

New Neutrino Oscillation Results from NOvA



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Neutrino oscillations and what we can learn from them

Neutrino oscillations



Create neutrinos in one lepton flavor state,
observe in another (possibly different) state

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

Flavor states are not energy
(mass) eigenstates

nonzero transition probabilities
since masses are different

Neutrino oscillations



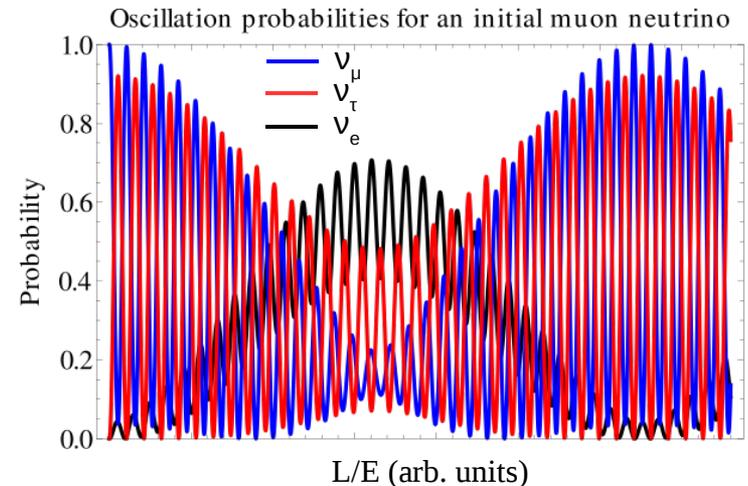
Create neutrinos in one lepton flavor state,
observe in another (possibly different) state

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{pmatrix} \text{yellow} & \text{blue} & \text{red} \\ \text{green} & \text{blue} & \text{yellow} \\ \text{green} & \text{blue} & \text{yellow} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

arXiv:1212.6374



Flavor states are not energy
(mass) eigenstates



Neutrino oscillations: mixing angles

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{pmatrix} \text{yellow} & \text{blue} & \text{red} \\ \text{green} & \text{blue} & \text{yellow} \\ \text{green} & \text{blue} & \text{yellow} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

“Atmospheric” sector:

best measured in experiments where ν_μ disappearance dominates: ν_s from cosmic ray muon decays; **accelerators**

“Reactor” sector:

θ_{13} best measured in experiments where ν_e disappearance dominates over short distances: ν_s from nuclear reactors (more on δ in a moment)

“Solar” sector:

best measured in experiments where ν_e disappearance dominates over long distances: ν_s from solar nuclear fusion

Neutrino oscillations: mixing angles

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

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Big question:

Is δ nonzero?

(If it is, neutrinos—and thus leptons—violate CP symmetry!
... leptogenesis??)

“Reactor” sector:

δ accessible
via ν_e appearance
in accelerator expts.

Neutrino oscillations: mixing angles

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

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“Atmospheric” sector:

best measured in experiments where ν_μ disappearance

dominates: ν_s from cosmic ray muon decays; **accelerators**

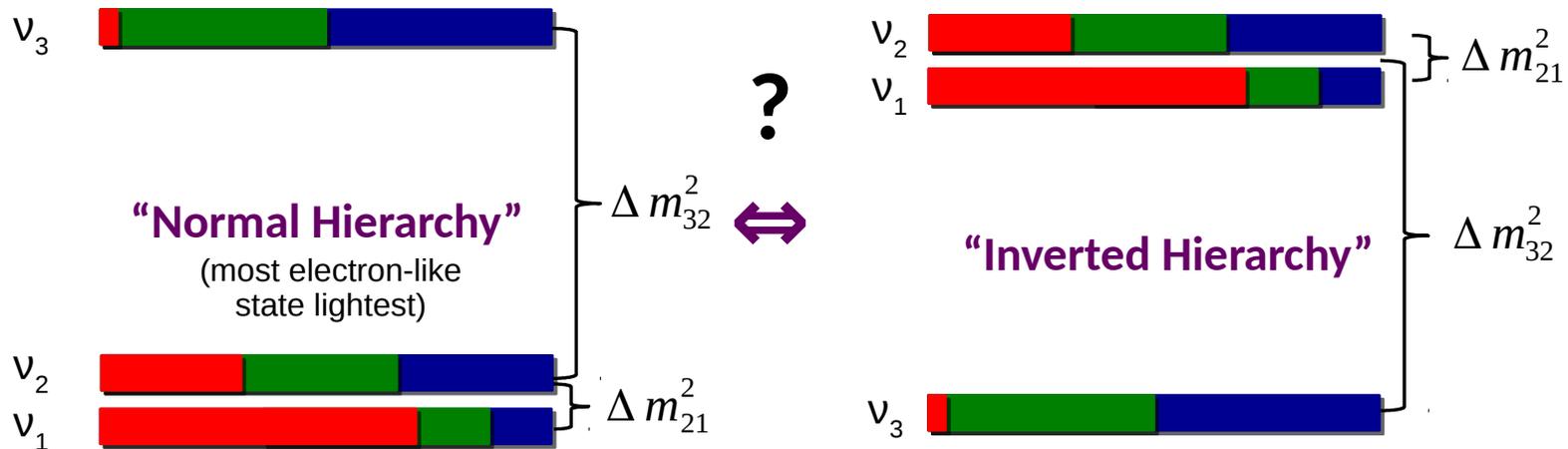
Big question:

Is there a symmetry governing the ν_μ/ν_τ mixing into the 2nd and 3rd mass states?
(Is θ_{23} “maximal” = 45°?)



Neutrino oscillations: mass splittings

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$



Big question:

Which way around are the mass states ordered?

(If "inverted," we might be able to conclusively find/rule out Majorana neutrinos soon.)

ν_e appearance from accelerator vs, also possibly reactor disappearance

Measuring neutrino oscillation parameters and NOvA

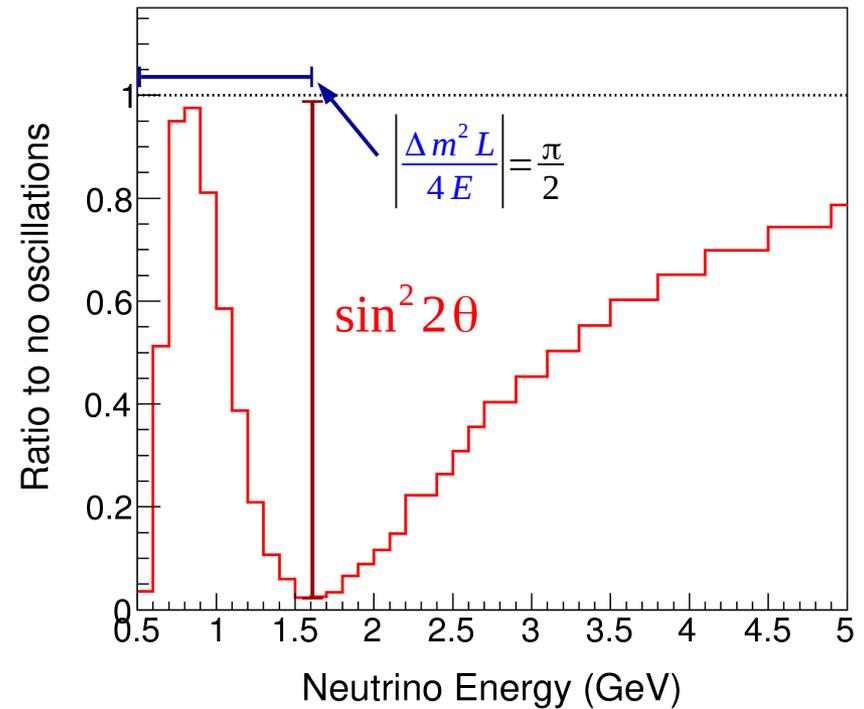
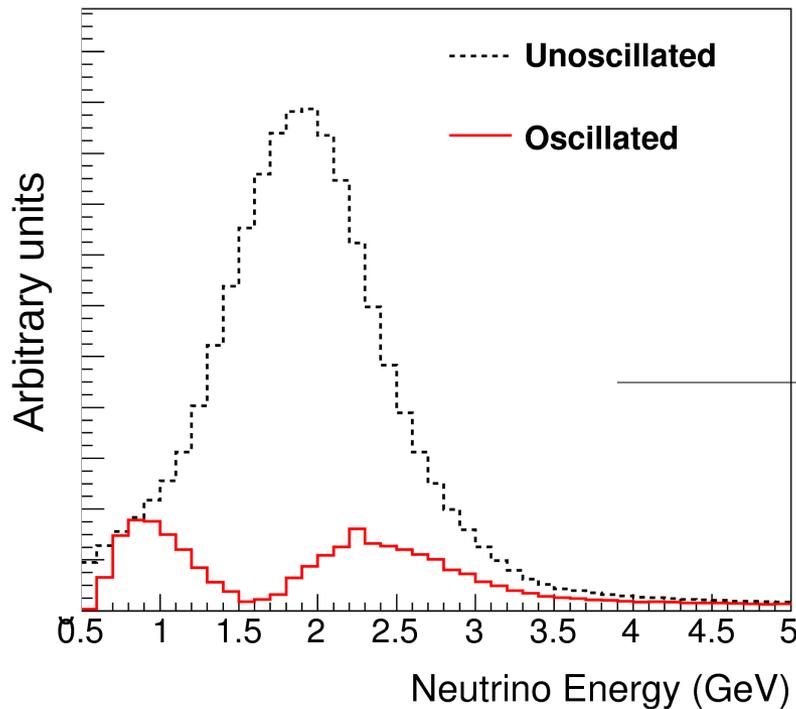
Long-baseline neutrino experiments

Imagine for a moment you're only oscillating between *two* flavors. Then:

$$P_{\nu_\alpha \rightarrow \nu_\beta} \approx \sin^2 2\theta \sin^2 \left(\Delta m^2 \frac{L}{4E} \right)$$

How far away from the source you build your detector

Energy spectrum of your neutrino beam



Long-baseline neutrino experiments

ν_μ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m_{32}^2 L / 4E)$$

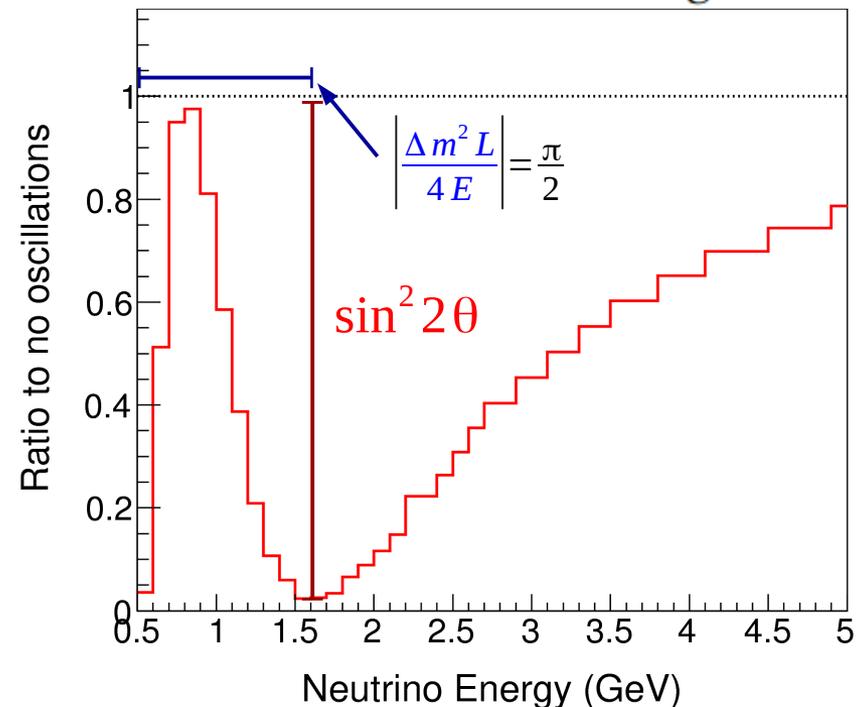
Because ν_μ/ν_τ is nearly 50/50 in all the mass states,



this is *nearly exactly* what you get when you start with ν_μ of a few GeV at distances of a few hundred km from the source.

➔ An experiment we can build.

... to leading order



Long-baseline neutrino experiments

ν_e appearance is quite a bit harder because θ_{13} is small...

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

sin²2θ₂₃ in ν_μ disappearance...

note sign flip
for
antineutrinos

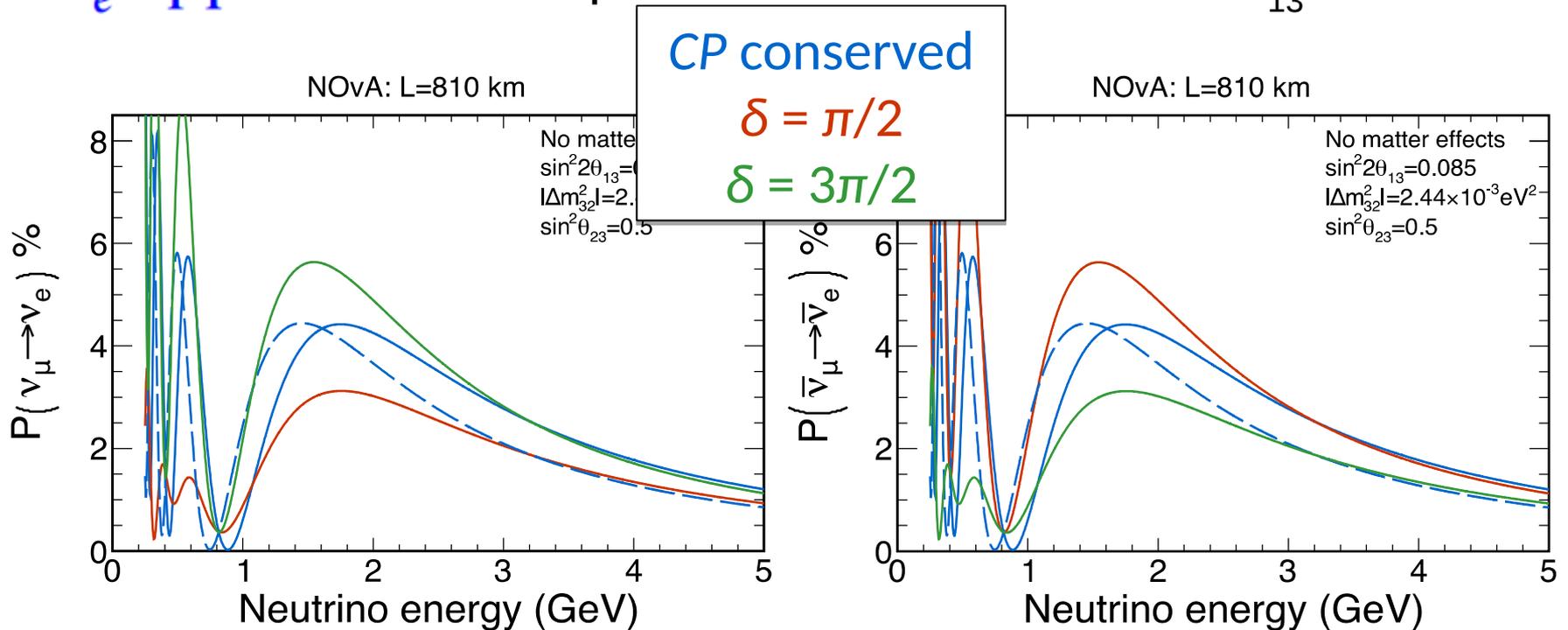
$$\begin{aligned} & - 2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin \Delta \\ & + 2\alpha \sin \theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos \Delta \end{aligned}$$

Where: $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$ $\Delta = \Delta m_{31}^2 \frac{L}{4E}$ $A = \frac{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$

... but if you can measure it well (for ν and $\bar{\nu}$),
you gain access to both δ and the mass ordering.
 LO θ_{23} dependence suggests *combining with ν_μ disappearance*

Long-baseline neutrino experiments

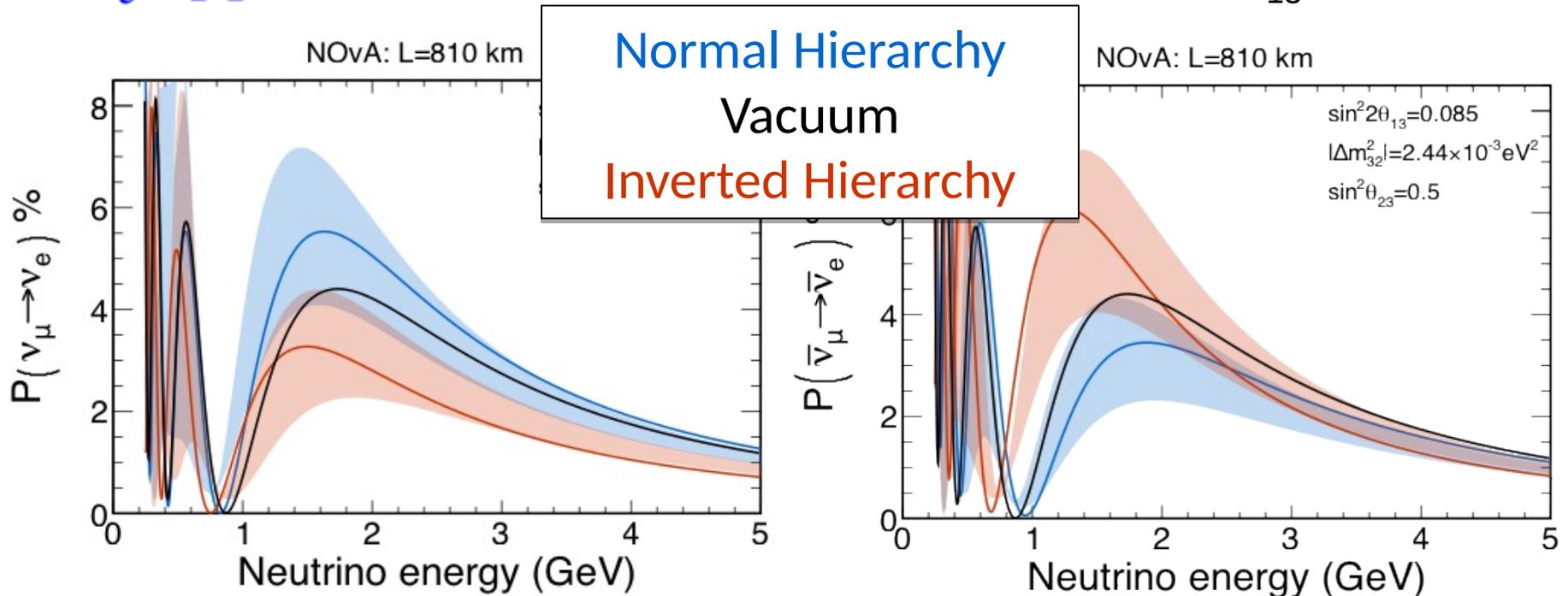
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Long-baseline neutrino experiments

ν_e appearance is quite a bit harder because θ_{13} is small...



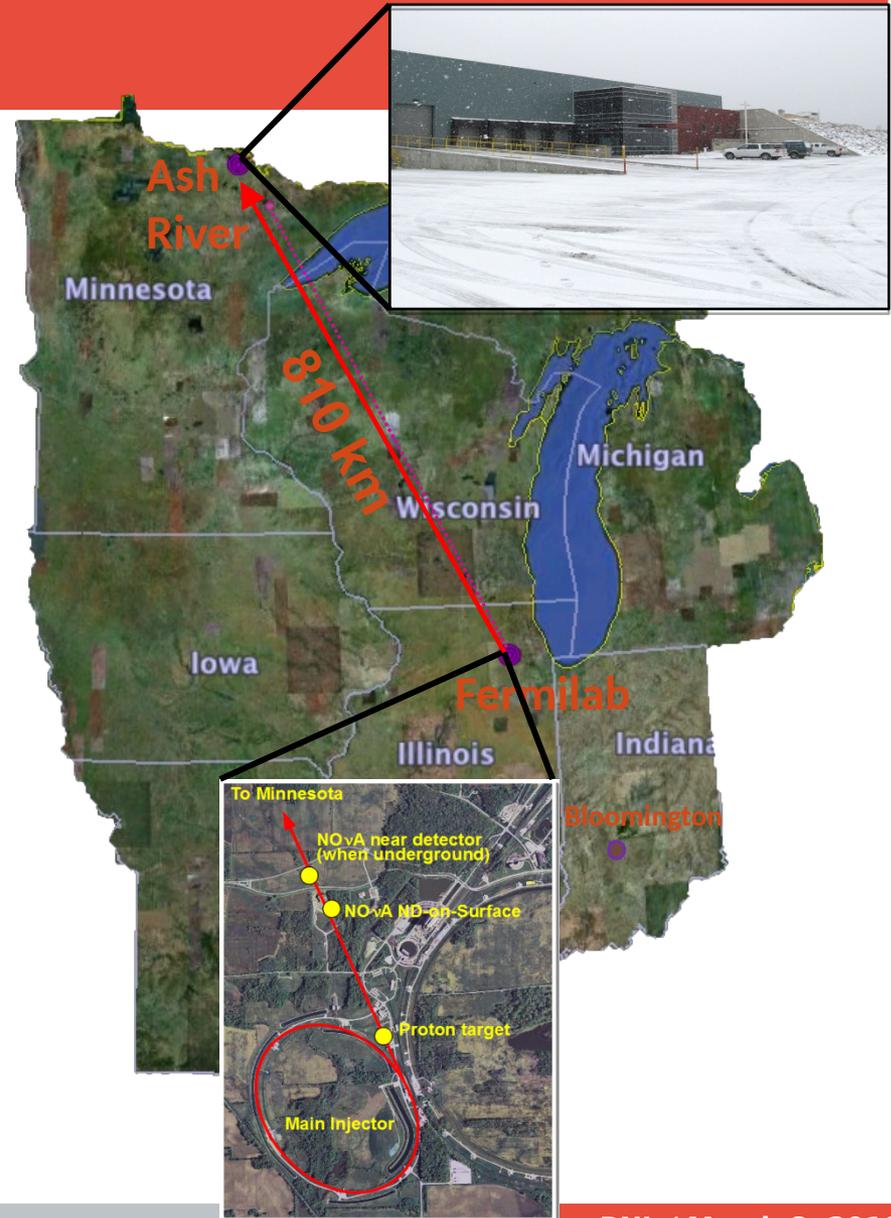
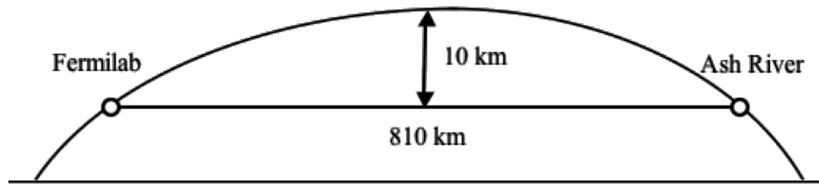
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 LO θ_{23} dependence suggests combining with ν_μ disappearance

The NOvA experiment

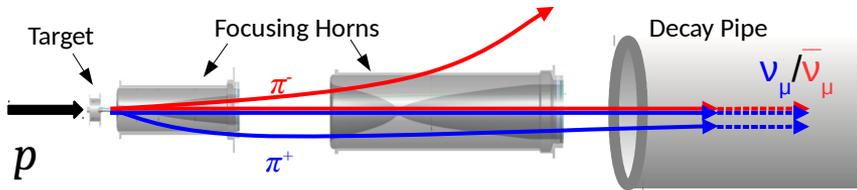
NuMI Off-axis ν_e Appearance Experiment

NuMI = Neutrinos at the Main Injector

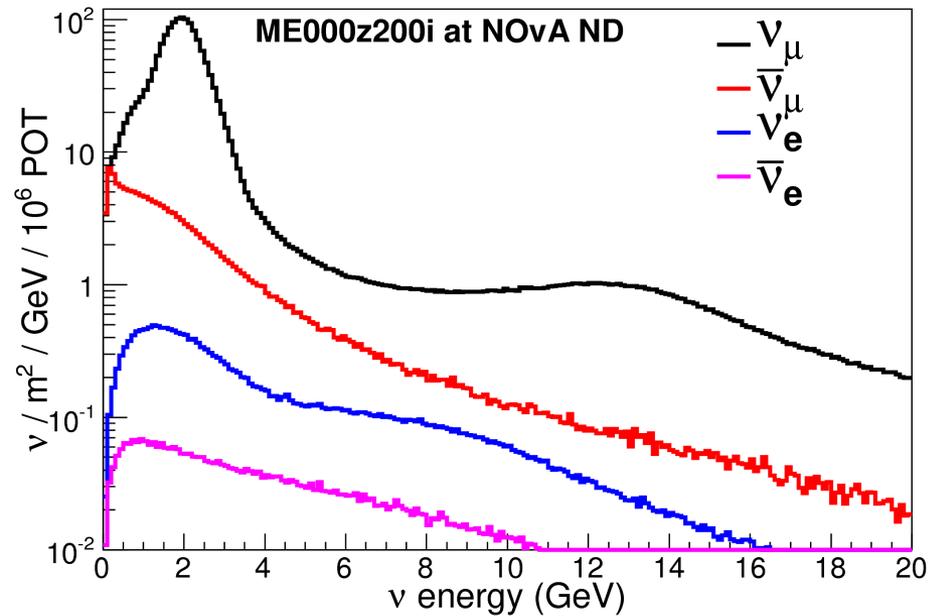
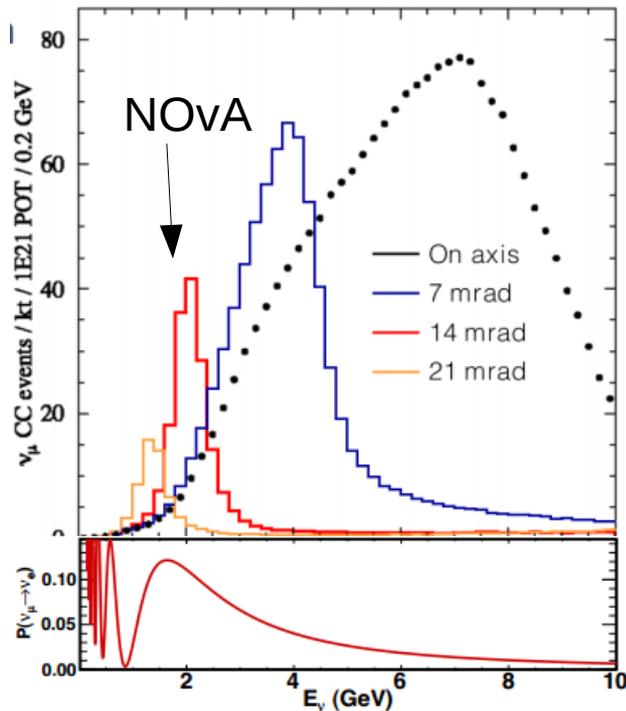
- Long-baseline (anti-)neutrino oscillation experiment
- Two functionally identical detectors, optimized for ν_e identification



The NuMI beam

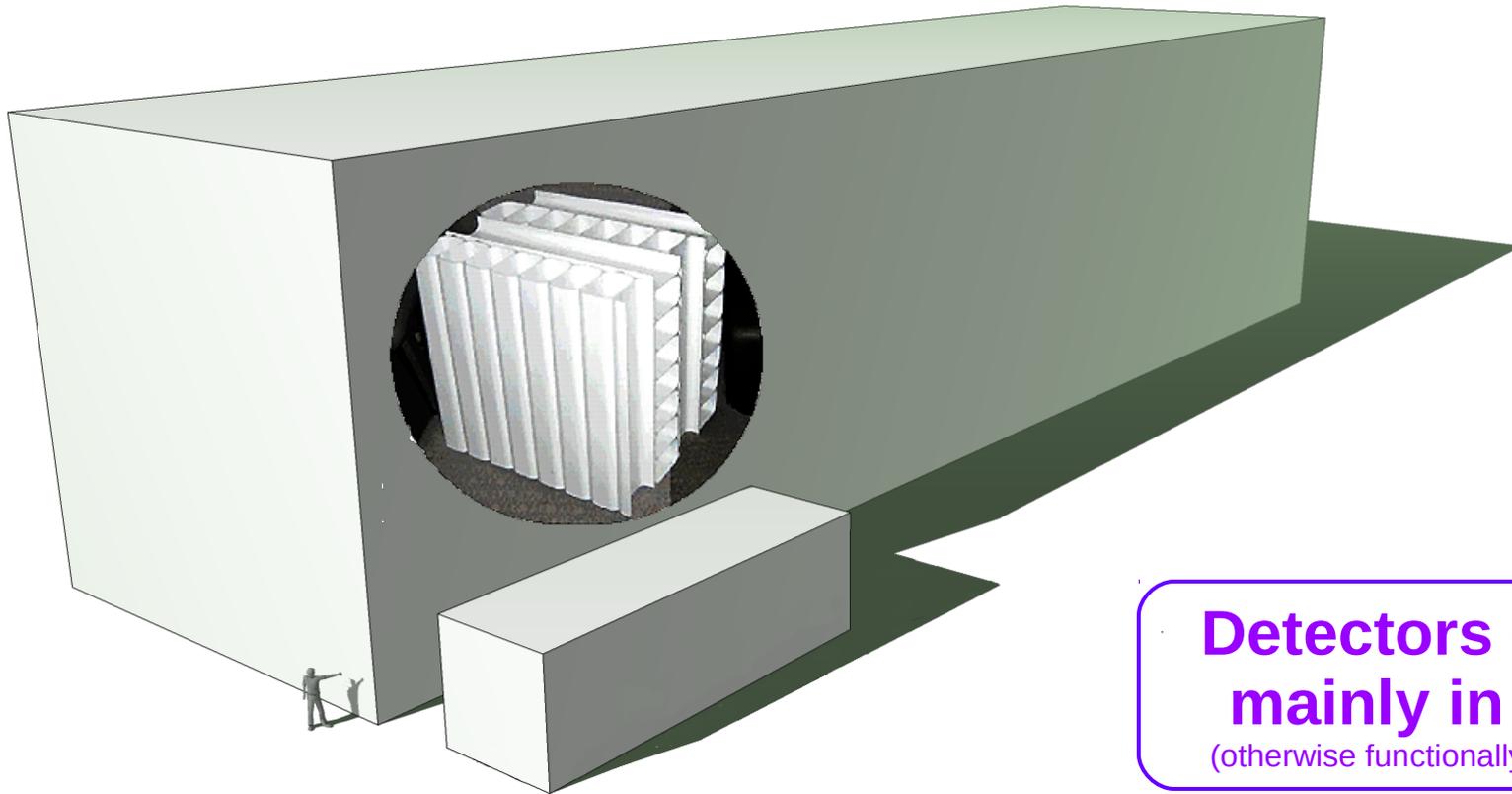


NOvA Simulation



- Combination of horn focusing and off-axis angle choice allows tuning of spectrum
- $> 97\%$ ν_μ in peak region

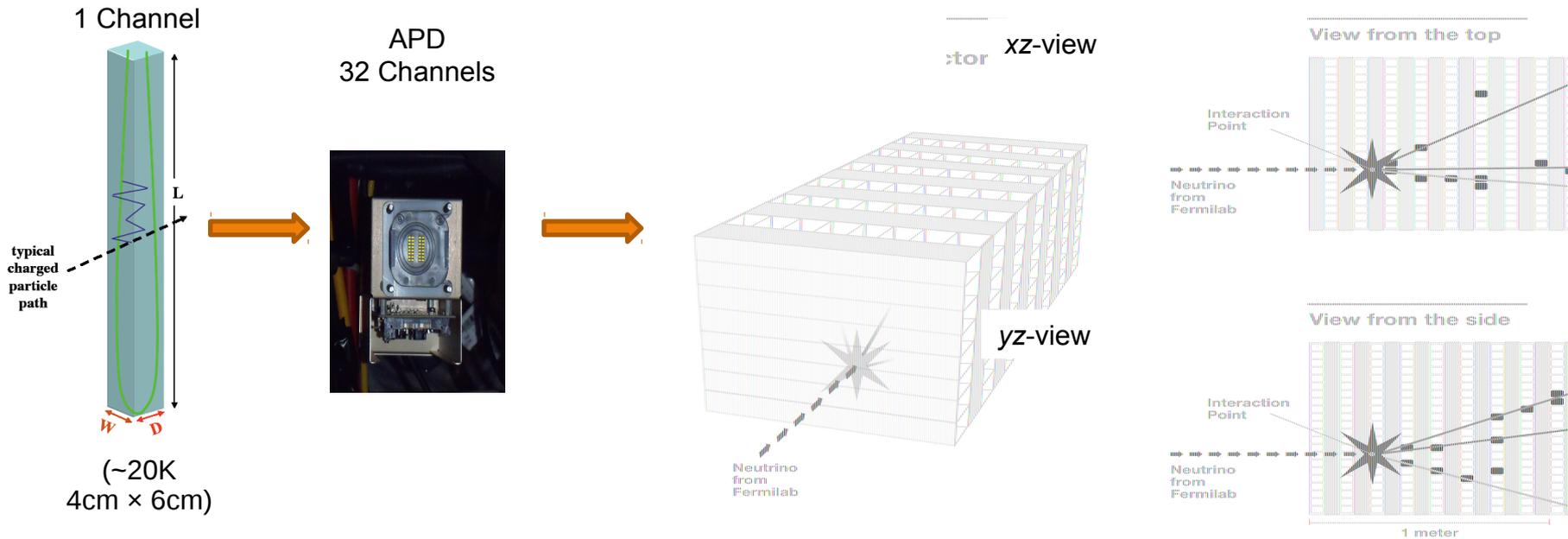
The NOvA detectors



**Detectors differ
mainly in size**
(otherwise functionally identical)

- Near Detector: 300 ton, 1 km from source
 - 100m underground, 20,000 channels
- Far Detector: 14 kton, 810 km from source
 - On the surface, 3m concrete+barite overburden; 344,000 channels

The NOvA detectors



- Good energy resolution for muons, electromagnetic & hadron showers:
 - Mostly (65%) active detector
 - Radiation length ~ 40 cm \rightarrow 6 samples per radiation length

Main idea:

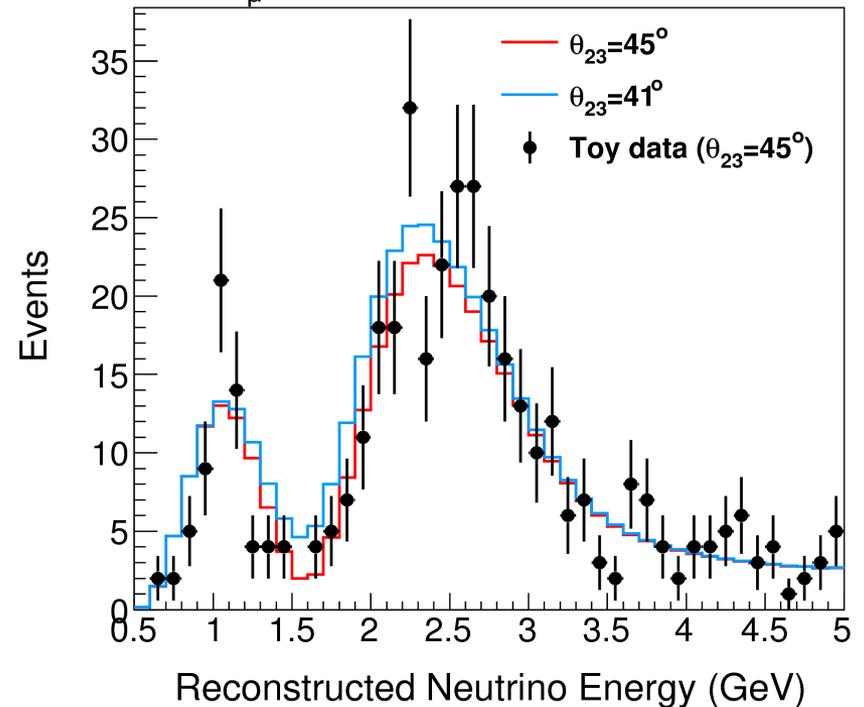
Compare

predicted spectrum at FD
to
observed spectrum at FD

to extract oscillation parameters

Discuss in two steps:
building the spectrum,
then details of prediction

ν_μ disappearance example



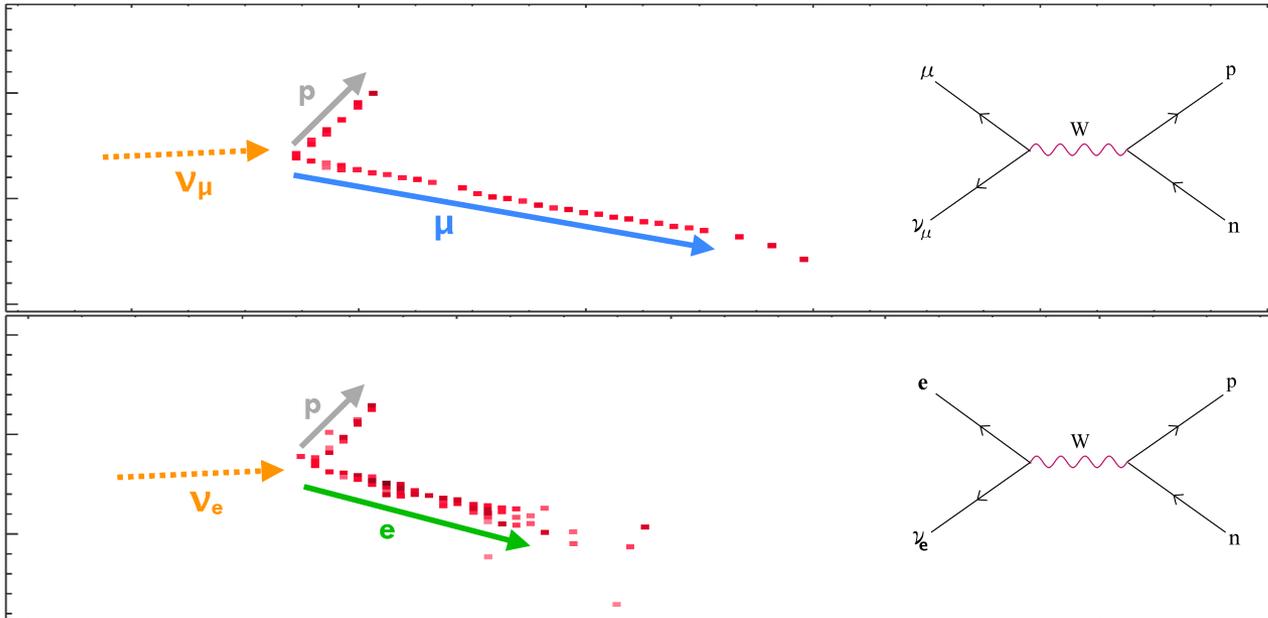
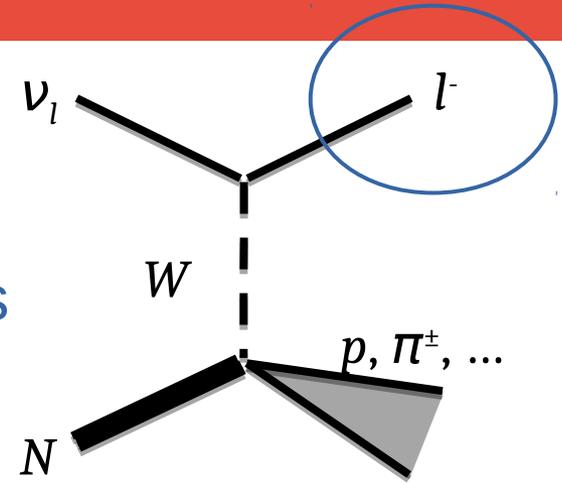
Spectrum construction

- (1) Event selection
- (2) Reconstruction & observables

Spectrum construction: identifying neutrino events

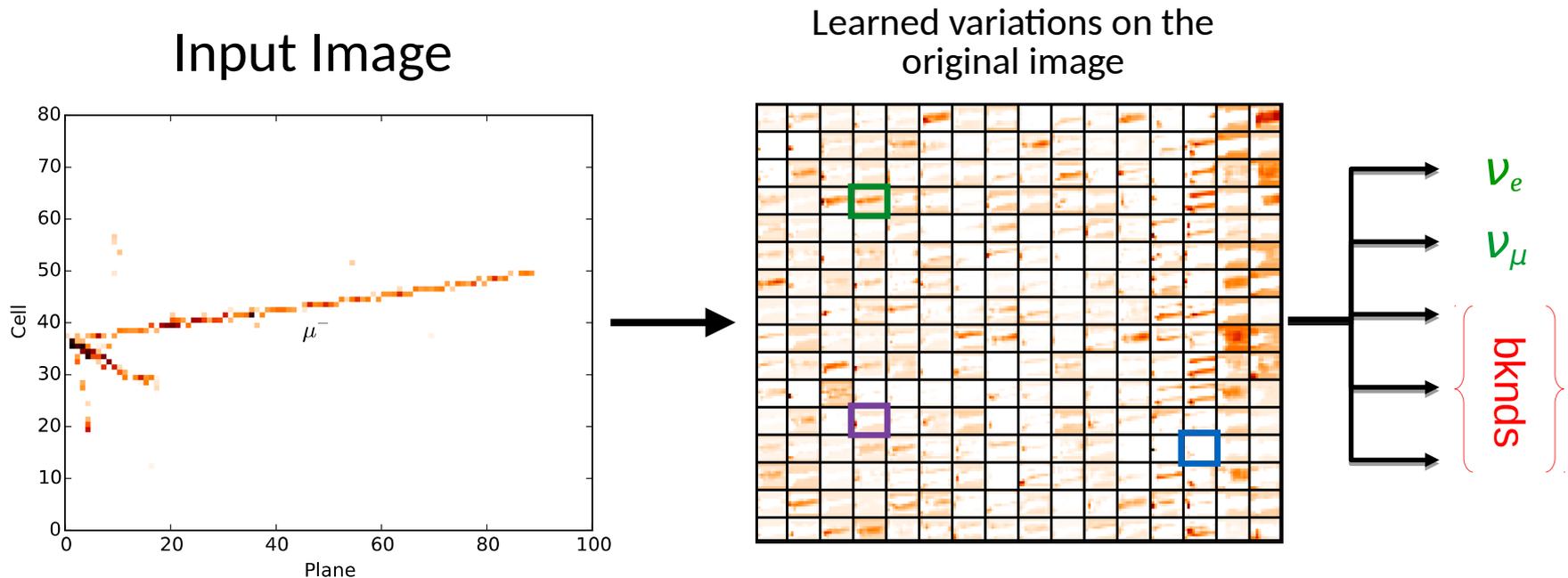
Q: How do you identify a ν_μ or ν_e ?

A: Look for charged-current reactions
(charged leptons differ & backgrounds have no primary charged lepton)



Selections share many ingredients; will discuss in parallel

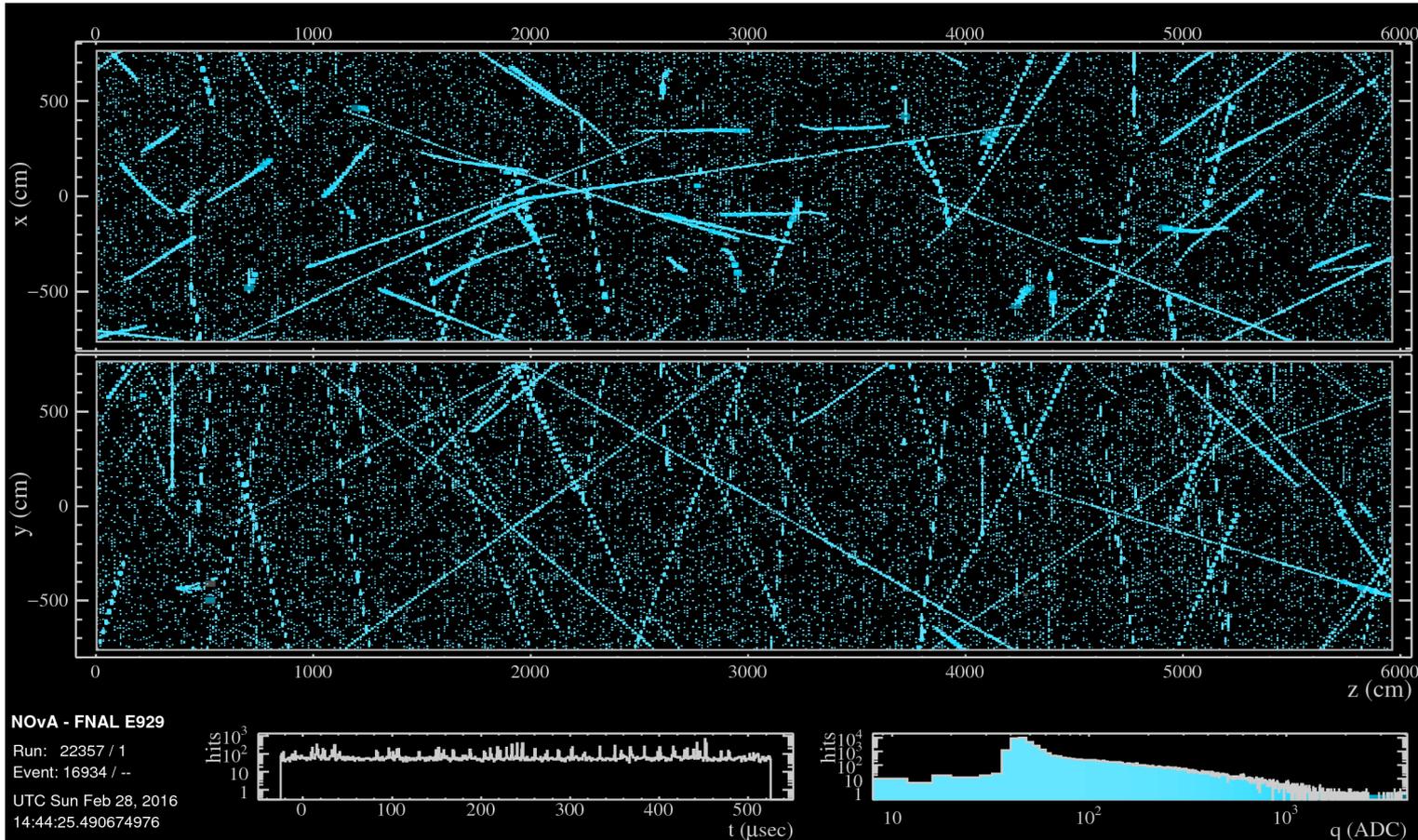
Spectrum construction: identifying neutrino events



- Use *convolutional neural network* (CNN) called **Convolutional Visual Network, CVN**:
 - Treat events like *images* (but use calibrated energy deposits in cells rather than colors)
 - The CNN learns *features* (smaller groupings of patterns)
 - Successive layers in network refine and abstract previous layers' features
 - Last layer in network is “conventional feed-forward NN” which maps onto desired output classes
- Trained on simulation (details later) and FD cosmic data

[A. Aurisano and A. Radovic and D. Rocco et. al, JINST **11** P09001 (2016)]

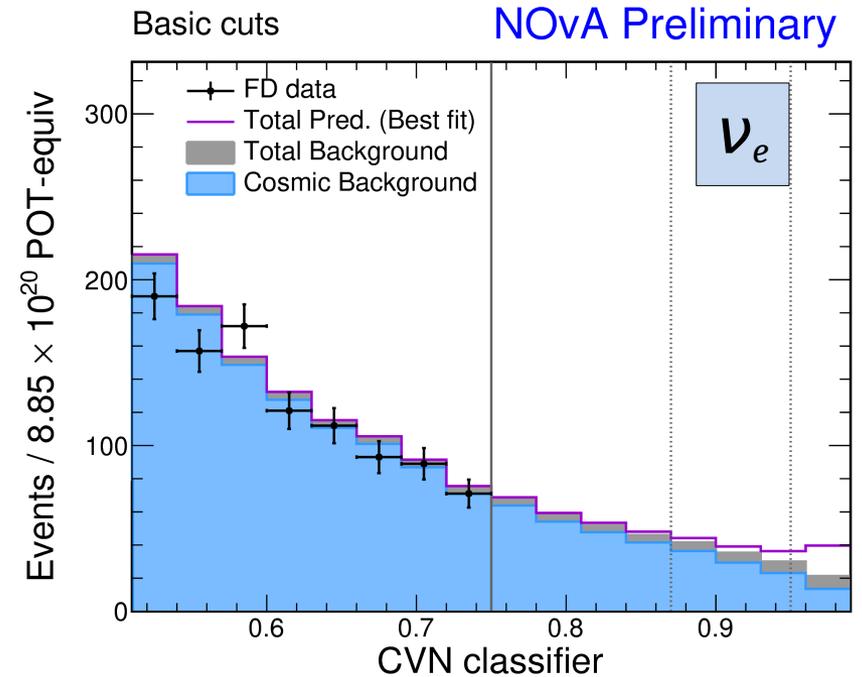
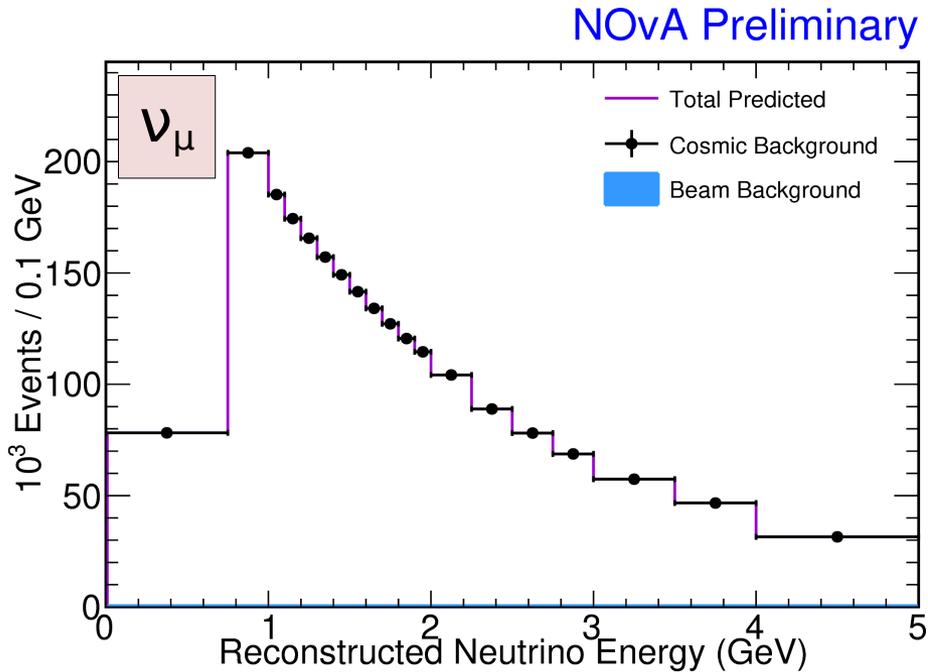
Spectrum construction: Identifying neutrino events



One 550 μs
readout window.
~All cosmics.

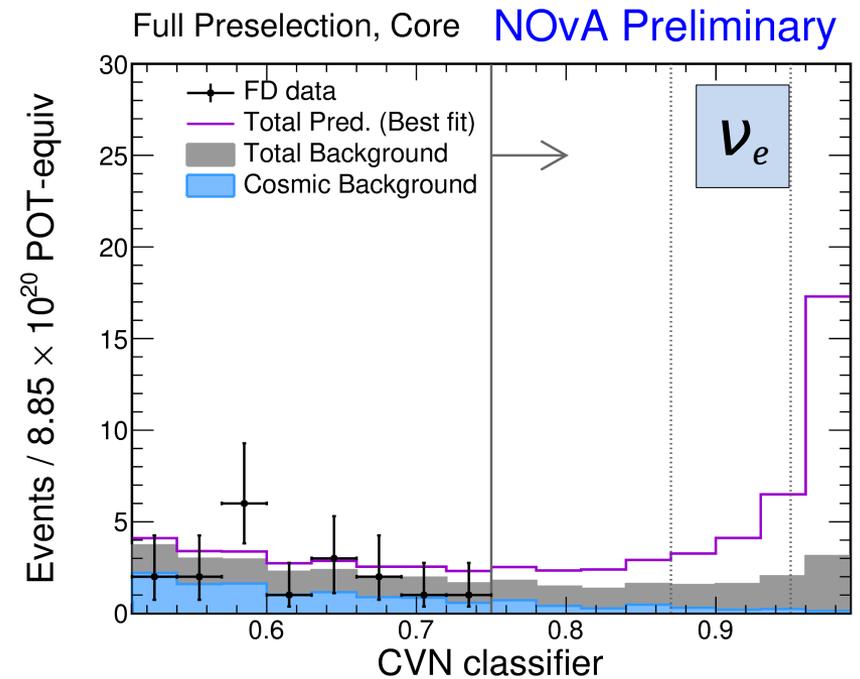
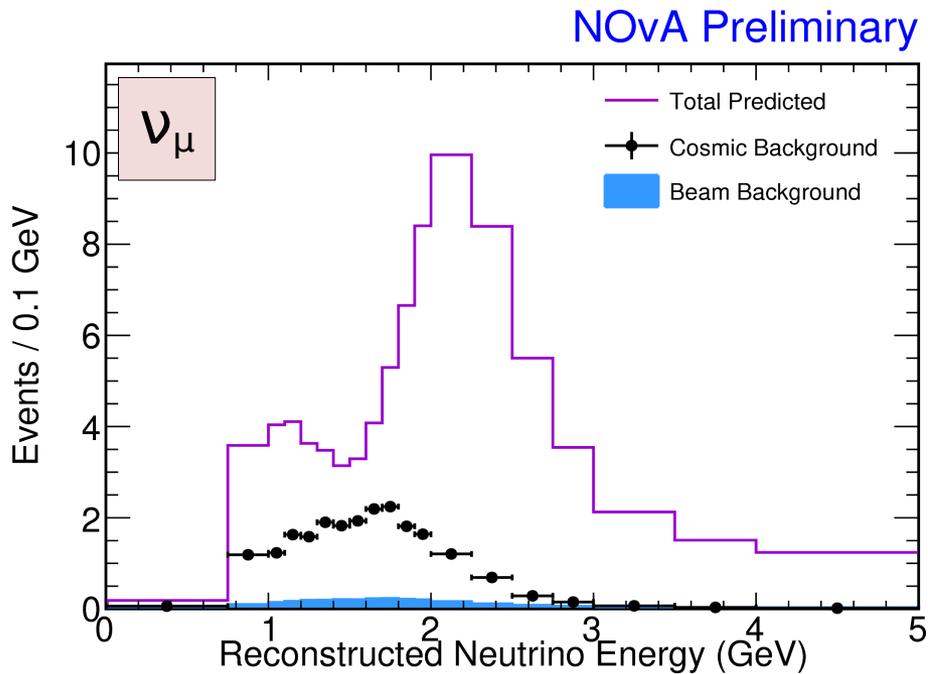
One more problem:
FD sits on the surface \rightarrow ~150 KHz cosmics!

Spectrum construction: Identifying neutrino events



Pulsed beam + good timing resolution
and **basic event quality/containment** requirements
help a lot, but still dominated by cosmics...

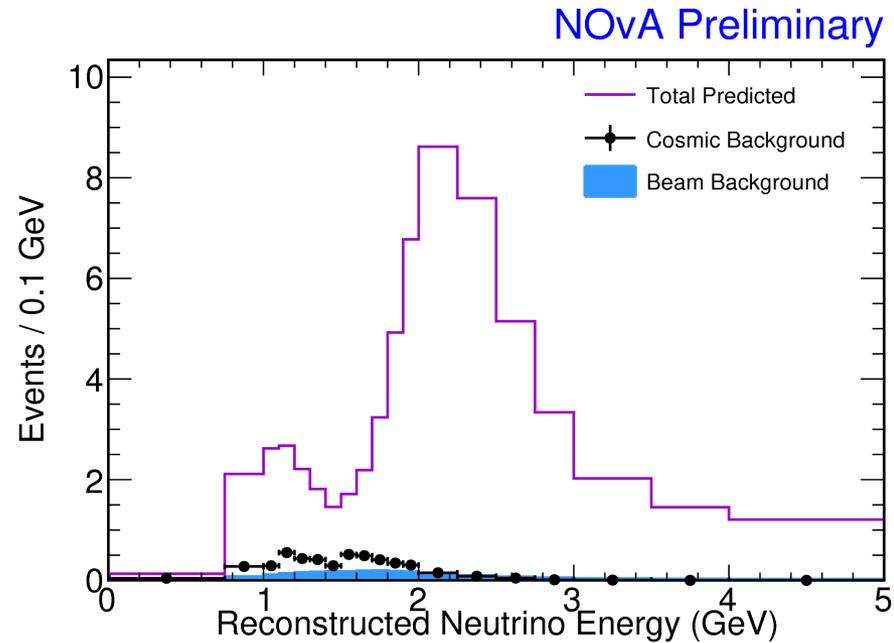
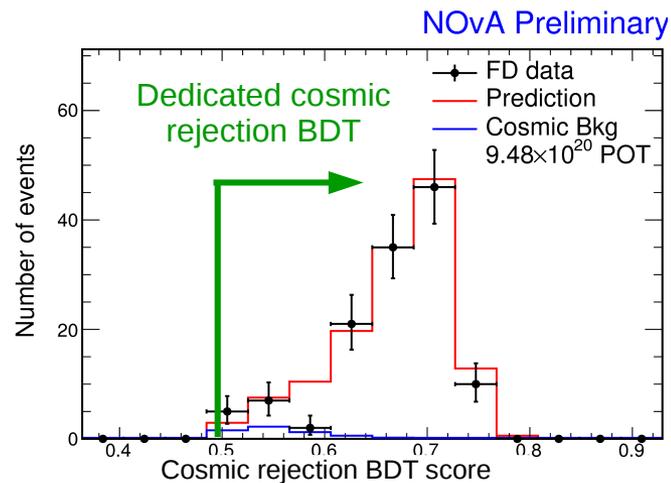
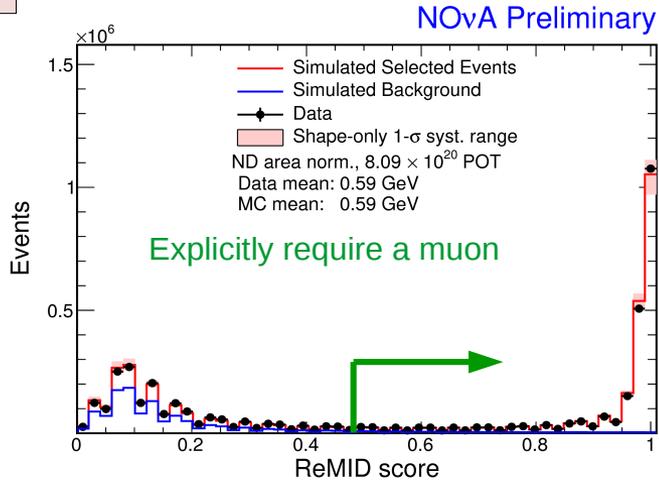
Spectrum construction: Identifying neutrino events



CVN particle ID & dedicated ν_e cosmic cuts
reduce cosmic background to manageable level,
but we can still do better
(CVN ν_μ new in 2017)

Spectrum construction: Identifying neutrino events

ν_μ

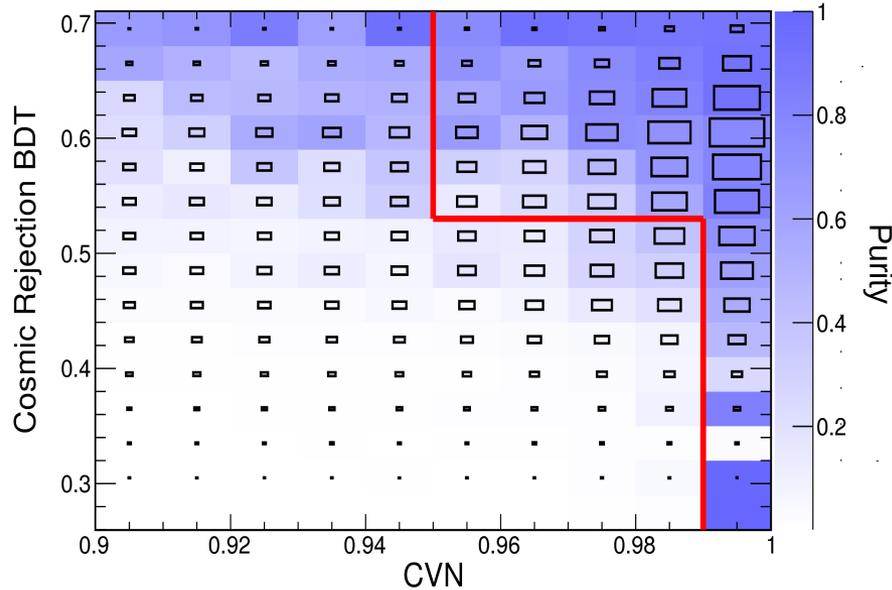


Spectrum construction: Identifying neutrino events

ν_e

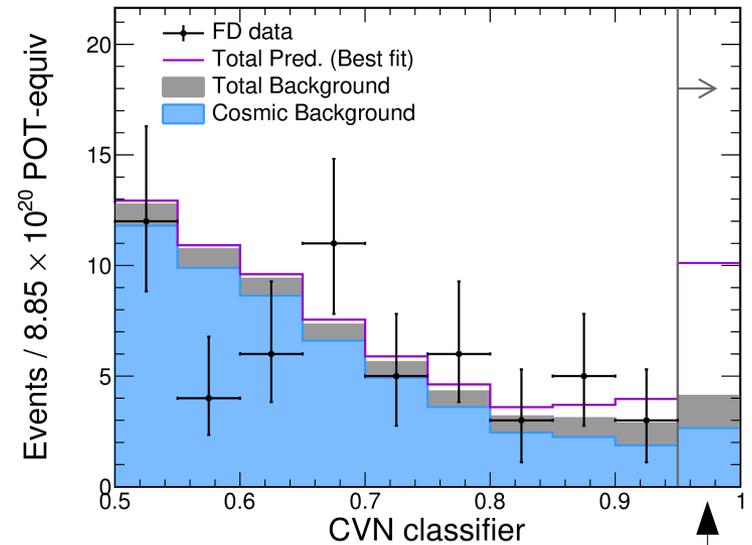
New in 2017

NOvA Preliminary



BDT cut, Peripheral

NOvA Preliminary



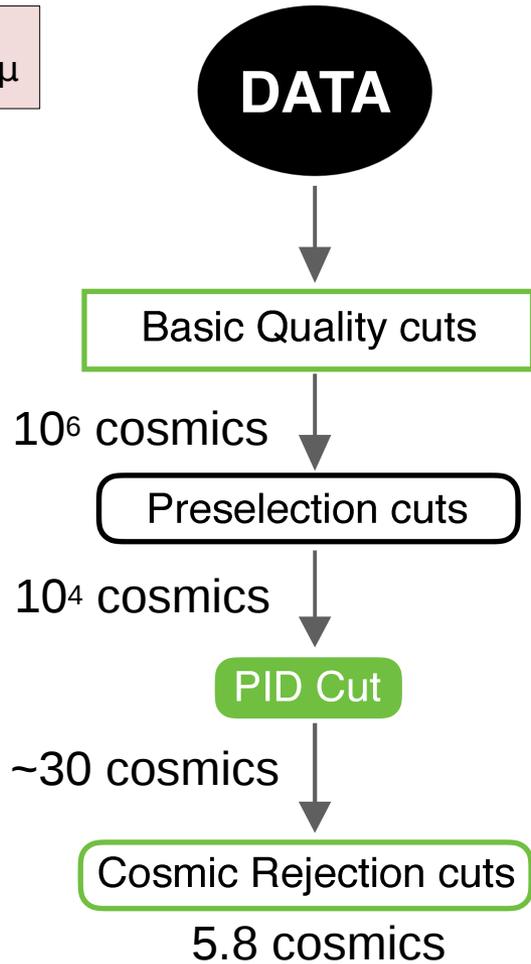
ν_e cosmic cuts are harsh.
 Recover events near edges
 but high PID (so lots of signal)
 w/ dedicated multivariate classifier

Retain these events

→ “Peripheral” sample

Spectrum construction: Identifying neutrino events

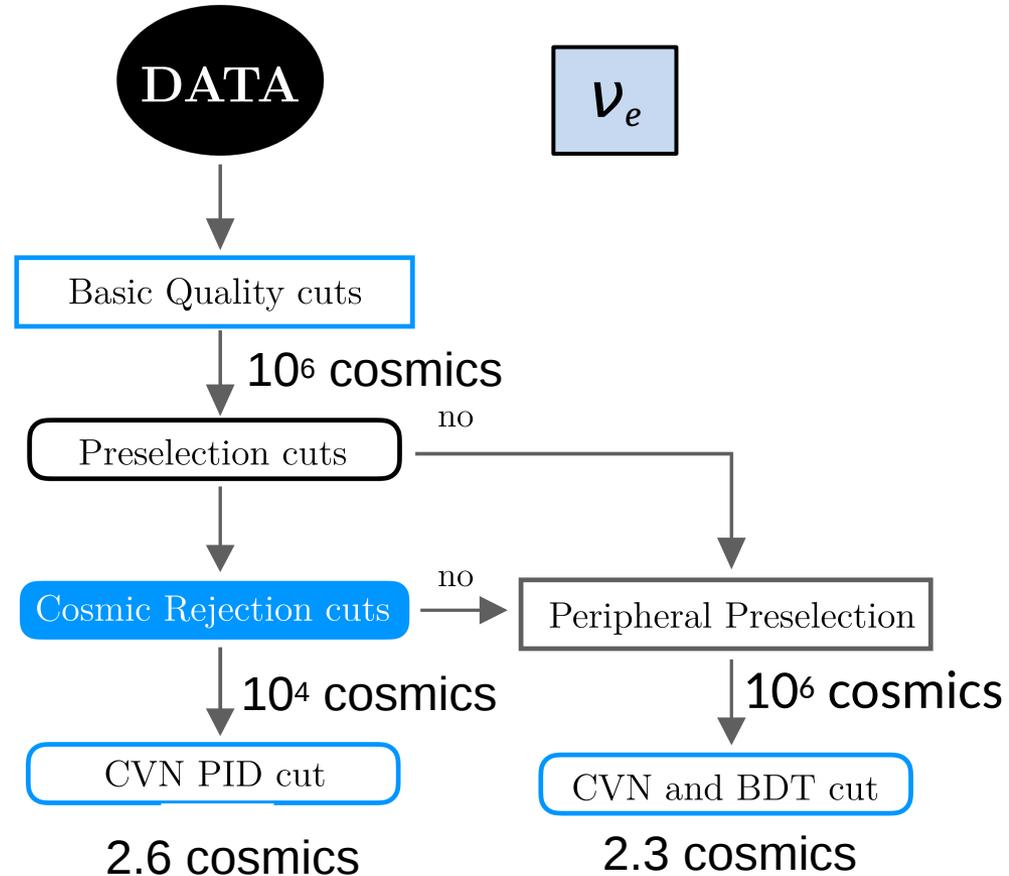
ν_μ



(c.f.: $\sim 130 \nu_\mu$ CC signal, 3.5 beam bknd)**

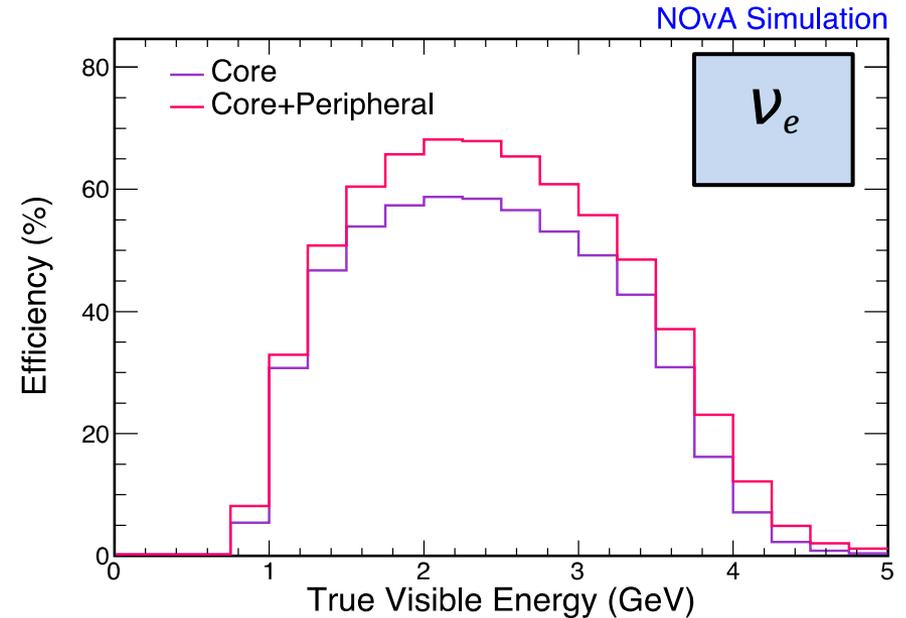
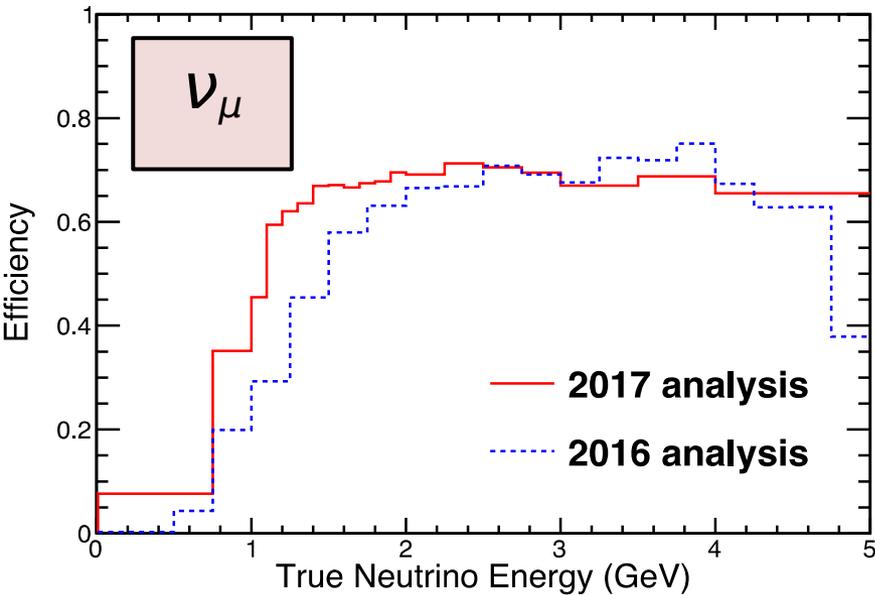
** These predictions will be discussed in more detail later

ν_e



(c.f.: $\sim 45 \nu_e$ CC signal, 15 beam bknd)**

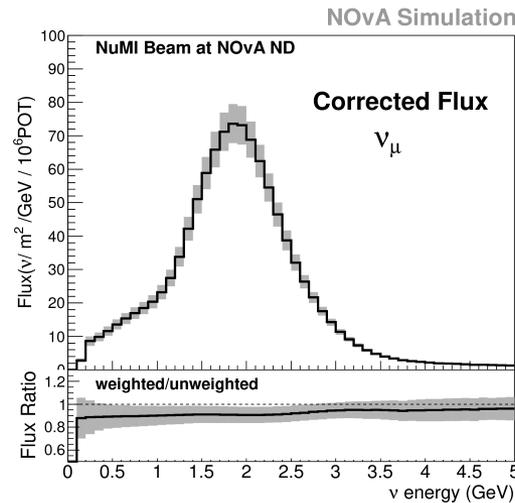
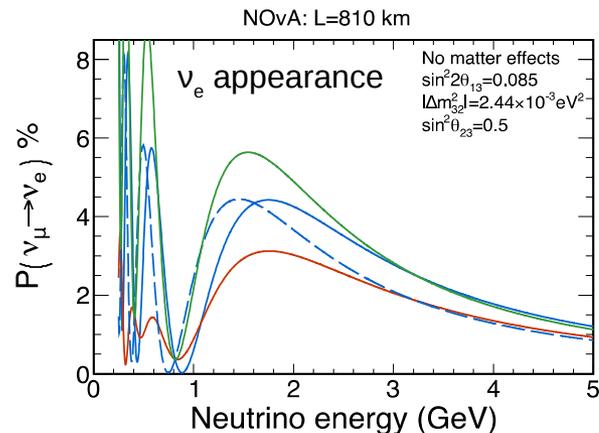
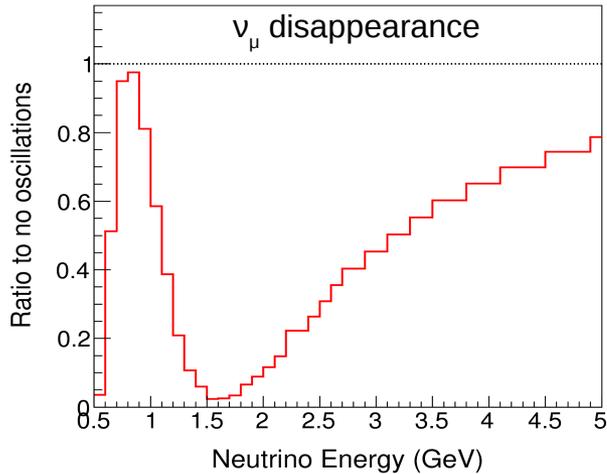
Spectrum construction: Identifying neutrino events



- New CVNm selector → Better efficiency at low energy in ν_μ
 - ~11% effective increase in exposure relative to 2016
- New peripheral sample → Better efficiency in ν_e
 - ~17% effective increase in exposure relative to 2016

Spectrum construction: Reconstructing neutrino energy

Oscillation is a function of *neutrino energy*:

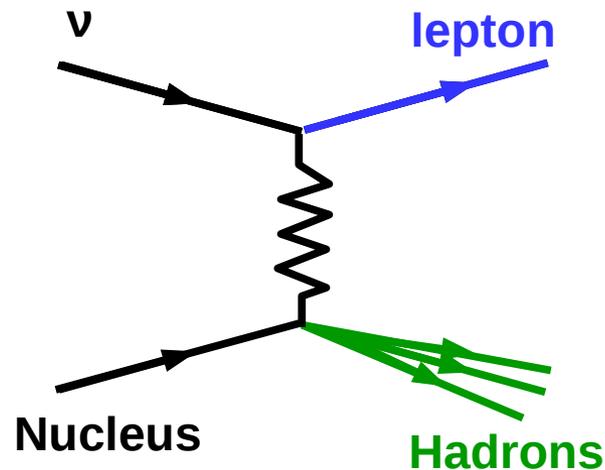


... SO we need to reconstruct neutrino energy from reaction byproducts event by event

... but neutrino beam isn't completely monochromatic (despite being off-axis) ...

Spectrum construction: Reconstructing neutrino energy

Strategy: divide and conquer

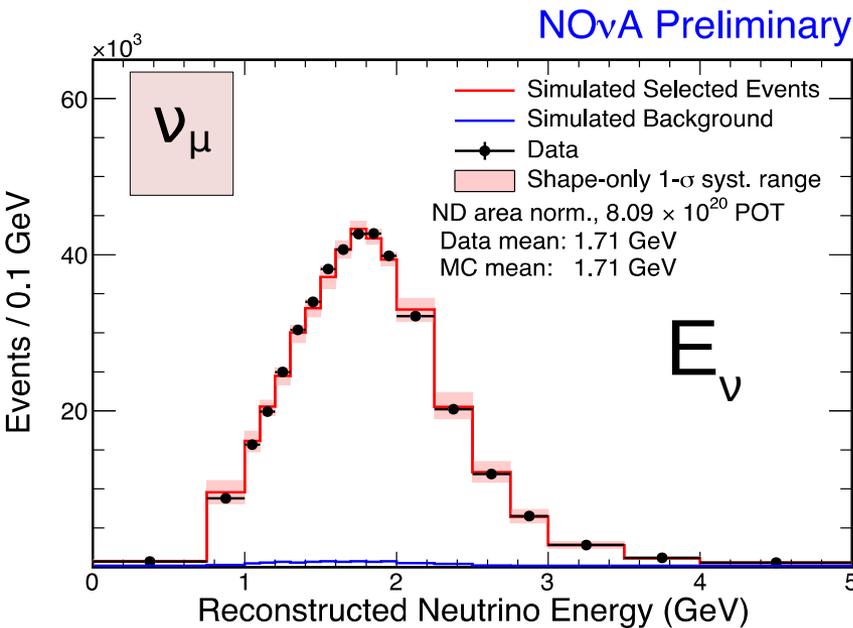


Evaluate the
lepton (muon or electron)
and
hadronic system
energies separately

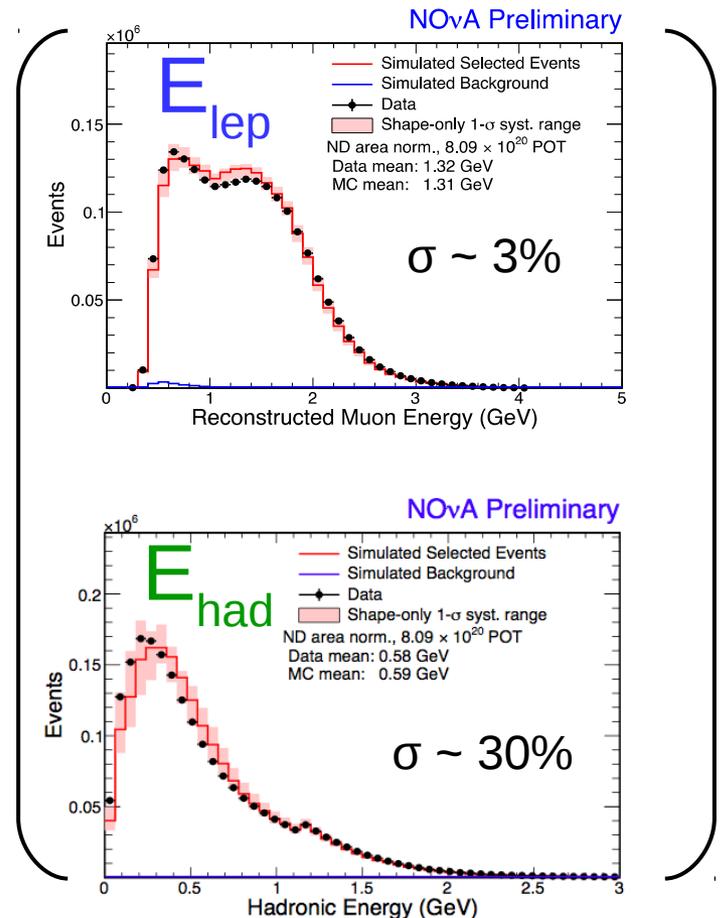
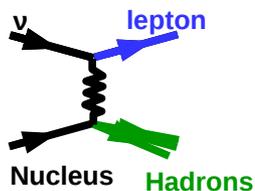
$$\longrightarrow E_{\nu} = f(E_{\text{lep}}, E_{\text{had}})$$

Spectrum construction: Reconstructing neutrino energy

Strategy: divide and conquer

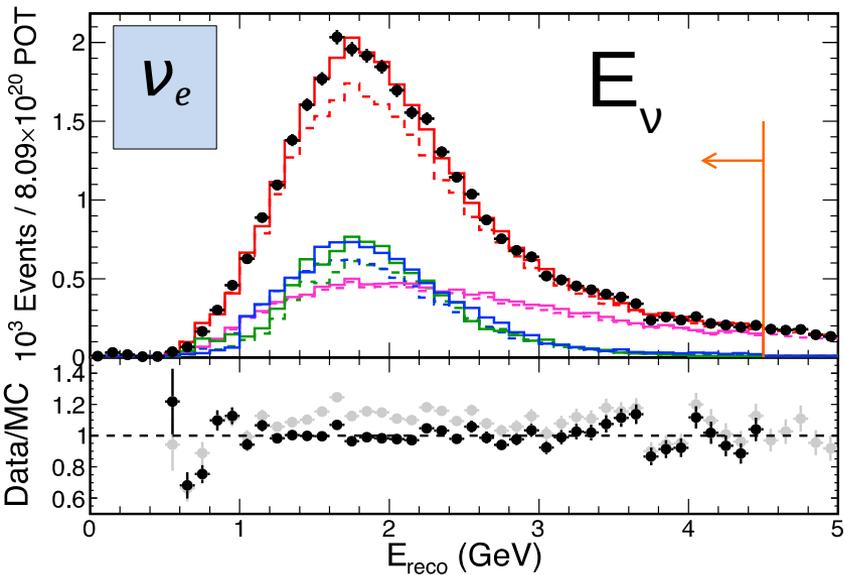


$= f$

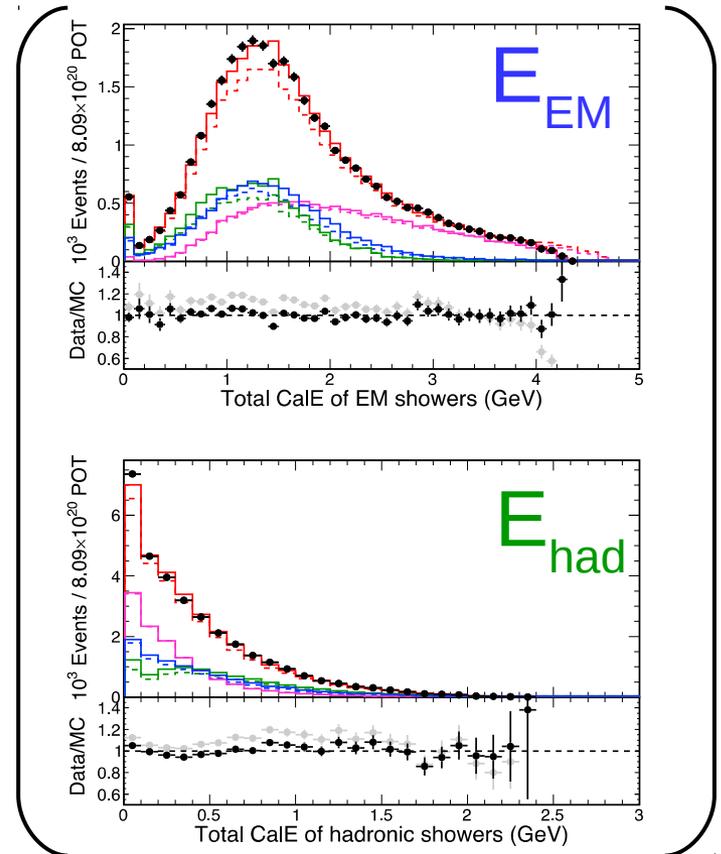
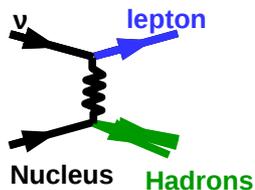


Spectrum construction: Reconstructing neutrino energy

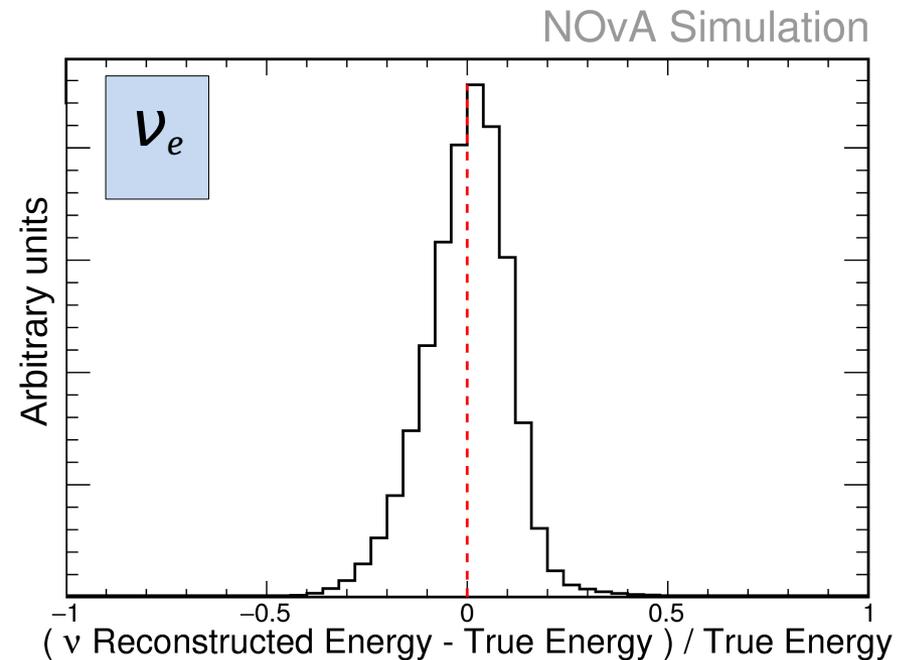
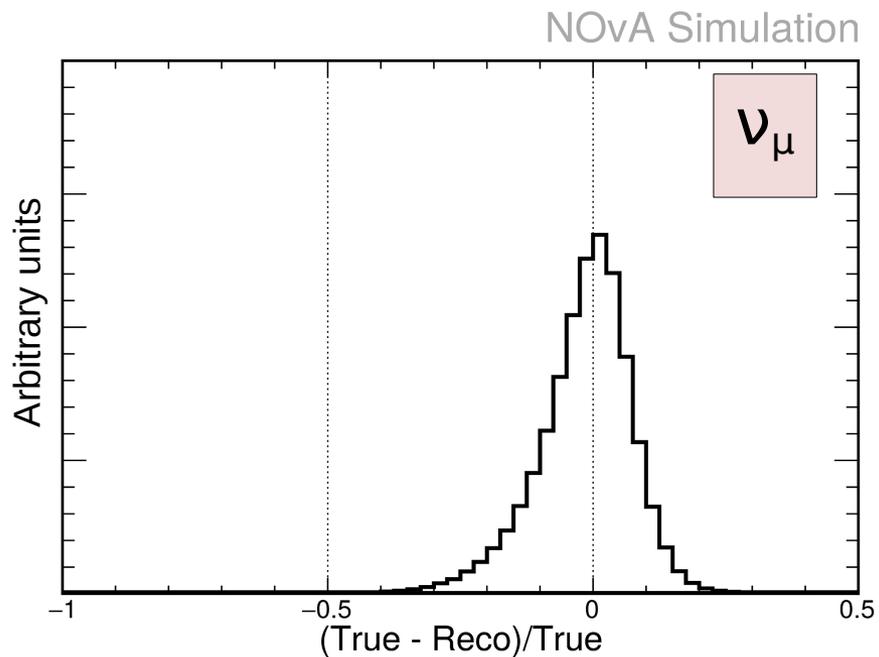
Strategy: divide and conquer



= f



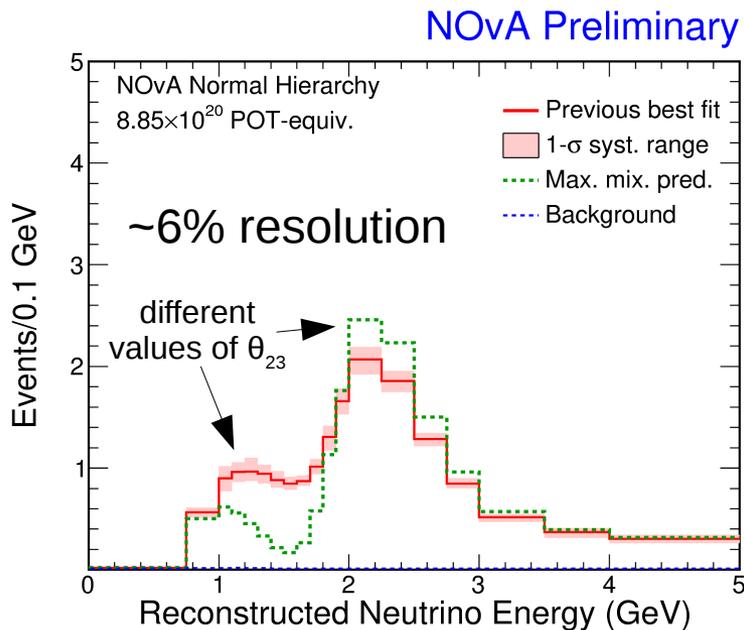
Spectrum construction: Reconstructing neutrino energy



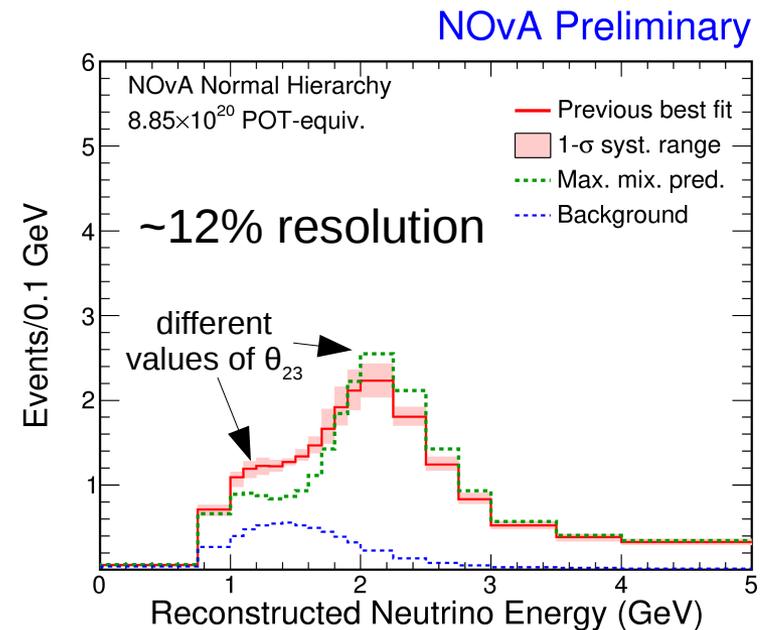
We reconstruct neutrino energy with
about 9% resolution for ν_μ s
and about 11% resolution for ν_e s.

Spectrum construction: ν_μ hadronic energy fraction binning

The power of the ν_μ disappearance analysis is from *shape* discrimination:

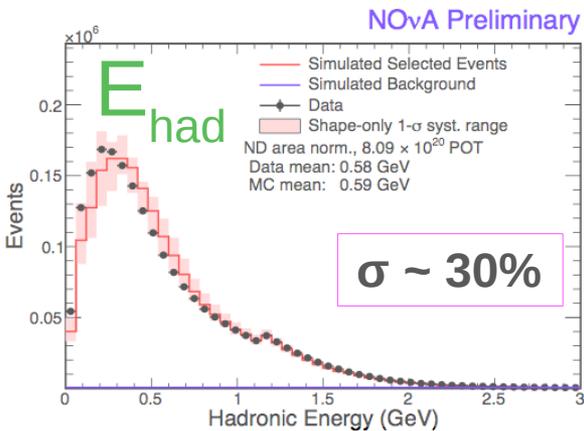
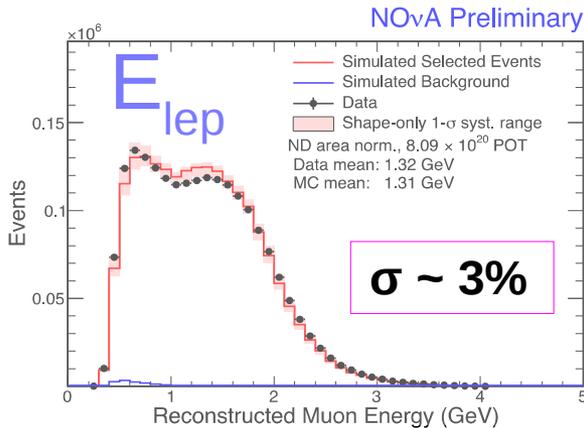


VS



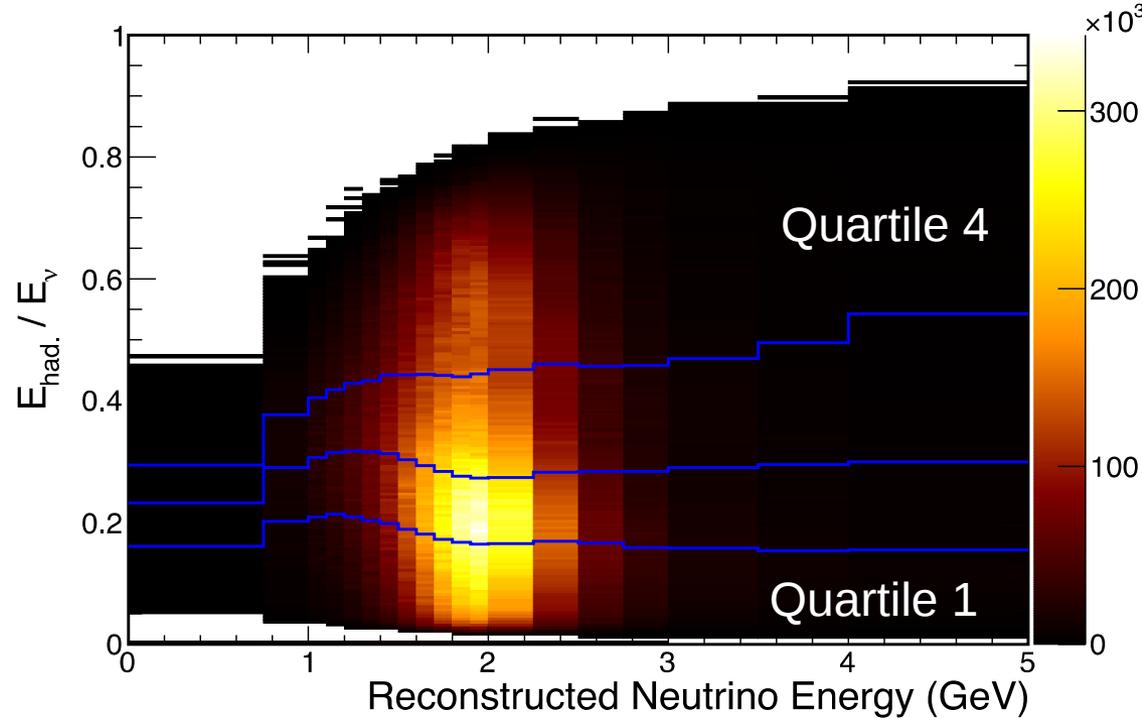
**Better resolution → less smearing in “dip”
→ better shape discrimination**

Spectrum construction: ν_μ hadronic energy fraction binning



Resolution for E_μ is
much better than E_{had}

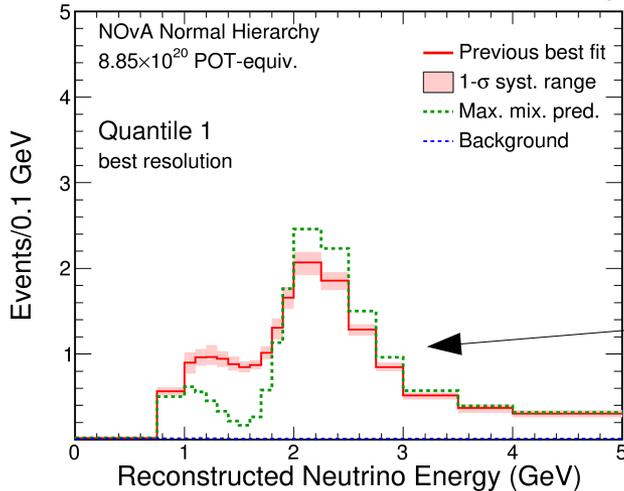
New in 2017



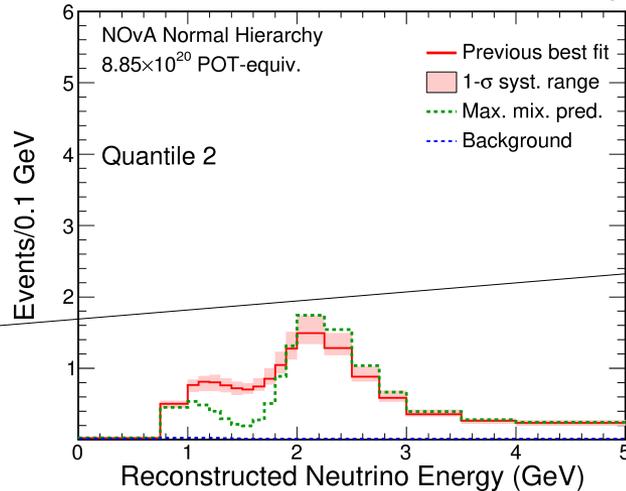
Dividing into four equal quartiles of
hadronic energy fraction = E_{had} / E_ν
roughly *separates best from worst resolved* populations

Spectrum construction: ν_μ hadronic energy fraction binning

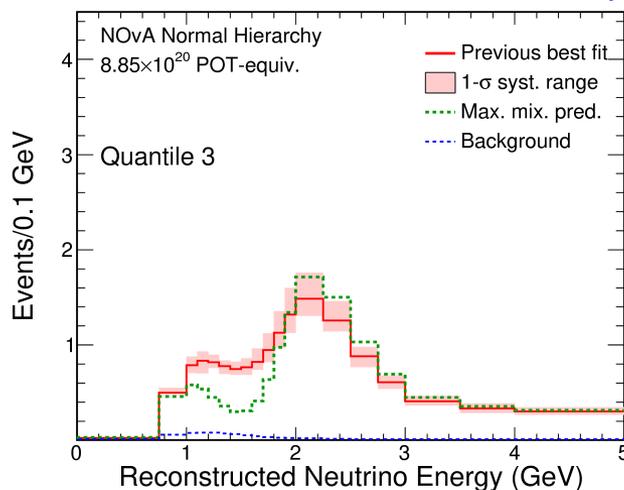
NOvA Preliminary



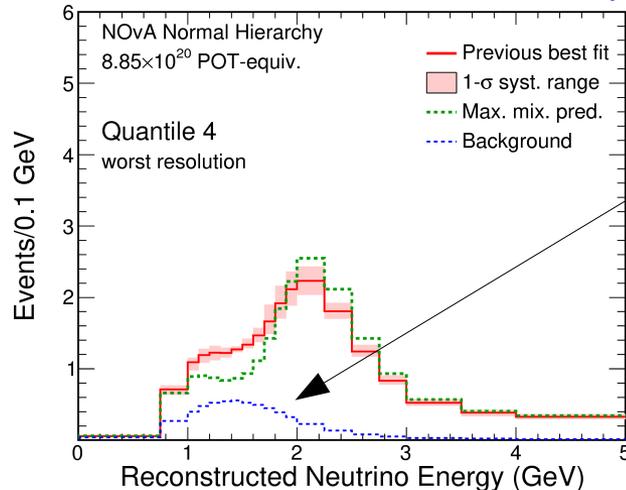
NOvA Preliminary



NOvA Preliminary



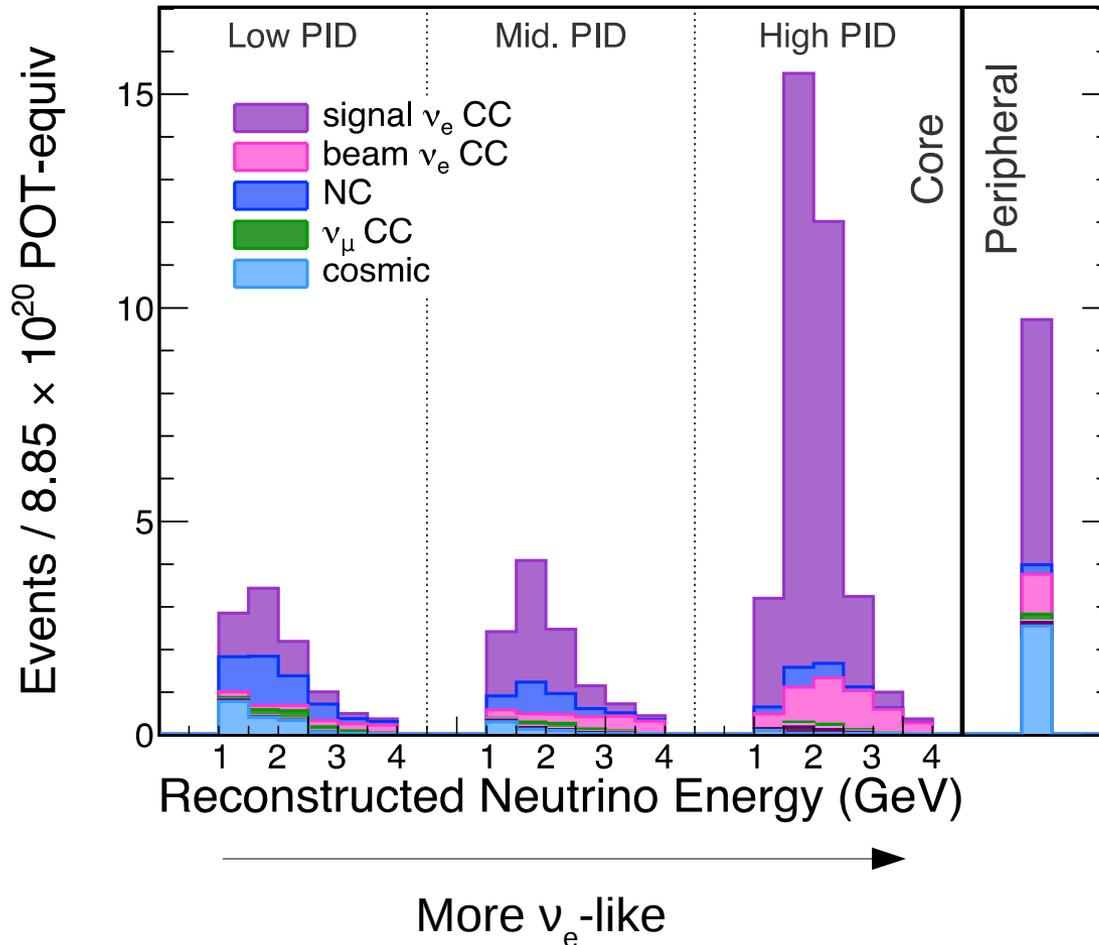
NOvA Preliminary



- Best shape discrimination in best resolution quartile (quartile 1)
- Most backgrounds also in worst resolution quartile (quartile 4) – both beam bknds and cosmics

Spectrum construction: ν_e binning

NOvA Preliminary



- Try to separate best-understood signal (high PID) from backgrounds
- Mild spectrum difference between appeared (signal) ν_e vs. intrinsic beam ν_e bknd (signal \sim lower E_ν)

Spectra

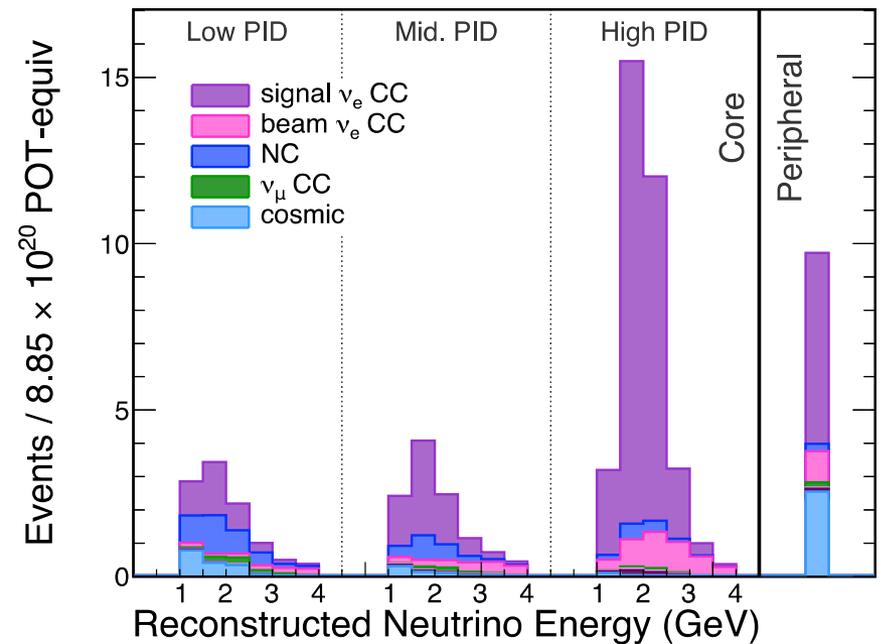
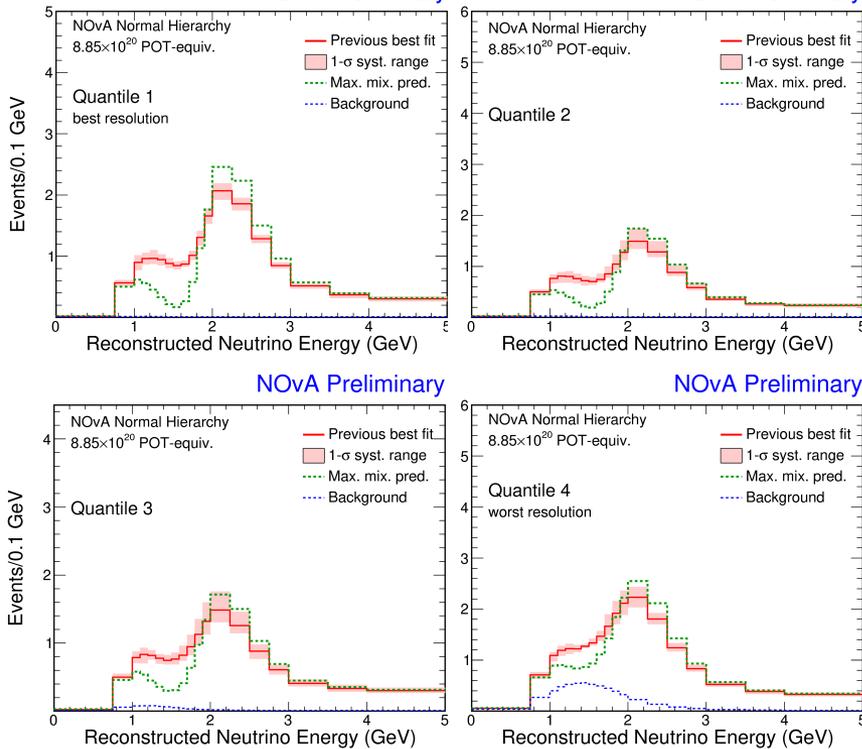
ν_μ disappearance

ν_e appearance

NOvA Preliminary

NOvA Preliminary

NOvA Preliminary



We fit these distributions to the FD data.
 Before looking at the data, though,
 let's examine the predictions in a bit more detail...

Predictions:
Simulation & constraints

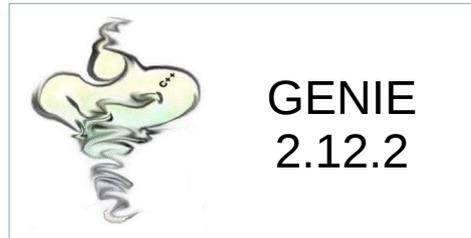
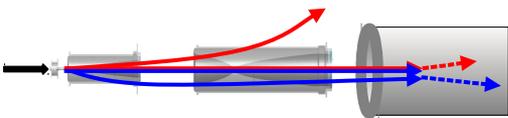
Predictions: simulation chain

Geant 4

+

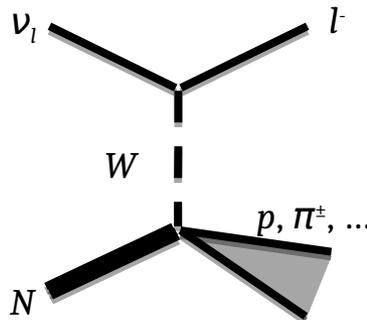
NuMI
PPFX

Neutrino flux



GENIE
2.12.2

Neutrino reactions
on detector materials



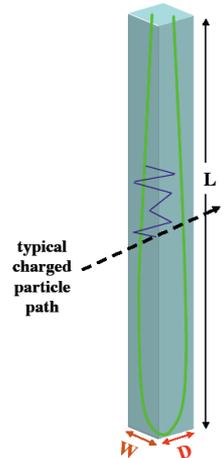
Geant 4

+



Custom
readout
software

Detector
response to
charged
particles and
light
propagation



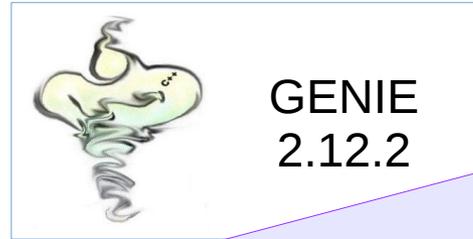
(with systematic uncertainties from each step)

Predictions: simulation chain

Geant 4

+

NuMI
PPFX



GENIE
2.12.2



Geant 4

+

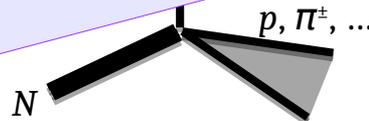


Custom
readout
software

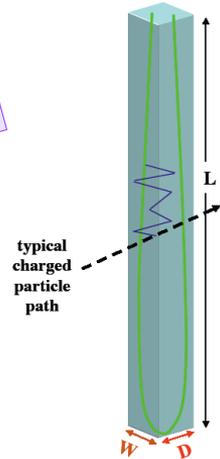
Neutrino



A few highlights of recent improvements...



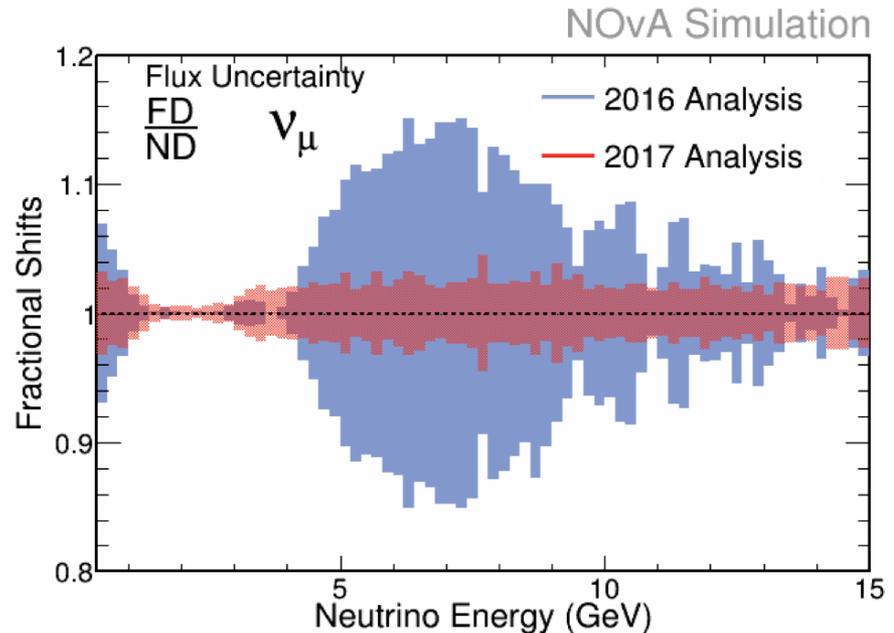
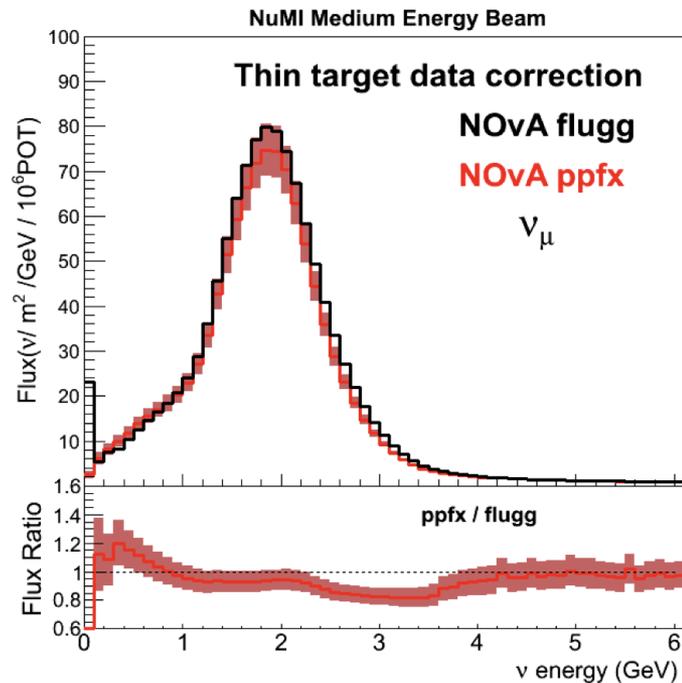
charged
particles and
light
propagation



(with systematic uncertainties from each step)

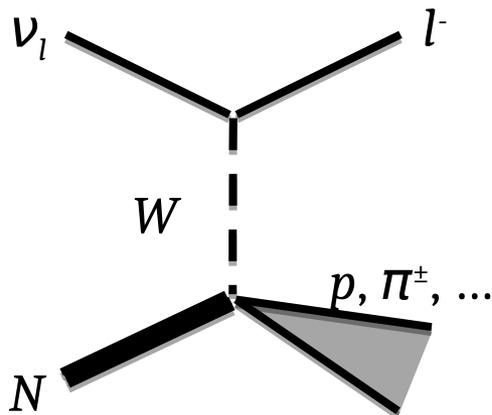
Predictions: flux

New in 2017

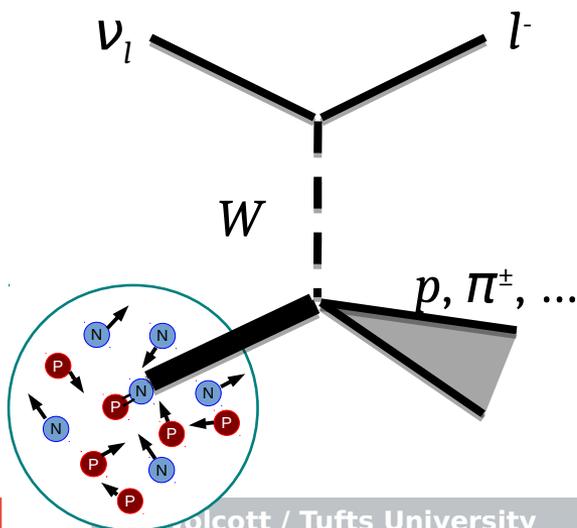


- Package to Predict the FluX (**PPFX**) from MINERvA
 - Extensive survey of thin target hadron production data (esp. NA49, MIPP)
- ~10% normalization change
- Significantly reduced systematic uncertainties

Predictions: cross sections



vs



Treating low-momentum-transfer effects not in GENIE 2.12 default

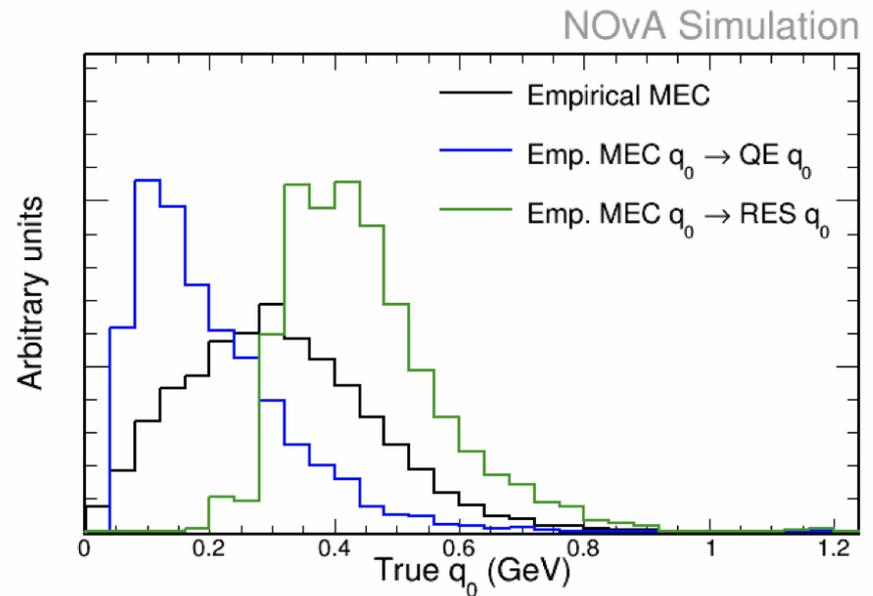
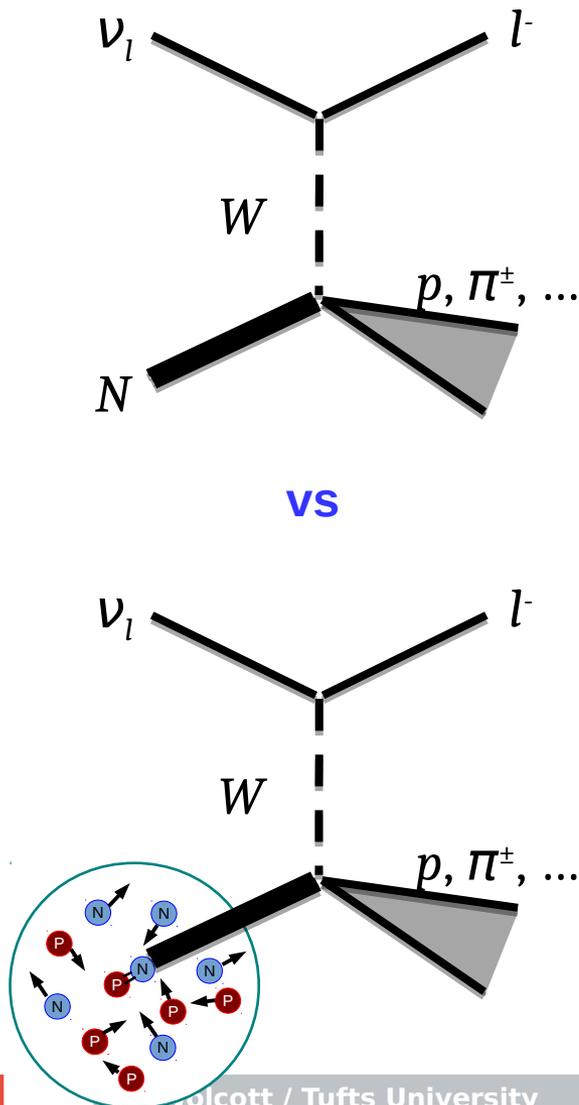
- **Shorter-range effects:** multi-nucleon ejection
 - Meson Exchange Currents thought to be most significant part of this for neutrino expts.
 - Enable Empirical MEC model*; tune rate to ND data
 - Construct custom uncertainty treatment
- **Longer-range effects:** nuclear charge screening – “RPA” model
 - Use calculation from the Valencia group adapted for GENIE (with uncertainties from F. Sanchez) via R. Gran†

* “Meson Exchange Current (MEC) Models in Neutrino Interaction Generators”, Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

† “Model uncertainties for Valencia RPA effect for MINERvA”, Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

Predictions: cross sections

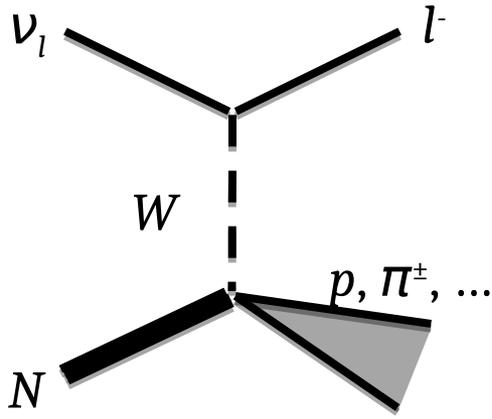
E.g.: shape of energy transfer (q_0) response



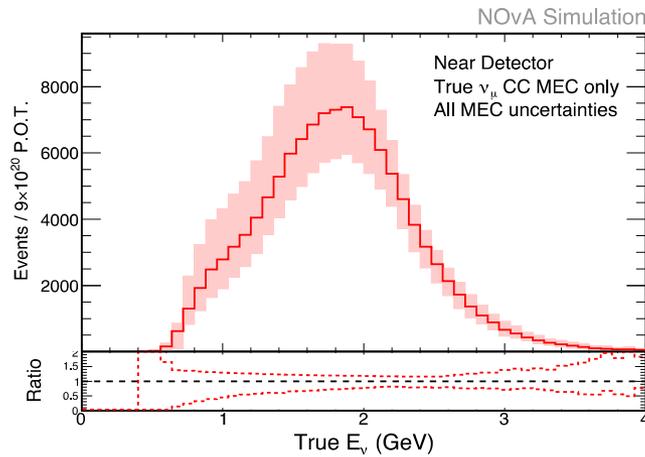
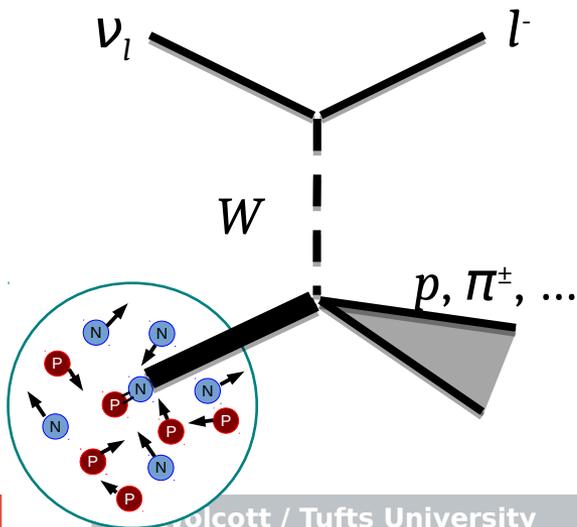
Based on observations from electron scattering, **MEC ought to lie between quasielastic and resonant Δ production.**

We use those as uncertainty bounds.

Predictions: cross sections

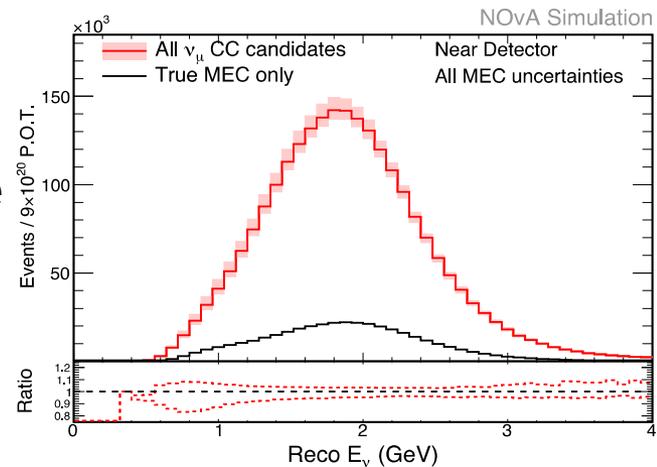


VS



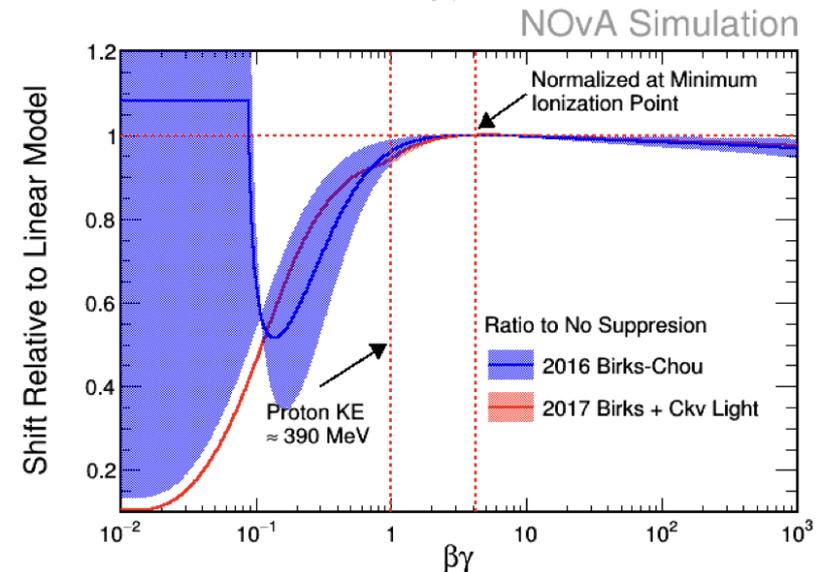
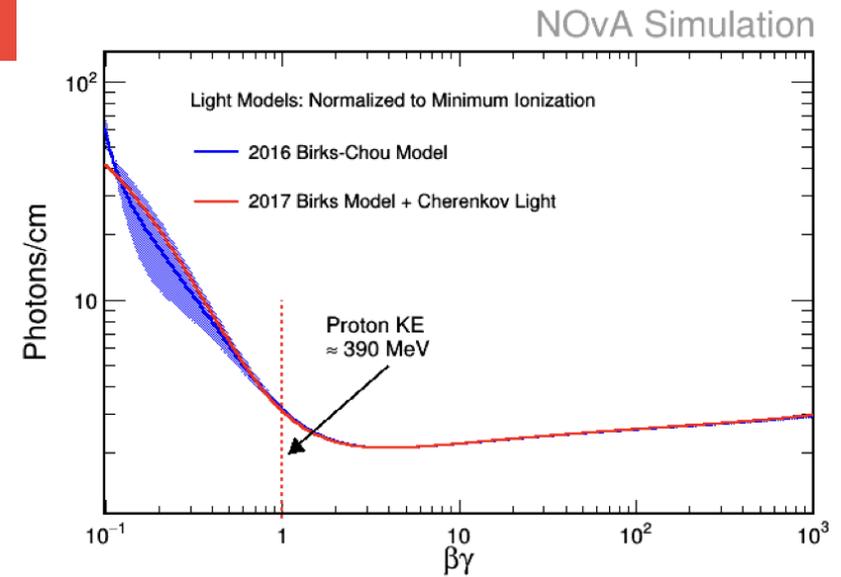
Effect of the MEC uncertainties we construct is $\sim 20\text{-}30\%$ on MEC...

... and about 5% on the total selected rate

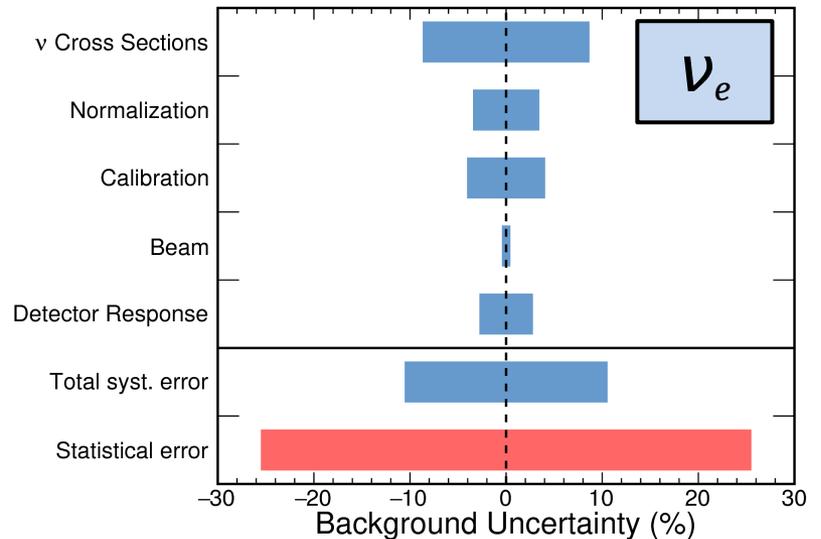
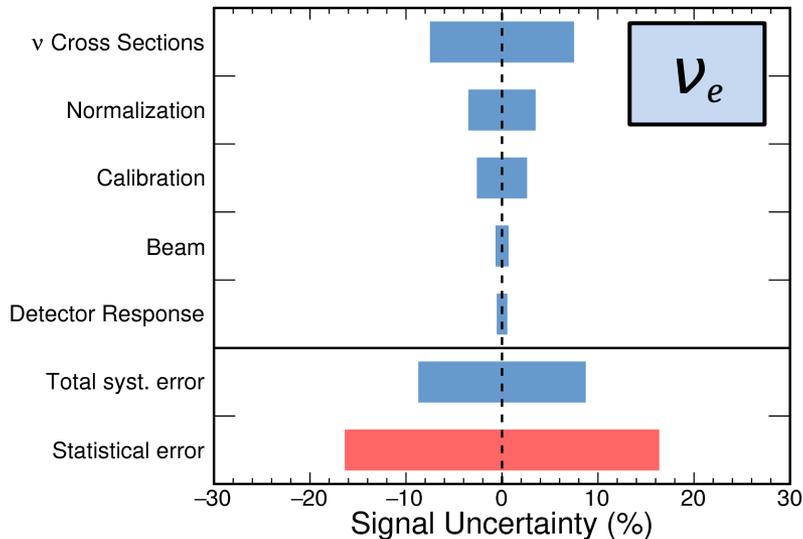
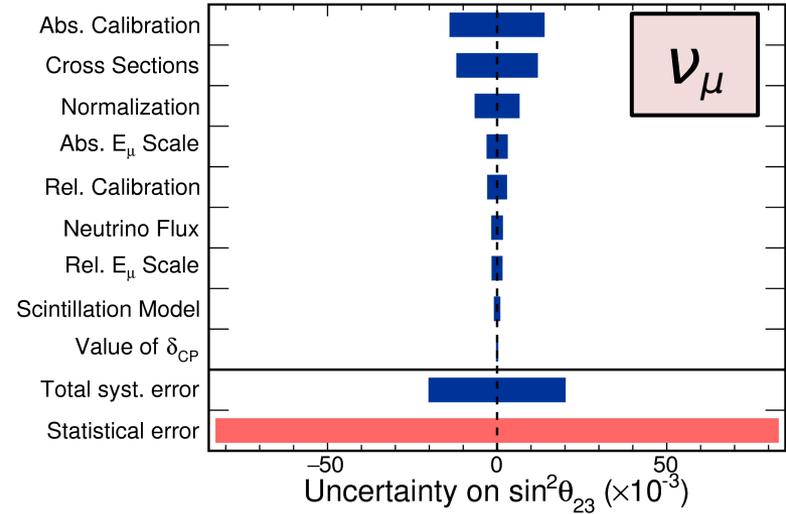
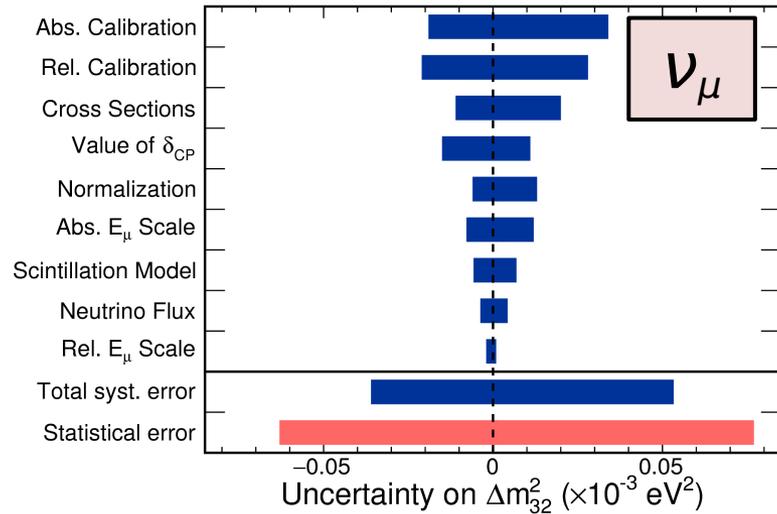


Predictions: light model

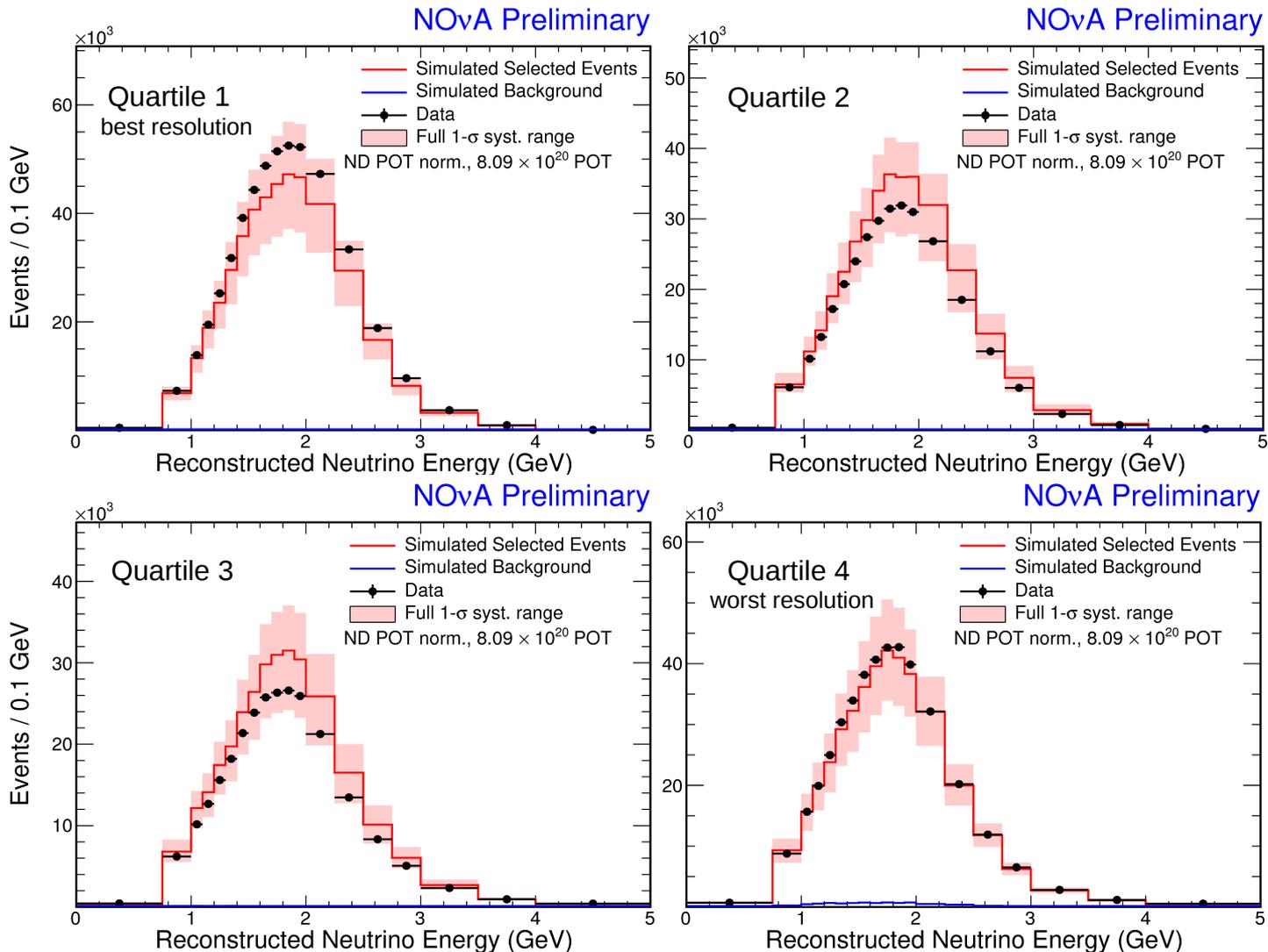
- Absorbed and re-emitted **Cherenkov light** affects low-energy protons in hadronic showers.
- 2017 light model systs ~order of magnitude smaller than previous
 - Previously accounted for Ckv with second order terms in our scintillator model
 - Those terms were unusual, so we took conservative systematics
- Expected energy resolution for ν_μ CC events increased from 7% to 9% when adding Ckv to model



Predictions: systematics



Constraining the prediction: ND extrapolation



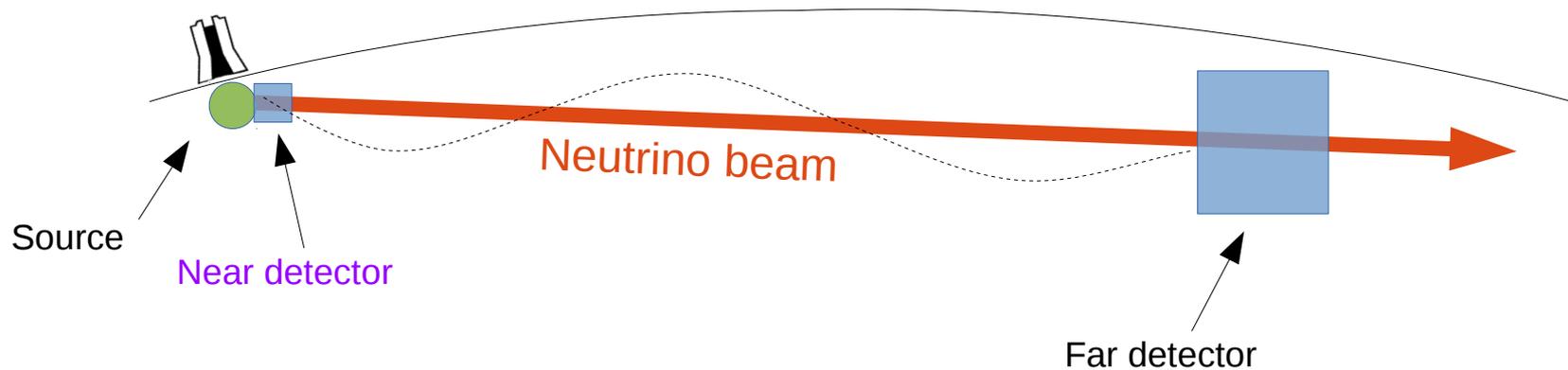
Though prediction agrees with ND data within our uncertainty budget, we can use (unoscillated) ND data to correct prediction for FD



“extrapolation”

Constraining the prediction: ND extrapolation

The NOvA strategy: “Far/Near ratio”



$$N(E_v^{rec}) = \Phi(E_v^{true}) \times P_{osc}(E_v^{true}) \times \sigma(E_v^{true}, A) \times R(E_v^{true}) \times \epsilon(\dots)$$

$$N^{ND}(E_v^{rec}) = \Phi(E_v^{true}) \times \sigma(E_v^{true}, A) \times R(E_v^{true}) \times \epsilon(\dots)$$

Concept:

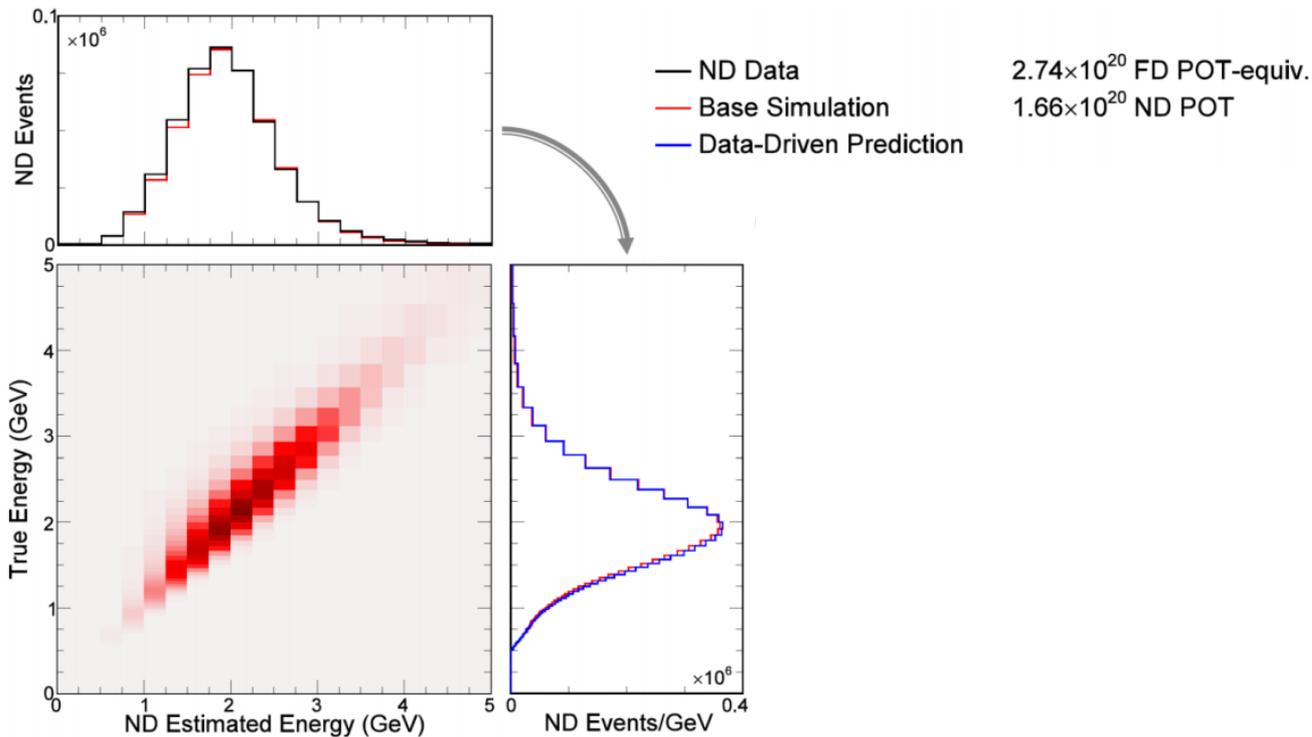
Identical detectors share all the ingredients except the oscillations



Correct the true event rate ($\Phi \times \sigma \times \dots$) using the ND and propagate that (F/N captures geometrical differences between detectors)

Constraining the prediction: ND extrapolation

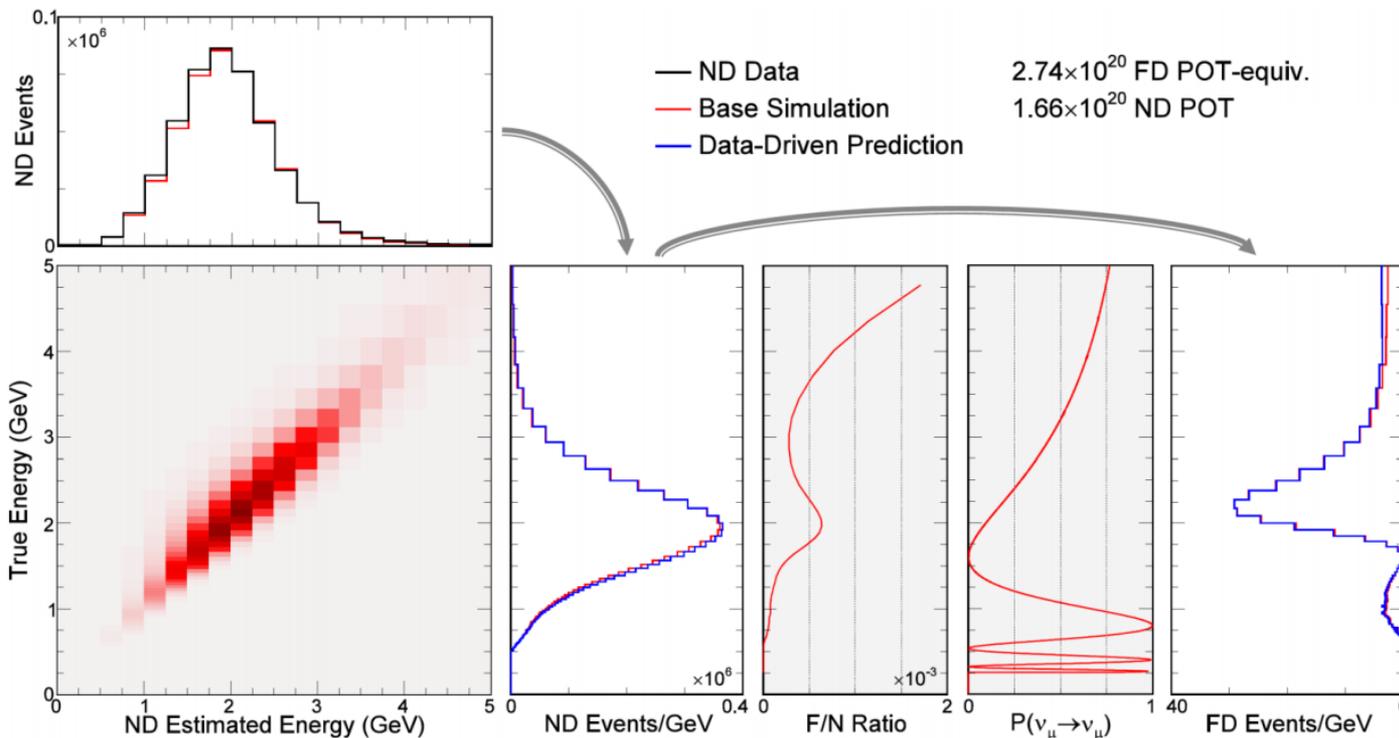
The NOvA strategy: “Far/Near ratio”



1. Using the predicted 'unsmearing' matrix, correct the underlying unoscillated (true) E_ν distribution based on the ND data.

Constraining the prediction: ND extrapolation

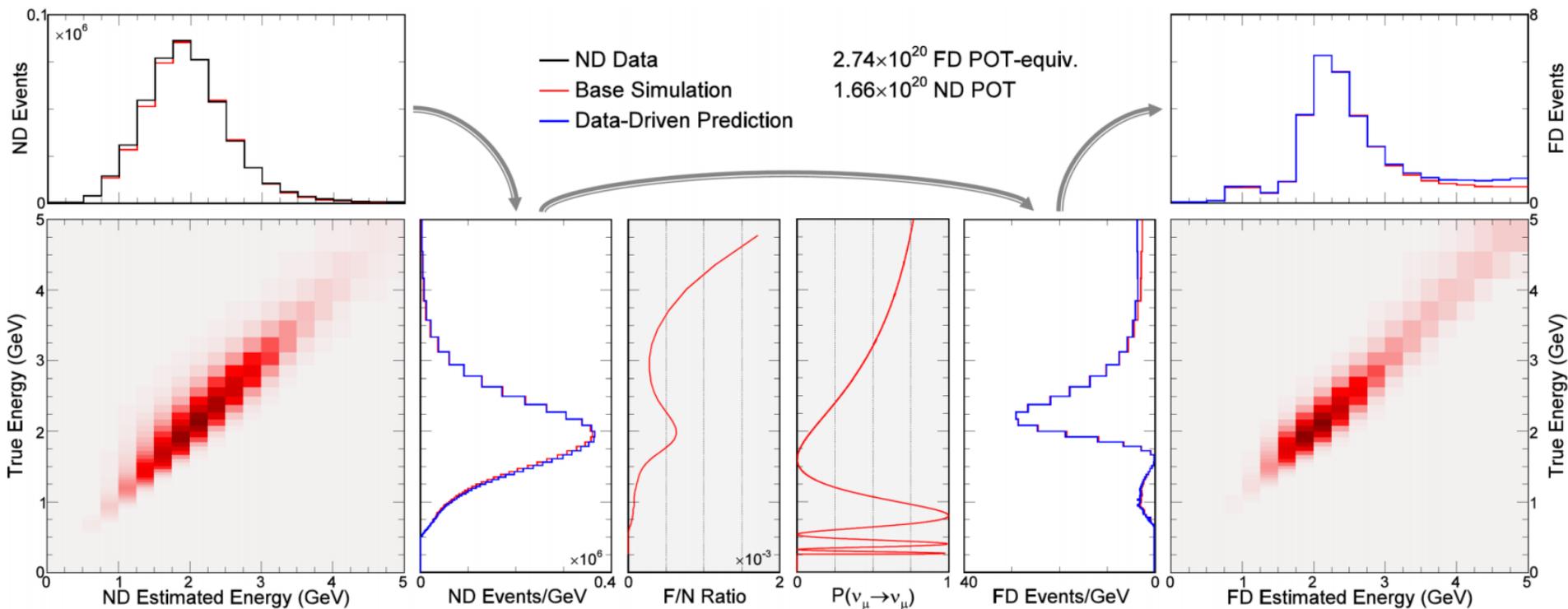
The NOvA strategy: “Far/Near ratio”



2. Multiply this corrected “true” spectrum by the geometric and oscillation functions to get the “extrapolated” true E_ν prediction at the FD.

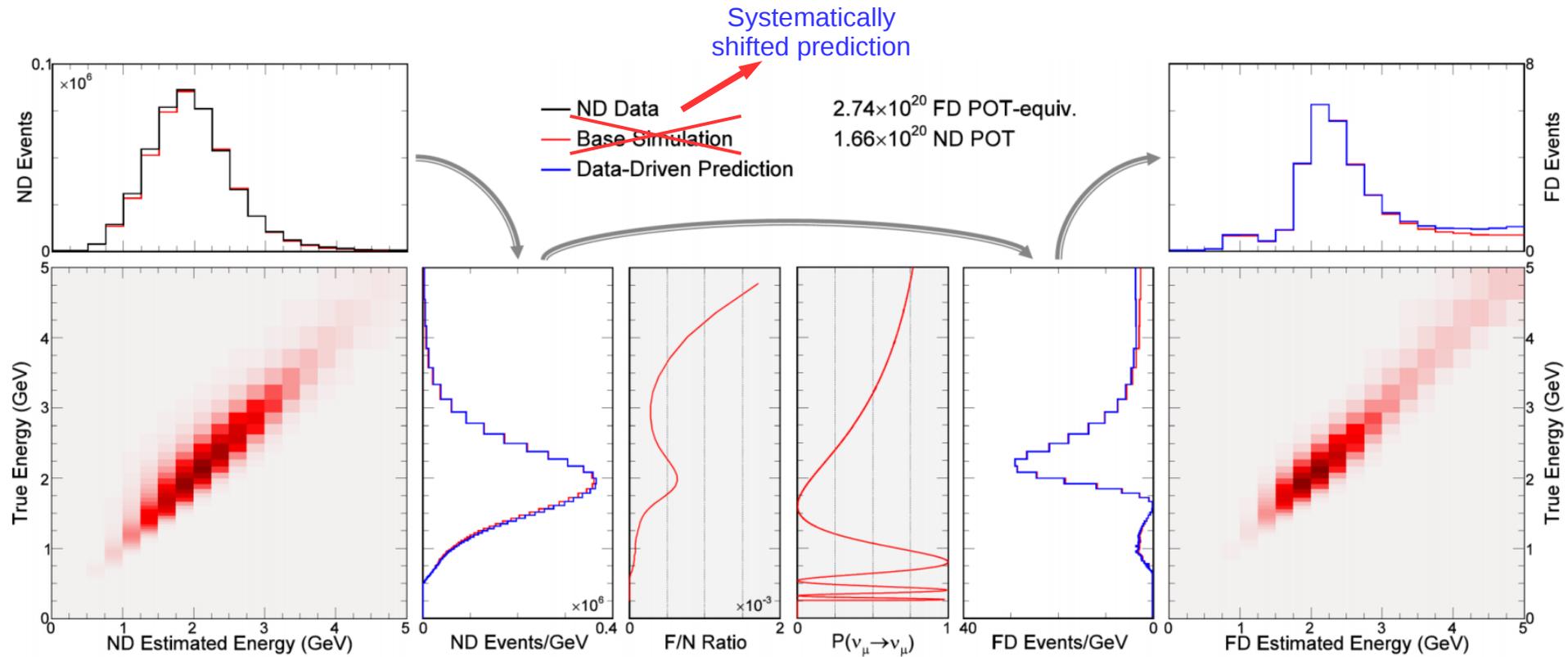
Constraining the prediction: ND extrapolation

The NOvA strategy: “Far/Near ratio”



3. Using the predicted mapping at the FD, convert back to reconstructed energy to compare to the observed FD spectrum.

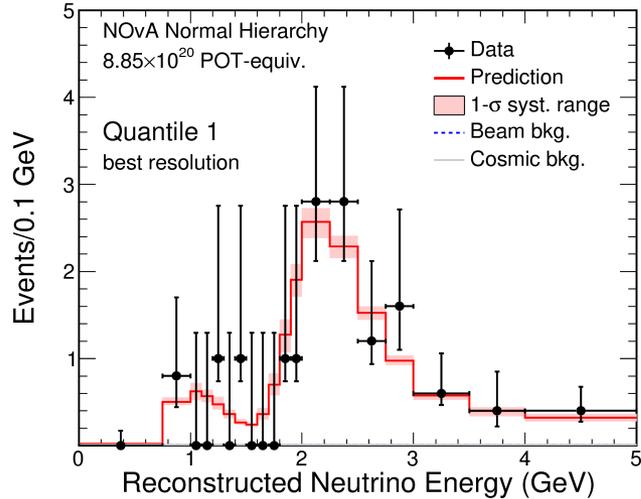
Constraining the prediction: ND extrapolation



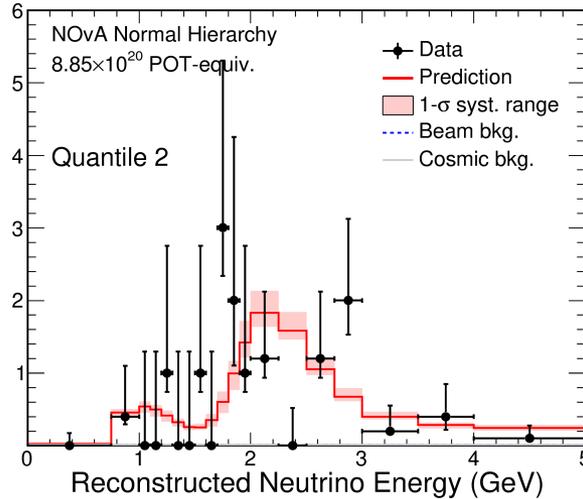
F/N constrains systematics too

Constrained ν_μ FD prediction vs. data

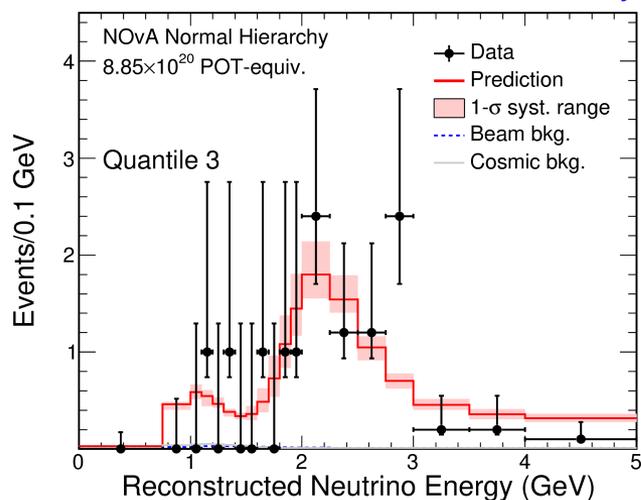
NOvA Preliminary



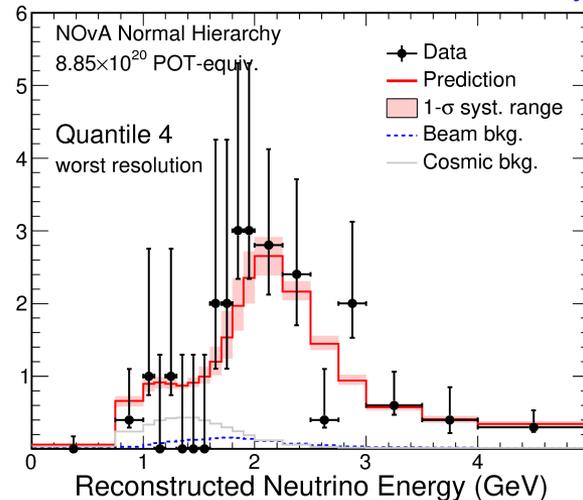
NOvA Preliminary



NOvA Preliminary

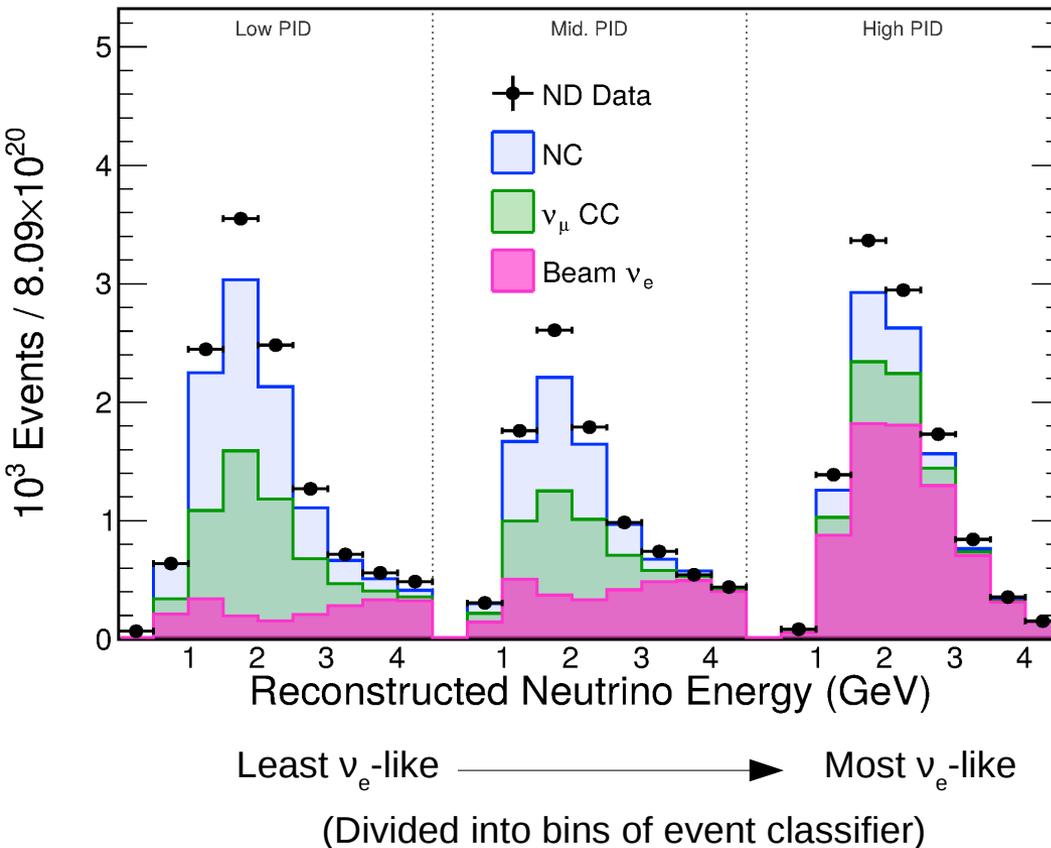


NOvA Preliminary



Total Observed	126
Best fit prediction	129
Cosmic Bkgd.	5.82
Beam Bkgd.	3.46

Constraining the prediction: ν_e extrapolation

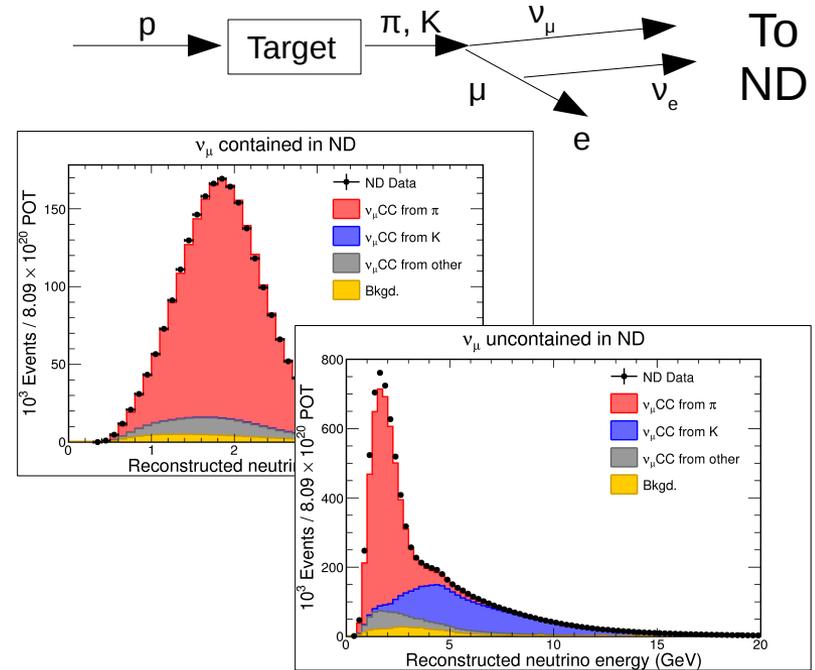
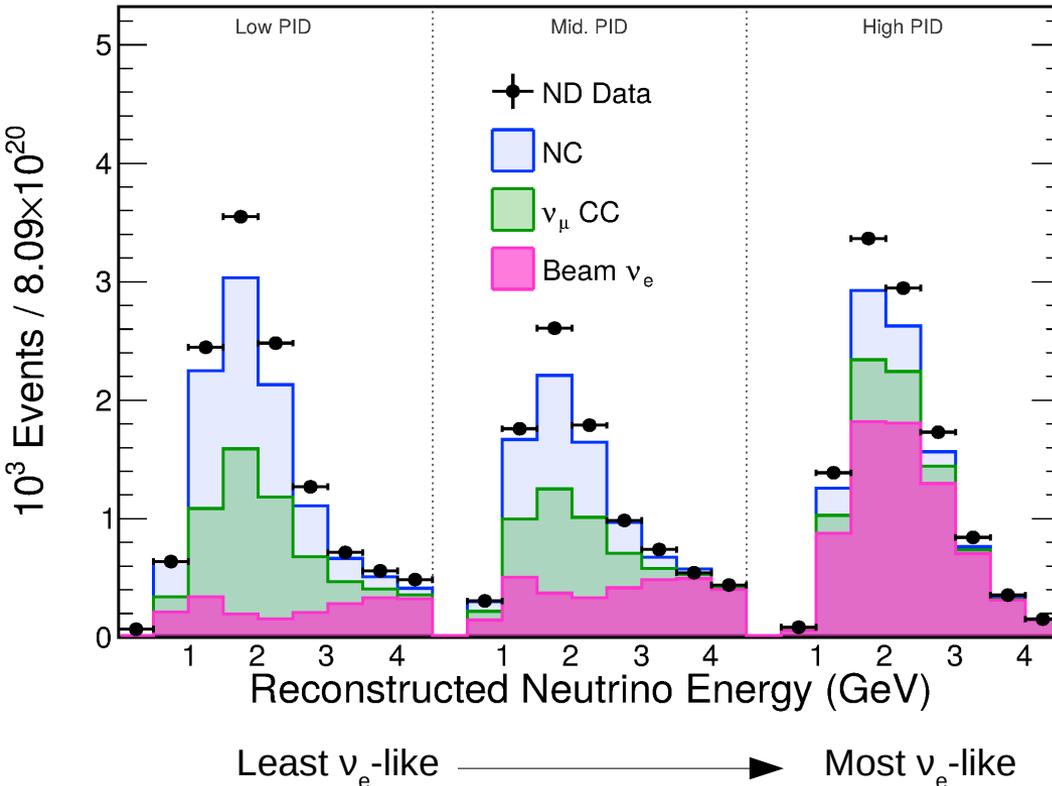


ν_e extrapolation
requires more care:

- **No signal** at ND
- **Beam ν_e** oscillate very little over this L/E
- **ν_μ** almost entirely disappear
- **NC** doesn't change due to oscillations (assume no steriles)

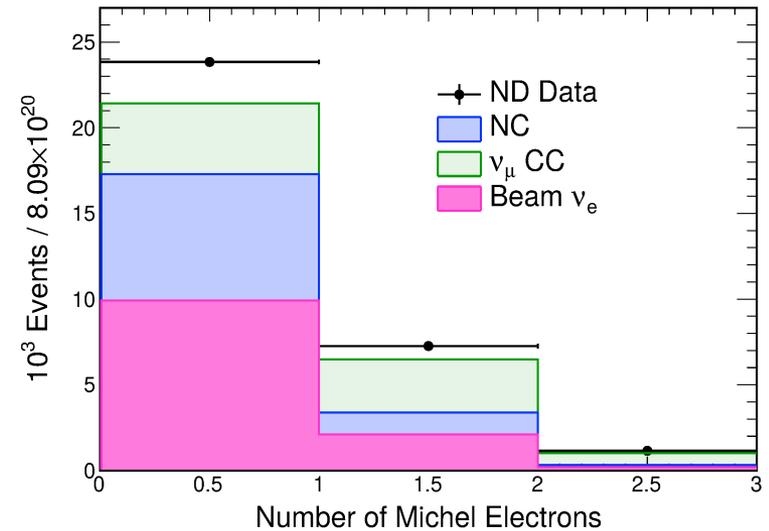
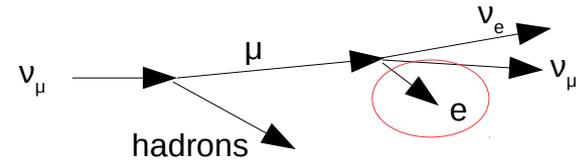
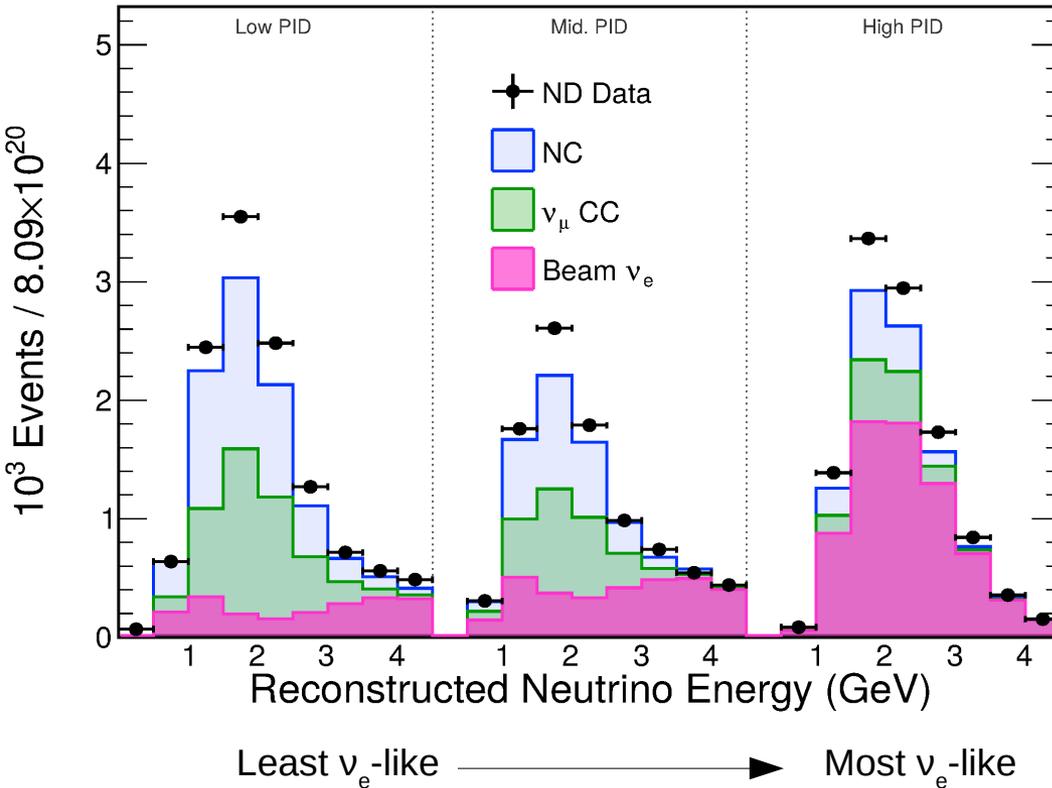
Need to disentangle
("decompose") before
applying Far/Near makes
any sense.

Constraining the prediction: ν_e extrapolation



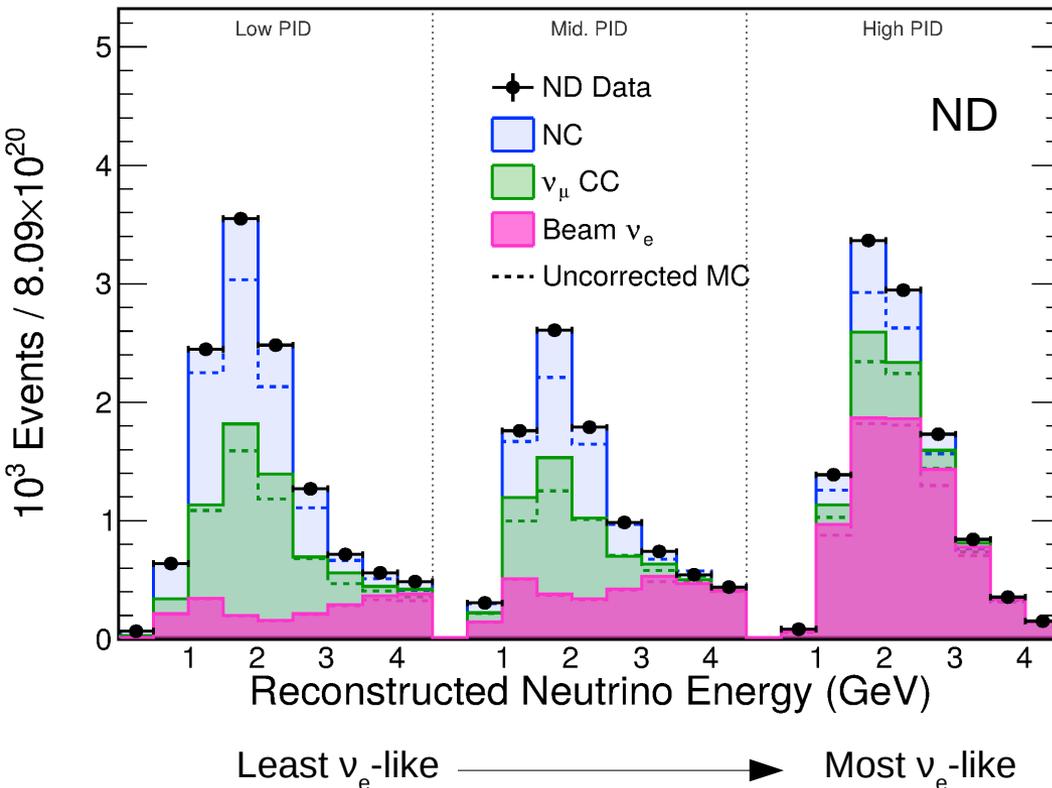
① Constraining the parent particle production via ND ν_μ interactions tells us about the CC components...

Constraining the prediction: ν_e extrapolation

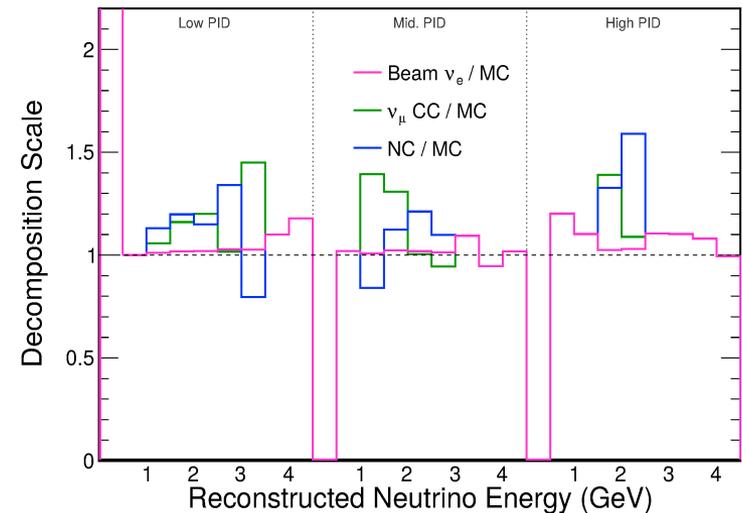


② ... while examining the Michel electron spectrum in candidate events tells us about the ν_μ fraction.

Constraining the prediction: ν_e extrapolation

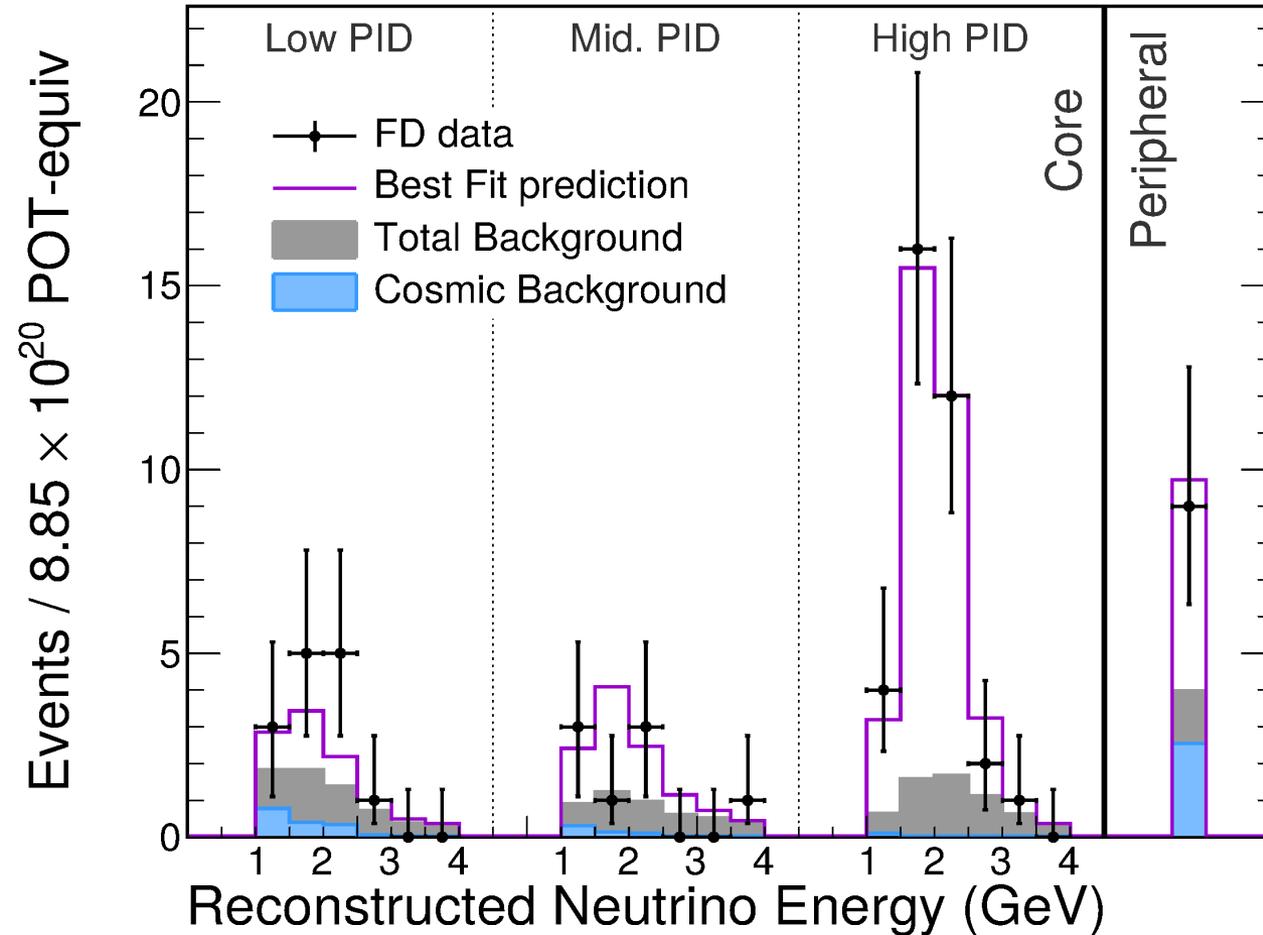


The “beam” and “Michel” constraints together tell us how to use the ND information to correct each *component* the FD spectrum.



Constrained ν_e FD prediction vs. data

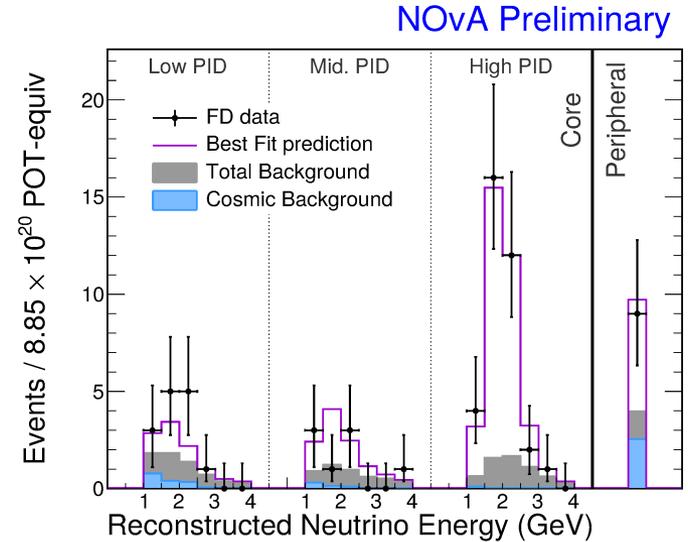
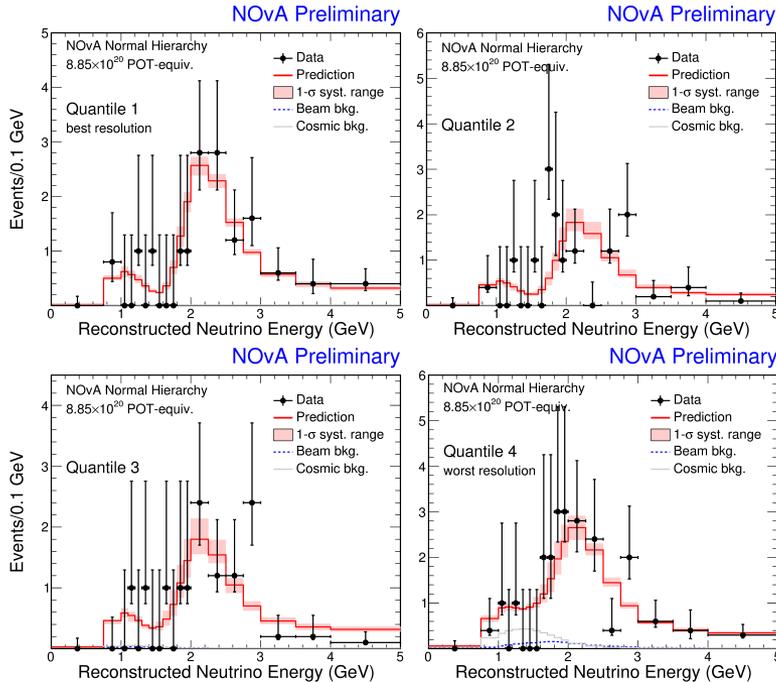
NOvA Preliminary



Total Observed	66
Signal Prediction	20-48
Cosmic Bkgd.	4.9
Beam Bkgd.	15.6

Extracting oscillation parameters

Fitting the spectra



- Apply external constraint for θ_{13} (PDG 2017, $\sin^2 2\theta_{13} = 0.082$)
- Perform joint analysis since θ_{23} affects both (includes correlated systematics)
- Mass hierarchy and δ sensitivity will grow with 2018 $\bar{\nu}$ sample

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m_{32}^2 L / 4E)$$

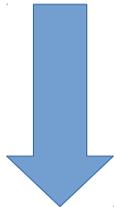
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$- 2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin \Delta + \dots$$

Oscillation results: atmospheric sector

Big question:

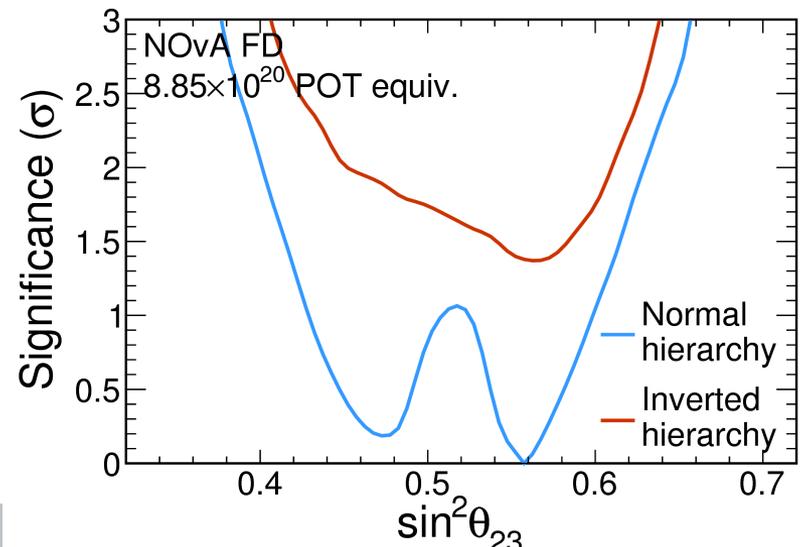
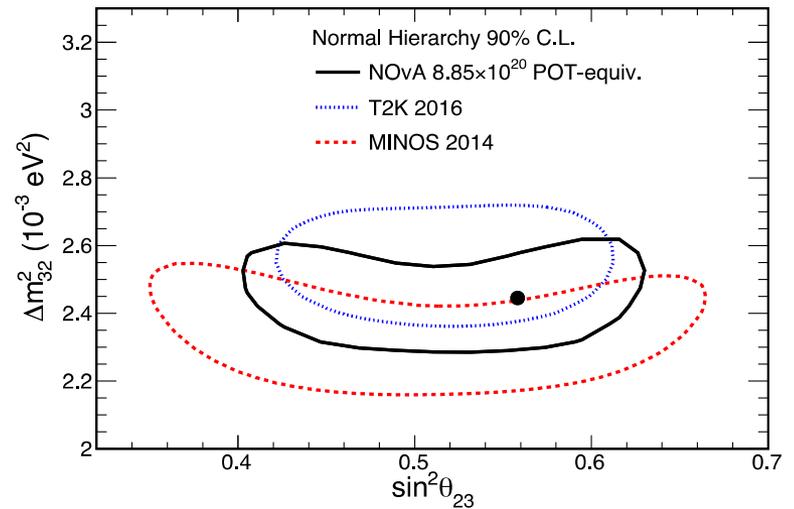
Is there a symmetry governing the ν_μ/ν_τ mixing into the 2nd and 3rd mass states?
(Is θ_{23} “maximal” = 45° ?)



Quite possibly.

Consistent with $\theta_{23} = 45^\circ$
at **0.8σ** .

NOvA Preliminary



Oscillation results: since last year

Previous result: 2.6σ
exclusion of maximal mixing

New simulation & calibration: $\sim 1.8\sigma$

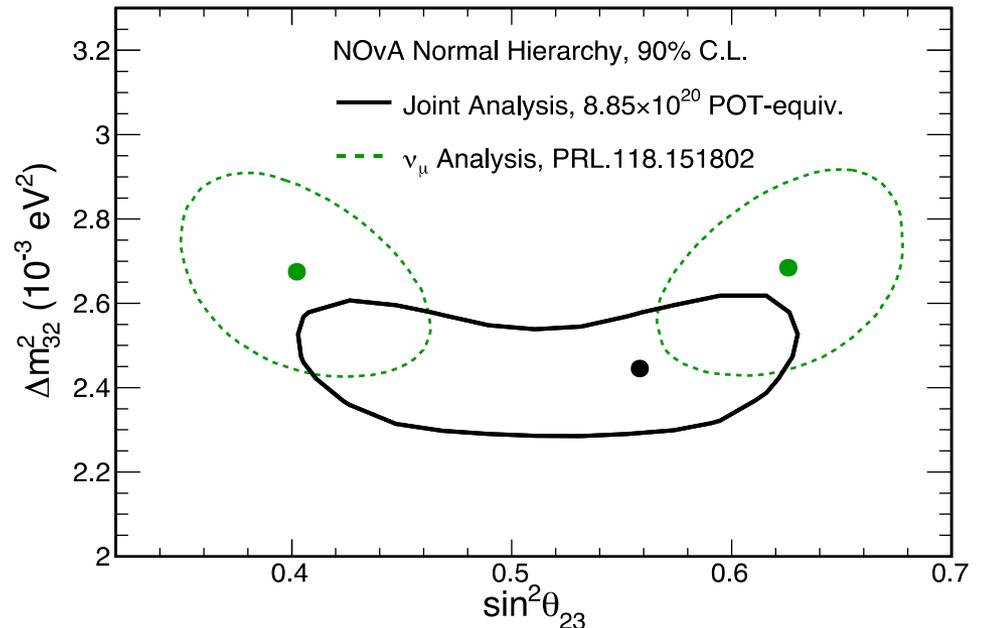
- Expected small shift due to change in energy resolution and scale.
- Had larger than expected event migration out of the dip region. (3 vs. 0.5)

New selection & analysis: $\sim 0.5\sigma$

- Large changes possible due to new cosmic rejection – we have a totally new set of background events.
- Saw changes this size or larger in 5% of pseudo-experiments.

New data: $\sim 0.4\sigma$

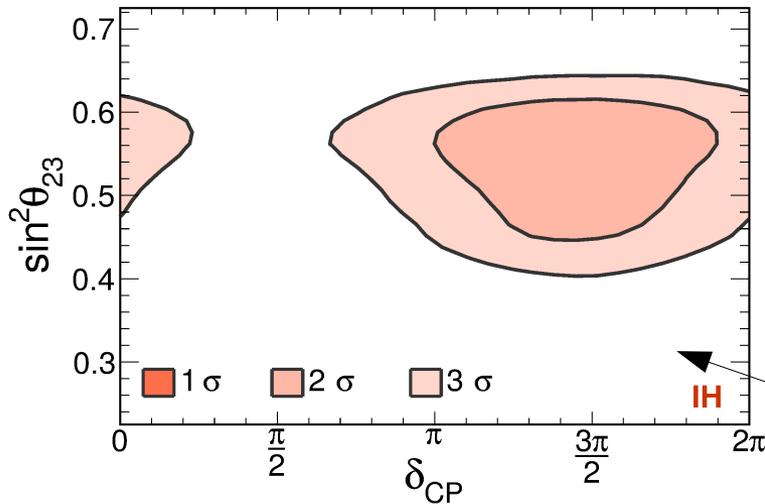
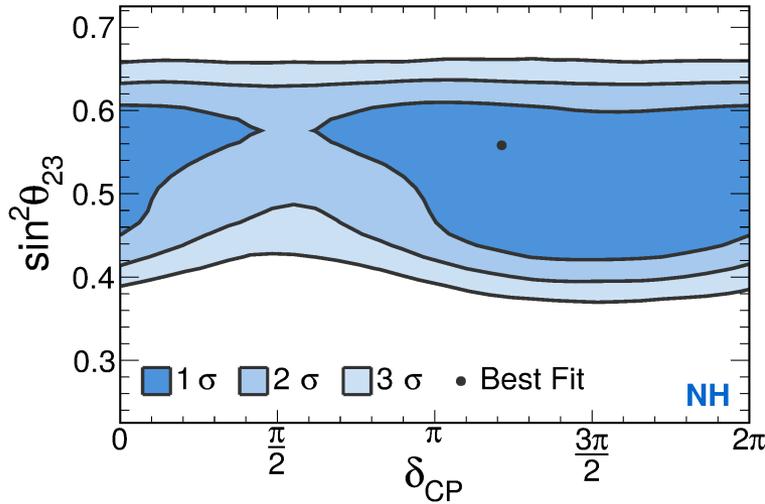
NOvA Preliminary



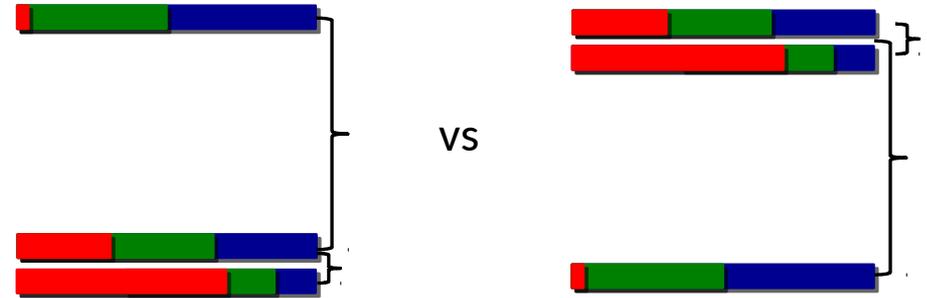
Final result: 0.8σ

Includes FC
corrections

Oscillation results: reactor sector



Entire IH excluded at 95.7% CL



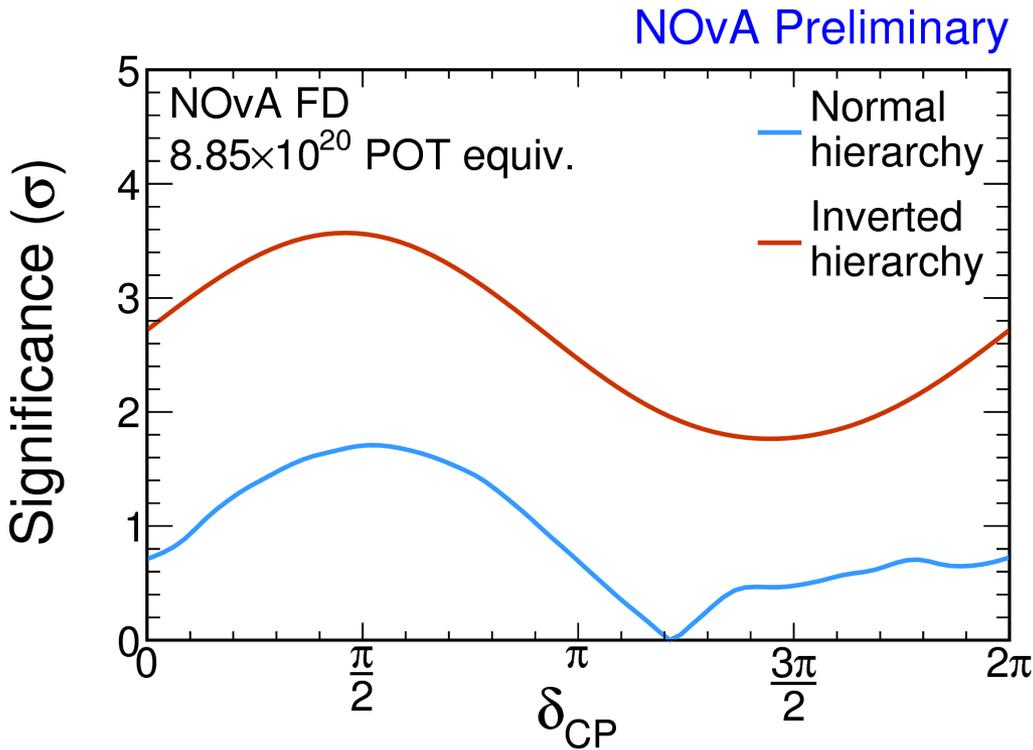
Big question:

Which way around are the mass states ordered?

Even without antineutrino data (expect new results later this year),

preference for NH at 95.7% CL

Oscillation results: reactor sector



$$\nu \stackrel{?}{\rightleftharpoons} \bar{\nu}$$

Big question:
Is CP symmetry violated by leptons?
(Is δ nonzero?)

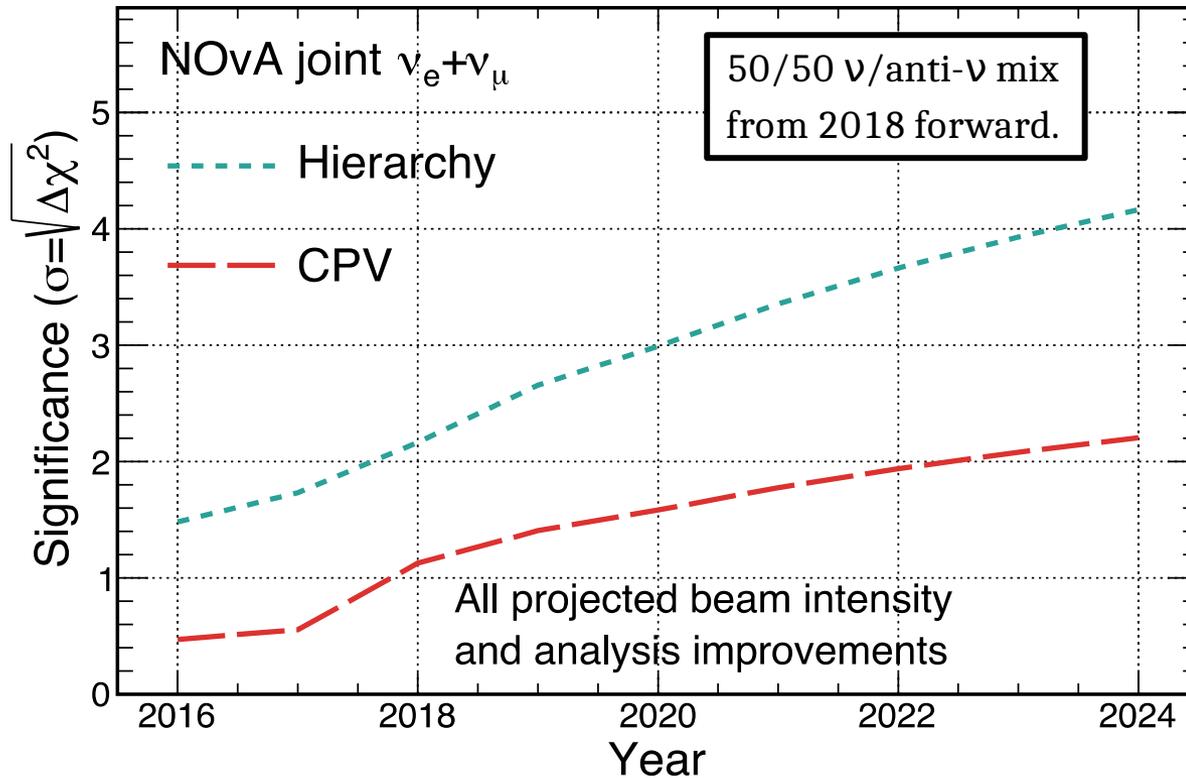
Mild preference for nonzero δ

Antineutrino data will improve sensitivity.

Looking ahead

Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}=0.500$
 $\Delta m_{32}^2=2.45\times 10^{-3}\text{eV}^2$, $\sin^2 2\theta_{13}=0.082$

NOvA Simulation



Very compelling milestones potentially not too far around the corner!

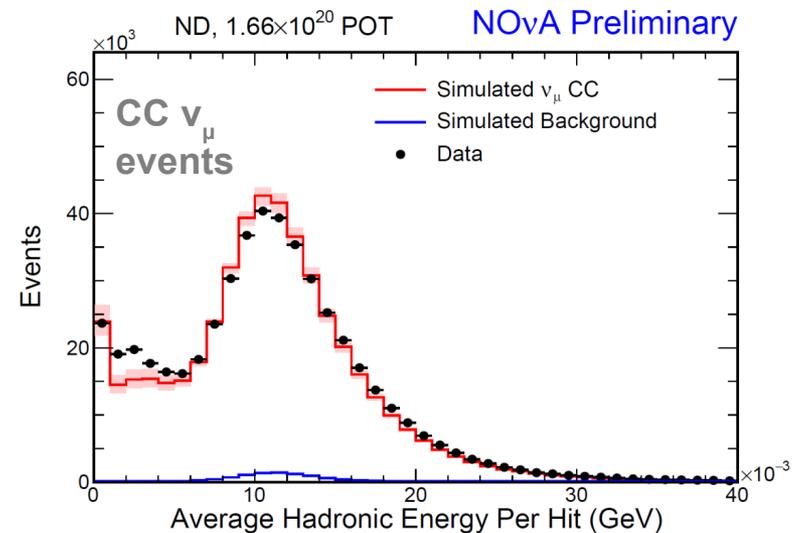
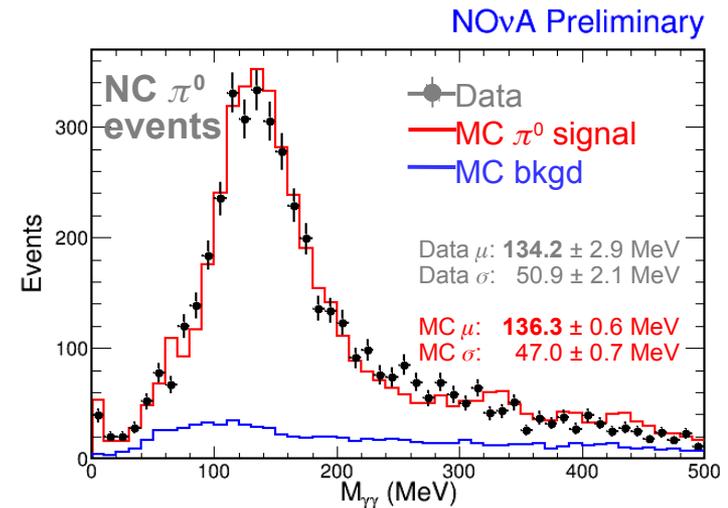
Summary

- **Significant improvements since previous analysis**
 - Substantially reduced flux & detector uncertainties
 - Analysis technique improvements → ~15% effective exposure increase
- **Indications of oscillation parameter values emerging:**
 - Consistent with maximal θ_{23} at 0.8σ
 - Favor normal hierarchy with 95.7% confidence
 - Mild preference for CP non-conservation
- **Data continues to stream in**
 - Expect first $\nu + \bar{\nu}$ analysis later this year
 - Looking forward to major milestones in oscillation physics in not-too-distant future!

Overflow

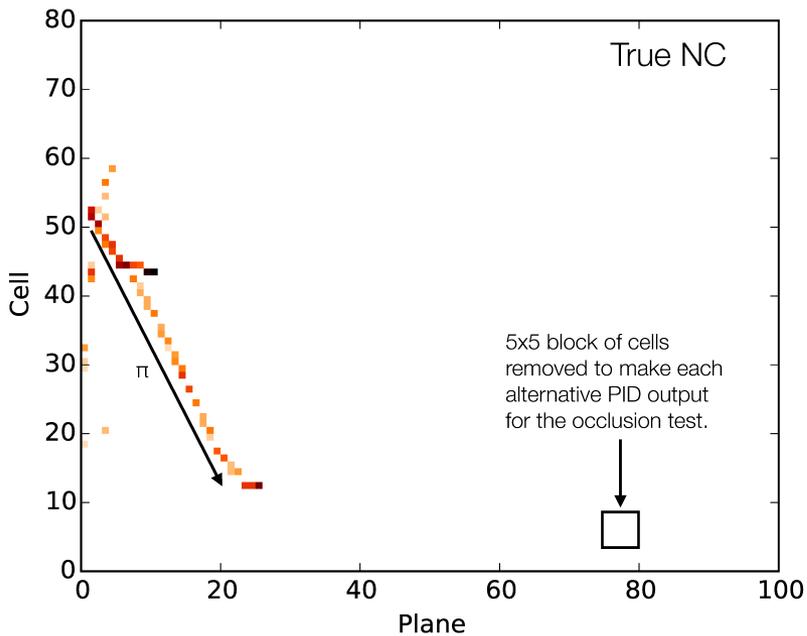
Fixing the energy scale

- Near Detector
 - cosmic μ dE/dx [\sim vertical]
 - beam μ dE/dx [\sim horizontal]
 - Michel e^- spectrum
 - π^0 mass
 - hadronic shower E -per-hit
- Far Detector
 - cosmic μ dE/dx [\sim vertical]
 - beam μ dE/dx [\sim horizontal]
 - Michel e^- spectrum
- All agree to 5%

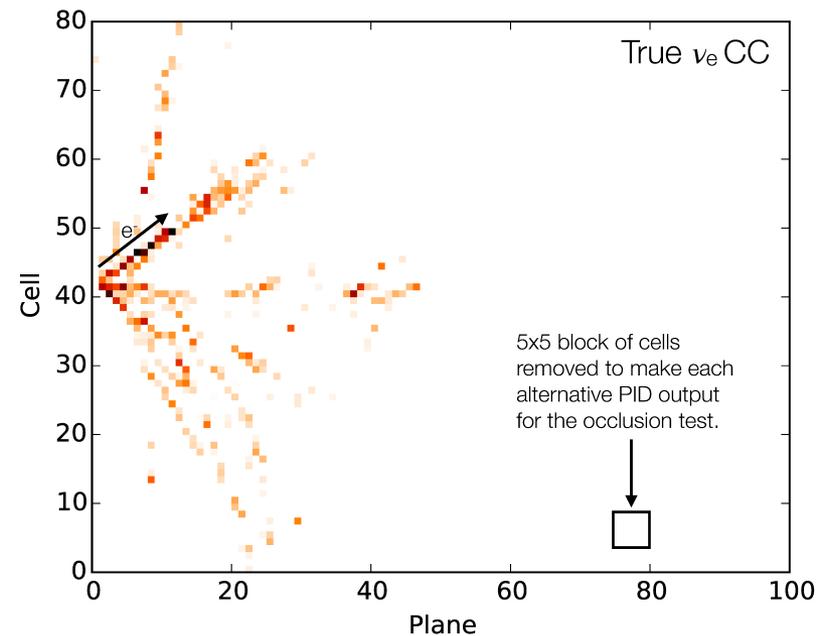


What did CVN learn?

NOvA Simulation

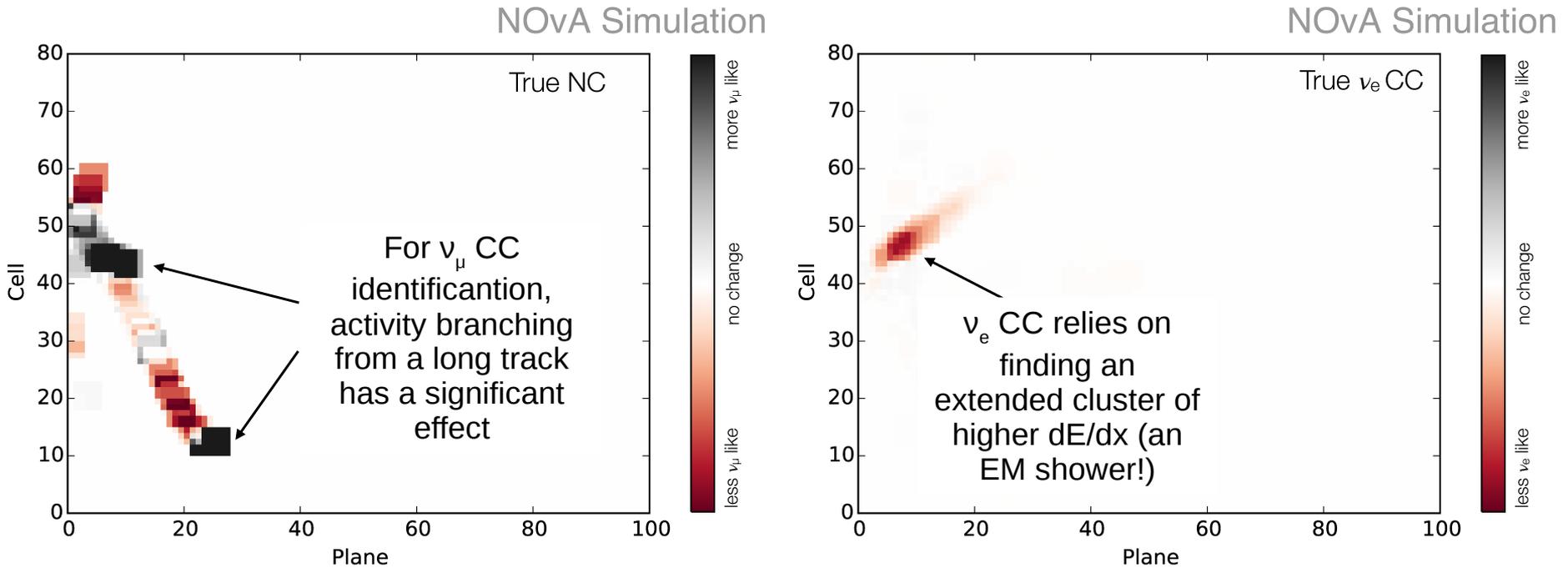


NOvA Simulation



“Occlusion” test:
Systematically mask out different regions of event
and see how CVN's inferred event type changes

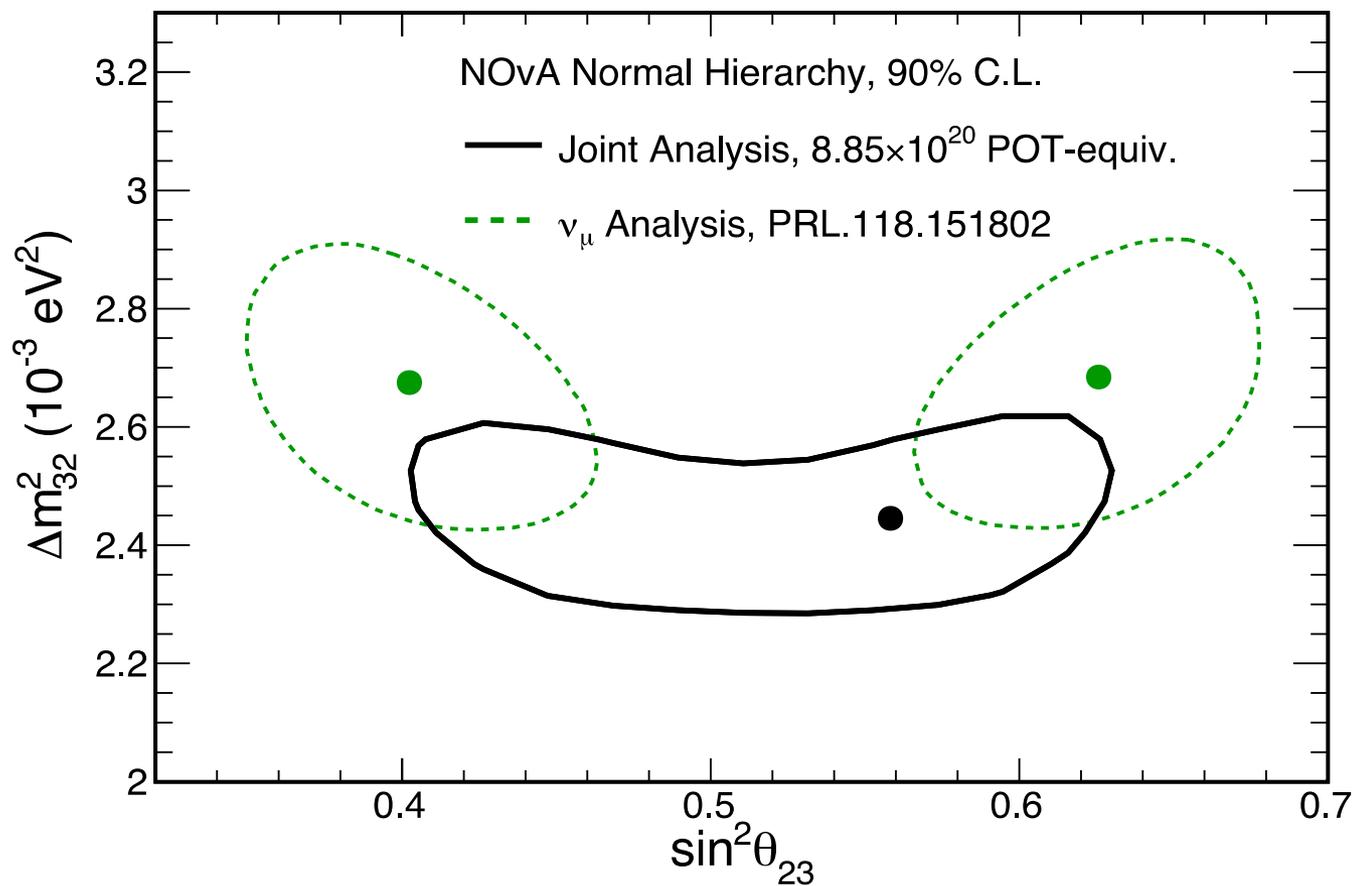
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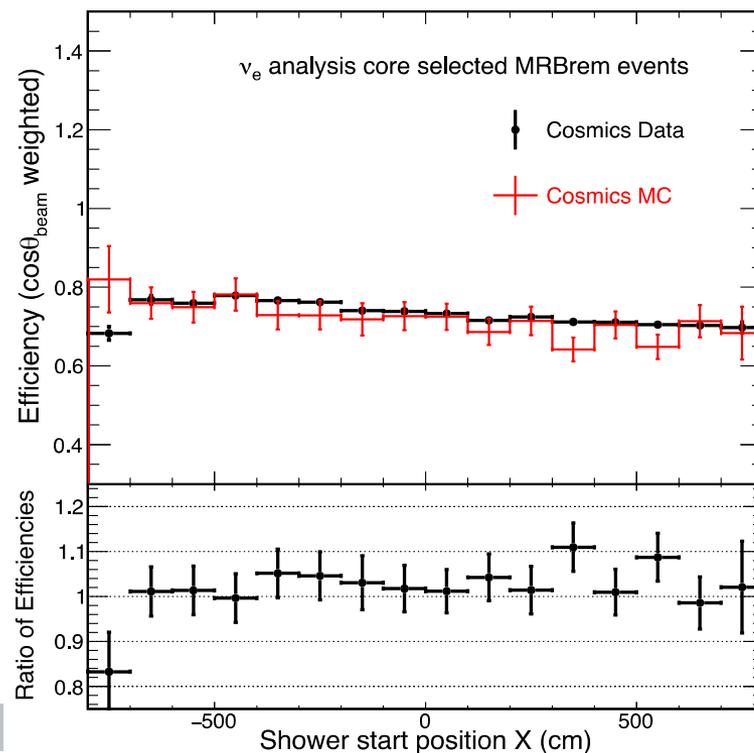
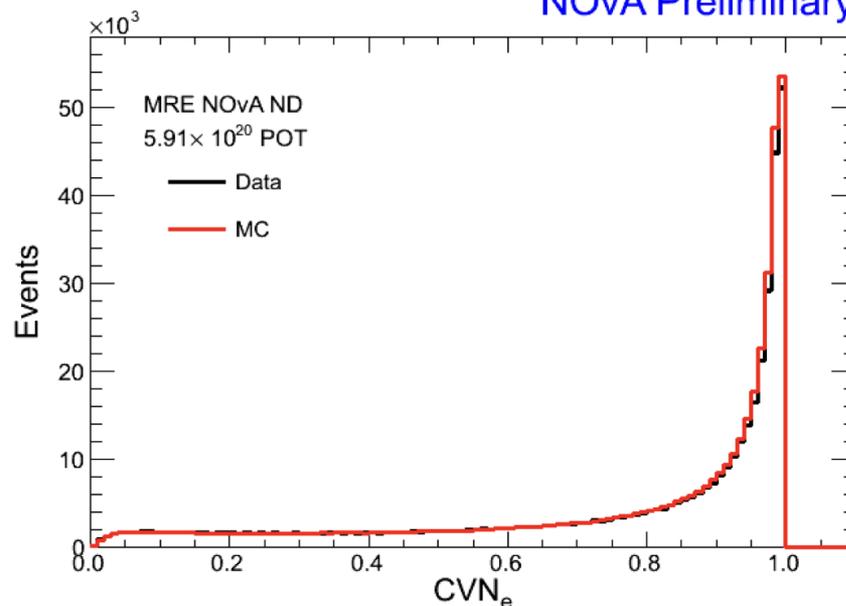
ν_μ disappearance: comparison to previous results

NOvA Preliminary

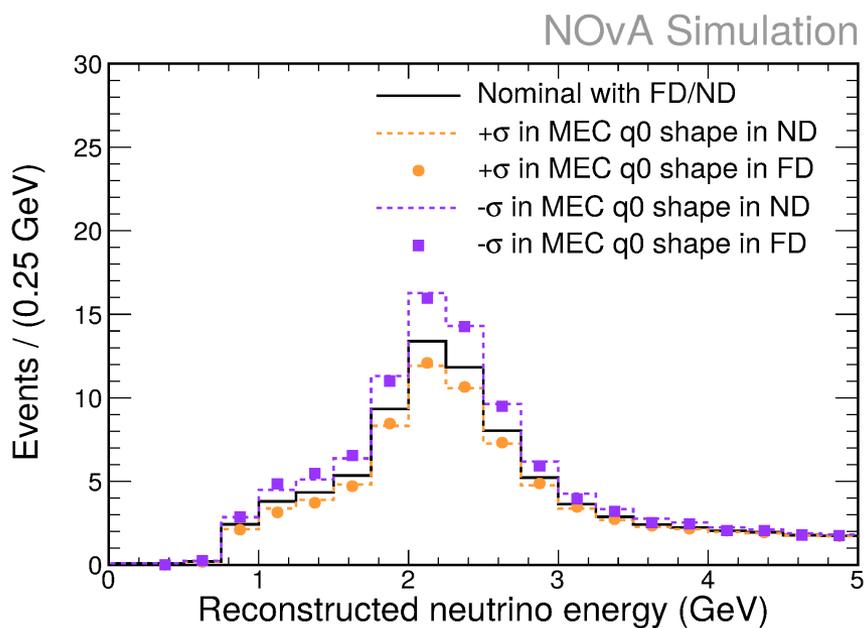


ν_e Efficiency Checks

- Test hadronic showers:
 - Muon removed, simulated electron added to ν_μ CC in ND events
 - Data & MC efficiencies agree within 2%
- Test electromagnetic showers:
 - Muon removed from bremsstrahlung in FD cosmic ray events
 - Good data-MC agreement in both core and peripheral samples



Effect of extrapolation



**~10-20% uncertainties become
~5% residual uncertainties
after extrapolation**

