Clarifying Neutrino Interactions (Experimental Aspects)

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SLAC Summer Institute

Who am I?

- This is the end of my fifth year as a prof at York U., with a joint appointment with Fermilab.
- Before that, I worked 20 years as a Scientist at Fermilab
- Before that, I was a postdoc for U of Rochester, also doing a neutrino experiment at Fermilab
- Before that, I was a grad student at U of Chicago, working on a Kaon Experiment at Fermilab
- Why am I giving this talk?
  - 1999: Started working on neutrino oscillation experiments (~GeV neutrinos)
    - Initially worked on neutrino beam designed for MINOS
    - Started worrying about neutrino interactions-enter MINERvA!
    - Collaborator on T2K & DUNE

Do we need to clarify neutrino interactions for Precision measurements?

- Slide 5 From Kevin's "Inspiring Precision" lecture:
- Precision measurements that succeed can alter the way we construct our understanding of physical phenomena.
- This happens in (at least) two different ways:

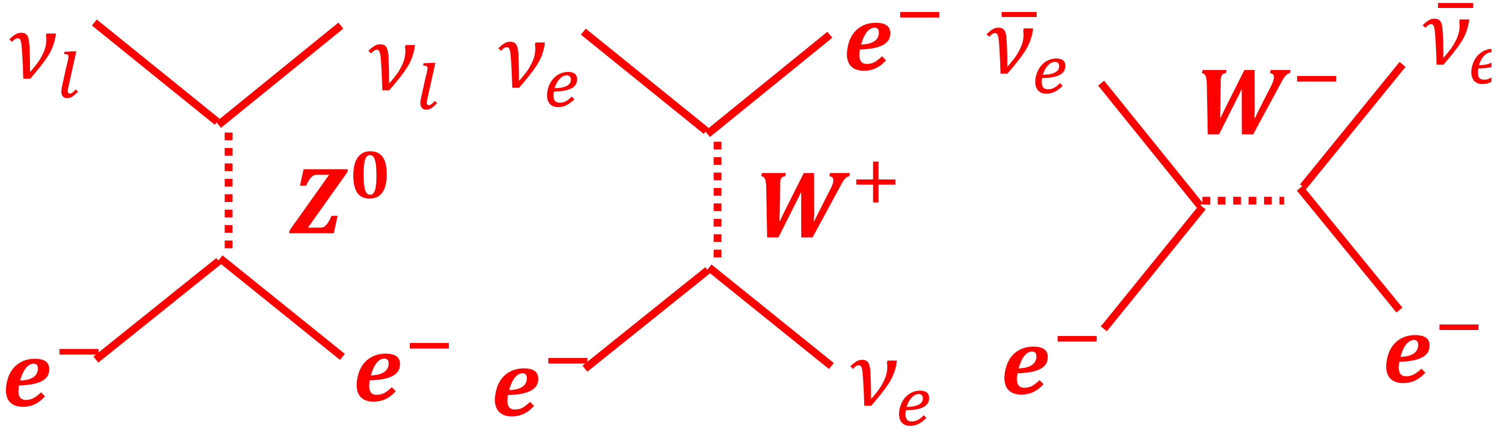
1. Precision measurements reveal a new symmetry/conservation law, or a violation thereof. Need Precision to see CP violation!
2. Precision measurements can be translated into a measure of a quantum correction, potentially involving a first measurement of a new particle or its interactions.

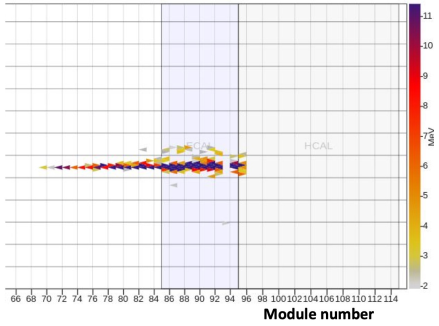
Why Clarify Neutrino Interactions?

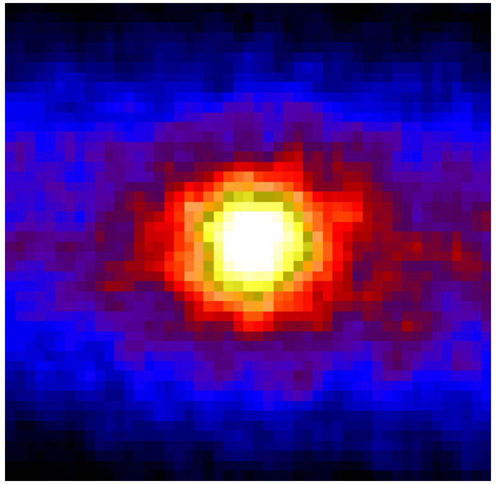
- Most (not all!) of the things we know about neutrinos are because of the way they interact
- Recall that the first time we learned that there was a Z boson in the first place was from seeing Neutral Current Interactions
  - "First discovery": not a precision measurement, but a big deal anyway!
- Oscillation Measurements are the best way to measure neutrino mass hierarchy and the ONLY (realistic?) way to measure CP violation in the lepton sector

Which Interactions are already Clear?

- Given our knowledge of $\sin\theta_W{}^2$, these interactions are understood:





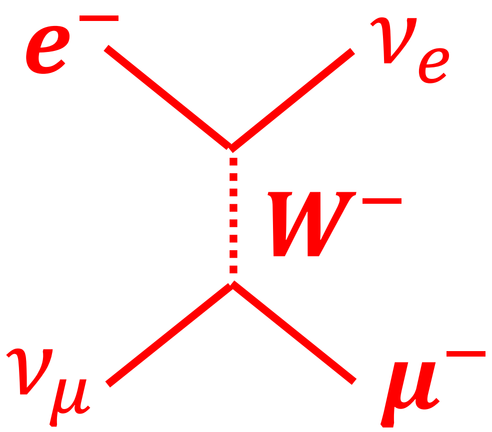


- They have been used to measure incoming neutrino beam flux at MINERvA:
  - Phys.Rev. D 100, 9 (2019), Phys.Rev.D 107 (2023) 1, 012001, Phys.Rev.D 104 (2021) 9, 092010
- They will be used by DUNE to measure the neutrino beam flux:
  - *Phys.Rev.D* 101 (2020) 3, 032002

Could be used to measure $\sin\theta_W{}^2$ more precisely than NuTeV, given the statistics…not the subject of this talk

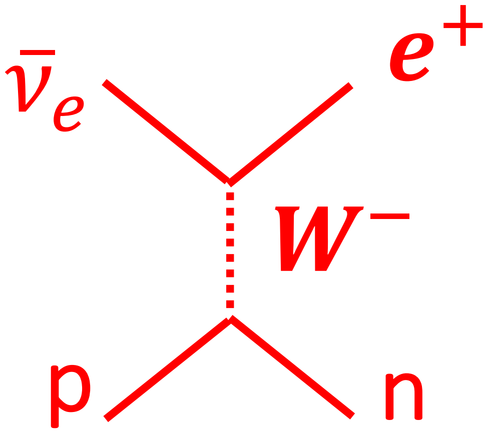
What about a ν_μ interacting with an e^-?

- Also very clear, cross section known well



- Catch: how much energy does a neutrino have to have in order for this interaction to take place? 100MeV? 1.1GeV? 11GeV? 110GeV?
- Still, can be used to constrain flux at high energies
  (See MINERvA's result here: Phys.Rev.D 104 (2021) 9, 092010)

Still another interaction that is (relatively) clear



- Low Energy antineutrinos on free protons
- Reactor Neutrinos have ~few MeV energies
- Threshold energy for $\bar{\nu}_e + p \rightarrow e^+ + n$ is 1.806MeV
- Can infer Electron antineutrino energy directly from positron energy since it takes away most of the energy in the process
- $E(\nu_e)$= E(visible) + 784keV

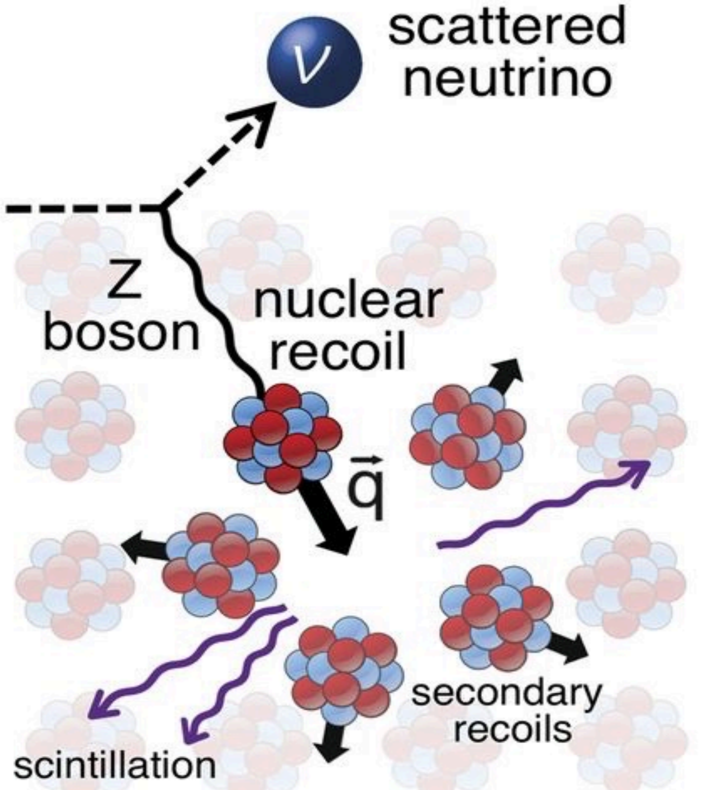
- But what about all the C inside your reactor detector?
(or O inside your water detector) have to overcome binding energy

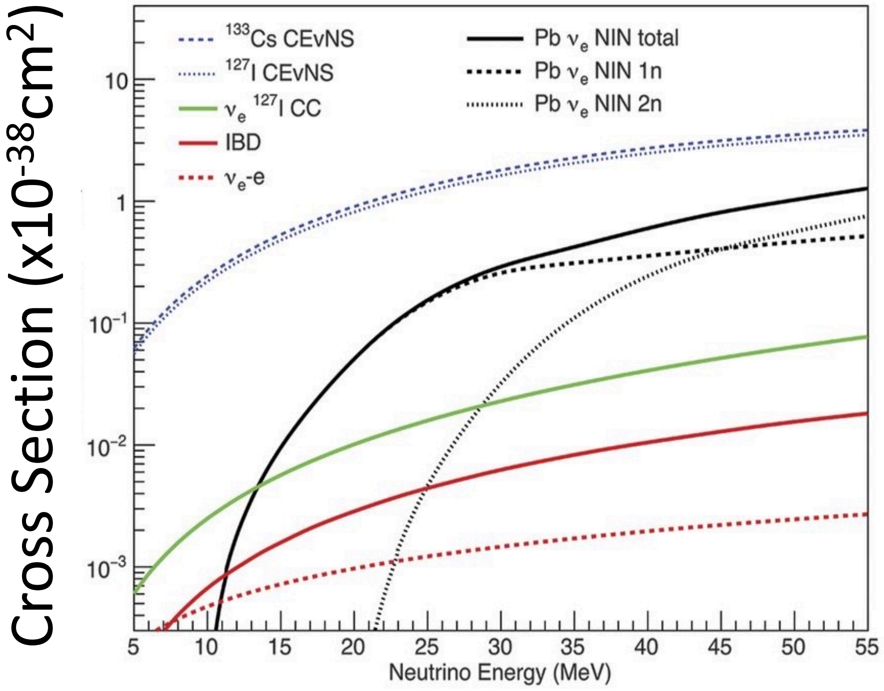
Another Interaction that is (relatively) Clear:

- Coherent Elastic Neutral Current Scattering (CEvNS)
- Predicted by the Standard Model
- DeBroglie wavelength for 50MeV ν:

$$\lambda = \frac{hc}{E} = \frac{1200 MeV \cdot fm}{50 MeV} \simeq 25 fm$$

- Background to dark matter searches



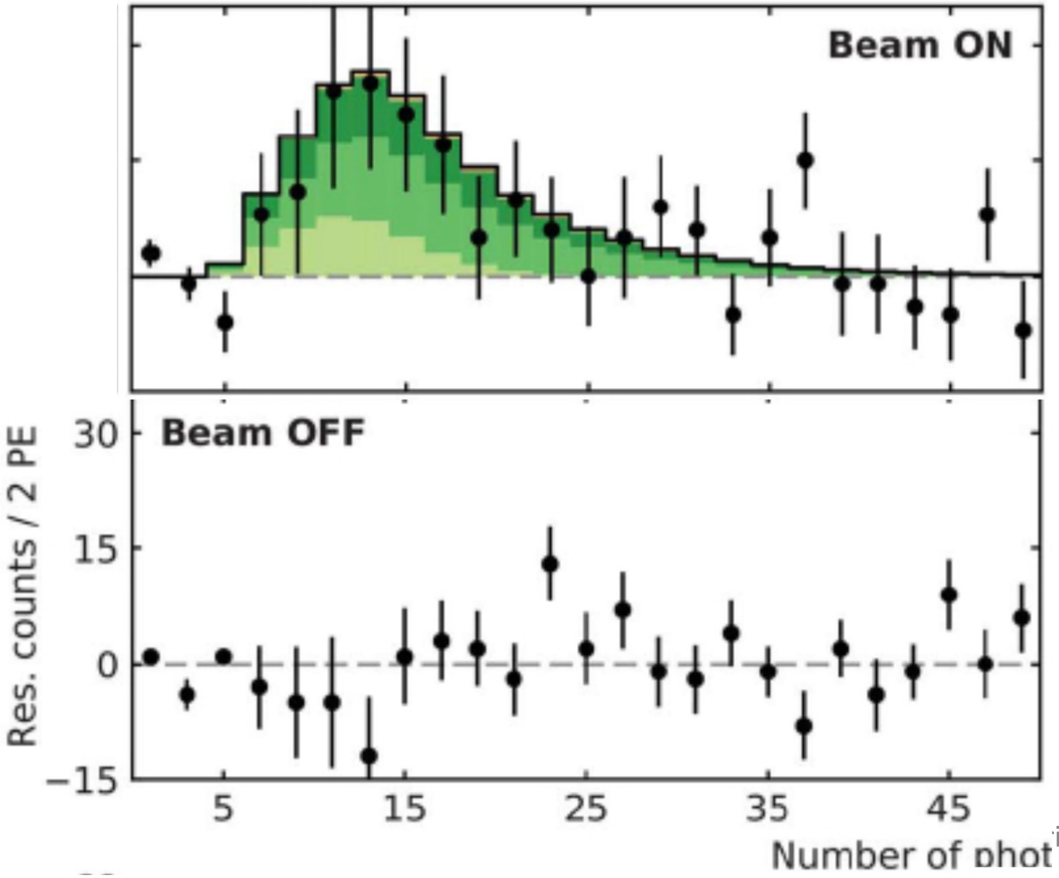


Science 357 (2017) 6356, 1123-1126

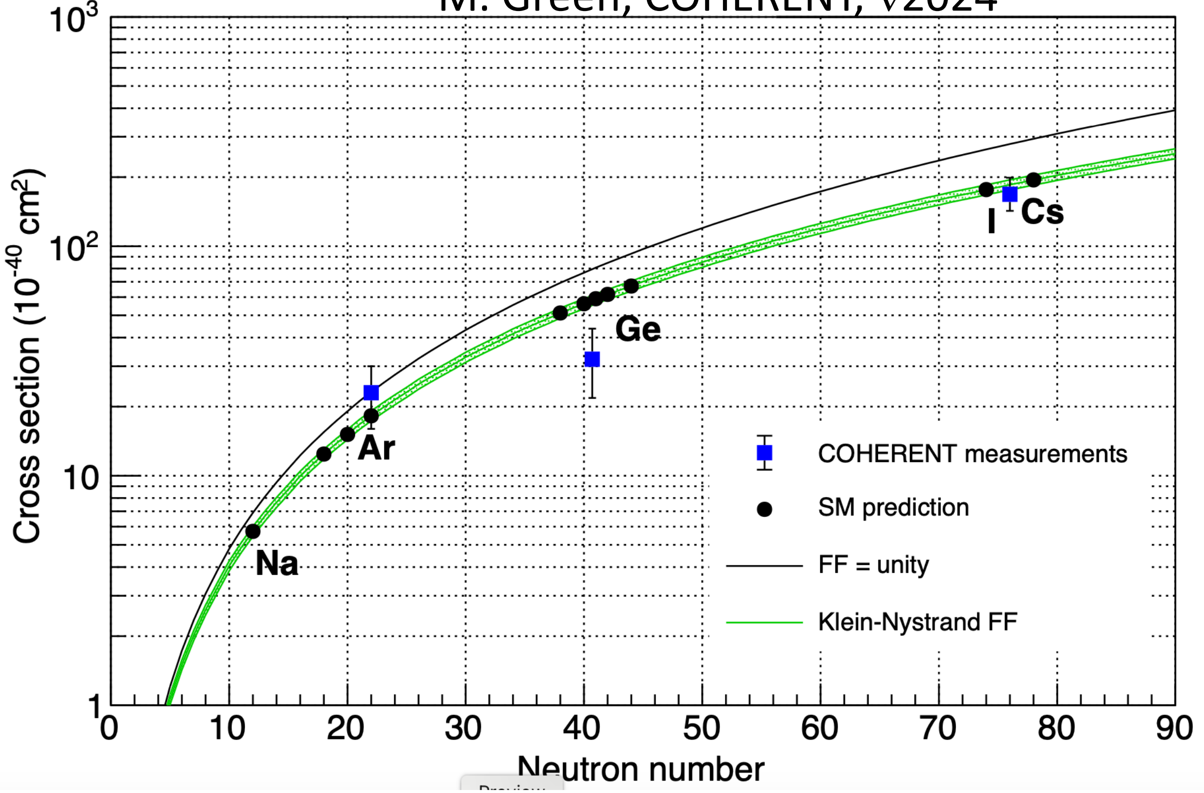
Discovery to A-Dependence of CEvNS

- If all the nucleons are scattering coherently, then how should the cross section scale as a function of A?

Science 357 (2017) no.6356, 1123-1126

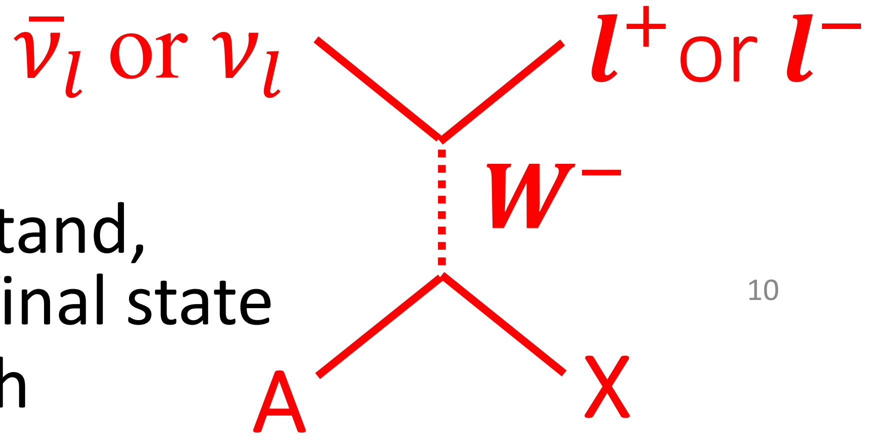


M. Green, COHERENT, ν2024



Recipe: How to measure ν Oscillations

- Prepare a beam of neutrinos ~~in a flavour eigenstate~~….
- Measure the flavor composition "at creation"
- Measure the flavor composition after some distance L
- How do you measure the flavor composition?
  - Charged Current Interactions
  - Bare minimum: have a detector that can distinguish electrons from muons
  - Practicality: given physics we want to understand, need >100MeV neutrinos to make muons in final state
  - Another practicality: kton/dollar must be high



Can’t we just use these interactions to measure oscillations?

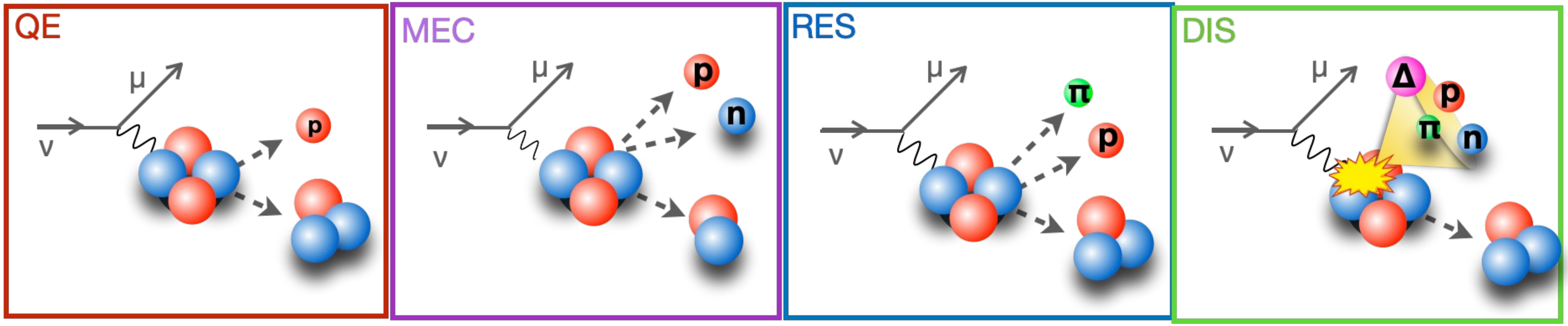
- CEvNS
    -
- Neutrino-Electron Scattering
    -
- High Energy Muon Neutrinos on Electrons
    -
- Low Energy Antineutrinos on free protons
    -
    -

Can’t we just use these interactions to measure oscillations?

- CEvNS
  - Neutral Current, can’t measure outgoing flavour of neutrino
- Neutrino-Electron Scattering
  - Also has big NC component, can’t measure outgoing flavour directly
- High Energy Muon Neutrinos on Electrons
  - No analog for antineutrinos, because we don’t have detectors w/positrons
- Low Energy Antineutrinos on free protons
  - Awesome, but interaction only clear at lowest energy antineutrinos
  - No analog for neutrinos because there are no free neutrons

How do ~GeV neutrinos Interact?

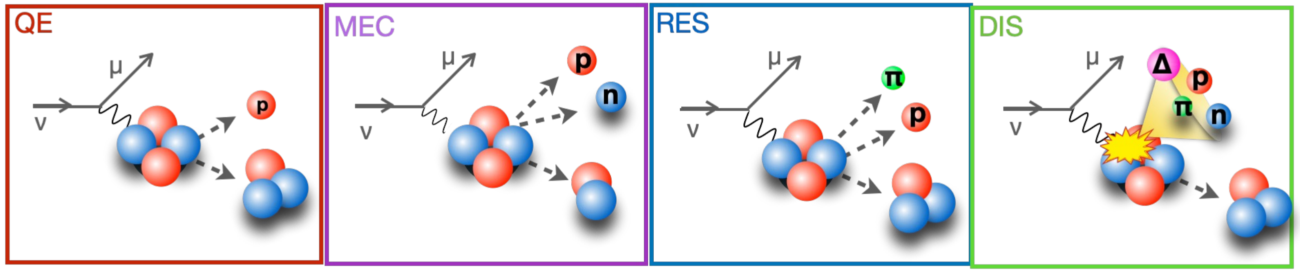
- With momentum transfers that are large enough that they are probing either the nucleus or the nucleon (proton or neutron) itself
- QuasiElastic, Meson Exchange Currents, Resonance Production, Deep Inelastic Scattering

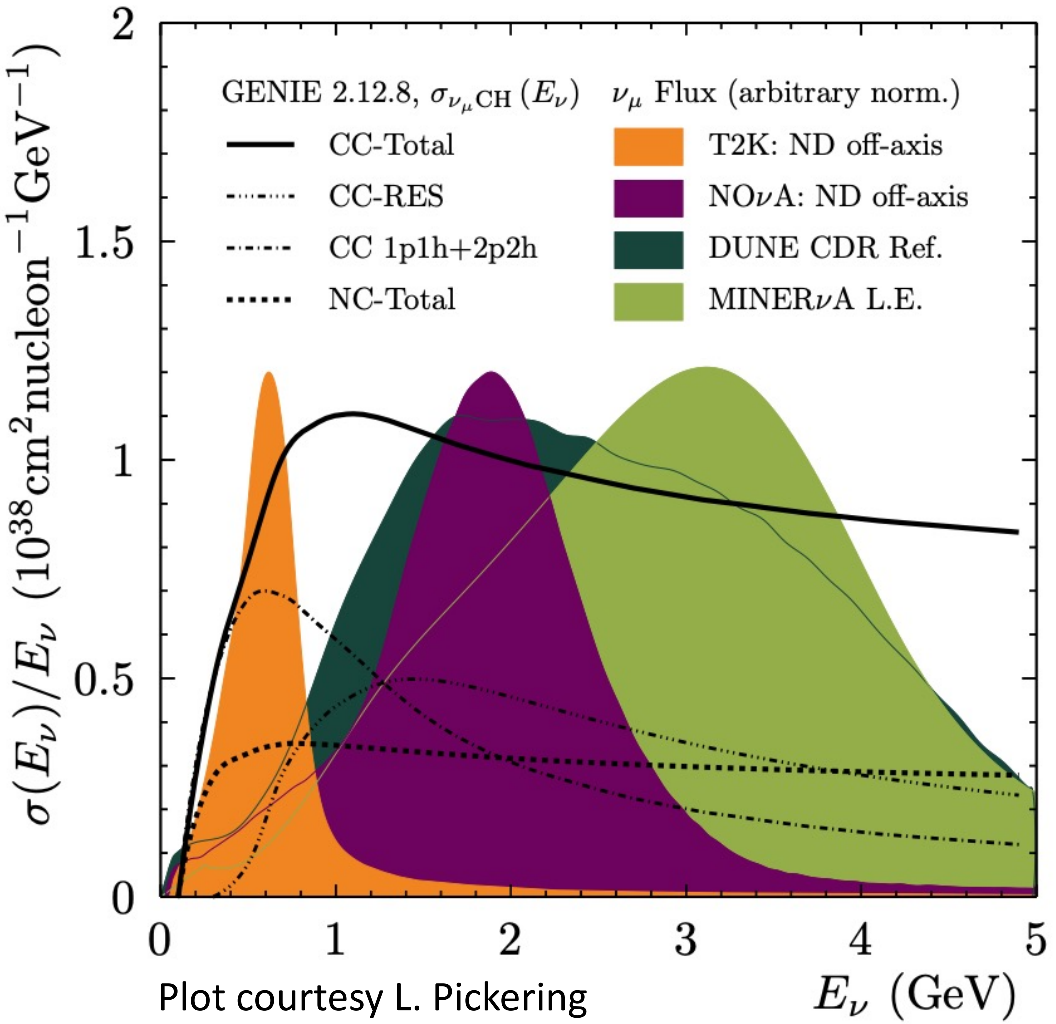


From N. Rocco, CERN NUSTEC Summer School 2024

Comparing Channels and Energies

- The neutrino energies that we are using for accelerator-based oscillation measurements are those where these processes dominate
- The rest of this talk will focus on these measurements





Plot courtesy L. Pickering

What do oscillation experiments *measure*?

- Count events of a given flavor and use this relationship:

$$N_{near}(\nu_\alpha) = \sigma(\nu_\alpha)\Phi_{near}(\nu_\alpha)\epsilon(\nu_\alpha)M_{near}$$

Interaction cross section (area per target)

Neutrino flux (ν's per unit area)

Detector effects, use event generator to estimate this

Mass (number of targets)

$$N_{far}(\nu_\beta) = \sigma(\nu_\beta)\Phi_{far}(\nu_\alpha)\epsilon(\nu_\beta)M_{far}P(\nu_\alpha \rightarrow \nu_\beta)$$

Simple, "just" solve for $P(\nu_\alpha \to \nu_\beta)$

- From those two equations, you would find that:

$$\frac{N_{far}(\nu_\beta)}{N_{near}(\nu_\alpha)} = \frac{\sigma(\nu_\beta)\Phi_{far}(\nu_\alpha)\epsilon(\nu_\beta)M_{far}P(\nu_\alpha \to \nu_\beta)}{\sigma(\nu_\alpha)\Phi_{near}(\nu_\alpha)\epsilon(\nu_\alpha)M_{near}}$$

- And then a miracle occurs:
  - $P(\nu_\alpha \to \nu_\beta) = \frac{N_{far}(\nu_\beta)}{N_{near}(\nu_\alpha)} \times \frac{\Phi_{near}(\nu_\alpha)}{\Phi_{far}(\nu_\alpha)} \times \frac{\sigma(\nu_\alpha)}{\sigma(\nu_\beta)} \times \frac{\epsilon(\nu_\alpha)}{\epsilon(\nu_\alpha)} \times \frac{M_{near}}{M_{far}}$
  - Some claim…all you need are cross section ratios $\frac{\sigma(\nu_\alpha)}{\sigma(\nu_\beta)}$, and flux ratios $\frac{\Phi_{near}(\nu_\alpha)}{\Phi_{far}(\nu_\alpha)}$!

Words you should never believe…

- "One Size Fits All"
- "This won't hurt much"
- "It's just a counting experiment"
- "Cross Section Uncertainties cancel in a 2-Detector Experiment"
  - Measure some number of neutrinos with some measured energy distribution
  - Have to understand the relationship between true and measured energy

- Why?
  - Near and Far fluxes (and backgrounds) are very different because of large ν_μ disappearance
  - Visible to True Energy relationship is what gives you Δm^2!

How to Measure Neutrino Energies >100MeV

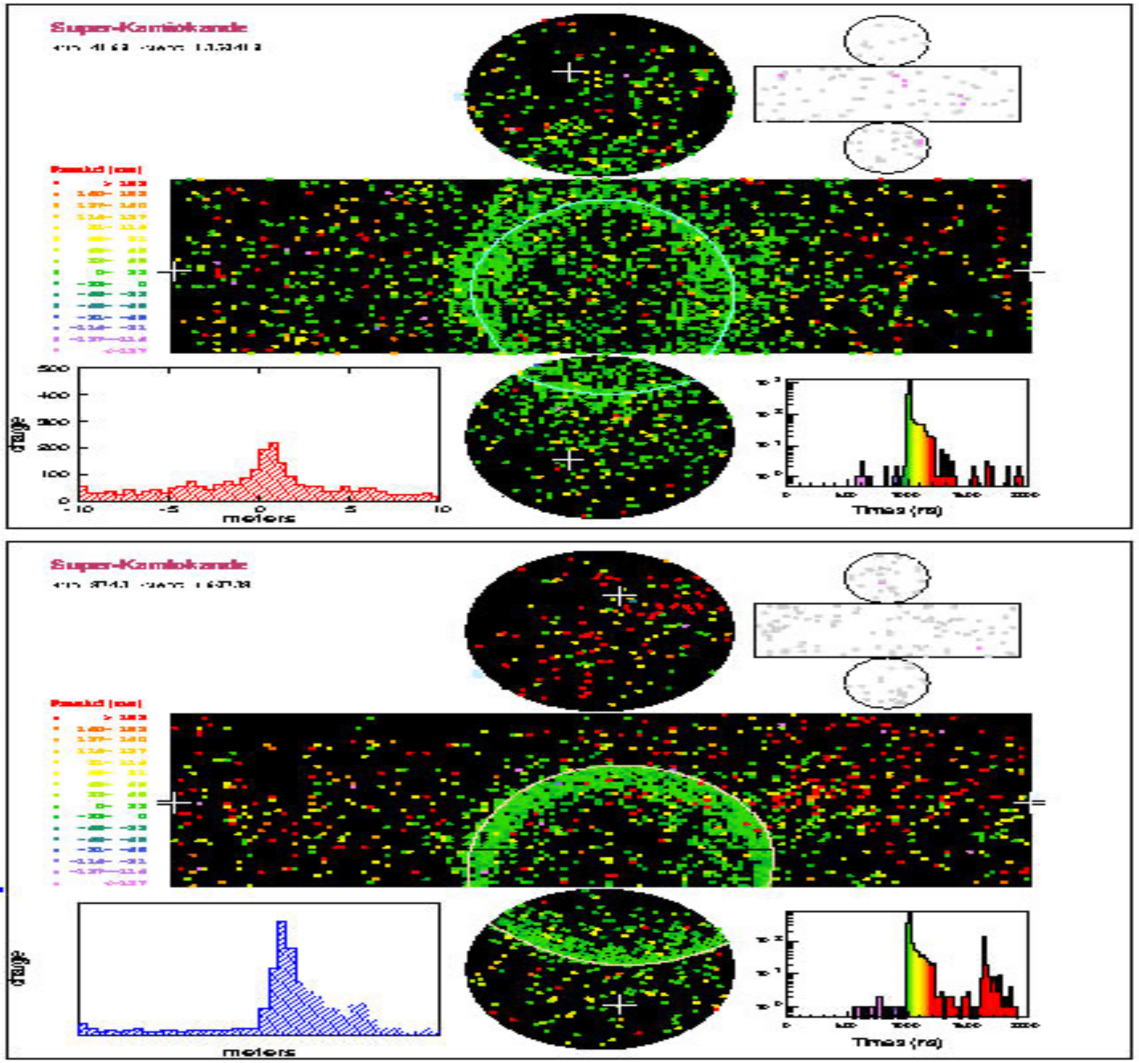
- Kinematic Reconstruction
  - Good if most of your events are quasielastic
  - Only need to measure outgoing lepton’s angle and momentum
  - That plus neutrino direction gives you what you need…

- Calorimetric Reconstruction
  - Good if you are using neutrinos at 1GeV and above
  - Need to measure as many of the outgoing particles in the hadronic system as possible
  - Catch: can’t see all final particles’ energy, calorimetric response is different between charged and neutral pions
  - $E_\nu \approx E_{lepton} + E_{hadron}$

Neutrino Events in Super-Kamiokande (and Hyper-K)

e-like

μ-like

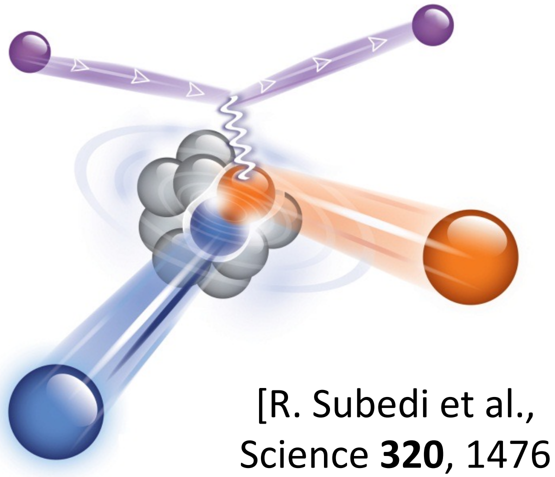


$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\mu - \left[(M_n - E_B)^2 + m_\mu^2 - M_p^2\right]}{2\left[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

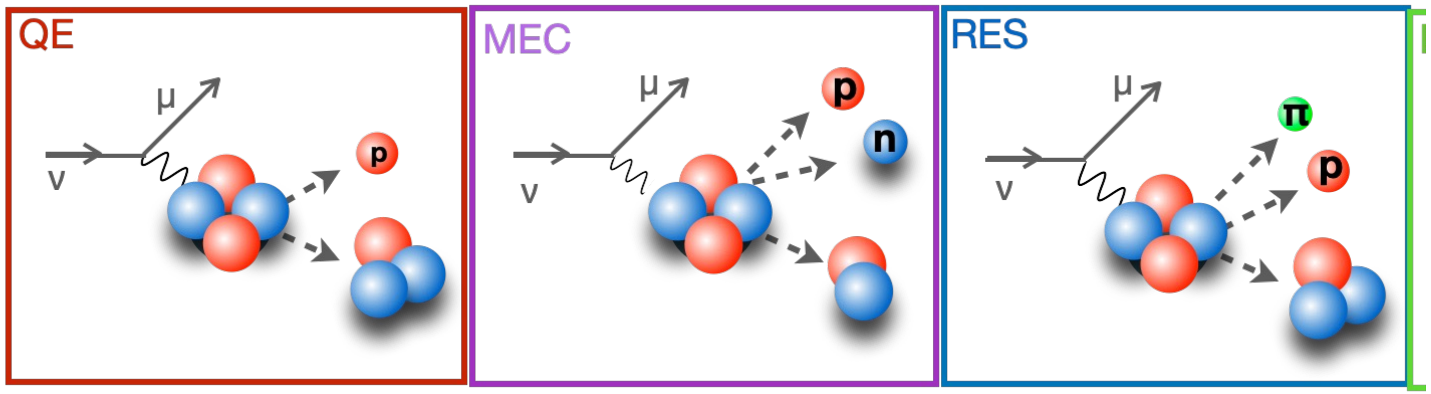
$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

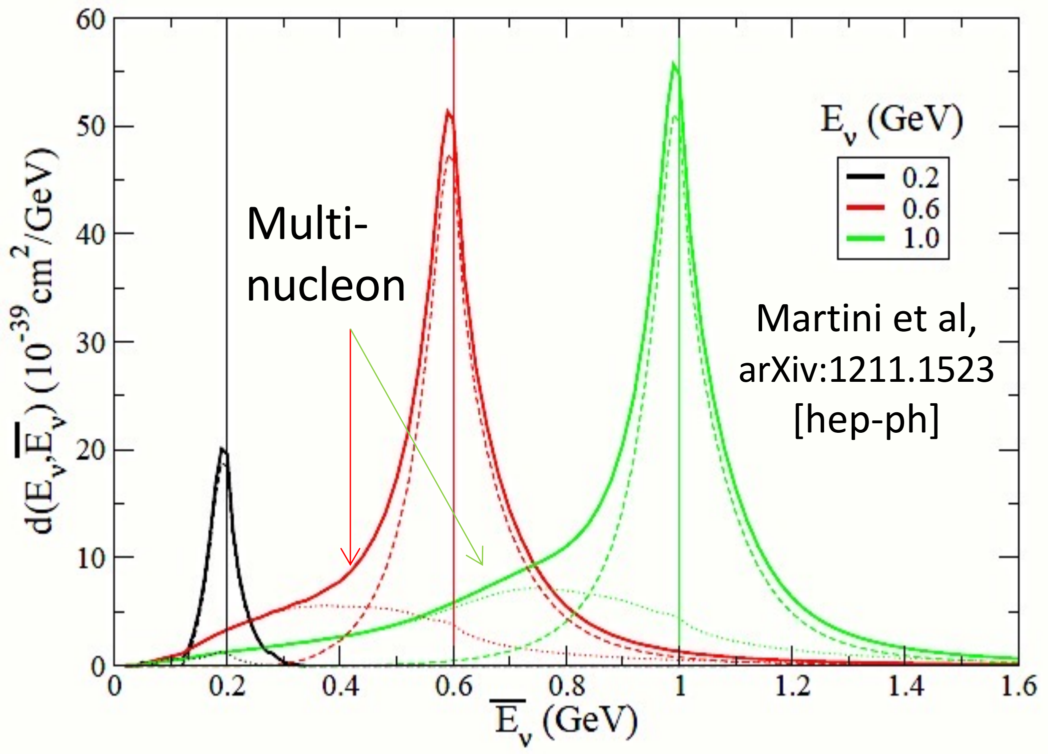
The problem with “Kinematic Reconstruction”

- Inside a nucleus, initial nucleon may have momentum
- Not everything that is quasielastic is quasielastic!
- Sometimes what happens in the nucleus stays in the nucleus



[R. Subedi et al., Science **320**, 1476 (2008)]





The problem with "Calorimetric Reconstruction"

- Measure lepton energy
- Measure as much about the hadronic system as you can
- Use a simulation to understand the relationship between visible hadronic energy and true hadronic energy
- Examples of what is seen in scintillator and liquid argon:

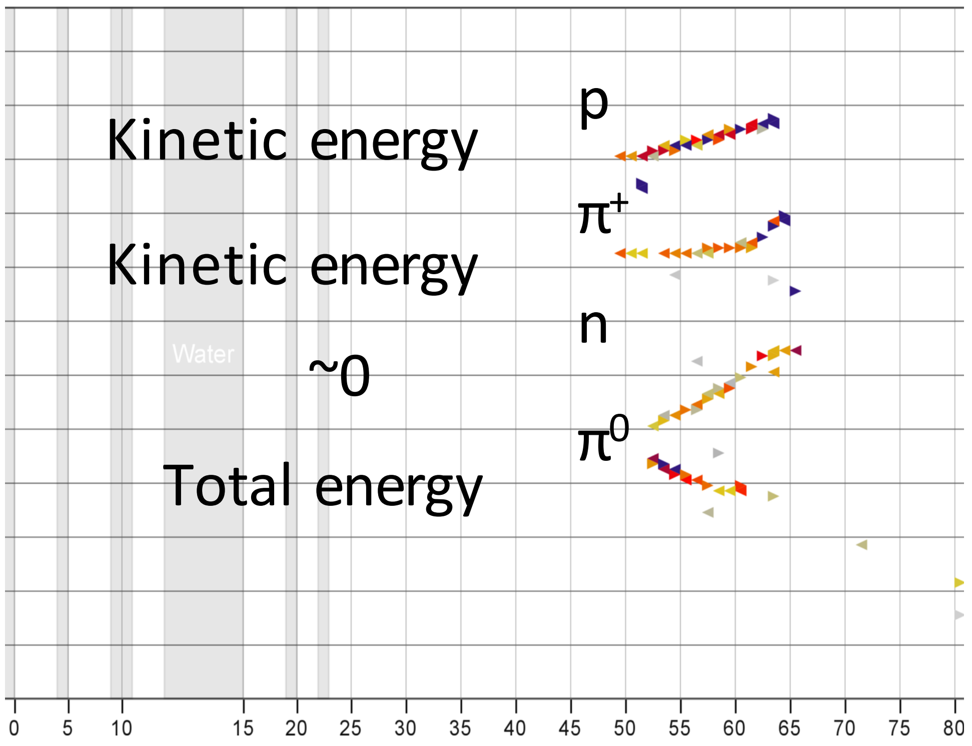
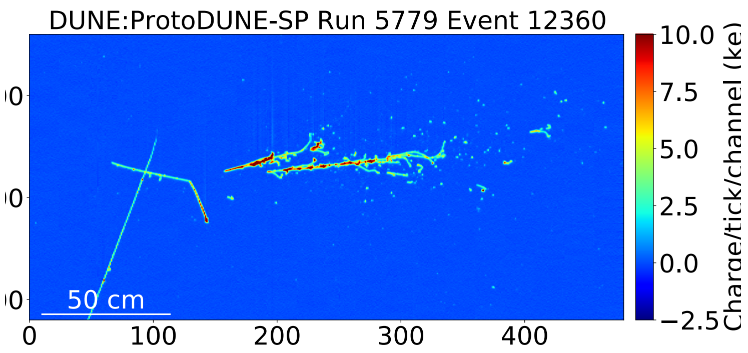
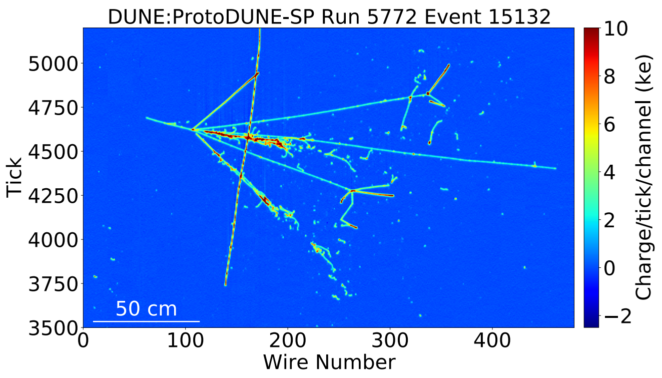


Figure courtesy P. Rodrigues





Goals of Current Cross Section Program

- Understand how neutrino energy is balanced between lepton and hadron in Charged Current Interactions
- Understand how much of hadronic energy is ”invisible”
  - Either because it’s below threshold for Cerenkov detectors like SK and HK
  - Or because the energy is in neutrons or charged pion rest mass
- Quantify what the backgrounds for oscillation experiments are

- Need close coordination with Theory to do reach precision!

How to measure a Cross Section

$$N(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)M$$

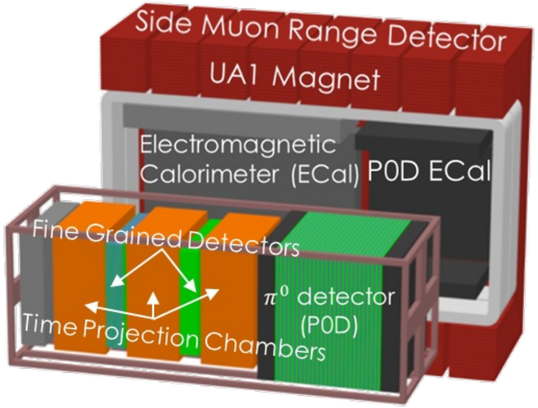
Mass (number of targets)

Interaction cross section (area per target)

Neutrino flux (ν's per unit area)

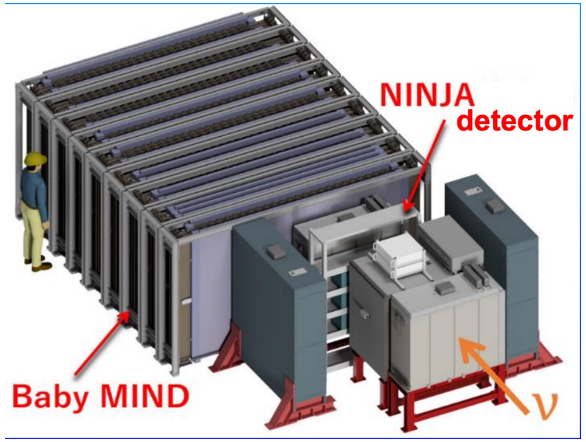
Detector effects, use event generator to estimate this

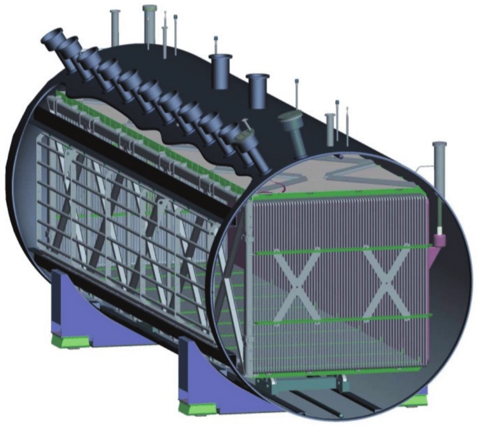
Experiments currently releasing Neutrino Interaction results (in 0.5-20GeV region)



T2K Near Detector: CH, H_2O

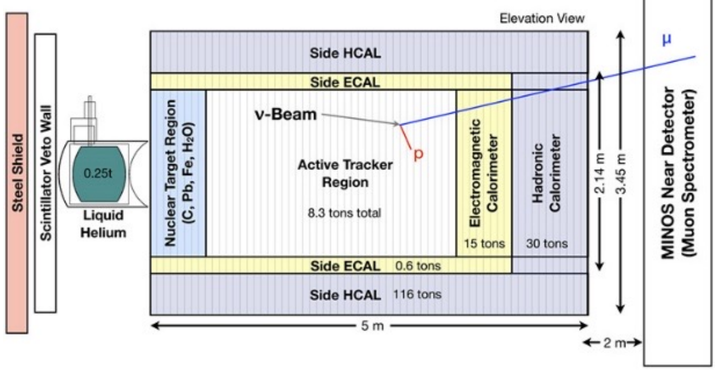
NINJA: CH, H_2O, Fe

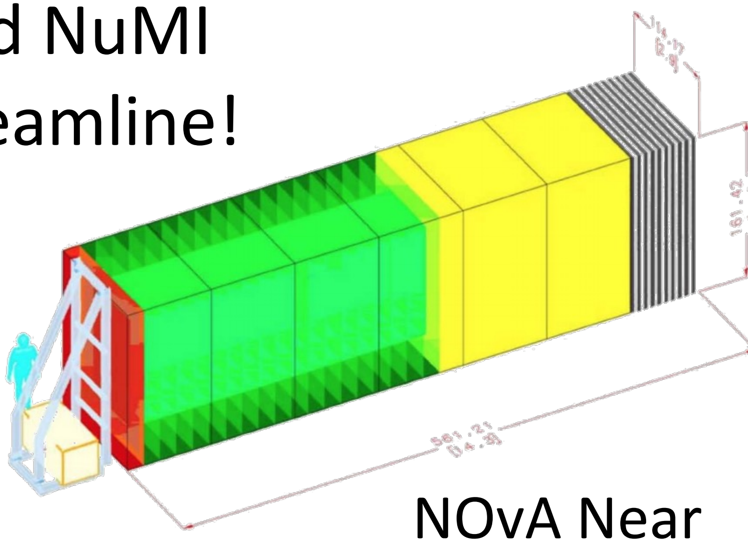




MicroBooNE: Liquid Argon TPC Booster and NuMI (off axis) beamline!

MINERvA: He, CH, C, H_2O, Fe, Pb

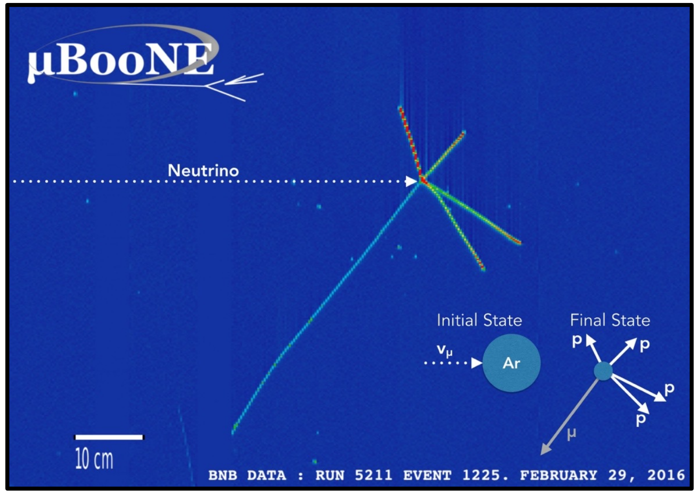


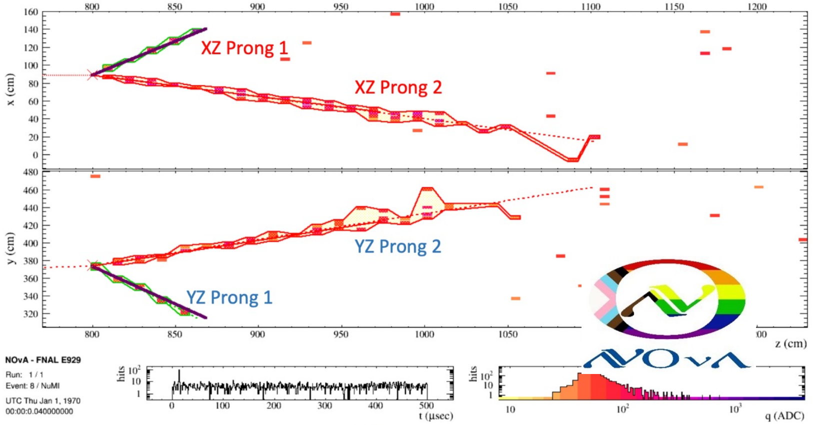


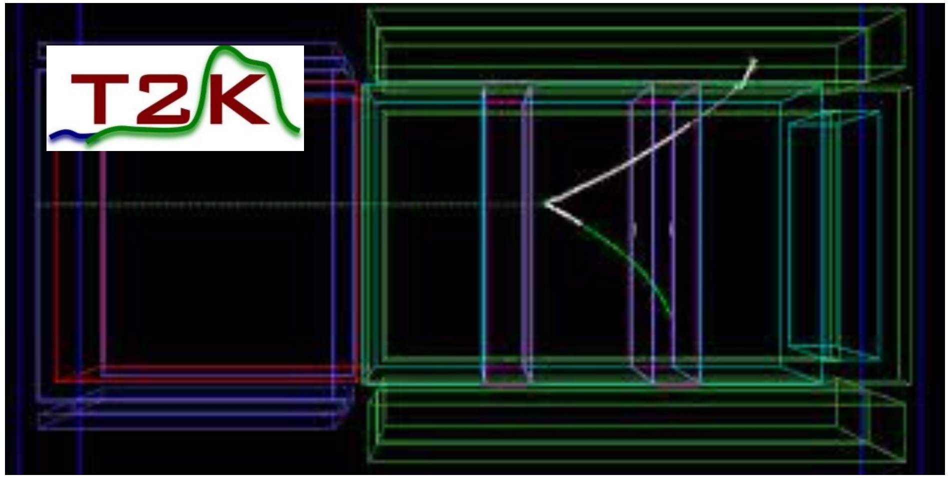
NOvA Near Detector: CH

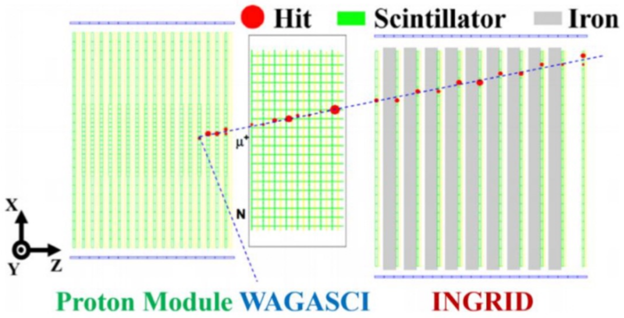
Fermilab YORK UNIVERSITÉ UNIVERSITY

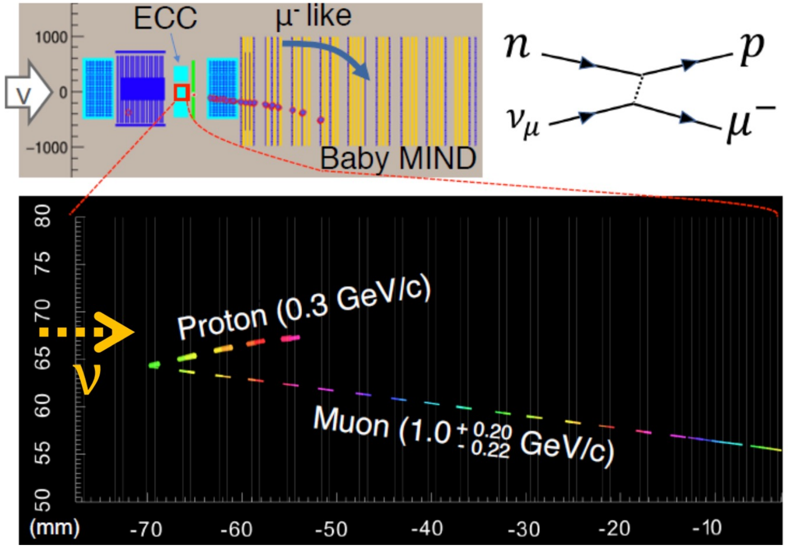
What can we actually measure?

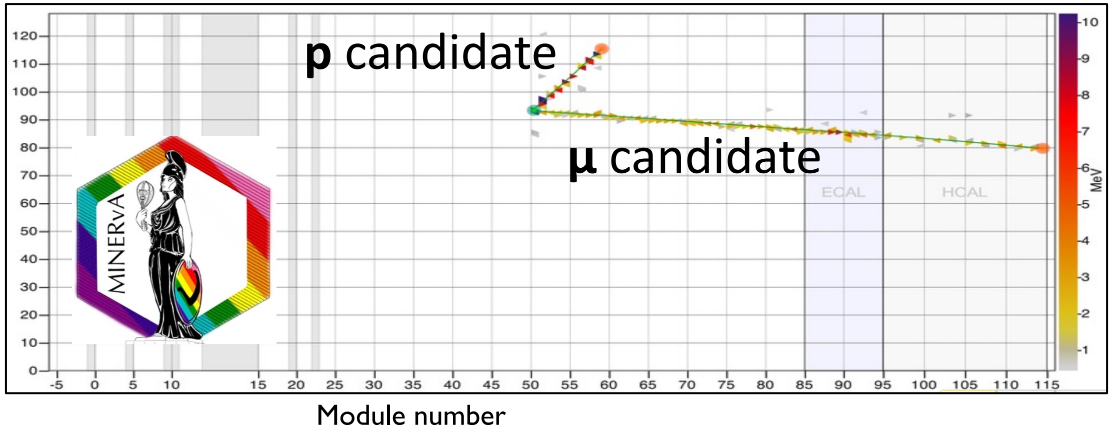








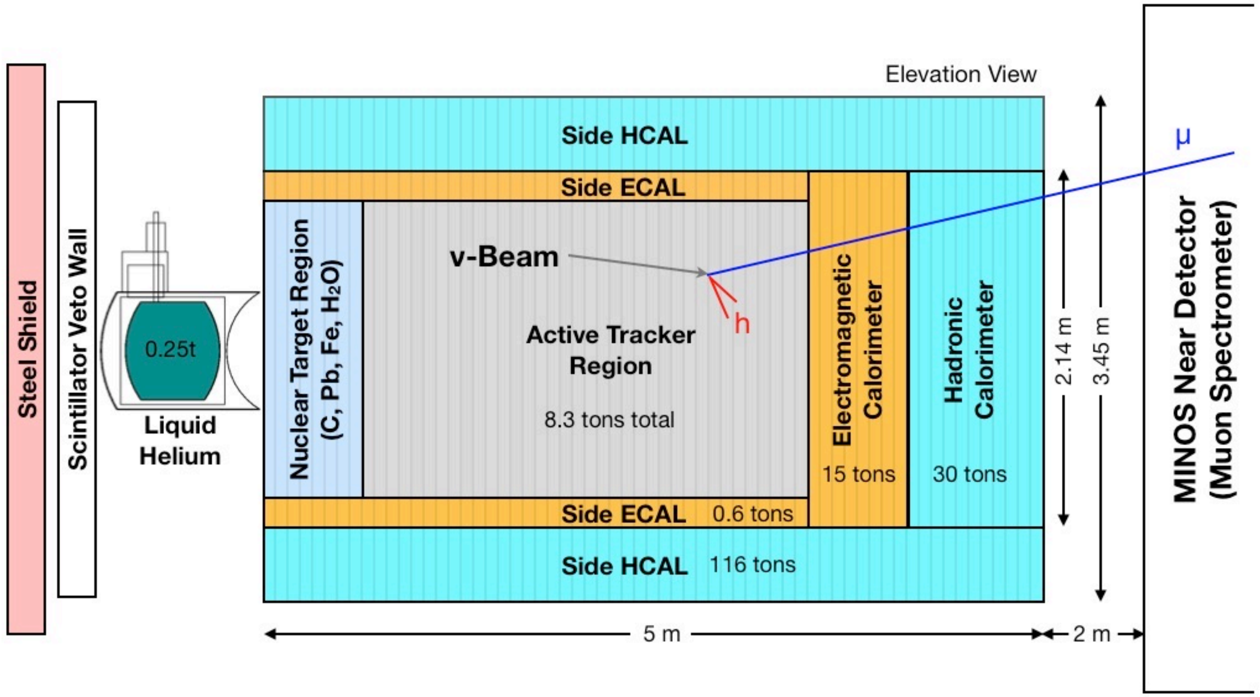


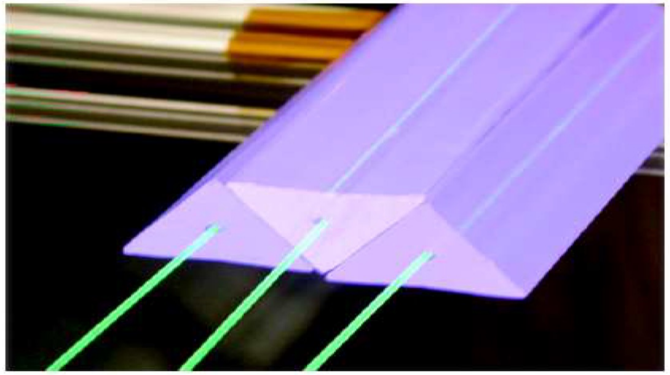


Modern Cross Section Experiments

Experiment	Beam Energy	Target Nucleus	B field?	Granularity	Status
COHERENT	25MeV, broad	CsI, Ar, ….	No	various	Data-taking
MINERvA	3.5GeV and 6GeV, broad band	He, CH, C, H_2O, Fe, Pb	For muons only	1.6cm x3.3 cm triangles (scint)	Last data: 2019 Still analyzing
T2K (Wagasci)	600MeV	CH, H_2O	Yes!	~few cm triangles + Gas TPC	Data-taking in 2024
NOvA	2GeV	CH	No	4cmx6cm (scint)	Data-taking in 2024
NINJA	700MeV	Pb, H_2O	For muons only	Emulsion!	
MicroBooNE	600MeV (BNB) and 2GeV (NuMI)	Ar	No	3mm wire pitch	Data-taking ended in 2022 Still analyzing
ICARUS	600MeV (BNB) and 2GeV (NuMI)	Ar	No	3mm wire pitch	Data-taking in 2023
SBND	600MeV (BNB)	Ar	No	3mm wire pitch	Data-taking soon!

MINERvA Detector





Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

- Core of detector was an active scintillator strip target, surrounded by calorimetry.
- Passive targets interspersed with scintillator upstream.
- Detector is mostly in trash cans now, but some has been recycled for DUNE tests.

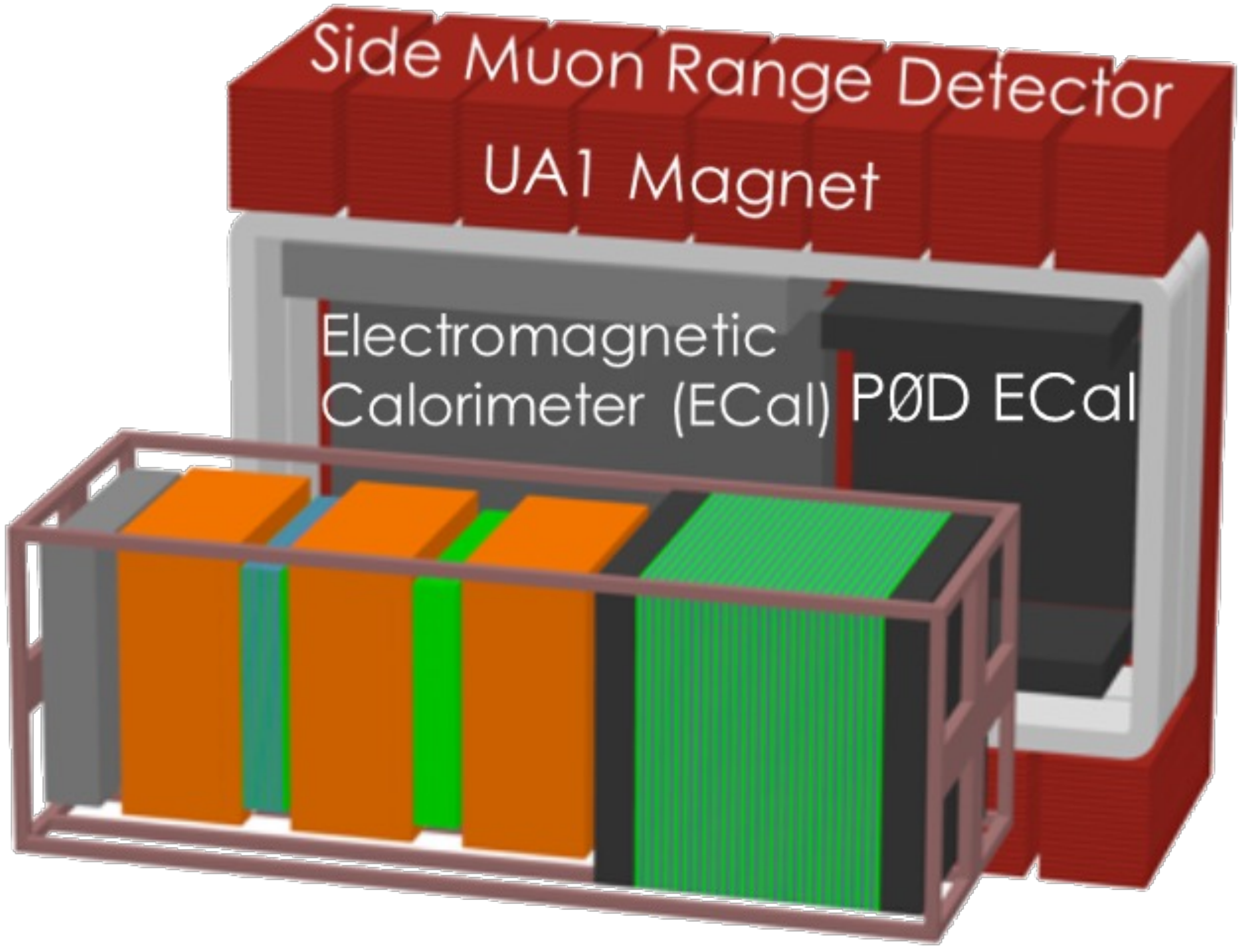
T2K Near Detector

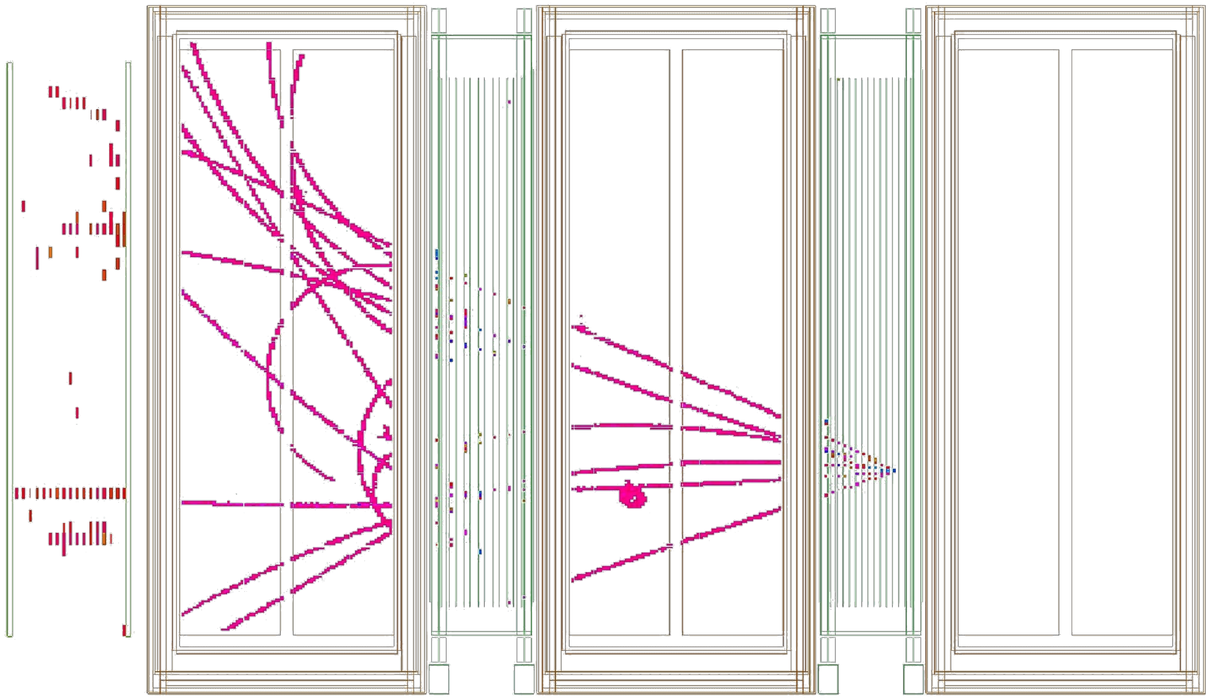
Time Projection Chambers (TPC):

- Excellent tracking
- High-resolution charged-particle momenta
- Accurate particle ID

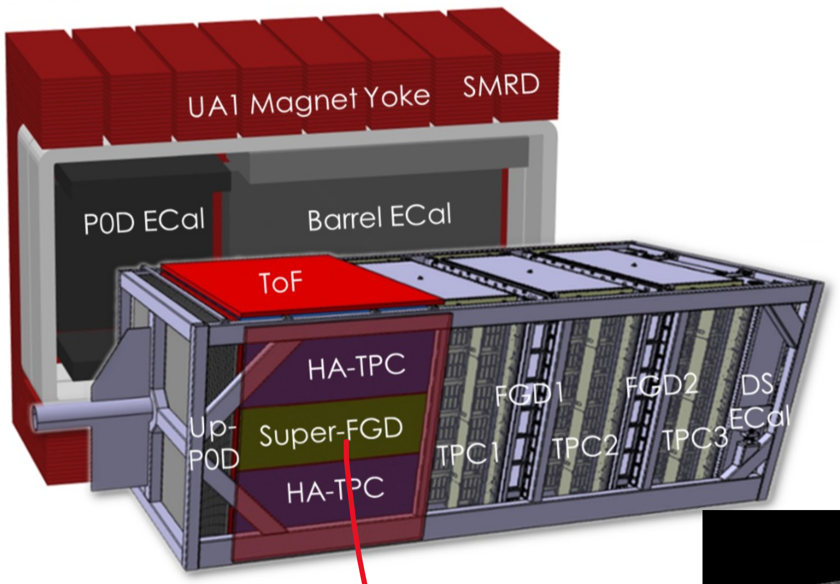
Fine-Grained Detectors (FGD 1 & 2):

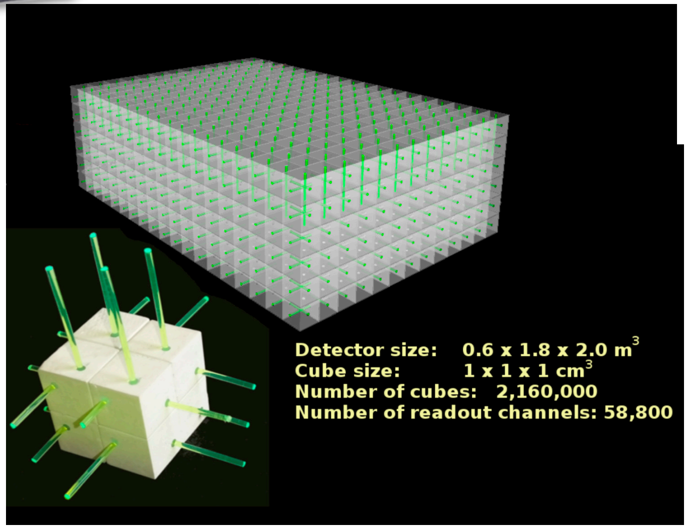
- CH scintillator tracker
- Target for ν
- FGD2 contains water

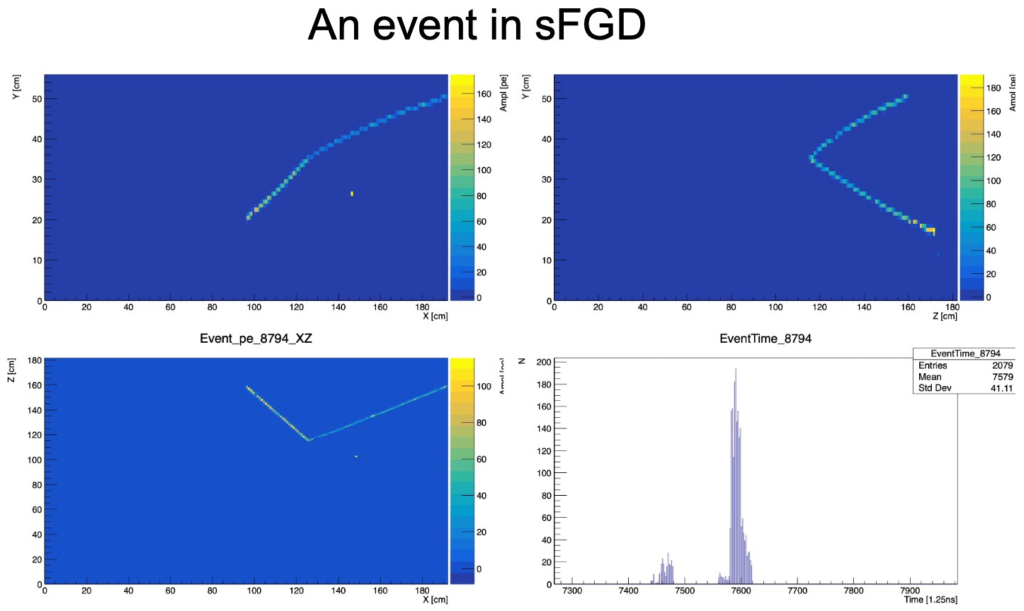




Upgrade to original T2K Near Detector

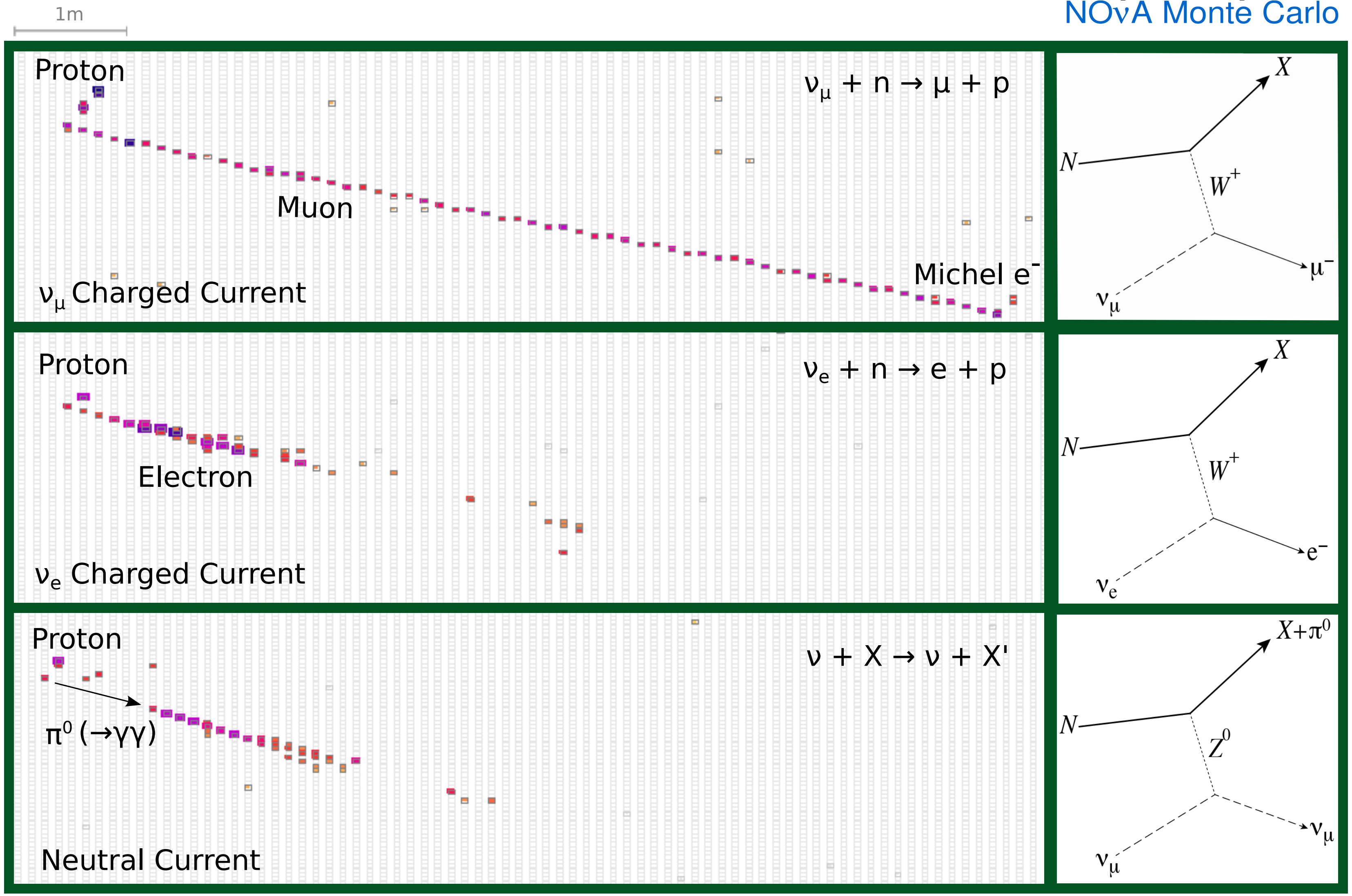






Same event seen in three different directions
K. Mahn, J-PARC PAC 2024

NOνA Data Event Displays



Near Detector used for cross sections has same cell size, same longitudinal segmentation

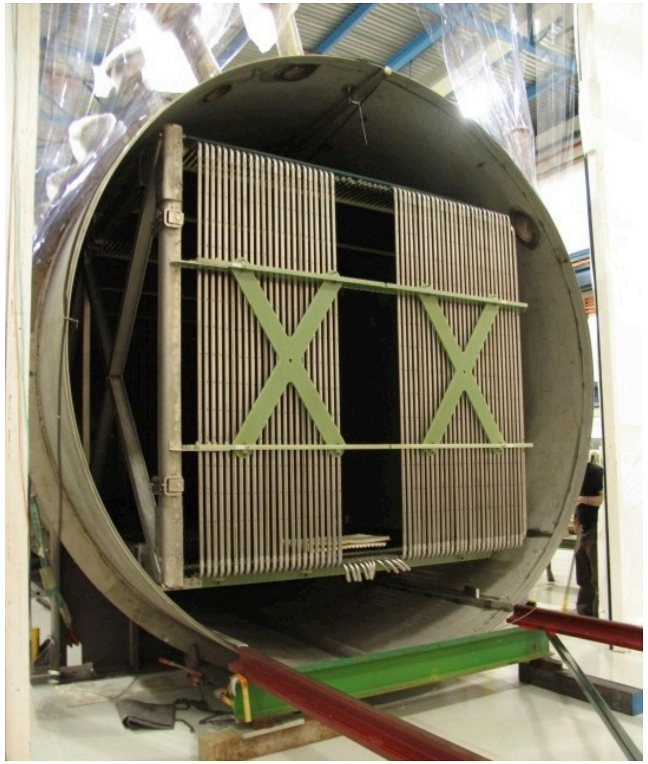
Reference:

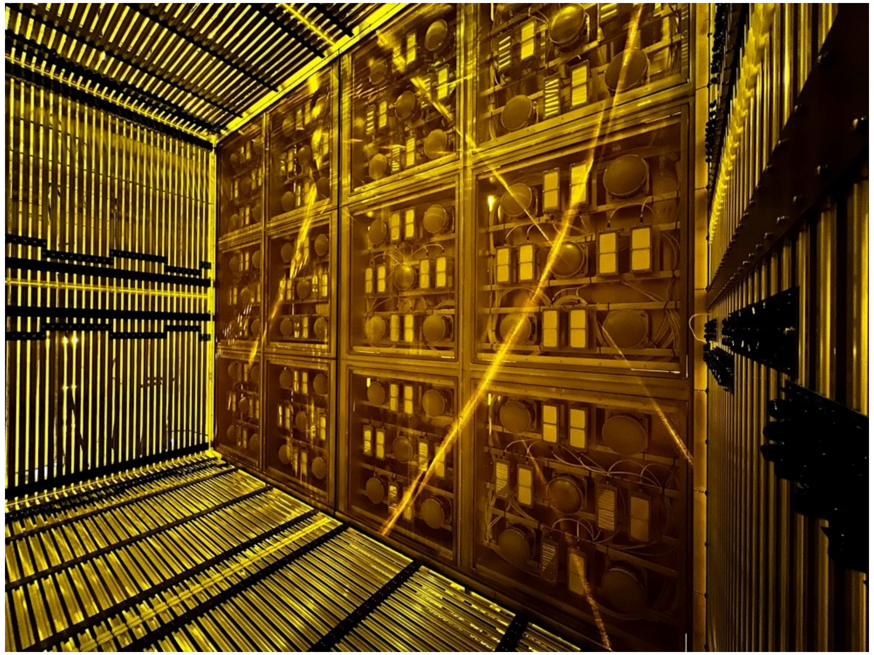
NOvA: half-time review
DOI: 10.1140/epjs/11734-021-00285-9

One unit is 4.9 cm (horizontal)
4.0 cm (vertical)

ICARUS/MicroBooNE/SBND

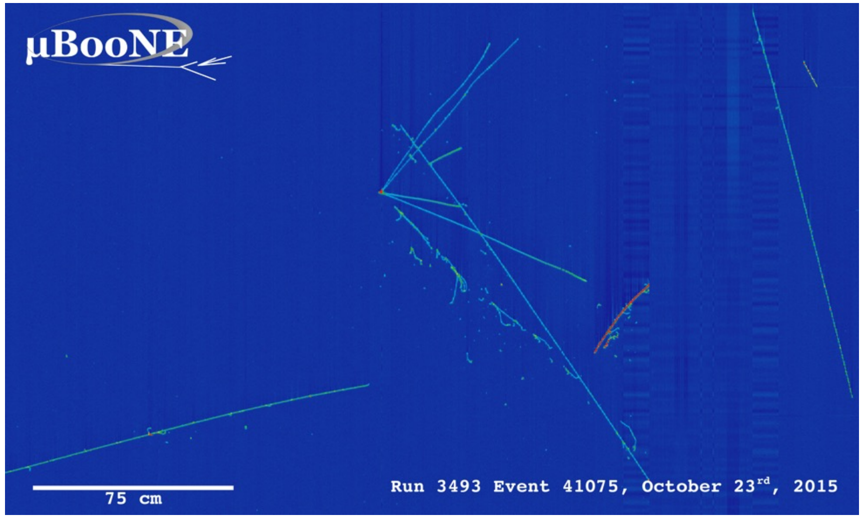
- Active mass: 476 tons / 87 tons/ 112 tons
- Wire spacing: 3mm (all)
- Electron drift distance: 1.5m/2.5m/1.5m
- 74/ 30 / 60 PMT's for scintillation light from pure Argon (timing)
- ICARUS: $<E_\nu>$ ~ 20GeV, L=730km
  - Took data in CNGS beamline, and in MiniBooNE beamline and NuMI Off-axis
- MicroBooNE: $<E_\nu>$~0.8GeV, L=1km
  - Data from MiniBooNE beamline (BNB) and NuMI Off-axis
- SBND: : $<E_\nu>$~0.8GeV, L=0.11km
  - Data in MiniBooNE beamline (BNB)



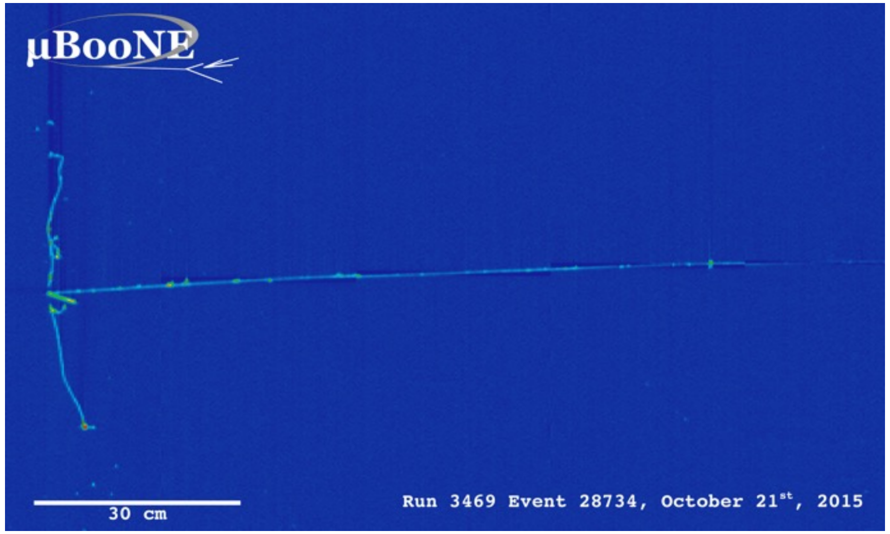


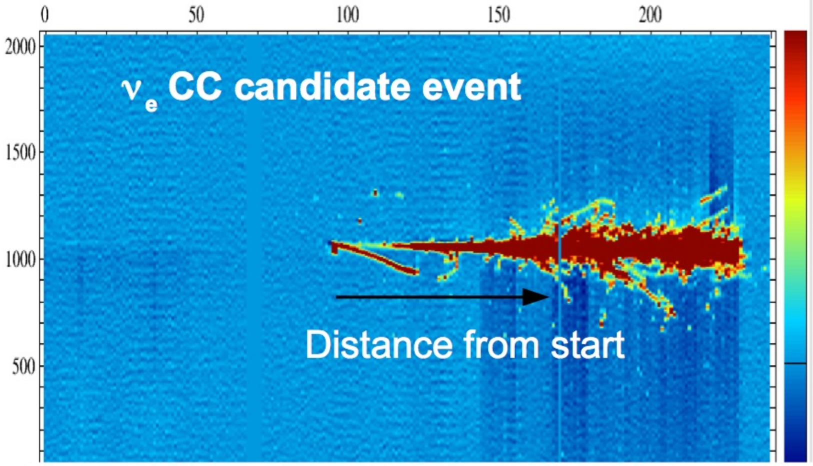
Examples of Liquid Argon Events

- Lots of information for every event…

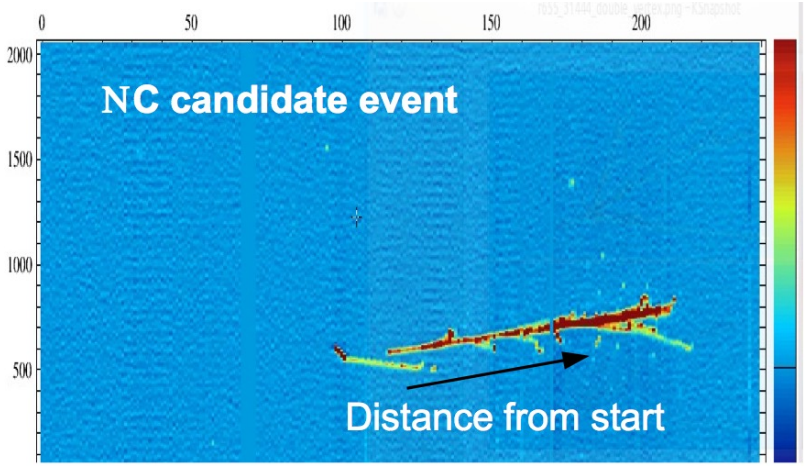


~1GeV beamline events





A. Szelc, ν2014, Argoneut in NuMI
B. ~3GeV beamline



How to measure a Cross Section

- Golden Rule in Cross Section Measurements:

$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)M$$

- More generally, consider an observable *x* that describes the interaction

$$\mathrm{N}(x_{true}) = \int \frac{d\sigma(E_\nu, x_{true})}{dx_{true}} \Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M dx_{true}$$

- And no detector is perfect, so what we really measure is as a function of “$\mathrm{N}(x_{measured})$” , so there’s an additional step

Measuring Cross Sections: Simplify notation

- Remove subscript from true variables, but t=bin of x_{true}, m=measured
- We'll write Φ but it really means "integrating over the flux"
- Switch from U^{-1} to U again just for simplicity, sometimes called "unfolding"

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

Easiest Cross Section to measure: “Inclusive Charged Current Interactions”

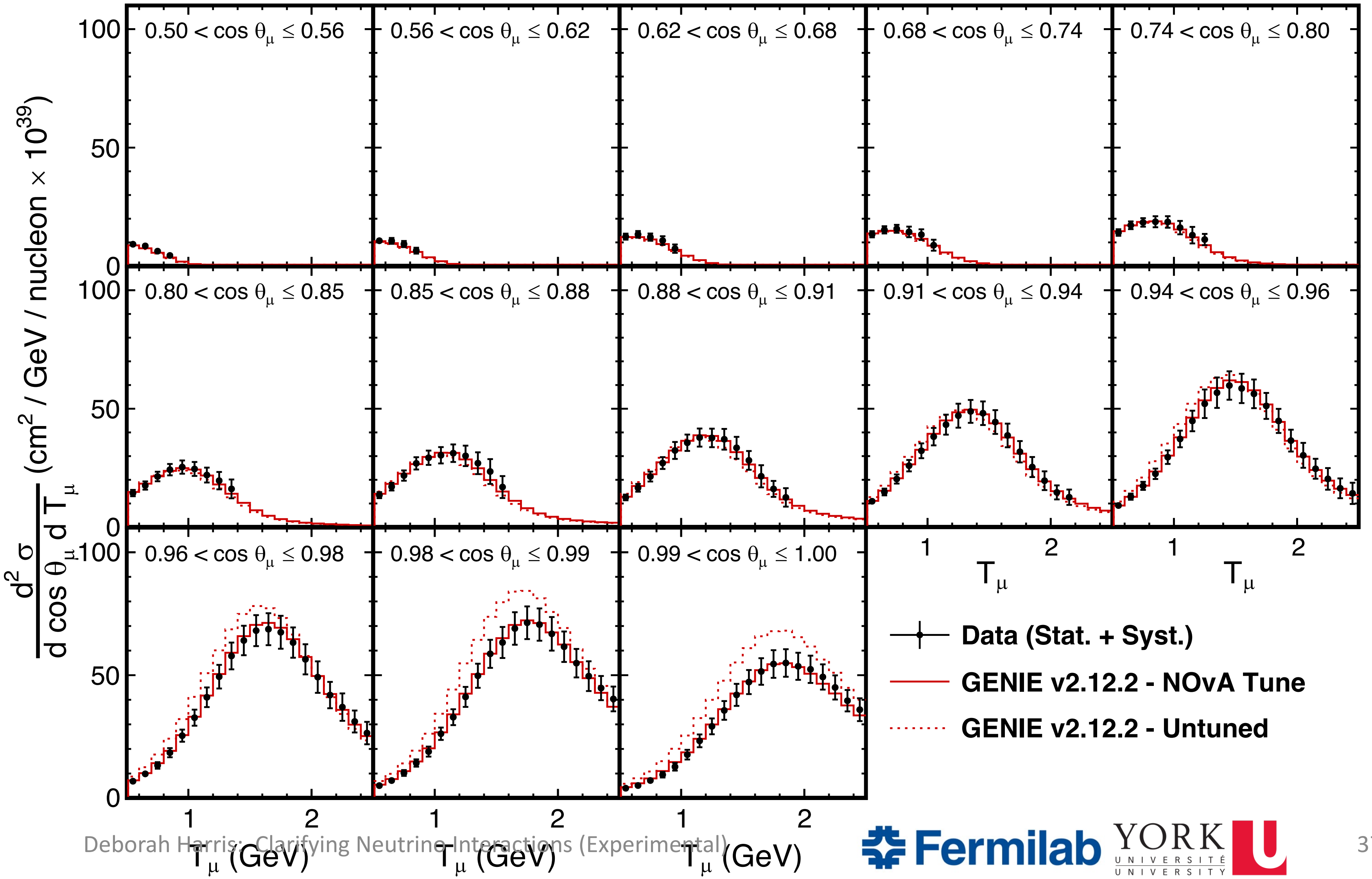
- Say you want to measure total Charged Current neutrino cross section
- What cuts would you use to isolate your signal?
  -
  -
- What are your backgrounds?
  -
  -
- “Easy” Observables to measure: Muon Kinetic Energy (T) and angle (θ) w/rt Neutrino beam

Easiest Cross Section to measure: "Inclusive Charged Current Interactions"

- Say you want to measure total Charged Current neutrino cross section
- What cuts would you use to isolate your signal?
  - Require a muon-like energy or an electron-like energy
  - If you have a magnetic field, might be able to cut on charge of final state lepton
- What are your backgrounds?
  - Antineutrino interactions (low if you have a B field)
  - Neutral Current Interactions
    - For muon neutrinos: $\pi^+ \rightarrow \mu^+(+\nu_\mu)$
    - For electron neutrinos: $\pi^0 \rightarrow \gamma\gamma$ and recall that γ might look like electrons in your detector
- "Easy" Observables to measure: Muon Kinetic Energy (T) and angle (θ) w/rt Neutrino beam

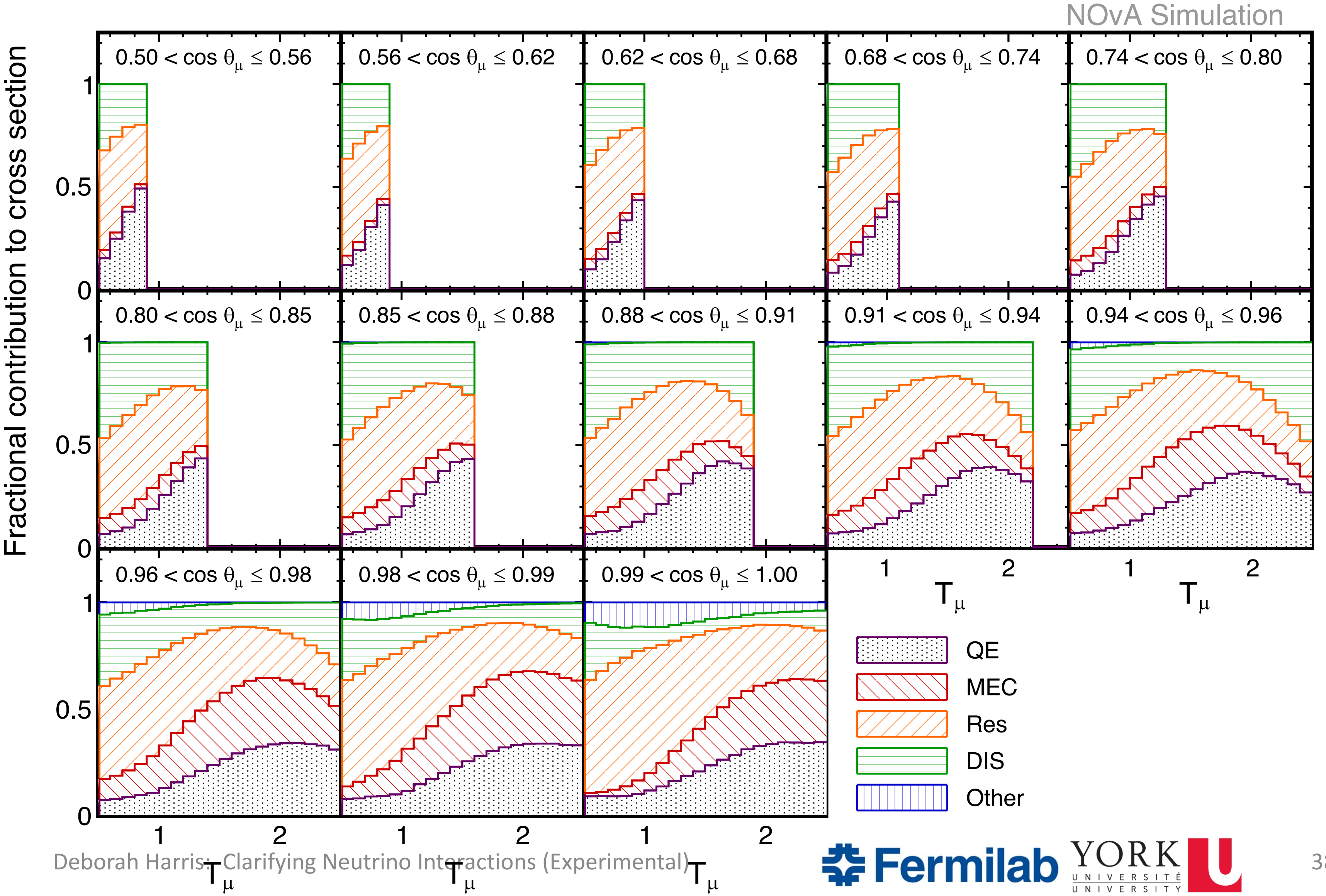
One example of Inclusive Cross Section Result

- NOvA ν_μCC Cross Section Result, vs. muon kinematics
- *Phys.Rev.D* 107 (2023) 5, 052011
- Even for a narrow range of neutrino energy (like NOvA) any one kinematic region still has a range of interactions that contribute.



The Catch with Inclusive Cross Sections

- NOvA ν_μCC Cross Section Result, vs. muon kinematics
- *Phys.Rev.D* 107 (2023) 5, 052011
- Even for a narrow range of neutrino energy (like NOvA) any one kinematic region still has a range of interactions that contribute.



Using both Lepton and Hadron Information

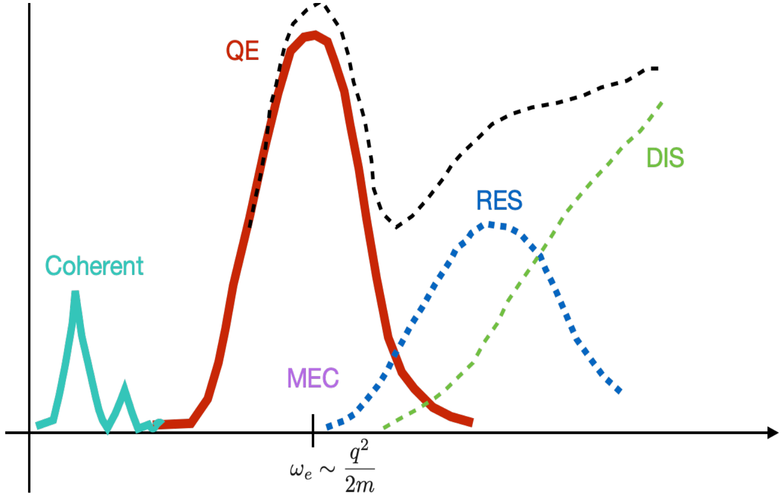
- Let's say you have measured the following quantities:
  - Final lepton charge and momentum 3-vector: can determine p_{lep}, E_{lep}, θ_{lep}
  - Total hadronic energy

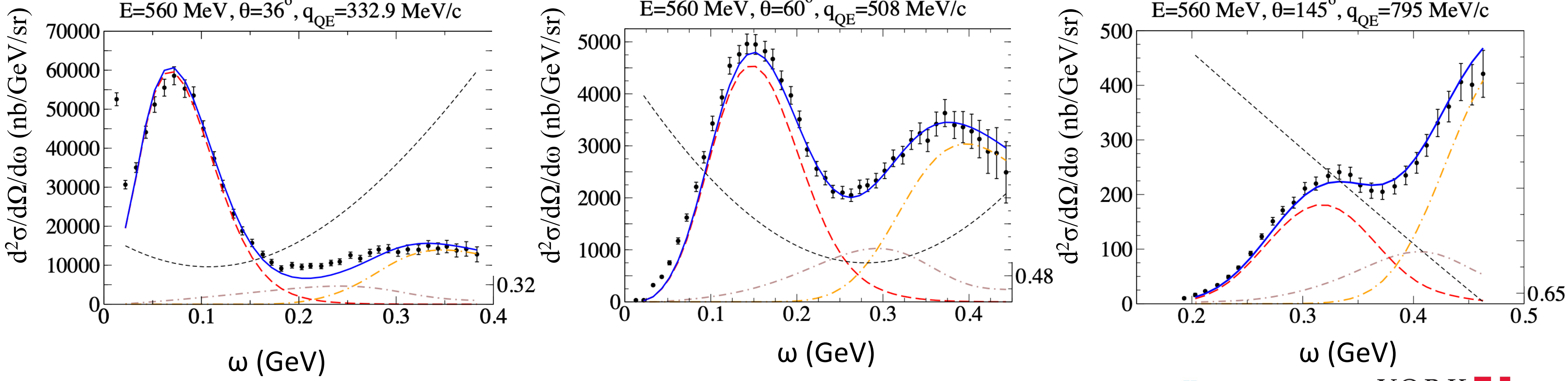
    (**pretend** you can see all of it, even the neutron energy) E_{had}
- Can define a few quantities:
  - Estimated Neutrino Energy $E_\nu = E_{lep} + E_{had}$
  - Estimated Momentum Transfer (squared) to the nucleus:

    (remember, W is virtual) $-q^2=Q^2 = 2\,E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$
  - Estimated Energy transferred to the nucleus = $\omega = E_{had}$
  - 3-momentum transferred to the nucleus: $Q^2+\omega^2=q_3^2$

Neutrino Observables w/hadrons & leptons

- Learning from from e⁻ scattering: e⁻ beam (energy E) comes in, scatters, you measure the outgoing electron energy distribution (E') at some angle, and ω=E-E'



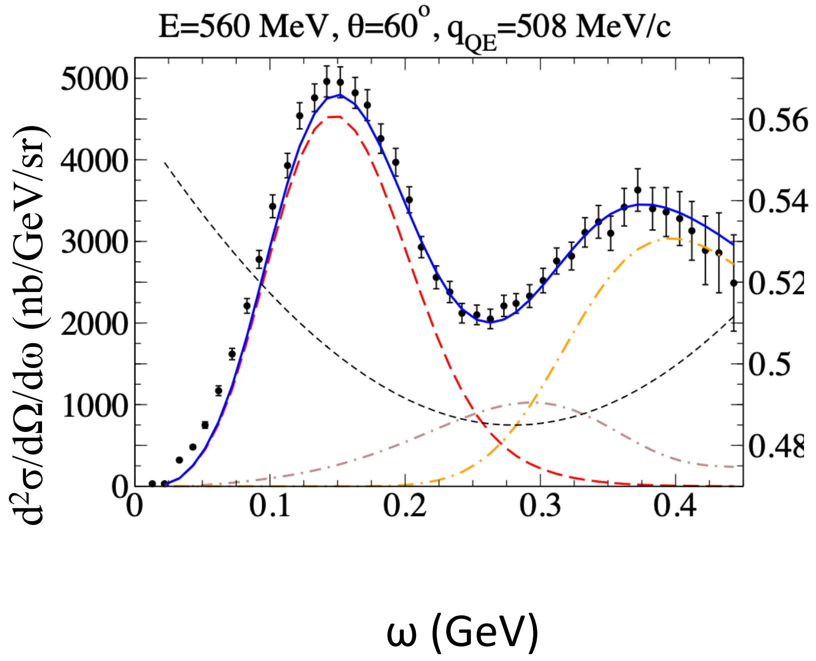


Phys. Rev. D 94, 013012 (2016)

Neutrino Observables w/hadrons & leptons

- Translating this picture to Neutrino Scattering

Graphics courtesy R. Gran

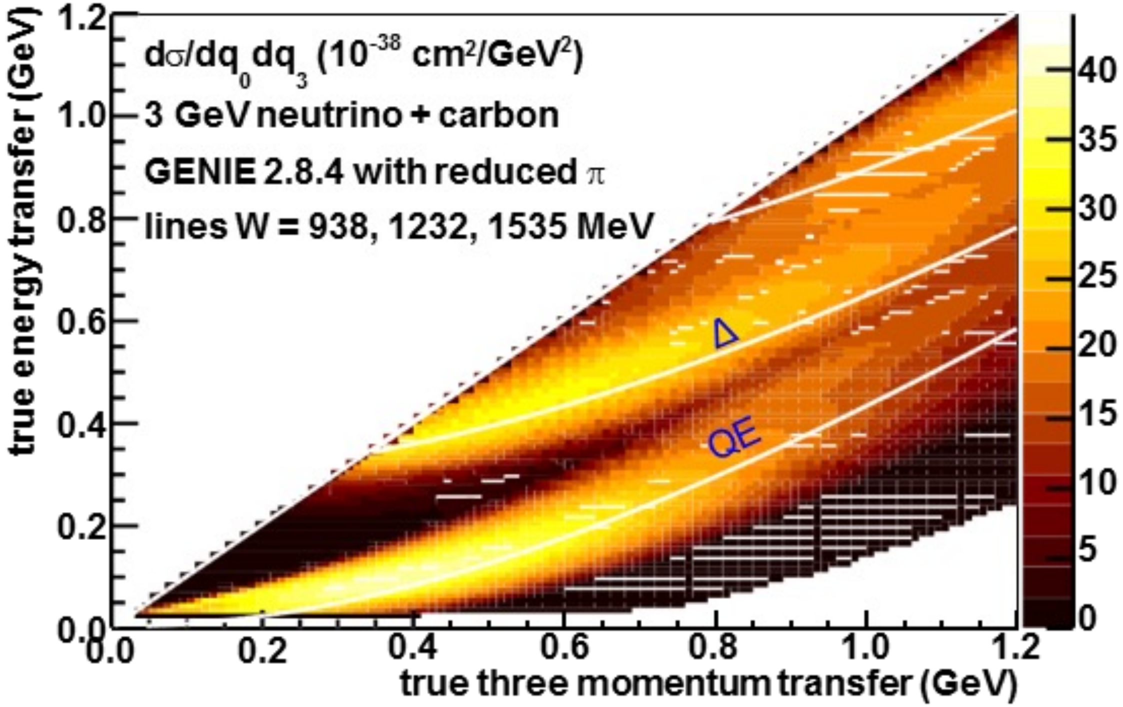


Initial and Final Electron energy and angle define a 3-momentum transfer

For neutrinos:

True Energy transfer: ω

True 3-momentum transfer: $Q^2+\omega^2=q_3^2$



Phys. Rev. D 94, 013012 (2016)

Proxy for True Energy transfer to Hadronic system: "Available Energy"

- Visible in scintillator (and argon)
- π^{+-} deposit their kinetic energy, but not their mass
- π^0 deposit their total energy
- Protons: deposit total kinetic energy
- Neutrons: deposit very little.
- "Available energy": sum of visible energy

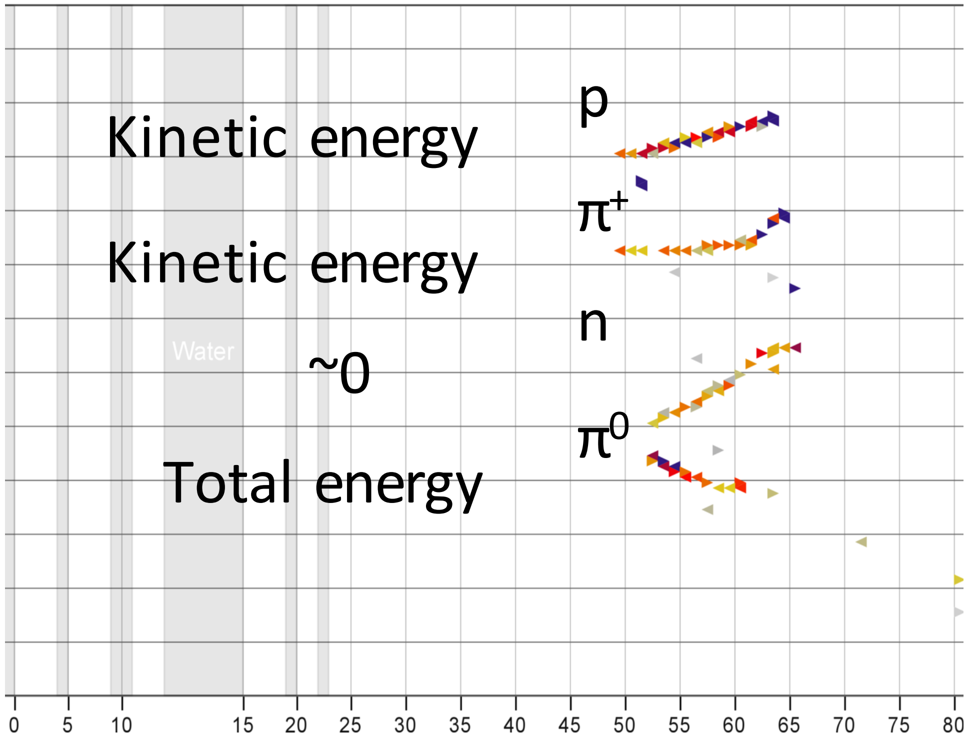


Figure courtesy P. Rodrigues

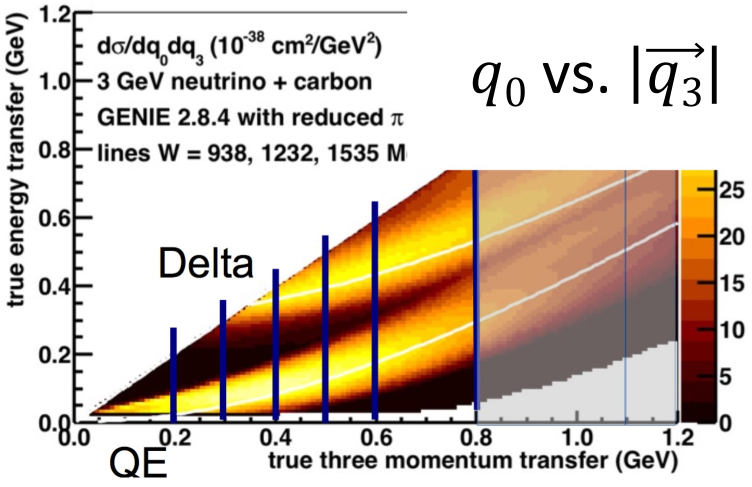
Example from MINERvA at right,
3.3cm plastic granularity
Similar in spirit to ~3cm wire pitch Liquid Argon (but different density, Z)

Phys. Rev. D 94, 013012 (2016)

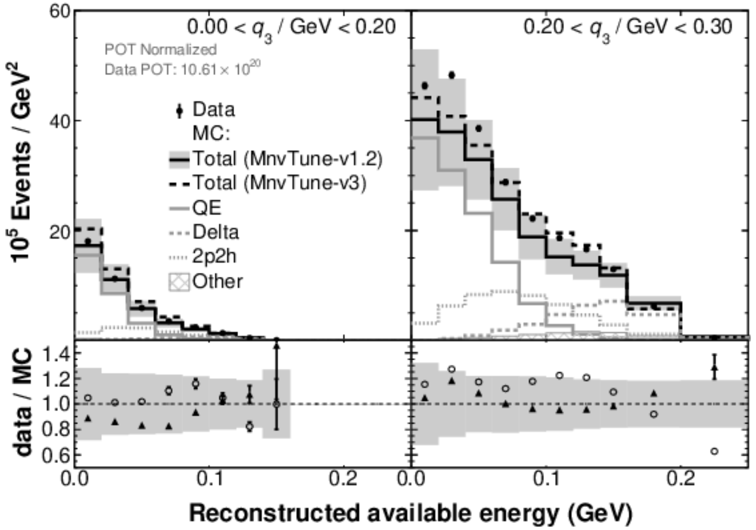
What does the Data Look like in this space?

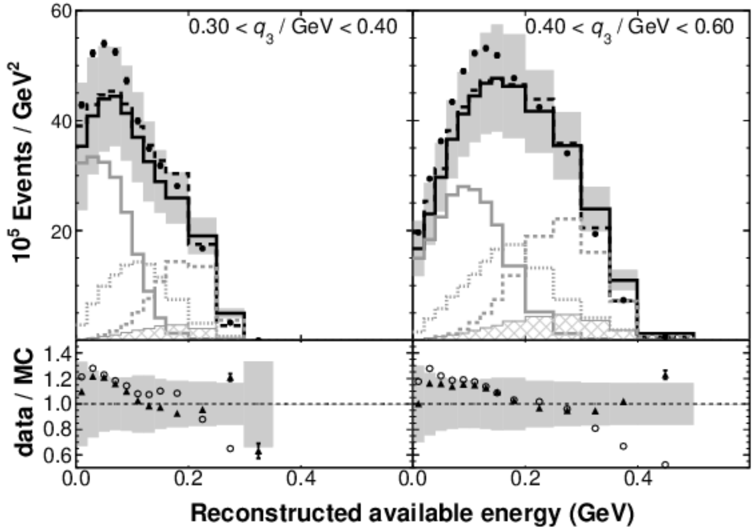
- Look at inclusive sample of events as function of energy AND momentum transferred
- Showing event distributions, but cross sections were extracted
- Cross sections were also extracted from these distributions
- Available Energy: “visible” energy in scintillator
- Unfolding this was tricky!

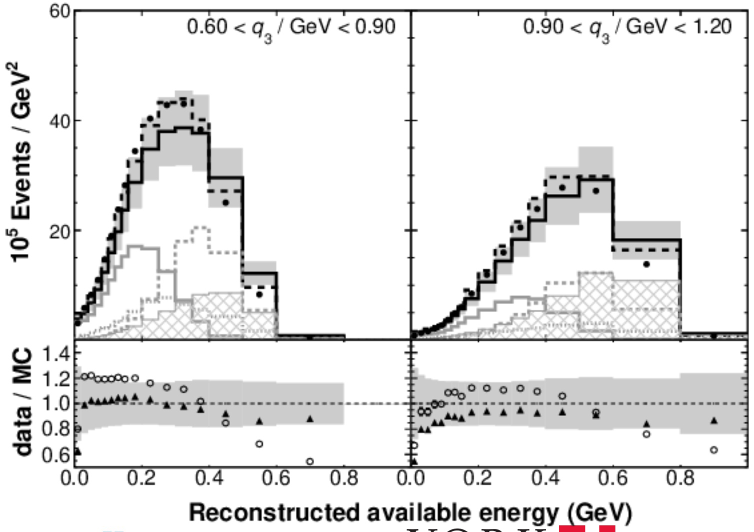
M. Ascencio et al,
Phys.Rev.D 106 (2022) 3, 032001



q_0 vs. $|\overrightarrow{q_3}|$

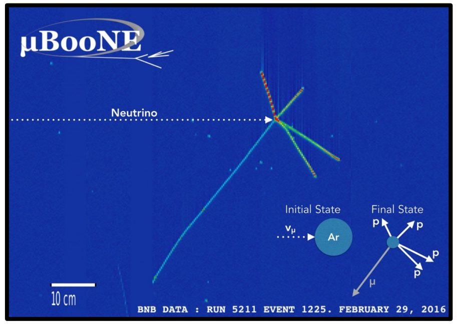


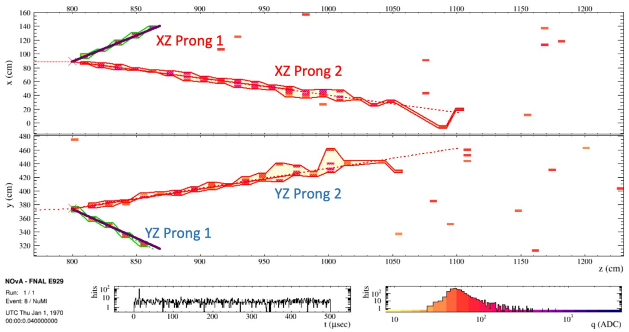


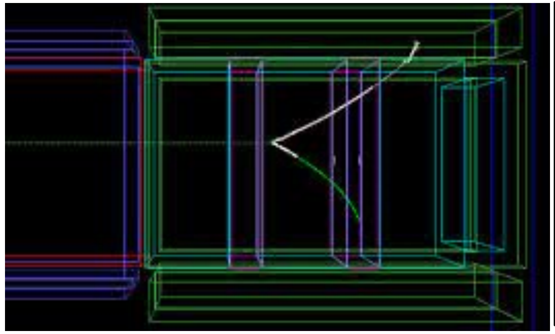
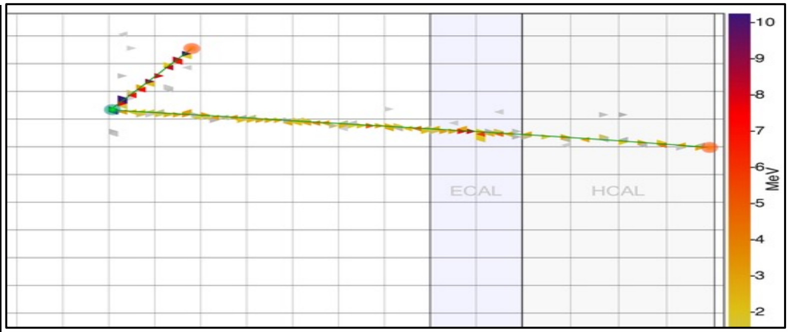


From Inclusive to Exclusive

- From these event displays, you know we can do better to isolate processes and look at only one (set of) final states



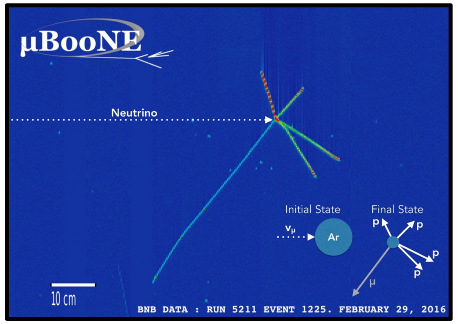


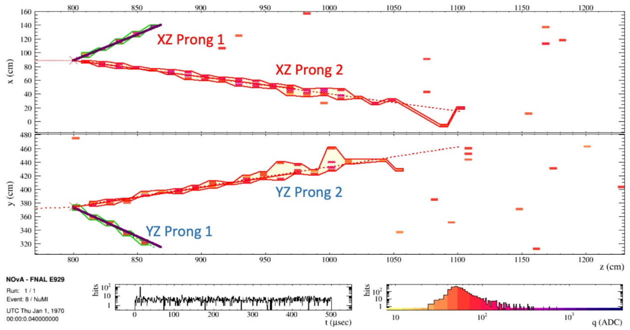



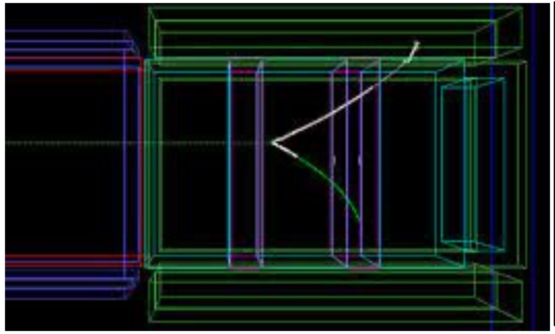
- How would you isolate events that are quasielastic?
  -
  -
  -

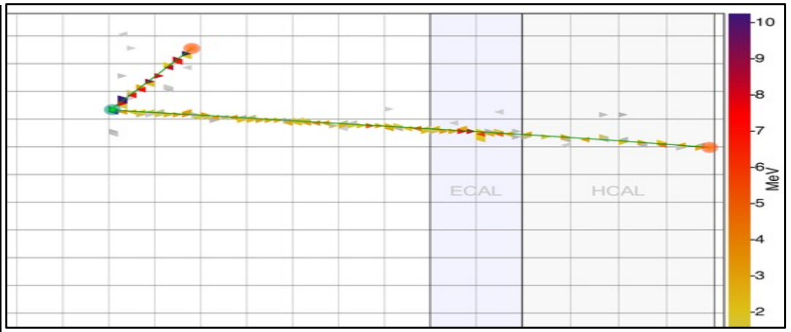
From Inclusive to Exclusive

- From these event displays, you know we can do better to isolate processes and look at only one (set of) final states



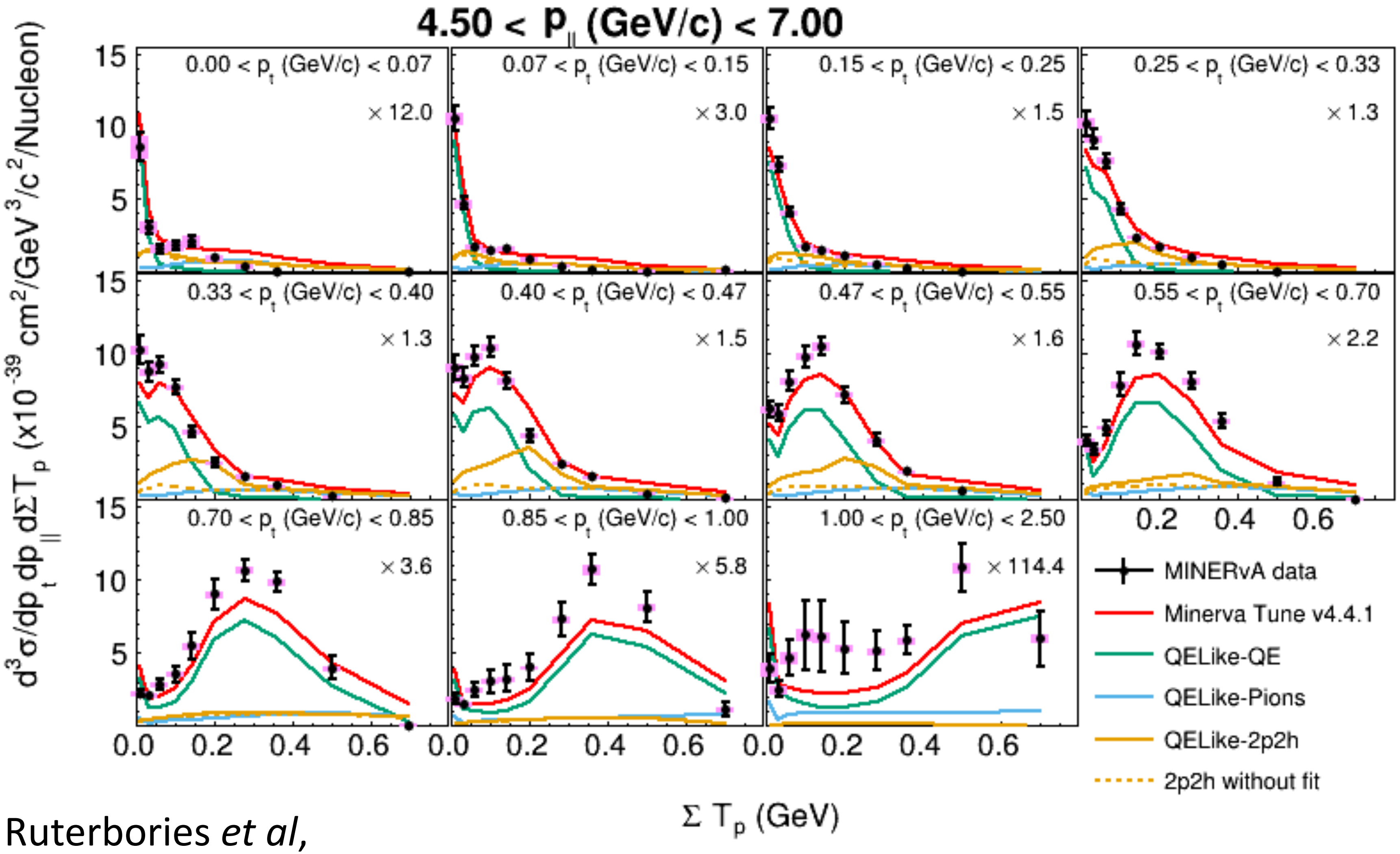






- How would you isolate events that are quasielastic?
  - Require one lepton (of the correct charge if possible)
  - Do you require a proton track? Or do you only require NO pion tracks?
  - What about Michel Electrons: what if you didn't see a pion track but you saw a tiny em-like shower right near the vertex?

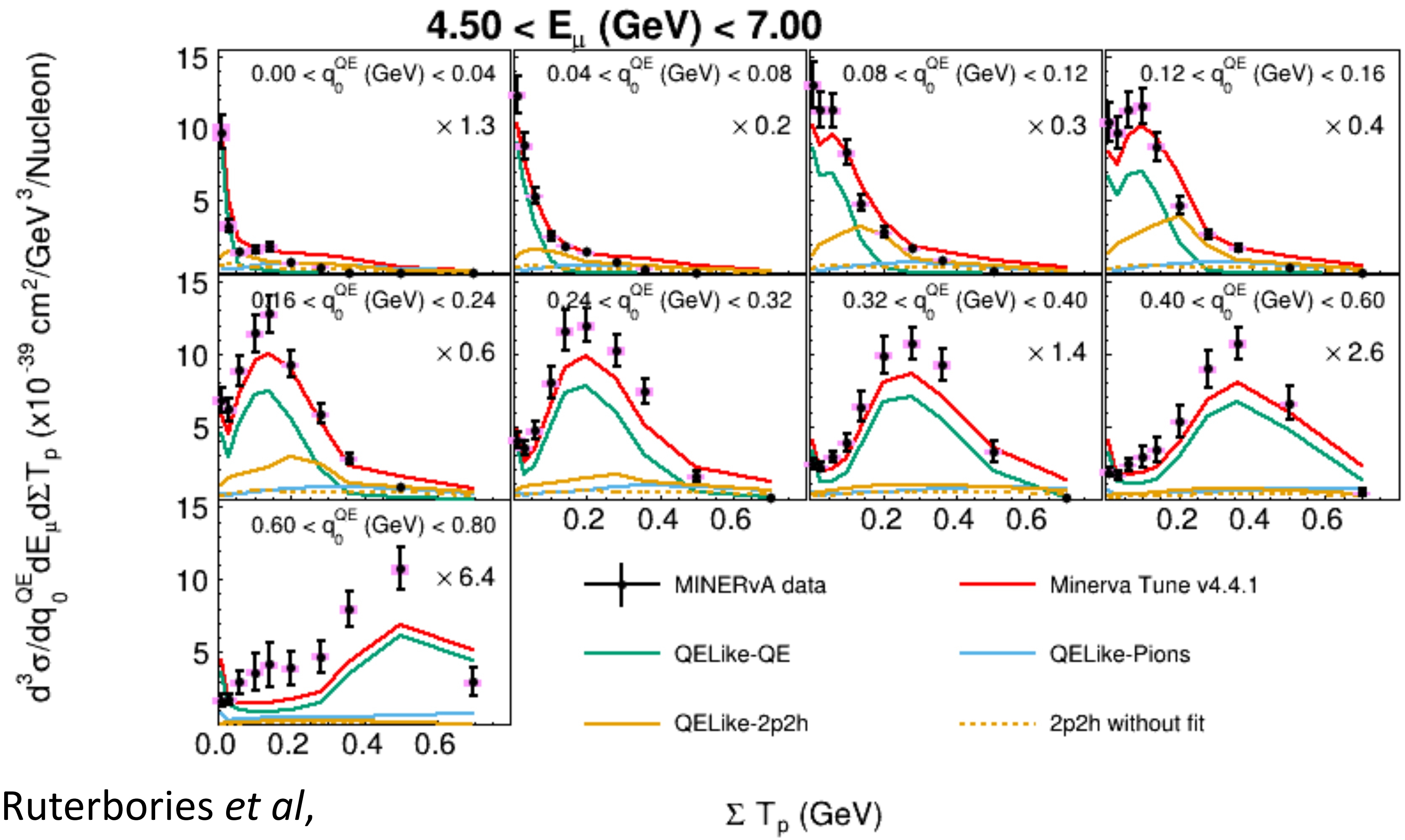
New vocabulary: Quasielastic-like



D. Ruterbories *et al*,
Phys.Rev.Lett. 129 (2022) 2, 021803

- After subtracting backgrounds, MINERvA has enough statistics to bin QE-like events along 3 axes: muon kinematics AND hadron energy
- Many processes contribute to "CC0π"
  - CCQE
  - 2p2h
  - Resonance+π absorption
  - DIS
- Lots of discrepancies with the model

Compare the two proxies we had for "neutrino energy-muon energy":



- T2K and HK: q_0^{QE} gets added
- NOvA, and LAr: add visible recoil energy

  ΣT_p (GeV)
- The two don't agree with the model for quasielastic-like events
- Need to improve models

D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022) 2, 021803

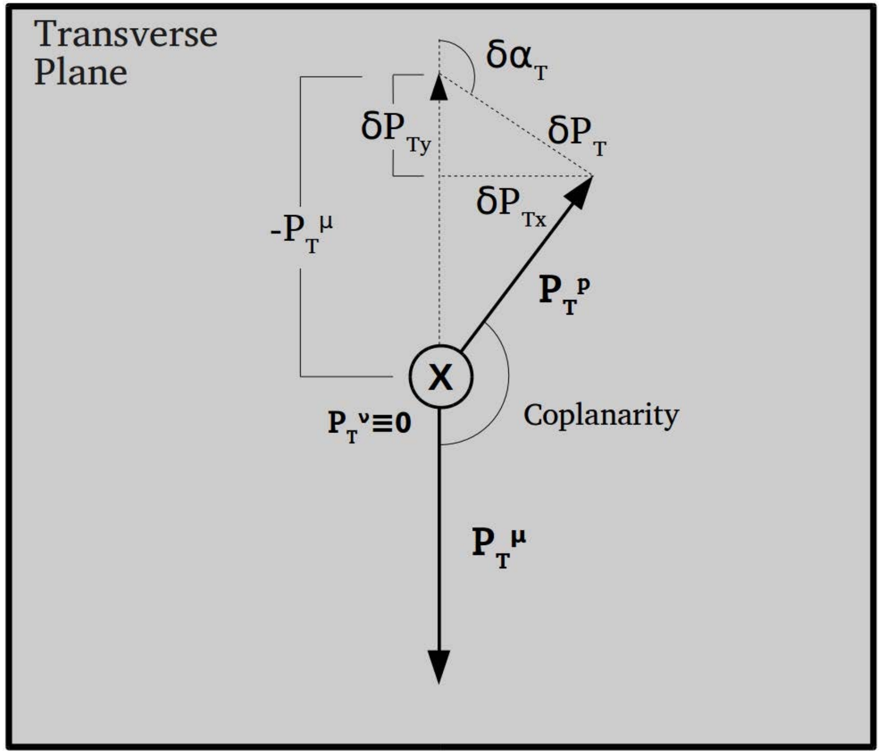
New Neutrino Observables: Transverse Kinematic Imbalance (TKI)

- If you know you're starting with a neutrino, and you see a muon and a proton in the final state, you can calculate kinematics in the plane transverse to the neutrino direction if you measure 3-vector of both final state particles, and you are SURE they are a muon and a proton

$$\delta p_T = |\delta \mathbf{p}_T| = |\mathbf{p}_T^{\mu} + \mathbf{p}_T^{p}| \,,$$

$$\delta \alpha_T = \arccos\left(-\frac{\mathbf{p}_T^{\mu} \cdot \delta \mathbf{p}_T}{p_T^{\mu} \delta p_T}\right),$$

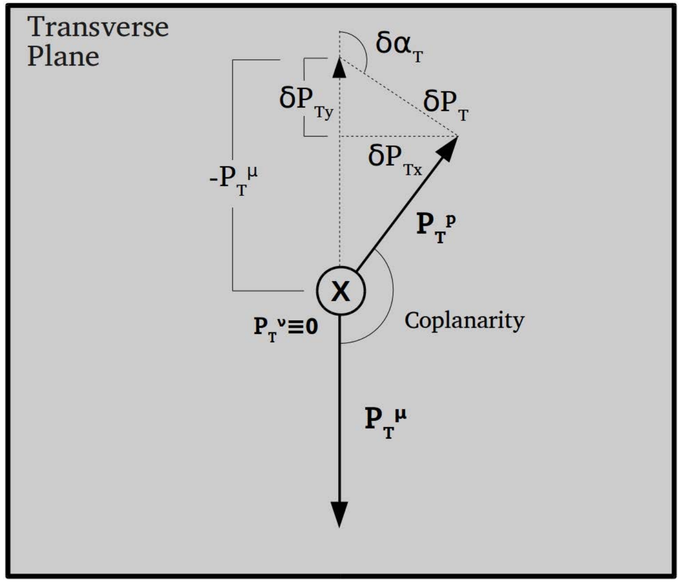
$$\delta \phi_T = \arccos\left(-\frac{\mathbf{p}_T^{\mu} \cdot \mathbf{p}_T^{p}}{p_T^{\mu} p_T^{p}}\right).$$



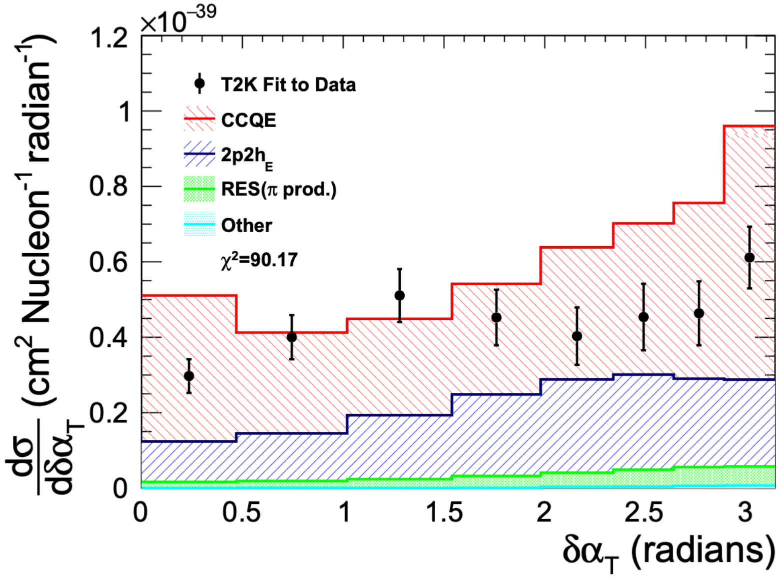
$$P_n \equiv \sqrt{\delta P_T{}^2 + \delta P_L{}^2}$$

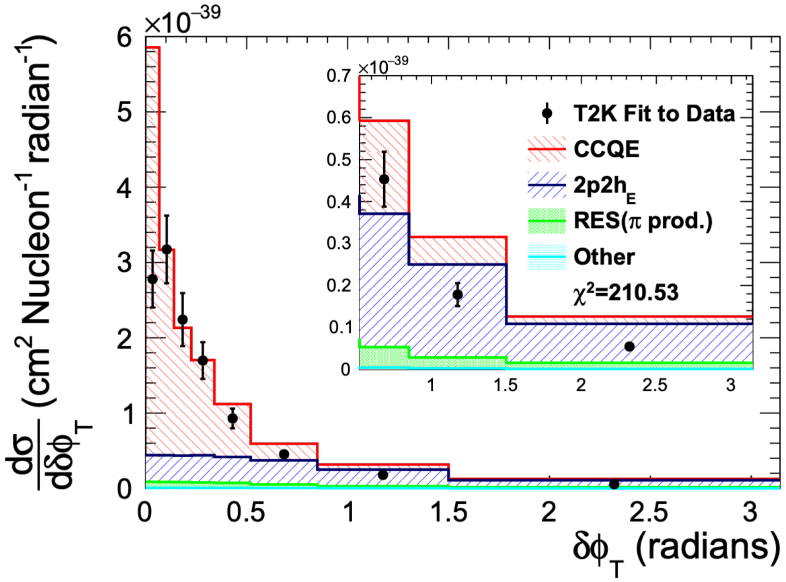
Phys. Rev. C **94**, (2016) 015503

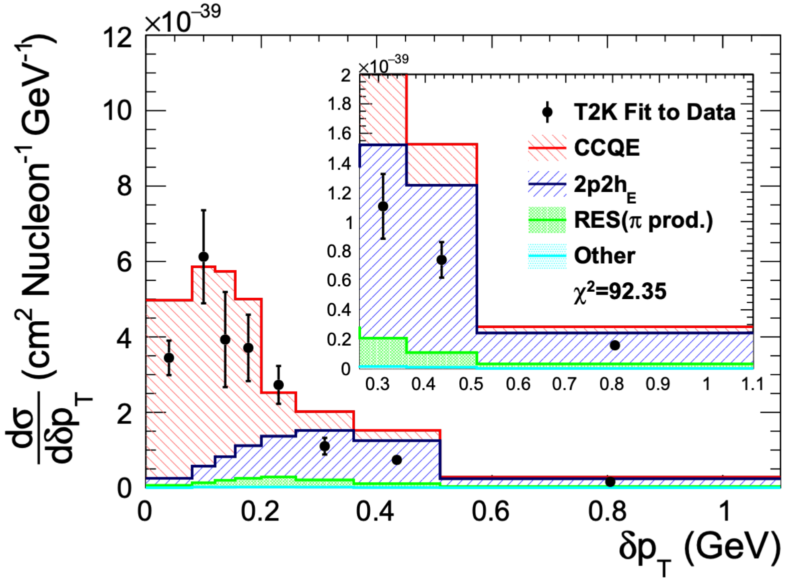
New Neutrino Observables: Transverse Kinematic Imbalance (TKI)



- Hopefully all these different variables will give you a consistent story about what all the different quasielastic-like processes might be there in your data (T2K, *Phys.Rev.D* 98 (2018) 3, 032003)

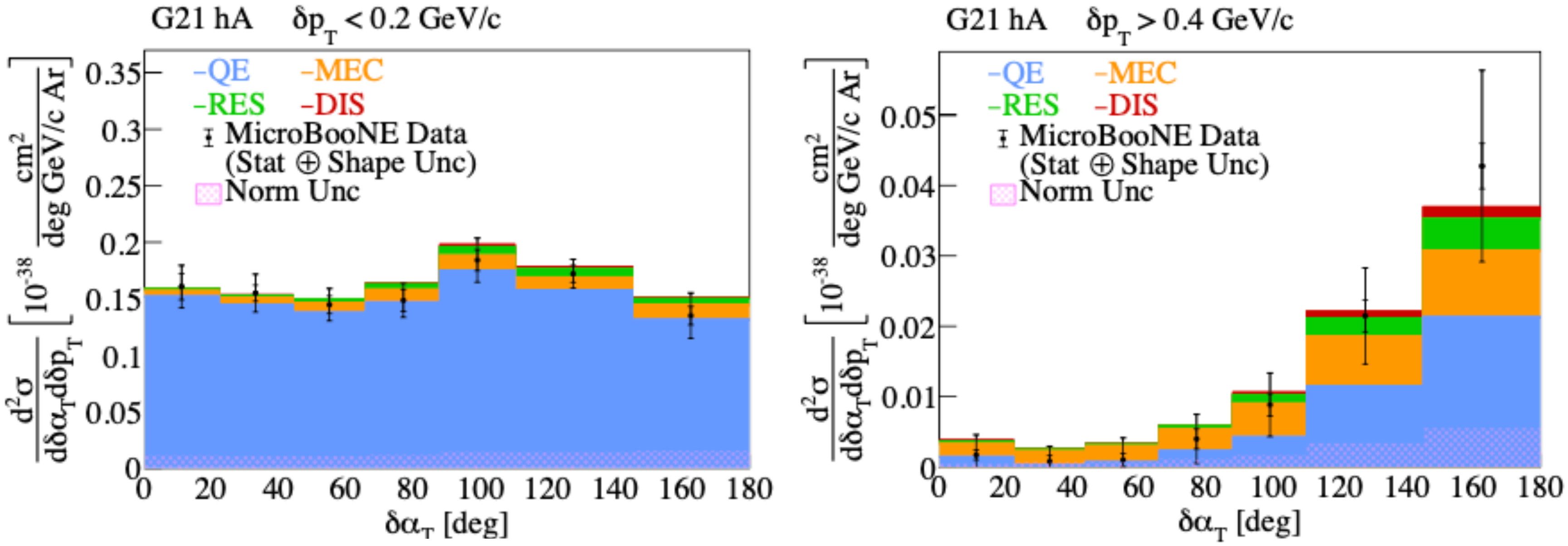


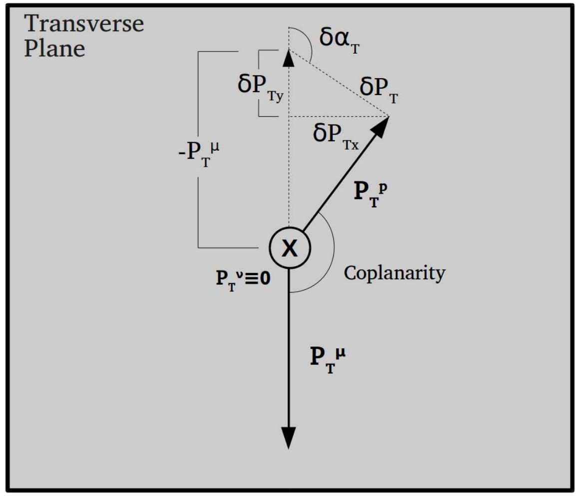




MicroBooNE: Looking at TKI in 2 dimensions

- MicroBooNE split these distributions up into "QE-rich" samples and "everything else" samples
- Can see different contributions in different regions

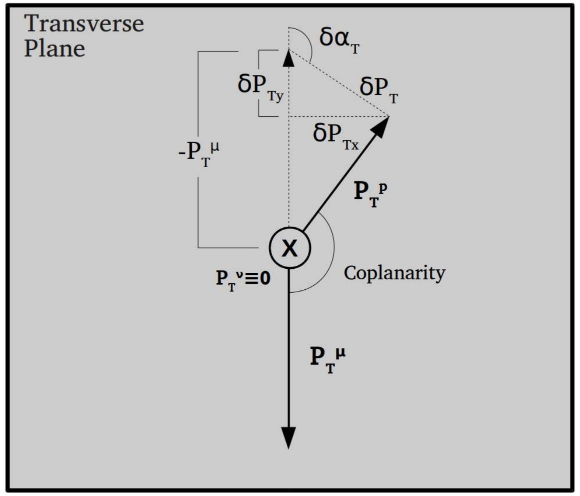


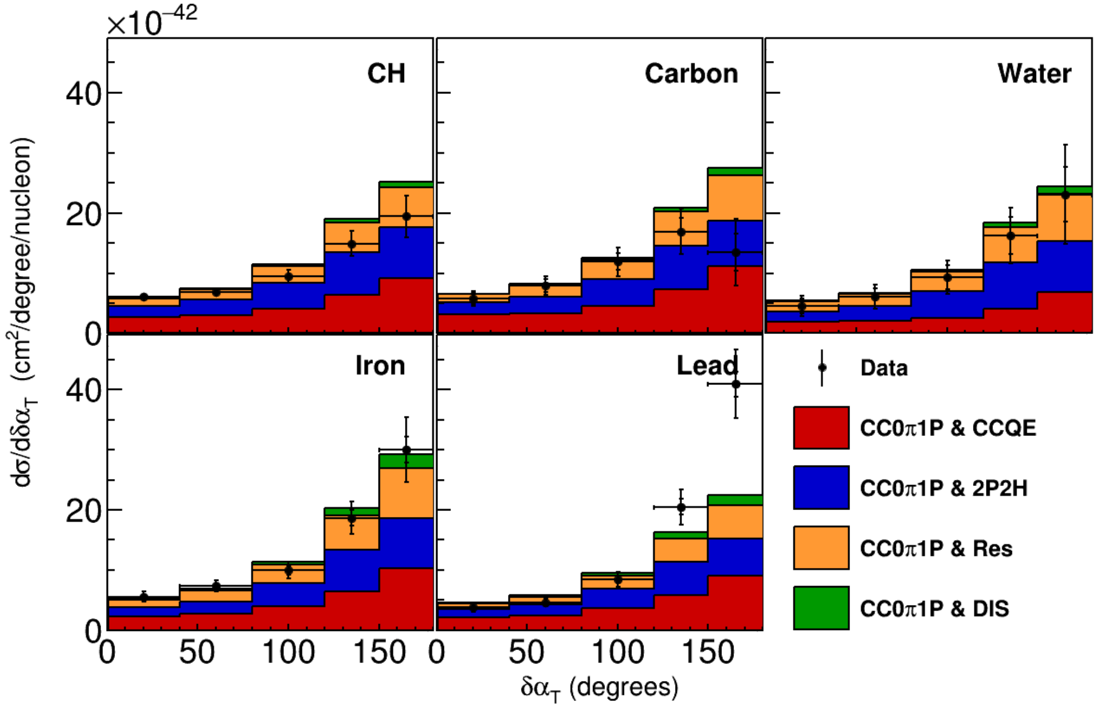


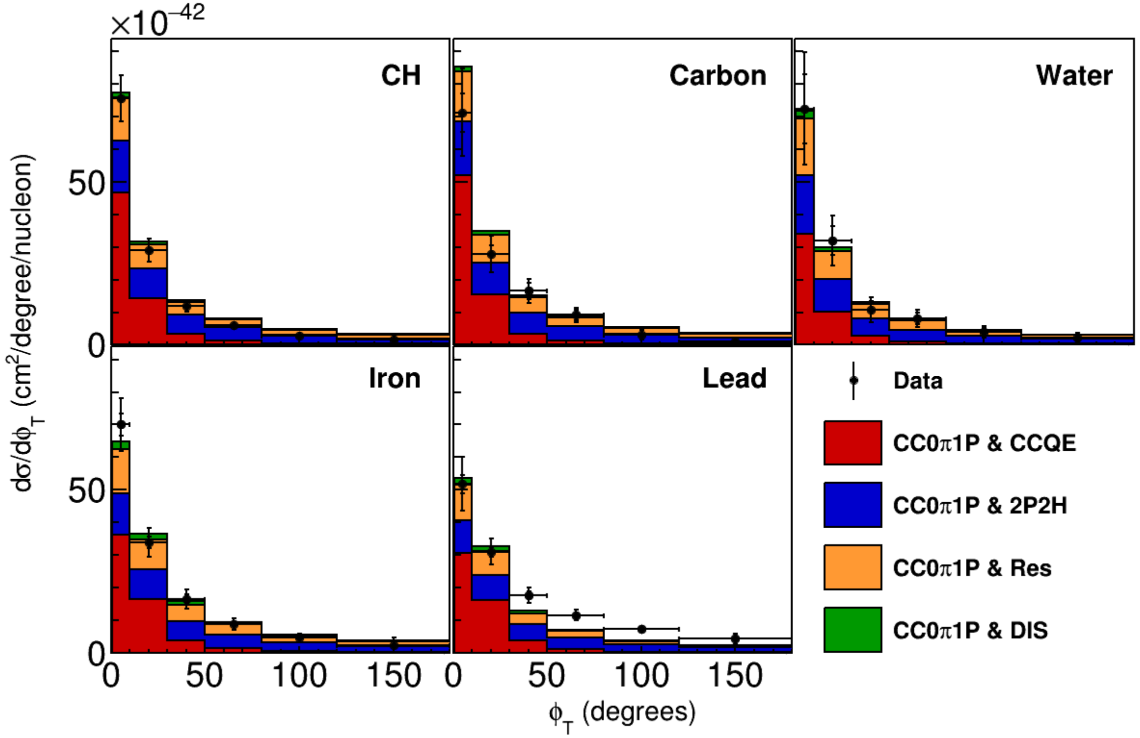
Phys.Rev.D 108 (2023) 5, 053002

MINERvA: Looking at TKI versus A (atomic #)

- GENIE (and other models) do okay with lower A, but nuclear effects in lead far from modeled correctly!





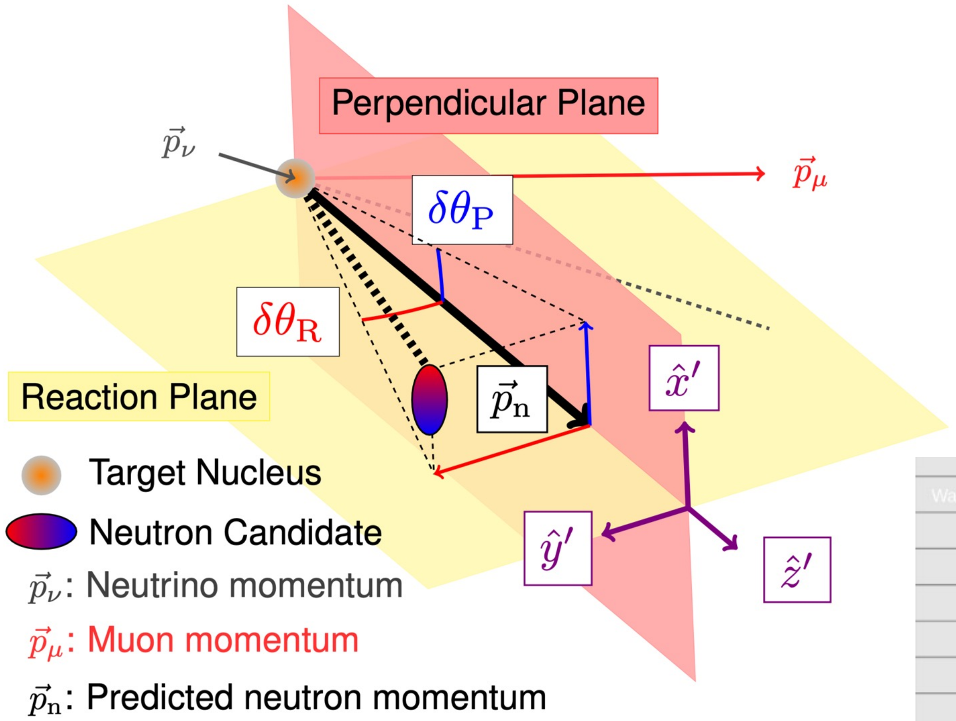


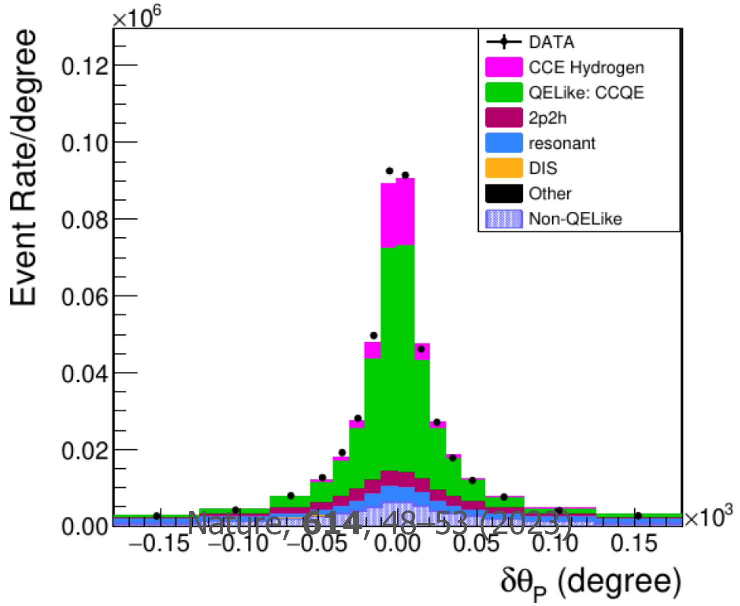
J. Kleykamp, NuINT 2022, paper in preparation

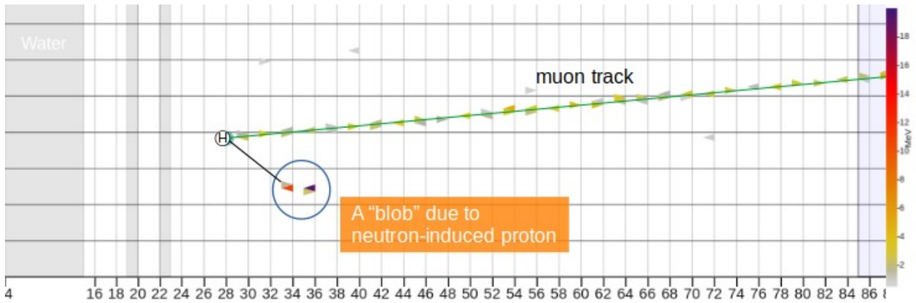
If only we could measure a cross section on H first…

Using "Transverse Kinematics" to see H alone

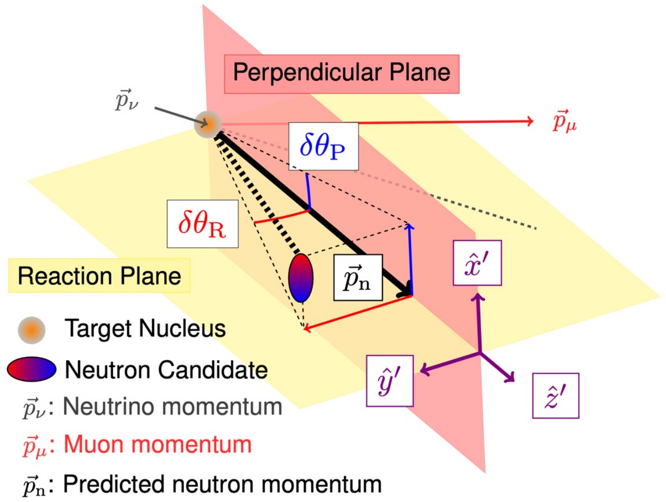
- Consider antineutrino QE-like scattering:
  - $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - If you have a plastic target, you have C and H
  - If you are trying to measure CCQE on H, then CCQE on C is a background
  - Use nuclear effects to isolate H!

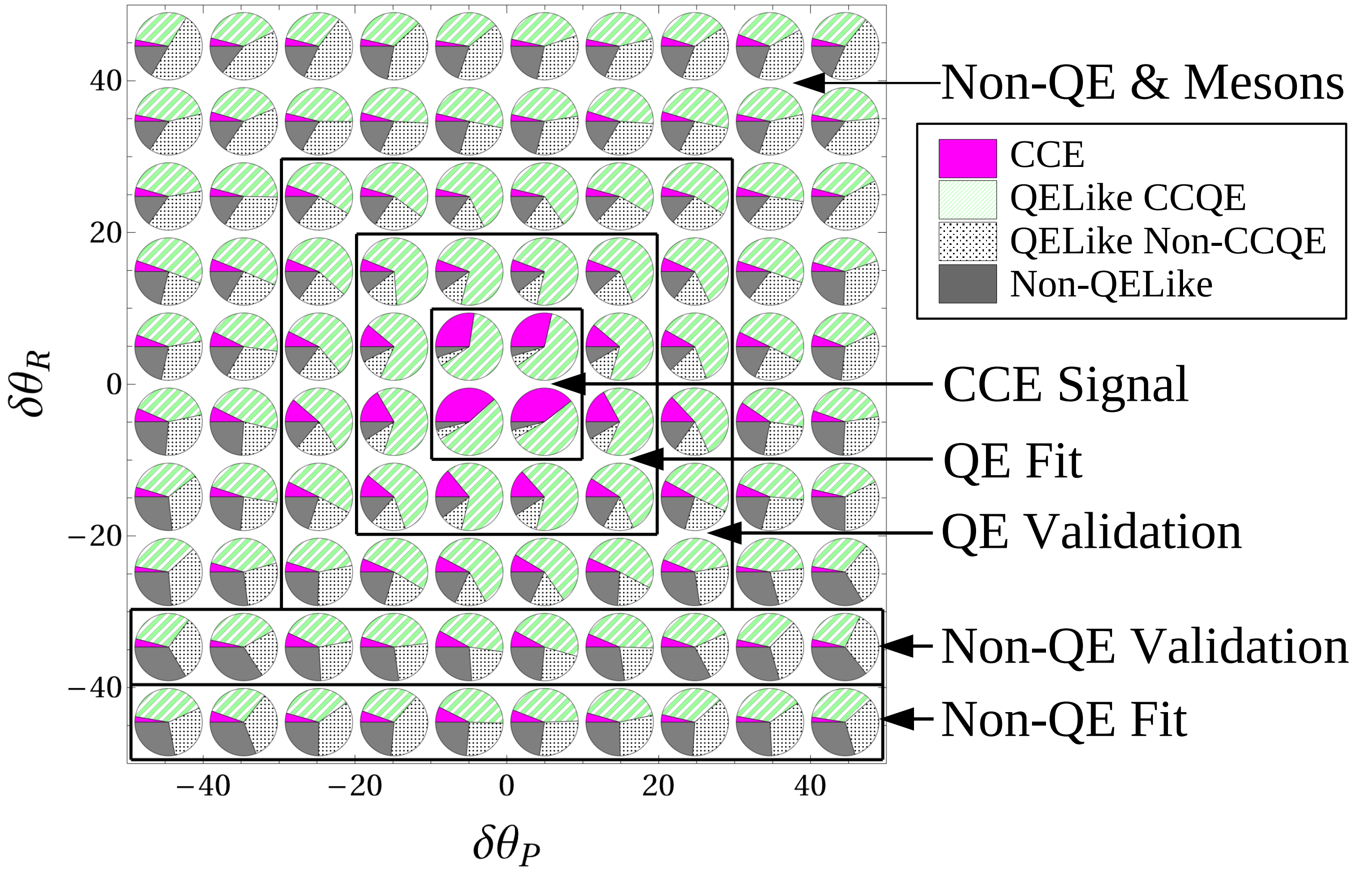


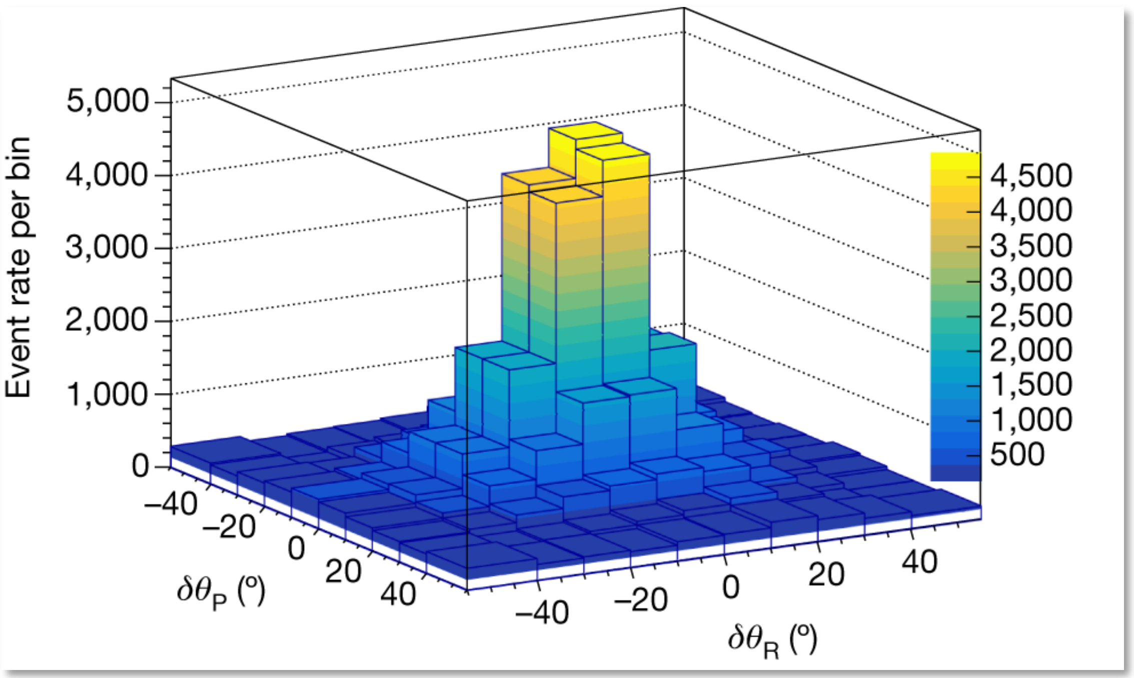




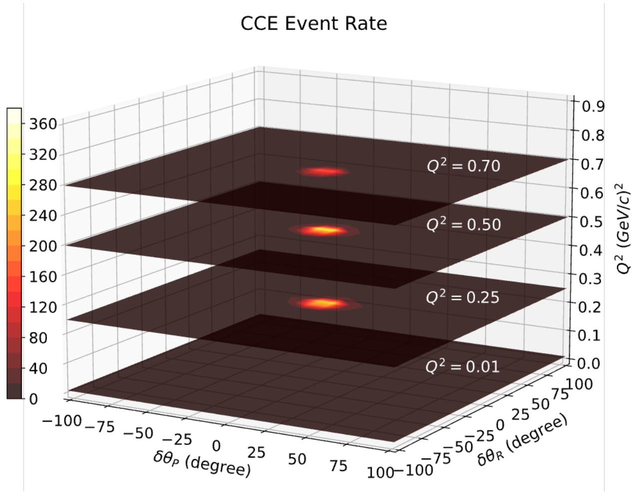
When life gives you lemons… make lemon meringue pie



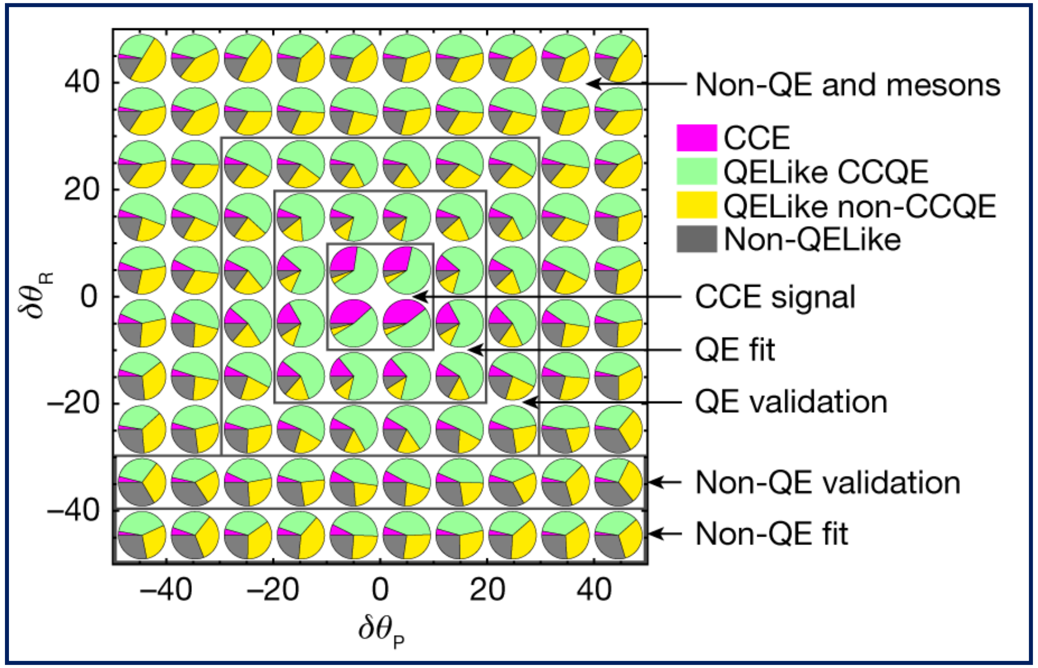


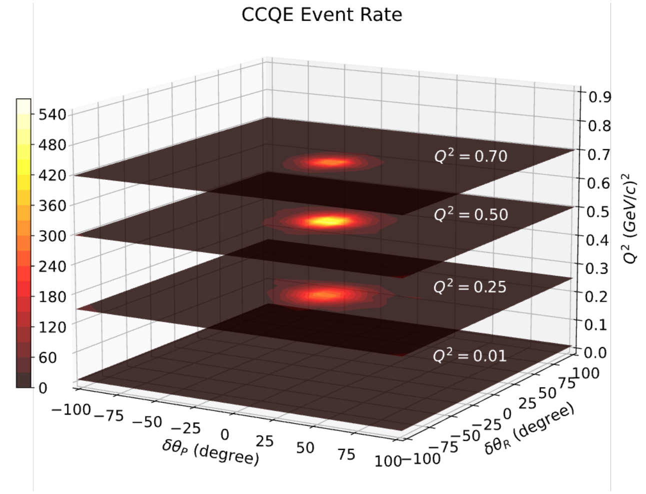


Different Reactions populate different regions

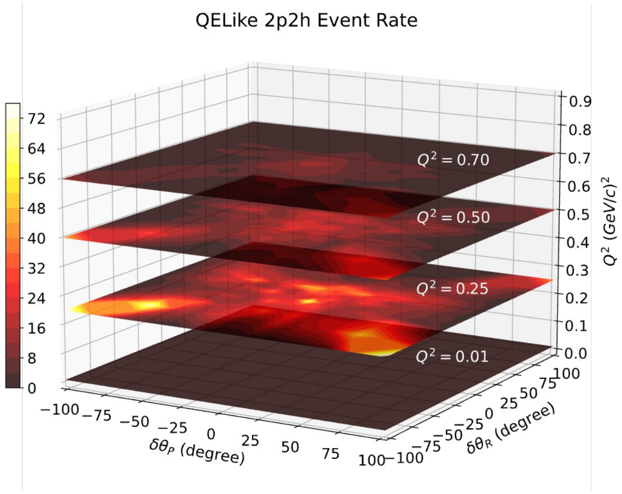


SIGNAL: Elastic on H



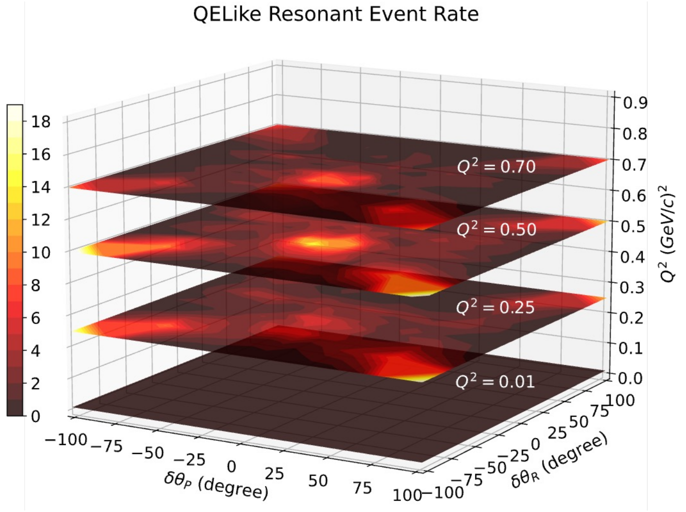


Background: QELike CCQE (on C)



Background: QELike 2p2h

Regions of the 2D angular distribution **used to fit the backgrounds** proportion **in the signal region**.

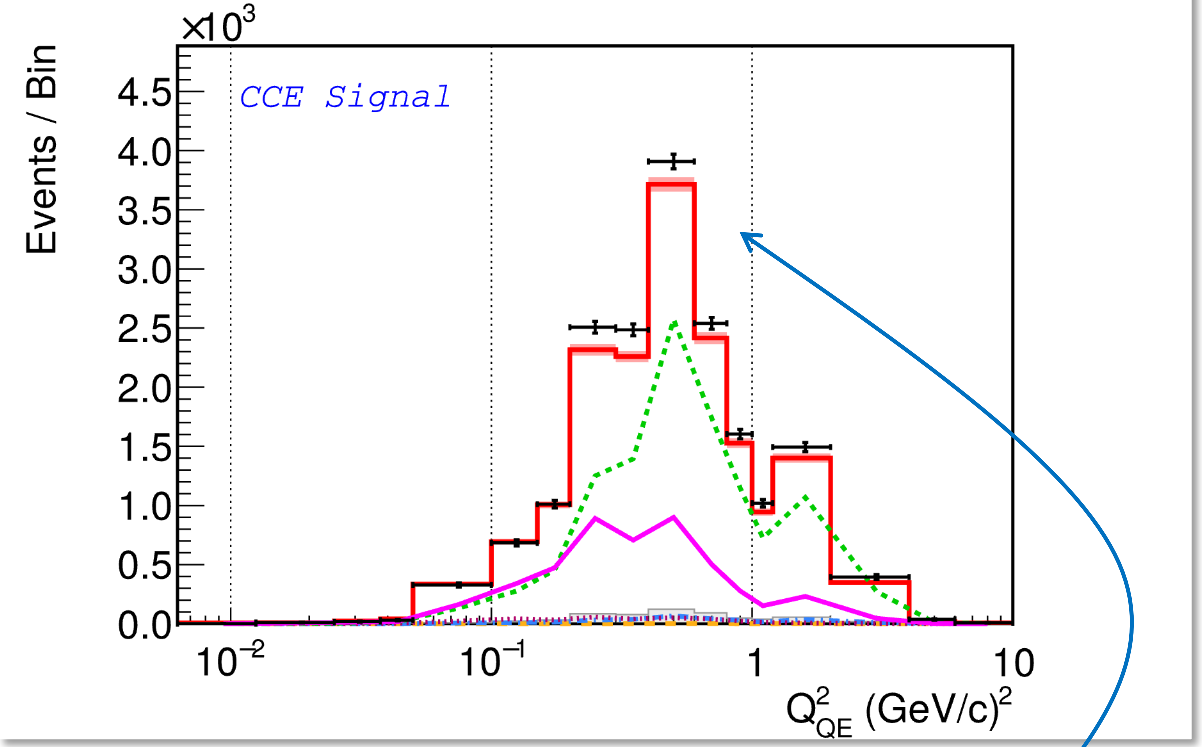


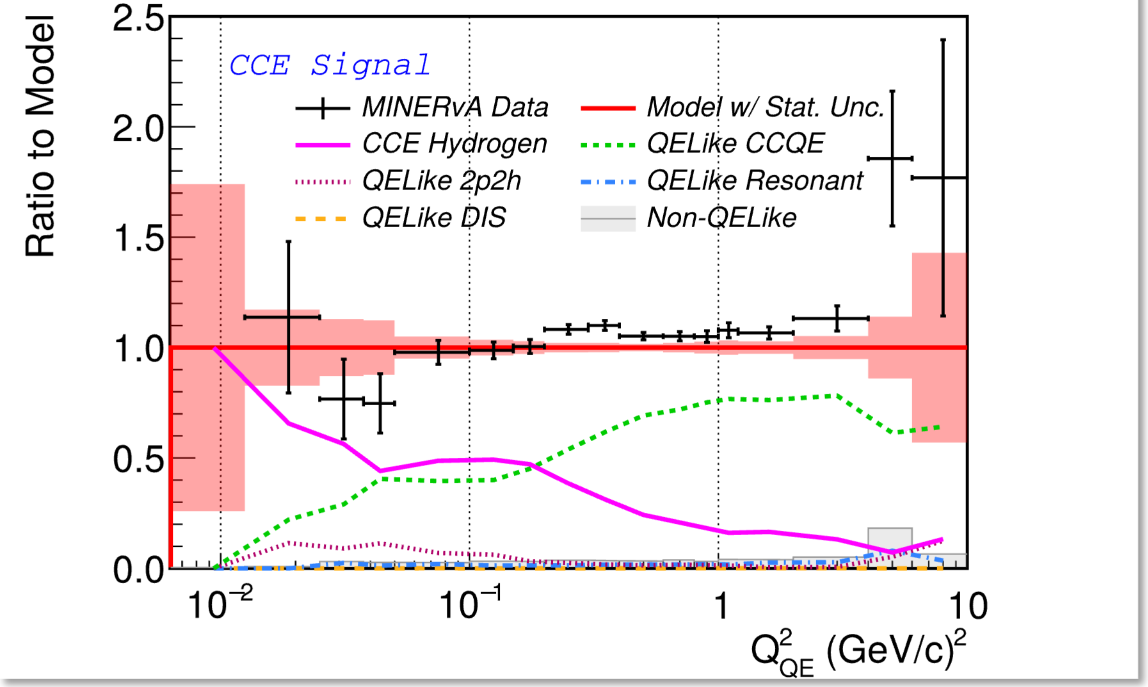
Background: QELike Resonant

Cross-section Extraction

[Nature 614, 48–53]

[Nature 614, 48–53]





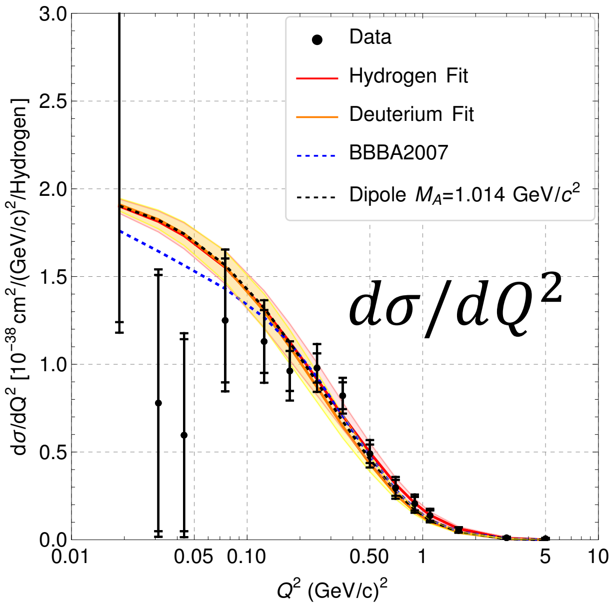
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_i = \frac{\sum_j U_{ji}\left(N_j^{\mathrm{data}} - N_j^{\mathrm{bkg-pred}}\right)}{\Phi N_H \epsilon_i (\Delta Q^2)_i}$$

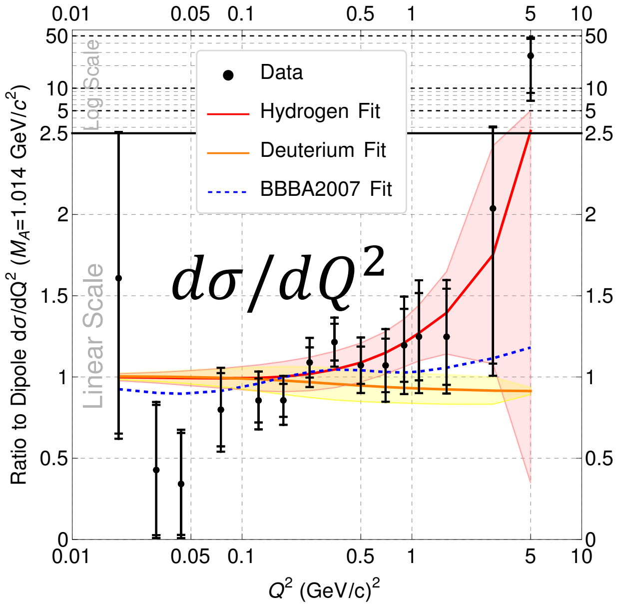
Ingredients:

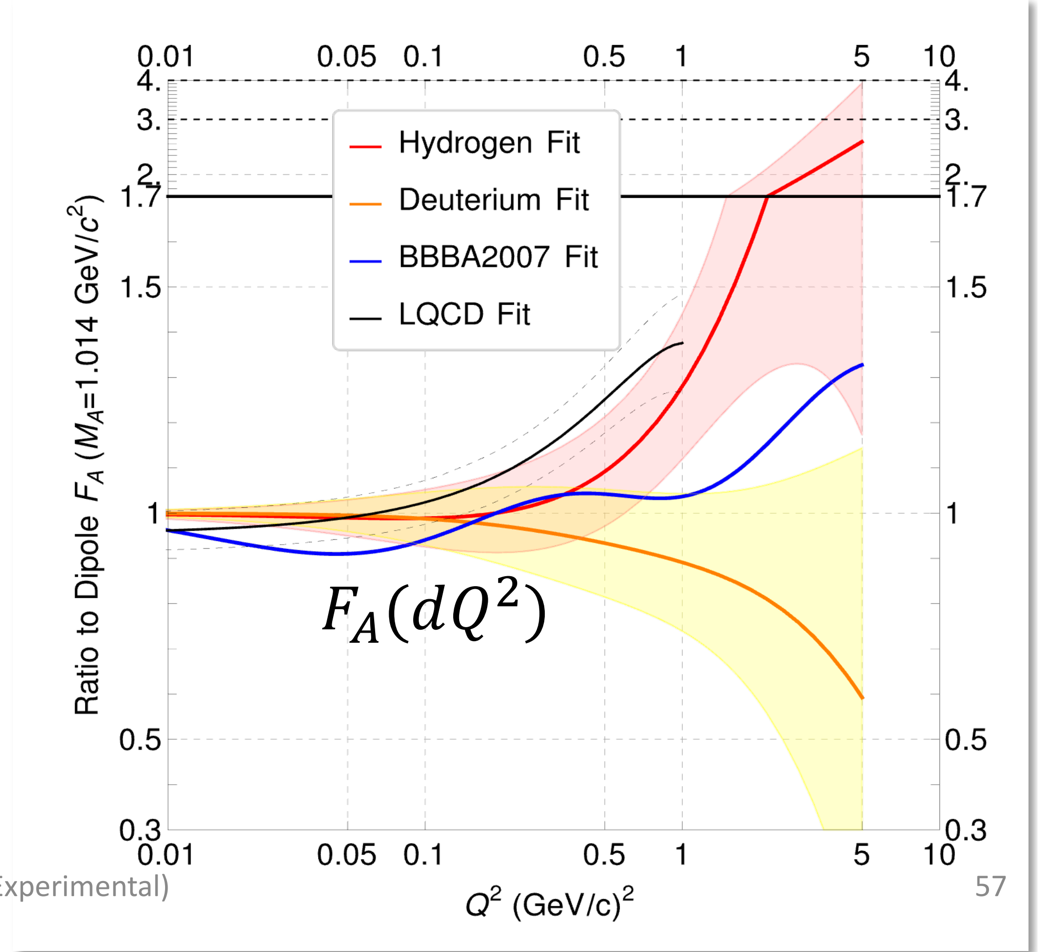
- Unfolding matrix and efficiency from Data and Simulation studies
- Flux from models and data measurements ($\nu e \rightarrow \nu e$)
- Number of Hydrogen targets from the detector assay.
- **Measured signal** from data – predicted background

Cross Section to “Form Factor” on free nucleon

- MINERvA found ~5800 such events on a background of ~12500.
- Lattice QCD prediction at high Q^2 is close, but maybe not at moderate Q^2.







Summary of Neutrino Interactions

	Calculating the cross section	Measuring the cross section
Neutrino scattering off of point-like fermions	Easy*	Hard
Neutrino Scattering off of composite objects	Hard	Easy*

After one process on free proton, what's next?

- Consider the various combinations: 6x4x5x6

Interaction
Inclusive Scattering
CC 0 π Production
CC $1\pi^+$ Production
CC $1\pi^0$ Production
CC Shallow or Deep Inelastic Scattering
Rare Chanels (ν-e, coherent scattering)

Flavour, Helicity
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

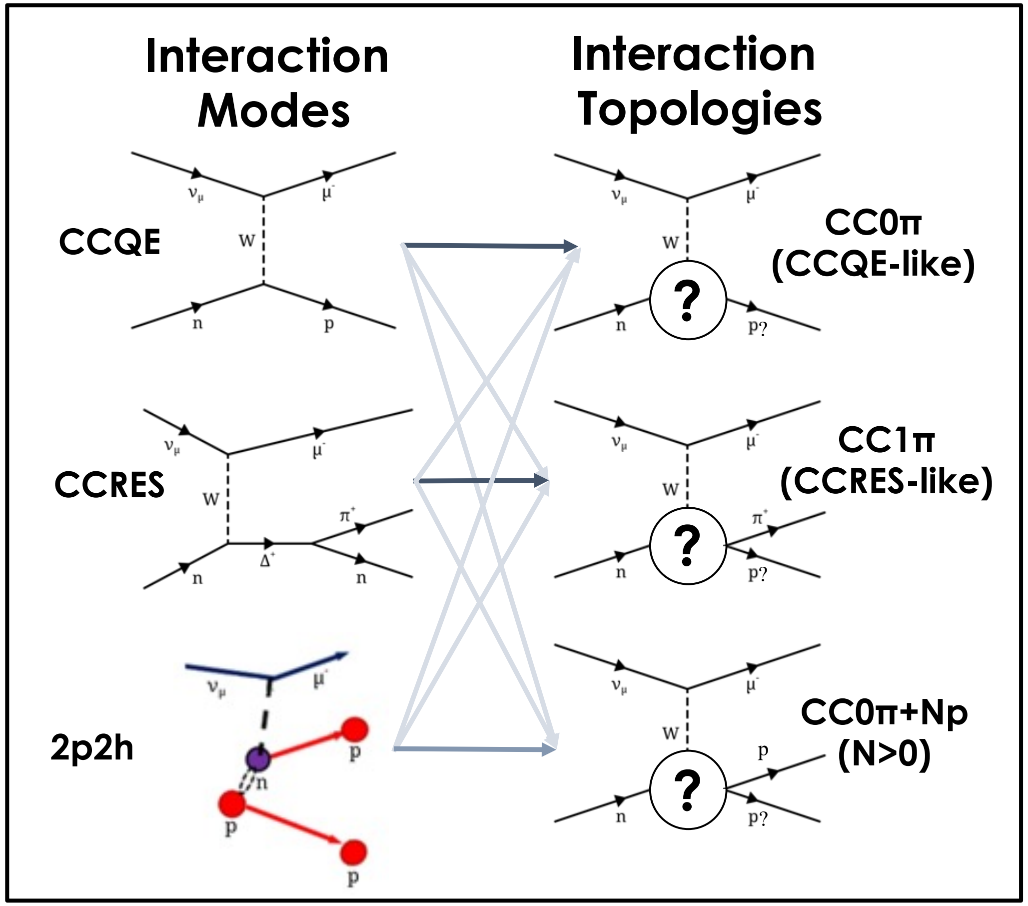
Target Nucleus
CH
H_2O
H, He, C, Pb
Ar
Pb

Observable
Lepton Kinematics
Momentum Transfer Squared (Q^2)
q_0 vs q_3
Proton Kinematics
Pion Kinematics
Transverse Kinematic Imbalance variables (many)
"Neutrino Energy"

But on all other nuclei, have to map Measurements on to Models

- Quasielastic Scattering
- 2p2h (correlated nucleon pairs) Scattering
- Resonant Pion Production (Δ's, etc.)
- Continuum Pion Production
- Coherent Pion Production
- Shallow Inelastic Scattering (?)
- Deep Inelastic Scattering

- Plus models for initial and final state effects



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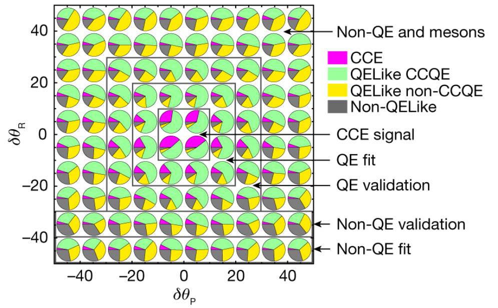
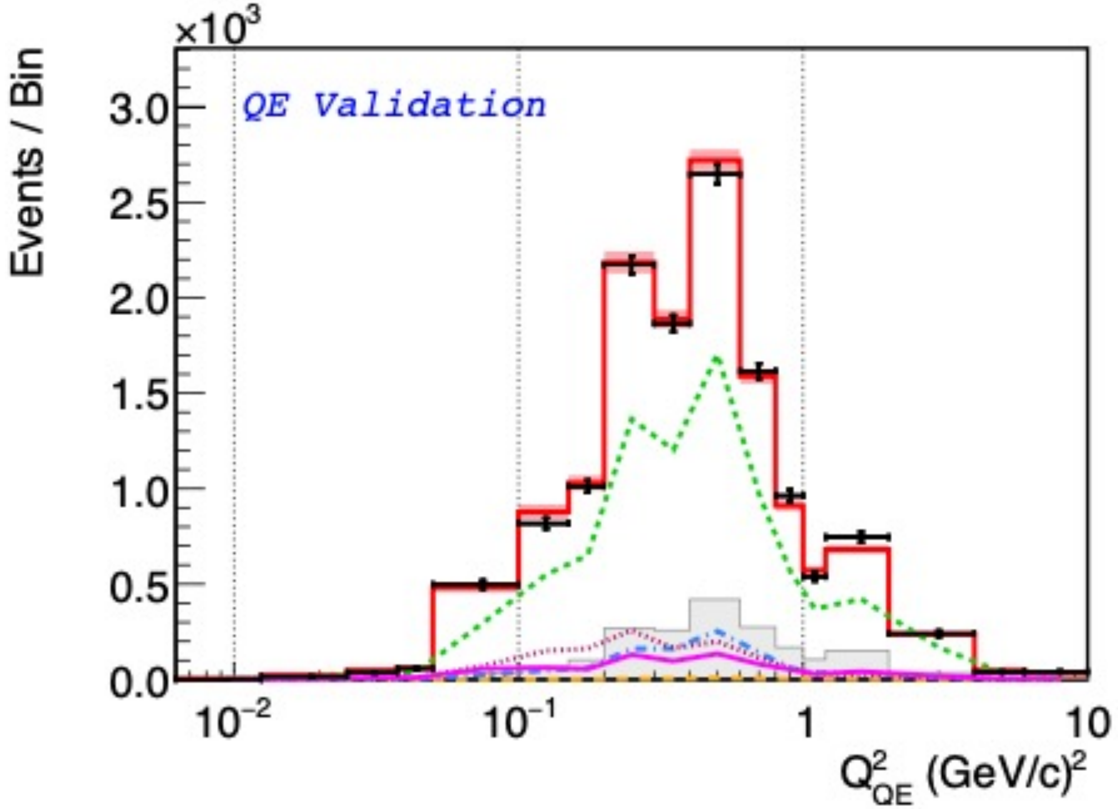
Conclusions

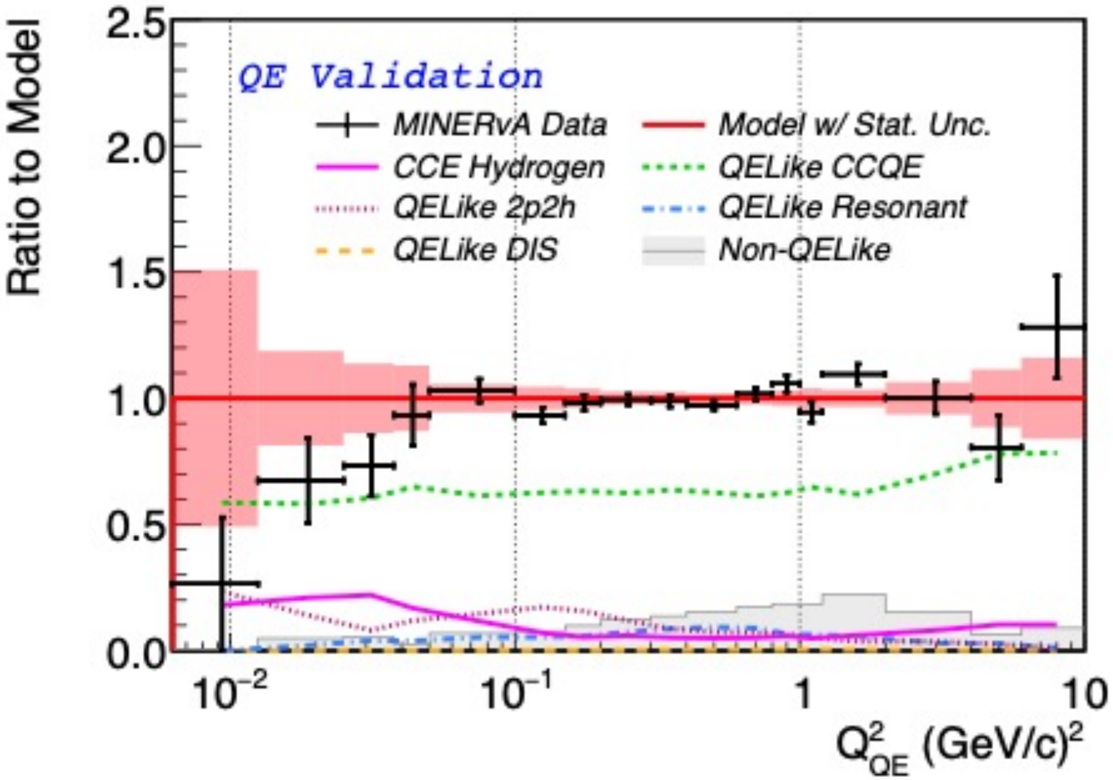
- Oscillation experiments require comparisons of PRECISE neutrino and antineutrino oscillation probabilities to see CP violation and measure neutrino mass ordering
- Need to understand relationship between
  - energy we measure and the incoming neutrino energy
  - what interactions we measure ("charged current events with no visible pions") to what theorists can model (individual processes)
- Fortunately, lots of handles to get there: new fine-grained detectors, multiple target nuclei, plus new clever ideas about observables

Backup Slides

Validating the Background Prediction



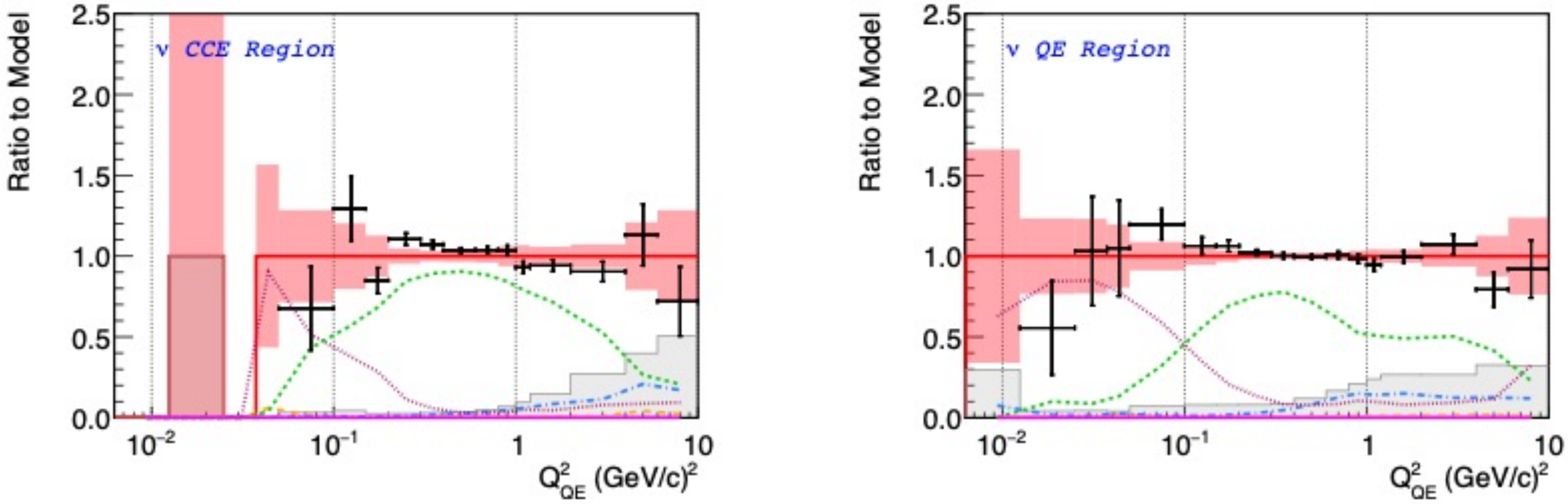




- CCQE is the dominant background. Small 2p2h, inelastic (absorbed), and Non-QELike contributions. The fitted model are well constrained by data.

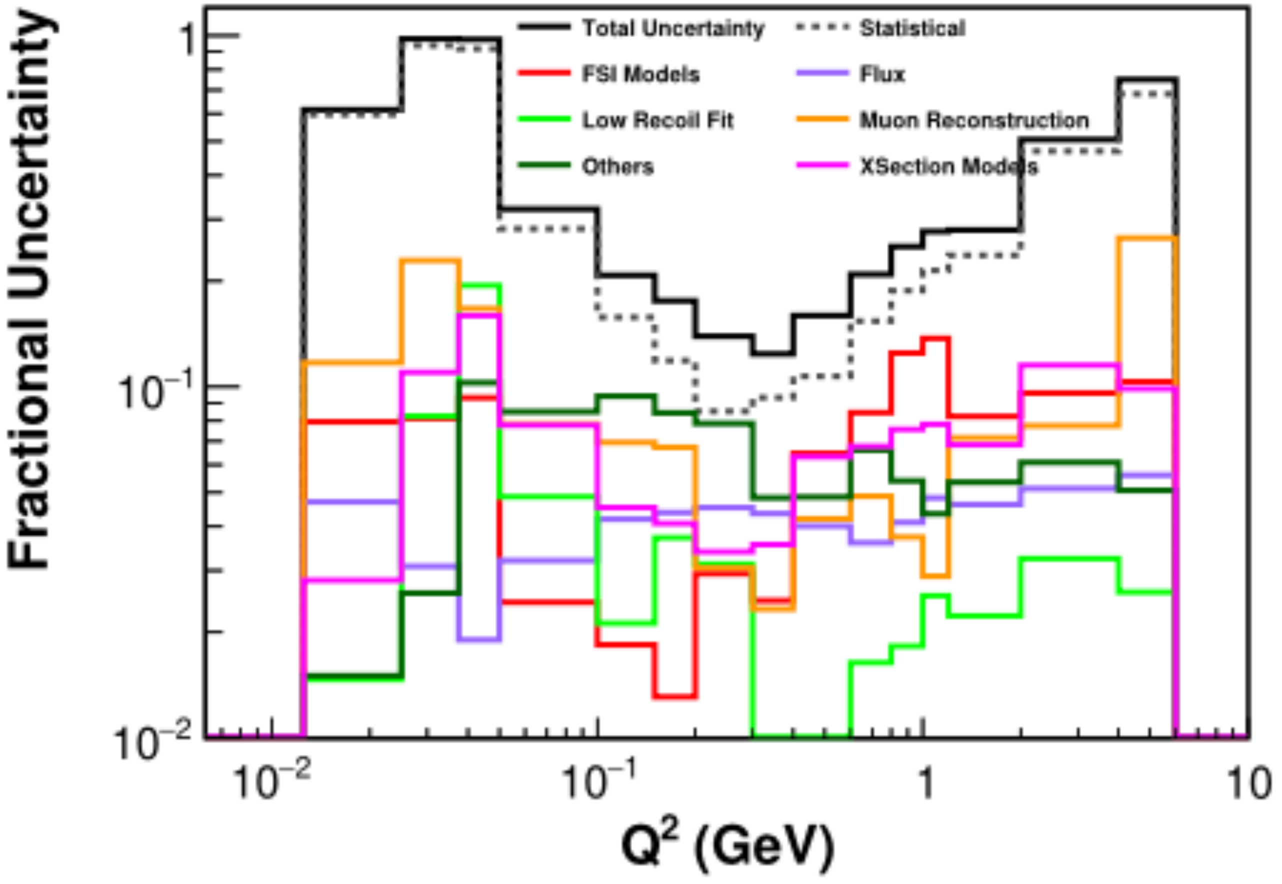
Another test: Neutrino Beam

$$\nu_\mu + n \rightarrow \mu^- + p$$



- Recipe: select events with trackable protons in a neutrino sample. Different final states and available kinematics. Apply same fitting mechanism. Data and MC mostly agree within uncertainty. Data and MC mostly agree. Disagreement can be explained by 2p2h uncertainty.

Uncertainties in the Axial Form Factor Cross-Sections



- Dominated by statistical uncertainty after the background subtraction.

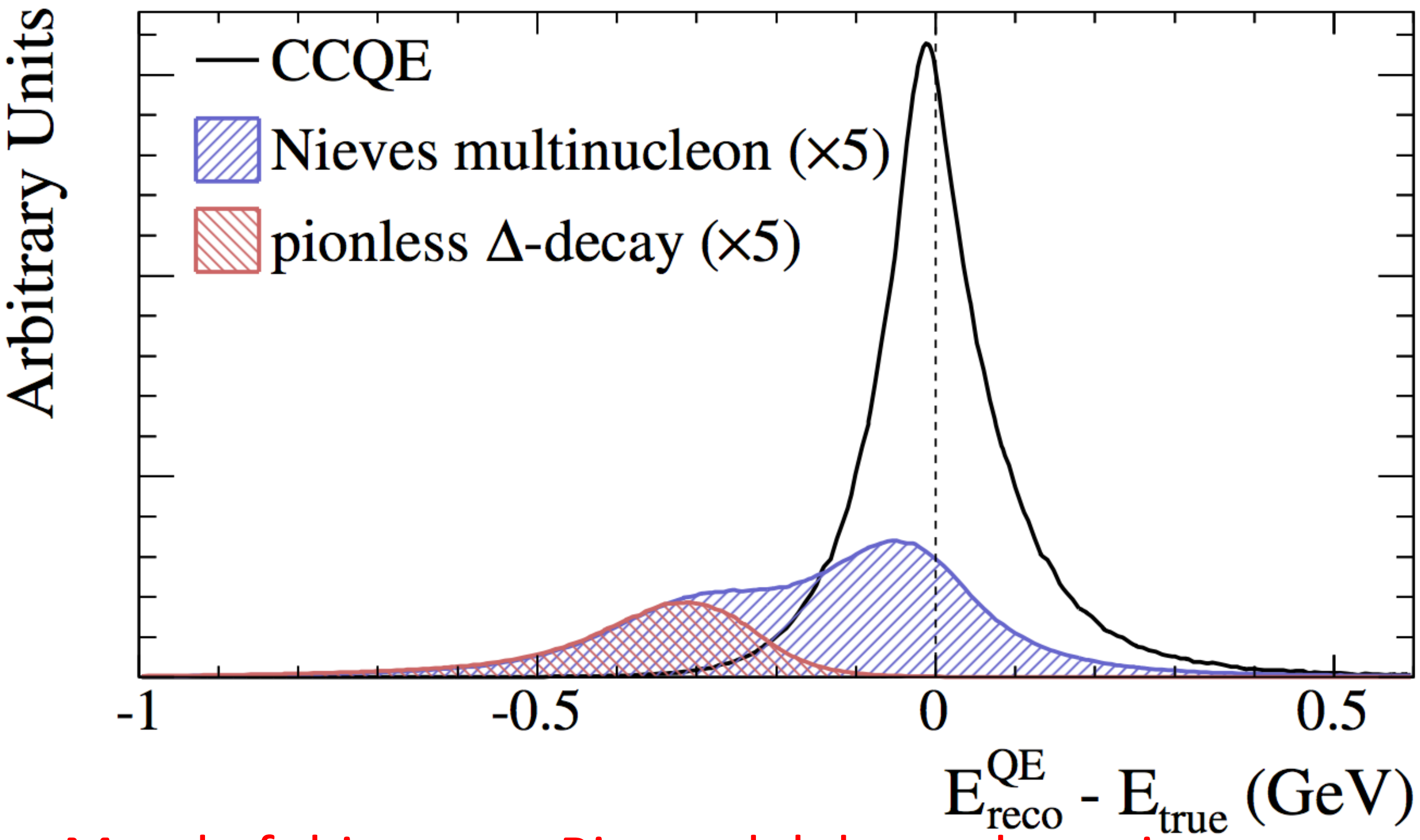
  Systematic uncertainties from residuals of background subtraction

  Particle responses in the "other" category, dominated by neutron systematics.

Always ask to see uncertainties!

What if you were to unfold to Neutrino Energy?

- The energy resolution you get using this formula (or ANY FORMULA) depends on what you assume about the events that pass all your cuts
- Plot at right is for T2K, one of their earliest oscillation papers
- *Phys.Rev.Lett.* 112 (2014) 18



Moral of this story: Big model dependence in unfolding to Neutrino Energy