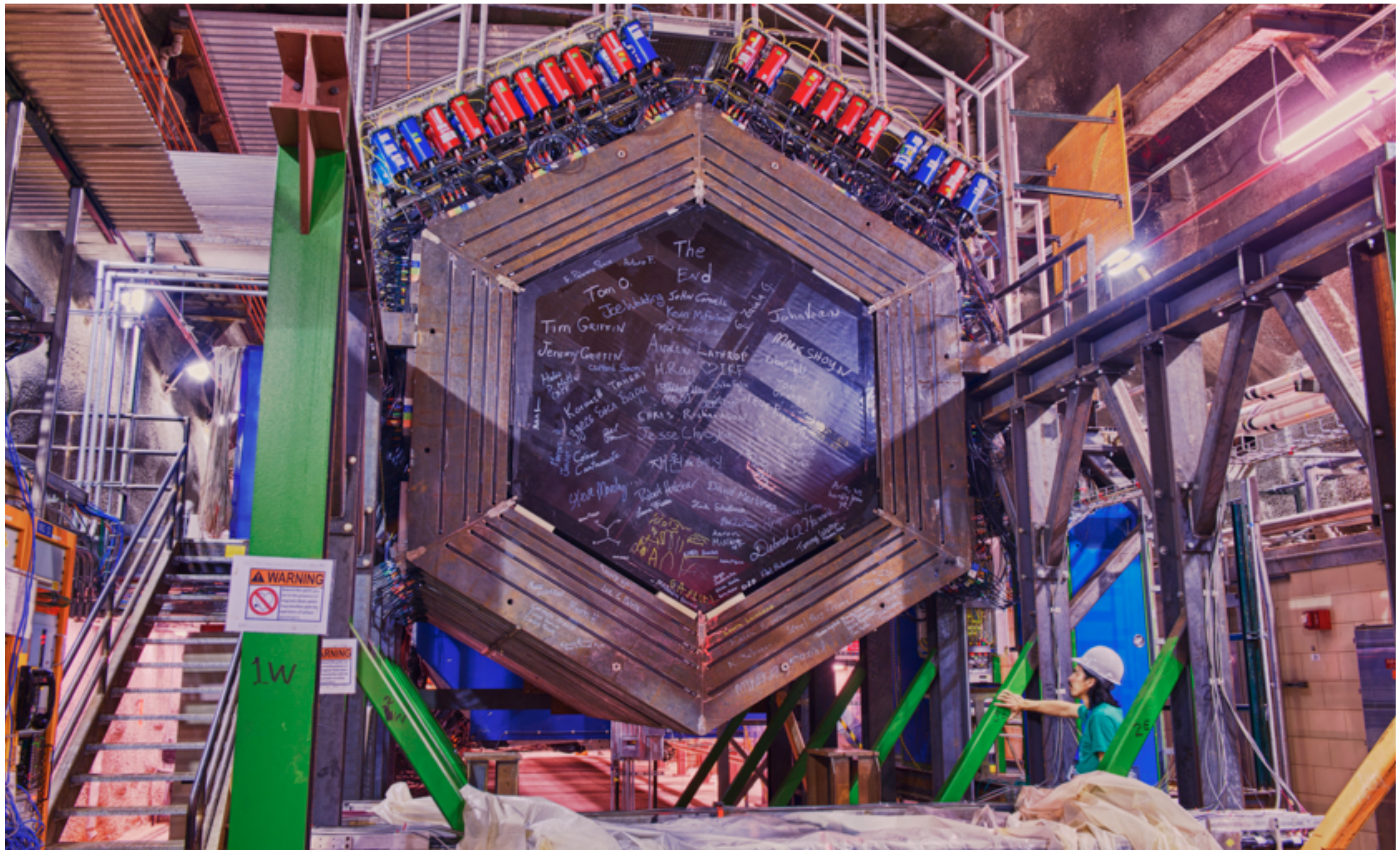


MINERvA Status Report and Request for Antineutrino Running

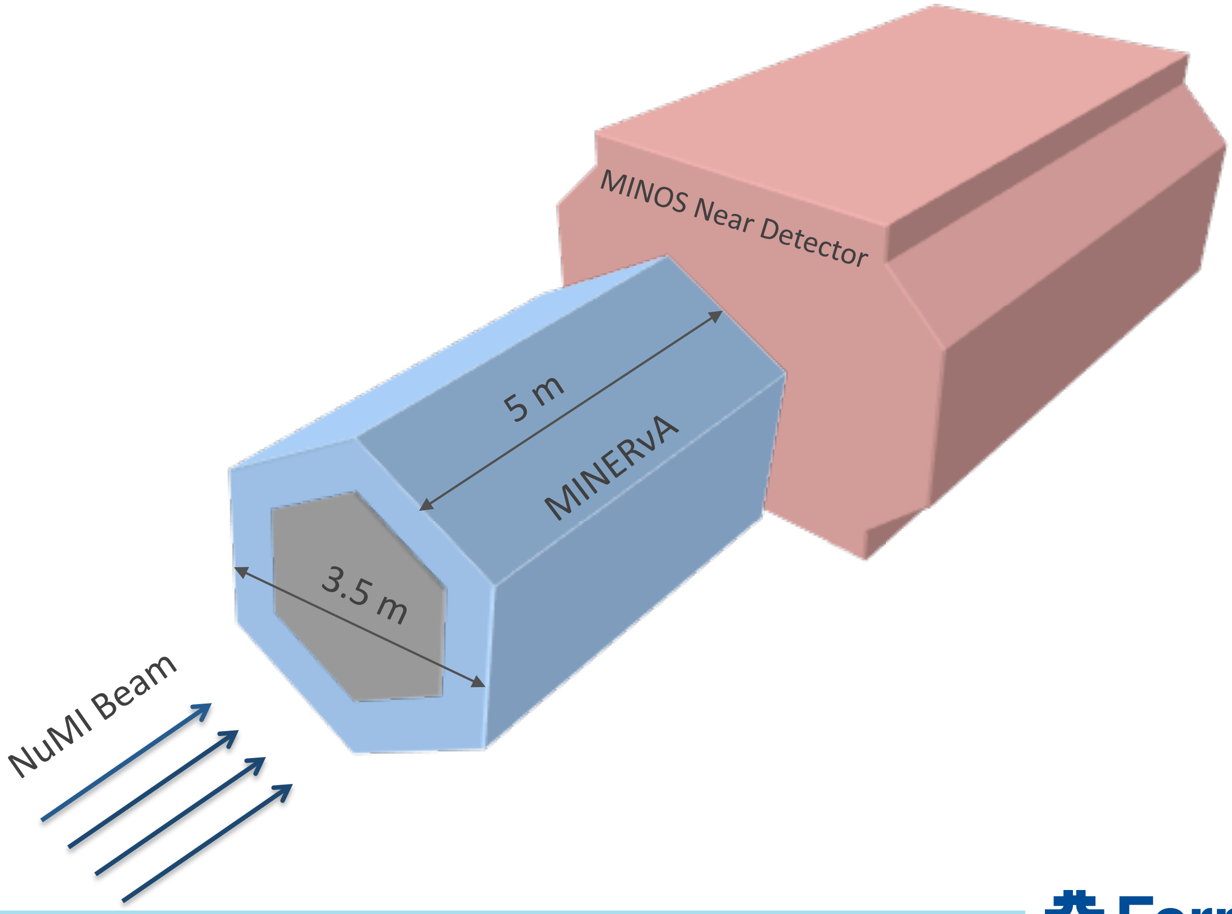
Laura Fields for the MINERvA Collaboration

Fermilab PAC Preparatory Meeting

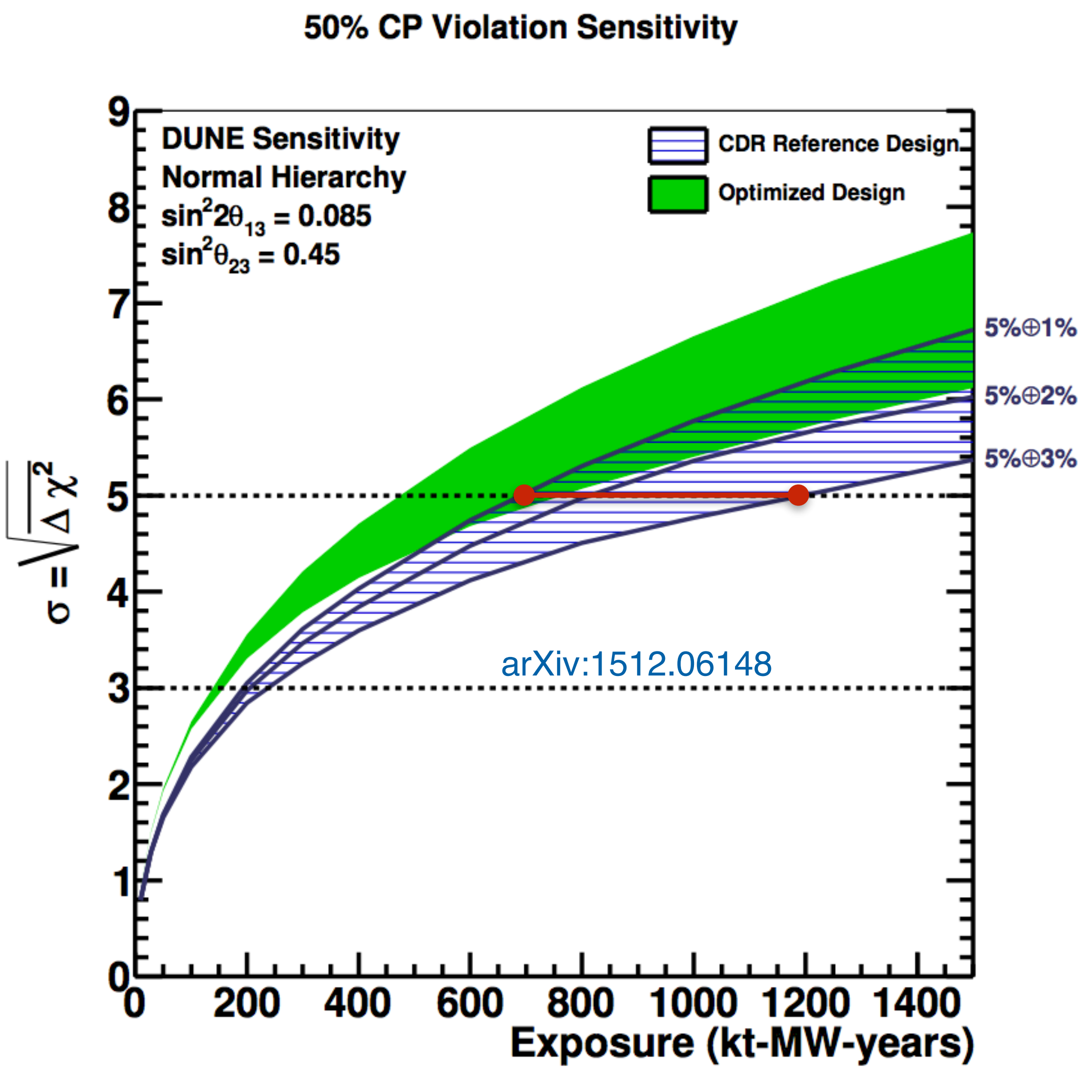
10 November 2017

MINERvA Overview

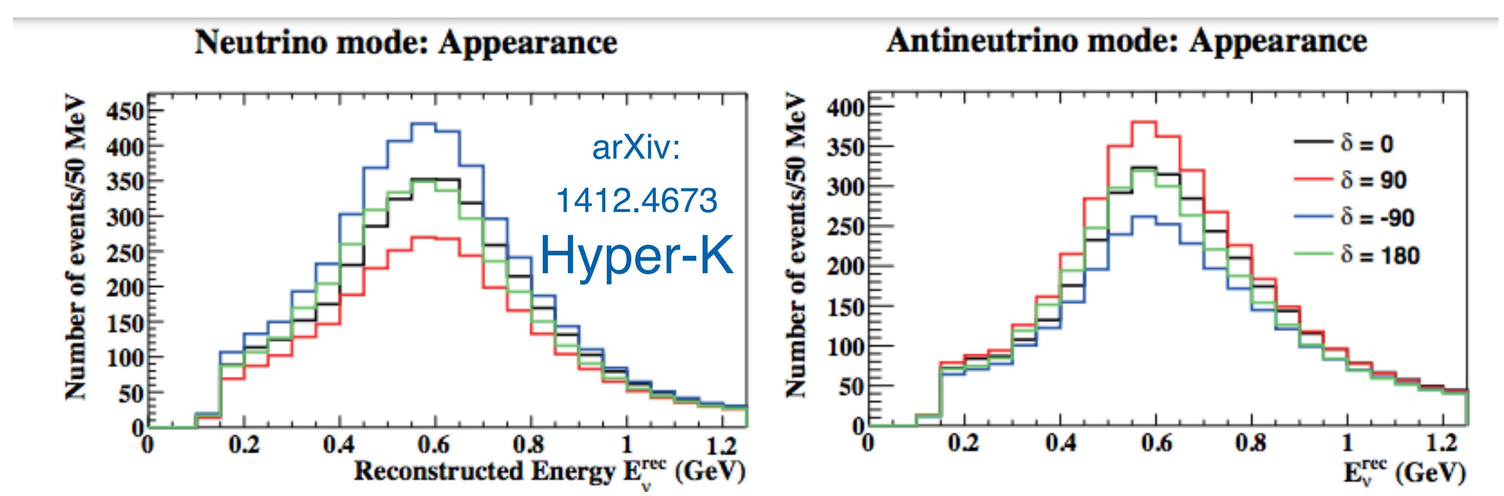
- Scintillator-based neutrino detector in NuMI beam at Fermilab
- Goals include:
  - Inclusive and exclusive measurements of **signals and backgrounds in oscillation measurements**
  - Study of **nuclear effects** via measurements on many nuclei in the same beam



MINERvA Motivation



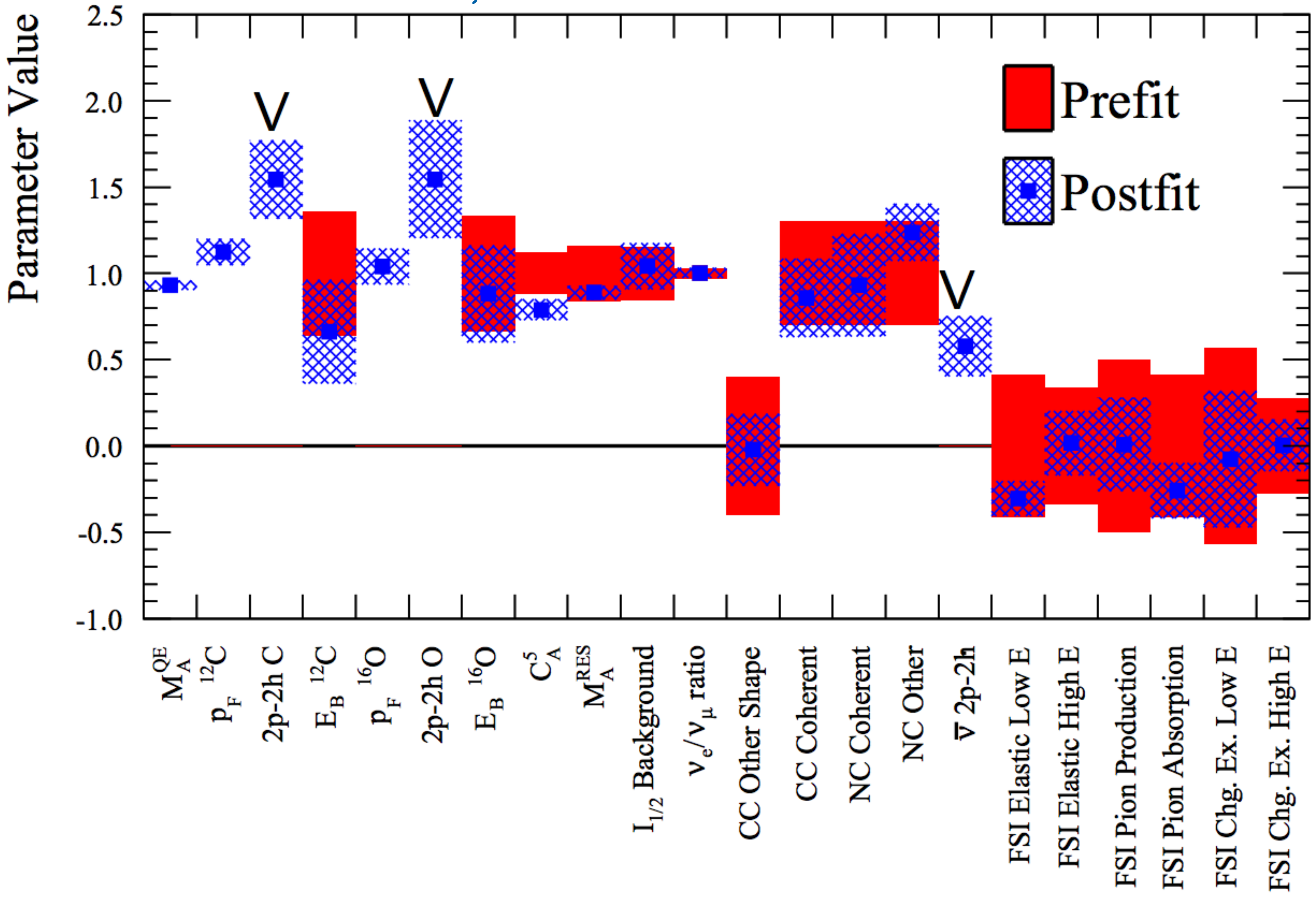
- For DUNE, the difference between two different systematic uncertainty scenarios is **equivalent to many years of runtime**
- The systematics that matter here are uncertainties on predicted energy in far detectors
- We will **need unprecedented precision in models** of beams, physics, and detectors



MINERvA Motivation

- MINERvA is needed **in addition to near detectors**:

T2K, S. Dennis NuInt 2017



- Data from MINERvA and other experiments **sets the prior uncertainties** on model parameters in near/far detector fits.
- But most crucially, these data help us understand **what models and what parameters should be used** in oscillation fits in the first place
- Our understanding of appropriate degrees of freedom in oscillation fits has **rapidly evolved** in the last few years, based in part on MINERvA data

MINERvA Motivation

- MINERvA has support from oscillation experiments:

Dr. Peter Shanahan
Neutrino Division/Neutrino Physics Department
Fermilab
NOvA Co-Spokesperson

Prof. Mark Messier
Department of Physics
Indiana University
NOvA Co-Spokesperson

Dr . Nigel Lockyer, Director
Fermilab
Batavia, IL 60510

May 24, 2016

Dear Nigel,

We understand from the MINERvA spokespersons that there are discussions underway that impact the proposed future cross-section measurement program in the NuMI beam, and that our recent experience with first measurements of neutrino oscillations using the NOvA detectors might provide some useful background information on the relationship between measurements of neutrino cross-sections and extraction of fundamental neutrino properties.

As you may recall, the initial data seen in the NOvA near detectors showed a large (14%) discrepancy in the hadronic component of neutrino charged-current interactions. This difference was not wholly unexpected as NOvA operates in a transitional energy region (1 - 3 GeV) where several interaction processes (quasi-elastic, resonant, deep inelastic) contribute in nearly equal amounts. Uncertainties in the hadronic system resulted in a 7% uncertainty in our initial measurements of neutrino energy. This uncertainty would have been a limiting factor in the measurements of $\sin^2 2\theta_{23}$ and Δm^2_{23} using muon-neutrino disappearance had they gone uncorrected. Likewise, uncertainties in the modeling of the hadronic components of electron-neutrino events caused us to assign a 14% uncertainty to the efficiency with which we find electron-neutrino charged-current candidates at the far detector which directly impacts our ability to map the electron-neutrino appearance rates to the oscillation parameters $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP} and neutrino mass hierarchy.

Over the past year, NOvA has worked to understand this discrepancy, homing in on the understanding of neutrino cross-sections as one of the most likely causes. Crucial to these investigations were, of course, our own high statistics near detector data, but we also relied on external measurements of quasi-elastic scattering, resonant production, and deep inelastic scattering by the MINERvA collaboration. Having those data available, and an engaged community of physicists who understood those data, enabled us to converge on a solution to the hadronic energy differences much faster that we would have otherwise. Knowing that our own data shows trends consistent with the MINERvA measurements gives us confidence in our solution.

At the Neutrino conference in July we expect to show updated results where the uncertainties in hadronic energy, neutrino energy, and electron neutrino selection efficiency uncertainties have been reduced to 5% (from 14%), 5% (from 7%), and ~2% (from 14%) which, when combined with improved reconstruction techniques, will improve the physics reach of our results by much more than what would have been projected with the increased statistics only.

Sincerely,

Peter Shanahan and Mark Messier
NOvA Co-spokespersons

Prof Tsuyoshi Nakaya
Kyoto University
Dr Morgan O. Wascko
Imperial College London

Dr Nigel Lockyer
Director, Fermi National Accelerator

cc: Dr Joseph Lykken, Dr Stephen Geer; Prof Kevin McFarland, Dr Deborah Harris

Wednesday, 8 June 2016

Dear Nigel:

We are writing in support of MINERvA's antineutrino data runs and the CAPTAIN-MINERvA project.

T2K has made use of Fermilab neutrino cross-section data in every oscillation analysis from its beginning. Initially it was MiniBooNE and SciBooNE data sets, but, as they have become available, multiple MINERvA results are now incorporated into T2K's external data fits. T2K has its own near detectors, both on and off-axis. Even with these, the external cross-section data play a critical role in selecting neutrino-scattering models for the oscillation analysis and in tuning/restricting parameters within those models.

The fact that these measurements are made in neutrinos and antineutrinos, at energies and on nuclei beyond those used by T2K in its oscillation analysis sample, is actually a strength of the datasets, in that it helps to test models in ways that T2K cannot do by itself. This stems from the fact that each neutrino beam is inherently wide-band in energy with respect to the nuclear effects that drive the systematic uncertainties of neutrino oscillation analyses. Accordingly, T2K expects to benefit from more antineutrino results from MINERvA.

Similarly, CAPTAIN-MINERvA data, because it offers a unique opportunity to compare measurements in two capable detectors with nuclei of significantly different size and density, should be beneficial to the T2K program of using MINERvA data to constrain nuclear models.

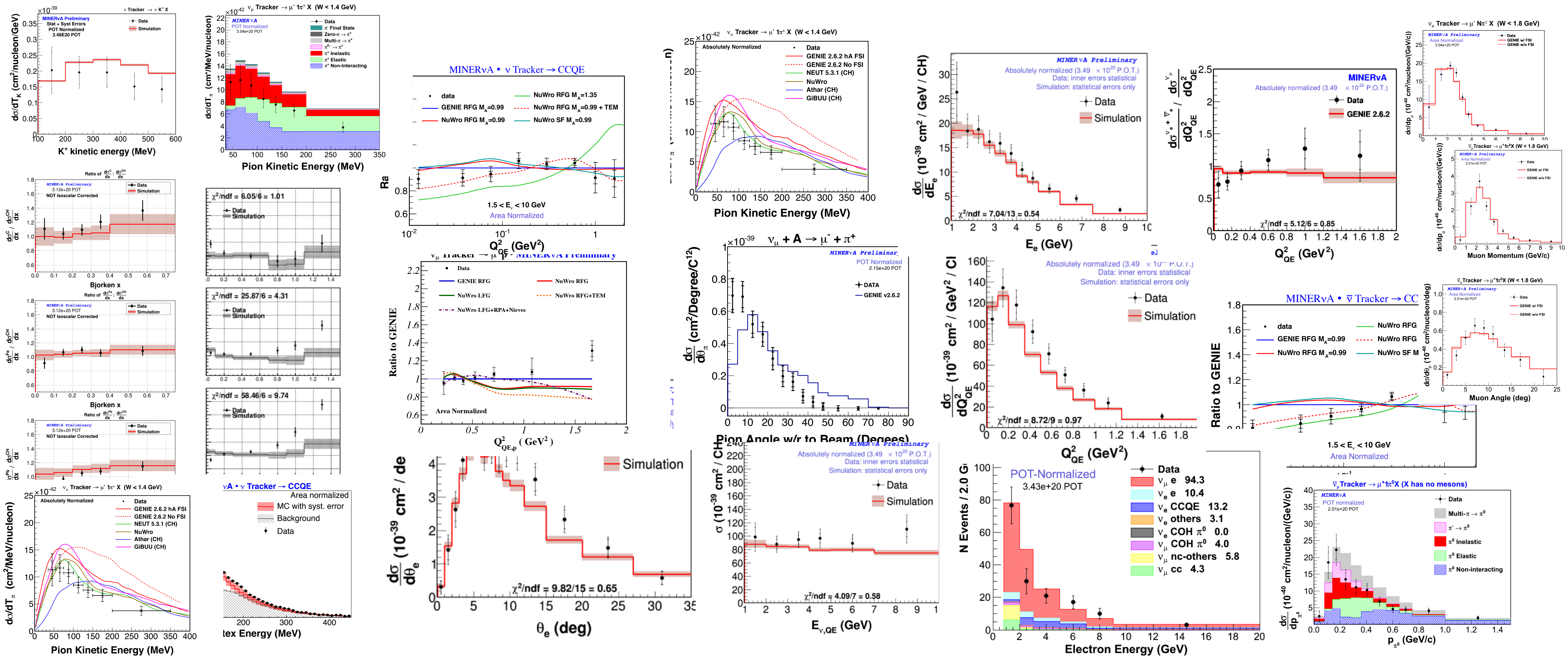
Having the legacy datasets from MiniBooNE and SciBooNE is valuable, but there is additional value from a contemporary experiment. There is active feedback between MINERvA and T2K that has resulted in new analyses being completed on MINERvA which then are applied to the T2K oscillation analysis. The coherent pion and low recoil ("2p2h") analysis are good examples of this.

The information provided by MINERvA has been important in not only formulating the systematic uncertainties for the oscillation results, but has also actively helped T2K reduce them to levels below what was foreseen in the original proposal. New data sets with antineutrinos and argon nuclear targets will certainly continue, and enhance, these benefits.

Best regards,
T. Nakaya and M. Wascko
T2K Spokespersons

MINERvA Low Energy Analysis Program

- MINERvA is building a large bank of data for model tuning:



- 21 physics publications and counting

MINERvA Low Energy Analysis Program

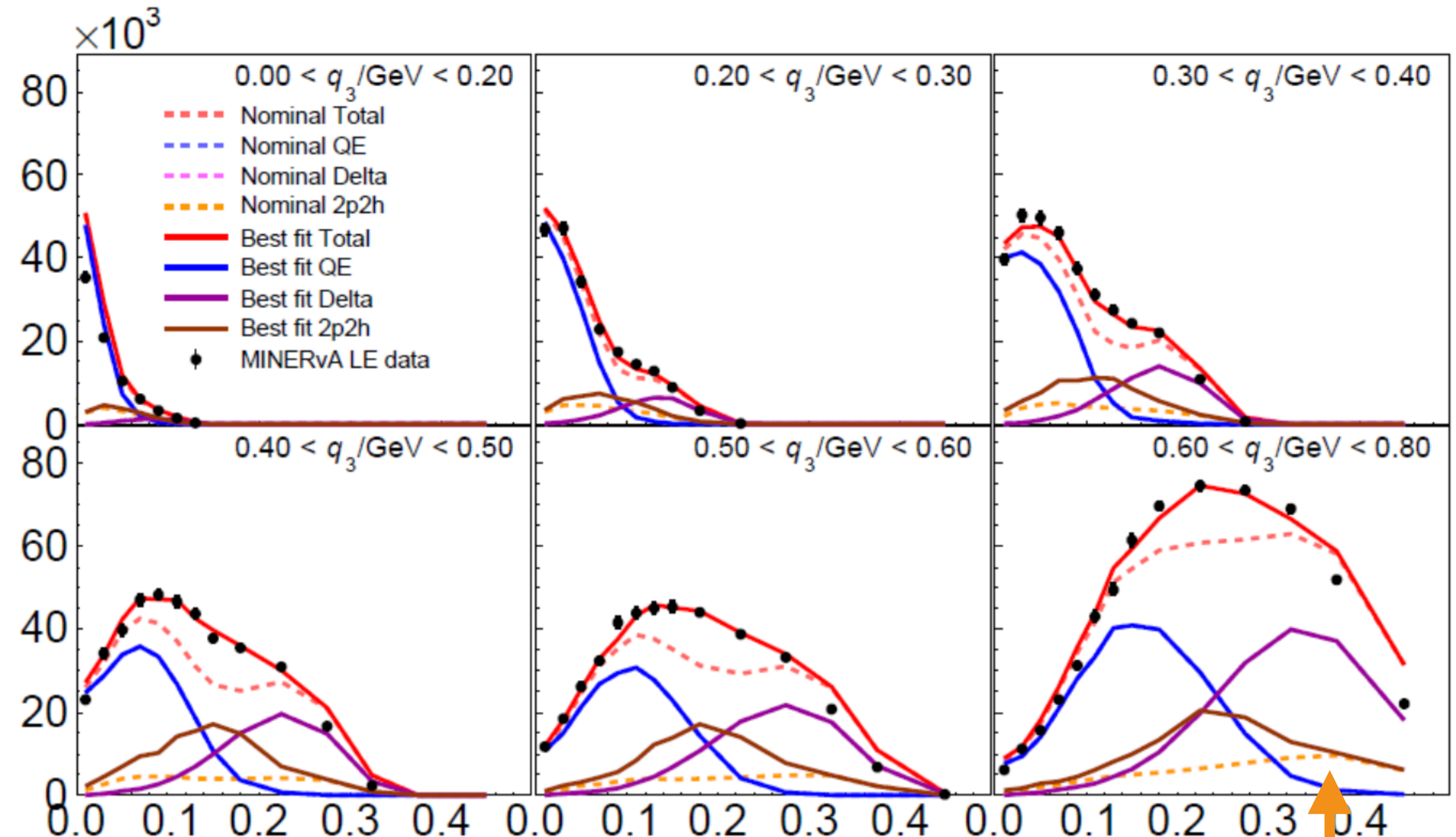
- One example:

- Several experiments have indicated evidence for neutrino interactions consistent with being **interactions with multinucleon-pairs** (also seen in electron scattering)

- Models of these interactions are beginning to appear

- MINERvA charged-current inclusive data indicates that, while these models modestly improve data/ model agreement, **we must tune these models by ~60%** to achieve good fits

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

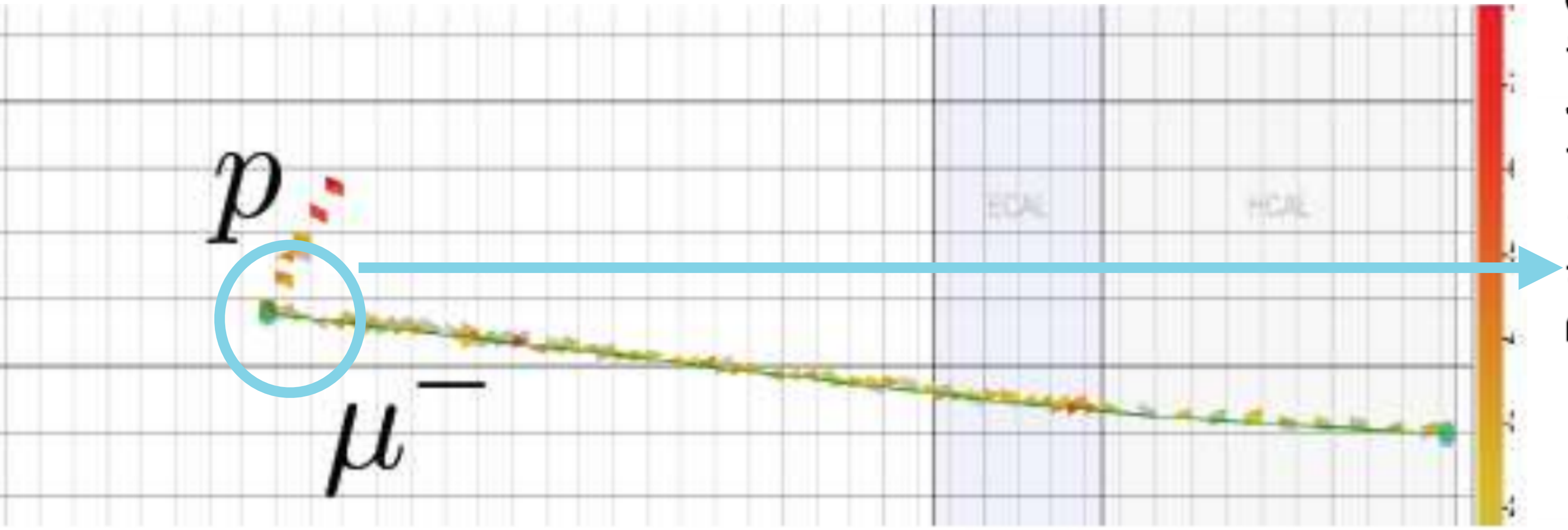


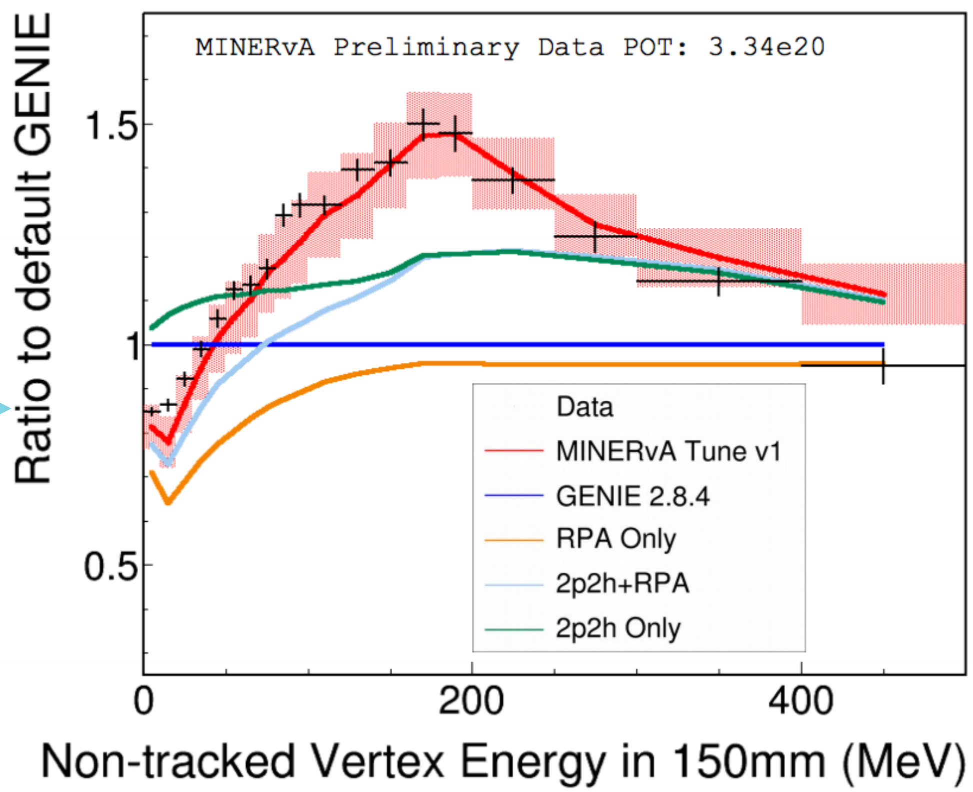
multinuclear "2p2h" model, did not exist until ~2 years ago

Fermilab

MINERvA Low Energy Analysis Program

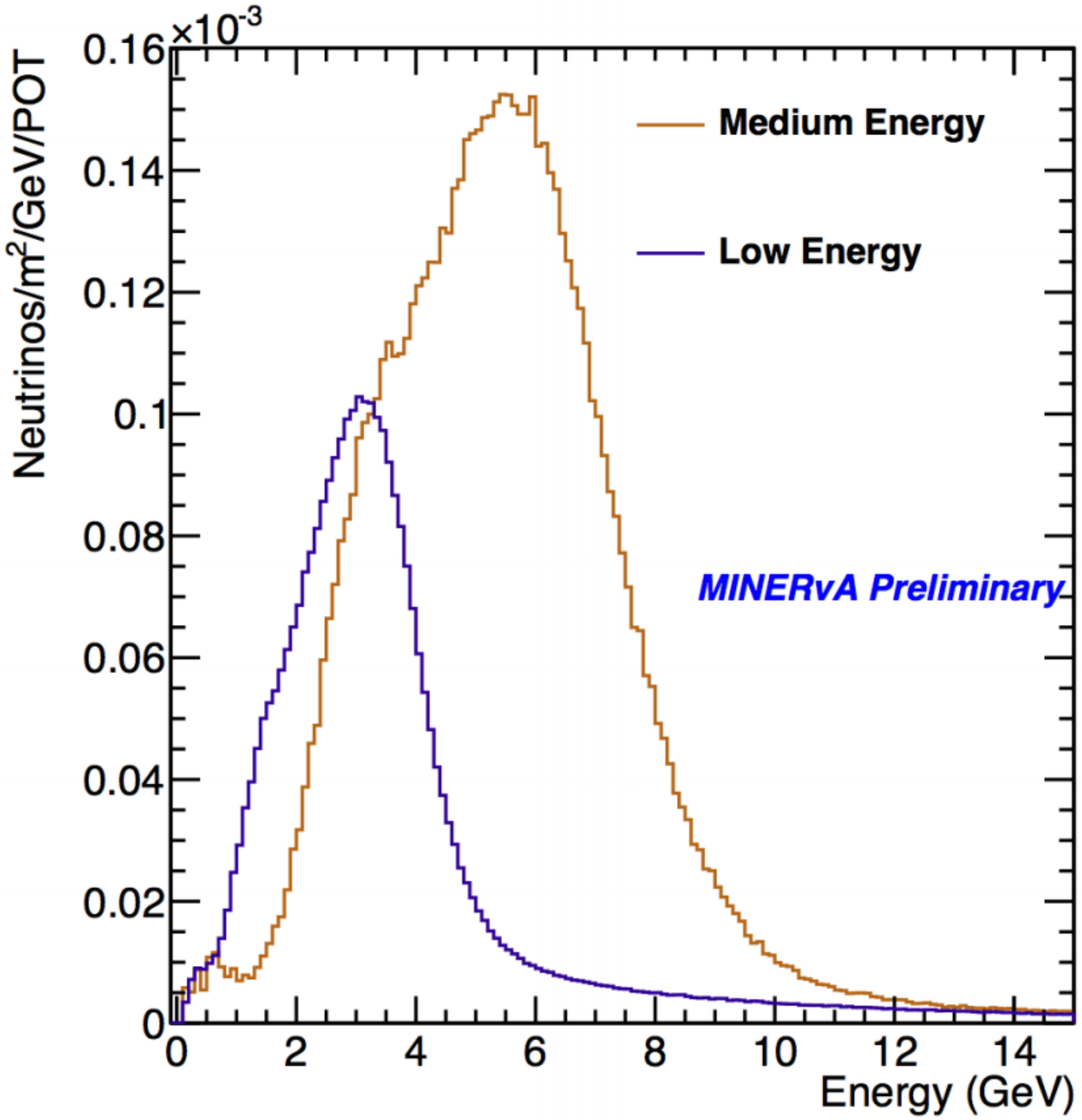
- Different analyses tell a consistent story





- When we look at other channels and other variables, **we see corroborating evidence** that current 2p2h models need significant enhancement
- Example above shows energy near vertex in **neutrino quasi-elastic** candidates
- Similar behavior seen in **antineutrino mode** data
- **NOvA has adapted** this analysis technique for their interaction model

Why Are We Here?



- All of the analyses on **previous slides use our "low energy"** data set
- We are now accumulating data in the "**medium energy**" NuMI beam.

	Low Energy	*Medium Energy*
Neutrino Mode	*3.4e20*	*12e20*
Antineutrino Mode	*2e20*	*3.7e20*

POT on Tape as of Summer 2017

Understanding differences between neutrino / antineutrino cross sections is exceptionally important for measurements of CP violation

Why Are We Here?

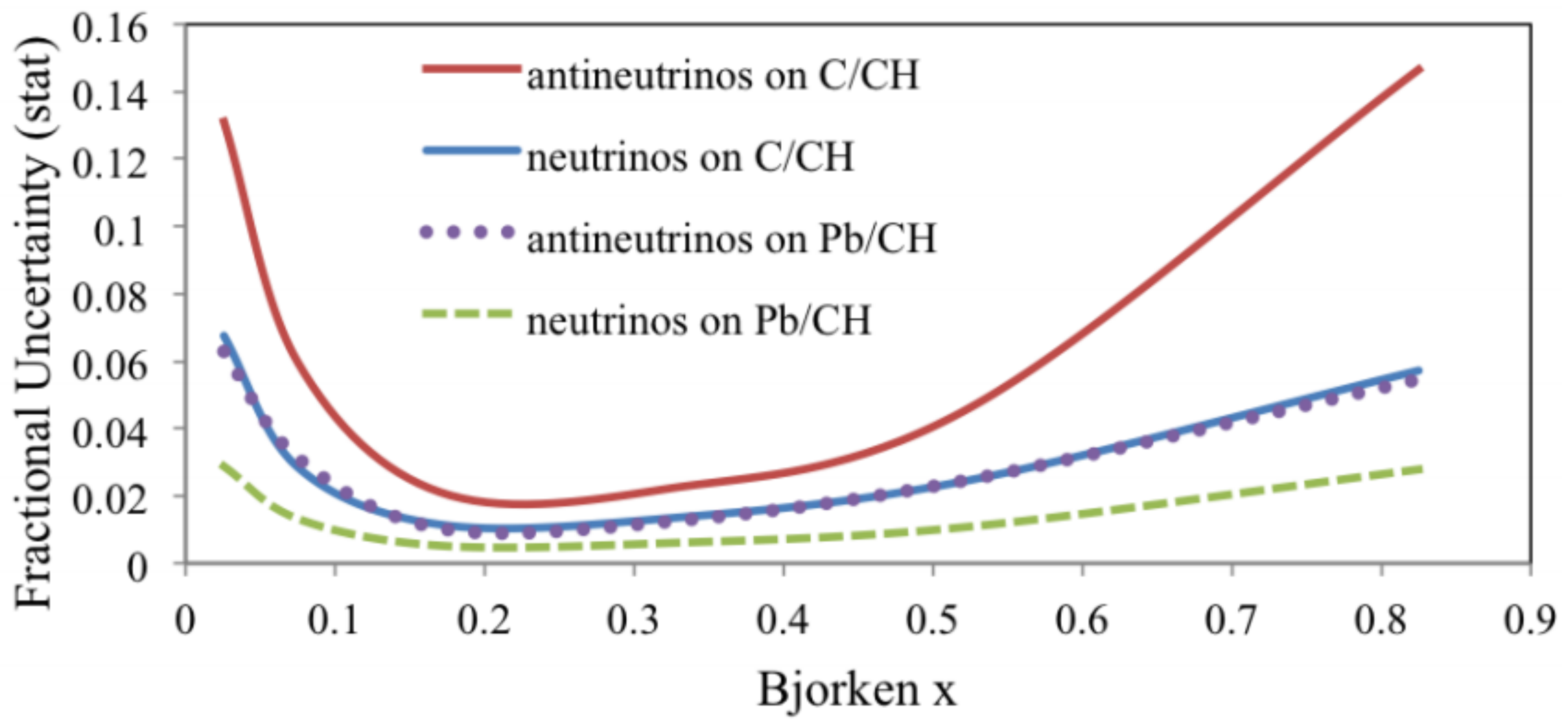
	Low Energy	Medium Energy
Neutrino Mode	3.4e20	12e20
Antineutrino Mode	2e20	3.7e20

By the summer 2018 shutdown, we expect to increase our ME exposure to ~8e20 in antineutrino mode

- In **December 2014 we submitted a document** to the PAC entitled "MINERvA's Medium Energy Physics Program"
- We requested **12e20 in antineutrino mode**, which would require running in part of FY2019
- We are speaking to you today to reiterate **that request for antineutrino mode running** with more analyses considered
  - We **provided a new document to you last month**; the following slides summarize the analyses described there

Why 12e20?

- Our initial 12e20 request was based on achieving comparable statistical and systematic errors on **Deep Inelastic Scattering (DIS)** cross section ratios on different nuclei

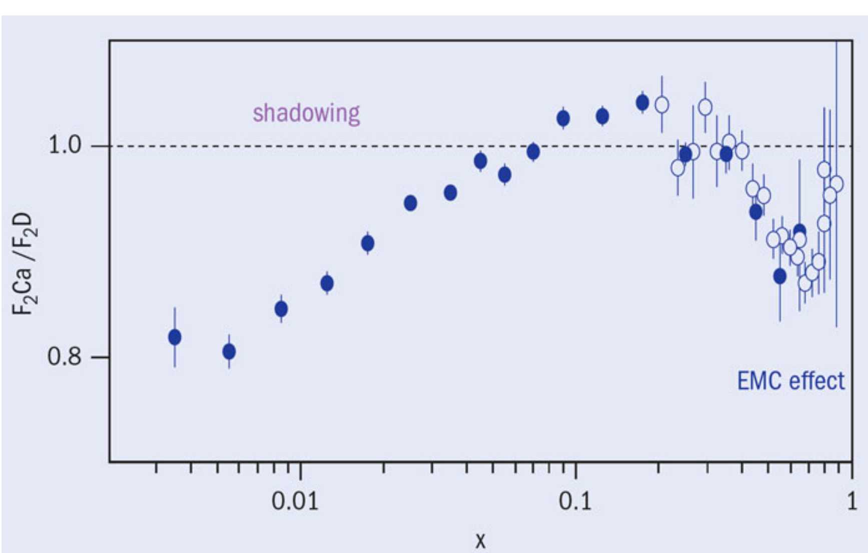


CERN COURIER

Apr 26, 2013

The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

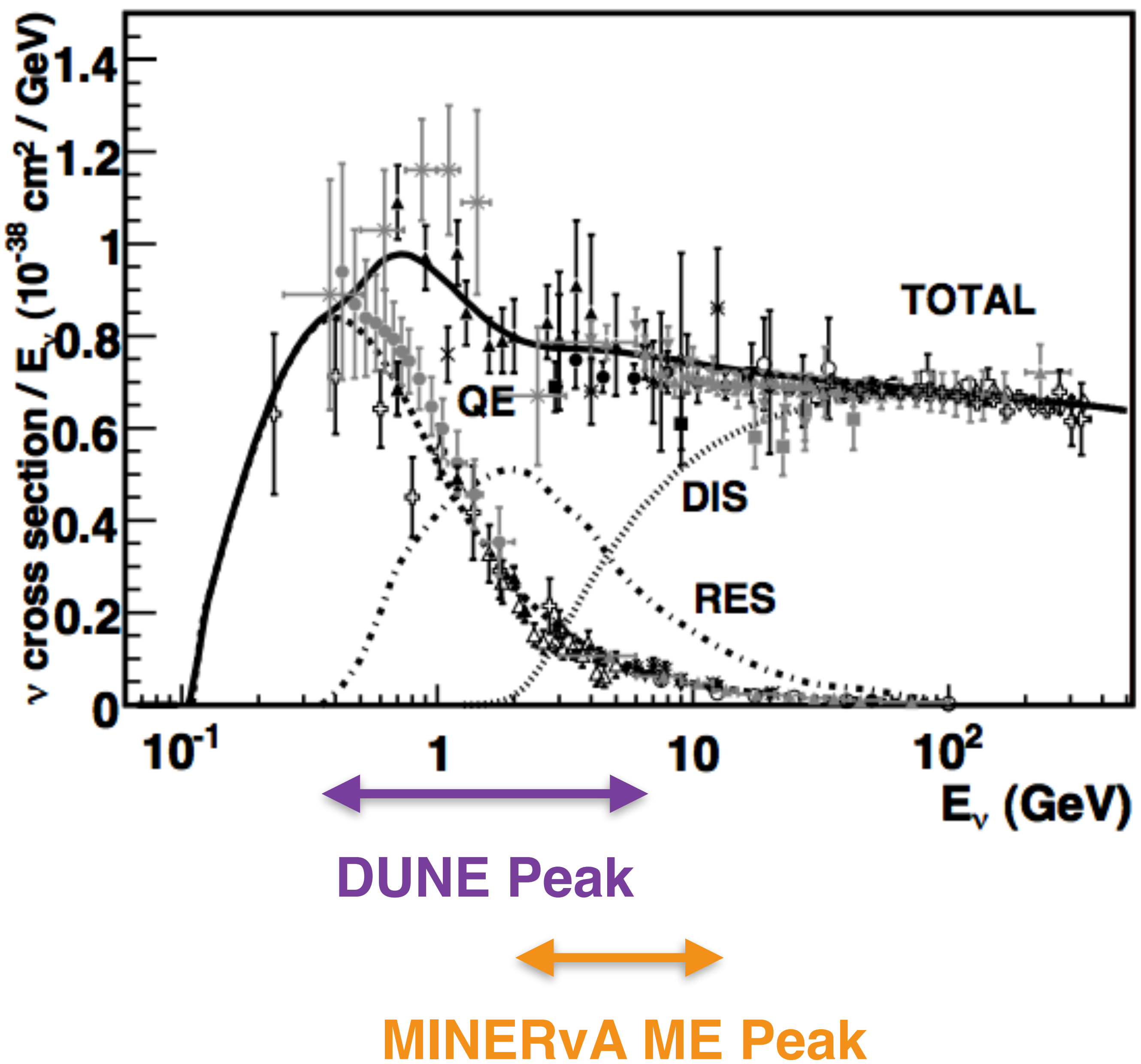


- MINERvA is the first neutrino experiment to address a **longstanding mystery in nuclear physics** (the “EMC Effect”) on neutrinos, and the more recently discovered behavior of shadowing

Why 12e20?

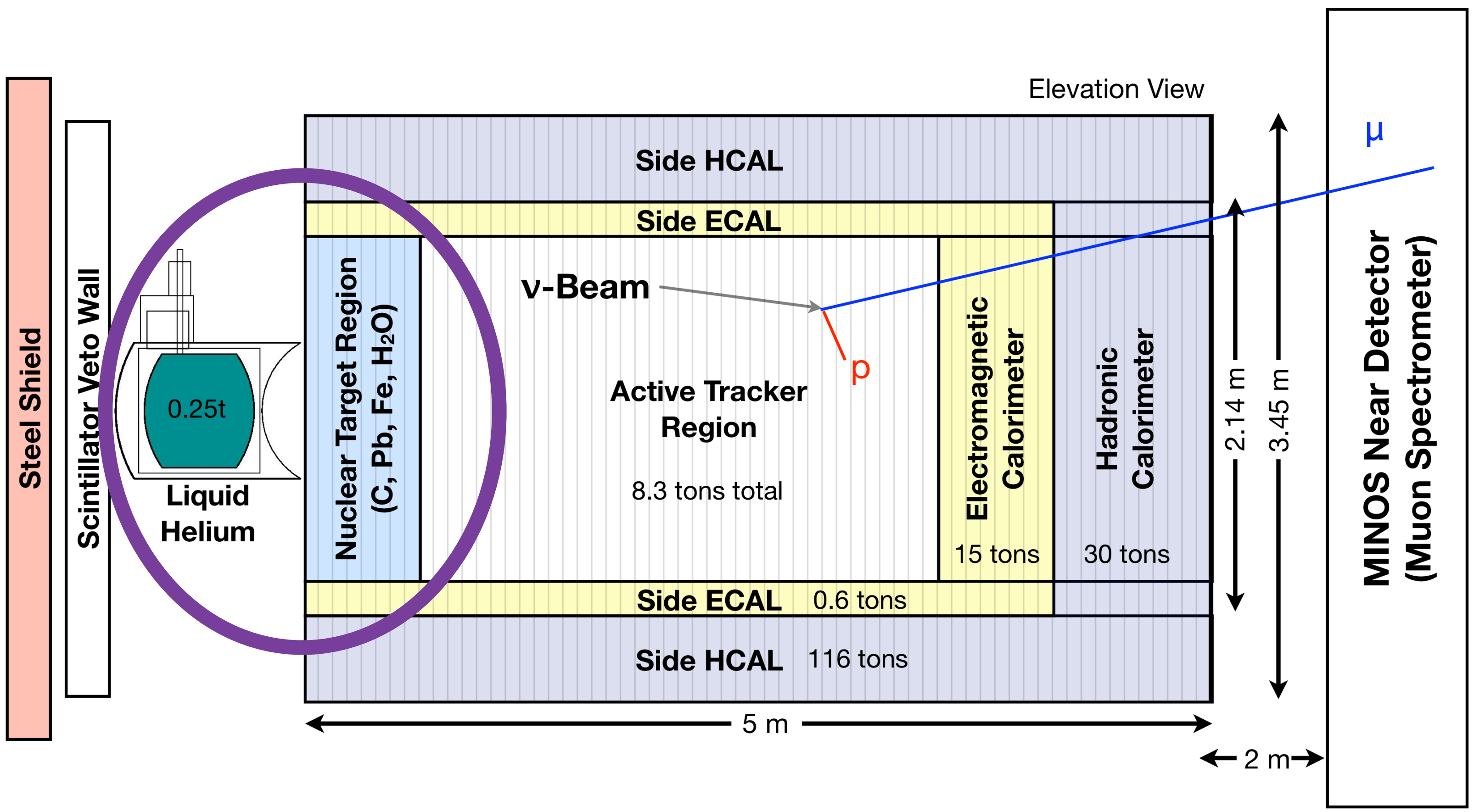
- Understanding the neutrino EMC effect, and Deep Inelastic Scattering in general, is **important for DUNE**
- Will be the **dominant source of events** at the falling edge of the focusing peak, and the high energy tail
- **MINERvA is the only modern experiment** with high statistics at these energies

Rev. Mod. Phys. 84, 1307 (2012)



Why 12e20?

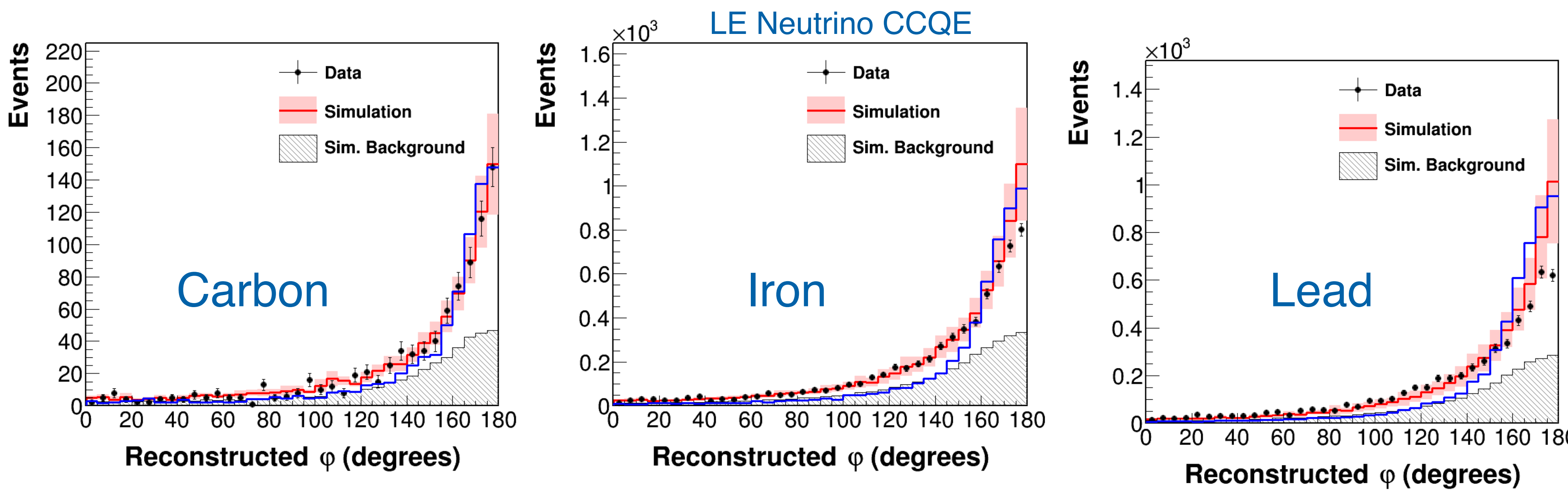
- As MINERvA has developed our Medium Energy analysis program, it has become clear that **12e20 will enable many other analyses**

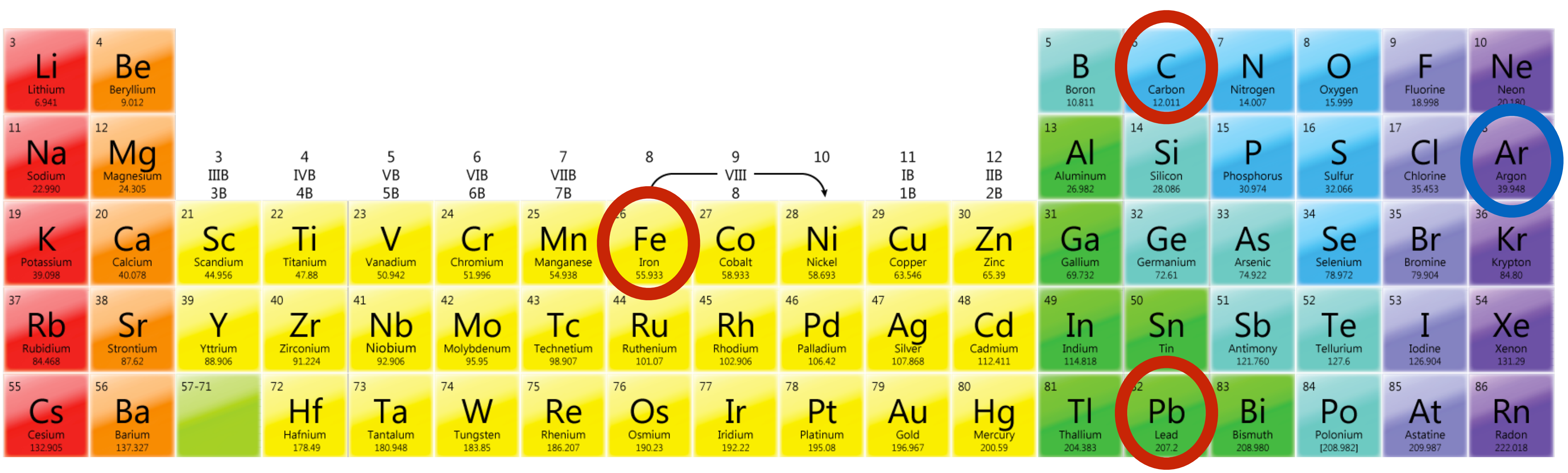


- 12e20 is **particularly critical for our comparisons of cross sections across different nuclei**, which use lower mass targets than our cross section measurements on scintillator

Importance of A-Dependance

- Measurements on **different nuclei are critical for disentangling** models of neutrino interactions on nucleons and the effect of the nuclear environment.

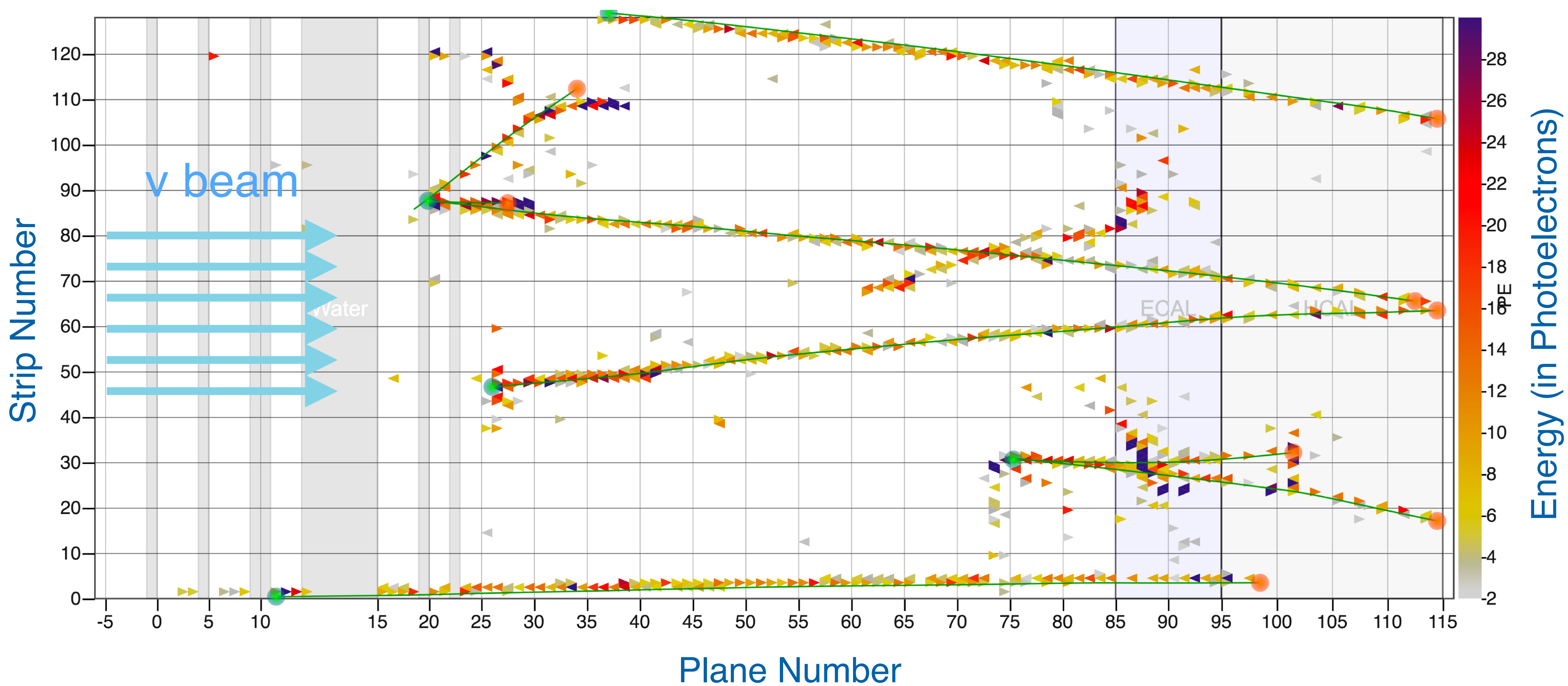




- MINERvA targets include water, bracket argon, and provide a long lever arm for measuring A-dependence

Medium Energy Analysis Strategy

- While accumulating our full neutrino-mode exposure, we have worked to tackle **many challenges that come with the intense ME-beam**:
  - For instance: MINERvA sees many neutrino events in a typical NuMI spill



Medium Energy Analysis Strategy

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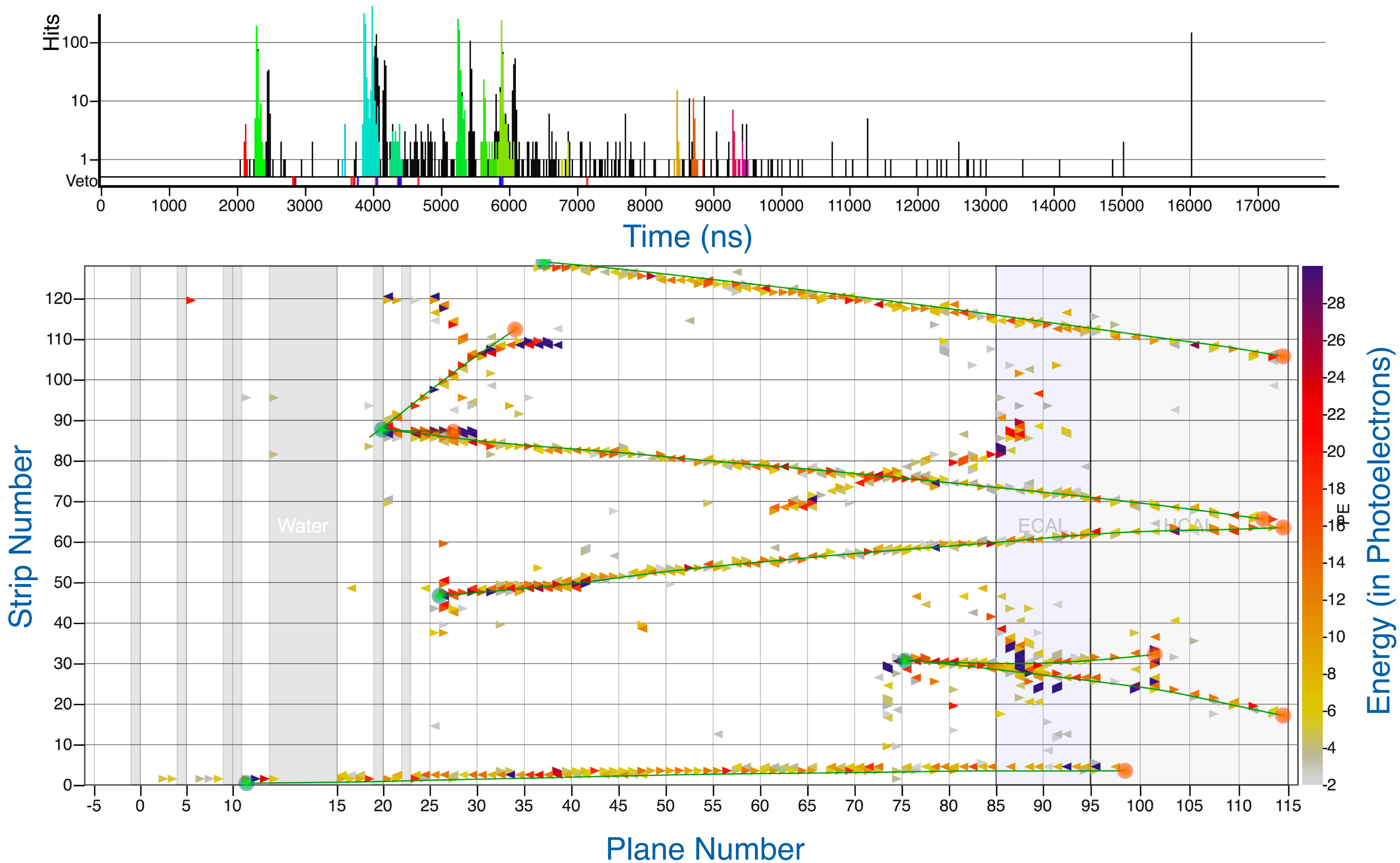
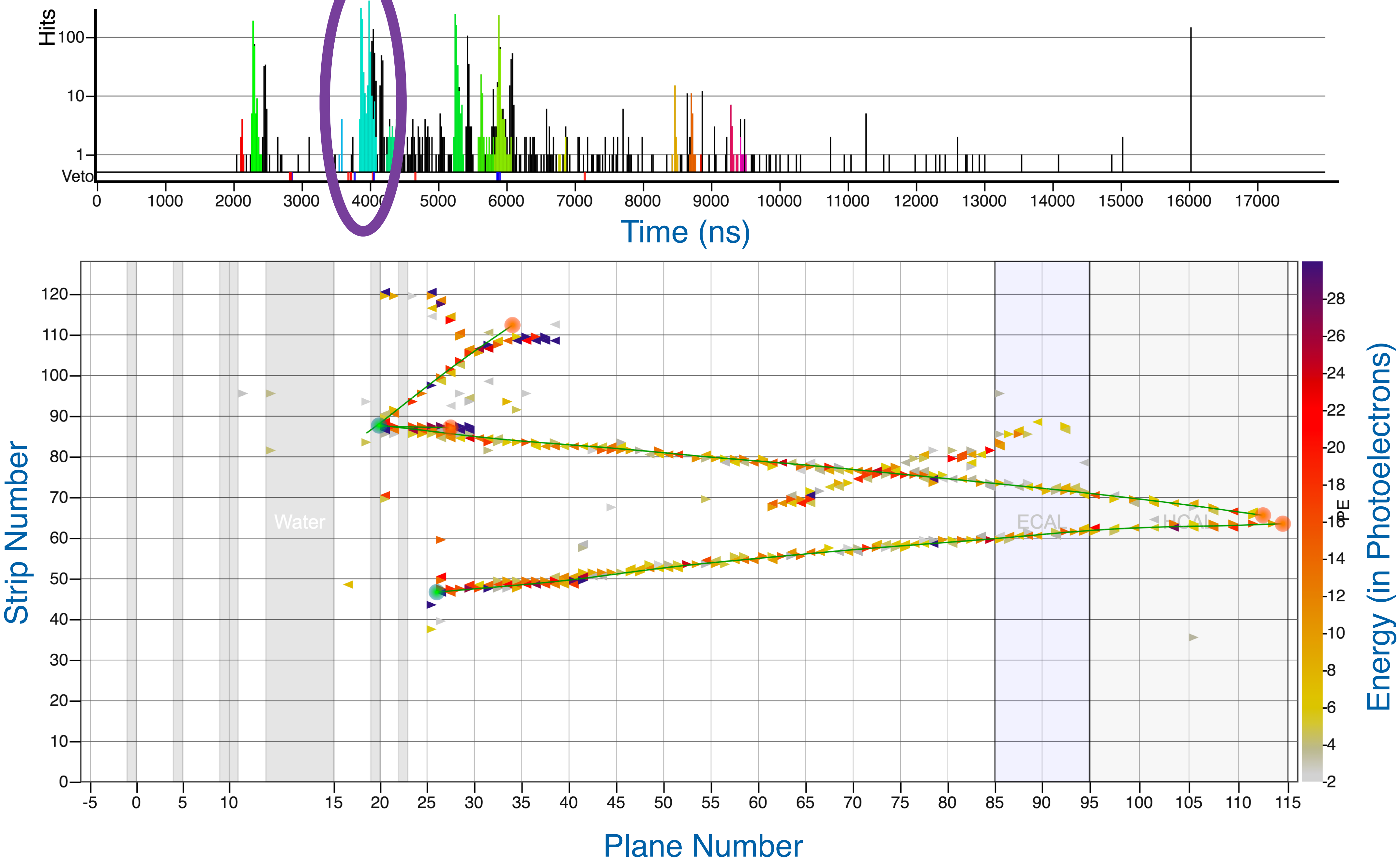


MINERvA's ns-scale timing resolution allows for separation of events in time

Medium Energy Analysis Strategy

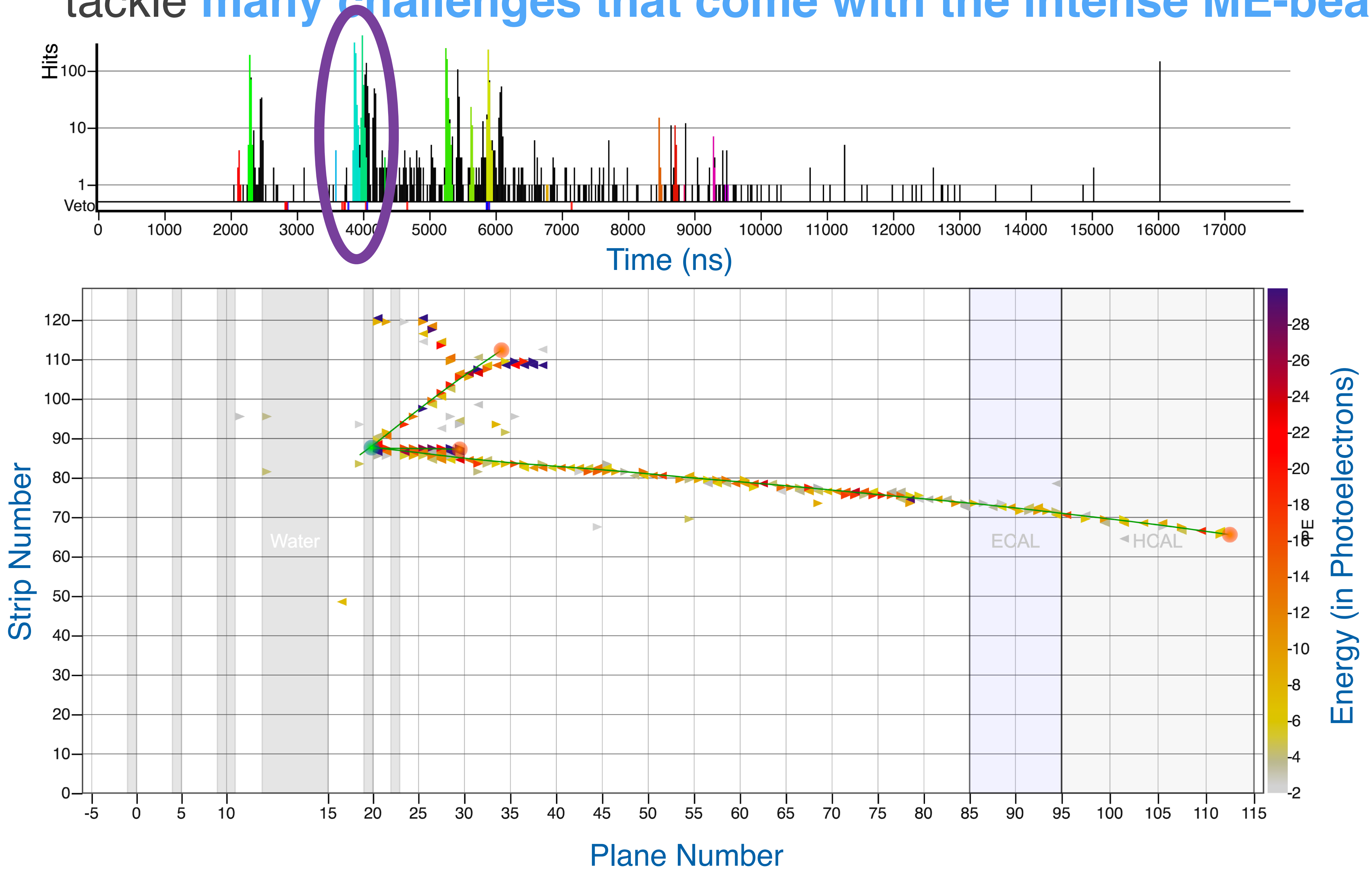
- While accumulating our full neutrino-mode exposure, we have worked to tackle **many challenges that come with the intense ME-beam**:



But dividing events in time became much more challenging in the ME beam

Medium Energy Analysis Strategy

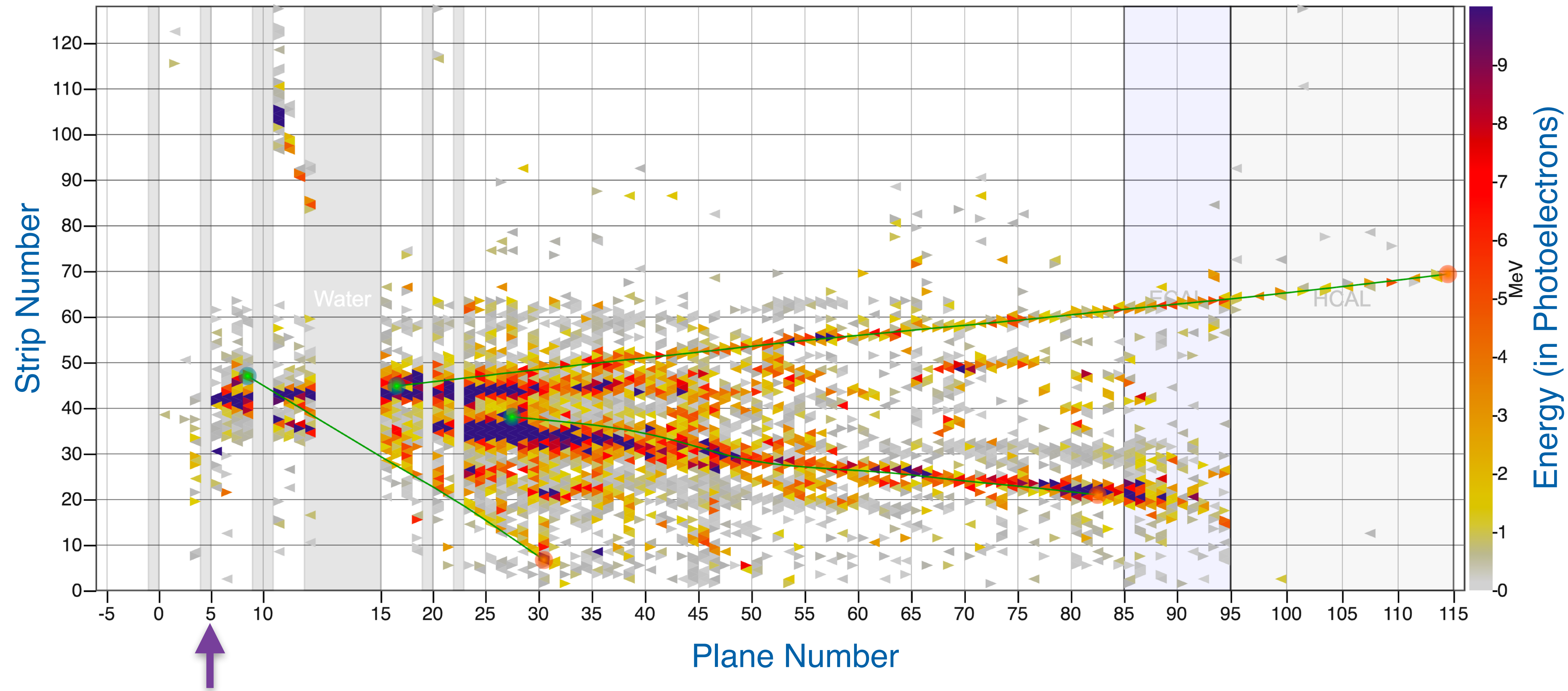
- While accumulating our full neutrino-mode exposure, we have worked to tackle **many challenges that come with the intense ME-beam**:



But we have retuned this algorithm to separate different events (but not divide events in two!)

Machine Learning for ME

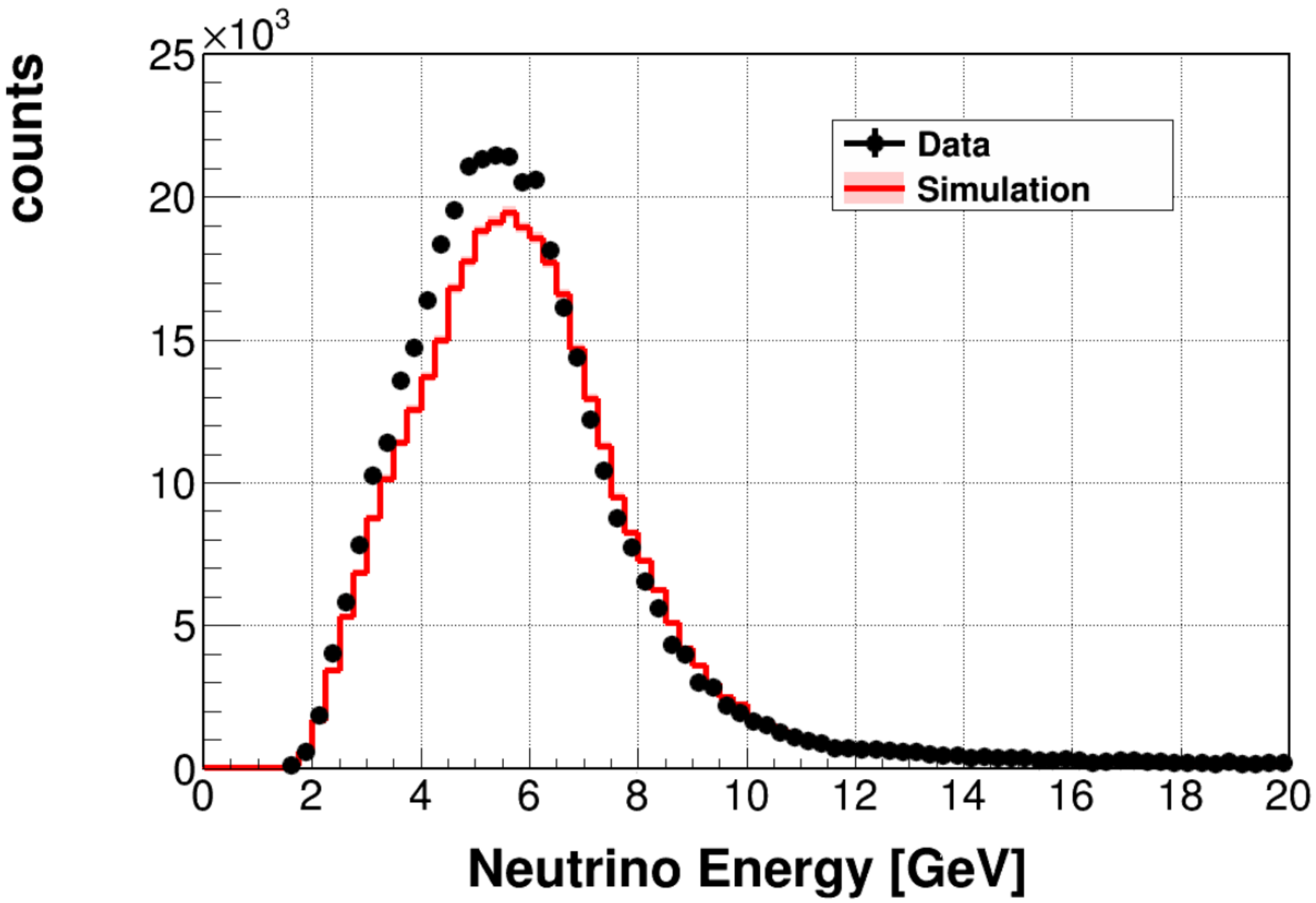
- We have begun to incorporate **machine learning** into our reconstruction, first to deal with events such as this one:



Real vertex is here; track-based reconstruction of the vertex totally fails, but the machine learning algorithm successfully finds it

NuMI Flux for ME

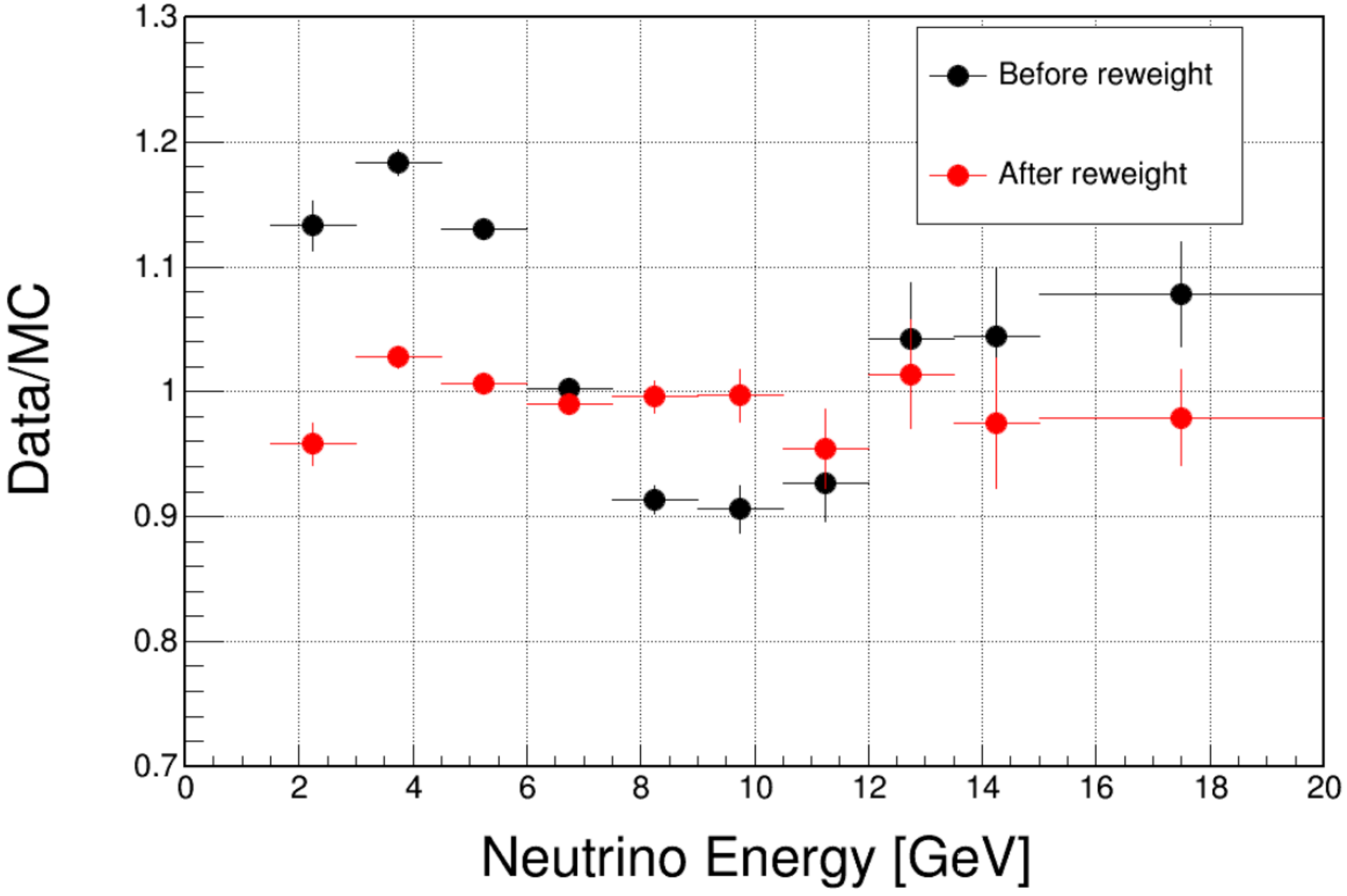
- A major concern for our ME data program:



- **Data/Simulation discrepancy** consistent with a **mismodeling of the NuMI focusing system**
- Efforts have been ongoing for more than a year to **search for possible culprits**
  - Those efforts continue
- But in order to begin ME publication, we have also **developed an alternate plan**

NuMI Flux for ME

- A major concern for our ME data program:

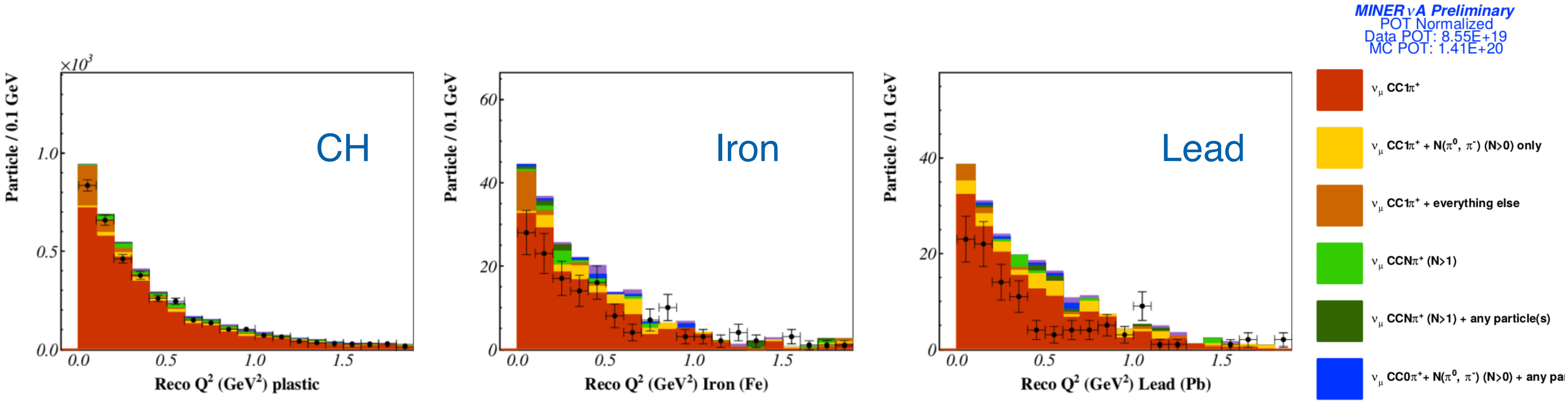


- We have **fit our low-nu data** (a sample with low model-related shape uncertainties)
  - Assume that the problem is **similar to one of our known focusing effects**

- First measurements will focus on processes insensitive to flux
  - Target ratios, nu/nubar ratios, shape measurements

ME Analysis Progress: Neutrino Pion Production

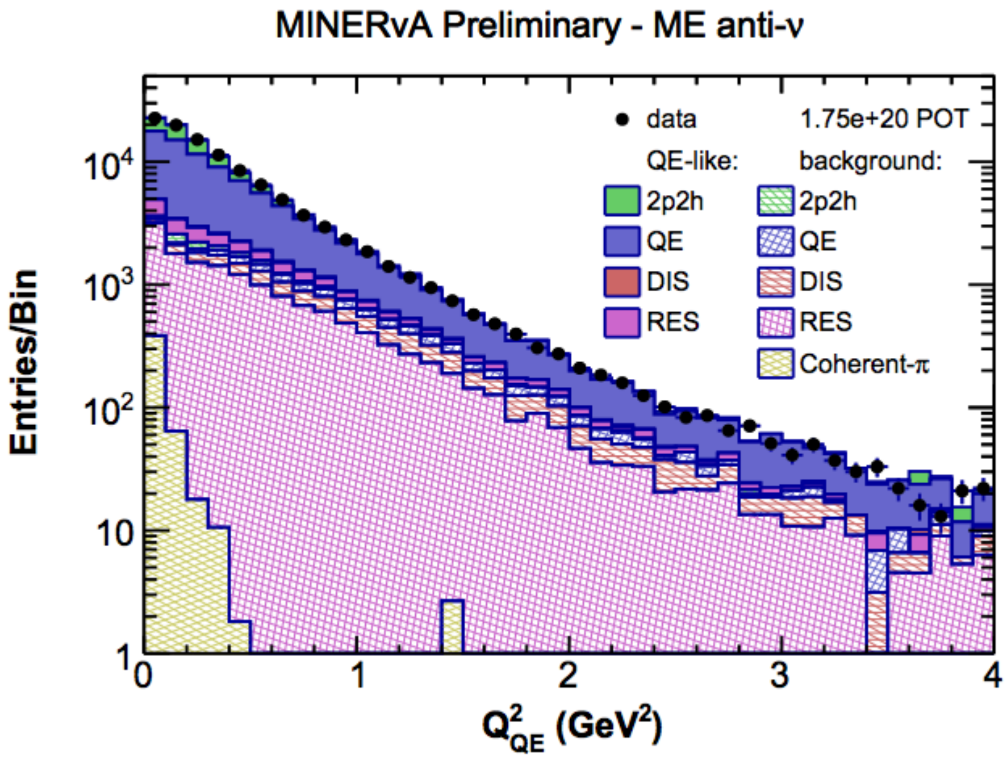
- In parallel with the reconstruction + flux work, we continue to develop many ME analyses, e.g. pion production across nuclei:

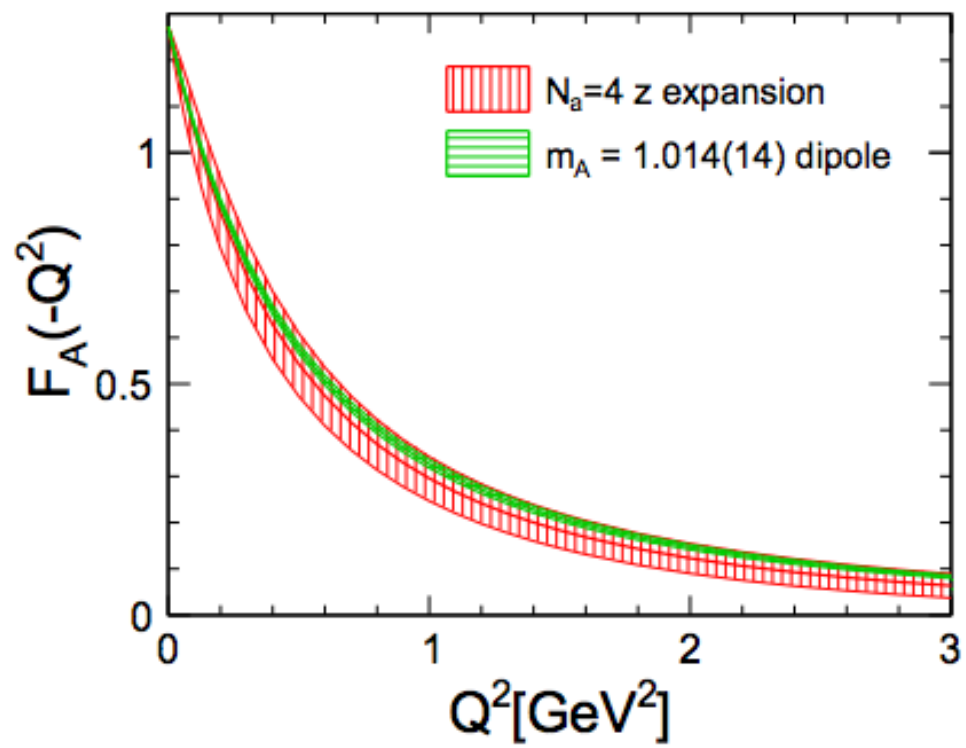


- Most events in DUNE will contain a pion
- ~Half of those will undergo final state interactions as they leave the primary nucleus
  - This sample has an unprecedented ability to see how final state interactions vary across nucleus
  - Plots above are for 1/10th of the neutrino-mode ME exposure; also plan an antineutrino analysis

ME Analysis Progress: Antineutrino Quasielastic Scattering

- The ME beam also provides **access to higher momentum transfers**:

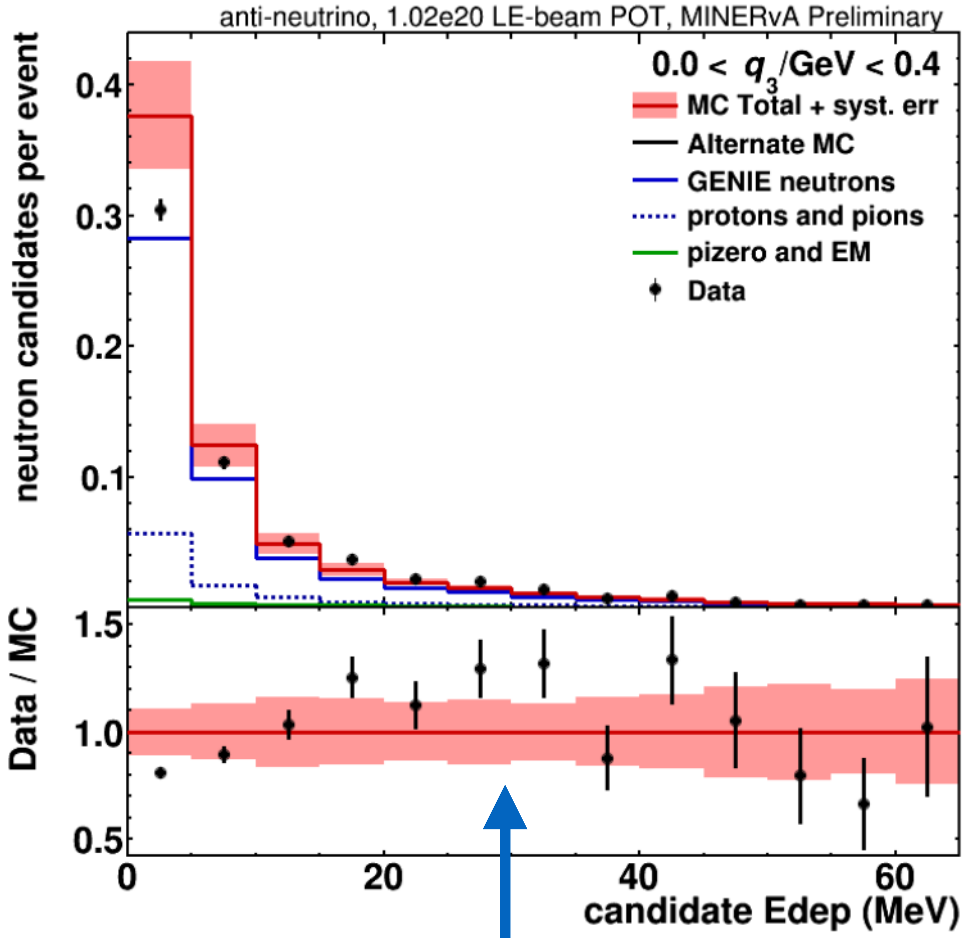




- **Quasielastic scattering** is governed by several form factors
  - Most of these are measurable through electron scattering; the **axial form factor** is best measured in neutrino scattering
- Recent fits to world data have **large uncertainties at high Q^2**
  - High Q2 data also valuable for **distinguishing new lattice predictions** (!)
- 12e20 ME antineutrino exposure will yield **10,000 signal events with $2 < Q^2 < 4$ GeV^2**

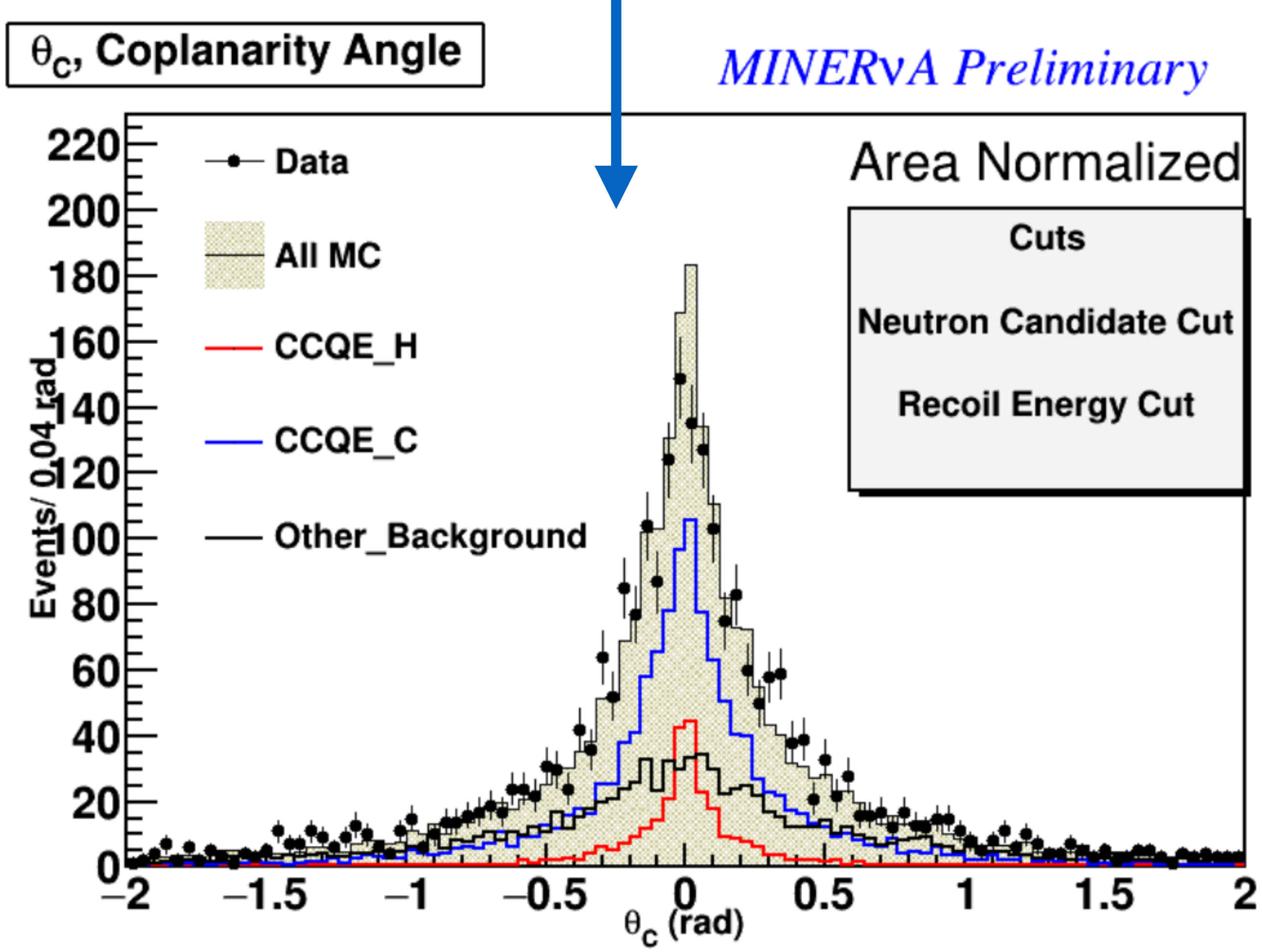
ME Analysis Progress: MINERvA sees Neutrons

- In the ME data, we are also expanding our **program of neutron measurements**:



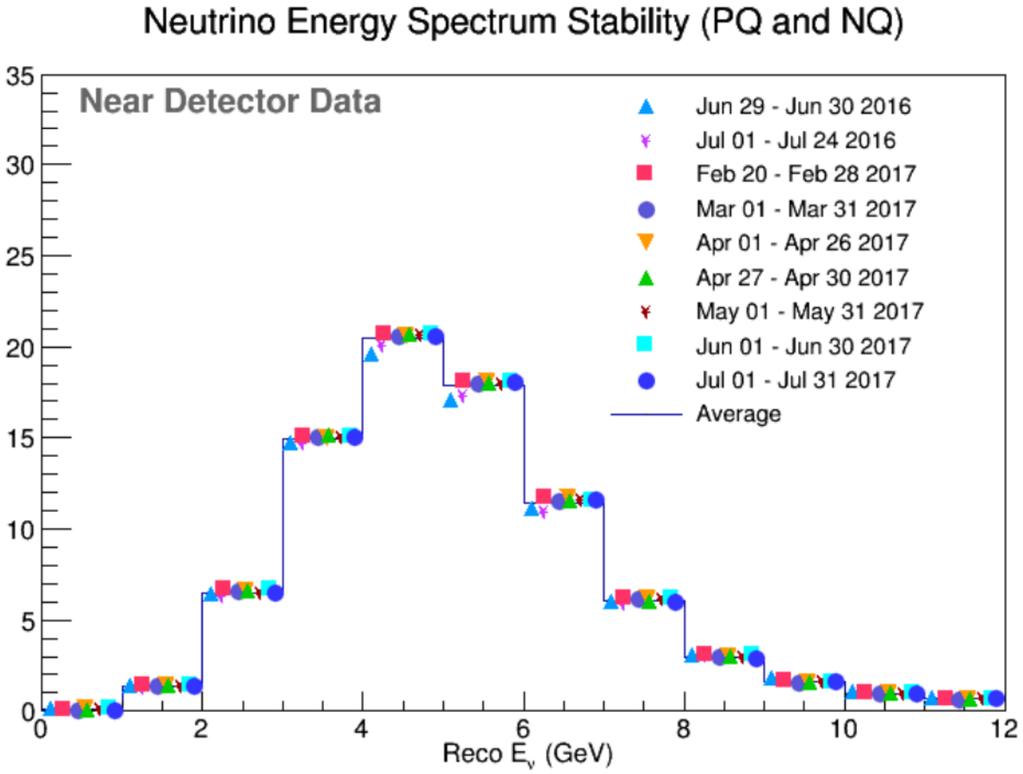
Neutron counting algorithm presented at **last week's Wine & Cheese** seminar by Rik Gran

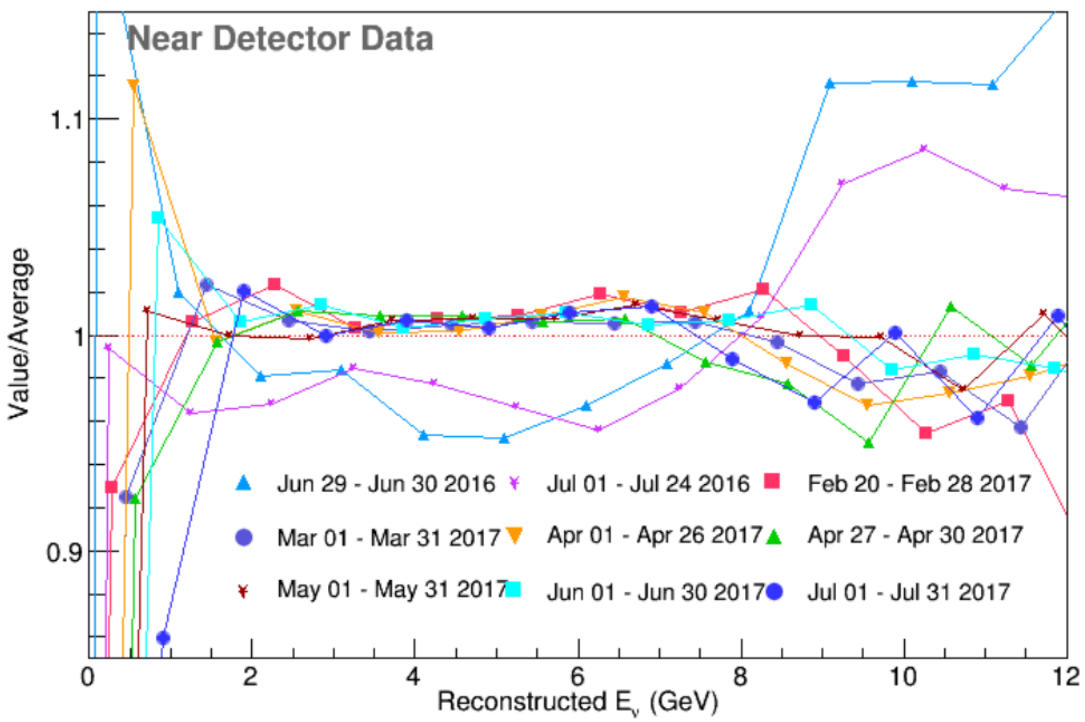
Expansion of neutron counting to **angle measurement in ME** antineutrino quasi-elastic data



MINERvA/MINOS as NuMI Beam Monitor

- MINERvA continues to operate MINOS as a NuMI Beam Monitor





- On axis detectors are **excellent monitors of stability** (or lack thereof) of the neutrino beamline
- **Low-nu standard candle distribution** in MINERvA requires ~1e20 exposure (more in antineutrino mode)
  - **Collaboration would be willing to collect and analyze** that data if requested in the future, to understand impact of e.g. new targets

Fermilab

Conclusions

- **MINERvA is building a large bank of cross-section data** that is being used by oscillation experiments
  - 21 physics publications so far
- ME **neutrino-mode data taking is complete**
  - 12e20 POT collected
  - Challenges related to intensity and flux have largely been addressed; production for first publications is underway now
- We are **reiterating our request for antineutrino running in 2019** to accumulate 12e20 in antineutrino mode
  - This exposure will make feasible many comparisons of antineutrino cross-sections across nuclear targets
  - Also provides access to the larger momentum transfer events that will be present at DUNE, but largely unseen by other running neutrino experiments

From the MINERvA Collaboration:

Thank You!!

MINERvA Person Power

- We take a **collaboration census** every spring
- Conclusions from this year's census:
  - We have **roughly the same FTE as we have had in past** years, spread over more people
  - More people **split time between DUNE** and MINERvA
    - A win-win for both collaborations — MINERvA provides opportunities for publications necessary to advance careers
  - But we have **added several new people and institutions**
  - Nine students currently working on neutrino ME analyses
  - Nine other students slated for antineutrino ME analyses
  - Also have a healthy group of postdocs
- **MINERvA collaborators remain enthusiastically committed to analyzing our data**

Cross Section Publication Scorecard

- Expected statistics for 12e20 antineutrino QE

Target Material	fiducial mass (kg)	1-track CCQE	neutron-tagged CCQE	high Q^2 CCQE	CC coherent pions	DIS (all targets)
C	160	30,000	2,000	260	600	3,000
Pb	729	140,000	9,000	1,200	2,500	18,000
Fe	641	120,000	8,000	1,000	2,200	18,000
Water	452	90,000	5,500	750	1,500	8,000
CH	6000	1,100,000	70,000	10,000	21,000	110,000

Cross Section Publication Scorecard

Published σ papers	PRL	PRD	PLB	Total
MINERvA	10	10	1	21
T2K	2	12		14
MiniBooNE	2	8		10
ArgoNEUT	2	3		5
SciBooNE		5		5
MINOS		3		3
NOvA				0
MicroBooNE				0

Operations Cost

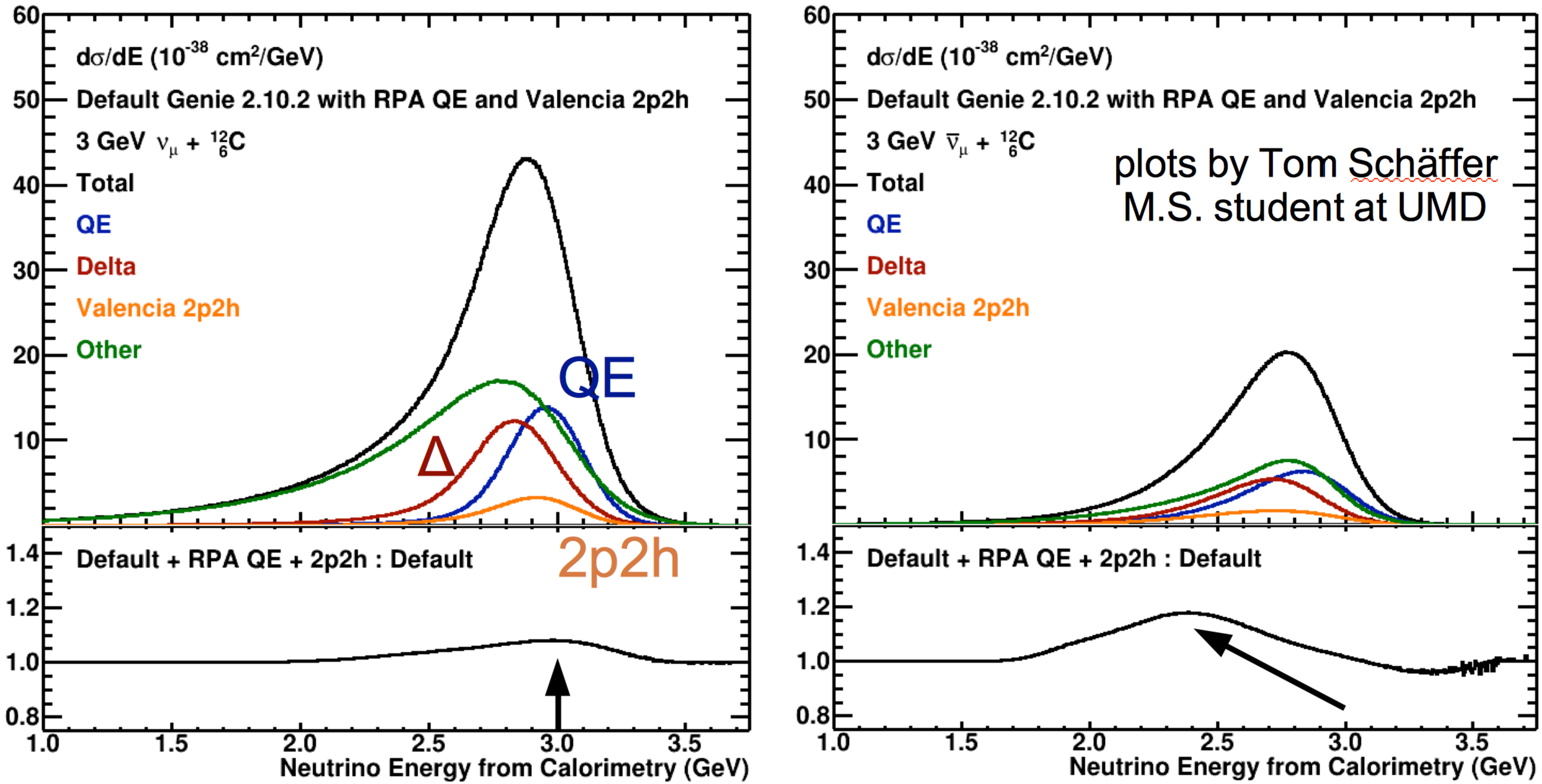
- Incremental cost of operating MINERvA is modest once NuMI is running for NOvA
- Expect costs going forward to be similar to those of FY2017 (no major purchases of He for He target or spare stock)
  - Total cost was $115k M&S
    - Dominated by costs associated with MINOS software license and electronics repair
  - 1.24 FTE were charged to MINERvA operations, spread over many people
- The collaboration has streamlined operations with no loss of detector uptime
  - Shifts staffed for 8 hours out of every 24 hour period
  - Collaboration dedicates 4.6 FTE to detector operations
    - This is about 10% of the full FTE of the collaboration
    - This includes 1 FTE of shifting

Operations Cost — Computing

- Collaboration expends 2.6 FTE on computing
  - This includes “keepup" processing for MINERvA and MINOS, offline production and software releases
  - Only keepup (0.5 FTE) is associate with detector operations

- Computing operations from SCD:
  - $42k on media and $136k on CPU (16 million CPU hours)
    - These costs are dominated by existing neutrino-mode sample; additional cost associated with FY2019 antineutrino data would be minimal
  - SCD expends 1.72 FTE on MINERvA computing operations
    - Spread over many people working on software development, computing operations, and computing facilities

Cross Sections Inform Neutrino Energy Resolution



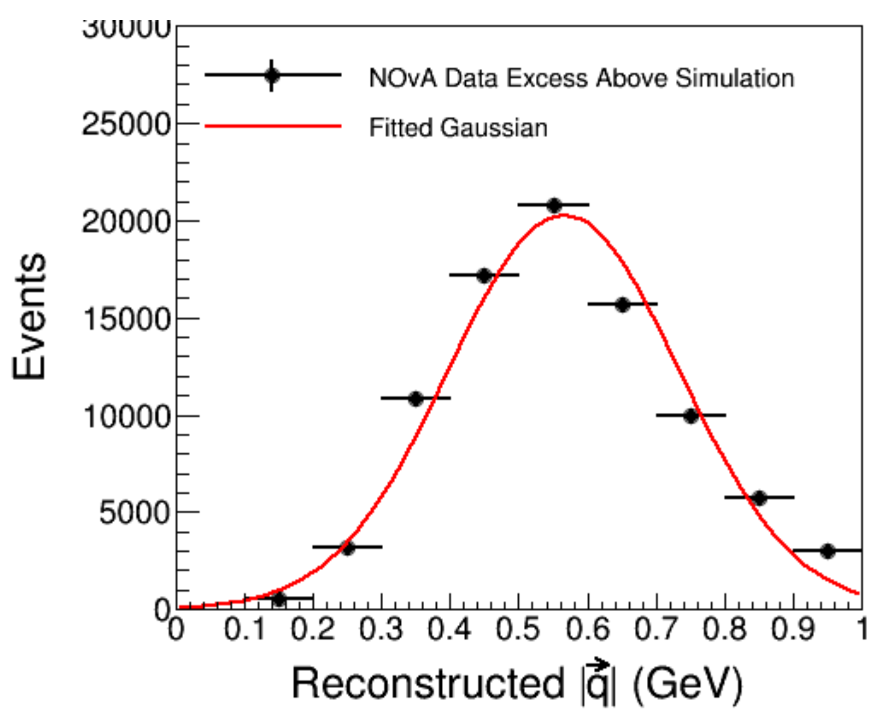
Changing cross section models distorts neutrino energy resolution, differently for neutrinos and antineutrinos -> fake CP violation, degrades sensitivity

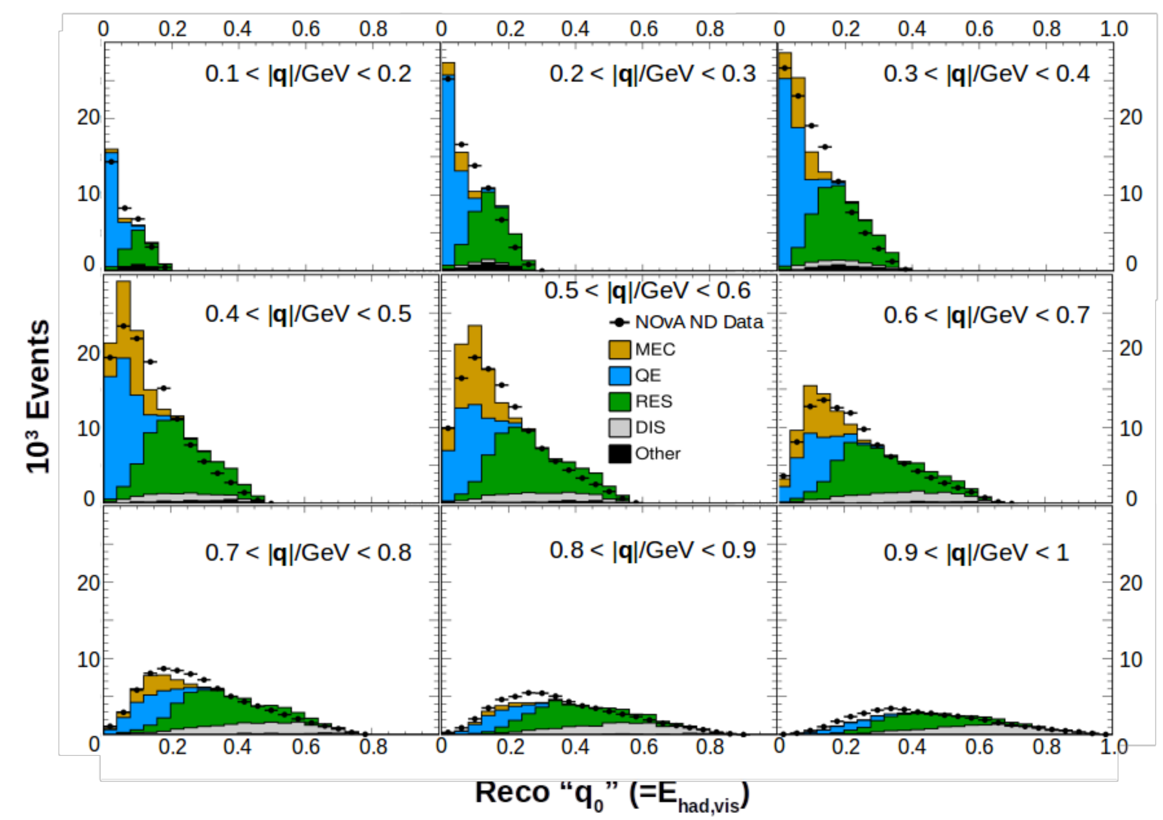
NOvA's Adaptation of Our Low Recoil Analysis

- NOvA is doing something very similar as part of its oscillation analysis evaluation of systematics

Second analyses (2016):

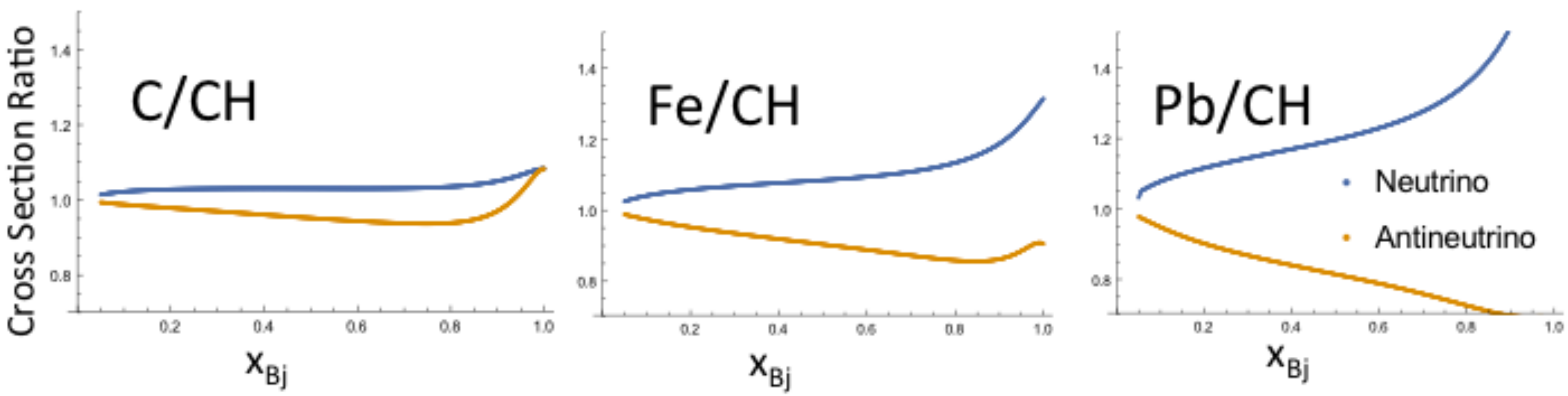
- Dytman 'empirical MEC' model is included in GENIE and used by NOvA
- Momentum transfer distribution fit to ND data; energy transfer set to match QE
- A 50% normalization uncertainty is taken





K. Bays, NuFact 2017

More on Deep Inelastic Scattering

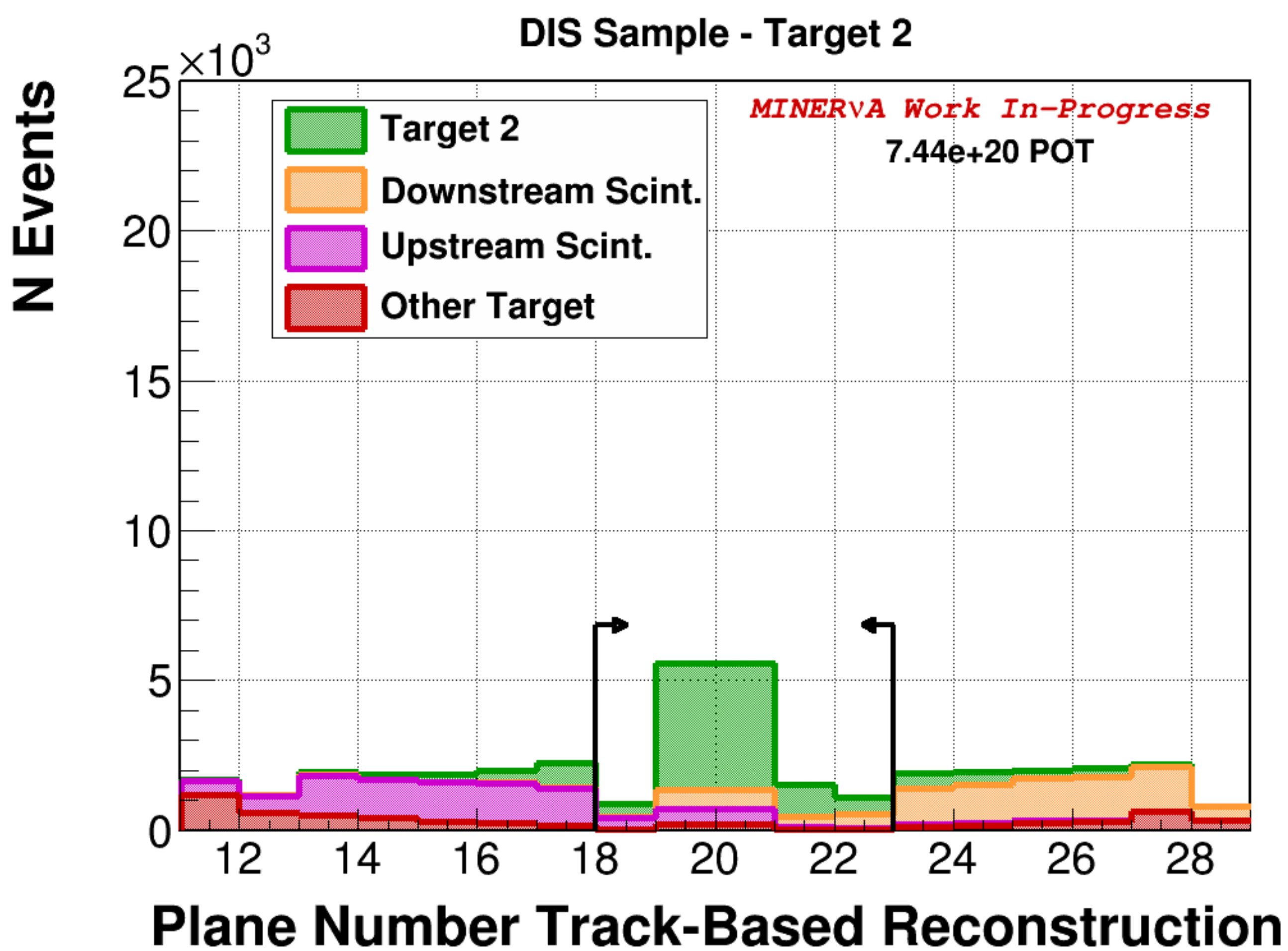


Prediction by Cloet of DIS ratios for Neutrino and Antineutrino

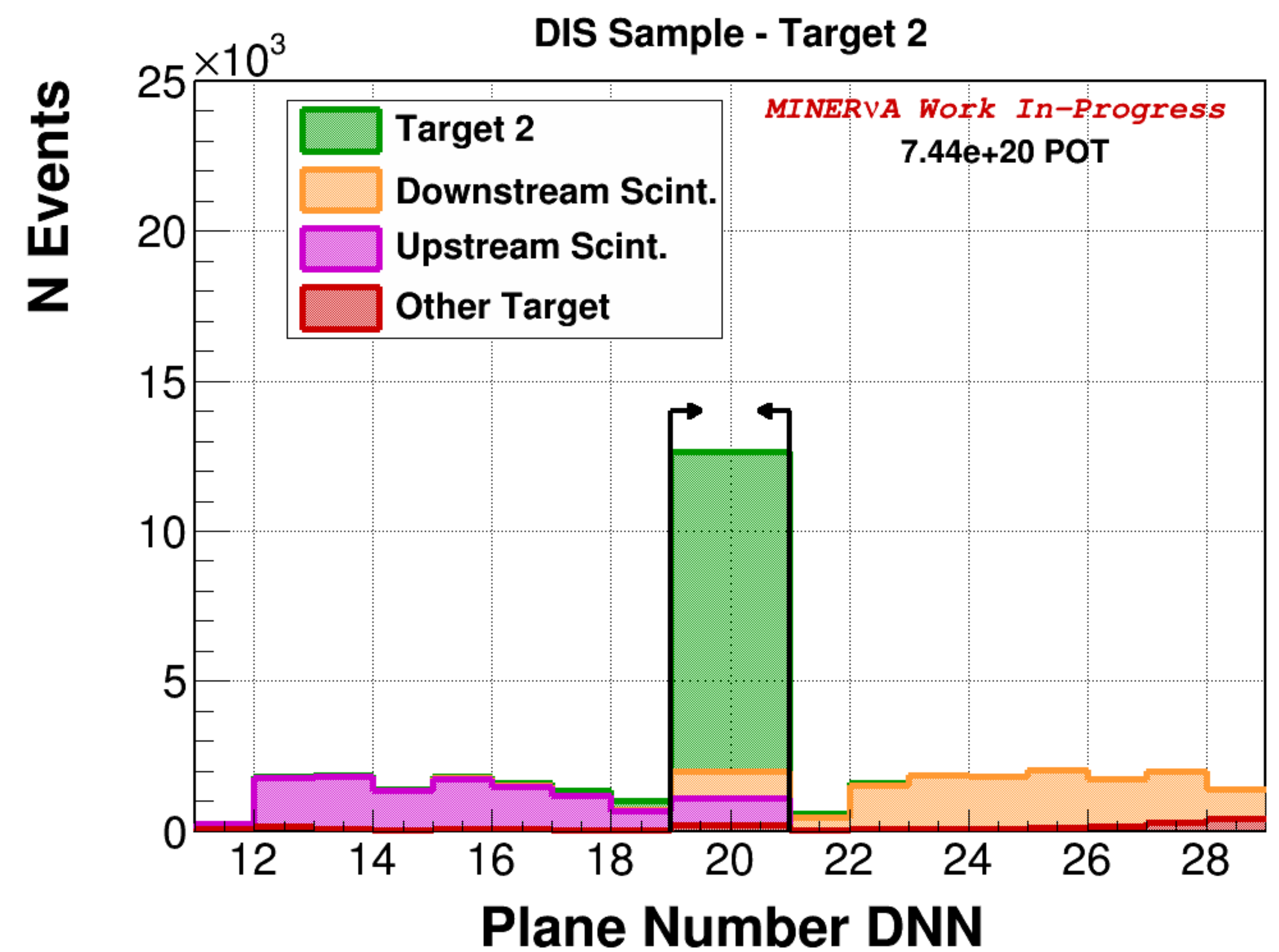
Need few percent precision in statistical uncertainty to clearly see differences at low X

Machine Learning for ME

- Machine learning yields big **increases in signal and decreases in background** for neutrino deep inelastic scattering:



Track Based



Machine Learning