THREE FLAVOR NEUTRINO OSCILLATION RESULTS FROM NOvA

[robust measurements
in an uncertain world]

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Joint Experimental-Theoretical Seminar
Fermilab
September 18, 2020

[DOE award #DE-SC0019032]

Preface: "an uncertain world"

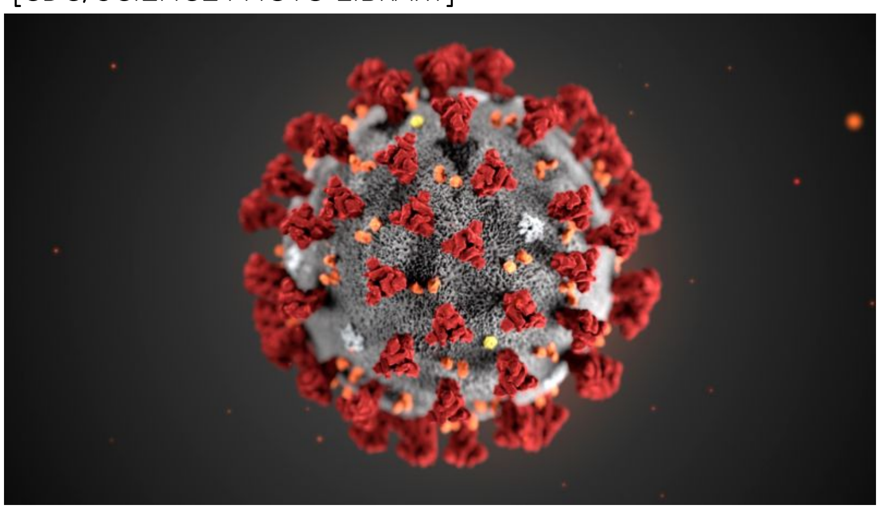
[this slide reflects the opinions of the author only]

Science happens in a context.

Acknowledge NOvA collaborators & Fermilab community
for whom the last few months have been even less "business as usual":

- Members of the Black community
- Those who have lost family/close friends/etc. to COVID-19

[CDC/SCIENCE PHOTO LIBRARY]



[Tyler LaRiviere/Chicago Sun-Times]

Let's listen to & support them. (There's work to be done!)

Plan for this talk

- Why study neutrino oscillations?
- NOvA: observing oscillations with a long-baseline experiment
- Interpretations: events into probabilities
- Inferences: NOvA oscillation results

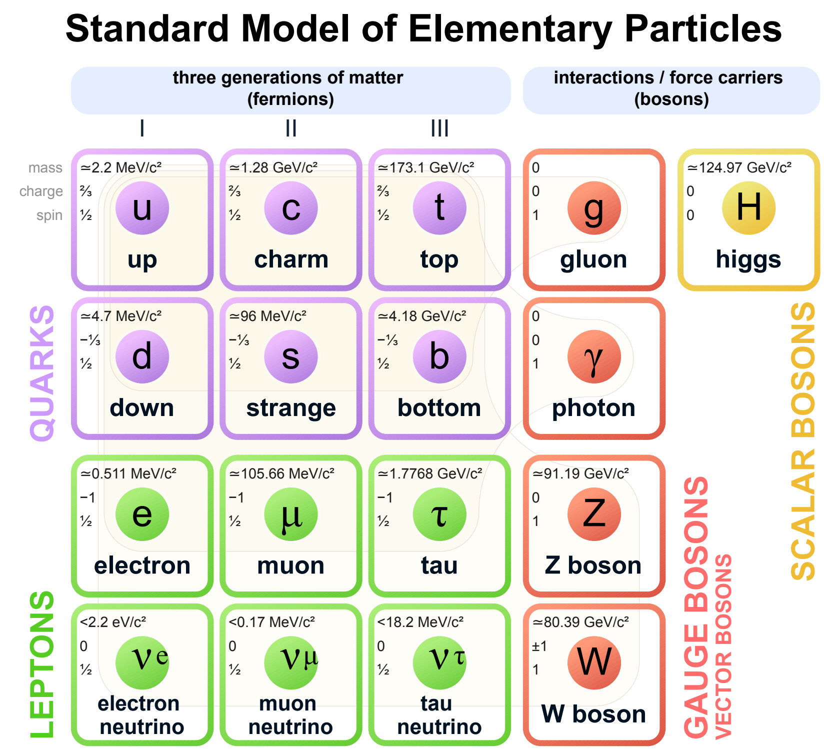
Part I: why study neutrino oscillations?

> "I suppose that I tend to be optimistic about the future of physics. And nothing makes me more optimistic than the discovery of broken symmetries."
>
> —Steven Weinberg (Nobel Lecture 1979)

Why study neutrino oscillations?

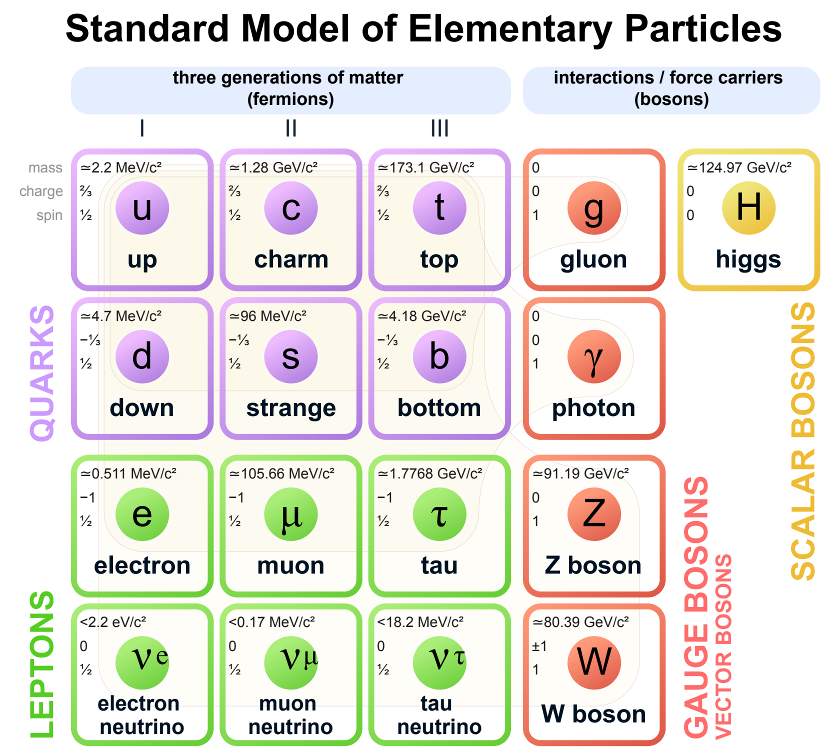
Despite our relatively complete picture of the fundamental particles & interactions, many questions remain.

Neutrino oscillations help us approach many of them…



Why study neutrino oscillations?

- ν oscillations probe symmetries:
  - Do the neutrino flavors mix in a predictable way?
  - Are the neutrino masses distributed in a 'regular' fashion? ... in a fashion resembling the other fermions?
  - Do neutrinos and antineutrinos oscillate the same way?
  - Are there exactly 3 ν flavors, like the charged leptons and quarks?



Why study neutrino oscillations?

- ν oscillations probe symmetries:
  - Do the neutrino flavors mix in a predictable way? → Does this help us understand "generations?"
  - Are the neutrino masses distributed in a 'regular' fashion? … in a fashion resembling the other fermions? → Maybe insights into neutrino mass generation mechanism?
  - Do neutrinos and antineutrinos oscillate the same way? → If not, can we learn more about other matter-antimatter differences? CP violation in leptons??
  - Are there exactly 3 ν flavors, like the charged leptons and quarks? → If not… where do the extras come from?

What do we know already?

Oscillations arise from transitions from one neutrino flavor eigenstate to another.

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

What do we know already?

Oscillations depend on two essential ingredients:

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

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

(1)

PMNS matrix
("mixing" matrix: connects flavor to mass states)
must have
off-diagonal elements

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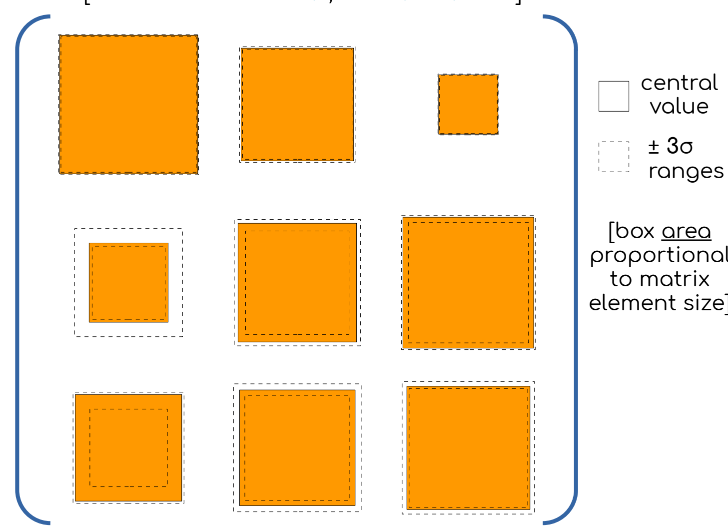
(1) **PMNS matrix**
("mixing" matrix: connects flavor to mass states)
must have
<u>off-diagonal</u> elements

[Values from NuFIT 5.0, arXiv:2007.14792]



... and it does.
(We know some of the elements much better than others...)

What do we know already?

Oscillations depend on two essential ingredients:

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

(2) neutrino mass states must have <u>differing</u> mass eigenvalues

What do we know already?

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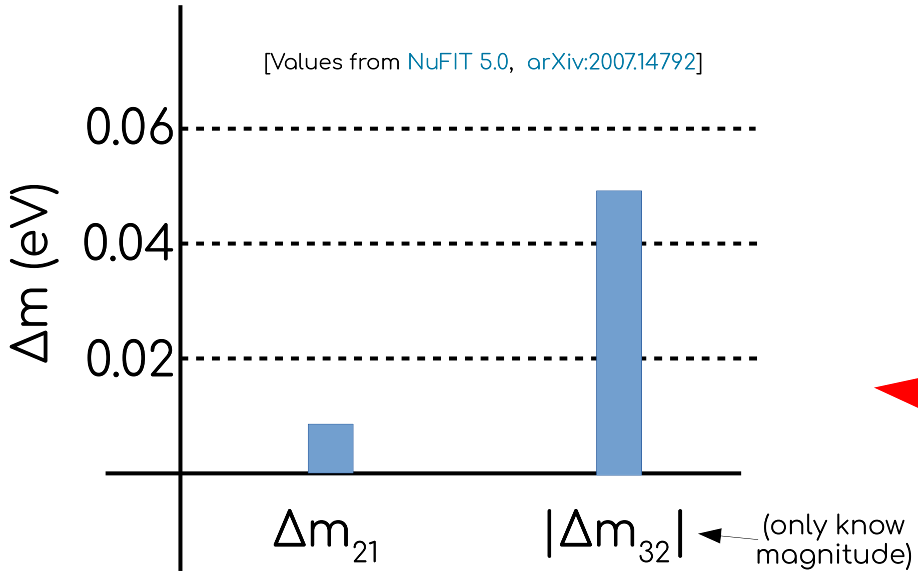
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$



(2) neutrino mass states must have differing mass eigenvalues

... and they do.
(These differences are known quite well, ~2-3%.)

Questions

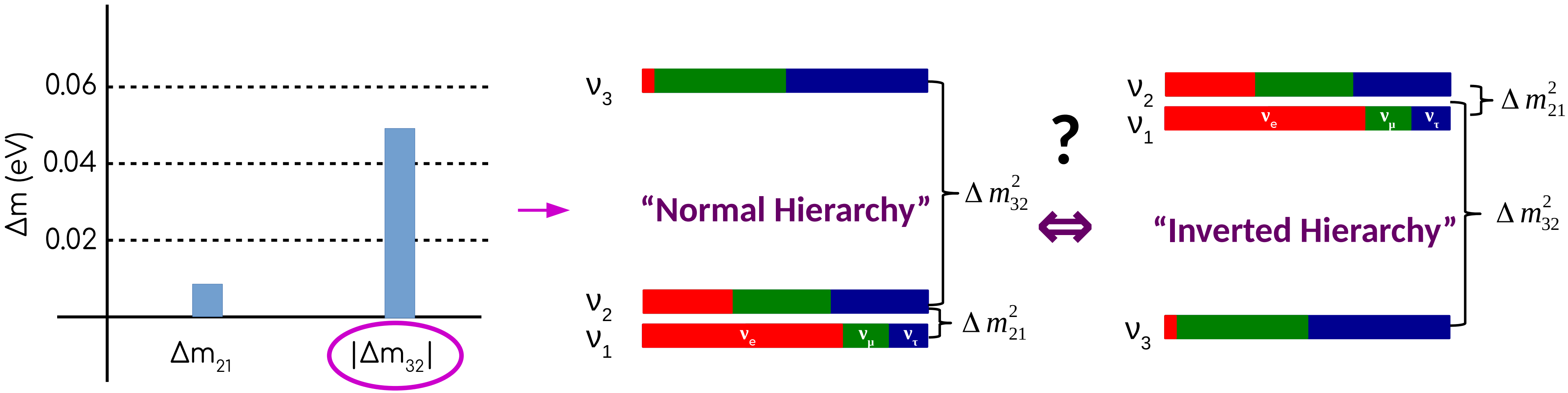
- ν oscillations probe symmetries:
  - Do the neutrino flavors mix in a predictable way?
  - Are the neutrino masses distributed in a 'regular' fashion? … in a fashion resembling the other fermions?
  - Do neutrinos and antineutrinos oscillate the same way?
  - Are there exactly 3 ν flavors, like the charged leptons and quarks?

Focus today on questions addressed by 3-flavor long-baseline accelerator neutrino oscillations:

E_ν ~ few GeV

L ~ 100s of km

Questions

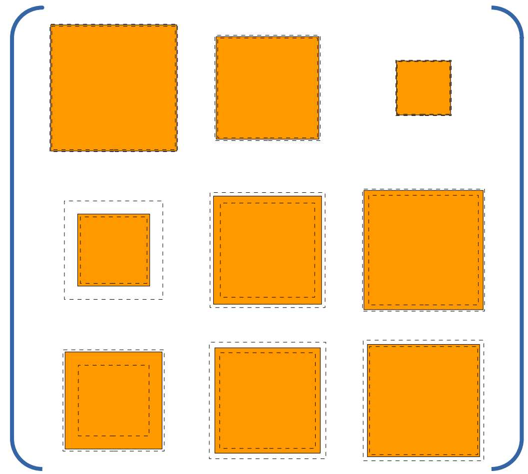


① Is there a symmetry governing the ordering of the lepton mass states?

Is the most electron-like state the lightest one, like with the charged leptons?

Questions

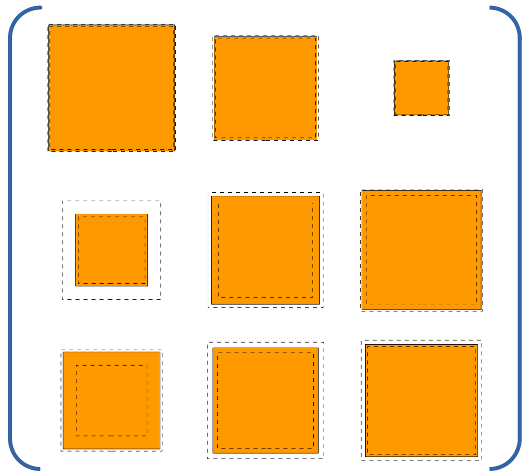
U =



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

Most poorly known parameters:
θ_{23} (~5%), δ_{CP} (weak constraints)

Questions

U = 

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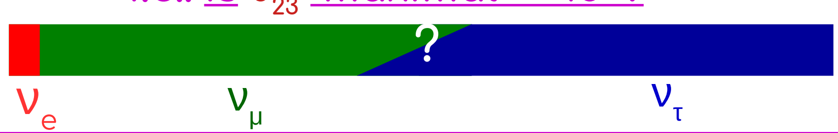
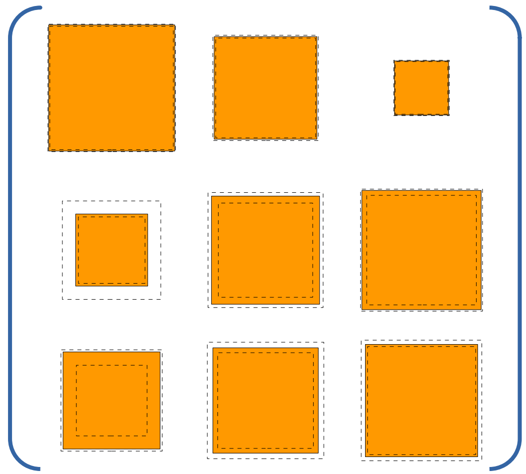
Most poorly known parameters:
θ_{23} (~5%), δ_{CP} (weak constraints)

② Is there a **symmetry** governing the ν_μ/ν_τ mixing into the 2nd and 3rd mass states?
i.e.: is θ_{23} "maximal" = 45°?

ν_3= 

Questions

U = 

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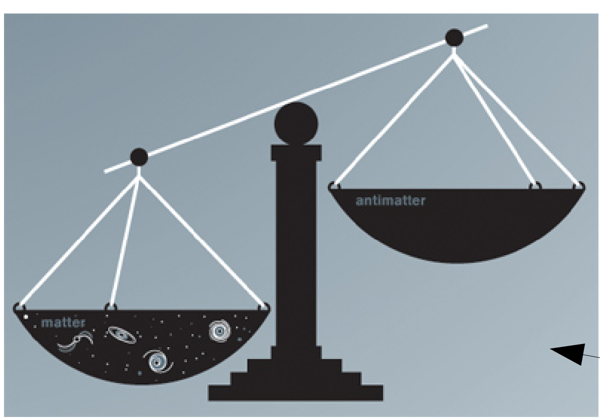


Most poorly known parameters:
θ_{23} (~5%), δ_{CP} (~unconstrained)

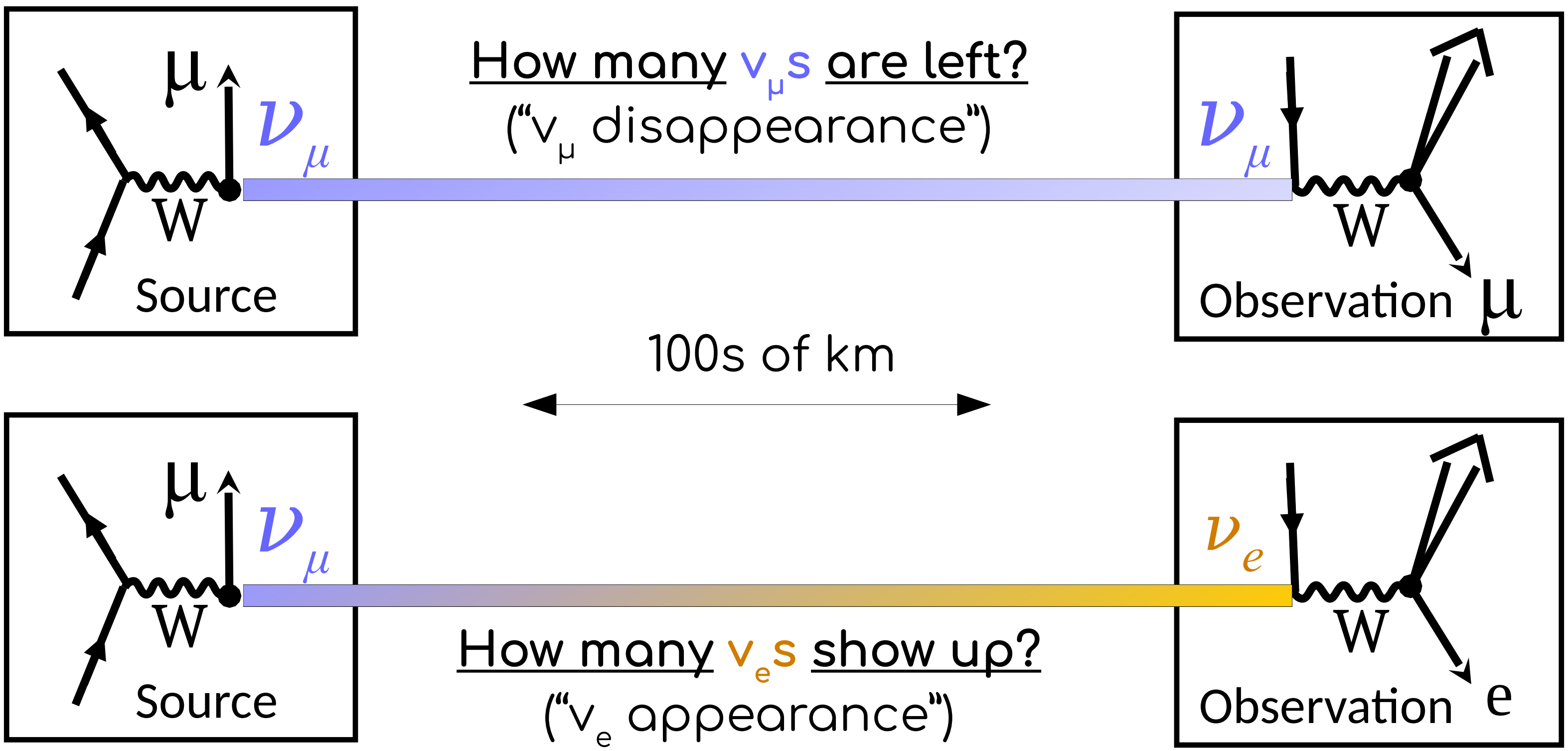
③ Is δ_{CP}/π non-integral?

If it is, neutrinos — and thus leptons — violate CP **symmetry**.
Related to wider matter/antimatter asymmetry in universe???

Part II:
Observing neutrinos over a long baseline with NOvA

LBL neutrino oscillations

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



LBL neutrino oscillations

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

ν_μ disappearance

$$P_{\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

→ θ_{23}

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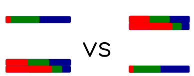
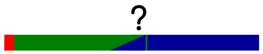
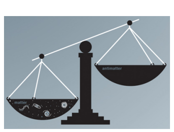
①  → Δm^2_{32}

②  → θ_{23}

③  → δ_{CP}

ν_e appearance

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

$$+ 2\alpha \sin\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

$$\times \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

$$\times (\cos\delta_{CP} \cos\Delta \mp \sin\delta_{CP} \sin\Delta)$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \Delta m^2_{31} \frac{L}{4E} \qquad A = \mp G_f N_e \frac{L}{\sqrt{2}\Delta}$$

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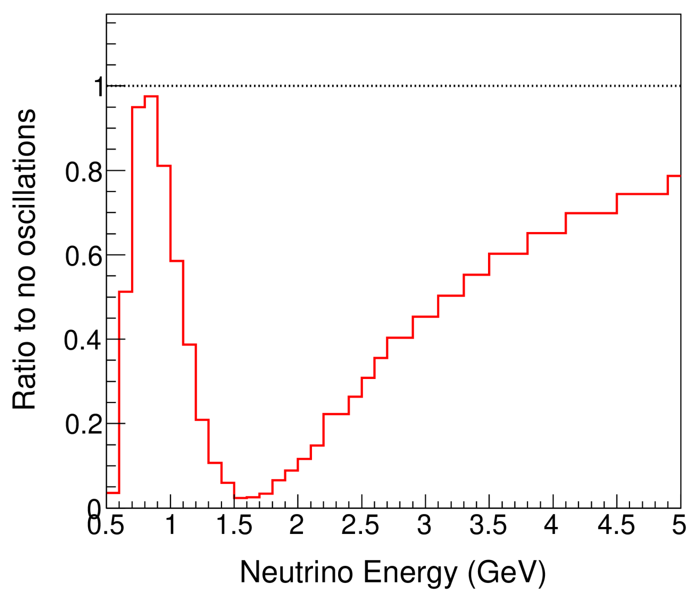
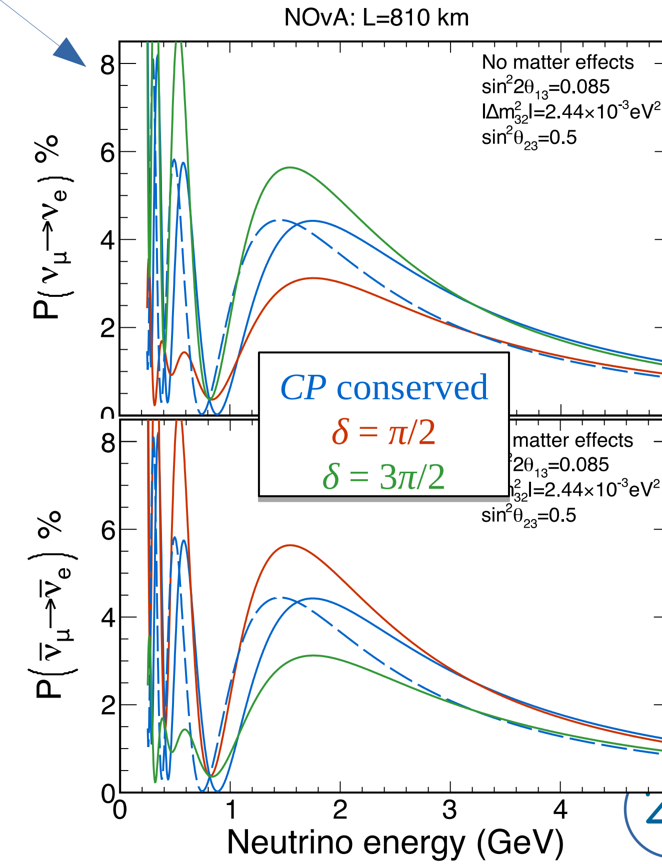


ν_e appearance



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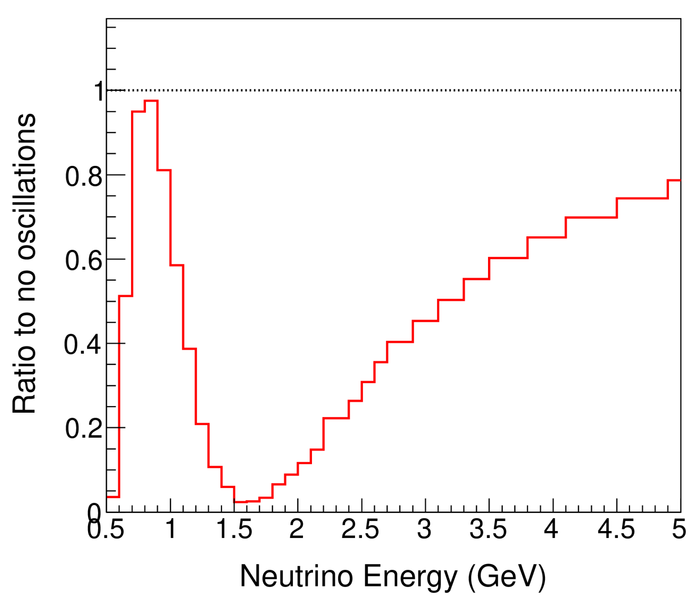
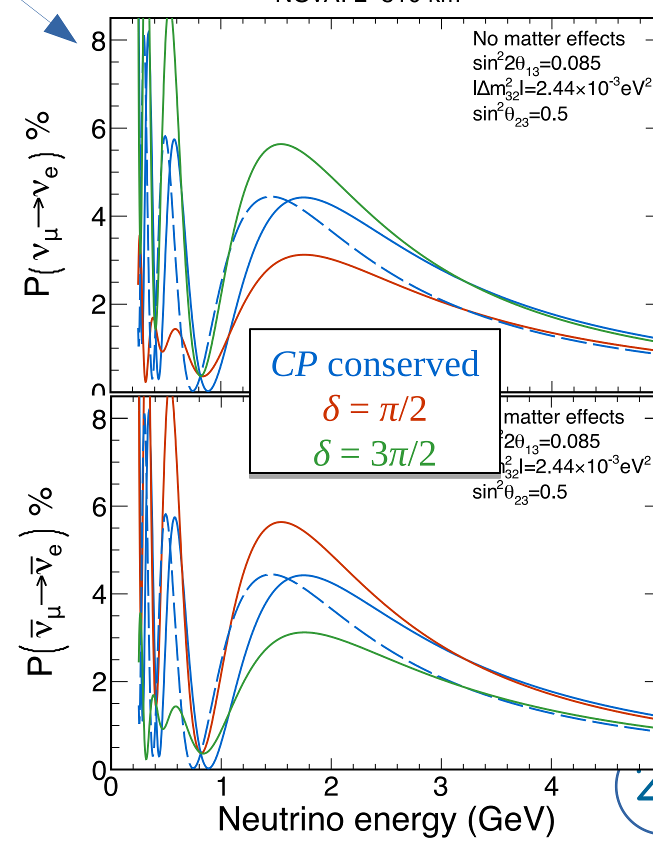


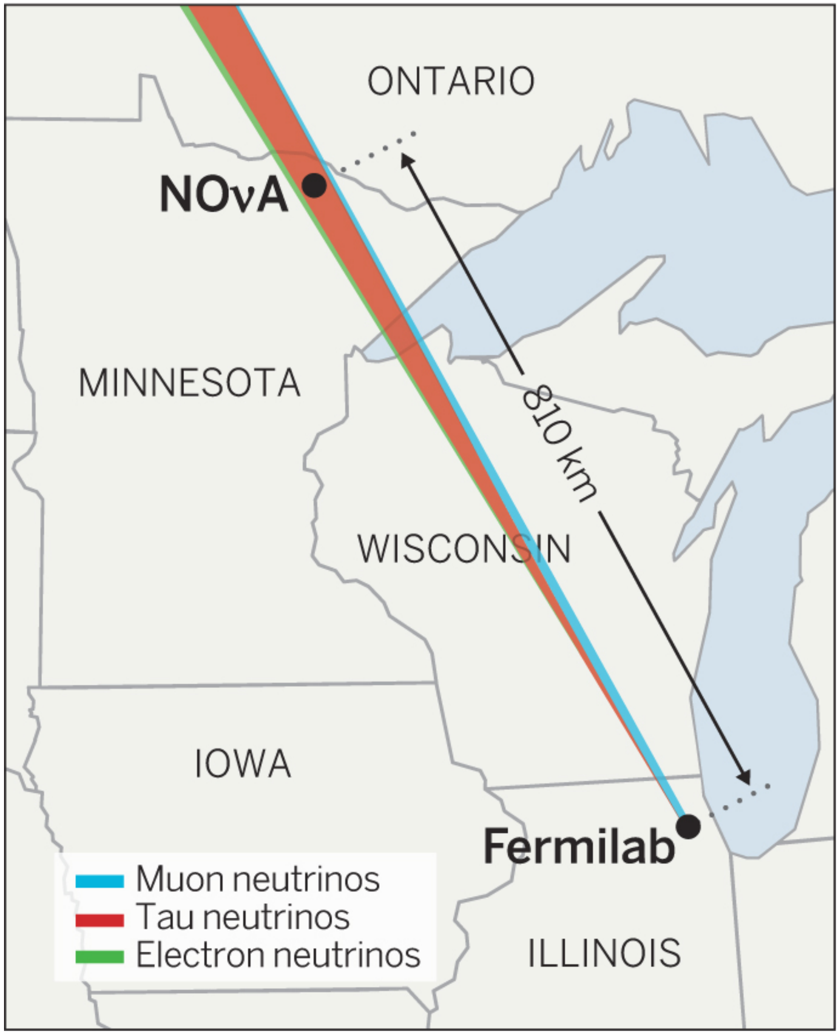
To measure the probabilities → parameters:

(1) Find ν_μs and ν_es
(2) Measure their energies

ν_e appearance



Where do neutrinos come from?



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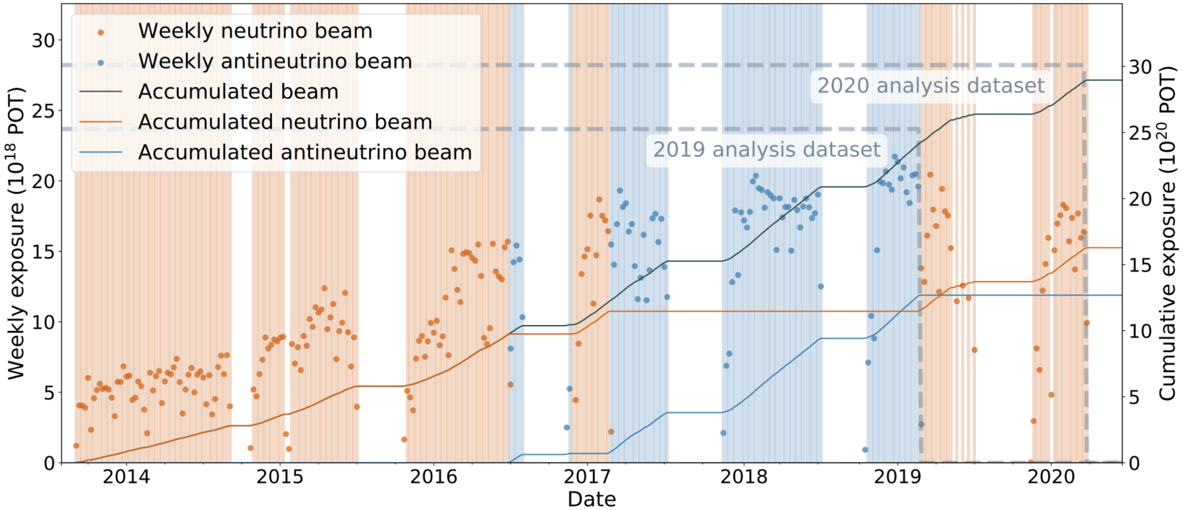
(Thanks to the fine folks at Fermilab!)



NuMI >700KW ν + $\bar{\nu}$ beam

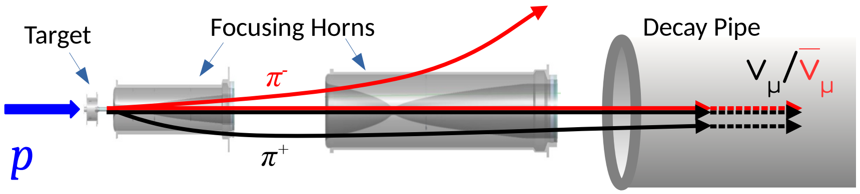
13.6×10^{20} POT ν (+54% over 2019)

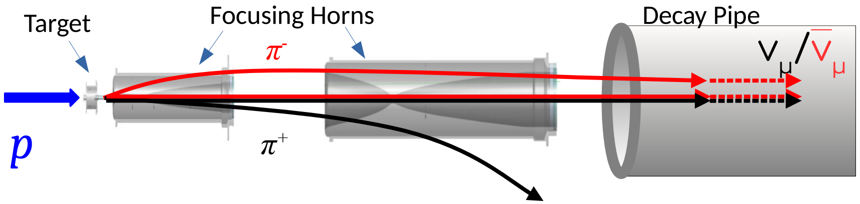
+

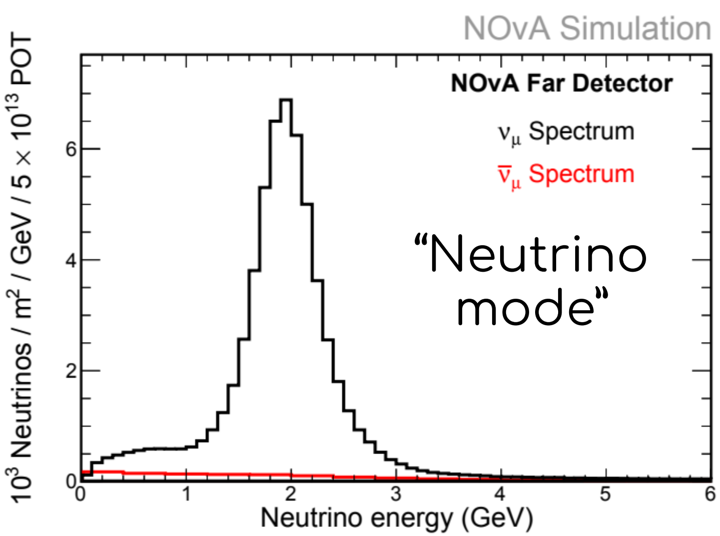
12.5×10^{20} POT $\bar{\nu}$

for 2020

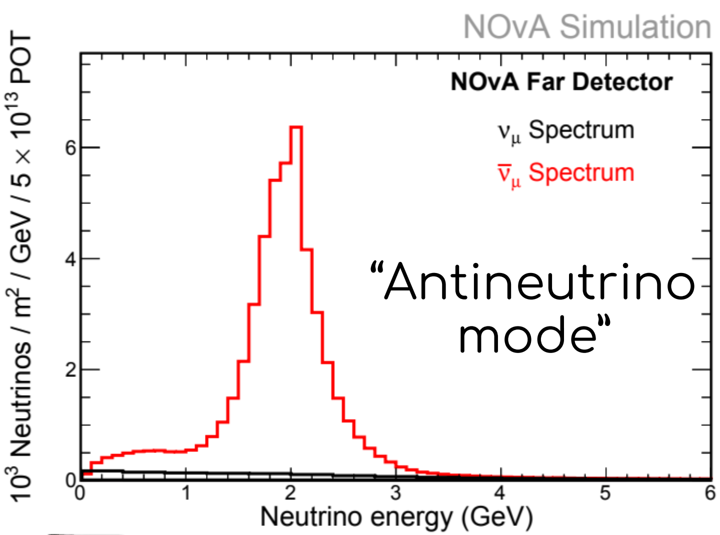
Where do neutrinos come from?

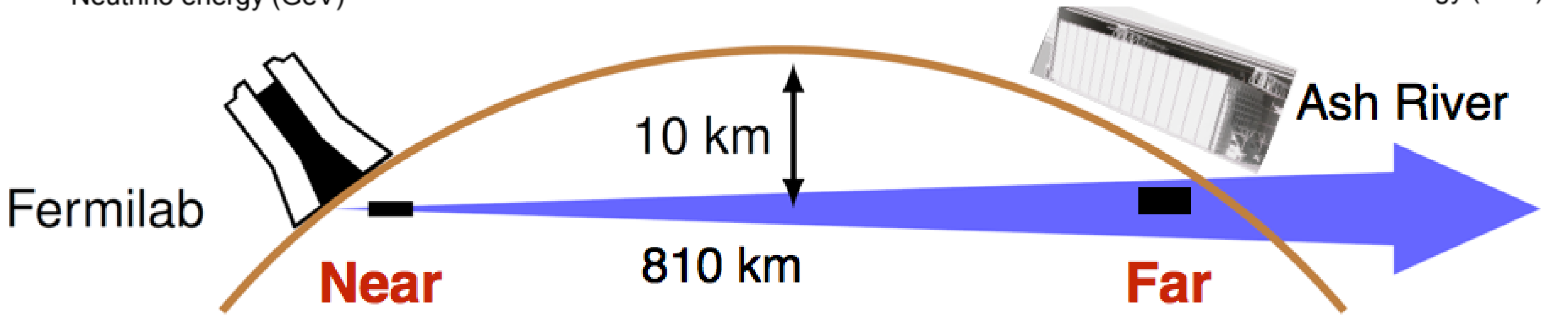






Neutrinos from NuMI beam





Where do neutrinos come from?

MW-capable target
(installed 2019)

MW-capable horn
(installing during 2020 shutdown)

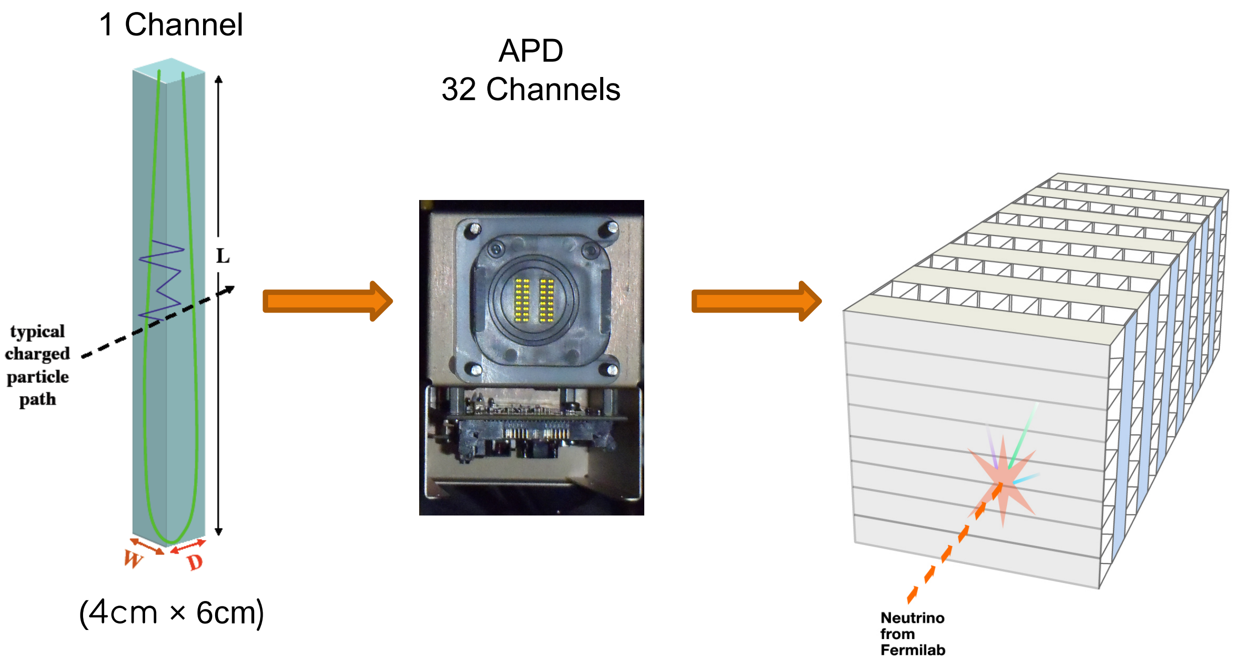
Working towards 900+ kW

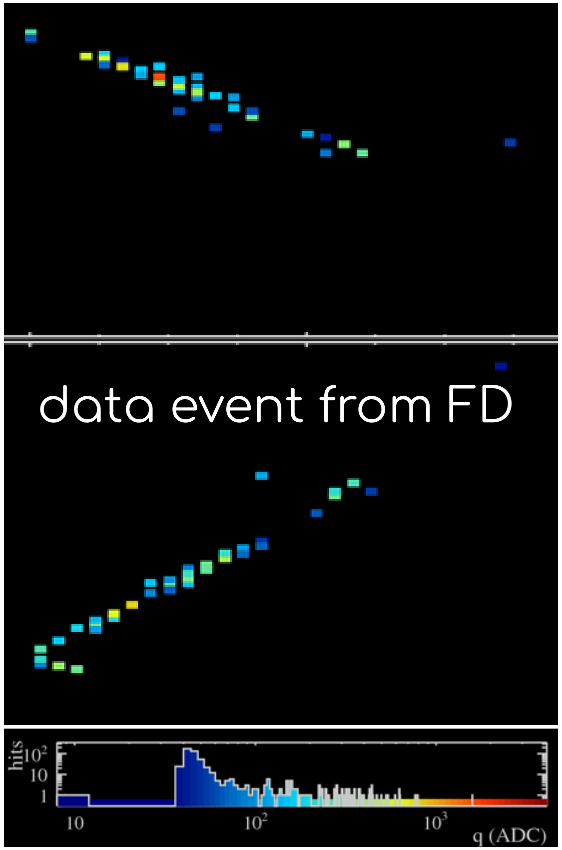
- With 2019-2020 improvements to NuMI beamline components, complex will support ~800 KW
- Early PIP-II improvements to Booster will allow 900+ KW with faster cycle times

Detecting neutrinos

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

Detecting neutrinos





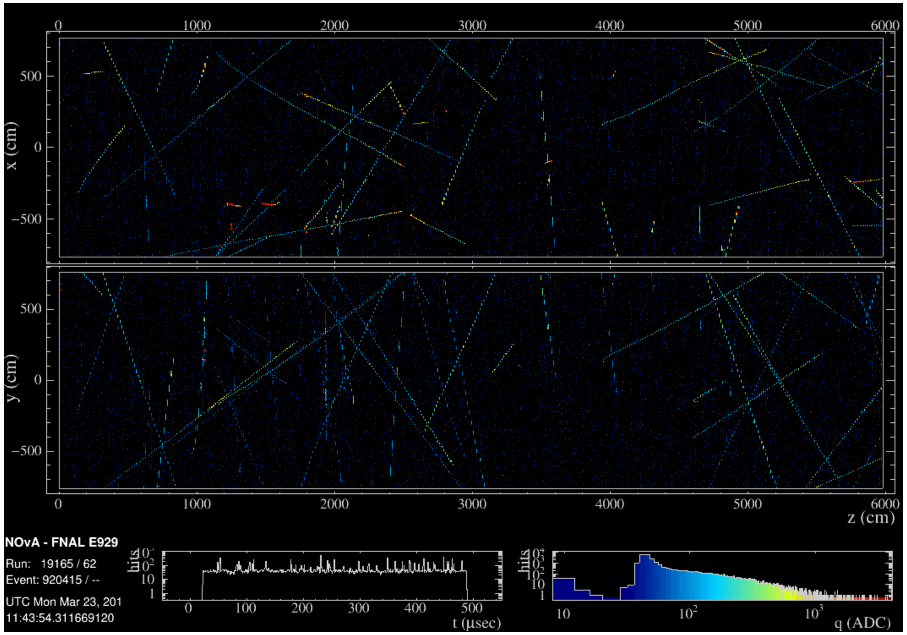
- Good energy resolution for muons, electromagnetic & hadron showers:
  - Mostly (65%) active detector
  - Radiation length ~ 40 cm → 6 samples per radiation length

Detectors differ mainly in size
(otherwise functionally identical)

Goal #1: finding ν_μs and ν_es

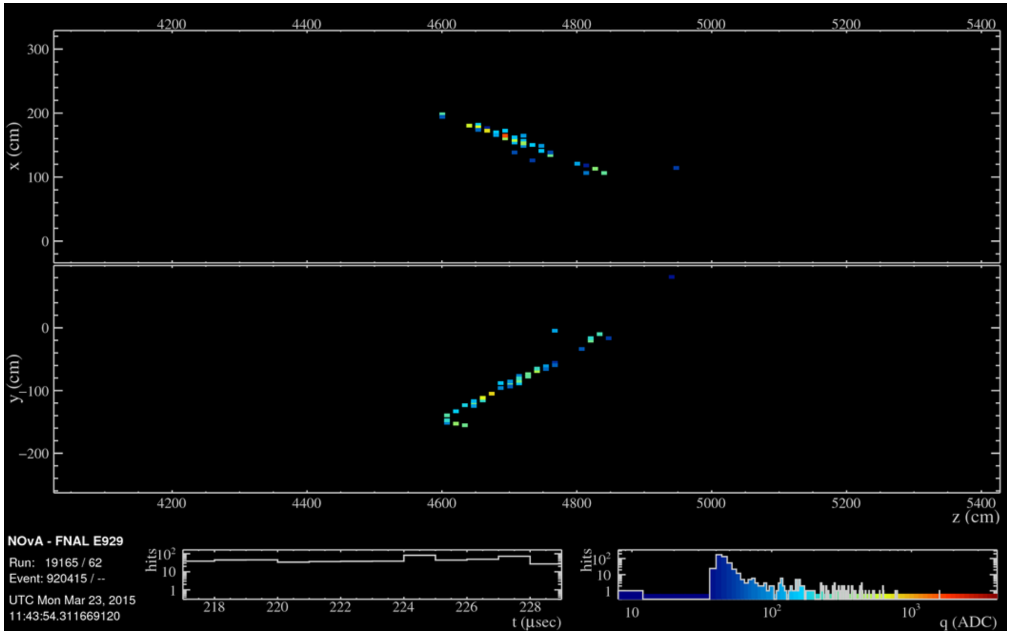
The task:

Get from this...



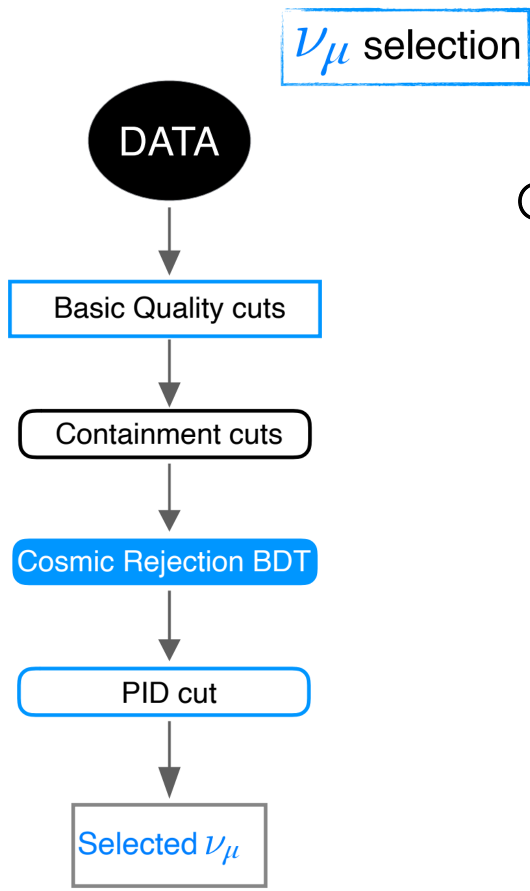
FD sits on the surface
→ ~150 KHz cosmics

... to this

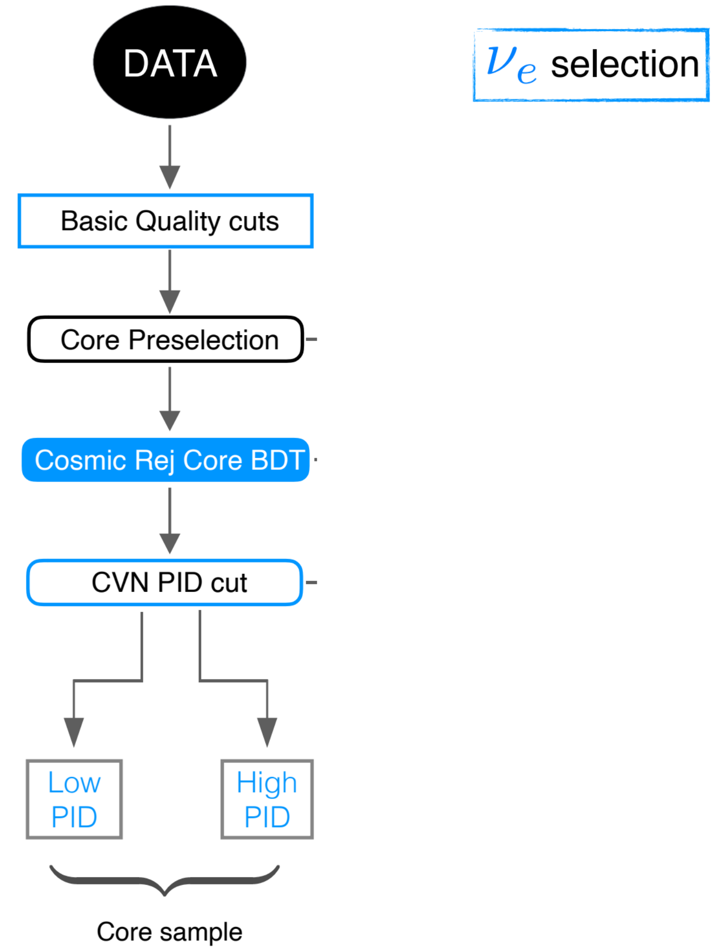


ν_e candidate

Goal #1: finding ν_μs and ν_es



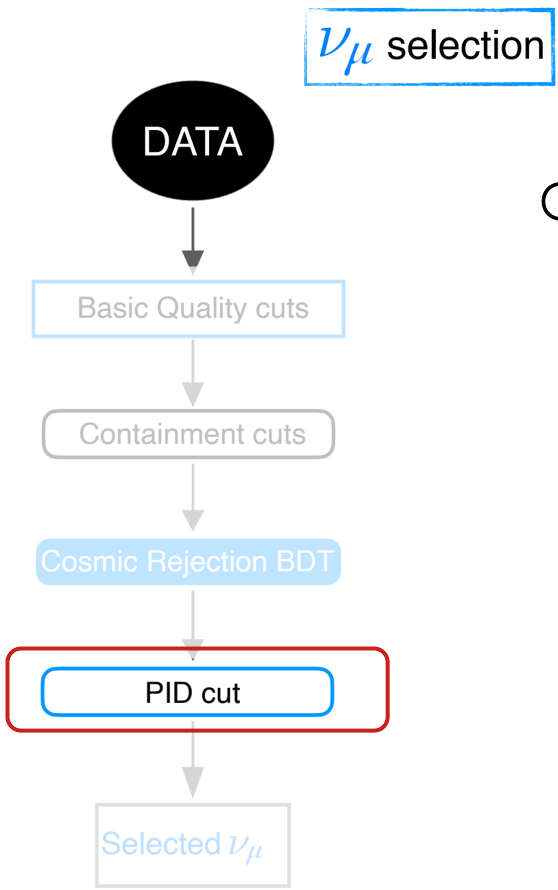
O(10^6) cosmics



O(5) cosmics
(vs. 100s $\nu_\mu/\bar{\nu}_\mu$)

O(1) cosmic
(vs. 30-80 $\nu_e/\bar{\nu}_e$)

Goal #1: finding ν_μs and ν_es



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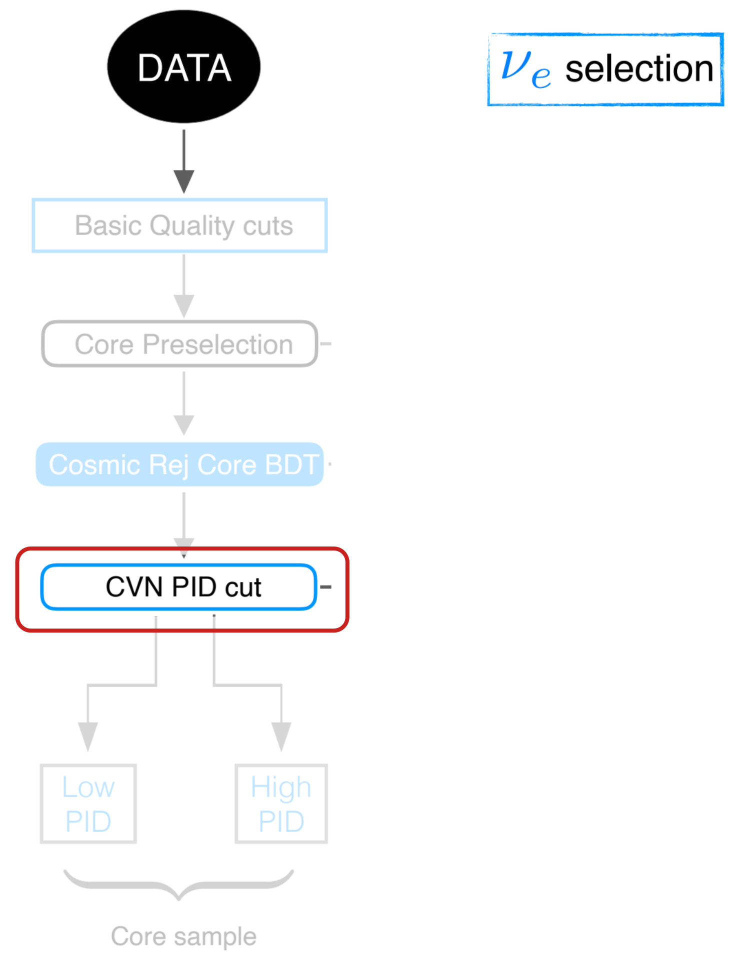
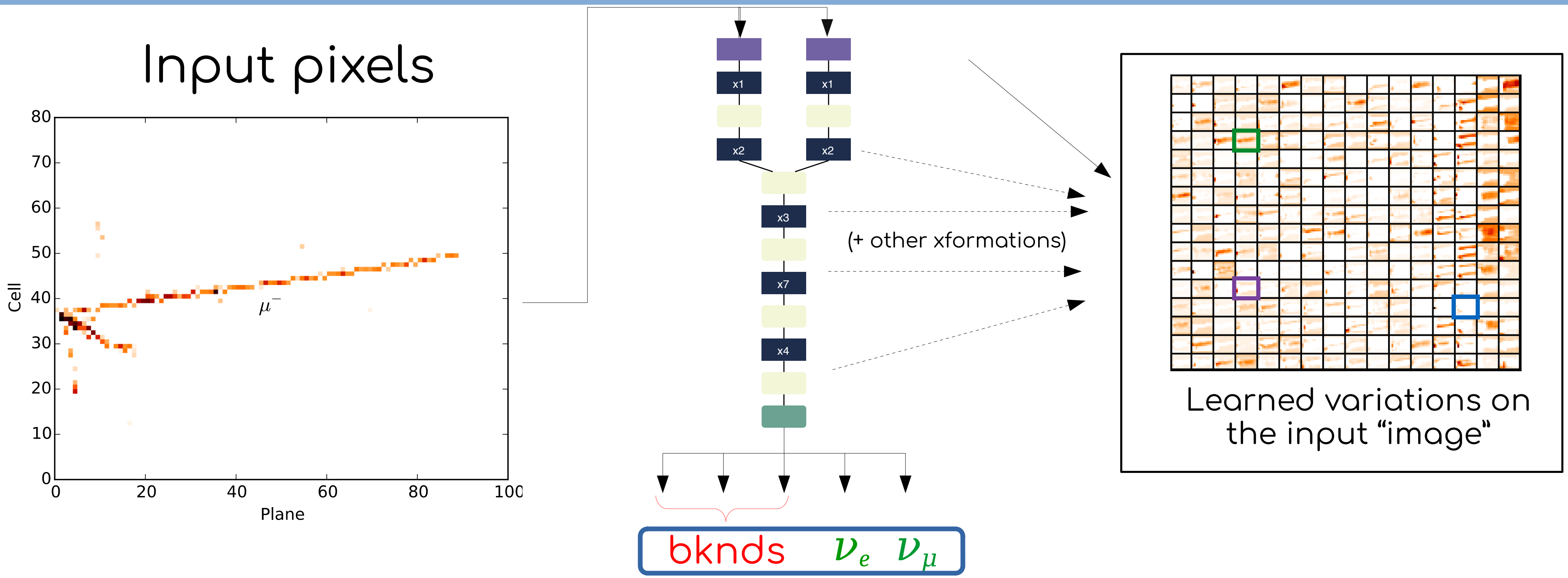


O(5) cosmics
(vs. 100s $\nu_\mu/\bar{\nu}_\mu$)

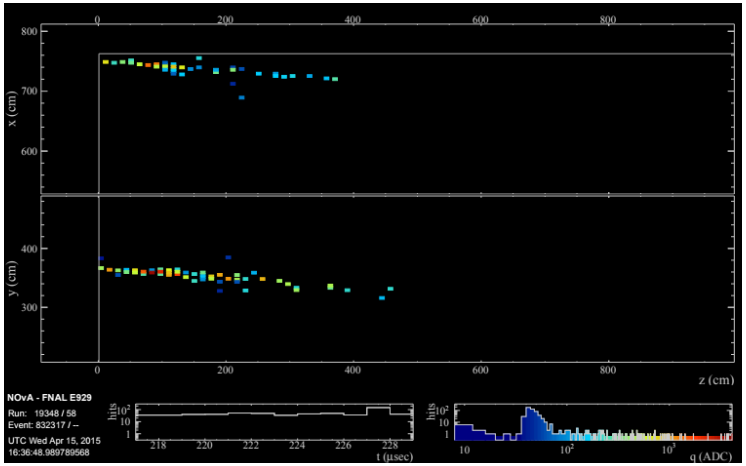
O(1) cosmic
(vs. 30-50 $\nu_e/\bar{\nu}_e$)

Goal #1: Finding ν_μs and ν_es

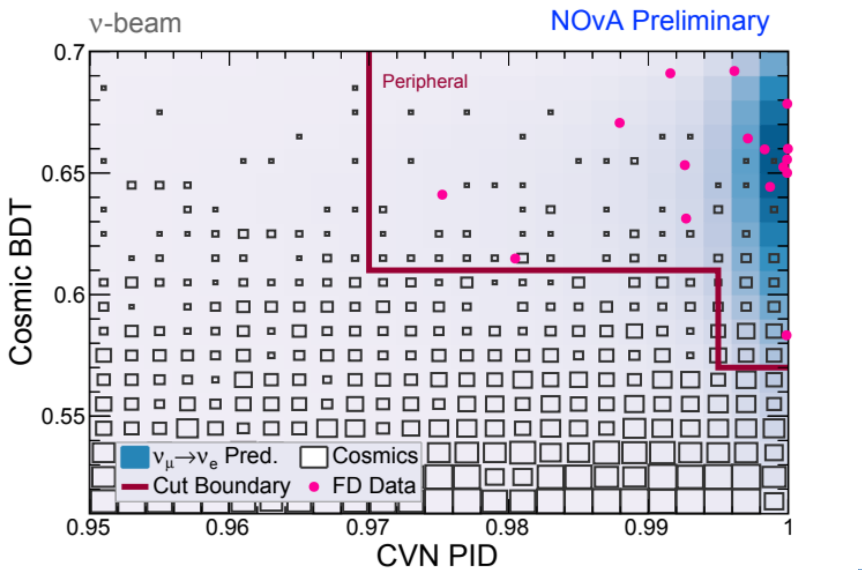


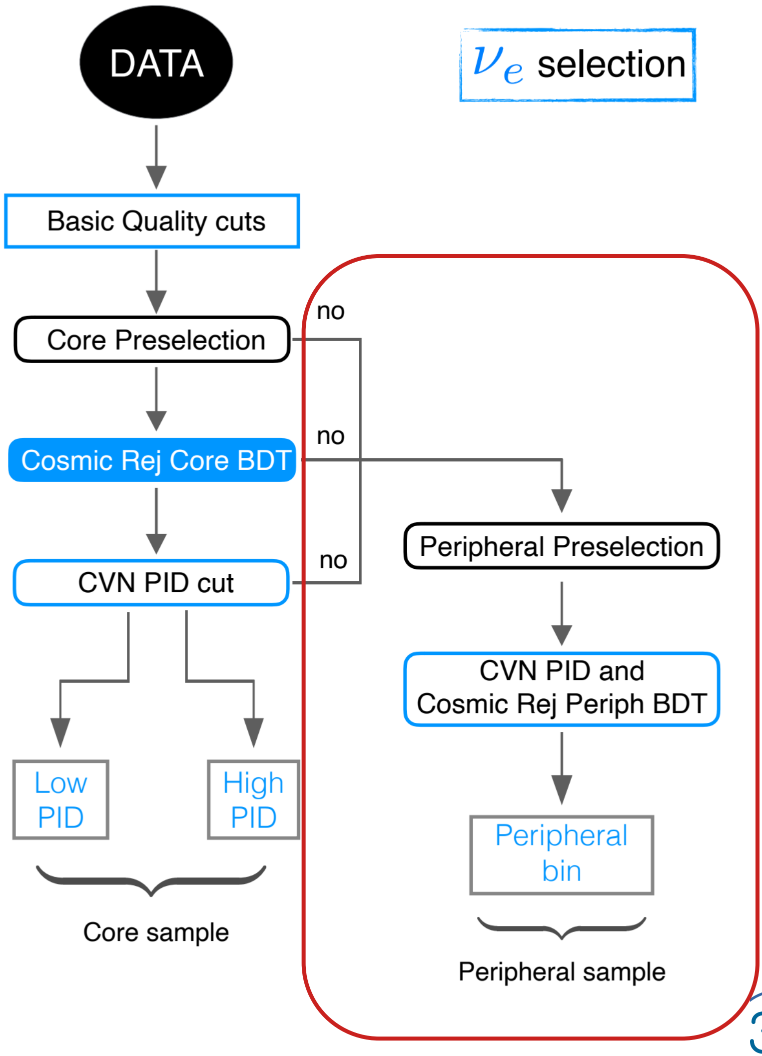
- Workhorse tool: convolutional neural network (CNN) called **CVN**
  - Technique borrowed from computer vision community:
    - Learns topological "features"
    - Eventually mapped onto desired output categories
  - Performs neutrino event classification; also important part of cosmic rejection
  - Updated for 2020 (3rd edition!)
    - Significantly (~×3) faster network architecture (modified MobileNet v2)
    - Slightly better physics performance
- Further reading: JINST 11, P09001

Goal #1: finding ν_μs and ν_es



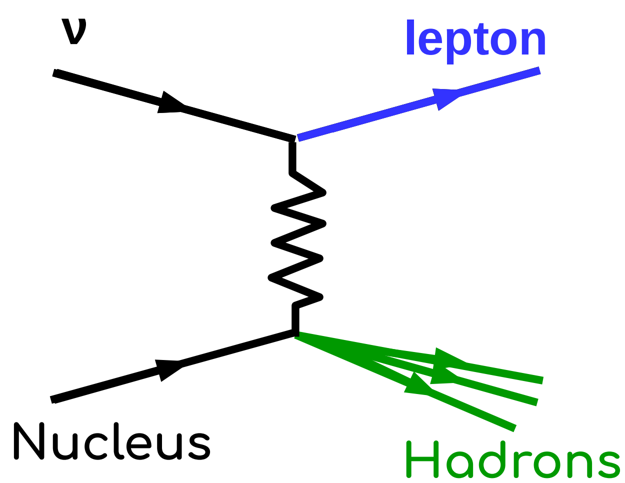
ν_e candidates near detector edges are recovered into **"peripheral" sample** using tighter PID cut & dedicated cosmic BDT





Goal #2: Measuring E_ν

Strategy: divide and conquer

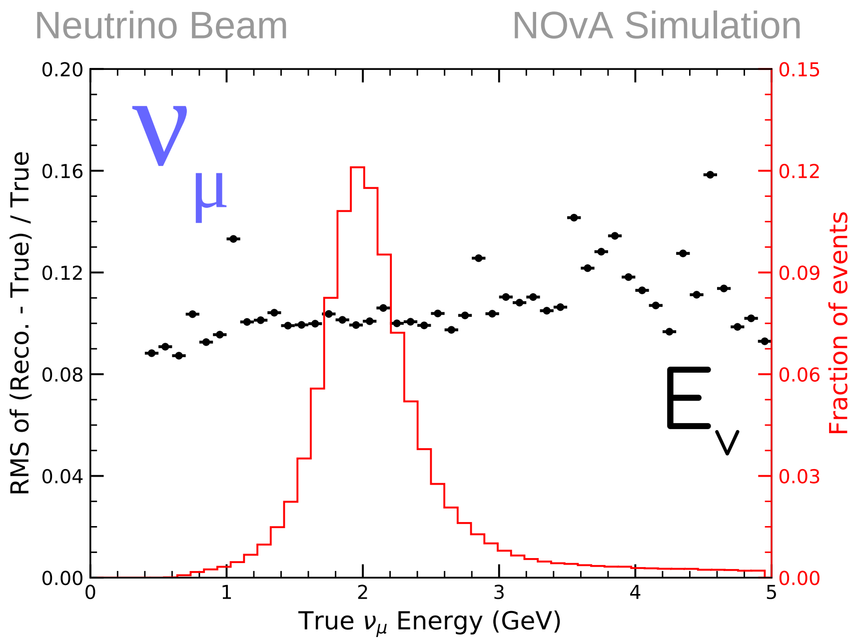


Evaluate the
lepton (muon or electron)
and
hadronic system
energies separately

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

Goal #2: Measuring E_ν (ν_μ)

Strategy: divide and conquer



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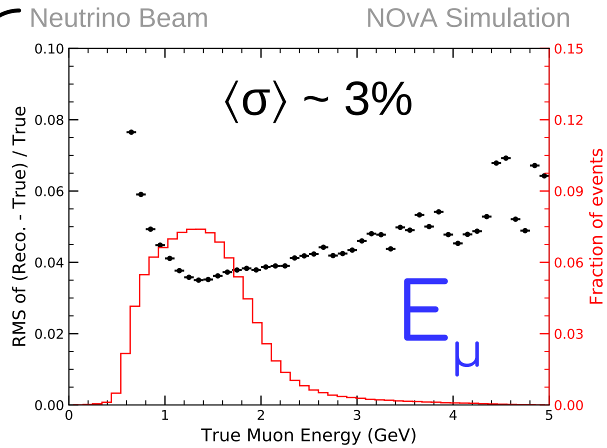
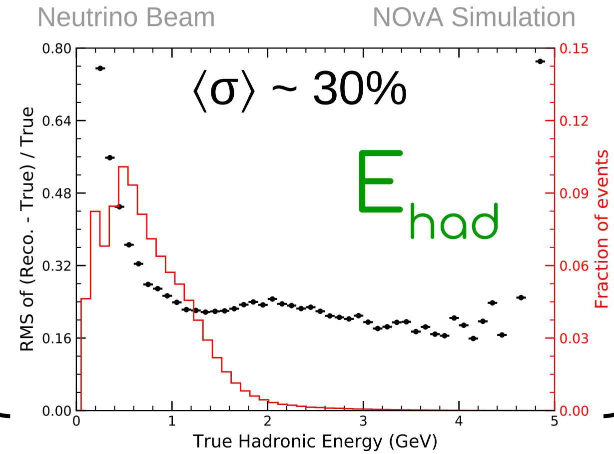
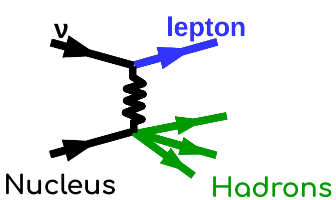


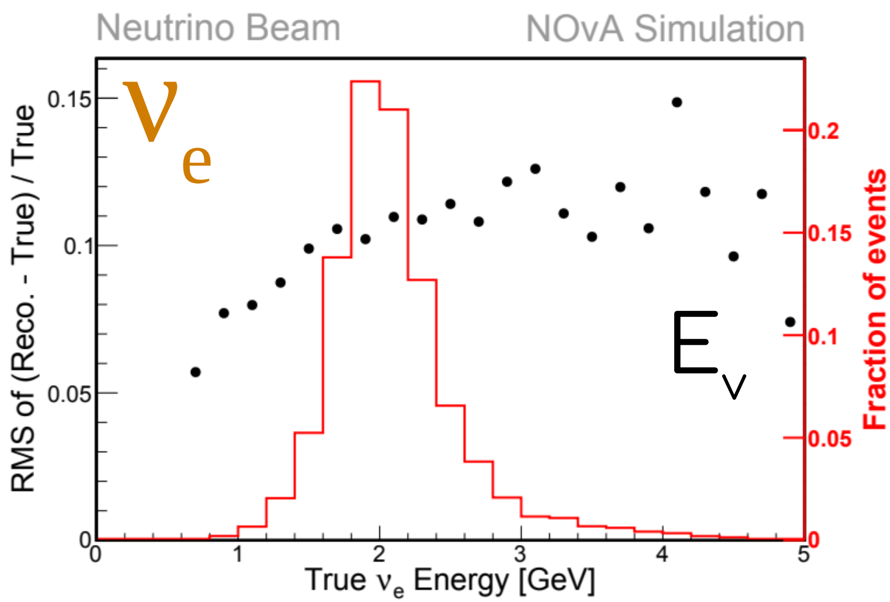




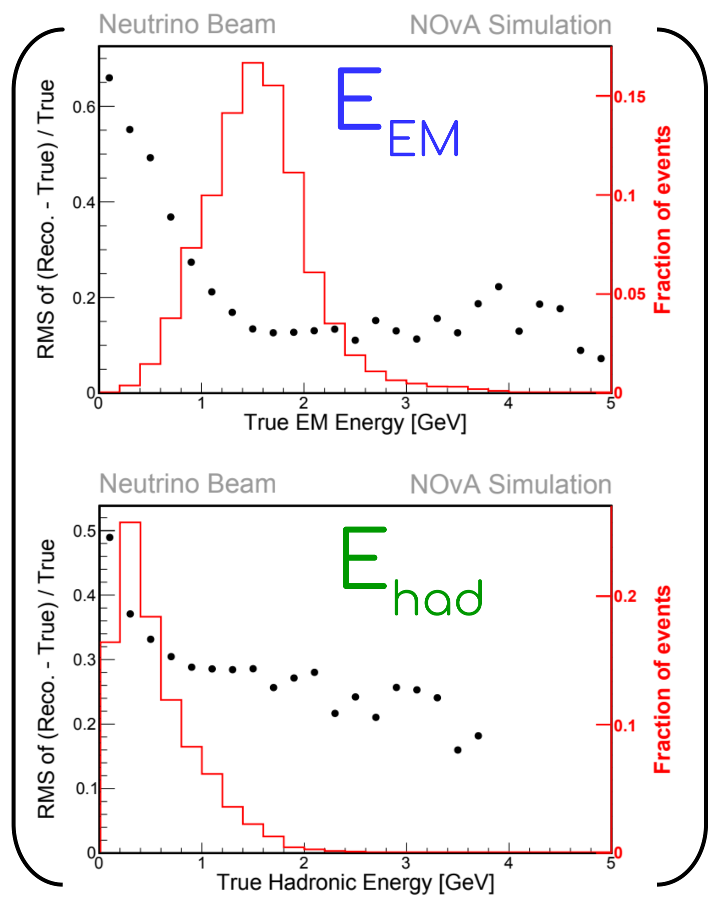
⟨E_ν resolution⟩: ~9%

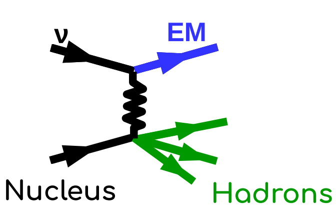
Goal #2: Measuring E_ν (ν_e)

Strategy: divide and conquer



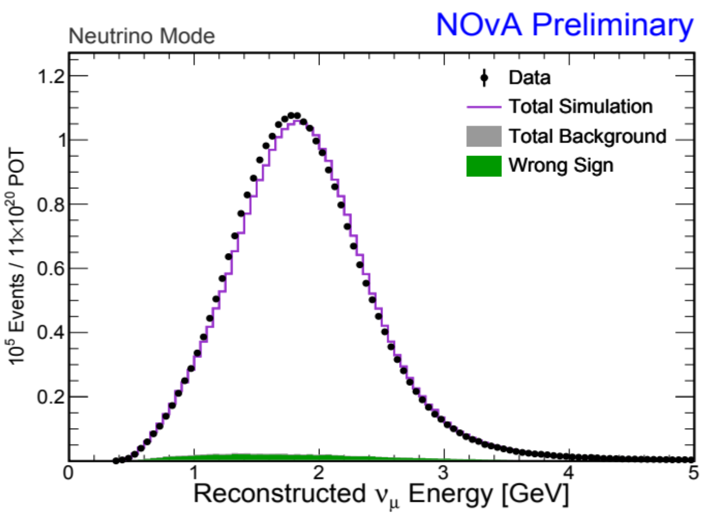
= f





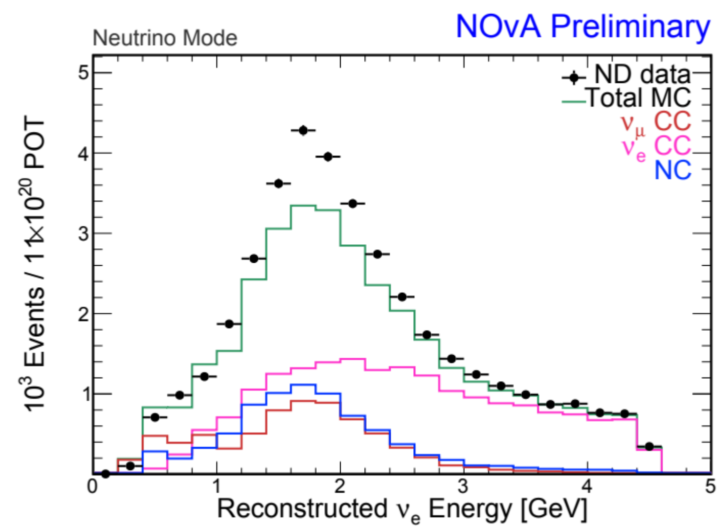
⟨E_ν resolution⟩: ~11%

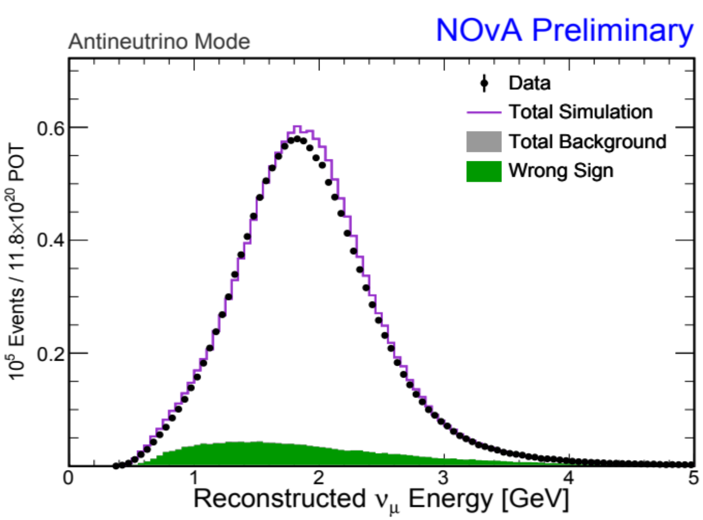
What do we observe?



ν_μ

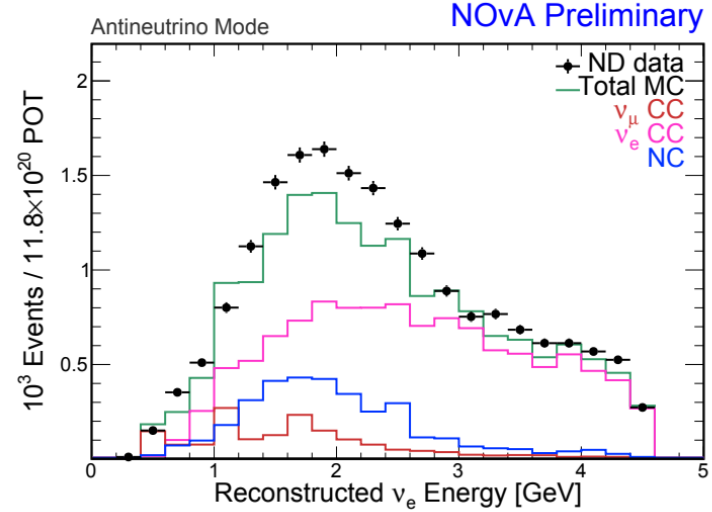
ν_e





$\bar{\nu}_\mu$

$\bar{\nu}_e$

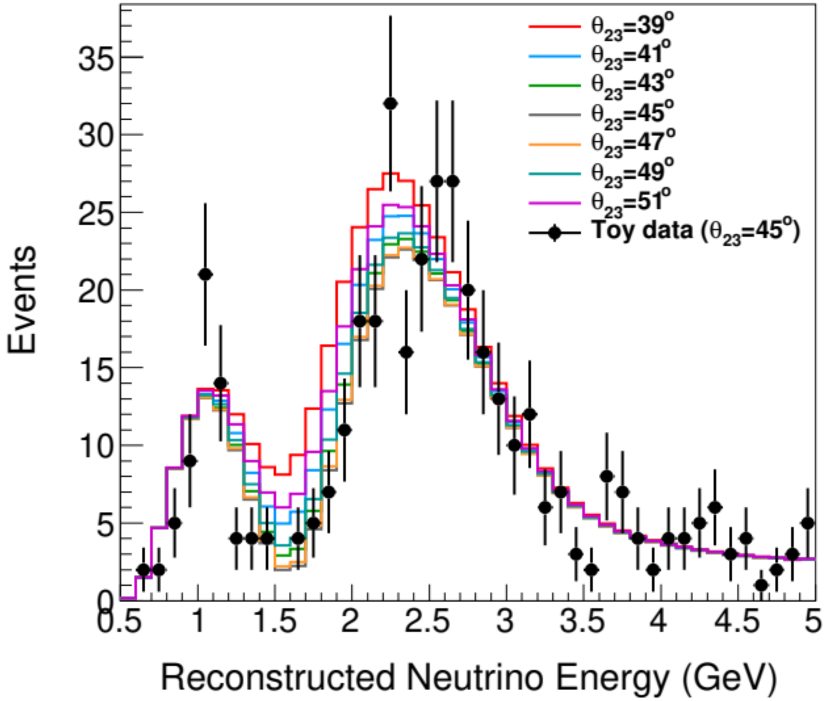


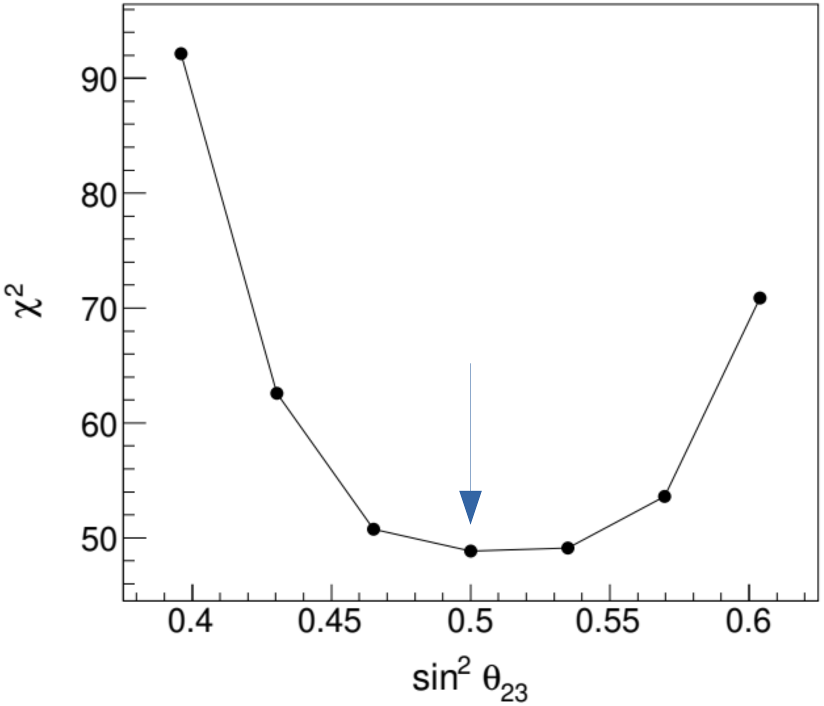
Unoscillated, high-stats ND distributions

Part III: Interpretations

Best fits

The <u>principle</u> of finding the values of the oscillation parameters most compatible with the data is straightforward…



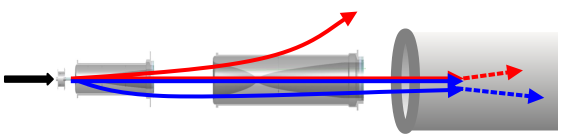


(use a fitter to find the values that minimize the data-prediction difference)

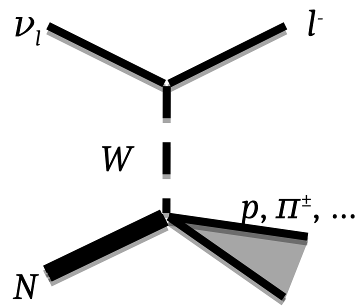
Making predictions

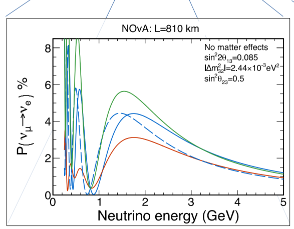
... but there's a lot hiding under the hood of the predicted specta

Neutrino flux



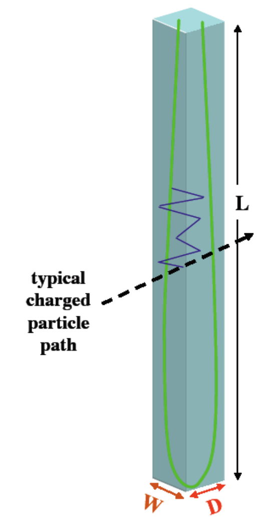
Neutrino reactions
on detector materials





Oscillations

Detector response
to charged particles and light propagation



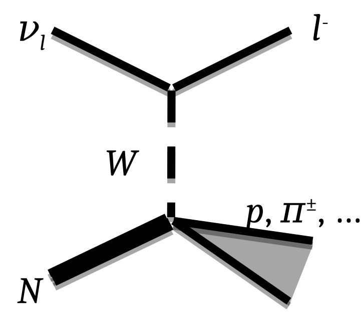
→ there are nontrivial uncertainties in each of these stages, which can affect oscillation interpretation

Making predictions

... but there's a lot hiding under the hood of the predicted specta

Neutrino flux

Neutrino reactions
on detector materials



Detector response
to charged particles and light propagation

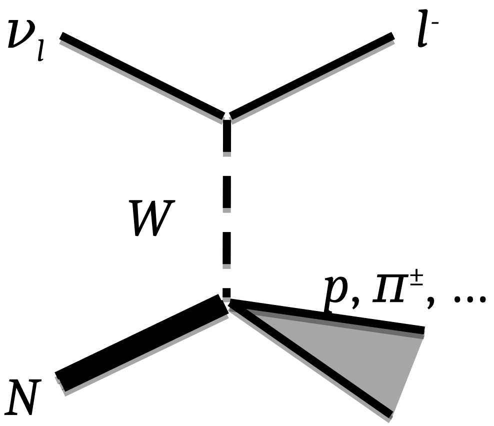
Oscilla

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

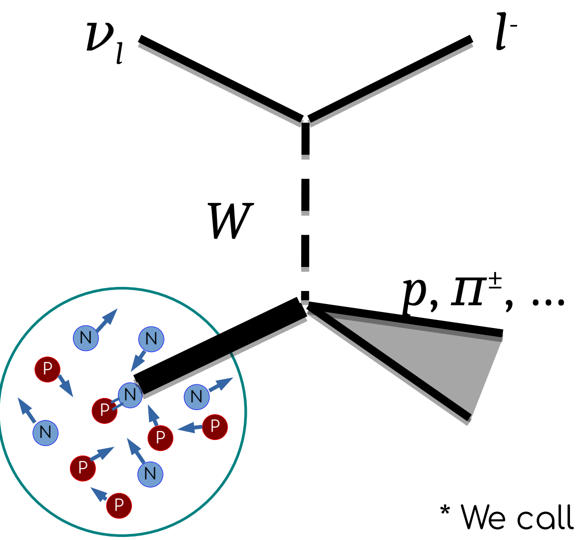
GENIE 3.0.6

ntrivial uncertainties
of these stages

Neutrino interaction modeling



vs

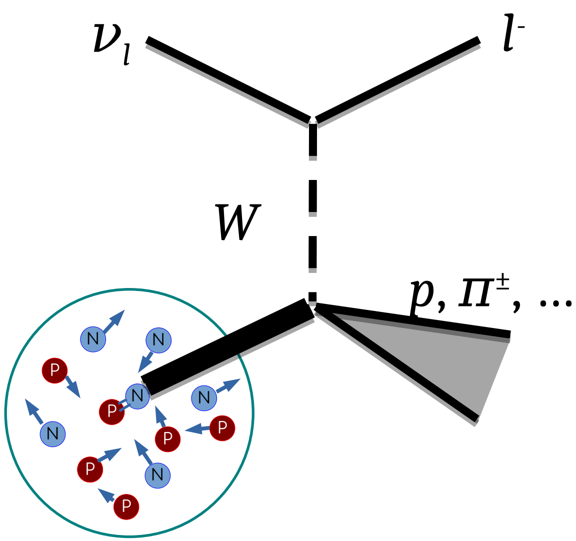


- For 2020: upgrade to GENIE 3.0.6
  - Introduces choices of prepackaged collections of models, often with tuning to data
  - We choose a "theory-driven" set of models w/ GENIE collaboration's tune to free-nucleon data*
- Challenges always arise treating <u>nuclear</u> dynamics of neutrino interactions
  - Low-Q^2 suppression of quasielastic scattering relative to free nucleon
  - Multinucleon knockout (2p2h, …)
  - Reinteraction of hadrons after primary scatter (FSI)

→ We apply custom tuning in two places

* We call our "tune" **`N1810j_0211a`.** It is built by starting with `G1810b_0211a` and substituting the Z-expansion QE axial form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.

Neutrino interaction modeling



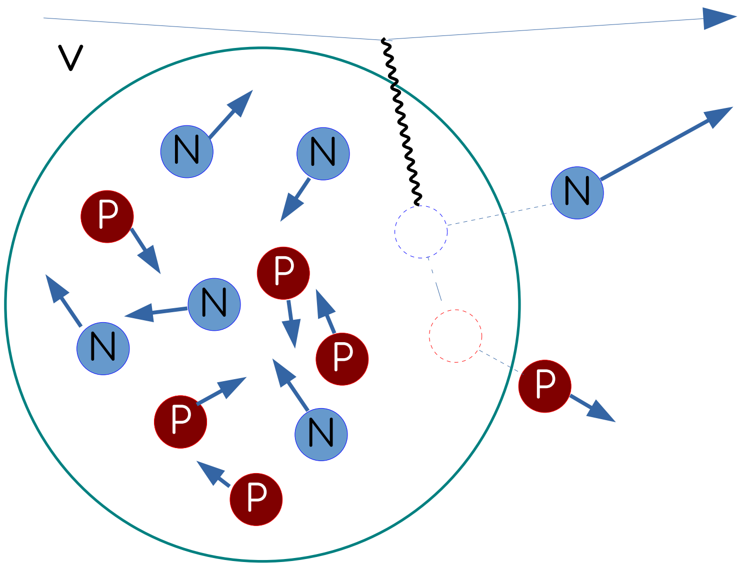
- For 2020: upgrade to GENIE 3.0.6
  - Introduces choices of prepackaged collections of models, often with tuning to data
  - We choose a "theory-driven" set of models w/ GENIE collaboration's tune to free-nucleon data*

QE	Multinucleon	RES	DIS	FSI
València 1p1h w/ Z-expansion axial form factor	València MEC	Berger-Sehgal	Bodek-Yang	hN semi-classical cascade

→ We apply custom tuning in two places

* We call our model collection **N1810j_0211a.** It is built by starting with GENIE's `G1810b_0211a` and substituting the Z-expansion QE axial form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.

Multinucleon knockout

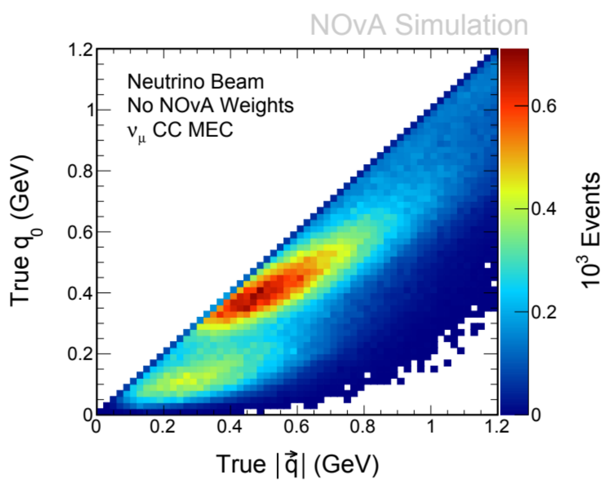


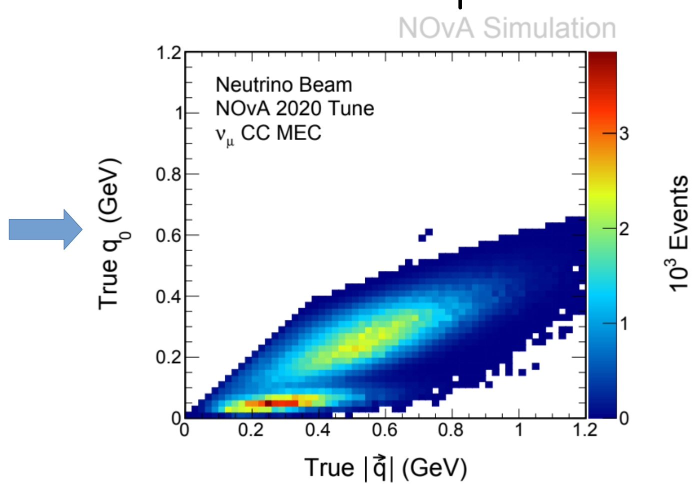
"2p2h"

Knock out two nucleons with an elastic-like interaction.

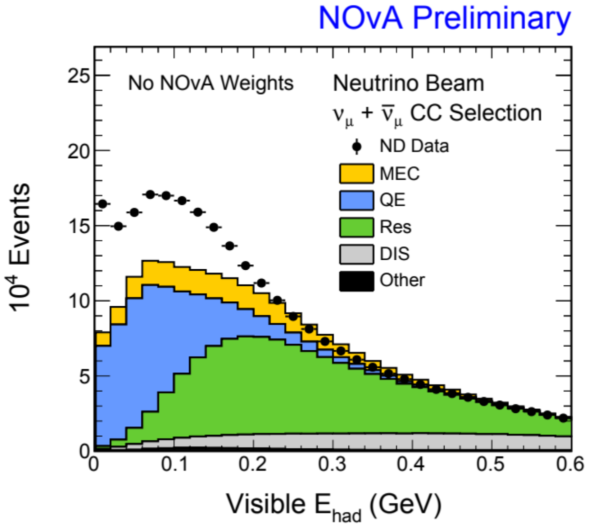
Lots of recent progress on theory, but no model in GENIE describes extant data well

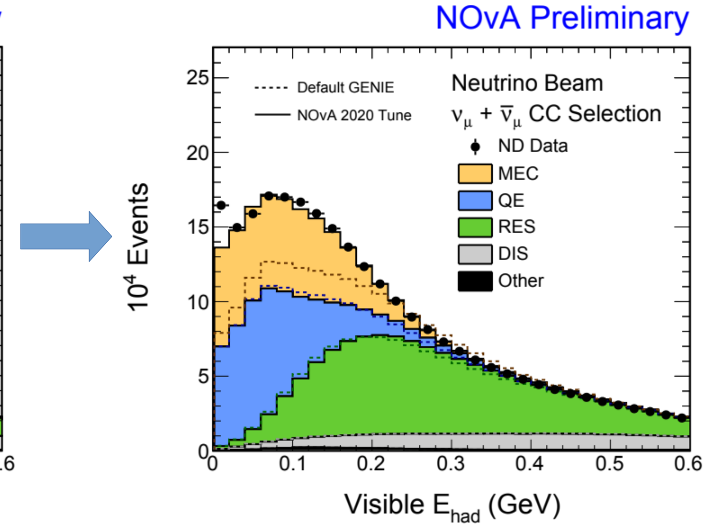
Employ **fits to NOvA ND data** in the meantime





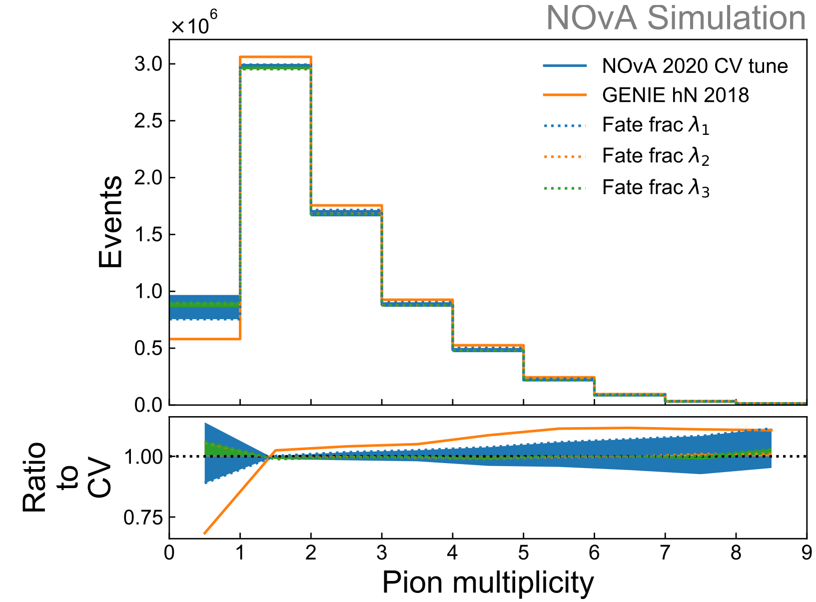
Central value prediction + uncertainties based on fits to ND data

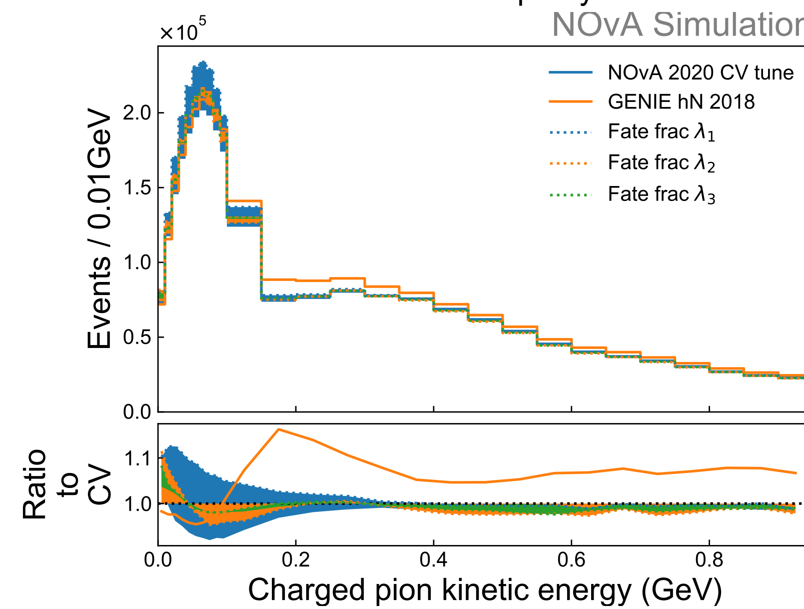




Final-state interactions

- FSI model choice: "hN 2018"
  - More rigorous theoretical foundation than older "hA" effective model
  - Challenge: not directly reweightable
- Some tuning required…
  - Use BDT reweighting technique adapted from DUNE (see overflow)
  - Adjust central value to agree better with pion scattering data at low energies where most relevant for NOvA
  - Construct uncertainty bands in same spirit as work from T2K [Phys. Rev. D99, 052007]
- 5-10% unc. on pion kinematics
  - → Ultimately subdominant for calorimetric E_ν reco. used in NOvA





Making predictions

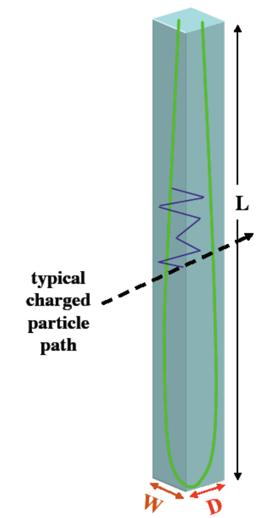
... but there's a lot hiding under the hood of the predicted specta

Neutrino flux

Neutrino reactions
on detector materials

Oscillations

Detector response
to charged particles and light propagation



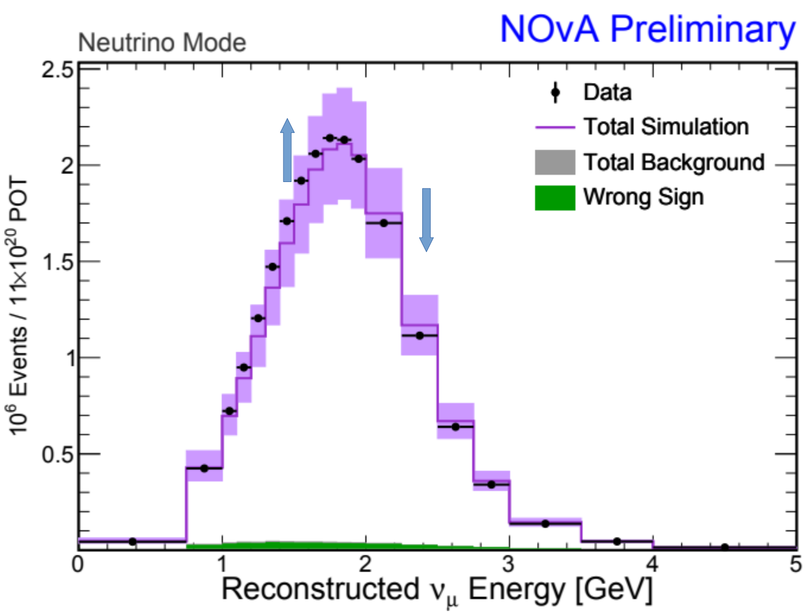
→ there are nontrivial uncertainties in each of these stages

Detector response

- Detector response is largest syst
  - Data-MC discrepancies in proton candidate response at 5% level
- NOvA Test Beam program underway
  - Should allow direct measurement of hadron responses
  - Expected to constrain detector energy scale uncertainty

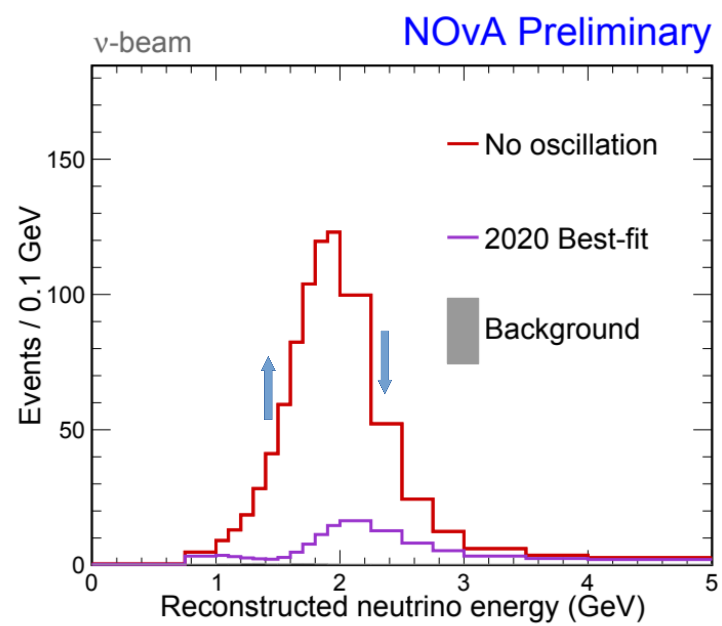
Limiting uncertainties

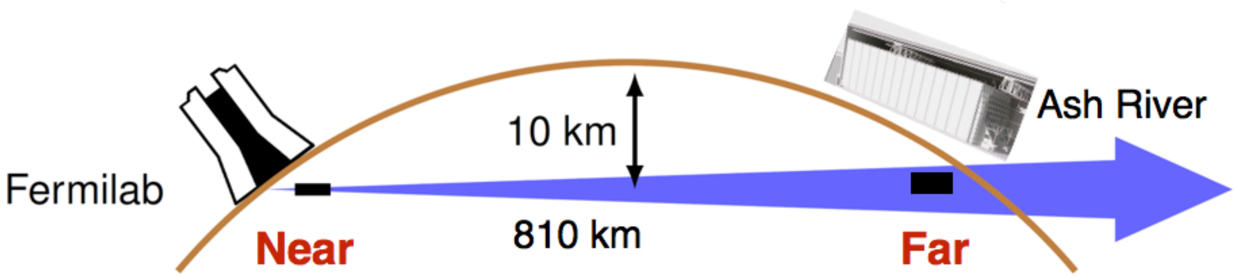
Extrapolating ND → FD mitigates both "known" and "unknown" effects



"Extrapolation"

(account for beam divergence, detector size difference, etc. w/ MC)





Limiting uncertainties

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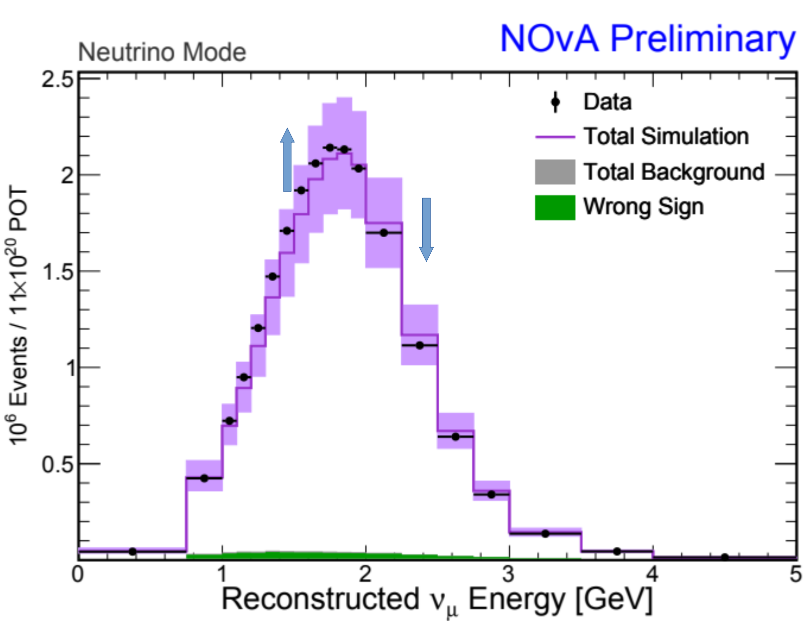

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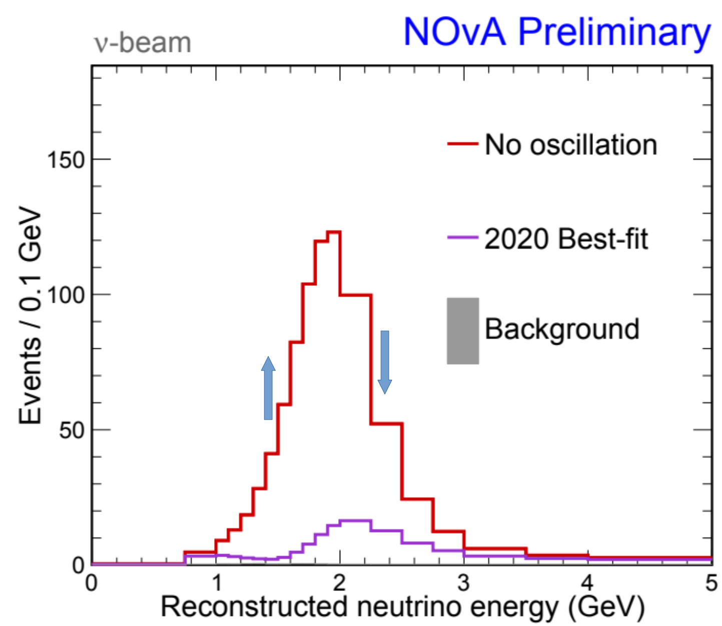
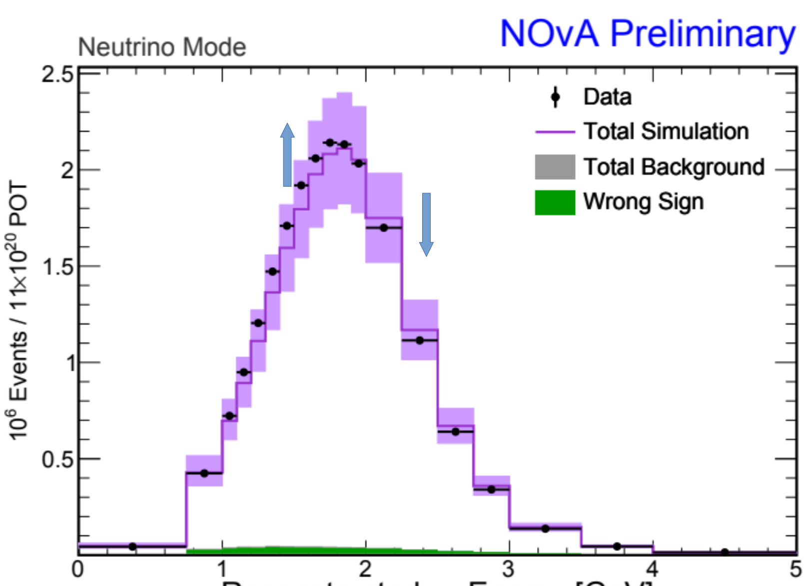


This technique applied both to
variations from <u>systematic uncertainties</u> ("known unknowns")
and
<u>central value</u> ("unknown unknowns")

Limiting uncertainties

Extrapolating ND → FD mitigates both "known" and "unknown" effects



"Extrapolation"

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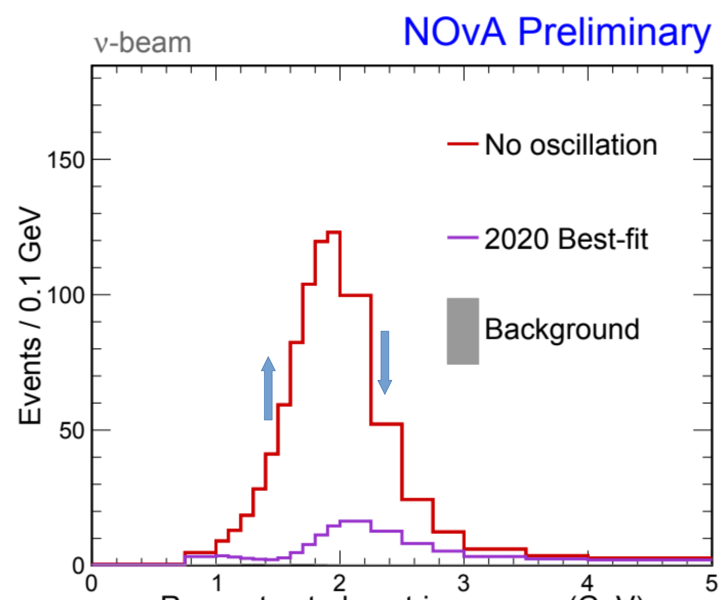
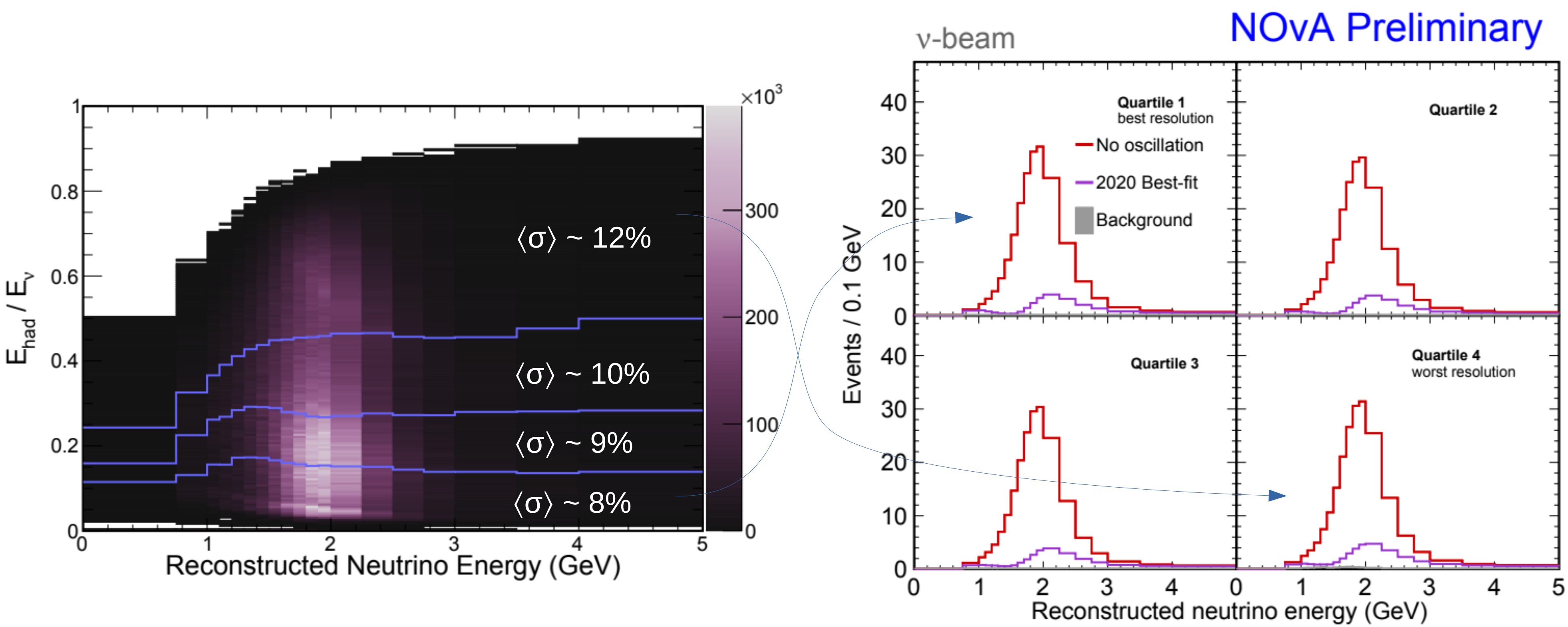


But… the energy resolution differs between detectors after oscillations

(Different shape → smearing from true → reco different)

Limiting uncertainties

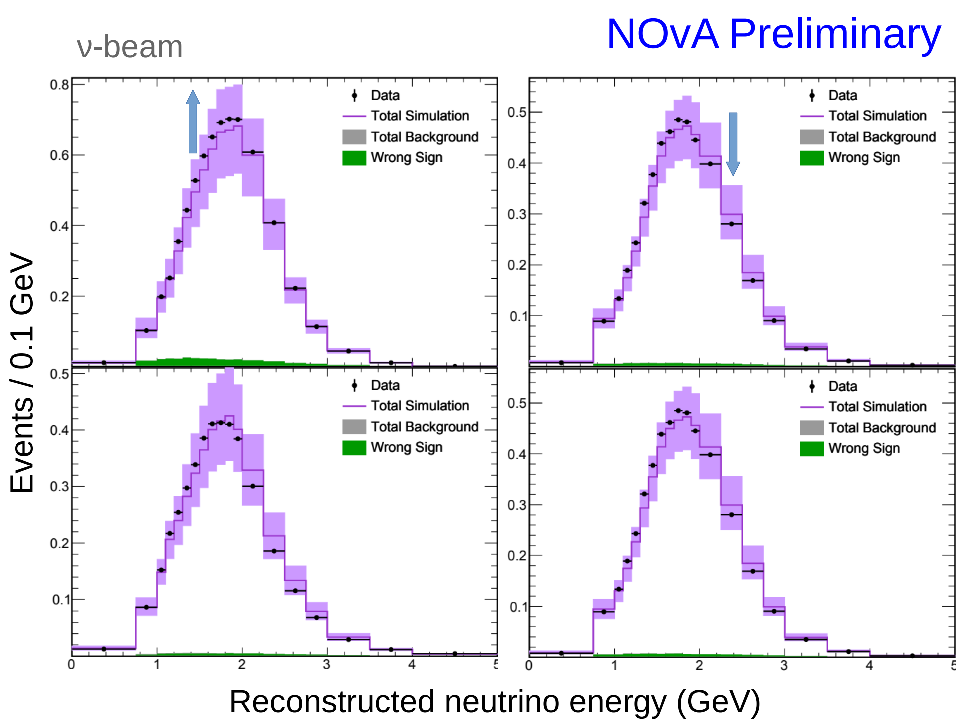
Extrapolating ND → FD mitigates both "known" and "unknown" effects

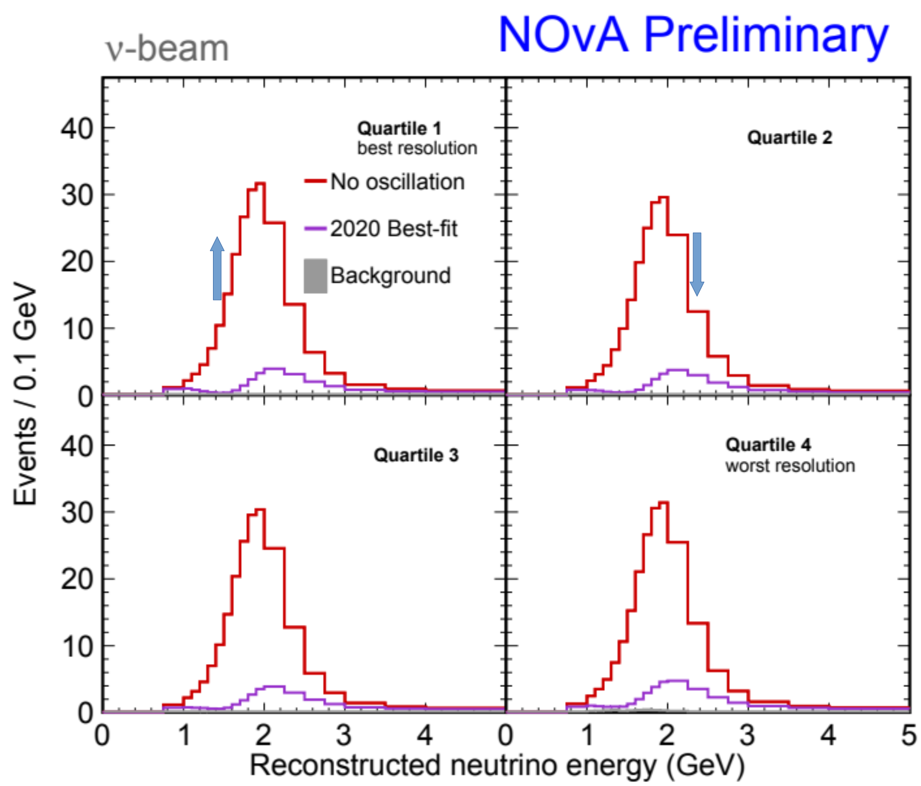


Extrapolating in quartiles of E_{had}/E_{ν}
matches the resolutions between detectors

Limiting uncertainties

Extrapolating ND → FD mitigates both “known” and “unknown” effects





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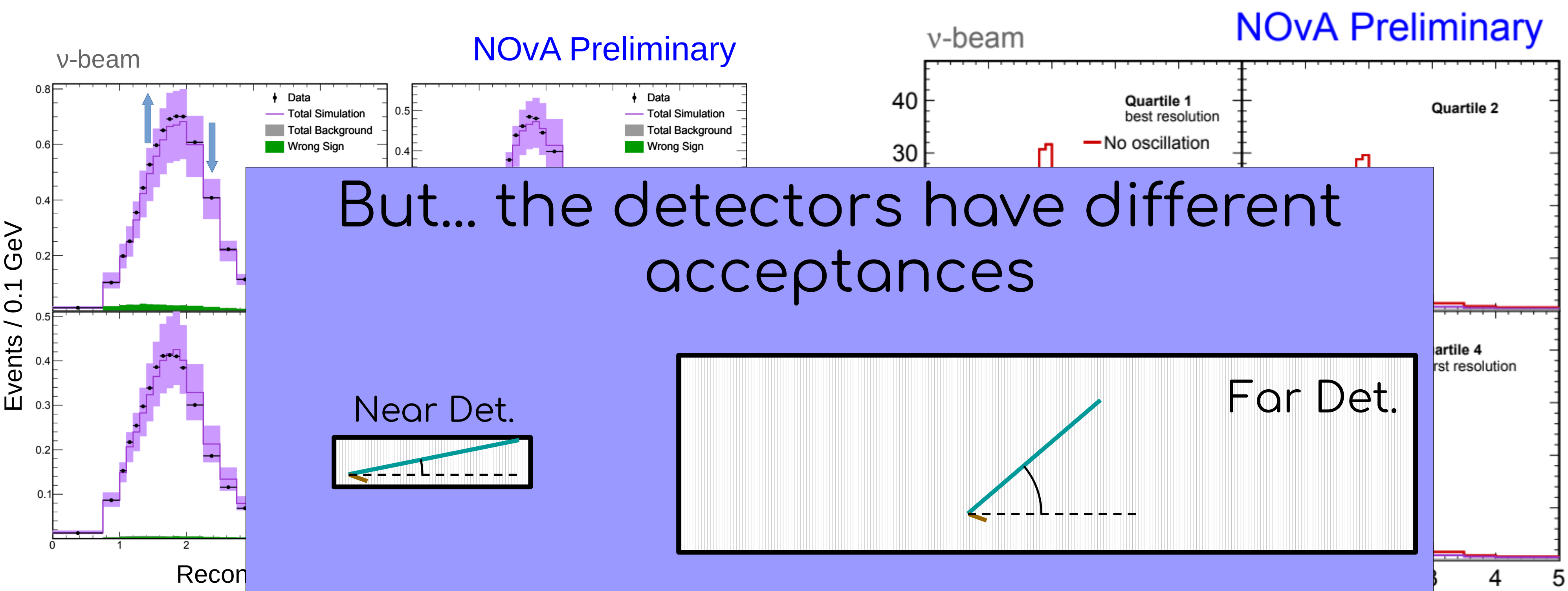
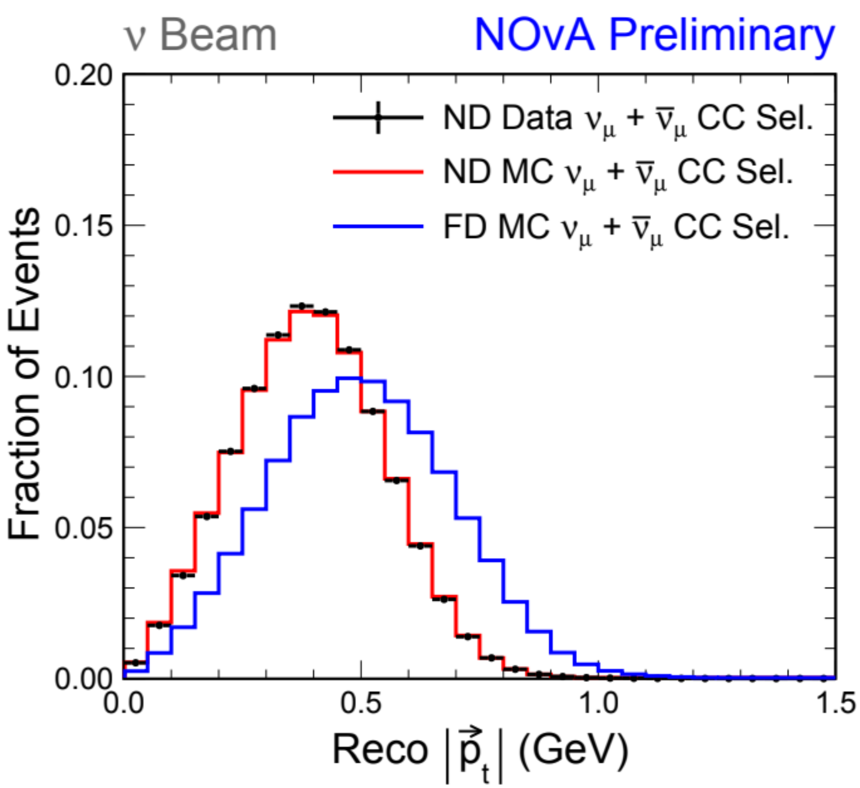


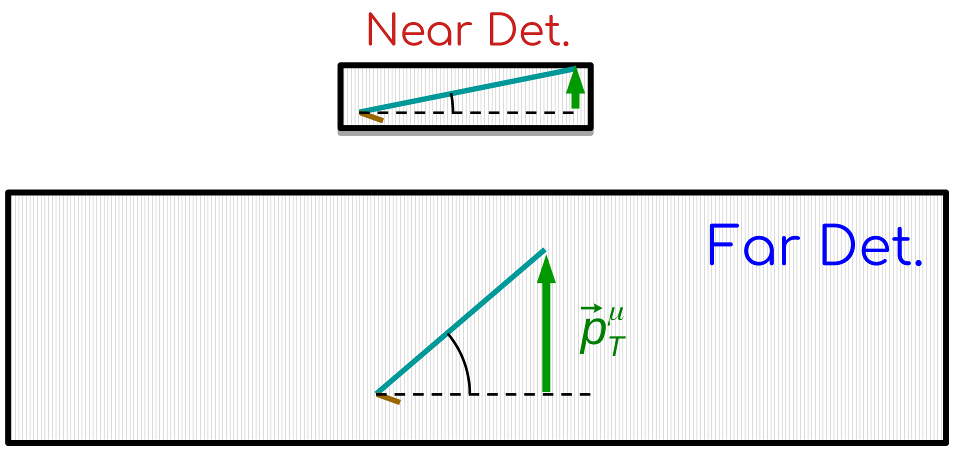
But… the detectors have different acceptances

(ND is much smaller)

Limiting uncertainties

Extrapolating ND → FD mitigates both "known" and "unknown" effects

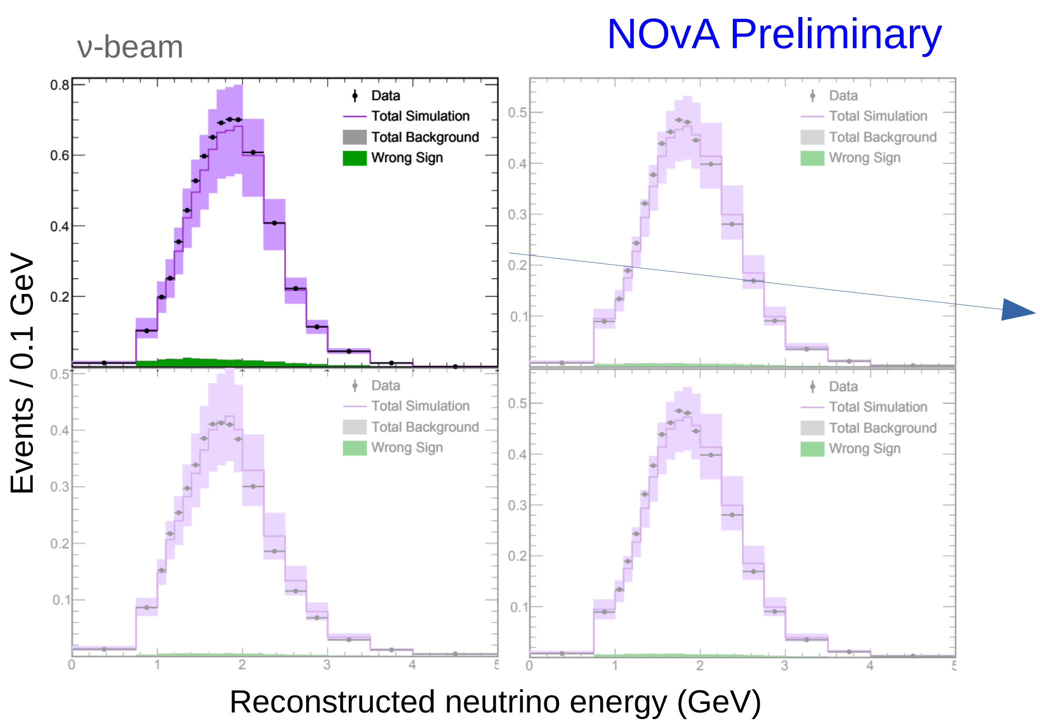


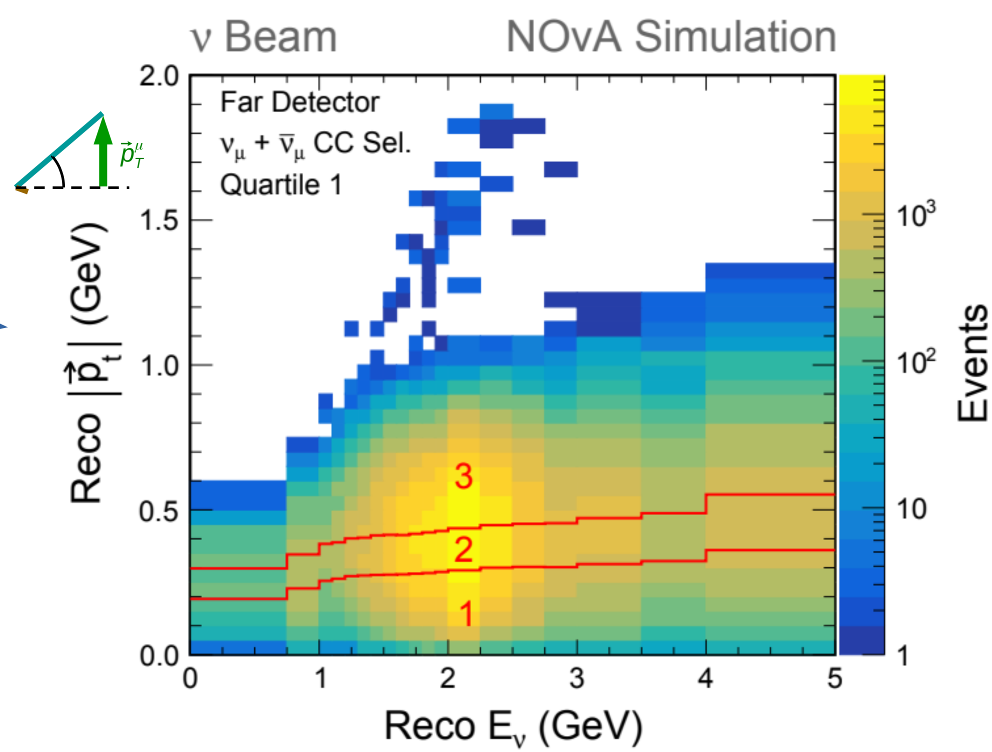


The acceptance difference is strongly correlated with the lepton transverse momentum, $|p_T|$

Limiting uncertainties

Extrapolating ND → FD mitigates both "known" and "unknown" effects

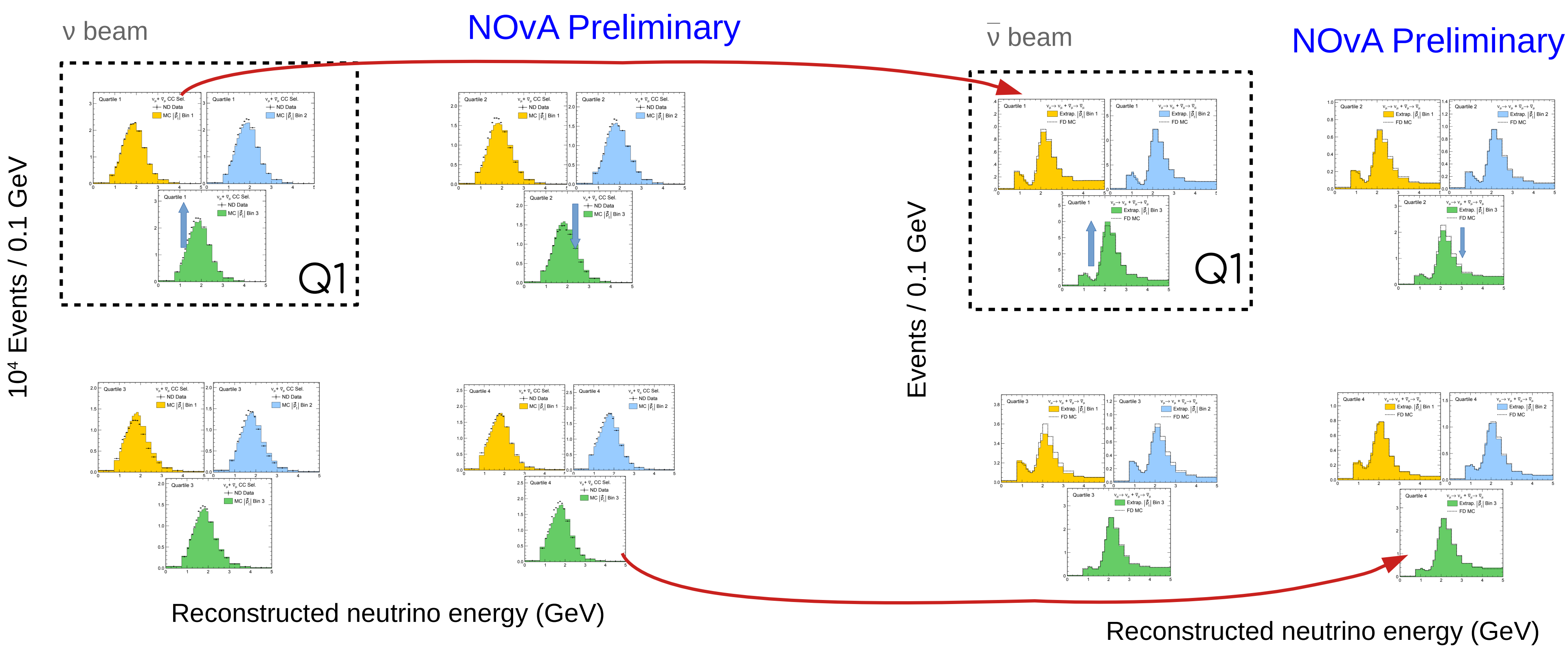




New in 2020: extrapolating in sub-ranges of lepton $|p_T|$ enables matching the acceptance between detectors

Limiting uncertainties

Extrapolating ND → FD mitigates both “known” and “unknown” effects



New in 2020: extrapolating in sub-ranges of lepton $|p_T|$ enables matching the acceptance between detectors

Applications of extrapolation

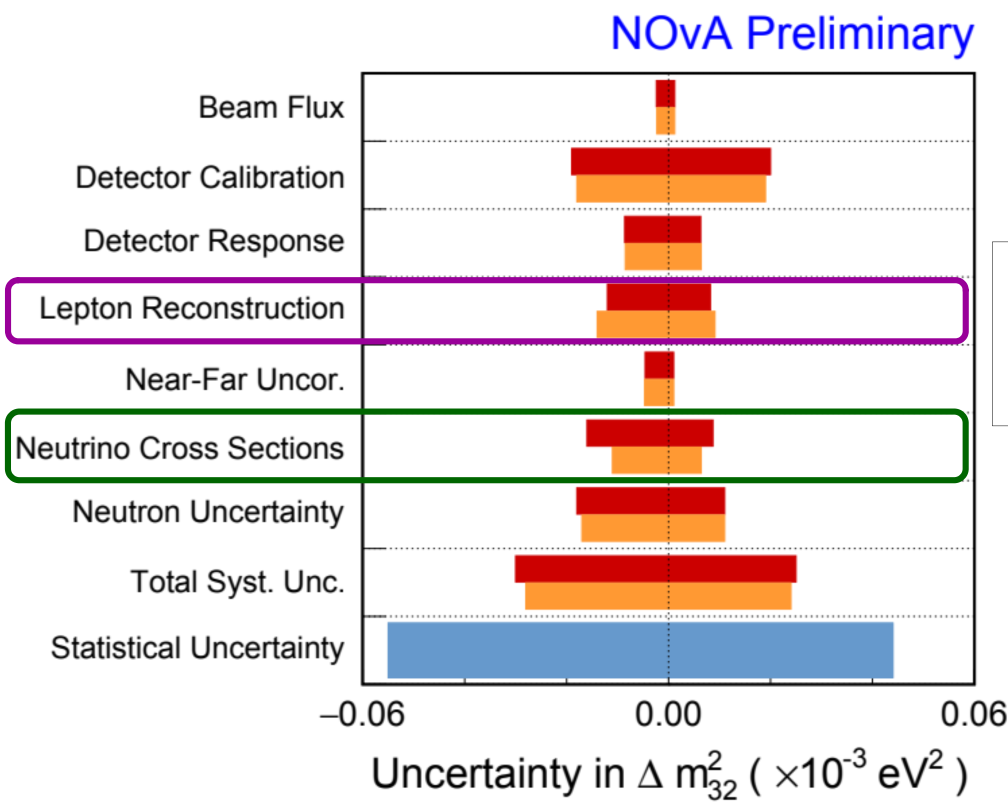
ND sample	Extrapolation method	FD predictions constrained
ν_μ candidates (contained)	$E_\nu \otimes (E_{had}/E_\nu) \otimes \lvert p_T \rvert$ →	ν_μ signal
ν_μ candidates (contained)	$E_\nu \otimes \lvert p_T \rvert$ →	ν_e signal (appeared)

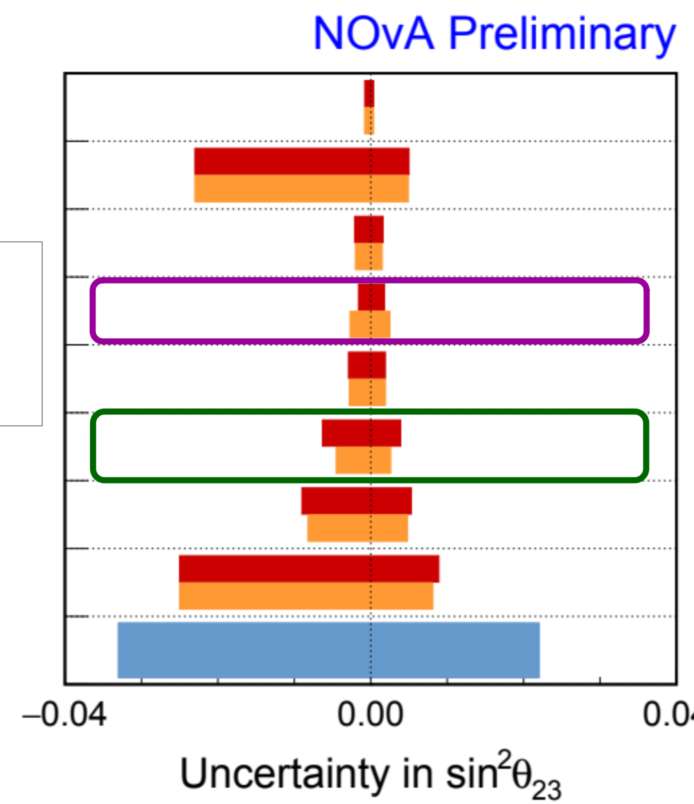
↑ previous slides

↓ unchanged from previous analysis (see overflow slides)

ND sample	Extrapolation method	FD predictions constrained
ν_μ candidates (contained & uncontained)	Parent hadron $(p_t, p_z) \otimes E_\nu$ →	ν_e background: beam ν_e
ν_e candidates	E_ν →	ν_e backgrounds: NC, ν_μ CC

Limiting uncertainties

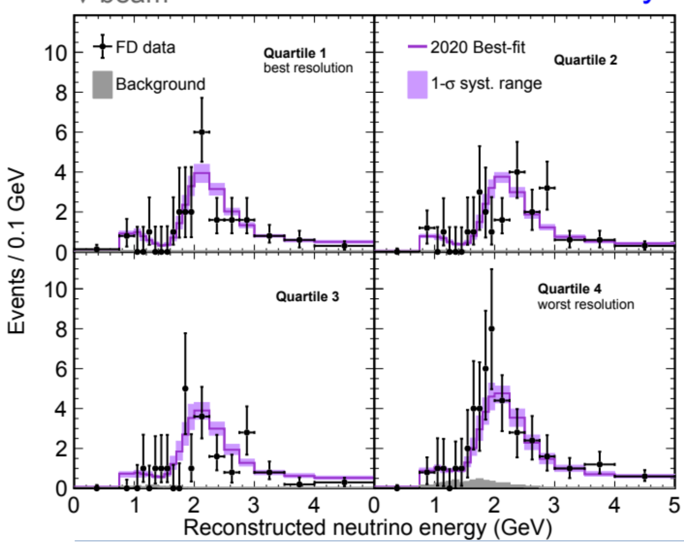




- New $|p_T|$ extrapolation improves analysis robustness
  - 30% reduction in cross section uncertainties vs. previous analyses
  - Slight increase from lepton reconstruction syst. (but well understood)
  - Overall decrease of 5-10%
- Dominated by detector energy scale uncertainties

Part IV: Inferences

The data to be interpreted

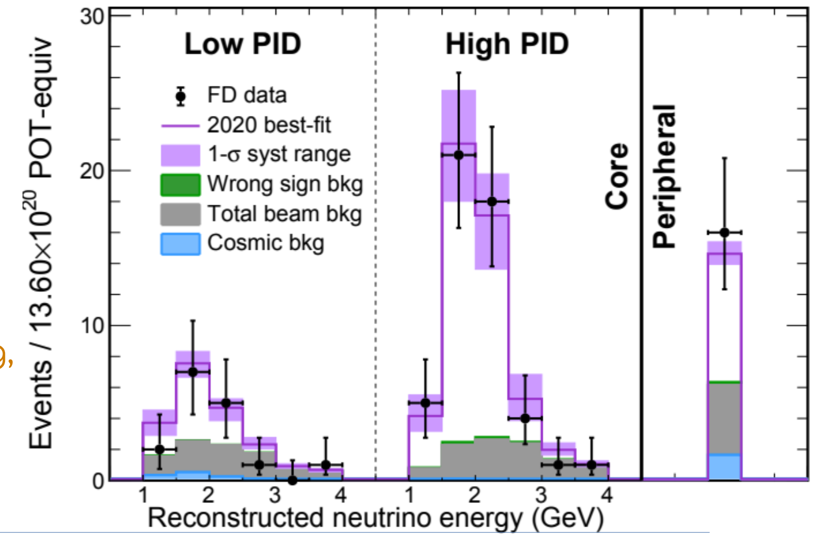


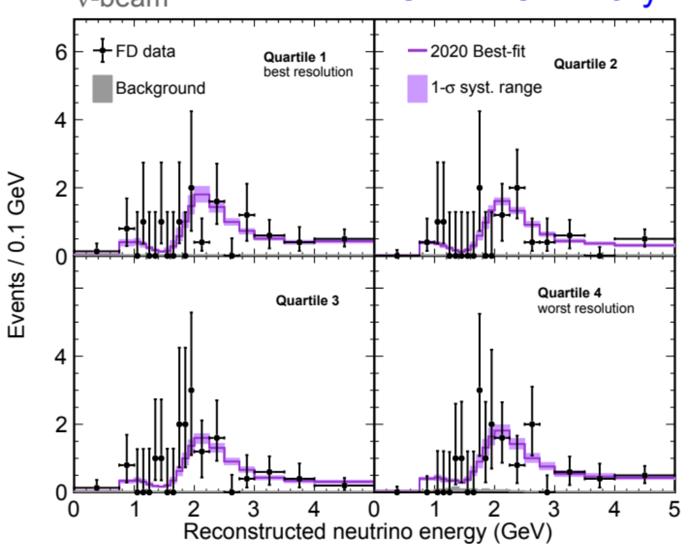
ν_μ

211 events
(8.2 bkgd)

ν_e

82 events
(1.0 $\bar{\nu}_e$,
22.7 beam bkdg,
3.1 cosmic)





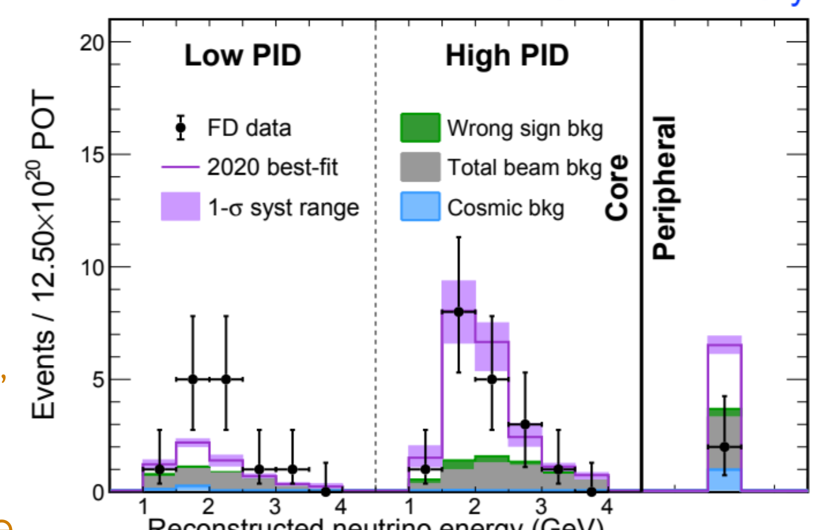
$\bar{\nu}_\mu$

105 events
(2.1 bkgd)

$\bar{\nu}_e$

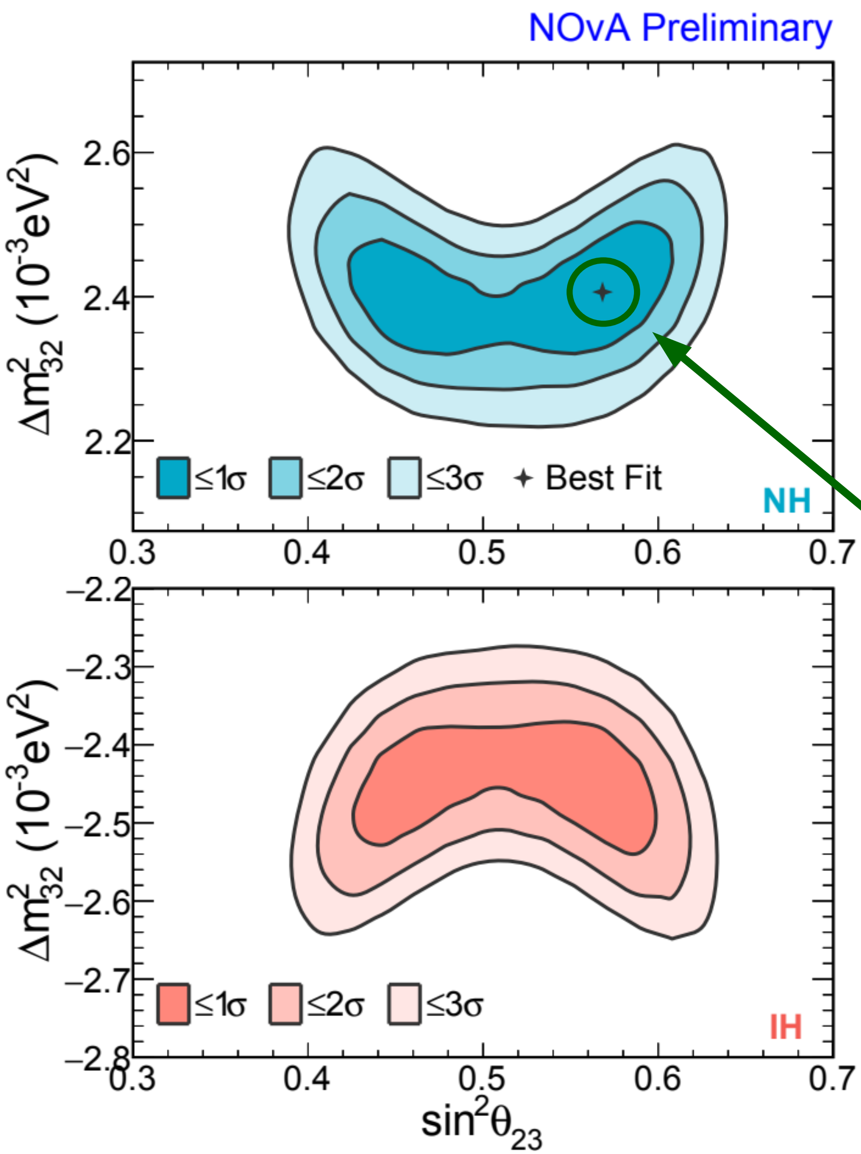
33 events
(2.3 ν_e,
10.2 beam bkgd,
1.6 cosmic)

>4σ $\bar{\nu}_e$
appearance



3-flavor oscillations describe these data well: ρ=0.705

Oscillation results: (θ_{23}, Δm^2_{32})



Thanks once again to Fermilab, SciDAC collaboration, and NERSC for computing resources & expertise!

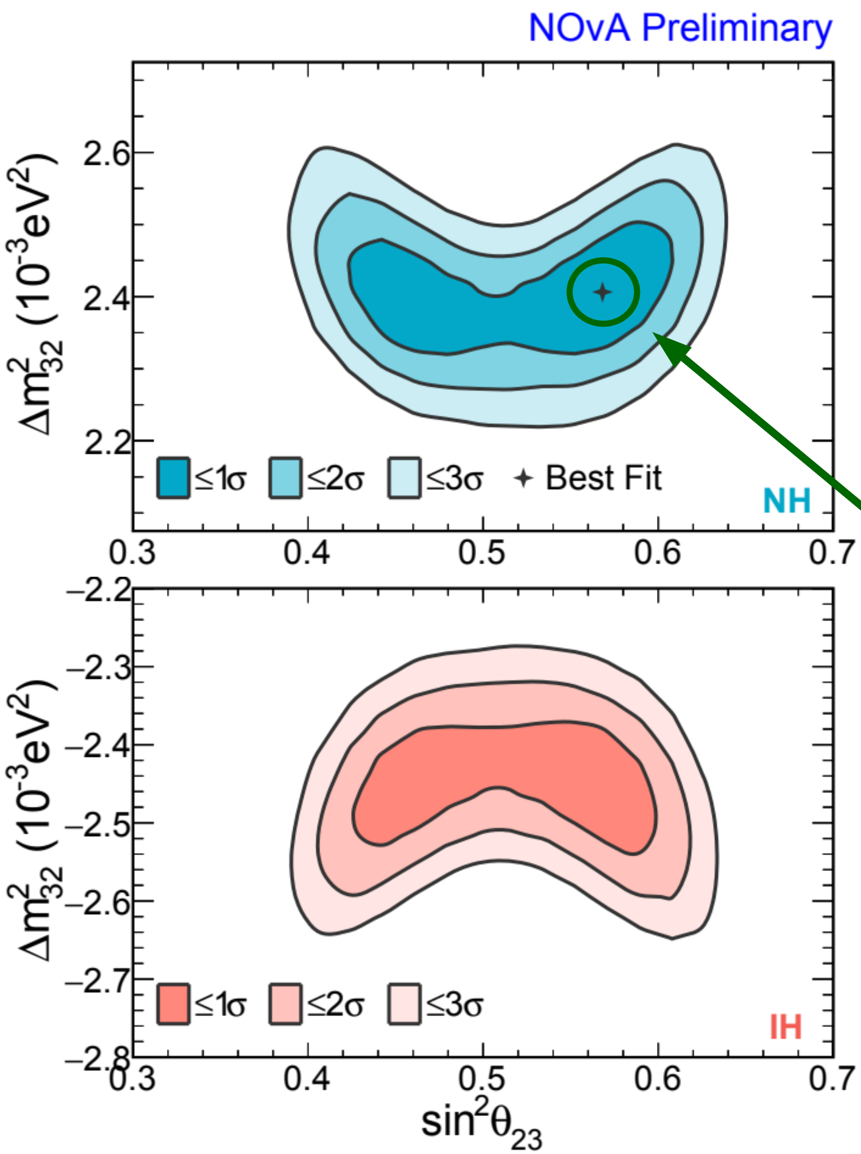
~6%

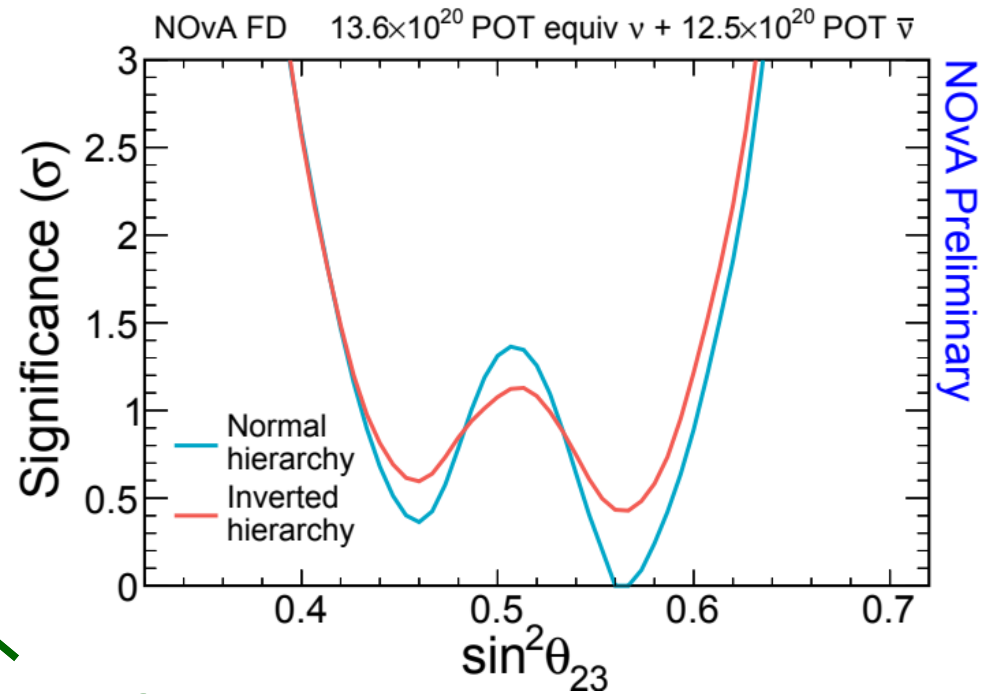
Best fit:

- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
- $\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\,\text{eV}^2/c^4$ (NH)

2.9%

Oscillation results: (θ_{23}, Δm^2_{32})





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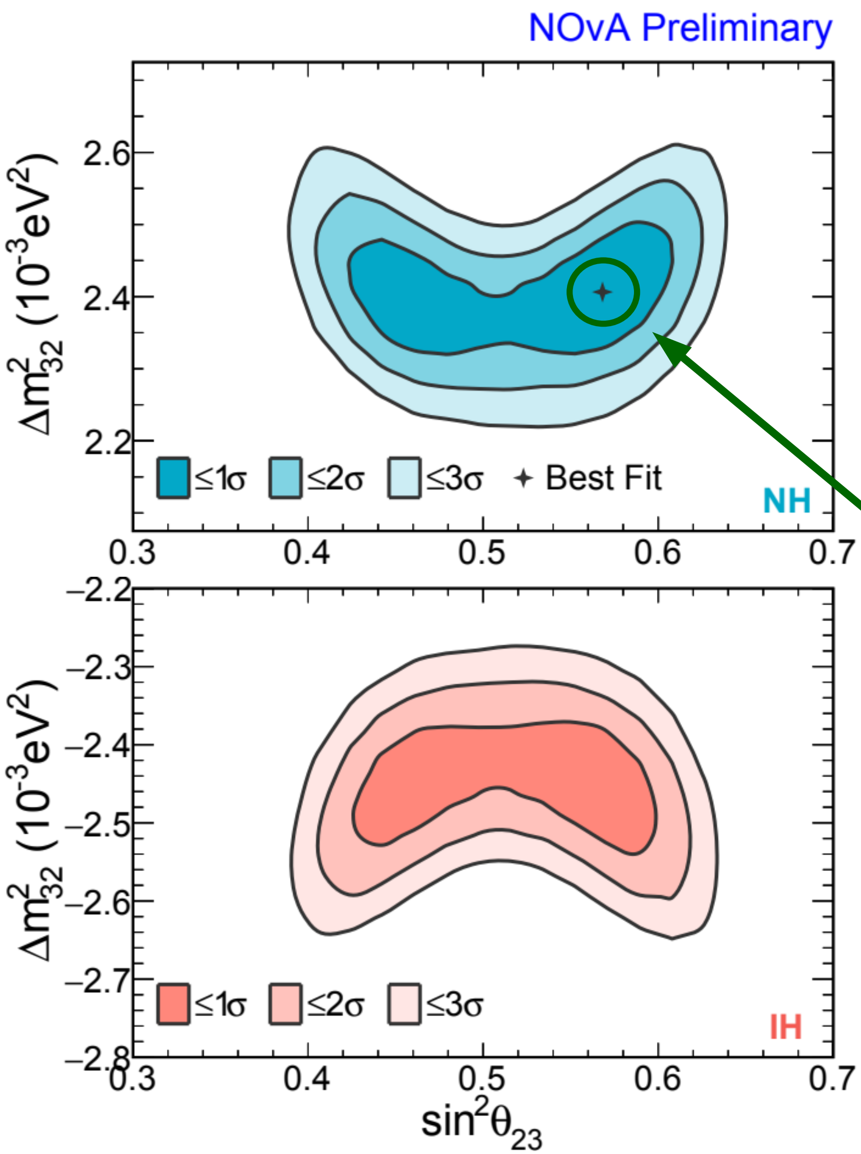
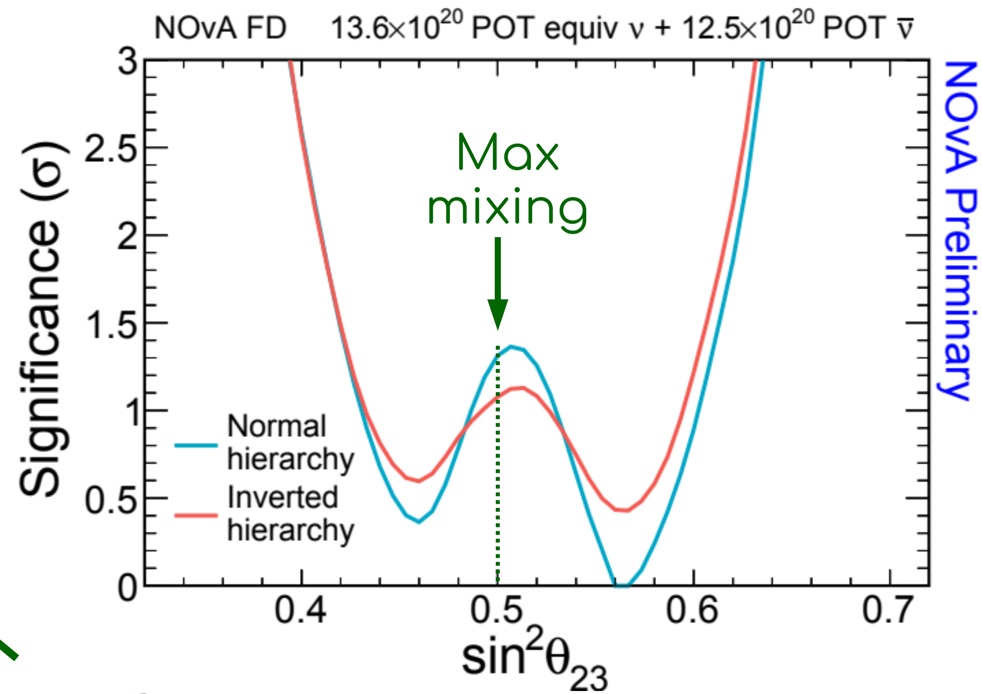
$\sin^2\theta_{23} < 0.5$ **(lower octant) disfavored at 1.2σ**

[All contours and significances calculated using Feldman-Cousins method thanks to NERSC]

Oscillation results: (θ_{23}, Δm^2_{32})





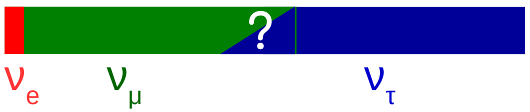
Best fit:

- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
- $\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2/c^4$ (NH)

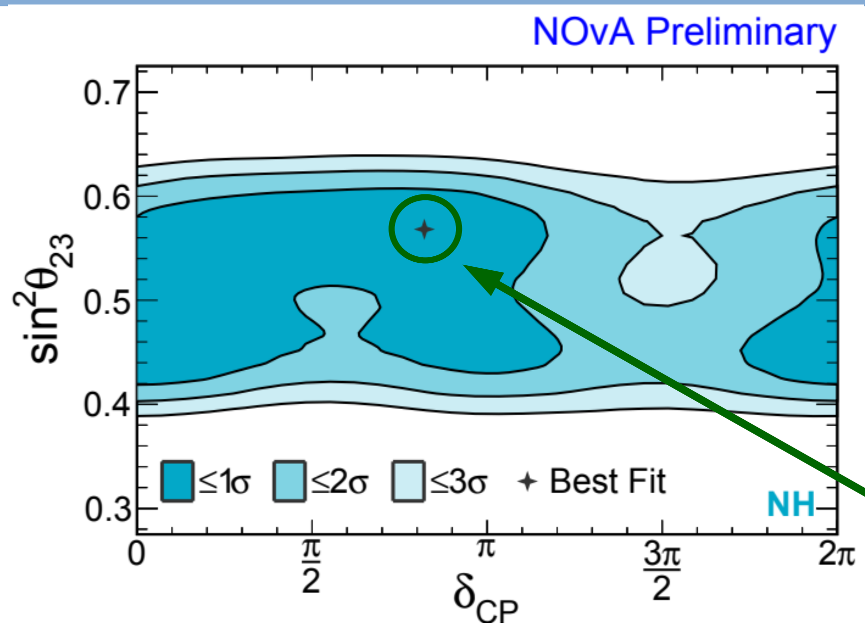
$\sin^2\theta_{23} < 0.5$ **(lower octant) disfavored at 1.2σ**

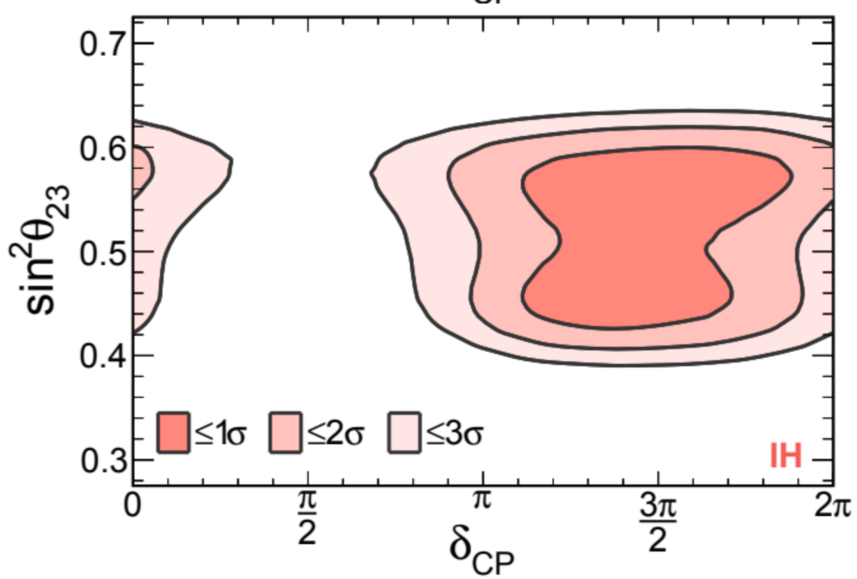
$\sin^2\theta_{23} = 0.5$ disfavored at 1.1σ

$\nu_3 =$



Oscillation results: (δ_{CP}, θ_{23})





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- $\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\, eV^2/c^4$ (NH
- $\delta_{CP} = 0.82\,\pi$

[All contours and significances calculated using Feldman-Cousins method thanks to NERSC]

[note: $\sin^2\theta_{13}$ = 0.085±0.005 (from PDG avg. of reactor data)]

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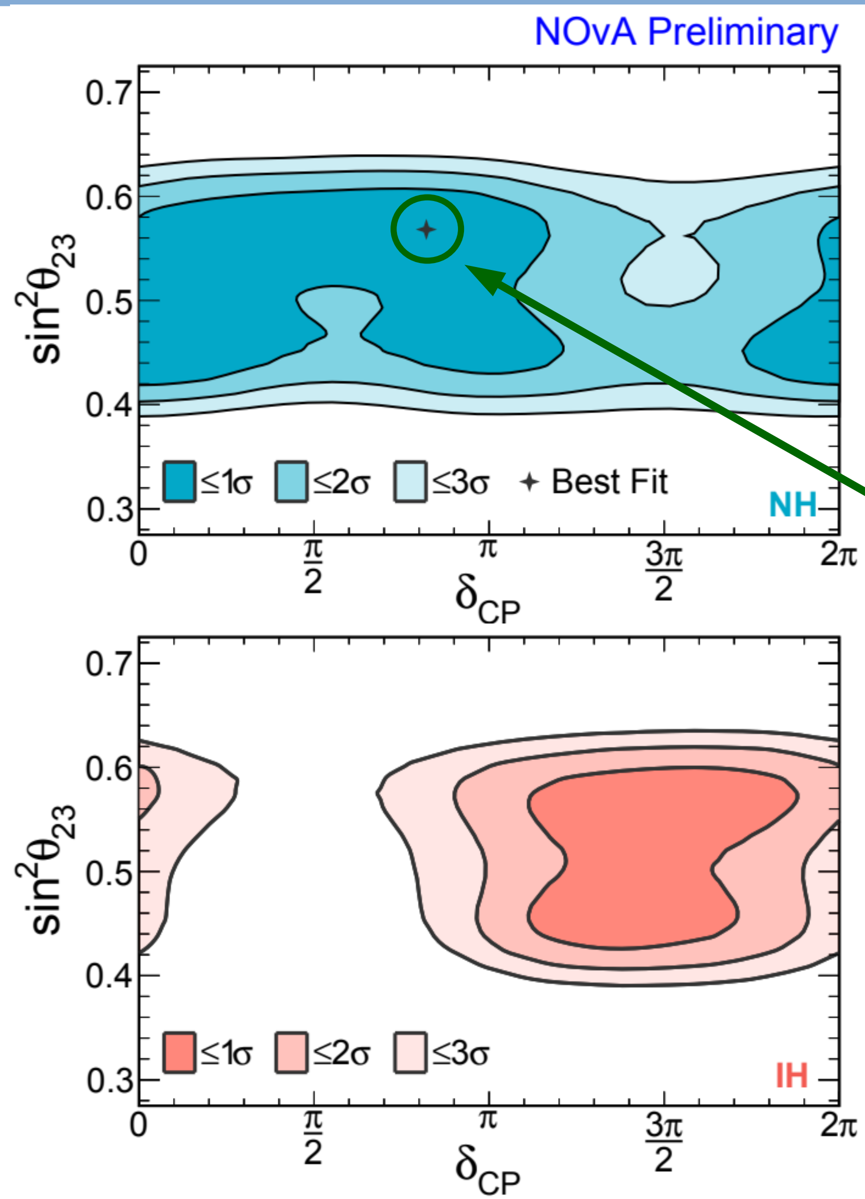

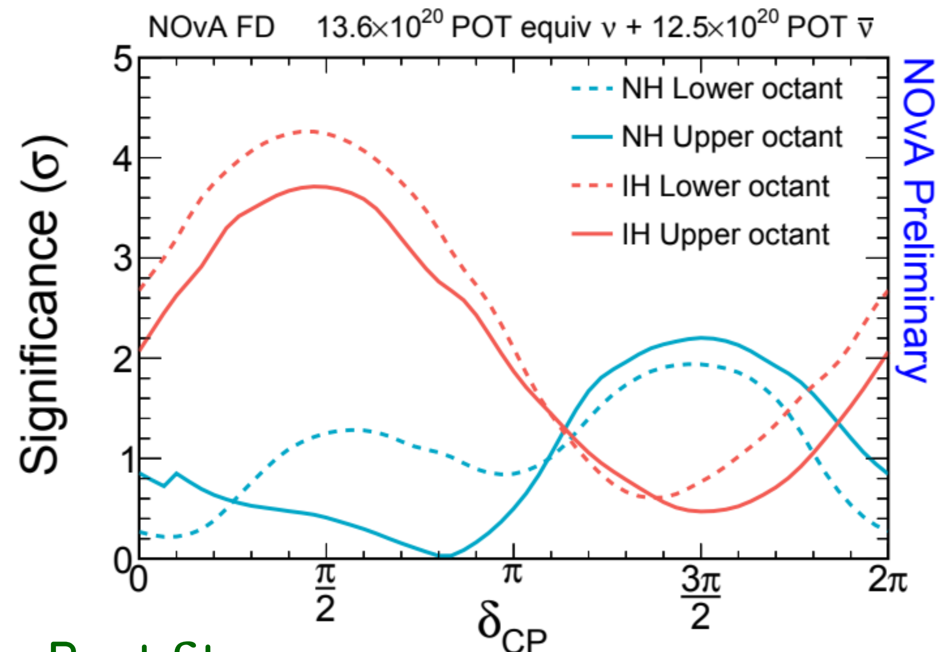

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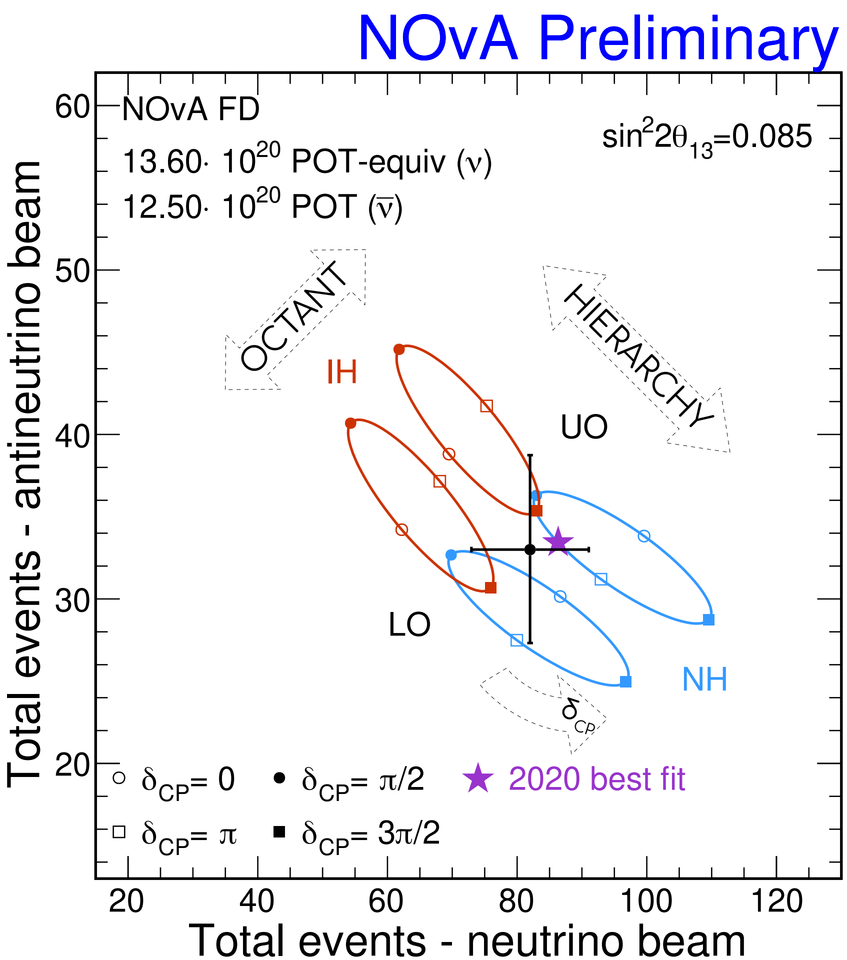
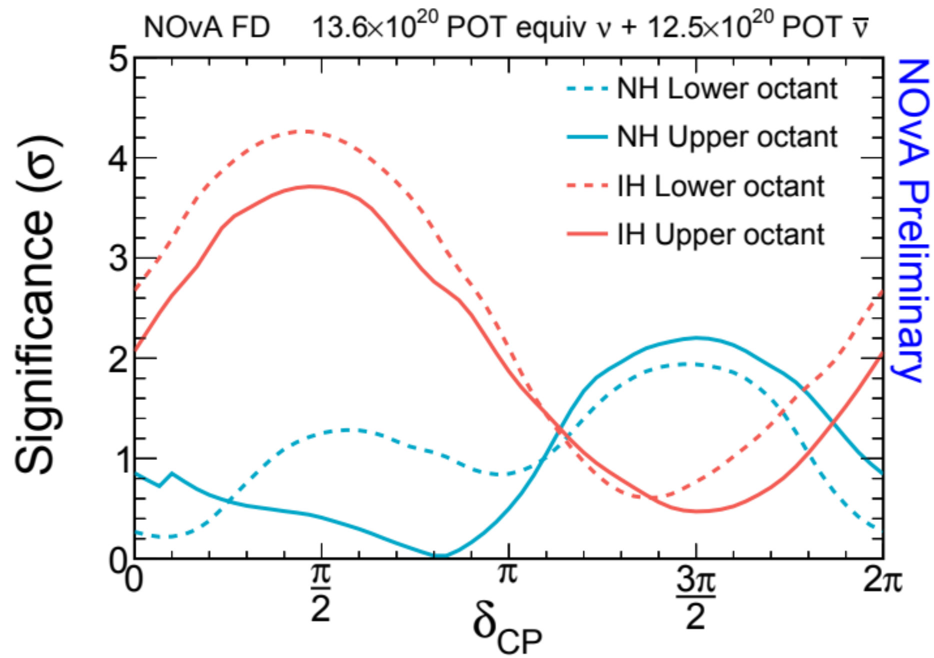
"No strong asymmetry"





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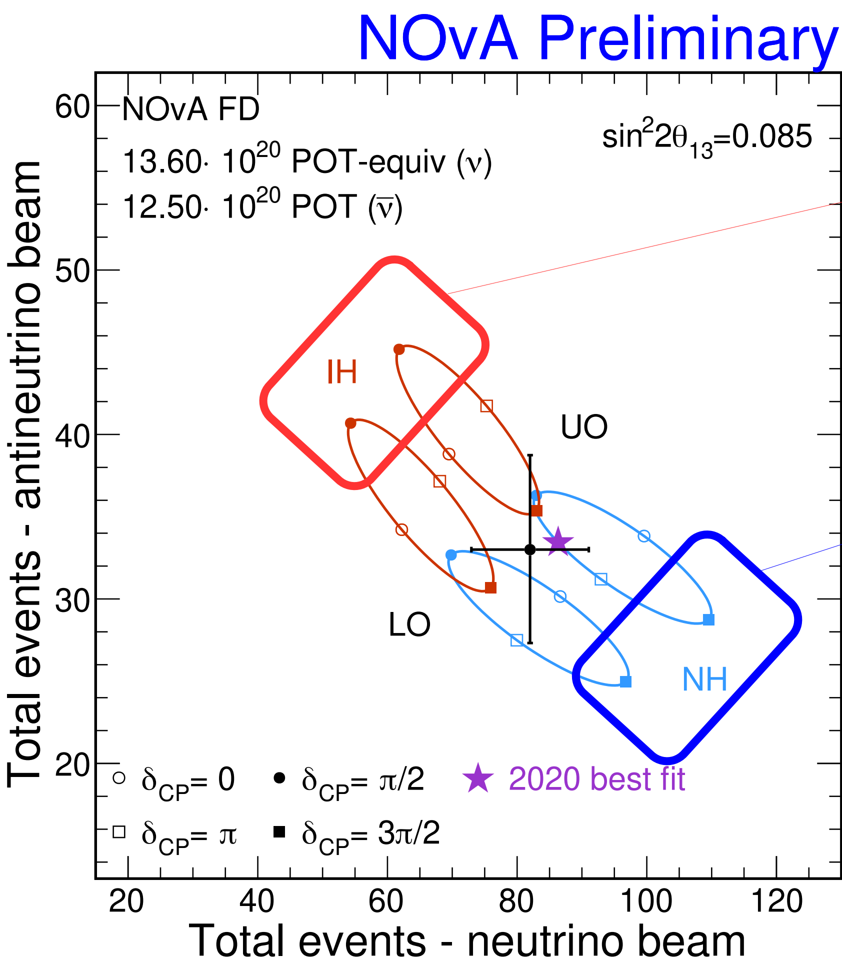

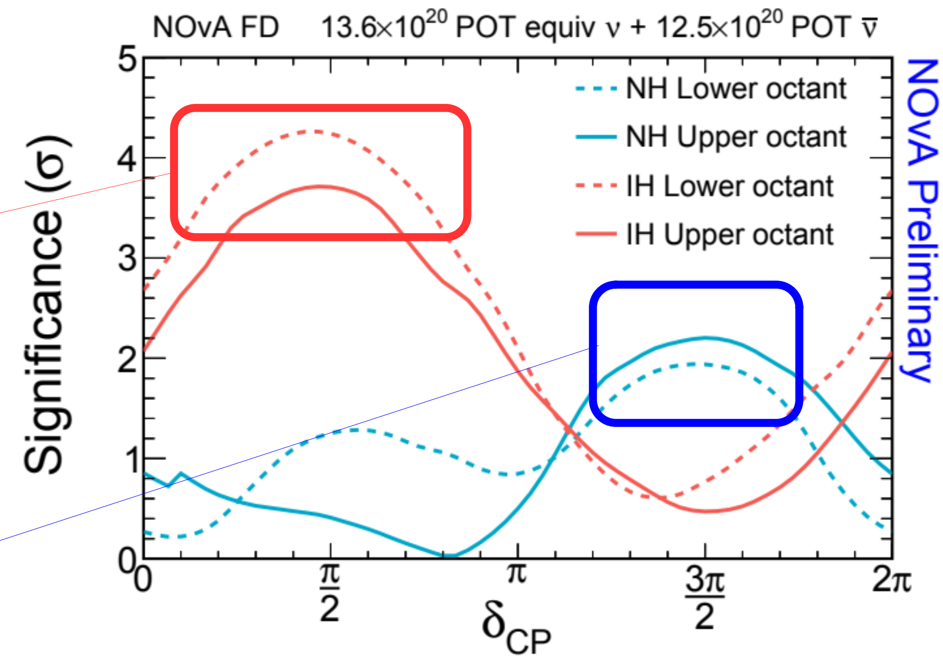

- Hie-oct-δ_{CP} combinations that produce 'asymmetric' ν_e-$\bar{\nu}_e$ appearance are disfavored

[All contours and significances calculated using Feldman-Cousins method thanks to NERSC]

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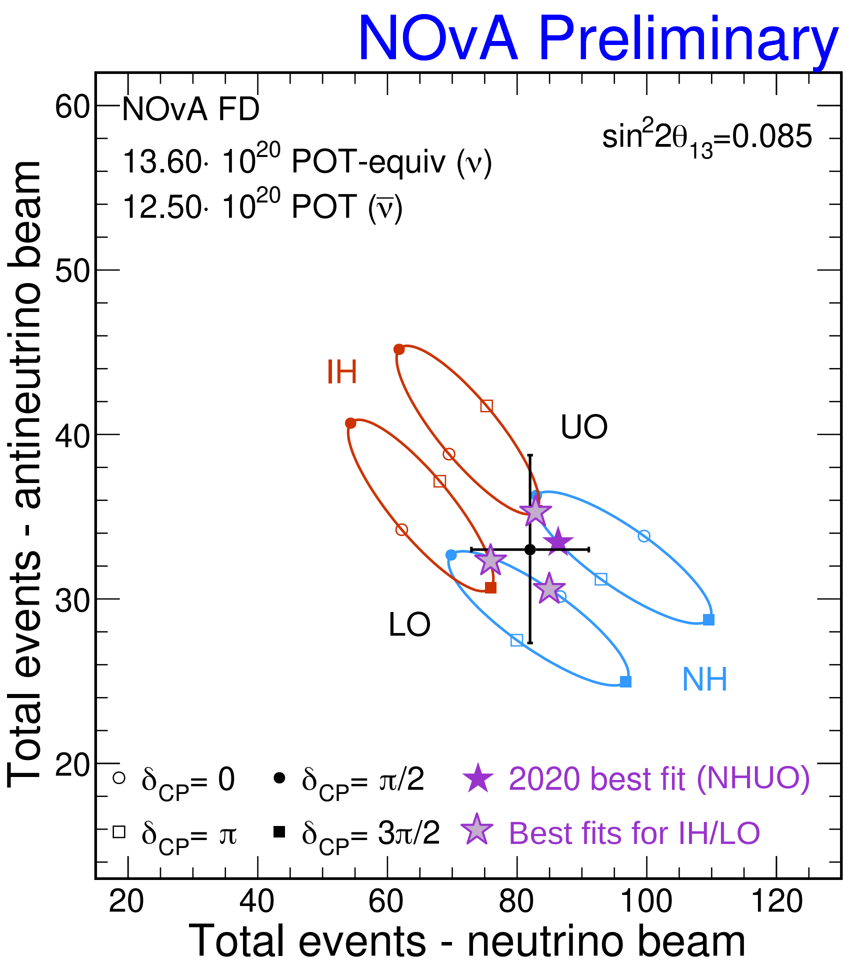

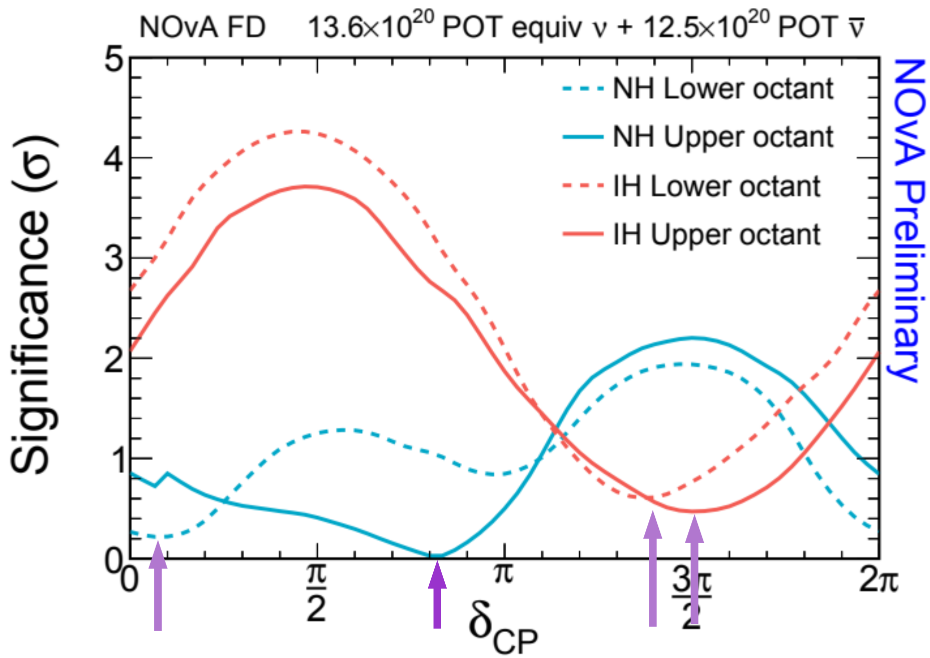

- Hie-oct-δ_{CP} combinations that produce 'asymmetric' ν_e-$\bar{\nu}_e$ appearance are disfavored
- Combinations that include some “cancellation” are preferred
  - There are such combinations for either hierarchy or octant → no strong preferences for hierarchy (or octant)

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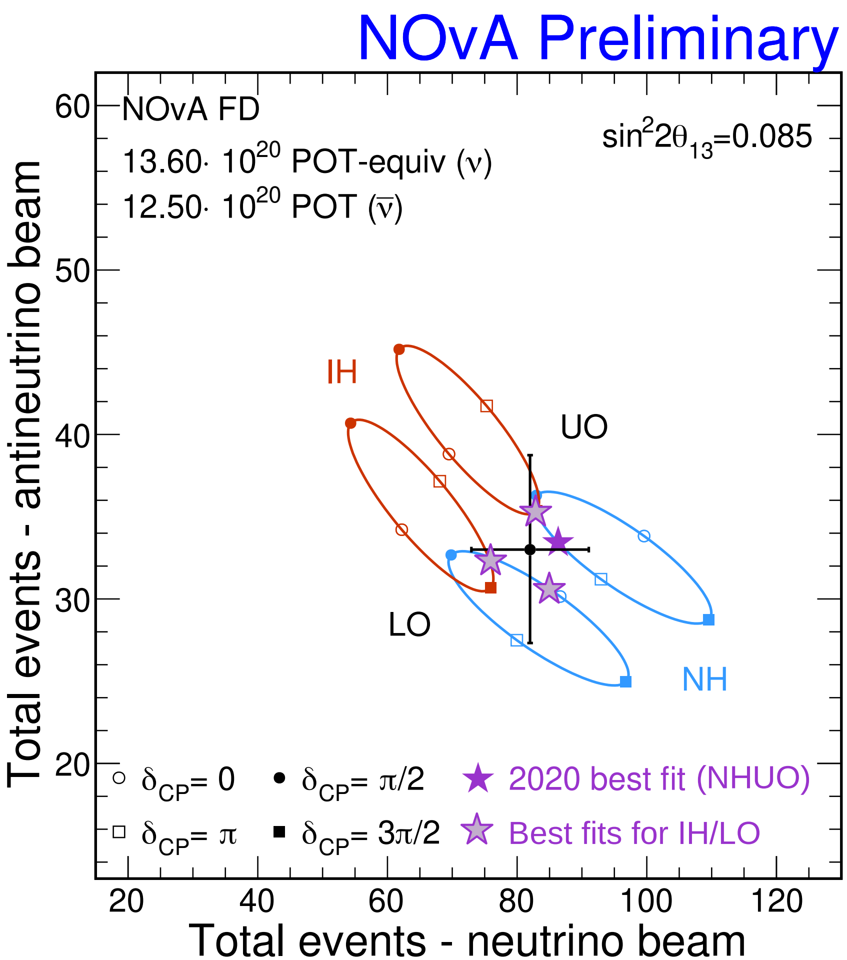

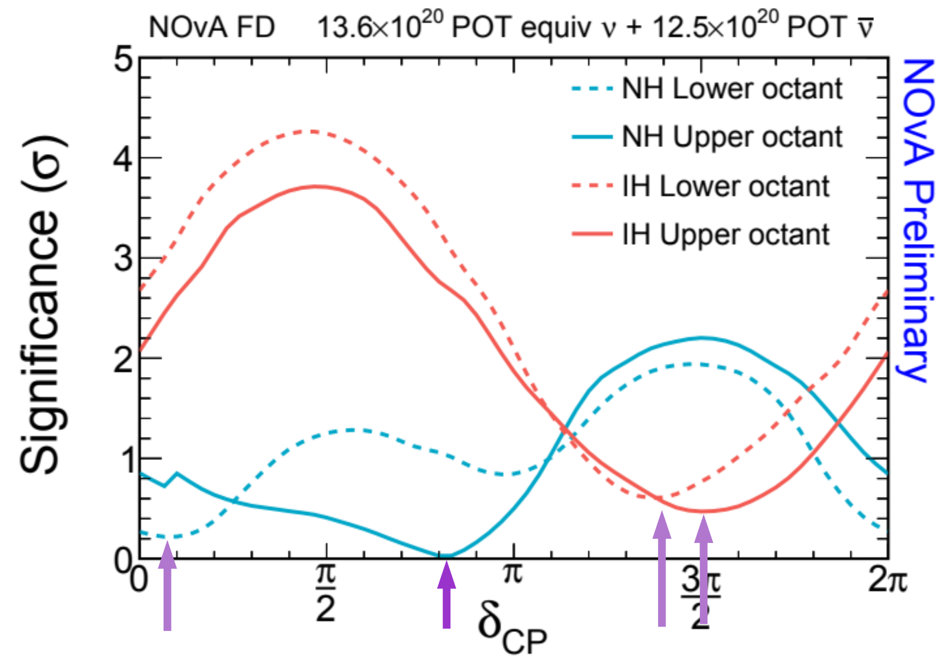

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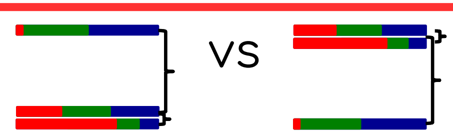


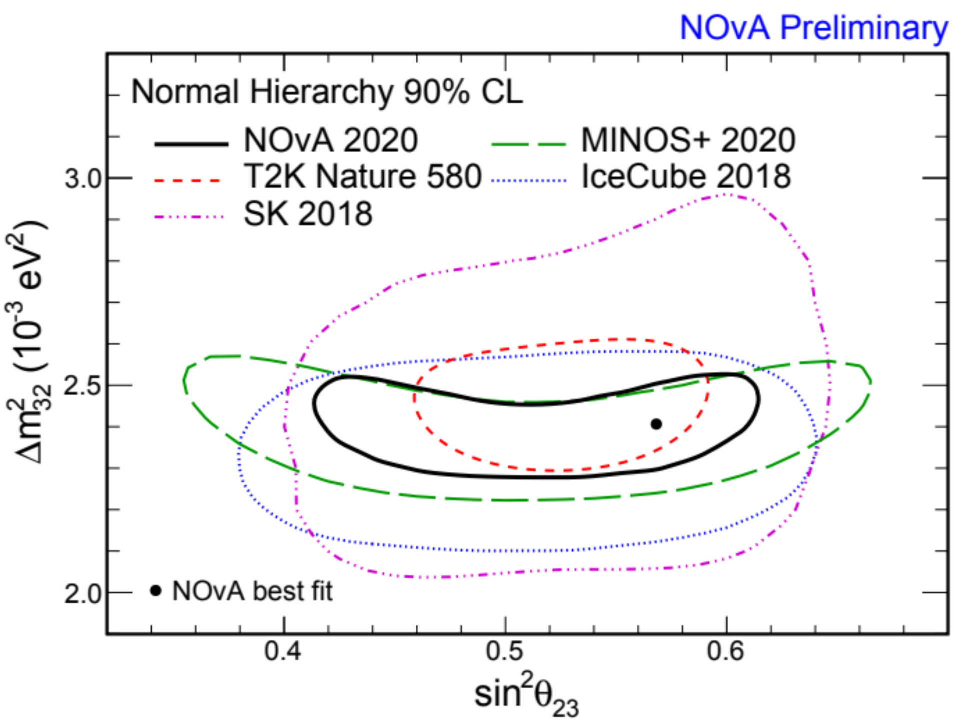
NH preferred by 1.0σ

$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

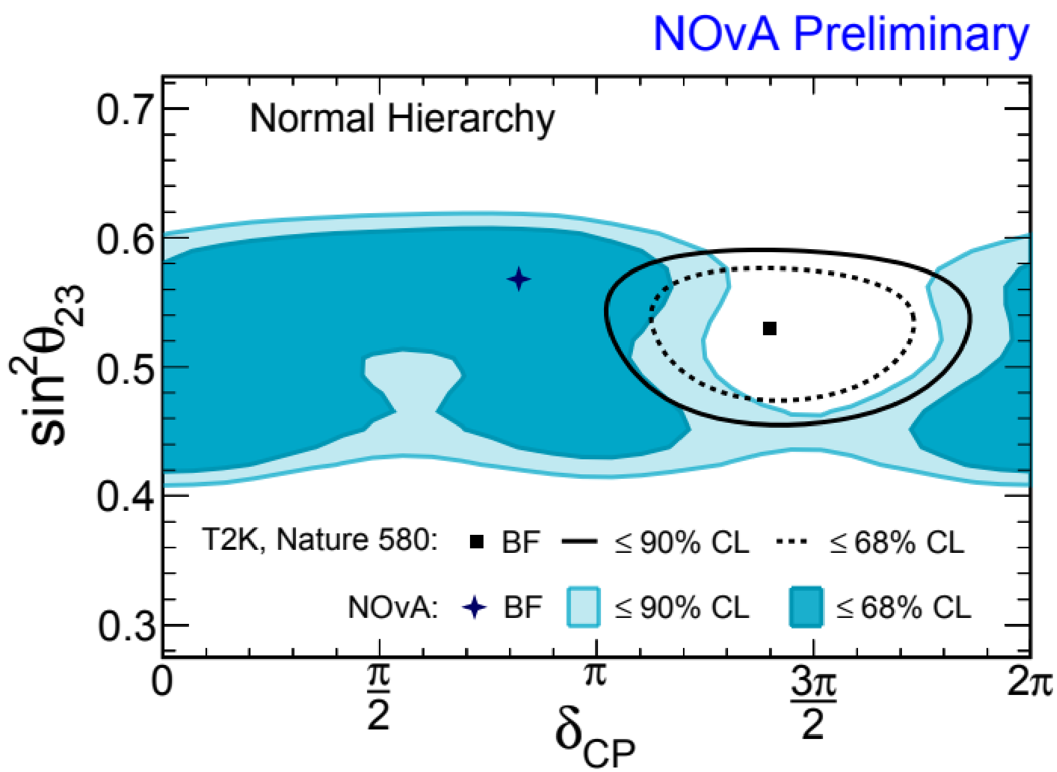
Exclude (IH, δ_{CP}=π/2) at >3σ
Disfavor (NH, δ_{CP}=3π/2) at ~2σ

Vs. other measurements

[n.b.: not yet updated for NEUTRINO 2020 results from all other expt's]



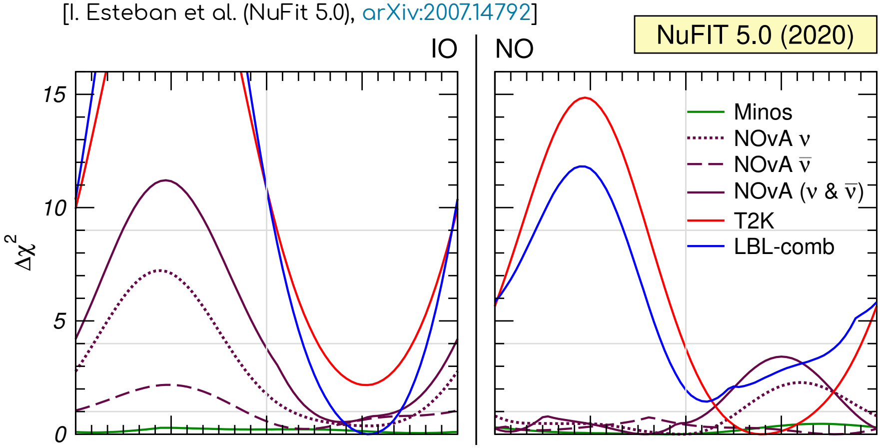
Agreement across many precision measurements about values of "atmospheric" parameters

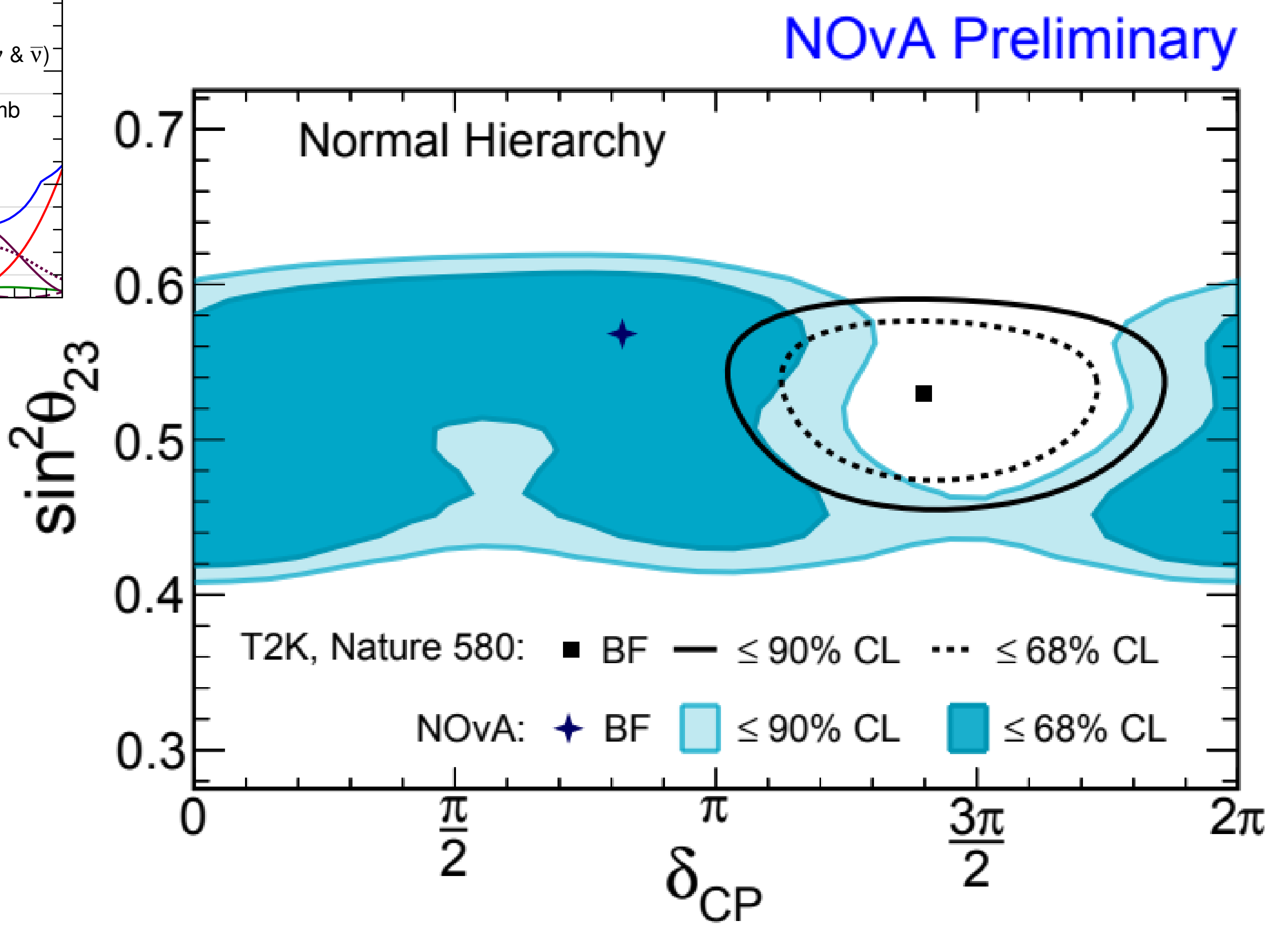


Apparent tension in allowed values of δ_{CP}

Vs. other measurements

[I. Esteban et al. (NuFit 5.0), arXiv:2007.14792]





Tension has stirred lots of excitement!

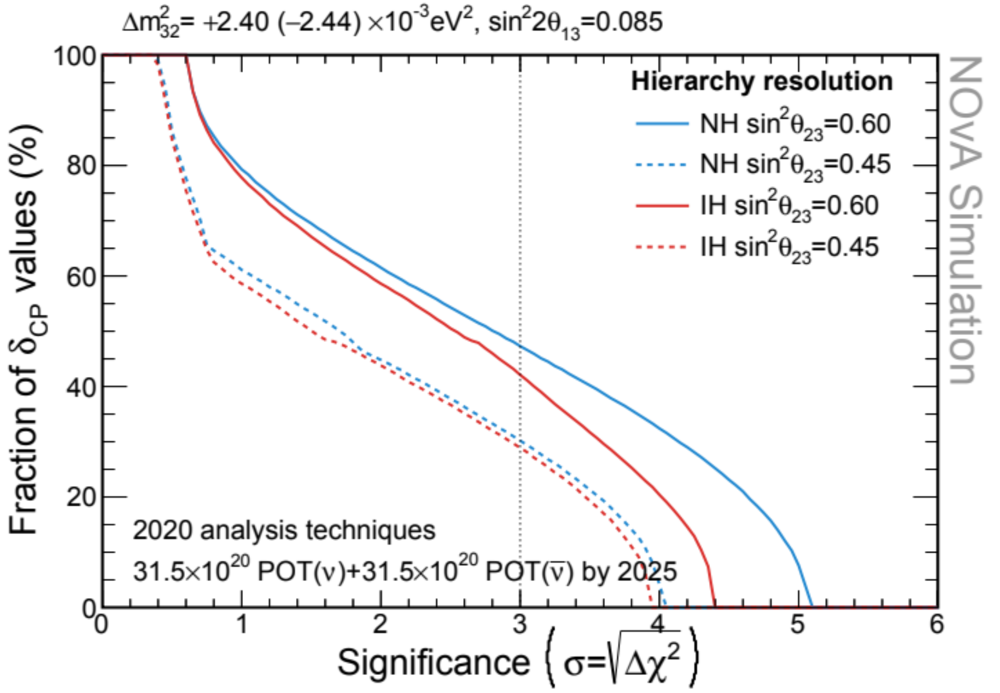
- IH may actually be best solution in 3-flavor paradigm, despite individual preferences for NH? (Kelly et al., arXiv:2007.08526)
- Hints for new physics: non-L/E dependent phenomena like NSI? (P. Denton et al., arXiv:2008.01110; S. Chatterjee & A. Palazzo, arXiv.2008.04161)

→ Essential that we learn as much from NOvA's unique 810km baseline as possible!

NOvA & T2K are working on a fully self-consistent joint fit (including systs)
(Regular meetings, workshops; signed agreement)

Looking ahead

- Will resume in neutrino mode after summer shutdown
  - Run plan: 50:50 $\nu:\bar{\nu}$
  - NOvA is expected to run until 2025
  - Beam improvements an important part of story!
- Good sensitivity to resolution of hierarchy at full exposure
  - 4-5σ for $\delta_{CP}=3\pi/2$
  - ≥3σ for 30-50% of δ_{CP} values (depending on θ_{23} & true hierarchy)
    → current measurements already beginning to show power
- Anticipating reductions in detector uncertainties that should further improve analysis robustness



Summary

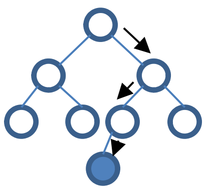
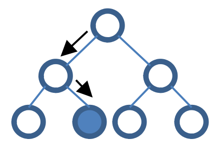
- With 13.6×10^{20} POT neutrino + 12.5×10^{20} POT antineutrino beam exposure, NOvA reports:
  - Precision measurements of atmospheric parameters:
    - Δm^2_{32} = $(2.41 \pm 0.07) \times 10^{-3}$ eV^2 (2.9%)
    - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$ $(\sim 6\%)$
  - Constraints on strongly asymmetric ν_e-$\bar{\nu}_e$ appearance PMNS solutions:
    - (IH, δ_{CP} = $\pi/2$) excluded at >3σ
    - (NH, δ_{CP} = $3\pi/2$) disfavored at ~2σ
  - Progress towards answering the "deep questions"!
- With continued running through 2025, NOvA anticipates:
  - ≥3σ sensitivity to mass hierarchy determination for 30-50% of δ_{CP} values
  - Input from NOvA Test Beam program, neutrino interactions community to further improve robustness to systematics


MAY 2020

Overflow

Reweighting using BDTs

To avoid having to fully resimulate ν scattering to apply tunes, we train BDTs using truth quantities to build reweights for each variation.

$f_{BDT} = \alpha_1$  $+ \ldots + \alpha_N$ 

$$\simeq \frac{1}{N} \sum_{\substack{tree\\ i=1}}^{N} \alpha_i \Theta\left(\vec{x} - \vec{x}_0^{\,i}\right)$$

↑ event values

↑ trained "cut" for tree *i*

with $\vec{x} = $ (# hadrons, hadron KE, ...)

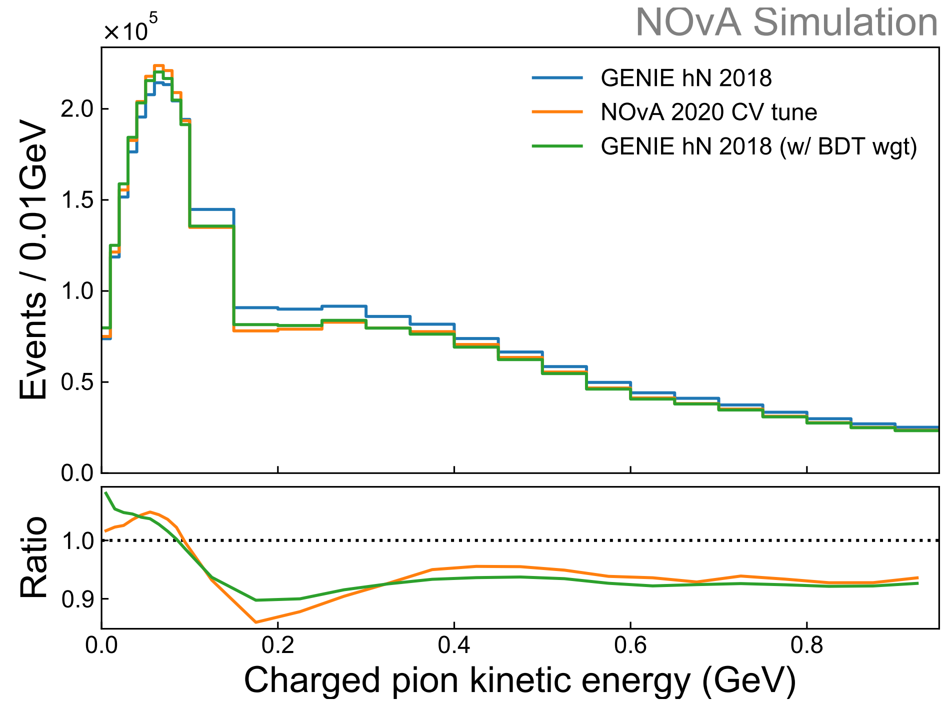
We use a binary logistic loss as the training objective:

$$L_{log} = \sum_{\substack{training\\ evt\, n}} -y_n \ln \hat{y}_n + \left(y_n - 1\right) \ln\left(1 - \hat{y}_n\right)$$

[Technique inspired by J. Phys. Conf. Series 762, 012036; built on work by C. Vilela for DUNE]

The desired weights for an event are:

$$w\left(\vec{x}\right) = \frac{f_{BDT}\left(\vec{x}\right)}{1 - f_{BDT}\left(\vec{x}\right)}$$

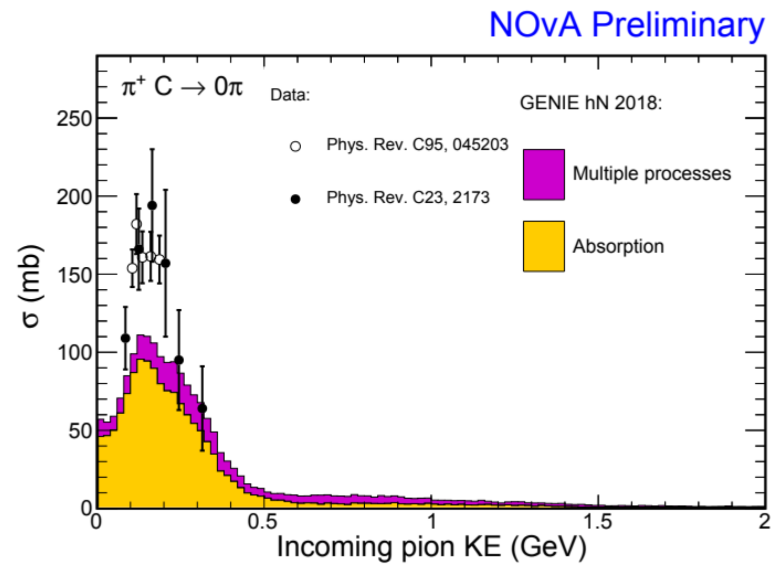


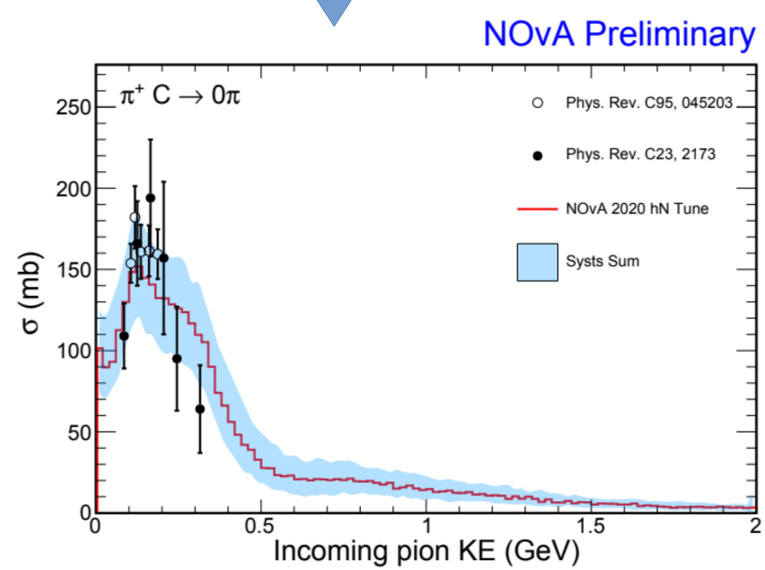
The weighted nominal distributions adequately reproduce the simulated variations.

FSI tuning & uncertainties

- FSI model choice: "hN"
  - Propagates hadrons through nucleus in finite steps
  - Interaction probabilities simulated according to Oset quantum model
  - More rigorous foundation than older "hA" effective model (hA applies hadron scattering data directly to FSI and ... hopes for the best)
- Challenge: hN not directly reweightable

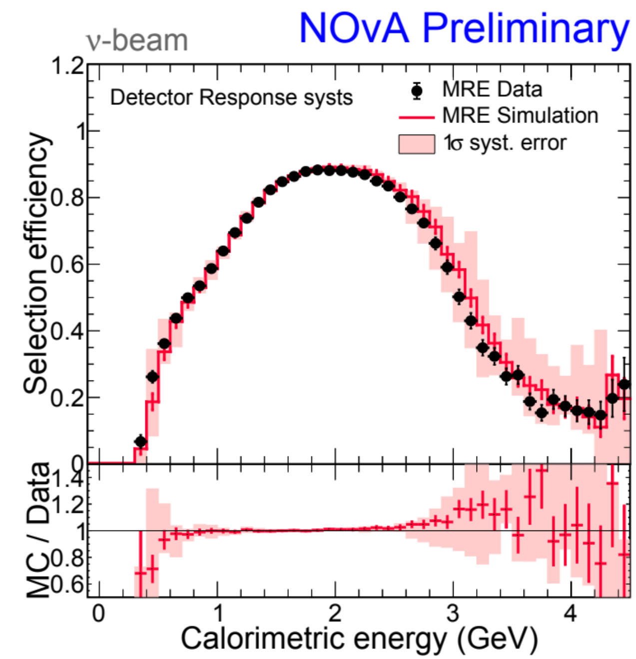
  → Addressed with novel BDT reweighting technique adapted from DUNE (see also J. Phys. Conf. Series 762, 012036)
- Tuning:
  - Adjust central value to agree better with pion scattering data at low energies where most relevant for NOvA
  - Construct uncertainty bands in same spirit as work from T2K [Phys. Rev. D99, 052007]

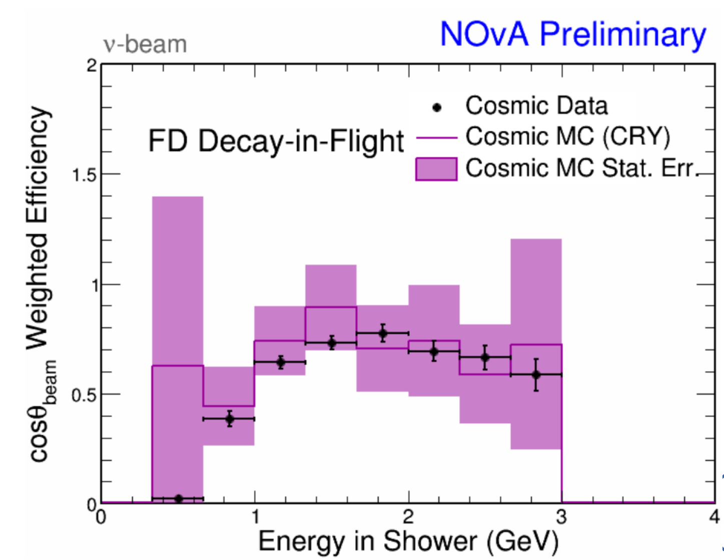




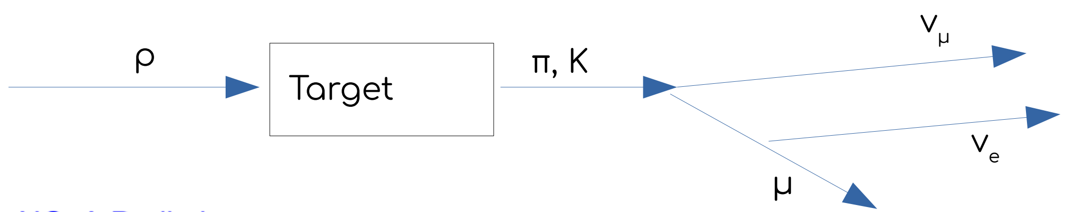
PID validation: MRE, MRDiF

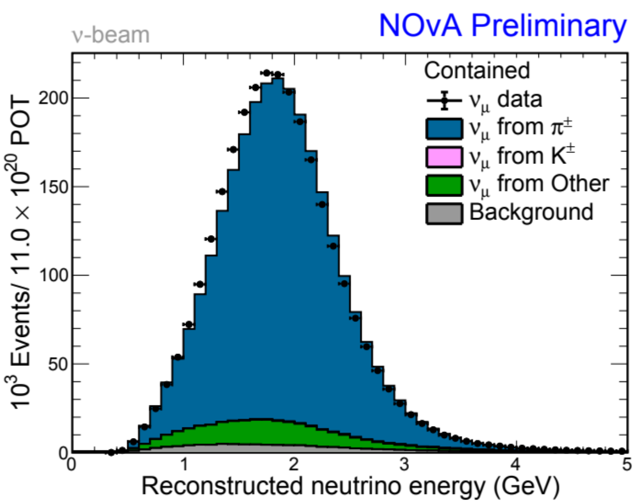
- Validating selection performance:
  - Remove muons in both data & MC
  - Compare PID efficiencies relative to a preselection
- ND: muon removal, electron addition (MRE):
  - Begin with ν_μ CC candidates
  - Replace the removed muon with simulated electron of same kinematics
- FD: muon removal from decay-in-flight (MRDiF)
  - Begin with cosmic-ray muons that decay in flight to electrons
  - Remove muon part, study electron shower

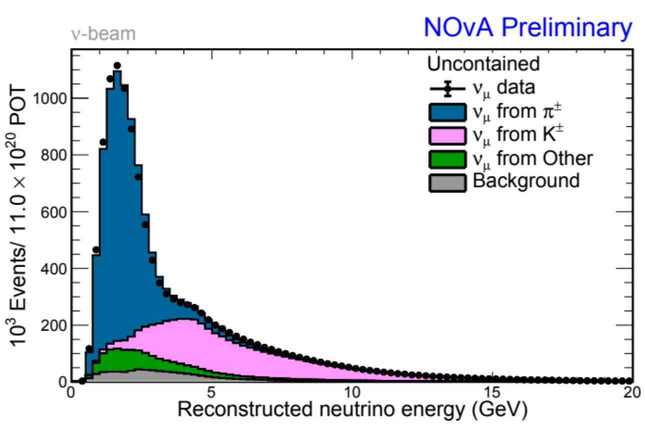




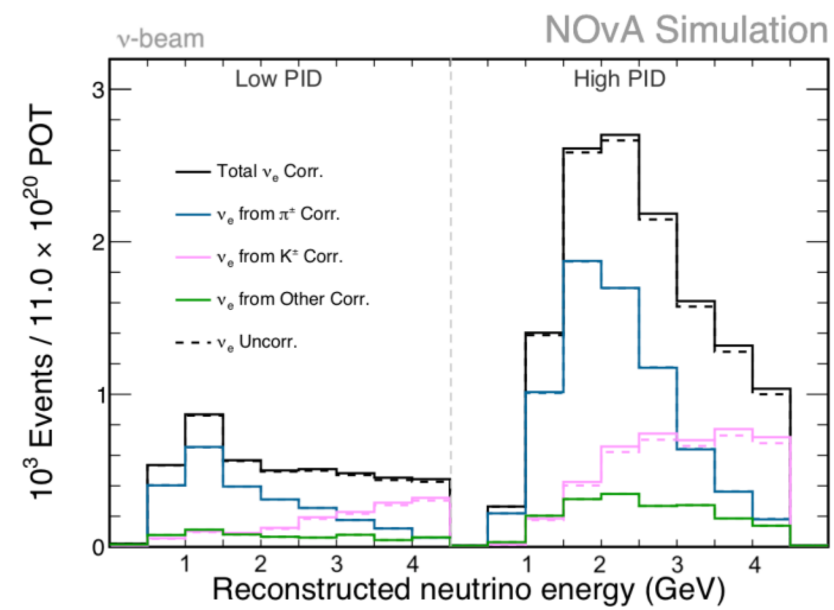
ν_e bkgds: beam ν_e constraints







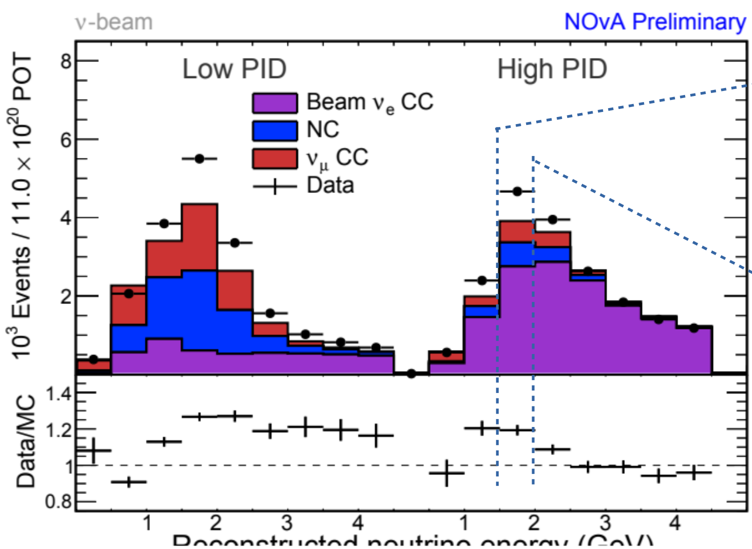
Assign discrepancies in ND ν_μ contained and uncontained samples to flux; **derive corrections according to parent mesons** (which also result in beam ν_e)

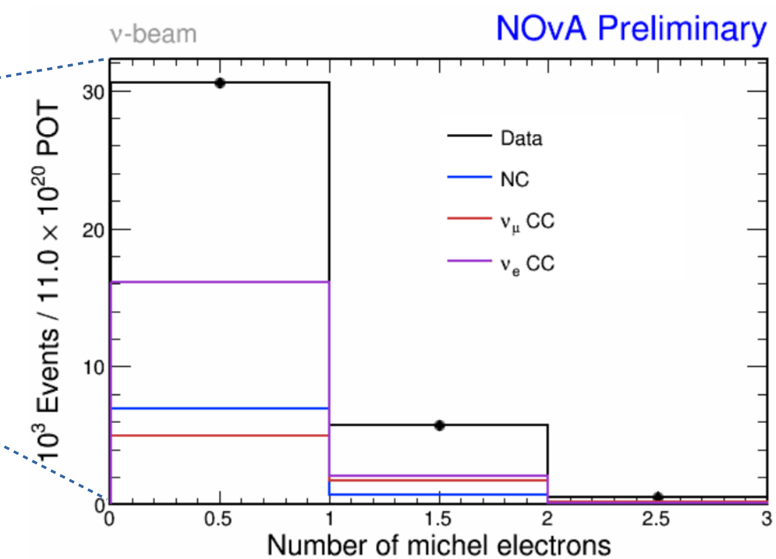


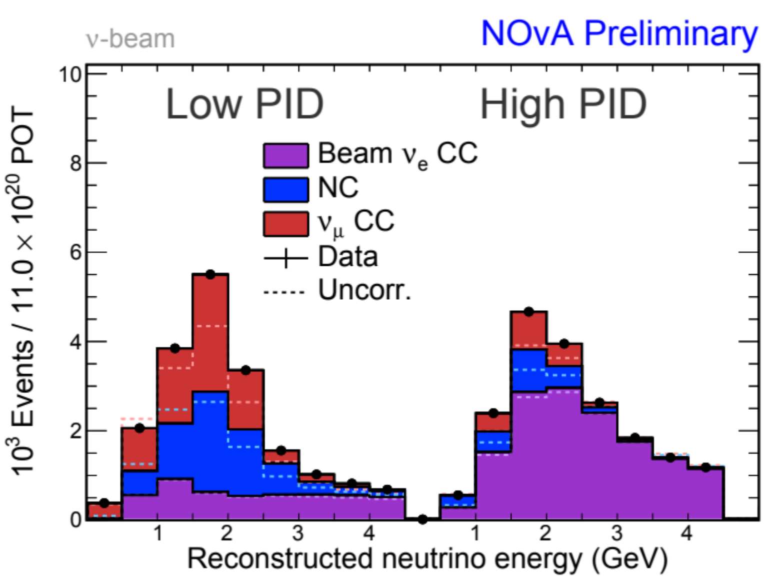
Pion-ancestor neutrinos are corrected in bins of parent (p_z, p_T). Average ~ +0.2%

Kaon-ancestor neutrinos get a single weight: +5.8%

ν_e bkgds: NC/ν_μ CC constraints







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

Fit these 18 distributions to determine ν_μ CC / NC corrections in each bin

A priori sensitivities