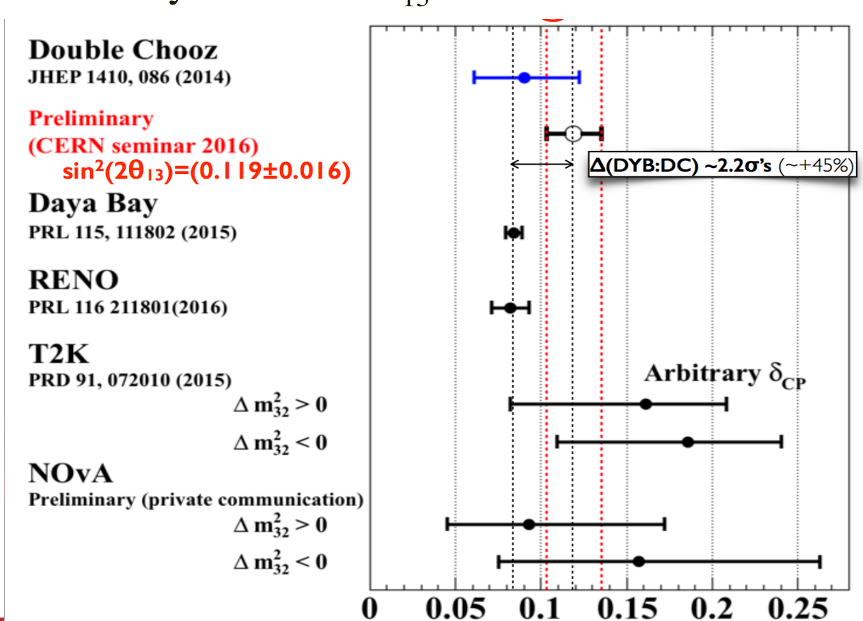




This Results: $\sin^2 2\theta_{13}$ (R+S) = (0.119 ± 0.016)

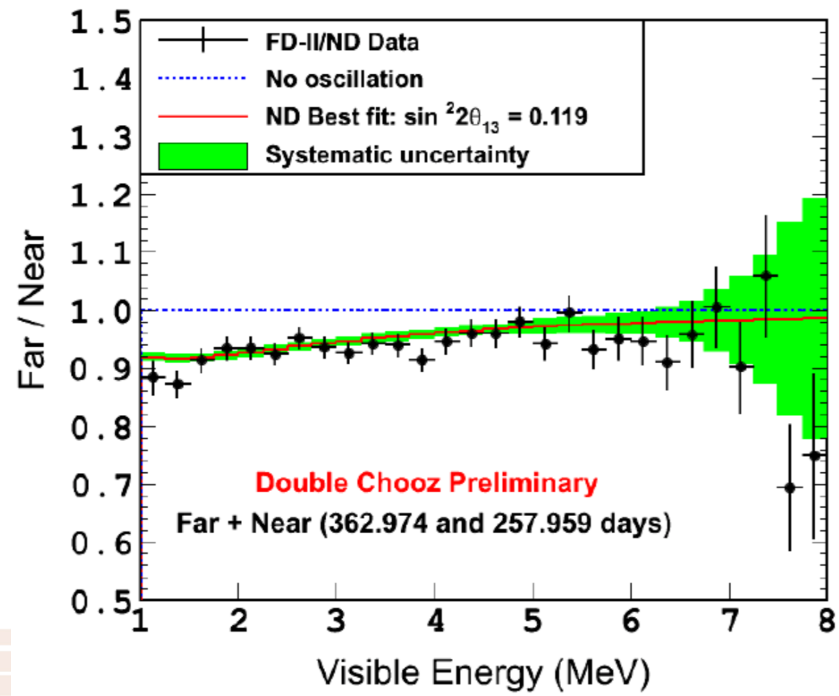
(marginalized over $\Delta m^2 = (2.44 \pm 0.09)\mathrm{eV}^2$
Parke et al. arXiv:1601.07464)

Summary of current θ_{13} Results



(Many thanks to NOvA: latest reference)

Ratio Plot (Far Detector/Near Detector) Data



Why is this important?

- Just about a five years ago the the θ_{13} was the last unmeasured neutrino mixing angle.
  - -Recently it become the most precise measured mixing angle.
  - -All experiments, both reactor and accelerator, show a very consistent results.
  - -The value of θ_{13} is not zero i.e. $\theta_{13} \approx 9^o$, or $\sin^2 2\theta_{13} \approx 0.095$.

- This successful determination of θ_{13} positioned us to aim at measurement of CP-violation and the mass hierarchy with long-baseline oscillation experiments

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

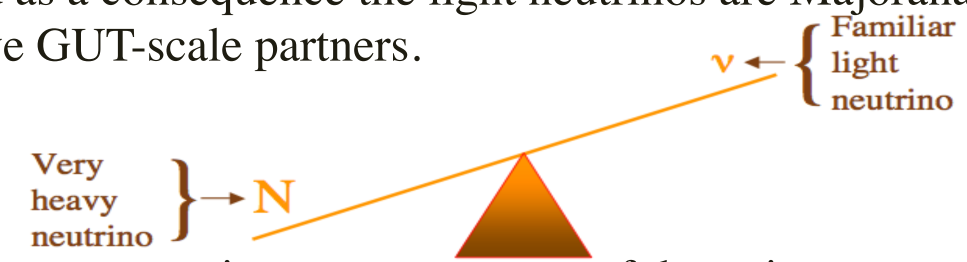
- If the value turned out to be $\theta_{13} = 0$ it would not rule the possible existence of leptonic CP-violation which could help explain dominance of matter over anti-matter.
  - -However $\theta_{13} = 0$ would make leptonic CP-violation impossible to measure through a neutrino oscillation measurement.

Why is CP-violation (i.e. $\delta_{CP} \neq 0$) with neutrinos so important?

-Striking feature of the Universe: only matter, virtually no anti-matter!

-Observation of CP-violation would make it more likely that the baryon-antibaryon asymmetry of the universe arose through leptogenesis.

-The theory of leptogenesis is linked to the see-saw theory and as a consequence the light neutrinos are Majorana and have GUT-scale partners.

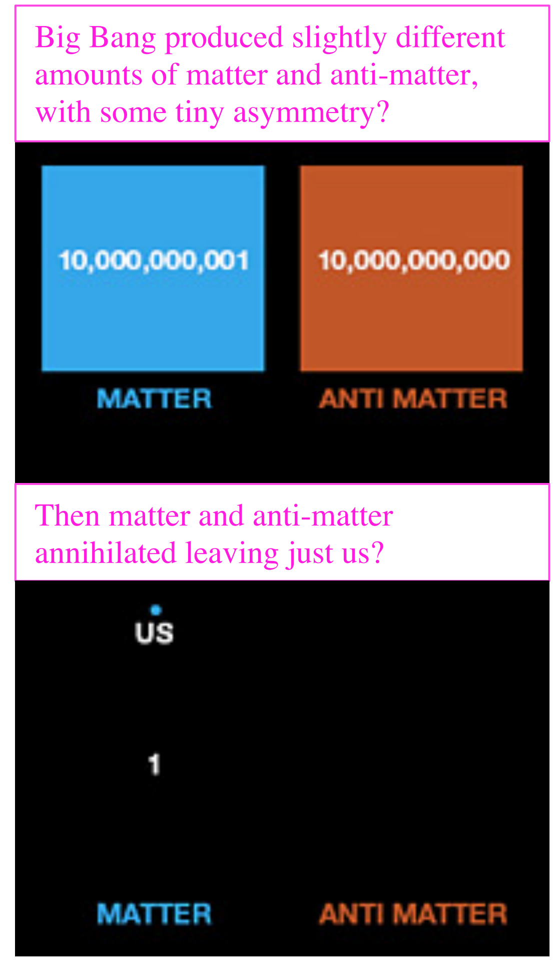


-The matter-antimatter asymmetry of the universe may be explained through CP-violating decays of the heavy partners, producing a state with unequal numbers of Standard Model leptons and antileptons.

$N \to L^- + \varphi^+$ and $N \to L^+ + \varphi^-$ (φ^+, φ^- - Standard-Model Higgs)

-The Standard Model processes convert such a state into the world around us with an unequal number of baryons and antibaryons.

-It is thought that CP-violation would be very unlikely to appear in the heavy sector without happening in light neutrinos.



Long Baseline Accelerator Experiments

(will focus on NOνA Experiment that I currently work on)

NOνA:
$\langle E_\nu \rangle \approx 2$ GeV
L = 810 km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

Long Baseline Accelerator Experiments

(will focus on NOνA Experiment that I currently work on)

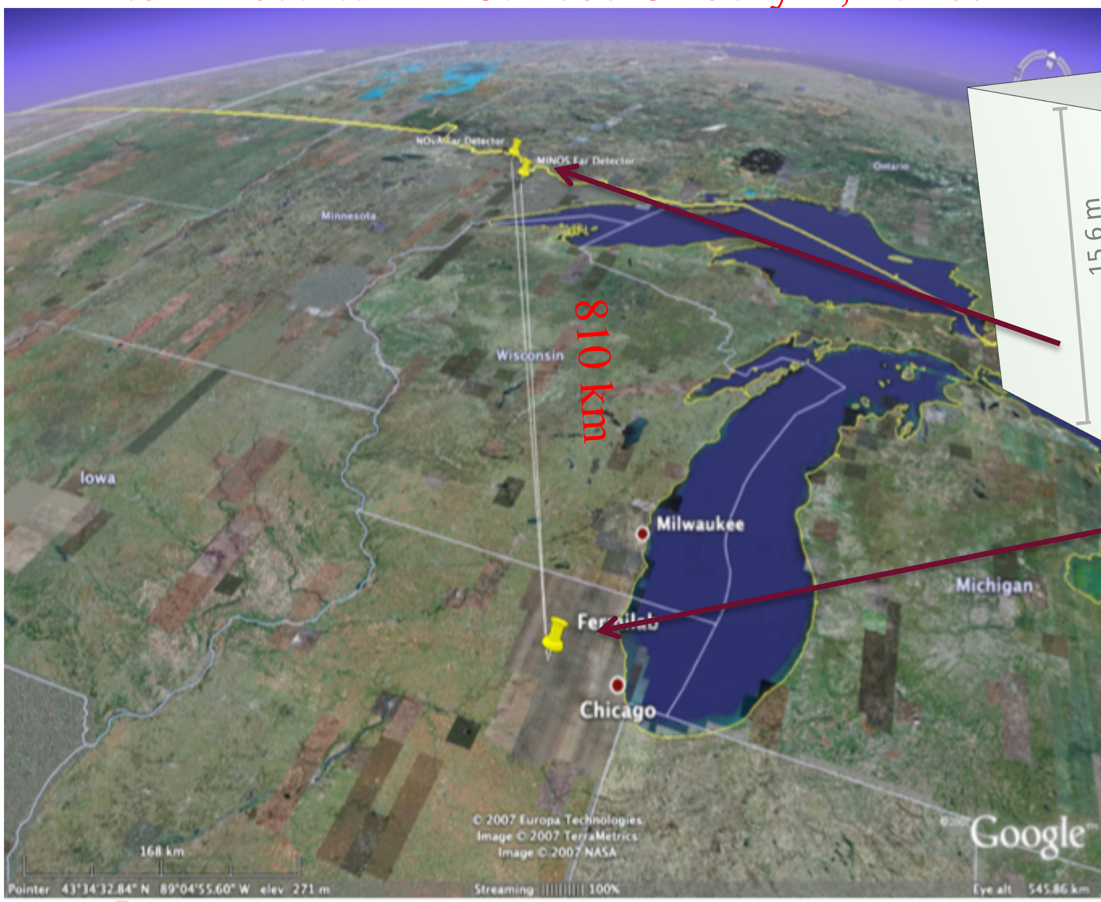
NOνA:
$\langle E_\nu \rangle \approx 2$ GeV
L = 810 km

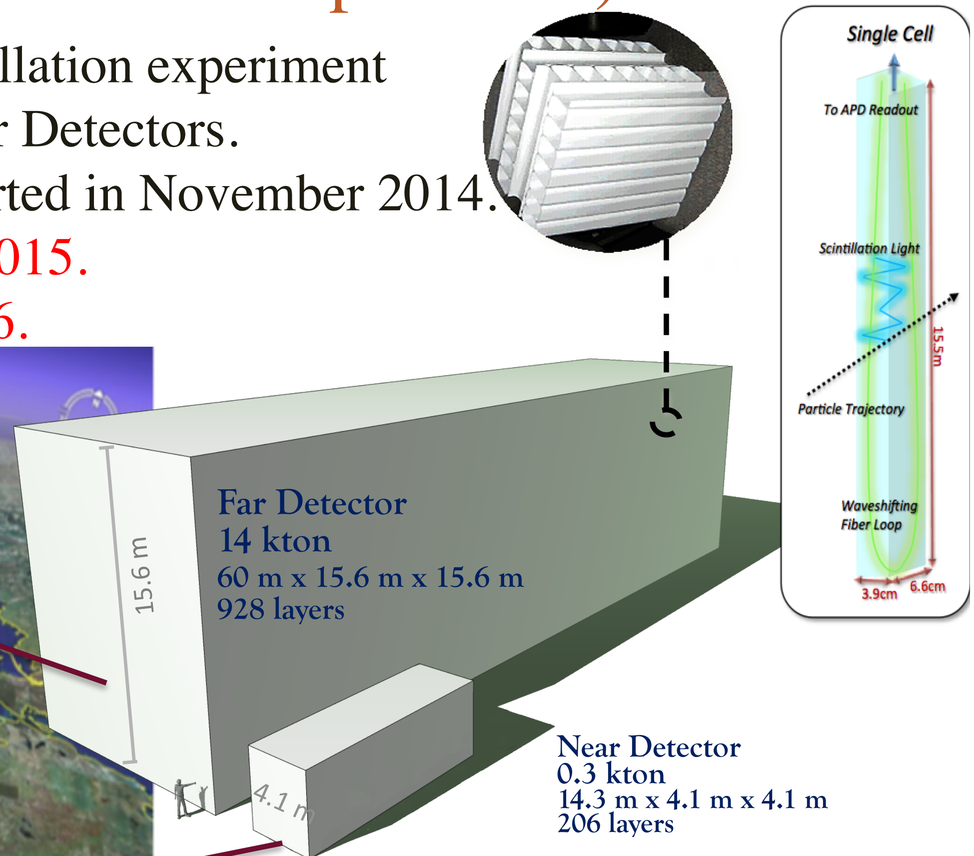
Will describe NOνA
✔ My experiment

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

NOνA (NuMI Off-axis ν_e Appearance Experiment)

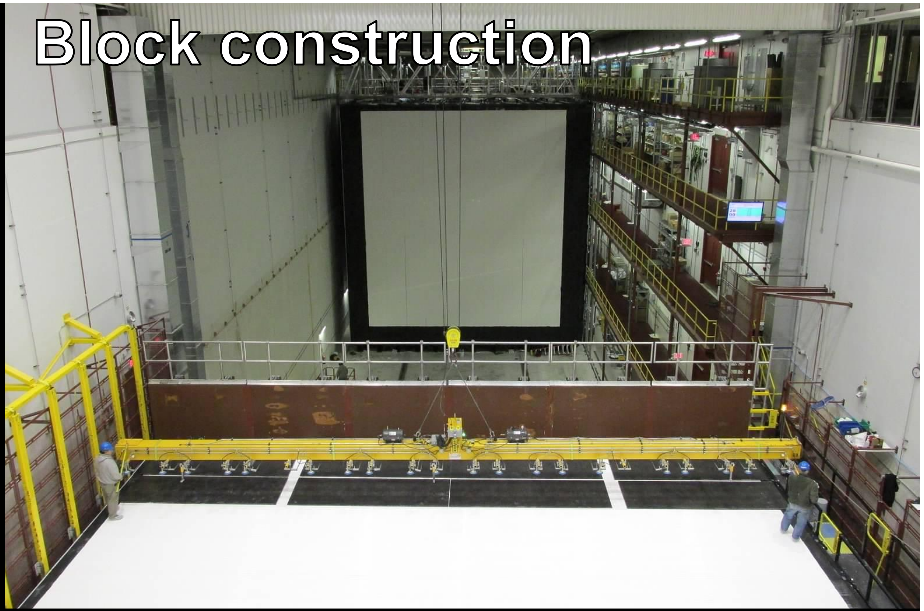
- The long-baseline off-axis neutrino oscillation experiment with functionally identical Near and Far Detectors.
- Data taking with complete detectors started in November 2014.
- First Results Announced on August 6, 2015.
- New Results Announced on July 4, 2016.



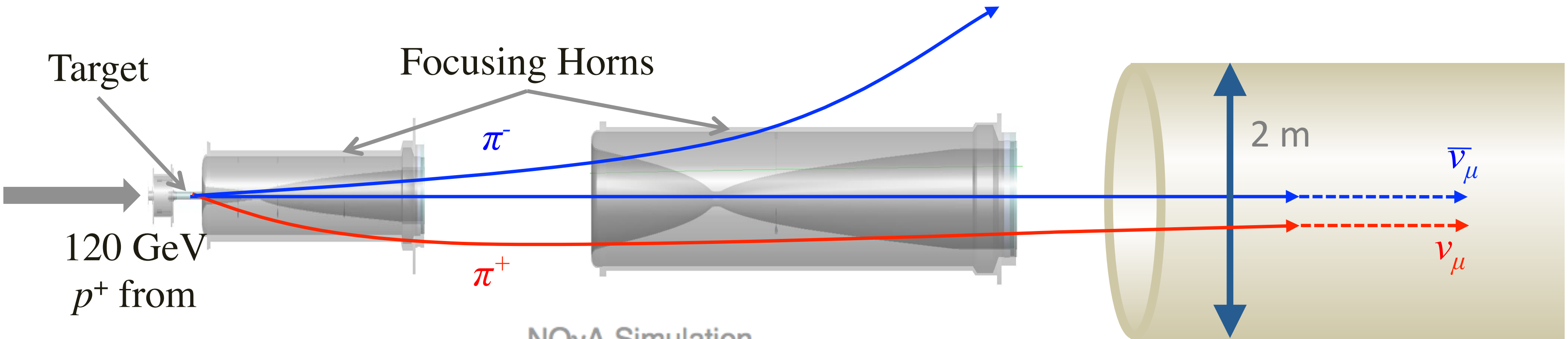


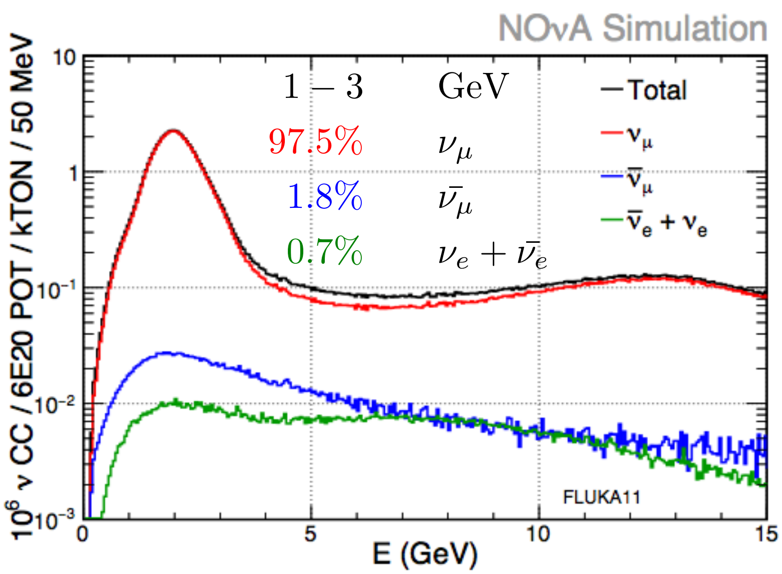
- Low-Z tracking calorimeters
- High power NuMI beam
  - -upgraded for NOνA to take the power 350 – 700 kW
  - -this result: 6.05×10^{20} POT, 700 kW peak intensity.
- Detectors are 14 mrad off-axis.

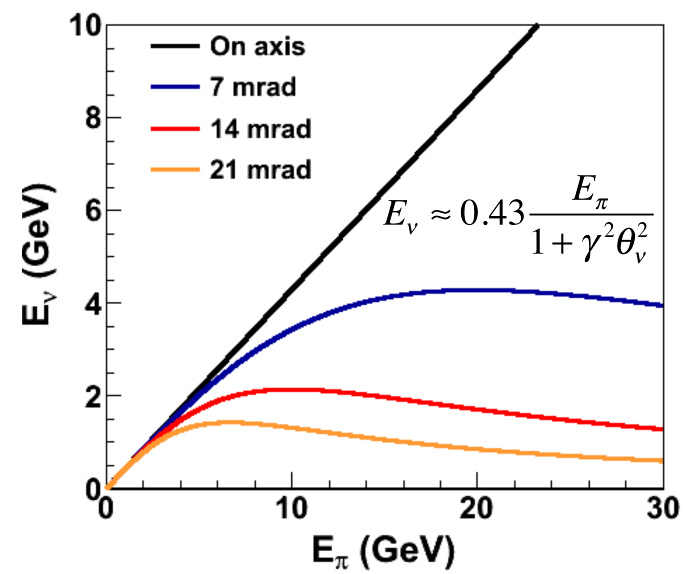
NOνA Detectors



NOνA Off-axis Neutrino Beam







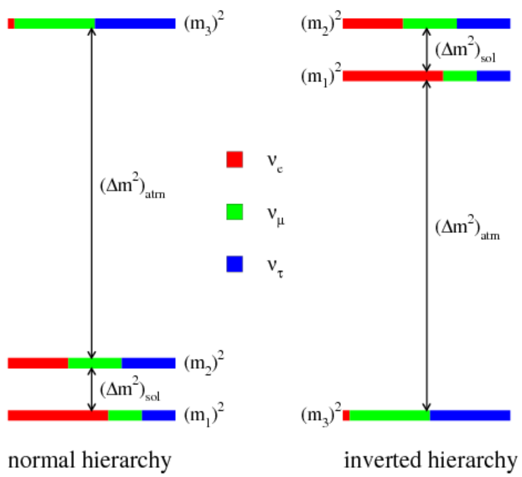
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events

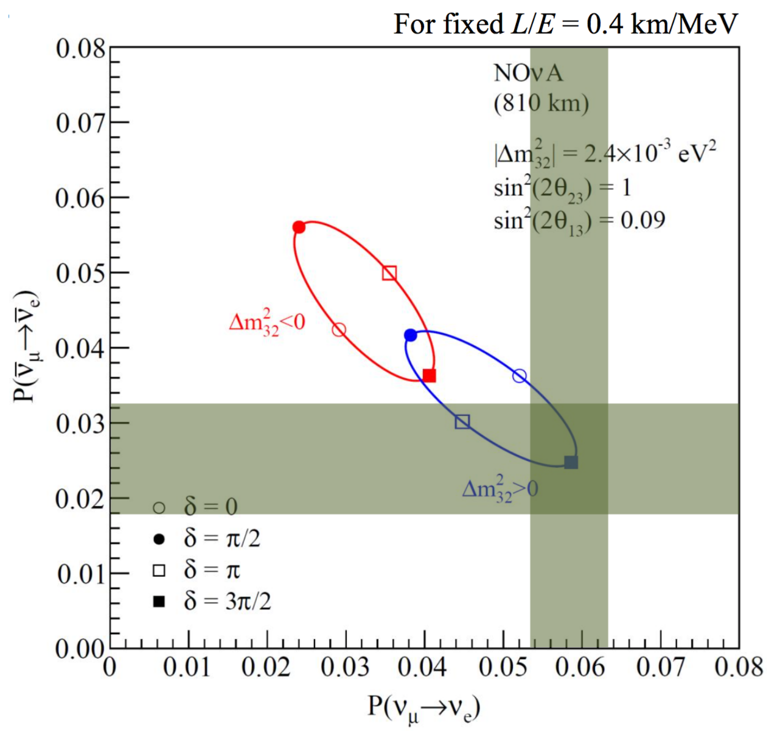
The Goals of NOνA Experiment

- Measure the oscillation probabilities of
  a) appearance channels: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  b) disappearance channels: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$?

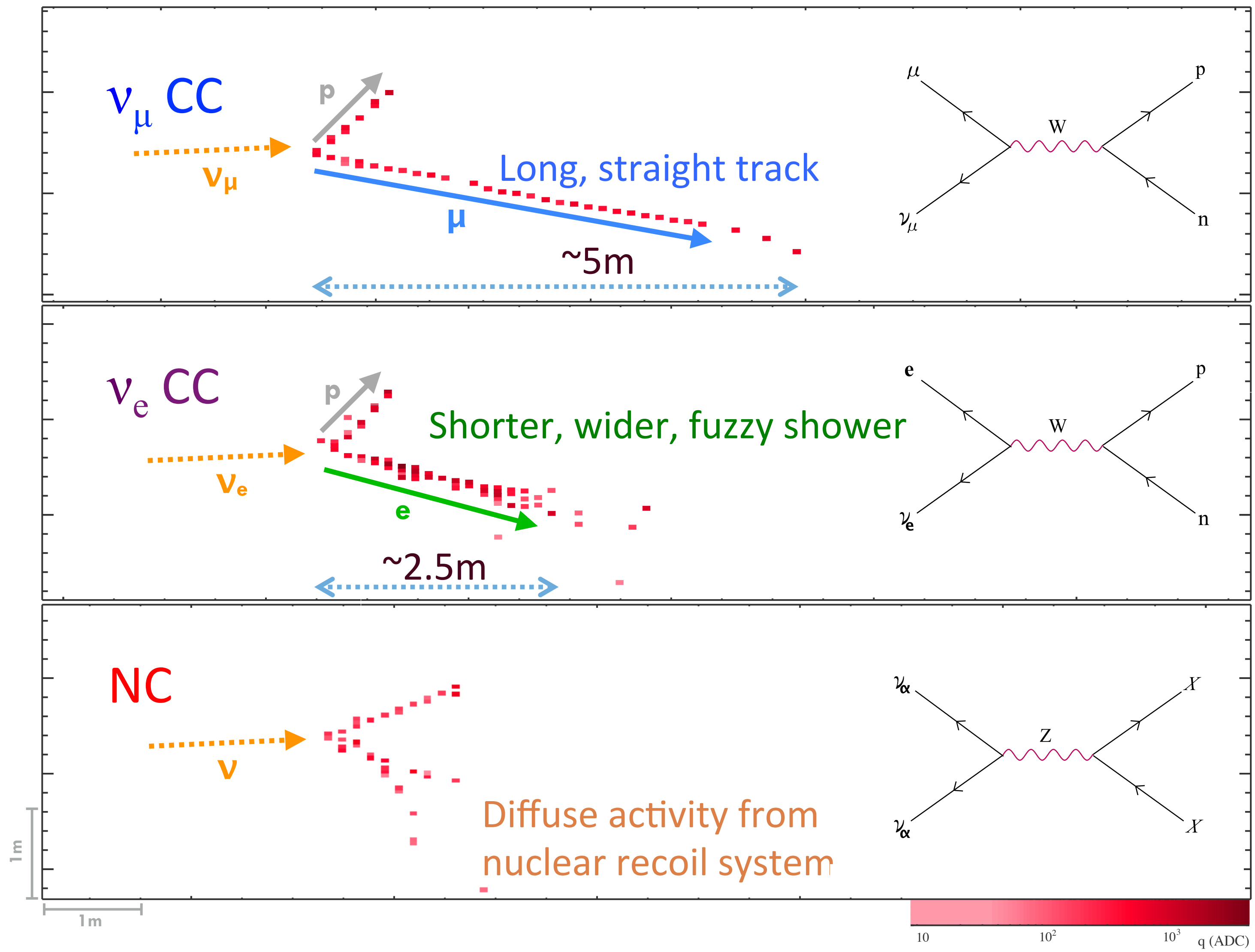
- Precision measurements of θ_{13}, Δm^2_{32}, θ_{23}
- Probe the neutrino mass hierarchy
- Study the CP violation parameter δ



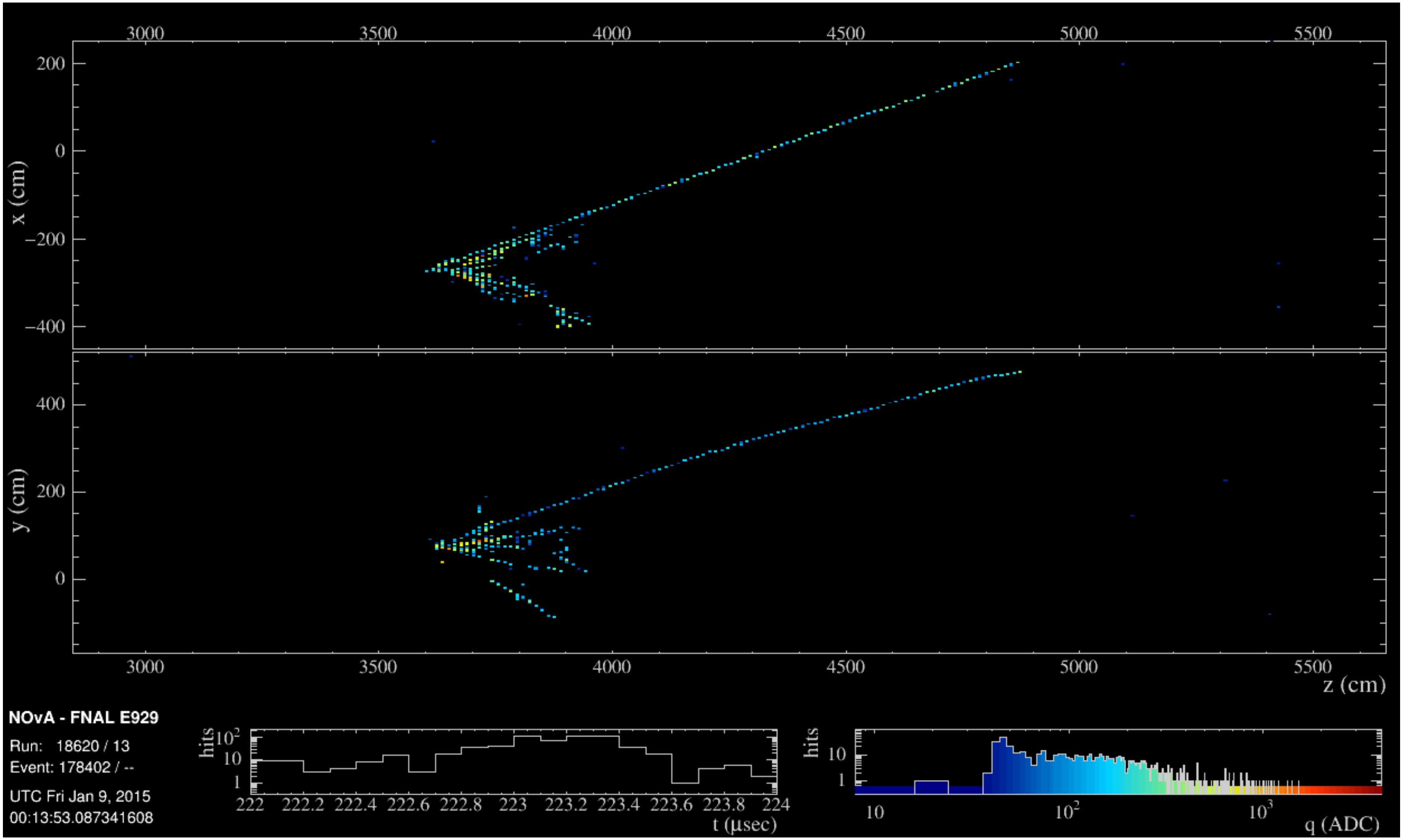


- Additional Physics Goals:
  -Neutrino cross-sections and interaction physics
  -Sterile Neutrinos
  -Supernovae and Exotic Searches

NOνA Event Topologies

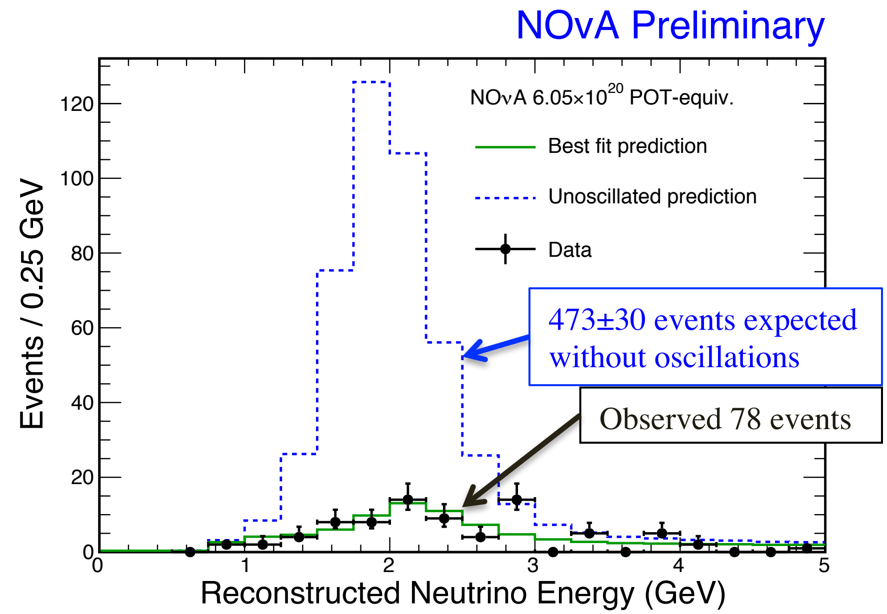


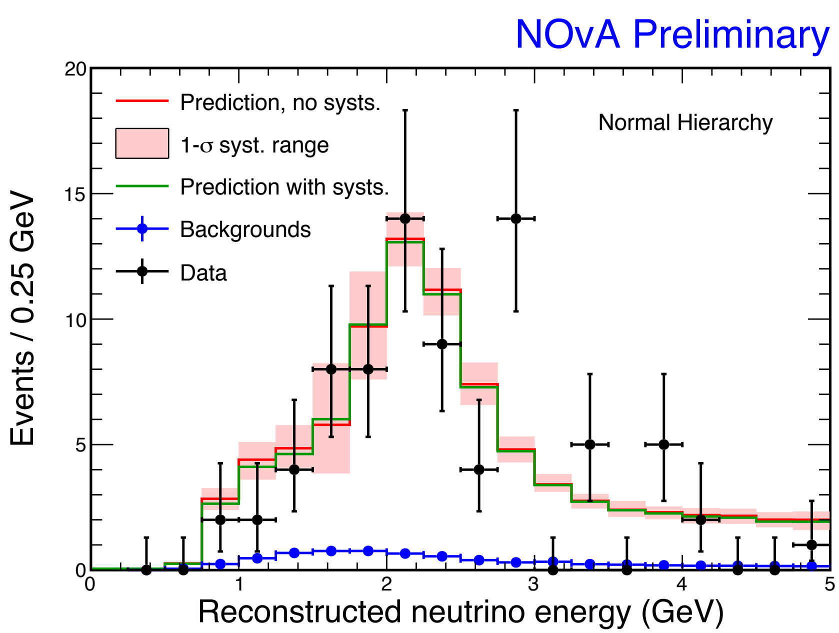
Neutrino Interaction the NOvA Far Detector

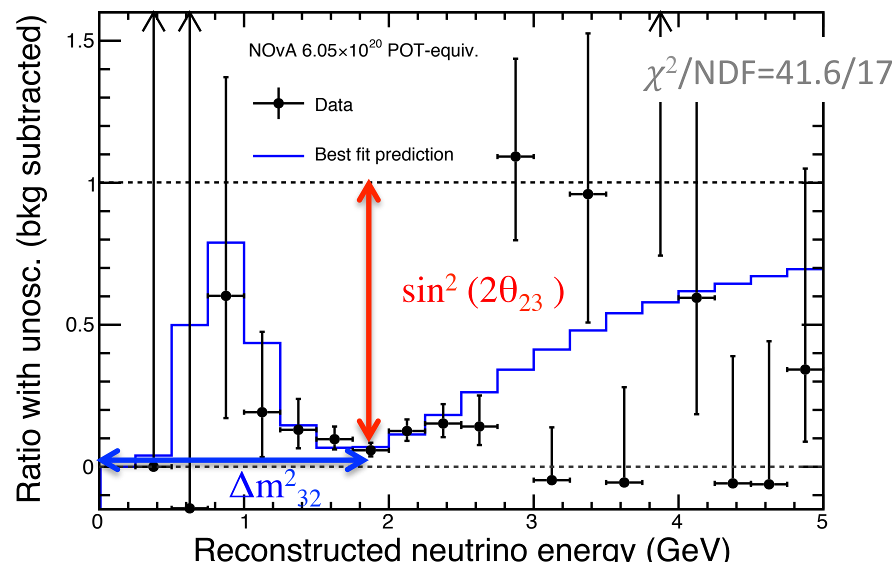


NOνA Far Detector ν_μ Disappearance

- Identify contained ν_μ CC events in both Near and Far Detector
- Measure Energy
- Extract oscillation information from differences between the Far and Near energy spectra







- Spectrum is well matched by oscillation fit for Δm^2 and θ_{23}.

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23}\ \sin^2(1.27\Delta m^2_{32} L[m] / E_\nu[MeV])$$

NOvA ν_μ Disappearance Result

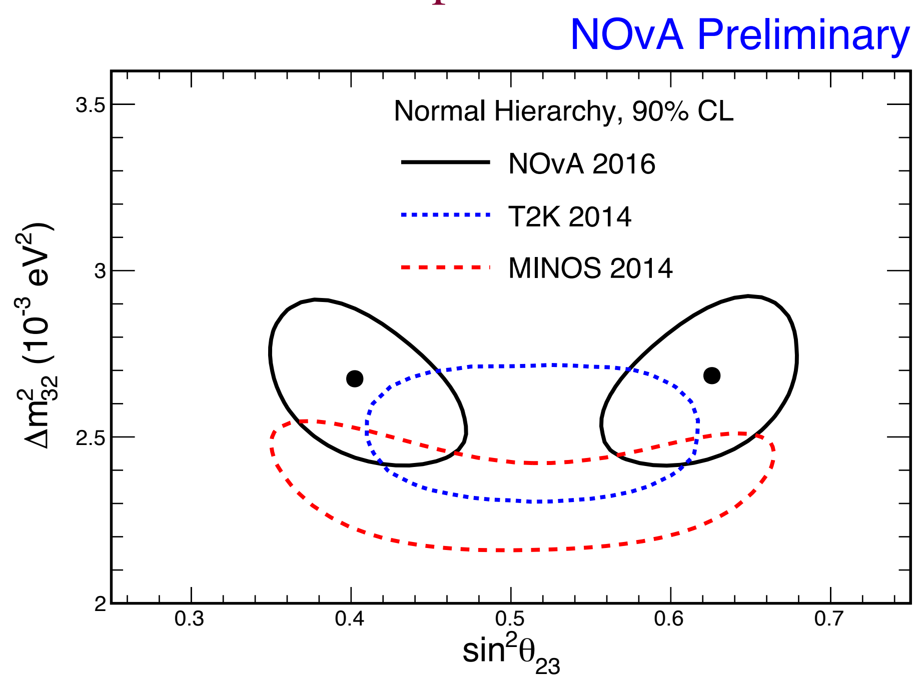
(need oscillation formula)

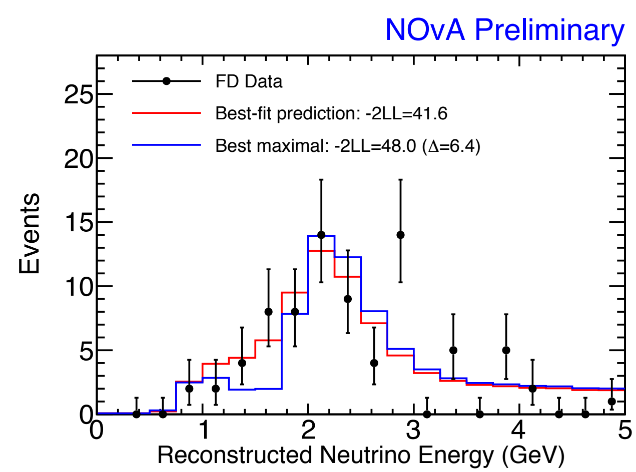
- NOvA allowed region in (Δm^2, $\sin^2\theta_{23}$)
- Best Fit Result (in NH):

$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

Contours compared





ν_e Appearance Search

- Let's talk about NOvA electron-neutrino appearance search
- Remember we now measure $\nu_\mu \to \nu_e$ oscillation:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\;& \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
&+ \cos\delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\Delta_{32} \left(\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)} \Delta_{21}\right) \\
&- \sin\delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin\Delta_{32} \left(\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)} \Delta_{21}\right) \\
&+ \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,
\end{aligned}
$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\upsilon$$

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

CP-violation parameter δ_{CP}

Mass hierarchy (sign of Δm_{31}^2)

} Need measure this!

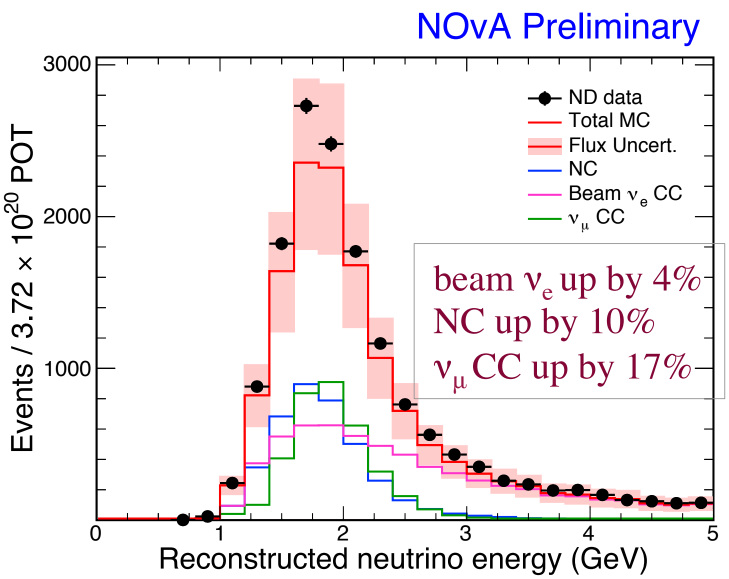
Size of $\sin^2\theta_{23}$ — Use the results of accelerator muon neutrino oscillation measurements

Mixing angle θ_{13} — Take the value from reactor electron anti-neutrino oscillation experiments

ν_e Appearance Search

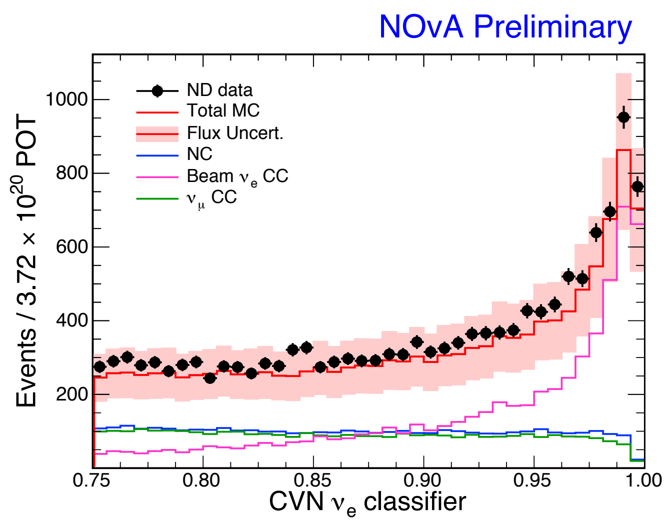
- Identify contained ν_e CC events in both Near and Far Detector
- Use Near Detector Data/MC to predict beam backgrounds in the Far Detector
- Extract oscillation information from Far Detector excess over predicted backgrounds

1[st] Analysis Published in PRL 116 (2016) no.15, 151806



ND data to predict background in FD

- NC, CC, beam ν_e each propagate differently
- constrain beam ν_e using selected ν_μ CC spectrum
- constrain ν_μ CC using Michel Electron distribution

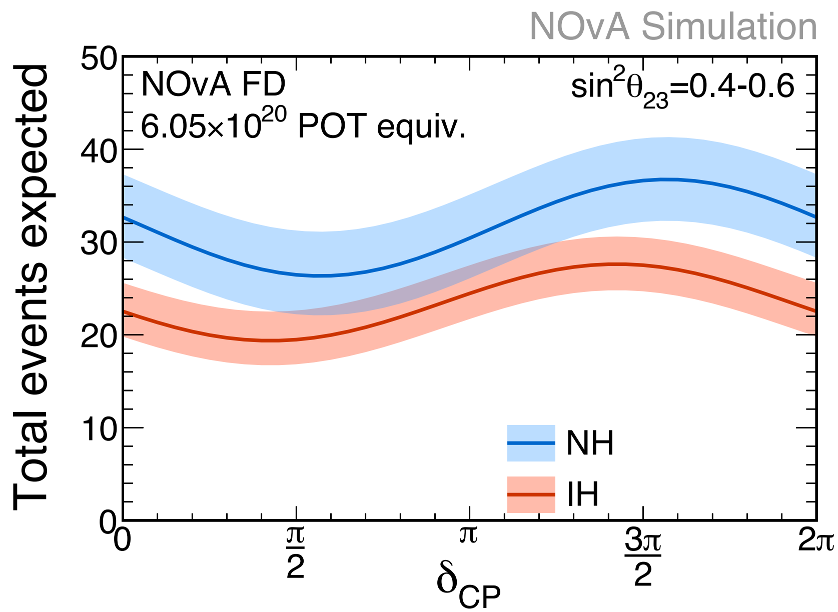


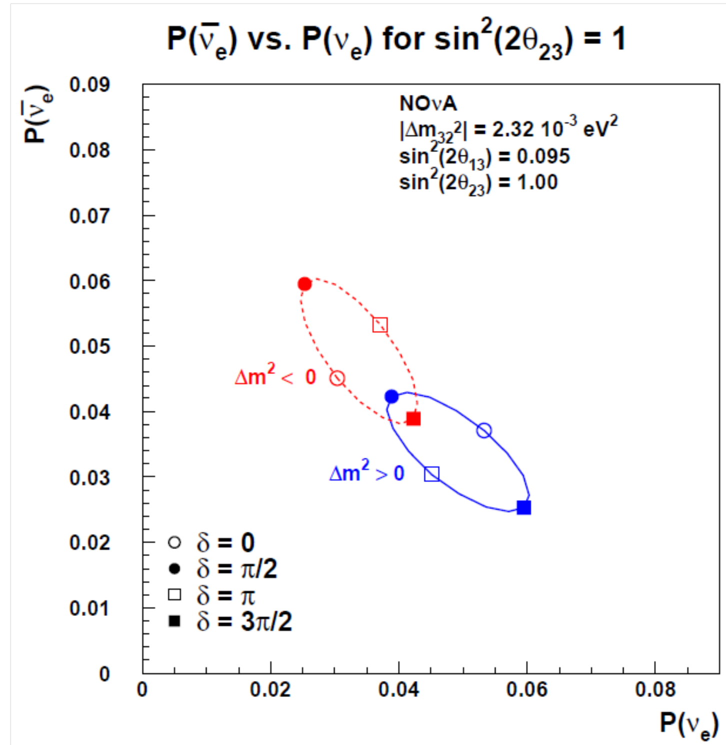
Selection that separates ν_e CC events from Backgrounds performed by CVN (Convolutional Neural Network) classifier

CVN technique published in JINST 11 (2016) no.09, P09001.

Far Detector ν_e Signal Prediction

- Extrapolate each background component in bins of energy and CVN output
- Expected event counts depend on oscillation parameters





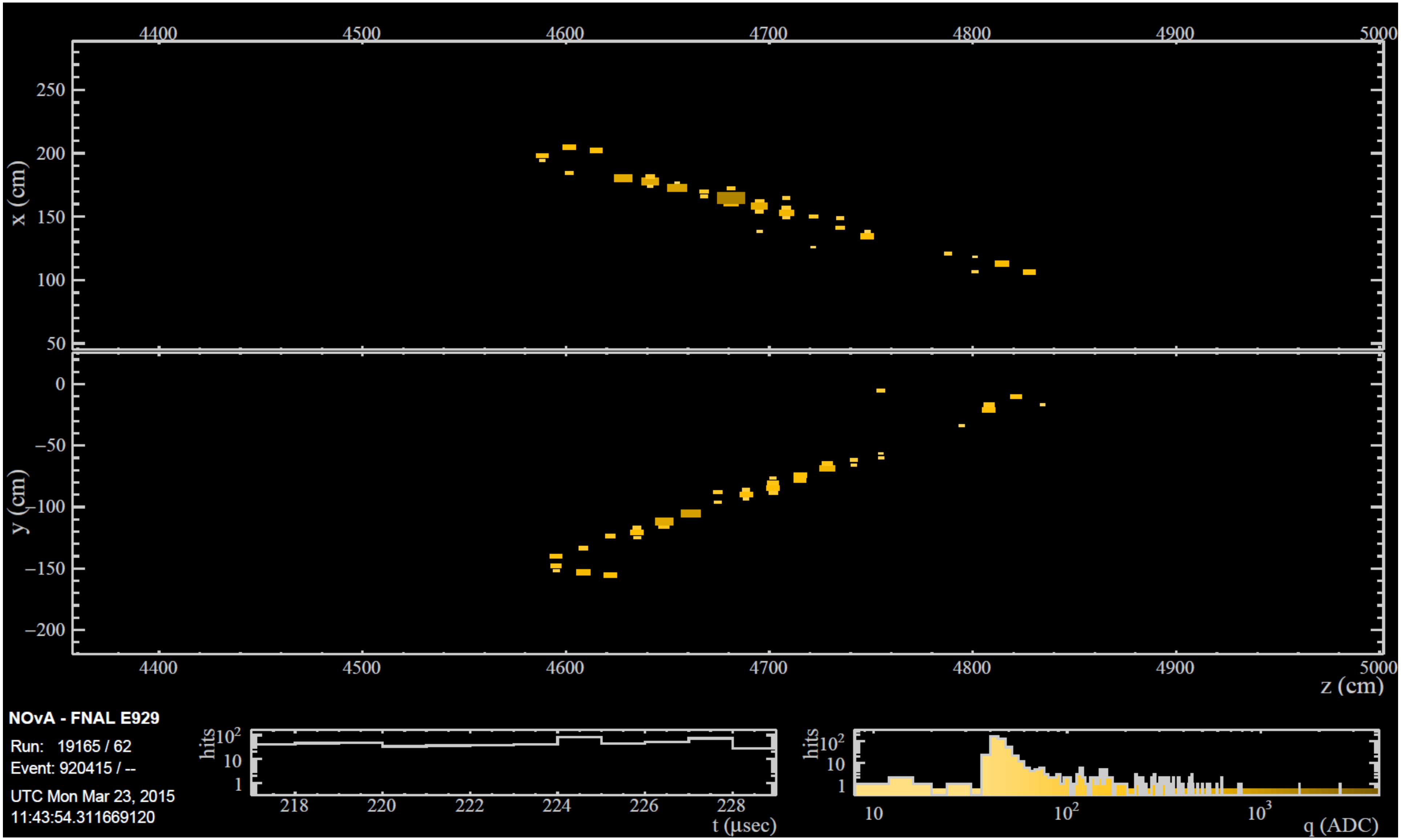
Signal events (±5% systematic uncertainty):

NH, 3π/2,	IH, π/2,
28.2	11.2

Background by component (±10% systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

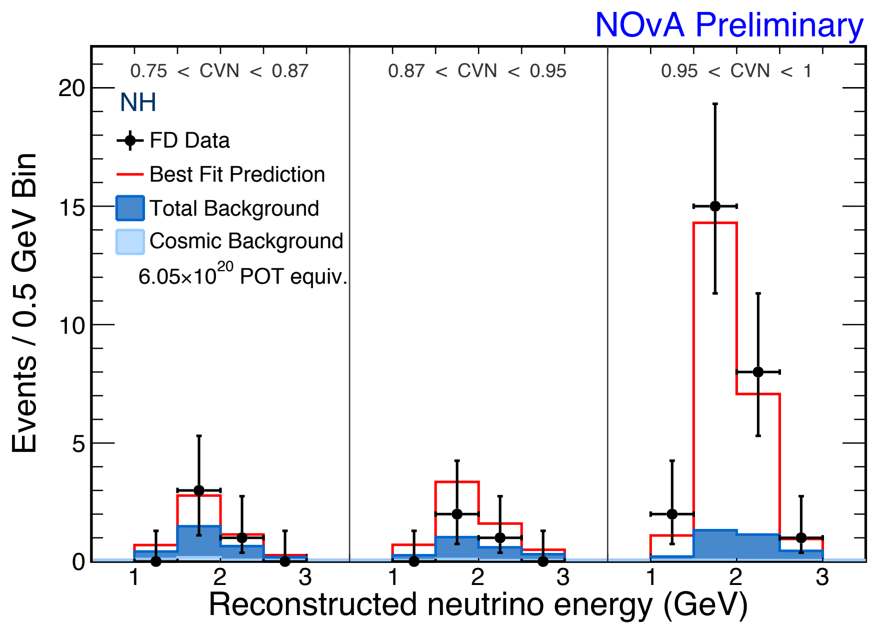
NOvA Far Detector Selected ν_e CC Candidate

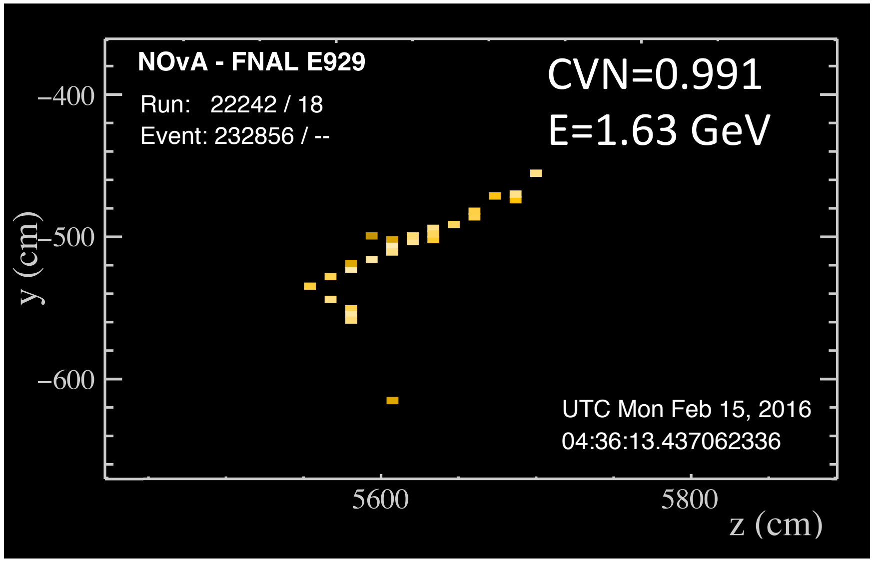


Far Detector ν_e Data vs Prediction

- Observed 33 events in FD
  - Background estimate: 8.2 ± 0.8

>8σ electron neutrino appearance signal





Alternate PID selection based on 2015 analysis show consistent results

- LID: 34 events, 12.2±1.2 BG expected
- LEM: 33 events, 10.3±1.0 BG expected

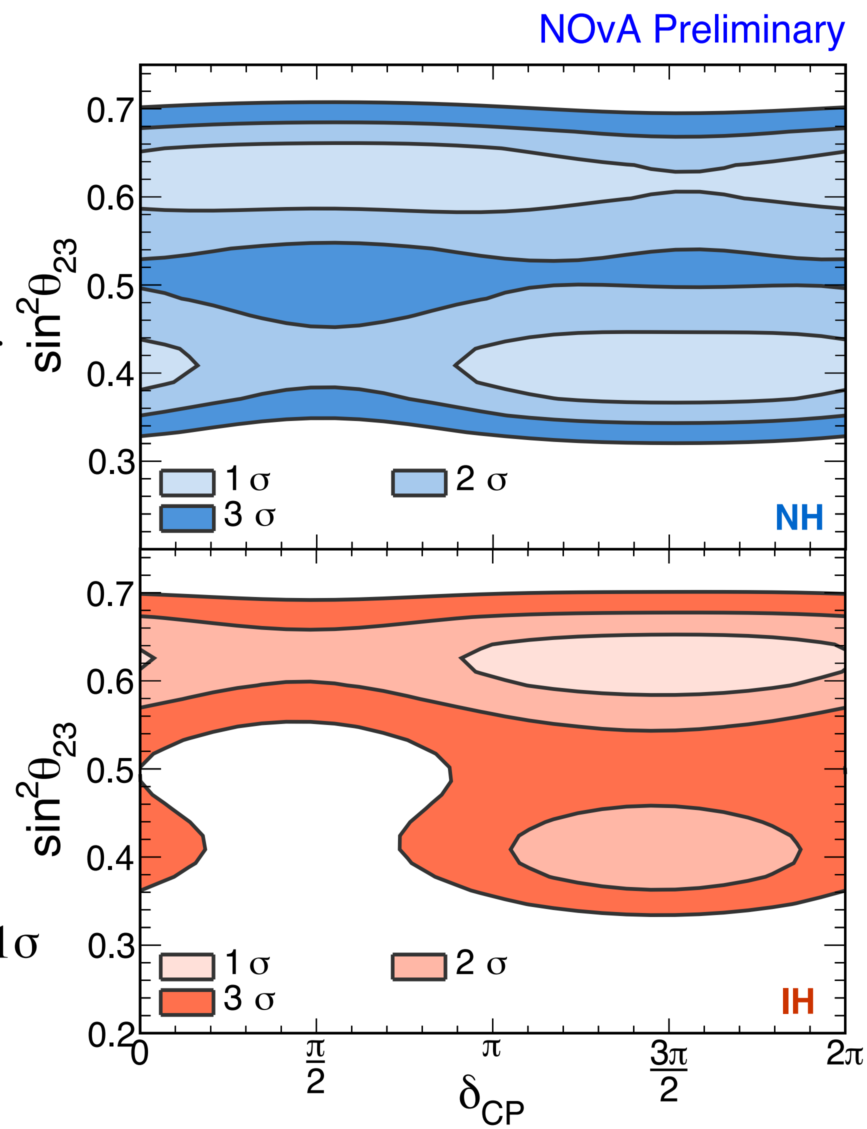
NOvA ν_e Appearance Results

- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated between two samples

- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

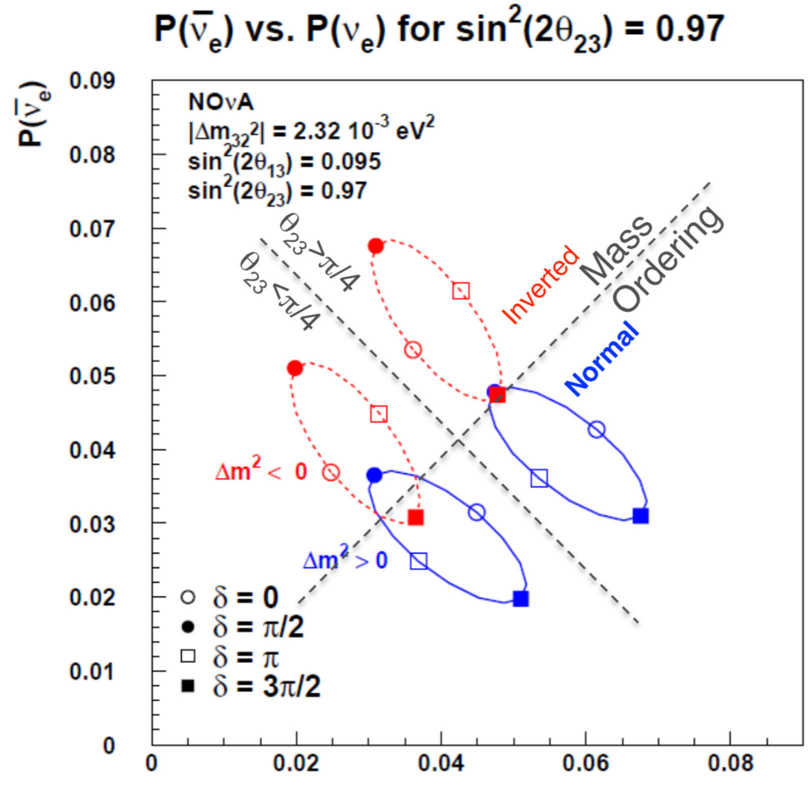
  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{CP}=\pi/2$



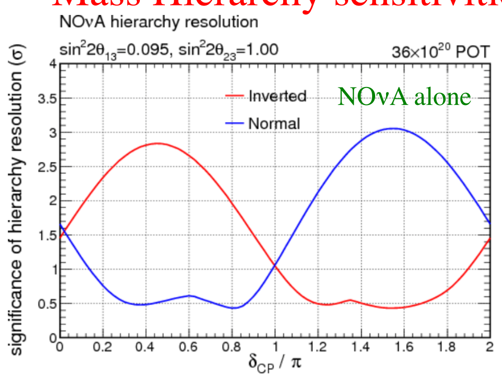
What to Expect from current NOνA (and T2K) Experiments?

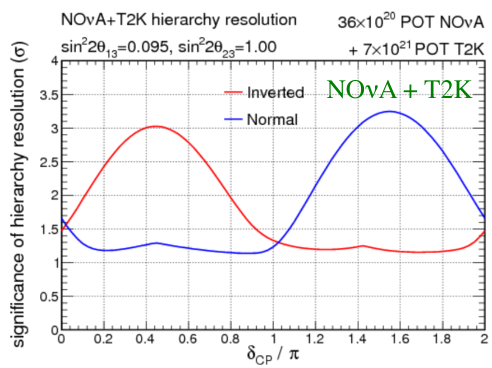
- Current results provide a hint of $\delta_{CP} \sim 1.5\,\pi$ and Normal Hierarchy
  - -But significance is low
  - -Both experiments will continue to operate for another >5 years

- NOνA Sensitivities after 6 x more exposure (alone and with T2K)

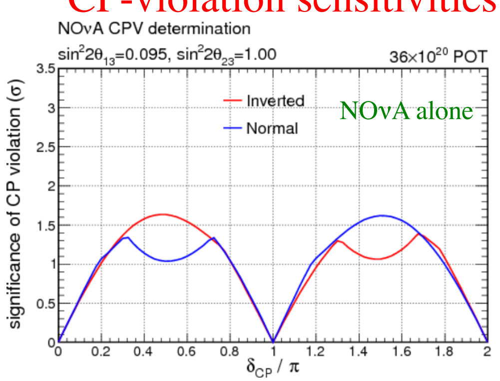


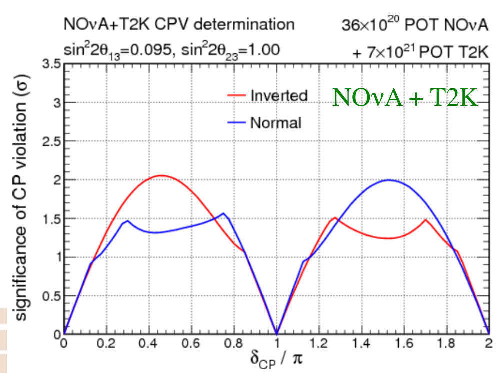
Mass Hierarchy sensitivities





CP-violation sensitivities





-NOνA delivered new results with 6.05 x 10^{20} POT exposure

-ν_μ Disappearance result
 Muon neutrinos disappear
 Best fit is non-maximal: Maximal mixing excluded at 2.5σ

-ν_e Appearance result
 Electron neutrinos appear at > 8σ
 Data prefers NH at low significance
 Region in IH, lower octant around $\boldsymbol{\delta}_{CP} = \pi/2$ is excluded

-NOνA prepares to take anti-neutrino data
 Short anti-neutrino run taken in Summer 2016
 Long anti-neutrino run anticipated to start in Spring 2017

The NOνA Collaboration

Argonne, Atlantico, Banaras Hindu University, Caltech, Cochin, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, U. Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, South Carolina, SD School of Mines, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL,Virginia, Wichita State, William and Mary, Winona State

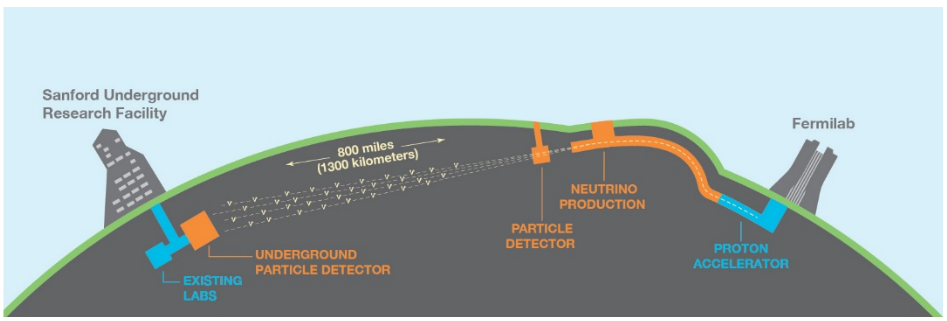
234 Collaborators
41 institutions
7 countries

Photo from the latest NOνA Collaboration Meeting at Argonne National Lab June 2016

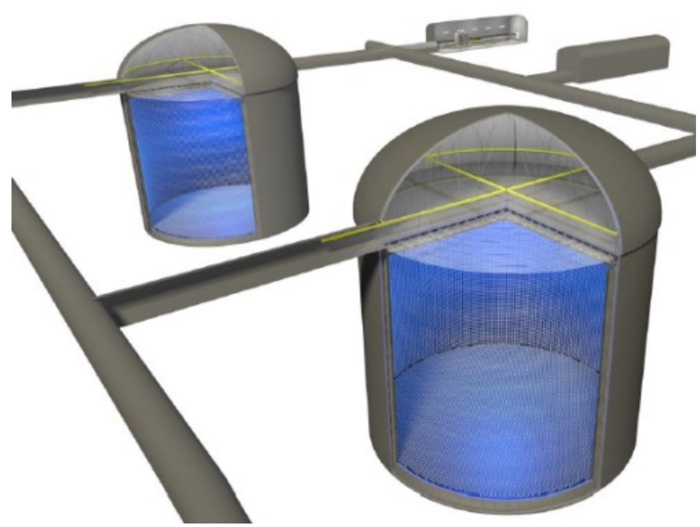
Next Generation of long-baseline Accelerator Neutrino Experiments

- To get convincing results physicist plan to measure δ_{CP} and definitely determine mass hierarchy in new generation of accelerator-based neutrino/antineutrino experiments.
  -DUNE (Deep Underground Neutrino Experiment) approved in US
  -Hyper-Kamiokande proposed in Japan.

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



Hyper-Kamiokande



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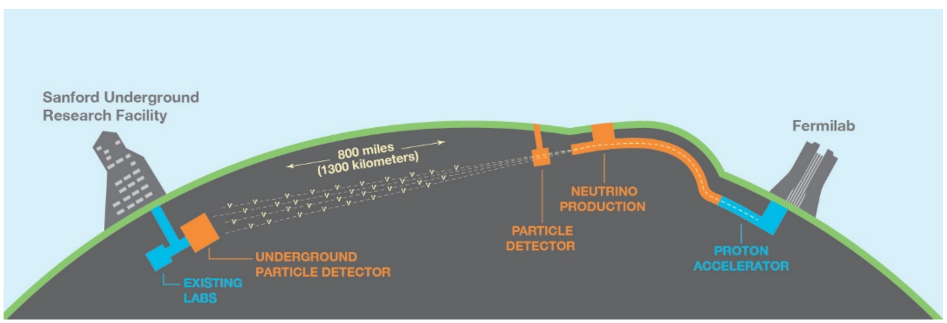
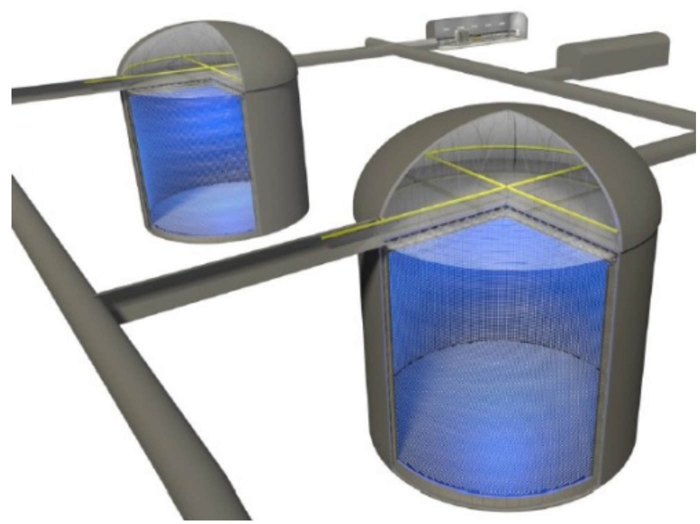
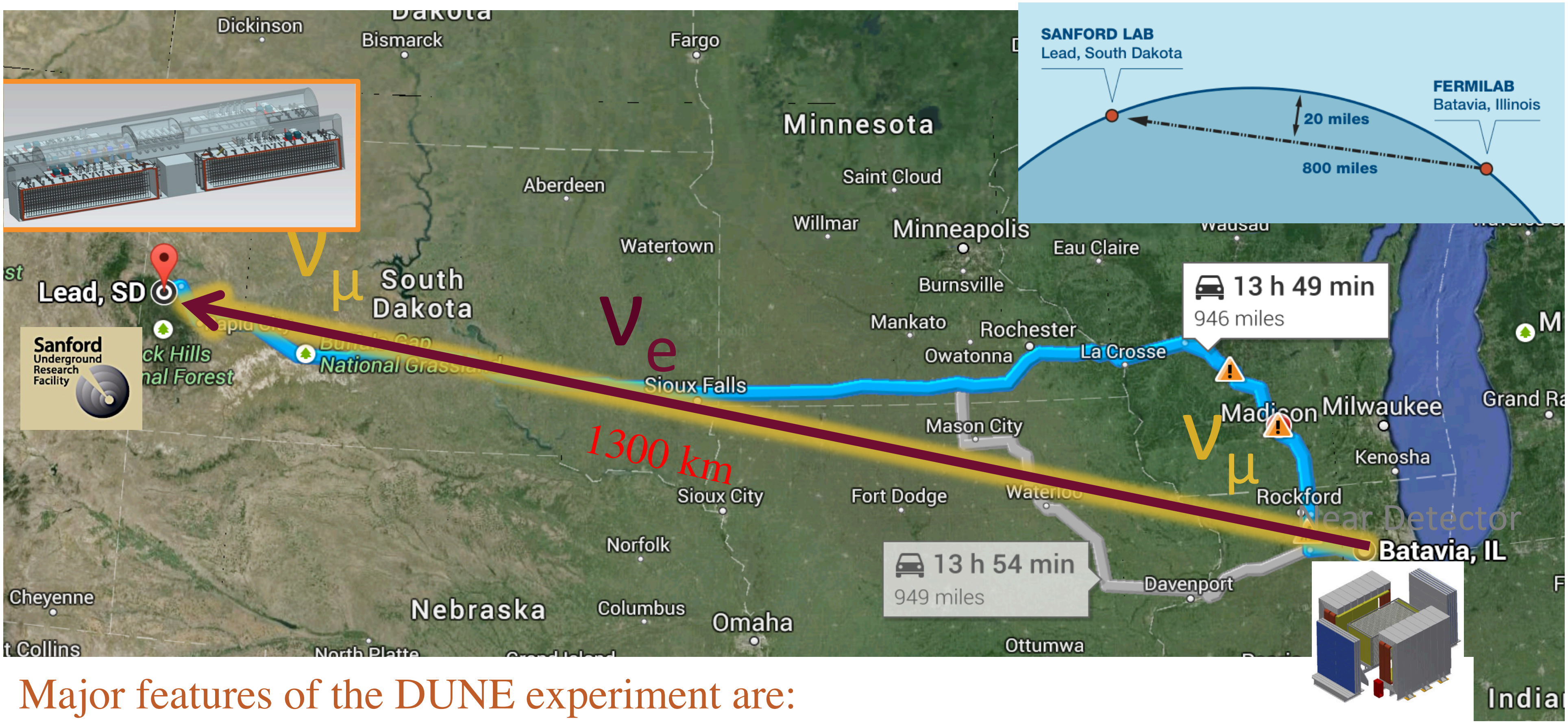


Will describe DUNE
✔ My experiment

Hyper-Kamiokande



Deep Underground Neutrino Experiment (DUNE)



Major features of the DUNE experiment are:

- A high-intensity wide-band neutrino beam originating at FNAL
  -1.2 MW proton beam upgradable to 2.4 MW
- A highly capable near detector to measure the neutrino flux
- A ~40 kt fiducial mass liquid argon far detector
  -Located 1300 km baseline at SURF's 1.5 km underground level (2300 mwe)
  -Staged construction of four ~10 kt detector modules. First module to be installed starting in 2021.

The Goals of DUNE Experiment

- Primary focus of the DUNE science program is on fundamental open questions in particle physics and astro-particle physics:

  1) Neutrino Oscillation Physics

     -CPV in the leptonic sector

       "Our best bet for explaining why there is matter in the universe"

     -Mass Hierarchy

     -Precision Oscillation Physics & testing the 3-flavor paradigm

  2) Nucleon Decay

     -Predicted in beyond the Standard Model theories [but not yet seen]

       e.g. the SUSY-favored mode, $p \rightarrow K^+\bar{\nu}$

  3) Supernova burst physics & astrophysics

     -Galactic core collapse supernova, sensitivity to ν_e

       Time information on neutron star or even black-hole formation

Any would be a major discovery

- DUNE Ancillary Science Program

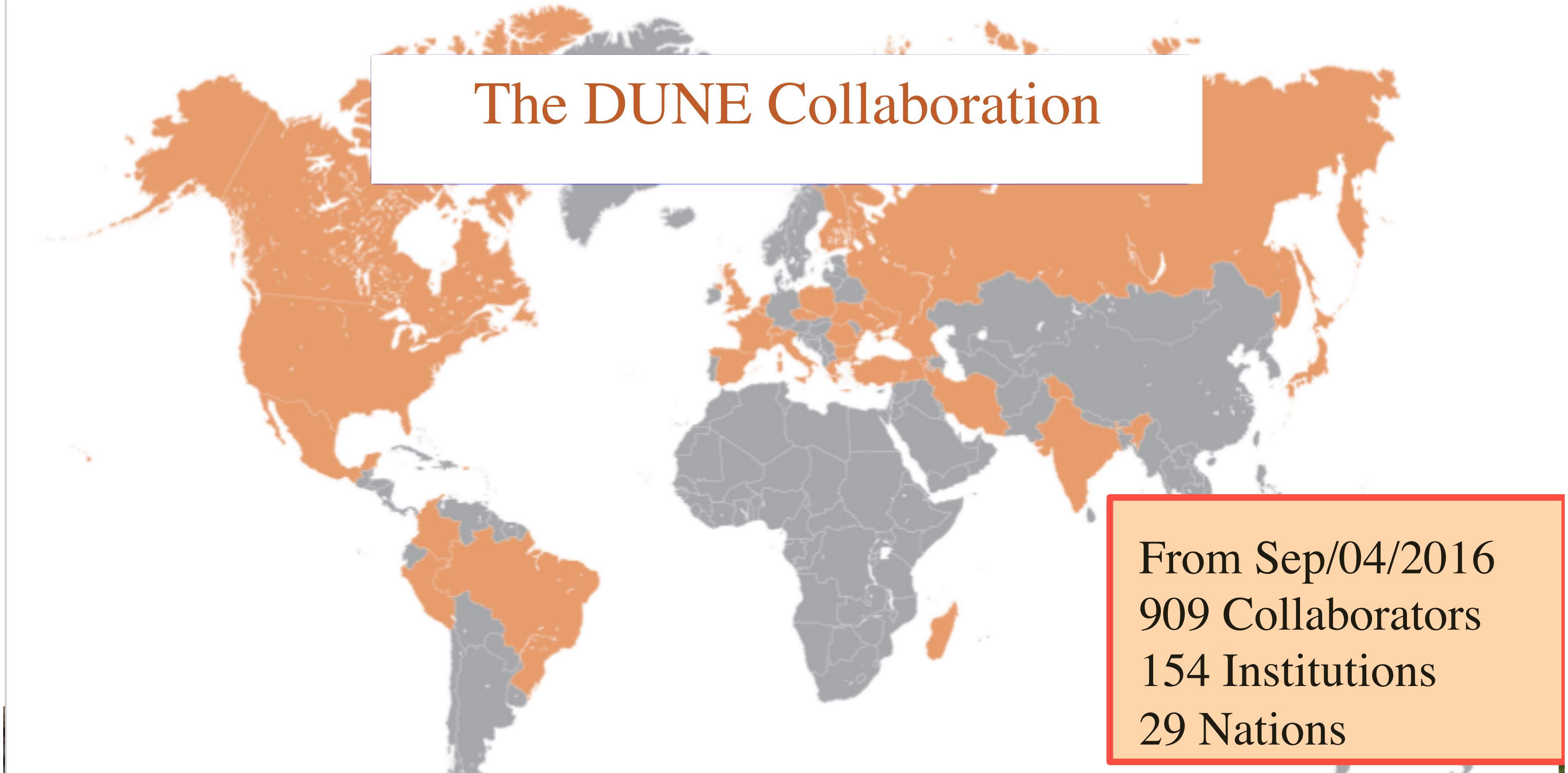
  -Other LBL oscillation physics with BSM sensitivity

  -Oscillation physics with atmospheric neutrinos

  -Neutrino Physics in the near detector

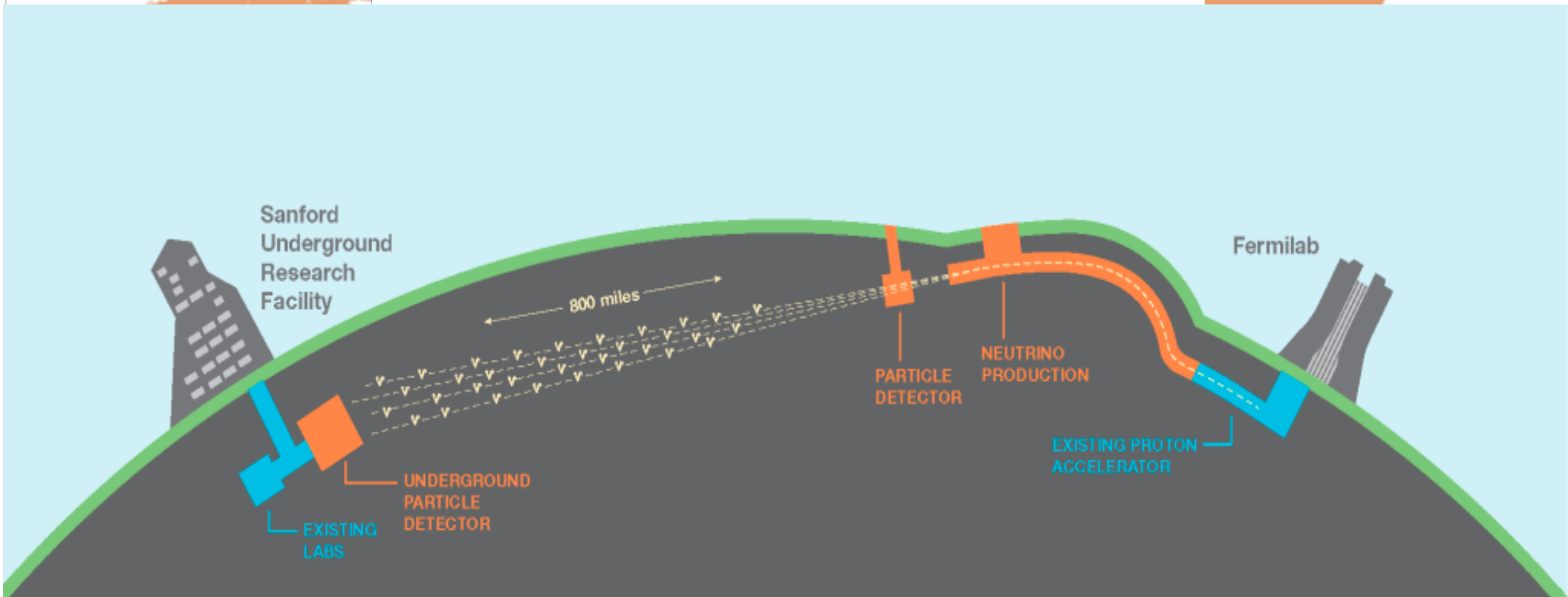
  -Search for signatures of Dark Matter

The DUNE Collaboration



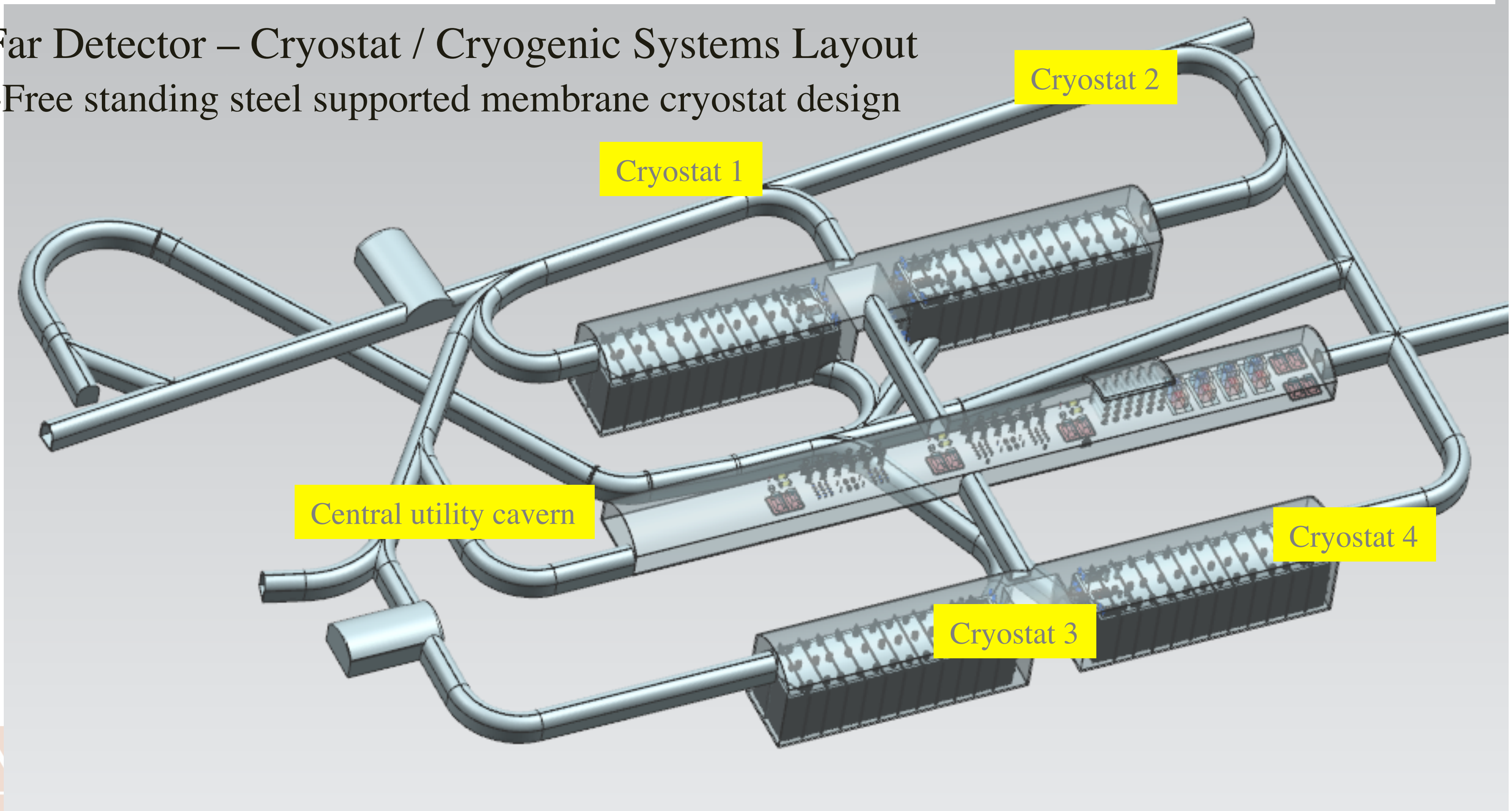
From Sep/04/2016
909 Collaborators
154 Institutions
29 Nations

The DUNE Collaboration



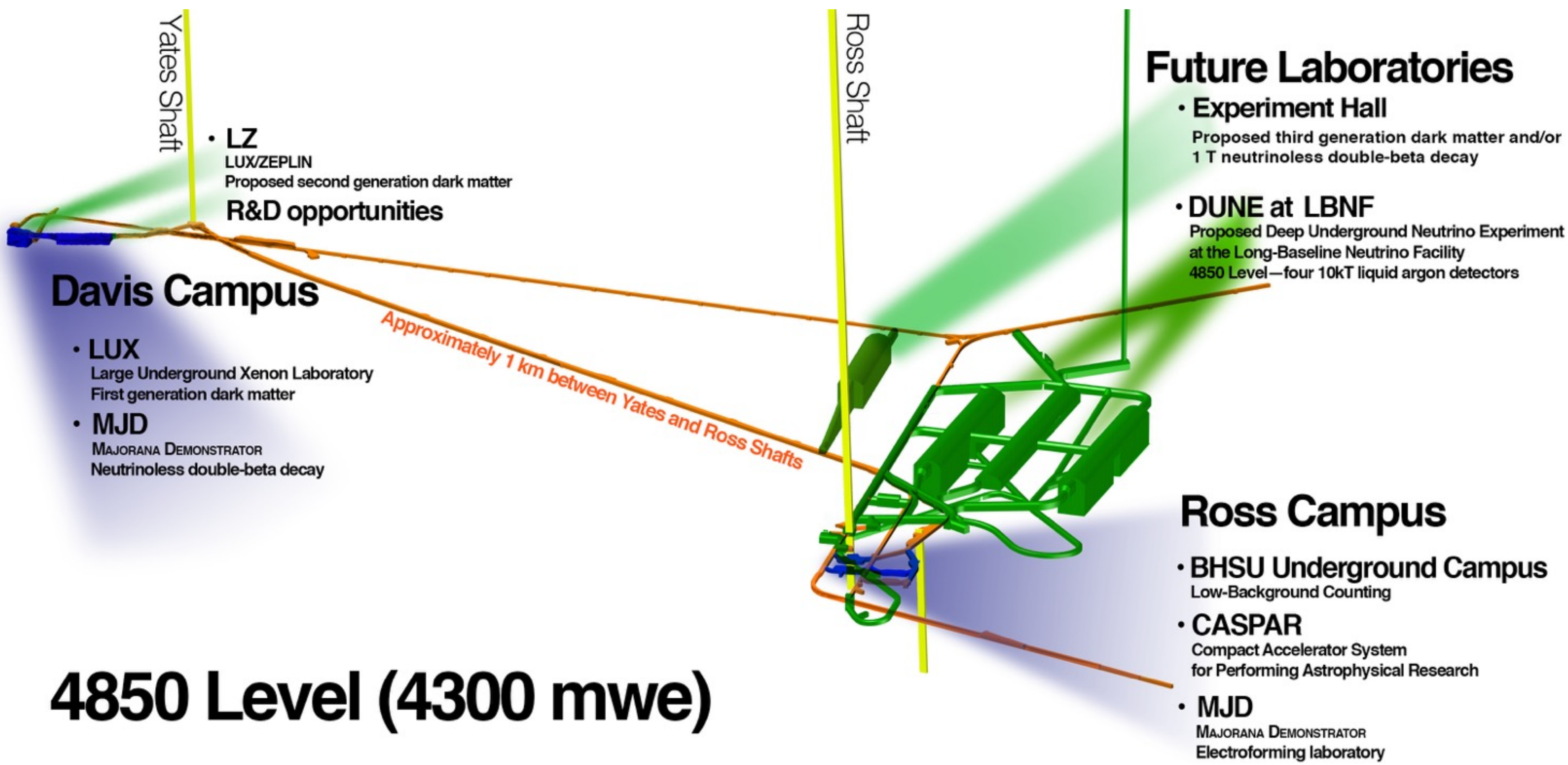
DUNE Far Detector Staged Approach

- Four-Cavern Layout at the Sanford Underground Research Facility (SURF) at the 4850 foot Level (4300 m.w.e.)
  - -Four independent 10-kt (fiducial mass) Far Detector liquid argon TPC modules
  - -Allows for staged construction of the Far Detector
  - -Gives flexibility for evolution of liquid argon (LAr) TPC technology design
- Far Detector – Cryostat / Cryogenic Systems Layout
  - -Free standing steel supported membrane cryostat design



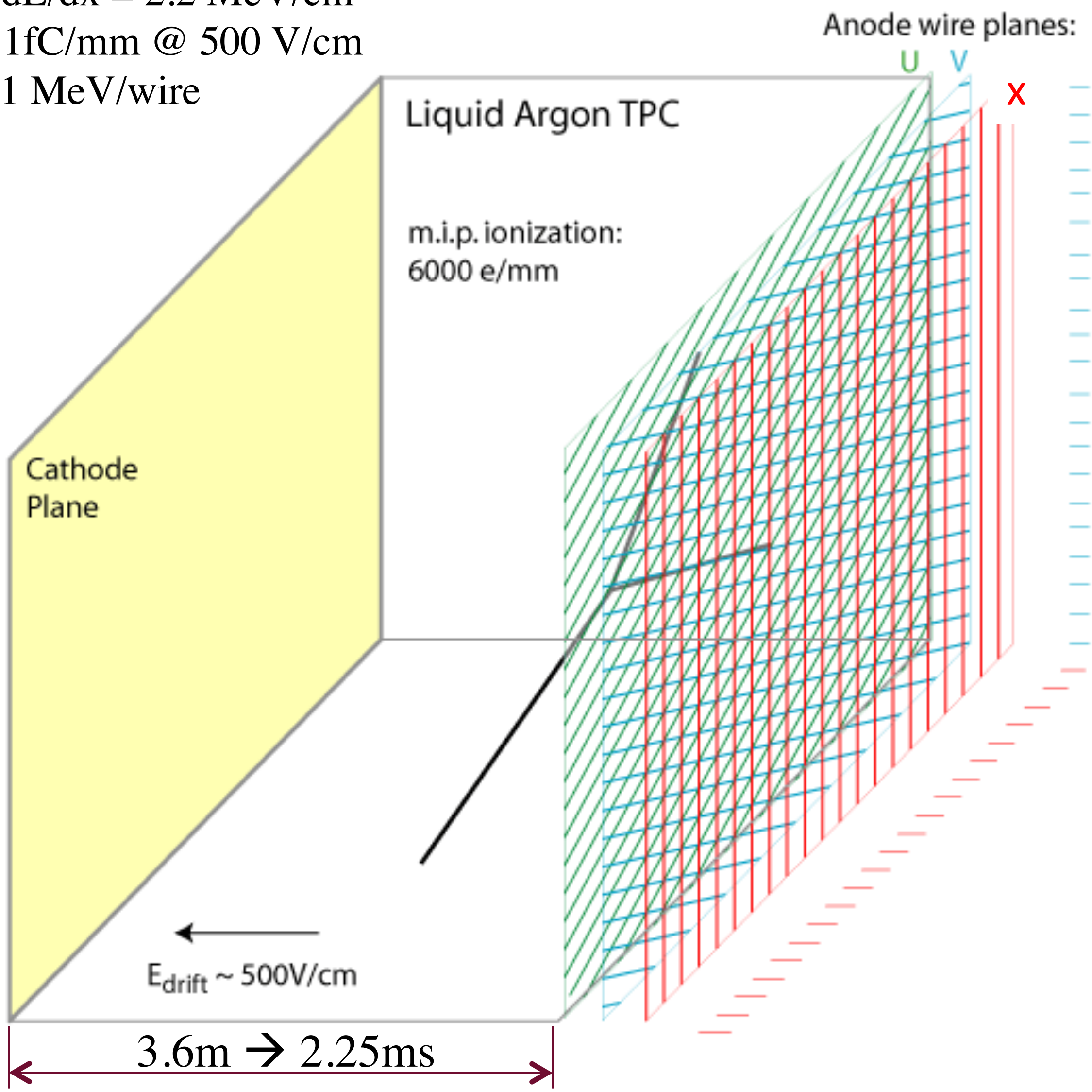
Sanford Underground Research Facility, Lead, S. Dakota

- Site has long & storied history as home to neutrino experiments
- LBNF scope: 4 detector chambers, utility cavern, connecting drifts
- Extensive preparatory work for LBNF/DUNE already done
- DOE approval pending to begin excavation & surface building construction

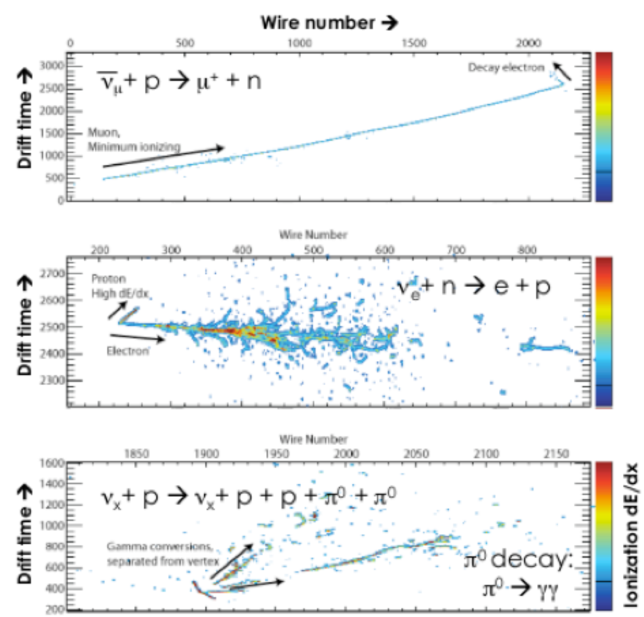


Liquid Argon Time Projection Chamber (TPC) Operation

MIP dE/dx = 2.2 MeV/cm
→ ~ 1fC/mm @ 500 V/cm
→ ~1 MeV/wire

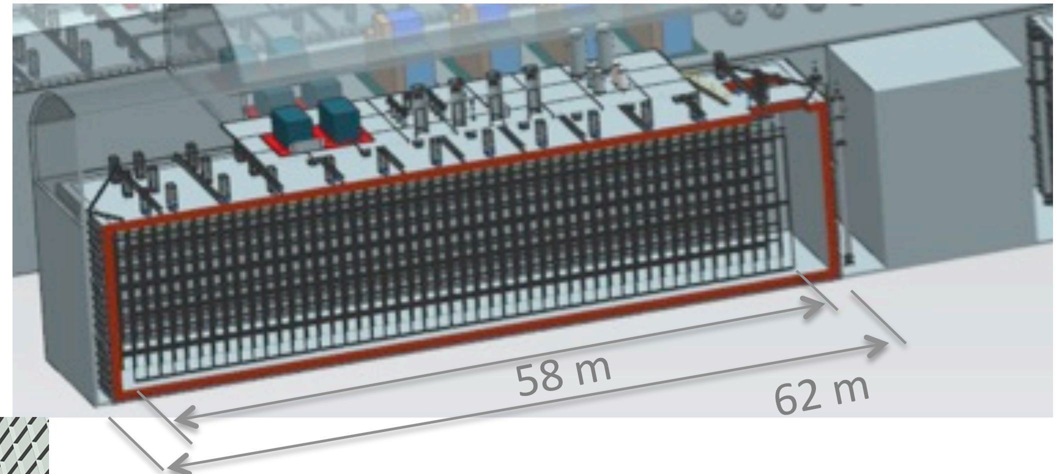


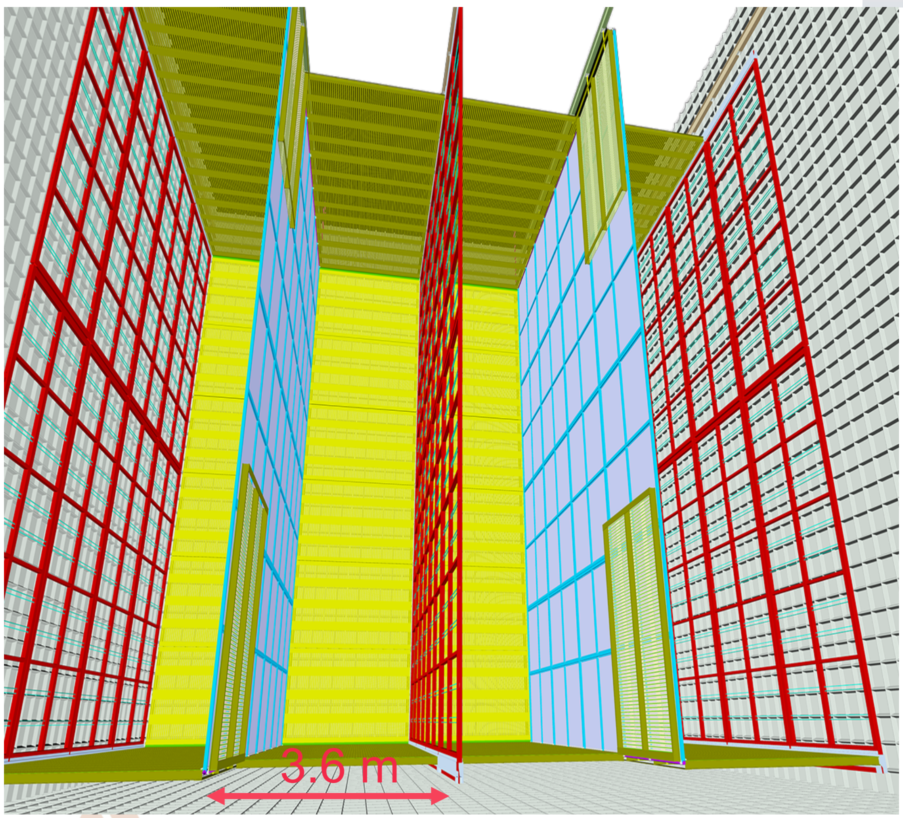
- Ionization charge drifts to finely segmented collection planes.
  - -high resolution data
  - - high event selection efficiency and efficient background rejection
- Scintillator light detected to determine interaction time.



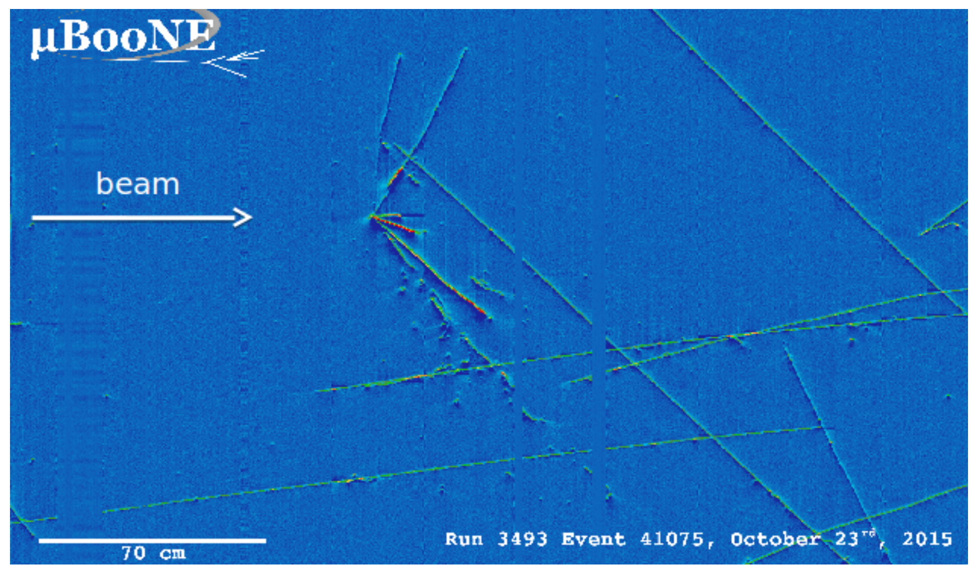
Far Detector Reference Design: Single-phase LAr TPC

- Liquid Argon Time projection chamber with both charge and optical readout.
- First 10kt detector will be single phase



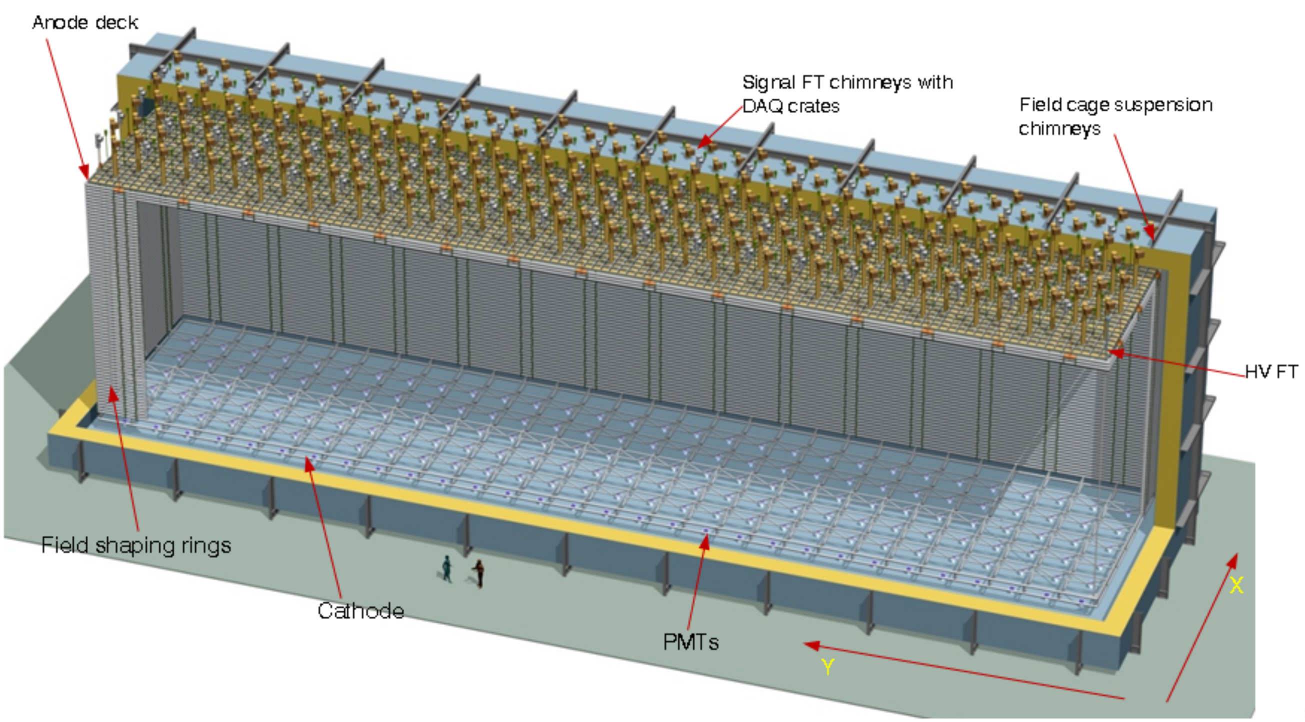


- MicroBooNE example: mm spatial resolution



Alternative Far Detector Design: Dual-phase LAr TPC

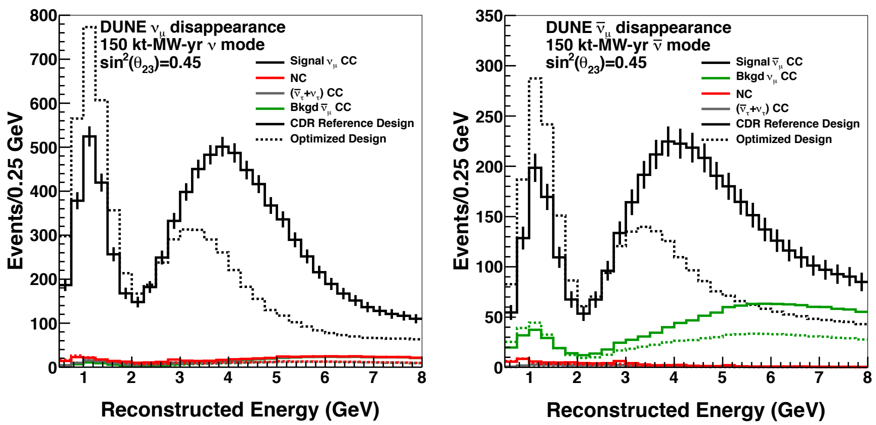
- DUNE collaboration recognizes the potential of the dual-phase technology
  - -A dual-phase implementation of the DUNE far detector is presented as an alternative design in the CDR (Conceptual Design Report).
  - -DUNE strongly supports the WA105 development program at the CERN neutrino platform
  - -If demonstrated, could form basis of second or subsequent 10-kt far detector modules



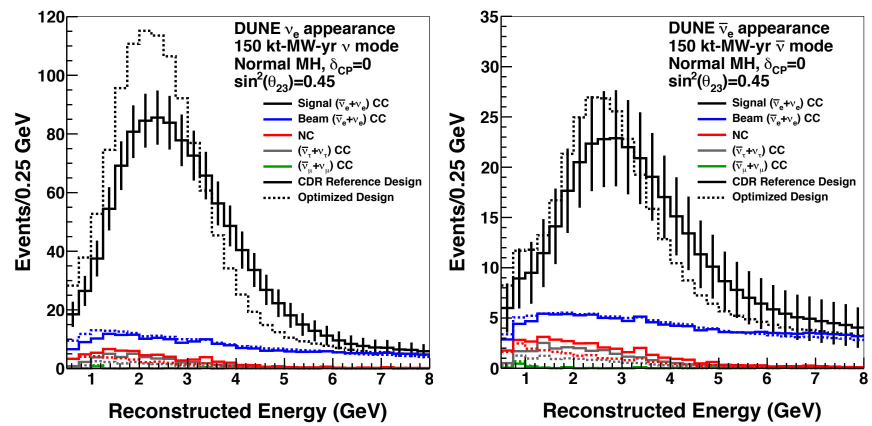
Neutrino Oscillation Strategy

- Measure neutrino spectra at 1300 km in a wide-band beam
  -Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for neutrino NSI in a single experiment
- Long baseline:
  Matter effects are large ~ 40%
- Wide-band beam:
  Measure ν_e appearance and ν_μ disappearance over range of energies
  MH & CPV effects are separable

ν_μ / $\bar{\nu}_\mu$ disappearance

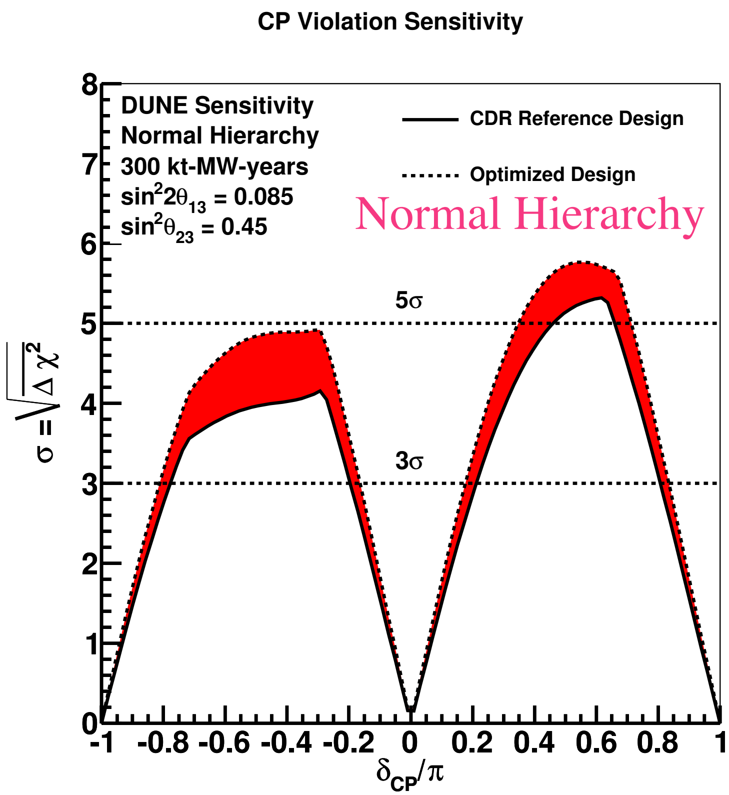


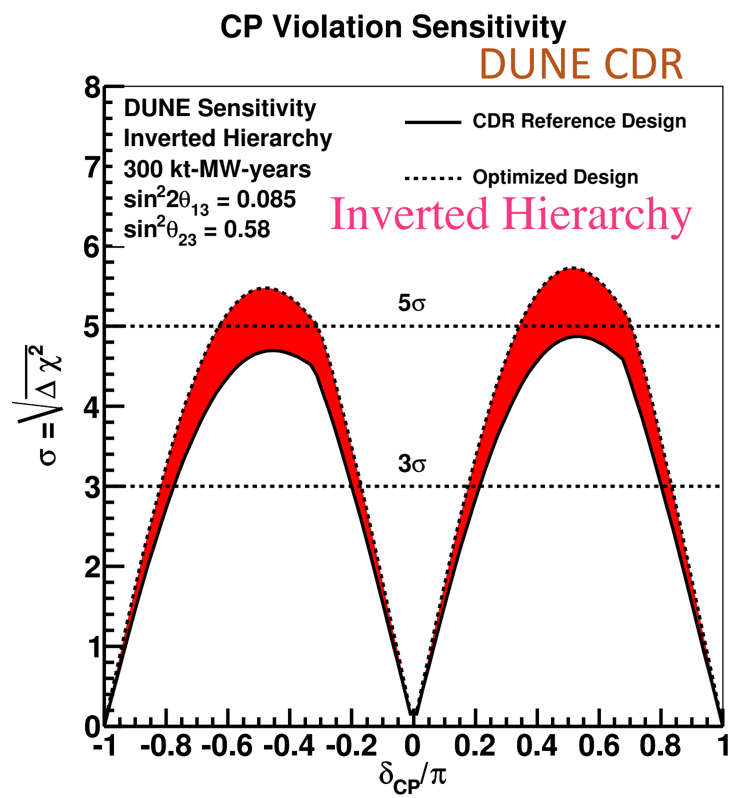
ν_e / $\bar{\nu}_e$ appearance



DUNE Sensitivity to CP Violation

- Sensitivity to CP Violation, after 300 kt-MW-yrs (3.5 + 3.5 yrs x 40kt @ 1.07 MW)



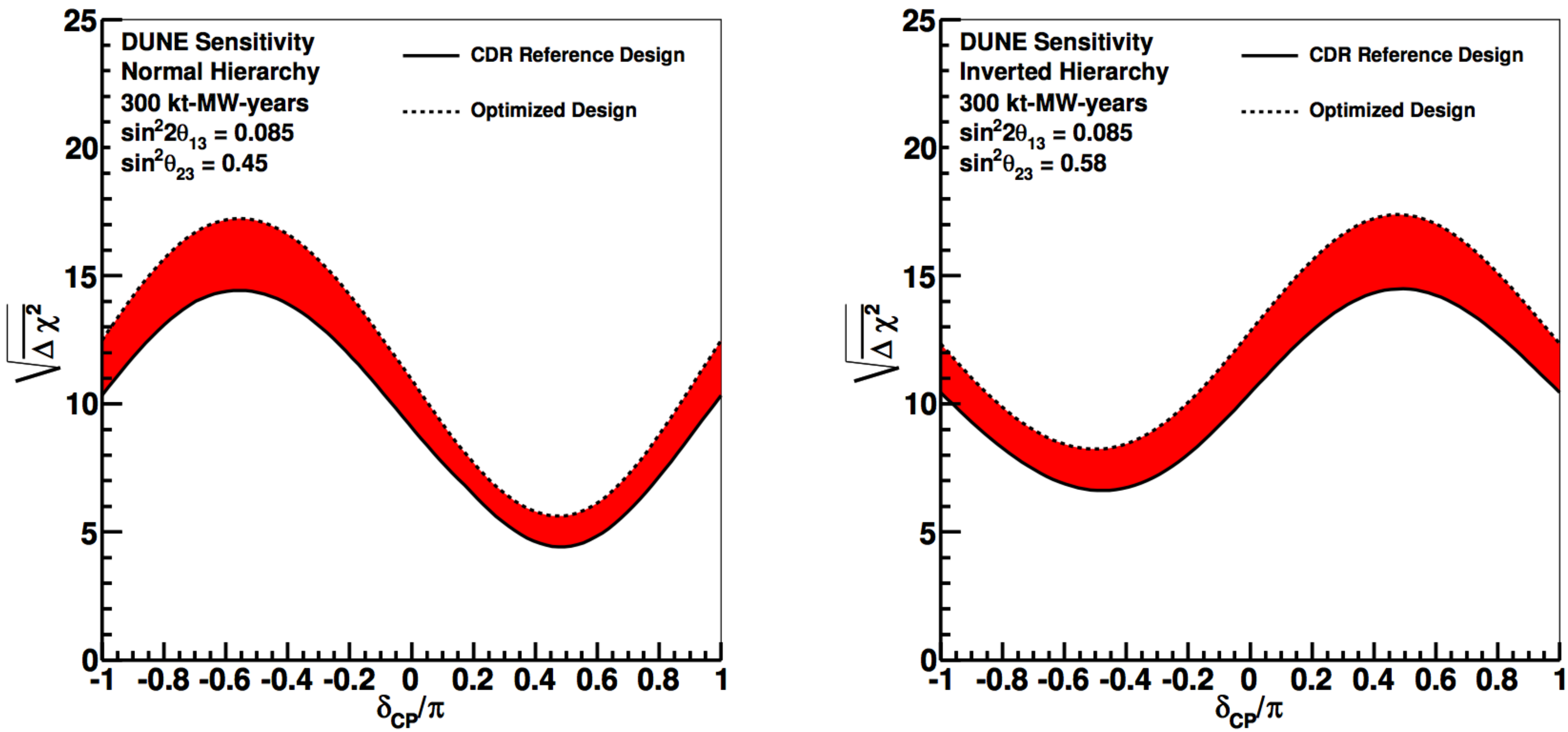


(Bands represent range of beam configurations)

- Experimental configuration (geometry, flux, detector response) used for sensitivity calculations shown here is published in **arXiV:1606.09550**

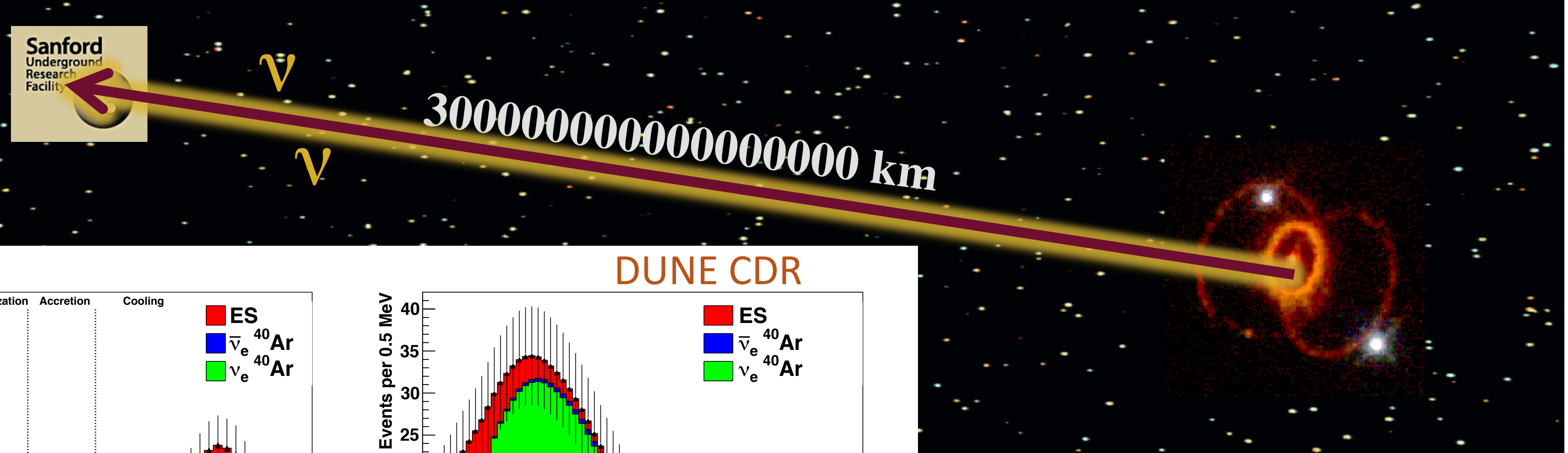
DUNE Mass Hierarchy Sensitivity

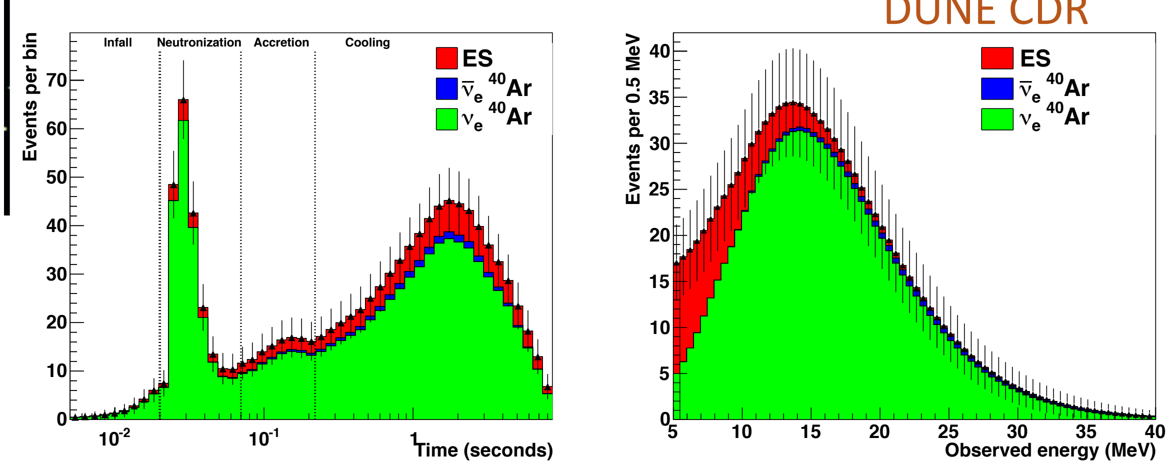
- Significance with which the mass hierarchy can be determined as a function of the value of δ_{CP} for an exposure of 300 kt · MW (3.5 + 3.5 yrs x 40kt @ 1.07 MW)



Neutrinos from Supernovae

- About 99% of the gravitational binding energy of the proto-neutron star goes into neutrinos.
- Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3000 neutrinos in 34kt LBNE for SN@10 kpc
- Unique sensitivity through $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$





-Note distinct features in time (left plot) and energy (right plot) spectra

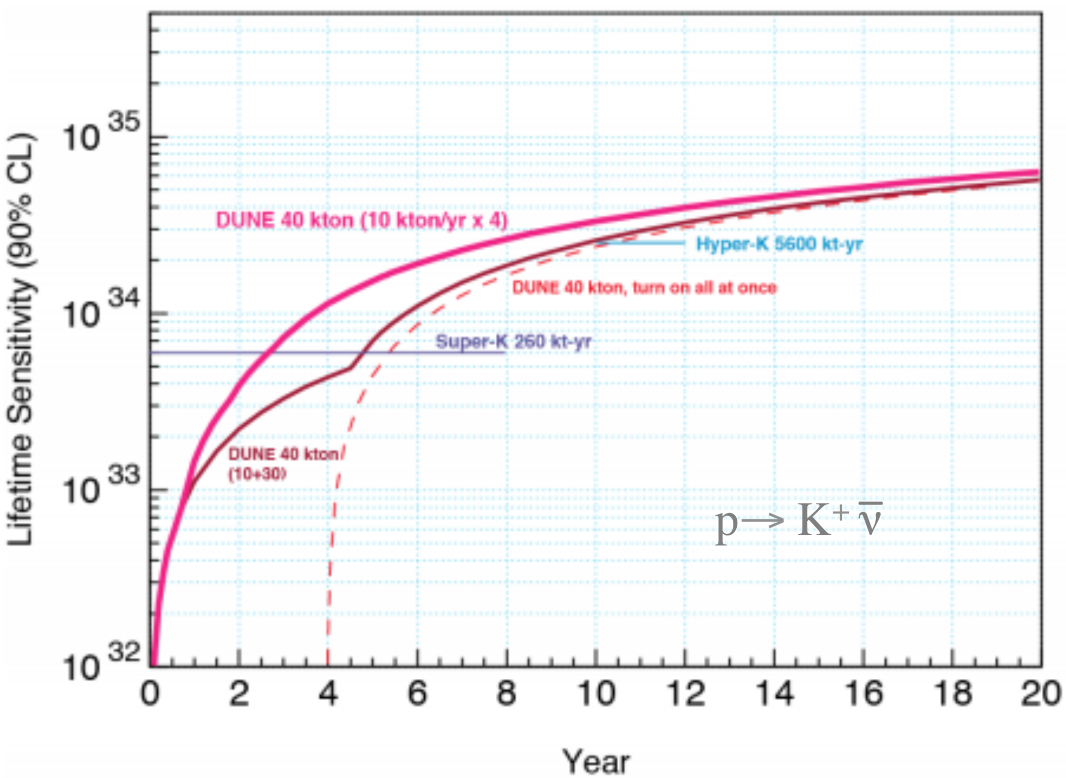
-A large theory effort is underway to understand neutrino related dynamics of the supernova. Both oscillations, mass, and self-interactions have large effects on observables e.g. mass hierarchy could have very distinct effects on the spectrum.

Nucleon Decay

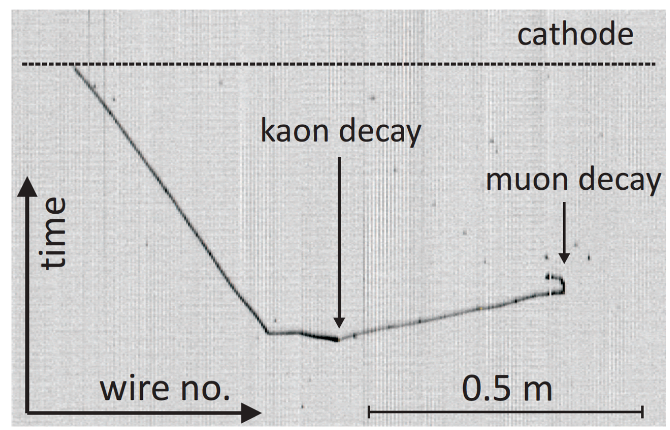
- Imaging, dE/dx, calorimetric capabilities of LArTPC enable sensitive, background-free searches
- Many modes accessible, superior detection efficiency for K production modes:

SUSY-favored p → $K^+ \bar{\nu}$

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8



Kaon observed entering ICARUS TPC in CNGS run



LArTPC Development Path to LBNF/DUNE

Fermilab and CERN neutrino platforms provide a strong LArTPC technology development and prototyping program.

Single-Phase LArTPCs

ICARUS@LNGS

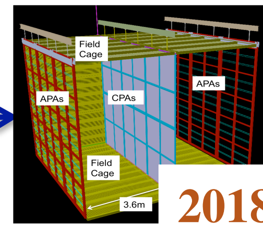
ArgoNeut
LArIAT

2015

DUNE 35t Prototype

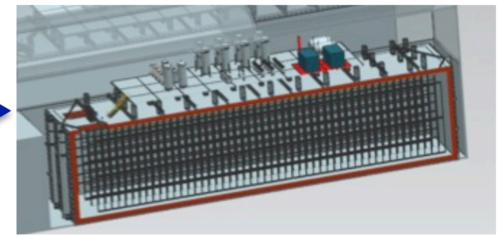
2015

protoDUNE @ CERN



2018

DUNE Reference Design

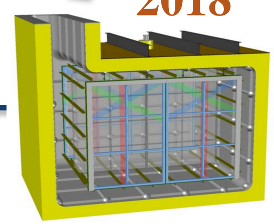


SBN

2015

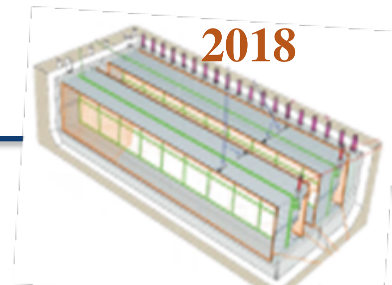
MicroBooNE

2018



SBND

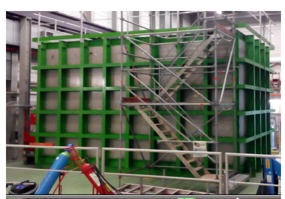
2018



ICARUS@SBN

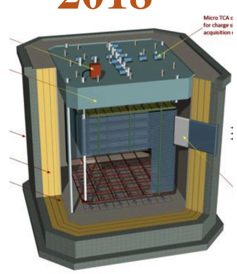
Dual-Phase LArTPCs

2016



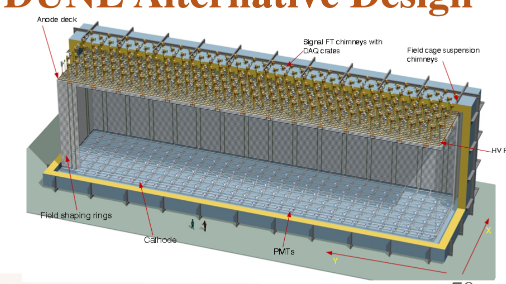
WA105: 1x1x3 m^3

2018



WA105

DUNE Alternative Design



DUNE/LBNF Timeline

- July 2015 "CD-1 Refresh" review. Conceptual design review.
- Dec. 2015 CD-3a CF Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting.
- 2017 Ongoing shaft renovation at SURF complete.
- 2017 Start of far site conventional facilities.
- 2018 Testing of "full-scale" far detector elements at CERN.
- 2019 Technical Design review.
- 2021 Ready for start of installation of the first far detector module.
- 2024 start of physics with one detector module.

  Additional far detector modules every ~2 years.
- 2026 Beam available.
- 2026 Near detector available.
- 2028 DUNE construction finished.
- Reach an exposure of 120 kt-MW-yr by 2035.

Many opportunities for early discoveries!

More About CP-violation

- Why is the Universe as we know it made of matter, with no antimatter present?
- What is the origin of this matter-antimatter asymmetry?
- Are neutrinos connected to the matter-antimatter asymmetry, and if so, how?
- If neutrinos exhibit CP violation, is it related to the CP violation observed in the quark interactions?
  - Already observed CP violation in the quark sector is not enough to explain the matter-antimatter asymmetry.
  - CP violation in the lepton sector could be enough to explain matter-antimatter-asymmetry if $|\sin\theta_{13}\sin\delta_{CP}| \gtrsim 0.11$ (hep-ph/0611338) $\Rightarrow |\sin\delta_{CP}| \gtrsim 0.7$ $(45^o \lesssim \delta_{CP} \lesssim 135^o$ or $225^o \lesssim \delta_{CP} \lesssim 315^o)$.
- Are neutrinos their own antiparticles (do we need Majorana phases)?
- What role did neutrinos play in the evolution of the universe?

Summary

- A few years ago the the θ_{13} was the last unmeasured neutrino mixing angle.
  - -Then about three ago it become the most precise measured mixing angle.
  - -All experiments, both reactor and accelerator, show a very consistent results.
  - -The value of θ_{13} is not zero! $\theta_{13} \approx 9^{o}$, or $\sin^2 2\theta_{13} \approx 0.095$.
- This successful determination of θ_{13} positioned us to start with measurement of CP-violation.
- There is a fundamental and practical motivation for the determination of mass-hierarchy.
- This is exciting time: stay tuned for new developments in neutrino sector.

My List of Important Neutrino Questions

1) Precision measurements of oscillation parameters
2) Do neutrinos violate CP symmetry and if so by how much?
3) What is the hierarchy of neutrino masses?
4) Is there a sterile neutrino?
5) What are the absolute values of neutrino masses?
6) Is neutrino its own anti-particle?
7) Can we detect Big-Bang relic neutrinos?
8) Is neutrino dark-matter?

Backup Slides

Notes

-Read Milind nu paper
-Read CERN Courier “The Neutrino Turns 60” articles
-Finish NOvA “New Thends in HEP Talk”
-Should I talk about “Oscillation and other experiments?”
(Reactor, NOvA (T2K), DUNE, … DBD status(?)

-Prvo napisi srz evega a jo veeza iz,edju “neutrino filed and mass states”
Tj stanje slabe interackcije I masenih stanja
-Onda poakiz Nilnky’s tip slide gde se simita experimentalna evidencije I spominje Nobelova Nagrada

P() = suma () * e^-iEt * U_ij

On charged lepton flavor violation size:
Id lambda is small yhane mu2e can see something but Bilenky personally
Does not believe lambda is so small

-intro: describe nus in SM

List nu properties:

Say what we have learned
-nu oscillation = moxing
-say we doscovered solar + atm, and recently measured theta-13 (DB, DC, RENO)

-npw nova: results

-next: DUNE

-beyond it: NLDBD

-other open questions?

$\bar{\nu}$ Detection Technique

- The reaction process is inverse β^- decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.

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

$\hookrightarrow$ *n capture*

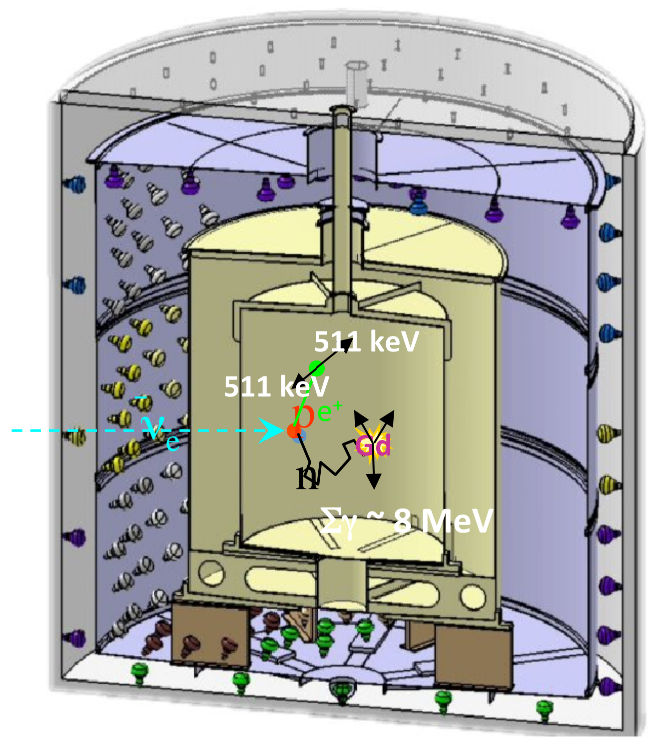
- Positron energy spectrum implies the neutrino spectrum ($e^+e^- \rightarrow \gamma\gamma$)

$$E_\nu = E_{vis} + 1.8\ \text{MeV} - 2m_e$$

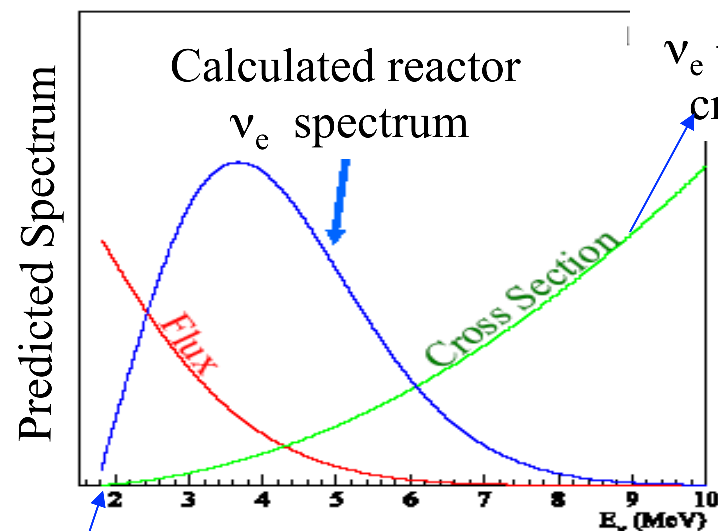
- The scintillator may be doped with gadolinium to enhance capture

$$n\ {}^{m}\text{Gd} \rightarrow {}^{m+1}\text{Gd}\ \gamma\text{'s (8 MeV)}$$

- Cross accurate to 0.2%



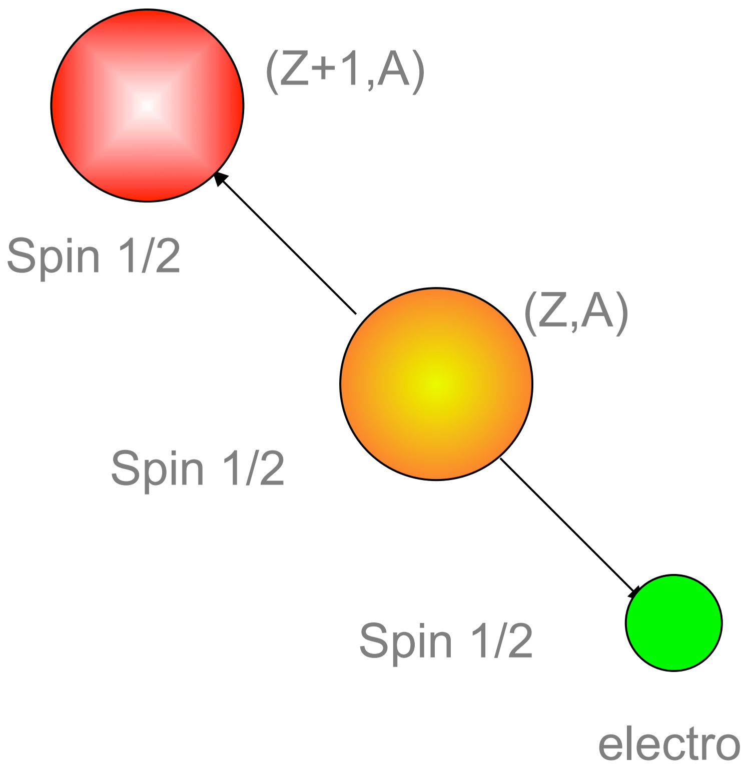
Signal = Positron signal + Neutron Signal (within a few capture times)

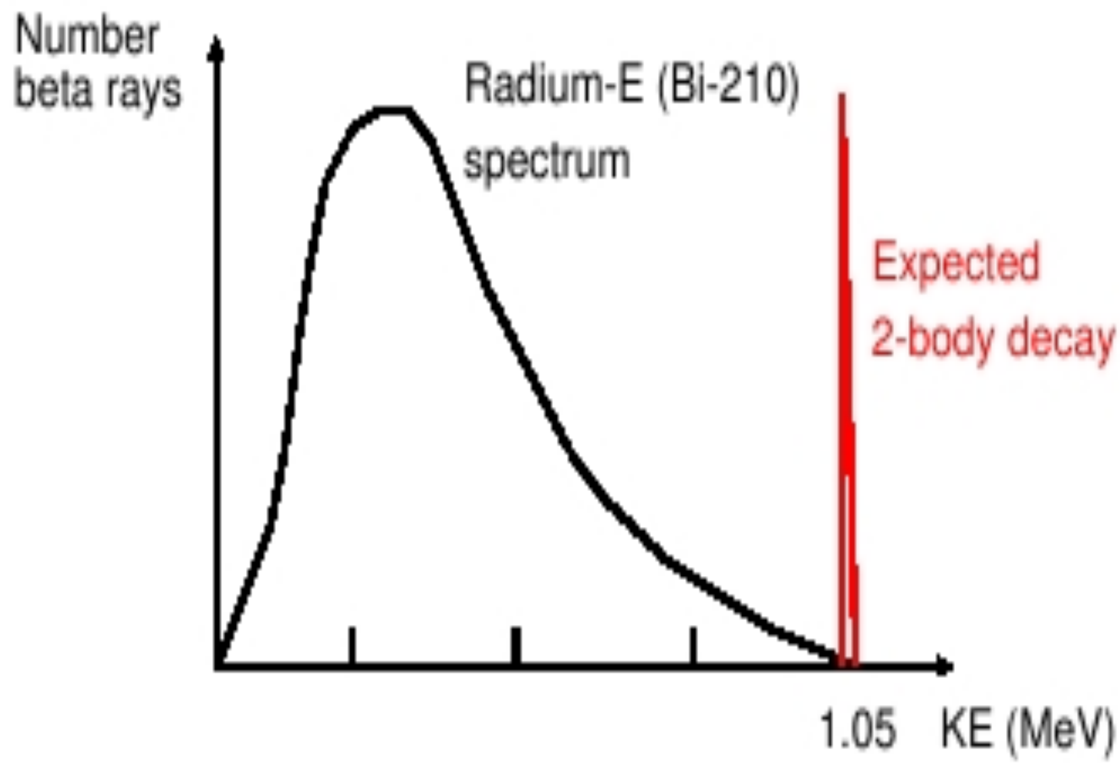


Neutrinos with E<1.8 MeV are not detected.

Crisis

It is 1914 – the new study of atomic physics is in trouble

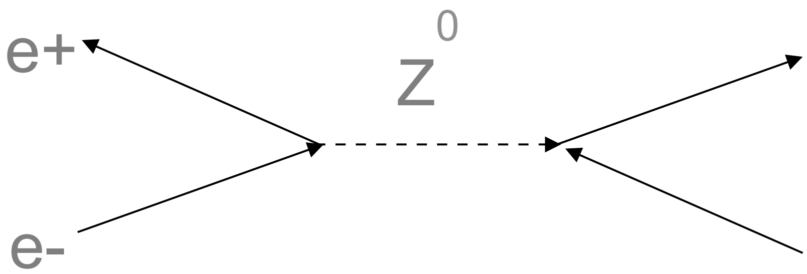




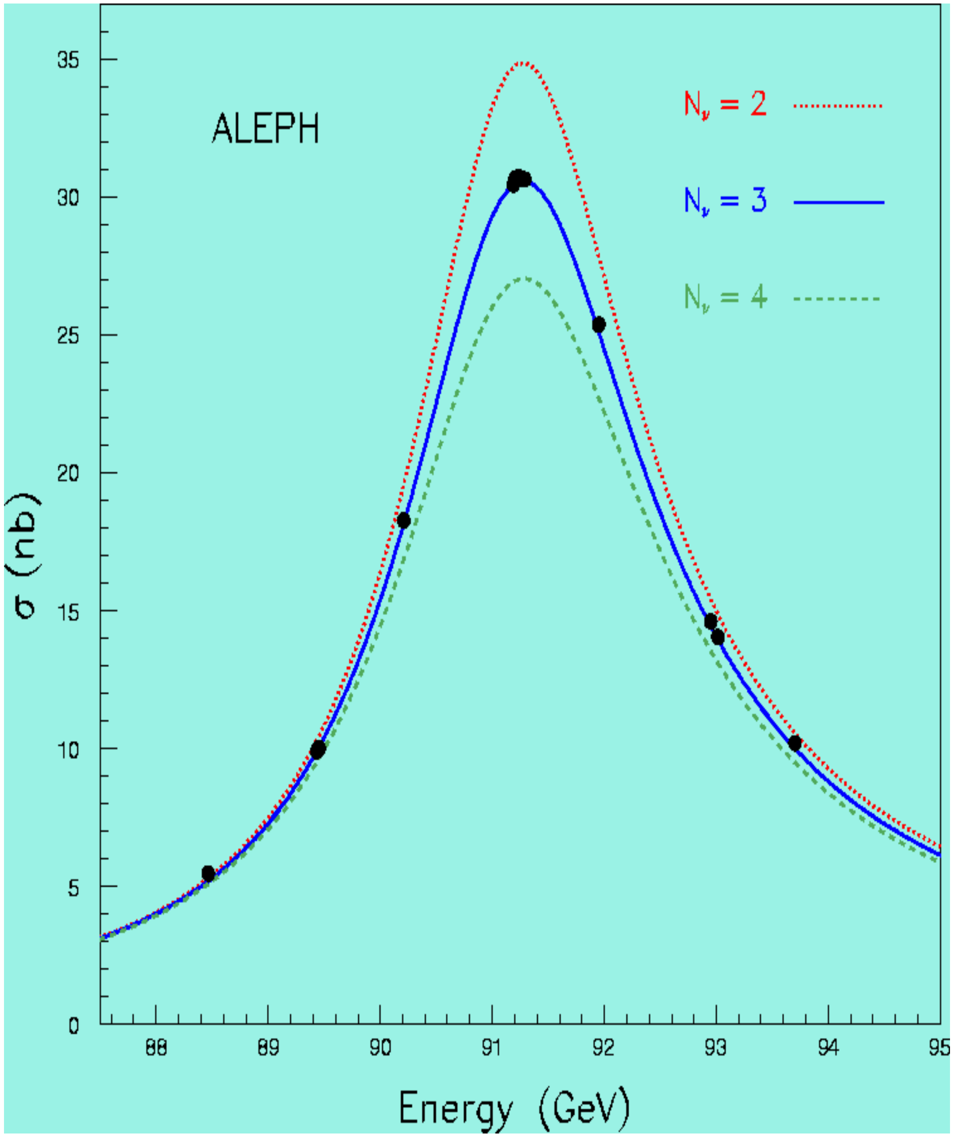
Spin ½ ≠ spin ½ + spin ½

$$E_{Ra} \neq E_{Bi} + e$$

Number of Light Neutrinos



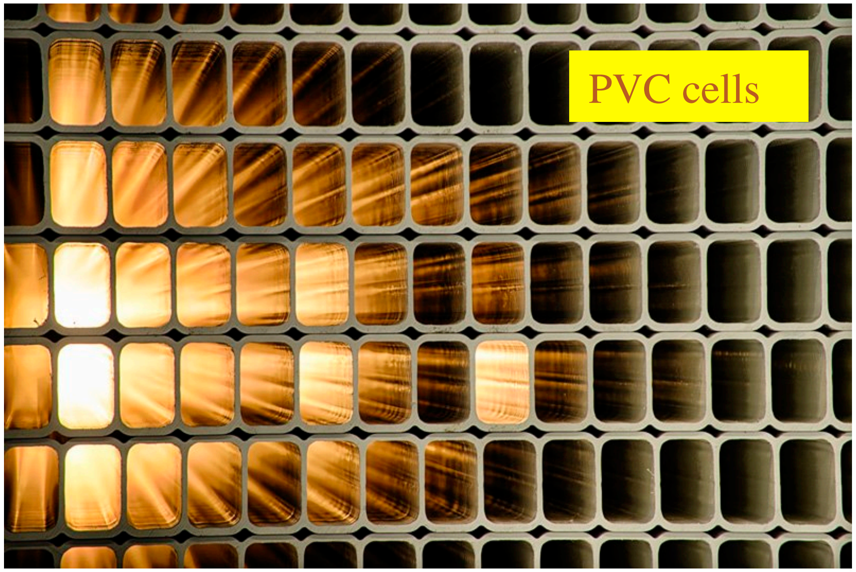
Discovery of Z0 allowed a measurement of the number of light neutrinos since the Z0 can decay to a neutrino and antineutrino



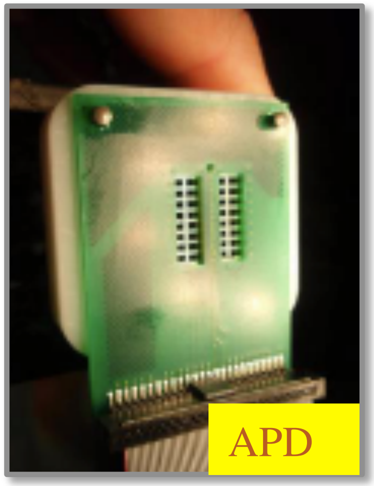
“The Big Bang Theory” paid attention to it …

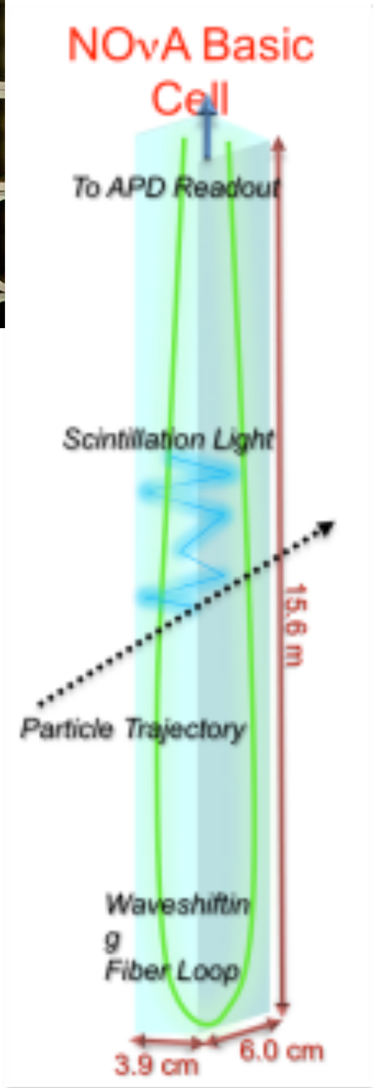
July 12th, 2016

NOνA Detectors



- PVC + Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer
- DAQ runs with zero dead-time
  - triggers for beam, SNEWS, cosmic ray calibration samples, exotic searches
  - 150kHz of cosmic induced events





ν_e Appearance Search

- Identify contained ν_e CC events in both Near and Far Detector
- Use Near Detector Data/MC to predict beam backgrounds in the Far Detector
- Extract oscillation information from Far Detector excess over predicted backgrounds

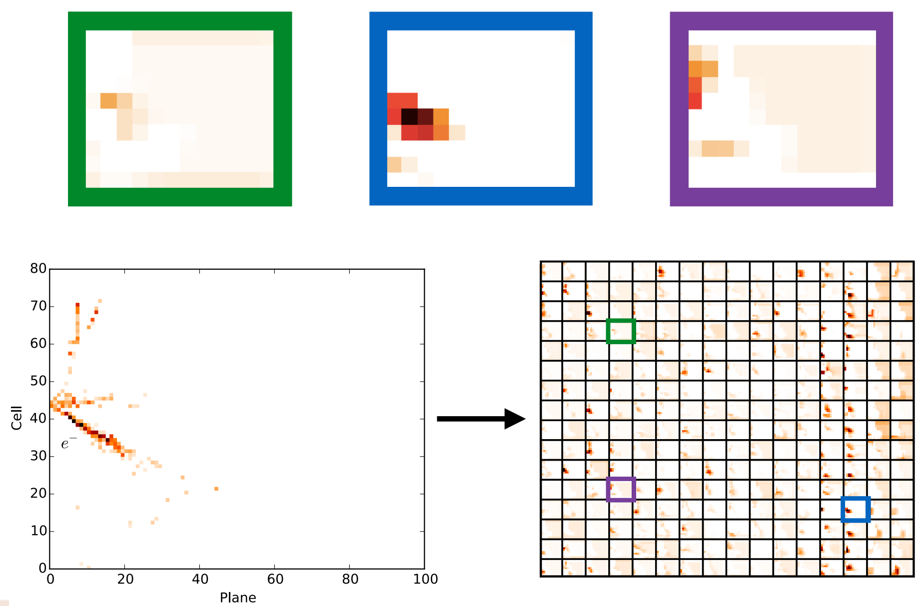
1st Analysis Published in PRL 116 (2016) no.15, 151806

Improved Event Selection

- A new particle ID techniques used to identify ν_e candidates: A convolutional neural network neutrino event classifier (CVN)

  -event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event



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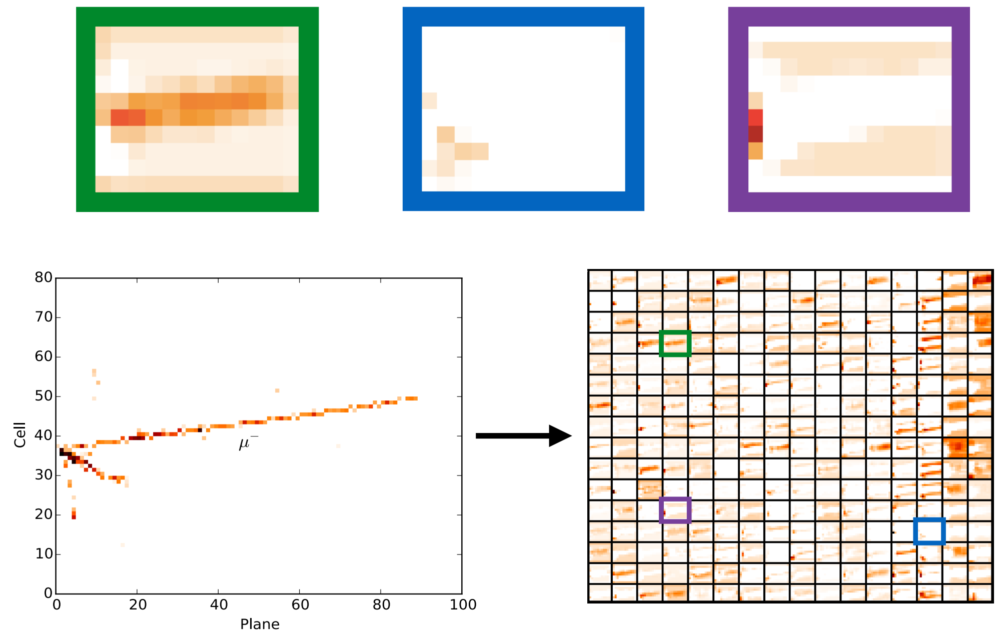

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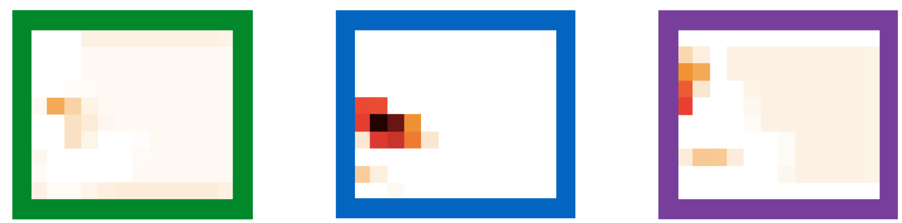
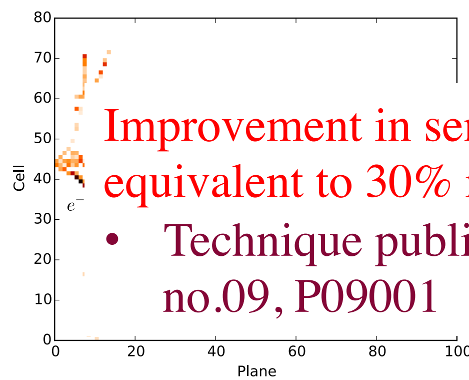
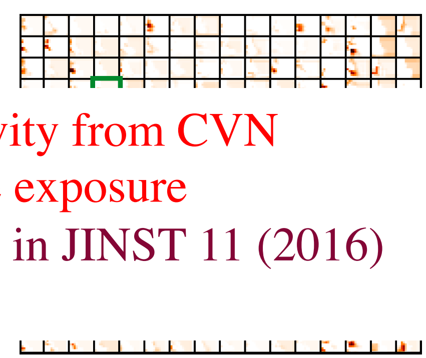




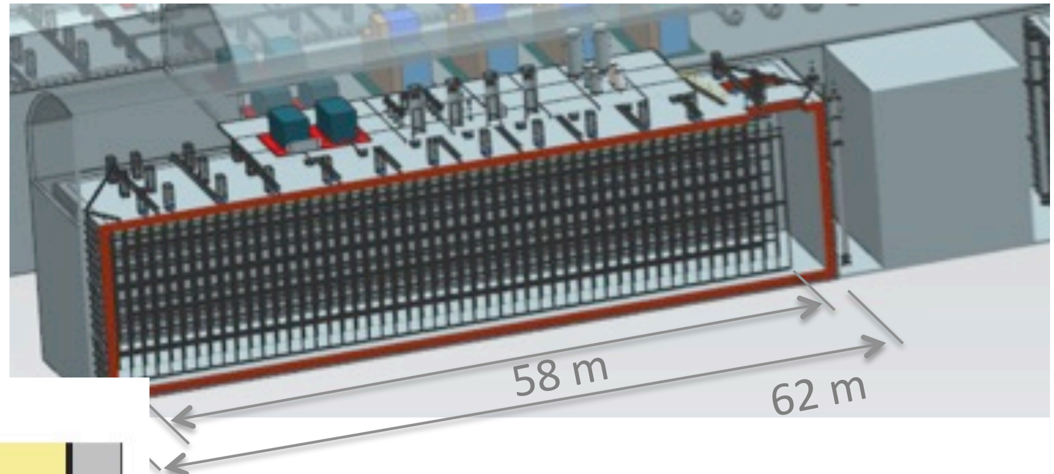


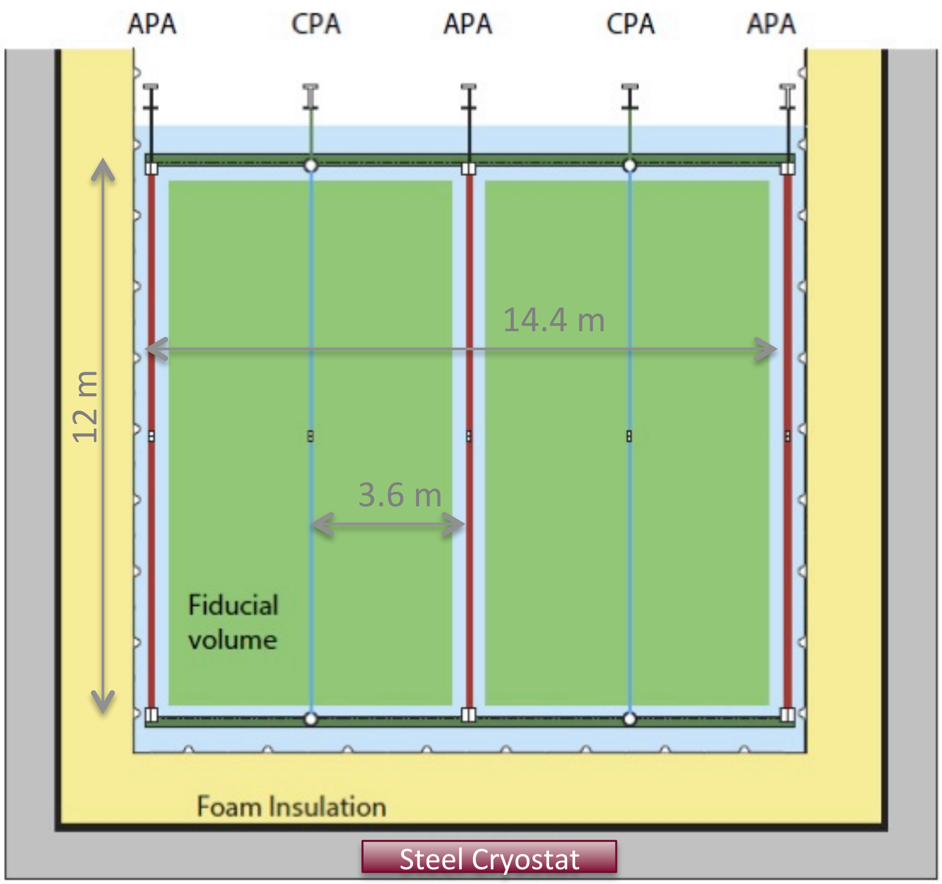
Improvement in sensitivity from CVN equivalent to 30% more exposure

- Technique published in JINST 11 (2016) no.09, P09001

Far Detector Reference Design: Single-phase LAr TPC

- Liquid Argon Time projection chamber with both charge and optical readout.
- First 10kt detector will be single phase





- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - -Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - -3.6 m drift length
- Photon detection for event interaction time determination for underground physics

Neutrino Oscillation Strategy (cont.)

- Physics (MH, θ_{23}, θ_{13}, δ) extracted from combined analysis of 4 samples:
  - -CDR estimates, assuming: CDR optimized beam, 56% LBNF uptime, FastMC detector response
  - -Physics inputs: $\boldsymbol{\delta = 0, \theta_{23} = 45^o}$, others from NuFIT: Gonzalez-Garcia, Maltoni, Schwetz, JHEP 1411 (2014)

ν mode / 150 kt-MW-yr	ν_e appearance	ν_μ disappearance
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam νe background	204	–
NC background	17	76
Other background	22	29

Anti-ν mode / 150 kt-MW-yr	$\bar{\nu}_e$ appearance	$\bar{\nu}_\mu$ disappearance
Signal events (NH / IH)	**168 (438)**	**2639**
Wrong-sign signal (NH /IH)	47 (28)	1525
Beam νe background	105	–
NC background	9	41
Other background	13	18