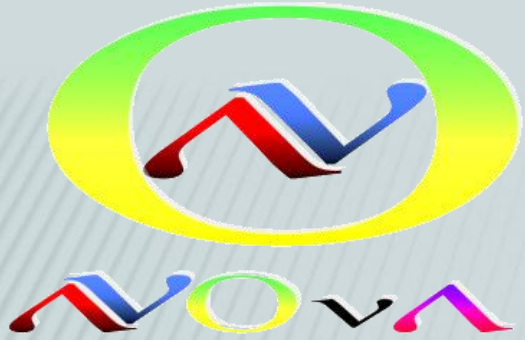

Neutrino Oscillations at the Intensity Frontier: the NOvA Experiment

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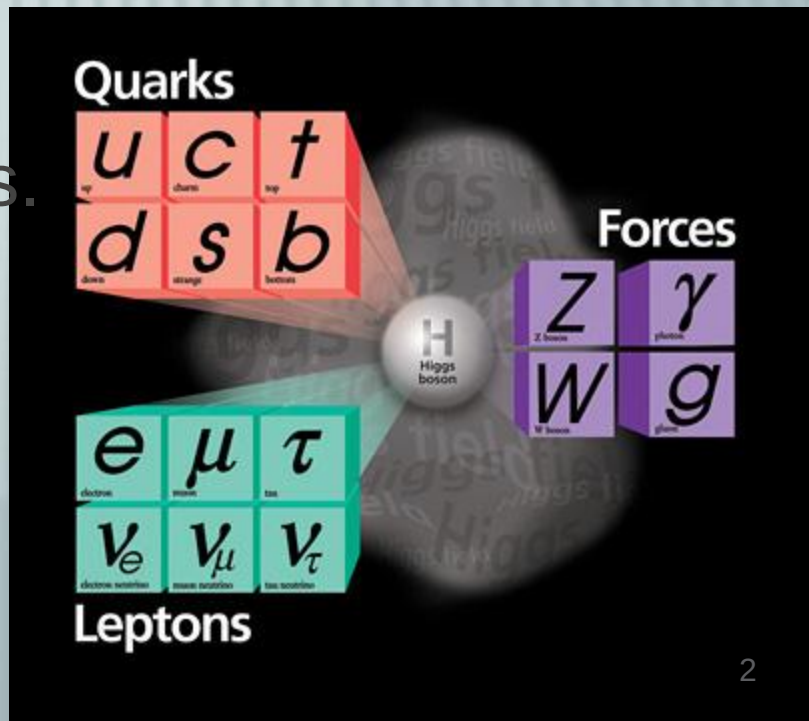
for the NOvA collaboration

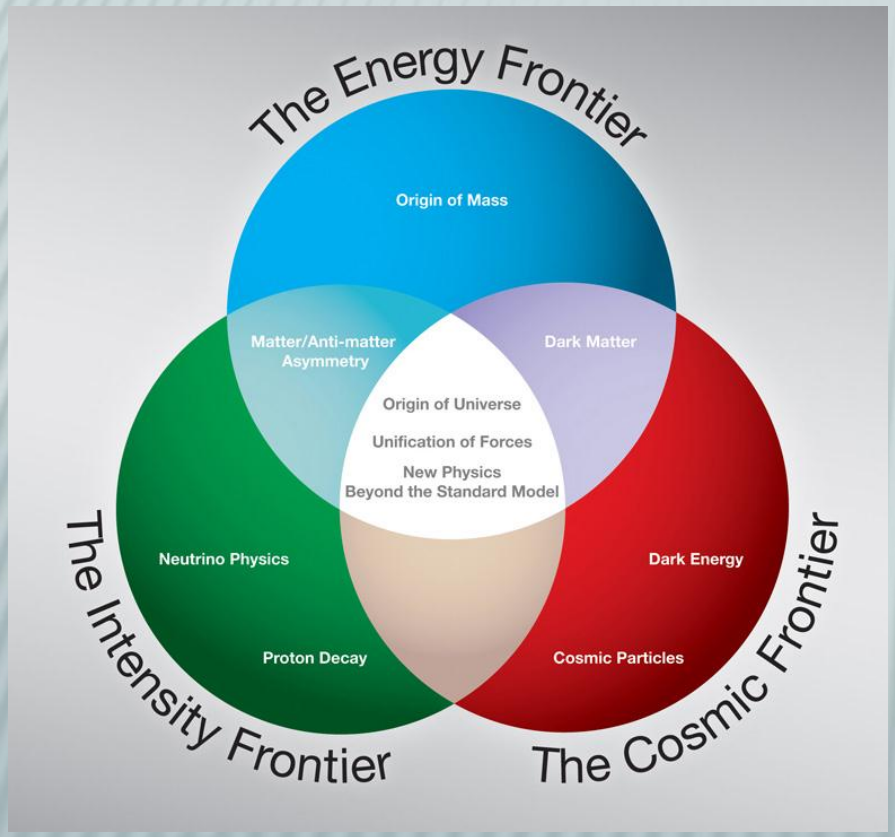
International Conference on Mathematical Modeling in Physical Sciences
September 3-7, 2012, Budapest, Hungary.

Outline

- Neutrino oscillation experiments.
  - Short and Long baselines.
- The NOvA experiment
  - The NOvA detectors.
  - The NOvA measurements.
  - Status and outlook.



Frontiers in Physics



- Energy frontier.
  - directly with colliders.
- Intensity frontier.
  - rare processes and small effects.
- Cosmic frontier.
  - observations.

- At the Intensity Frontier
  - Precision measurements
    - particle properties
      - (mass , couplings, mixing, etc).
  - New points of view into high energies/short distances.
    - Particularly now that new particles are found at the Energy Frontier.

Neutrino Oscillations Principles

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$\nu_\mu \rightarrow \nu_\tau$
(23) Sector: Atmospheric + Accelerator
L/E ~500 km/GeV
$|\Delta m^2_{32}|$ (Δm^2_{atm}) = 2.3×10^{-3} eV^2
$\sin^2(2\theta_{23}) > 0.96$

$\nu_\mu \rightarrow \nu_e$
(13) Sector

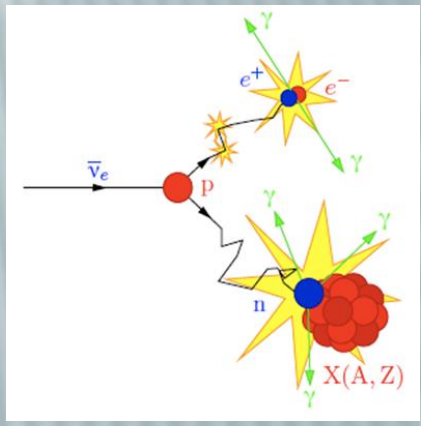
$\nu_e \rightarrow \nu_\mu, \nu_\tau$
(12) Sector: Reactor + Solar
L/E ~15000 km/GeV
Δm^2_{21} (Δm^2_{sol}) = 7.5×10^{-5} eV^2
$\tan^2\theta_{12} = 0.45$

Analogous to CKM Quark Mixing Matrix :
Mixing in lepton sector larger than in quark sector.

Short baseline oscillations

- Survival probability of anti-ν_e

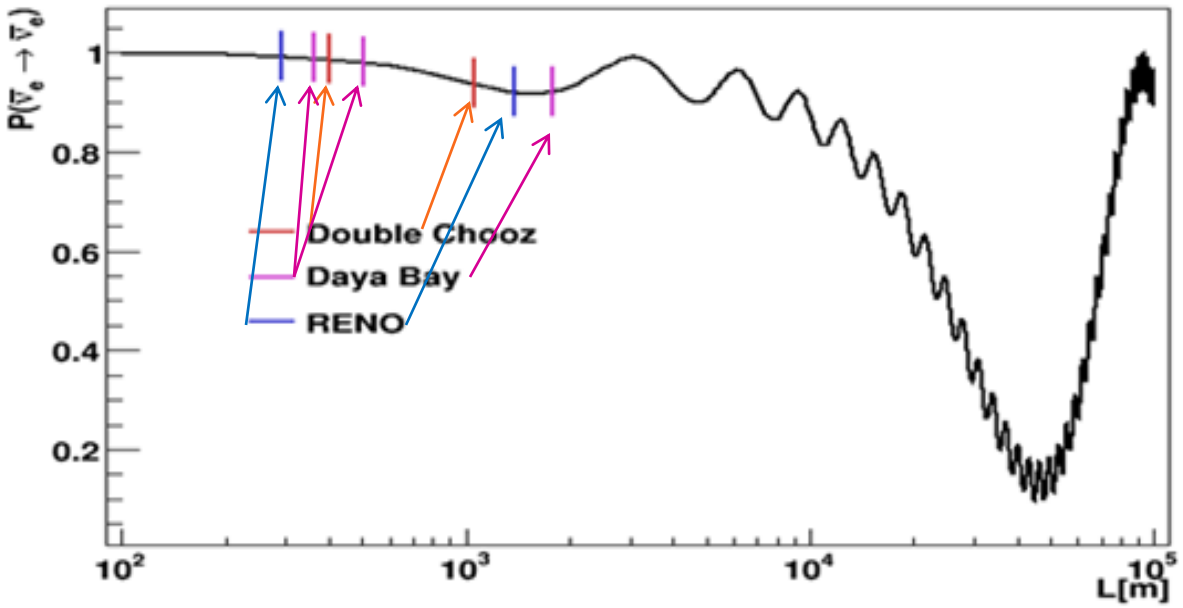
$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{13} \sin^2 \left(1.267 \frac{\Delta m^2_{31}[\mathrm{eV}^2] L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]} \right)$$

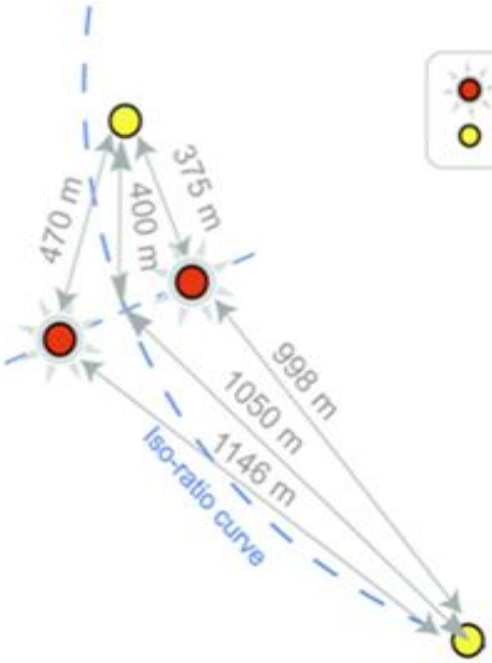


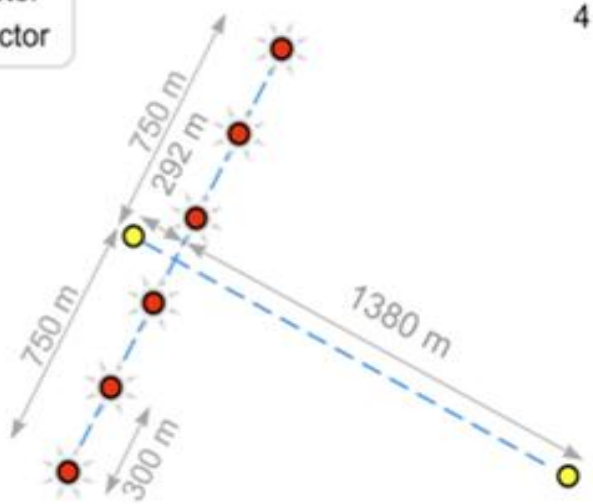
- No matter effects
- No CP violation contribution.

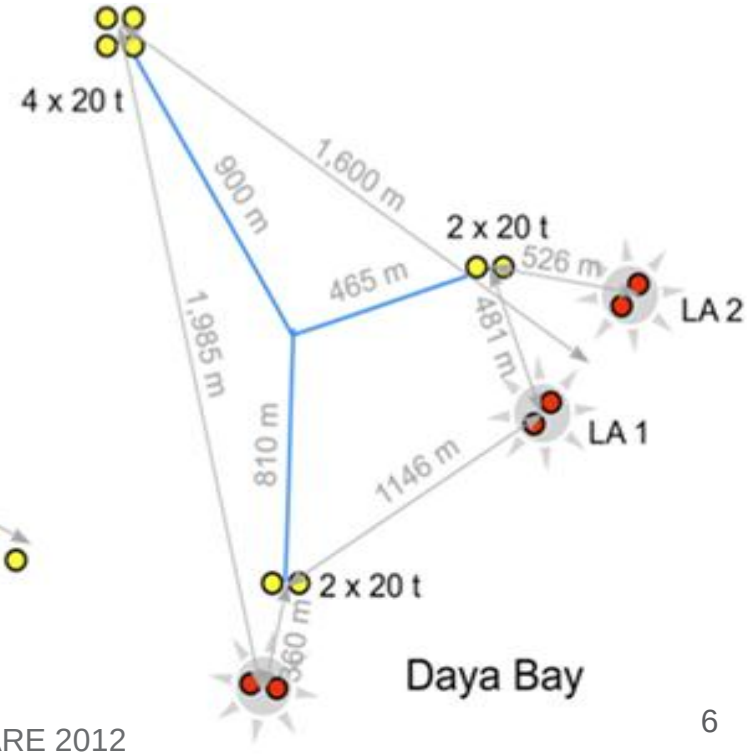
- Detection Signal: $\bar{\nu}_e + p \to e^+ + n$
  - Prompt signal from the positron
    - 0.7 < E < 12.2 MeV
  - Delayed signal from the neutron capture.

Ranging Short Baselines









Oscillations with long baseline

- Accelerator driven.
  - Muon neutrino beam.
- Matter effects present.
- CP violation and mass hierarchy dependence.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) + (\text{CPV term}) + (\text{matter term}) \ldots$$

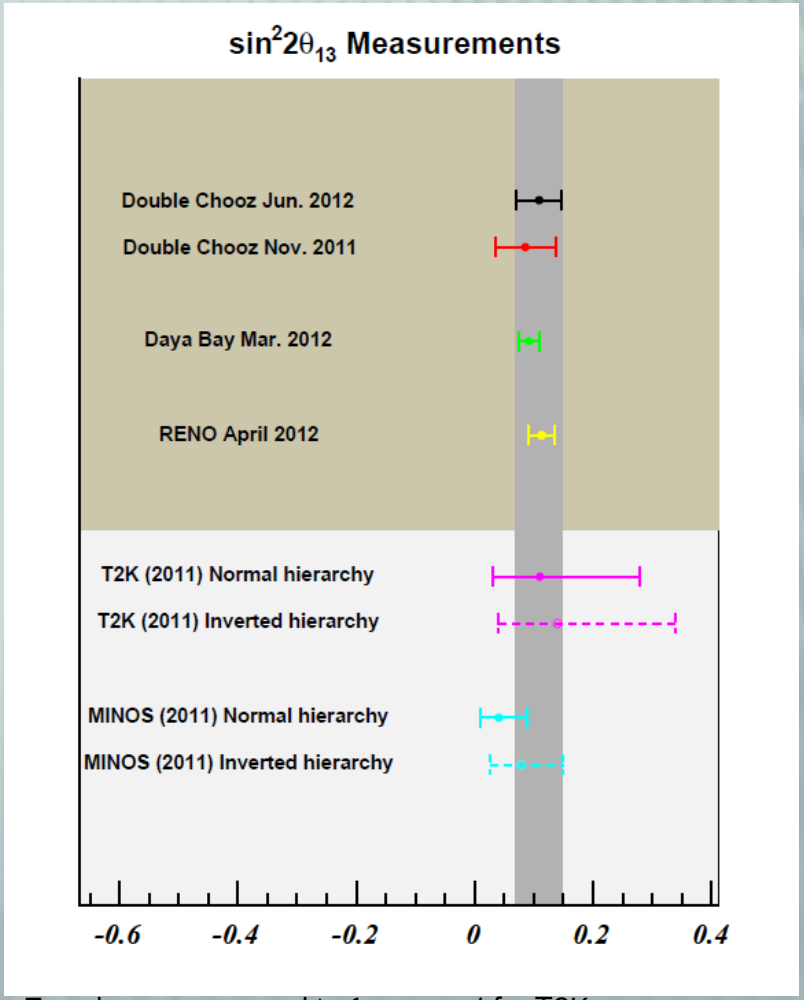
CPV term in $P(\nu_\mu \rightarrow \nu_e) \propto \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) = 2\cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\delta * \sin\left(\Delta m^2_{31}\frac{L}{4E}\right) \sin\left(\Delta m^2_{32}\frac{L}{4E}\right) \sin\left(\Delta m^2_{23}\frac{L}{4E}\right)$$

The latest measurements

From arXiv:1207.6632

- Oscillation measurements:
  - 3 mixing angles.
  - 2 mass differences.
  - 1 CP violating phase.
- The mixing angles and the complex phase are connected in the PMNS matrix.
- The θ_{13} went from the last unknown angle to the best measured in a year.

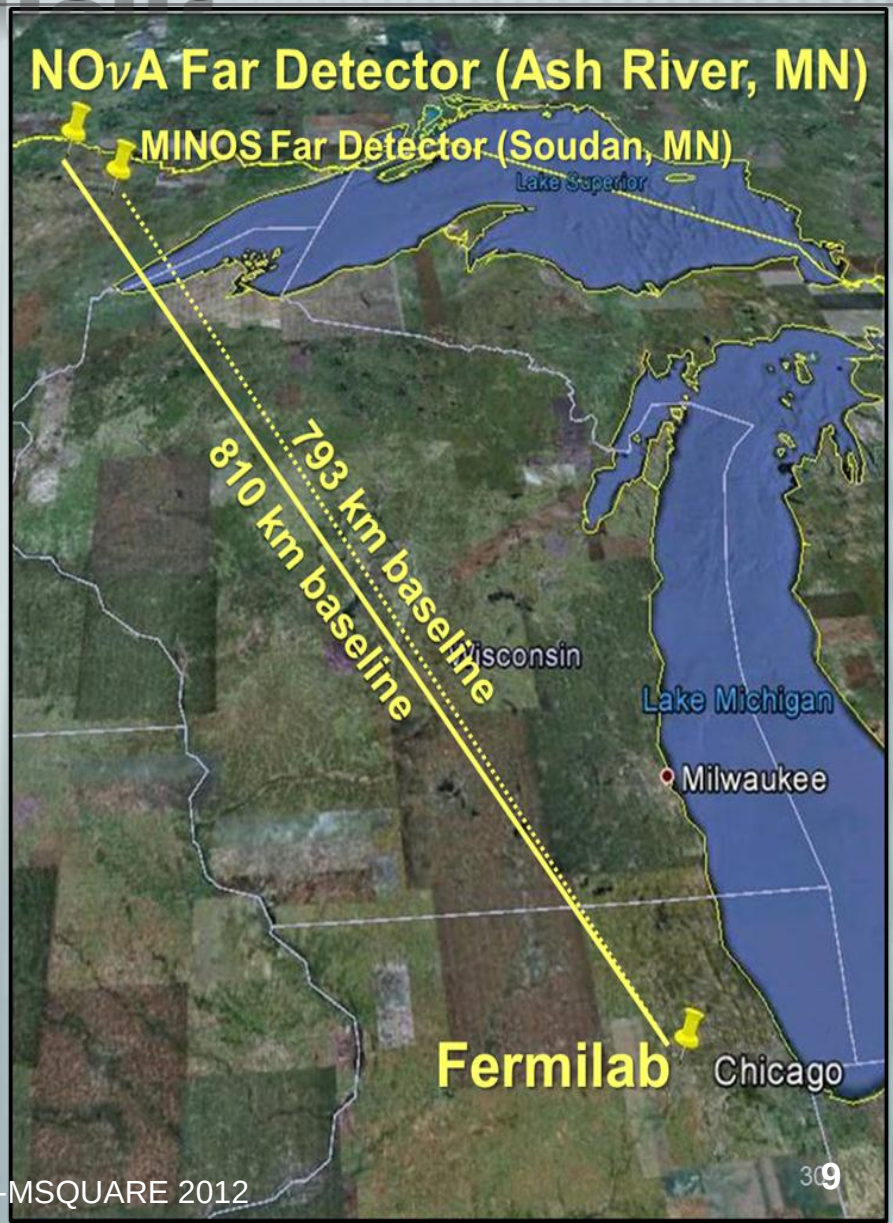


Error bars correspond to 1σ, except for T2K, where the 90% CL interval is shown. For T2K and MINOS the CP phase δ has been fixed (arbitrarily) to δ = 0.

- K. Abe et al., Phys.Rev.Lett. "T2K" 107, 041801 (2011), 1106.2822.
- P. Adamson et al., "MINOS" Phys. Rev. Lett. 107, 181802 (2011), hep-ex/1108.0015v1.
- F. P. An et al, "Daya Bay" PRL 108,171803(2012), arXiv:1203.1669 [hep-ex].
- Y. Abe et al, "Double Chooz "arXiv:1207.6632v1[hep-ex] 27 A July 2012, DC first indications arXiv:1112.6353[hep-ex] 13 March 2012.

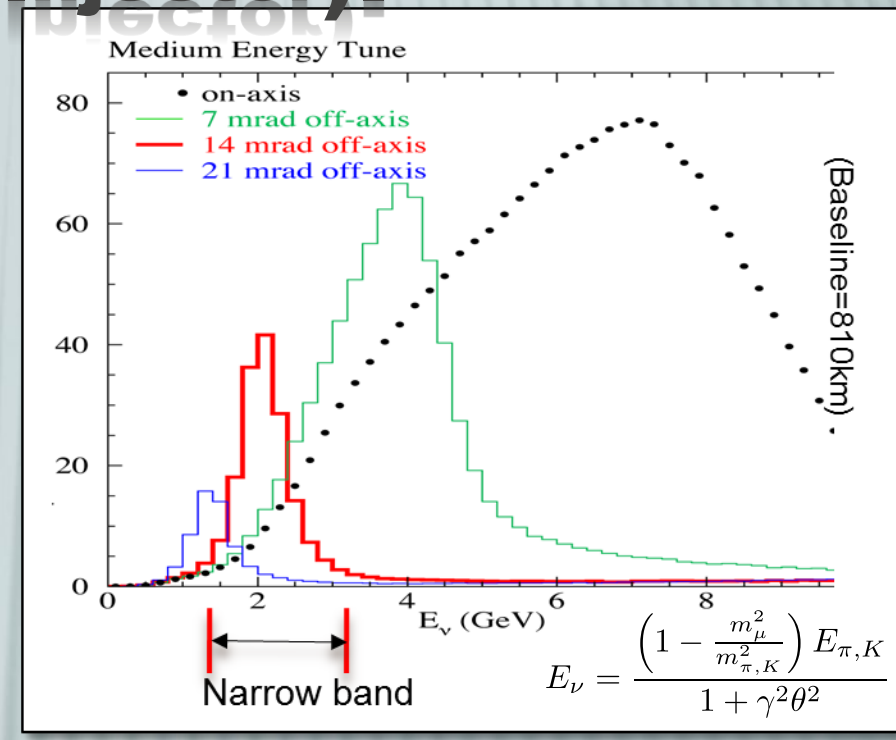
The NOvA Experiment

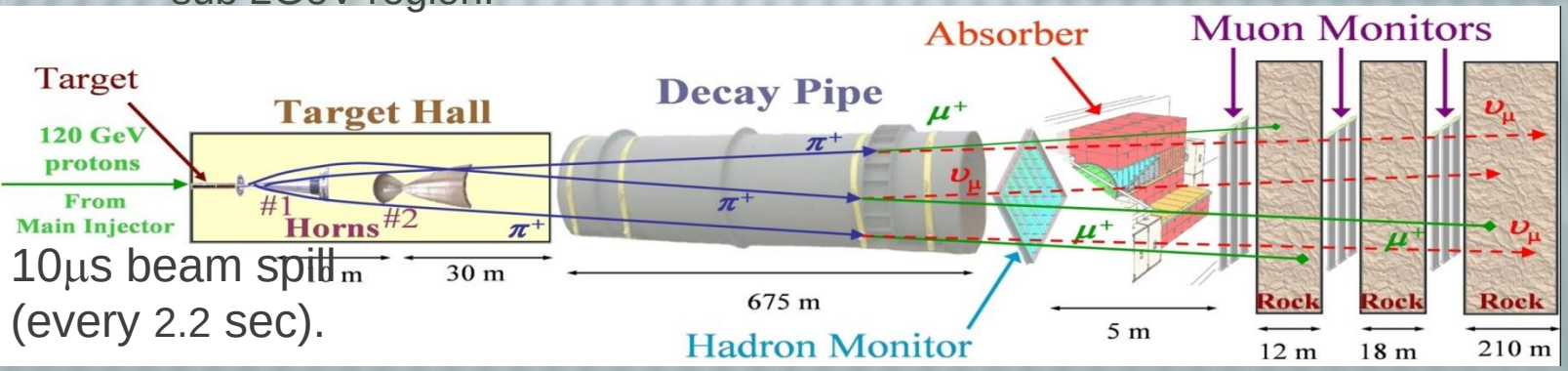
- Long Baseline Neutrino Oscillation Experiment.
- Designed to measure:
  - $\nu_\mu \rightarrow \nu_e$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$, $\nu_\mu \rightarrow \nu_\mu$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$
- Precision Measurement: of θ_{13} , θ_{23}.
- Goals:
  - Determination of the mass hierarchy.
  - Observation of CP violation in the lepton sector.
  - Resolution of θ_{23} octant (θ_{23} < or > 45º).
  - Cross section of ν at 2 GeV.
- The Collaboration:
  - 150+ scientists and engineers from 27 institutions, 6 countries.



The NuMI beam (Neutrinos at the Main Injector).

- Off-axis Neutrino energy spectrum
  - flattens out (tightens):
- 14 mrad off-axis yields a narrows band.
  - peaked at 2GeV
  - with E_ν width ≈20%
- The detector technology, geometry and baseline are tuned to give:
  - L/E for 1st Oscillation Maximum.
  - Energy resolution for ν_μ CC events ≈4%
  - High efficiency EM shower reconstruction in sub 2GeV region.

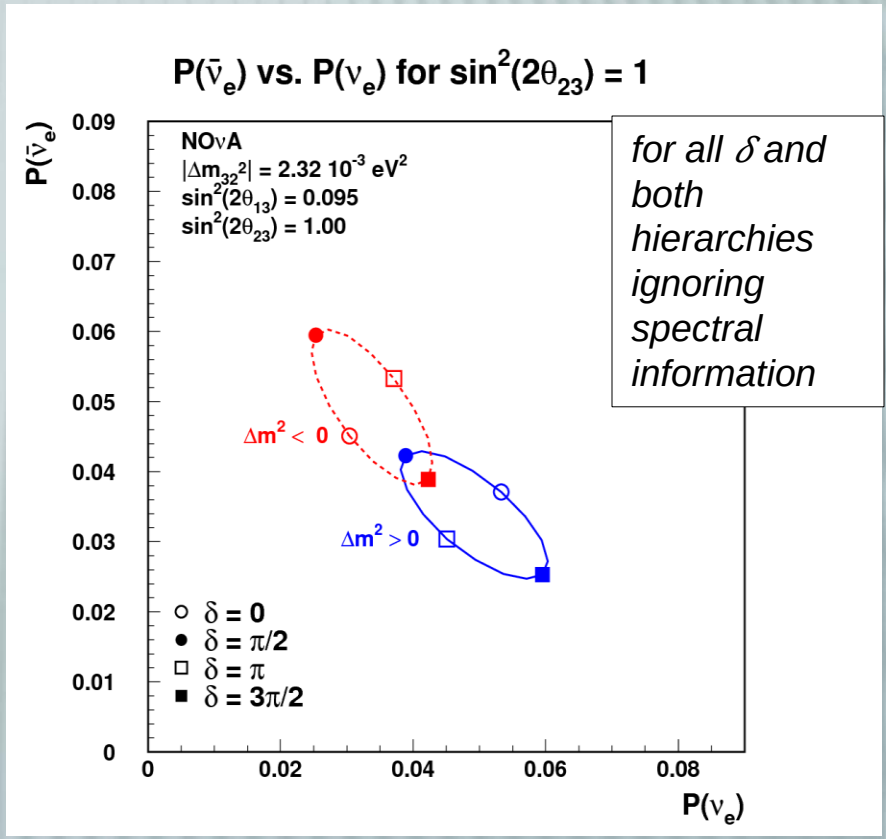




10μs beam spill (every 2.2 sec).

The measurement principle

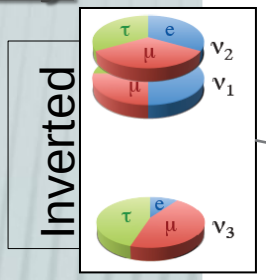
- Independently measured appearance probabilities:
  - At 2 GeV neutrino energy.
- The result depends on :
  - CP phase δ
  - sign(Δm^2) .
- Allows for comparison of rates to theory, parameterized in the CP-violation parameter.

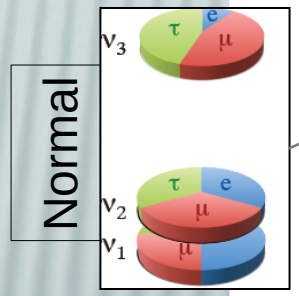


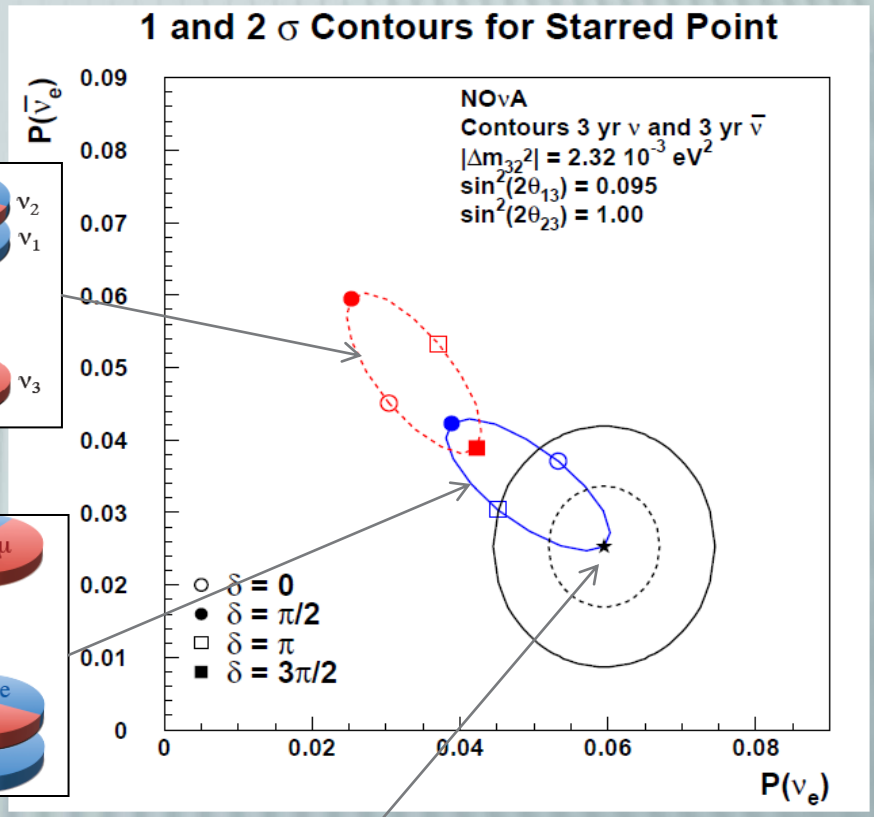
The NOvA measurement

Example (for a maximal θ_{23}) :

- Resolving Mass Hierarchy
- Enhancement or suppression of rates :
  - ~ 30% from the baseline due to matter effects.
- Potential for 2σ resolution
  - over 38% of the space in δ_{CP}

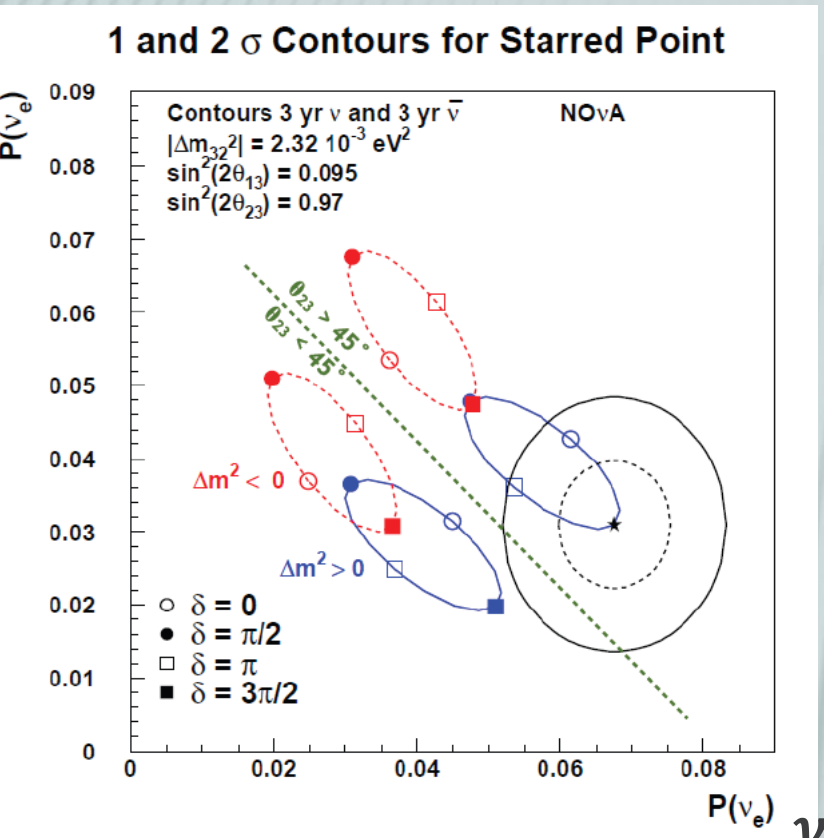




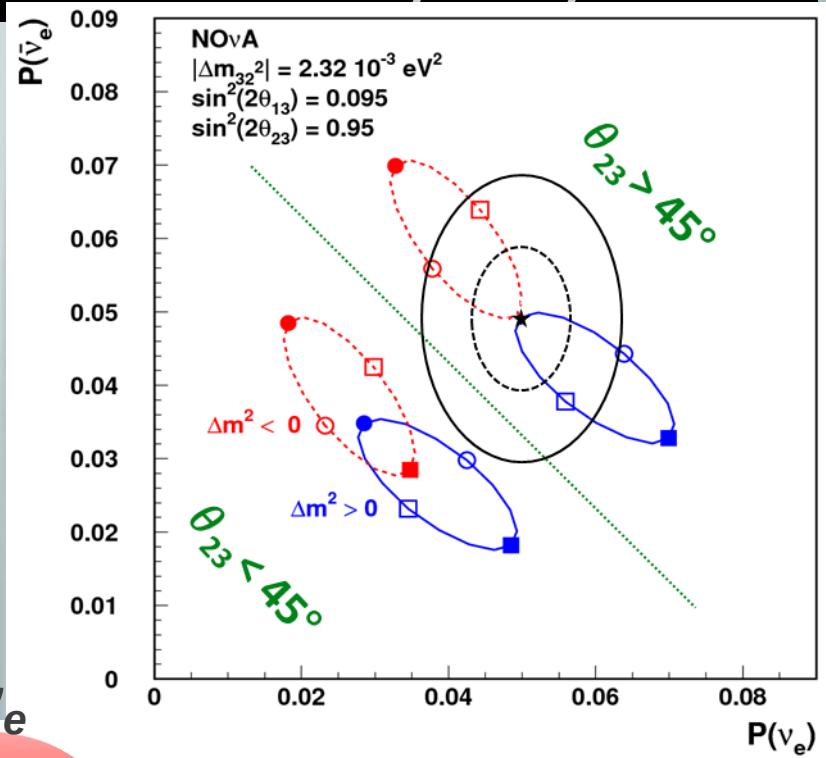


3 year NOvA run on each mode

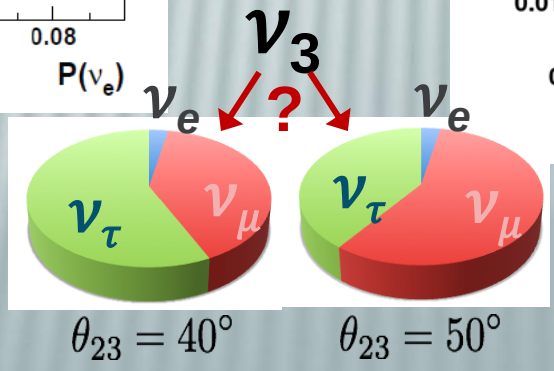
NOvA measurement examples:
θ_{23} octant sensitivity



Expected NOνA contours for one example scenario at 3 yr + 3 yr

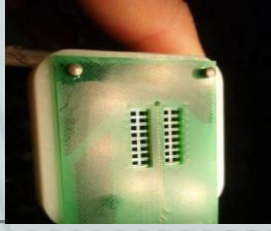


Simultaneous <u>hierarchy</u>, <u>CP phase</u>, and θ_{23} <u>octant</u> information from NOνA



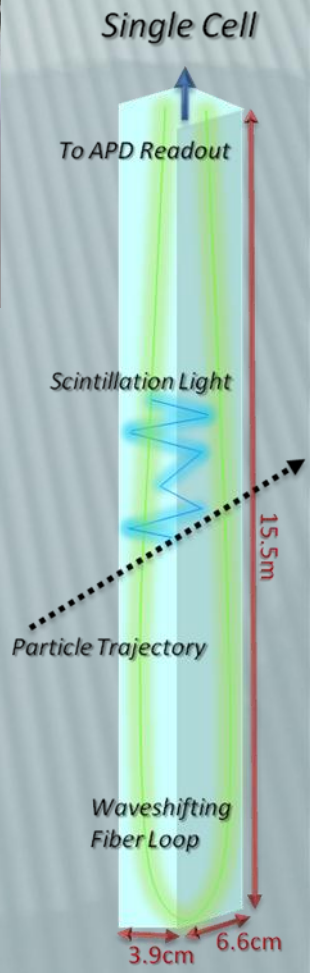
In "degenerate" cases, hierarchy and δ information is coupled. θ_{23} octant information is not.

The NOvA detector design



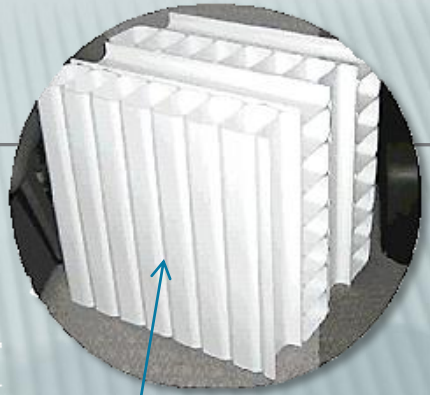
32 pixel APD

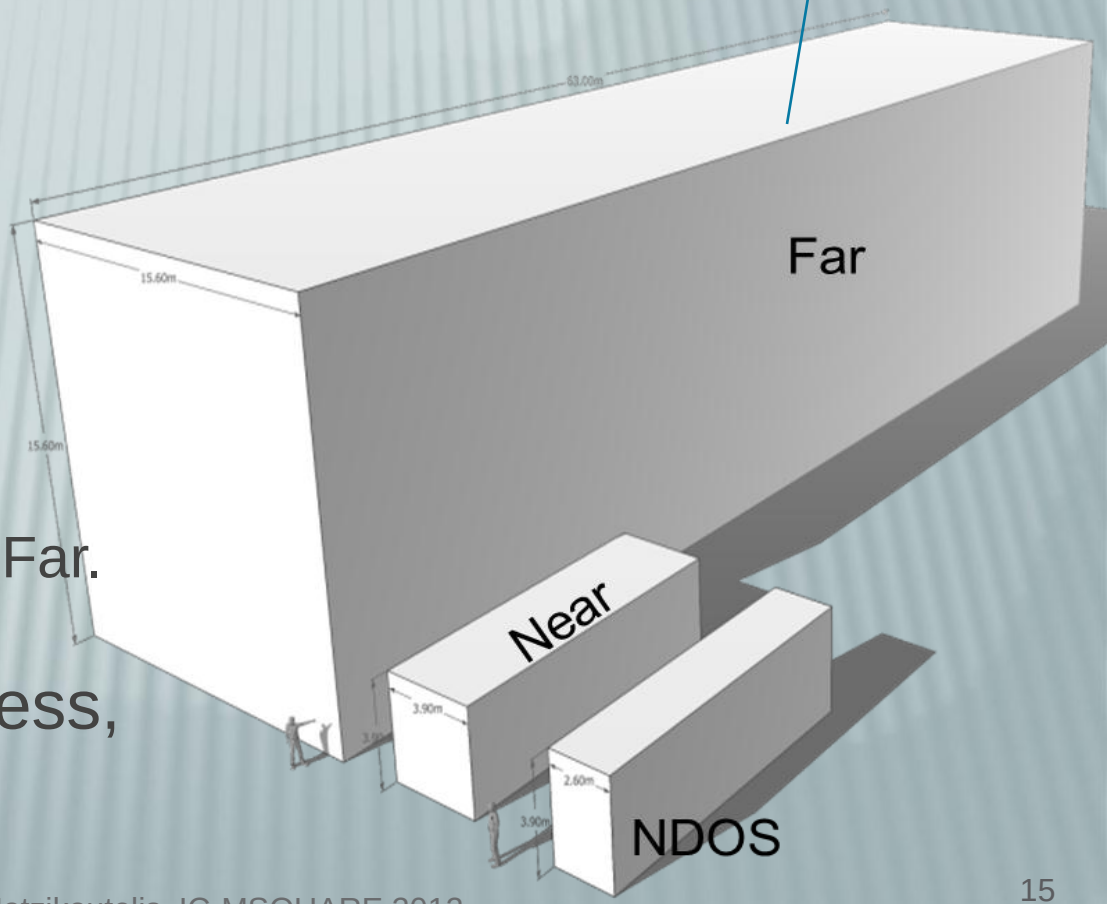
- **The Detector Cell**
  - **Extruded PVC walls.**
  - **Filled with liquid scintillator**
  - **Instrumented with wavelength-shifting fiber**
  - **Read out by avalanche photodiode (APD).**
- **The Readout & Digitization**
  - **32 pixel APD reads out fibers from 32 cells.**
  - **Custom electronics provides amplifier/shaper.**
  - **Each pixel/cell continuously digitized.**
  - **Detection threshold set at ~1/2 MIP**
    - **(6-8 MeV) for muon at far end of cell.**



The NOvA detectors

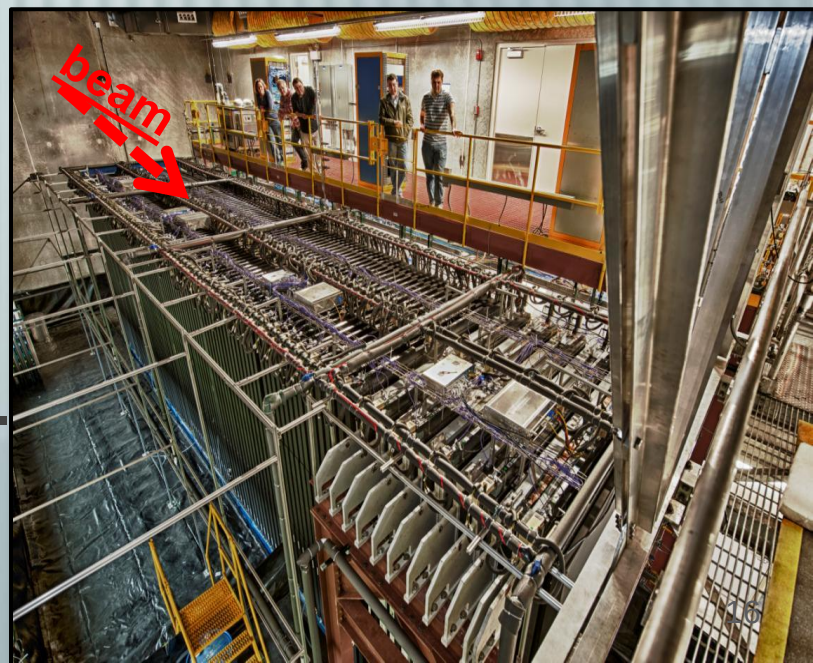
- Far detector:
  - ~14-kton, ~14,700 m^2sr acceptance.
  - tracking calorimeter.
  - low-Z, highly-active.
    - 64% active by mass.
    - X0=38cm (~6cells)
  - High segmentation.
    - 960 planes x384 cells.
    - 360,000 total channels.
- Near detector:
  - 0.3-kton.
  - Functionally identical as Far.
  - 18,000 channels.
- High speed, dead-timeless, continuous readout.





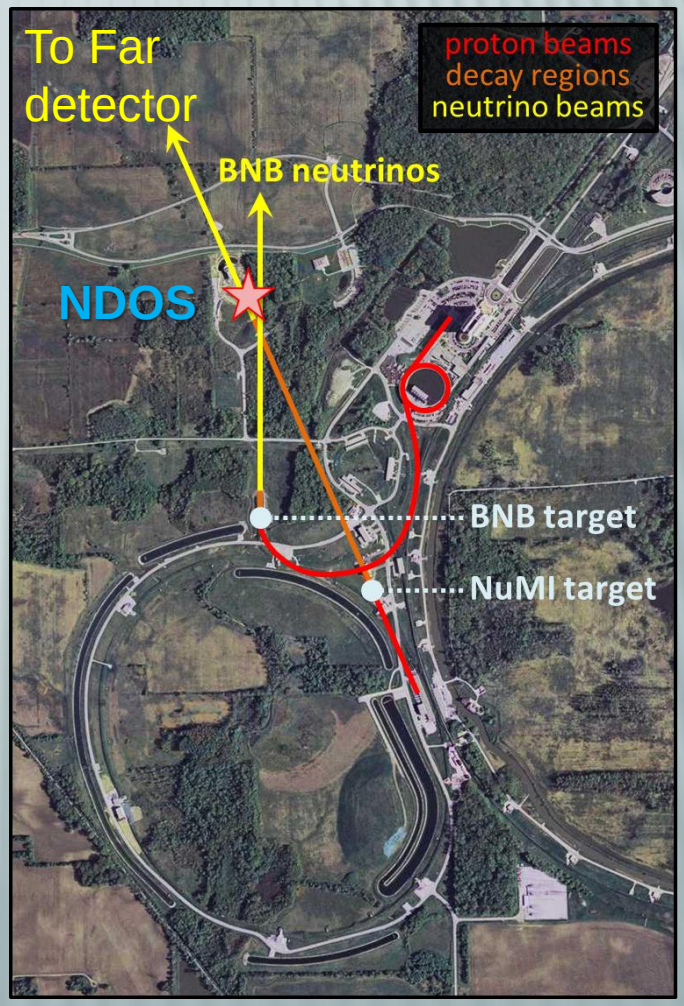
NOvA prototype Near detector

- Near Detector On the Surface (NDOS).
- Used for component production, installation, and integration.
- Used for development of:
  - DAQ and Controls
  - Calibration procedures,
  - Validation of simulation,
  - Reconstruction algorithms.



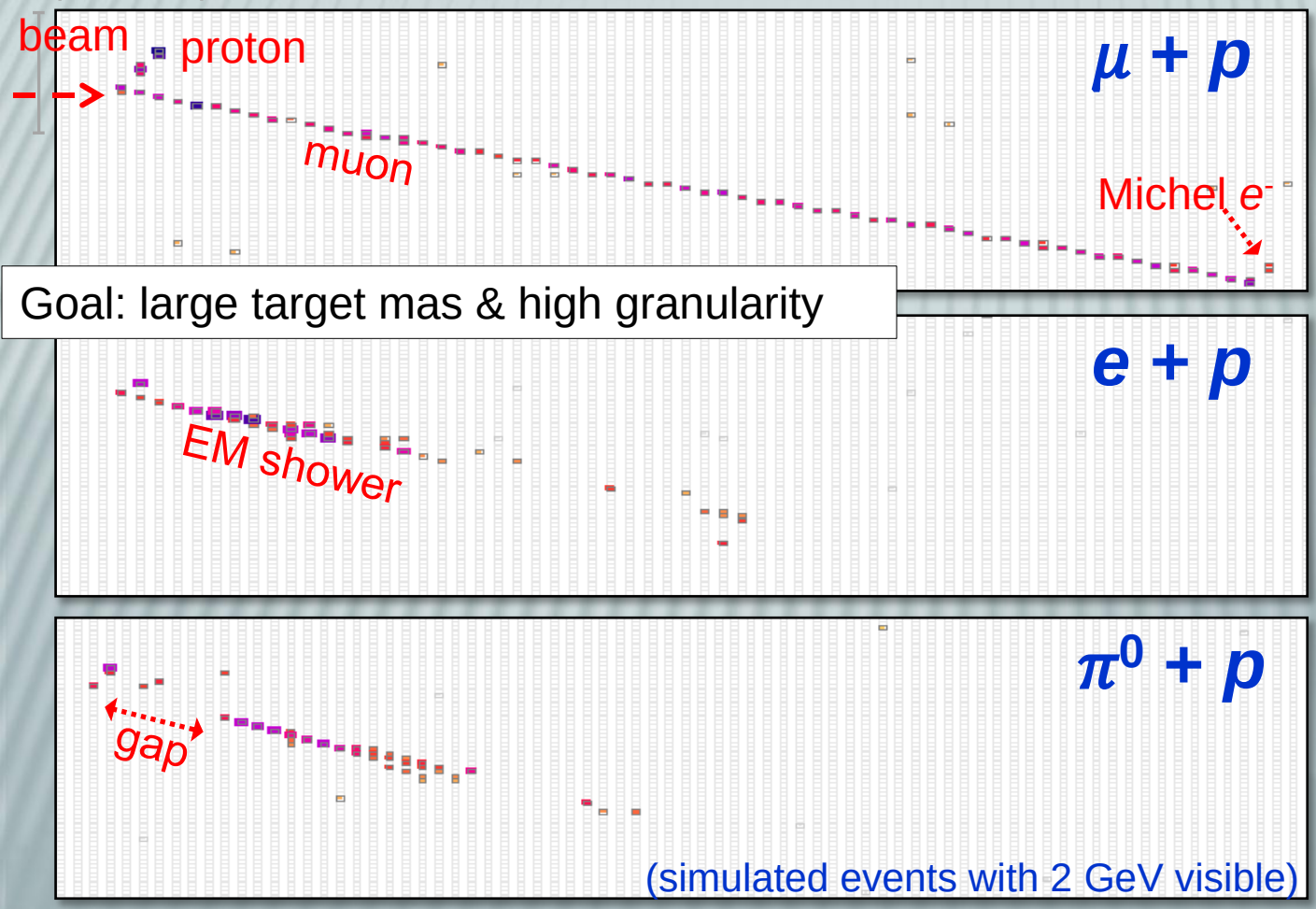
NDOS runs

- Installation completed in May 2011.
- Positioned
  - 900 m from the NuMI target.
  - Between 2 beams
    - NuMI: Parallel and 110mrad off center.
    - Booster: 23º rotated and inline.
  - 100m above the beams.
- Physics runs until May 2012.
- Continuing engineering runs.

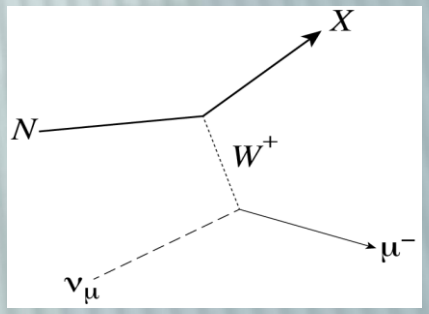


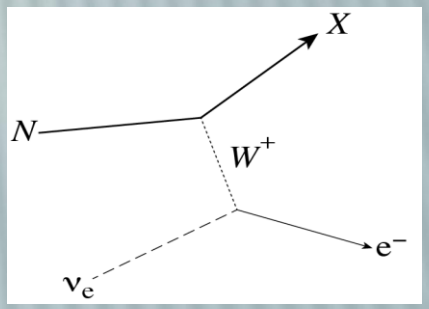
Topologies of the basic interactions

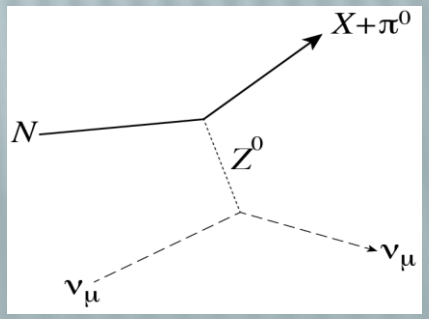
Efficiency 48% identifying ν_e CCQE and 1% fake NC rate
Proton recoil ~ few MeV.



Goal: large target mas & high granularity

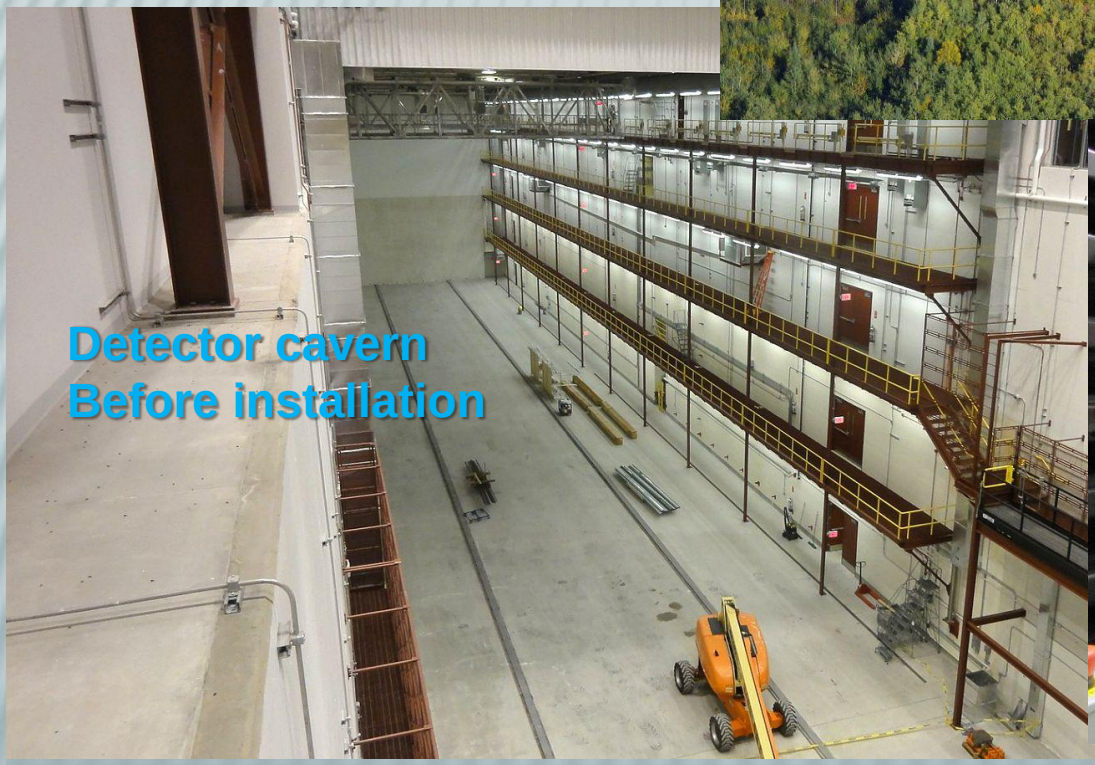




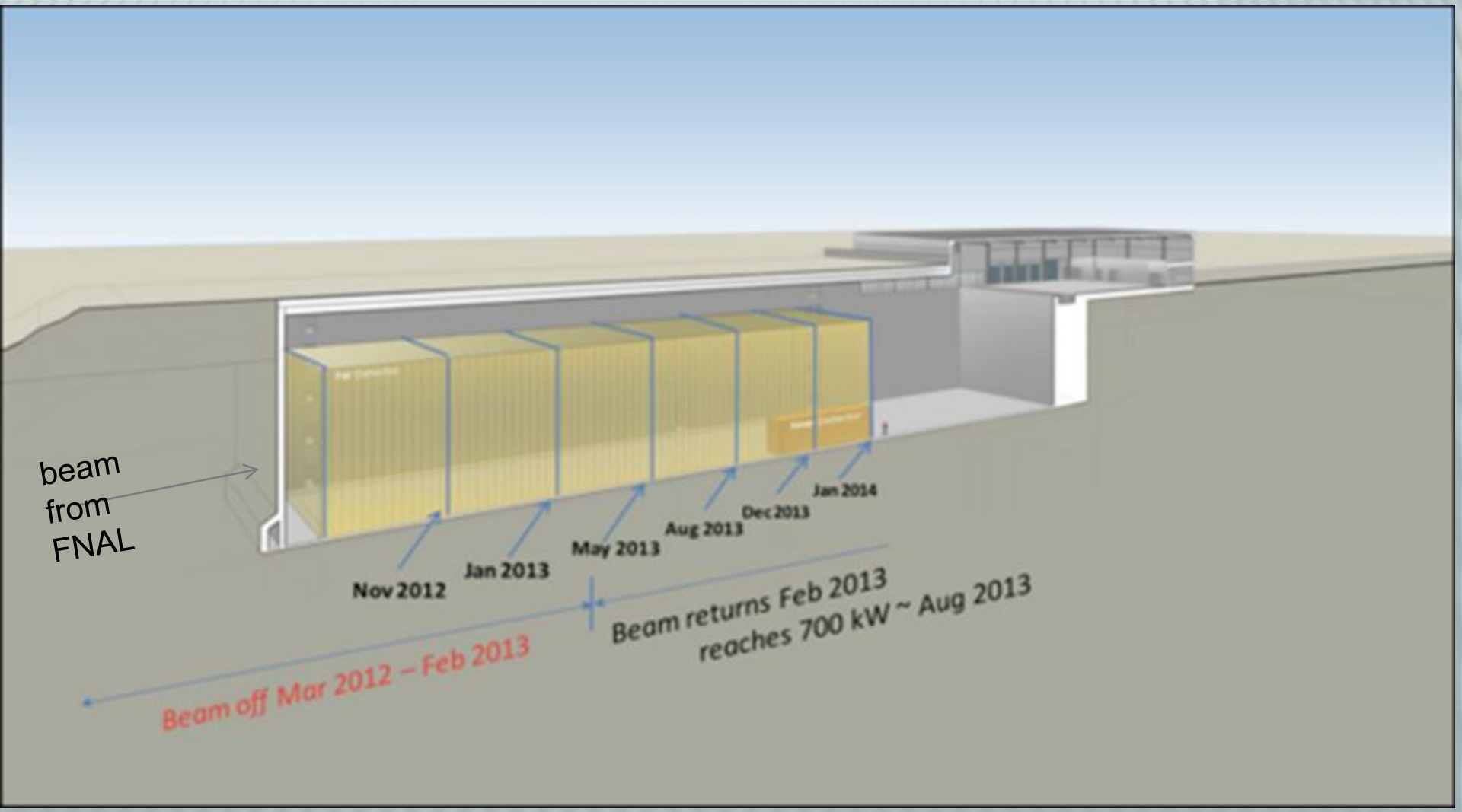


Far detector Status

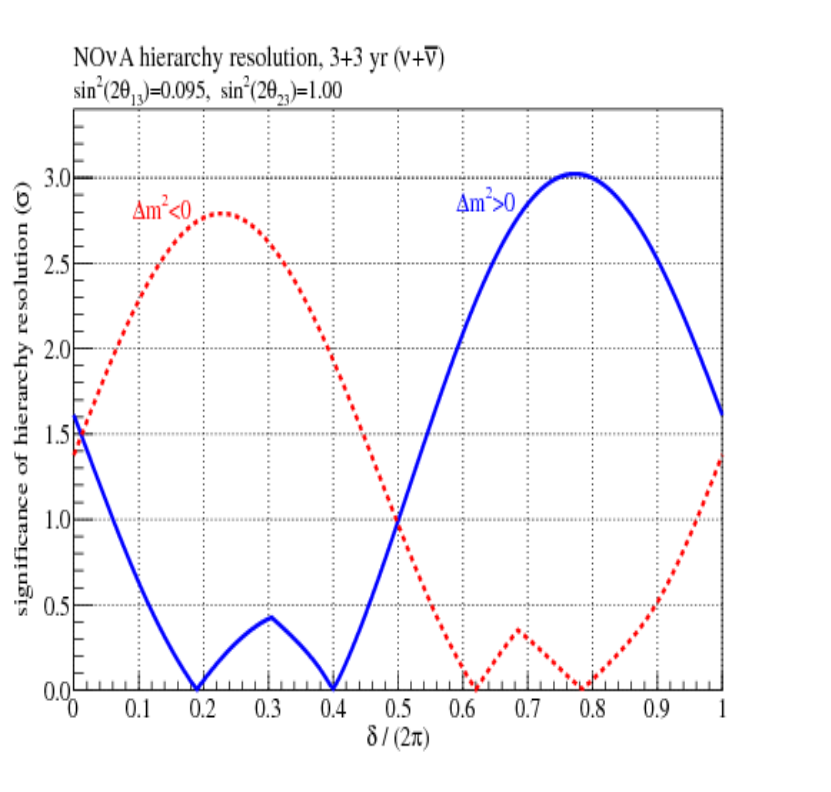
Beneficial occupancy of the building since April 2011.
Construction started Summer 2012.

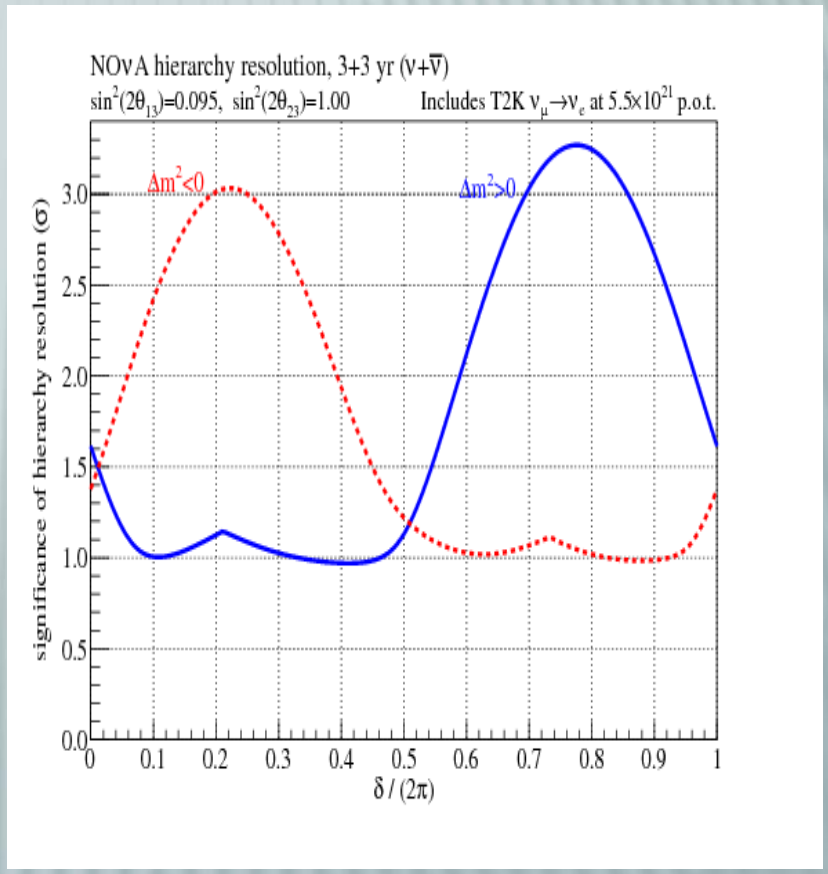


NOvA construction plans



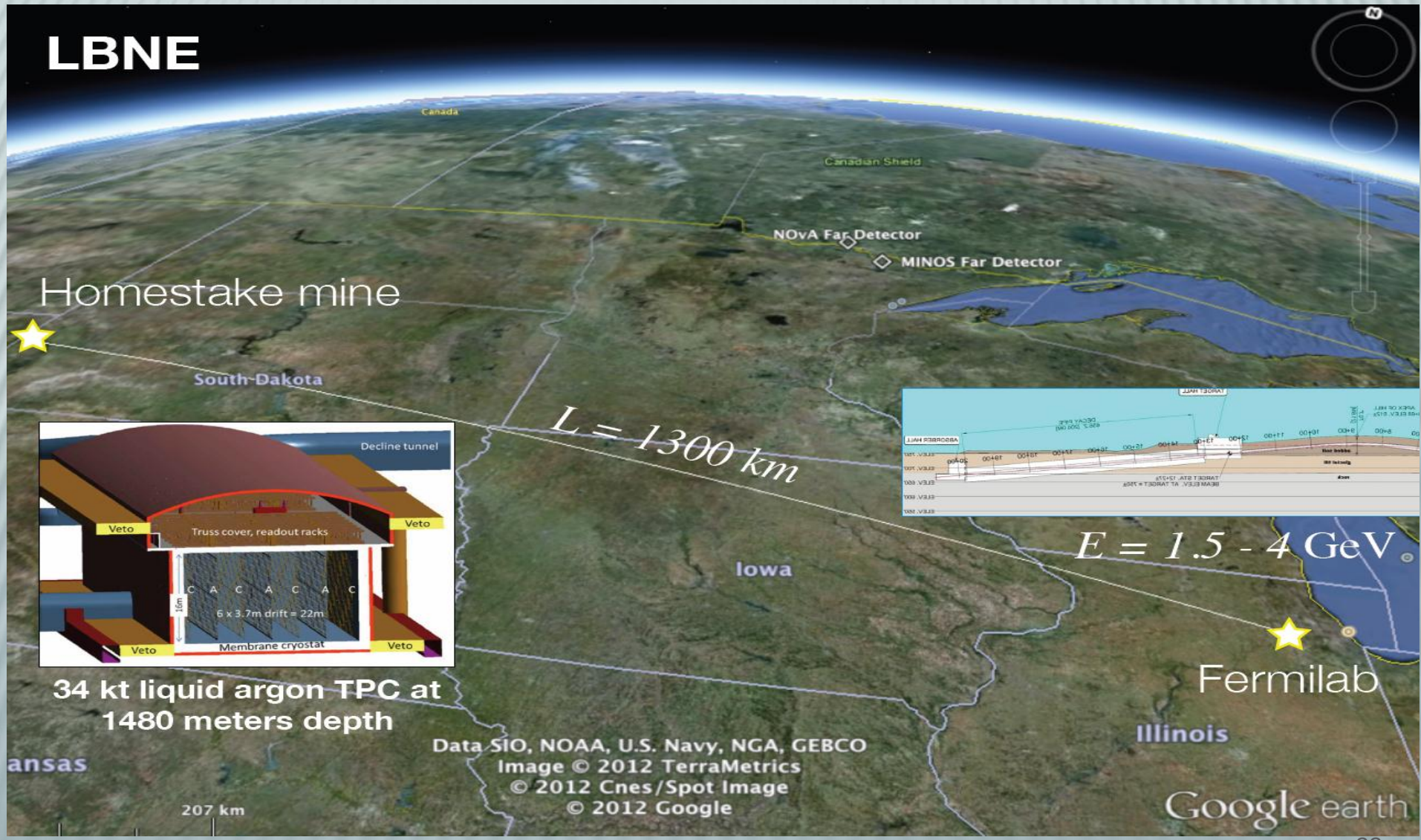
Mass Hierarchy resolution



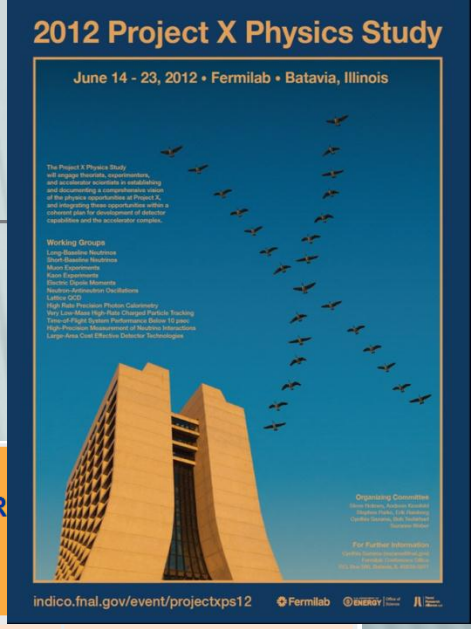


NOvA alone (left) and with T2K predictions (right) based on numbers in their 2011 publication and on 5.5E21 p.o.t., a number that comes from projections for 2019,

Next at the Intensity Frontier



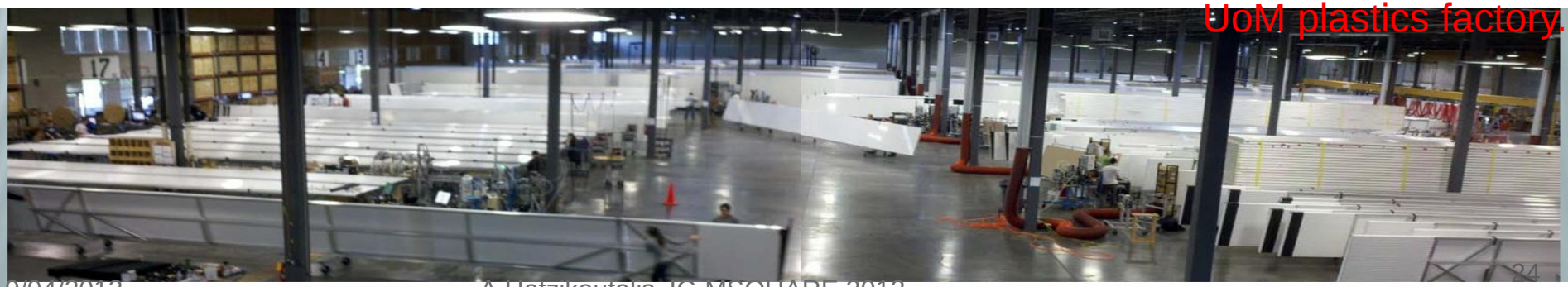
...and beyond



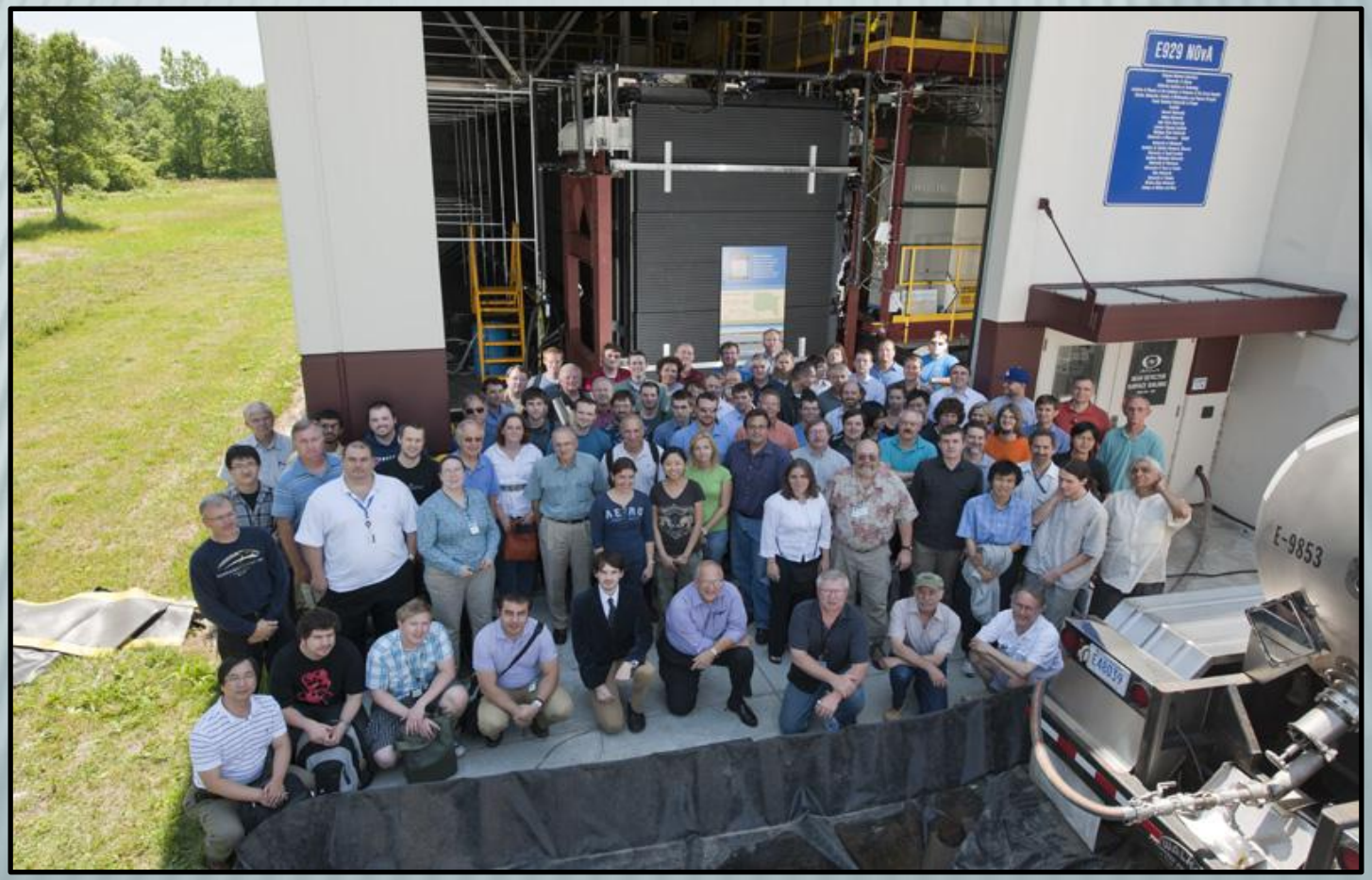
	NOvA era	LBNE era	Muon era		
Program:	**Stage-0:** Proton Improvement Plan	**Stage-1:** 1 GeV CW Linac driving Booster & Muon, EDM programs	**Stage-2:** Upgrade to 3 GeV CW Linac (MI>70 GeV)	**Stage-3:** Project X R (MI>60GeV)	
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1100 kW	1100 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
# Programs:	4	8	8	8	8
Total* power:	585-735 kW	1660-2240 kW	4230 kW	5490 kW	11300kW

Conclusions

- The latest remarkable measurements in θ_{13} open the road for NOvA to address some of the most imposing questions.
  - NOvA may be able to resolve the mass hierarchy of neutrinos.
  - Define the θ_{23} octant.
  - NOvA may see or at least constrain the extent of CP violation.
- The NOvA Far detector is being assembled now and the Near detector will be ready by 2014.
- The prototype NDOS has been valuable in the preparation.
- The next 20 years will be a very exciting time in neutrino experiments at the Intensity Frontier of physics research.



UoM plastics factory.

NOvA Collaboration

Argonne National Lab / Athens / Caltech / Institute of Physics ASCR / Charles University, Prague / Cincinnati / FNAL / Harvard / India Universities Consortium / Indiana / Iowa State / Lebedev / Michigan State / Minnesota, Crookston / Minnesota, Duluth / Minnesota, Twin Cities / INR Moscow / South Carolina / Southern Methodist University / Stanford / Sussex / Tennessee, Knoxville / Texas, Austin / Tufts / Virginia / Wichita State University / William & Mary