THE STATE OF NEUTRINO OSCILLATIONS
THIS YEAR’S NOBEL PRIZE
“for the discovery of neutrino oscillations, which shows that neutrinos have mass”
THE ATMOSPHERIC NEUTRINO ANOMALY

- Deficit first observed by IMB and Kamiokande, water based experiments. Experiments were designed for proton decay.

- A perfect example that having more than one experiment is very desirable.

- SuperK (lead by Kajita) observes the smoking gun for neutrino oscillations.
THE SOLAR NEUTRINO PROBLEM

• In the early 1960s Davis and Bahcall argued for a CL detector for solar neutrinos.

• In 1968 Davis (2002 Nobel Prize) publishes the first results indicating that only 1/3 of the neutrinos were observed, i.e. the solar neutrino problem.

• The SNO experiment (lead by McDonald) announces in 1999 that oscillations explains the solar neutrino problem.

Ray Davis (1971)
NEUTRINO OSCILLATIONS

• Three flavor eigenstates are linear combinations of the mass eigenstates:

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

• There is thus a non-zero probability of detecting a different neutrino flavor than that produced at the source:

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2
\]

• The probability depends on the distance traveled and energy (experimental parameters) as well as the mixing amplitudes and the difference of the square of the masses (Nature’s parameters).
NEUTRINO OSCILLATIONS

Three flavor eigenstates are linear combinations of the mass eigenstates:

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

Where the mixing matrix has 3 mixing angles and one phase (ignoring Majorana):

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

- The (12) sector: Solar + Reactor, L/E 15,000 km/GeV
- The (23) sector: Atmospheric and Accelerator, L/E 500 km/GeV
- The (13) sector: Reactor and Accelerator, L/E 500 km/GeV
NEUTRINO OSCILLATIONS

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

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\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

- For non-zero \(\sin^2 2\theta_{13}\) we can access \(\delta_{CP}\) which might be a key to the matter anti-matter asymmetry of the universe.

- Precision measurements of neutrino oscillations might reveal new physics.
Two mass scales:
- The “atmospheric” mass scale: $\Delta m_{32}^2$
- The “solar” mass scale: $\Delta m_{21}^2$

Large mixing angle for atmospheric neutrino oscillations.

Solar neutrino oscillations are subject to matter effects with a non-maximal mixing angle.

Third mixing angle is small and has been measured.

CP violation in the lepton sector has NOT been measured.

Mass ordering is NOT known for atmospheric neutrinos but known for the solar mass scale.

The octant of the large mixing angle is NOT known!

EXPERIMENTAL PICTURE EVOLVING QUICKLY!
NEUTRINOS MASSES AND MIXING

How well are these measured?

• Global analysis presented by A. Marrone at TAUP 2015 (before NOvA results).
• This analysis combines the World’s data from solar, reactor, atmospheric and long baseline neutrinos.

Accuracy (2014):
\[ \delta m^2 \quad 2.6 \% \]
\[ \Delta m^2 \quad 2.6 \% \]
\[ \sin^2 \theta_{12} \quad 5.4 \% \]
\[ \sin^2 \theta_{13} \quad 5.8 \% \]
\[ \sin^2 \theta_{23} \quad \sim 10 \% \]

EXPERIMENTAL PICTURE EVOLVING QUICKLY!
THE NOVA EXPERIMENT
The NOVA Collaboration

40 Institutions from 7 countries
over 200 collaborators

Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University · Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Indian Institute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · Iowa State University · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · College of William and Mary

Mayly Sanchez - ISU
THE NOVA EXPERIMENT IN A NUTSHELL

• Upgrade existing high intensity NuMI beam of muon neutrinos at Fermilab from 350 to 700kW.

• Construct a highly active liquid scintillator 14-kton detector off the main axis of the beam.

• If neutrinos oscillate, muon neutrinos disappear as they travel and electron neutrinos appear at the Far Detector in Ash River, 810 km away.

2nd generation

long baseline

L/E ~ 500 km
THE GOALS OF THE NOVA EXPERIMENT

- Measure the oscillation probabilities of $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ as well as $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$.
- Precision measurements of $\Delta m^2_{32}, \theta_{23}$.
- Determine neutrino mass hierarchy.
- Study the phase parameter for CP violation $\delta_{CP}$.
- Resolution of the $\theta_{23}$ octant.

As well as:
- $\nu$ cross sections and interaction physics.
- Sterile neutrinos.
- Supernovae and monopoles!
PRODUCING NEUTRINOS: NUMI BEAM

- Produce protons in accelerator, shoot them at the target. Produce other particles.
- Horns focus positive pions and kaons which decay into neutrinos.
- Higher energy anti-neutrinos come from very forward negative pions.

Monte Carlo
Neutrino mode
Horns focus $\pi^+, K^+$

Monte Carlo Spectrum
$\nu_\mu$ Spectrum

$\nu_\mu = 91.7\%$
$\bar{\nu}_\mu = 7.0\%$
$\nu_e + \bar{\nu}_e = 1.3\%$

Target
Focusing Horns

120 GeV $p$'s from MI

2 m
15 m
675 m
30 m
THE OFF-AXIS NUMI BEAM

- NOνA detectors are located 14 mrad off the NuMI beam axis.
- With the medium-energy NuMI configuration, it yields a narrow 2-GeV spectrum at the NOνA detectors due to meson decay kinematics:
  \[ E_{\nu} = \frac{1 - (m_\mu/m_\pi)^2}{1 + \gamma^2 \tan^2 \theta} E_\pi \]
- Location reduces NC and νe CC backgrounds in the oscillation analyses while maintaining high νμ flux at 2 GeV.
The Off-Axis NUMI Beam

- In FY15 NuMI beam routinely operated at 400 kW for NOvA.
- Overall uptime: 85%. Peak intensity of 520 kW achieved.
- A total of $3.45 \times 10^{20}$ POT delivered is used for these analyses equivalent to $2.74 \times 10^{20}$ POT with full 14 kton detector.
- Data taken from February 6, 2014 and May 15, 2015 with detector still under construction.
THE NOVA DETECTORS

- 14 kton Far Detector (FD), low-Z, tracking calorimeter.
- 810 km from source, on the surface, 3 m.w.e. overburden.
- 65% active detector mass.
- Largest free standing plastic structure in the world.

- 0.3 kton Near Detector (ND)
  - Functionally identical to the Far.
  - 300 ton, 1 km from source, 100 m depth.
THE NOVA DETECTORS

- PVC extrusion + Liquid Scintillator
  - 11M liters of mineral oil + 5% pseudocumene
- Read out via WLS fiber to 32-pixel APD
  - FD has 344,064 channels
  - ND has 18,000 channels
- muon crossing far end at FD~25 PE
- Layered planes of orthogonal views
- 0.15 $X_0$ per layer, excellent for $e$- identification.

Mayly Sanchez - ISU
THE NOVA FAR DETECTOR
THE NOVA FAR DETECTOR

344,064 channels!
99.5% operational
BUT WHERE ARE THE NEUTRINOS?

5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)
SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: 500 µsec

NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341508

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SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: zoom 10 µsec

NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608

Mayly Sanchez - ISU
A MUON NEUTRINO CANDIDATE

Zoomed in spatially
AN ELECTRON NEUTRINO CANDIDATE

Zoomed in spatially
NEUTRINOS IN THE NEAR DETECTOR
NEUTRINOS IN THE NEAR DETECTOR
NEUTRINOS IN THE NEAR DETECTOR
NEUTRINOS IN THE NEAR DETECTOR
CALIBRATION AND THE ABSOLUTE ENERGY SCALE

• Stopping muons provide a standard candle for setting absolute energy scale.
• Several samples demonstrate successful energy scale calibration:
  • cosmic $\mu$ dE/dx [~vertical]
  • beam $\mu$ dE/dx [~horizontal]
  • Michel e- spectrum
  • $\pi^0$ mass
  • hadronc shower energy/hit

ALL SAMPLES AGREE WITHIN ±5%
MUON NEUTRINO DISAPPEARANCE
In long-baseline experiments, we compare a prediction of the muon neutrino spectrum obtained from Near Detector data with a Far Detector measurement. Neutrino oscillations deplete rate and distort the energy spectrum.

\[ P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2 \left( 1.267\Delta m^2_{32} \frac{L}{E} \right) \]

*In an off-axis experiment near the oscillation maximum, the effect is even more dramatic.*
MUON NEUTRINO SELECTION

- We apply first basic containment cuts requiring no activity close to the wall of the detector.
- Excellent agreement of muon based data vs MC.
- We have developed a particle identification algorithm (k-nearest-neighbors) based on muon characteristics:
  - **track length**
  - dE/dx along the track
  - scattering along track
  - track-only plane fraction
COSMIC REJECTION FOR MUON NEUTRINOS

- Final cosmic background rate is measured directly from data taken concurrently with beam spill by using the out-of-time window.
- Selecting a narrow window around the 9.6 µsec spill gives a rejection factor of $10^5$.
- For the cosmic rejection of the muon neutrino disappearance analysis, we use a boosted decision tree algorithm based on:
  - Reconstructed track direction, position, and length; and energy and number of hits in event.
  - Event topology gives an additional factor of $10^7$ rejection.
MUON NEUTRINO CANDIDATE

[Graph showing data points with axes labeled x (cm), y (cm), and z (cm)]

NOvA - FNAL E929
Run: 18756 / 37
Event: 597960 / --
UTC Sun Jan 25, 2015 13:29:18.710709824

36
MUON NEUTRINO ENERGY

- Data vs MC show good agreement for muon neutrino selected events.
  - Muons are very well described by our MC.
- However, Monte Carlo has 21% more energy in the hadron system than seen in data.
- The hadron energy is thus recalibrated such that the total energy peak of the data matches the MC.
- This results in 6% overall neutrino energy scale uncertainty.

ND DATA IS USED TO PRODUCE A DATA DRIVEN PREDICTION IN THE FD
MUON NEUTRINO ENERGY

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ND DATA IS USED TO PRODUCE A DATA DRIVEN PREDICTION IN THE FD
 MUON NEUTRINO SELECTED SPECTRUM

- We expect 201 events before oscillations.
- We observe 33 events.

NOVÅA Preliminary

NOVÅ 2.74×10^{20} POT-equiv.

- Data
- Best fit prediction
- Unoscillated prediction
MUON NEUTRINO DISAPPEARANCE RESULTS

- The spectrum is matched **beautifully** by the oscillation fit.
- Largest systematic is hadronic neutrino energy.
- Parameter measurements:

\[
\begin{align*}
\Delta m^2_{32} &= +2.37^{+0.16}_{-0.15} \text{ [normal ordering]} \\
\Delta m^2_{32} &= -2.40^{+0.14}_{-0.17} \text{ [inverted ordering]} \\
\sin^2 \theta_{23} &= 0.51 \pm 0.10
\end{align*}
\]

**COMPELLING MEASUREMENT WITH 7.6% OF NOMINAL EXPOSURE**

Mayly Sanchez - ISU
ELECTRON NEUTRINO APPEARANCE
The probability of $\nu_e$ appearance in a $\nu_\mu$ beam:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A - 1)\Delta}{(A - 1)^2}$$

$$+ 2\alpha \sin \theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A - 1)\Delta}{(A - 1)} \cos \Delta$$

$$- 2\alpha \sin \theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A - 1)\Delta}{(A - 1)} \sin \Delta$$

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11 \text{ GeV}}$$

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$$

- Searching for $\nu_e$ events in NOvA, we can access $\sin^2 (2\theta_{13})$.
- Probability depends not only on $\theta_{13}$ but also on $\delta_{CP}$ which might be the key to matter anti-matter asymmetry of the universe.
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy i.e. the sign of $\Delta m_{31}^2 \sim \Delta m_{32}^2$ as well as neutrino vs anti-neutrino running.

NOVA PROBES THE MASS HIERARCHY AND CP VIOLATION SPACE

Mayly Sanchez - ISU
**Electron Neutrino Appearance in NOVA**

- The probability of $\nu_e$ appearance in a $\nu_\mu$ beam:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A - 1)\Delta}{(A - 1)^2} + 2\alpha \sin \theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta \sin (A - 1)\Delta}{A} \cos \Delta - 2\alpha \sin \theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta \sin (A - 1)\Delta}{A} \sin \Delta$$

$A \equiv \frac{G_f n_\nu L}{\sqrt{2}\Delta} \approx \frac{E}{11 \text{ GeV}}$

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$$

### νμ CC spectrum at 810 km, $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$

- $\sin^2 2\theta_{13} = 0, \delta_{cp} = \text{n/a}$
- $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = \pi/2$
- $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$
- $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = \pi/2$

### Anti-νμ CC spectrum at 810 km, $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$

- $\sin^2 2\theta_{13} = 0, \delta_{cp} = \text{n/a}$
- $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = \pi/2$
- $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$
- $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = \pi/2$
**ELECTRON NEUTRINO SELECTION**

- Two particle ID algorithms based on pattern recognition techniques have been developed:
  
  - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for e/μ/π/p particles hypotheses. Uses a neural net.
  
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns identification to trial event according to top matches in library.
  
- Good separation of electron neutrino signal from background including cosmic background.
ELECTRON NEUTRINO SELECTION

- Two particle ID algorithms based on pattern recognition techniques have been developed:
  
  - **LID**: evaluates the leading shower longitudinal and transverse \( \text{dE/dx} \) profiles against probability density functions for various particles hypothesis. Uses a neural net.
  
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns characteristics according to top matches.

- Identical performance. Signal efficiency relative to containment cuts: 35%. After all selection, 0.7% of NC events remain, relative to those after containment. Expected overlap in LID and LEM signal samples: 62%.
ELECTRON NEUTRINO SELECTION

• Two particle ID algorithms based on pattern recognition techniques have been developed:
  
  • **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for various particles hypothesis. Uses a neural net.
  
  • **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns characteristics according to top matches.

PRIOR TO UNBLINDING
DECIDED TO SHOW BOTH
RESULTS AND USE LID AS
PRIMARY SELECTOR

Mayly Sanchez - ISU
PREDICTING THE BACKGROUND IN THE FD

- Calorimetric energy after electron neutrino selection (shown for LID) shows good agreement.

- ND data is translated to FD background expectation in each energy bin, using Far/Near ratios from simulation.

- A small 5% excess in data is observed in the ND which is used as a correction to the FD background prediction.
PREDICTING THE SIGNAL IN THE FD

- FD signal expectation is predicted using the ND-selected $\nu_\mu$ CC spectrum using same technique as for muon neutrino disappearance.

- Most systematics are assessed by modifying the Far/Near simulated ratios and calculating the variation in the prediction both for signal and background.

SEVERAL INDEPENDENT EM SAMPLES SHOW GOOD DATA/MC AGREEMENT
COSMIC REJECTION FOR ELECTRON NEUTRINOS

- Containment and topological cuts such as removing events with large $p_T/p$ remove significant factors of this background.

- The electron neutrino selectors themselves provide the remaining level of rejection to achieve $10^8$ removal of cosmic ray interactions.

- Measurement of background on out-of-time spill data.

EXPECTED COSMIC BACKGROUND: 0.06 EVENTS
THE PREDICTION

- Background predictions are about 1 count each, 10% error. Few percent dependence on other oscillation parameters.
- Dominated by beam electron neutrinos and neutral current interactions.
- Cosmic background comparable to smallest beam backgrounds.

<table>
<thead>
<tr>
<th>PID</th>
<th>total bkg</th>
<th>$\nu_e$ CC bkg</th>
<th>NC bkg</th>
<th>$\nu_\mu$ CC bkg</th>
<th>$\nu_\mu$ CC bkg</th>
<th>cosmic bkg</th>
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<td>LID</td>
<td><strong>0.94±0.09</strong></td>
<td>0.46</td>
<td>0.35</td>
<td>0.05</td>
<td>0.02</td>
<td>0.06</td>
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<tr>
<td>LEM</td>
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- Signal prediction depends on oscillation parameters, the extremes are:

2 ± 0.3 (IH $\delta_{CP}=\pi/2$) ↔ 6 ± 0.7 (NH $\delta_{CP}=3\pi/2$)
THE ANSWER

- Background predictions for both selectors are about 1 count each, 10% systematic. Few percent dependence on oscillation parameters.
- Dominated by beam electron neutrinos and NC.
- Cosmic background comparable to smallest beam backgrounds.

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- We observe:

6 ELECTRON NEUTRINOS

(11 WITH LEM)
ELECTRON NEUTRINO CANDIDATE

ALL 11 OF THEM ARE ABSOLUTELY GORGEOUS!
ELECTRON NEUTRINO SELECTED EVENTS

- LID selects 6 events. The significance of appearance is $3.3\sigma$
- LEM selects 11. The significance of appearance is $5.5\sigma$
- The expected background in each case is 1 event.
- All 6 of LID events are also selected by LEM. The P-value for selecting the combination (11:6/5/0) is 9.2%.
  - Note that LID and LEM have a difference in energy cuts in the low end.
- Other reassuring distributions include time, spatial and angular distributions.

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ELECTRON NEUTRINO APPEARANCE RESULTS

• Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).

• Agreement is \( \sim 1\sigma \) better for the normal ordering.

• This plot is for LID selector (n=6).
ELECTRON NEUTRINO APPEARANCE RESULTS

• Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).

• Agreement is ~1σ better for the normal ordering.

• For LEM (n=11) the s-curves shift by a factor of 2 to the right increasing tension for the inverted mass ordering.
**ELECTRON NEUTRINO APPEARANCE RESULTS**

- Taking the reactor measurement of $\theta_{13}$ as an input, we can explore compatibility with the mass hierarchy and $\delta_{CP}$ using Feldman-Cousins.

- There is a significant deviation from gaussian limits in this case. Also non-smooth shape due to discreet nature of counting experiment.

- Resulting significances show that at maximal mixing, we disfavor the IH for $\delta \in [0, 0.6\pi]$ at 90% C.L. with primary selector.

\[
\sin^2 2\theta_{13} = 0.086 \pm 0.005
\]
ELECTRON NEUTRINO APPEARANCE RESULTS

• Both selectors prefer normal hierarchy.

• Both selectors prefer $\delta$ near $3\pi/2$.

• Given expected correlations, the observed event counts yield a reasonable mutual p-value of 9.2%.

• The specific point IH, $\delta=\pi/2$ is disfavored at $1.6\sigma$ (LID) and $3.2\sigma$ (LEM)* for $\sin^2\theta_{23} = 0.4\text{--}0.6$.

CONSISTENT HINTS!

Beware of trials factor of choosing LEM over LID after seeing results.

with $\sin^22\theta_{13} = 0.086 \pm 0.005$
GLOBAL ANALYSIS FOR CP VIOLATION

A. MARRONE (TAUP 2015)

The combination with SK atm. data moves \( \delta/\pi \sim 1.3-1.4 \) and slightly shrinks its allowed range.
GLOBAL ANALYSIS FOR CP VIOLATION
INCLUDES NOVA’S LATEST RESULTS
A. MARRONE (TAUP 2015)

LBL Acc + Solar + KL

+ SBL Reactors

+ SK Atm

\[ \frac{\sin^2 \theta_{13}}{\delta \pi} \]

\[ \frac{\sin^2 \theta_{13}}{\delta \pi} \]

\[ \frac{\sin^2 \theta_{13}}{\delta \pi} \]

Normal Hierarchy

Inverted Hierarchy

Allowed regions reduced with NO

NH

IH

GLOBAL ANALYSIS FOR CP VIOLATION
INCLUDES NOVA’S LATEST RESULTS
A. MARRONE (TAUP 2015)
SUMMARY

• NOvA has observed muon neutrino disappearance and electron neutrino appearance with 1/13th of baseline exposure:
  - Obtains 6.5% measurement of atmospheric mass splitting, and $\theta_{23}$ measurement consistent with maximal mixing.
  - Observes electron neutrino appearance signal at $3.3\sigma$ for primary $\nu_e$ selector, $5.5\sigma$ for secondary selector.
  - Consistent with hints of a preference for $\pi<\delta_{CP}<2\pi$ normal mass ordering.
  - In global analysis the preference for $\pi<\delta_{CP}<2\pi$ is clear.

• Stay tuned for doubling of the data set by next summer!