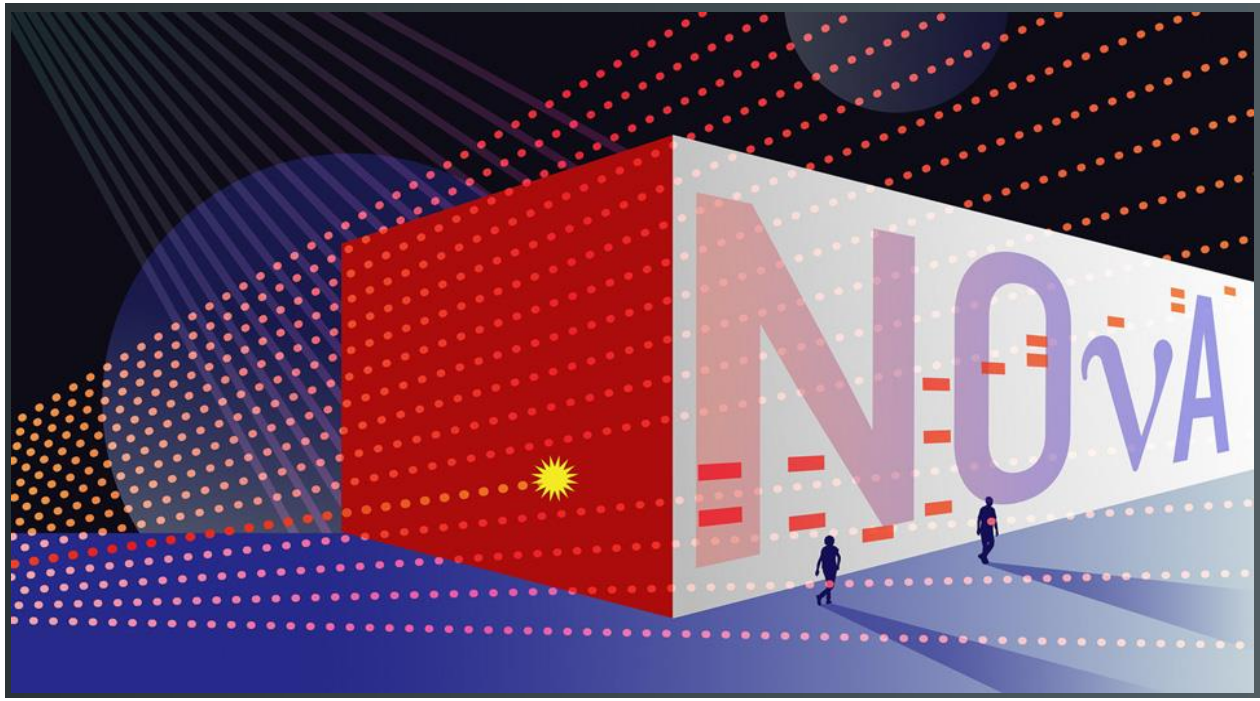
THE NOνA EXPERIMENT

NuMI OFF-AXIS NEUTRINO APPEARANCE

→ NEUTRINOS AT THE MAIN INJECTOR



MIRIAM DIAMOND

PHY2408

DEC 2014

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The NOvA Neutrino Experiment

Organization

Timeline | About | Photos | Videos | More ▾

The NOvA Neutrino Experiment shared a link.
October 9

We're getting a lot of exposure right now. Here we are in Science magazine (subscription may be required)

NOvA's shining moment
www.sciencemag.org

It takes a big snare to catch a subatomic ghost. The newly completed NOvA neutrino detector is the size of a warehouse—five stories tall and more than three times that long—and consists of 896 planes of extruded plastic tubes filled with 10 million liters of mineral oil. "This is the world's largest...

The NOvA Neutrino Experiment shared a link.
October 9

Our most impressive detector got a write-up in Engineering.com

FermiLabs 500-Mile Neutrino Experiment Up and Running > ENGINEERING.com
www.engineering.com

With it's 500-Mile long accelorator up & running, researchers at FermiLab are set to start searching for neutrinos.

The NOvA Neutrino Experiment shared a link.
October 7

Top UK newspaper The Guardian picked up the story about our experiment being up and running. Global exposure!

A huge new neutrino experiment, Nova, is up and running at Fermilab
www.theguardian.com

Jon Butterworth: Neutrinos are everywhere, keep on changing, and are incredibly difficult to detect. Two videos show the contruction and operation of new experiment, involving an 800km neutrino beam, which has just begun

PEOPLE

582 likes

ABOUT

Follow us on Twitter @NOvANuz. Neutrino Oscillation experiment operating between Fermilab in Batavia, IL and Ash River, MN

http://www-nova.fnal.gov/

Guest Blog

Commentary invited by editors of Scientific American

U.S. Particle Physics Program Aims for the Future

By Don Lincoln | November 25, 2014 |

"Using the current Fermilab accelerator complex, physicists are studying the interactions of neutrinos with matter. Neutrinos only experience the weak nuclear force and can pass through a lot of matter without interacting ... Given this reluctance to interact, the only way to ensure enough neutrino interactions to study is to generate incredibly intense beams and analyze them with massive particle detectors."

NuMI OFF-AXIS NEUTRINO APPEARANCE EXPERIMENT

- "Long-baseline"
- Neutrinos at the Main Injector (NuMI) beam @Fermilab, 2 possible modes
  1. Beam mostly ν_μ
  2. Beam mostly $\overline{\nu}_\mu$
- Compare Near-detector @Fermilab vs Far-detector @Ash River for $\nu_\mu \rightarrow \nu_e$ ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$) oscillations
  - #of ν_e ($\overline{\nu}_e$) : "appearance"
  - #of ν_μ ($\overline{\nu}_\mu$) : "disappearance"
- Up-and-running since mid-October!

[1]

OUTLINE

- Review: neutrino masses & mixing
- Main measurement program
  - Mixing parameter θ_{13}
  - CP violation parameter δ
  - Distinguishing the hierarchy
- "Atmospheric ν" measurement program
  - Mixing parameter θ_{23}
  - Mass parameter $\Delta^2 m_{23}$
- BSM: sterile ν search
- Experimental design
  - Backgrounds
  - Sensitivity
  - Beam
  - Detector positioning
  - Detector construction
  - Prototype detector

REVIEW: NEUTRINO MASSES & MIXING
PMNS MATRIX

flavour eigenstates

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

mass eigenstates

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

REVIEW: NEUTRINO MASSES & MIXING
PMNS MATRIX

flavour eigenstates

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

mass eigenstates

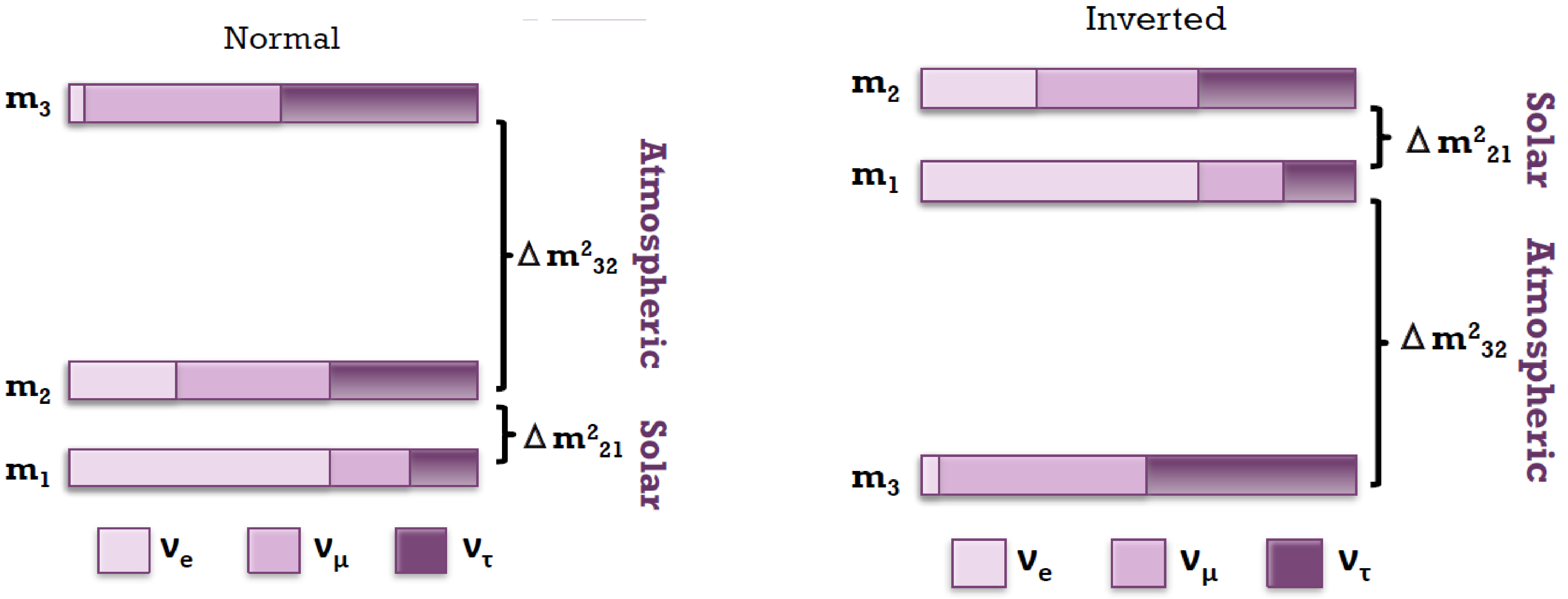
θ_{23} "atmospheric" θ_{13} "atmospheric / reactor" θ_{12} "solar"

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

δ = "CP-violating phase"

REVIEW: NEUTRINO MASSES & MIXING
MASS HIERARCHY

Sign of Δm^2_{32} ?



[4]

REVIEW: NEUTRINO MASSES & MIXING FLAVOUR OSCILLATIONS

In vacuum:

$P(\nu_\mu \to \nu_e) = T_1 + (T_3 - T_2) + T_4$

Atmospheric: $T_1 = \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\Delta_{13}$

$\Delta_{ab} = \Delta m^2_{ab} L / (4E)$

Solar: $T_4 = \cos^2\theta_{23} \cos^2\theta_{13} \sin^2(2\theta_{12}) \sin^2\Delta_{12}$

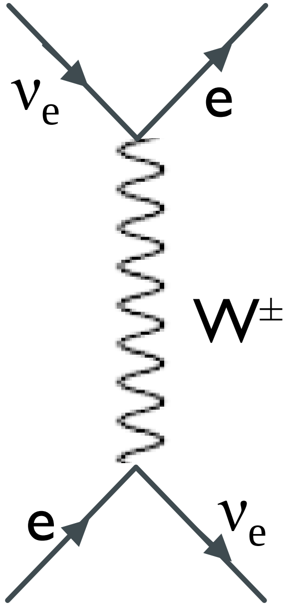
Interference: $T_2 = \sin\delta \sin(\theta_{23}) \sin(\theta_{12}) \sin(\theta_{13}) \cos\theta_{13} \sin\Delta_{12} \sin\Delta_{13} \sin\Delta_{23}$

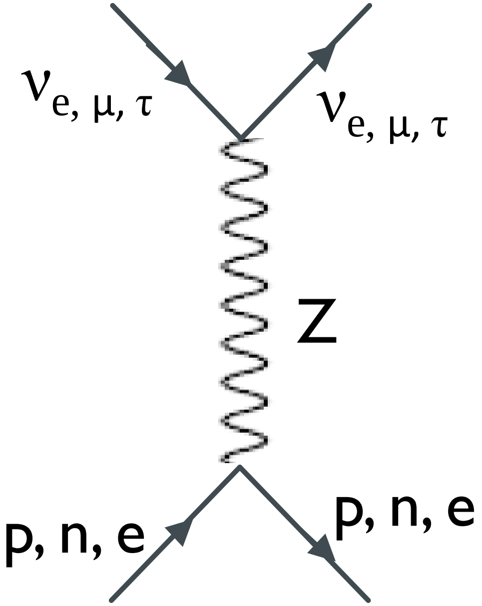
$T_3 = \cos\delta \sin(\theta_{23}) \sin(\theta_{12}) \sin(\theta_{13}) \cos\theta_{13} \sin\Delta_{12} \sin\Delta_{13} \cos\Delta_{23}$

- Multiple parameters involved
- Note degeneracies
- T_2 changes sign for anti-neutrinos (CP-violating!)

REVIEW: NEUTRINO MASSES & MIXING
MATTER INTERACTIONS

CC





NC

Matter interactions quantified by $A = G_F \rho_e / \sqrt{2}$

A switches sign for anti-neutrinos

A switches sign for inverted hierarchy

REVIEW: NEUTRINO MASSES & MIXING
MATTER INTERACTIONS

$P(\nu_\mu \rightarrow \nu_e) = T_1 + (T_3 - T_2) + T_4$

Atmospheric: $T_1 = \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\Delta_{13}$ $\quad \Delta_{ab} = \Delta m^2_{ab} L / (4E)$

Solar: $T_4 = \sin^2(2\theta_{12}) \cos^2\theta_{23} \cos^2\theta_{13} \sin^2\Delta_{12}$

Interference: $T_2 = \sin\delta \sin(\theta_{23}) \sin(\theta_{12}) \sin(\theta_{13}) \cos\theta_{13} \sin\Delta_{12} \sin\Delta_{13} \sin\Delta_{23}$

$T_3 = \cos\delta \sin(\theta_{23}) \sin(\theta_{12}) \sin(\theta_{13}) \cos\theta_{13} \sin\Delta_{12} \sin\Delta_{13} \cos\Delta_{23}$

$A = G_F \rho_e / \sqrt{2}$ (-A for anti-neutrinos or inverted hierarchy)

$\sin\Delta_{12} \rightarrow \sin(\Delta_{12} - AL)\, \Delta_{12} / (\Delta_{12} - AL)$

$\sin\Delta_{13} \rightarrow \sin(\Delta_{13} - AL)\, \Delta_{13} / (\Delta_{13} - AL)$

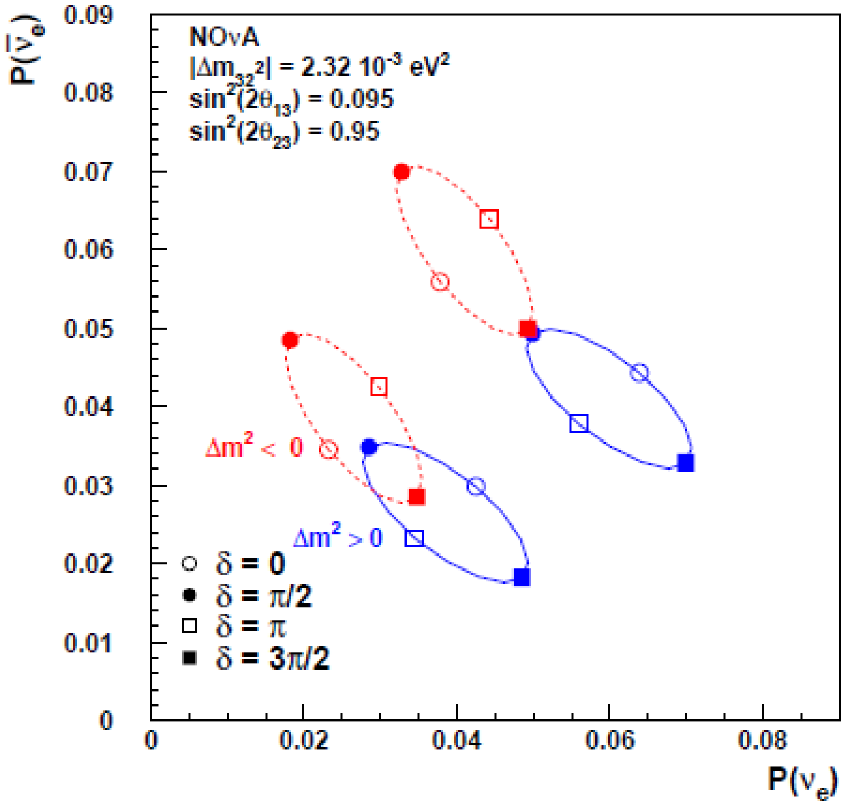
REVIEW: NEUTRINO MASSES & MIXING
CURRENT LIMITS ON OSCILLATION PARAMETERS

Parameter	Best-fit [+/- 1σ]	3σ
Δm^2_{12}	7.58 [+0.22 / -0.26]	6.99 – 8.18
$\lvert \Delta m^2_{23} \rvert$	2.35 [+0.12 / -0.09]	2.06 – 2.67
$\sin^2(\theta_{12})$	0.306 [+0.018 / -0.015]	0.259 – 0.359
$\sin^2(\theta_{13})$	0.021 [+0.007 / -0.008]	0.001 – 0.044
$\sin^2(\theta_{23})$	0.42 [+0.08 / -0.03]	0.34 – 0.64
δ	?	?

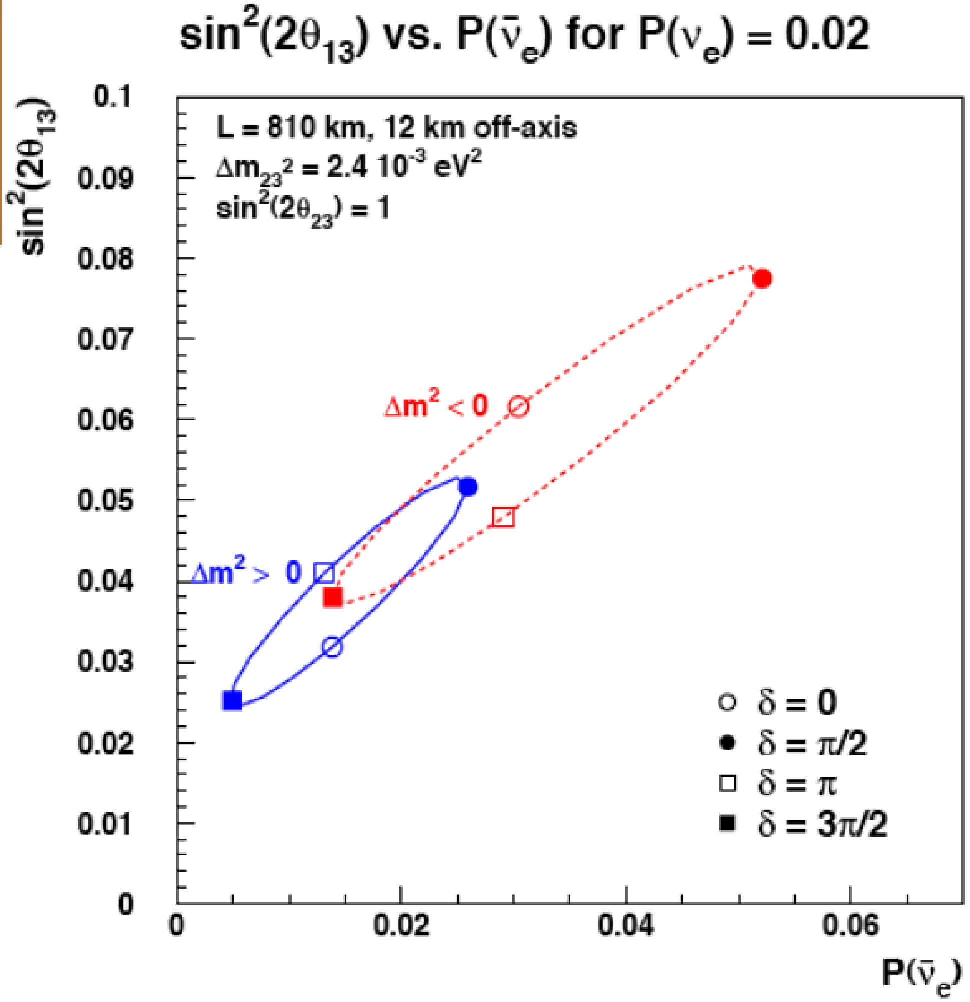
[5]

MAIN MEASUREMENT PROGRAM θ_{13} , δ , HIERARCHY

- Take existing best-fit $|\Delta m^2_{23}|$, $\sin^2(\theta_{23})$
- From NOvA $\nu_\mu \rightarrow \nu_e$ ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$), constrain θ_{13} as function of δ
  - Different for normal vs inverted hierarchy!



[3]

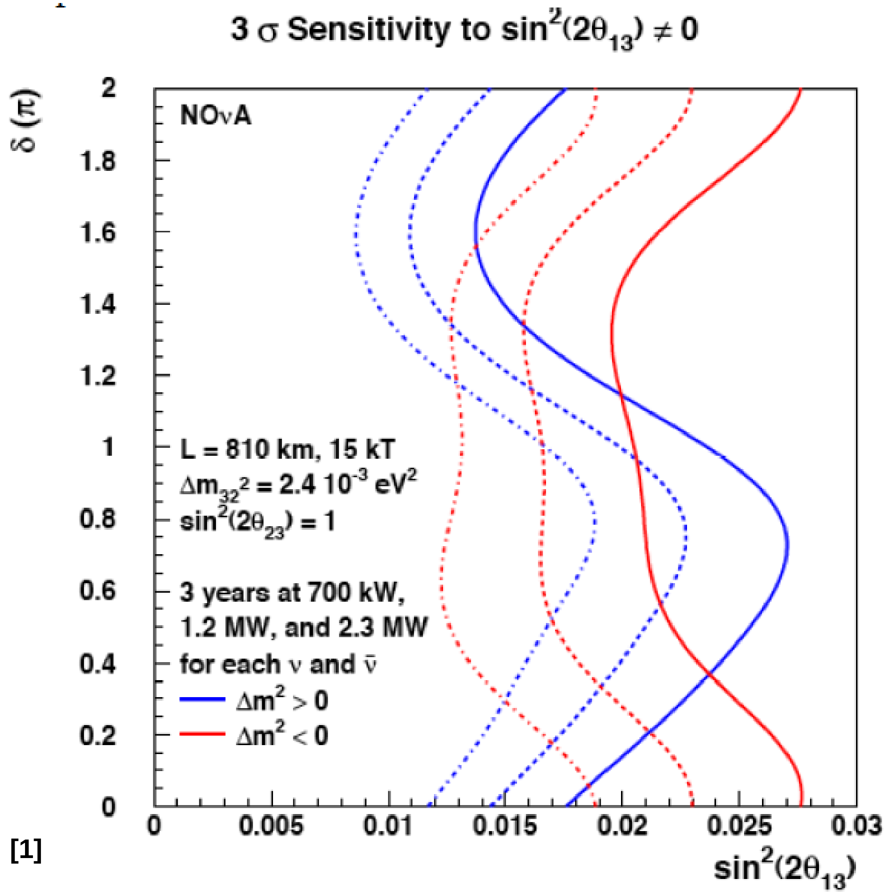


[1]

- CP-violation and Matter effects same sign ("convenient δ"): can determine which hierarchy
  - Otherwise: inherent ambiguity. Higher θ_{13} → higher chance of convenient δ

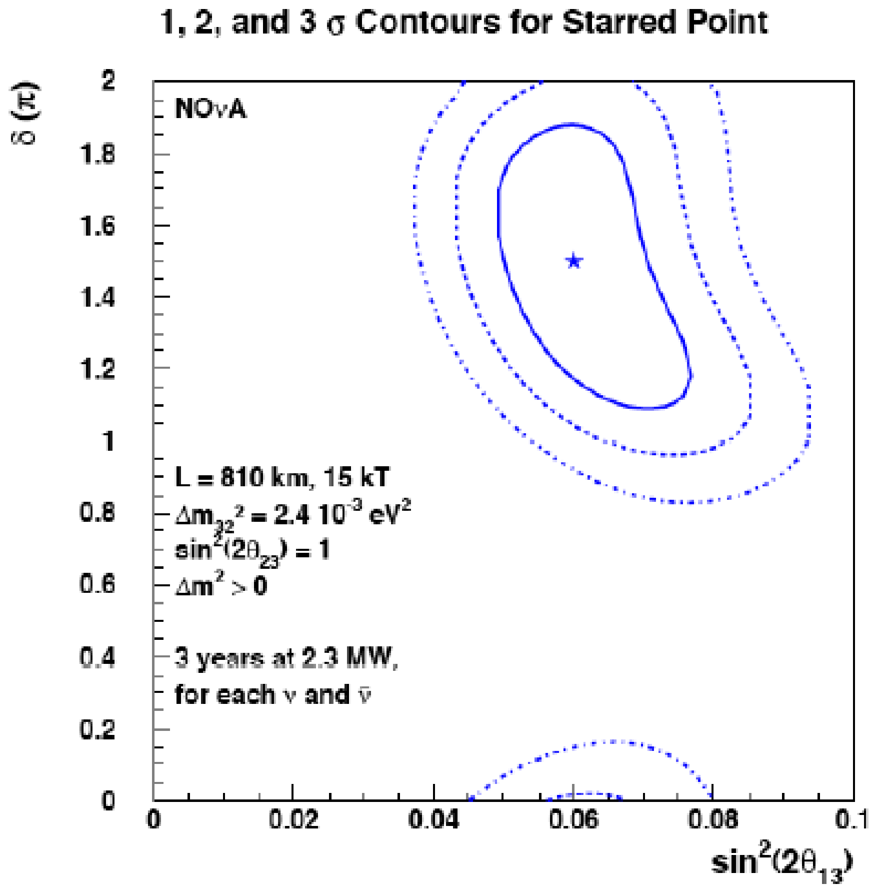
MAIN MEASUREMENT PROGRAM
θ_{13} , δ , HIERARCHY

- How small a θ_{13} will NOνA be able to accurately measure?



[1]

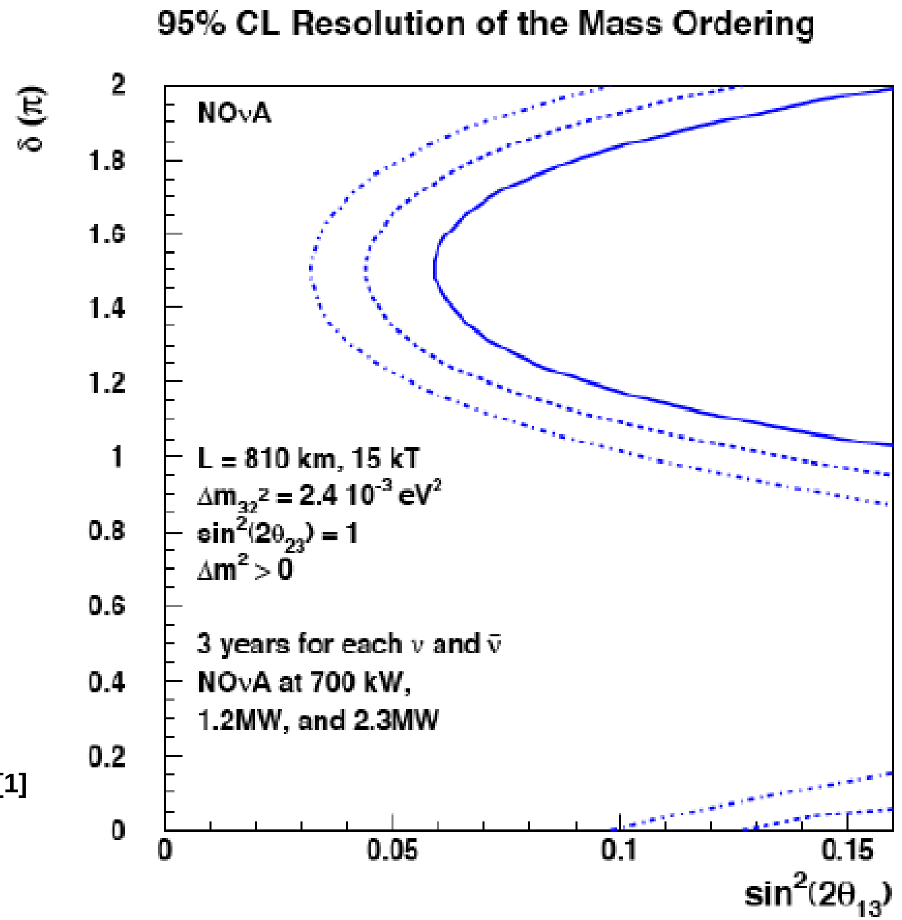
- Once NOνA finds best-fit (θ_{13}, δ), how big will the uncertainties be?



[1]

MAIN MEASUREMENT PROGRAM
θ_{13} , δ , HIERARCHY

- For what (θ_{13} , δ) range will the hierarchy be resolved?



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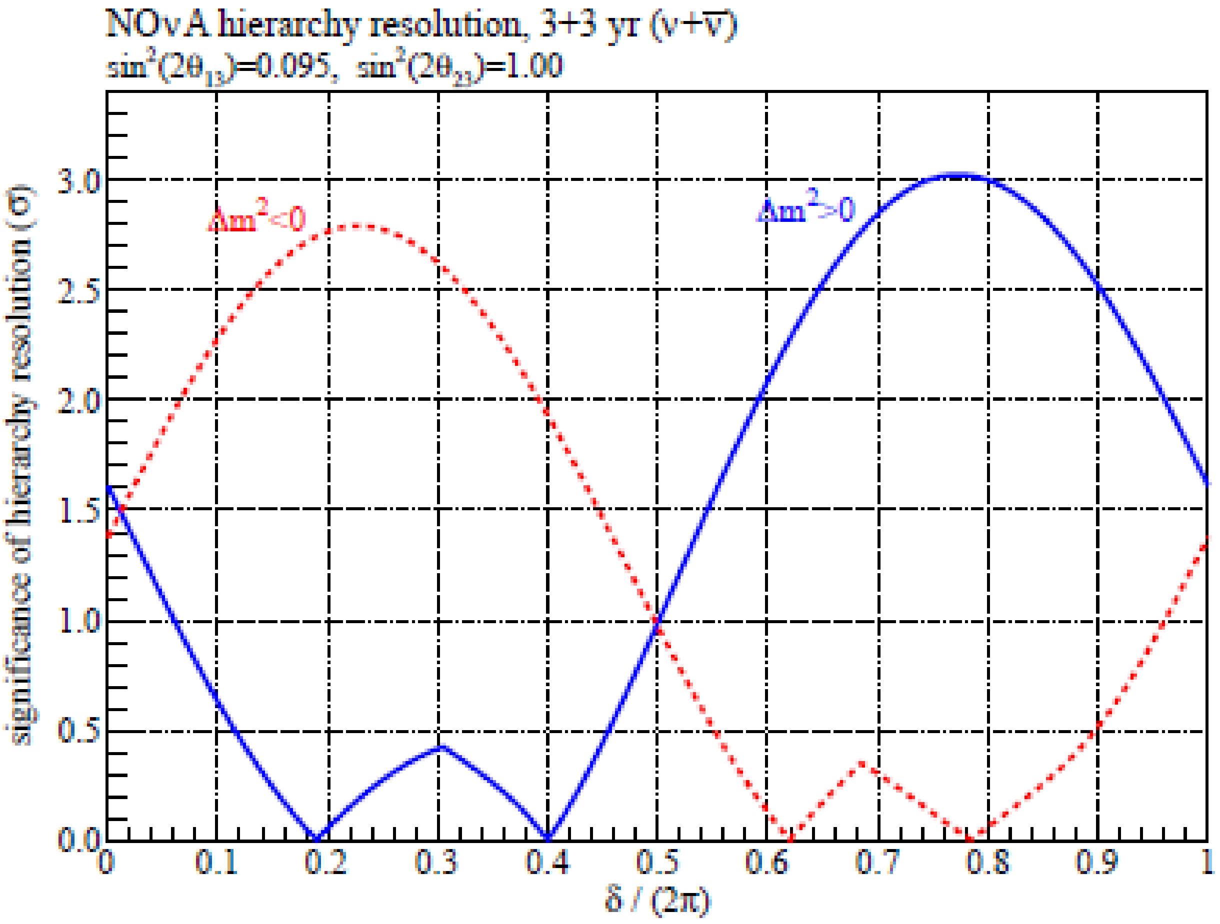
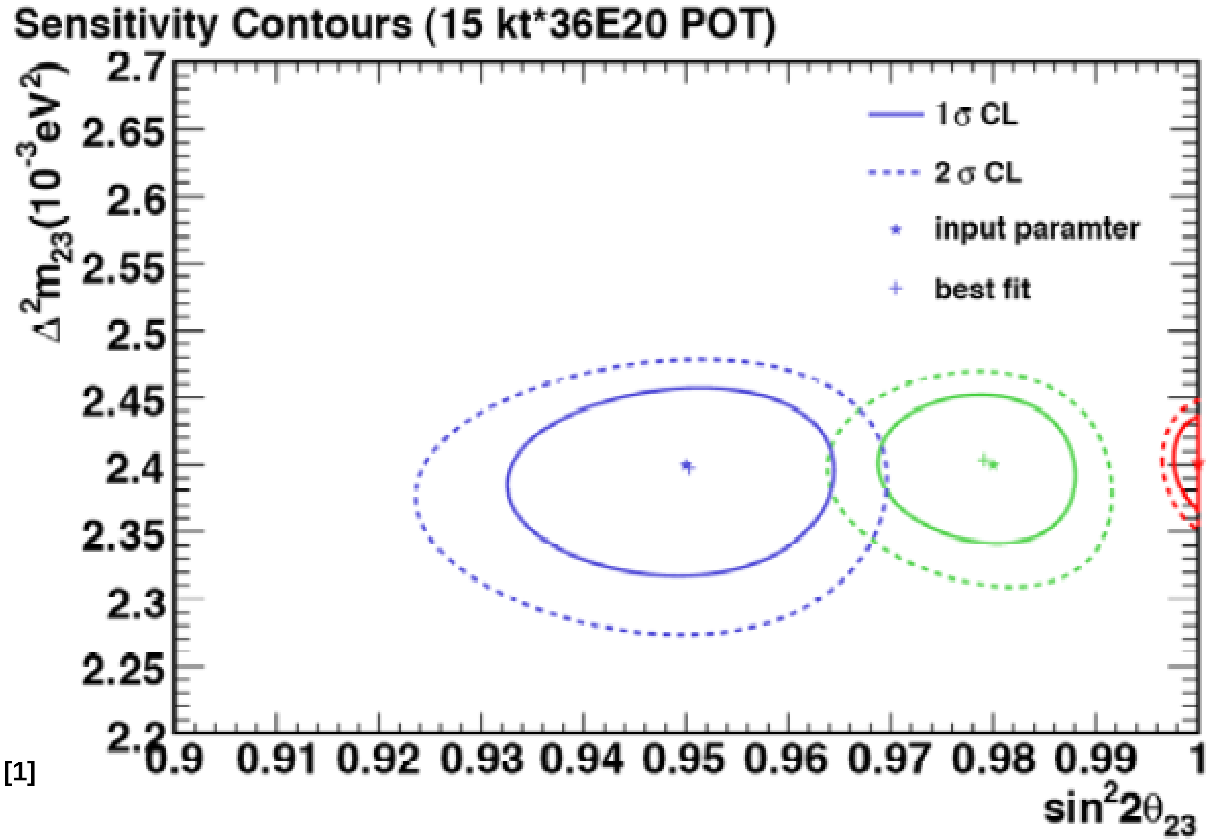


[3]

ATMOSPHERIC ν MEASUREMENT PROGRAM
θ_{23} , $|\Delta m^2_{23}|$

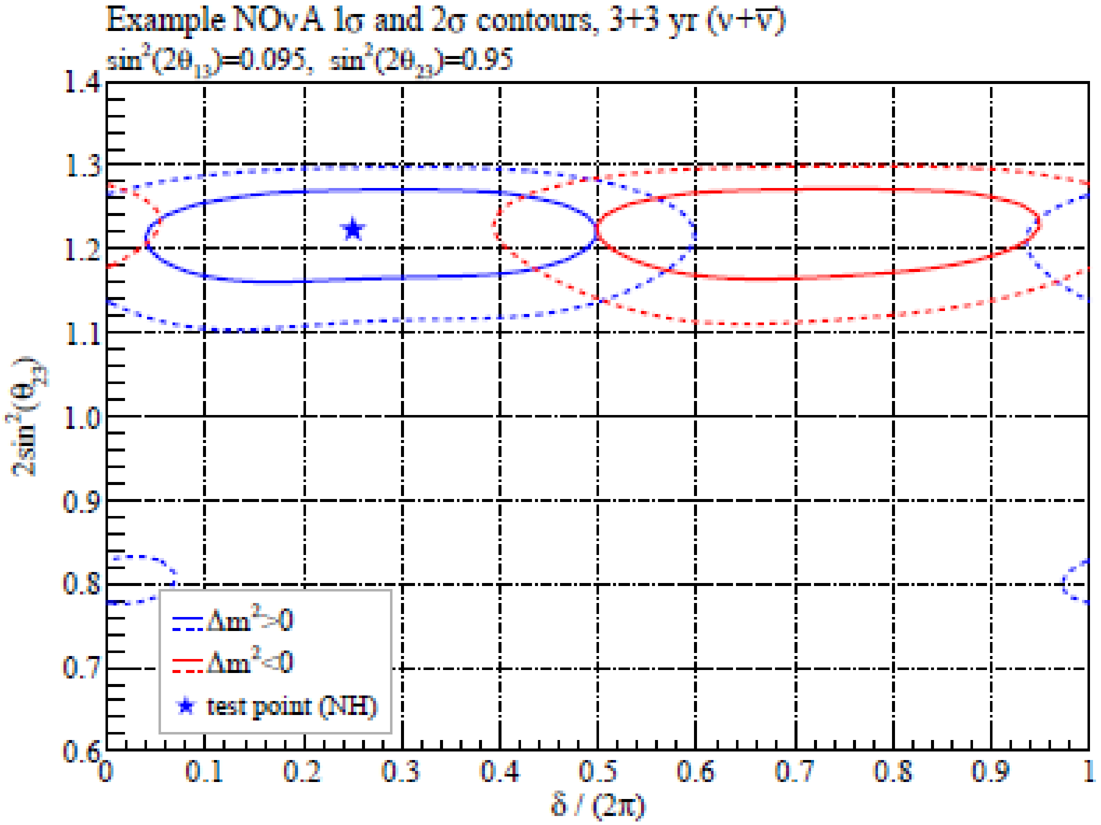
Usefulness of NOνA results for atmospheric parameters: how big will the uncertainties be?

- Simultaneous best-fit to { $|\Delta m^2_{23}|$, $\sin^2(\theta_{23})$ }



[1]

- $\sin^2(\theta_{23})$ as a function of δ

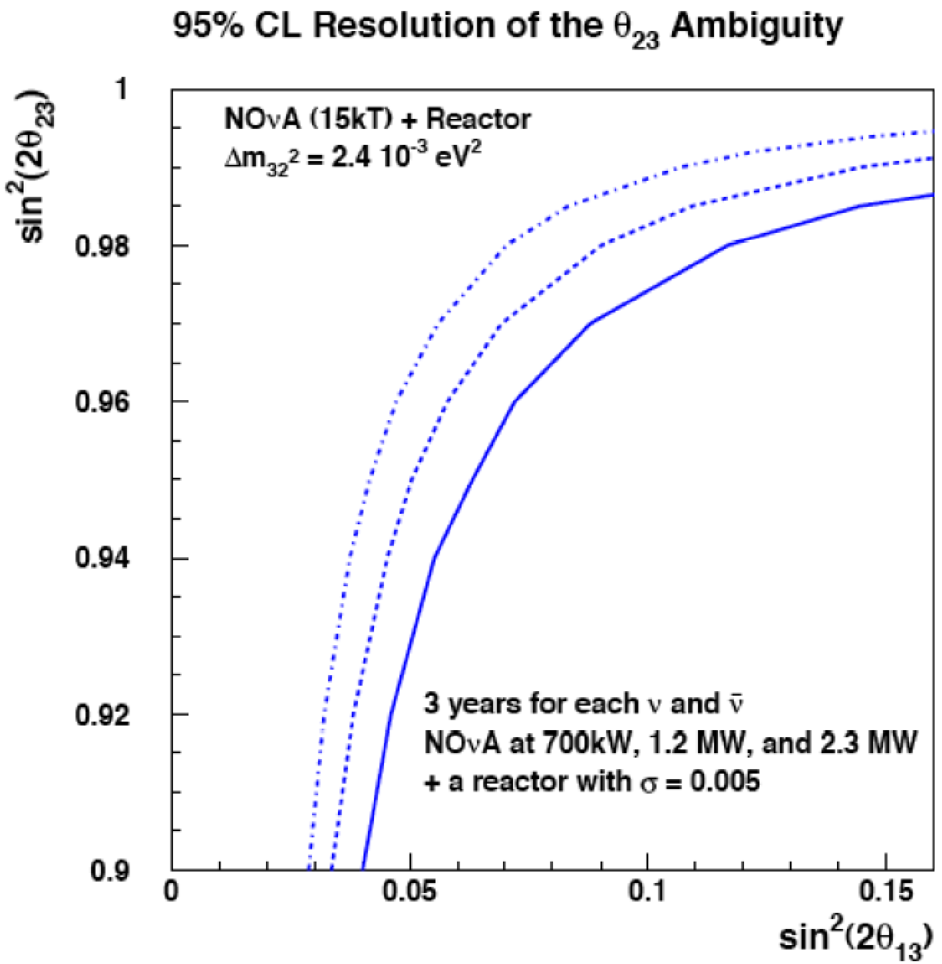


[3]

ATMOSPHERIC ν MEASUREMENT PROGRAM θ_{23} , $|\Delta m^2_{23}|$

- Take existing best-fit $|\Delta m^2_{23}|$, $\sin^2(\theta_{13})$
- Determine sign of $\cos(2\theta_{23})$, i.e. whether ν_e oscillates more strongly to ν_μ or ν_τ
  - Requires comparing NOνA to reactor results

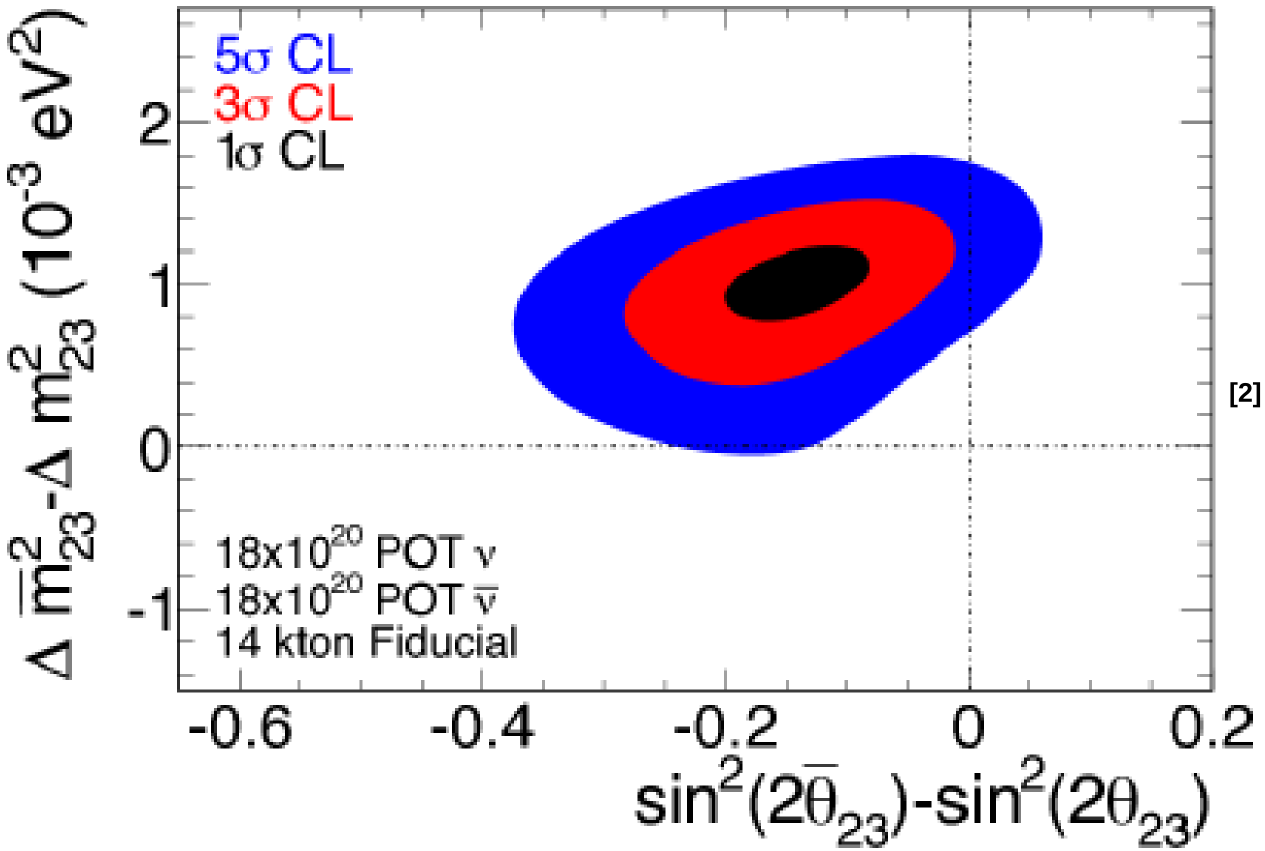
For what (θ_{13}, θ_{23}) range will NOνA resolve sign?



[1]

ATMOSPHERIC ν MEASUREMENT PROGRAM
θ_{23} , $|\Delta m^2_{23}|$

- Possibility $|\Delta m^2_{23}|$ and/or θ_{23} different for neutrinos vs anti-neutrinos
- How accurately could NOνA pin down such an asymmetry?



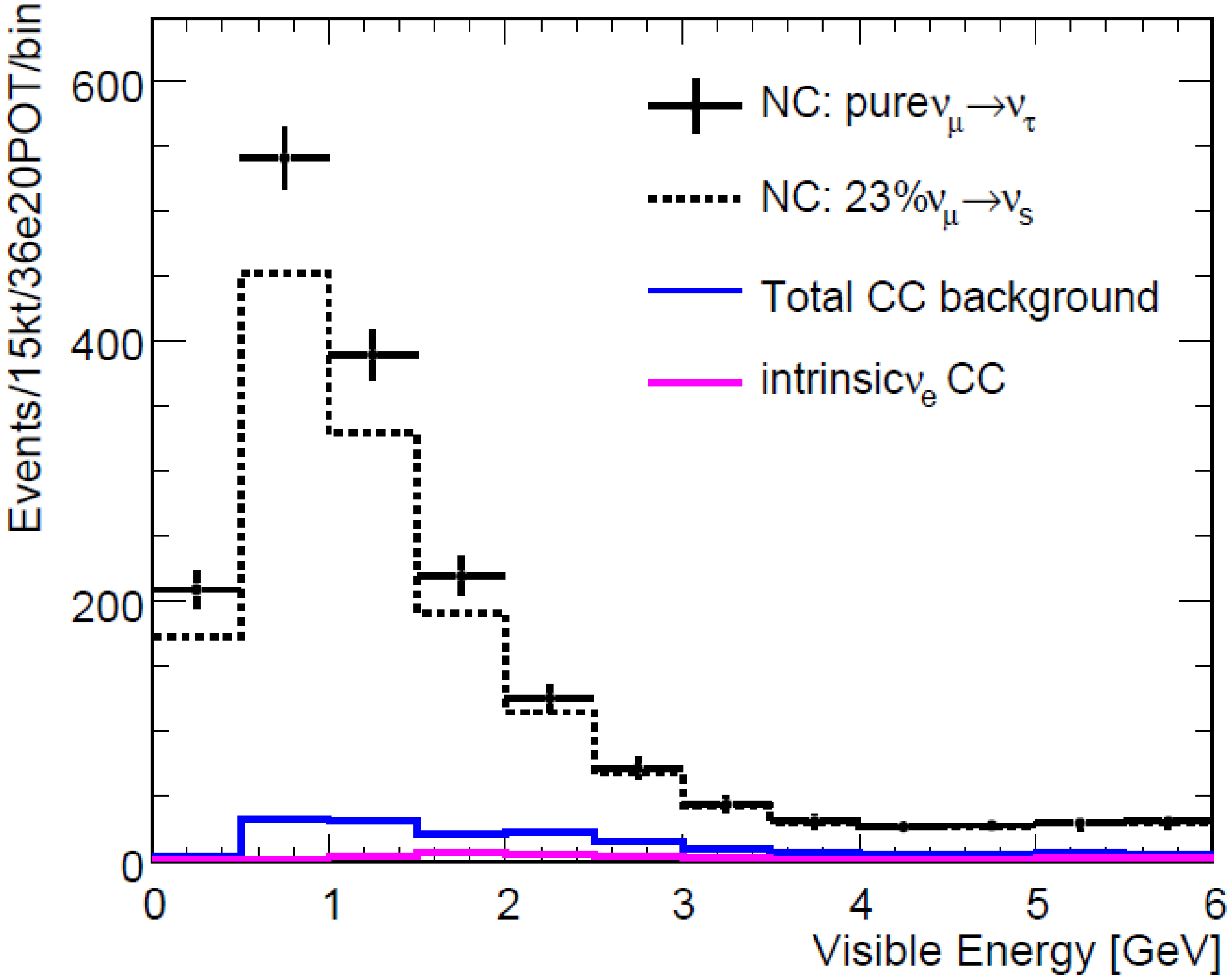
[2]

BSM: STERILE ν SEARCH

- BSM possibility: 4th light neutrino state, ν_s
  - "Sterile" (no coupling to Z or W)
- Have $\nu_\mu \rightarrow \nu_?$ (with $\nu_?$ = admixture of ν_τ, ν_s)?
  - Consequence: fewer than expected NC events in NOνA Far-detector

Current 90%CL bounds on $\nu_?$:
< 20% ν_s

Expected NOνA sensitivity:
~10% ν_s



[1]

EXPERIMENTAL DESIGN : OVERALL LAYOUT

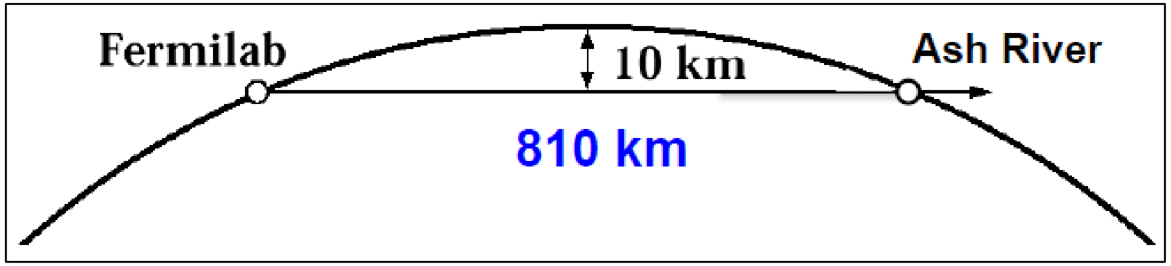
Near-detector: 330 metric-ton @Fermilab

- Mainly detect leptonic showers from CC interactions
- Optimize for 2 GeV ν's ($\nu_\mu \rightarrow \nu_e$ oscillation max)
- "Baseline exposure": 6 yrs of running

Far-detector: 14000 metric-ton @Ash River

[2]

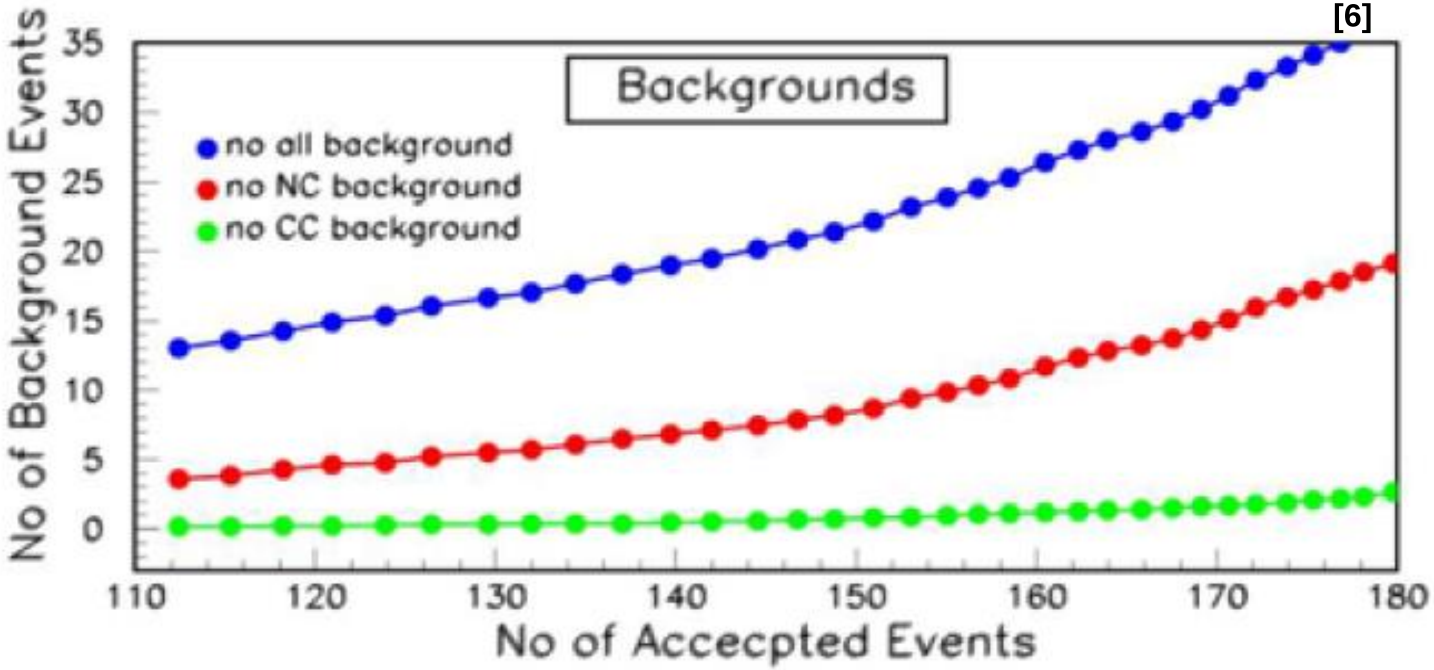
[7]



EXPERIMENTAL DESIGN : BACKGROUNDS

- Non-signal ν events (~0.5%)
  - Energy cuts, requiring good energy resolution
- Mistaking NC for ν_e CC (~0.1%)
  - Highly-segmented detector
  - Careful choice and understanding of detector materials
- "Wrong-sign" ν beam component (~1%)

[6]



- Precise estimates made for unavoidable bg
- Dominant uncertainties will be statistical

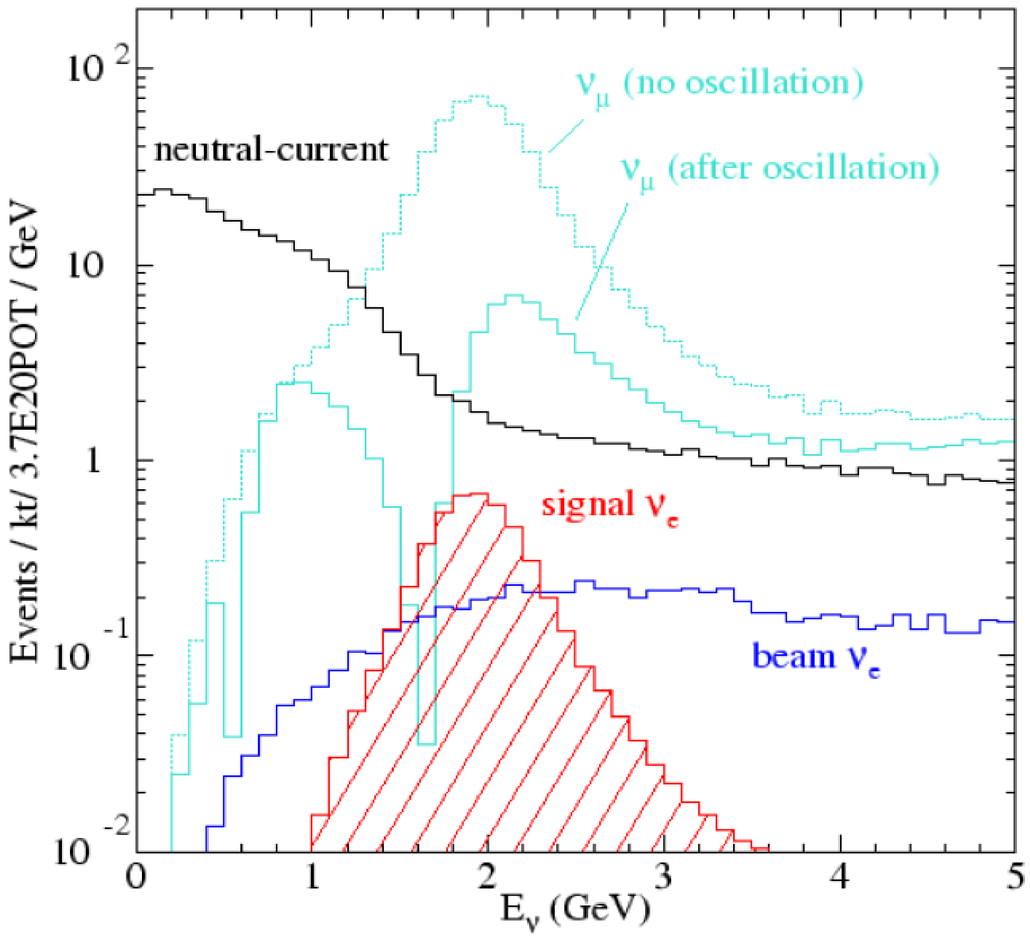
EXPERIMENTAL DESIGN : SENSITIVITY

- Signal ~ √[exposure time] until systematics-limited
- High signal efficiency + good bg rejection requires tracking + calorimetry: frequent sampling in low-Z material
- >100:1 bg rejection
- ν event detection efficiency ≈ 0.4

Candidate events expected in Far-detector [3 yrs running each mode, $\sin^2(2\theta_{13})$=0.095]

[7]

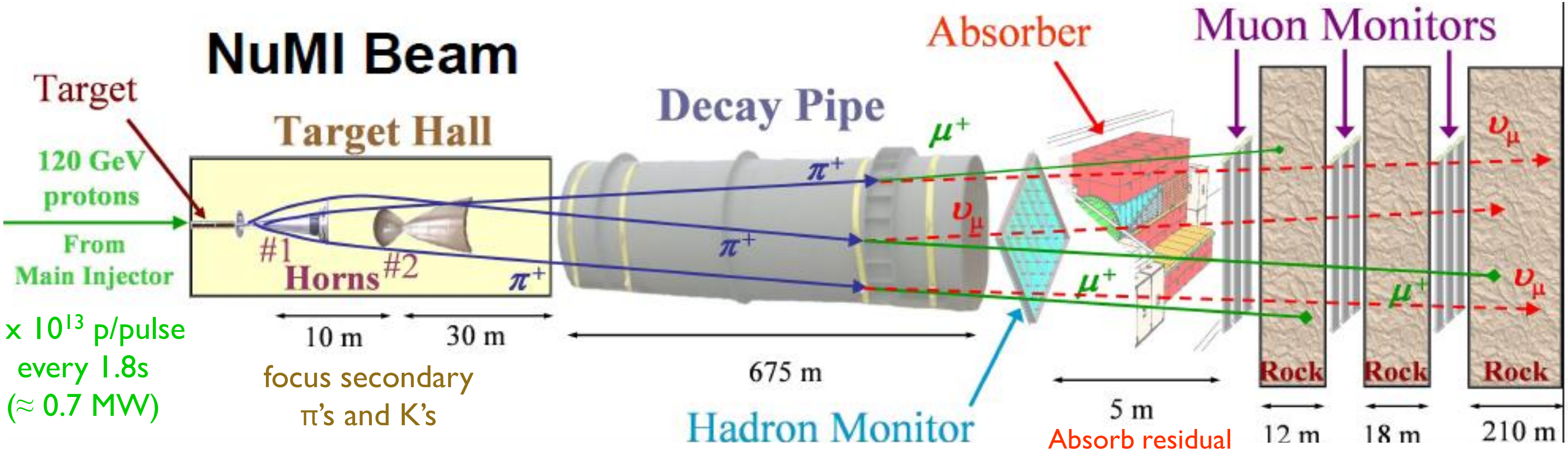
	ν	$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
total bg.	32	15
$\nu_\mu \rightarrow \nu_e$ CC	68	32



[6]

Event rate in anti-neutrino mode: ~30% lower

EXPERIMENTAL DESIGN: BEAM



[7]

6 x 10^{13} p/pulse every 1.8s ($\approx$ 0.7 MW)

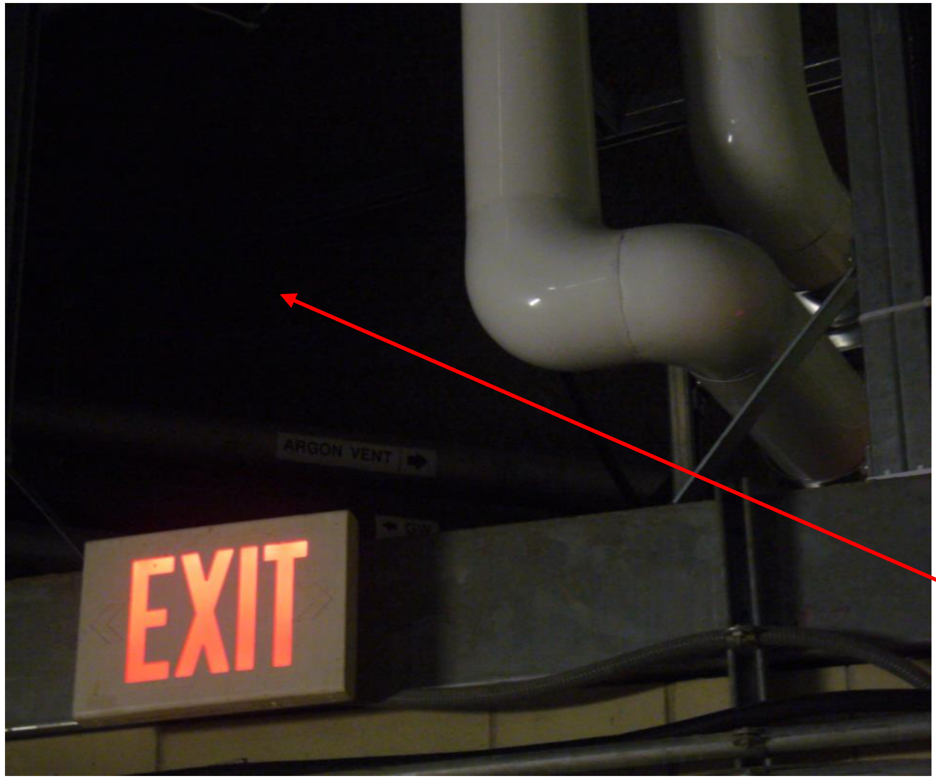
focus secondary π's and K's

Absorb residual protons, secondary mesons

Absorb muons

- 3 "beam tunes" (low-, medium-, high- energy)

EXPERIMENTAL DESIGN: BEAM



Underground tunnel
@Near-detector:
ν beam comes out
here

I stood in the beam
(nothing happened) and
took these photos!

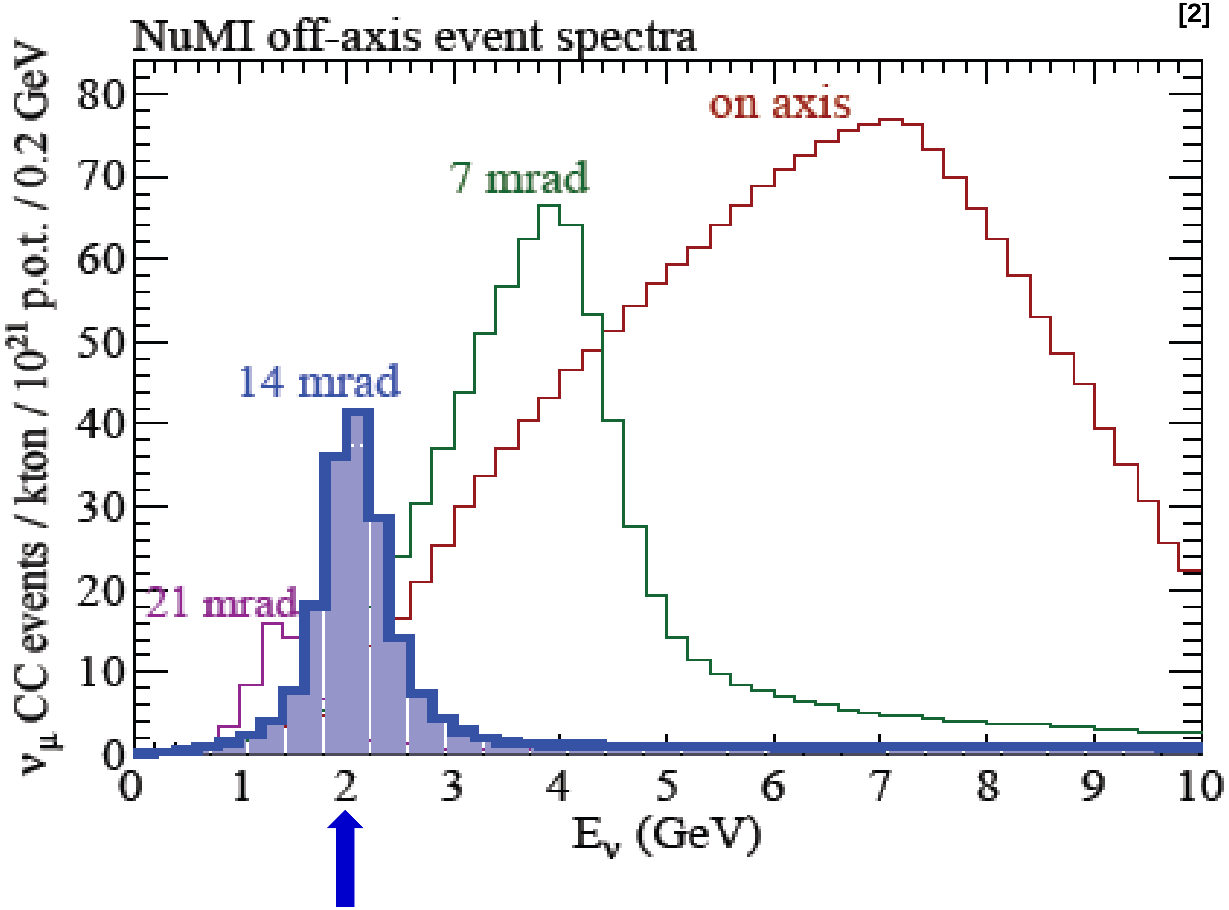
EXPERIMENTAL DESIGN : DETECTOR POSITIONING

- In-flight pion decay: ν flux peaks in forward direction
- But, lab-frame Eπ vs Eν relationship changes with θ

$$\mathcal{F} = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}, \quad E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

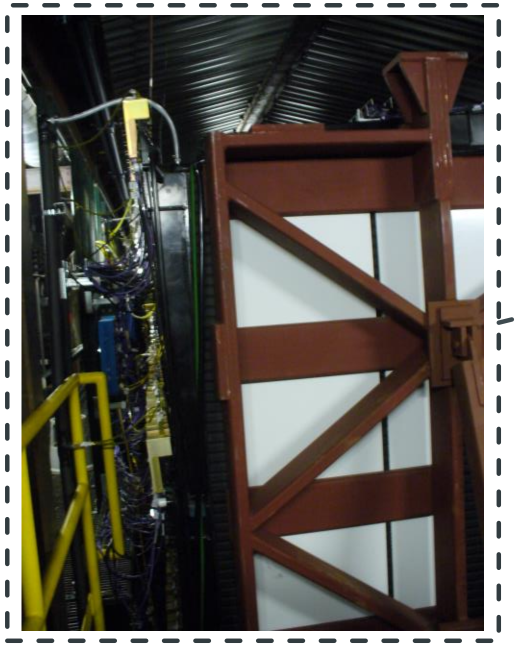
- See nearly mono-energetic ν_μ beam by placing detector slightly off-axis
  - Total ν flux lower than on-axis
  - But, much higher ν fraction in target energy range

[2]

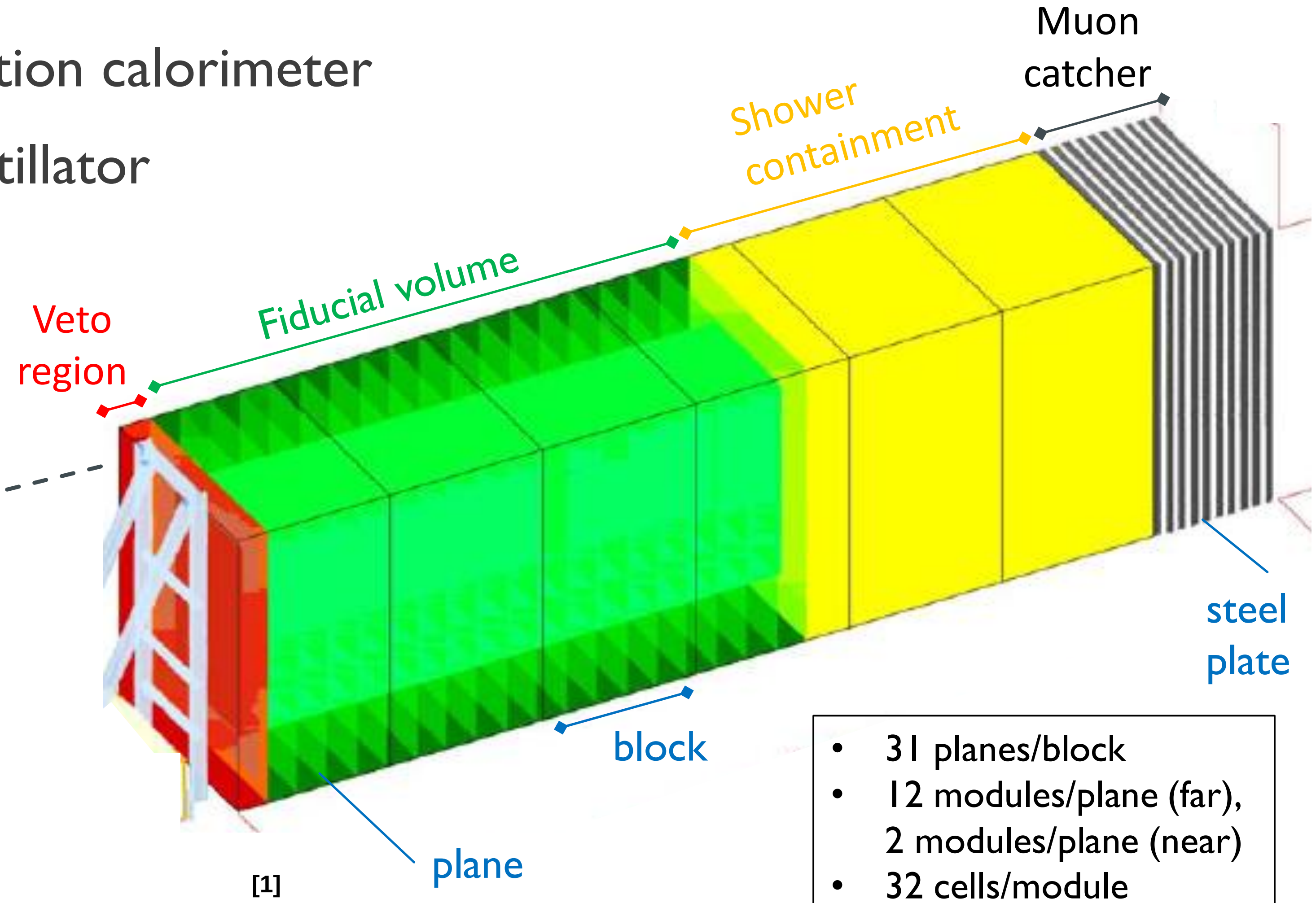


EXPERIMENTAL DESIGN : DETECTOR CONSTRUCTION

- Acts as tracker *and* total absorption calorimeter
- 80% detector mass is active scintillator



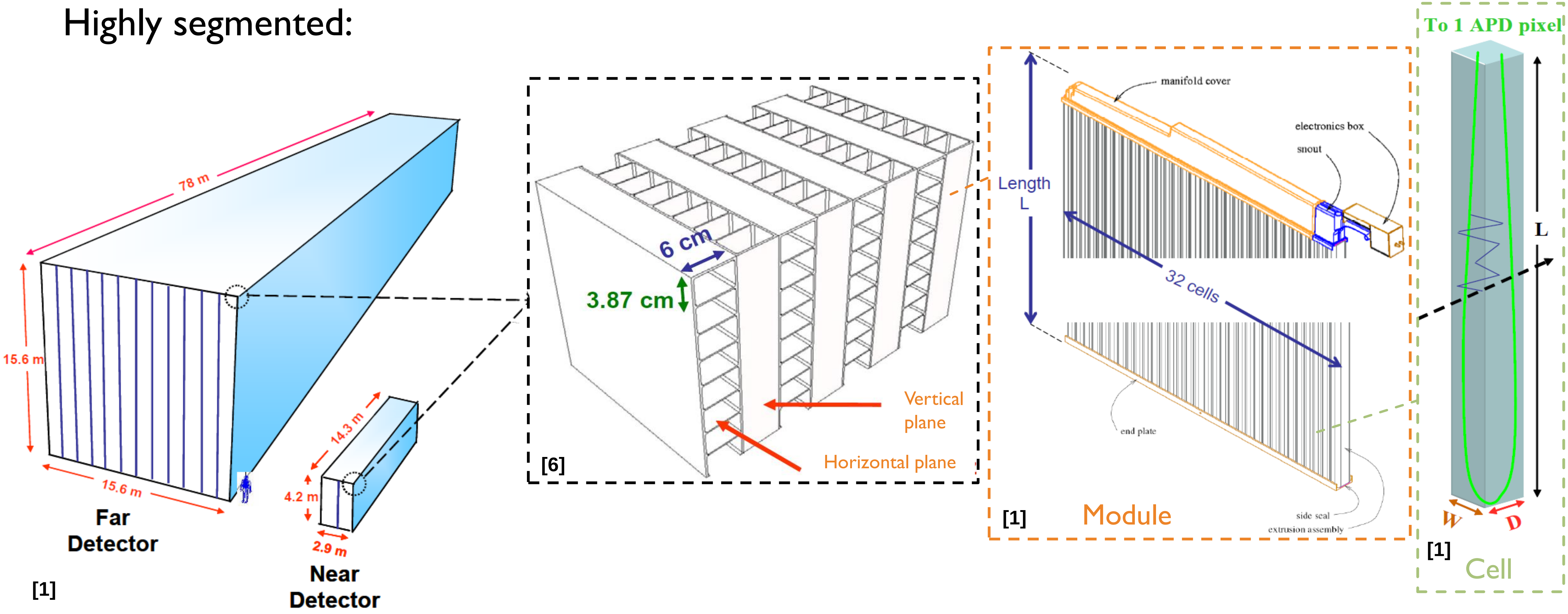
(My photo of Near-detector)



- 31 planes/block
- 12 modules/plane (far), 2 modules/plane (near)
- 32 cells/module

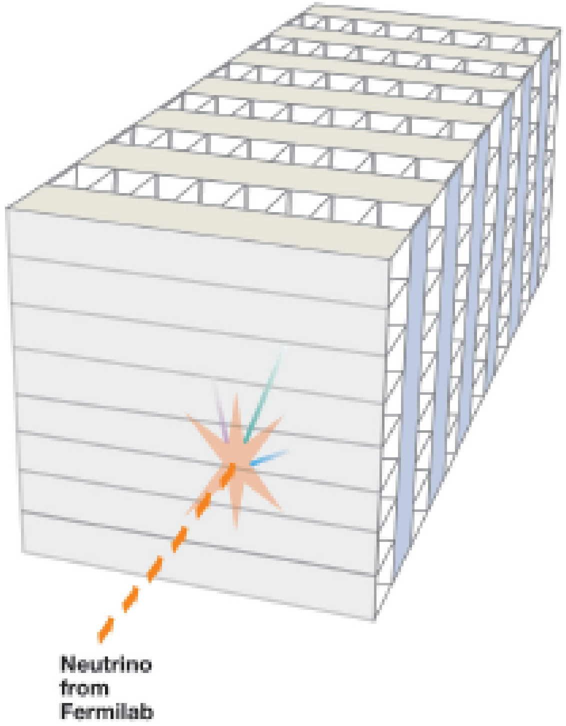
EXPERIMENTAL DESIGN : DETECTOR CONSTRUCTION

Highly segmented:

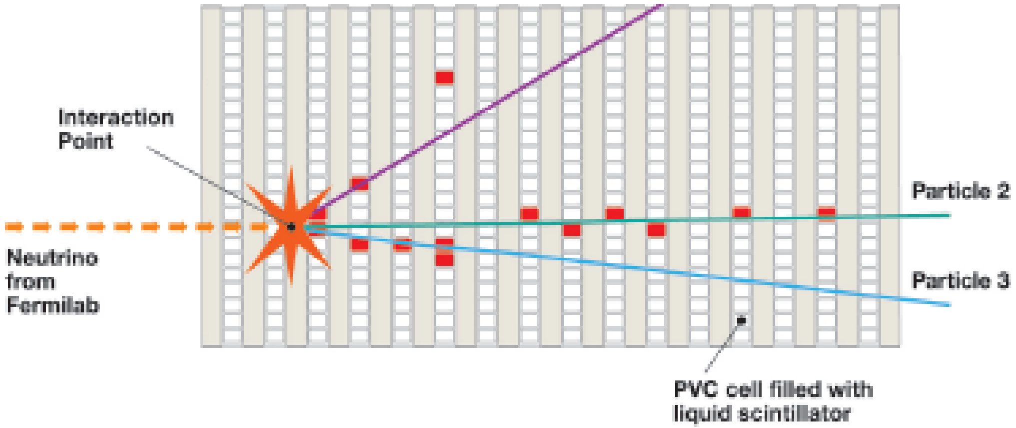


EXPERIMENTAL DESIGN : DETECTOR CONSTRUCTION

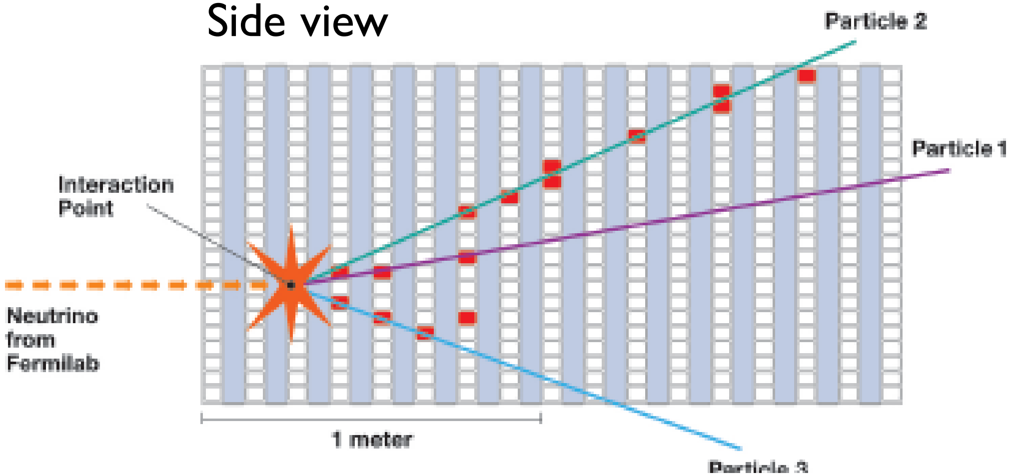
3D schematic of
NOvA particle detector



Top view



Side view

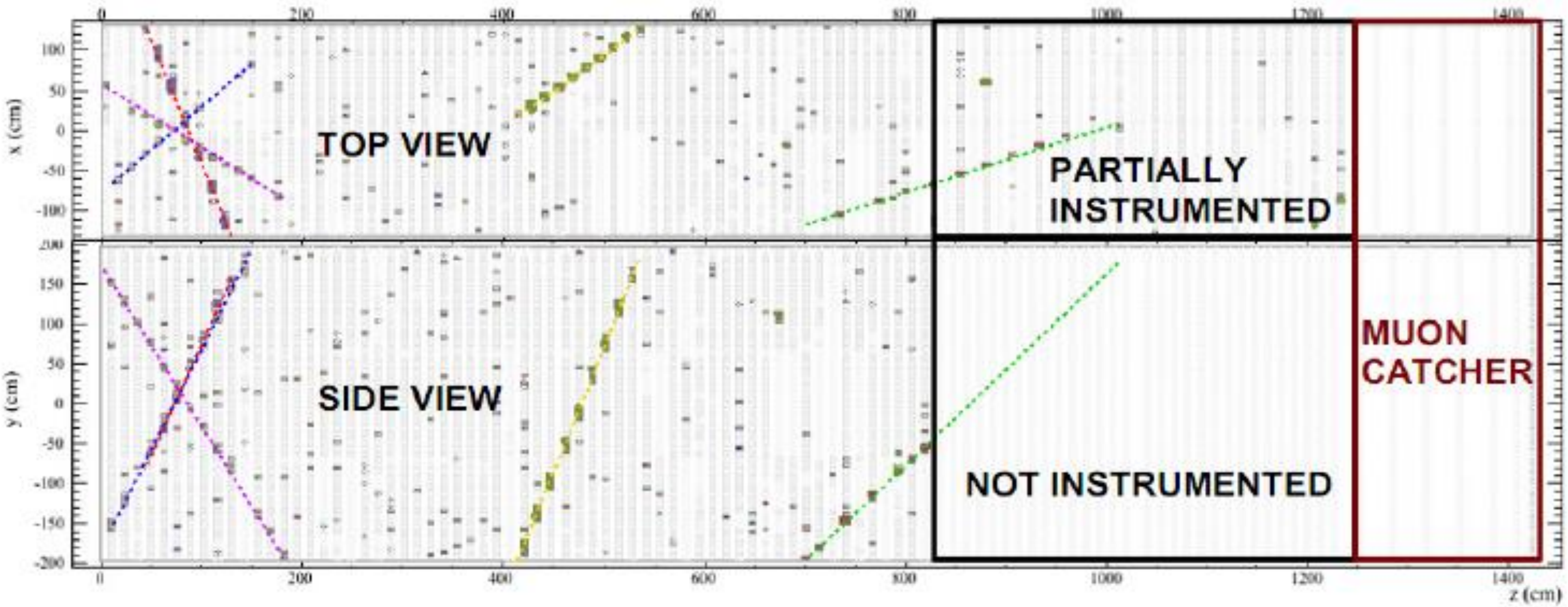


[4]

EXPERIMENTAL DESIGN : PROTOTYPE DETECTOR

- Near Detector on the Surface (NDOS) : installation completed May 2011
- Full-scale detector assembly & integration tests, electronics & DAQ development, calibration R&D, simulation tuning, early analysis R&D, etc.

Has recorded hundreds of ν interactions from NuMI, millions from cosmic rays



[2]

SUMMARY

- NOvA uses ν_μ ($\overline{\nu}_\mu$) beam, Near-detector, and Far-detector to measure $\nu_\mu \rightarrow \nu_e$ ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)
  - 700 kW beam from Fermilab
  - Off-axis, highly-segmented liquid scintillator detectors separated by ~800 km
  - Optimized for neutrino energies at the oscillation max (~2 GeV)
  - Capable of tracking + calorimetry, to meet demanding signal-to-background requirements
- Main measurement program: θ_{13} , δ , hierarchy determination
- Will also contribute to θ_{23} , $|\Delta m^2_{23}|$, ν_s measurements
- Prototype detector operational since mid-2011, full setup running since mid-October
- ~6 yrs running time expected to greatly enhance our understanding of the neutrino sector's unsolved mysteries

REFERENCES

[1] The NOνA Collaboration. NOνA Technical Design Report. Oct 2007.

[2] Davies, Gavin. NOνA: Present and Future. Proceedings of the DPF-2011 Conference, Providence, RI. Oct 2011. arXiv:1110.0112 [hep-ex]

[3] Patterson, R.B. The NOνA Experiment: Status and Outlook. Nuclear Physics B Proceedings Supplement – Preprint. Sept 2012. arXiv:1209.0716 [hep-ex]

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[5] PDG 2012.

[6] The NOνA Collaboration. Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\nu_\mu \rightarrow \nu_e$ Oscillations in the NuMI Beamline. March 2005.

[7] Hartnell, Jeff. NOνA: Exploring Neutrino and Antineutrino Oscillations. Workshop on Baryon and Lepton Number Violation 2013. April 2013.

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http://www.fnal.gov/pub/today/ Oct 31

Ghostbuster team finds ghostly neutrinos in Batavia

Ghostly neutrinos are more difficult to capture than ghosts, but the famed ghostbusting crew of New York City managed to get the job done — and then some.

"It is all about good karma," Venkman said, and he encourages particle physicists, in particular, to "start thinking outside the box."

On a hunch that short- and long-baseline experiments might not be adequate for finding ghostly neutrinos, Fermilab management went retro earlier this year and hired the original Ghostbuster team to carry out its own independent, unimpeded search for the elusive particles.

The gamble paid off. At a pre-Halloween press conference earlier this week, members of Fermilab management and the Ghostbusters team announced finding neutrinos along the neutrino beamline in complex 80sGB, a special undisclosed Fermilab facility built just for the New York-based team.

"We got slimed, as we knew we would," said senior ghostbuster Peter Venkman. "But we found them, and we are not telling how. It was so &%#@& scary!"

In addition to bagging the neutrinos, Venkman's team also reviewed earlier Fermilab neutrino experiment protocols. Venkman said there were major flaws in the way the experiments were conducted and the data made public.

"The problem with one of the older experiments was that the team gave too much away," Venkman said. "They were too loose and mouthed off to other scientists. That is not the way do science, let alone go after neutrinos."

Despite his team's refusal to disclose details and data, Venkman said his team's experiment will be both reproducible and disprovable.

"That smarty pants Karl Popper would be a-ok with our research. It is Karl Popper, right?" he publicly surmised. "Or was it Carl Yaz who came up with the test?"

Fermilab confirms that the Ghostbuster experiment's results will be published in a January issue of *Nature* and its antiresults in *Science* that same month.

Venkman said being down "in the neutrino beam area with all that gooey stuff and then seeing the ghostly neutrinos was scary beyond words."

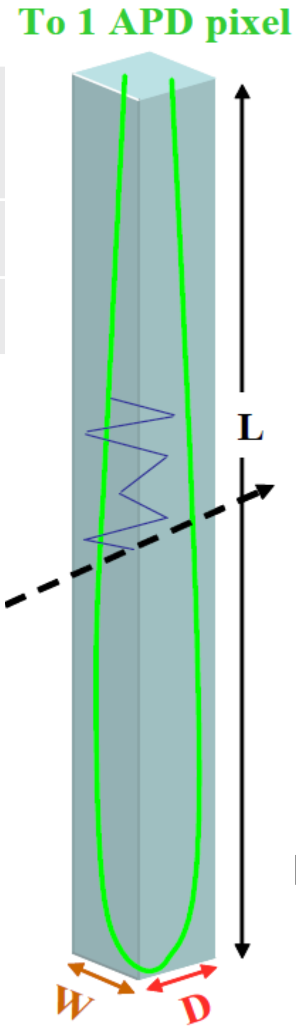
He added that he is very proud of his team's good work.

BACKUP

EXPERIMENTAL DESIGN : DETECTOR CONSTRUCTION

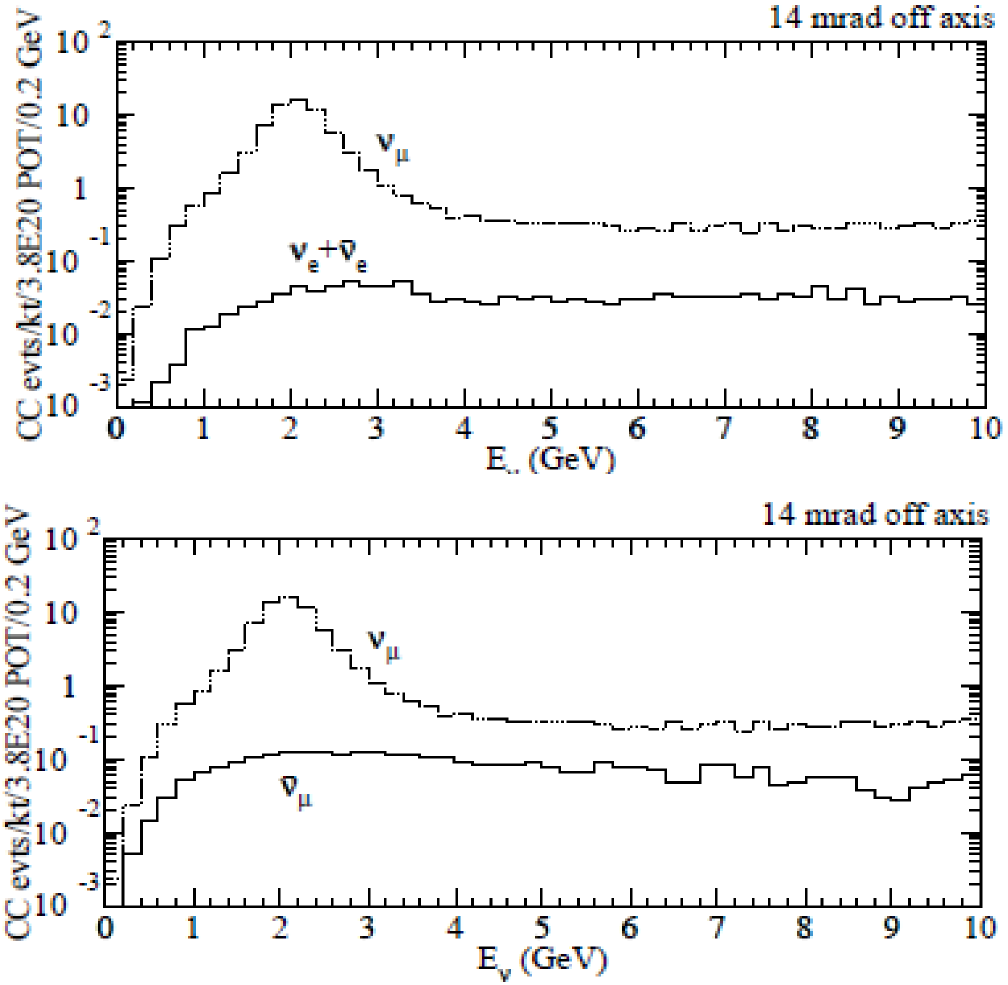
- Each cell has
  - Titanium dioxide-loaded PVC shell
  - Liquid scintillator: mineral oil + 4.1% pseudocumene [1,2,4-Trimethybenzene]
  - Wavelength-shifting fiber loop
- Charged particles produce scintillator light
- Fiber carries captured scintillator light to pixel on Avalanche Photodiode Array → electronic pulse
- Charged-particle energy of event = sum of all cell pulse heights

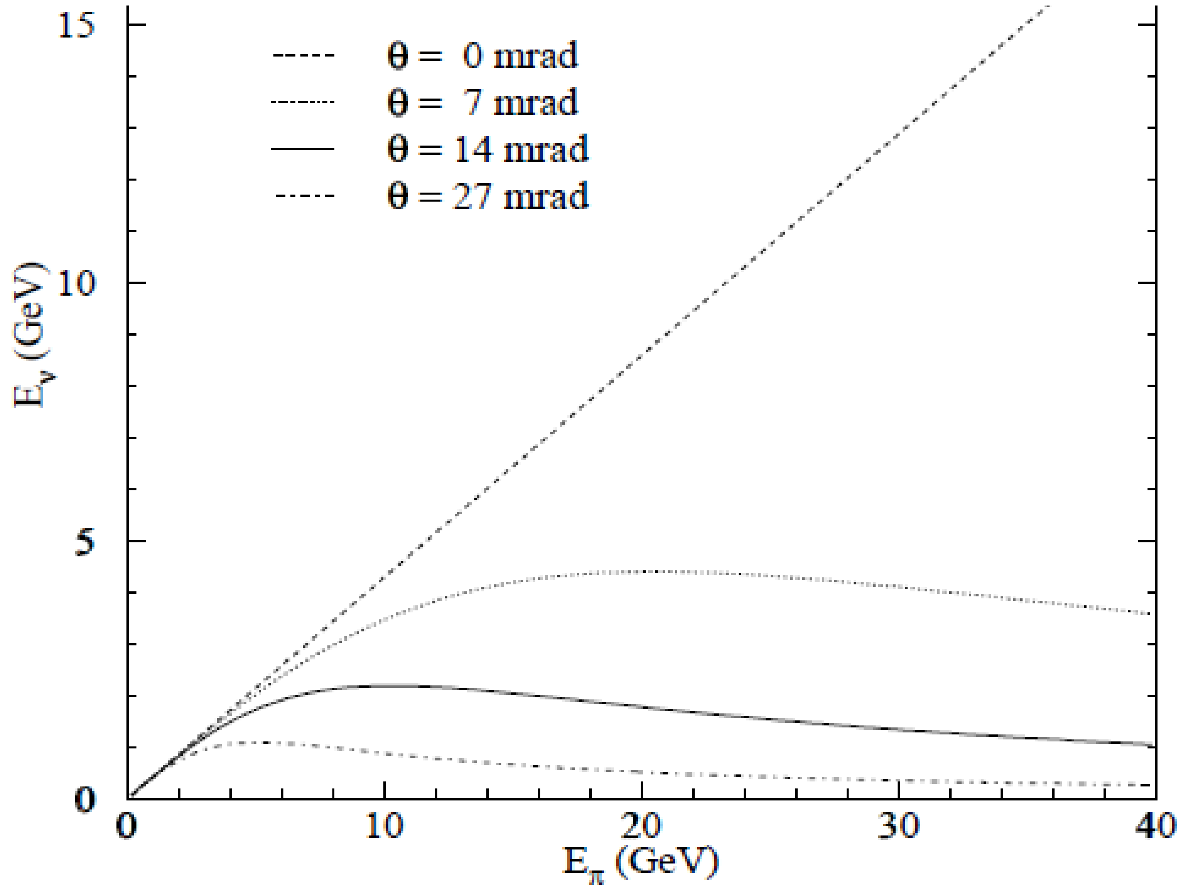
L	4.2 m 15.7 m
W	3.9 cm
D	6.0 cm



[1]

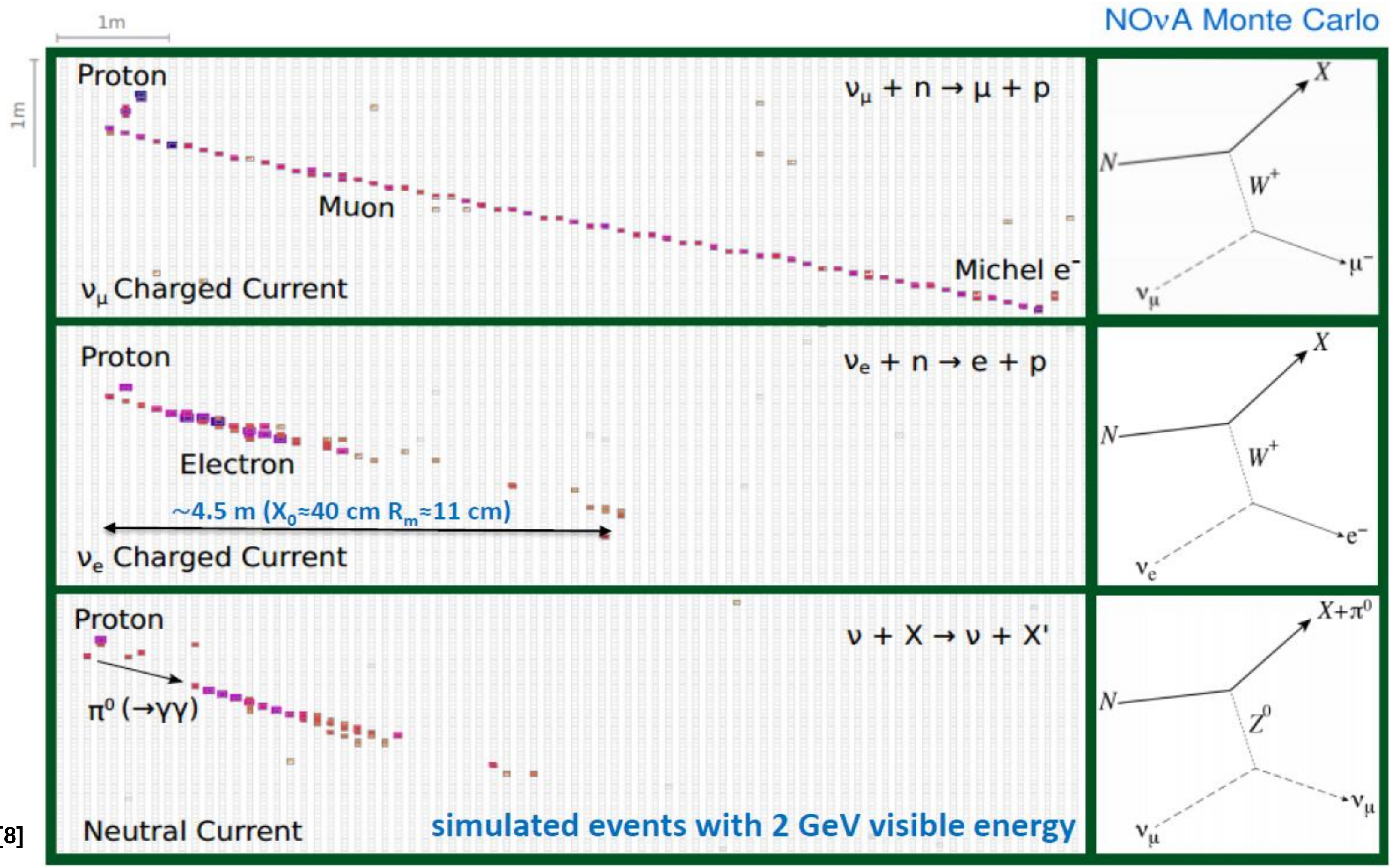
EXPERIMENTAL DESIGN: DETECTOR POSITIONING





EXPERIMENTAL DESIGN : EVENT RECONSTRUCTION

- μ: long, straight path
- π decay: gap between ν interaction and γ conversion
- Proton: distinct dE/dx profile
- EM showers: high detector granularity allows easy identification



[8]