First oscillation results from NOνA

Physics In Collision – University of Warwick
September 18, 2015

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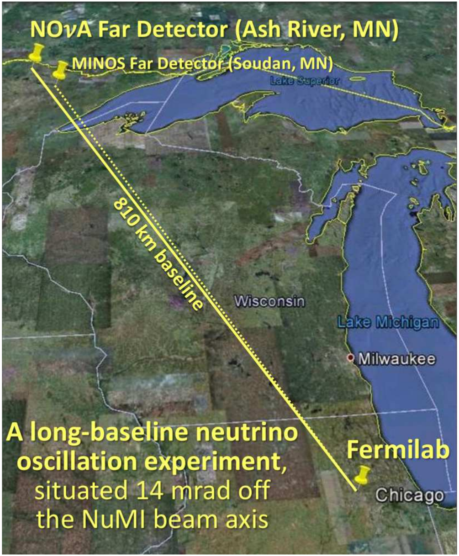
Caltech

for the NOνA Collaboration

NOνA physics goals

$\nu_\mu \to \nu_e$

- Measure θ_{13} via ν_e appearance



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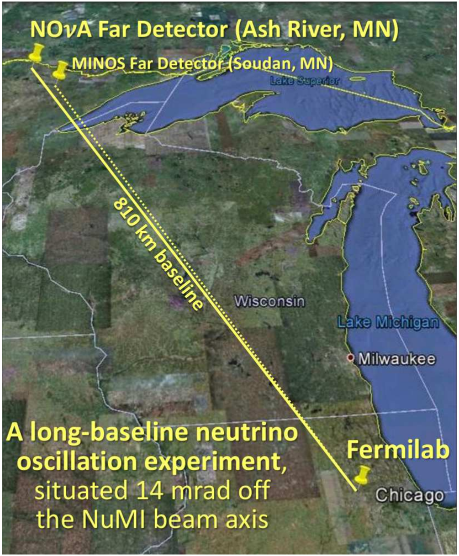
- Could exclude maximal mixing



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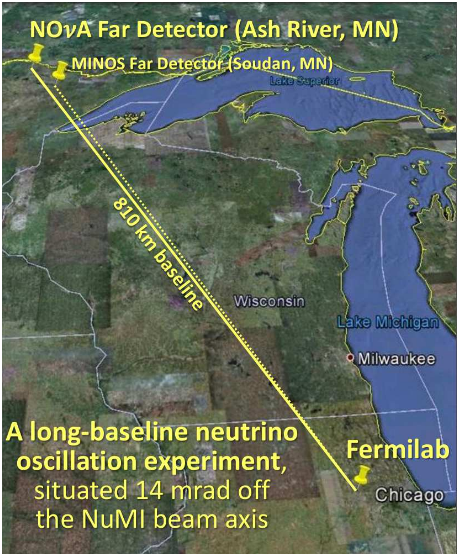

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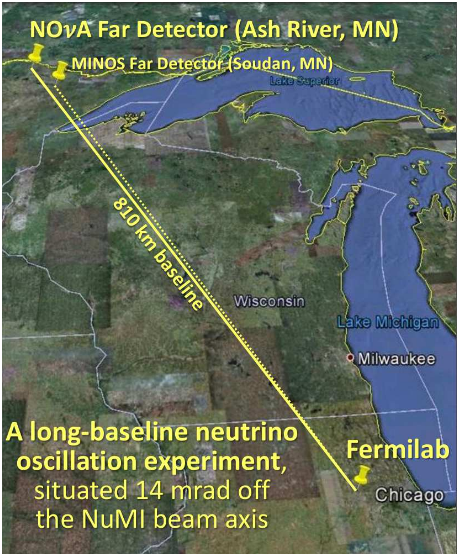

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- Search for $\delta_{CP} \neq 0$

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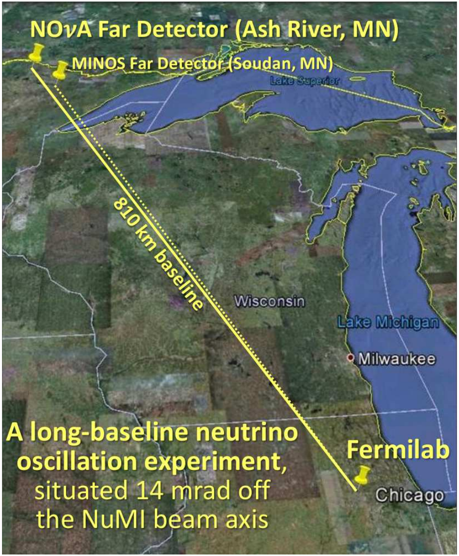

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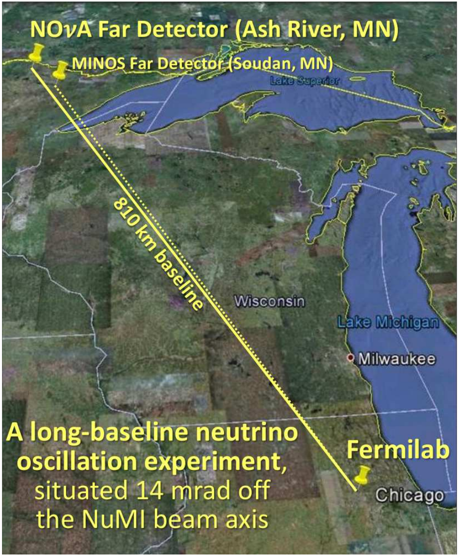
And...

- Cross-sections from the ND
- Steriles, supernovae, exotica



The NOνA collaboration

40 institutions, 7 countries, over 200 collaborators

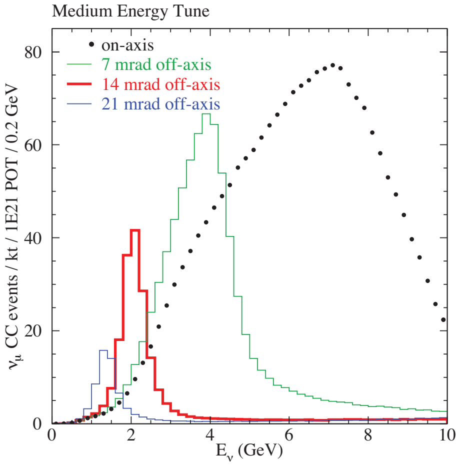
Argonne, Athens, Banaras Hindu, Caltech, CUSAT, Czech Academy of Sciences, Charles, Cincinnati, Colorado State, Czech Technical University, Delhi, Dubna, Fermilab, Goias, IIT-Guwahati, Harvard, IIT-Hyderabad, Hyderabad, Indiana, Iowa State, Jammu, Lebedev Physical Institute, UCL, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, SDMT, South Carolina, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, Virginia, Wichita State, William and Mary, Winona State.

Accelerator and NuMI upgrades

- 14mrad off-axis location gives sharply-peaked 2GeV ν_μ beam with $\sim 1\%$ ν_e contamination

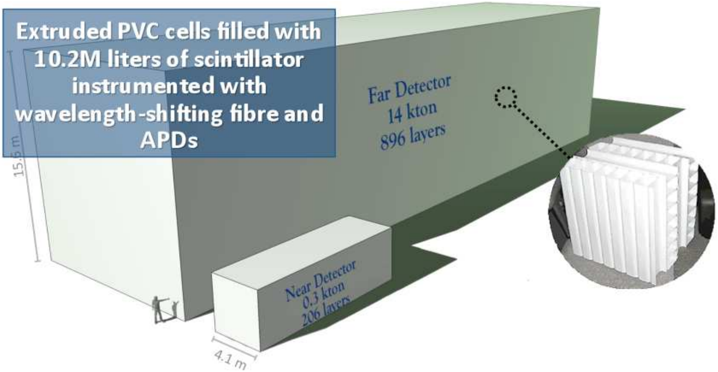
- NuMI beam routinely operated at 400kW with 85% uptime.
- Peak intensity 520kW

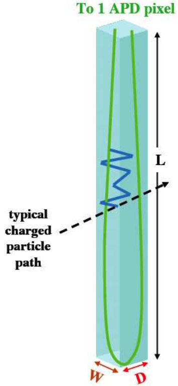
- Using data from Feb 16 2014 to May 15 2015 with detector still under construction
- Total of 3.45×10^{20} POT
- Equivalent of 2.74×10^{20} POT with full 14kt detector



14mrad off-axis beam peaks sharply at 2GeV

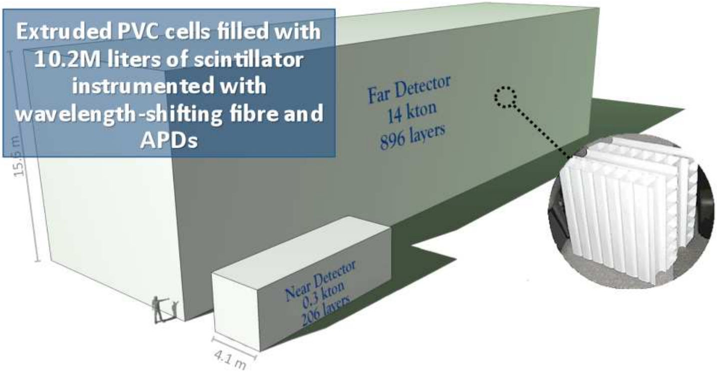
Detector technology

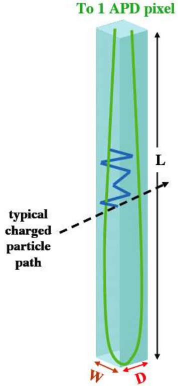




- Fine-grained low-Z, highly active, tracking calorimeter
- 64% liquid scintillator by mass
- WLS fibres looped in 4x6cm cells of PVC extrusion
- Each to one of 32 pixels of Hamamatsu APD
- ~85% quantum eff. Gain ~100×. Cooled to −15°C

Detector technology





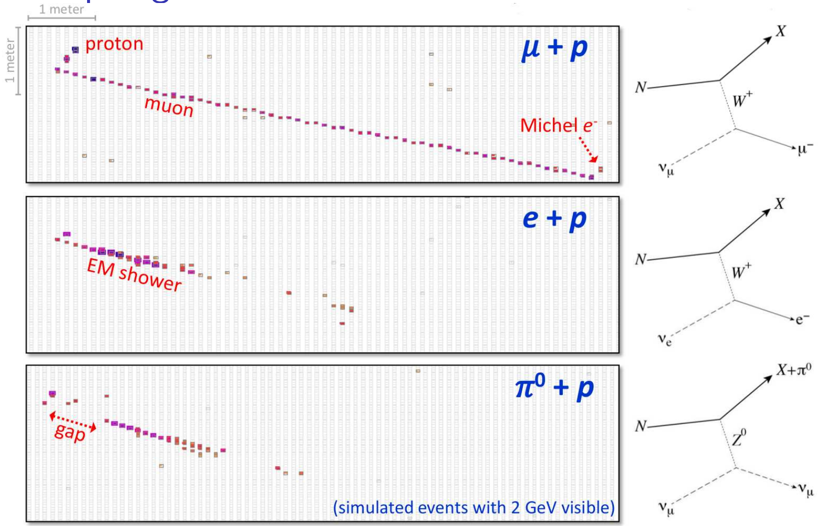
Far Detector

- 14 kton
- 344,000 channels
- On the surface

Near Detector

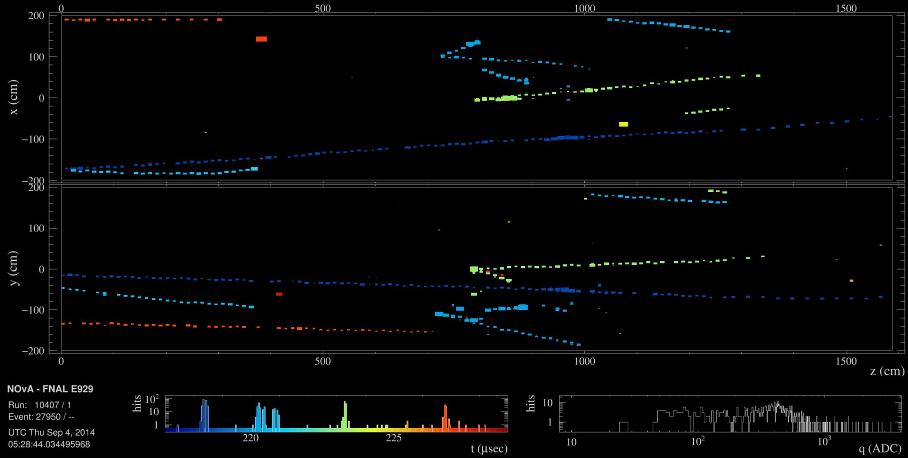
- 0.3 kton
- 18,000 channels

Event topologies



- Very good granularity, especially considering scale
- $X_0 = 38$cm (6 cell depths, 10 cell widths)

ND neutrinos



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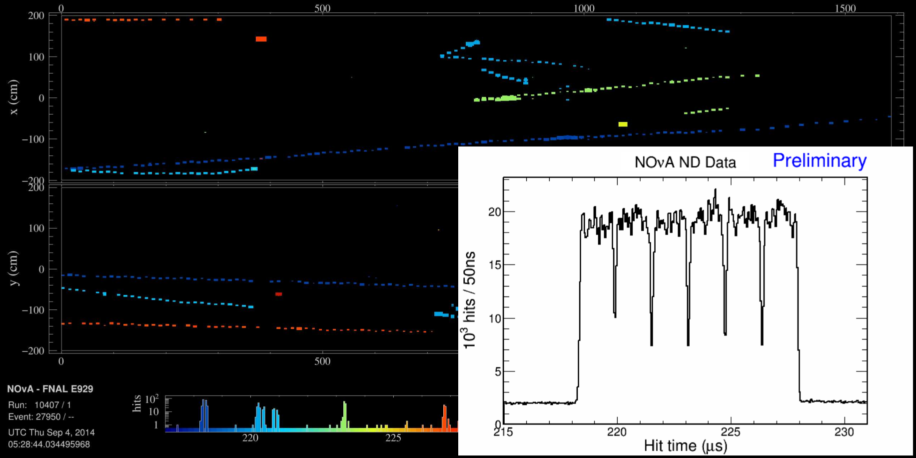
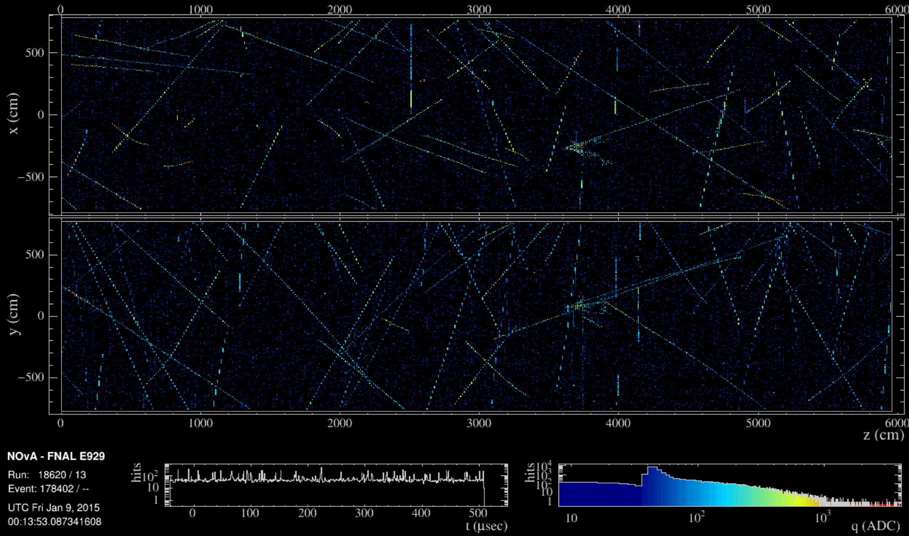


FD neutrino search



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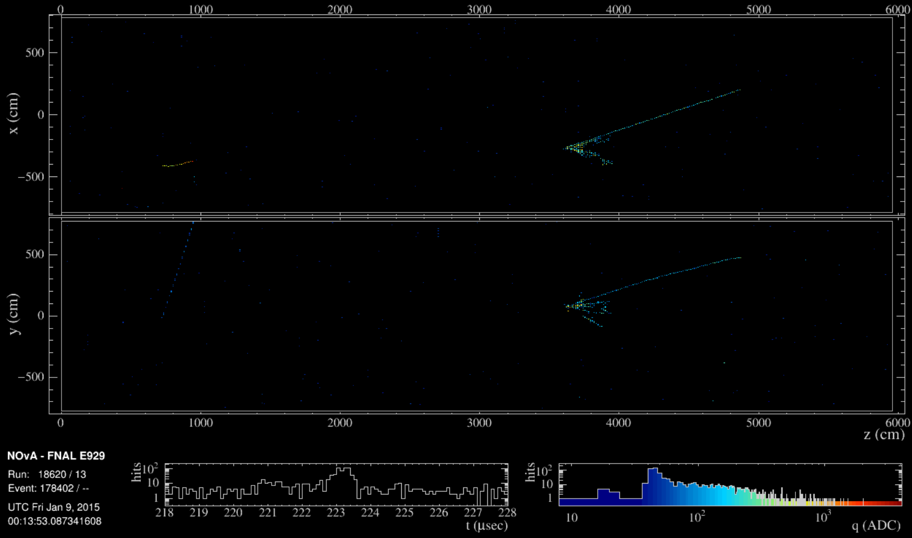

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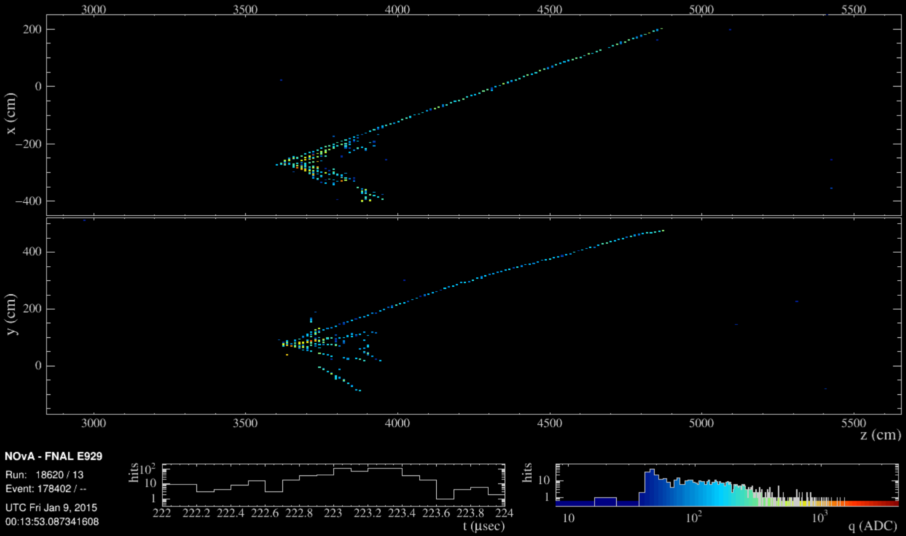
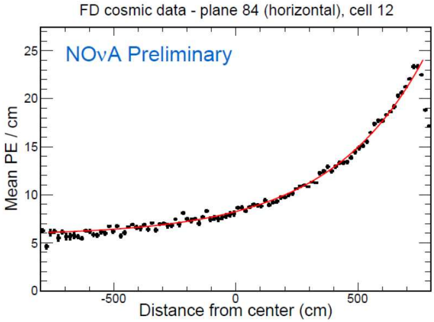


Calibration and energy scale

- Channel-to-channel and attenuation calibration with cosmic muons
- Absolute energy scale uses stopping muons as a standard candle
- Multiple calibration cross-checks
  - Cosmic muon dE/dx
  - Beam muon dE/dx
  - Michel energy spectrum
  - π^0 mass peak
  - Hadronic energy/hit



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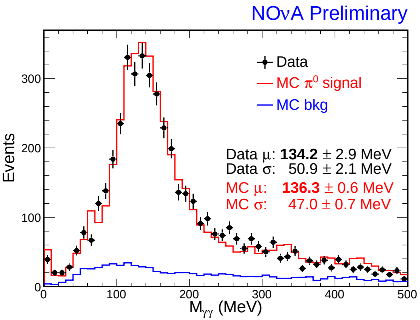
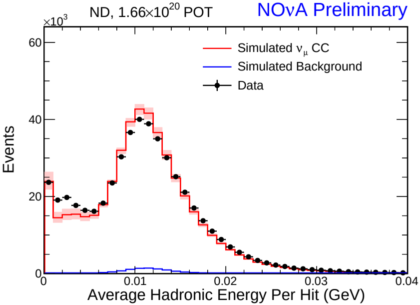
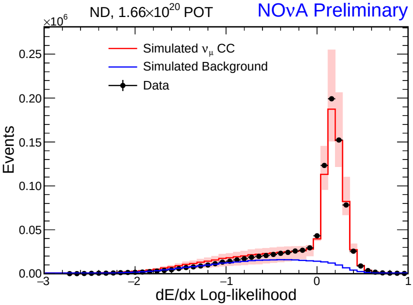
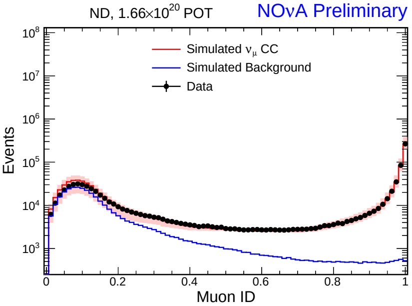




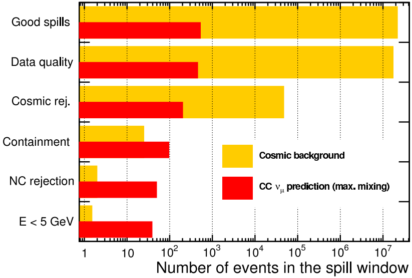
Selecting muon neutrinos

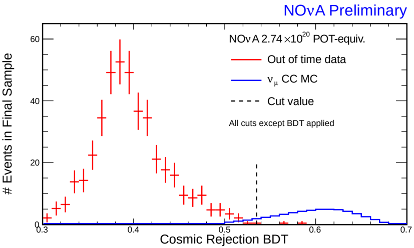
- Basic containment cuts requiring no activity close to detector walls
- kNN-based ν_μ classifier using 4 inputs
  - Track length
  - dE/dx
  - Scattering
  - Fraction of planes that have track-only
- Selection 70% efficient for ν_μ signal, 2% for NC background





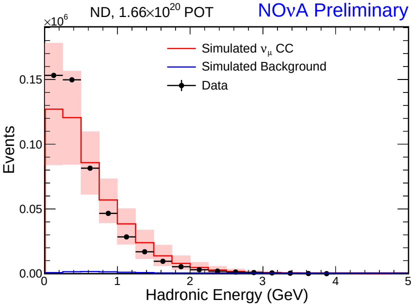
Cosmic rejection for ν_μ analysis





- Cosmic background rate measured from data adjacent in time to the beam spill window
- 10μs spill window at $\sim$ 1Hz gives 10^5 rejection
- Additional factor 10^7 from event topology plus boosted decision tree based on
  - Track direction
  - Track start and end points
  - Track length
  - Energy
  - Number of hits

Muon neutrino energy reconstruction



- Good data/MC agreement for muon neutrino selected events
- But, 21% more energy in MC hadronic system compared to data
- Recalibrate to make neutrino energy peak match
- Take the entire shift as a systematic $\rightarrow$ 6% neutrino energy scale uncertainty

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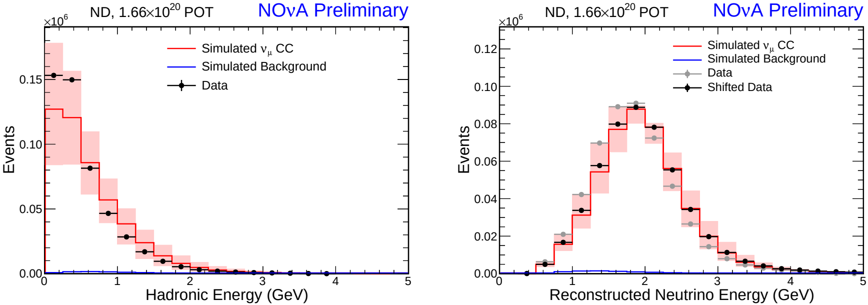

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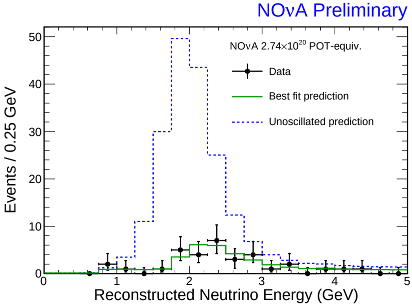
- Use ND data to predict FD neutrino spectrum

ν_μ disappearance results

- Expect 201 events w/o oscillations
- We observe 33 events



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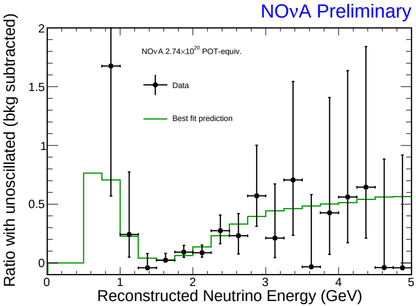

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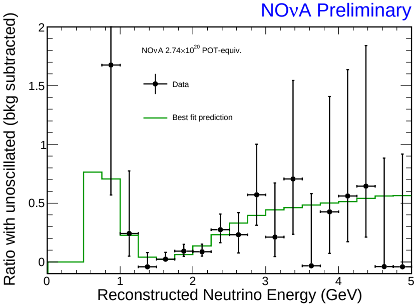
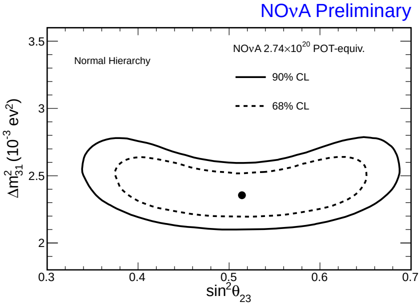
- $\Delta m^2_{32} = +2.37^{+0.16}_{-0.15}$ or $-2.40^{+0.14}_{-0.17}$
- $\sin^2\theta_{23} = 0.51 \pm 0.10$





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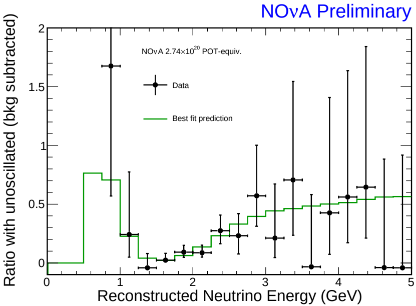
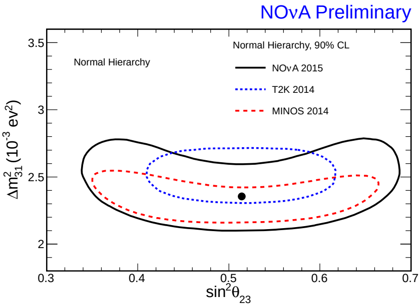
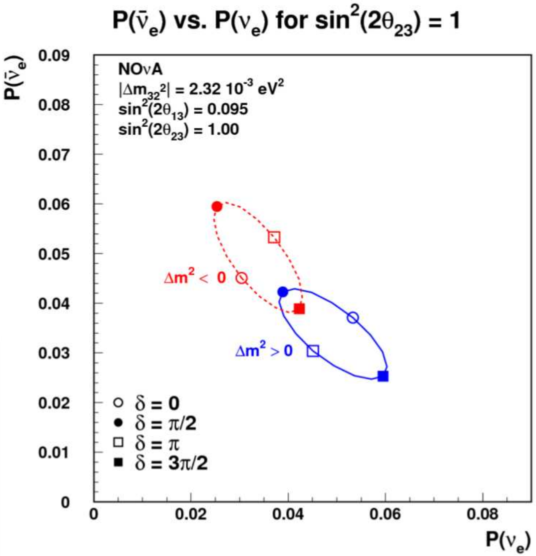
- Very competitive with $\sim 8\%$ of nominal exposure





Principle of the ν_e measurement

- To first order, NOνA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ evaluated at 2GeV
- These depend differently on sign(Δm^2) and δ_{CP}



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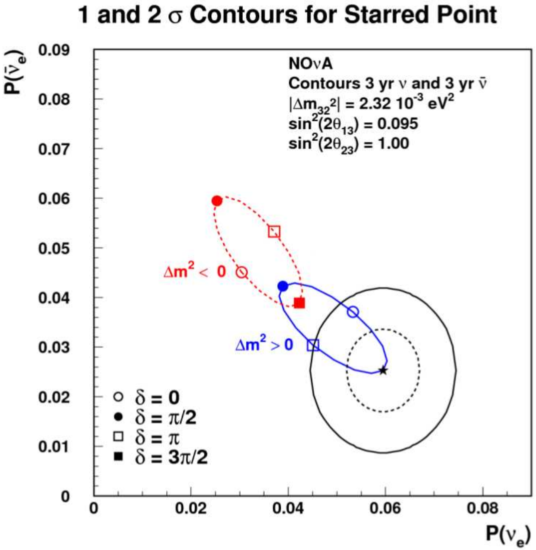
- Ultimately constrain to some region of this space



Selecting electron neutrinos

- Two ν_e classifiers developed based on very different techniques

- **LID** Uses PDFs of leading shower longitudinal and transverse profiles

- **LEM** Finds best matches in a Monte Carlo library based on entire event topology

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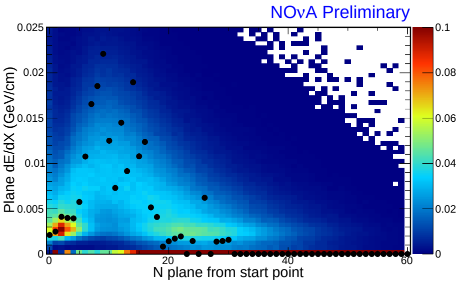

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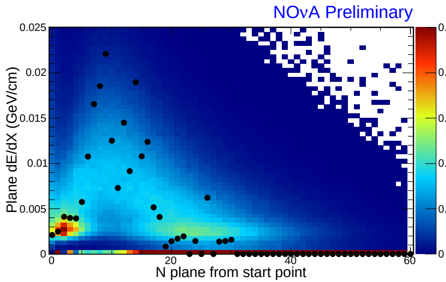

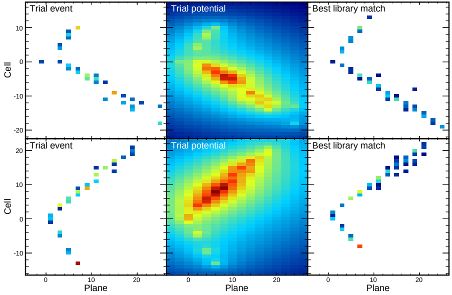

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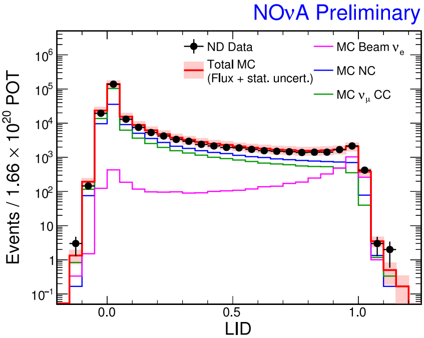

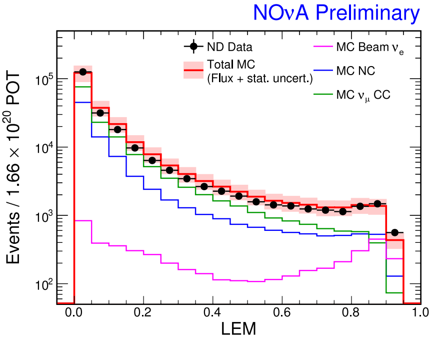

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- Identical performance. 35% signal efficiency, 0.7% NC events remain. 62% expected overlap between samples

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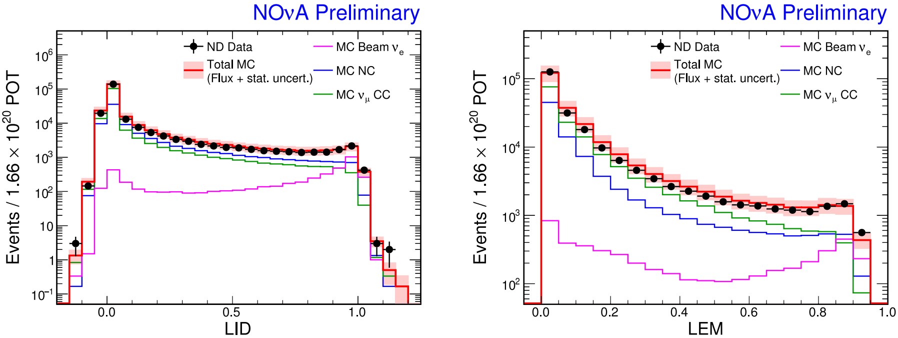

- Good separation of signal from background, including cosmic backgrounds
- Identical performance. 35% signal efficiency, 0.7% NC events remain. 62% expected overlap between samples
- **Before unblinding FD data, decided to show both results and use LID as the primary selector**

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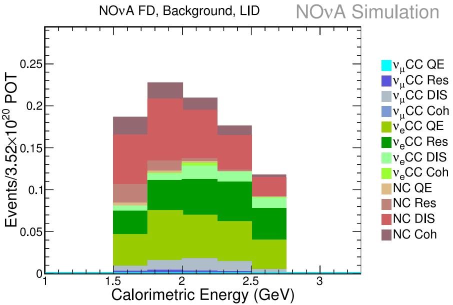

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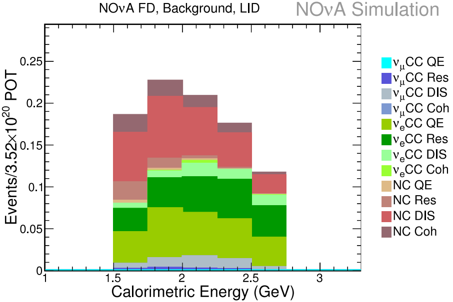
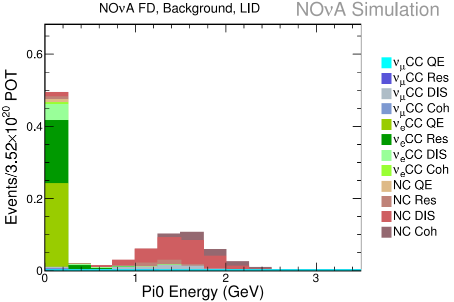
Selecting electron neutrinos





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- ~ 1.5GeV π^0 in most NCs

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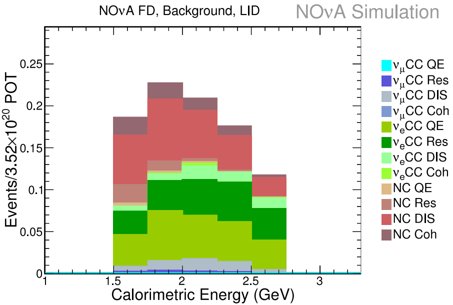
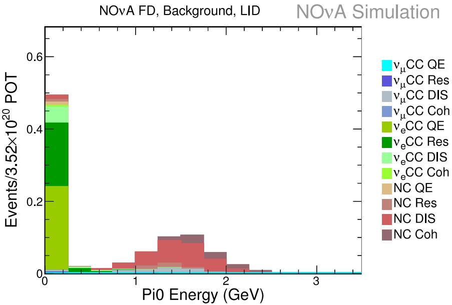
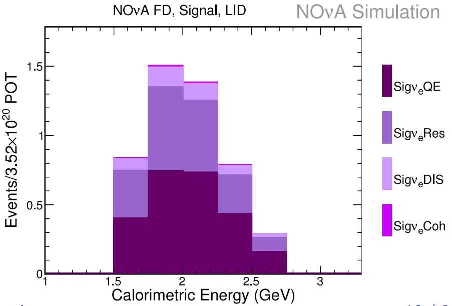


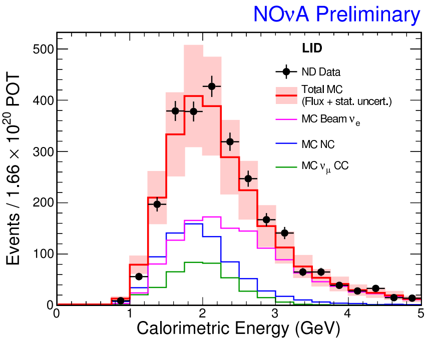


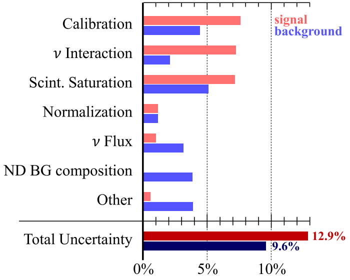
- Selected FD background dominated by NC DIS and intrinsic beam ν_e contamination
- ~ 1.5GeV π^0 in most NCs
- Signal dominated by QE and RES, minimal impact dependence on hadronic system



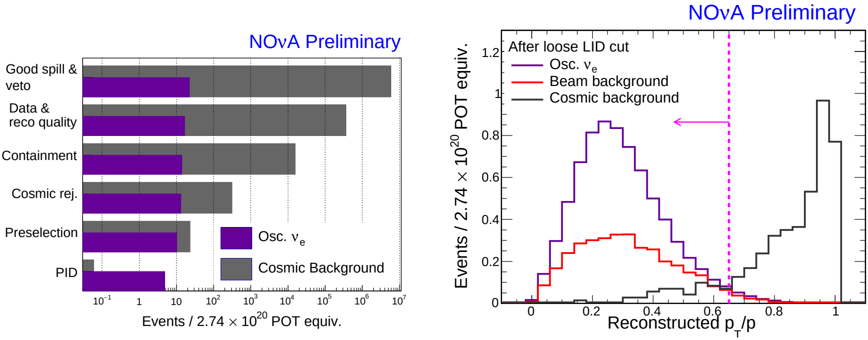
FD prediction

- Good data/MC agreement for ND energy spectrum
- Extrapolate 5% ND data background excess bin-by-bin to FD using Far/Near ratio
- FD signal expectation uses the same procedure and ND ν_μ spectrum as the disappearance analysis
- Most systematics assessed by modifying the Near and Far MC and calculating the variation in the prediction





Cosmic rejection for ν_e analysis



- Containment and topological cuts (*e.g.* p_T/p)
- Classifiers themselves provide remaining rejection
- Achieve 10^8 removal of cosmic rays

- Measure rate using out-of-time spill data as for ν_μ analysis
- Cosmic background expectation **0.06 events**

Signal and background predictions

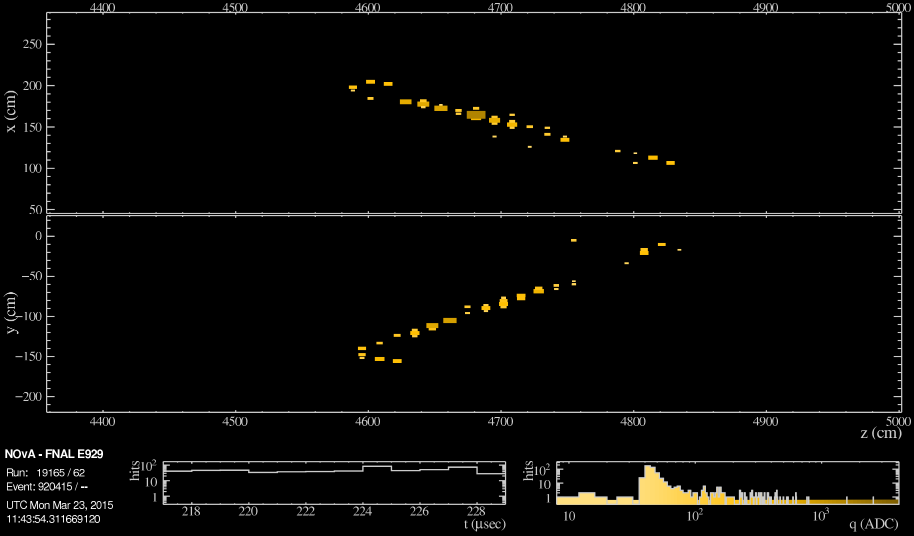
- Background prediction for both selectors is ~ 1 event $\pm 10\%$ (syst)
- Few percent dependence on oscillation parameters
- Dominated by beam ν_e and NC
- Cosmic background comparable to smallest beam backgrounds

PID	Total bkg	ν_e CC	NC	ν_μ CC	ν_τ CC	cosmic
LID	0.94 ± 0.09	0.46	0.35	0.05	0.02	0.06
LEM	1.00 ± 0.11	0.46	0.40	0.06	0.02	0.06

- Range of signal predictions
- NH, $\delta_{CP} = 3\pi/2 \rightarrow 6 \pm 0.7$
- IH, $\delta_{CP} = \pi/2 \rightarrow 2 \pm 0.3$

  (for LID, LEM similar)

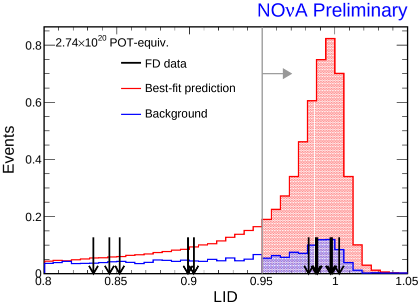
Example selected event

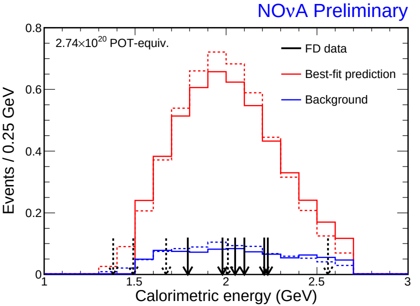


Selected events

- LID selects 6 events and LEM selects 11
- Significance 3.3σ (LID) or 5.5σ (LEM)

- All 6 LID events are also selected by LEM
- p-value for 11=6/5/0 is 9.2%
- NB, low-end energy cut trained differently for LID and LEM

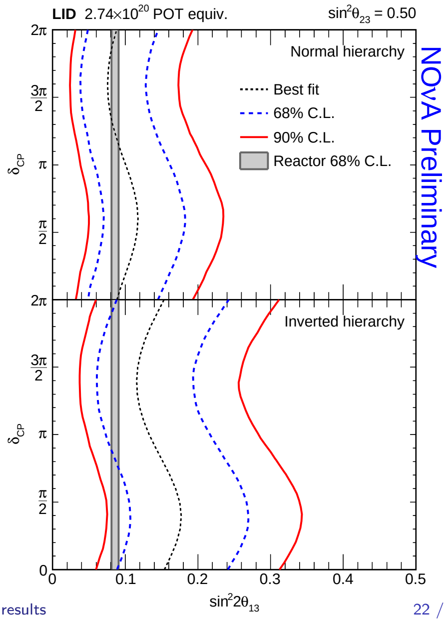




ν_e appearance results

LIDLID (N=6)

- Compatible with reactor constraints
- Slightly better for NH



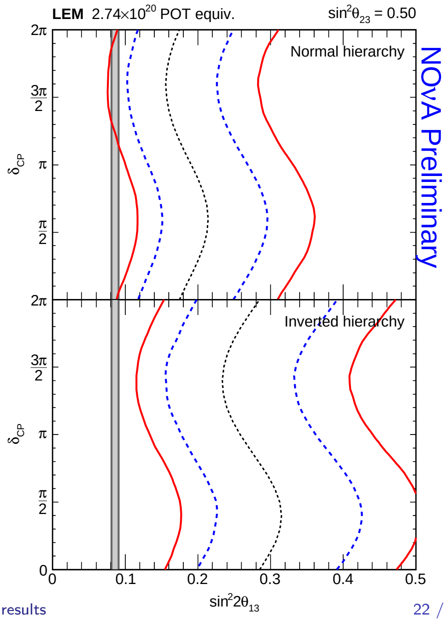
ν_e appearance results

LID (N=6)

- Compatible with reactor constraints
- Slightly better for NH

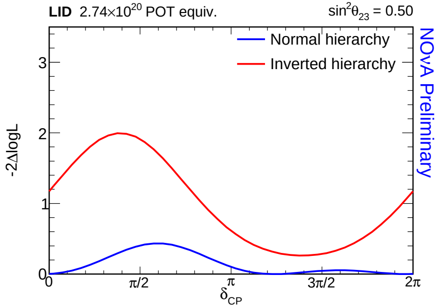
LEM (N=11)

- Curves shifted right $\sim 2\times$
- Increases tension



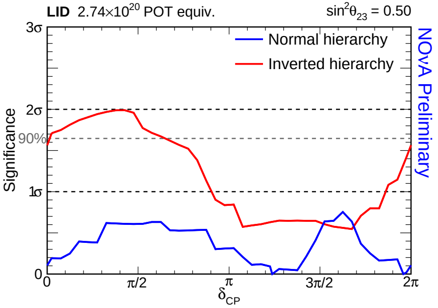
ν_e appearance results

- Include reactor θ_{13} measurement
- Plot compatibility as a function of hierarchy and δ_{CP}



ν_e appearance results

- Include reactor θ_{13} measurement
- Plot compatibility as a function of hierarchy and δ_{CP}
- Deviations from gaussian statistics, discontinuous shape due to discrete set of possible outcomes
- Disfavour IH for $0 < \delta_{CP} < 0.6\pi$ at 90% with primary selector



ν_e appearance results

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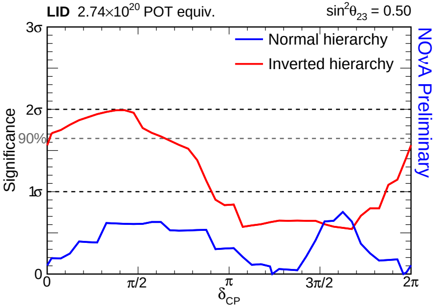

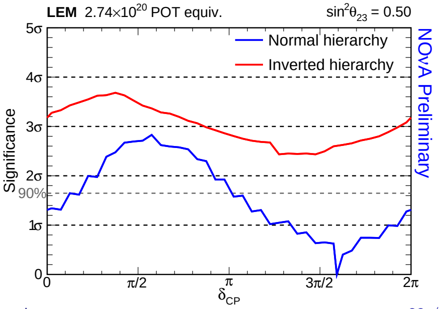

- Both selectors prefer NH, both prefer δ_{CP} near $3\pi/2$
- Disfavour IH, $\delta_{CP} = \pi/2$ at 1.6σ (3.2σ) using LID (LEM) for all $0.4 < \sin^2\theta_{23} < 0.6$

Conclusion

- NOνA has observed muon neutrino disappearance and electron neutrino appearance

- 6.5% measurement of atmospheric mass splitting, θ_{23} consistent with maximal mixing
- ν_e appearance signal at 3.3σ
- Consistent with hints for $\pi < \delta_{CP} < 2\pi$ and NH

- Only $\sim$ 8% of nominal exposure, much more to come
- Stay tuned for next summer!

Find us on twitter/facebook/youtube/instagram

www-nova.fnal.gov

Thank you!

Questions?