# Exploring neutrino & antineutrino oscillations with 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

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$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Flavor states are not energy (mass) eigenstates

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

nonzero transition probabilities since *masses are different*

# Neutrino oscillations




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

Not predicted by the Standard Model!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Neutrino oscillations can potentially ask and answer BSM questions...

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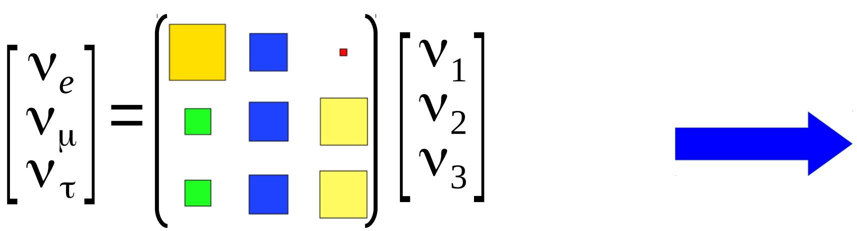
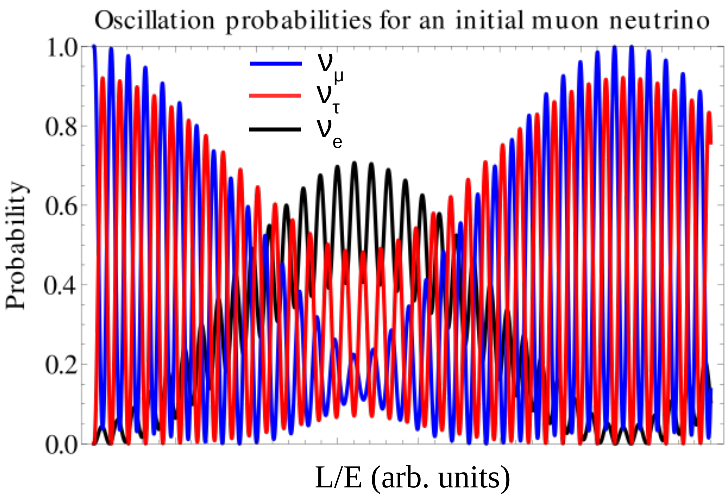
# Neutrino oscillations


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



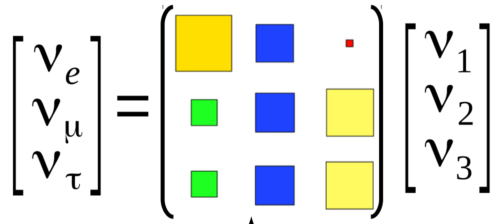

arXiv:1212.6374

Flavor states are not energy (mass) eigentstates



# Neutrino oscillations: mixing parameters

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



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

**“Atmospheric” sector:**
best measured in experiments where $\nu_\mu$ **disappearance** dominates: νs from cosmic ray muon decays; **accelerators**

**“Reactor” sector:**
$\theta_{13}$ best measured in experiments where $\nu_e$ **disappearance** dominates over short distances: νs from nuclear reactors (more on δ shortly)

**“Solar” sector:**
best measured in experiments where $\nu_e$ **disappearance** dominates over long distances: νs from solar nuclear fusion

# Neutrino oscillations: mixing parameters

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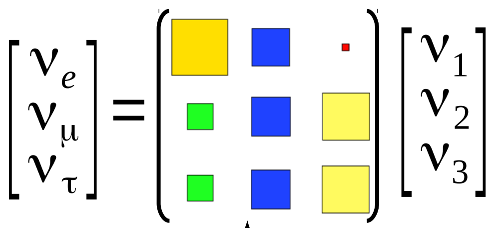

$$\mathbf{U} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{bmatrix} \begin{bmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13}) e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13}) e^{i\delta} & 0 & \cos(\theta_{13}) \end{bmatrix}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

"Reactor" sector:
δ accessible
via **$\nu_e$ appearance**
in accelerator expts.

# Neutrino oscillations: mixing parameters

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$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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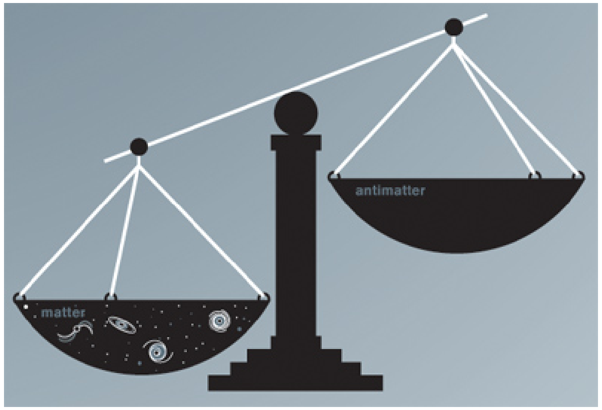
**Big question:**
Is δ nonzero?
(If it is, neutrinos—and thus leptons—violate CP **symmetry**!
… leptogenesis??)

"Reactor" sector:
δ accessible
via $\nu_e$ **appearance**
in accelerator expts.



# Neutrino oscillations: mixing parameters

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

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} =$$



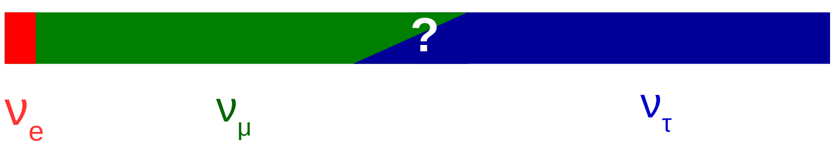
$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\mathbf{U} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\boxed{\theta_{23}}) & \sin(\boxed{\theta_{23}}) \\ 0 & -\sin(\boxed{\theta_{23}}) & \cos(\boxed{\theta_{23}}) \end{bmatrix} \begin{bmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13}) e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13}) e^{i\delta} & 0 & \cos(\theta_{13}) \end{bmatrix} \begin{bmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

<u>"Atmospheric" sector</u>:
best measured in experiments where **$\nu_\mu$ disappearance** dominates: νs from cosmic ray muon decays; **<u>accelerators</u>**

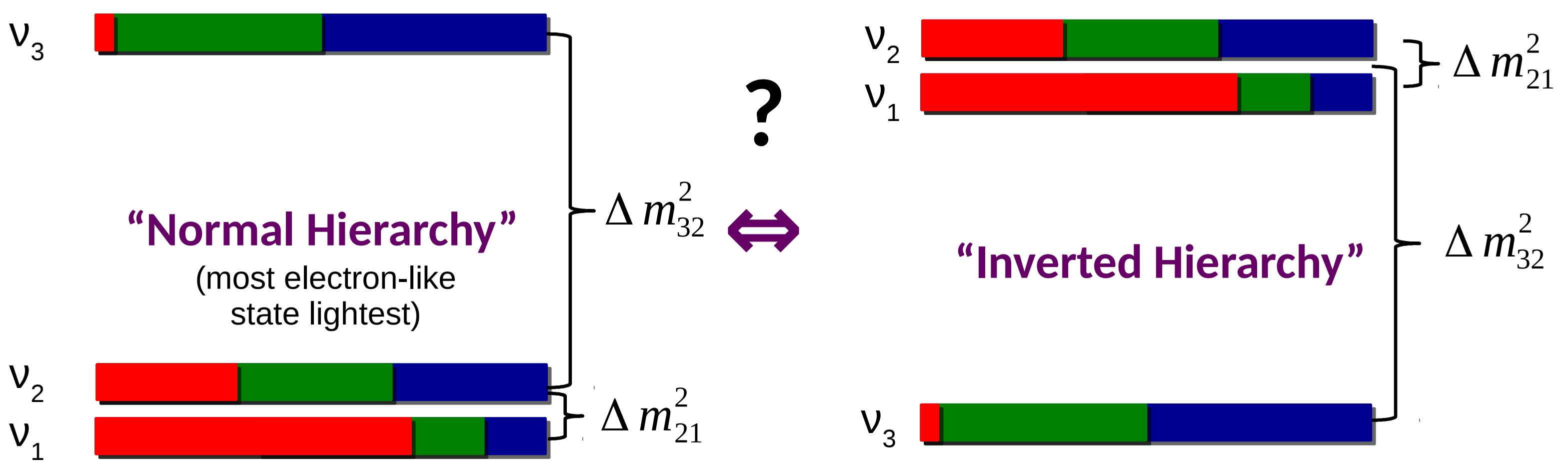
**<u>Big question:</u>**
Is there a **symmetry** governing the $\nu_\mu/\nu_\tau$ mixing into the 2nd and 3rd mass states?
(Is $\theta_{23}$ "maximal" = 45º?)

$\nu_3$=



# Neutrino oscillations: mass splittings

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




**Big question**:

Which way around are the mass states ordered?

$\nu_e$ **appearance** from accelerator vs, also possibly reactor disappearance

Measuring neutrino oscillation parameters

with

# NOvA

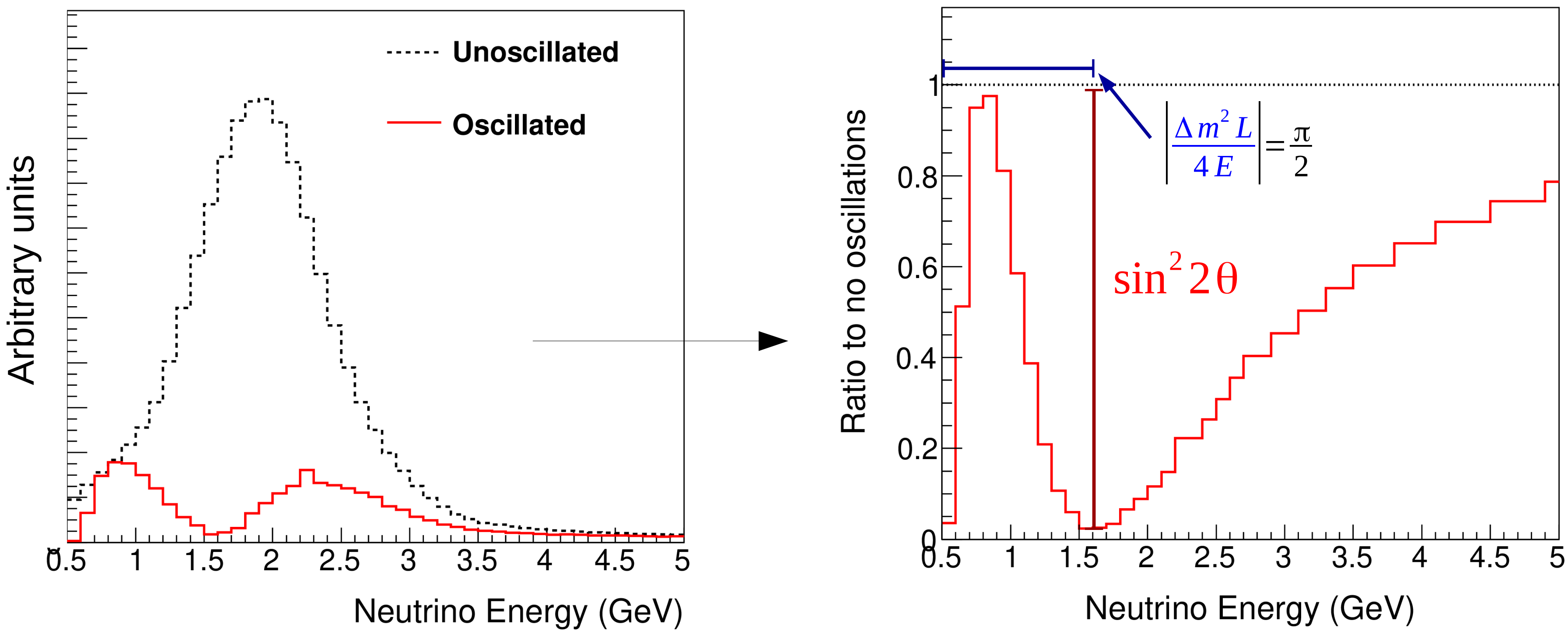
# Long-baseline neutrino experiments

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

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

How far away from the source you build your detector

Energy spectrum of your neutrino beam

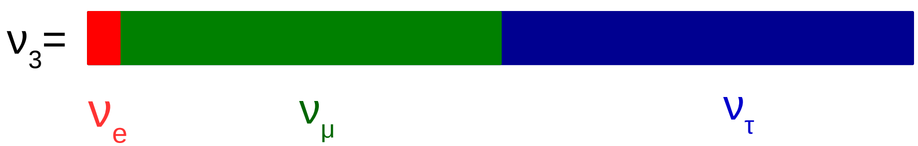


## $\nu_\mu$ disappearance:

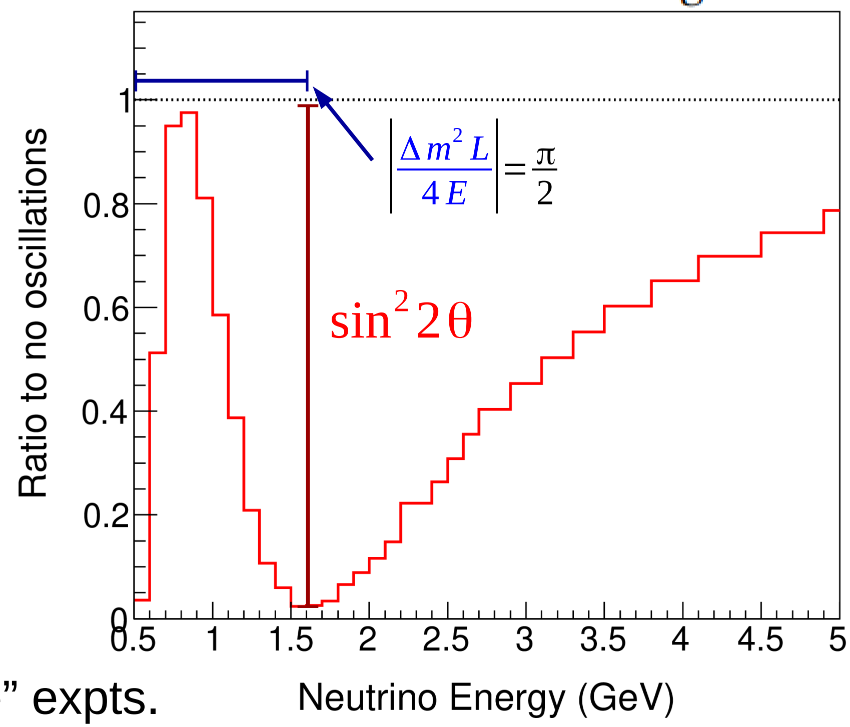
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

*... to leading order*

Because $\nu_\mu/\nu_\tau$ is nearly 50/50 in all the mass states,




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




→ Paradigm for modern "long-baseline" expts.

## $\nu_e$ appearance is quite a bit harder because $\theta_{13}$ is small...

$\sin^2 2\theta_{23}$ in $\nu_\mu$ disappearance...

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

note sign flip for antineutrinos →

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

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

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

… but if you can measure it well (for ν *and* $\bar{\nu}$),
**you gain access to both δ *and* the mass hierarchy**.
(Hierarchy dependence enters through *matter effects*...)

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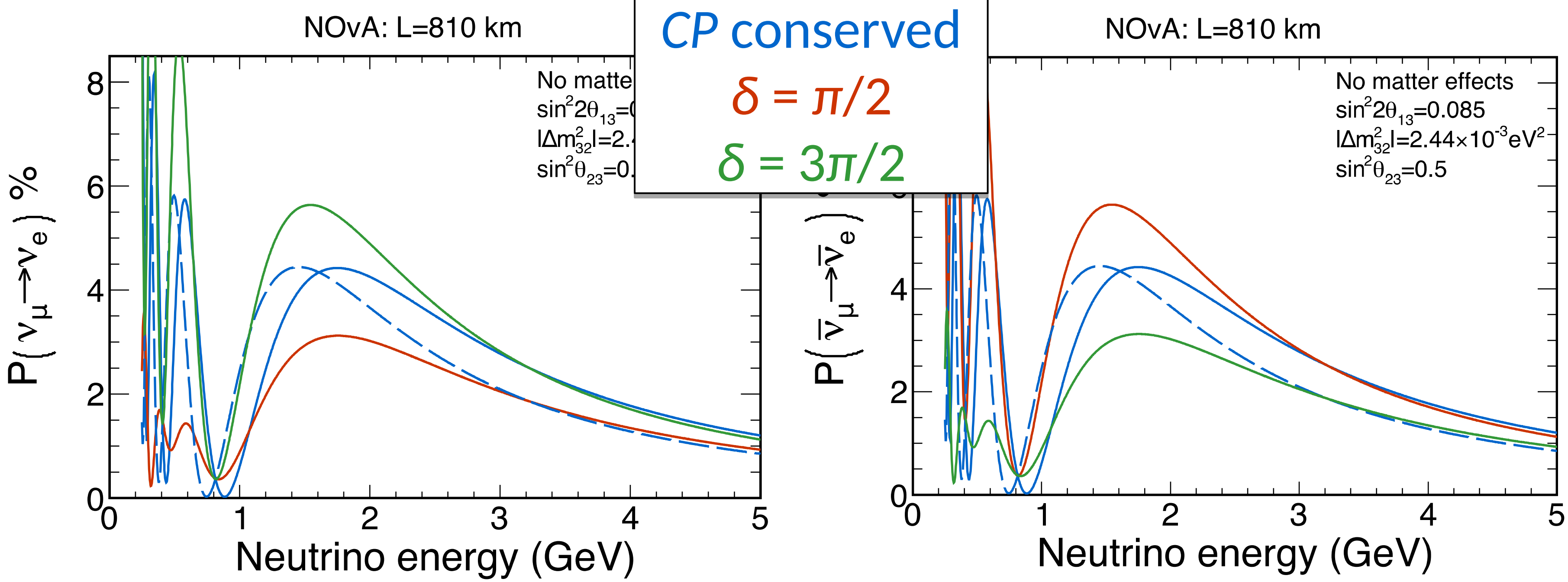


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# Long-baseline neutrino experiments

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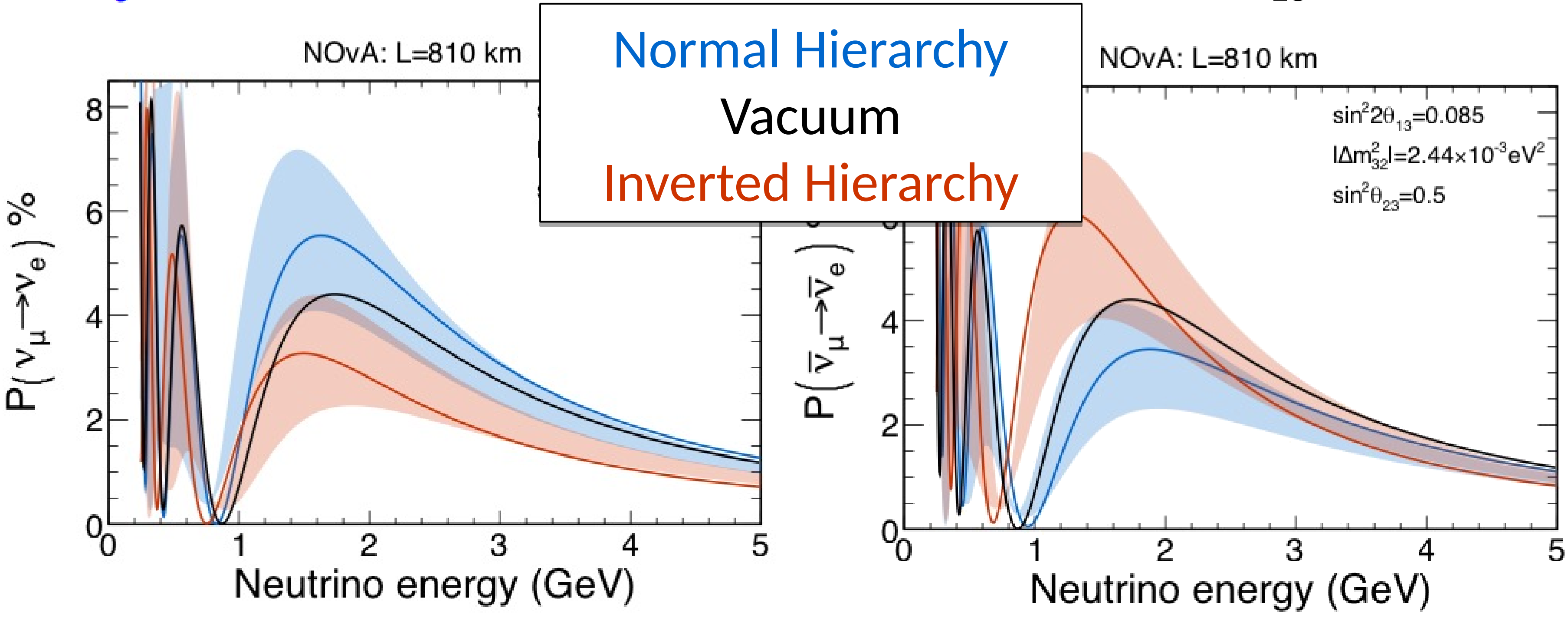


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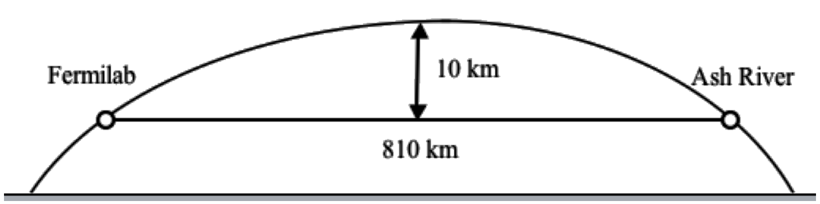
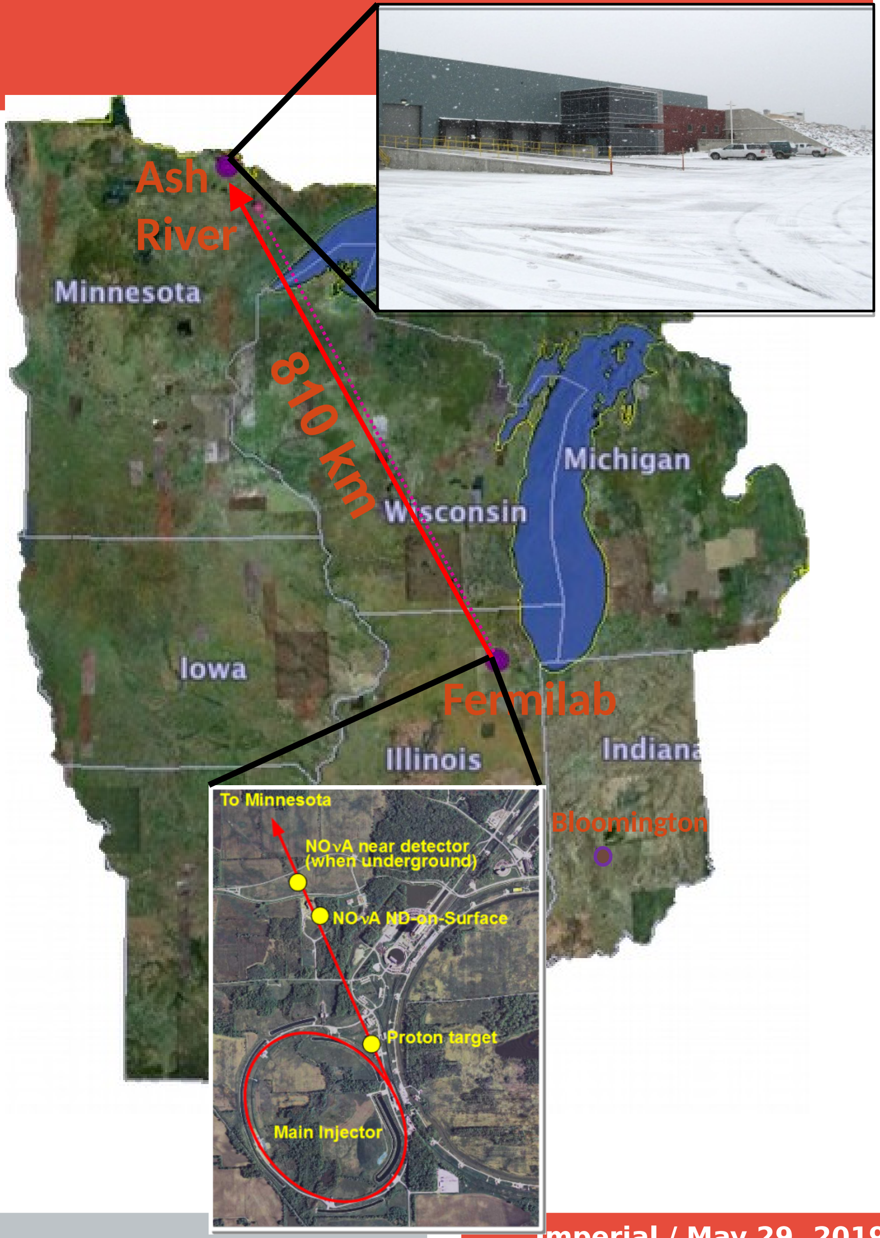
# The NOvA experiment

**N**uMI **O**ff-axis $\nu_e$ **A**ppearance Experiment

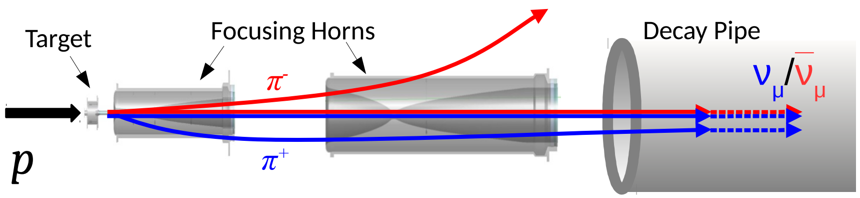
NuMI = **N**eutrinos at the **M**ain **I**njector

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



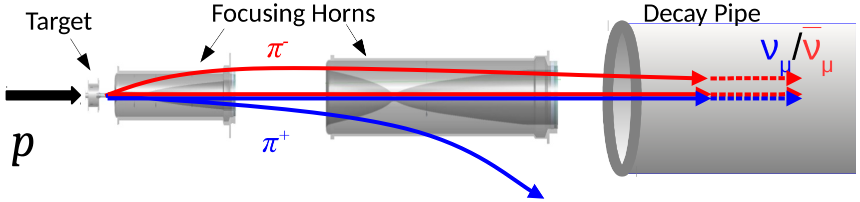
# The NuMI beam

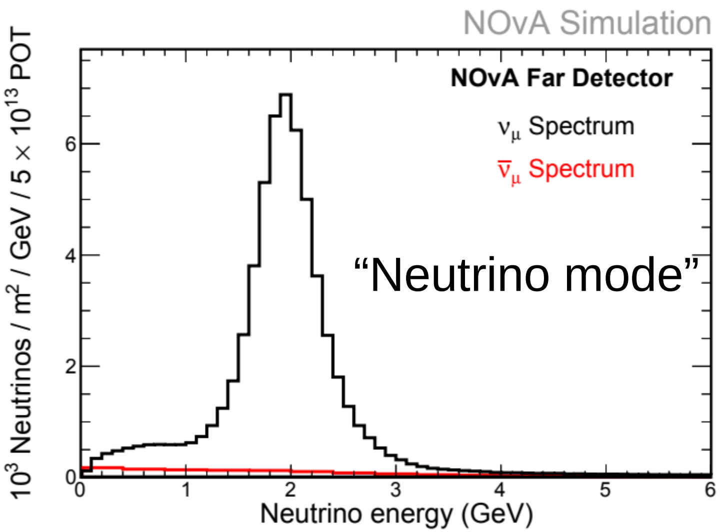


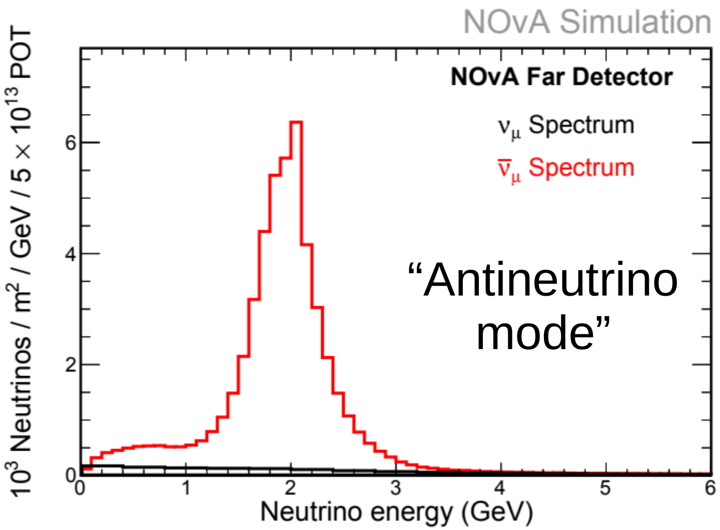

Magnetic "horns" focus mesons from proton beam-$^{12}$C target interactions

Detectors are 14mrad off main beam axis:

- Results in narrow energy spectrum around 2 GeV
- Reduces "wrong-sign" ($\bar{\nu}$ in $\nu$ beam and vice versa) component → 3% (5%) contamination for $\nu$ ($\bar{\nu}$)



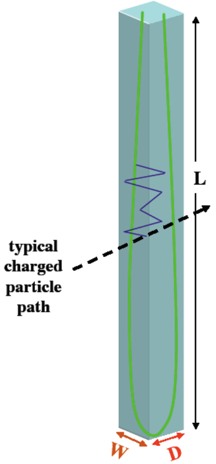
# The NOvA detectors


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

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

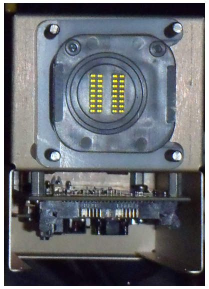
# The NOvA detectors

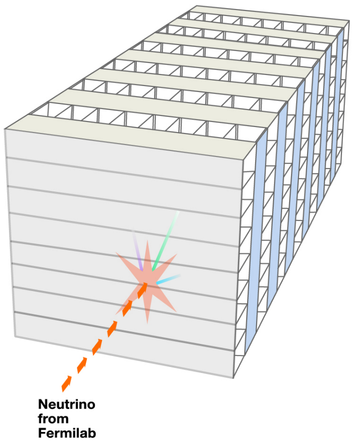
1 Channel

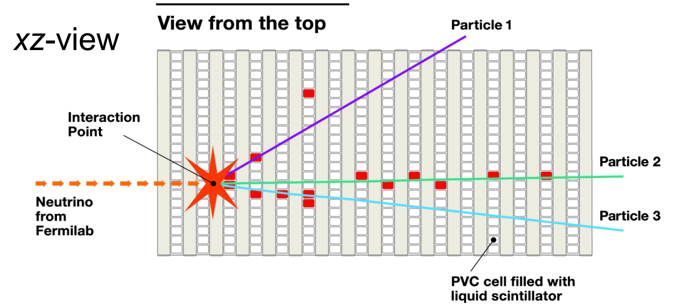


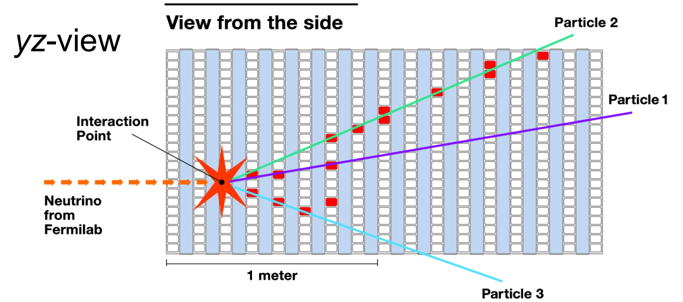

(~20K
4cm × 6cm)

APD
32 Channels






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

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

# Main idea:

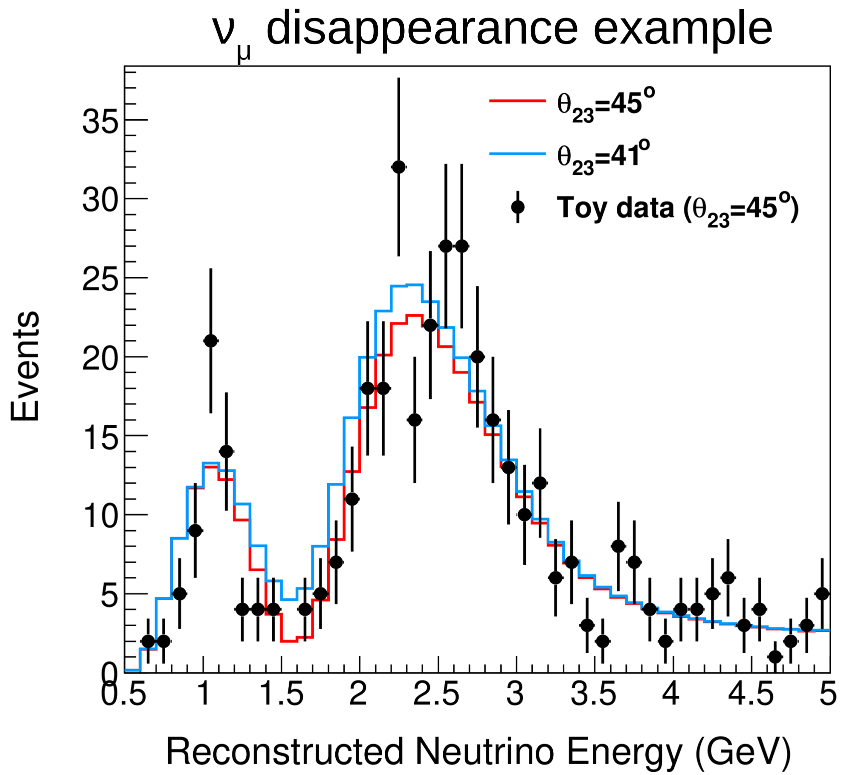
Compare

**predicted spectrum at FD**

to

**observed spectrum at FD**

to extract oscillation parameters



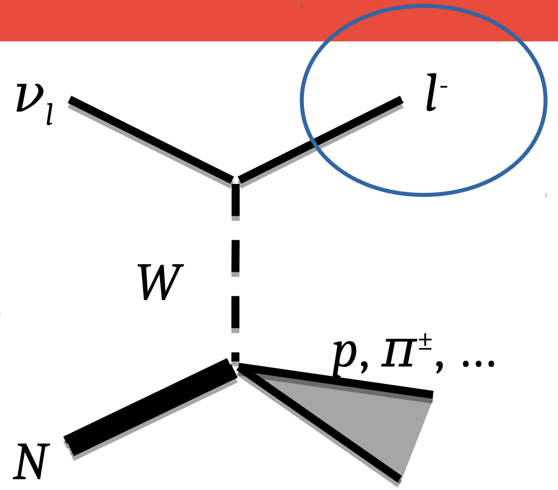

**Discuss in two steps:**
**building the spectrum,**
then **details of prediction**

# Spectrum construction

(1) Event selection
(2) Reconstruction & observables

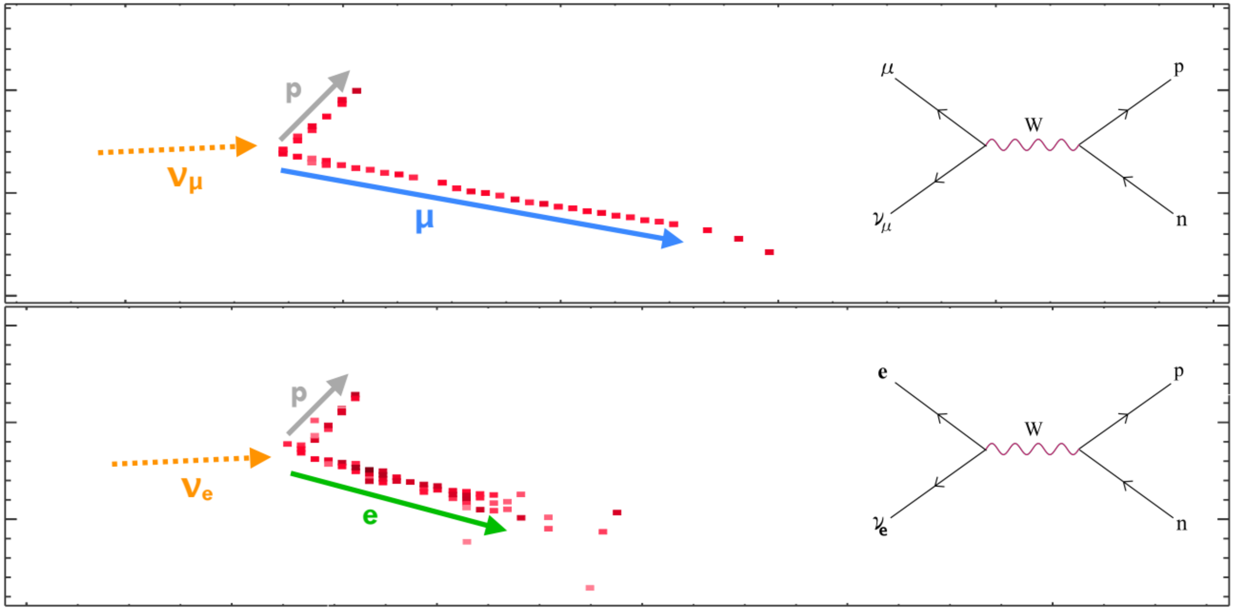
# Spectrum construction: identifying neutrino events

Q: How do you identify a $\nu_\mu$ or $\nu_e$?




A: Look for charged-current reactions

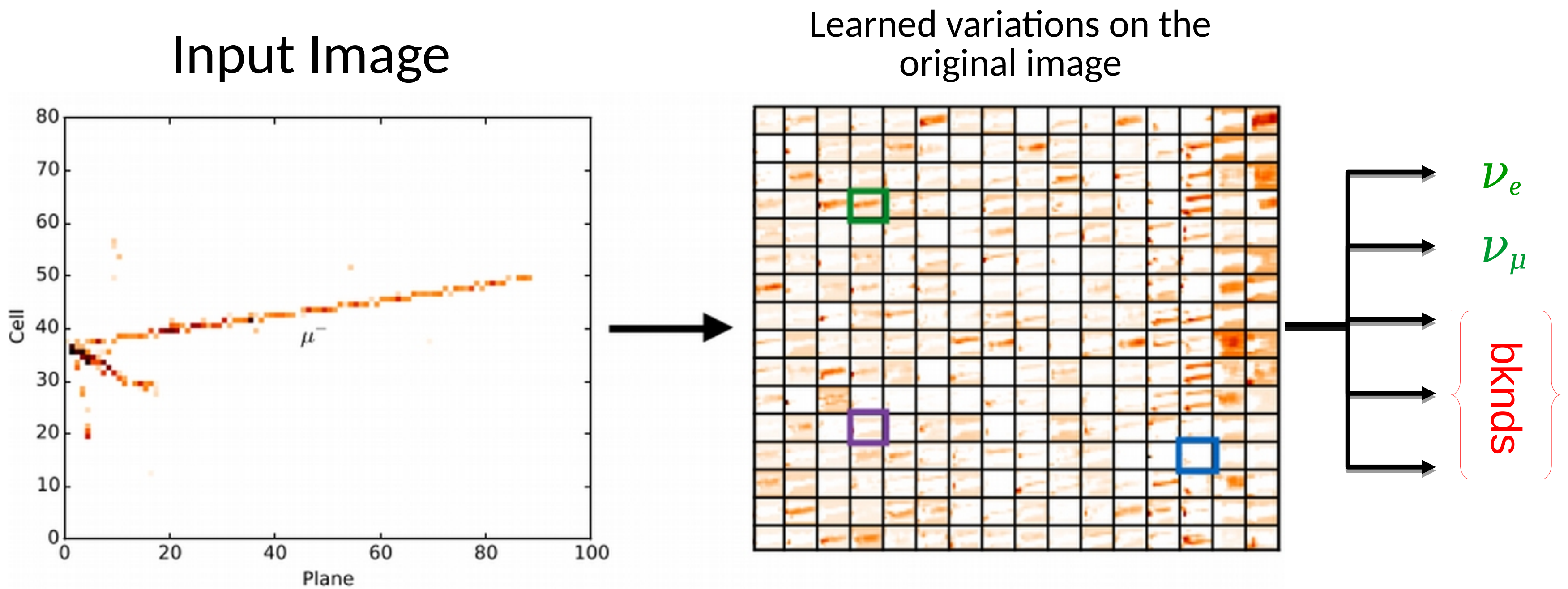
(charged leptons differ & backgrounds have no primary charged lepton)




Selections share many ingredients; will discuss in parallel.

Illustrate using *neutrino* mode (antineutrinos shown where different)

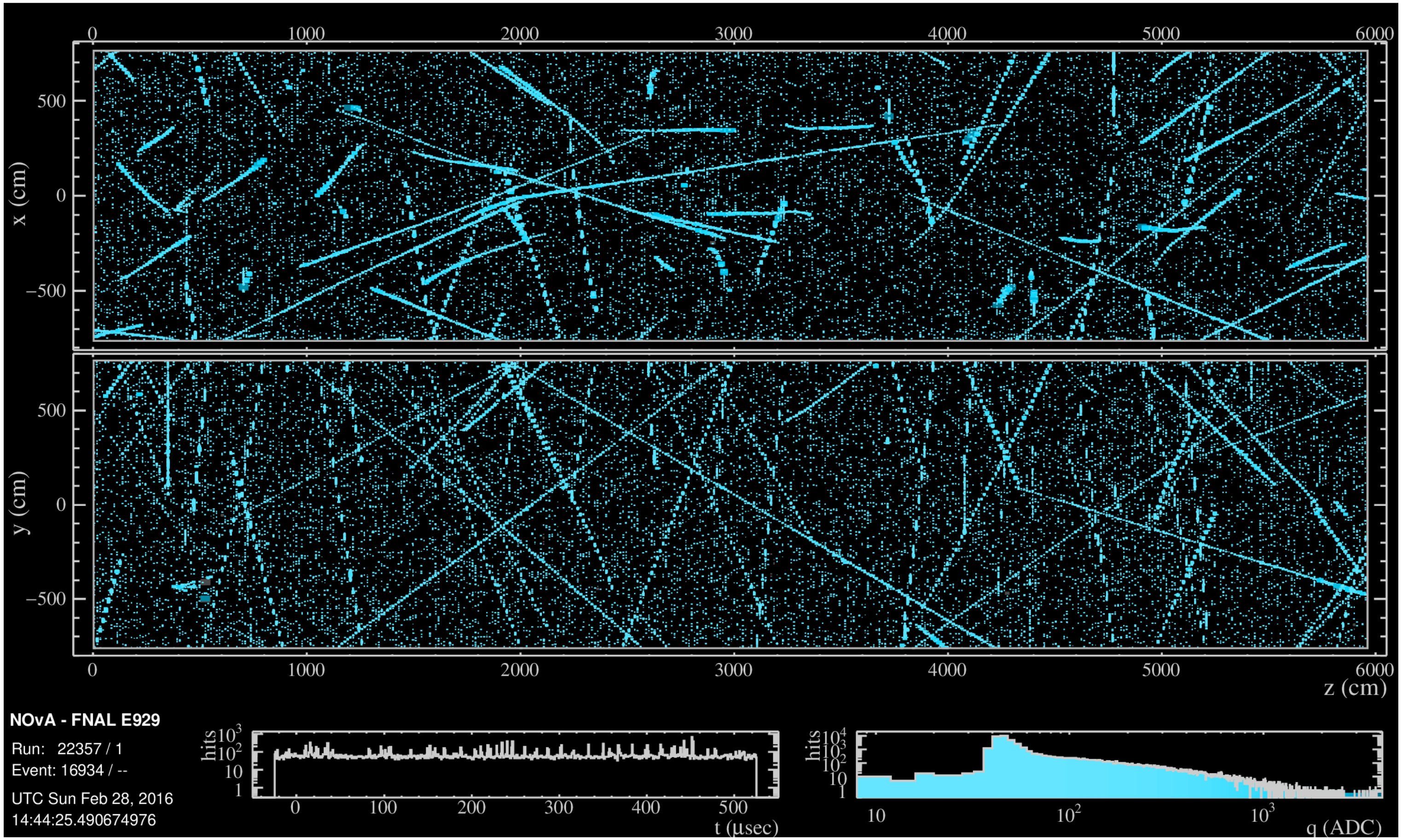
# Spectrum construction: identifying neutrino events




- 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

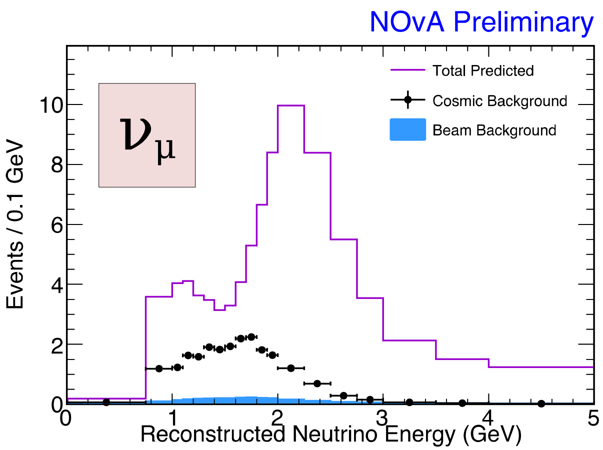
[A. Aurisano and A. Radovic and D. Rocco et. al, JINST **11** P09001 (2016)]

# Spectrum construction: Identifying neutrino events

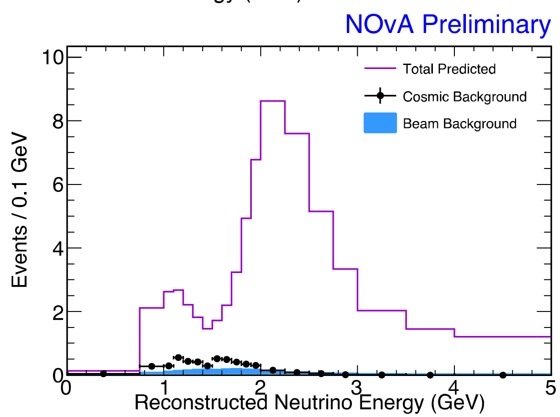


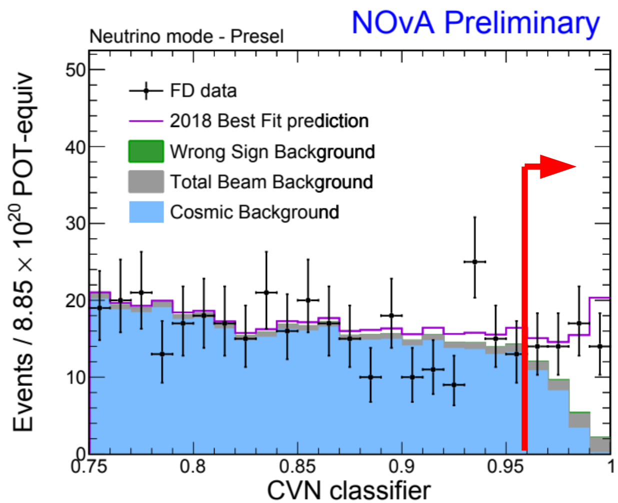

One 550 μs readout window.
~All cosmics.

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

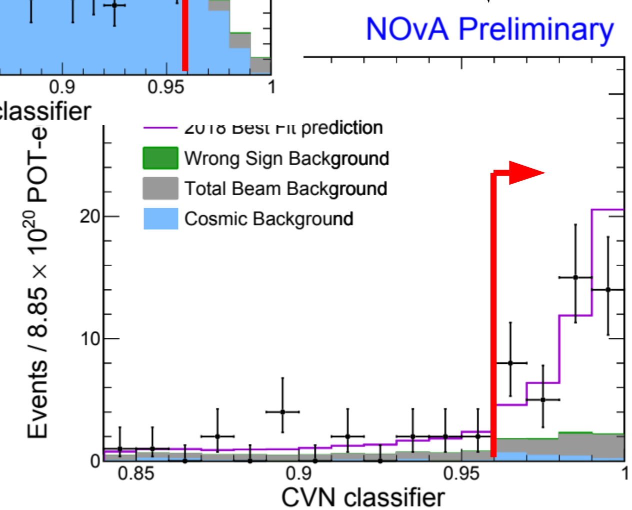



cosmic kNN




2D cut on ($y$, $p_T/|\mathbf{p}|$)

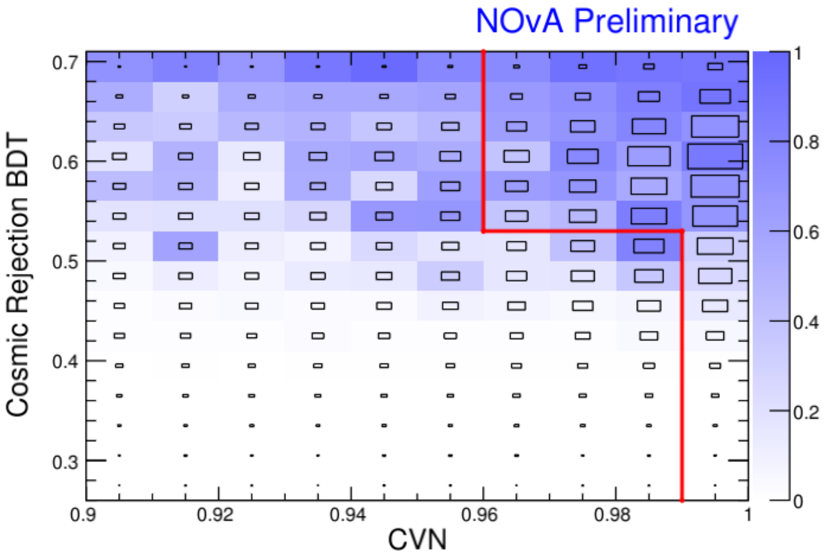


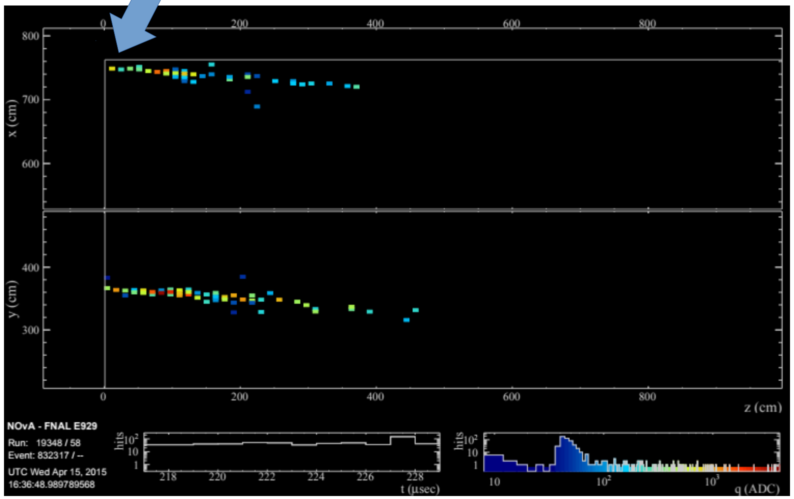

**Pulsed beam + good timing resolution**
and **containment + CVN** requirements help a lot,
but still need further cosmics rejection

# Spectrum construction: Identifying neutrino events

$\nu_e$

Vertex is near detector edge

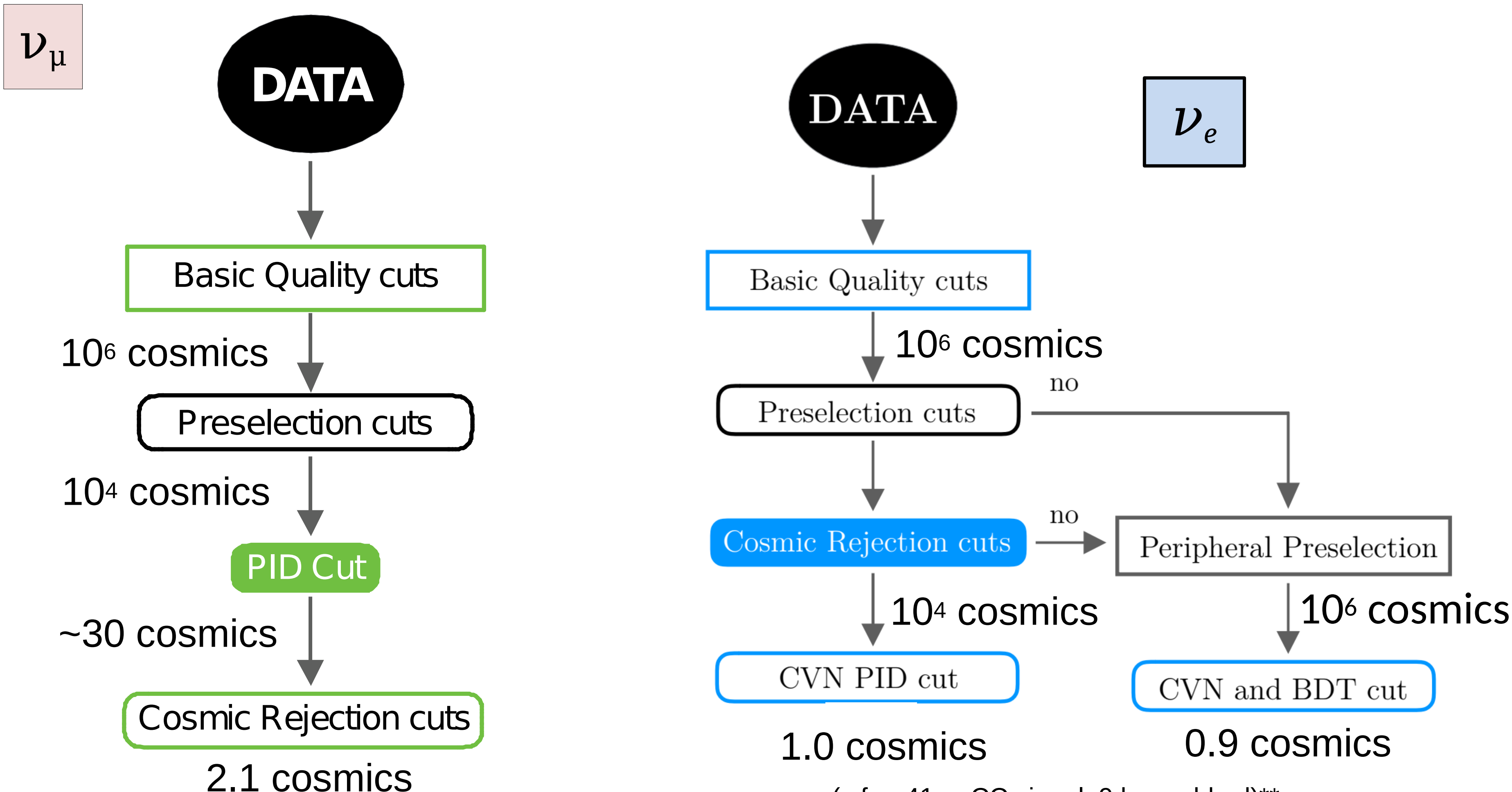



$\nu_e$ cosmic cuts are harsh.
Recover events near edges
but high PID (so lots of signal)
w/ dedicated multivariate classifier

→ **“Peripheral”** sample

# Spectrum construction: Identifying neutrino events



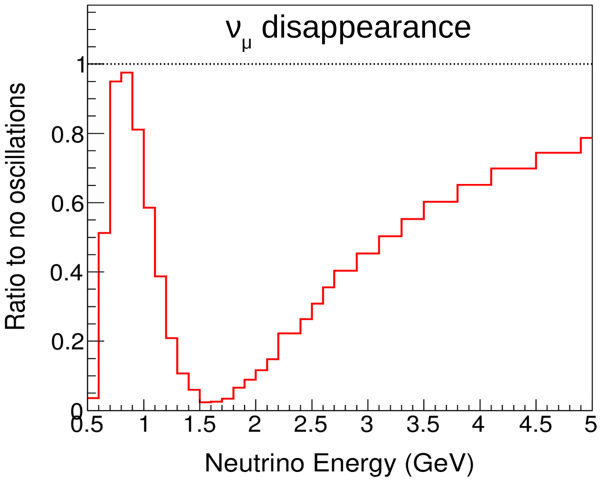

(c.f.: ~120 $\nu_\mu$ CC signal, 2 beam bknd)**

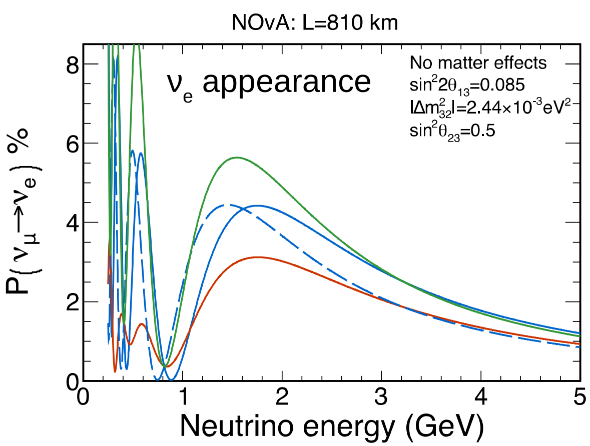
(c.f.: ~41 $\nu_e$ CC signal, 9 beam bknd)**

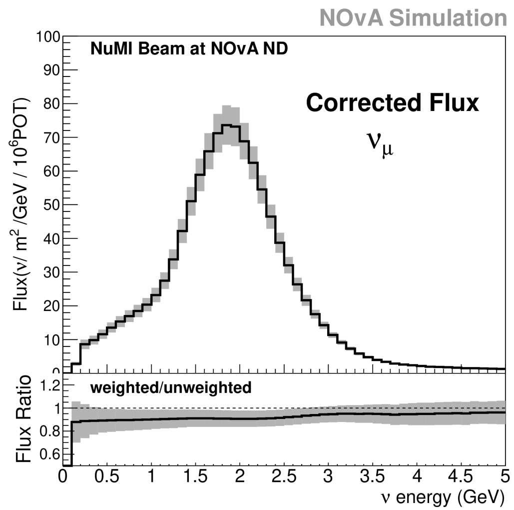
** These predictions will be discussed in more detail later

# Spectrum construction: Reconstructing neutrino energy

Oscillation is a function of *neutrino energy*:



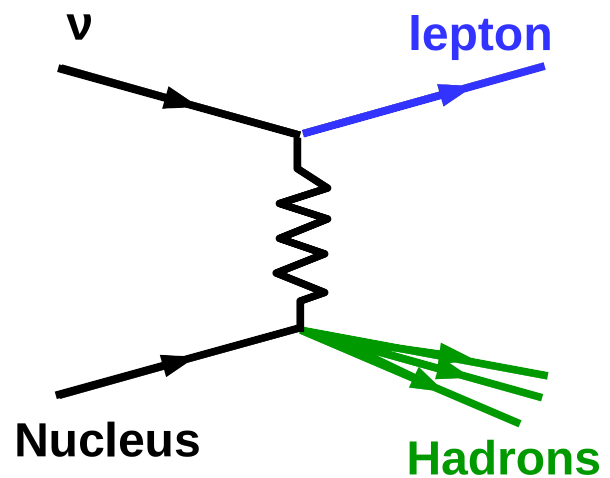




… but neutrino beam isn't completely monochromatic (despite being off-axis) ...

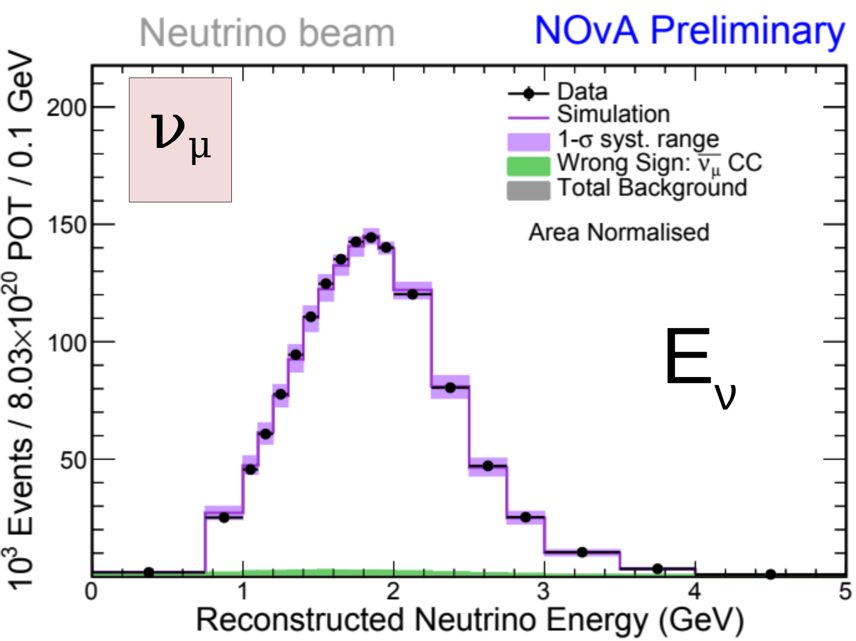
… so we need to reconstruct neutrino energy from reaction byproducts event by event

**Strategy:** divide and conquer




Evaluate the lepton (muon or electron) and hadronic system energies separately → $E_\nu = f(E_{lep}, E_{had})$

# **Strategy:** divide and conquer

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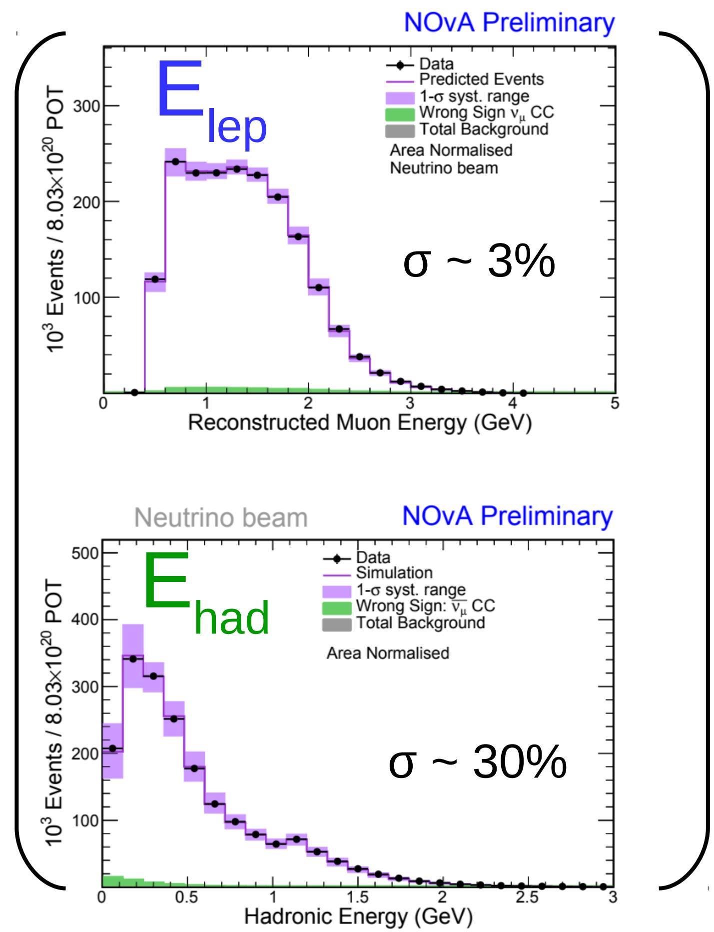
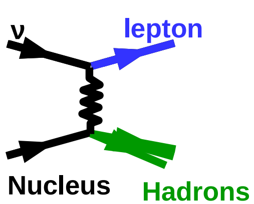
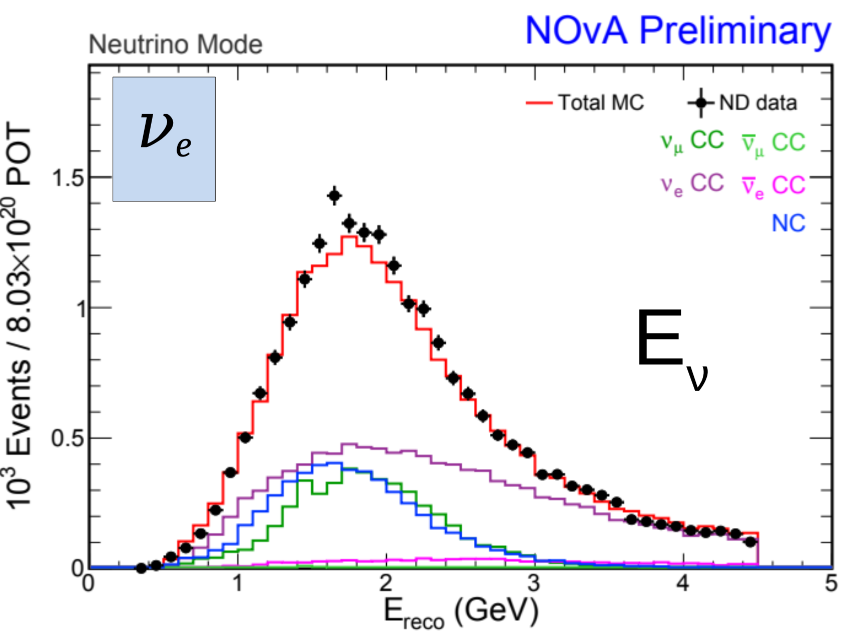



$E_\nu$ resolution: ~9%

# **Strategy:** divide and conquer

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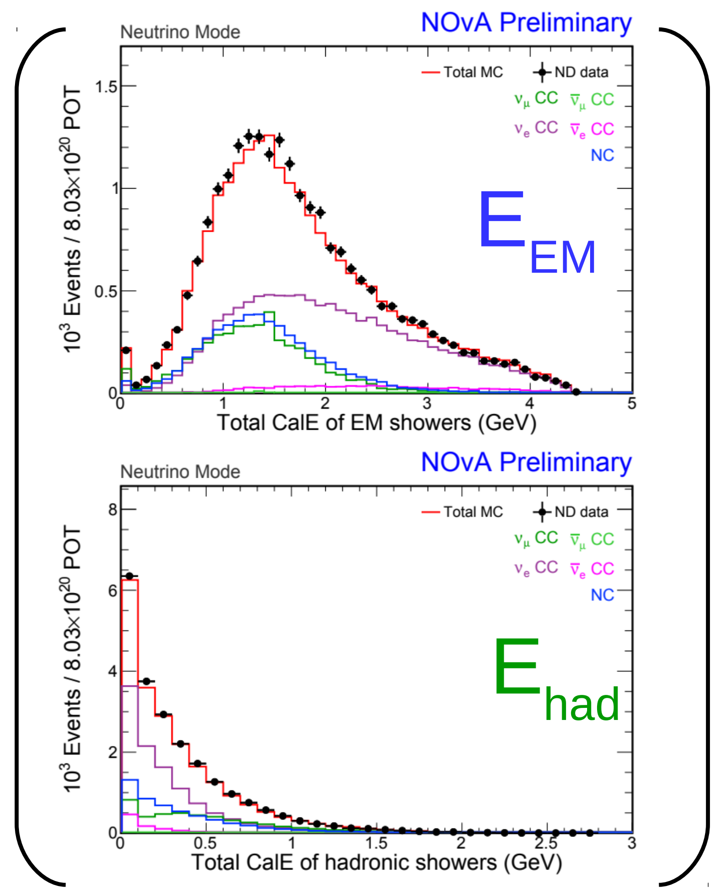
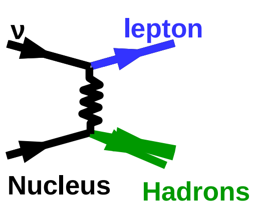
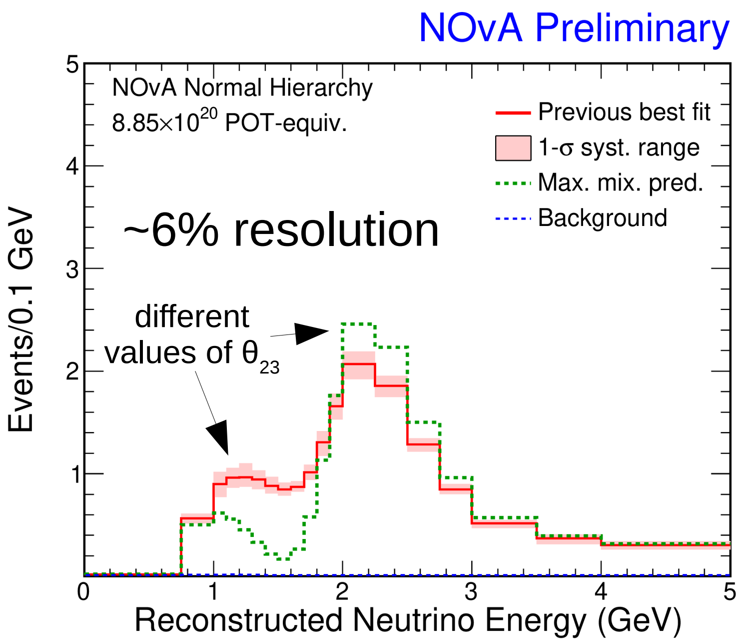


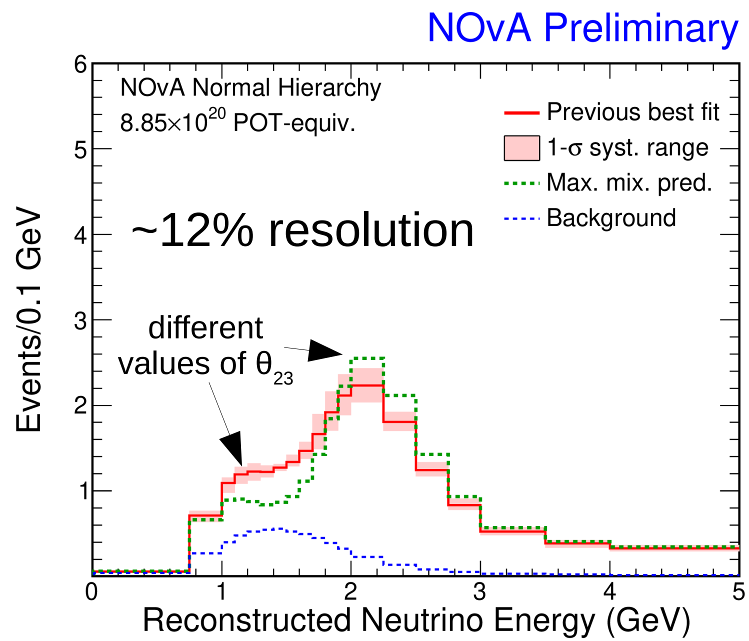

$E_\nu$ resolution: ~11%

# Spectrum construction: $\nu_\mu$ hadronic energy fraction binning

The power of the $\nu_\mu$ disappearance analysis is from *shape* discrimination:

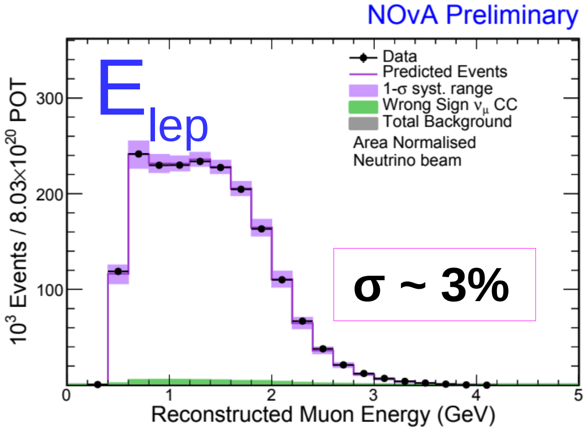


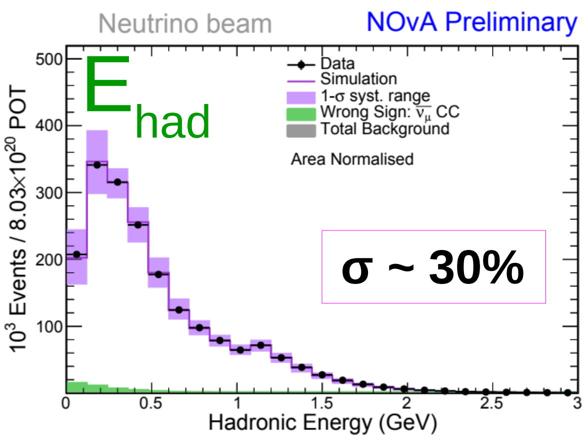

VS

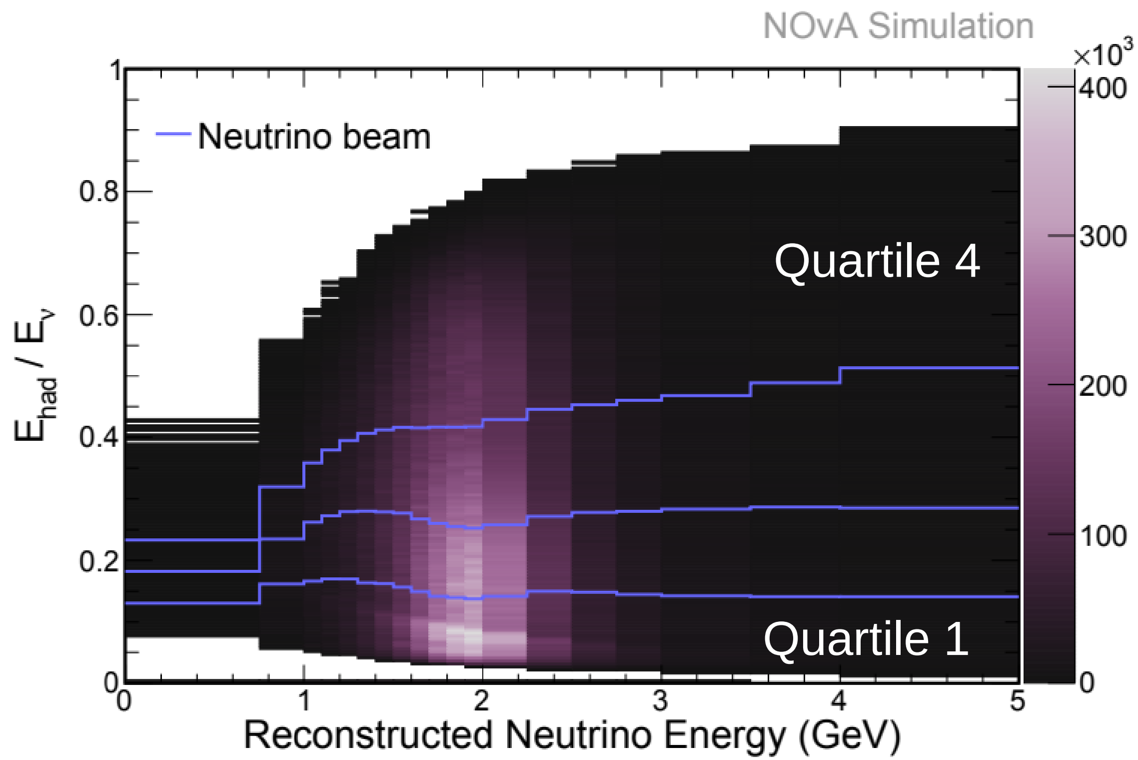



**Better resolution → less smearing in "dip"**
**→ better shape discrimination**

# Spectrum construction: $\nu_\mu$ hadronic energy fraction binning



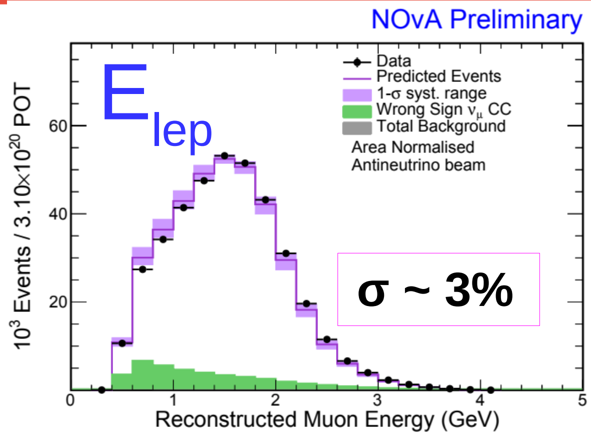



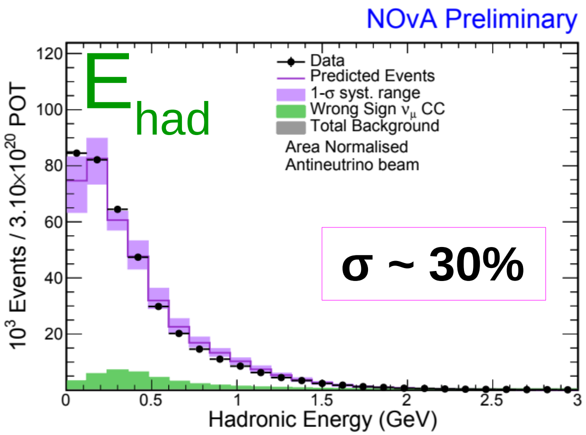



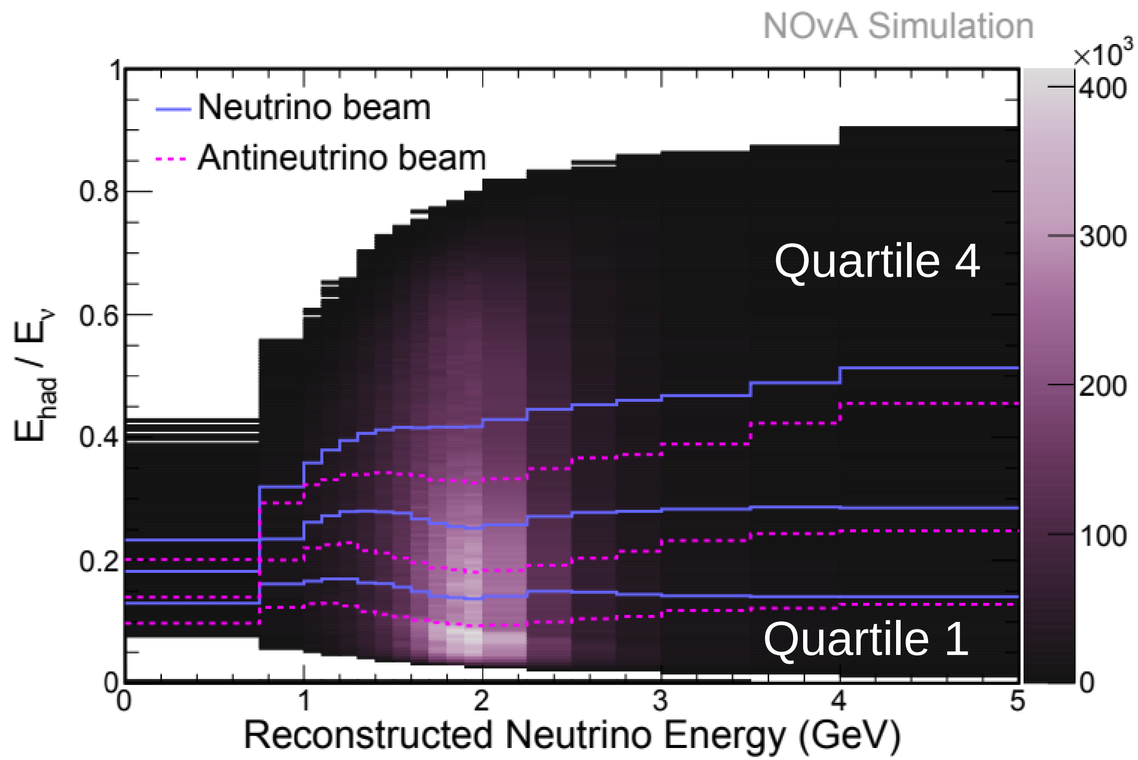

Resolution for $E_\mu$ is *much* better than $E_{had}$

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

# Spectrum construction: $\nu_\mu$ hadronic energy fraction binning



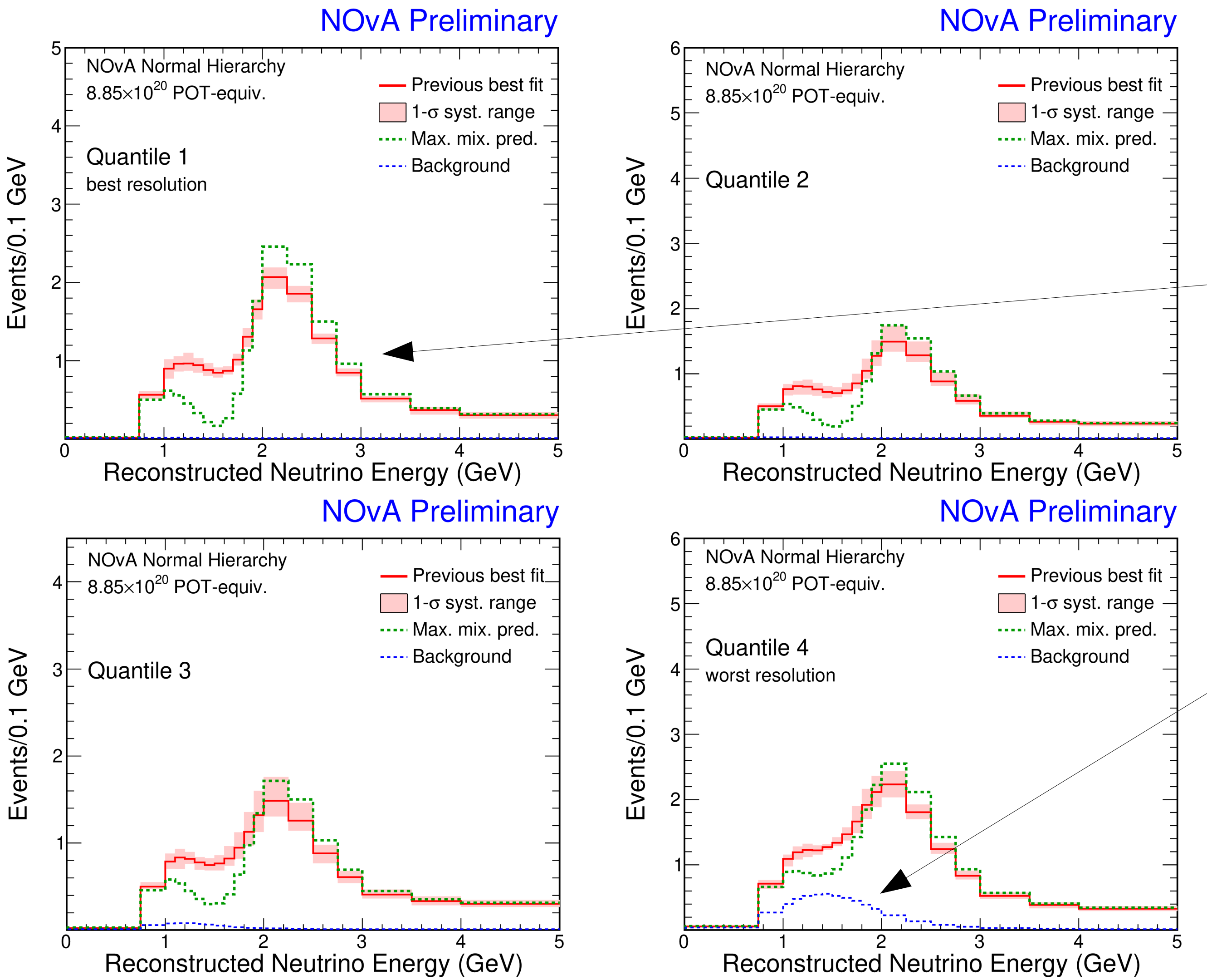




Though the component resolutions don't change much ...

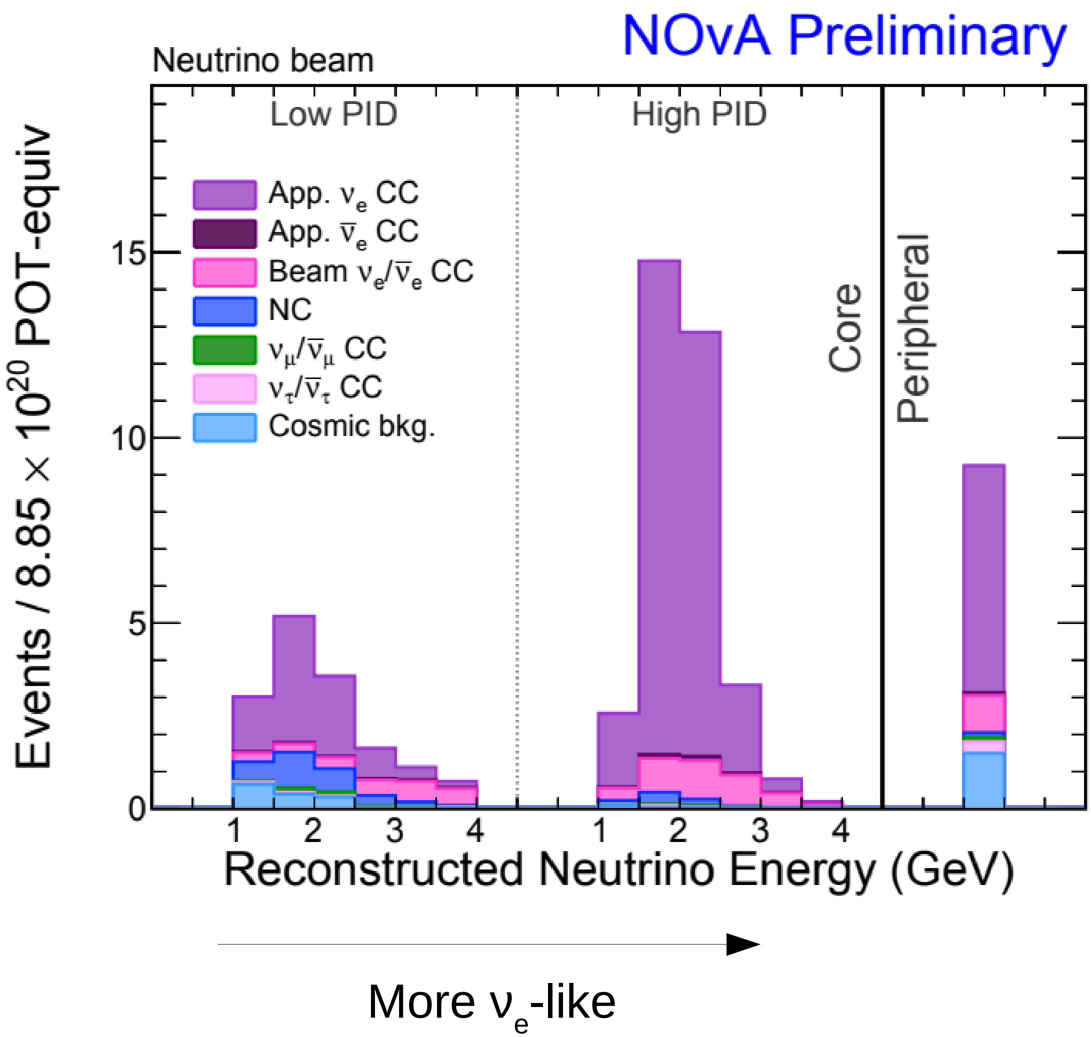
... **antineutrinos** typically have lower $E_{had}/E_\nu$ than neutrinos, so the boundaries are different

# Spectrum construction: $\nu_\mu$ hadronic energy fraction binning




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

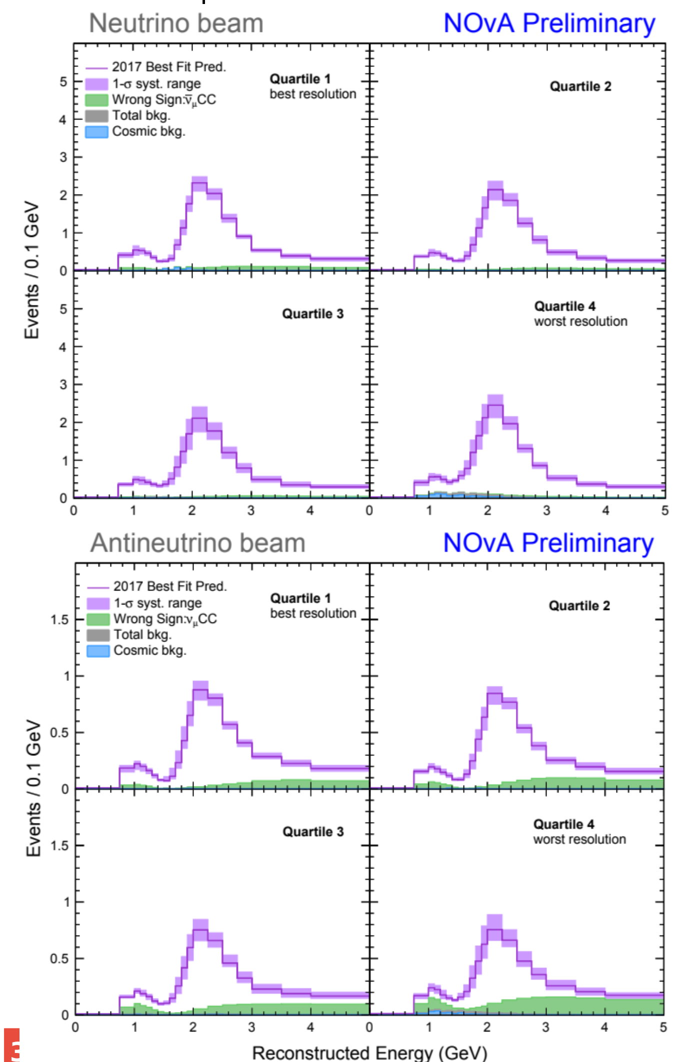
# Spectrum construction: $\nu_e$ binning




- Try to separate best-understood signal (high PID) from backgrounds
- Mild spectrum difference between appeared (signal) $\nu_e$ vs. intrinsic beam $\nu_e$ bknd (signal ~lower $E_\nu$)

# Spectra

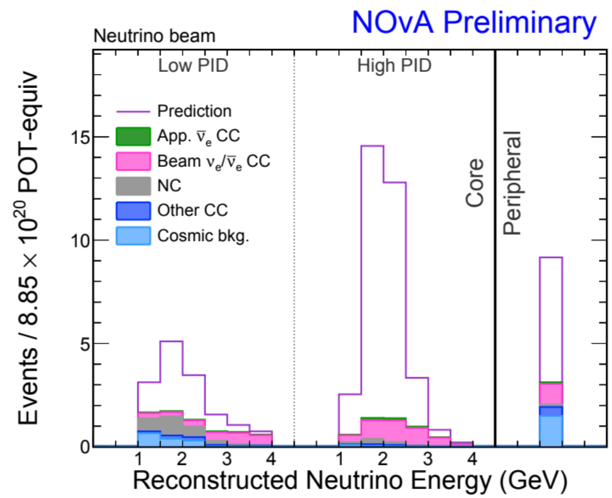
## $\nu_\mu$ disappearance

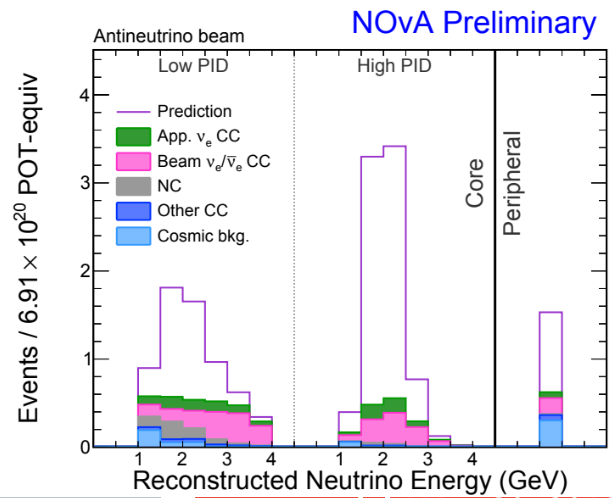



**We vary the oscillation parameters in these 4+4+3+3=17 predictions simultaneously to find the best fit with the FD data.**

Before looking at the data, though, let's examine the predictions in a bit more detail...

## $\nu_e$ appearance



# Predictions:
# Simulation & constraints

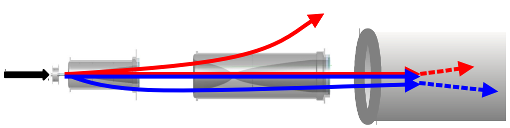
# Predictions: simulation chain

Geant 4

+

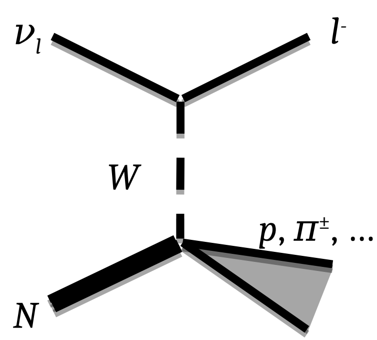
NuMI
PPFX

**Neutrino flux**



GENIE
2.12.2

**Neutrino reactions** on detector materials

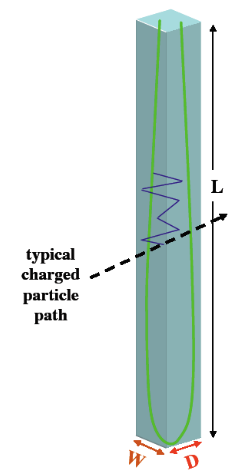



Geant 4

+

Custom readout software

**Detector response** to charged particles and **light propagation**




(with systematic uncertainties from each step)

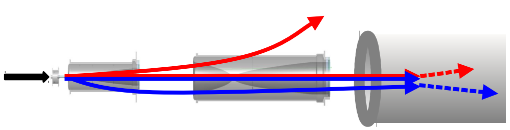
# Predictions: simulation chain

Geant 4

+

NuMI
PPFX

**Neutrino flux**



GENIE
2.12.2

**Neutrino reactions**
on detector materials




Geant 4

+

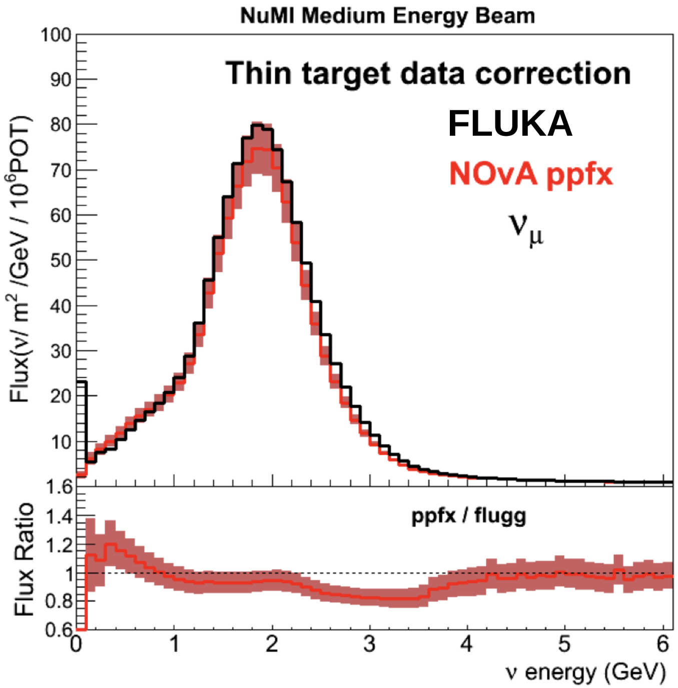
Custom
readout
software

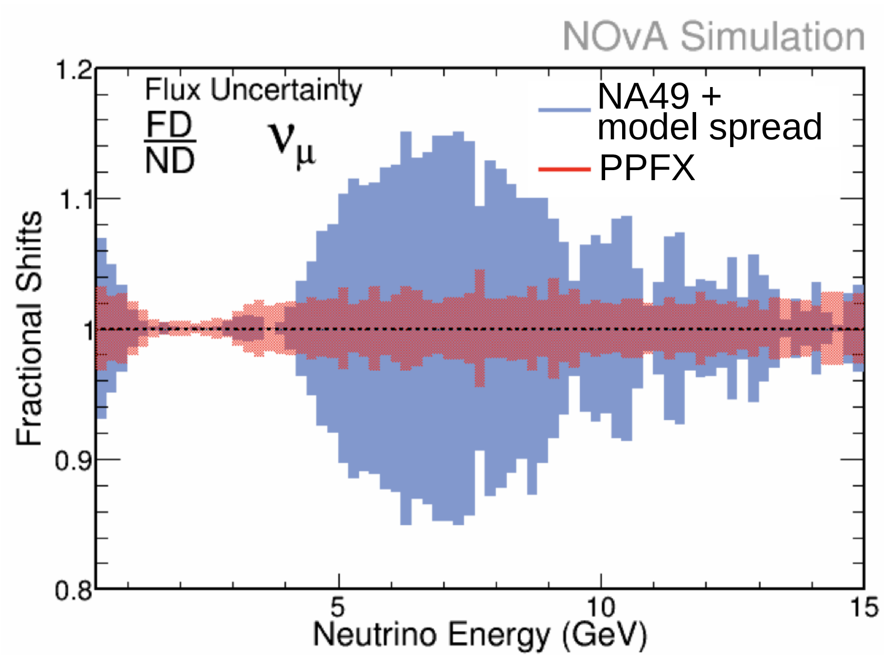
**Detector response** to charged particles and **light propagation**




(with systematic uncertainties from each step)

# Predictions: flux




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

# Predictions: simulation chain

Geant 4

+

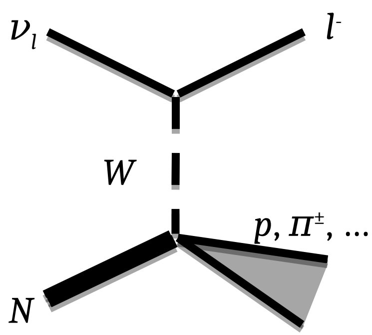
NuMI
PPFX

**Neutrino flux**



GENIE
2.12.2

**Neutrino reactions**
on detector materials




Geant 4

+

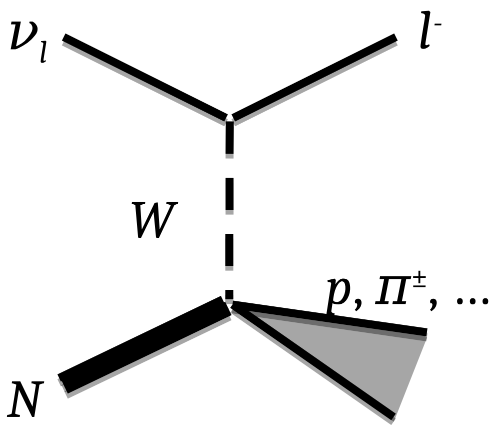
Custom
readout
software

**Detector response** to charged particles and **light propagation**

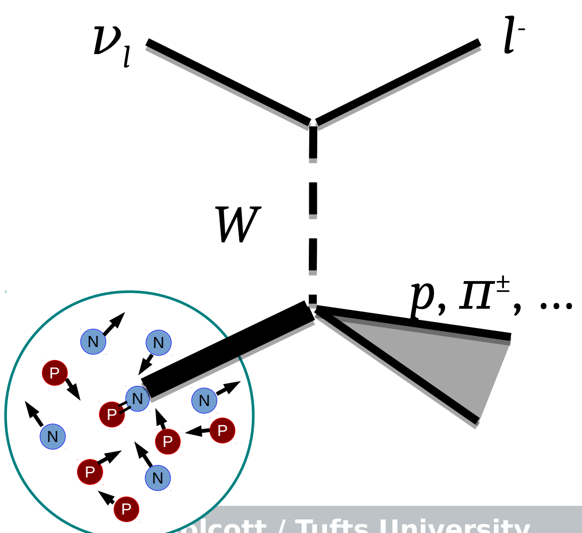



(with systematic uncertainties from each step)

# Predictions: neutrino scattering model




vs

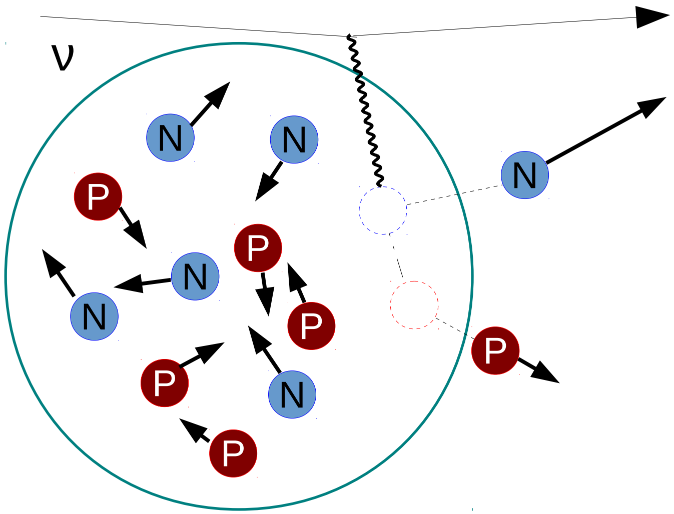



<u>Nuclear effects not in GENIE 2.12.2 are important</u>

- Elastic-like (no pions produced):
  - Multi-nucleon knockout (short range): tuned empirical model
  - Nuclear charge screening (long range): theory-based corrections†
- Pion production:
  - Empirical correction inspired by observed suppression in data

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

# Predictions: neutrino scattering model

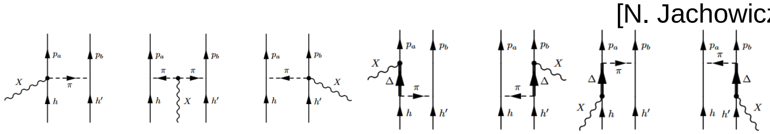


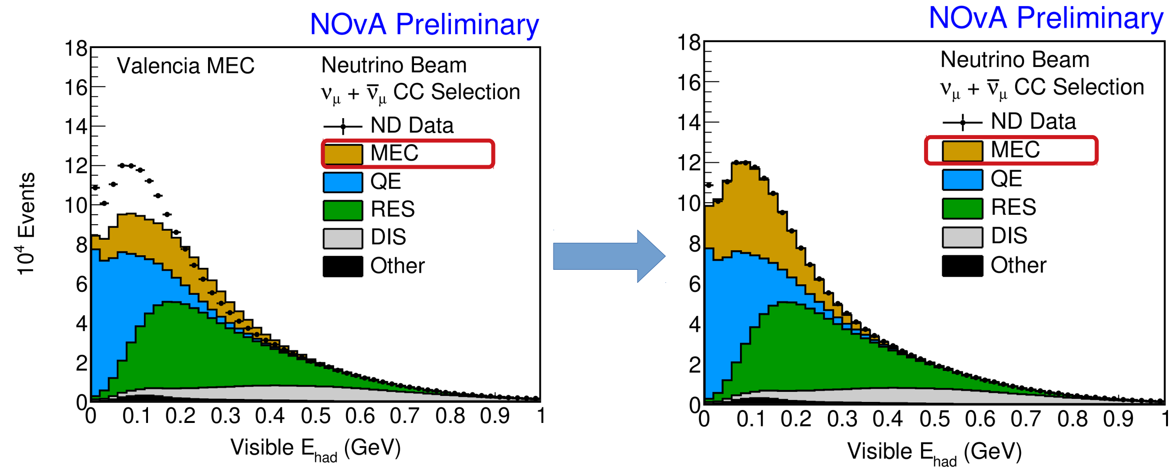

“2p2h”

Knock out two nucleons with an elastic-like interaction.

Models are a work in progress... resort to fits based on empirical “model*” in meantime

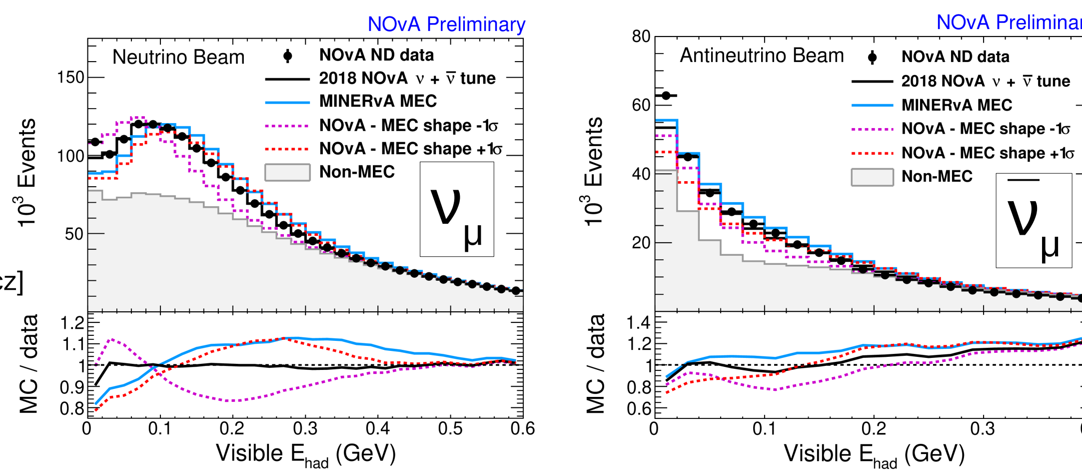
[N. Jachowicz]






**Fully empirical prescription for 2p2h derived from fitting data excess in ND**

(w/ tunes from alternate base MC as uncertainties)



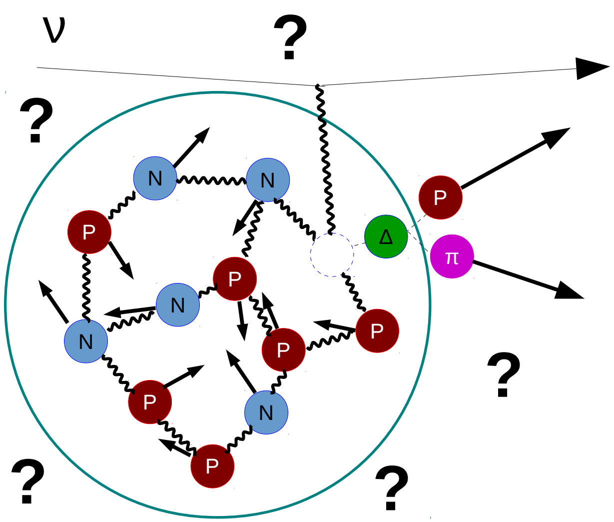

* “Meson Exchange Current (MEC) Models in Neutrino Interaction Generators”, Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

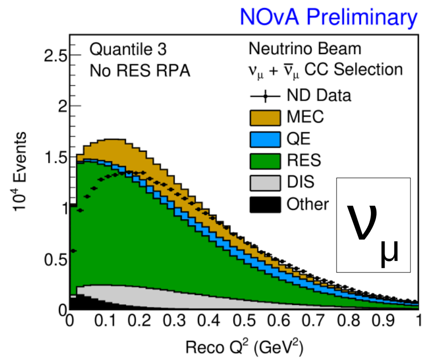
# Predictions: neutrino scattering model

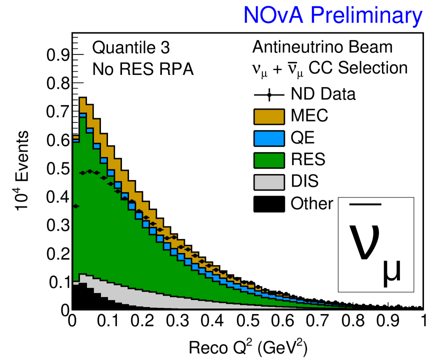
## Pion production

Apparent suppression at low momentum transfer relative to model...

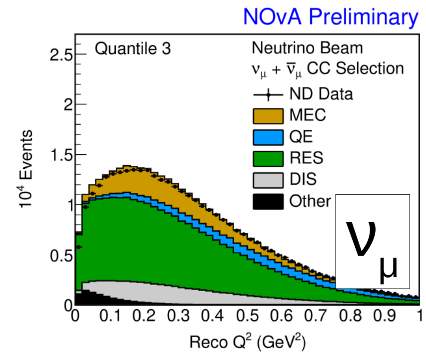
No theory to guide here.
"Adapt" *elastic* long-range correlation model ("RPA")

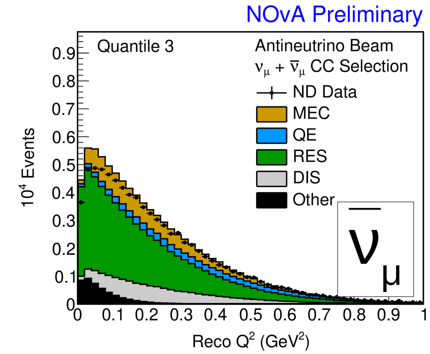


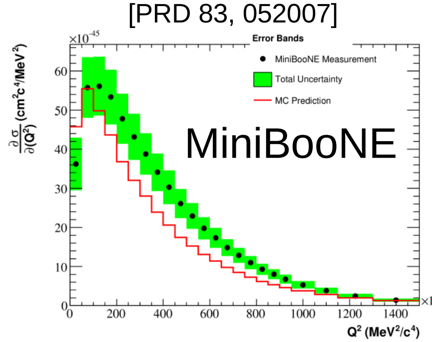




**Apply $Q^2$-based Valencia RPA weight from QE to resonant production as a stand-in for whatever nuclear effect we see at low $Q^2$**
(w/ unmodified version as uncertainty variation)

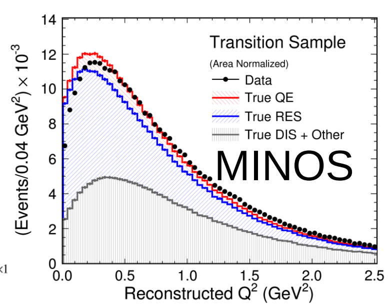


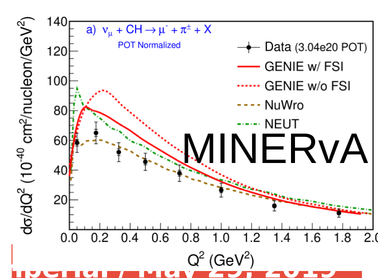

[PRD 83, 052007]




[PRD 91, 012005]




[PRD 94, 052005]



# Predictions: simulation chain

Geant 4

+

NuMI
PPFX

**Neutrino flux**



GENIE
2.12.2

**Neutrino reactions**
on detector materials

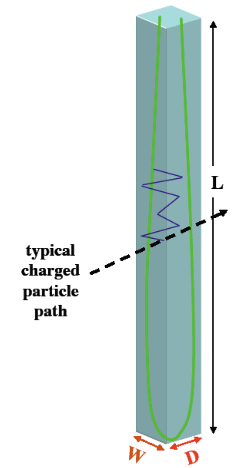



Geant 4

+

Custom
readout
software

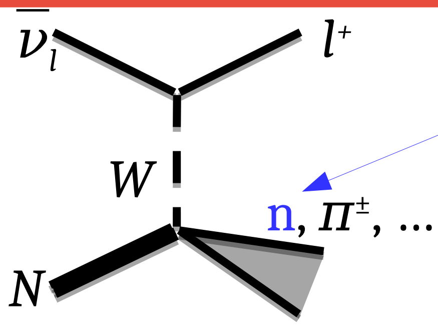
**Detector response** to charged particles and **light propagation**



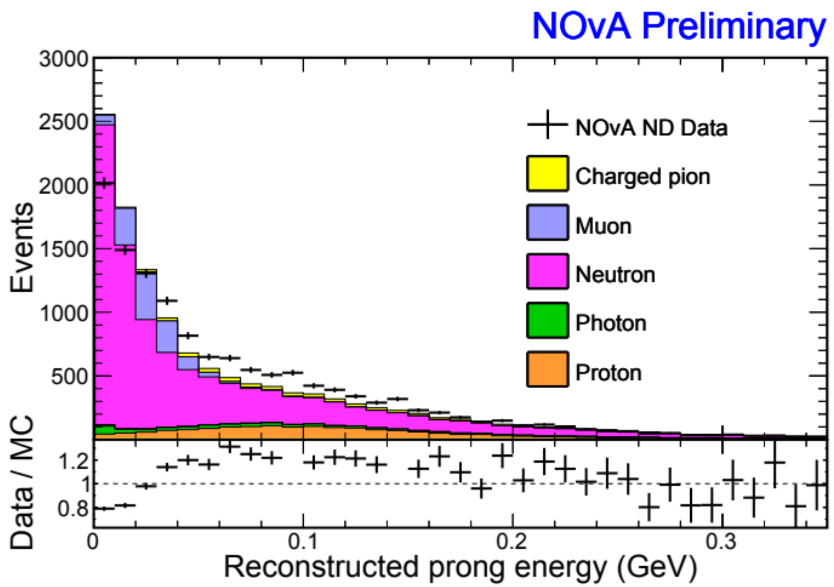

(with systematic uncertainties from each step)

# Predictions: simulation chain

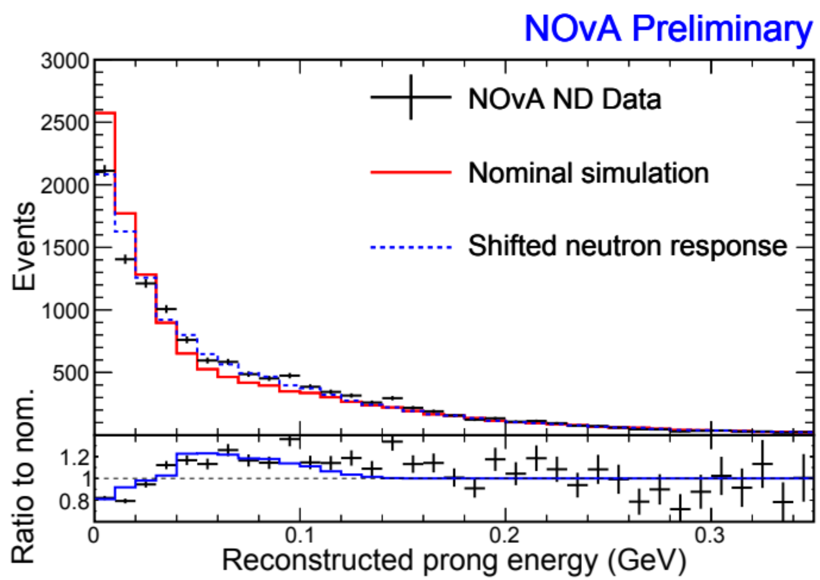
**Neutron response is important in $\bar{\nu}$ mode:**




neutrons dominate in antineutrino reactions



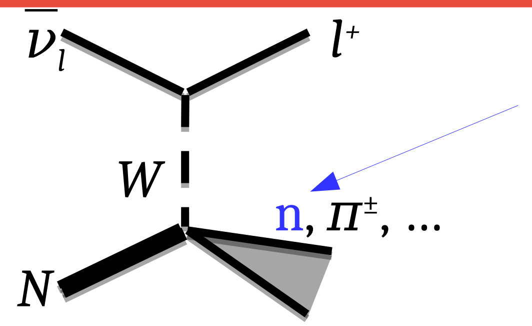

Search for $\bar{\nu}$ QE-like events (μ + no other tracks) with compact displaced energy deposits

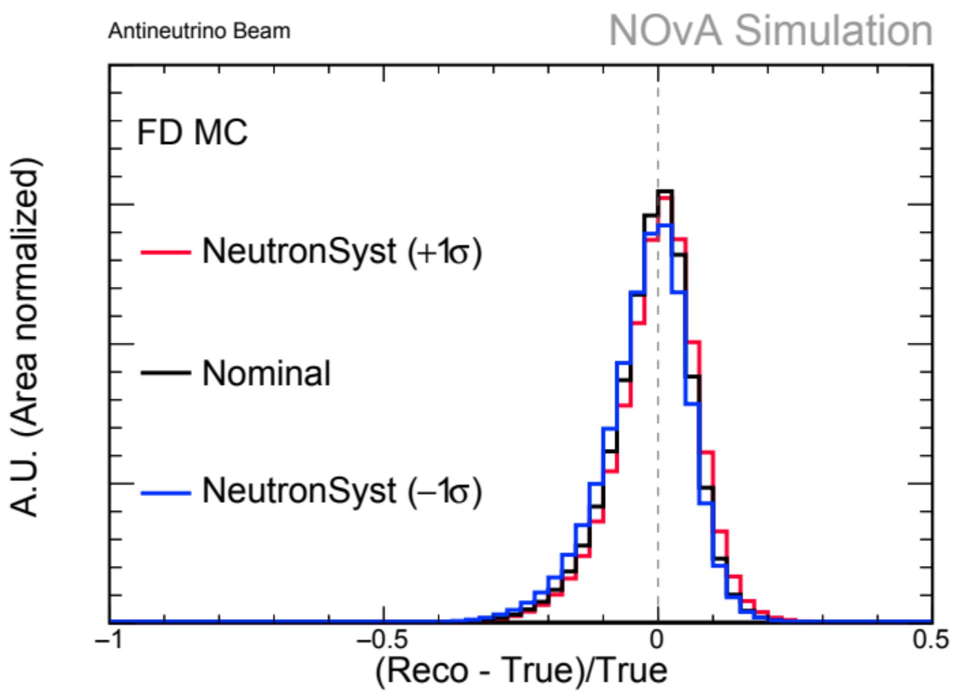



Design uncertainty to bound data-simulation difference in observed energy

# Predictions: simulation chain

**Neutron response is important in $\bar{\nu}$ mode:**




Fortunately, **syst has a ~1% effect shift in mean energy**, negligible change to resolution (+ negligible change to selection efficiency)

# Predictions: simulation chain

Geant 4

+

NuMI PPFX

**Neutrino flux**



GENIE 2.12.2

**Neutrino reactions** on detector materials

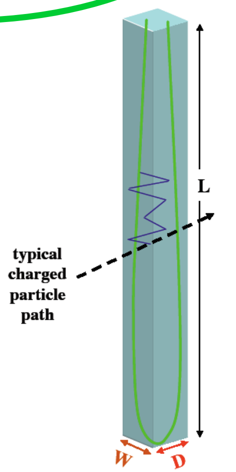



Geant 4

+

Custom readout software

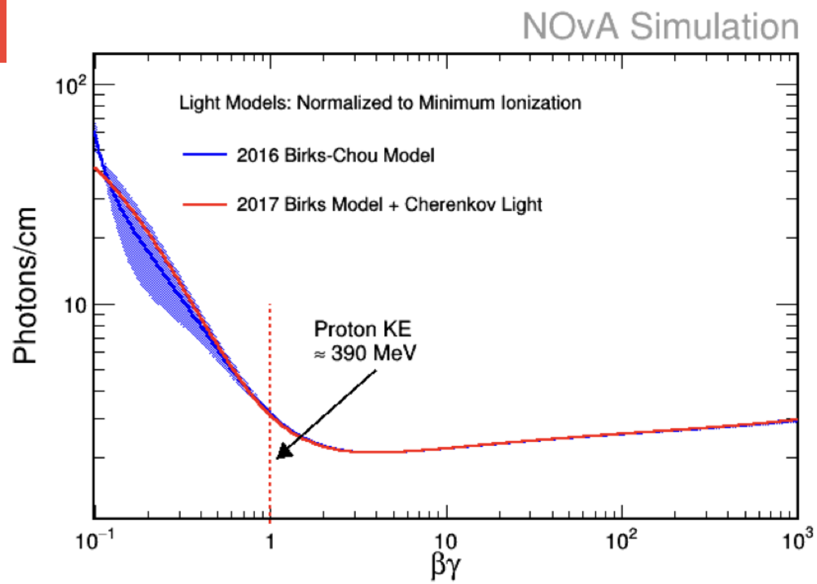
**Detector response** to charged particles and **light propagation**

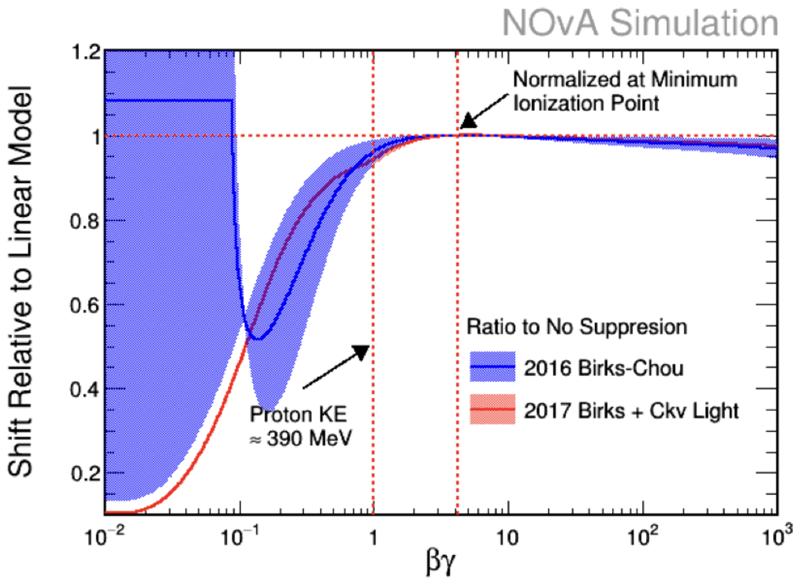



(with systematic uncertainties from each step)

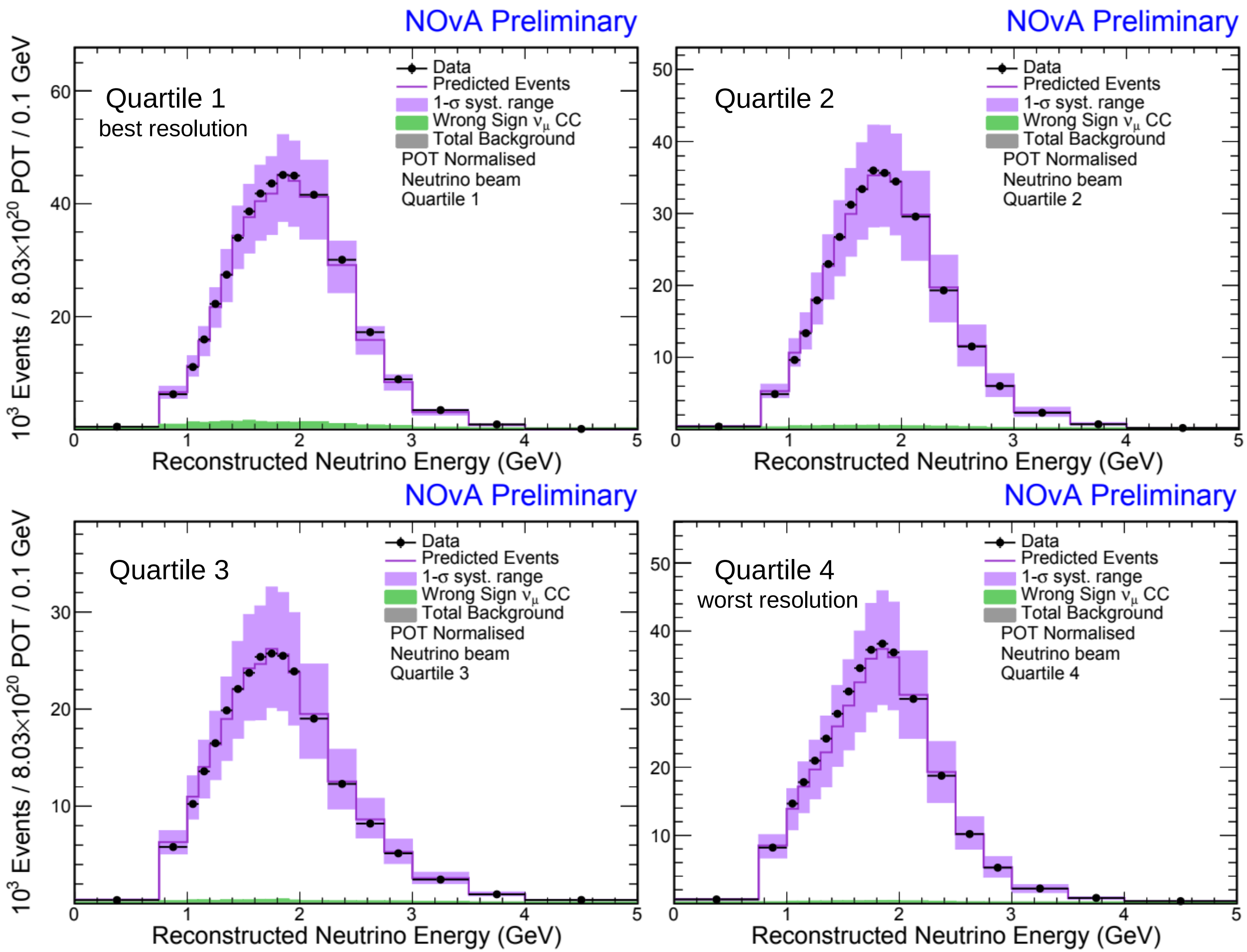
# Predictions: light model

- 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 $\nu_\mu$ CC events increased from 7% to 9% when adding Ckv to model



# Constraining the prediction: ND extrapolation

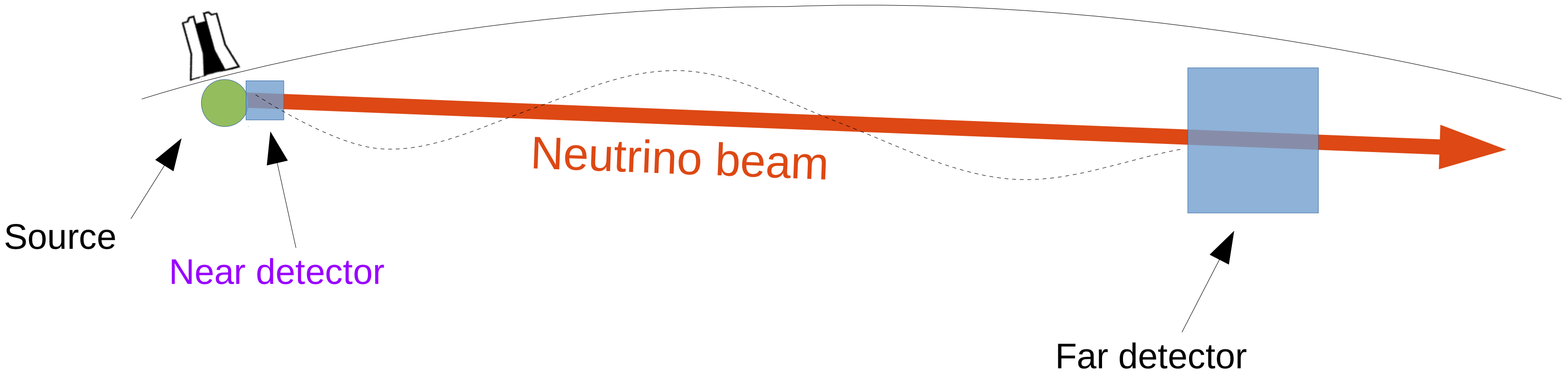



Though prediction agrees with ND data within our uncertainty budget, we can use (unoscillated) ND data to correct prediction for FD

**“extrapolation”**

# Constraining the prediction: ND extrapolation

## The NOvA strategy: “Far/Near ratio”

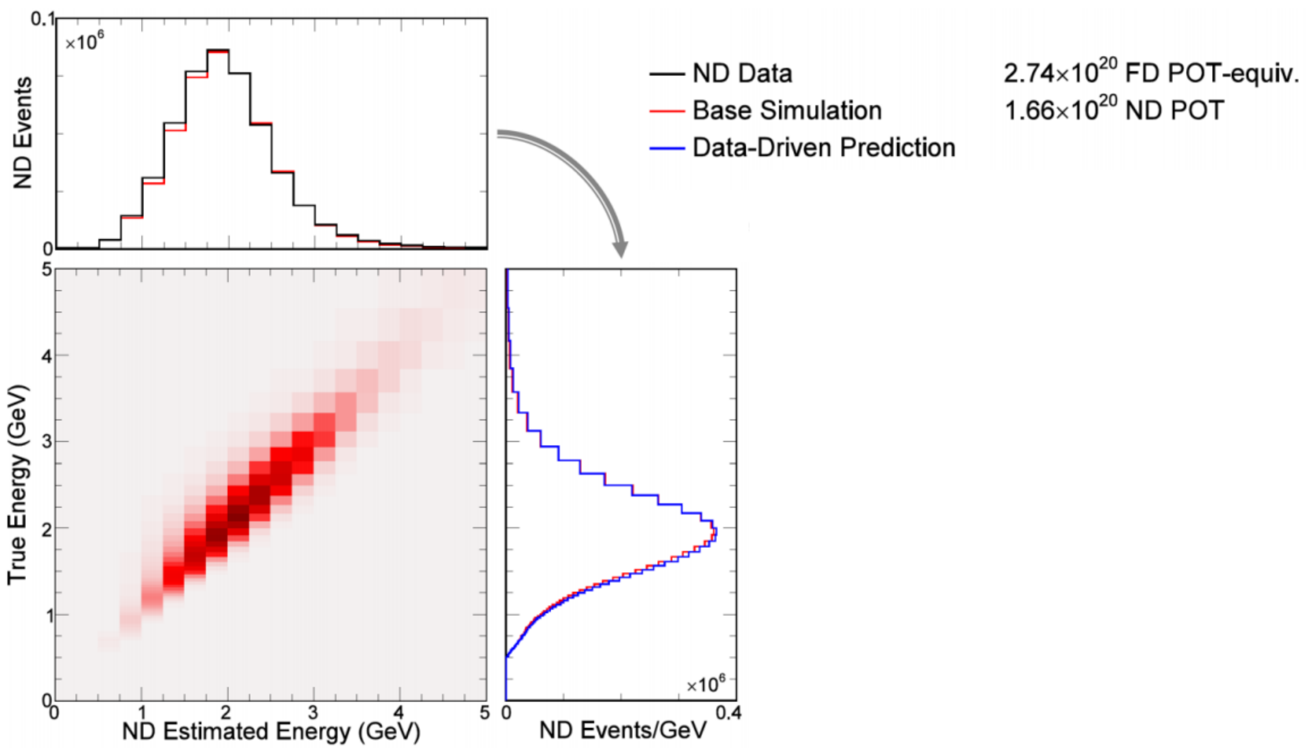



$$N(E_\nu^{rec}) = \Phi(E_\nu^{true}) \times P_{osc}(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(\ldots)$$

$$N^{ND}(E_\nu^{rec}) = \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(\ldots)$$

**Concept:** Identical detectors share all the ingredients except the oscilliations → Correct the true *event rate* (Φ×σ×...) using the ND and propagate that (F/N captures geometrical differences between detectors)

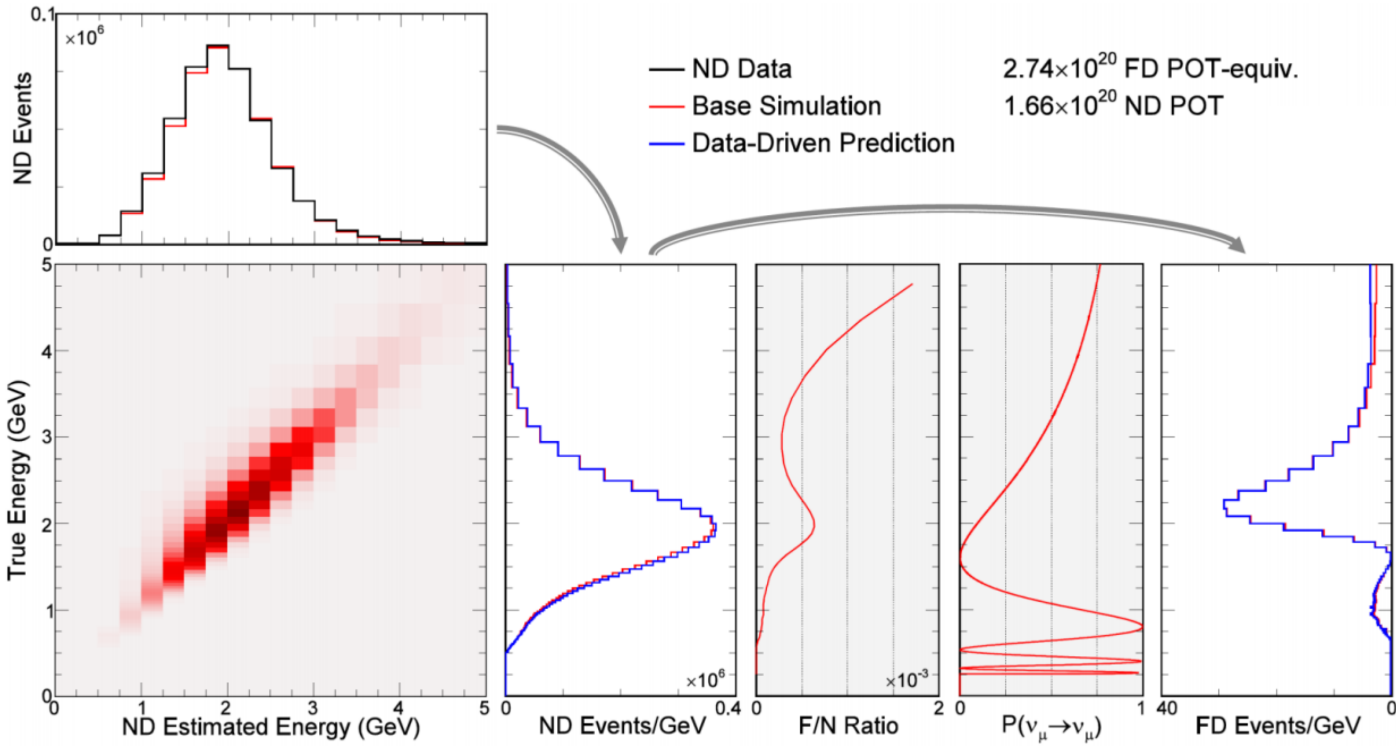
## The NOvA strategy: “Far/Near ratio”




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

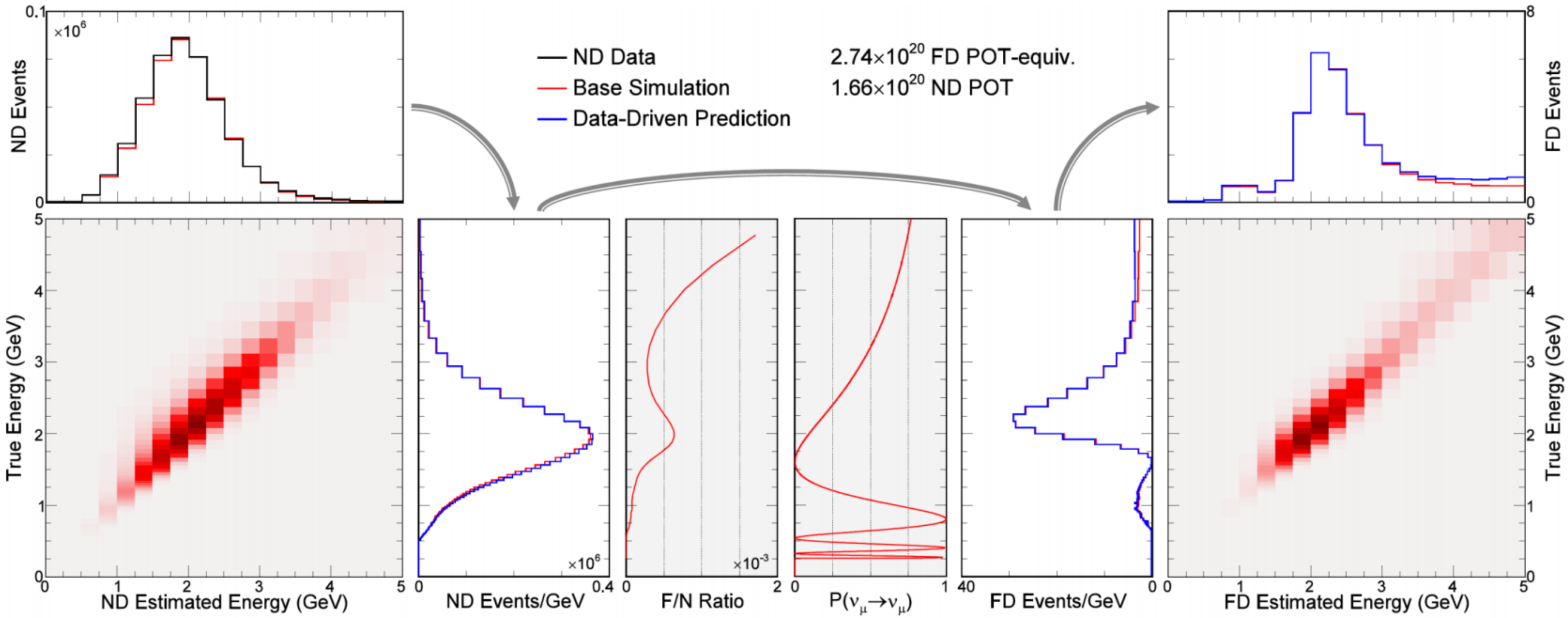
# Constraining the prediction: ND extrapolation

## The NOvA strategy: “Far/Near ratio”

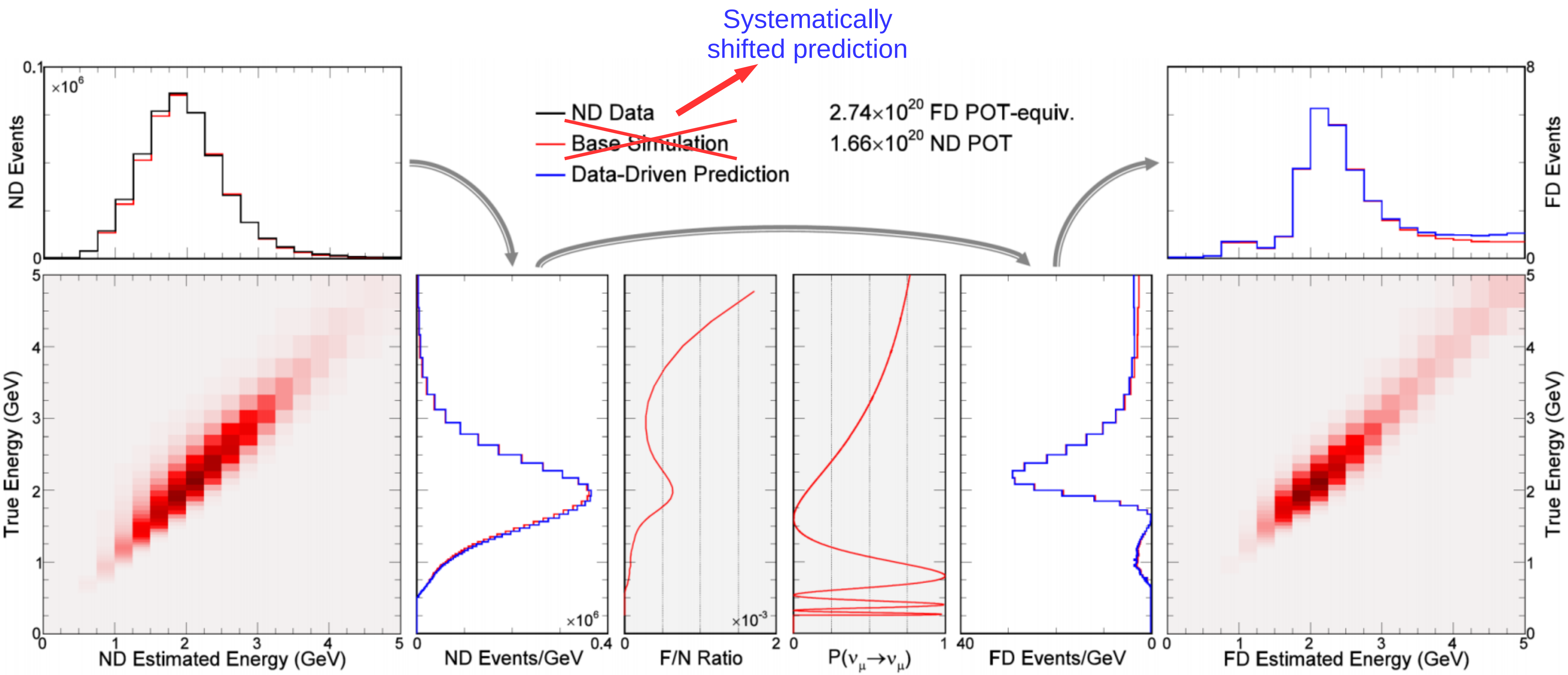



2. Multiply this corrected “true” spectrum by the geometric and oscillation functions to get the “extrapolated” true $E_\nu$ prediction at the FD.

## The NOvA strategy: "Far/Near ratio"

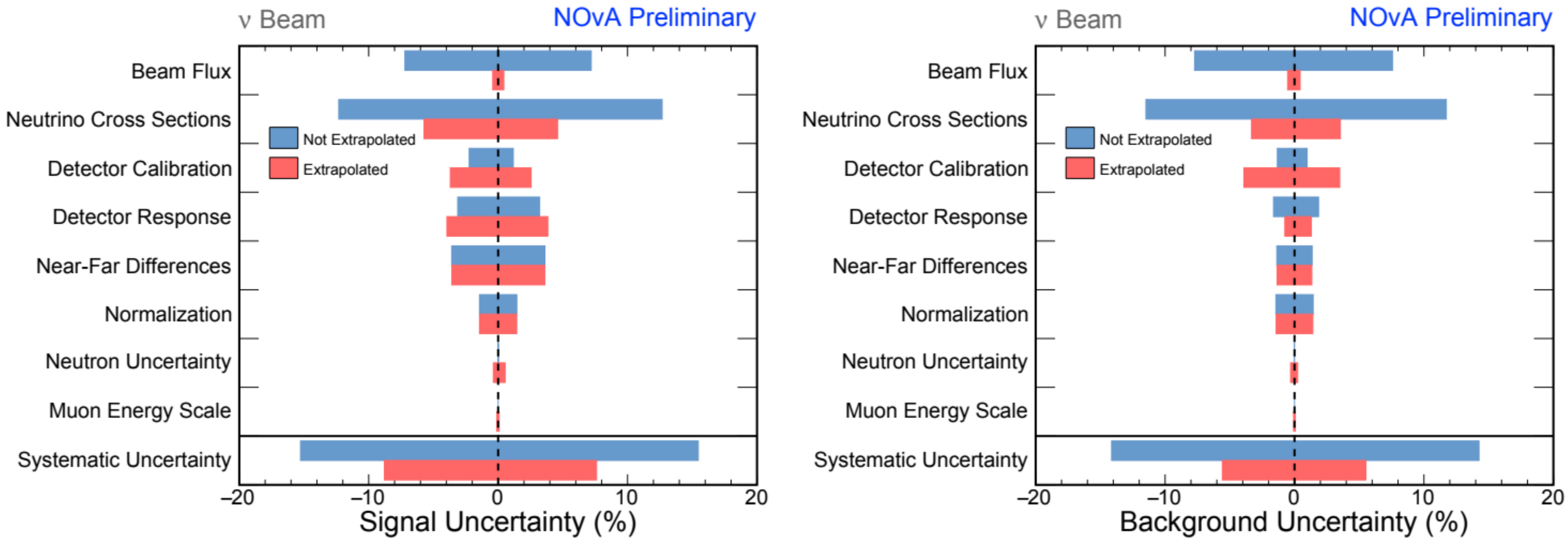



3. Using the predicted mapping at the FD, convert back to reconstructed energy to compare to the observed FD spectrum.




**F/N constrains systematics too**

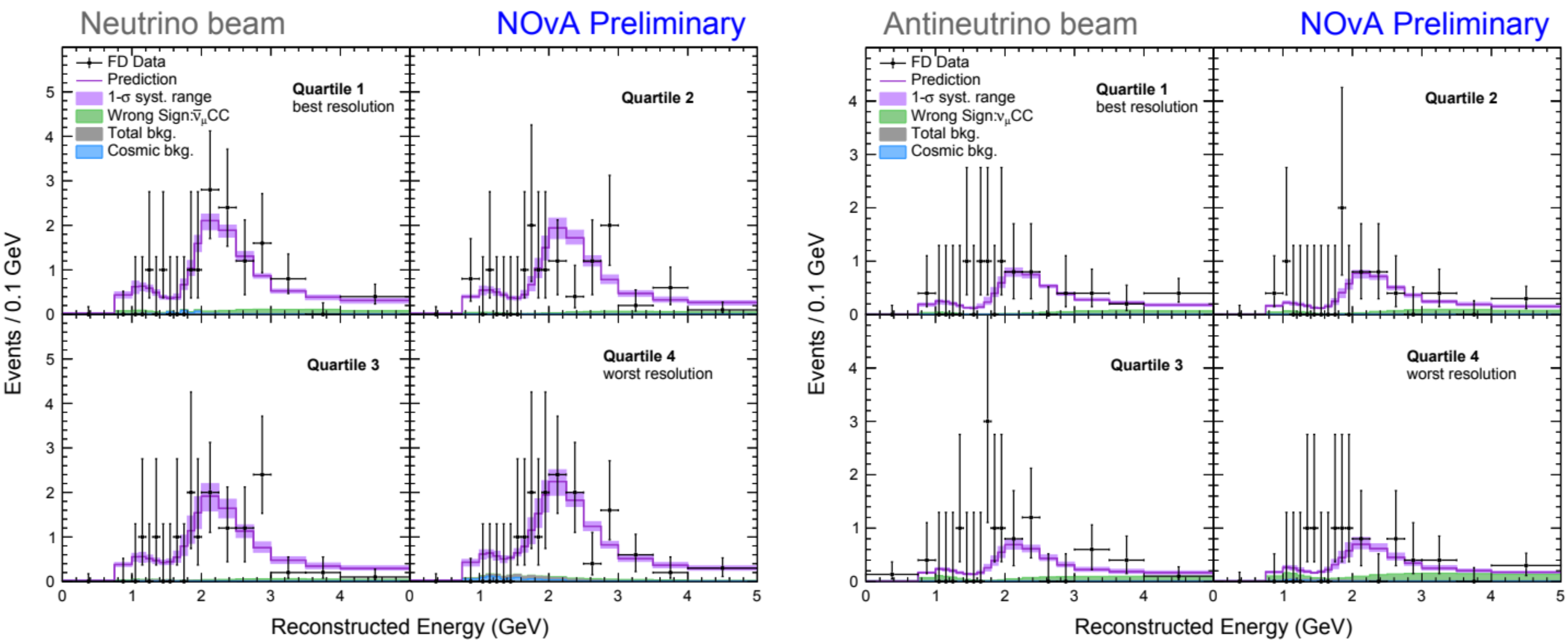
# Constraining the prediction: ND extrapolation




(these for $\nu_e$ event count, but effect on $\nu_\mu$ similar)

**F/N constrains systematics too**

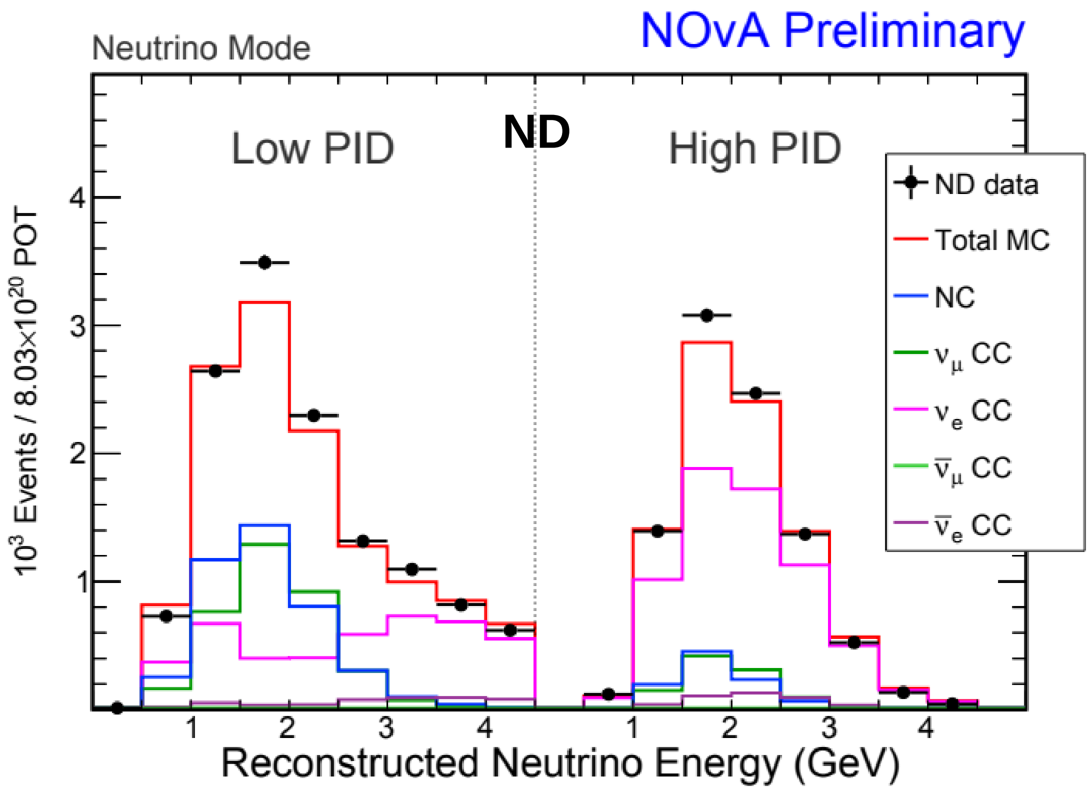
# Constrained $\nu_\mu$ FD prediction vs. data




| Data neutrino candidates | 113 |
|---|---|
| Best fit total prediction | 124 |
| ↳ cosmic bkgd. | 2.1 |
| ↳ beam bkgd. | 2.0 |

| Data antineutrino candidates | 65 |
|---|---|
| Best fit total prediction | 52 |
| ↳ cosmic bkgd. | 0.5 |
| ↳ beam bkgd. | 0.7 |

# Constraining the prediction: $\nu_e$ extrapolation




Least $\nu_e$-like → Most $\nu_e$-like

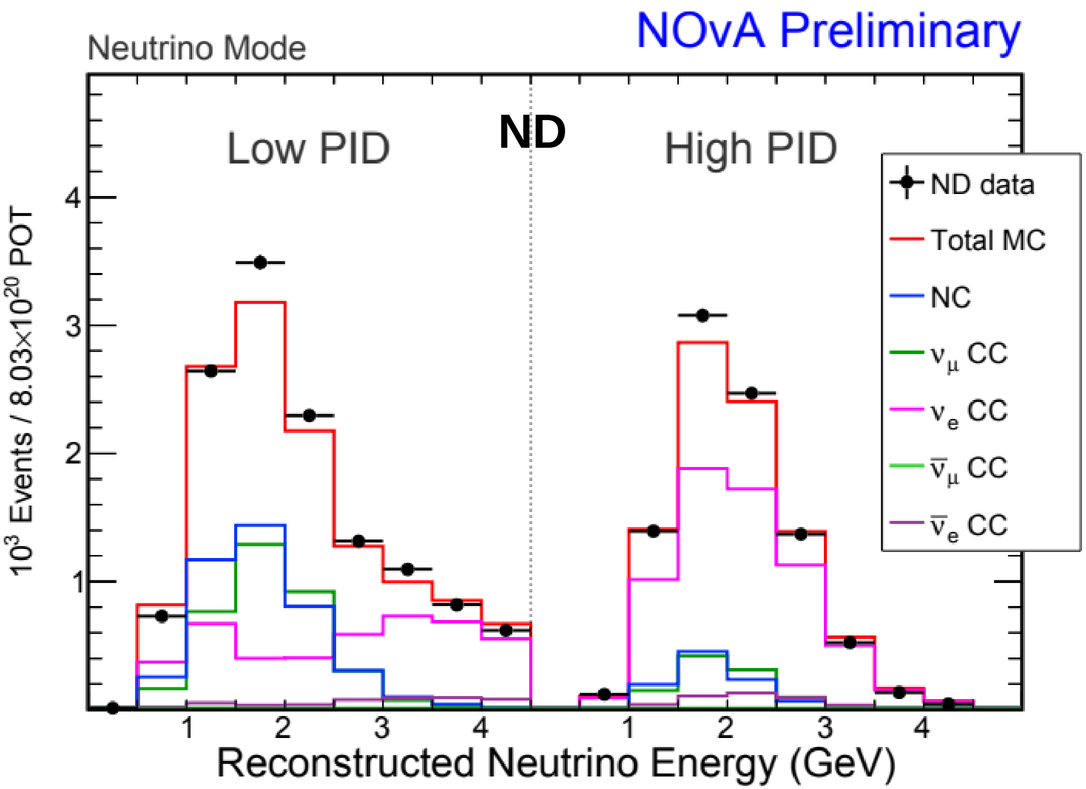
(Divided into bins of event classifier)

## $\nu_e$ extrapolation requires more care:

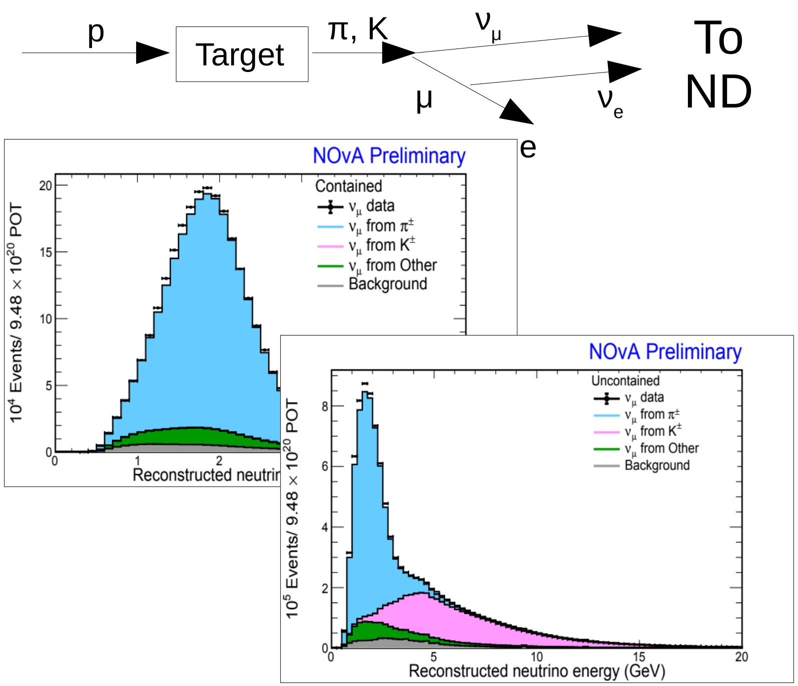
- **No signal** at ND (use $\nu_\mu$...)
- **Beam $\nu_e$** oscillate very little over this L/E
- **$\nu_\mu$** almost entirely disappear
- **NC** doesn't change due to oscillations (assume no steriles)

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

# Constraining the prediction: $\nu_e$ extrapolation

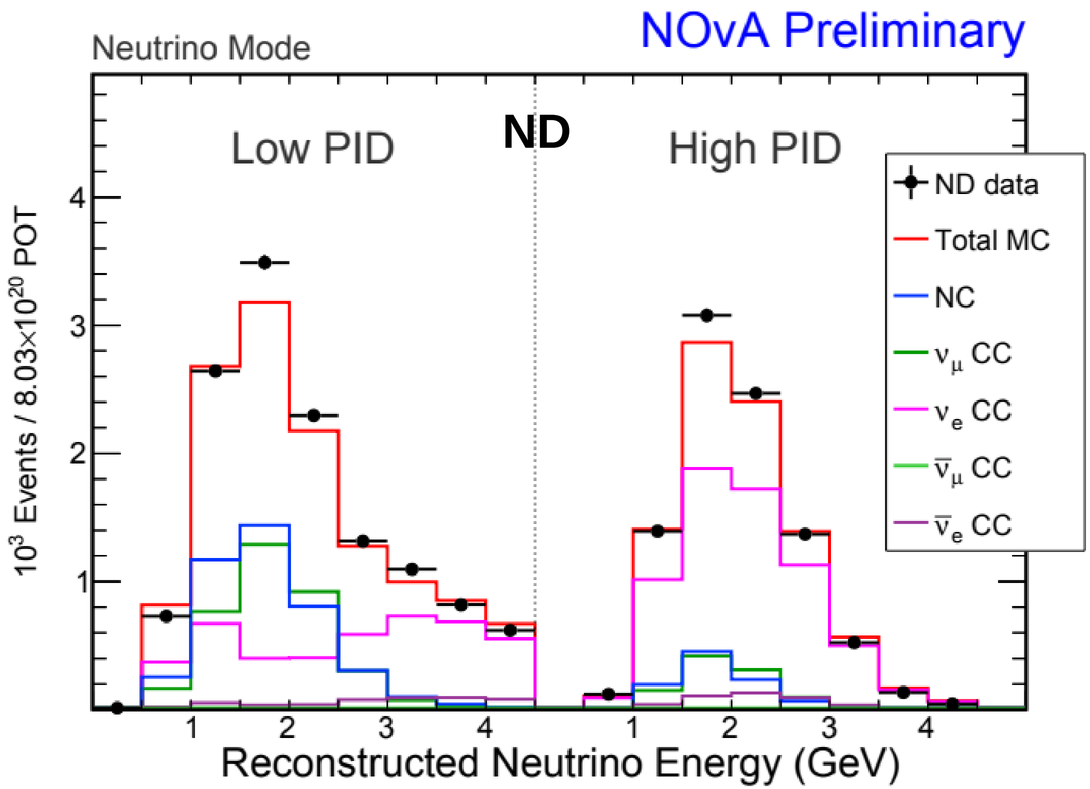



Least $\nu_e$-like → Most $\nu_e$-like

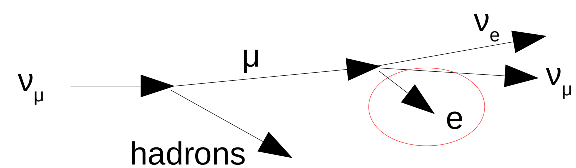


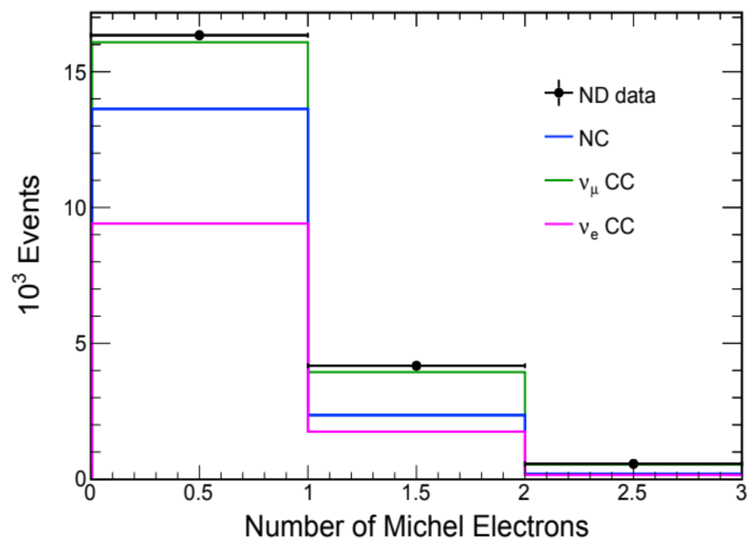

① Constraining the parent particle production via ND $\nu_\mu$ interactions tells us about the CC components...

# Constraining the prediction: $\nu_e$ extrapolation



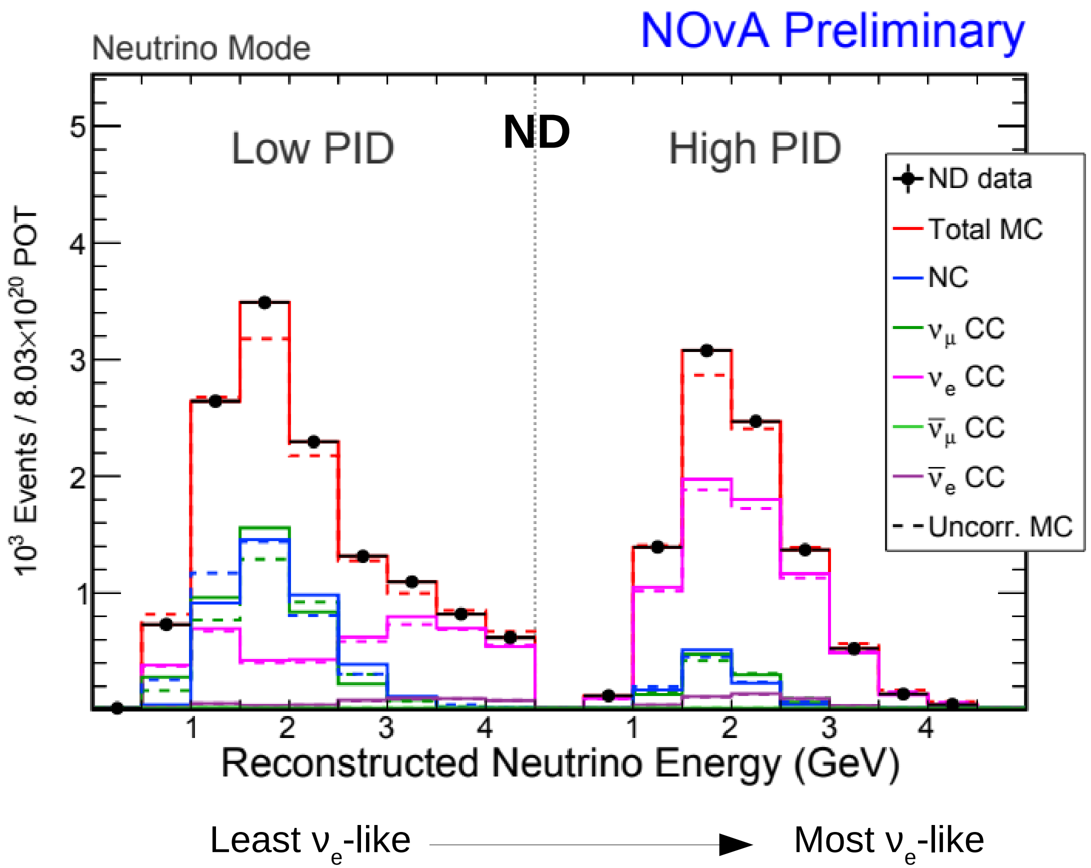

Least $\nu_e$-like → Most $\nu_e$-like



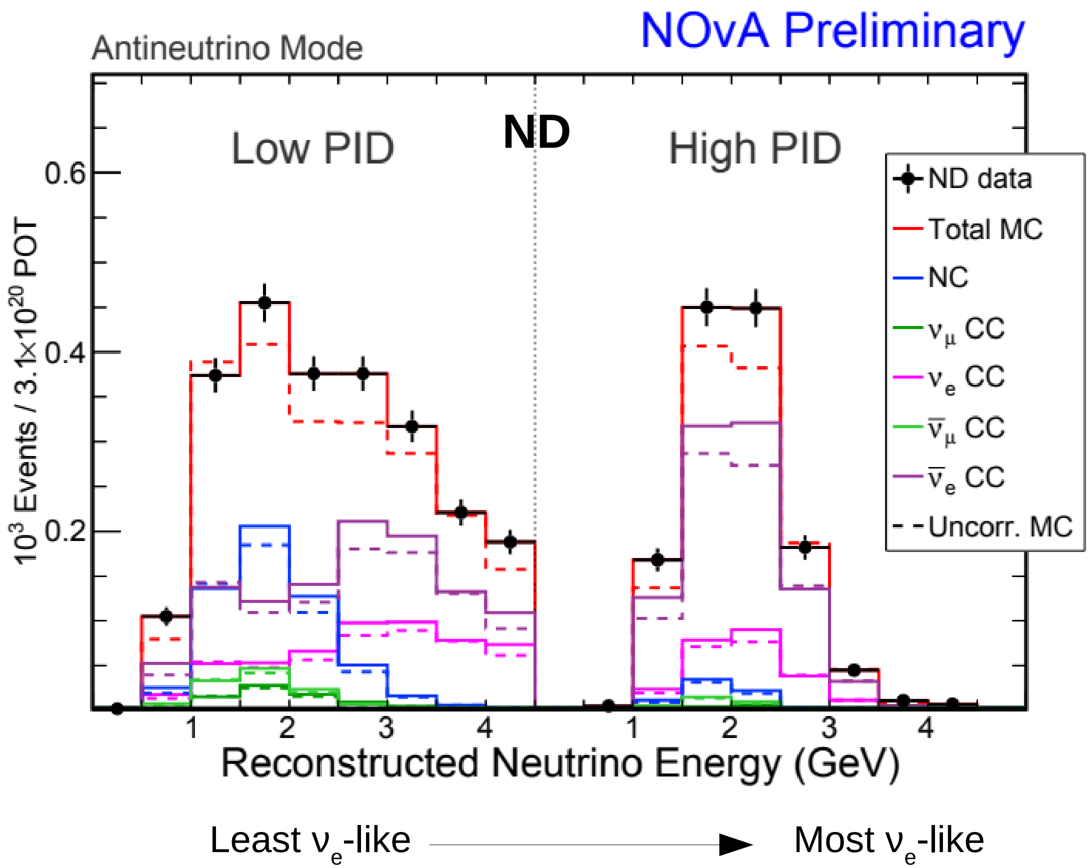

② … while examining the Michel electron spectrum in candidate events tells us about the $\nu_\mu$ fraction.

# Constraining the prediction: $\nu_e$ extrapolation




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

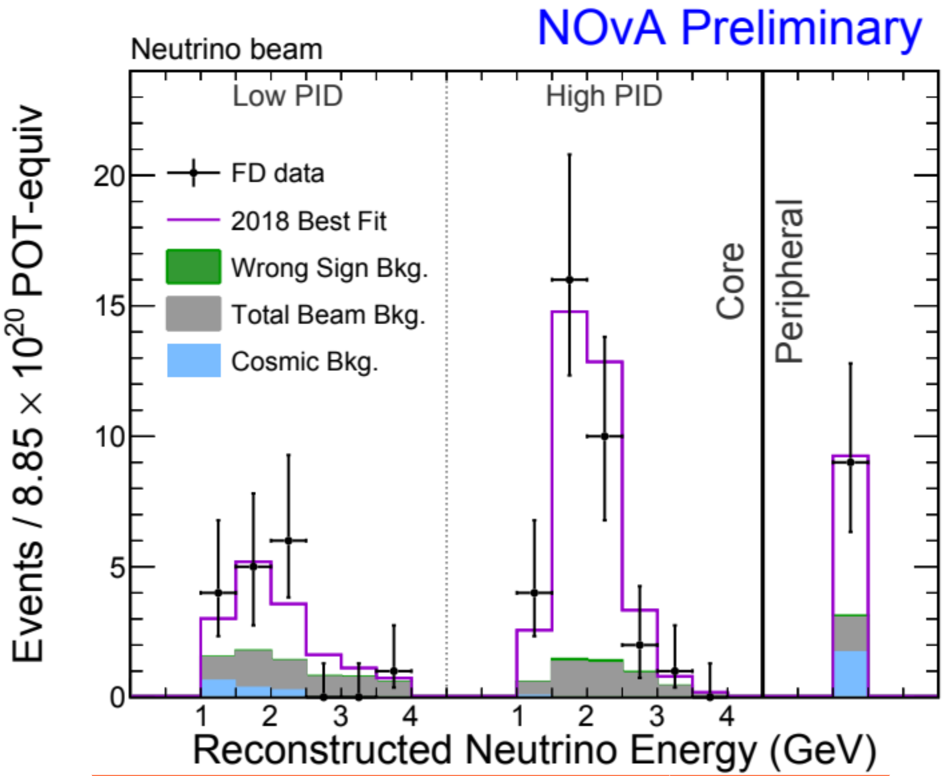
# Constraining the prediction: $\nu_e$ extrapolation

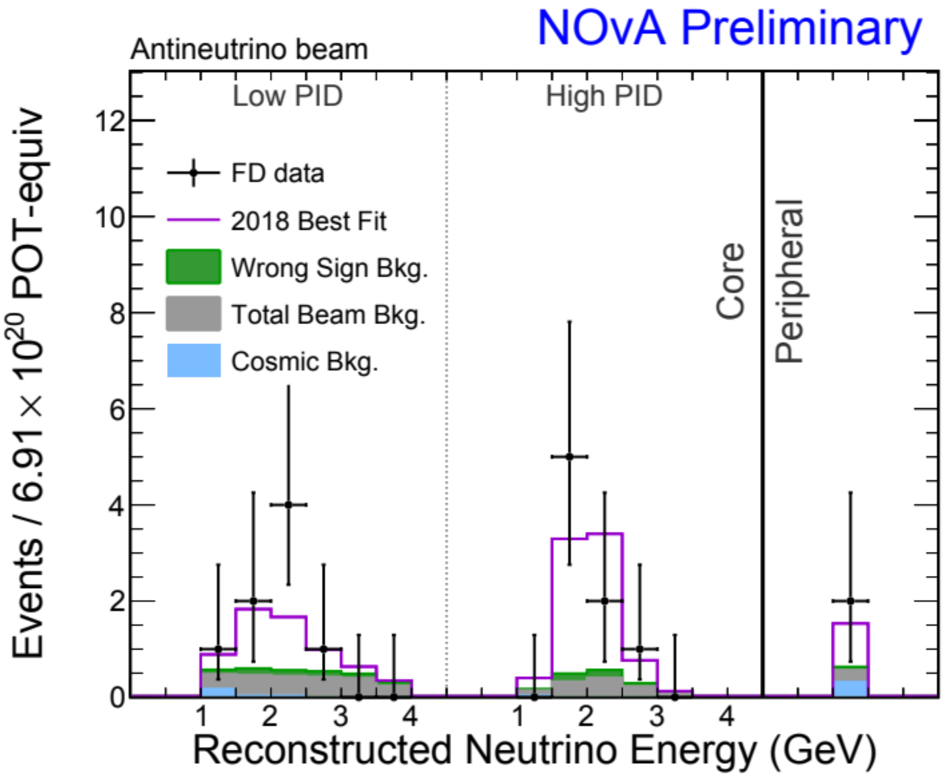



**For *antineutrinos***, addition of a significant "wrong-sign" component (neutrinos) means more deg of freedom than constraints

Component-wise constraint a work in progress→ **correcting according to MC proportions in each bin** for now

# Constrained $\nu_e$ FD prediction vs. data

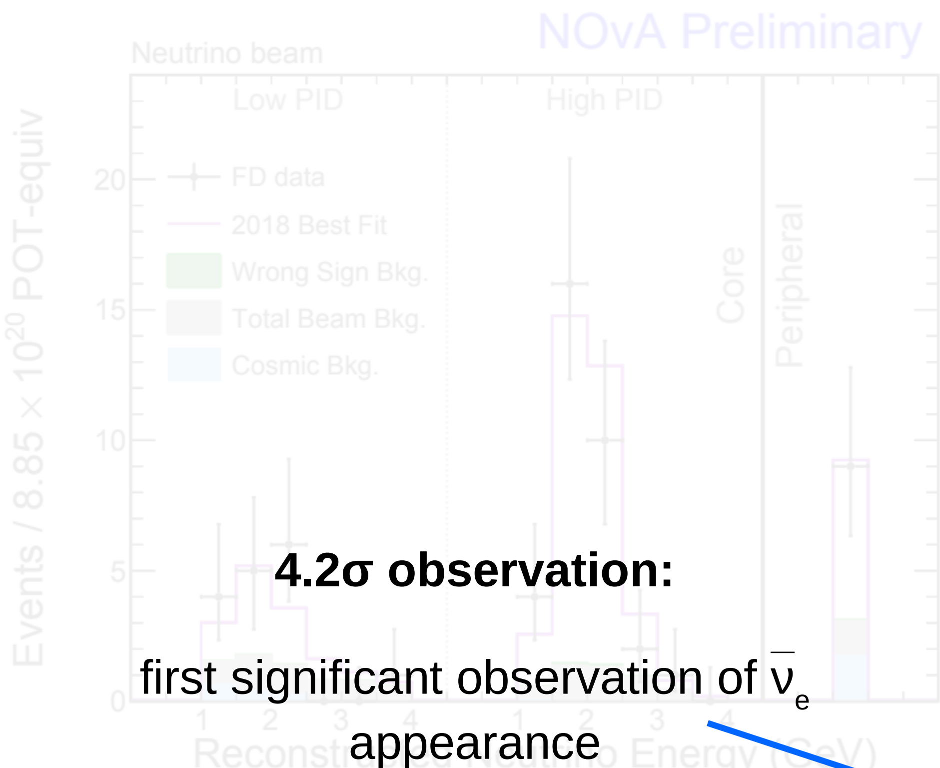



| Data neutrino candidates | 58 |
|---|---|
| Best fit total prediction | 59 |
| ↳ cosmic bkgd. | 3.3 |
| ↳ beam bkgd. / app. $\overline{\nu}_e$ | 11.1 / 0.7 |

| Data antineutrino candidates | 18 |
|---|---|
| Best fit total prediction | 16 |
| ↳ cosmic bkgd. | 0.7 |
| ↳ beam bkgd. / app. $\nu_e$ | 5.3 / 1.1 |

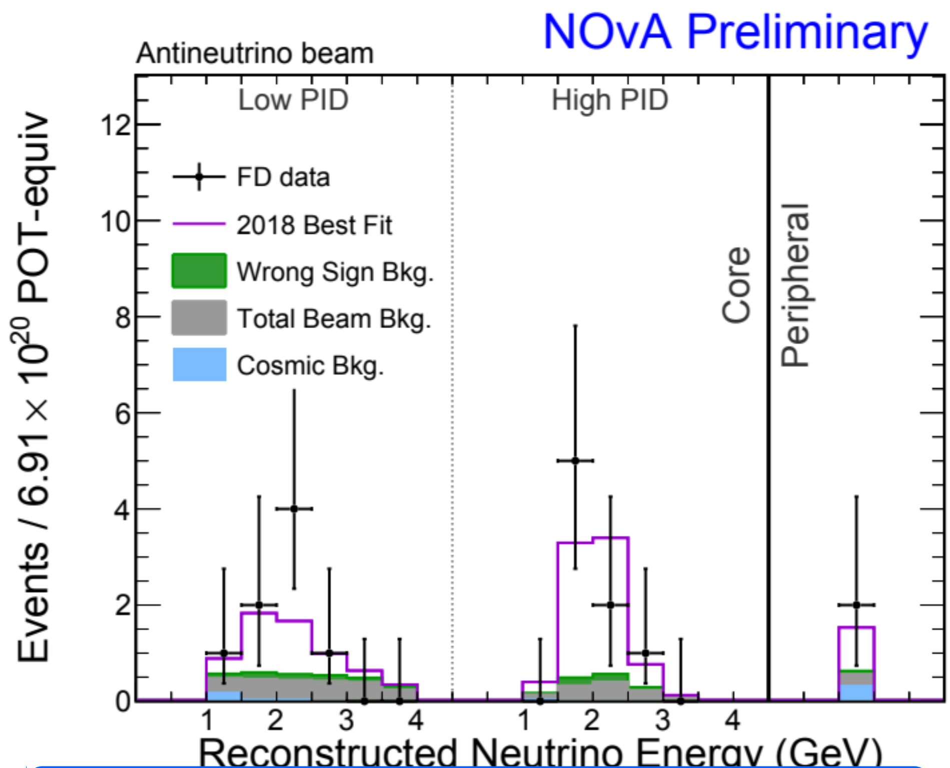
# Constrained $\nu_e$ FD prediction vs. data




| Data neutrino candidates | 58 |
|---|---|
| Best fit total prediction | 59 |
| ↳ cosmic bkgd. | 3.3 |
| ↳ beam bkgd. (app. $\bar{\nu}_e$) | 15.1 (0.7) |

**4.2σ observation:**

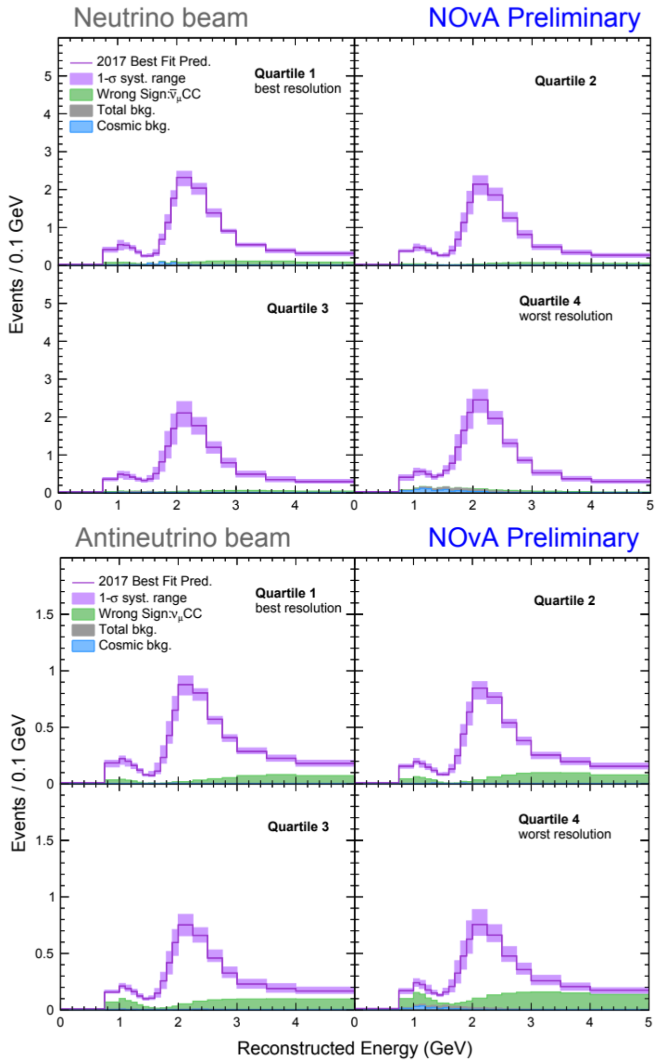
first significant observation of $\bar{\nu}_e$ appearance



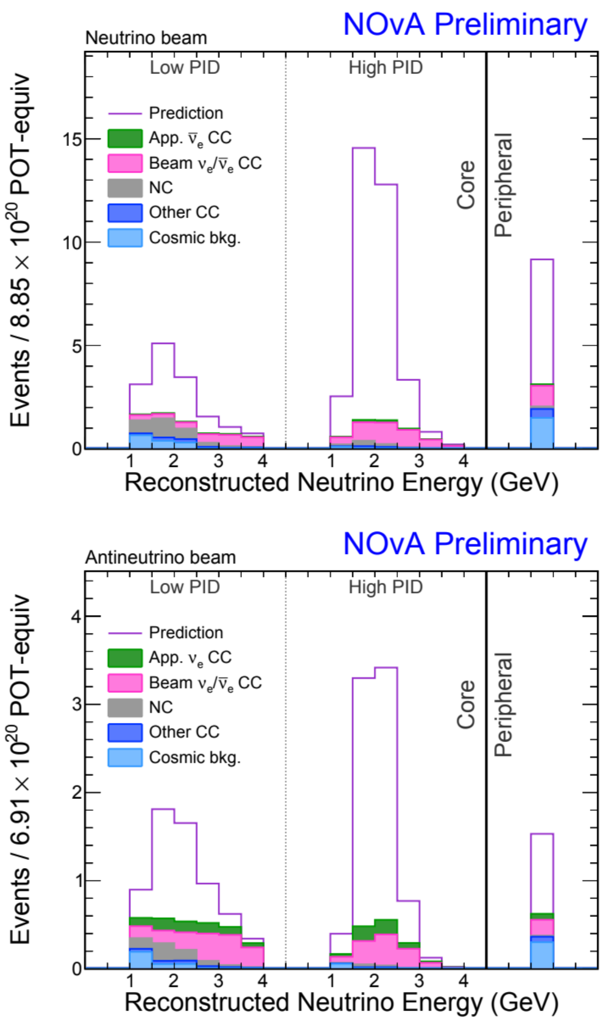

| Data antineutrino candidates | 18 |
|---|---|
| Best fit total prediction | 16 |
| ↳ cosmic bkgd. | 0.7 |
| ↳ beam bkgd. (app. $\nu_e$) | 5.3 (1.1) |

# Extracting oscillation parameters

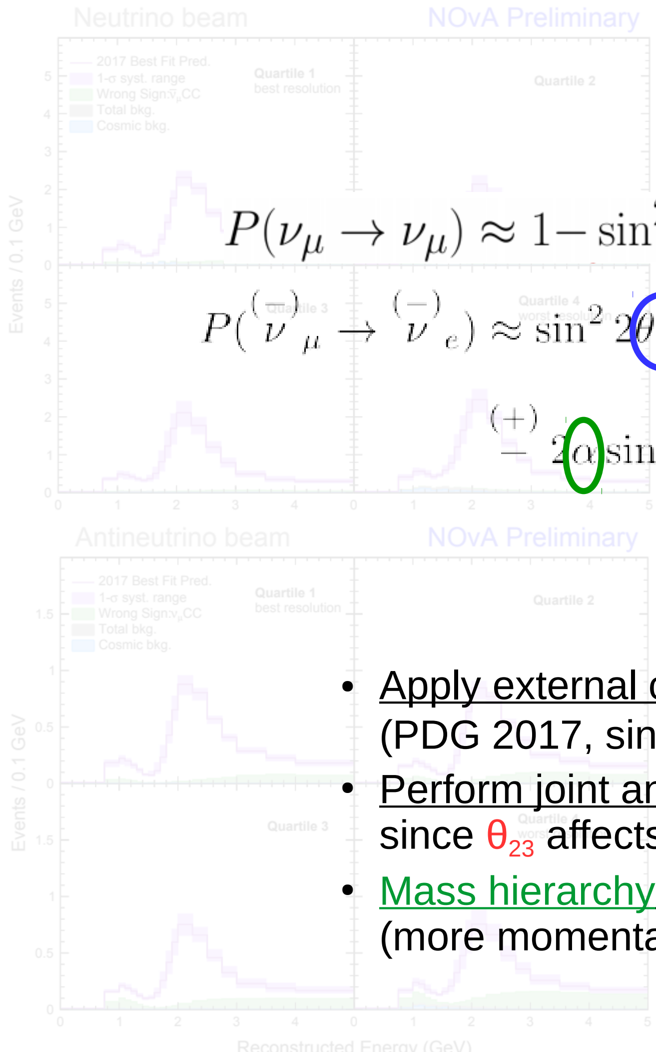
# Fitting the spectra

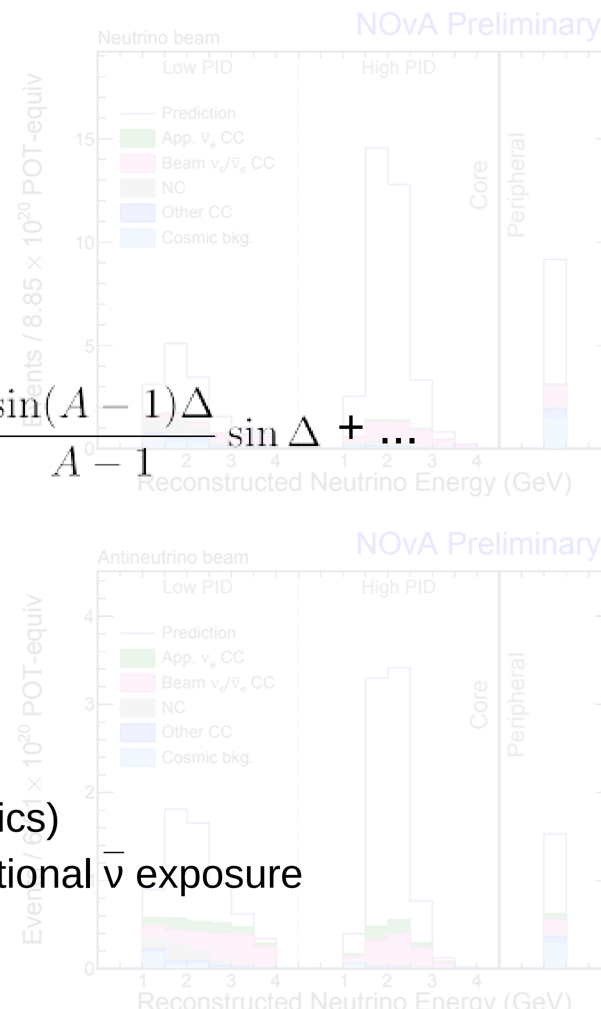



**We vary the oscillation parameters in these 4+4+3+3=17 predictions simultaneously to find the best fit with the FD data.**



# Fitting the spectra




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

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

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

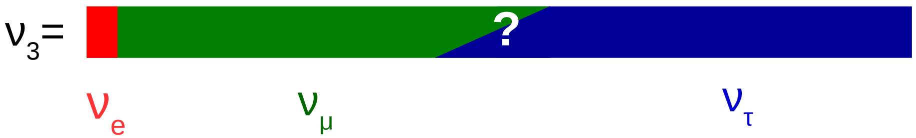
oscillation parameters in these 4+4+3+3=17 predictions simultaneously to find the best fit with the FD data.

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

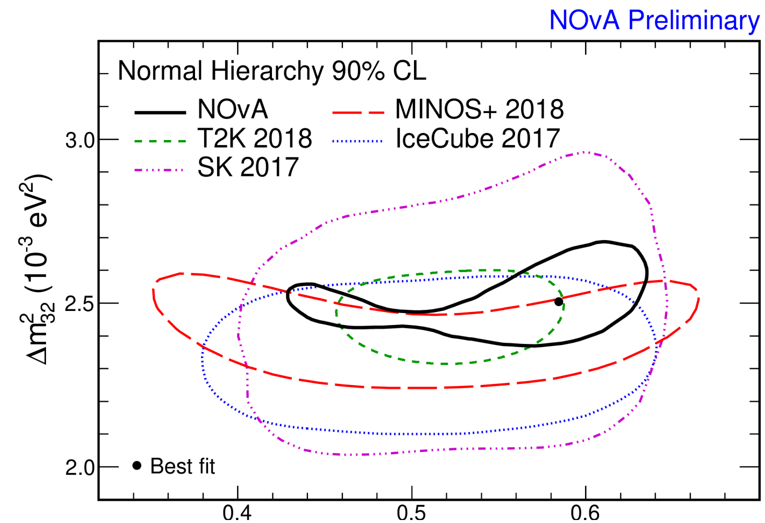
# Oscillation results: atmospheric sector

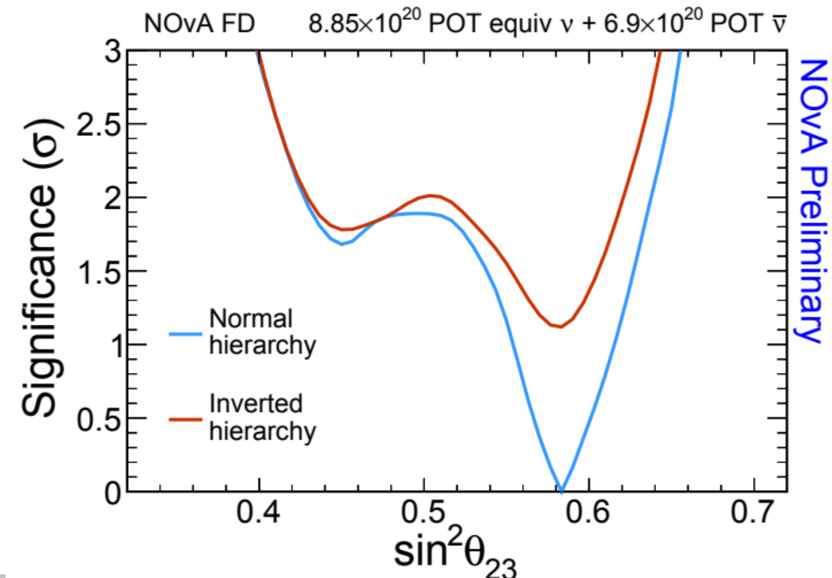
**<u>Big question:</u>**

Is there a symmetry governing the $\nu_\mu/\nu_\tau$ mixing into the 2nd and 3rd mass states?
(Is $\theta_{23}$ "maximal" = 45º?)




## Leaning towards "no", at about 1.8σ confidence



# Oscillation results: since the last time

Previous result ($\nu$ only):

consistent with maximal mixing (0.8σ)

↓

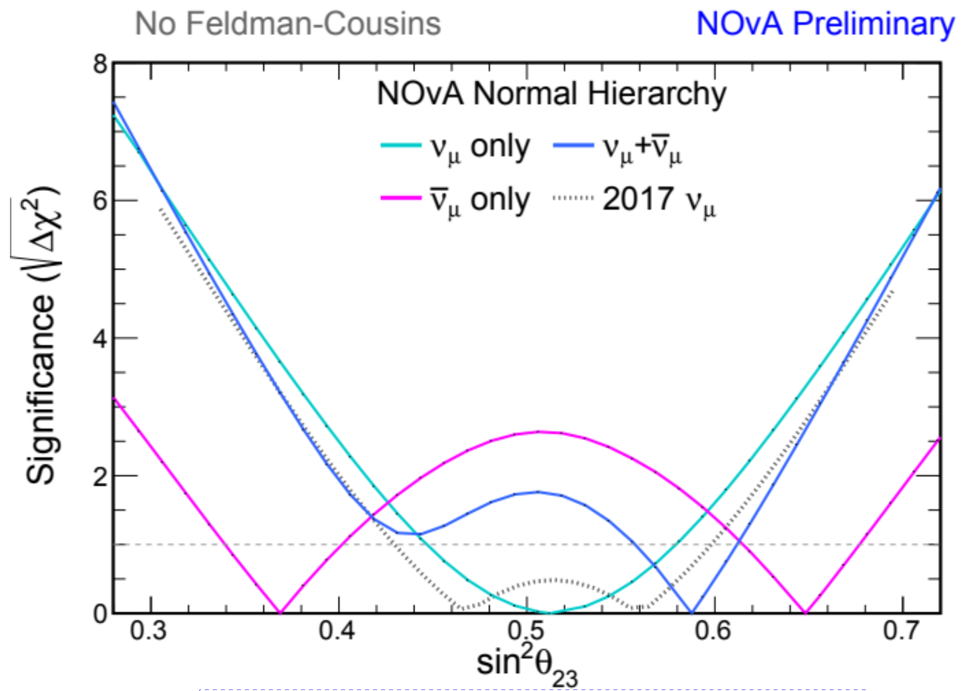
Updated analysis ($\nu$ only):

favors *maximal* mixing

+

New $\bar{\nu}$ data

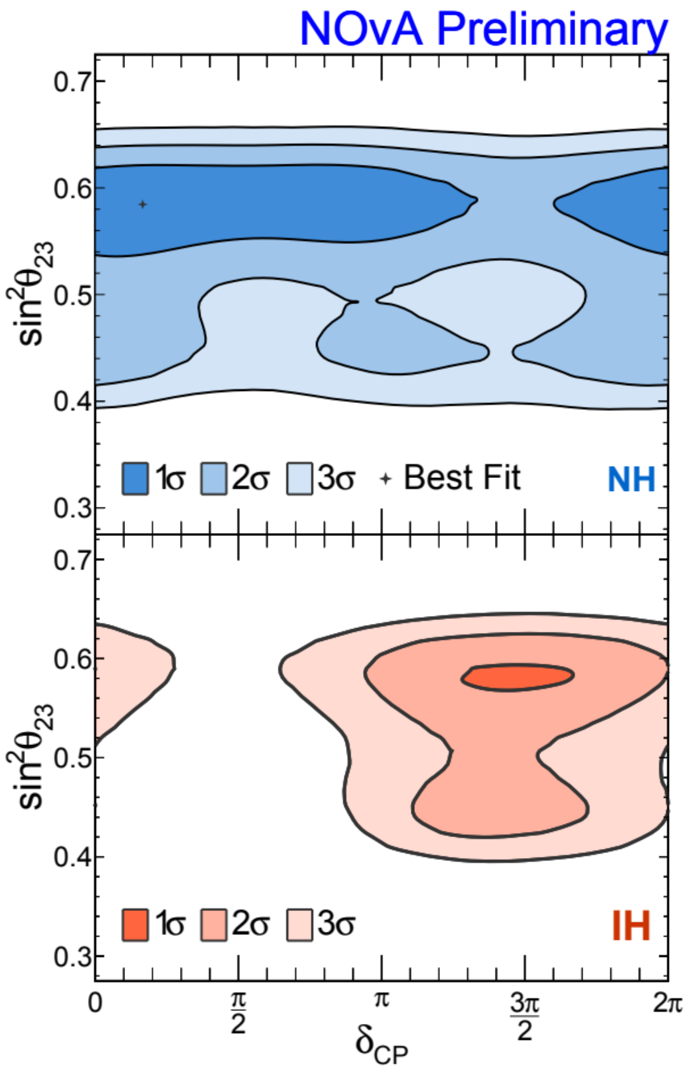
strongly favors *nonmaximal* mixing

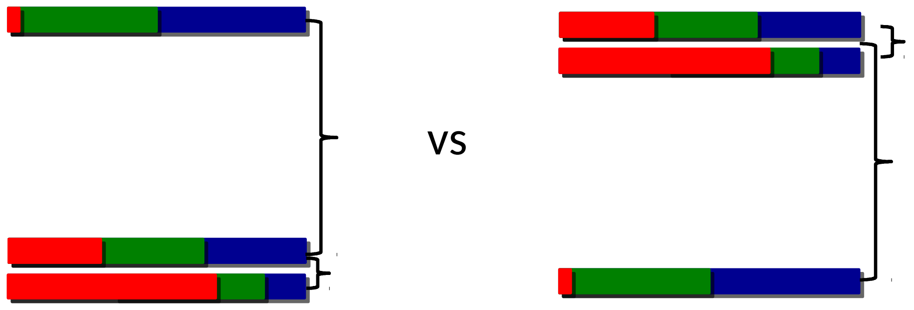



**Joint $\nu_\mu$ + $\bar{\nu}_\mu$ fit prefers upper octant** (~1σ)
(the rest from $\nu_e$ app)

Asymmetry in maximal disappearance for $\nu_\mu$ vs $\bar{\nu}_\mu$ due to matter effects → NH implies UO

# Oscillation results: reactor sector

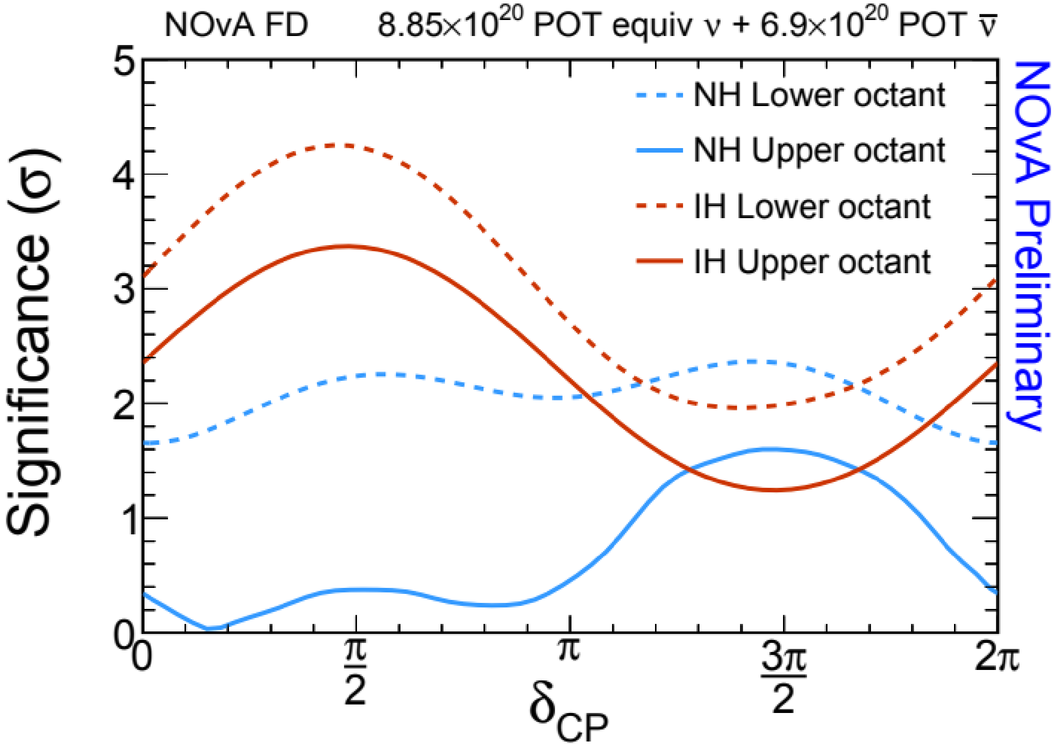



**<u>Big question</u>**:
Which way around
are the mass states ordered?

**Preference for NH (IH excluded at 1.8σ)**

# Oscillation results: reactor sector



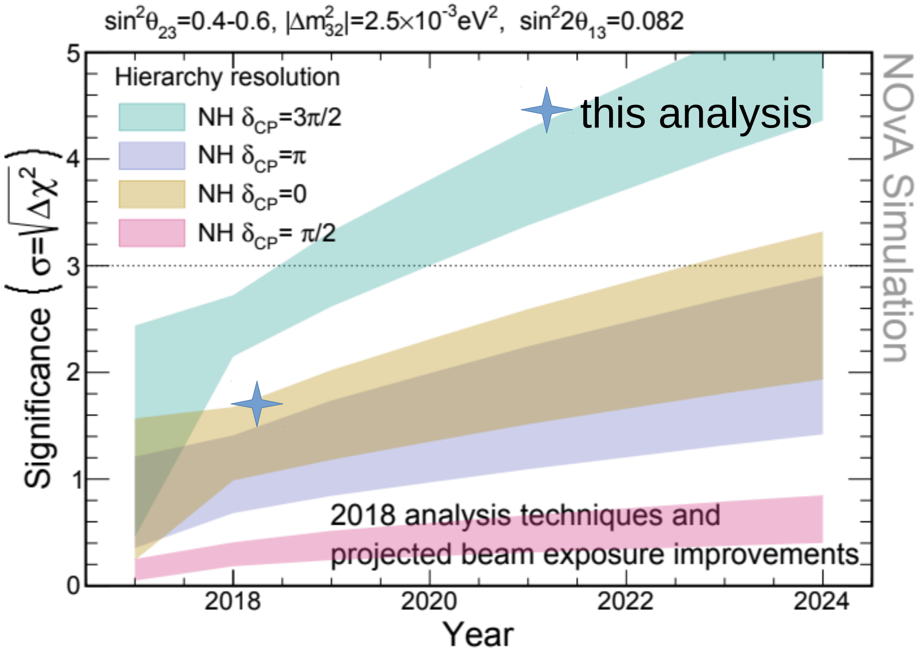

$\nu \overset{?}{\Leftrightarrow} \overline{\nu}$

**<u>Big question:</u>**
Is CP symmetry violated by leptons?
(Is δ nonzero?)

**Consistent with CP conservation.**

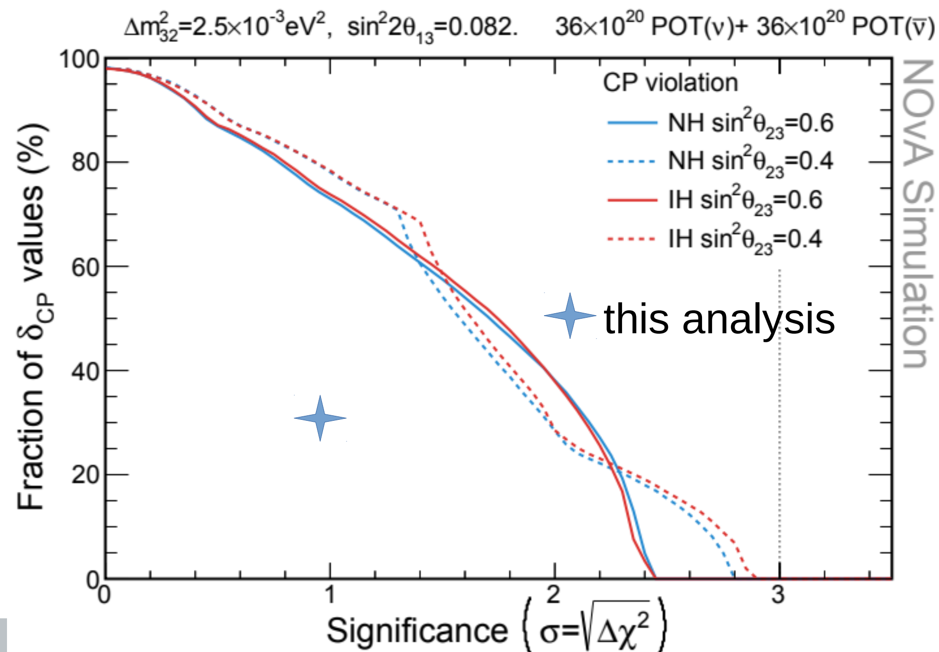
(δ=3π/2 excluded at >1σ)

# Looking ahead

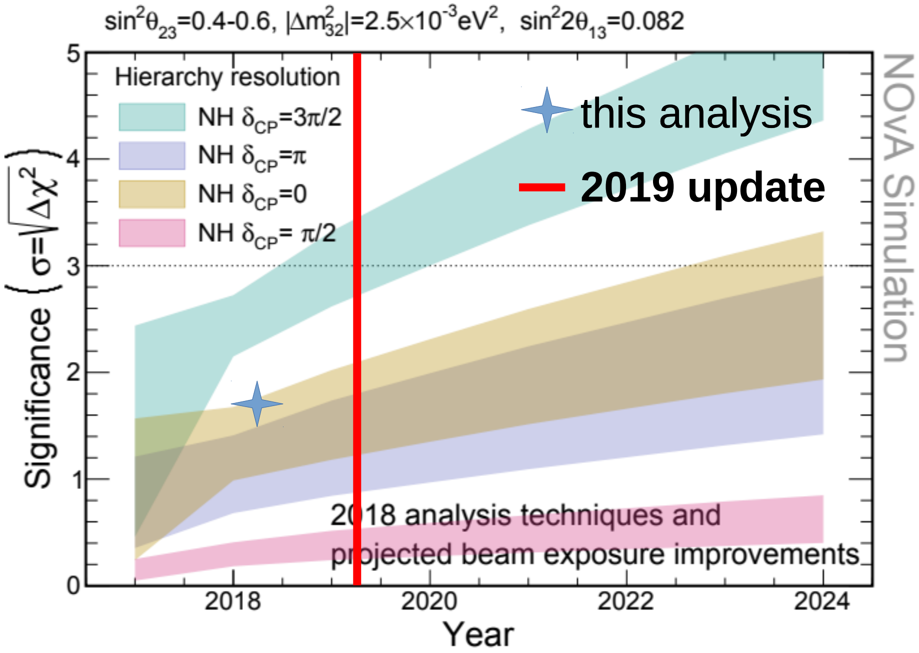



For current favored parameters, **reach 3σ on mass hierarchy** by end of run in 2024

**2σ sensitivity to CP violation** for ~30-40% of parameter space by 2024



## Looking ahead




For current favored parameters, **reach 3σ on mass hierarchy** by end of run in 2024

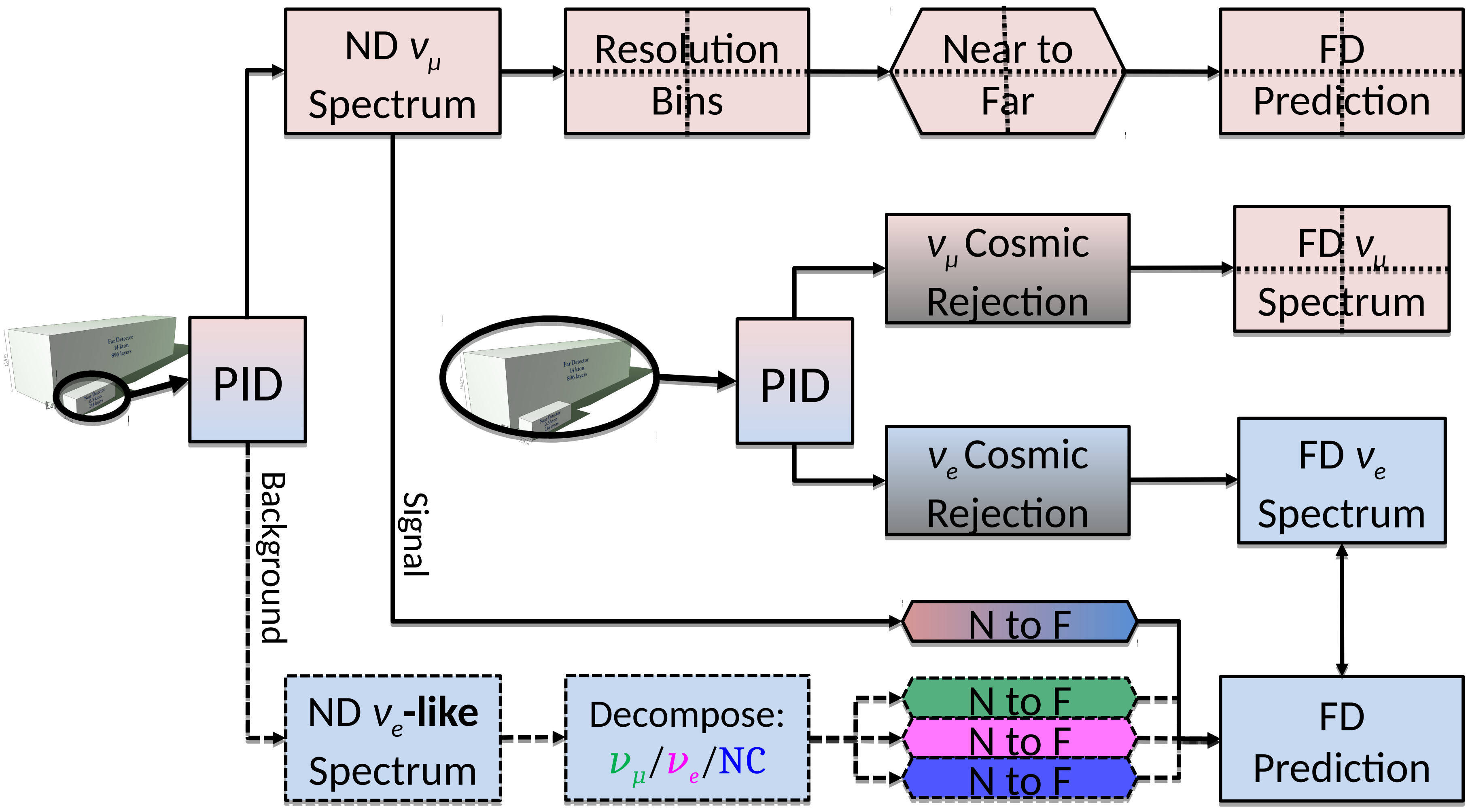
**2019 update** coming (hopefully) at Fermilab Users Meeting in June!

# Summary

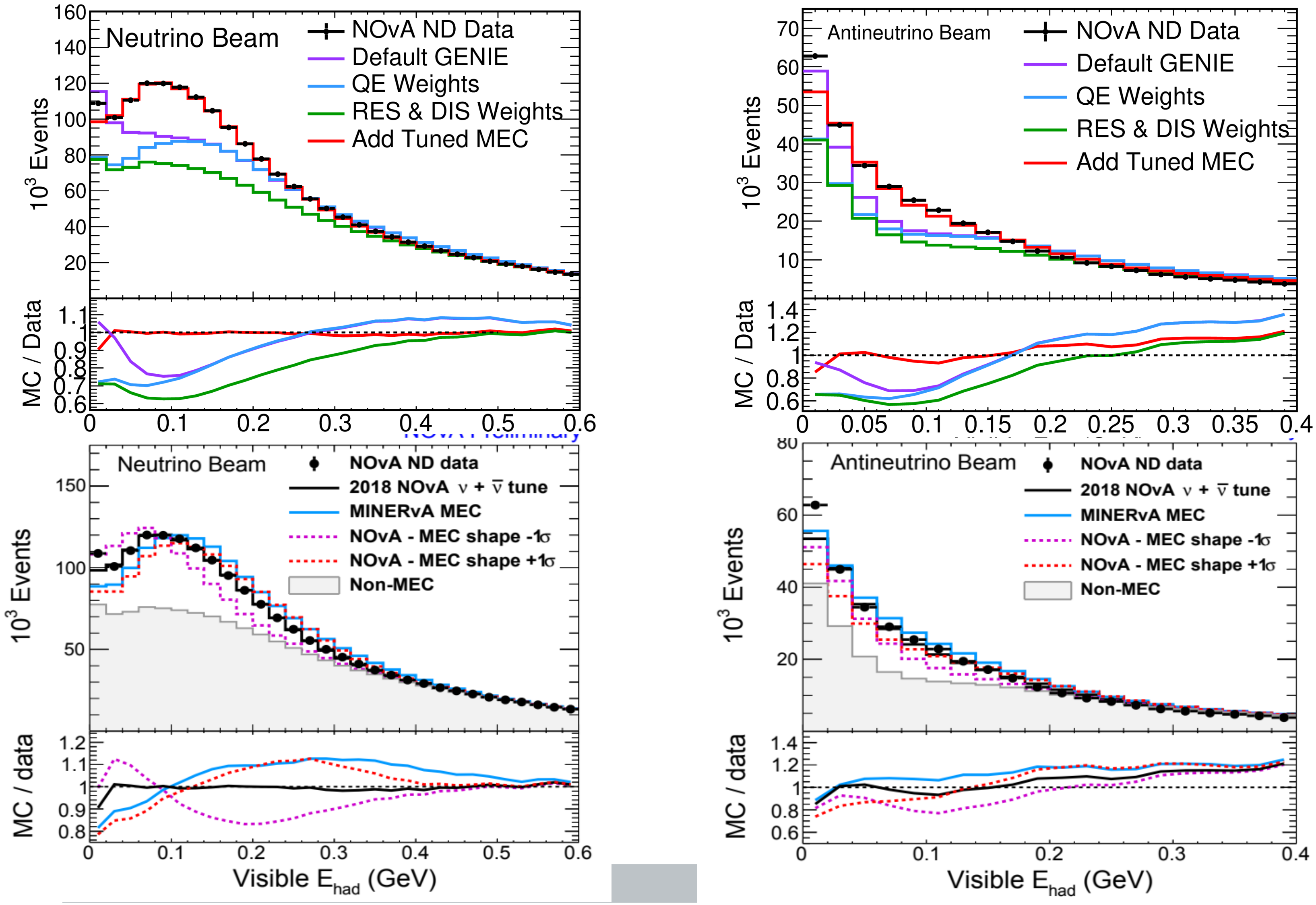
- **NOvA has a robust 3-flavor neutrino oscillation analysis**
  - $\nu_\mu$ disappearance and $\nu_e$ appearance selections efficient and well characterized
  - Systematics well constrained by careful analysis & extrapolation technique
- **Neutrino oscillation takeaways shaping up:**
  - Reject maximal $\theta_{23}$ at 1.8σ (indications of no μ-τ symmetry in mixing)
  - Favor normal hierarchy at 1.8σ (potential symmetry to charged lepton ordering)
  - Consistent with CP conservation
  - **4.2σ observation of $\bar{\nu}_e$ appearance** (standard framework applies to $\bar{\nu}$)
- **Data continues to stream in**
  - Update with ~80% more antineutrino data right around the corner
  - Looking forward to major milestones in particle physics in not-too-distant future!

Overflow

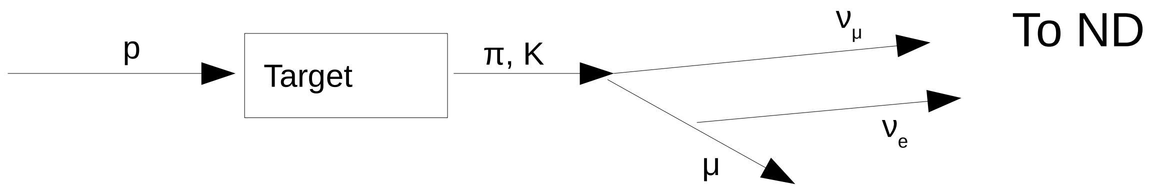
# Analysis flow

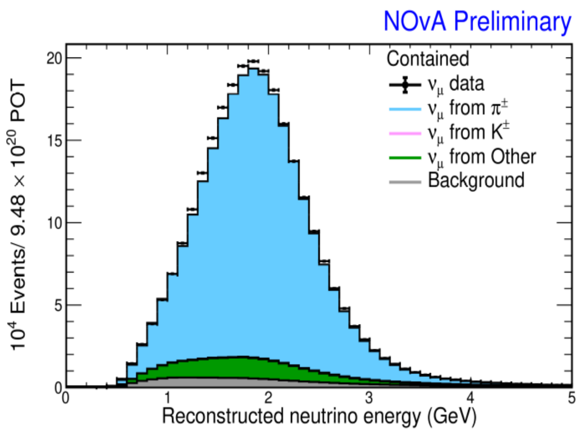


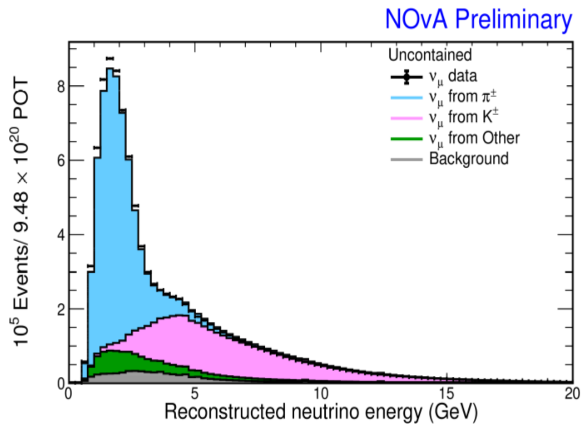
# Neutrino interaction model adjustments



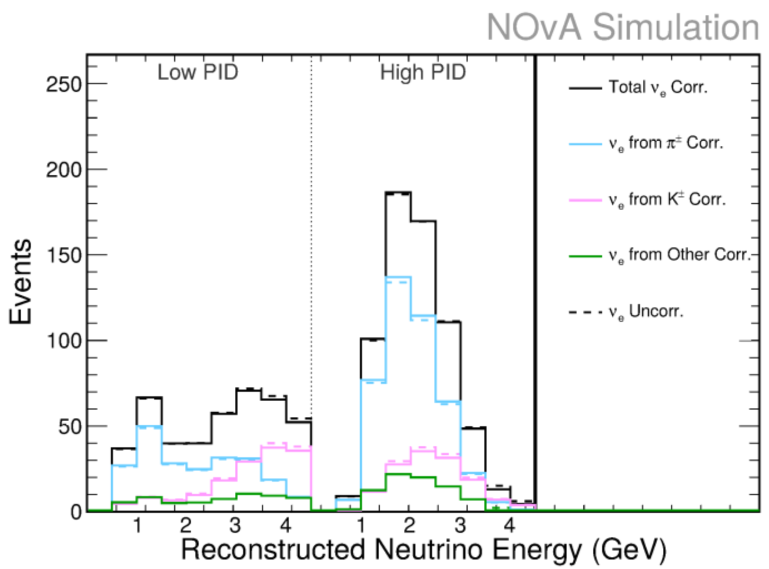
# $\nu_e$ appearance: constraining beam $\nu_e$ bknd



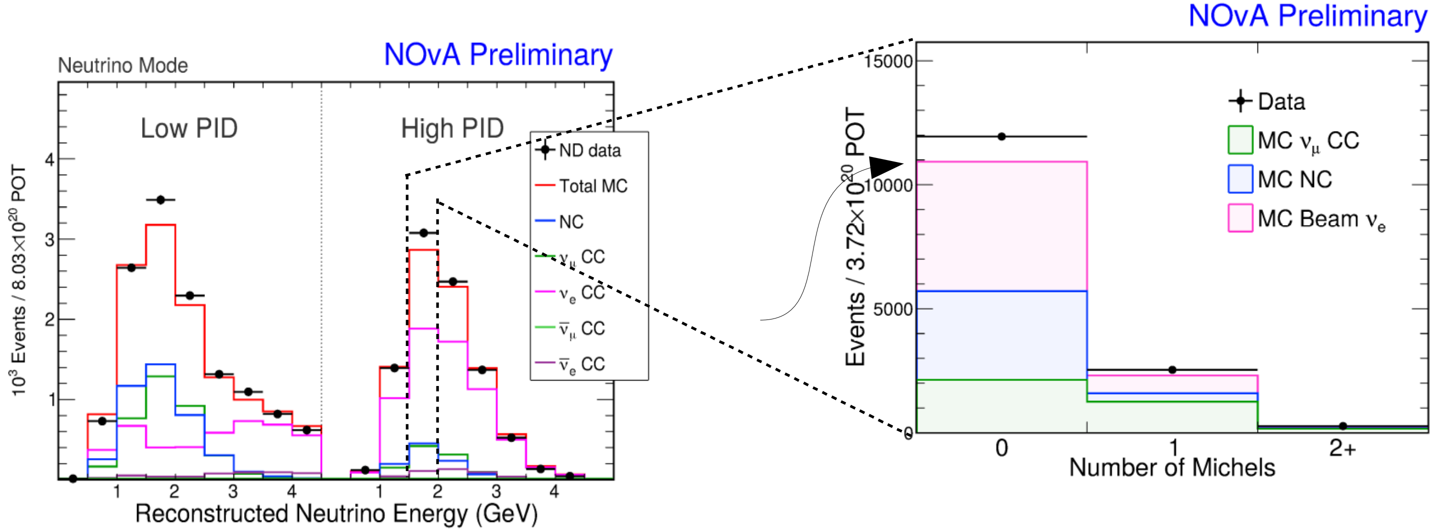

Assign discrepancies in ND $\nu_\mu$ contained and uncontained samples to flux; **derive corrections according to parent mesons** (which also result in beam $\nu_e$)




Pion-ancestor neutrinos are corrected in bins of parent ($p_z$, $p_T$). Average ~ +2%

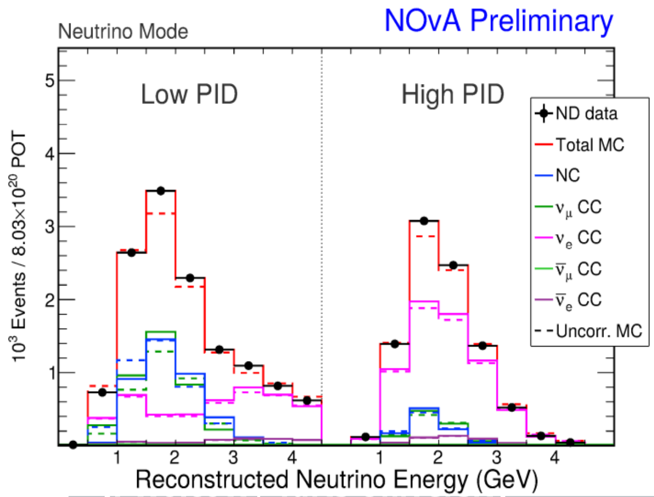
Kaon-ancestor neutrinos get a single weight: -6.3%

# $\nu_e$ appearance: constraining $\nu_\mu$ CC/NC ratio



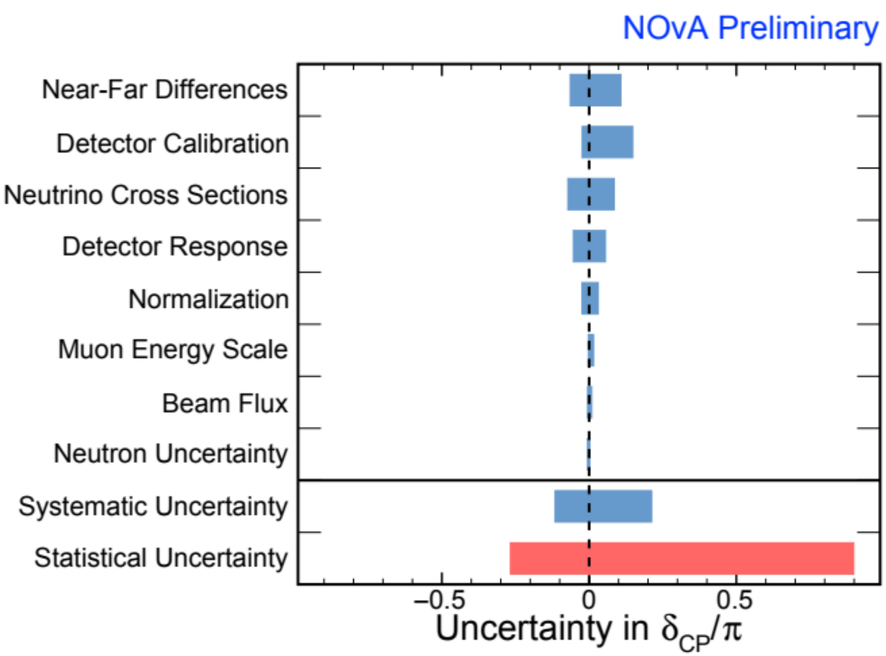

Examine distribution of Michel electrons in each bin of ND $\nu_e$ selected sample after beam $\nu_e$ constraint (prev slide)

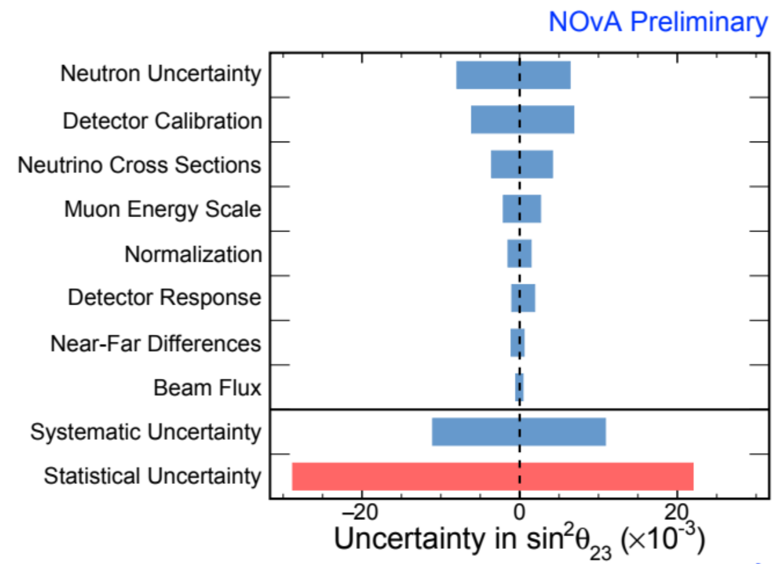
Fit these 18 distributions to determine $\nu_\mu$ CC / NC corrections in each bin

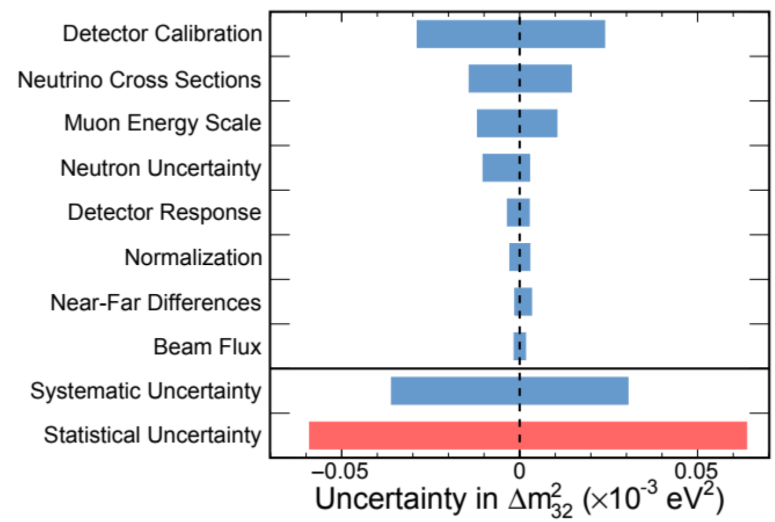


# Systematics

**Uncertainties dominated by statistics**,
but
detector calibration
and neutrino interactions
growing in importance

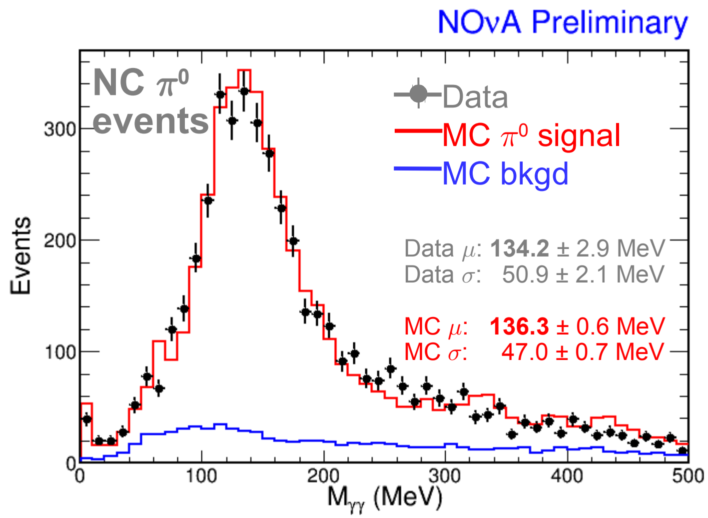


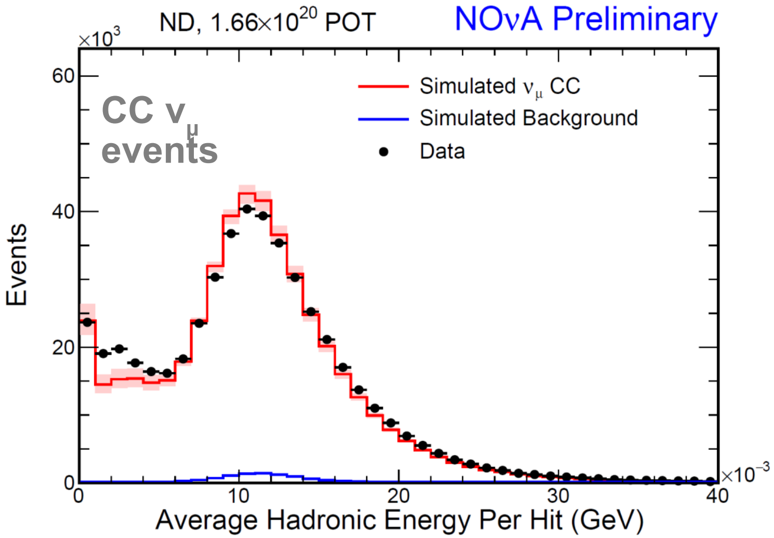



# Fixing the energy scale

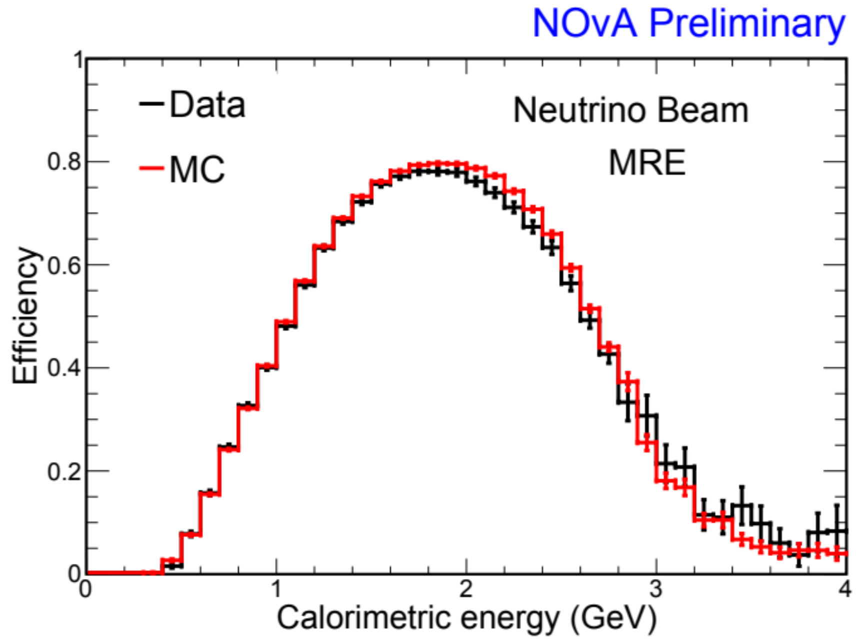
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel $e^-$ spectrum
  - $\pi^0$ mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel $e^-$ spectrum
- All agree to 5%

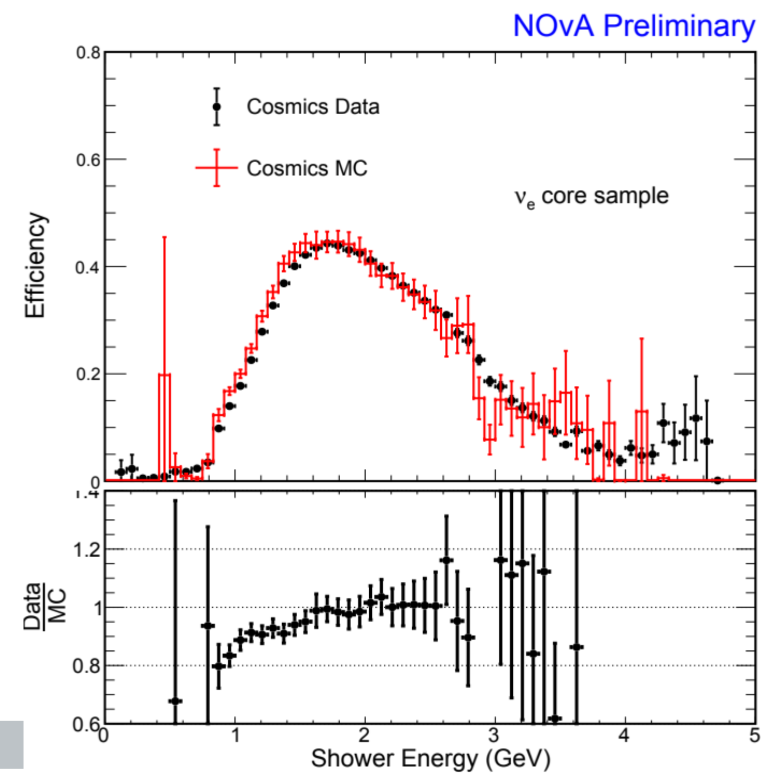


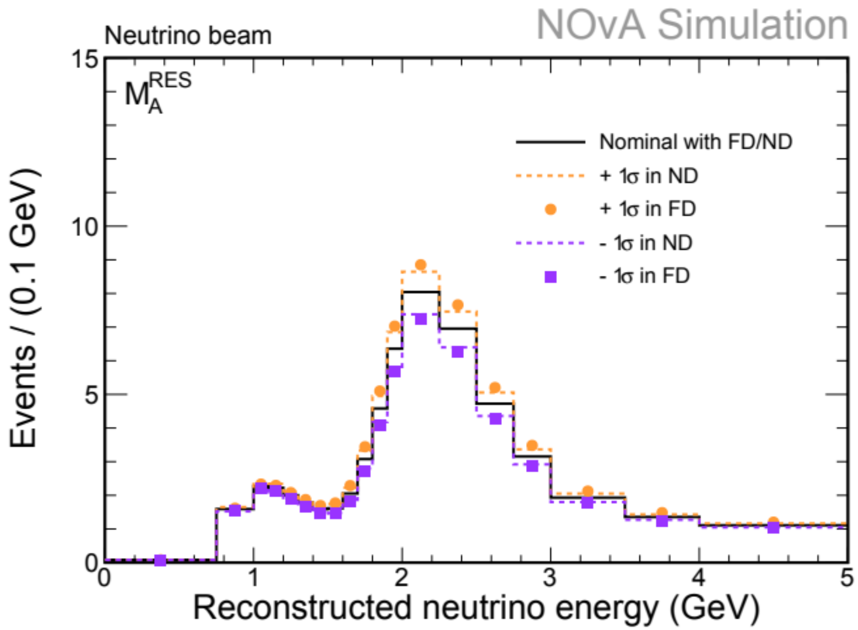
# $\nu_e$ Efficiency Checks

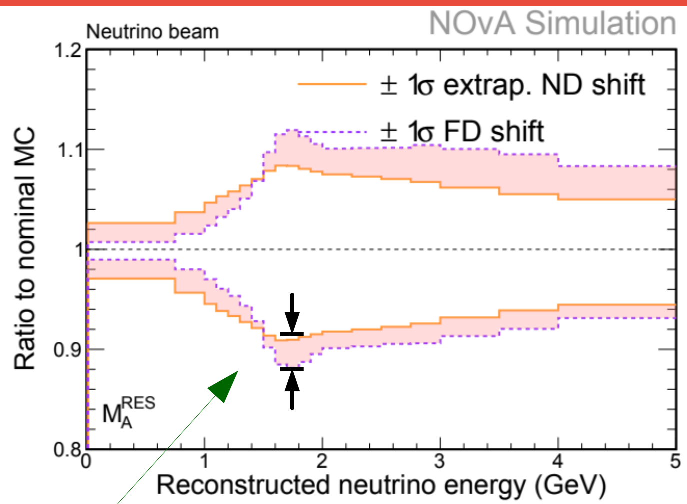
- Test hadronic showers:
  - Muon removed, simulated electron added to $\nu_\mu$ CC in ND events
  - Data & MC efficiencies agree within 2%
- Test electromagnetic showers:
  - Muon removed from bremsstrahlung in FD cosmic ray events
  - Good data-MC agreement in both core and peripheral samples

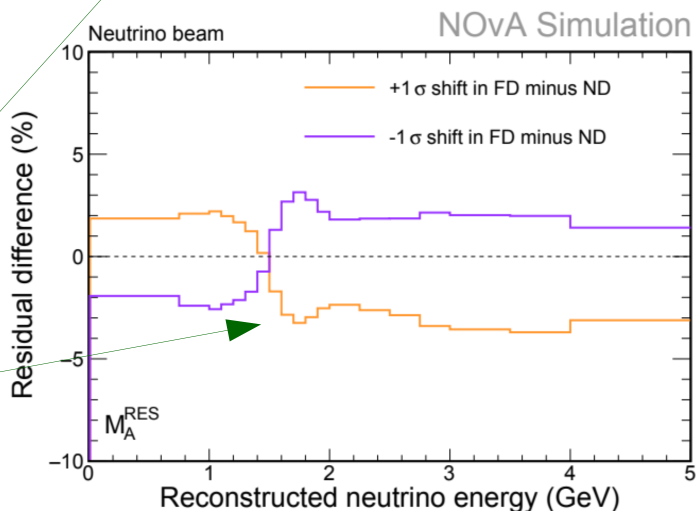


# Effect of extrapolation

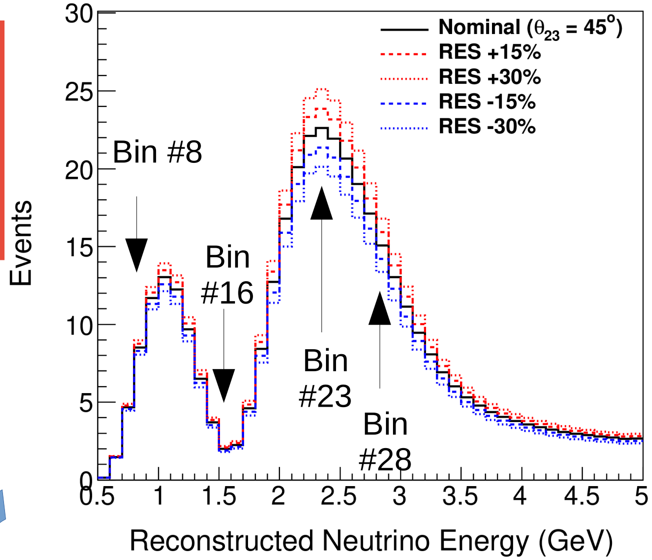


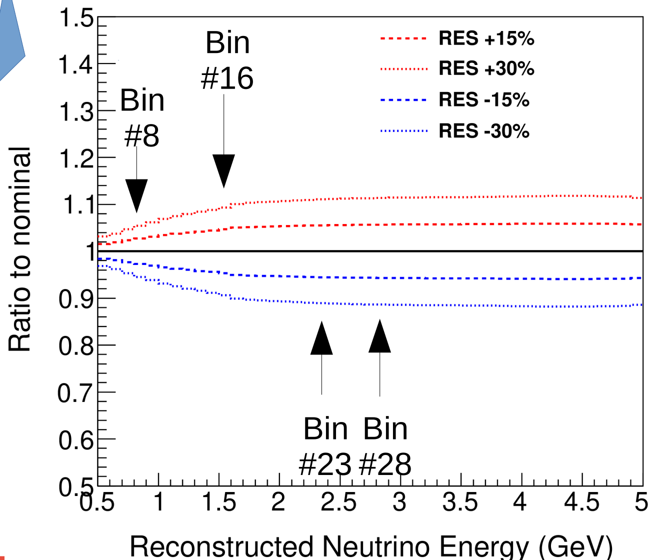




**~10-15% uncertainties become ~2-3% *residual* uncertainties after extrapolation**

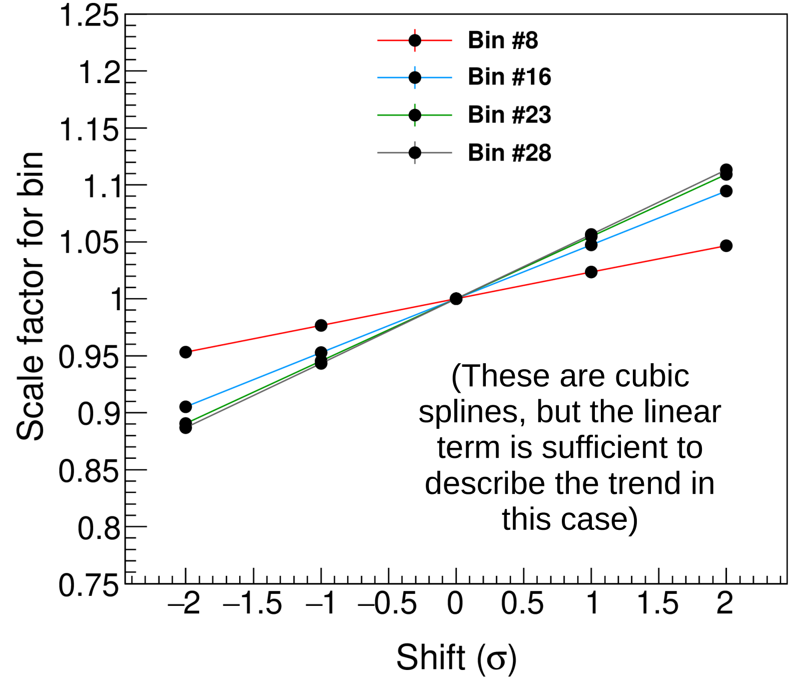
# Parameterizing systematic effects




**1. Construct predictions for ±1σ, ±2σ variations in each uncertainty for the target distribution**
(for given ($\Delta m^2_{32}$,$\theta_{23}$))...

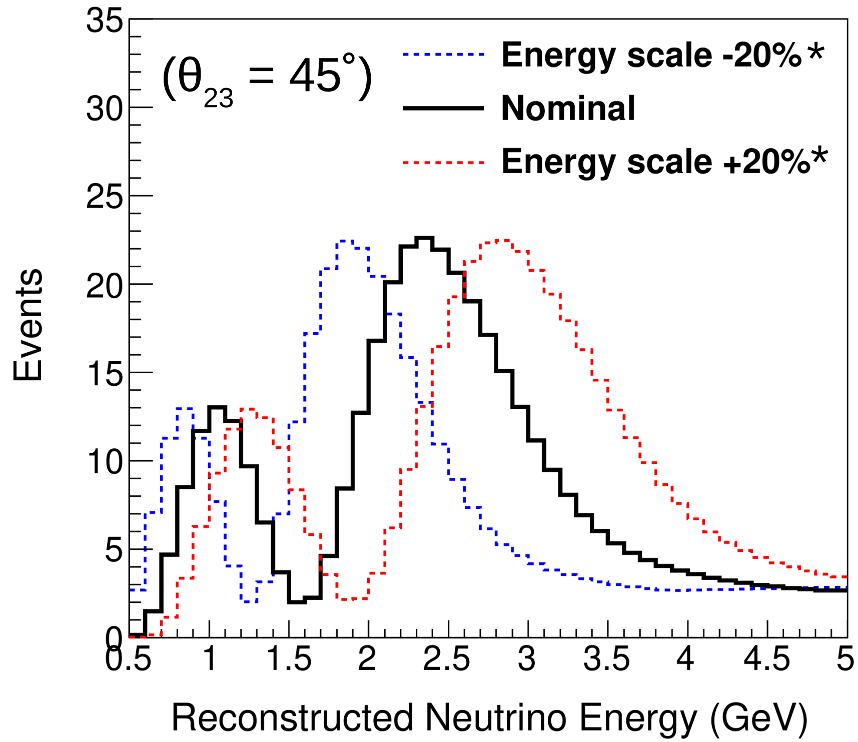


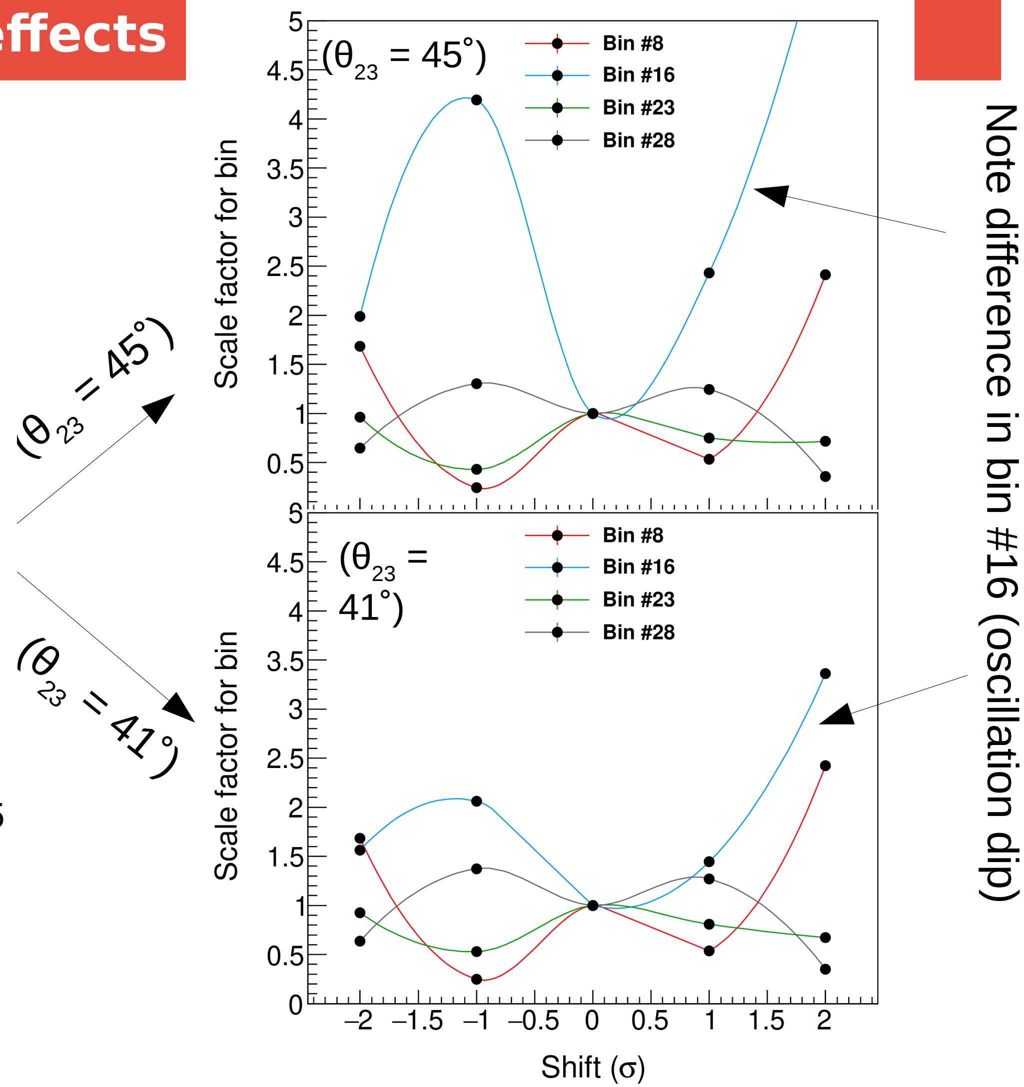

**2. Examine the ratio of each of these to the nominal prediction...**




**3. Construct parameterized functions describing the variation in each bin of the target distribution**
(enables us to quickly get arbitrary size shifts for each systematic)

# Parameterizing systematic effects

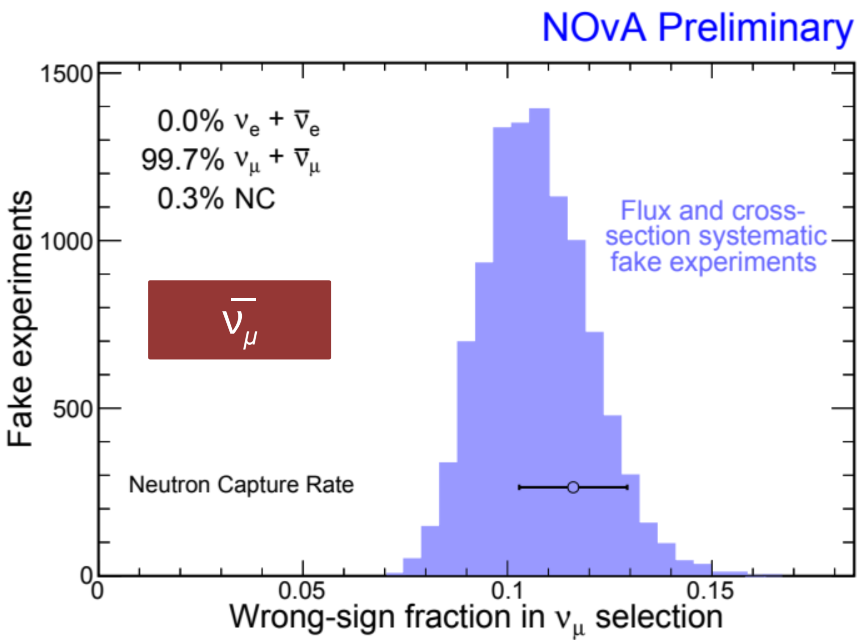


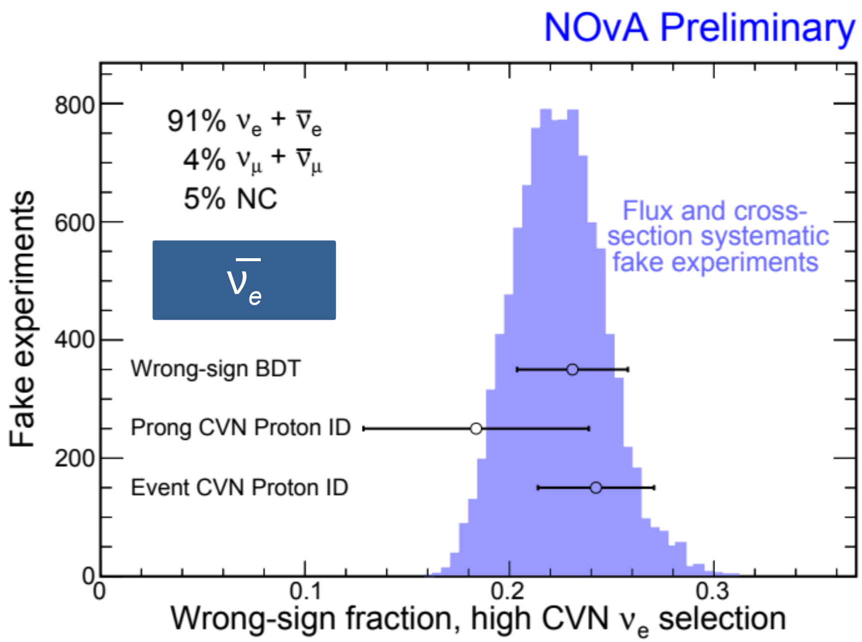




(*reminder: 20% is for illustration only.
~5% is current actual uncertainty,
but harder to see the effect)

Systematics that **shift events between bins of the prediction** can be problematic
(this bin-by-bin ratio adjument isn't handling them 'correctly')

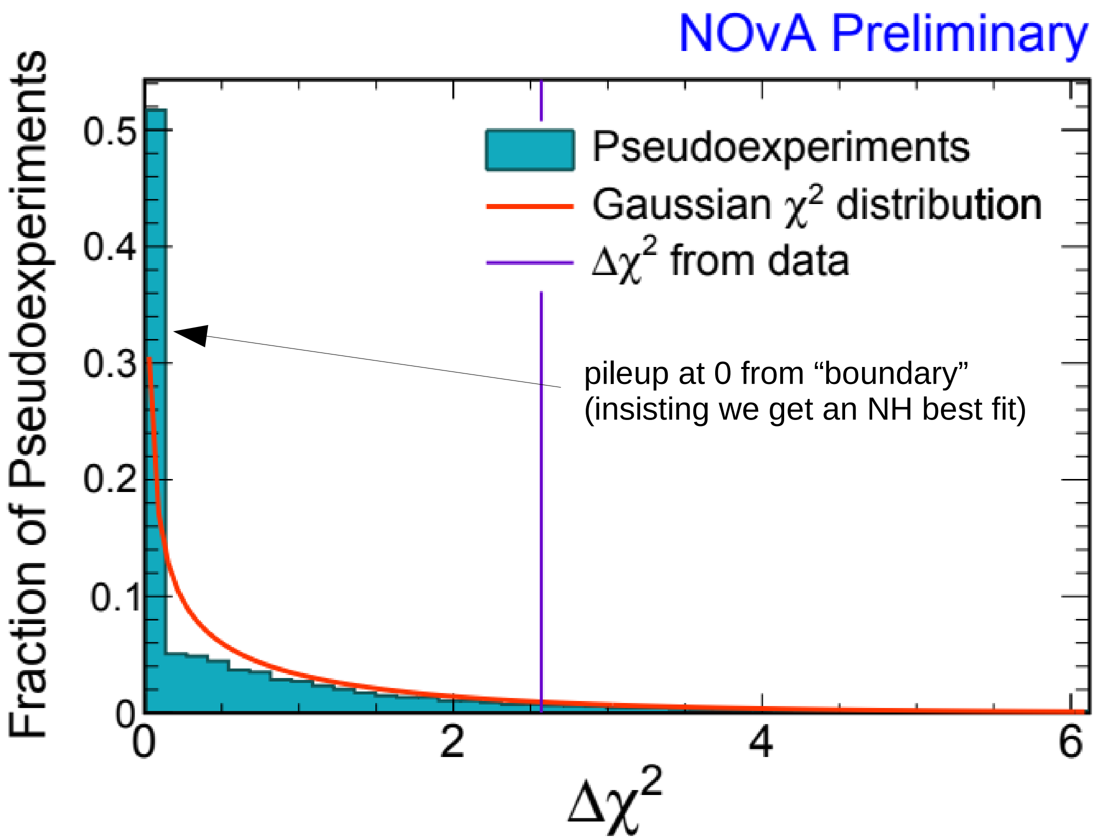
# Wrong-sign cross-checks




- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Both in $\nu_\mu$-like and $\nu_e$-like events.
  - Does not include uncertainties from detector effects.
- Confirm using data-driven cross-checks of the wrong-sign contamination
  - 11% wrong-sign in the $\nu_\mu$ sample checked using neutron captures.
  - 22% wrong-sign in beam $\nu_e$ checked using identified protons and event kinematics.

# Calculation of mass hierarchy significance




- Throw pseudoexperiments at best fit *in IH*
  - Run fitting procedure for each
  - Compute $\chi^2$ between best fit for this pseudoexpt and global best fit (NH,UO)
    - if best fit is in IH, set $\Delta\chi^2 = 0$

  → creates distribution at left
- Integrate to the right from observed $\Delta\chi^2$ in data
- Use this p-val to look up Gaussian significance

**Want to know:**

"how often could the true IH solution fluctuate to NH and give us a $\Delta\chi^2$ at least as poor as we observe?"

# $\nu_e$-$\bar{\nu}_e$ dependence on parameters