New results from NOvA

UCL HEP seminar
January 19, 2018

Chris Backhouse

Neutrino oscillations

The NOvA experiment

ν_μ disappearance

- symmetries in neutrino mixing

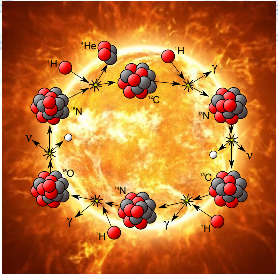
ν_e appearance

- neutrino mass ordering
- CP-violation

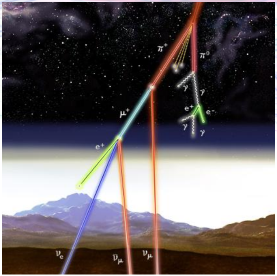
Future

Neutrinos are everywhere

Solar



Atmospheric



Reactor

Supernova

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

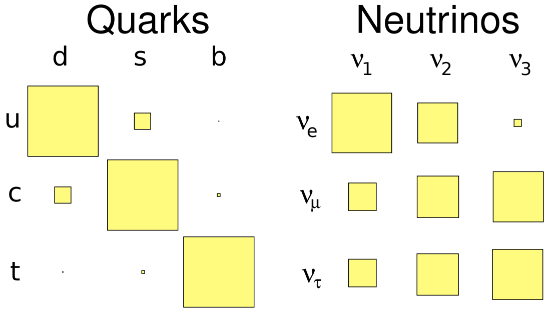
- Second most abundant particle in the universe
- But we know almost nothing about them
- Only interact via the weak force
- Need powerful sources and huge detectors

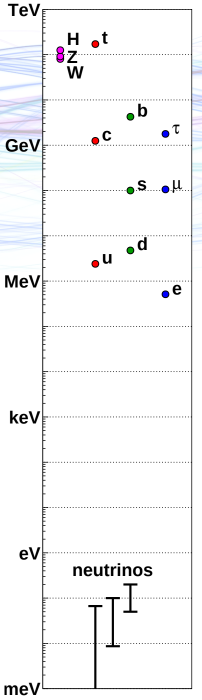
Neutrinos are unique

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

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

- Very different mixing structure to quarks





Neutrino flavour mixing

- Neutrinos mix, just like the quarks

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

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

- PMNS matrix. ∼CKM matrix for leptons
- Unlike the quarks, mixings are large

Neutrino oscillations

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

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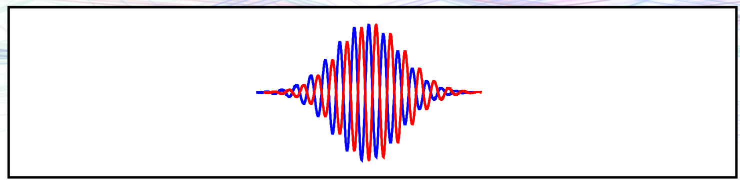
Neutrino oscillations



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

Neutrino oscillations

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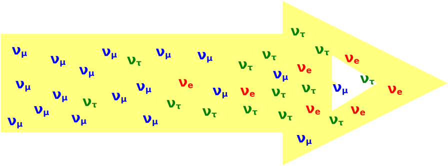
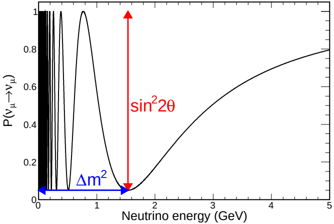
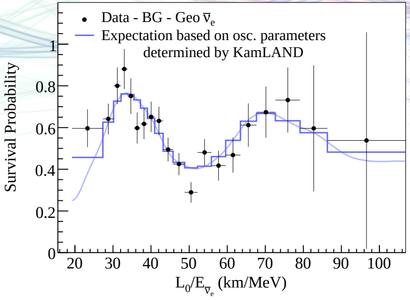
Neutrino oscillations

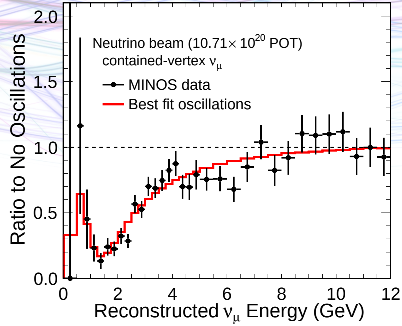
$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \quad \rightarrow \quad P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

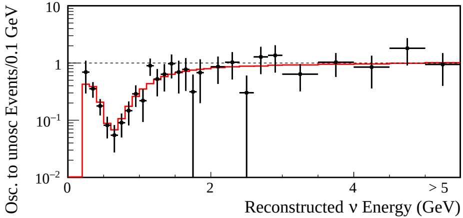


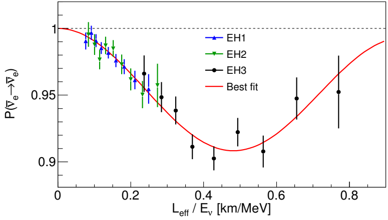


Oscillation structure









Current world knowledge

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

$\theta_{23} \sim 45^\circ$

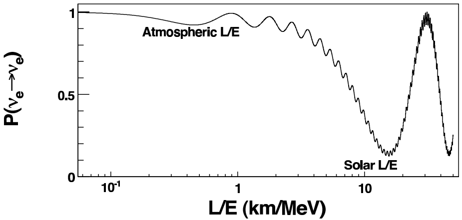
$\Delta m^2_{32} \sim 2.5 \times 10^{-3}\text{eV}^2$

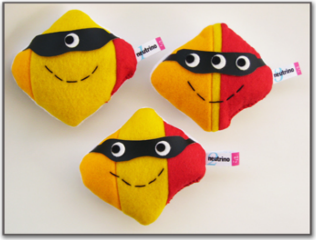
$\theta_{13} \sim 8.5^\circ$

$\delta_{CP} = ?$

$\theta_{12} \sim 33^\circ$

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





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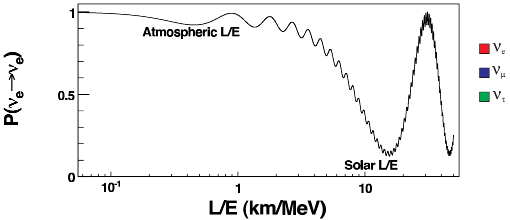

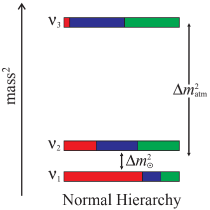

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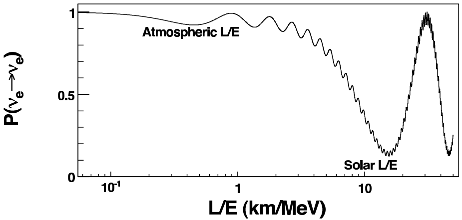
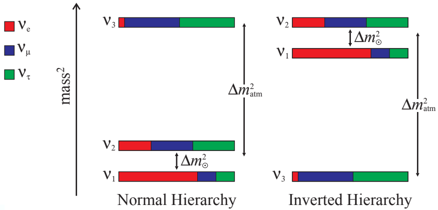
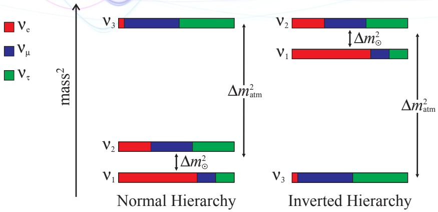




Open neutrino questions

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



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

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- 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

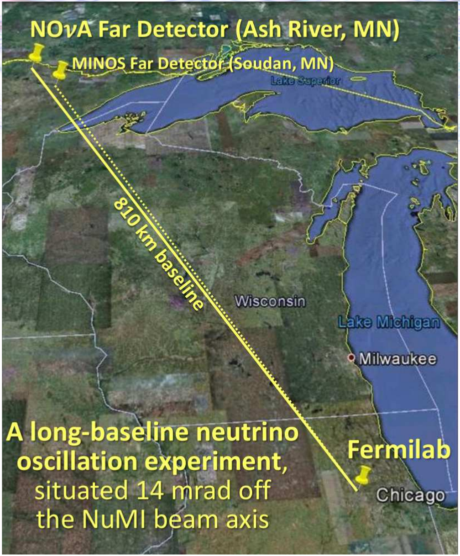
The NOvA collaboration

47 institutions, 7 countries, over 200 collaborators

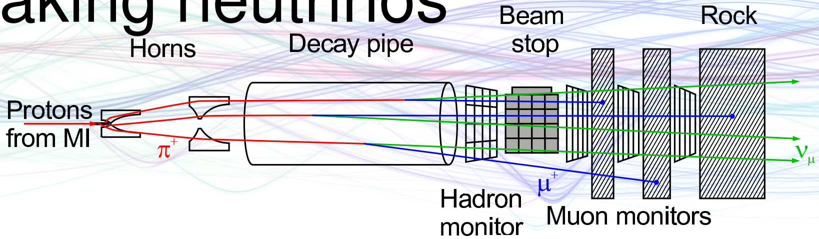
Argonne, Atlantico, Austin, Banaras Hindu, Caltech, CUSAT, Czech Academy of Sciences, Charles, Cincinnati, Colorado State, Czech Technical University, Dallas, Delhi, Dubna, Fermilab, Goias, IIT-Guwahati, Harvard, Houston, IIT-Hyderabad, Hyderabad, Illinois Instute of Technology, Indiana, Iowa State, 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

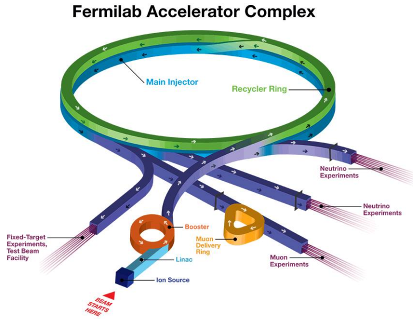
- ν_μ beam from Fermilab, IL
- Detector 810km away in MN
- Smaller detector onsite to measure flux before oscillations
  - $\nu_\mu \to \nu_\mu$
  - $\nu_\mu \to \nu_e$
  - $\bar{\nu}_\mu \to \bar{\nu}_\mu$
  - $\bar{\nu}_\mu \to \bar{\nu}_e$
- Precision measurements of $|\Delta m^2_{32}|$ and θ_{23}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



Making neutrinos

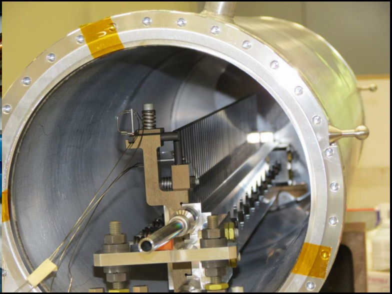
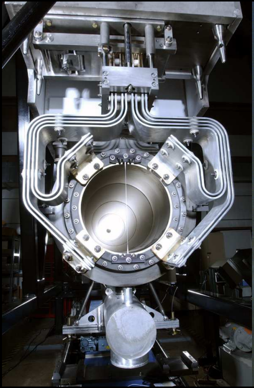


- 120 GeV protons from Main Injector
- Strike graphite target
- Produce mainly $\pi^{\pm}$ and $K^{\pm}$



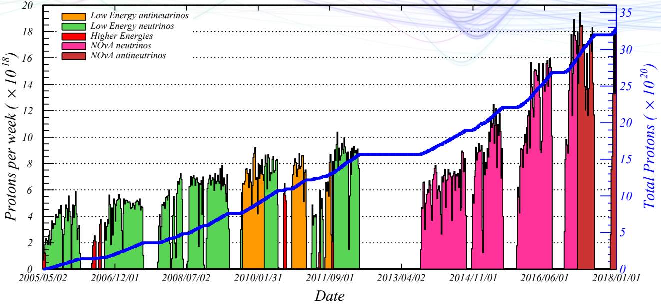
- Focused by two magnetic horns
- Allow us to select charge sign for a neutrino or antineutrino beam

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

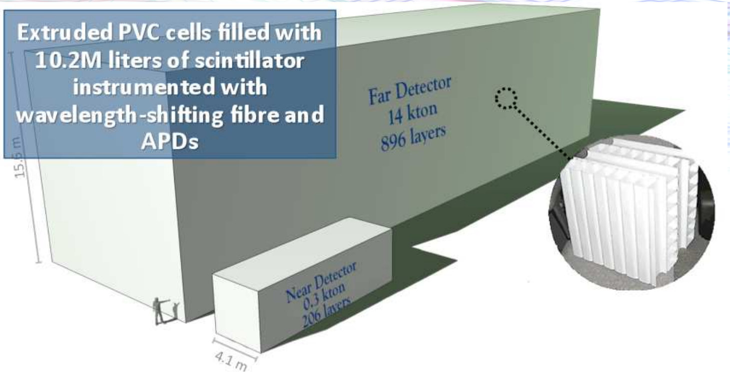

NuMI performance

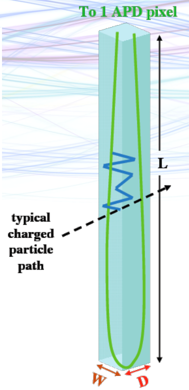
- World's highest power neutrino beam
- 700kW design power since June 2016, $\sim 4 \times 10^{13}$ protons / pulse



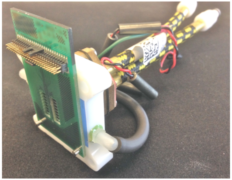
- These results use data from Feb 6 2014 to Feb 20 2017
- Beam power ramping up, detector under construction at start
- 8.85×10^{20} POT equivalent, about 1.5 years of nominal running

Detector technology

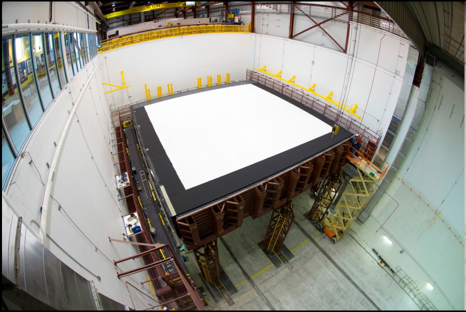
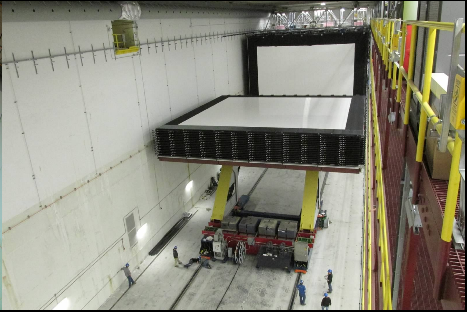
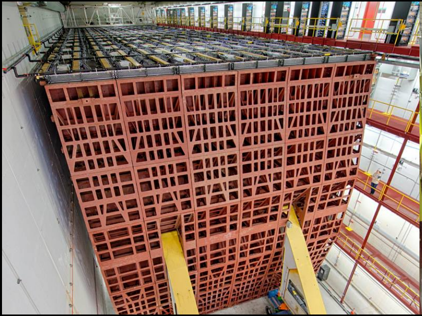




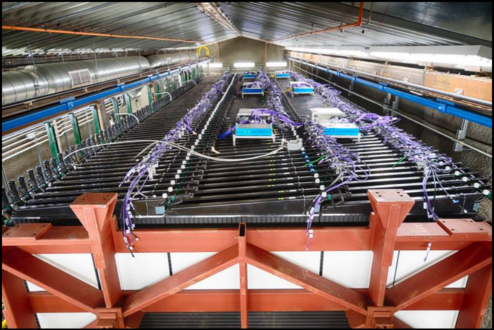
- 64% liquid scintillator by mass
- 4×6cm resolution, two views for 3D reco.
- 344,000 channels in 14 kton FD, on surface
- 300 ton ND, underground at FNAL



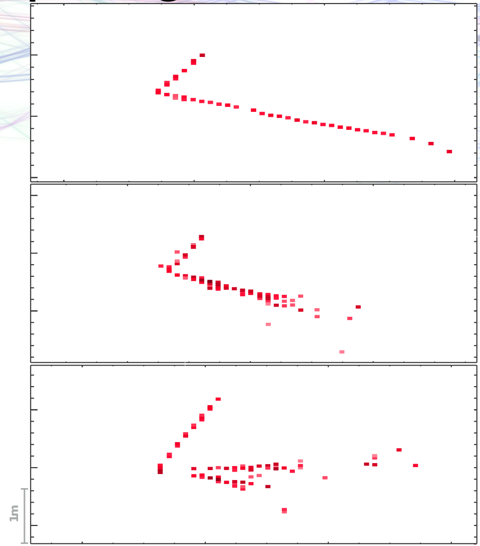
Assembly


Near Detector



Event topologies



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

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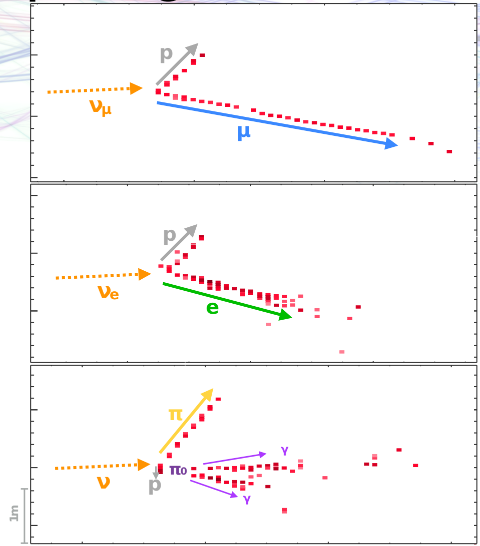

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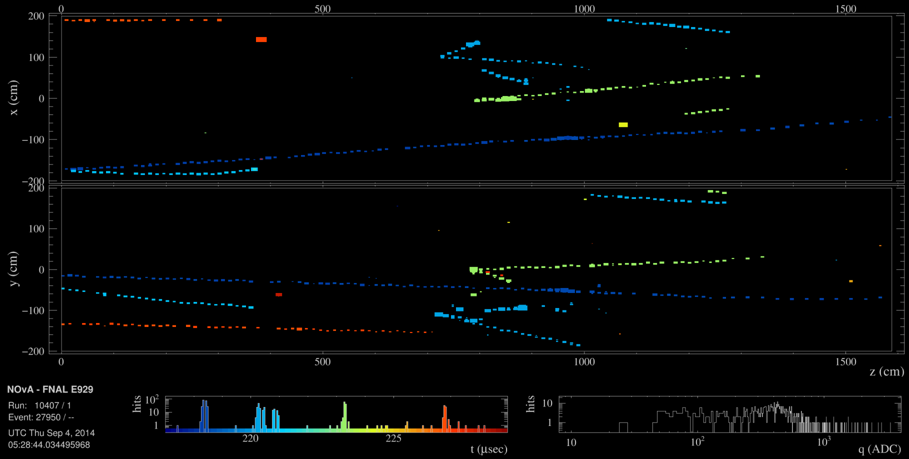
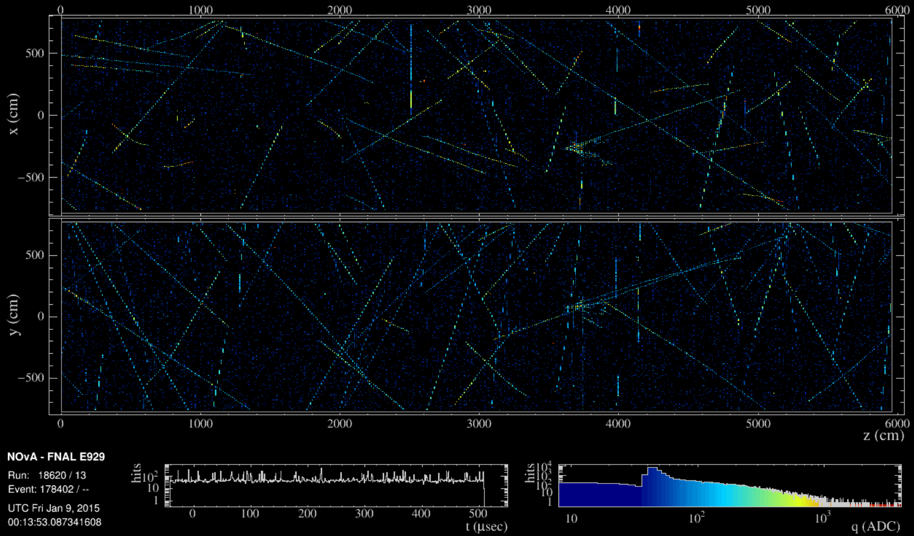
ND neutrinos



FD neutrinos



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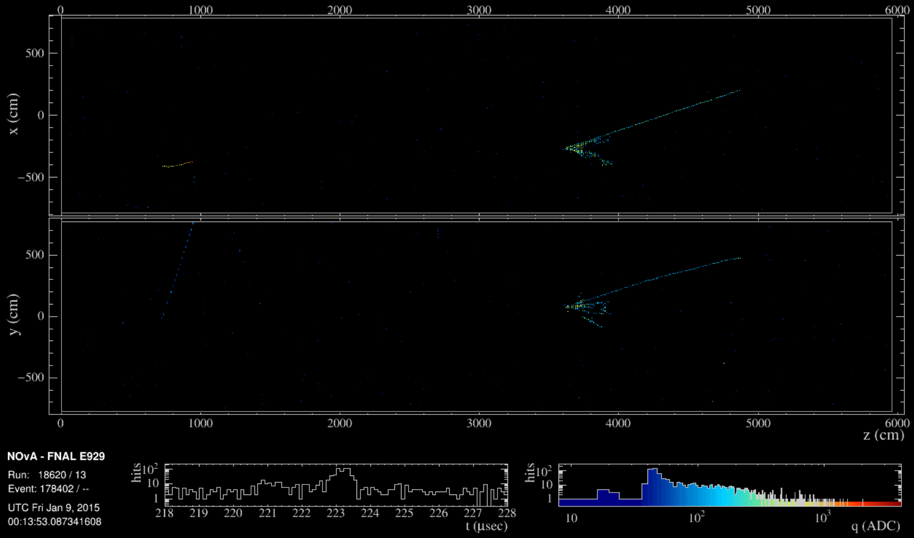

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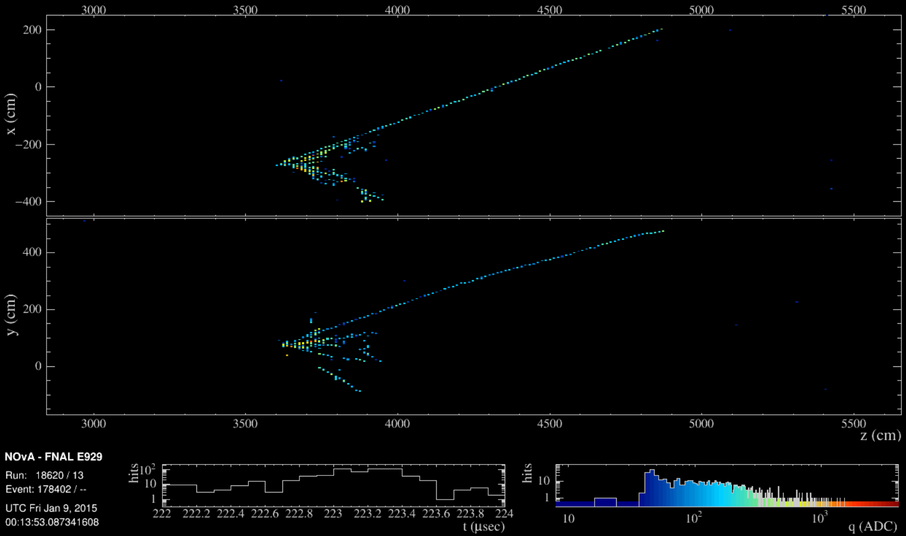
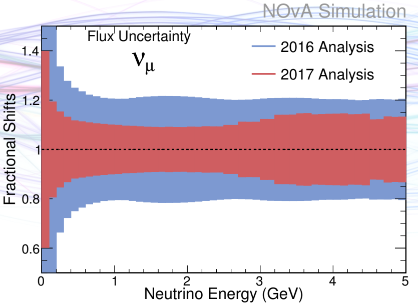
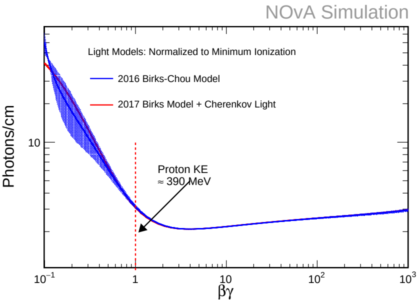


What's new?

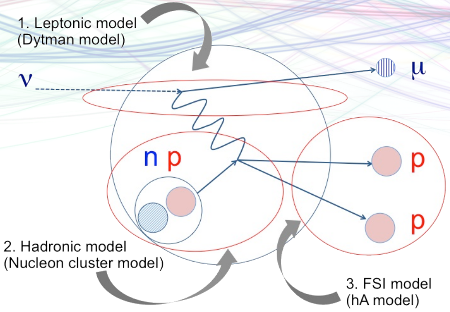
- 50% additional data
- Data-driven flux estimates from MINERvA[1]
- Retuned cross-section model
- Detector sim. improvements (E_{res} : 7% $\rightarrow$ 9%)
- Using computer vision classifier for all analyses
- Analysis improvements
  - Resolution binning for ν_μ
  - "Peripheral" sample for ν_e

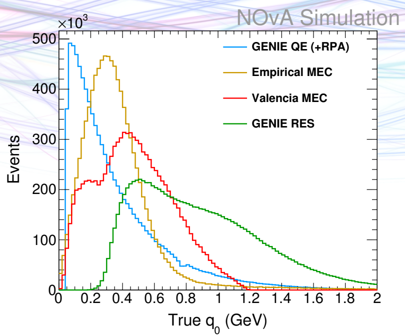




1 Phys. Rev. D94 (2016) 092005

Nuclear correlations





- ND data reveals some data/MC disagreement in E_{had} spectrum
- Inter-nucleon correlations a hot topic in neutrino xsecs currently
- Evidence for extra “MEC” component from NOvA, MINERvA, etc
- We pick the model that best matches our data, but allow a lot of freedom in the shape of the energy transfer distribution

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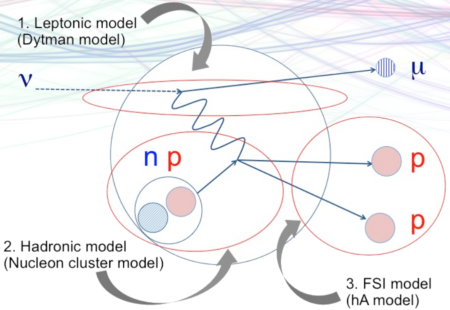

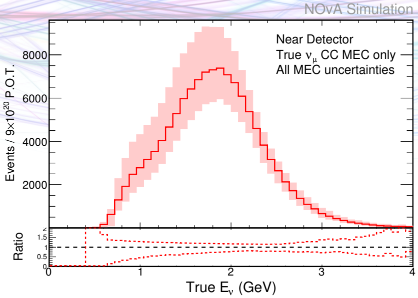

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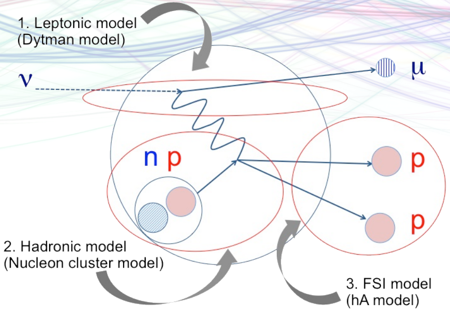

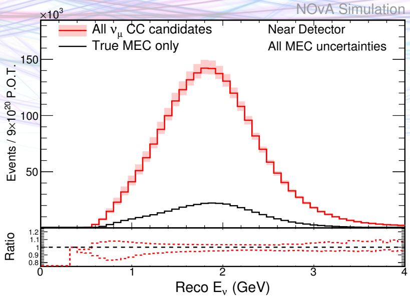

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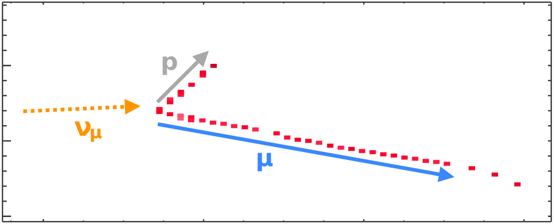
Principle of the ν_μ measurement

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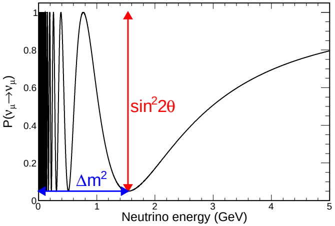
- Two flavor approx. works well here
- $P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right)$
- $\theta_{23} \approx 45^\circ \rightarrow$ almost all ν_μ expected to disappear at oscillation max.

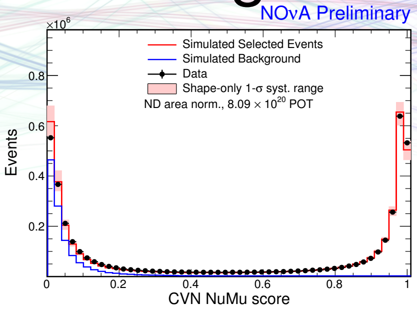


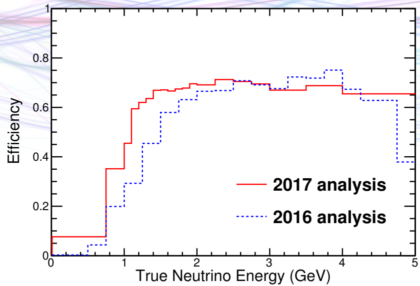
Mixing patterns

- 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)

Selecting muon neutrinos



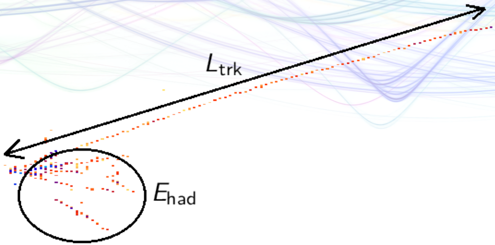


- Selecting ν_μ CC relatively easy – long μ track, characteristic dE/dx
- Occasionally a $\pi^\pm$ from an NC event can be confused
- Use same convolutional neural network ("CVN") as for ν_e selection

- 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

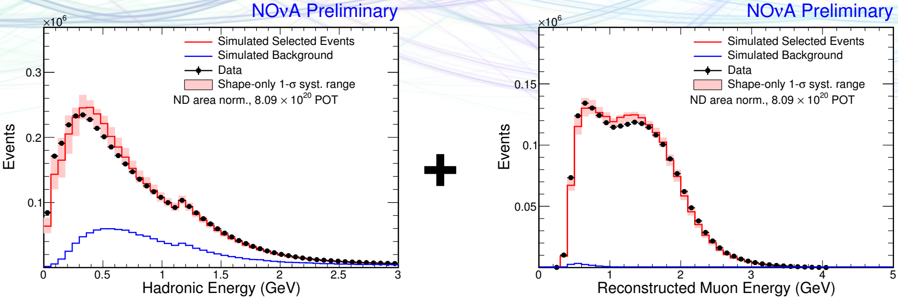
- 93% pure FD ν_μ CC sample, 11% higher efficiency than prev. sel.

ν_μ energy estimation



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

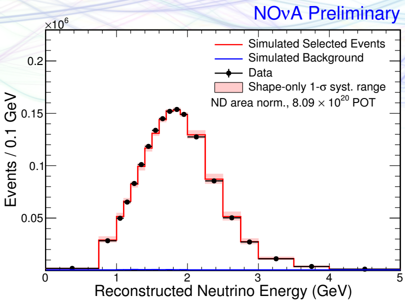
ν_μ energy estimation



(30%) + (3%)

- Good data/MC agreement for muon neutrino selected events
- Hadronic scale uncertainty 5%

ν_μ energy estimation



(9%)

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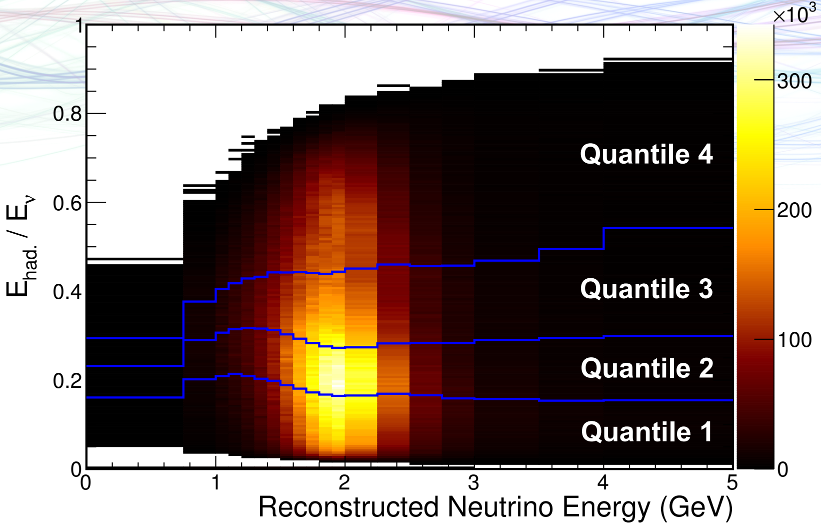
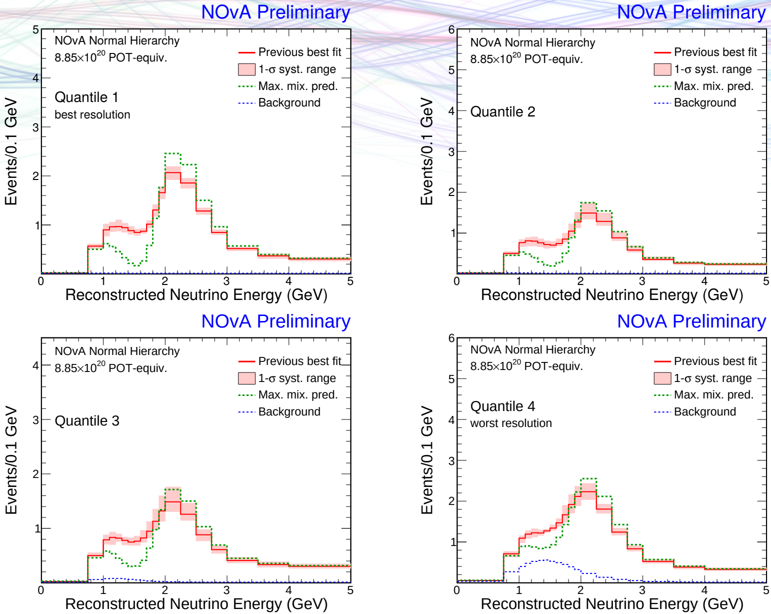
ν_μ resolution bins



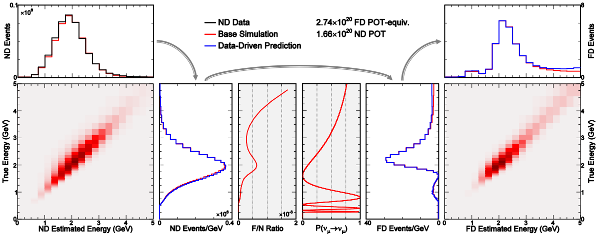
- Bin into 4 equal quantiles by hadronic energy fraction
- Energy resolution varies from $\sim 6\%$ to $\sim 12\%$ between bins

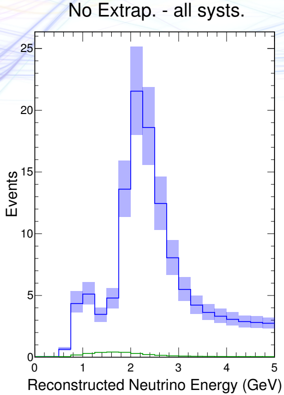
ν_μ resolution bins



Extrapolation procedure

- 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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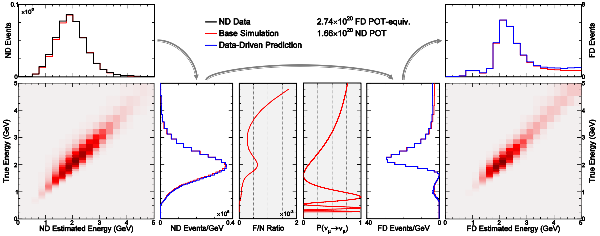
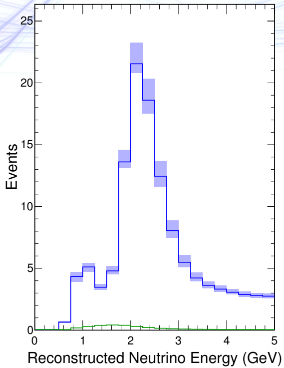
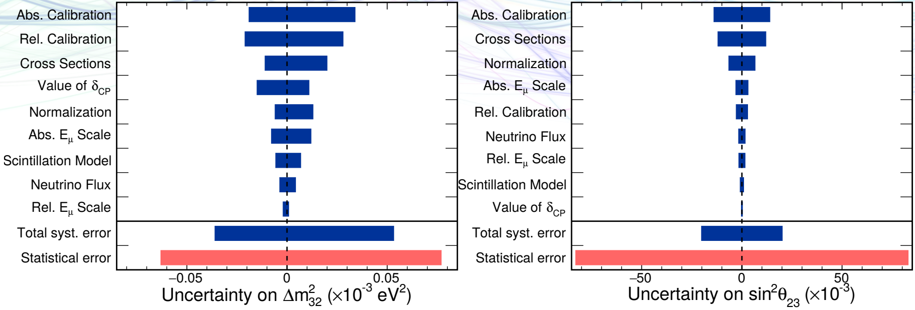


Full Extrap. - all systs.

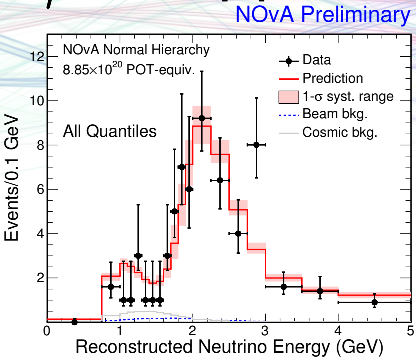


ν_μ systematics



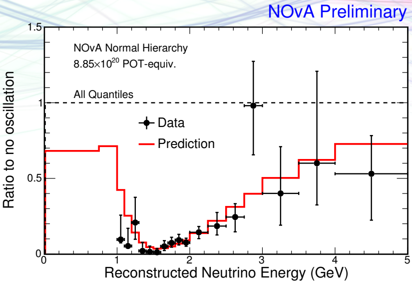
- Evaluate systematics by replacing nominal MC by shifted versions
- Hard work here means we're still stats limited
- Calibration and cross-section (MEC) systematics largest

ν_μ disappearance results



- Expect 763 FD ν_μ CC events with no oscillation
- Observe 126 (inc. 3.4 beam bkg. and 5.8 cosmic)

ν_μ disappearance results



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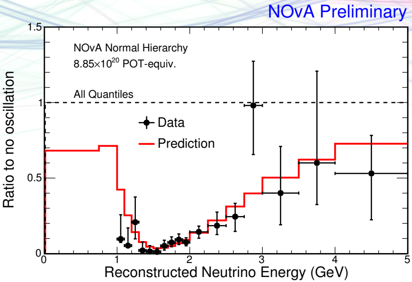

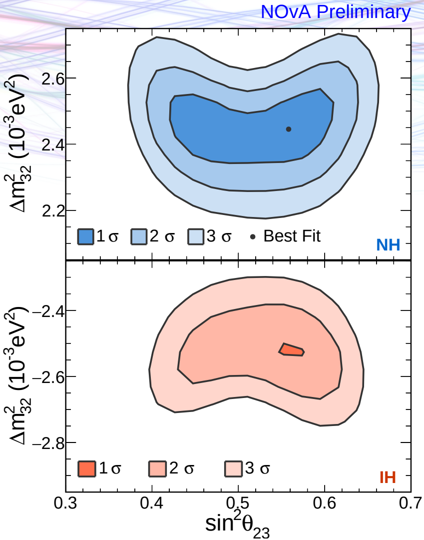

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$$\Delta m^2_{32} = (2.44 \pm 0.08) \times 10^{-3}\text{eV}^2 \text{ (NH)}$$
$$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03} \quad \text{or} \quad 0.48^{+0.04}_{-0.04}$$

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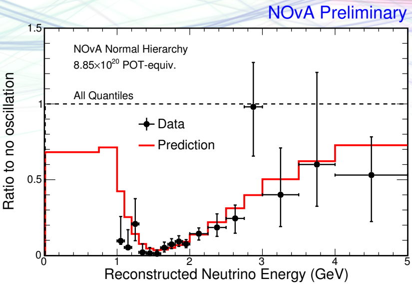

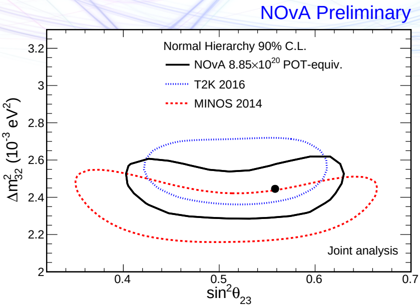

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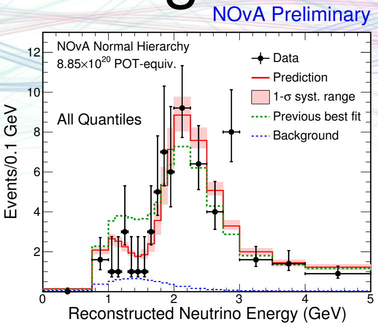
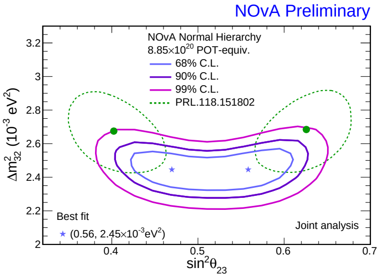
Changes from previous result





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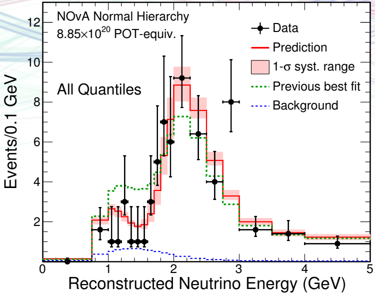
NOvA Preliminary



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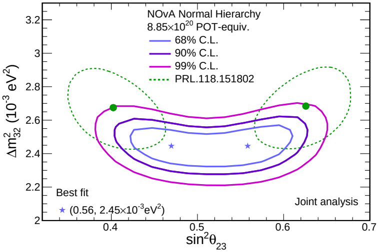

- **New simulation**
  - Some effect from decreased E_{res}
  - $\langle$70 MeV$\rangle$ shift in energies $\rightarrow$ expect (observe) 0.5 (3) events migrating out of dip region

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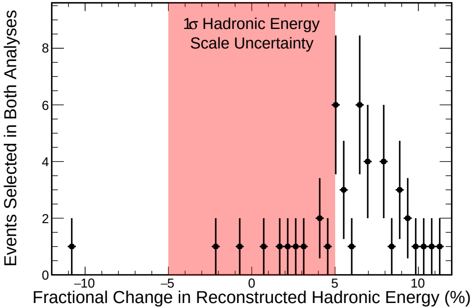
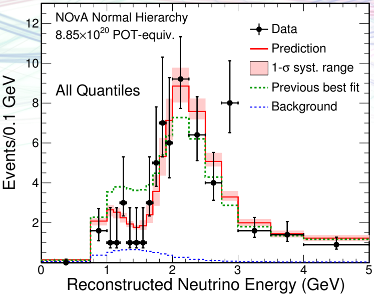
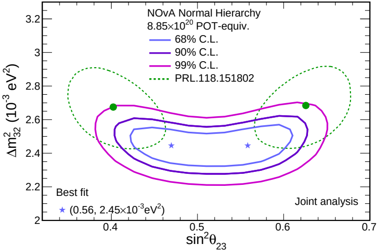


Changes from previous result

NOVA Preliminary



NOvA Preliminary



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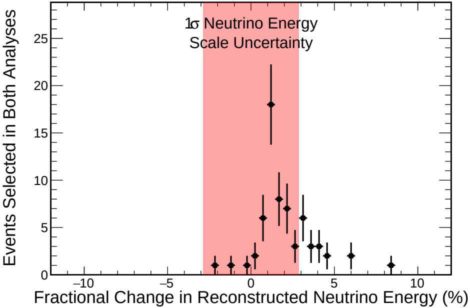

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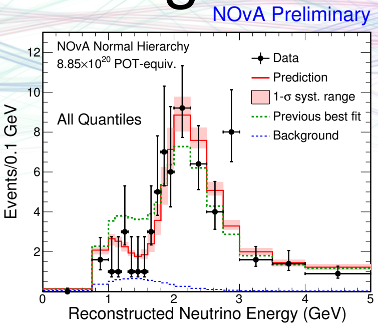

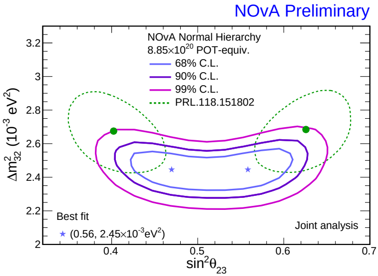

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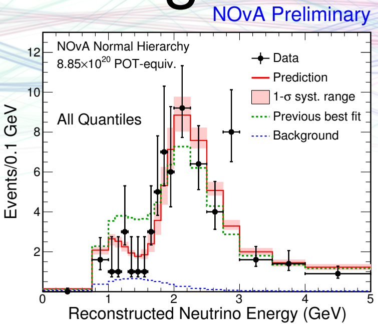
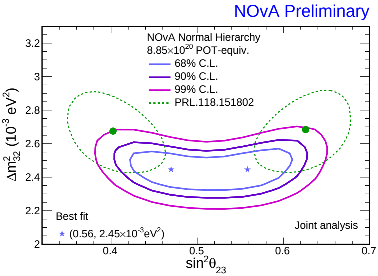
  - 5% of mock experiments have a larger change, mostly driven by low selection overlap (especially cosmics)

Changes from previous result





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- **New selection and analysis**
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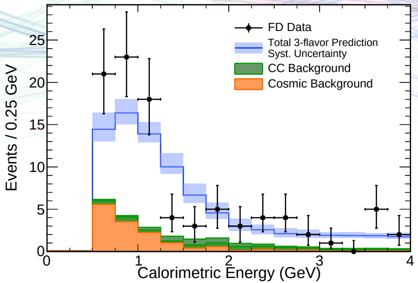
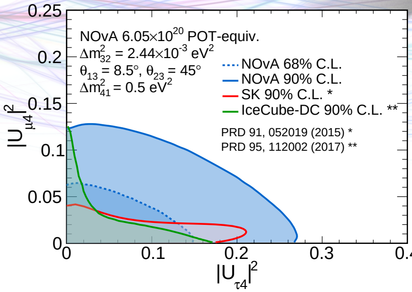
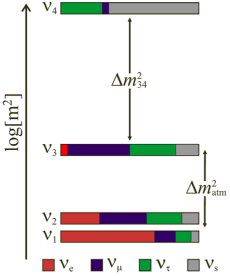
- **New data**
  - New 2.8×10^{20} POT of data prefers maximal mixing

Aside: sterile neutrinos





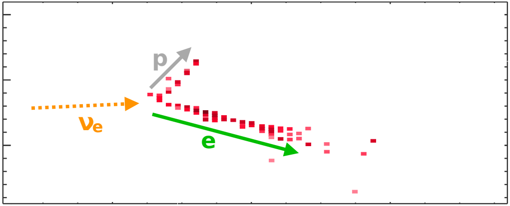
- Are all the disappearing ν_μ going to ν_e or ν_τ?
- Might some fraction be oscillating to a a 4th, sterile, state?
- Would expect a depletion of NC events at FD
- Expect $83.5 \pm 9.7(\text{stat}) \pm 9.4(\text{syst})$ see 95
- Set limits on $U_{\mu4}$ and $U_{\tau4}$



Phys. Rev. D 96, 072006 (2017)

Principle of the ν_e measurement

- Separate ν_e CC interactions from beam backgrounds
  - Harder problem 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



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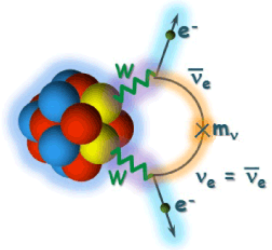
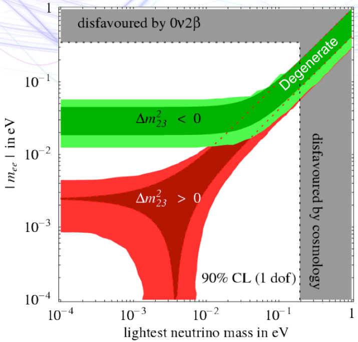
- An excess in the FD is the sign of $\nu_\mu \to \nu_e$ oscillations
- $P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) + f(\text{sign}(\Delta m^2_{32})) + f(\delta_{CP})$
- θ_{13} only 8.5° degrees, most ν_μ go to ν_τ instead
- Sensitive to mass ordering (“hierarchy”), δ_{CP} and θ_{23} octant

Why hierarchy?

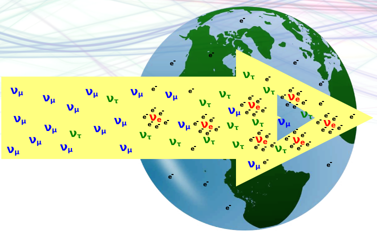
- Is the electron-like state lightest?
- *i.e.* Does the pattern of the masses match the charged leptons?

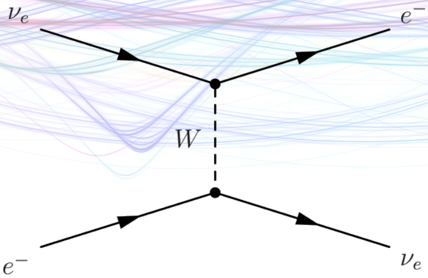




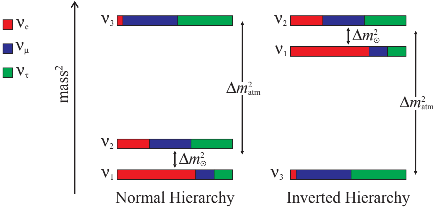
- Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- Observation of $0\nu\beta\beta$ would be proof they are
- Impact of **IH** determination: lack of $0\nu\beta\beta$ implies Dirac nature

Matter effects



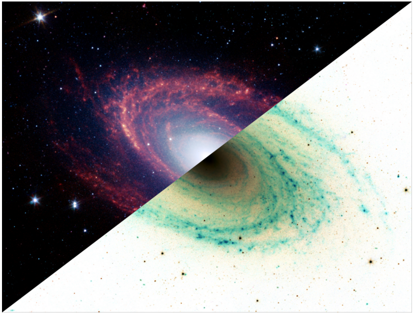


- Electrons in the Earth drag on the “electron” neutrino states
- Sign of the effect opposite for antineutrinos and for NH/IH



Neutrino/antineutrino symmetry

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



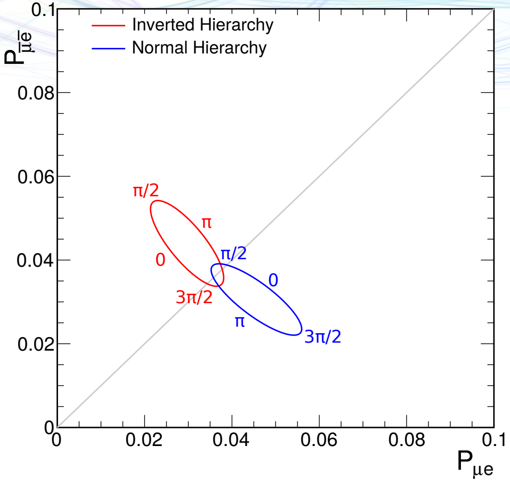
- Why is the universe not equal parts matter and antimatter?
- Need ppb early universe asymm.
- Existing CP-violation insufficient
- *"Leptogenesis"*: generate $\nu/\bar{\nu}$ imbalance, transfer to baryons

- 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}



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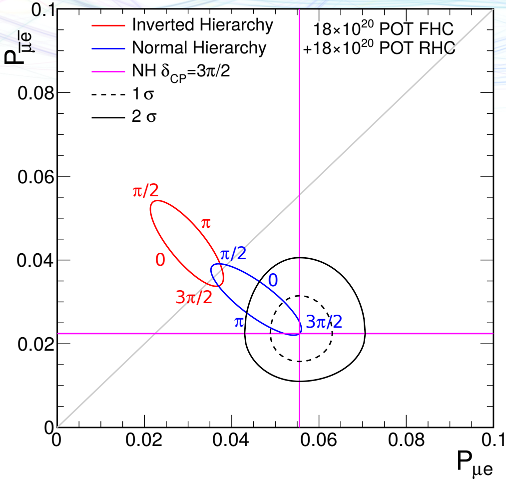
- Ultimately constrain to some region of this space



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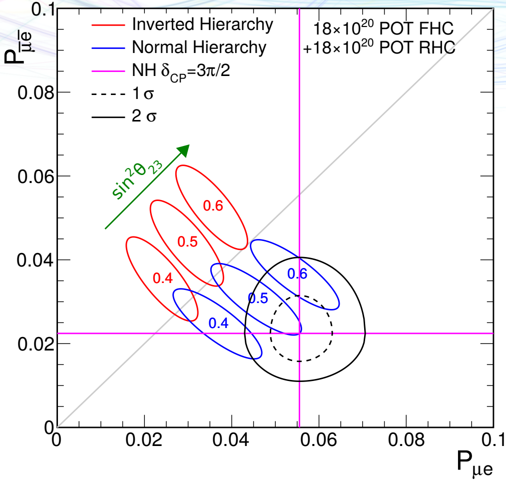
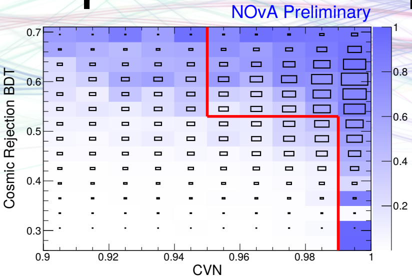
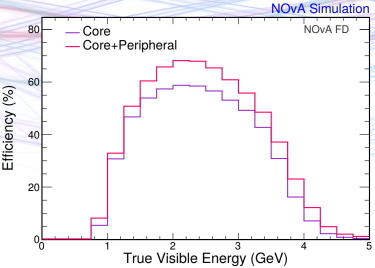
- P also $\propto \sin^2\theta_{23}$

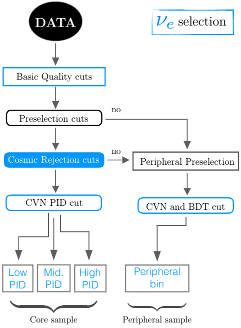


Peripheral sample

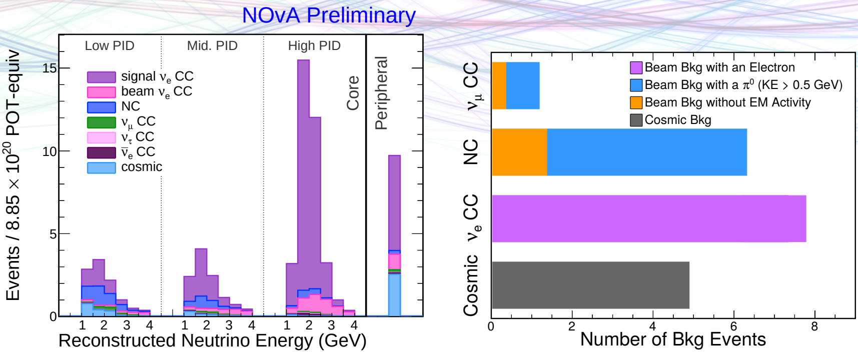




- Events that fail containment and cosrej cuts given a second chance
- Require high CVN score plus specialized cosmic rejection BDT
- Equivalent to 16% more exposure



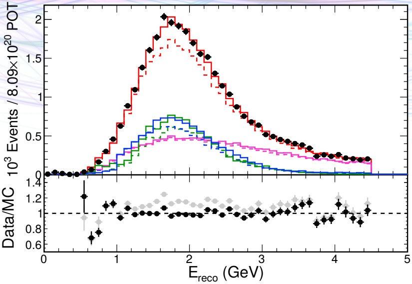
Sample composition



- Break spectrum down into 3 PID bins (low to high purity)
- Plus additional peripheral sample
- Backgrounds predominantly have EM activity: $\pi^0 \rightarrow \gamma\gamma$ or intrinsic beam ν_e

Making FD bkg prediction

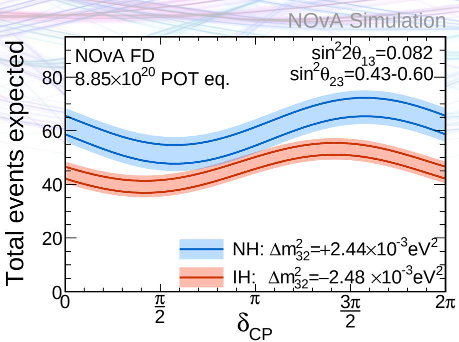
- Use ND data to predict three FD background components
  - Beam ν_e CC
  - NC
  - ν_μ CC



- Can separate statistically:
- ν_e/ν_μ share common π^+/K^+ ancestors
- μ in ν_μ CC events leaves decay electron
- Beam ν_e ↑1%, NC ↑20%, ν_μ CC ↑10%
- Extrapolate 3 components for FD prediction

Event count expectations

$P(\nu_\mu \to \nu_e)$	More	Less
Hie.	NH	IH
δ_{CP}	$\sim \frac{3\pi}{2}$	$\sim \frac{\pi}{2}$
θ_{23}	$> 45^\circ$	$< 45^\circ$



Signal prediction

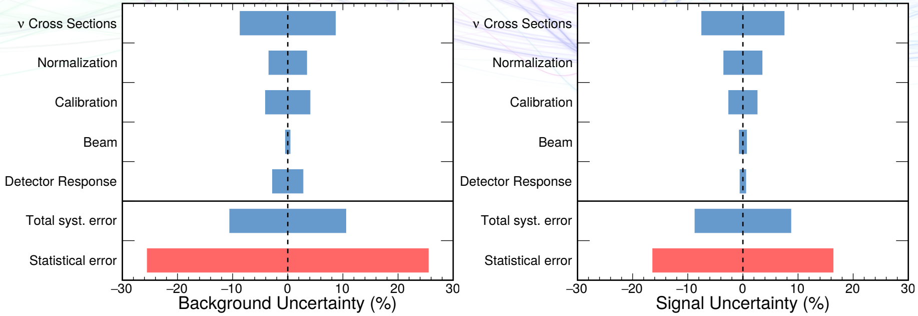
NH $\frac{3\pi}{2}$	IH $\frac{\pi}{2}$	for $\theta_{23} = 45^\circ$
48	20	$\pm$9% syst.

Background components

Total bkg	NC	beam ν_e	ν_μ CC	ν_τ CC	cosmics	
20.5	6.6	7.1	1.1	0.3	4.9	$\pm$10% syst.

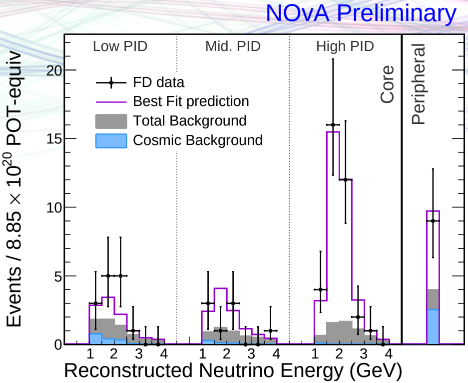
Essentially independent of oscillation parameters

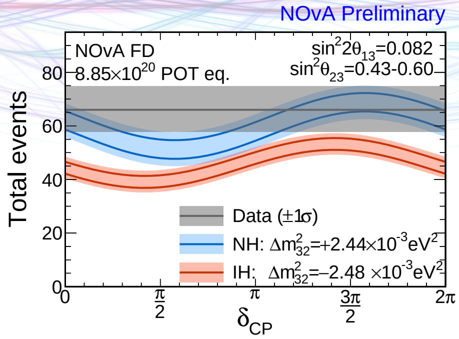
ν_e systematics



- Dominated by statistics and then cross sections (MEC shape)

ν_e appearance results

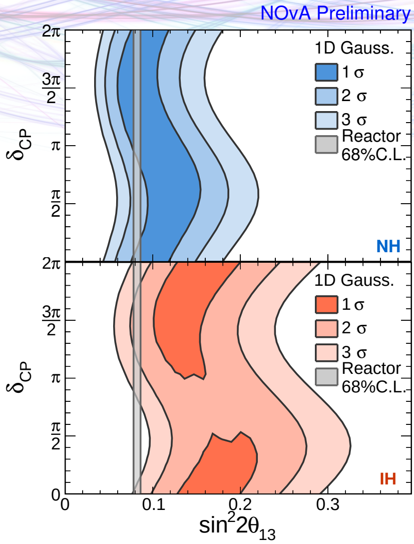




- Observe **66** events passing ν_e selection
- On 20.5 background
- Towards the higher end of expectations

ν_e fit results

- Joint fit from ν_μ and ν_e spectra
- Constrain θ_{13} to reactor avg. $\sin^2 2\theta_{13} = 0.082 \pm 0.005$



ν_e fit results

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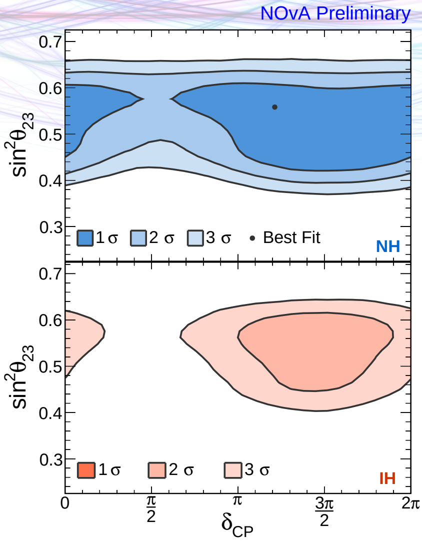

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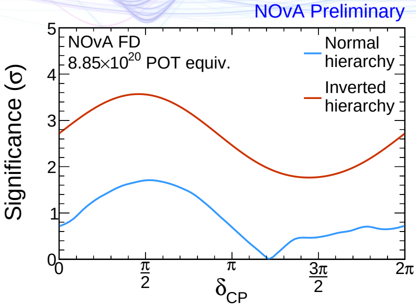
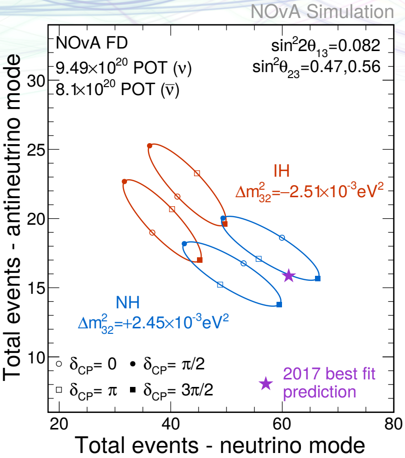
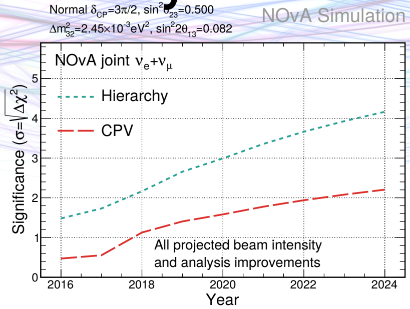


NOvA future sensitivity





- Currently favoured values avoid ambiguous region
- Will release large sample ($\sim 7 \times 10^{20}$ POT) of antineutrino data in June
- 4σ hierarchy measurement by end of experiment?

Conclusion

- Muon neutrino disappearance now compatible with maximal
- Very competitive measurement of Δm^2_{32}

- ν_e appearance favours NH, $\delta_{CP} \sim 3\pi/2$
- IH at $\delta_{CP} = \pi/2$ disfavoured at $>3\sigma$, approaching 2σ IH rejection

- Syst. reductions from testbeam this year
- Opening large sample of antineutrinos at Neutrino 2018

- Stay tuned!

www-nova.fnal.gov

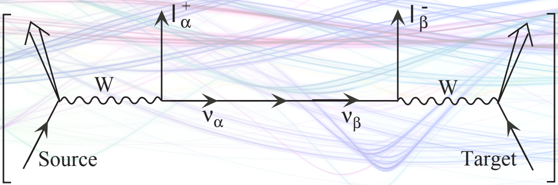

Thank you!
Fermilab
Fermilab
Fermilab
Fermilab
AISLE 1
AISLE 2
NORMA F. RAMSEY

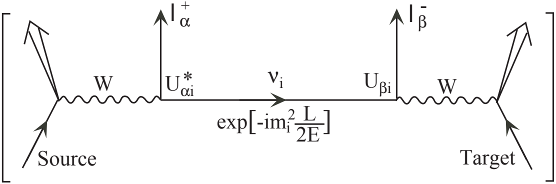
Backup

Particle physics confidence levels

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

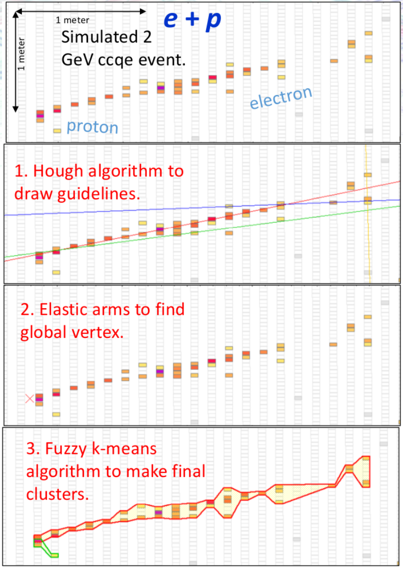
Neutrino oscillations

Amp


$= \sum_i$ Amp


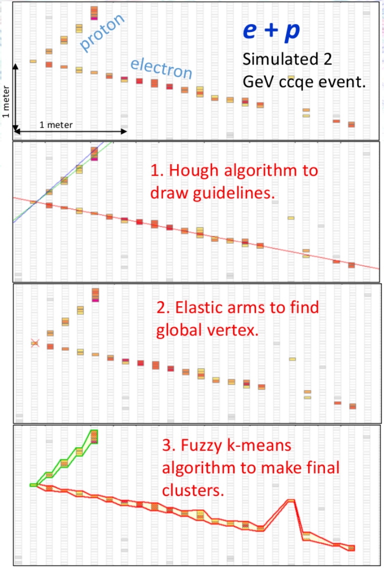
$$P_{\alpha\beta} = \left| \sum_i U^\star_{\alpha i} e^{-i m_i^2 L/2E} U_{\beta i} \right|^2$$

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

Event reconstruction



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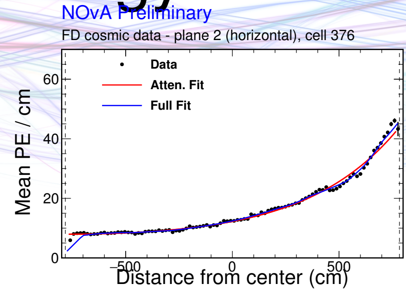
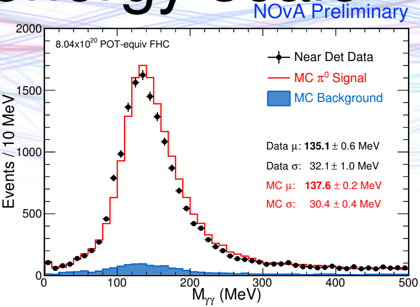
Calibration and energy scale

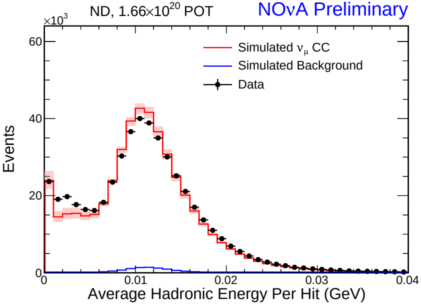
- Response varies substantially along cell due to light atten.
- Use cosmic ray muons as a standard candle to calibrate 300,000 channels individually
- Use dE/dx near the end of stopping muon to set abs. scale



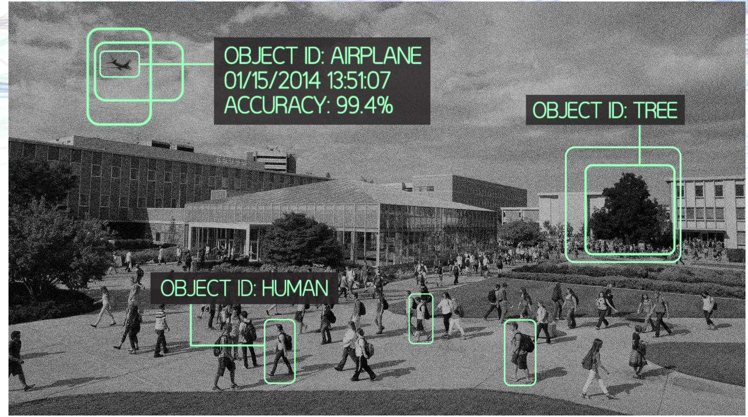
Calibration and energy scale

- 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





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

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

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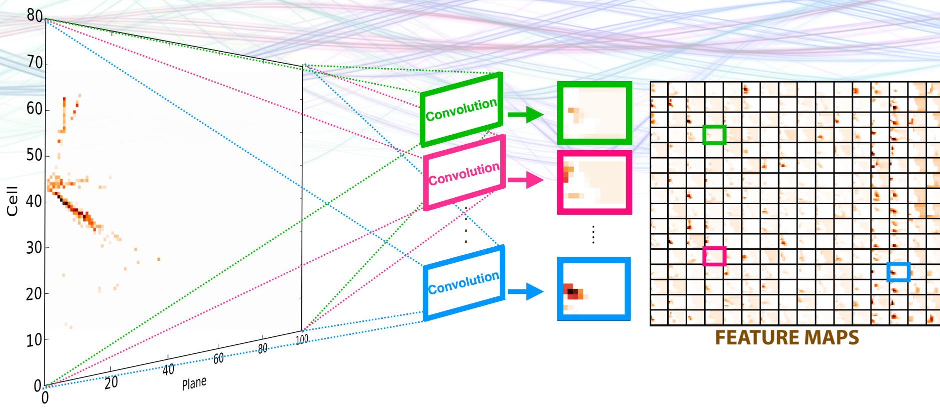

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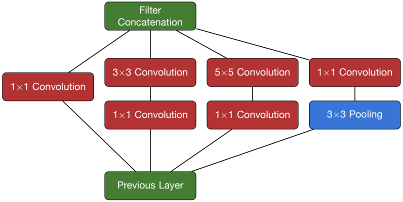
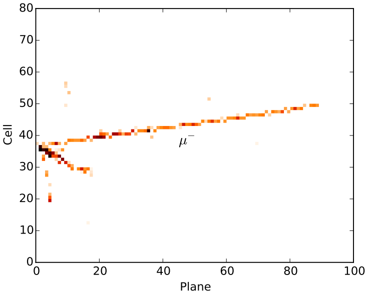
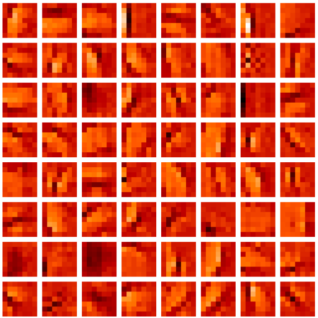
CVN architecture



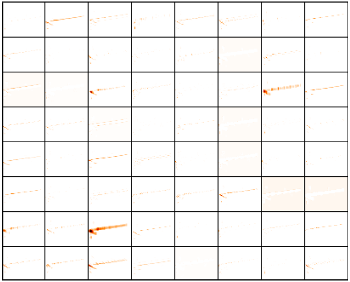
CVN example



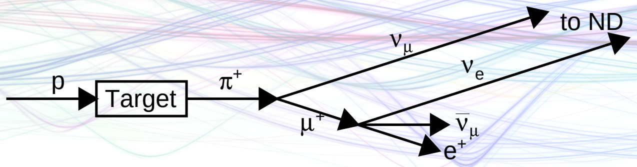
$\otimes$



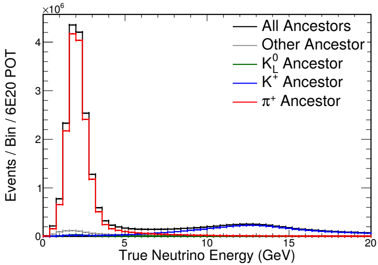
$=$

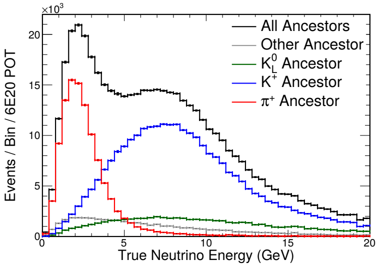


ND decomposition – beam ν_e

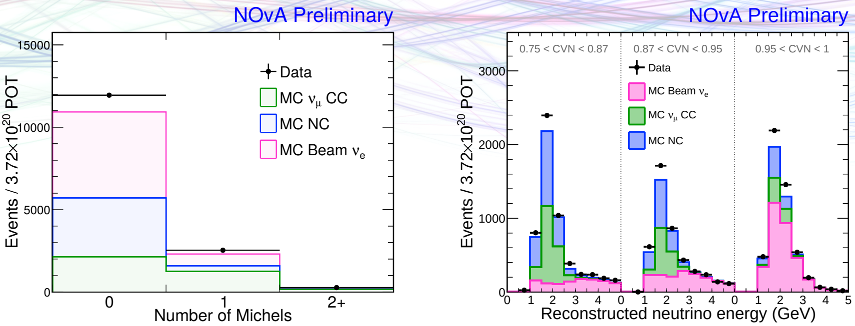


- Low-E ν_μ and ν_e trace back to the same π^+ ancestors



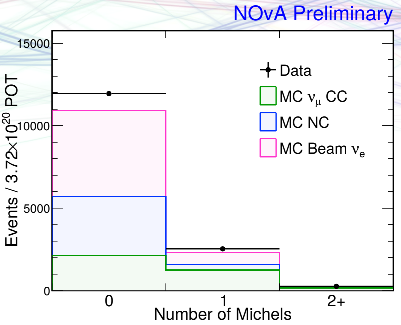


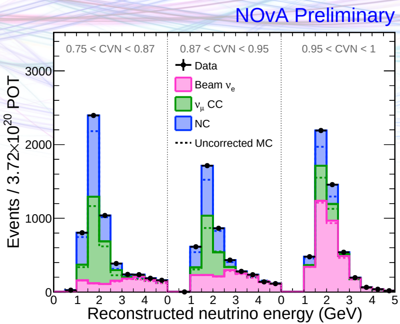
ND decomposition – Michels



- 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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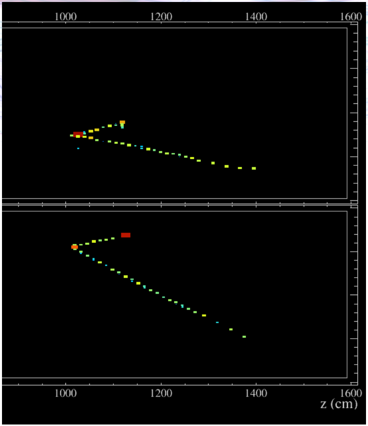
ν_e selection efficiency – MRE

- 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



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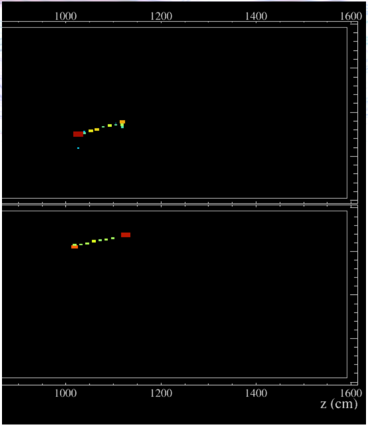

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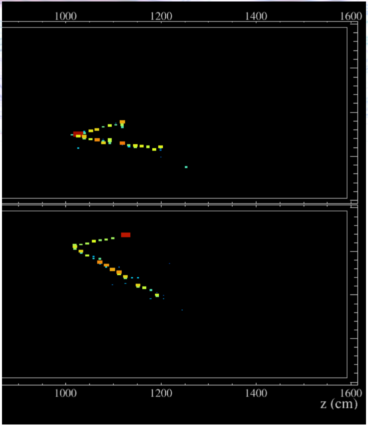

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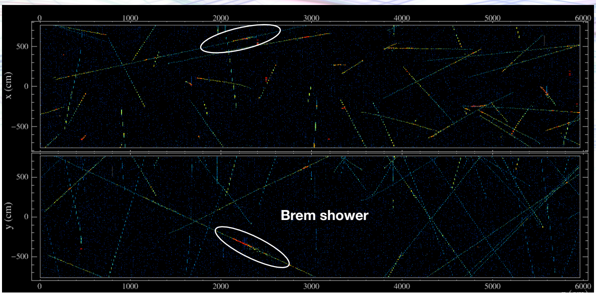
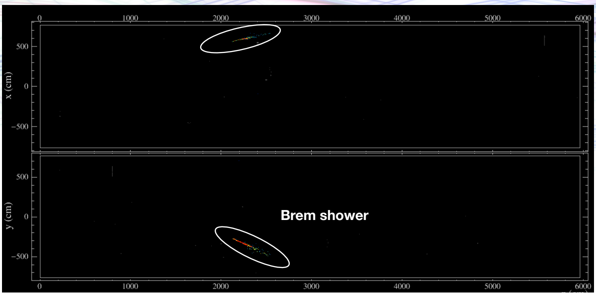
ν_e selection efficiency – EM activity

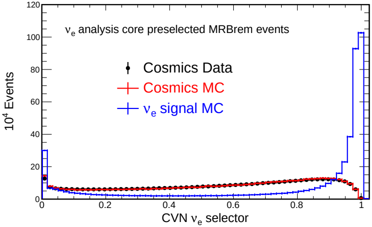


- Find FD data cosmic rays w/ brems

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



Evolution of ν_μ result

ν_μ Result- Comparison To Previous Result

50

A. Radovic, JETP January 2018

Our previous result*: 2.6σ

Our rejection of maximal mixing has moved from 2.6σ to 0.8σ. This change in the character of our result comes from a few key changes which I'll break down below.

↓

New simulation & Calibration: ~1.8σ

Driven by updates to energy response model. Drop to 2.3σ expected due to new energy resolution. Additionally we have a <70 MeV> shift in our hadronic energy response. This energy shift would be expected to move 0.5 events out of the "dip" region. However it instead pushes 3 "dip" events past a bin boundary.

↓

New selection and analysis: ~0.5σ

For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

↓

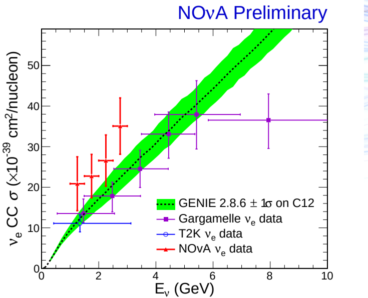
Full dataset: ~0.4σ → **Full dataset*: 0.8σ**

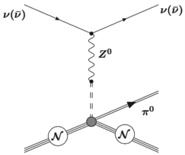
New, 3×10^{20} POT, data prefers maximal mixing.

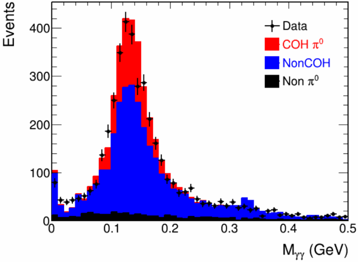
*Feldman-cousins corrected significance.

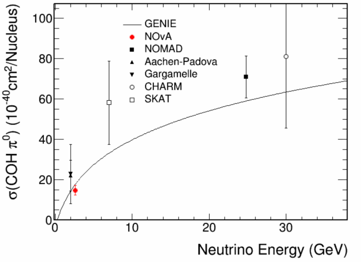
Cross-sections

- 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

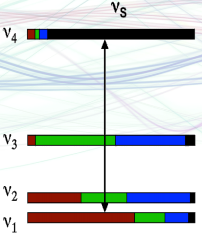






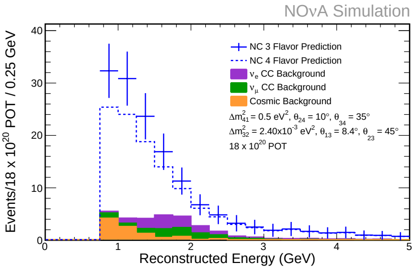


Sterile neutrinos

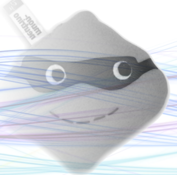


- More than the standard three neutrino states?
- There can only be three light “active” flavors
- “Sterile” neutrinos natural in some models

- ν_μ disappearance isn't entirely to ν_s, we see ν_e appear, OPERA sees $\sim$ expected number of ν_τ
- Could be a smaller admixture. Wouldn't interact even by NC, look for a deficit in FD and ND
- Hints for $\nu_\mu \to \nu_e$ at a small rate over short L, look in ND

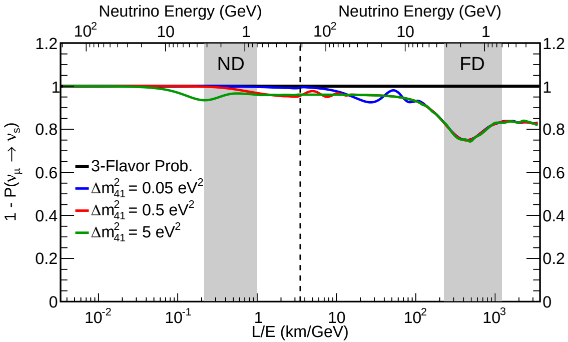


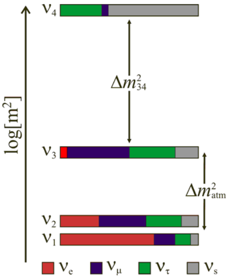
Principle of the NC measurement



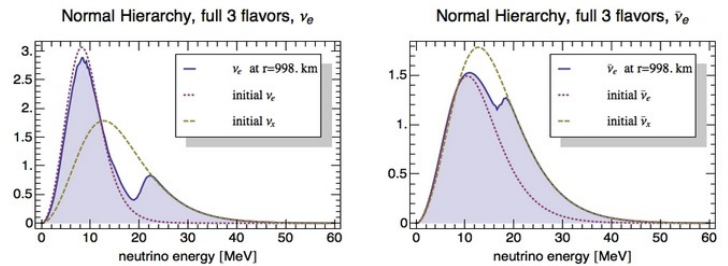
- Where do those ν_μ go?
- Do any oscillate to a sterile state? (ν_s)

- NC spectrum unaffected by oscillations among active flavours
- Select NC events in ND, extrapolate to FD prediction
- Count NC events in FD, compare to prediction
- Fix $\Delta m^2_{41} = 0.5\,\text{eV}^2$, rapid osc in FD, minimal in ND





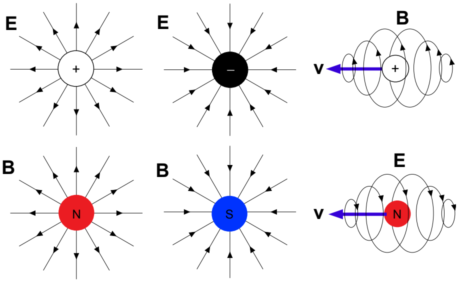
Supernova neutrinos

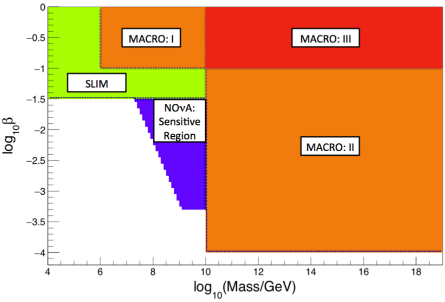


- Last (near)galactic supernova SN1987a
- 19 νs observed (Kamiokande and IMB)
- Detectors have improved a lot, expect 1000s of events
- Low *E* for NOvA, hook into SNEWS
- Astrophysical and ν information
- Expected rate “few / century”

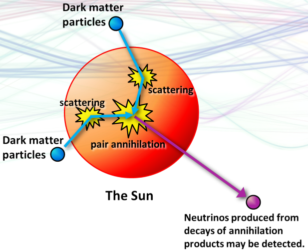
Monopole search

- Magnetic monopole would produce straight track with high dE/dx
- High mass monopole would travel notably slowly
- Large detector on surface → lower mass range

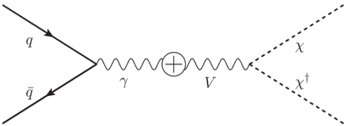


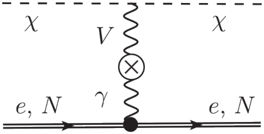


Dark matter



- DM annihilation in sun produces neutrinos visible in the detector
- High cosmic ray rate $\rightarrow$ look for upward events at night
- Same directional sensitivity used for atmospheric neutrinos





- Light dark matter could be produced in the target by the beam
- Interact in the Near Detector
- Sensitive to mass range below threshold of direct-detection expts