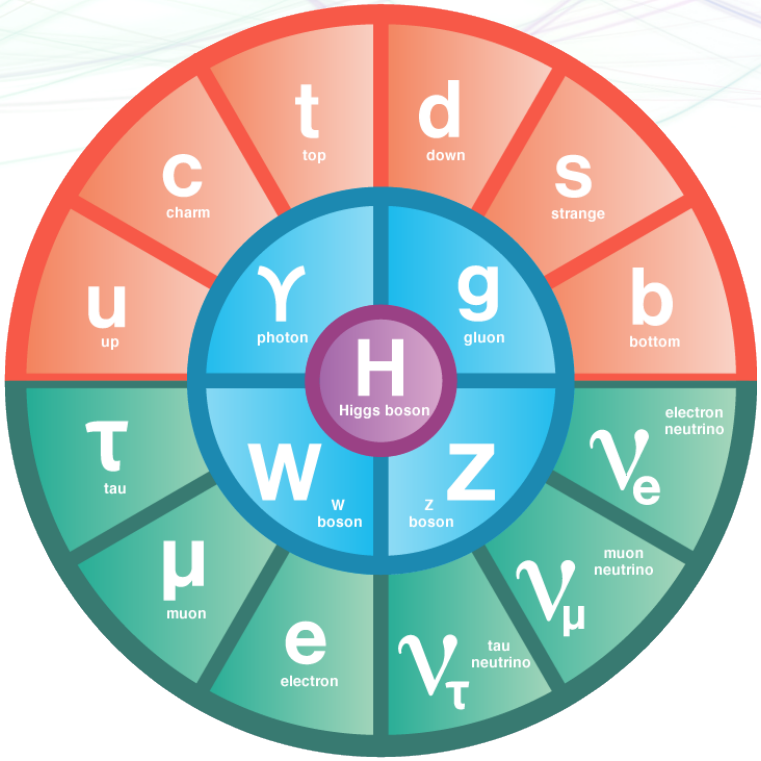
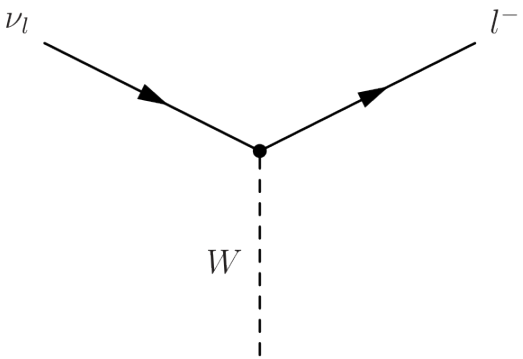
New oscillation results from NOvA

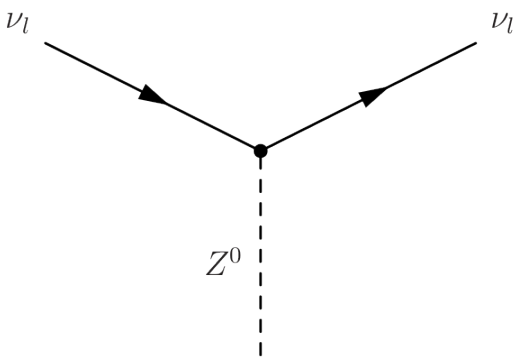
Fermilab JETP seminar
July 20, 2016

Christopher Backhouse – Caltech
for the NOvA collaboration

The neutrino







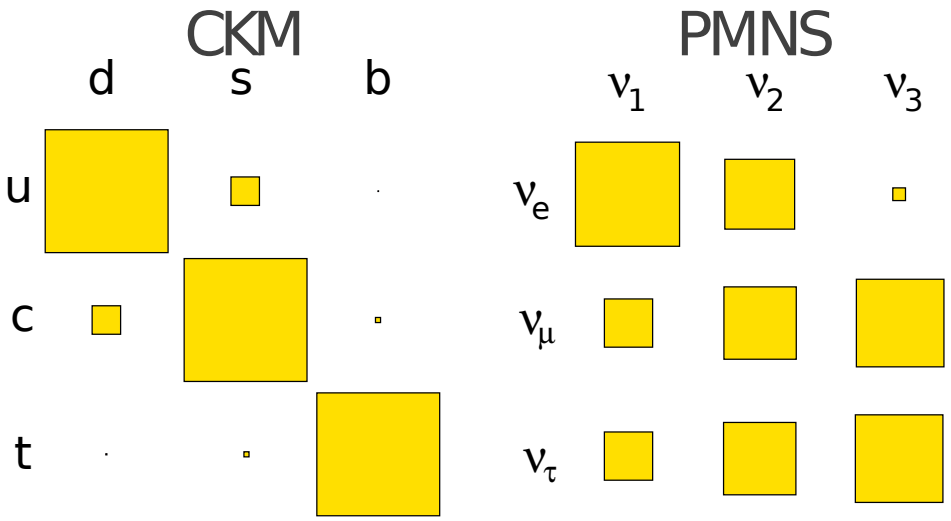
The neutrino

- 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



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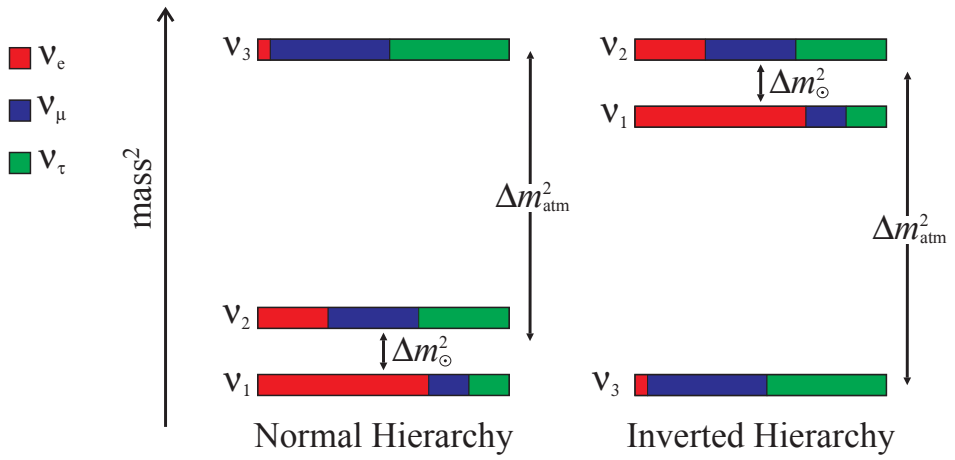
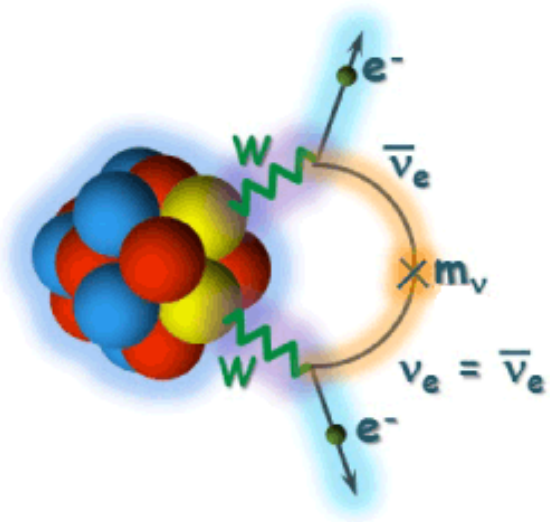
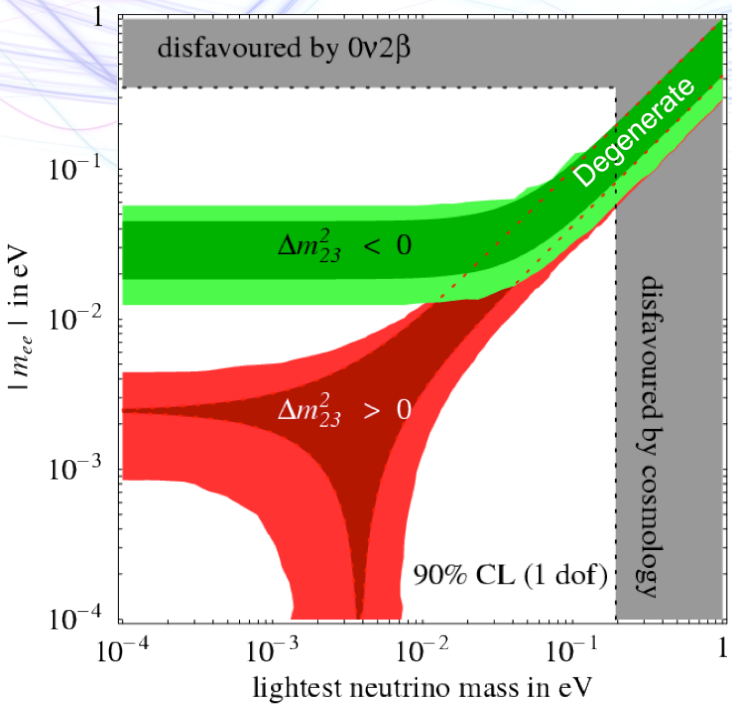
- Open neutrino questions:
  - Dirac or Majorana?
  - Absolute masses
  - Ordering of the mass states
  - *CP*-violation?
  - Random mixing parameters, or patterns?



Why hierarchy?

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



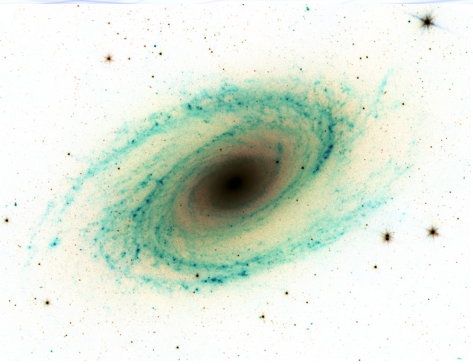


- Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- Observation of $0\nu\beta\beta$ would be proof they are
- Impact of **IH** determination: lack of $0\nu\beta\beta$ implies Dirac nature

Why CPV?

- Does *e.g.* $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$?
- Insight into fundamental symmetries of the lepton sector

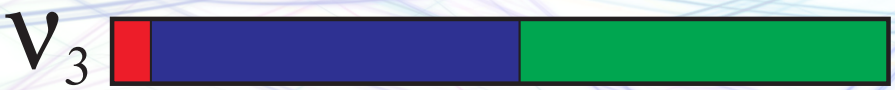
- Why is the universe not equal parts matter and antimatter?
- Sakharov conditions
  - Baryon number violation
  - Out of thermal equilibrium
  - C and CP violation



- CPV in the Standard Model, eg for K and B mesons, but too small
- "Leptogenesis": generate asymmetry in neutrinos, transfer to baryons

- Require neutrino **appearance** experiment to discover

Mixing patterns



- Only a small fraction of ν_e in $|\nu_3\rangle$ (the famous $\sin^2 2\theta_{13}$)
- 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...
  - $< 45°$ ($|\nu_3\rangle$ more ν_τ, like the quarks)
  - $> 45°$ ($|\nu_3\rangle$ more ν_μ, unlike quarks)

Neutrino oscillations

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

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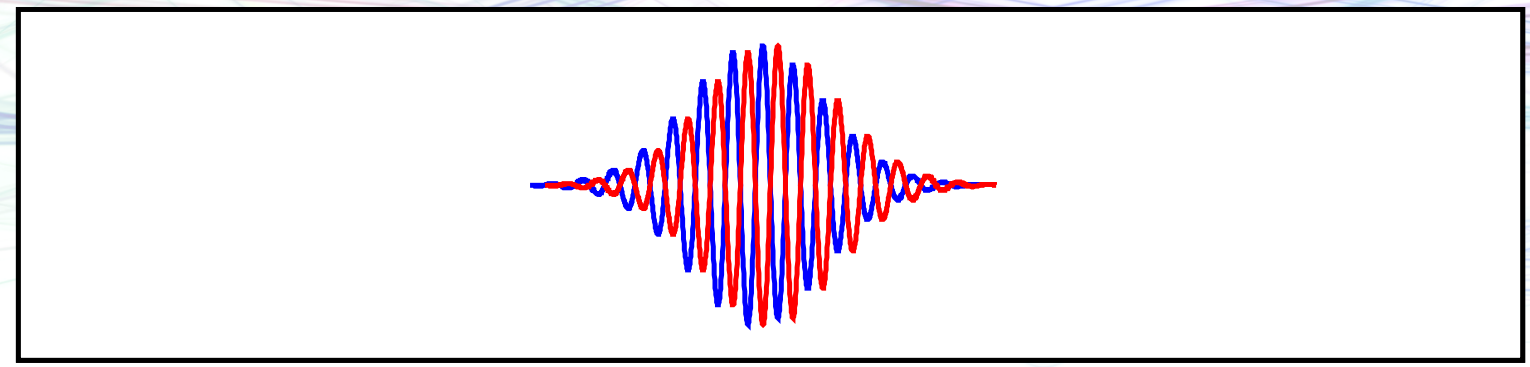

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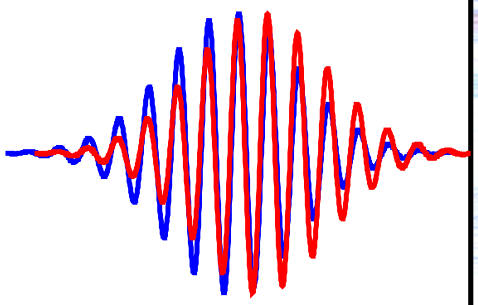
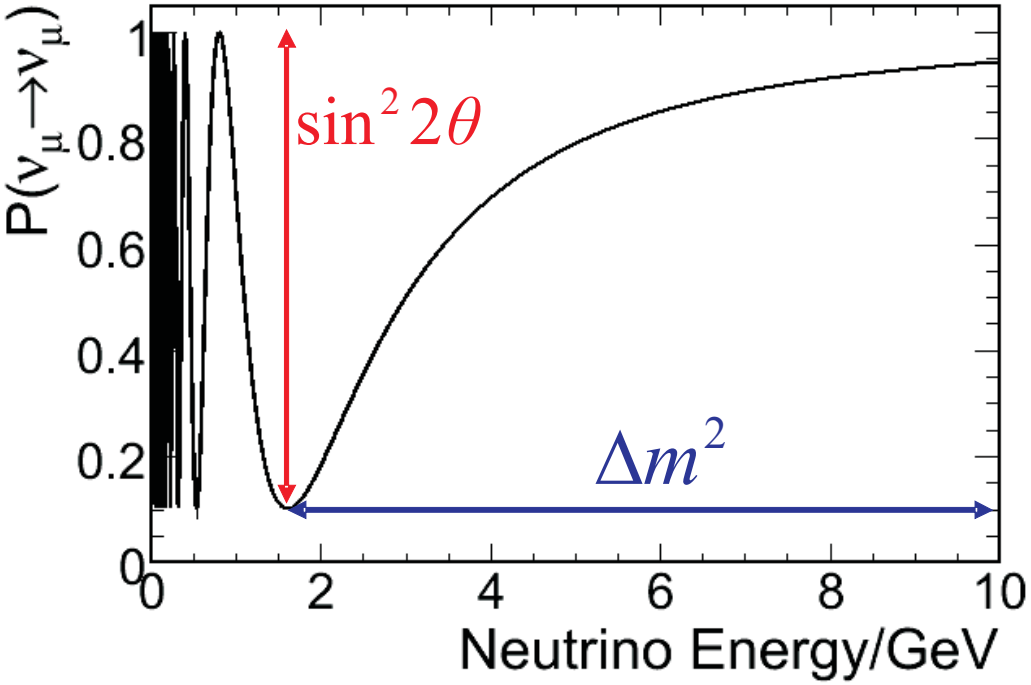


$$|\nu_\alpha\rangle = \sum_i U^\star_{\alpha i}|\nu_i\rangle$$

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

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



Three flavors

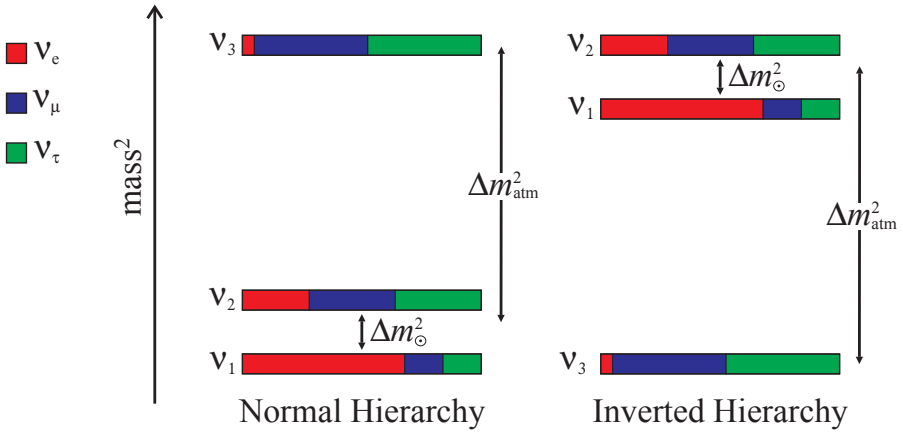
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

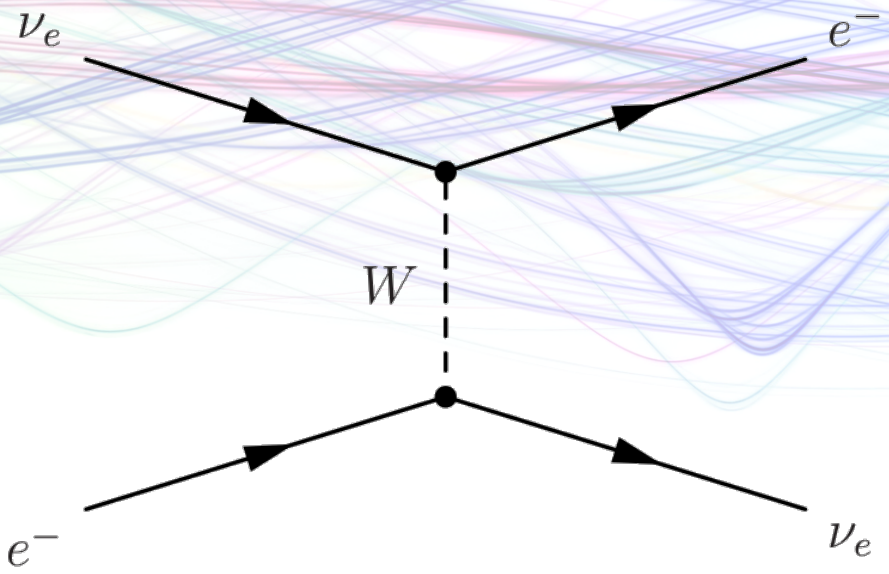
$\theta_{13} \sim 8.5^\circ$

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

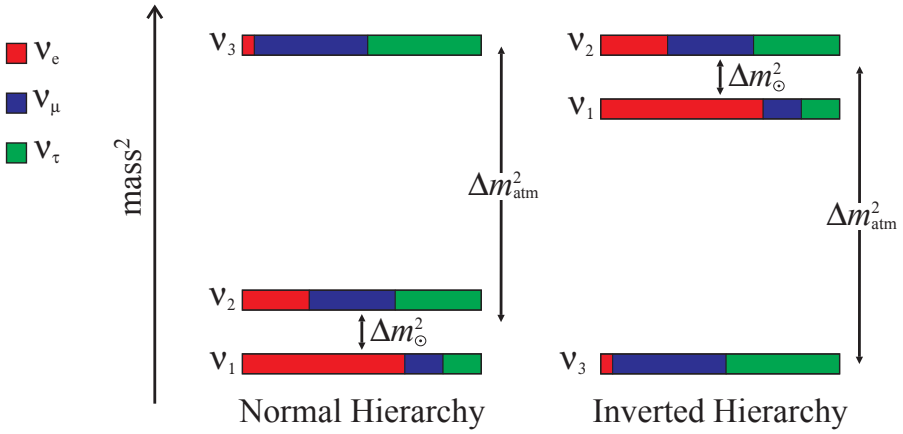
$\delta_{CP} = ?$



Matter effects

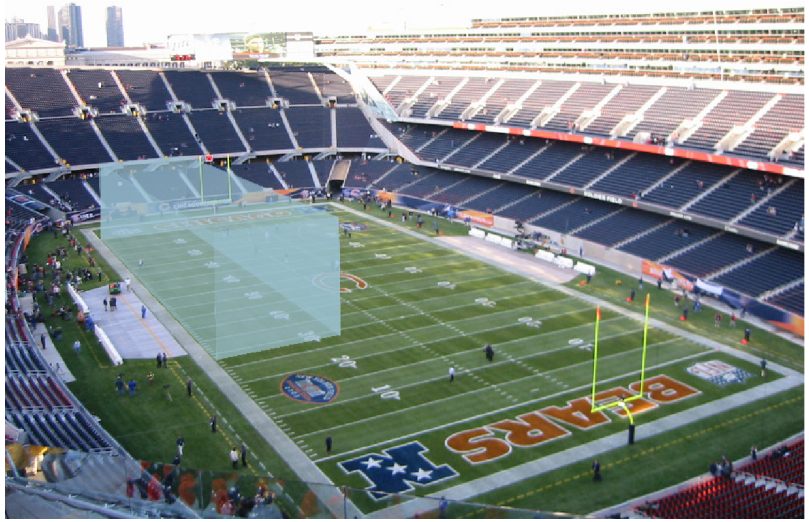


- Electrons in the Earth drag on the "electron" neutrino states
- Sign of the effect opposite for antineutrinos and for NH/IH



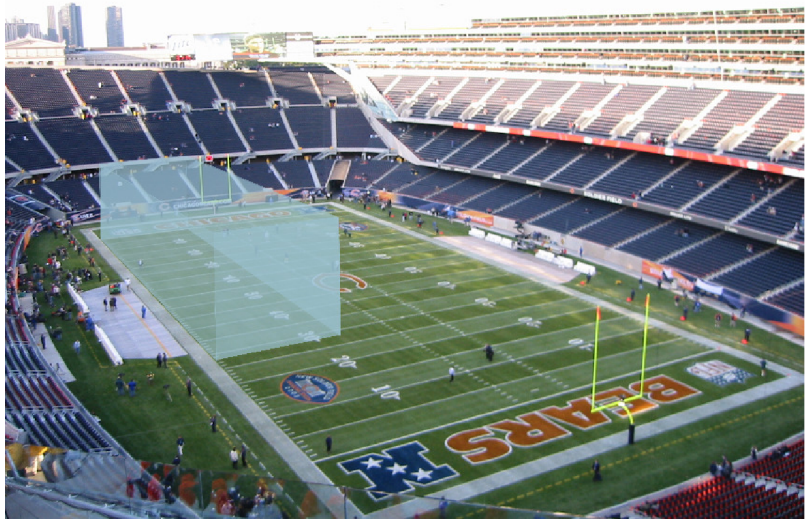
NOvA

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



NOvA

- Requirements for neutrino oscillation experiment
  - High power neutrino source
  - Large detector
  - Good resolution of signal from background
  - Good control of systematic uncertainties
- For hierarchy and CPV
  - Appearance mode
  - Long baseline
  - Ability to study neutrinos and antineutrinos



The NOvA collaboration

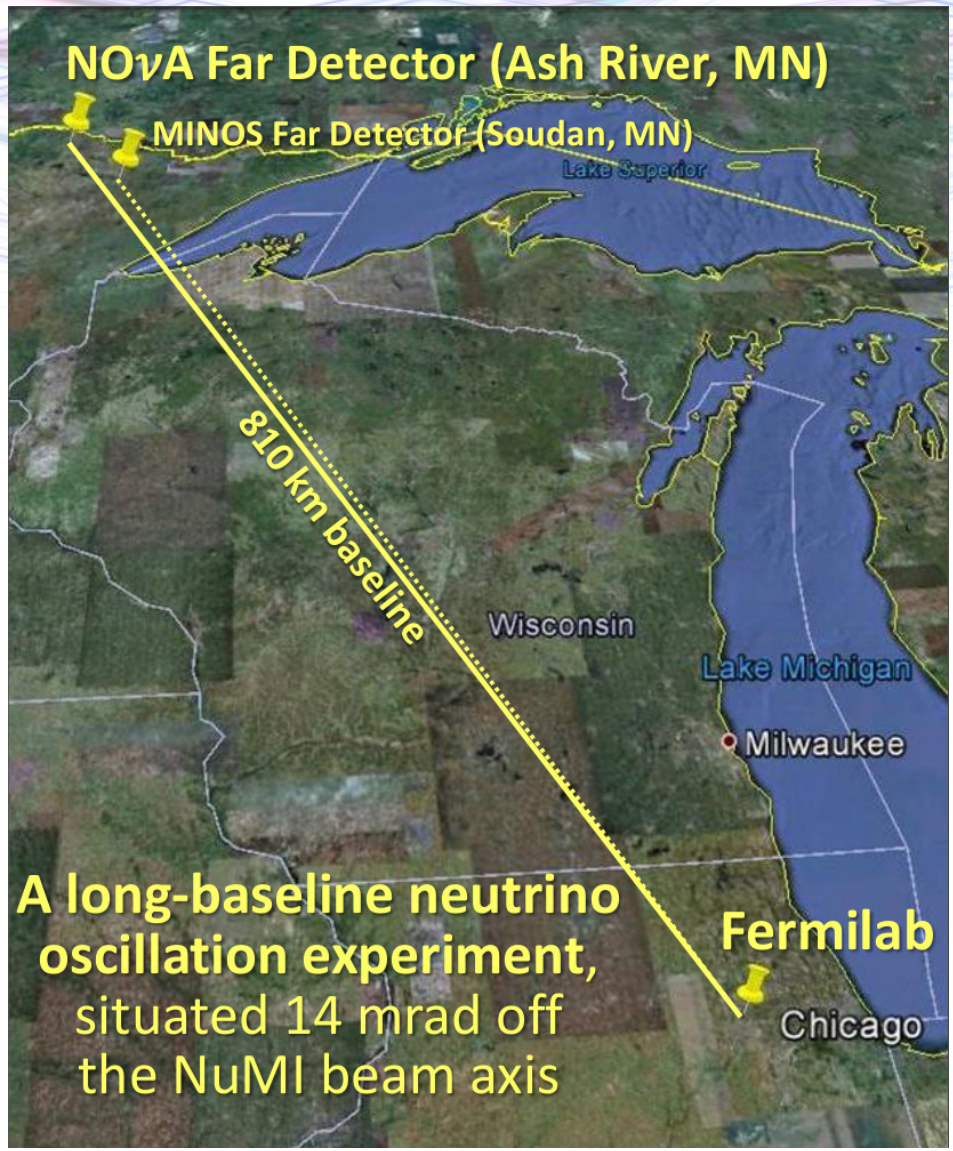
41 institutions, 7 countries, over 200 collaborators

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

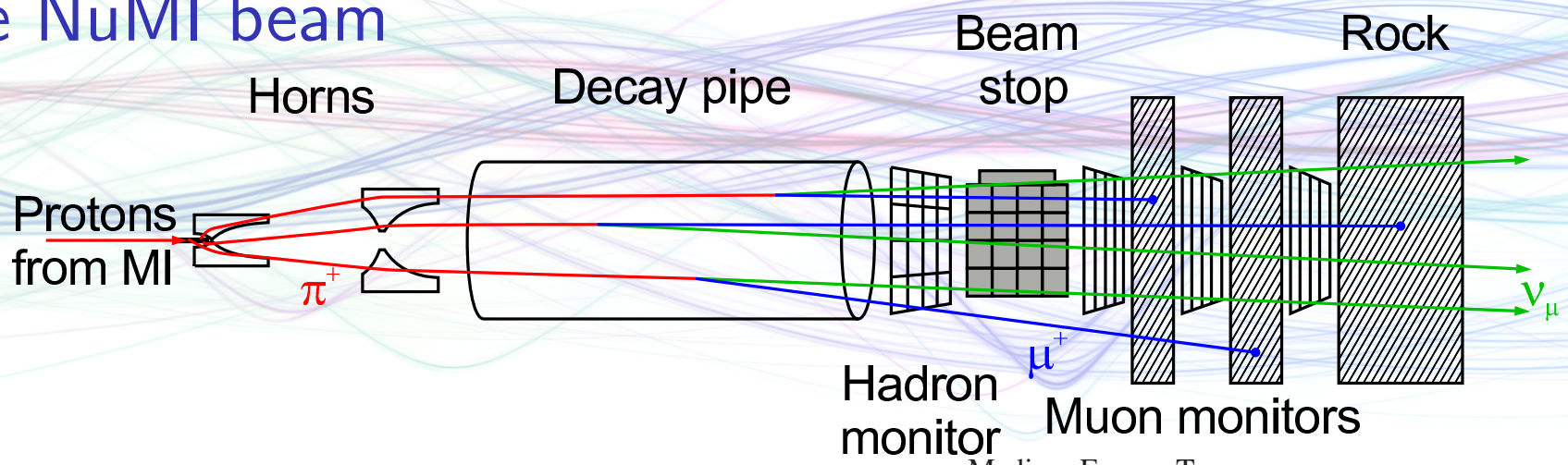
NOvA 10,000ft view

- ν_μ beam from Fermilab
- 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 $\delta_{CP} \neq 0$

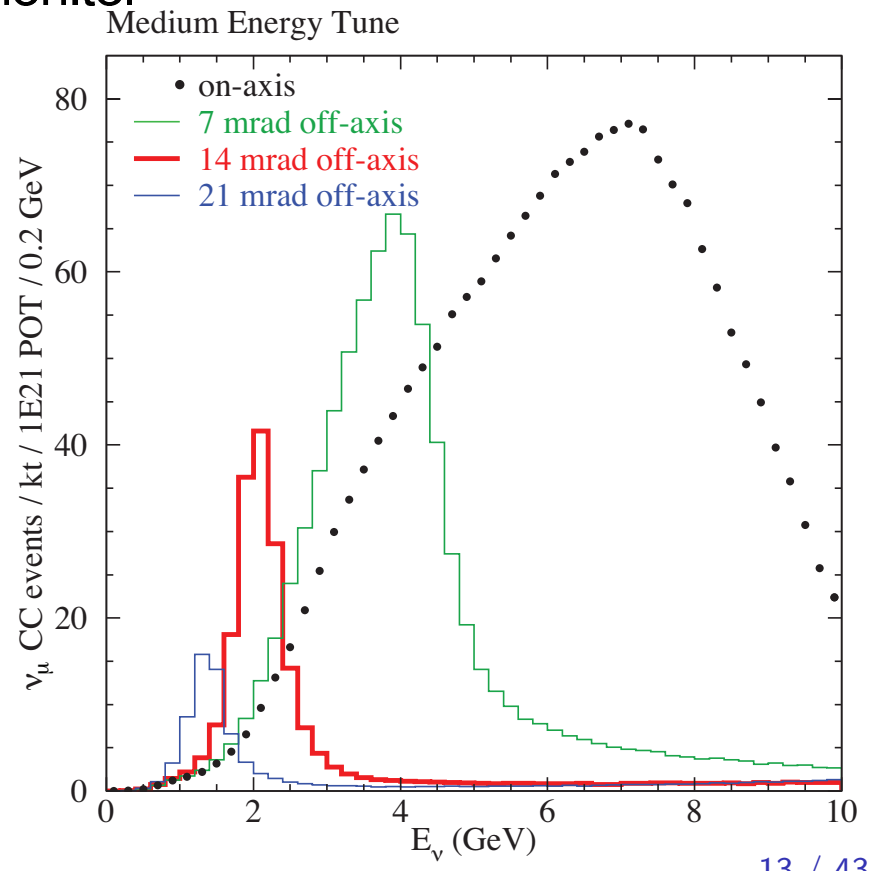
- Plus: xsec in the ND, exotics
- Sterile neutrinos, next week!



The NuMI beam

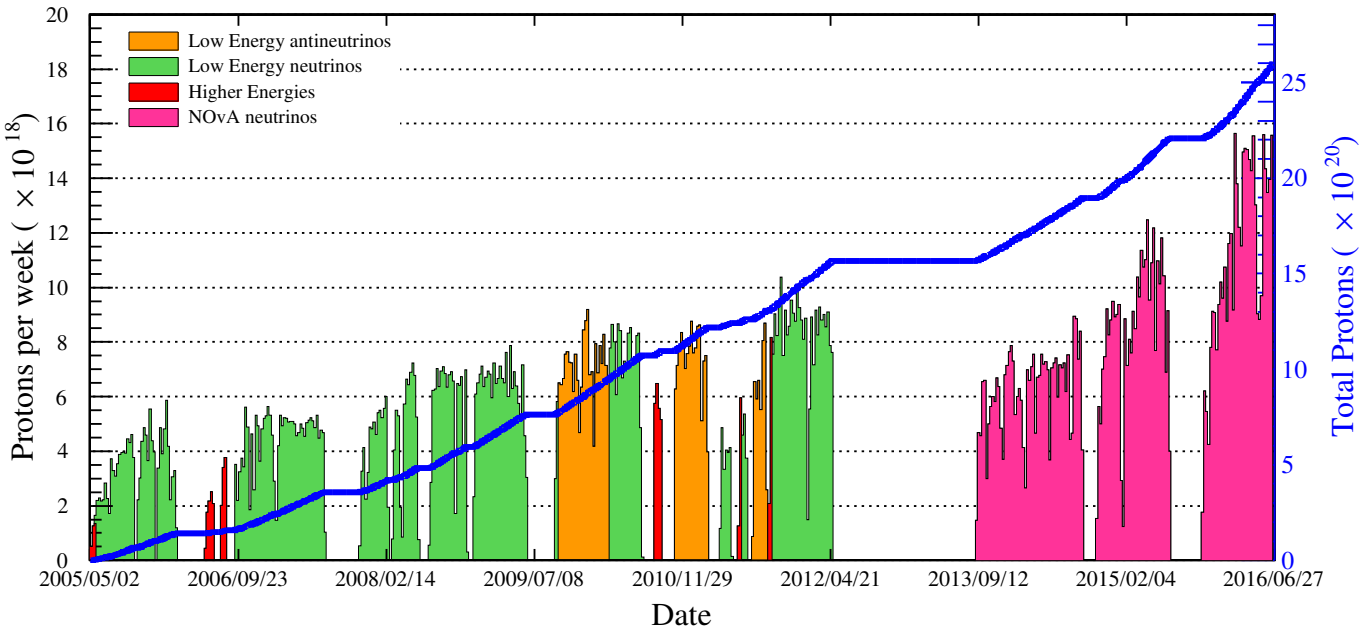


- 120 GeV protons from Main Injector
- Produce mainly $\pi^{\pm}$ and $K^{\pm}$
- Focused by two magnetic horns
- Allow us to select charge sign for a neutrino or antineutrino beam
- 14.6mrad off-axis: neutrino energy $\sim$ independent of pion energy
- Beam peak from 1-3GeV

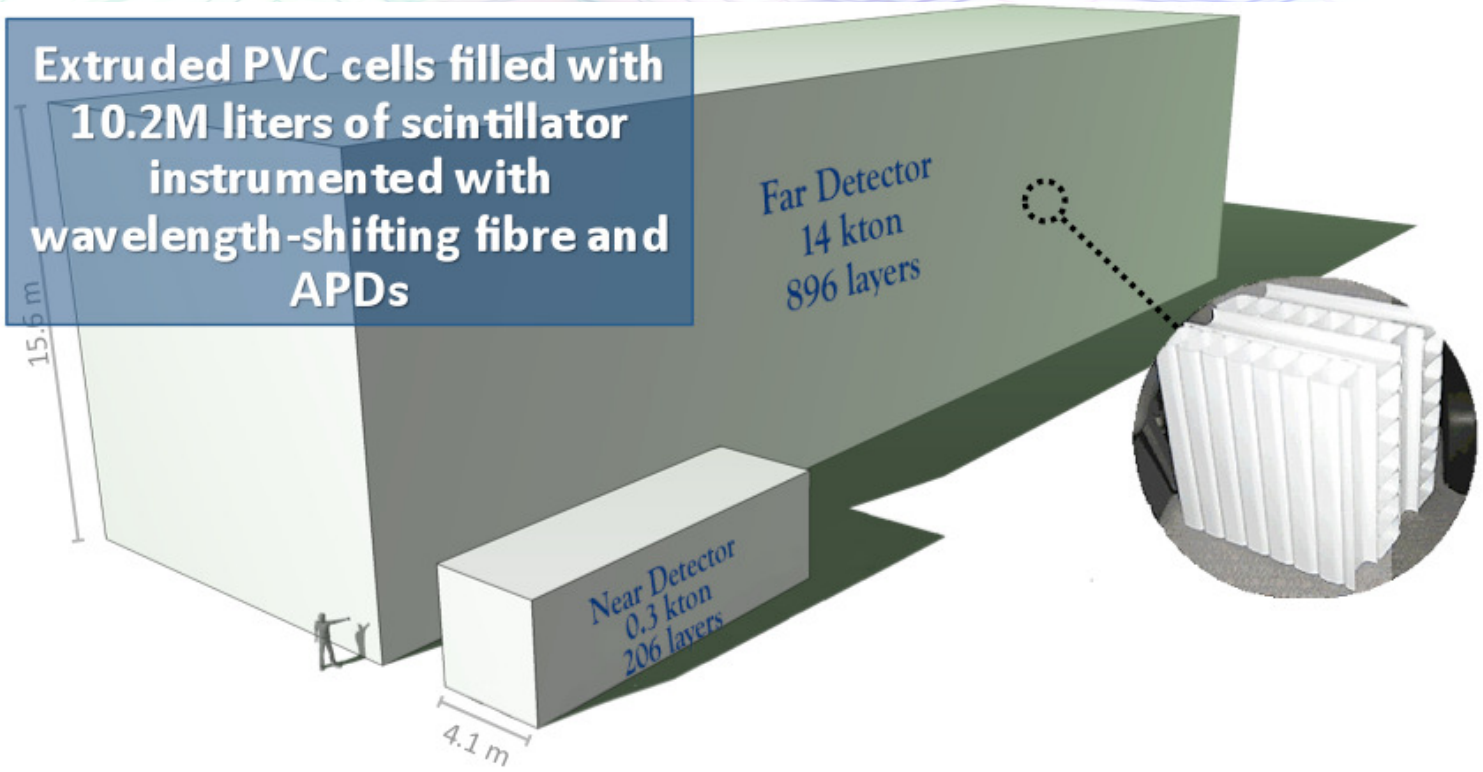


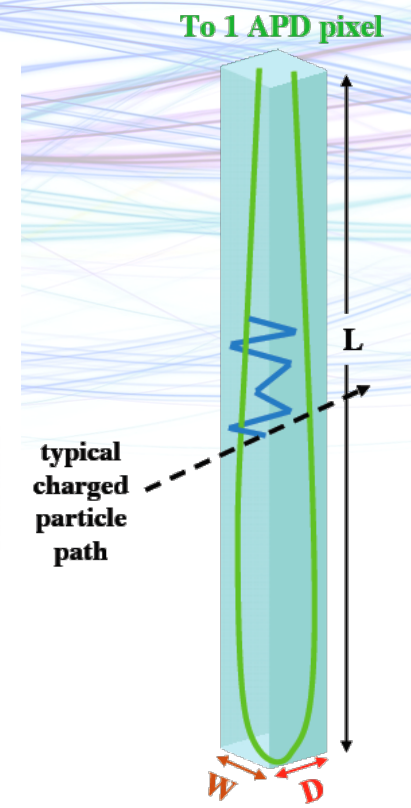
NuMI performance

- Fantastic beam performance
- Currently running at 560kW
- Achieved 700kW design intensity (briefly) in tests on June 13
- Analysis uses data from Feb 6 2014 to May 2 2016
- Equivalent to 6.05×10^{20} POT in full 14 kton detector (1 TDR year)



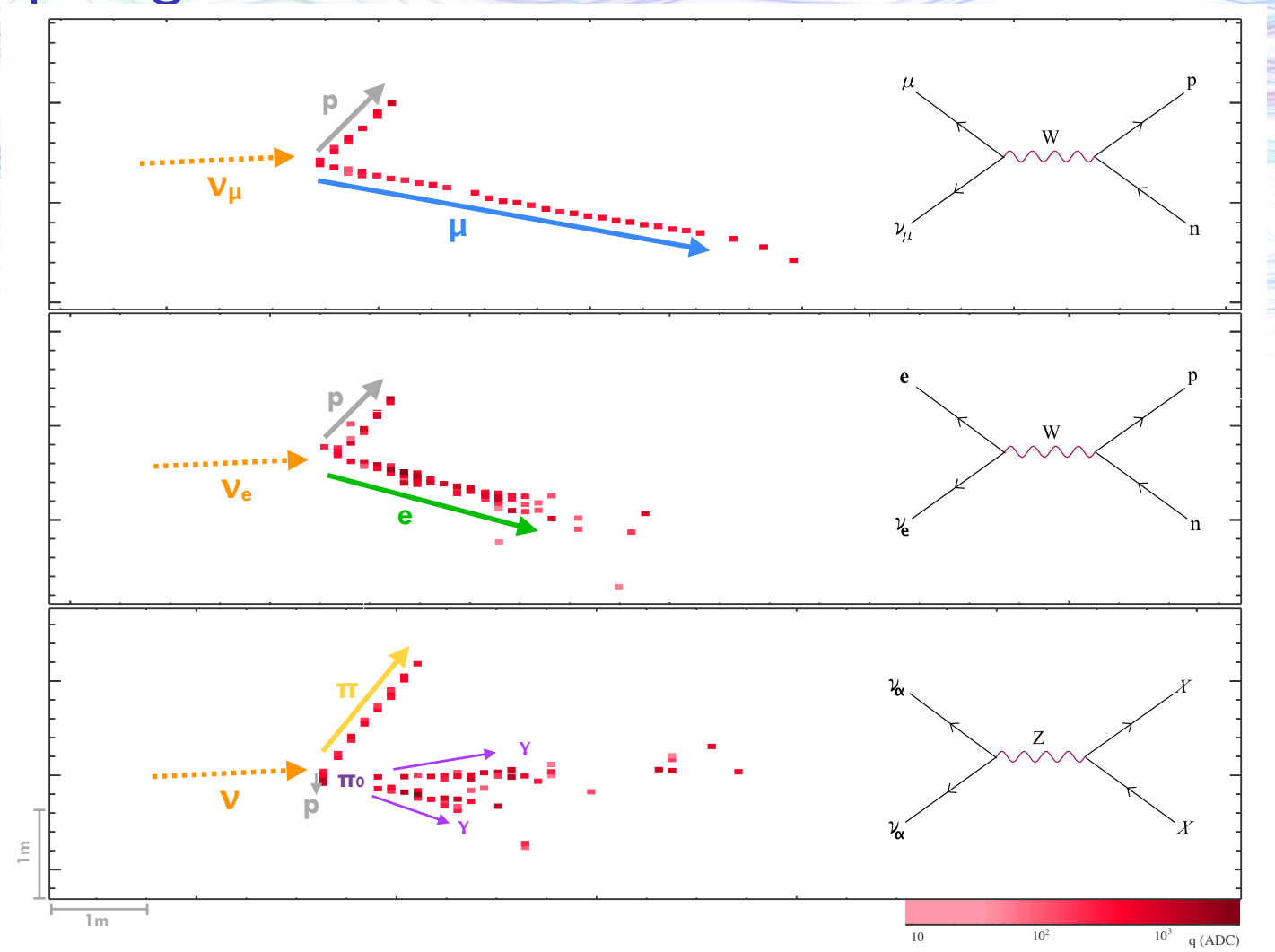
Detector technology





- Fine-grained low-Z, highly active, tracking calorimeter
- 64% liquid scintillator by mass
- 344,000 channels in 14 kton FD, on surface
- 300 ton ND, underground at FNAL

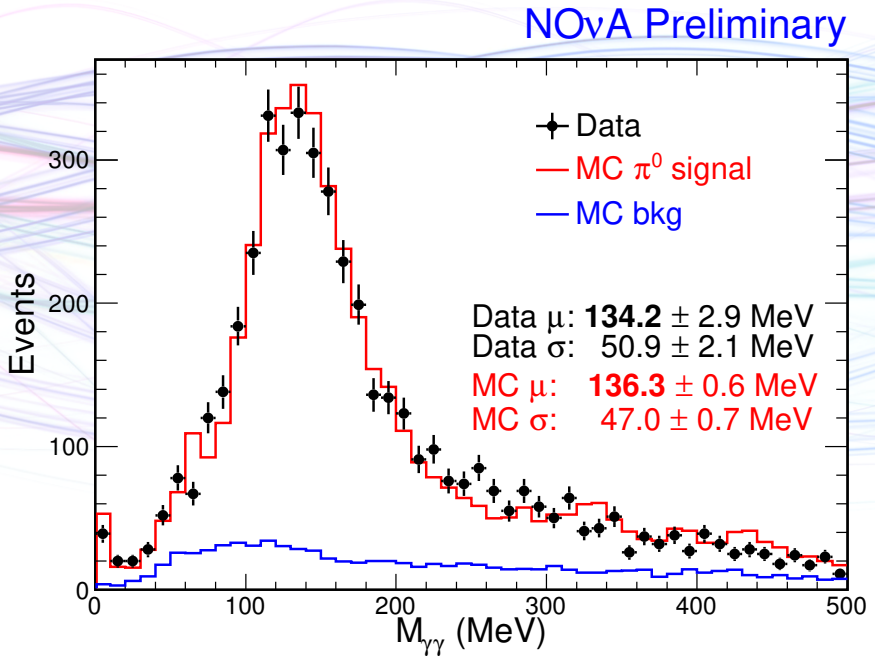
Event topologies

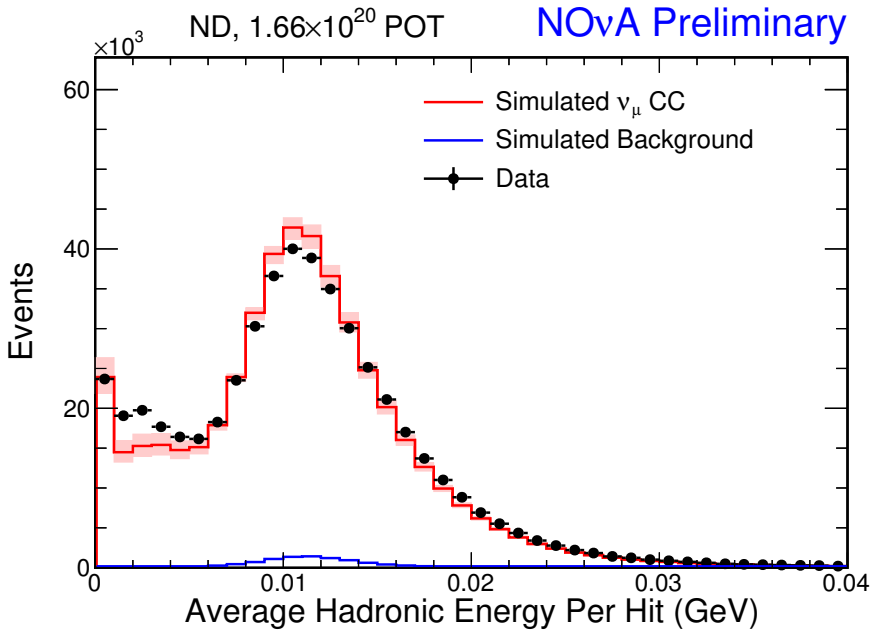


- Very good granularity, especially considering scale
- $X_0 = 38$cm (6 cell depths, 10 cell widths)

Calibration and energy scale

- Response varies substantially along cell due to light atten.
- Use cosmic ray muons as a standard candle to calibrate every channel 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

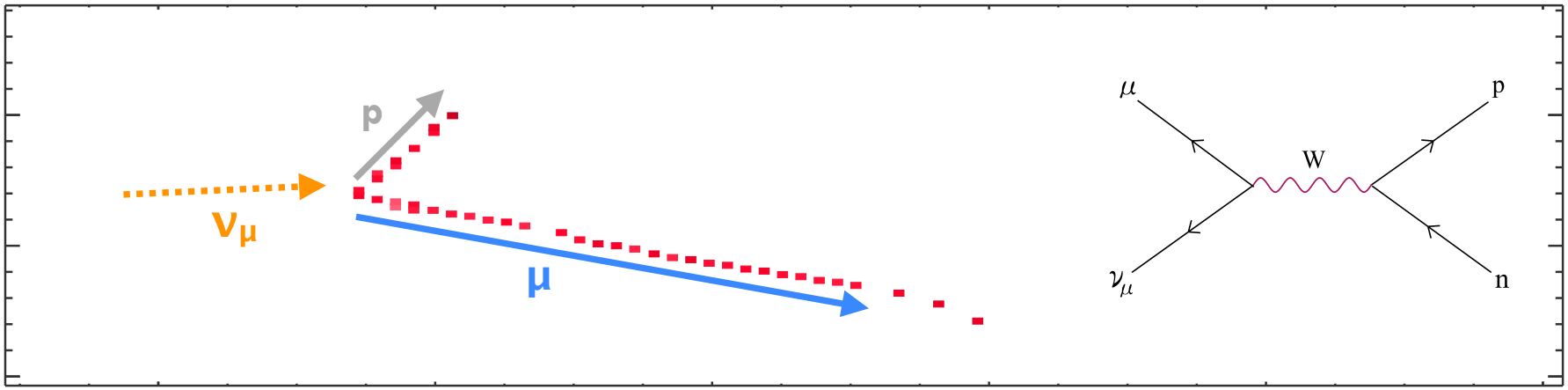




Principle of the ν_μ measurement

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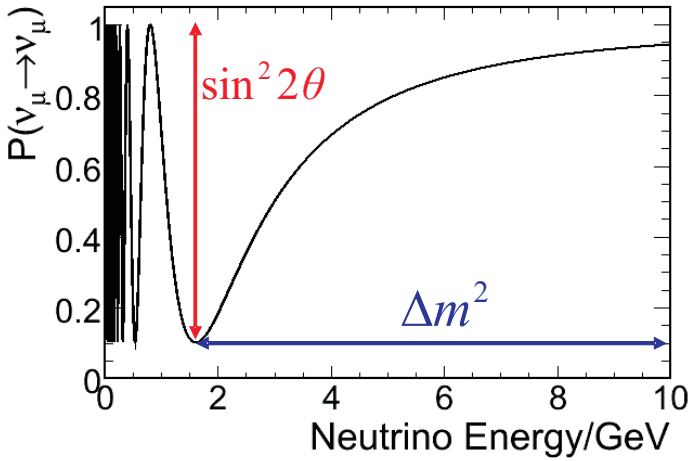
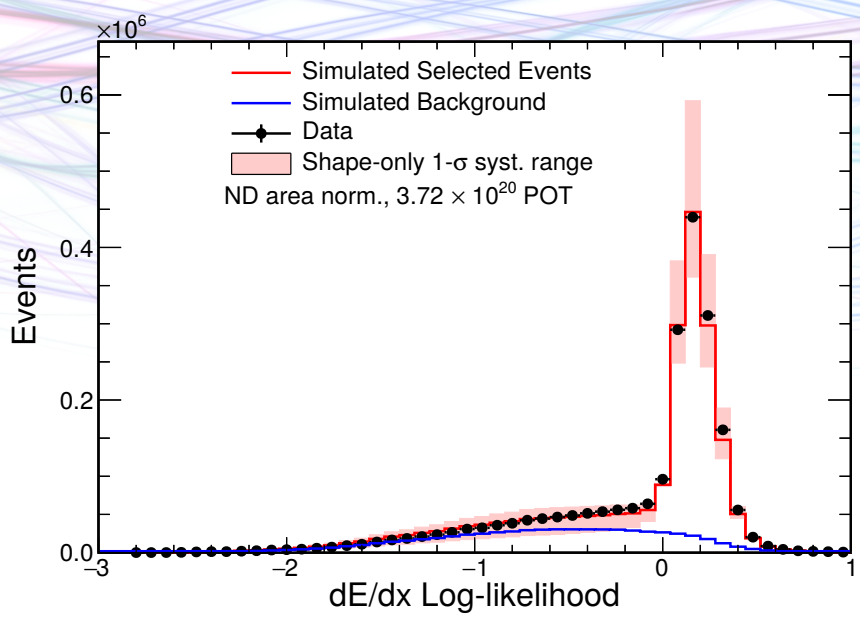
- Two flavor approx. works well here
- $P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$
- $\theta_{23} \approx 45^\circ \rightarrow$ almost all ν_μ expected to disappear at oscillation max.

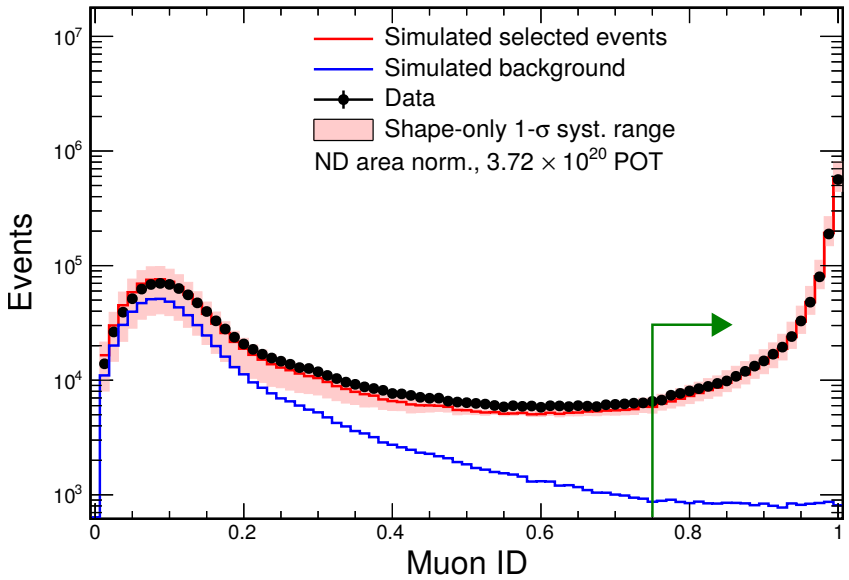


Selecting muon neutrinos

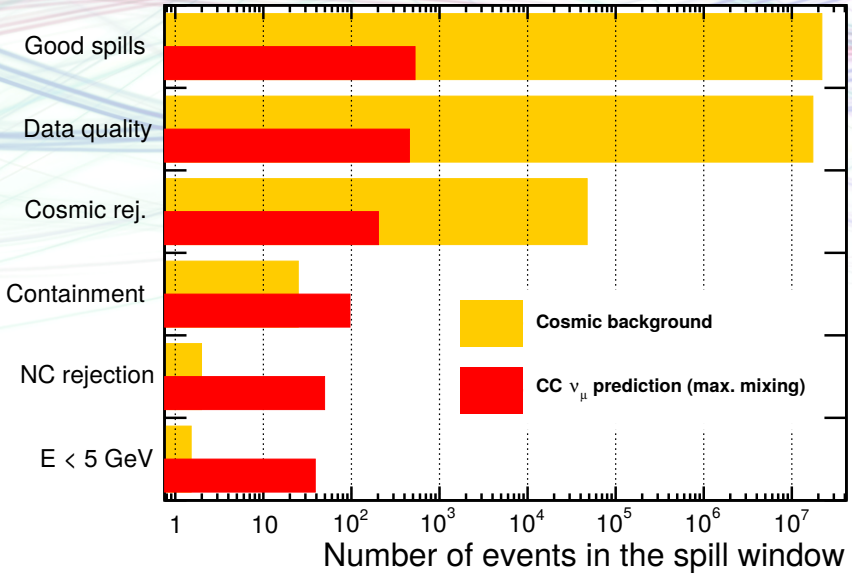
- Basic containment cuts requiring no activity close to detector walls
- kNN-based ν_μ classifier using 4 inputs
  - Track length
  - dE/dx
  - Scattering
  - Fraction of planes that have track-only
- Selection 81% efficient for ν_μ signal, 95% pure

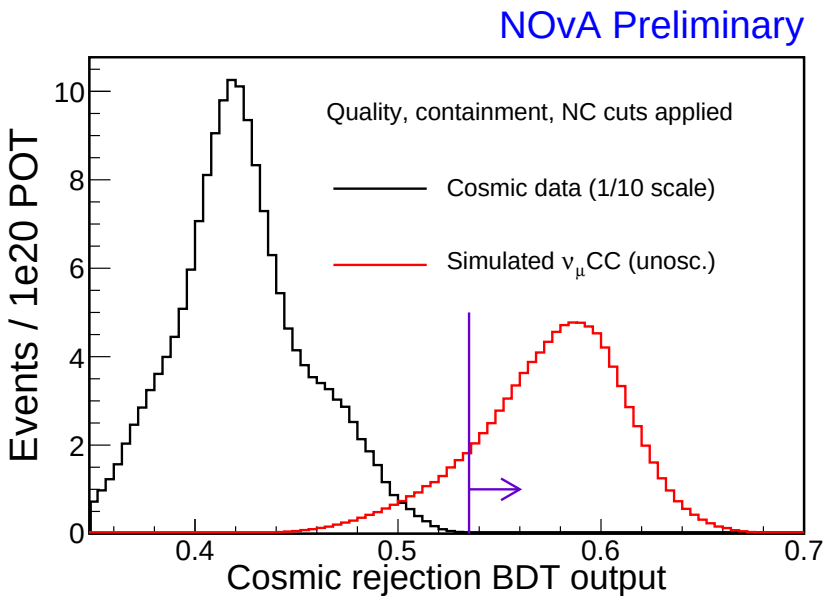


NOvA Preliminary



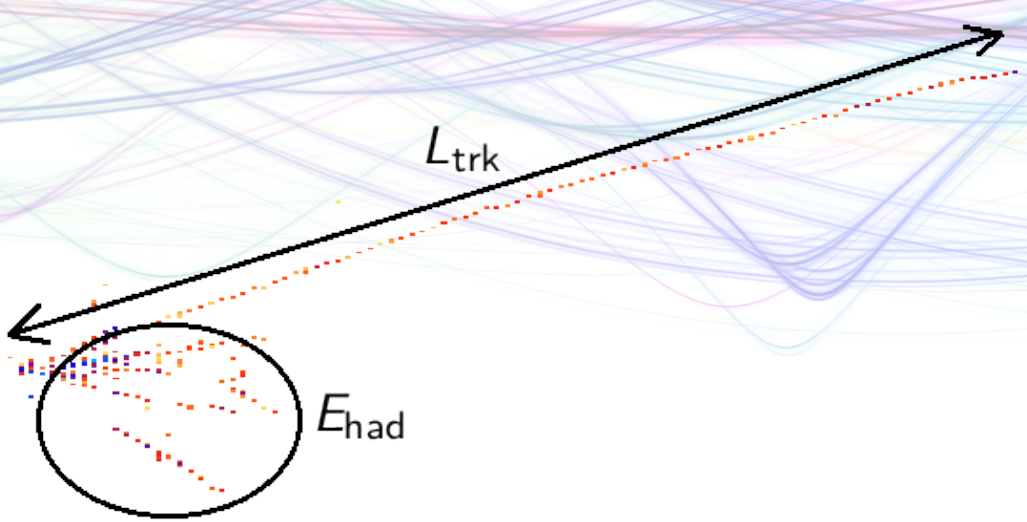
Cosmic rejection for ν_μ analysis





- 10μs spill window at $\sim$ 1Hz gives 10^5 rejection
- Cosmic background rate measured from data adjacent in time to the beam spill window
- Additional factor 10^7 from event topology plus boosted decision tree based on
  - Track direction
  - Track start and end points
  - Track length
  - Energy
  - Number of hits

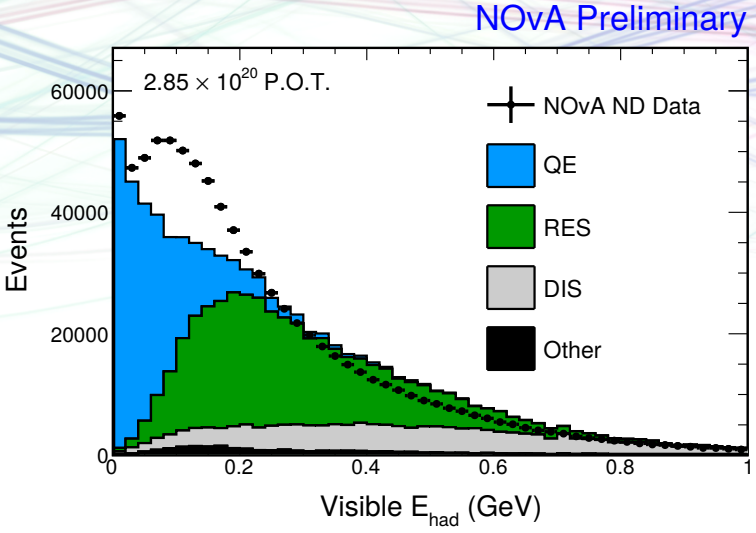
Muon neutrino energy reconstruction



- Estimate energy of selected events to trace out oscillation 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

- $E_\nu = f(L_{trk}) + E_{\text{had}}$
- Achieve 7% energy resolution

Nuclear correlations



- ND hadE distributions suggest extra process between QE and Δ prod.
- MINERvA report similar excess in their data[1]

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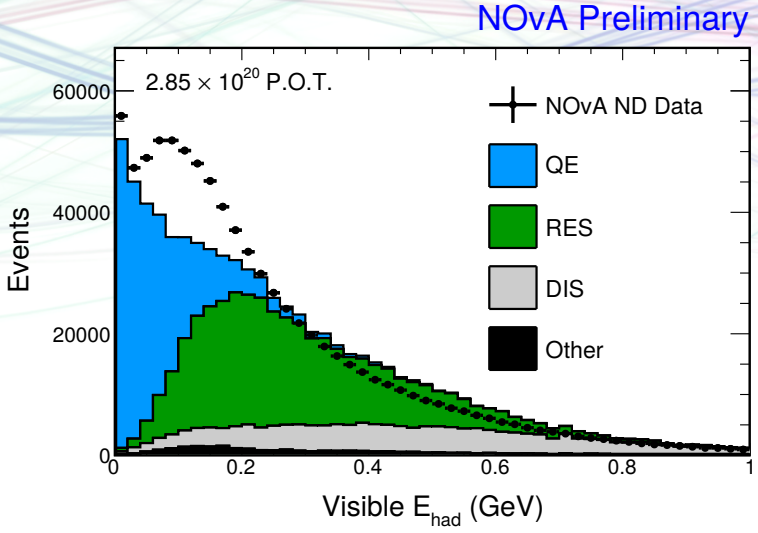

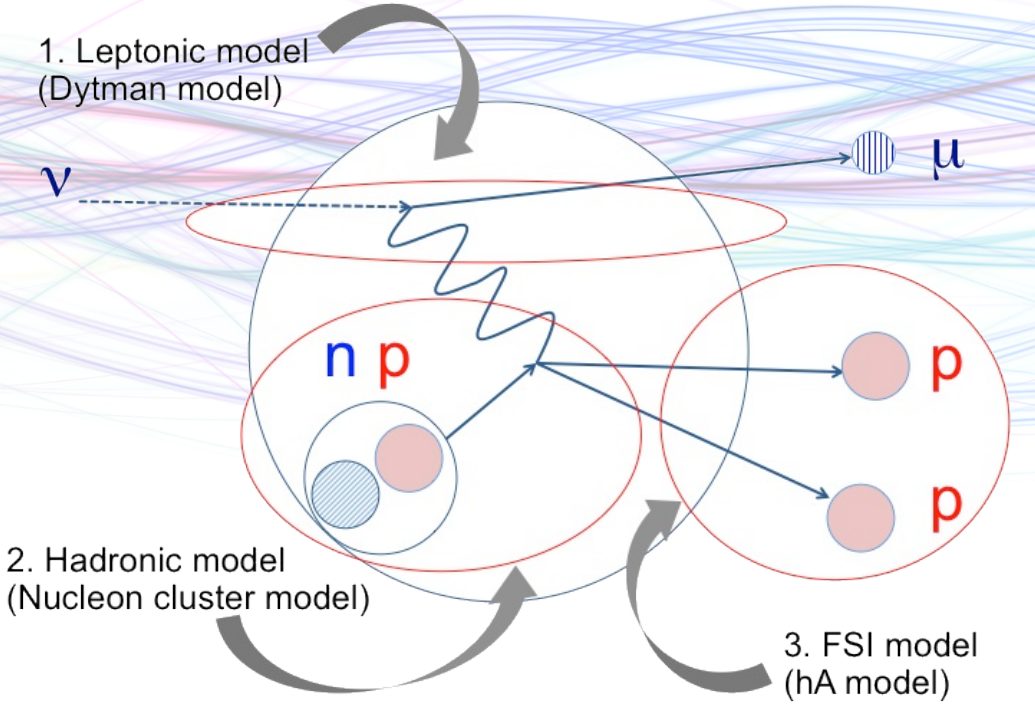

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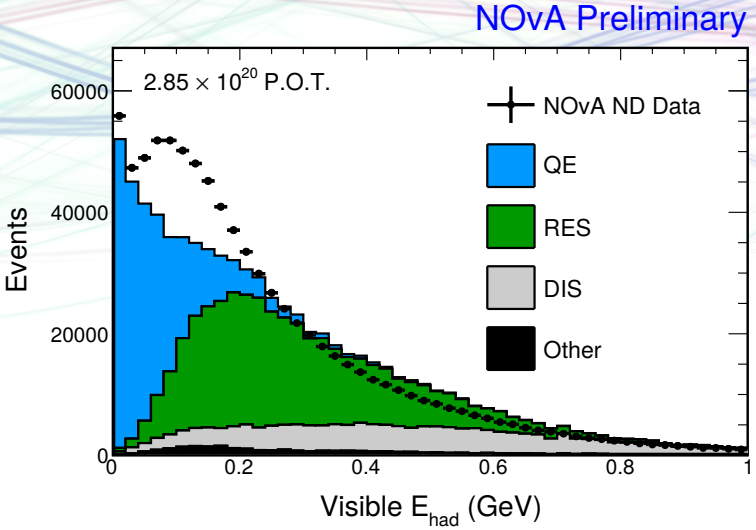

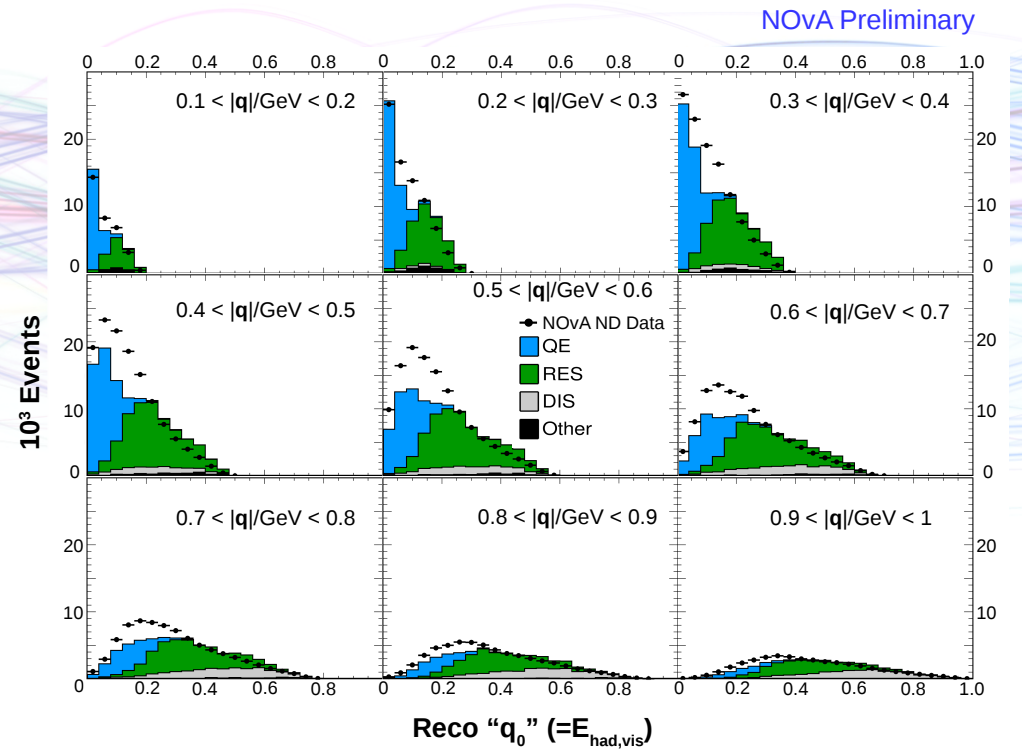

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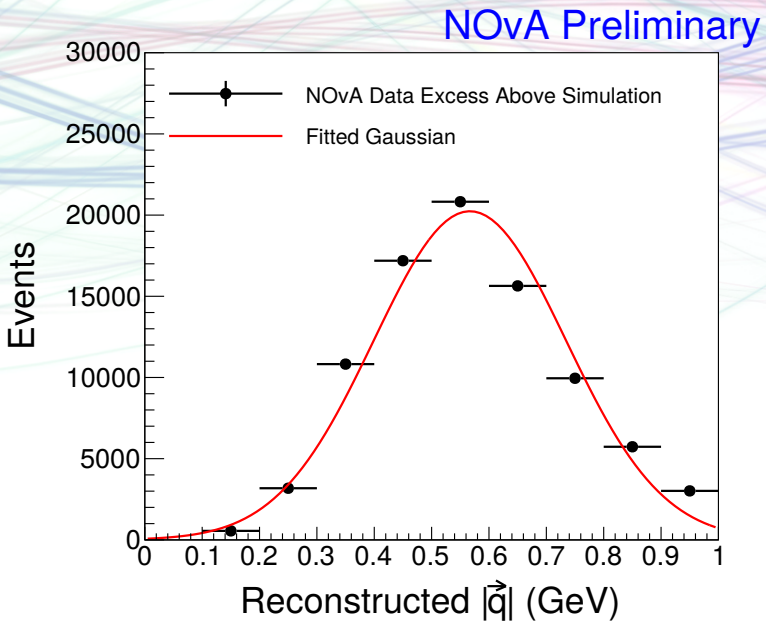

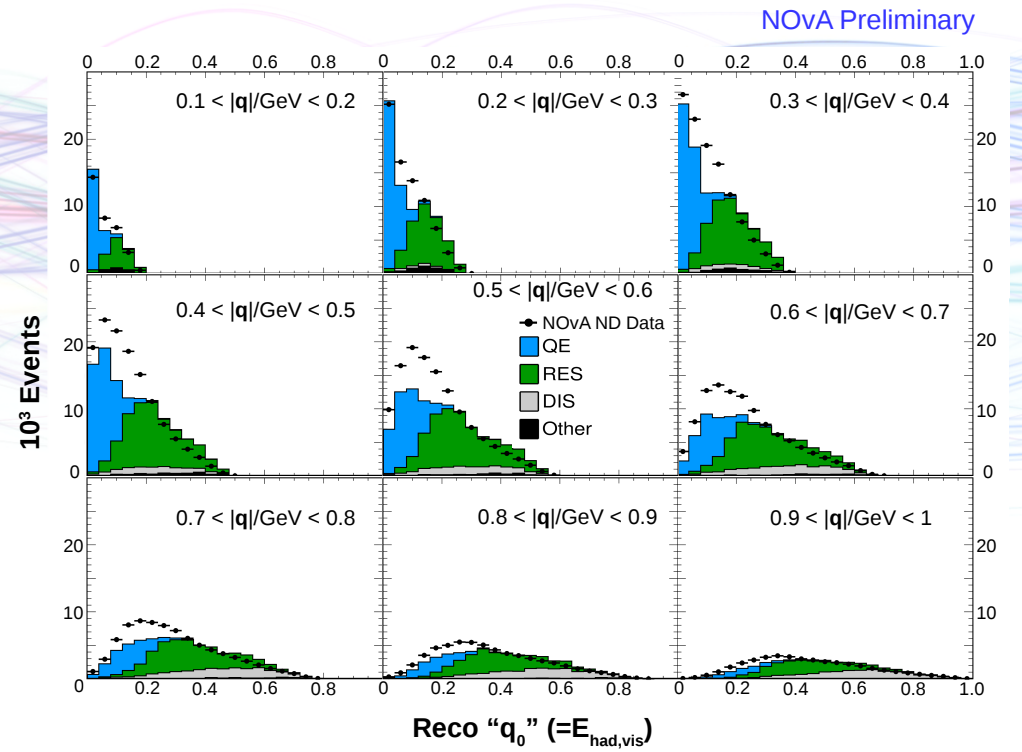

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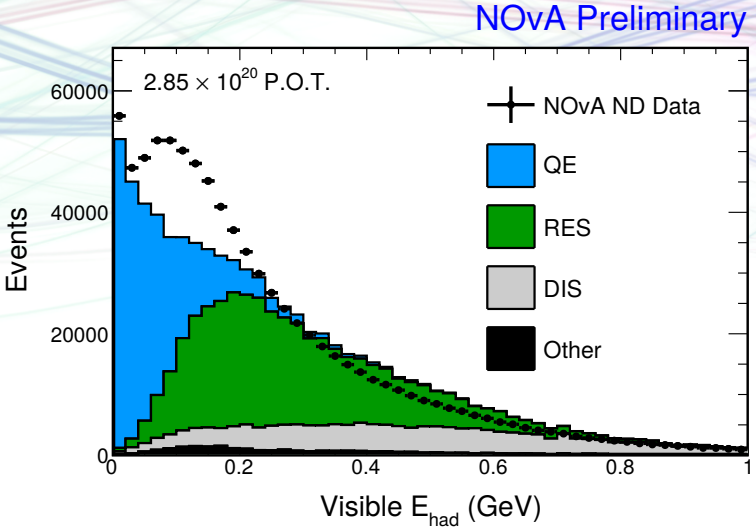
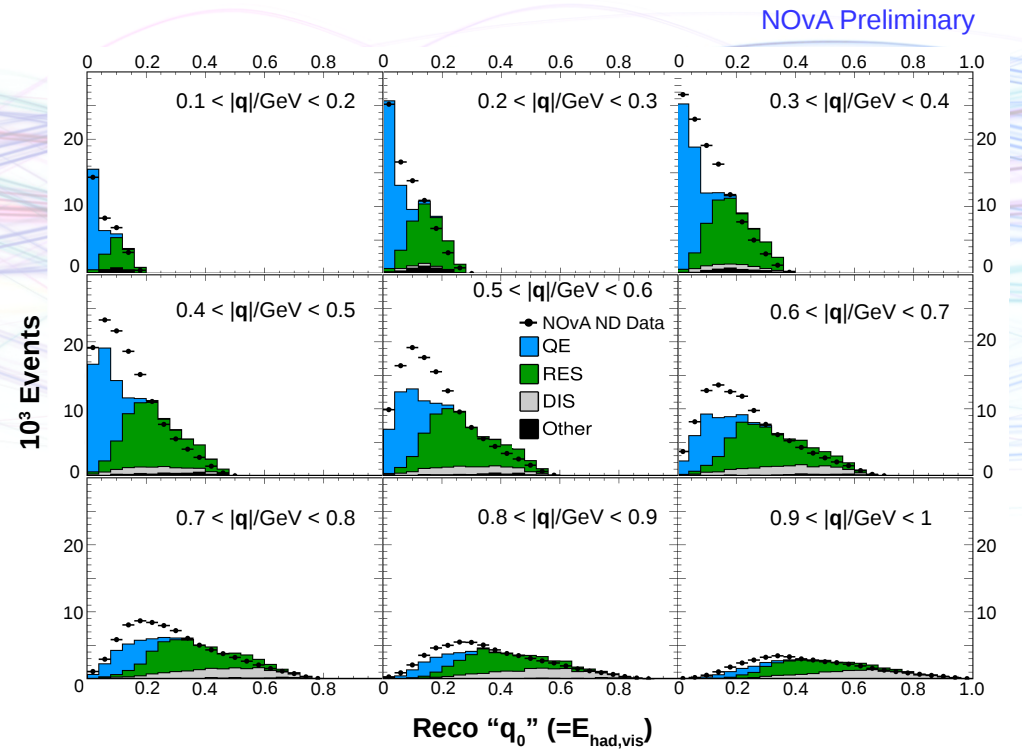
Nuclear correlations





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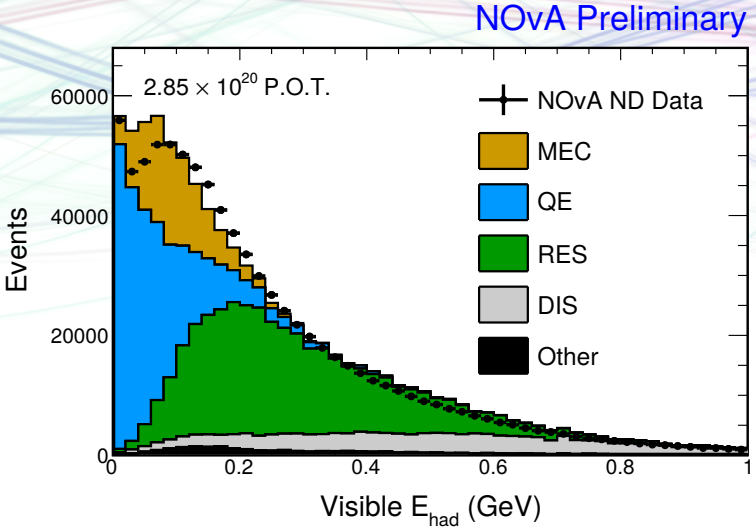

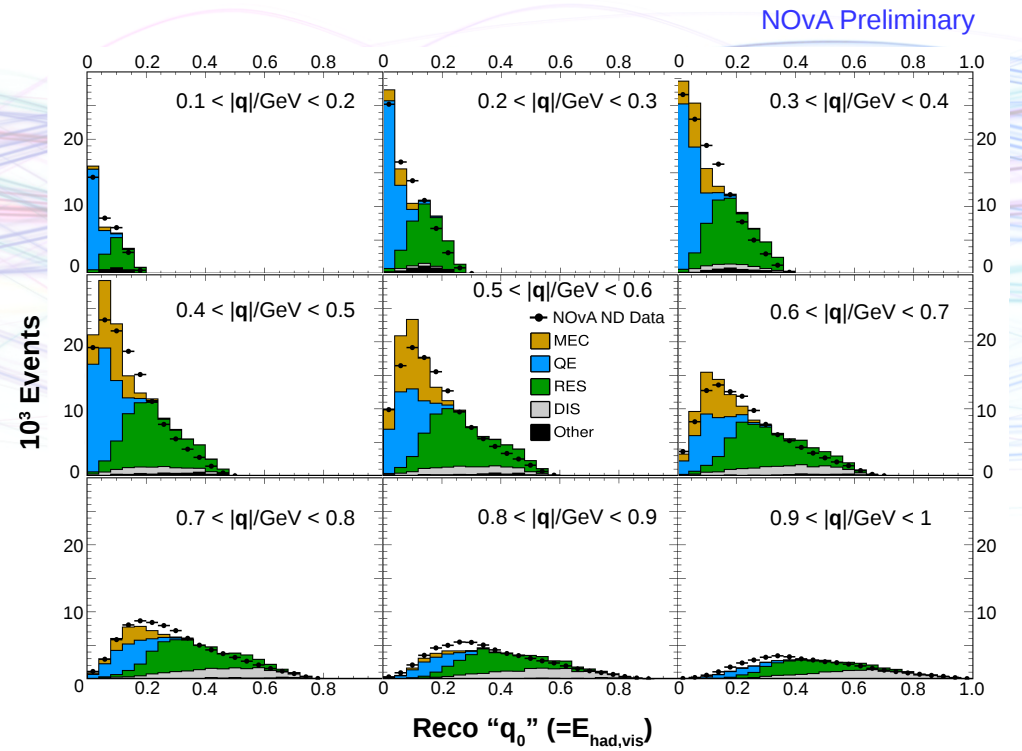

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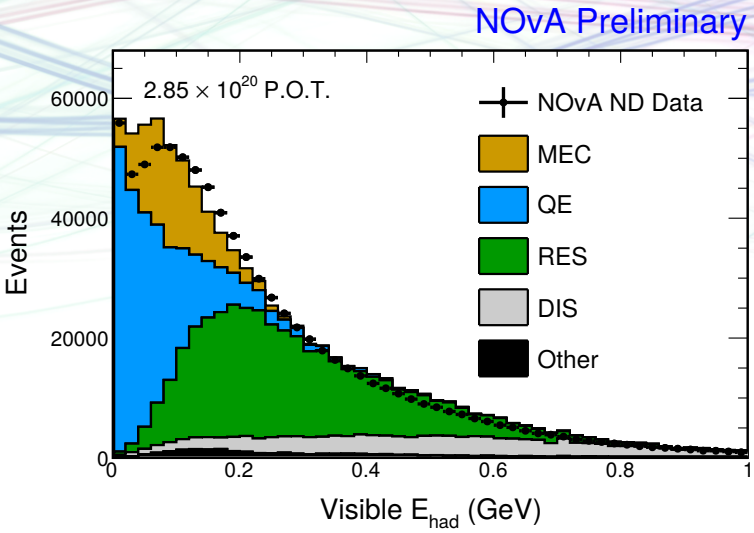
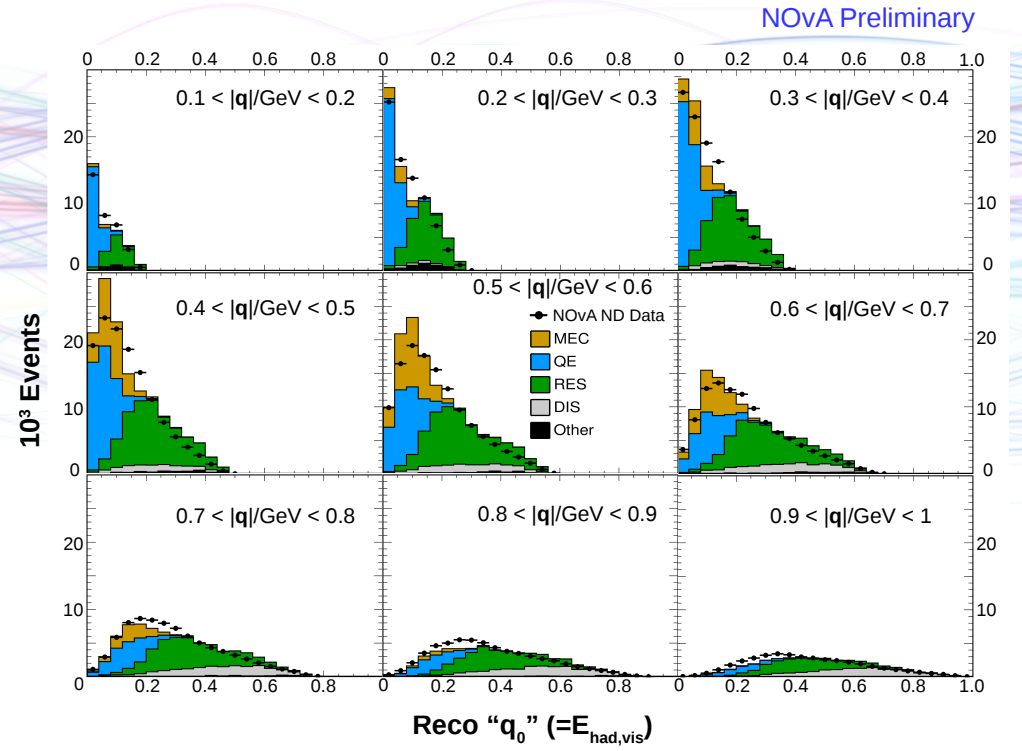
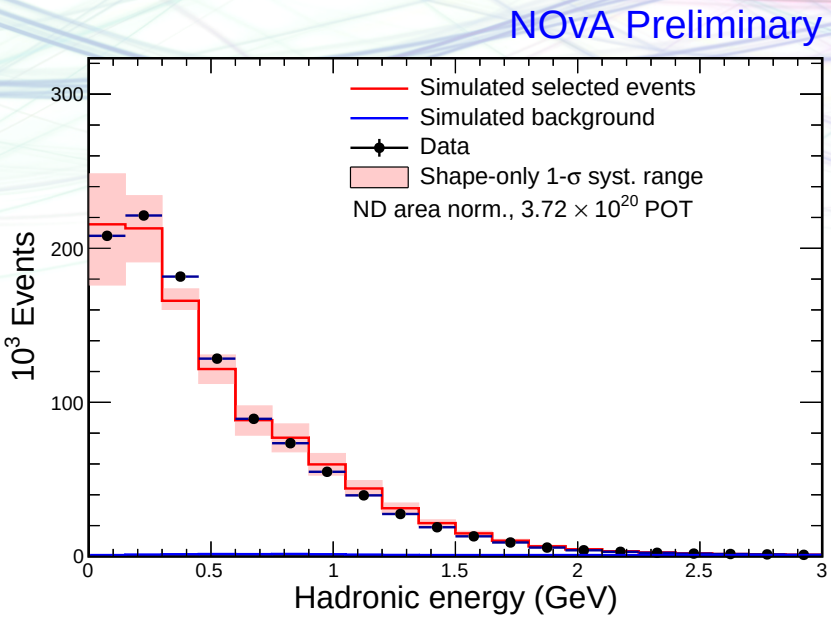
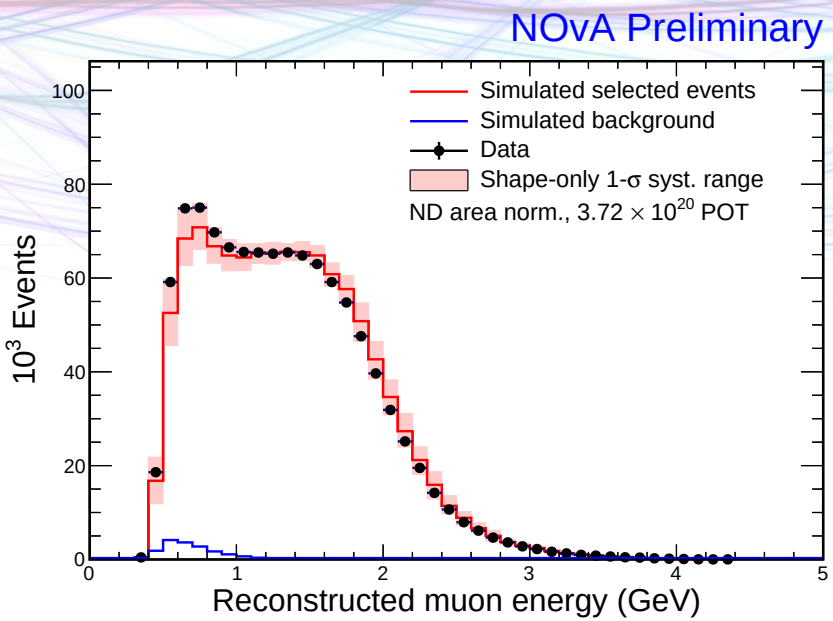




- Take 50% systematic on MEC component
- Reduced analysis' hadronic energy scale and QE xsec systematics

Muon neutrino energy reconstruction





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- Hadronic energy scale uncertainty improved to 5%

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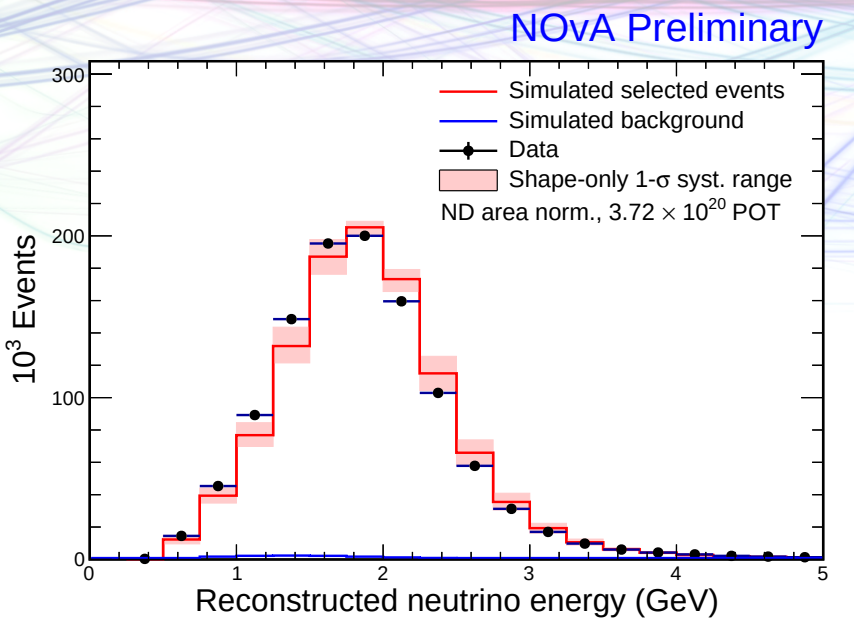

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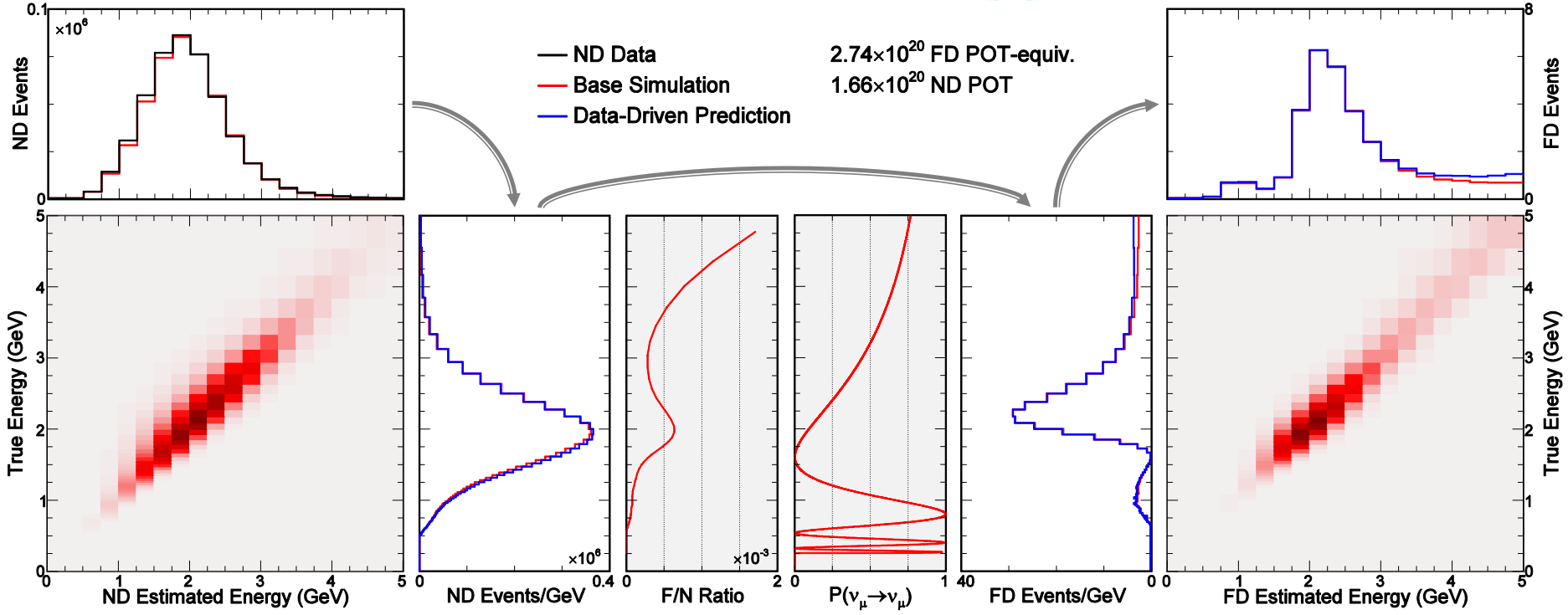
- Use ND data to predict FD neutrino spectrum

Extrapolation procedure

- Translate ND observations to true energy
- Transport to far detector and oscillate
- Smear back to reco energy

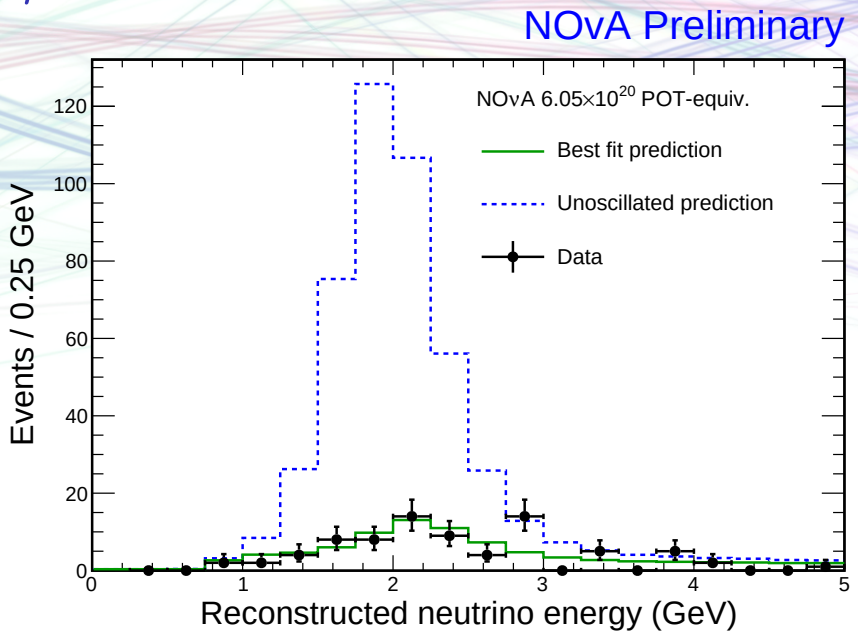


Systematic uncertainties

Source of uncertainty	Fractional uncertainty $\sin^2\theta_{23}$ ($\pm$%)	Fractional uncertainty Δm^2_{32} ($\pm$%)
Normalization	1.0	0.2
Muon E scale	2.2	0.8
Calibration	2.0	0.2
Relative E scale	2.0	0.9
Cross sections + FSI	0.6	0.5
Osc. parameters	0.7	1.5
Beam backgrounds	0.9	0.5
Scintillation model	0.7	0.1
Total systematic	3.4	2.4
Statistical uncertainty	4.1	3.5

- Consider multiple possible sources of systematic error
- Propagate effect of each through extrapolation
- Include as pull terms in fit
- Quoting increase (in quadrature) of measurement error

ν_μ disappearance results



- Expect 473 FD ν_μ CC events with no oscillation
- Observe 82 (inc. 3.7 beam bkg. and 2.9 cosmic)

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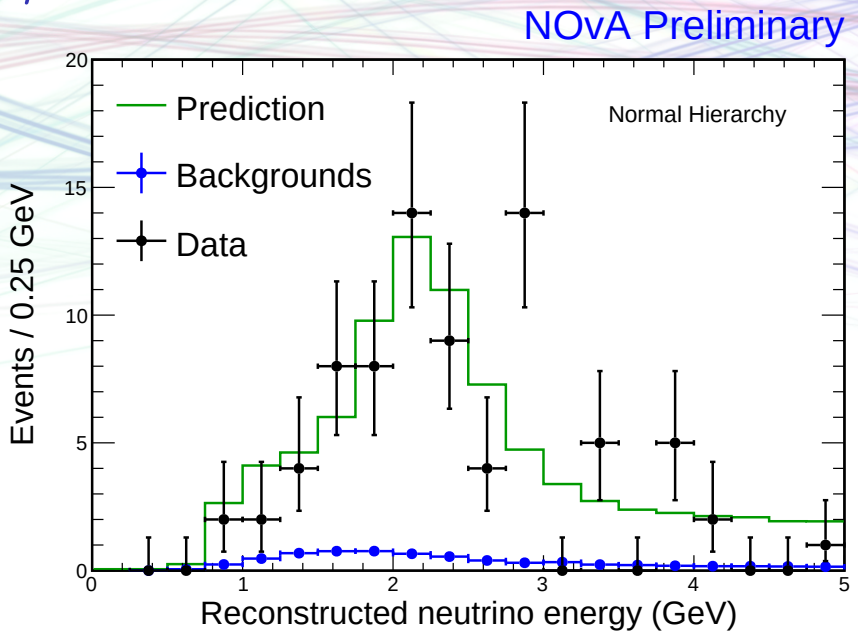

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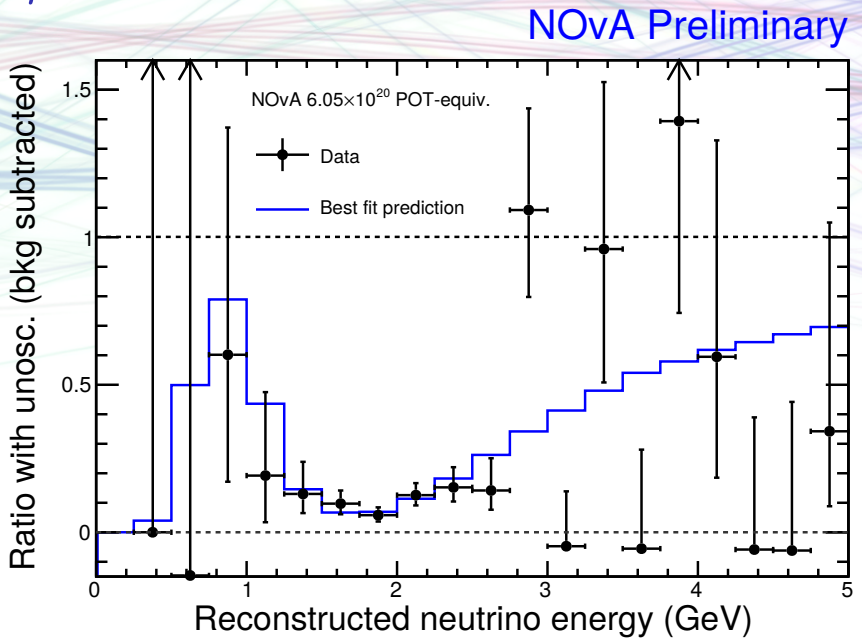

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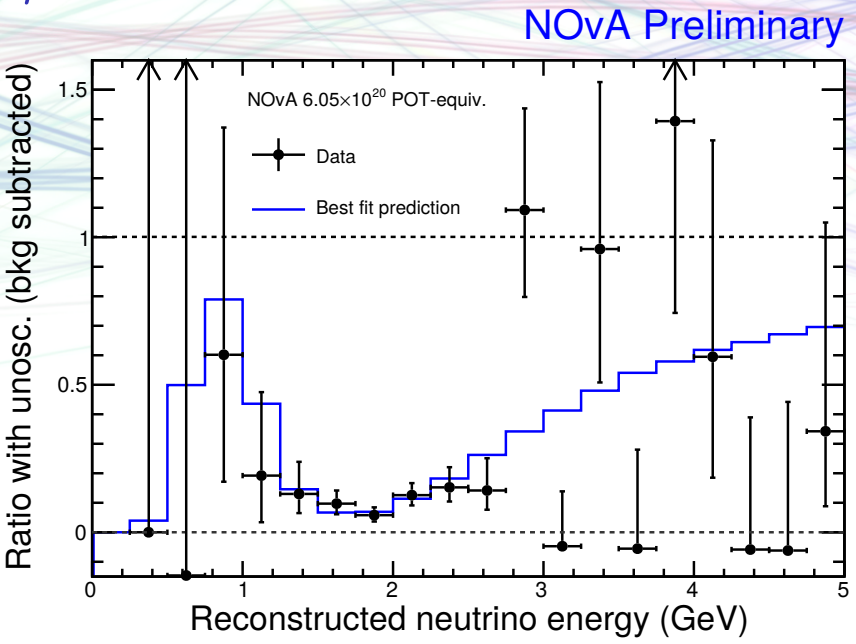

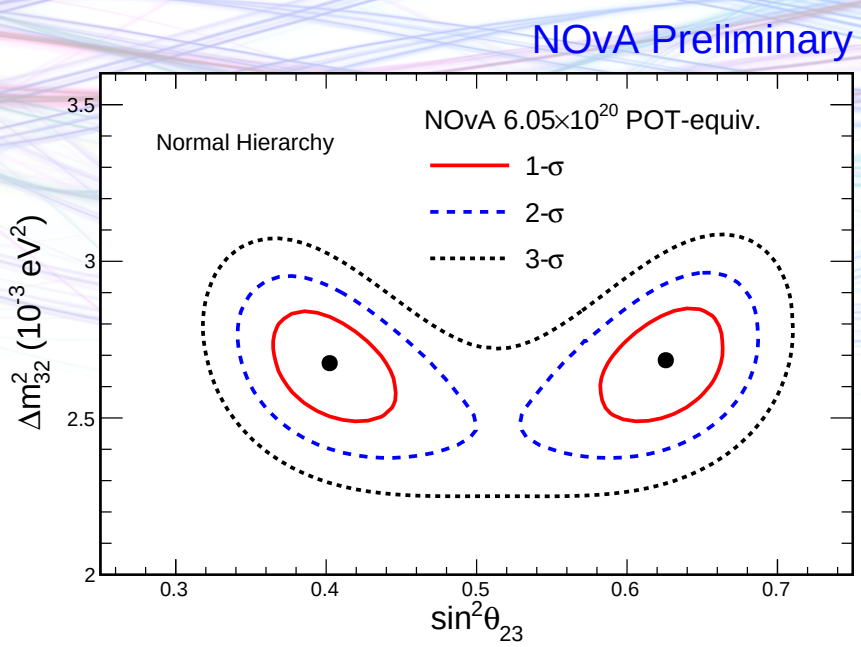

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$$\begin{aligned} \Delta m^2_{32} &= (2.67 \pm 0.12) \times 10^{-3}\text{eV}^2 \text{ (NH)} \\ \sin^2\theta_{23} &= 0.40^{+0.03}_{-0.02}\ (0.63^{+0.02}_{-0.03}) \end{aligned}$$

- Maximal mixing excluded at 2.5σ (FC corrections in progress)

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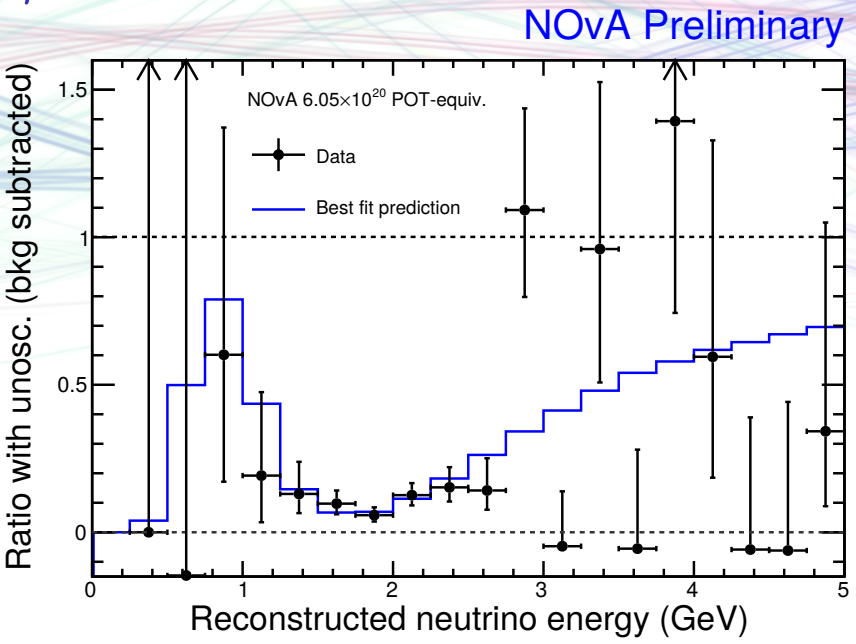

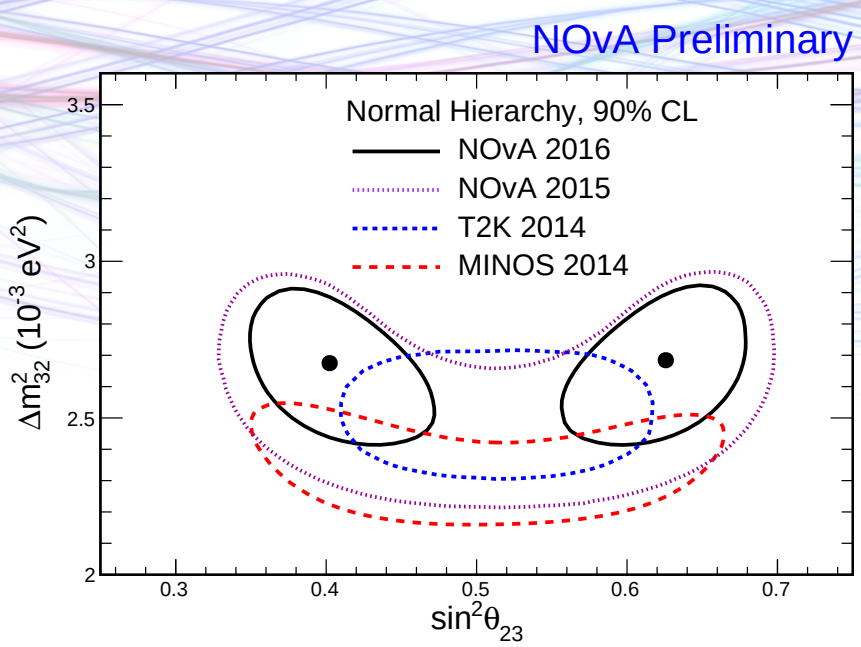

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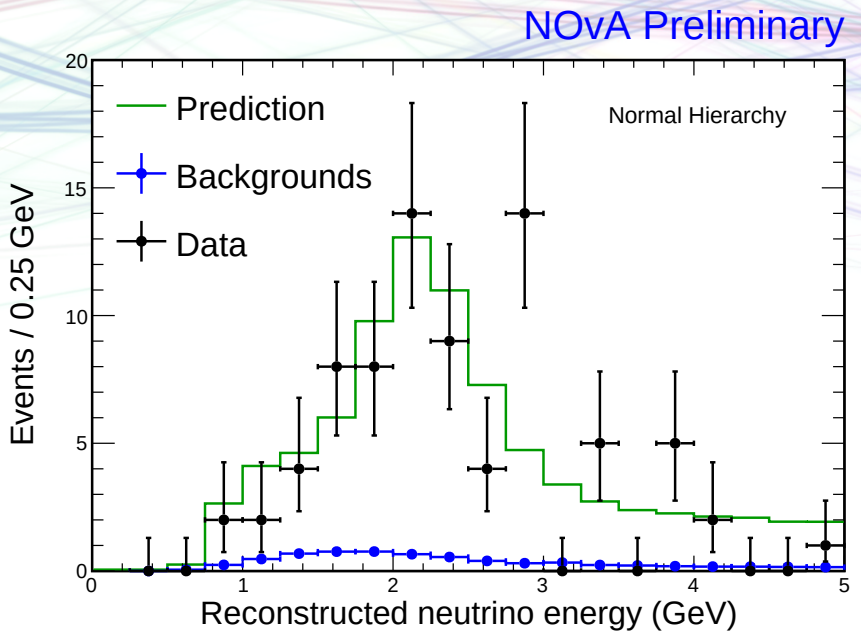

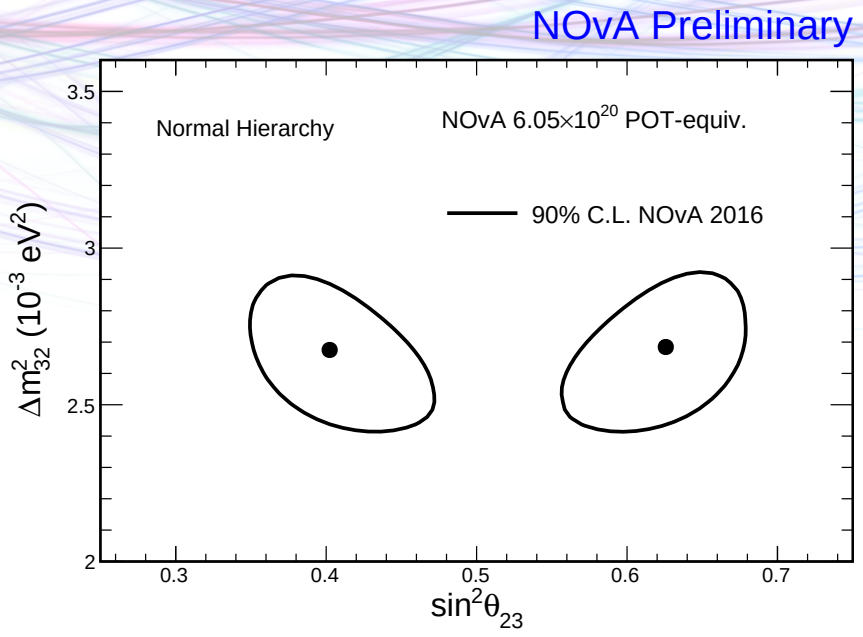

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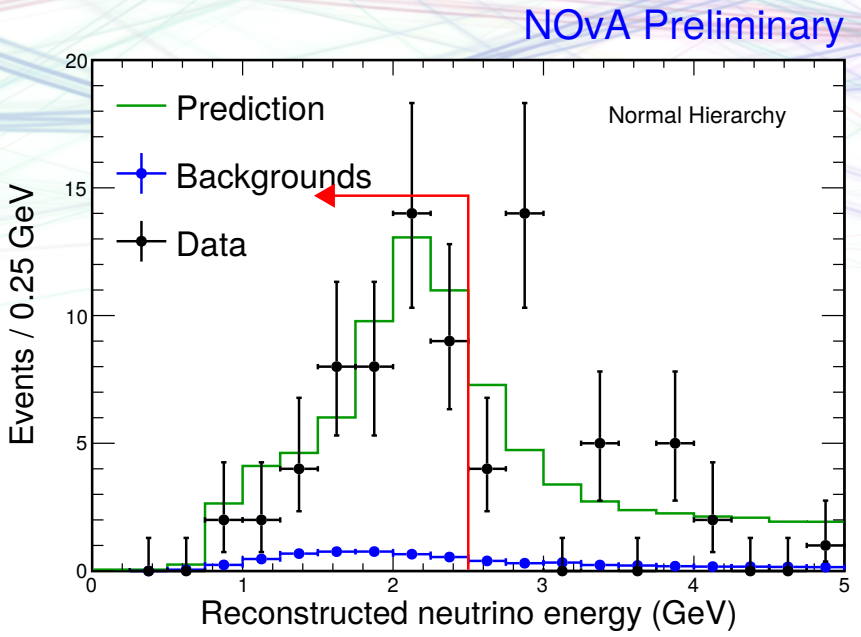

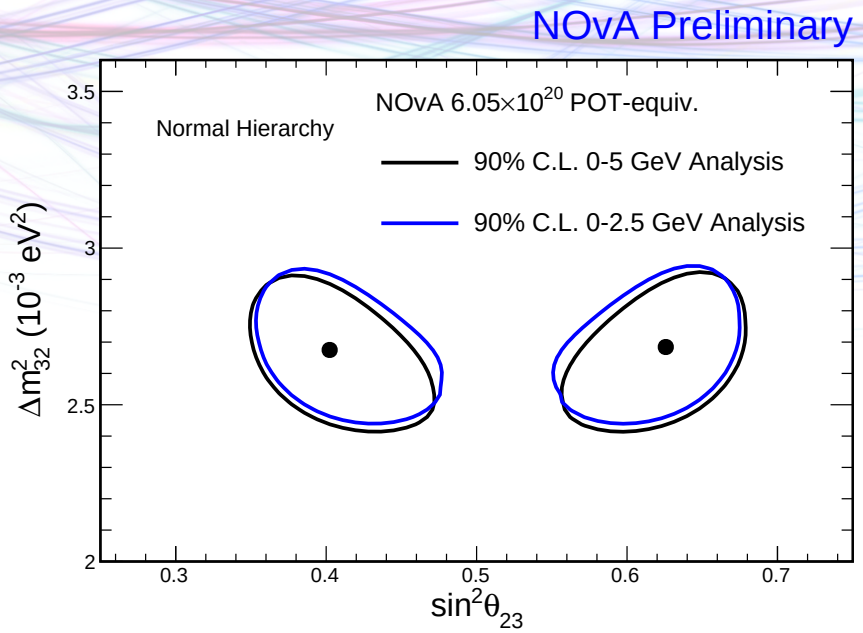

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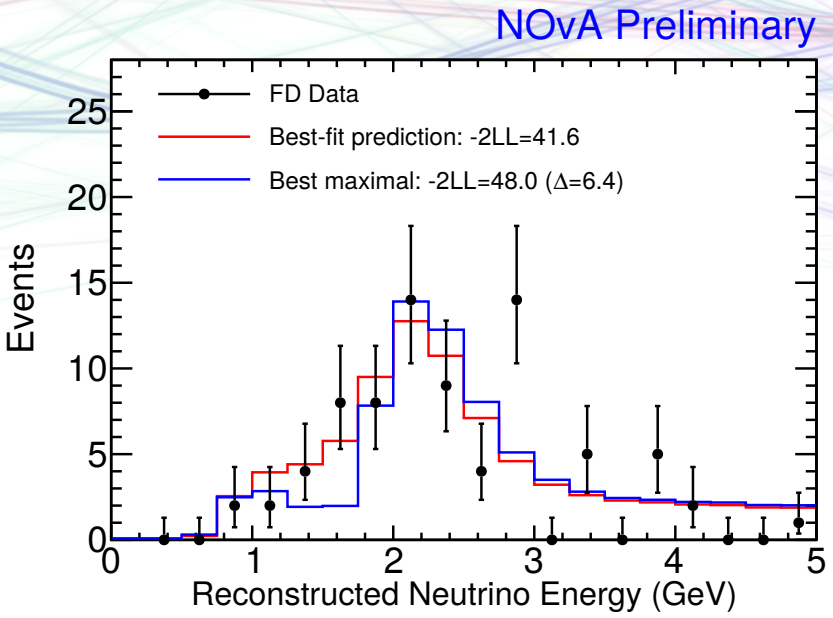
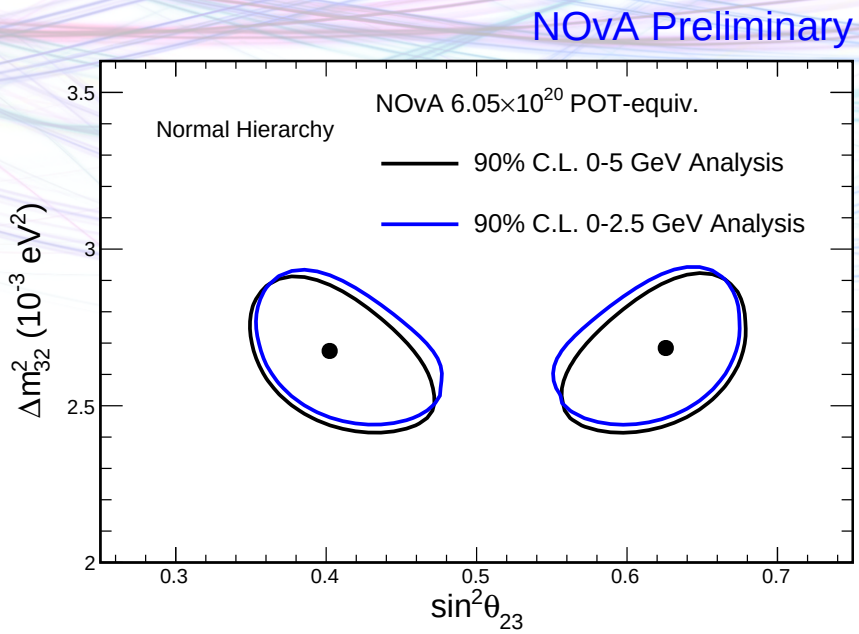
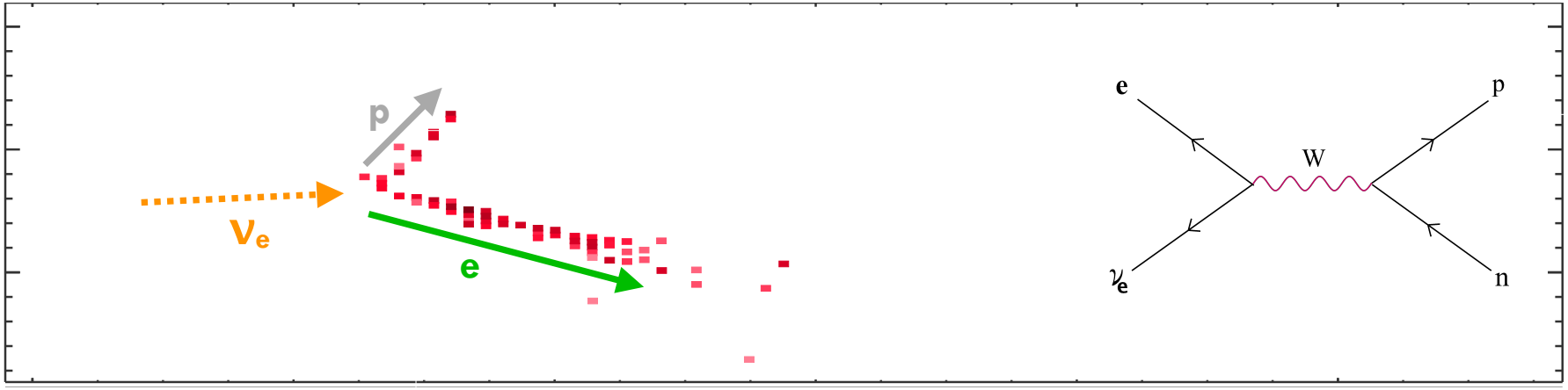




- $\chi^2/\text{dof} = 41.5/17$, driven by fluctuations in the tail
- No significant pull on oscillation fit from these bins
- Non-maximal best fit driven by bins in oscillation dip, as expected
  - $\Delta m^2_{32} = 2.46 \times 10^{-3}$ eV^2 when forcing maximal mixing
  - $\Delta\chi^2 = 6.4$ above non-maximal fit

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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- $P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E}\right) + f(\mathrm{sign}(\Delta m^2_{32})) + f(\delta_{CP})$
- θ_{13} only 8.5° degrees, most ν_μ go to ν_τ instead
- Look for deviations due to hierarchy (matter effects) and CP-violation

Principle of the ν_e measurement

- To first order, NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ evaluated at 2GeV
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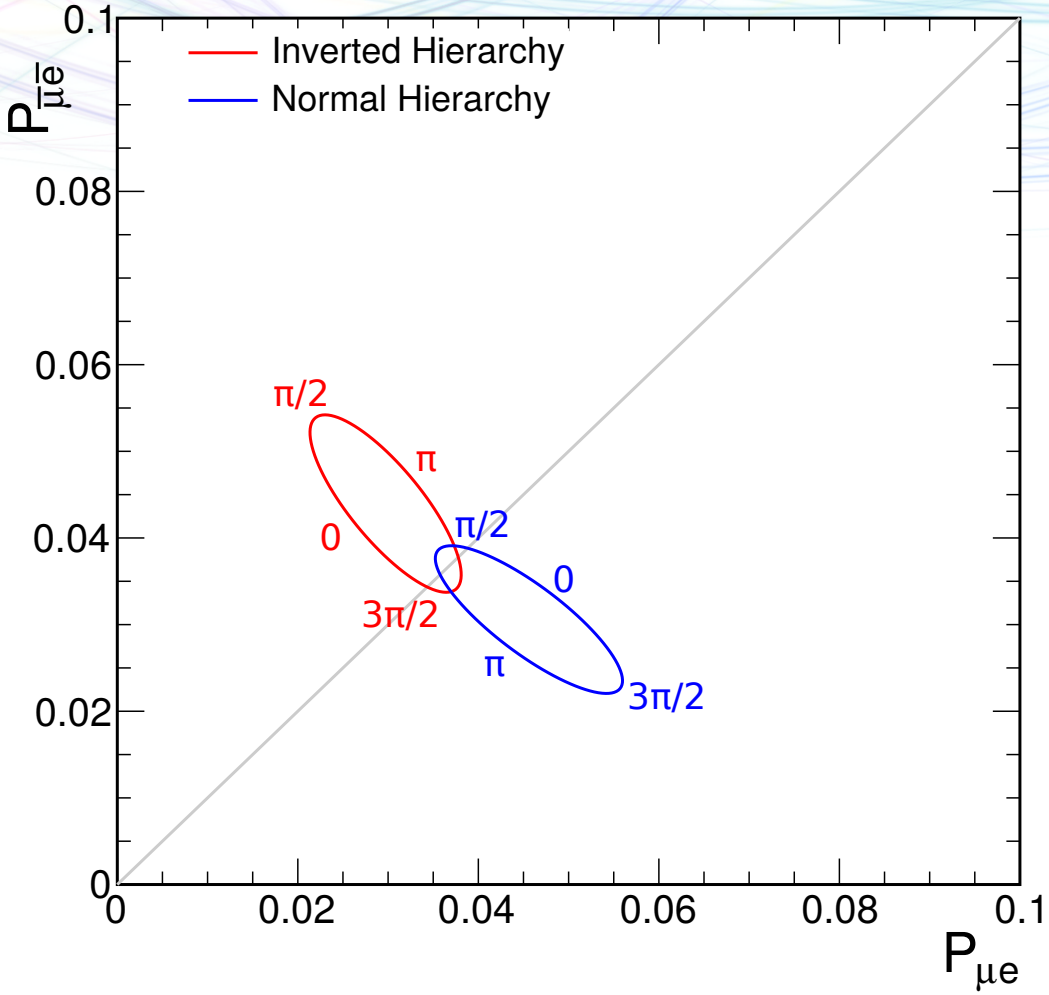

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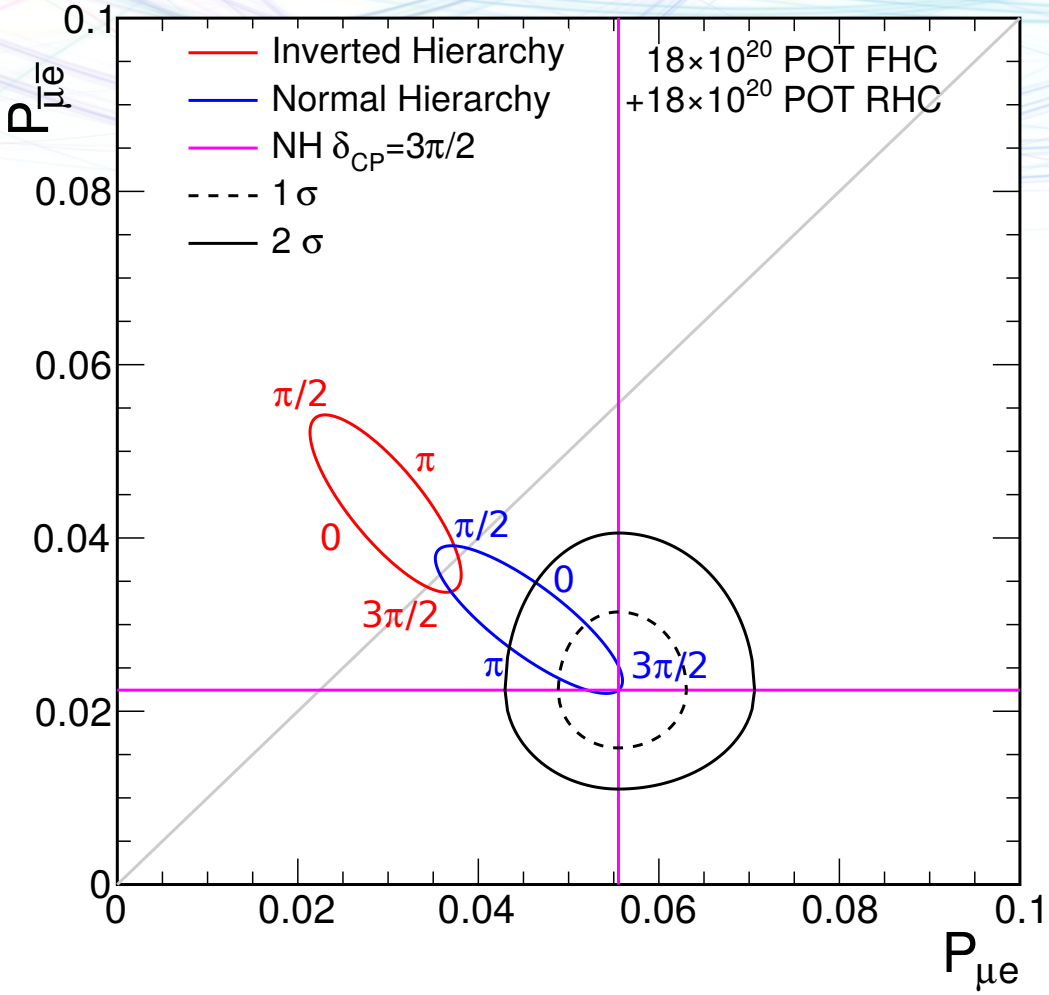

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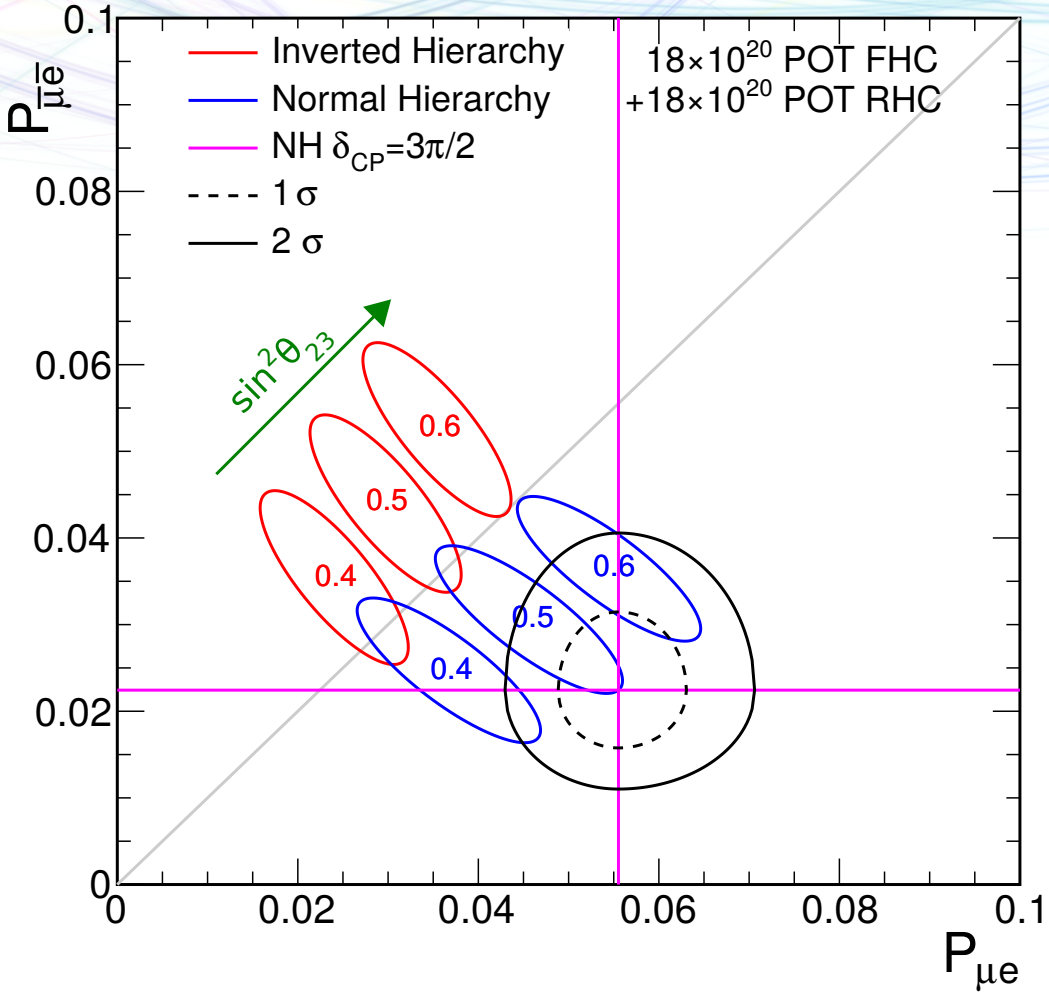
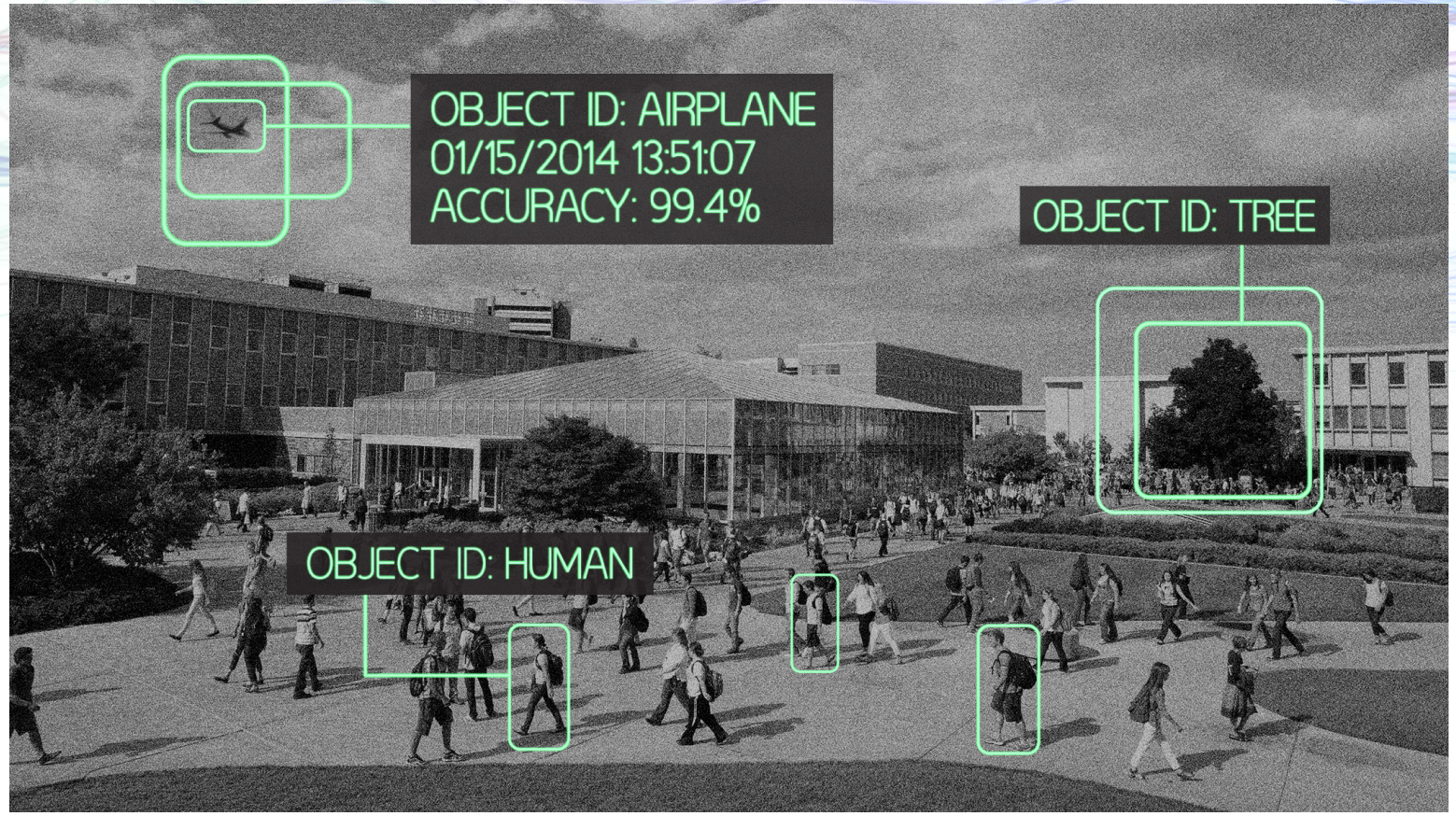


Convolution Neural Networks



- Recent advances in machine learning/computer vision
- Achieving near-human performance on image classification tasks
- Why not classify event-displays?

Convolution Neural Networks

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

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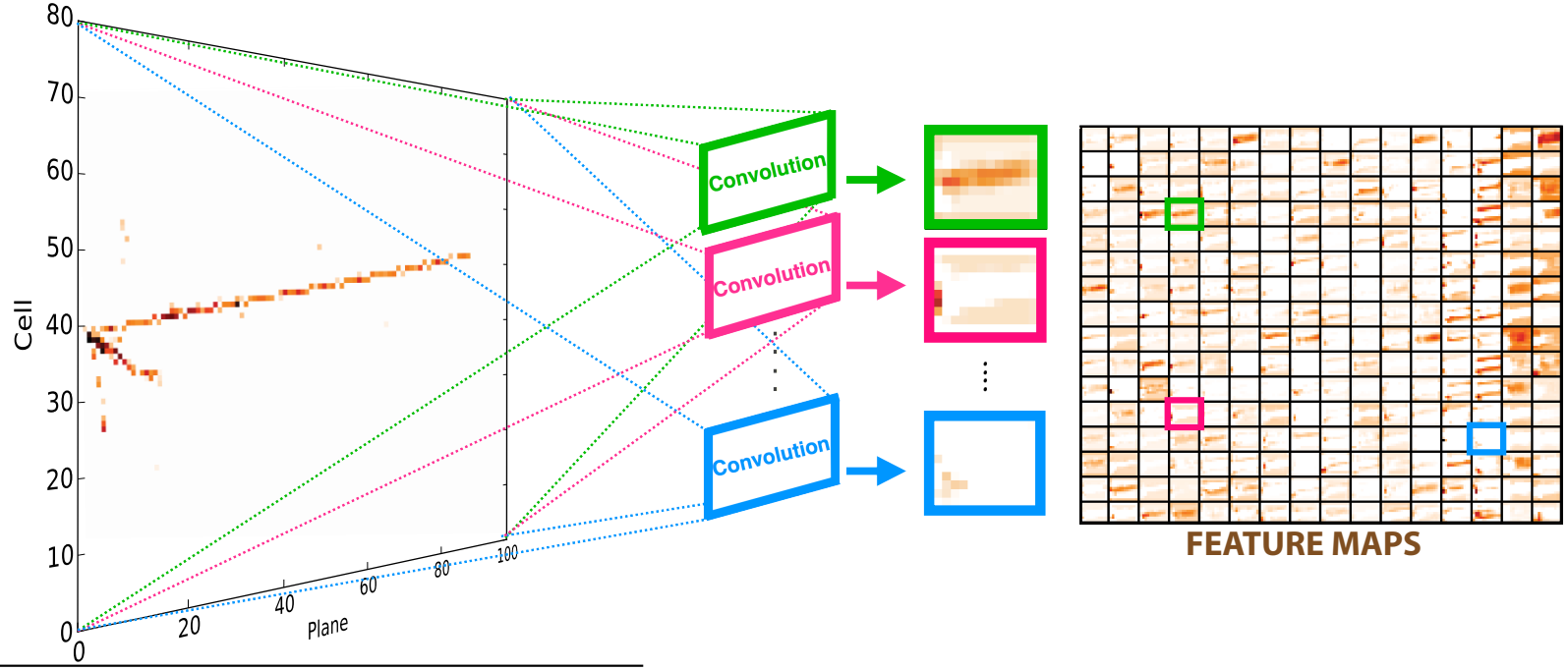
Selecting electron neutrinos – CVN

- **C**onvolutional **V**isual **N**etwork (CVN)
- Early layers perform convolutions to pick out abstract features
- Fully-connected final layers
- Trained using FNAL's Wilson Cluster GPUs
- Statistical power equivalent to 30% more exposure than previous IDs



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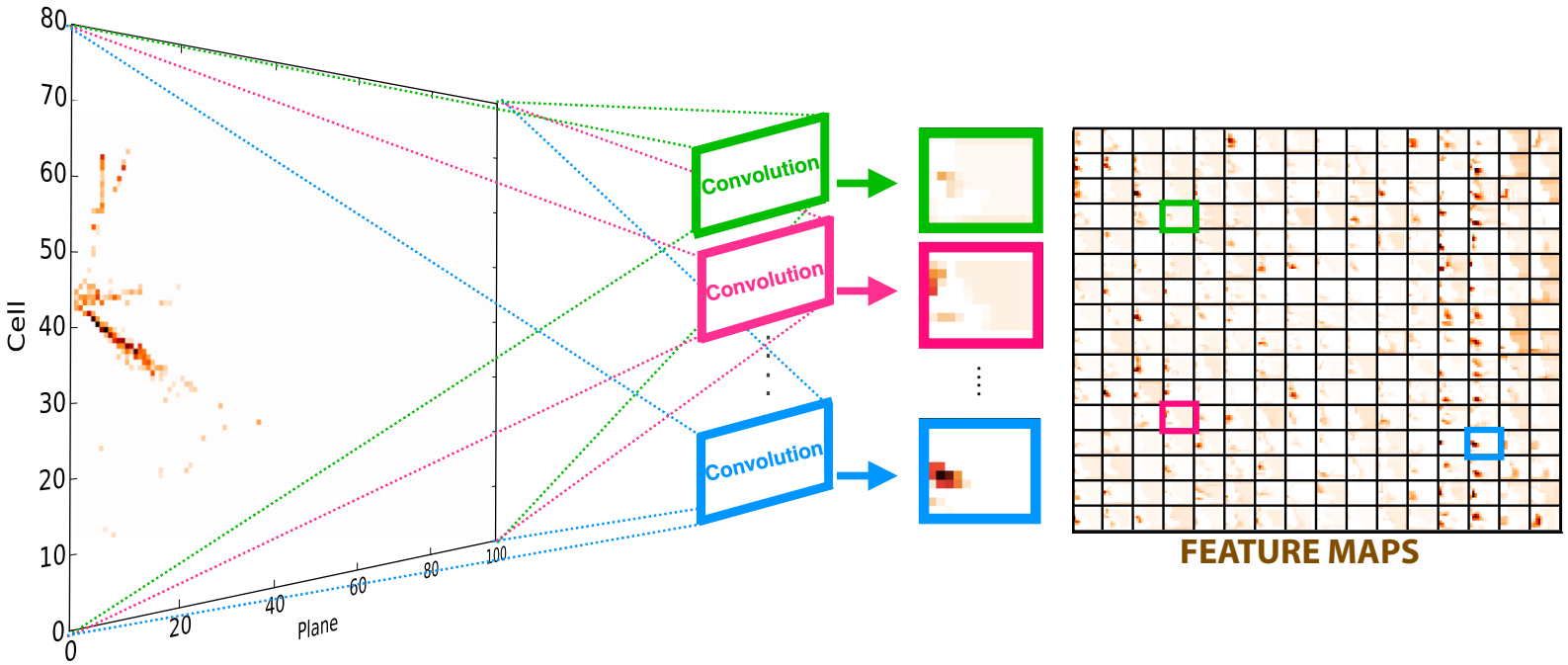

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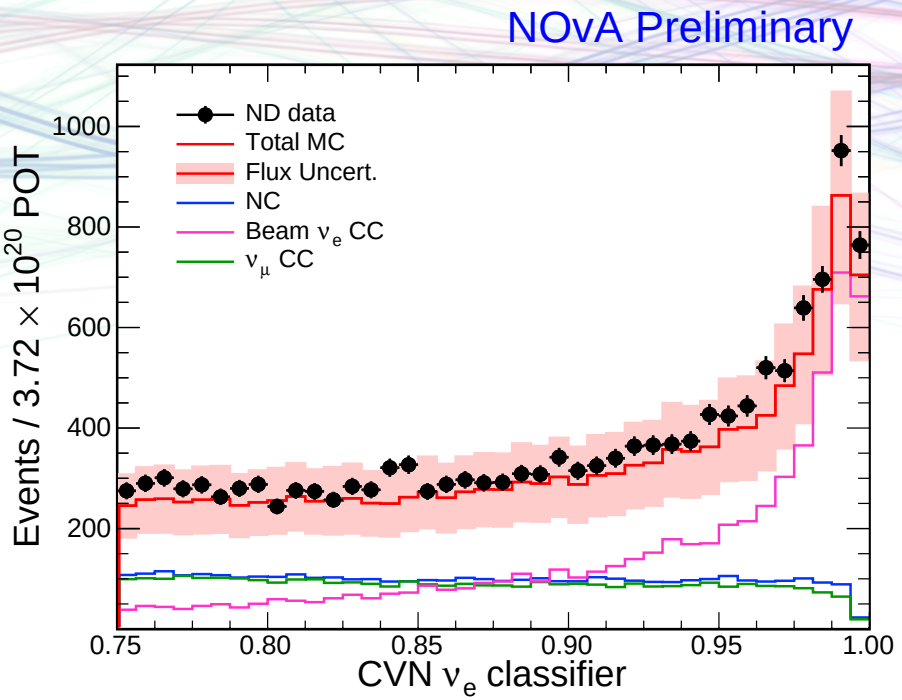

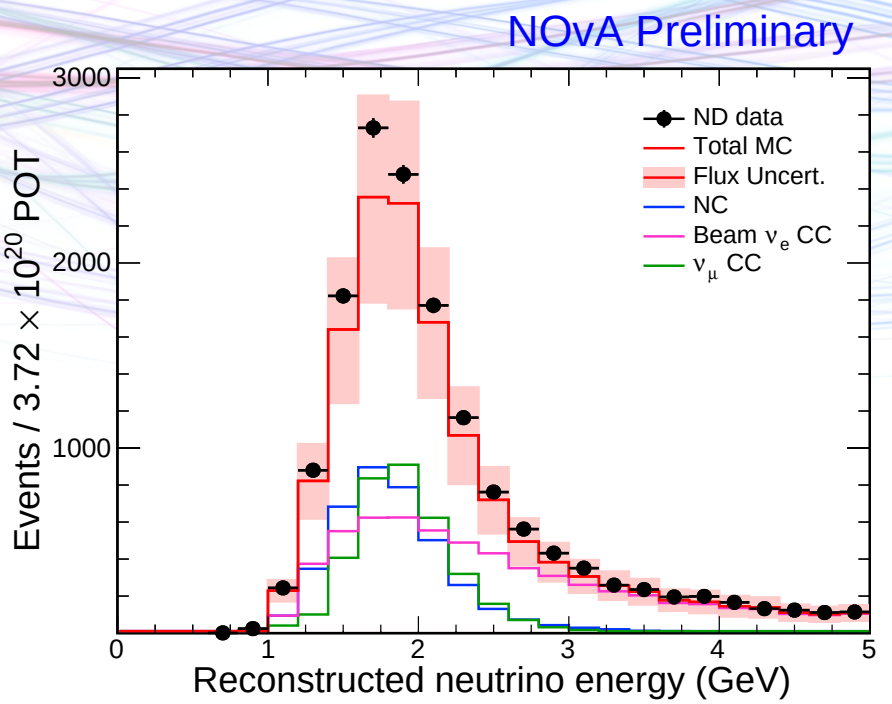

- 73% ν_e signal efficiency, 76% purity
- Loosen PID cut to maximize $s/\sqrt{s+b}$
- Analyze in 3 PID × 4 energy bins

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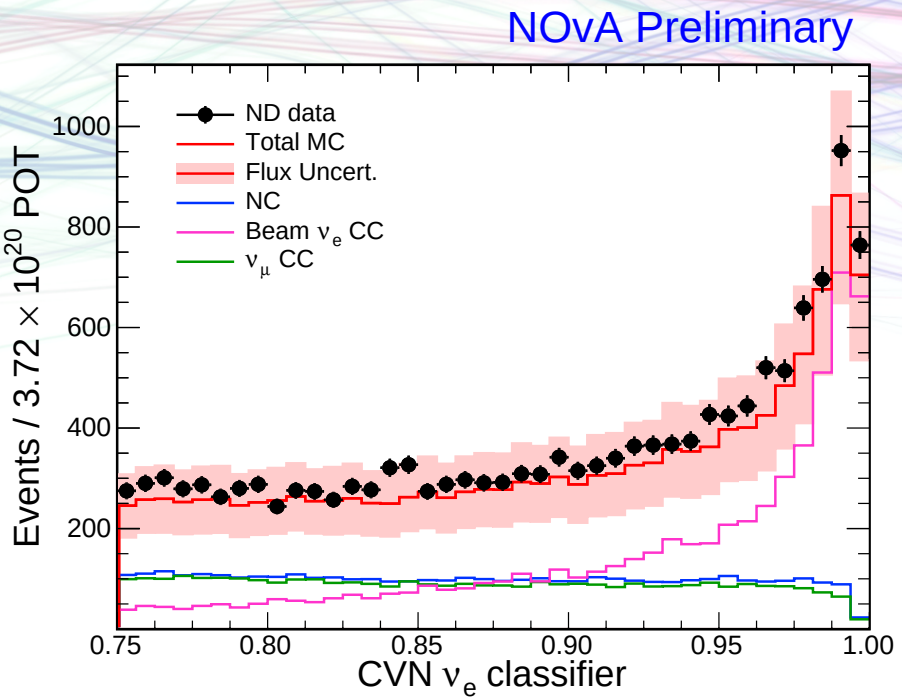

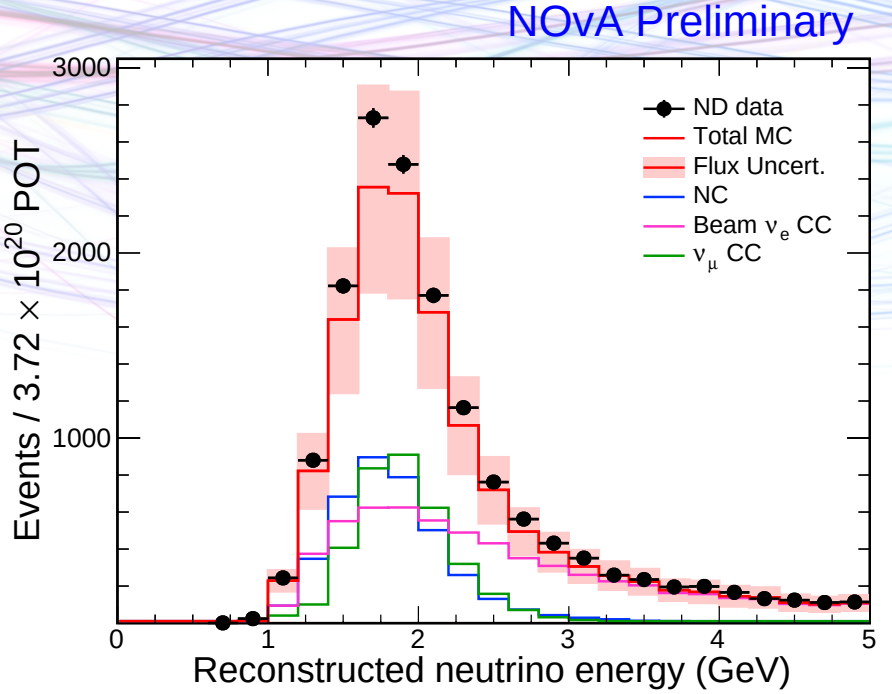

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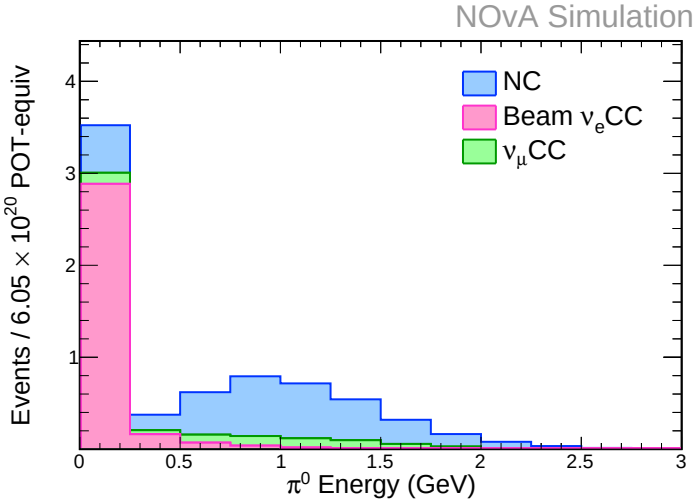
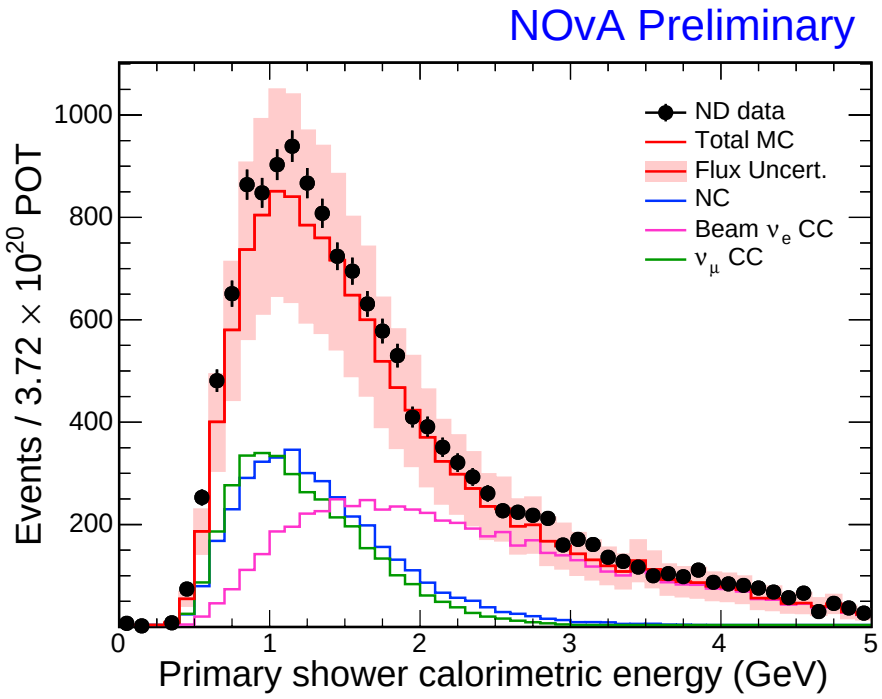
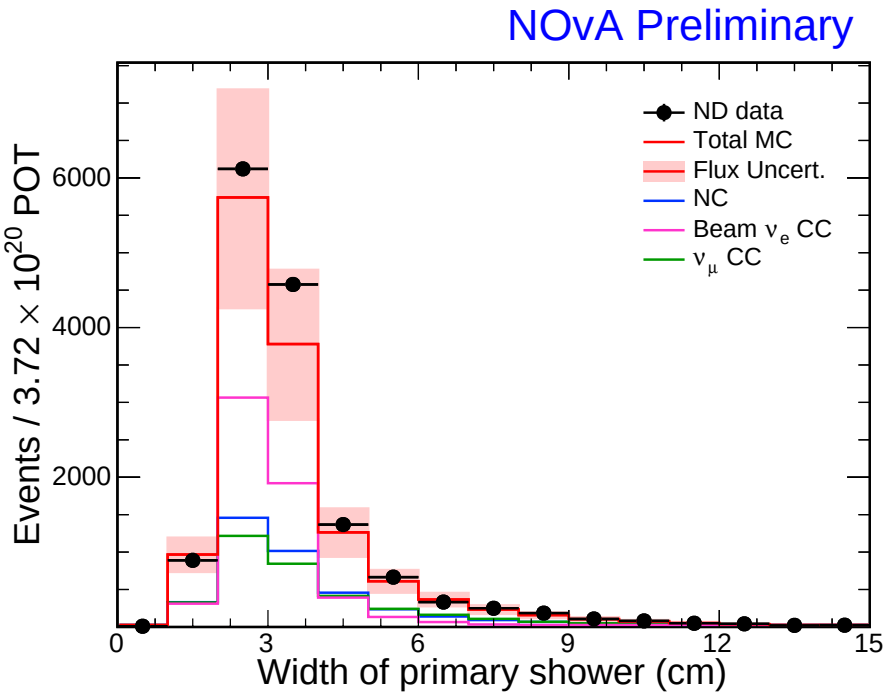


Selector checks

- CVN subjected to the same (or greater) scrutiny than past PIDs

- ND data/MC is good
- Better cosmic rejection and similar systematics to other PID options





ν_e selection efficiency – MRE

- EM showers should be well modelled
- Any ν_e signal efficiency differences coming from the hadronic side?
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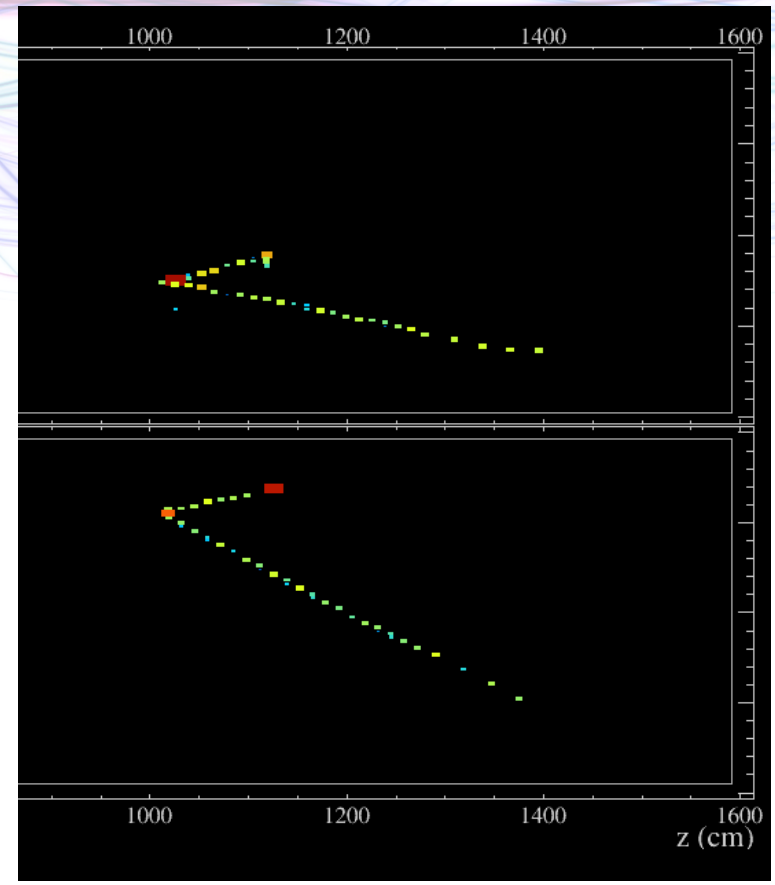

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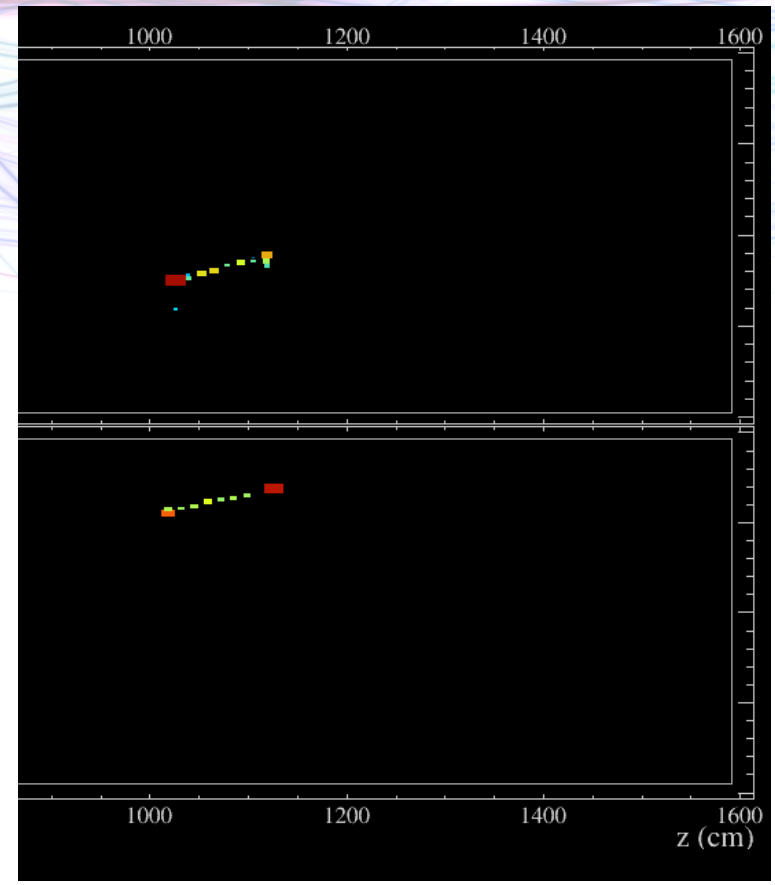

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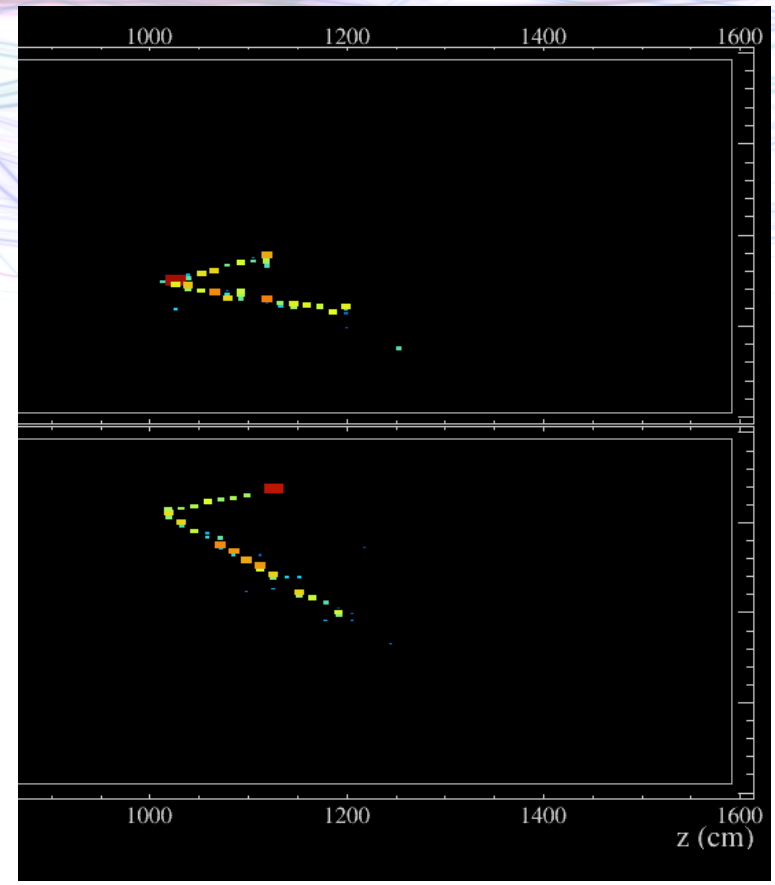
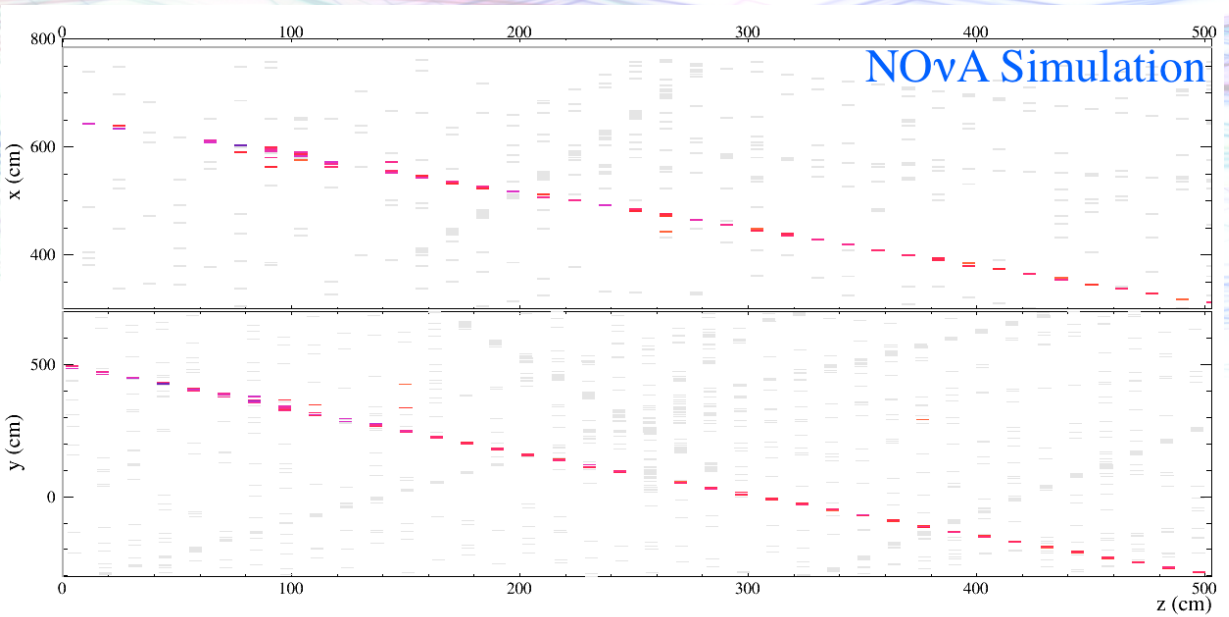


- $\mathcal{O}(1\%)$ efficiency difference to select MRE data/MC events

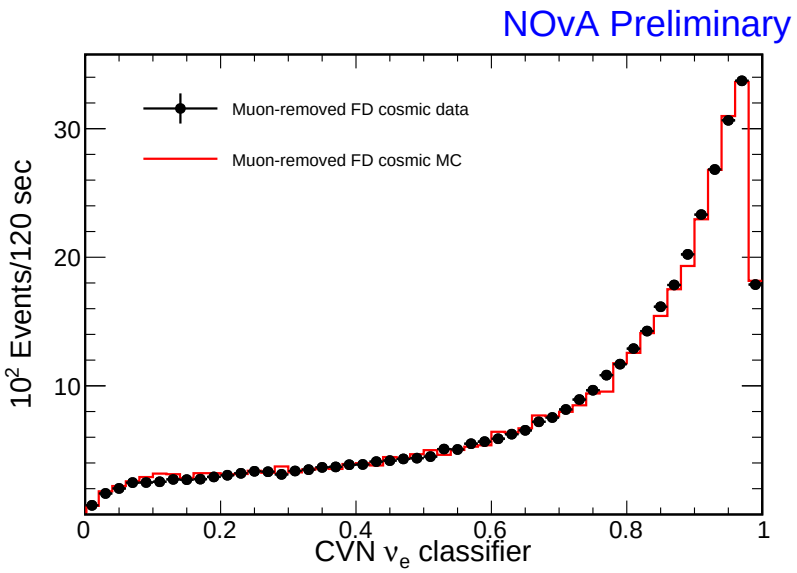
ν_e selection efficiency – EM activity



- Find FD data cosmic rays w/ brems

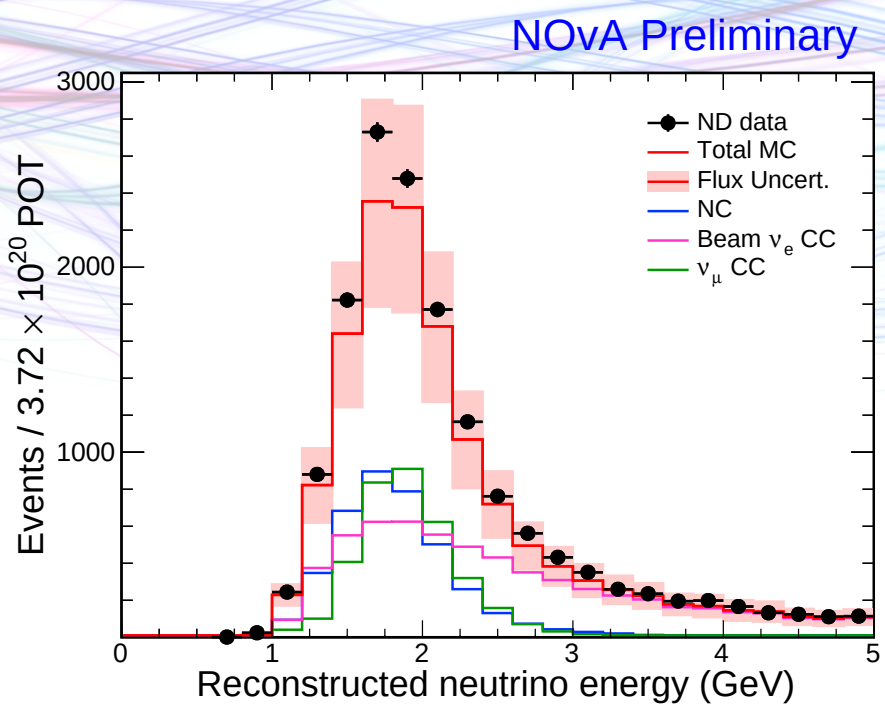
ν_e selection efficiency – EM activity

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



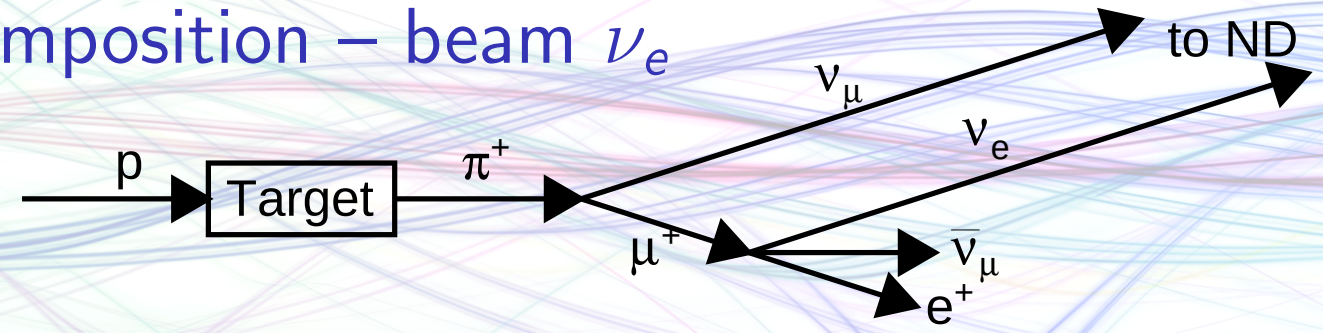
ND decomposition

- Use ND data to predict FD backgrounds
  - Beam ν_e CC
  - NC
  - ν_μ CC
- $\sim$ 10% excess of data over MC

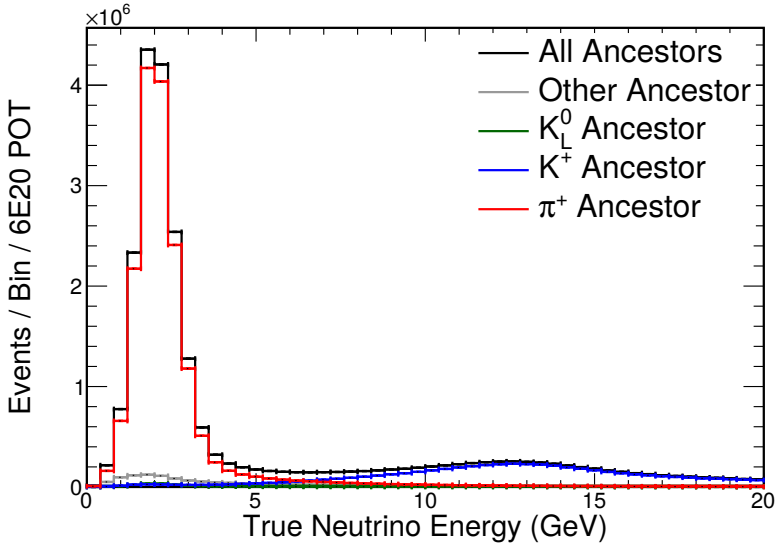


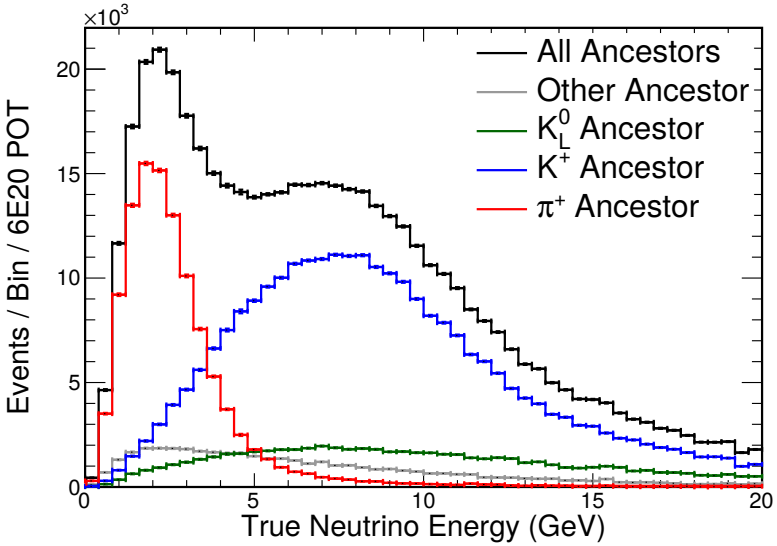
- How to divide between the components?
- *e.g.* most ν_μ CC oscillate away before FD

ND decomposition – beam ν_e

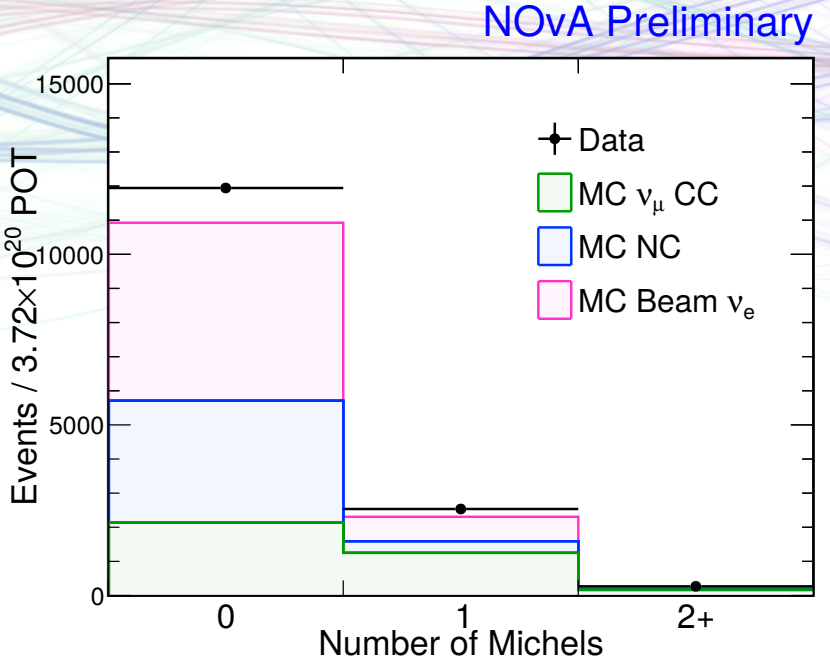


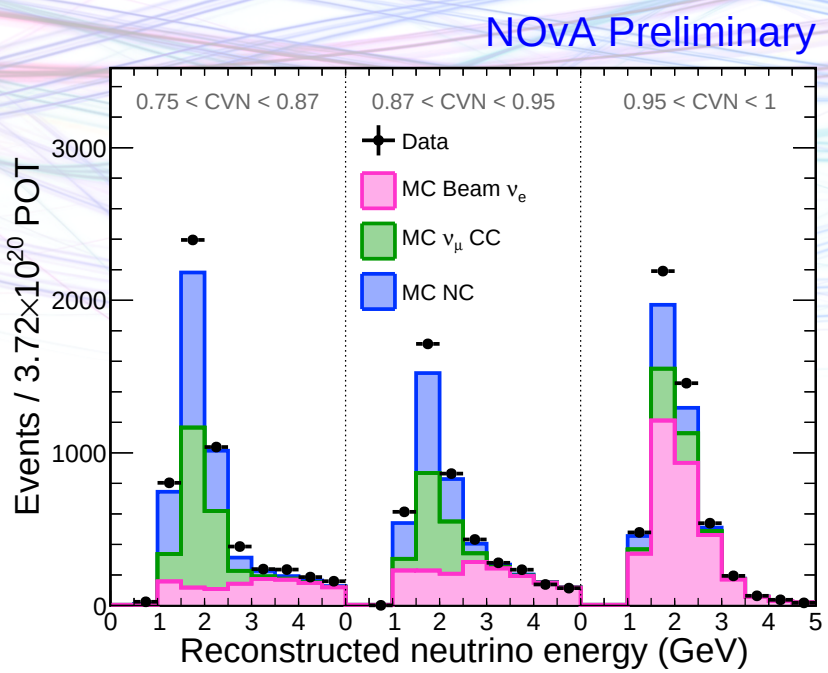
- Low-E ν_μ and ν_e trace back to the same π^+ ancestors
- Weight ν_e with K^+ parents up 17% based on ν_μ high-E tail
- Use ν_μ at lower energy to reweight decaying pions in (p_T, p_z) space
- Decreases ν_e with π^+ parent 3-4%
- Overall effect is 3% increase in 1-3 GeV range





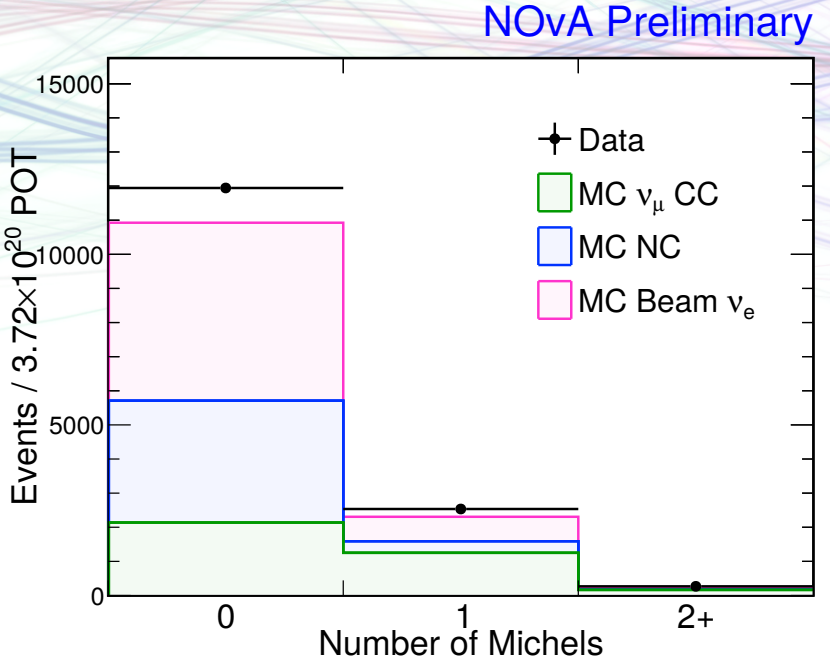
ND decomposition – Michels

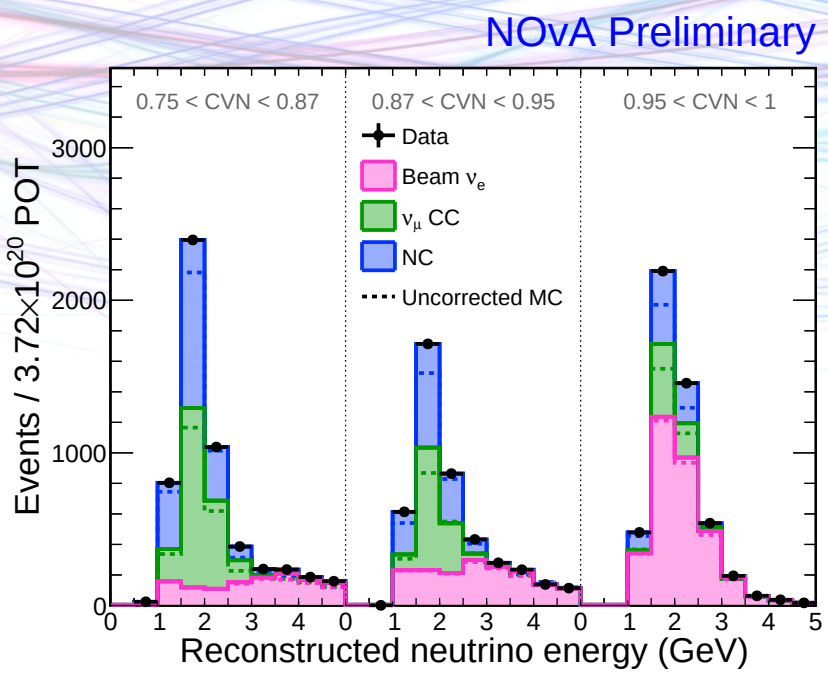




- ν_μ CC background events have Michel electron from muon decay
- Also produced in ν_e CC and NC by pions, but ν_μ have ~ 1 more
- Fit observed N_{michel} spectrum in each bin by varying components
- ν_e and NC near-degenerate, fix ν_e to parent-reweight estimate
- Data excess assigned between NC (+17%) and ν_μ CC (+10%)

ND decomposition – Michels





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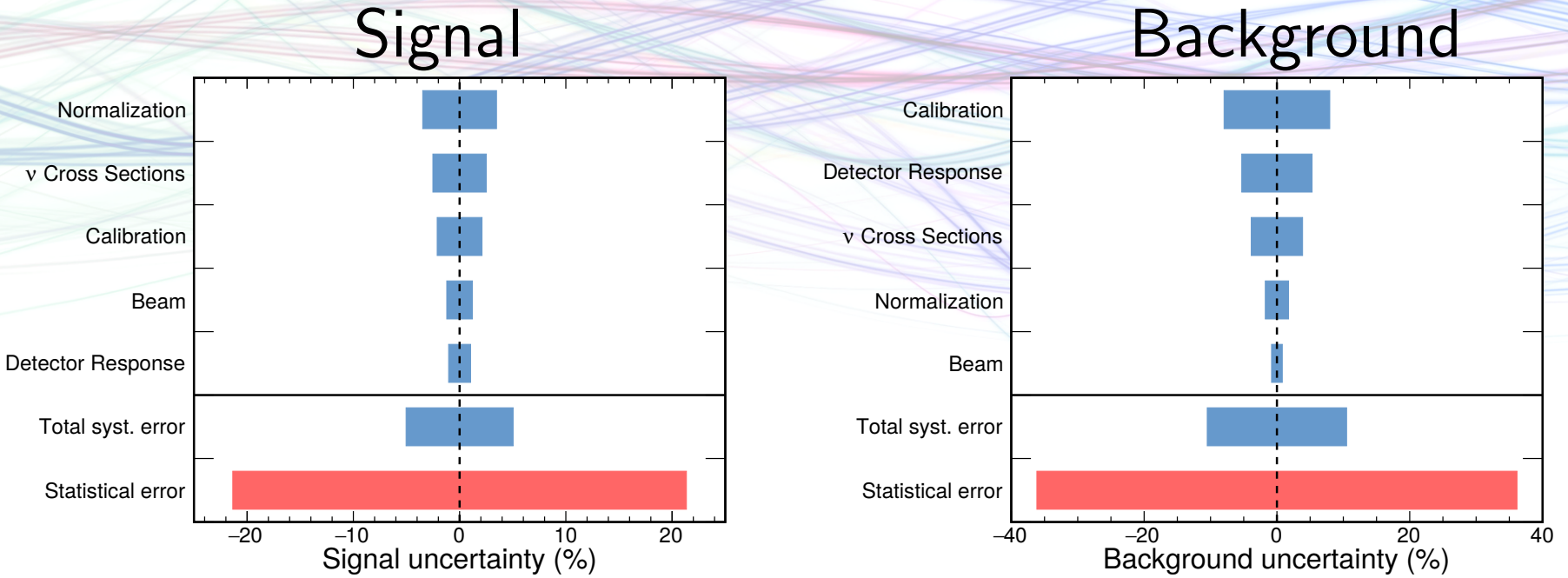
Systematics



- Considered multiple possible sources of systematic error
- Propagate shifts through to update FD prediction

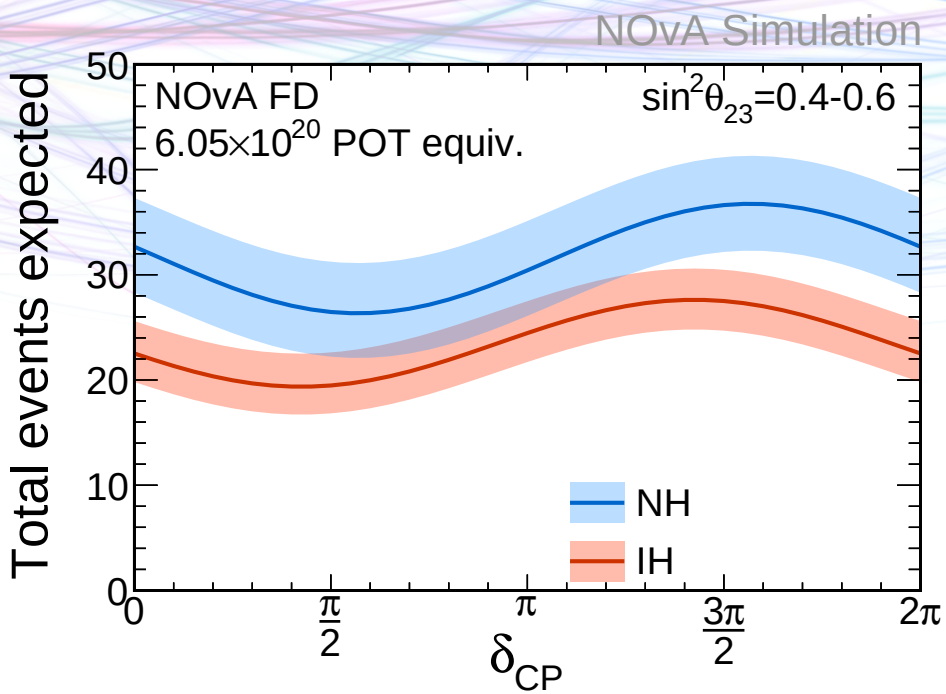
- Total $\sim$ 5% error on signal, 10% on bkg.
- Fit nuisance parameters as pull terms
- Dominated by statistical error

Event count expectations

Total prediction

NH $\frac{3\pi}{2}$	IH $\frac{\pi}{2}$	$\sin^2\theta_{23} = 0.5$
36.4	19.4	$\pm 5\%$ syst.

$P_{\nu_\mu \to \nu_e} \propto \sin^2\theta_{23} \sin^2 2\theta_{13}$

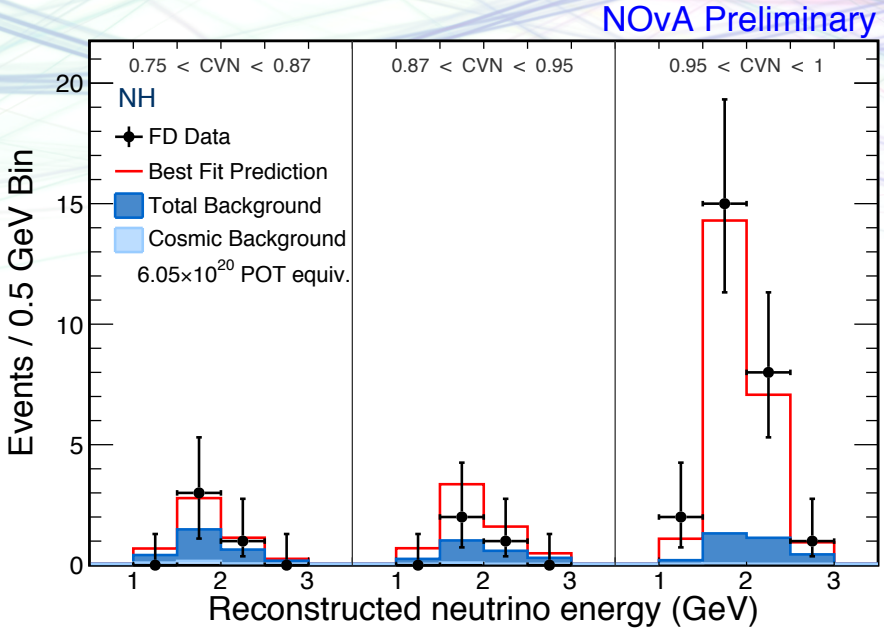


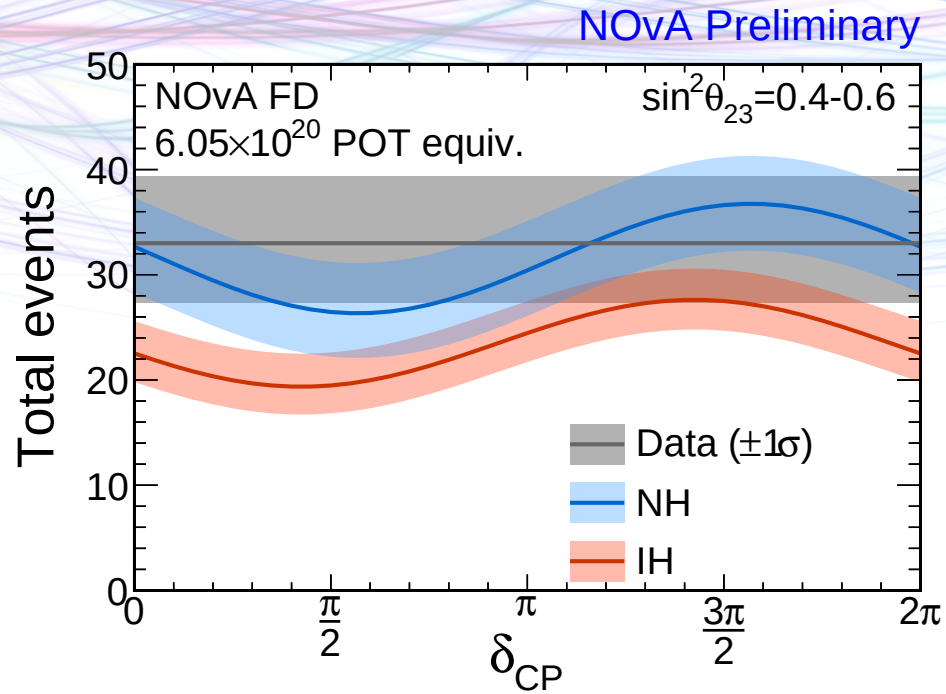
Background components

Total bkg	NC	beam ν_e	ν_μ CC	ν_τ CC	cosmics	
8.2	3.7	3.1	0.7	0.1	0.5	$\pm 10\%$ syst.

Essentially independent of oscillation parameters

ν_e appearance results



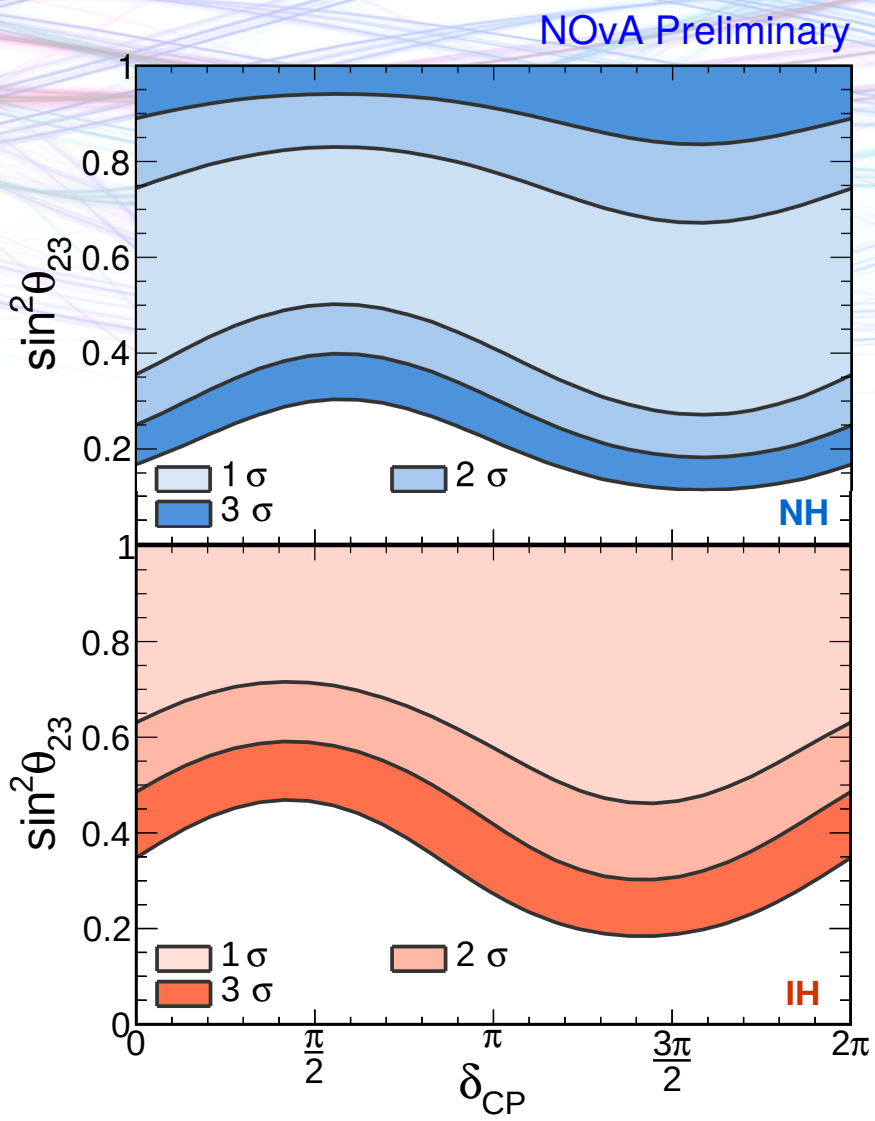


- Observe **33** events passing ν_e selection
- On 8.2 background
- Towards the higher end of expectations

Previous result PIDs: LID(LEM) sees 34(33) events on bkg. of 12.2(10.3)

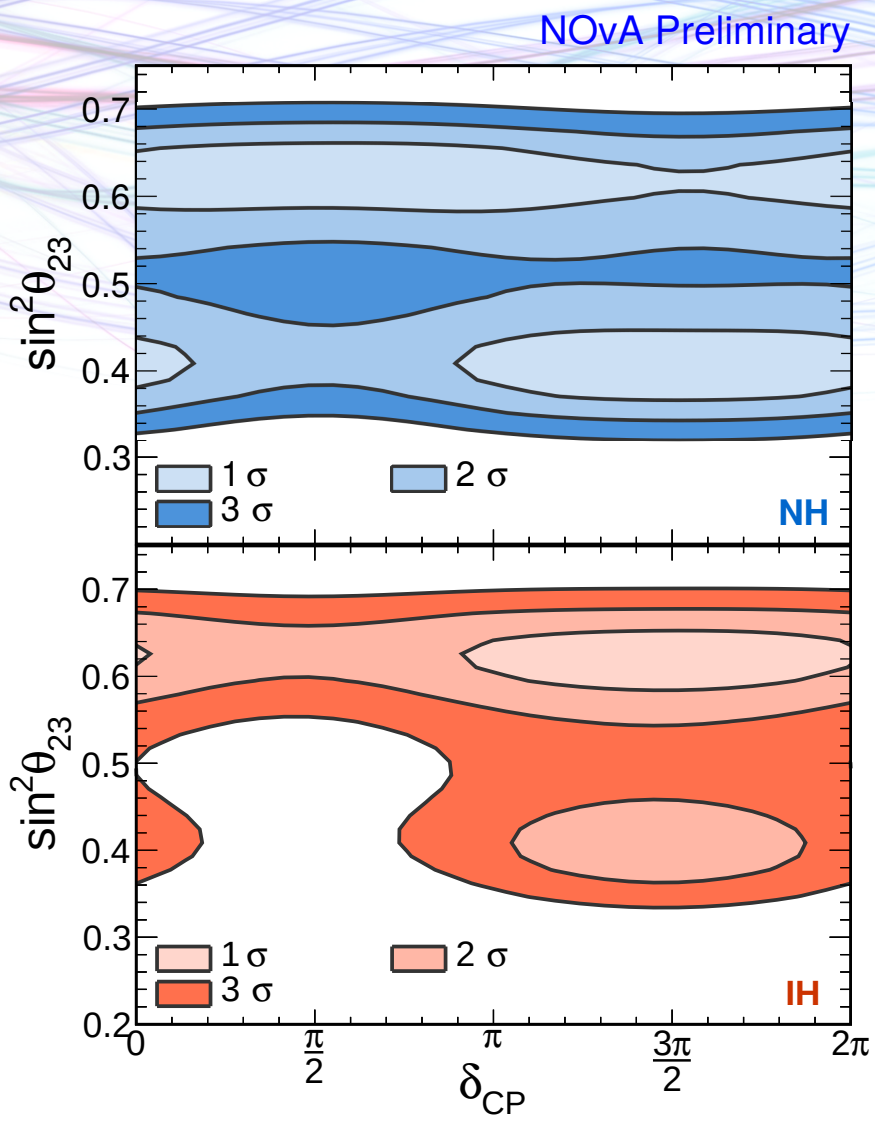
ν_e fit results

- Constrain θ_{13} to reactor average $\sin^2 2\theta_{13} = 0.085 \pm 0.005$



ν_e fit results

- Constrain θ_{13} to reactor average $\sin^2 2\theta_{13} = 0.085 \pm 0.005$
- Add $\Delta m^2_{32}/\theta_{23}$ results from ν_μ analysis
- Not a full joint fit. No syst./osc. param correlations. No FC.



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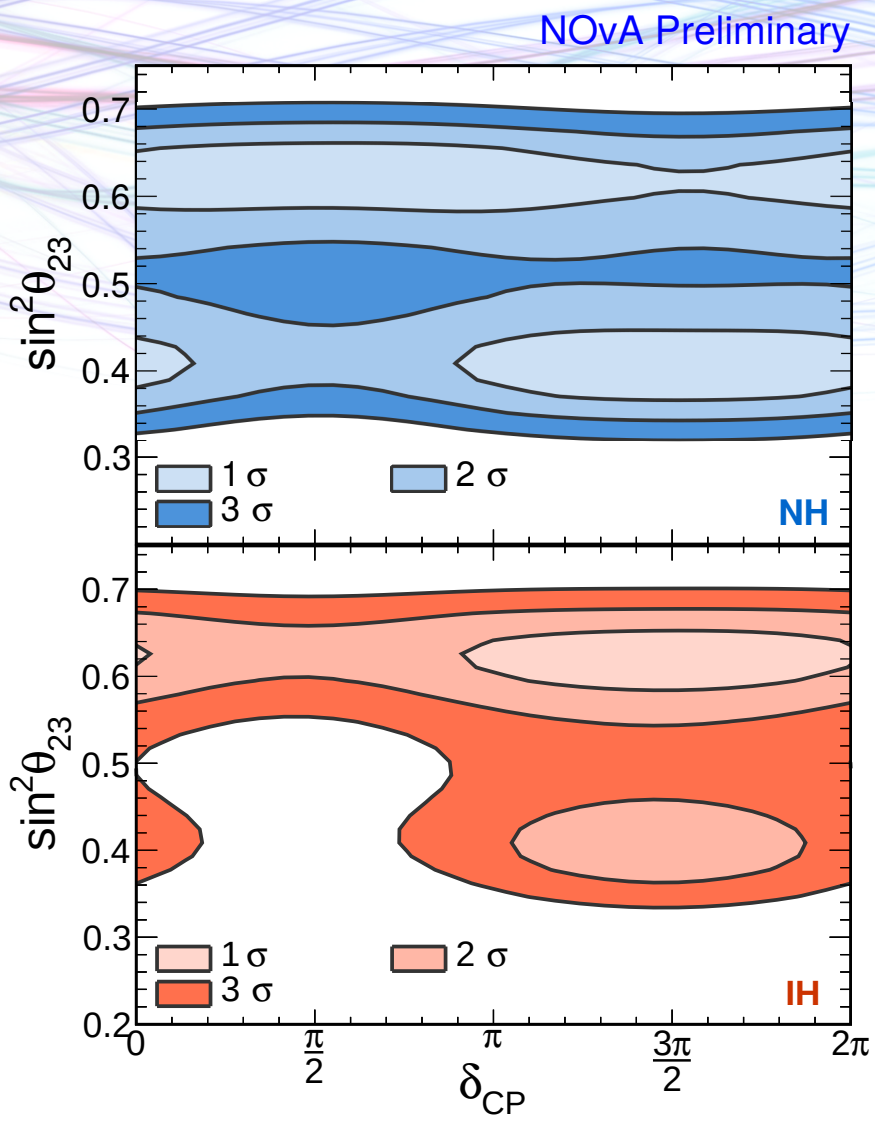
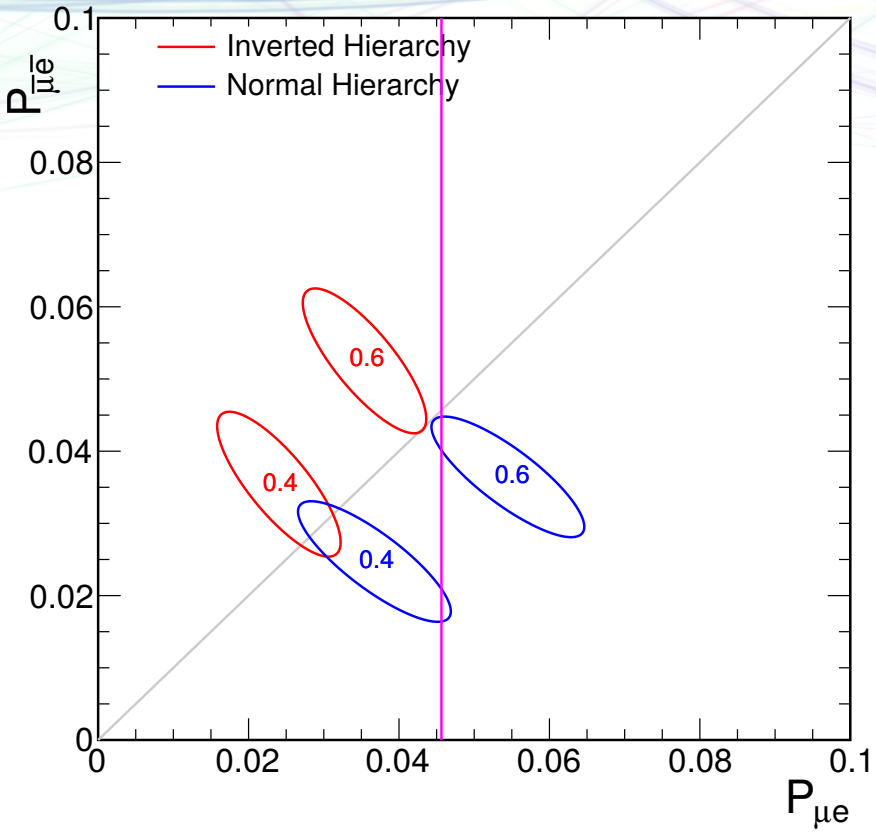
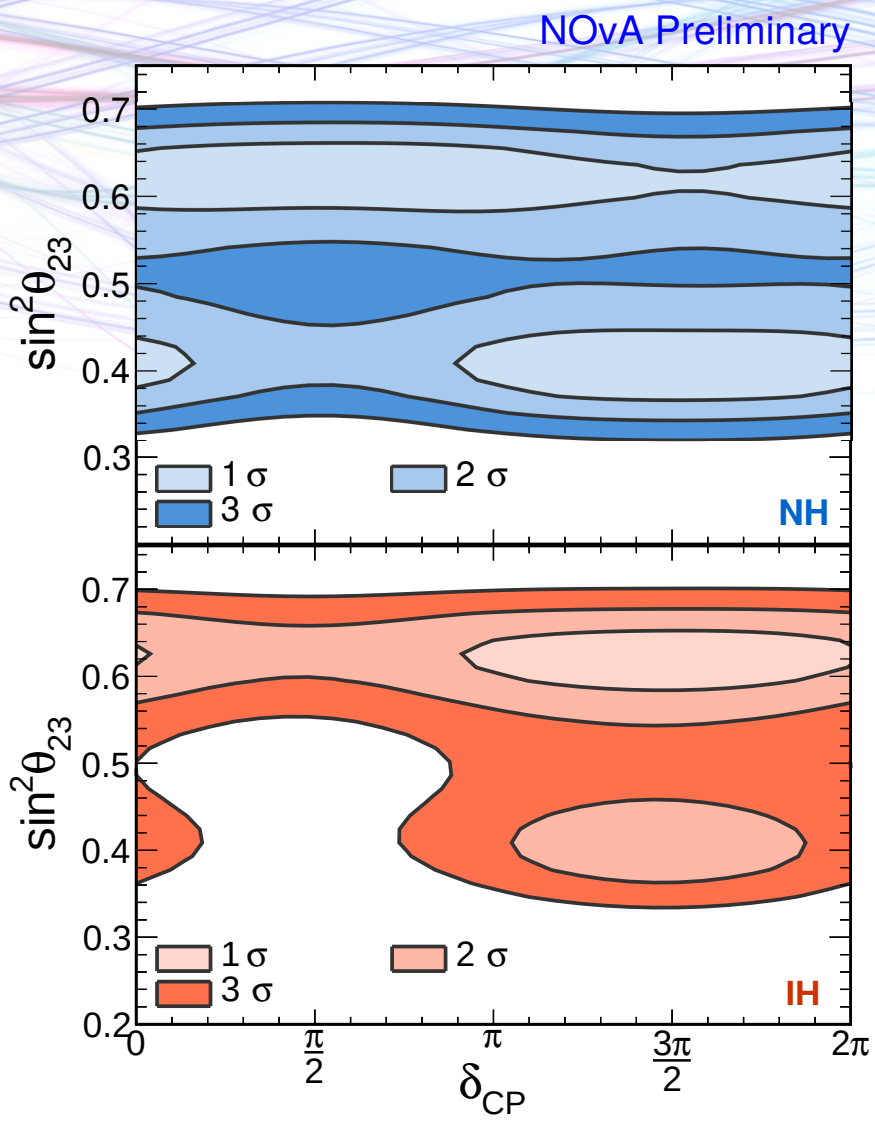
- Not a full joint fit. No syst./osc. param correlations. No FC.

- Prefer NH, not statistically significant $\Delta\chi^2 = 0.46$
- Exclude region in IH, lower octant, around $\delta_{CP} = \pi/2$ at 3σ

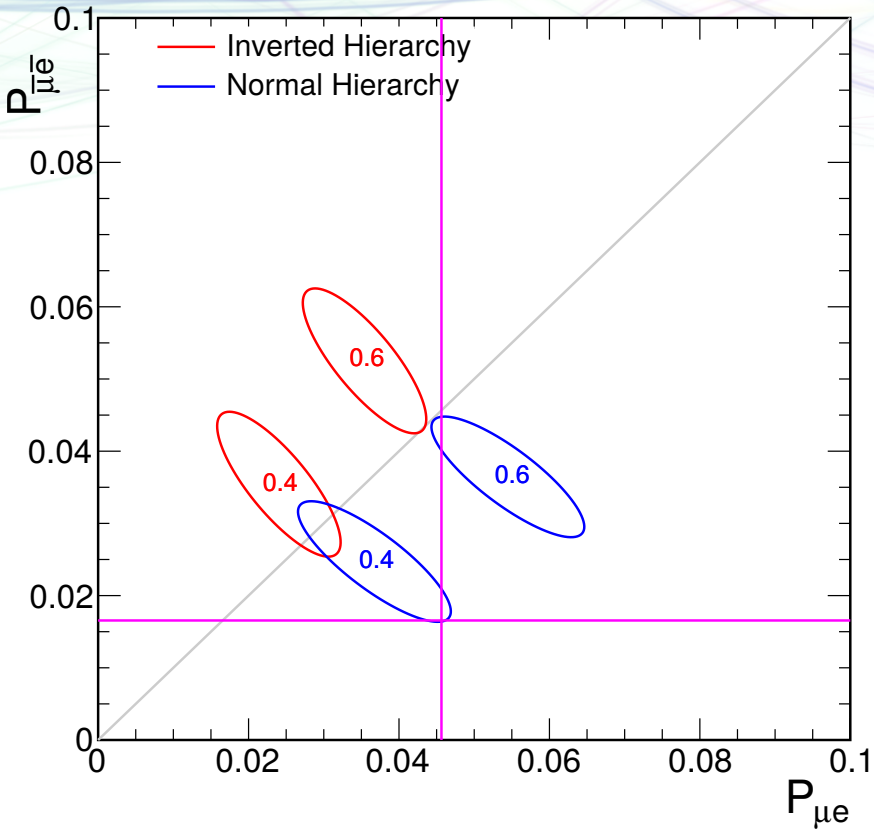


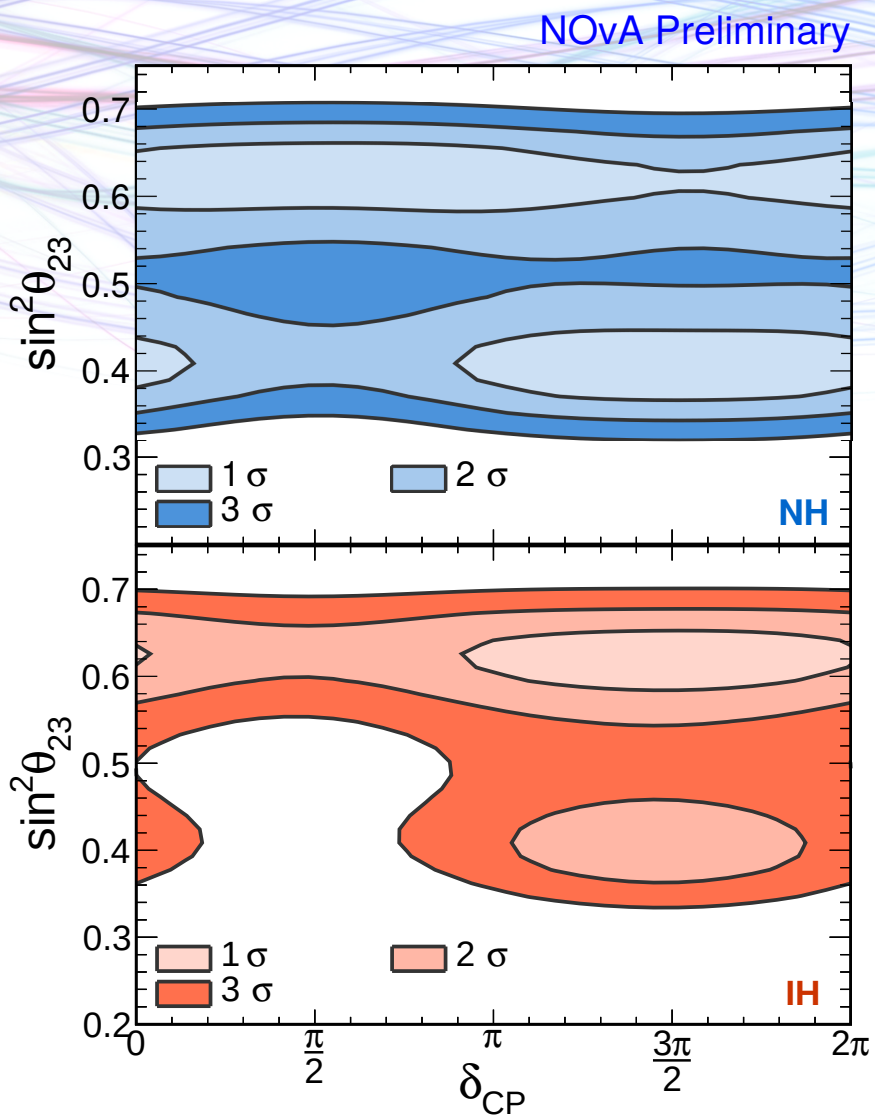
ν_e fit results





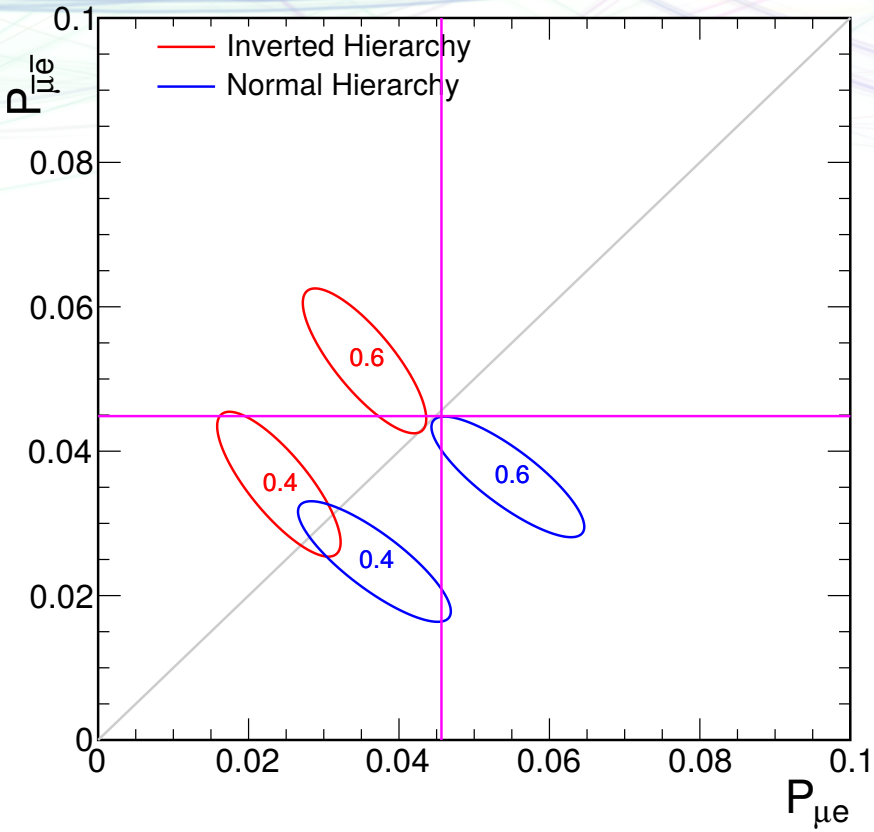
ν_e fit results

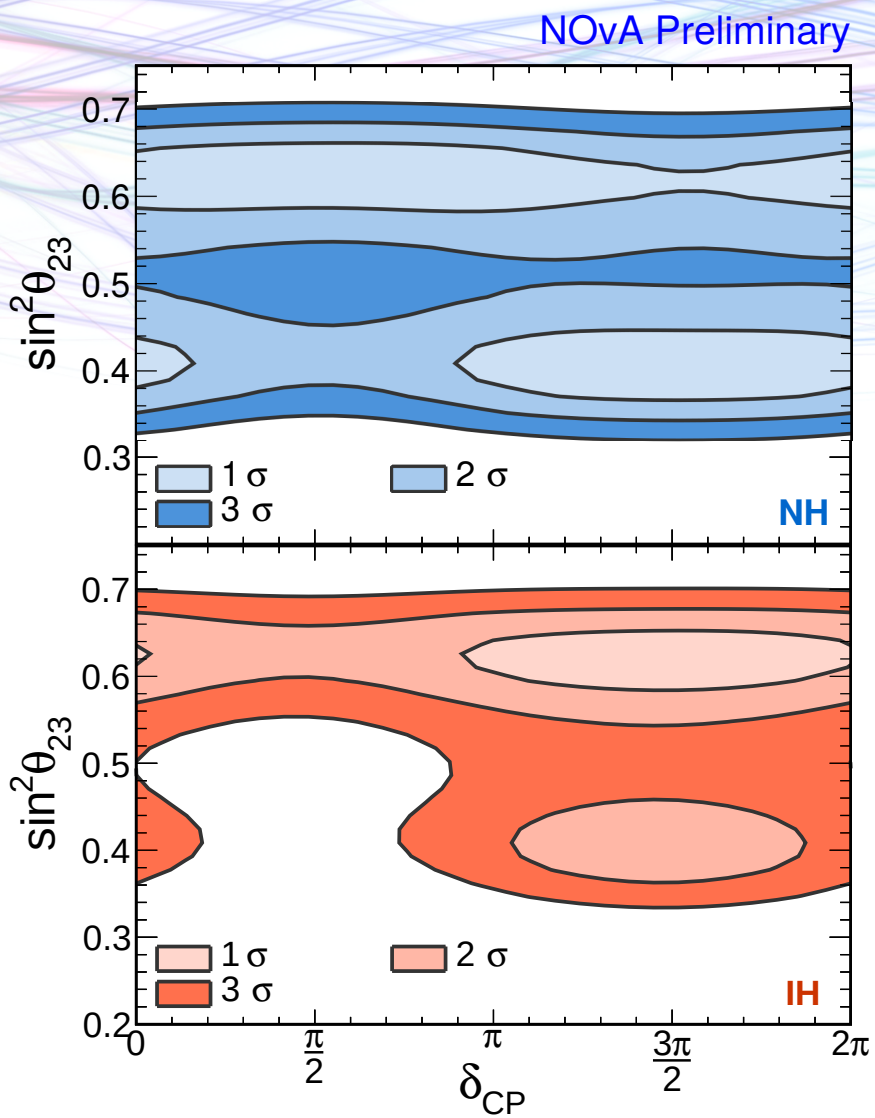




- Antineutrino data will help to resolve degeneracies
- $> 2\times$ difference in $\bar{\nu}_e$ rate between solutions

ν_e fit results





- Antineutrino data will help to resolve degeneracies
- $> 2\times$ difference in $\bar{\nu}_e$ rate between solutions

Conclusion

- Muon neutrinos disappear (for sure)
- But not quite maximally (2.5σ)

- Electron neutrinos appear ($> 8\sigma$)
- Rate towards upper end of expected range
- Slight preference for NH, octant degenerate
- IH/lower/$\frac{\pi}{2}$ ruled out ($> 3\sigma$)

- Will run antineutrinos in Spring 2017

- Thanks to everyone at Fermilab who contributed to NOvA's success!

www-nova.fnal.gov

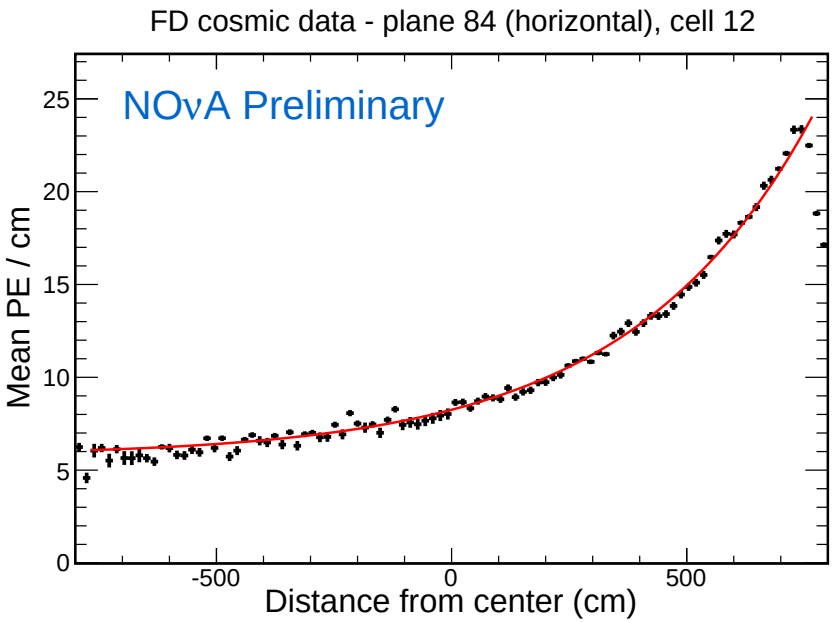
Thank you!

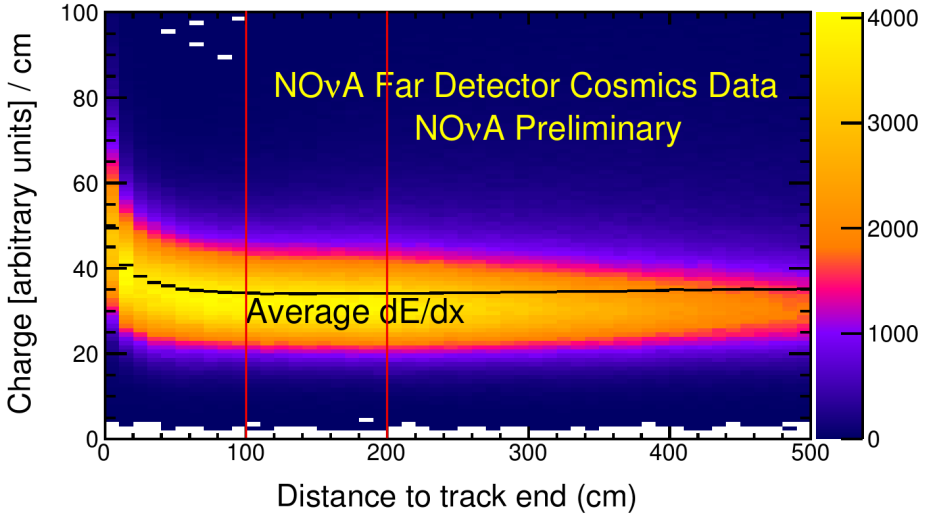
Questions?

Calibration and energy scale

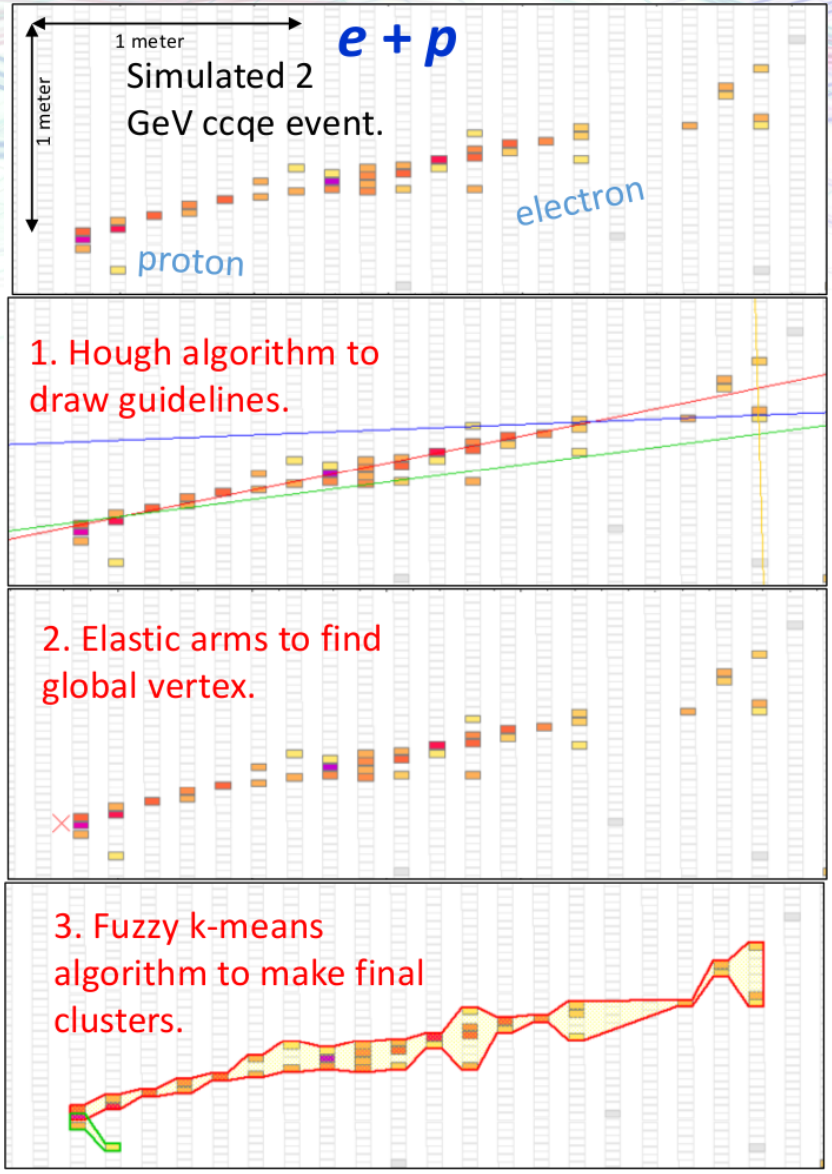
- Detector response varies substantially over length of cell due to attenuation in fiber
- Use cosmic ray muons as a standard candle
- Calibrate every channel (344,064) individually

- Use dE/dx near the end of stopping muons to set absolute scale



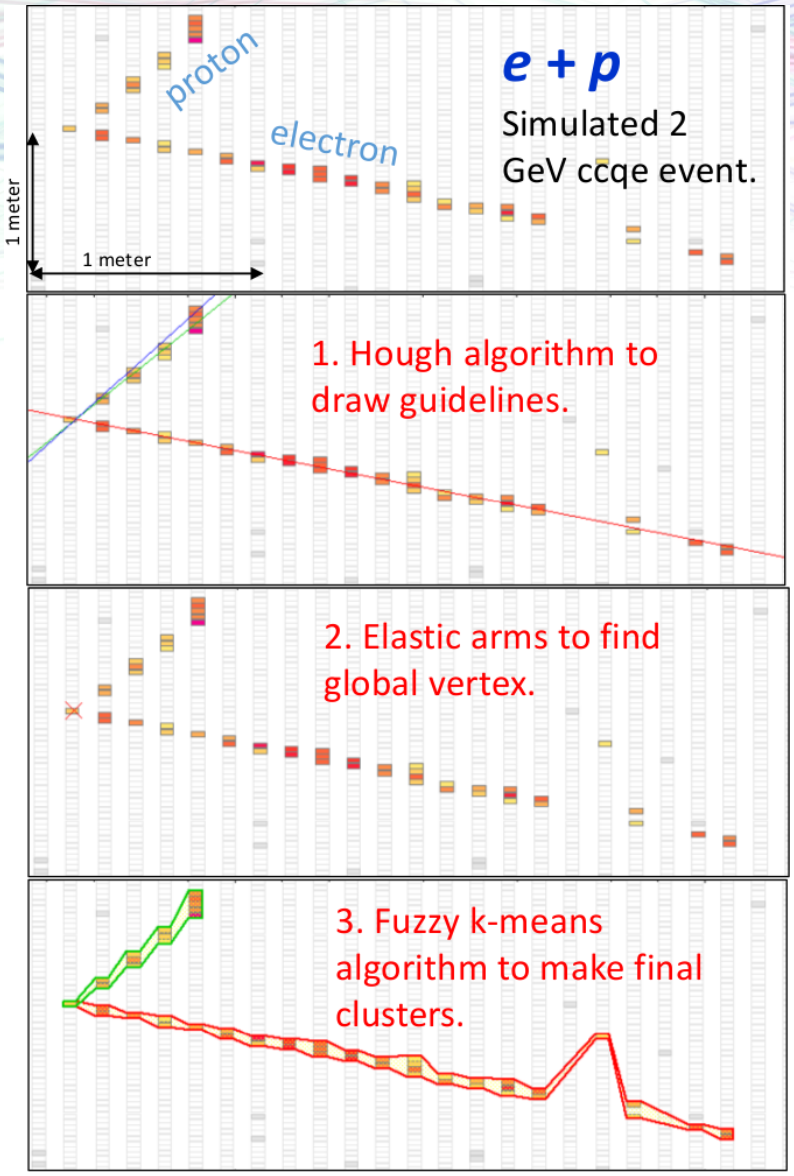


Event reconstruction



- 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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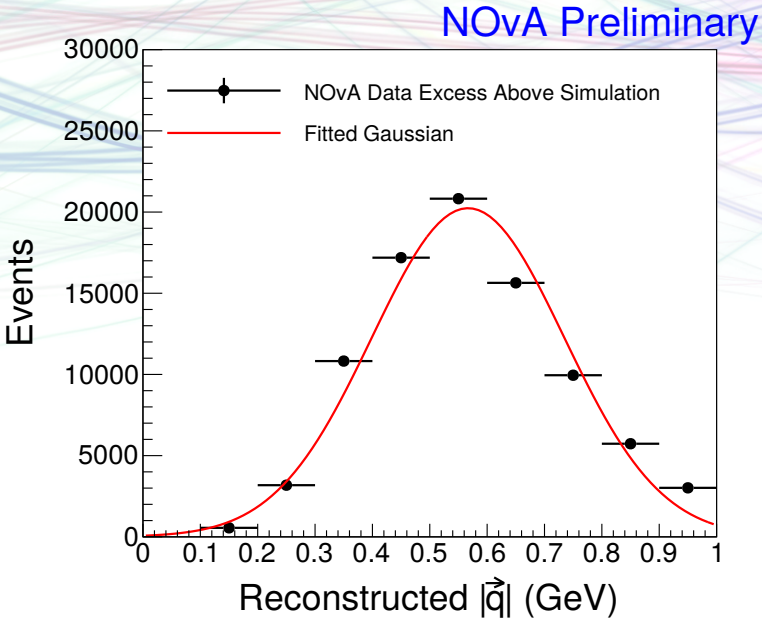
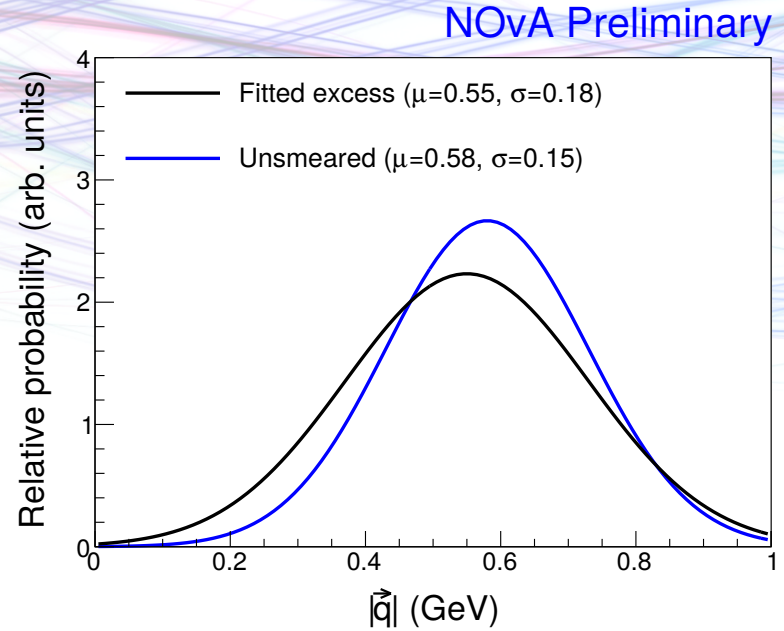
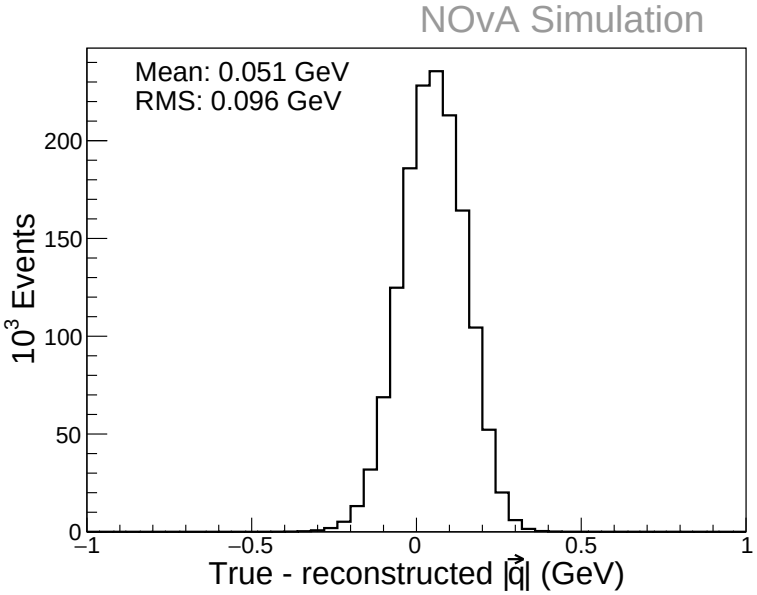
MEC details

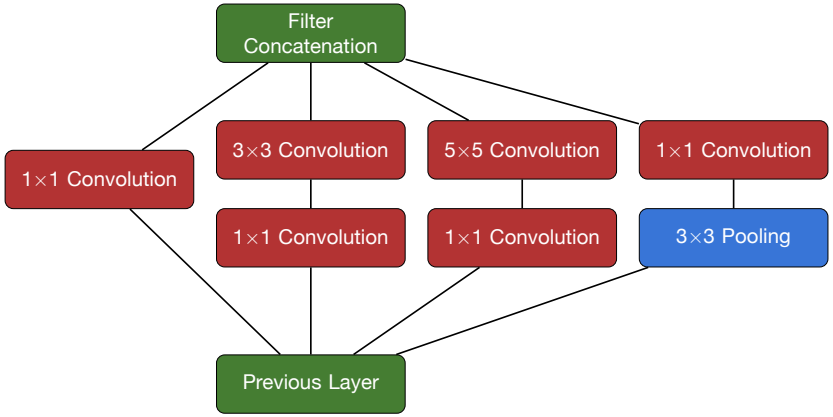




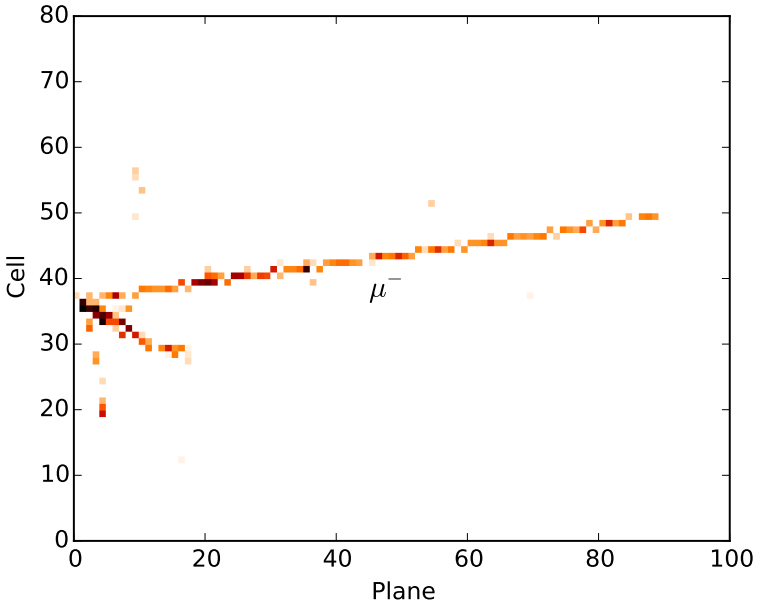


- Match q^0 distribution to GENIE's QE distribution
- Take RPA (nuclear charge screening) on/off as a systematic

CVN architecture



CVN example



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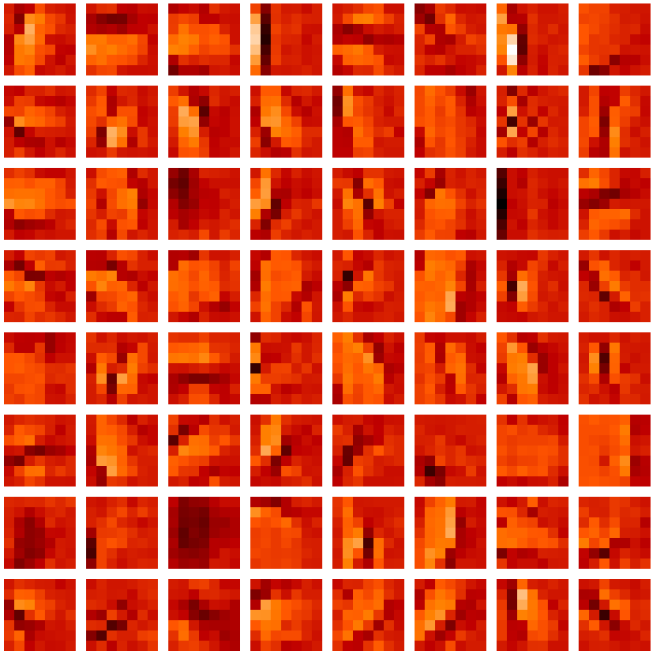

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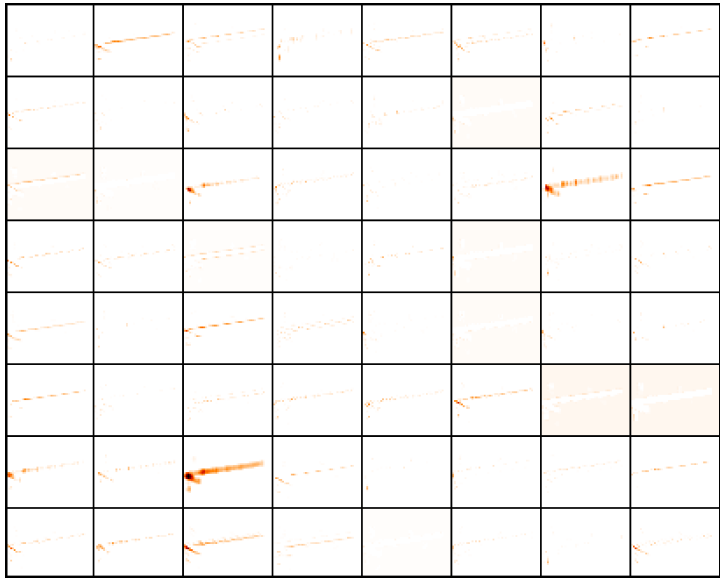
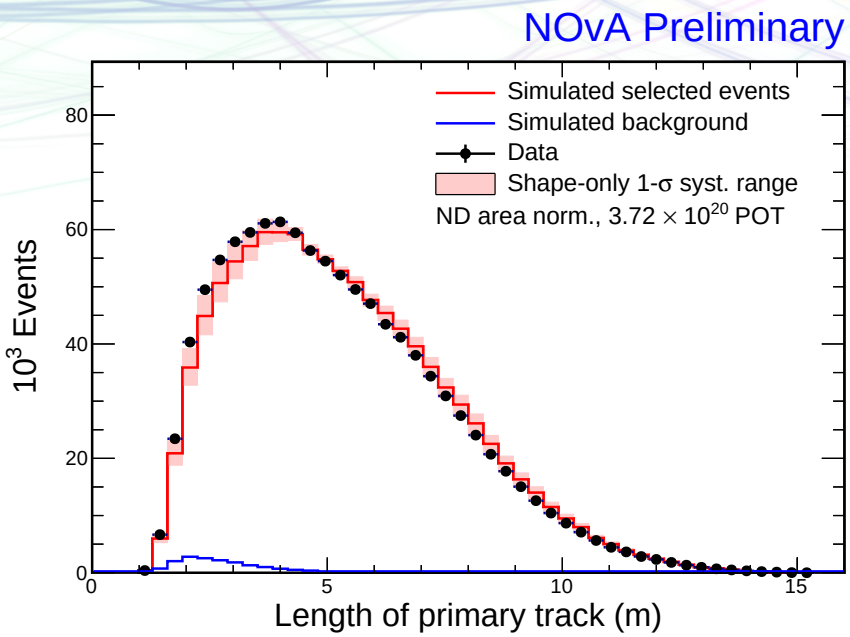
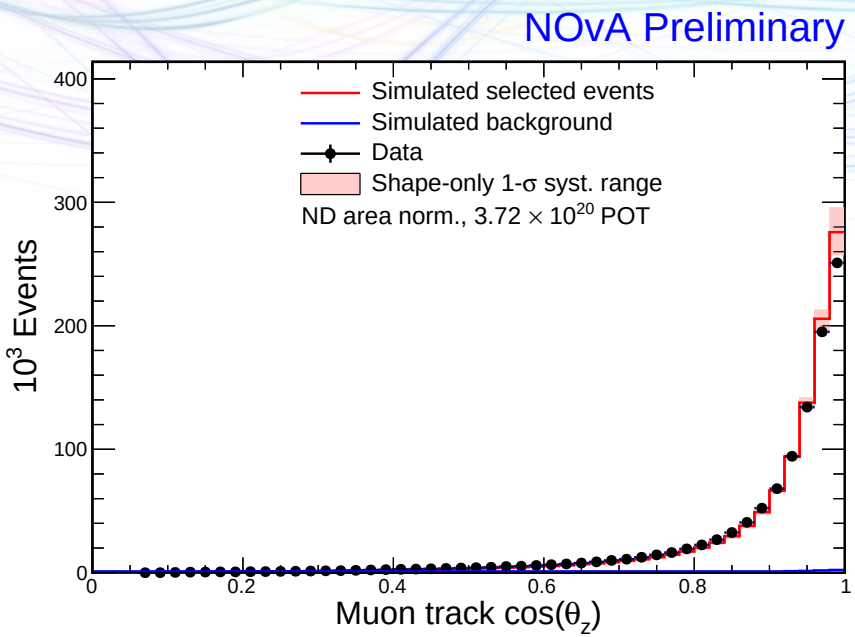
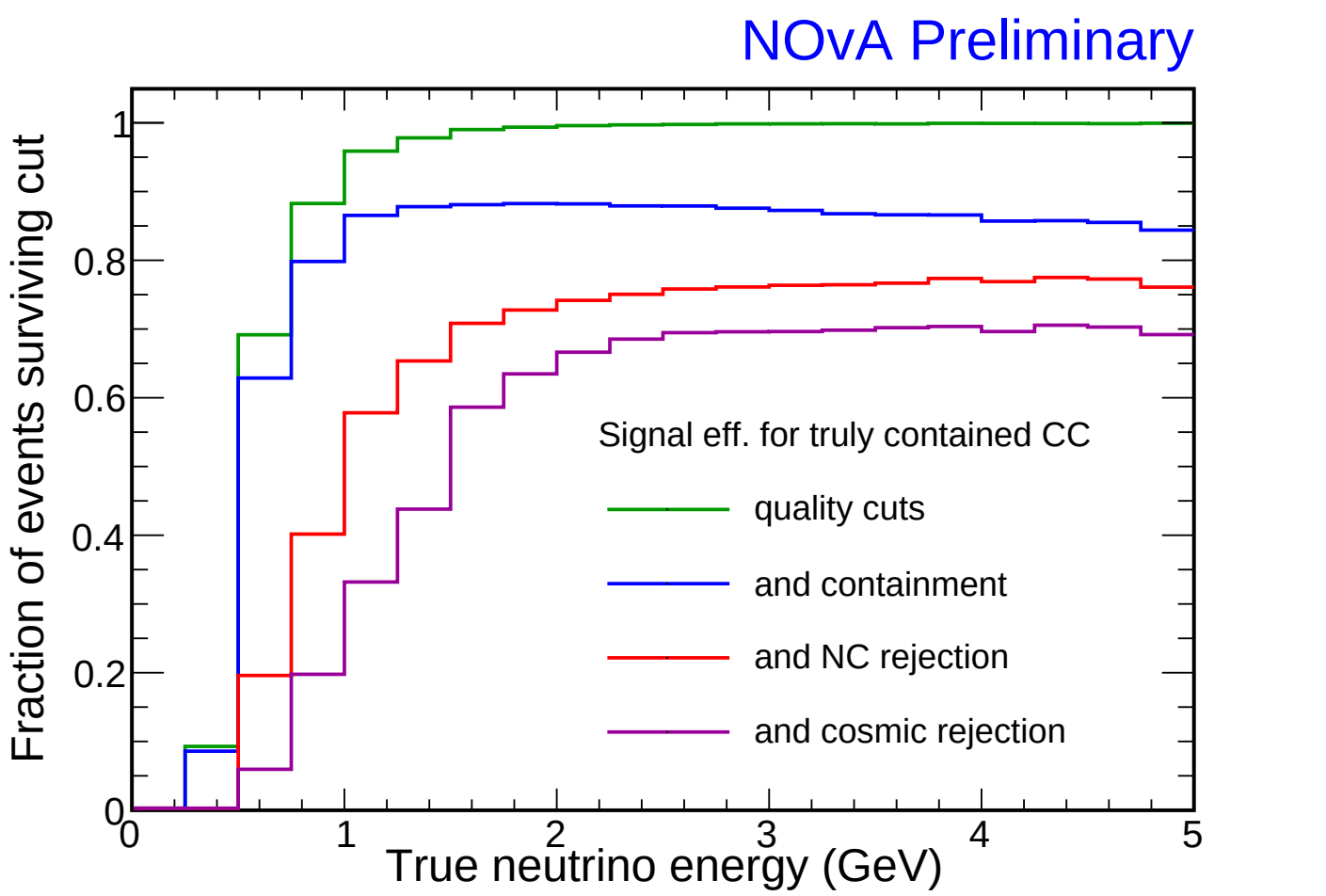


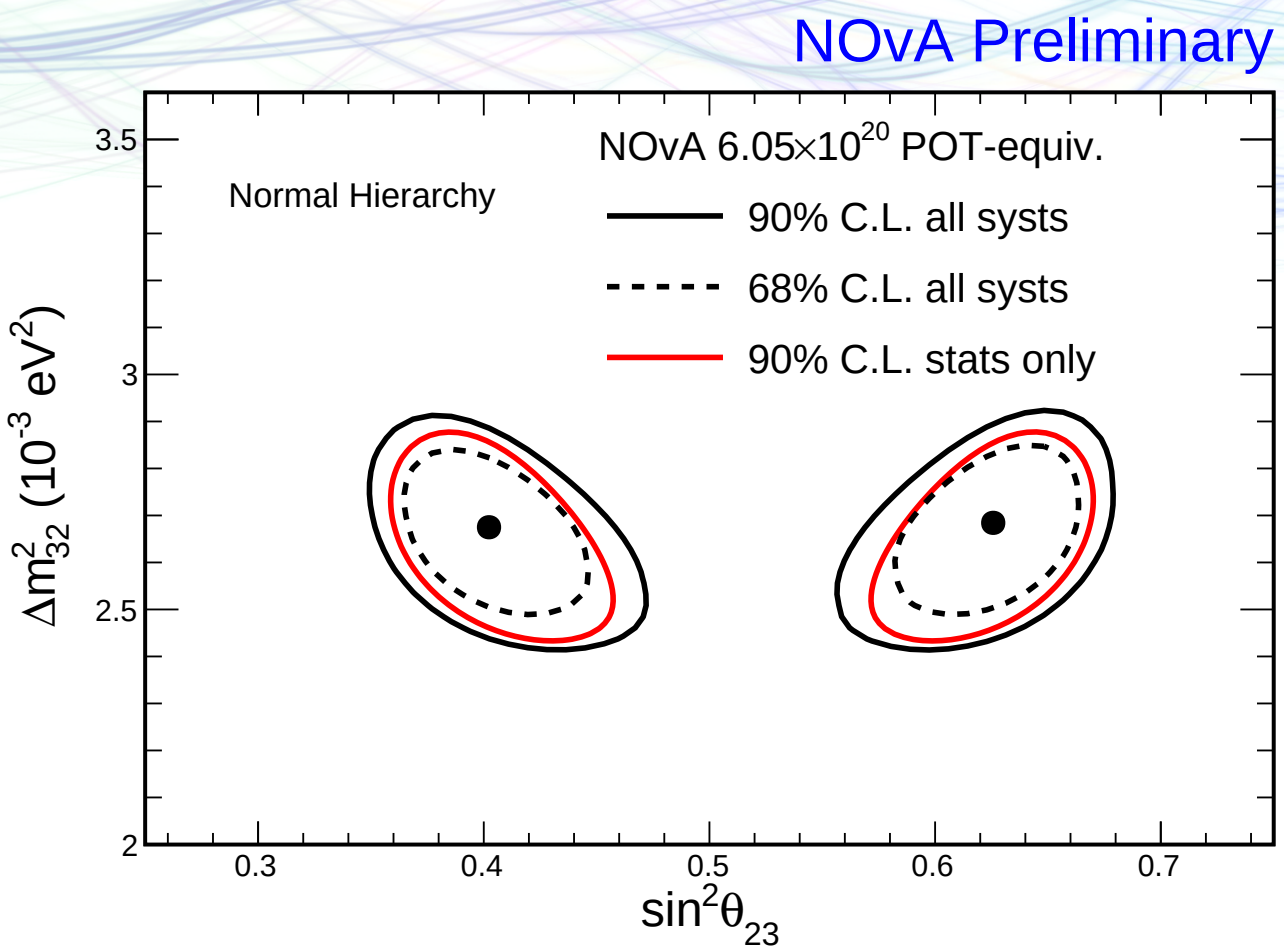

NOvA Preliminary
Simulated selected events
Simulated background
Data
Shape-only 1-σ syst. range
ND area norm., 3.72 × 10^20 POT
10^3 Events
Length of primary track (m)
0
20
40
60
80
0
5
10
15


NOvA Preliminary
Simulated selected events
Simulated background
Data
Shape-only 1-σ syst. range
ND area norm., 3.72 × 10^20 POT
10^3 Events
Muon track cos(θ_z)
0
100
200
300
400
0
0.2
0.4
0.6
0.8
1

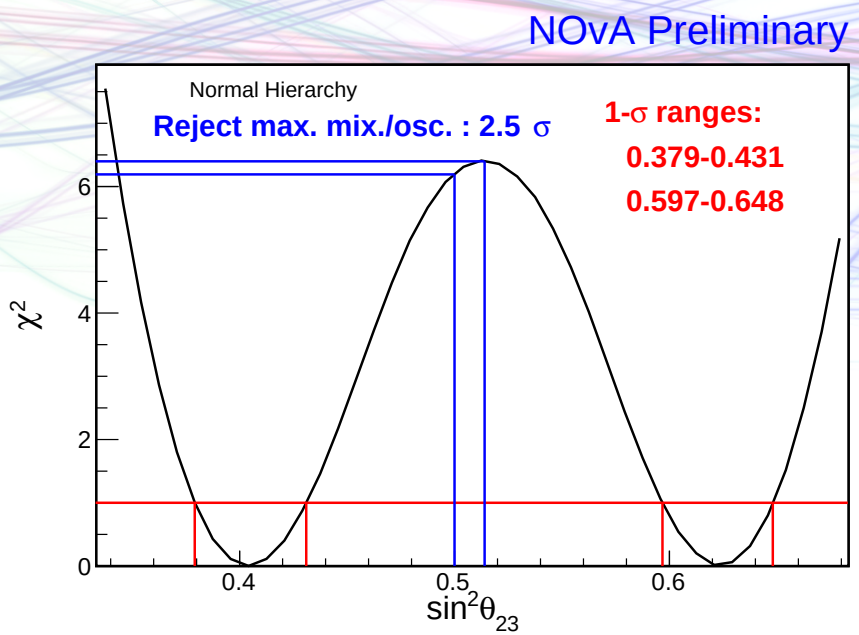
ν_μ selection efficiency

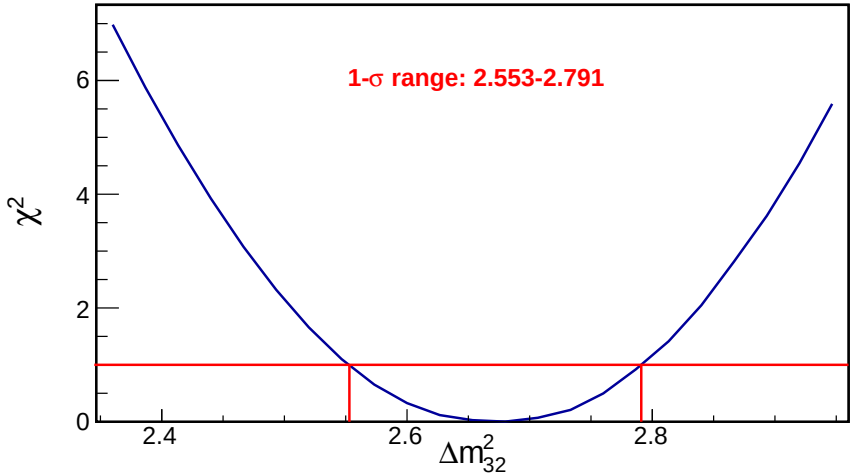


ν_μ impact of systematics

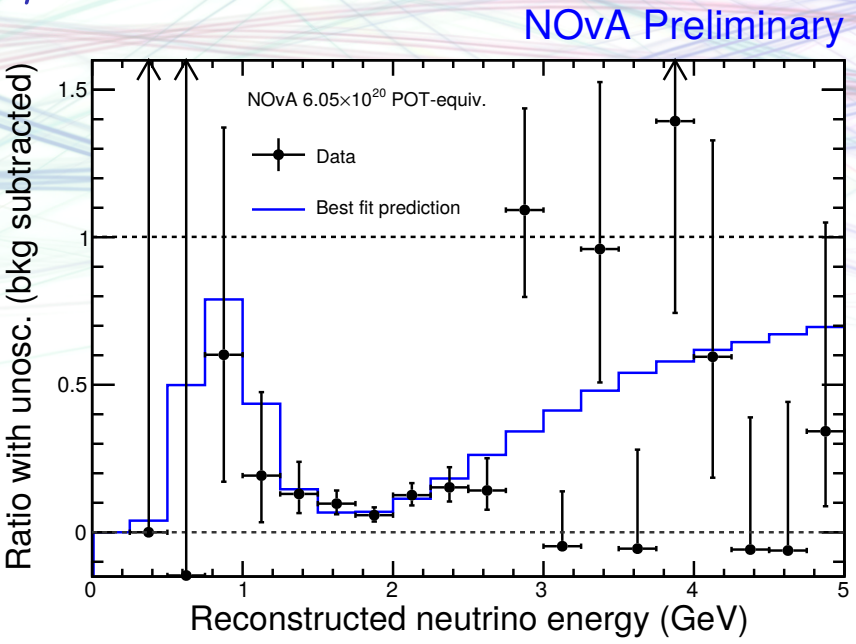


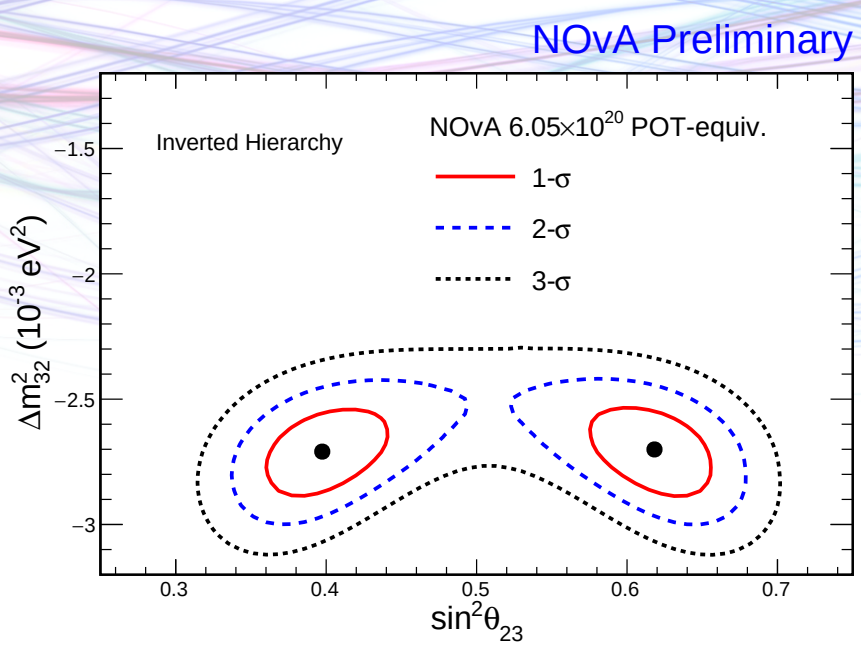
ν_μ 1D profiles





ν_μ disappearance results – IH

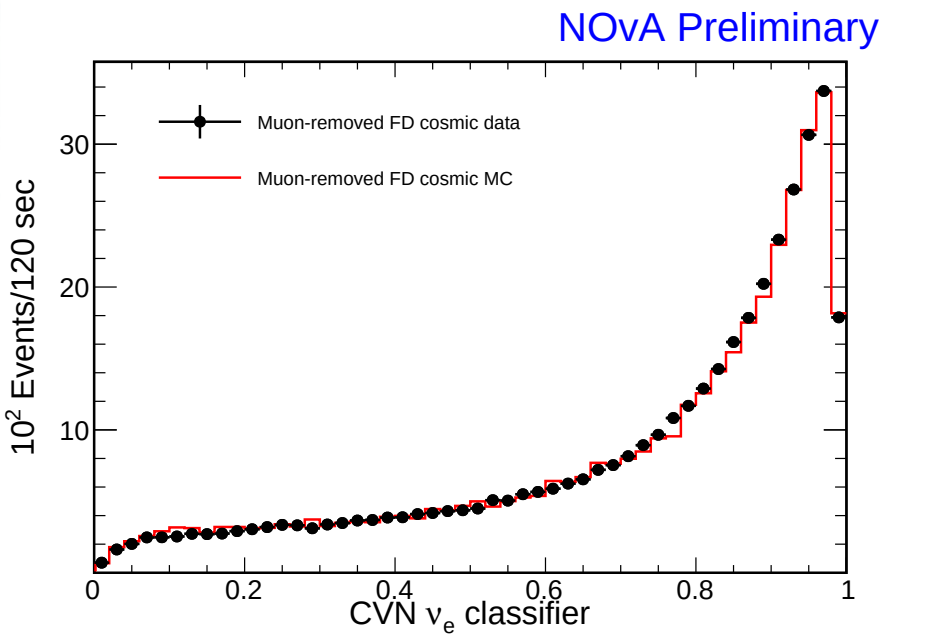




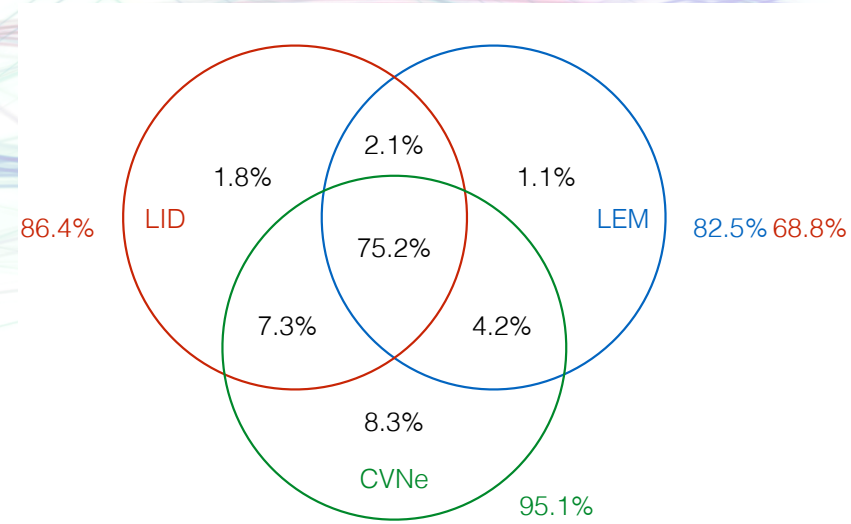
- Expect 473 FD ν_μ CC events with no oscillation
- Observe 82 (inc. 3.7 beam bkg. and 2.9 cosmic)

$$\Delta m^2_{32} = -2.71 \pm 0.12 \times 10^{-3}\text{eV}^2 \text{ (NH)}$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}\ (0.62^{+0.02}_{-0.03})$$

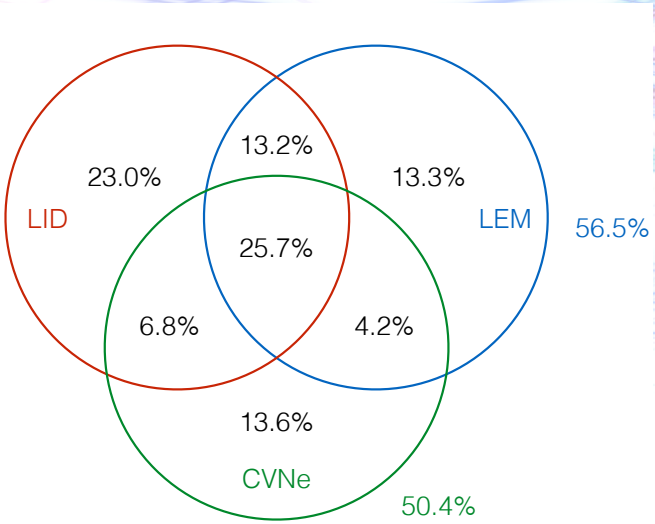
- Maximal mixing excluded at 2.5σ (FC corrections in progress)


NOvA Preliminary
Muon-removed FD cosmic data
Muon-removed FD cosmic MC
10^2 Events/120 sec
30
20
10
0
0.2
0.4
0.6
0.8
1
CVN ν_e classifier

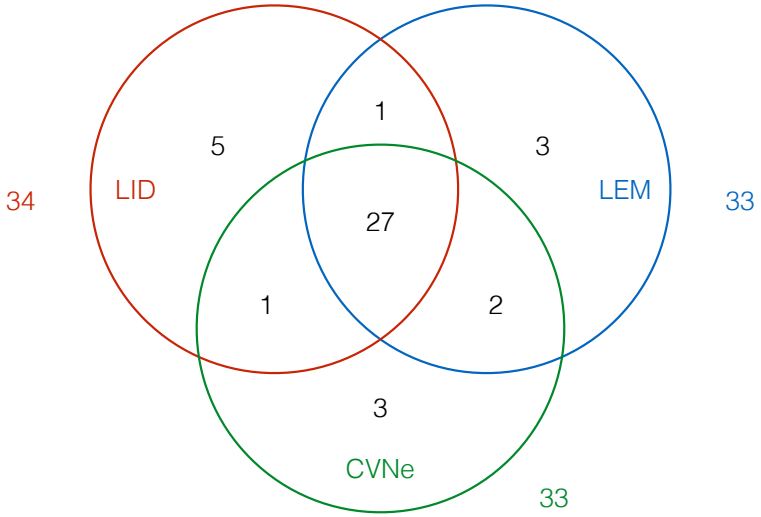
Signal MC



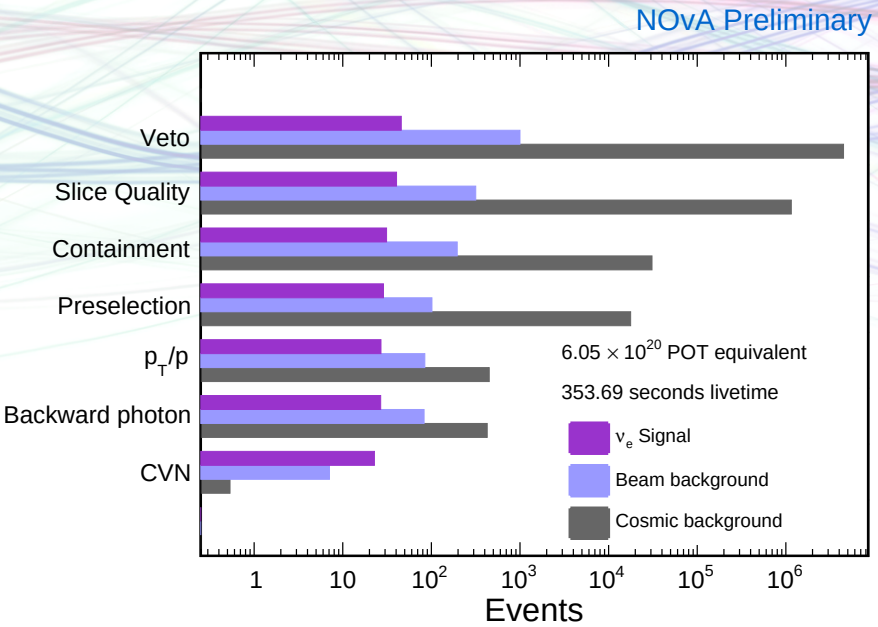
Background MC

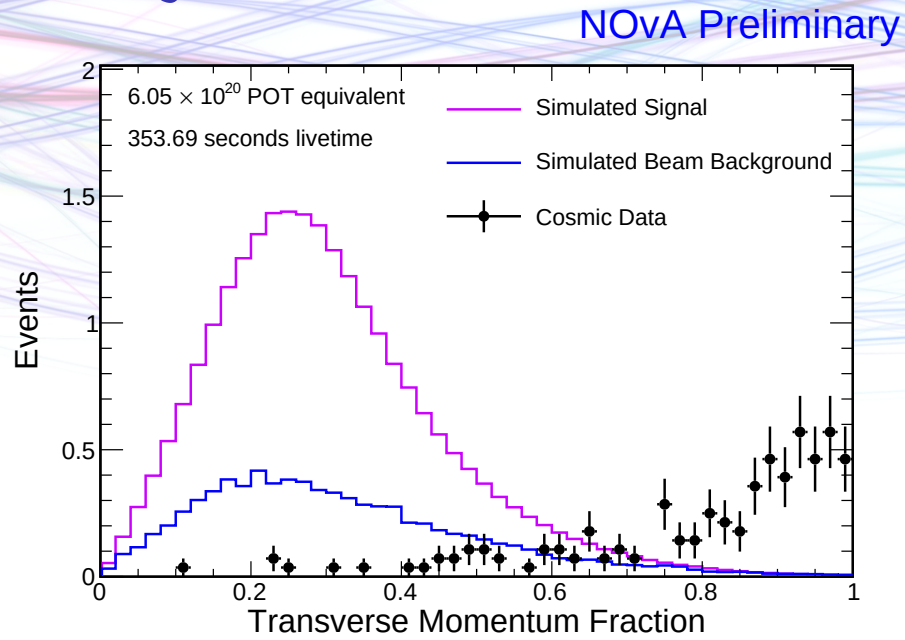


Data



ν_e extrapolation and FD cosmic rejection

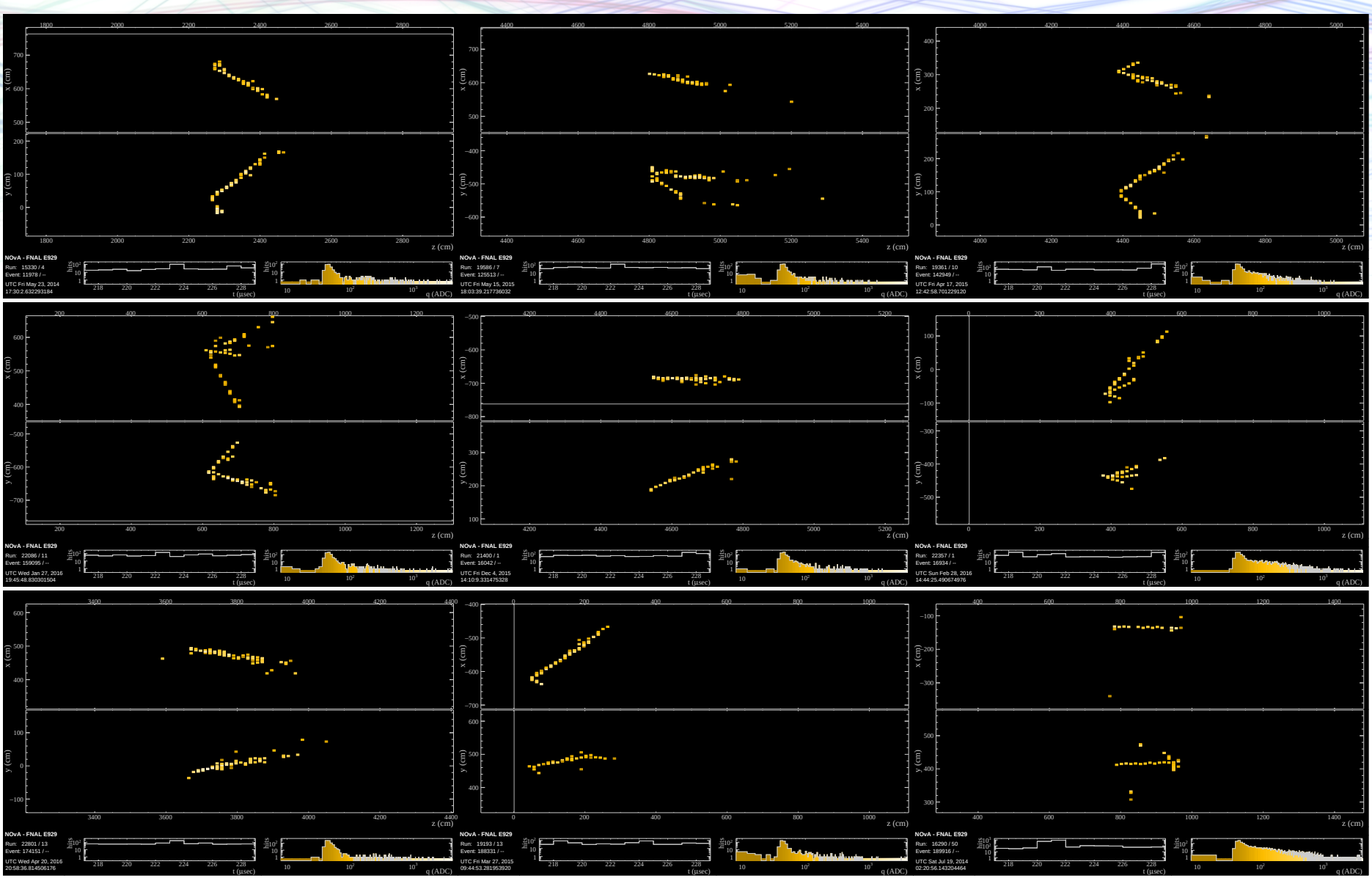




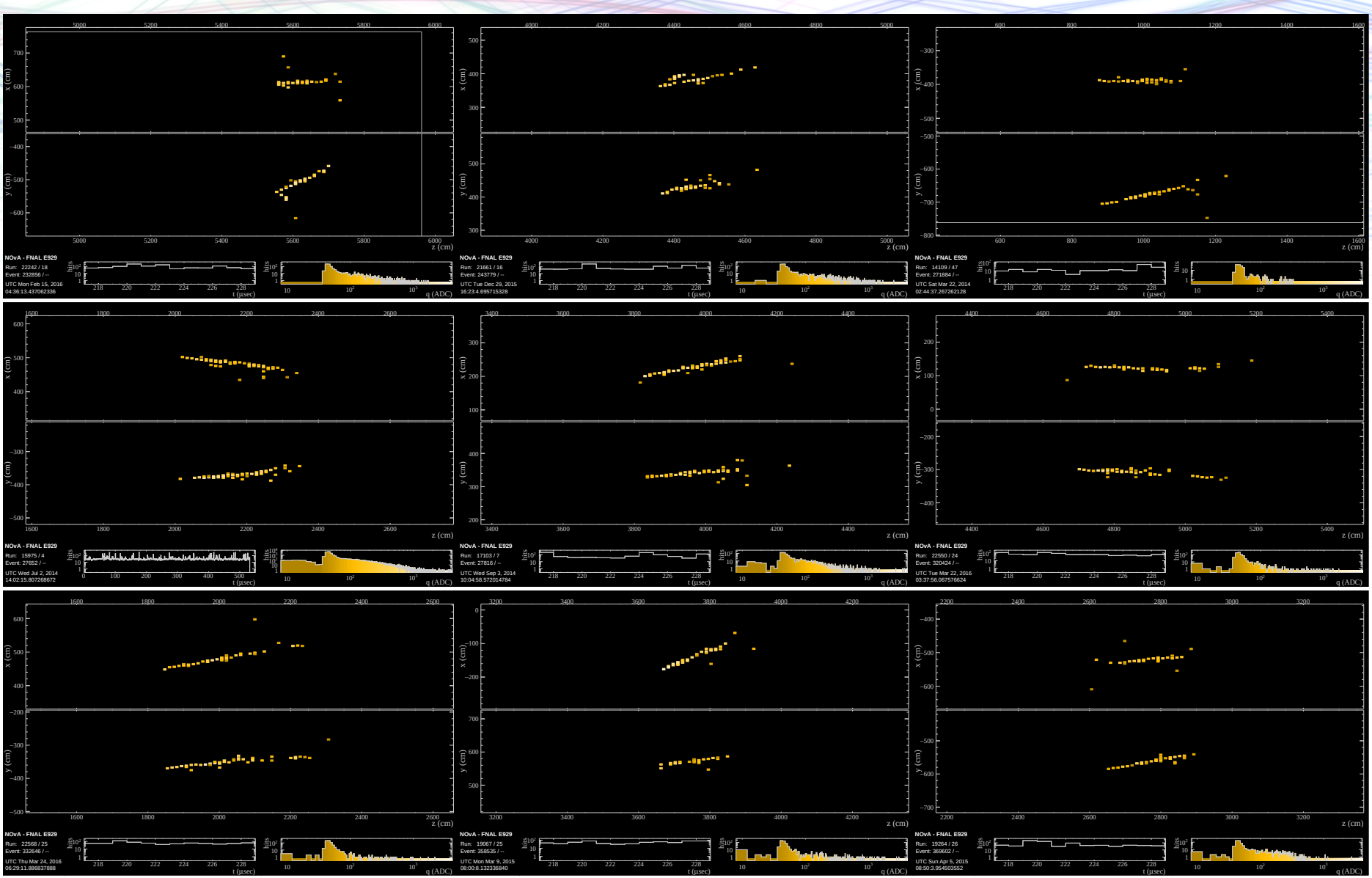
- After decomposition, background components extrapolated by F/N
- Signal comes from oscillated ND ν_μ, extrapolate ν_μ spectrum

- Require containment of candidate electron shower
- Transverse momentum fraction: $p_T/p < 0.65$
- CVN also removes a lot of background
- Final cosmic-ray bkg. from timing sideband: 0.5 events

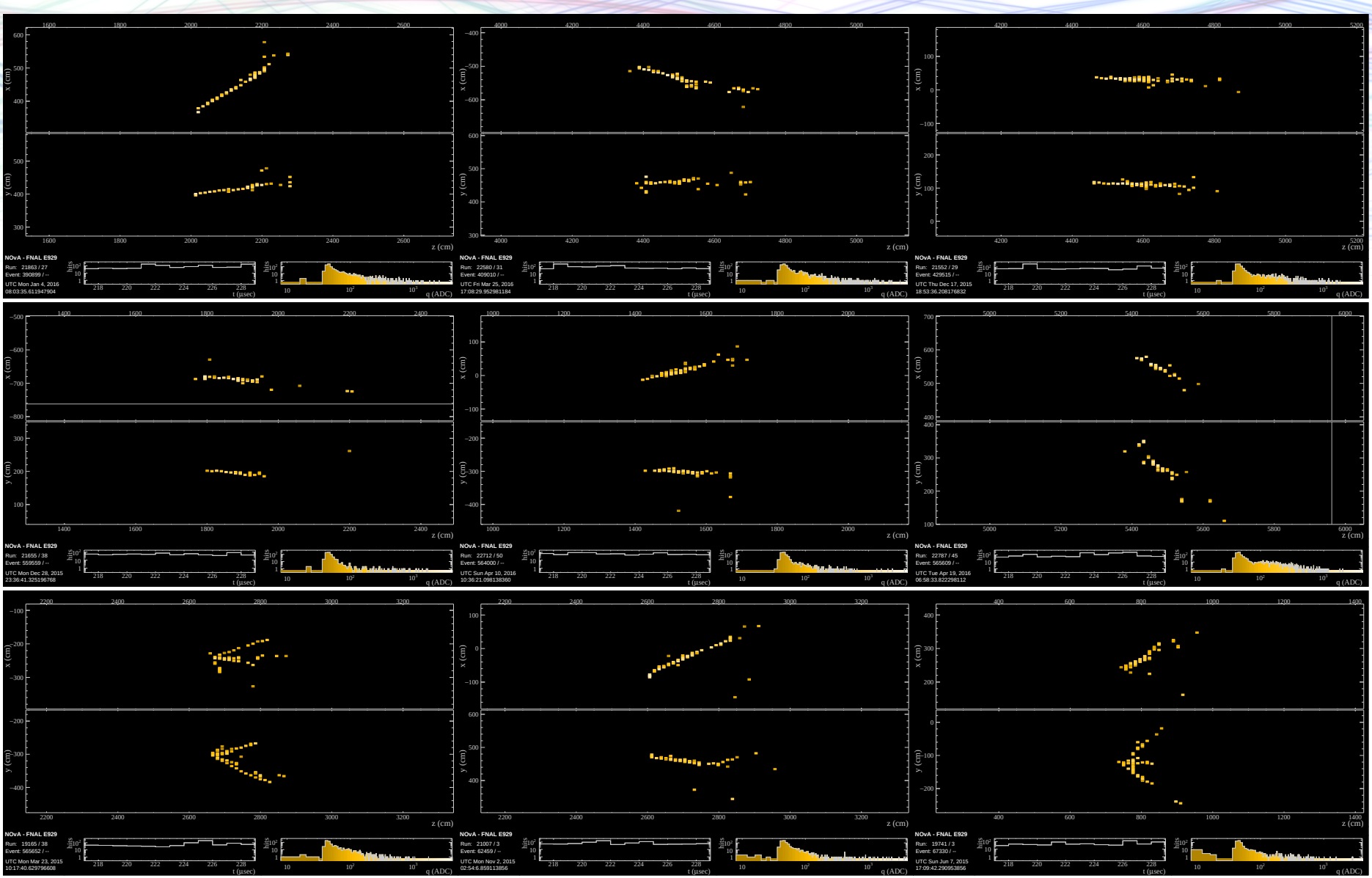
ν_e evds


NOvA - FNAL E929
Run: 15330 / 4
Event: 11978 / --
UTC Fri May 23, 2014
17:30:2.632293184
NOvA - FNAL E929
Run: 19586 / 7
Event: 125513 / --
UTC Fri May 15, 2015
18:03:39.217736032
NOvA - FNAL E929
Run: 19361 / 10
Event: 142949 / --
UTC Fri Apr 17, 2015
12:42:58.701229120
NOvA - FNAL E929
Run: 22086 / 11
Event: 159095 / --
UTC Wed Jan 27, 2016
19:45:48.830301504
NOvA - FNAL E929
Run: 21400 / 1
Event: 16042 / --
UTC Fri Dec 4, 2015
14:10:9.331475328
NOvA - FNAL E929
Run: 22357 / 1
Event: 16934 / --
UTC Sun Feb 28, 2016
14:44:25.490674976
NOvA - FNAL E929
Run: 22801 / 13
Event: 174151 / --
UTC Wed Apr 20, 2016
20:58:36.814506176
NOvA - FNAL E929
Run: 19193 / 13
Event: 188331 / --
UTC Fri Mar 27, 2015
09:44:53.281953920
NOvA - FNAL E929
Run: 16290 / 50
Event: 189916 / --
UTC Sat Jul 19, 2014
02:20:56.143204464
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

ν_e evds


NOvA - FNAL E929
Run: 22242 / 18
Event: 232856 / --
UTC Mon Feb 15, 2016
04:36:13.437062336
NOvA - FNAL E929
Run: 21661 / 16
Event: 243779 / --
UTC Tue Dec 29, 2015
16:23:4.695715328
NOvA - FNAL E929
Run: 14109 / 47
Event: 271884 / --
UTC Sat Mar 22, 2014
02:44:37.267262128
NOvA - FNAL E929
Run: 15975 / 4
Event: 27652 / --
UTC Wed Jul 2, 2014
14:02:15.807268672
NOvA - FNAL E929
Run: 17103 / 7
Event: 27816 / --
UTC Wed Sep 3, 2014
10:04:58.572014784
NOvA - FNAL E929
Run: 22550 / 24
Event: 320424 / --
UTC Tue Mar 22, 2016
03:37:56.067576624
NOvA - FNAL E929
Run: 22568 / 25
Event: 332646 / --
UTC Thu Mar 24, 2016
06:29:11.886837888
NOvA - FNAL E929
Run: 19067 / 25
Event: 358535 / --
UTC Mon Mar 9, 2015
08:00:8.132336840
NOvA - FNAL E929
Run: 19264 / 26
Event: 369602 / --
UTC Sun Apr 5, 2015
08:50:3.954503552
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

ν_e evds


NOvA - FNAL E929
Run: 21863 / 27
Event: 390899 / --
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NOvA - FNAL E929
Run: 22580 / 31
Event: 409010 / --
UTC Fri Mar 25, 2016
17:08:29.952981184
NOvA - FNAL E929
Run: 21552 / 29
Event: 429515 / --
UTC Thu Dec 17, 2015
18:53:36.208176832
NOvA - FNAL E929
Run: 21655 / 38
Event: 559559 / --
UTC Mon Dec 28, 2015
23:36:41.325196768
NOvA - FNAL E929
Run: 22712 / 50
Event: 564000 / --
UTC Sun Apr 10, 2016
10:36:21.098138360
NOvA - FNAL E929
Run: 22787 / 45
Event: 565609 / --
UTC Tue Apr 19, 2016
06:58:33.822298112
NOvA - FNAL E929
Run: 19165 / 38
Event: 565652 / --
UTC Mon Mar 23, 2015
10:17:40.629796608
NOvA - FNAL E929
Run: 21007 / 3
Event: 62459 / --
UTC Mon Nov 2, 2015
02:54:6.859113856
NOvA - FNAL E929
Run: 19741 / 3
Event: 67330 / --
UTC Sun Jun 7, 2015
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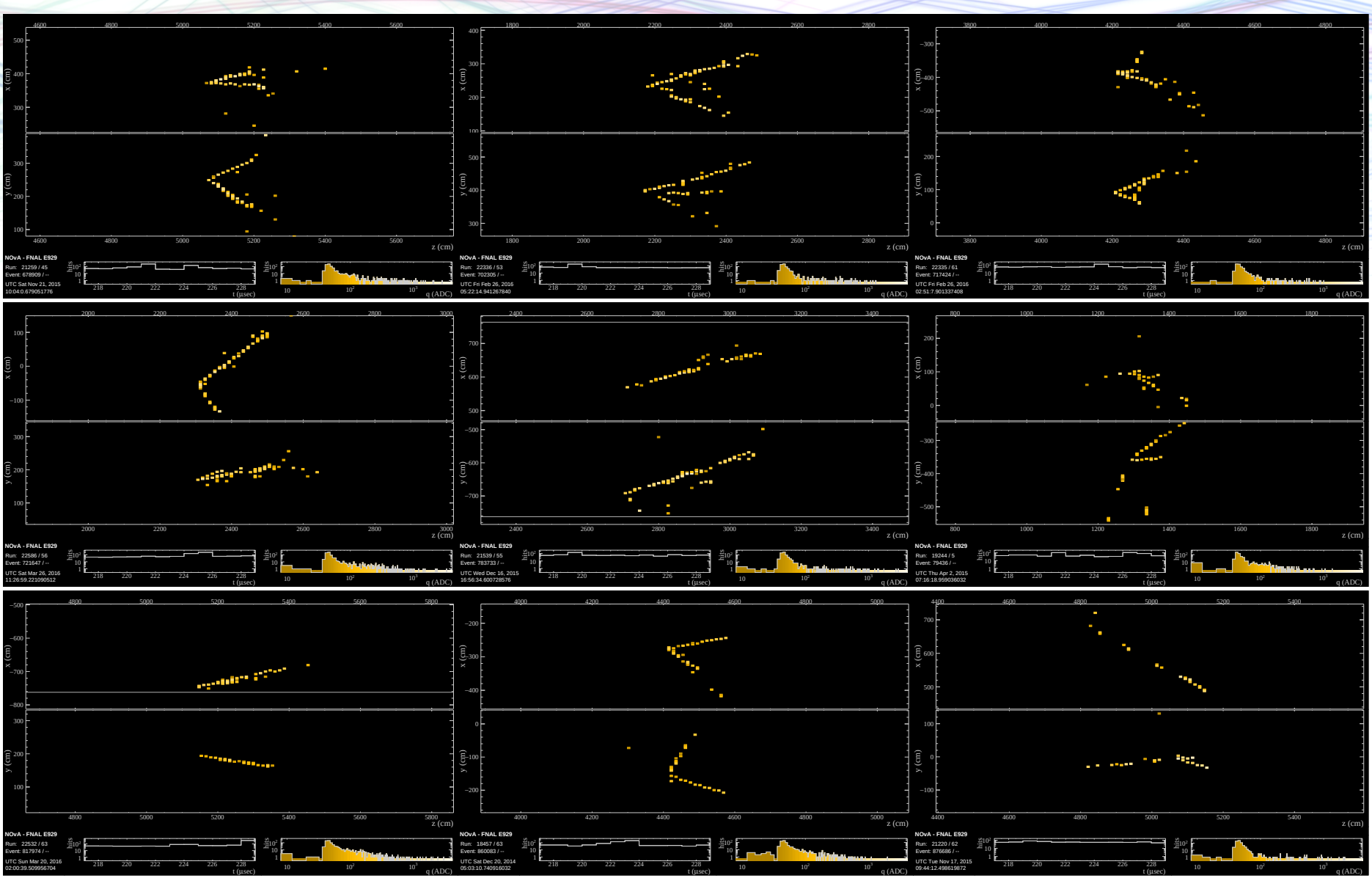
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

ν_e evds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Run: 21259 / 45
Event: 678909 / --
UTC Sat Nov 21, 2015
10:04:0.679051776
NOvA - FNAL E929
Run: 22336 / 53
Event: 702305 / --
UTC Fri Feb 26, 2016
05:22:14.941267840
NOvA - FNAL E929
Run: 22335 / 61
Event: 717424 / --
UTC Fri Feb 26, 2016
02:51:7.901337408
NOvA - FNAL E929
Run: 22586 / 56
Event: 721647 / --
UTC Sat Mar 26, 2016
11:26:59.221090512
NOvA - FNAL E929
Run: 21539 / 55
Event: 783733 / --
UTC Wed Dec 16, 2015
16:56:34.600728576
NOvA - FNAL E929
Run: 19244 / 5
Event: 794436 / --
UTC Thu Apr 2, 2015
07:16:18.959036032
NOvA - FNAL E929
Run: 22532 / 63
Event: 817974 / --
UTC Sun Mar 20, 2016
02:00:39.509956704
NOvA - FNAL E929
Run: 18457 / 63
Event: 860083 / --
UTC Sat Dec 20, 2014
05:03:10.740916032
NOvA - FNAL E929
Run: 21220 / 62
Event: 876686 / --
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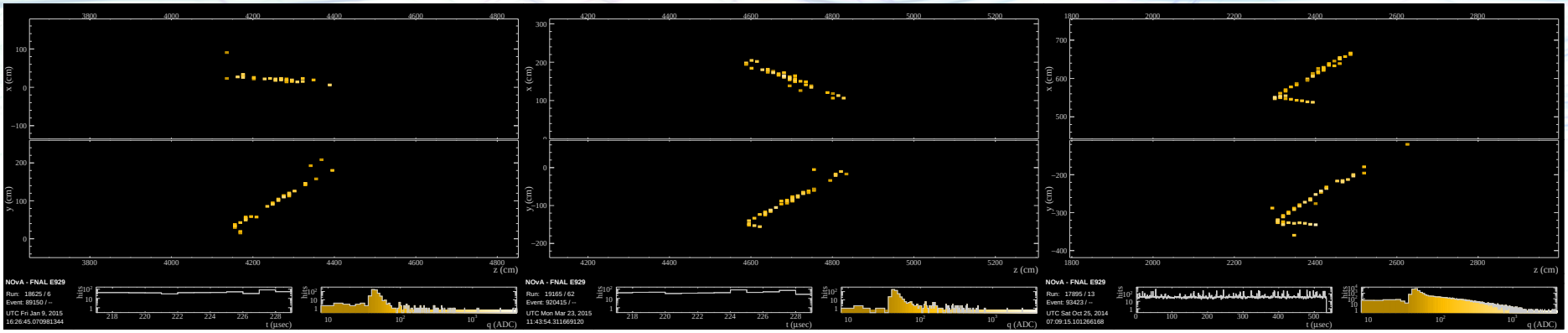
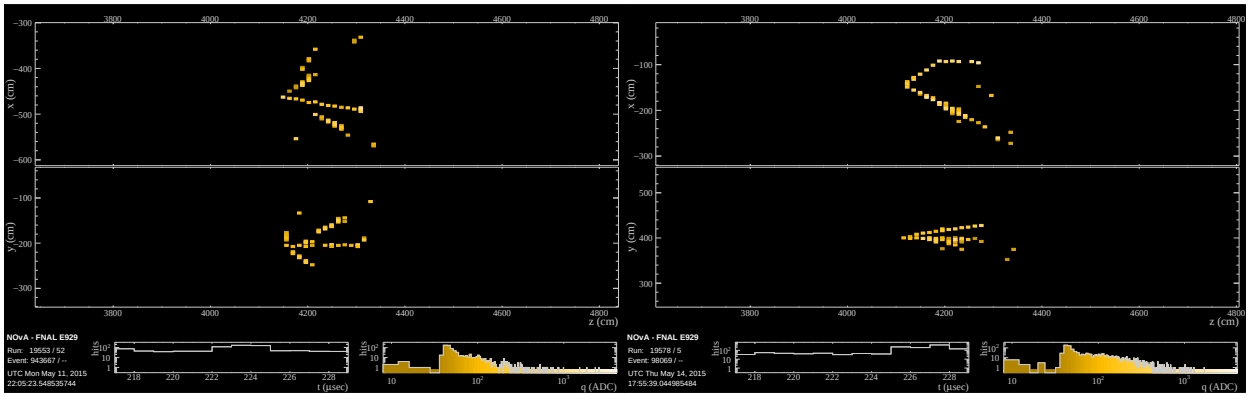
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

ν_e evds


NOvA - FNAL E929
Run: 18625 / 6
Event: 89150 / --
UTC Fri Jan 9, 2015
16:26:45.070981344
NOvA - FNAL E929
Run: 19165 / 62
Event: 920415 / --
UTC Mon Mar 23, 2015
11:43:54.311669120
NOvA - FNAL E929
Run: 17895 / 13
Event: 93423 / --
UTC Sat Oct 25, 2014
07:09:15.101266168
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)


NOvA - FNAL E929
Run: 19553 / 52
Event: 943667 / --
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22:05:23.548535744
NOvA - FNAL E929
Run: 19578 / 5
Event: 98069 / --
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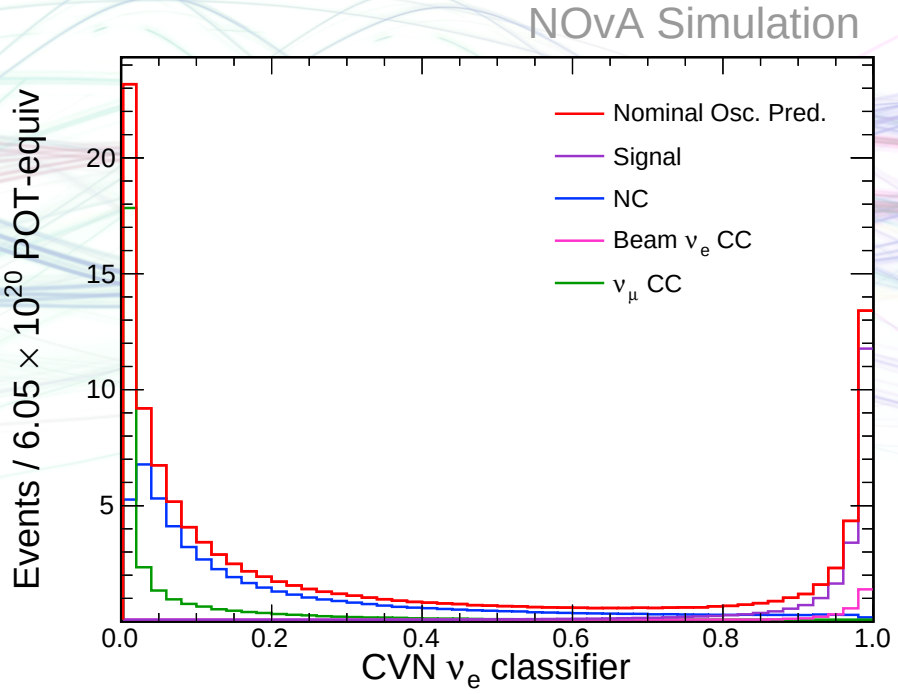
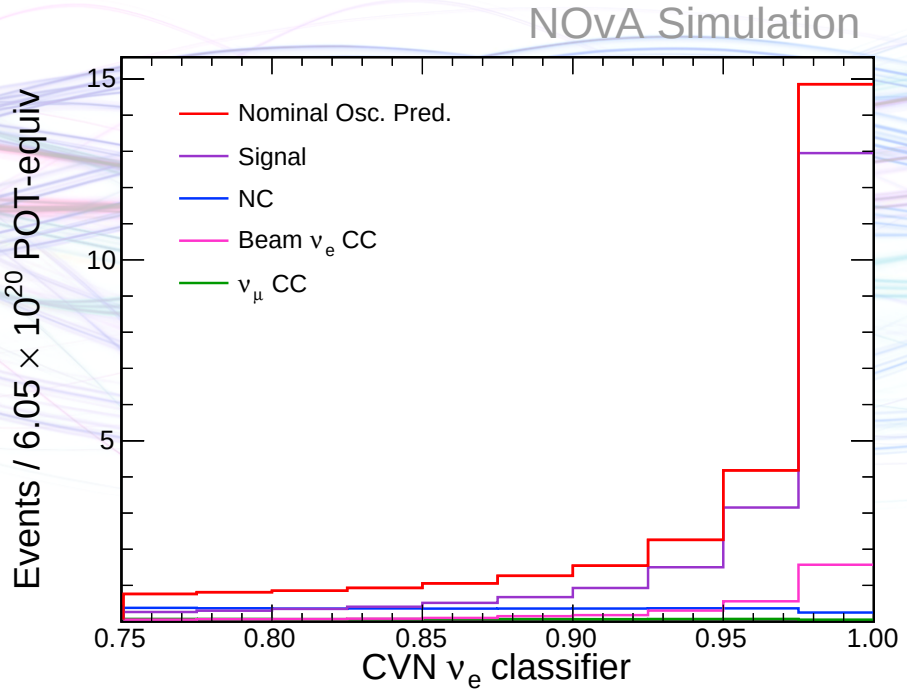
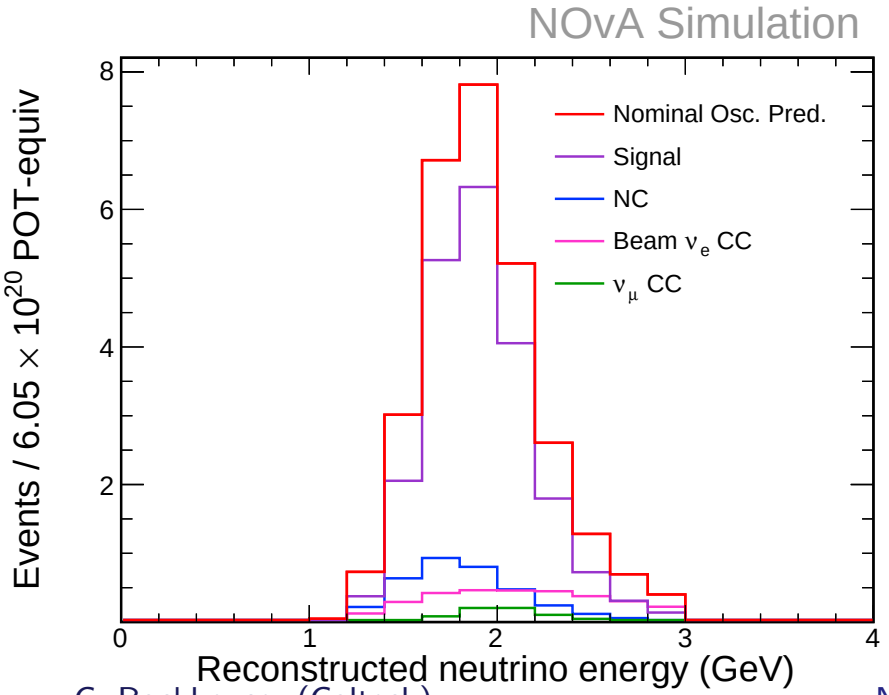
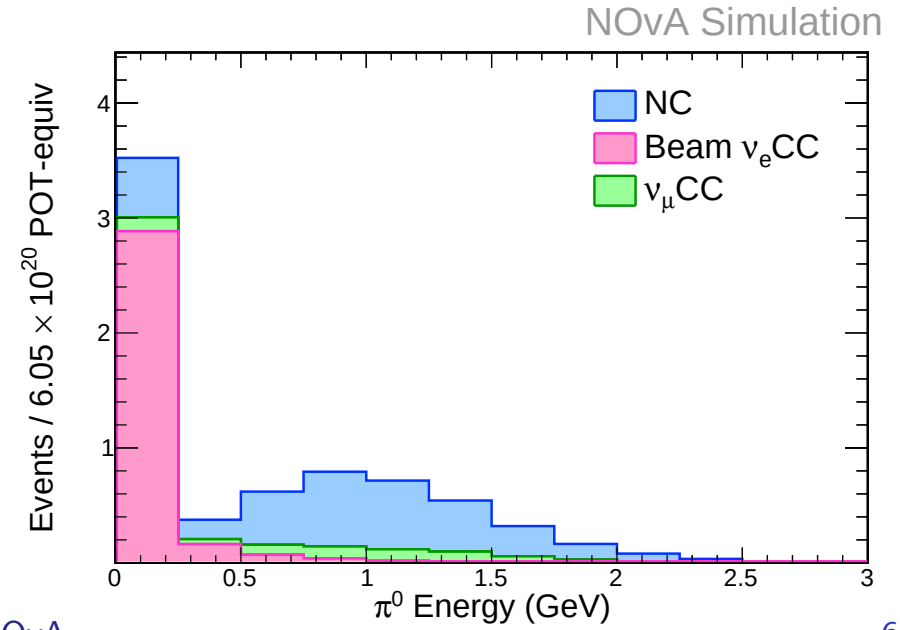
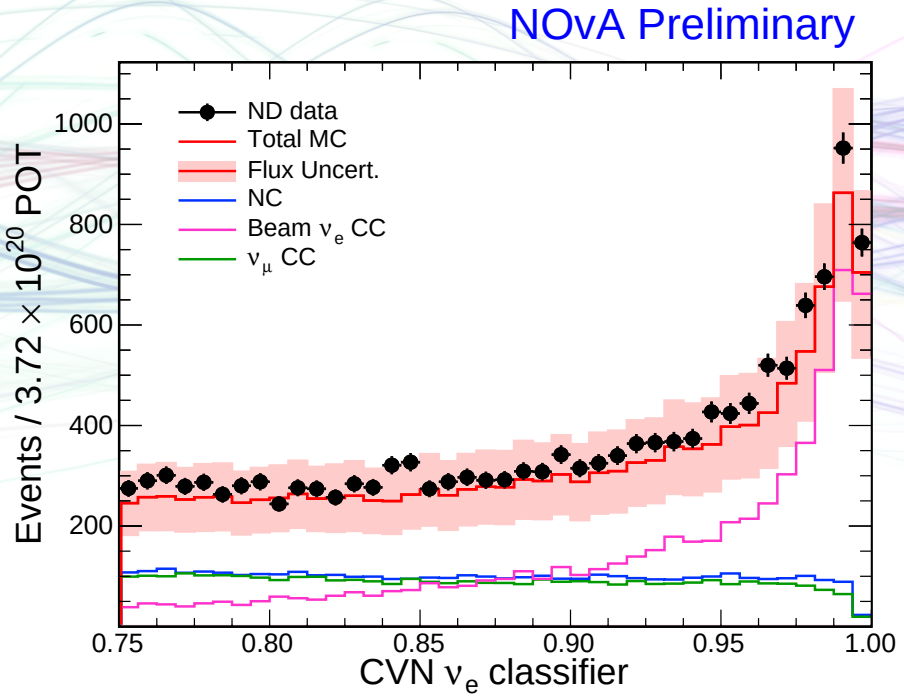
17:55:39.044985484
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

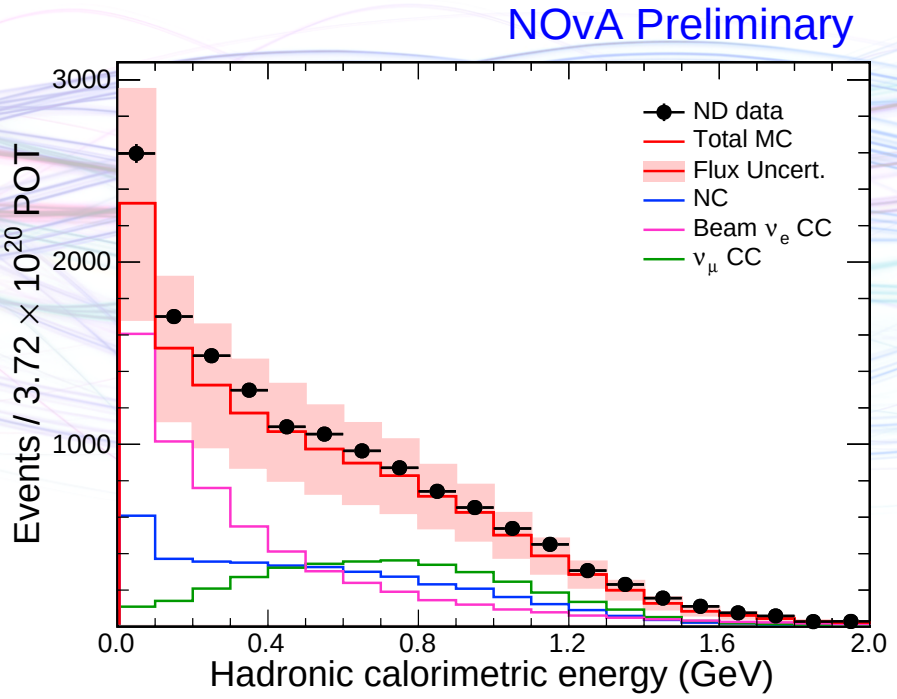

NOvA Simulation
Nominal Osc. Pred.
Signal
NC
Beam ν_e CC
ν_μ CC
Events / 6.05 × 10^{20} POT-equiv
CVN ν_e classifier

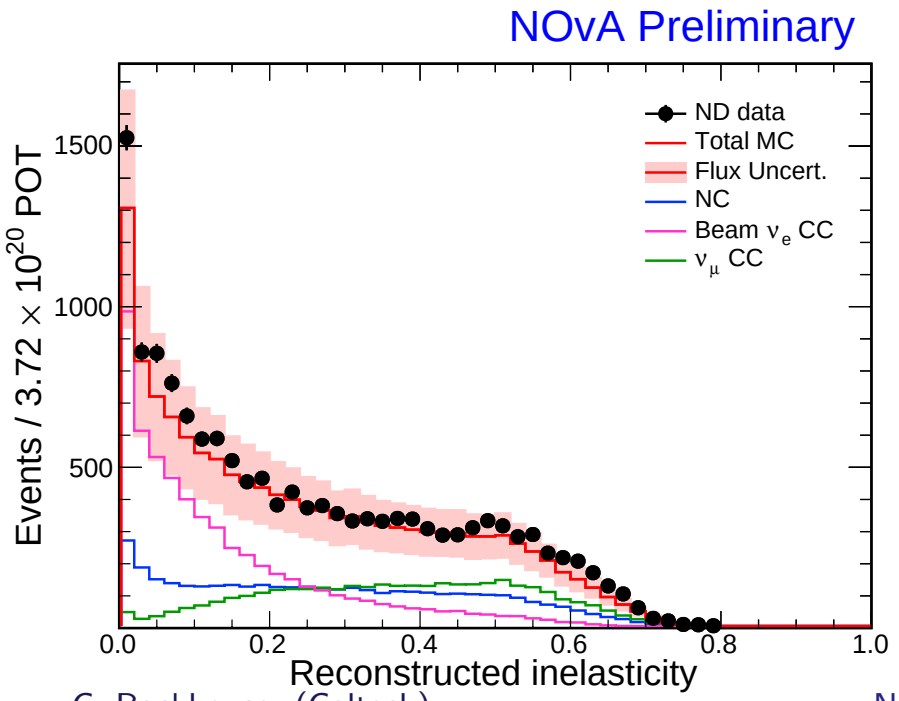

NOvA Simulation
Nominal Osc. Pred.
Signal
NC
Beam ν_e CC
ν_μ CC
Events / 6.05 × 10^{20} POT-equiv
CVN ν_e classifier

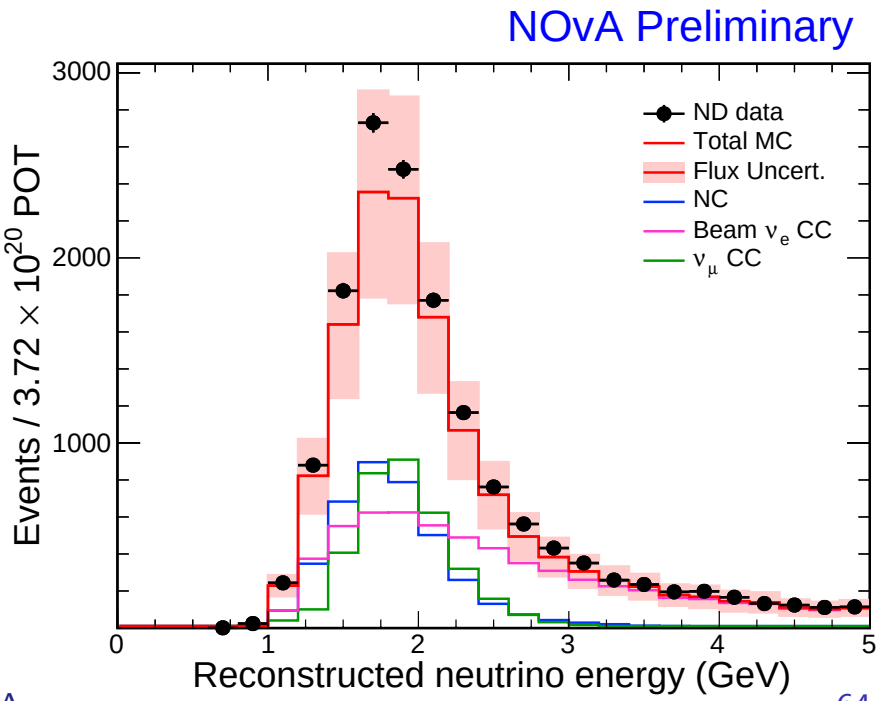

NOvA Simulation
Nominal Osc. Pred.
Signal
NC
Beam ν_e CC
ν_μ CC
Events / 6.05 × 10^{20} POT-equiv
Reconstructed neutrino energy (GeV)

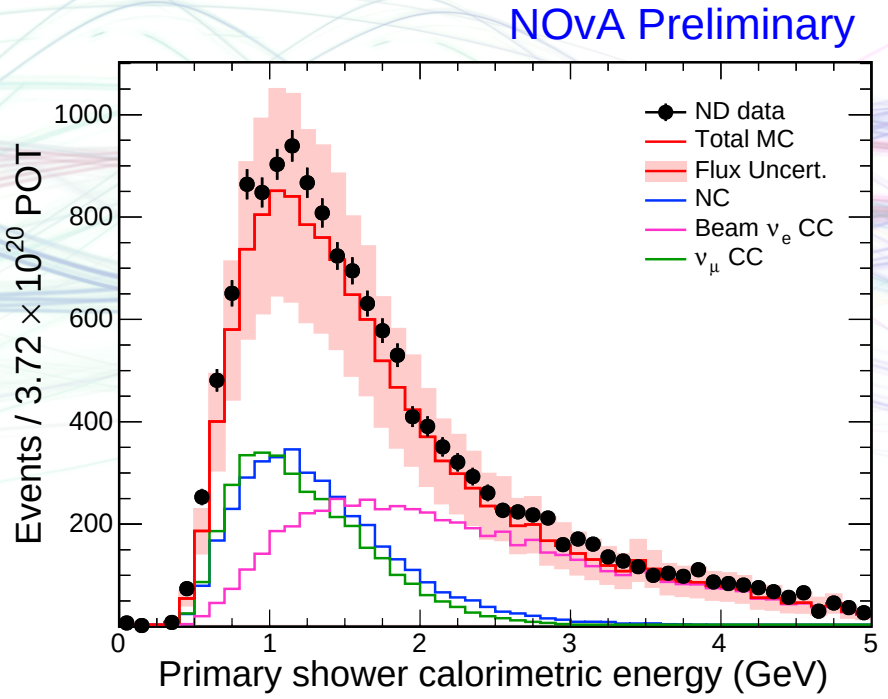

NOvA Simulation
NC
Beam ν_eCC
ν_μCC
Events / 6.05 × 10^{20} POT-equiv
π^0 Energy (GeV)

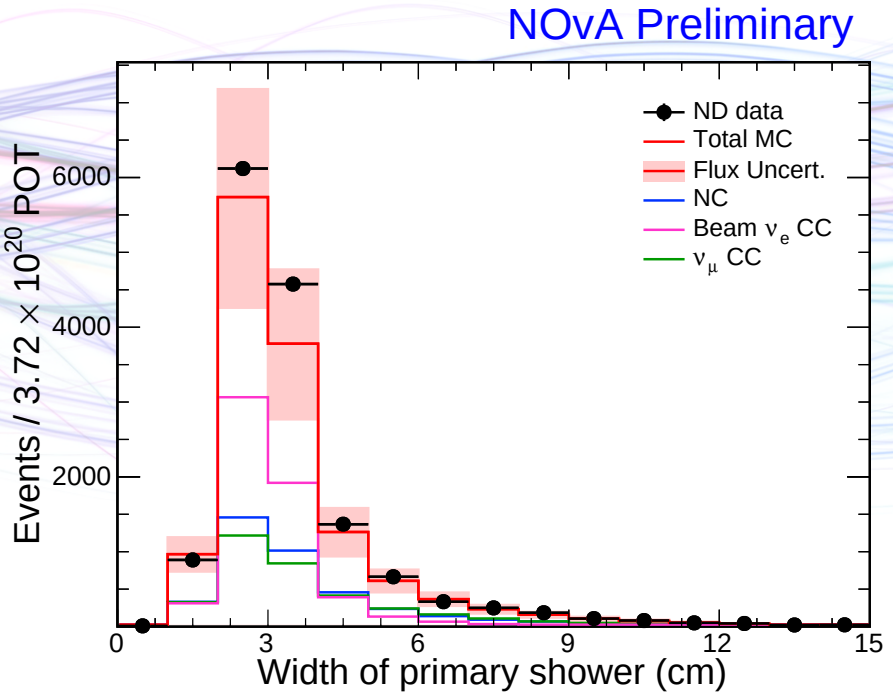

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
CVN ν_e classifier

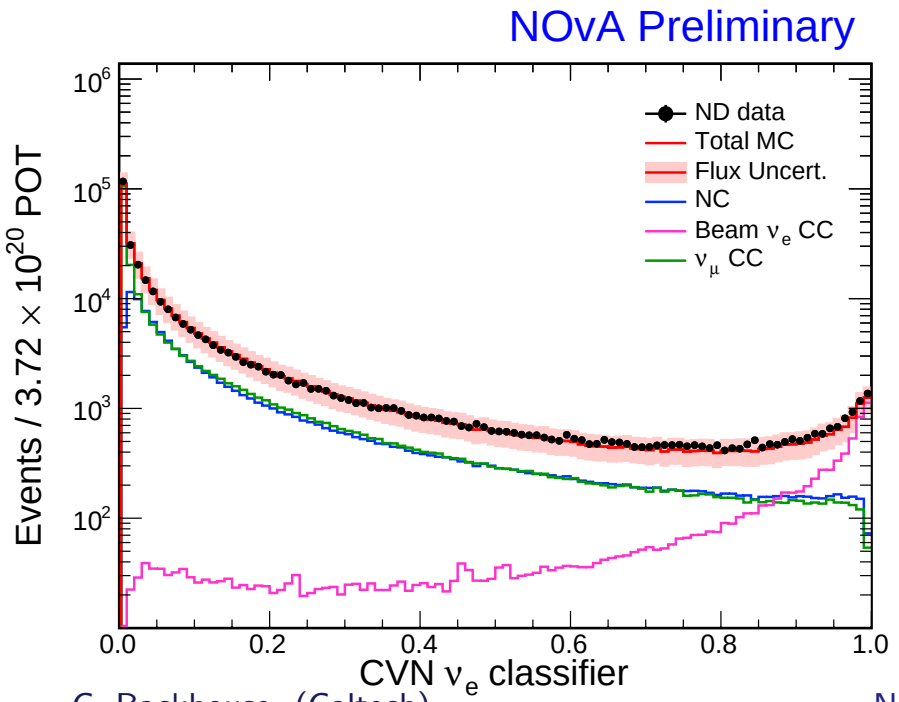

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
Hadronic calorimetric energy (GeV)

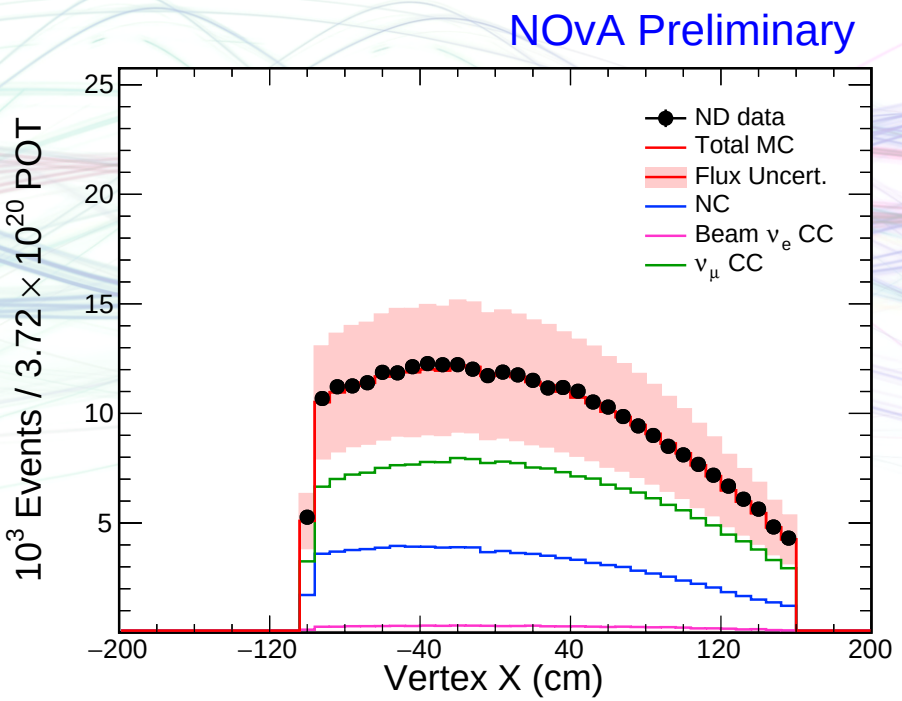

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
Reconstructed inelasticity

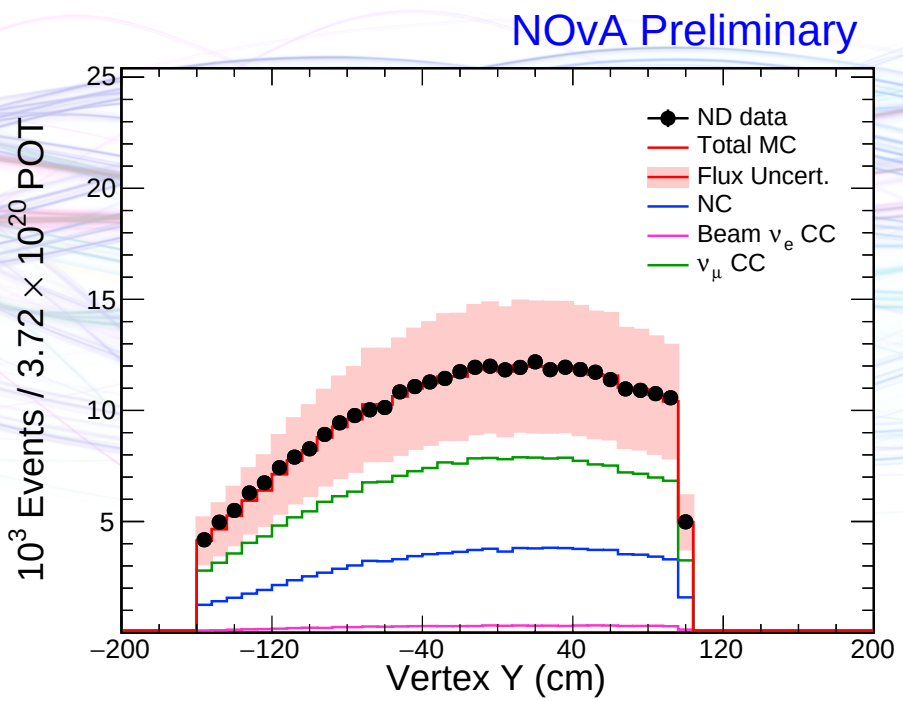

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
Reconstructed neutrino energy (GeV)

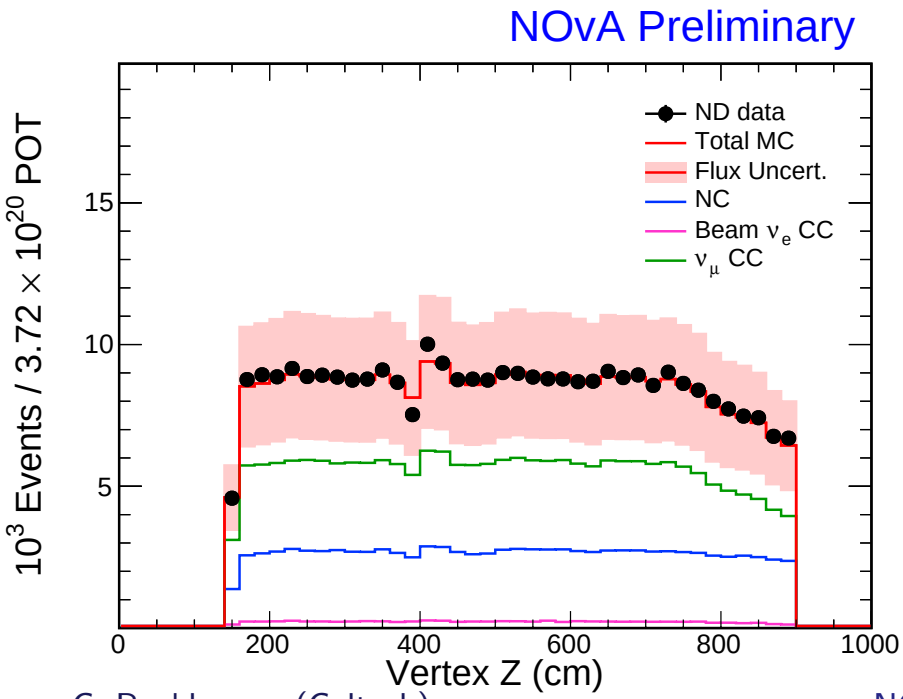

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
Primary shower calorimetric energy (GeV)

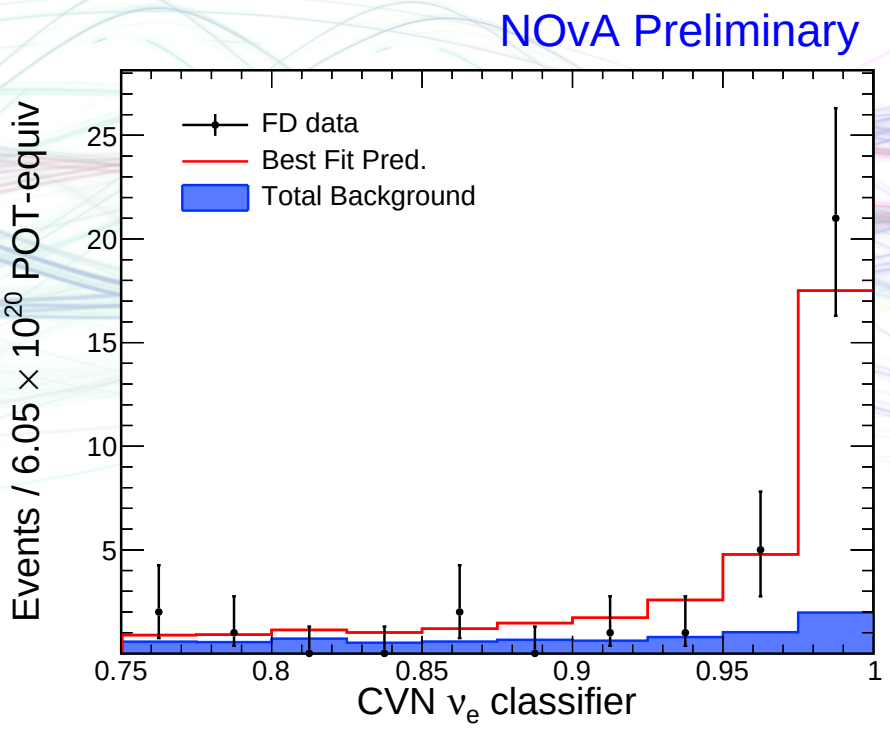

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
Width of primary shower (cm)

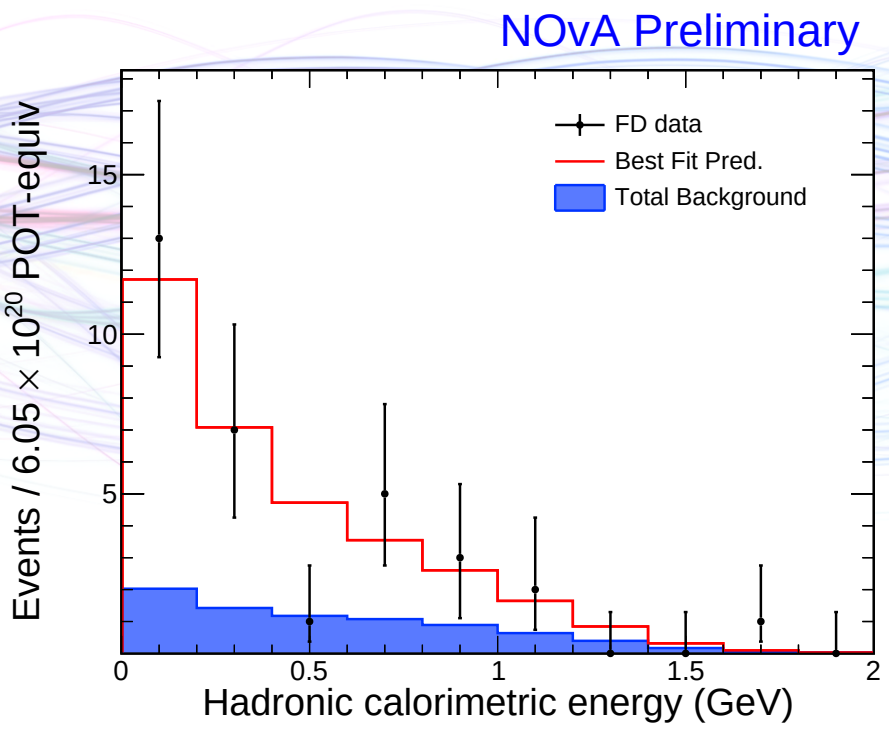

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
Events / 3.72 × 10^{20} POT
CVN ν_e classifier

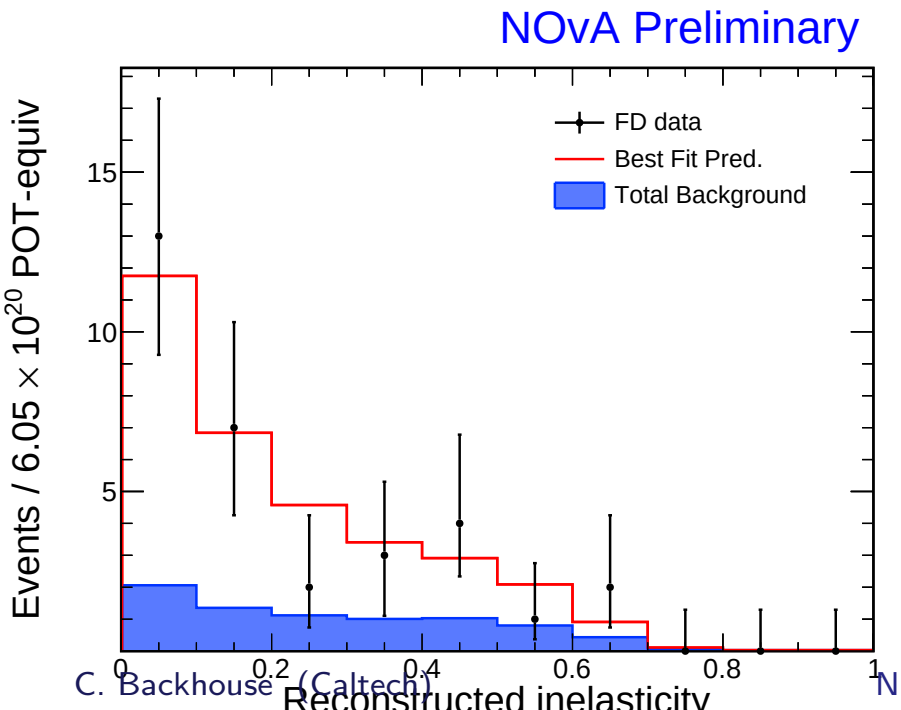

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
10^3 Events / 3.72×10^{20} POT
Vertex X (cm)

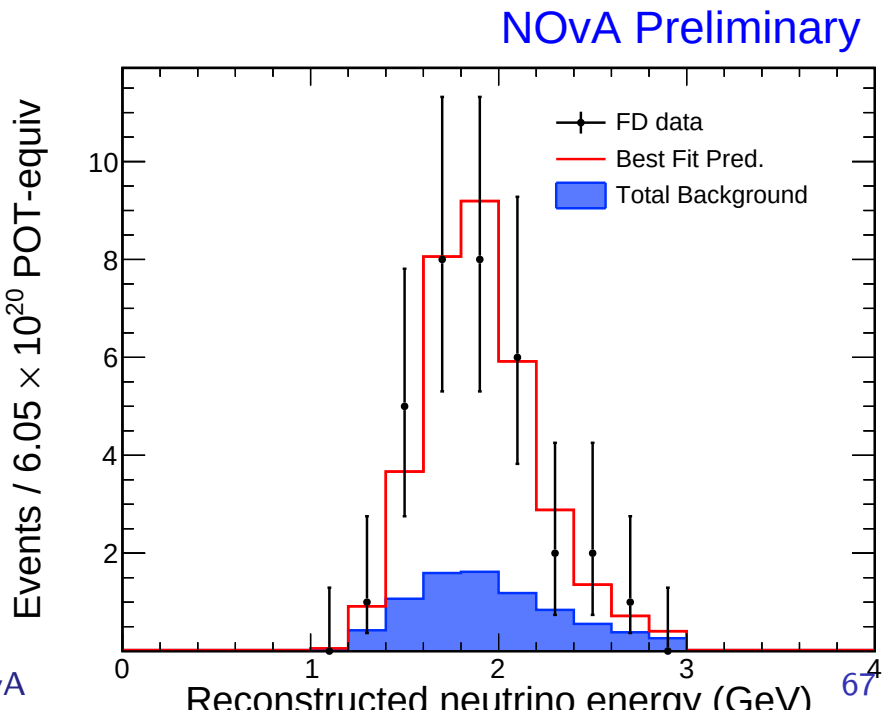

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
10^3 Events / 3.72×10^{20} POT
Vertex Y (cm)

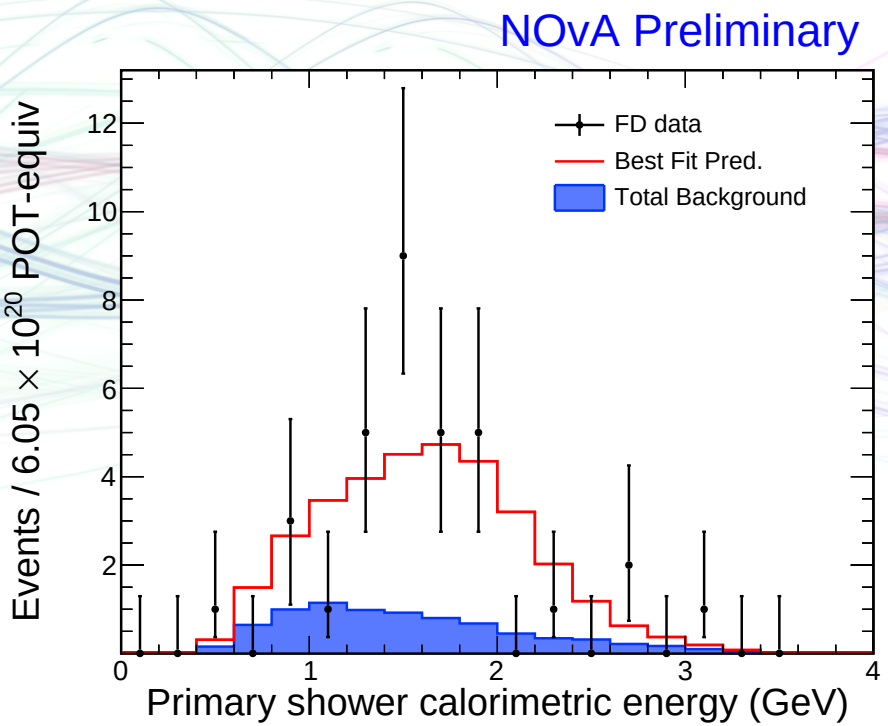

NOvA Preliminary
ND data
Total MC
Flux Uncert.
NC
Beam ν_e CC
ν_μ CC
10^3 Events / 3.72×10^{20} POT
Vertex Z (cm)

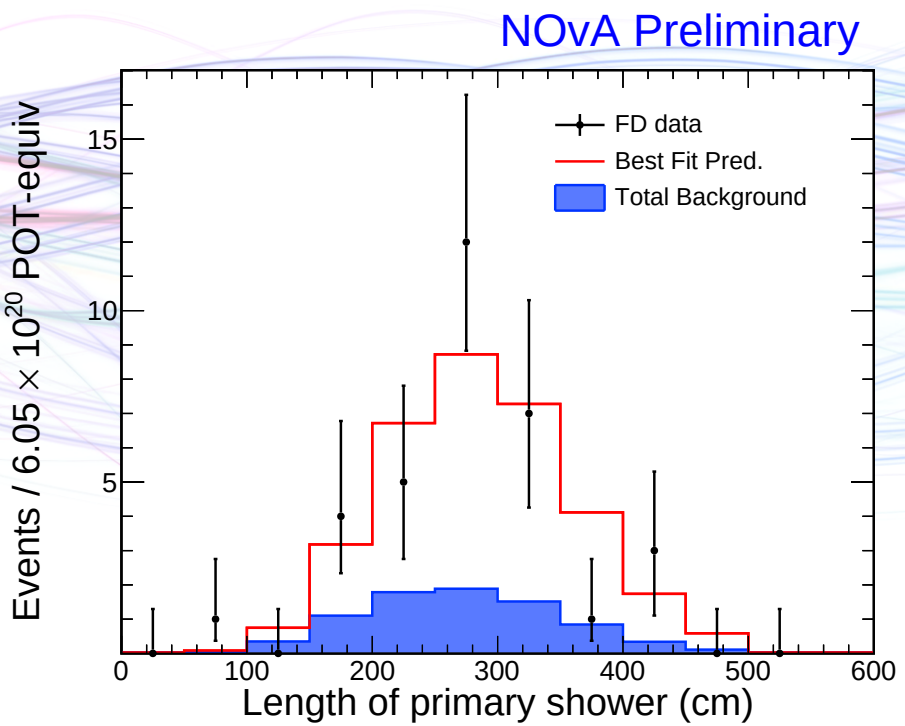

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
CVN νe classifier

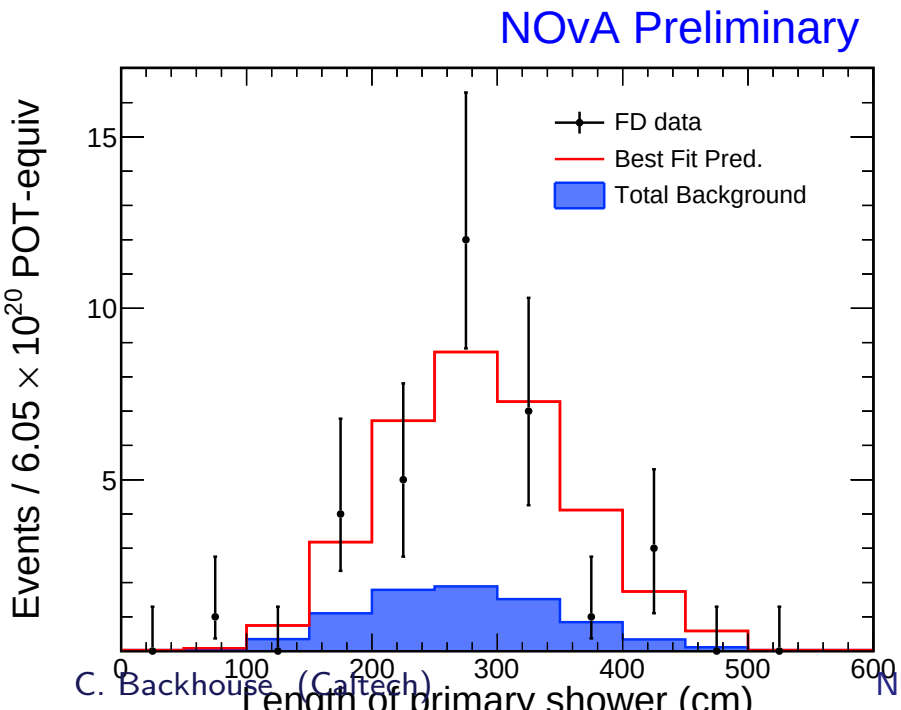

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Hadronic calorimetric energy (GeV)

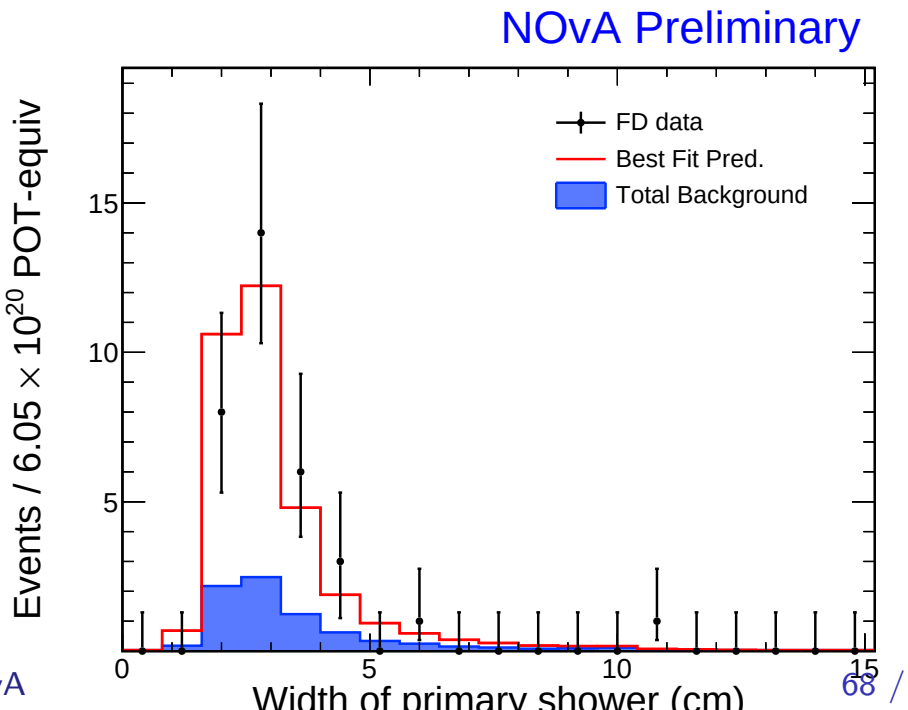

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Reconstructed inelasticity

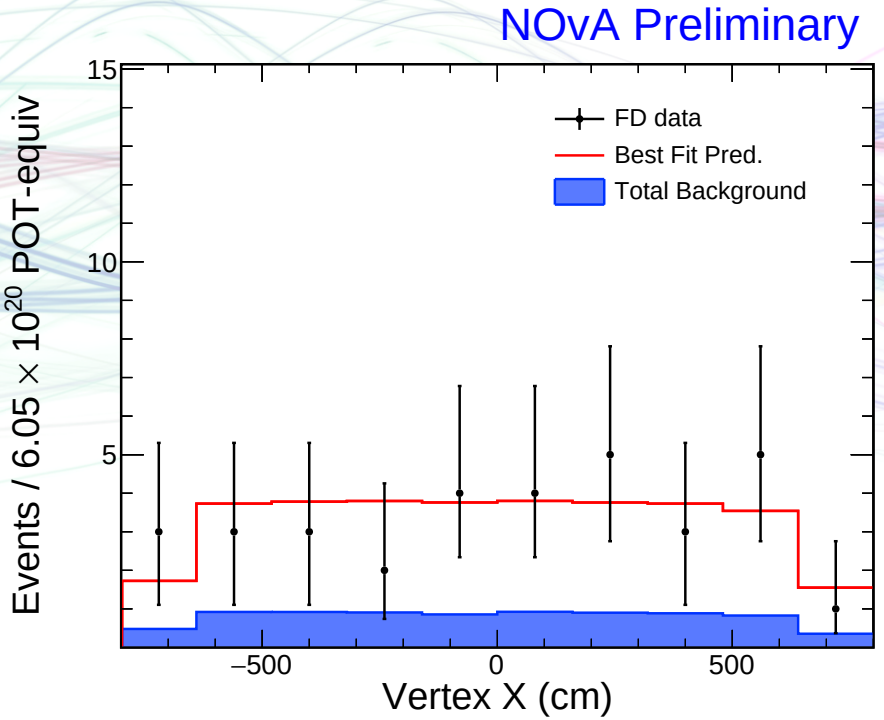

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Reconstructed neutrino energy (GeV)

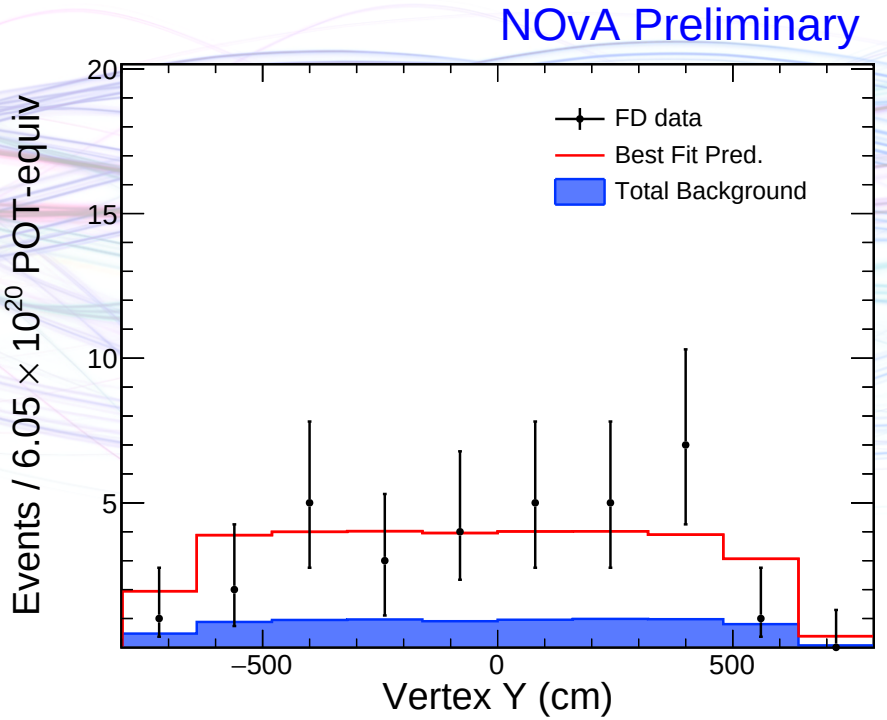

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Primary shower calorimetric energy (GeV)

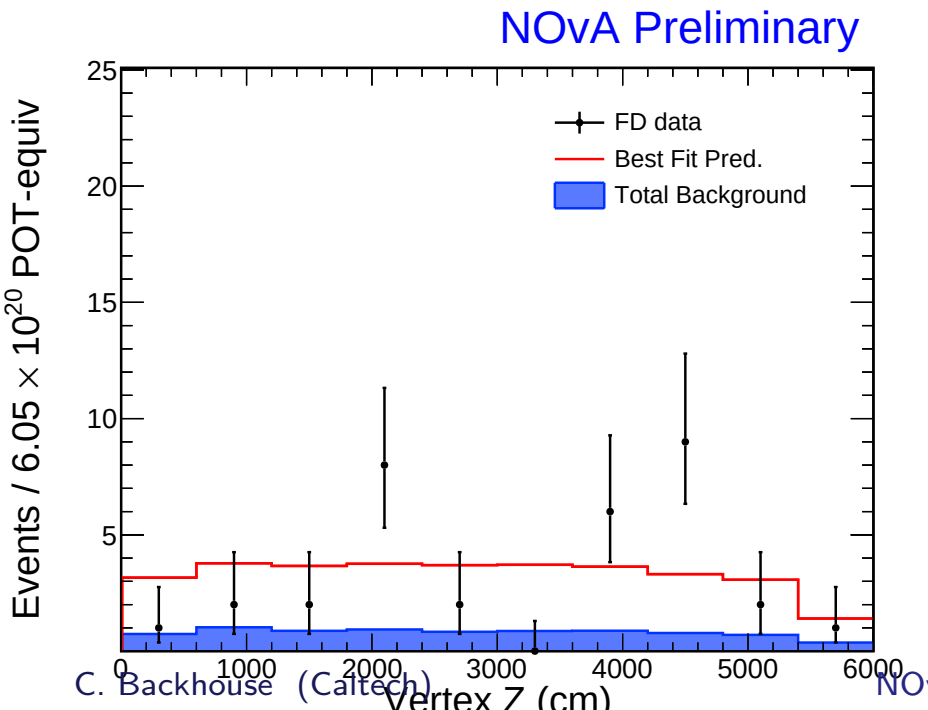

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Length of primary shower (cm)

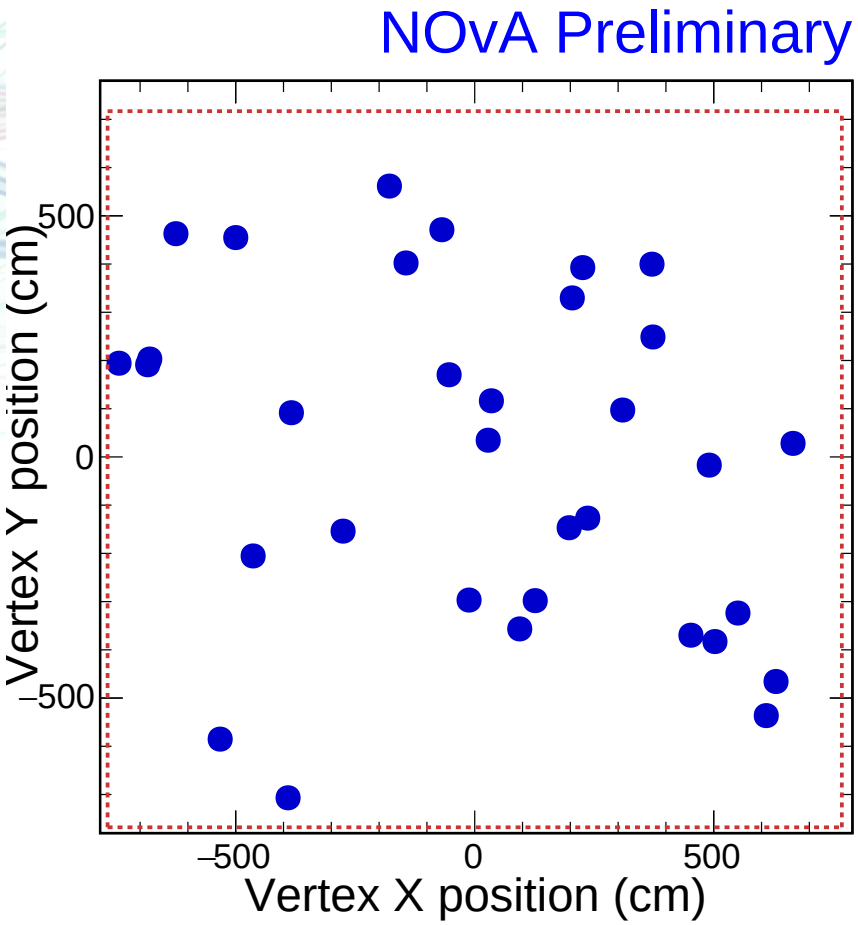

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Length of primary shower (cm)

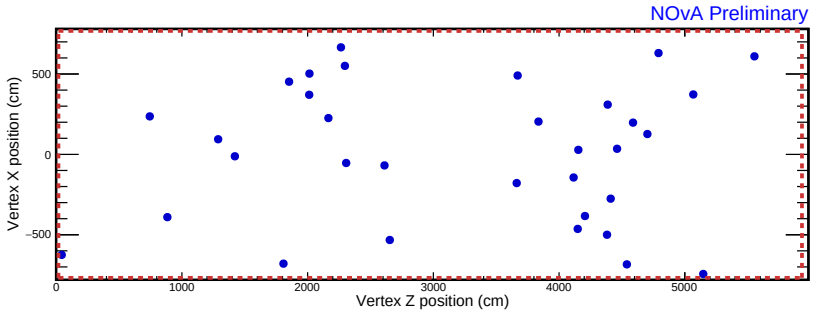

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Width of primary shower (cm)

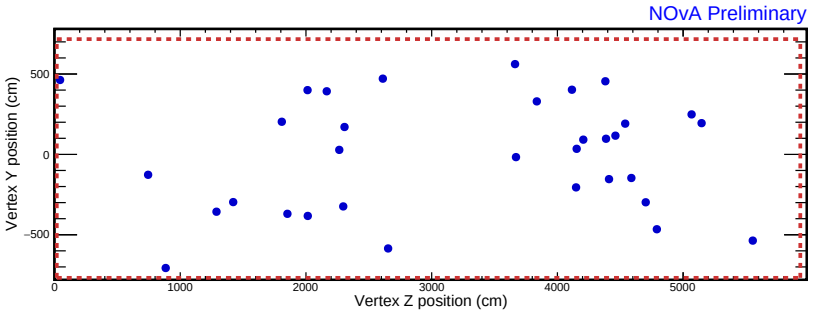

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Vertex X (cm)

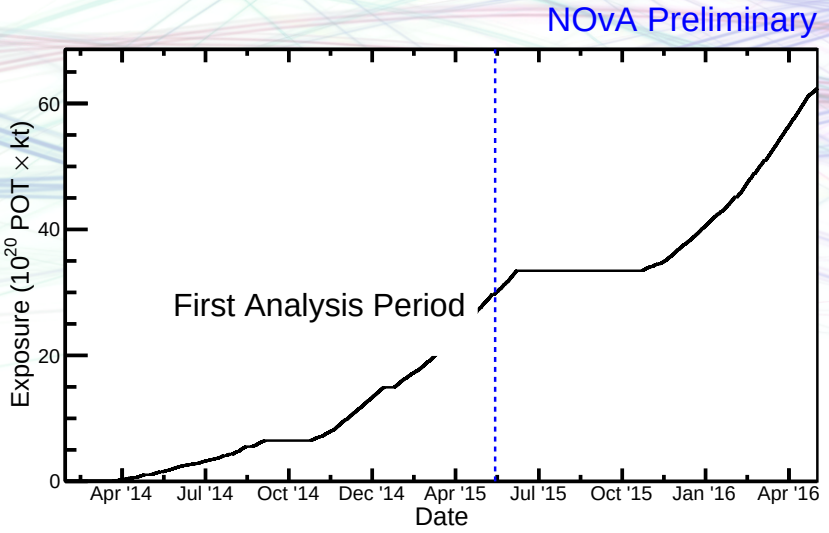

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Vertex Y (cm)

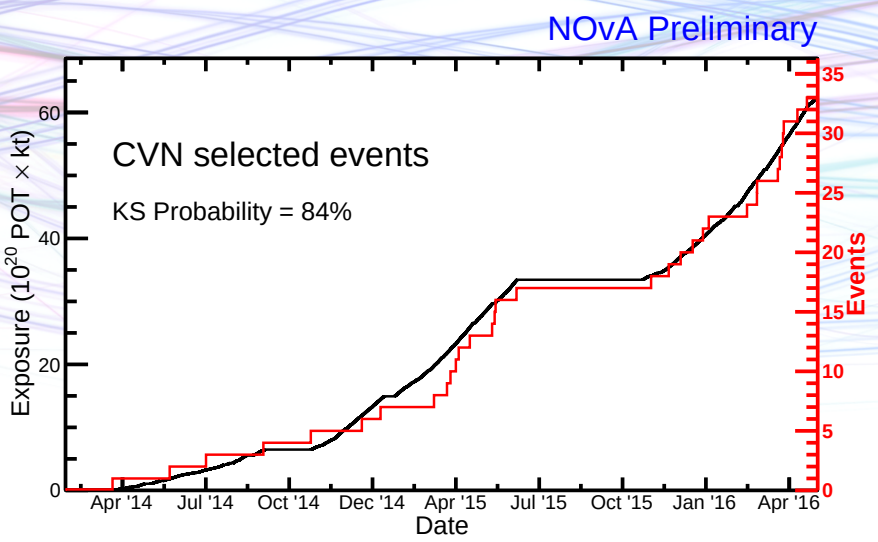

NOvA Preliminary
FD data
Best Fit Pred.
Total Background
Events / 6.05 × 10^20 POT-equiv
Vertex Z (cm)

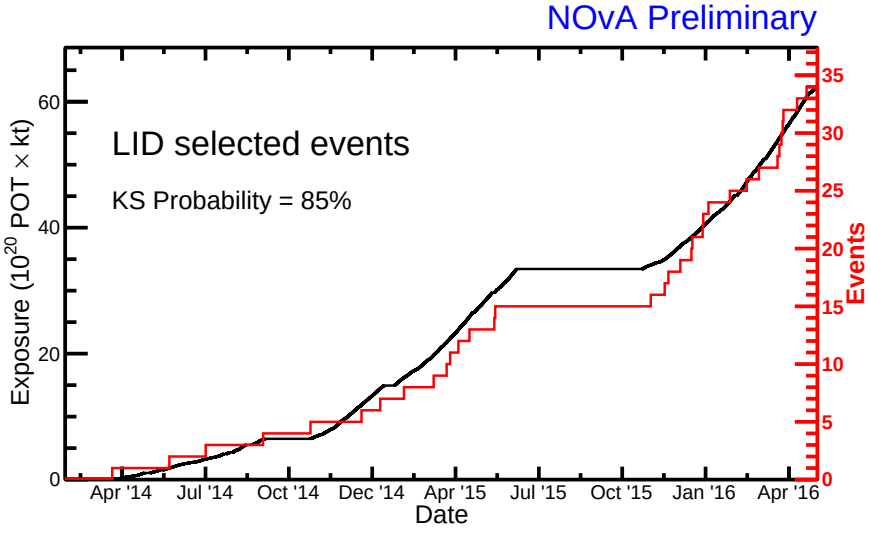

NOvA Preliminary
Vertex Y position (cm)
500
0
–500
–500
0
500
Vertex X position (cm)

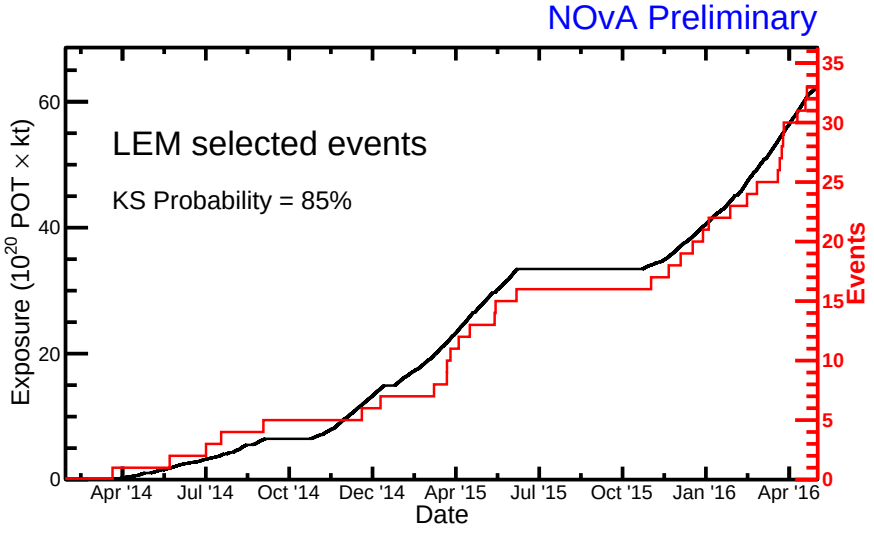

NOvA Preliminary
Vertex X position (cm)
500
0
–500
0
1000
2000
3000
4000
5000
Vertex Z position (cm)

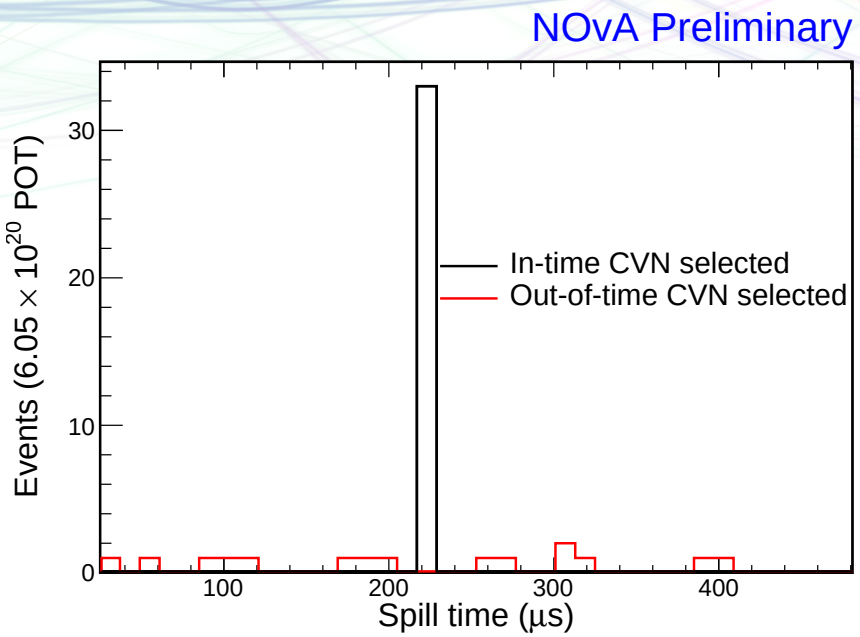

NOvA Preliminary
Vertex Y position (cm)
500
0
–500
0
1000
2000
3000
4000
5000
Vertex Z position (cm)

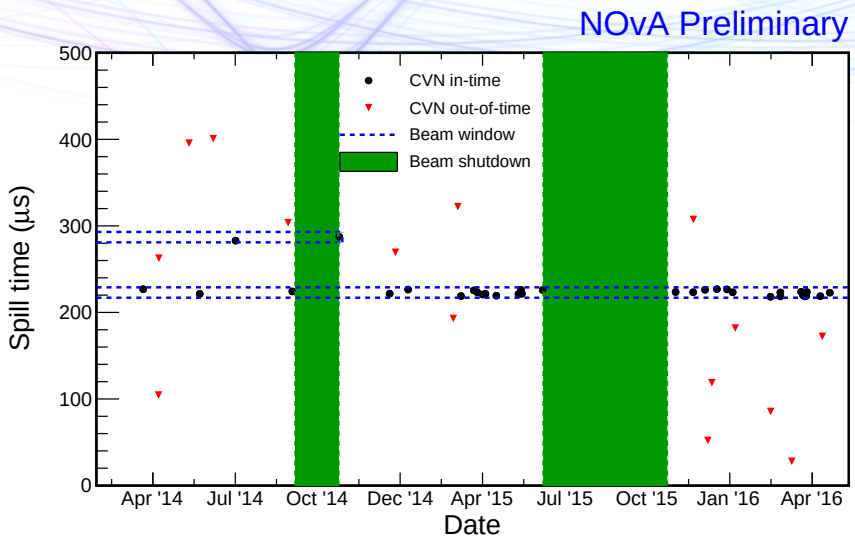

NOvA Preliminary
First Analysis Period
Exposure (10^{20} POT × kt)
0
20
40
60
Apr '14
Jul '14
Oct '14
Dec '14
Apr '15
Jul '15
Oct '15
Jan '16
Apr '16
Date

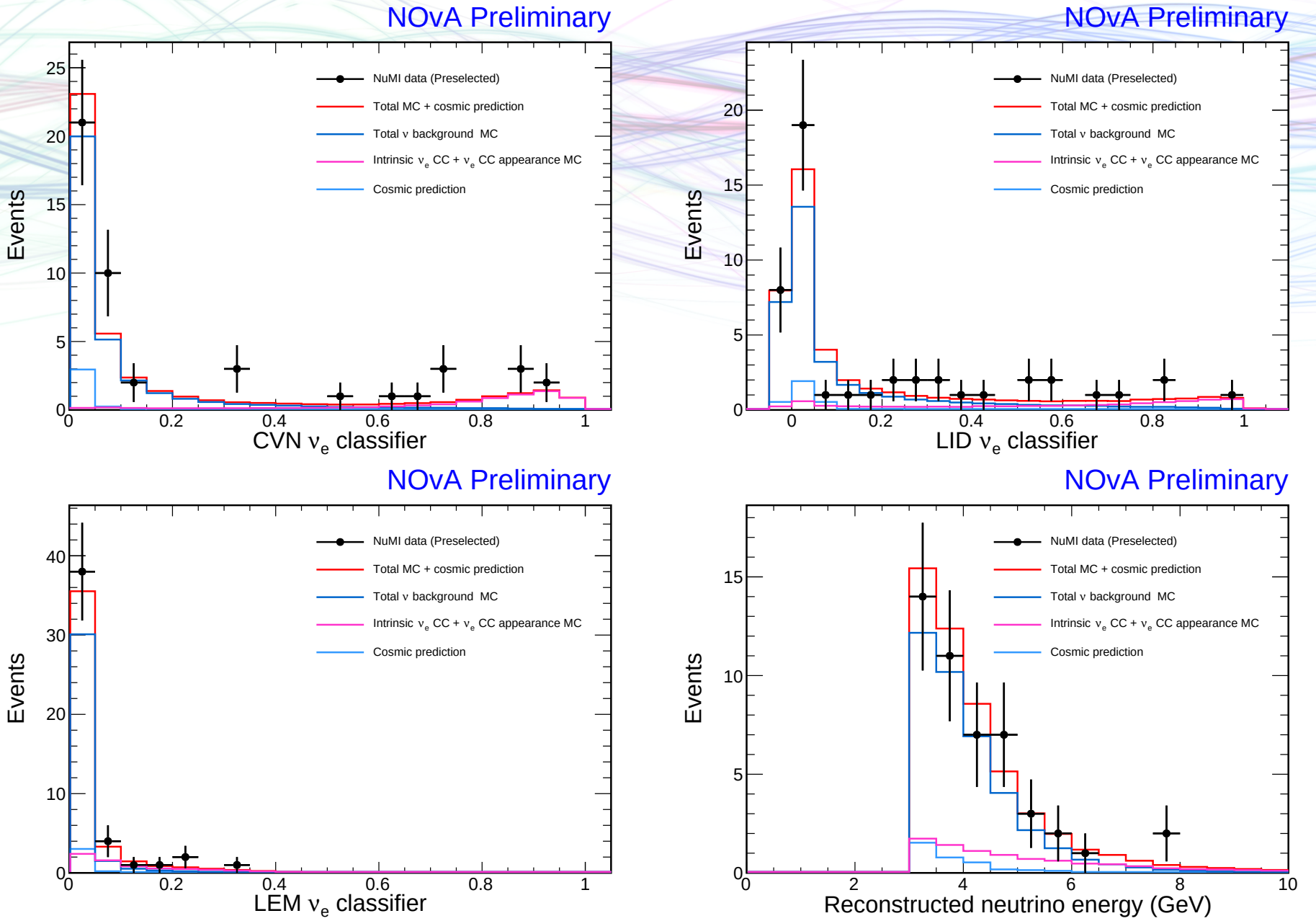

NOvA Preliminary
CVN selected events
KS Probability = 84%
Exposure (10^{20} POT × kt)
Events
0
20
40
60
0
5
10
15
20
25
30
35
Apr '14
Jul '14
Oct '14
Dec '14
Apr '15
Jul '15
Oct '15
Jan '16
Apr '16
Date


NOvA Preliminary
LID selected events
KS Probability = 85%
Exposure (10^{20} POT × kt)
Events
0
20
40
60
0
5
10
15
20
25
30
35
Apr '14
Jul '14
Oct '14
Dec '14
Apr '15
Jul '15
Oct '15
Jan '16
Apr '16
Date

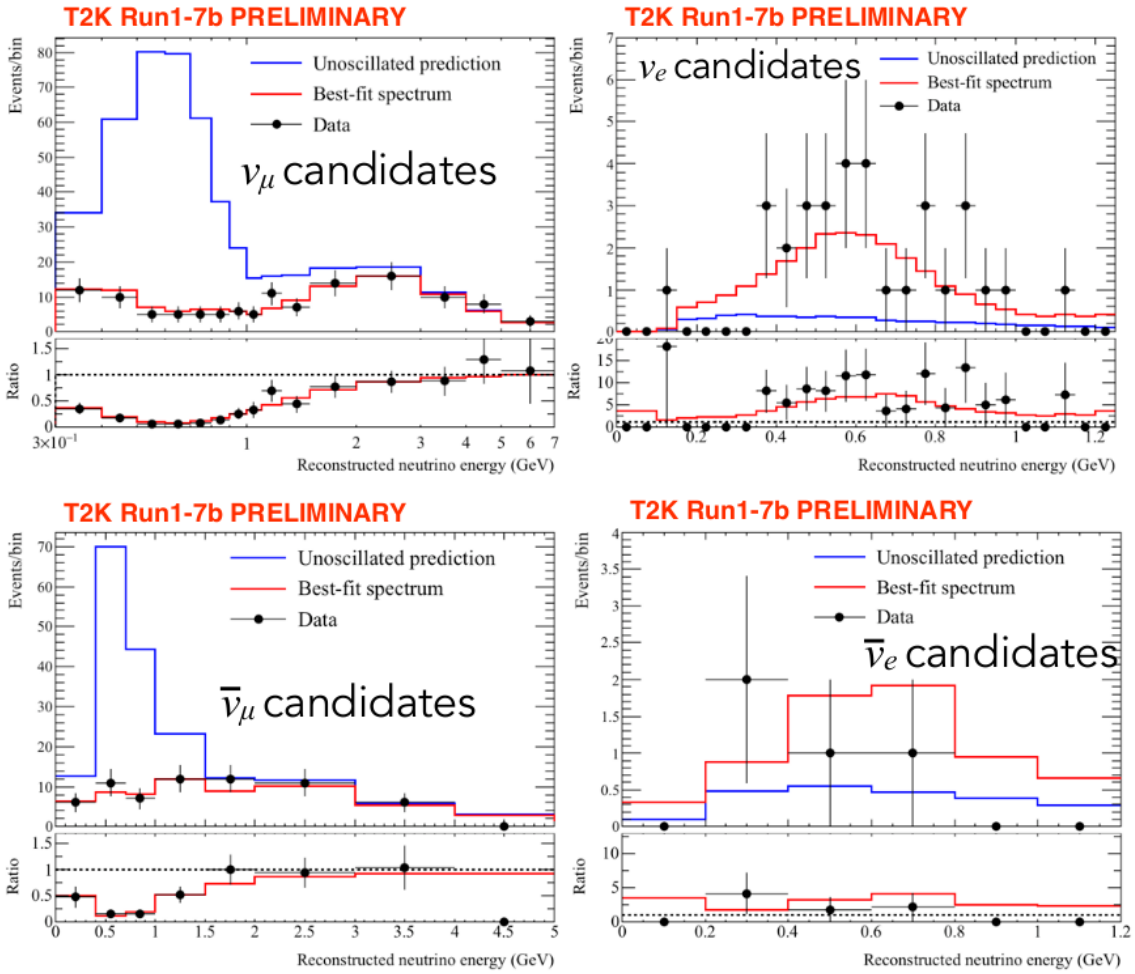

NOvA Preliminary
LEM selected events
KS Probability = 85%
Exposure (10^{20} POT × kt)
Events
0
20
40
60
0
5
10
15
20
25
30
35
Apr '14
Jul '14
Oct '14
Dec '14
Apr '15
Jul '15
Oct '15
Jan '16
Apr '16
Date


NOvA Preliminary
Events (6.05 × 10^20 POT)
Spill time (μs)
In-time CVN selected
Out-of-time CVN selected
0
10
20
30
100
200
300
400


NOvA Preliminary
Spill time (μs)
Date
CVN in-time
CVN out-of-time
Beam window
Beam shutdown
0
100
200
300
400
500
Apr '14
Jul '14
Oct '14
Dec '14
Apr '15
Jul '15
Oct '15
Jan '16
Apr '16


NOvA Preliminary
NuMI data (Preselected)
Total MC + cosmic prediction
Total ν background MC
Intrinsic ν_e CC + ν_e CC appearance MC
Cosmic prediction
Events
CVN ν_e classifier
NOvA Preliminary
NuMI data (Preselected)
Total MC + cosmic prediction
Total ν background MC
Intrinsic ν_e CC + ν_e CC appearance MC
Cosmic prediction
Events
LID ν_e classifier
NOvA Preliminary
NuMI data (Preselected)
Total MC + cosmic prediction
Total ν background MC
Intrinsic ν_e CC + ν_e CC appearance MC
Cosmic prediction
Events
LEM ν_e classifier
NOvA Preliminary
NuMI data (Preselected)
Total MC + cosmic prediction
Total ν background MC
Intrinsic ν_e CC + ν_e CC appearance MC
Cosmic prediction
Events
Reconstructed neutrino energy (GeV)

EVENTS AT SUPER-KAMIOKANDE



	OBS.	EXP. (NH, $\sin^2\Theta_{23}$=0.528, NH)			
		$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_μ	**125**	127.9	127.6	127.8	128.1
ν_e	**32**	27.0	22.7	18.5	22.7
$\bar{\nu}_\mu$	**66**	64.4	64.3	64.4	64.6
$\bar{\nu}_e$	**4**	6.0	6.9	7.7	6.8

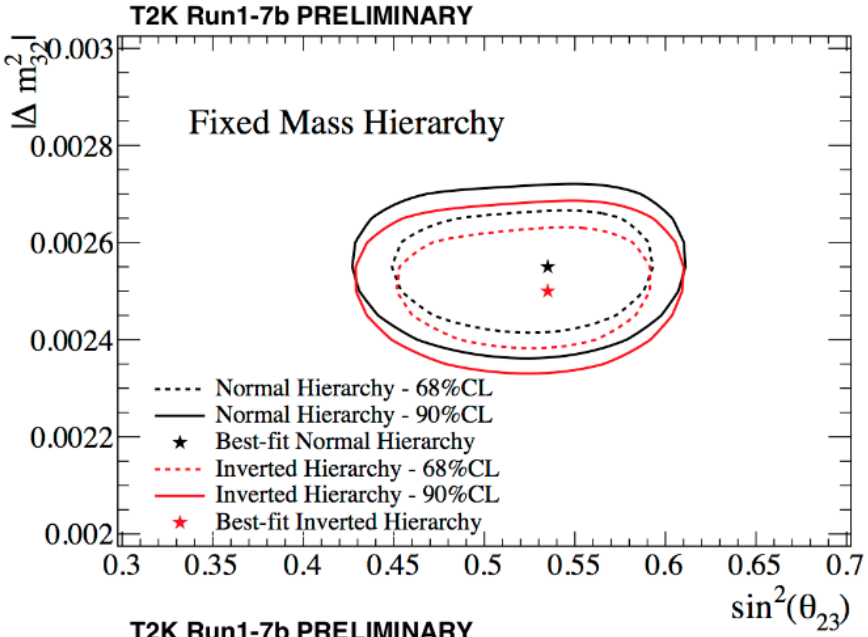
E_{rec} distributions assuming 2-body ("QE") kinematics

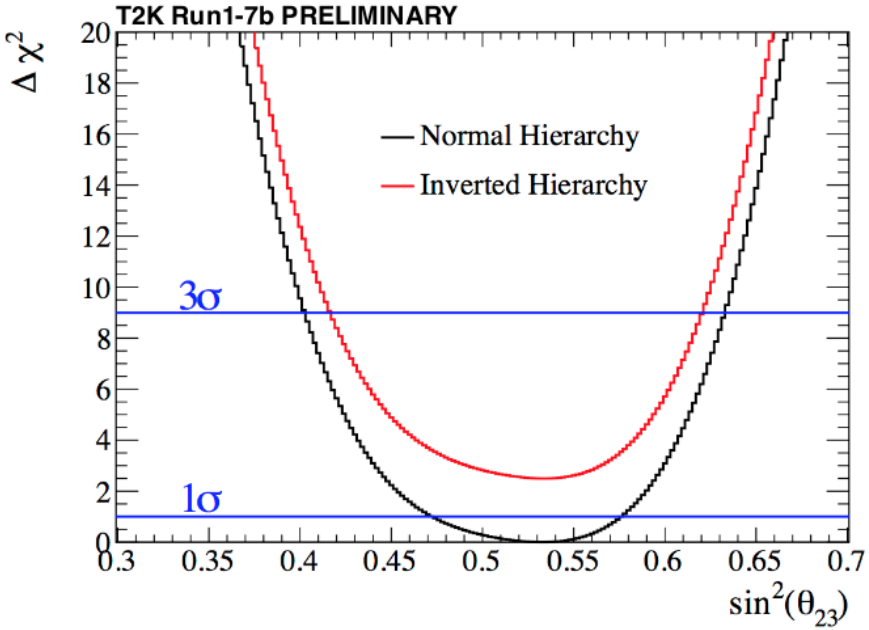
P1.041 R. Shah

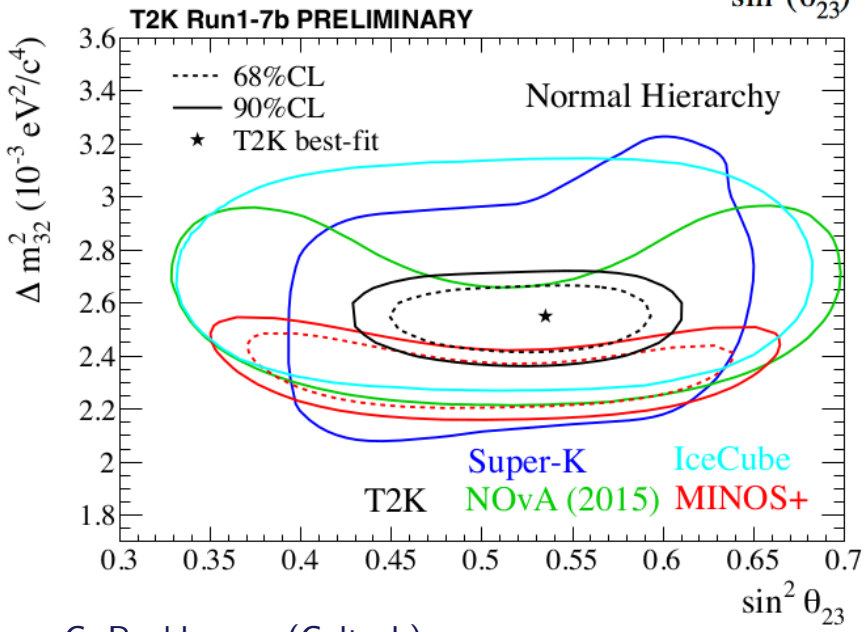
Analysis frameworks

- Frequentist with $\Delta\chi^2$ fit to
  - E_{rec}/θ_{lep} for $\nu_e/\bar{\nu}_e$
  - E_{rec} for $\nu_\mu/\bar{\nu}_\mu$
- Bayesian with likelihood fit to
  - p_{lep}/θ_{lep} for $\nu_e/\bar{\nu}_e$
  - E_{rec} for $\nu_\mu/\bar{\nu}_\mu$
- Bayesian with Markov Chain MC
  - E_{rec} for all samples
  - simultaneous fit with near detector

$\sin^2\theta_{23}$ AND Δm^2_{32}







	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\lvert\Delta m^2_{32}\rvert$ ($/10^{-3}$eV^2)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

- Results continue to be consistent with maximal mixing/oscillation

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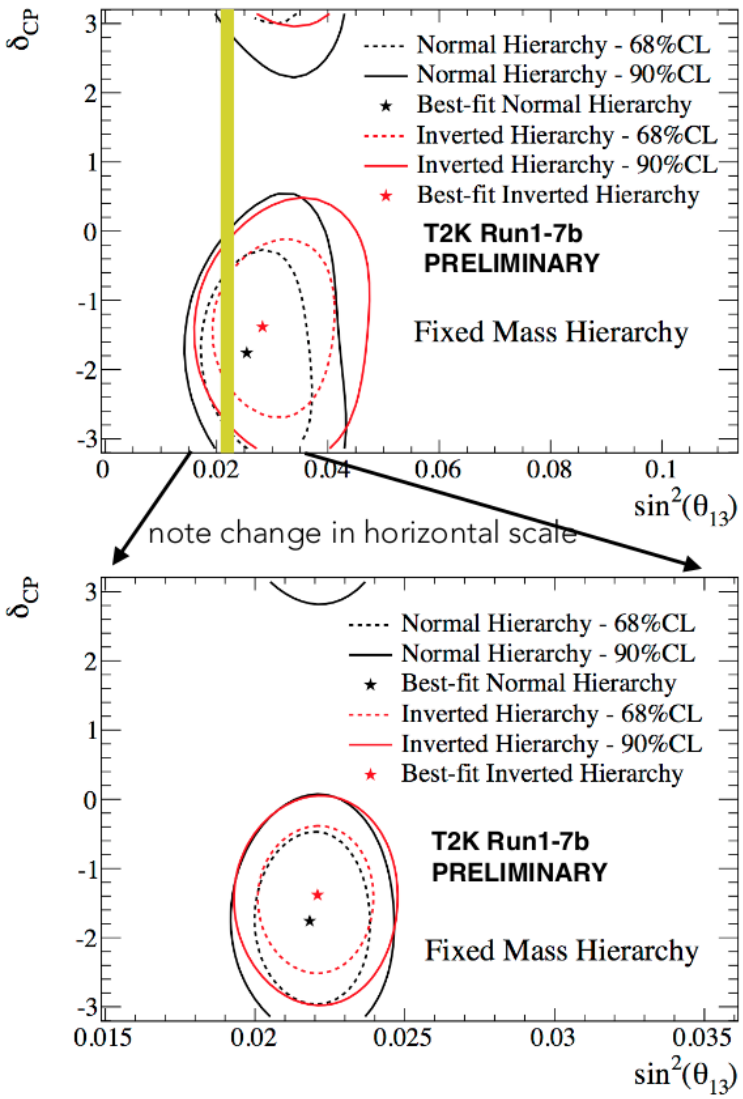
δ_{CP} VS. θ_{13}

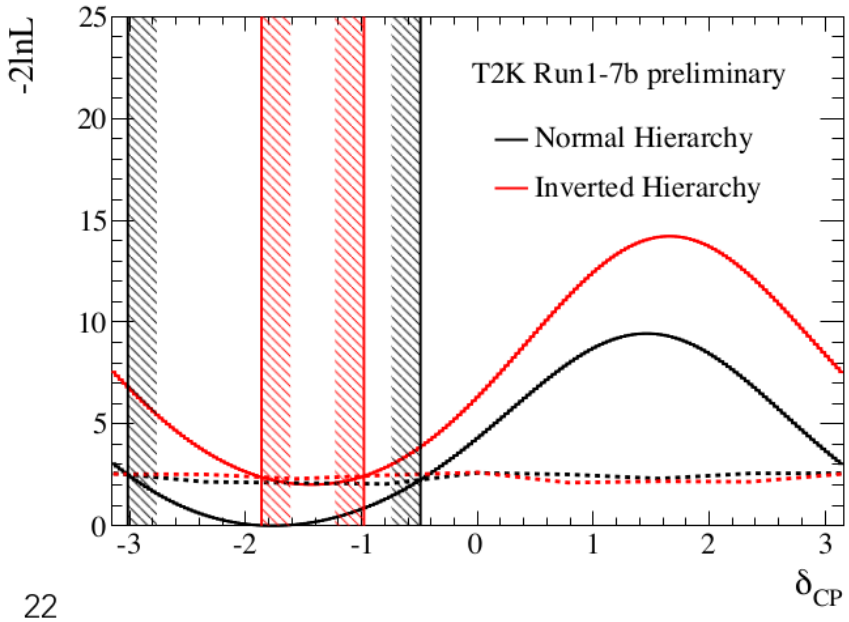


Left: δ_{CP} vs. θ_{13} (fixed $\Delta\chi^2$, fixed hierarchy)

- T2K-only
- T2K with reactor $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

Below: δ_{CP} with Feldman-Cousins critical values and reactor θ_{13}

δ_{CP} = [-3.02, -0.49] (NH), [-1.87, -0.98] (IH) @90% CL



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