Recent Results from Long Baseline Neutrino Experiments

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Fermilab

From Nucleons to Nuclei:
Enabling Discovery for Neutrinos, Dark Matter
Institute for Nuclear Theory, Seattle, WA
June 26th, 2018

Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

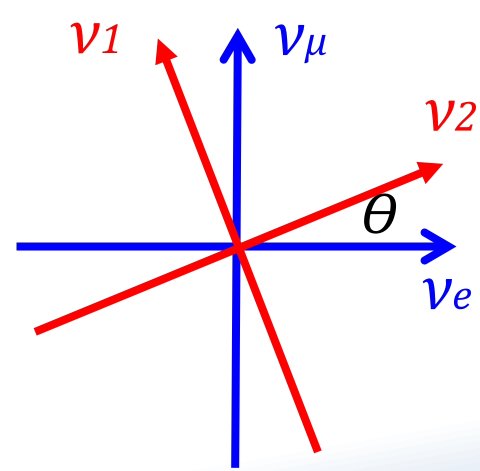
Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

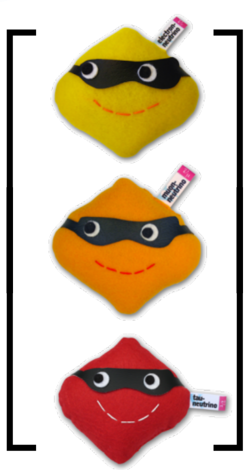
- Each flavor (e, μ) is a superposition of different masses (1, 2)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

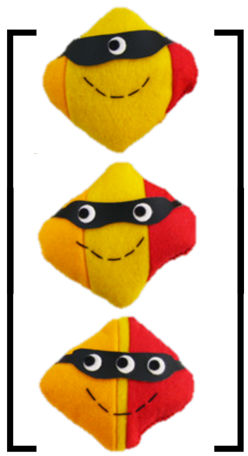
"Mixing Matrix"



Three-flavor Neutrino Oscillations

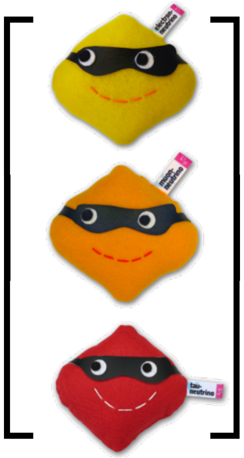


$$= U_{\mathrm{PMNS}}$$

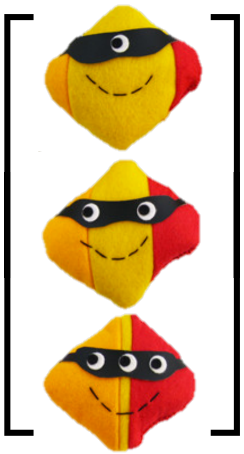


- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix

Three-flavor Neutrino Oscillations



$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



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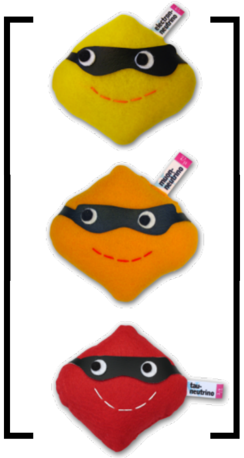
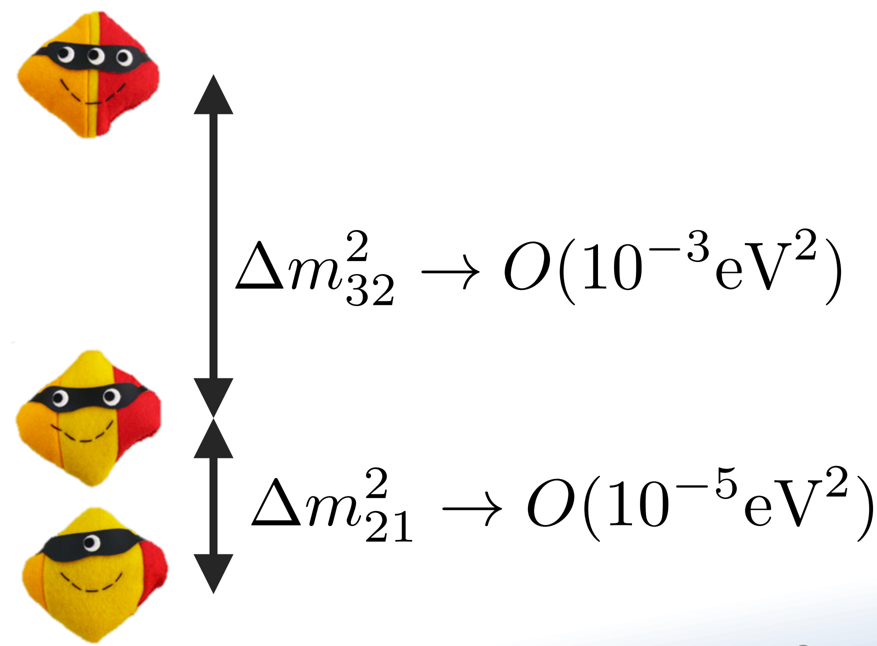
  - The mixing matrix
    - θ_{23}, θ_{13}, δ_{CP}, θ_{12}

Three-flavor Neutrino Oscillations



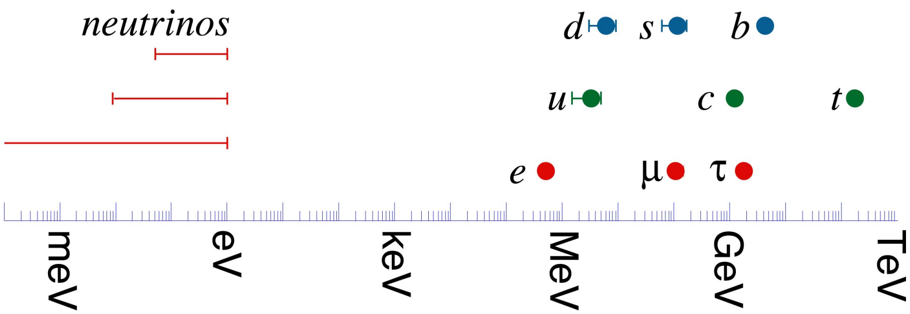
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

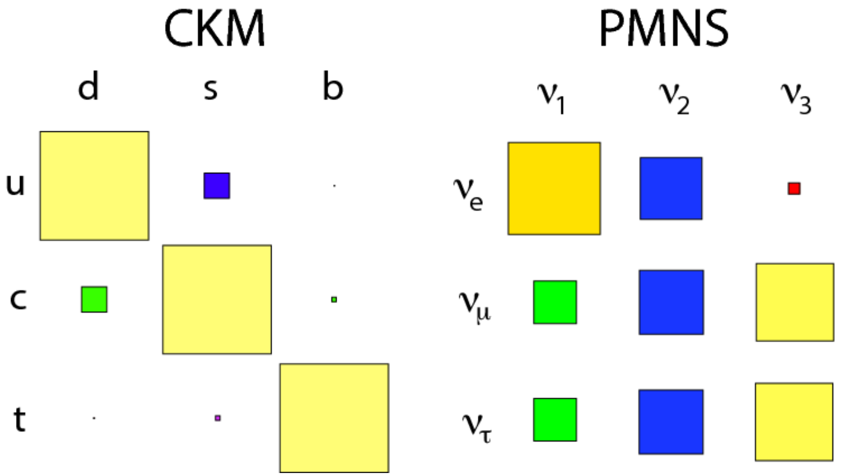
- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix
    - θ_{23}, θ_{13}, δ_{CP}, θ_{12}
  - The mass differences
    - $\Delta m^2{}_{32}$, $\Delta m^2{}_{21}$



Why study neutrino oscillations?

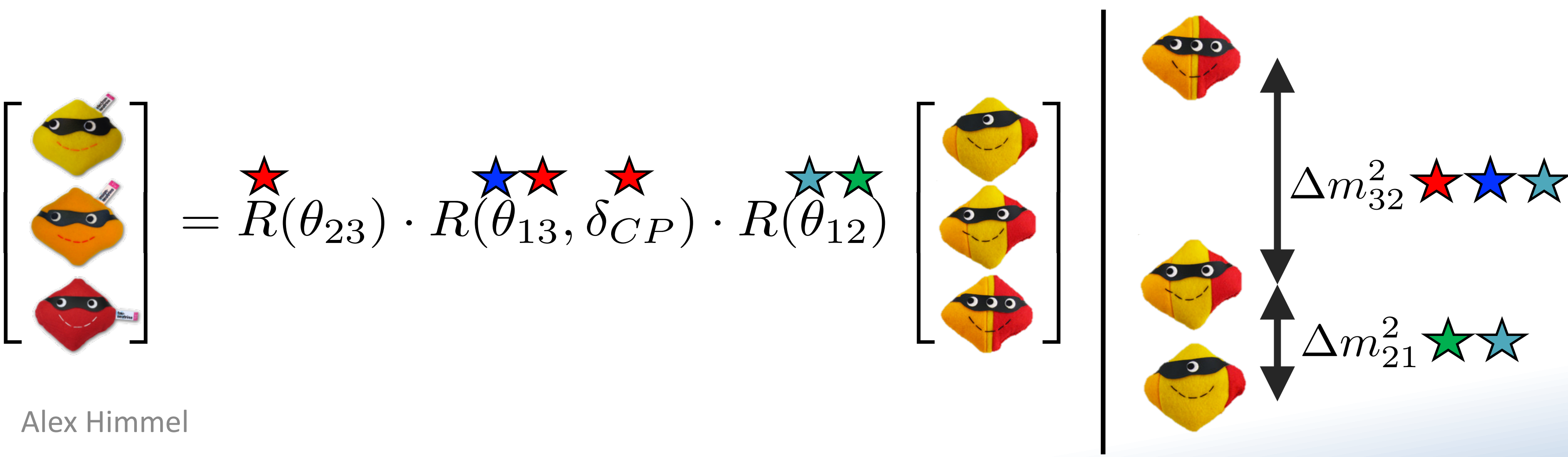
- Neutrinos are "weird":
  - Neutrino masses are *really* small compared to the rest of the SM.
  - Neutrino mixing looks very different from CKM.
- Potentially *CP*-violating
  - Might be a window into matter-antimatter asymmetry.
- Physics beyond the standard model
  - Oscillations are an interferometric effect – gives access to high-scale physics.
- Open questions remain in the oscillation model!





PoS (ICHEP2012) 033

Understanding oscillations: a world-wide effort



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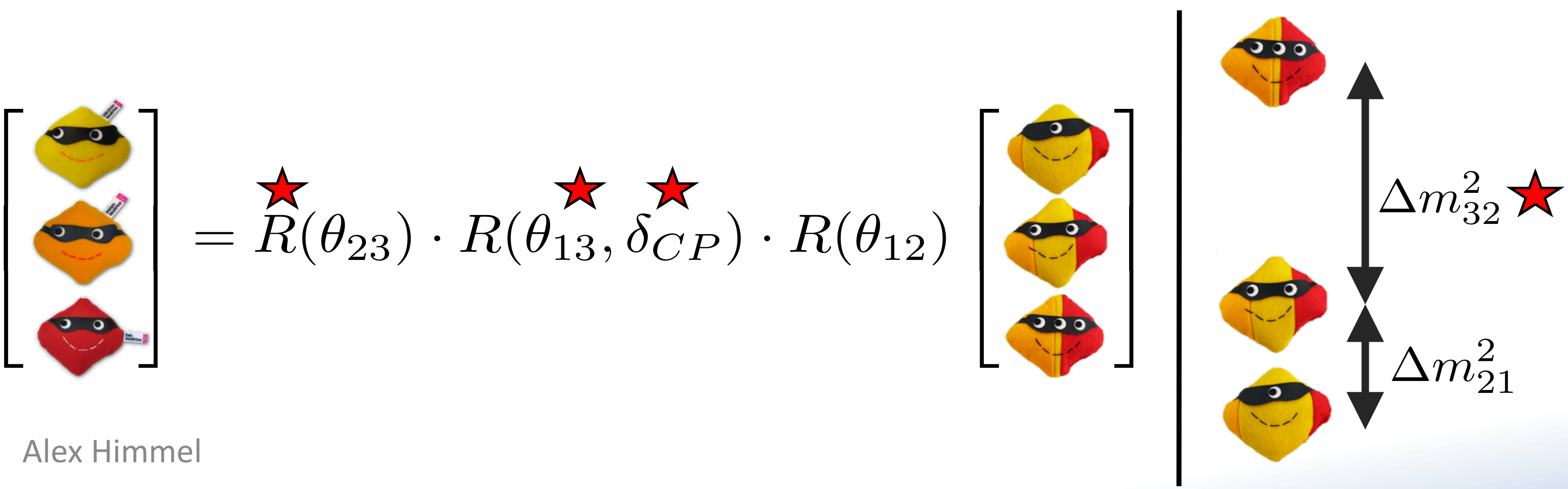
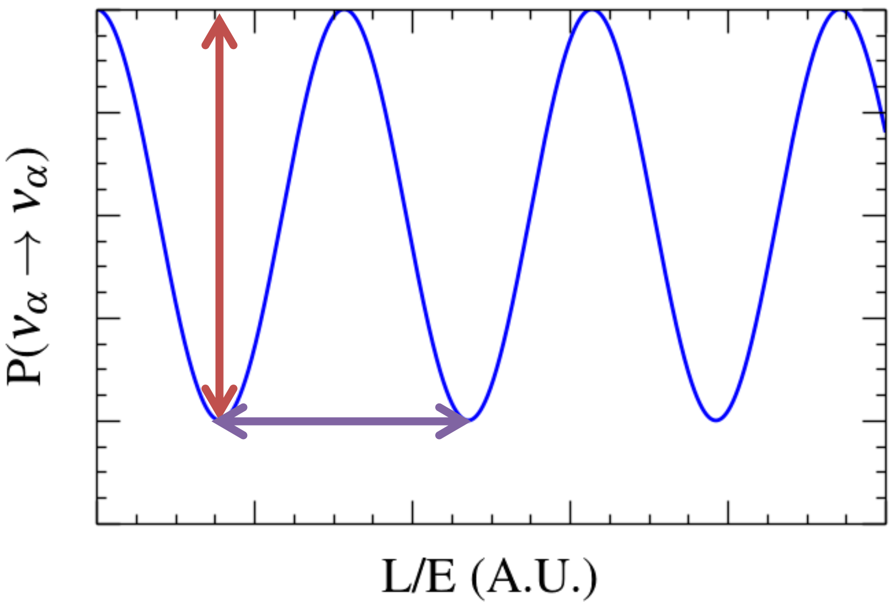
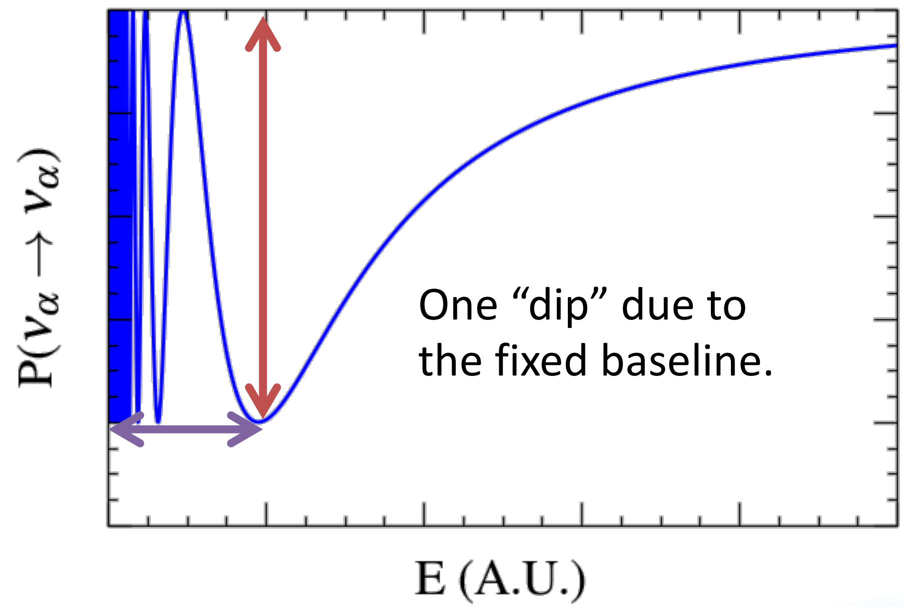


How to study oscillations: Disappearance

Sub-dominant term due to small θ_{13}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E} \right)$$

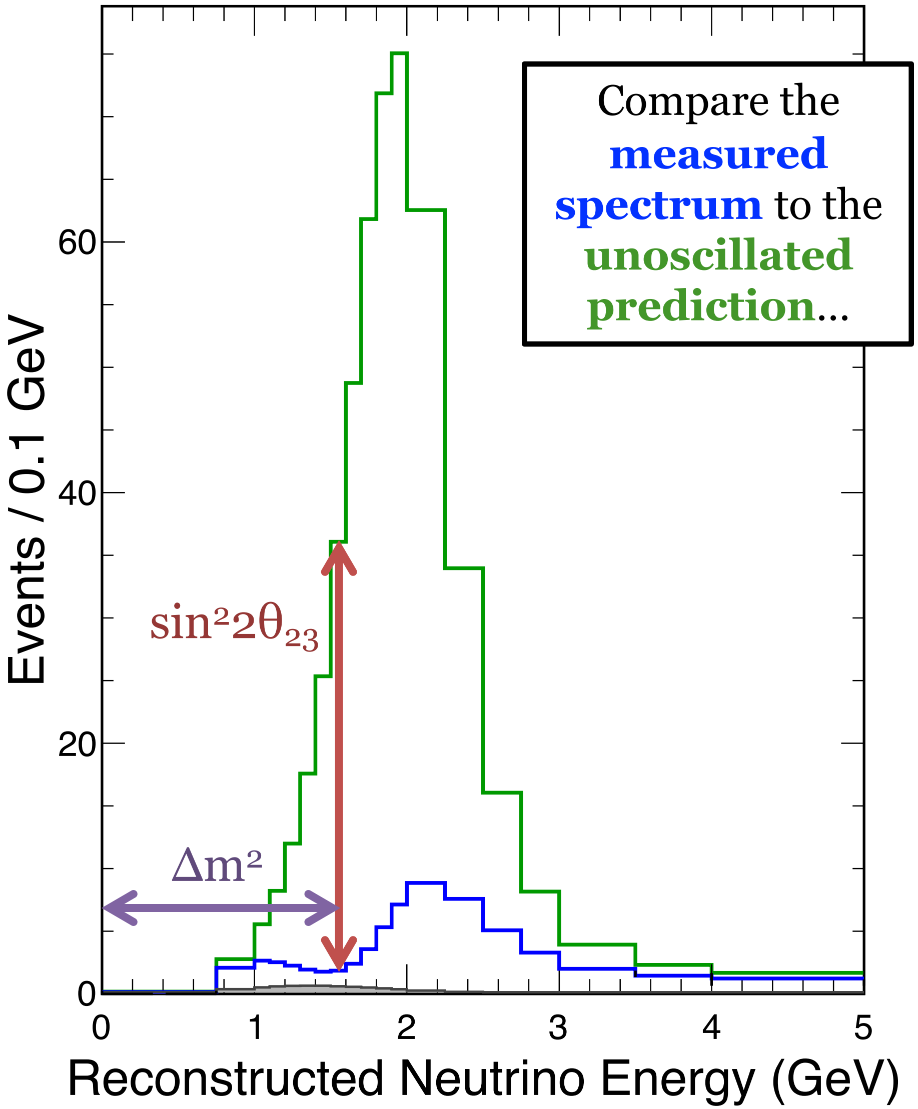


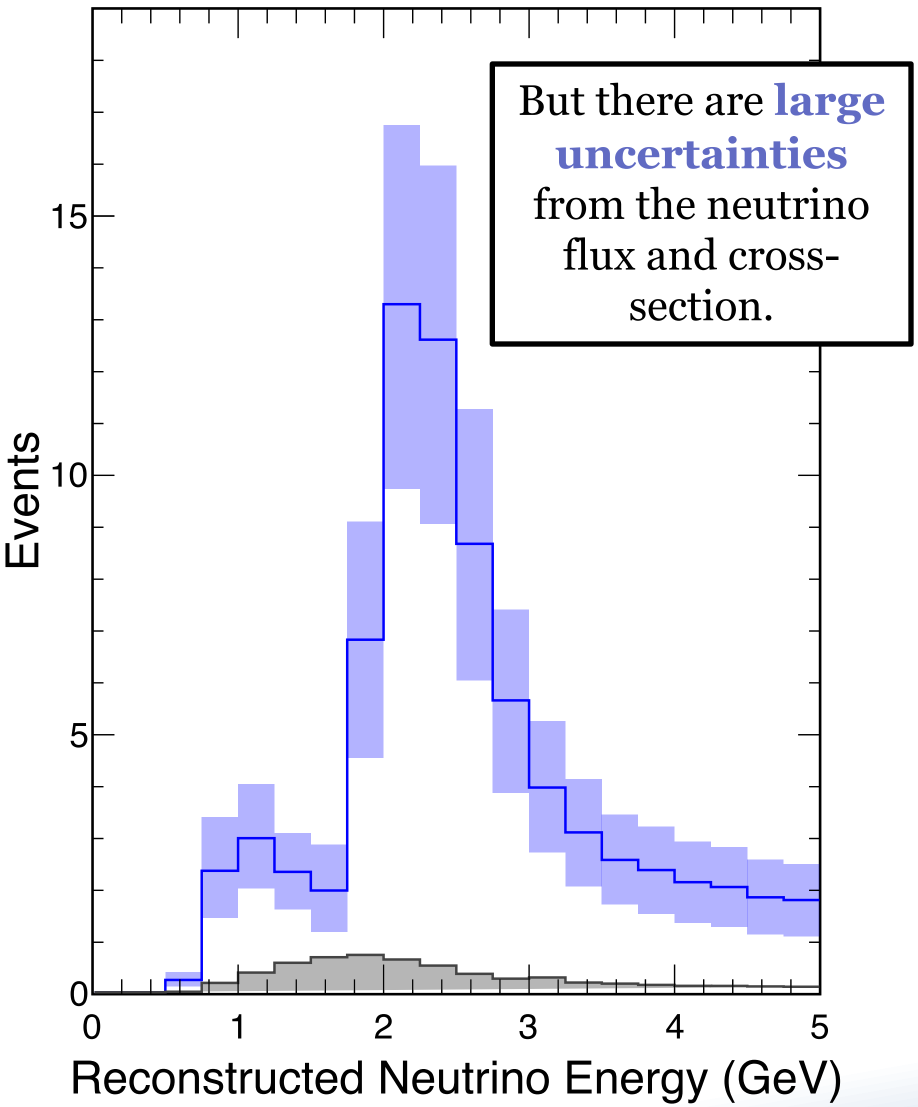


Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

How to study oscillations: Disappearance

NOvA Simulation





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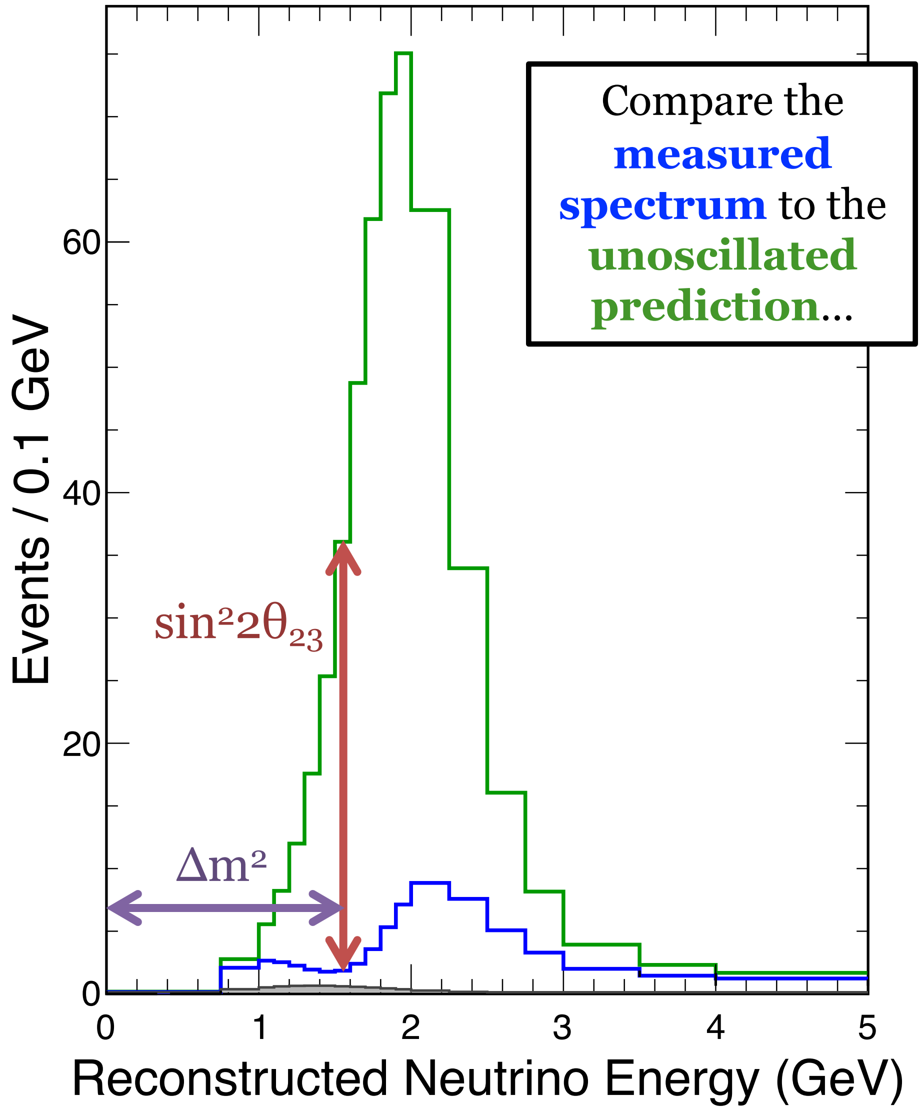
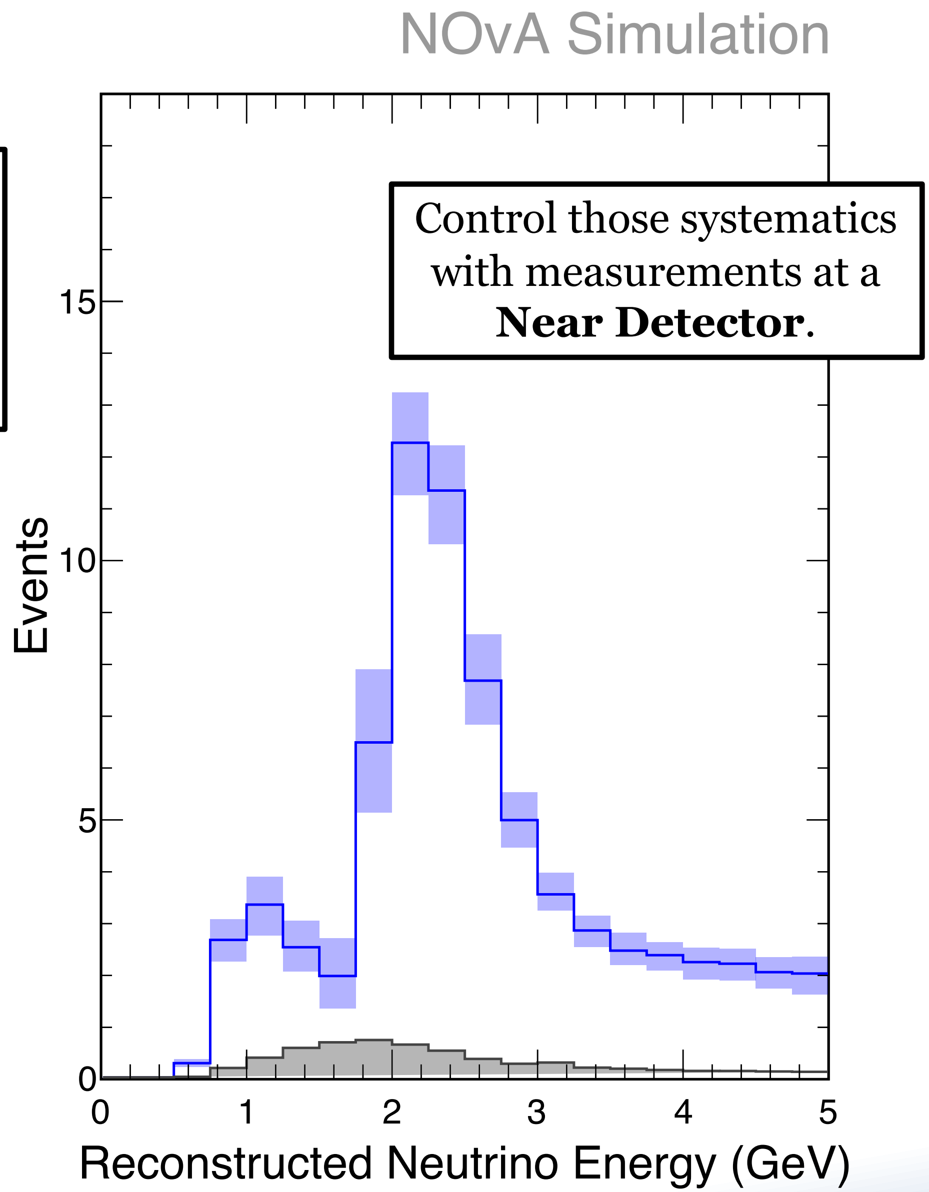


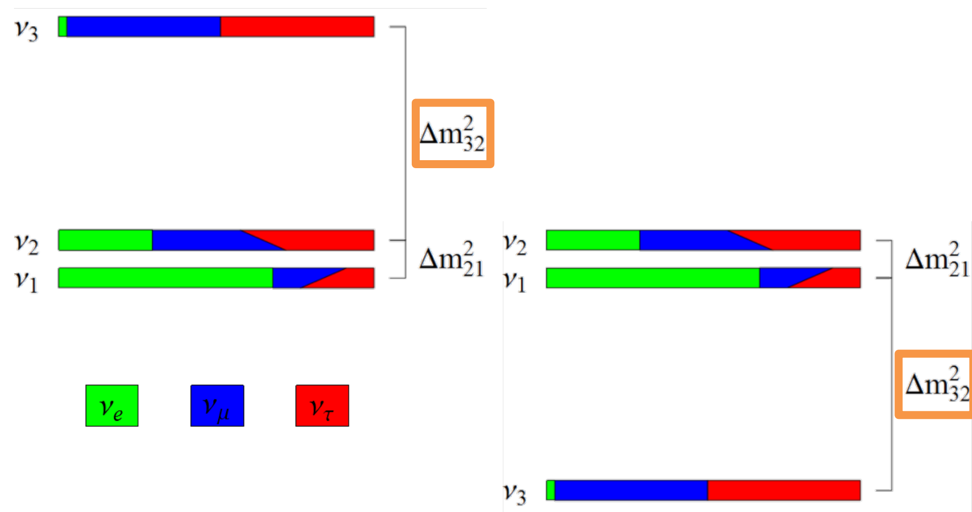


Open questions in neutrino oscillations

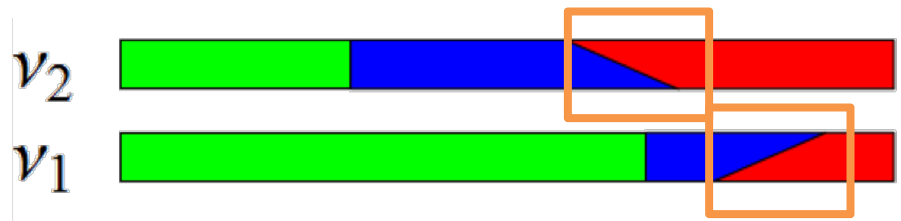
1. Do neutrino oscillations violate *CP* symmetry directly via δ_{CP}?

$$R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

2. Is the mass hierarchy “normal” or “inverted?



3. What is the “octant” of θ_{23}?
   - Or is the mixing “maximal” (e.g. θ_{23} = 45°)?



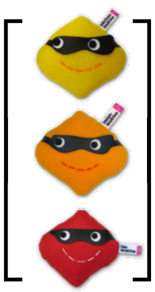
How to study oscillations: Appearance

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

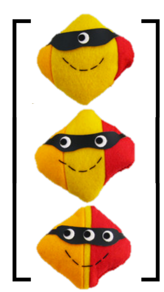
$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

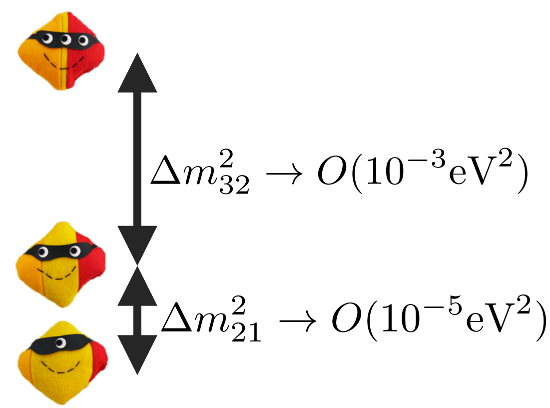
$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

- Depends some on *every* oscillation parameter.
- **Benefit**: can answer more questions.
- **Drawback**: degeneracies make things difficult.



$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$





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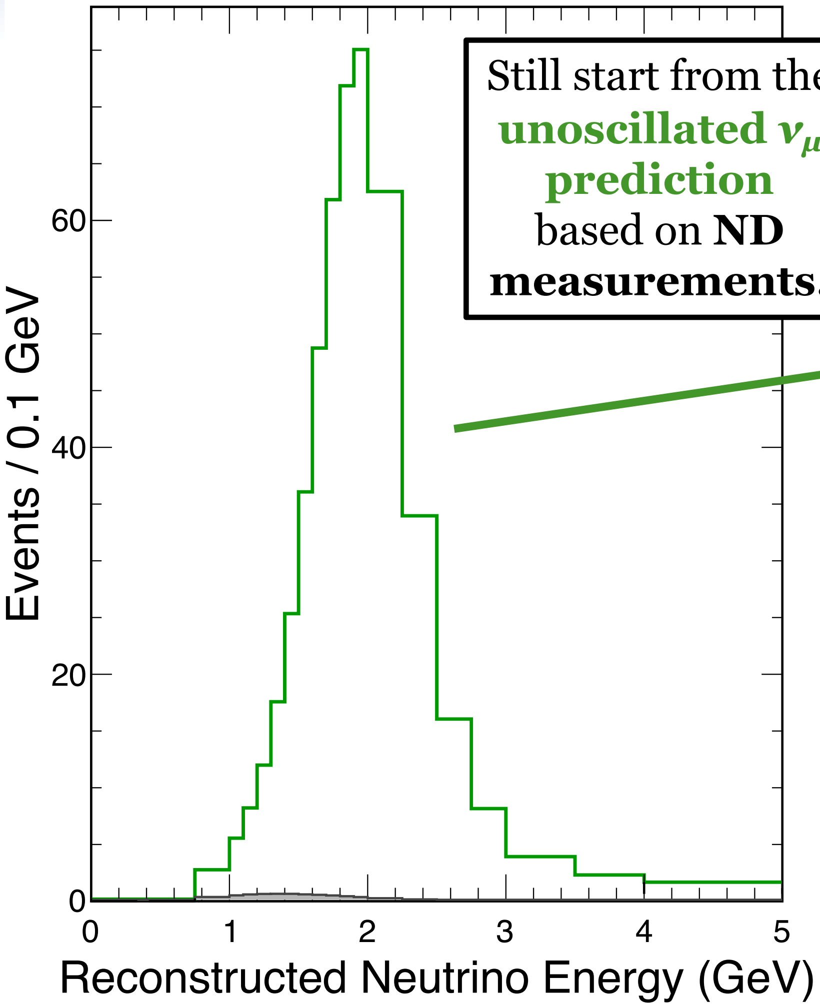
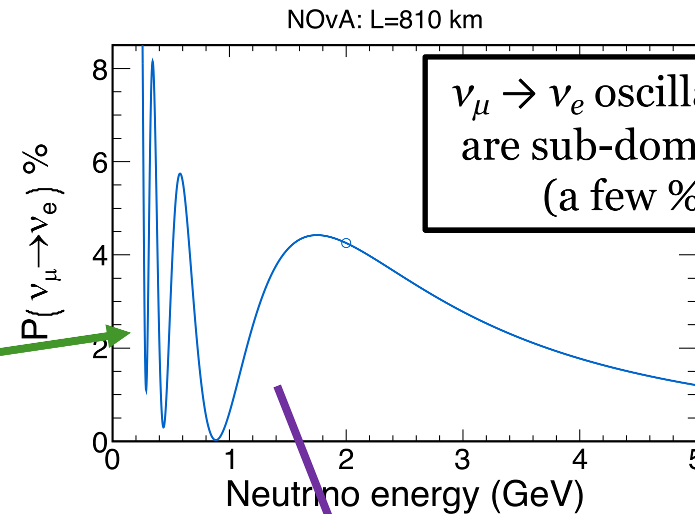
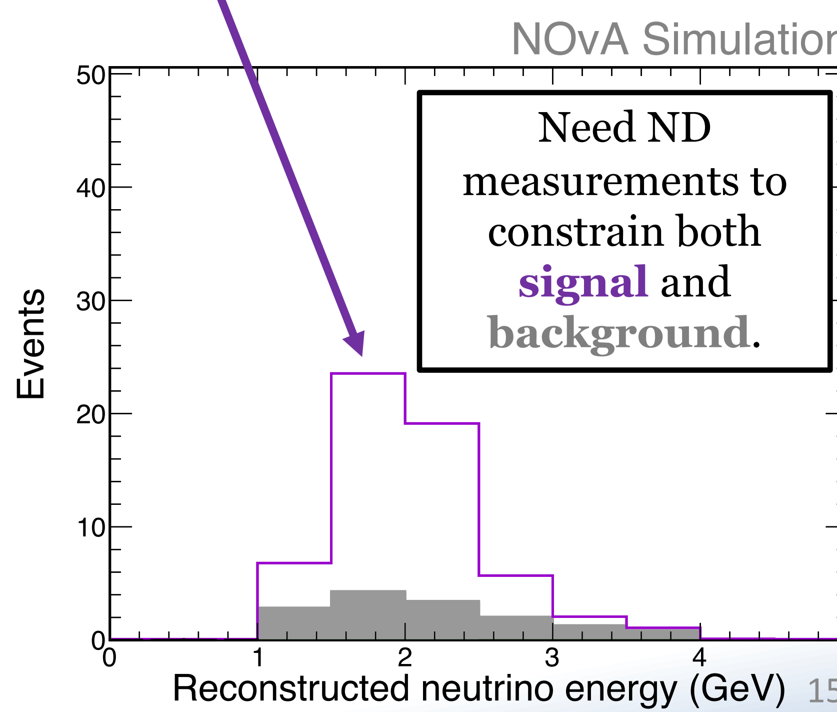


Still start from the **unoscillated ν_μ prediction** based on **ND measurements.**



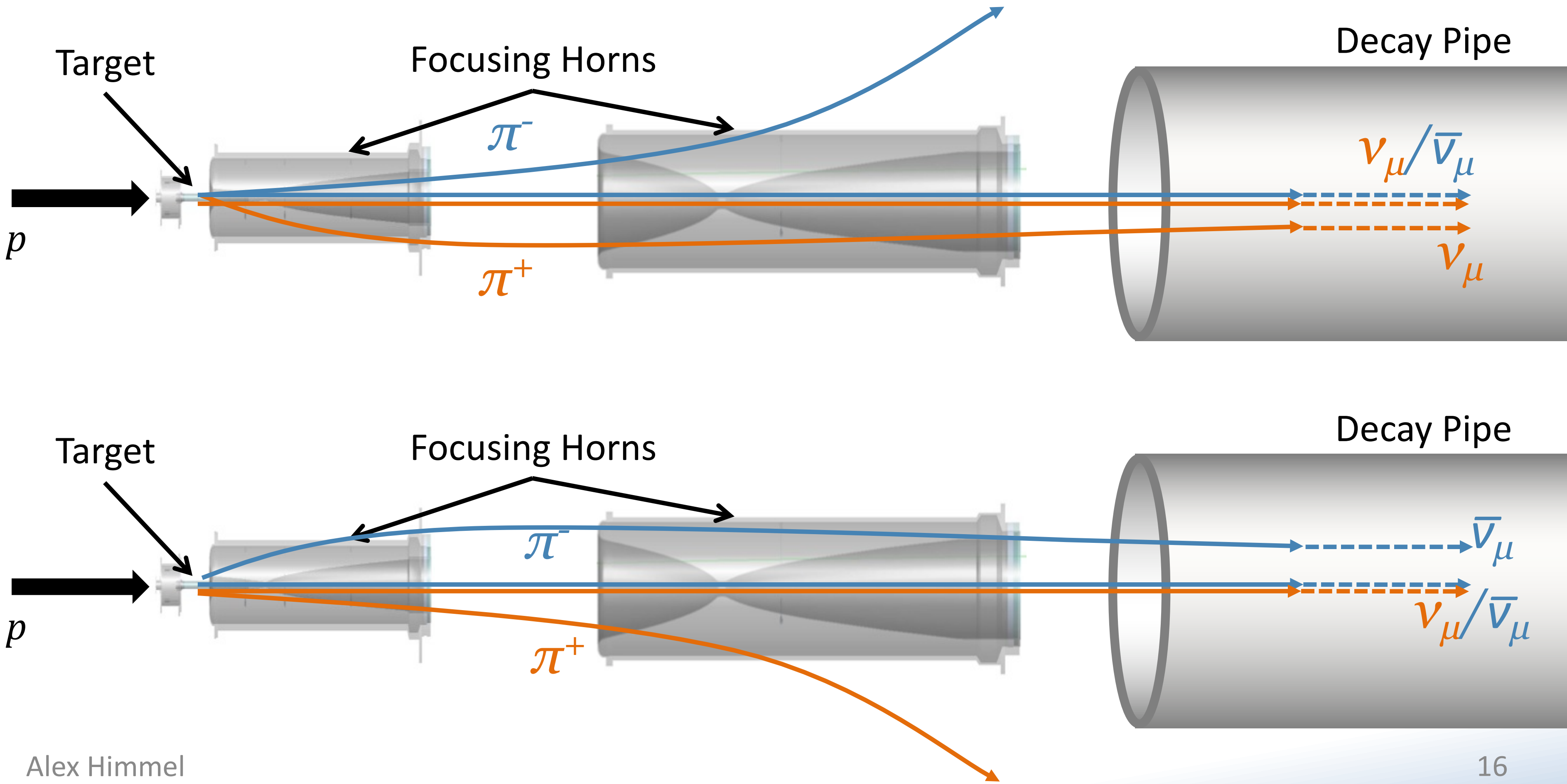
$\nu_\mu \rightarrow \nu_e$ oscillations are sub-dominant (a few %)



Need ND measurements to constrain both **signal** and **background**.

Neutrino and Antineutrino Beams

Measuring $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ helps resolve degeneracies in the oscillation probability.



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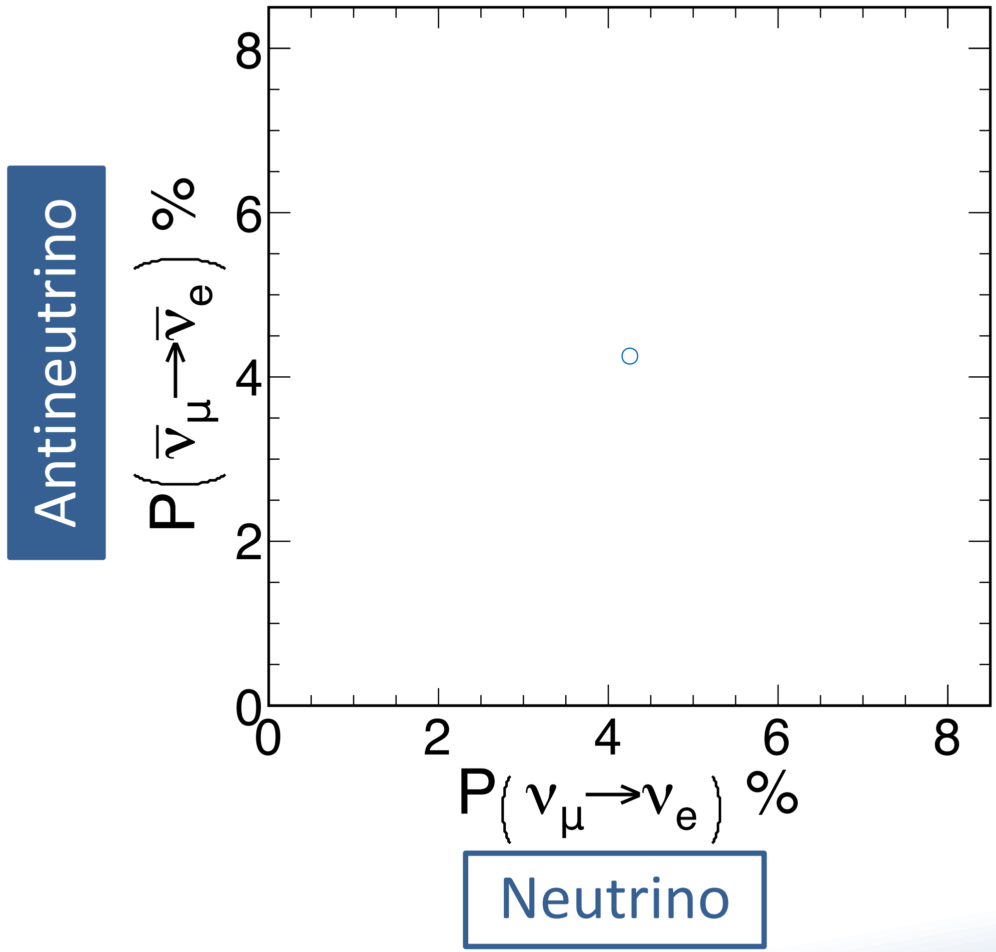

Vacuum and no CP violation: neutrinos and antineutrinos are the same

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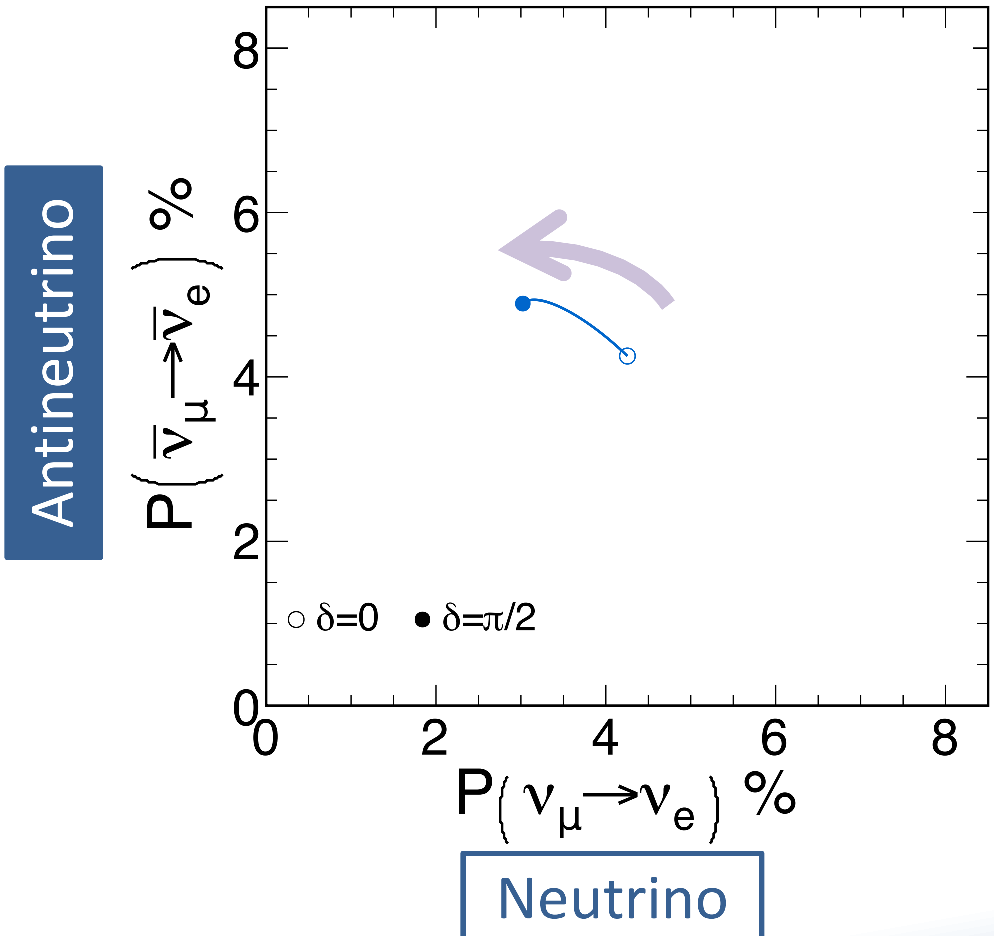

CP-violation through δ creates opposite effects in neutrinos and antineutrinos

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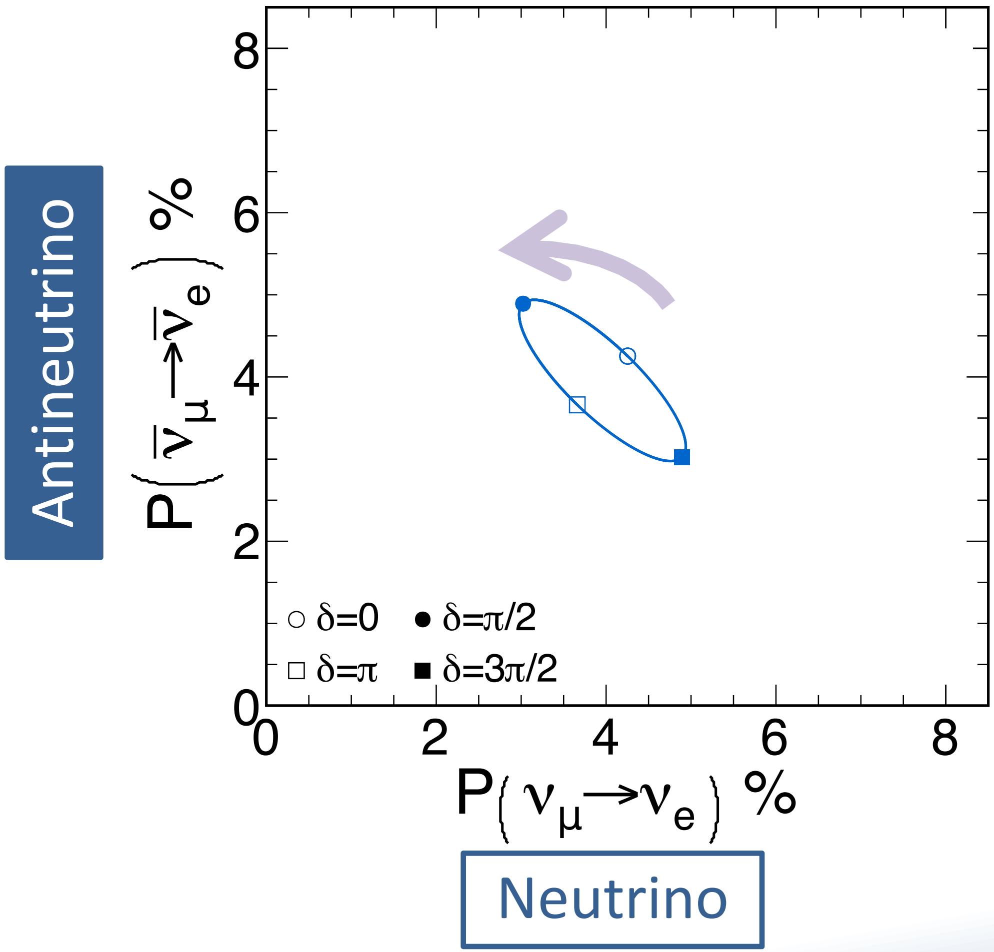

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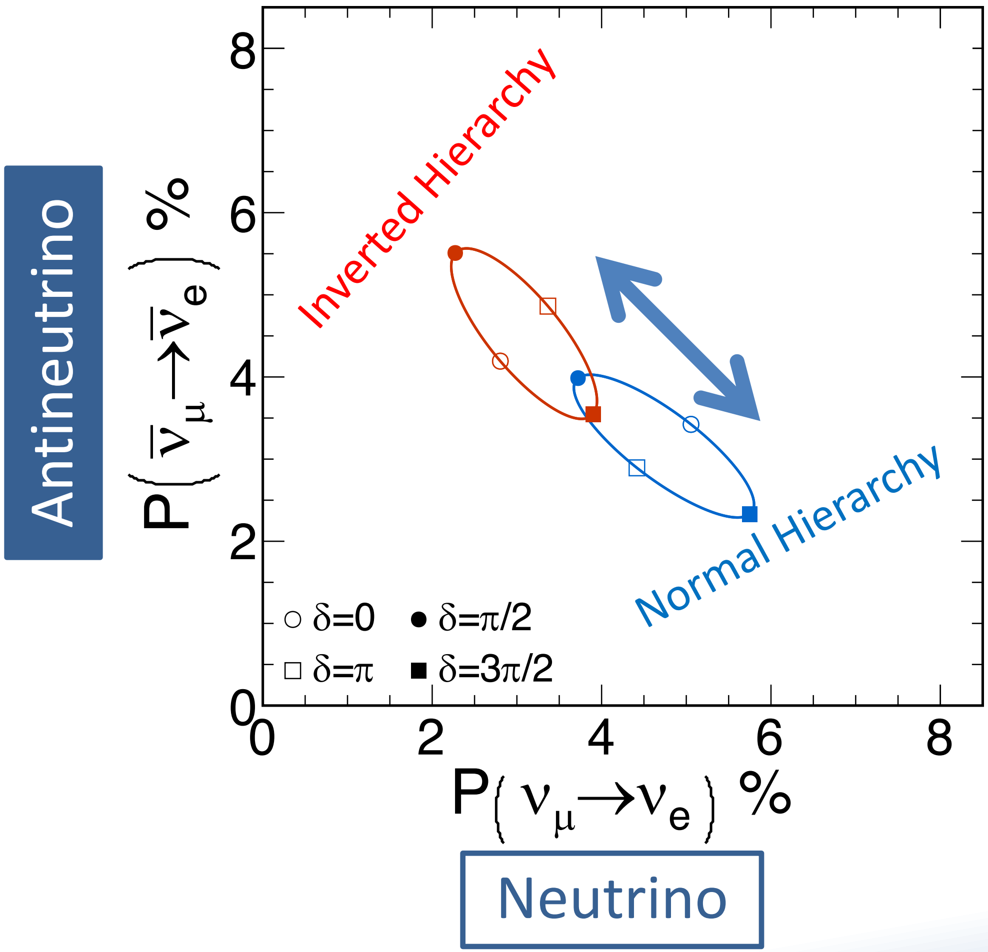

Matter effects also introduce opposite neutrino-antineutrino effects.

1. Is the mass hierarchy "normal" or "inverted?
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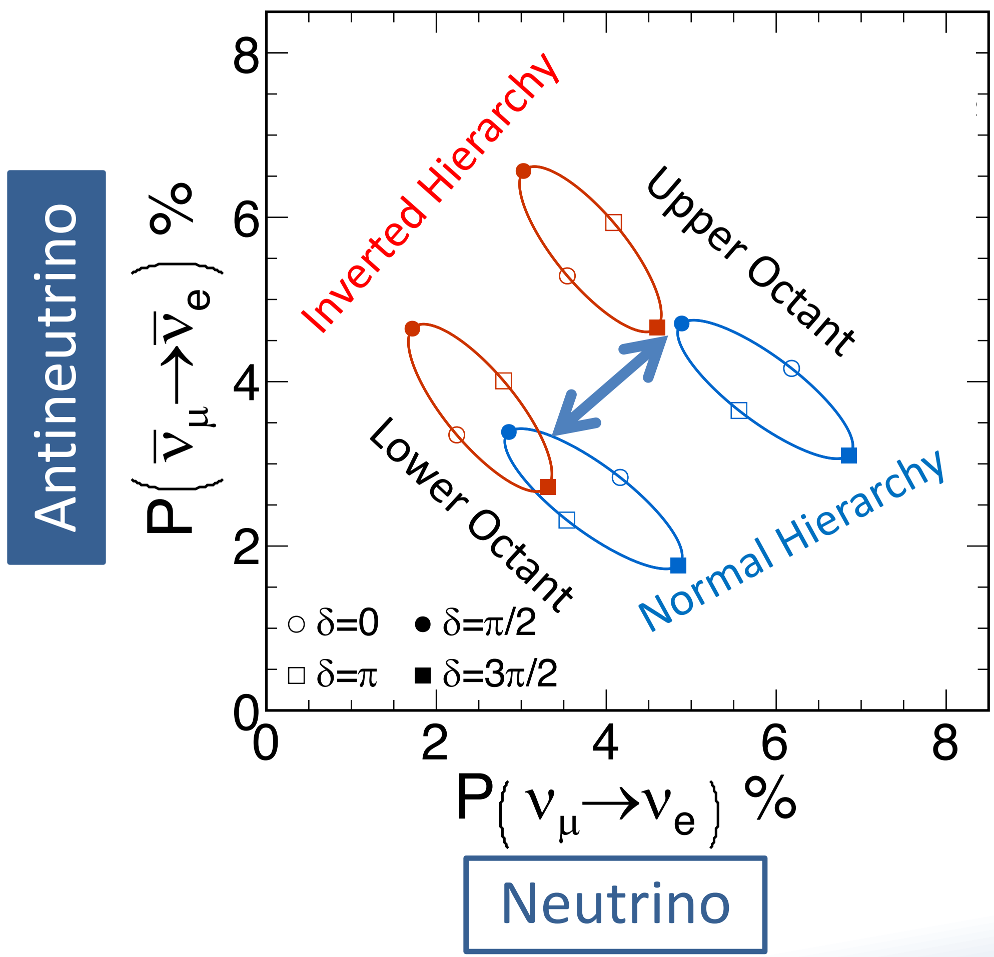
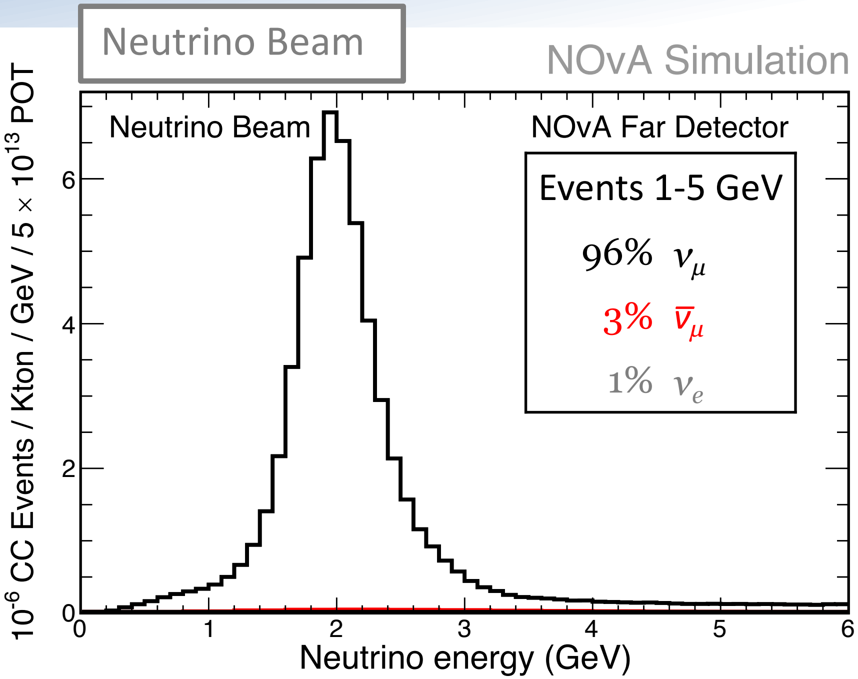
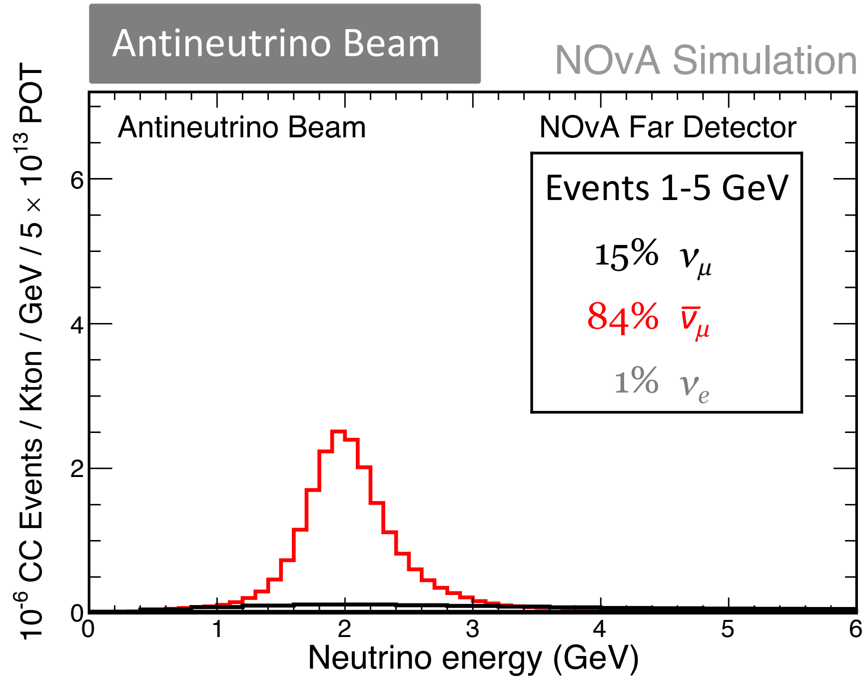
3. What is the "octant" of θ_{23}?

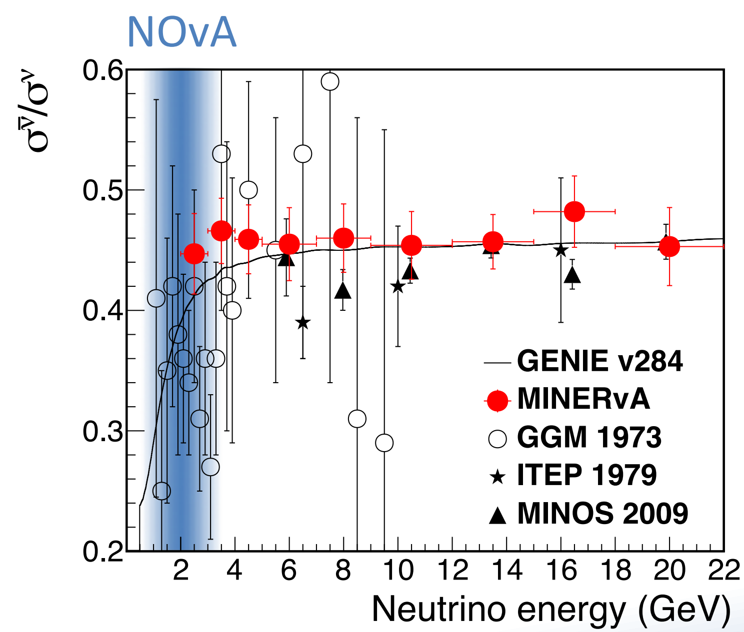


The octant creates the *same* effect in neutrinos and antineutrinos.





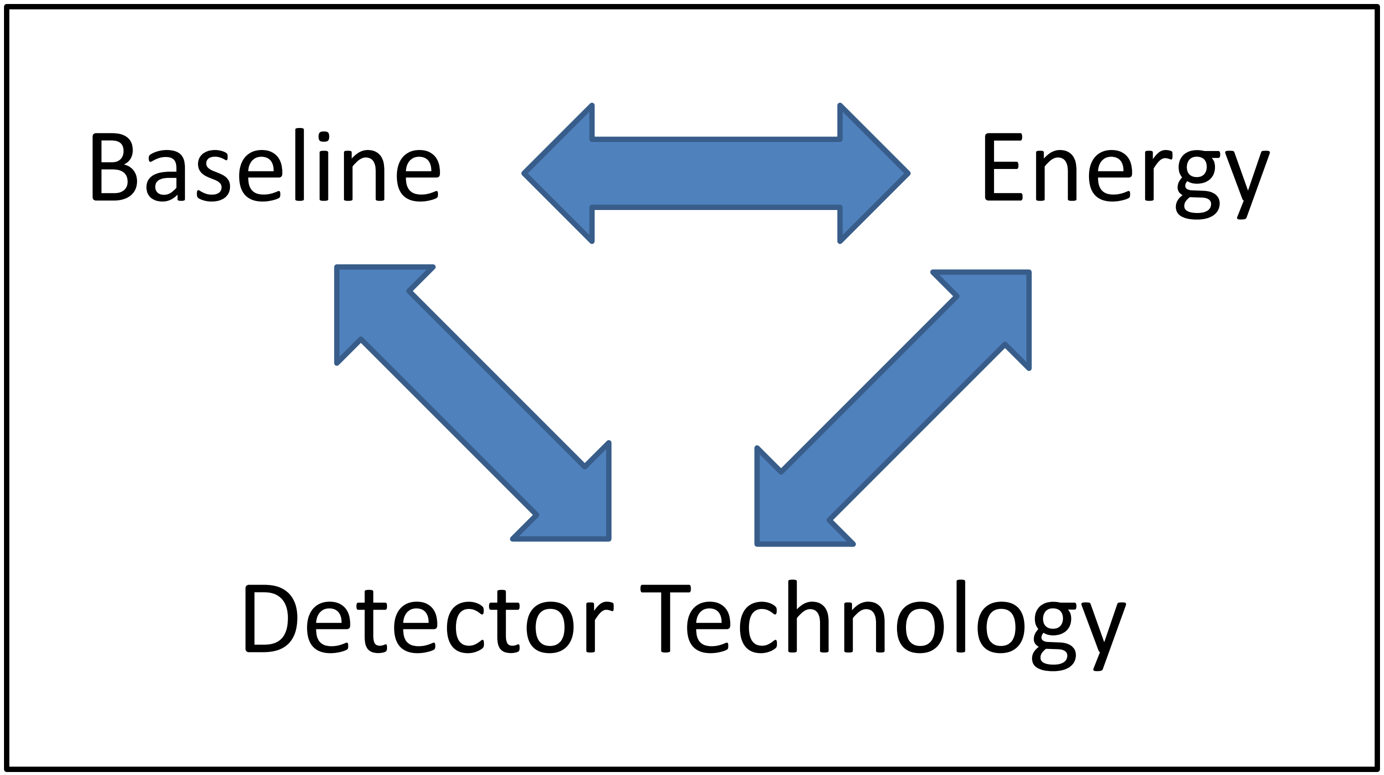
- The cross section for antineutrinos is **~2.8 times lower** than for neutrinos at 2 GeV.
  - The flux also has a small bias towards neutrinos.
- Means that "wrong-sign" is a bigger issue in antineutrinos than neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.
  - Lower kinematic *y*



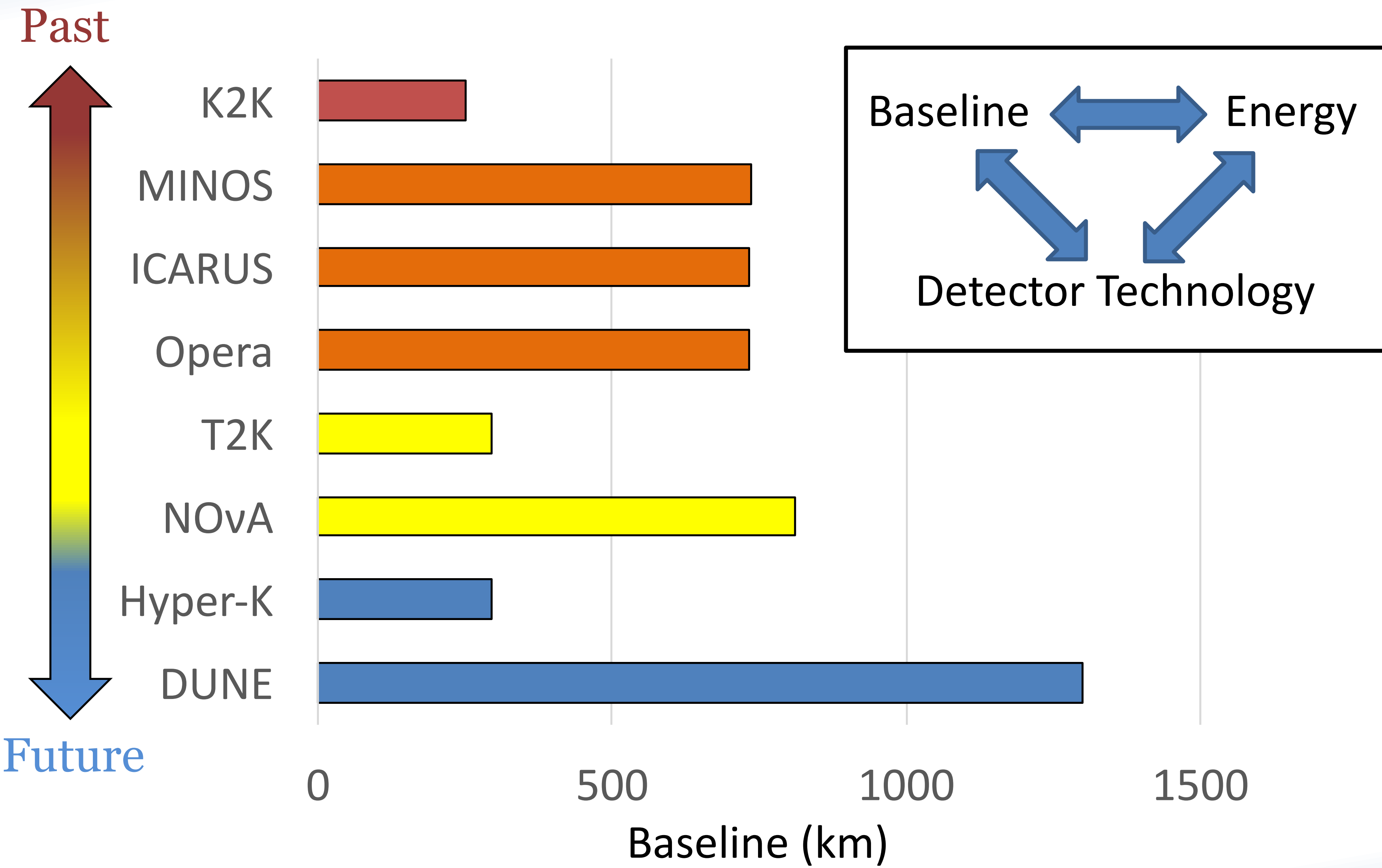
MINERvA, Phys.Rev. D95 (2017) no.7, 072009

Long Baseline Experiments

Designing an Accelerator ν Experiment



Designing an Accelerator ν Experiment



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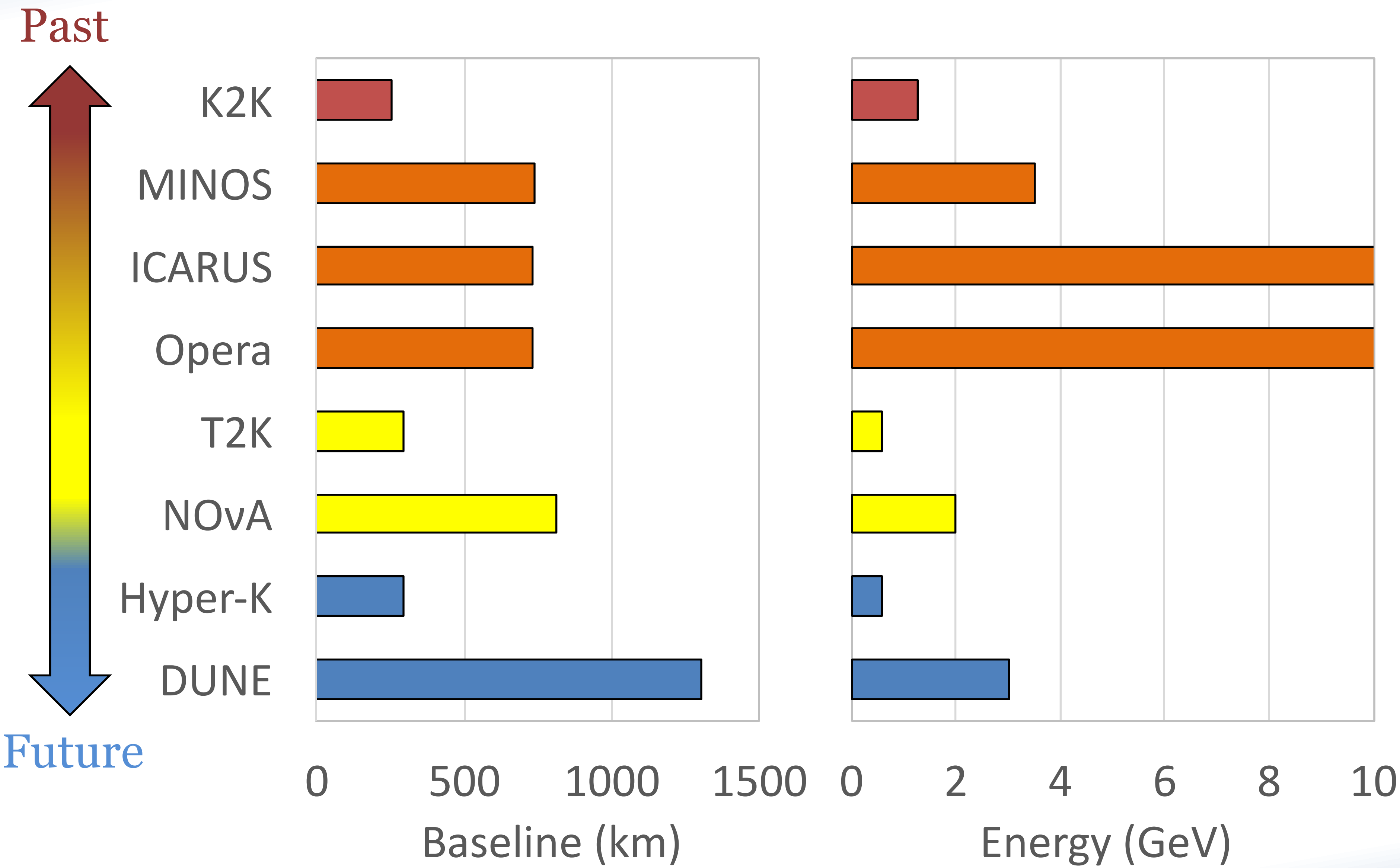
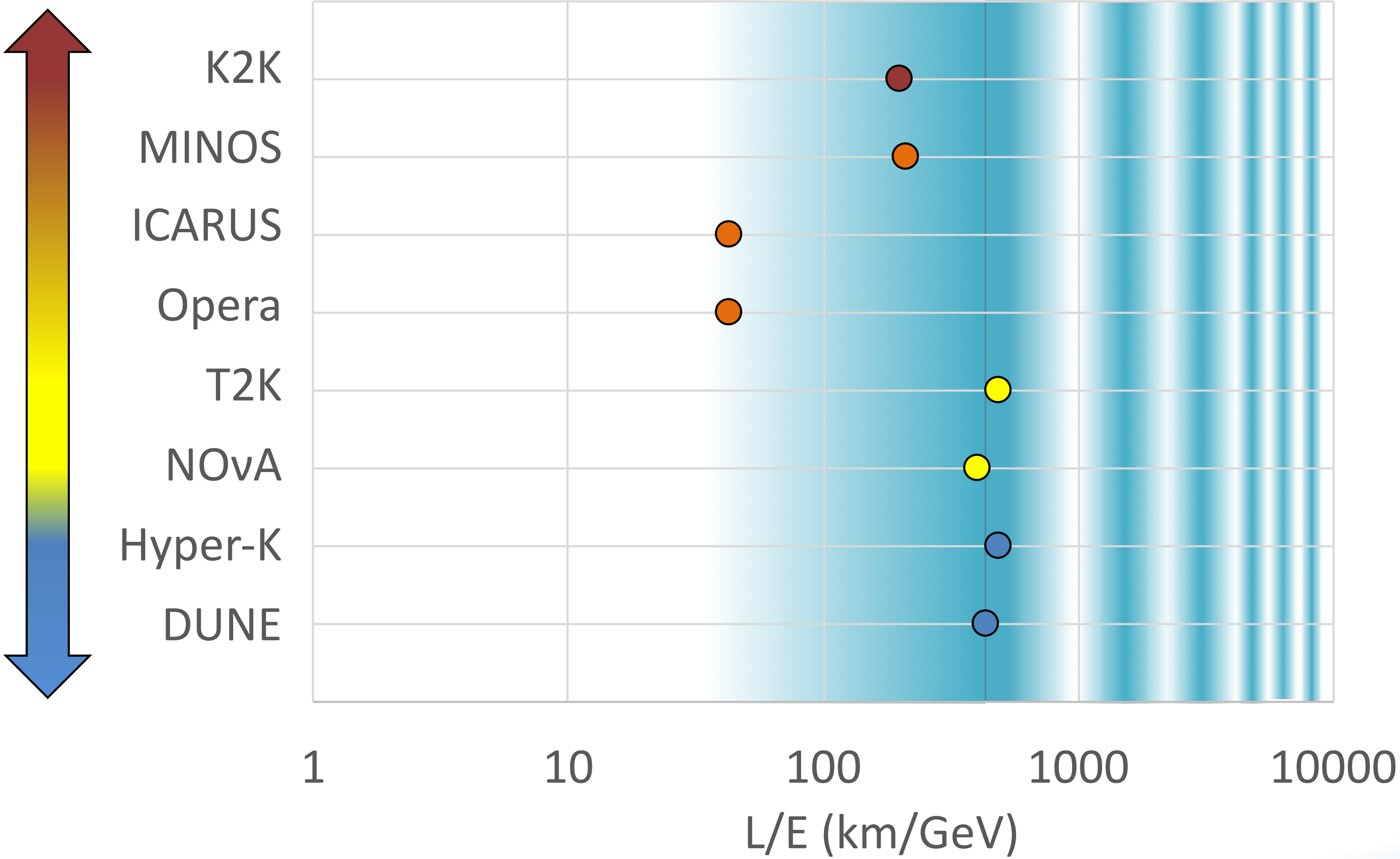


Designing an Accelerator ν Experiment



Designing an Accelerator ν Experiment

T2K

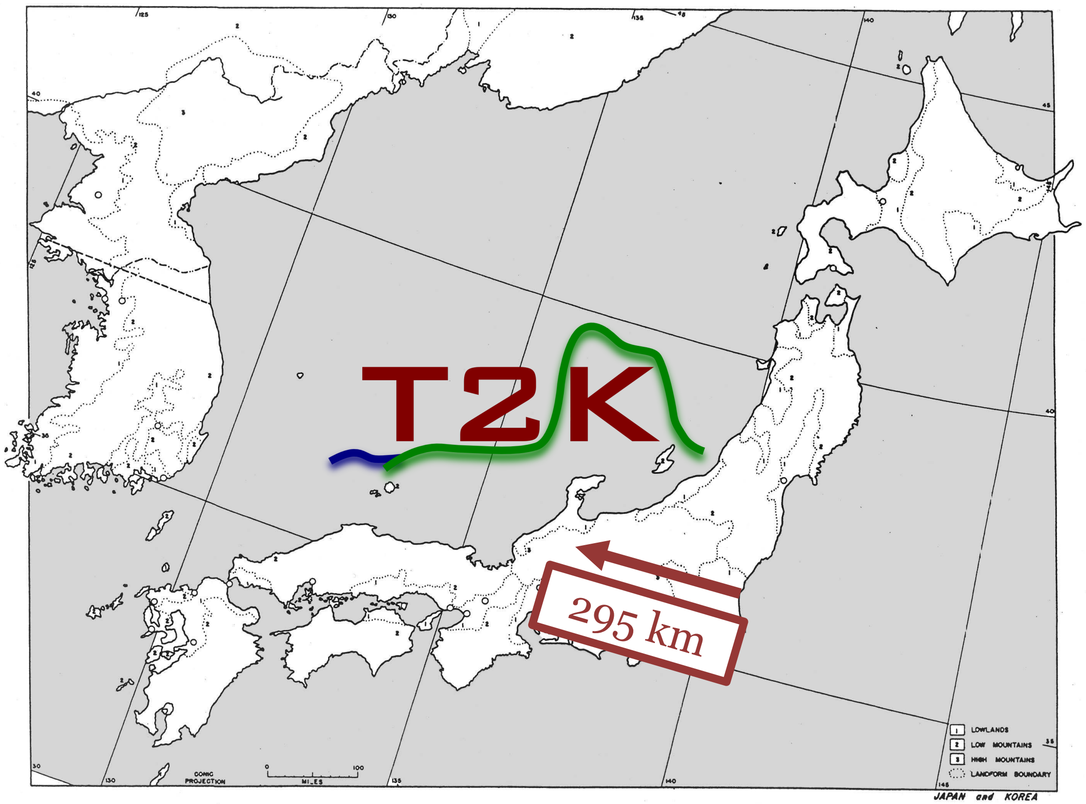
MINOS+ NOνA

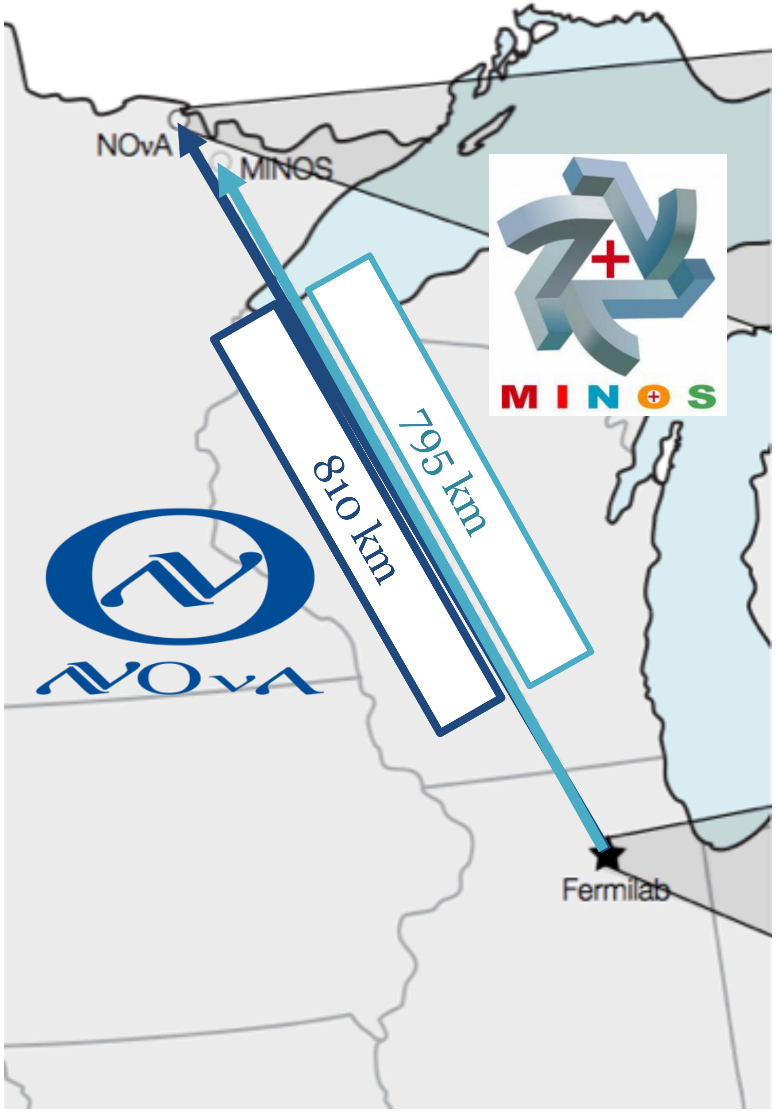
J-PARC

Fermilab

A neutrino beam from a proton accelerator

Designing an Accelerator ν Experiment

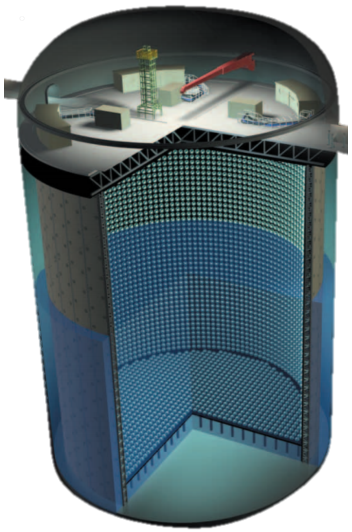




A long baseline

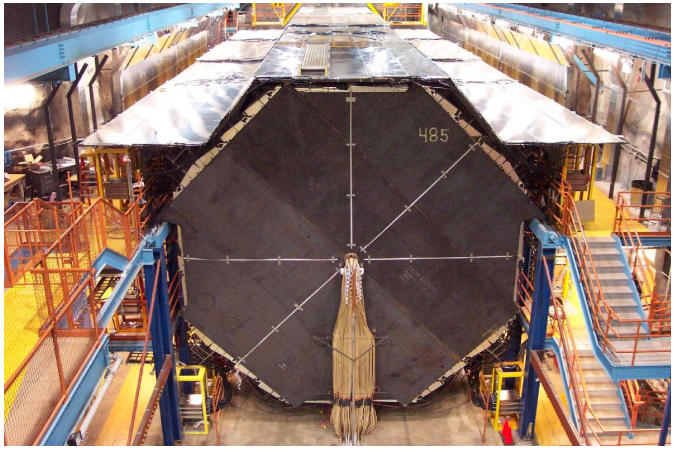
Designing an Accelerator ν Experiment

T2K



50 kton
Water Cherenkov

MINOS



5.4 kton
Alternating iron and plastic scintillator

NOνA

14 kton
Segmented liquid scintillator

A far detector

Designing an Accelerator ν Experiment

50 kton
Water Cherenkov

- Very large mass
- Good e/μ separation
  - But often cannot see the hadronic system

5.4 kton
Alternating iron and plastic scintillator

- Magnet allows for charge-sign ID
- Steel planes are a challenge for non-muons.

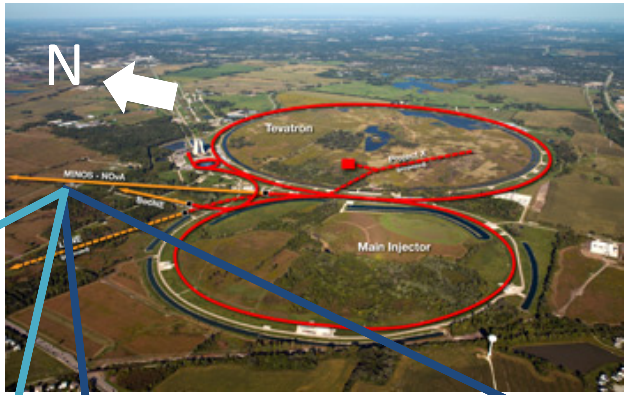
14 kton
Segmented liquid scintillator

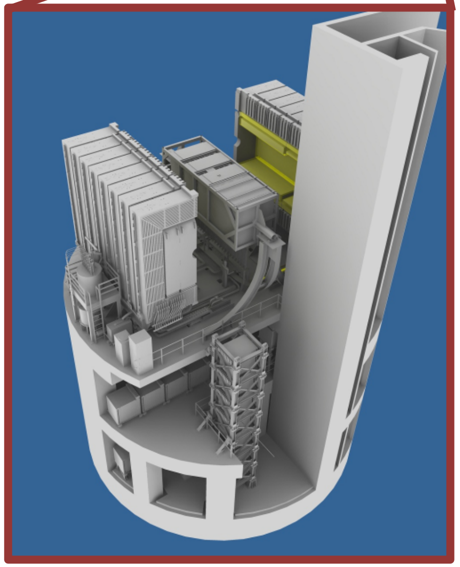
- Mostly-active design optimized for *e* ID
- Less mass, no magnet, but much lower single particle threshold.

A far detector

Designing an Accelerator ν Experiment

A near detector





T2K

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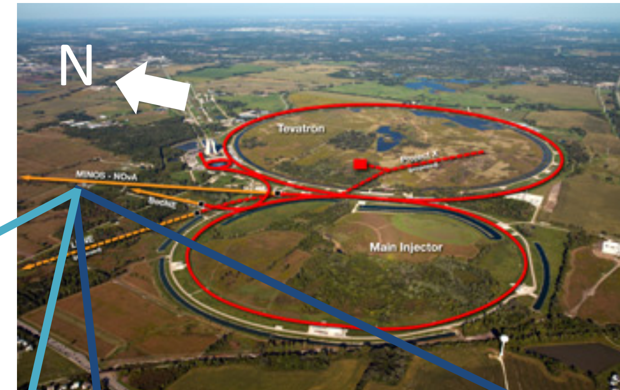
Designing an Accelerator ν Experiment

A near detector



Multi-component detector for precise tracking and calorimetry.

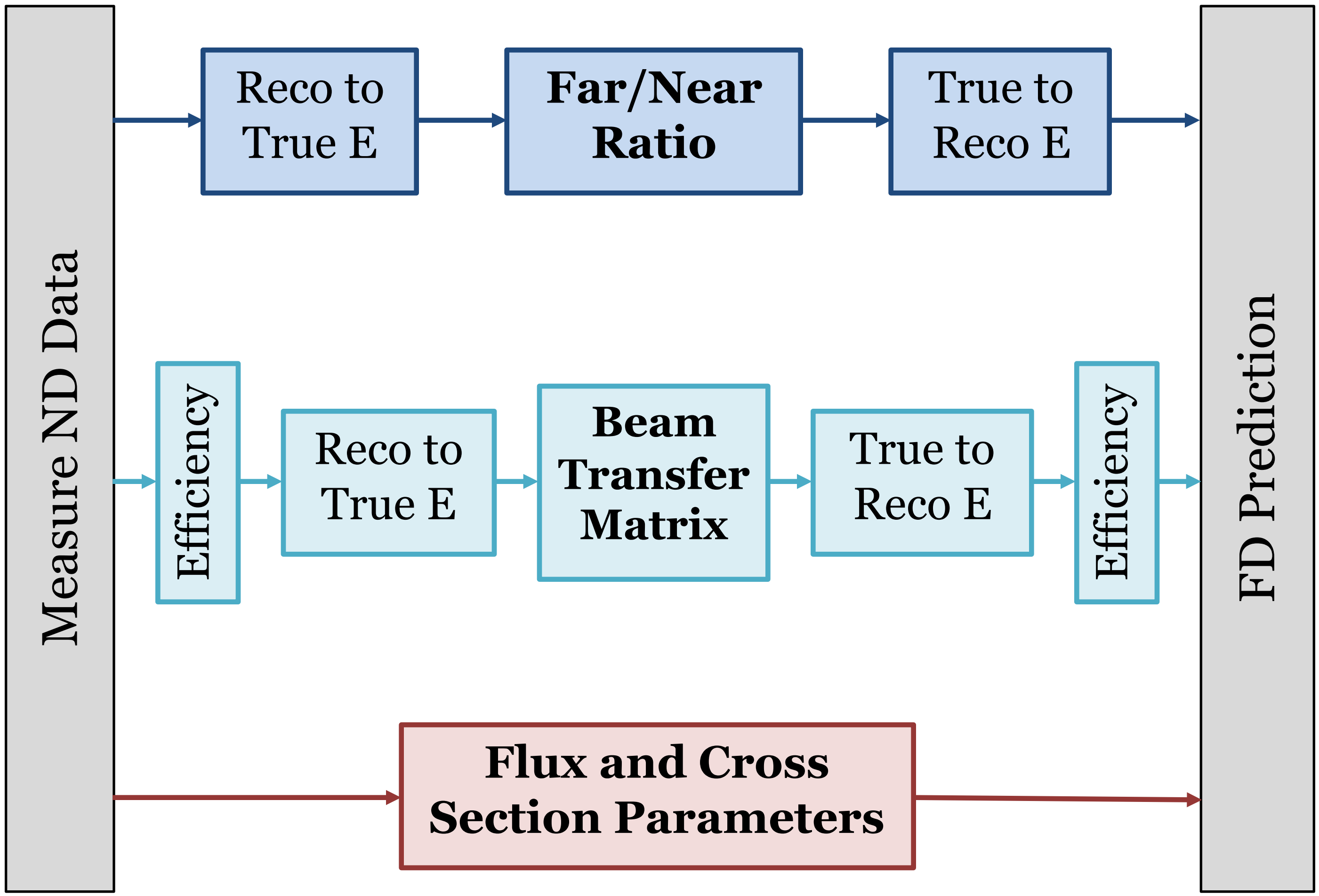
Designs functionally identical between Near and Far detectors.

T2K

MINOS

NOvA

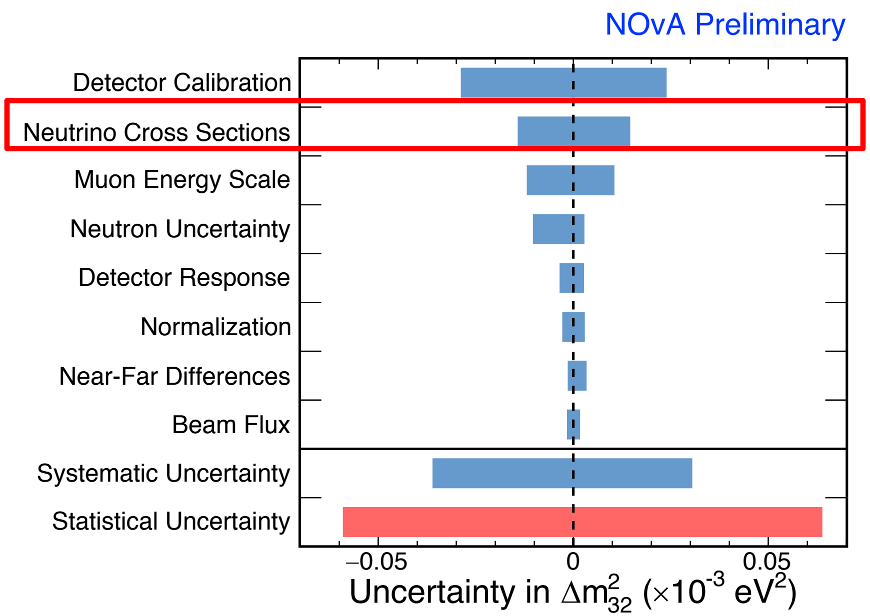
Designing an Accelerator ν Experiment

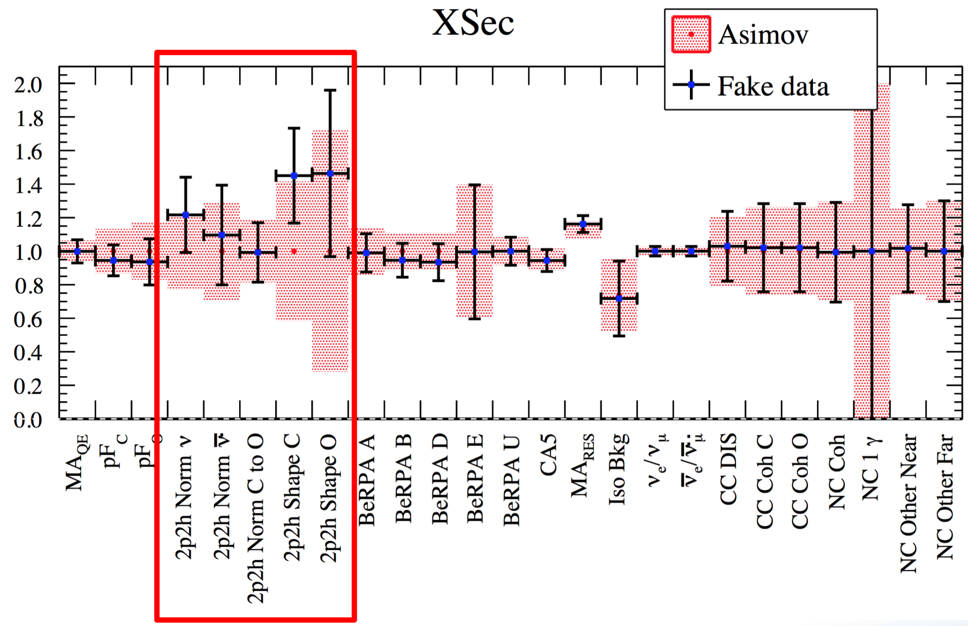


An analysis strategy

Cross-section Systematics

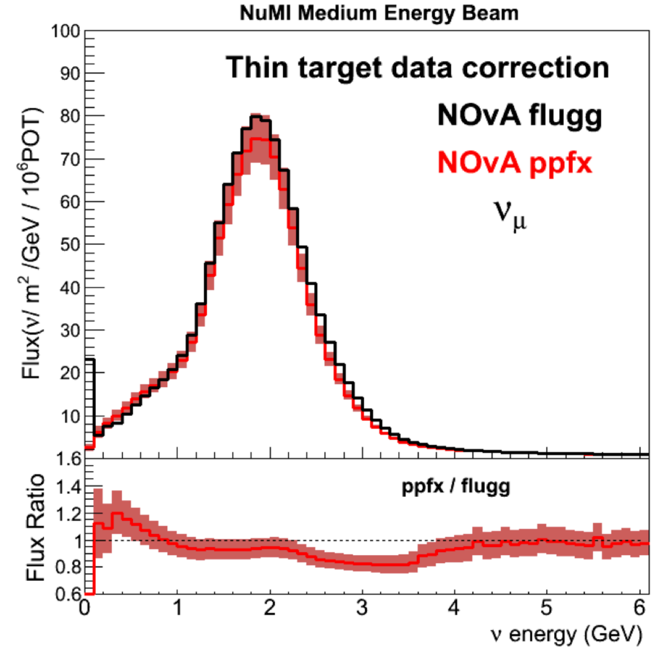
- Even with a near detector, cross-section systematics are a significant source of uncertainty in long-baseline experiments.
- Right now, nuclear effects (MEC/2p2h, Charge Screening/RPA) are among largest pieces of that uncertainty.

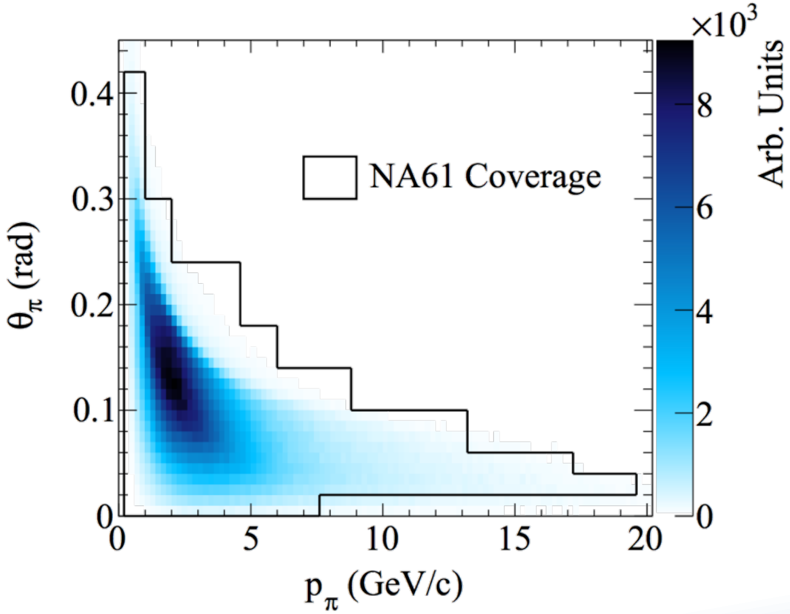




Simulation Tuning: Flux

- We tune our simulation to get a better central value *and* to set systematic uncertainties.
- **NOvA flux** is tuned using the Package to Predict the FluX.
  - **Minerva**, Phys. Rev. D 94, 092005 (2016)
- **T2K flux** is tuned with NA61/SHINE.
  - There is close cooperation between the experiments.
  - **T2K**, Phys. Rev. D 87, 012001 (2013)
- **MINOS flux** is constrained using alternative focusing configurations.
  - Particularly horn-off to constrain un-focused high energy tail.





(a) π^+

Simulation Tuning: Cross section

- **T2K** needs to extrapolate between different detectors with different targets.
  - Model choice is important!
  - Informed by fits to other neutrino scattering experiments.

- **NOvA** tunes the cross-section model primarily to account for **nuclear effects.**
  - Backstory: disagreements are seen in cross sections as measured on a single nucleons vs. in more complex nuclei.
  - Nuclear effects are a likely solution, but the theory for them remains incomplete.
  - So, tune using a combination of **external theory** inputs and **ND data**.

- Discussed at length yesterday – ask at the end and we can talk more about it.

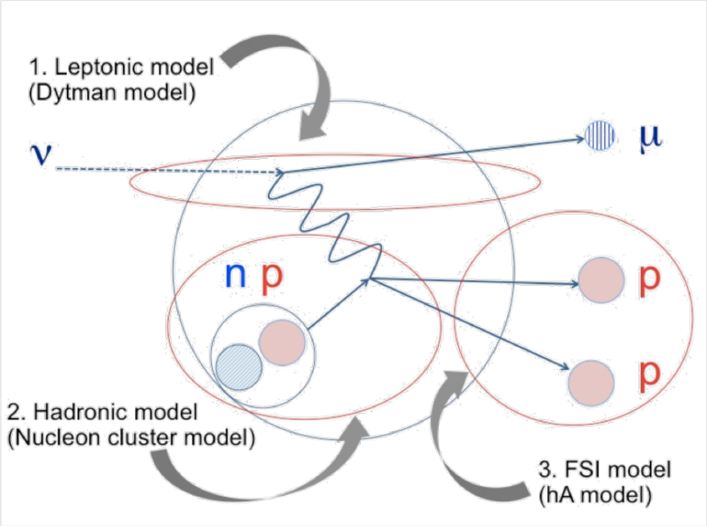
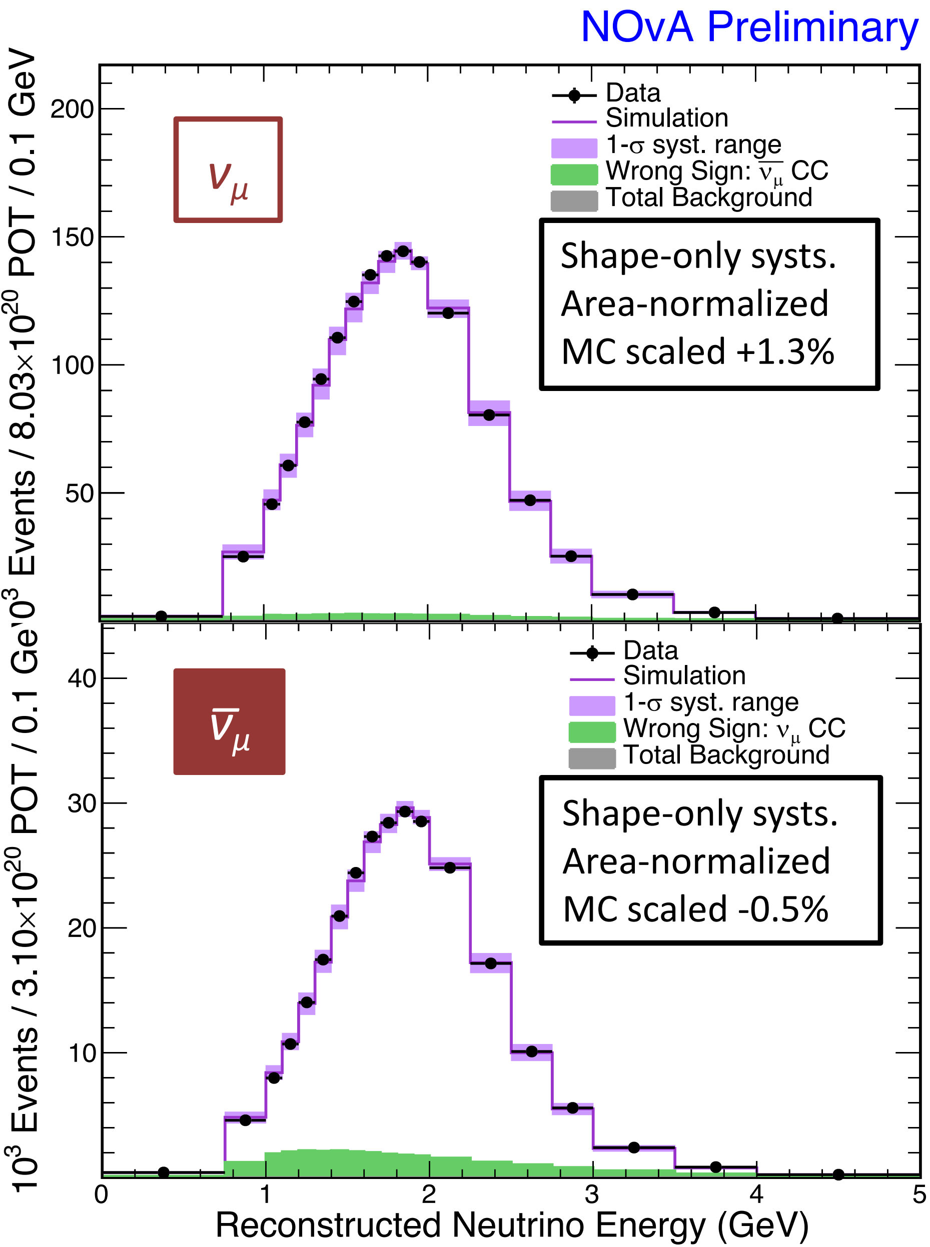
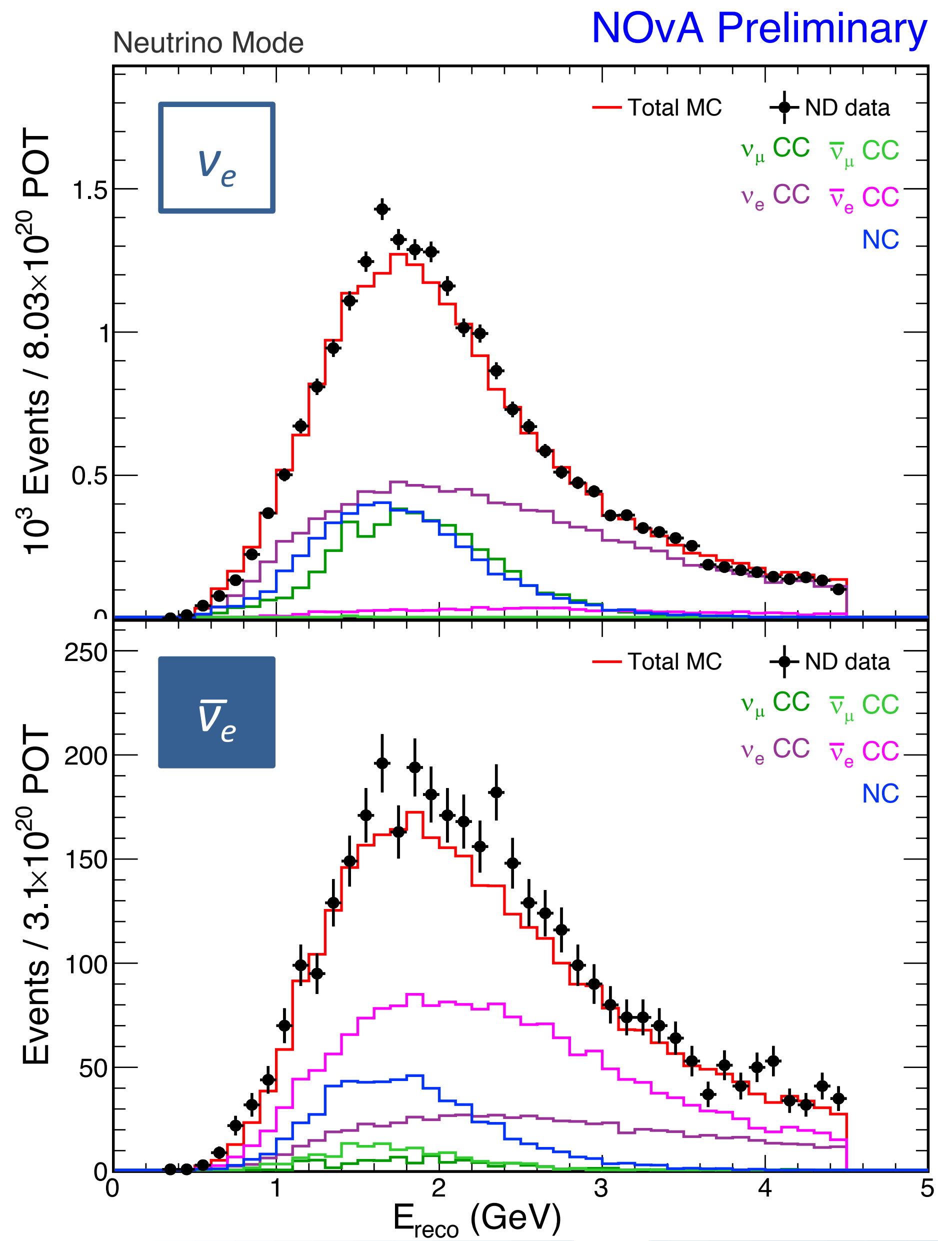


Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

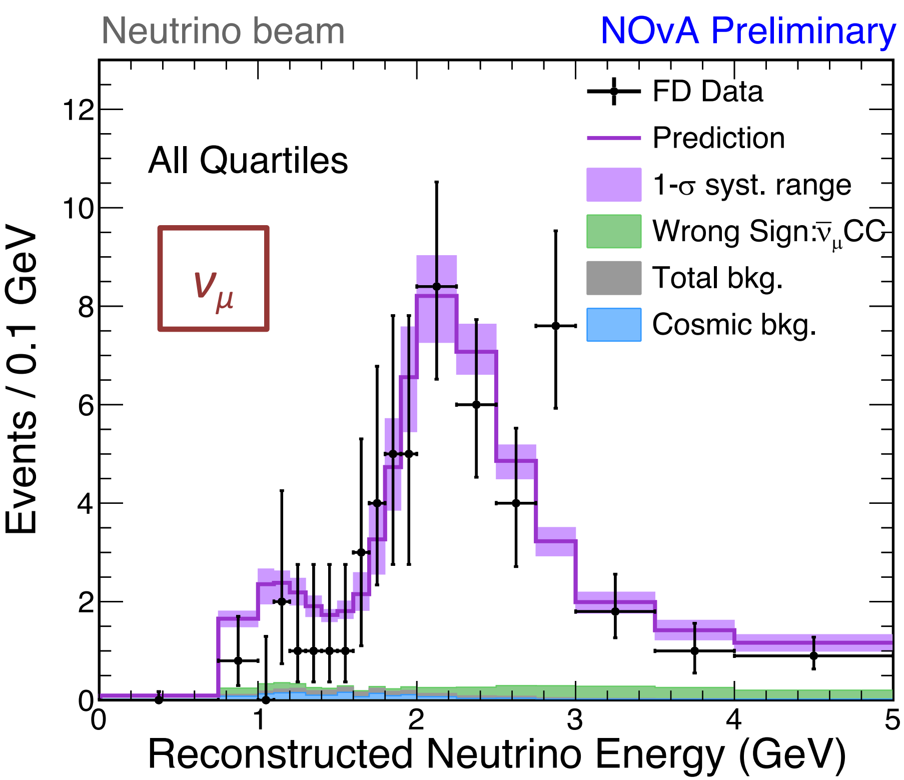
Recent Results from NEUTRINO 2018

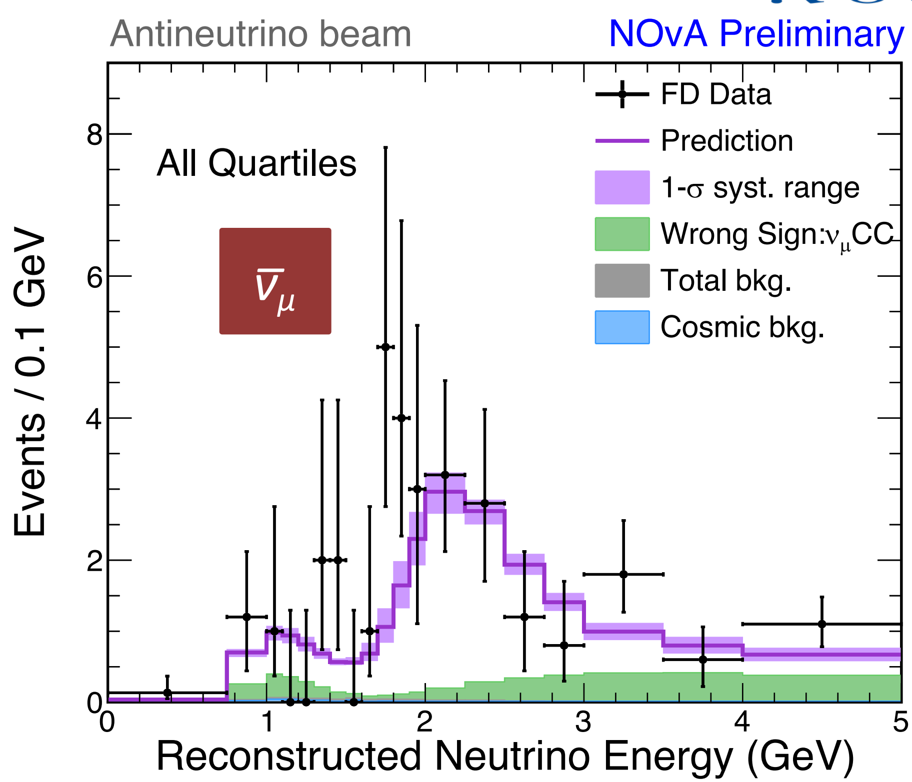
NOvA Near Detector Data





NOvA ν_μ Disappearance Data

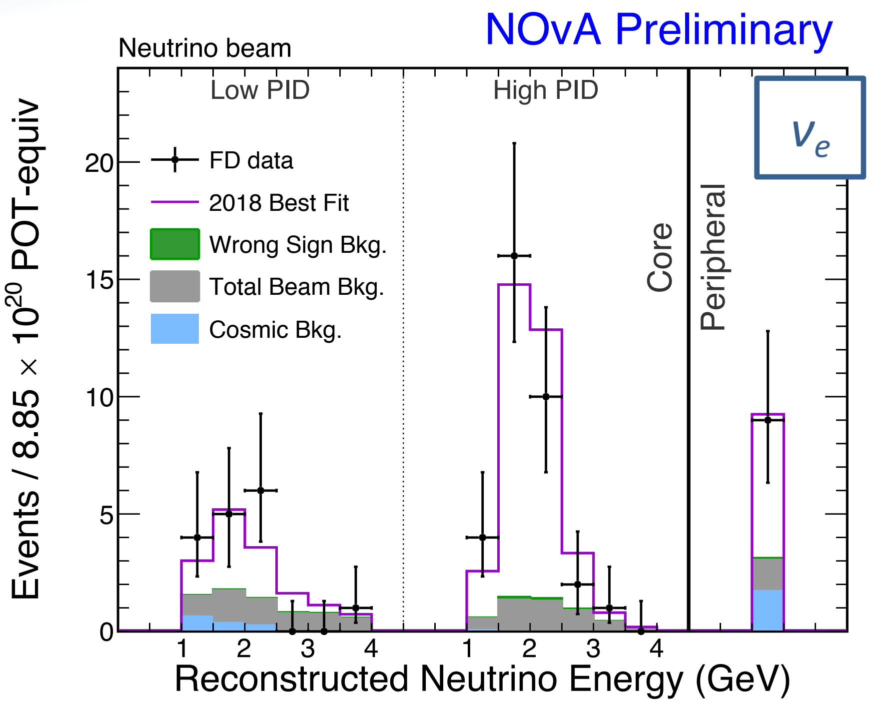




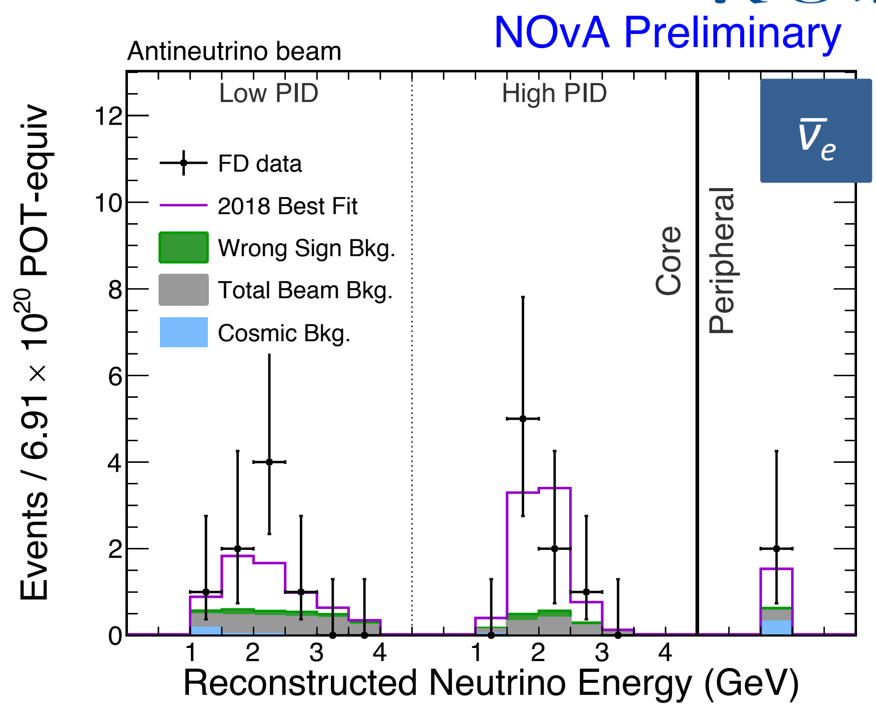
Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

NOvA ν_e Appearance Data



Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4



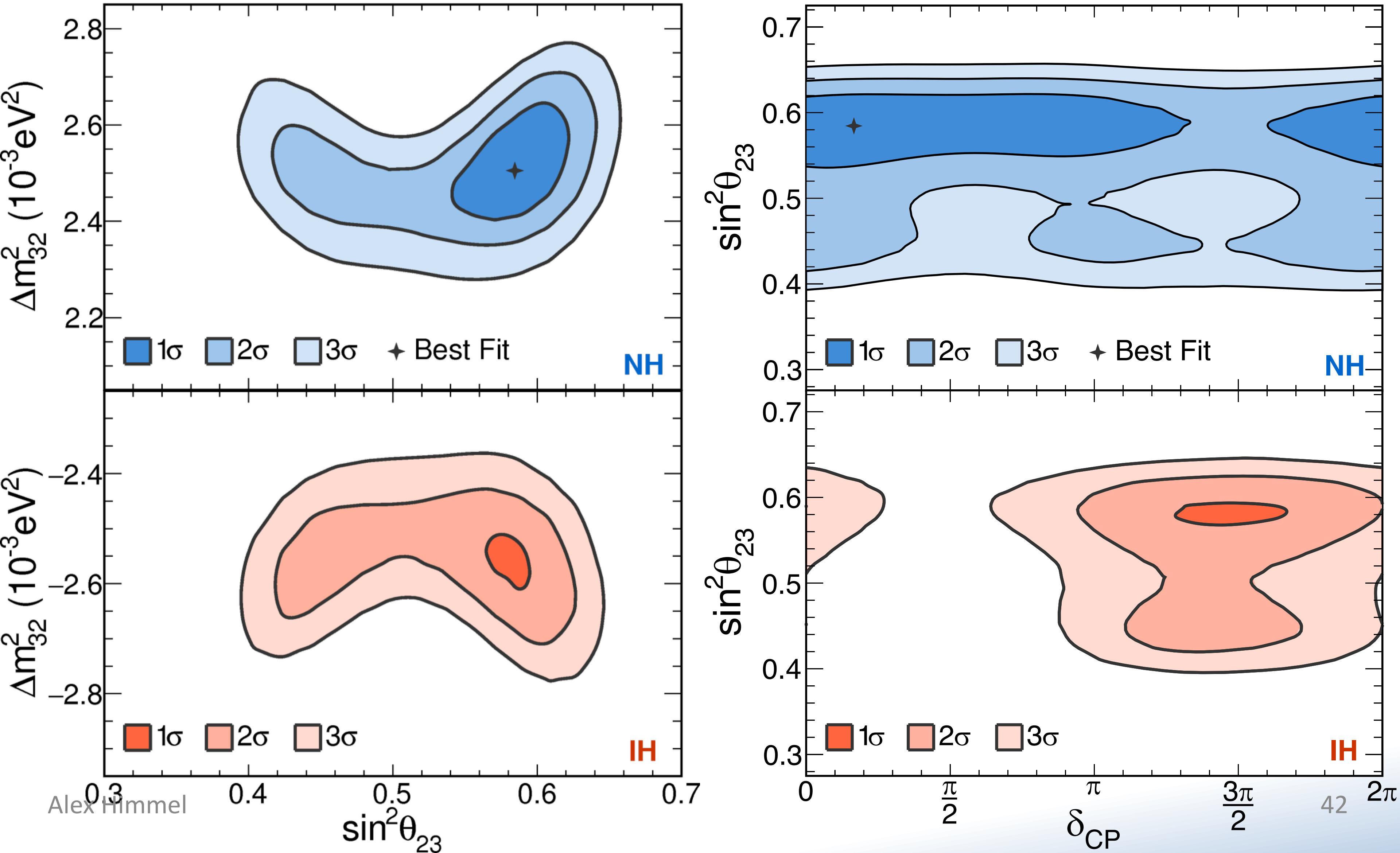
Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

Strong (>4σ) evidence of $\bar{\nu}_e$ appearance

NOvA Results

Favor non-maximal at ~1.8σ
Favor NH at 1.8σ
Exclude IH, $\pi/2$ at >3σ

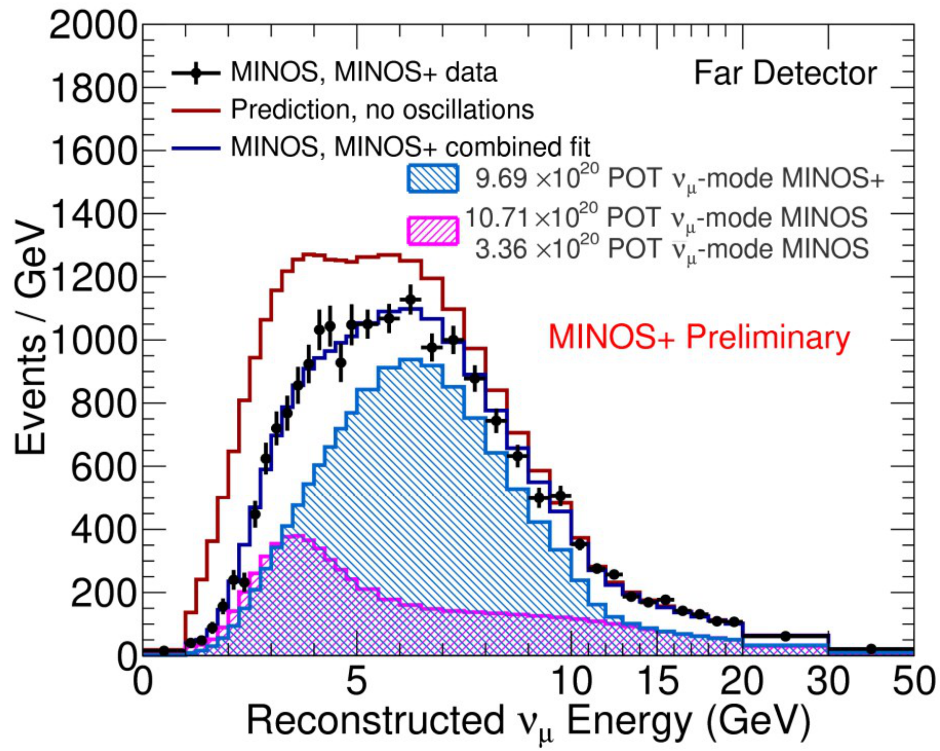
NOvA Preliminary

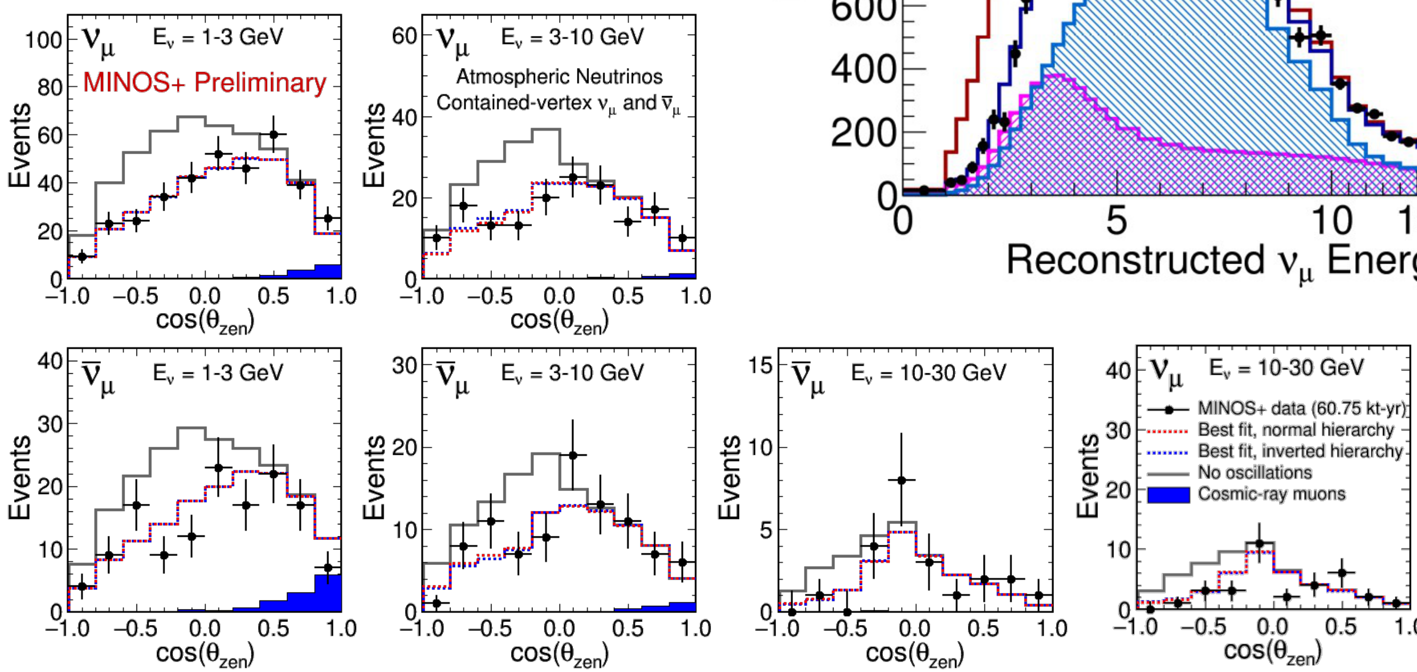


MINOS+ Data

A joint fit to:

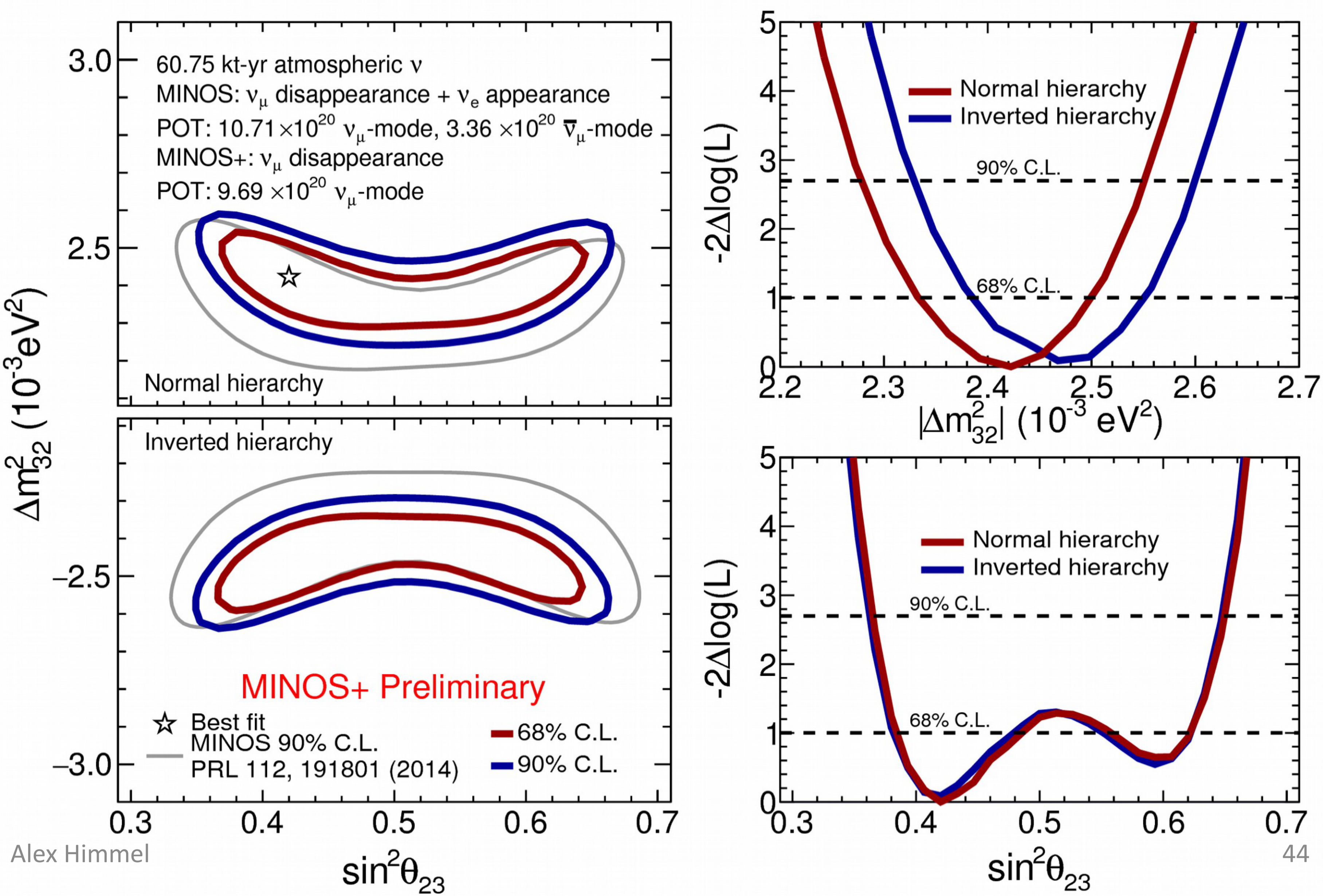
- MINOS ν_μ beam data
- MINOS $\bar{\nu}_\mu$ beam data
- MINOS atm. data
- MINOS+ ν_μ beam data



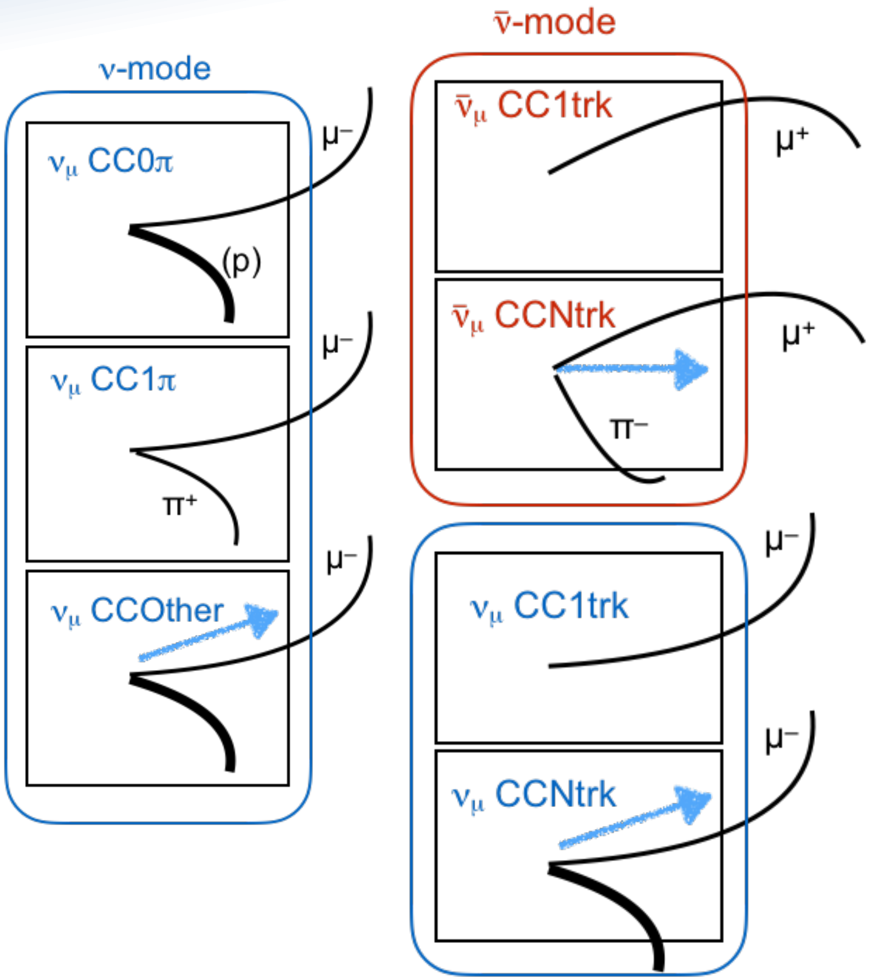


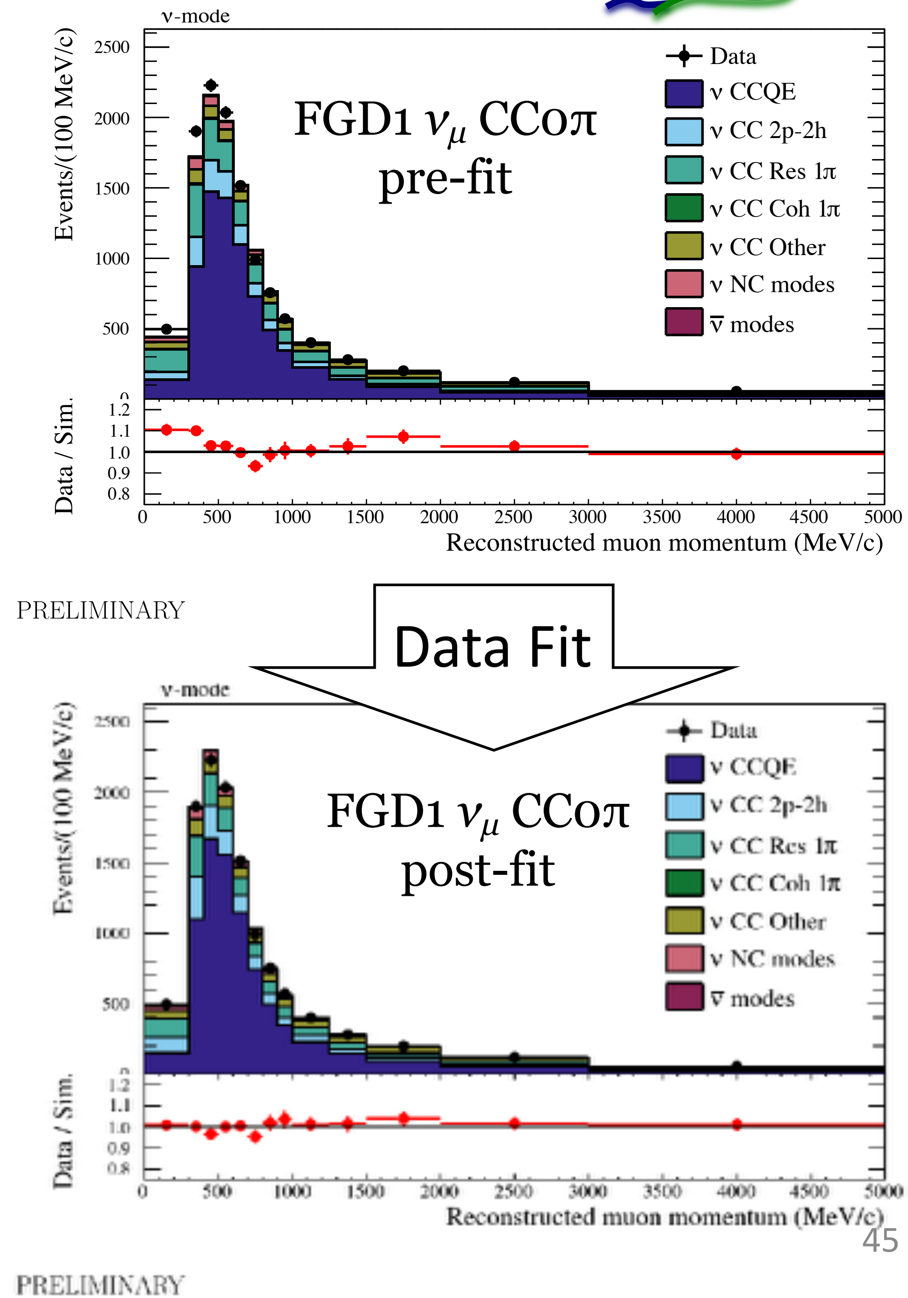
MINOS+ Results

Favor non-maximal at 1.1σ
Favor LO at 0.8σ



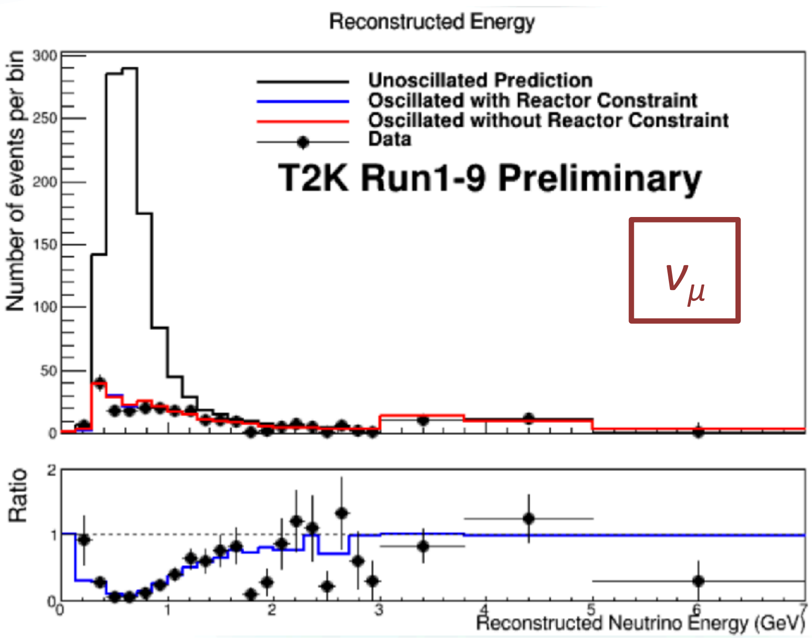
T2K Near Detector Data

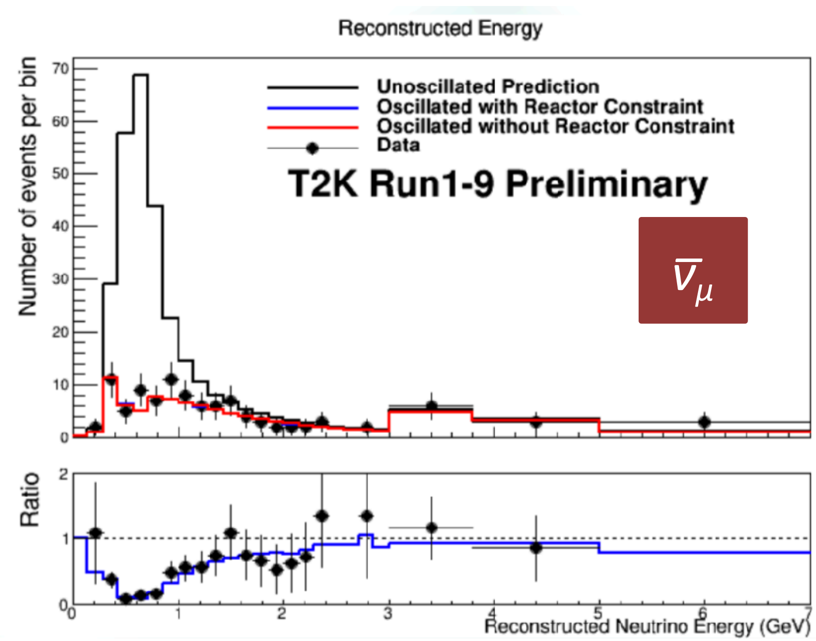


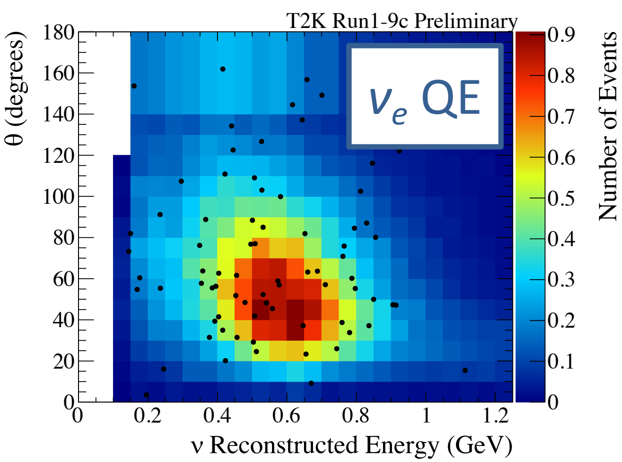


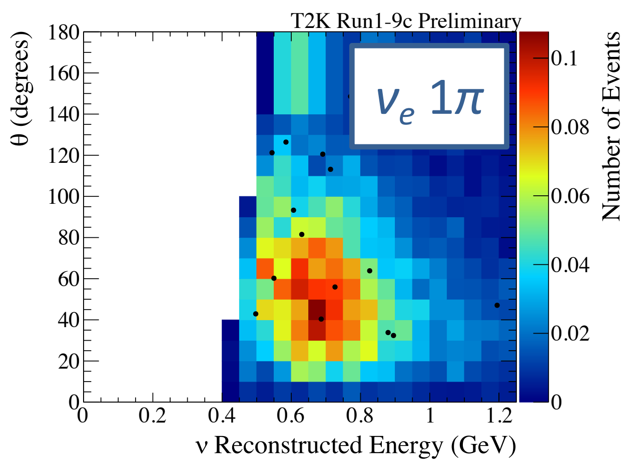
- Fit a total of 14 samples.
  - 6 in neutrino
  - 8 in antineutrino

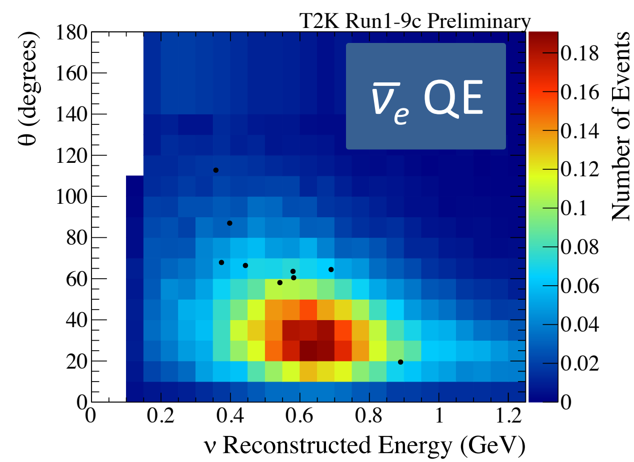
T2K Far Detector Data



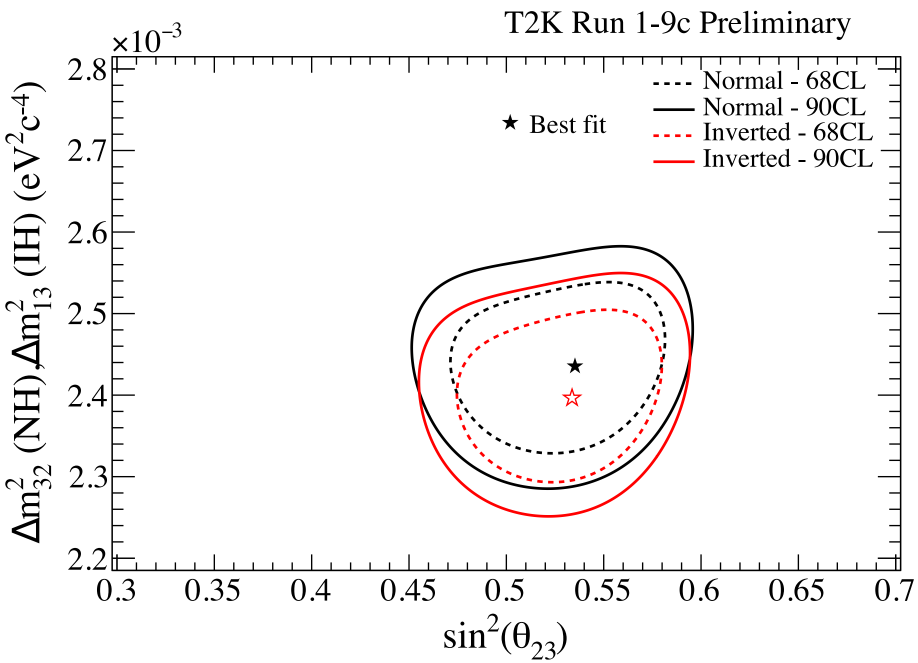


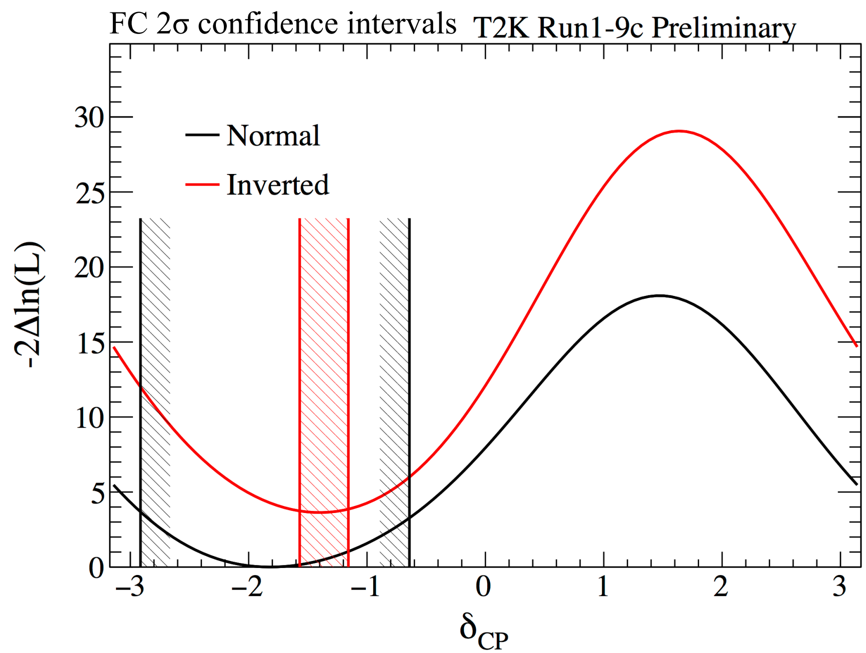






T2K Results





Octant

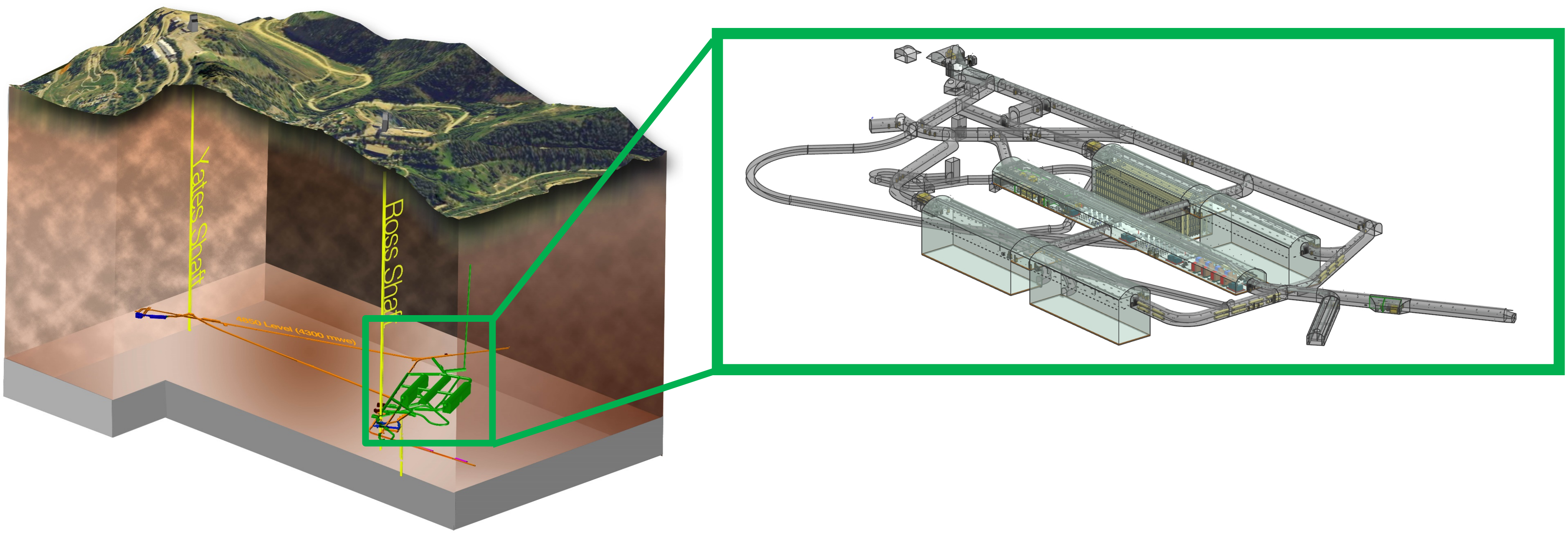
Hierarchy	Lower	Upper	Sum
Normal	0.204	0.684	0.888
Inverted	0.023	0.089	0.112
Sum	0.227	0.773	1

CP-conserving δ_{CP} outside of 2σ

Bayes factor for NH/IH is 7.9

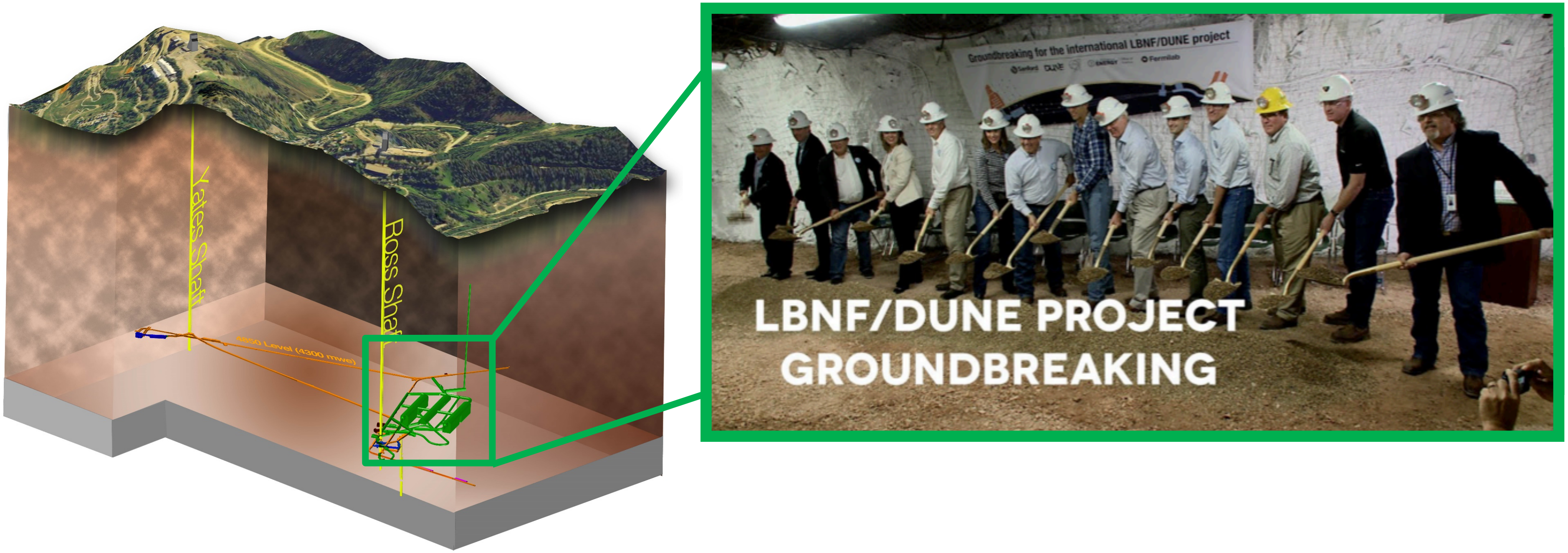
The Future

DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 40 kton liquid argon TPCs
  - Single and dual phase modules
- 4850 ft underground in the Homestake mine in SD
- 1.2 MW beam, 1300 km from Fermilab
- Installation begins in 2022, first beam in 2026

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



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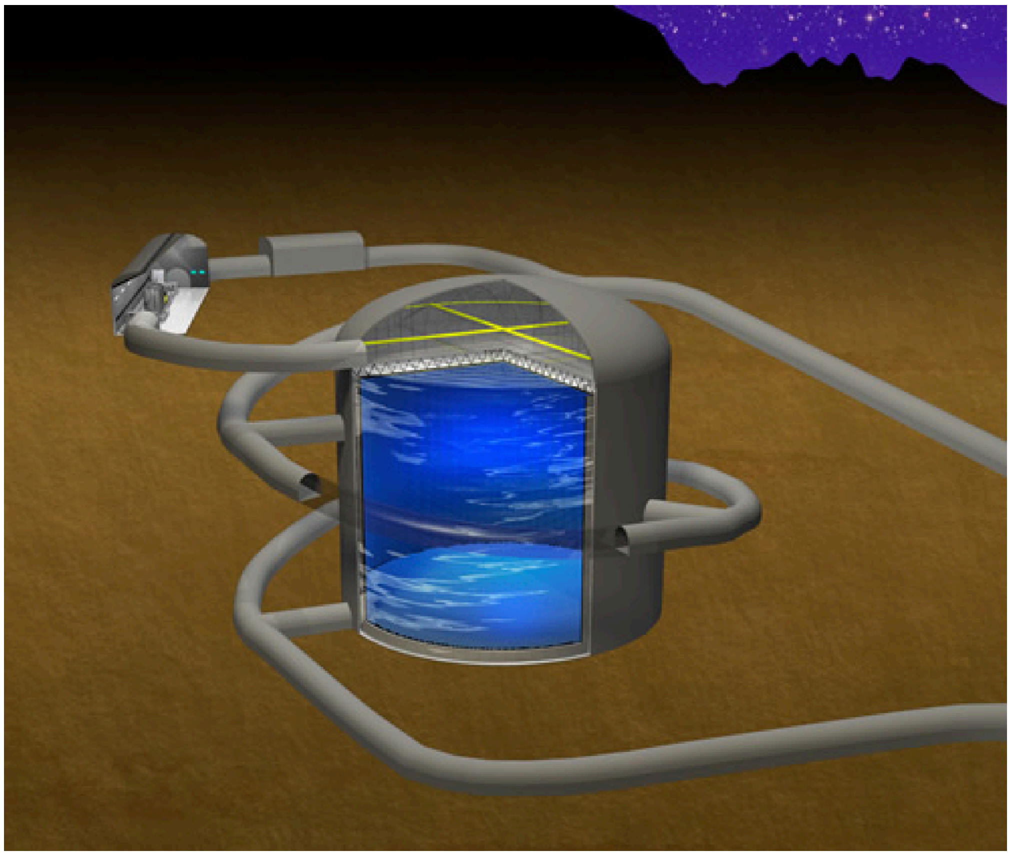
Hyper-Kamiokande

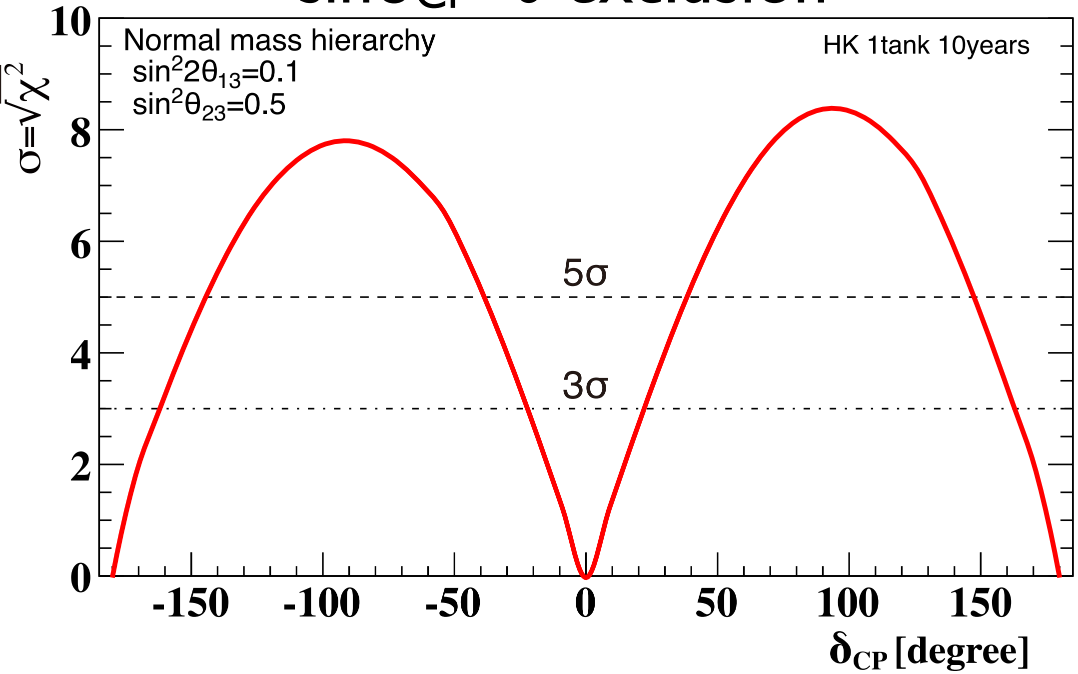


- 186 kton water Cherenkov
  - ~10x Super-K
- 650 m underground in the Tochibora mine
- MW beam from JPARC
- Aiming for construction start in 2019 and operation in 2026

CP Violation Sensitivity

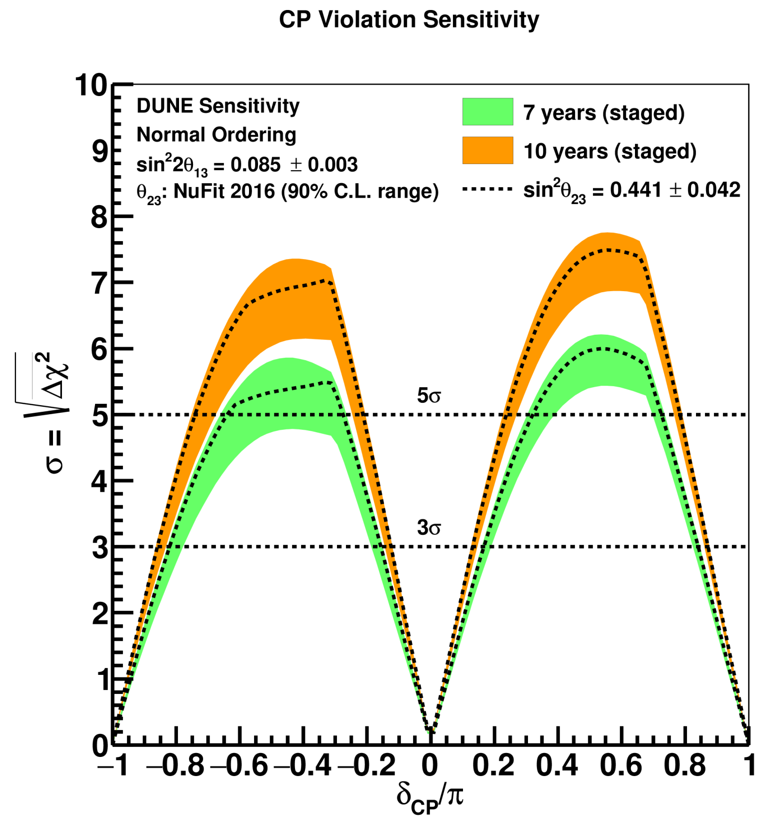
Hyper-Kamiokande

$\sin\delta_{CP}=0$ exclusion



NEUTRINO 2018

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



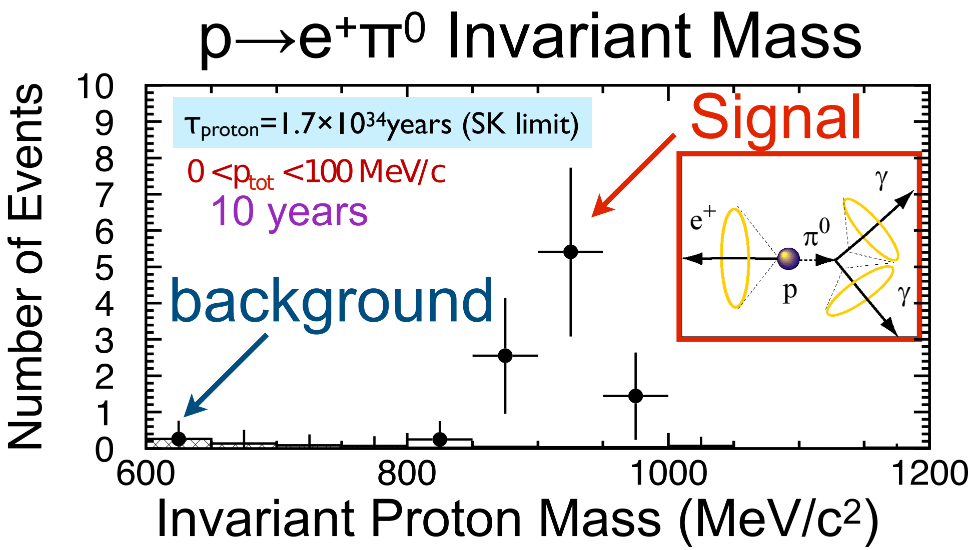
DUNE CDR

If neutrino oscillations violate *CP* at any reasonable rate, DUNE and Hyper-K will see it.

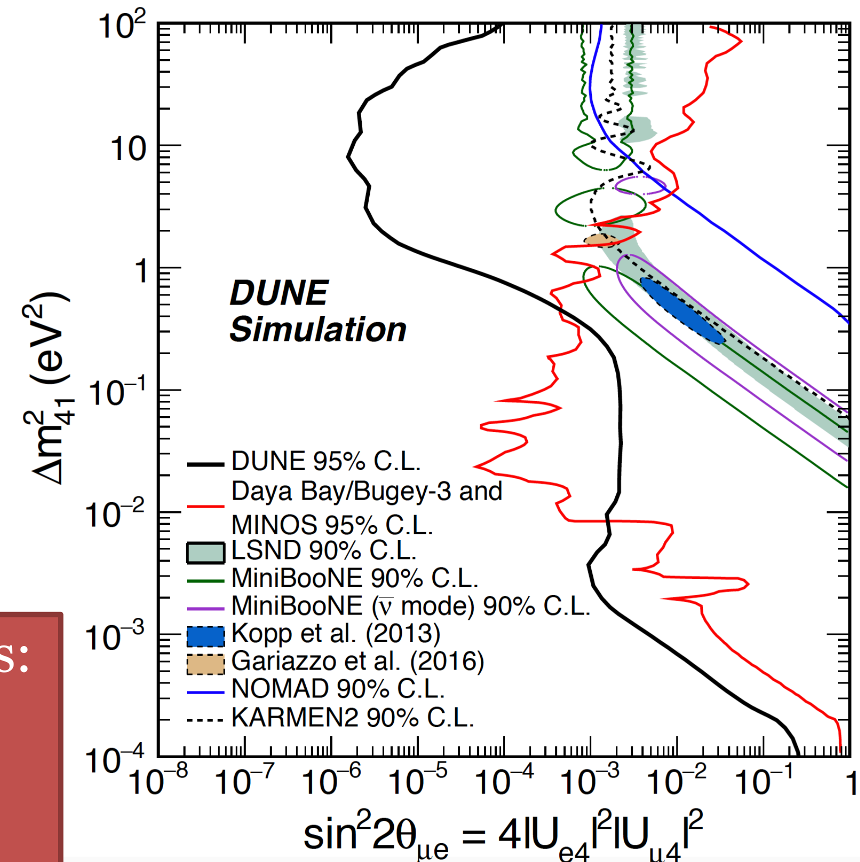
Beyond the Standard Model

Hyper-Kamiokande

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Sterile Neutrino Sensitivity
(ν_e CC appearance at ND)

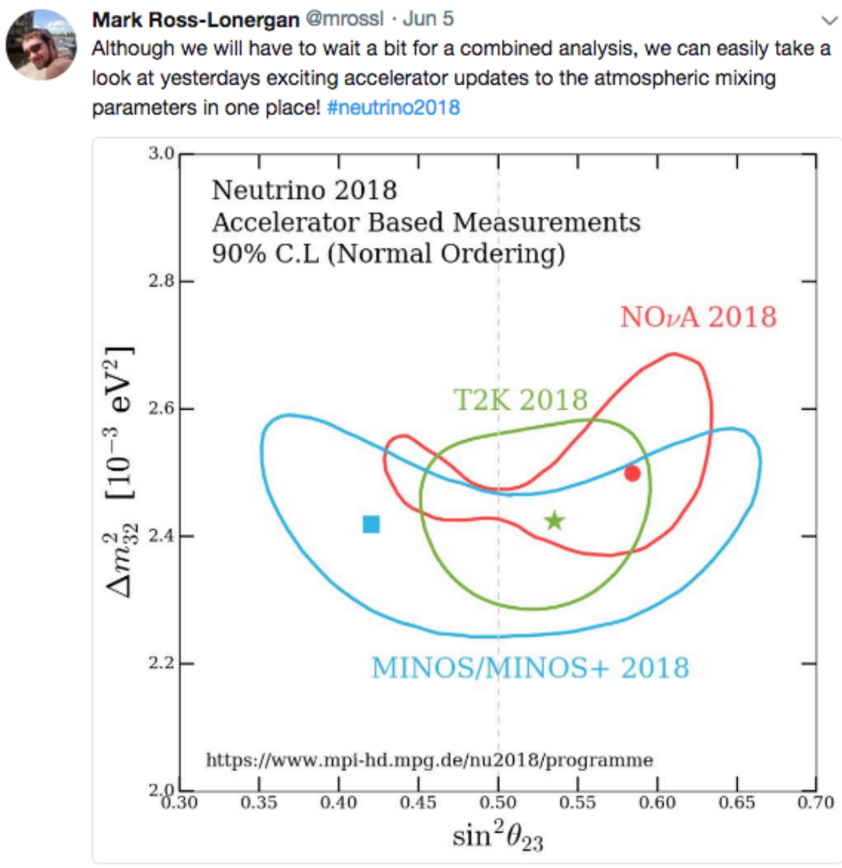


More physics beyond standard oscillations:

- Sterile neutrinos
- Nucleon decay
- Supernova neutrinos
- Solar neutrinos

Conclusions

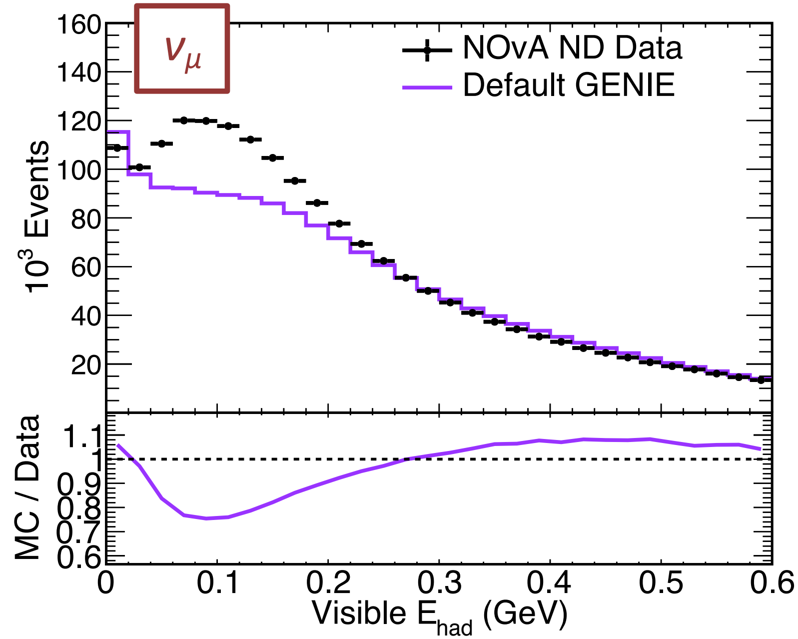
- Accelerator neutrinos are a powerful tool for studying neutrino oscillations.
- Current experiments are…
  - increasing precision on measurements of the 3-flavor parameters and
  - beginning to constrain the octant, *CP* violation, and the mass hierarchy.
- In the future, accelerator neutrino experiments…
  - will measure CP violation in neutrinos if it is there
  - as part of a diverse program of physics beyond 3-flavor oscillations.

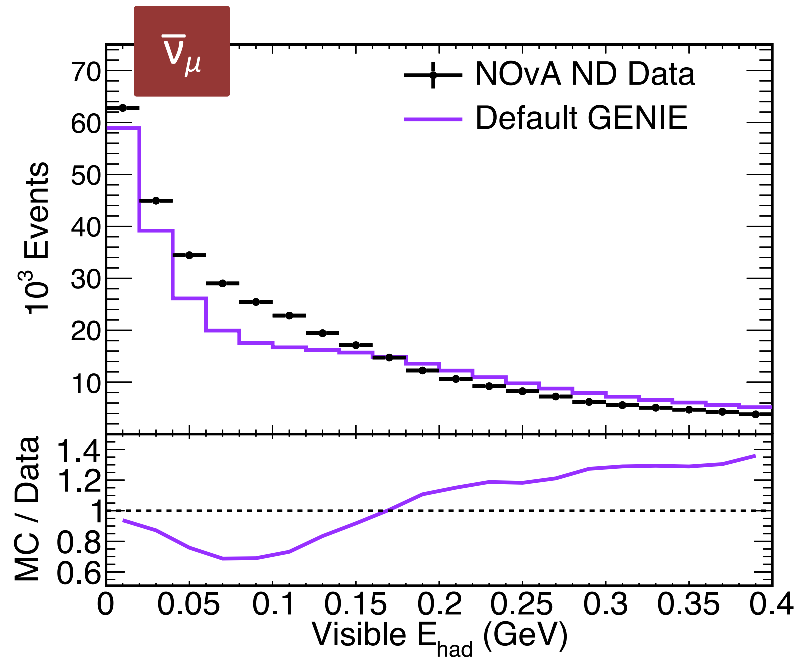


Questions

Backups

NOvA Neutrino Interaction Tune

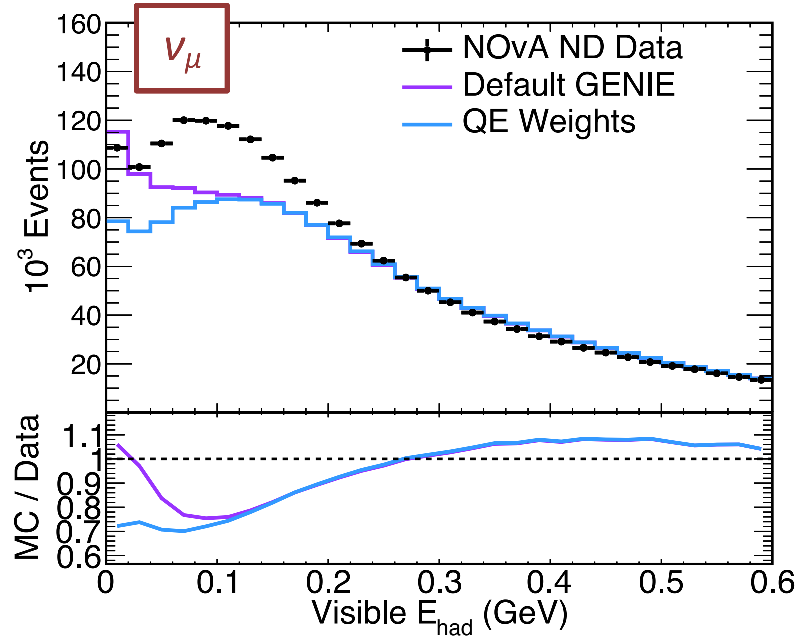


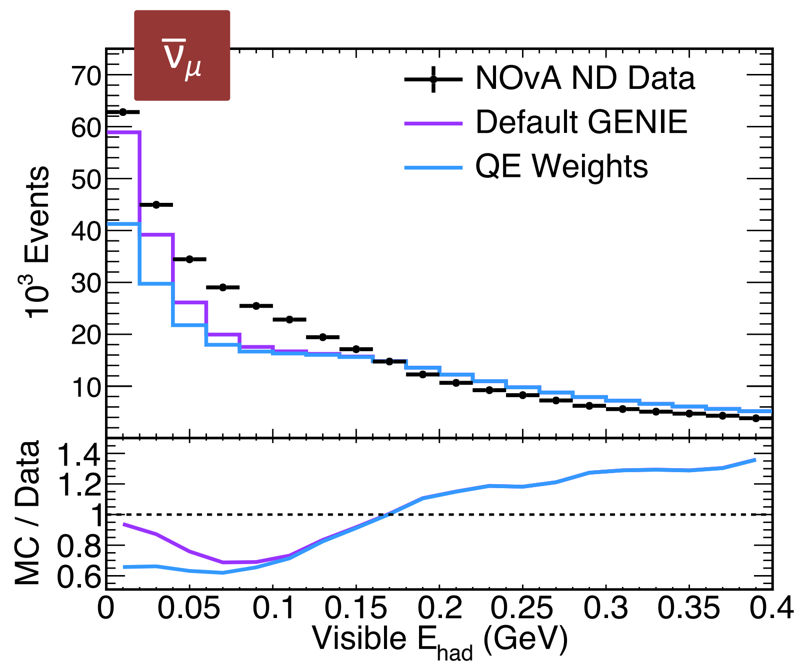


NOvA Neutrino Interaction Tune

From **external theory**:

- Valencia RPA model† of nuclear charge screening applied to QE.





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

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

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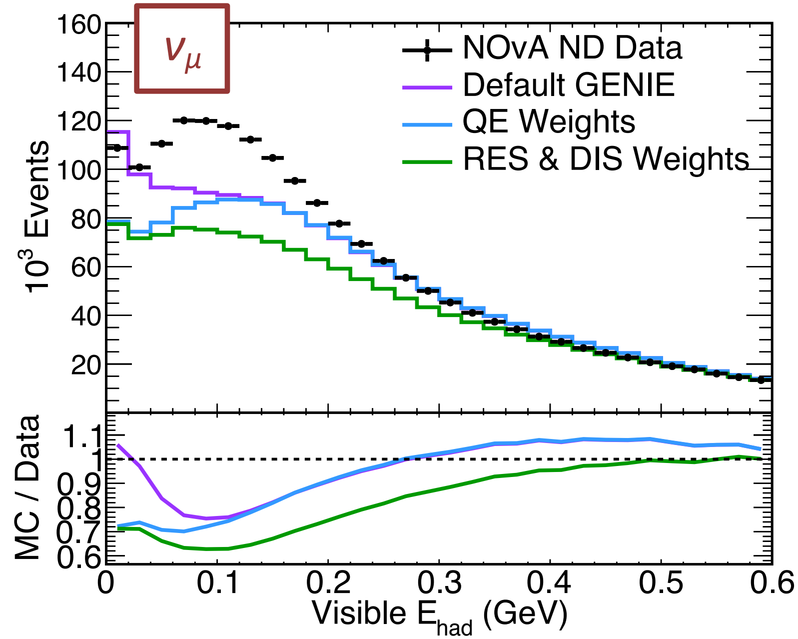
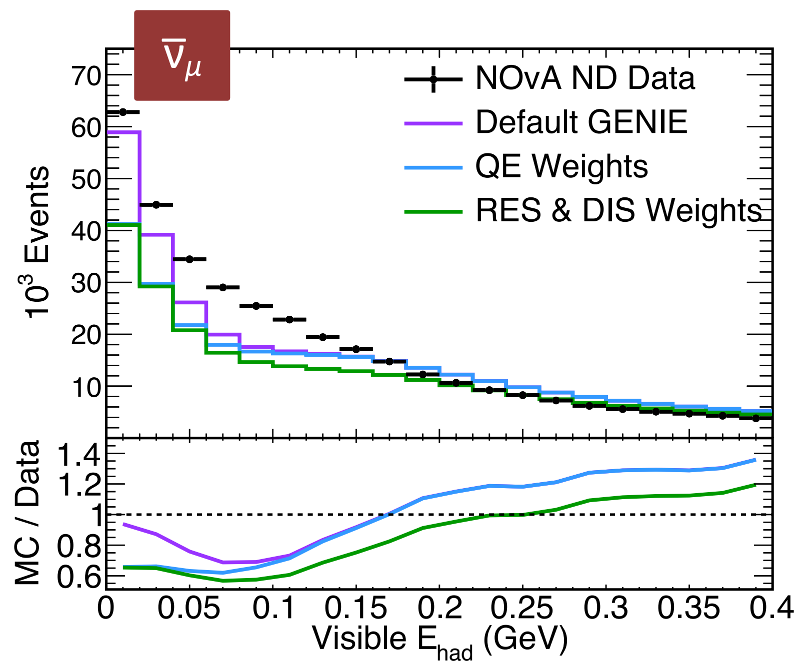
- Same model applied to resonance.

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.





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NOvA Neutrino Interaction Tune

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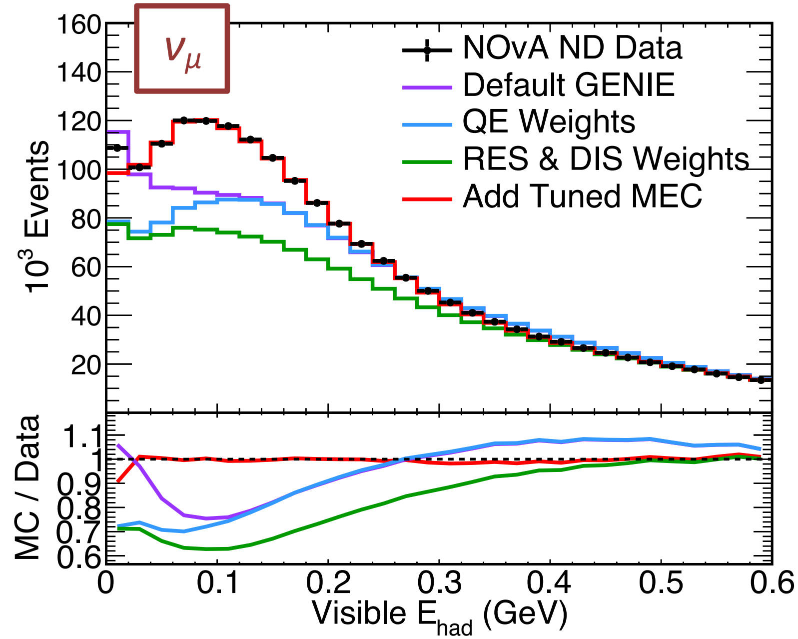
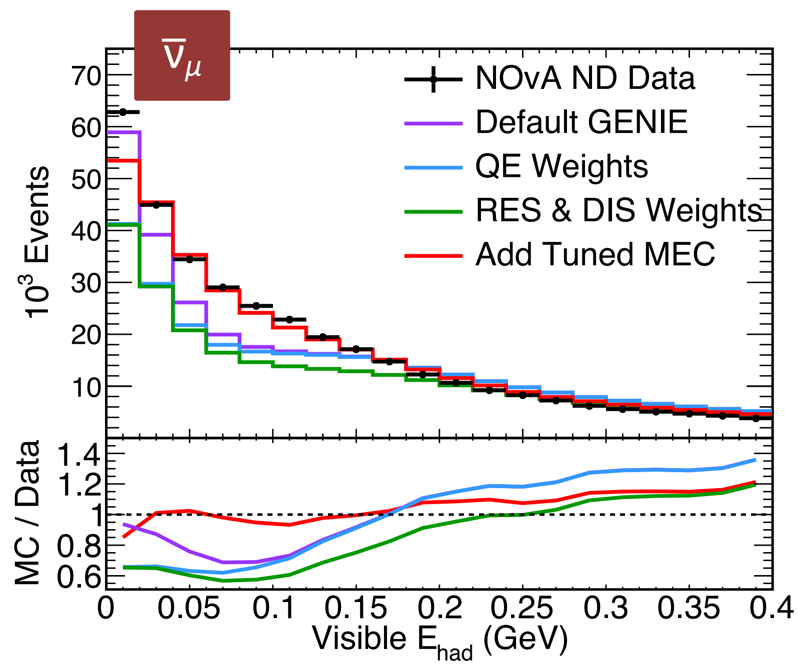
- Valencia RPA model† of nuclear charge screening applied to QE.
- Same model applied to resonance.

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.
- Add MEC interactions
  - Start from Empirical MEC*
  - Retune in $(q_0, |\boldsymbol{q}|)$ to match ND data
  - Tune separately for $\nu / \bar{\nu}$





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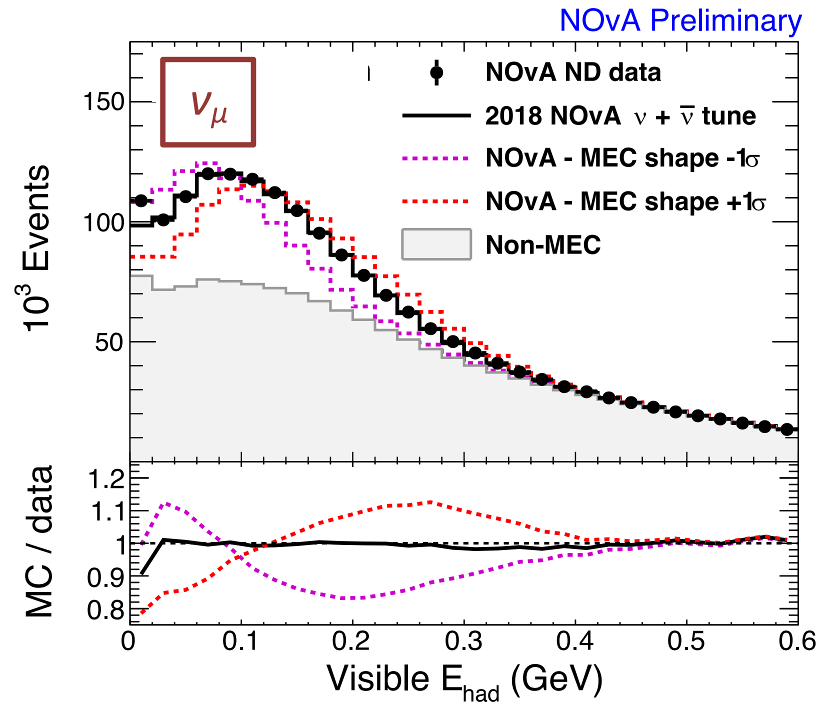
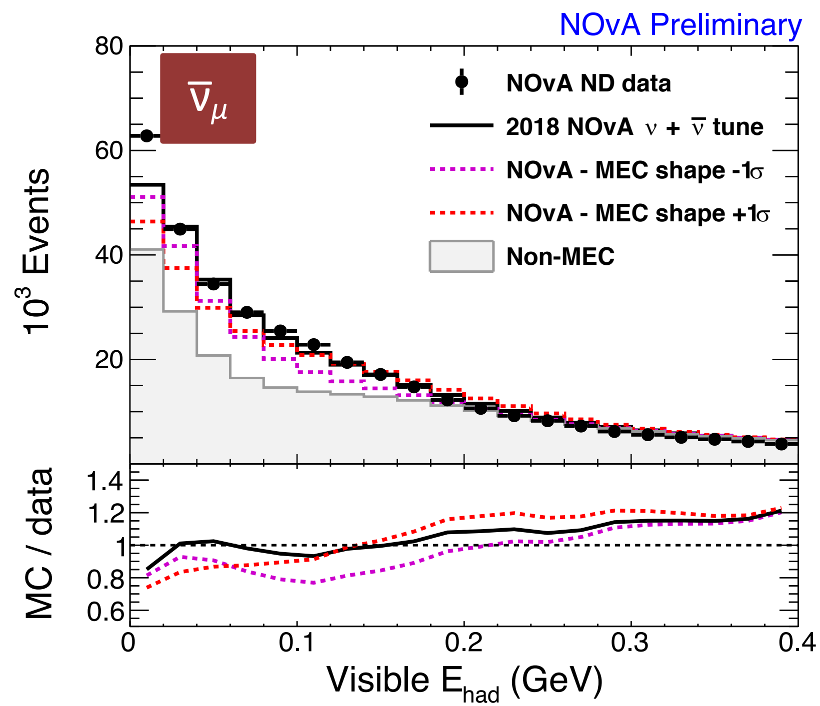
MEC Uncertainties

- We also determine uncertainties on the MEC component we introduce.
  - Both on shape and total rate.
- Repeat the tuning procedure with shifts in the Genie model.
  - Turn Genie systematic knobs coherently to push the non-MEC x-sec more QE-like or more RES-like.





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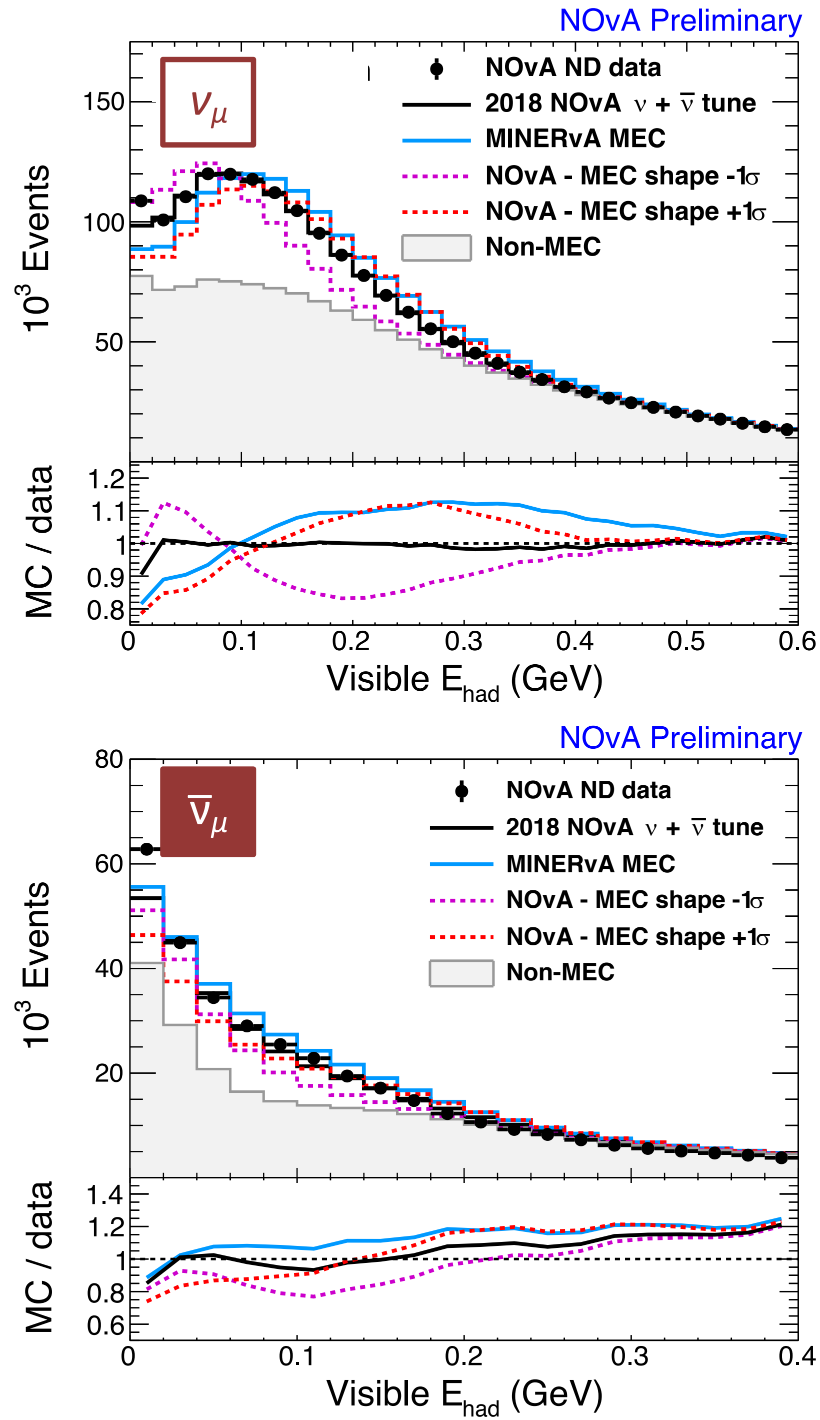
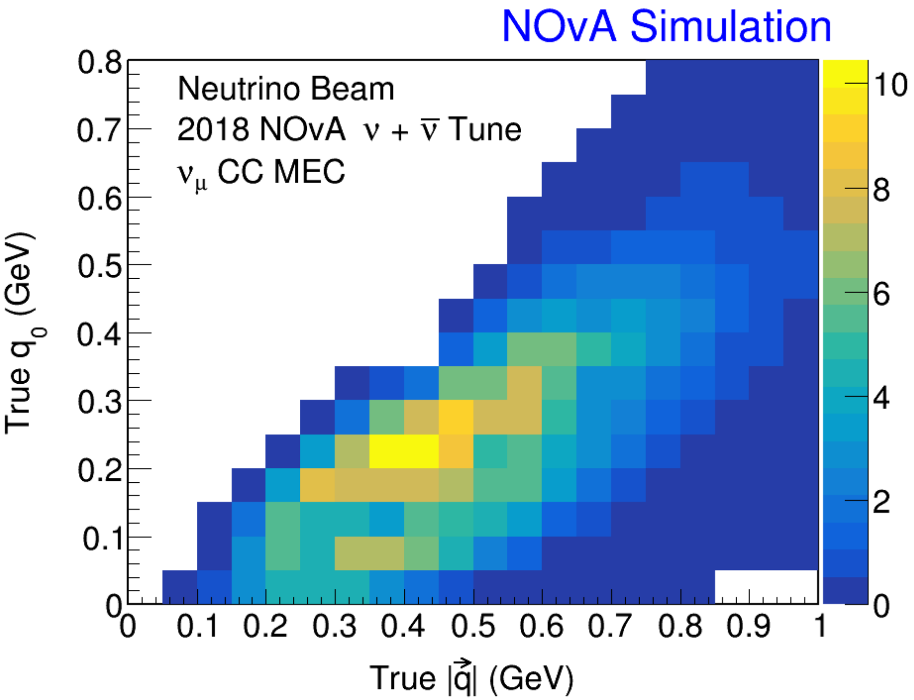
- Repeat the tuning procedure with shifts in the Genie model.
  - Turn Genie systematic knobs coherently to push the non-MEC x-sec more QE-like or more RES-like.
- Independently, **Minerva*** has also tuned a multi-nucleon component to their data.
- The resulting tune is ~1σ away from the NOvA tune.

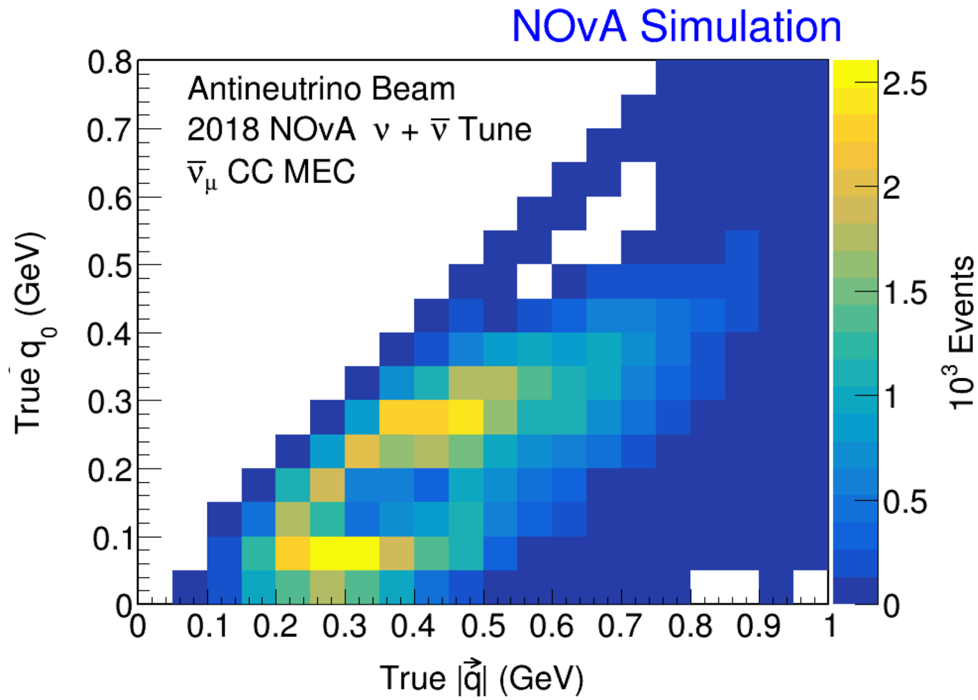


* Minerva, Phys. Rev. Lett. 116, 071802 (2016)

Minerva, Phys. Rev. Lett. 120, 221805 (2018)

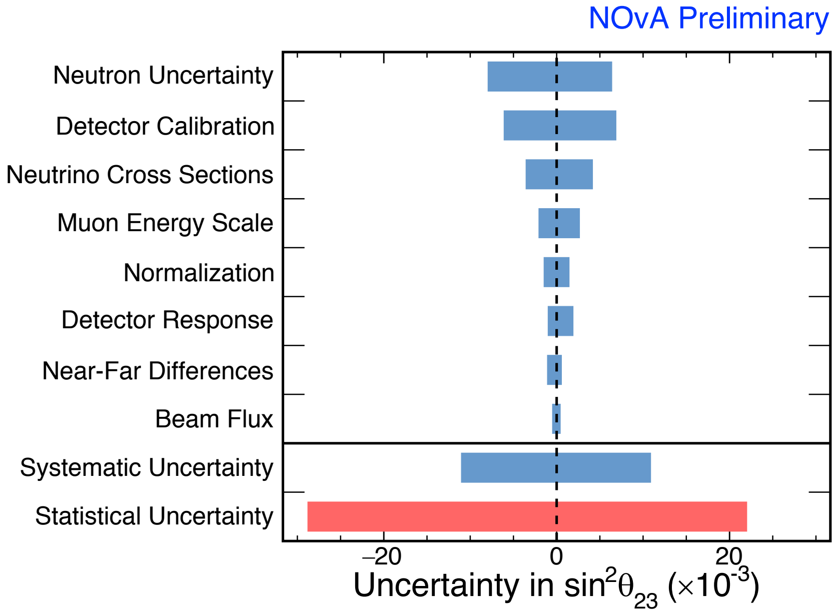
MEC Neutrino vs. Antineutrino

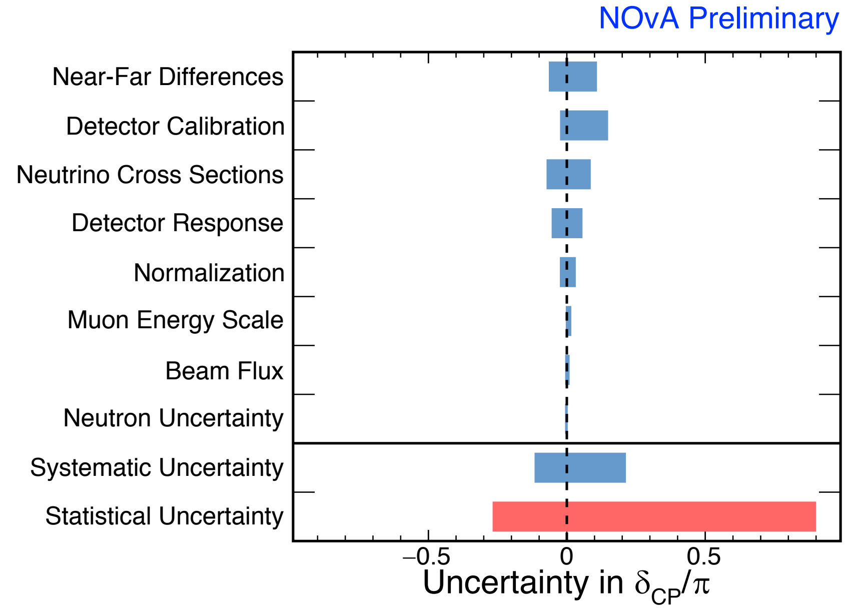


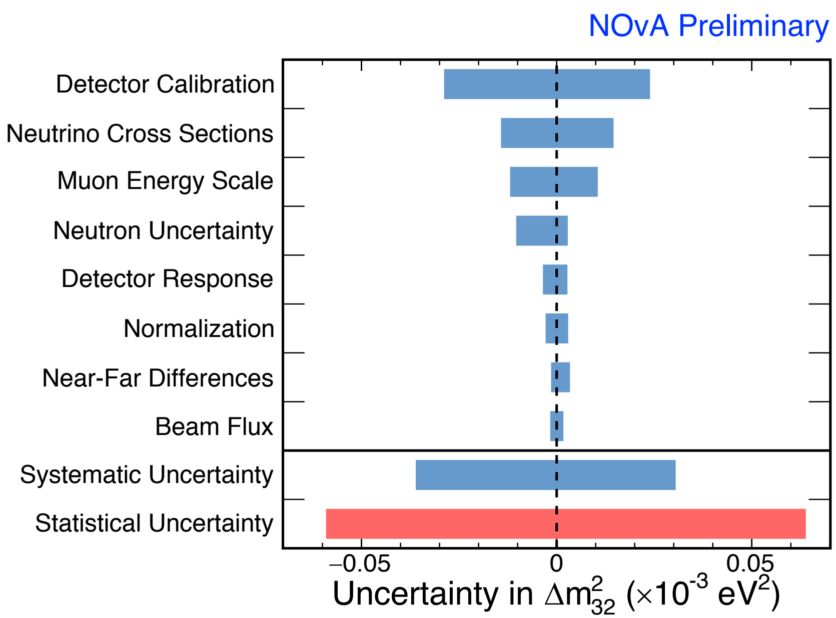


- Separate tuning and *uncertainty*.
  - Did not want to pre-suppose correlation given the uncertain underlying model.
  - Separate uncertainties leads to larger overall systematic.
- Shapes are similar qualitatively, though they are not identical.
  - 2-peak structure, shift to lower q_0

Systematic Uncertainties



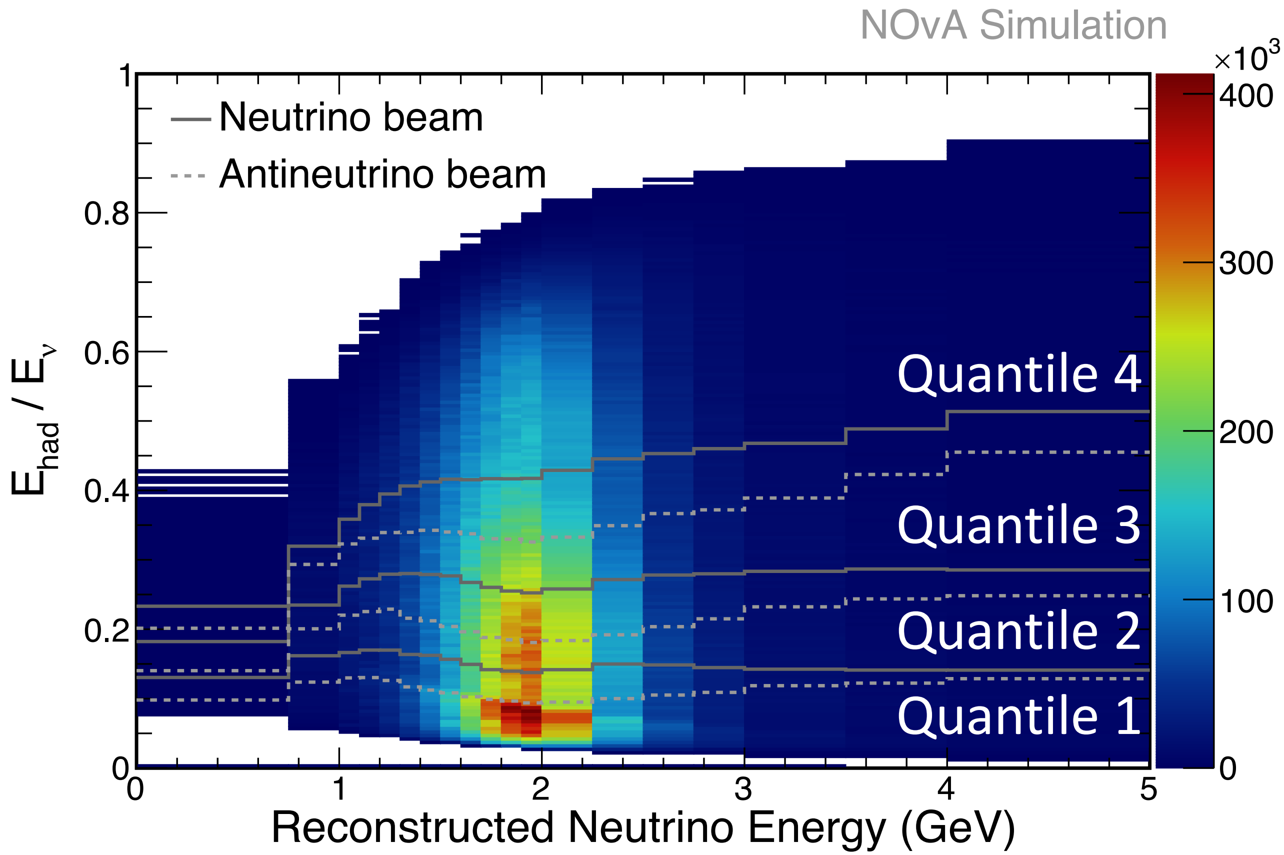




Most important systematics:

- Detector Calibration
  - Will be improved by the 2019 test beam program
- Neutrino cross sections
  - Particularly nuclear effects (RPA, MEC)
- Muon energy scale
- Neutron uncertainty – **new** with $\bar{\nu}$'s

Binning for Sensitivity: ν_μ Events



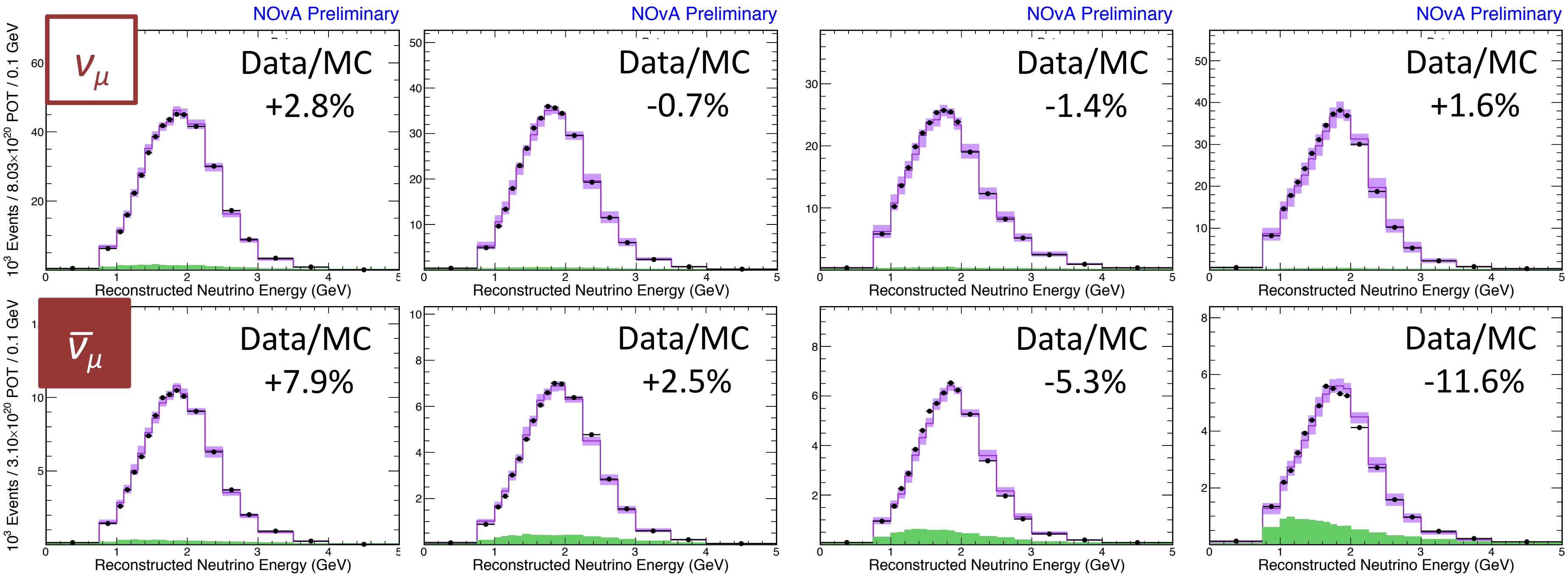
- Oscillation sensitivity depends on spectrum shape
- Improve sensitivity by separating high-resolution and low-resolution events.
- Split into 4 quantiles by hadronic energy fraction.
  - Muon energy resolution (3%) is much better than hadronic energy resolution (30%).

Binning for Sensitivity: ν_μ Events

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

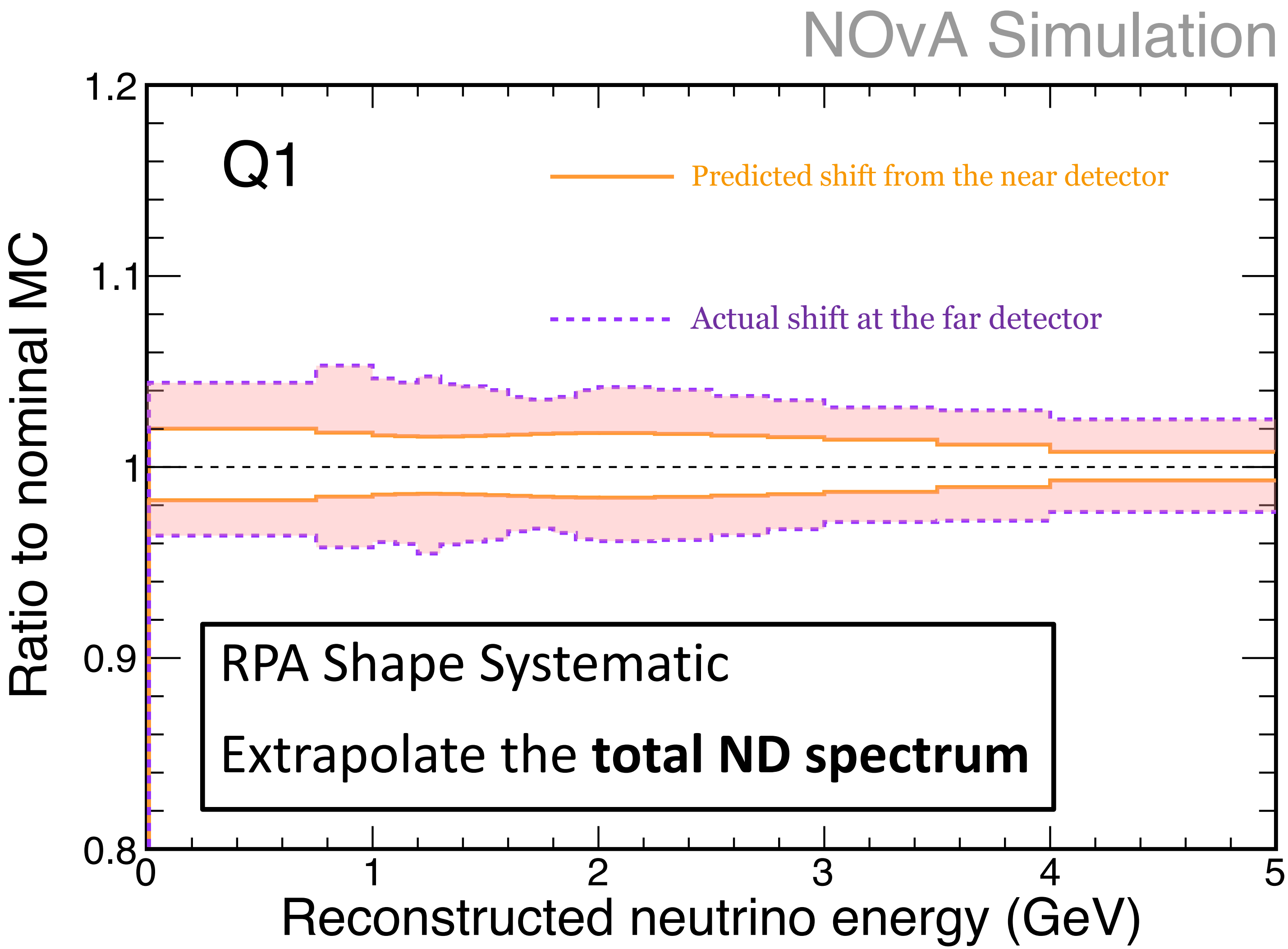
Quantile 1
Best Resolution ~6%

Quantile 4
Worst Resolution ~12%

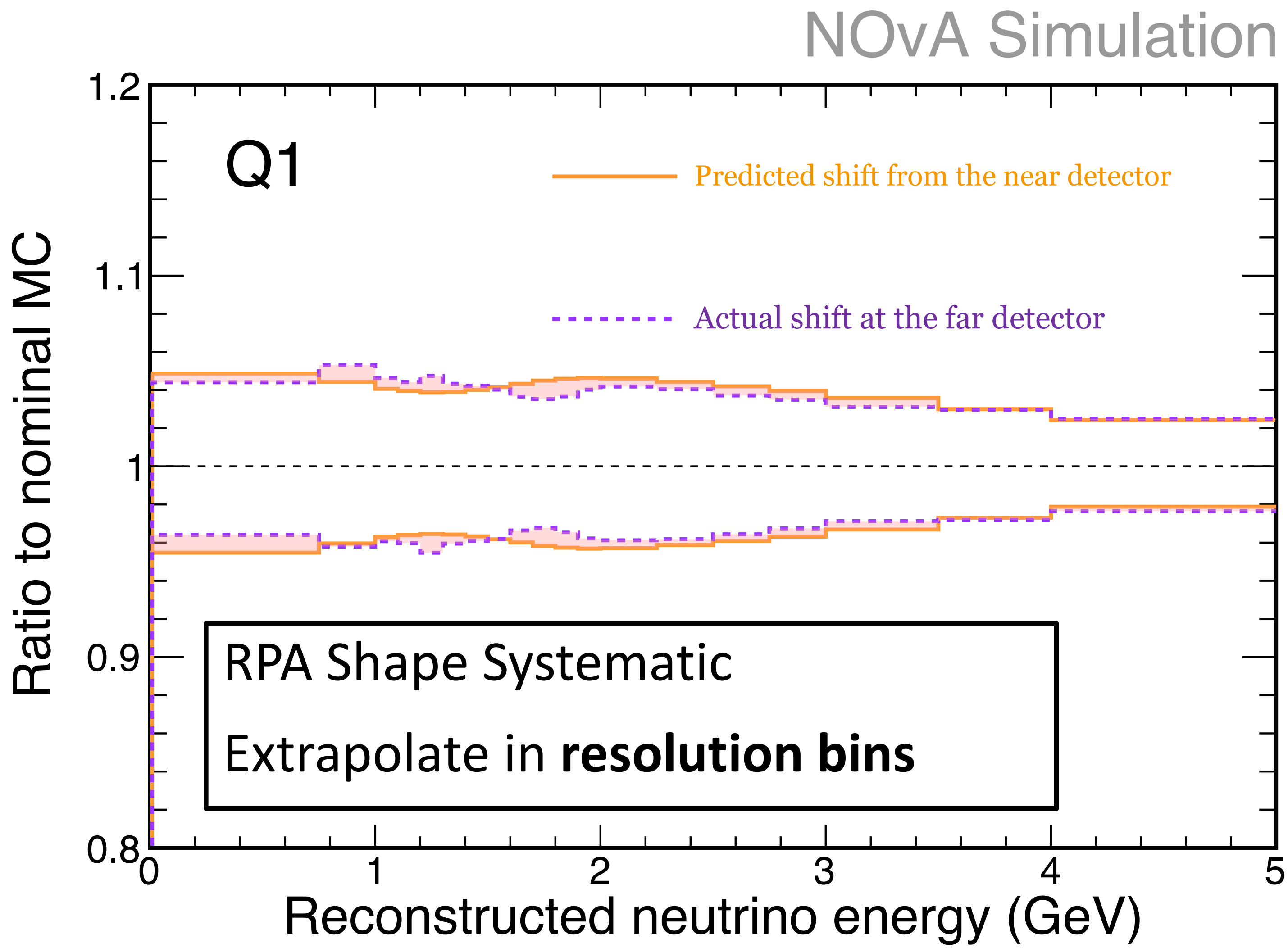


- Data-MC shape agreement good within each quantile.
- By extrapolating each separately, we transport kinematic differences between data and simulation to the FD.
  - Can see this in the different normalizations applied to each quantile.

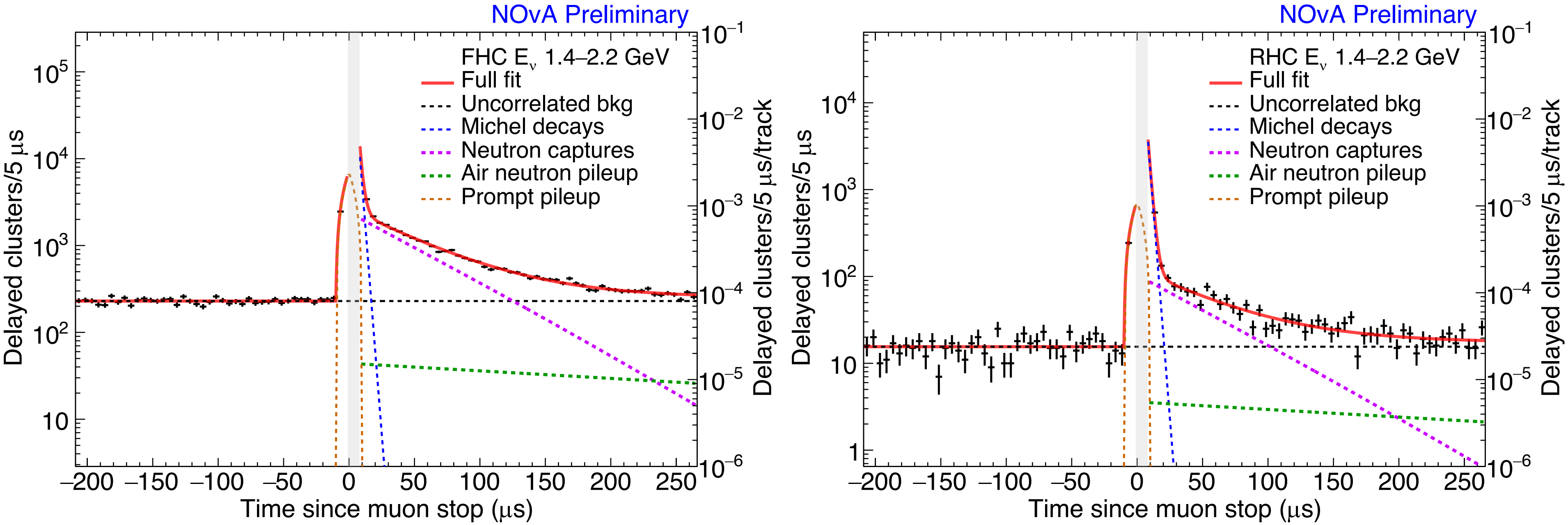
Extrapolation with Resolution Bins



Extrapolation with Resolution Bins



Wrong-sign Constraint with Neutron Capture



- Look for delayed clusters of hits following stopping muons.
- Fit the various time components to measure the rate of neutron captures in bins of neutrino energy.
- Then fit the neutron captures vs. reconstructed energy to extract the number of ν_μ CC and NC events in the neutrino and antineutrino beams.

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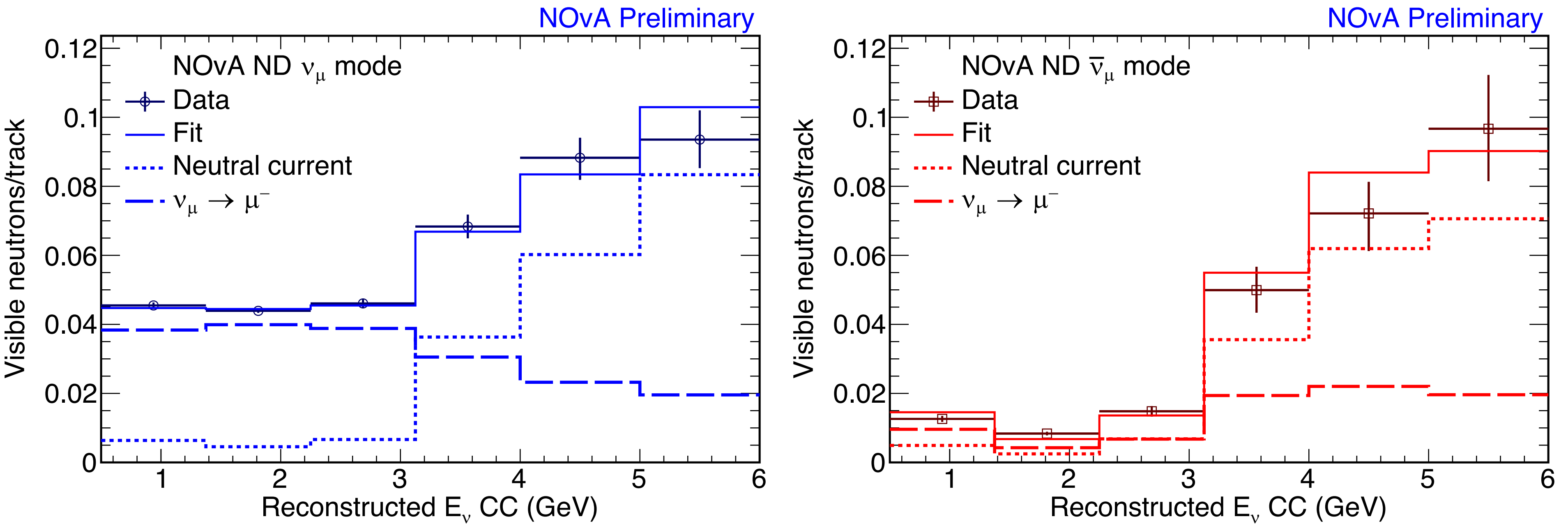

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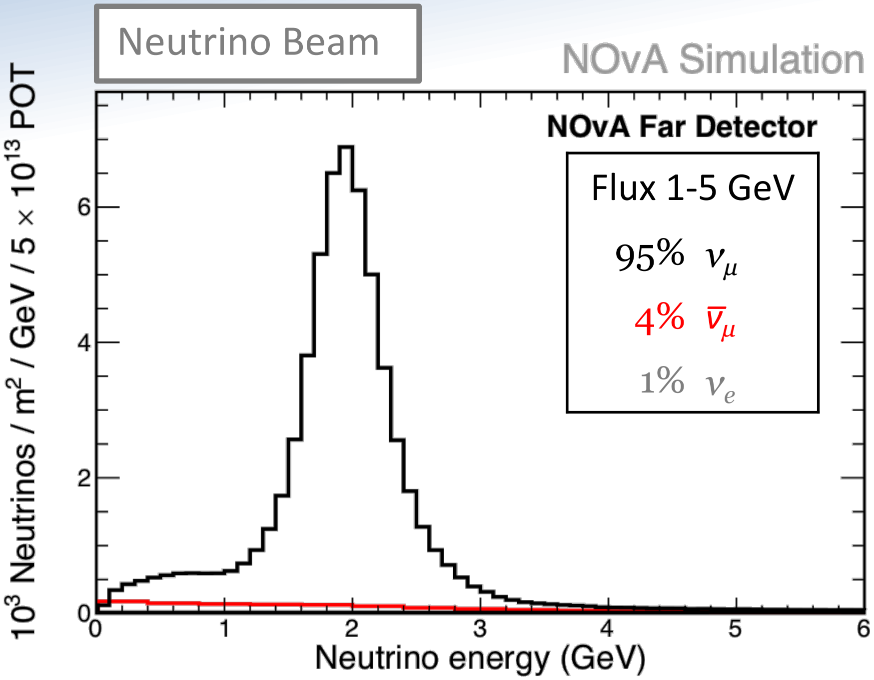
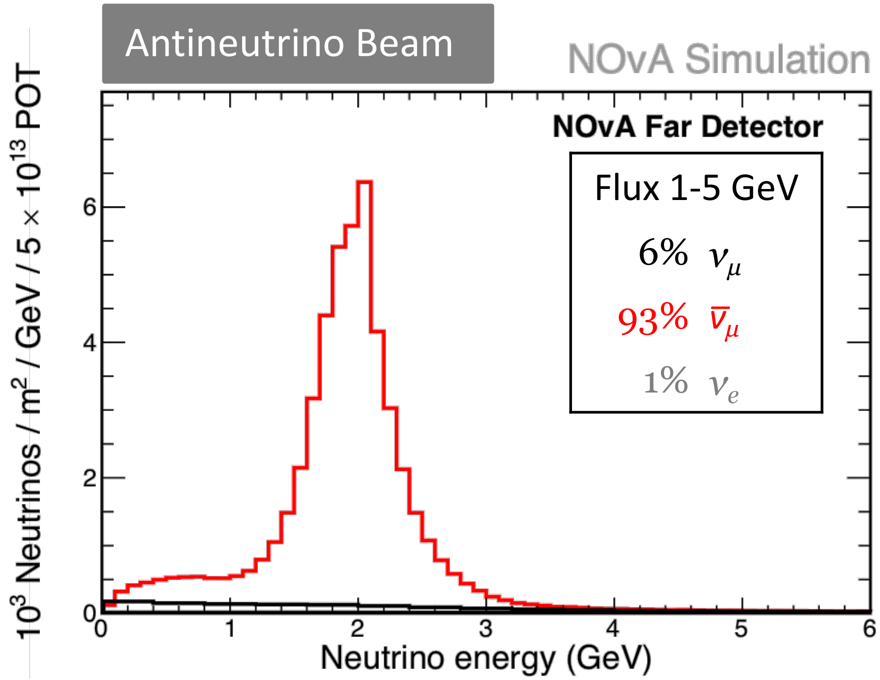
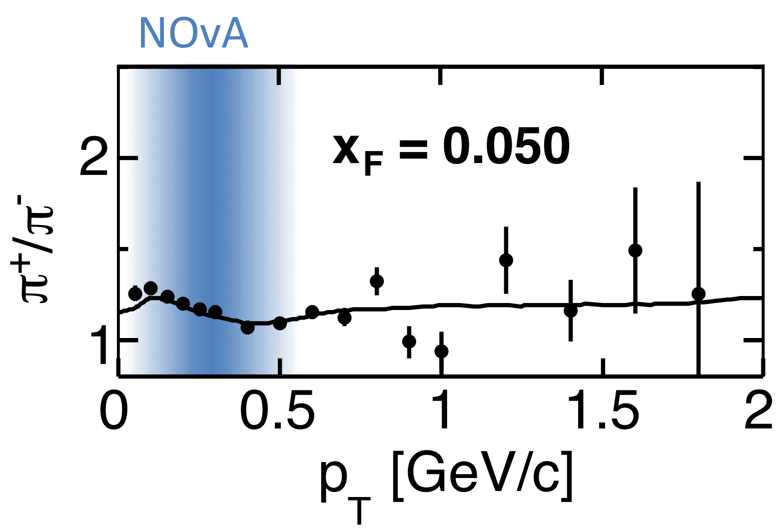
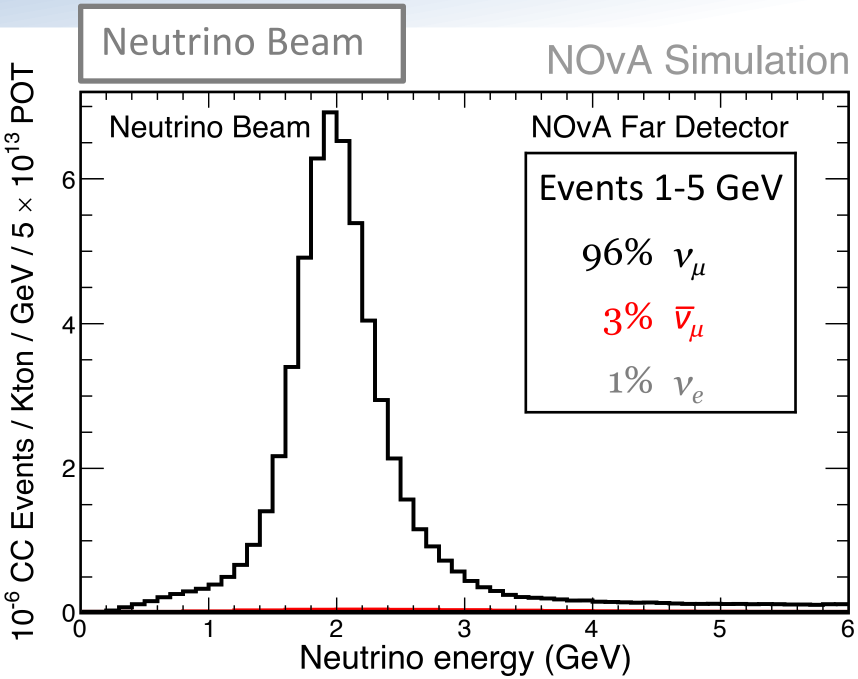


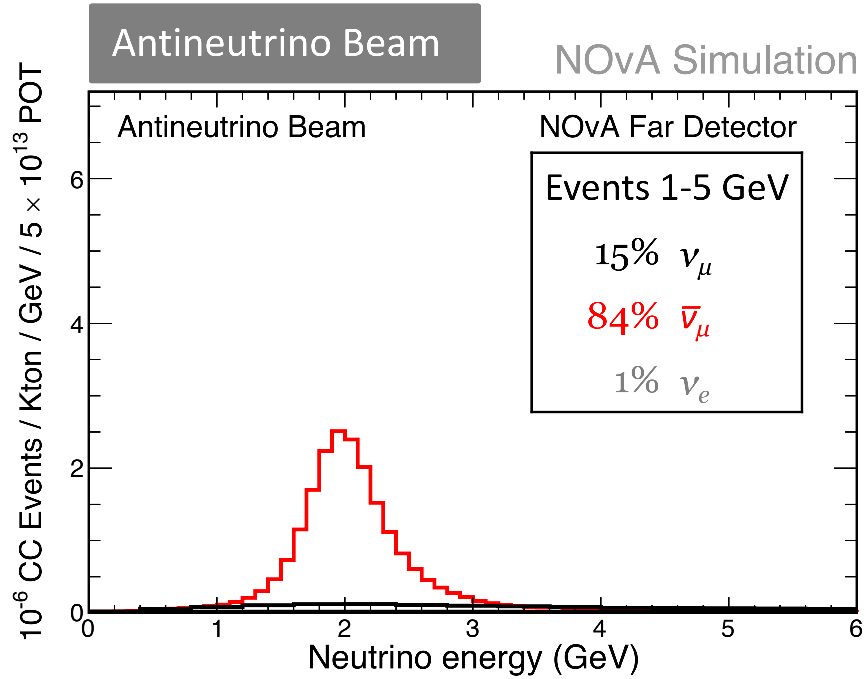


- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
  - p^+ colliding with p^+ and n^0 in the target
- *Wrong-sign*: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign.
  - WS primarily would primarily come from the unfocused high-energy tail.

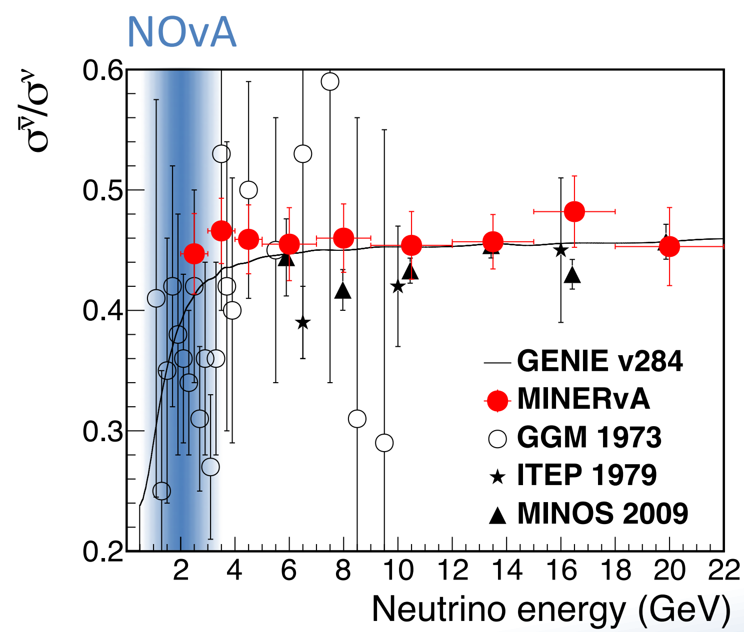


NA49, Eur. Phys. J. C 49 897 (2007)





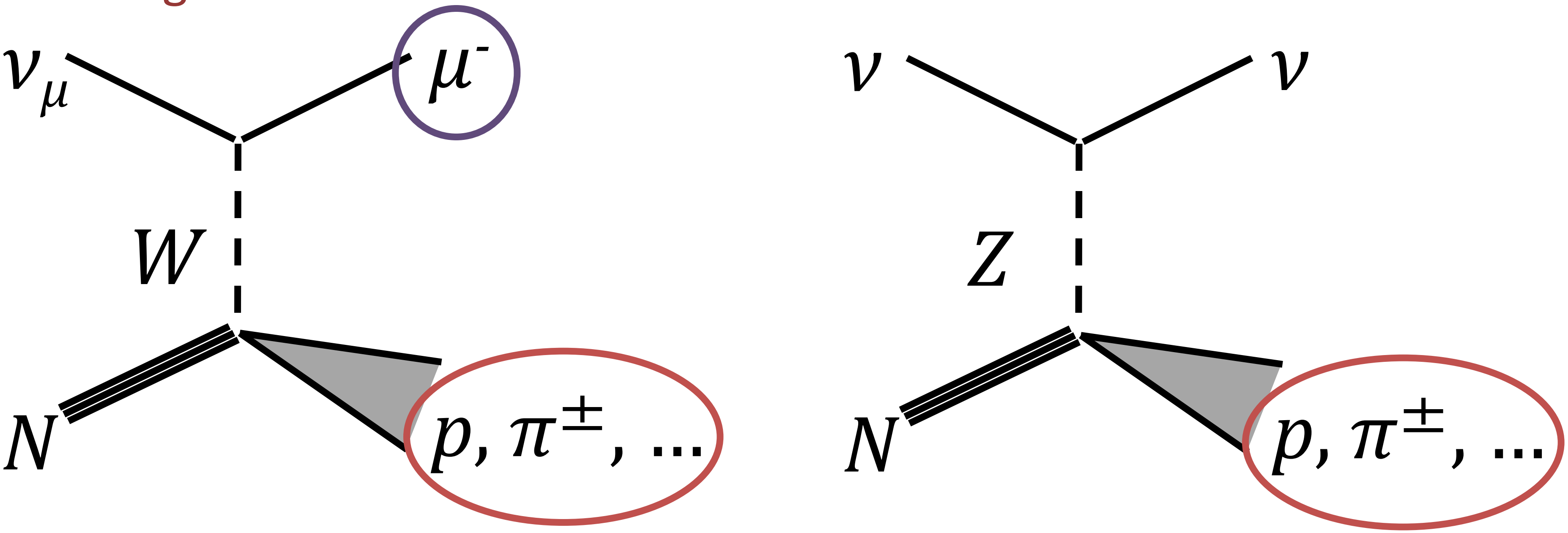
- The big difference is in the interaction: the cross section for antineutrinos is **~2.8 times lower** than for neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.
  - Lower kinematic *y*
  - More forward-going



MINERvA, Phys.Rev. D95 (2017) no.7, 072009

How to Detect a Neutrino

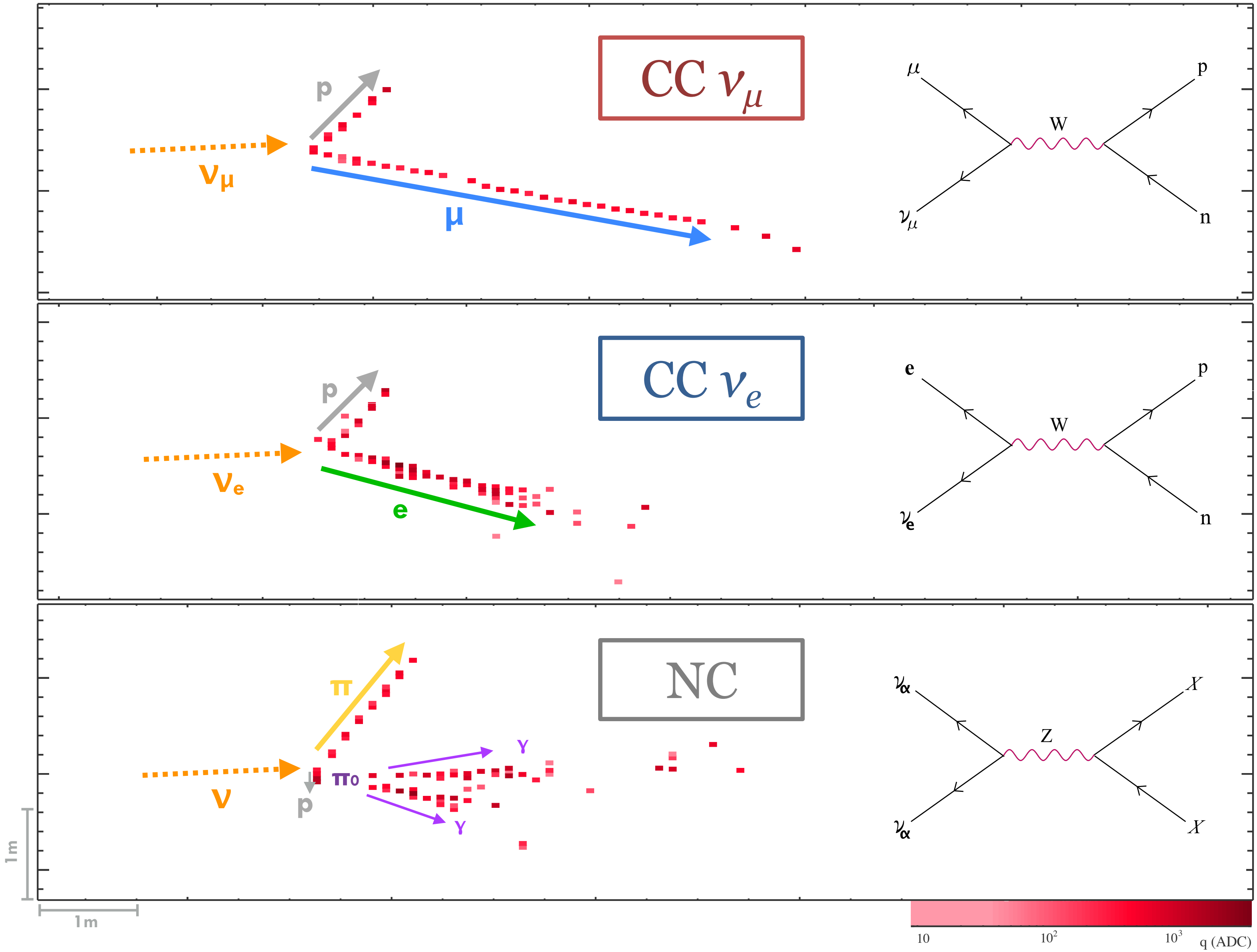
Charged Current — Neutral Current



- Observe the charged particles after a neutrino interacts with a nucleus:

- Lepton
  - CC $\nu_\mu \rightarrow \mu^-$, CC $\nu_e \rightarrow e^-$
  - NC → no visible lepton
- Hadronic shower
  - Neutrinos typically produce a proton
  - Antineutrinos typically produce a neutron
  - May one or more $\pi^\pm$, additional p, n, etc.
  - May also contain EM from $\pi^0 \rightarrow \gamma\gamma$

Neutrino Candidates from ND Data

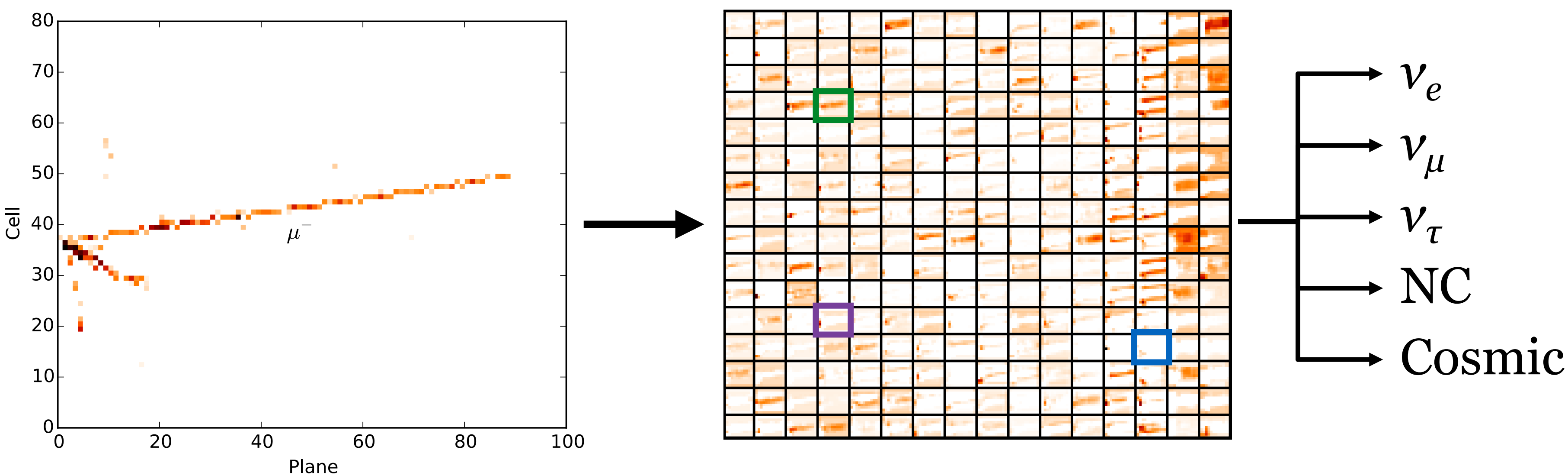


Selecting ν_e's and ν_μ's with Computer Vision

Input Image

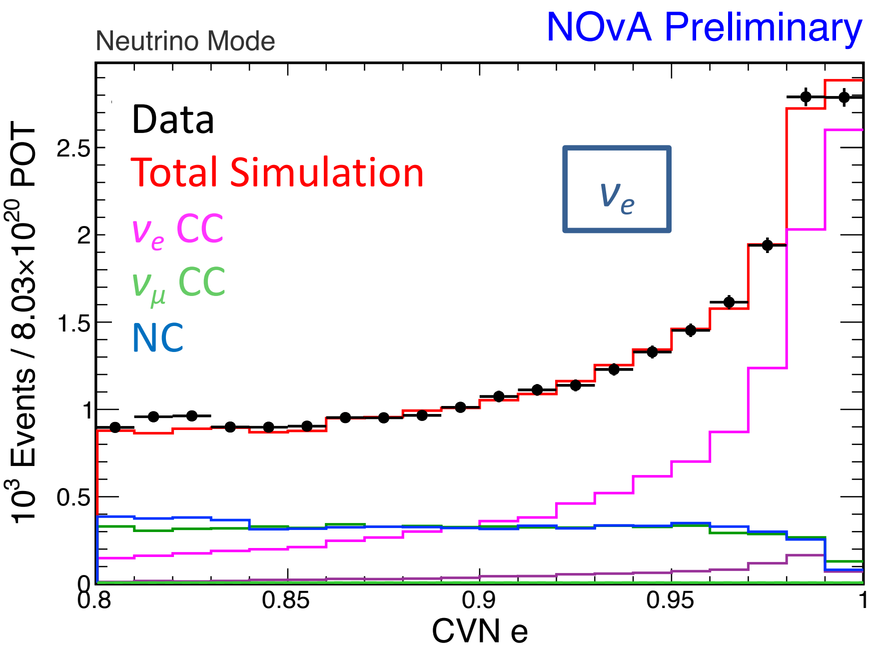
256 Feature Maps

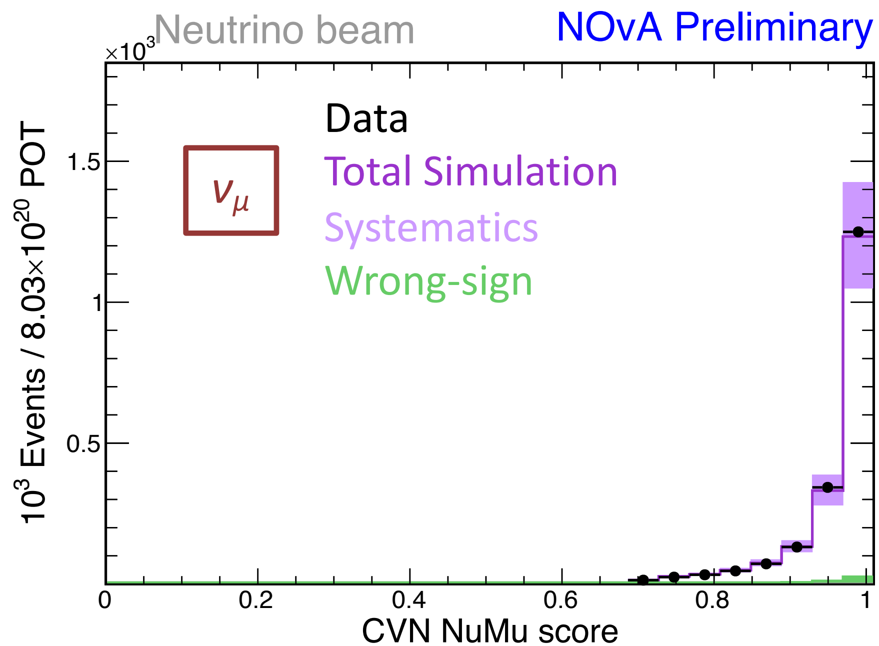
Learned variations on the original image



- We use a *convolutional neural network* based on the GoogLeNet.
  - Successive layers of "feature maps" create variants of the original image which enhance different features at growing levels of abstraction.
- Multi-label classifier – the same network used in multiple analyses.

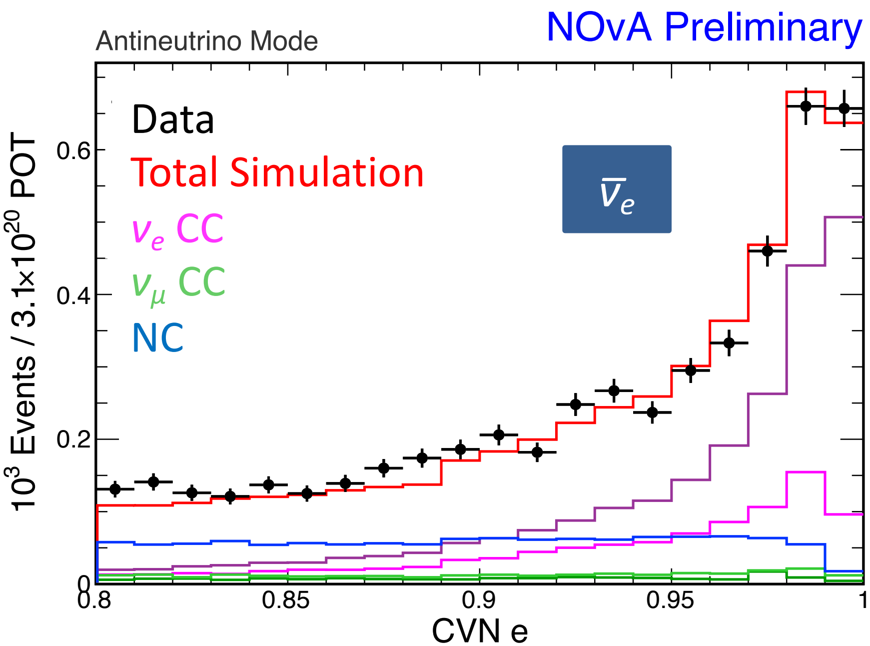
A. Aurisano and A. Radovic and D. Rocco et. al,
JINST **11** P09001 (2016)

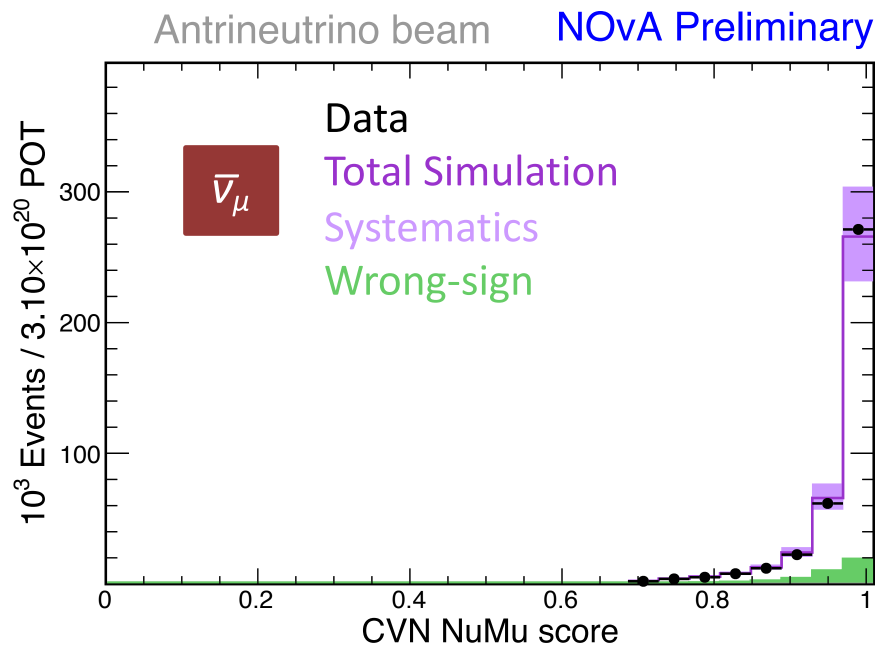




New for this analysis:

- A shorter, simpler architecture trained on updated simulation.
- Replaced Genie truth labels with final state labels.
  - Exploring using final states with protons to constrain WS backgrounds.
- Separate training for the neutrino and antineutrino beams.
  - Wrong-sign treated as signal in training.
  - 14% better efficiency for $\bar{\nu}_e$ with a dedicated network.





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