Results on Neutrino and Antineutrino Oscillations from the NOvA Experiment

New Trends in High-Energy Physics 2019
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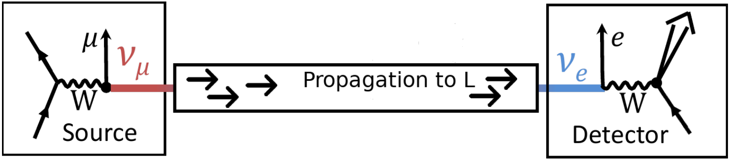
Outline

1. Neutrino oscillations phenomenon in standard 3ν model
2. The NOvA experiment
3. Features of NOvA ν_μ and ν_e analysis
4. 2018 analysis observations
5. 2018 constraints on oscillation parameters
6. Future prospects, progress and summary

Neutrino Oscillations

Neutrino oscillations



- Source producing neutrinos of certain flavor – e.g. ν_μ
- Detector (at certain distance) observes reduction in the flux of neutrinos of the produced flavor

  $\Rightarrow$ **Neutrino disappearance:** $\nu_\mu \longrightarrow \nu_\mu$
- Detector observes increase in the flux of neutrinos of different flavors from the one produced

  $\Rightarrow$ **Neutrino appearance:** $\nu_\mu \longrightarrow \nu_e$
- Each flavor state ν_α is a superposition of mass states ν_i (ν mixing)
- The (dis)appearance of ν has an oscillatory pattern as a function of distance/energy $\Rightarrow$ **neutrino oscillations**

Neutrino oscillations and neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{\mathrm{CP}}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Similar to CKM mixing, still very different (U_{PMNS}, small ν masses)
- ν mixing – up to 9 parameters, ν oscillations – 6 parameters:

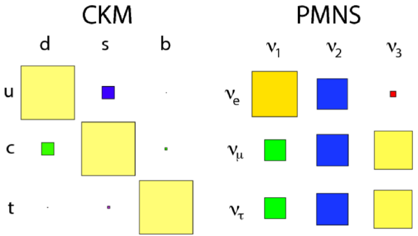
$$\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \Delta m^2_{21}, \Delta m^2_{31}$$

ν oscillations open questions

Mass hierarchy (ordering)?
Is $\theta_{23} = 45^\circ$ or $>, <$?
Is there a CPV in lepton sector?

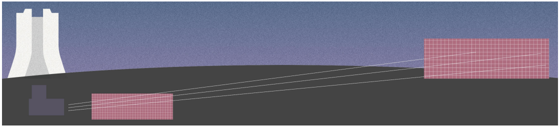
NH = NO = normal hierarchy (ordering)
IH = IO = inverted hierarchy (ordering)
Phys.Lett.B 782(2018), pp.633-640

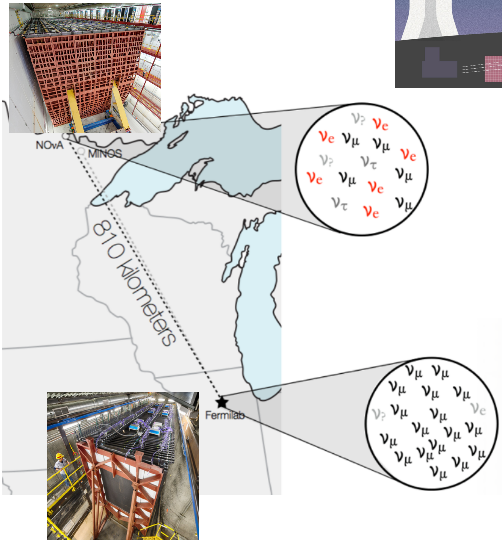
parameter	best fit $\pm 1\sigma$	3σ range	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%



The NOvA Experiment

The NOvA experiment





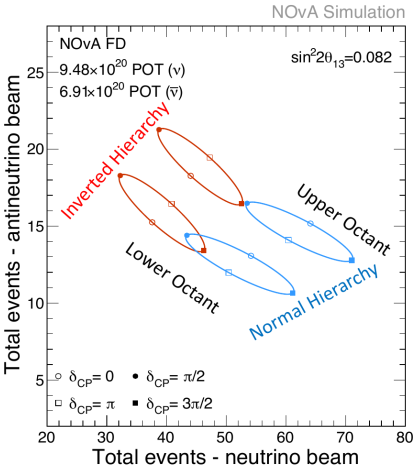
- NOvA is a long-baseline neutrino oscillation experiment
- NuMI ν_μ 700 kW beam, $\nu/\bar{\nu}$ modes
- Two functionally identical detectors, 14.6 mrad off-axis, 810 km apart

Physics interests:

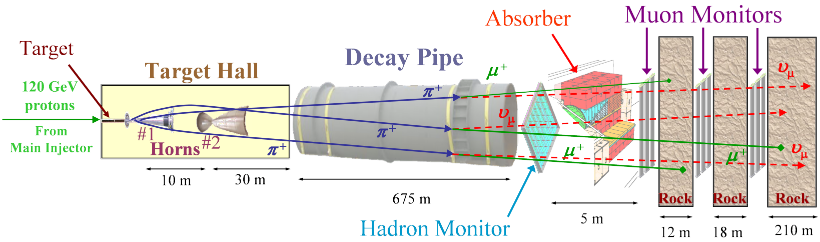
- ν_μ disappearance: $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$
- ν_e appearance: $\sin^2\theta_{23}$, Δm^2_{32}, δ_{CP}
- NC: 3ν model tests, sterile ν
- Xsecs physics
- Supernovae, multi-μ, monopoles, ν magnetic moments, LDM...

$\nu_e + \bar{\nu}_e$ bi-event plot (prediction)

- Predicted event counts of ν_e and $\bar{\nu}_e$ vary due to oscillation parameters (possible CP violation) and matter effect (affecting ν_e and $\bar{\nu}_e$ differently)
- NOvA has the longest baseline of experiments with artificial ν sources, consequent matter effect has an impact of up to ca $\pm 30\%$ of ν_e events
- Ellipses are drawn as a function of δ_{CP} for normal and inverted neutrino mass ordering and for upper ($> 45^\circ$) and lower ($< 45^\circ$) octant of θ_{23}



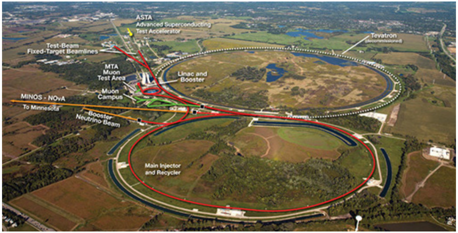
Fermilab NuMI beam



2018 analysis collected exposure:

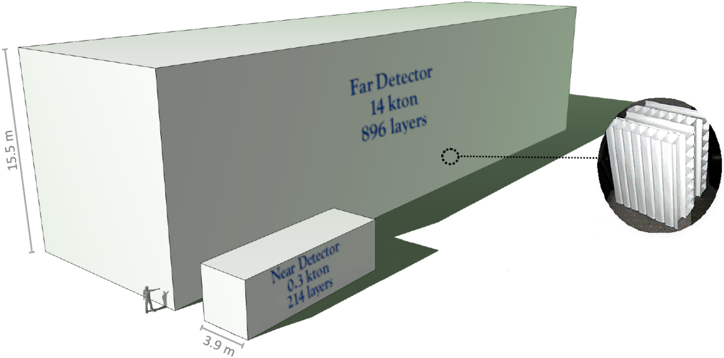
neutrino: 8.85×10^{20} POT of 14 kton equivalent

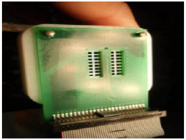
antineutrino: 6.91×10^{20} POT (to Apr 2018)

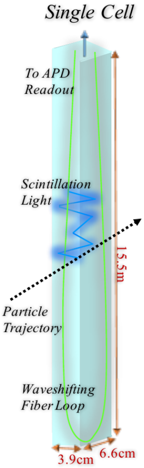


- Since Jan 2017 at designed 700 kW ($> 18 \times 10^{18}$ protons/week) – the most powerful neutrino beam
- 120 GeV protons from the Main Injector at Fermilab in 10 μs spills
- Magnetic focusing horns allow selection of charge sign of secondary particles (π, K), thus effectively selecting a neutrino or antineutrino beam

NOvA detectors

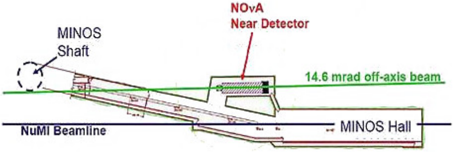




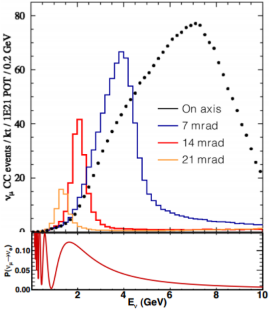


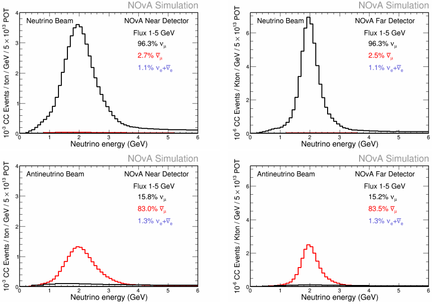
- Two functionally identical detectors, 810 km apart – Near (ND) and Far (FD) detector
- FD on the surface, ND more than 90 m underground
- Consist of extruded plastic cells with alternating vertical and horizontal orientation for 3D reconstruction
- Filled with liquid scintillator, tracking calorimeter with 65% active mass (FD 14 kton, ND 0.3 kton)
- More than 344 000 (FD) and 20 000 (ND) readout channels

Off-axis concept



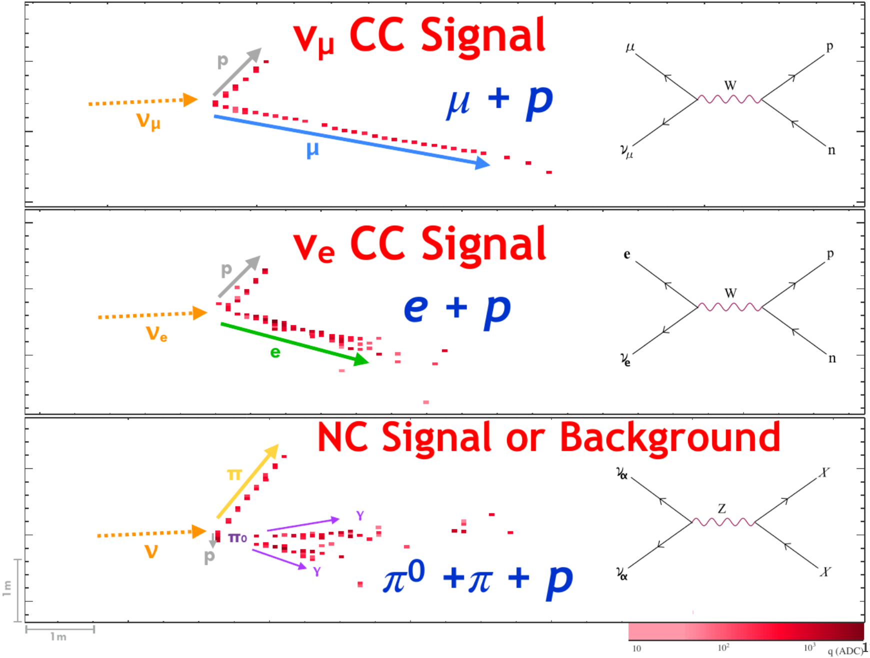
- Both detectors 14.6 mrad off the NuMI beam axis
- Narrowing the energy spectrum around the oscillation maximum (∼2 GeV)
- Reducing backgrounds with broad energy distributions
- Reducing contamination of wrong-sign neutrinos
- $\bar{\nu}$ cross-section about 3× lower than for ν



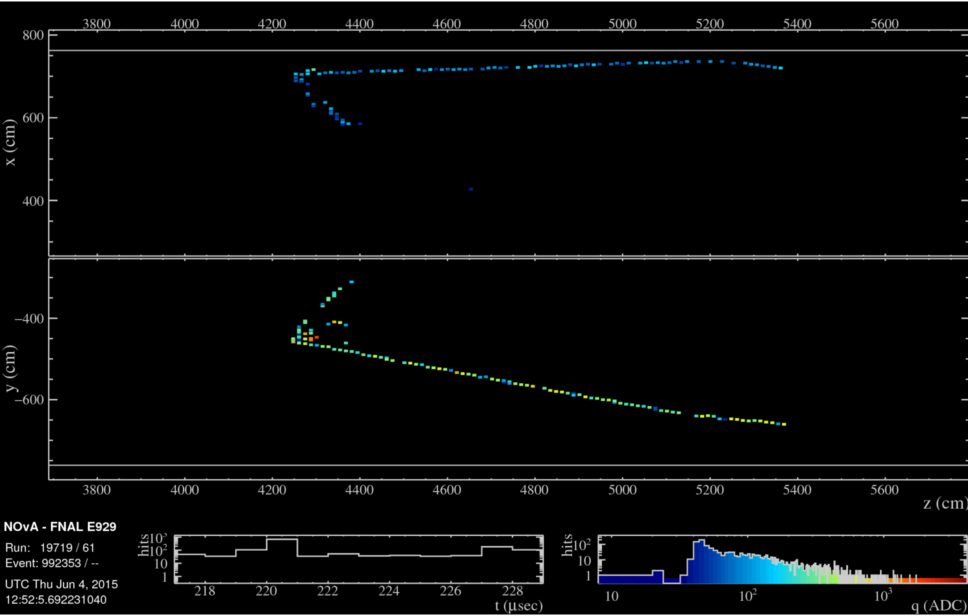


NOvA Analysis Features

NOvA event topologies

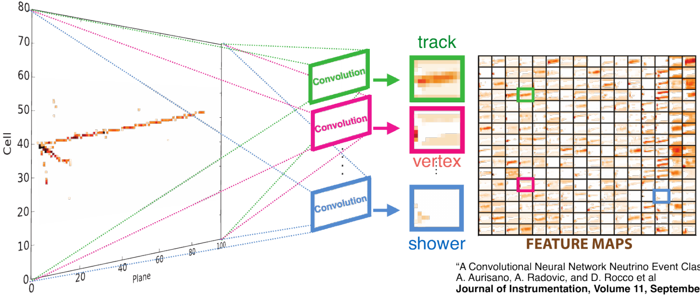


NOvA ν_μ event



Classification of neutrino interactions

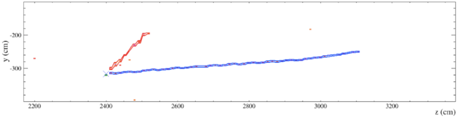
- Pioneering the use of CNN (Convolutional Neural Networks) for particle classification in neutrino physics
- CVN = Convolutional Visual Network treats every interaction in the detector as an image with cells being pixels and collected charge being their color, extracting basic "features" from the data
- INPUT: calibrated 2D pixelmaps; OUTPUT: multi-label classifier based on final state particle multiplicities
- Used in all main analyses (ν_μ, ν_e and NC) together with additional supporting PIDs (separate ν_μ/ν_e cosmic rejection, muon reconstructed track)
- CVN trained separately for neutrinos and antineutrinos, included cosmic data



"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

Energy reconstruction

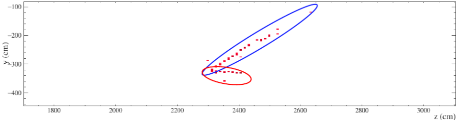
ν_μ energy



$$E_{\nu_\mu} = E_\mu + E_{\text{had}}$$

- ν_μ energy as a sum of μ and hadronic energy
- μ energy estimated from the length of the track
- Hadronic energy from calorimetric reconstruction

ν_e energy



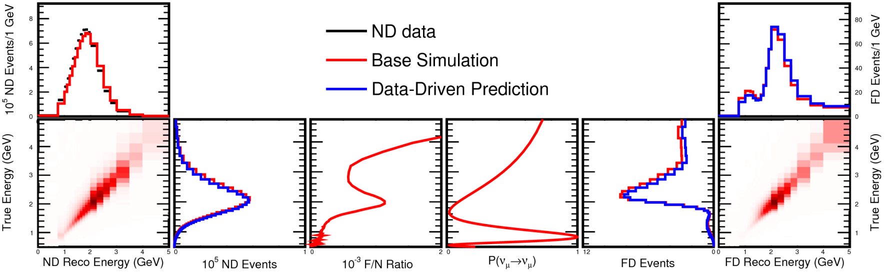
E_{ν_e} = quadratic func. of E_{EM} and E_{had}

- Both energies reconstructed calorimetrically
- EM shower (EM "prong") identified with a single-prong CVN variant
- Remaining activity is accounted for hadronic energy

Data-driven predictions

- The neutrino spectra is measured in ND before oscillations, this is a combination of neutrino flux, cross section and efficiency
- The measured spectra are used to make predictions of observations in FD using the Far/Near (F/N) ratio, i.e. adjusting FD MC
- Due to similar functionality of both detectors, this technique largely cancels the flux and cross section systematic uncertainties

$$\text{ND } \nu_\mu \longrightarrow \text{FD } \nu_\mu \text{ sample}$$
$$\text{ND } \nu_\mu \longrightarrow \text{FD } \nu_e \text{ signal}$$
$$\text{ND } \nu_e \longrightarrow \text{FD } \nu_e \text{ background}$$

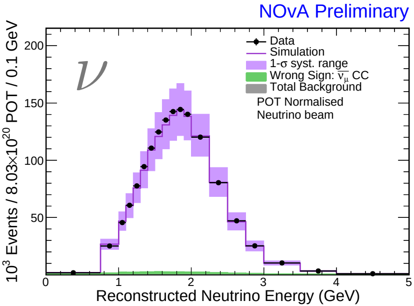


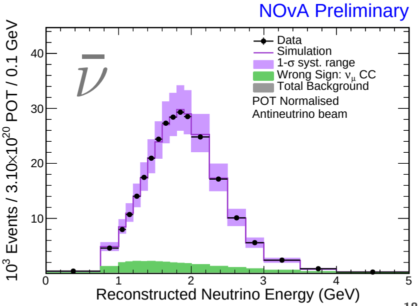
2018 $\nu + \bar{\nu}$ Oscillation Analysis

$\nu_\mu + \bar{\nu}_\mu$ disappearance analysis

Near detector data

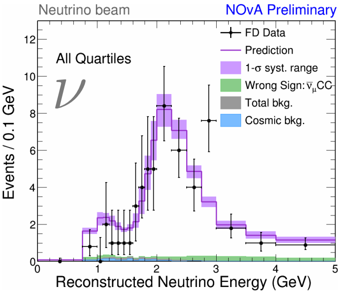
- Selected ν_μ and $\bar{\nu}_\mu$ charged current events in ND
- Wrong sign contamination in ND is estimated to be 3% for ν and 11% for $\bar{\nu}$ beam
- The data is split in 4 equal populations (quantiles) of hadronic energy fraction as a function of reconstructed energy
- Energy resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for ν ($\bar{\nu}$) beam, better for lower hadronic energy fractions
- Most background appears in quantiles with higher hadronic energy fraction

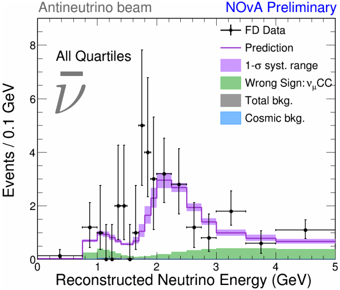




$\nu_\mu + \bar{\nu}_\mu$ disappearance analysis

Far detector data





- Selection efficiency 31.2% (33.9%) and purity 98.6% (98.8%) for ν_μ ($\bar{\nu}_\mu$) CC
- F/N ratio applied seperately for each quantile
- Cosmic background rate is estimated from the timing sidebands of NuMI beam triggers and cosmic trigger data

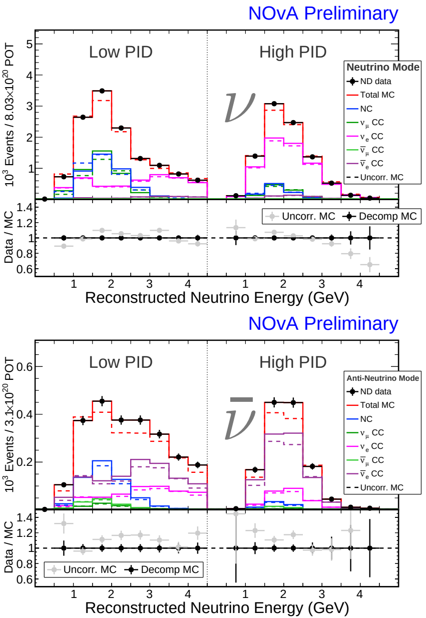
Observed 113 ν_μ CC events			
Exp. $730^{+38}_{-49}(\text{syst}) \pm 27(\text{stat})$ w/o osc.			
Total bkg. 11.0 events			
$\bar{\nu}_\mu$	NC	other beam bkg.	cosmic
7.24	1.19	0.51	2.07

Observed 65 $\bar{\nu}_\mu$ CC events			
Exp. $266^{+12}_{-14}(\text{syst}) \pm 16(\text{stat})$ w/o osc.			
Total bkg. 13.7 events			
ν_μ	NC	other beam bkg.	cosmic
12.58	0.39	0.23	0.46

$\nu_e + \bar{\nu}_e$ appearance analysis

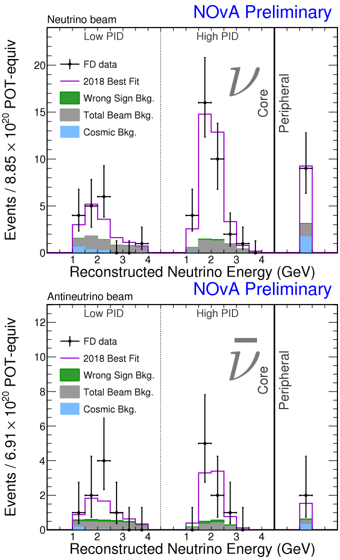
Near detector data

- Split into regions of low and high PID (CVN score)
- Used to predict FD appeared ν_e background
- ν beam background components constrained:
  1. beam ν_e share the common parents with $\nu_\mu - \nu_e$ content can be estimated by constraining π and K from contained and uncontained samples of ν_μ
  2. ν_μ component using Michel electrons
  3. remaining data/MC discrepancy is accounted for NC interactions
- $\bar{\nu}$ beam components scaled evenly to match the data



$\nu_e + \bar{\nu}_e$ appearance analysis

Far detector data



- ND ν_e data used to predict FD ν_e background, each component propagated independently in energy and particle ID bins
- Peripheral sample with less stringent containment and high particle ID, usually not fully contained events
- $> 4\sigma$ evidence of $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam

Observed 58 ν_e CC events

Exp. 30 ($\pi/2$ IH) to 75 ($3\pi/2$ NH)

Total bkg. 15.1 events

$\bar{\nu}_e$	beam ν_e	ν_μ	ν_τ	NC	cosmic
0.66	6.85	0.63	0.37	3.21	3.33

Observed 18 $\bar{\nu}_e$ CC events

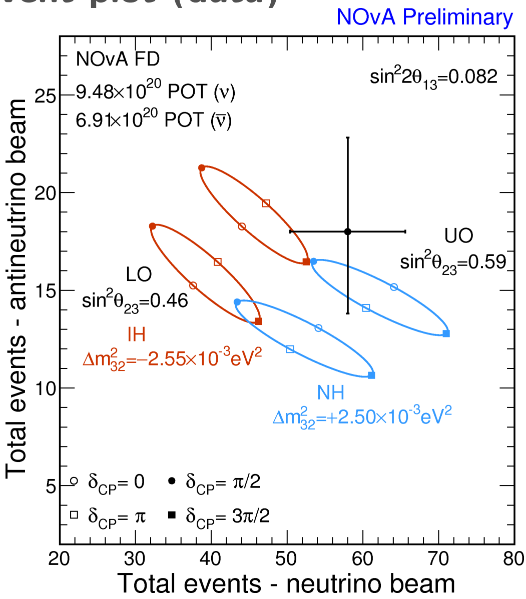
Exp. 10 ($3\pi/2$ NH) to 22 ($\pi/2$ IH)

Total bkg. 5.3 events

ν_e	beam ν_e	ν_μ	ν_τ	NC	cosmic
1.13	2.57	0.07	0.15	0.67	0.71

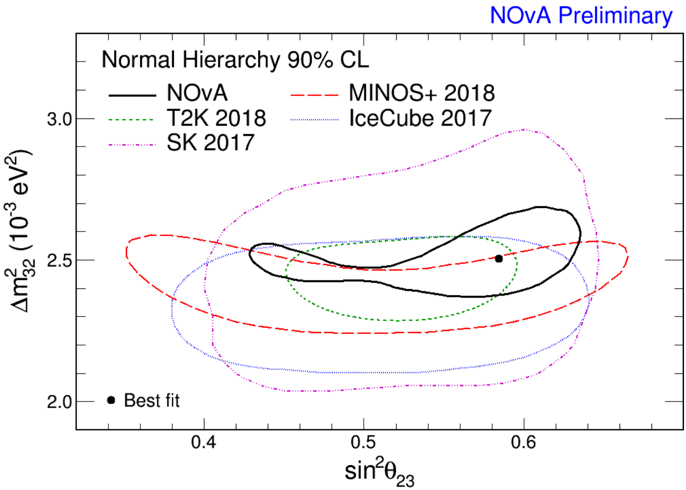
2018 Constraints on Oscillation Parameters

$\nu_e + \bar{\nu}_e$ bi-event plot (data)



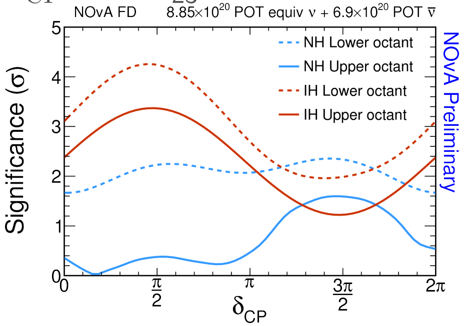
- All the constraints to be shown are from joint $\nu + \bar{\nu}$ and $\nu_\mu + \nu_e$ fit

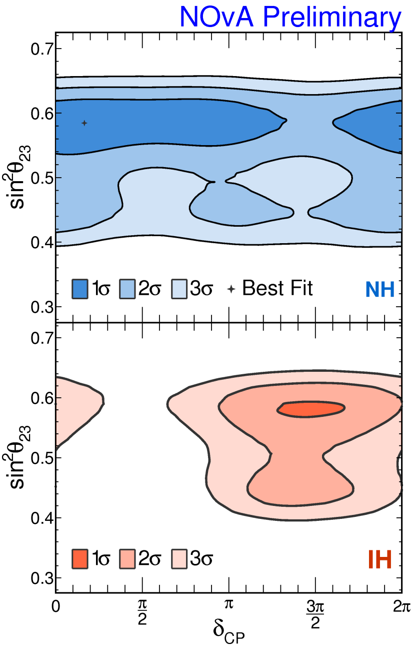
θ_{23} and Δm^2_{32} with NOvA's friends



- 90% C.L. region is consistent with other experiments

δ_{CP} and θ_{23}





- Joint $\nu + \bar{\nu}$, $\nu_\mu + \nu_e$ fit
- Prefers non-maximal θ_{23} at 1.8σ, disfavors lower θ_{23} octant
- Prefers NH for all δ_{CP} at 1.8σ
- Disfavors $\delta_{CP} = \pi/2$ in IH

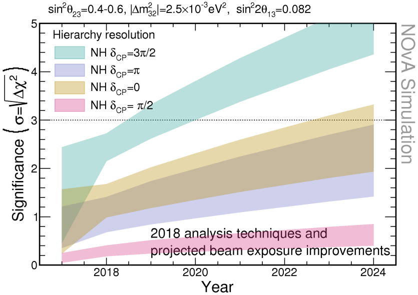
Best fit:

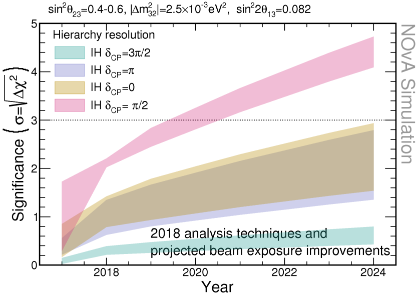
Normal hierarchy, $\delta_{CP} = 0.17\pi$
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (upper octant)
$\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}$ eV^2

Future Prospects and Summary

Future prospects

Mass hierarchy determination





- Expect to extend running until 2024 with accelerator upgrades and an equal total exposure in both ν and $\bar{\nu}$ beam modes
- Based on projected 2018 analysis techniques
  - Possible 3σ sensitivity to hierarchy by 2020 in case of favorable true values of parameters (NH + $\delta_{\mathrm{CP}} = 3\pi/2$)
  - 3σ for 30-50% of all δ_{CP} values by 2024 otherwise

In progress

- 2019 top up analysis with 12.33×10^{20} POT (additional $\sim 5.4 \times 10^{20}$ POT, $+75\%$) antineutrino data finishing soon
- $\nu + \bar{\nu}$ paper in preparation
- Test beam program running to study detector response in detail and get potential analysis improvements – systematics reduction, validation and training of reconstruction or machine learning algorithms, simulation improvements
- Beam switched back to neutrino mode, expecting about additional 5-6×10^{20} POT of neutrino data for 2020
- Plans of improvements for 2020 analysis

Summary

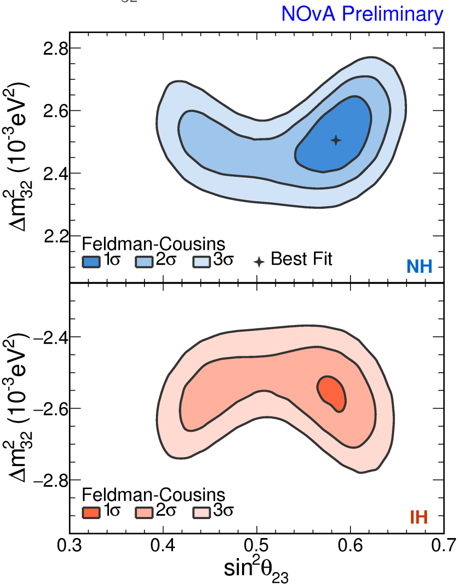
- First antineutrino data from NOvA (6.91 $\times 10^{20}$ POT) has been analyzed together with neutrino data (8.85 $\times 10^{20}$ POT)
- Neutrino data results published: Phys. Rev. D 98, 032012
- NOvA observes $> 4\sigma$ evidence for $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam
- Joint $\nu_e + \nu_\mu$ analysis of complete $\nu + \bar{\nu}$ datasets
  - $\sin^2\theta_{23} = 0.58 \pm 0.03, \Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}$ eV^2
  - Prefers normal hierarchy at 1.8σ and disfavors inverted hierarchy for $\delta_{\rm CP} = 3\pi/2$ at $> 3\sigma$
  - Rejects maximal mixing at 1.8σ and the lower octant at a similar level
- Expect running up to 2024 with equal total exposure in both ν and $\bar{\nu}$ beam modes
- NOvA can reach 3σ sensitivity for the mass hierarchy by 2020 in the most favorable case (NH, $\delta_{\rm CP} = 3\pi/2$) and cover more than 30% of all values of $\delta_{\rm CP}$ by 2024

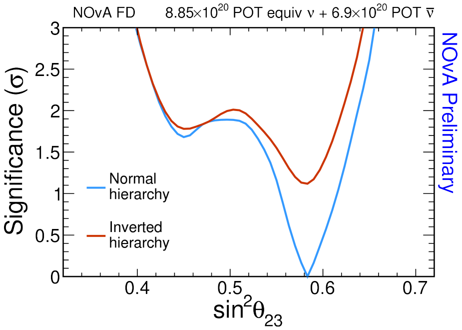
Thank you for your attention

BACKUPS

Backups

θ_{23} **and** Δm^2_{32}





- Joint $\nu + \bar{\nu}$, $\nu_\mu + \nu_e$ fit
- Prefers non-maximal θ_{23} at 1.8σ, disfavors lower θ_{23} octant

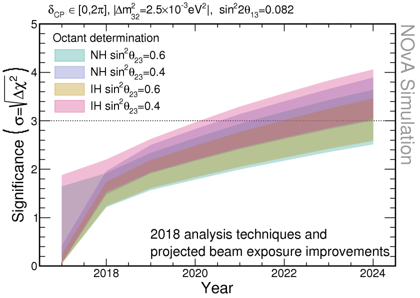
Best fit:

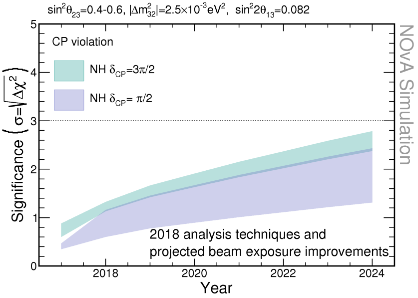
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (upper octant)

$\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}$ eV^2

Backups

Octant θ_{23} and δ_{CP}

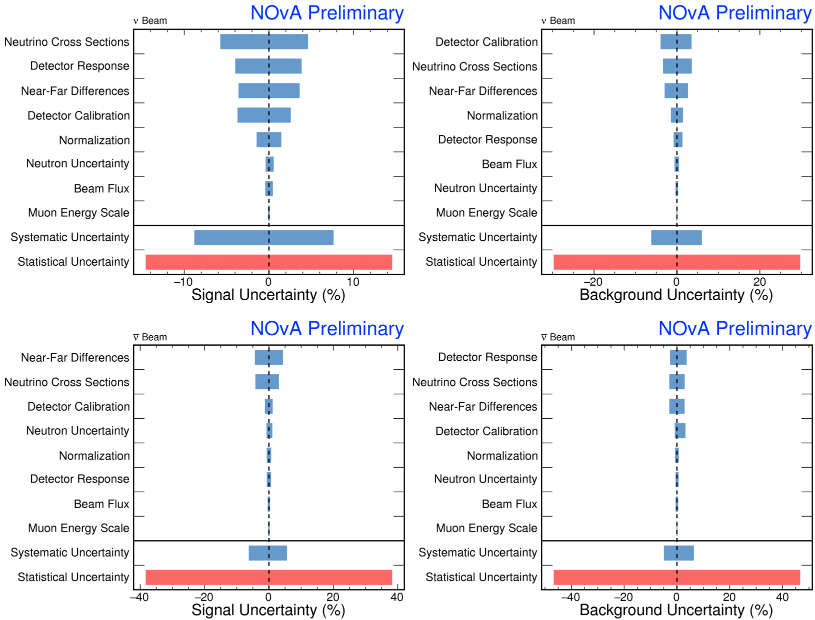




- Based on projected 2018 analysis techniques
  - Depending on the true values of parameters about 3σ sensitivity to θ_{23} by 2024 (both orderings, all δ_{CP})
  - $2+\ \sigma$ sensitivity to CP violation in case of $\delta_{\mathrm{CP}} = \pi/2$ or $3\pi/2$ by 2024

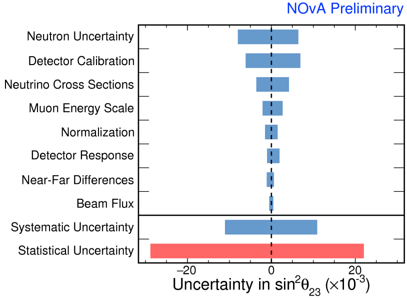
Backups

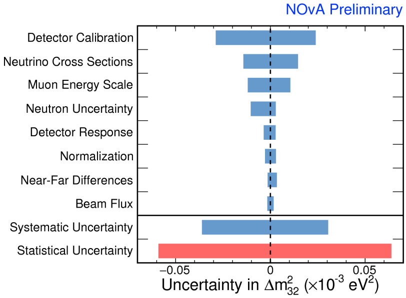
ν_e systematics

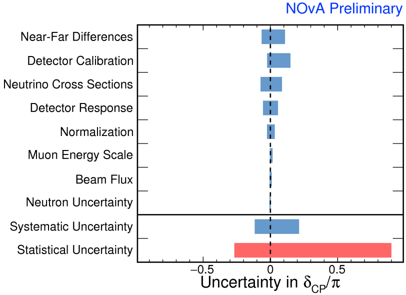


Backups

Joint fit systematics

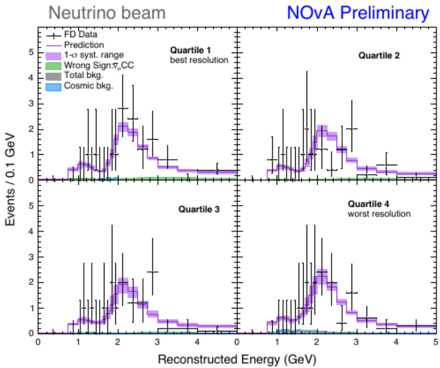


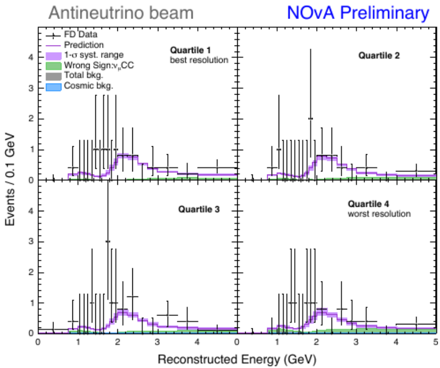




Backups

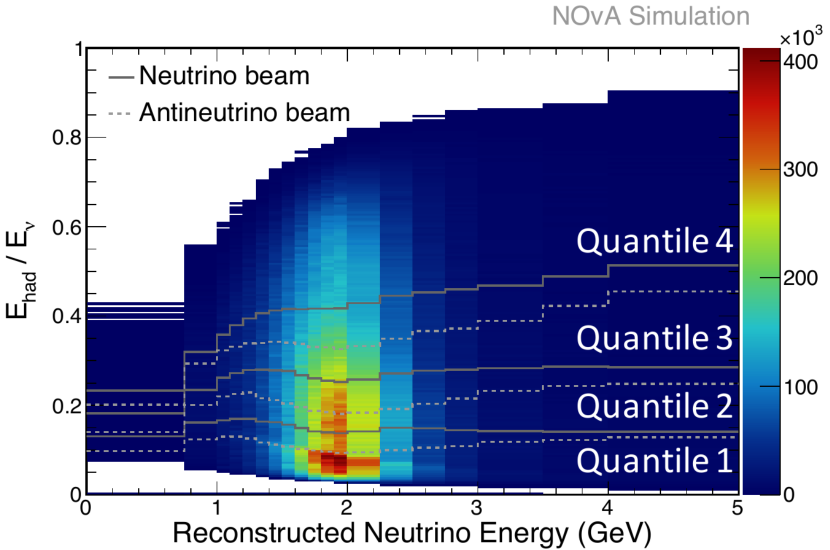
ν_μ quantiles





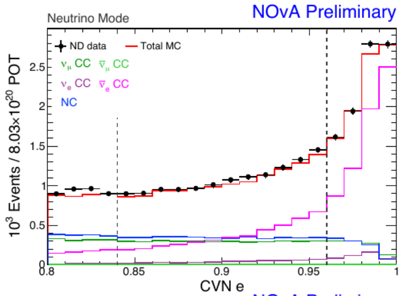
Backups

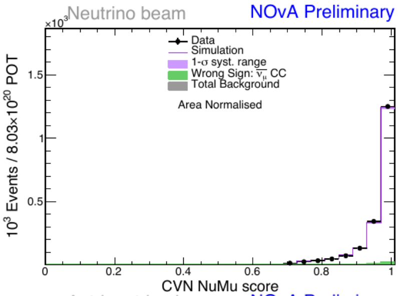
ν_μ resolution binning

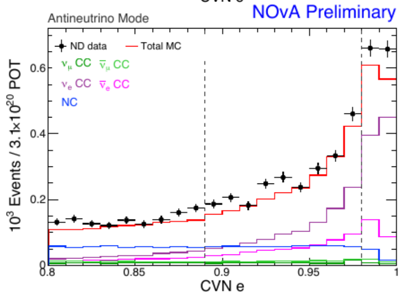


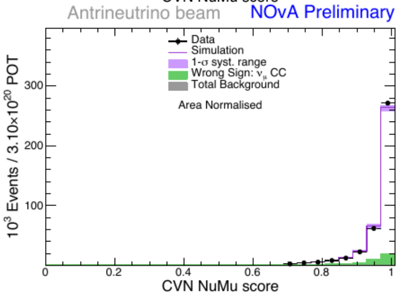
Backups

CVN distributions



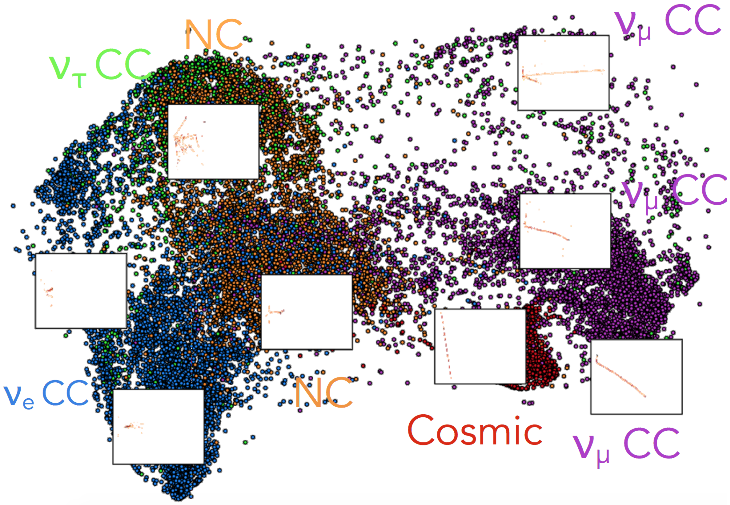






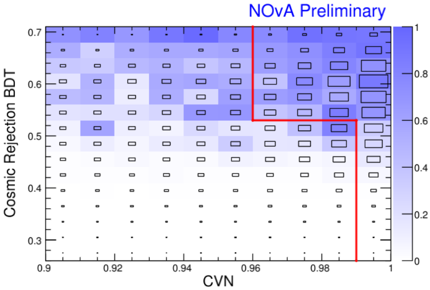
Backups

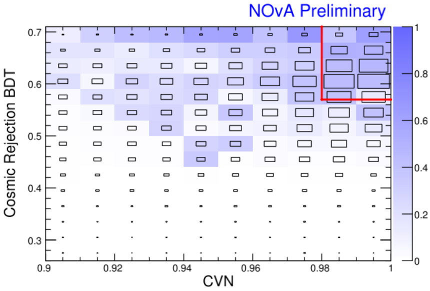
Classification of neutrino interactions



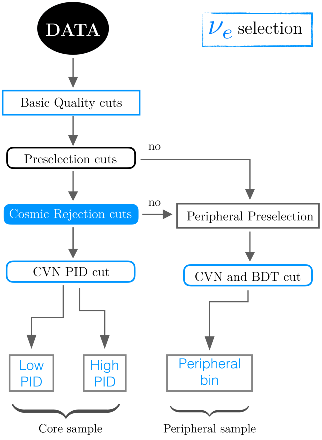
Backups

ν_e peripheral sample



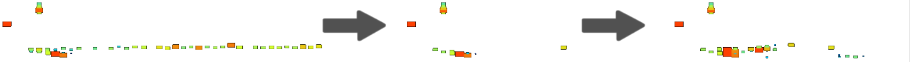


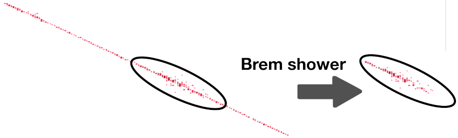
- Events failing the "core" selection can pass a BDT cut plus a tight CVN cut



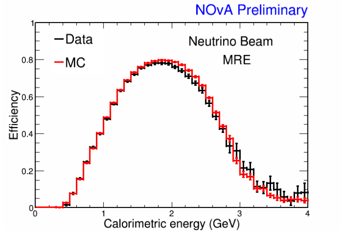
Backups

Data-driven checks of CVN



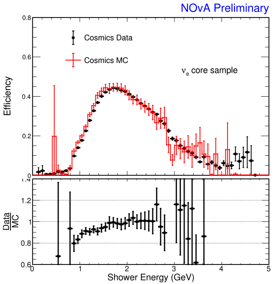


- In ND remove μ track and replace with simulated electron in both data and MC



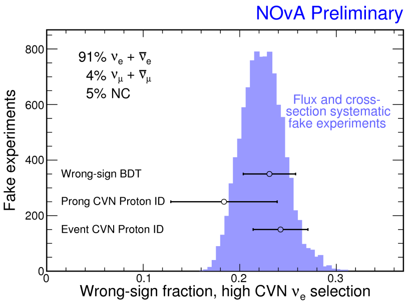
	ν	$\bar{\nu}$
Data eff.	65.0%	67.7%
MC eff.	66.7%	68.6%
Diff.	+2.6%	+1.2%

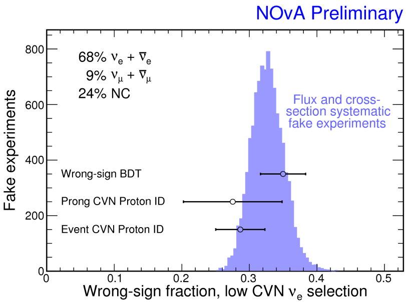
- In FD isolate the bremsstrahlung showers in cosmic rays data and MC to create a control sample

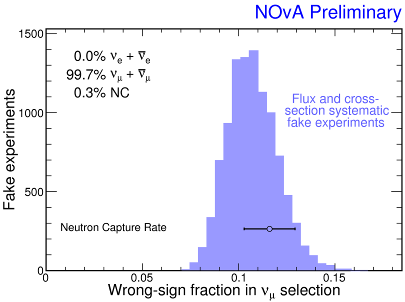


Backups

Wron-sign fraction cross check



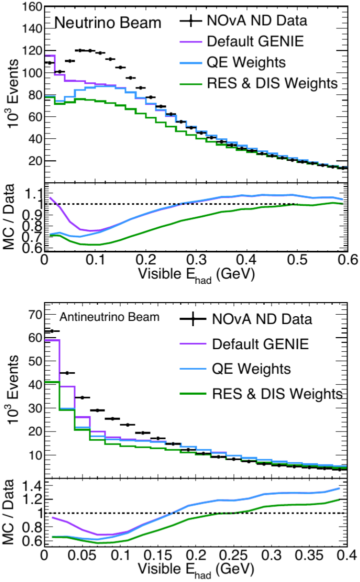




Backups

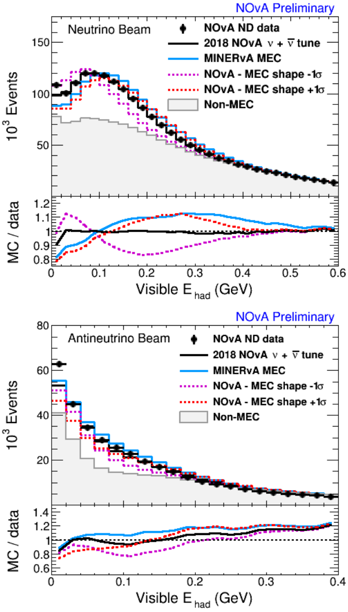
Neutrino interaction tuning

- Tuning done independently for ν and $\bar{\nu}$ beam samples
- Correct quasielastic (QE) component to account for effect of long-range nuclear correlations using model of ValÃÍncia group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
- Apply same long-range effect as for QE to resonant (RES) baryon production.
- Nonresonant inelastic scattering (DIS) at high invariant mass (W >1.7 GeV/c^2) weighted up 10% based on NOvA data



Backups

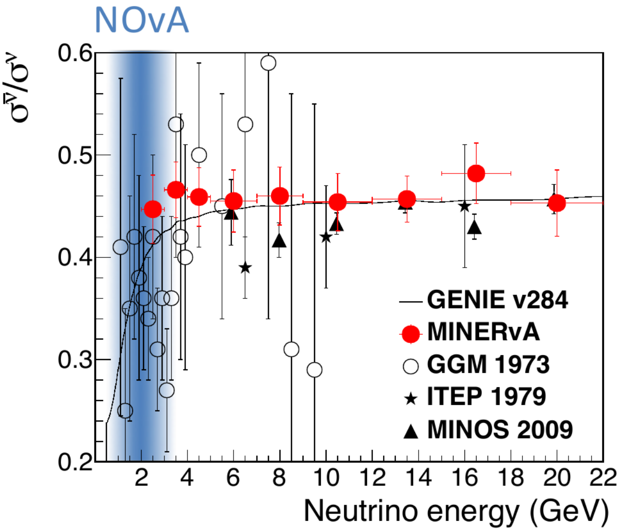
Neutrino interaction tuning



- Introduce custom tuning of GENIE "Empirical MEC" [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] based on NOvA ND data to account for multinucleon knockout (2p2h)
- Shape uncertainty on the NOvA 2p2h tune is established by re-fitting using variation of the model with correlated systematic shifts to QE and RES
- The MINERvA collaborationâĂŹs tuning to their data resulted in similar shape features to our assumed uncertainties

Backups

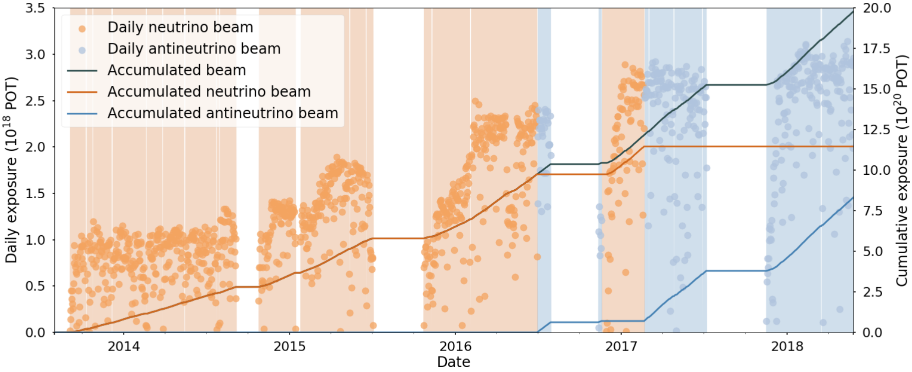
Cross section ratio



MINERvA, Phys.Rev. D95 (2017) no.7, 072009

Backups

2018 NuMI beam performance



- Running since 2013
- Since Jan 2017 at designed 700 kW ($> 18 \times 10^{18}$ protons delivered/week) – the most powerful neutrino beam