Cross-sections and neutrino oscillations in NOvA

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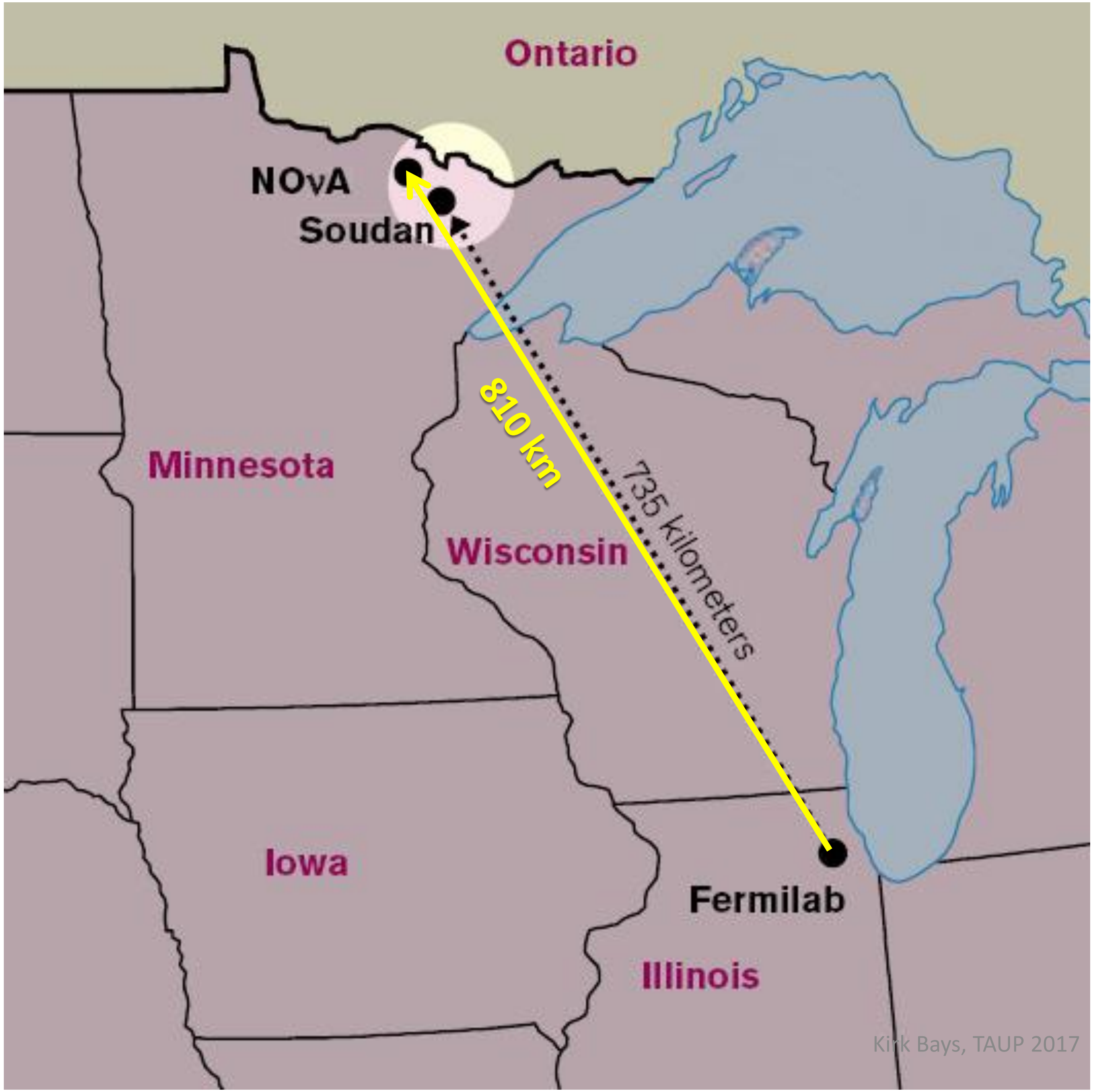
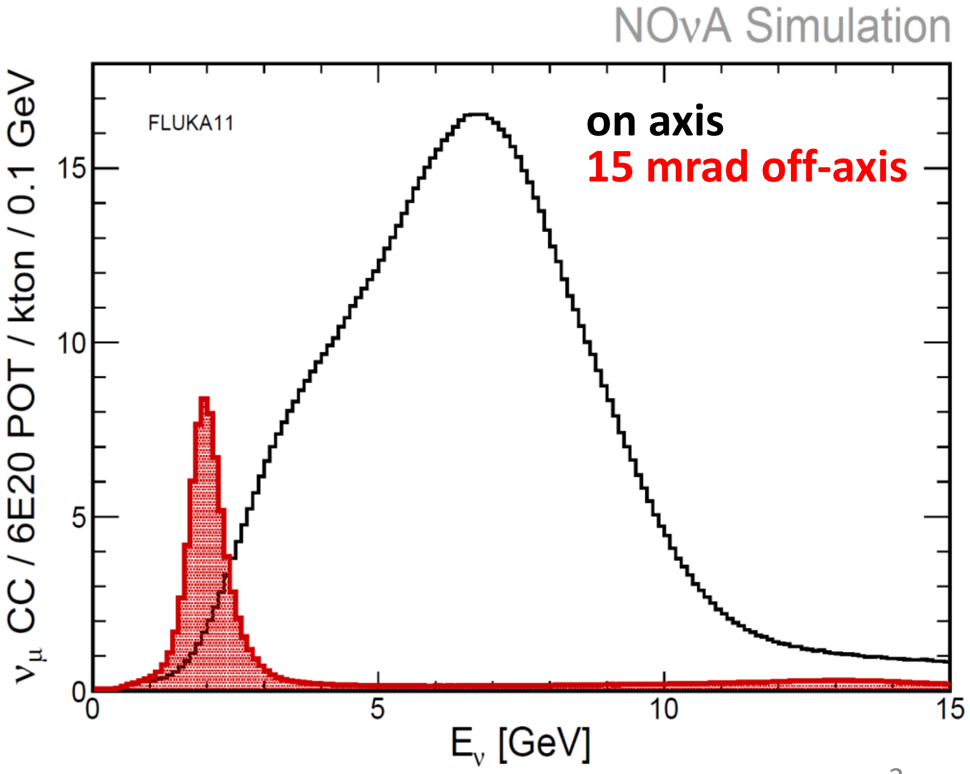
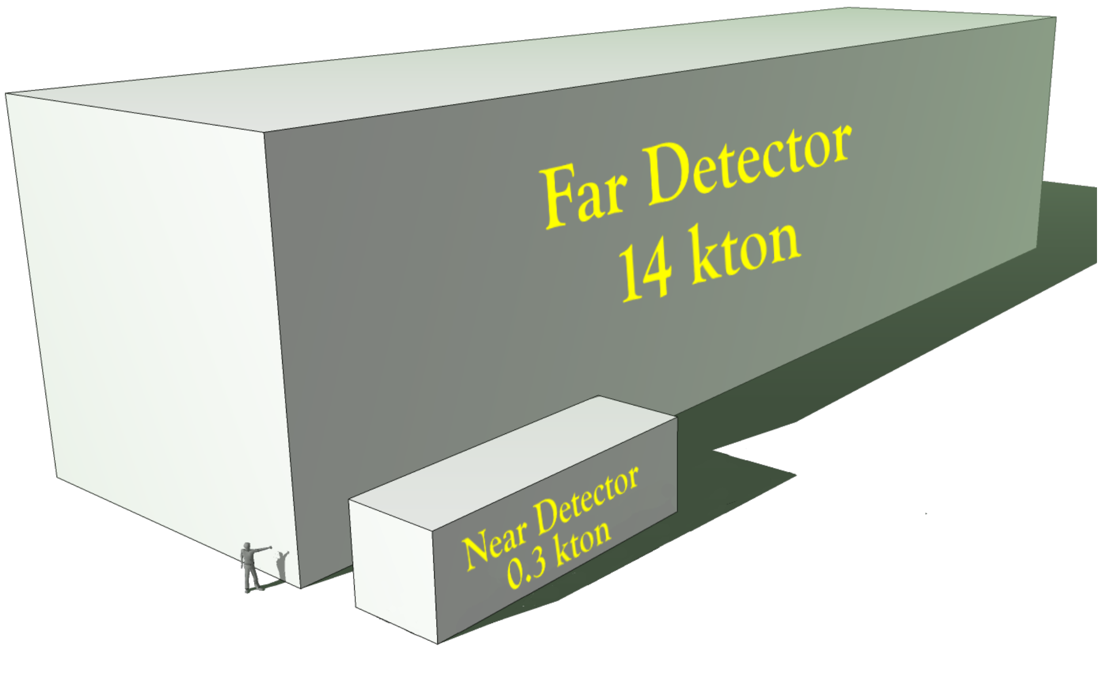
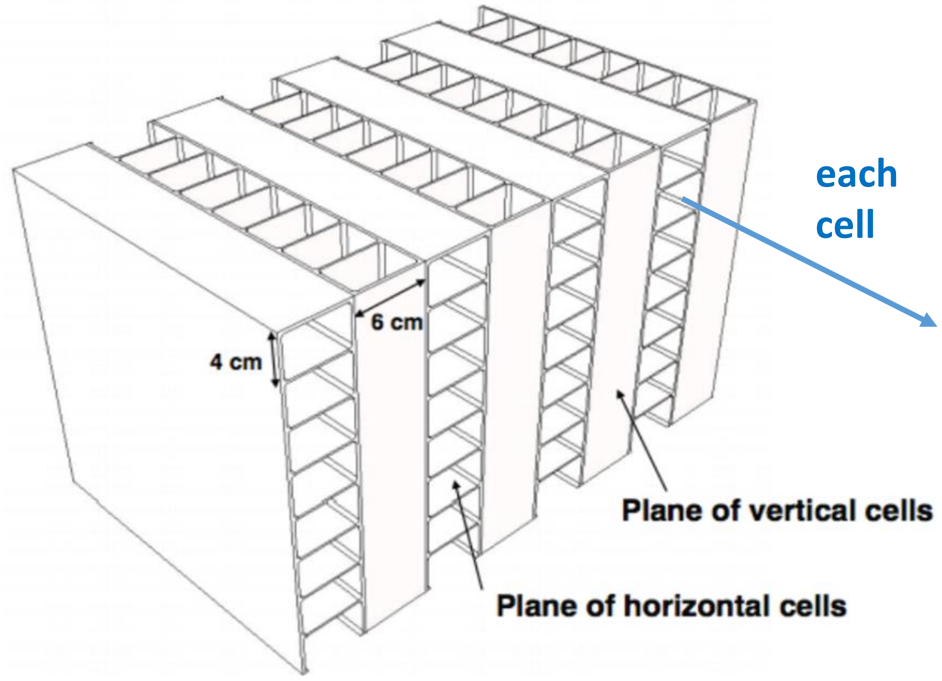


NOνA Overview

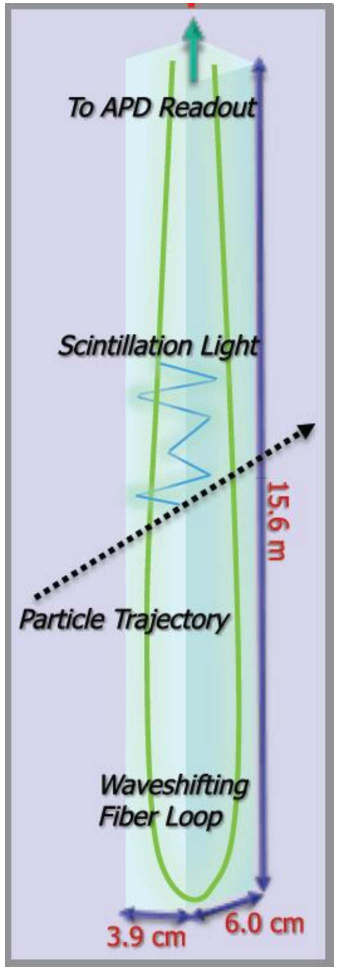
- NOνA (NuMI Off-axis ν Appearance)
- Source: NuMI ν_μ beam (FNAL)
- Far Det (FD) (810 km @ Ash River, MN)
- Near Detector (ND) (1km @ FNAL)
- 15 mrad off-axis (tight energy peak)







each cell

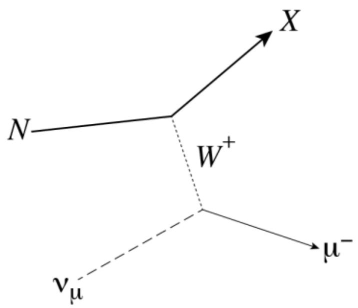


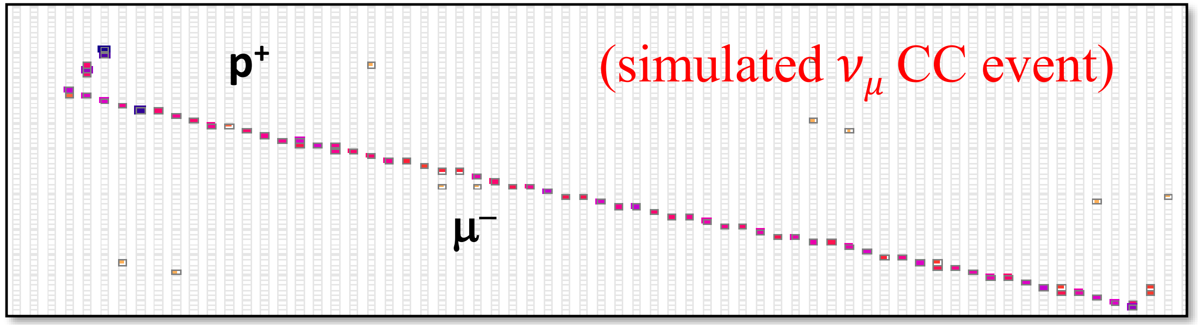
- Detectors are long-baseline tracking calorimeters
- FD (at Ash River, MN, 810 km baseline):
  - 16m x 16m x 60m, 14 kton, on surface
  - ~2/3 LS by mass, ~344,000 cells (99.5% operational), 896 planes
- ND (@ FNAL, 1km from NuMI target):
  - 4m x 4m x 16m, 0.3kton, underground
  - ~20,000 cells, design similar to FD
  - functionally identical; main differences: size and ND `muon catcher', a range stack at the back end of alternating steel and scintillator planes

NOvA oscillation channels

ν_μ Disappearance

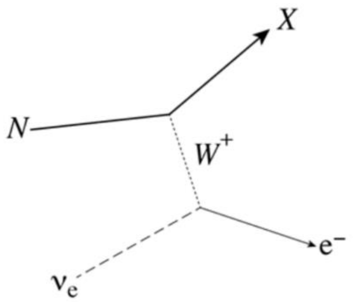
- $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E)$
- Direct measurement of θ_{23} (maximal?), Δm^2_{32}
- Backgrounds: NC neutrinos, cosmic rays
- Signature: high E muon, vertex hadronic activity

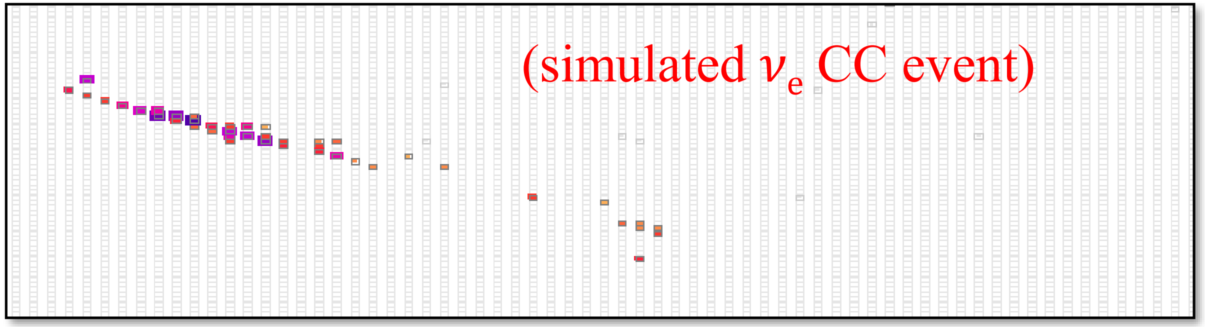


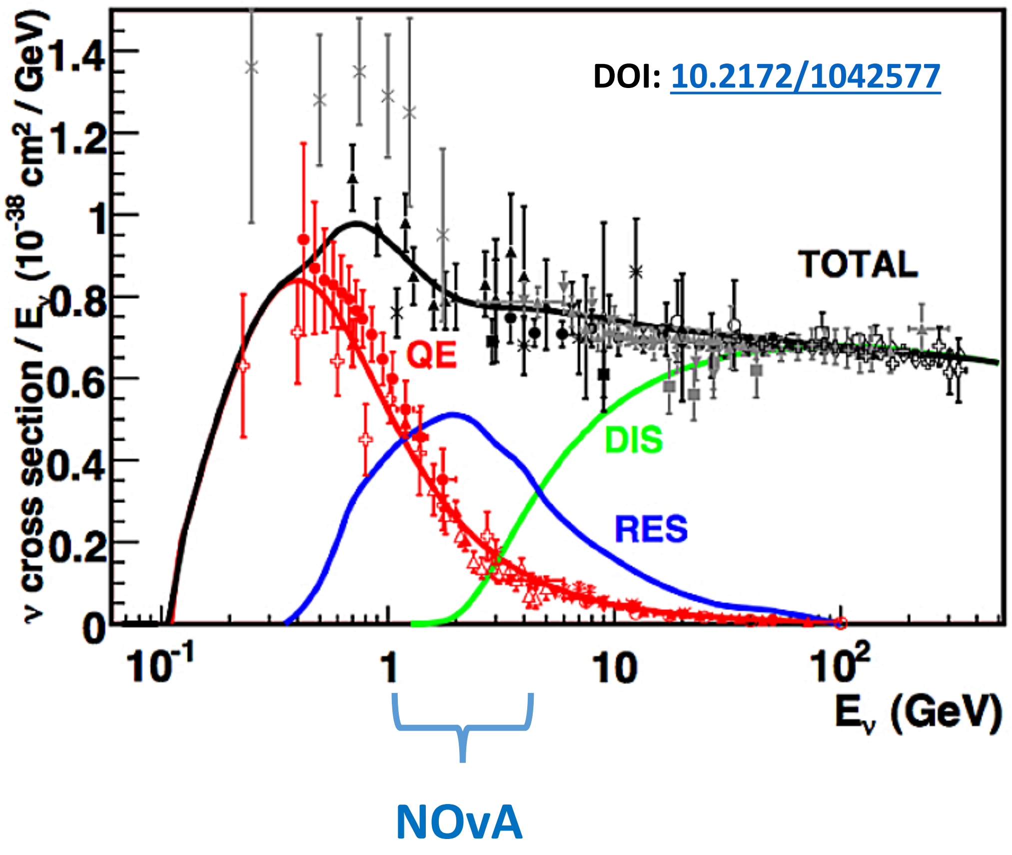


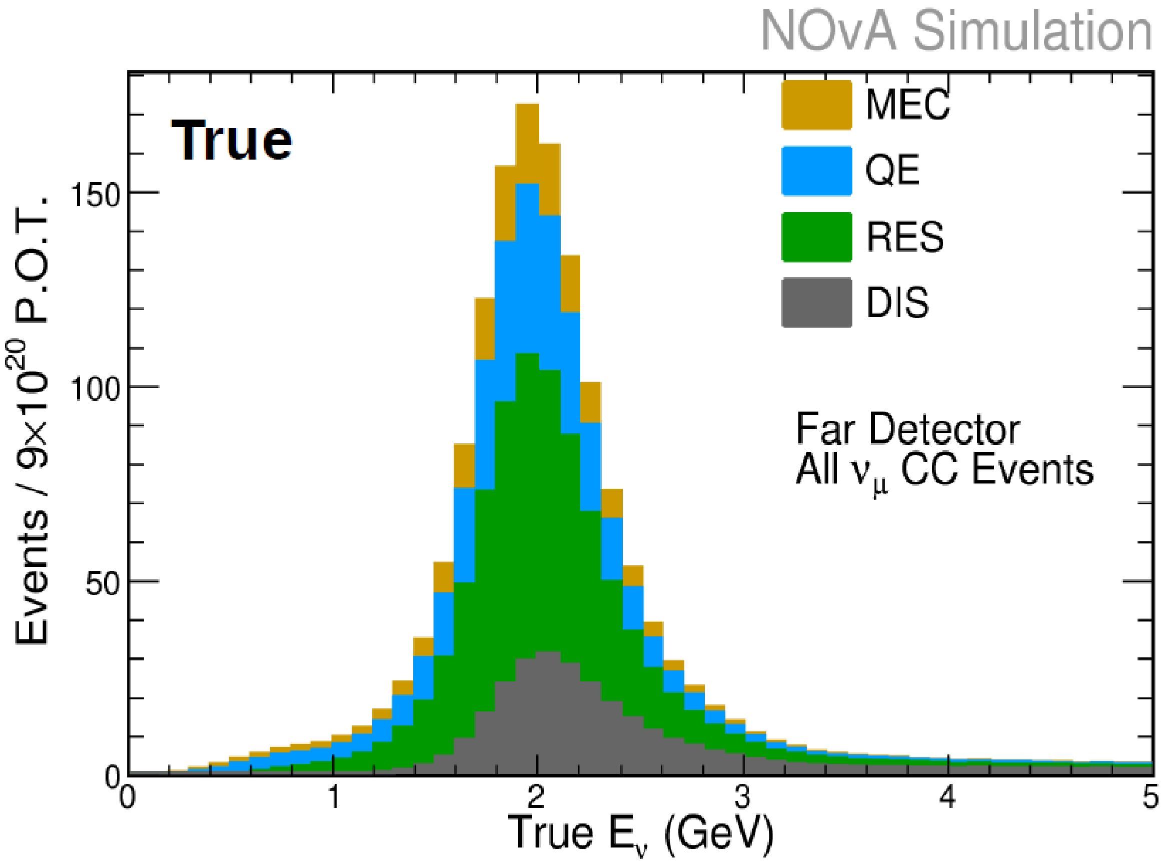
ν_e Appearance

- $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta m^2_{31}L/4E)$
- Measure θ_{13}, possibly hierarchy, constrain δ_{CP}
- Background: beam contamination, NC, cosmics
- Signature is EM shower from electron

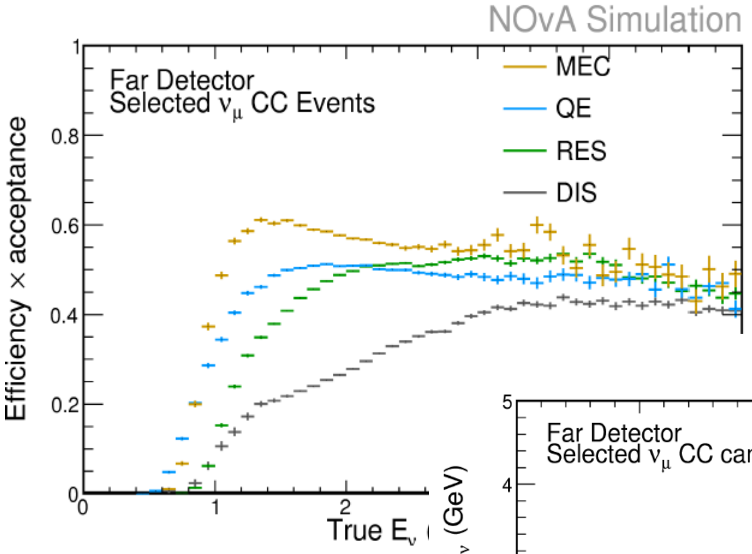


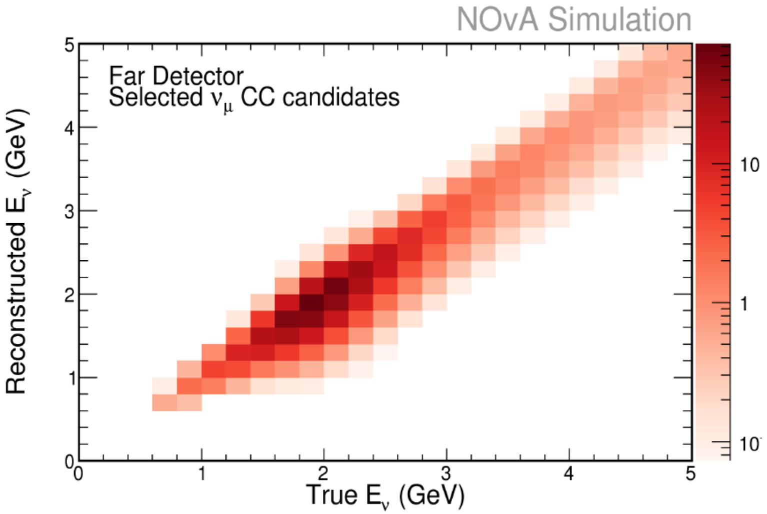


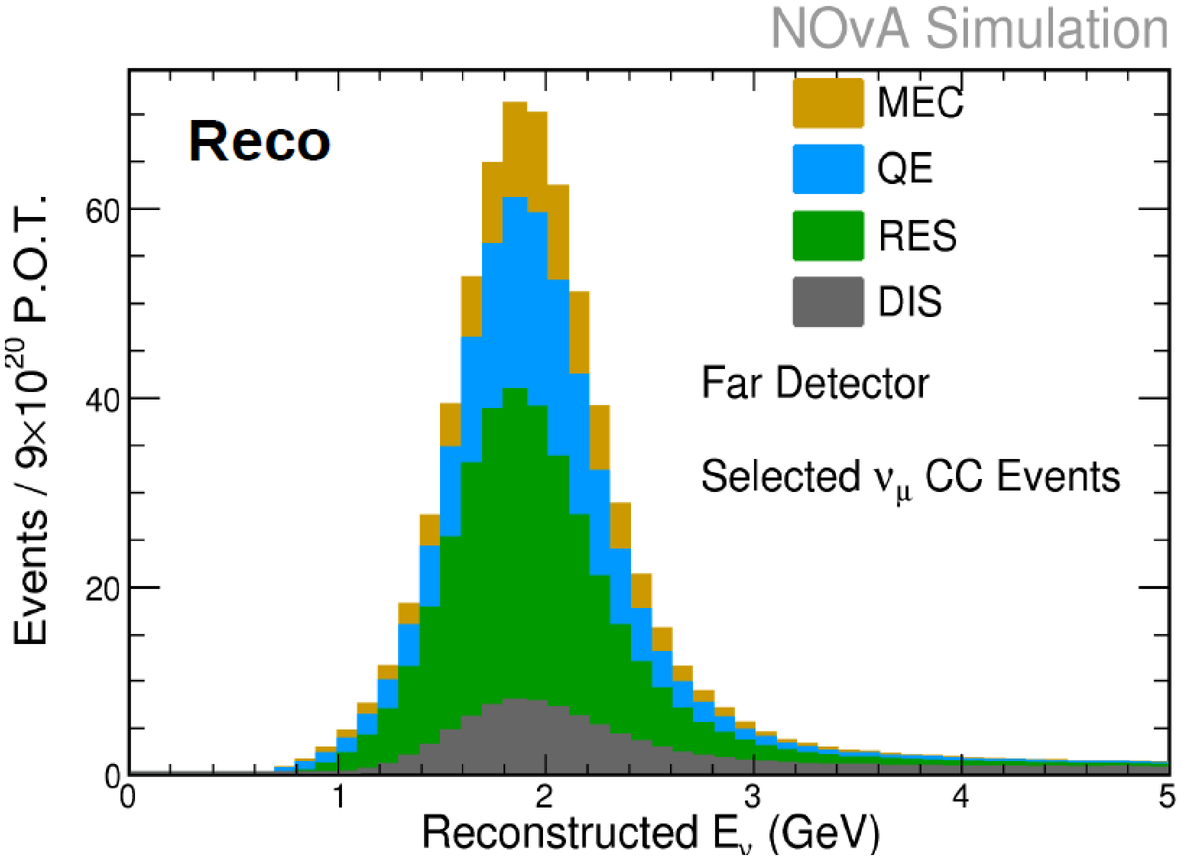




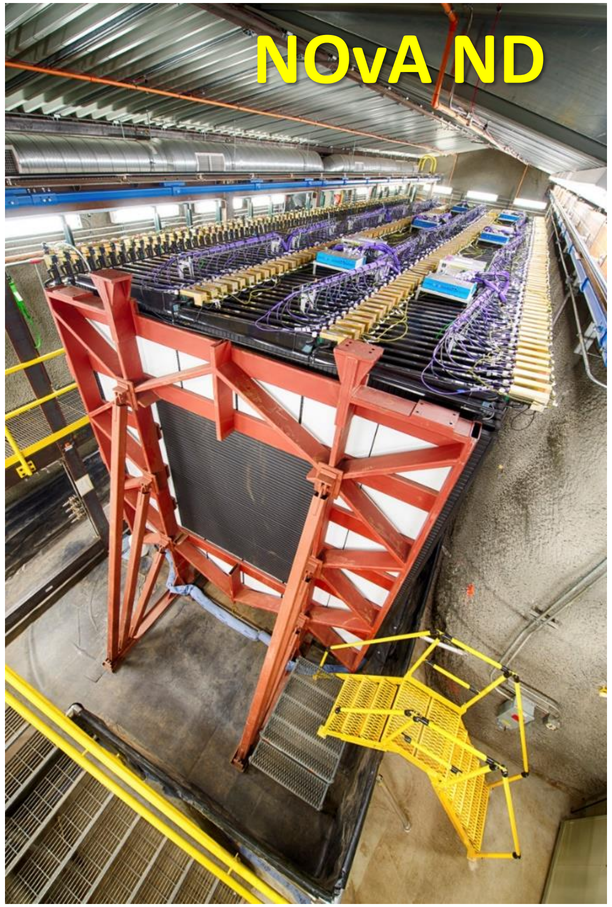
- NOvA's energy range of 1-4 GeV sits right in a region that allows all different interaction modes. QE, RES, DIS, (and 2p2h/MEC!) are all important to us. This makes things complicated!



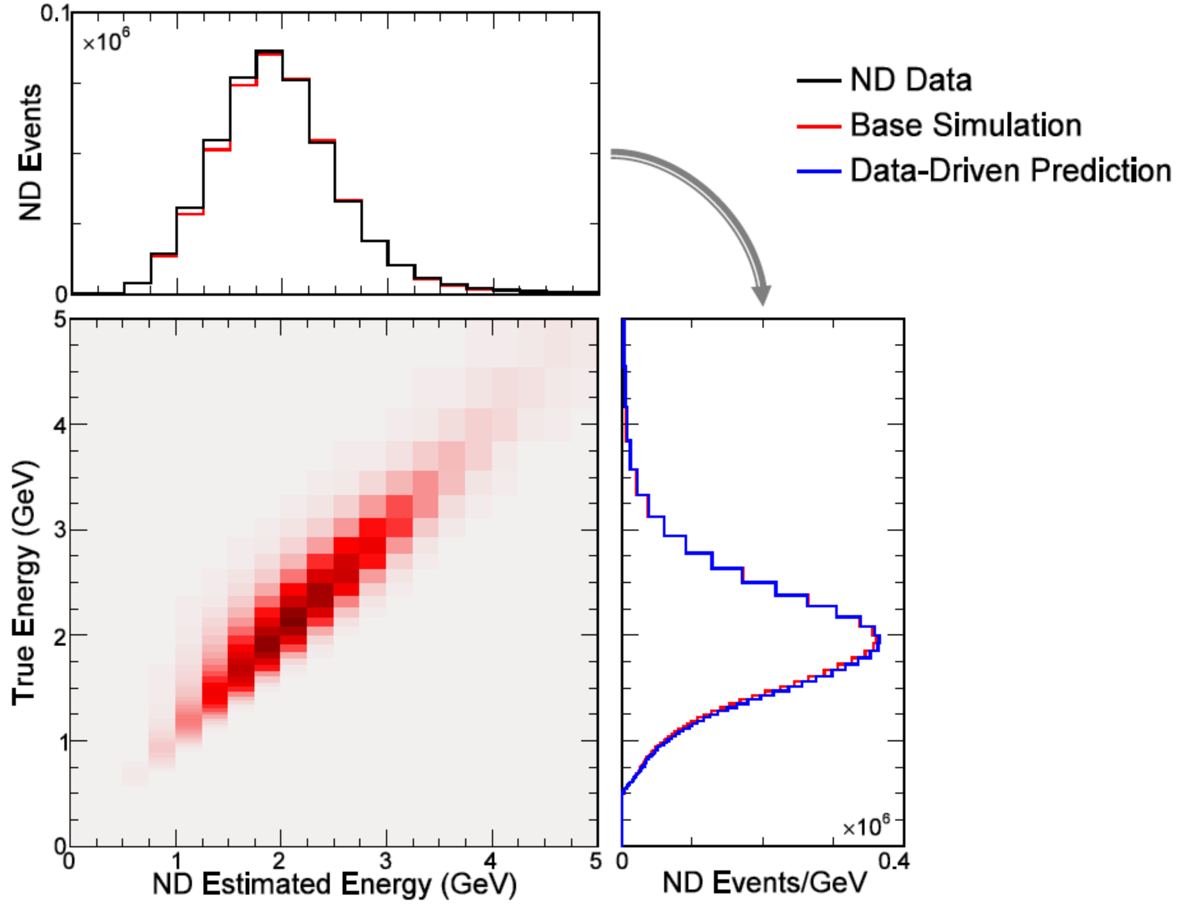




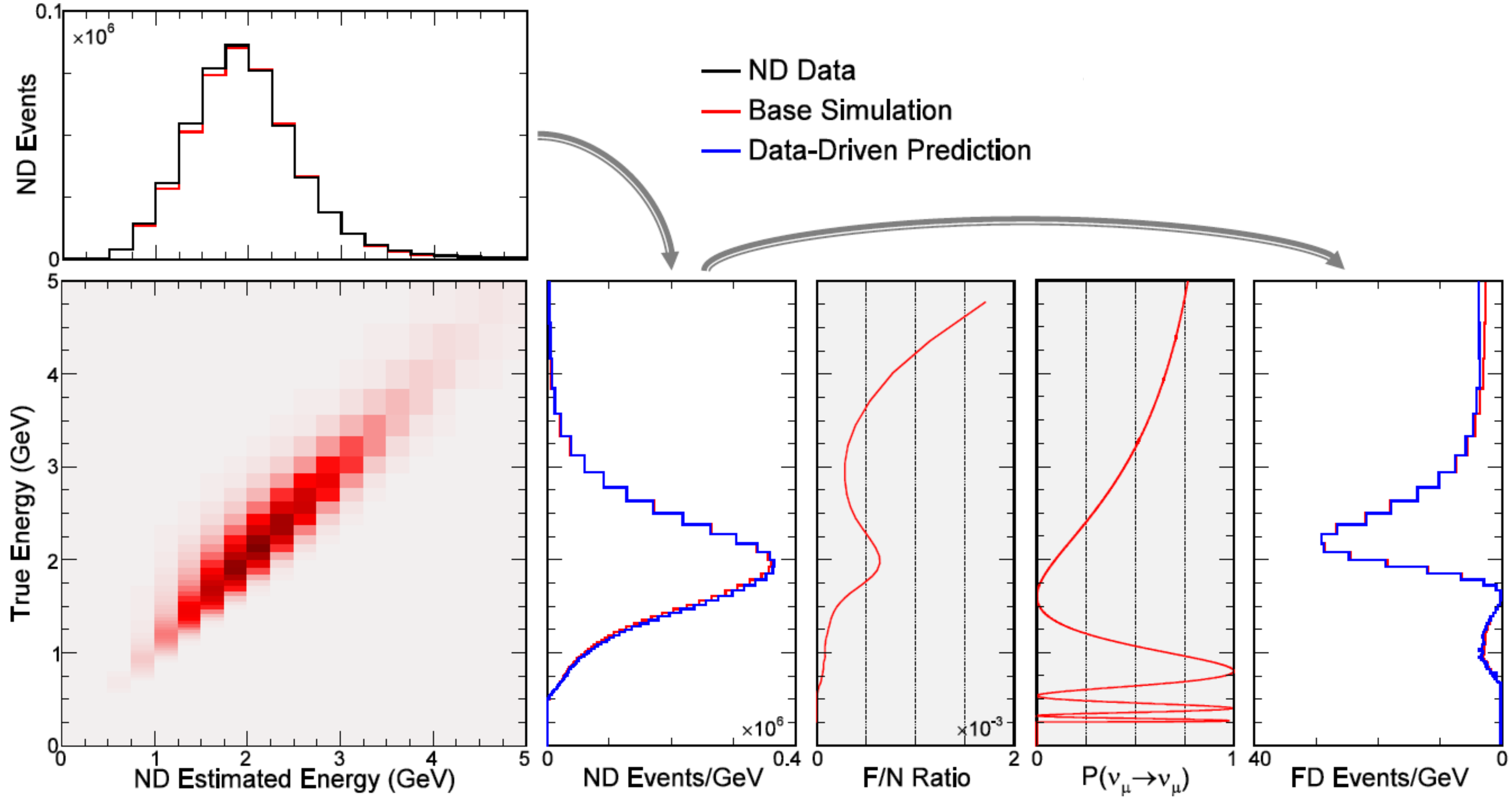
- Each of these channels have different selection efficiency and reconstructed energy biases. We measure $\mathbf{E_{reco}}$, but oscillations are a function of $\mathbf{E_{true}}$, and we bridge the two with simulation. Getting the relative contribution of each correct in our simulation is thus a critical part of an oscillation analysis.



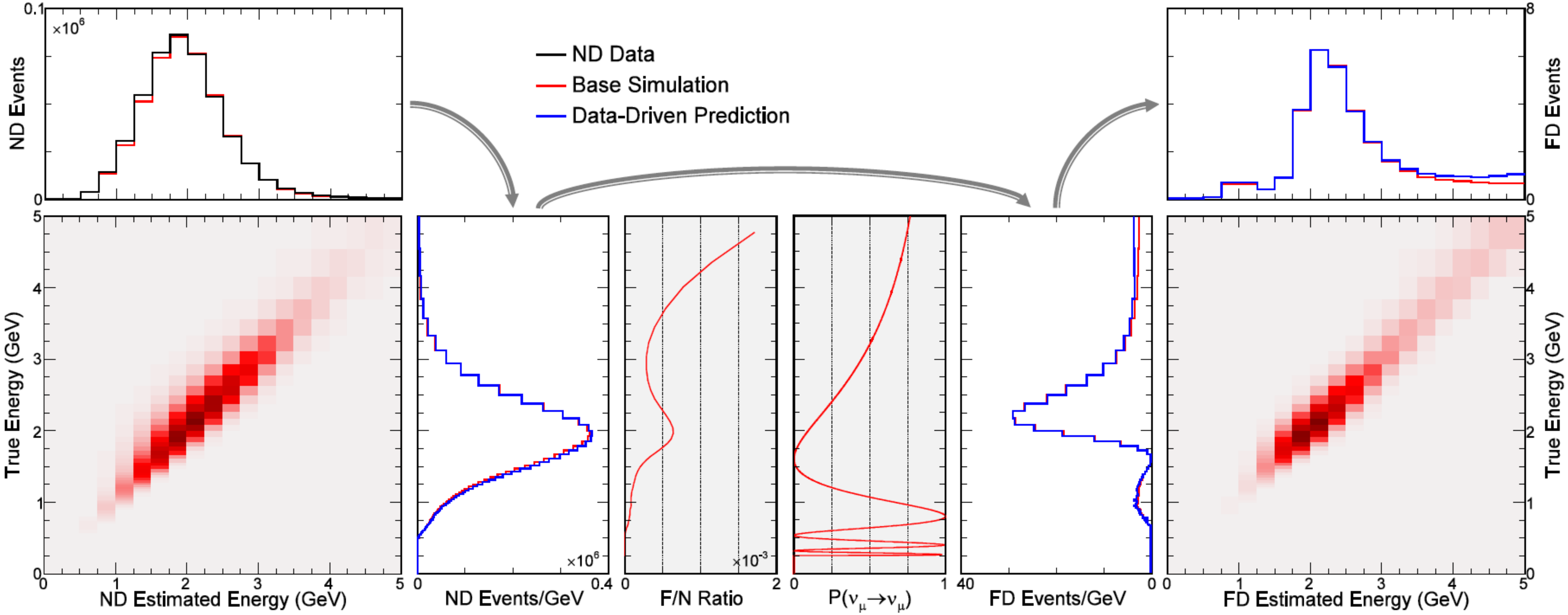
- But we know our simulation is imperfect. So what do we do? One thing we do is extrapolate. Our ND is functionally identical to our FD (except for size), has incredible statistics, and can be used to measure flux and cross section effects. An extrapolation example from our first disappearance analysis follows:



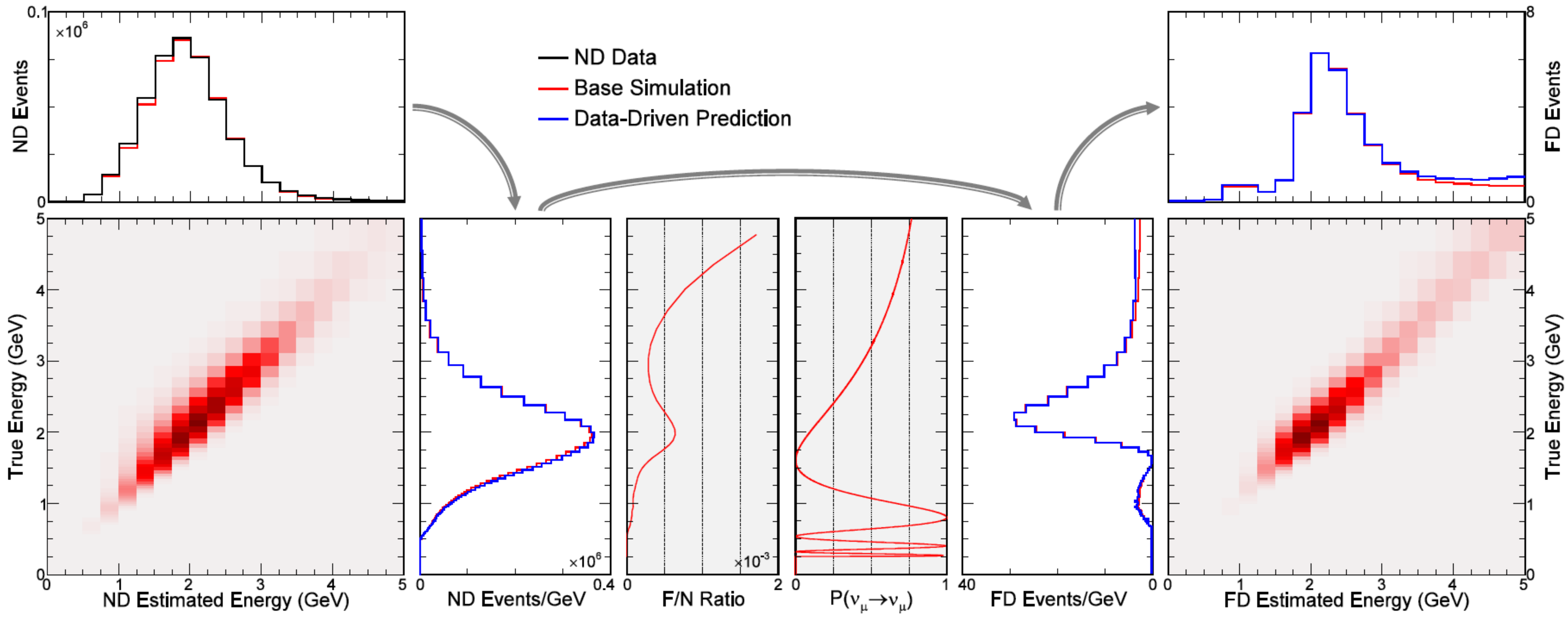
First, our ND simulation is reweighted to match the measured ND reconstructed energy spectrum. This reweighted energy is transformed into true energy via the simulation reco to true matrix.



This true energy spectrum has our known FD/ND detector differences applied, taking into account the different detector efficiencies and angles subtended. Oscillations are also applied.

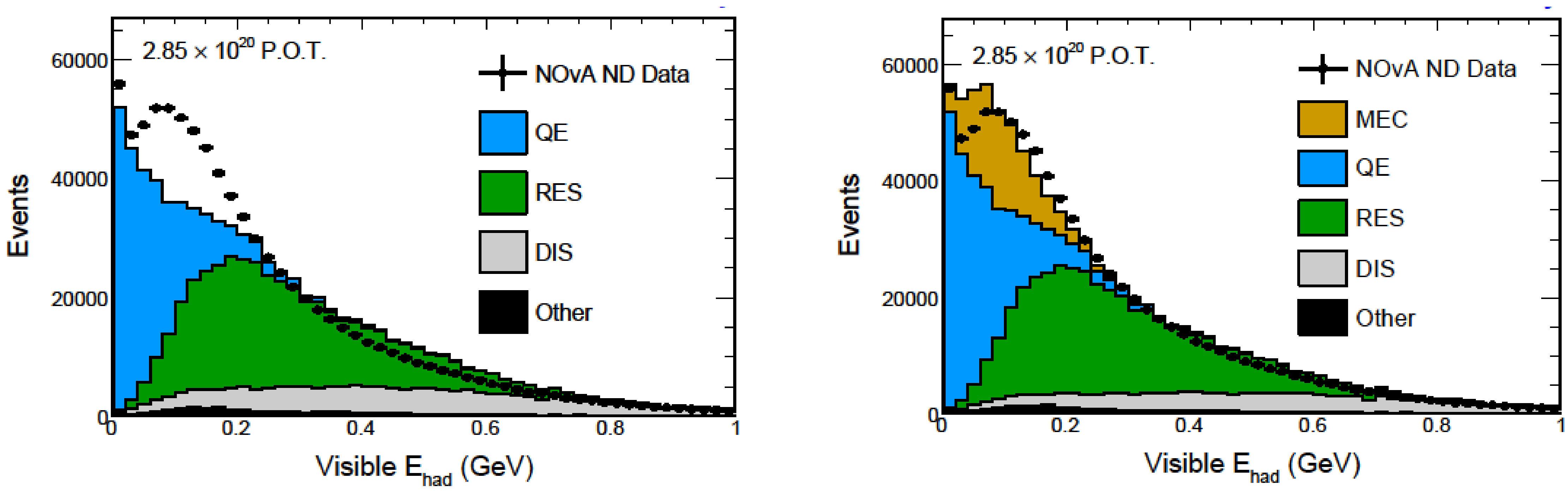


Finally, this true FD energy spectrum is transformed back to reconstructed energy, again using simulation, to obtain our final extrapolated prediction.



- This entire procedure is re-done beginning to end for each combination of oscillation parameters or systematics being tested
- The extrapolation provides a data-driven approach to help fix any simulation errors and constrain uncertainties
- It is not perfect though – it deals well with normalization effects, but poorly with large energy shifts
- Thus it is also important to make the simulation as accurate as possible

Tuning NOvA simulation



- Early on we discovered a significant anomaly in our ND data. Including 2p2h/MEC significantly improved this discrepancy.
- We're currently wrapping up our third iteration of oscillation analyses and gearing up for our fourth. Each time our treatment of 2p2h has grown more sophisticated.

Brief history of 2p2h tuning in NOvA

- First analyses (late 2015):
  - No 2p2h included (very large systematics covered discrepancies)

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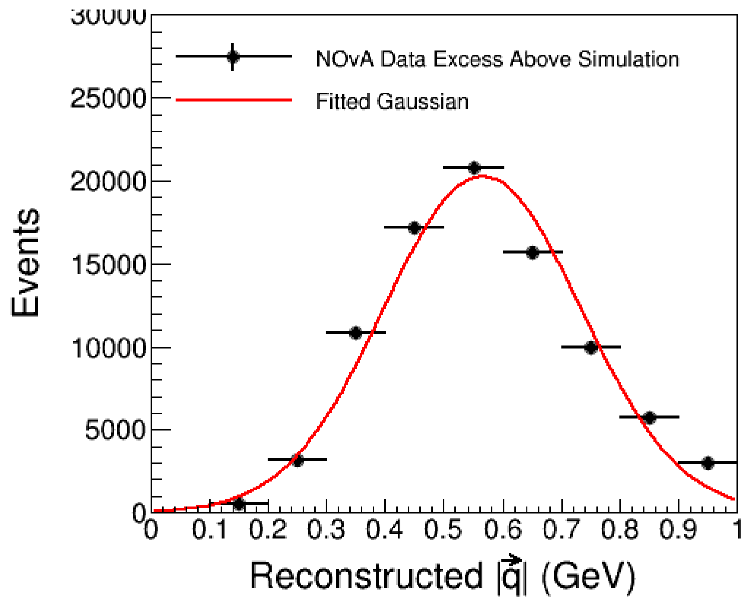
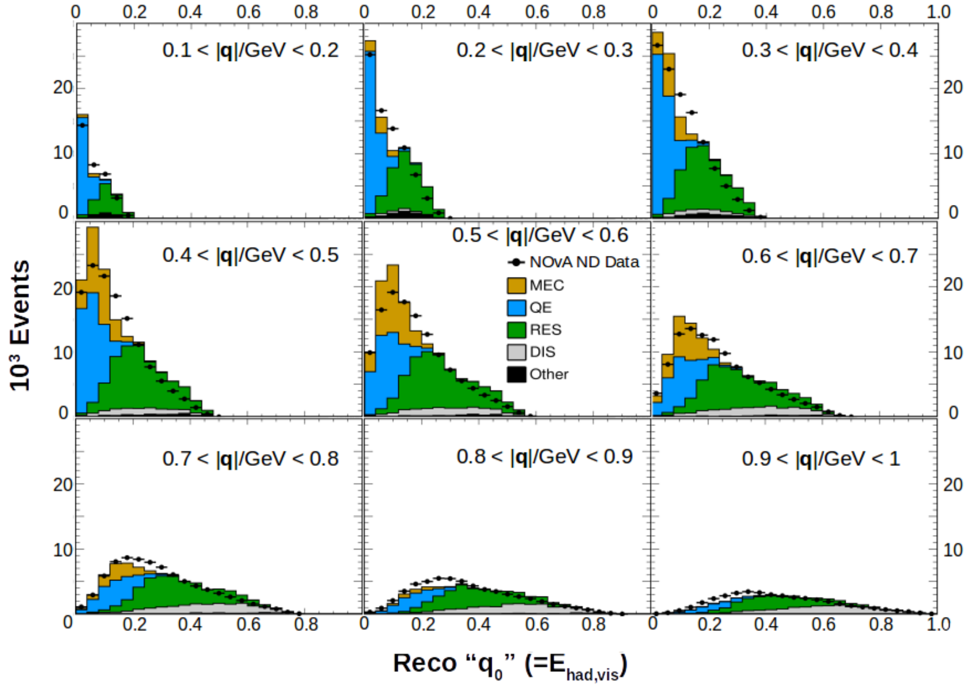
  - Momentum transfer distribution fit to ND data; energy transfer set to match QE
  - A 50% normalization uncertainty is taken





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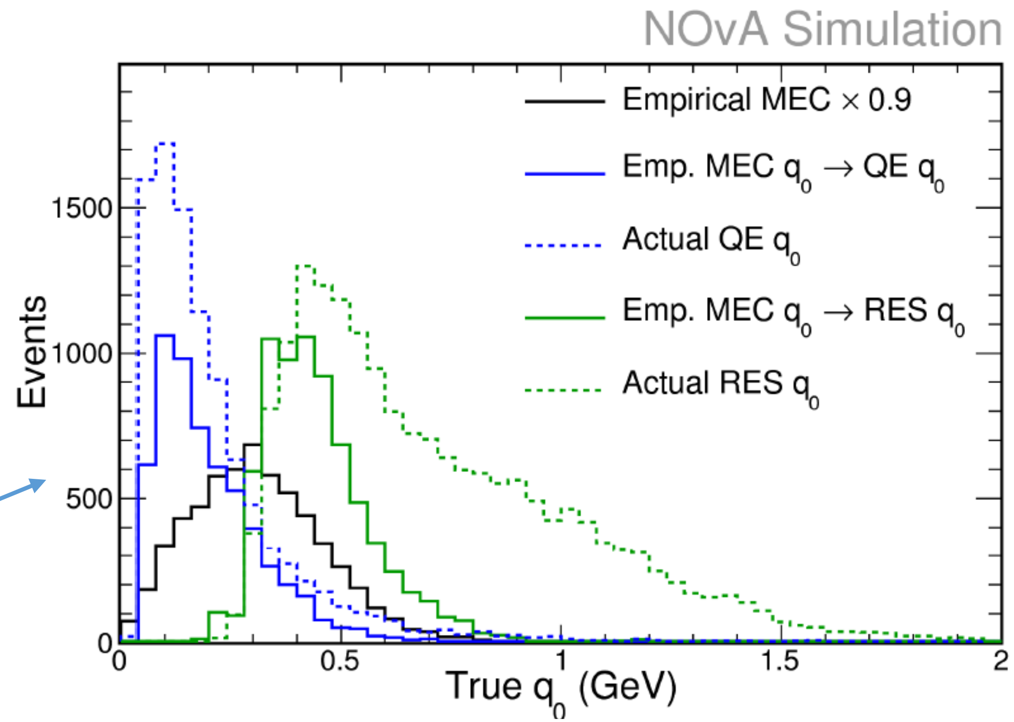
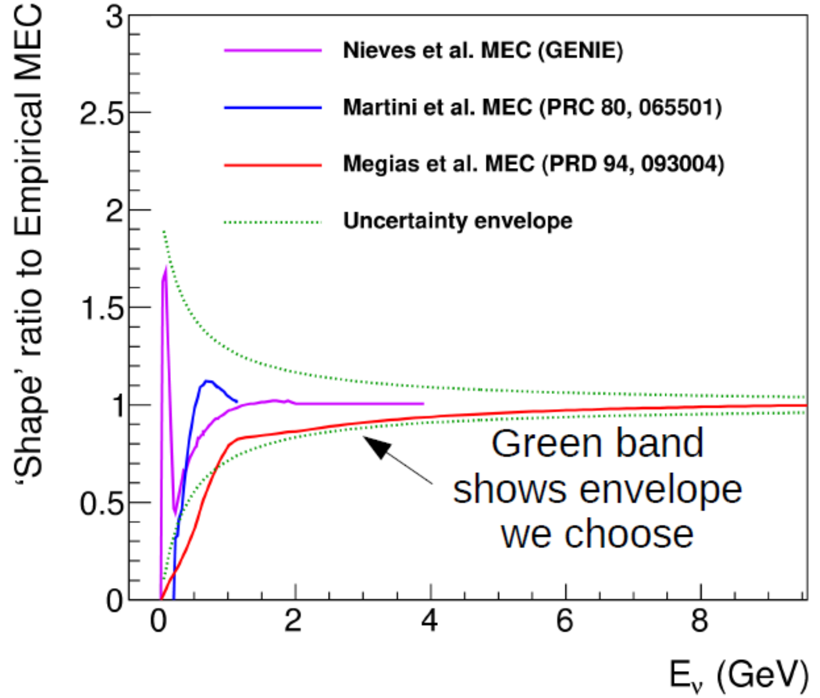
  - A 50% normalization uncertainty is taken
- Third analyses (2017 - ongoing, results by end of year):
  - New 2p2h models added to GENIE (Valencia, used by other experiments and TEM), but empirical MEC is still the best match to data
  - Energy transfer no longer set to QE, left as implemented in GENIE
  - Fitting the |q| distribution to ND data yields similar result as simple scaling
  - Result: central value tune is just GENIE empirical MEC * 1.2 normalization factor
  - Robust systematics added

Third analysis x-sec tune

- Will be used for upcoming analyses
- 2p2h:
  - Empirical MEC scaled up 20%, same result as fitting |q| to ND data
  - New systematics: energy transfer shape, np/nn ratio, x-sec normalization
- DIS:
  - Additional systematics for 'transition region' DIS, with W>1.7 GeV, and for >2 pion events, to cover anomalies in GENIE
- RPA applied
- Non-res single π fix (arXiv:1601.01888v3)
- Tuned simulation agrees within uncertainties



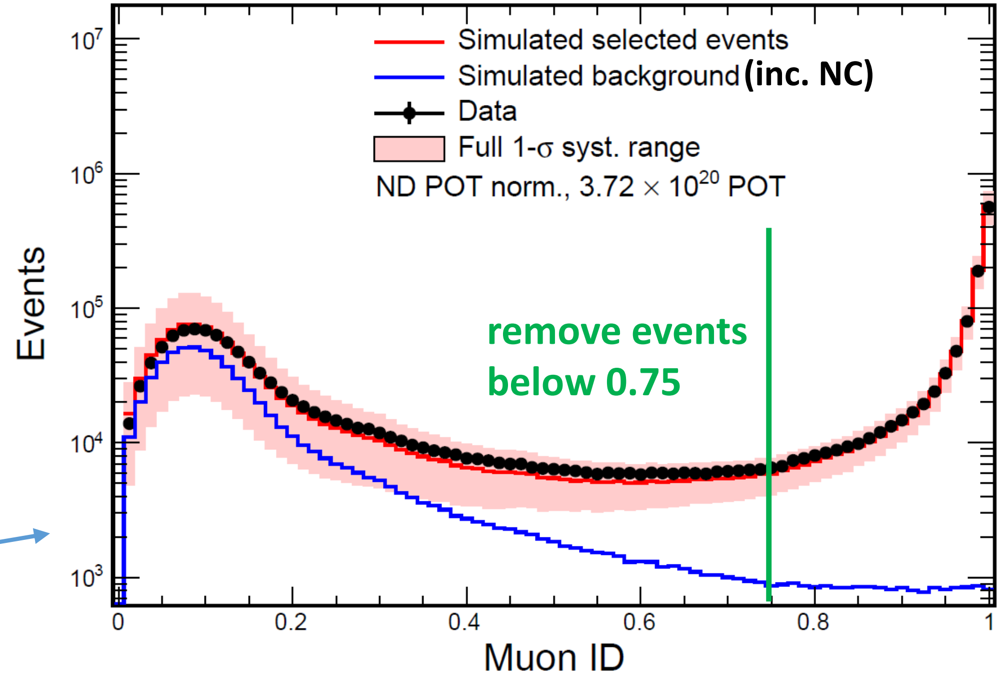


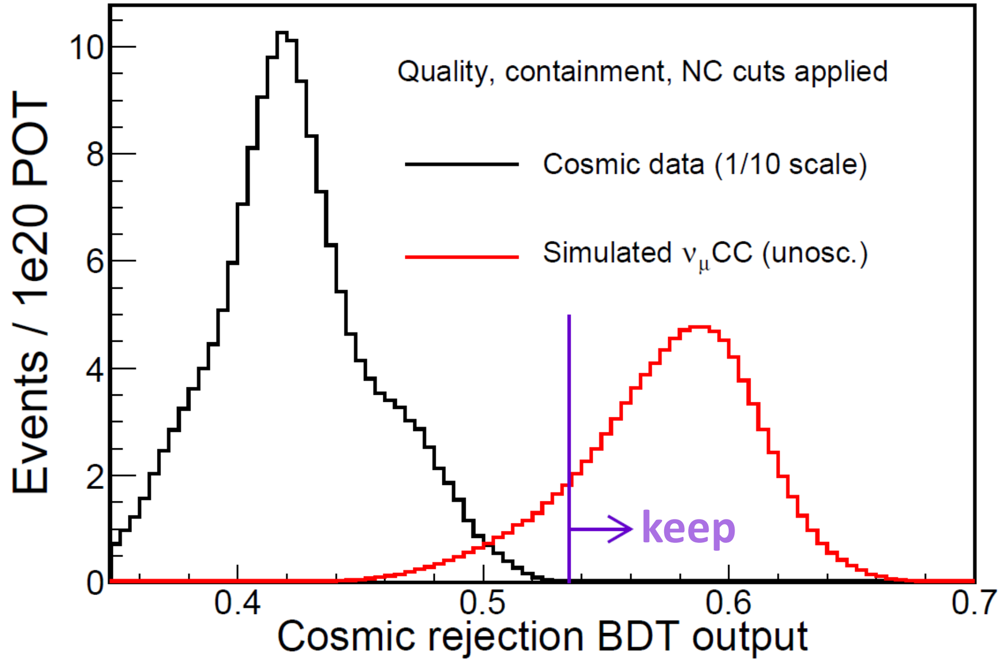
Cross-section systematics

- We use a combination of GENIE standard and custom systematics
- Processes (> 50 knobs):
  - QE: reduced M_A, vector form factor
  - 2p2h: q_0 shape, np/nn ratio, x-sec
  - RES: M_A, M_V
  - DIS: Bodek-Yang parameters custom 50% normalization
  - Coh: M_A, R_0
- FSI (~20 knobs, standard GENIE):
  - hadronization, intranuclear rescattering
- QE RPA:
  - Use prescription from R. Gran (arxiv.org/abs/1705.02932)
  - Built in uncertainties
- RES RPA:
  - Considered possible but never calculated; use Q^2-dependent QE formulation applied to RES events as a systematic
- 2p2h: q_0 shape, nn/pn ratio, x-sec E-dependent normalization

NOvA disappearance

- Brief summary of analysis (arXiv:1701.05891v2) :
- Cuts are applied to remove backgrounds:
  - Containment ensures E reconstruction is possible
  - NC removed by requiring a clear muon track
  - Cosmics are removed by putting track directions, containment, hadronic activity and more into a BDT





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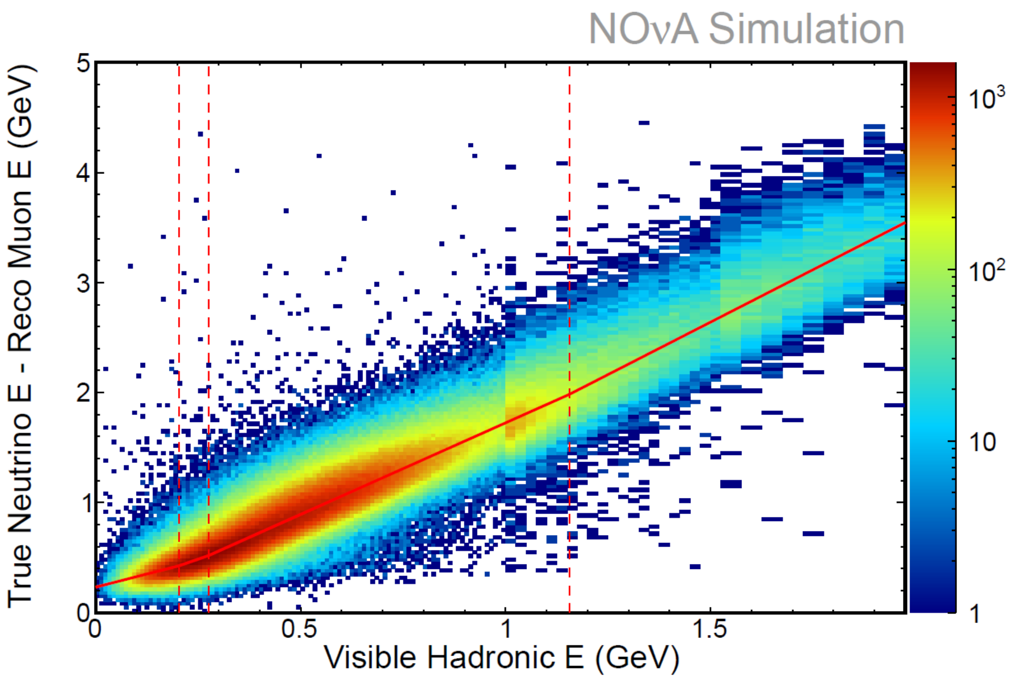

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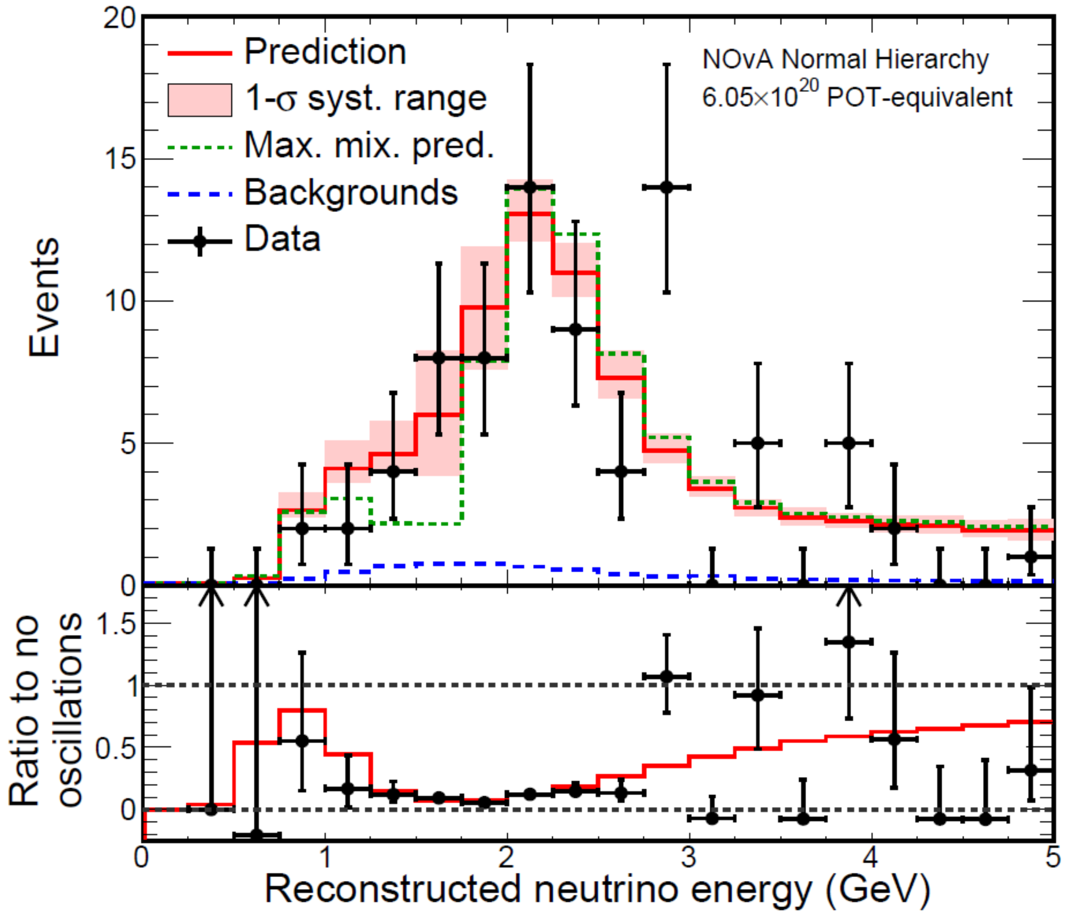
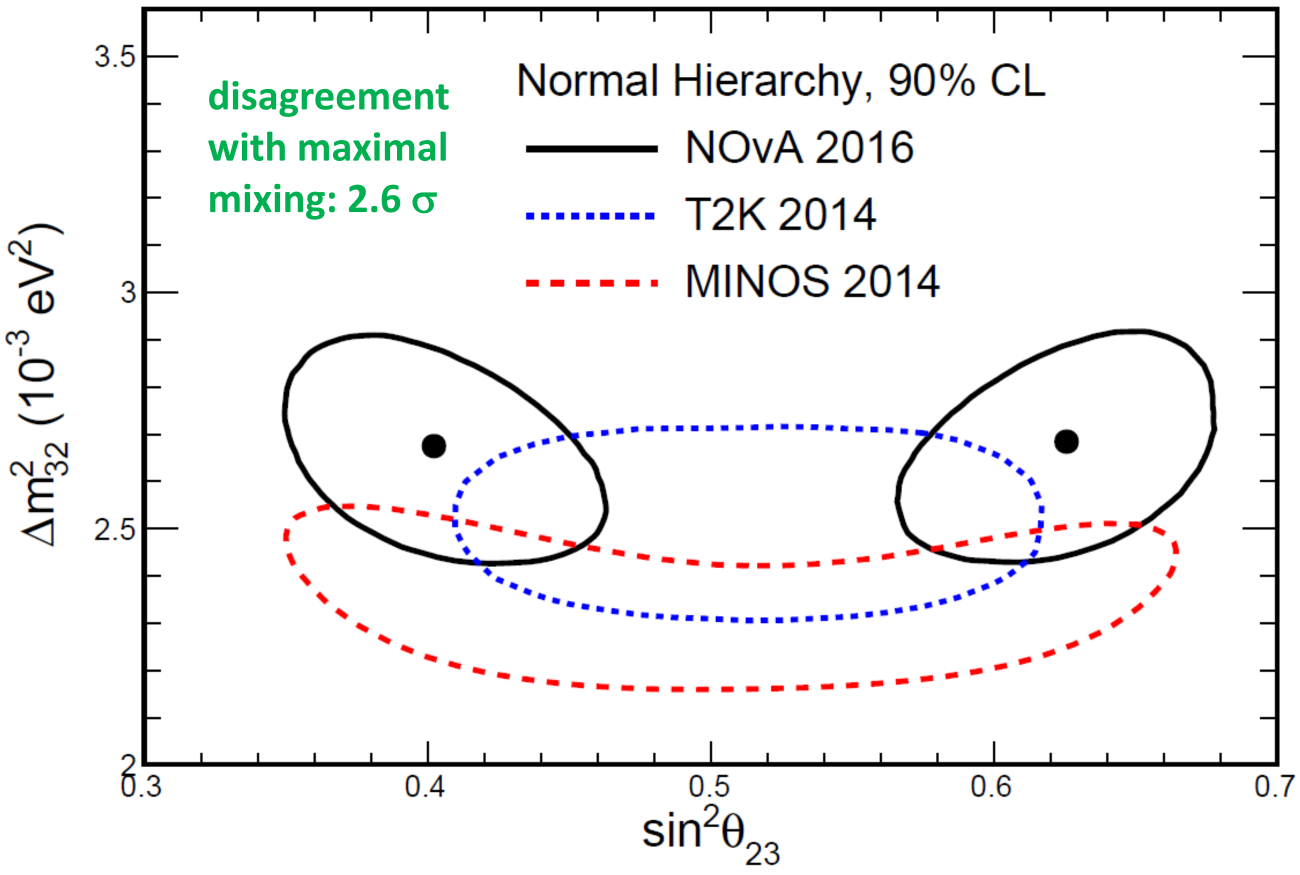
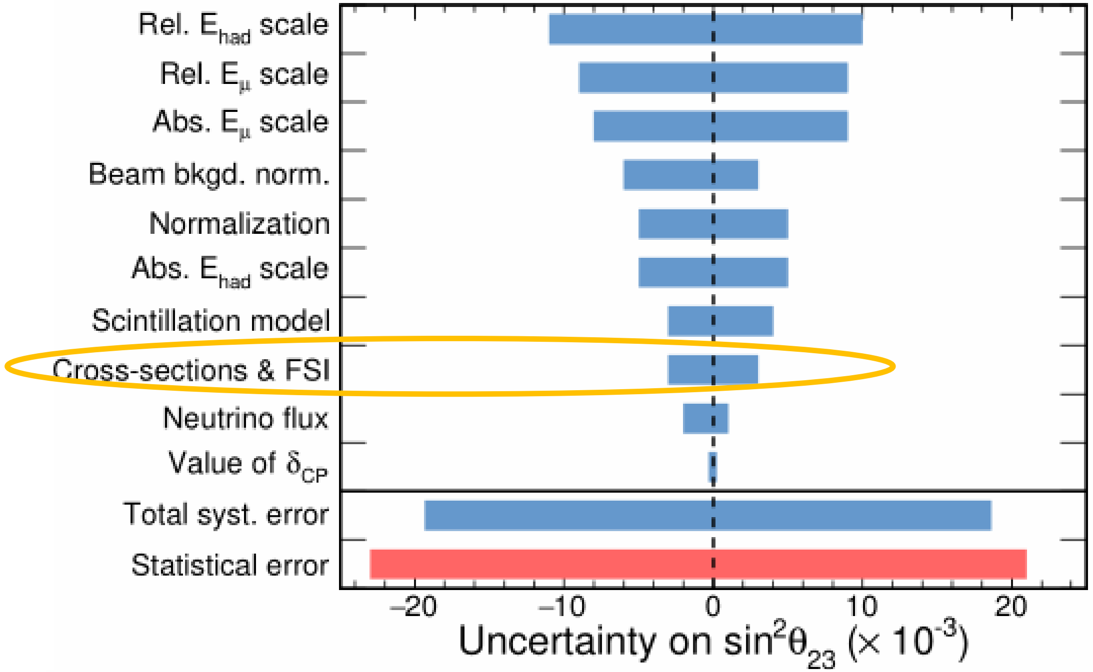
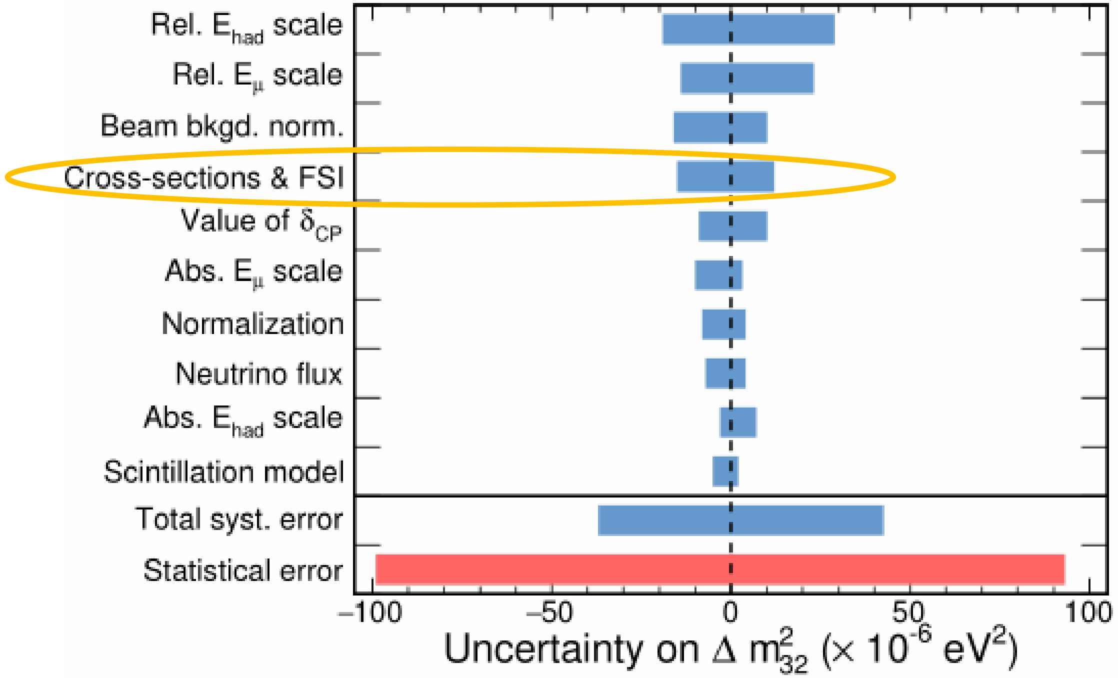
- Energy is reconstructed by fitting the reco->true shape from simulation
- Extrapolated predictions at different oscillation assumptions compared to data to find the best fit
- Systematics are included as penalty terms
- Final fit is good (χ^2 for E < 2.5 GeV = 3.4 / 7 d.o.f), but not consistent with maximal mixing



- In our second analysis, cross-sections were a secondary source of systematic uncertainty, behind detector response

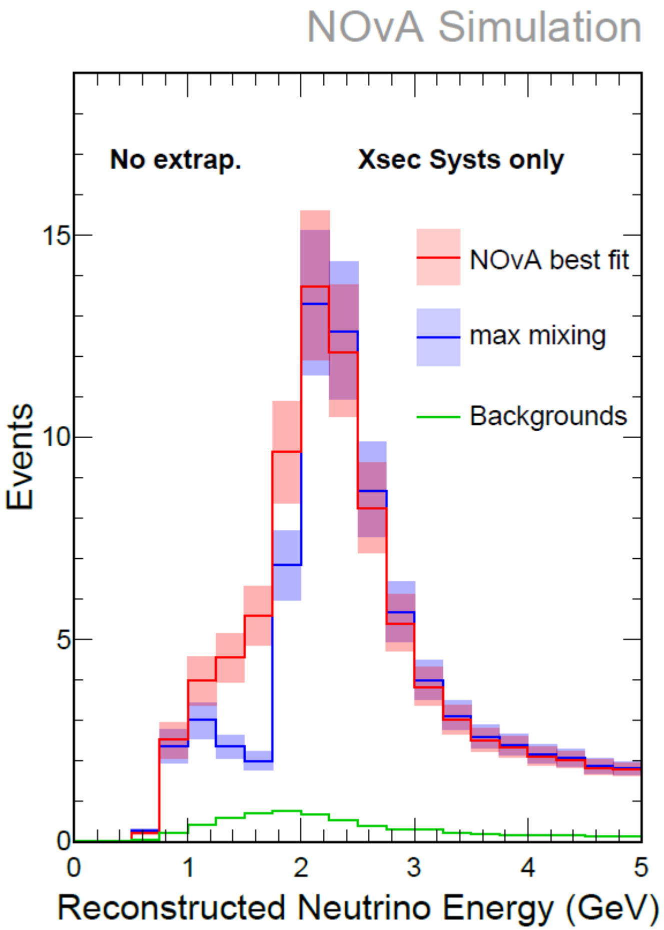






X-section uncertainty effects on disappearance

without extrapolation



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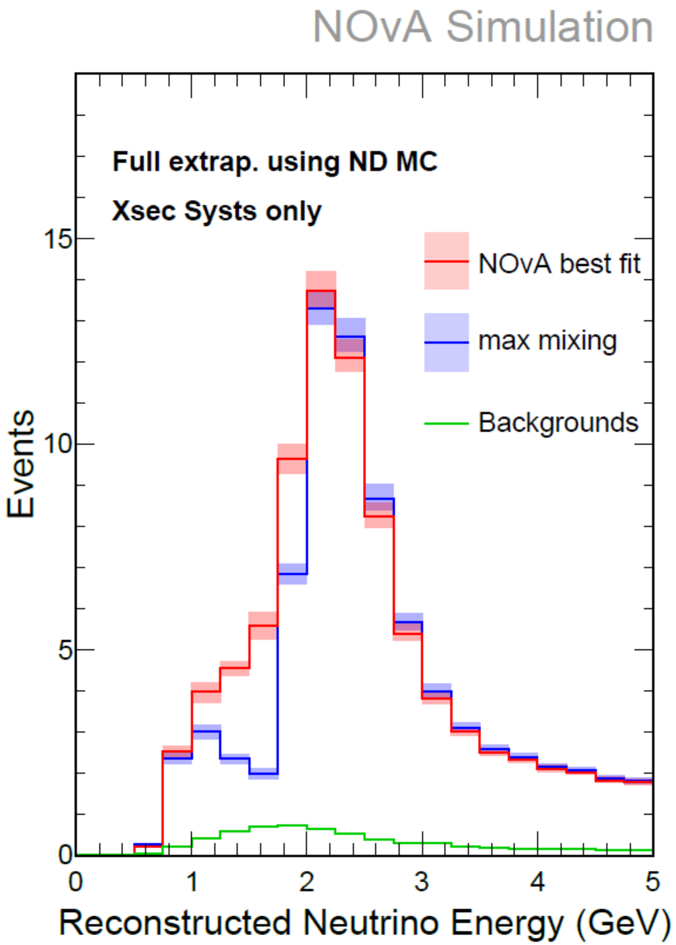
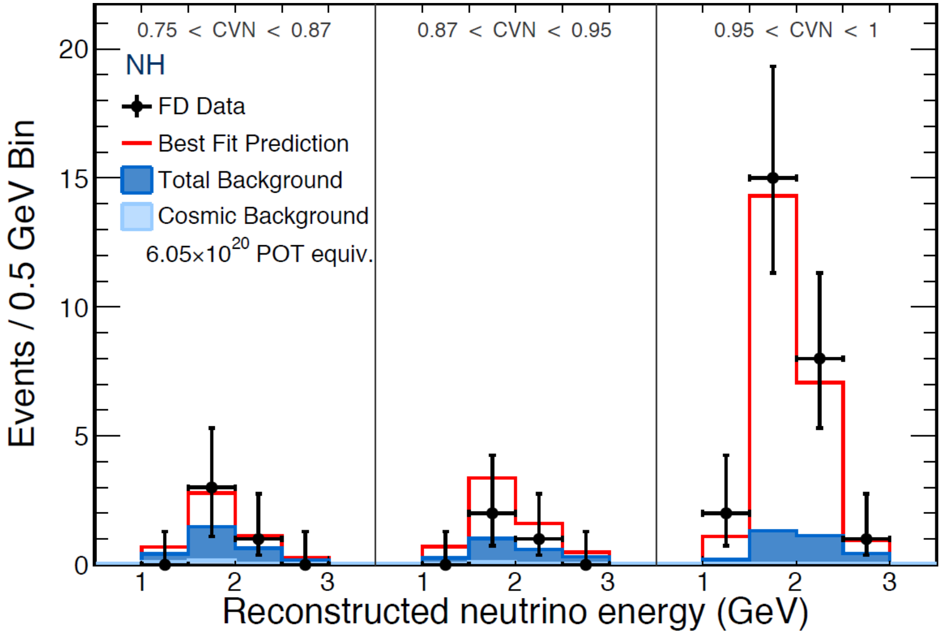
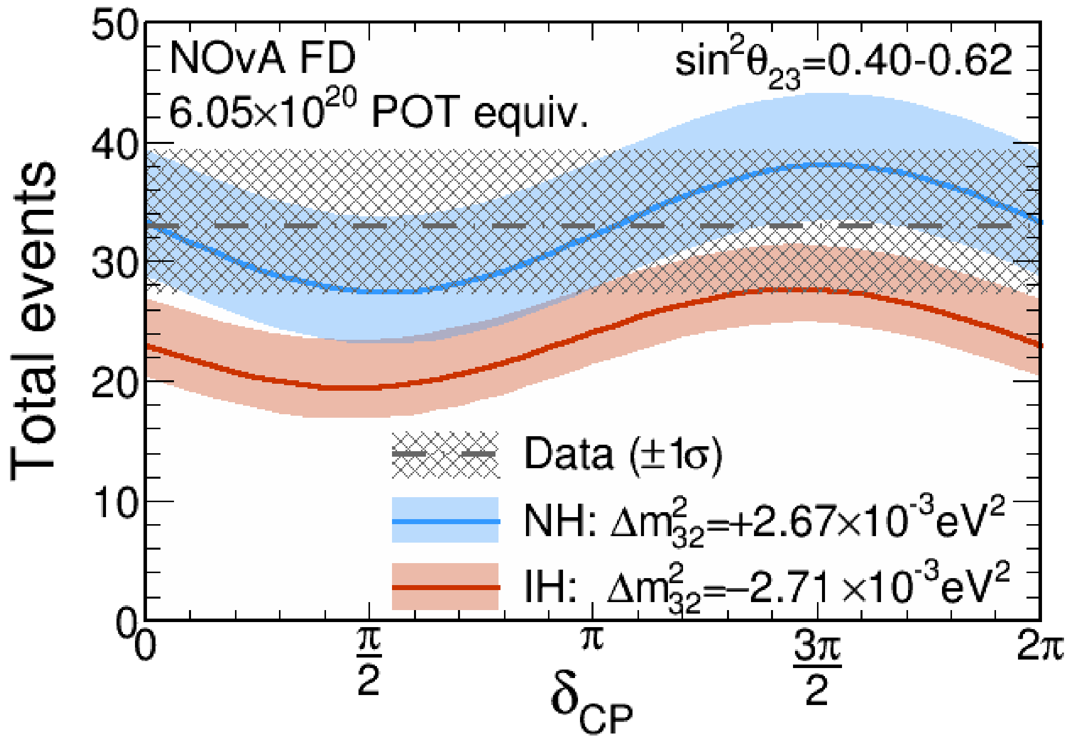


- Without extrapolation, cross section uncertainties are very large and would have severely impacted the analysis

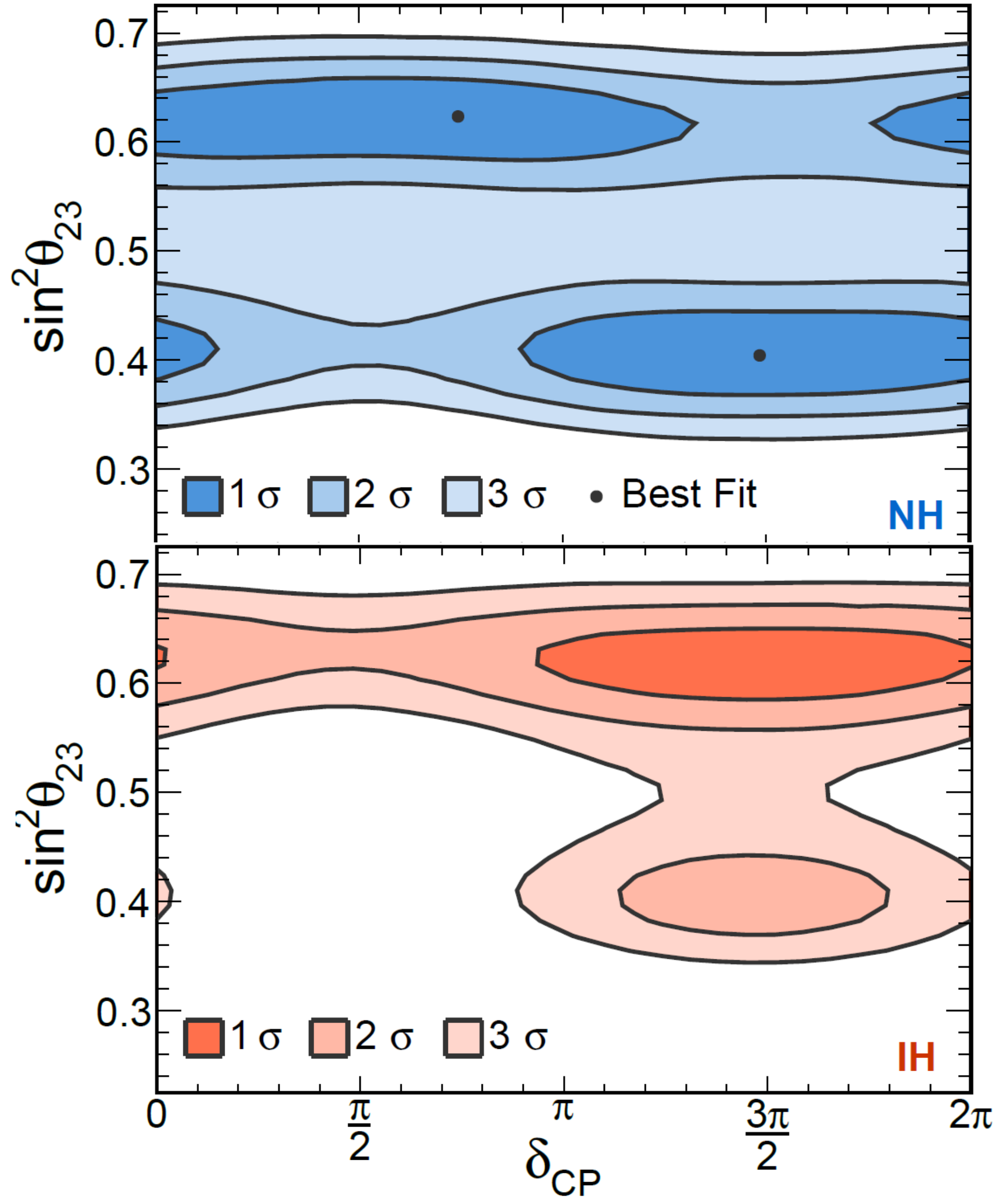
Appearance analysis

- Signal isolated via new technique: 'Convolutional Visual Network' (CVN)
- Further containment, cosmic cuts
- Extrapolation more complicated; for disappearance, measure ν_μ in both ND and FD. Here must measure ν_μ in ND to predict ν_e signal in FD
- Significant NC and intrinsic ν_e background components; to measure in ND requires a decomposition technique
- Recent published result (arXiv:1703.03328v2) found 33 events over a predicted background of 8.2

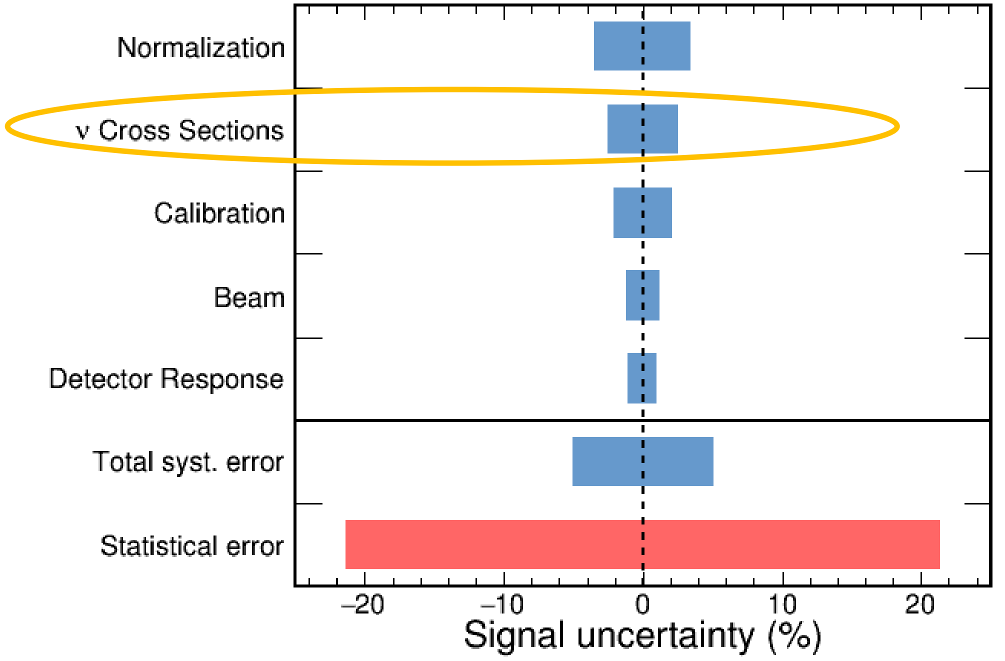


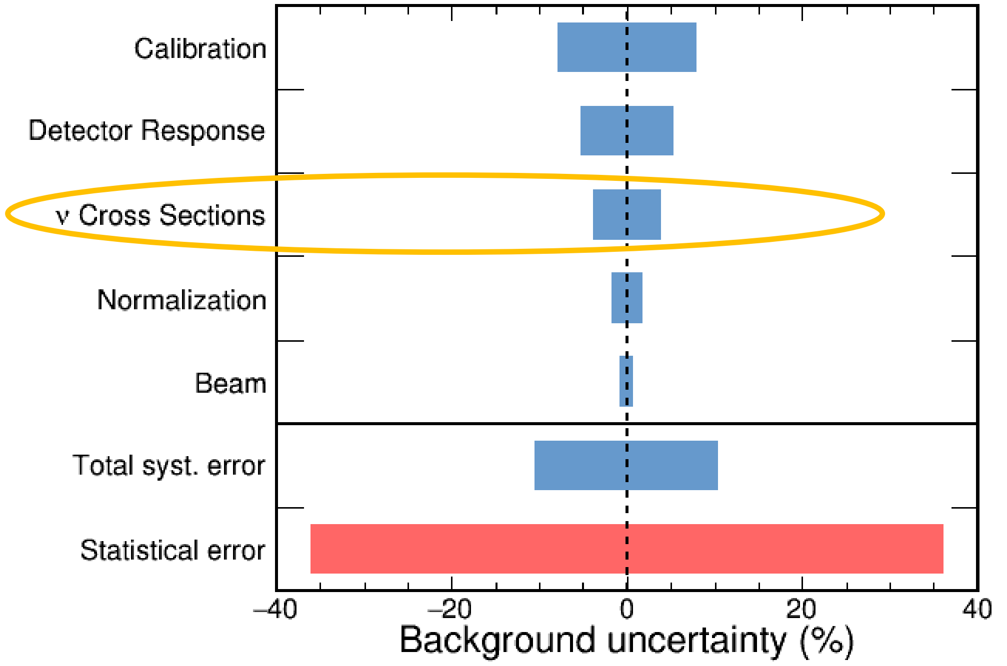


Joint appearance/disappearance



combine appearance and disappearance channels to constrain δ_{CP} as a function of $\sin^2\theta_{23}$; x-sec uncertainties here also sub-dominant





What’s next for NOvA?

- Beam currently off, but reached 700 kW. So far we’ve recorded:
    - ~9e20 POT neutrino-mode data
    - ~3.5e20 POT anti-neutrino-mode data
- Getting more serious about x-section tuning! Dedicated sub-group; recently started new combined neutrino / anti-neutrino mode tune
- Some goals:
    - does applying RES RPA makes things agree better?
    - are DIS many-pion events under-produced in GENIE neutrino-mode?
    - is there a 2p2h tuning that works for both neutrinos and anti-neutrinos?
    - does anything look funny?
    - …
- Double-check with GIBUU and NEUT, do extensive cross-checks
- This tune will be used for joint neutrino/anti-neutrino analyses to be released in 2018
- Many direct x-section measurements also underway; see L Cremonesi’s talk yesterday

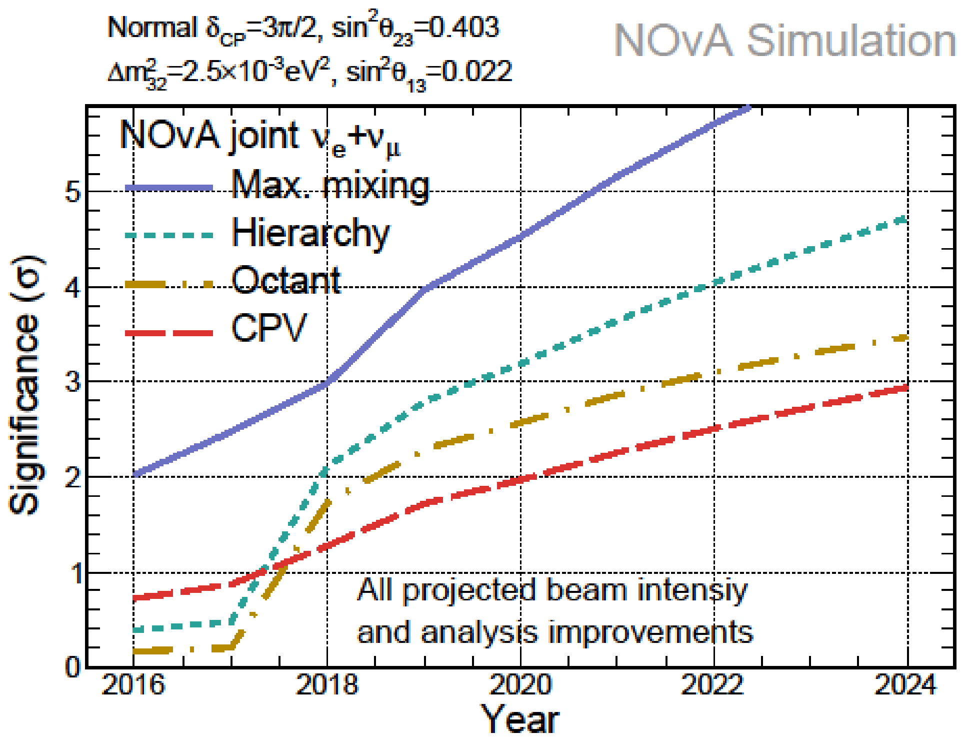
Conclusions

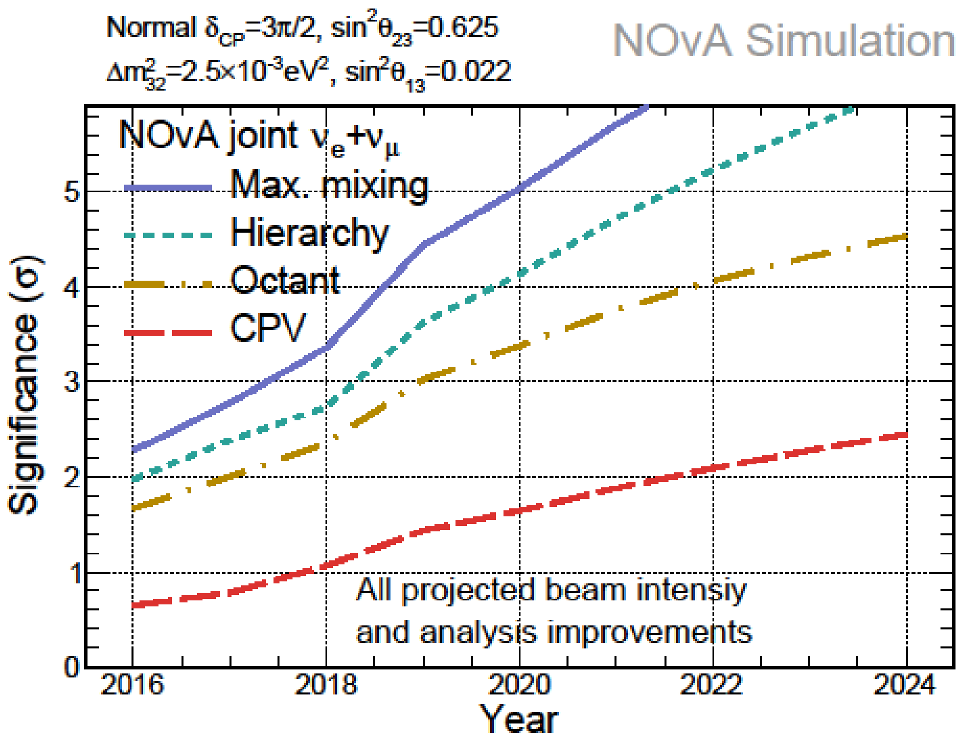
- Cross-section uncertainties are large and many, but end up as a sub-dominant effect in our oscillation analyses. This may change as we get more statistics and a better handle on our detector response!
- Functionally identical near/far detectors allow for easy extrapolation
- Cross-section tuning becoming more and more important. 2p2h and RPA are both relatively new and there is still much to learn about them. As we look more closely we find other areas where GENIE isn't perfect as well.
  - NOvA is stepping up our efforts to do comprehensive tuning
- New tuning with new 2p2h systematics ready for our next set of oscillation results due out this year
- A combined neutrino/anti-neutrino x-sec tune in preparation for use in 2018 joint neutrino/anti-neutrino oscillation analyses

- End

Backup

Projections





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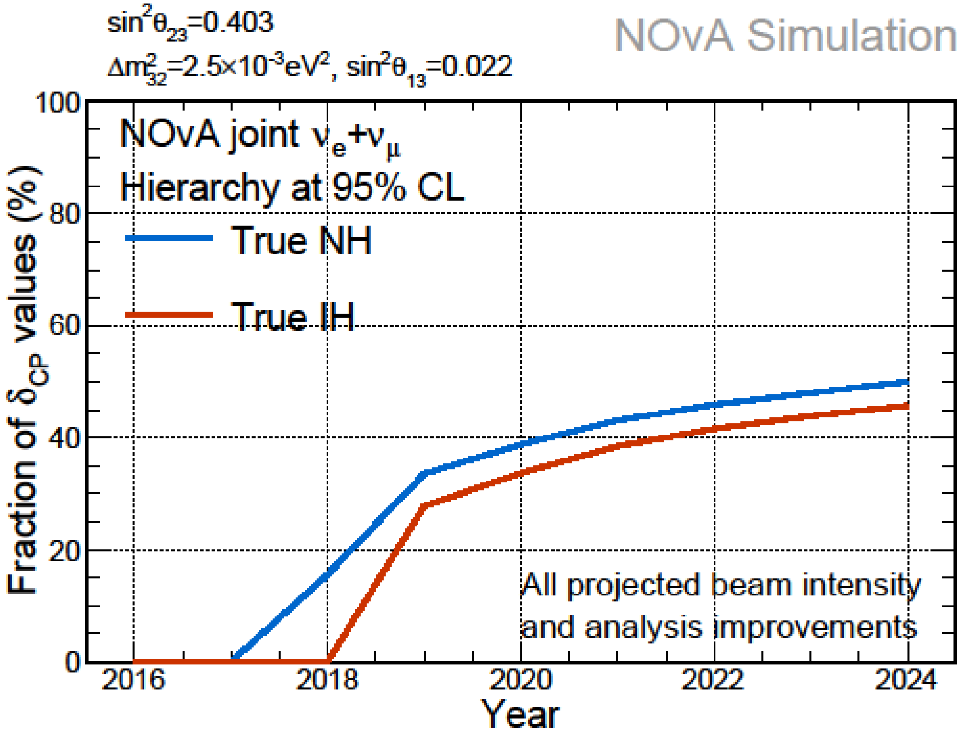
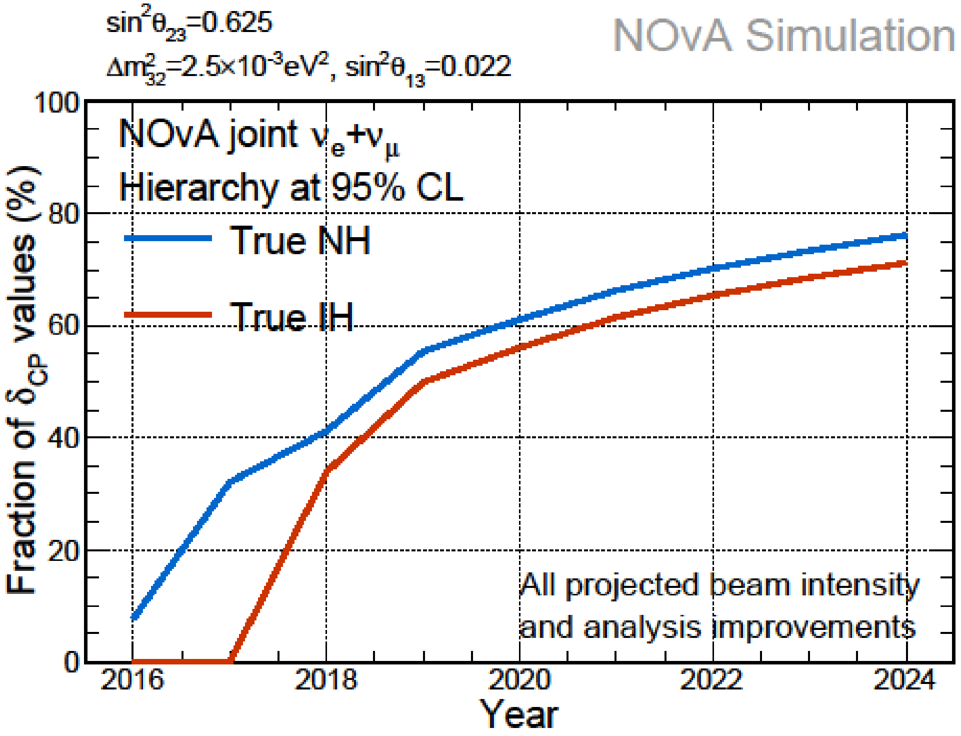
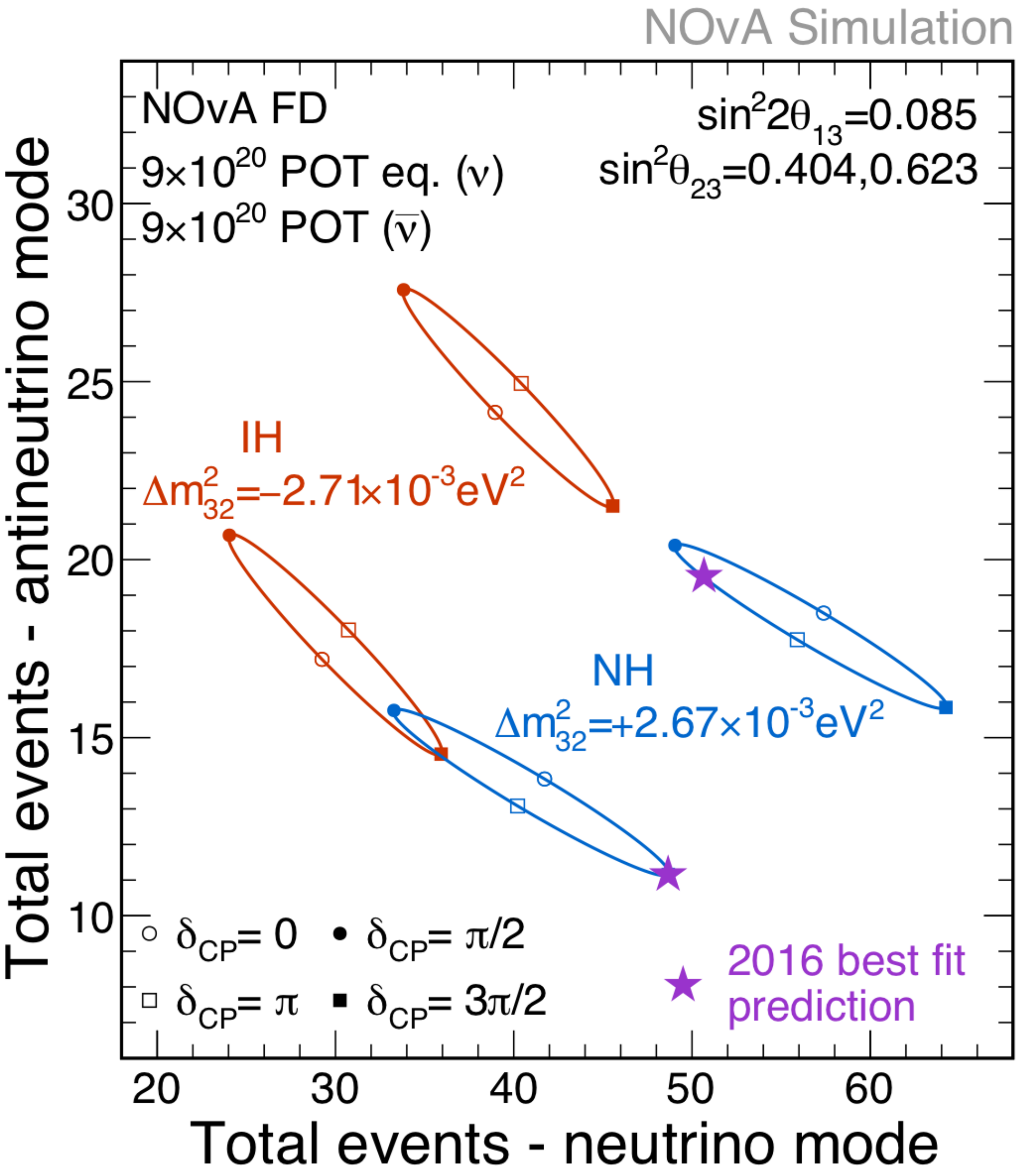






Total number of events expected in the Far Detector as a function of δ_{CP} for NH (blue) and IH (red), with fixed $\sin^2\theta_{23}$=0.404 / 0.623.

Assuming an exposure of 9E20 POT eq. in neutrino mode, and 9E20 POT in antineutrino mode.

Stars represent predictions using the 2016 best fit values. Other oscillation parameters are set to:

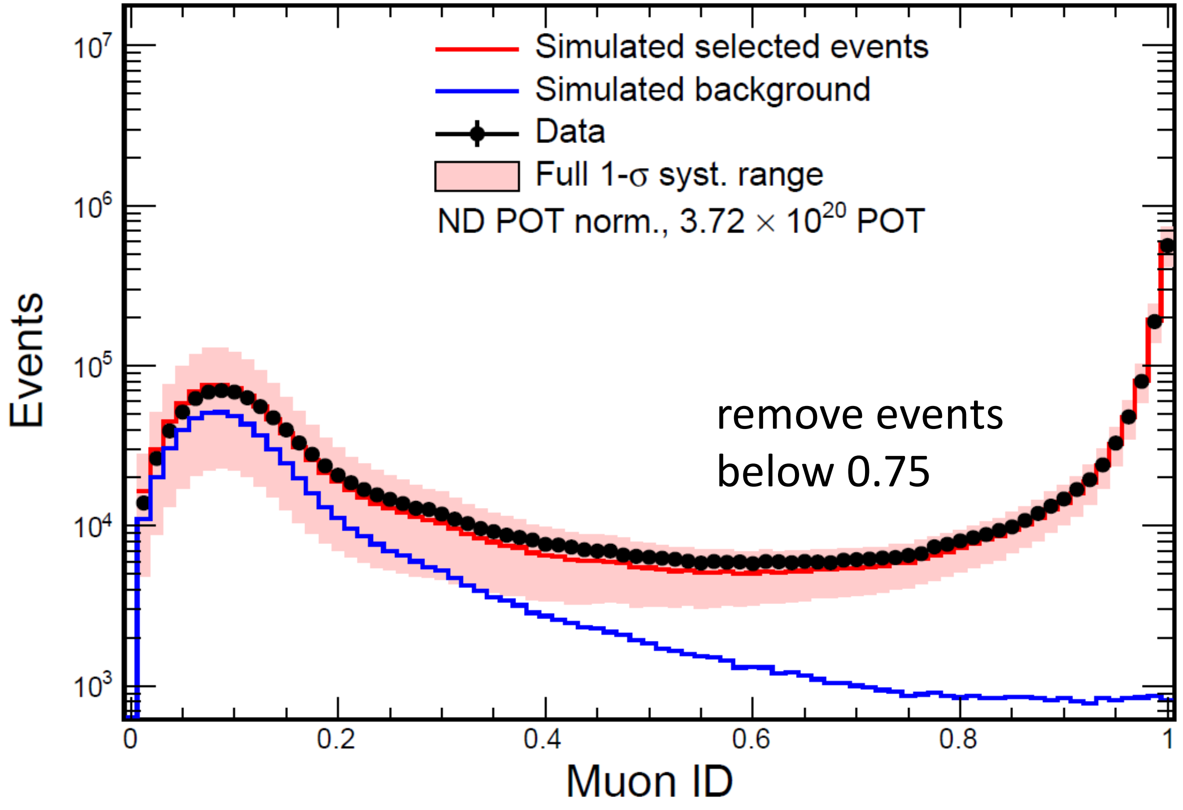
L=810km, ρ=2.84g/cm3 $\Delta m^2_{21}=7.53\times10^{-5}\text{eV}^2$

$\sin^2 2\theta_{12}=0.846$ $\sin 2^2\theta_{13}=0.085$

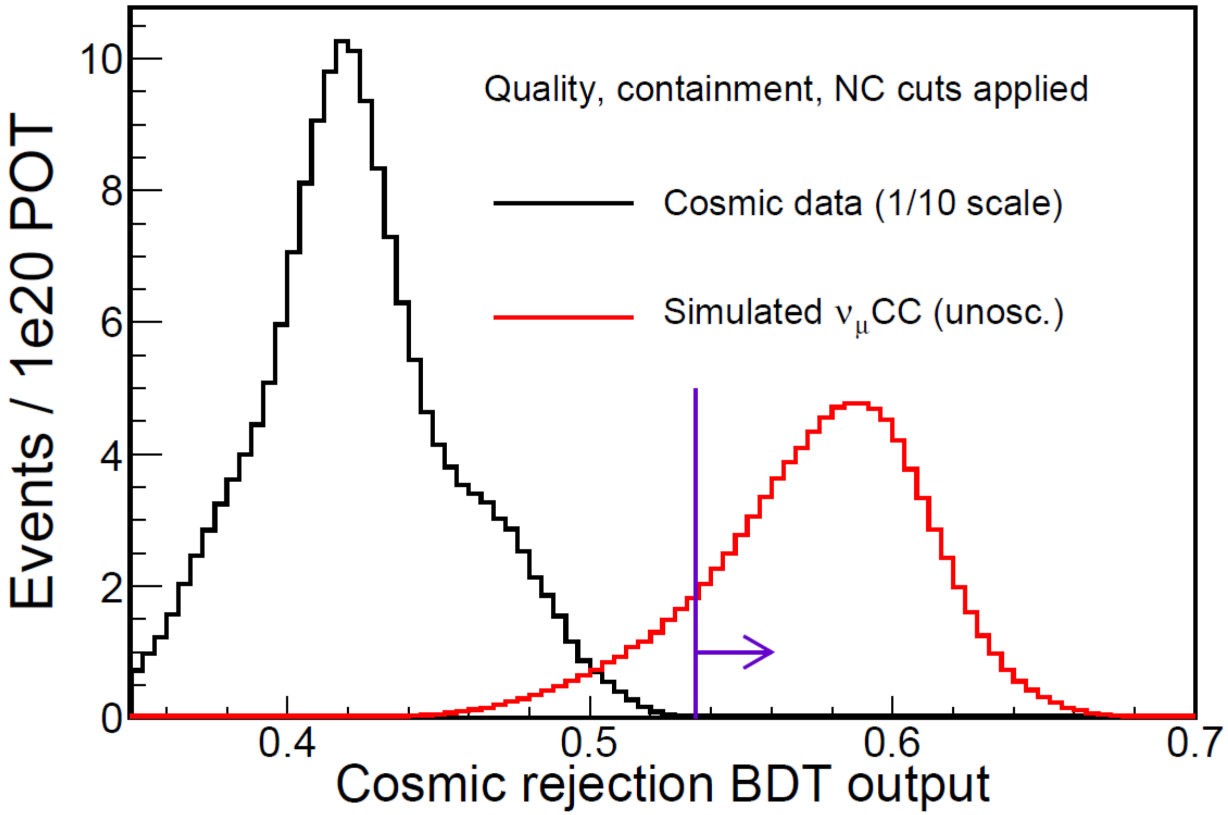
$\Delta m^2_{32}=2.67(-2.71)\times10^{-3}\text{eV}^2$.

NB: The degenerate best fit points from the 2016 joint analysis correspond to $\delta_{CP}=1.48\pi(0.74\pi)$ and $\sin^2\theta_{23}=0.404(0.623)$

disappearance details



remove events below 0.75



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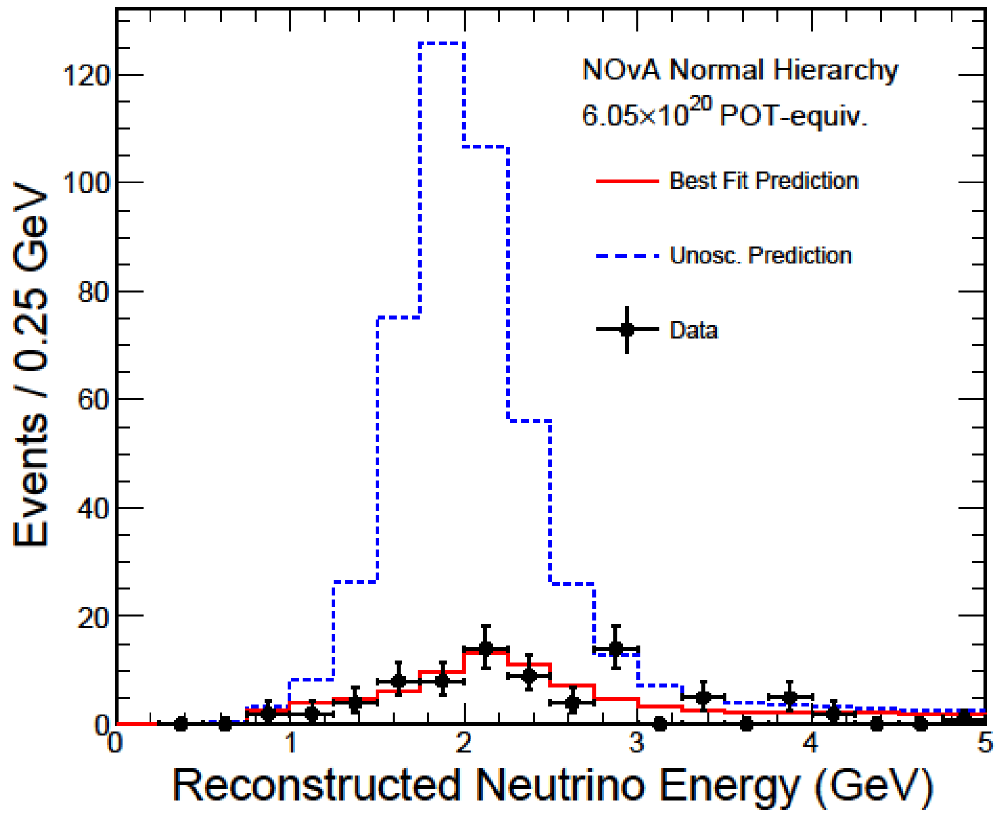

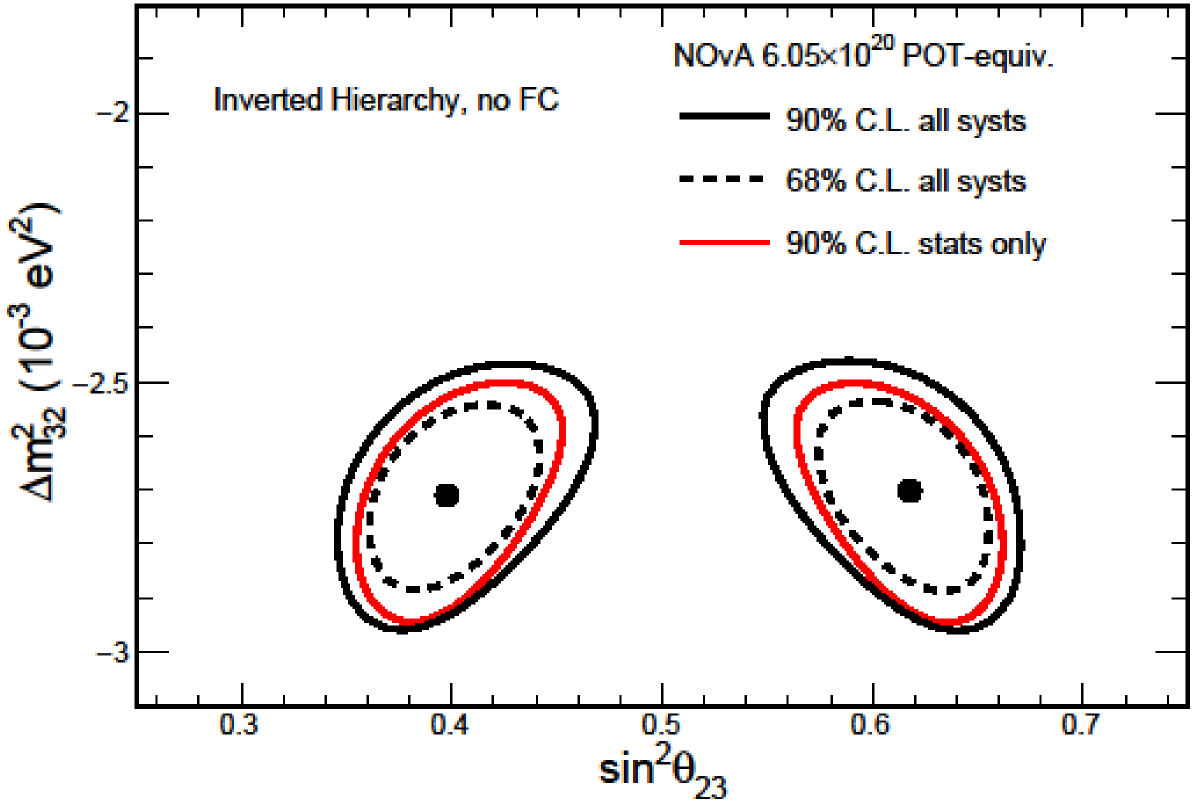

Run History

~3.5e20 POT
anti-neutrinos