Latest results from NOvA

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The NOvA experiment

ν_μ disappearance

symmetries in neutrino mixing

ν_e appearance

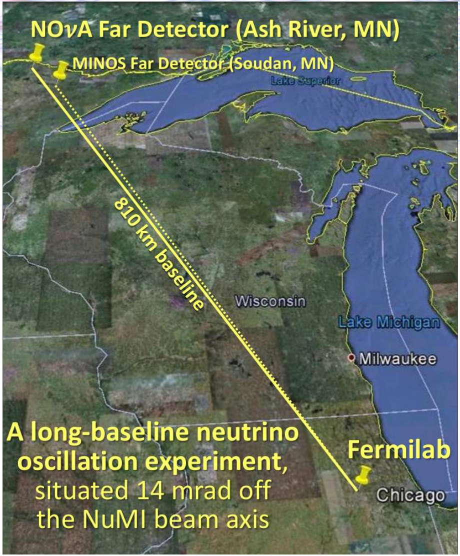
neutrino mass ordering

CP-violation

Future

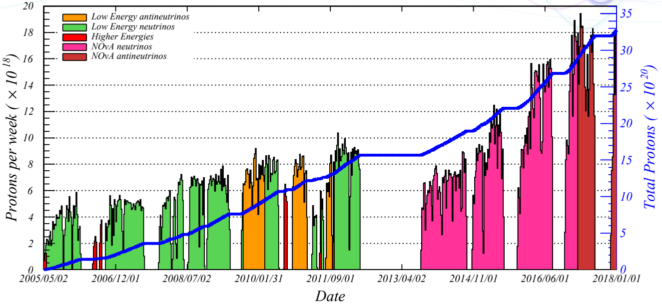
NOvA 10,000ft view

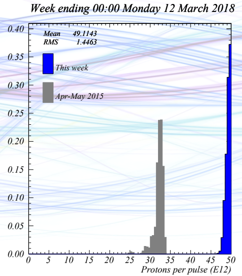
- ν_μ beam from Fermilab, IL
- Detector 810km away in MN
- Smaller detector onsite to measure flux before oscillations
  - $\nu_\mu \to \nu_\mu$
  - $\nu_\mu \to \nu_e$
  - $\bar{\nu}_\mu \to \bar{\nu}_\mu$
  - $\bar{\nu}_\mu \to \bar{\nu}_e$
- Precision measurements of $|\Delta m^2_{32}|$ and θ_{23}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

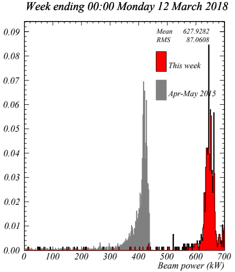


NuMI performance

- World's highest power neutrino beam
- 700kW design power since June 2016
  $\sim 5 \times 10^{13}$ protons / pulse

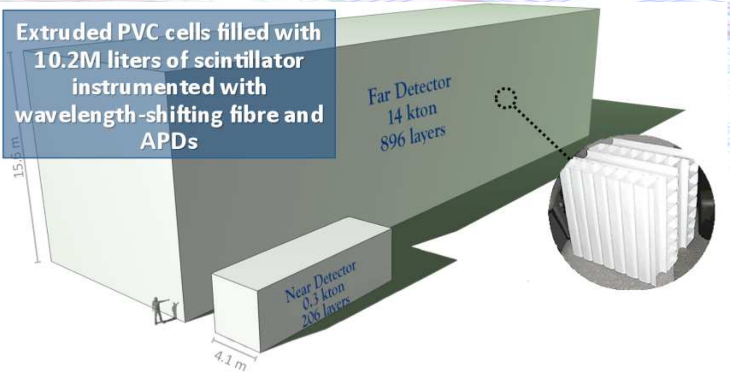


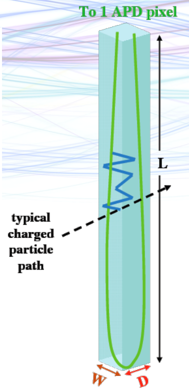




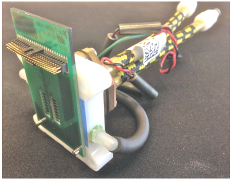
- These results use data from Feb 6 2014 to Feb 20 2017
- Beam power ramping up, detector under construction at start
- 8.85×10^{20} POT equivalent, about 1.5 years of nominal running

Detector technology

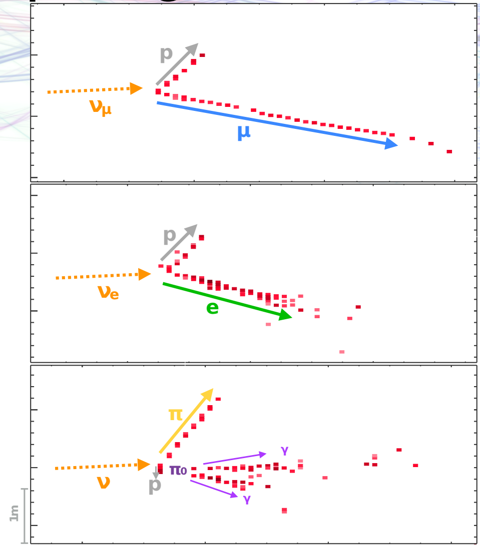




- 64% liquid scintillator by mass
- 4×6cm resolution, two views for 3D reco.
- 344,000 channels in 14 kton FD, on surface
- 300 ton ND, underground at FNAL



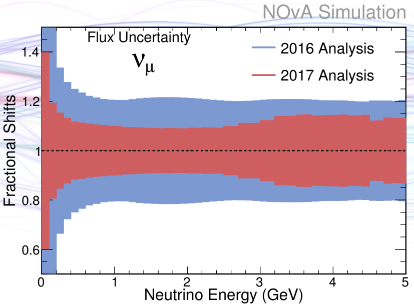
Event topologies

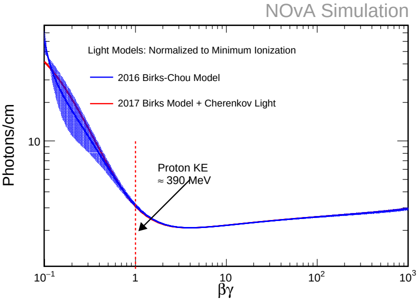


- Very good granularity, especially considering scale
- $X_0 = 38$cm (6 cell depths, 10 cell widths)

What's new?

- 50% more data than previous results[1] ($\sim 6 \longrightarrow 9 \times 10^{20}$ POT)
- Data-driven flux estimates from MINERvA[2]
- Retuned cross-section model
- Detector sim. improvements
- Using CVN computer vision classifier for all analyses
- Analysis improvements
  - Resolution binning for ν_μ
  - "Peripheral" sample for ν_e

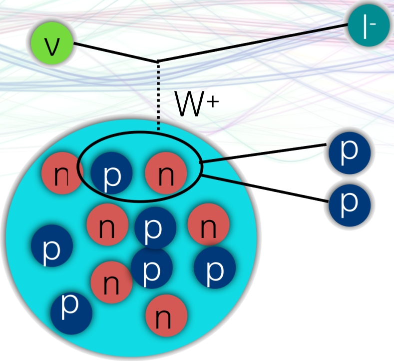




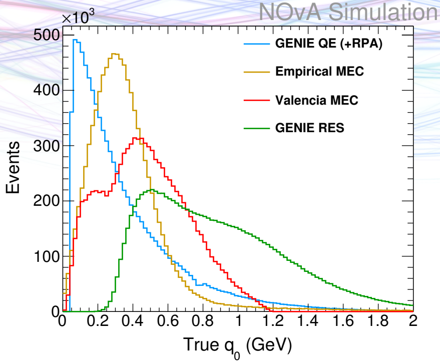
1 Phys. Rev. Lett. 118 (2017) 151802 and 231801

2 Phys. Rev. D94 (2016) 092005

Nuclear correlations

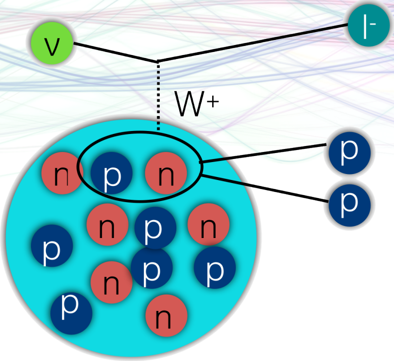


(Mark Hartz)



- 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

Nuclear correlations



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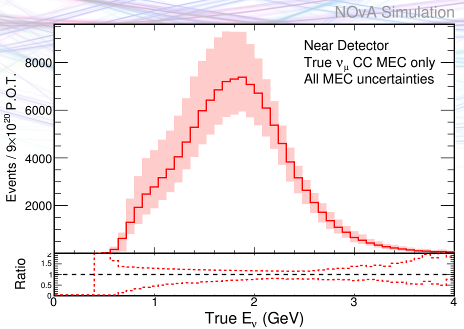

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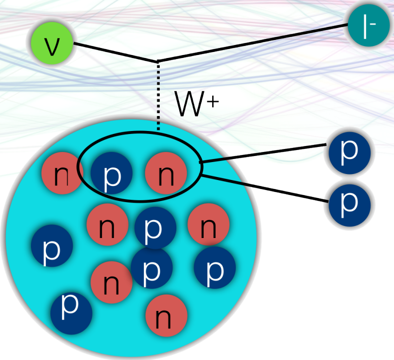

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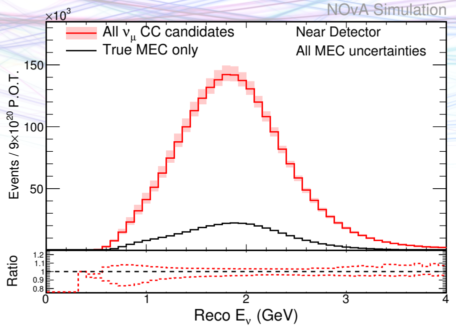

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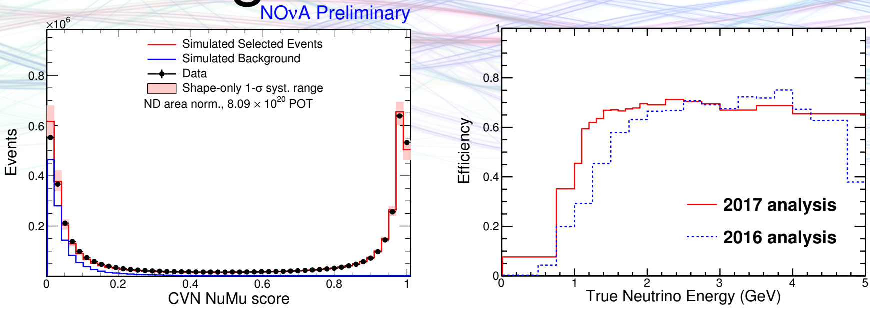
Selecting muon neutrinos

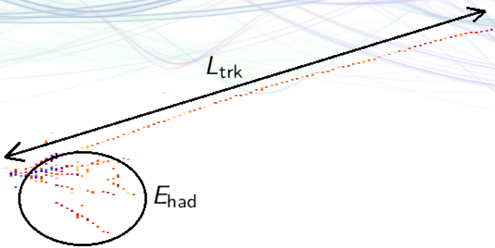


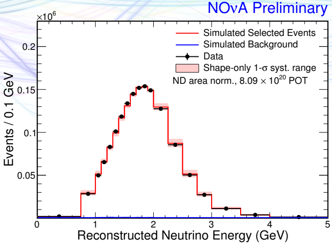
- Now using same convolutional neural net ("CVN") as ν_e analysis

- 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.
- Particularly at lower energies important to resolve osc. dip

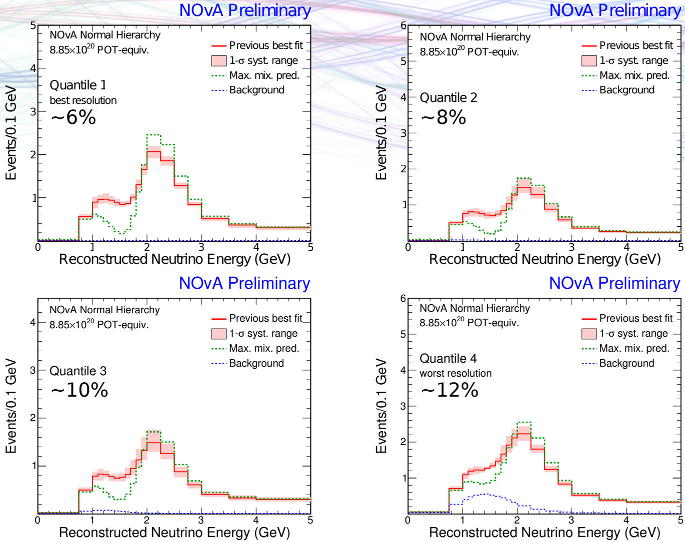
ν_μ energy estimation





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

ν_μ resolution bins



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

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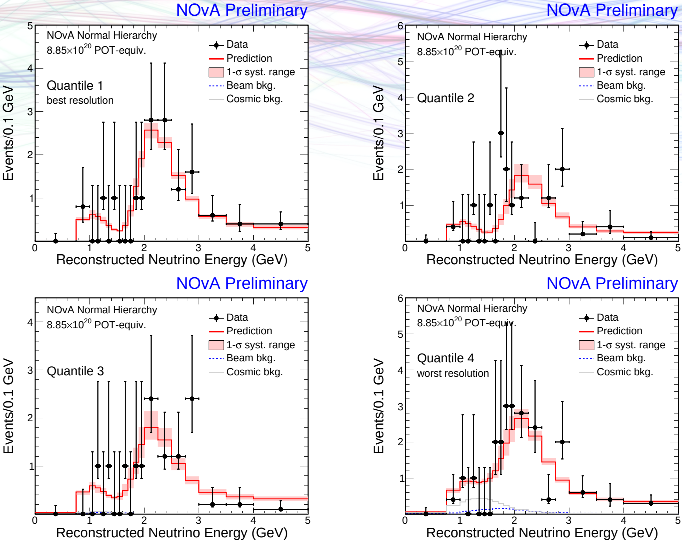

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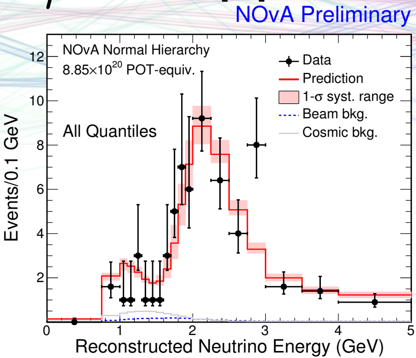
ν_μ disappearance results



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

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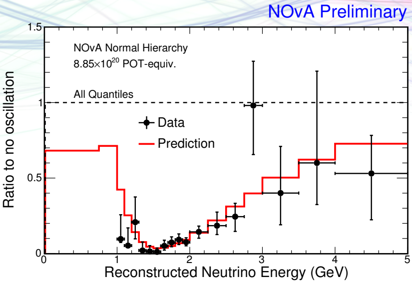

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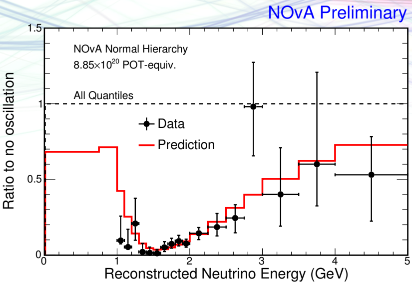

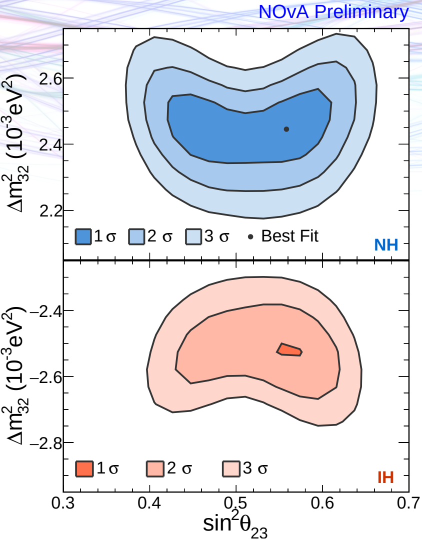

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$$\Delta m^2_{32} = (2.44 \pm 0.08) \times 10^{-3}\text{eV}^2 \text{ (NH)}$$
$$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03} \quad \text{or} \quad 0.48^{+0.04}_{-0.04}$$

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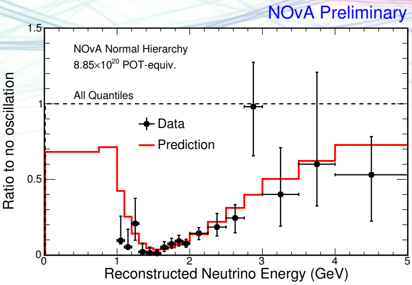

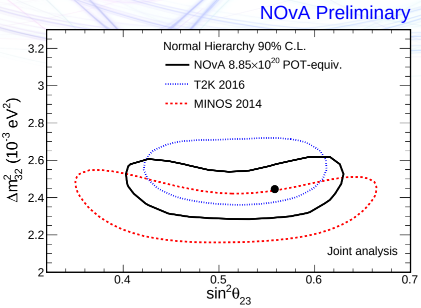

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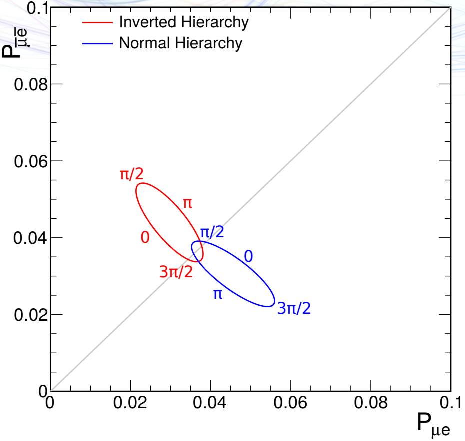
Principle of the ν_e measurement

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



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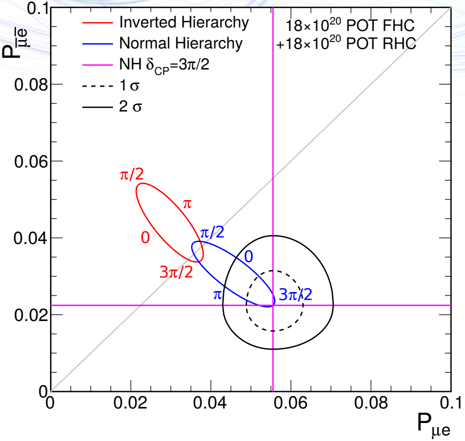
- Ultimately constrain to some region of this space



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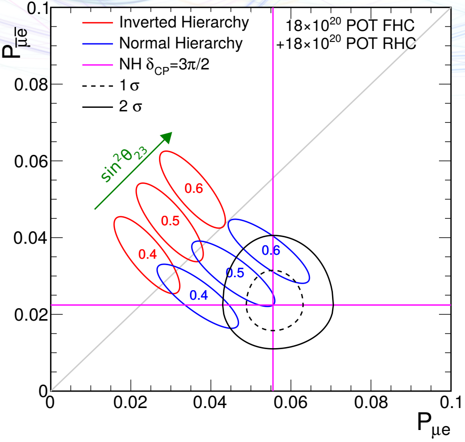
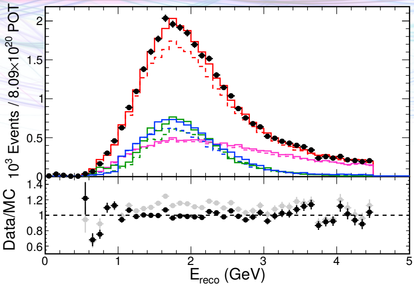
- P also $\propto \sin^2\theta_{23}$



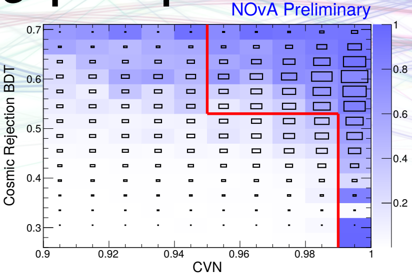
Making FD bkg prediction

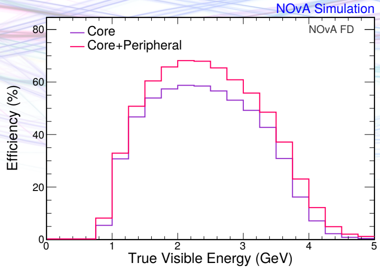
- Use ND data to predict three FD background components
  - Beam ν_e CC
  - NC
  - ν_μ CC



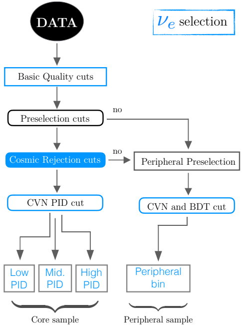
- Can separate statistically:
- ν_e/ν_μ share common π^+/K^+ ancestors
- μ in ν_μ CC events leaves decay electron
- Beam ν_e ↑1%, NC ↑20%, ν_μ CC ↑10%
- Extrapolate 3 components for FD prediction

ν_e peripheral sample



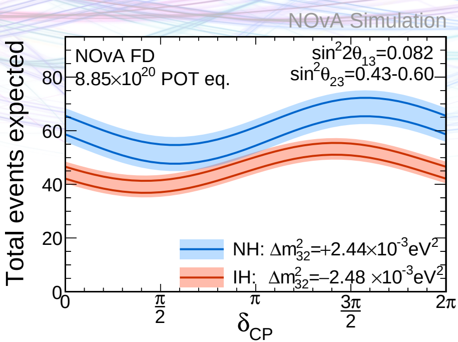


- FD data broken down by PID value (low→high purity)
- Events that fail containment and cosmic rejection cuts given a second chance
- Require high CVN score plus specialized cosmic rejection BDT
- Equivalent to 16% more exposure



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 $\frac{\pi}{2}$
48	20

for $\theta_{23} = 45^\circ$
$\pm 9\%$ syst.

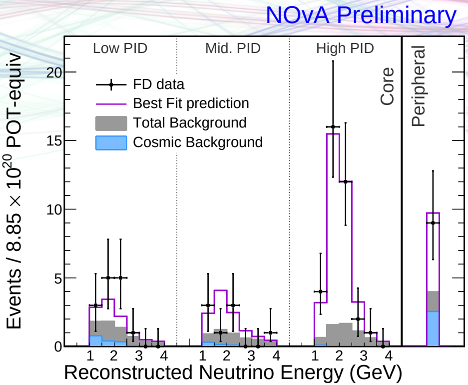
Background components

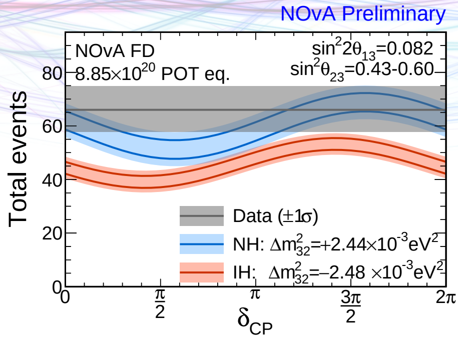
Total bkg	NC	beam ν_e	ν_μ CC	ν_τ CC	cosmics
20.5	6.6	7.1	1.1	0.3	4.9

$\pm 10\%$ syst.

Essentially independent of oscillation parameters

ν_e appearance results

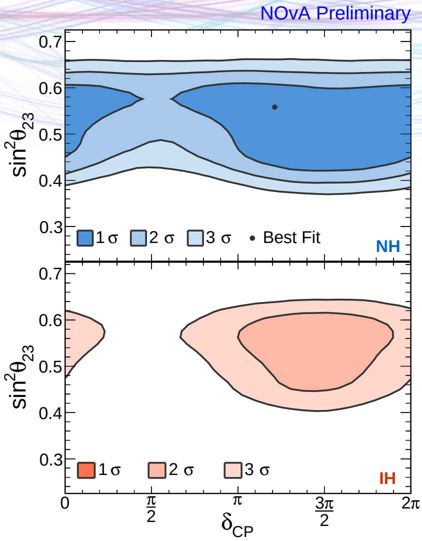




- Observe **66** events passing ν_e selection
- On 20.5 background
- Towards the higher end of expectations

ν_e fit results

- Joint fit from ν_μ and ν_e spectra
- Constrain θ_{13} to reactor avg. $\sin^2 2\theta_{13} = 0.082 \pm 0.005$
- Prefer NH and (weakly) $\delta_{CP} \sim 3\pi/2$



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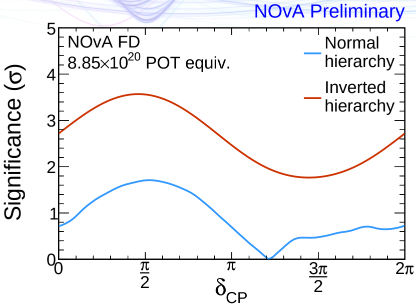
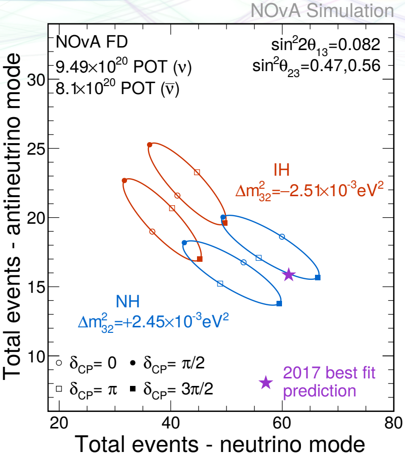
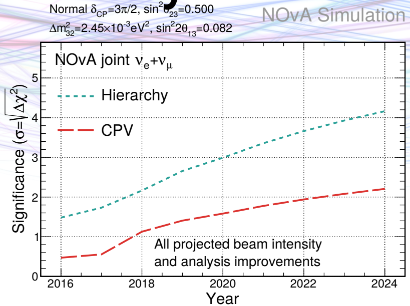
- IH disfavoured at 2σ level



NOvA future sensitivity





(Including incremental beam improvements to 900kW by 2021)

- 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!

Backup

Current world knowledge

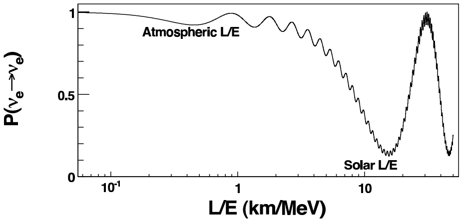
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

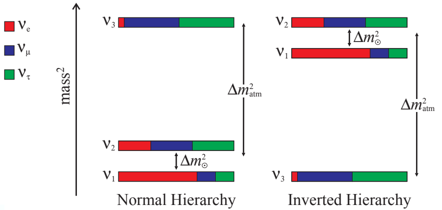
$\theta_{23} \sim 45^\circ$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} \mathrm{eV}^2$

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

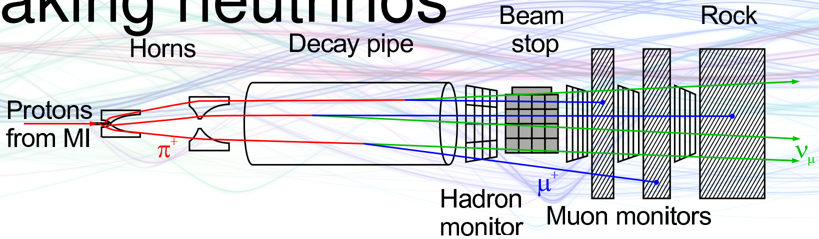
$\theta_{12} \sim 33^\circ$
$\Delta m^2_{21} \sim 7.5 \times 10^{-5} \mathrm{eV}^2$

$\delta_{CP} = ?$





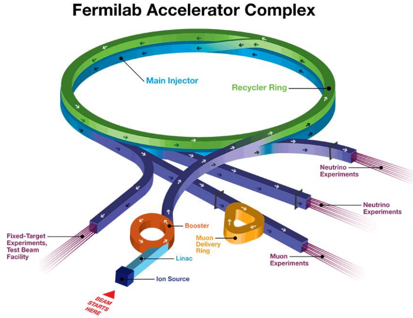
Making neutrinos



- 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

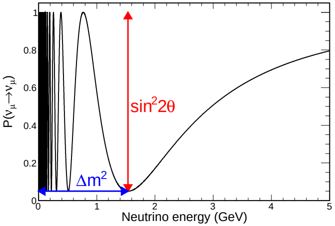


Principle of the ν_μ measurement

- 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

- 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.



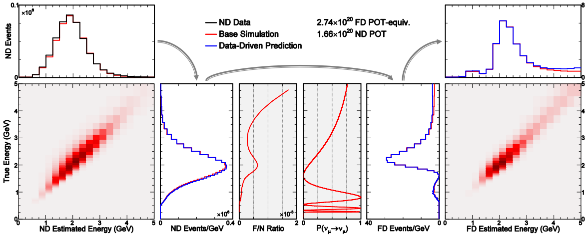
Mixing patterns

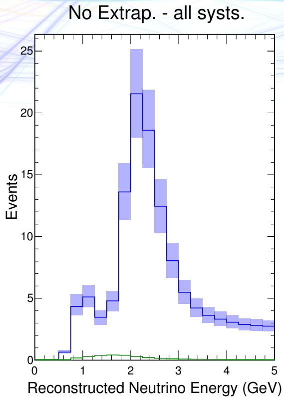
- Only a small fraction of ν_e in $|\nu_3\rangle$ ($\sin^2 2\theta_{13}$)
- The remainder is split $\sim 50/50$ ν_μ/ν_τ ($\sin^2\theta_{23}$)
- Accident? Or a sign of underlying structure?

- 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)

Extrapolation procedure

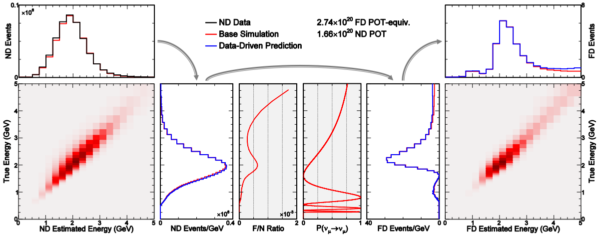
- Translate ND observations to true energy
- Transport to far detector and oscillate
- Smear back to reco energy
- Cosmics prediction from out-of-time data



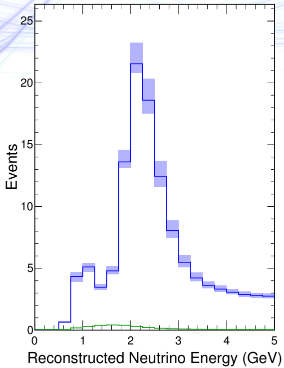


Extrapolation procedure

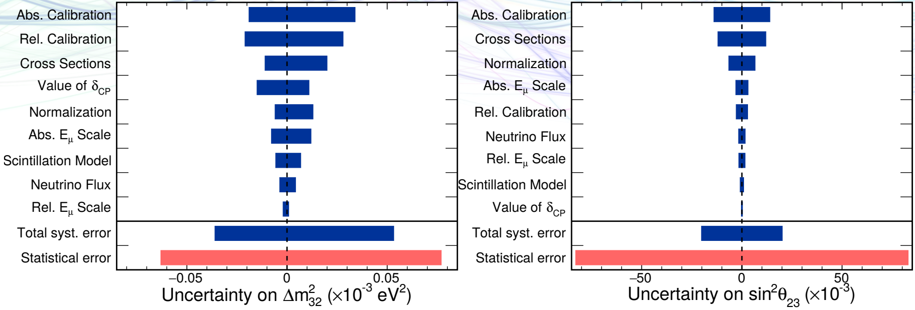
- Translate ND observations to true energy
- Transport to far detector and oscillate
- Smear back to reco energy
- Cosmics prediction from out-of-time data



Full Extrap. - all systs.

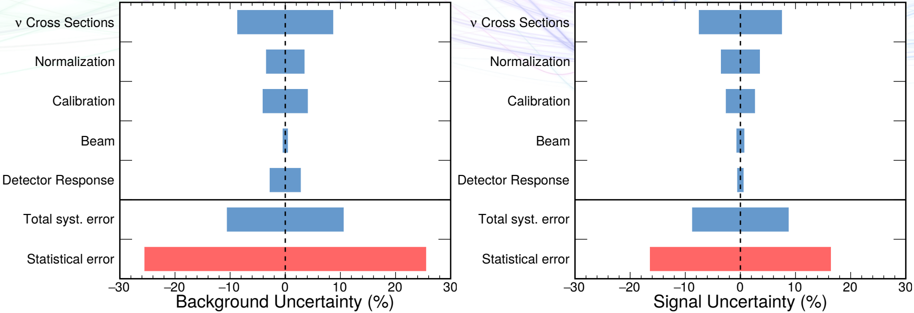


ν_μ systematics



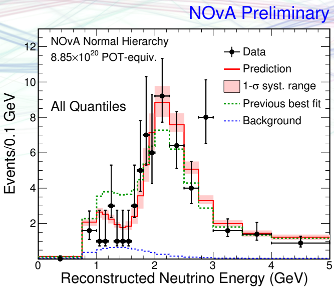
- Evaluate systematics by replacing nominal MC by shifted versions
- Hard work here means we're still stats limited
- Calibration and cross-section (MEC) systematics largest

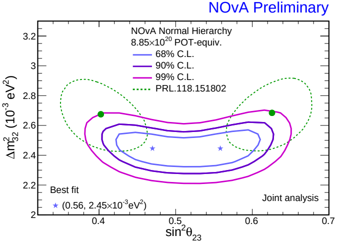
ν_e systematics



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

Changes from previous result





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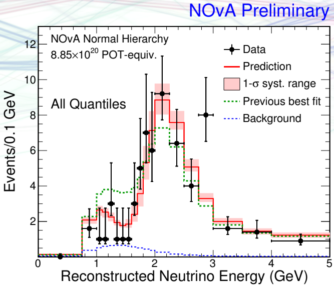
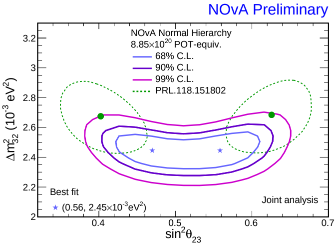
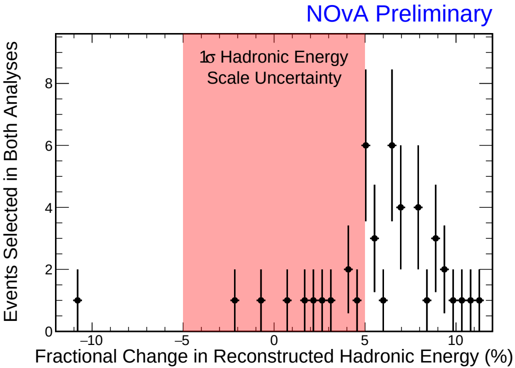
Changes from previous result





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



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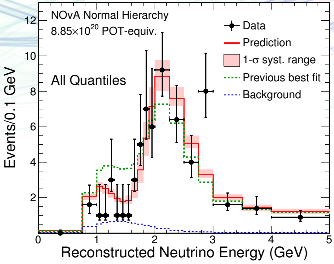
NOvA Preliminary



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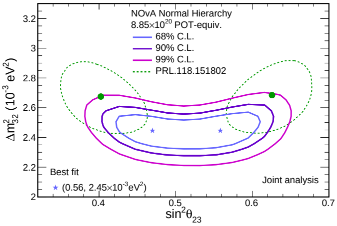

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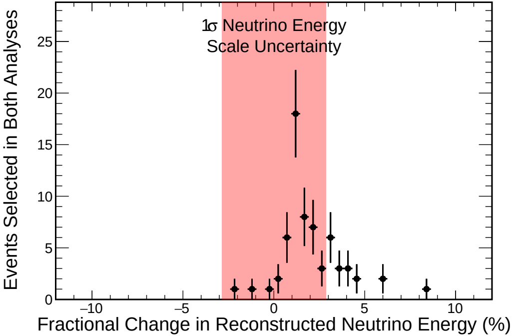

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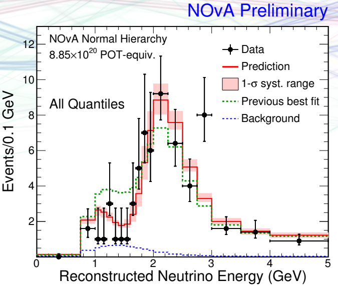

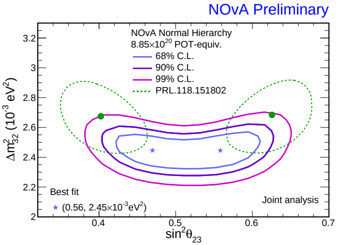

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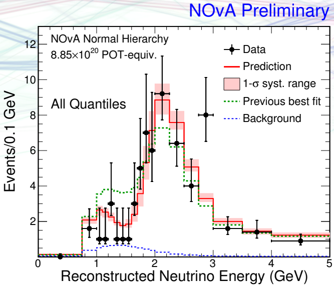

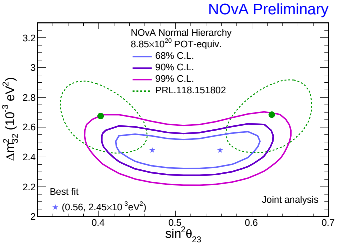

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  - 5% of mock experiments have a larger change, mostly driven by low selection overlap (especially cosmics)
- **New data**
  - New 2.8×10^{20} POT of data prefers maximal mixing

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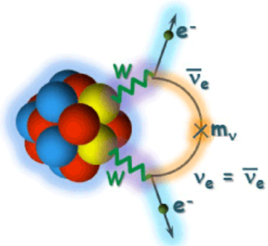
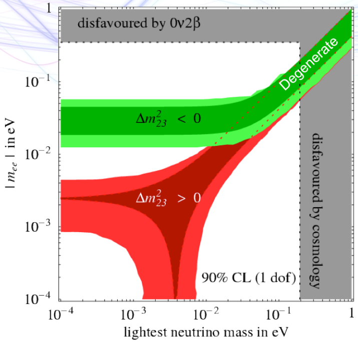
Principle of the ν_e measurement

- 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 $\nu_\mu \to \nu_e$ 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?

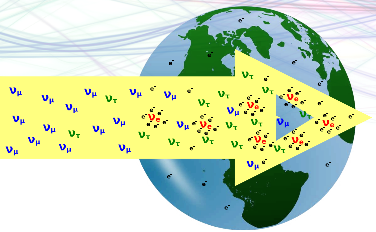
- Is the electron-like state lightest?
- *i.e.* Does the pattern of the masses match the charged leptons?

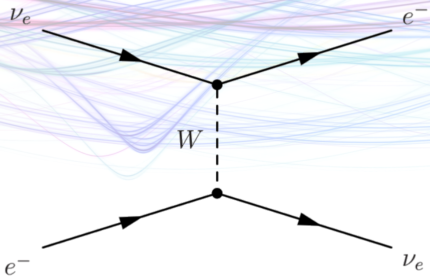




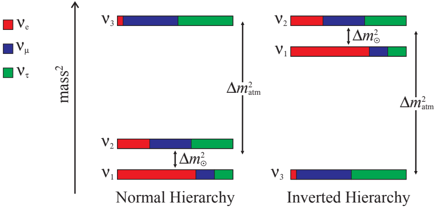
- Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- Observation of $0\nu\beta\beta$ would be proof they are
- Impact of **IH** determination: lack of $0\nu\beta\beta$ implies Dirac nature

Matter effects



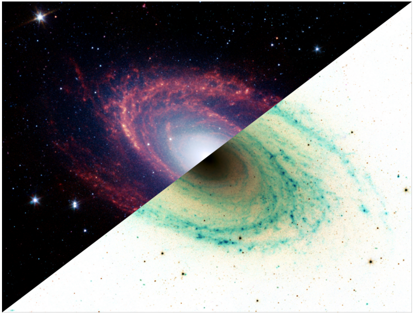


- Electrons in the Earth drag on the “electron” neutrino states
- Sign of the effect opposite for antineutrinos and for NH/IH



Neutrino/antineutrino symmetry

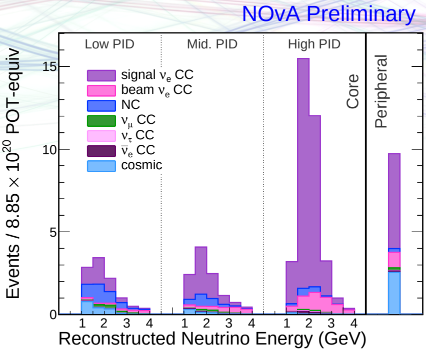
- Does $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- Insight into fundamental symmetries of the lepton sector
- “CP violation” – described by oscillation parameter δ_{CP}

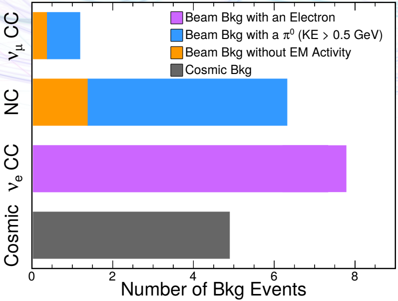


- Why is the universe not equal parts matter and antimatter?
- Need ppb early universe asymm.
- Existing CP-violation insufficient
- *“Leptogenesis”*: generate $\nu/\bar{\nu}$ imbalance, transfer to baryons

- Require neutrino **appearance** experiment to discover

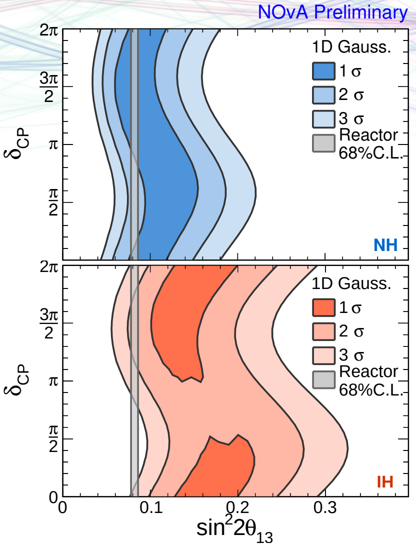
Sample composition





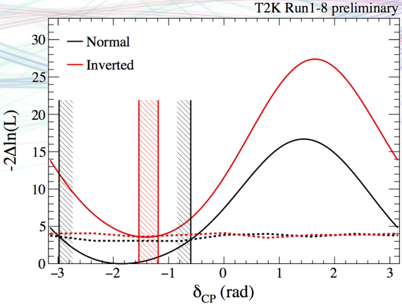
- Break spectrum down into 3 PID bins (low to high purity)
- Plus additional peripheral sample
- Backgrounds predominantly have EM activity:
  $\pi^0 \to \gamma\gamma$ or intrinsic beam ν_e

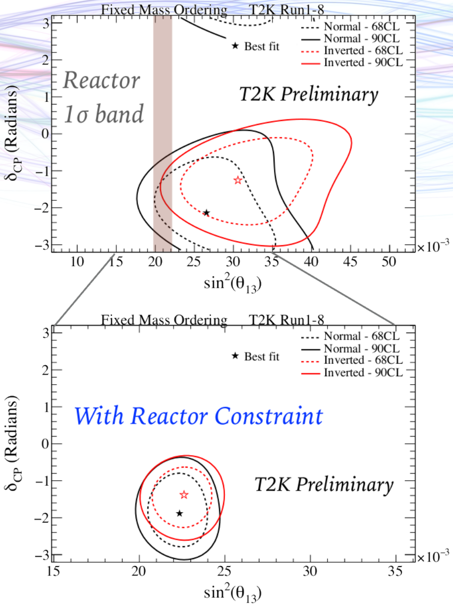
θ_{13}



NOvA Preliminary
1D Gauss.
1 σ
2 σ
3 σ
Reactor
68%C.L.
NH
IH
δCP
2π
3π/2
π
π/2
0
0.1
0.2
0.3
sin²2θ13

T2K latest



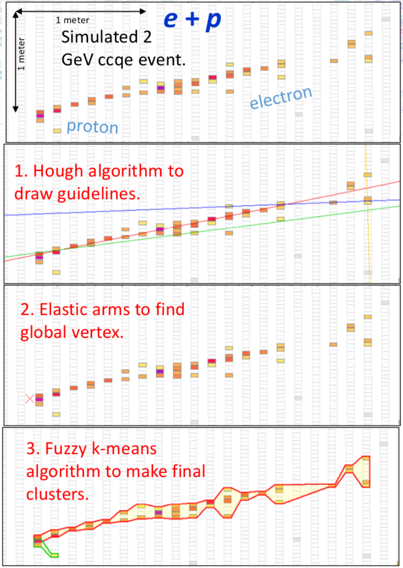


	Obs	Exp (no-CPV)
ν_e	89	67
$\bar{\nu}_e$	7	9

- 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

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

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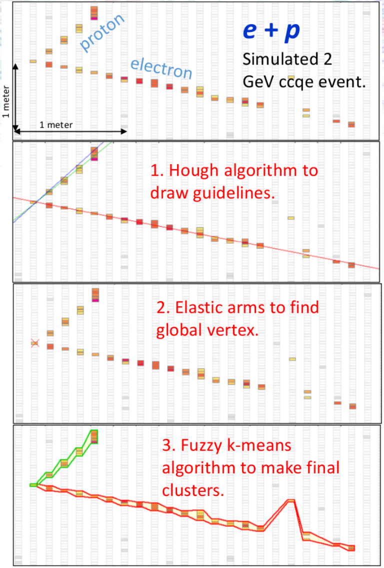

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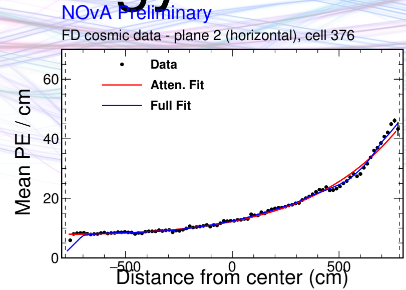
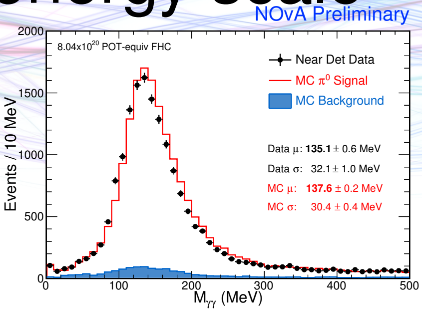
Calibration and energy scale

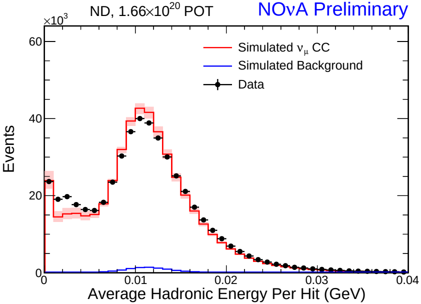
- Response varies substantially along cell due to light atten.
- Use cosmic ray muons as a standard candle to calibrate 300,000 channels individually
- Use dE/dx near the end of stopping muon to set abs. scale



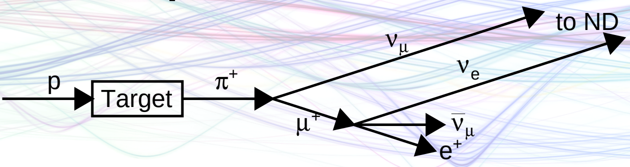
Calibration and energy scale

- 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

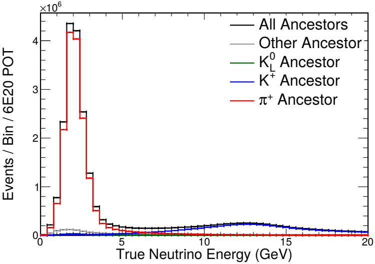


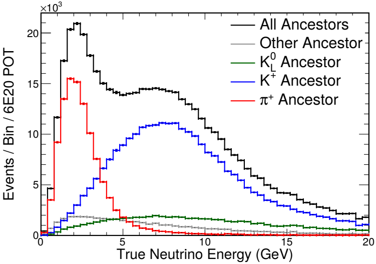


ND decomposition – beam ν_e

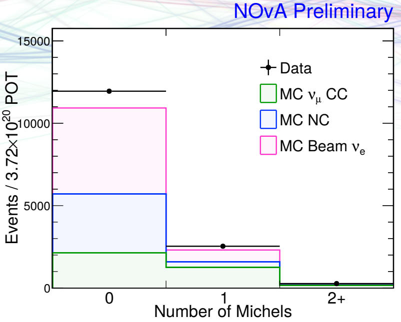


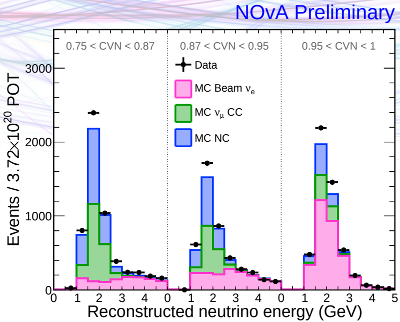
- Low-E ν_μ and ν_e trace back to the same π^+ ancestors





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

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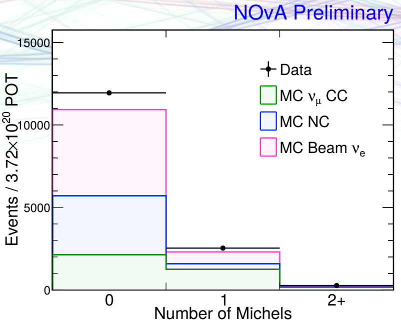

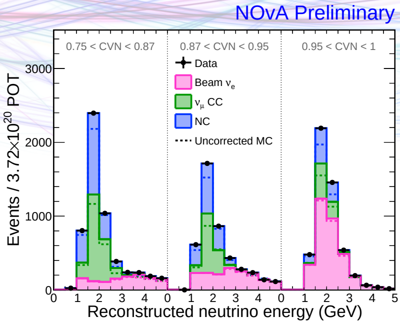

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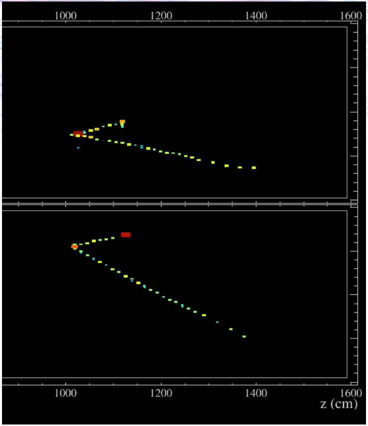
ν_e selection efficiency – MRE

- 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

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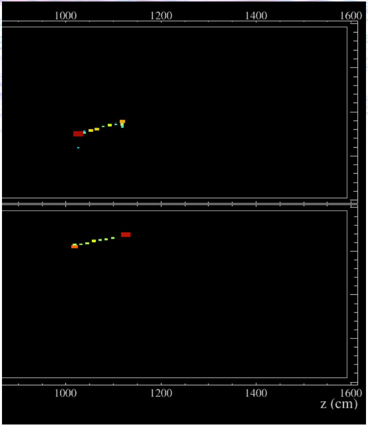

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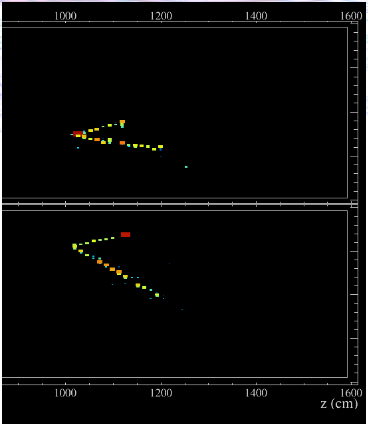

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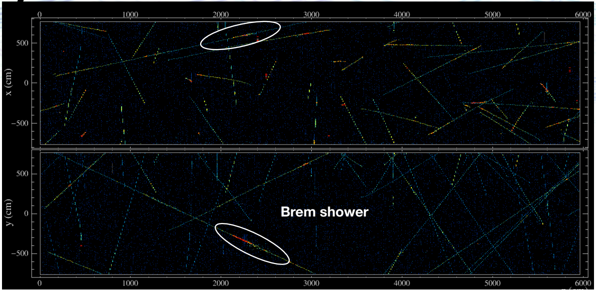
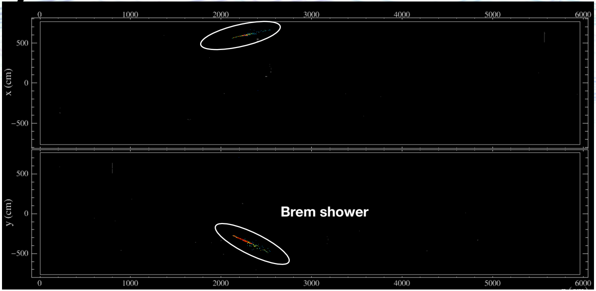
ν_e selection efficiency – EM activity

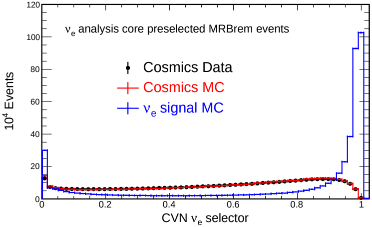


- Find FD data cosmic rays w/ brems

ν_e selection efficiency – EM activity



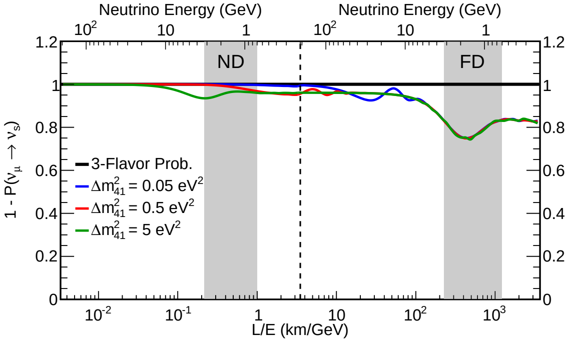
- Find FD data cosmic rays w/ brems
- Remove μ leaving pure EM activity
- Run through PID in data and MC
- Very good agreement

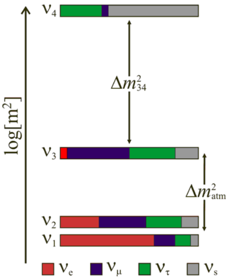


Principle of the NCs

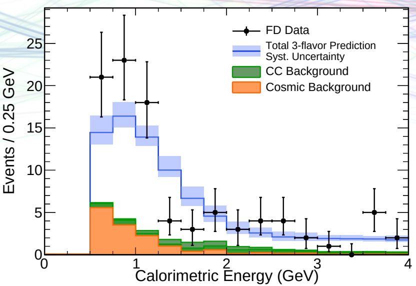
- Where do those ν_μ go?
- Do any oscillate to a sterile state? (ν_s)

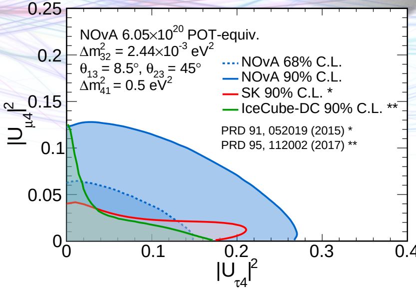
- NC spectrum unaffected by oscillations among active flavours
- Select NC events in ND, extrapolate to FD prediction
- Count NC events in FD, compare to prediction
- Fix $\Delta m^2_{41} = 0.5\,\mathrm{eV}^2$, rapid osc in FD, minimal in ND





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 ± 9.7(stat) ± 9.4(syst) see 95
- Set limits on $U_{\mu 4}$ and $U_{\tau 4}$

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