# Latest from NOvA

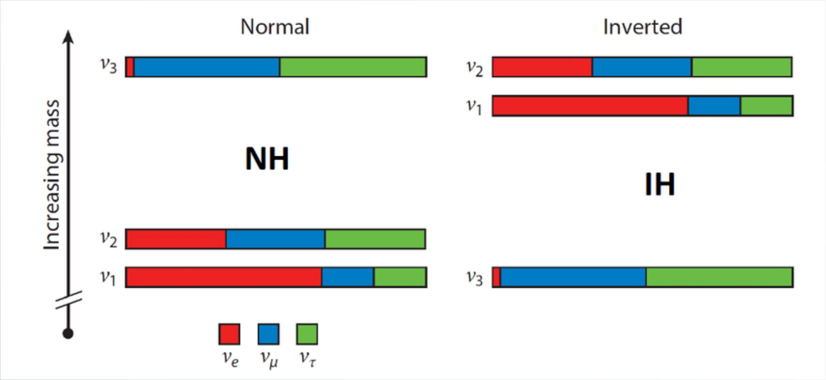
Kirk Bays (UMN) on behalf of the NOvA collaboration

Oct 25, 2023

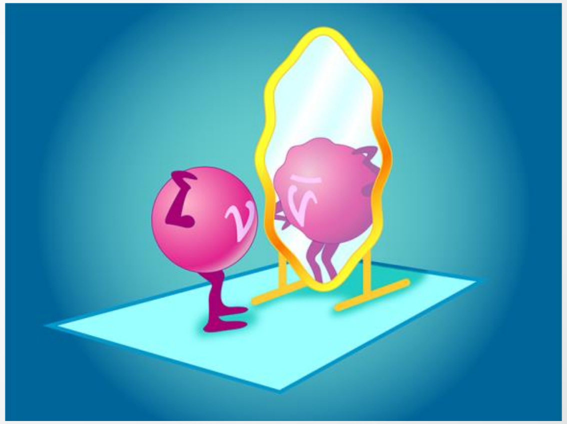
Neutrino Telescopes Conference

# Questions in neutrino physics

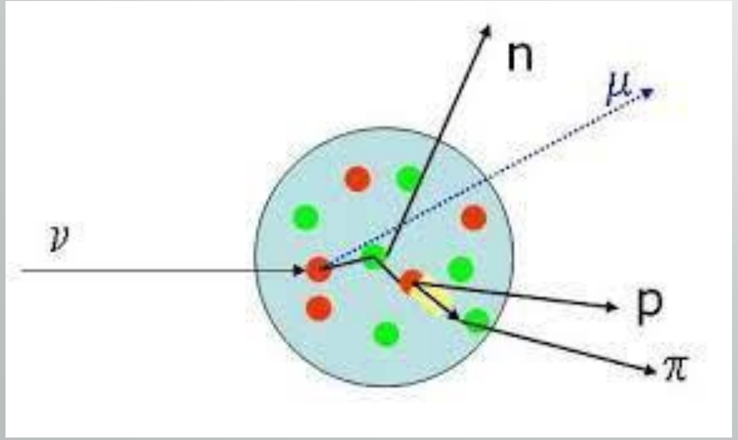
## What are the neutrino masses?



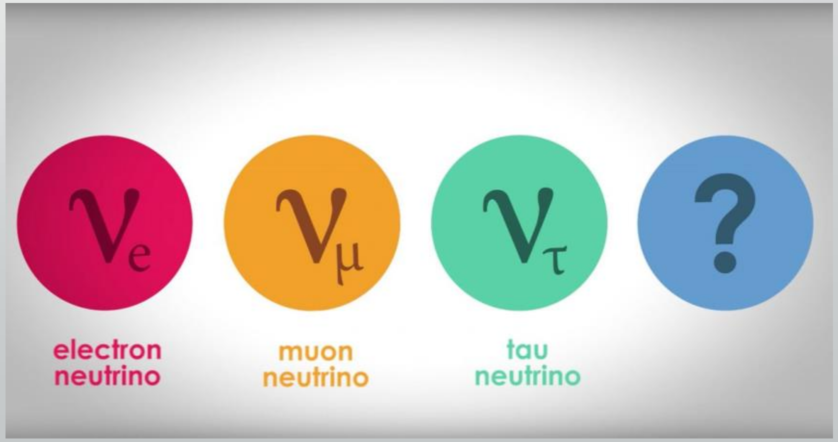

## Do neutrino violate CP symmetry?



## Do we understand neutrino scattering?

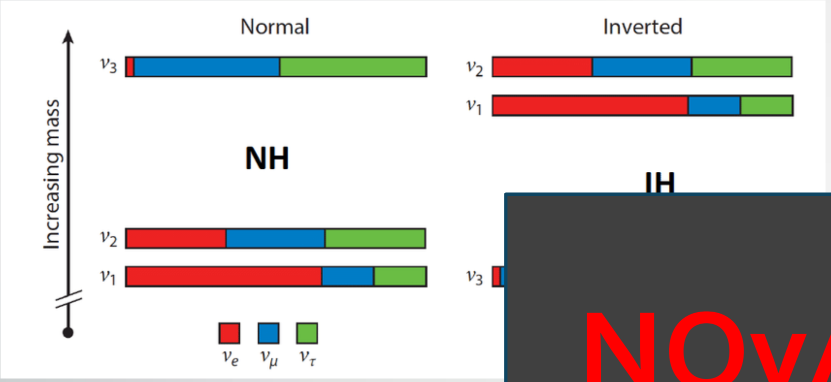



## Are 3-flavor oscillations the full story?

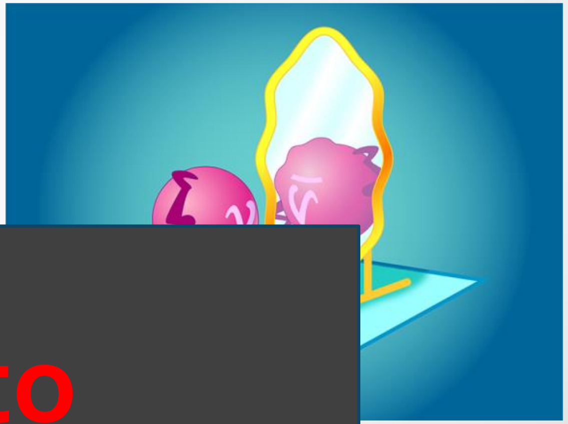


# Questions in neutrino physics

## What are the neutrino masses?

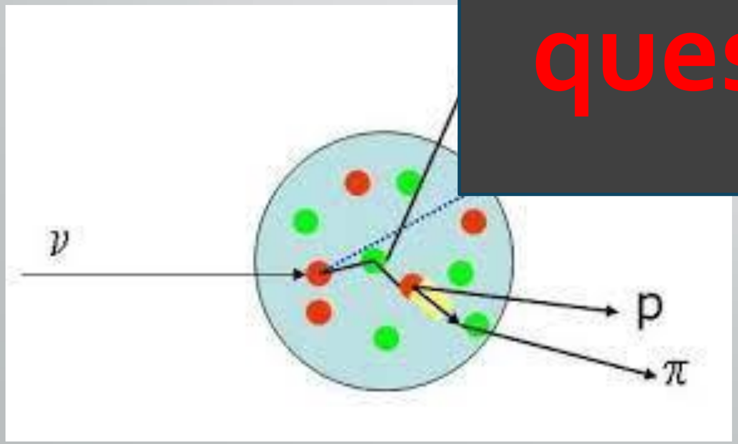



## Do neutrino violate CP symmetry?

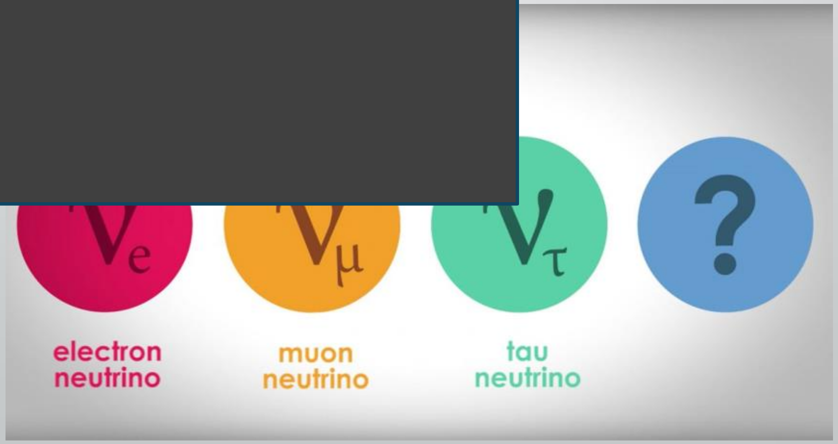


**NOvA is working to answer all of these questions**

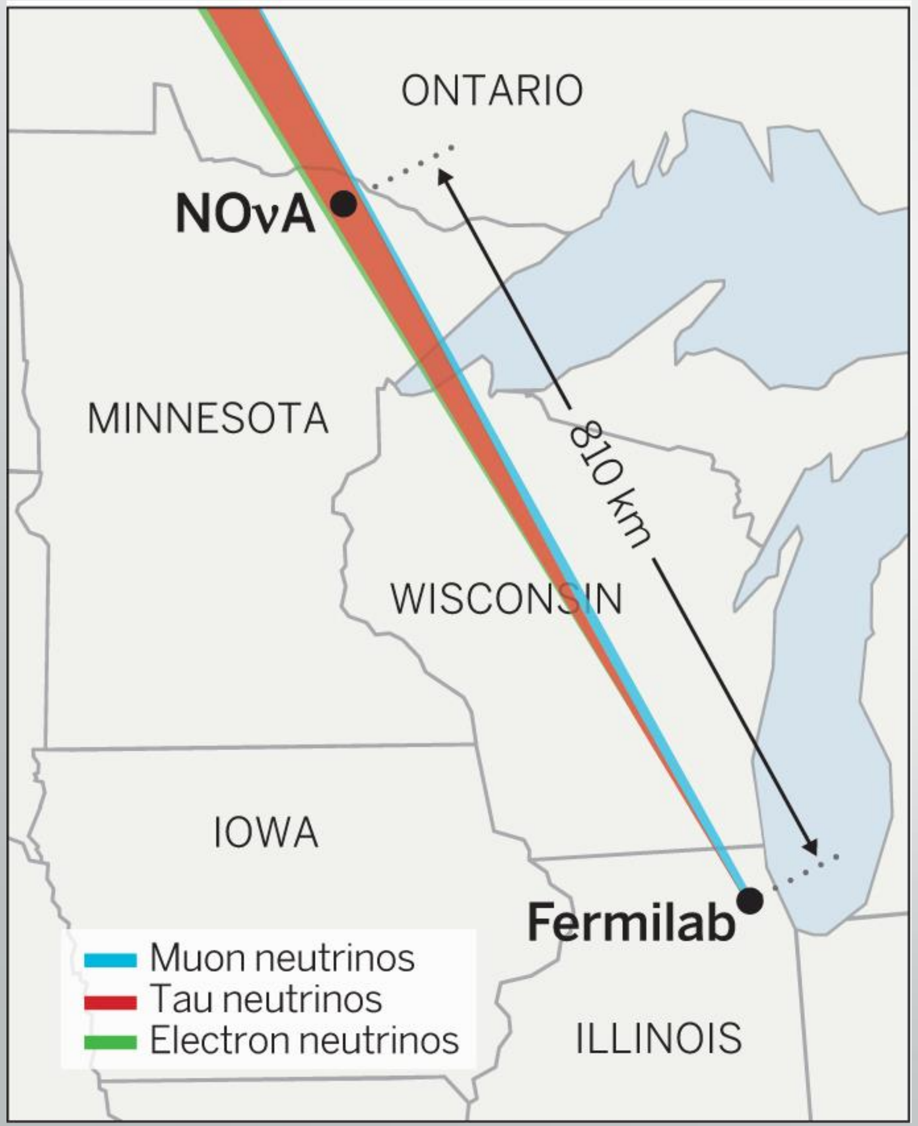
## Do we understand ne

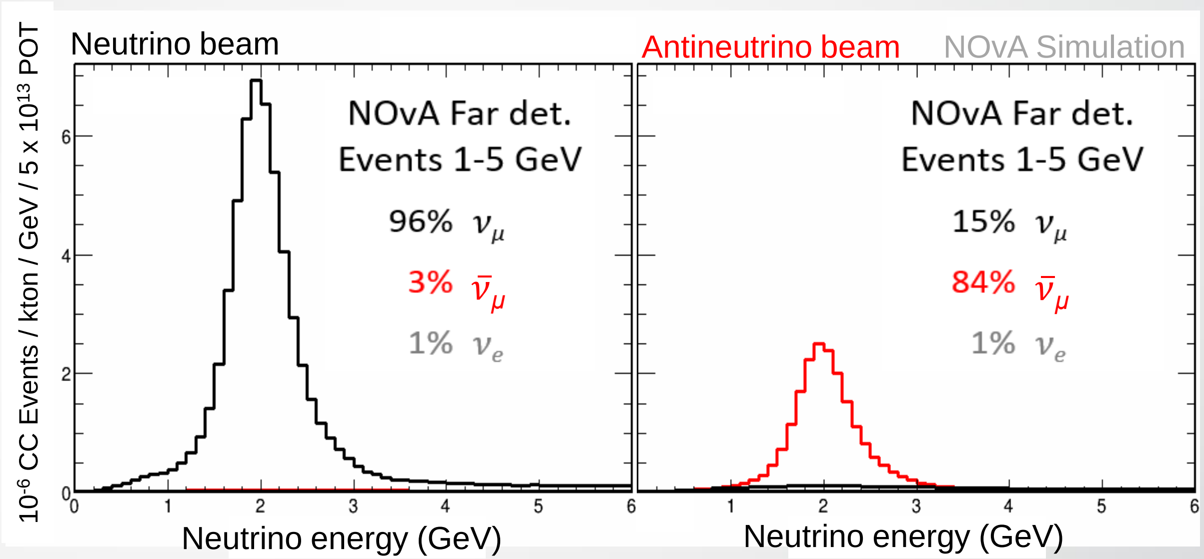



## s the full story?



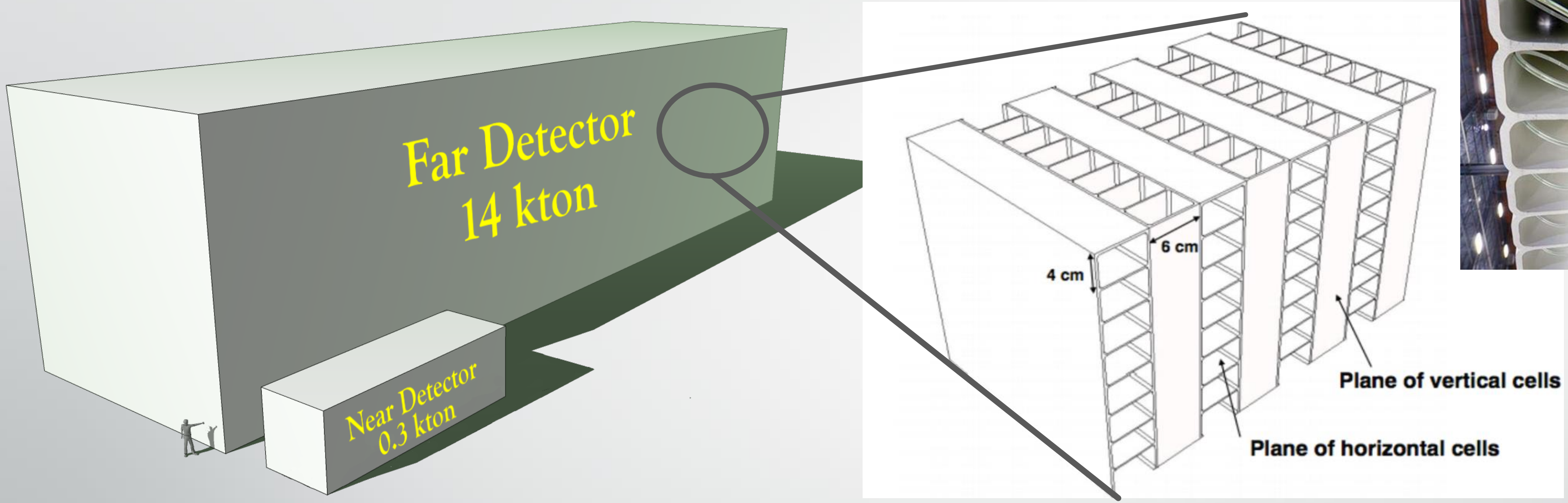
# About NOvA

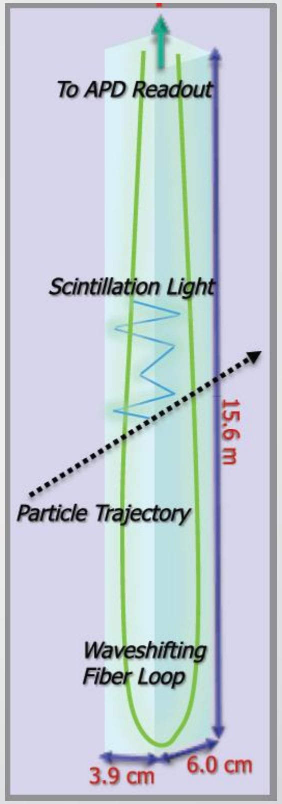



- Utilizes NuMI $\pi$ decay-in flight beam from Fermilab
- 14.6 mrad off-axis beam for narrow peak @ 2 GeV
- High-purity neutrino or antineutrino mode polarities
- Two detectors – 14 kton far detector (FD) 810 km from beam source, 300 ton near detector (ND) @ 1 km
- ND has high (>1M $\nu_\mu$ interactions) stats

# NOvA detectors

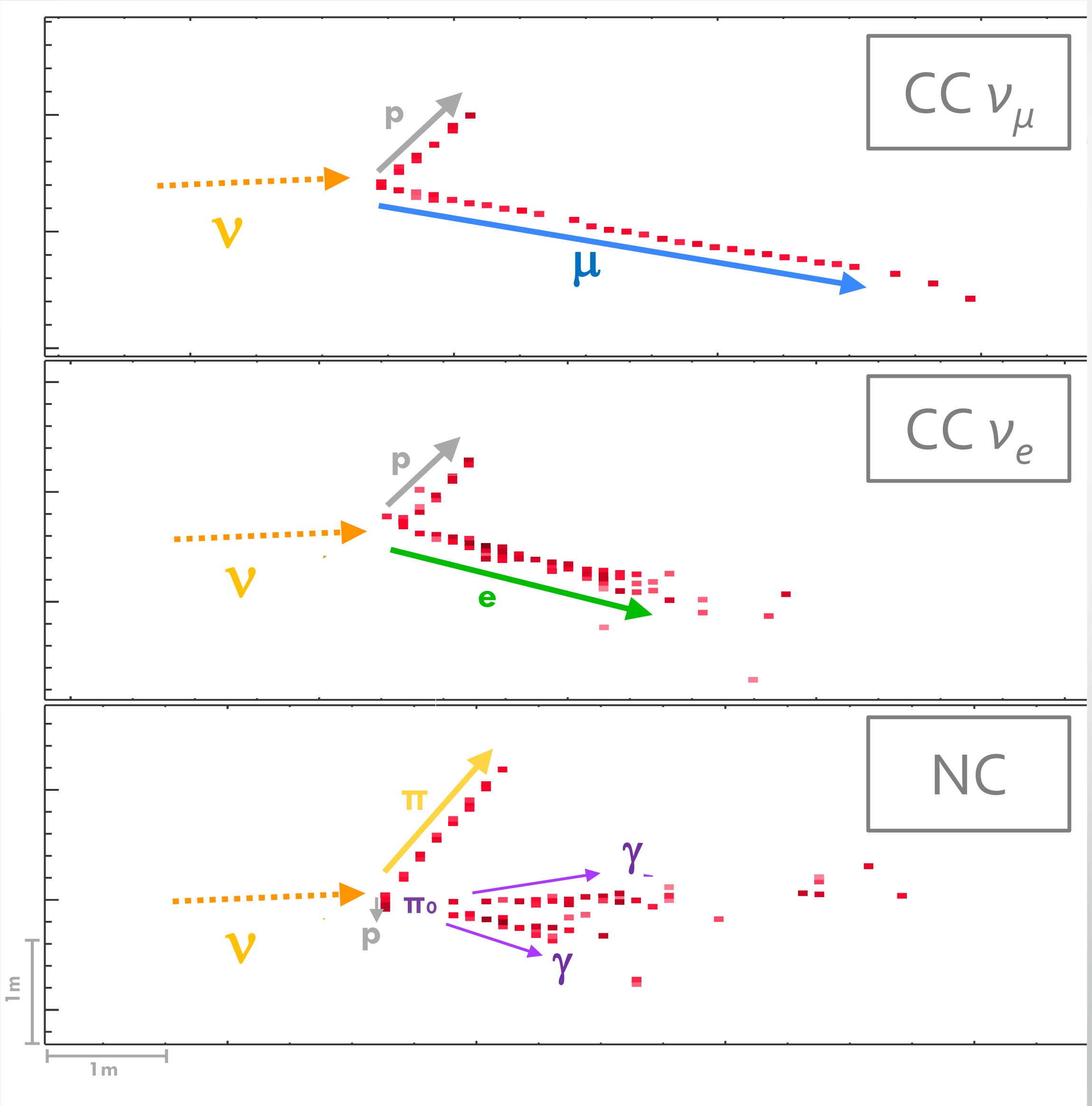



- Detectors are tracking calorimeters
- 4 cm x 6 cm x 16 m (FD) 'cells' are extruded plastic filled with liquid scintillator
- Wavelength-shifting fibers connected to APDs collect light
- Cells are alternately oriented horizontally or vertically for full 3D picture


NOvA FD (14 ktons)
Installation finished Sept. 2012

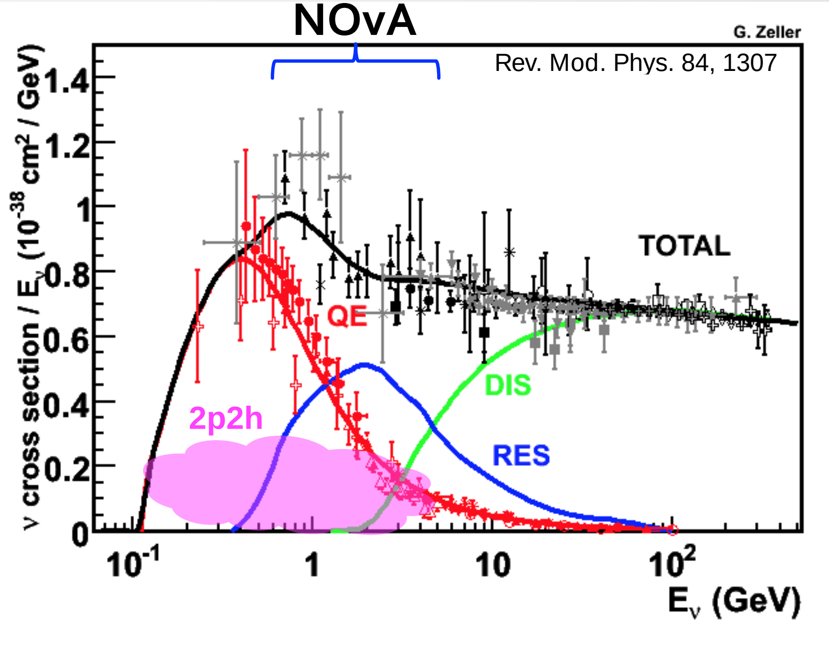
# Interactions in NOvA

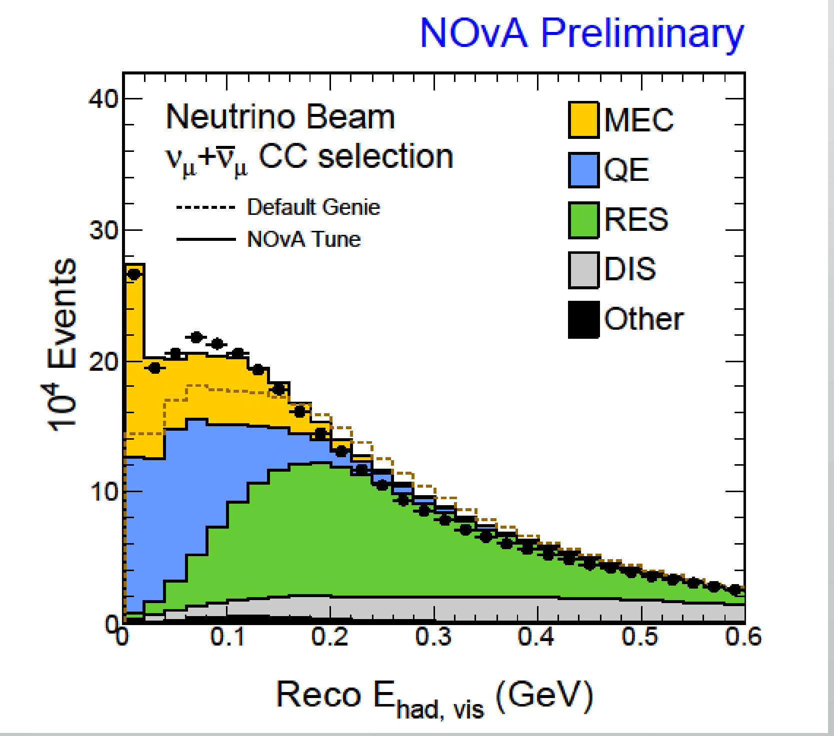


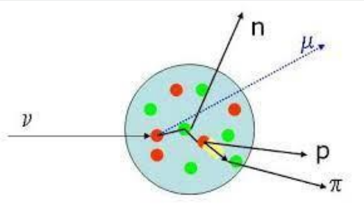

- Clear long, straight muons
- Higher density electron showers
- Hadronic particles more difficult but can be clearly differentiated
- Use machine learning to identify single particles (ND cross-section analyses)
- Use convolutional neural network to look at entire events and ID neutrino flavor

# NOvA simulation

- Many neutrino interaction types – all matter for NOvA
- NOvA uses GENIE to simulated neutrino interactions
- 2p2h (MEC) interactions are modeled poorly
- NOvA corrects by fitting MEC model to ND data holding other simulation fixed
- We know other models aren't perfect; compensate with large, robust uncertainties
- This is a problem for all experiments; important to measure MEC directly

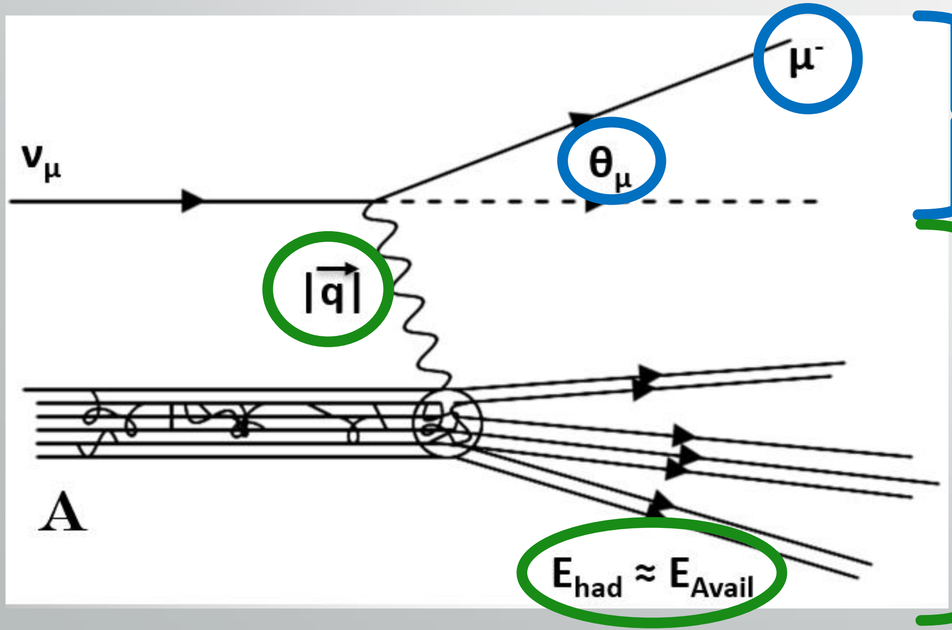





# NOvA cross-section measurements

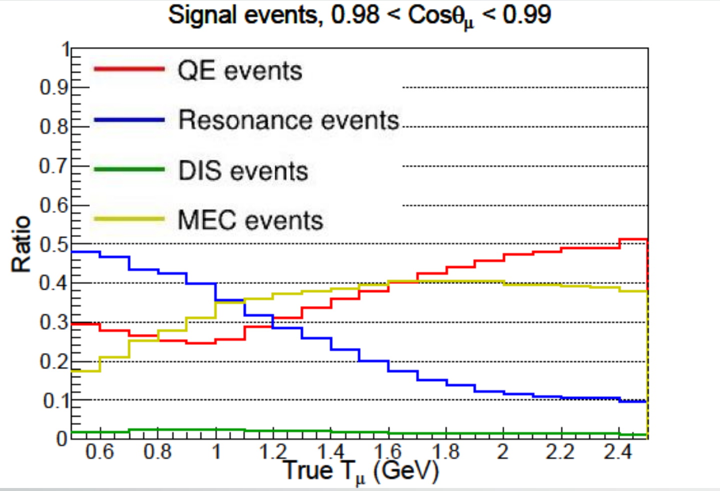
- $\nu_\mu$ interactions with MEC-enriched samples
- Measure **muon** properties (analysis 1) or **hadronic** properties (analysis 2) – double differential measurements

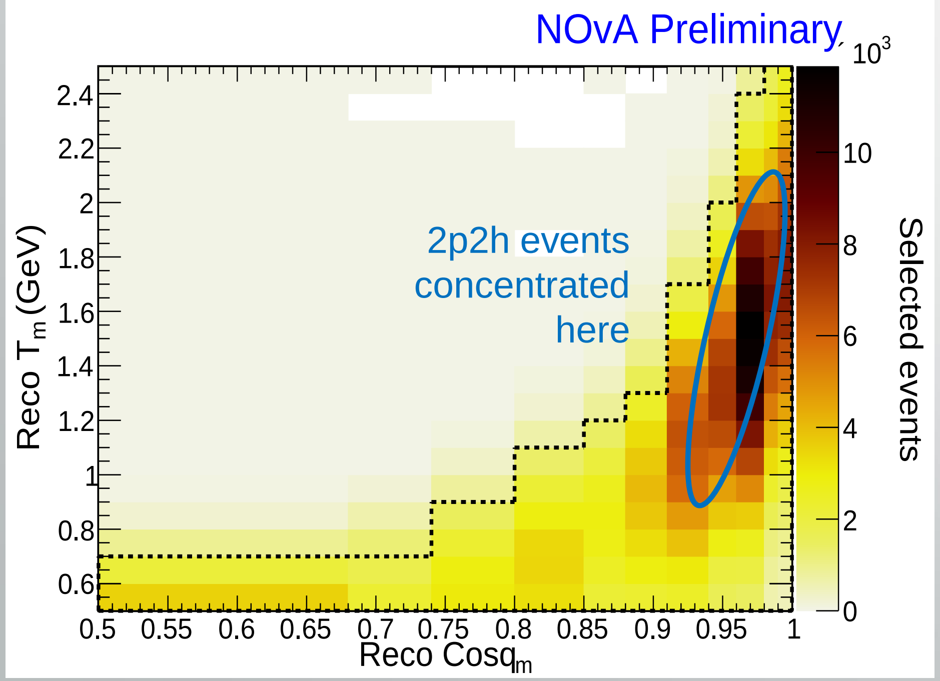



**Muon System** ⇨ Energy and angle

**Hadronic System** ⇨ 3-momentum transfer $|\vec{q}|$ and energy

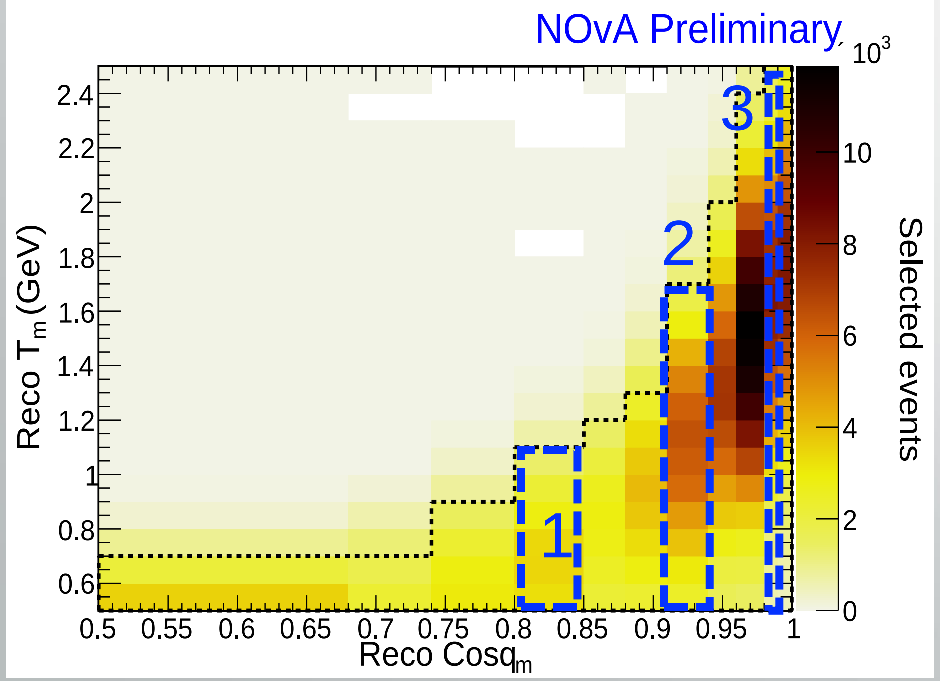
# Cross-section measurement: muon system

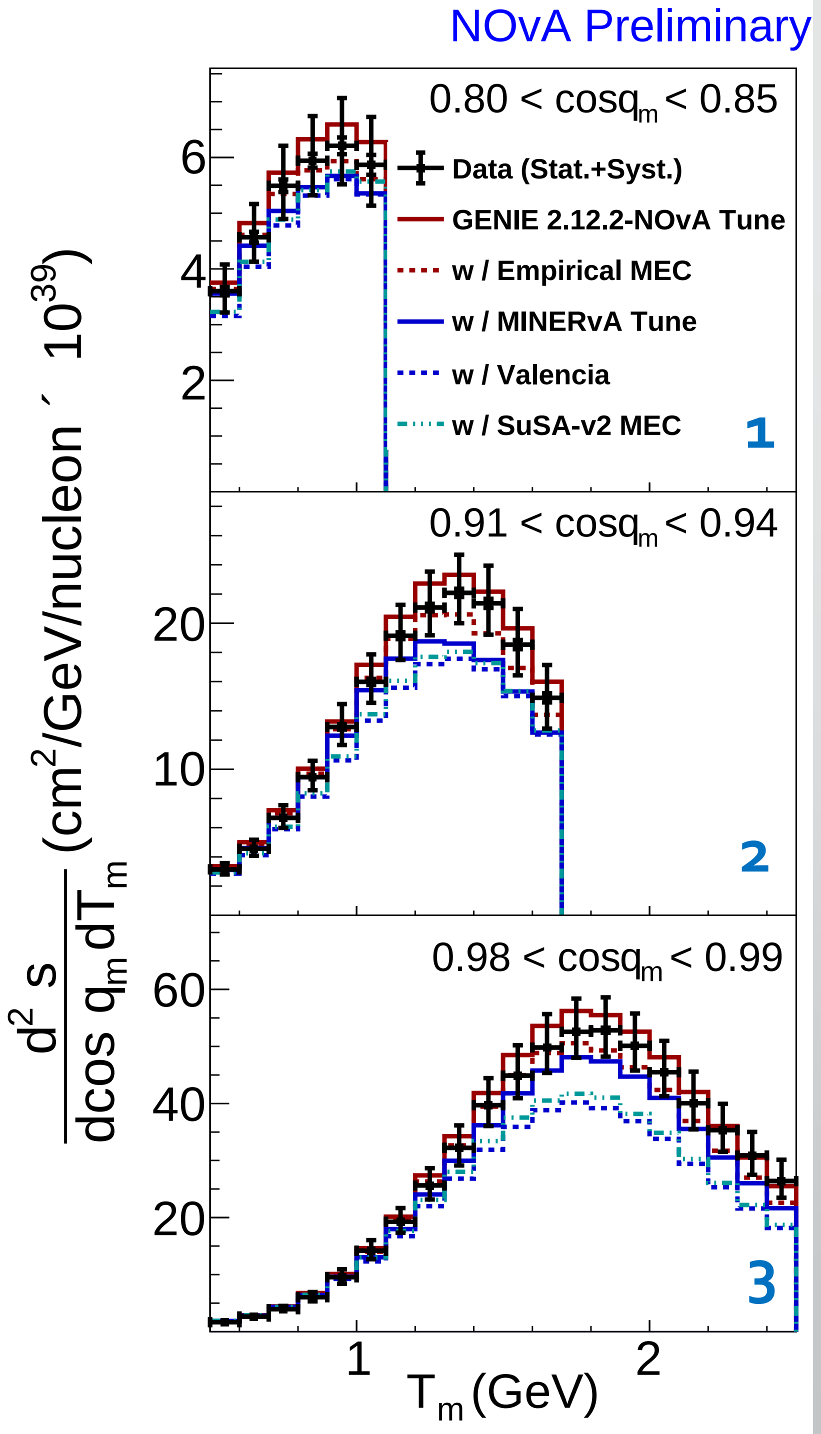


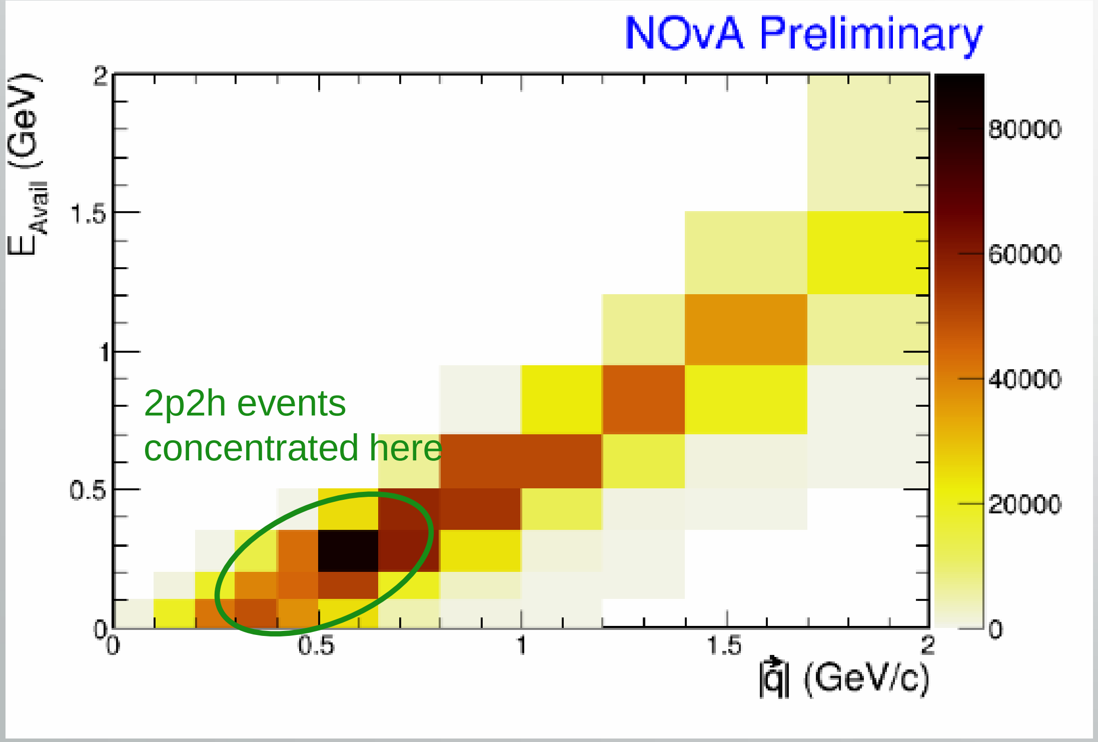

- Require only 1 clear track
  - This is the muon
  - Low-energy hadronic particles won't make tracks
- This greatly reduces interactions that make higher-energy hadronic activity
  - RES, DIS reduced
  - Leaves a sample that is enriched in MEC
- Phase space cut (dotted line)
  - 115 kinematic bins
  - 12-15% uncertainty in each bin (mostly flux)
- Selected sample > 500k events

- Unfolded results are compared to different MEC model predictions
- Some are ‘untuned’ models, also an adjusted MEC model developed by MINERvA
- In areas with the most MEC, can see large differences in models, mostly don’t agree with data



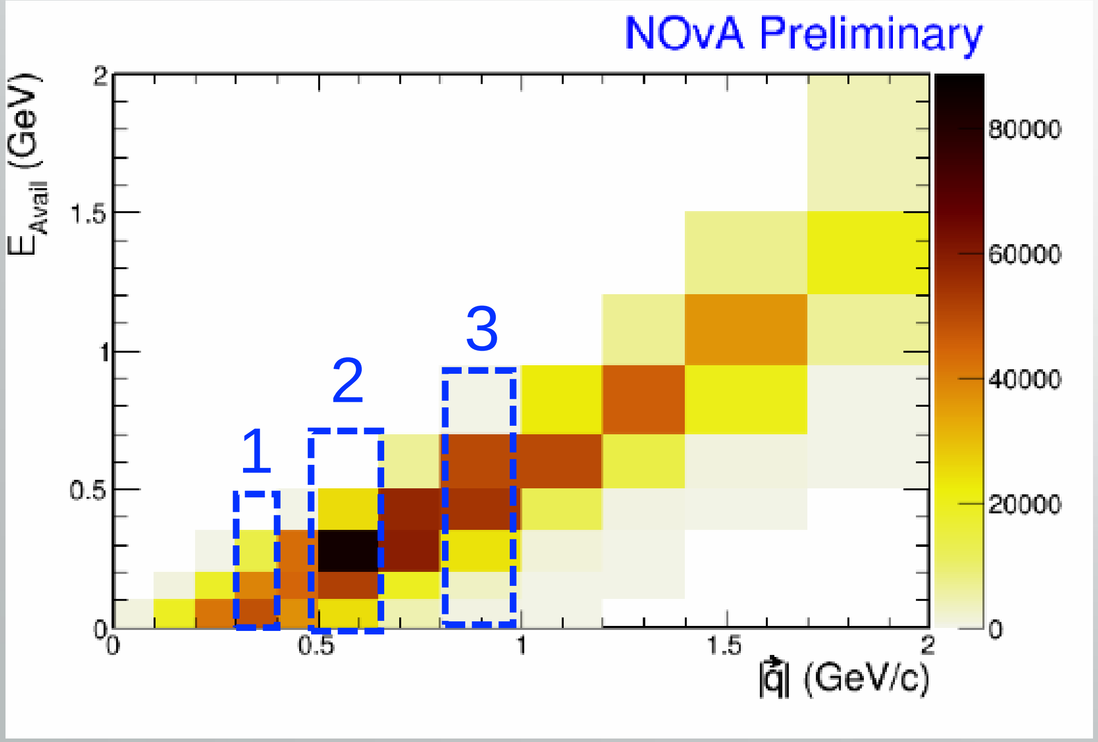



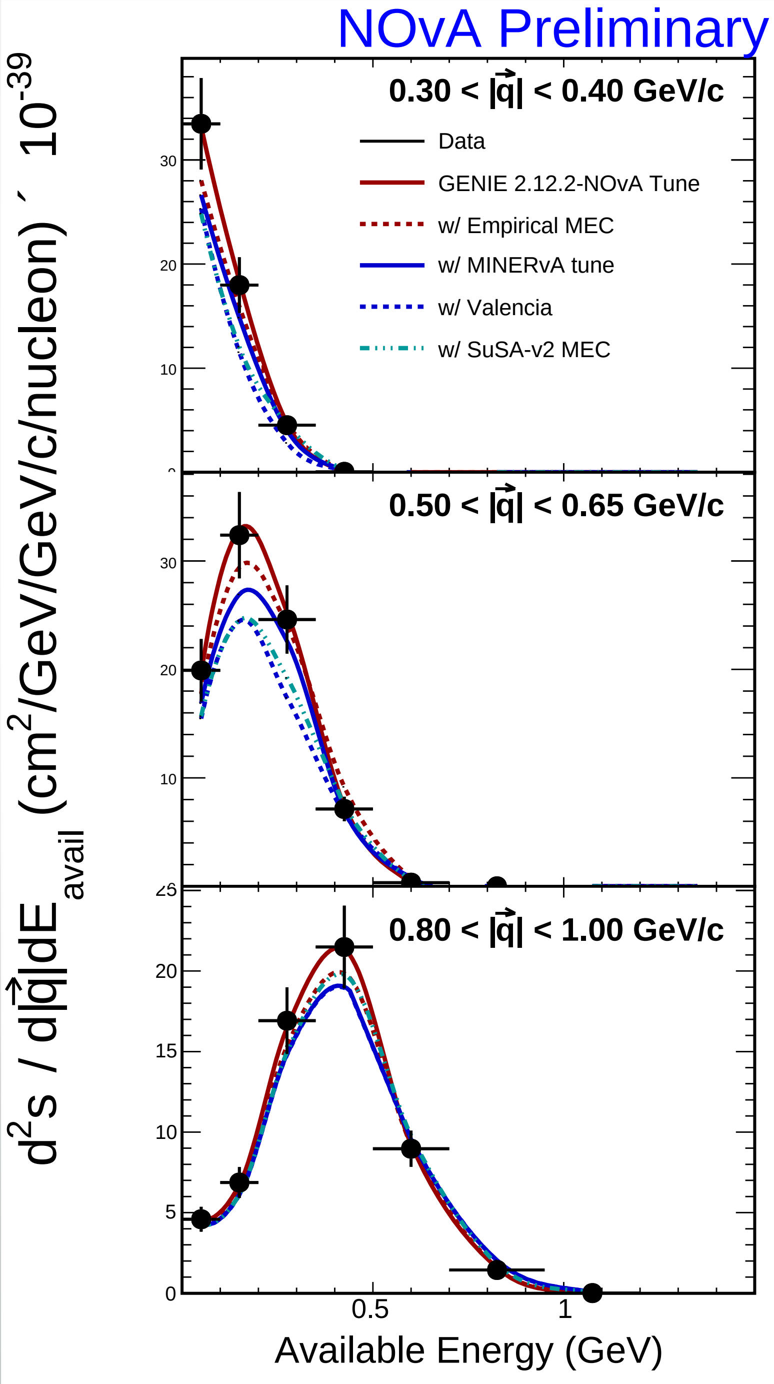
# Cross-section measurement: hadronic system




- Previous analysis required low hadronic energy to enrich MEC
- Here hadronic energy is a variable, look at low E regions where MEC dominates
- 67 analysis bins
- ~12% uncertainty each (mostly flux)

- Again compare to different MEC predictions
- Again, where most MEC is expected, different models make the most difference and are generally discrepant



# Comparing models

**muon analysis**

| 2p2h Model | $\chi^2$ (115 d.o.f.) |
|---|---|
| GENIE v2-12.2 NOvA Tune | 200 |
| Empirical MEC | 190 |
| Valencia w/ MINERvA Tune | 340 |
| Valencia | 630 |
| SuSA - v2 | 620 |

'tuned' models (GENIE v2-12.2 NOvA Tune, Empirical MEC, Valencia w/ MINERvA Tune)

'theory' models (Valencia, SuSA - v2)

**hadronic analysis**

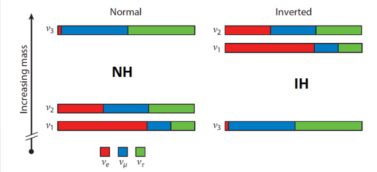
| 2p2h model | $\chi^2$ (67 d.o.f.) (includes 12 \|q\| slices) |
|---|---|
| GENIE 2.12.2 + NOvA tune | 560 |
| Empirical MEC | 910 |
| València + MINERvA tune | 970 |
| València | 1900 |
| SuSA v2 | 1000 |

'tuned' models (GENIE 2.12.2 + NOvA tune, Empirical MEC, València + MINERvA tune)

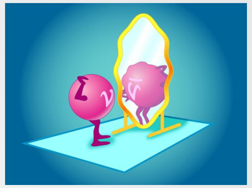
'theory' models (València, SuSA v2)

- Calculate $\chi^2$ for different models vs data (full covariance + uncertainty treatment)
- 'Tuned' models do best (none do great)
  - Theory isn't accurate yet
- NOvA tune generally best (our MEC fitting procedure is roughly okay)
- Publications being prepared for these analyses

What are the neutrino masses?



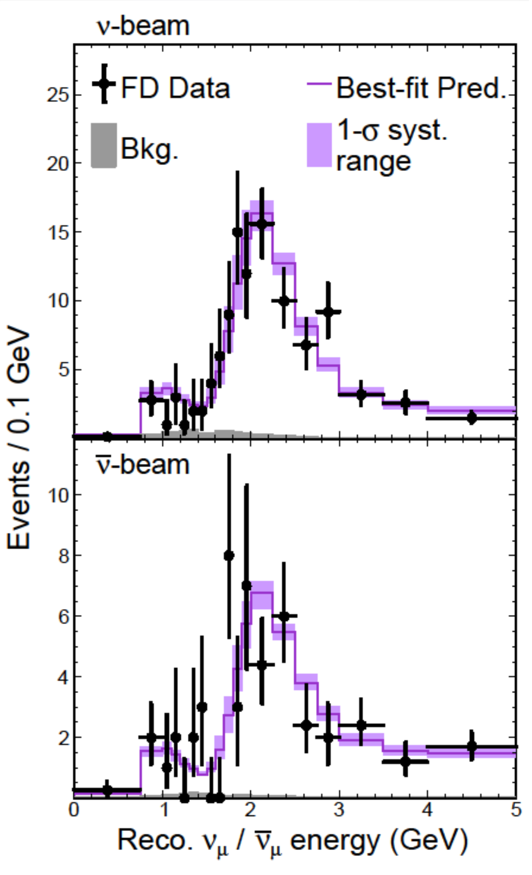

Do neutrino violate CP symmetry?



# NOvA oscillation results

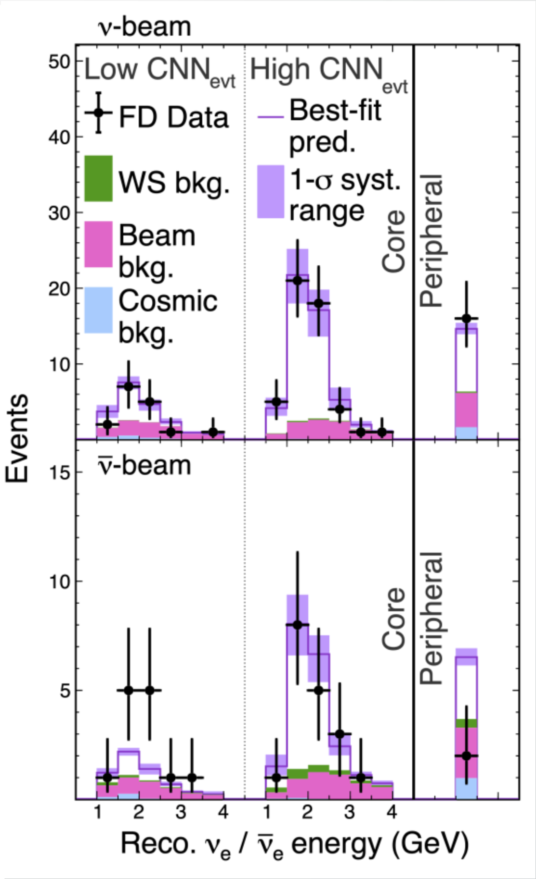
- NOvA has both frequentist (*Phys.Rev.D 106 (2022) 3, 032004*) and Bayesian (Markov-chain MC) (paper in preparation, see [Fermilab W&C talk]) oscillation measurements
- Having two identical detectors allows for mitigation of flux and cross-section uncertainties (extrapolation)
- 13.6e20 pot (neutrino mode) and 12.5e20 pot (antineutrino mode)

211 $\nu_\mu$ candidates



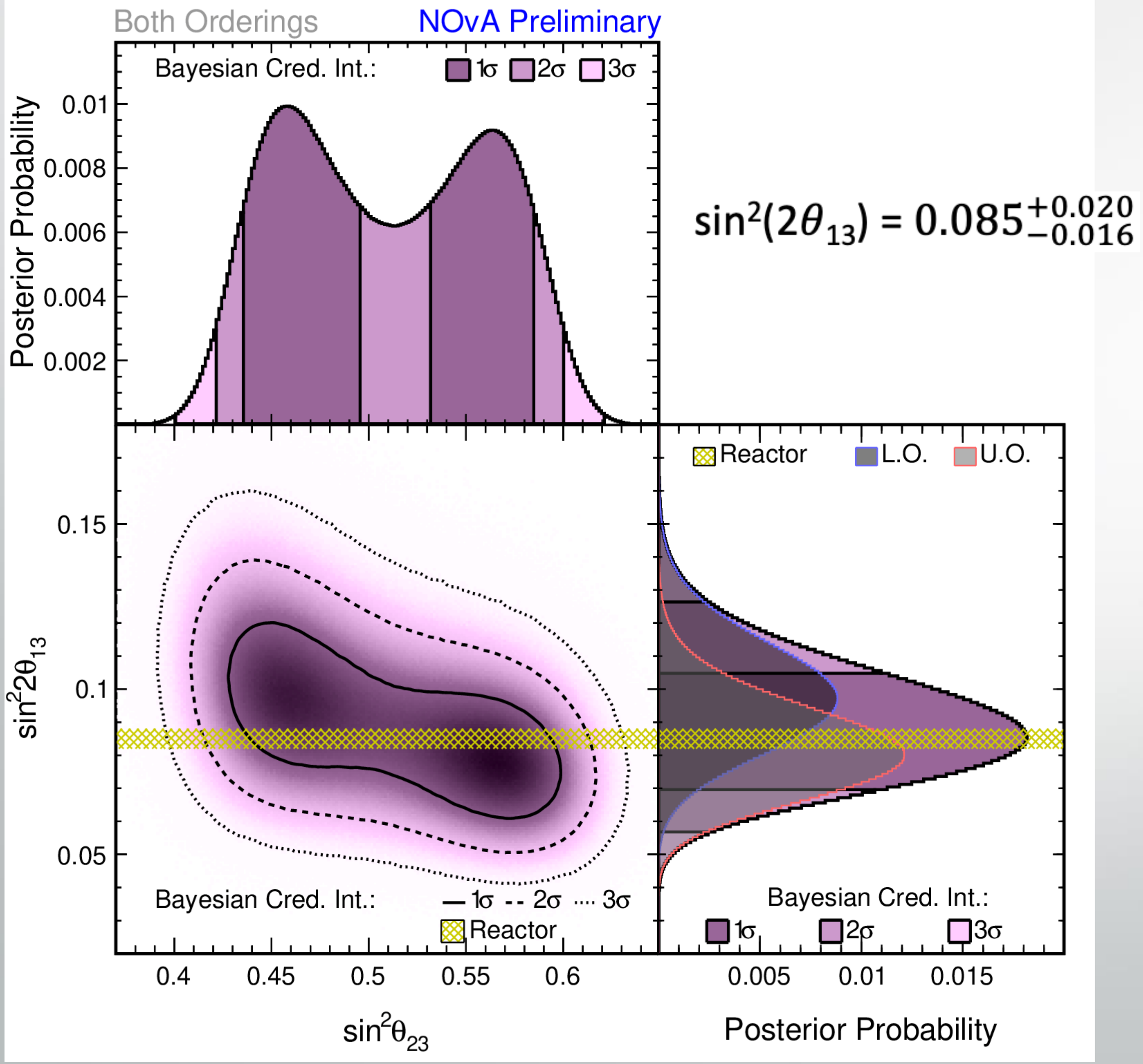

105 anti- $\nu_\mu$ candidates

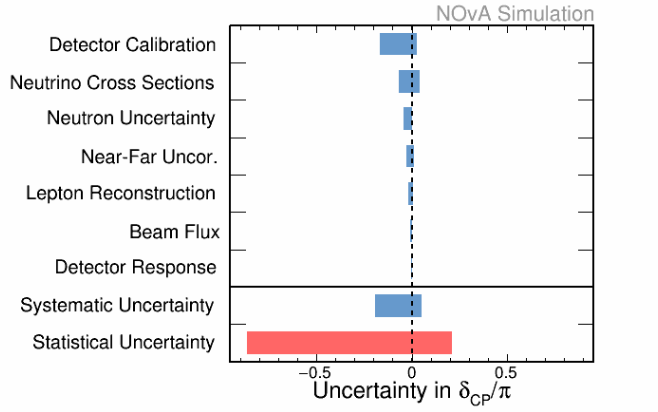
82 $\nu_e$ candidates

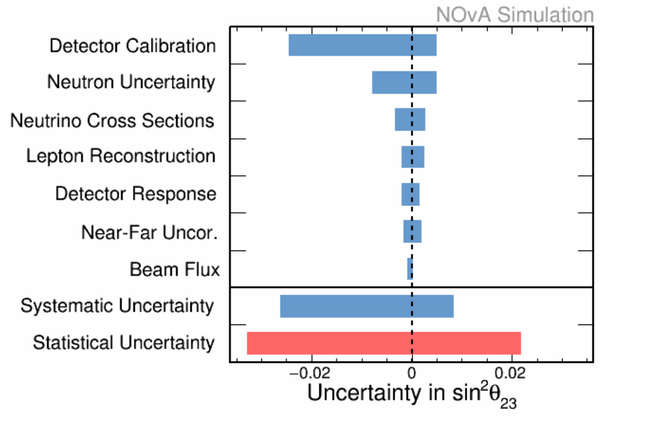



33 anti-$\nu_e$ candidates

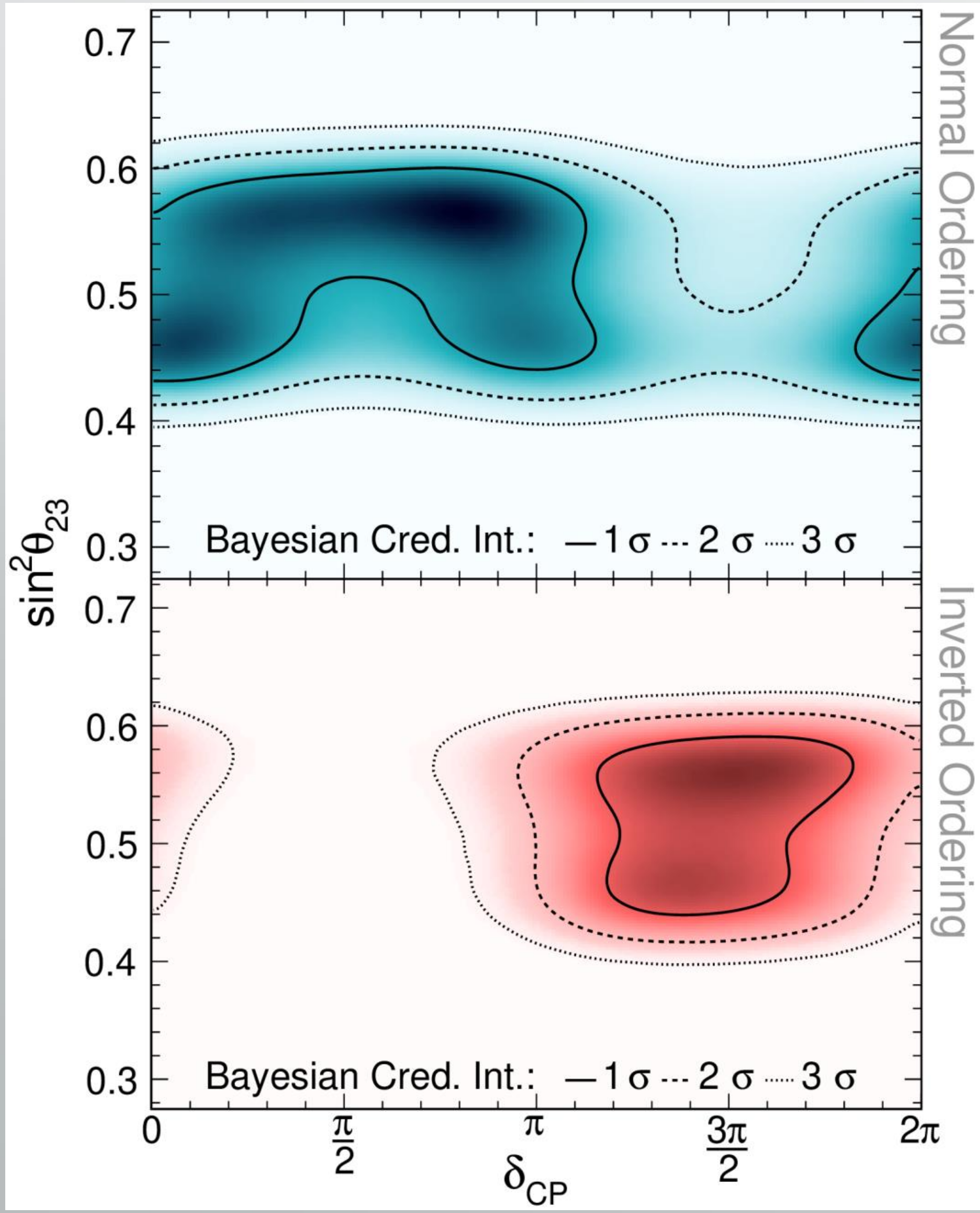
- NOvA can measure $\theta_{13}$ and $\theta_{23}$
- Use reactor measurement for 3F fit, but NOvA's measurement agrees



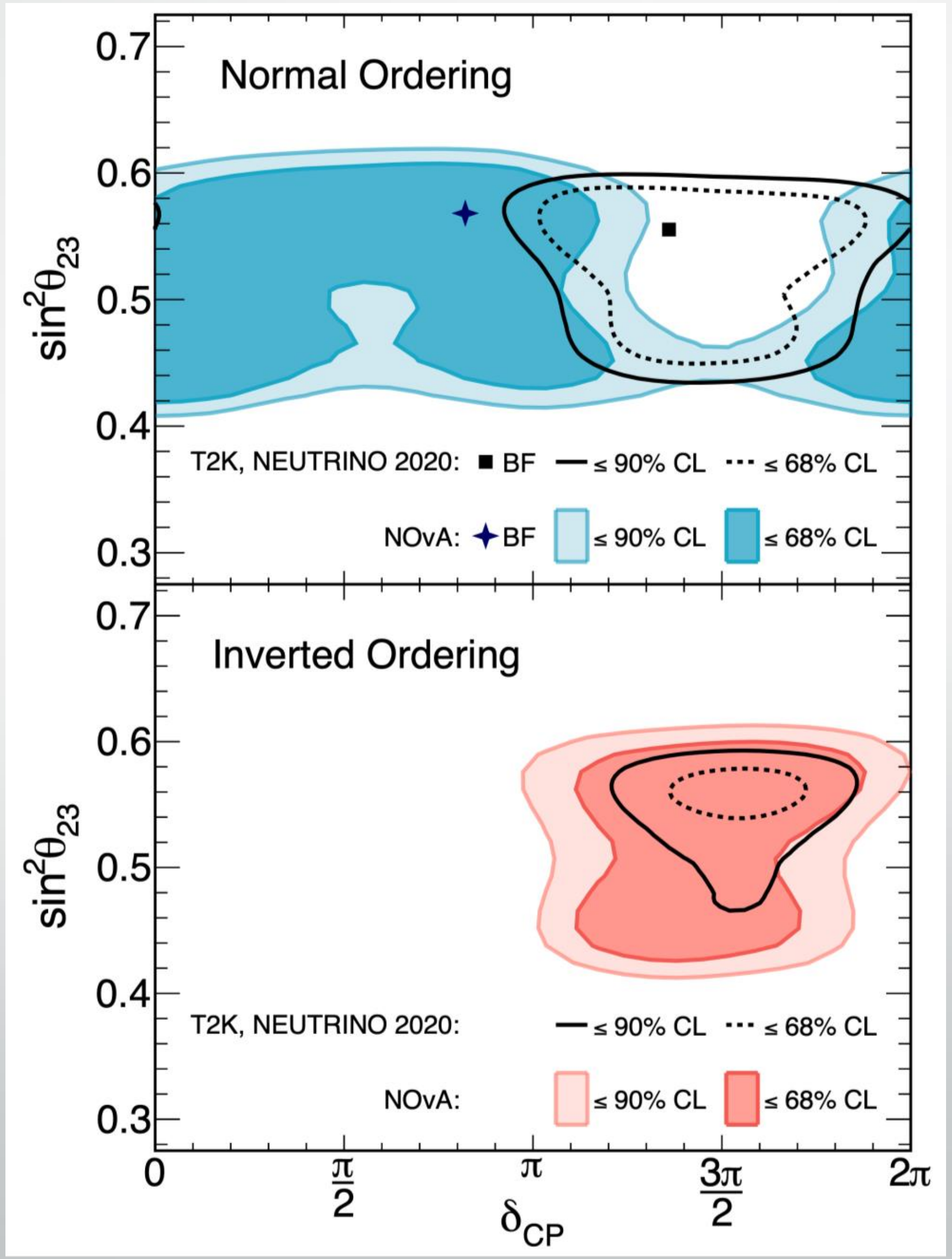



**Bayesian**




**Frequentist**




- **Bayesian and frequentist results agree**
- **1σ regions for NOvA and T2K overlap in NO**
- **Large parts of IO excluded**

Best Fit:

Normal hierarchy

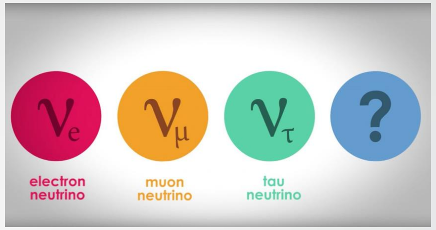
$\Delta m232 = (2.41 \pm 0.07)\times 10$

$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$

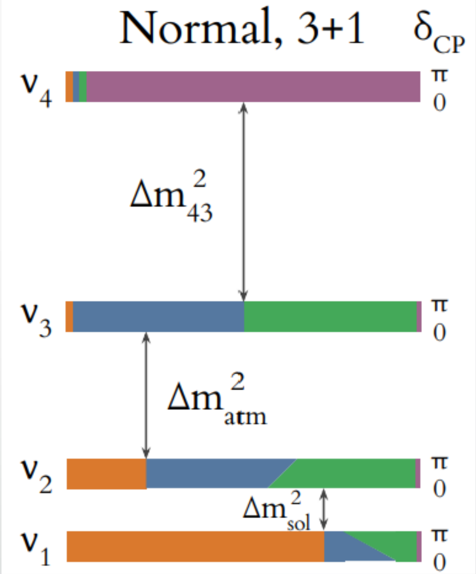
$\delta = 0.82\pi$

# Beyond 3-flavor: Sterile neutrinos

Are 3-flavor oscillations the full story?




- Could there be a 4th, 'sterile' neutrino? (can't interact, but other neutrino flavors could oscillate into this flavor)
- Would affect all oscillations (adds 2 angles, a mass term and phase)



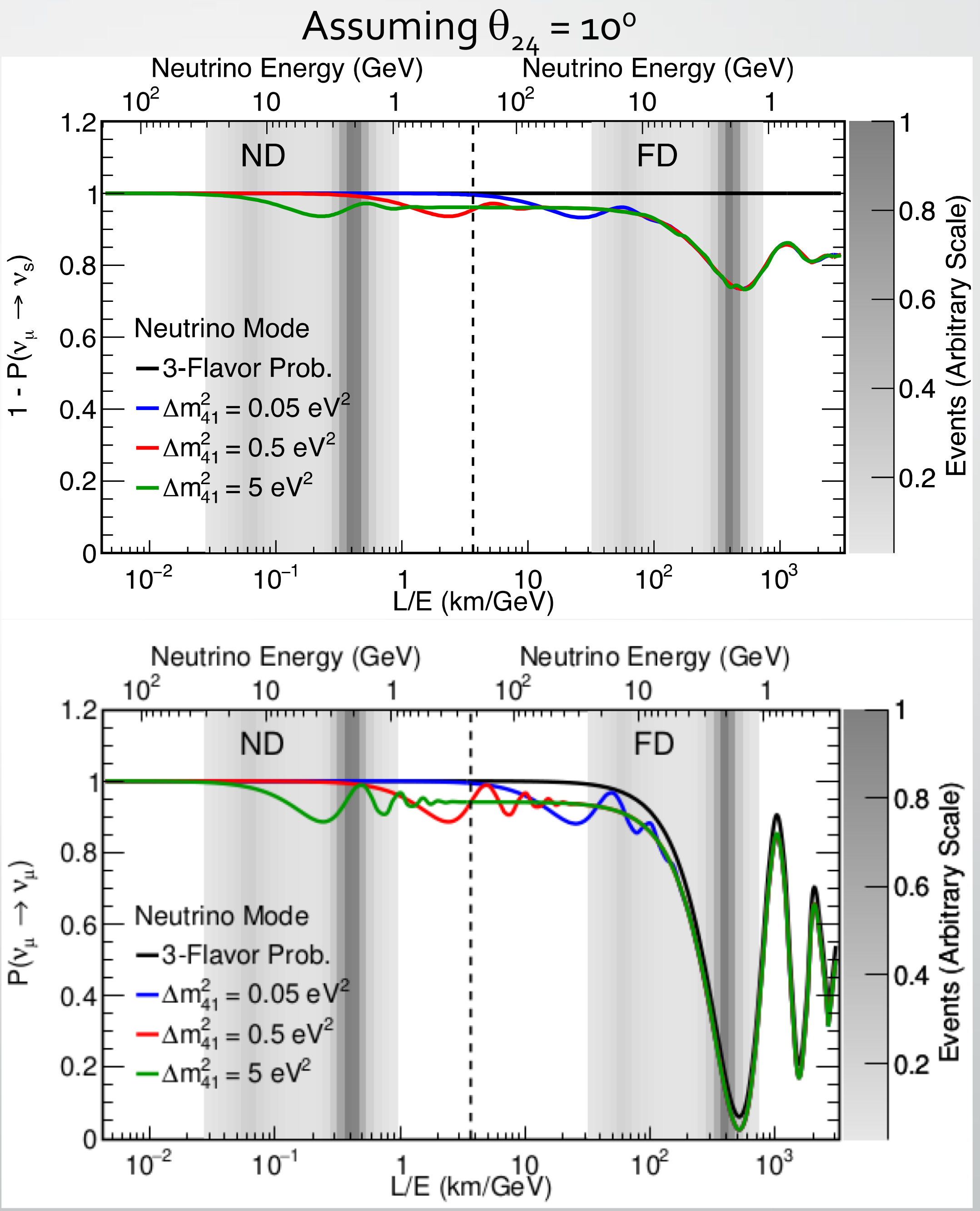

$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41} - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}.$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23}\sin^2\Delta_{31} + 2\sin^2 2\theta_{23}\sin^2\theta_{24}\sin^2\Delta_{31} - \sin^2 2\theta_{24}\sin^2\Delta_{41}.$$

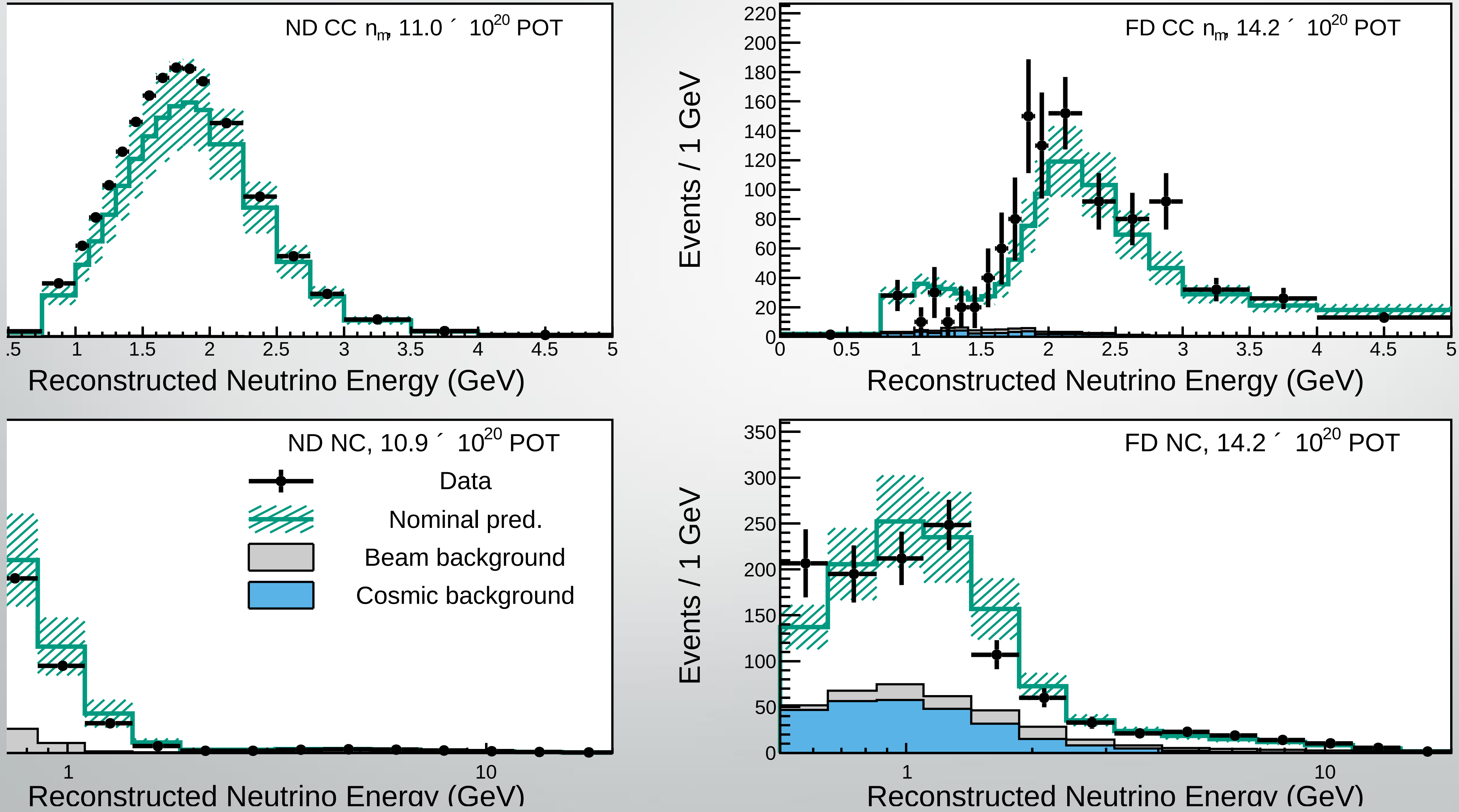
standard 3F oscillations

new with sterile ν; adds 2 new oscillation angles, a mass term, and a phase

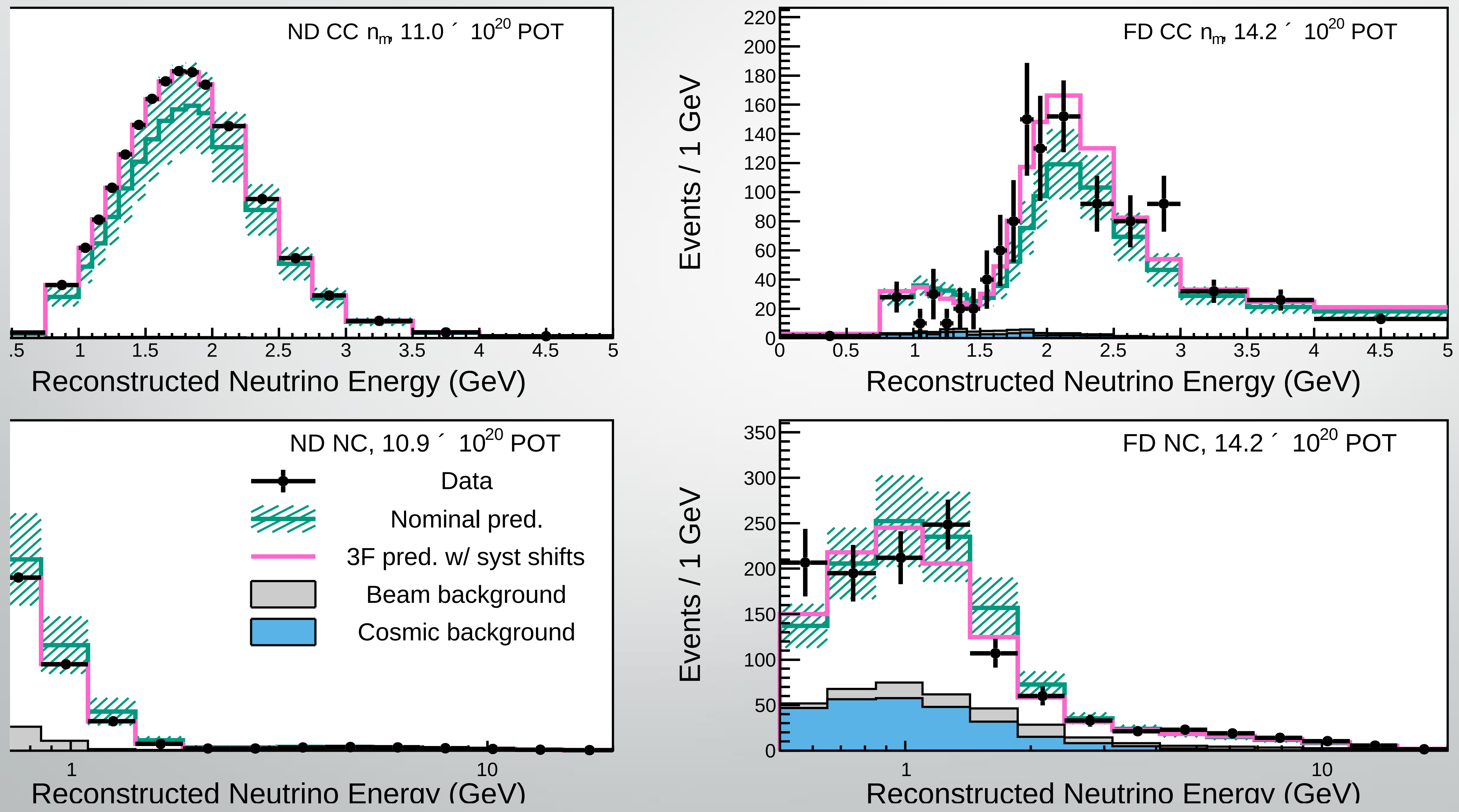
- Differences from 3F oscillations could be visible in ND and FD
- Published NOvA analysis on anti-neutrino data: *Phys.Rev.Lett.* 127 (2021) 20, 201801
  - measures NC only
- Update analysis uses neutrino mode data
  - NC + $\nu_\mu$ data
  - Simultaneous 2-detector fit
  - Assumes 3+1 model, covariance matrix fit
  - Systematic uncertainties in fit
  - No MEC alterations



# Sterile sample pre-fit

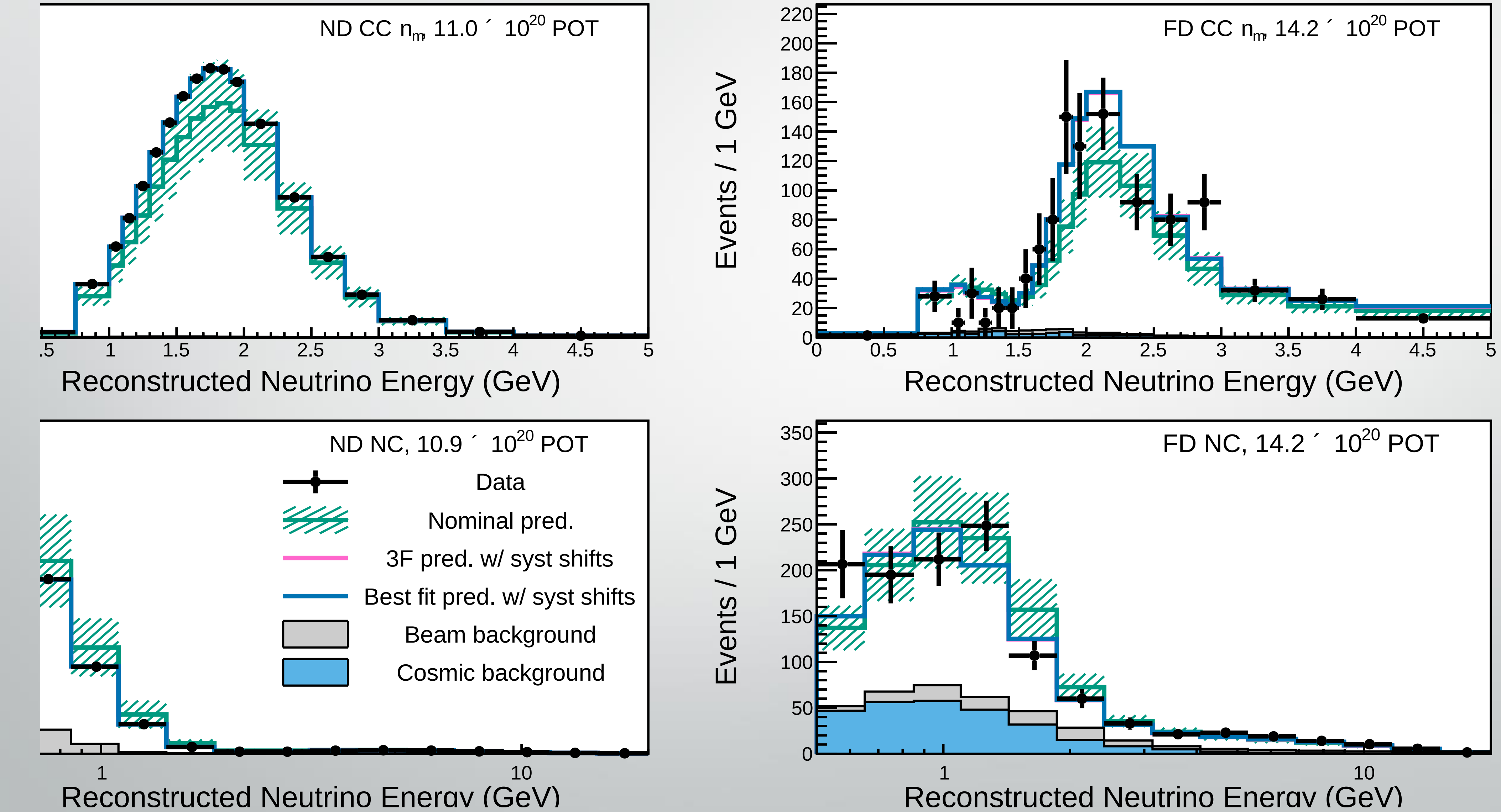


# Sterile sample 3-flavor fit



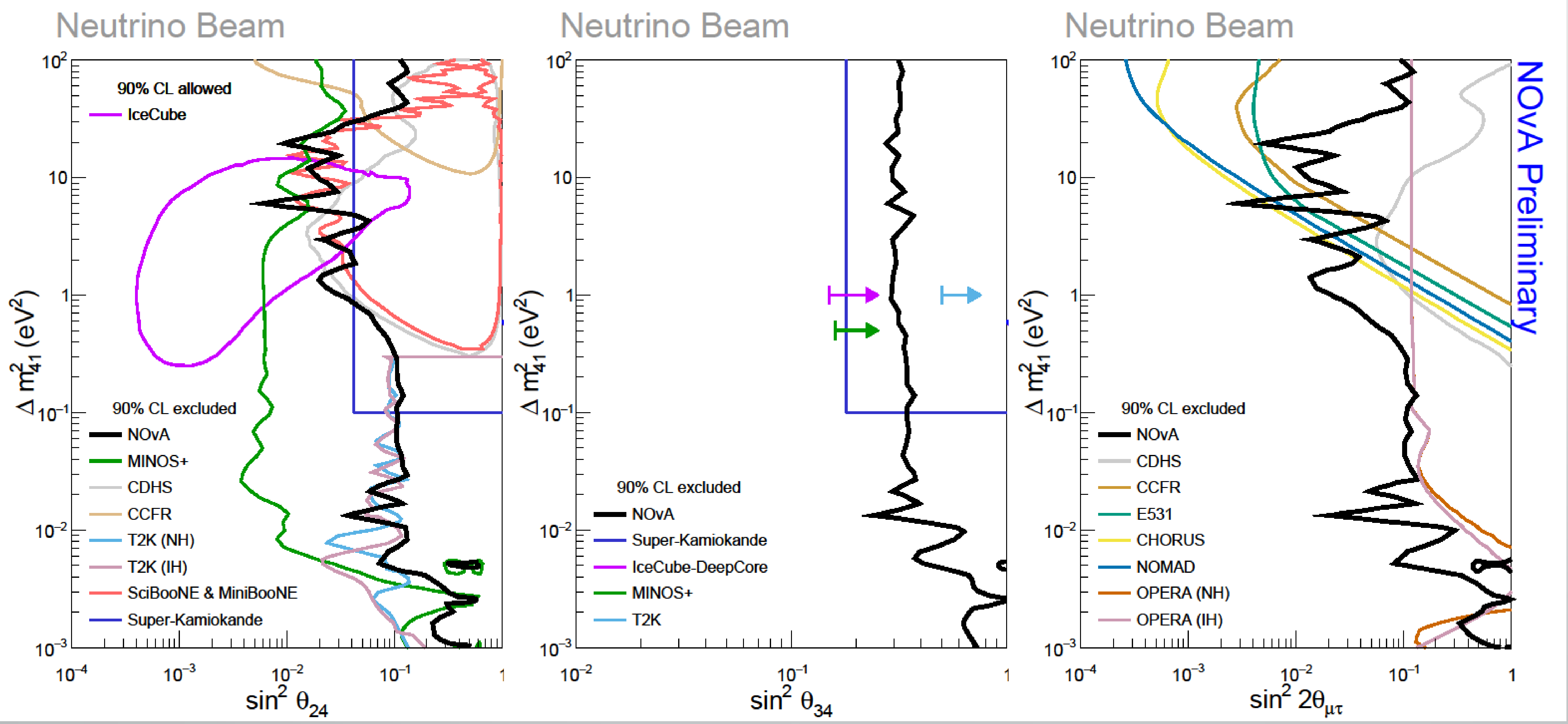
3+1 fit same as 3F fit
no evidence for steriles

# Sterile sample 3+1 fit



paper in preparation

# Sterile neutrino mixing parameter limits

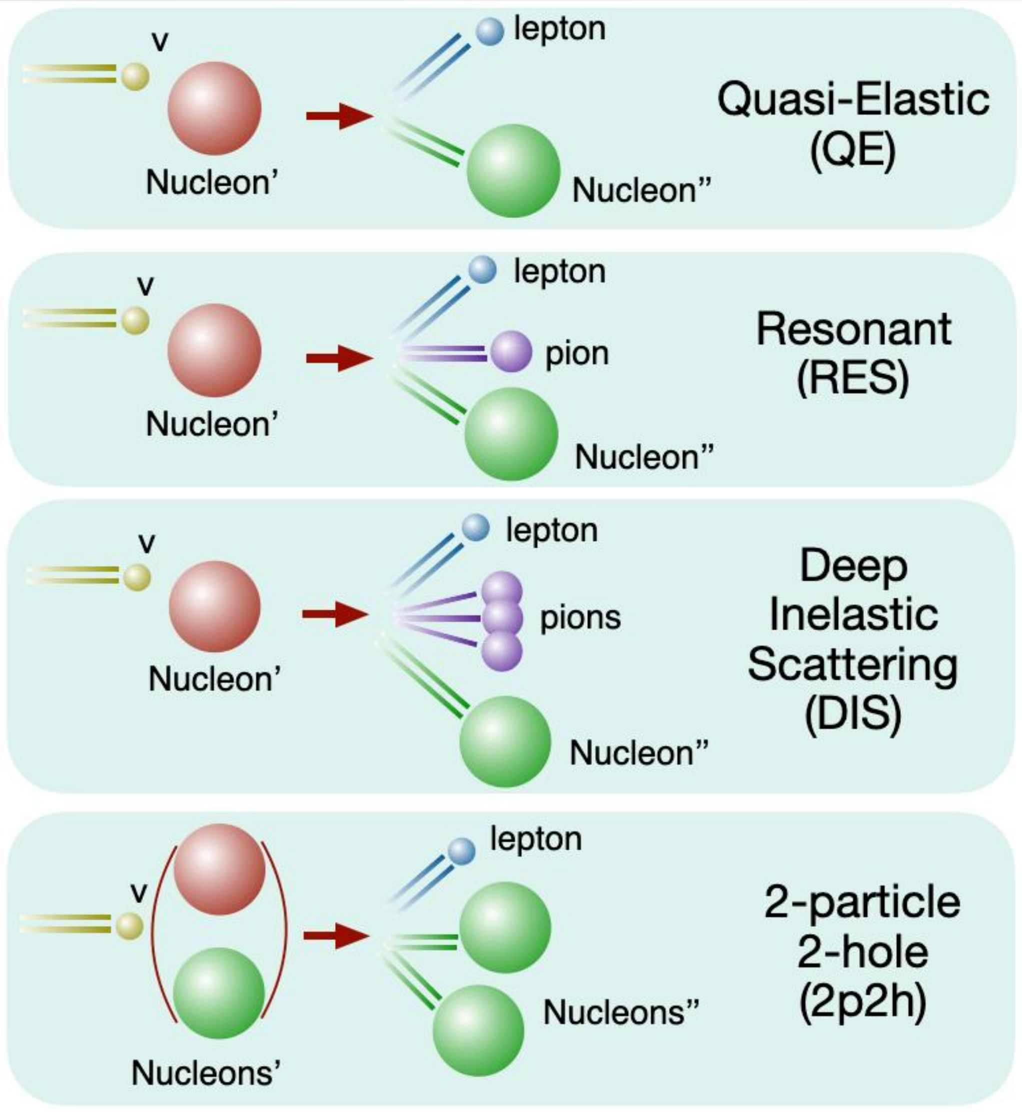


# What's next for NOvA

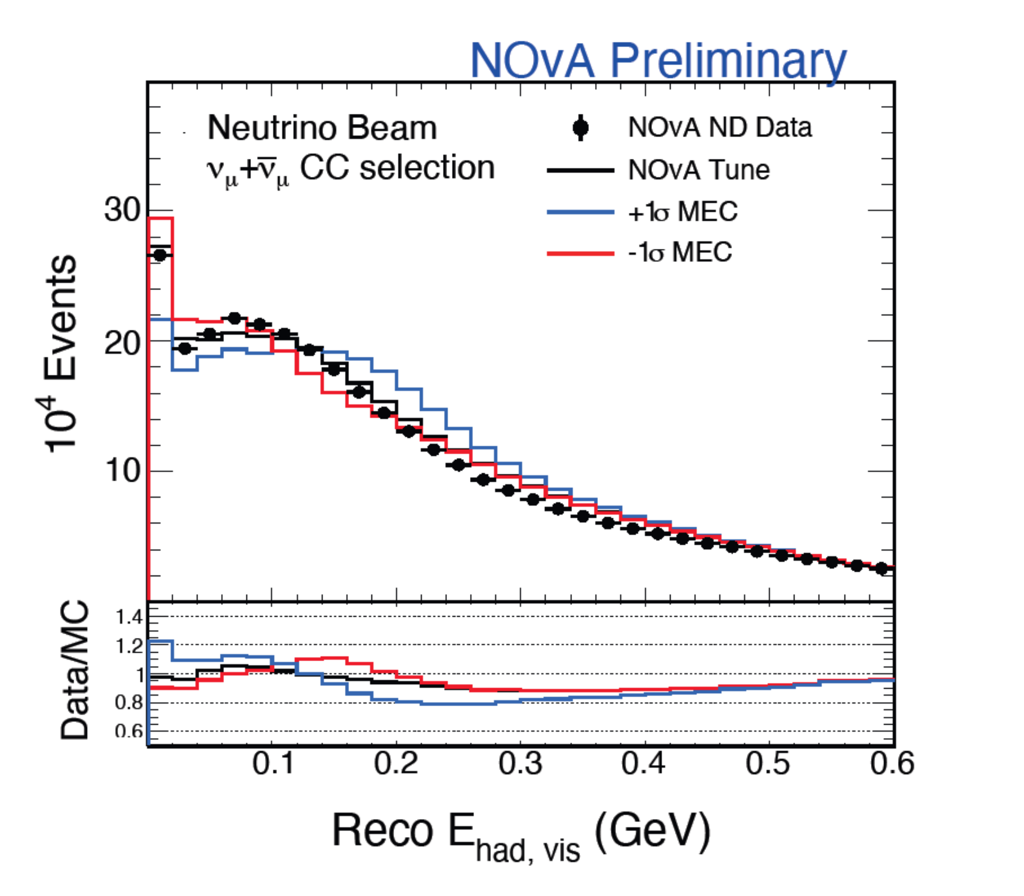
- Studying new models in new versions of GENIE
- More sophisticated treatment of MEC
- New oscillation results:
  - ~2x neutrino-mode statistics, updated simulation and reconstruction – next year
- New cross-section results:
  - Antineutrino $\nu_\mu$ CC inclusive – look for Fermilab seminar soon
  - Many more in pipeline
- Sterile neutrinos: add anti-neutrino mode data, $\nu_e$ data
- NOvA-T2K joint fit result: converging now, results soon
- Beam: have achieved >950 kW power, heading to 1 MW this year
- NOvA test beam – dedicated experiment to reduce uncertainties

# Thanks!

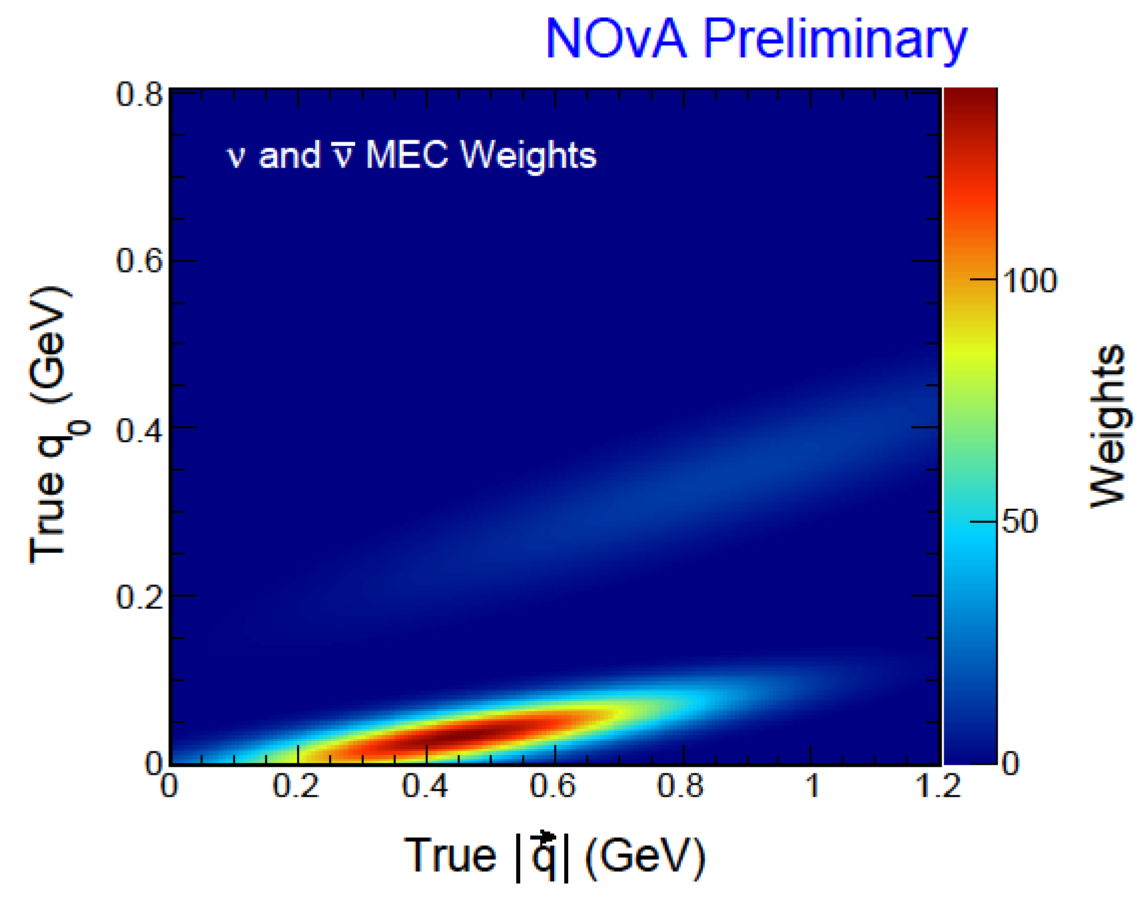
# Backup


v
lepton
Nucleon'
Nucleon"
Quasi-Elastic (QE)
v
lepton
pion
Nucleon'
Nucleon"
Resonant (RES)
v
lepton
pions
Nucleon'
Nucleon"
Deep Inelastic Scattering (DIS)
v
lepton
Nucleons'
Nucleons"
2-particle 2-hole (2p2h)

Main MEC uncertainty

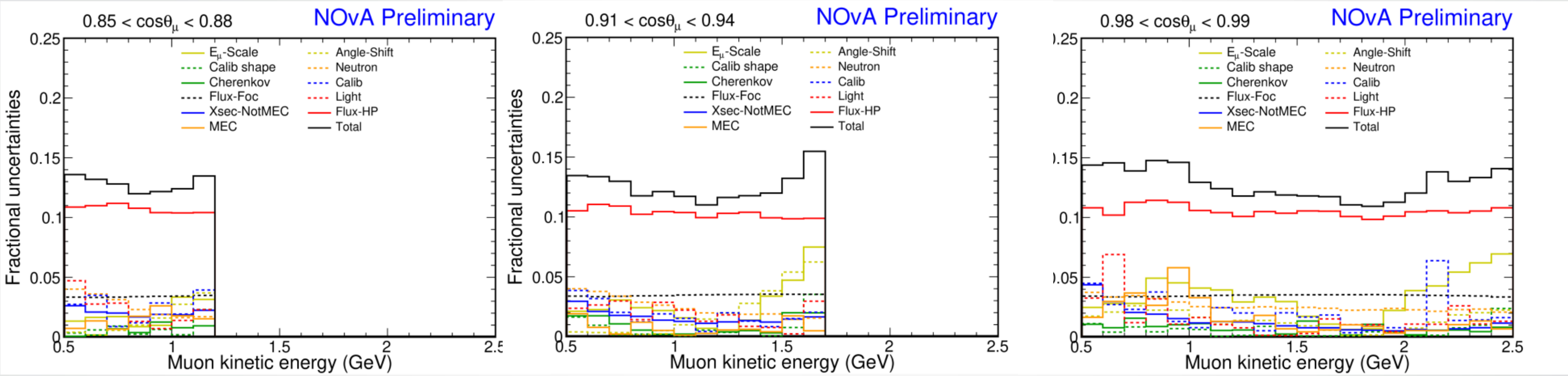



MEC weights – two 2D Gaussians

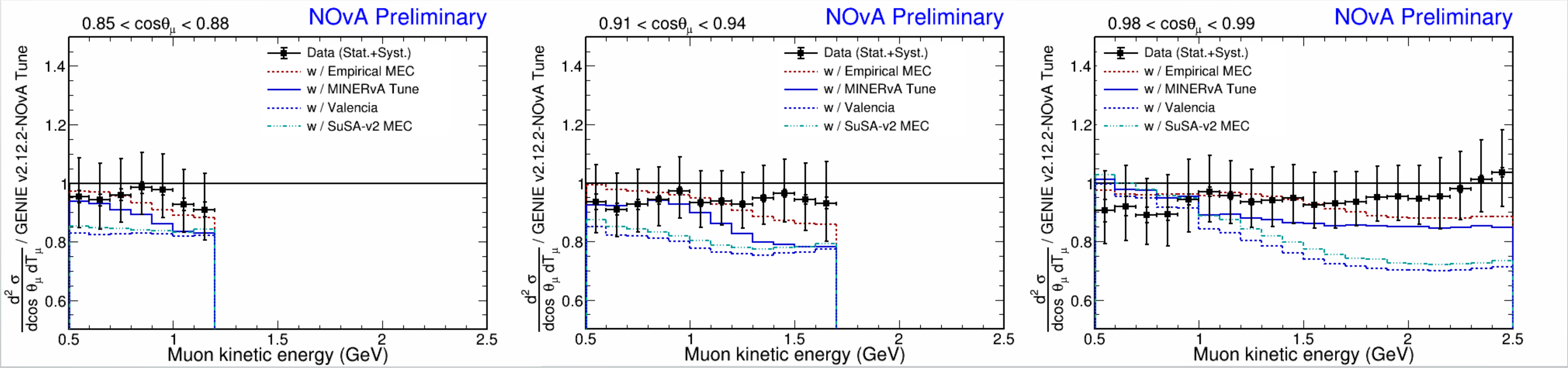


# Cross-section analysis: muon system

uncertainties




result ratios

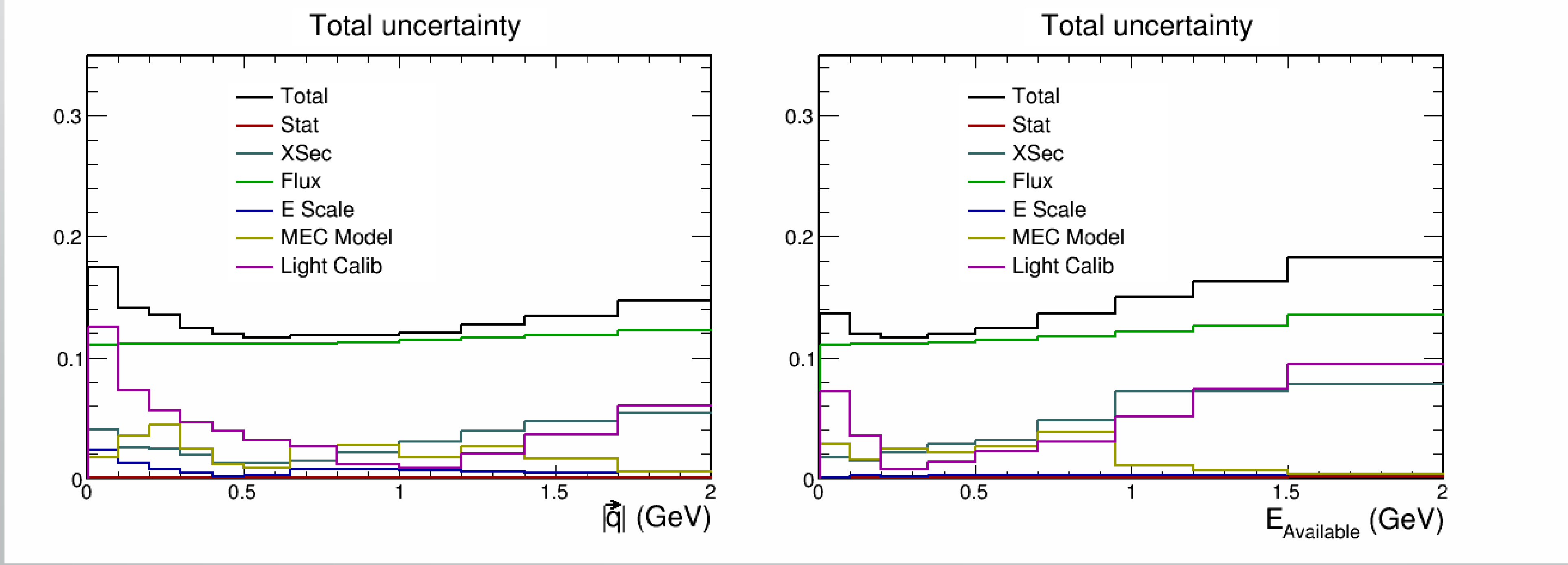


# Cross-section measurement: hadronic system

| Selection cut | Selected signal events | Efficiency |
|---|---|---|
| All true signal | 1,956,000 | 100% |
| Quality | 1,952,000 | 99.9% |
| Track reconstruction | 1,951,000 | 99.8% |
| Muon identification | 1,667,000 | 85.3% |
| Vertex fiducial | 1,609,000 | 82.3% |
| Muon containment | 482,600 | 24.7% |
| Muon phase space | 432,200 | 22.1% |
| Shower containment | 365,300 | 18.7% |

background selection

| Process | Selected events | Event fraction |
|---|---|---|
| Signal | 372,000 | 91.85% |
| Total background | 33,000 | 8.15% |
| Outside phase space | 15,000 | 3.70% |
| Non-fiducial | 7,600 | 1.78% |
| CC Anti-neutrino | 6,000 | 1.48% |
| Neutral current | 4,200 | 1.04% |
| Electron neutrino | 160 | 0.04% |



- 3F contours (Bayesian)