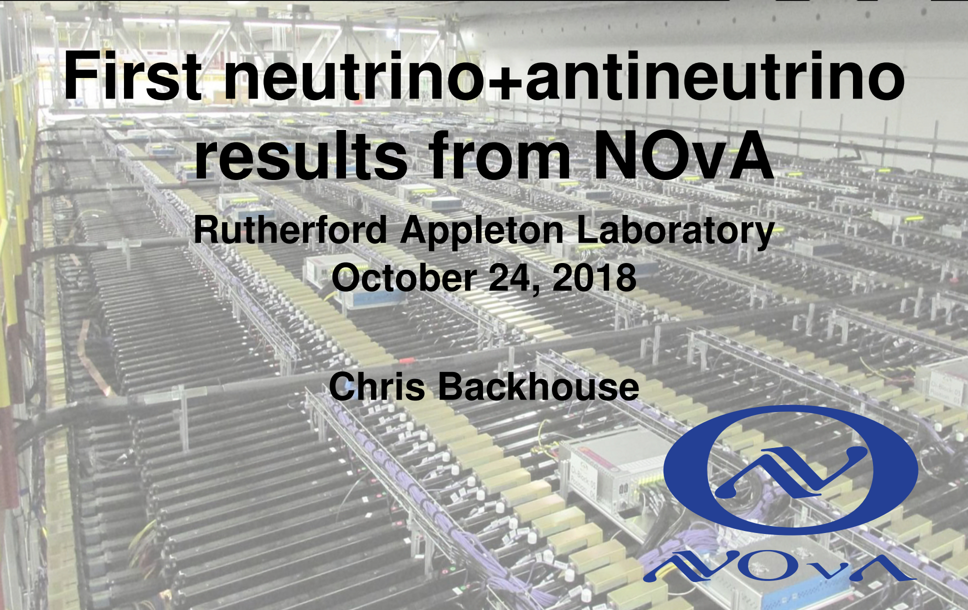


First neutrino+antineutrino results from NOvA

Rutherford Appleton Laboratory
October 24, 2018

Chris Backhouse

Neutrino oscillations

The NOvA experiment

ν_μ disappearance

- symmetries in neutrino mixing

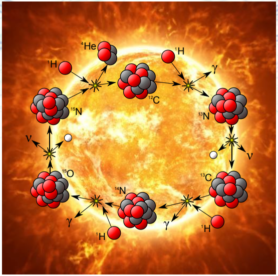
ν_e appearance

- neutrino mass ordering
- CP-violation

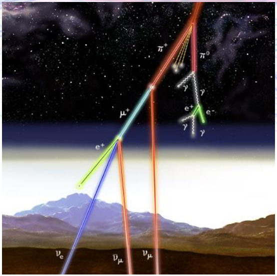
Future

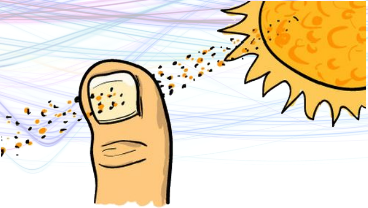
Neutrinos are everywhere

Solar



Atmospheric





FACT: about 65 million neutrinos pass through your thumbnail every second.

Reactor

Supernova

- Second most abundant particle in the universe
- But we know almost nothing about them
- Only interact via the weak force
- Need powerful sources and huge detectors

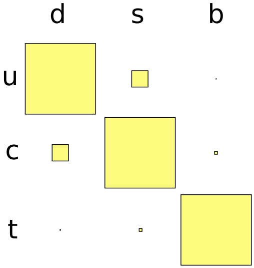
Neutrinos are unique

- Far lighter than the quarks and charged leptons
- May get their masses by a different mechanism

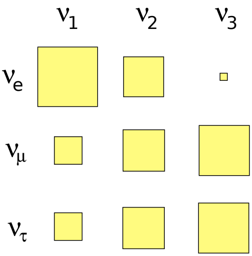
$$m_{\mathrm{EW}}^2/m_\nu \sim 10^{15}\,\mathrm{GeV} \sim m_{\mathrm{GUT}}$$

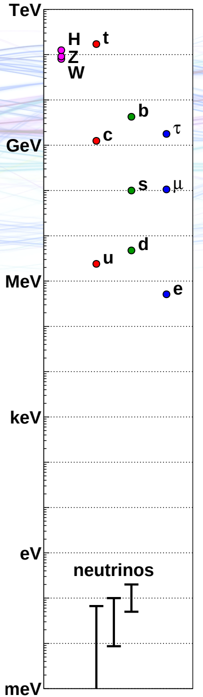
- Very different mixing structure to quarks

Quarks



Neutrinos





Neutrino oscillations

$$|\nu_\alpha\rangle = \frac{1}{\sqrt{2}}\left(|\nu_1\rangle + |\nu_2\rangle\right)$$

Neutrino oscillations

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Neutrino oscillations

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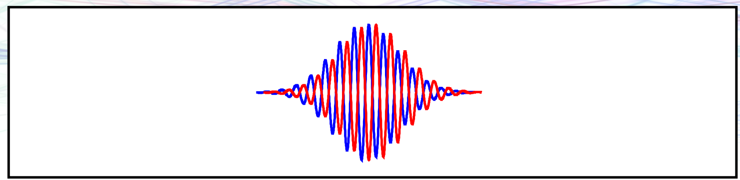
$m_2 > m_1$

Neutrino oscillations



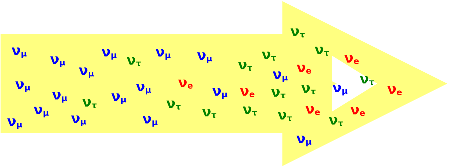
$$|\nu_\alpha\rangle = \frac{1}{\sqrt{2}}\left(|\nu_1\rangle + |\nu_2\rangle\right) \qquad |\nu_\beta\rangle = \frac{1}{\sqrt{2}}\left(|\nu_1\rangle - |\nu_2\rangle\right) \qquad m_2 > m_1$$

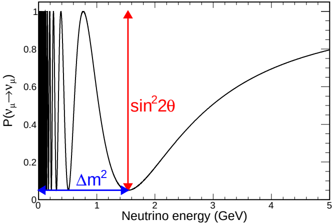
Neutrino oscillations

$|\nu_\alpha\rangle = \frac{1}{\sqrt{2}}\left(|\nu_1\rangle + |\nu_2\rangle\right)$ $|\nu_\beta\rangle = \frac{1}{\sqrt{2}}\left(|\nu_1\rangle - |\nu_2\rangle\right)$ $m_2 > m_1$

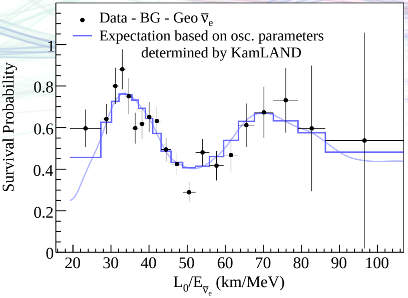
Neutrino oscillations

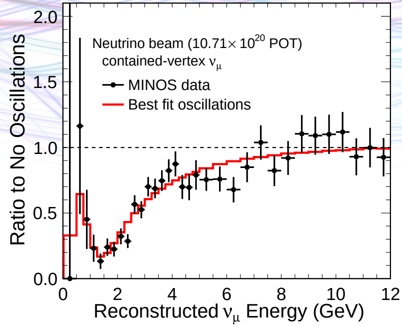
$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \quad \rightarrow \quad P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

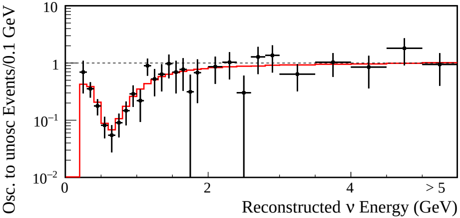


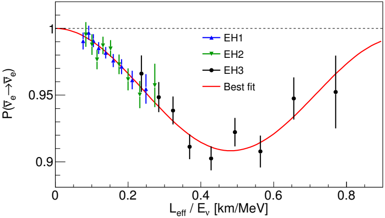


Oscillation structure









Current world knowledge

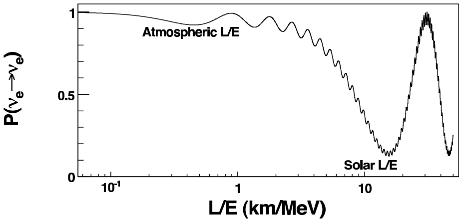
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

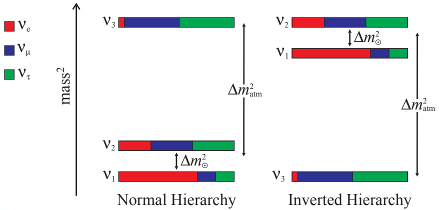
$\theta_{23} \sim 45^\circ$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3}\text{eV}^2$

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

$\theta_{12} \sim 33^\circ$
$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\text{eV}^2$

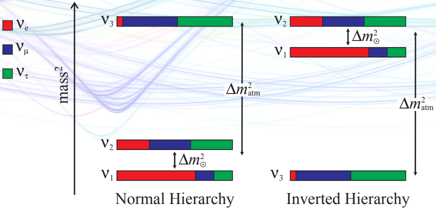
$\delta_{CP} = ?$

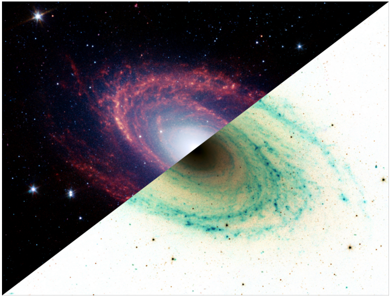


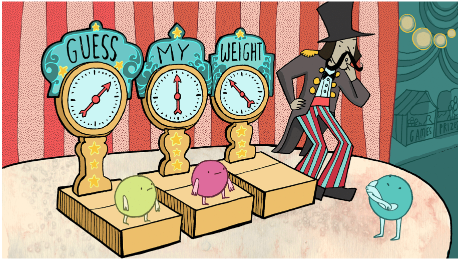


Open neutrino questions

- Dirac or Majorana?
  - Is $\bar{\nu}$ just a right-handed ν?
- Absolute masses
- *CP*-violation?
  - Do ν and $\bar{\nu}$ oscillations differ?
- Ordering of the mass states
- Random mixing parameters, or patterns?







symmetry magazine

What do we need?

- Requirements for neutrino oscillation experiment
  - High power neutrino source
  - Large detector
  - Good resolution of signal from background
  - Good control of systematic uncertainties

What do we need?

- Requirements for neutrino oscillation experiment
  - High power neutrino source
  - Large detector
  - Good resolution of signal from background
  - Good control of systematic uncertainties

- For mass ordering and CP-violation
  - Both disappearance ($\nu_\mu \rightarrow \nu_\mu$) and appearance ($\nu_\mu \rightarrow \nu_e$) modes
  - Long baseline
  - Ability to study neutrinos and antineutrinos

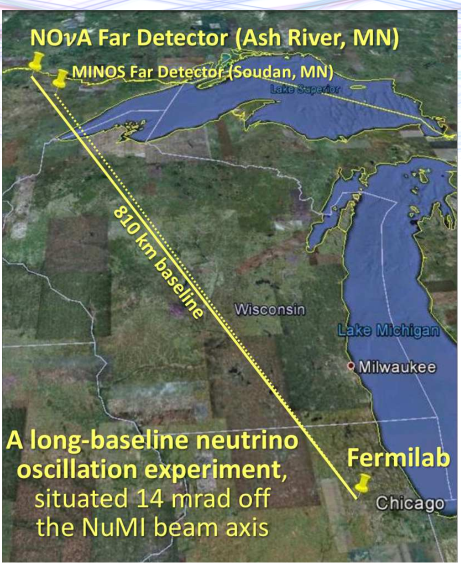
The NOvA collaboration

47 institutions, 7 countries, over 200 collaborators

Argonne, Atlantico, Austin, Banaras Hindu, Caltech, CUSAT, Czech Academy of Sciences, Charles, Cincinnati, Colorado State, Czech Technical University, Dallas, Delhi, Dubna, Fermilab, Goias, IIT-Guwahati, Harvard, Houston, IIT-Hyderabad, Hyderabad, Illinois Instute of Technology, Indiana, Iowa State, Irvine, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, NISR, Panjab, Pittsburg, South Alabama, SDMT, South Carolina, SMU, Stanford, Sussex, Tennessee, Tufts, UCL, Virginia, Wichita State, William and Mary, Winona State.

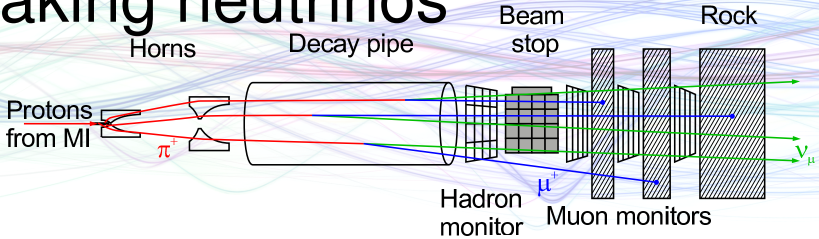
NOvA 10,000ft view

- ν_μ beam from Fermilab, IL
- Detector 810km away in MN
- Smaller detector onsite to measure flux before oscillations
  - $\nu_\mu \to \nu_\mu$
  - $\bar{\nu}_\mu \to \bar{\nu}_\mu$
  - $\nu_\mu \to \nu_e$
  - $\bar{\nu}_\mu \to \bar{\nu}_e$
- Precision measurements of $|\Delta m^2_{32}|$ and θ_{23}
- Determine the mass hierarchy
- Search for $\sin\delta_{CP} \neq 0$



A long-baseline neutrino oscillation experiment, situated 14 mrad off the NuMI beam axis

Making neutrinos

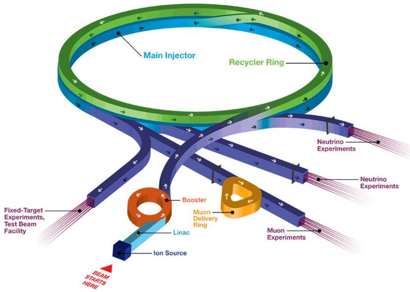


- 120 GeV protons from Main Injector
- Strike graphite target
- Produce mainly $\pi^\pm$ and $K^\pm$

- Focused by two magnetic horns
- Allow us to select charge sign for a neutrino or antineutrino beam

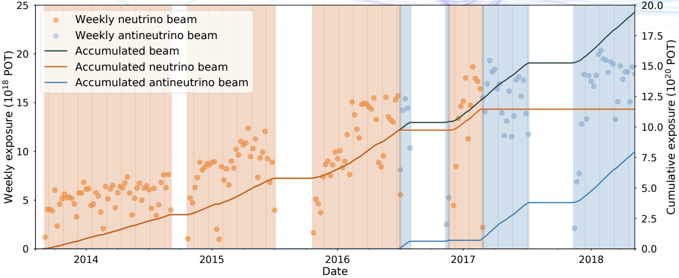
- 675m decay-pipe: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Muons absorbed by rock

Fermilab Accelerator Complex



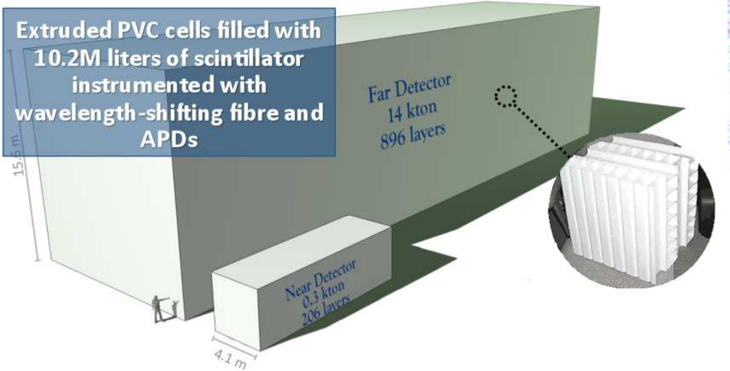
NuMI performance

- 700kW design power since Jun 2017
- World's highest power neutrino beam, $\sim 4 \times 10^{13}$ protons / pulse

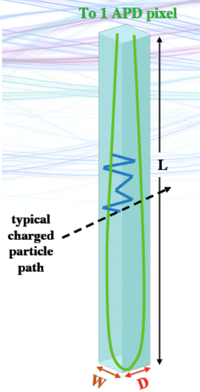


- Neutrino data from Feb 2014 to Feb 2017 – 8.85×10^{20} POT
- *Antineutrino* data from Feb 2017 to Apr 2018 – 6.9×10^{20} POT
- Approx 6×10^{20} POT / yr going forward

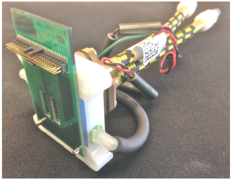
Detector technology

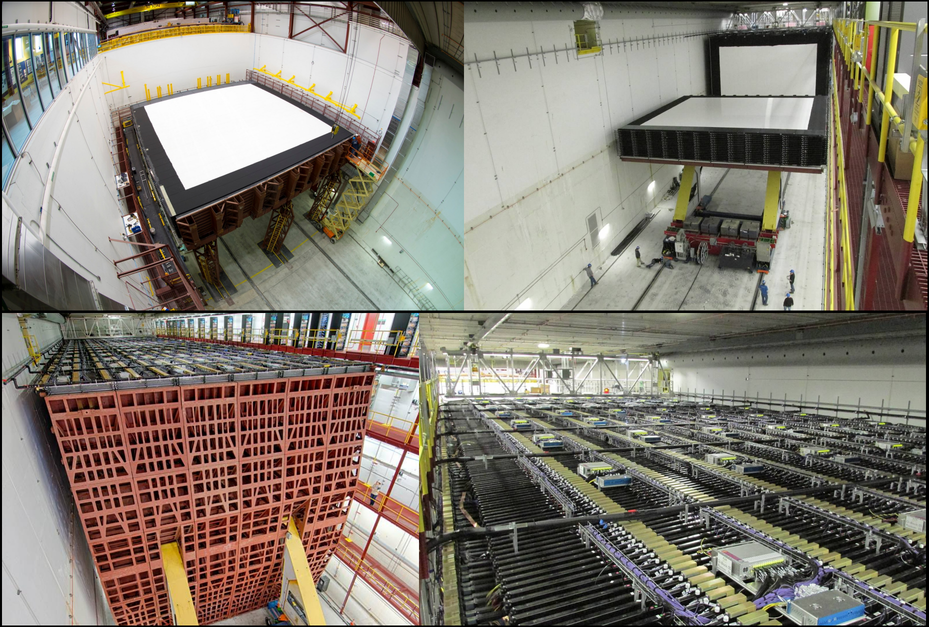


Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs

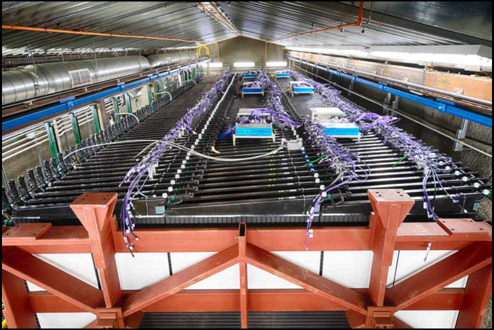


- 64% liquid scintillator by mass
- 4×6cm resolution, two views for 3D reco.
- 344,000 channels in 14 kton FD, on surface
- 300 ton ND, underground at FNAL

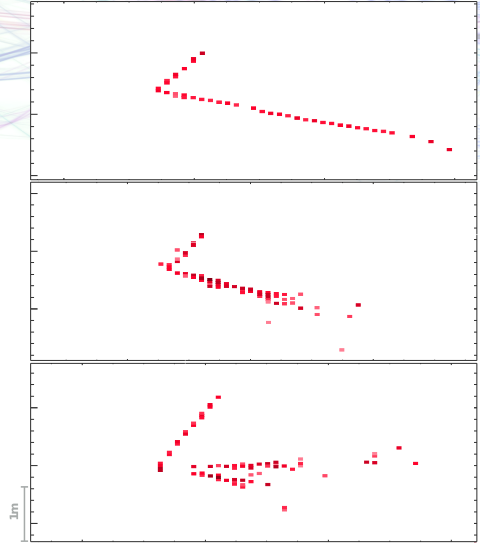




Near Detector

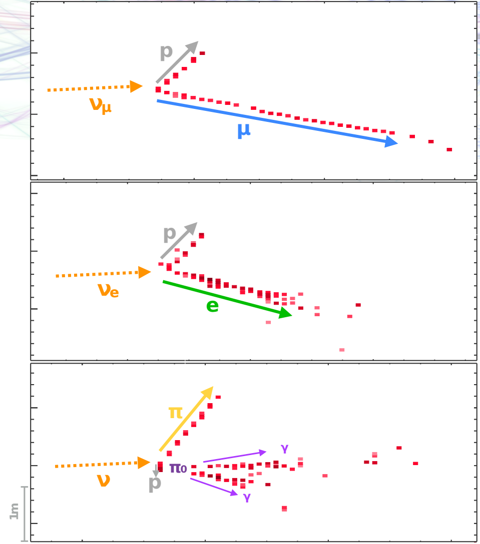


Event topologies



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

Event topologies



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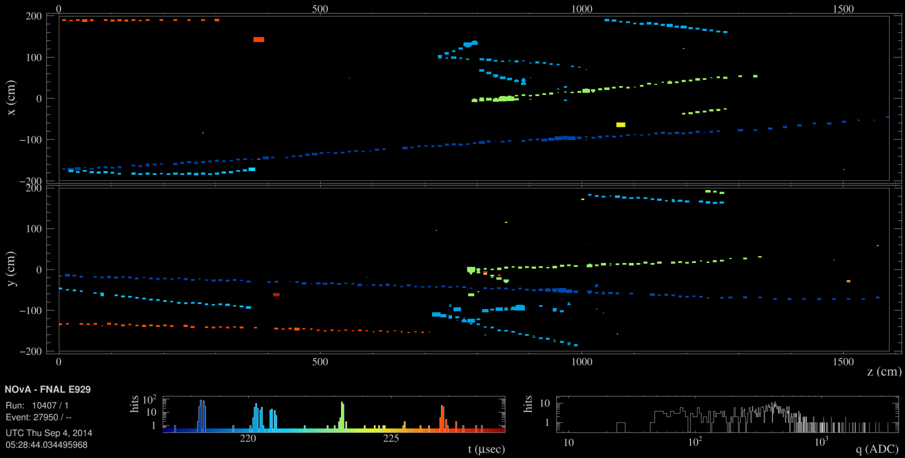
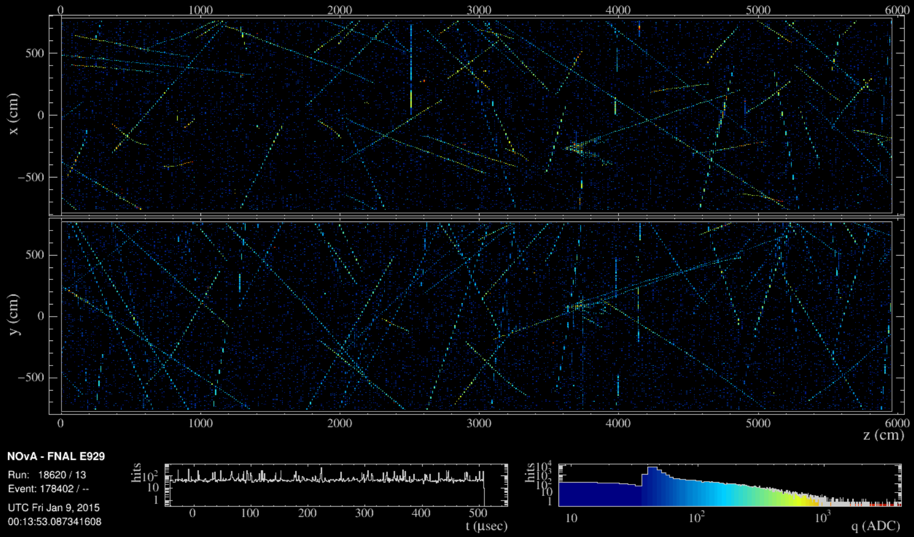
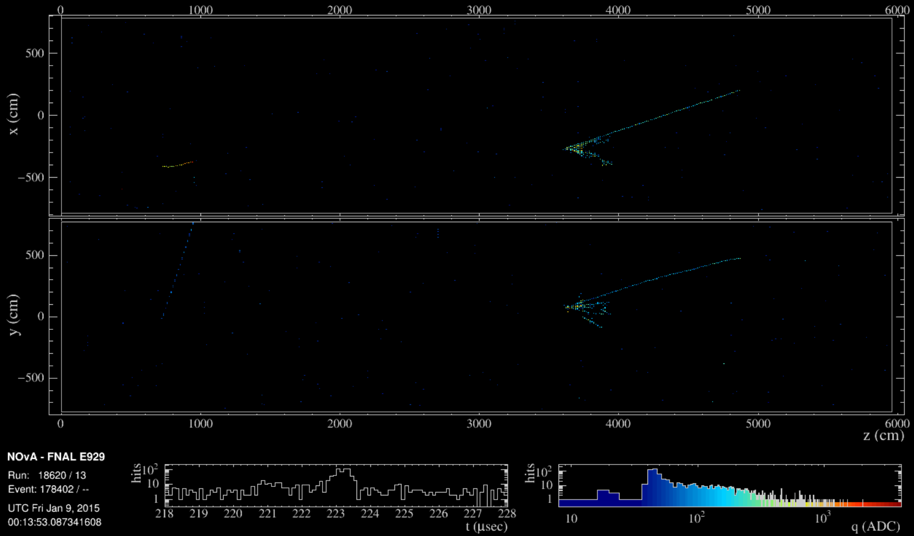
ND neutrinos



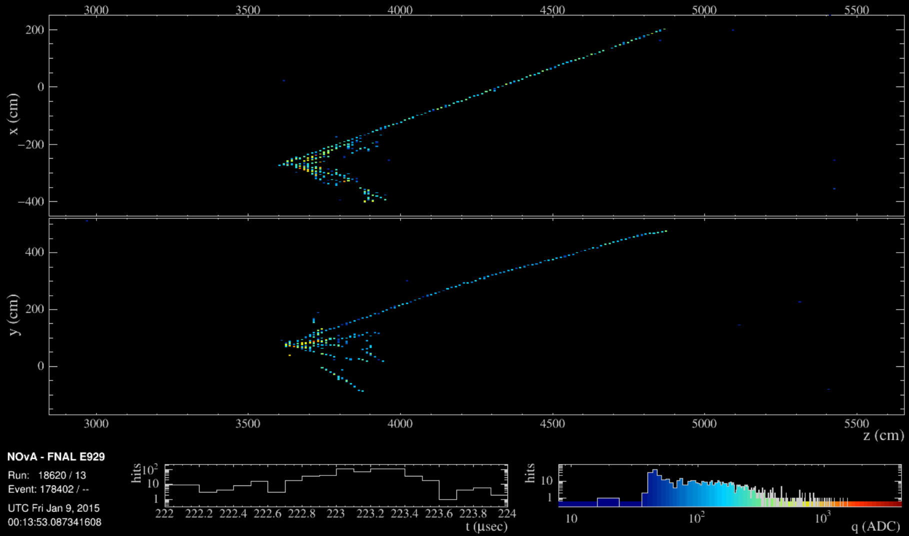
FD neutrinos



FD neutrinos

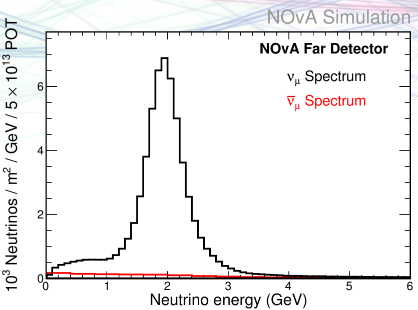


FD neutrinos

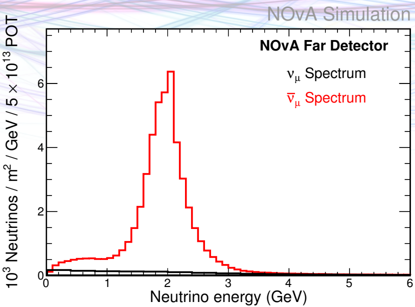


Neutrino vs antineutrino mode

Neutrino beam

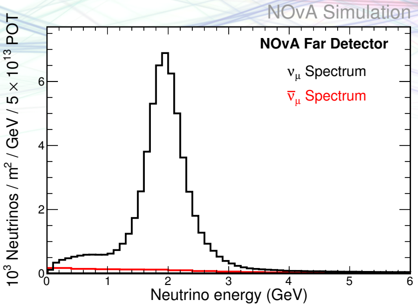


Antineutrino beam

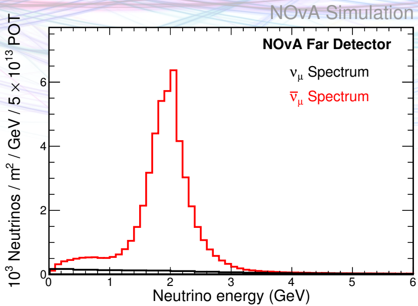


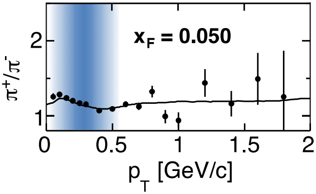
Neutrino vs antineutrino mode

Neutrino beam



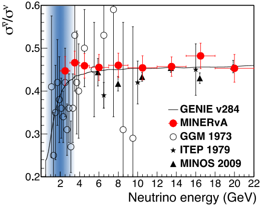
Antineutrino beam





NA49, Eur. Phys. J. C 49 897 (2007)

NOvA Focusing Peak

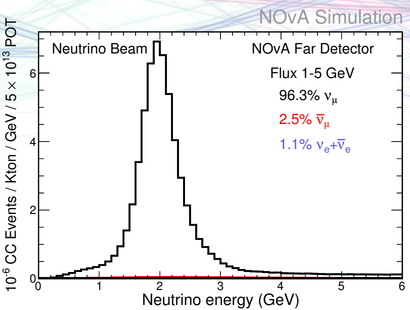


MINERvA, Phys.Rev. D95 (2017) no.7, 072009

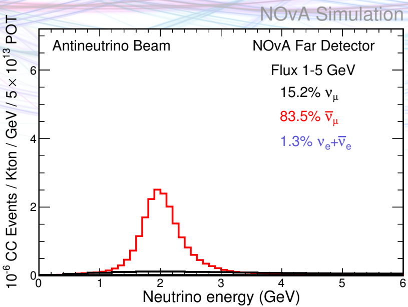
NOvA Focusing Peak

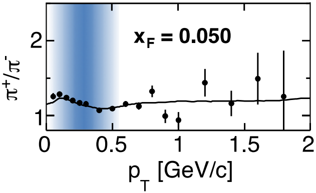
Neutrino vs antineutrino mode

Neutrino beam



Antineutrino beam





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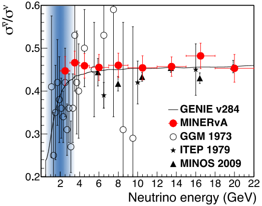


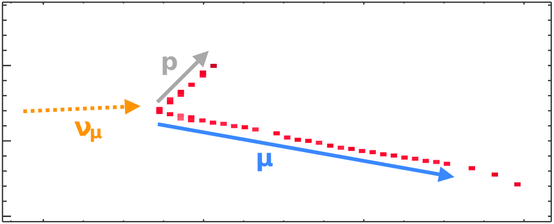
MINERvA, Phys.Rev. D95 (2017) no.7, 072009

NOvA Focusing Peak

Principle of the ν_μ measurement

- Separate ν_μ CC interactions from backgrounds
  - Long muon track with distinctive dE/dx easy to spot

- Extrapolate observed ND spectrum to make FD unosc. prediction
- Measure shape of ν_μ deficit in the FD



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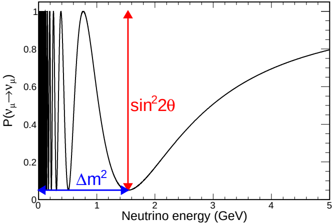
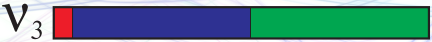
- Separate ν_μ CC interactions from backgrounds
    - Long muon track with distinctive dE/dx easy to spot

- Extrapolate observed ND spectrum to make FD unosc. prediction
- Measure shape of ν_μ deficit in the FD

- Two flavor approx. works well here
- $P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$
- $\theta_{23} \approx 45^\circ \rightarrow$ almost all ν_μ expected to disappear at oscillation max.



Mixing patterns

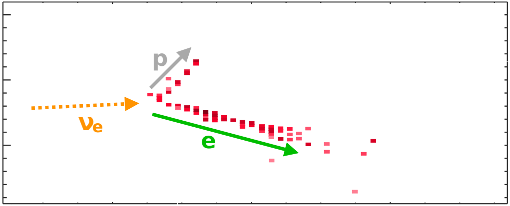


- Only a small fraction of ν_e in $|\nu_3\rangle$ ($\sin^2 2\theta_{13}$)
- The remainder is split $\sim 50/50$ ν_μ/ν_τ ($\sin^2\theta_{23}$)
- Accident? Or a sign of underlying structure?

- Is θ_{23} exactly 45°?
- If not, is it…
  - $< 45^\circ$ ($|\nu_3\rangle$ more ν_τ, like the quarks)
  - $> 45^\circ$ ($|\nu_3\rangle$ more ν_μ, unlike quarks)

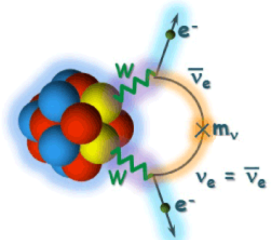
Principle of the ν_e measurement

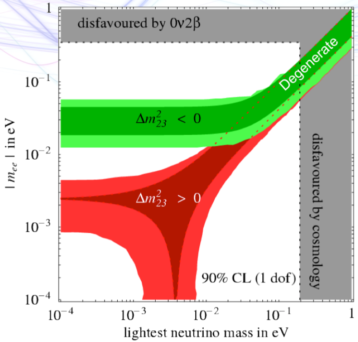
- Separate ν_e CC interactions from beam backgrounds
  - More challenging than ν_μ CC selection
- Evaluate remaining backgrounds in ND
  - Intrinsic beam ν_e
  - Neutral currents
  - ν_μ CC – mostly oscillates away
- An excess in the FD is the sign of $\nu_\mu \rightarrow \nu_e$ oscillations



Why hierarchy?

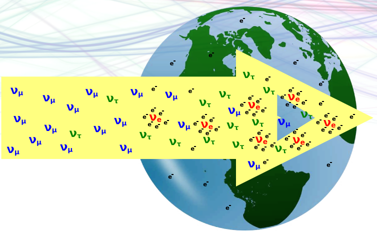
- Is the electron-like state lightest?
- *i.e.* Does the pattern of the masses match the charged leptons?

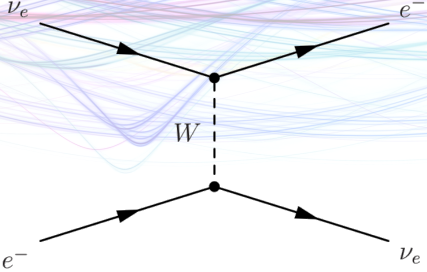




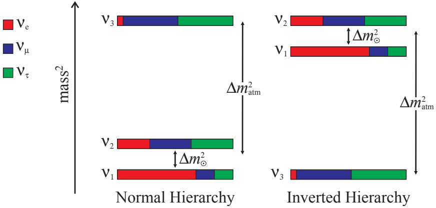
- Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- Observation of $0\nu\beta\beta$ would be proof they are
- Impact of **IH** determination: lack of $0\nu\beta\beta$ implies Dirac nature

Matter effects



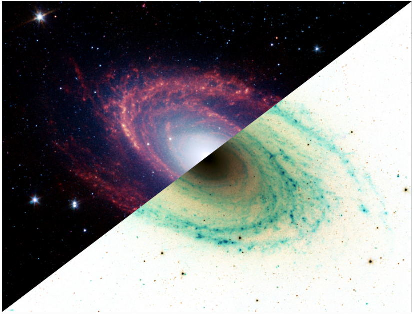


- Electrons in the Earth drag on the “electron” neutrino states
- Sign of the effect opposite for antineutrinos and for NH/IH



Neutrino/antineutrino symmetry

- Does $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- Insight into fundamental symmetries of the lepton sector
- "CP violation" – described by oscillation parameter δ_{CP}

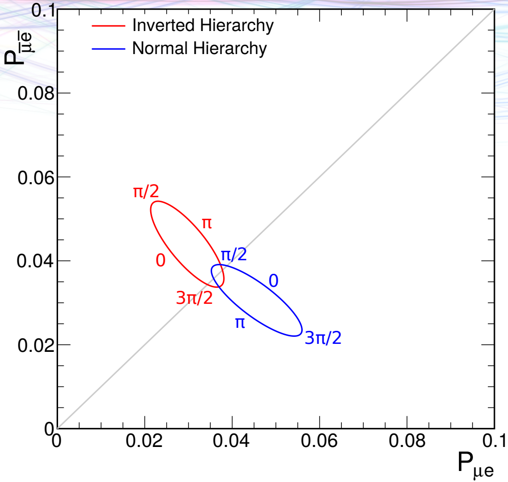


- Why is the universe not equal parts matter and antimatter?
- Need ppb early universe asymm.
- Existing CP-violation insufficient
- *"Leptogenesis"*: generate $\nu/\bar{\nu}$ imbalance, transfer to baryons

- Require neutrino **appearance** experiment to discover

Principle of the ν_e measurement

- To first order, NOvA measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ evaluated at 2GeV
- These depend differently on $\text{sign}(\Delta m^2_{32})$ and δ_{CP}



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) + f(\text{sign}(\Delta m^2_{32})) + f(\delta_{CP})$$

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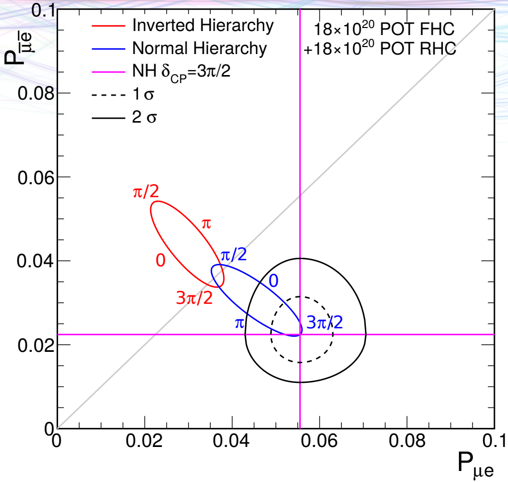

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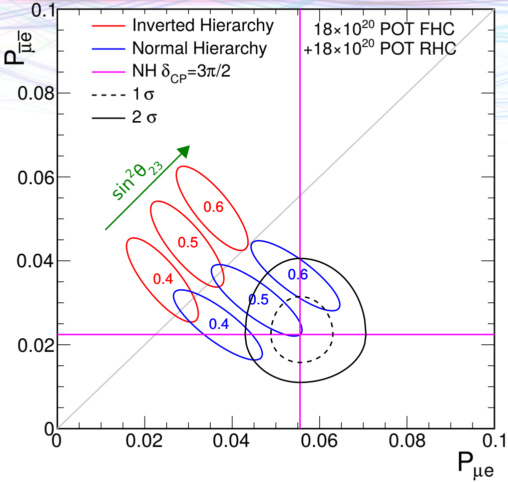

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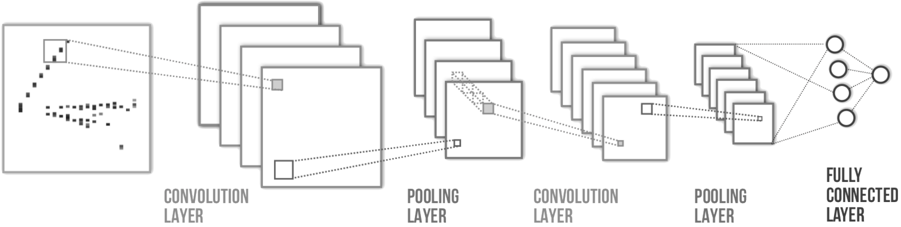
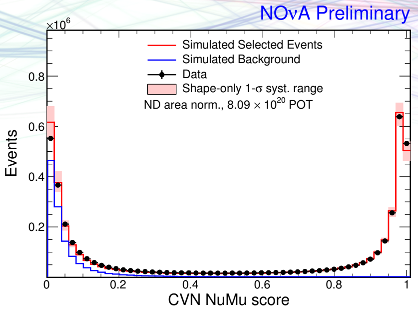
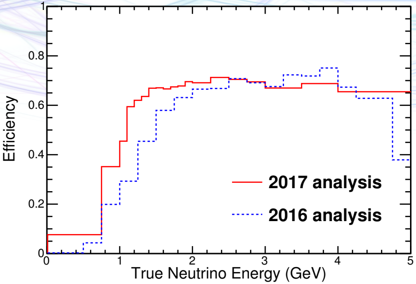
Event selection

- Events classified as ν_e / ν_μ / NC by Convolutional Neural Network
- Deep Learning technique from computer vision research
- Treat the whole event as an input “image”
- Improvement in performance equivalent to 30% more data



Selecting muon neutrinos



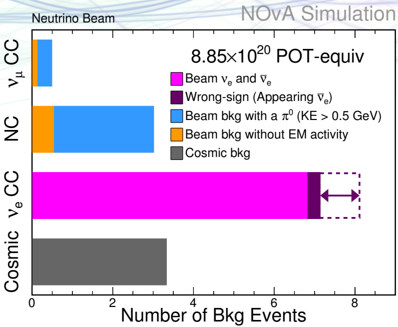


- Also have to reject cosmic rays, use containment, dir. and size
- Factor 10^5 from 10μs spill window vs 1Hz beam, 10^7 from cuts

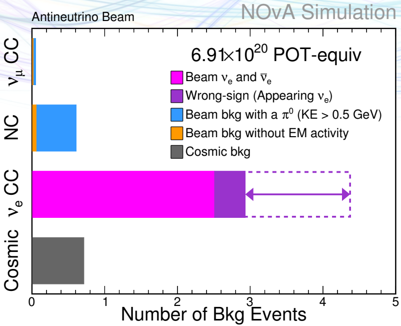
- Achieve 98.6% pure FD ν_μ CC sample, 78% efficiency

Selecting electron neutrinos

Neutrino mode

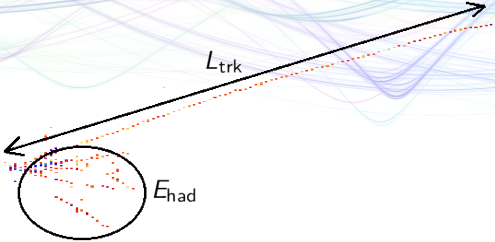


Antineutrino mode



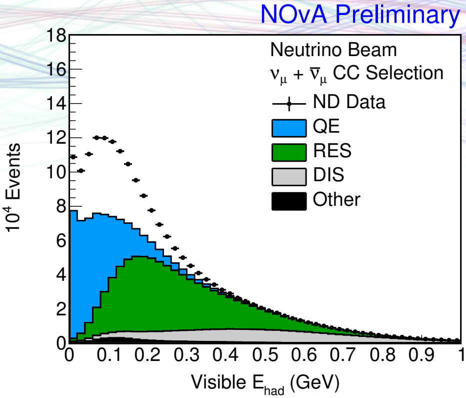
- Biggest background is intrinsic beam ν_e's
- "Wrong sign" appearing neutrinos significant in antineutrino mode
- Majority of other background contains a π^0

ν_μ energy estimation



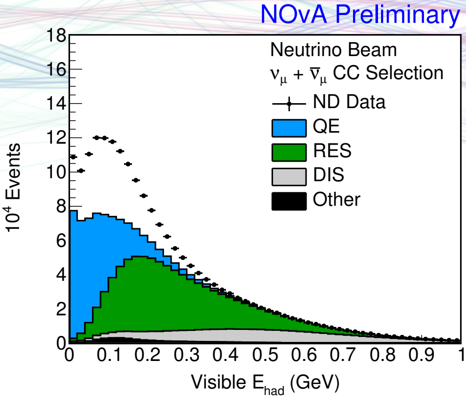
- Estimate energy of selected events to trace out osc. structure
- Known muon dE/dx → $E_\mu = f(L_{\text{trk}}) \sim k \times L_{\text{trk}}$
- Hadronic part of the event estimated calorimetrically
- $E_\nu = f(L_{trk}) + E_{\text{had}}$

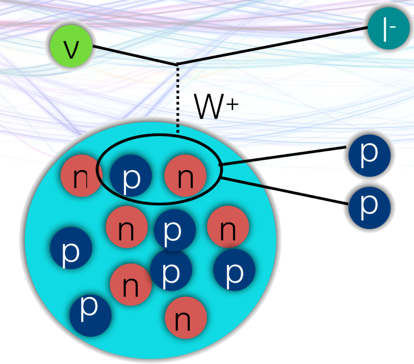
Near detector – ν_μ



- Clear deficit in NOvA ND simulation (also seen by MINERvA)

Near detector – ν_μ





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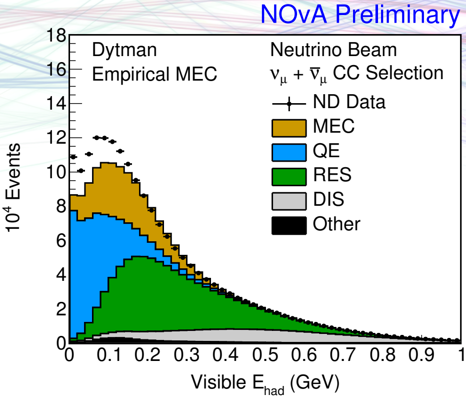
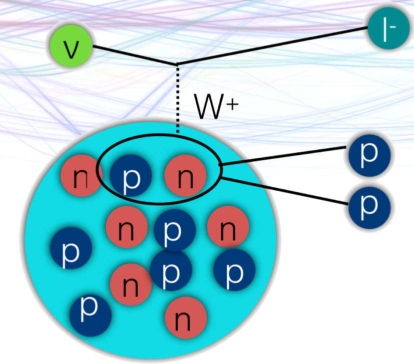
- Attributed to inter-nucleon correlations (“2p2h”)

Near detector – ν_μ





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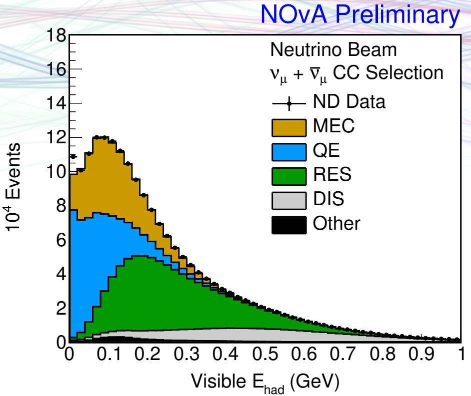
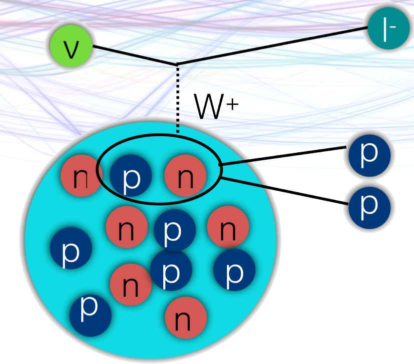
- Enable GENIE’s “empirical Meson Exchange Current” model

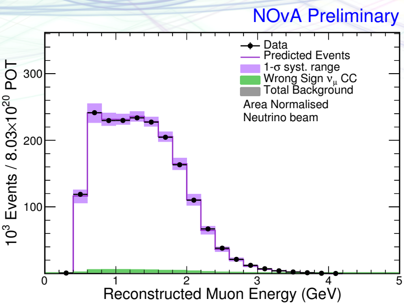
Near detector – ν_μ





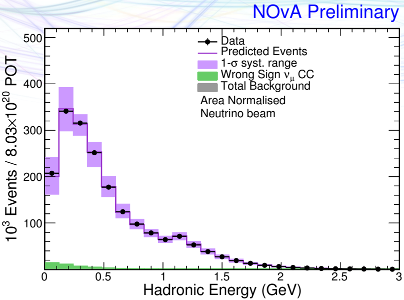
- Clear deficit in NOvA ND simulation (also seen by MINERvA)
- Attributed to inter-nucleon correlations ("2p2h")
- Enable GENIE's "empirical Meson Exchange Current" model
- Tune to match our data in $(q^0, |\vec{q}|)$ space
- Evaluate uncertainties by repeating tune on top of more-QE-like and more-RES-like simulations

ν_μ energy estimation



(∼3%)

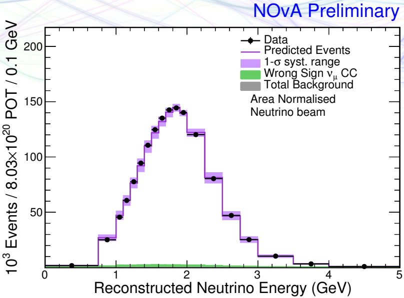
+



(∼30%)

- Good data/MC agreement for muon neutrino selected events

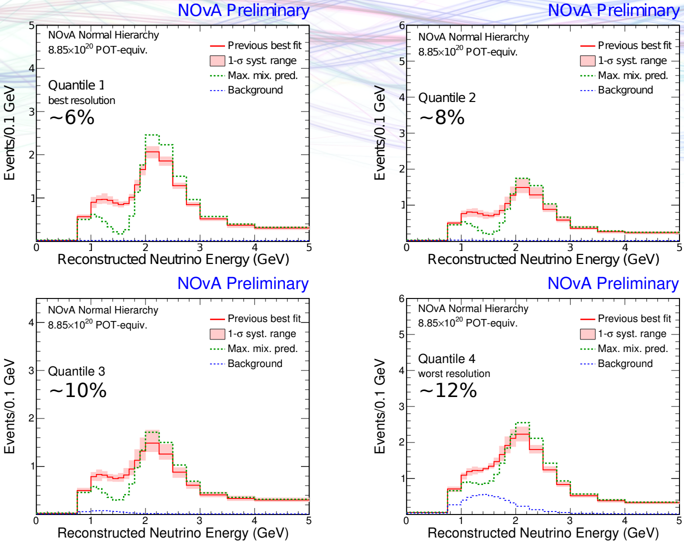
ν_μ energy estimation



(∼9%)

- Good data/MC agreement for muon neutrino selected events

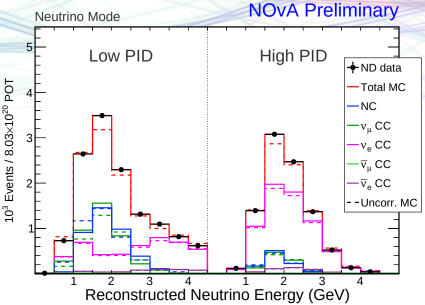
ν_μ resolution bins



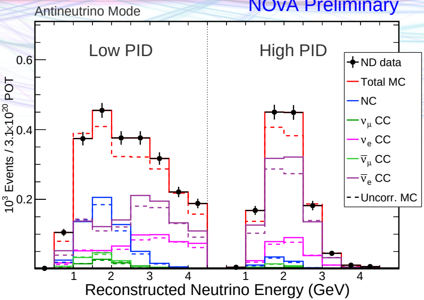
- Bin into 4 equal quantiles by hadronic energy fraction
- Energy resolution varies from $\sim 6\%$ to $\sim 12\%$ between bins

Near detector – ν_e

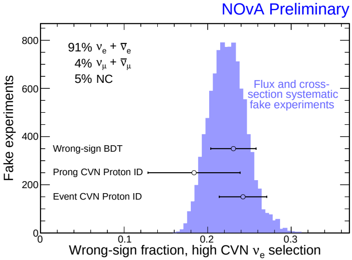
Neutrino mode



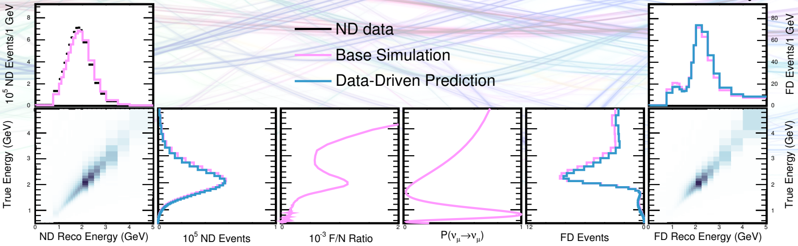
Antineutrino mode

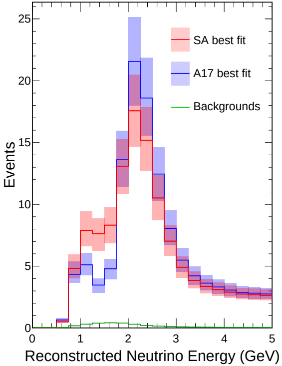


- ν_e spectra split into low and high confidence bins
- FD spectrum will have additional “peripheral” bin
- “Decompose” ν mode to NC+ν_μ+ν_e
- In $\bar{\nu}$, check ν contamination



Extrapolation procedure – ν_μ





- Translate ND observations to true energy
- Transport to far detector and oscillate
- Smear back to reco energy
- Cosmics prediction from out-of-time data

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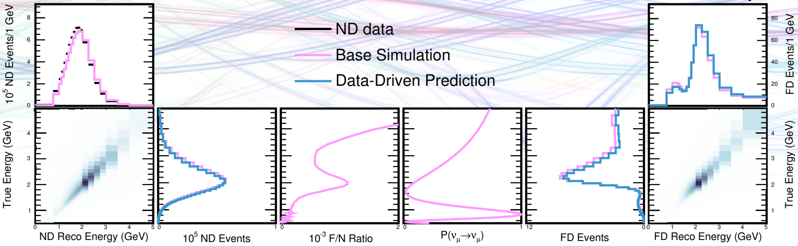

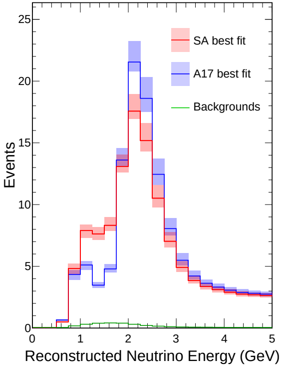

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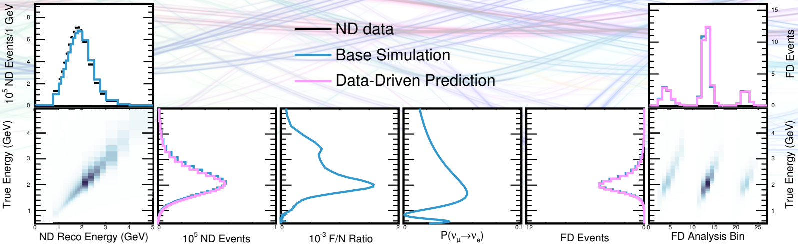
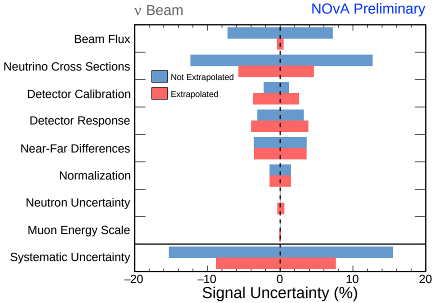
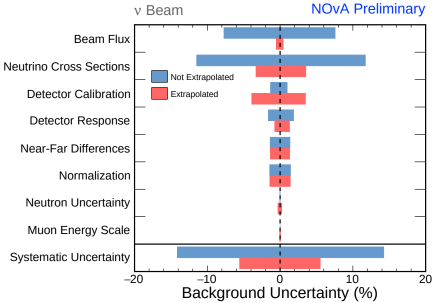
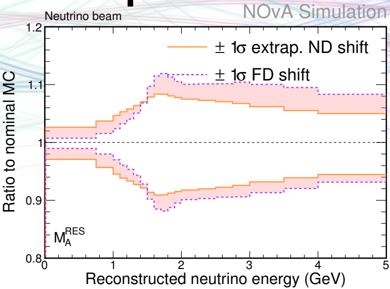
Extrapolation procedure – ν_e

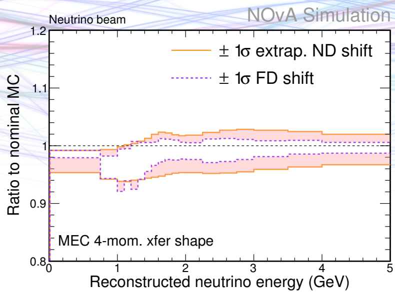


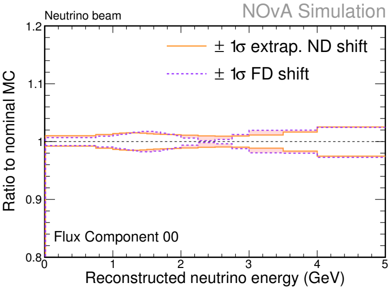


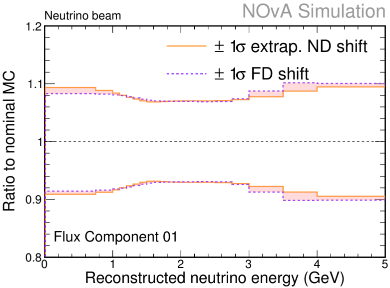


Extrapolation tests









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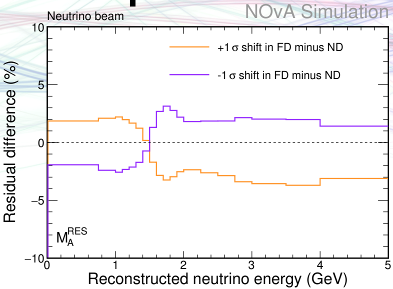
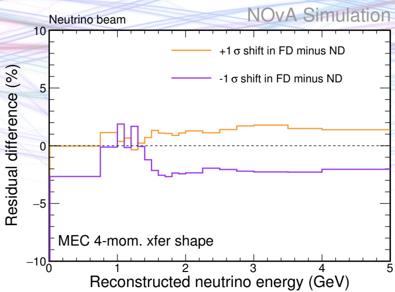
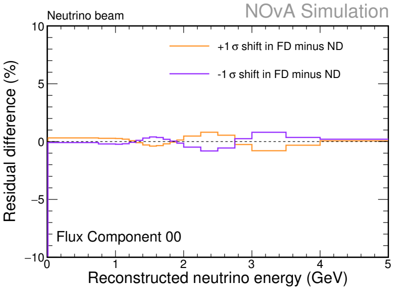
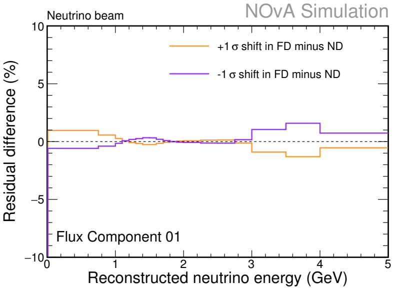


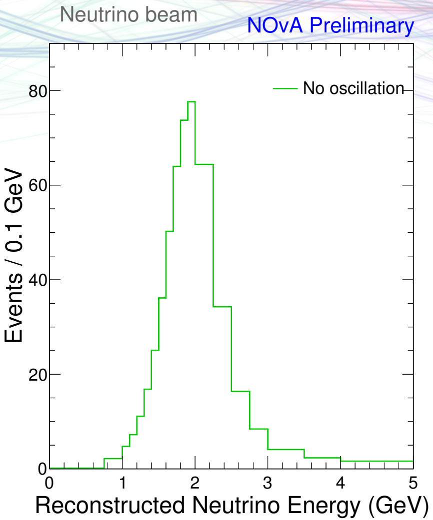






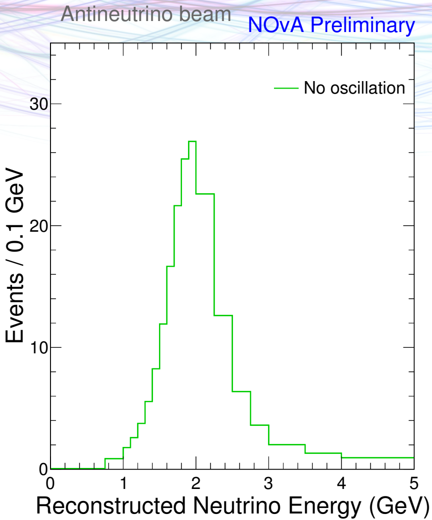
ν_μ spectra

Neutrino mode



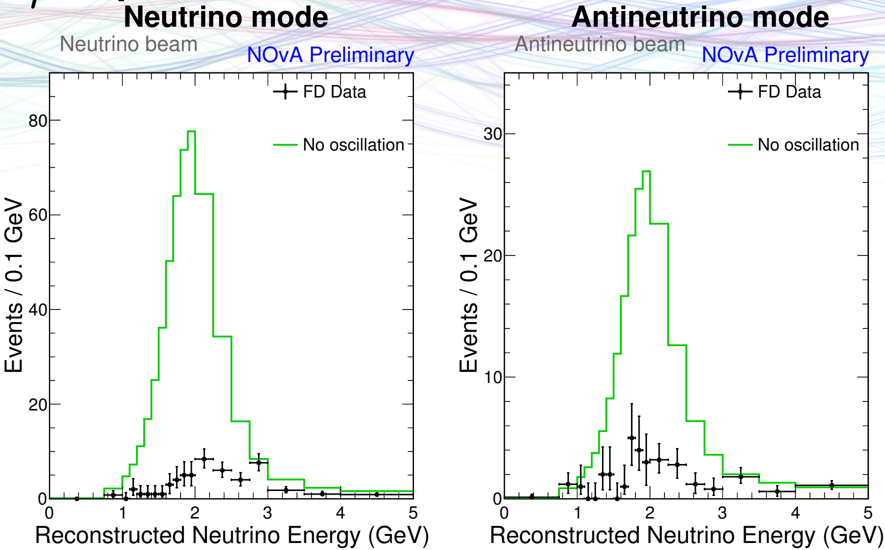
- Expect 730 w/o oscillations

Antineutrino mode



- Expect 266 w/o oscillations

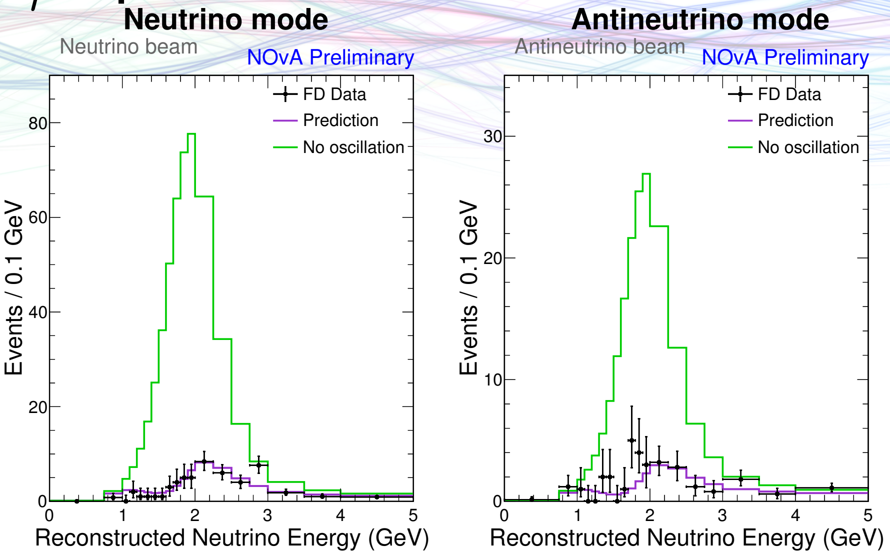
ν_μ spectra



- Expect 730 w/o oscillations
- Observe 113 events

- Expect 266 w/o oscillations
- Observe 65 events

ν_μ spectra



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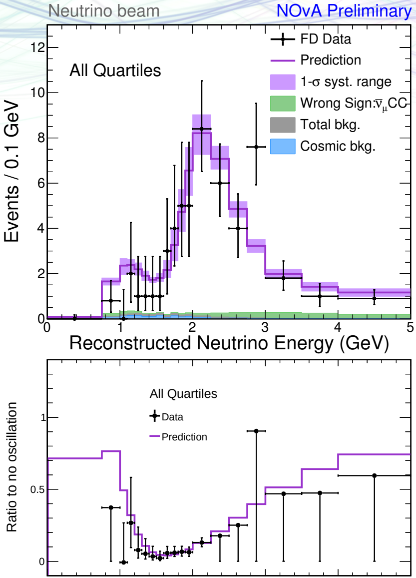
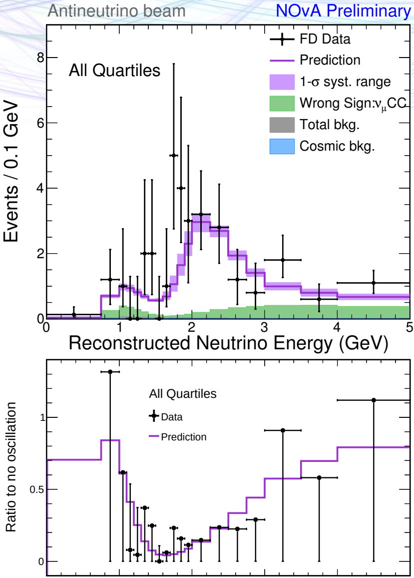
ν_μ spectra

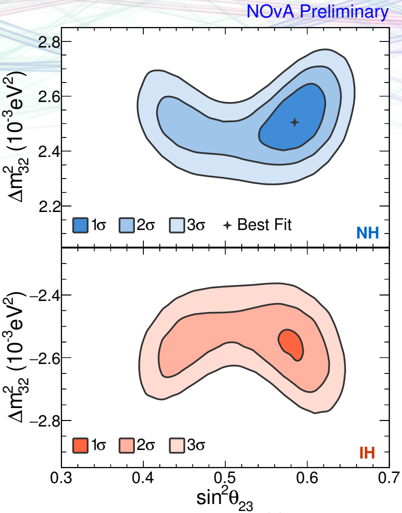
Neutrino mode

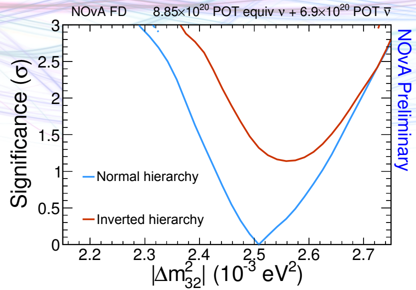


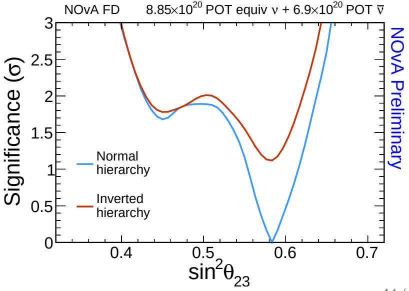
Antineutrino mode



Δm^2 and $\sin^2\theta$



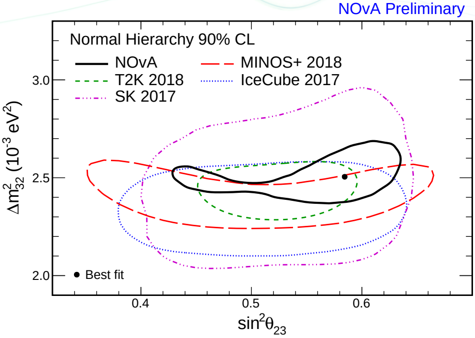


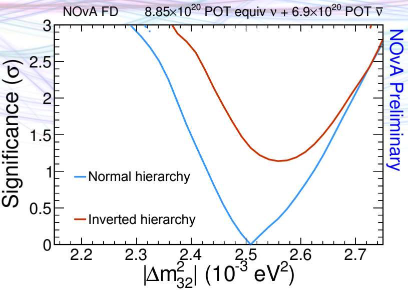


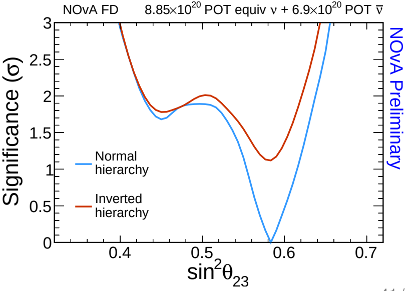
$$\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}\,\text{eV}^2\ (\text{NH})$$

$$\sin^2\theta_{23} = 0.58 \pm 0.03\ (\text{UO})$$

Δm^2 and $\sin^2\theta$

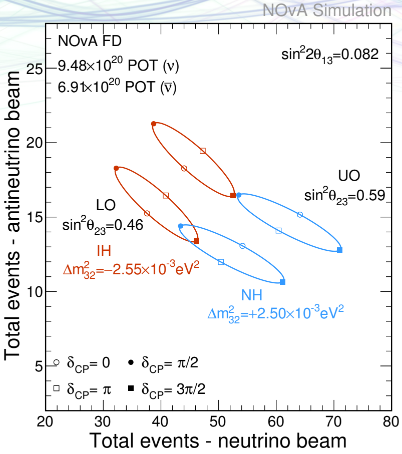




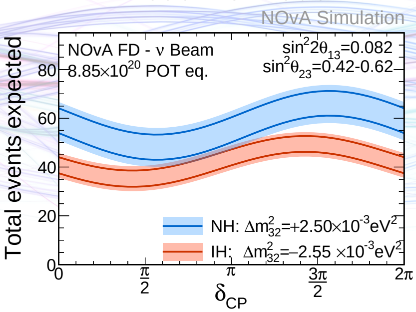


ν_e spectra

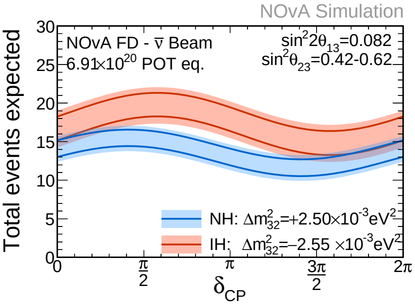
Neutrino vs antineutrino



Neutrino mode

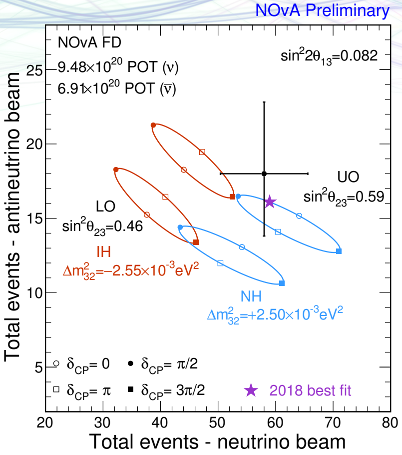


Antineutrino mode

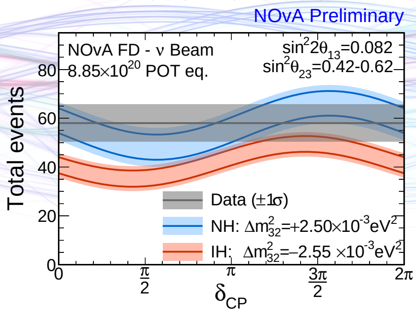


ν_e spectra

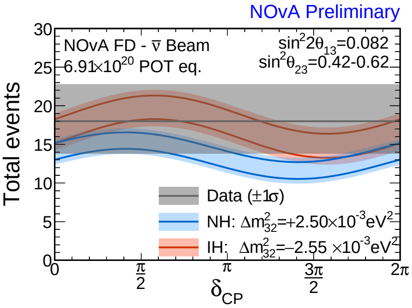
Neutrino vs antineutrino



Neutrino mode



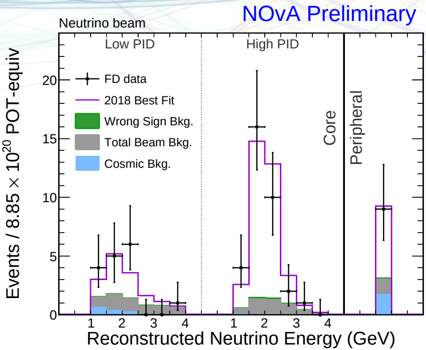
Antineutrino mode



- Observe 58 ν_e and 18 $\bar{\nu}_e$

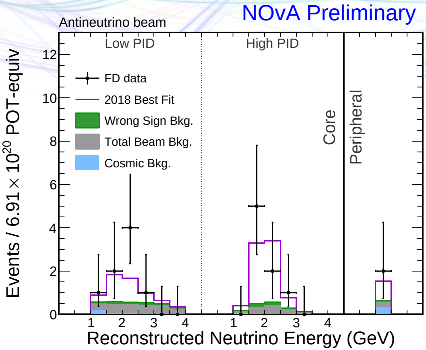
ν_e spectra

Neutrino mode



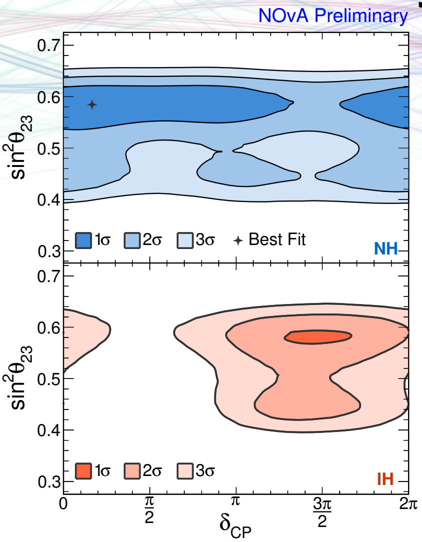
- Observe 58 events
- Expect 15 background

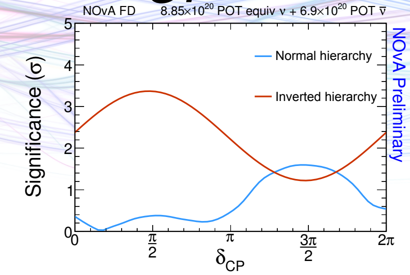
Antineutrino mode

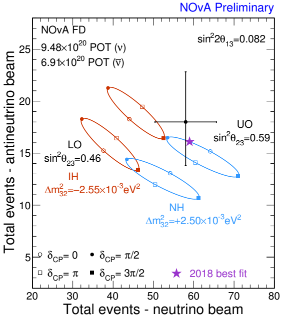


- Observe 18 events
- Expect 5.3 background

Mass hierarchy and δ_{CP}

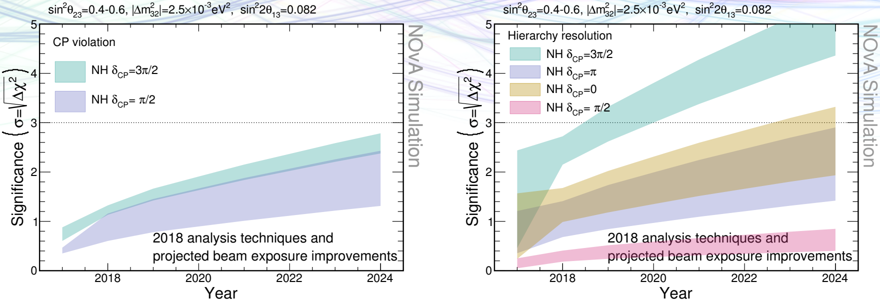






- Prefer NH by 1.8σ
- Exclude $\delta_{CP} = \frac{3\pi}{2}$ in IH at $> 3\sigma$

Future



- *CP*-violation remains challenging for NOvA
- But could have $>4\sigma$ determination of the hierarchy!
  - Strongly dependent on true parameters (degeneracies)
  - Global best-fit is for the most favourable scenario

Conclusion

- Presented first NOvA neutrino+antineutrino results
- 4σ evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

- Prefer NH at 1.8σ
- Exclude IH, $\delta_{CP} = \pi/2$ at $>3\sigma$
- Disfavours maximal mixing by 1.8σ and lower octant similarly

- 3σ sensitivity to mass hierarchy by 2020

- Stay tuned!

www-nova.fnal.gov

Thank you!


Fermilab
Fermilab
Fermilab
Fermilab
NORMAN F. RAMSEY
AUDITORIUM
AISLE 1
AISLE 2

Backup

pics params calib

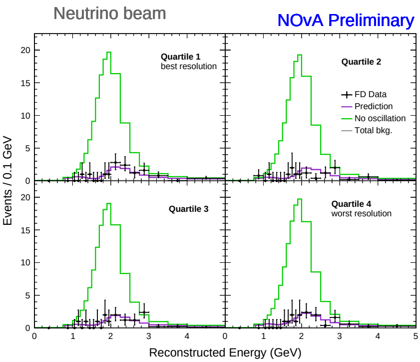
numuSel numuE extrap breakdown

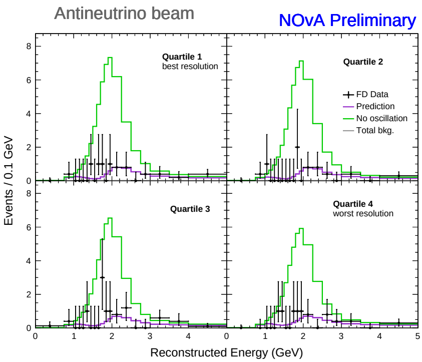
new MEC res bins steriles T2K

sigmas oscs CNNs CVN

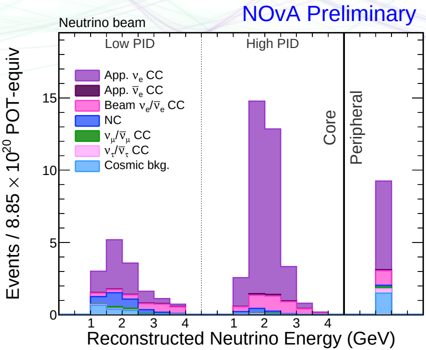
decomp MRE mrbrem xsec

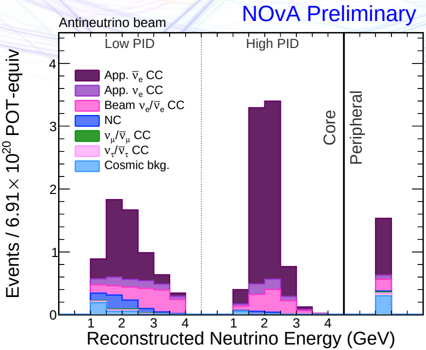
ν_μ details





ν_e details


Neutrino beam
NOvA Preliminary
Low PID
High PID
Core
Peripheral
App. ν_e CC
App. $\bar{\nu}_e$ CC
Beam $\nu_e/\bar{\nu}_e$ CC
NC
$\nu_\mu/\bar{\nu}_\mu$ CC
$\nu_\tau/\bar{\nu}_\tau$ CC
Cosmic bkg.
Events / 8.85×10^{20} POT-equiv
0
5
10
15
1
2
3
4
1
2
3
4
Reconstructed Neutrino Energy (GeV)


Antineutrino beam
NOvA Preliminary
Low PID
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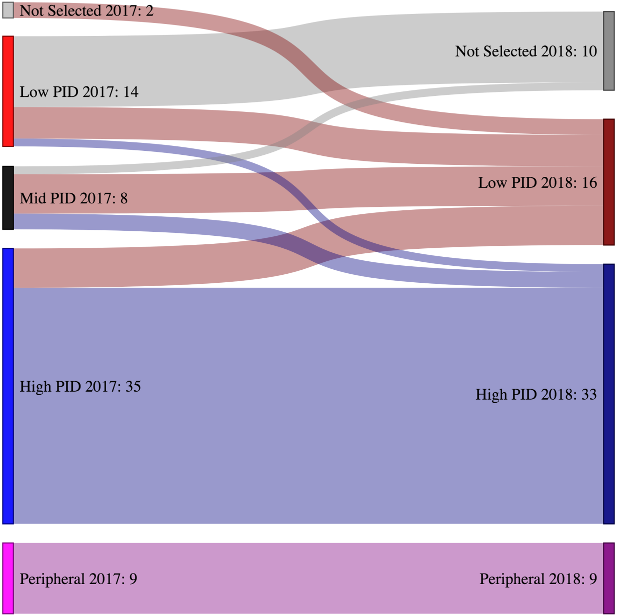
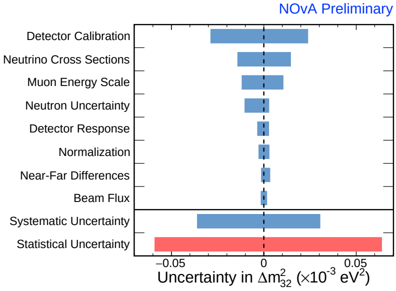
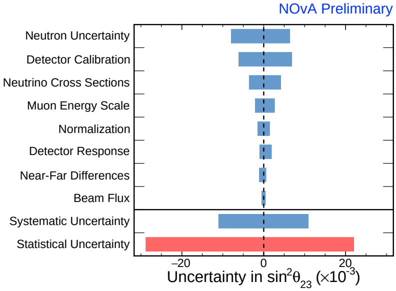
App. $\bar{\nu}_e$ CC
App. ν_e CC
Beam $\nu_e/\bar{\nu}_e$ CC
NC
$\nu_\mu/\bar{\nu}_\mu$ CC
$\nu_\tau/\bar{\nu}_\tau$ CC
Cosmic bkg.
Events / 6.91×10^{20} POT-equiv
0
1
2
3
4
1
2
3
4
1
2
3
4
Reconstructed Neutrino Energy (GeV)

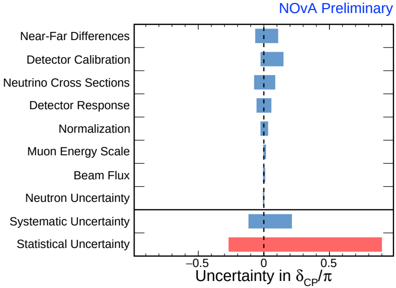
ν_e details


Not Selected 2017: 2
Low PID 2017: 14
Mid PID 2017: 8
High PID 2017: 35
Peripheral 2017: 9
Not Selected 2018: 10
Low PID 2018: 16
High PID 2018: 33
Peripheral 2018: 9

Systematics

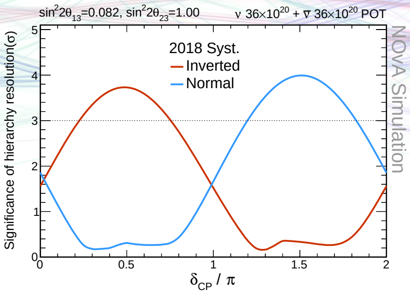


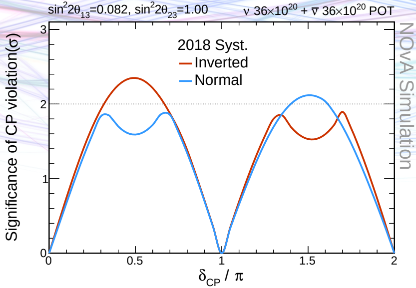


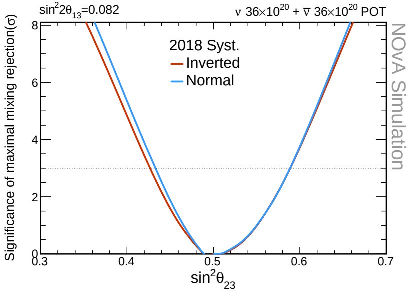


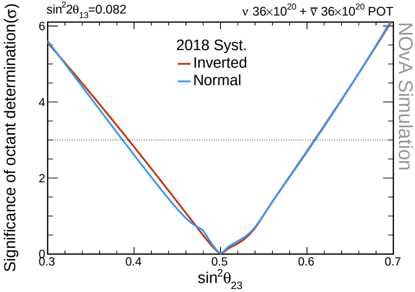
Source of Uncertainty	$\sin^2\theta_{23}$ ($\times 10^{-3}$)	δ_{CP}/π	Δm^2_{32} ($\times 10^{-3}$ eV^2)
Beam Flux	+0.42 / -0.48	+0.0088 / -0.0048	+0.0016 / -0.0015
Detector Calibration	+6.9 / -6.1	+0.15 / -0.023	+0.024 / -0.029
Detector Response	+1.9 / -0.99	+0.055 / -0.054	+0.0027 / -0.0034
Muon Energy Scale	+2.6 / -2.1	+0.015 / -0.0026	+0.01 / -0.012
Near-Far Differences	+0.56 / -1.1	+0.11 / -0.064	+0.0033 / -0.0013
Neutrino Cross Sections	+4.2 / -3.5	+0.085 / -0.072	+0.015 / -0.014
Neutron Uncertainty	+6.4 / -7.9	+0.002 / -0.0052	+0.0028 / -0.01
Normalization	+1.4 / -1.5	+0.031 / -0.024	+0.0029 / -0.0027
Systematic Uncertainty	+9.6 / -11	+0.21 / -0.11	+0.032 / -0.035
Statistical Uncertainty	+22 / -29	+0.9 / -0.27	+0.064 / -0.059

Sensitivities

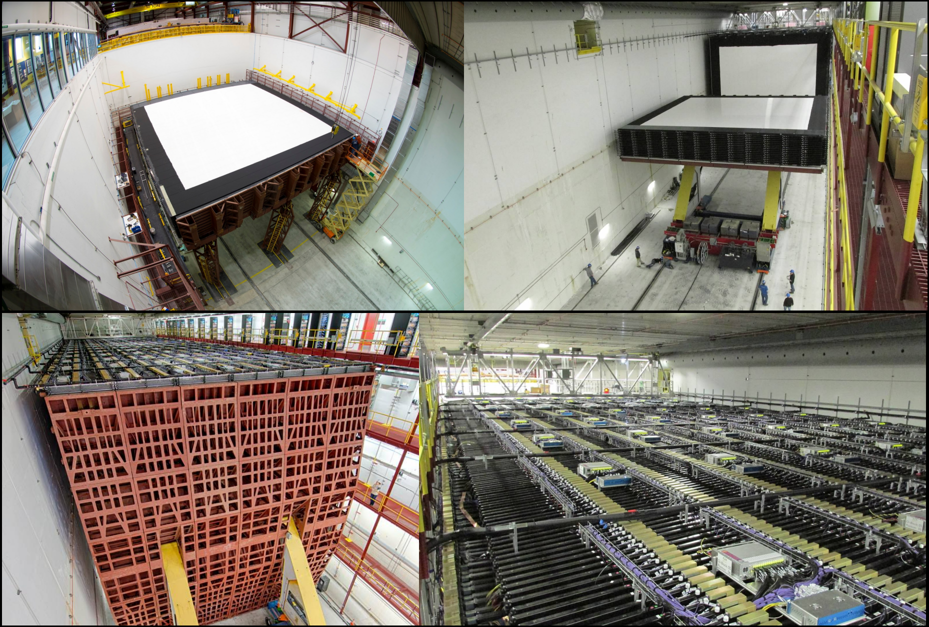






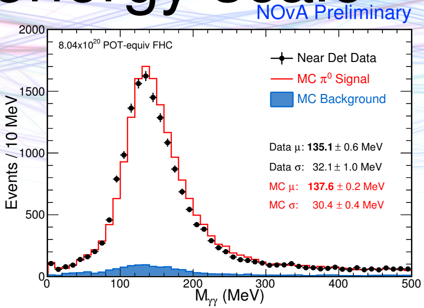


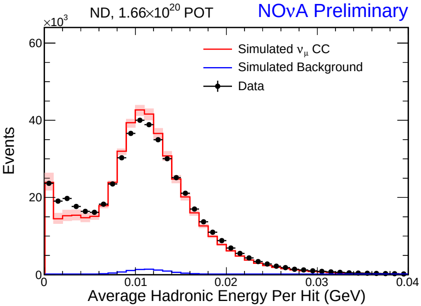
Assembly


10 TON

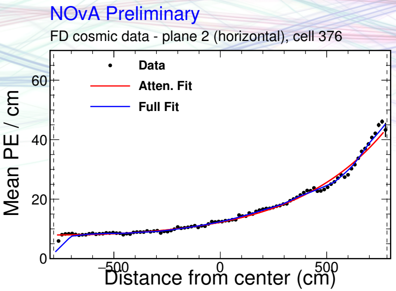
Calibration and energy scale

- Response varies substantially along cell due to light atten.
- Use cosmic ray muons as a standard candle to calibrate 300,000 channels individually
- Use *dE*/*dx* near the end of stopping muon to set abs. scale
- Multiple calibration x-checks
  - Beam muon dE/dx
  - Michel energy spectrum
  - π^0 mass peak
  - Hadronic energy/hit
- Take 5% abs. and rel. errors on energy scale





Calibration



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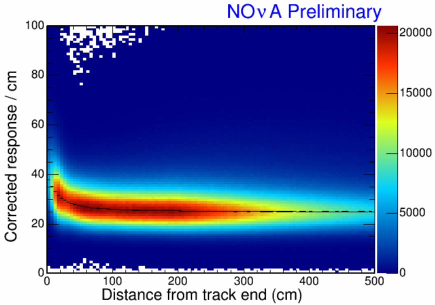
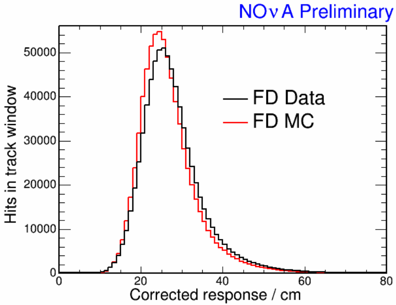
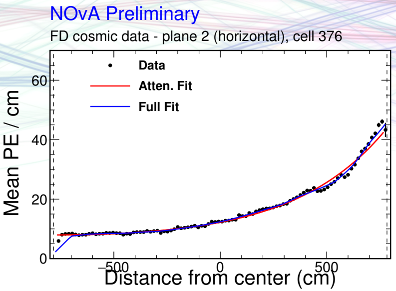




Calibration



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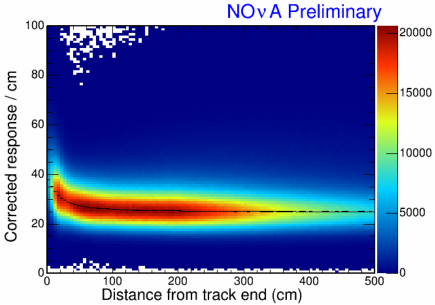
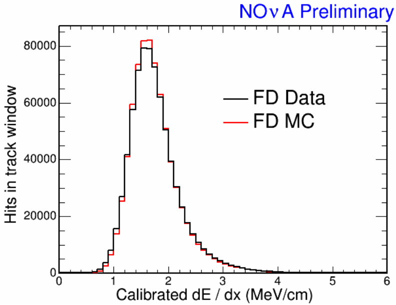
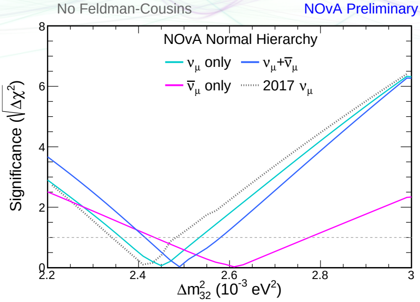
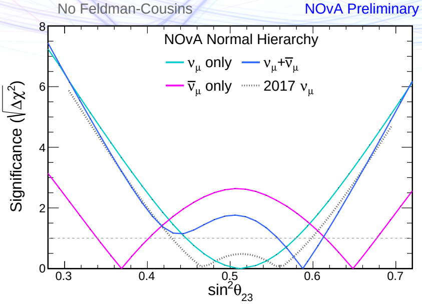




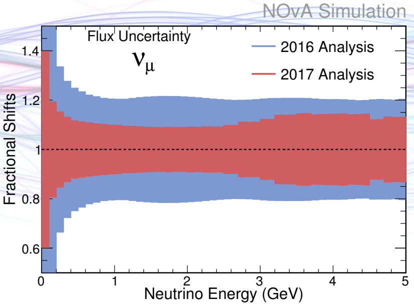
Data subsets

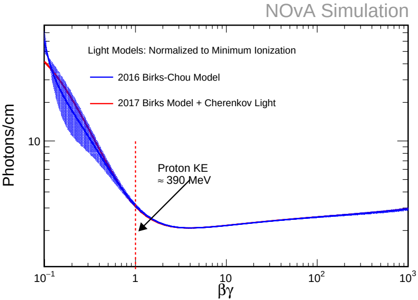




What's new?

- 50% additional data
- Data-driven flux estimates from MINERvA[1]
- Retuned cross-section model
- Detector sim. improvements (E_{res} : 7% $\rightarrow$ 9%)
- Using computer vision classifier for all analyses
- Analysis improvements
  - Resolution binning for ν_μ
  - "Peripheral" sample for ν_e





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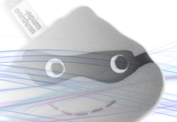
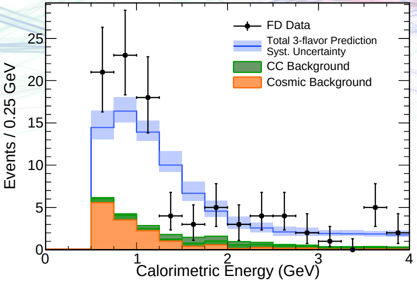
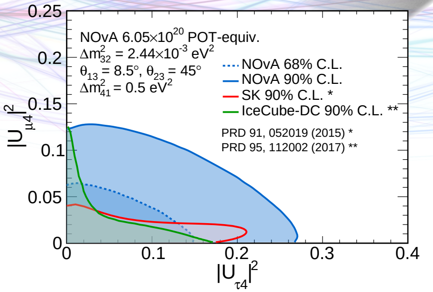
[1] Phys. Rev. D94 (2016) 092005

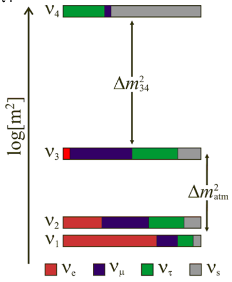
Sterile neutrinos





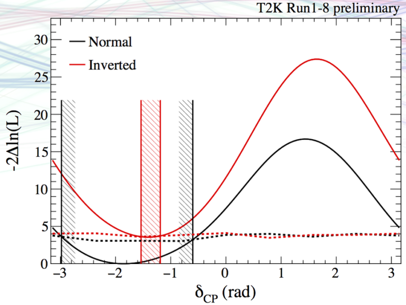


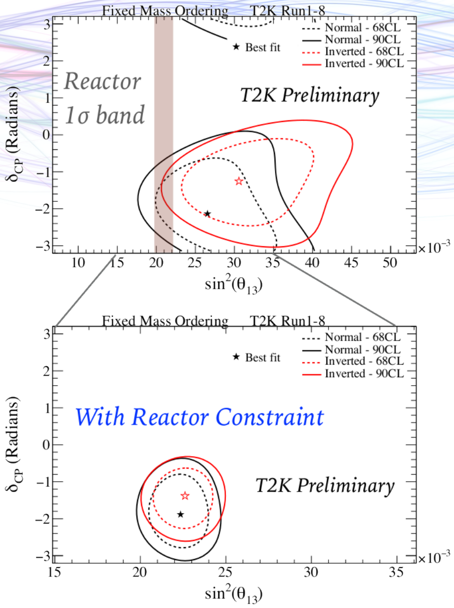
- Are all the disappearing ν_μ going to ν_e or ν_τ?
- Might some fraction be oscillating to a a 4th, sterile, state?
- Would expect a depletion of NC events at FD
- Expect 83.5 $\pm$ 9.7(stat) $\pm$ 9.4(syst) see 95
- Set limits on $U_{\mu4}$ and $U_{\tau4}$



Phys. Rev. D 96, 072006 (2017)

T2K latest





	Obs	Exp (no-CPV)
ν_e	89	67
$\bar{\nu}_e$	7	9

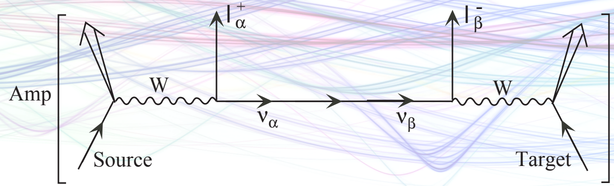
- Used $(14.7 + 7.6) \times 10^{20}$ POT
- Approved to 7.8×10^{21} POT
- Proposal for 20×10^{21} by 2026

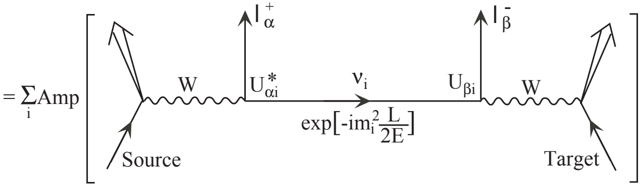
Mark Hartz colloquium @ KEK, Aug 2017

Particle physics confidence levels

Significance	Confidence level
1σ	68.3%
2σ	95.5%
3σ	99.7%
4σ	99.994%
5σ	99.99994%

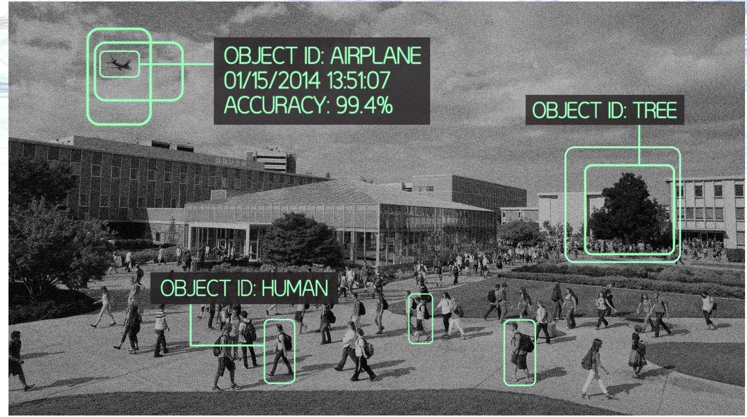
Neutrino oscillations





$$P_{\alpha\beta} = \left| \sum_i U^\star_{\alpha i} e^{-im_i^2 L/2E} U_{\beta i} \right|^2$$

Convolutional Neural Networks



- Recent advances in machine learning/computer vision
- Achieving near-human performance on image classification tasks
- Why not classify event-displays?
- **CNN** – deep neural network, inputs are the pixels of the image
- Take advantage of translational invariance → convolutions

Convolutional Neural Networks

$$\frac{1}{8}\begin{bmatrix} -1 & -1 & -1 \\ -1 & +8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

Edge-detection kernel

- Recent advances in machine learning/computer vision
- Achieving near-human performance on image classification tasks
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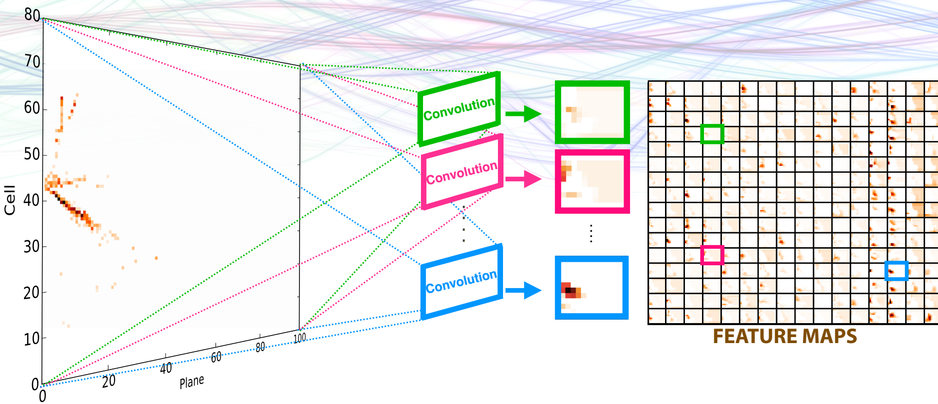
Convolutional Neural Networks



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- Why not classify event-displays?
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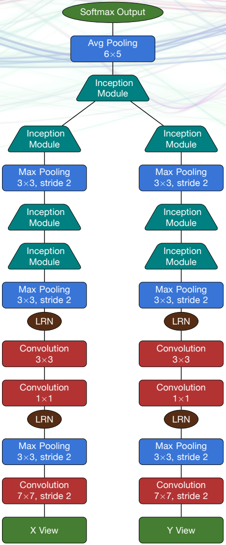
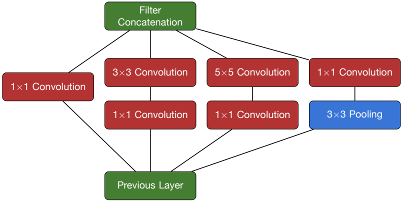
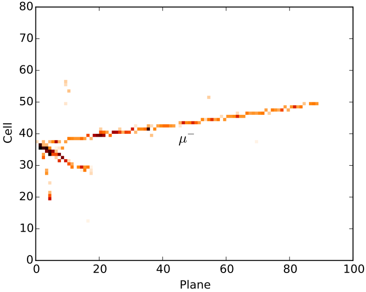
CVN architecture

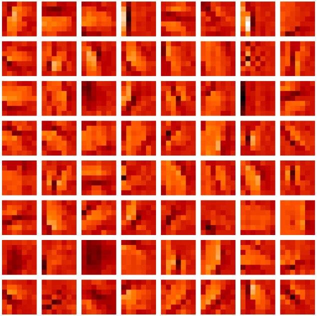




CVN example



$\otimes$



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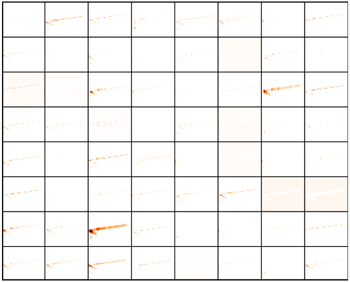
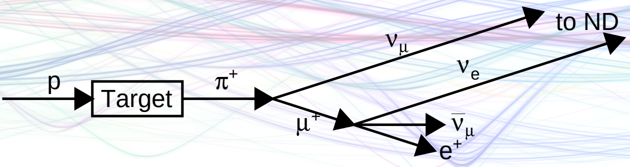


ND decomposition – beam ν_e



p

Target

π^+

ν_μ

to ND

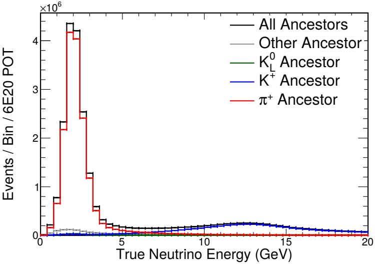
ν_e

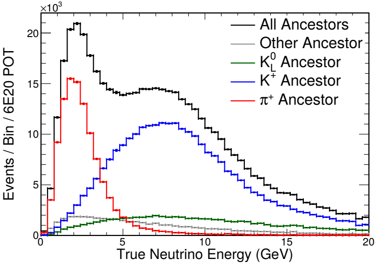
μ^+

$\bar{\nu}_\mu$

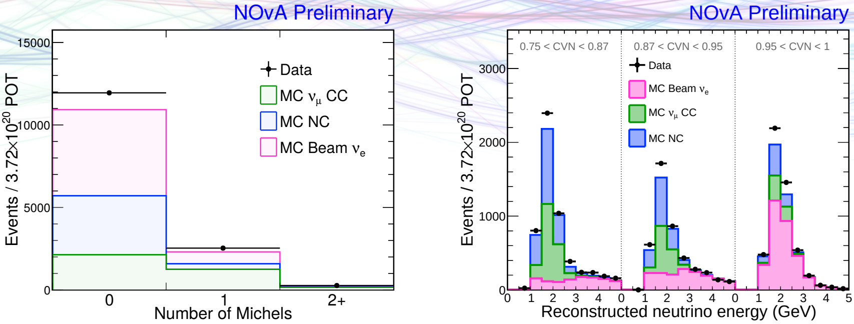
e^+

- Low-*E* ν_μ and ν_e trace back to the same π^+ ancestors



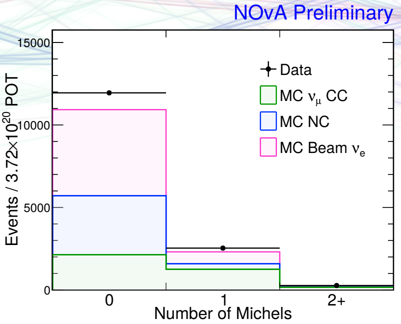


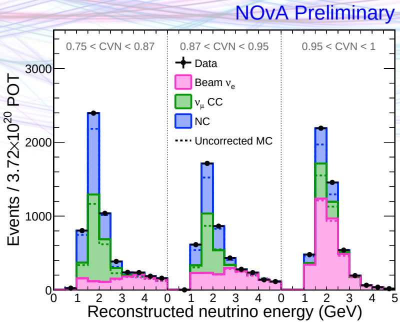
ND decomposition – Michels



- ν_μ CC background events have Michel electron from muon decay
- Also produced in ν_e CC and NC by pions, but ν_μ have $\sim$ 1 more
- Fit observed N_{michel} spectrum in each bin by varying components
- ν_e and NC near-degenerate, fix ν_e to parent-reweight estimate

ND decomposition – Michels





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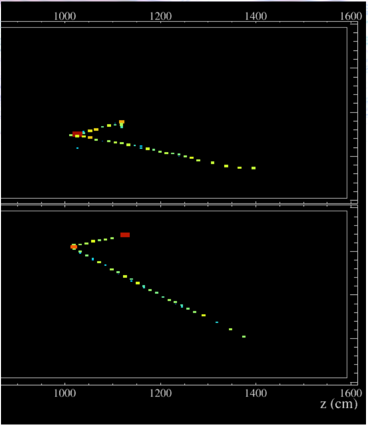
ν_e selection efficiency – MRE

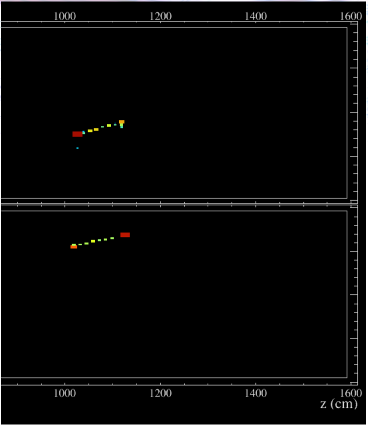
- EM showers should be well modelled
- Any ν_e signal efficiency differences coming from the hadronic side?
- Remove muon from clear ν_μ CC events in ND, replace with simulated shower



- $\mathcal{O}(1\%)$ efficiency difference to select MRE data/MC events

ν_e selection efficiency – MRE

- EM showers should be well modelled
- Any ν_e signal efficiency differences coming from the hadronic side?
- Remove muon from clear ν_μ CC events in ND, replace with simulated shower



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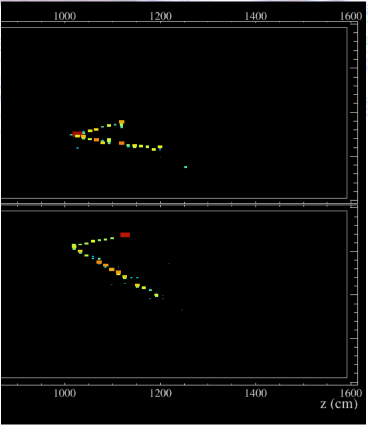

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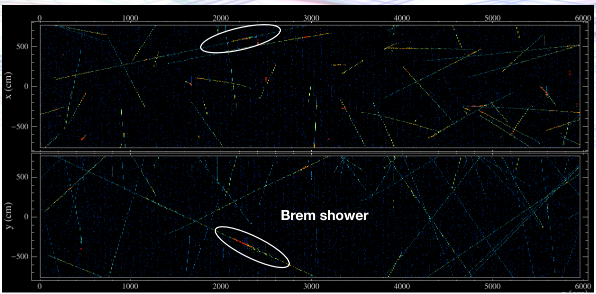
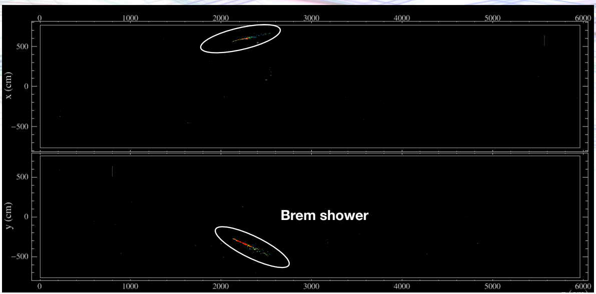
ν_e selection efficiency – EM activity

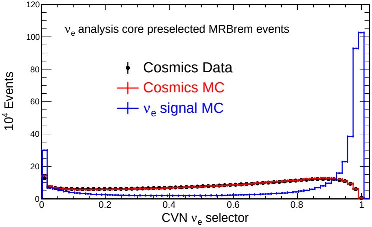


- Find FD data cosmic rays w/ brems

ν_e selection efficiency – EM activity

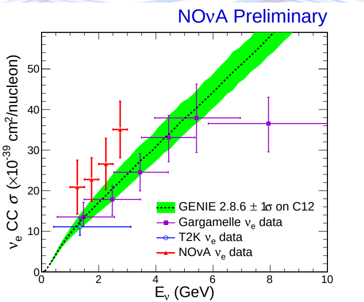


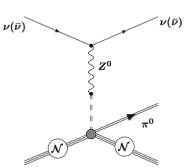
- Find FD data cosmic rays w/ brems
- Remove μ leaving pure EM activity
- Run through PID in data and MC
- Very good agreement

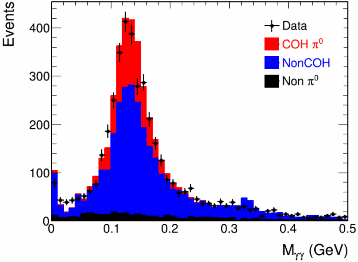


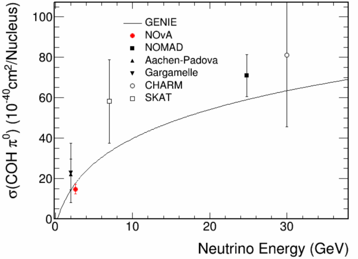
Cross-sections

- Neutrino cross-sections poorly known
- Learn about nuclear physics
- Interpretation of other experiments
- Important for precision future
- High powered beam, fine-grained ND
- Many channels to study

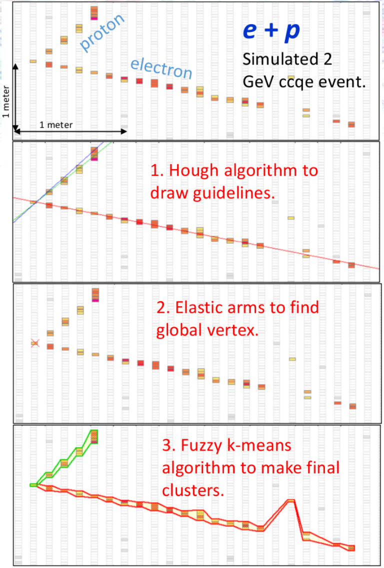








Event reconstruction



- First cluster hits in space and time
- Start with 2-point Hough transform
  - Line-crossing are vertex seeds
- ElasticArms finds vertex
- Fuzzy *k*-means clustering forms prongs
- ν_μ analysis uses a Kalman filter to reconstruct any muon track