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Queen Mary
University of London

NOvA

Neutrino Cross Sections using the NOvA Experiment

Prabhjot Singh, on behalf of the NOvA Collaboration

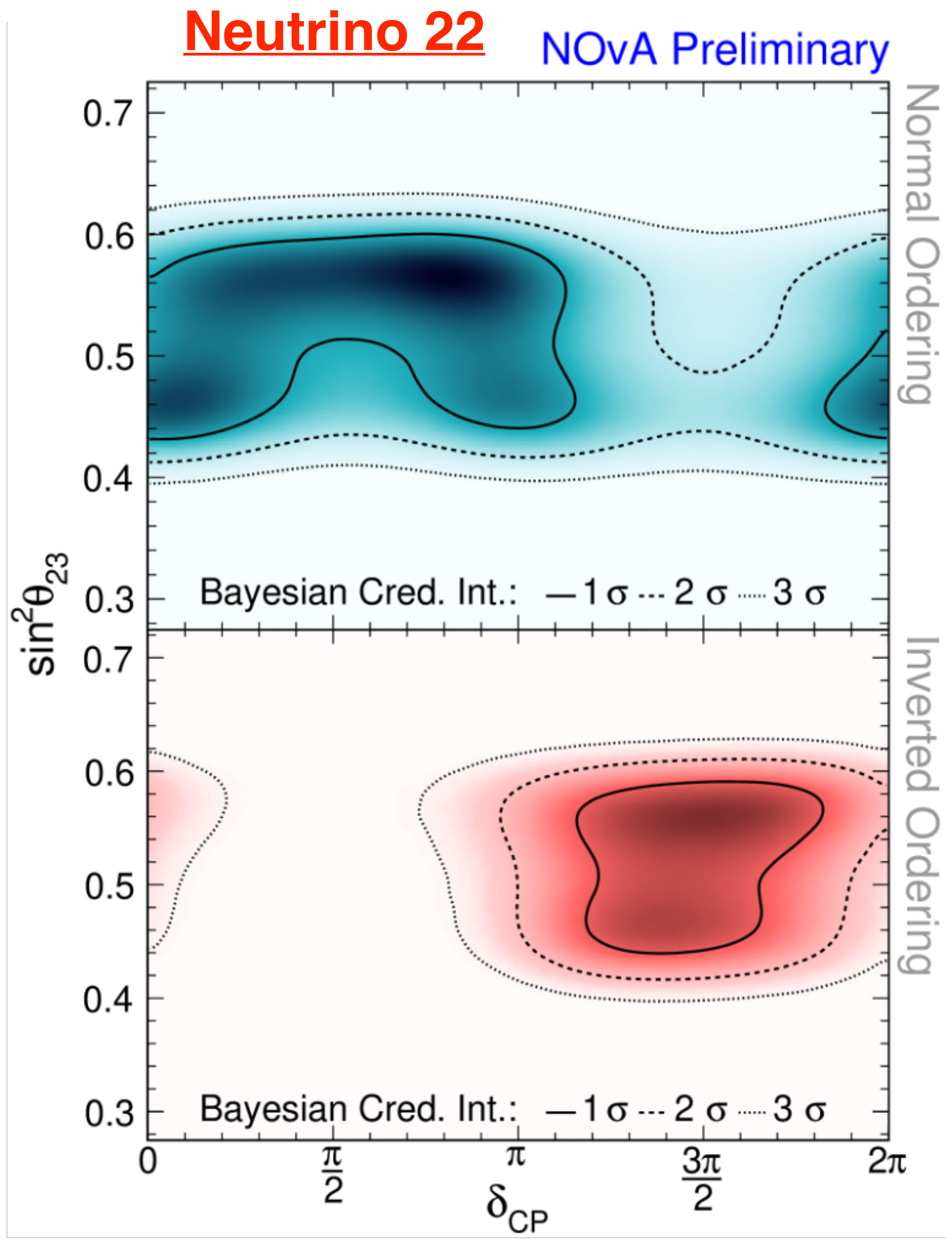
Users Meeting 2023, Fermilab

30 June 2023

NOvA - Physics Program

NOvA has a broad neutrino physics program

- 3-flavor neutrino oscillations
- Searches beyond standard model
  - Sterile Neutrinos
  - Non-standard Interactions
- Exotic searches
  - Supernova neutrinos
  - Magnetic Monopoles



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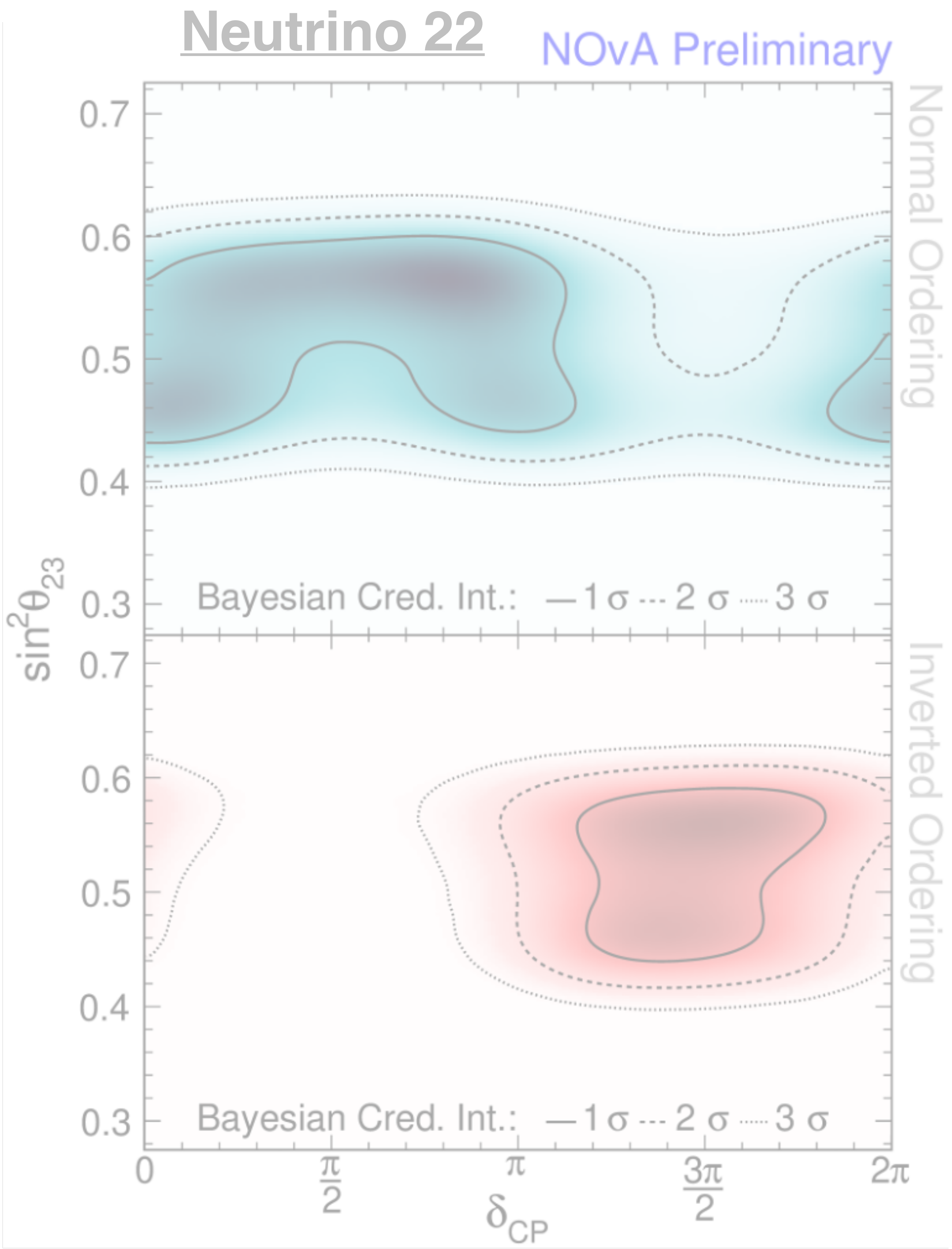
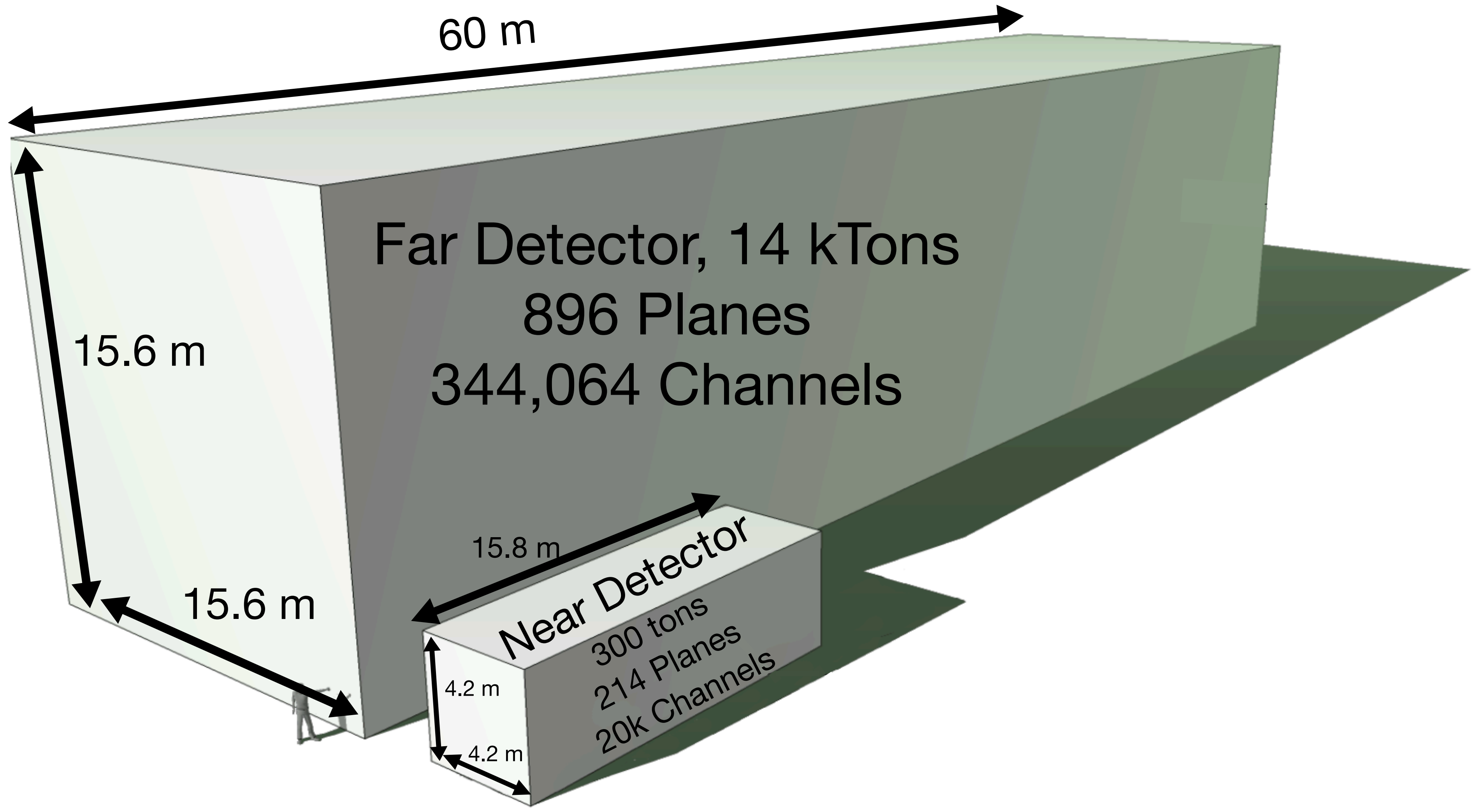
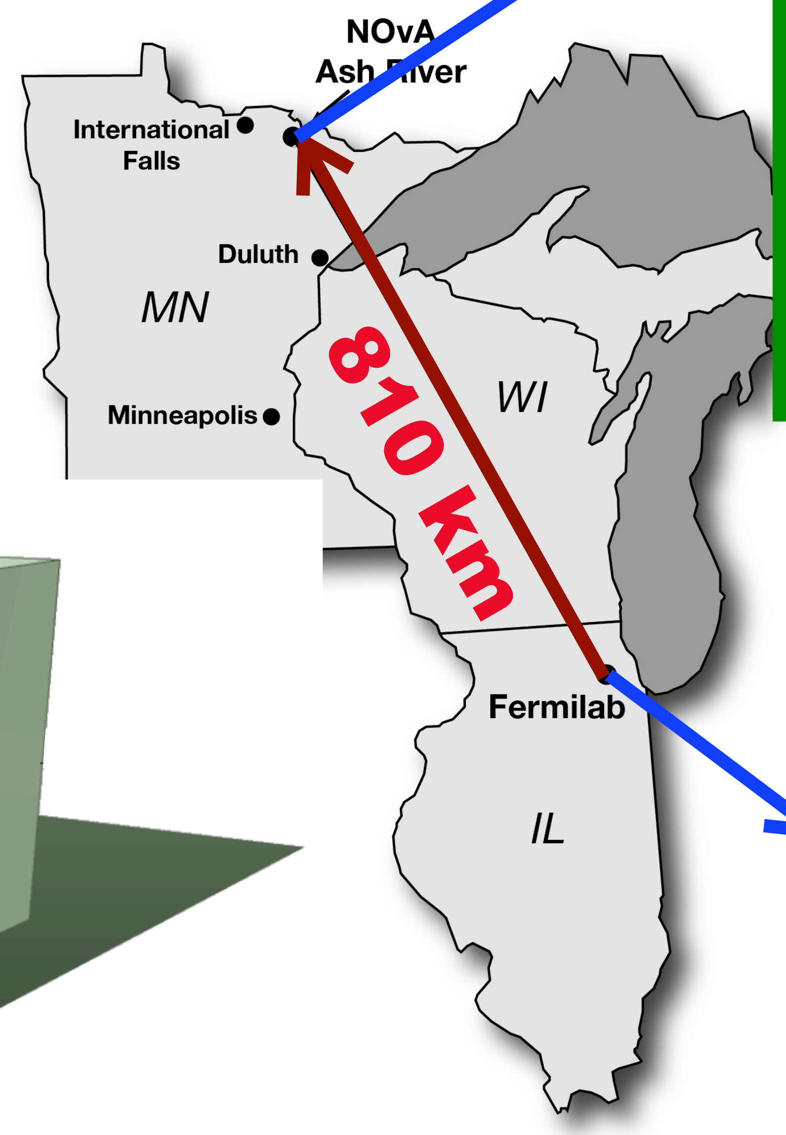


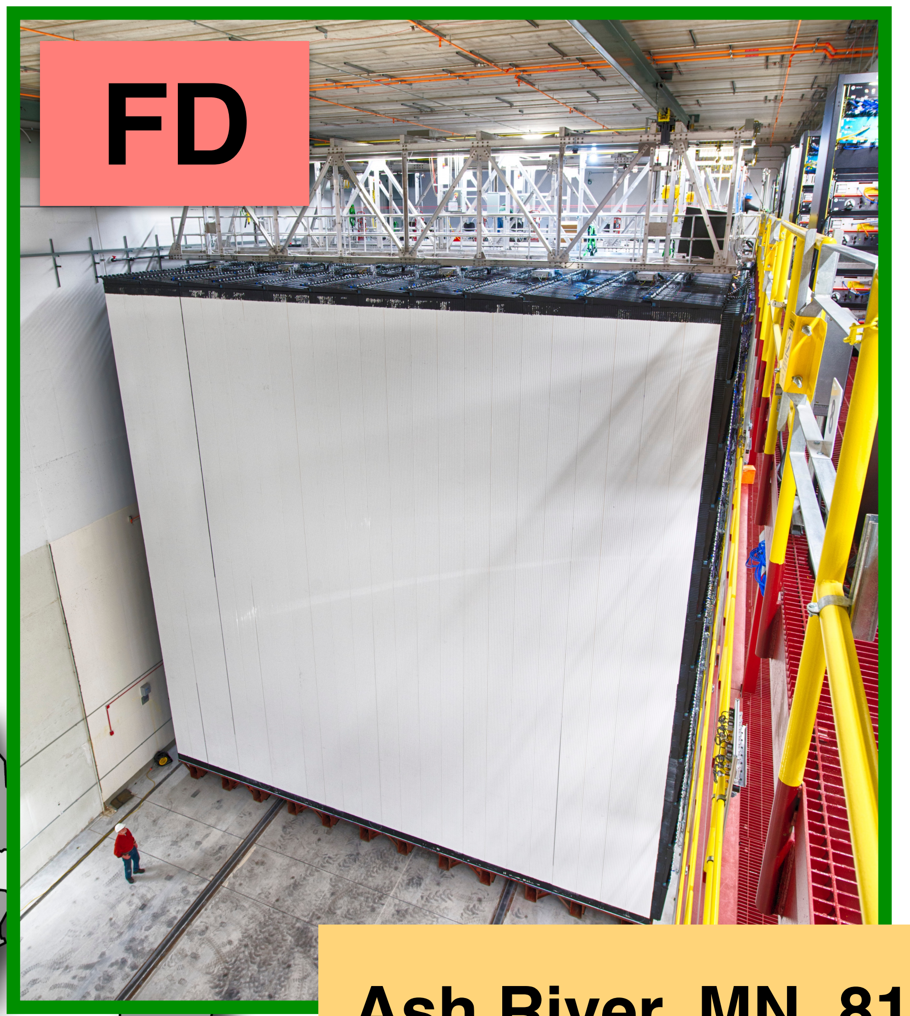
- Neutrino cross section measurements

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
- Functionally identical detectors to reduce systematic uncertainties





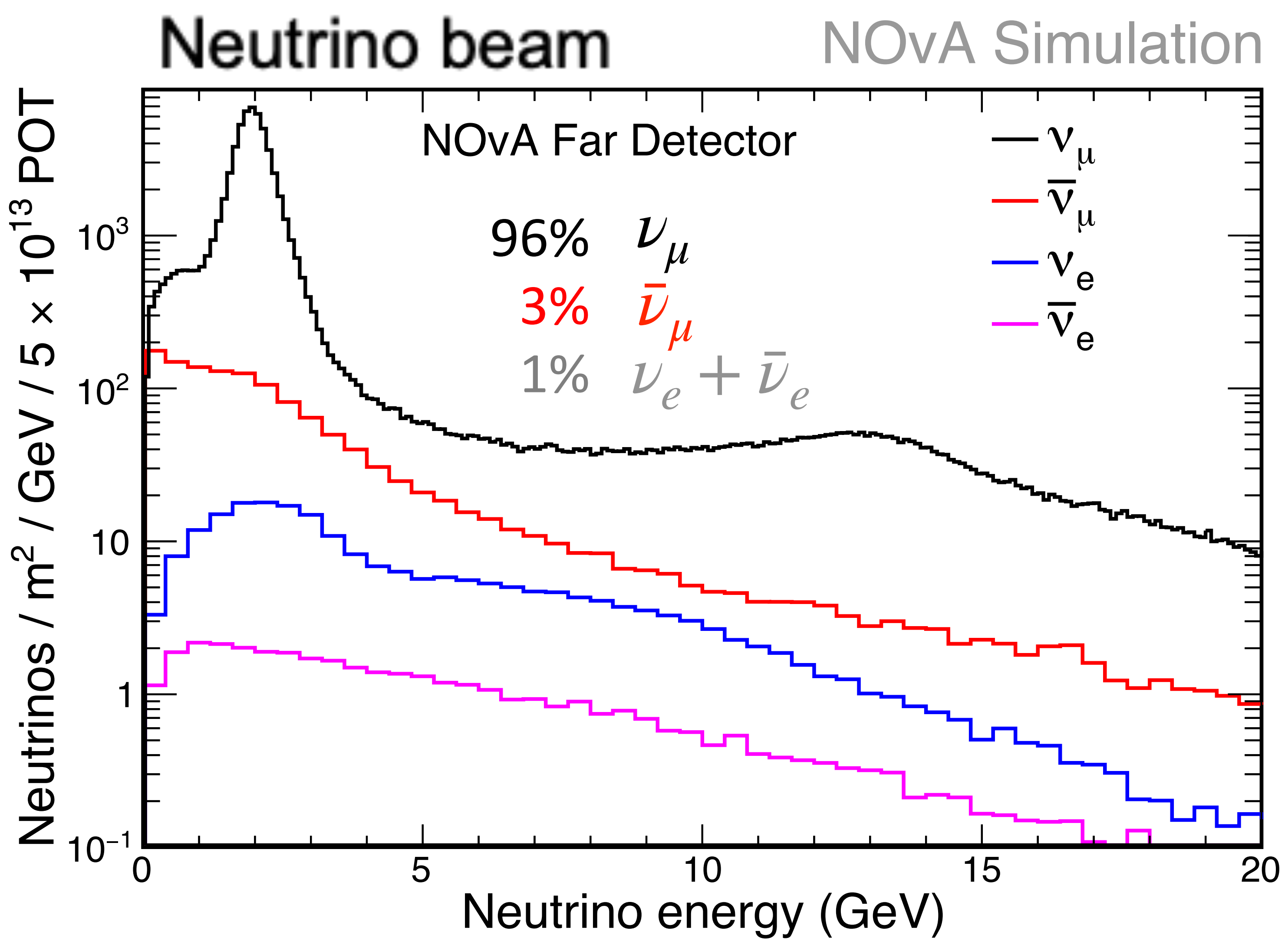


Ash River, MN, 810 km from neutrino source

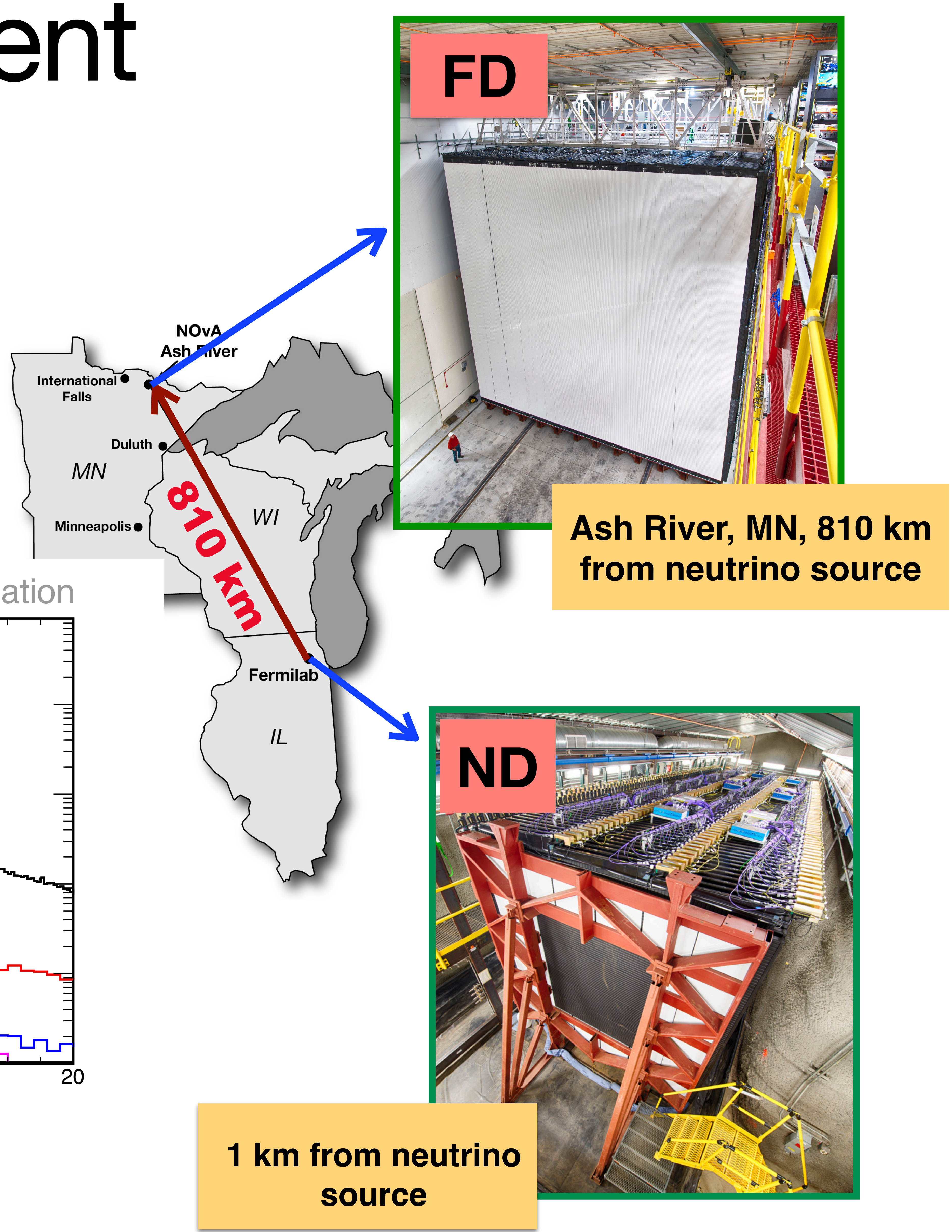
1 km from neutrino source

NOvA Experiment

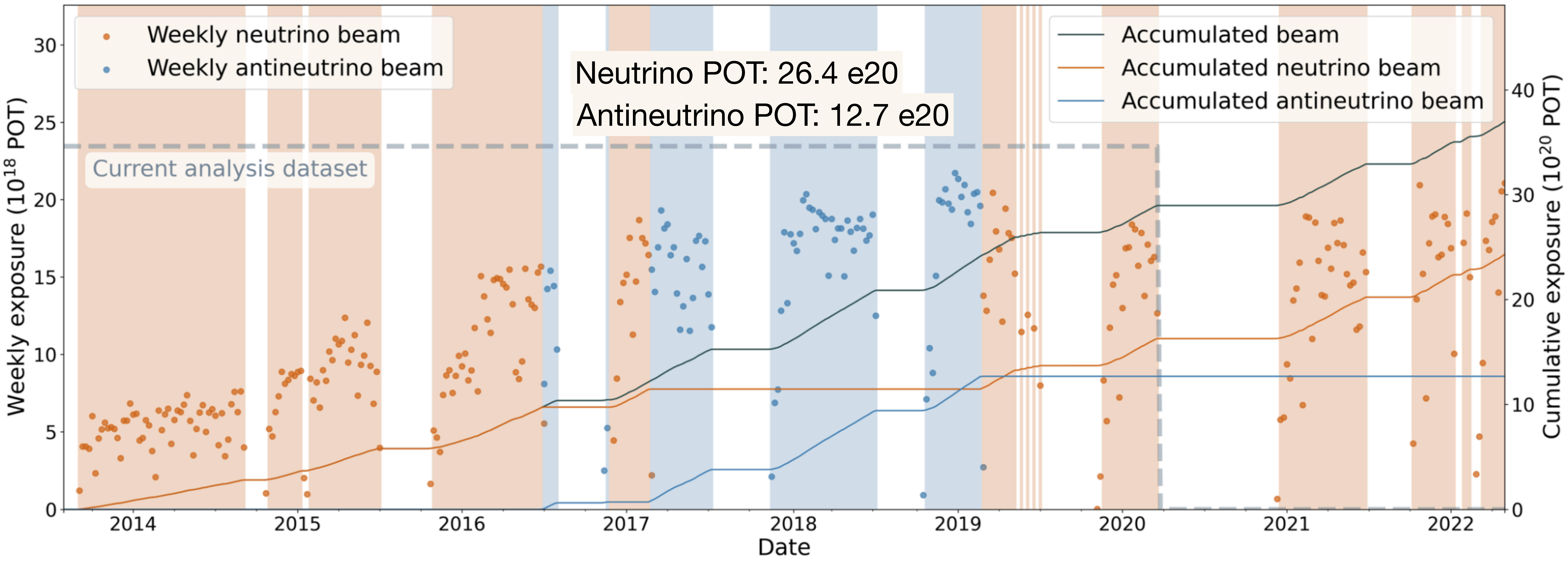
- NOvA is a long-baseline two-detector neutrino oscillation experiment
- Both detectors filled with liquid scintillator and composed of 77% CH_2, 16% chlorine, 6% TiO_2 by mass
- Functionally identical detectors to reduce systematic uncertainties
- 14.6 mrad off-axis detectors
- Neutrino beam peaks at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



High purity ν_μ beam



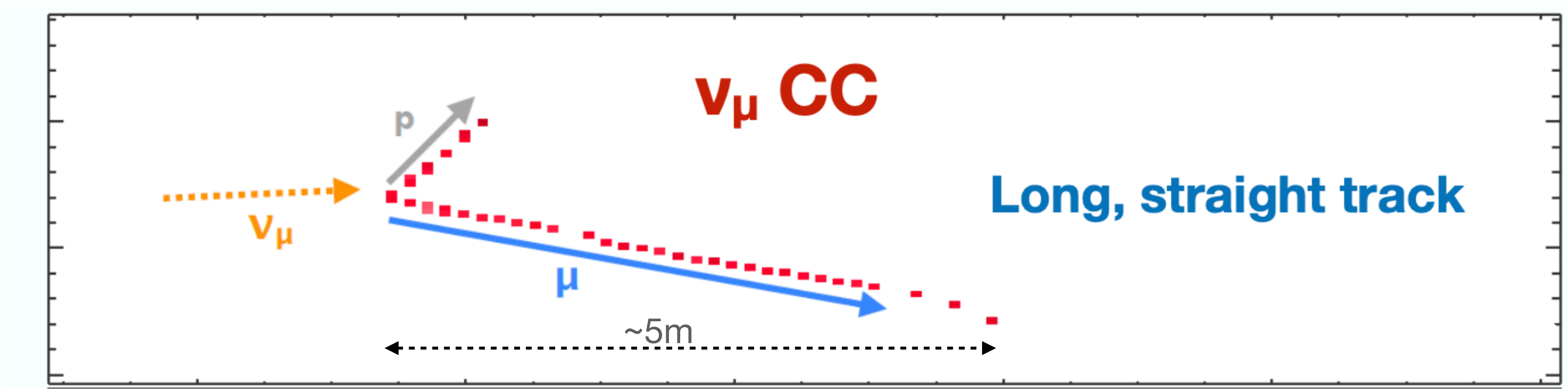
Beam Exposure

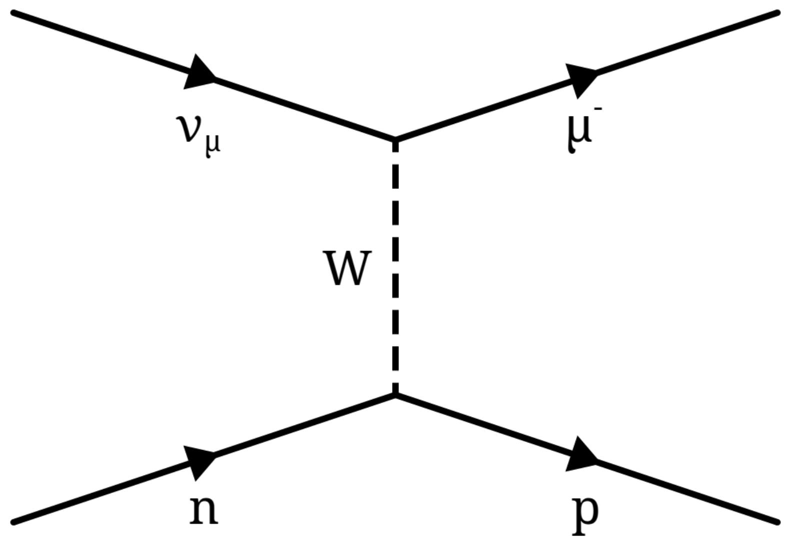


- Total protons on target recorded so far 39e20
- New power record 950+ kW in FY23

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

Event Topologies





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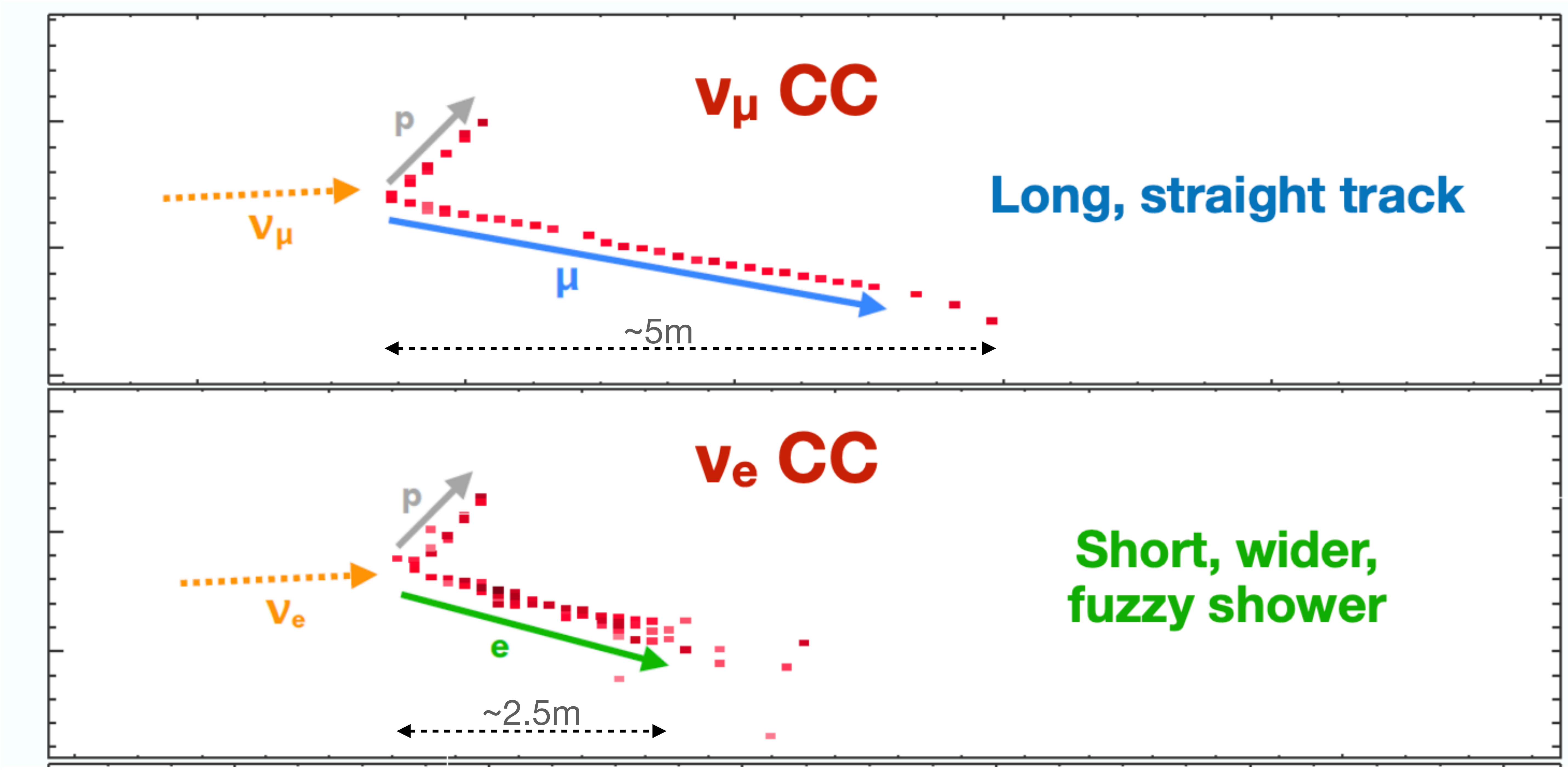

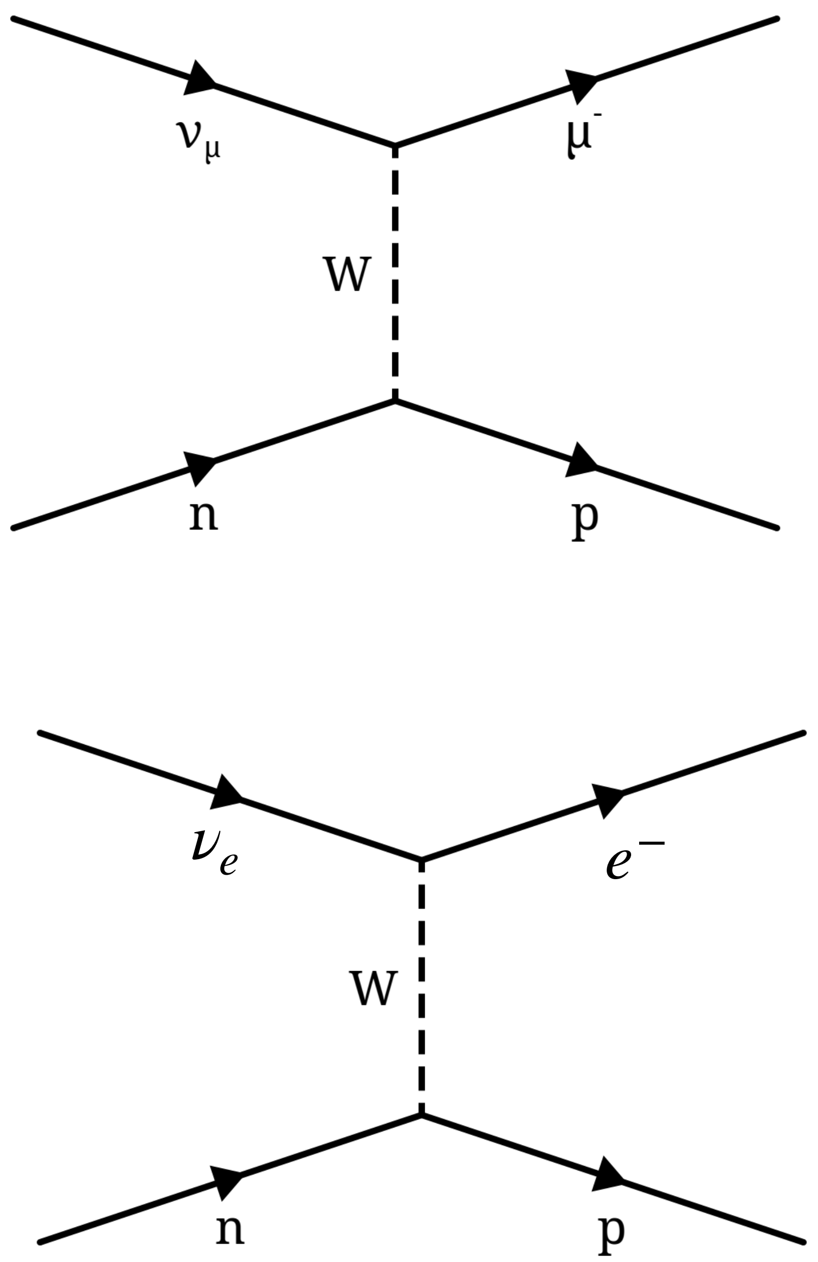

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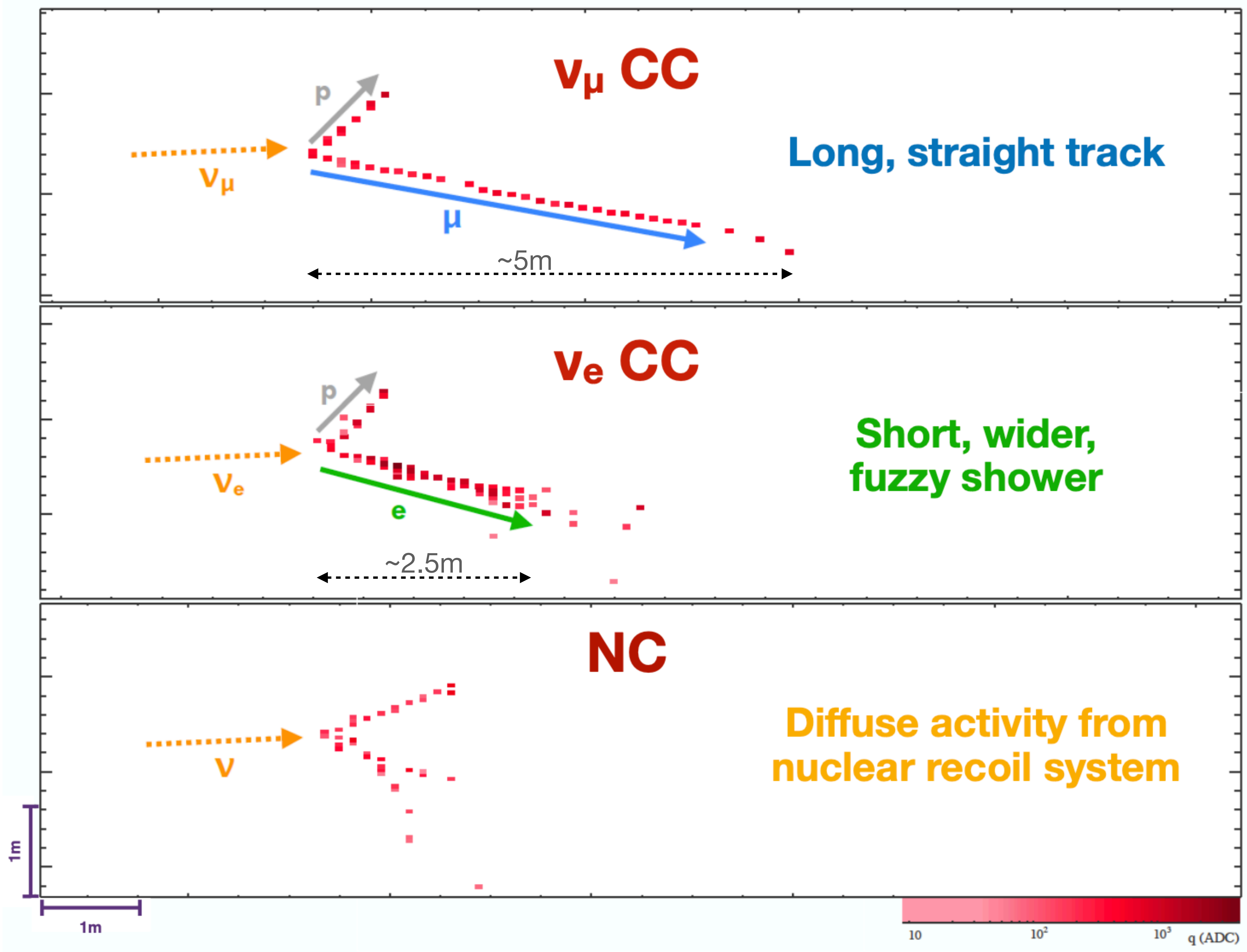
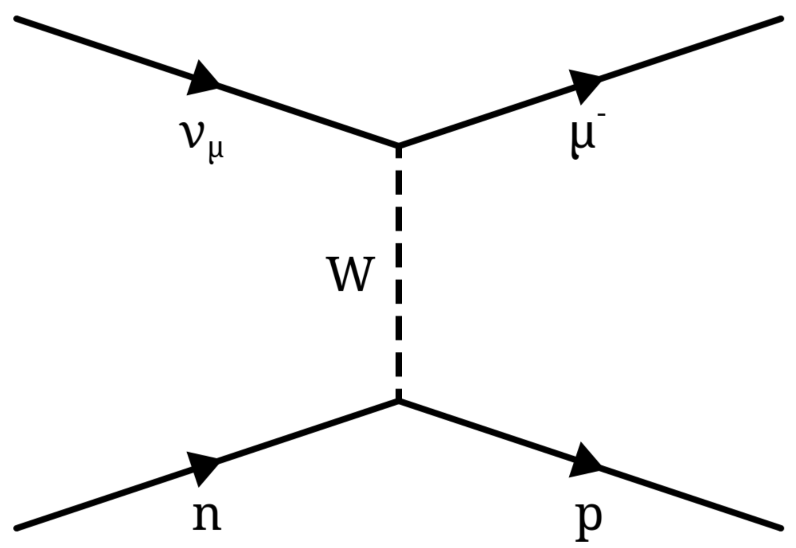
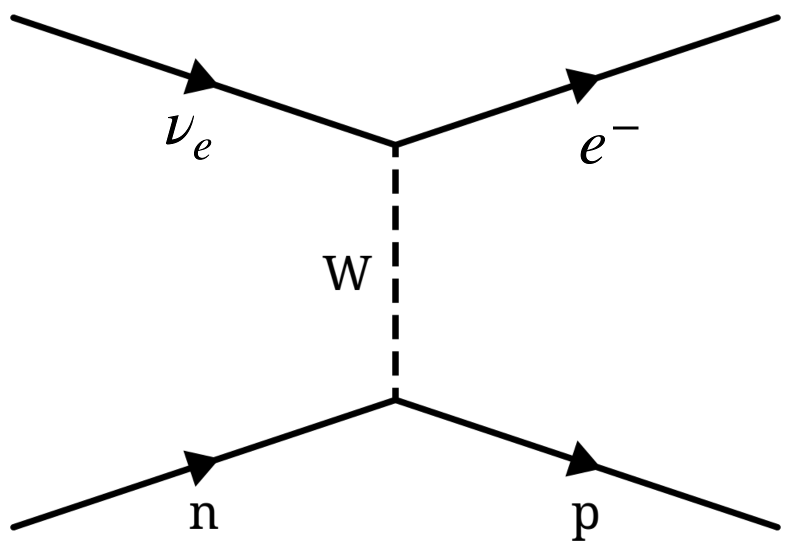
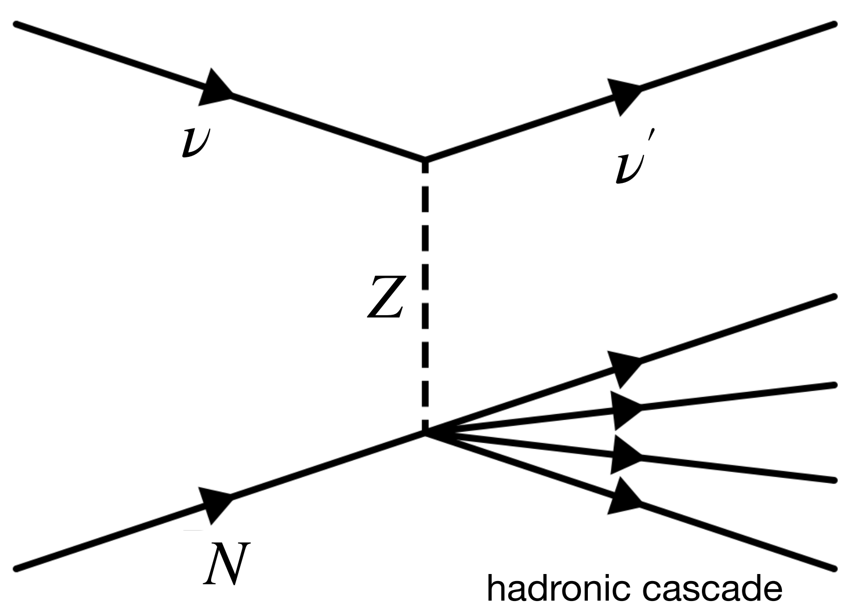
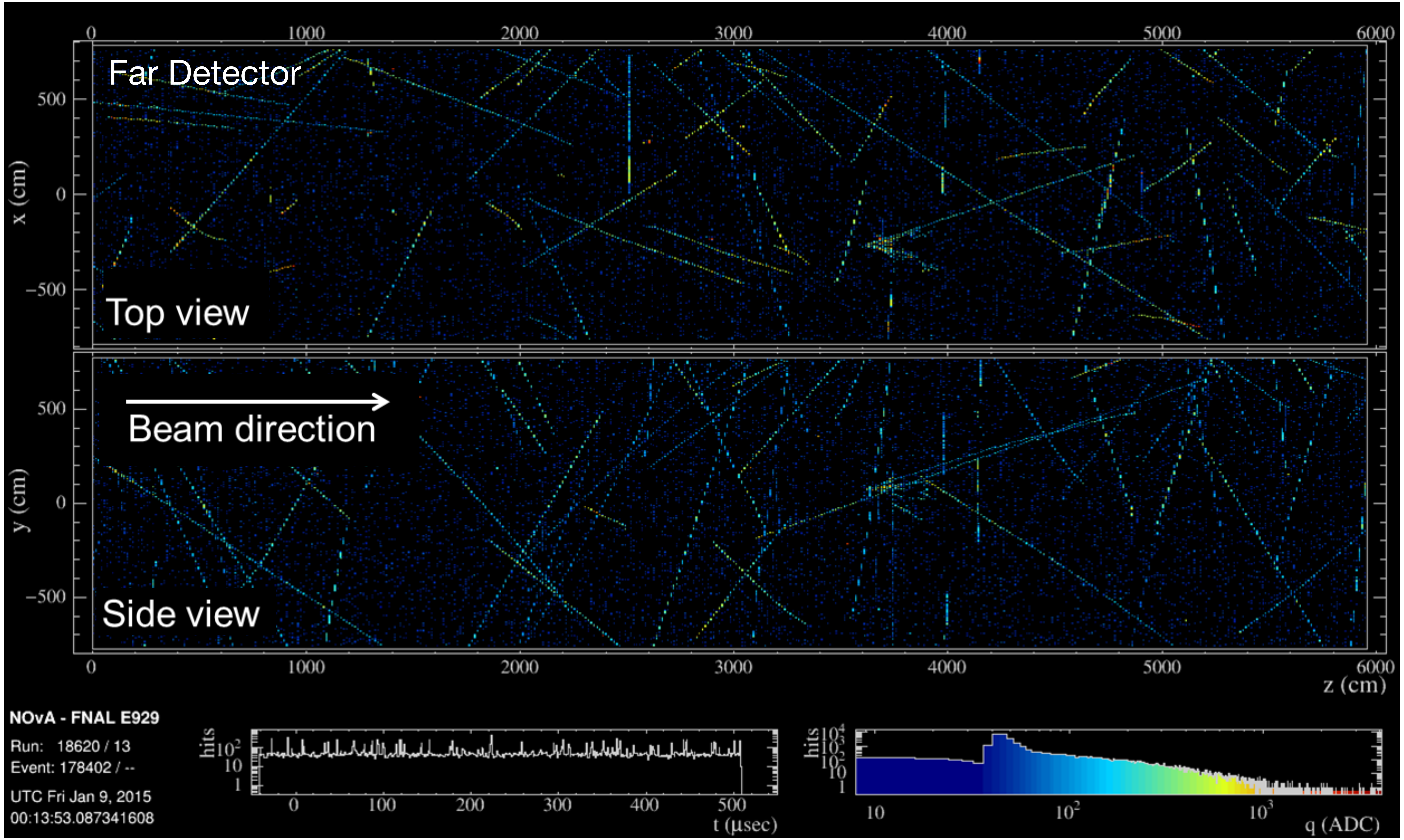








Event Display - Far Detector



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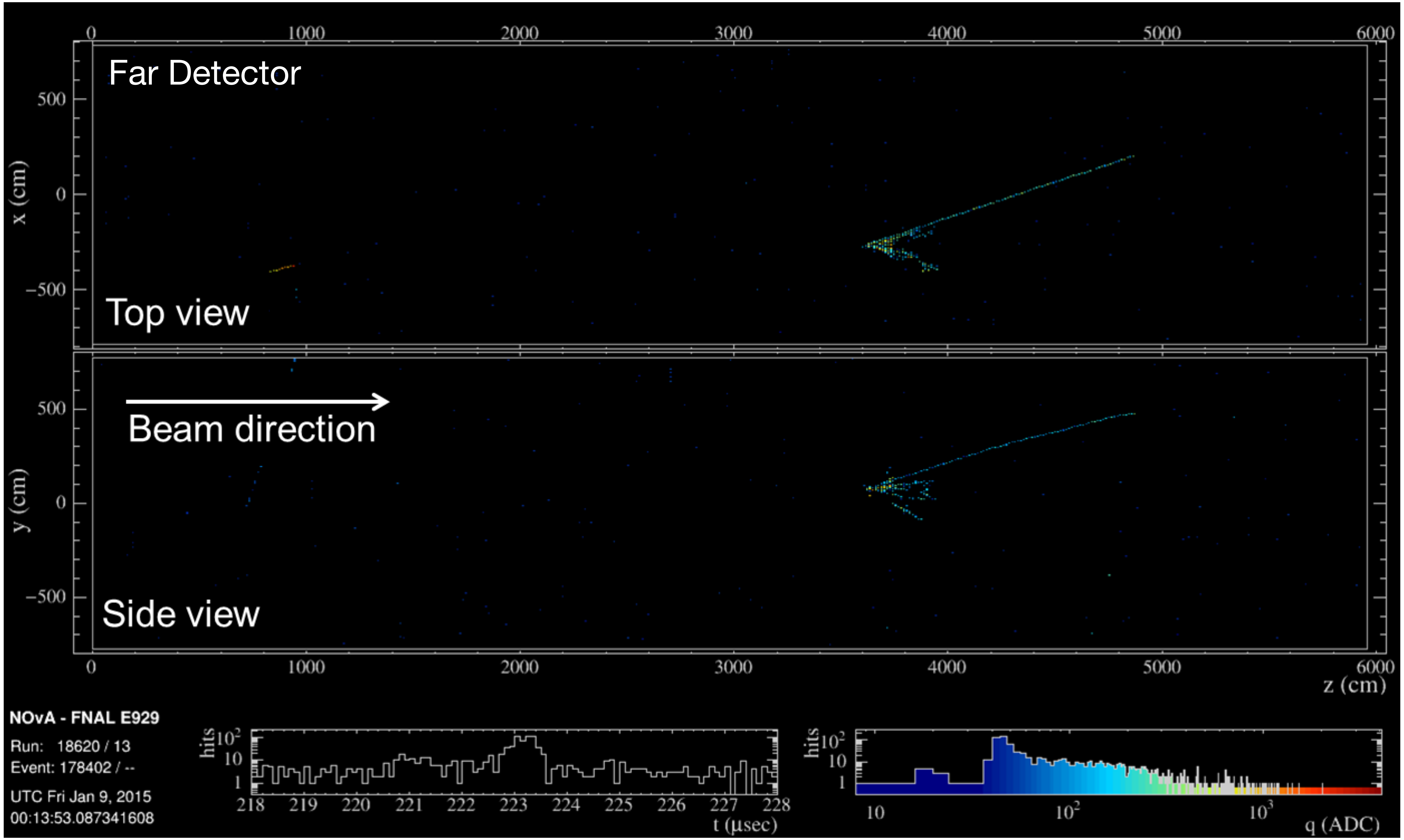

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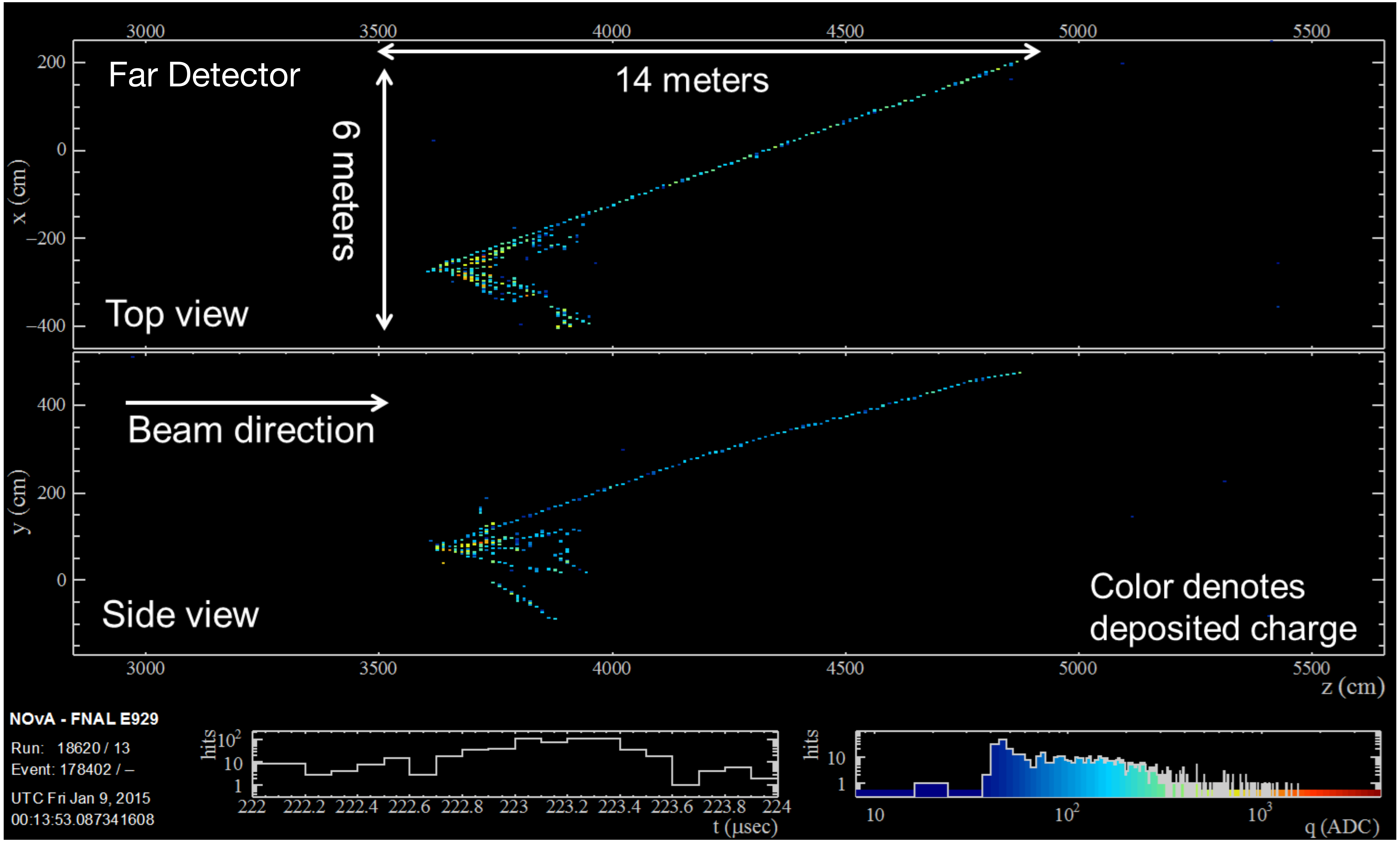
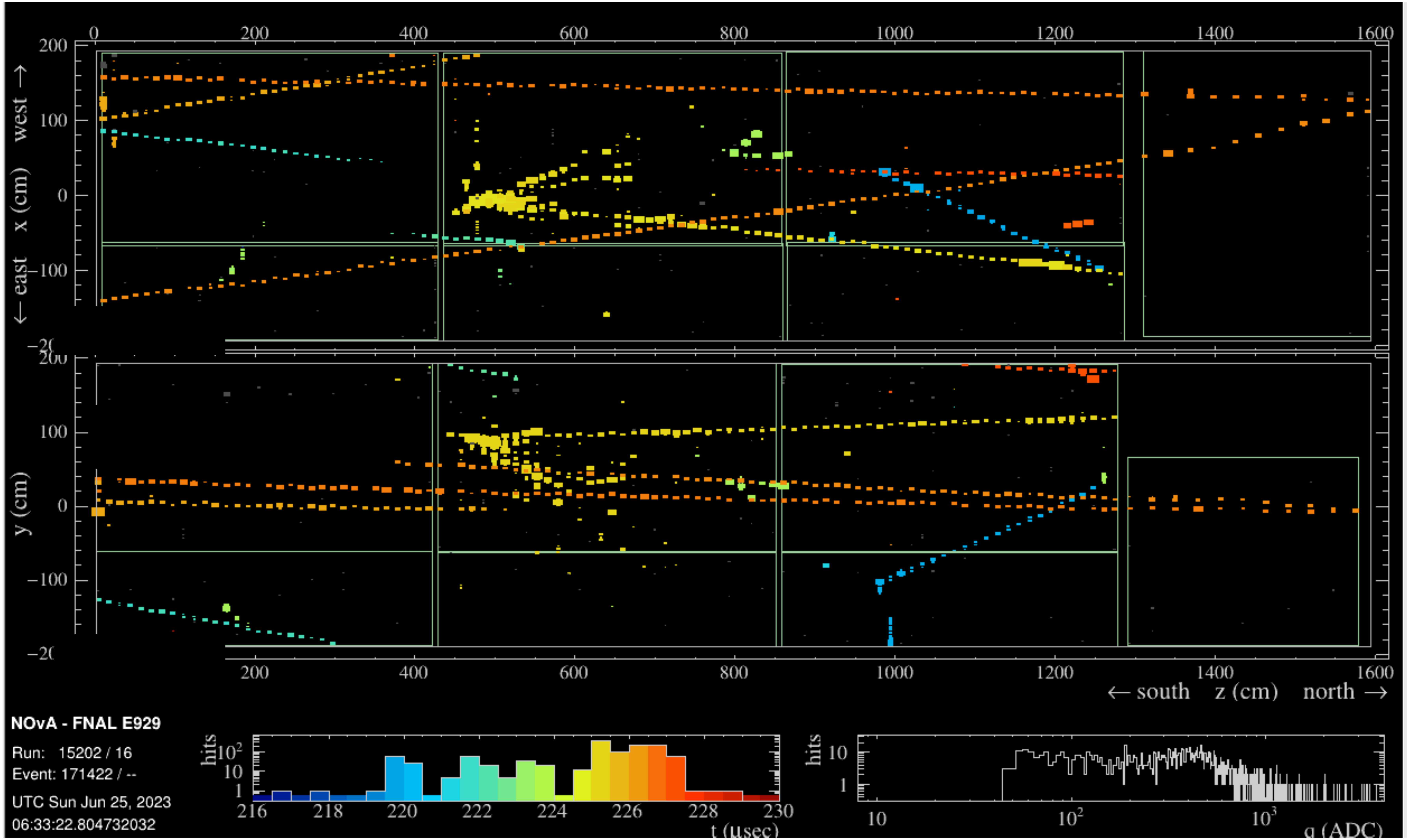


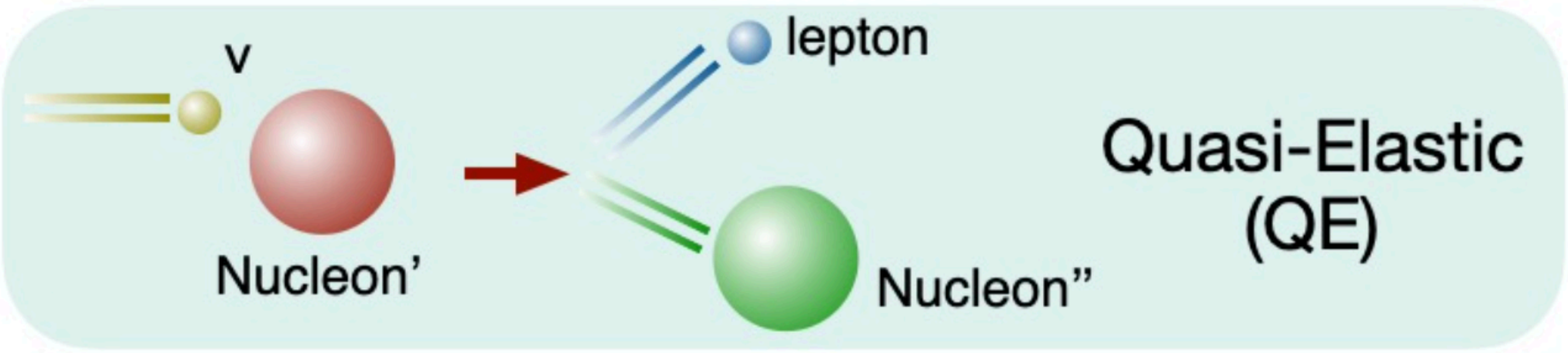
Event Display - Near Detector



Near Detector sees high intensity neutrino beam due to its close proximity to the source

We use this opportunity to do high statistics cross section measurements

Neutrino Interactions in NOvA



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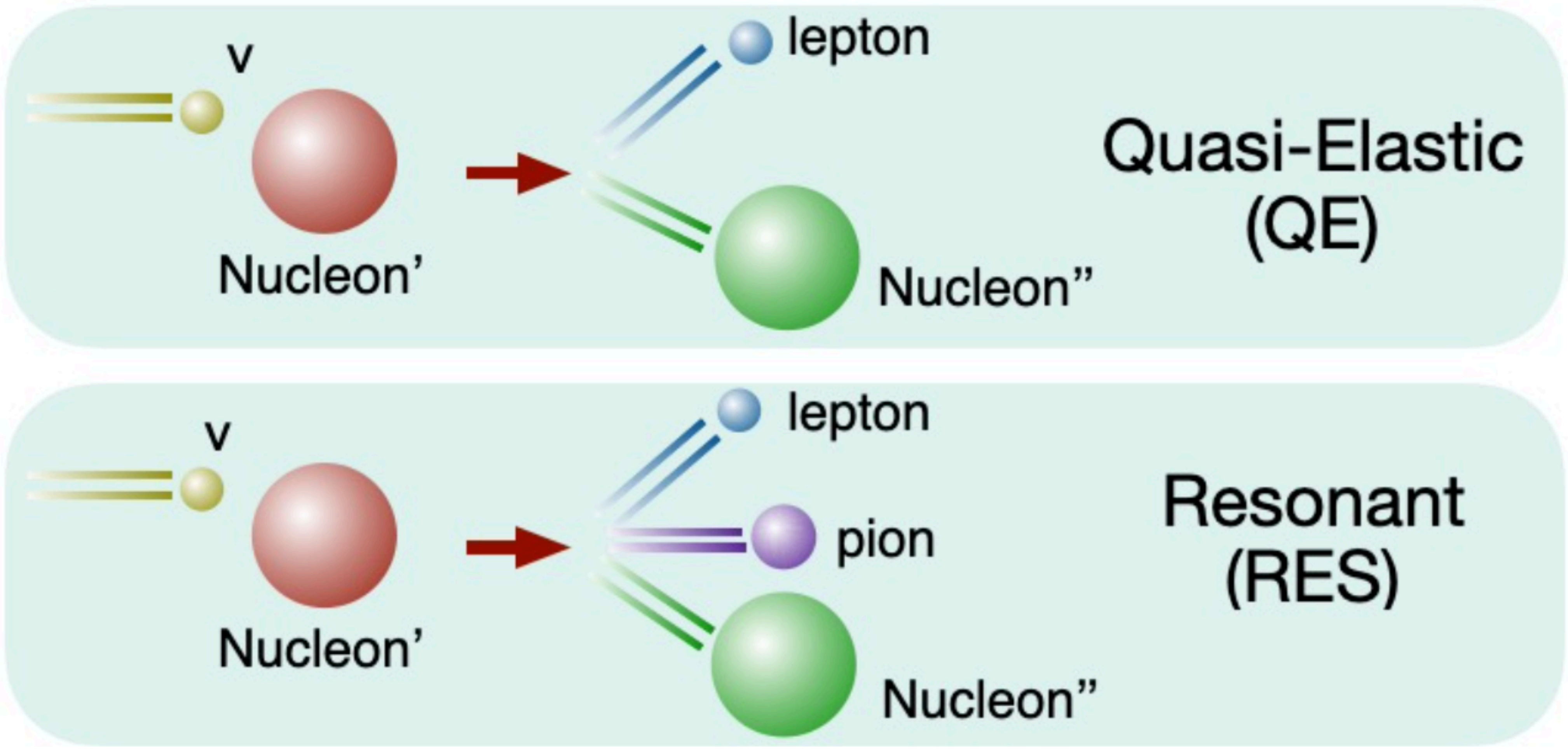

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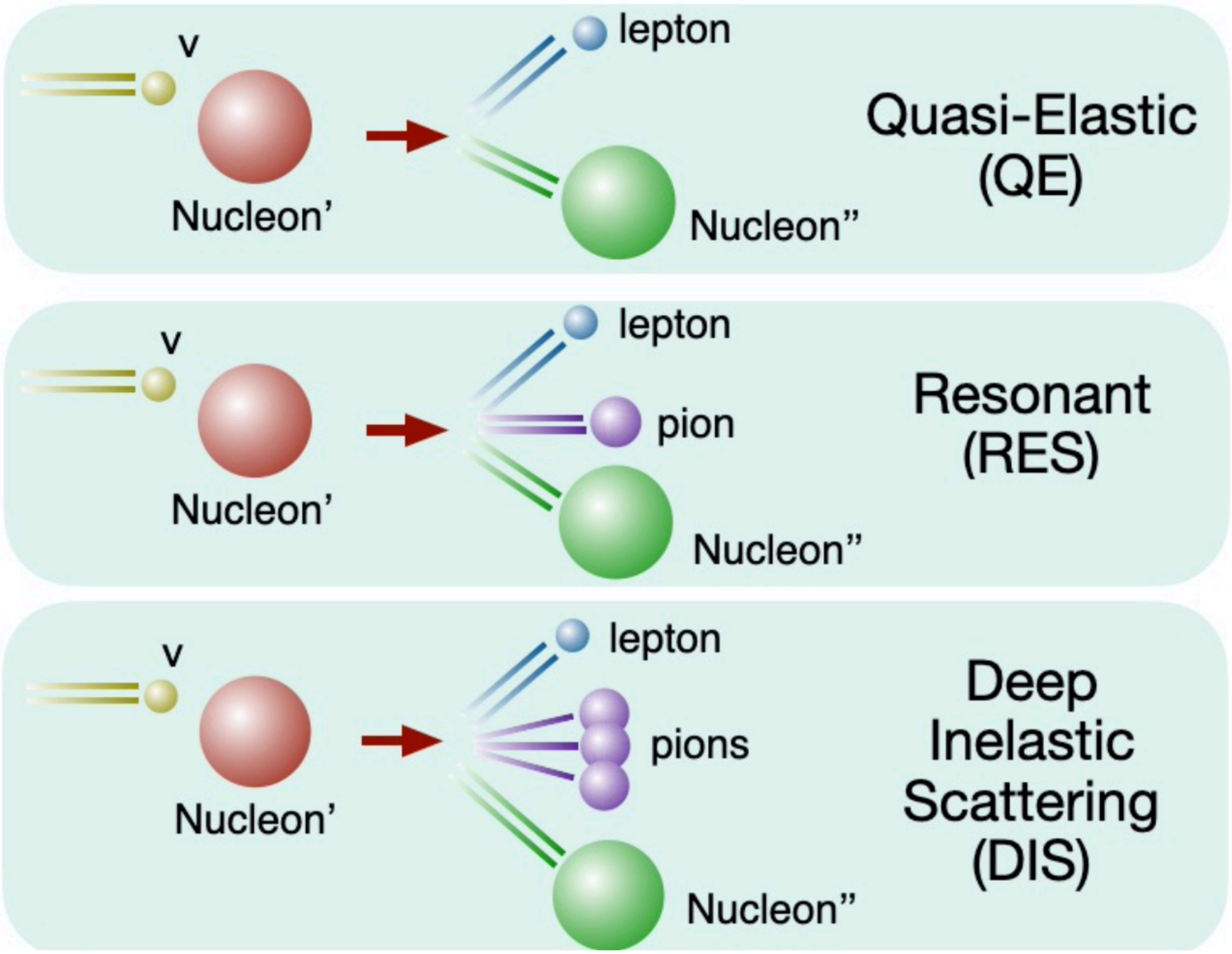

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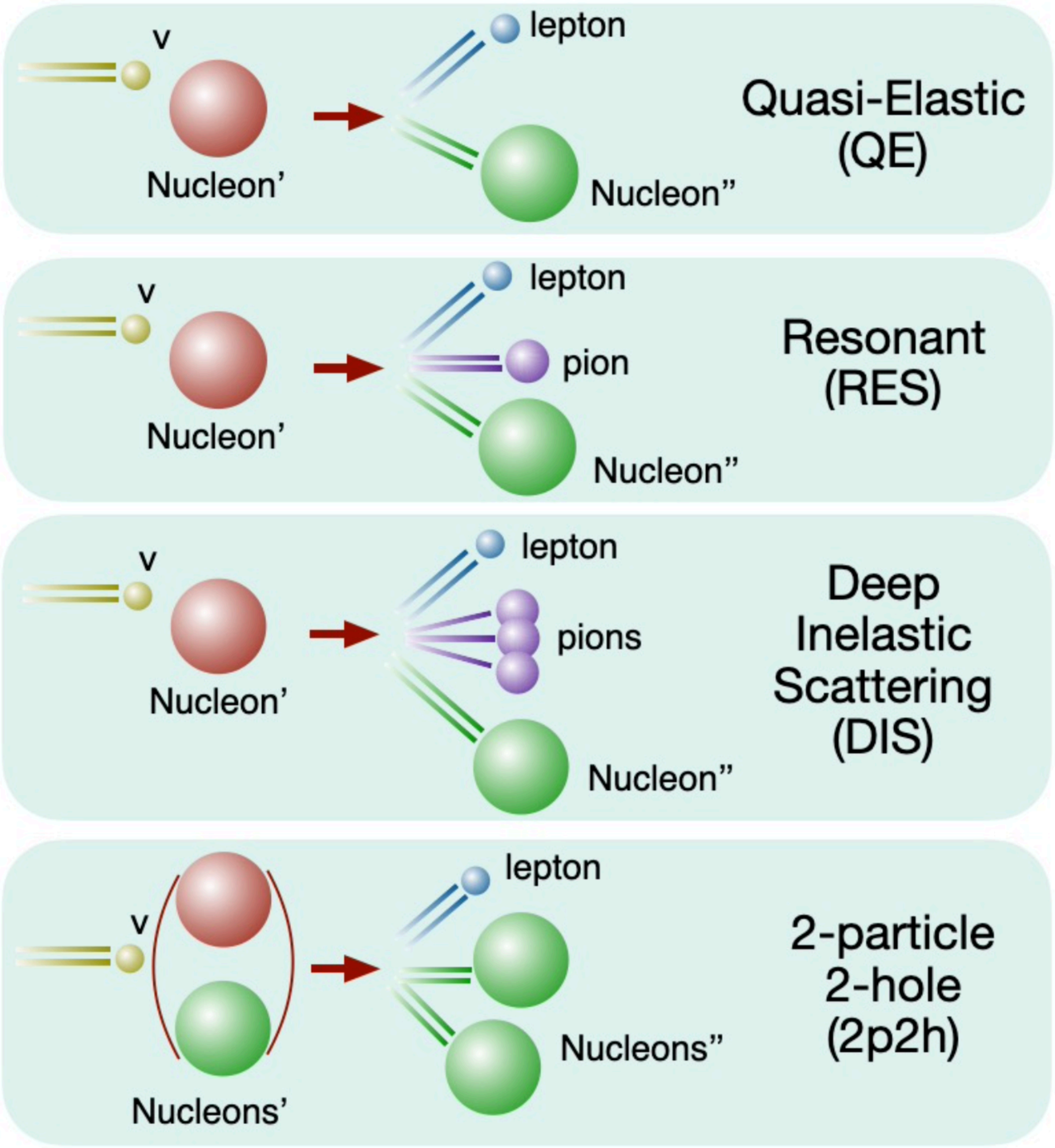
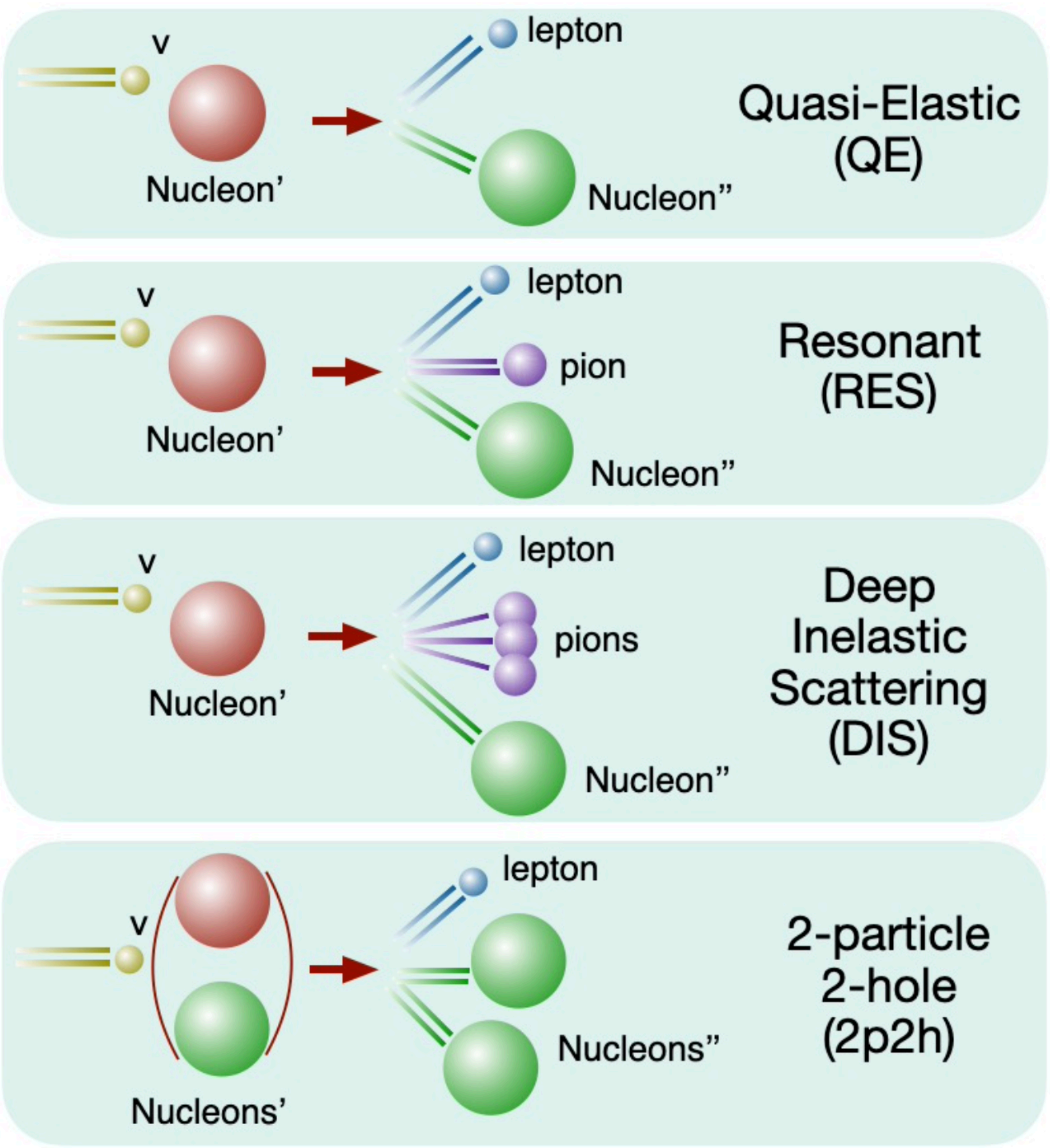
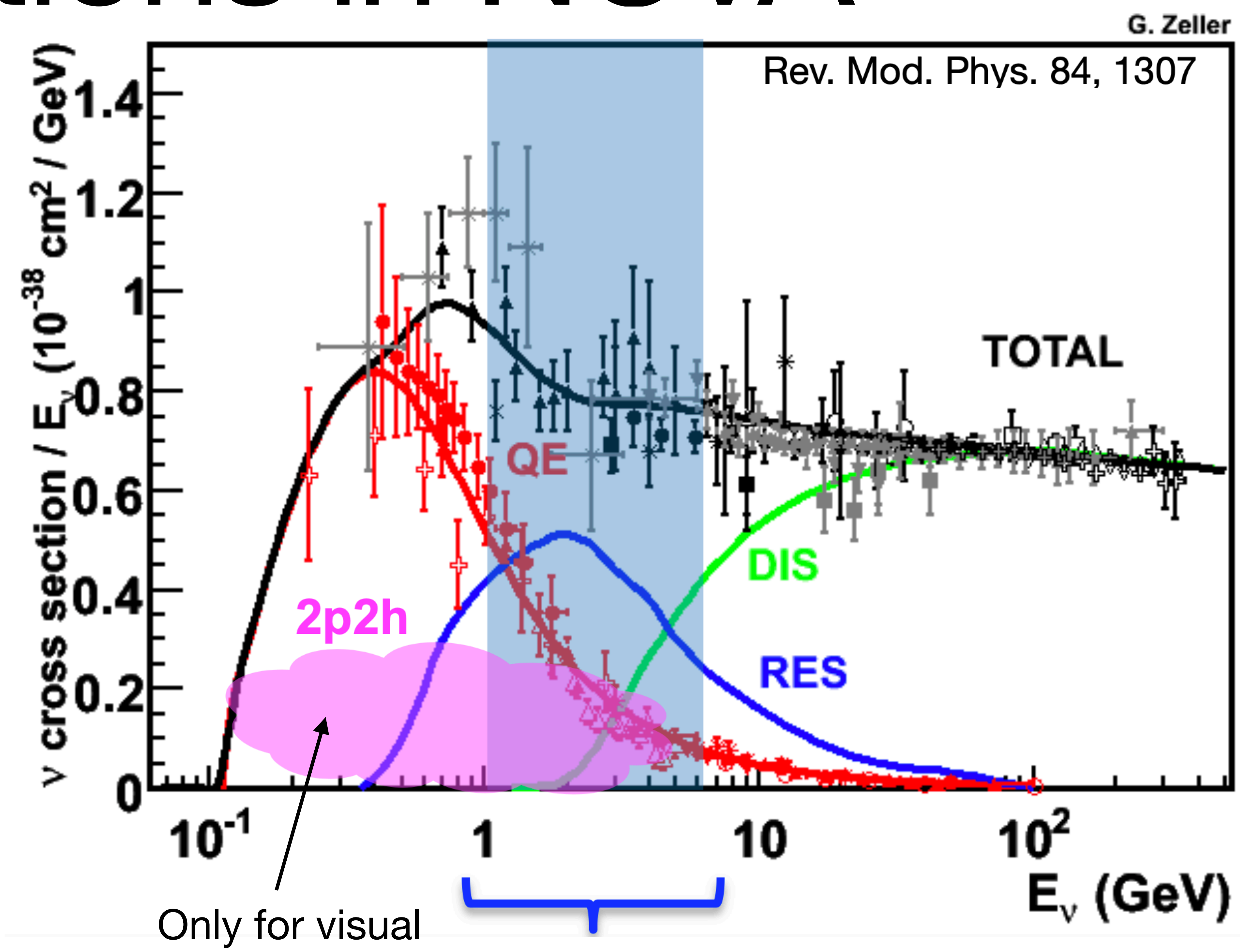


Neutrino Interactions in NOvA





- 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?

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

Event rate (Measured in detector)

Neutrino flux

Neutrino-nucleus interaction cross section

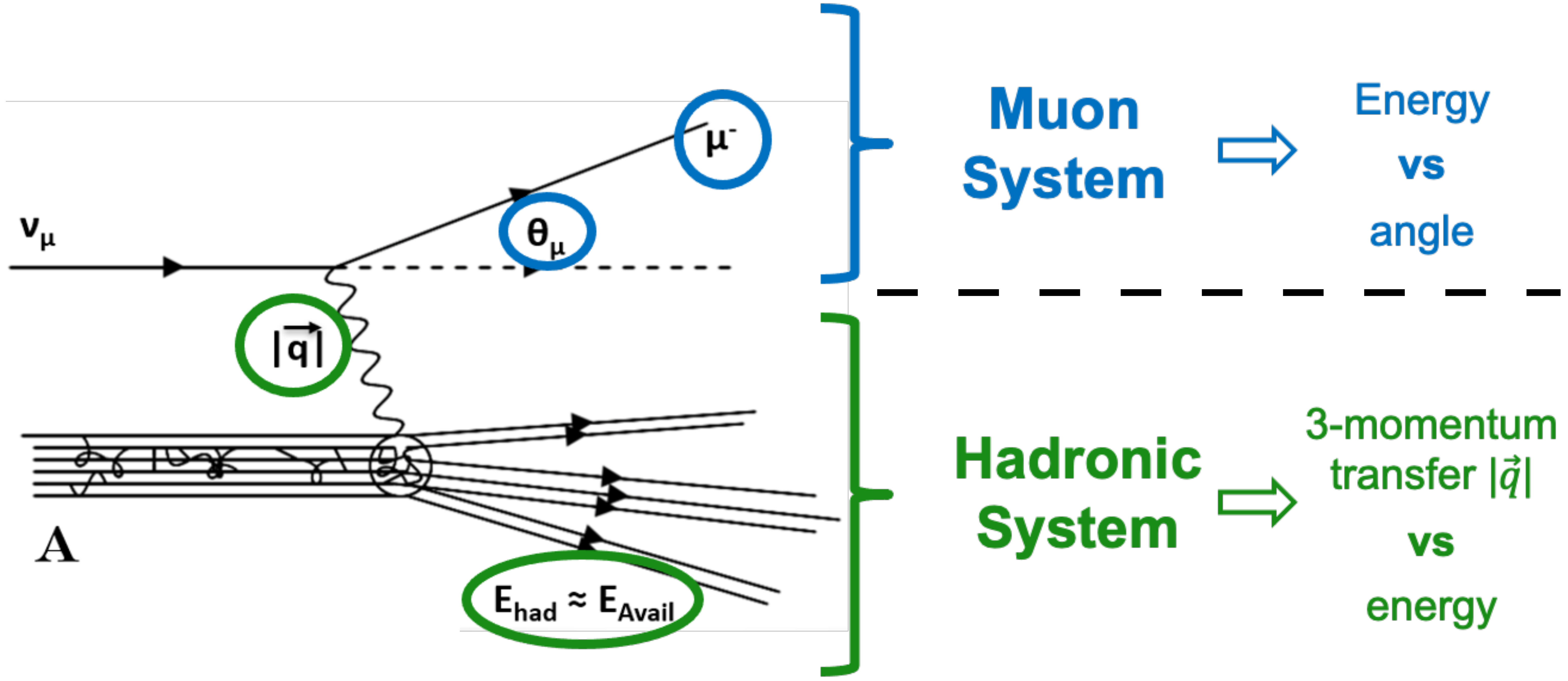
Detector response

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

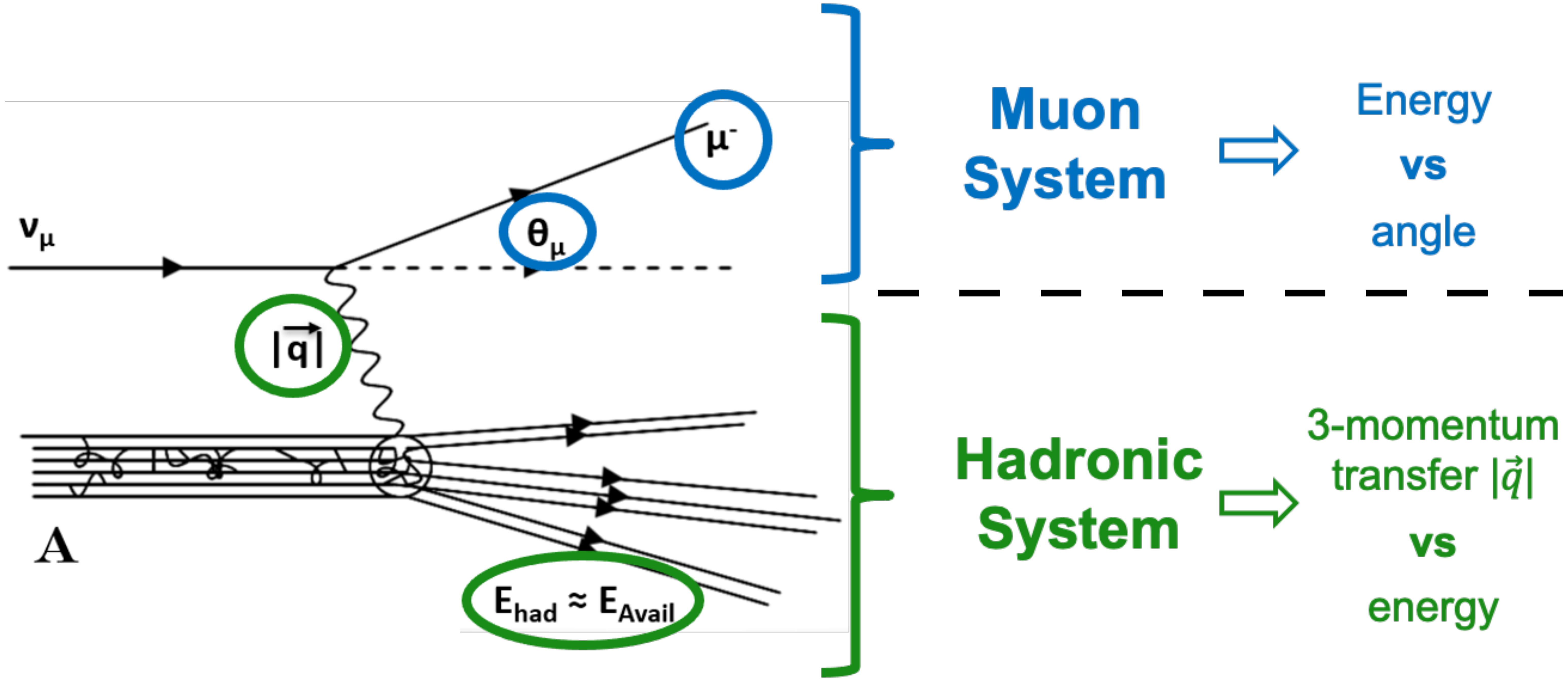
Two New ν_μ CC Cross-section Analyses

- Double differential cross-section measurements



Two New ν_μ CC Cross-section Analyses

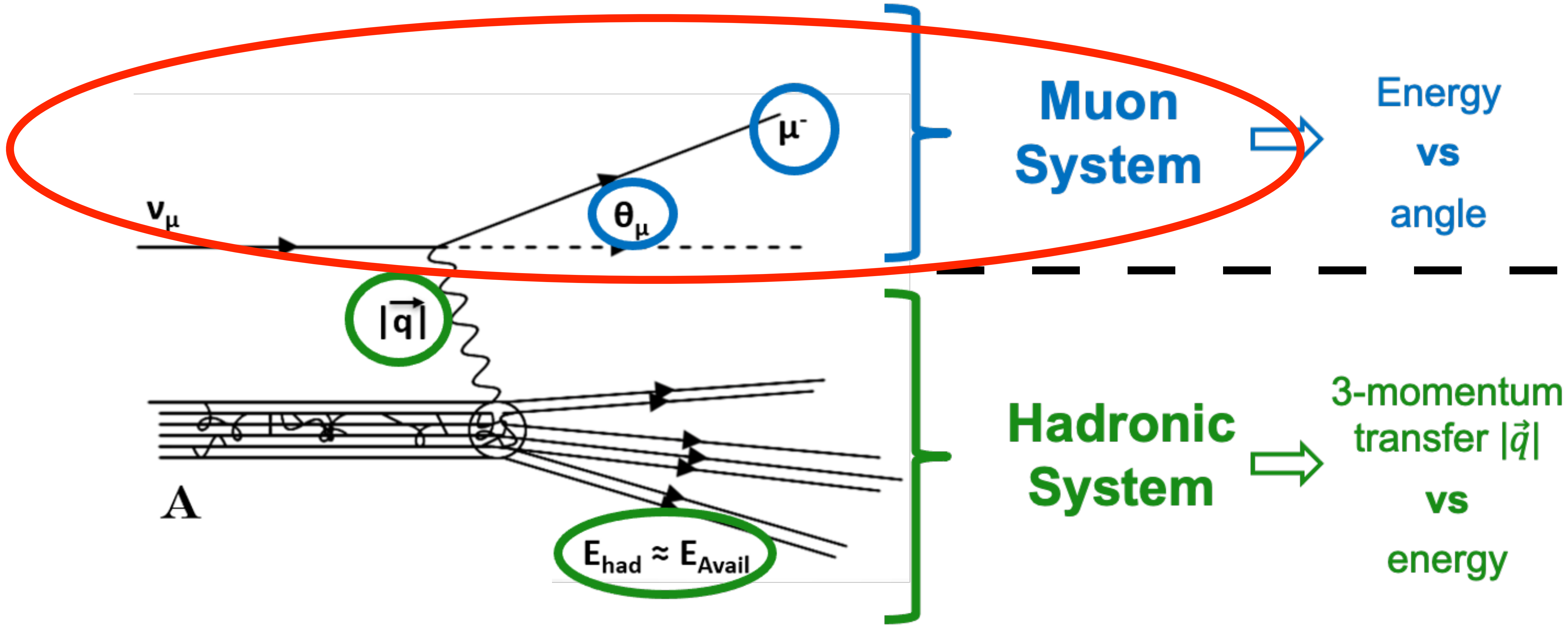
- Double differential cross-section measurements
- Both focus on 2p2h interactions



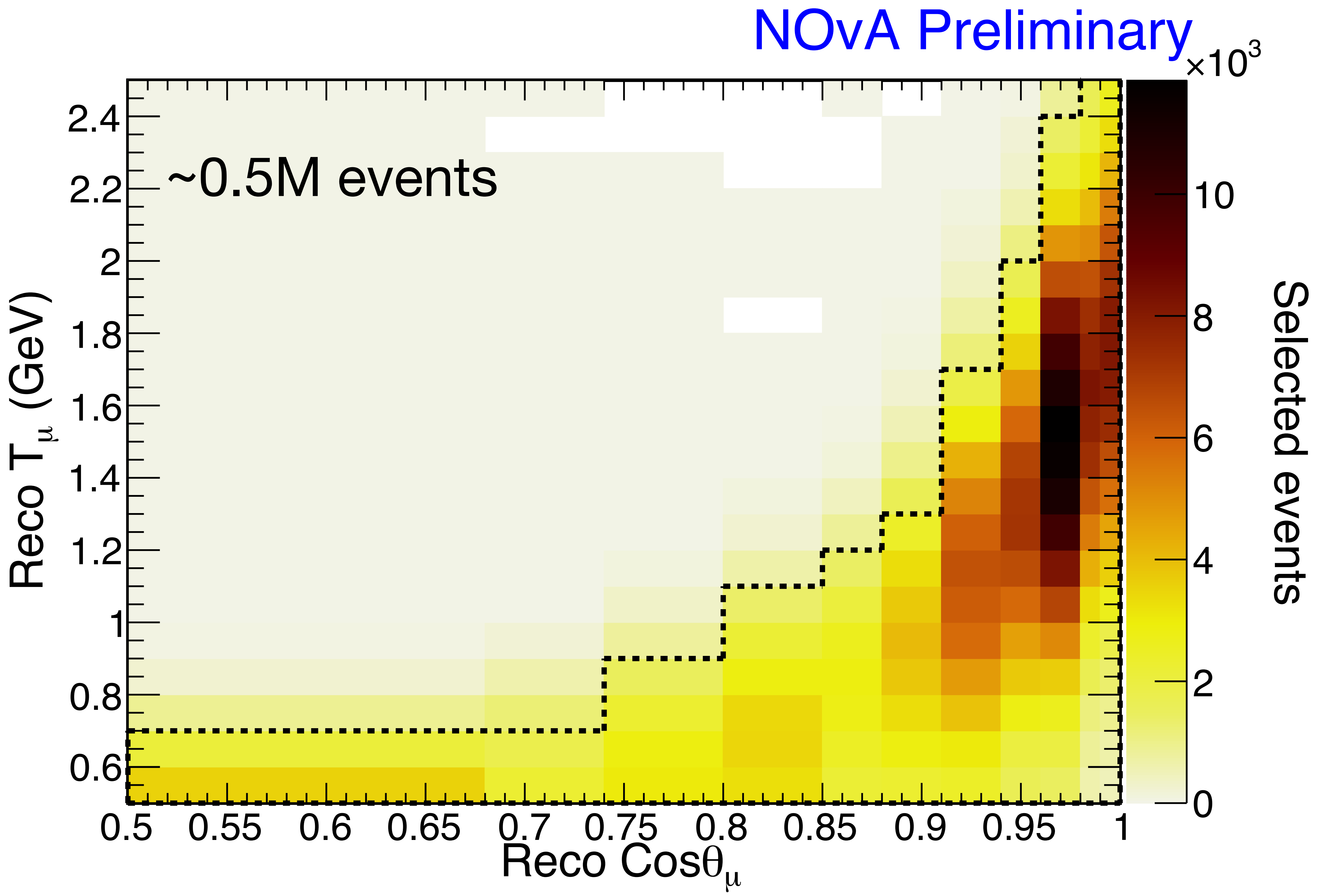
Both built on previous ν_μ CC inclusive measurement Phys. Rev. D 107, 052011 (2023)

Muon System

- Double differential measurement in
  - T_μ - outgoing muon K.E.
  - $\cos\theta_\mu$ - outgoing muon scattering angle wrt to neutrino beam



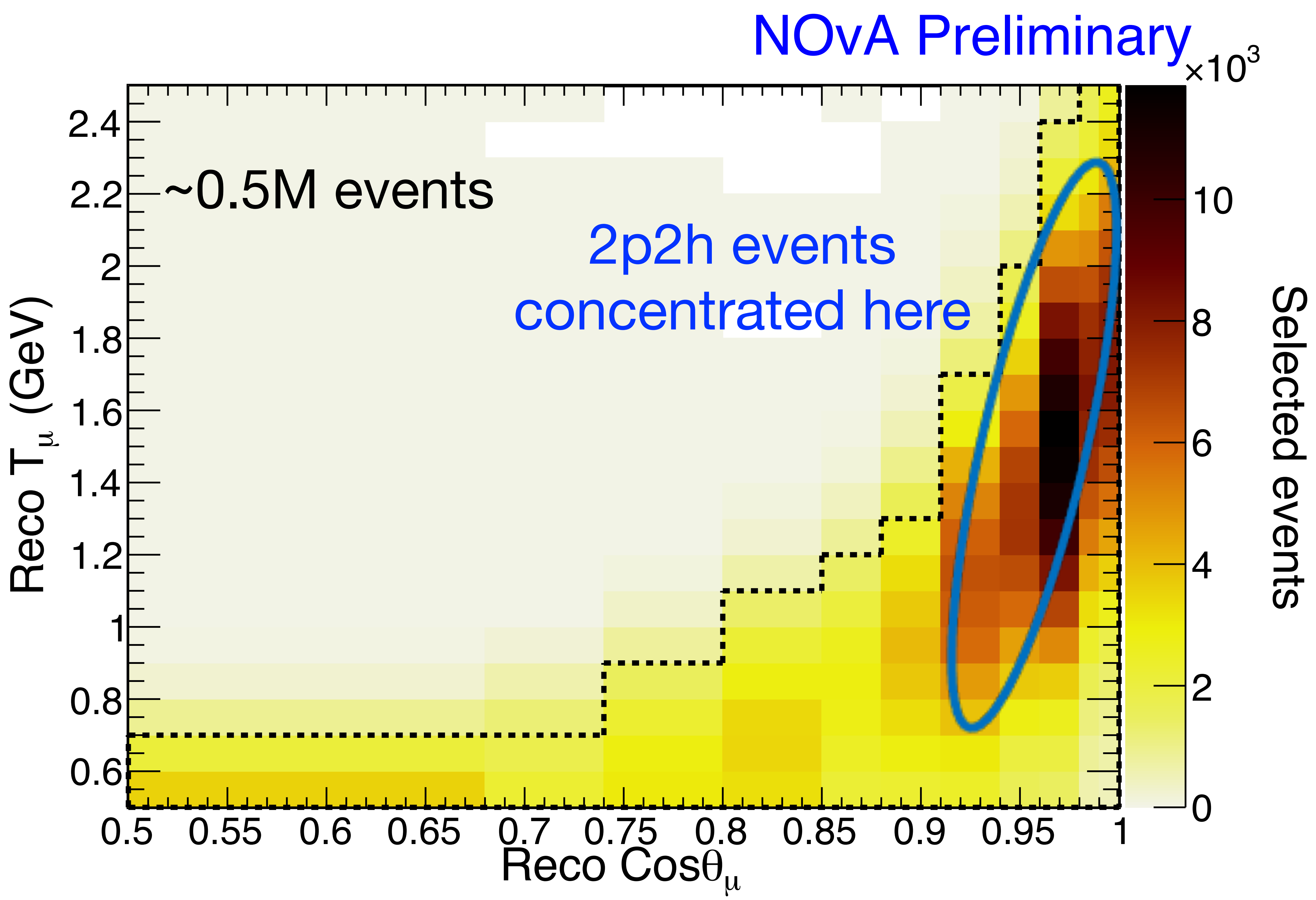
Muon System



Signal defnition

- Only one reconstructed track (muon candidate)
- ν_μ CC interaction within detector's fiducial volume
- $T_p^{max} = 200\ MeV$, and $T_\pi^{max} = 175\ MeV$

Muon System



Signal defnition

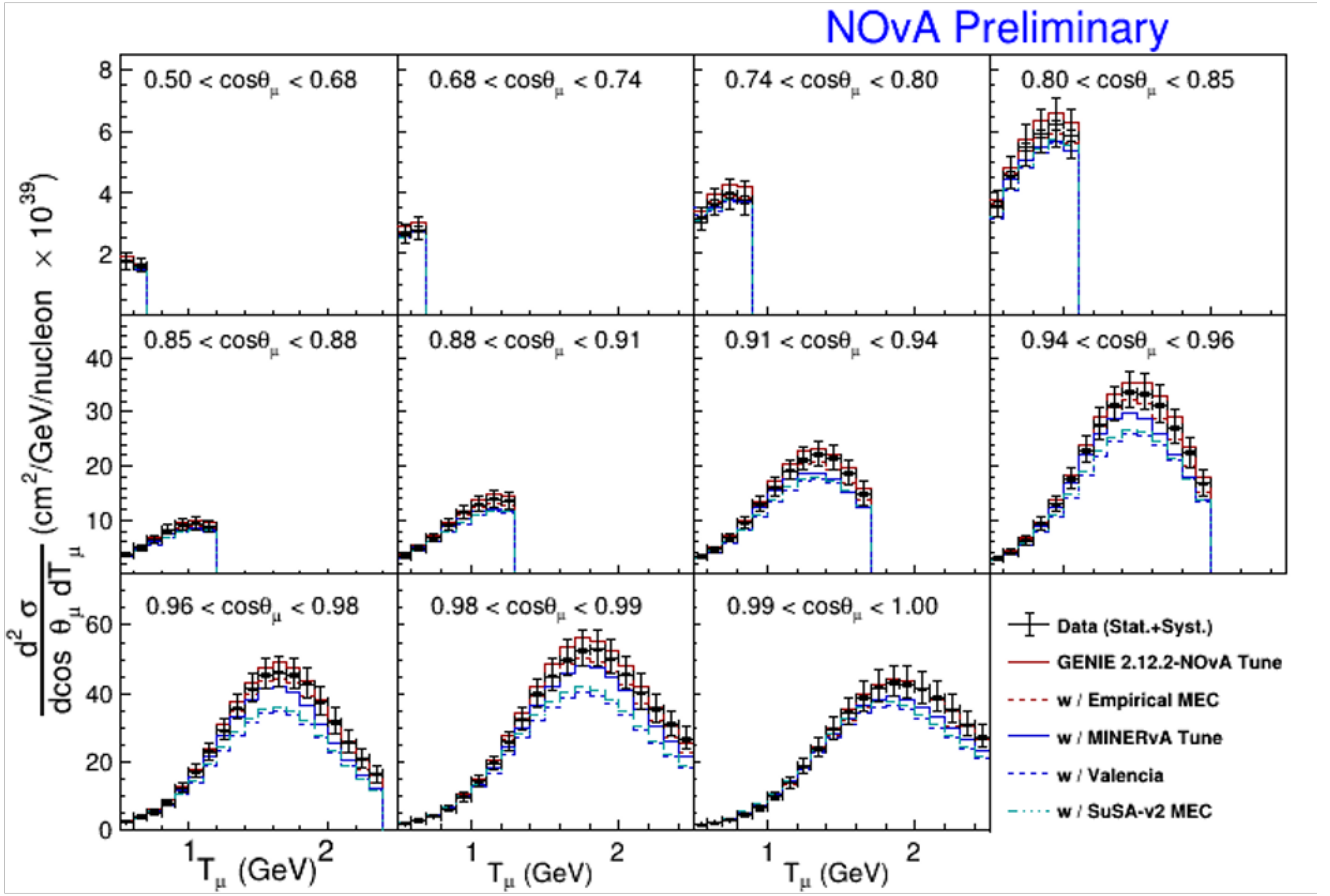
- Only one reconstructed track (muon candidate)
- ν_μ CC interaction within detector's fiducial volume
- $T_p^{max} = 200\ MeV$, and $T_\pi^{max} = 175\ MeV$
- Boosts 2p2h, reduces DIS and RES interactions

QE	MEC	RES	DIS	COH
39.7%	33.7%	23.0%	2.5%	1.1%

Muon System

cross section results are compared to various theory models

Theory models are underestimating cross sections in 2p2h region



Muon System

Both tuned and untuned models under predicts the cross sections in 2p2h regions

Pure theory models have larger discrepancy

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

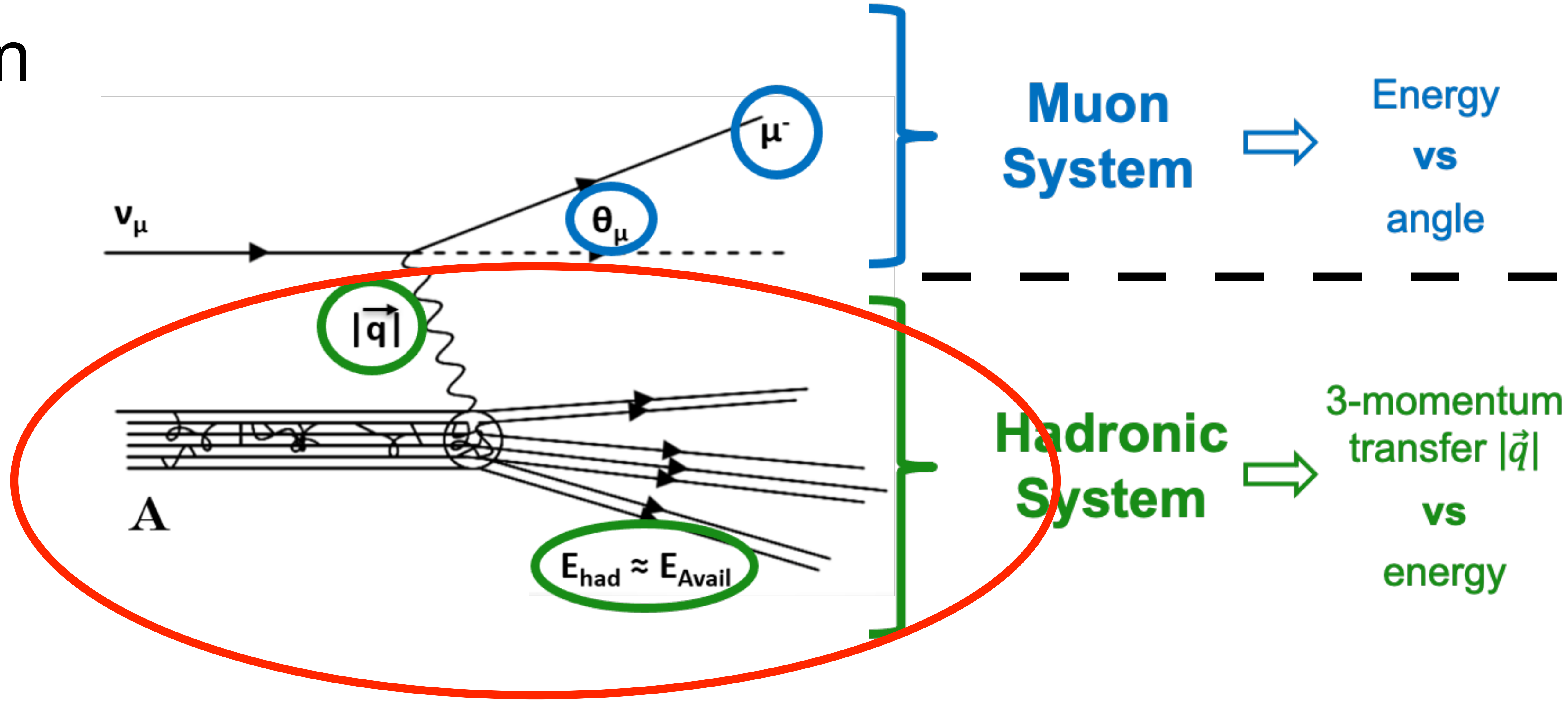
Tuned models (GENIE v2-12.2 NOvA Tune, Empirical MEC, Valencia w/ MINERvA Tune)

Theoretical models (Valencia, SuSA - v2)

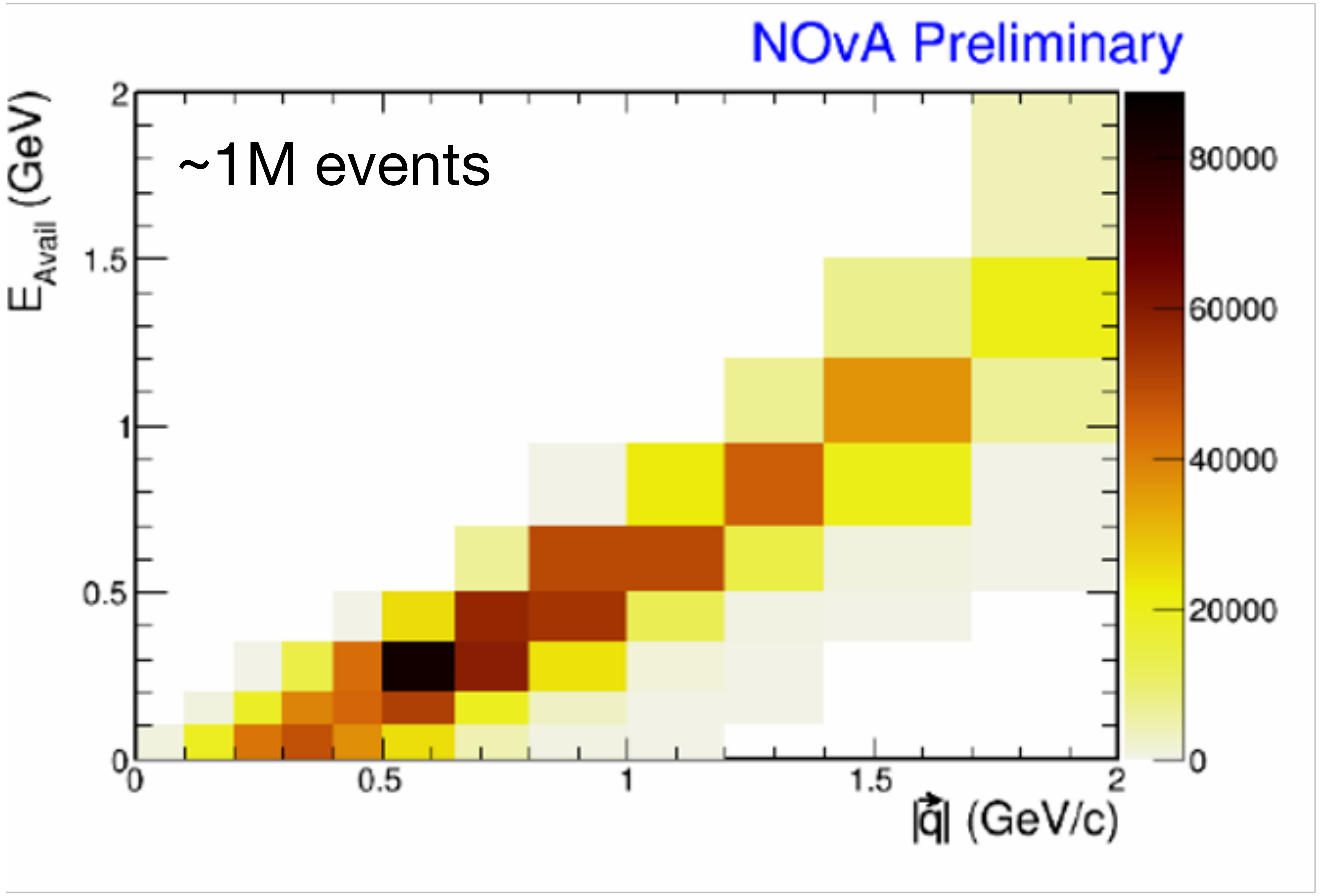
Hadronic System

NOvA's first double differential measurement in

- $|\vec{q}|$ - magnitude of three momentum transferred from the leptonic to hadronic system
- E_{avail} - available energy
  - expected visible hadronic energy (excluding neutrons)



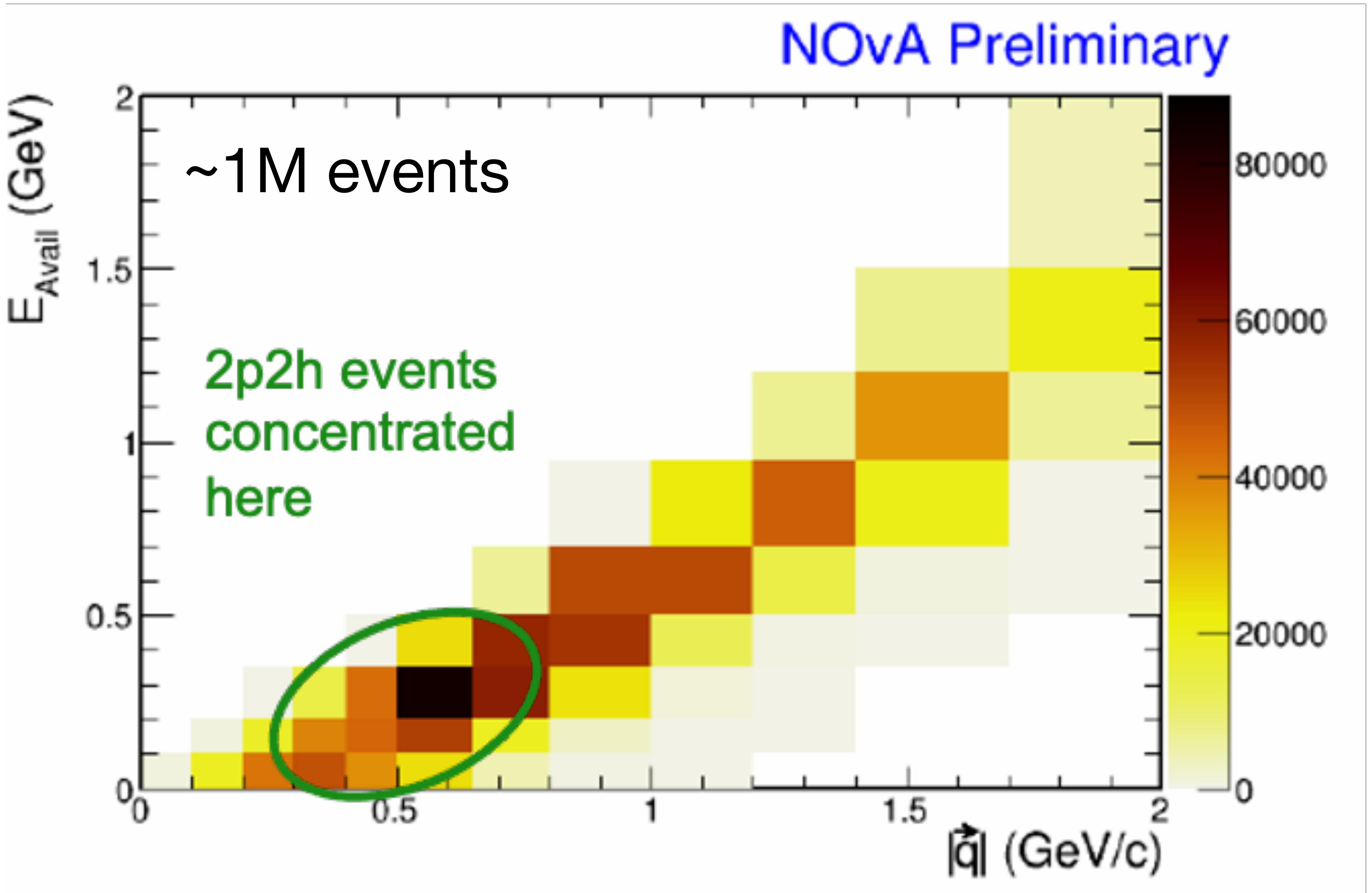
Hadronic System



Signal defnition

- ν_μ CC interaction with vertex within detector's fiducial volume
- whole interaction contained in the Near Detector

Hadronic System



2p2h concentrated at low values

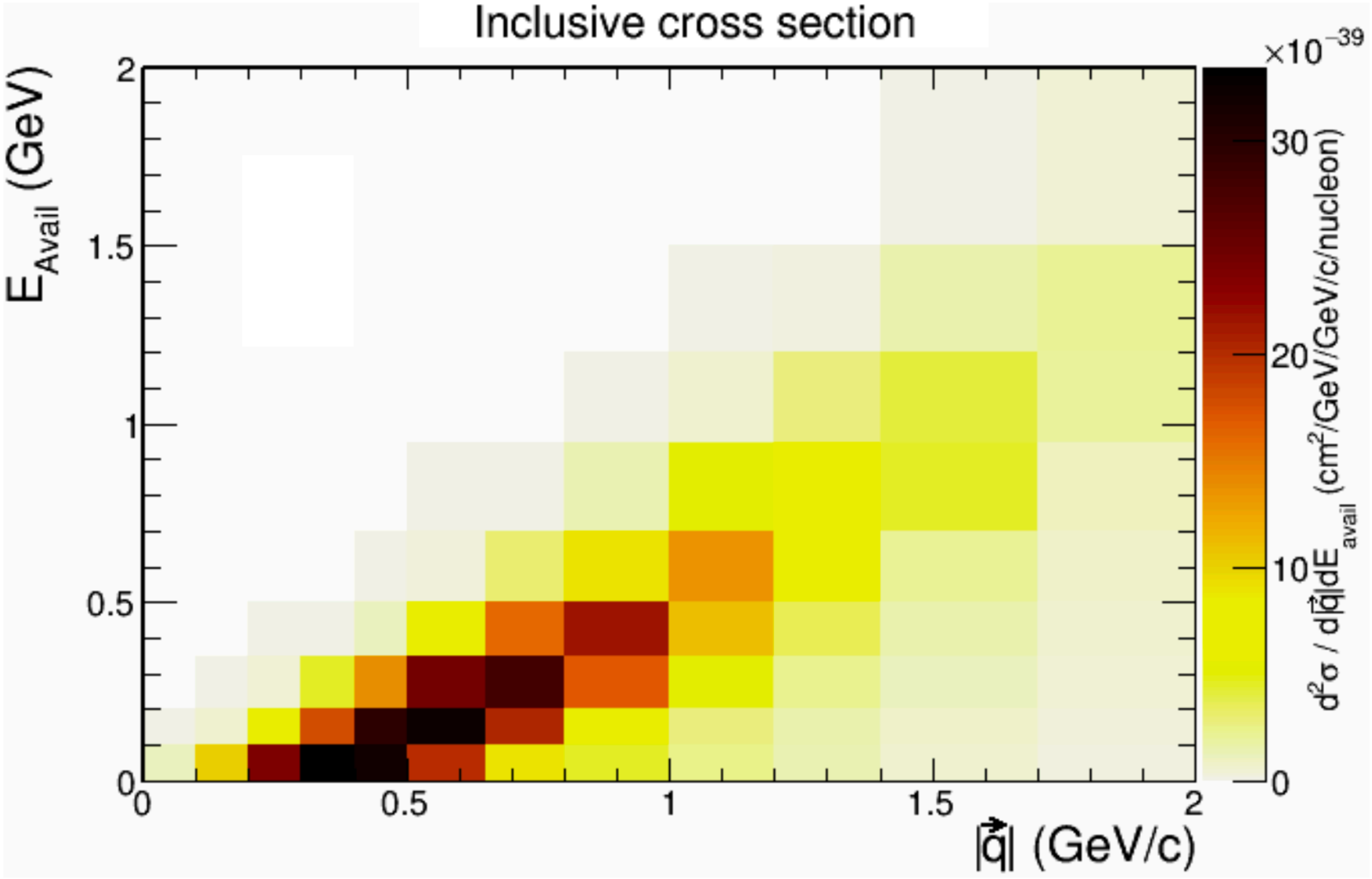
Signal defnition

- ν_μ CC interaction with vertex within detector's fiducial volume
- whole interaction contained in the Near Detector
- muon kinematics to enhance selection efficiency and sample purity
  - $0.5 < T_\mu < 2.5\ GeV$
  - $\cos\theta_\mu > 0.5$
- 27% selection efficiency, 92% sample purity

Hadronic System

Selected signal is unfolded using D'Agostini iterative unfolding algorithm

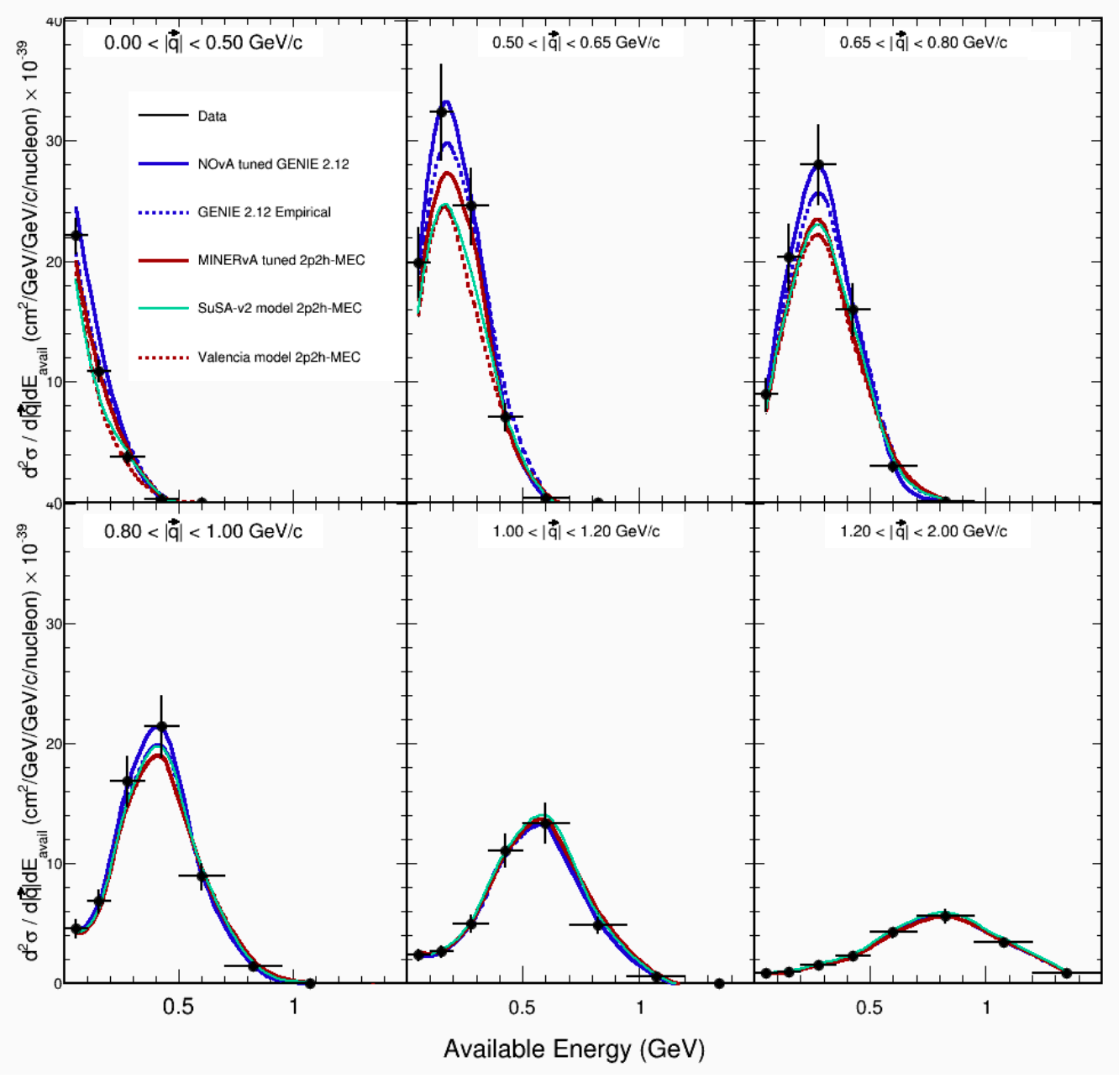
Unfolded data is converted into cross section measurement



Hadronic System

Data cross section measurements are compared to various theory models

Theory models are underestimating cross section in 2p2h region



Conclusions and Outlook

- 2p2h models have discrepancies and are under predicting neutrino-nucleus interaction cross sections

- Papers to be submitted soon for these two presented cross section analyses

- Two anti neutrino analyses are in advanced stages
  - $\bar{\nu}_\mu\ CC$ inclusive analysis - triple differential in T_μ, $\cos\theta_\mu$, and E_{avail}
  - $\bar{\nu}_e\ CC$ inclusive analysis - double differential in E_e, $\cos\theta_e$

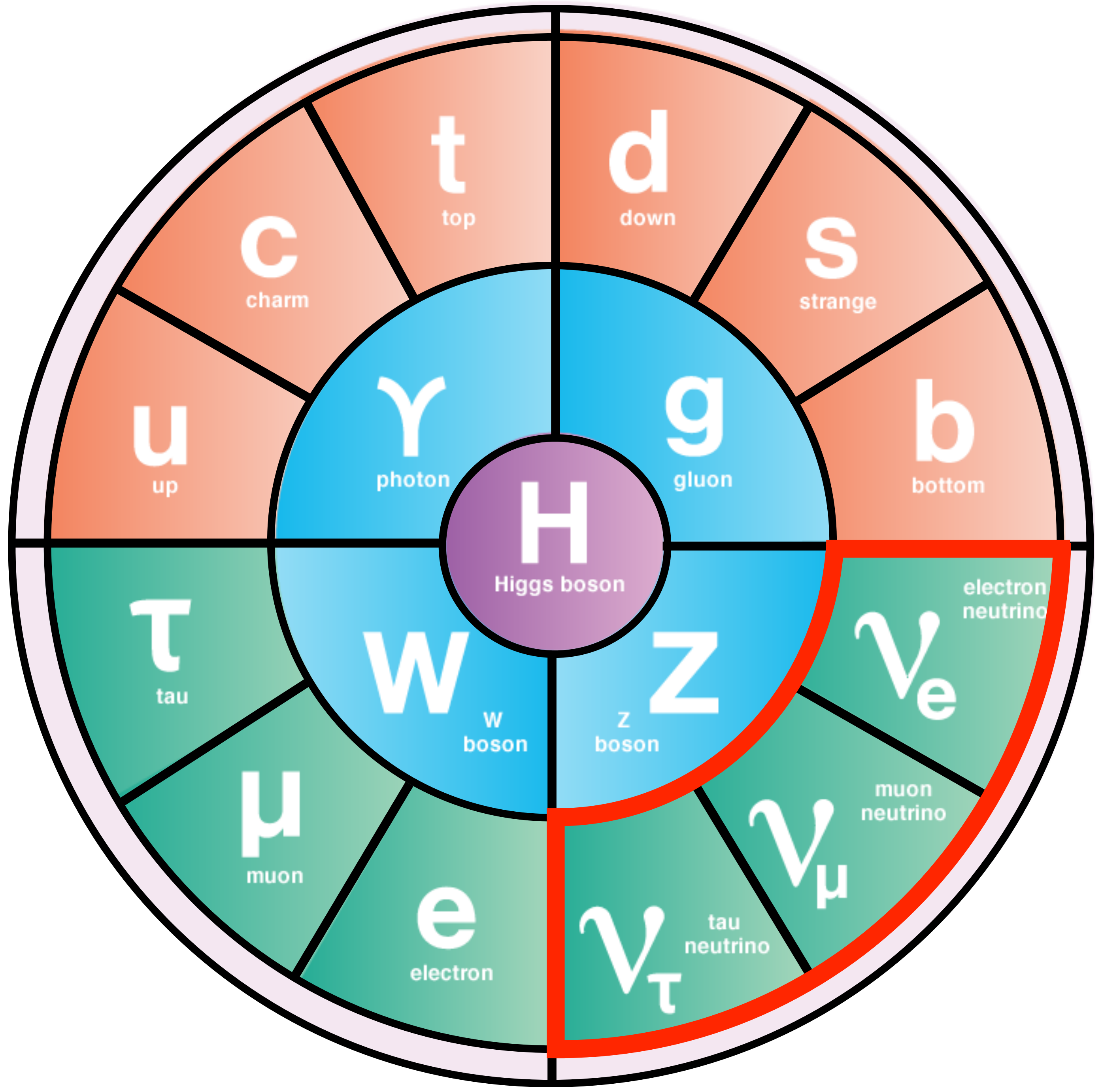
- Anti neutrino to neutrino cross section ratios also in the pipeline

The NOvA Collaboration

> 240 people, ~ 50 institutions, 7 countries

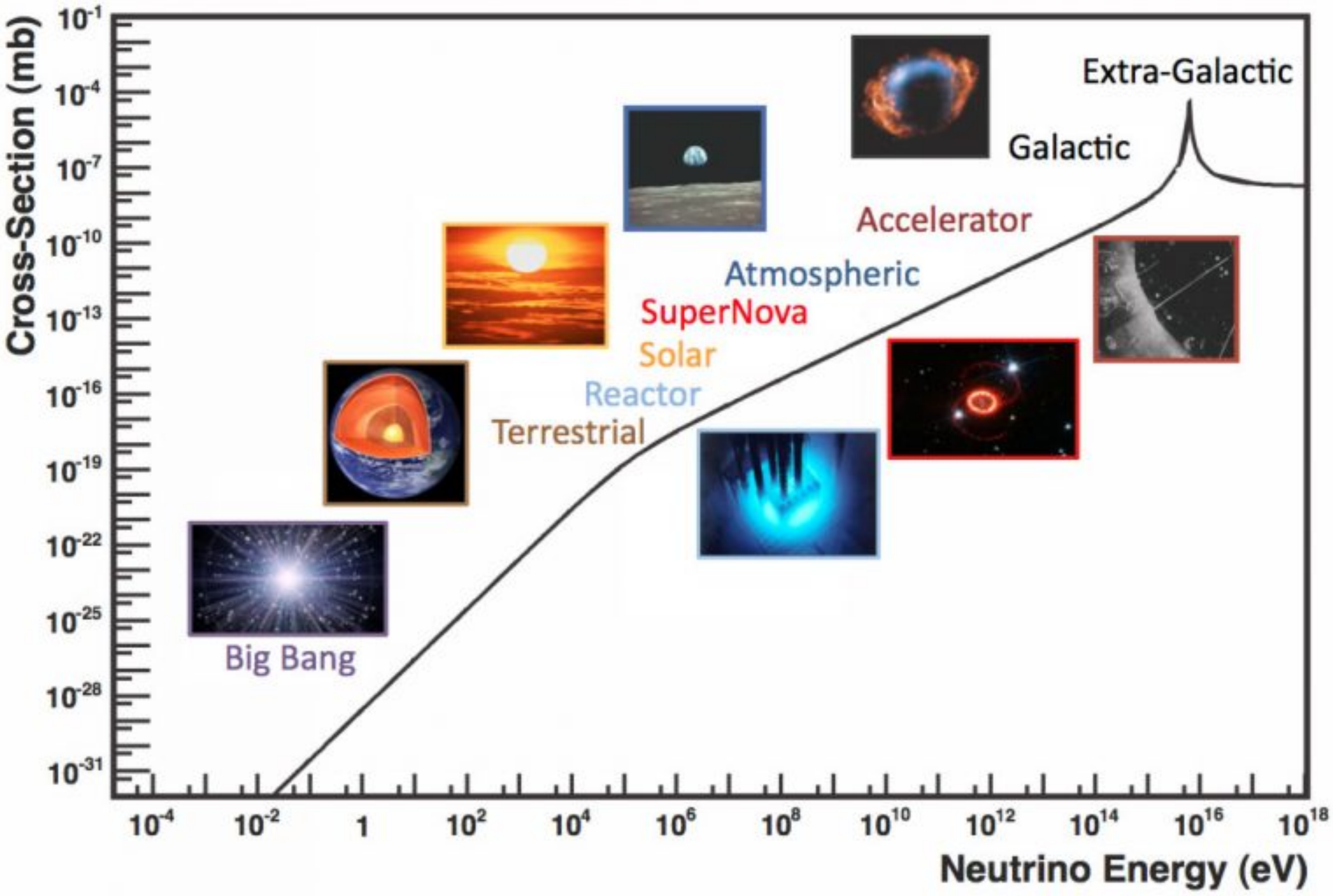
Backup

Brief Introduction to Neutrinos



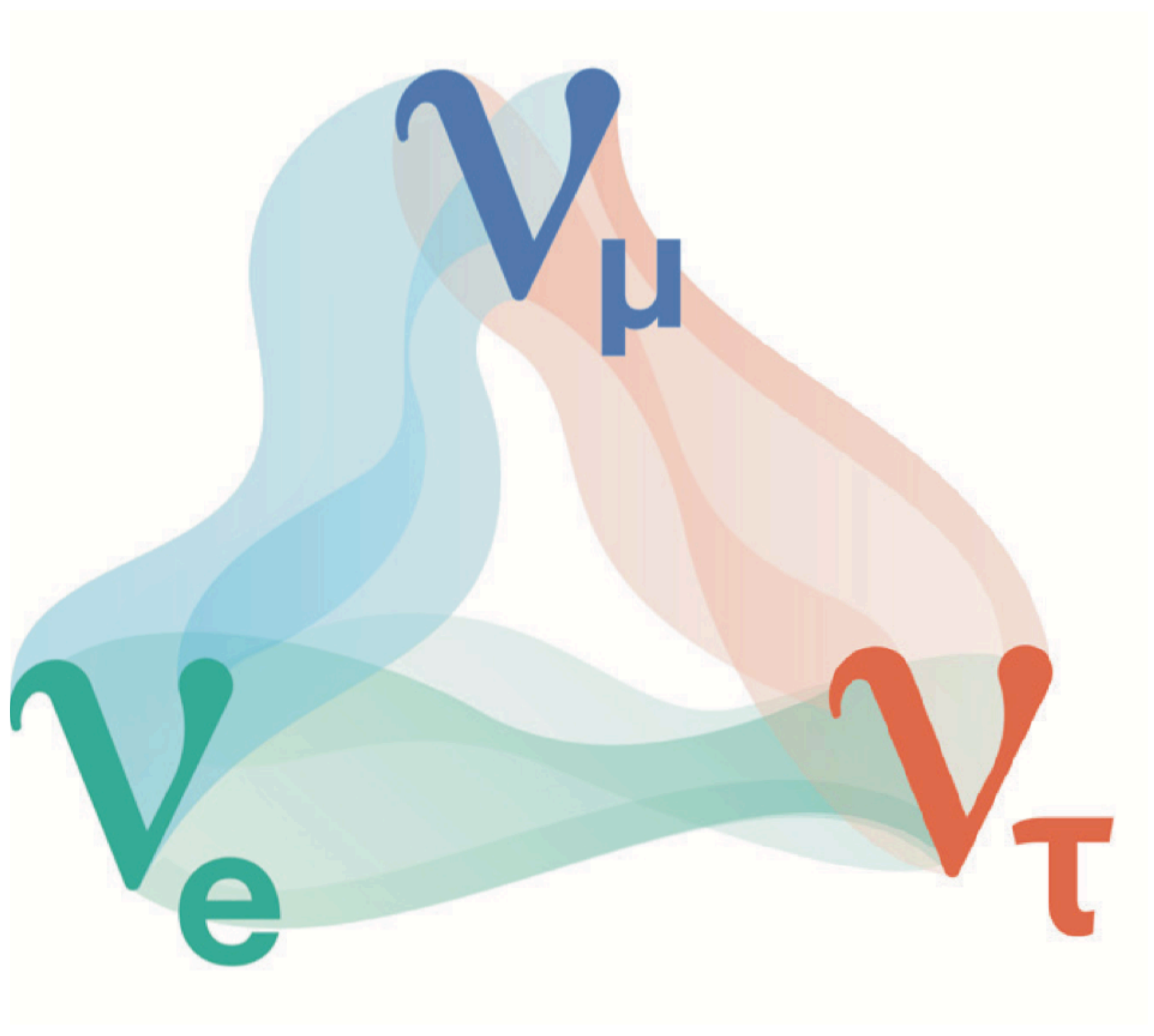
- The most abundant particles in the Universe after photon
- Postulated in 1930 by W. Pauli to explain the continuous spectrum of beta decay
- Charge-less, spin 1/2, weakly interacting and massless in the Standard Model (SM)
- Three generations: ν_e , ν_μ and ν_τ (and anti-neutrinos)

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

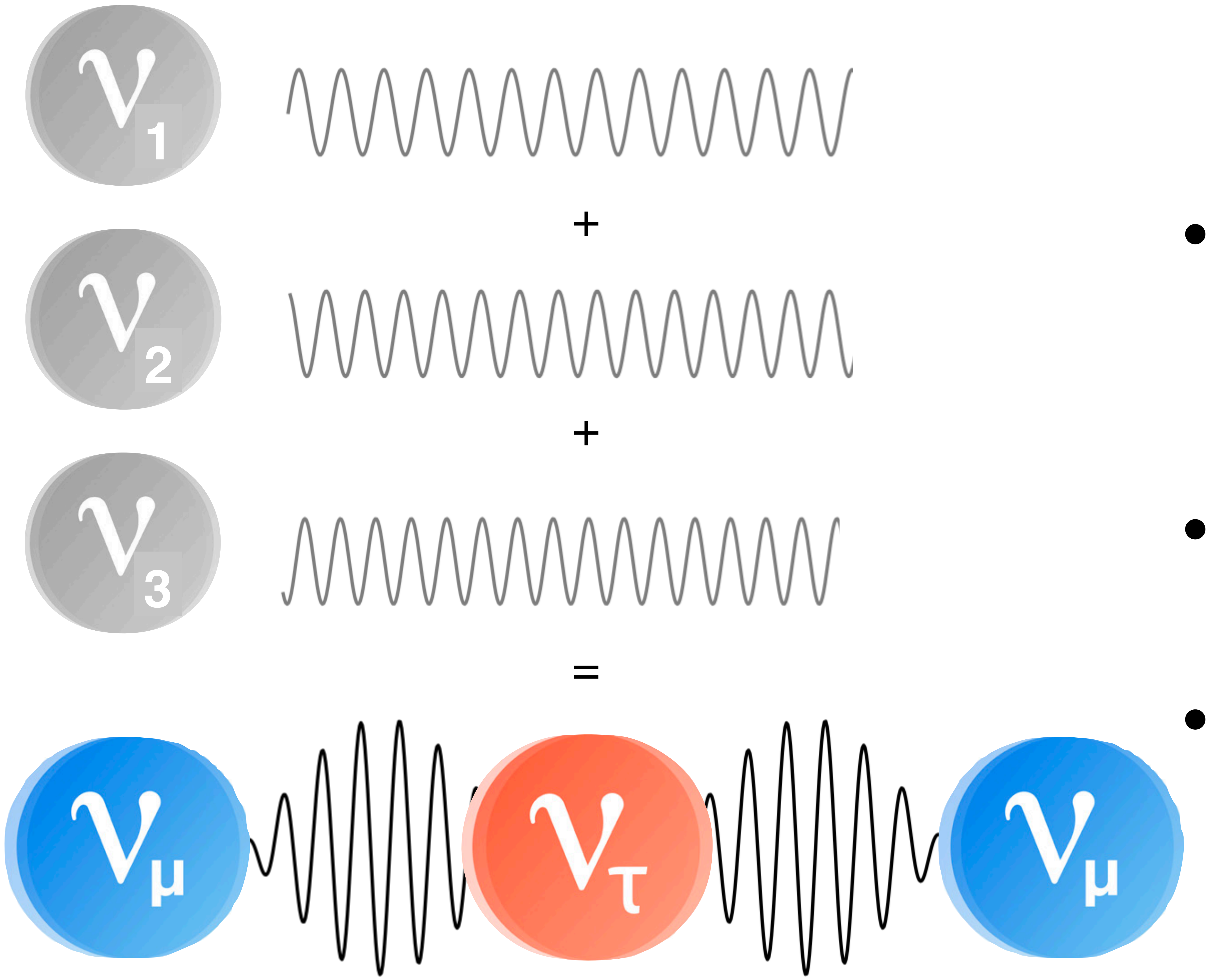
Oscillation Phenomenology



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

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

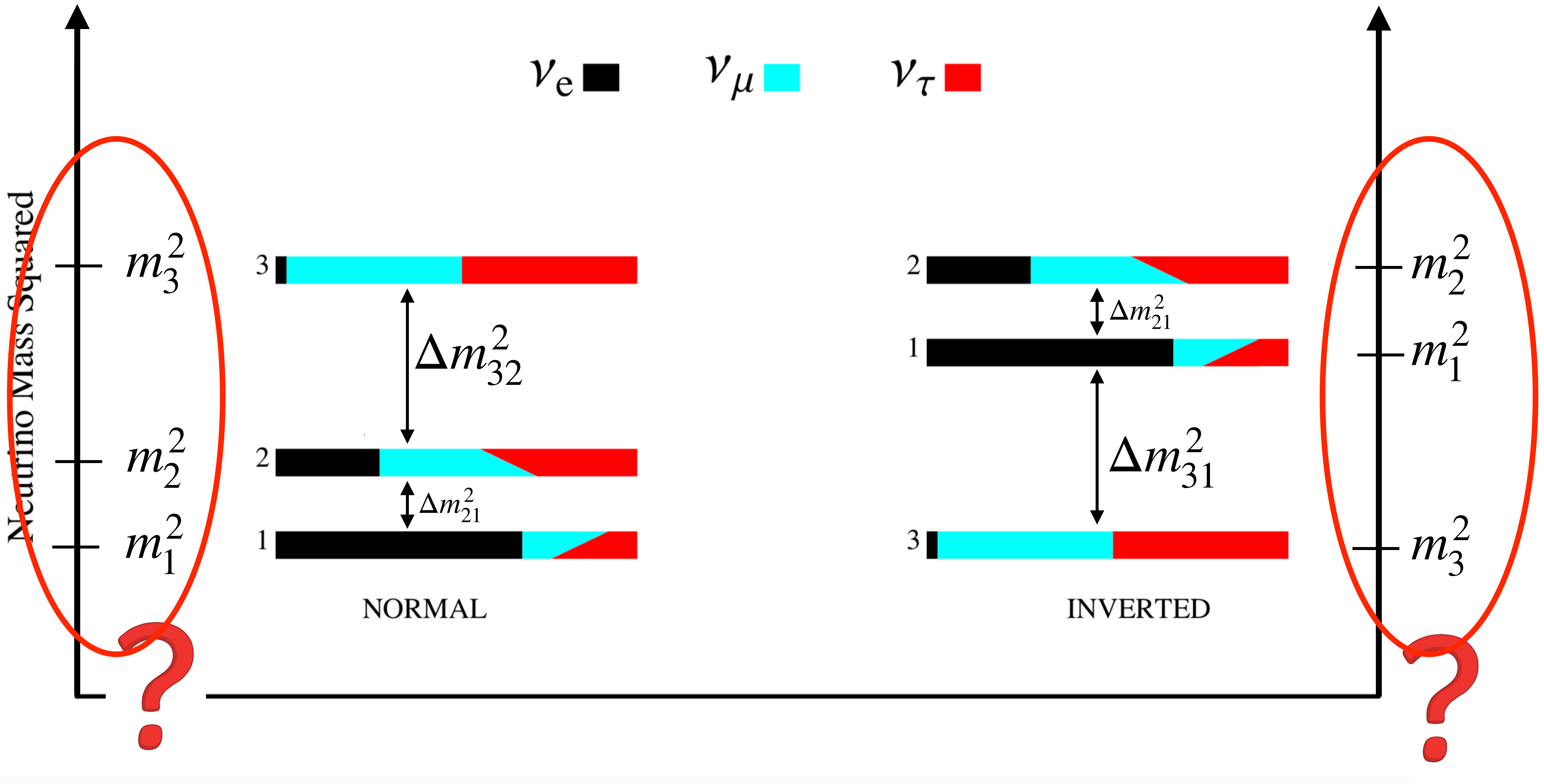
Neutrino Oscillations



- 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

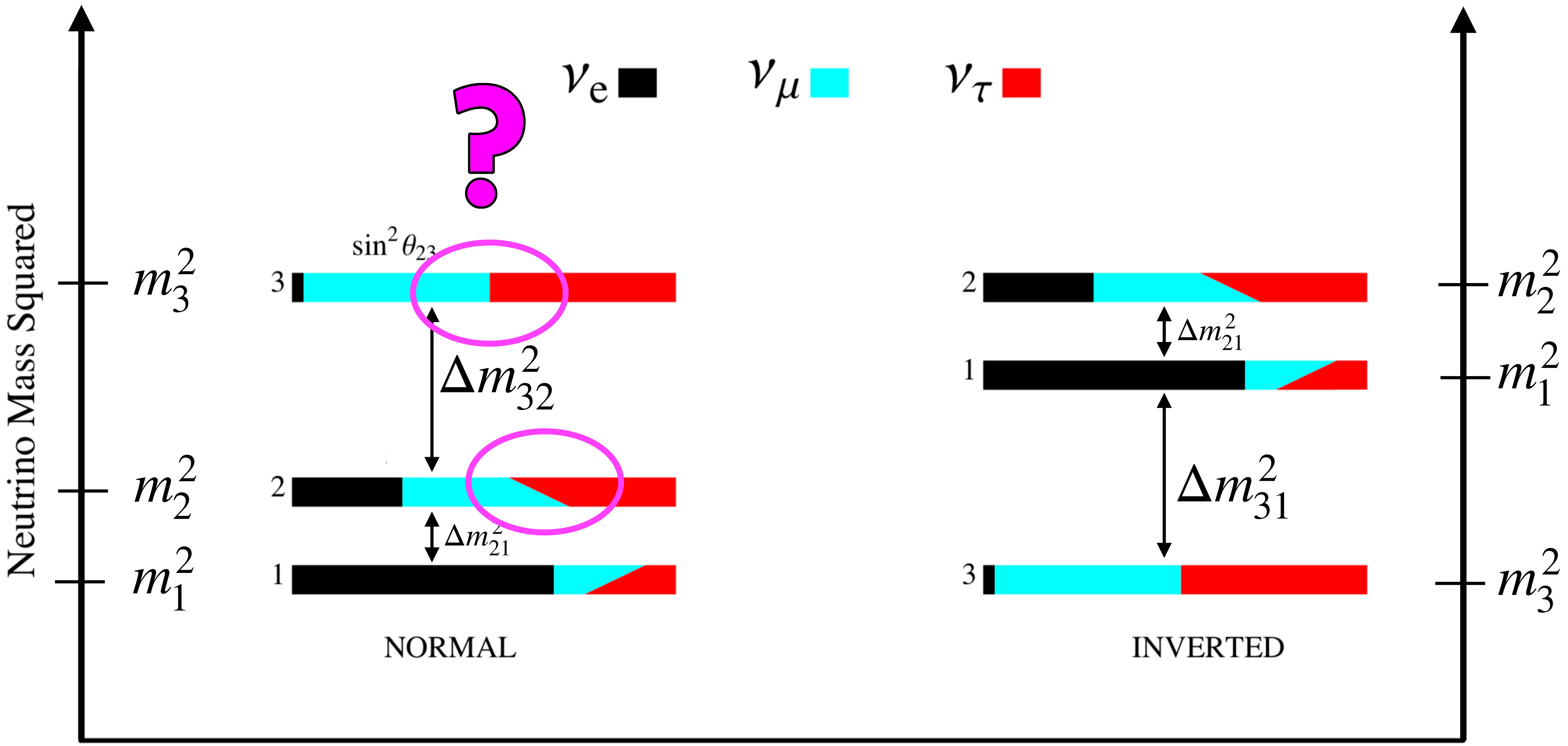
Open Questions

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



Open Questions

- Ordering of neutrino masses: sign of $|\Delta m^2_{32}|$?
- Maximal or non-maximal $\nu_\mu - \nu_\tau$ mixing?



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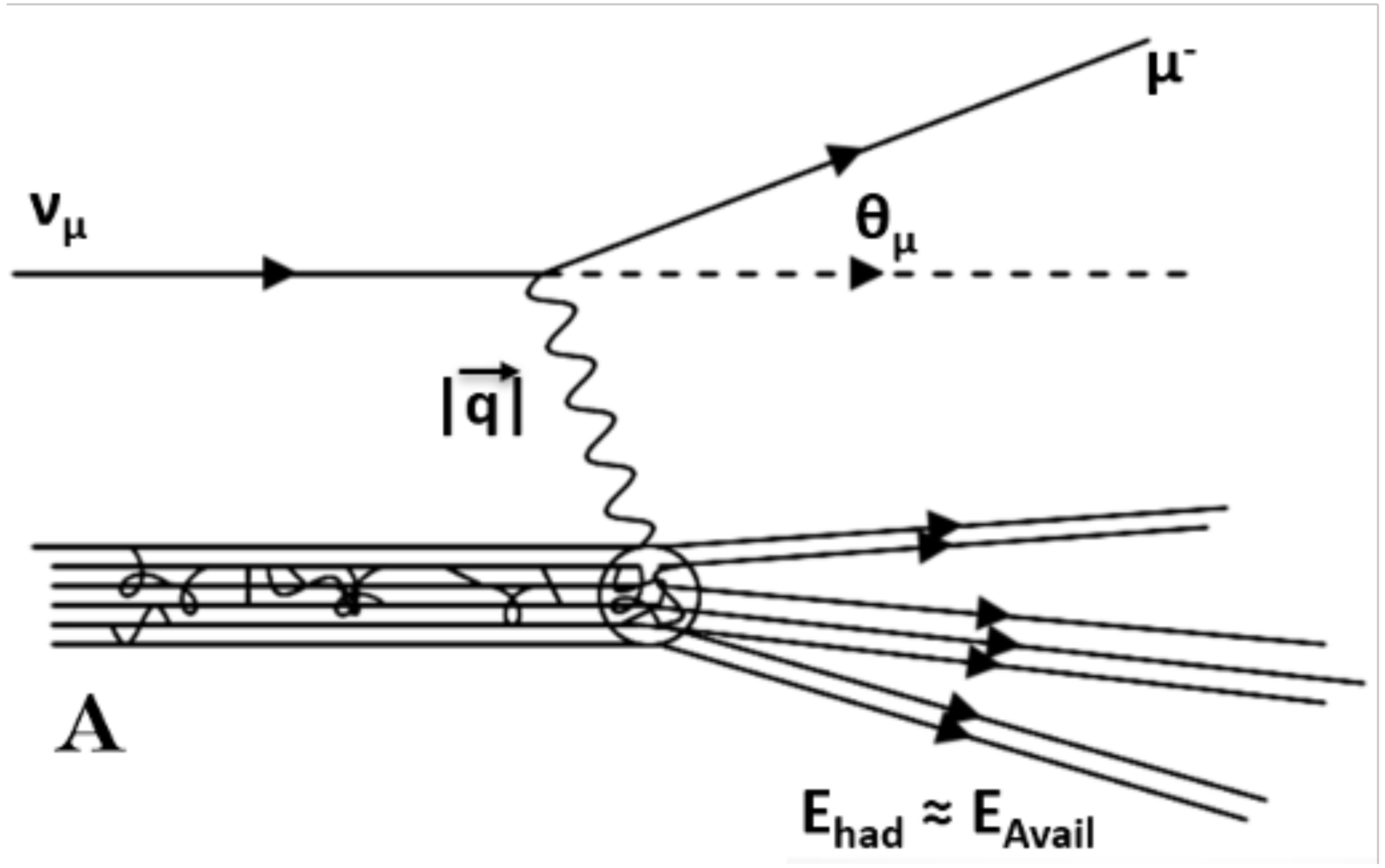
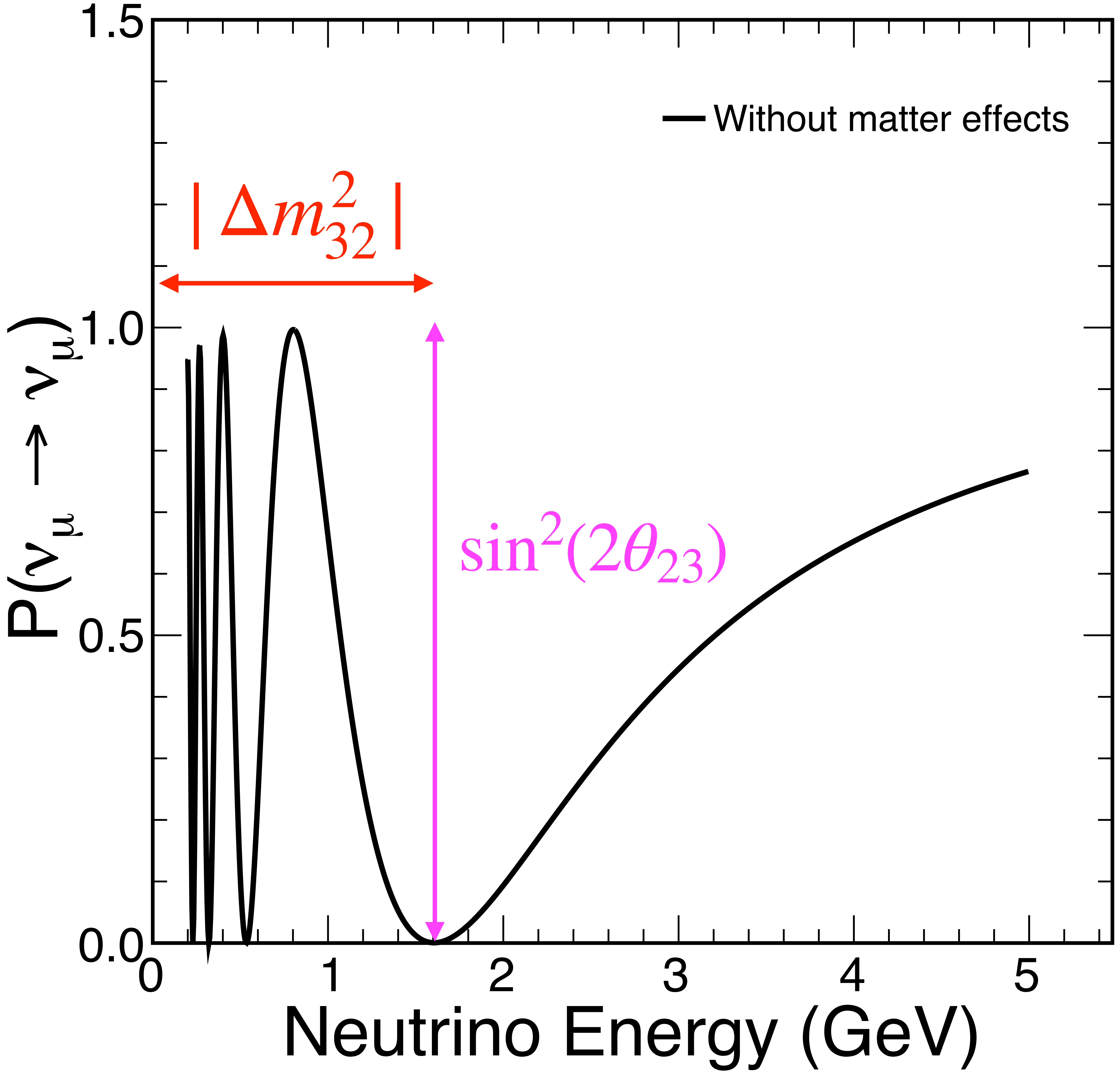
- Ordering of neutrino masses: sign of $|\Delta m^2_{32}|$?
- Maximal or non-maximal $\nu_\mu - \nu_\tau$ mixing?
- Any CP violation by neutrinos?
- Nuclear effects on the neutrino-nucleus interactions



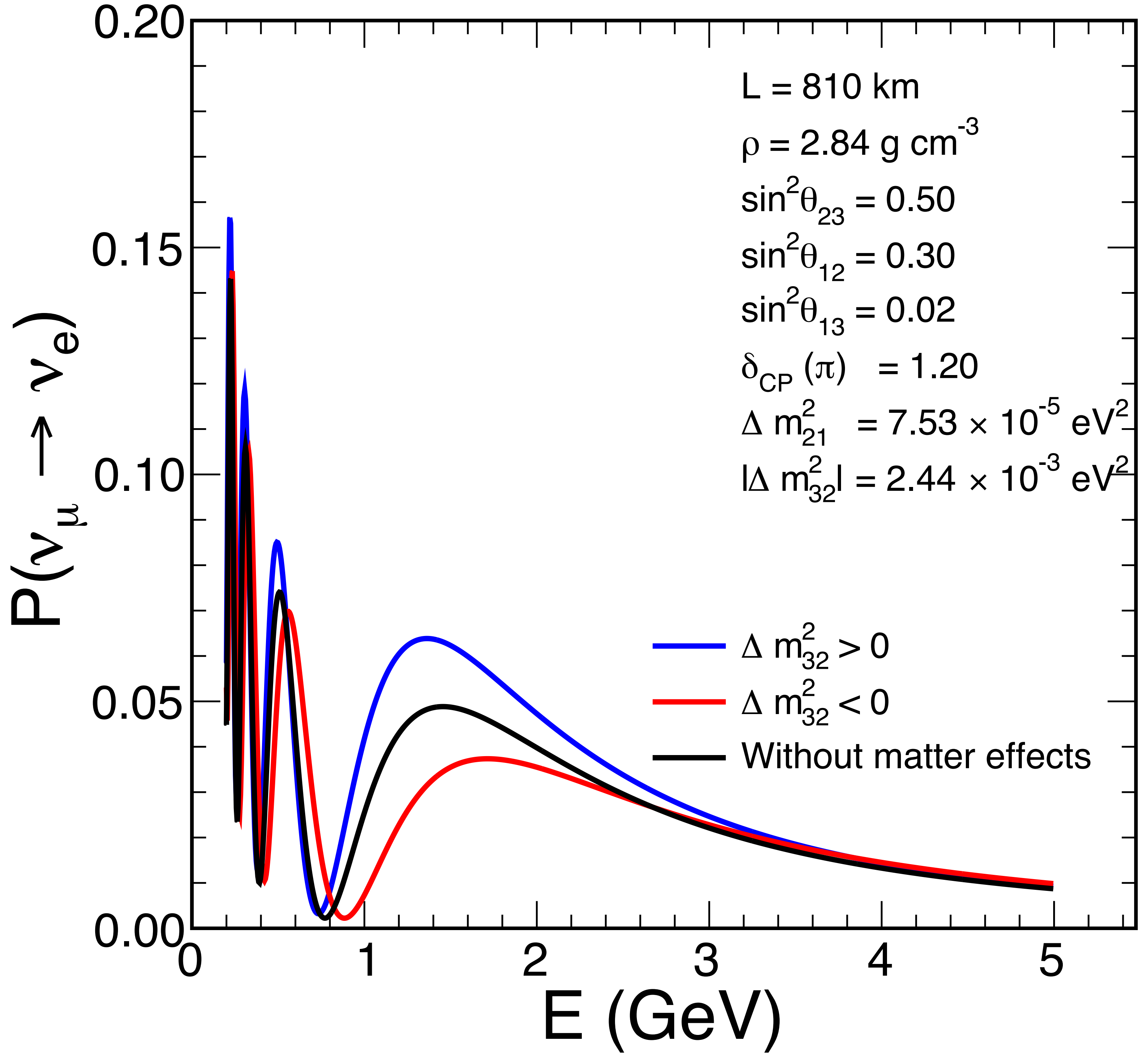
$\nu_\mu \rightarrow \nu_\mu$ Disappearance Oscillations

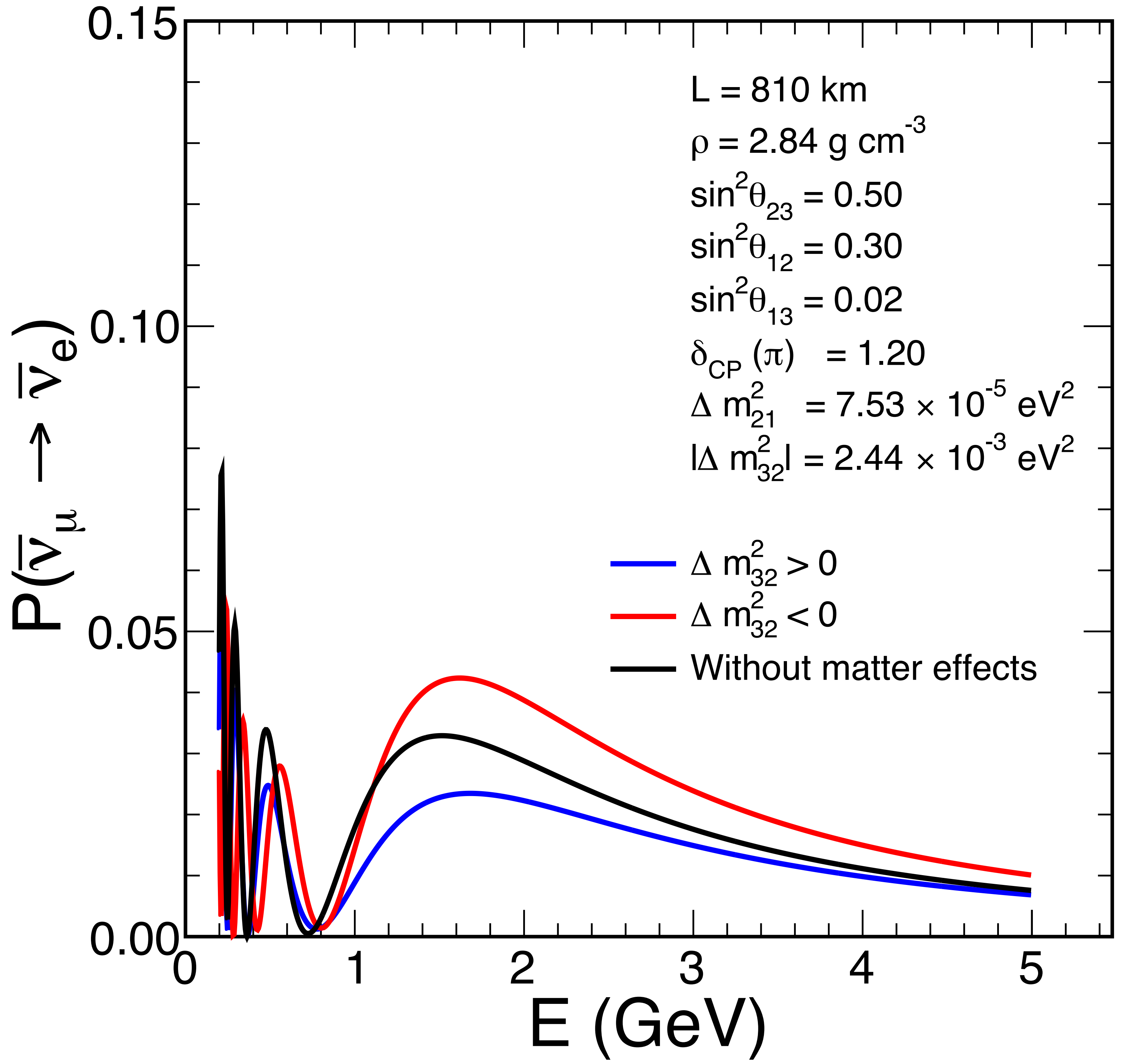


$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta_{23} \ \sin^2\left(\frac{1.27\ \Delta m^2_{32}\ (eV^2)\ L\ (km)}{E\ (GeV)}\right)$$

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

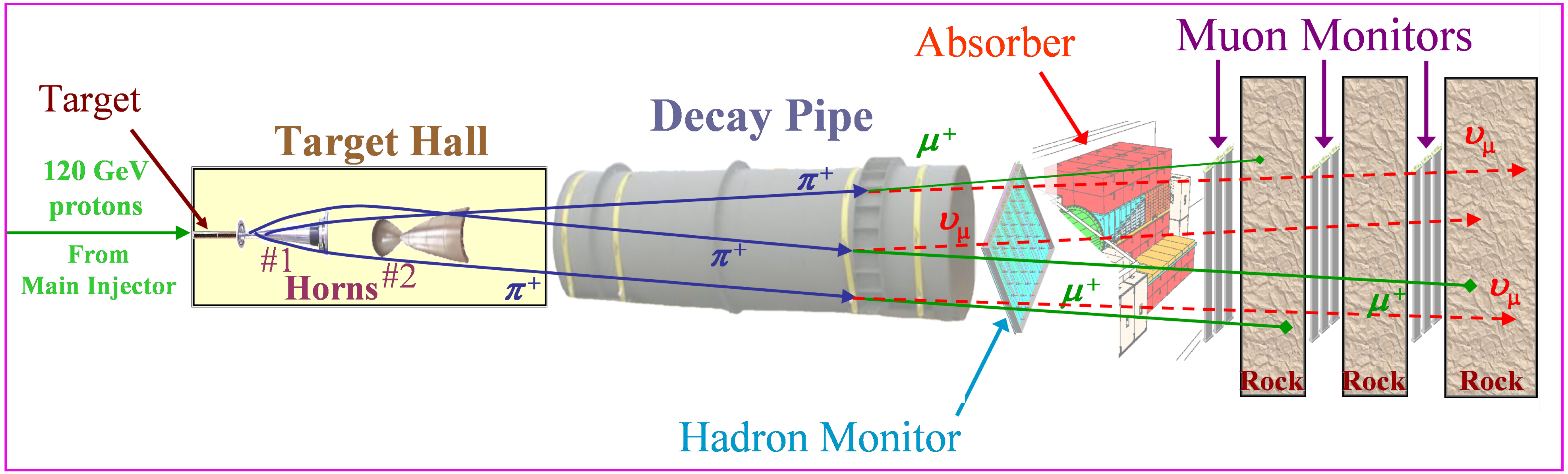
$\nu_\mu \rightarrow \nu_e$ Appearance Oscillations



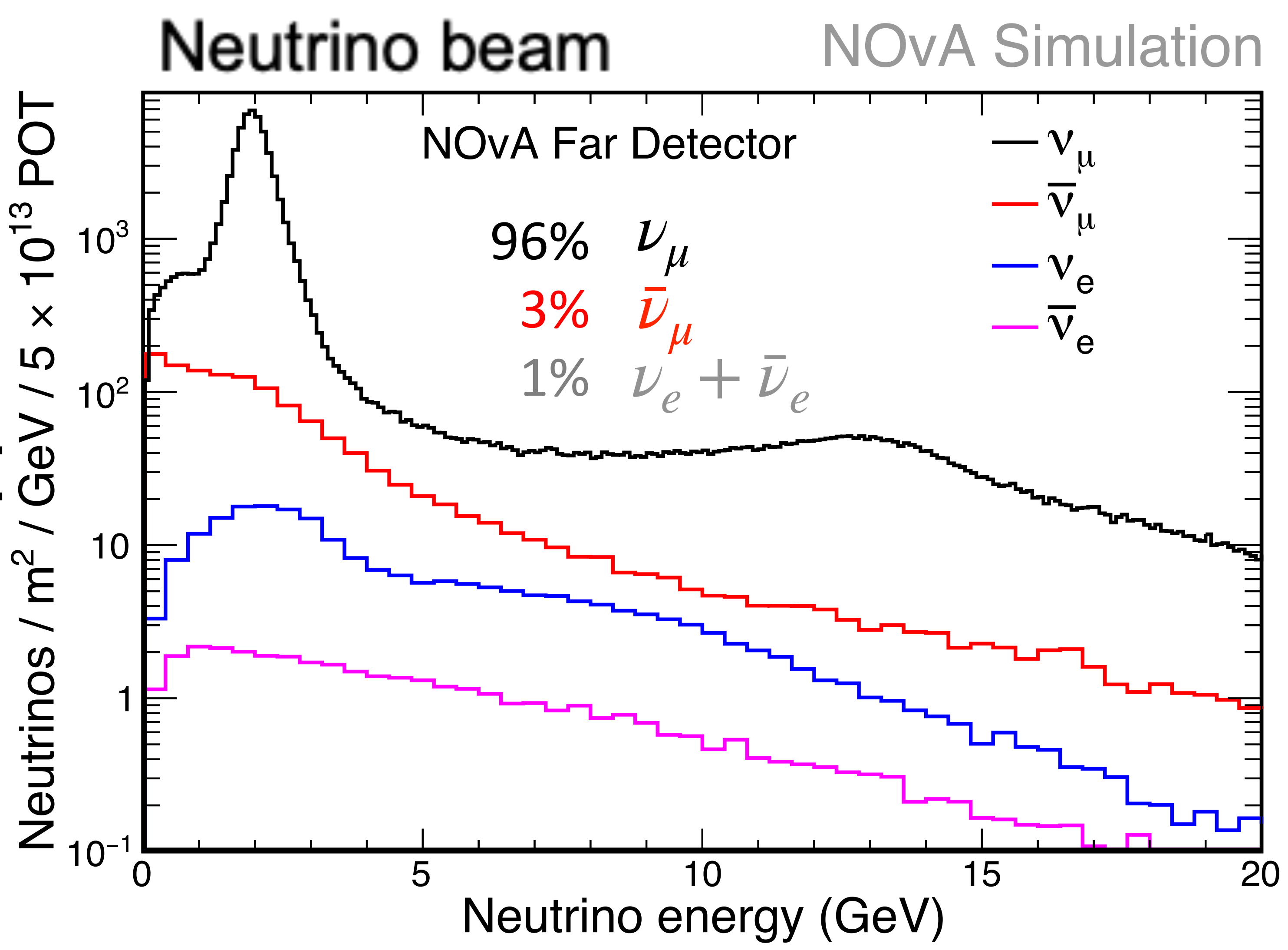


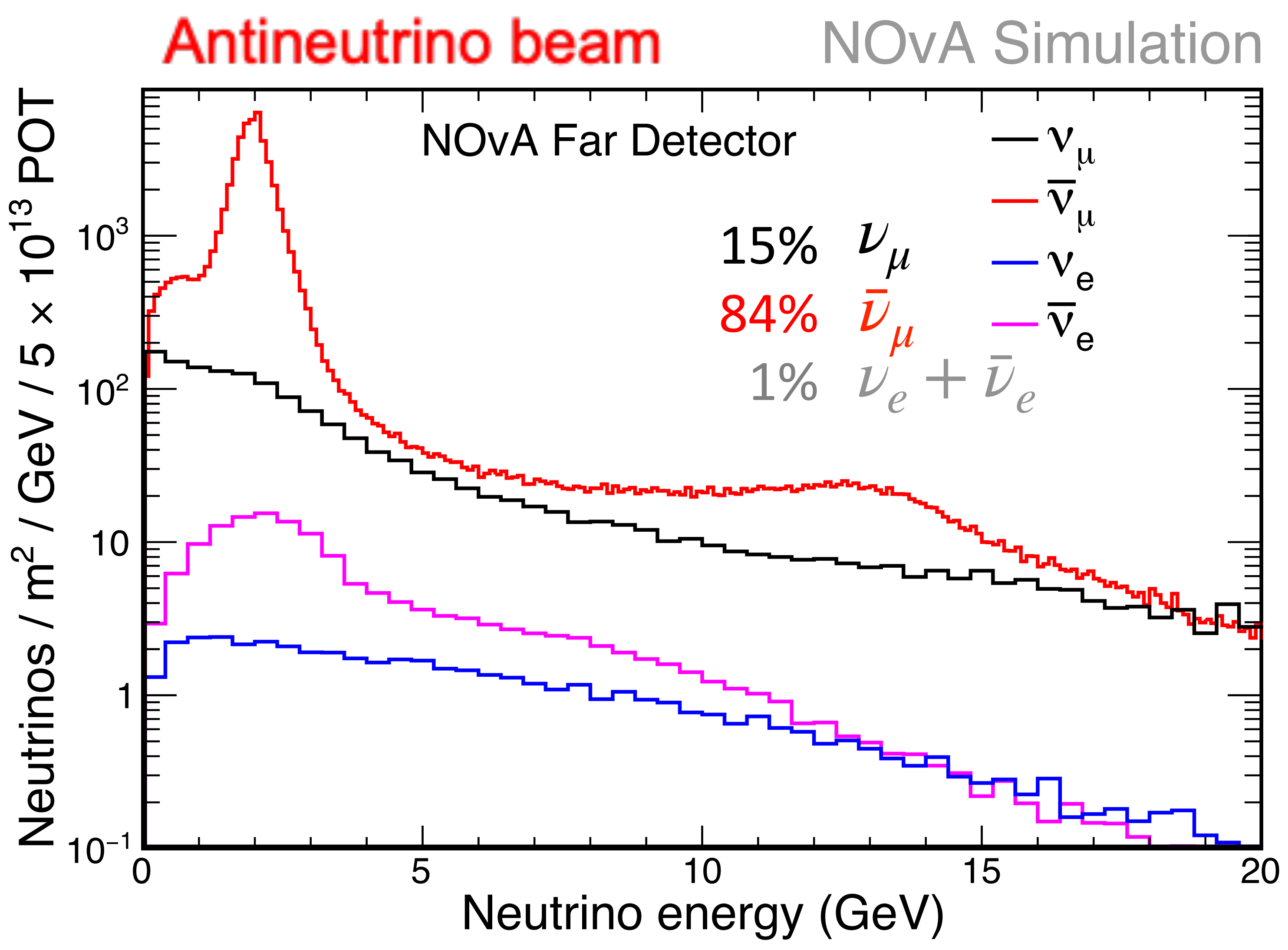
- Matter has the opposite effect on neutrino and anti-neutrino oscillation
- Matter effect determine the CP-violating phase and the sign of the $|\Delta m^2_{32}|$

Neutrino Beam at Fermilab

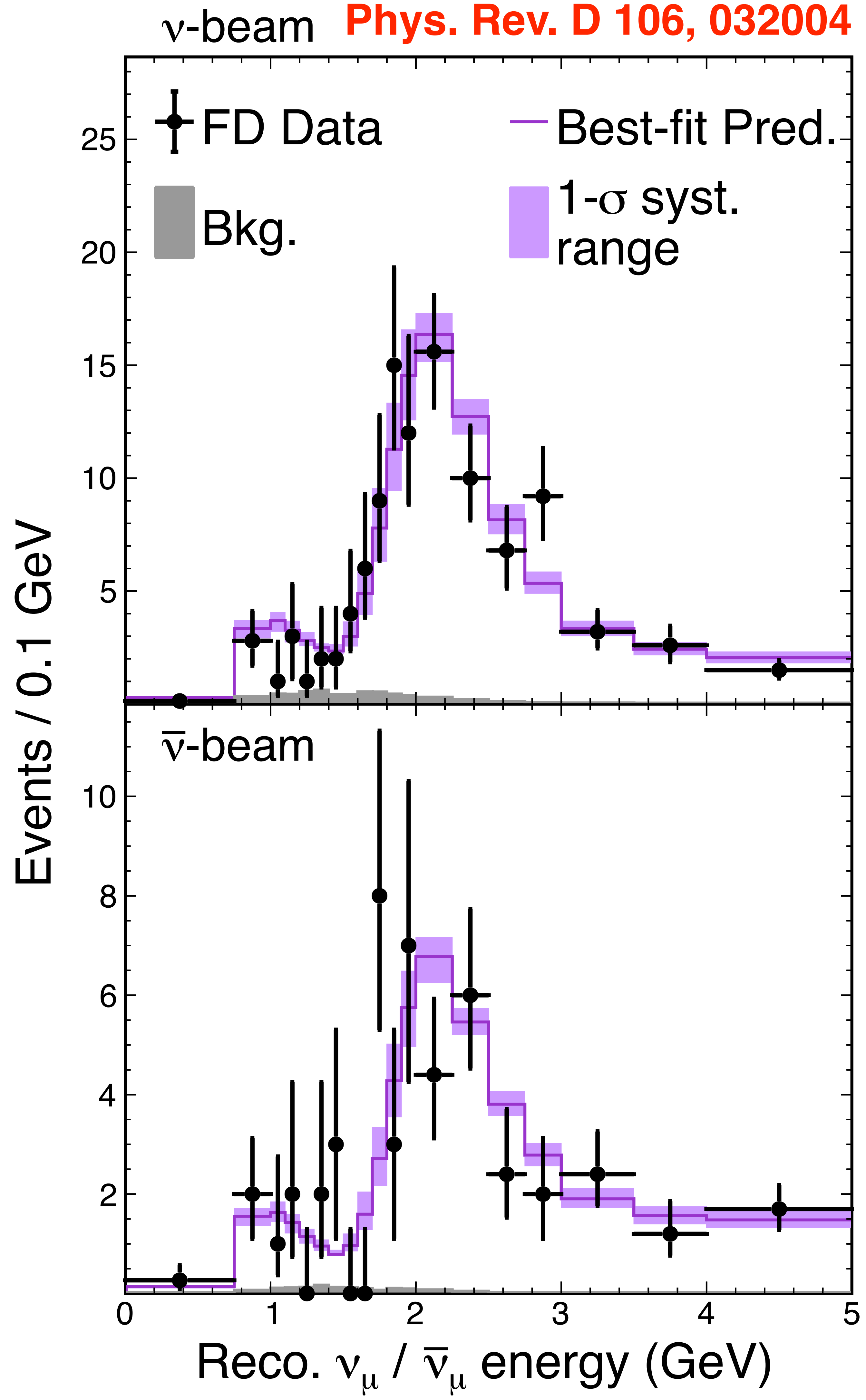


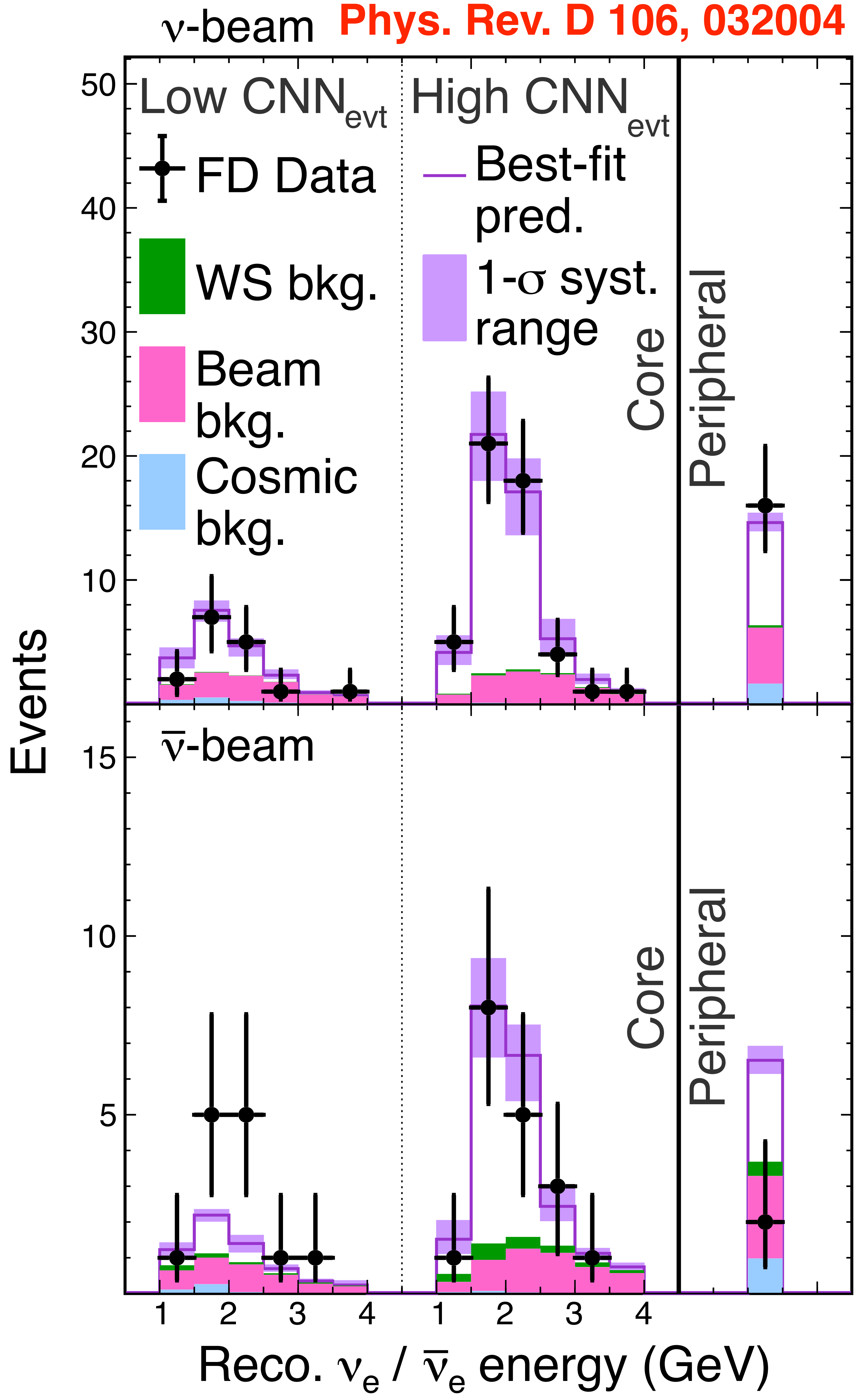
- Neutrino and antineutrino modes
- Total protons-on-target 39 x 10^{20}
- High $\nu_\mu(\bar{\nu}_\mu)$ purity





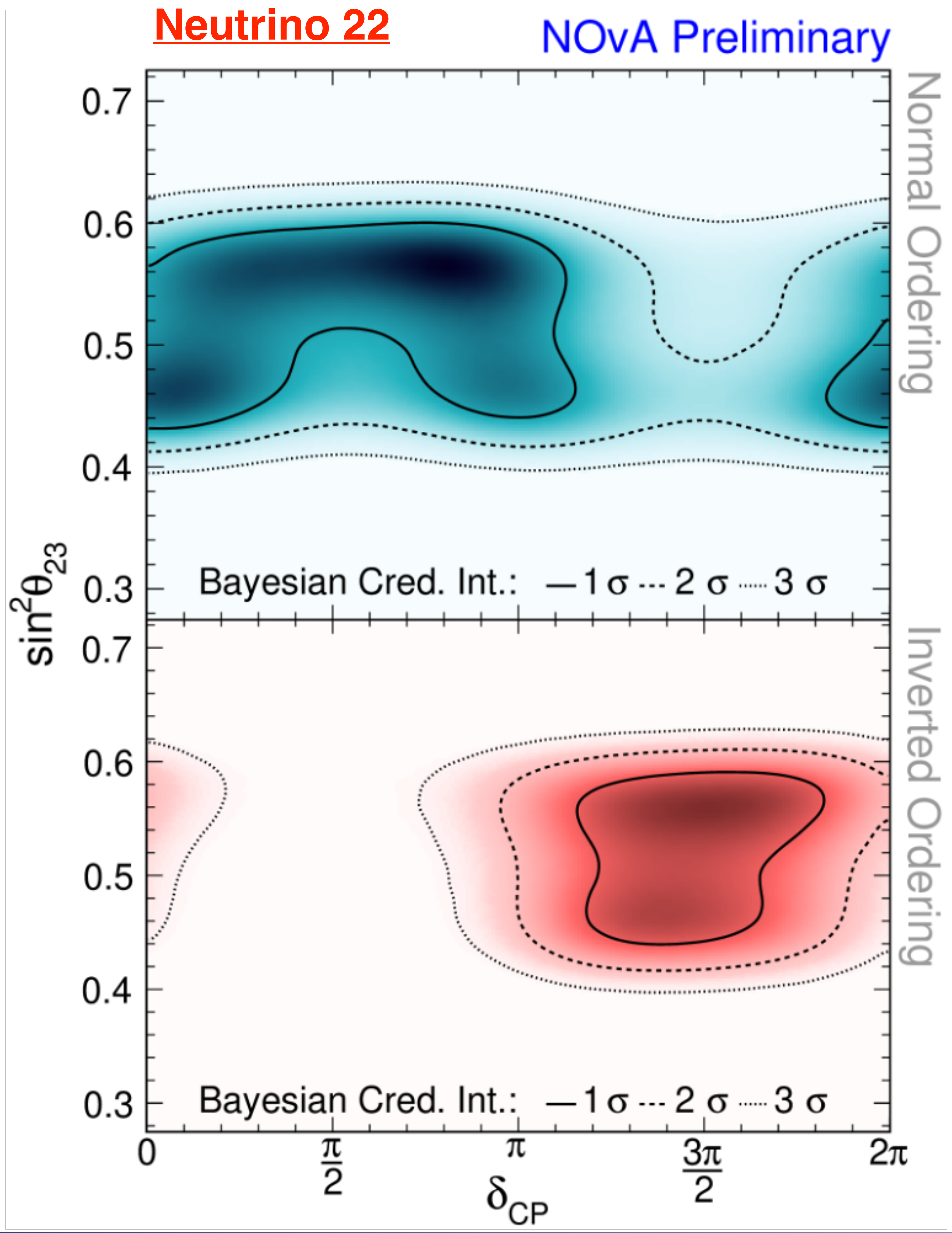
$\nu_\mu \to \nu_\mu$ Disappearance and $\nu_\mu \to \nu_e$ Appearance data





- 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

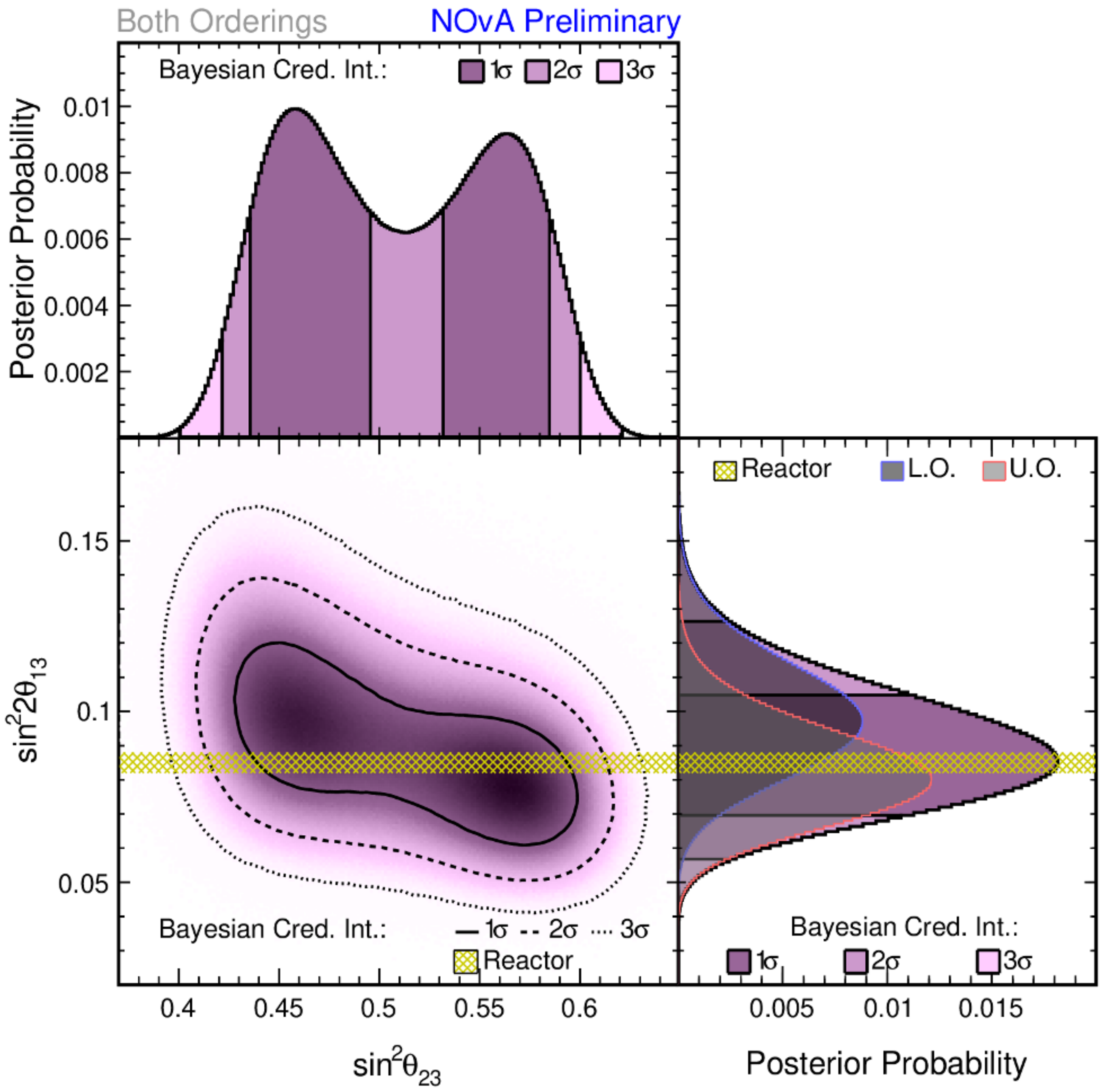
Bayesian Treatment



- 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

Cross-section Formula

Unfolding matrix

Observed events

Purity

$$\sigma_i = \frac{\sum_j U_{ij}(N_j \times P_j)}{\epsilon_i \; N_{\mathrm{t}} \; \phi}$$

Efficiency

Number of target

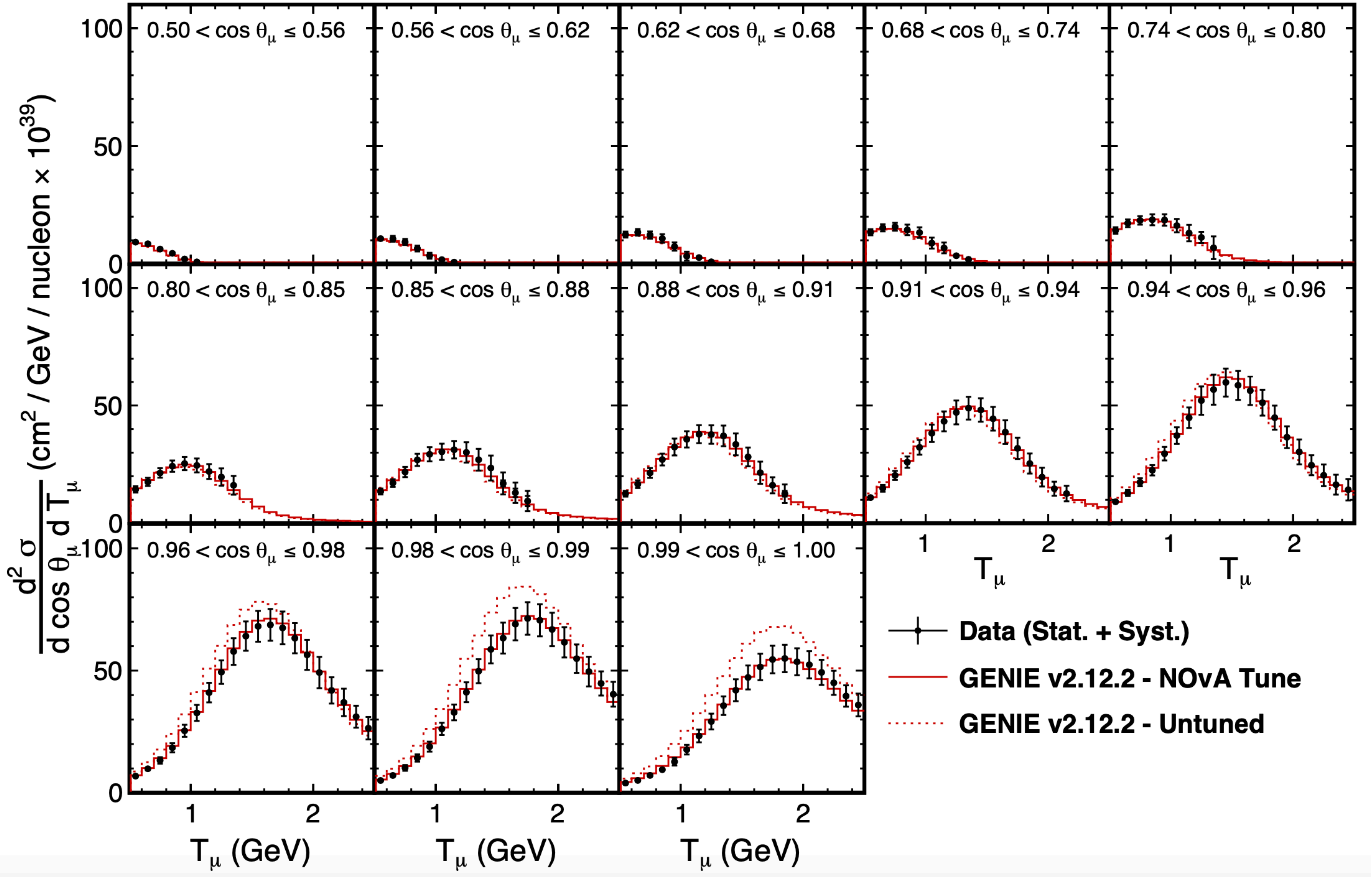
Neutrino beam flux

GENIE 2.12.2

- Global Fermi Gas with high momentum single nucleon tail from short-range correlations
  - QE: Llewellyn Smith
  - MEC: Emperical MEC reweighted to ND data
  - RES: Rein-Sehgal
  - DIS: Bodek-Yang
  - FSI: hA (effective model for FSI)

ν_μ CC Inclusive Cross section

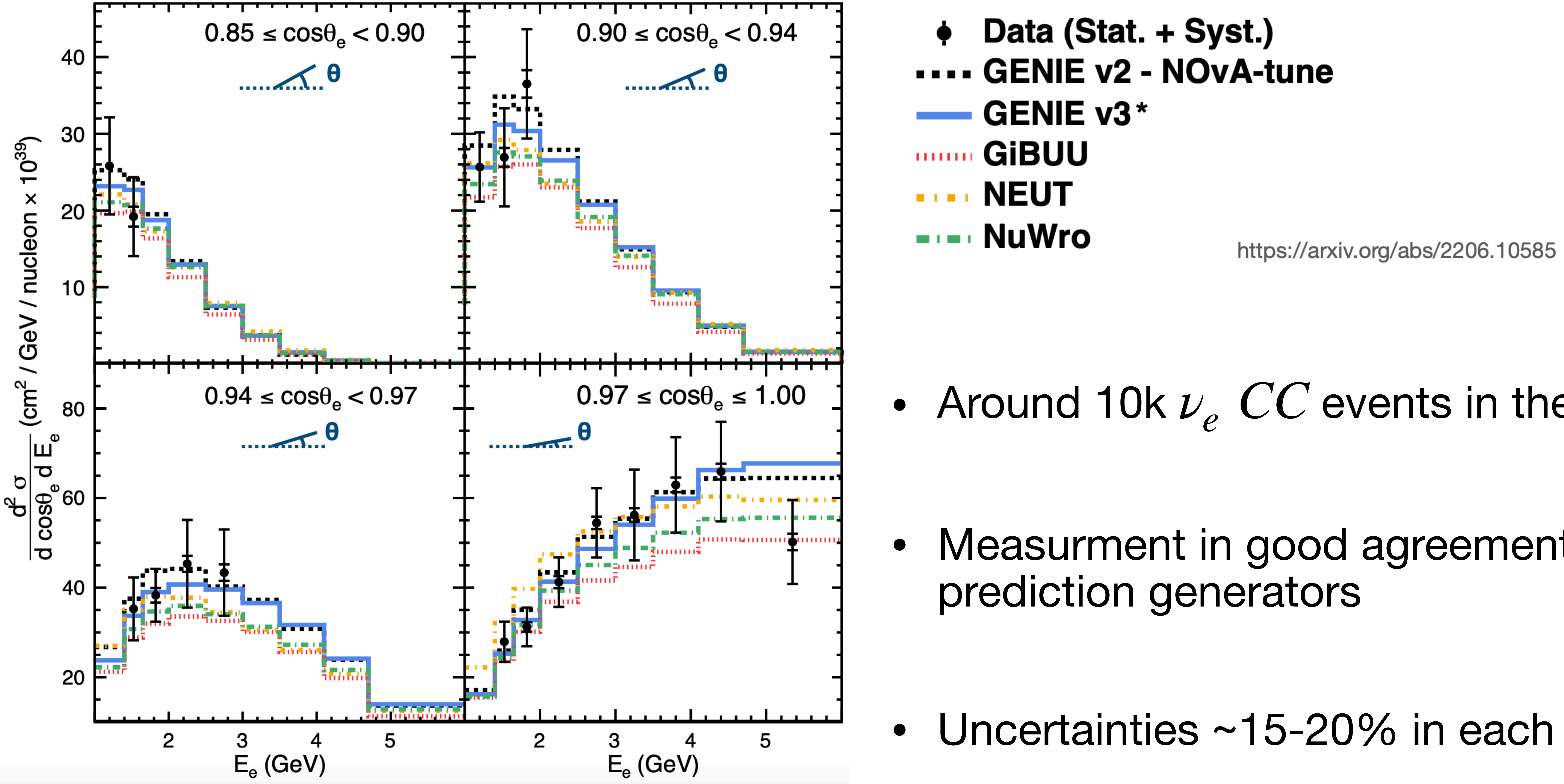
https://arxiv.org/abs/2109.12220



- 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



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