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Queen Mary
University of London

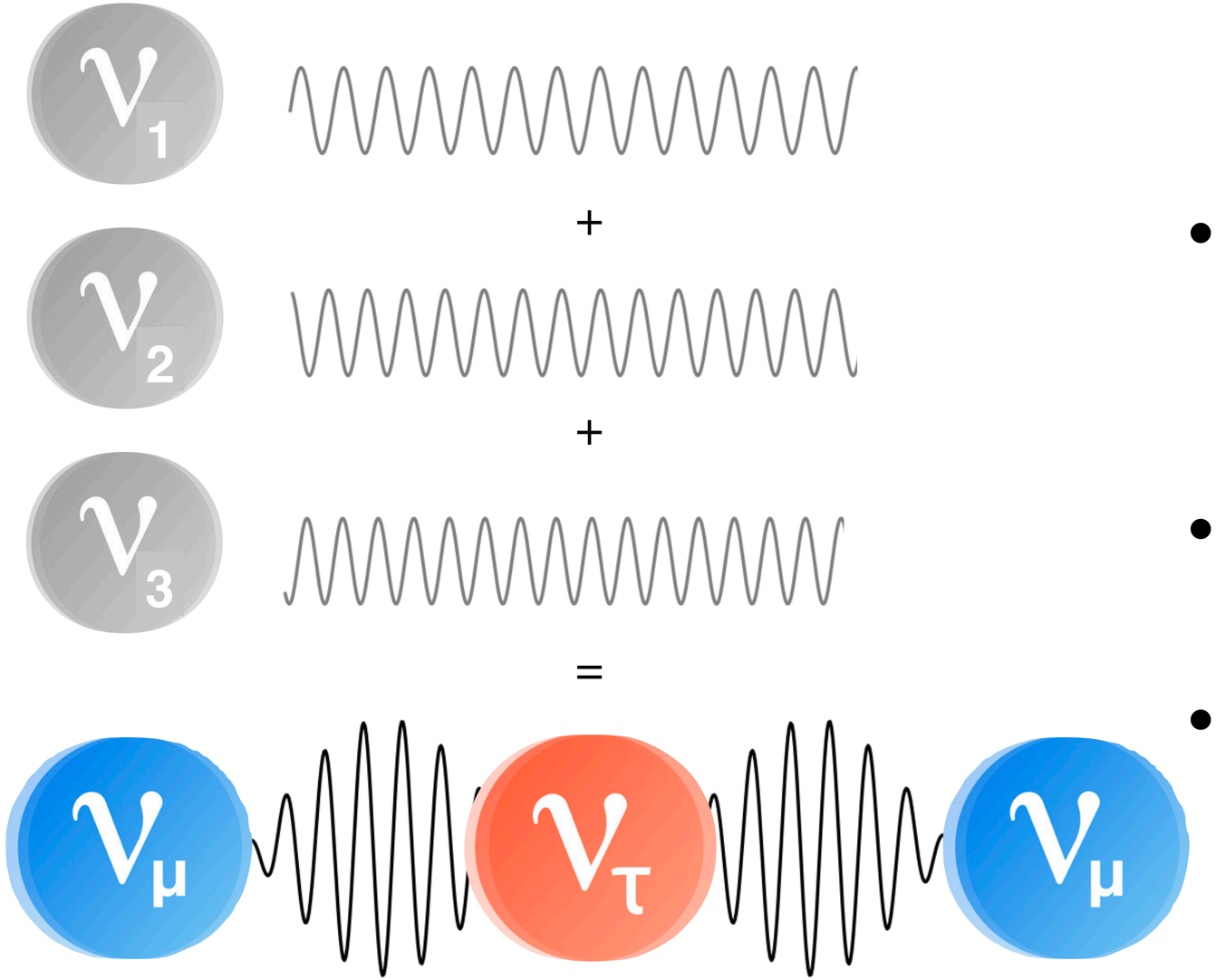
Physics of Neutrino Oscillations and Neutrino Cross Sections using the NOvA Experiment

Prabhjot Singh, on behalf of the NOvA Collaboration

Users Meeting 2023, Fermilab

30 June 2023

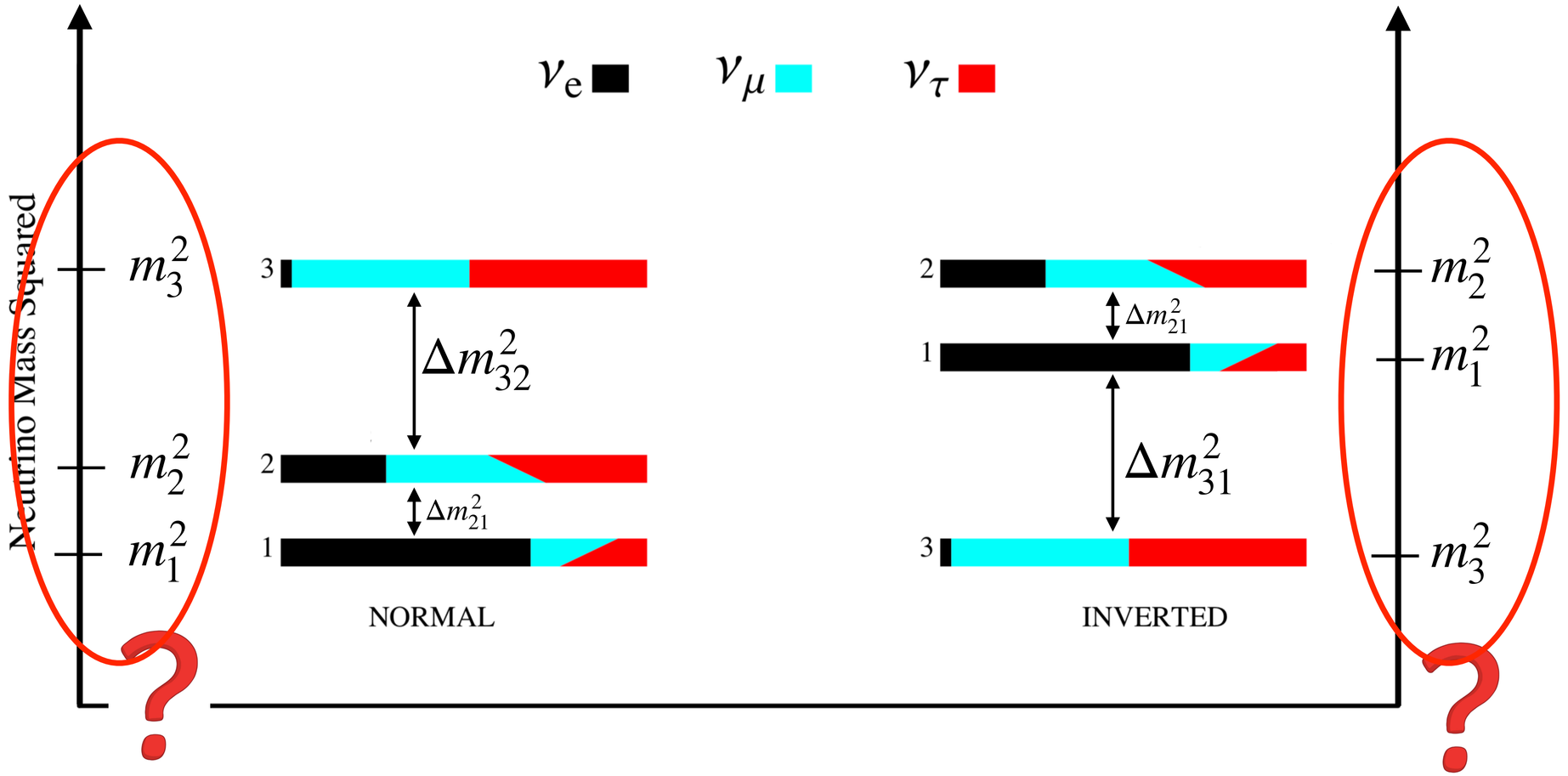
Neutrino Oscillations



- Neutrino flavor states (ν_e , ν_μ and ν_τ) are superposition states of mass states (ν_1 , ν_2 and ν_3)
- Neutrinos oscillate between different flavors
- Oscillations imply non-zero masses of neutrinos

Open Questions

- Ordering of neutrino masses: sign of $|\Delta m^2_{32}|$?



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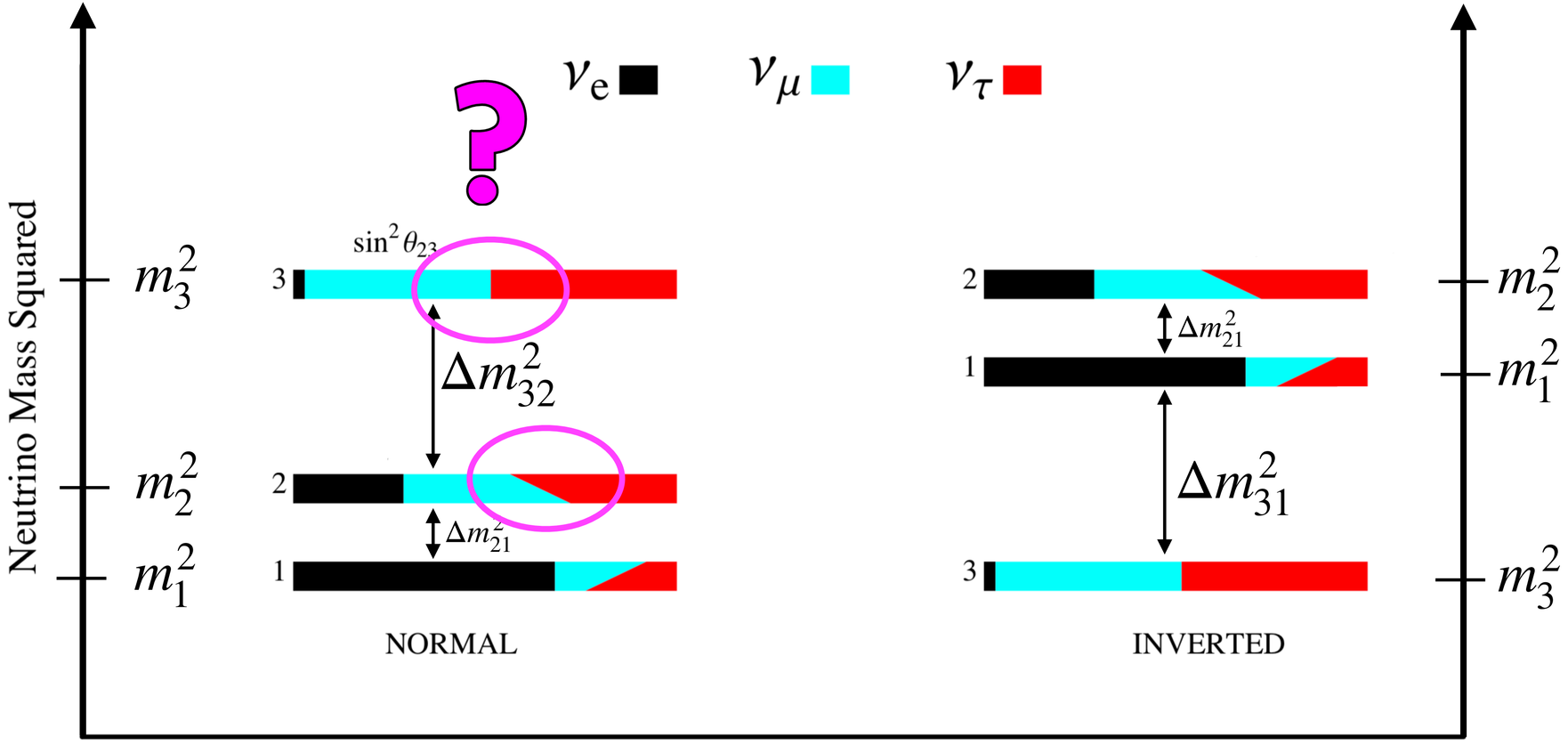
- Maximal or non-maximal $\nu_\mu - \nu_\tau$ mixing?



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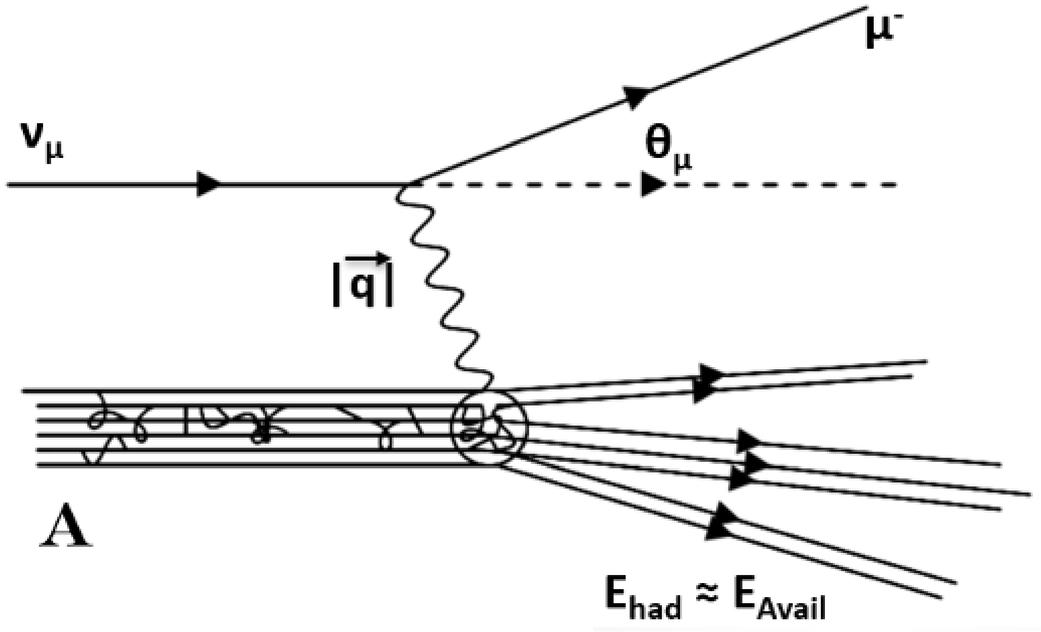
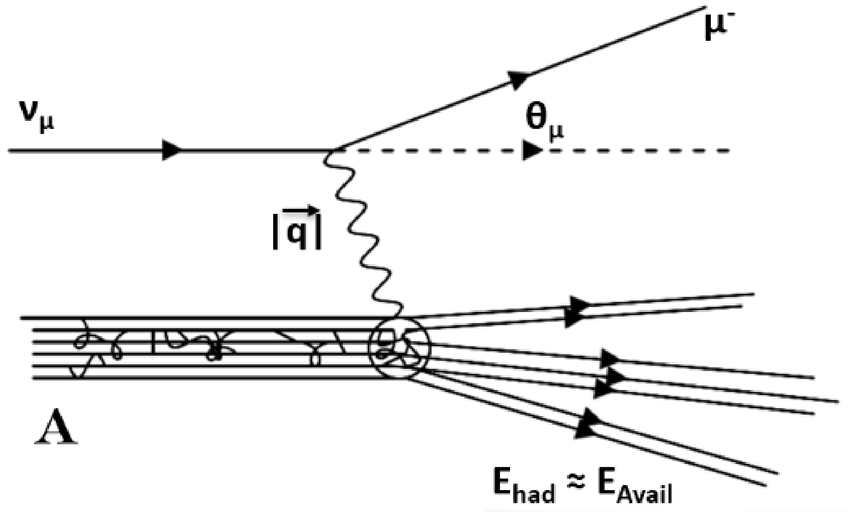
- Nuclear effects on the neutrino-nucleus interactions



In this Talk



Cross-section measurements
- nuclear effects, e.g. 2p2h/MEC interactions

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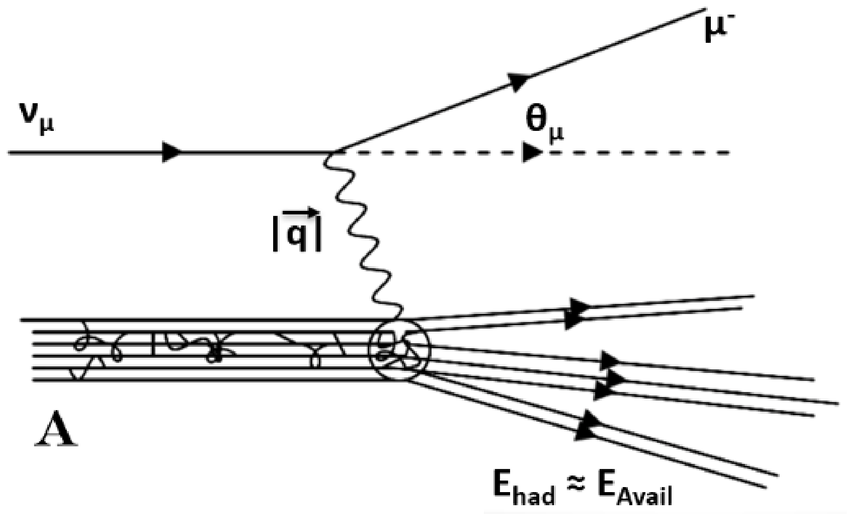

Cross-section measurements
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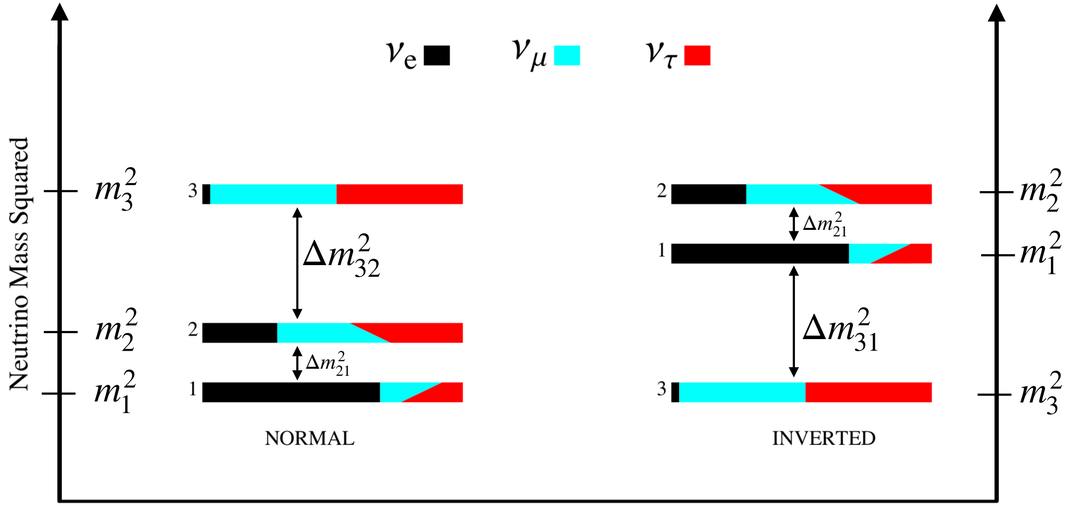


- 3-flavor oscillation results
  - Markov Chain MC bayesian analysis

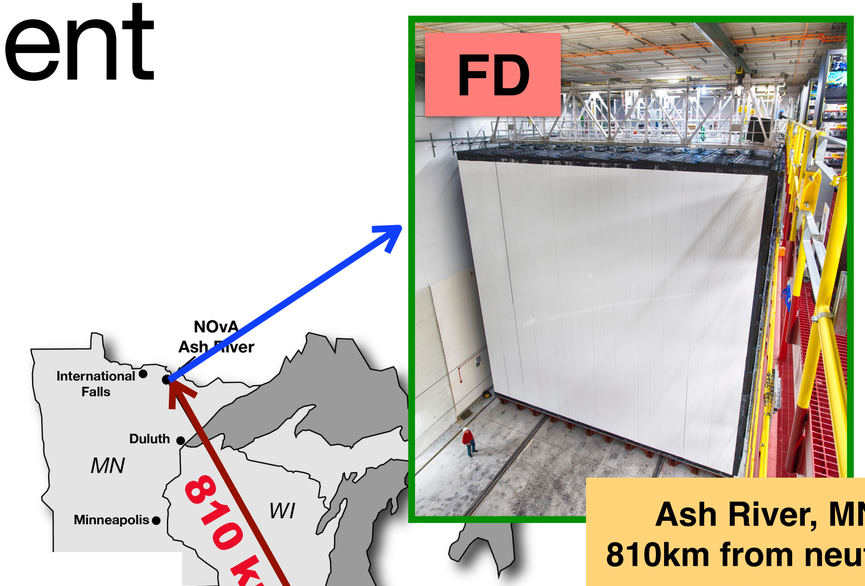
NOvA Experiment

The NOvA Collaboration

> 240 people, ~ 50 institutions, 7 countries

NOvA Experiment

- NOvA is a long-baseline two-detector neutrino oscillation experiment



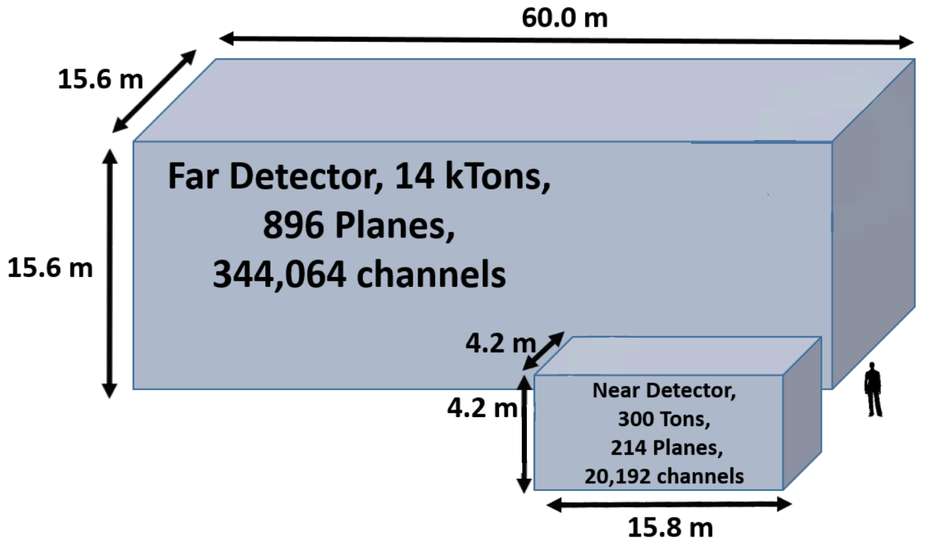
Ash River, MN, 810km from neutrino source

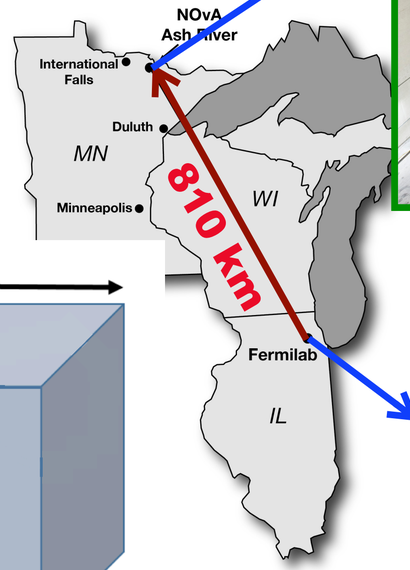
1 km from neutrino source

NOvA Experiment

- NOvA is a long-baseline two-detector neutrino oscillation experiment

- Both detectors filled with liquid scintillator and composed of 77% CH_2, 16% chlorine, 6% TiO_2 by mass





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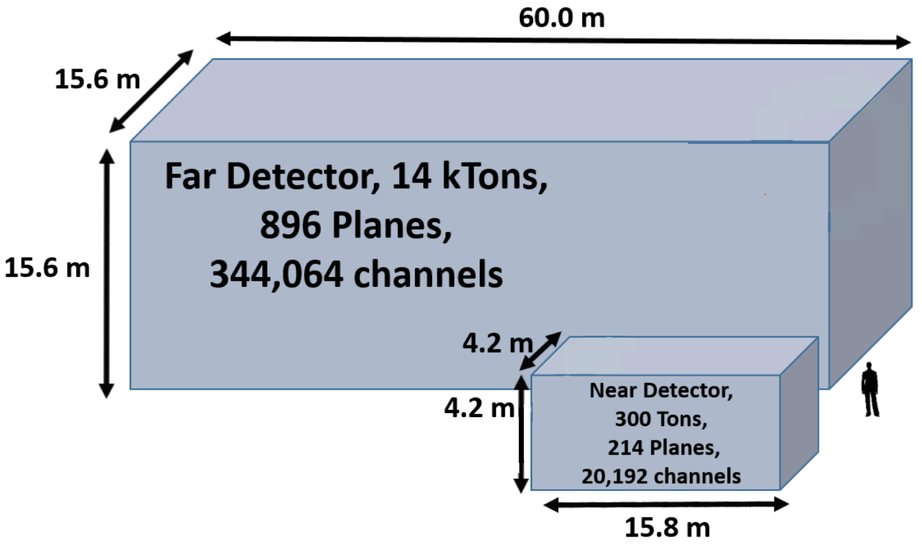
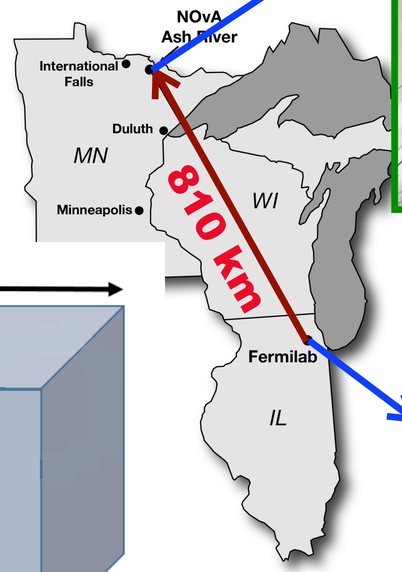
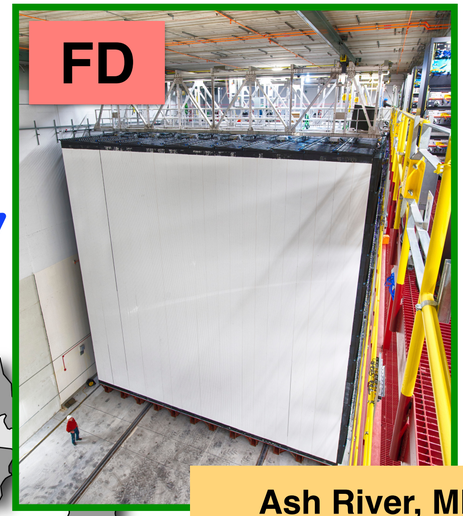
NOvA Experiment

- NOvA is a long-baseline two-detector neutrino oscillation experiment
- Both detectors filled with liquid scintillator and composed of 77% CH_2, 16% chlorine, 6% TiO_2 by mass
- 14.6 mrad off-axis detectors
- Neutrino beam peaks at 2 GeV
- Functionally identical detectors to reduce systematic uncertainties



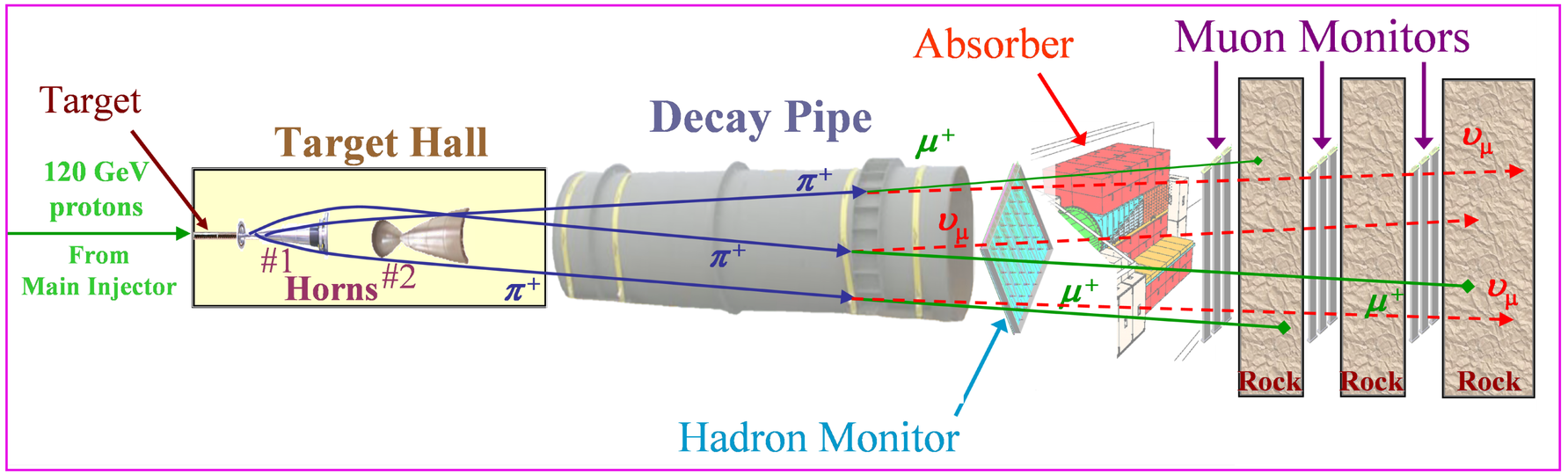




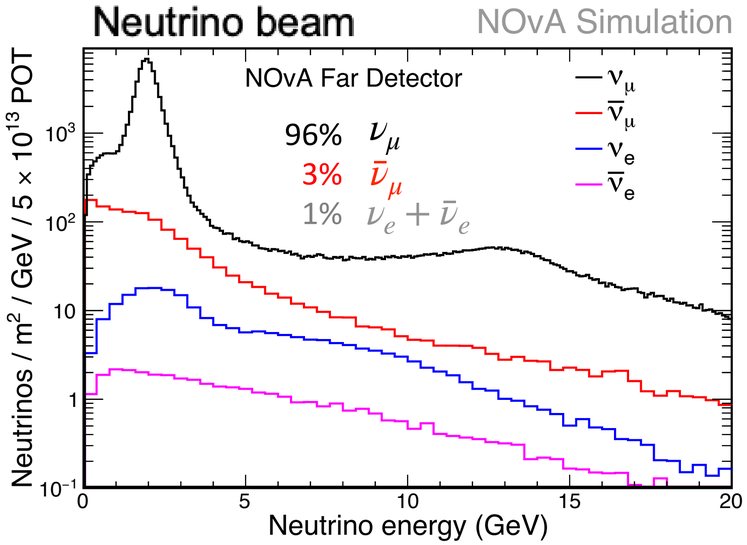
Ash River, MN, 810km from neutrino source

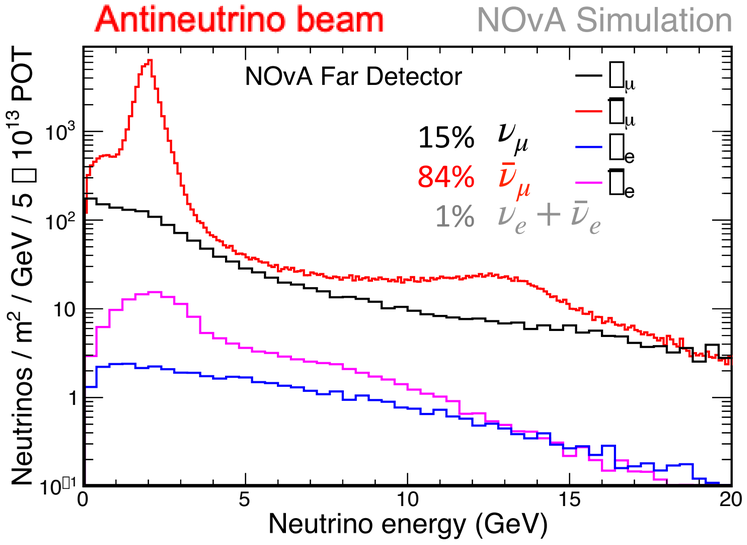
1 km from neutrino source

Neutrino Beam at Fermilab

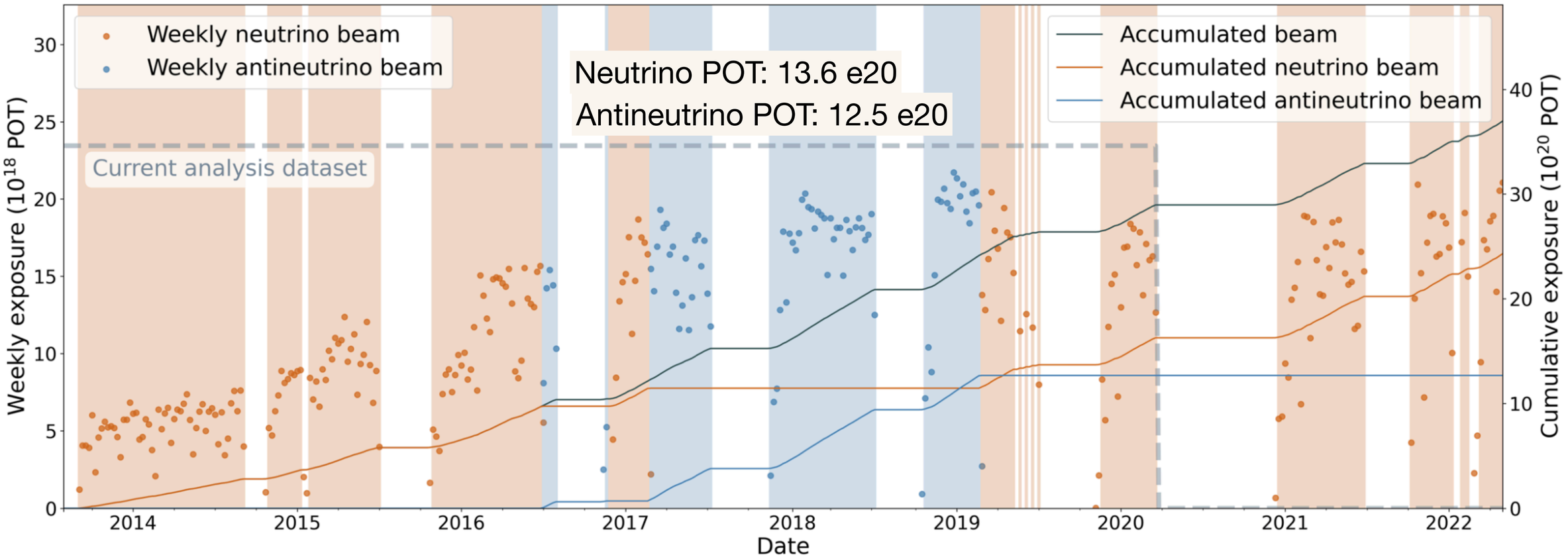


- Neutrino and antineutrino modes
- High $\nu_\mu(\bar{\nu}_\mu)$ purity





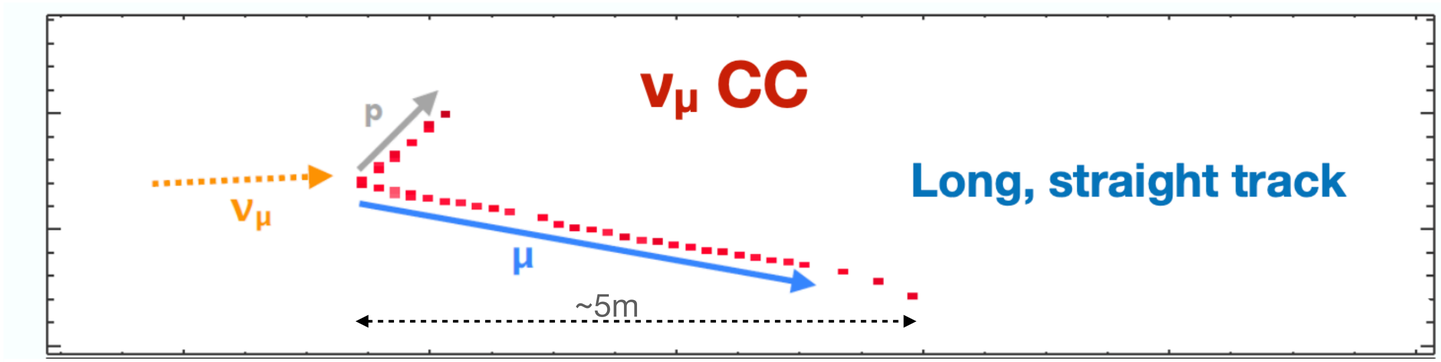
Beam Exposure

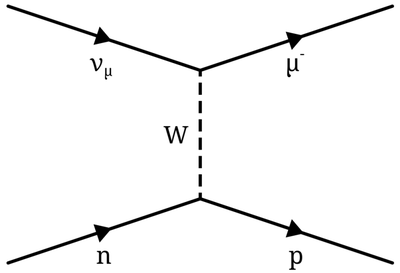


- Total protons on target so far 38e20
- New power record +950 kW

1MW, here we come! - Thanks to the hard work of many people in front and behind the scenes

Event Topologies





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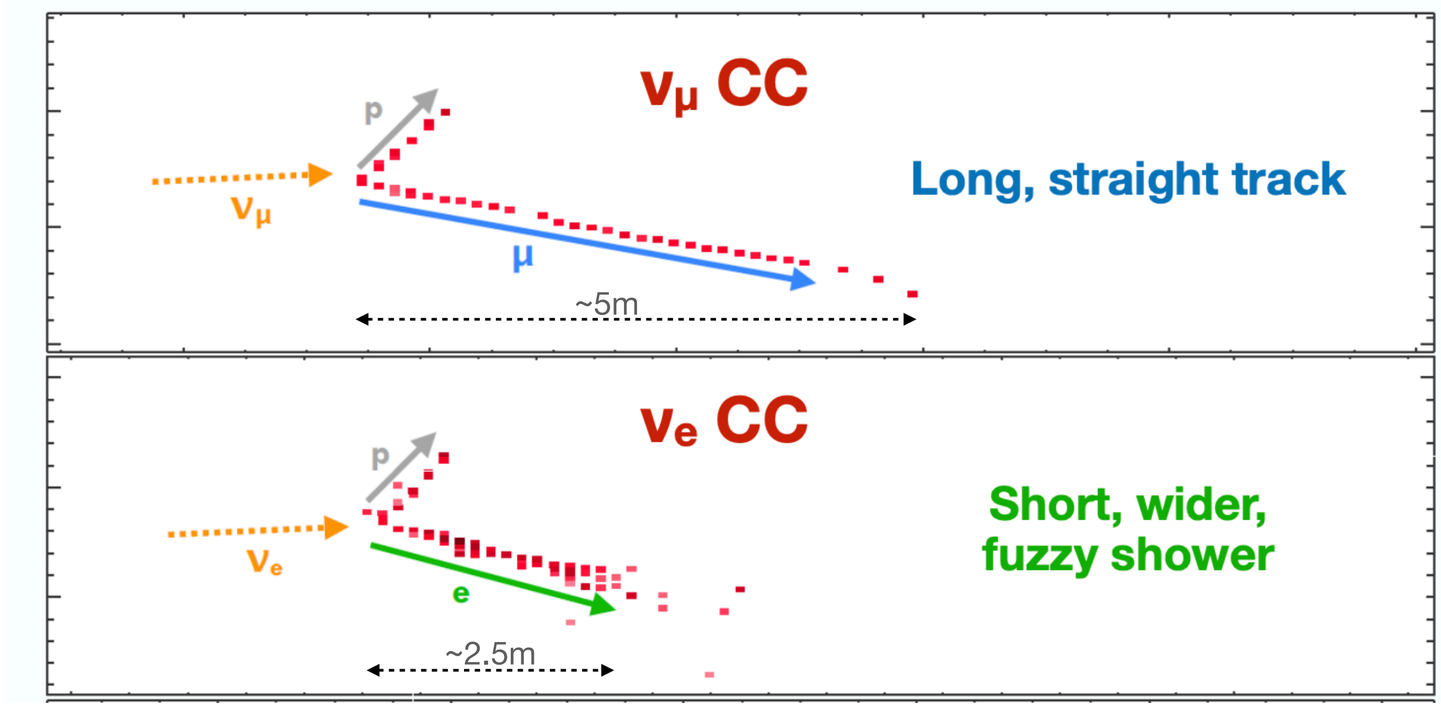

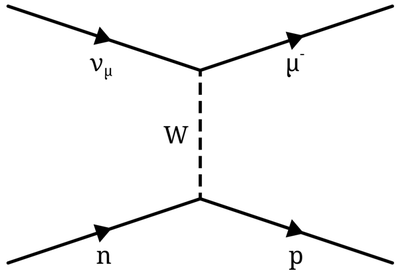

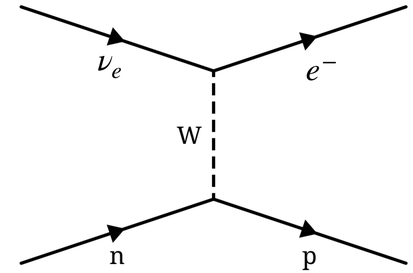

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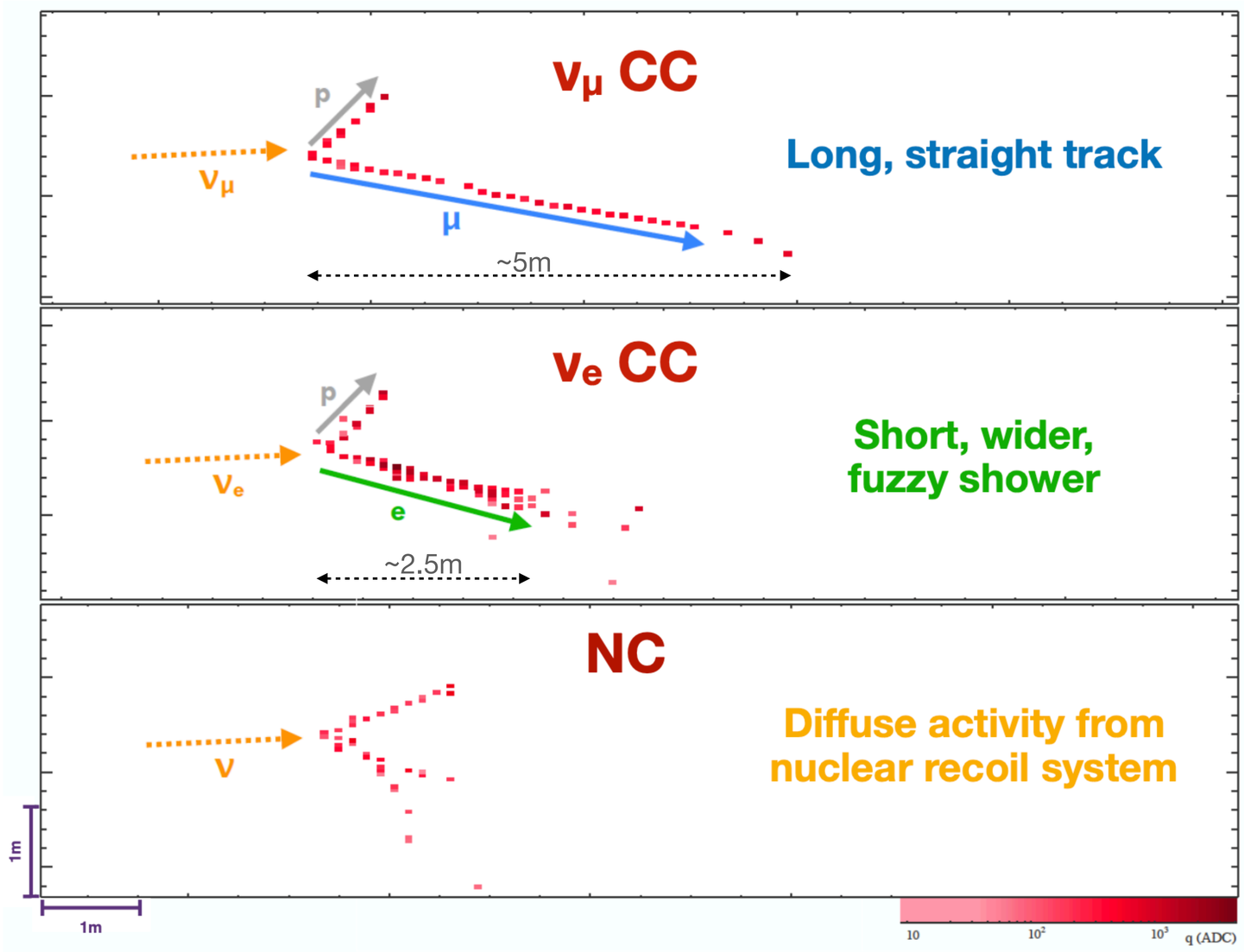
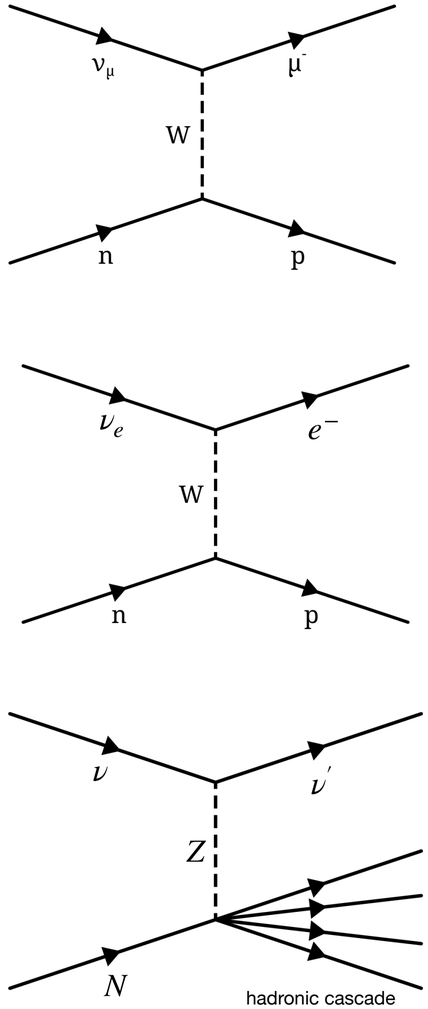
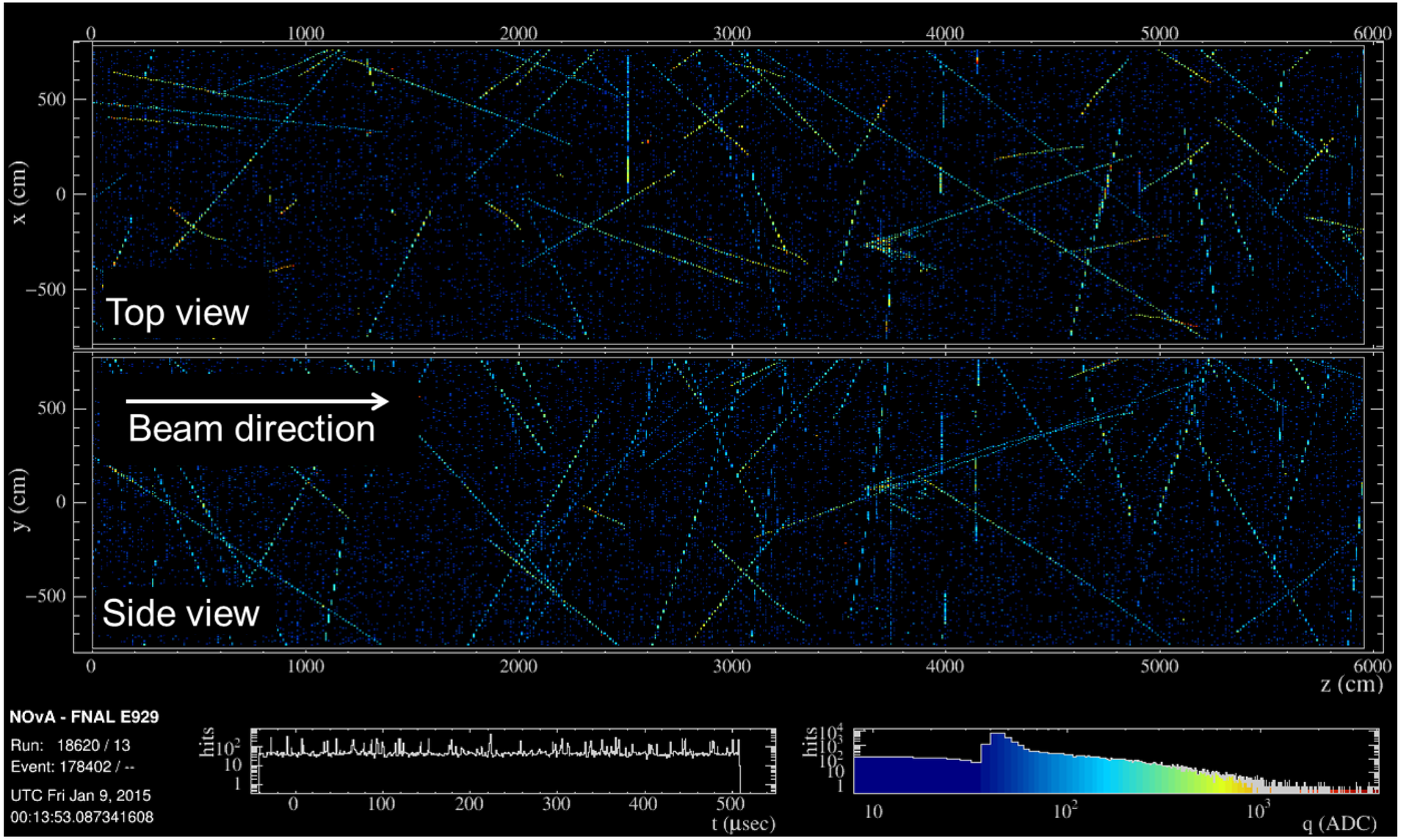




Event Display



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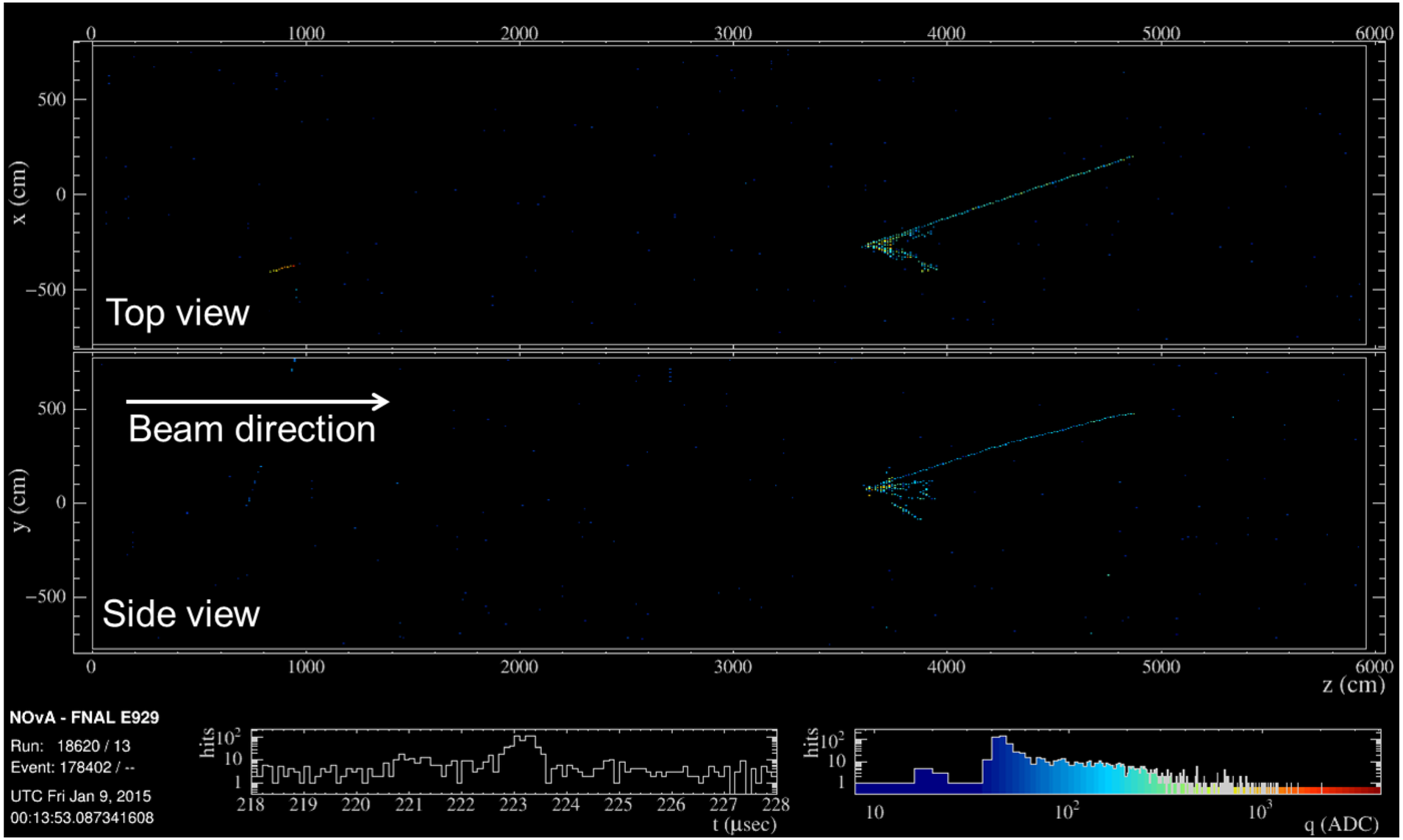

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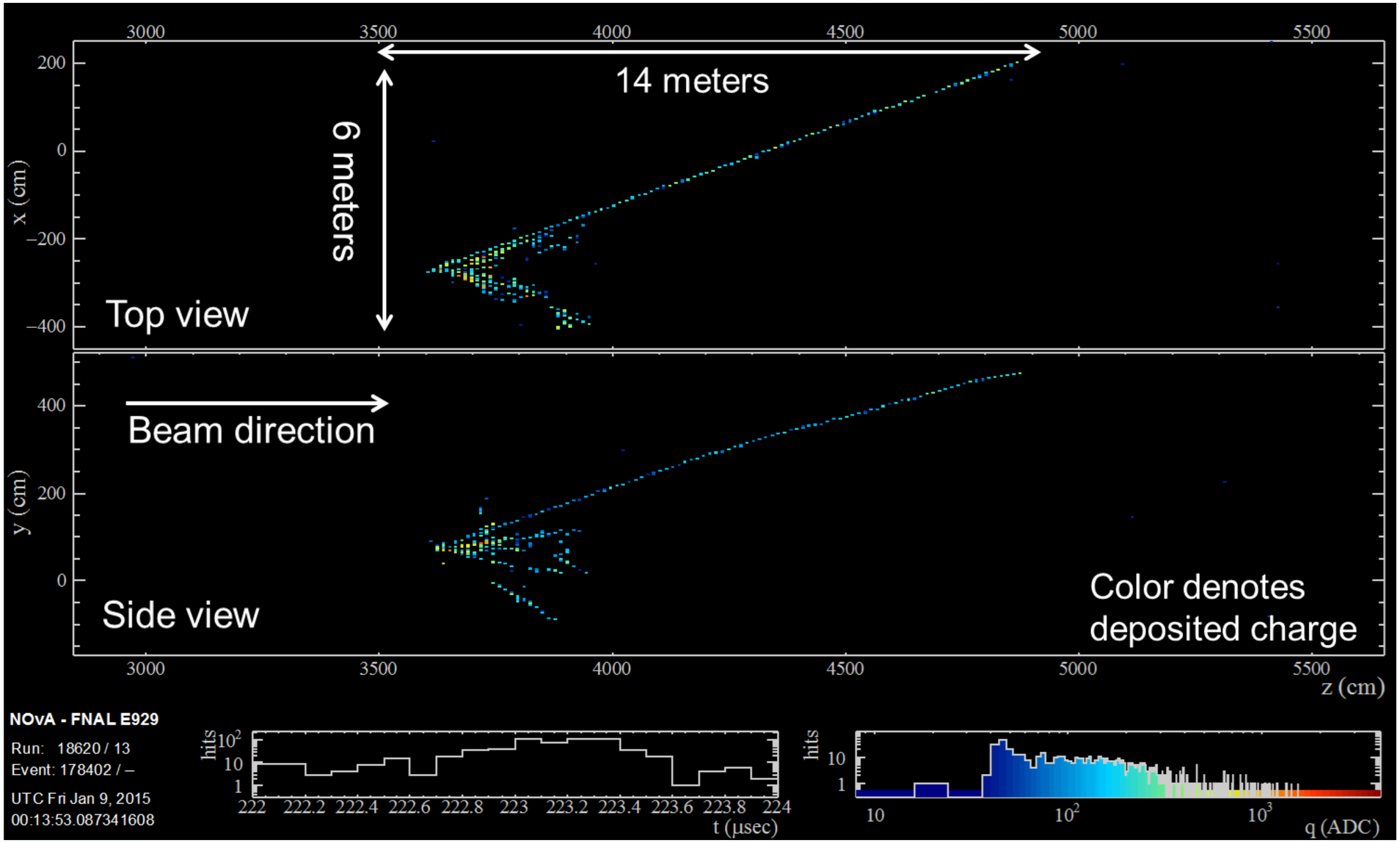
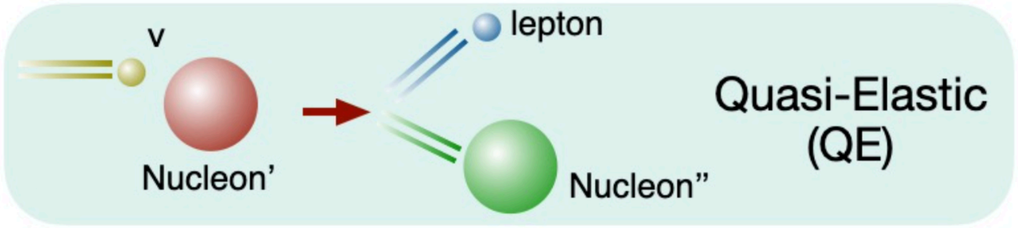


Neutrino Interactions in NOvA



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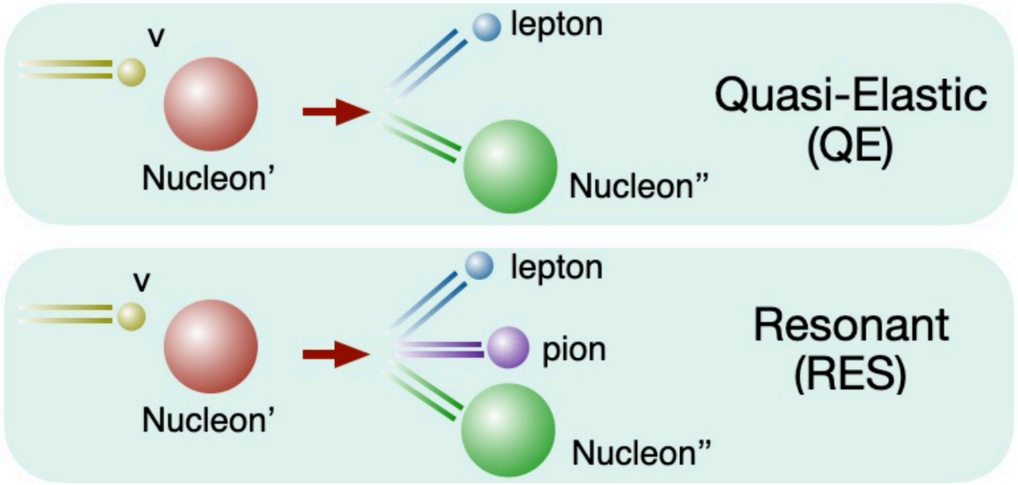

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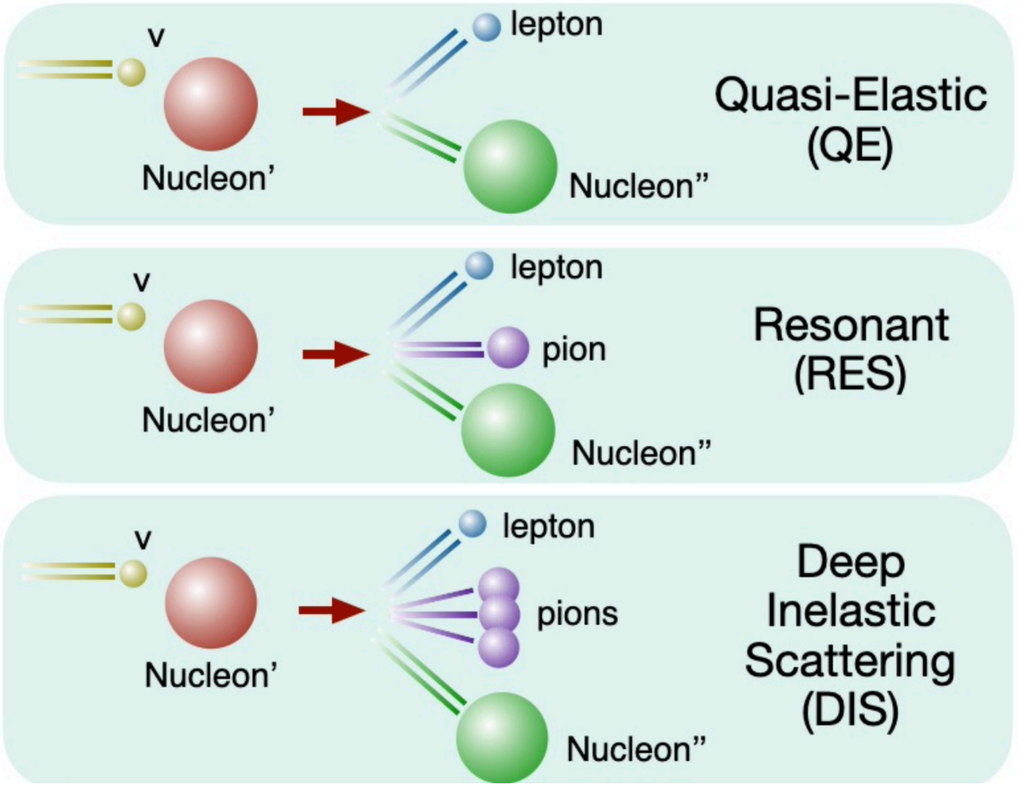

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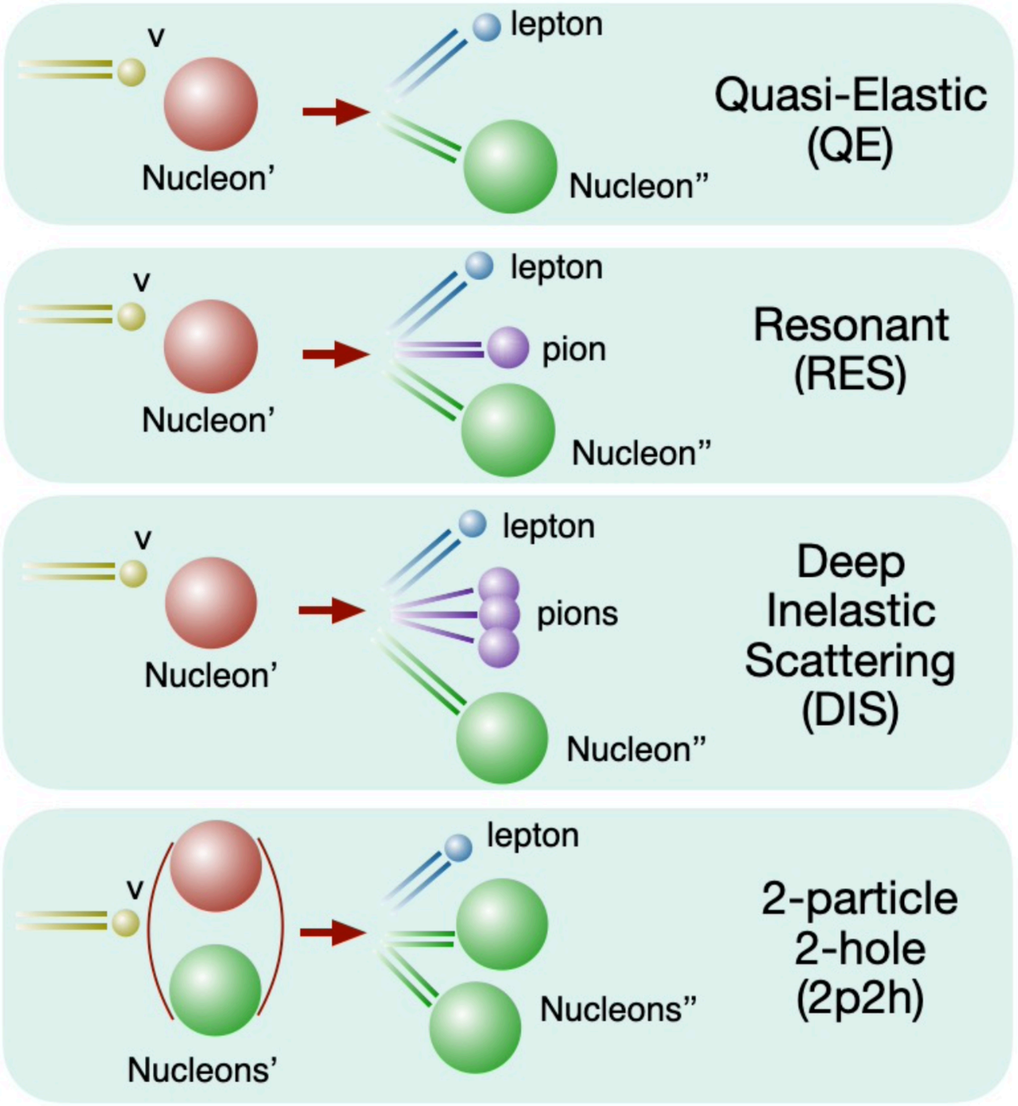

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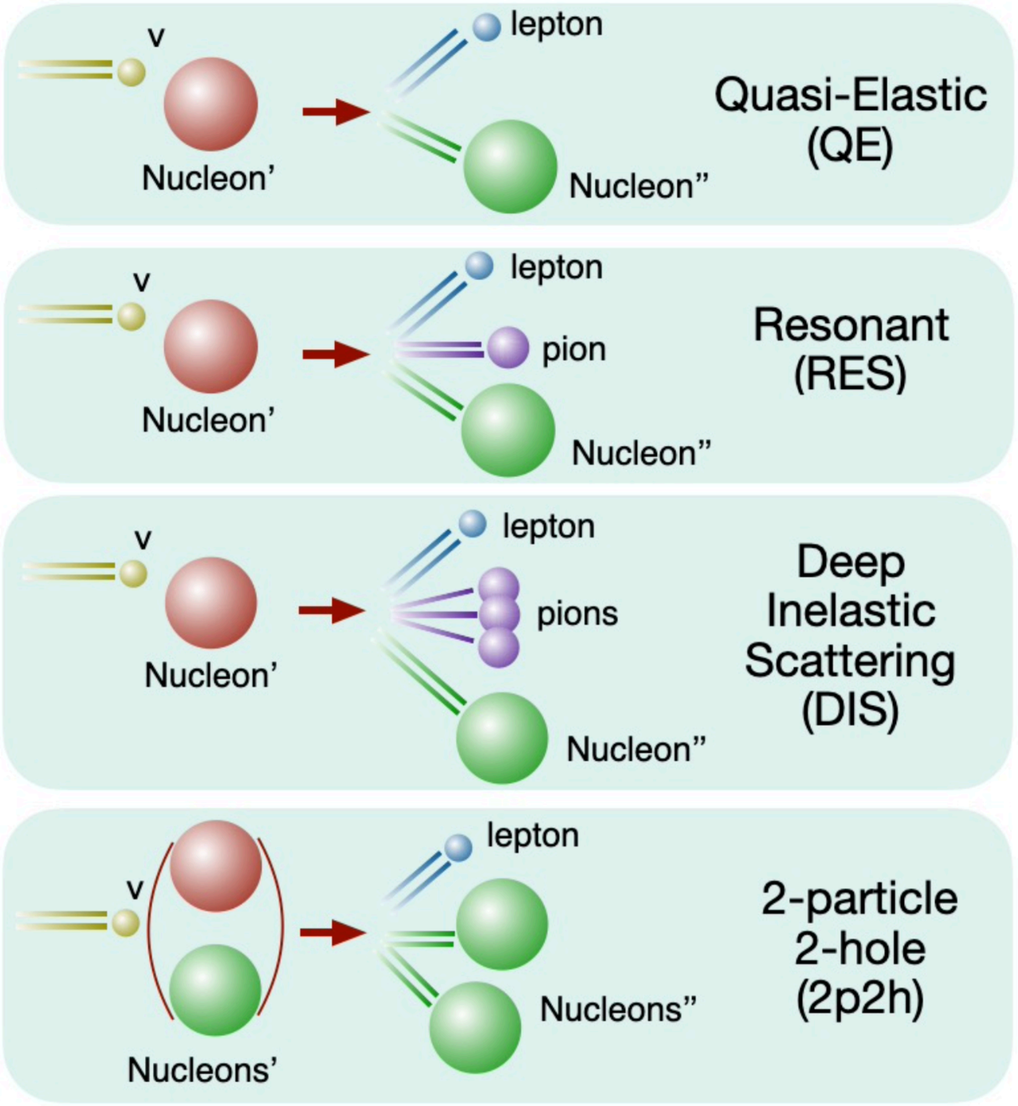
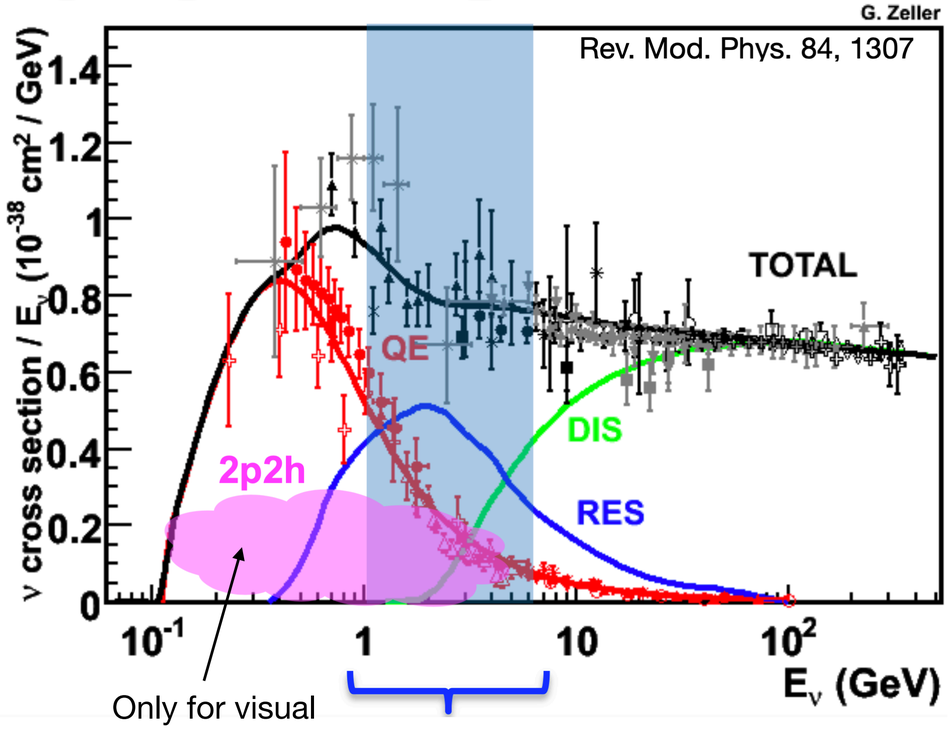




- NOvA sits in the transition region of all interaction types
- Need better understanding of neutrino interactions to reduce systematic uncertainties on oscillation measurements

Why Cross sections are Important?

$$R(x) = \phi(E_\nu) \times \sigma(E_\nu, x) \times \epsilon(x) \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Event rate
(Measured in detector)

Neutrino flux

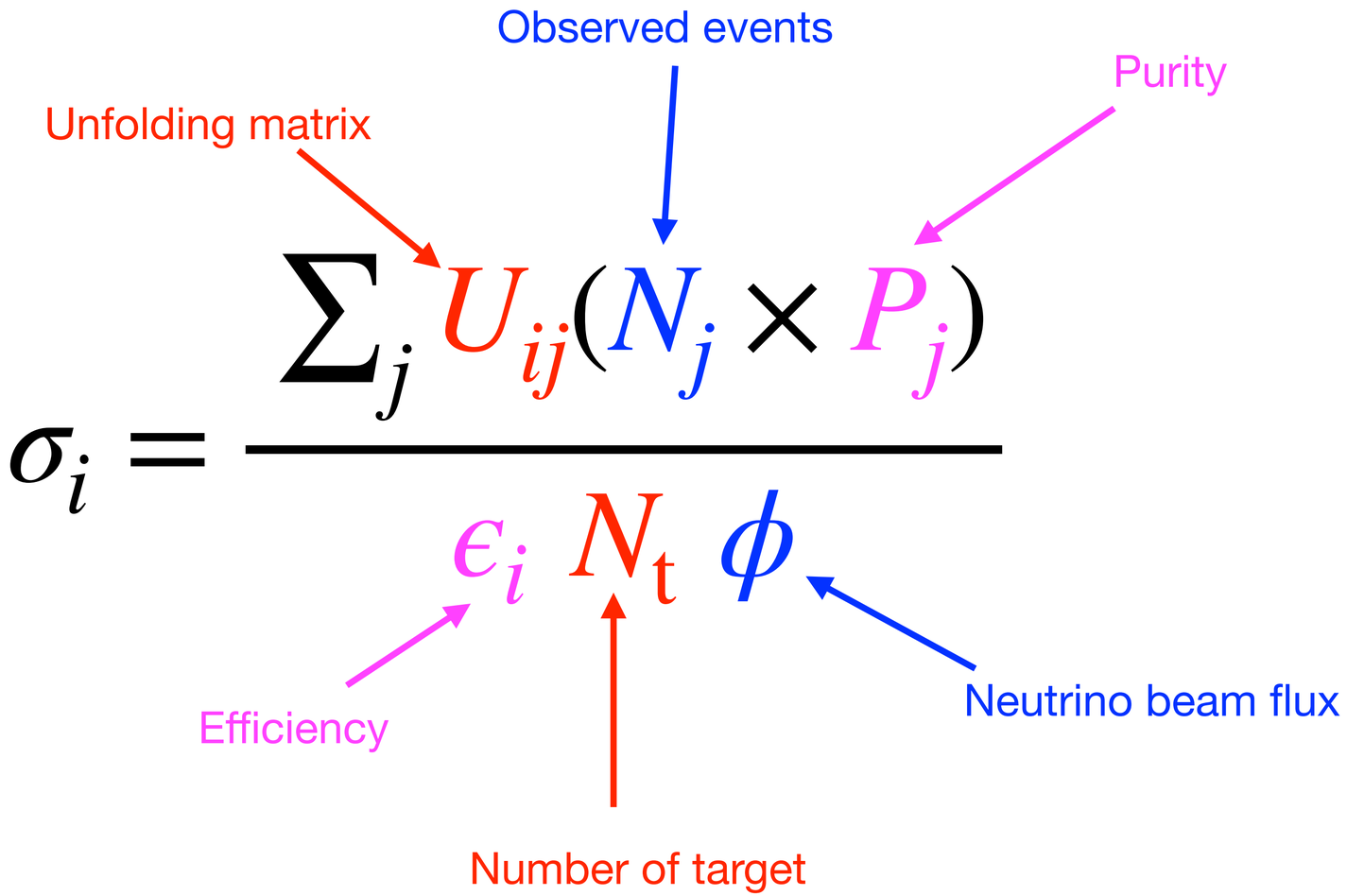
Neutrino-nucleus interaction
cross section

Detector response

Oscillation probability
(This is what we want to know)

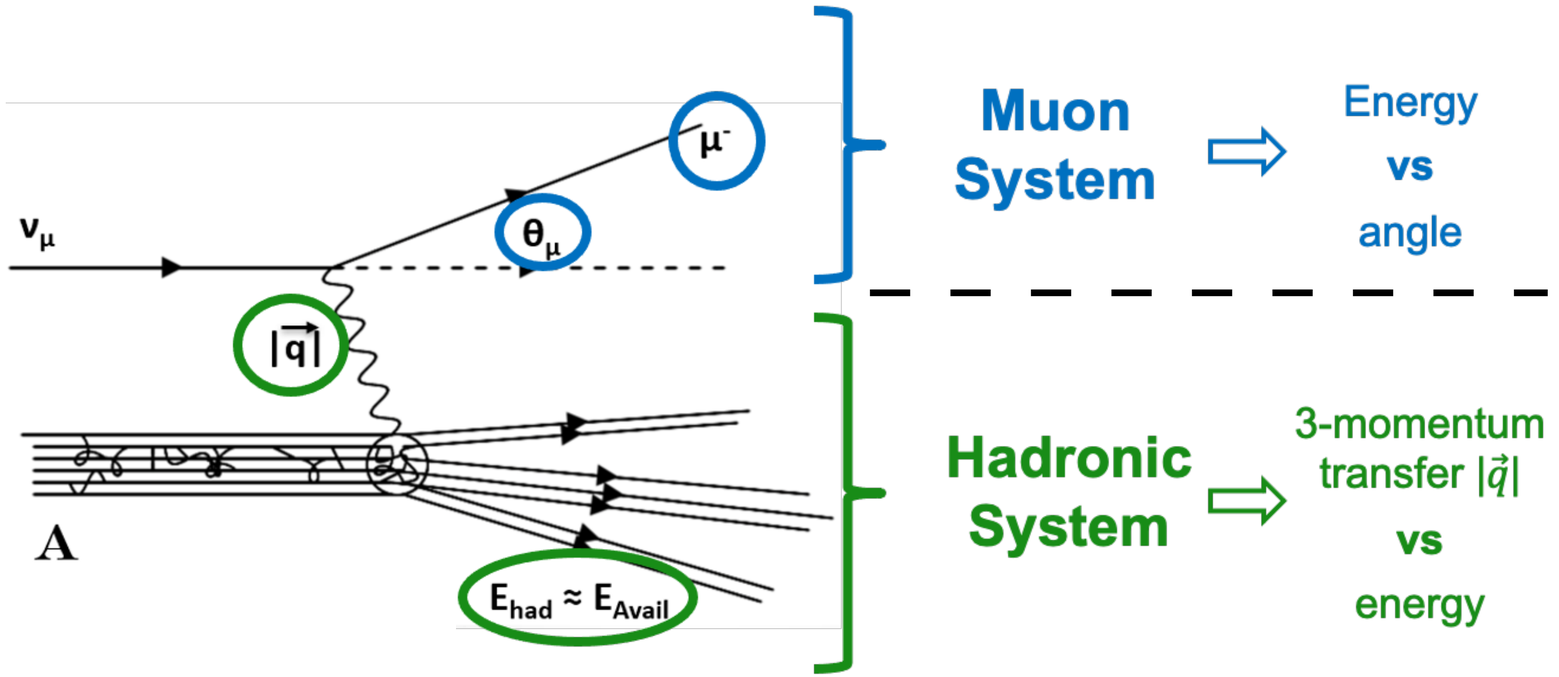
To get oscillation probabilities from the event rate, we need to know neutrino-nucleus cross section well, along with neutrino flux, and detector response efficiencies

Cross-section Formula



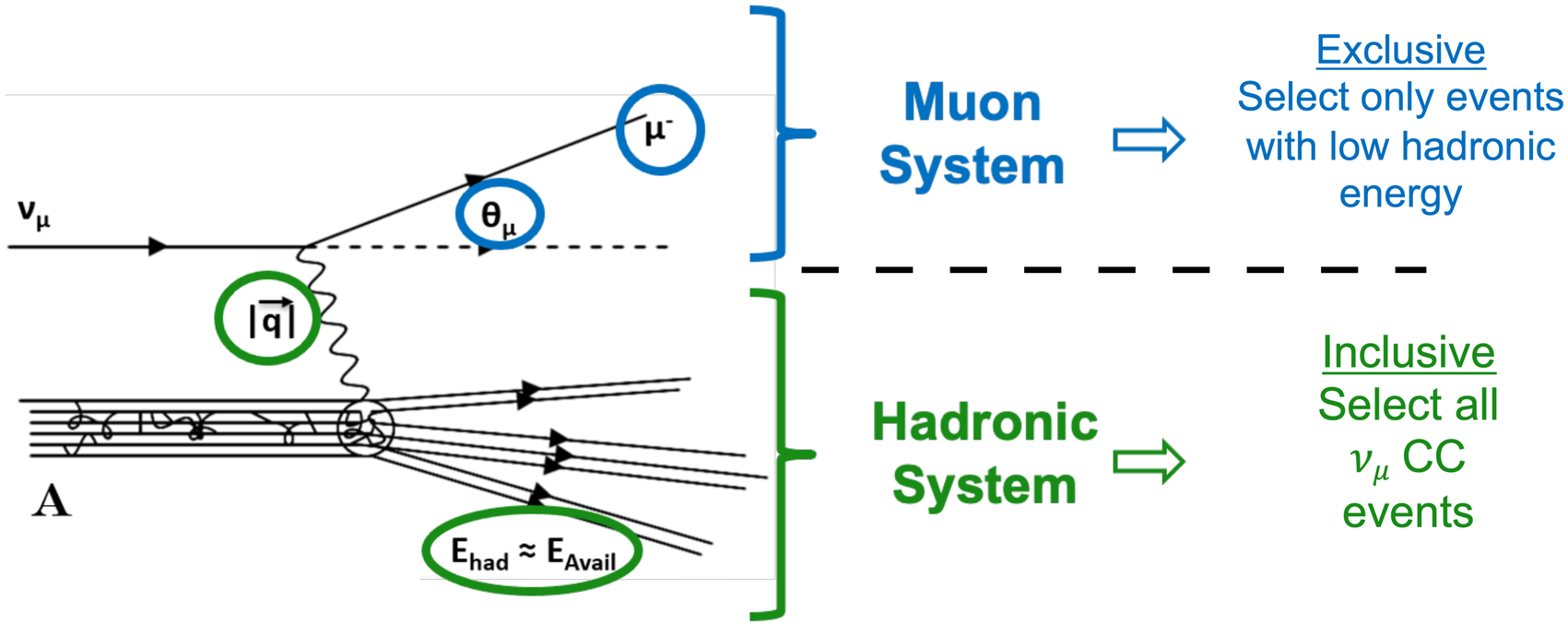
Two New ν_μ CC Cross-section Analyses

- Double differential cross sections



Two New ν_μ CC Cross-section Analyses

- Double differential cross sections
- Both focus on 2p2h interactions

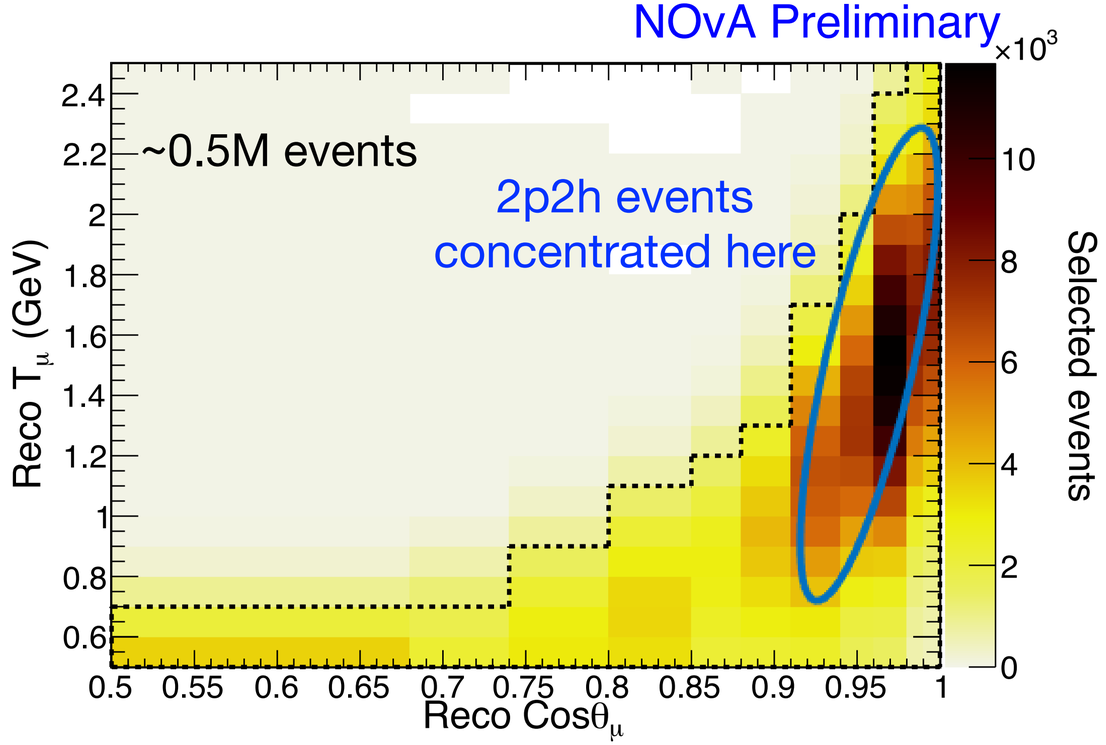


Both built on previous ν_μ CC inclusive measurement [Phys. Rev. D 107, 052011 (2023)]

Muon System

- Exactly one reconstructed track associated with outgoing muon (low E_{had})

- Boosts 2p2h, reduces DIS and RES interactions



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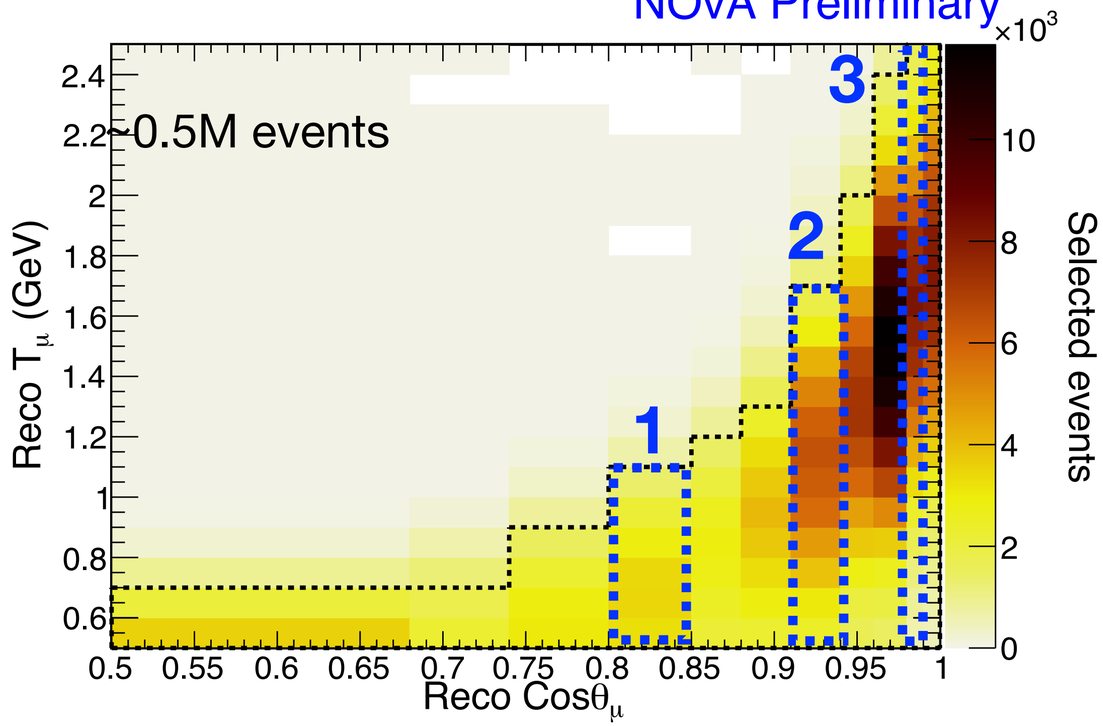
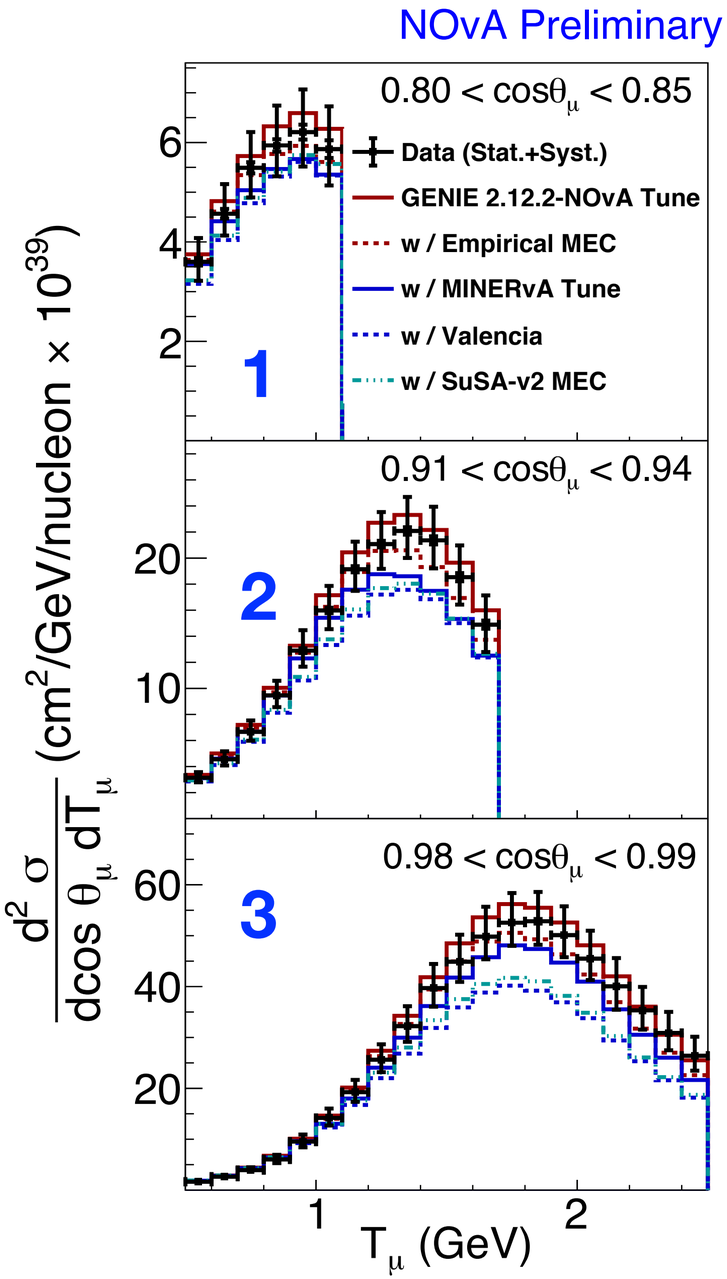
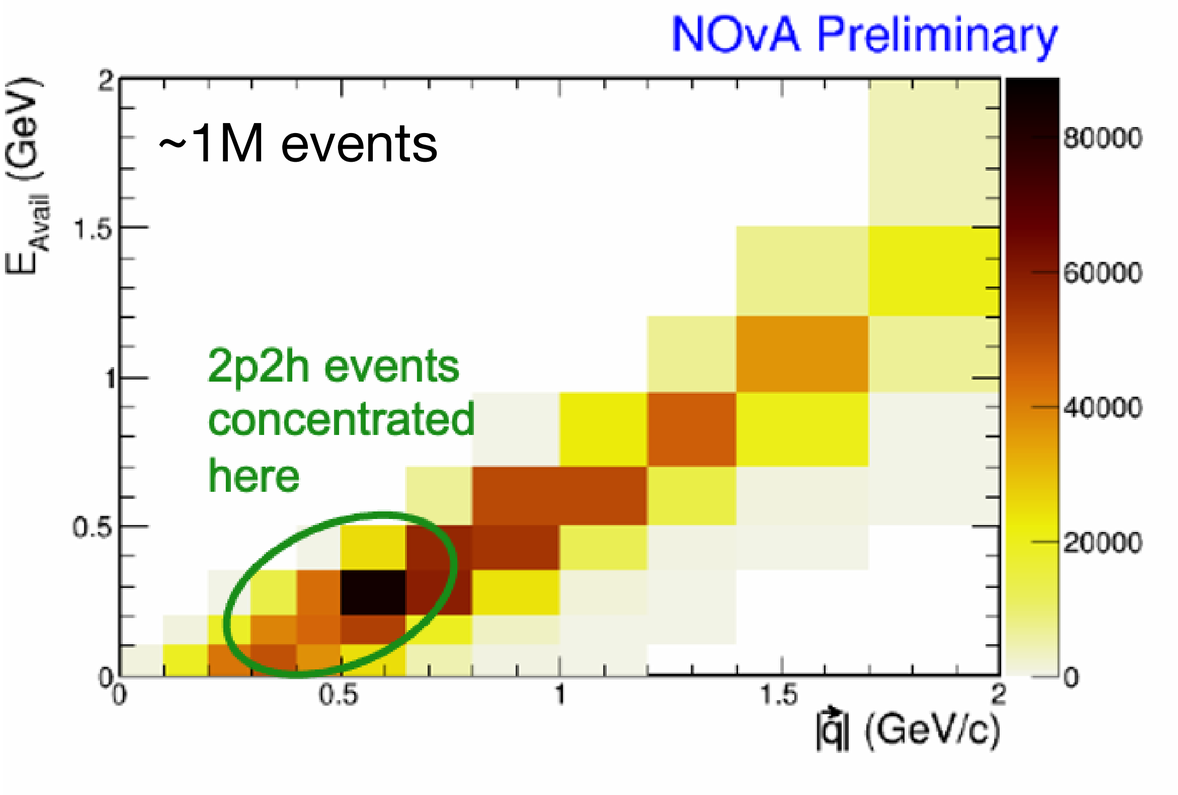


- ~12-15% uncertainties dominated by flux systematics



Hadronic System

- NOvA's first measurement in $|\vec{q}|$ and E_{avail}
- 2p2h concentrated at low values



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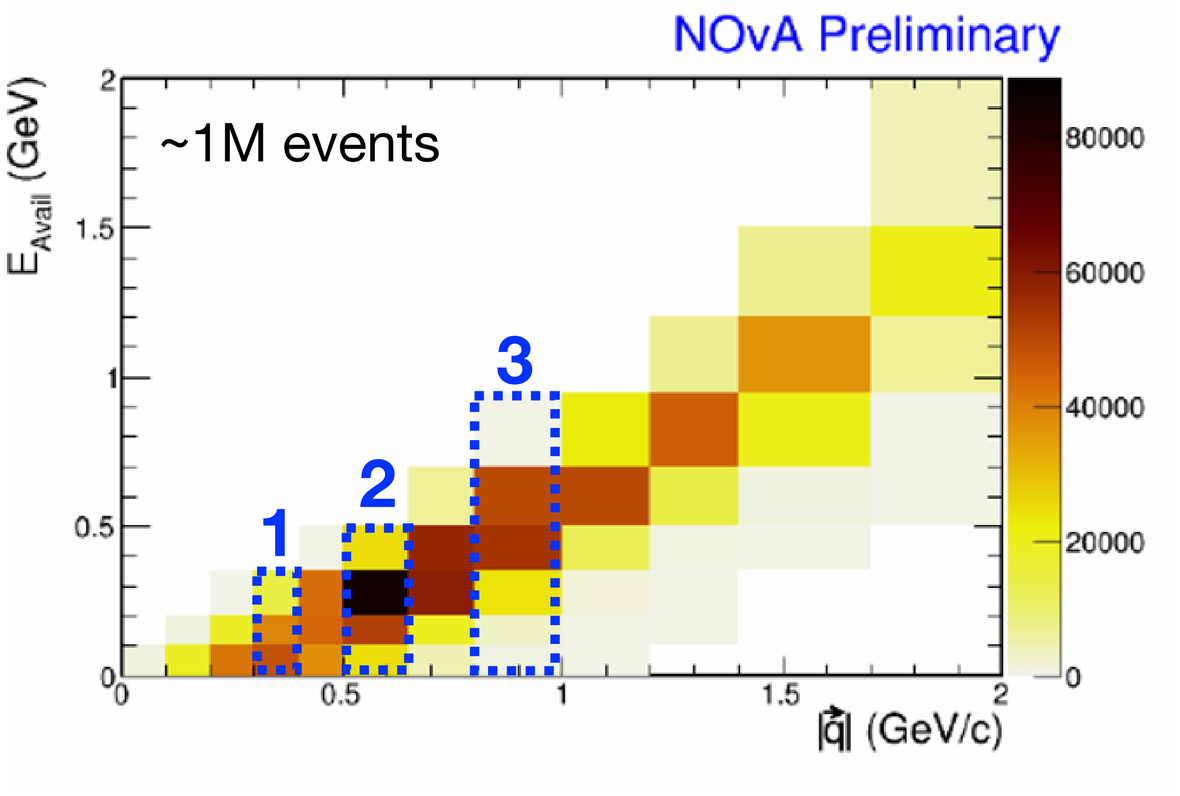

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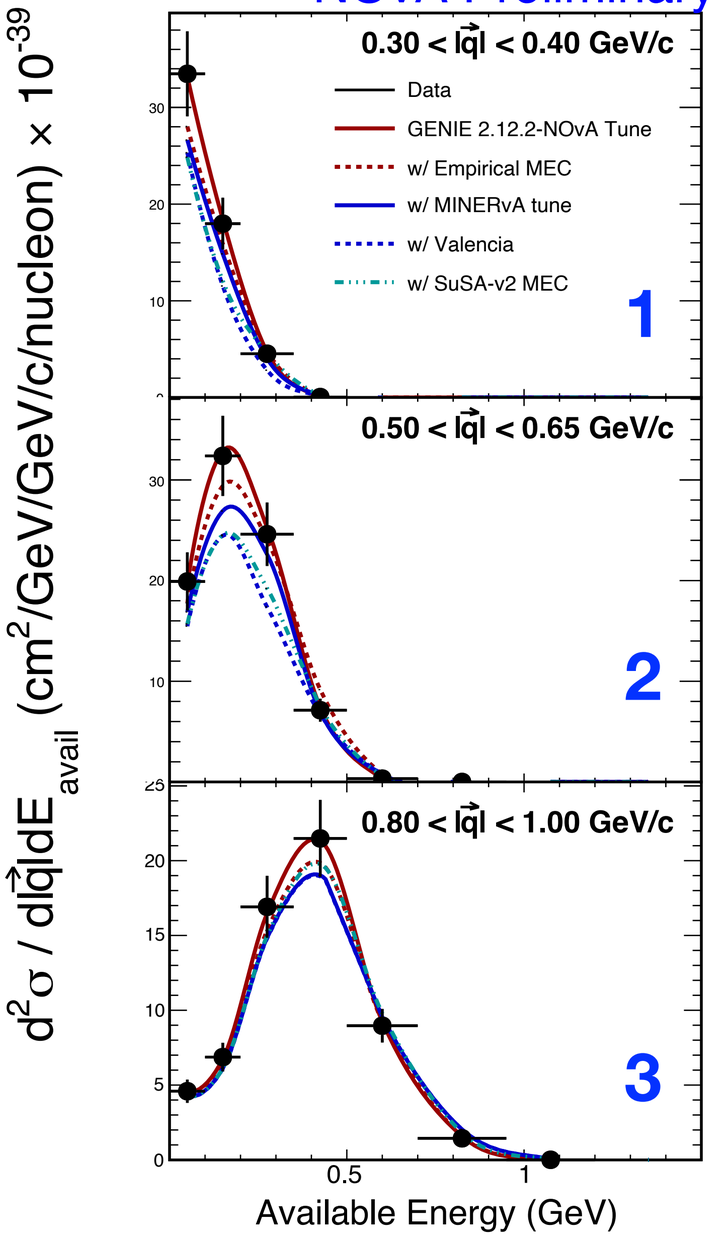


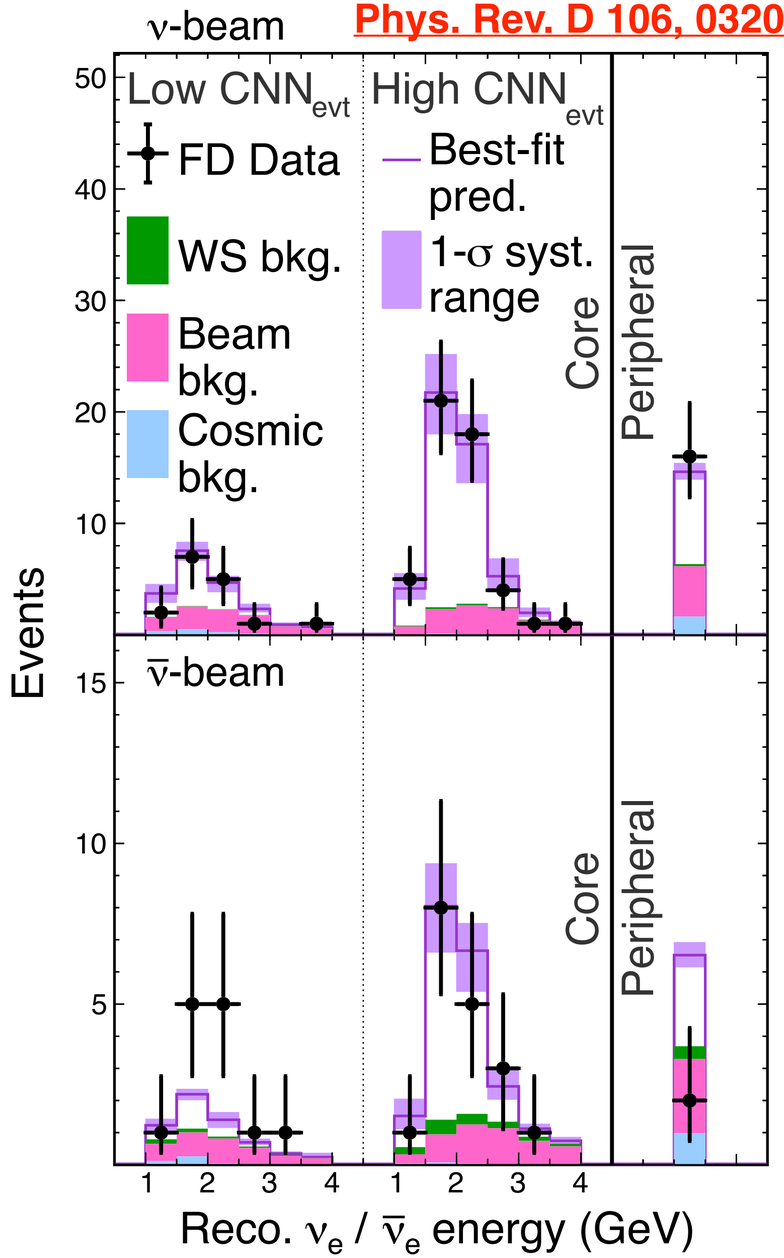
Oscillation Results

Far Detector ν_e and $\bar{\nu}_e$ Data

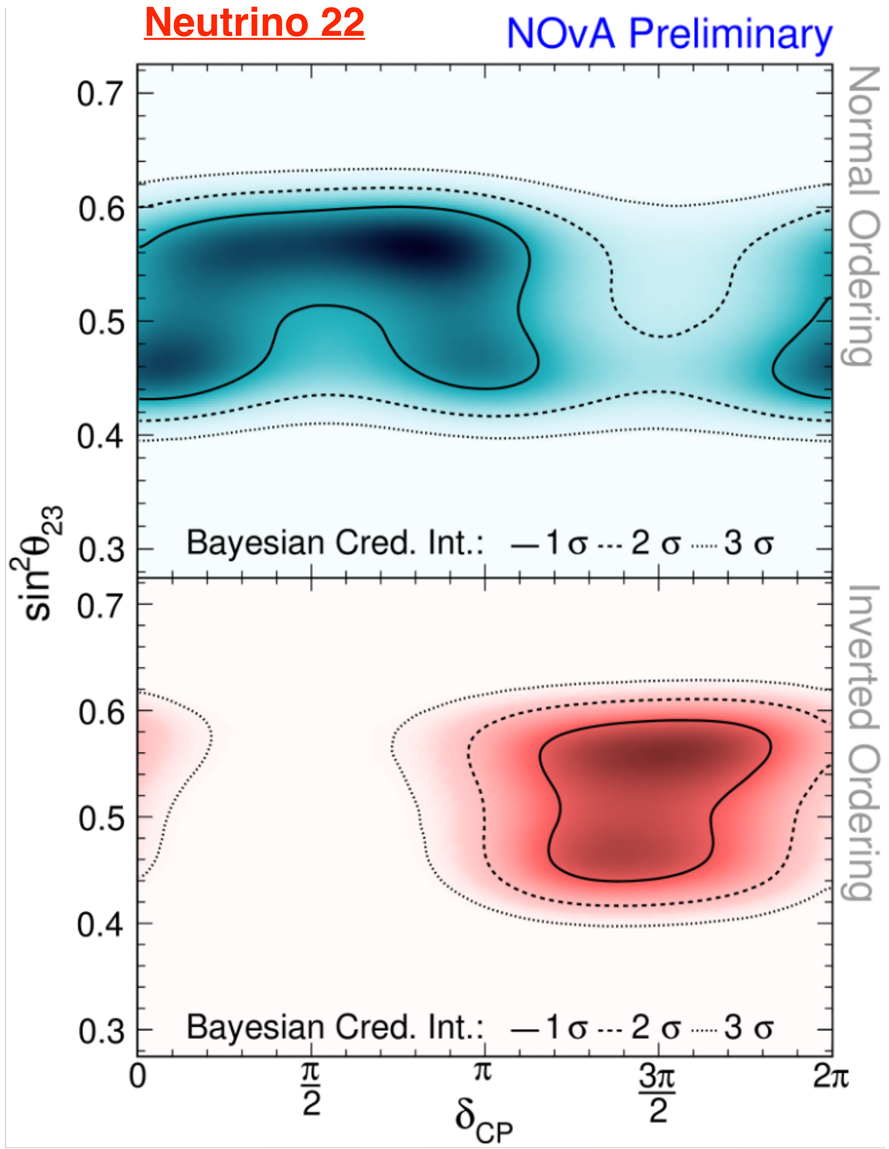
- Observe
  - 82 ν_e candidates (27 bkg)
  - 33 $\bar{\nu}_e$ candidates (14 bkg)

- Large significance of ν_e appearance

- >4σ evidence of $\bar{\nu}_e$ appearance



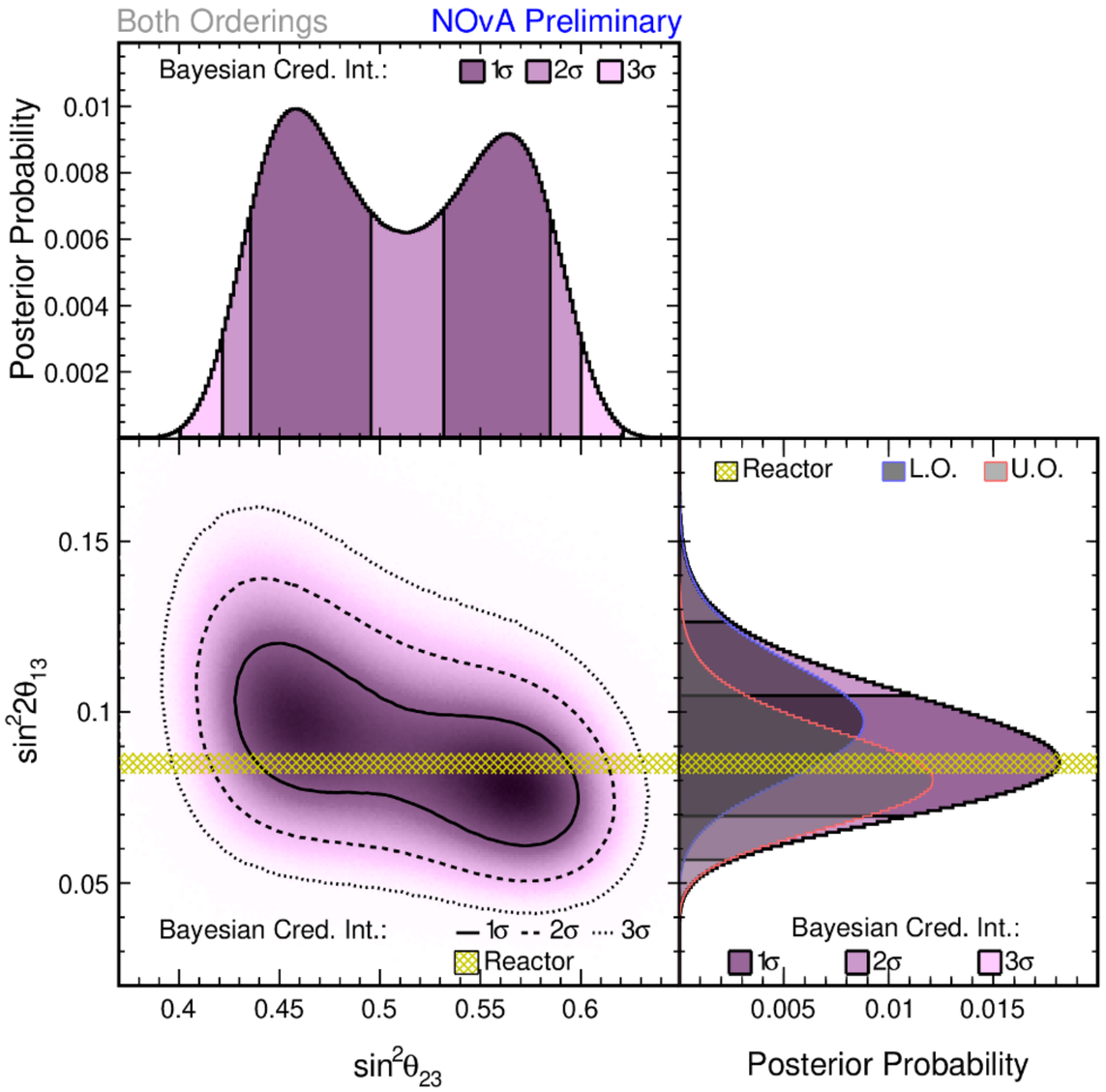
Bayesian Treatment



- Markov Chain MC bayesian analysis
- Alternative method of analyzing same dataset
- Same conclusions as the frequentist approach
- Slight preference to upper octant and normal ordering of neutrino masses
- Exclude inverted ordering, $\delta_{cp} = \pi/2$ at $> 3\sigma$

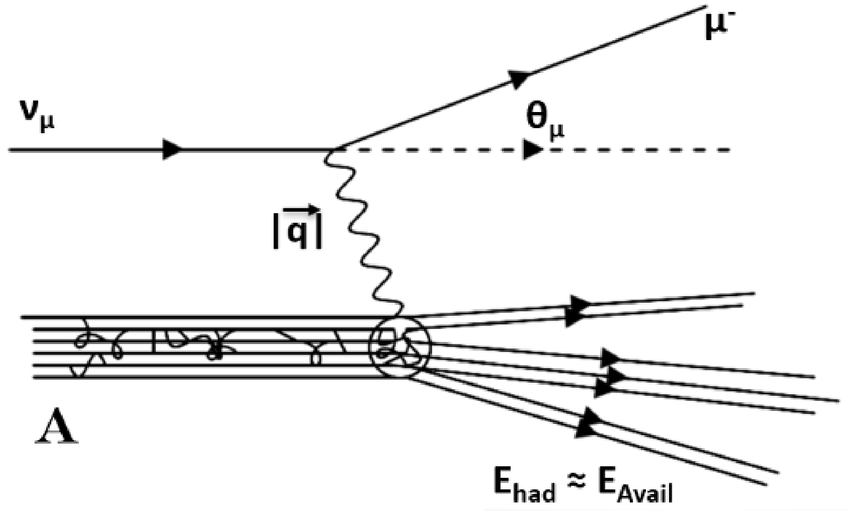
NOvA-only θ_{13} and θ_{23} Results

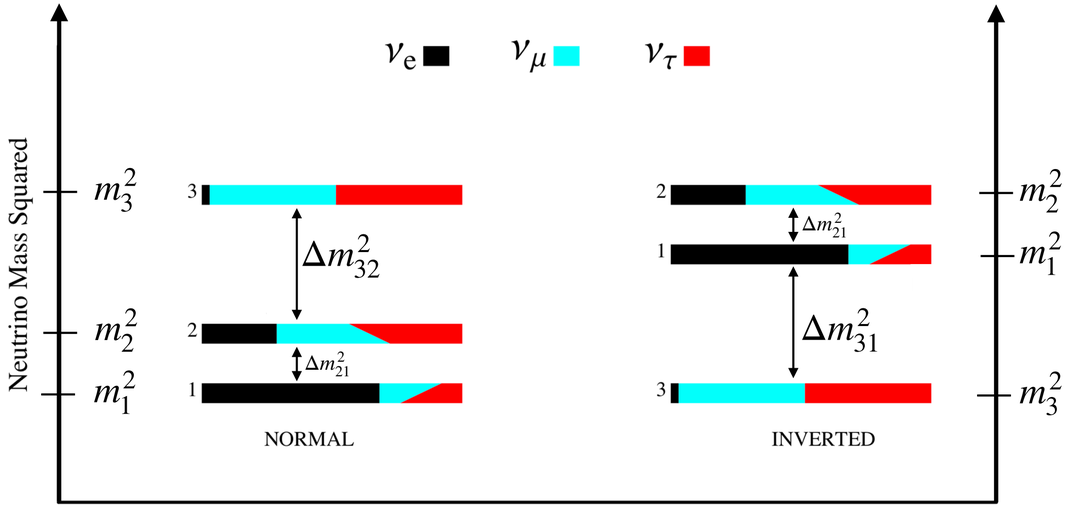
Neutrino 22



- Larger θ_{13} prefers lower octant for θ_{23} and vice verse
- Normally we use reactor θ_{13} constraint in oscillation fit from PDG
- Here θ_{13} is measured by NOvA using bayesian analysis
- $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$
- Consistent results with reactor measurements

Conclusions and Outlook





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- Asymmetry in $\nu_e - \bar{\nu}_e$ appearance consistent with zero

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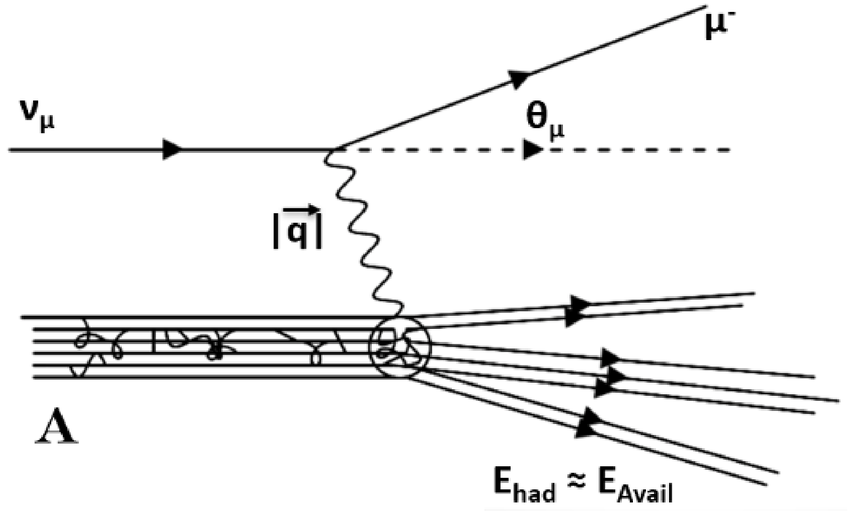

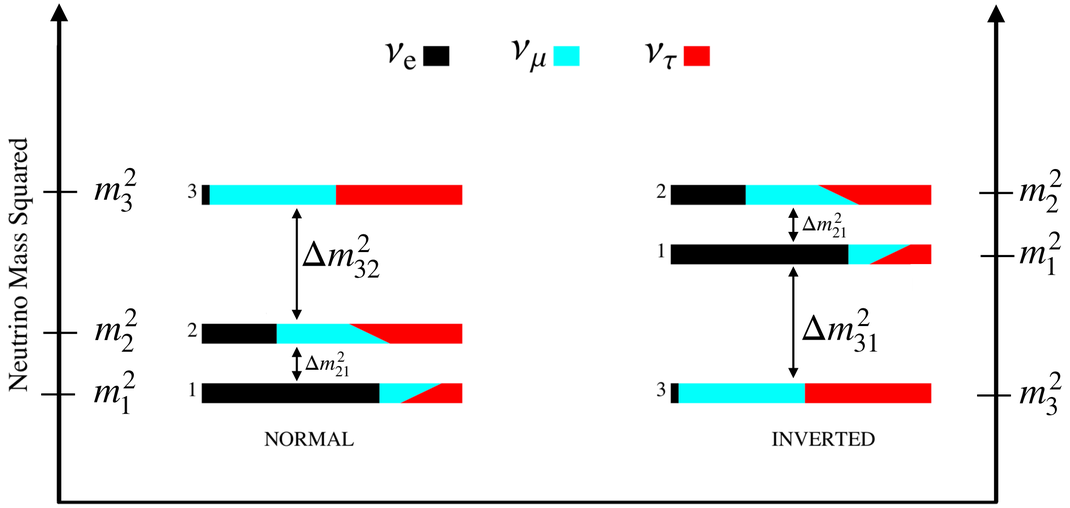

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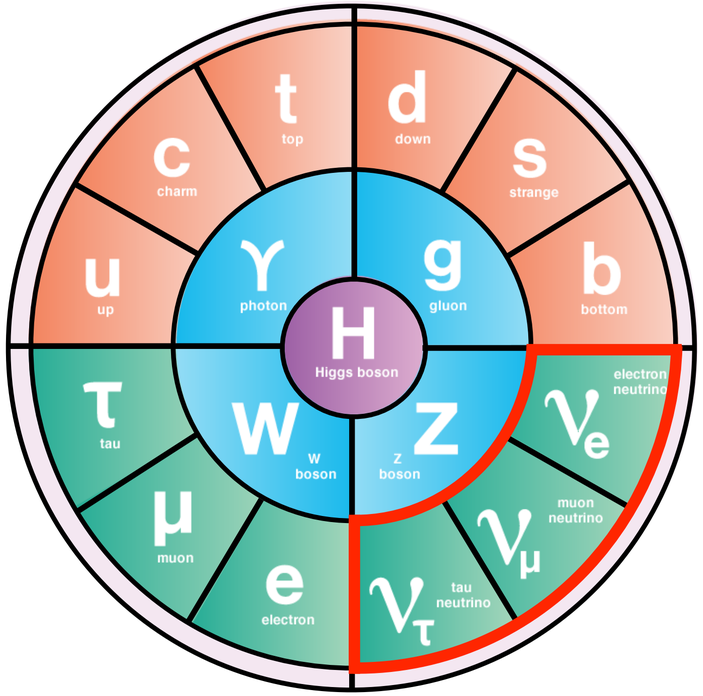
- Asymmetry in $\nu_e - \bar{\nu}_e$ appearance consistent with zero
- Antineutrino beam cross-section measurements are in progress
- NOvA and T2K are working towards joint fit results
- Much new data and results to come

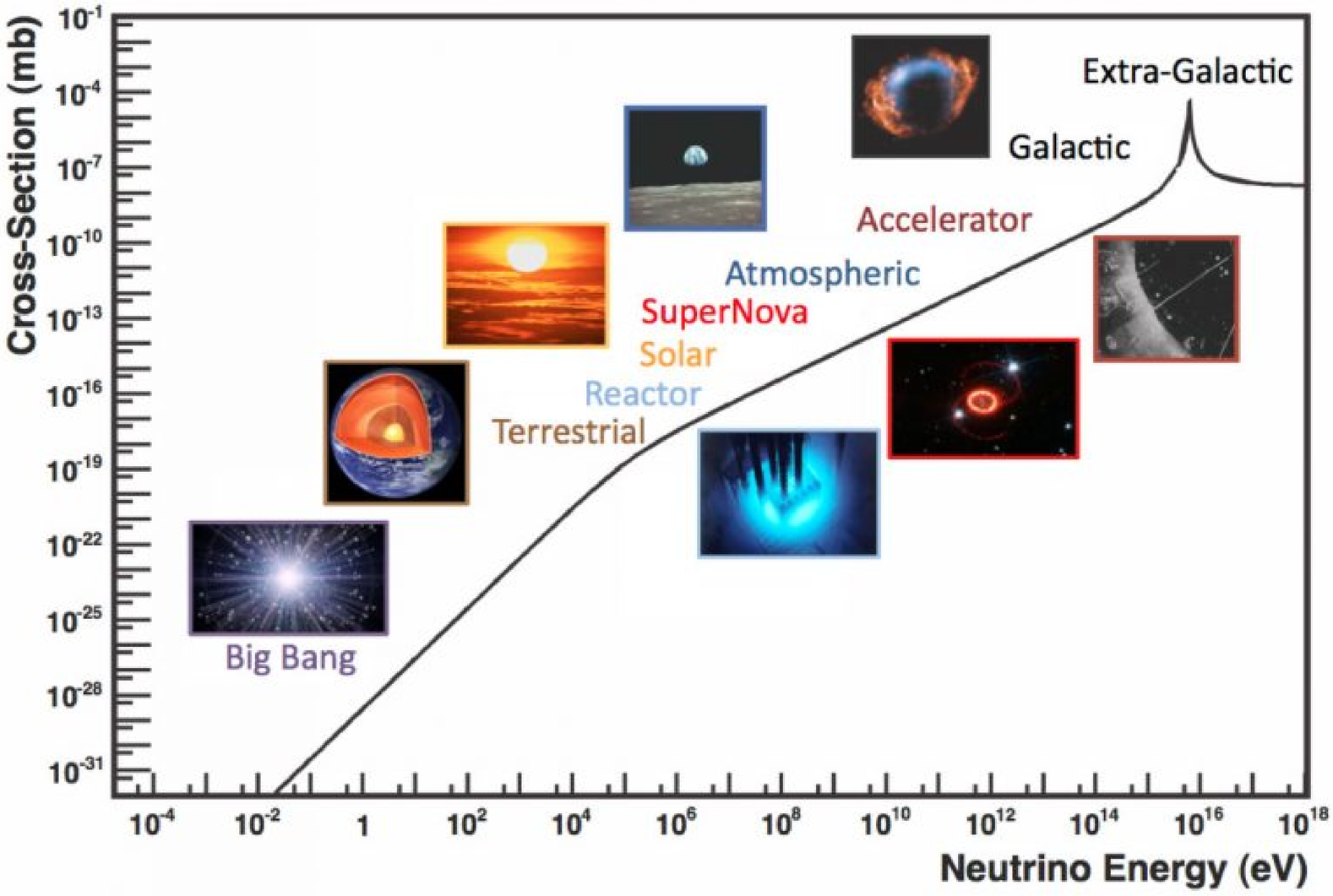
Backup

Brief Introduction to Neutrinos

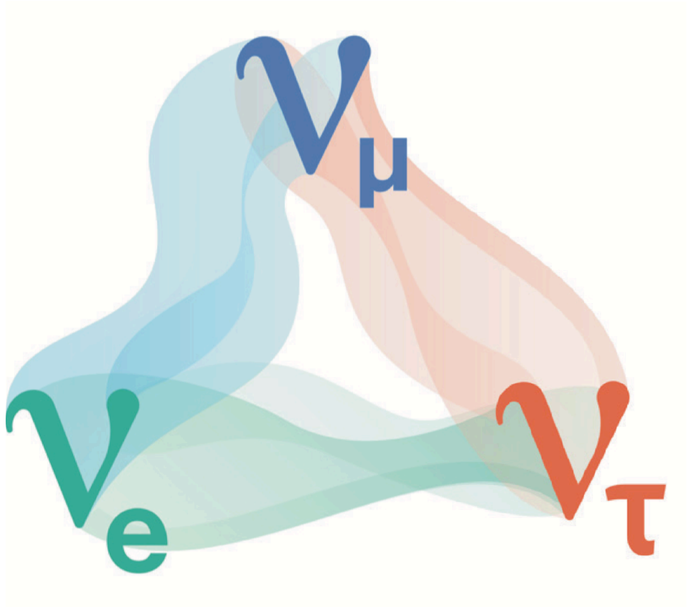


- The most abundant particles in the Universe after photon
- Postulated in 1930 by W. Pauli to explain the continuous spectrum of beta decay
- Charge-less, spin 1/2, weakly interacting and massless in the Standard Model (SM)
- Three generations: ν_e , ν_μ and ν_τ (and anti-neutrinos)

Sources

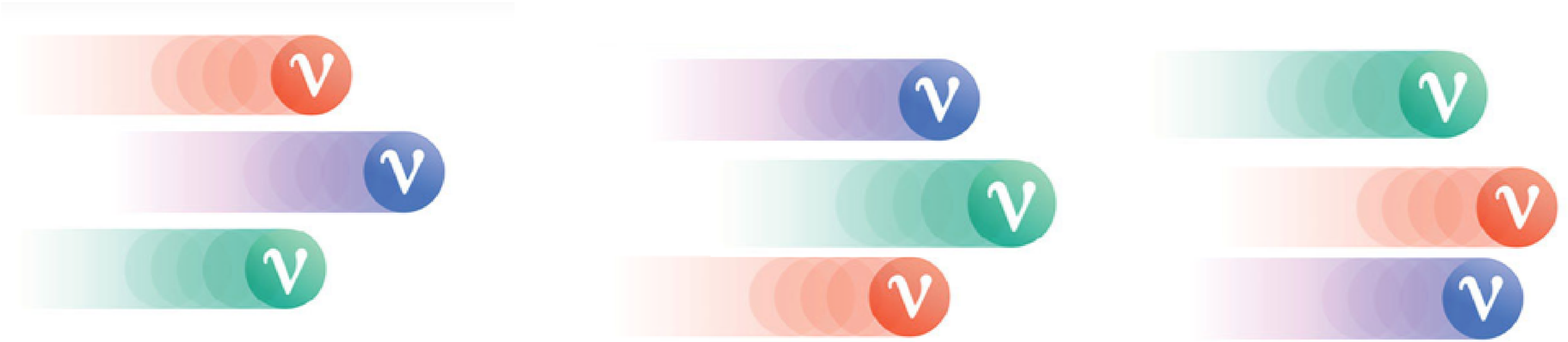

Cross-Section (mb)
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Neutrino Energy (eV)
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang

Oscillation Phenomenology

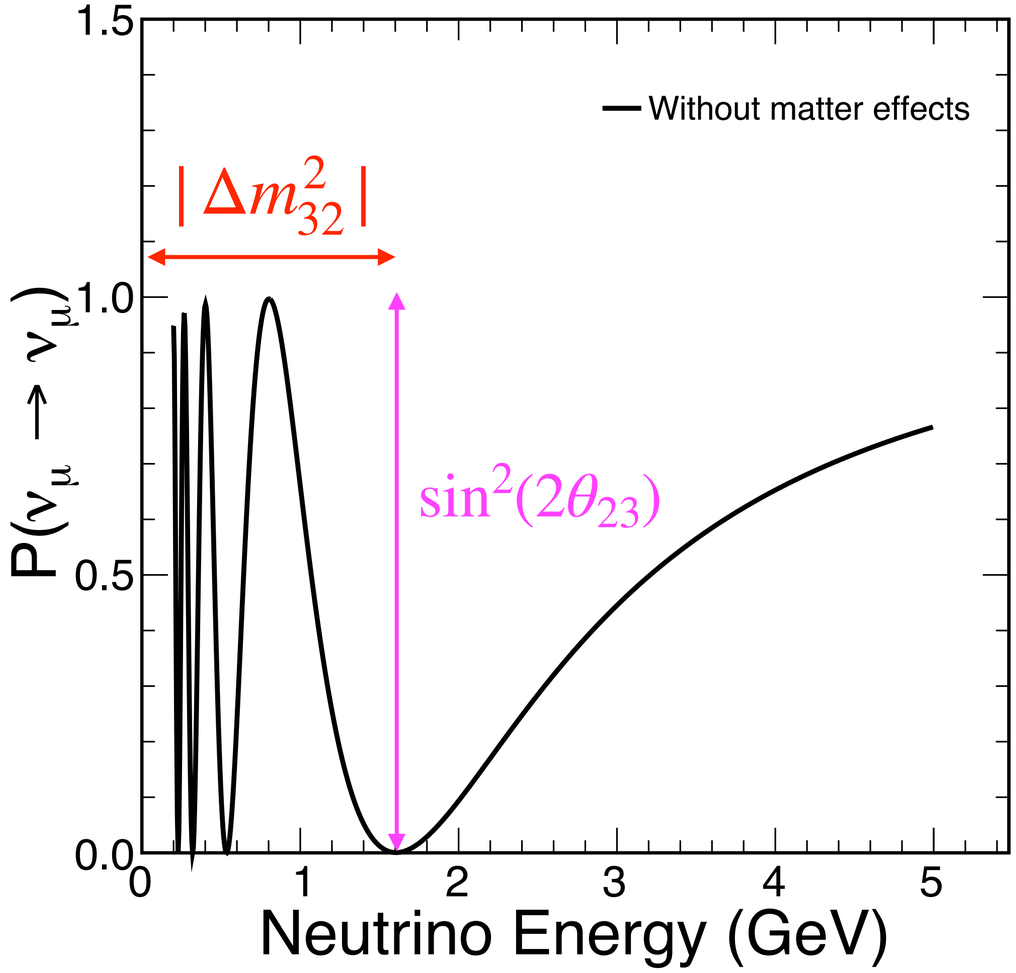


$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

- Neutrinos oscillate between different flavors
- Oscillation implies non-zero masses of neutrinos



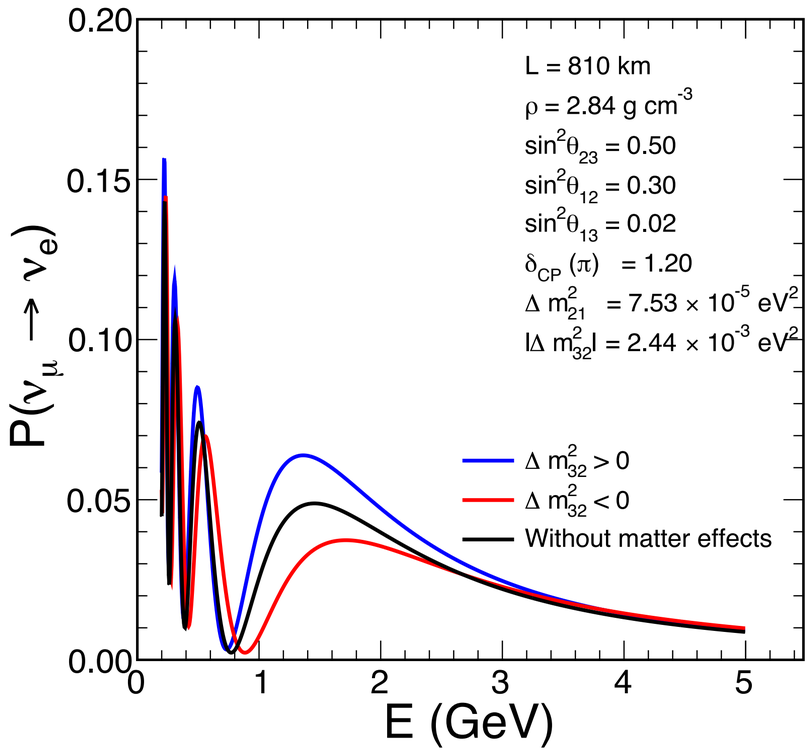
$\nu_\mu \rightarrow \nu_\mu$ Disappearance Oscillations

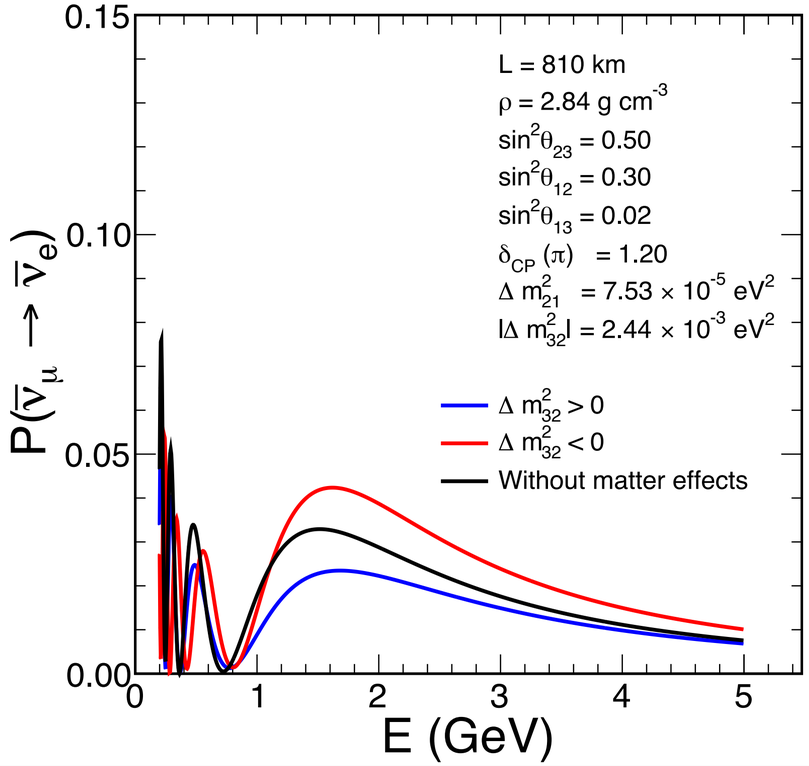


$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta_{23} \ \sin^2\left(\frac{1.27 \ \Delta m^2_{32} \ (eV^2) \ L \ (km)}{E \ (GeV)}\right)$$

Survival probability gives direct measurement of $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$

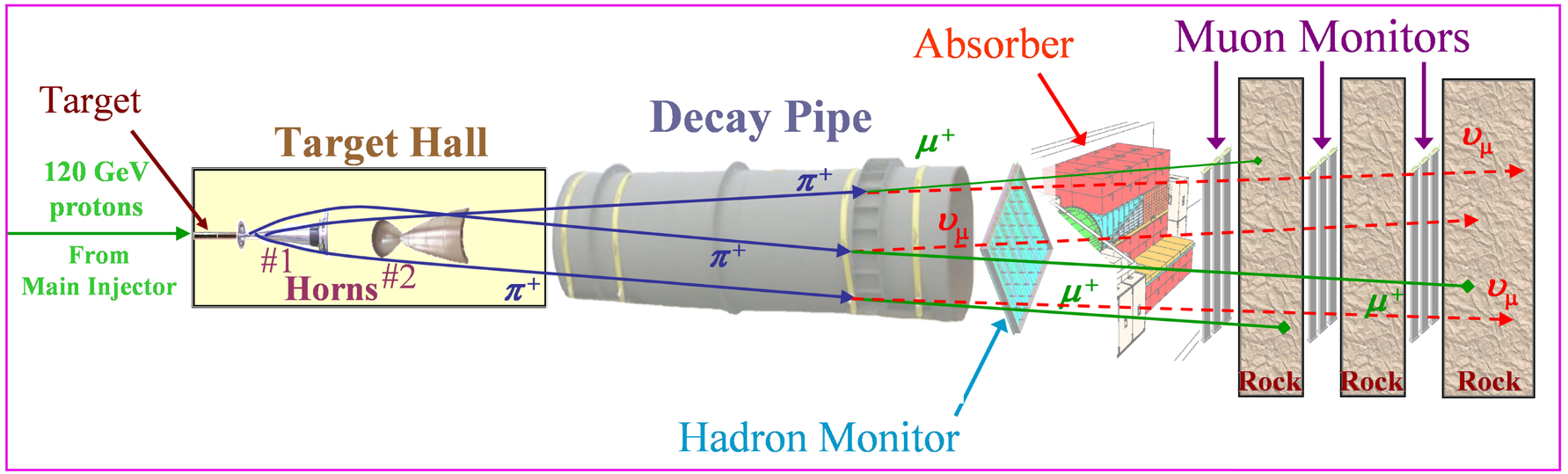
$\nu_\mu \rightarrow \nu_e$ Appearance Oscillations



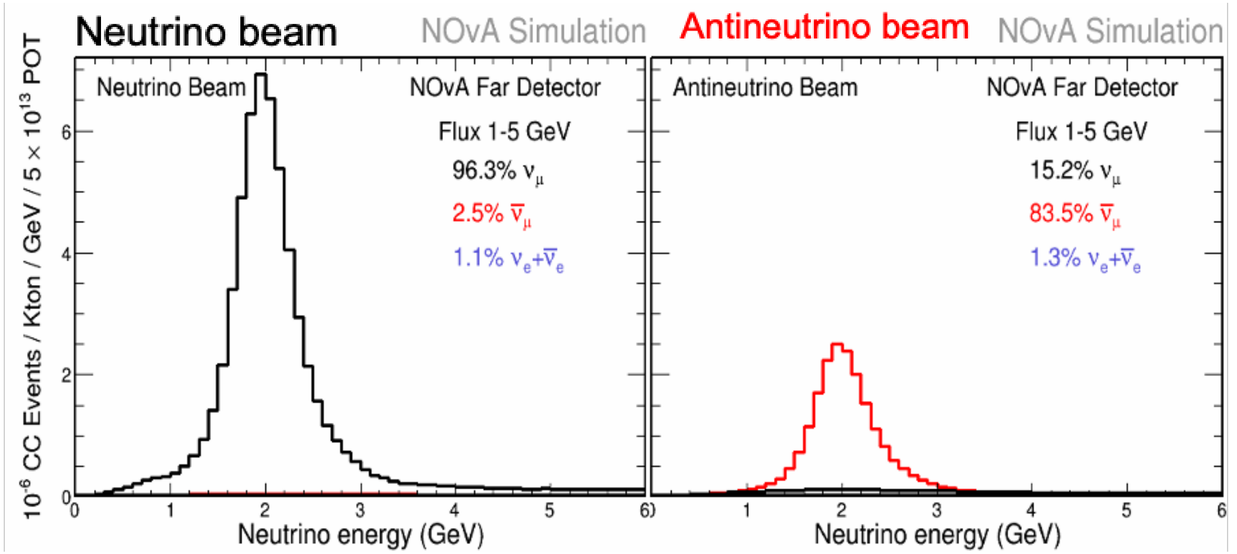


- Matter has the opposite effect on neutrino and anti-neutrino oscillation
- Matter effect determine the CP-violating phase and the sign of the $|\Delta m^2_{32}|$

Neutrino Beam at Fermilab



- Neutrino and antineutrino modes
- Total protons-on-target 38 x 10^{20}
- High $\nu_\mu(\bar{\nu}_\mu)$ purity



Neutrino Oscillation Analysis

- Aim of the oscillation analysis is to measure $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$ and δ_{cp} parameters

- Parameters are extracted by analyzing the $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance data

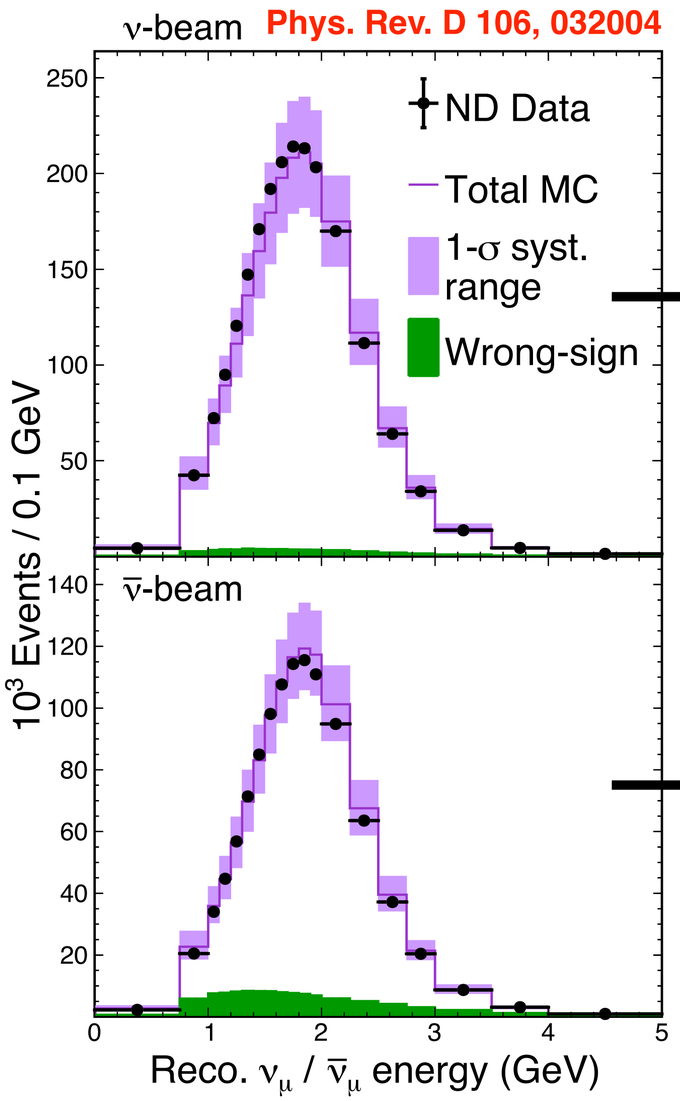
- Both neutrino and anti-neutrino data is used for the parameter extraction

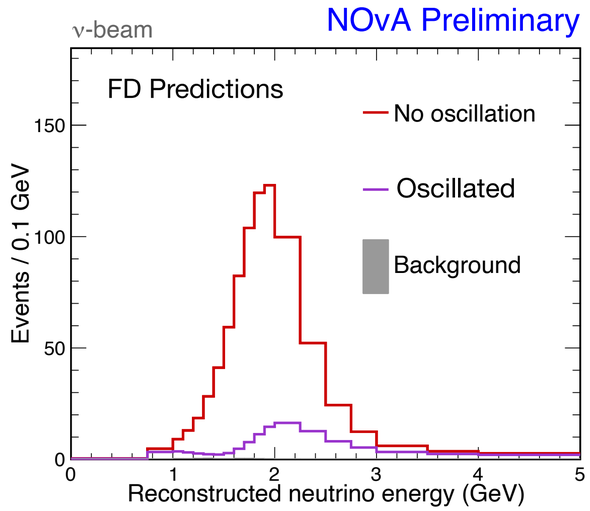
Best fit values of the oscillation parameter are extracted from the χ^2 fit

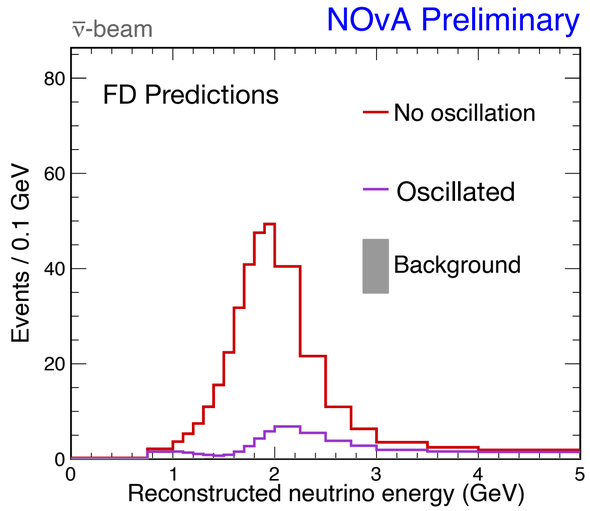
$$\chi^2_i = 2 \times \left(F_i^{Pred.} - F_i^{Data} + F_i^{Data} \ln \frac{F_i^{Data}}{F_i^{Pred.}} \right)$$

- Systematic uncertainties are treated as nuisance parameters

ND Data

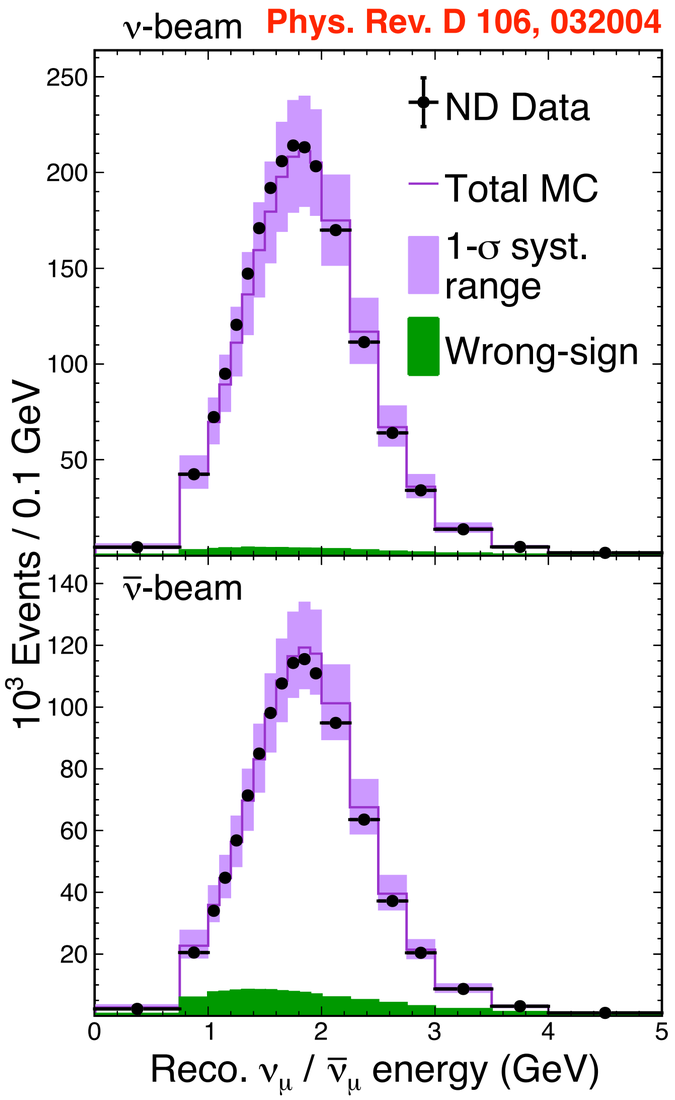


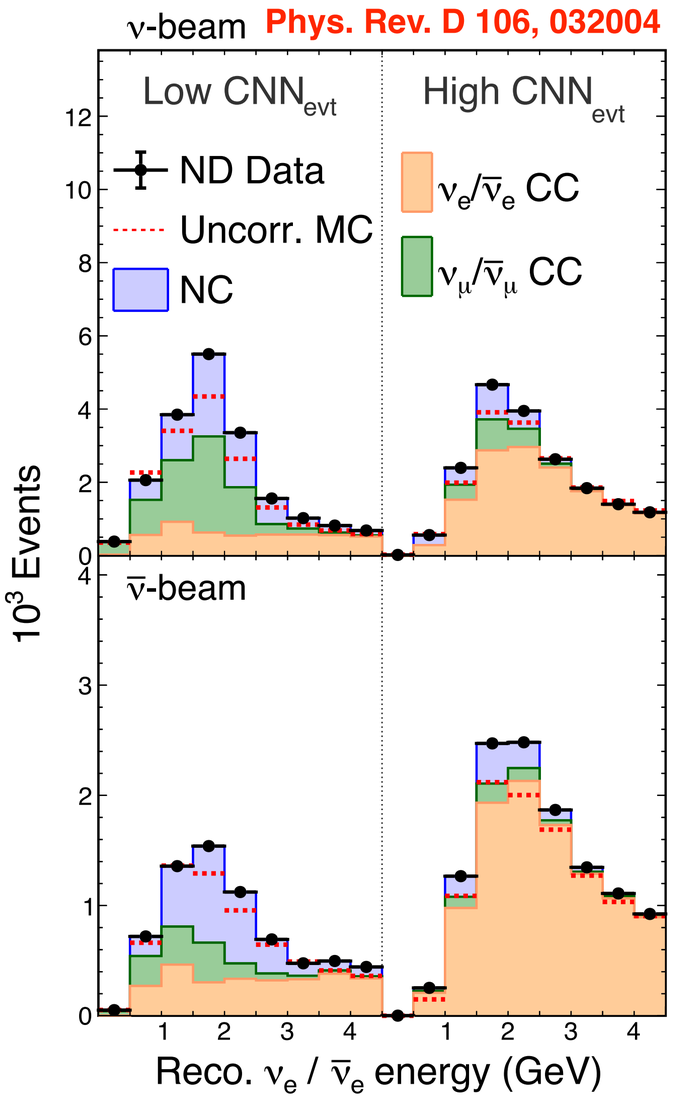




- ND observes un-oscillated neutrino beam
- ND spectra is used to generate signal and background predictions in the FD
- ND also helps to constrain systematic uncertainties in the FD

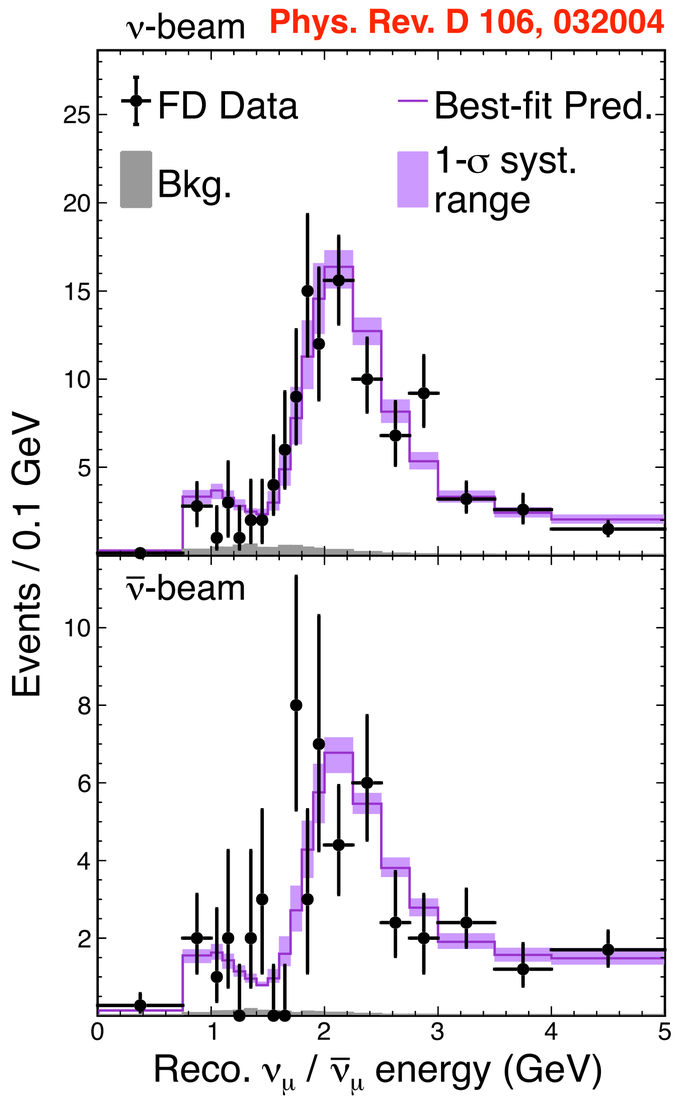
ND Data

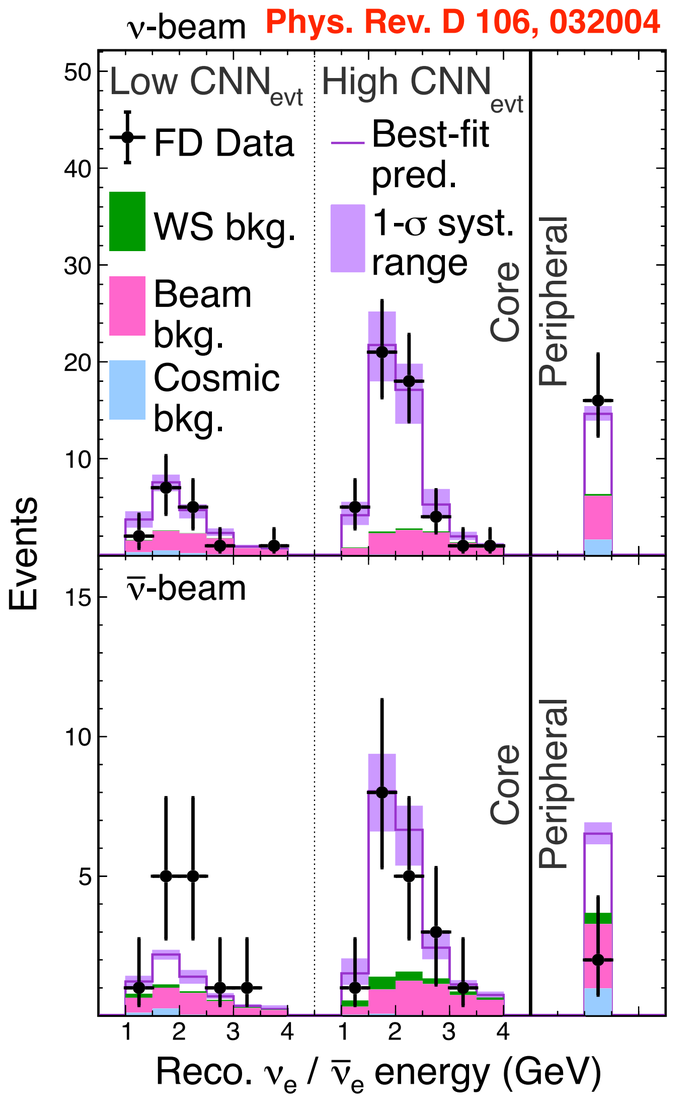




- The ND data helps to constrain systematic uncertainties in the FD

$\nu_\mu \rightarrow \nu_\mu$ Disappearance and $\nu_\mu \rightarrow \nu_e$ Appearance data

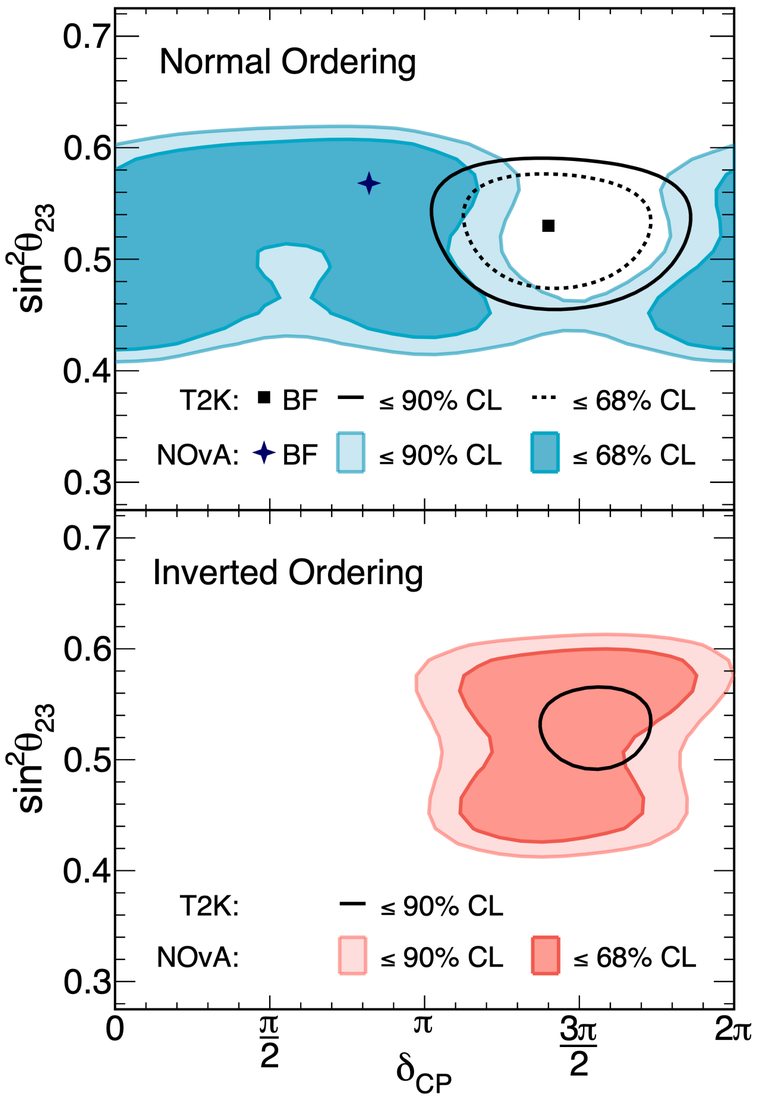




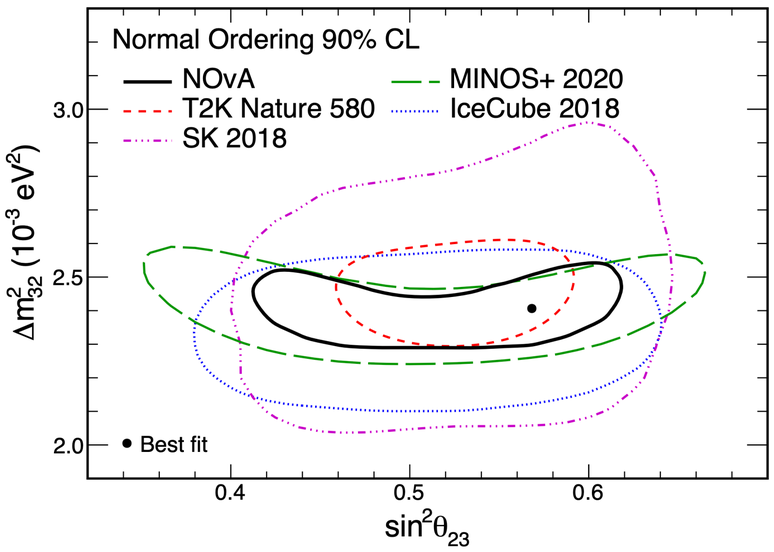
- Observe
  - 82 ν_e candidates (27 bkg)
  - 33 $\bar{\nu}_e$ candidates (14 bkg)
- There is a large significance of ν_e appearance
- >4σ evidence of $\bar{\nu}_e$ appearance

Oscillation Results

Phys. Rev. D 106, 032004 NOvA Preliminary



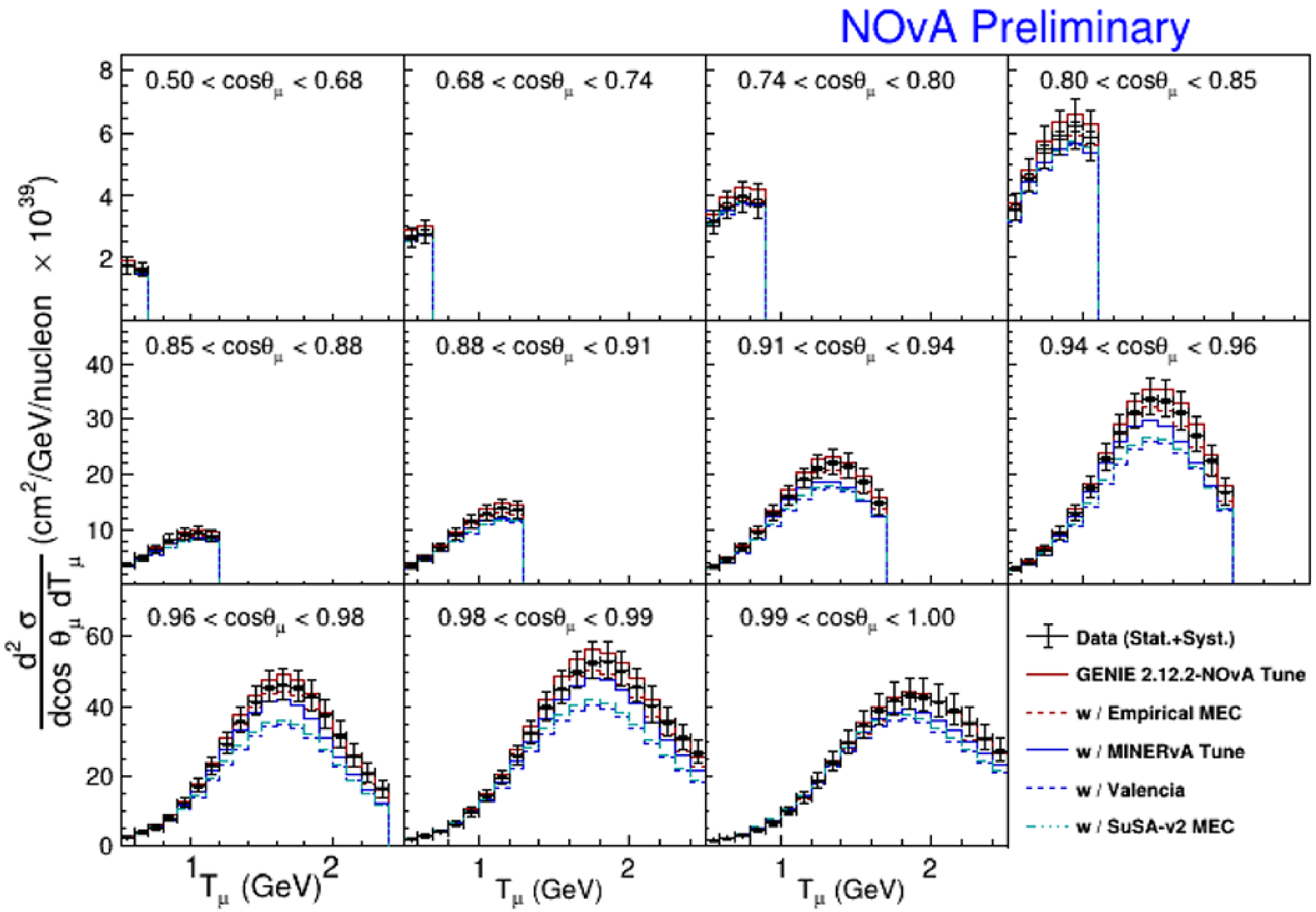
Phys. Rev. D 106, 032004 NOvA Preliminary



Oscillation Parameters	Values
Δm^2_{32} (10^{-3}) eV²/c⁴	$+2.41 \pm 0.07$
$\sin^2\theta_{23}$	$0.57^{+0.03}_{-0.04}$
δ_{cp} (π)	$0.82^{+0.27}_{-0.87}$

- LO disfavoured at 1.2σ
- IH disfavoured at 1σ
- IH $\delta_{cp} = \pi/2$ excluded at $>3\sigma$
- NH $\delta_{cp} = 3\pi/2$ excluded at ~2σ

Muon System



- Exactly one reconstructed track associated with outgoing muon
- Boosts 2p2h, reduces DIS and RES interactions
- Uncertainties ~12-15% in each bin dominated by flux systematic

Comparisons of 2p2h Models to Data

- Large χ^2 values seen for all 2p2h models/tunes
- Tuned models match data better than Valencia/SuSA-v2
- Hadronic system analysis suggests similar conclusions

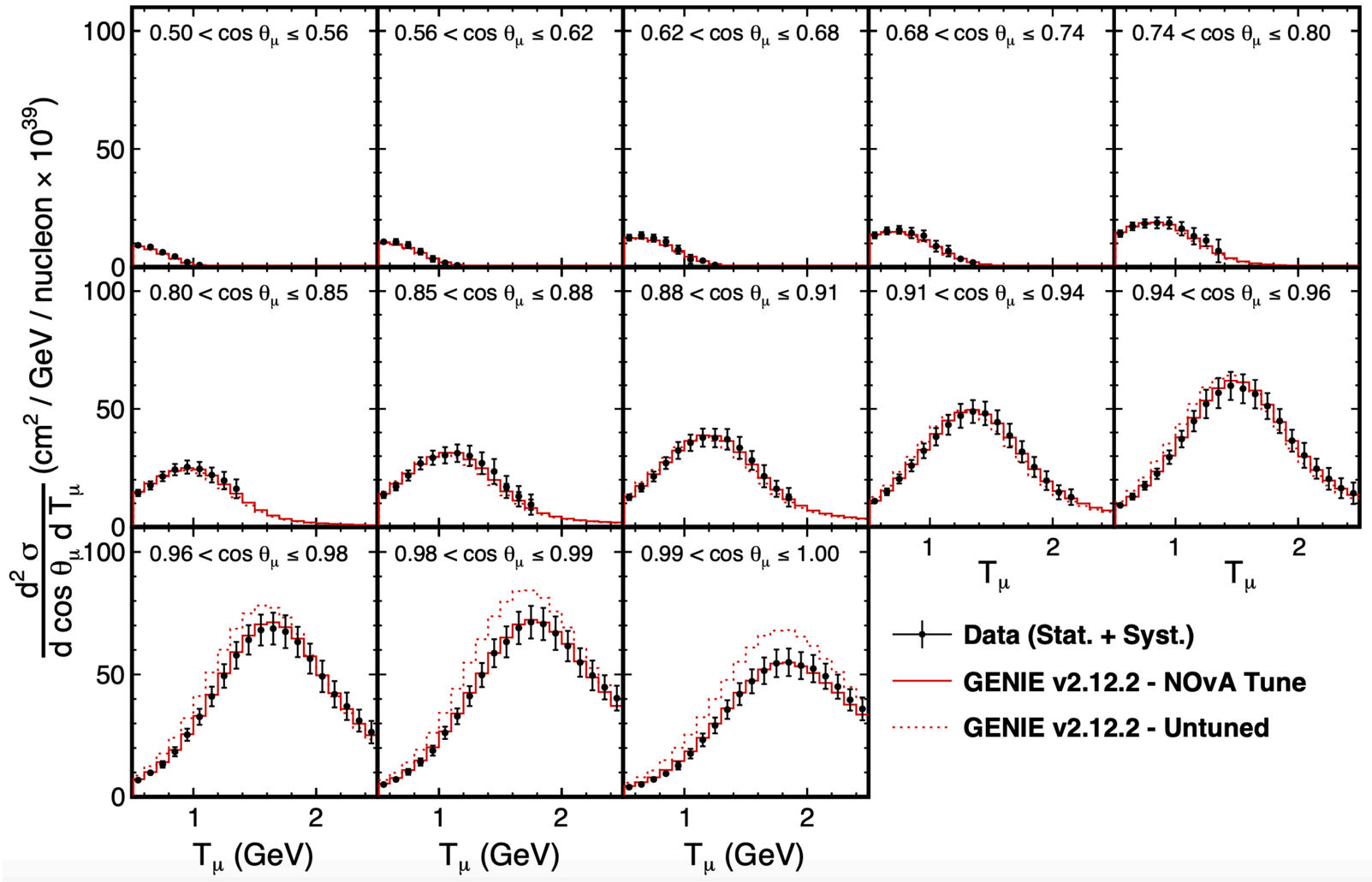
2p2h Model	χ^2 (115 d.o.f.)
GENIE v2-12.2 NOvA Tune	200
Empirical MEC	190
Valencia w/ MINERvA Tune	340
Valencia	630
SuSA - v2	620

Tuned models

Theoretical models

ν_μ CC Inclusive Cross section

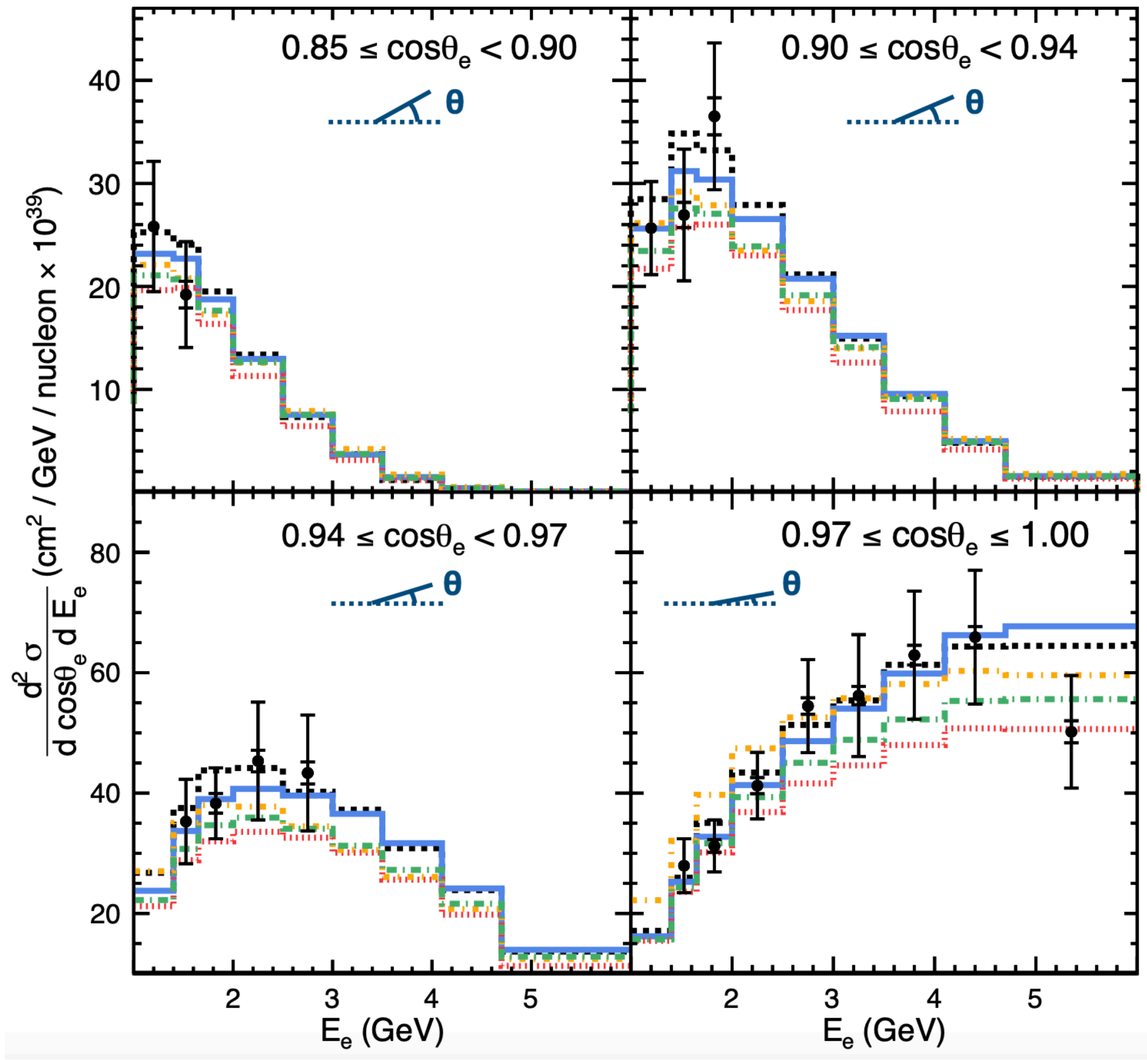
https://arxiv.org/abs/2109.12220

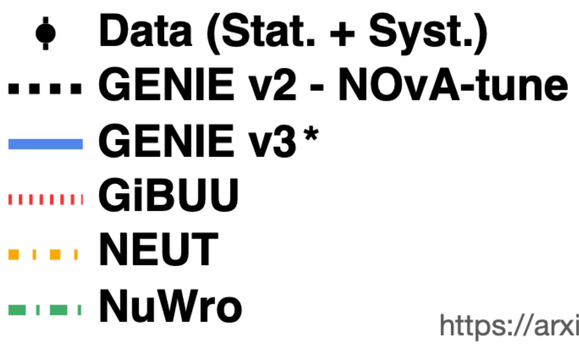


- More than 1M ν_μ CC events in the analysis
- Good agreement between GENIE and Data
- Uncertainties ~12% in each bin

ν_e CC Inclusive Cross section

https://arxiv.org/abs/2206.10585



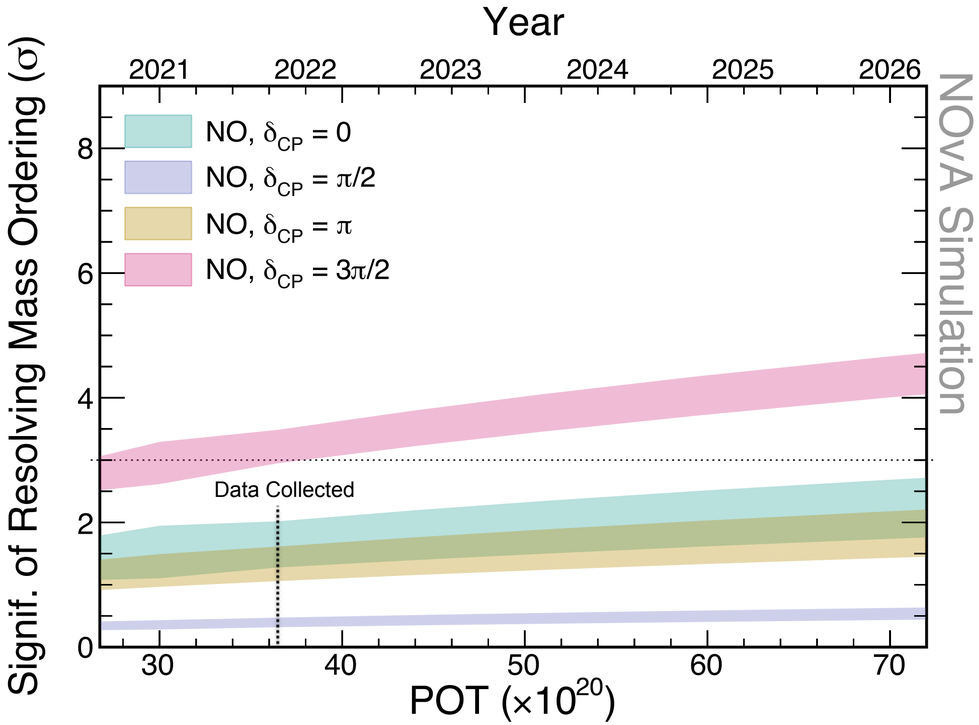


https://arxiv.org/abs/2206.10585

- Around 10k ν_e CC events in the analysis
- Measurment in good agreement with prediction generators
- Uncertainties ~15-20% in each bin

Future Outlook

- Oscillations
  - Increasing sensitivity to mass ordering to come
  - More than double data both in neutrino and antineutrino modes
  - We can reach >3σ mass-hierarchy sensitivity for 30-50% of the δ_{cp} values



- Cross sections
  - Antineutrino beam cross-section measurements and ratios

Conclusions

- NOvA is a globally competitive neutrino oscillation experiment with many exciting results
- NOvA and T2K are both working together towards joint fit results
- Other exciting NOvA analyses are
  - Sterile Neutrinos (First ever look at NC disappearance in antineutrinos https://inspirehep.net/literature/1867930)
  - Supernova neutrinos https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.063024
  - Magnetic Monopoles https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.012007
  - Non-standard Interactions

Conclusions

- Both Frequentist and Bayesian methods give same oscillation results
- Measured $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$ - consistent with reactor measurements
- Observe discrepancies w/2p2h models
- More new data and results to come