Muon neutrino cross section measurements at the NOvA ND

Leo Aliaga

February 4, 2020

Fermilab Postdoc Meeting of the Scientific Computing Division

Outline

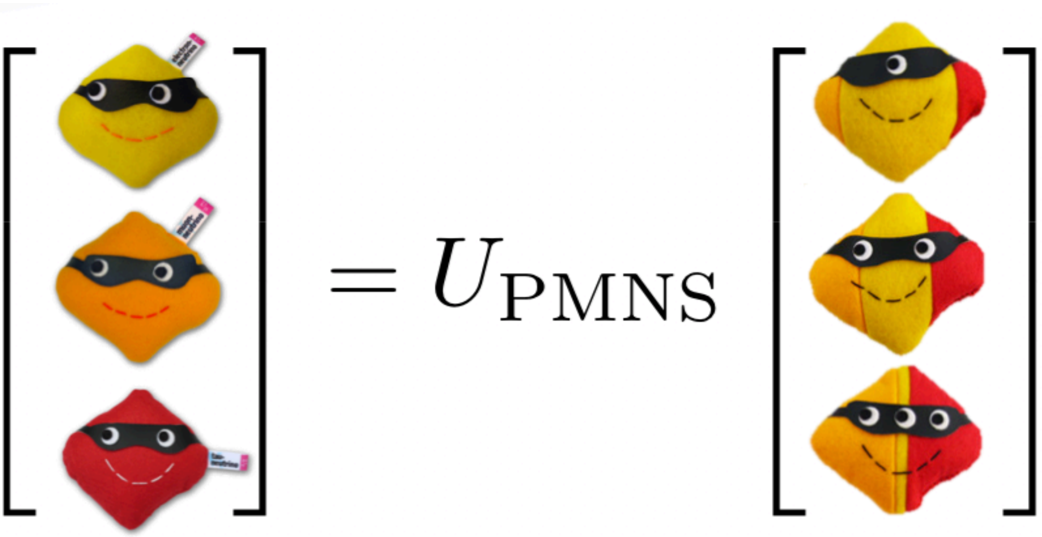
- Introduction to NOvA
- Cross sections at the NOvA ND
- Status of the inclusive muon-neutrino cross-section analysis at the NOvA ND
- Status of the muon-neutrino pionless analysis at the NOvA ND

Introduction

Neutrinos oscillate

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

Each flavor (e, μ, τ) is a superposition of different masses (1, 2, 3)



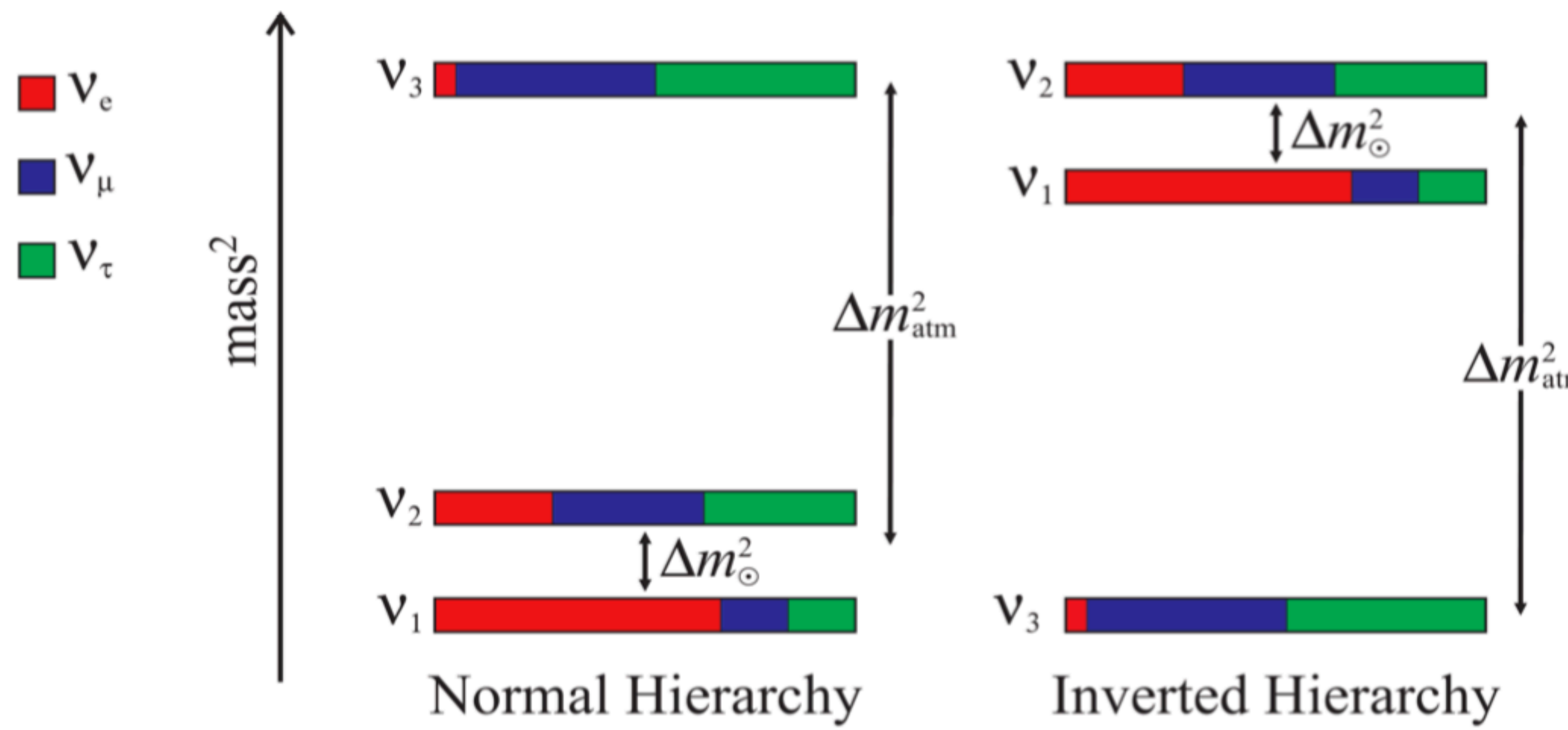
Oscillations depend on:

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

The mass difference: Δm^2_{32}, Δm^2_{21}

Unanswered Questions in Neutrino Physics

Hierarchy of neutrino mass states:
Normal or Inverted?



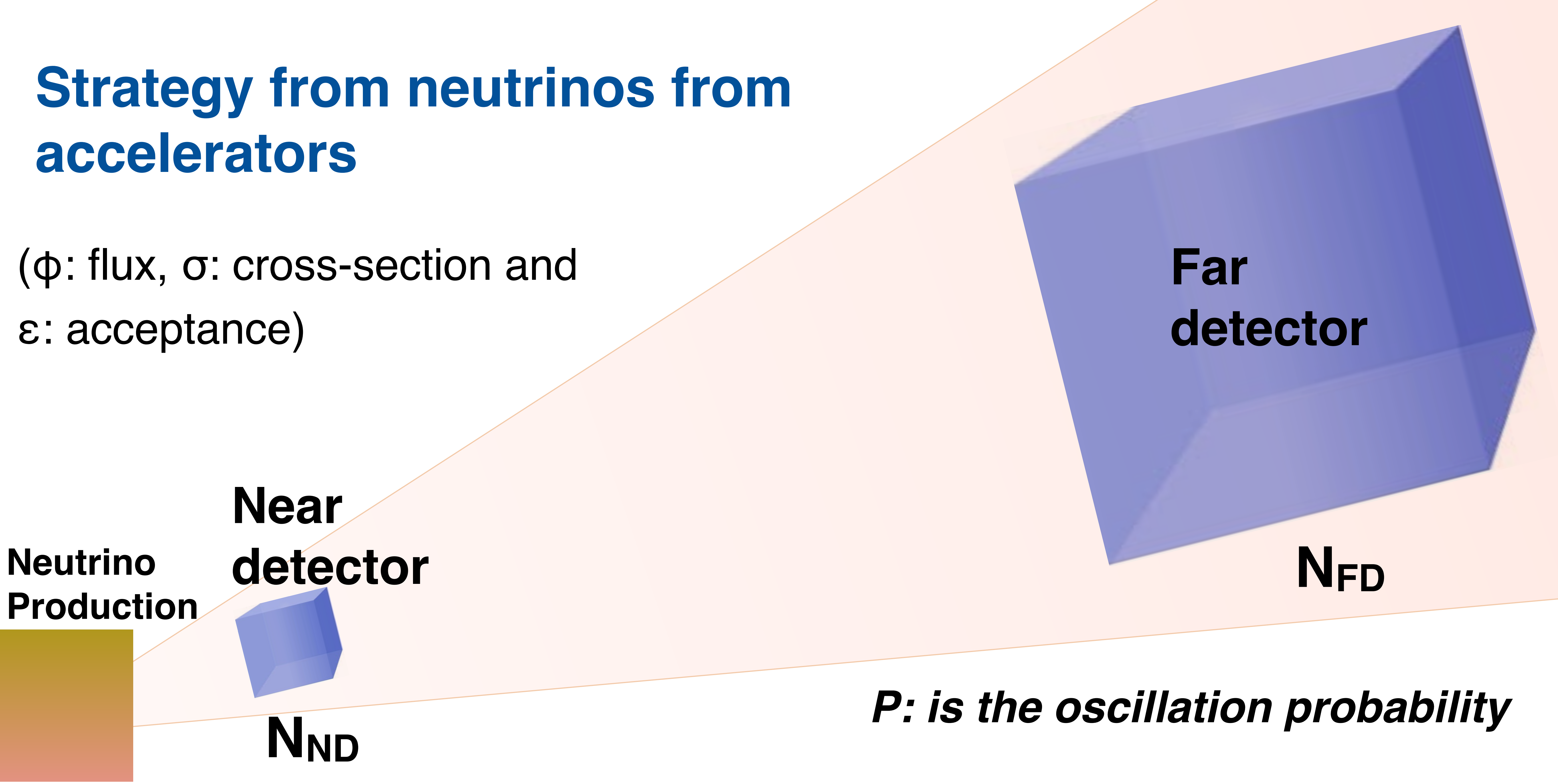
Flavor content of ν_3:
is θ_{23} maximal, ie $\pi/4$?

Is CP violated by neutrinos: do neutrinos and anti-neutrinos oscillate differently?

The NOvA experiment is aimed these questions

Strategy from neutrinos from accelerators

(ϕ: flux, σ: cross-section and ε: acceptance)

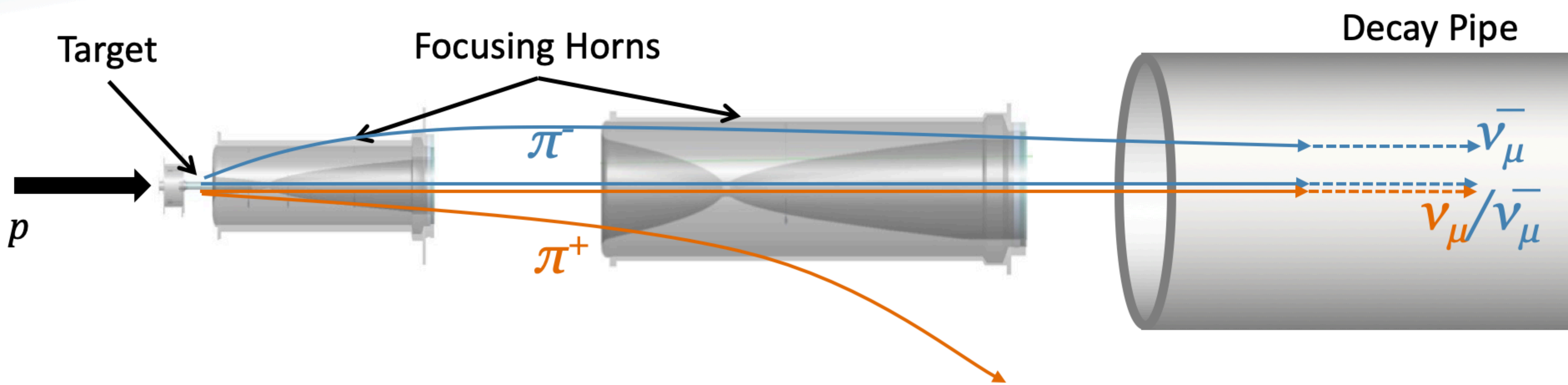


P: is the oscillation probability

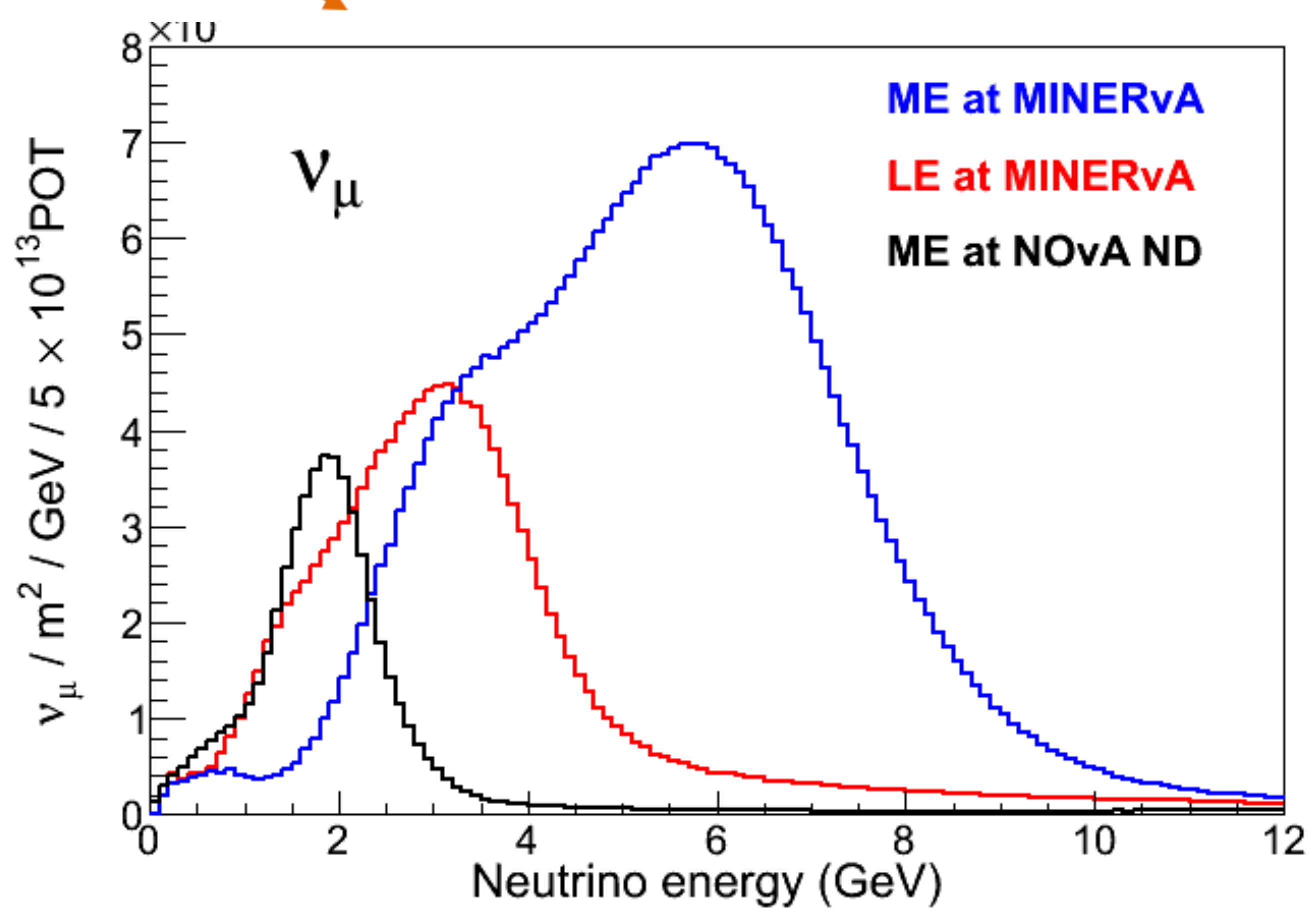
Compare what we expected without oscillation respect to what we see: the ***discrepancy comes from the neutrino oscillation***

$$N_{ND} = \phi_{ND}\ \sigma\ \varepsilon_{ND} \longrightarrow N_{FD} = P\ \phi_{FD}\ \sigma\ \varepsilon_{FD}$$

NuMI Beam

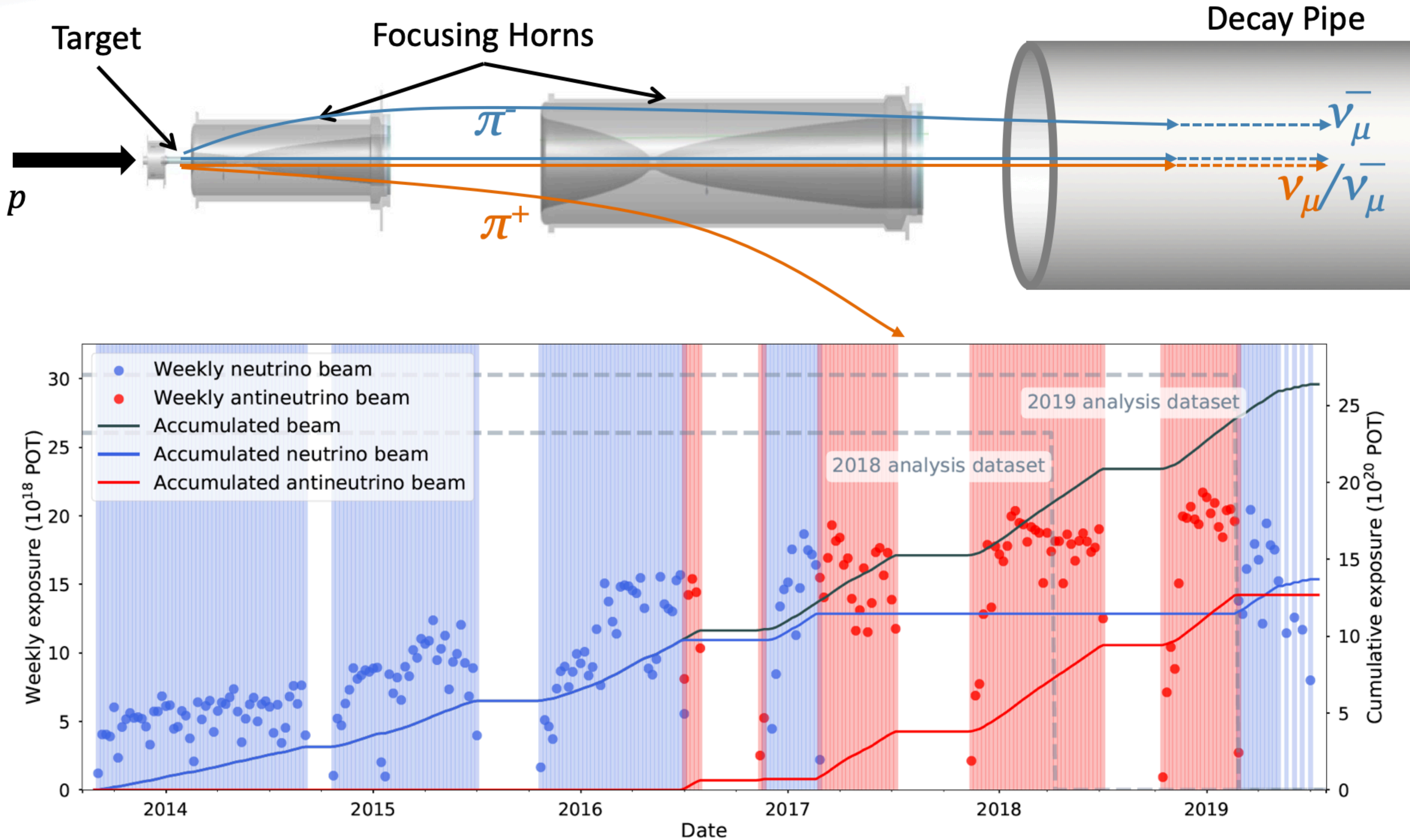


- **Low energy mode** (LE): 2005-2012 (at ~250 kW).
- **Medium energy mode** (ME): 2013-present (~750 kW):



Alternating between neutrino enhanced mode and antineutrino enhanced mode.

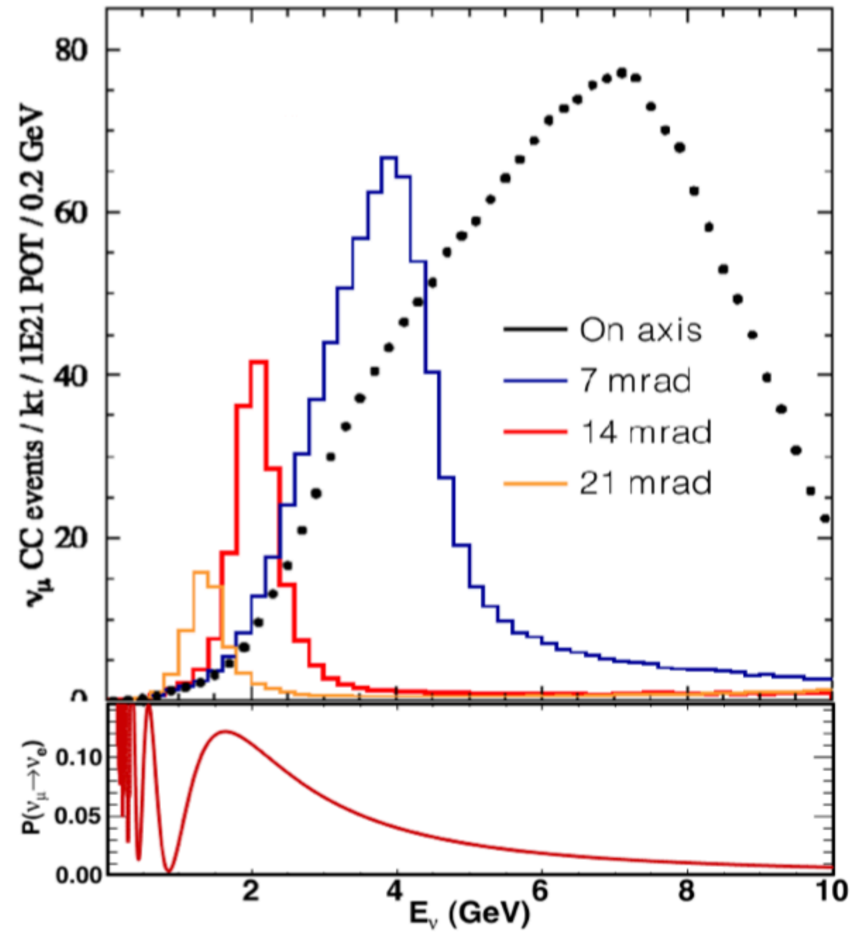
NuMI Beam



Target
Focusing Horns
Decay Pipe
p
π^-
π^+
$\bar{\nu}_\mu$
$\nu_\mu/\bar{\nu}_\mu$
Weekly neutrino beam
Weekly antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam
2019 analysis dataset
2018 analysis dataset
Weekly exposure (10^{18} POT)
Cumulative exposure (10^{20} POT)
Date
2014
2015
2016
2017
2018
2019

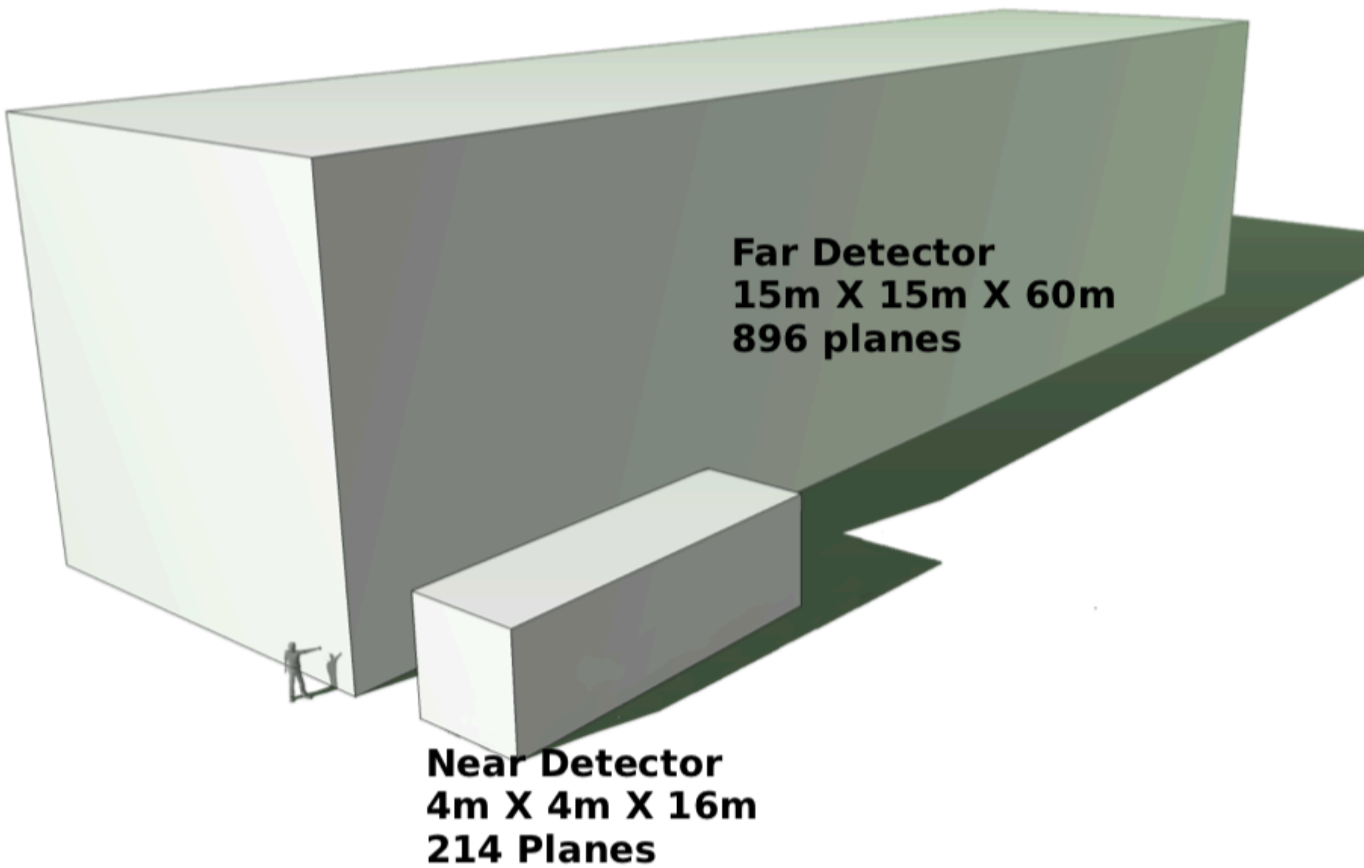
The NOvA Experiment

- NOvA (**N**uMI **O**ff-axis ν_e **A**ppearance) is a neutrino oscillation experiment
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - 14 mrad off-axis from the beam



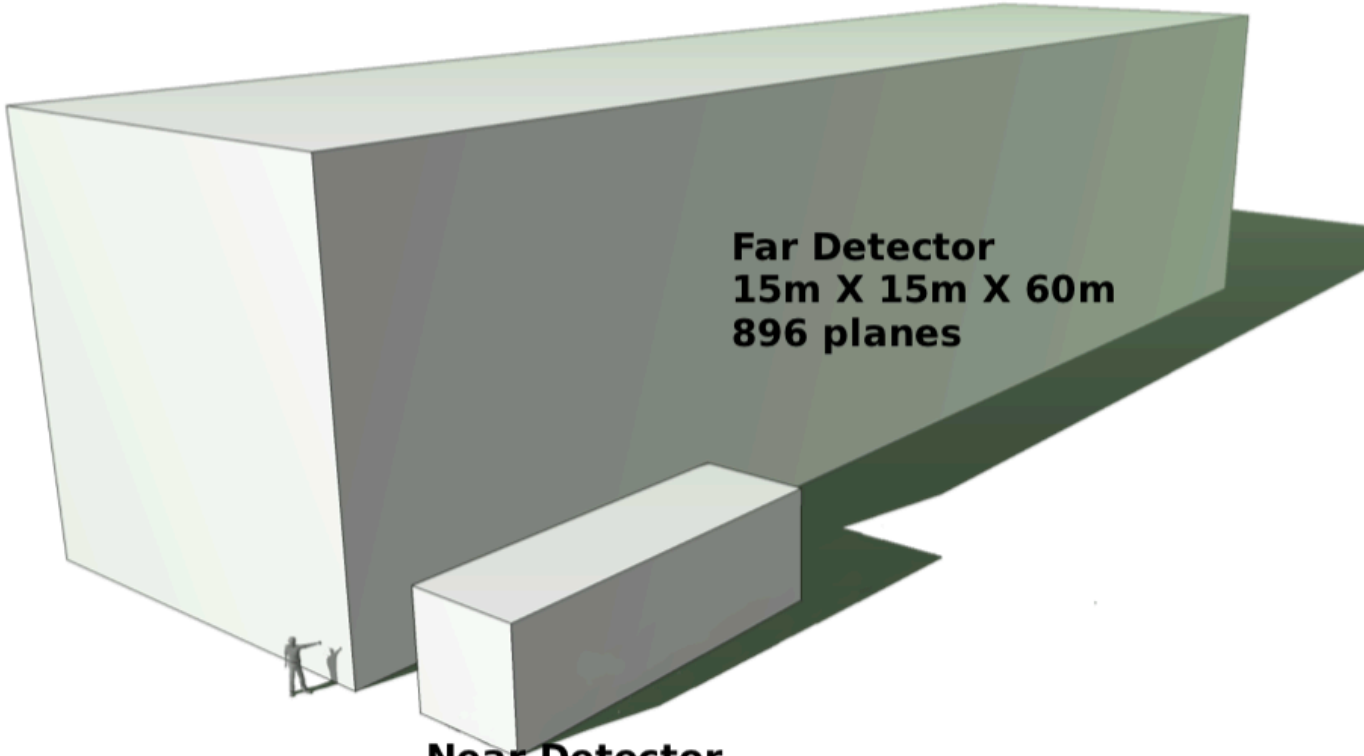
The NOvA Experiment

- NOvA (**N**uMI **O**ff-axis ν_e **A**ppearance) is a neutrino oscillation experiment
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - 14 mrad off-axis from the beam
  - Two functionally identical detectors



The NOvA Experiment

- NOvA (**N**uMI **O**ff-axis ν_e **A**ppearance) is a neutrino oscillation experiment
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - 14 mrad off-axis from the beam
  - Two functionally identical detectors
- Physics program
  - ν_μ to $\nu_\mu(\nu_e)$ oscillation
  - Sterile neutrino search
  - **Cross-section measurements**
  - Supernovae, search for BSM phenomena, etc.



Challenge for the Oscillation program

$$N_{ND} = \phi_{ND}\, \sigma\, \varepsilon_{ND}$$

↓

$$N_{FD} = P\, \phi_{FD}\, \sigma\, \varepsilon_{FD}$$

The oscillation parameters are extracted from **P** as a function of reconstructed neutrino energy.

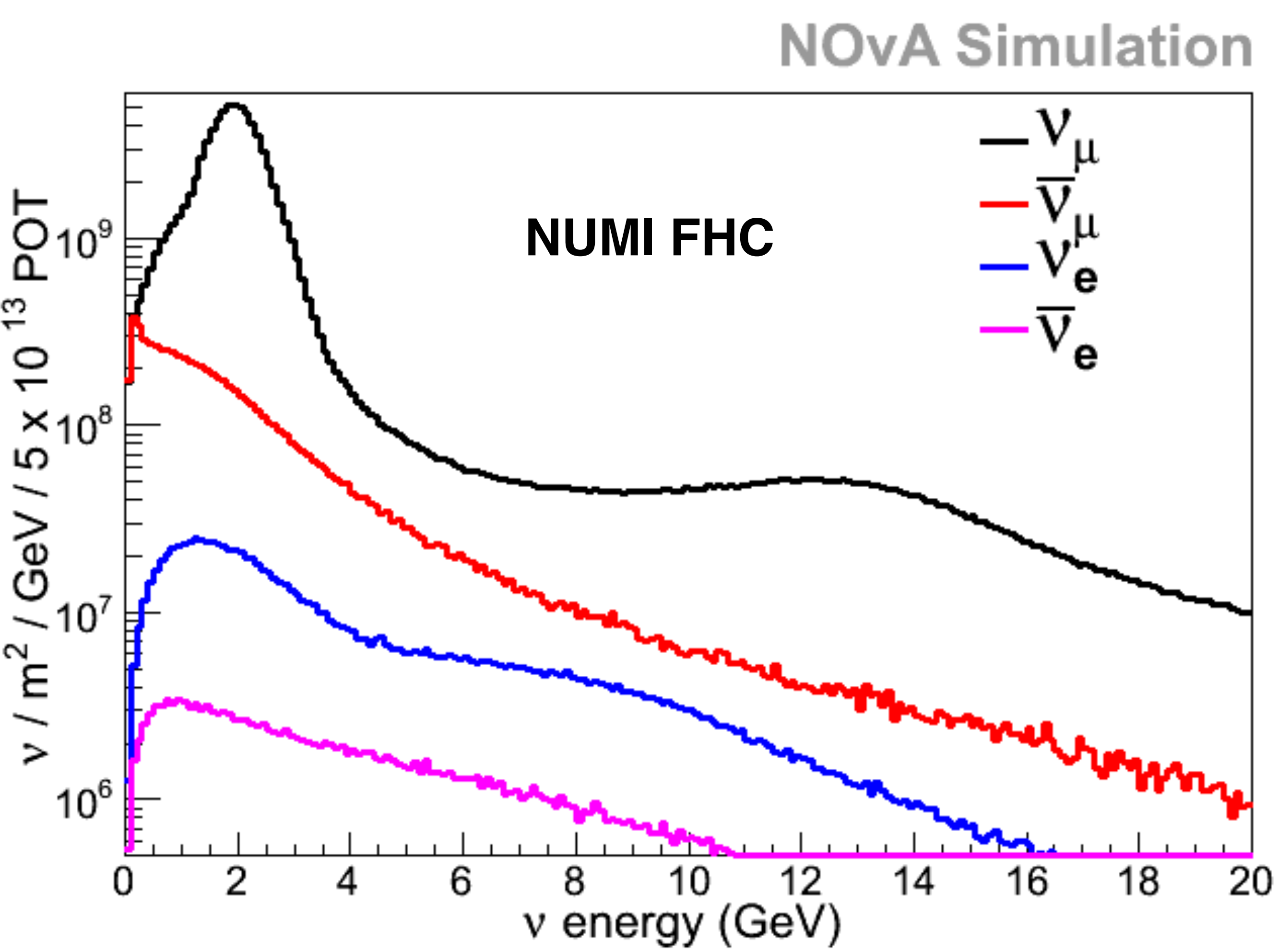
- ϕ: is not monochromatic, it is reconstructed from final states: baseline prediction used for energy spectra at the detectors.
- σ : model of neutrino interactions in the nucleus is not complete.

NOvA uses calorimetric energy reconstruction: $\mathbf{E_\nu = E_\mu + E_{shower}}$

- Needs a good understanding of the final states of the reactions

NuMI Beam at NOvA

- NOvA detectors are off-axis, **14 mrad** w.r.t NuMI beam axis.
  - It is a narrow-band beam centered around **2GeV**, right on the 1st DUNE oscillation maximum.
  - Both neutrino mode and anti-neutrino mode



Uncertainties

Beam optics model

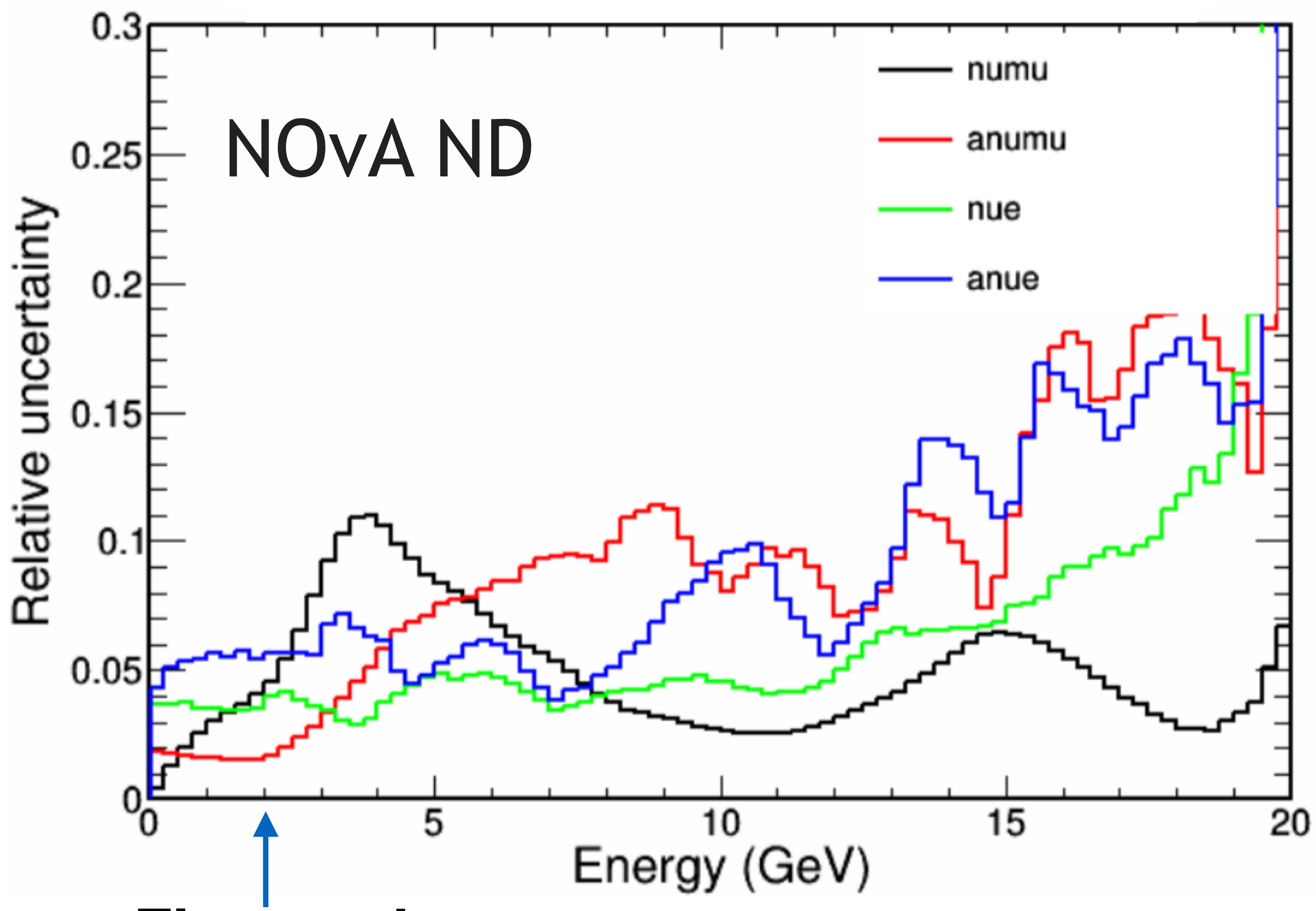
Any misalignment in the beamline components affect the expected flux.

Hadron Production model:

Physics of the interactions in the hadronic cascade that follows the primary proton beam until the meson decay is not complete.

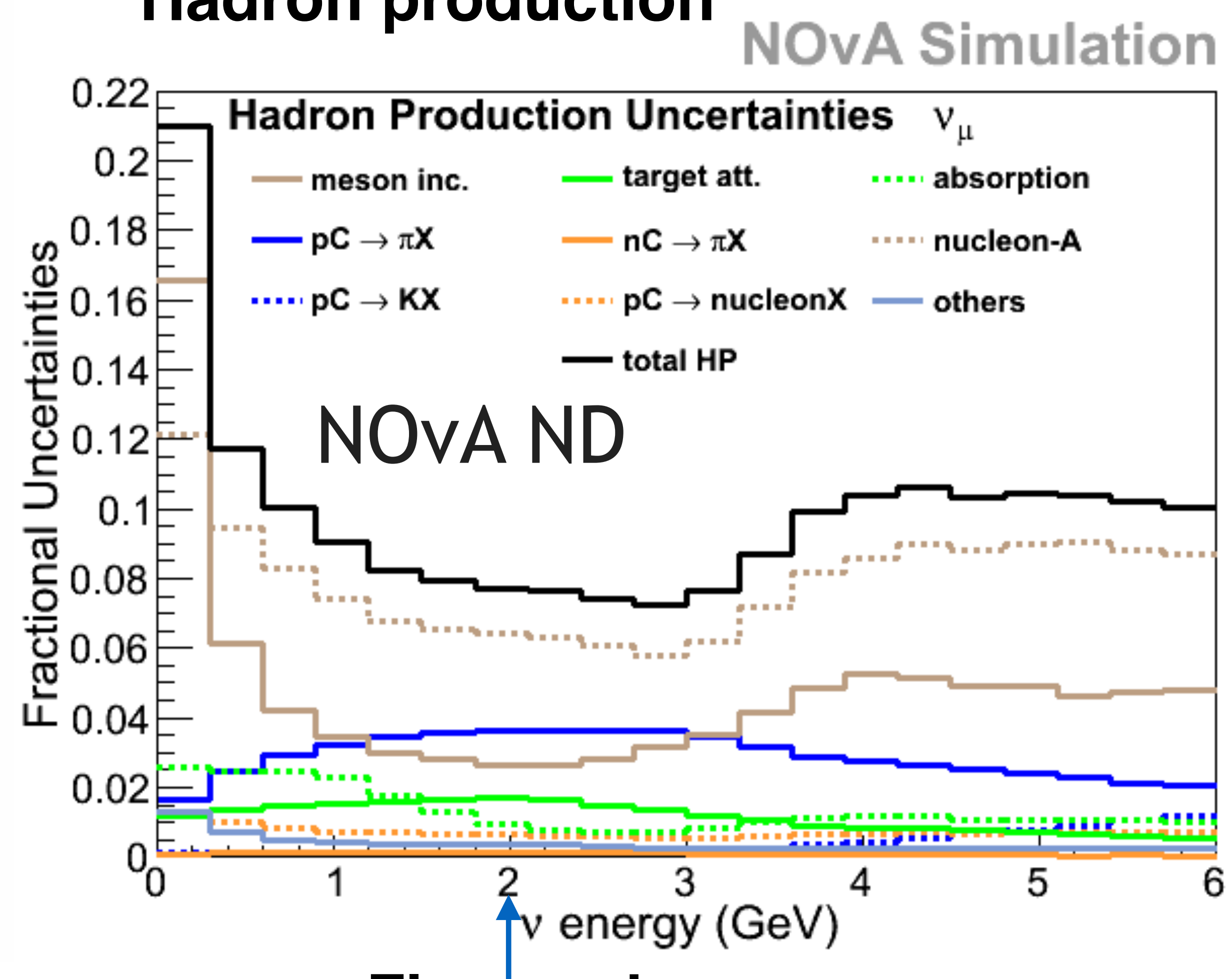
Flux Uncertainties

Beam optics



Flux peak

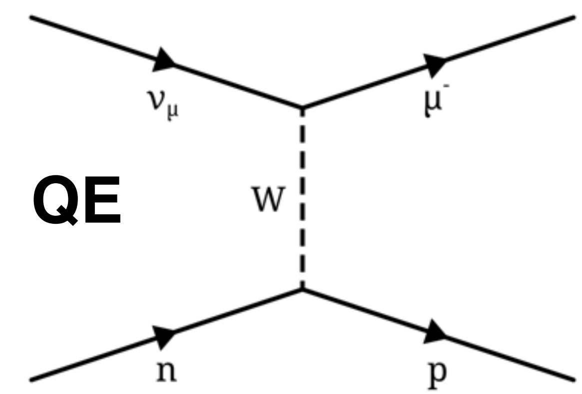
Hadron production



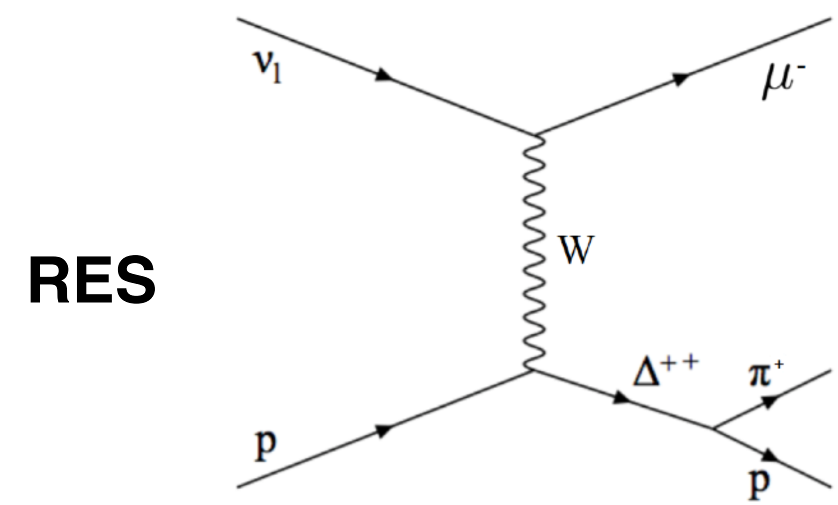
Flux peak

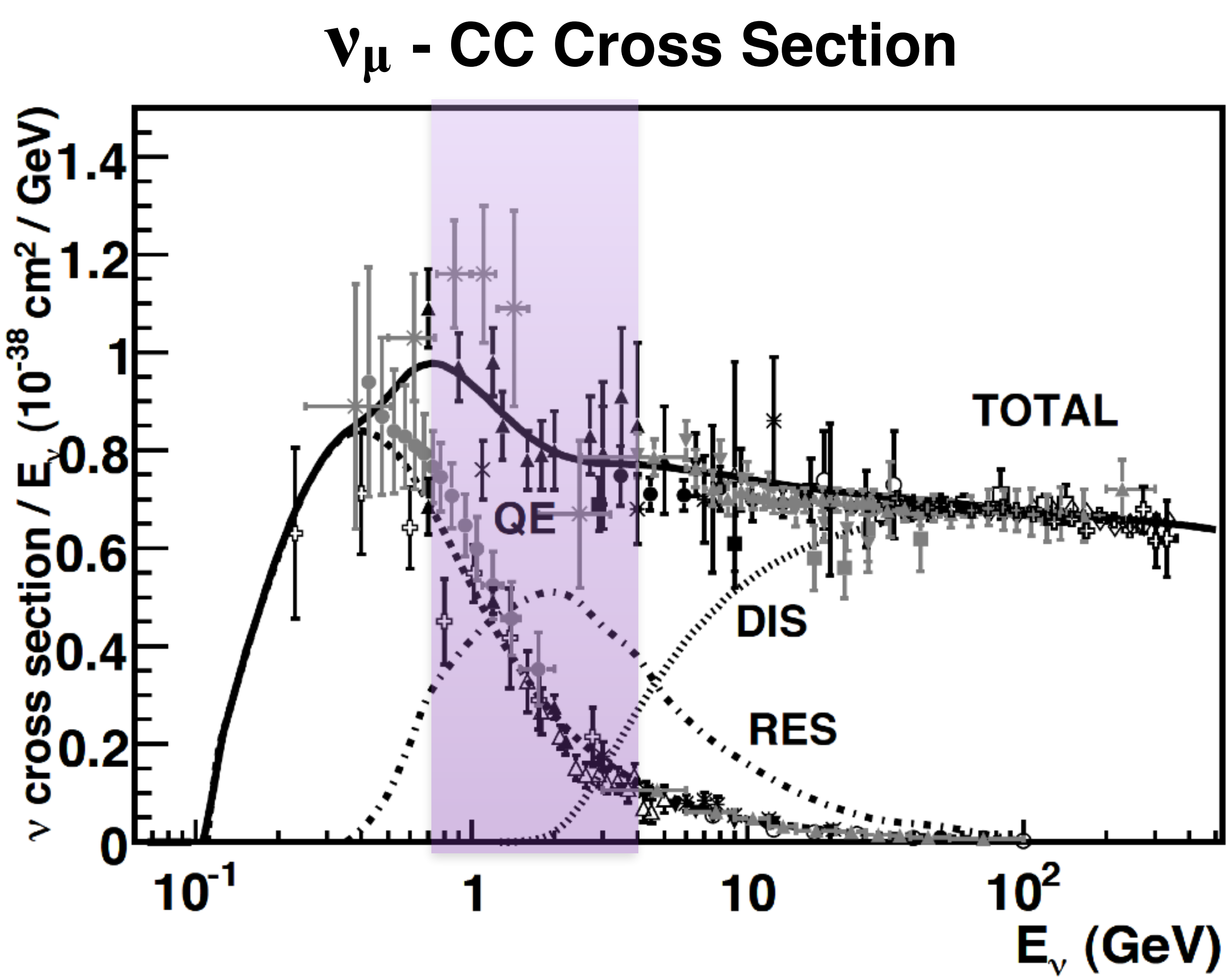
- ~4% from beam optics and ~8% from hadron production at the NOvA spectrum peak for ν_μ

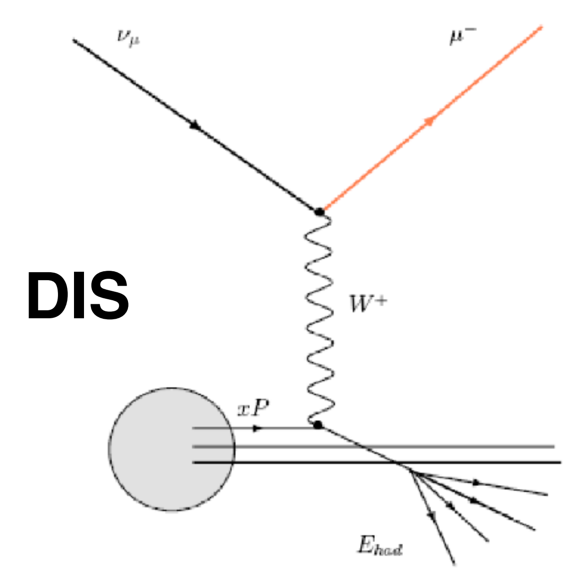
Neutrino-nucleus Cross Section



NuMu-CC Inclusive = Nuclear resonances + Quasielastic + Multinuclear excitations + Deep inelastic scattering





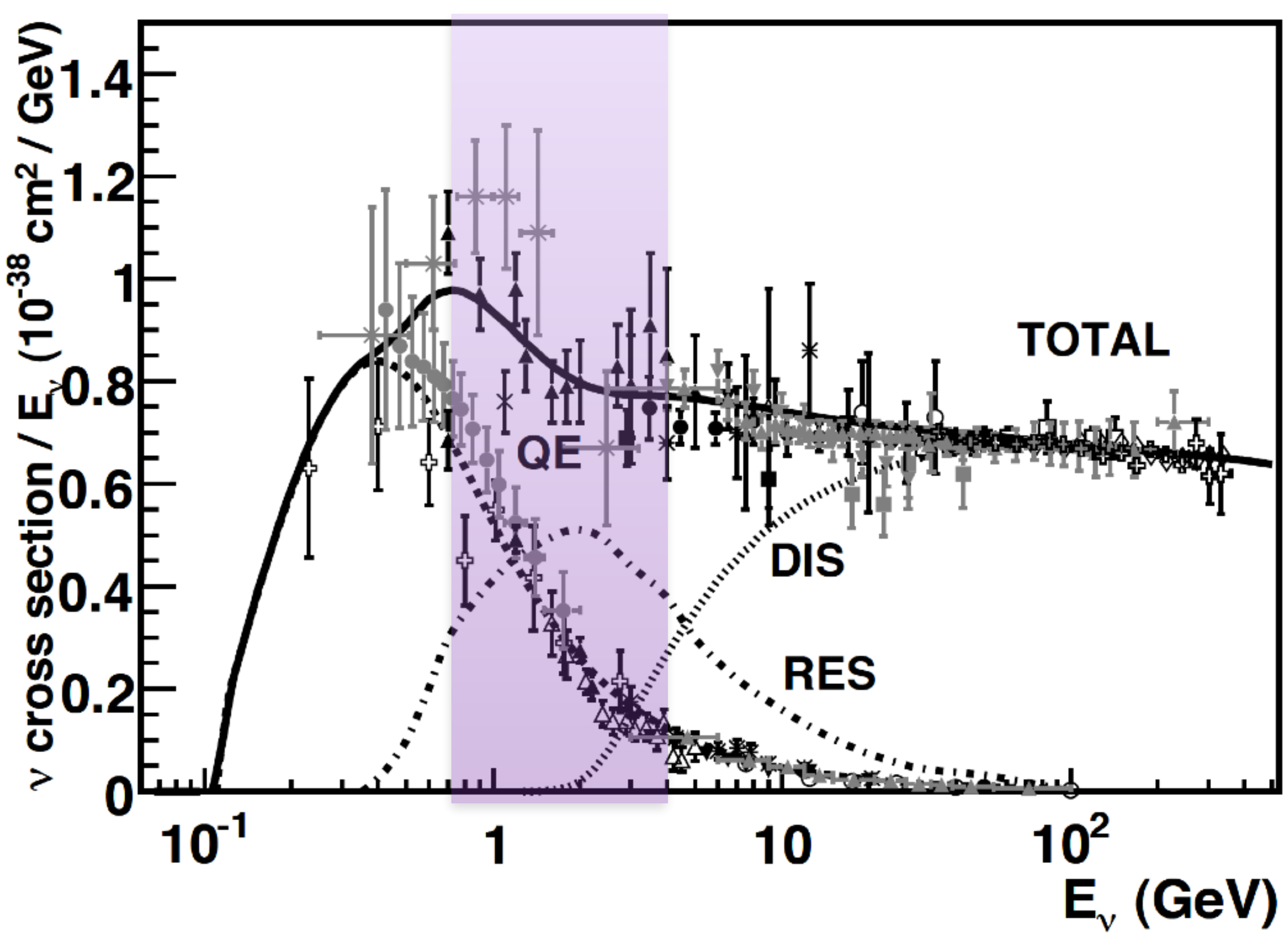


Event Rates at NOvA ND

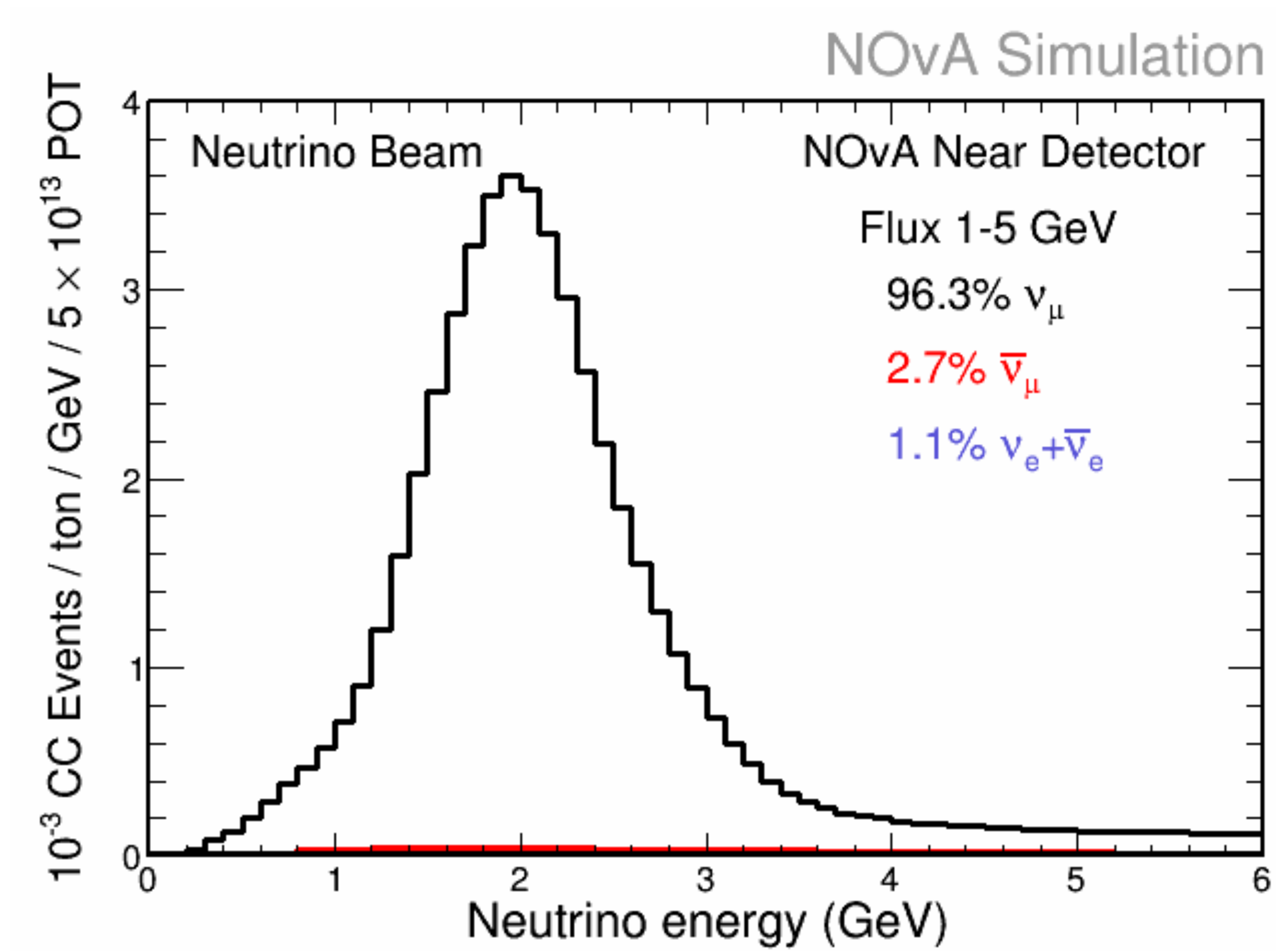
Protons on target

- FHC ~ **12 x 10^{20}**
- RHC ~ **12 x 10^{20}**

Even with a narrow band beam, NOvA is still sensitive to many different nu+A channels.



High data rate at the ND (~10^6 interactions in the whole data taking period).



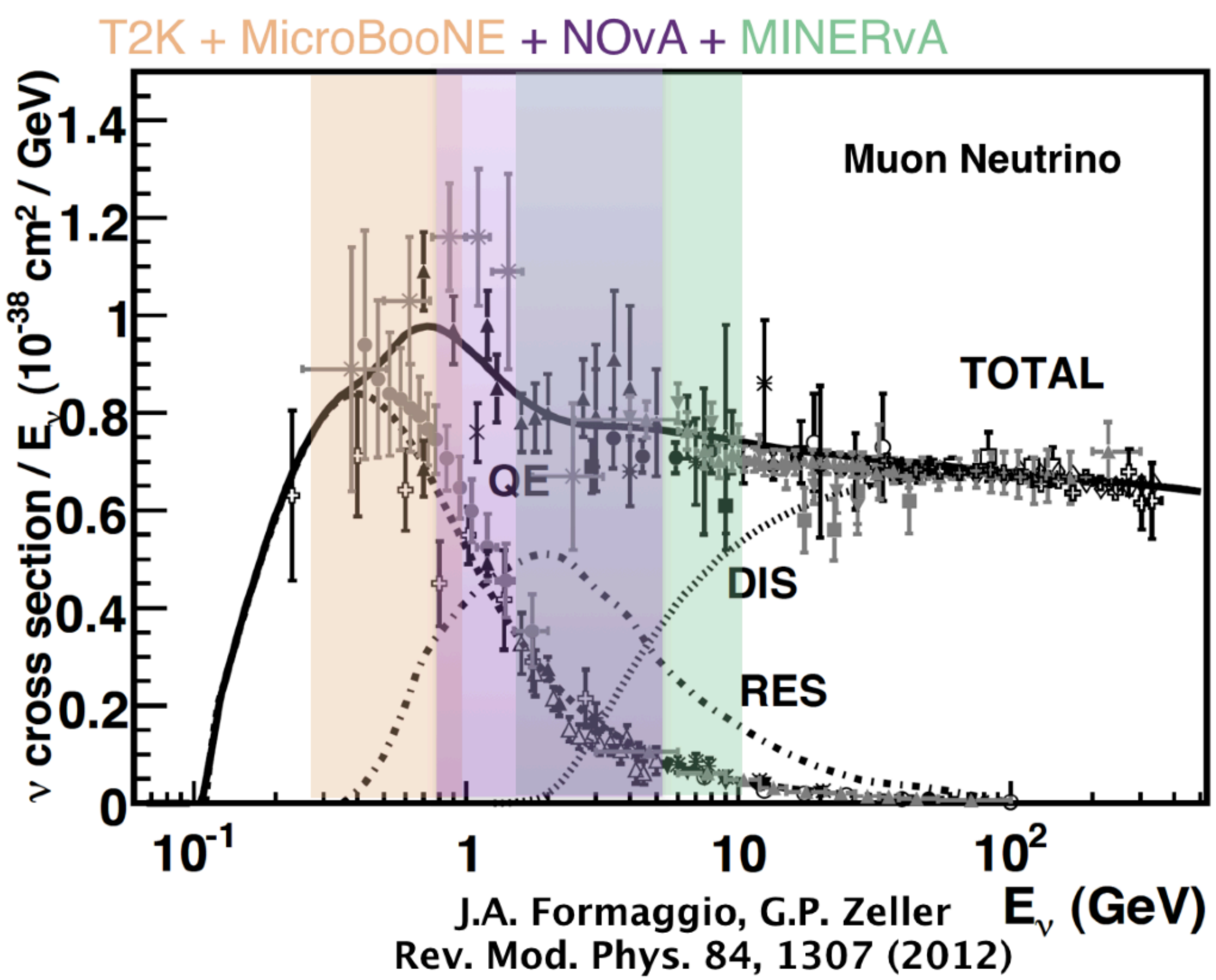
Event Rates at NOvA ND

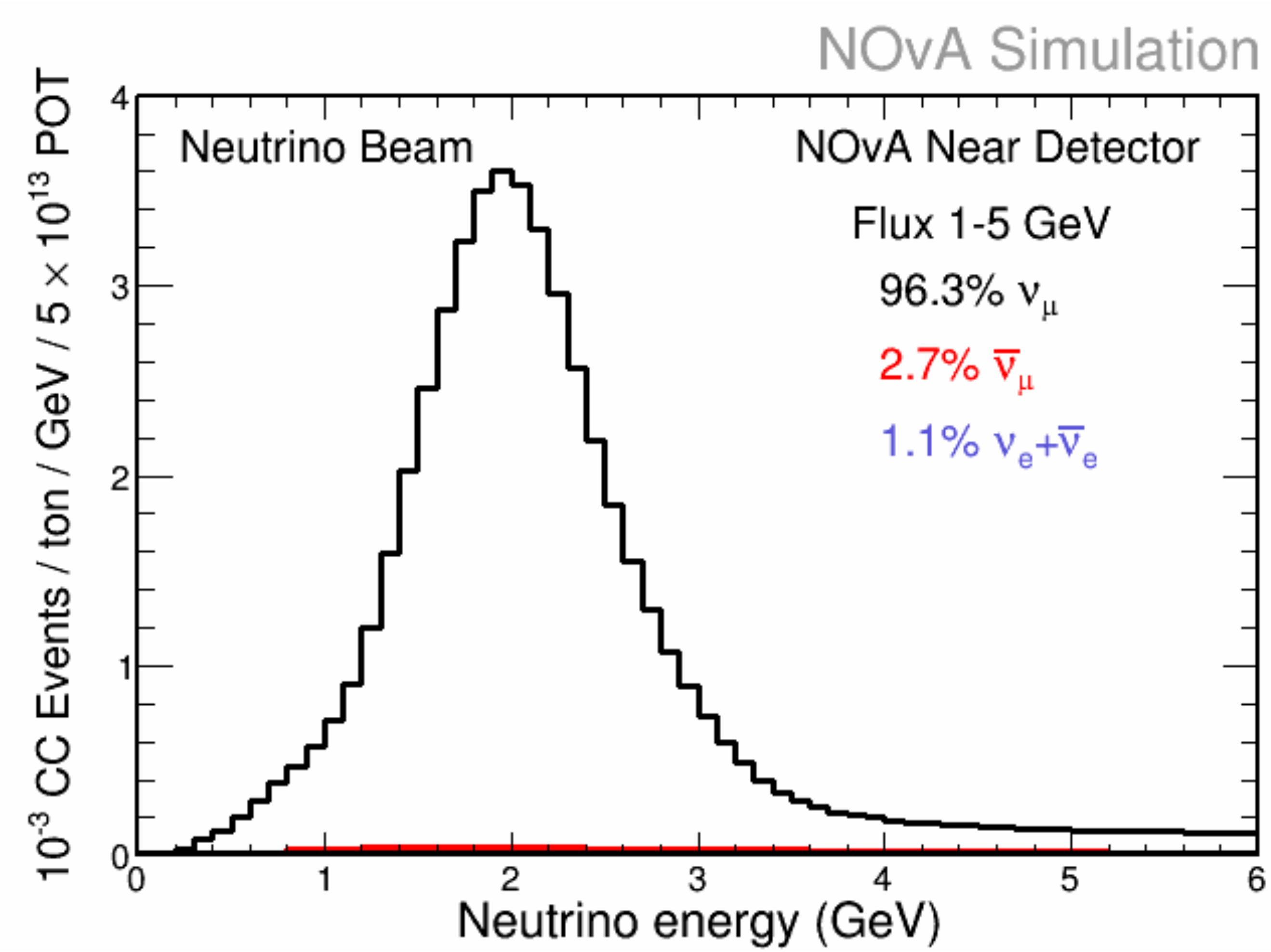
Protons on target

- FHC ~ **12 x 10[20]**
- RHC ~ **12 x 10[20]**

Even with a narrow band beam, NOvA is still sensitive to many different nu+A channels.

High data rate at the ND (~10[6] interactions in the whole data taking period).



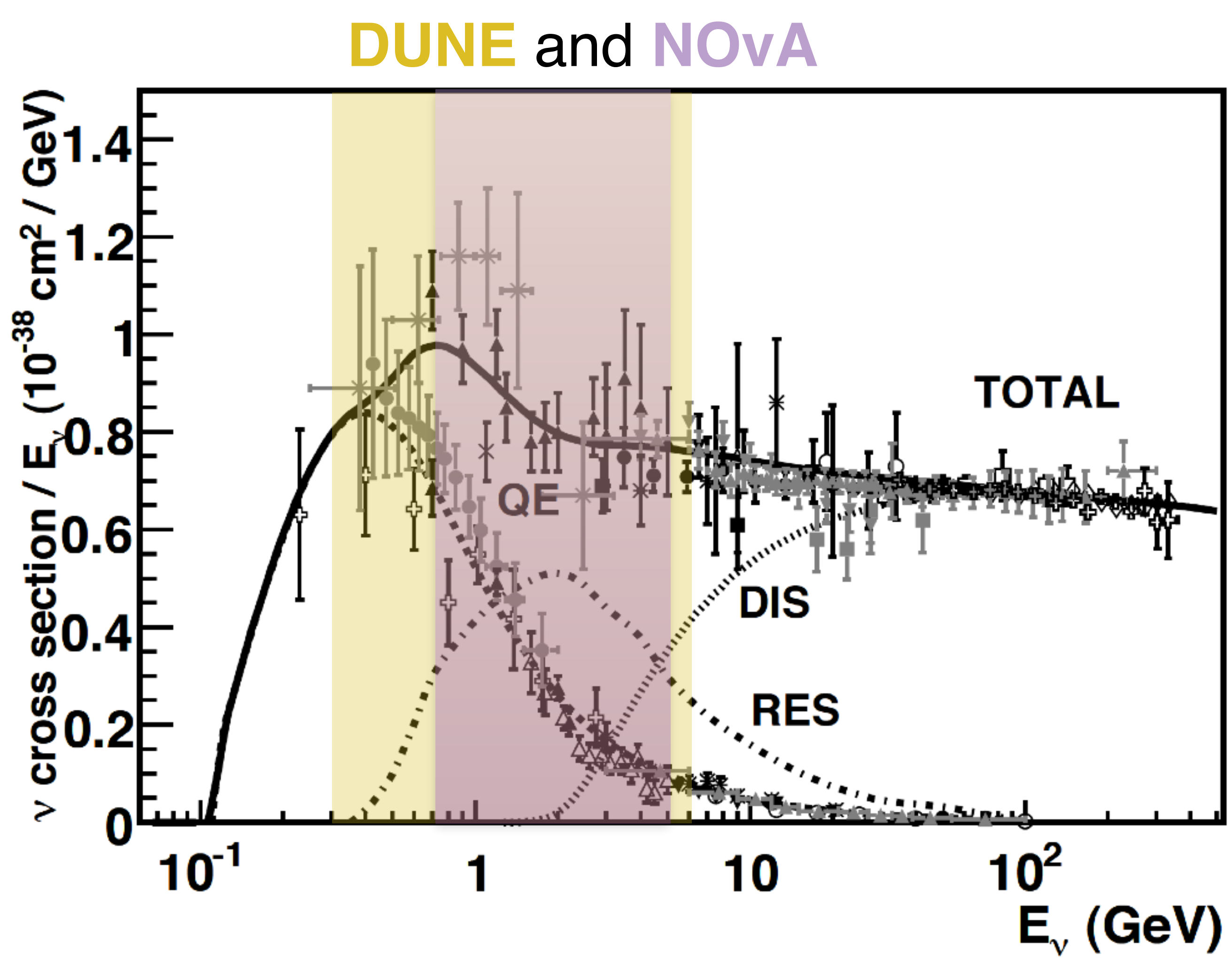


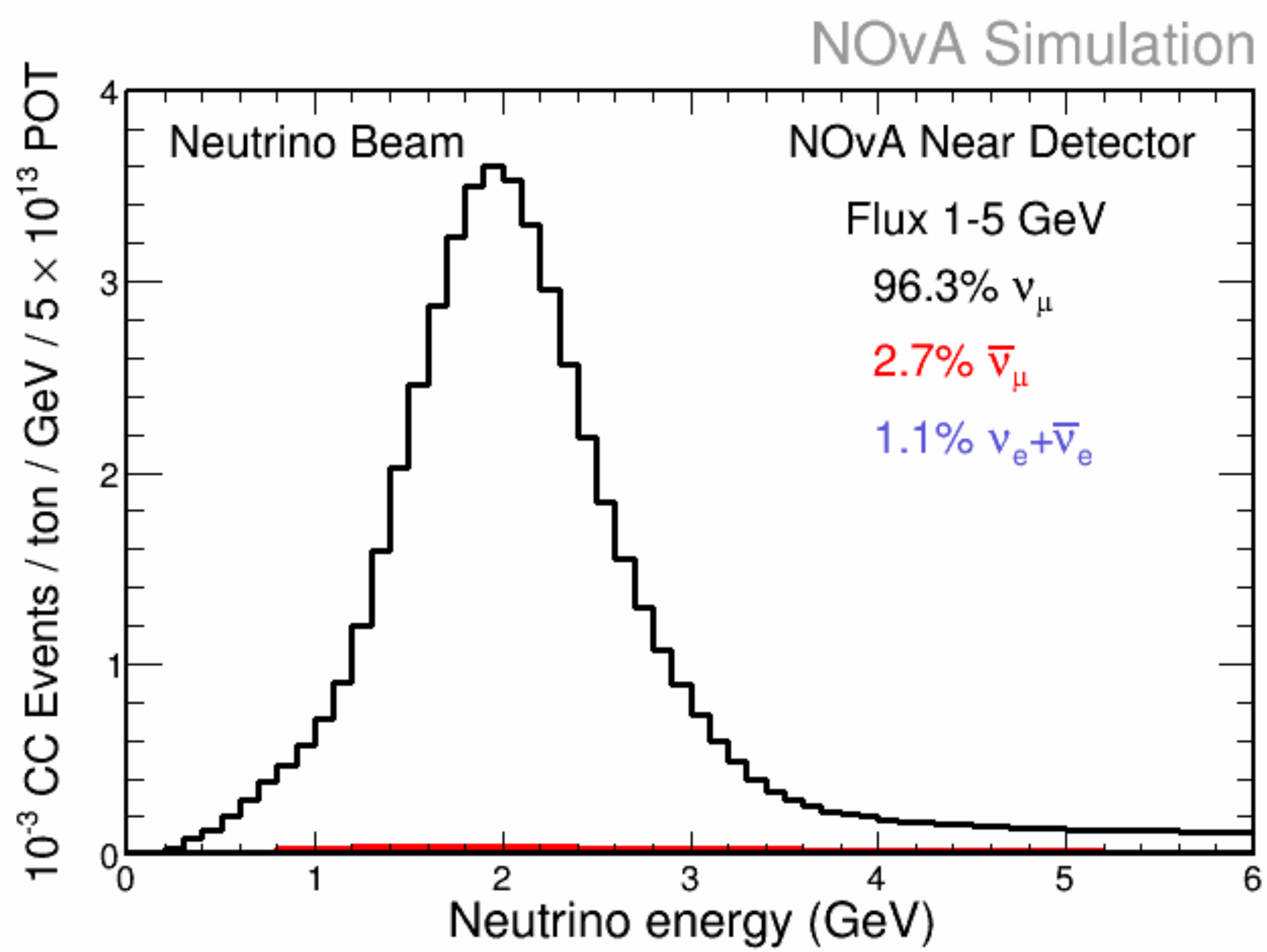
Event Rates at NOvA ND

Protons on target
- FHC ~ **12 x 10[20]**
- RHC ~ **12 x 10[20]**

Even with a narrow band beam, NOvA is still sensitive to many different nu+A channels.

High data rate at the ND (~10[6] interactions in the whole data taking period).





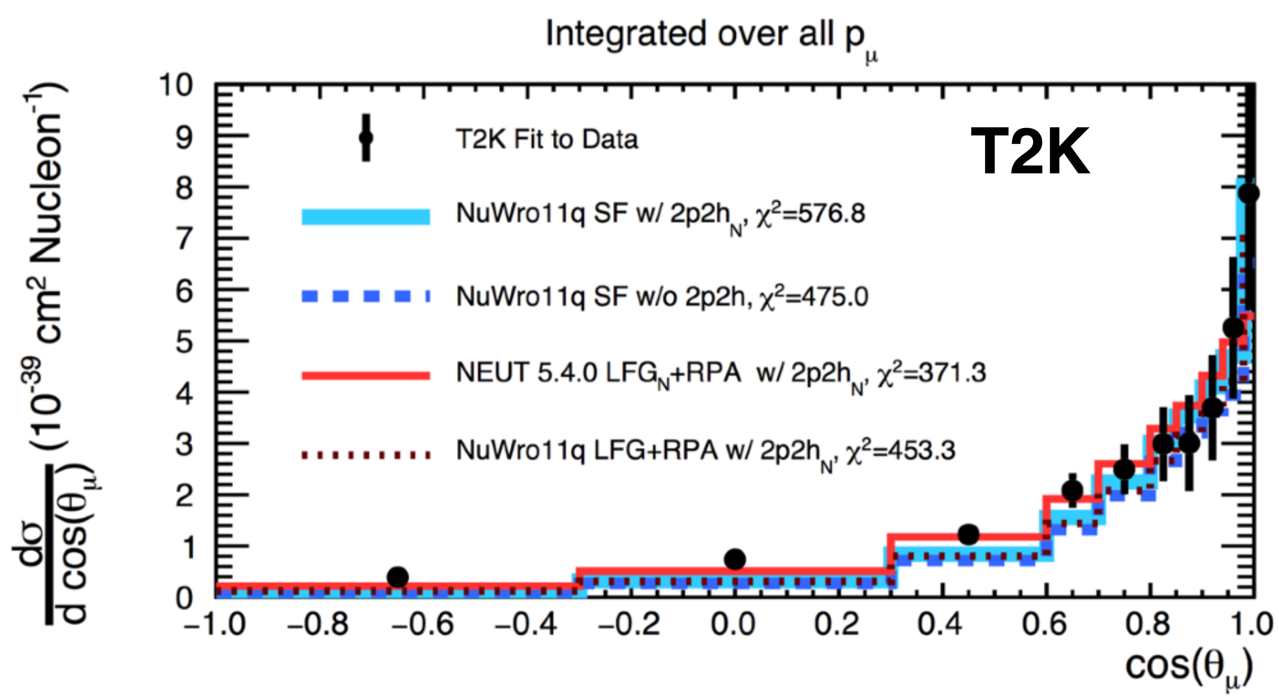
Challenges

- Nuclear effects complicate the reconstruction of the neutrino energy from the final-state kinematics.

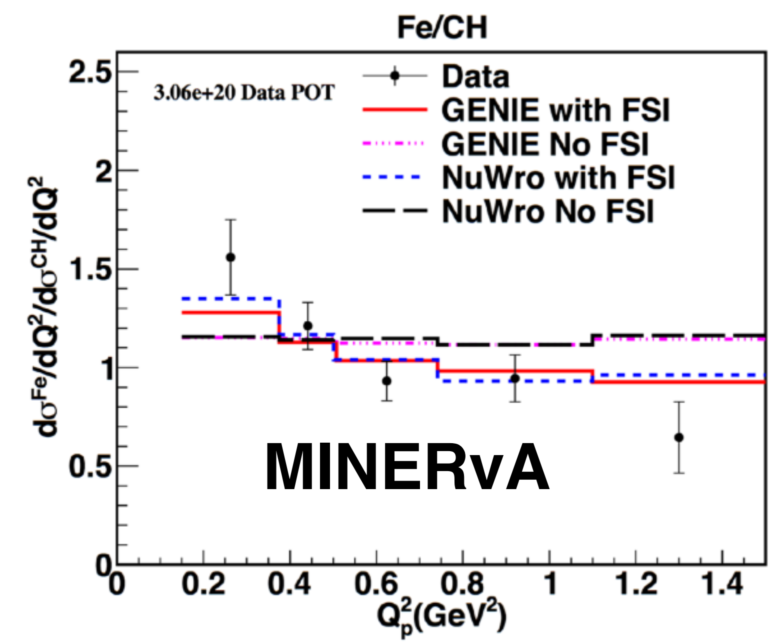
- **e-A** and **ν-A** results indicate that the RFG model is incomplete to describe heavy nucleus:
  - *There are multi-nuclear correlations that need to be considered.*
  - *Particles can be absorbed or created in heavy nucleus before leaving the nucleus.*

Measurements show tensions with the models.

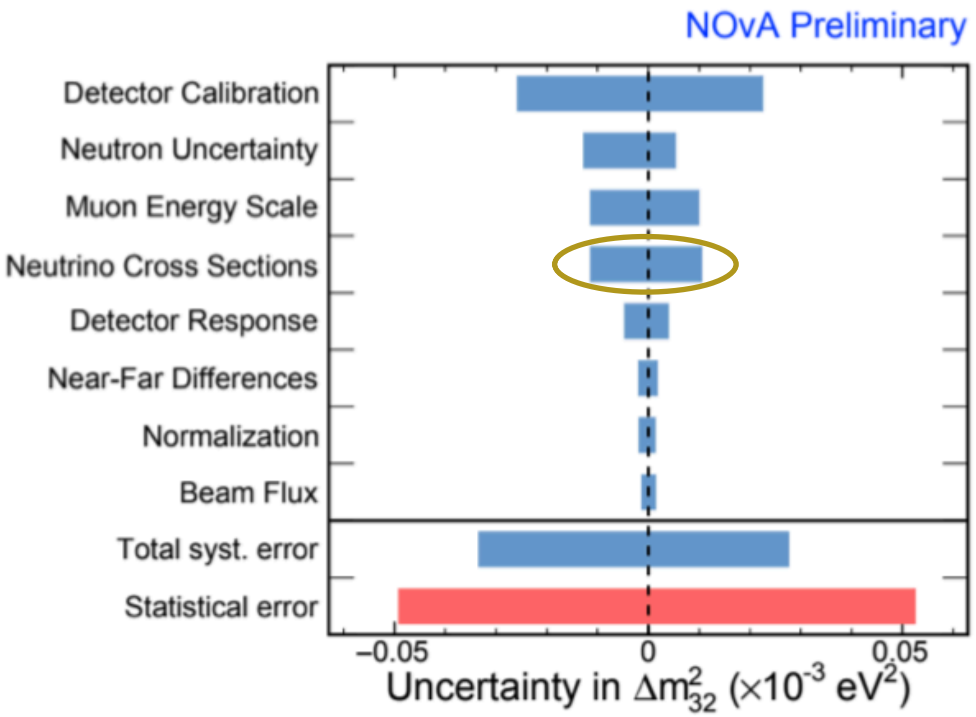
arXiv:1802.05078 [hep-ex]

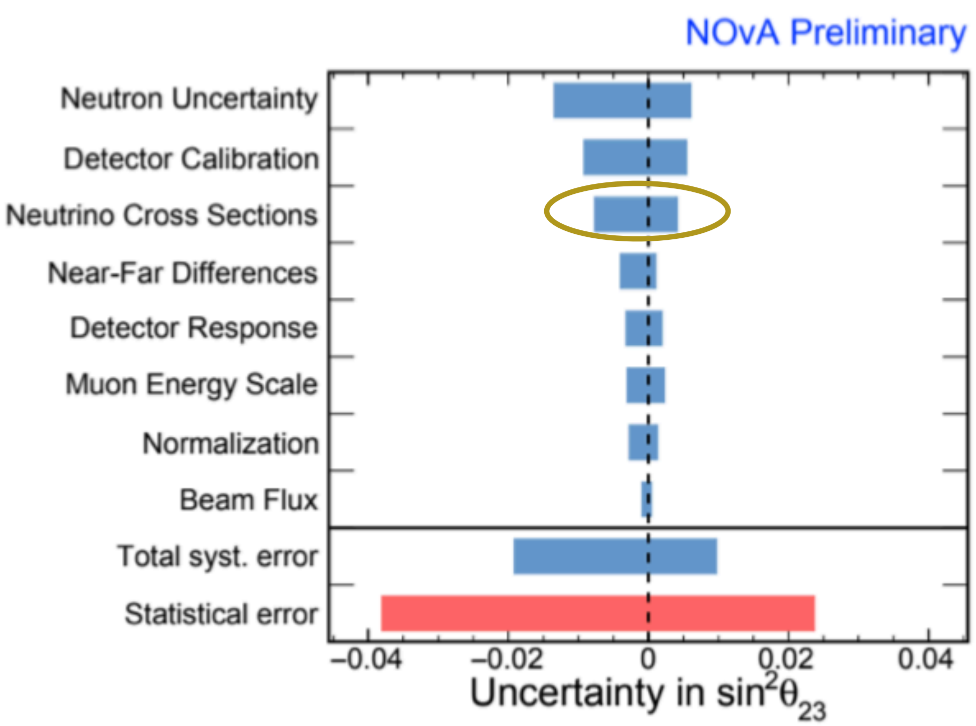


Phys. Rev. Lett. 119, 082001 (2017)

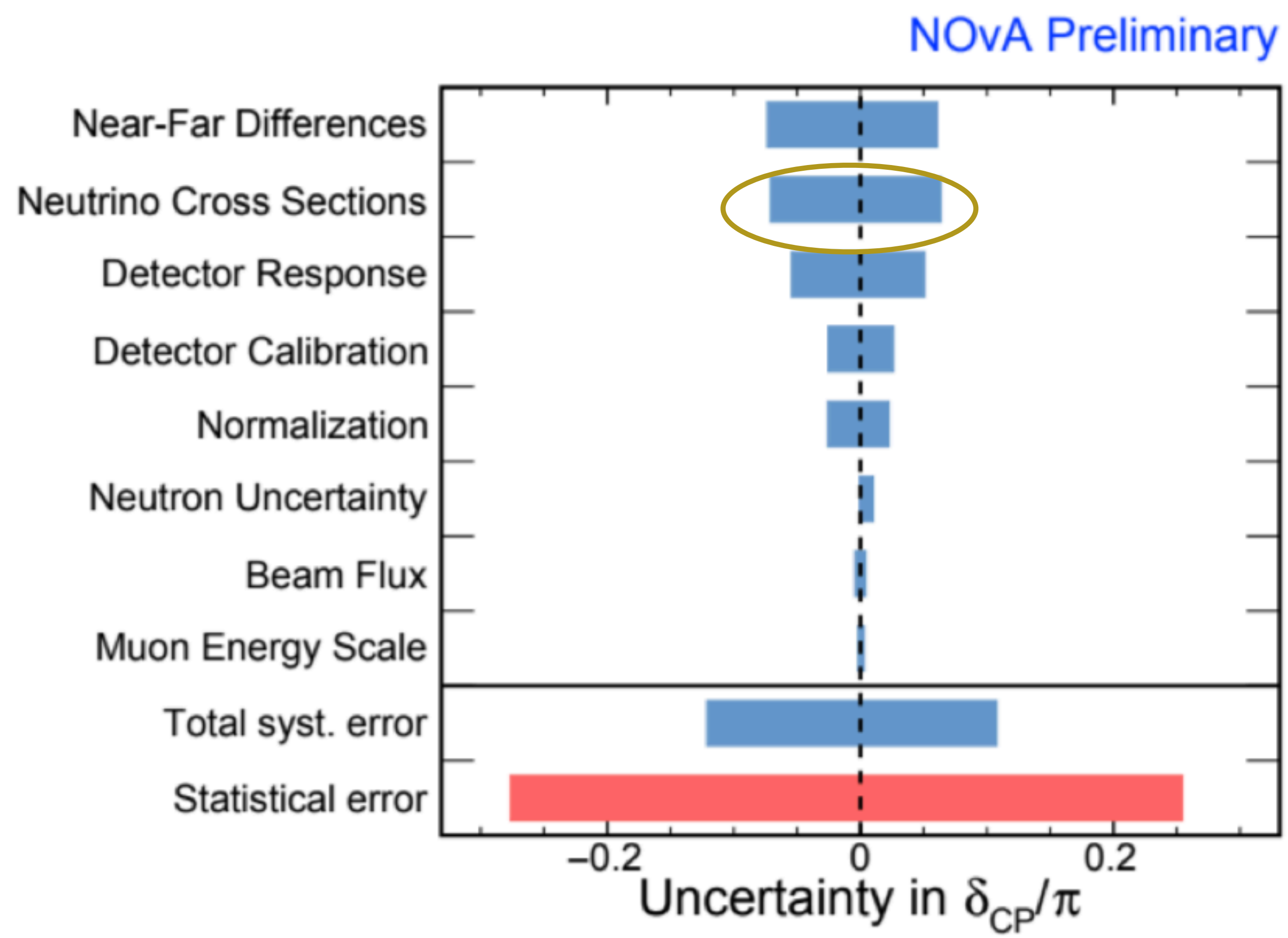


Oscillation Uncertainties





***Cross section uncertainties** is one of the main uncertainties to the oscillation parameter measurements at NOvA*



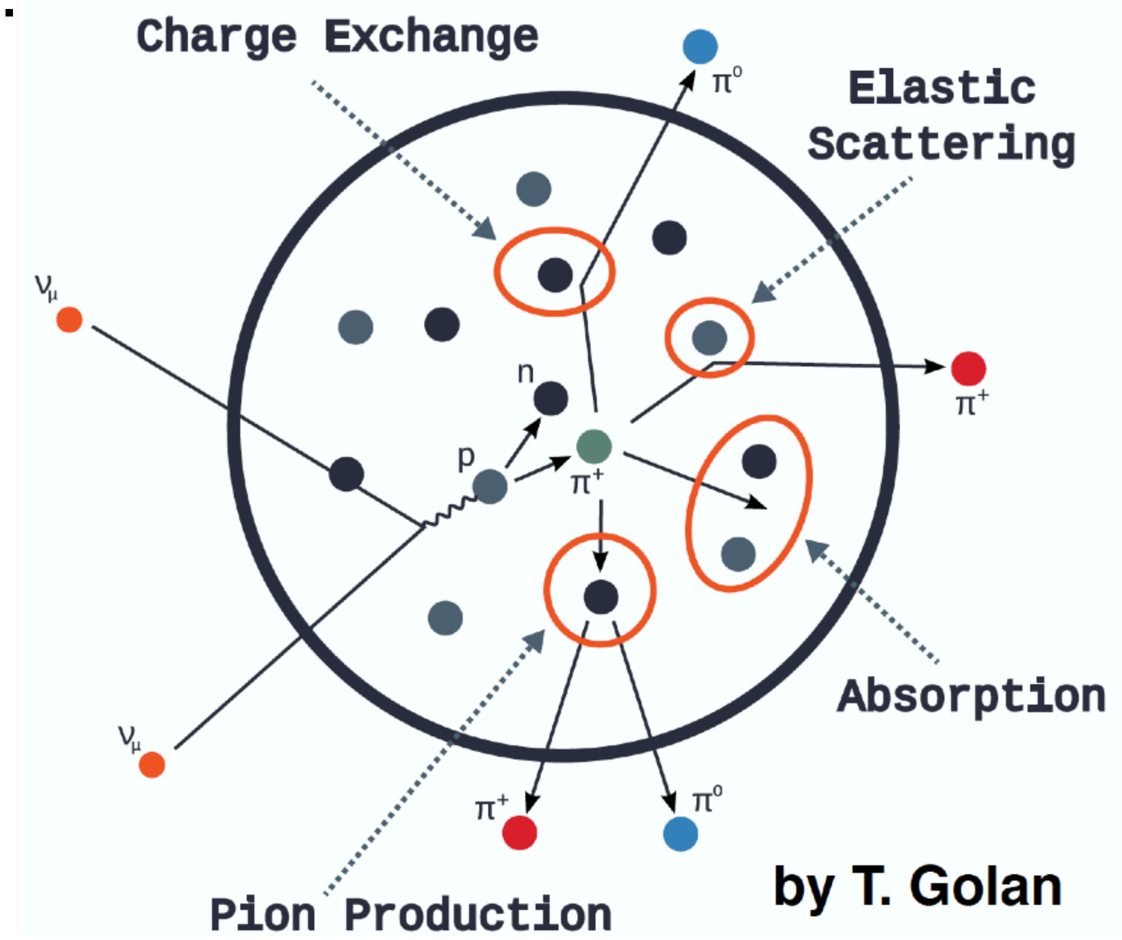
$\nu + \overline{\nu}$ analysis presented at the Fermilab Users Meeting, June 2019

Cross Sections at the NOvA ND

Cross Section Measurements

- Cross-sections are rich in **physics themselves**.
- Also important to **oscillation systematic uncertainties**:
  - All channels are **signals** and **backgrounds** to the oscillation analysis.
  - Many of our measurements are sensitive to **nuclear effects** (fermi motion, nucleon correlation, final-state interaction…).

We want to understand those issues in our own detector



The NOvA ND

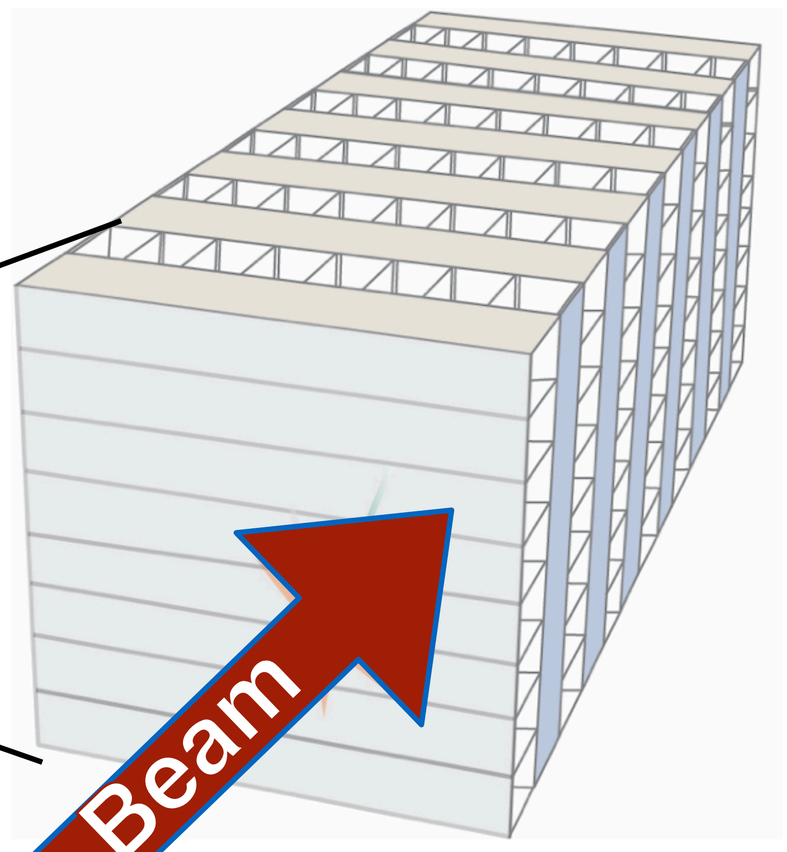
The ND is **1 km** from source, **underground** at Fermilab.

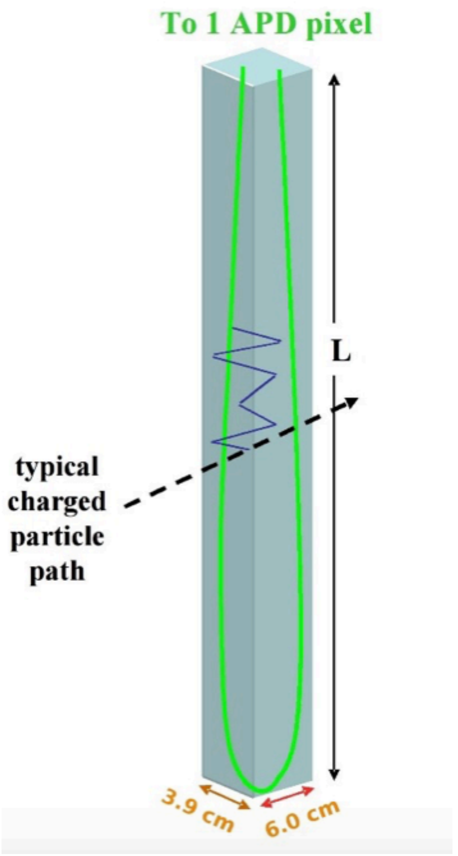
- PVC cells filled with **liquid scintillator, 193 ton** fully active mass and 97 ton downstream muon catcher.
- Alternating planes of orthogonal views.

Low-Z, fine-grained:
1 plane ~$0.15X_0$ (38 cm)

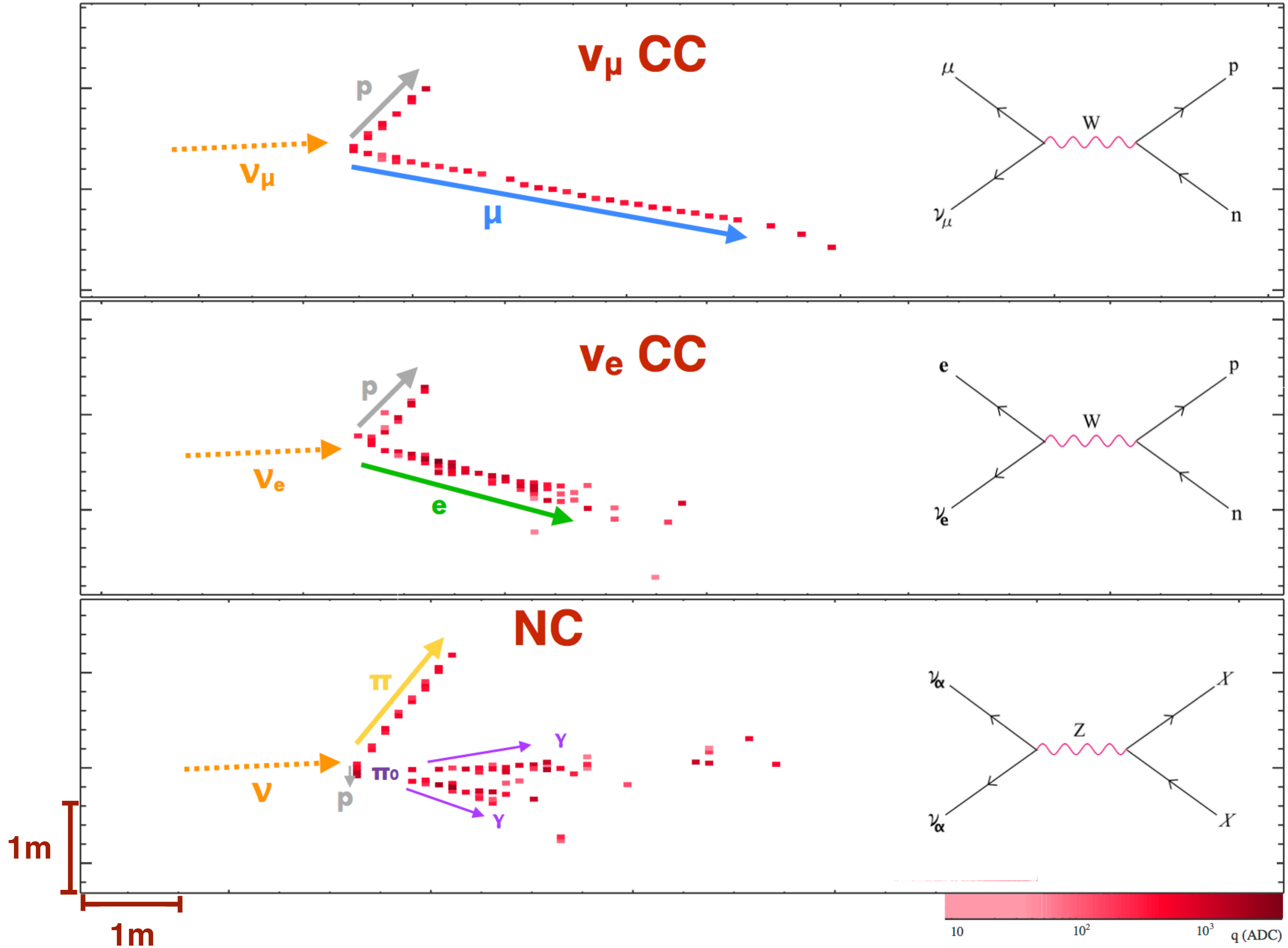
Percentage of total detector mass

C	Cl	H	O	Ti
65.9%	16.1%	10.7%	3.0%	2.4%



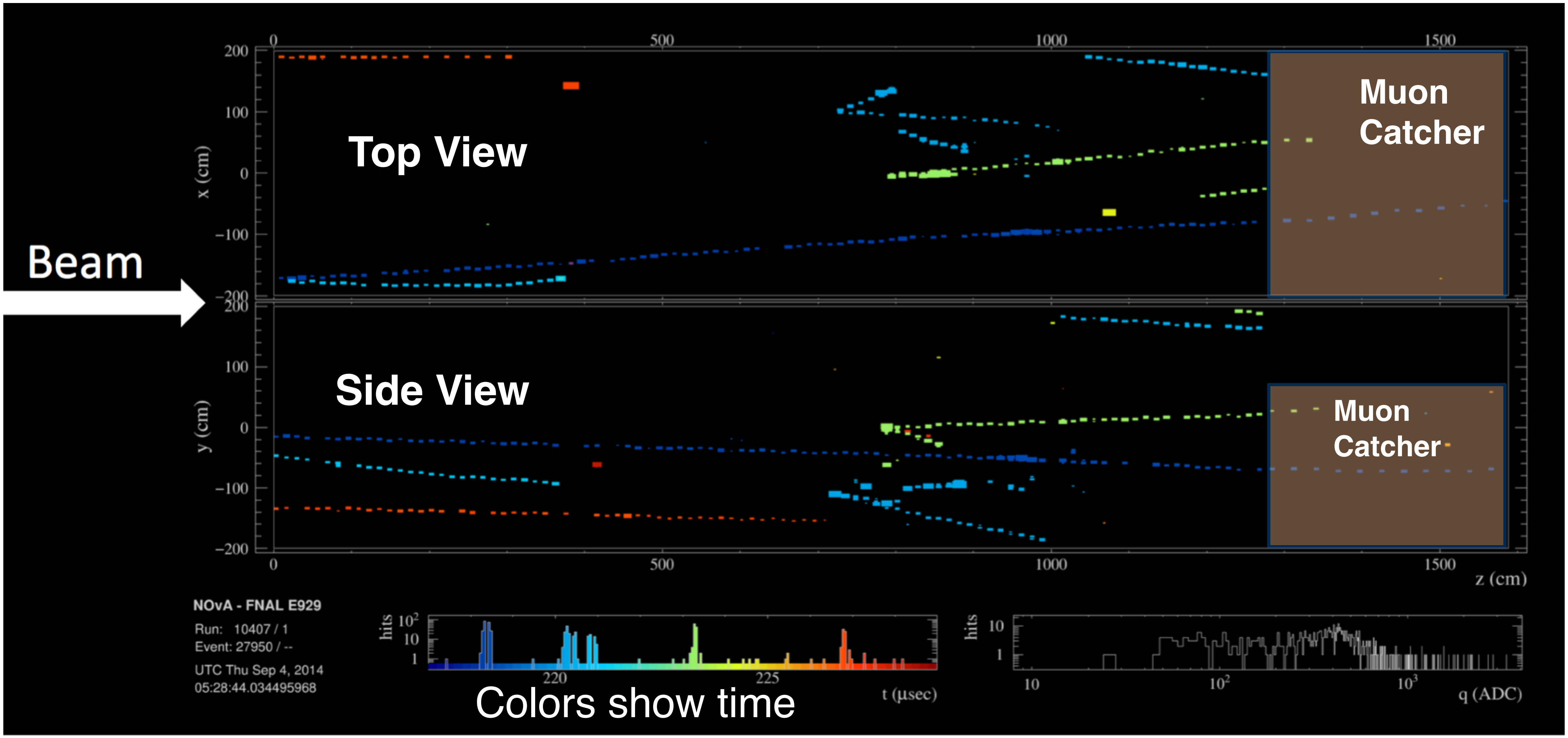


Examples of Event topologies



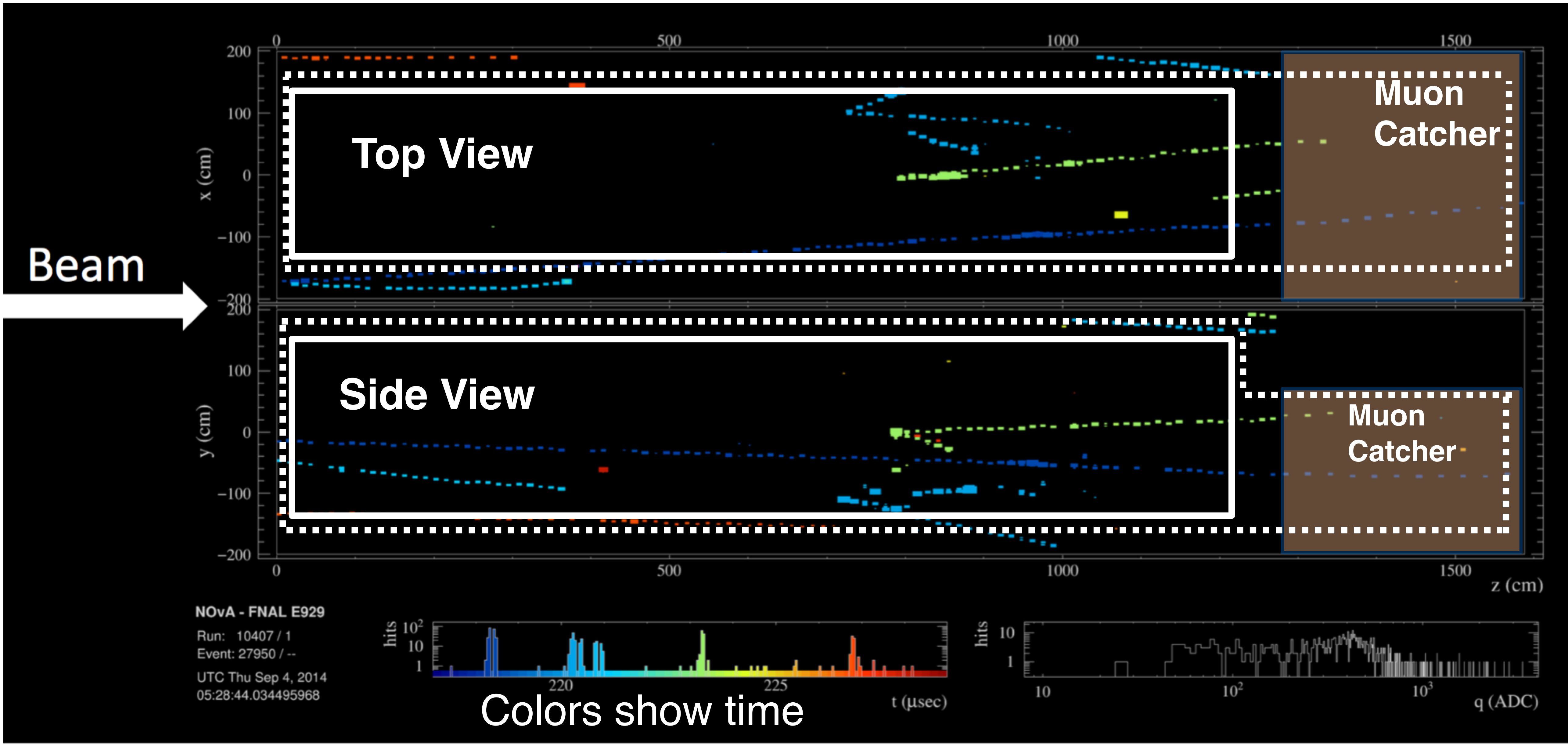
Interactions in the ND

- Hits associated in time and space are used to form a candidate interaction. Tracks and showers are reconstructed from these hits.



Event Display

- Vertices should be inside a fully active (fiducial) region to cut rock muons.



- Muon candidates should be contained in the active region + Muon Catcher and any other track only in the active region to avoid shower leaking.

Simulation Strategy

- We use **G4NuMI** for the beam simulation, **GENIE** (2.12.2) for the neutrino interactions and **GEANT4** (4.10.1) for propagating the particles.
- The **central value** prediction is made from:
  - The beam: correction of the hadrons production yield in the beamline.
  - The cross section: tuning is applied to account for nuclear effects knowledge
- **The beam and cross section systematics** are determined by hadron production uncertainties and beam components misalignments, and the GENIE reweighting scheme, respectively.
- **The simulation of the intensity dependent of rock muon rates** use data and it is integrated overlaying with the neutrino events .
- **The detector response** is also simulated and the uncertainties on the calibration parameters are dealt with systematic shifted MC.

Main Analyses in the NOvA ND

- NC Coh π^0
- ν_μ-CC Semi-inclusive π^0

First results

- ν_μ-CC Inclusive
- ν_e-CCInclusive

Priority: template for other analyses

- ν_μ-CC Semi-inclusive π^{+-}
- $\bar{\nu}_\mu$-CC Semi-inclusive π^0
- ν_μ-CC 0 π

Analyses in their first stages

Others…

Main Analyses in the NOvA ND

- NC Coh π^0
- ν_μ-CC Semi-inclusive π^0

First results

Main focused of this talk →

- ν_μ-CC Inclusive
- ν_e-CCInclusive

Priority: template for other analyses

- ν_μ-CC Semi-inclusive π^{+-}
- $\bar{\nu}_\mu$-CC Semi-inclusive π^0
- ν_μ-CC 0 π

Analyses in their first stages

I will show recent progress on this analysis → ν_μ-CC 0 π

Muon-Neutrino

Inclusive Cross Section

ν_μ-CC Inclusive

Measurement is defined as the one in which only the muon is detected.

NuMu-CC Inclusive = Nuclear resonances + Quasielastic + Multinuclear excitations + Deep inelastic scattering

- This measurement is less affected by background subtraction with respect to exclusive channels measurements.
- The asymmetry of the nuclear effects for neutrino and antineutrino is important for CP violation studies.
- Difference between the ν_e and ν_μ cross sections are interesting quantities to study: kinematic limits, radiative corrections, uncertainties in nucleon form factors.

ν_μ-CC Inclusive

- **Goal: double differential cross section as a function of muon kinematics ($\cos\theta_\mu$ vs T_μ).**

- **Philosophy**: this measurement is systematics-limited, so relevant **GENIE** and **detector response** uncertainties are included in the FOM:

$$\sigma = \frac{N_{sel} - N_{bkg}}{\phi T \epsilon} = \frac{P N_{sel}}{\phi T \epsilon}$$

P: purity
ϵ: efficiency
ϕ: neutrino flux
T: number of targets

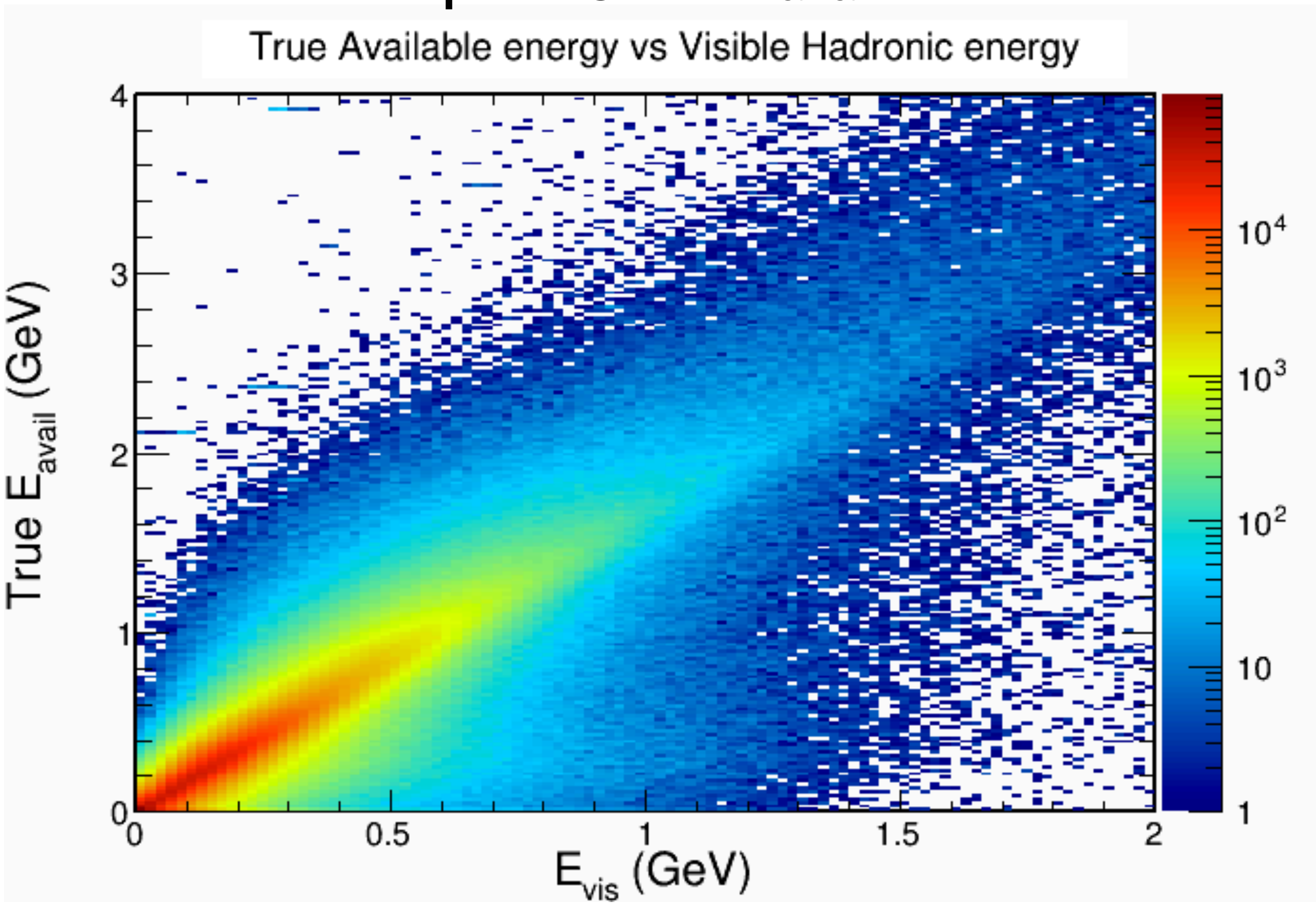
$$\frac{\delta\sigma}{\sigma} \approx \sqrt{\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

- Analysis is performed completely in 3D of quasi-orthogonal variables: $(\cos\theta_\mu, T_\mu, E_{avail})$ and projected to 2D.

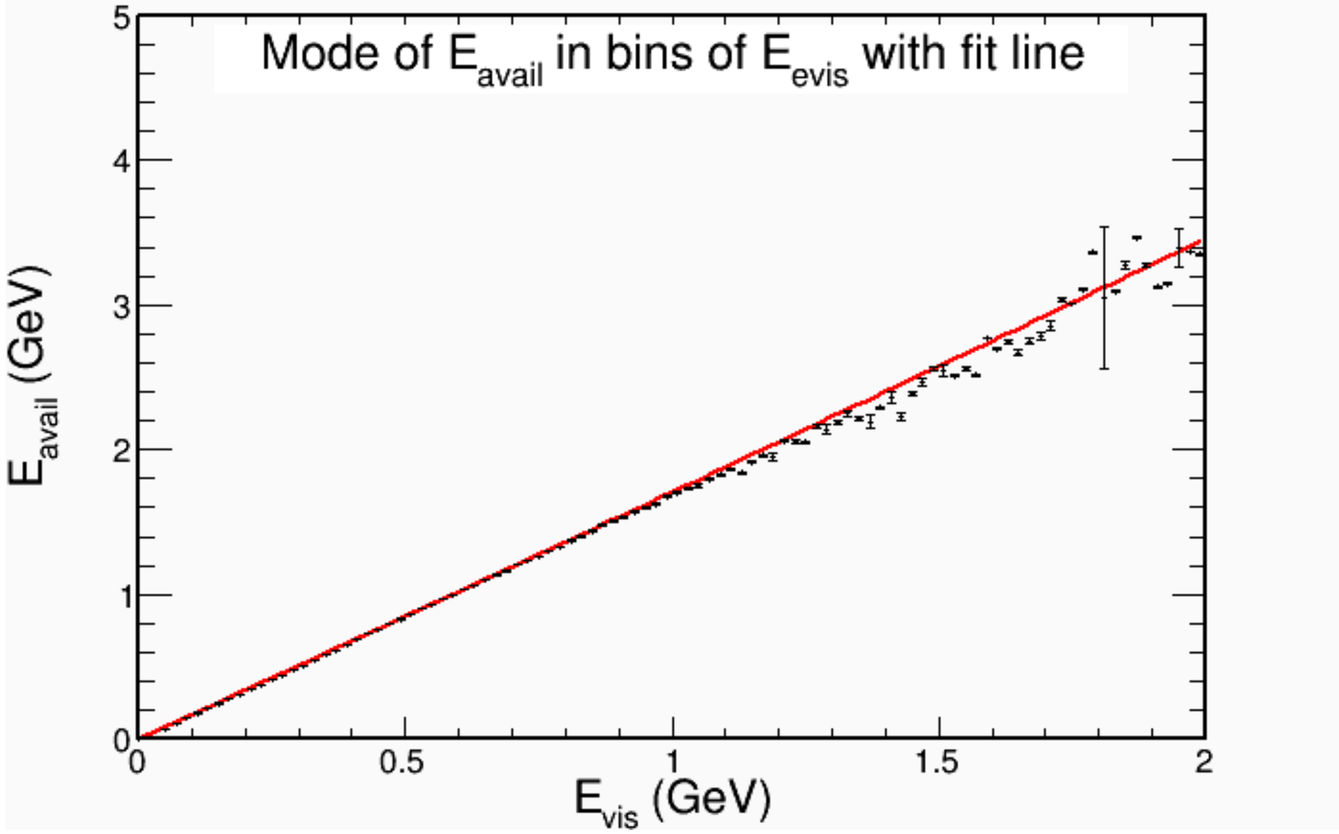
Available Energy

- E_{avail} is a proxy for the hadronic energy and independent of the muon kinematics.
    - E_{avail} is the energy that can be reliably observed in the detector with less model dependence.

Map E_{vis} vs E_{avail}



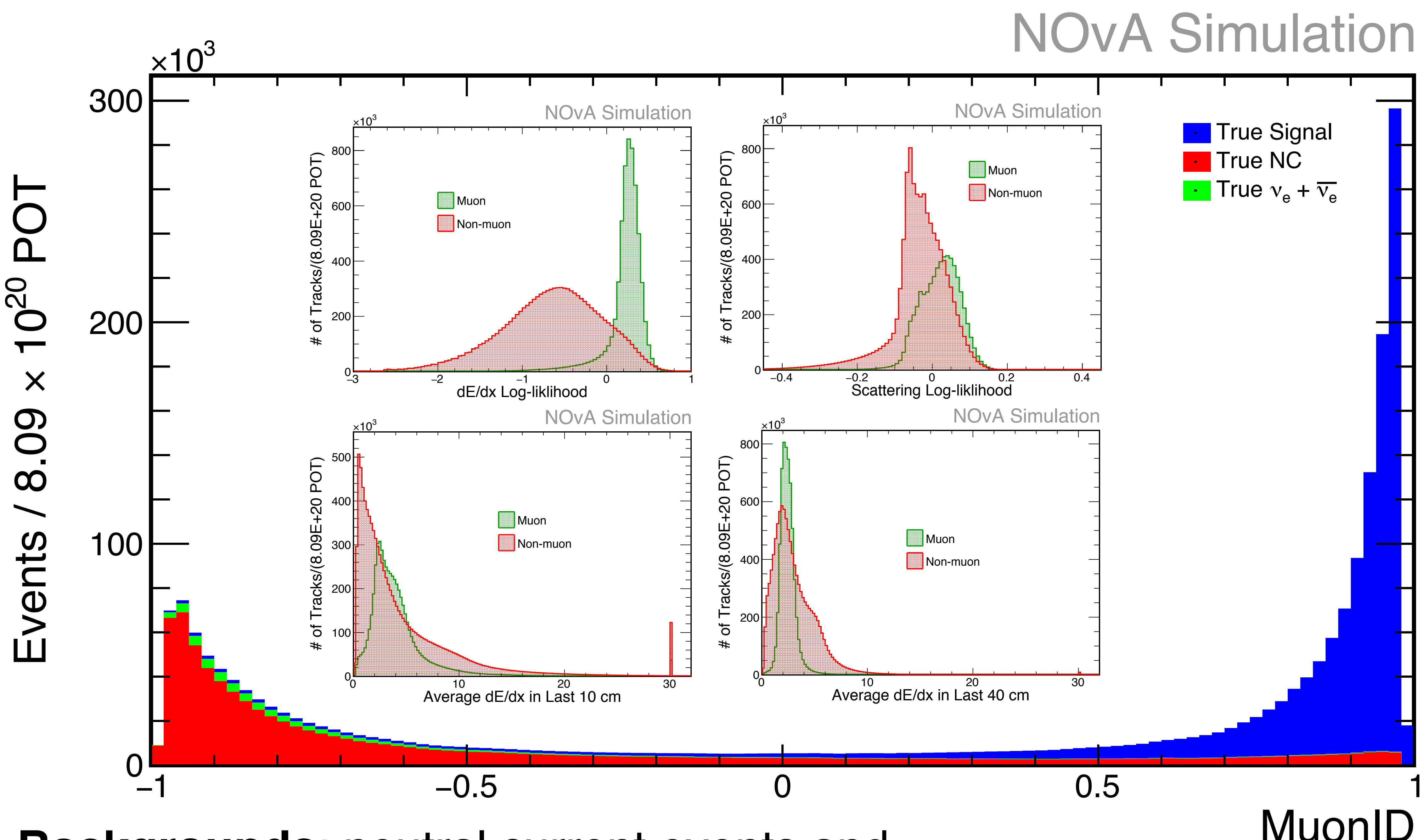
Estimator of E_{avail}



$E_{avail} \sim T_p + T_{\pi^{+/-}} + E(e,\gamma,\pi^0,K)$.

Muon ID

- A muonID using a BDT has been developed based on the dE/dx and scattering of the tracks:

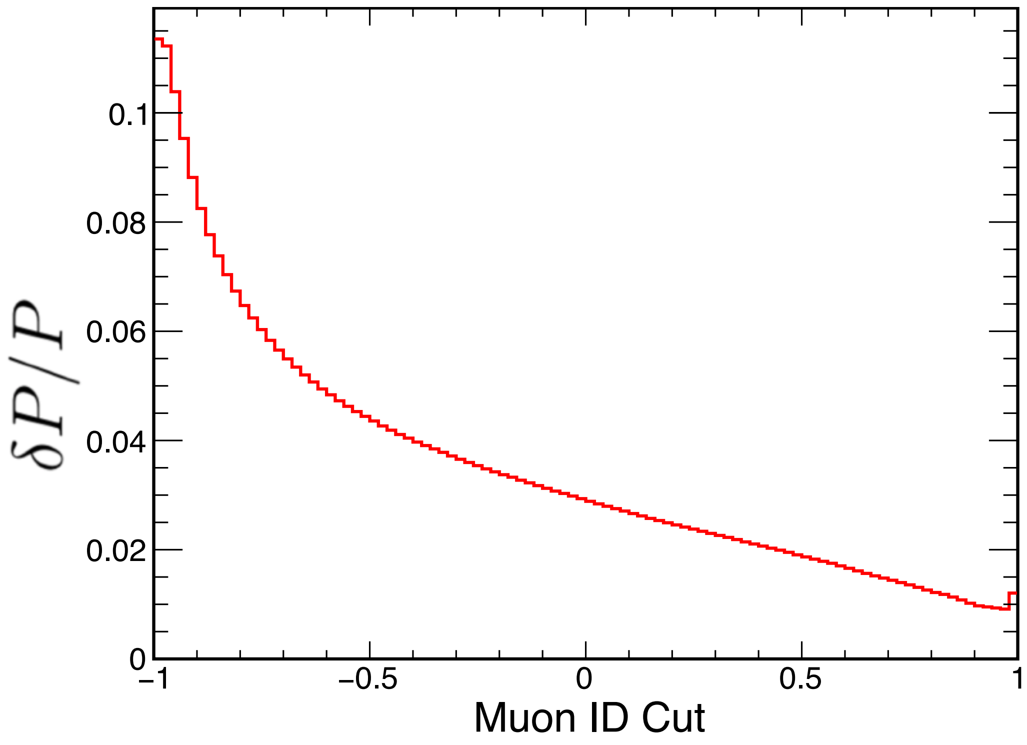


- **Backgrounds**: neutral current events and ν_e.

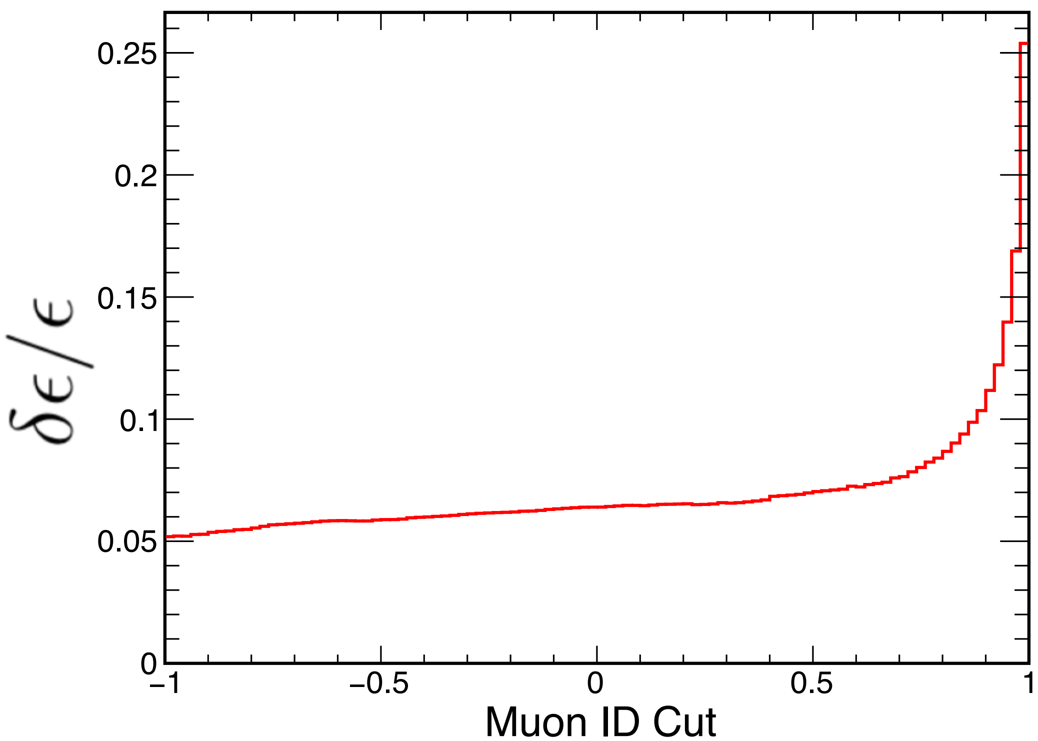
Event Selection Optimization

$$\frac{\delta\sigma}{\sigma} \approx \sqrt{\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

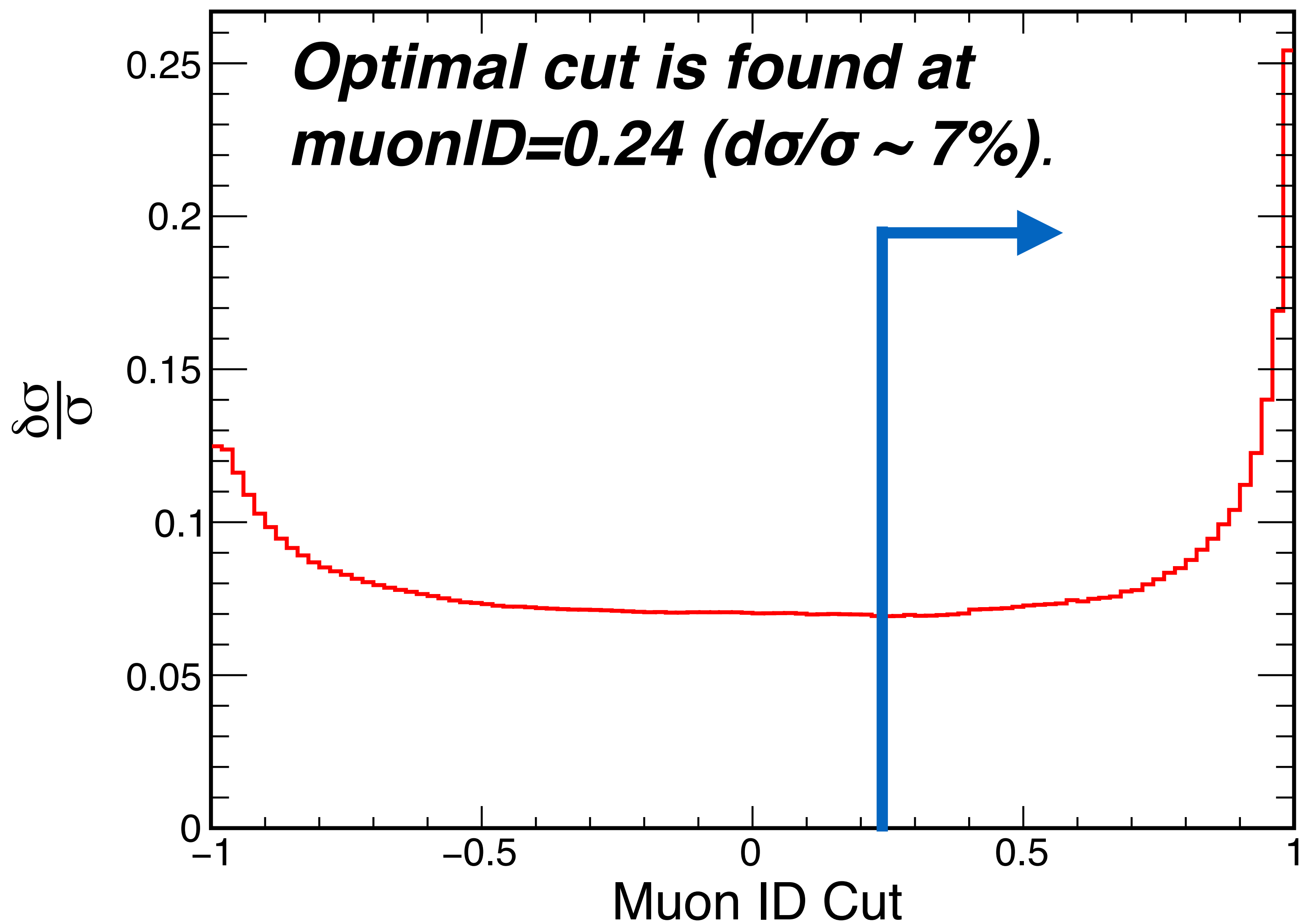
Relative Syst. Uncertainty on Purity



Relative Syst. Uncertainty on Eff.



Relative Uncertainty on Cross-section



Event Selection

- The event selection cuts include: quality, fiducial, containment and the MuonID cut.

Signal CC Inc. ν_μ	CC Inc. $\bar{\nu}_\mu$	NC	CC Inc. $\nu_e + \bar{\nu}_e$	Non-fiducial
86.4 % (1.18×10^6)	2.57%	7.60%	0.44%	2.96%

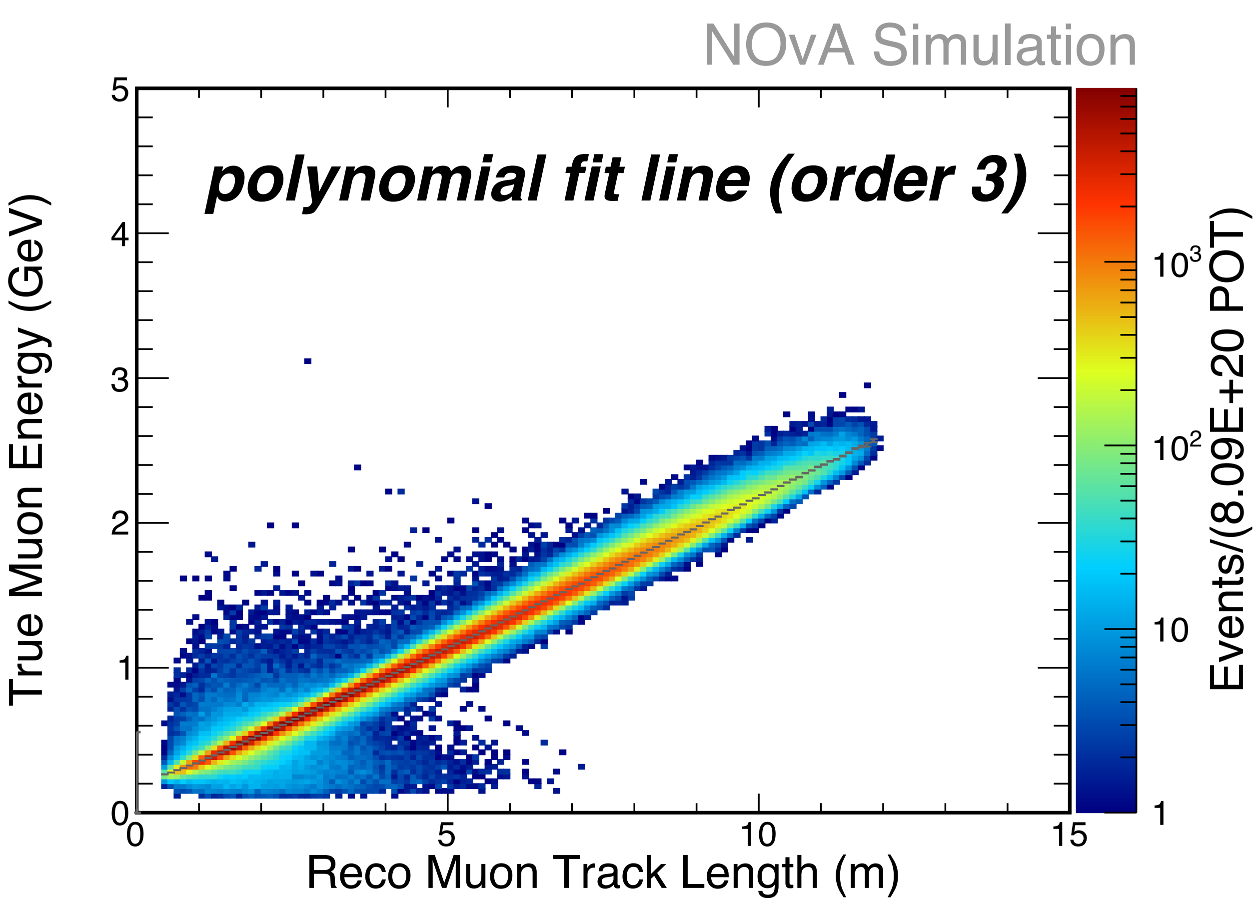
- Fraction of signal events per interaction mode:

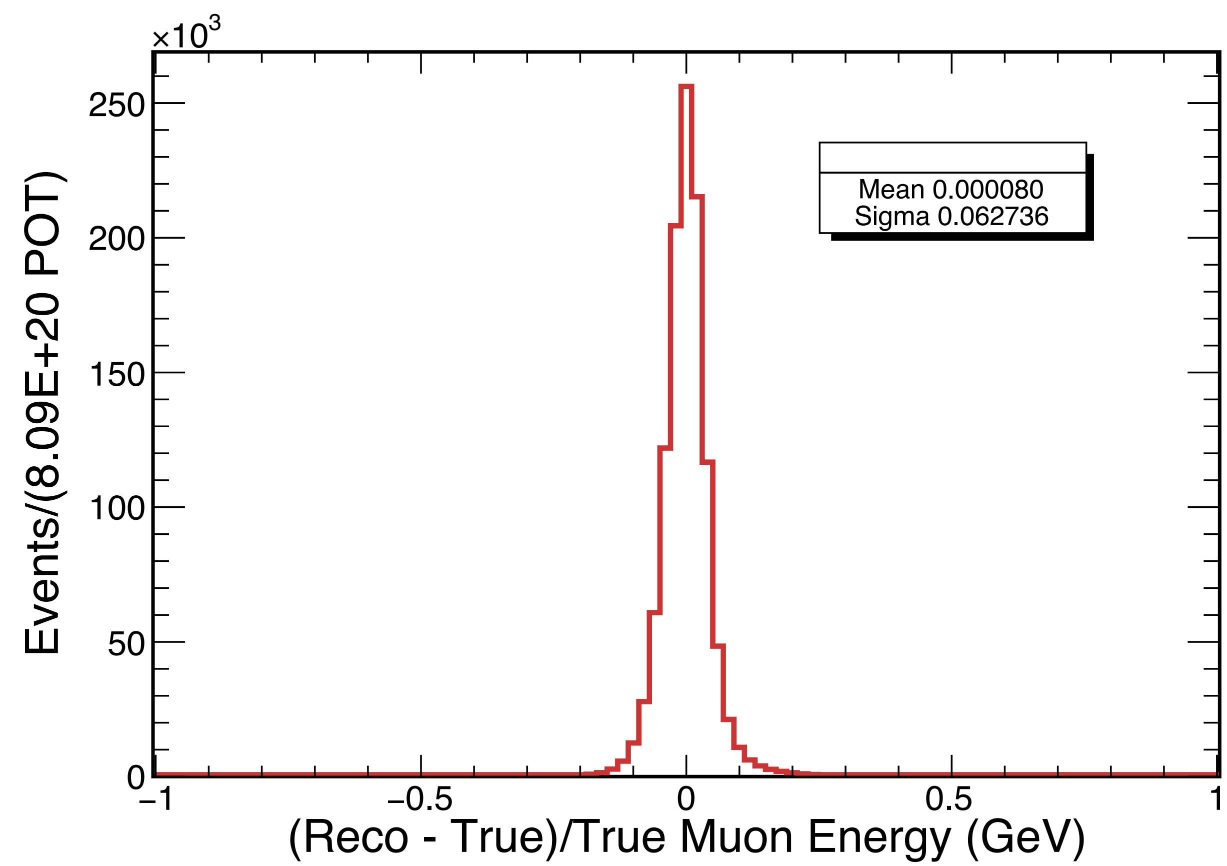
QE	Res	DIS	Coh	MEC
20.85%	38.68%	19.80%	1.79%	18.88%

Energy Estimator and Resolution

- Muon energy measured by range.

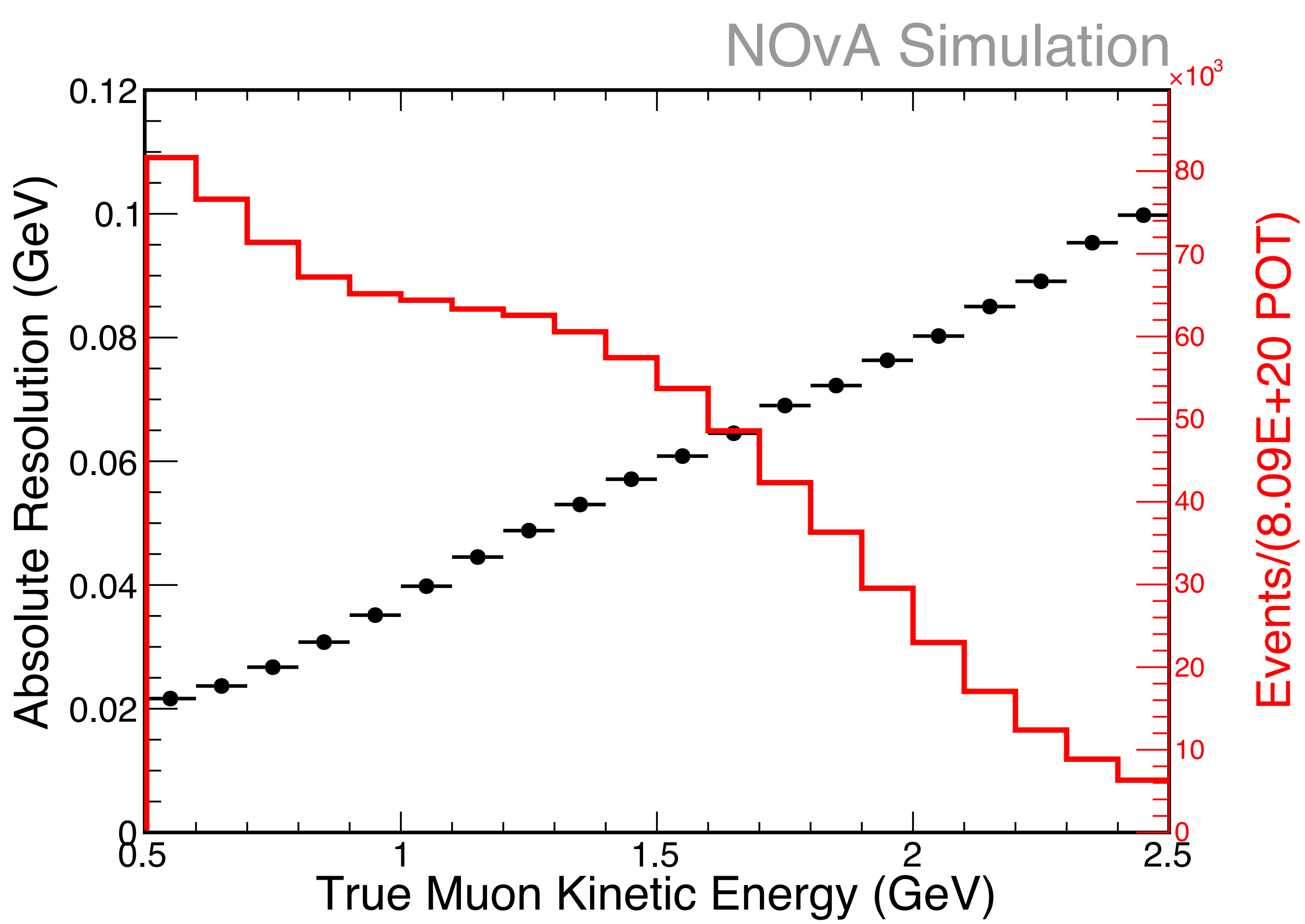
- Good muon energy resolution.

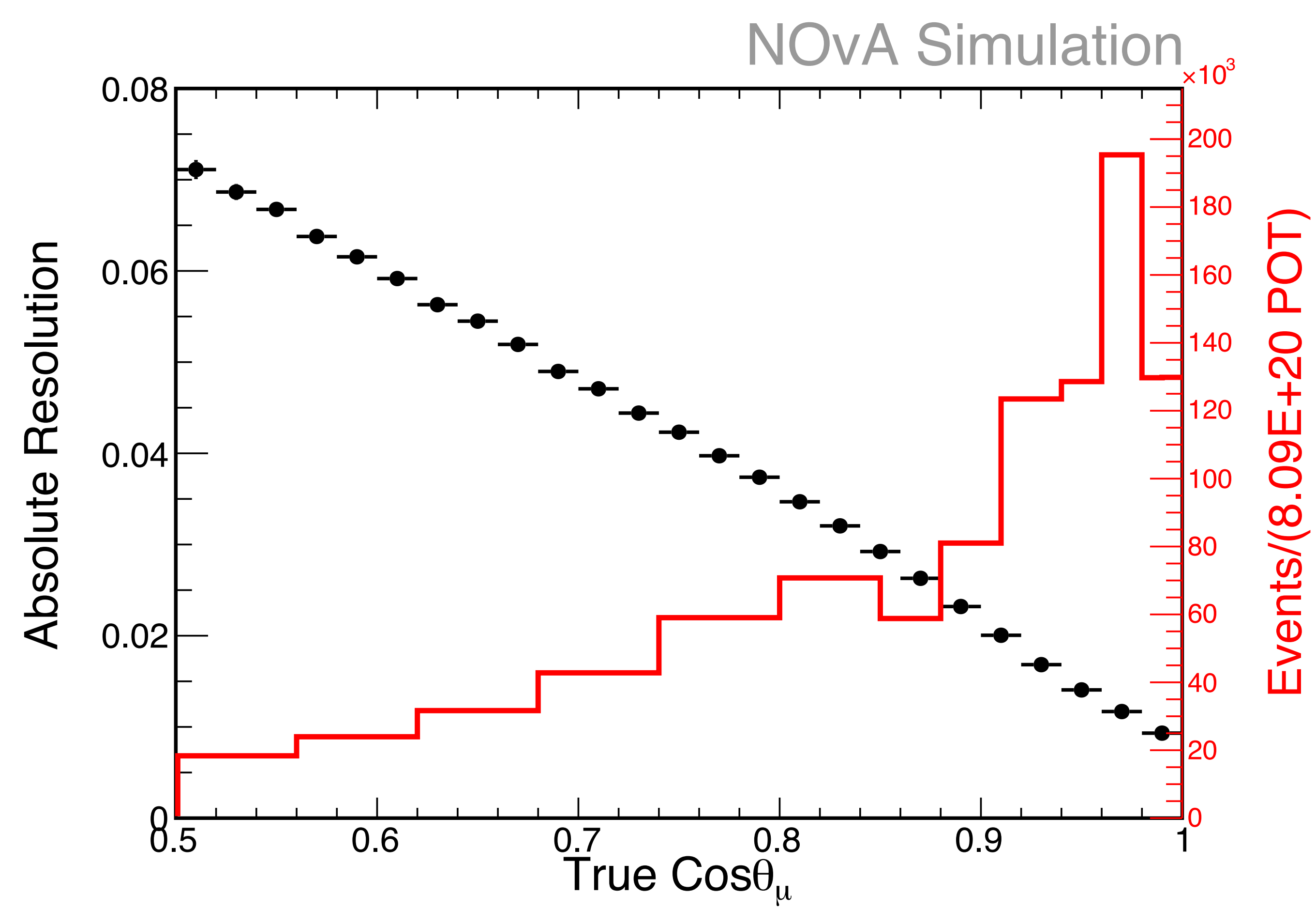




Resolution and Binning

- Muon energy resolution is ~4%. Resolution is 1-3% for shallow angles ($\theta > 45^0$).
- Binning is determined by combination of resolution and statistics.

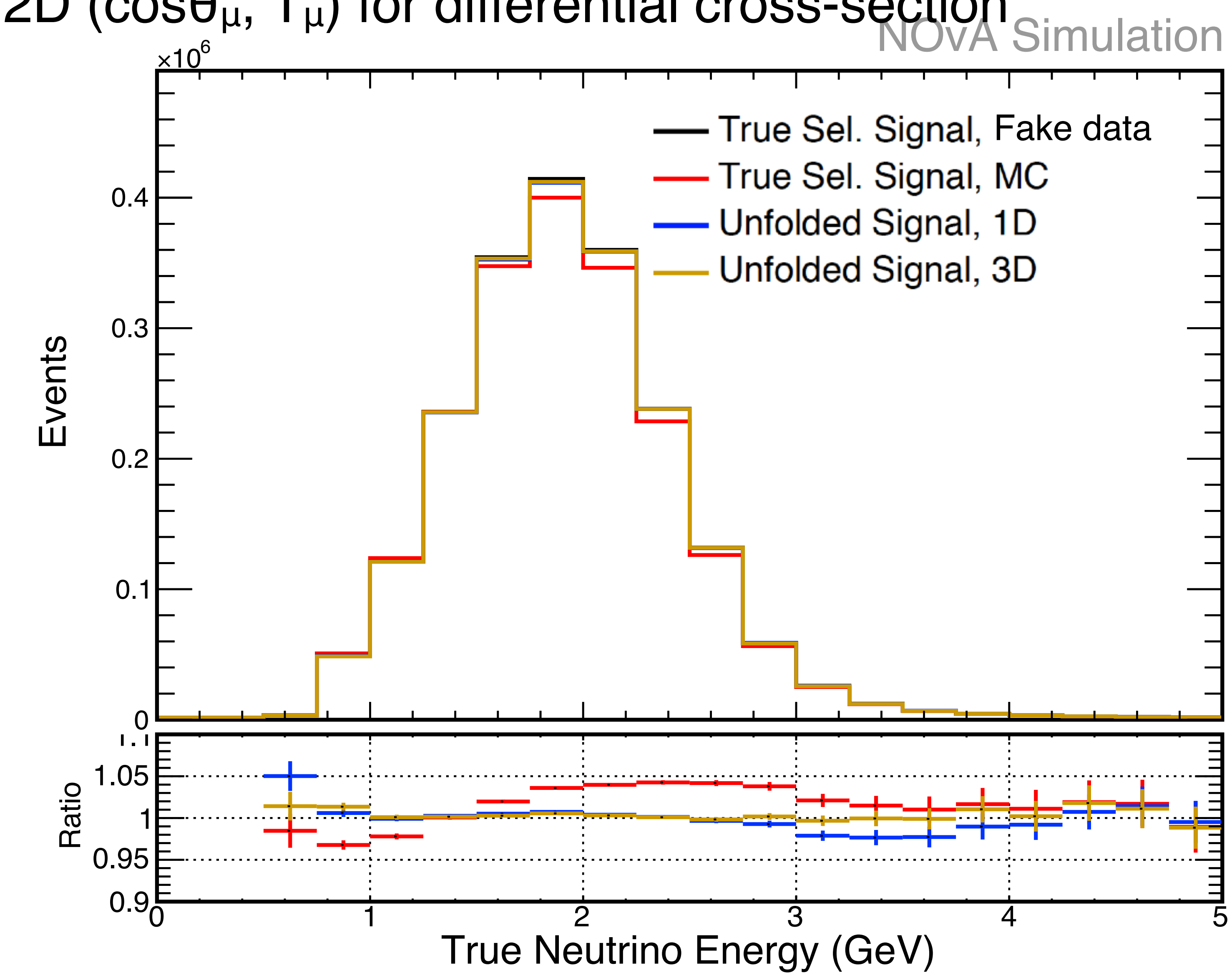




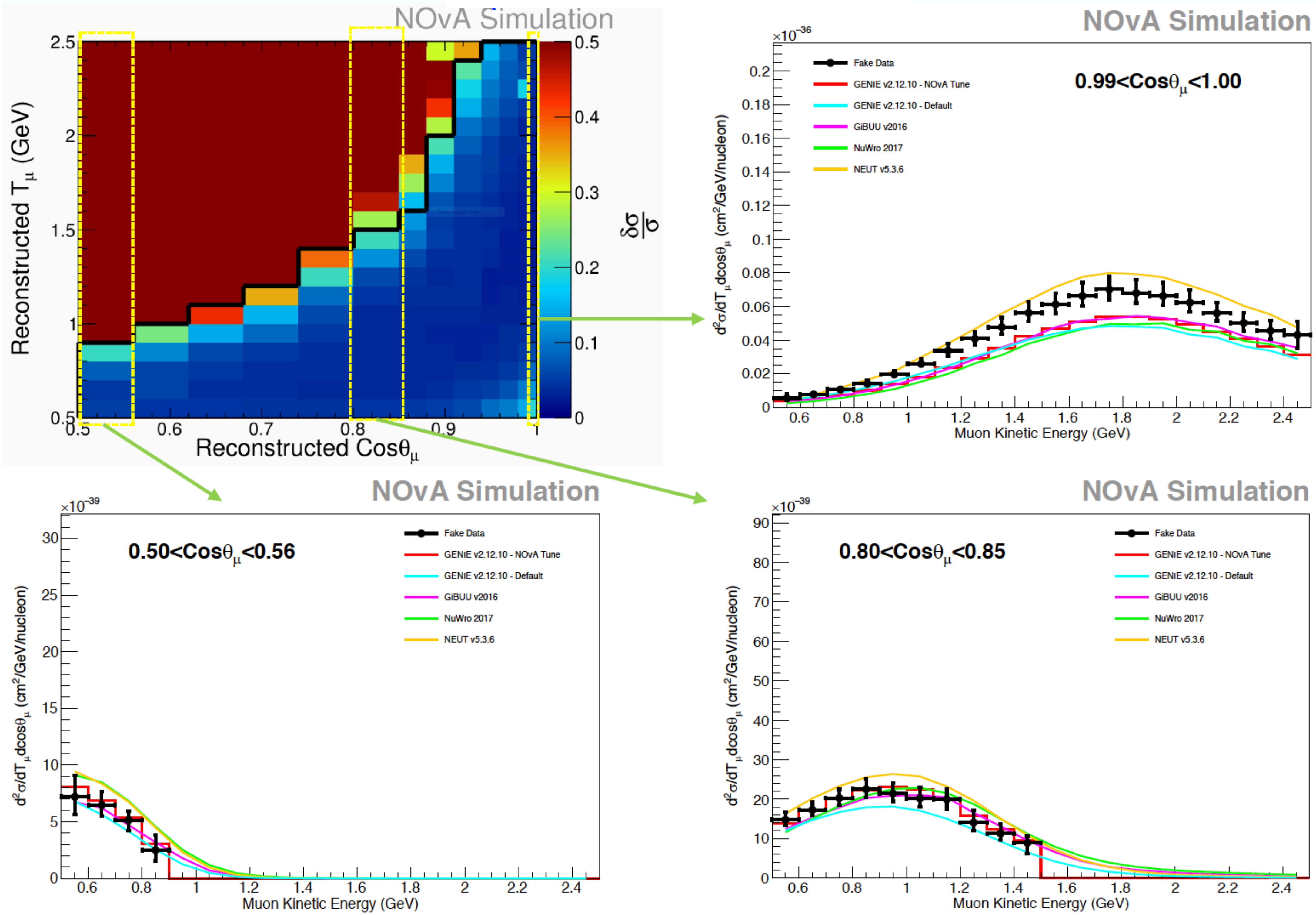
Analysis in 3D

- **Unfolding and efficiency correction are performed in 3D ($\cos\theta_{\mu}$, T_{μ}, E_{avail}).**
  - This is to take into account correlations between lepton and hadron kinematic variables.
- Projection to 1D (E_{avail}) and 2D ($\cos\theta_{\mu}$, T_{μ}) for differential cross-section measurement.

Test of the 3D vs 1D unfolding on the neutrino energy distribution:



Expected Uncertainty and Mock-data Study



Analysis is in final stage… expect a publication soon!

Beyond the inclusive analysis:

muon-neutrino pionless final state

ν_μ-CC 0π

Signal defined as CC interactions with no pions and at least a muon in the final state.

- They look like QEL but:
  - It can be QEL.
  - Or any other interaction when pions were absorbed.
- And they are not all QEL we had.
  - The nucleon may interact in the nucleus and make pions.
  - Some correlated nucleus may interact in the nucleus and make pions.

Challenges

- Existing tools in NOvA are optimized for leptonic particles.
- Rejection of pions is hard.

Pros

Excellent channels to understand nuclear effect: based on what it see in the detector.

This work can inform models of nuclear effects.

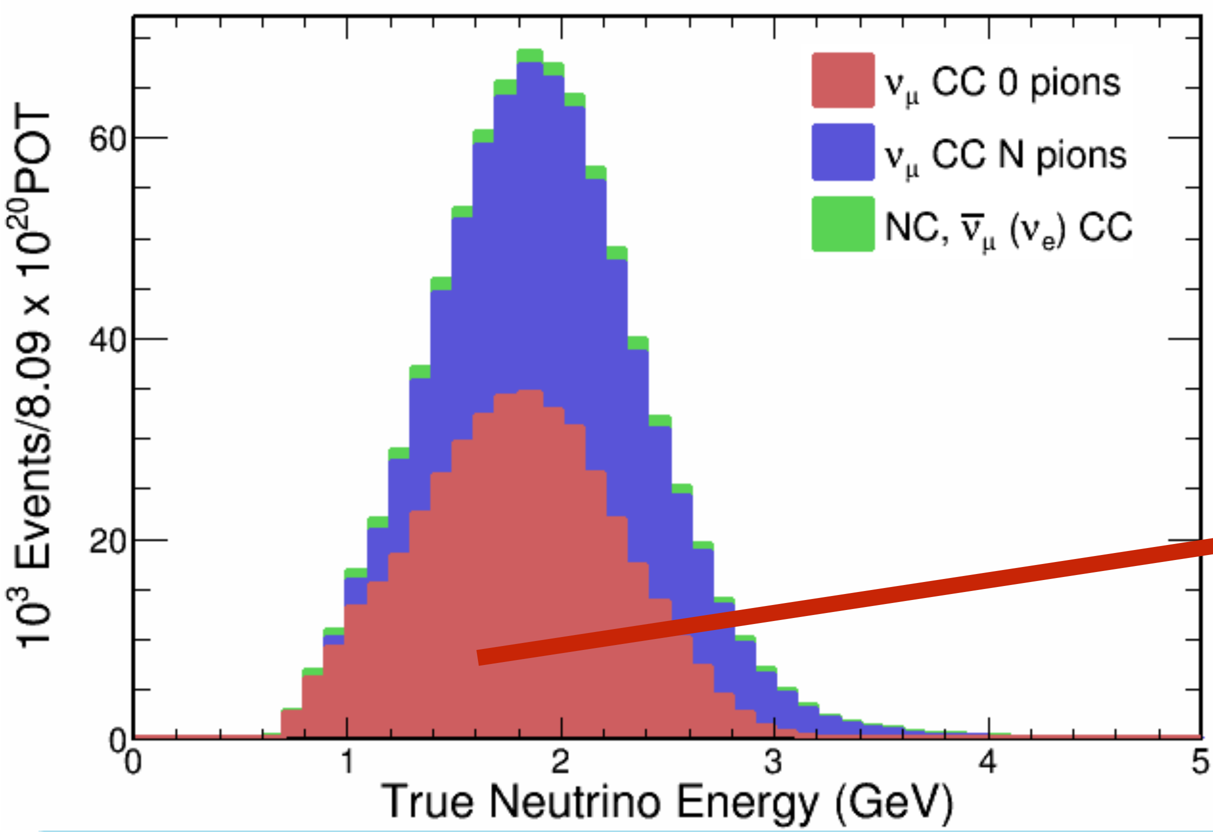
ν_μ-CC 0π

Signal defined as CC interactions with no pions and at least a muon in the final state.

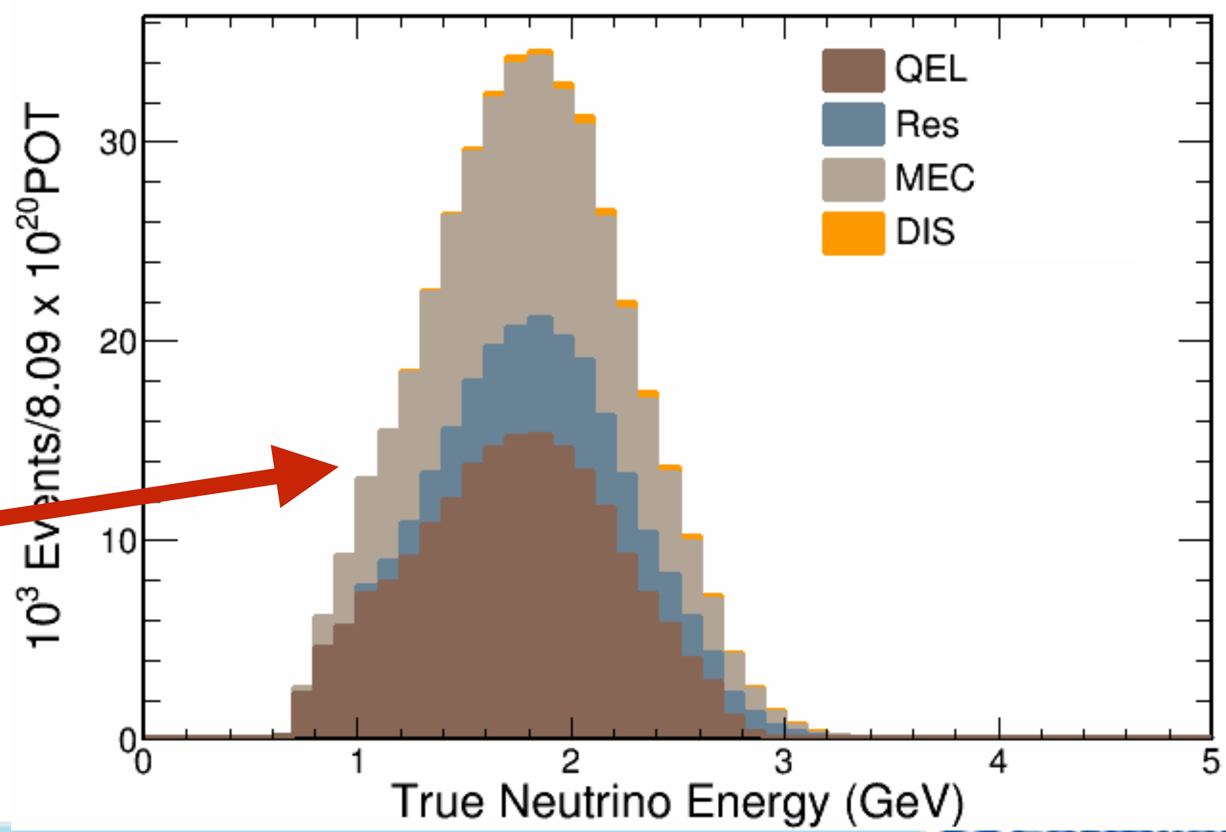
- Starting point: the ν_μ-CC inclusive sample. We expect high stats and only systematic limited.

Deliverables:
- *Cross section w.r.t. the μ kinematics.*
- *Analysis of the nuclear effects.*
- *Ratios w.r.t inclusive results.*

Events that pass the ν_μ selection



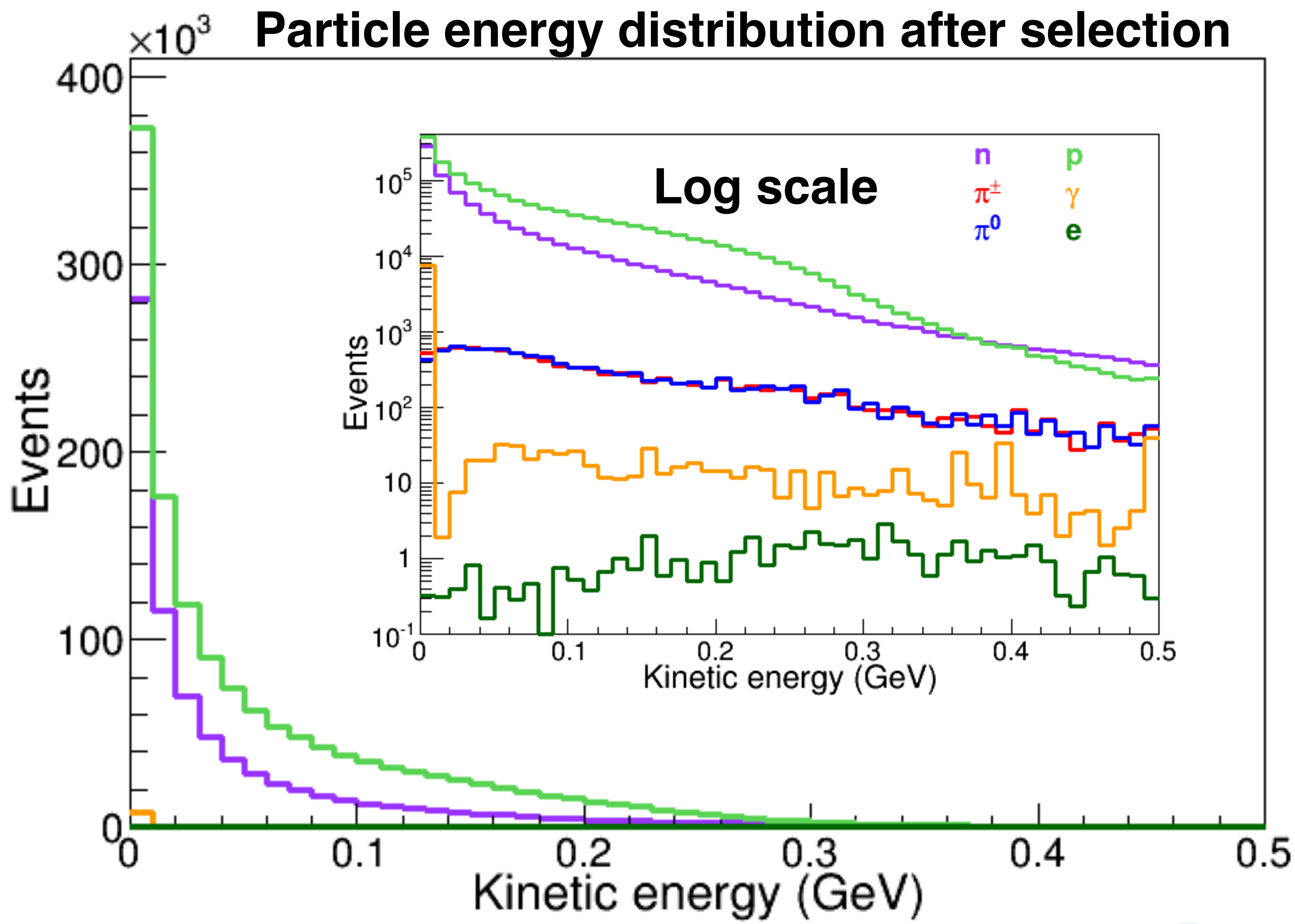
Signal (ν_μ CC 0π) events in ν_μ selection



NuMu-CC with 1 track

- One of our main challenges comes from identifying non-leptonic particles in the detector such as **protons** and **pions**.
- In our first approach, we are looking at **events with only 1 reconstructed track (muon)**

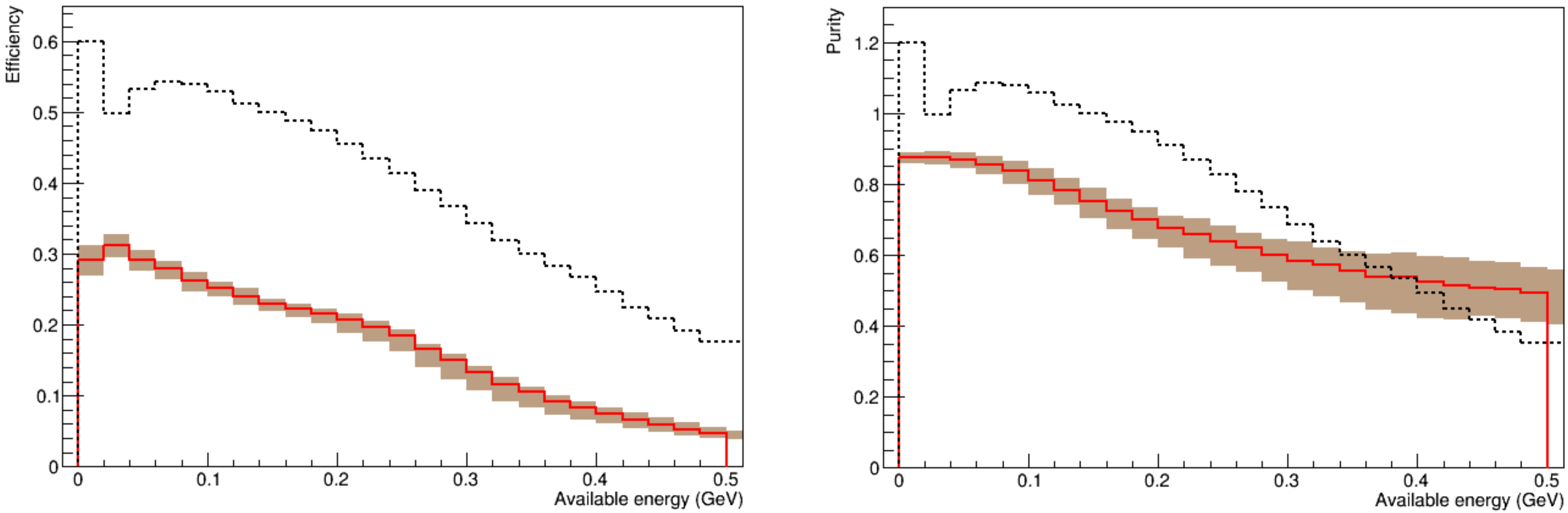
Selection: ν_μ-CC with only 1 reconstructed track



Efficiency and Purity

Selection: ν_μ-CC with only 1 reconstructed track

Efficiency and Purity respect to the ν_μ-CC 0π final state



Dashed line is the true available energy distribution (arbitrary units)

Uncertainty bands include detector systematics and GENIE uncetainties

Conclusions

- The NOvA experiment has an excellent opportunity to make a high precision neutrino-nucleus cross section measurements for both, FHC and RHC.
- The NuMu-CC inclusive channels have the highest priority now and they are in the last stages before publication.
- Semi in[ex]-clusive channels are currently in progress. Between them, the NuMu-CC pionless analysis looks promising to provide many physics insights on the nuclear effects.