New $\nu + \bar{\nu}$ Oscillation Results from NOvA

Jeremy Wolcott (Tufts University)

52nd Fermilab Users Meeting

June 13, 2019

Neutrino oscillations

Neutrino oscillations are a **rich laboratory** for understanding the **implications of neutrino mass**

(... so the global program is healthy and diverse!)

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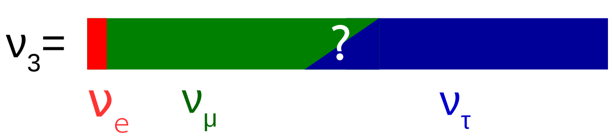
Is there a **symmetry** governing the ν_μ/ν_τ mixing into the mass states?
(Is θ_{23} "maximal" = 45°?)



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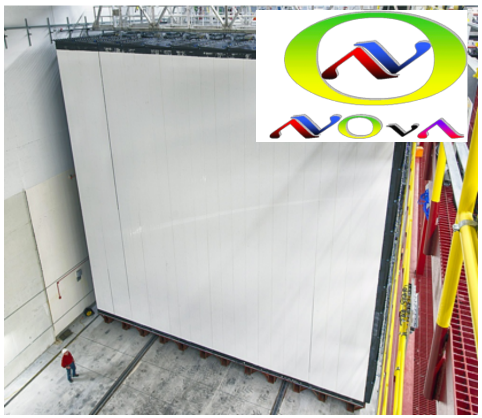

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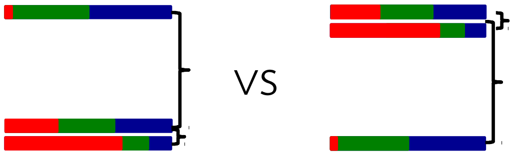
Is there a **symmetry** between the **ordering of the neutrino** & charged lepton **mass states**?
(Is the mass hierarchy "normal" or "inverted?")



Neutrino oscillations

Neutrino oscillations are a **rich laboratory** for understanding the **implications of neutrino mass**

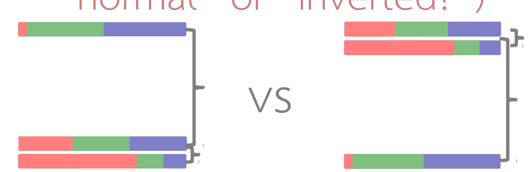
NOvA is uniquely positioned to investigate several of the **biggest remaining physics questions:**

Is there a **symmetry** governing the ν_μ/ν_τ mixing into the mass states? (Is θ_{23} "maximal" = 45°?)

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

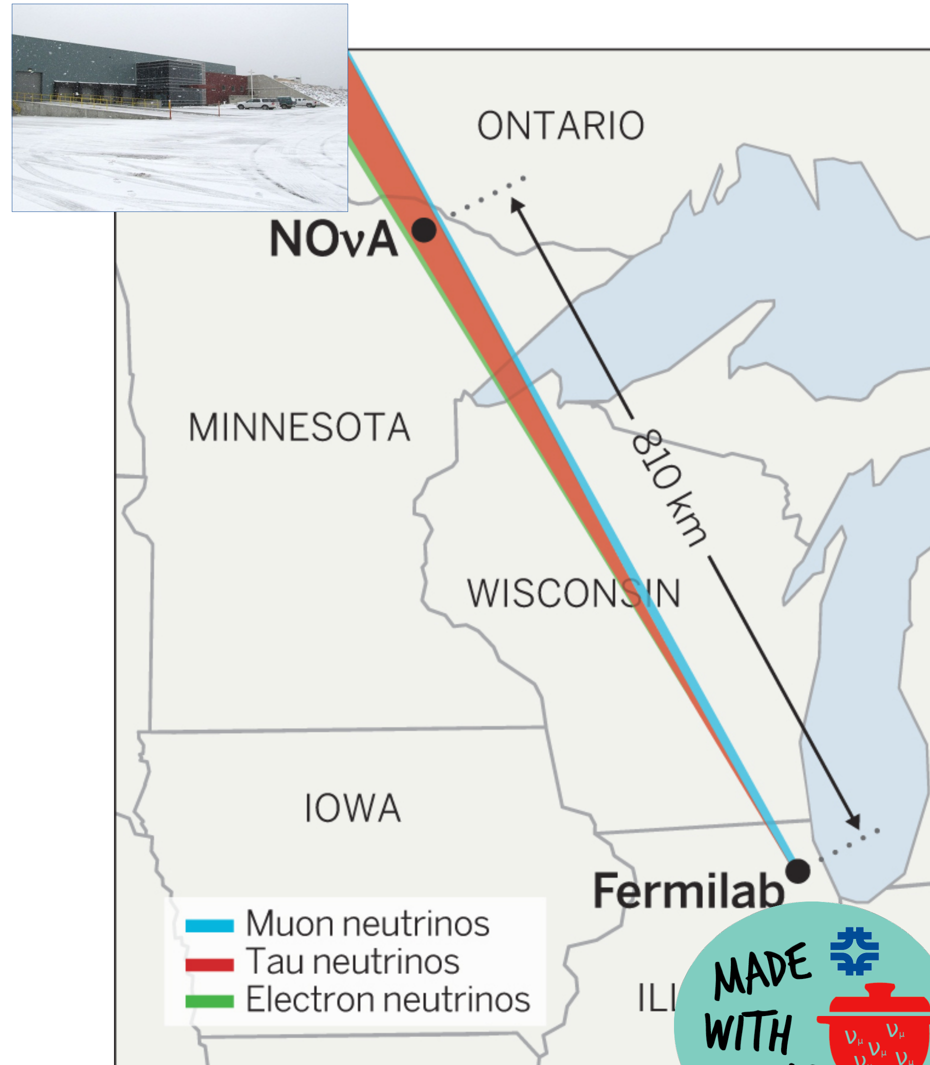
Is there **'direct' violation of CP symmetry** by leptons? (Is δ_{CP}/π non-integral?)

Is there a **symmetry** between the **ordering of the neutrino** & charged lepton **mass states**? (Is the mass hierarchy "normal" or "inverted?")



NOvA

- NOvA investigates with:
  - 700 kW NuMI beam
  - 810km baseline from FNAL to Ash River, MN
  - 300t Near and 14kt Far detectors 14mrad off axis



K. ENGMAN/*SCIENCE 345, 6204*

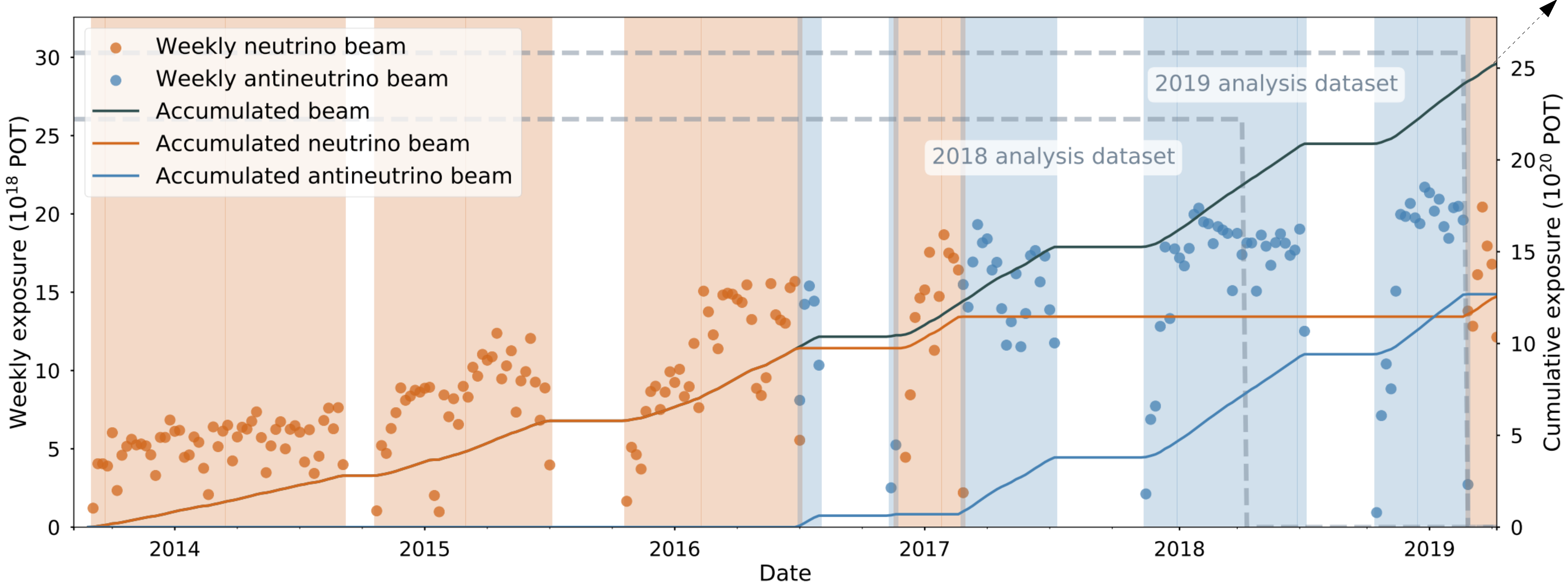
NOvA

- NOvA investigates with:
  - **700 kW NuMI beam**

Thank you Fermilab!!

758 kW peak hourly avg: currently highest in the world

(even higher beam power to be realized with higher power NuMI target, planned accelerator improvements)



(See also New Perspectives talk from Y. Yu)

NOvA

- NOvA investigates with:
  - **700 kW NuMI beam**

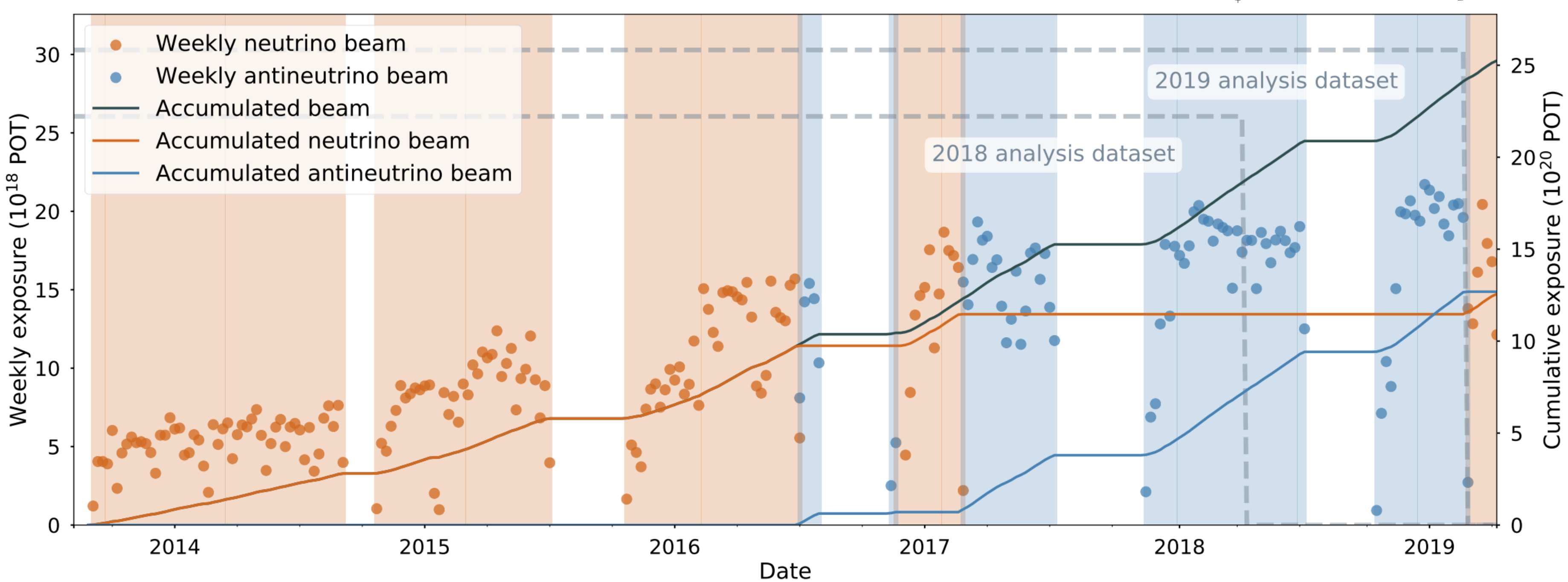
Combined with 99.23% detector uptime,

78% increase in $\bar{\nu}$ exposure

($6.91\times10^{20} \rightarrow 12.33\times10^{20}$ POT)

since last year's Users Meeting

New results unveiled today!



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- Neutrino scattering /cross sections (new: arXiv:1902.00558)
- Short-baseline sterile ν searches

Capable all-purpose detectors
also conducting many other measurements!
(Posters from S. Lin, S. Calvez, M. Judah)

NOvA

- NOvA investigates with:
  - **700 kW NuMI beam**
  - 810km baseline from FNAL to Ash River, MN
  - 300t Near and **14kt Far detector**s 14mrad off axis

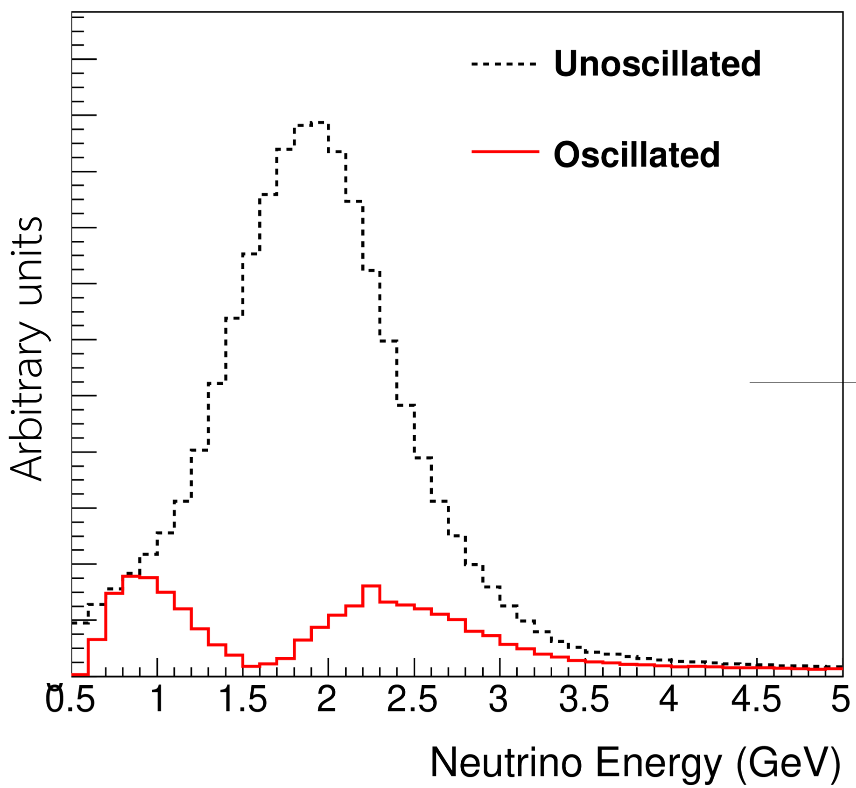
- Long-baseline sterile **ν** searches
- Seasonal cosmic ray studies (new: arXiv:1904.12975)
- Supernova νs
- Exotic searches:
  - Magnetic monopoles
  - N-N oscillations
  - Gravitational wave coincidence

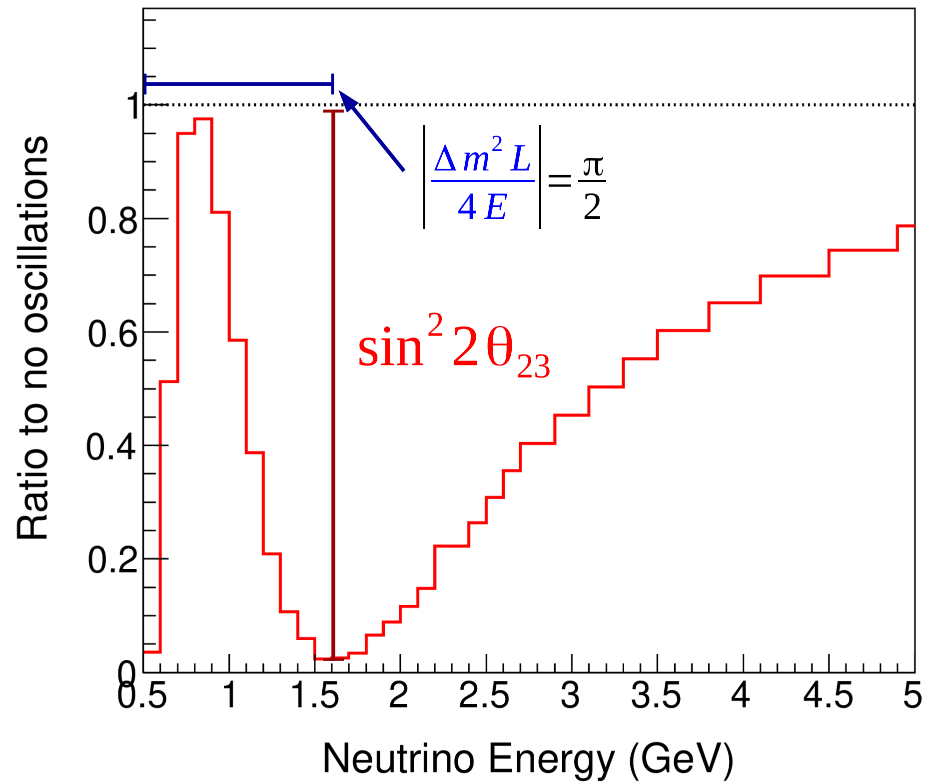
  …

Capable all-purpose detectors also conducting many other measurements!
(Poster from A. Norrick)

3-flavor neutrino oscillations

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





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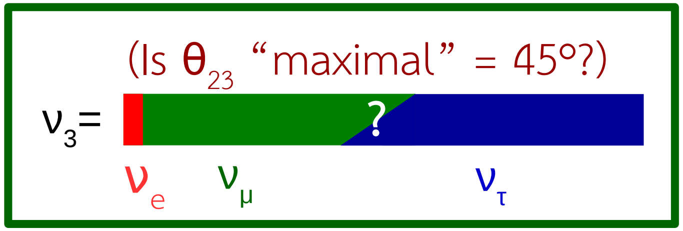

Muon neutrino disappearance → θ_{23}

3-flavor neutrino oscillations

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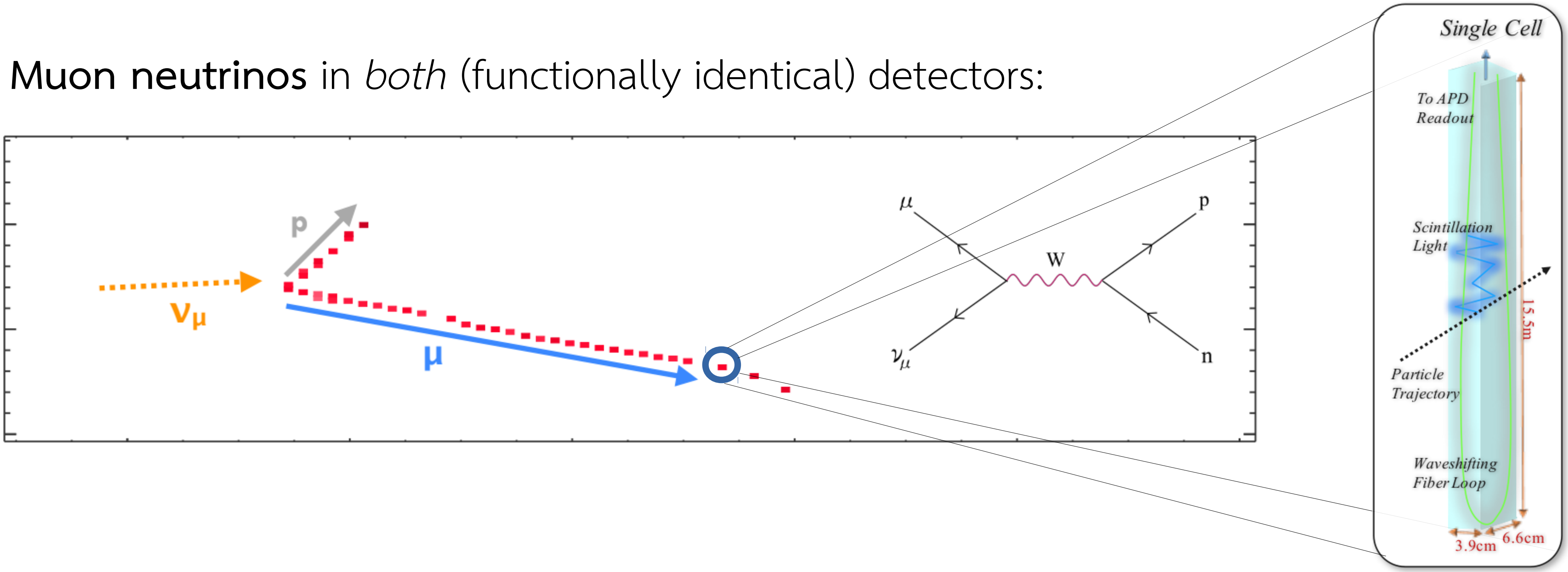
Muon neutrinos in *both* (functionally identical) detectors:



3-flavor neutrino oscillations

[Nunokawa, Parke, Valle, Prog. Part. Nucl. Phys. 60, 338]

$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e\right) \approx \left|\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}}\right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)^*$$

with

$$\begin{aligned}\sqrt{P_{\text{atm}}} &\equiv \sin\theta_{23}\sin 2\theta_{13}\sin\Delta_{31} \\ \sqrt{P_{\text{sol}}} &\equiv \cos\theta_{23}\cos\theta_{13}\sin 2\theta_{12}\sin\Delta_{21}\end{aligned}$$

(in *vacuum*)

* In fits to data the full three-flavor probability is used with no approximations

3-flavor neutrino oscillations

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ν vs $\bar{\nu}$

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(Is θ_{23} <, >, = 45°?)

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

Is δ_{CP}/π non-integral?

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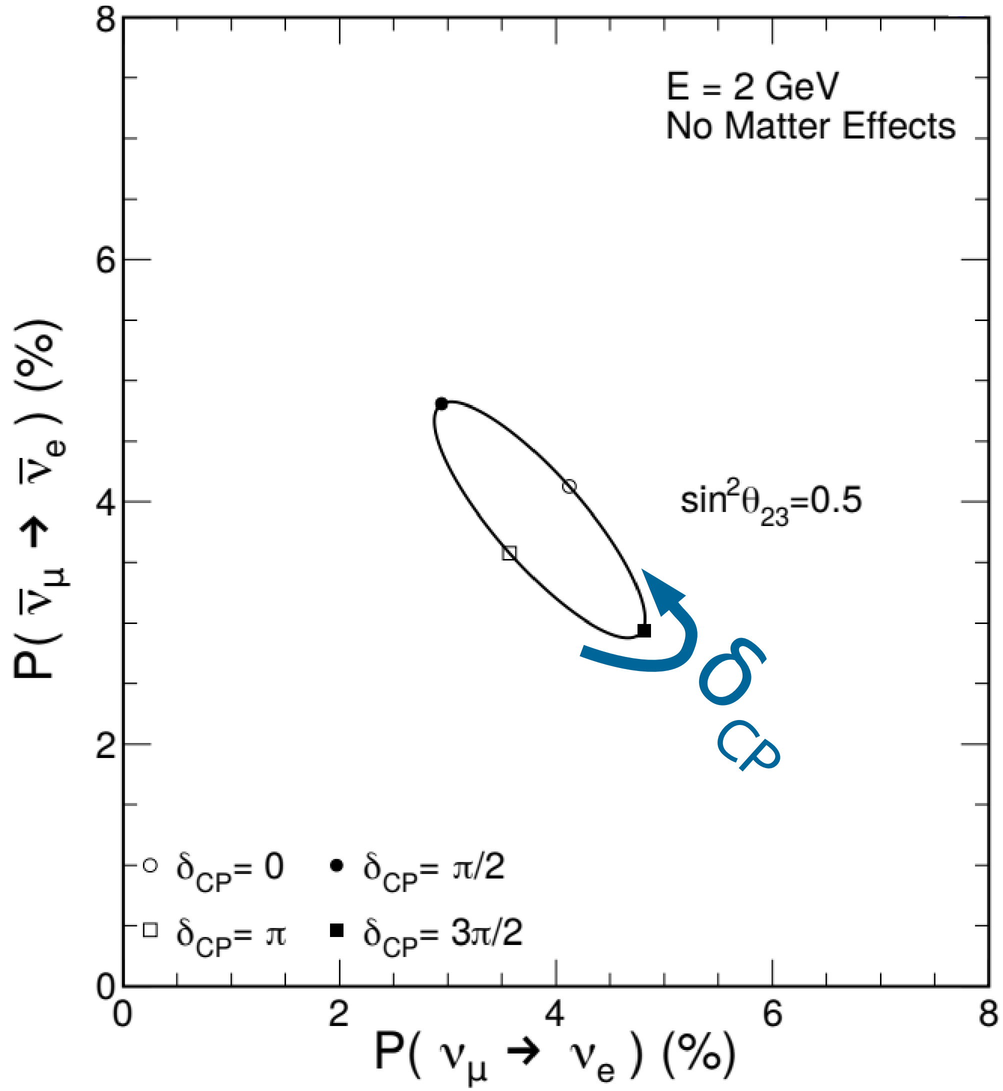
3-flavor neutrino oscillations



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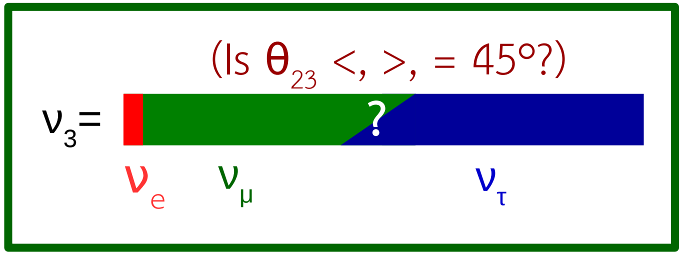

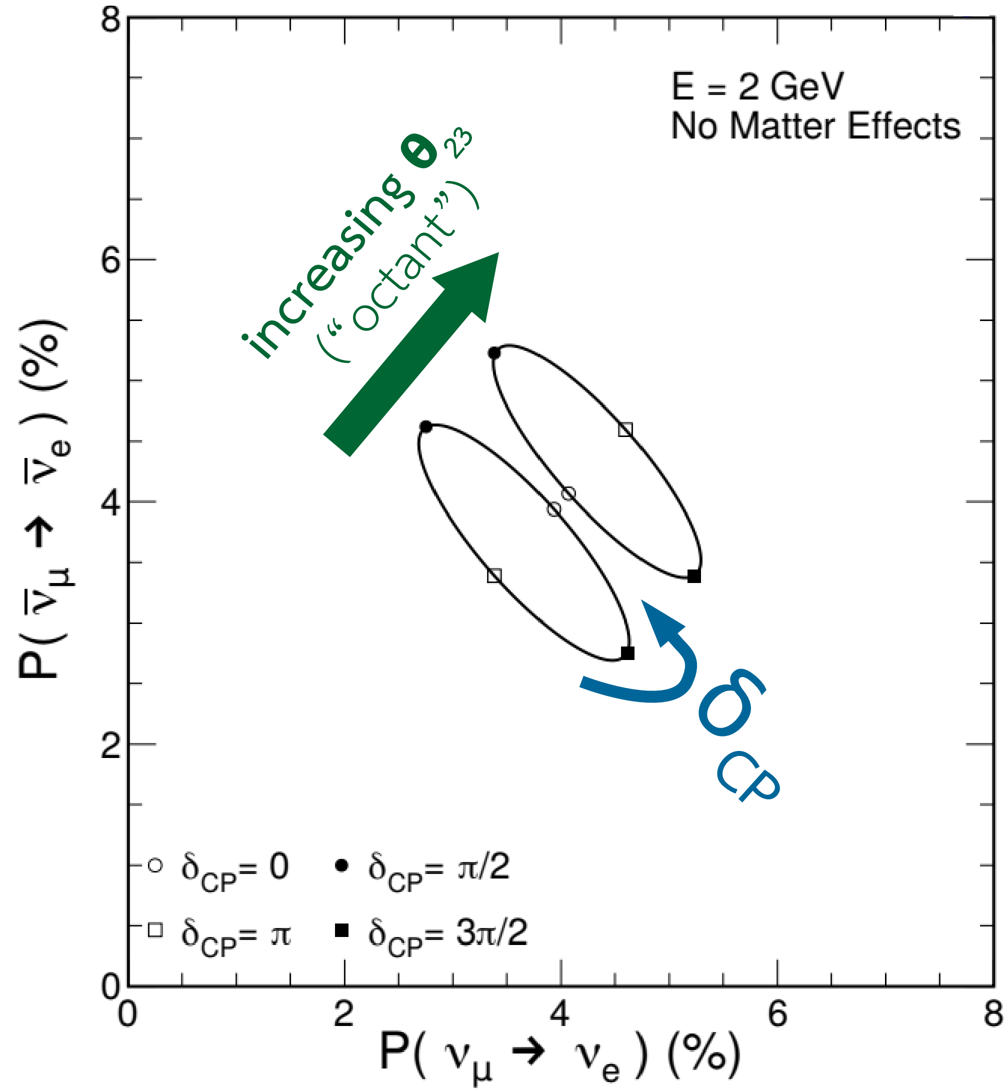

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3-flavor neutrino oscillations

[Nunokawa, Parke, Valle, Prog. Part. Nucl. Phys. 60, 338]

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$$\sqrt{P_{\rm atm}} = \sin(\boxed{\theta_{23}})\sin(2\theta_{13})\frac{\sin(\boxed{\Delta_{31} - aL})}{\boxed{\Delta_{31} - aL}}\Delta_{31}$$

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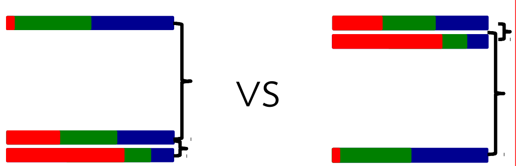

Is the mass hierarchy "normal" or "inverted?"

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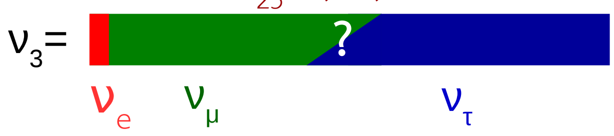
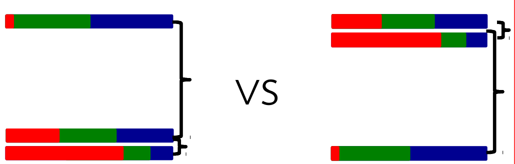
Is δ_{CP}/π non-integral?

(in *matter*)

3-flavor neutrino oscillations

(Is θ_{23} <, >, = 45°?)





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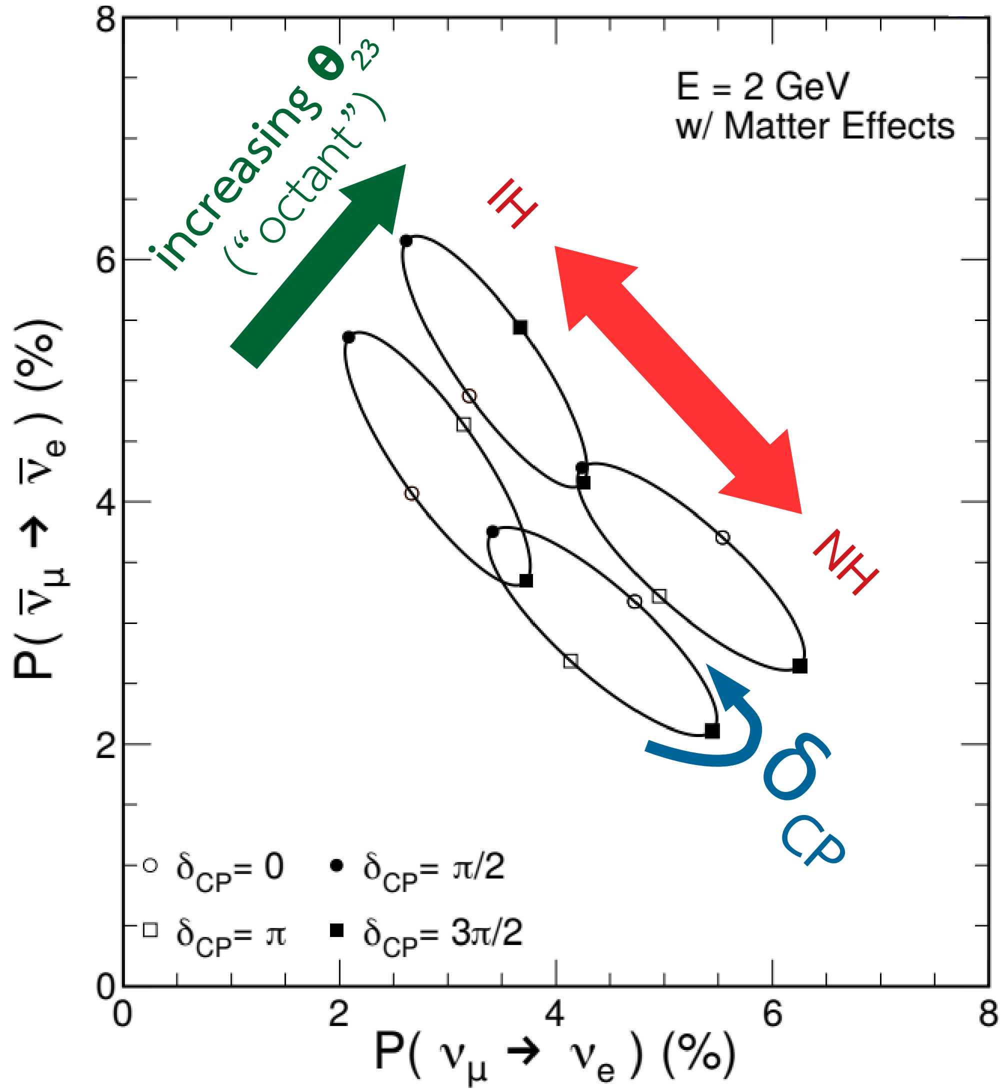

Electron neutrino appearance → θ_{23}, MH, δ

3-flavor neutrino oscillations

[Nunokawa, Parke, Valle, Prog. Part. Nucl. Phys. 60, 338]

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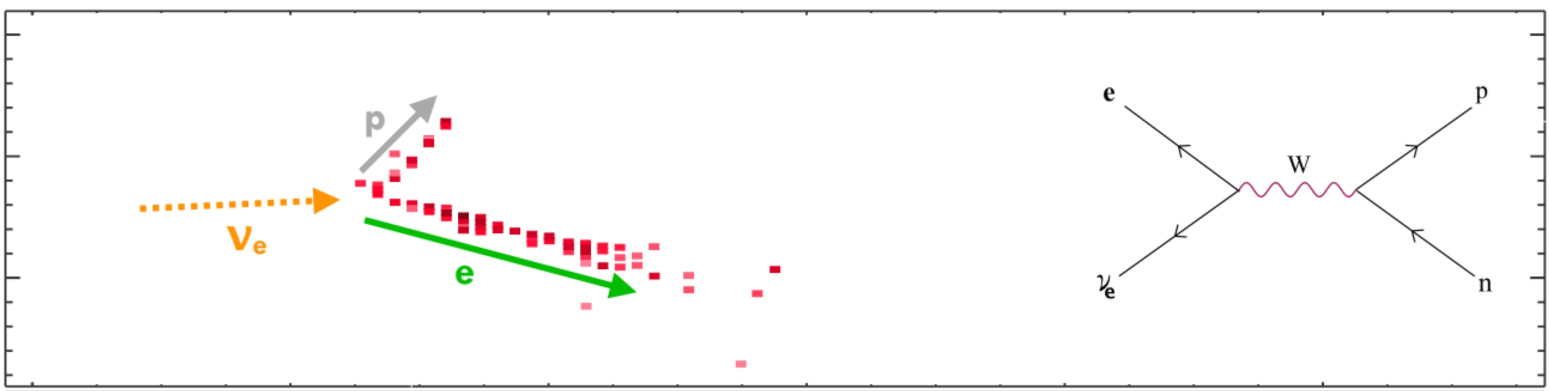
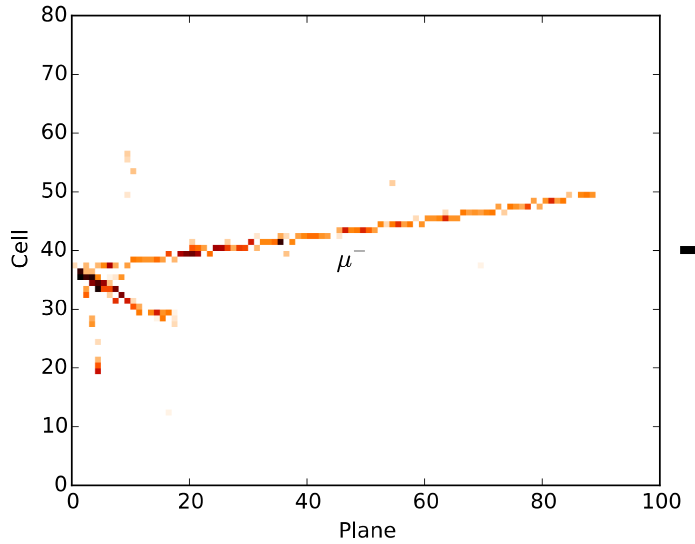
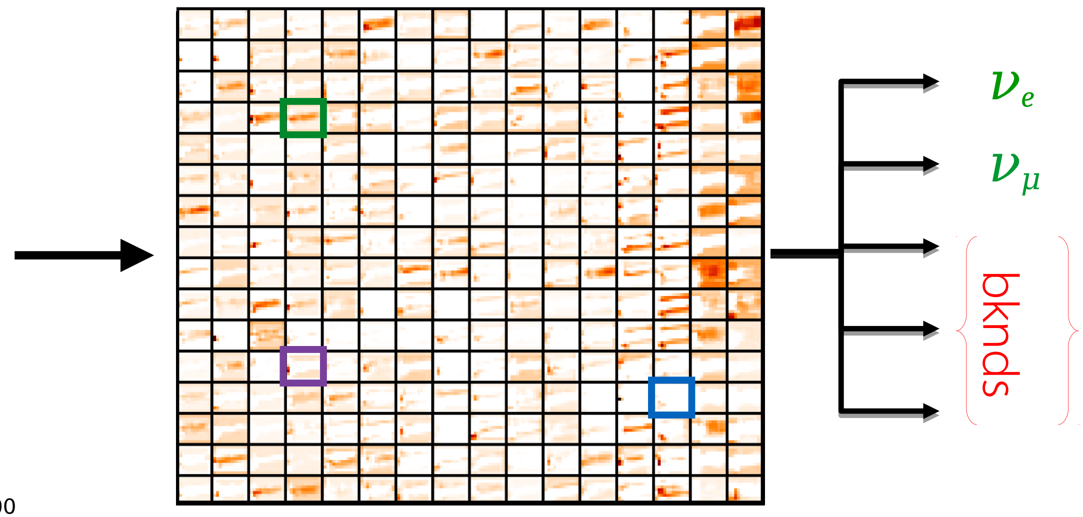


Identifying neutrino interactions

Input Image



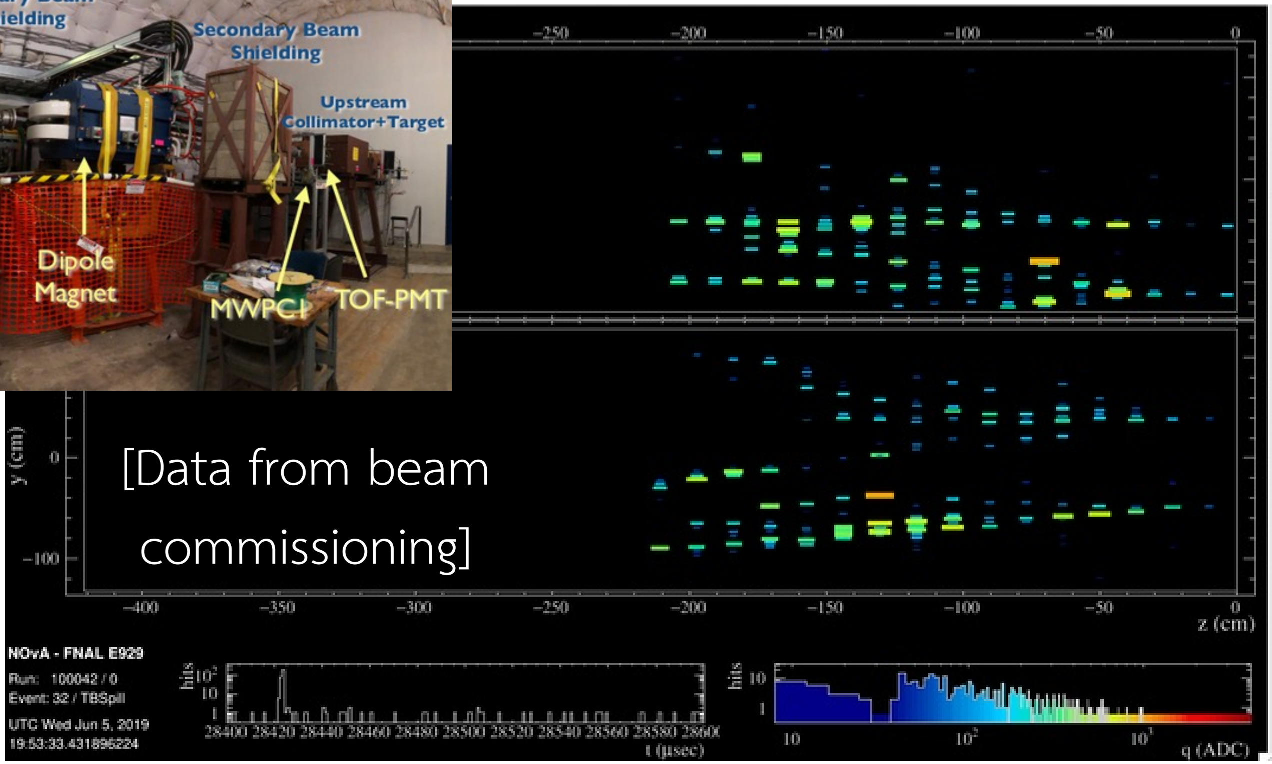
Learned variations on the original image



- Use *convolutional neural network* (CNN) called **CVN**
  - Technique borrowed from computer vision community
  - Learns topological "features", eventually mapped onto desired output categories
- **NOvA pioneered this use** in particle physics (JINST 11, P09001)
  → effective exposure increase of 30% for ν_e selection
- **3 theses, 3 papers** (and counting) from Deep Learning applications to NOvA

(NP talk G. Nikseresht)

Identifying neutrino interactions



Thank you Fermilab for support!

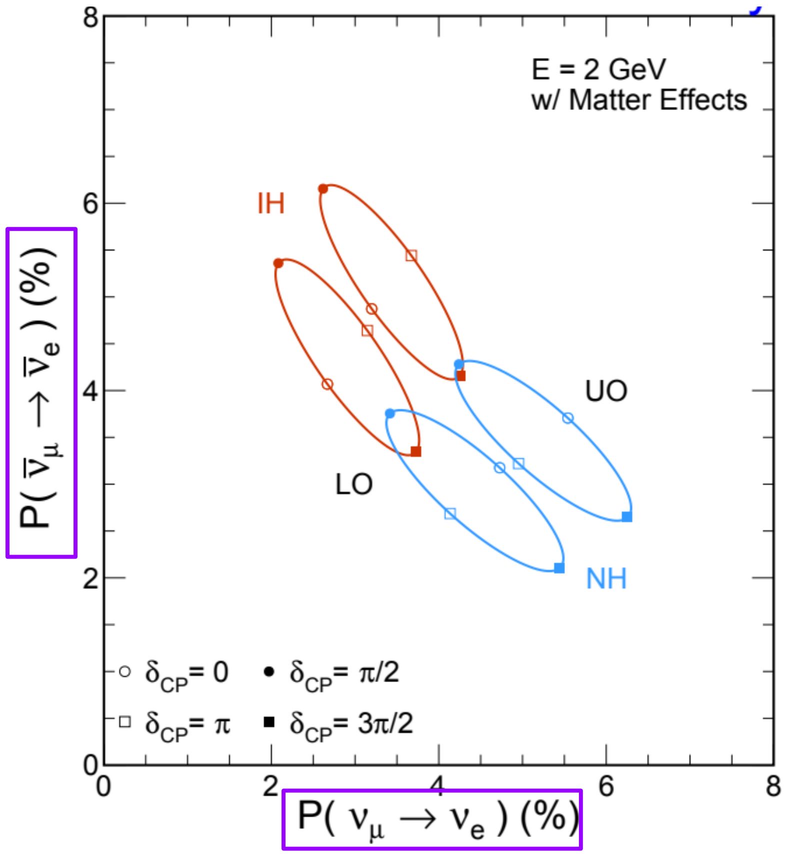
Further PID & energy scale validation coming soon using

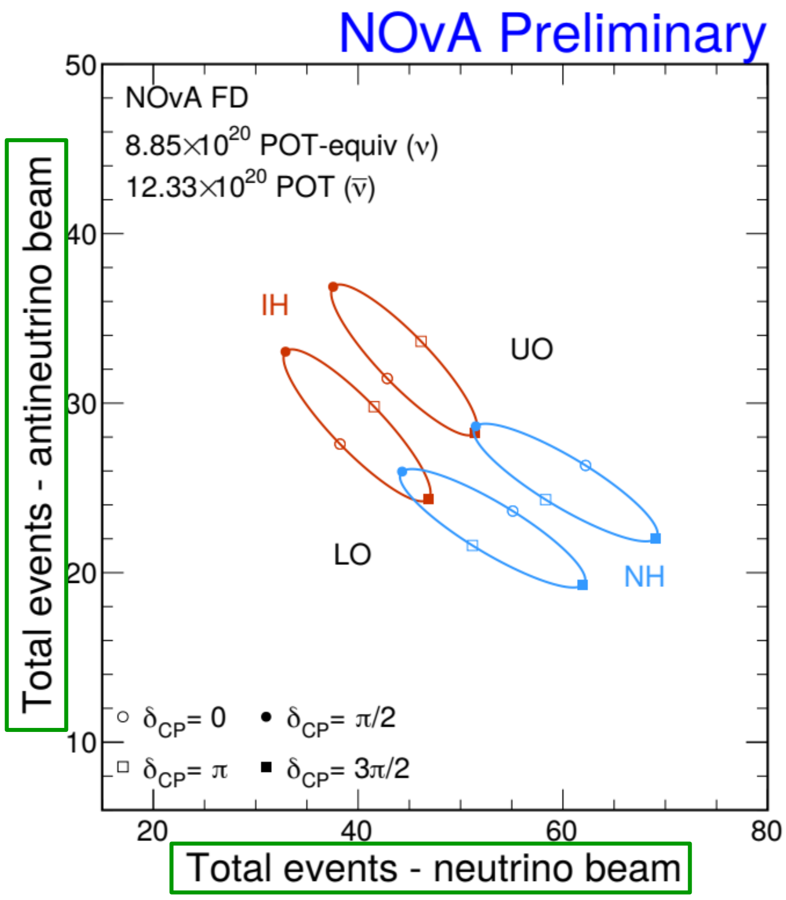
NOvA Test Beam

Efforts from **7 postdocs, 11 grad students, 11 undergrads**
Taking **cosmic & beam commissioning data** now – beam run in fall 2019

(Poster from D. Phan; NP talk T. Lackey)

Predictions

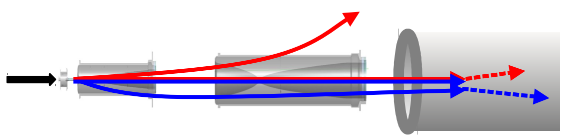




Converting an oscillation probability
to a prediction (event count) we can use to extract
parameters from data **is a deceptively complex process…**

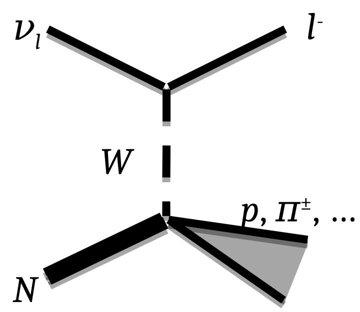
Predictions

Neutrino flux



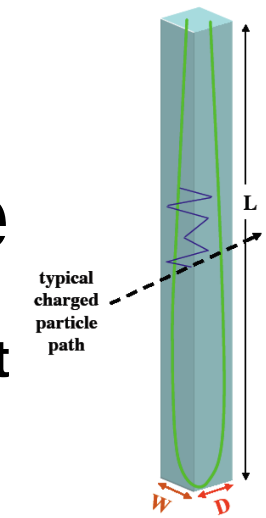
Neutrino reactions

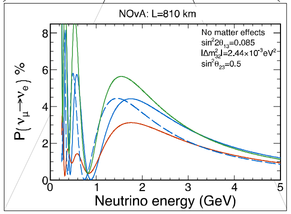
on detector materials



Detector response

to charged particles and **light propagation**





Oscillations

Predictions

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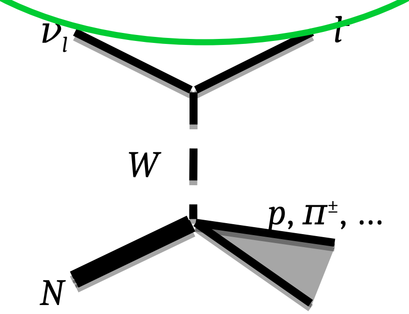
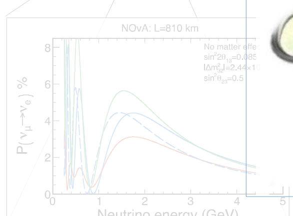


GENIE
2.12.2



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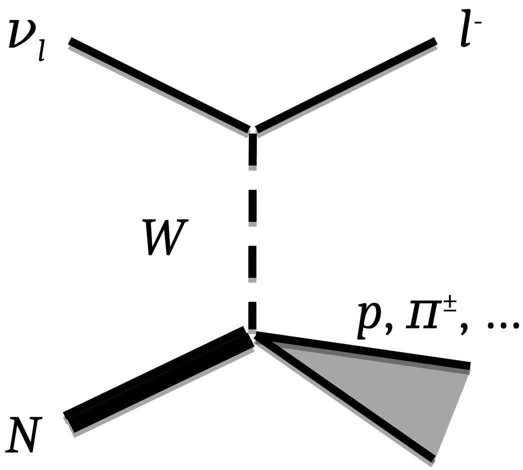
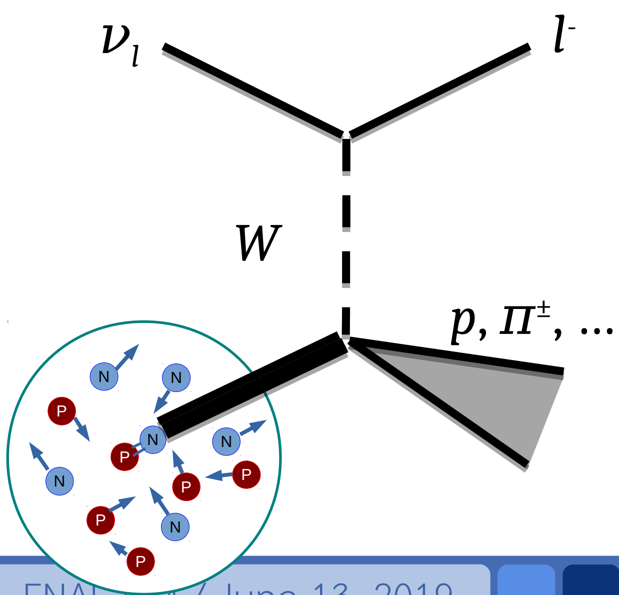


vs



Nuclear physics is important (and *hard*)

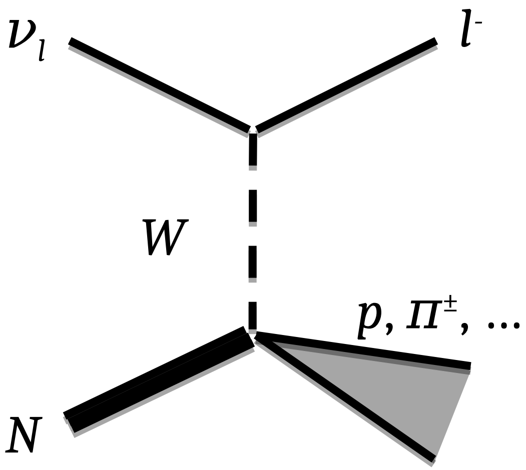
Some effects need to be added to GENIE 2.12.2 (our default) *post hoc*

- 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

(NP talk from M. Martinez Casales)

Predictions



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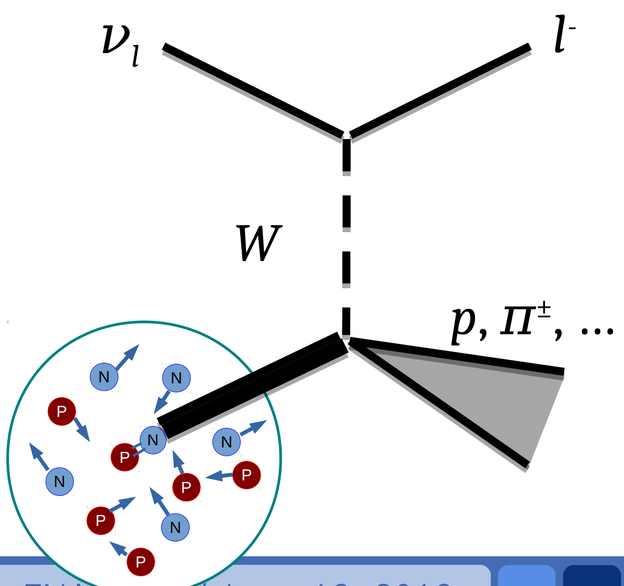

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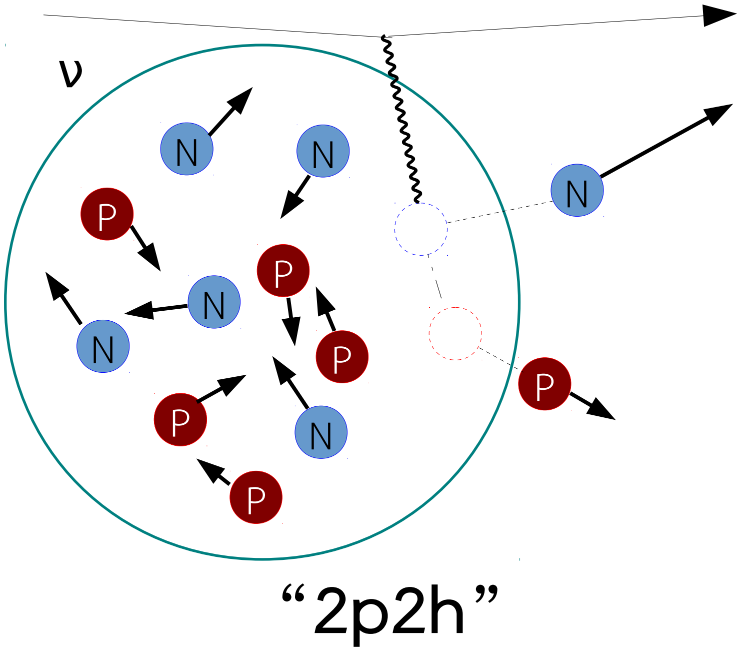
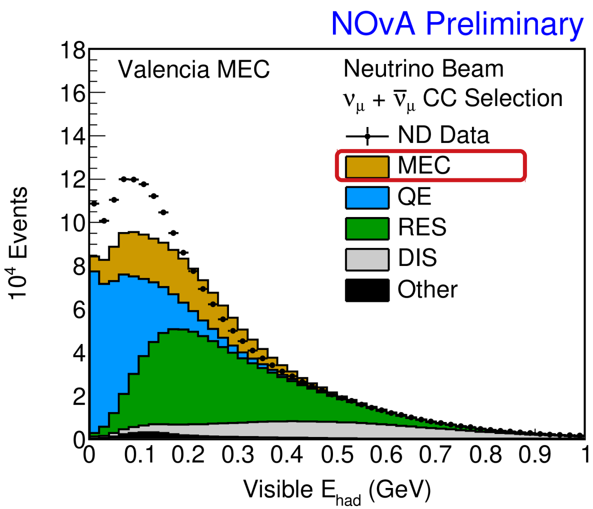
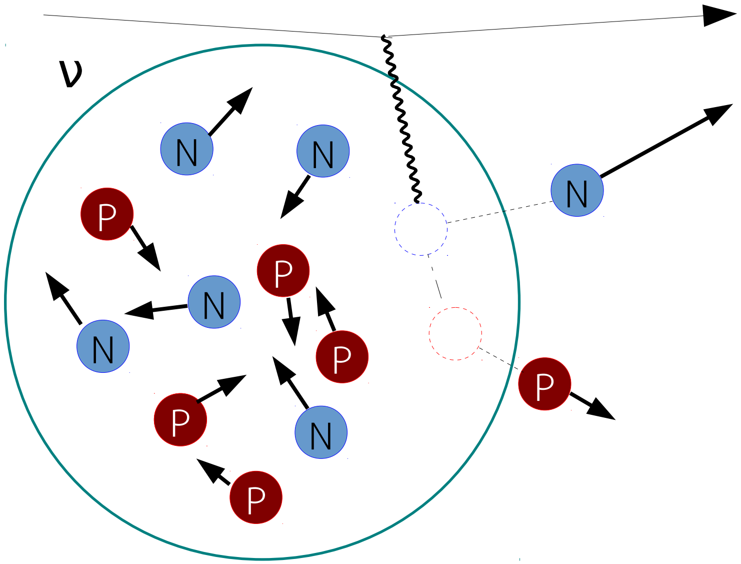




Knock out two nucleons with an elastic-like interaction.

Theory is a work in progress…
("meson exchange currents," **MEC**)

Predictions

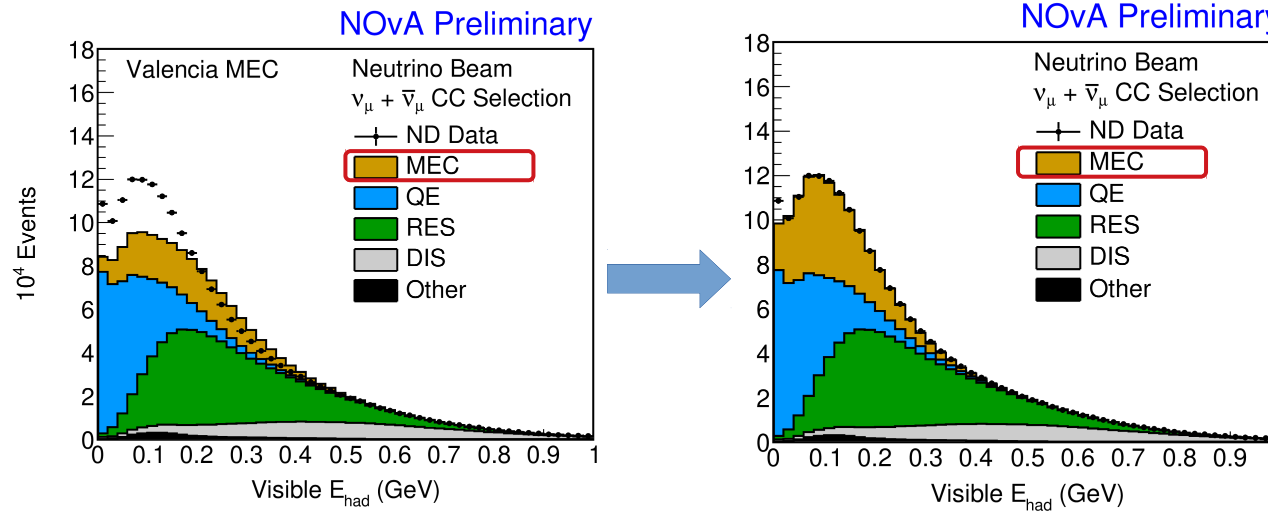


“2p2h”

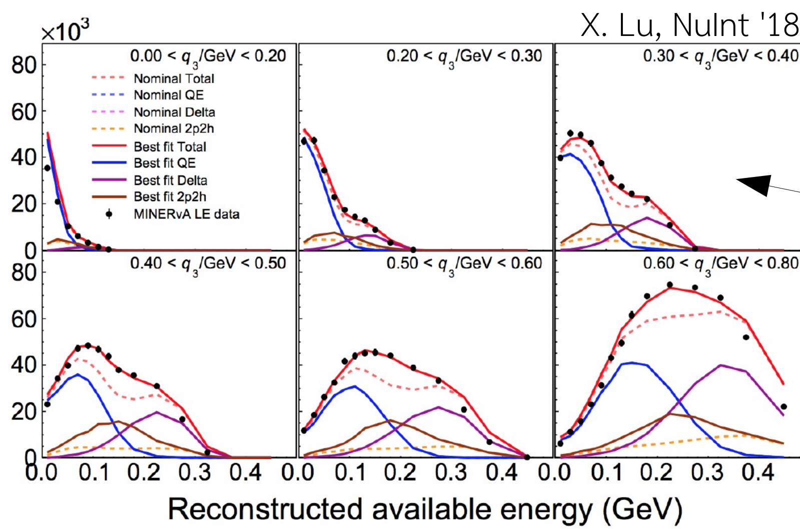
Knock out two nucleons with an elastic-like interaction.

Theory is a work in progress…

employ fits based on empirical model* in meantime



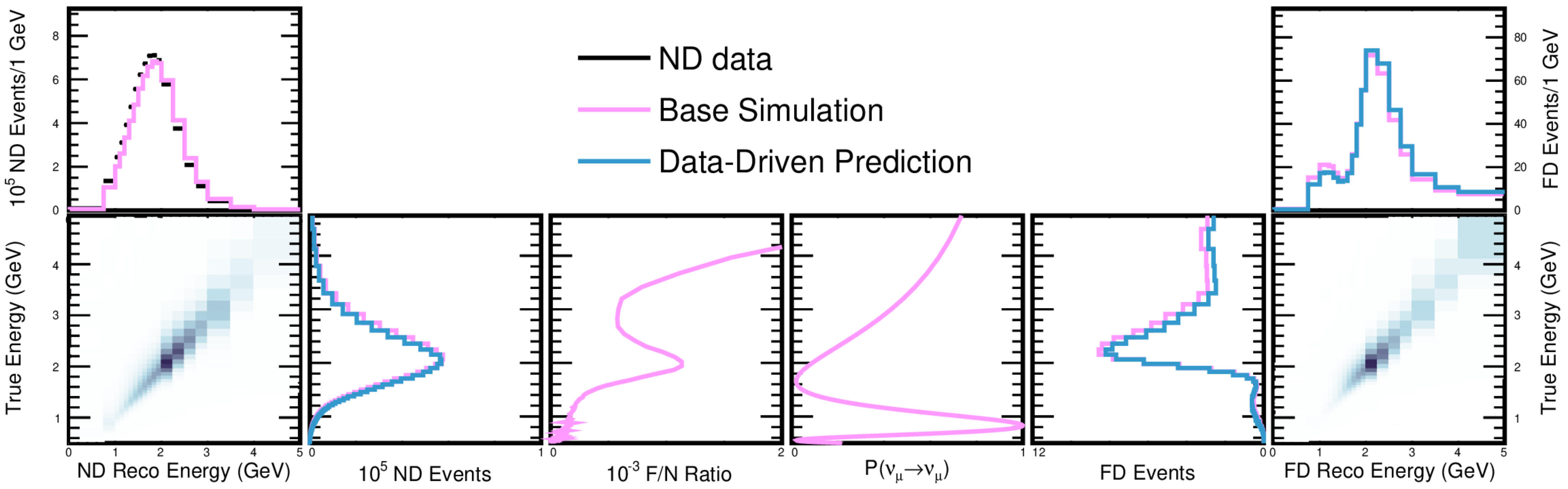
Empirical prediction + uncertainties based on fits to ND data



Inspiration and helpful discussion from our colleagues on MINERvA!

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

Constraining predictions



Constrain predictions w/ ND

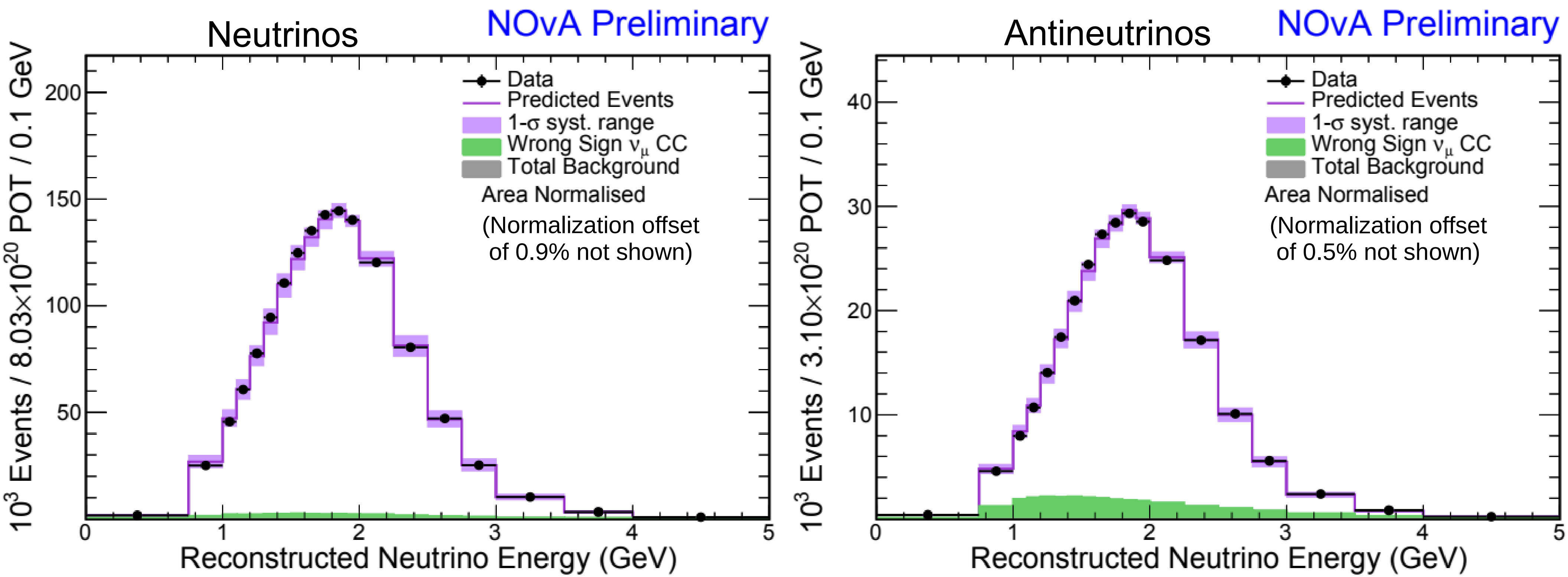
Geometry, oscillations

Compare to FD data

High-stats, unoscillated **Near Detector data constrains predictions** (*including systematics*)

(Poster K. Warburton; NP talk A. Back)

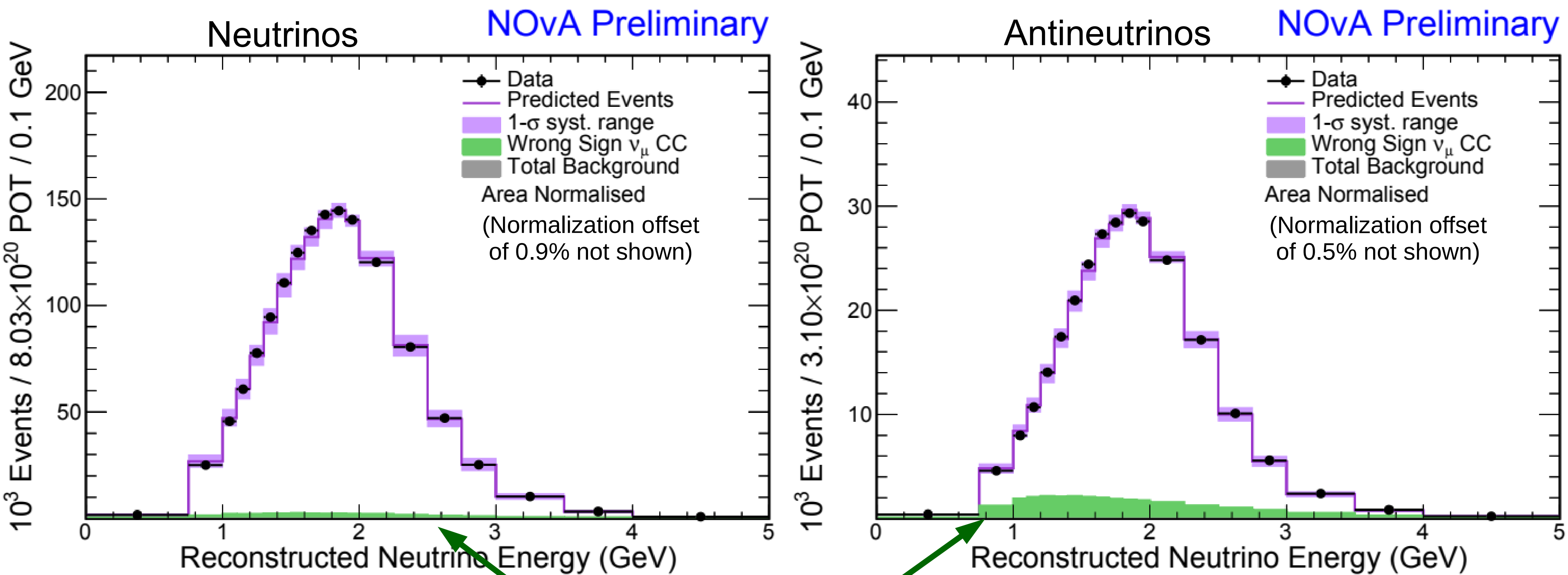
ND Data – ν_μ



Intense beam → large sample of ND events

→ strong constraints on FD predictions

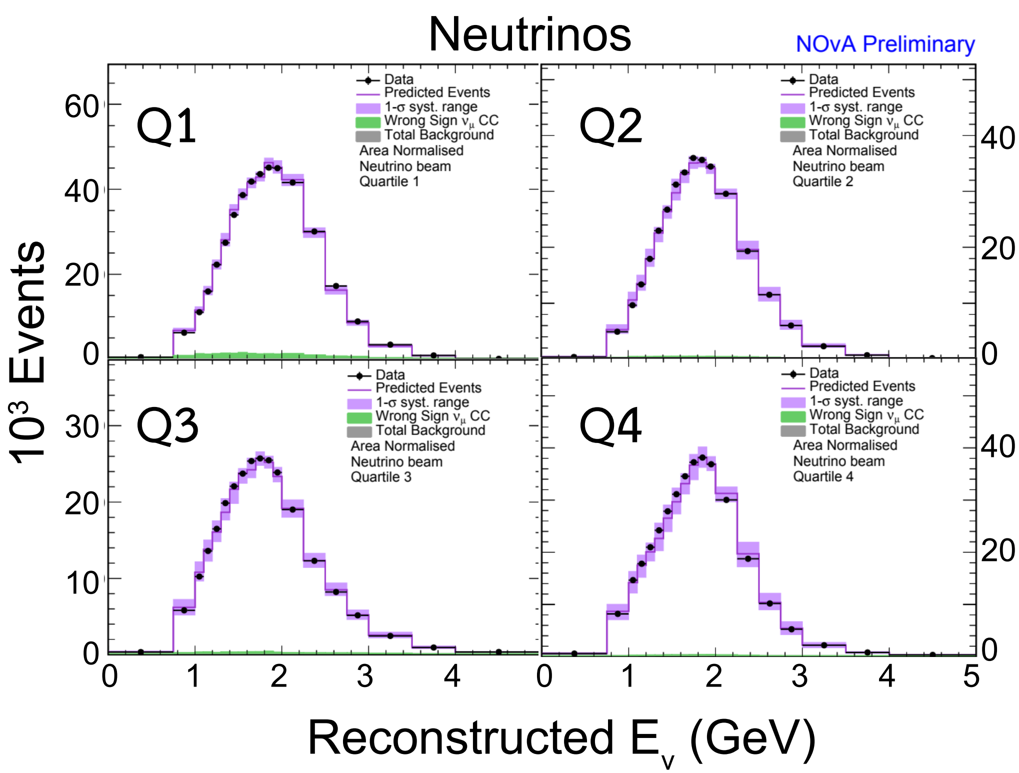
ND Data – ν_μ

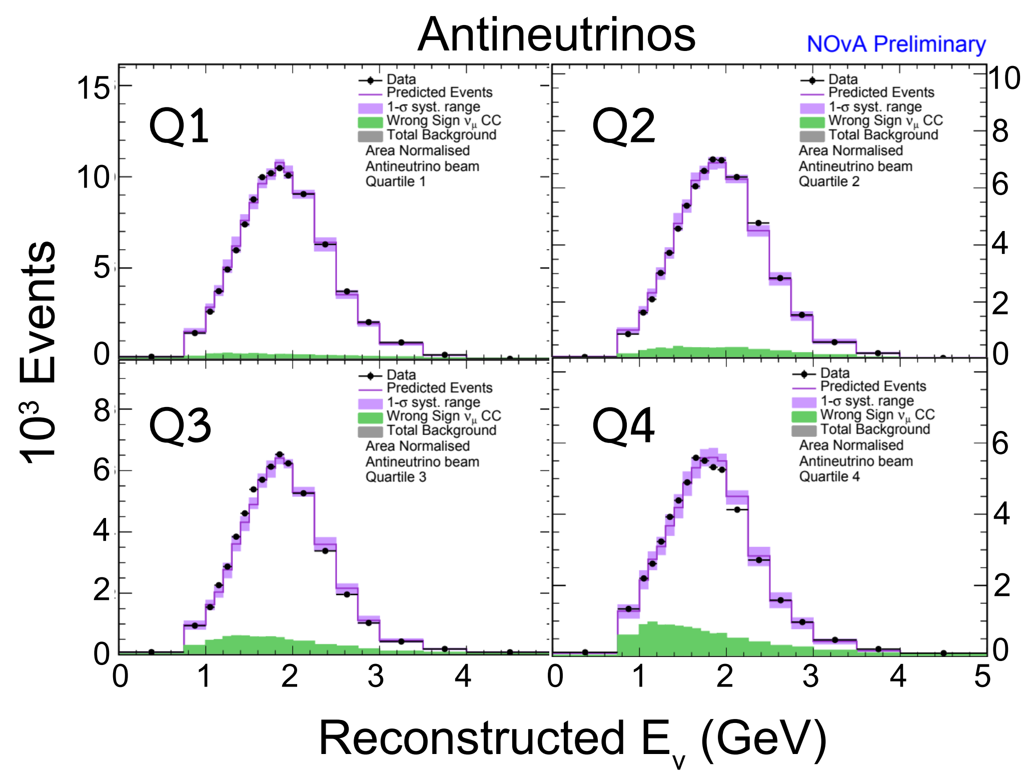


"Wrong sign" is about 3% in ν beam,
11% in $\bar{\nu}$ beam.

(NP talk A. Dombara)

ND Data – ν_μ

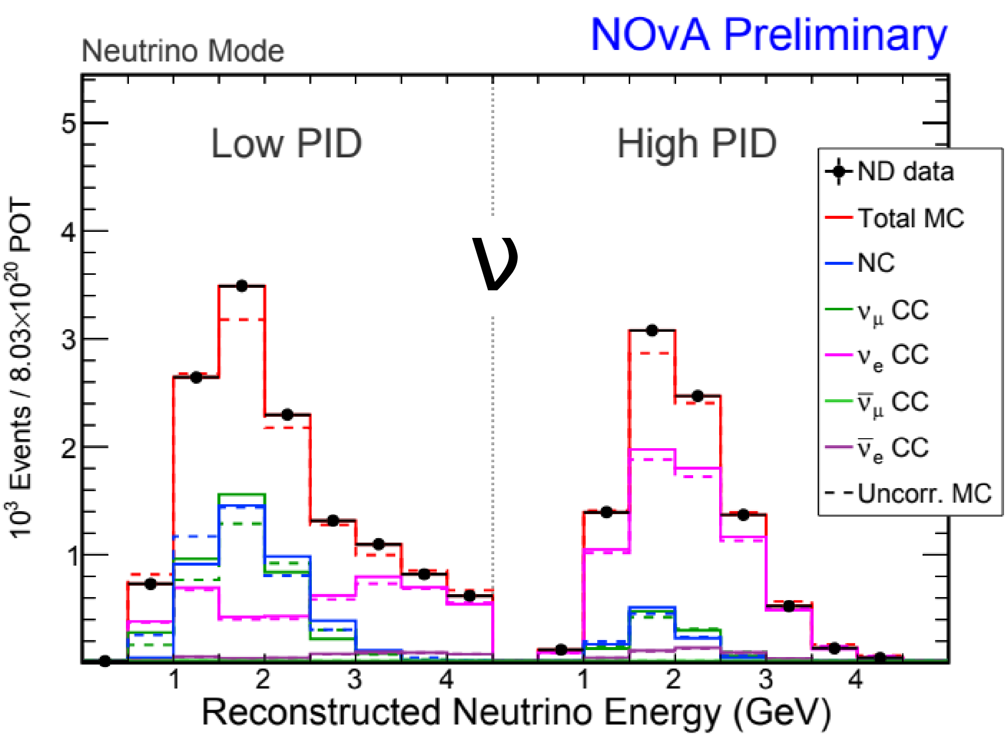


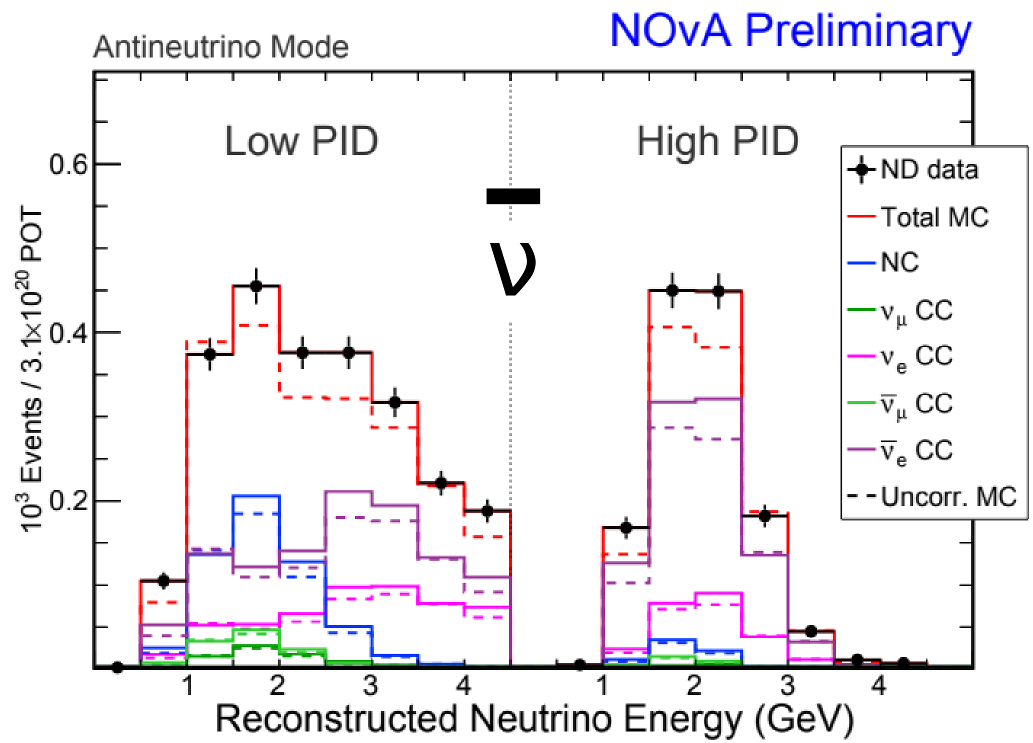


Muon neutrino candidate sample divided into four “quartiles” based on E_{had} / E_ν:

Q1		Q4
smallest E_{had}/E_ν ~6% E_ν resolution	→ (each quartile extrapolated separately)	largest E_{had}/E_ν ~12% E_ν resolution

ND Data – ν_e





More ν_e-like

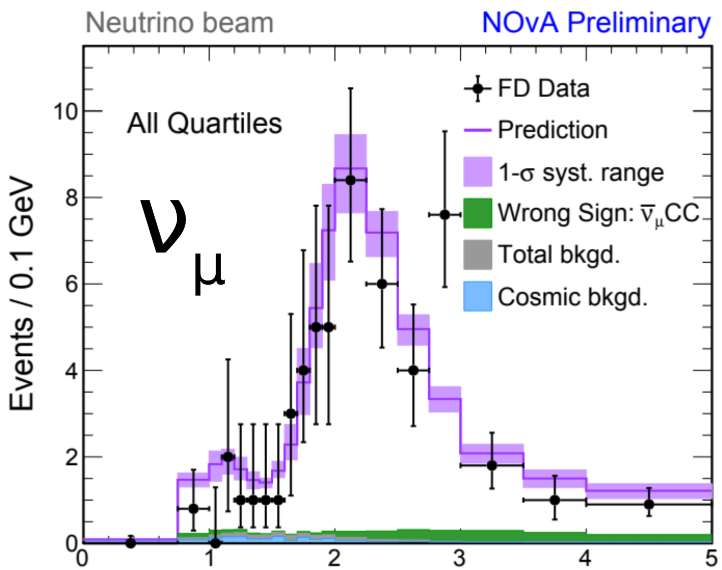
More ν_e-like

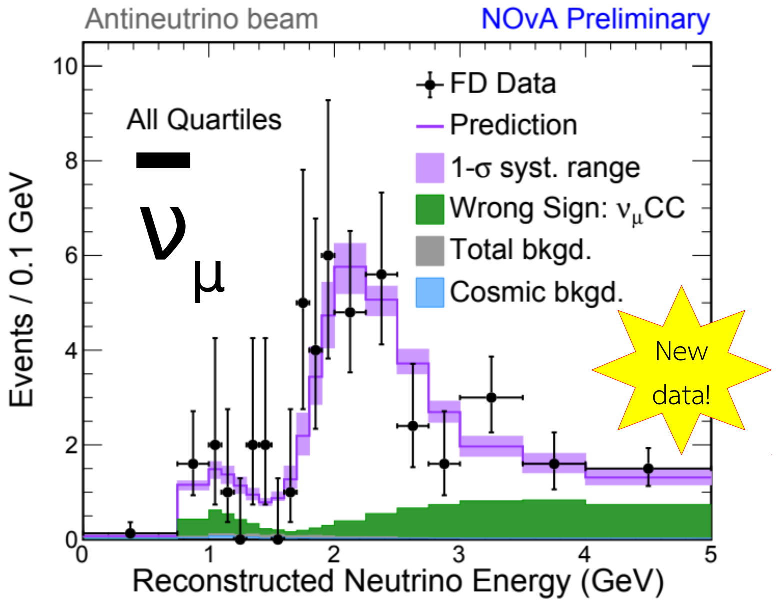
ND ν_e candidates are all background (no oscillations yet):

correct & extrapolate each category separately;

use corrected ND ν_μ prediction for ν_e appearance signal correction

FD data (with *new* $\bar{\nu}$ sample!)





Data neutrino candidates	113
Best fit total prediction	**124**
total bkgd.:	4.2
↳ cosmic bkgd.	2.1
↳ beam bkgd.	2.1

3-flavor oscillations describe data well
(goodness-of-fit p = 0.91)

Data antineutrino candidates	102
Best fit total prediction	**96**
total bkgd.:	2.2
↳ cosmic bkgd.	0.8
↳ beam bkgd.	1.4

Now with 78% more $\bar{\nu}$ data!

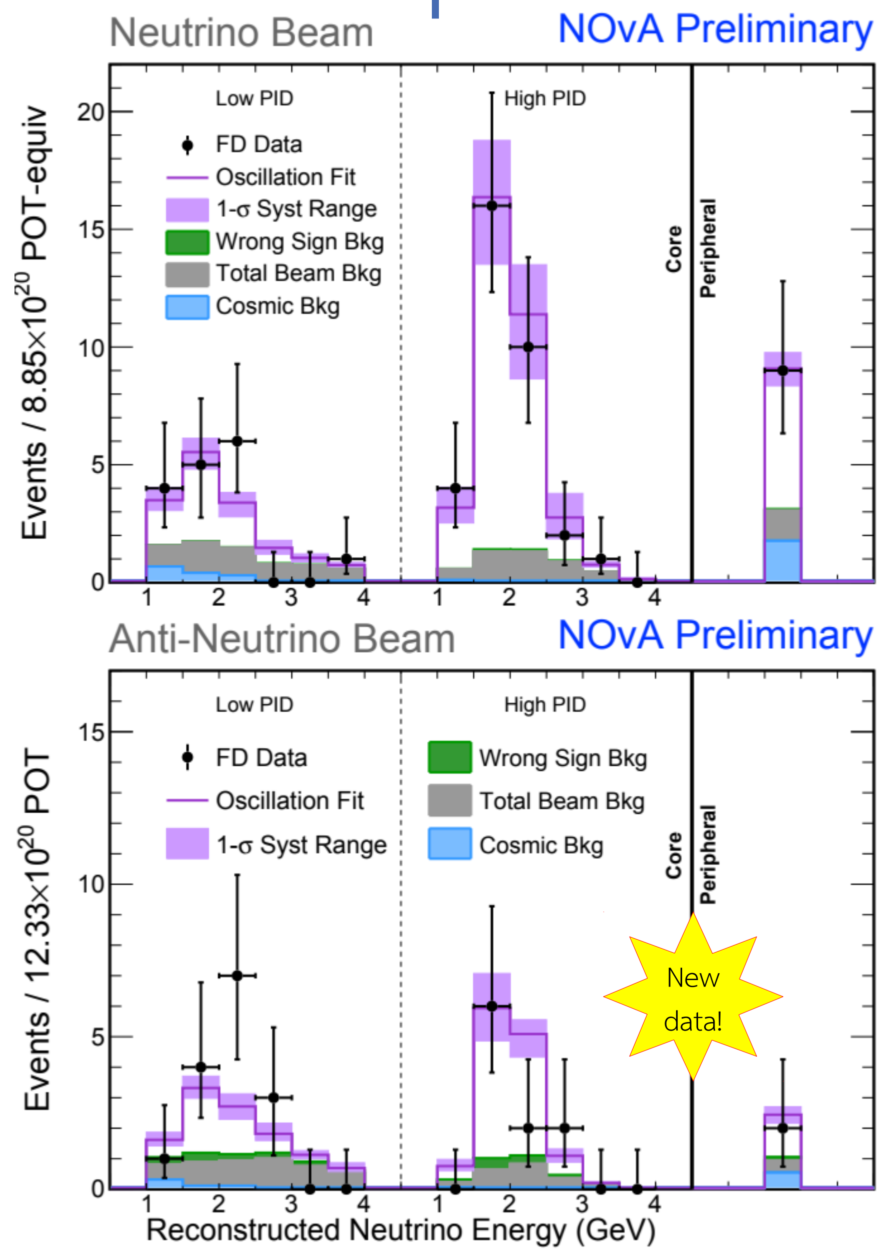
FD data (with *new* $\bar{\nu}$ sample!)

Data neutrino candidates	58
Best fit total prediction	**59**
total bkgd.:	15.0
↳ cosmic bkgd.	3.3
↳ beam bkgd.	11.1
↳ wrong-sign (app. $\bar{\nu}_e$)	0.7

3-flavor oscillations describe data well
(goodness-of-fit p = 0.91)

Now with 78% more $\bar{\nu}$ data!

Data antineutrino candidates	27
Best fit total prediction	**27**
total bkgd.:	10.3
↳ cosmic bkgd.	1.1
↳ beam bkgd.	7.0
↳ wrong-sign (app. ν_e)	2.2



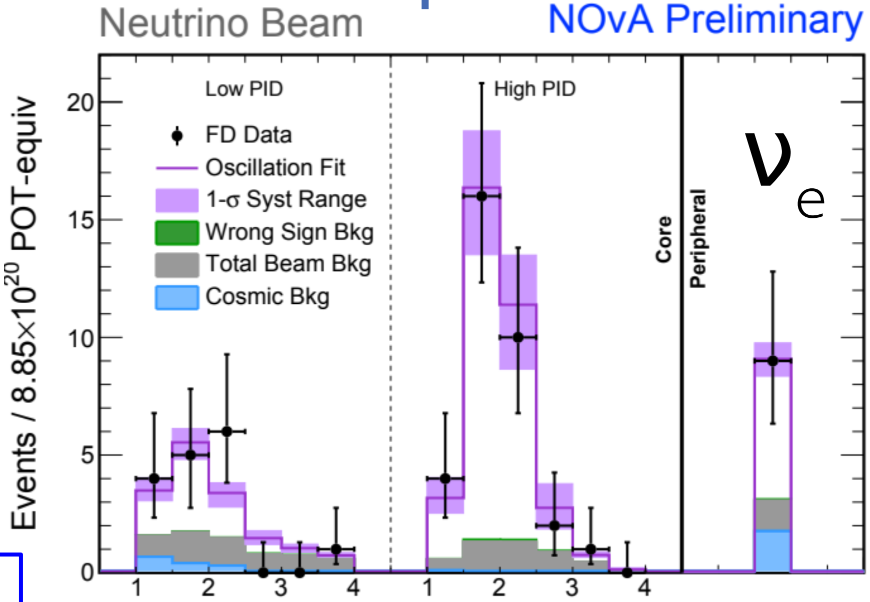
FD data (with *new* $\bar{\nu}$ sample!)

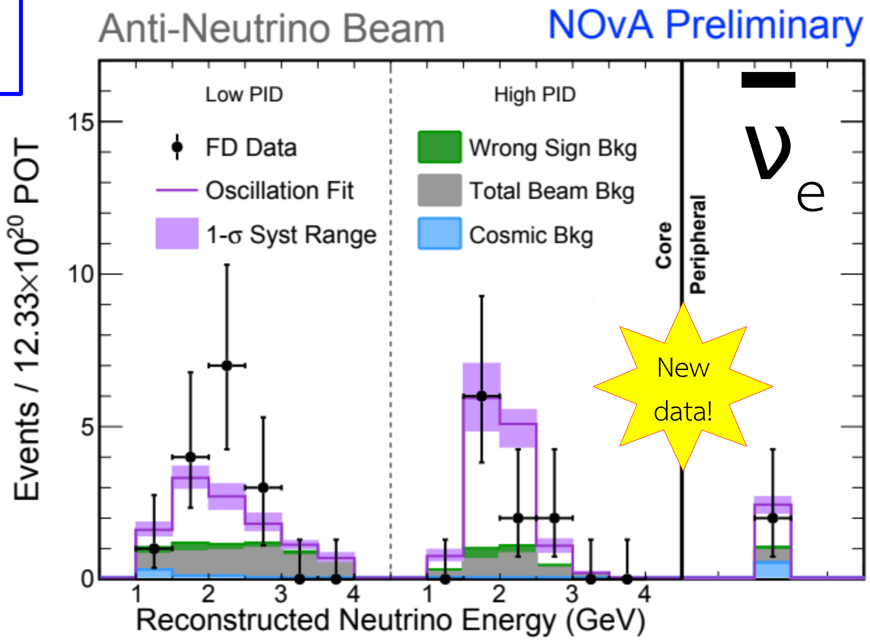
Data neutrino candidates	58
Best fit total prediction	**59**
total bkgd.:	15.0
↳ cosmic bkgd.	3.3
↳ beam bkgd.	11.1
↳ wrong-sign (app. $\bar{\nu}_e$)	0.7

Evidence for $\bar{\nu}_e$ appearance at 4.4σ

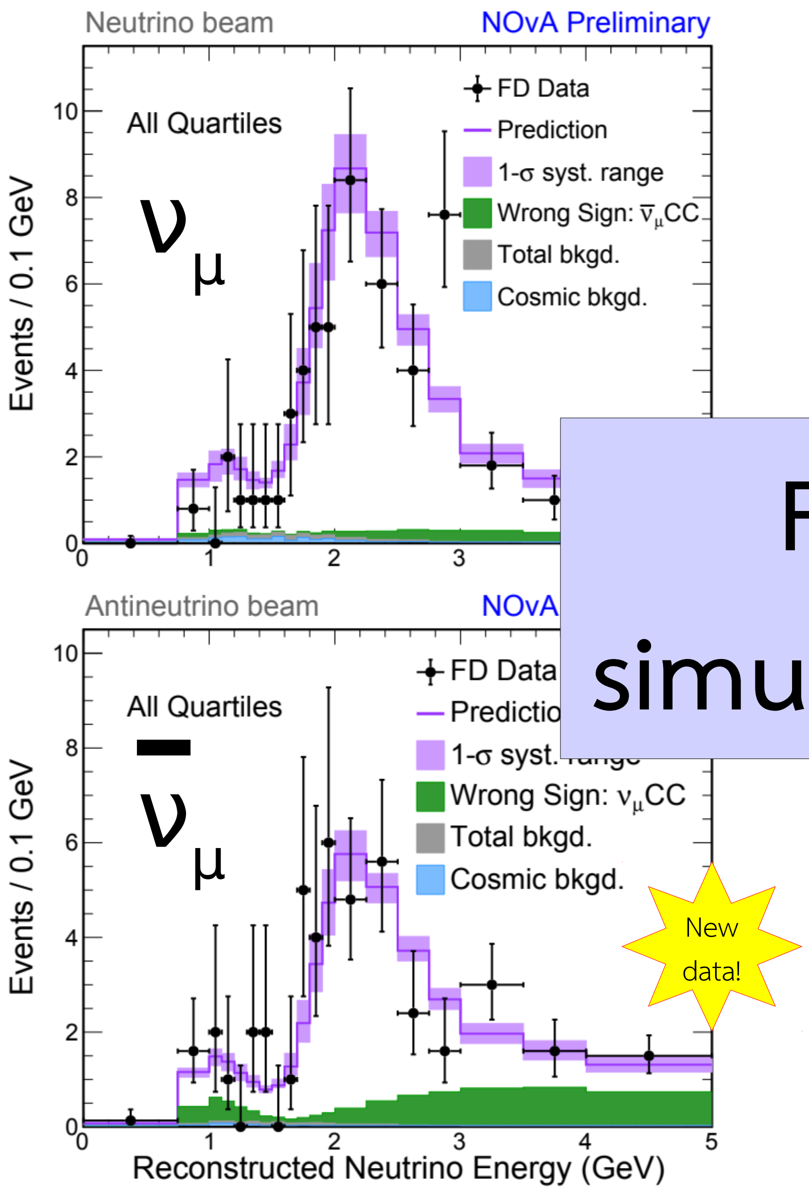
Now with 78% more $\bar{\nu}$ data!

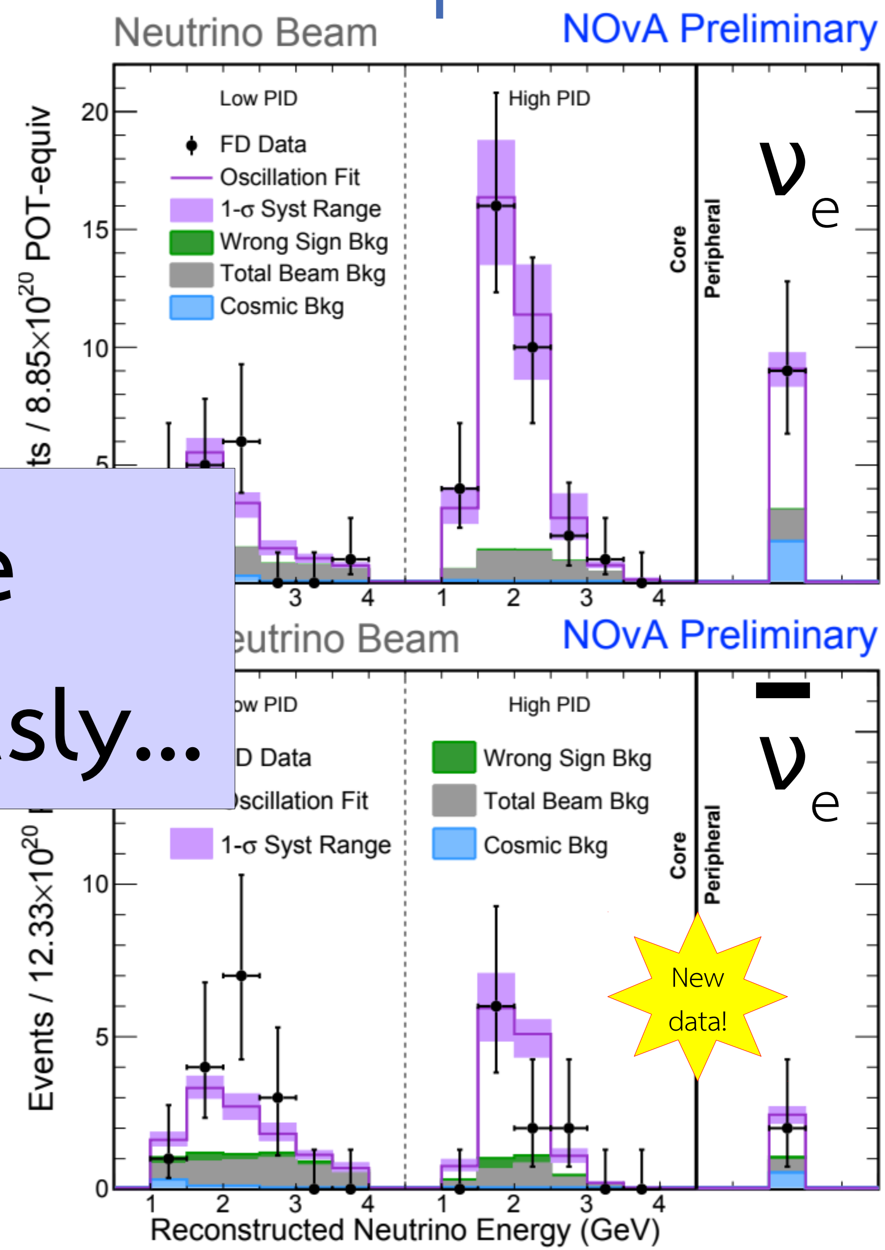
Data antineutrino candidates	27
Best fit total prediction	**27**
total bkgd.:	10.3
↳ cosmic bkgd.	1.1
↳ beam bkgd.	7.0
↳ wrong-sign (app. ν_e)	2.2





FD data (with *new* $\bar{\nu}$ sample!)

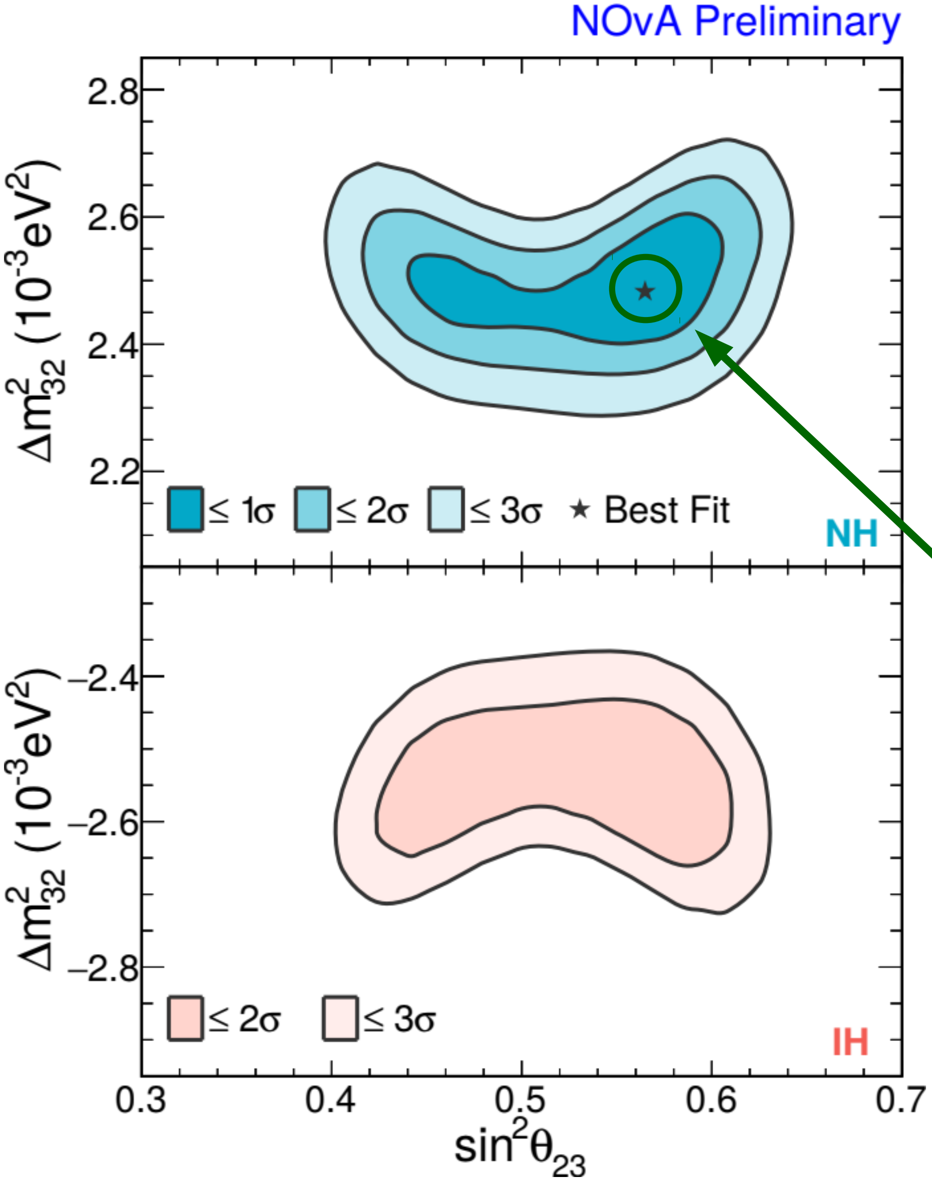


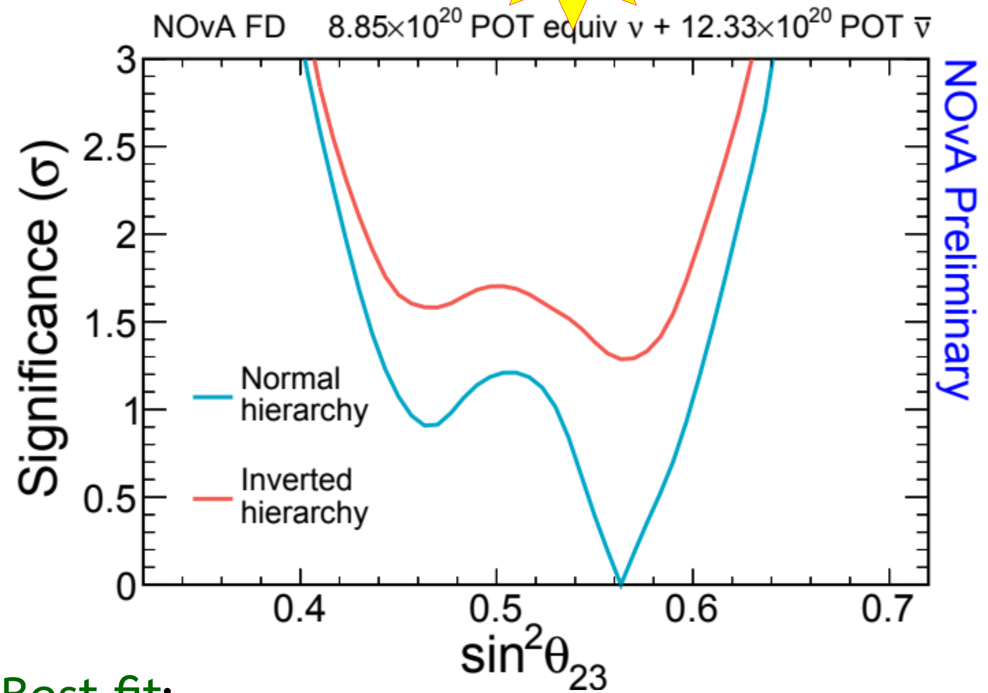


Fit these simultaneously…

Oscillation results

New data!





Best fit:

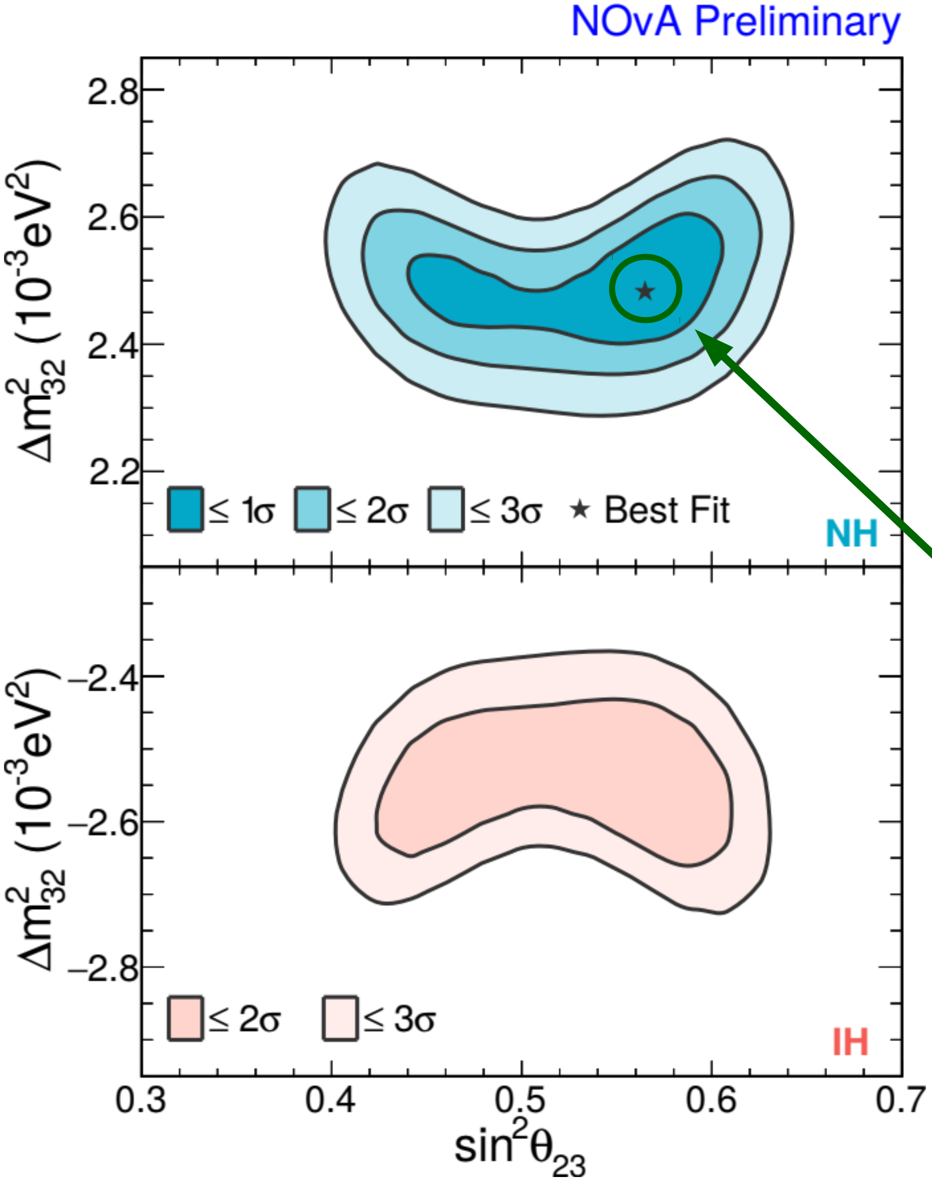
- $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$
- $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\,\mathrm{eV}^2/c^4$ (NH)

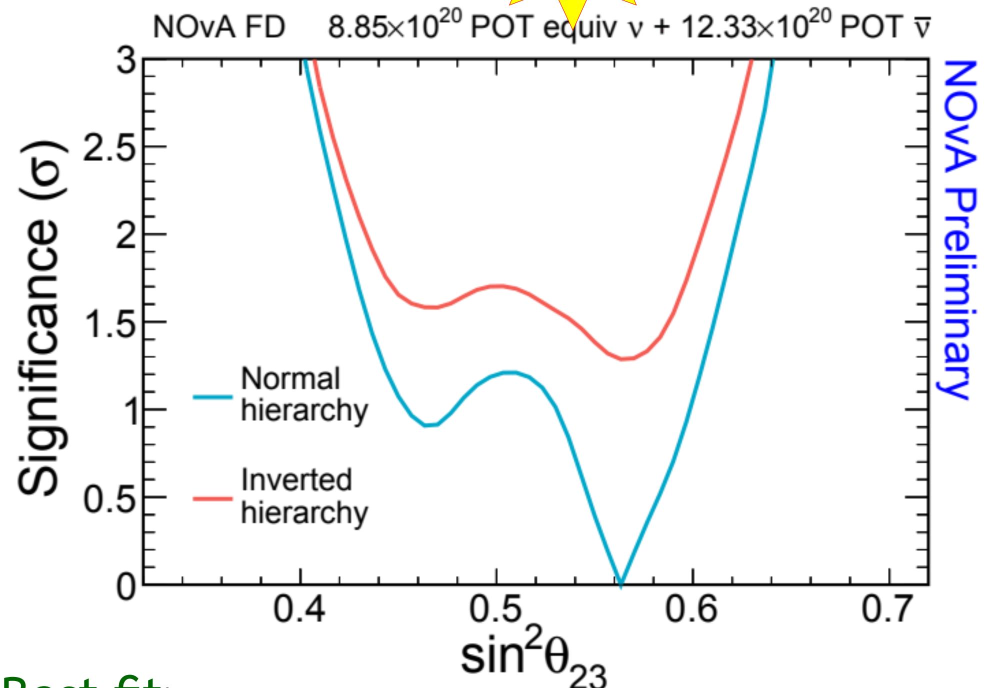
$\sin^2\theta_{23} < 0.5$ **(lower octant) disfavored at 1.6σ**

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

Oscillation results

New data!





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$\sin^2\theta_{23} < 0.5$ **(lower octant) disfavored at 1.6σ**

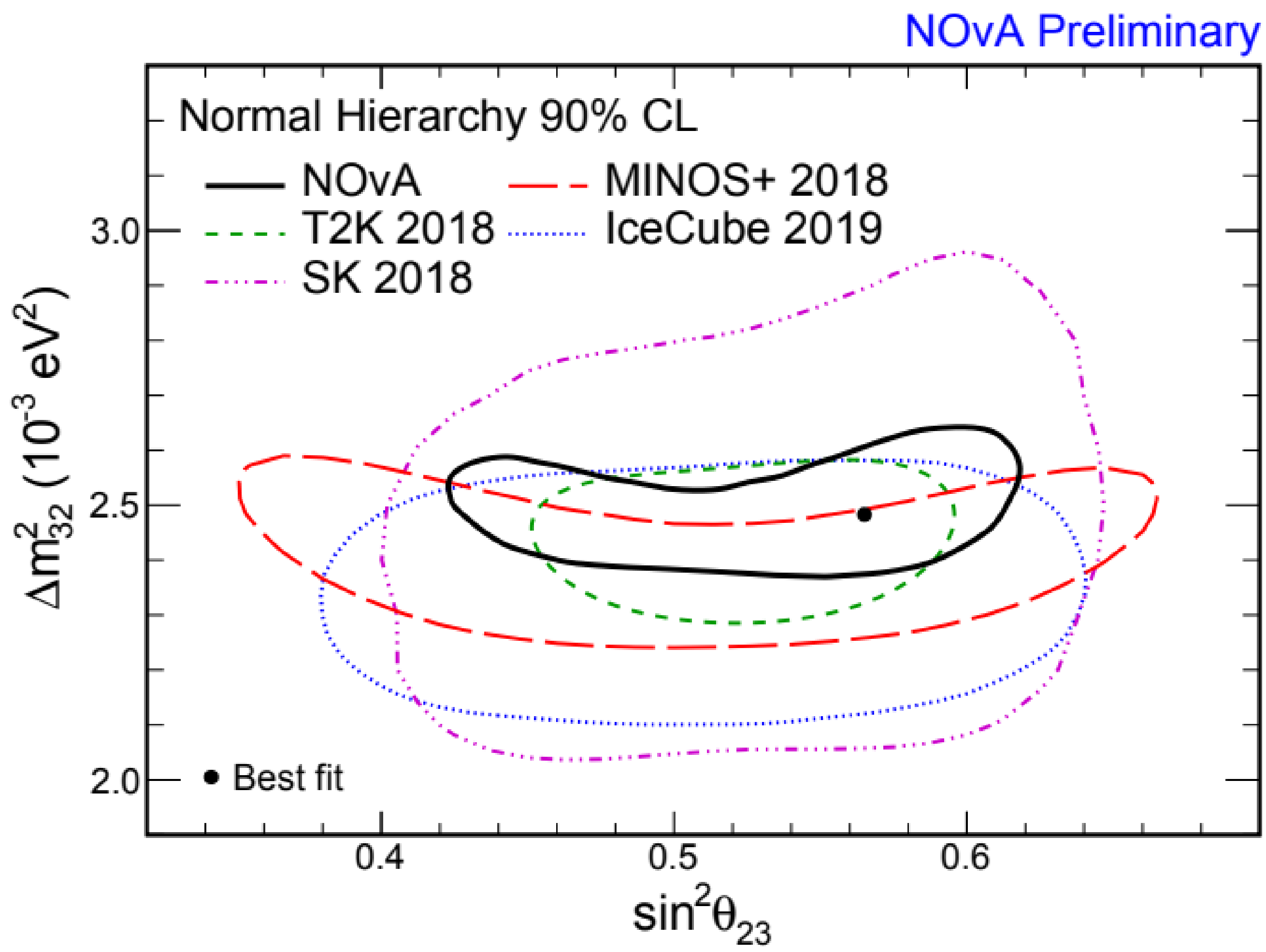
$\sin^2\theta_{23} = 0.5$ disfavored at 1.2σ

$\nu_3 =$?

ν_e ν_μ ν_τ

Oscillation results

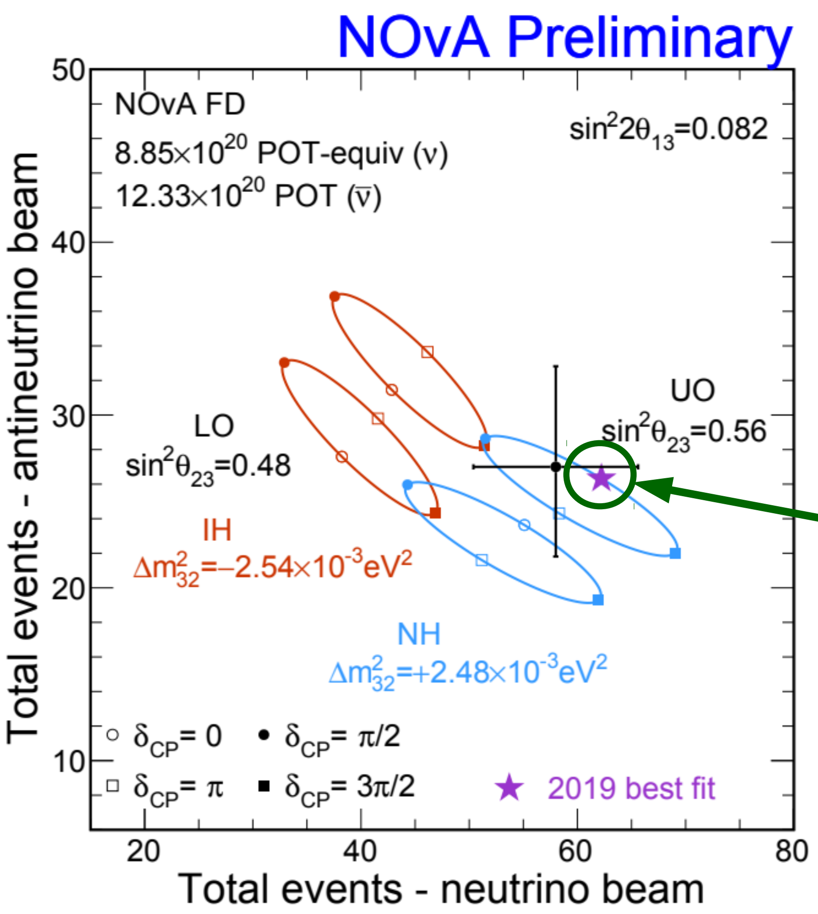
New data!



Precision measurement of atmospheric parameters

Oscillation results

New data!



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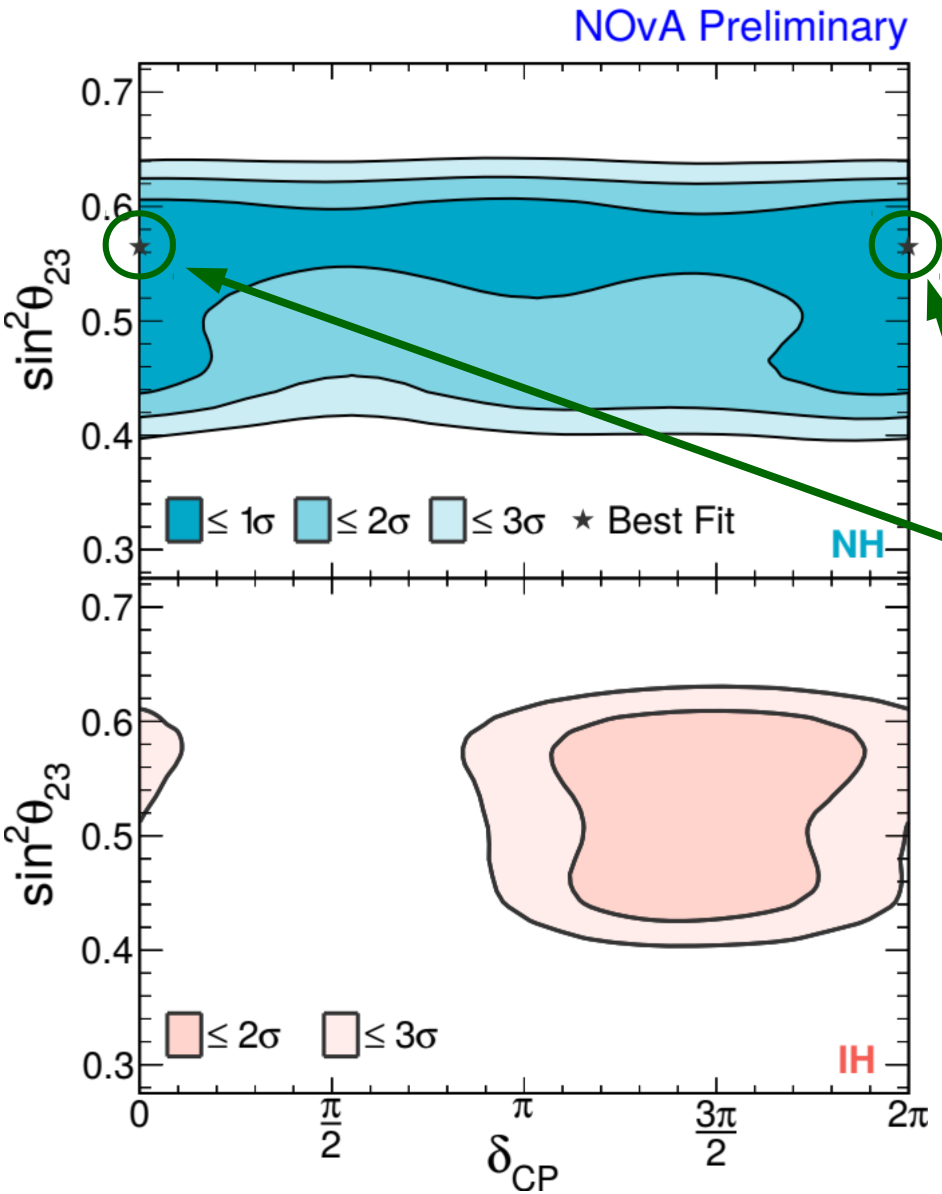
- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\,\pi$

Oscillation results

New data!



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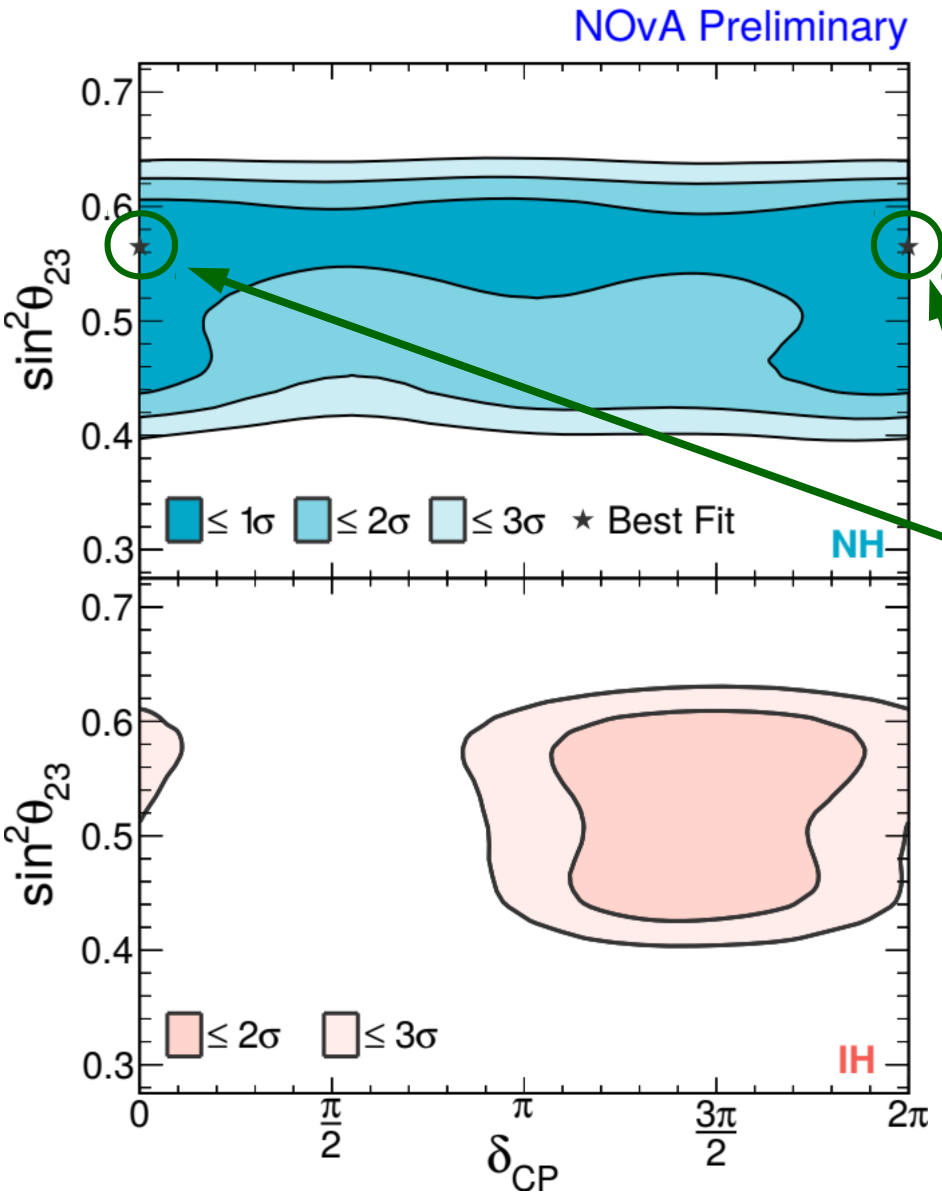
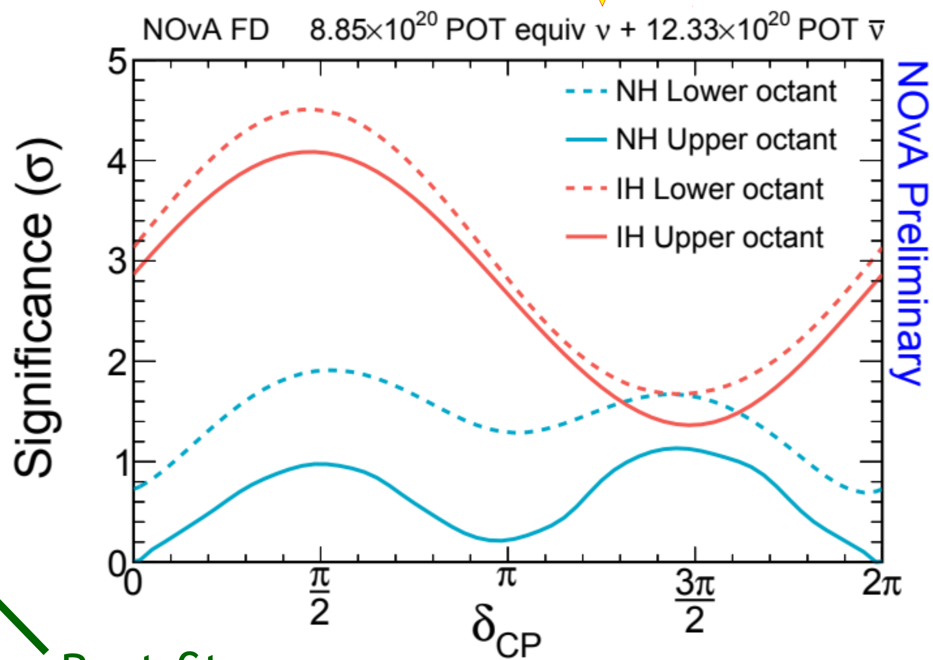
- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

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

Oscillation results

New data!





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- $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\,\mathrm{eV}^2/c^4\,(\mathrm{NH})$
- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

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

NHUO: All values of δ allowed at 1.1σ

IH: δ= π/2 ruled out > 4σ

Oscillation results

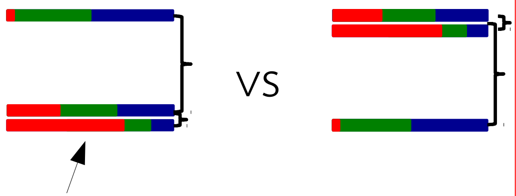
New data!

[Feldman-Cousins corrected significances]

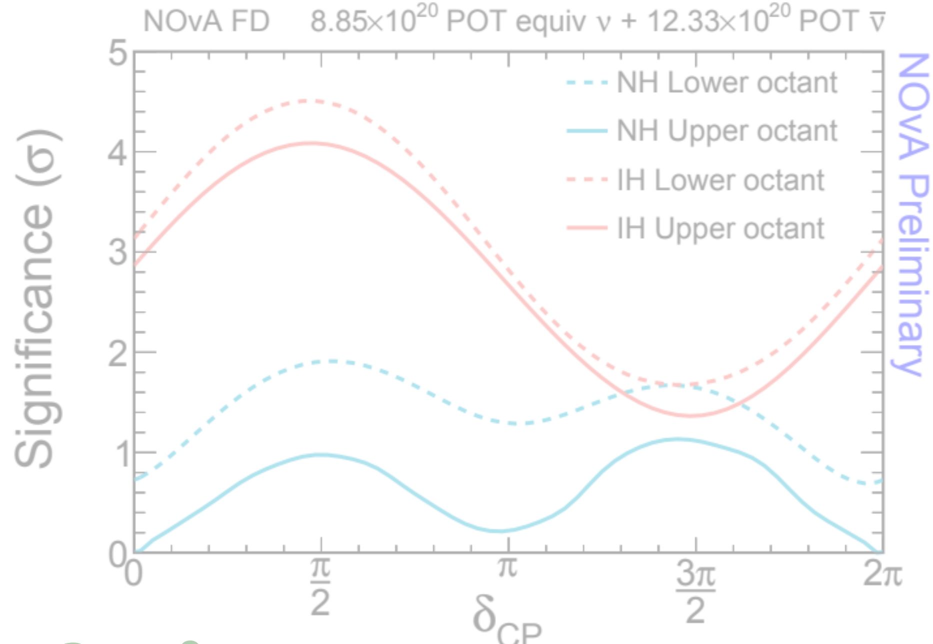
NH UO Best fit	**IH UO** Disfavored 1.8σ
NH LO Disfavored 1.6σ	**IH LO** Disfavored 2.0σ

LO Disfavored 1.6σ

IH Disfavored 1.9σ



NH preferred by 1.9σ



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- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

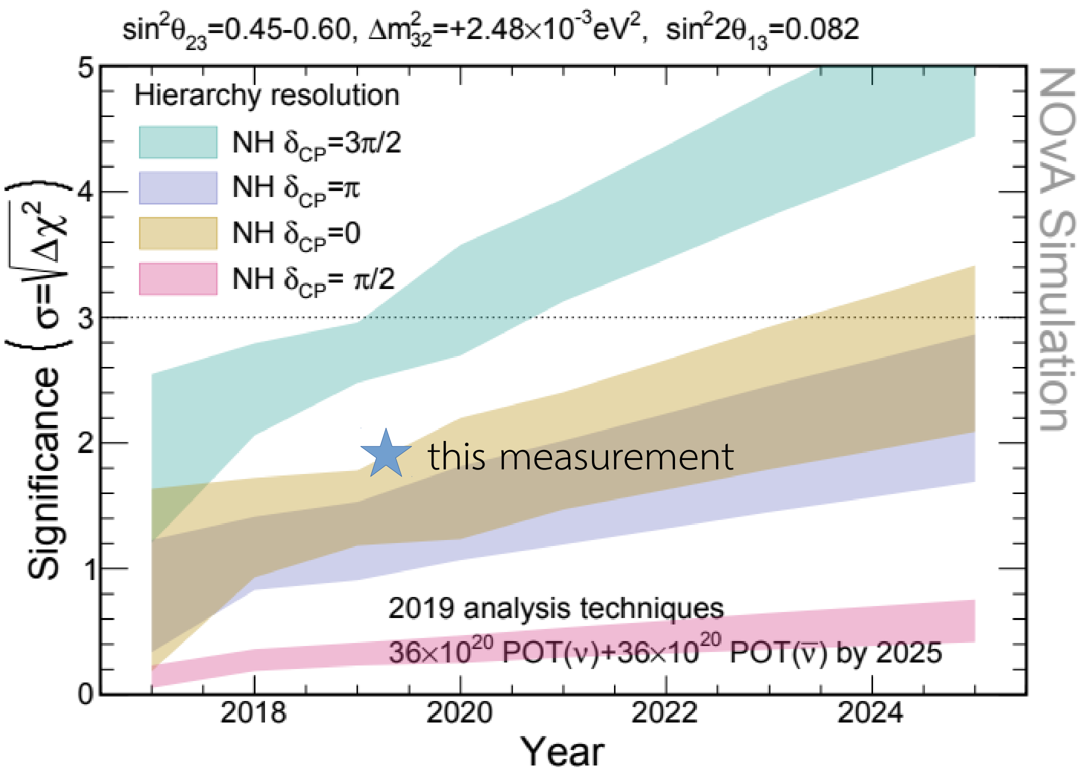
$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

NHUO: All values of δ allowed at 1.1σ

IH: δ= π/2 ruled out > 4σ

Future

- Currently running in neutrino mode
  - Run plan: 50:50 $\nu:\bar{\nu}$
  - NOvA is expected to run until 2025
  - Beam improvements an important part of story!
- With current analysis, expect:
  - **Potential 3-5σ sensitivity to hierarchy** with favorable parameters
  - **Possible >2σ sensitivity to CP violation**
- Anticipating improvements in simulations that should improve analysis robustness
  - Test Beam / improved det. response model
  - GENIE 3.0 / improved cross section models



Summary

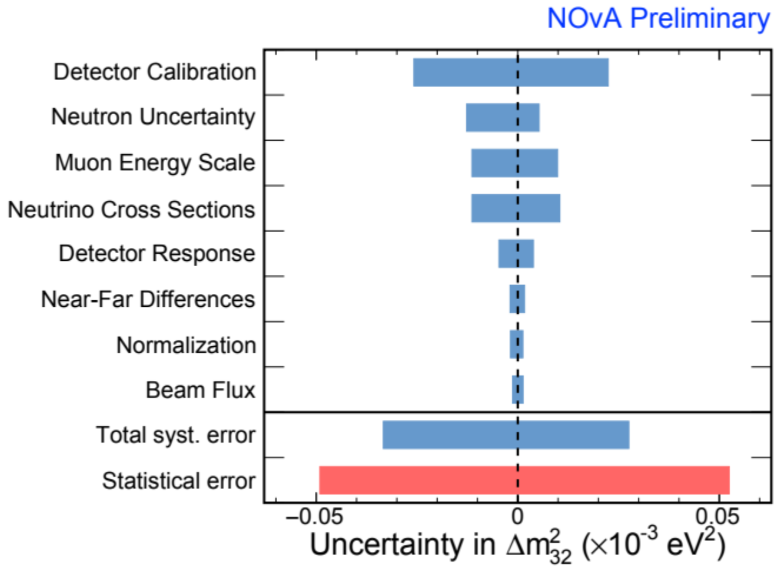
- With 8.85×10^{20} POT neutrino + 12.33×10^{20} POT antineutrino beam exposure, NOvA finds:
  - **4.4σ evidence for electron antineutrino appearance** in a muon antineutrino beam
  - **1.9σ preference for the Normal neutrino mass hierarchy**
  - **1.6σ preference for θ_{23} residing in the Upper Octant** (maximal mixing disfavored at 1.2σ)
- With continued running through 2025, NOvA anticipates:
  - **Possible 3-5σ sensitivity to the mass hierarchy**
  - **Potential sensitivity to CP violation >**2σ
  - Input from NOvA Test Beam program, neutrino interactions community to **further improve robustness** to systematics
- Come join the fun!
  30 doctoral / 9 masters / 1 bachelors NOvA theses (and counting)!

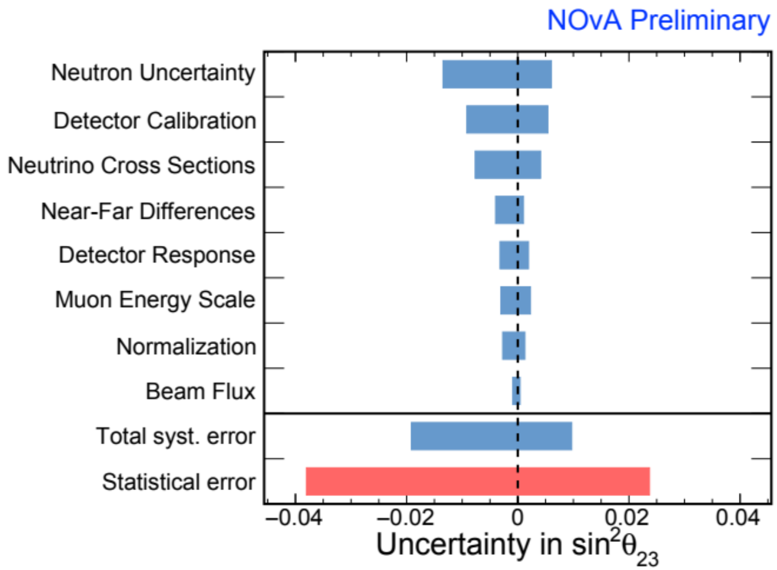
Paper reference for today's new result: arXiv:1906.04907

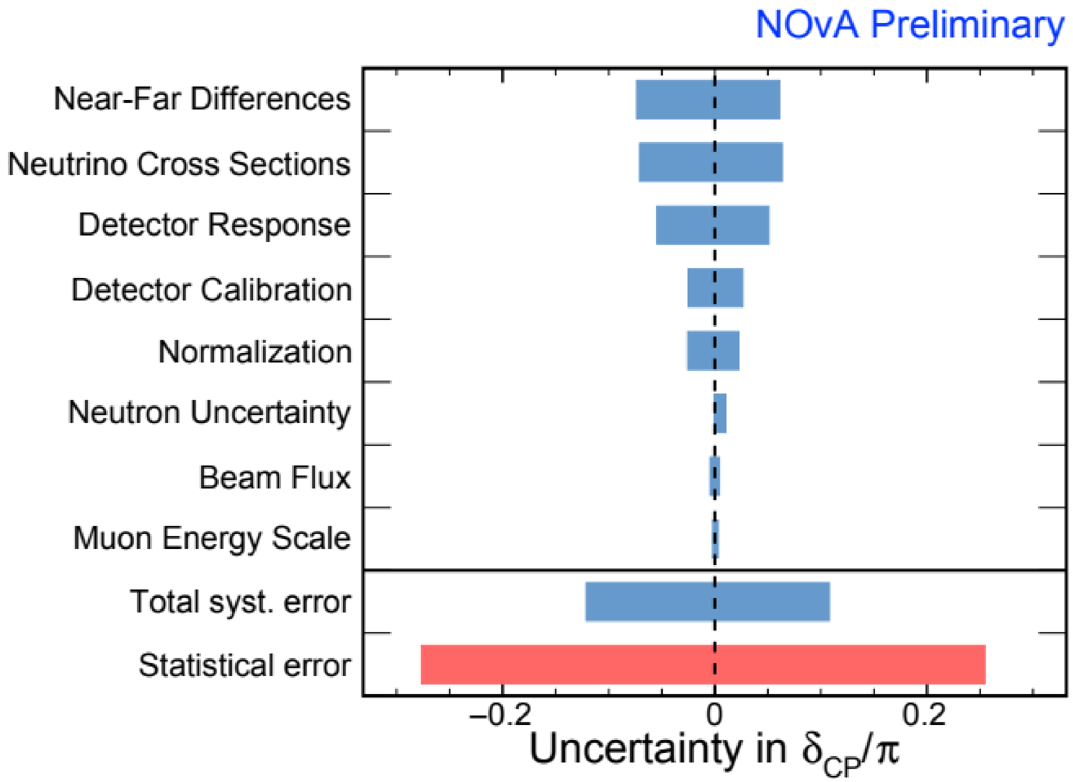
[June 2019 meeting @ Sussex University, Brighton, UK]

Overflow

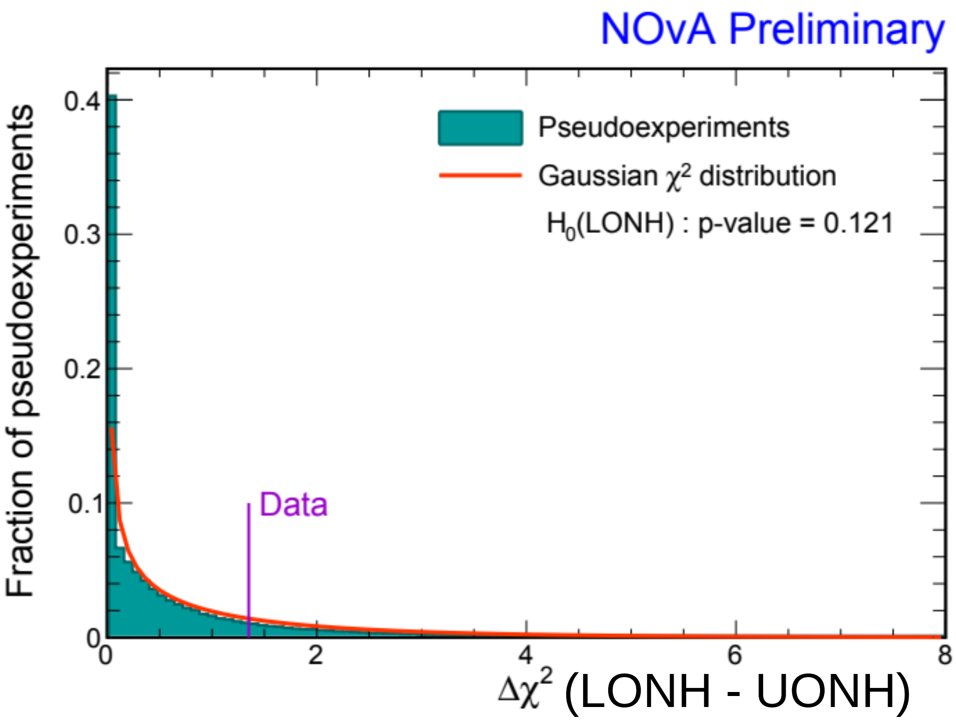
Systematics





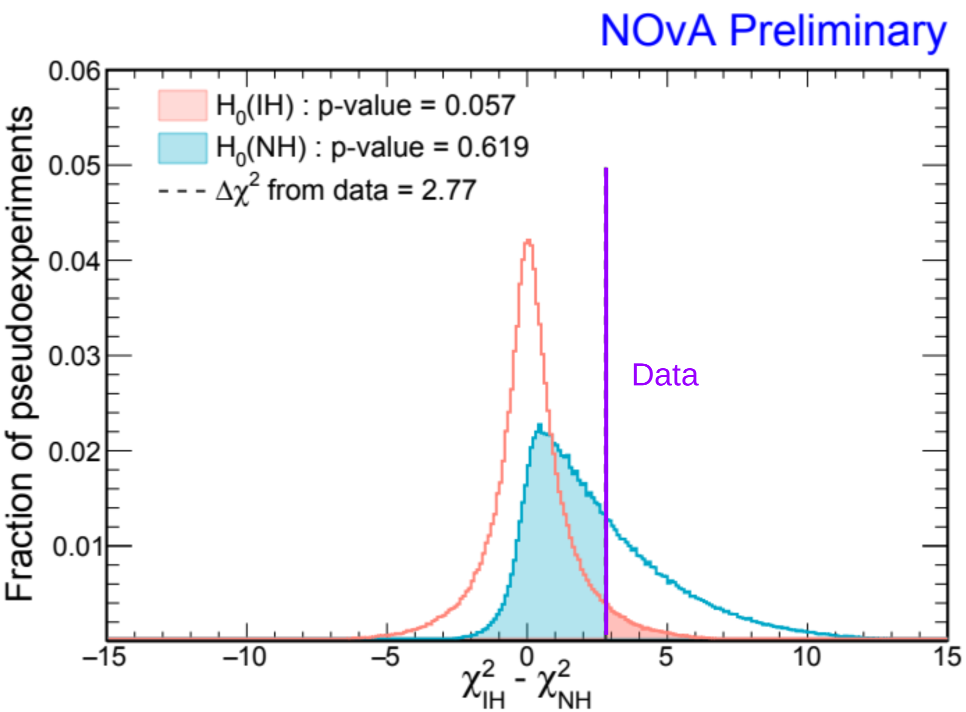


Calculating significances



Feldman-Cousins method

Generate many pseudoexperiments w/ null hypothesis: measure *p*-value of data exclusion of null "empirically"



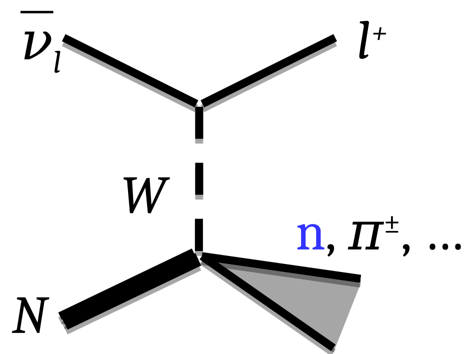
CL_s:

Compute *p*-values of *both* hypotheses; if p_{null}/p_{alt} is large, exclusion of null is suspicious.

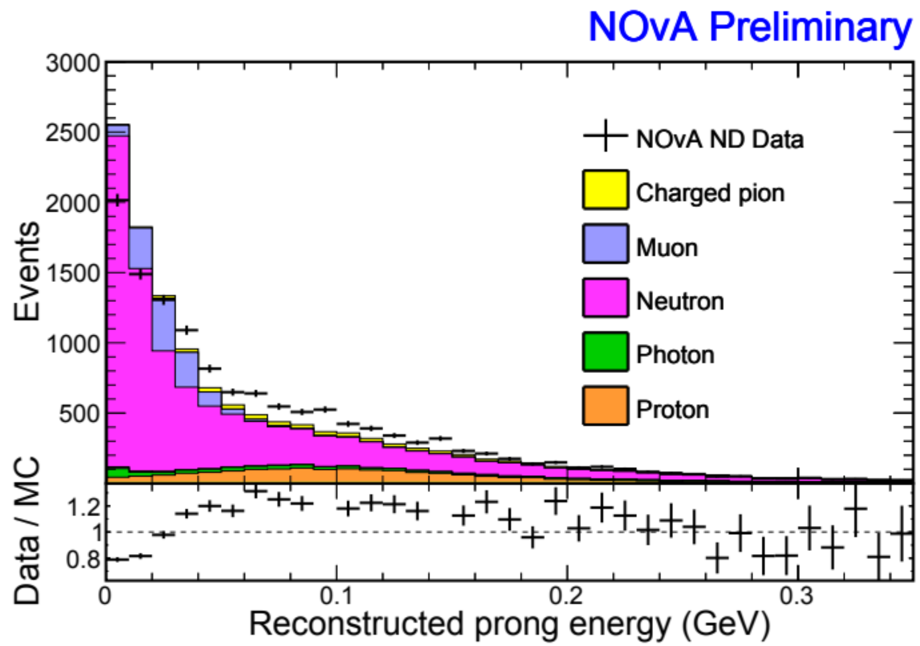
$$CL_S = 0.094$$

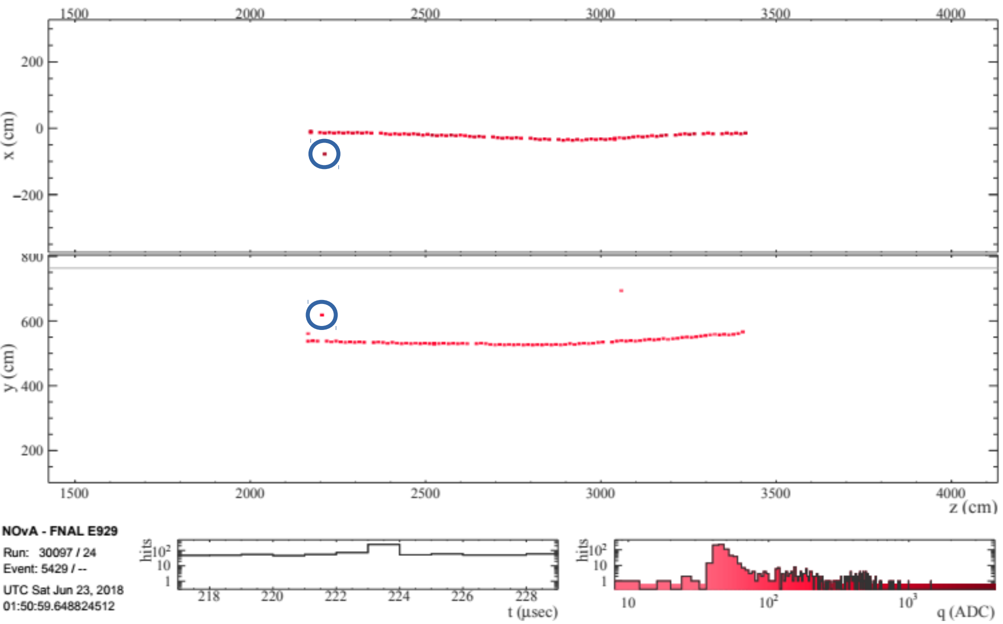
Neutron response

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



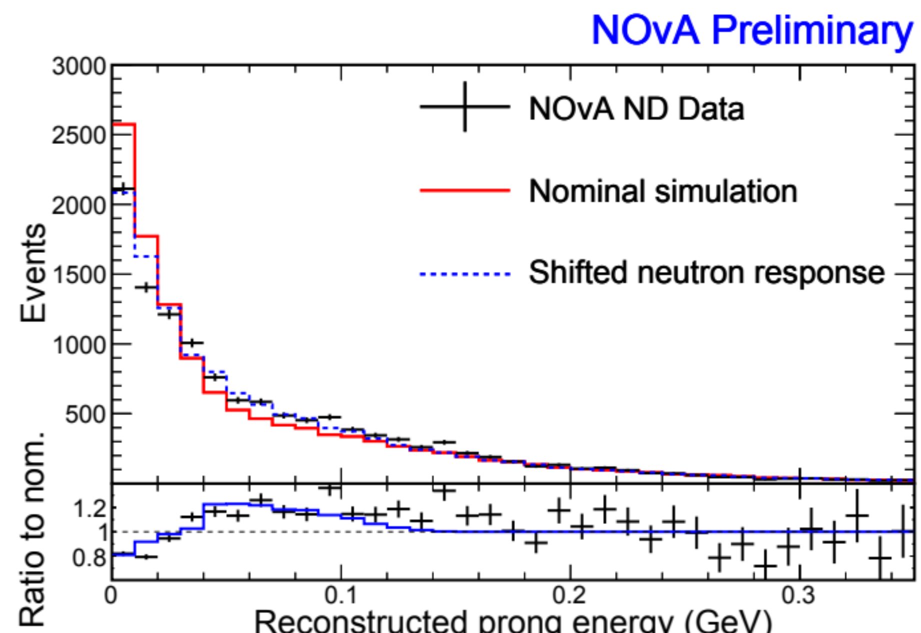
neutrons dominate in antineutrino reactions





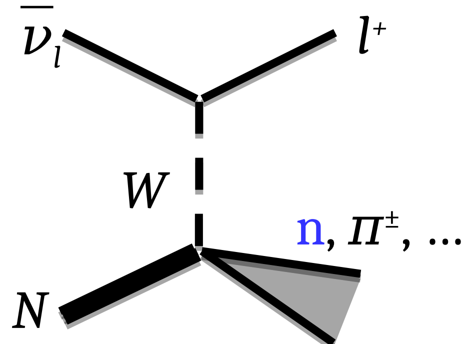
Search for $\bar{\nu}$ QE-like events
(μ + no other tracks)
with compact displaced energy deposits...

... and design uncertainty to bound
data-simulation difference in observed energy



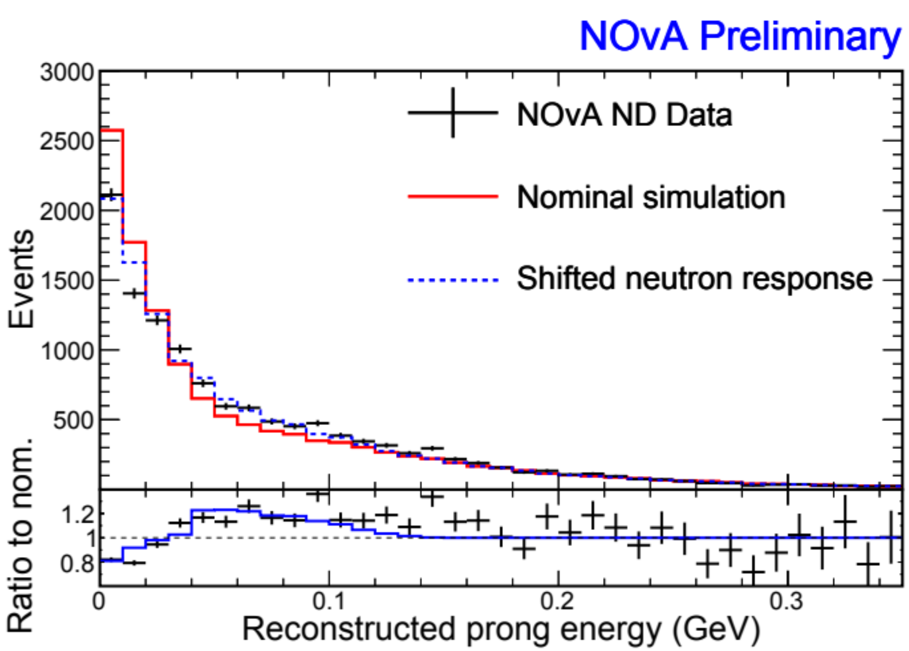
Neutron response

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

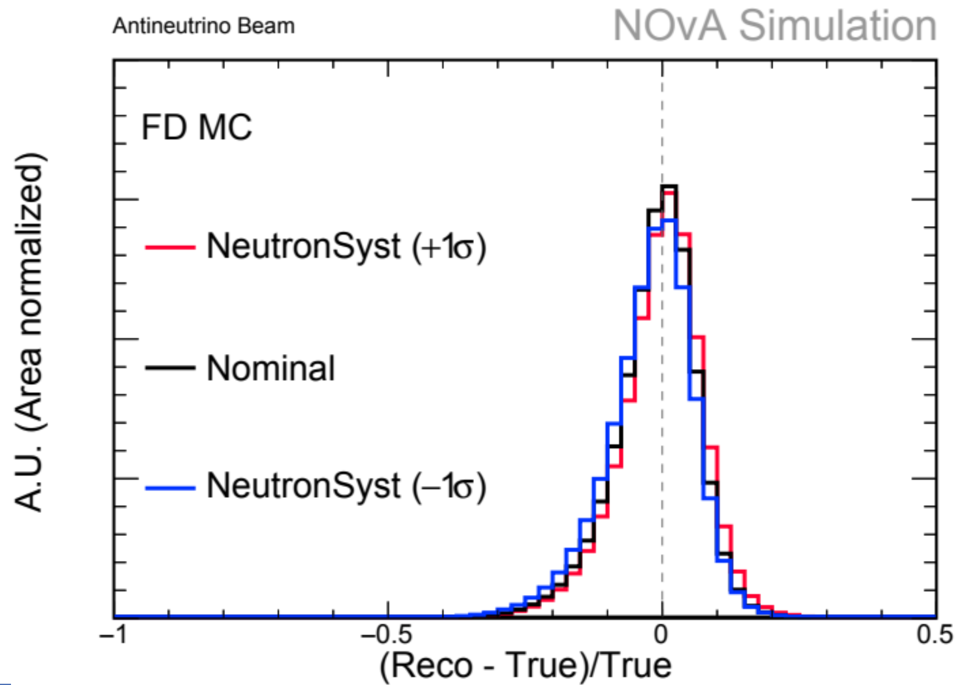


neutrons dominate in antineutrino reactions

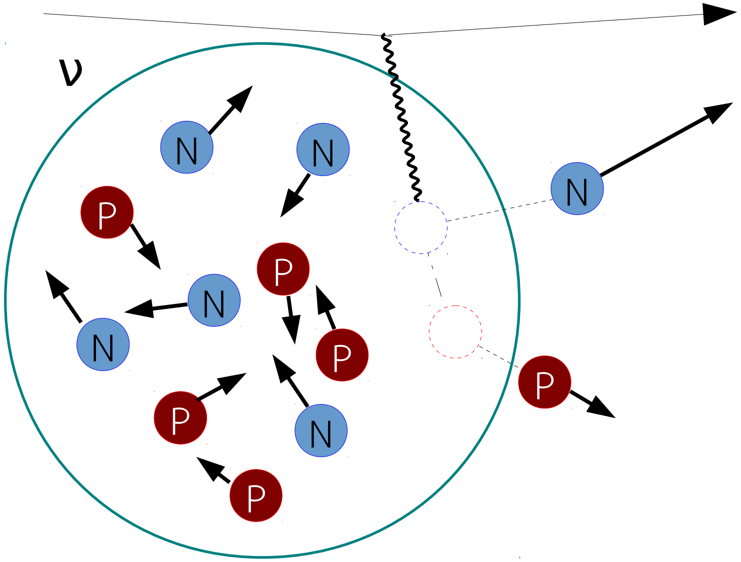
~1% effect shift in mean energy,
negligible change to resolution,
negligible change to selection efficiencies



→



Xsec model tuning: 2p2h

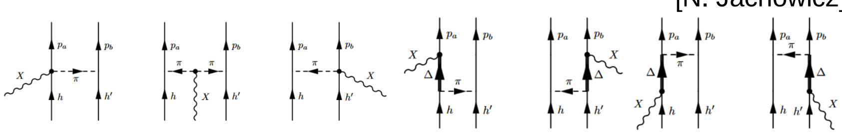


“2p2h”

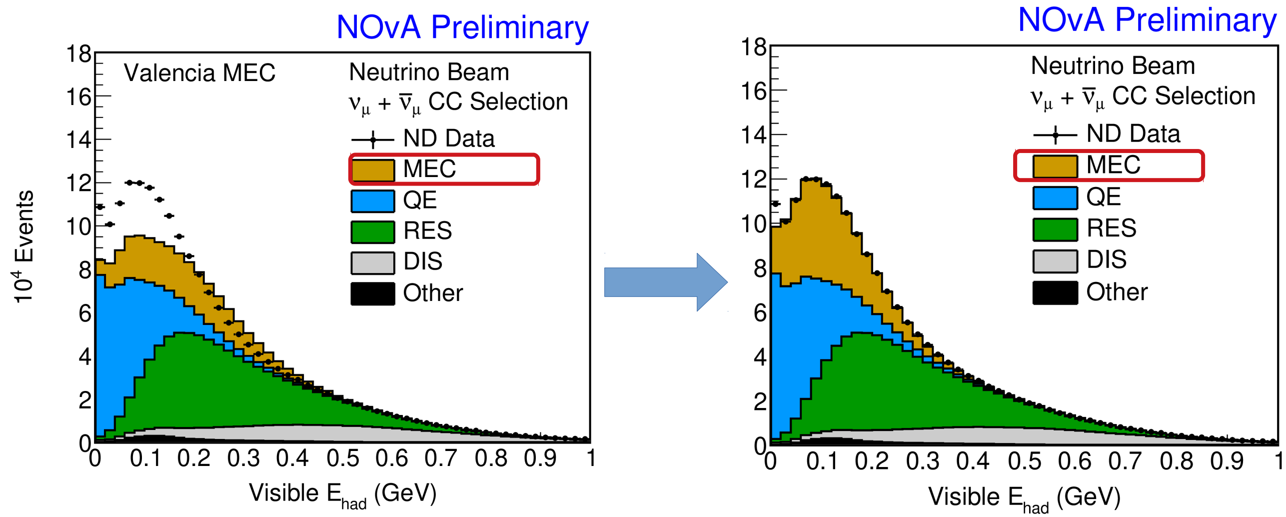
Knock out two nucleons with an elastic-like interaction.

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

[N. Jachowicz]

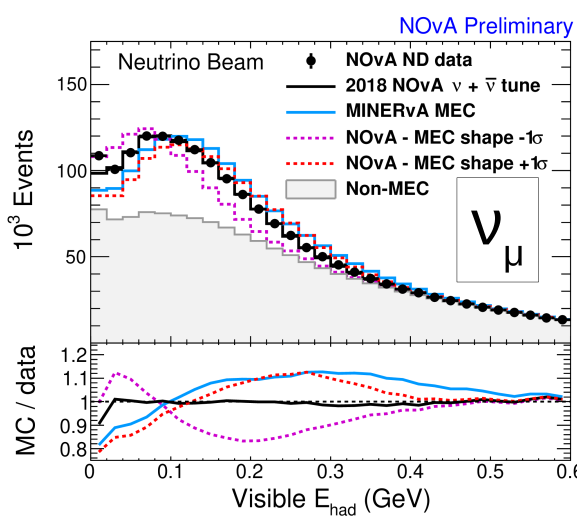


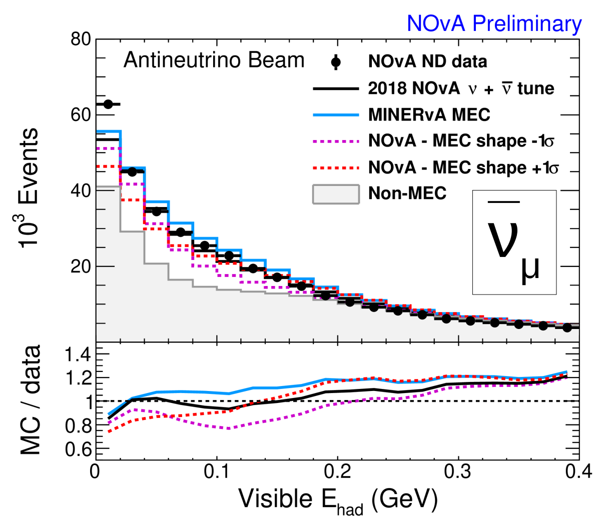
* “Meson Exchange Current (MEC) Models in Neutrino Interaction Generators”, Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014



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

(w/ tunes from alternate base MC as uncertainties)



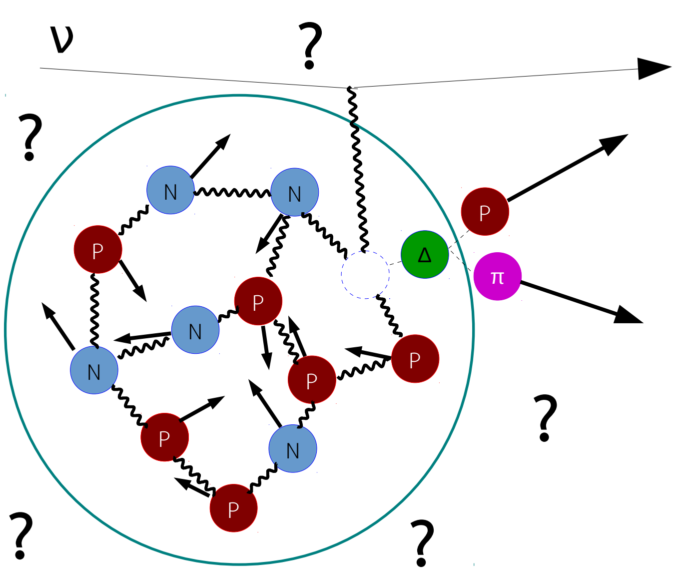


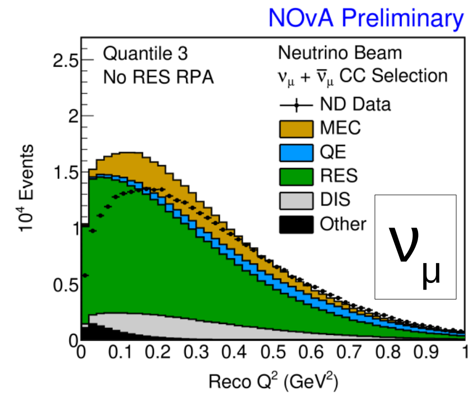
Xsec model tuning: pion production

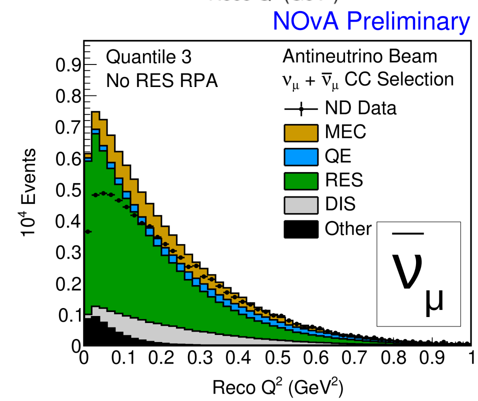
Pion production

Apparent suppression at low momentum transfer (Q^2) relative to model...

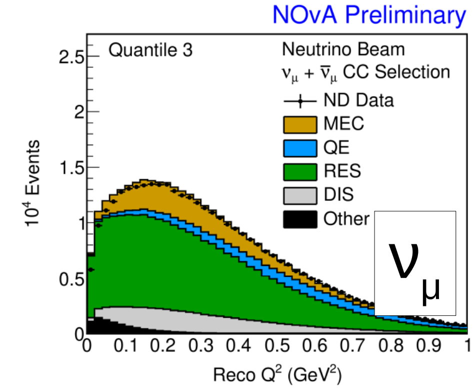
No theory to guide here.
"Adapt" *elastic* long-range correlation model ("RPA")

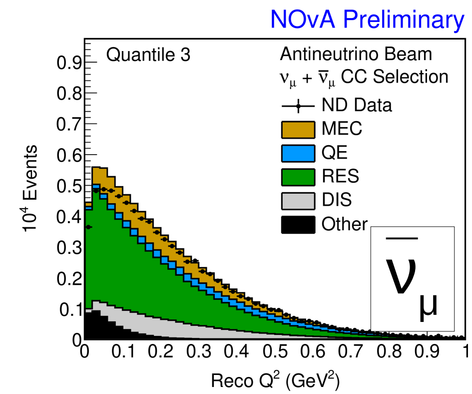




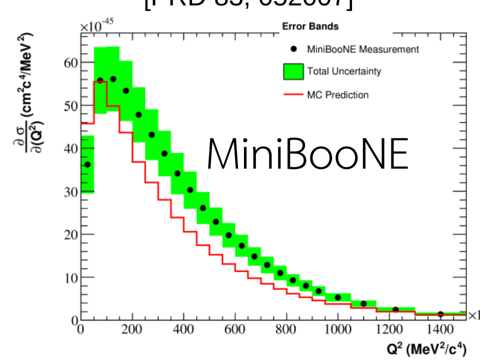


Apply Q^2-based Valencia RPA weight from QE to resonant production as a stand-in for whatever nuclear effect we see at low Q^2
(w/ unmodified version as uncertainty variation)

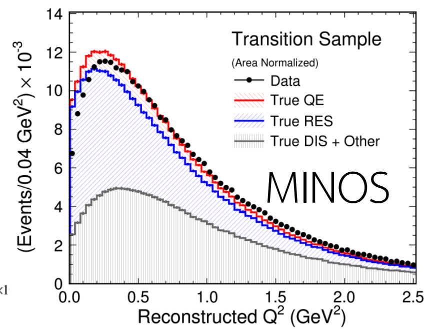




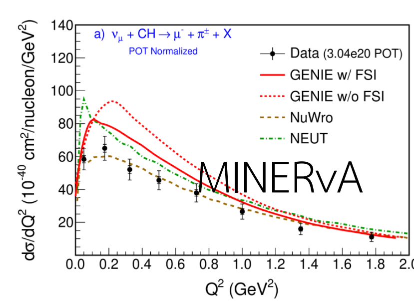
[PRD 83, 052007]



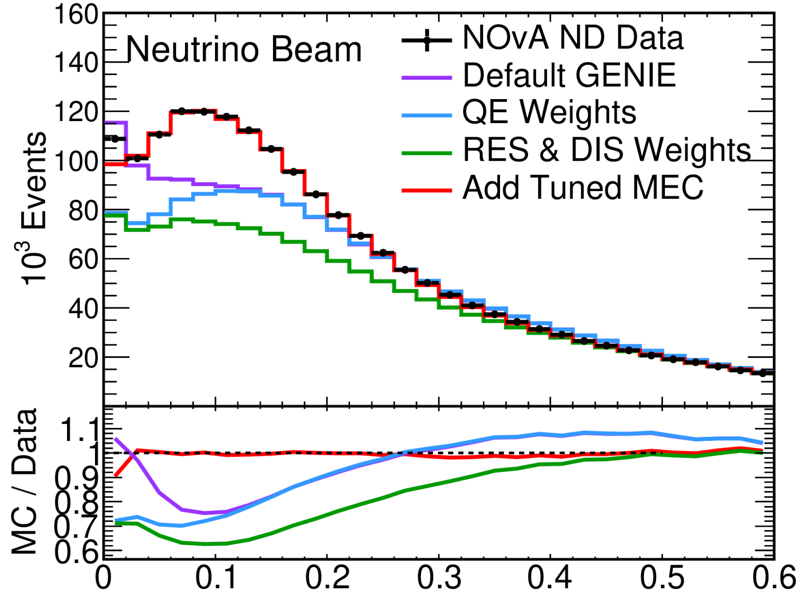
[PRD 91, 012005]

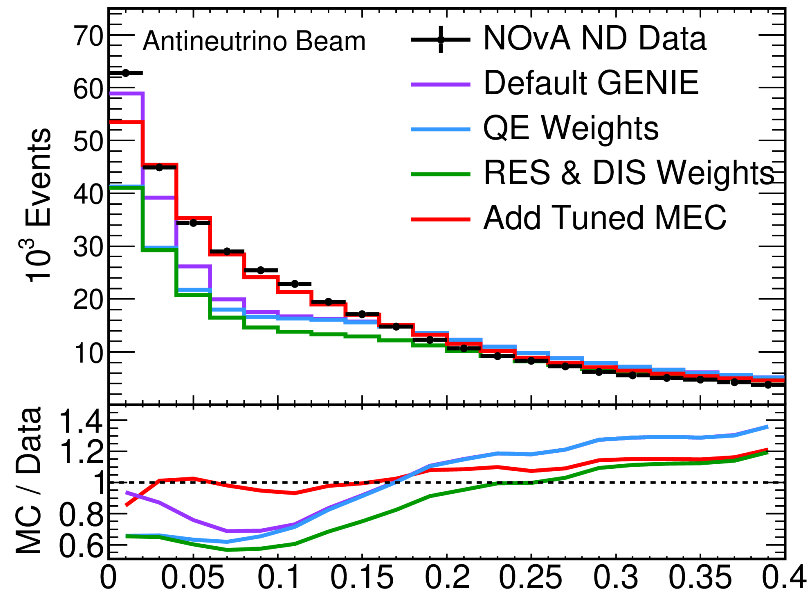


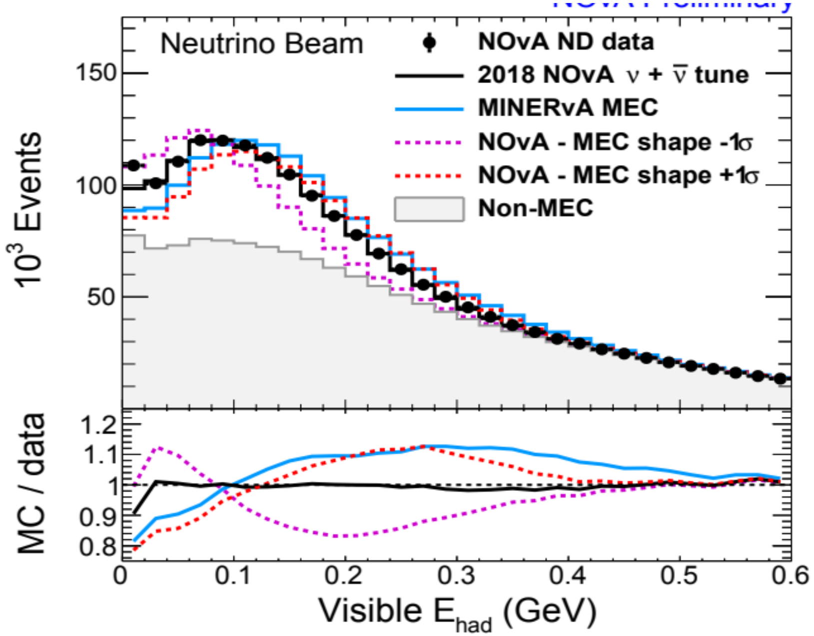
[PRD 94, 052005]

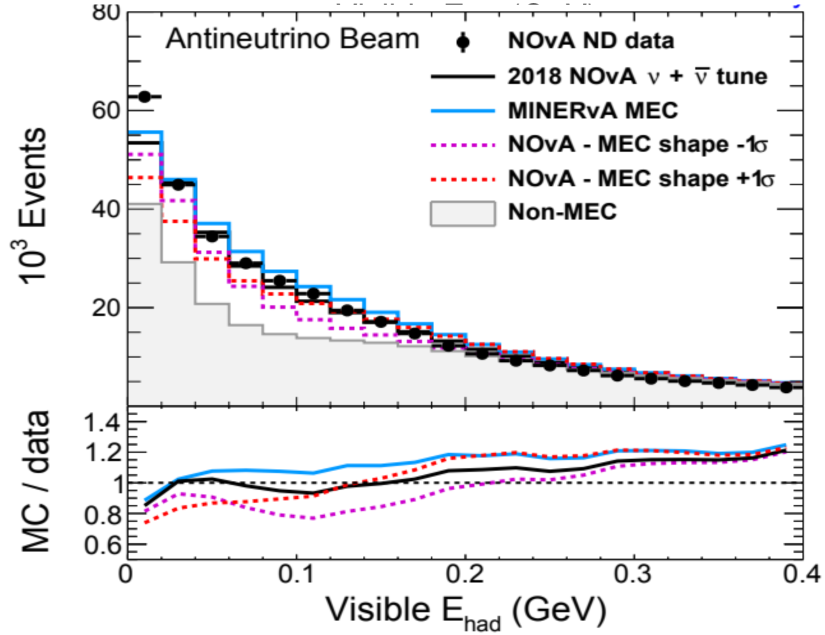


Xsec model tuning

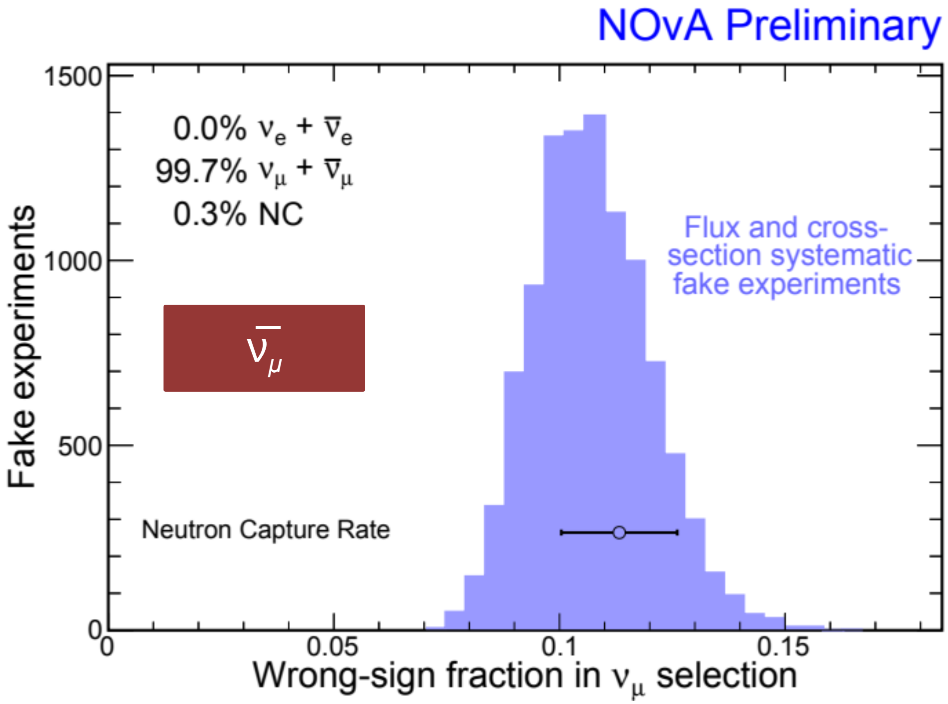


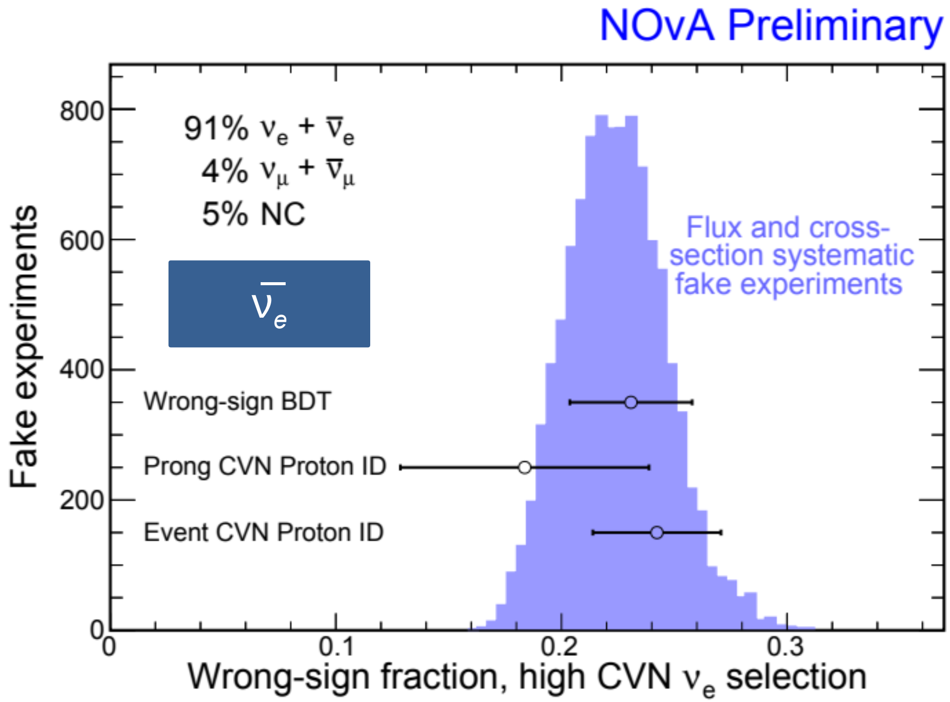






Wrong-sign background





- ~10% systematic uncertainty on RHC wrong-sign from flux and cross section
  - Both in ν_μ-like and ν_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 ν_μ sample checked using neutron captures.
  - 22% wrong-sign in beam ν_e checked using identified protons and event kinematics.