Первый совместный анализ с нейтринным и антинейтринным пучком в эксперименте NOvA

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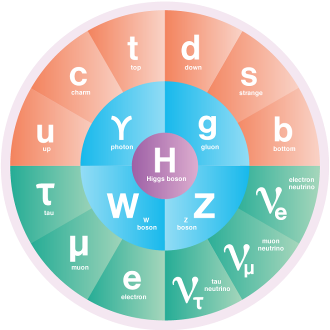
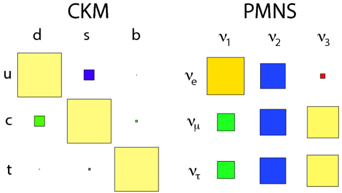
Neutrinos





Neutrinos mix like quarks (but mixings are large):

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$i = 1, 2, 3 \quad \alpha = e, \mu, \tau$

Nobel Prizes in neutrino physics

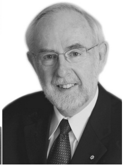
1988 — L. Lederman, M. Schwartz and J. Steinberger were awarded the Nobel Prize for "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".



1995 — F.Reines was awarded the Nobel Prize "for the detection of the neutrino".

2002 — R. Davis and M. Koshiba were awarded the Nobel Prize for "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos".

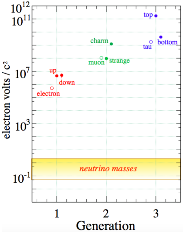

2015 — NP was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

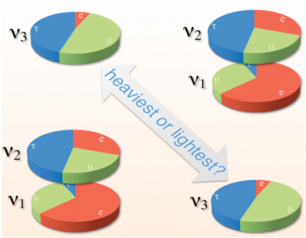



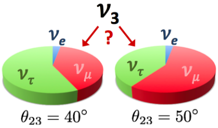
Motivations to study neutrino oscillations

- One of the most wide spread particle in the Universe
- Many open questions:
  - Dirac or Majorana nature
  - Neutrino masses themselves
  - Measurement of θ_{13} (Complete. Reactor experiments result)
  - Mass Hierarchy Problem
  - CP violating phase
  - Precise measurements of oscillation parameters
  - Sterile neutrinos
  - Understanding fundamental principals of all these phenomena
  - ...

} NOvA goals (Mass Hierarchy Problem, CP violating phase, Precise measurements of oscillation parameters)







Why is it important?

- ✳ neutrino mass hierarchy

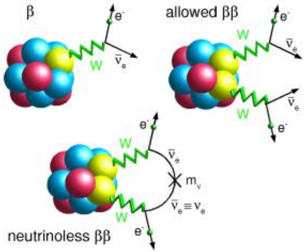
Implications for: $0\nu\beta\beta$ data and Majorana nature of ν; approach to m_β; cosmology; astrophysics; theoretical frameworks for mass generation, quark/lepton unification; Is the lightest charged lepton associated with the heaviest light neutrino?

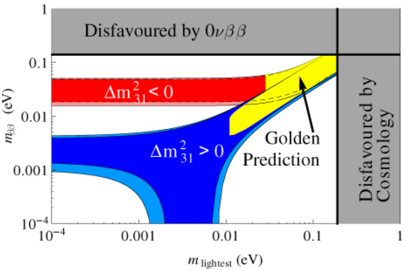
- ✳ CP violation

baryon asymmetry through see-saw/leptogenesis; fundamental question in the Standard Model (is CP respected by leptons?)

- ✳ ν_3 flavor mixing

Is ν_3 more strongly coupled to μ or τ flavor?; frameworks for mass generation, unification





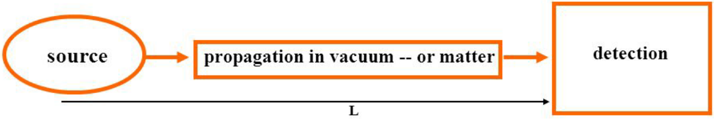
Theory of neutrino oscillations

$\theta_{13} \sim 8.5^\circ$

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{vmatrix}\Bigg\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{vmatrix}\Bigg\rangle$$

$\lvert\Delta m^2_{32}\rvert = \lvert m^2_3 - m^2_2\rvert \simeq 2.5 \times 10^{-3}$ eV^2	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} = \lvert m^2_2 - m^2_1\rvert \simeq 7.5 \times 10^{-5}$ eV^2
$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$	$\nu_e \to \nu_e$
$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$	$\nu_e \to \nu_\mu, \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor

Oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, CP phase δ, $|\Delta m^2_{13}|$, Δm^2_{12}



Oscillation Probability

ν_μ Disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \underbrace{\sin^2 2\theta_{23}}_{\text{maximal mixing}} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

leading order,
no matter effect,
no CP violation terms ...

ν_e Appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \underbrace{\sin^2 2\theta_{13}}_{\sin^2 2\theta_{13} = 0.084 \pm 0.005} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

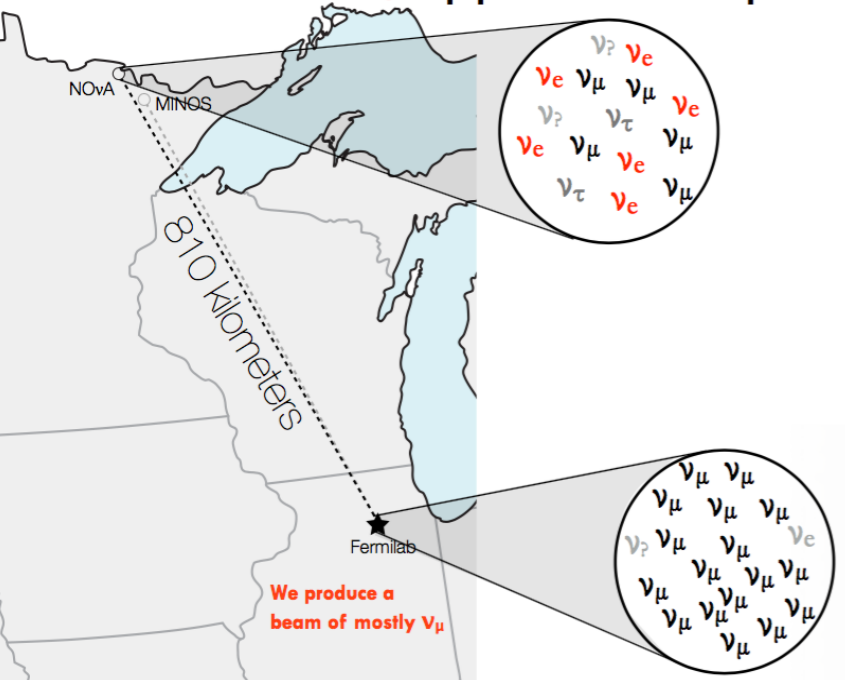
Oscilation Probability in matter (approximate formula):

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

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

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad A \equiv \pm \frac{G_f n_e L}{\sqrt{2}\Delta}$$

NuMI Off-axis ν_e Appearance Experiment



The NuMI Off-Axis ν_e Appearance Experiment. Goals

NOvA experiment goals :

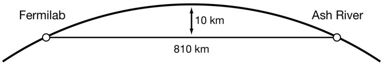
Using $\nu_\mu \to \nu_e$ ($\overline{\nu}_\mu \to \overline{\nu}_e$)

- ✳ neutrino mass hierarchy
- ✳ CP violating phase

Using $\nu_\mu \to \nu_\mu$ ($\overline{\nu}_\mu \to \overline{\nu}_\mu$)

- ✳ precision measurement Δm^2_{32}
- ✳ mixing angle θ_{23} octant (more 45° or less).

Also exotics:
sterile neutrino, supernova, neutrino cross section measurements in Near Det., monopoles etc.

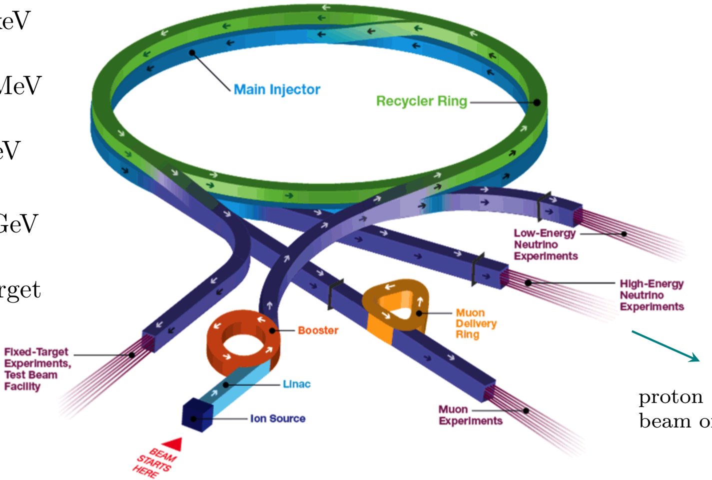



NOvA Collaboration
7 countries
49 institutions
240 collaborators
Fermilab
Fermilab
AISLE 2

FermiLab accelerator complex

Neutrinos at the Main Injector (NuMI)

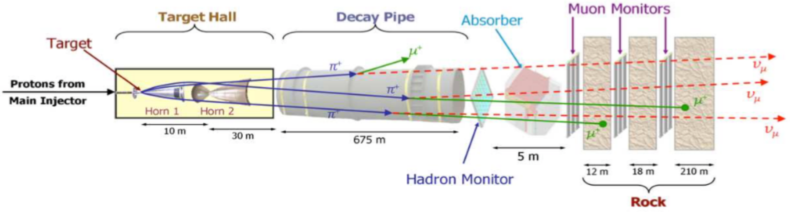
750 keV → 400 MeV → 8 GeV → 120 GeV → to target



proton 120 GeV beam on target

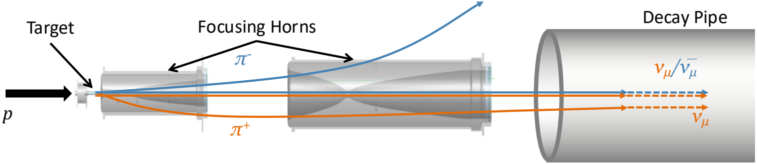
Fermilab Accelerator Complex 2020

Initial neutrino flux production

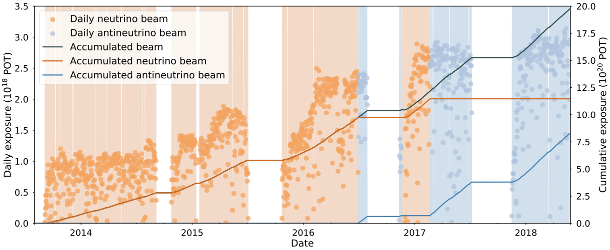


- 120 GeV protons on a carbon target, produce mesons which yield neutrinos. Beam purity: $\nu_\mu \sim 97\%$, $\overline{\nu}_\mu \sim 2\%$, $\nu_e \sim 1\%$.
- NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT/year. (POT = Proton On Target)
- We are running at 700 kW now!
- Every 1.3s 6 doubled batches of protons hit the target (1 beam spill). 1 spill is 10 us.

Recorded POT and Far Detector dataset

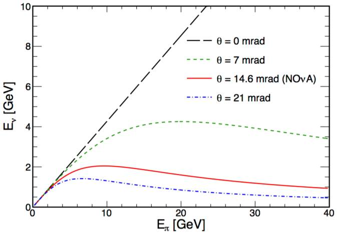


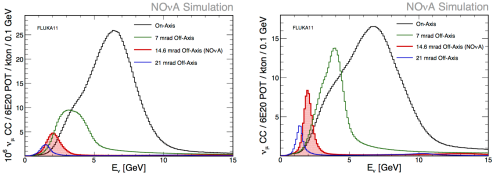
- The way to count the statistics in accelerator neutrino physics - POT = proton on target.
- 120 GeV protons on a carbon target, produce mesons which yield neutrinos.
- Every 1.3s 6 doubled batches of protons hit the target.



- neutrino beam: 8.85×10^{20} POT
- antineutrino beam: 6.91×10^{20} POT

Off-axis detector scheme





Narrowly peaked ν flux centered at 2 GeV

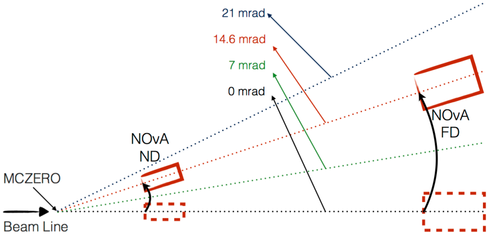
$$E_\nu = \frac{\left(1-\frac{m_\mu^2}{m_{\pi,K}^2}\right)E_{\pi,K}}{1+\gamma^2\theta^2}$$

For π decay-in-flight, E_ν dependent on angle π decay and ν interaction.
Off-axis have flat E_π dependence.

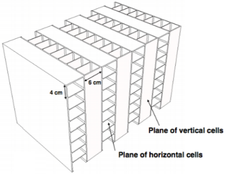
Achieves near maximal oscillation

Suppresses high energy tail

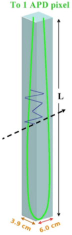
14 mrad off-axis

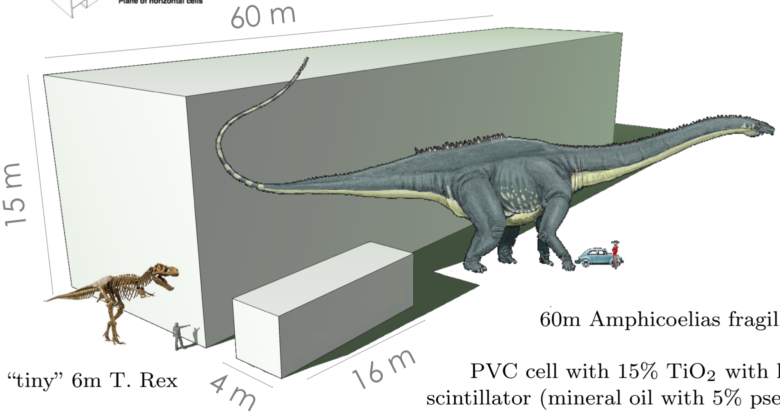


Two NOvA detectors - huge tracking calorimeters



FD: 344 064 cells
ND: 20 193 cells



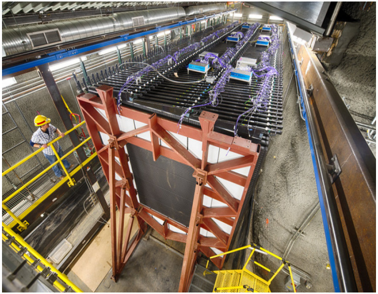


"tiny" 6m T. Rex

60m Amphicoelias fragillimus

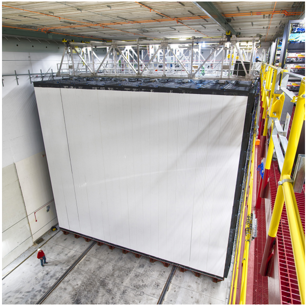
PVC cell with 15% TiO_2 with liquid scintillator (mineral oil with 5% pseudocumene)

Two detector scheme



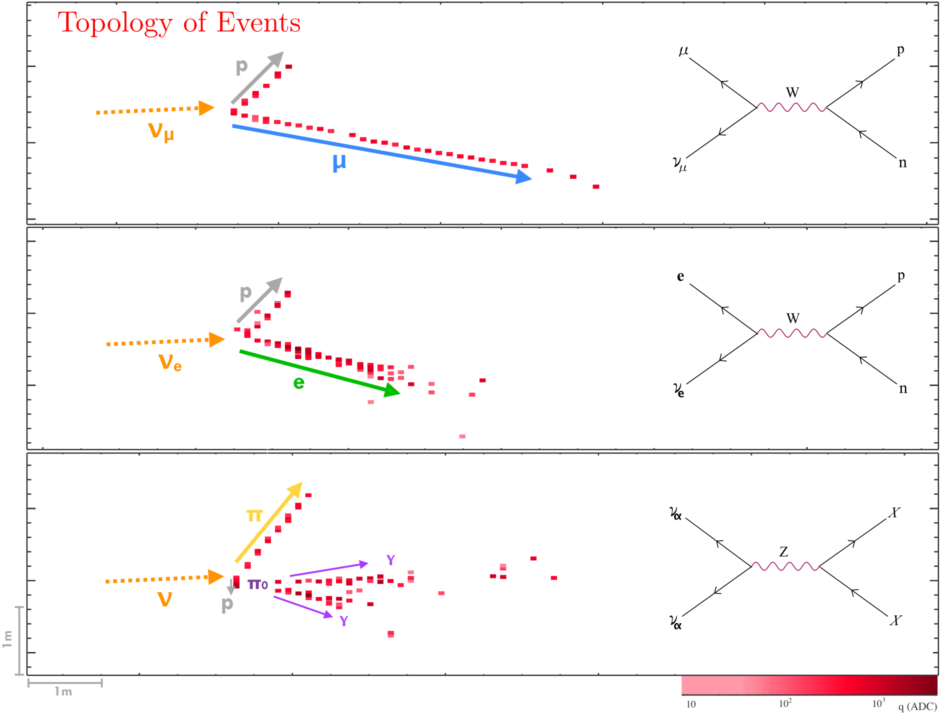
Near Detector (ND):

- ✳ 1 km after target
- ✳ measure flux composition before oscillations
- ✳ ND data used for prediction data in FD (extrapolation procedure)



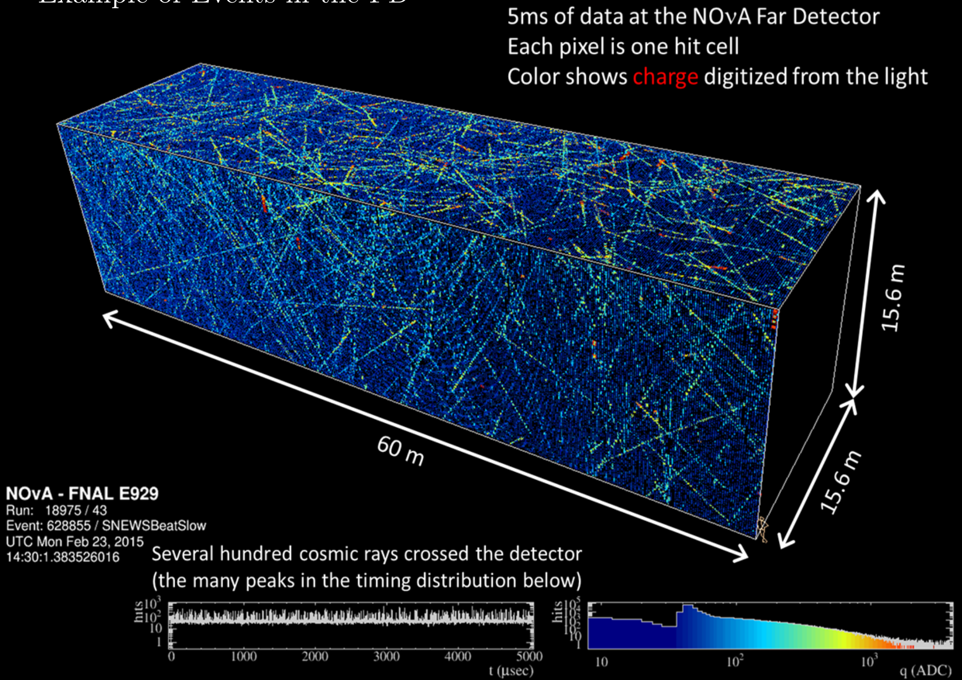
Far Detector (FD):

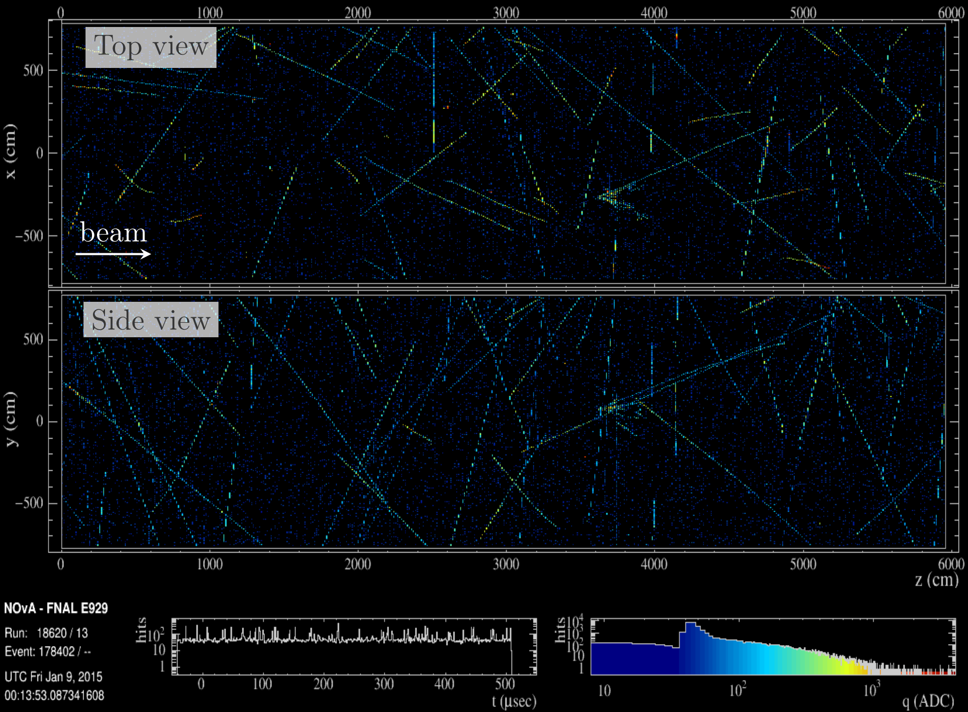
- ✳ 810 km after target
- ✳ measure neutrino flux after oscillations
- ✳ extrapolation cancels most systematics
- ✳ FD identical to ND



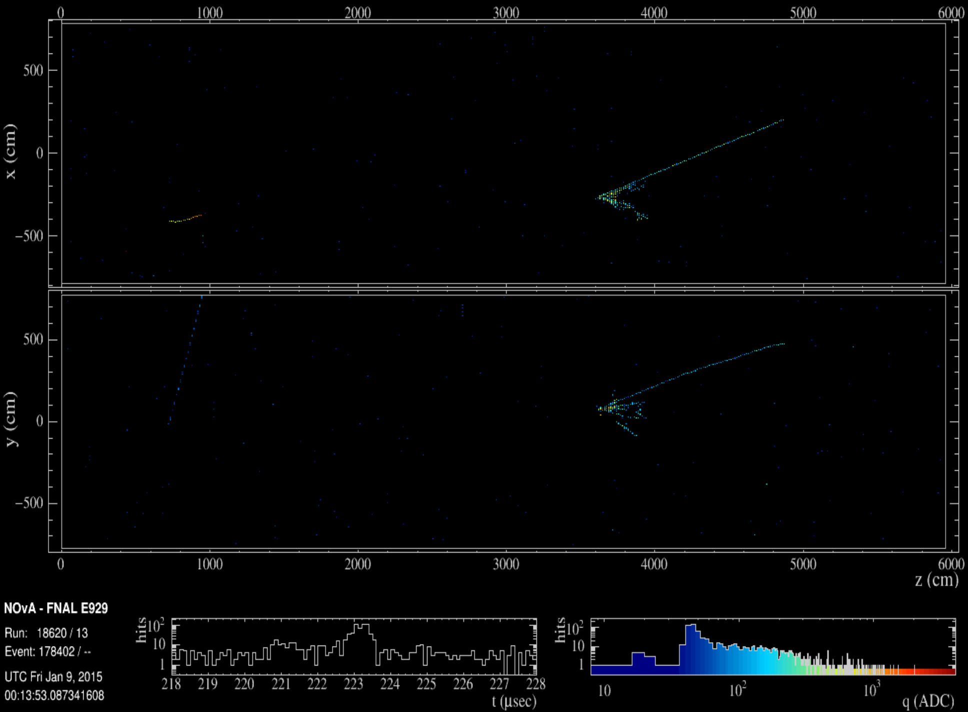
Topology of Events
p
ν_μ
μ
μ
p
W
ν_μ
n
p
ν_e
e
e
p
W
ν_e
n
π
ν
π0
p
γ
γ
ν_α
X
Z
ν_α
X
1m
1m
10
10^2
10^3
q (ADC)

Example of Events in the FD

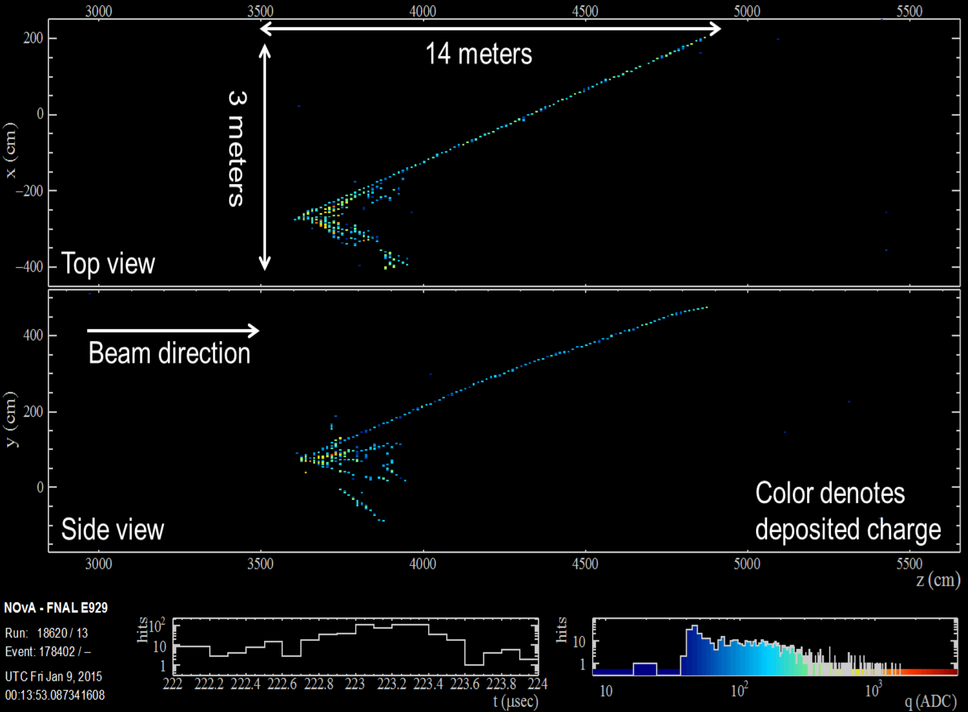




Top view
beam
x (cm)
Side view
y (cm)
z (cm)
0
1000
2000
3000
4000
5000
6000
500
0
−500
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)



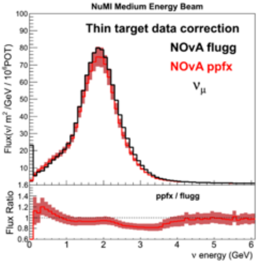
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (µsec)
q (ADC)



14 meters
3 meters
Top view
Beam direction
Side view
Color denotes deposited charge
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (µsec)
q (ADC)

Simulation

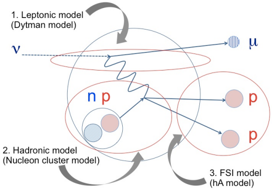
- Beam hadron production, propagation; neutrino flux: GEANT4/External Data
  - New data-driven flux based on thin target hadron production data from NA49 and MIPP. Beam flux is tuned using the Package to Predict the FluX using external data. (Minerva, Phys. Rev. D 94, 092005 (2016))

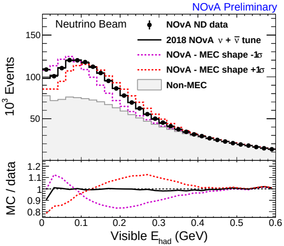


- Cosmic ray flux: Data Triggers
- Neutrino interactions and FSI modeling: GENIE v2.12.2
- Detector simulation: GEANT4
- Readout electronics and DAQ: Custom simulation routines

Simulation

- Beam hadron production, propagation; neutrino flux: GEANT4/External Data
- Cosmic ray flux: Data Triggers
- Neutrino interactions and FSI modeling: GENIE v2.12.2
  - Nuclear effects on the initial state and reactions themselves (via Meson Exchange Currents) remain important components of the NOvA interaction model.
  - New MEC and RPA uncertainties that better capture limits of theory and data constraints.

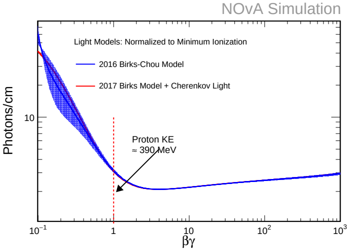




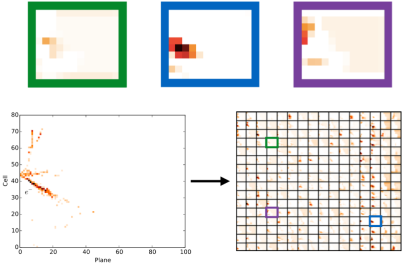
- Detector simulation: GEANT4
- Readout electronics and DAQ: Custom simulation routines

Simulation

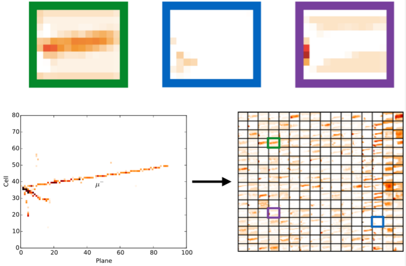
- Beam hadron production, propagation; neutrino flux: GEANT4/External Data
- Cosmic ray flux: Data Triggers
- Neutrino interactions and FSI modeling: GENIE v2.12.2
- Detector simulation: GEANT4
  - New detector simulation, addition of Cherenkov radiation (an important part in modeling the detector response to hadronic activity).
  - Detector response uncertainties were reduced by an order of magnitude in the new detector simulation.
- Readout electronics and DAQ: Custom simulation routines



Event classifier for ν_e and ν_μ analyses



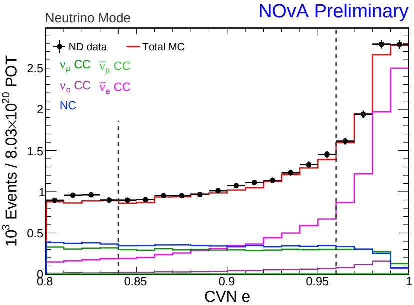
ν_e event

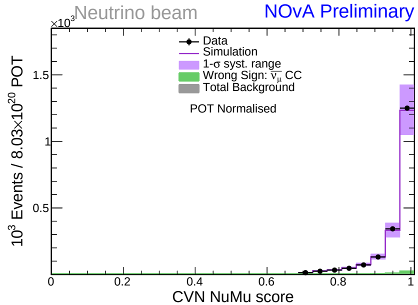


ν_μ event

- “Convolutional Visual Network” (CVN) - particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic

Event classifier for ν_e and ν_μ analyses. Output

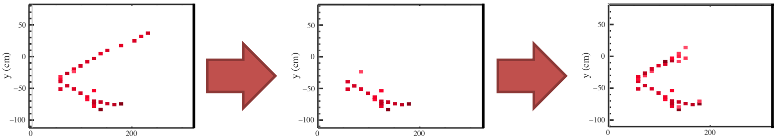


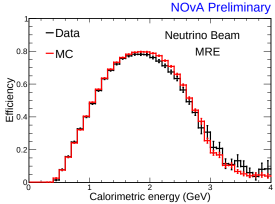


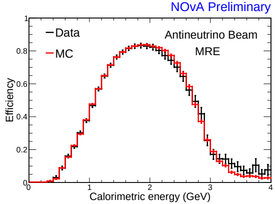
New for this analysis:

- A shorter, simpler architecture trained on updated simulation.
- Separate training for the neutrino and antineutrino beams.
  - Wrong-sign treated as signal in training.
  - 14% better efficiency for $\bar{\nu}_e$ with a dedicated network.

CVN crosschecks in ν_e analysis: MRE

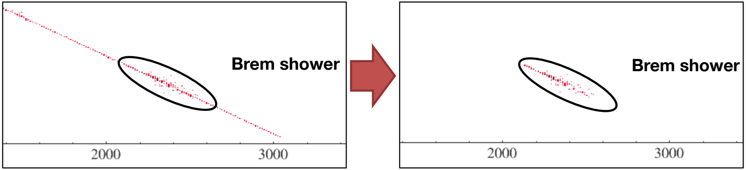


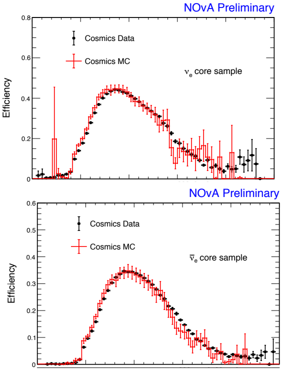




- We can create a control sample of "electron neutrino" events by removing the muon and replacing it with a simulated electron (Muon Removed Electron)
- Compare the efficiency between MRE events with real and simulated hadronic showers (Allows us to focus on the effect of the hadronic shower on efficiency)
- Efficiency agrees between data and MC at the 2% level for both neutrino and antineutrino beams.

CVN crosschecks in ν_e analysis: MRBrem

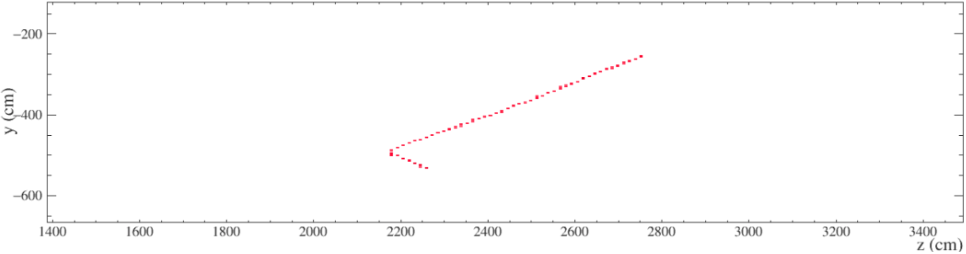




- Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector.
- Efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.

ν_μ Disappearance Mode

- Select and measure ν_μCC events in each detector.
- Extract oscillations from differences between the Far and Near energy spectra.

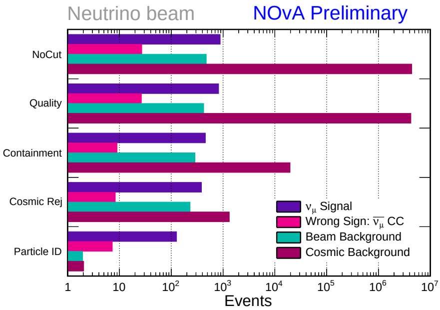


Event selection in numu disappearance analysis

Cut flow for ν_μ disappearance analysis is pretty straight forward:

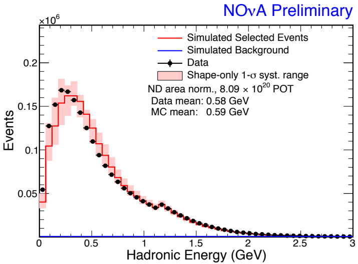
- NOvA FD places at the Earth surface → 11 billion cosmic rays/day
- After applying timing cuts we have 10^7 events

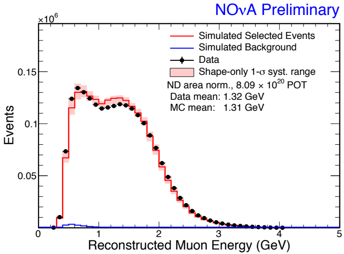
- 5 main groups of cuts, which requires event to be in fiducial volume, well-reconstructed, fully contained in the det.
- ν_μ analysis uses CVN classifier and special kNN which identifies the muon itself.
  - kNN inputs: Track length, dE/dx, scattering, fraction of track-only planes
- ν_μ uses BDT for the cosmic rejection:
  - inputs: track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN



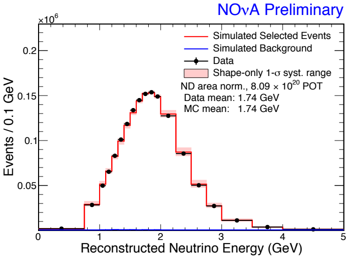
cut flow for ν mode (similar $\bar{\nu}$)

Energy Estimation in ν_μ Disappearance mode

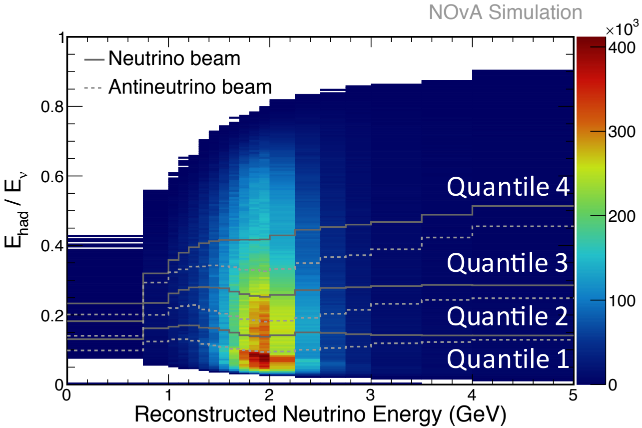




- Final E_ν is function of E_{had} and E_μ:
  - muon energy is a function of track length
  - hadronic energy reconstructed calorimetrically
- $\sigma_{\text{had}} \sim 30\%$,
- $\sigma_\mu \sim 3\%$
- energy resolution is $\sigma_\nu \sim 9\%$



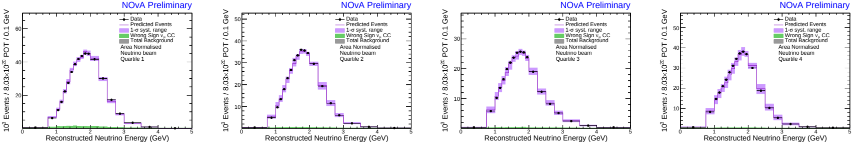
ν_μ resolution binning



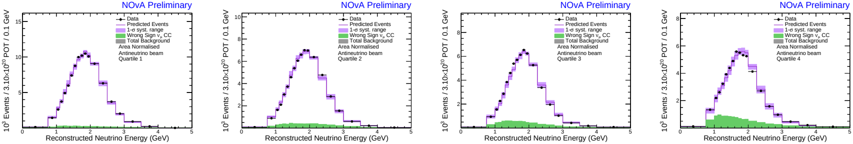
- Muon energy resolution (σ_μ) is much better than hadronic energy resolution (σ_{had}).
- Split into 4 equal quantiles based on hadronic energy fraction.
- Resolution varies from ~6% to ~12% from the best to worst resolution bins.

ν_μ ND predictions vs. data

Neutrino beam:



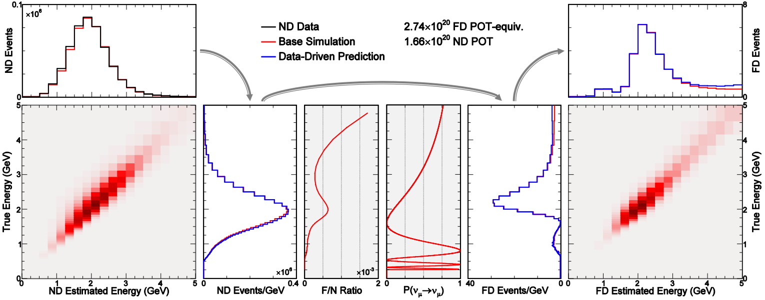
Antineutrino beam:



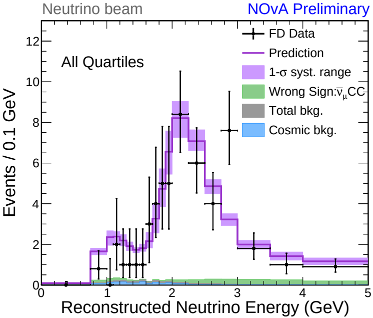
- ✳ Area normalized MC, shape-only systematics (violet bands)
- ✳ Data-MC shape agreement good within each quantile

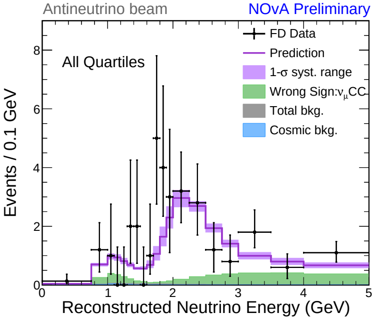
Extrapolation to Far Detector

- Estimate true energy distribution of selected ND events.
- Multiply by expected Far/Near event ratio and oscillation probability as a function of true energy.
- Convert FD true energy distribution into predicted FD reco energy distribution.
- Systematic uncertainties assessed by varying all MC-based steps.



The Box opening results: ν_μ Far Detector spectrum





- Expected unoscillated - 730 ν_μ CC
- Observed 113 ν_μ CC candidates (expectation at BF 121 ν_μ CC)
- Background prediction (in total 11.0 events):

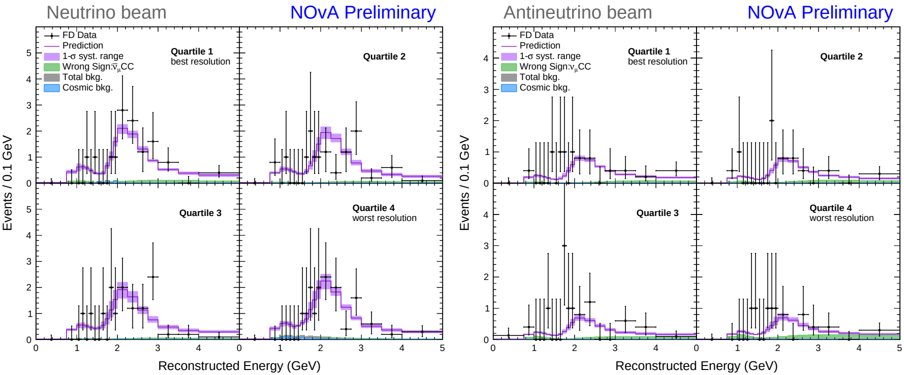
$\bar{\nu}_\mu$ CC	NC	other	cosmic
7.24	1.19	0.51	2.07

- Expected unoscillated - 266 ν_μ CC
- Observed 65 ν_μ CC candidates (expectation at BF 50 ν_μ CC)
- Background prediction (in total 13.7 events):

$\bar{\nu}_\mu$ CC	NC	other	cosmic
12.58	0.39	0.23	0.46

ν_μ Far Detector Quantiles

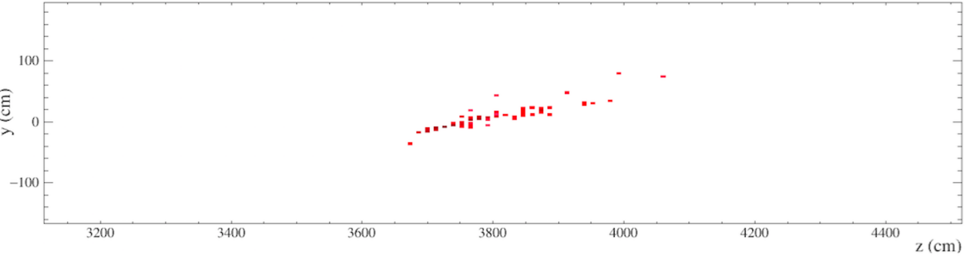
These 4 x 2 panels are the fit inputs on the ν_μ ($\bar{\nu}_\mu$) side



▸▸ Jump to the joint $\nu_\mu + \nu_e$ fit oscillation result

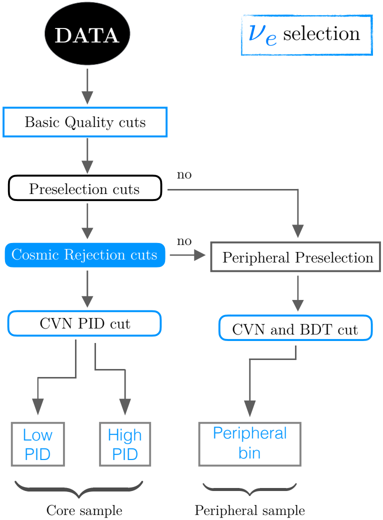
ν_e Appearance Mode

- Identify ν_e CC candidates in the FD.
- Use ND events to predict beam backgrounds in the FD.
- The excess over the background is a signal.



ν_e appearance event selection

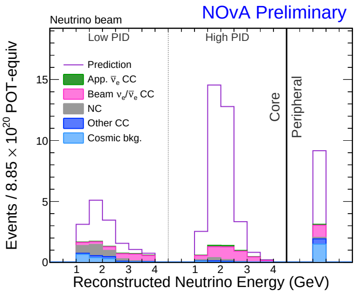
- Start with the same challenge at the FD - 10^7 events after applying timing cuts.
- Use CVN for PID cut
- A bit more complicated cut flow:
  - sequence of conventional cuts on energy, event quality, positioning etc.;
  - but we reclaim events that fail main selection chain and give them one more chance in the Peripheral sample;
  - tight CVN and BDT cuts clean up this sample
- As a result of this flow we have 3 spectra for different CVN PID binning and Peripheral sample separately

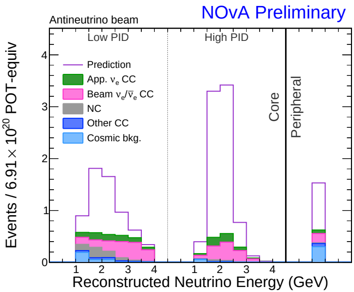


ν_e appearance event selection

- Oscillation sensitivity depends on separating ν_e signal from background
- Bin by PID to separate a high-purity and low-purity sample.
- No energy bins in the peripheral sample where uncontained events make energy unreliable.

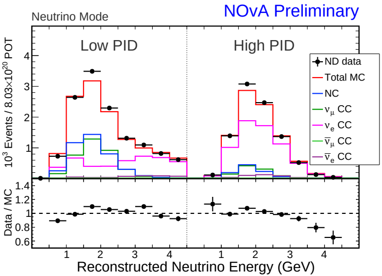
The cut flow result is the next:

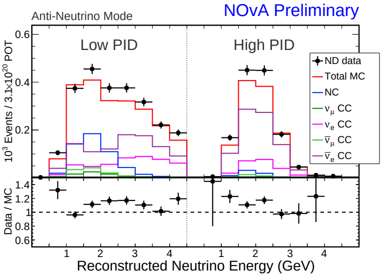




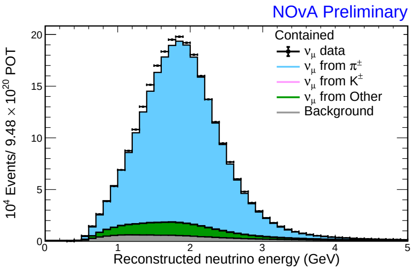
ND driven predictions in the ν_e appearance analysis

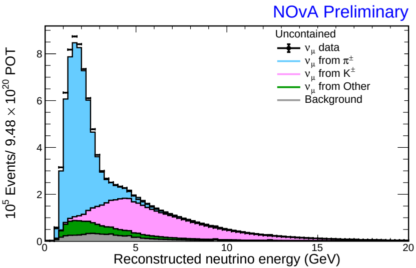
- Data vs. MC is not perfect → use ND to correct MC
- Each MC component should be reweighted and oscillated to the FD
- Use two types of decomposition:
  - For neutrino mode - Combo decomposition: consist of two steps
  - For antineutrino mode - proportional decomposition for now (assume MC proportions are right, scale all together to the data)





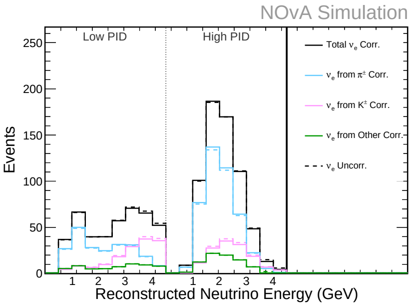
ND driven predictions in the ν_e appearance analysis





Combo decomposition, step # 1 - correct beam ν_e events with the help of ν_μ:

- ν_e and ν_μ come from the same parents: Lower energy ν from the π decay: $\pi^+ \to \mu^+ + \nu_\mu,\ \mu \to e^+ + \nu_e + \bar{\nu}_\mu$ Higher energy ν from the K decay: $K \to \pi^0 + e^+ + \nu_e$
- Use contained ν_μ spectrum to constrain the π flux
- Use uncontained ν_μ spectrum to constrain the K flux

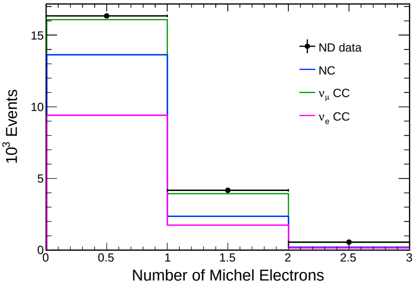


ND driven predictions in the ν_e appearance analysis

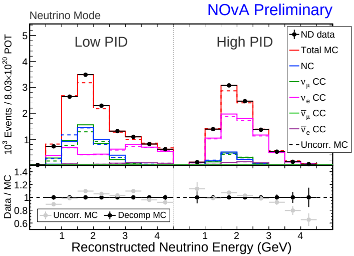
Combo decomposition, step # 2 - correct the CC/NC ratio with the help of Michel electrons:

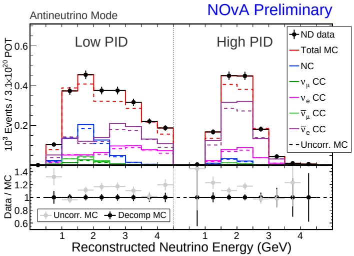
- ν_μ CC interaction with high probability will produce Michel electron in μ decay
- in ν_e and NC interaction can have Michel e in the hadron shower due to π decay

Produced changes:
ν_e CC +3%, ν_μ CC +7%, NC -4%

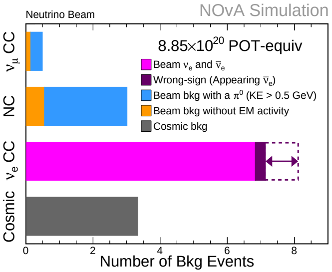


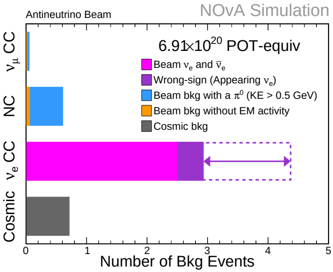
Result of ND decomposition:



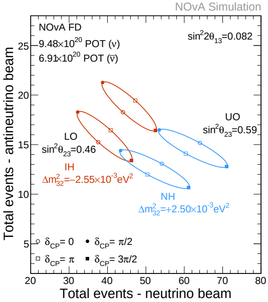


Far Detector Signal and Background Expectations

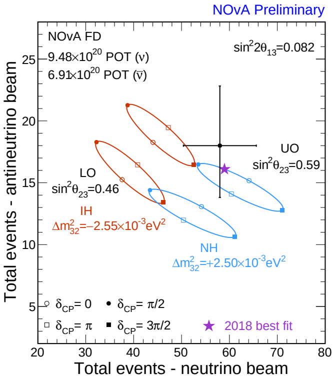




- Total bkg counts:
  in neutrino mode: 14.7 – 15.4 total ν_e bkg
  in antineutrino mode: 4.7 – 5.7 total ν_e bkg
- Wrong-sign background depends on the oscillation parameters
- Largest backgrounds are from real electrons: beam $\nu_e/\bar{\nu}_e$ and wrong-sign.
- Most other beam backgrounds contain a π^0
- Total signal + bkg expectations: 10 - 22 $\bar{\nu}_e$ events and 30 - 75 ν_e events



ν_e Appearance box opening result

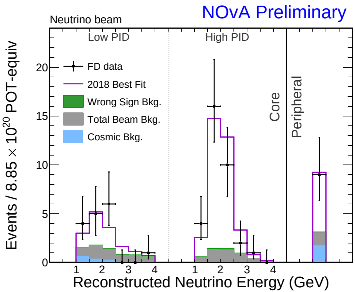


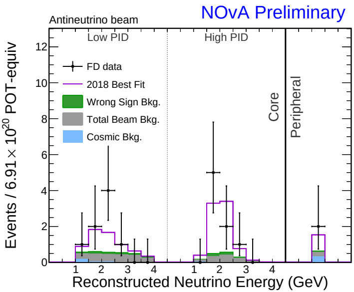
With 8.85 $\times 10^{20}$ POT in ν mode and 6.91 $\times 10^{20}$ POT in $\bar{\nu}$ mode we found:

- 58 ν_e CC candidate events
- 18 $\bar{\nu}_e$ CC candidate events

ν_e Appearance FD spectra

With 8.85 $\times 10^{20}$ POT in ν mode and 6.91 $\times 10^{20}$ POT in $\bar{\nu}$ mode we found:





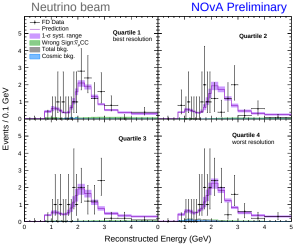
- 58 ν_e CC candidates in the Far Detector
- expect 30 ($\pi/2$, IH) - 75 ($3\pi/2$, NH)
- total background: 15.1 events (beam bkg + cosmic)

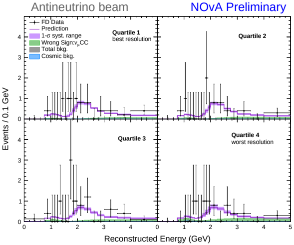
- 18 $\bar{\nu}_e$ CC candidates in the Far Detector
- expect 10 ($3\pi/2$, NH) - 22 ($\pi/2$, IH)
- total background: 5.3 events (beam bkg + cosmic)

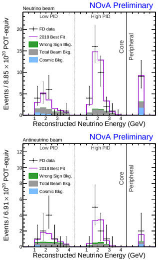
Jump to the joint $\nu_\mu + \nu_e$ fit oscillation result

Oscillation fit results

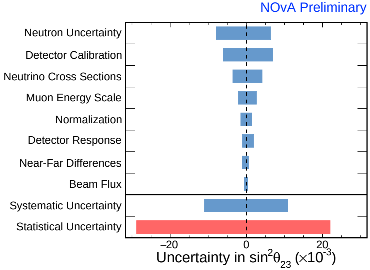
* Joint fit of ν_μ ($\bar{\nu}_\mu$) and ν_e ($\bar{\nu}_e$) results.
* All systematics and oscillation pull terms shared.
* All contours and 1D ranges are Feldman-Cousins corrected.
* PDG constraint on $\sin^2 2\theta_{13} = 0.082$

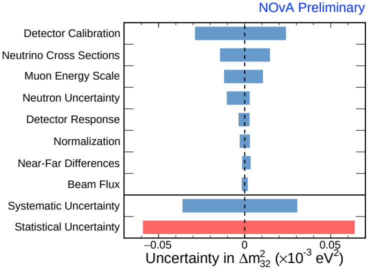






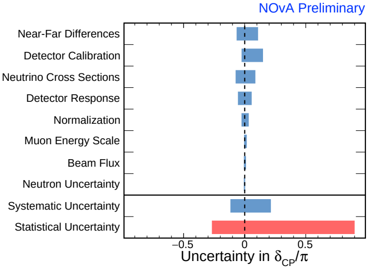
Joint fit systematics



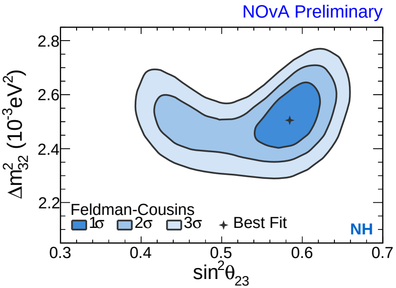


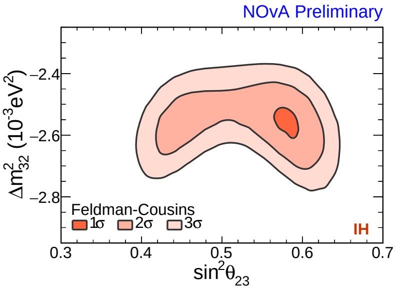
Most important systematics:

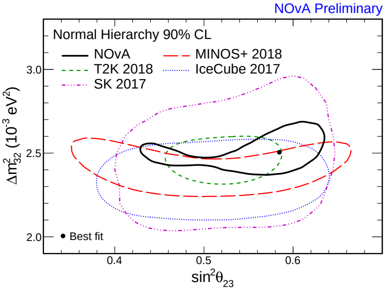
- Detector Calibration (Will be improved by the 2019 test beam program + JINR measurements)
- Neutrino cross sections (Particularly nuclear effects - RPA, MEC)
- Muon energy scale
- Neutron uncertainty – new with $\bar{\nu}_e$



Joint $\nu_e + \nu_\mu$ fit 2018 analysis results



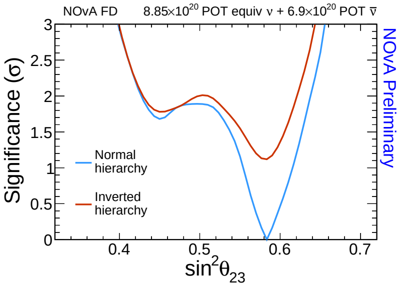


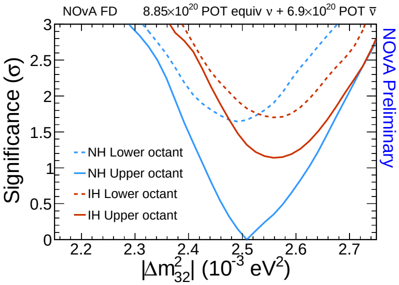


Joint fit results:

- Best fit:
  NH, $\delta_{CP} = 0.17\pi$,
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO),
  $\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}$ eV^2
- Consistent with other atmospheric neutrino experiments.

Joint $\nu_e + \nu_\mu$ fit 2018 analysis results



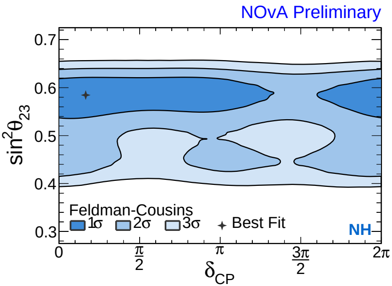


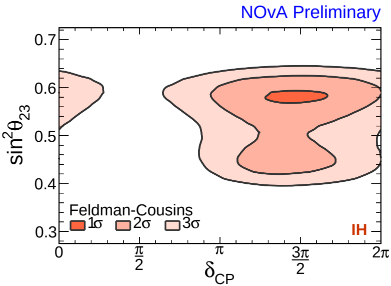
Reject maximal mixing at 1.8σ
Prefer UO at the same level

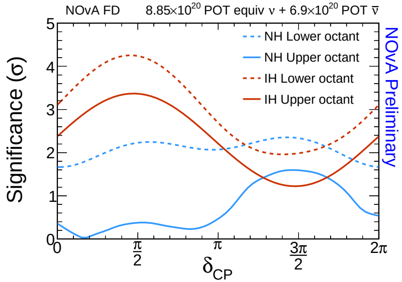
Joint fit results:

- Best fit:
  NH, $\delta_{CP} = 0.17\pi$,
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO),
  $\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}$ eV^2

Joint $\nu_e + \nu_\mu$ fit 2018 analysis results





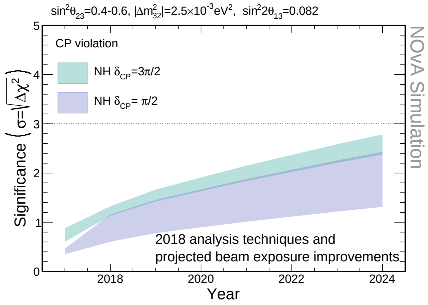


Joint fit results:

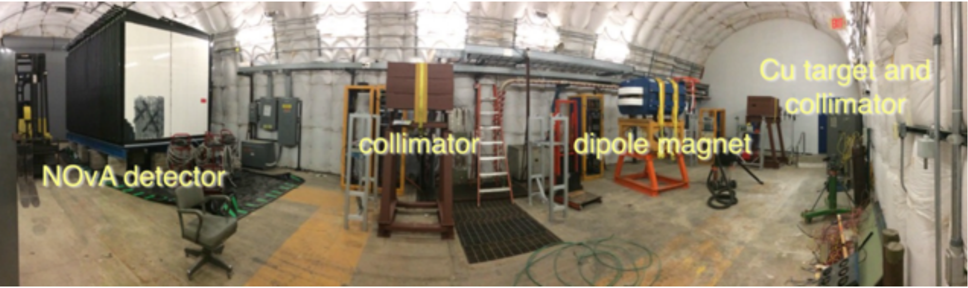
- Best fit:
  NH, $\delta_{CP} = 0.17\pi$,
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO),
  $\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}$ eV^2
- Reject the IH, $\delta_{CP} = \pi/2$ at $>3\sigma$, reject IH, all values of δ_{CP} at 1.8σ.

The Future

- Nova's reach can be improved by extended running through 2024 along with proposed accelerator improvement projects and analysis improvements.
- 2σ sensitivity to CP violation in 2024 for favorable parameters (3σ sensitivity for 30-50% of δ_{CP} range by 2024.)
- 3σ sensitivity to the hierarchy possible in 2020 with favorable parameters.

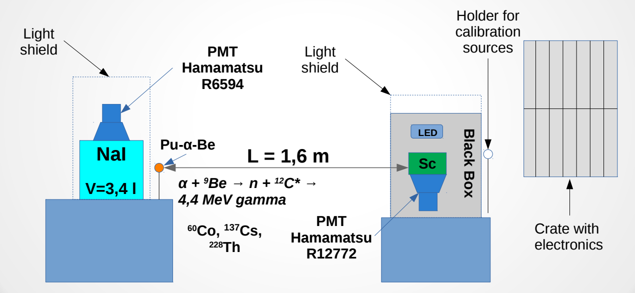


Test beam



- The test beam program is how we will realize those analysis improvements:
  - Reduced systematics
  - Additional validation of ML techniques
  - Simulation improvements
- Installation and commissioning started this summer
- Beam in the first half of 2019, planning on 2 million particles

JINR test stand



- Stand to measure NOvA's scintillator properties - Birks constants, Cherenkov radiation (?) etc.
- Birks constant measurement almost done, will be placed in the simulation soon

NOvA team at JINR

25 JINR collaborators (13 authors) in NOvA with the following activities:

- Detector construction and response; NOvA test bench at JINR (Nikolay Anfimov, Alexander Antoshkin, Albert Sotnikov)
- Dubna Remote Operation Center for NOvA (Nikolay Anfimov, Alexander Antoshkin, Oleg Samoylov, Chris Kullenberg, Andrey Sheshukov)
- JINR data center for NOvA and IT support (Nikita Balashov, Alexandr Baranov, Andrey Dolbilov, Evgeniy Kuznetsov)
- Theoretical group (Vadim Naumov, Konstantin Kuzmin, Igor Kakorin)
- Reconstruction (Oleg Klimov, Chris Kullenberg (for xsec measurements))
- Detector simulation and calibration (Oleg Samoylov, Olga Petrova)
- Exotics:
  - supernova detection (Andrey Sheshukov, Maria Petropavlova)
  - east-west asymmetry (Olga Petrova)
  - pentaquark search (Vladimir Allakhverdian)
  - monopole search (Alexander Antoshkin)
  - atmospheric muons (Anna Morozova)
- Data Analysis:
  - ν_e group (Liudmila Kolupaeva, Anastasia Kalitkina)
  - ν_μ group (Veniamin Amvrosov)

Summary

With 8.85 $\times 10^{20}$ POT in ν mode and 6.91 $\times 10^{20}$ POT in $\bar{\nu}$ mode statistics NOvA got the next results:

* Our best fit is in the Normal Hierarchy, $\delta_{CP} = 0.17\pi$, $\sin^2\theta_{23} = 0.58$ (Upper Octant), $\Delta m^2_{32} = 2.51 \times 10^{-3}$ eV^2
* Current data prefer the Normal Hierarchy at 1.8σ, exclude the Inverted Hierarchy, $\delta_{CP} = \pi/2$ at $> 3\sigma$.
* Prefer the Upper Octant of θ_{23} at 2.35 σ.
* NOvA can reach 3σ sensitivity to the Mass Hierarchy in 2020.

We keep running with antineutrino beam, x2 more statistics in a year.

Stay tuned!