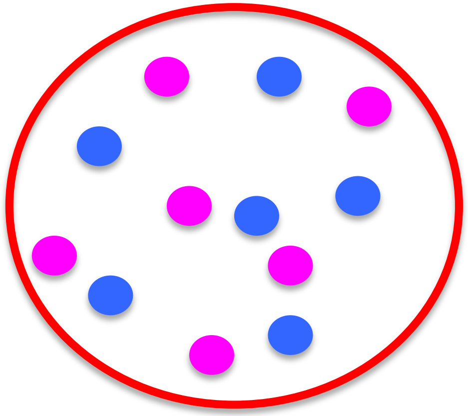
Overview of Neutrino-Nucleus Interactions



Deborah Harris

NNN'19

November 7, 2019

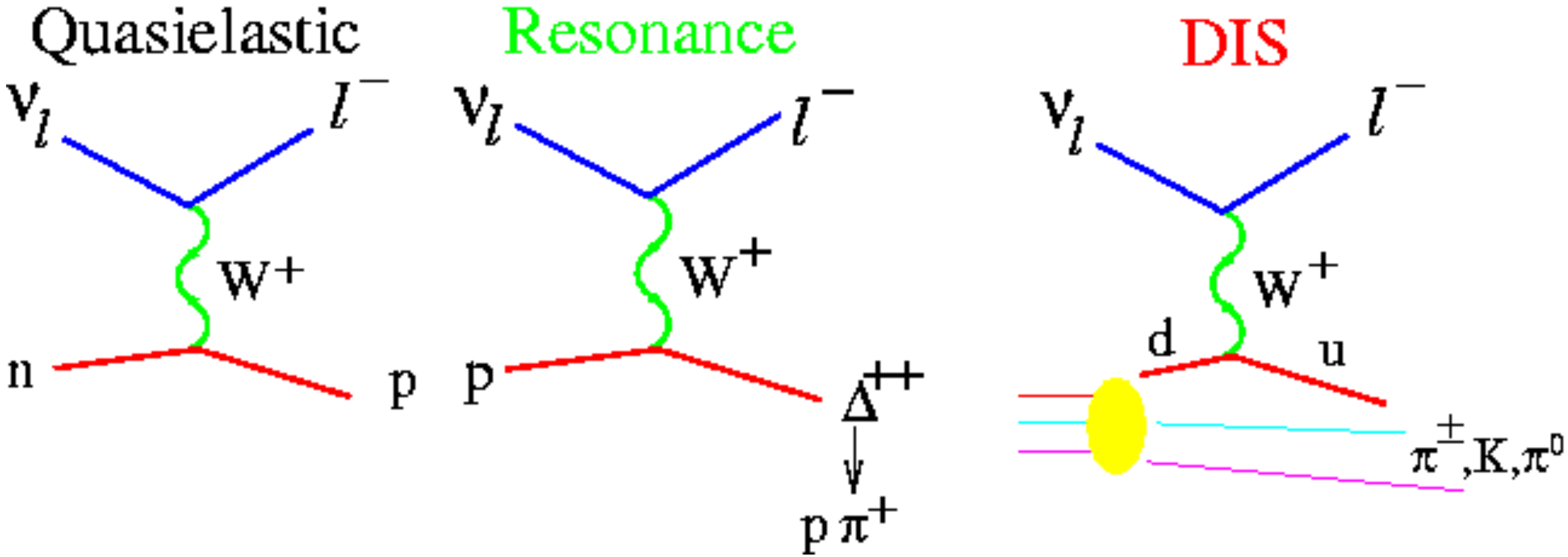
Medellin, Colombia

Outline

- Neutrino Interactions on nuclei in Theory
  - The nucleus is a scary place…
- Neutrino Interactions on nuclei in Practice
  - We have some very sensitive detectors to come to the rescue
- A few intriguing results
  - Looking at nuclear effects in the transverse plane
  - Looking at nuclear effects by energy and momentum transfer space
  - Neutral Current interactions (γ production, coherent π^0 production)
  - Caveat: some of the newest Neutrino Interaction results not shown here
    - Please see talks by Pickering, McFarland, Prince for the big news!
- Lessons we are learning now

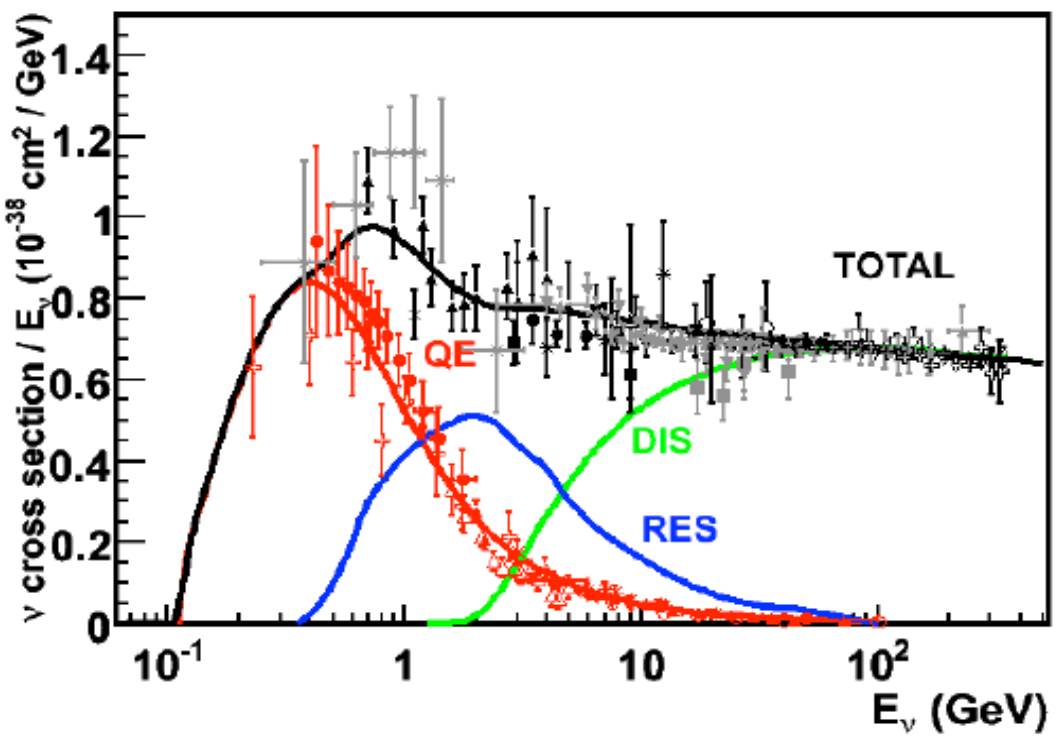
Neutrino Interactions on NucleONS (at a few GeV)

- Optics analogy: the wavelength of your probe determines what you can see
- High energy neutrinos can transfer more momentum, which means they can see smaller structure (quarks)



Interactions and Neutrino Fluxes

- The more energy a neutrino has, the higher the range of energy transfer to the nucleus



Formaggio and Zeller, Rev Mod Phys.84.1307

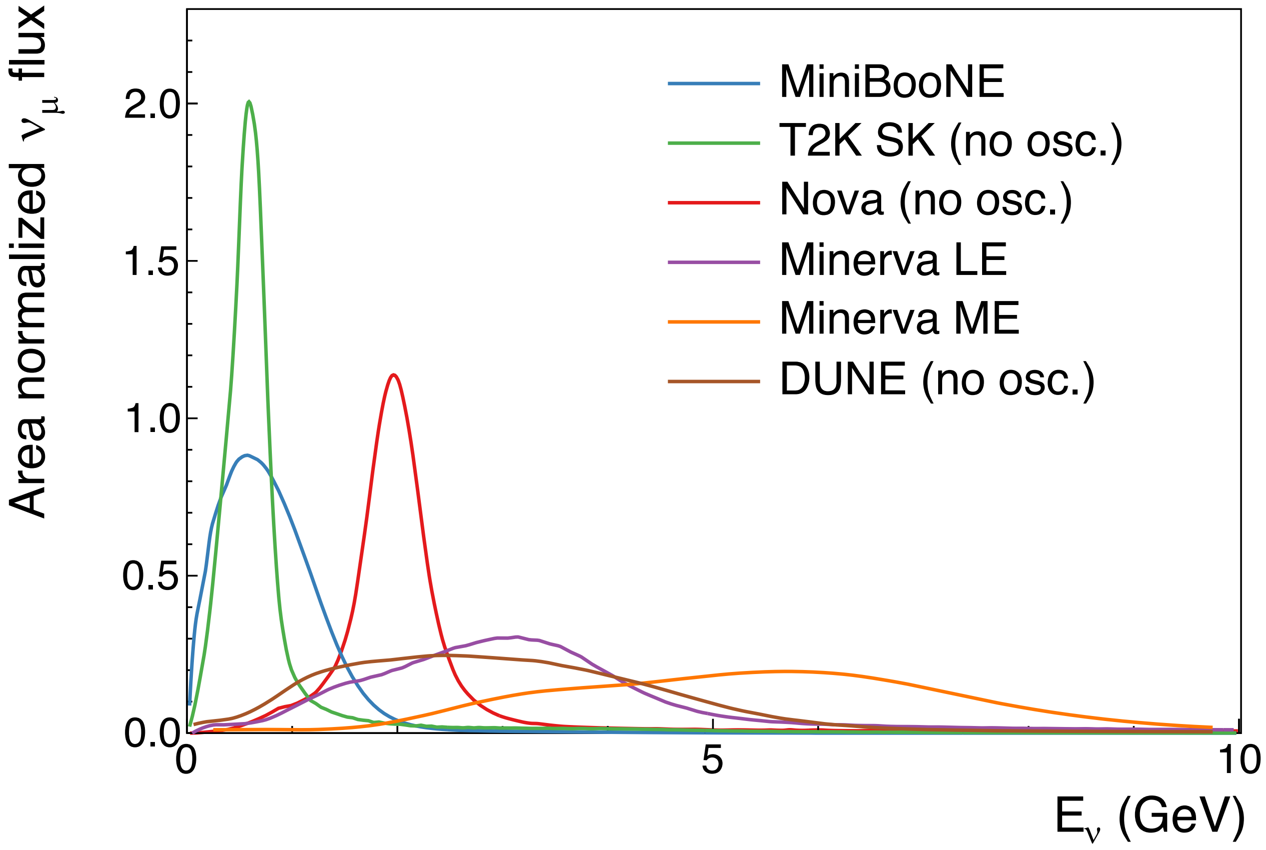
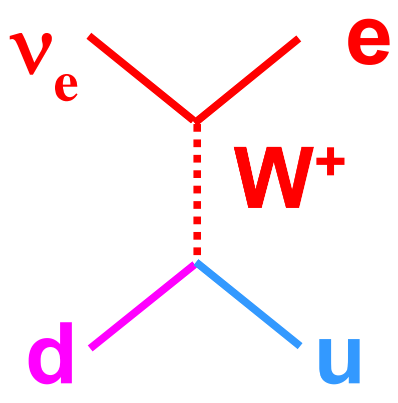
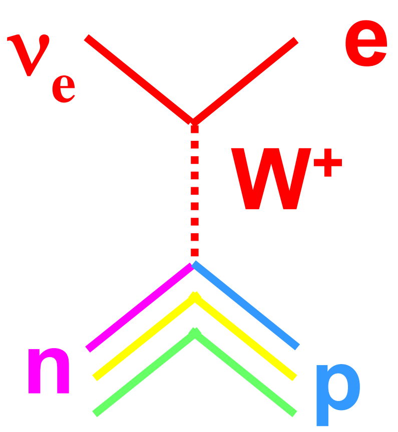


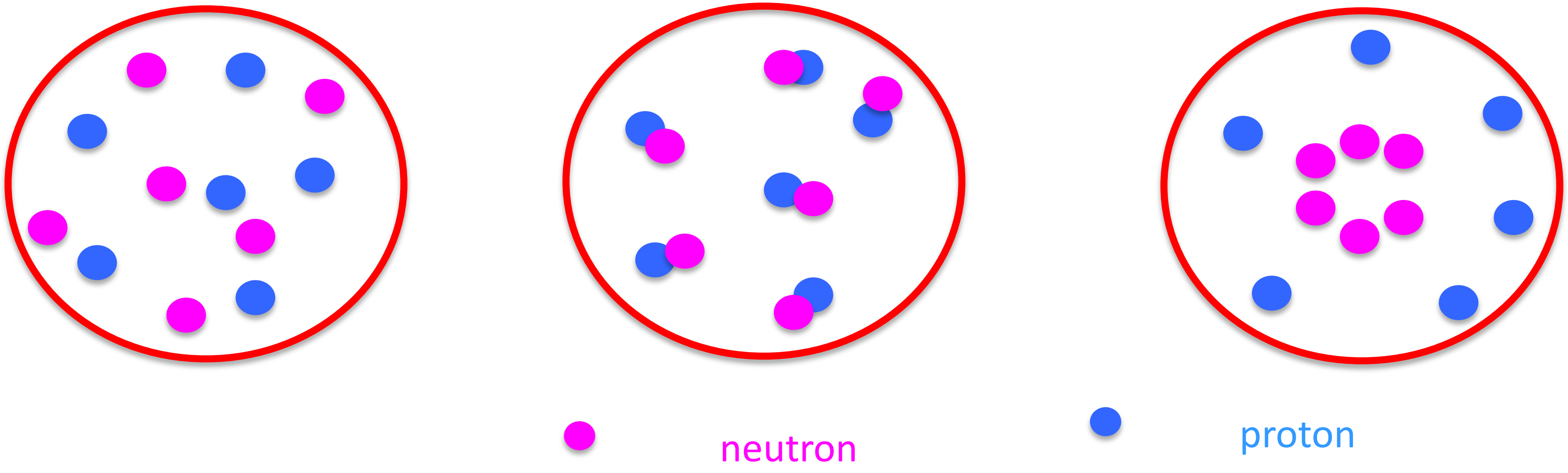
Fig. courtesy L. Fields

Neutrino Interactions on NUCLEI



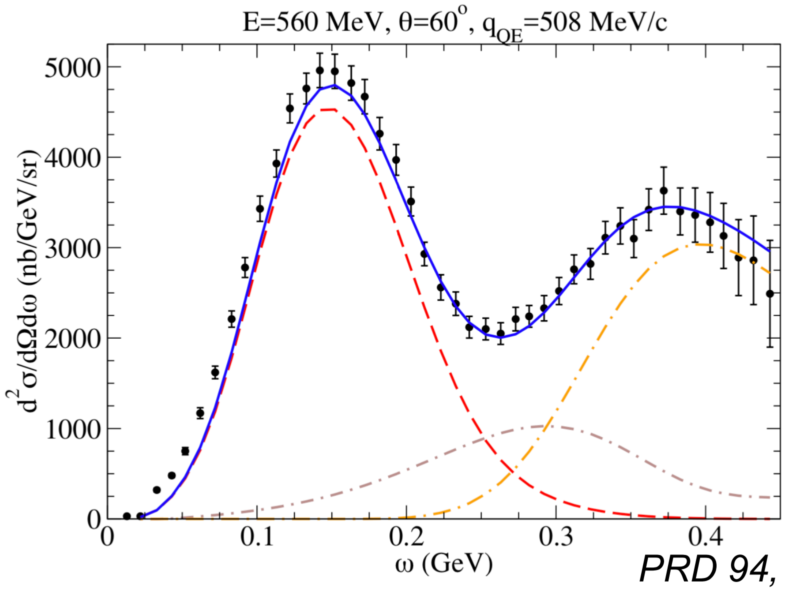
- Just one diagram shown, but…for all interactions on nucleons:
  - The quarks are in a proton or neutron
  - The protons and neutrons are inside a nucleus
- What is the nucleus like?



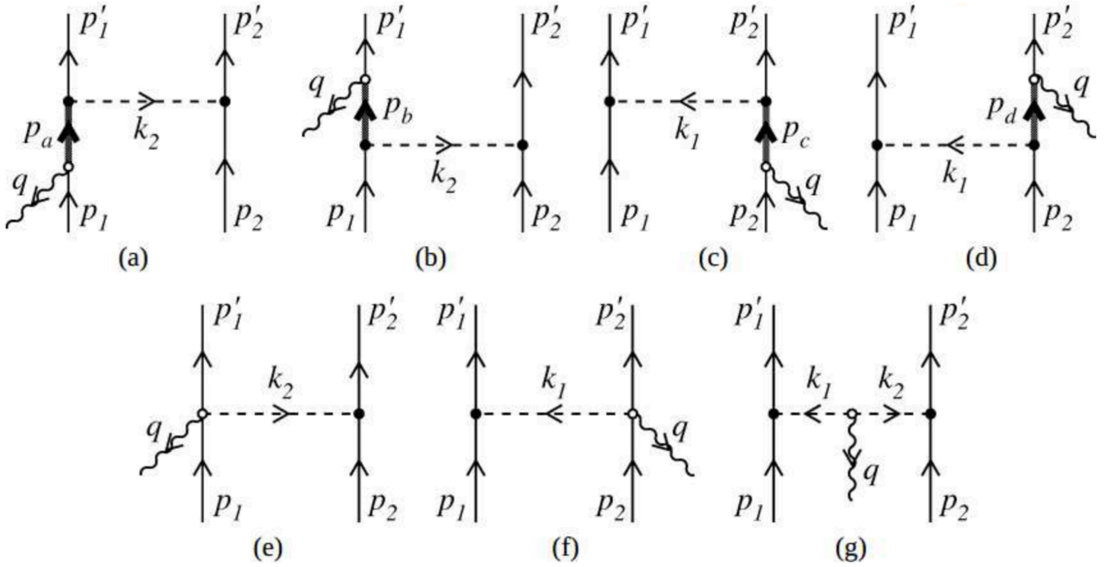


Other processes available on nuclei

- 2-particle 2-hole interactions "2p2h"
  - Seen first in electron scattering
    Shows up in between energy transfers between Quasi-elastic and Resonance processes



PRD 94, 013012 (2016)



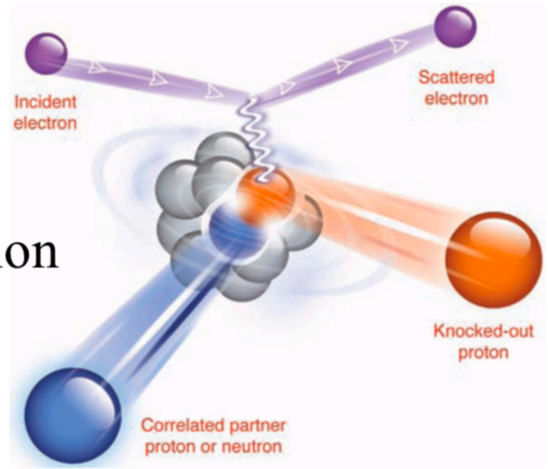
+…

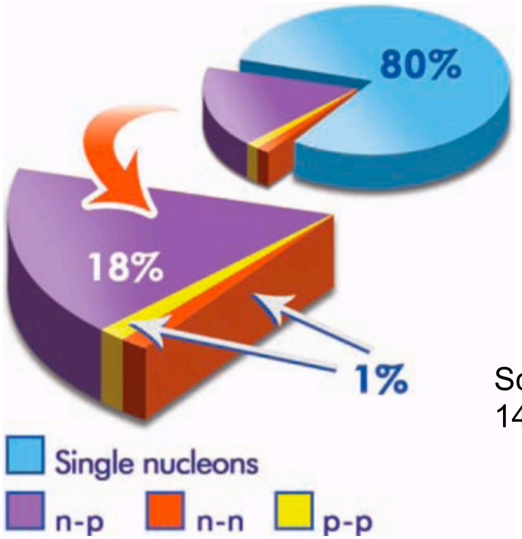
G. Megias, ECT* 2018

How does this look for neutrino scattering?

- In Neutrino scattering, instead of only one proton leaving the nucleus, there are two protons leaving the nucleus
- In antineutrino scattering, the two protons become two neutrons
- But there could be correlated nn and pp pairs in the nucleus too, e- scattering says that the correlations are 90% np pairs

initial correlation
large relative motion





Science 320 (2008) 1476-1478

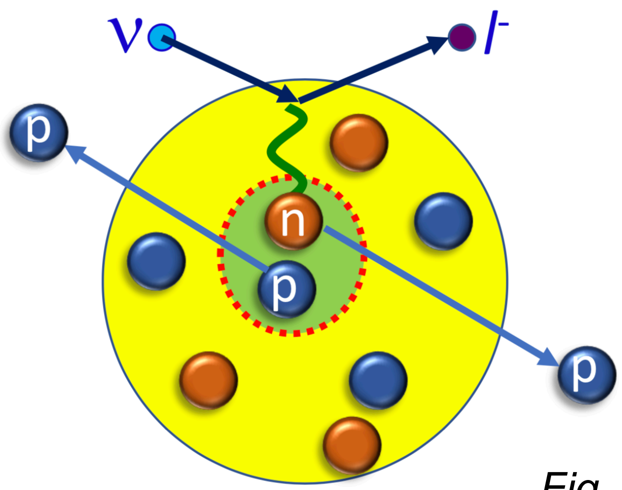
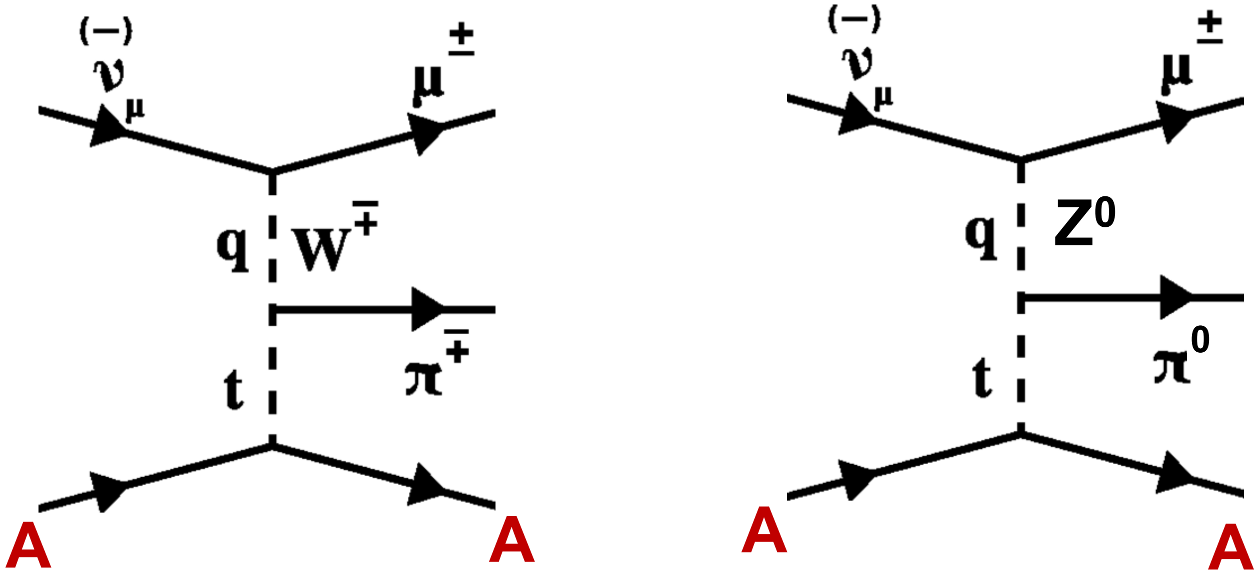


Fig. Y. Hayato

Another process that is available on nuclei

- Coherent (pion) scattering
  - Relatively rare process
  - NC analog is small but poorly known background for ν_e appearance
  - Signature: charged or neutral pion, very little energy transferred to the nucleus



Effects of the nucleus on the Final State

- Particles produced at the interaction point propagate through the nucleus
- Particles (esp. pions) can get absorbed completely
- Particles can undergo charge exchange and come out in a “new” state
- Particles can lose energy on their way out
- Consequence:
  - when we measure neutrino interactions, we’re only measuring whatever ”looks like” the signal process: “quasielastic-like” or “CC0π ”
  - Measurements of π^0 and π^+ have contributions from both processes

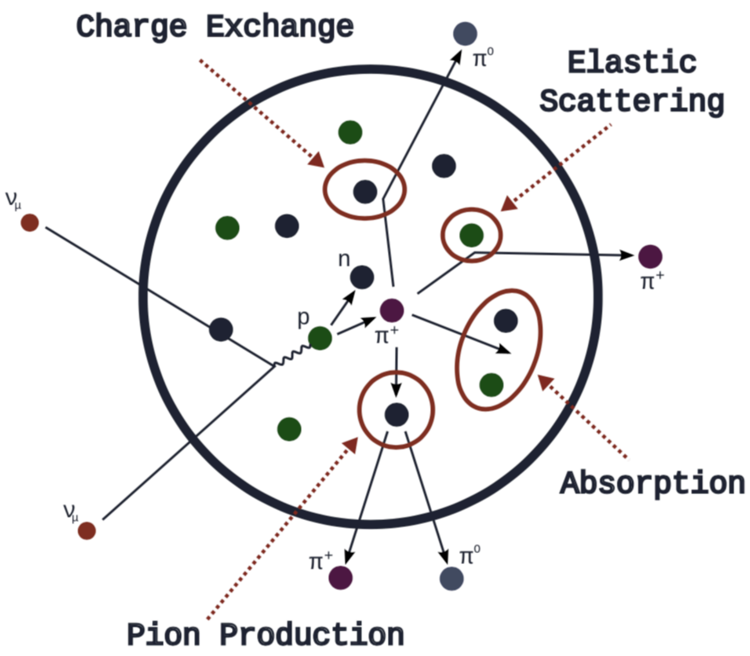
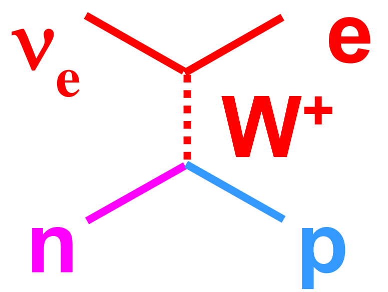
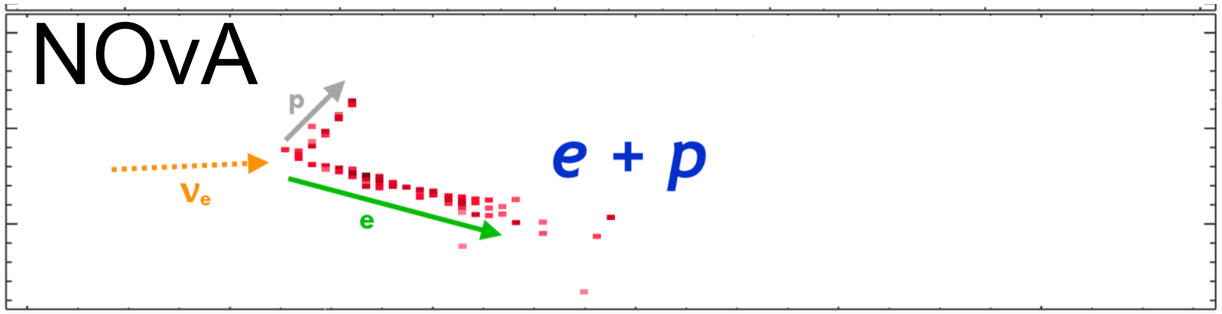


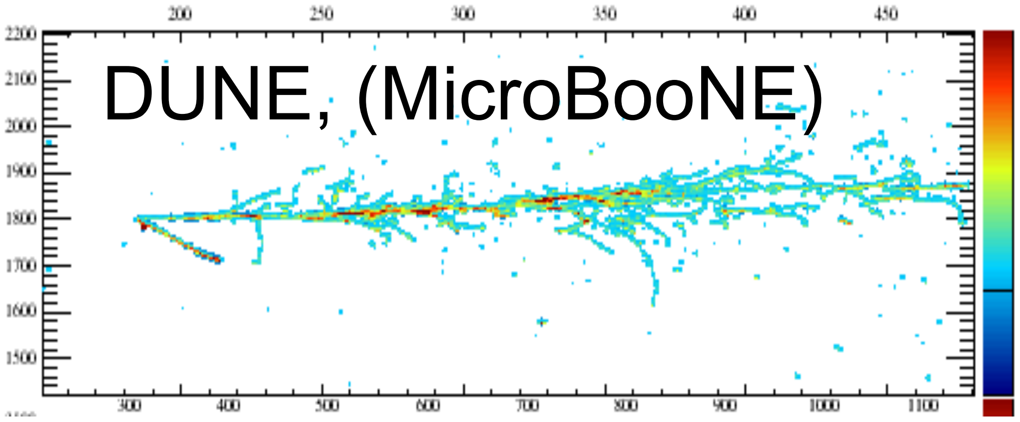
Fig: T. Golan

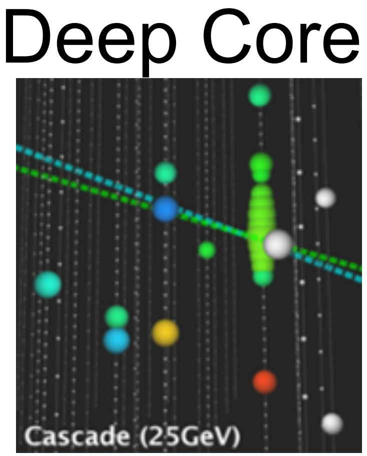
Interactions on ν-Oscillation Detectors

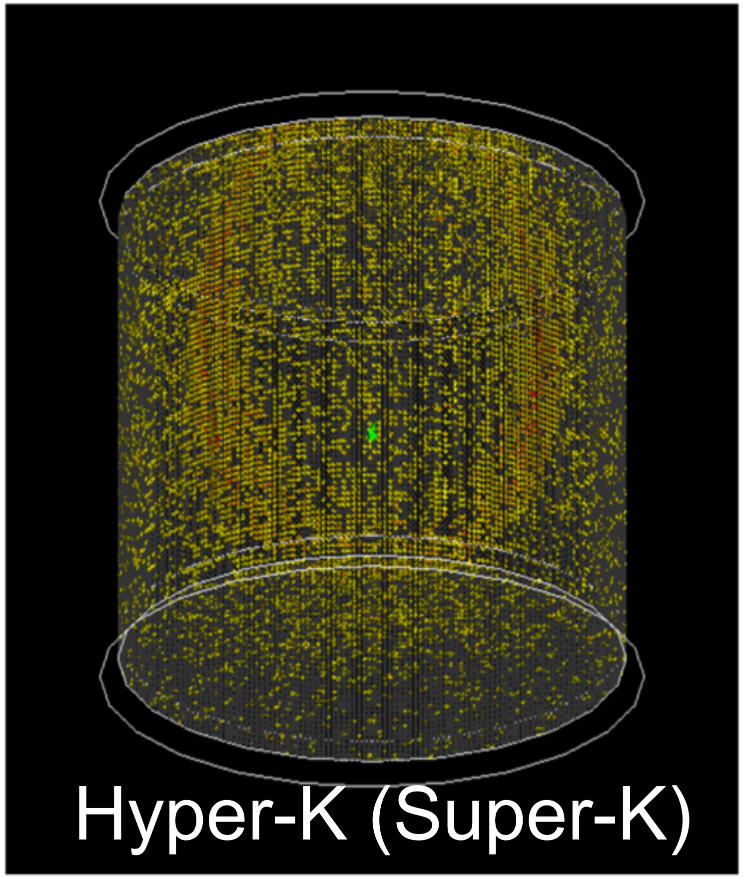


- ν_e charged current interactions, 3 very different ways
- Have to trade off between segmentation and detector mass









But beware: neutrinos can interact in a lot more complicated ways than this…

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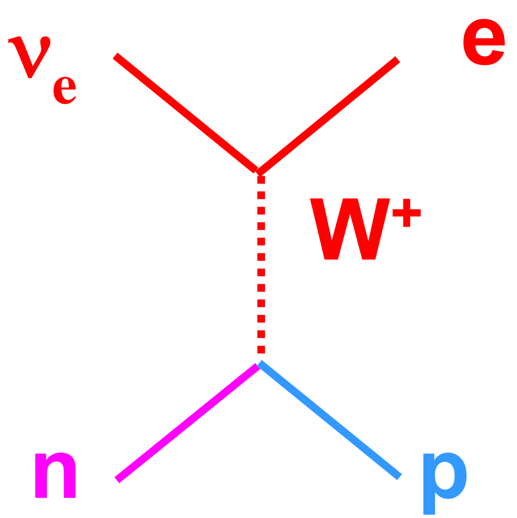
Measuring Neutrino Energy

- Should be easy, right?
  - Assume neutron at rest
  - IF you know initial direction of neutrino…
  - Final direction and energy of electron should suffice to get to the neutrino energy

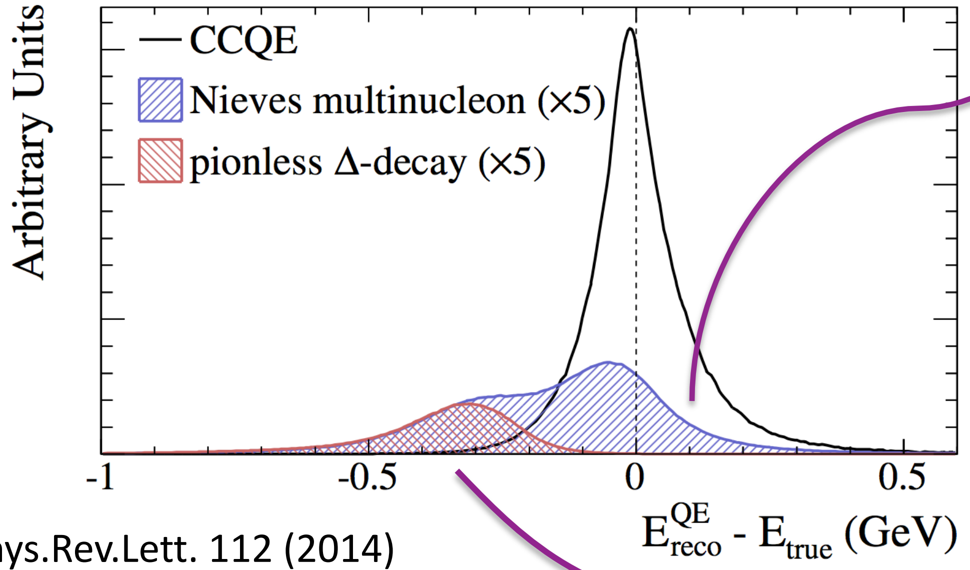


$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\mu - \left[(M_n - E_B)^2 + m_\mu^2 - M_p^2\right]}{2\left[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

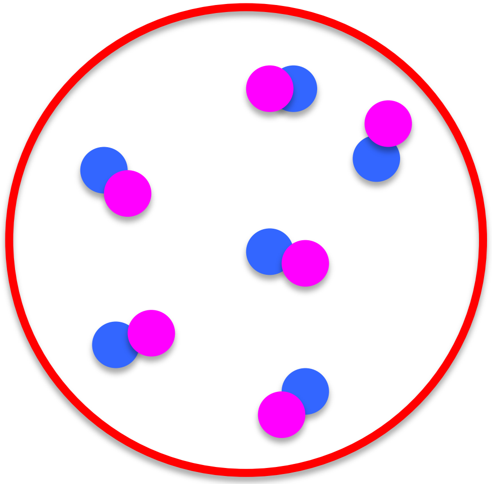
$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

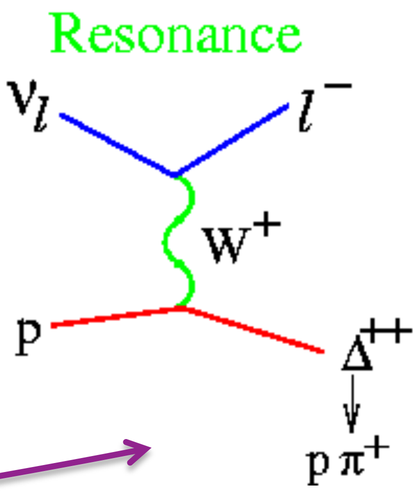
What does this mean for oscillation experiments?

- The neutrino energy you reconstruct can be biased.
- Today's experiments are already worrying about this!



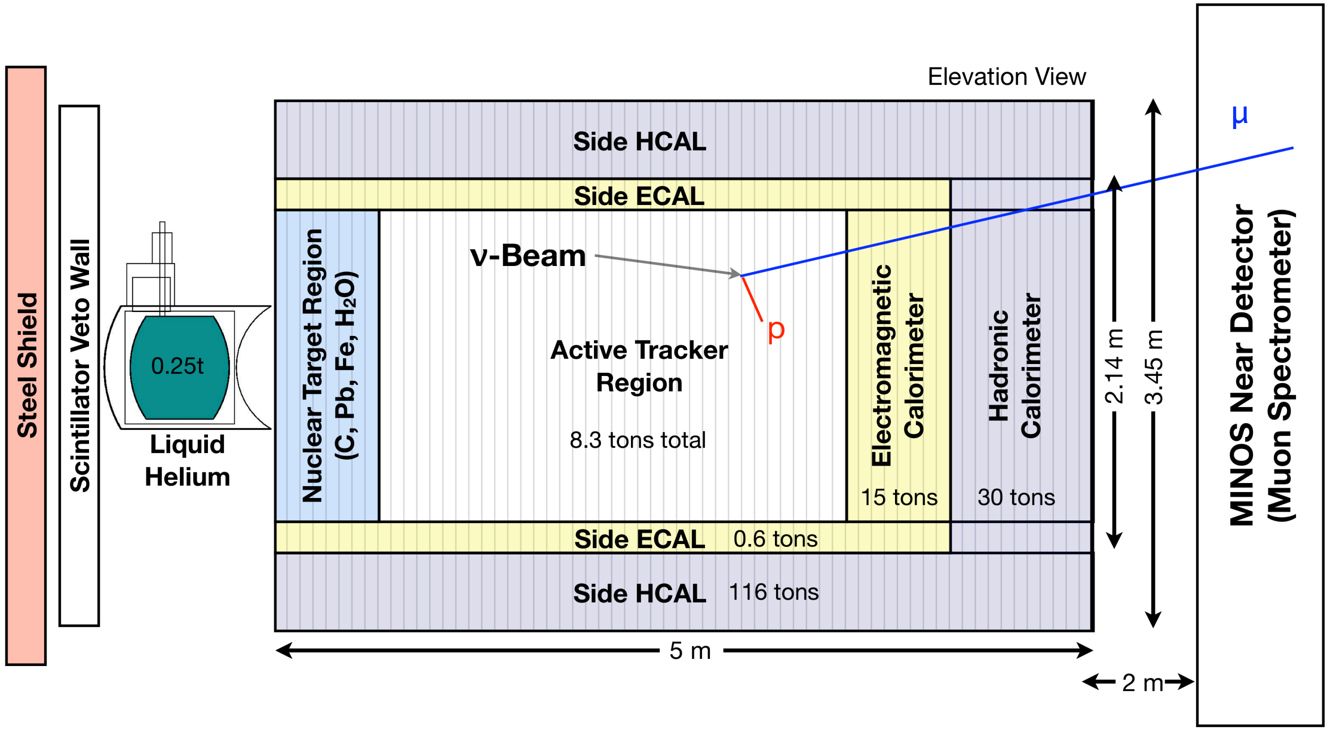
T2K, Phys.Rev.Lett. 112 (2014)



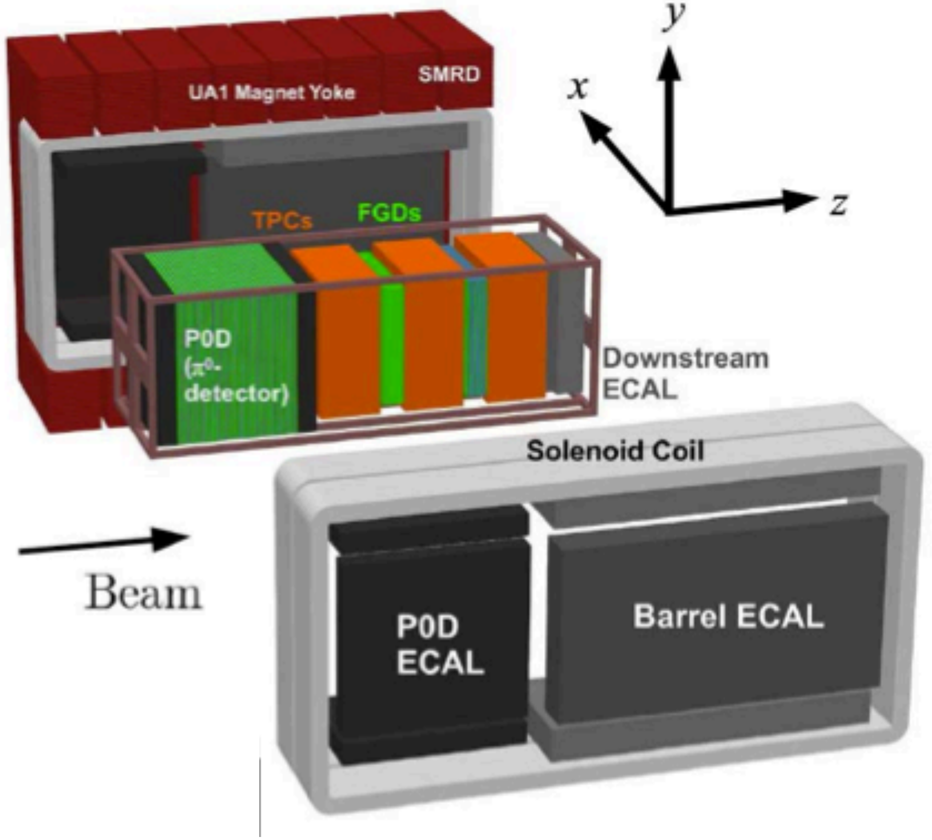


Interactions on ν cross section detectors

- Not burdened by the requirement to make ktons of detector
- MINERvA: Scintillator, μ spectrometer, nuclear targets (He, H_2O, C, Fe, Pb)



- T2K: off axis: Scintillator,/Gas TPC inside magnetized volume, water target



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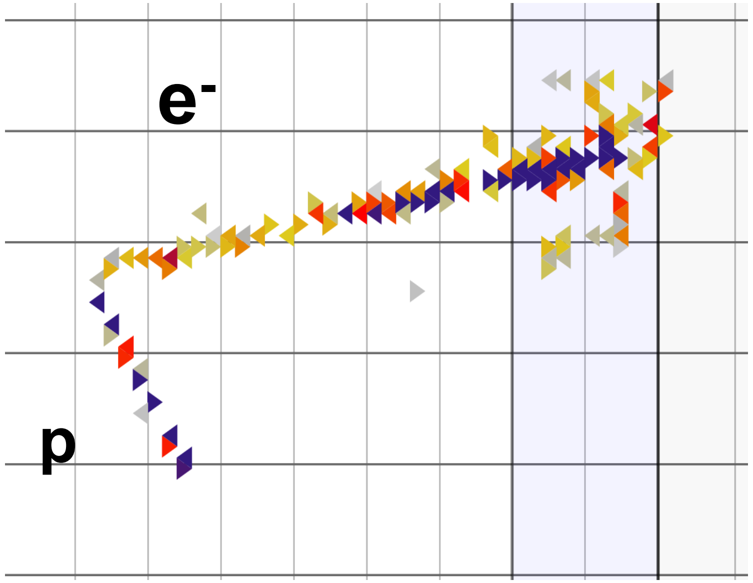

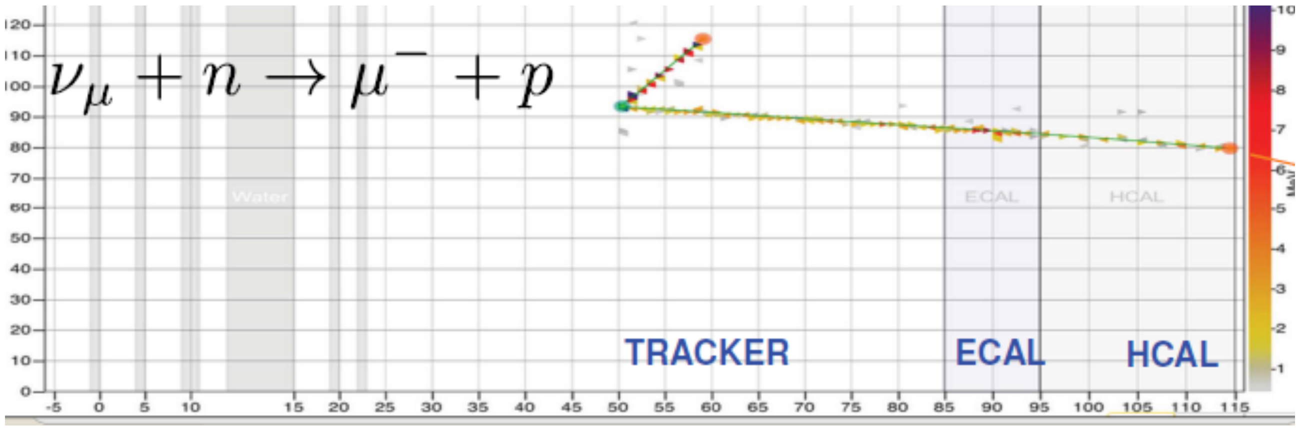

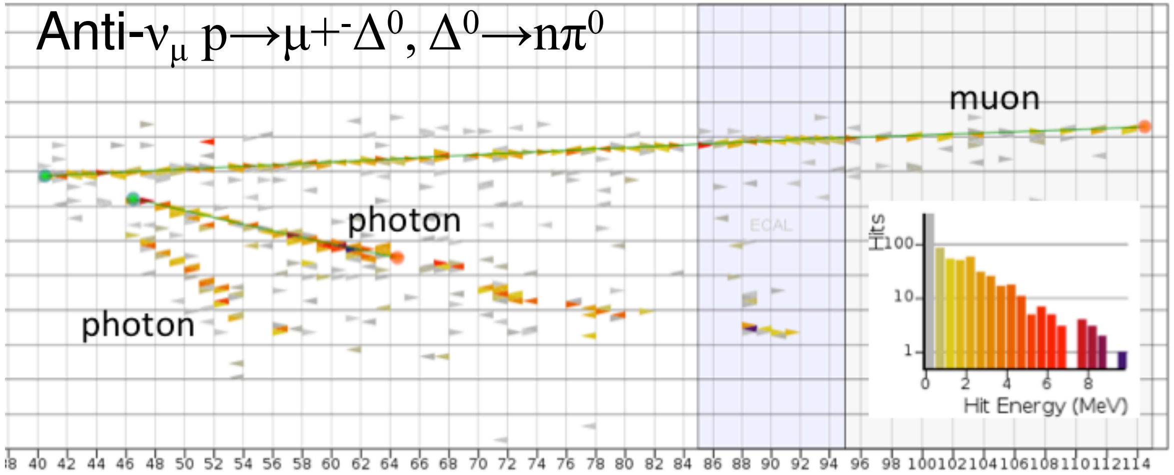

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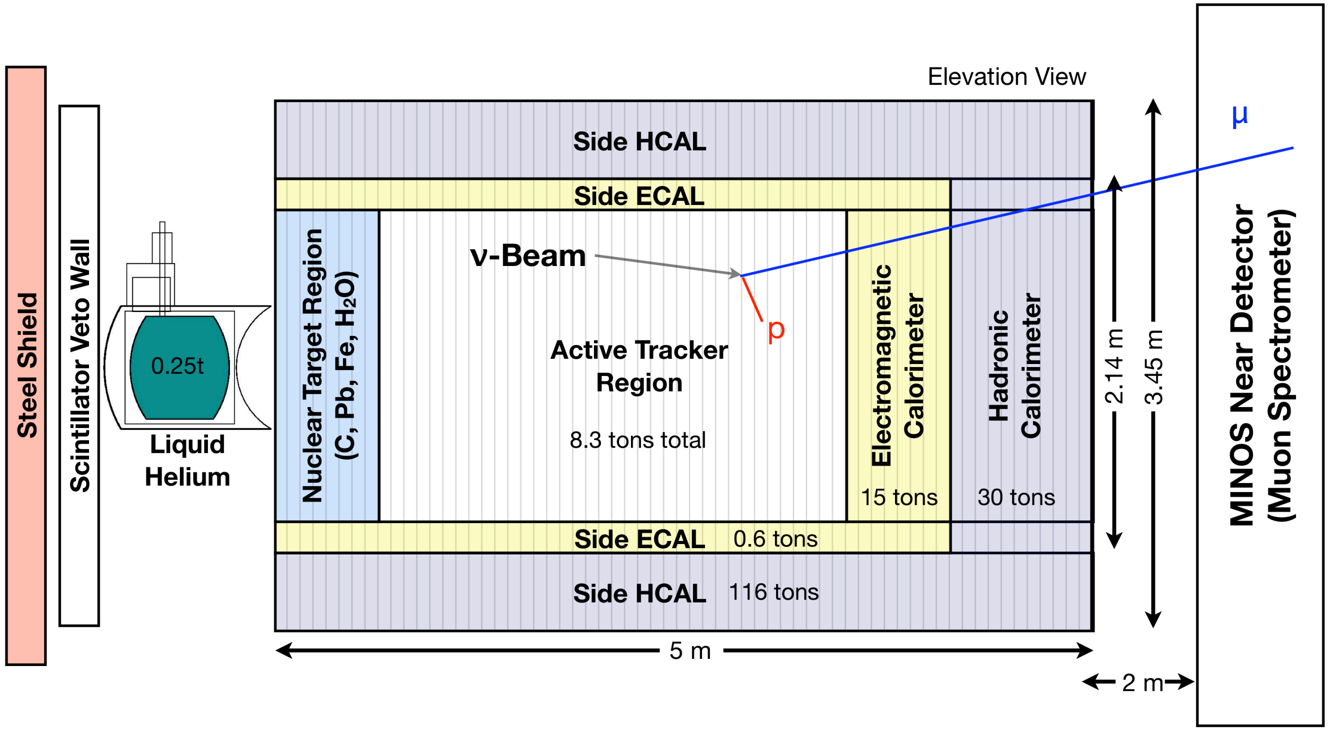

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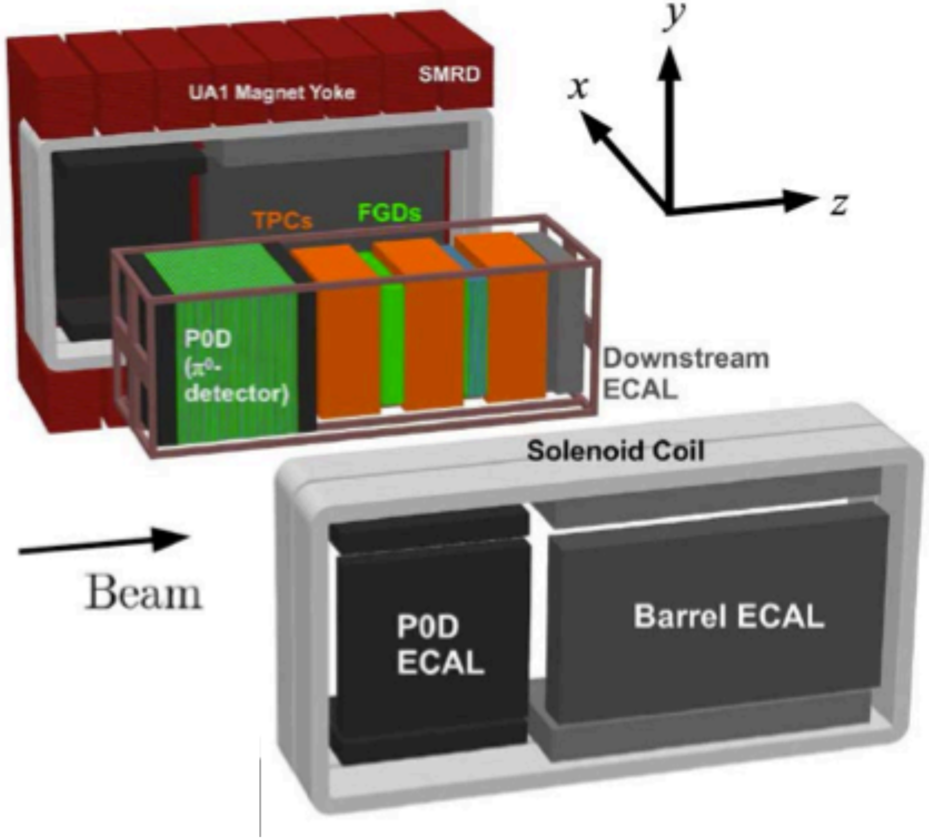

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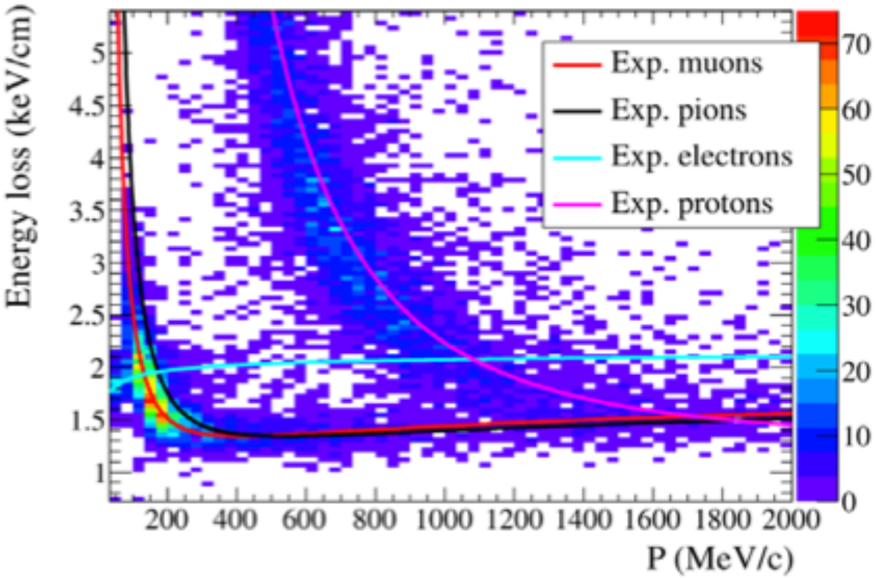
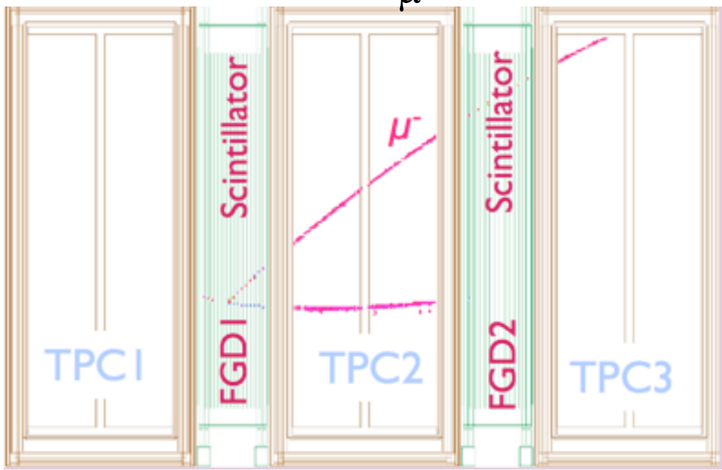
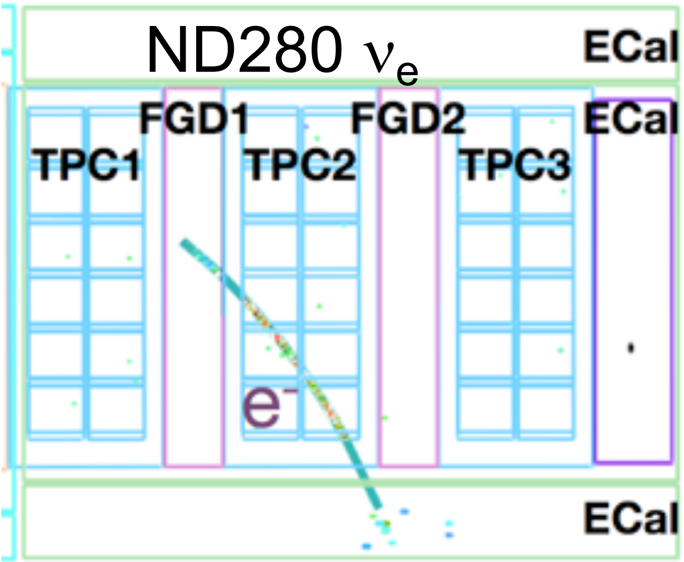


ND280 ν_μ





Not shown: T2K On Axis detector, INGRID

From Interactions to Detectors: event generators

- There is no model that describes all these channels even on a single nucleon.
- Have to piece together different models, and put them into event generators
- All of them treat the primary interaction as if it's on a nucleon (or maybe even quark if it's a DIS event)
  - Add 2p2h as a separate process
  - Add coherent interactions as a separate process (usually)
  - Reweight some channels to account for weak nuclear screening
- Then they add the propagation of the final state particles through the nucleus
- Several event generators are on the market right now

Neutrino Event Generators

- GENIE:
  - In use by NOvA, MicroBooNE, MINERvA, SBND and ICARUS, and DUNE
  - Also being tested in MINERvA, and used by T2K's near detector analyses
- NEUT
  - In use by Super-K (atmospheric neutrino analyses), T2K's far and near detectors
  - Cascade model tuned by external DUET data
- NuWro
  - PYTHIA used for hadronization in DIS
  - Follows NEUT and GENIE in many respects
- FLUKA (NUNDIS)
  - Adapting FLUKA framework to accommodate neutrino interactions
- GIBUU
  - Full cascade model for propagation through nucleus, "first principles" generator for all processes, but still has to add in coherent scattering off entire nucleus

And now a word from our sponsors

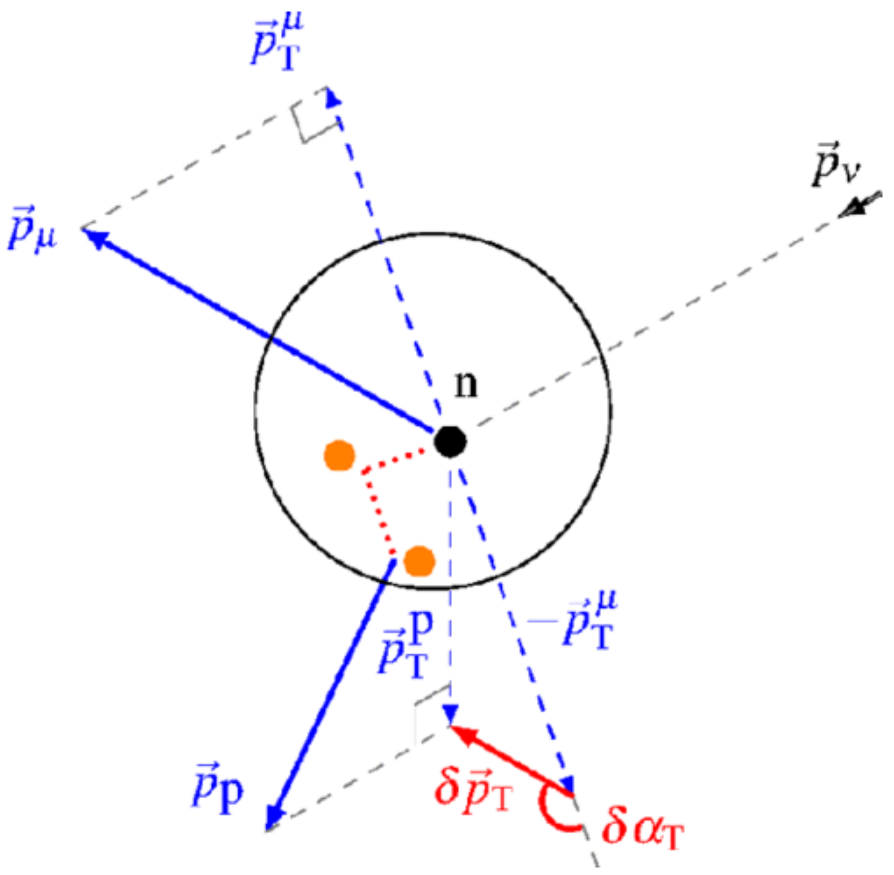
- NUISANCE: a framework for comparing different model predictions and different generators against different data sets
- Important step in being able to figure out best practices as a community!
- Authors: Luke Pickering, Patrick Stowell, Callum Wilkinson, Clarence Wret

How to understand ν interactions on nuclei:

- Try to find the best models you can
- Those models may have free parameters
- Try to make measurements of interactions that can
  - Chose between models
  - Constrain parameters in those models
- But the problem is:
  - Any one process will have effects of the initial interactions, several different (competing) nuclear effects, detector resolution
  - Models usually only cover one process, or maybe one process but as seen by neutrino and antineutrinos both
  - Need to figure out ways to isolate different channels to constrain models of specific interactions, and find new observables in those channels to separate out these different effects

One way to isolate different nuclear effects:

- What's the one thing you know about the ν's from an accelerator? Their direction
- Can calculate several things if you can measure the final state proton and muon direction:
  - Initial state neutron momentum (assume binding energy): is it really equivalent to just the Fermi momentum, or do some neutrons have a lot of initial momentum?
  - Angle between neutrino-muon plane and neutrino-proton plane (should be 180 degrees if it's a 2x2 scattering process
  - Total Transverse momentum change (δp_t)

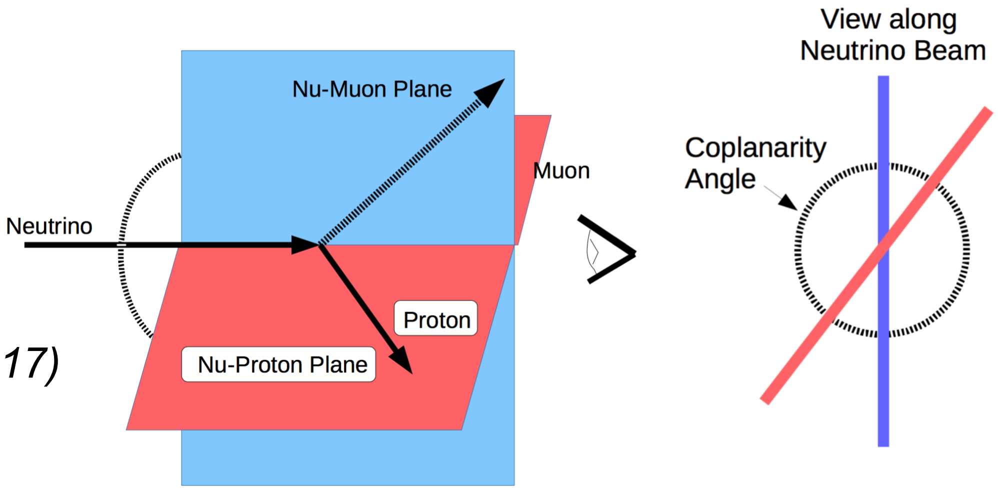


X.G. Lu et al, Phys.Rev.Lett. 121 (2018) no.2, 022504

Nuclear effects change transverse variables

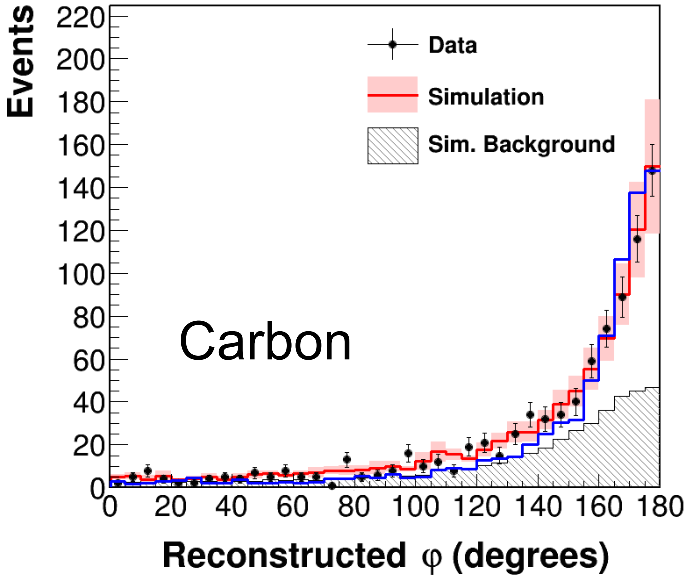
MINERvA's direct evidence:
compare events with proton+μ+no π across 3 different nuclei

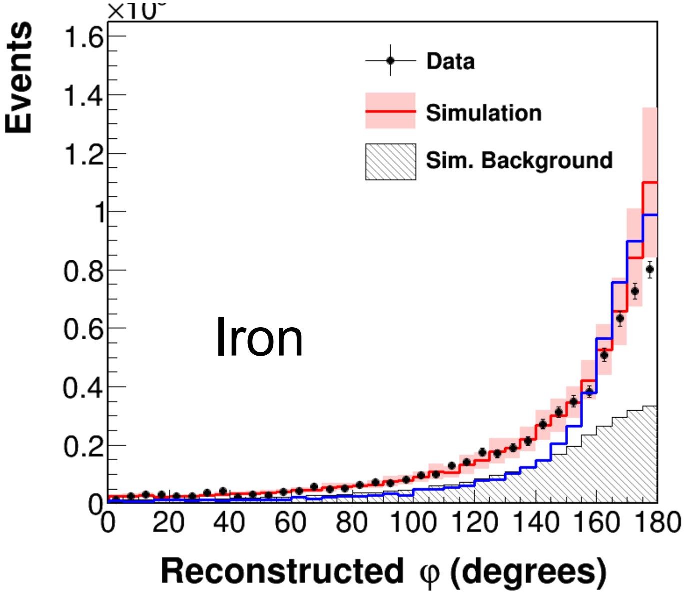
*M. Betancourt et al, PRL **119**, 082001 (2017)*

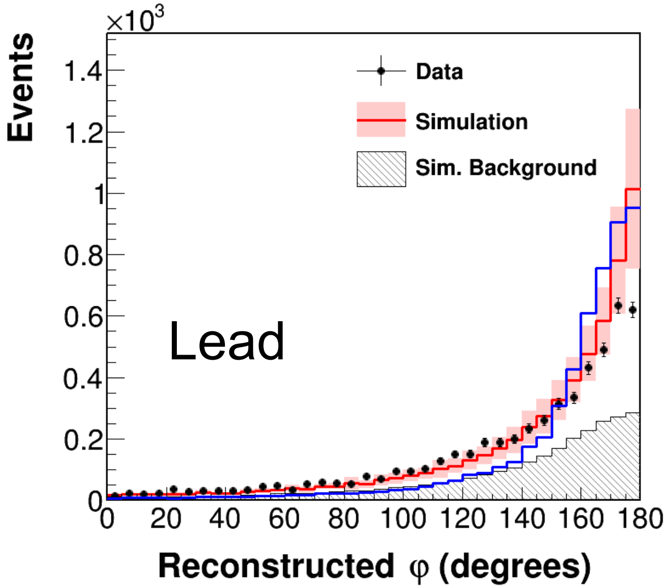


ϕ: Coplanarity

180º for proton at rest and 2-body interaction and no final state interactions







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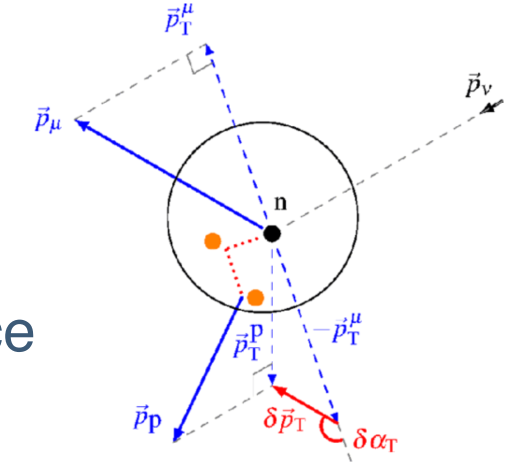
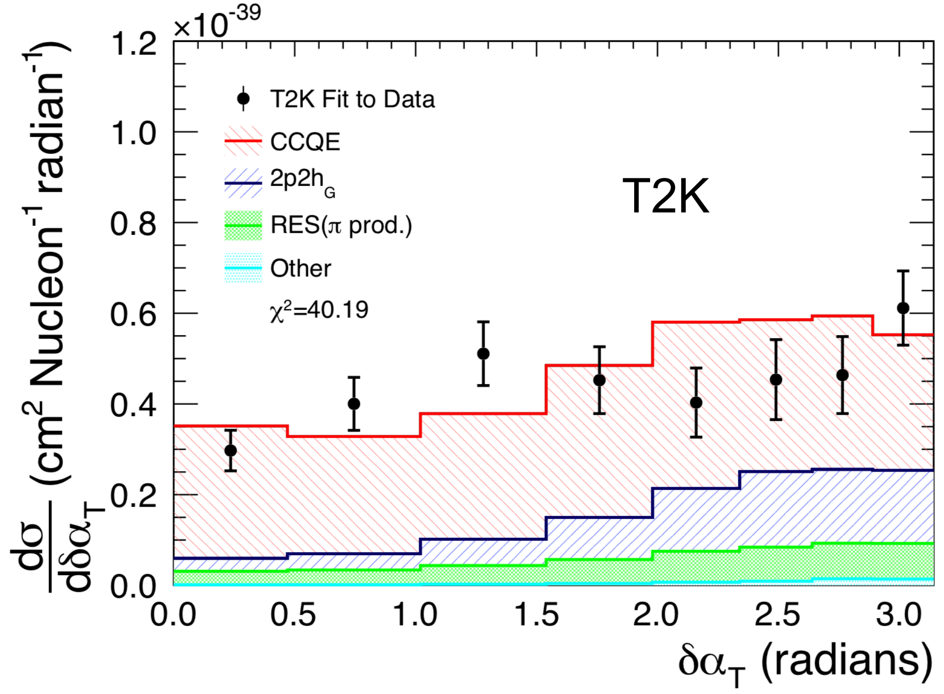
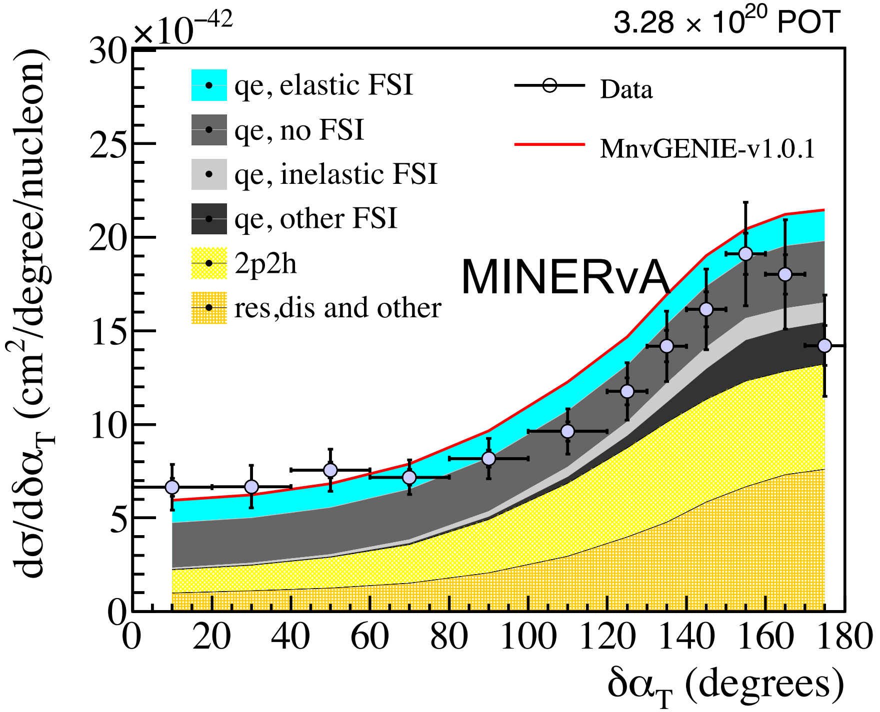
Transverse variables vs energy…

- Compare transverse variables across different experiments.
- T2K: lower energy neutrinos than MINERvA, so they see fewer produce
- They also see fewer "stuck" (absorbed) pions





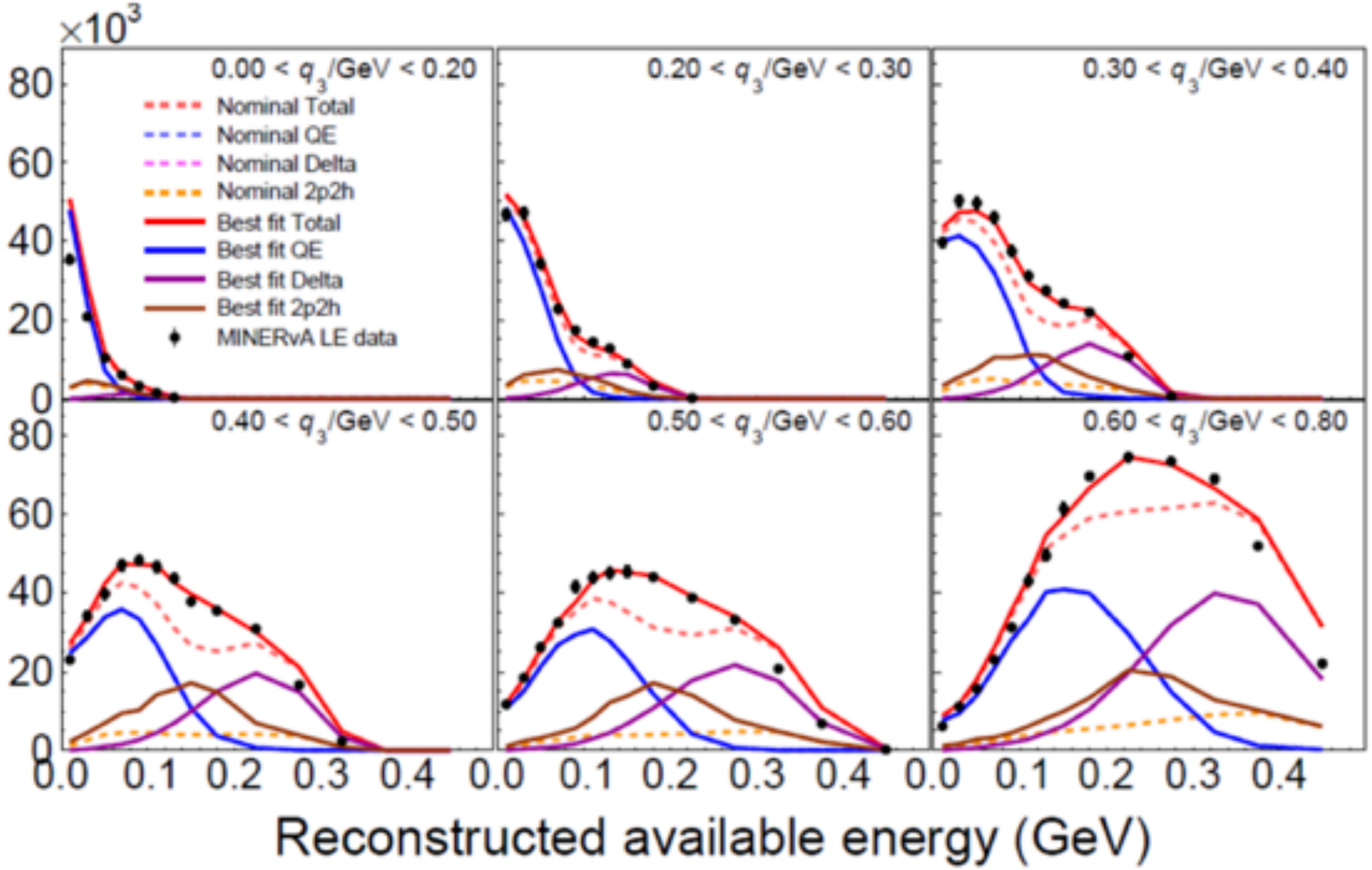


K. Abe et al, Phys.Rev. D98 (2018) no.3, 032003

X.G. Lu et al, Phys.Rev.Lett. 121 (2018) no.2, 022504

Another way to untangle nuclear effects

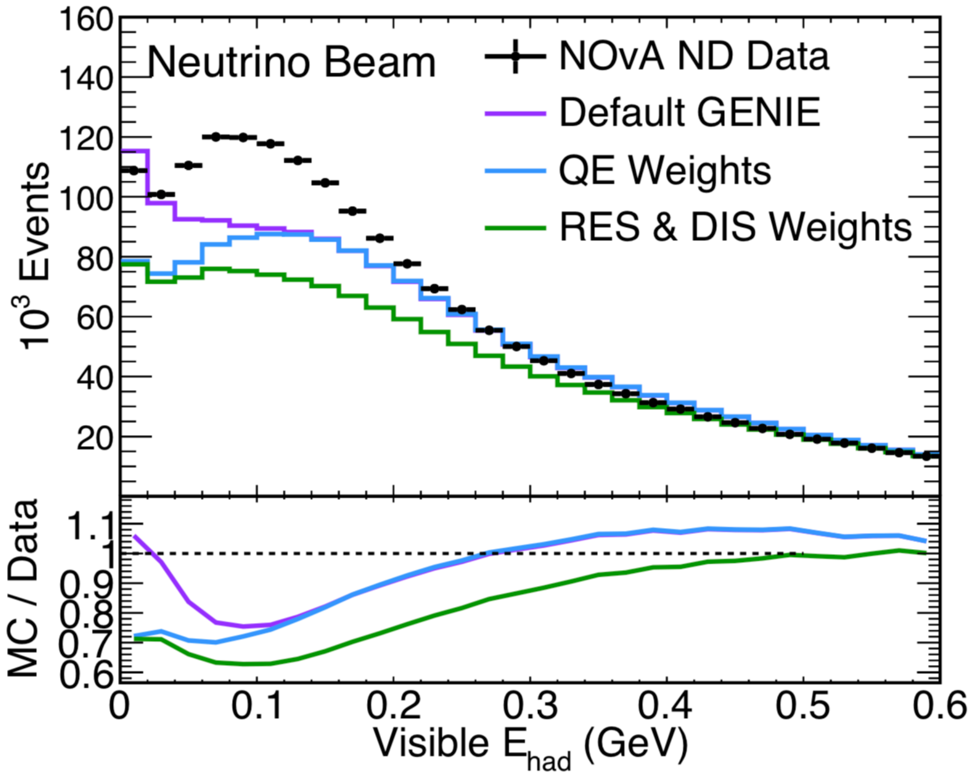
- MINERvA: Looking at momentum transfer in momentum (q_3) versus transferred energy (q_0)
- "Available energy": purely hadronic variable, but direction of energy transfer comes from muon kinematics and hadron kinematics
- Added strength to model in specific q_0q_3 space, checked model in in antineutrino mode: works!

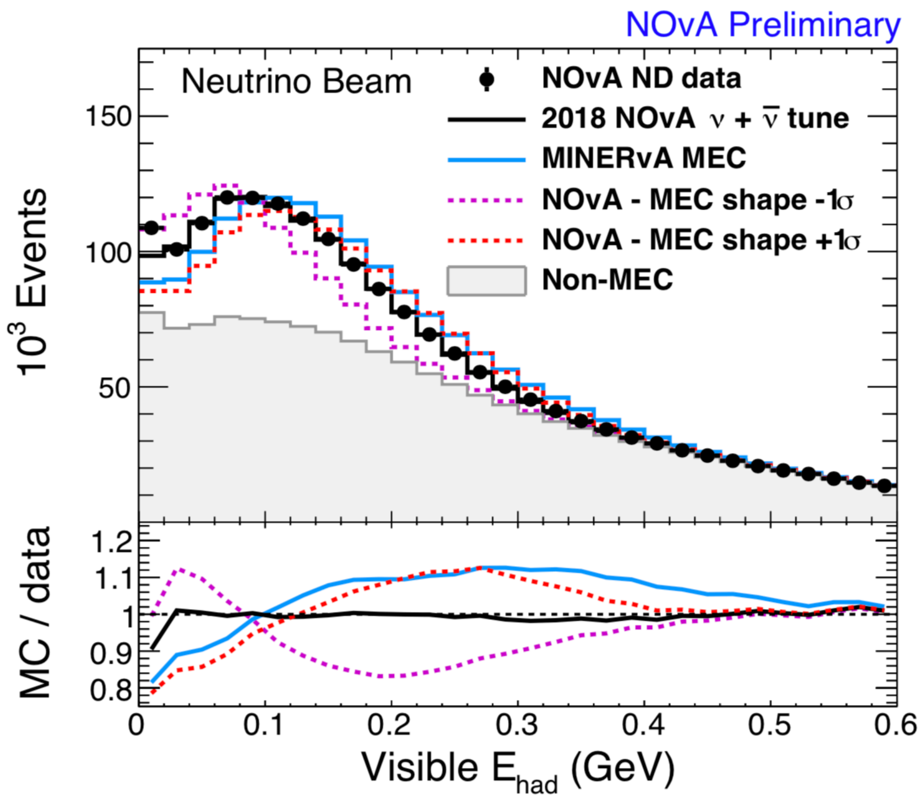


P. Rodrigues et al, Phys. Rev. Lett. 116, 071802 (2016)

Implications for NOvA

- NOvA saw big discrepancy in Near Detector data with “out of the box” GENIE
- Tuned their own data a la MINERvA to add more strength to the “dip” region
- Similar effect to simply adding prediction based on MINERvA’s analysis





Sanchez, Mayly. (2018, June). NOvA Results and Prospects. Zenodo. http://doi.org/10.5281/zenodo.1286758

Implications for NOvA-antineutrinos

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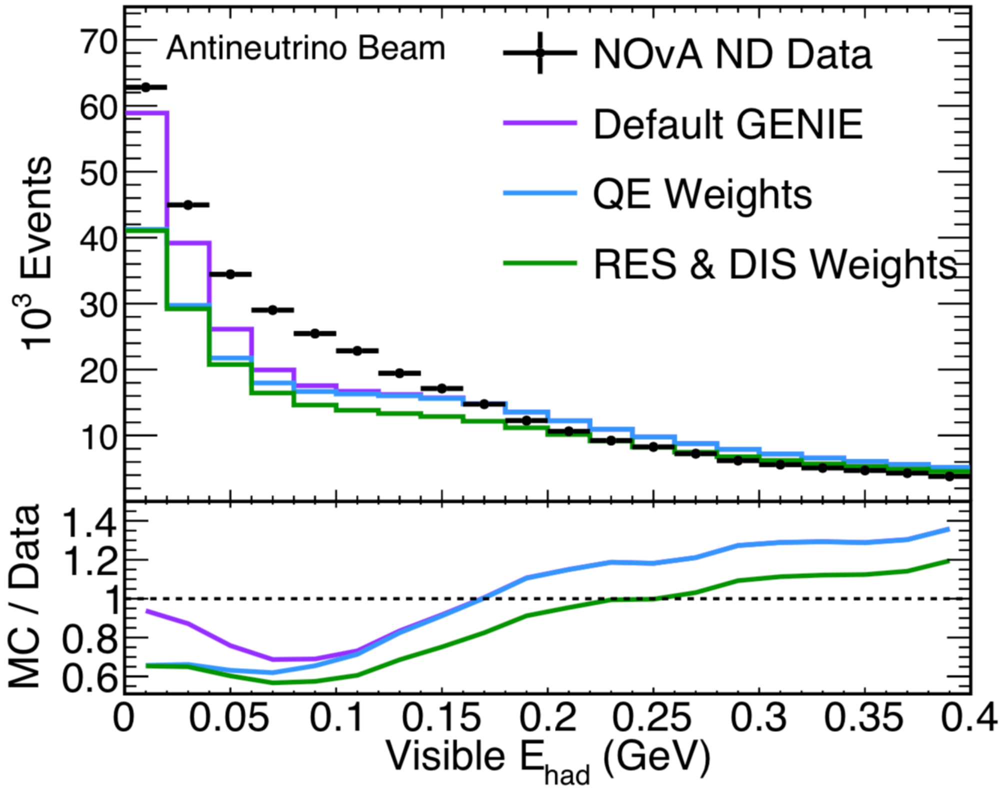
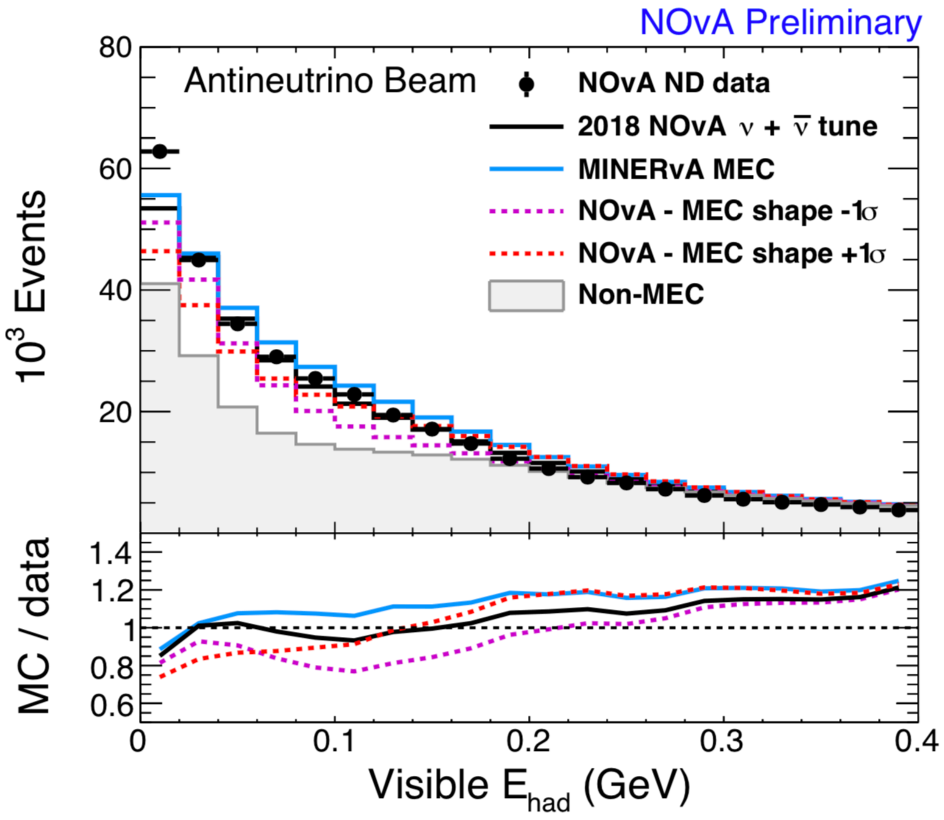
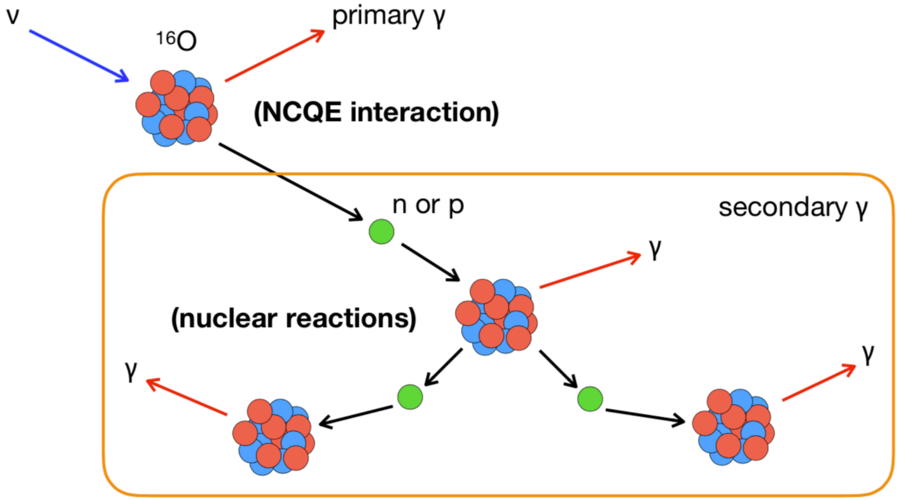




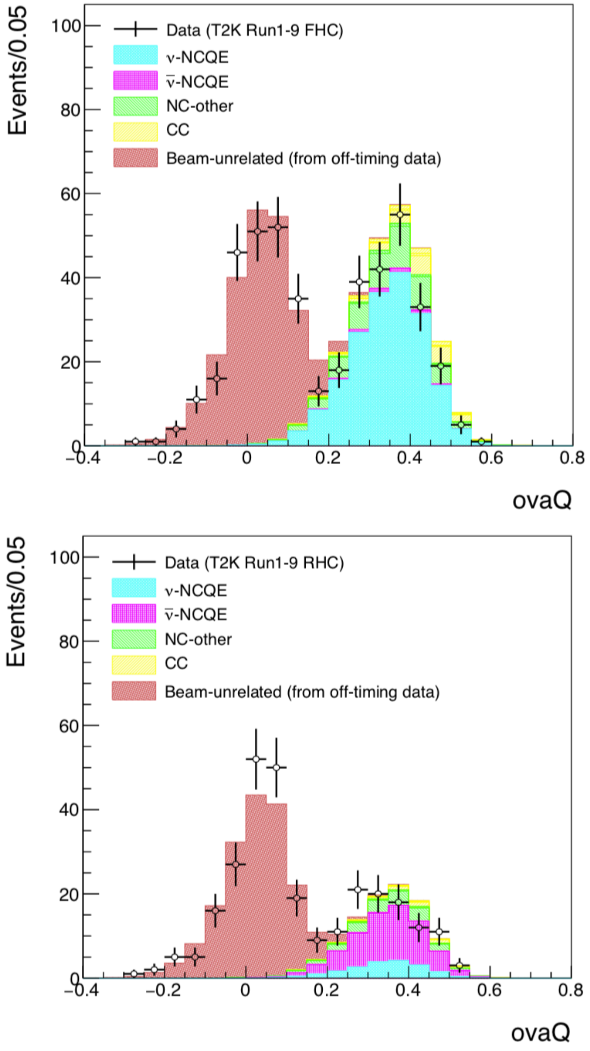
Sanchez, Mayly. (2018, June). NOvA Results and Prospects. Zenodo. http://doi.org/10.5281/zenodo.1286758

What about Neutral Current Interactions?

- Today's signal is tomorrow's background
- T2K has looked for NC quasi-elastic interactions in beam from J-PARC:



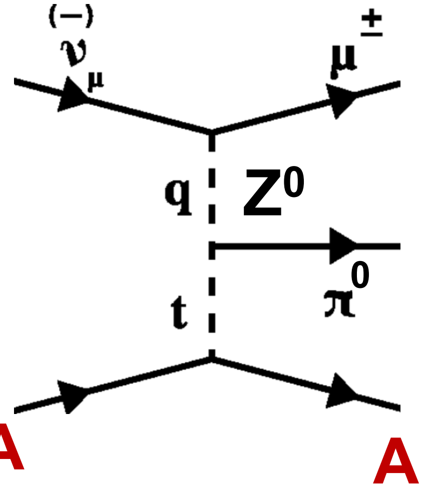
  - Neutrino and antineutrino beams separately
  - See de-excitation photons converting—few MeV signal!
  - Key observables: vertex location, angle of electron, distance from the wall (overall reconstruction Quality, ovaQ)

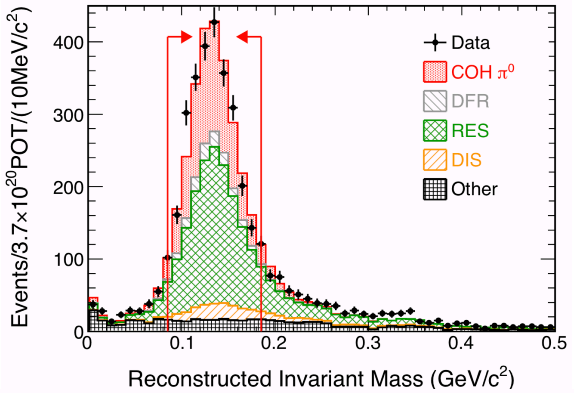


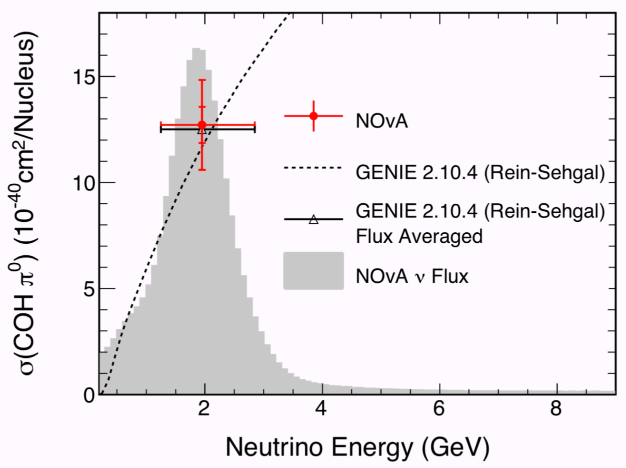
K. Abe et al, arXiv:1910.09439

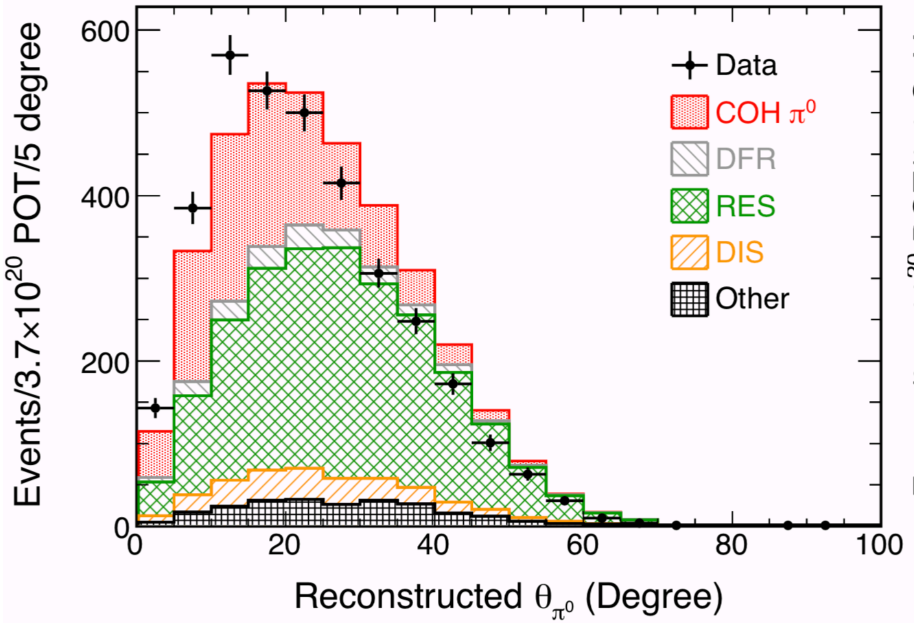
NC Coherent π^0 measurement from NOvA

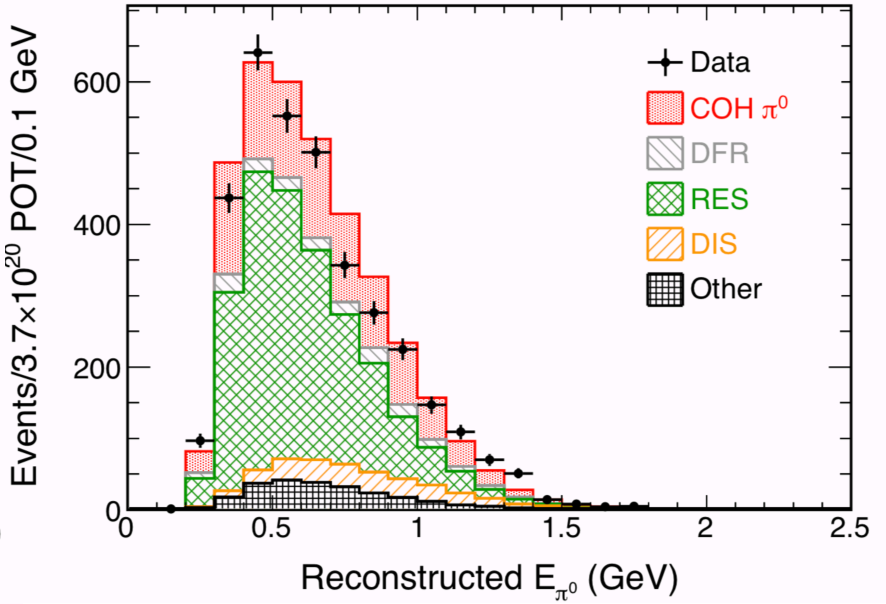
- Try to determine coherent fraction by looking at π^0 events vs energy and angle: flux integrated measurement











M. Acero et al, arXiv:1902.00558

arXiv:1902.00558

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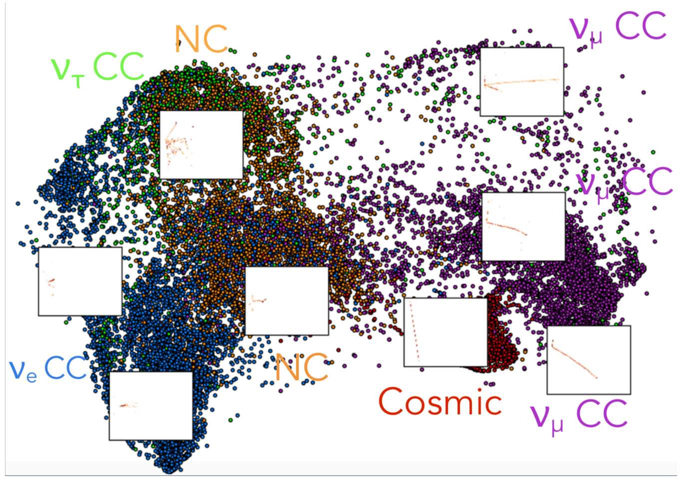
Machine Learning in ν Interaction Measurements

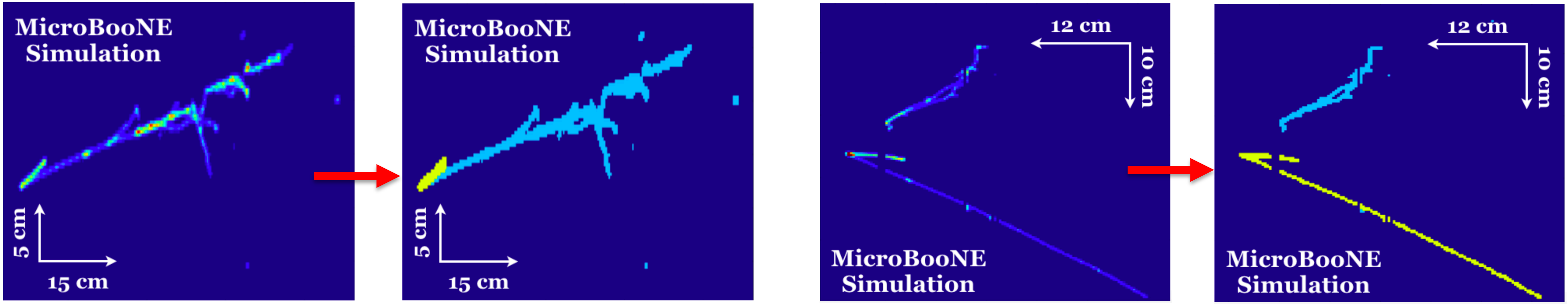
- Machine learning techniques used for event classification
  - Classifying interactions as ν_e CC, ν_μCC, ν_τCC, NC like (NOvA)
  - Classifying the neutrino interaction point (MINERvA)
  - Classifying energy deposits as electromagnetic (MicroBooNE)



M. Sanchez, ν2018

ν_e Charged Current

ν_μ Charged Current



C. Adams et al, Phys. Rev. D99 092001 (2018)

Lessons we are learning now

- Neutrino Interactions on Nuclei are tricky
  - Many different channels of neutrinos on nucleons
  - many different ways for neutrinos to leave energy in detectors
  - The effects of the nucleus on these channels also vary widely
- We are finding more and more ways to probe these interactions
  - New inclusive measurements of (relatively) rare channels
  - Higher statistics measurements of common (CC0π) channels mean new observables are available
    - **Best way to isolate different classes of effects are through hadron-lepton correlations**
- Just starting to pass "best fits" between experiments—would like to see more of this!