Cross Section Measurements (Detectors)

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NuSTEC 2024 Summer School

Summary from Yesterday, Plan for today

- Particle Propagation through Materials
- Examples of detector technologies
- Today’s lecture:
  - Segmented Active/Passive Detectors (leftover)
  - Hybrid Detectors (T2K’s ND280, MINERvA)
  - Estimating Backgrounds, constraining with data
  - Estimating Efficiency, checking with data
  - The challenge of migrating from measurement to truth
  - From Inclusive to Exclusive Cross sections
  - If time allows: how to measure $\bar{\nu} + p \rightarrow \mu^{+} + n$

Homework question #1:

- How far does a proton with 100MeV Kinetic Energy go in
  - Plastic Scintillator (could consider C alone)
  - Iron
  - Argon
- How far does a muon with 2000 MeV Kinetic Energy go in
  - Plastic Scintillator
  - Iron
  - Argon

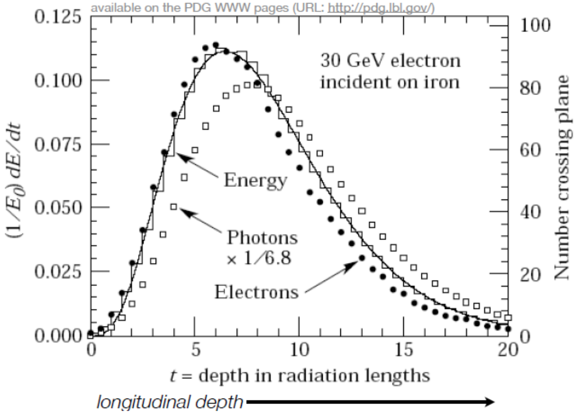
Homework question #1:

- How far does a proton with 100MeV Kinetic Energy go in
  - Plastic Scintillator (could consider C alone)
  - Iron
  - Argon

Target	Range (g/cm^2)	Density (g/cm^3)	Range (cm)
C	8.67	0.92	9.4
H	3.63	0.08	47.2
Fe	11.3	7.90	1.4
Ar	10.9	1.40	7.8

- How far does a muon with 2000 MeV Kinetic Energy go in
  - Plastic Scintillator
  - Iron
  - Argon

Target	dE/dx (min) (MeV/g/cm^3)	Density (g/cm^3)	dE/dx (MeV/cm)	Range (m)
Polystyrene	1.9	1.1	2.1	10
Fe	1.5	7.9	11.5	2
Ar	1.5	1.4	2.1	10

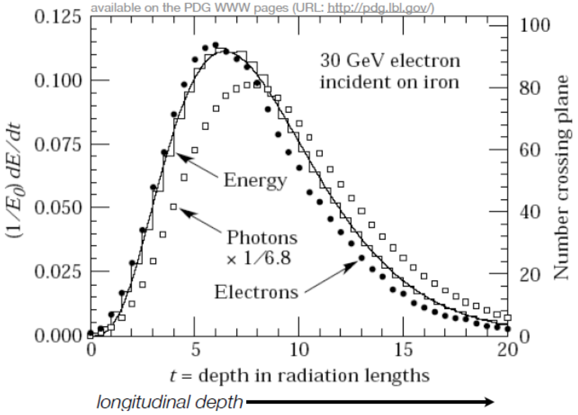

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

Homework question #2:

- What is the shower max (in cm) for a 1GeV electron:
  - Plastic Scintillator
  - Iron
  - Argon
  - Lead

- What is the shower max (in cm) for a 2GeV electron:
  - Plastic Scintillator
  - Iron
  - Argon
  - Lead

Homework question #2:



W.-M. Yao et al., Journal of Physics G 33, 1 (2006) available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

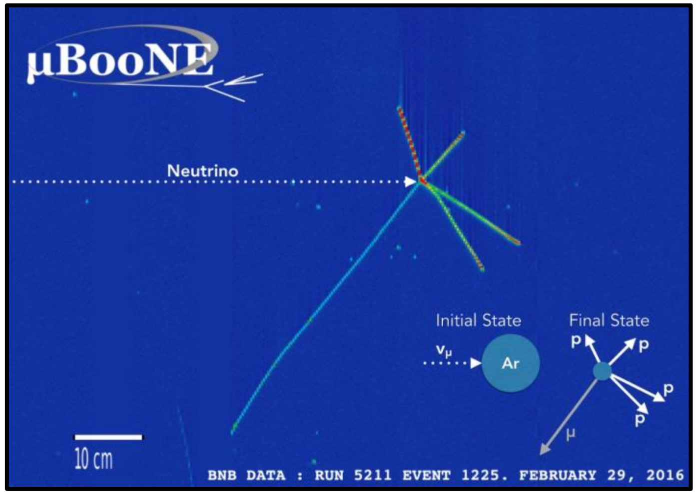
- What is the shower max (in cm) for a 1GeV electron:
  - Plastic Scintillator
  - Iron
  - Argon
  - Lead

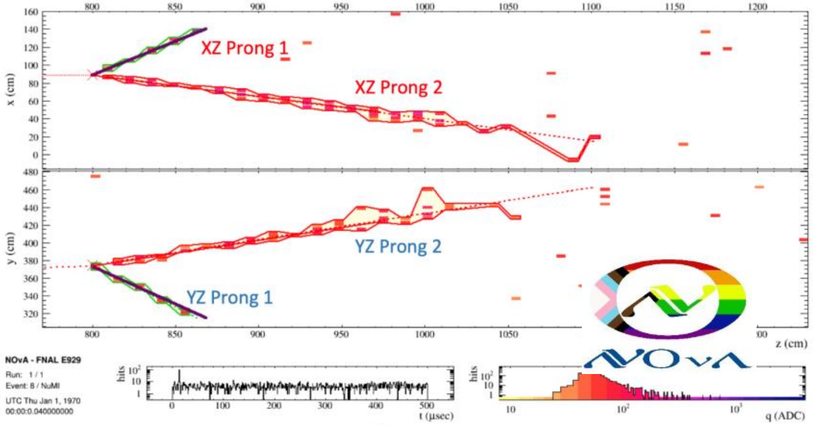
	Z	Ec (MeV)	X0	ln(1000/Ec)-0.5	t_max (cm)
Plastic Scintillator	6	111	42	1.7	71.3
Iron	26	29	1.76	3.0	5.3
Argon	18	42	14	2.7	37.5
Lead	82	10	0.56	4.1	2.3

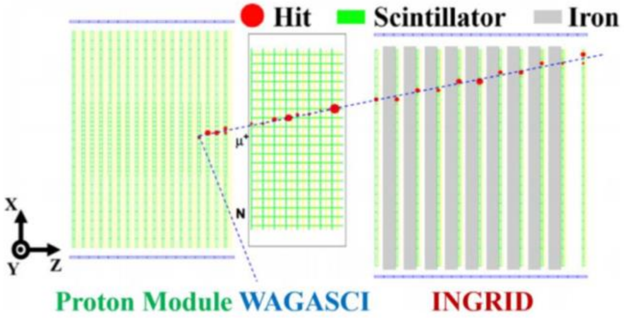
- What is the shower max (in cm) for a 2GeV electron:
  - Plastic Scintillator
  - Iron
  - Argon
  - Lead

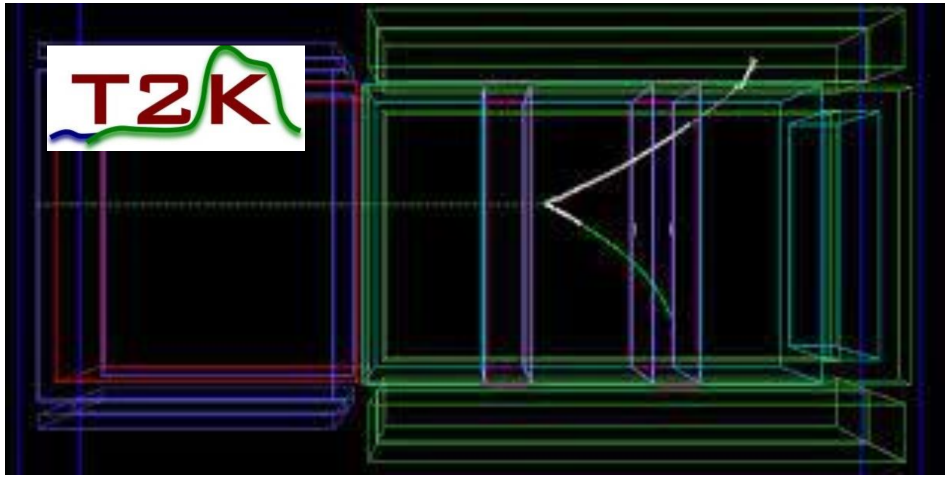
	Z	Ec (MeV)	X0	ln(2000/Ec)-0.5	t_max (cm)
Plastic Scintillator	6	111	42	2.4	100.4
Iron	26	29	1.76	3.7	6.5
Argon	18	42	14	3.4	47.2
Lead	82	10	0.56	4.8	2.7

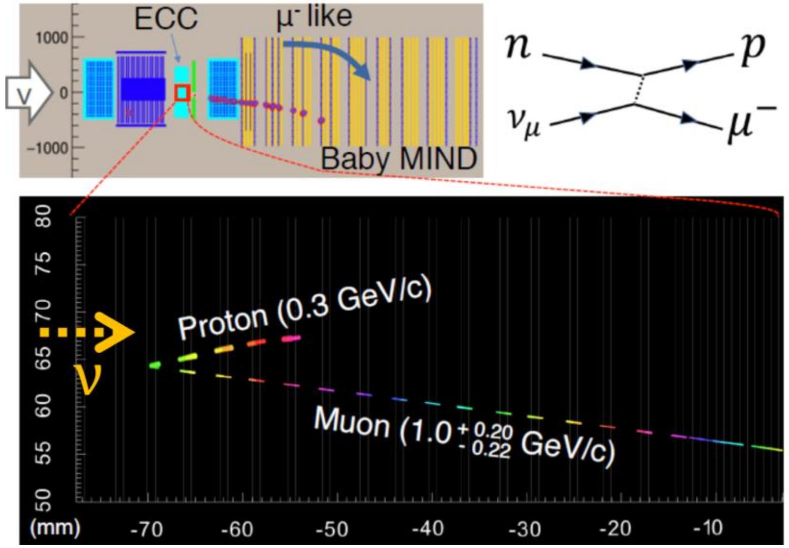
Neutrino Events at Some Experiments

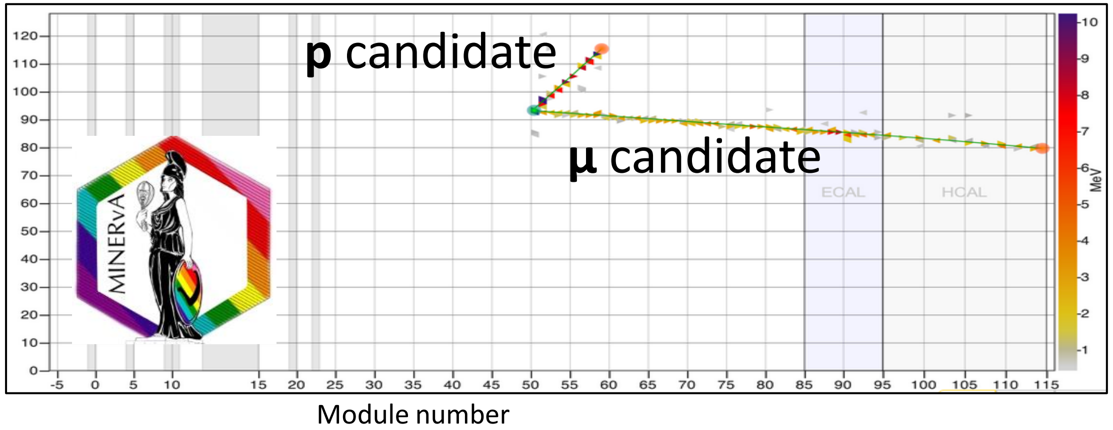






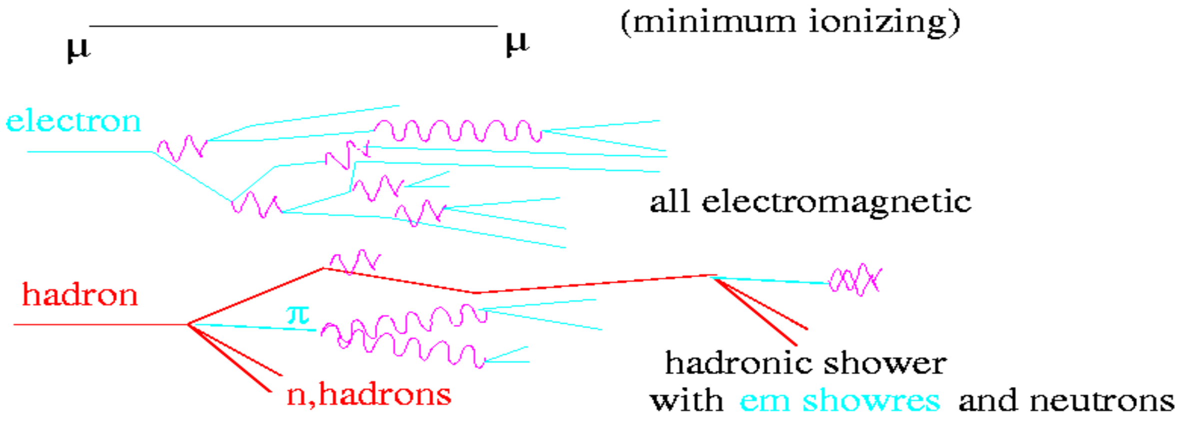






Active/Passive Detectors

From Fully Active to Sampling Detectors

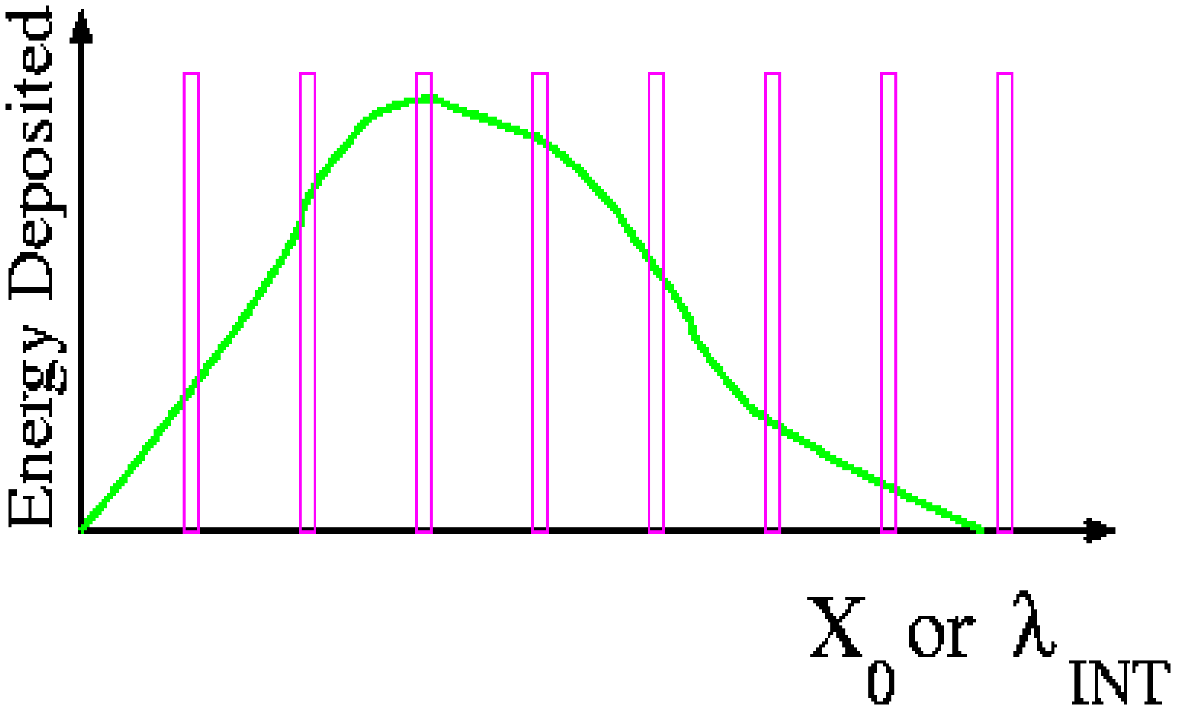


$$\frac{\delta E}{E} \propto \frac{1}{\sqrt{N}}, N = samples$$

$$\frac{\delta E(hadron)}{E(hadron)} \propto \sqrt{\frac{\lambda_{INT}}{N}}$$

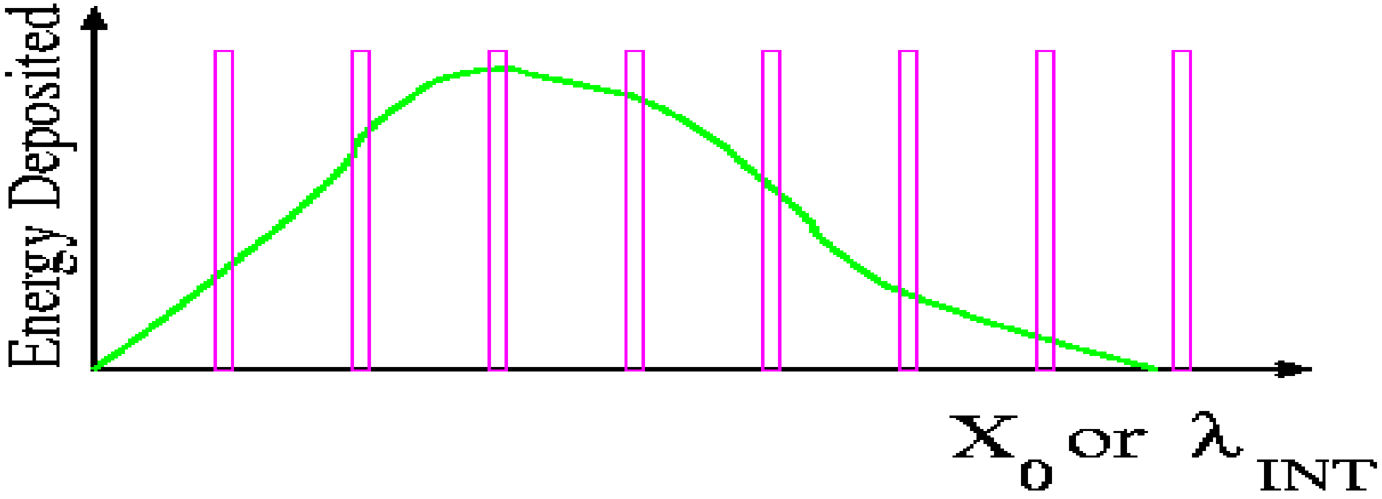
$$\frac{\delta E(electron)}{E(electron)} \propto \sqrt{\frac{X_0}{N}}$$

- Advantages to Sampling:
  - Cheaper readout costs
  - Fewer readout channels
  - Denser material can be used
    - More N, more interactions
    - Could combine emulsion with readout
  - Can use magnetized material!
- Disadvantages to Sampling
  - Loss of information
  - Particle ID is harder (except emulsion for tau final state)



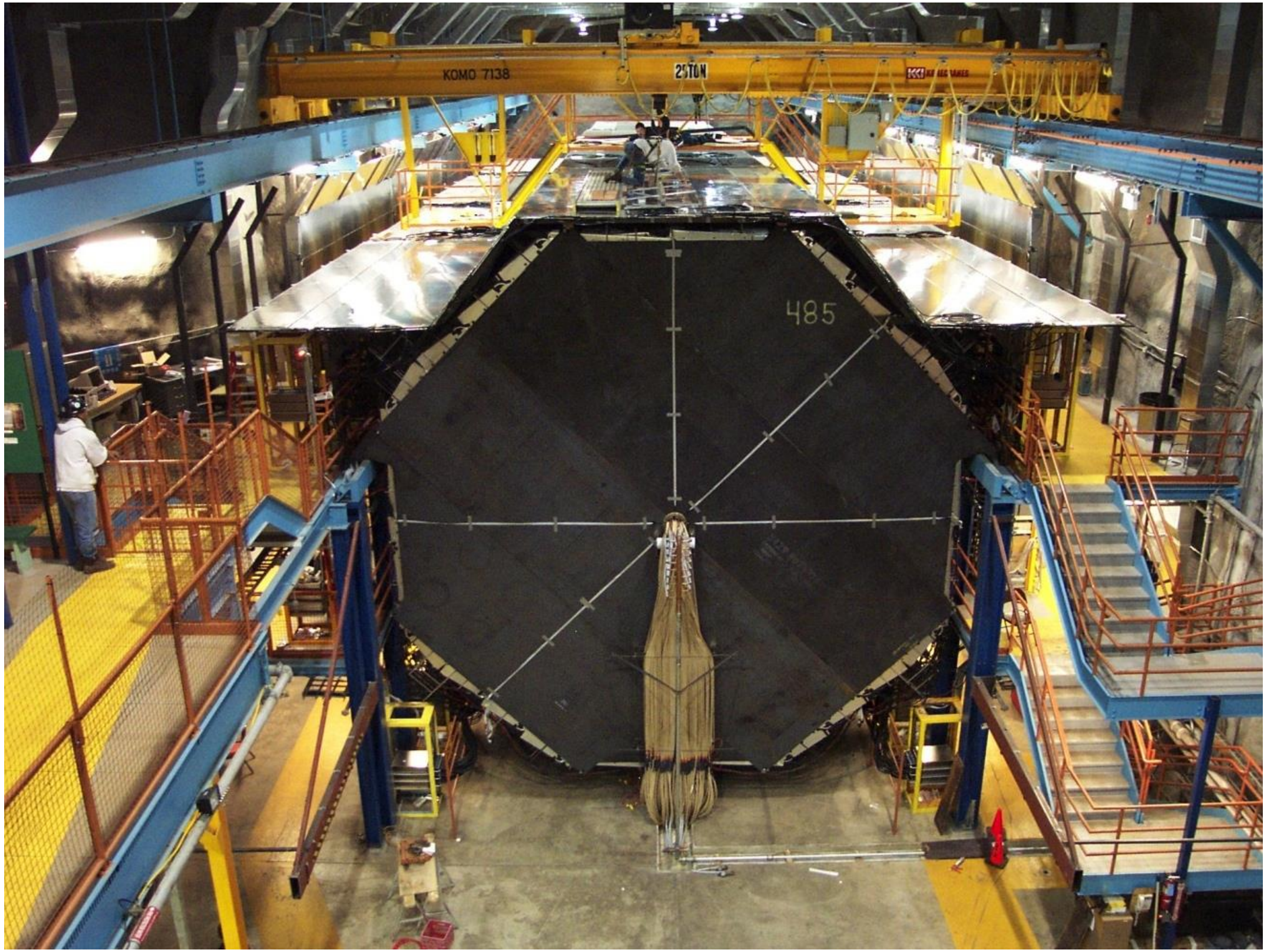
Sampling calorimeters

- High Z materials:
  - mean smaller showers,
  - more compact detector
  - Finer transverse segmentation needed
- Low Z materials:
  - more mass/X_0 (more mass per instrumented plane)
  - Coarser transverse segmentation
  - “big” events (harsh fiducial cuts for containment)



Material	X_o (cm)	λ_{INT} (cm)	Sampling (X_o)	X_o (g/cm^2)
L.Argon	14	83.5	0.02 (ICARUS)	20
Steel	1.76	17	1.4 (MINOS)	14
Scintillator	42	~80	0.13 (NOνA)	40
Lead	0.56	17	.2 (OPERA)	6

Steel/Scintillator Detector (MINOS)

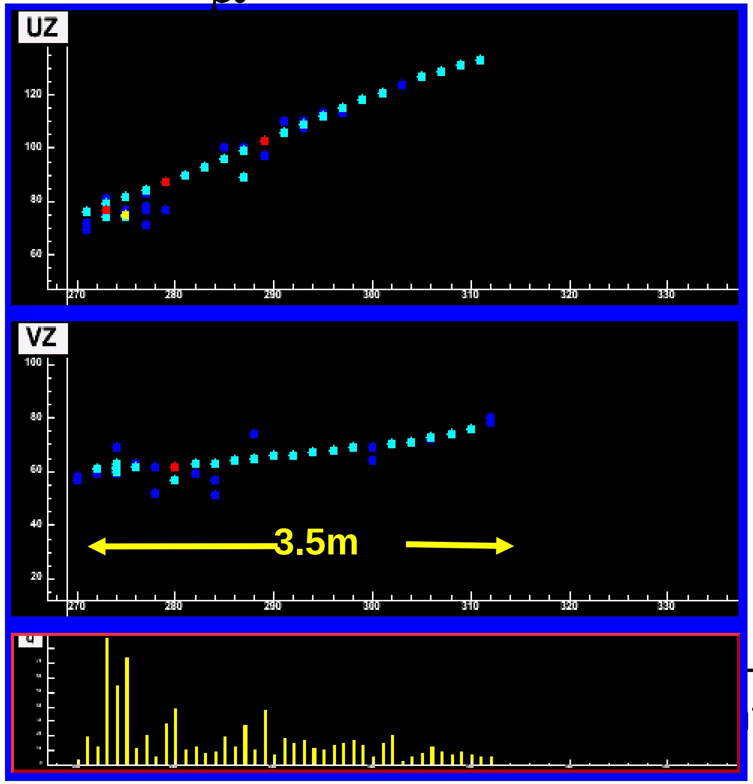


- 8m octagon steel & scintillator calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 5.4 kton total mass
- 486 planes of scintillator
  - 95,000 strips

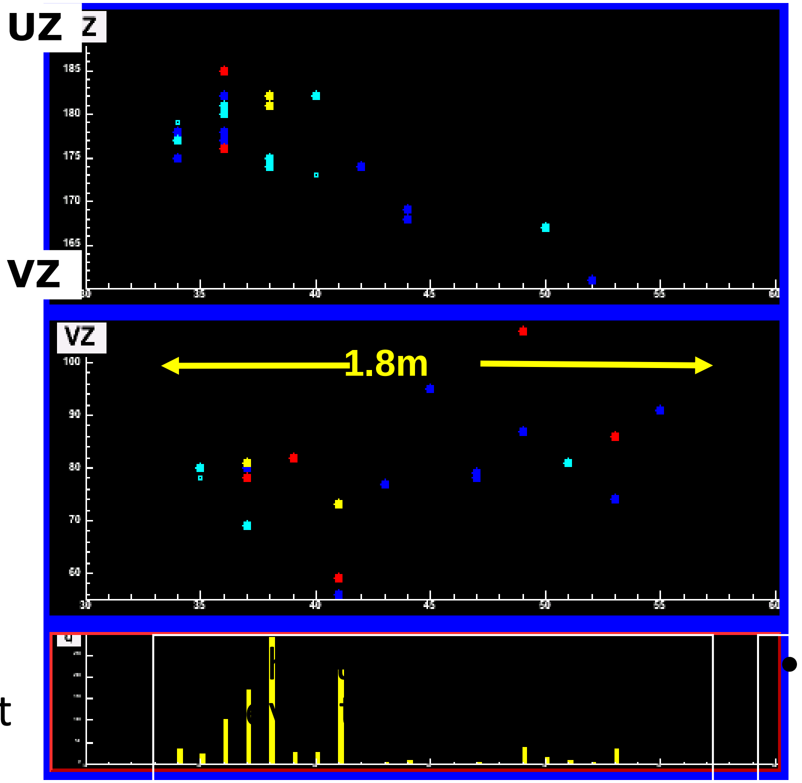
MINOS Event Topologies

Courtesy Chris Smith, FNAL Seminar

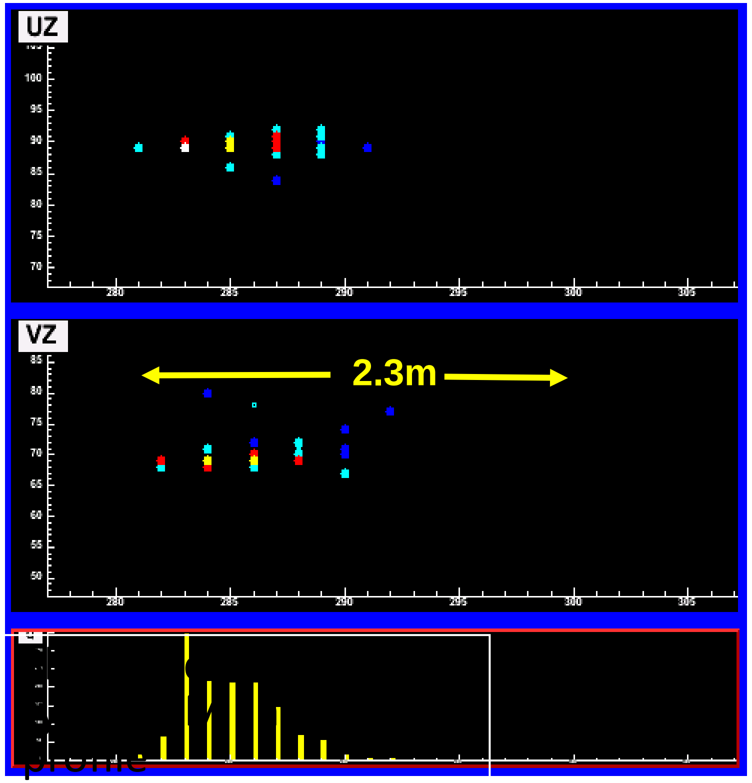
ν_μ CC Event



NC Event



ν_e CC Event



$$E_\nu = E_{shower} + P_\mu$$

Shower energy resolution: 55%/√E

Muon momentum resolution: 6% range; 13% curvature

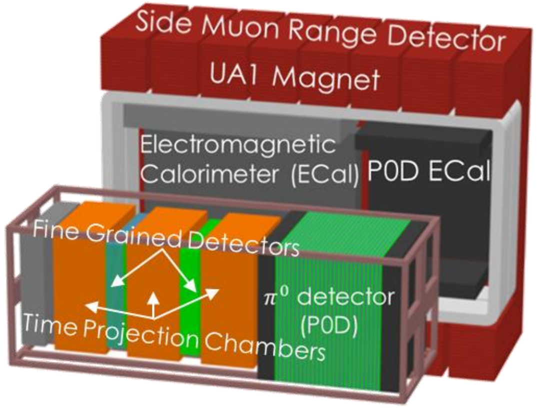
(Oscillation) Detector Summary

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal n Energy Range
		ν_e	ν_m	ν_t		
LAR TPC	0.8	✓	✓		Not yet	huge
Water Cerenkov	50	✓	✓			<2GeV
Emulsion/Pb/Fe	0.27	✓	✓	✓		>.5GeV
Scintillator++	14	✓	✓			huge
Steel/Scint.	5.4		✓		✓	>.5GeV

Cross Section Detectors

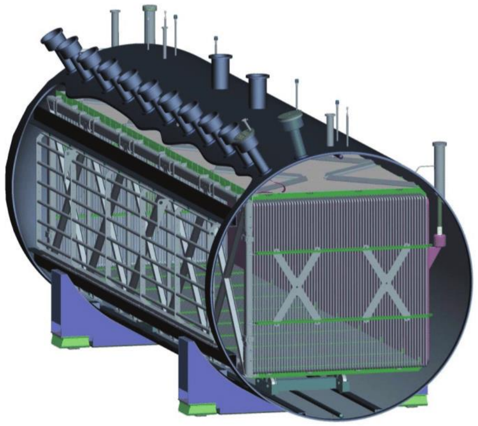
- Given the lengths of the muon tracks we saw earlier
- Given the intense beams close to where neutrinos are produced
- Will need to combine detector strategies to fit into allowed real estate for Near Detector Halls

Experiments current releasing results (in 0.5-20GeV region)

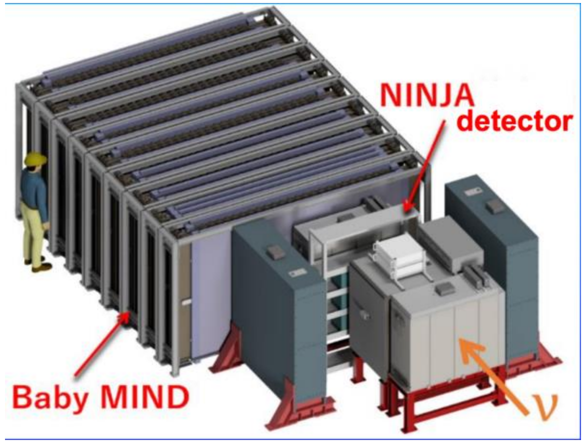


T2K Near Detector:
CH, H_2O

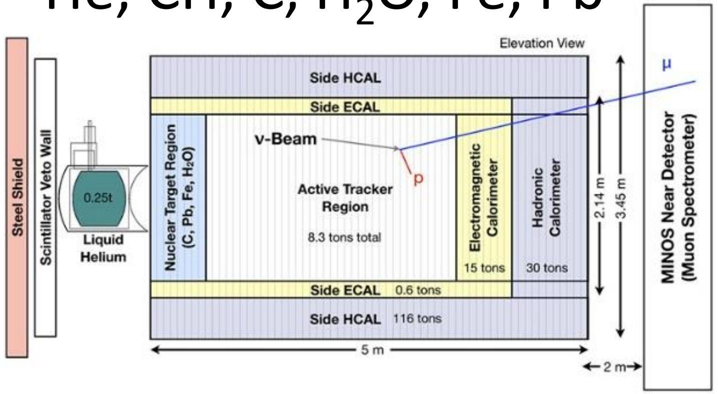
NINJA:
CH, H_2O, Fe

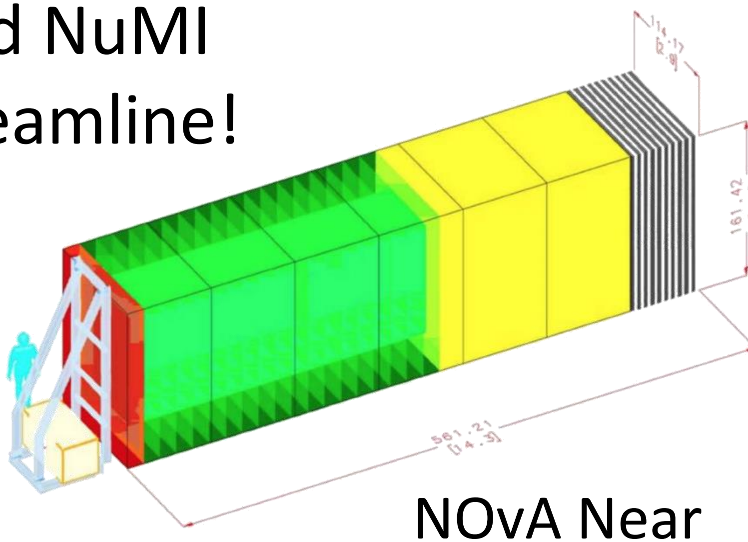


MicroBooNE:
Liquid Argon TPC
Booster and NuMI
(off axis) beamline!



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





NOvA Near Detector: CH

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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 2023
NOvA	2GeV	CH	No	4cmx6cm (scint)	Data-taking in 2023
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			No	3mm wire pitch	Data-taking in 2023
SBND	600MeV (BNB)		No	3mm wire pitch	Data-taking soon!

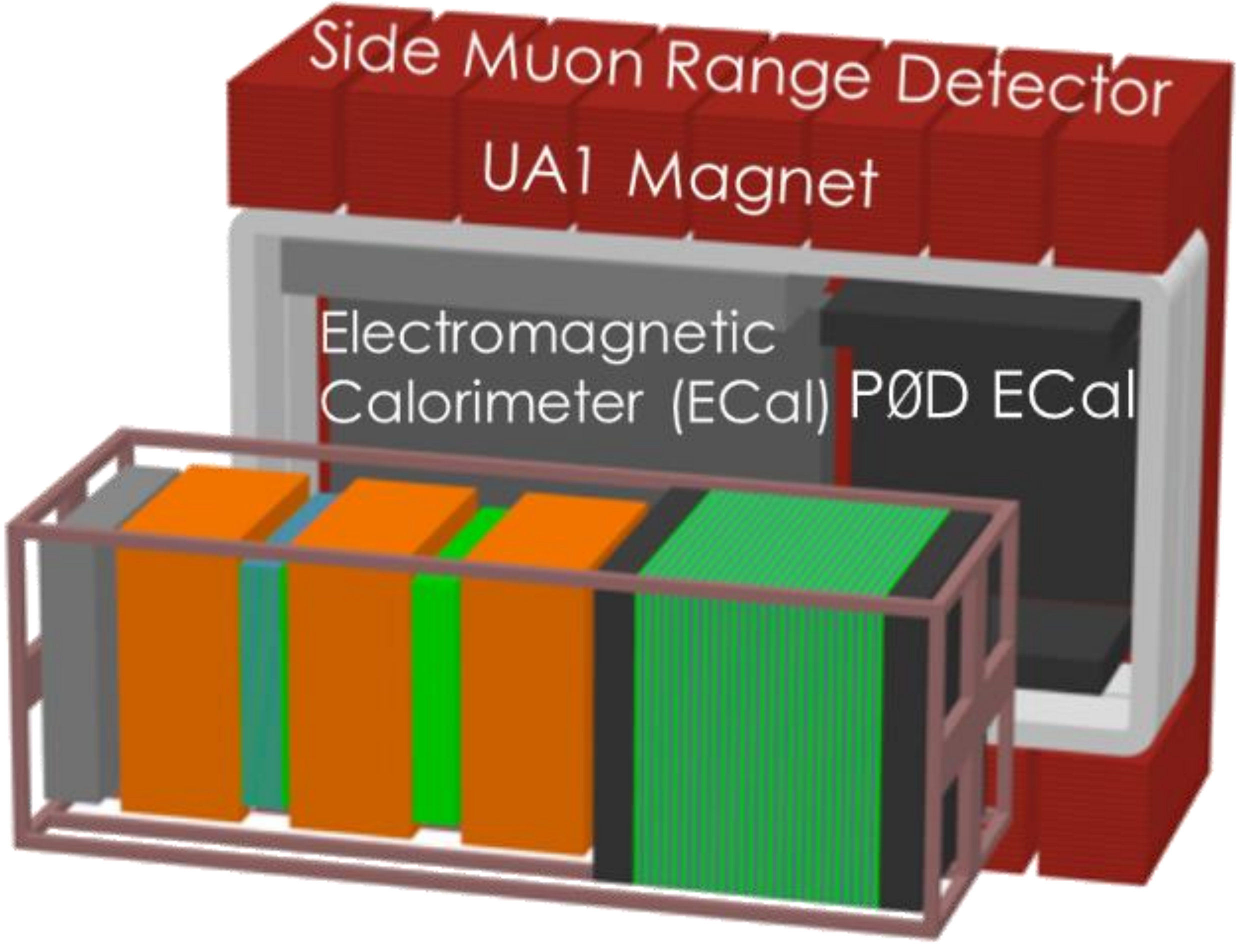
T2K Near Detector

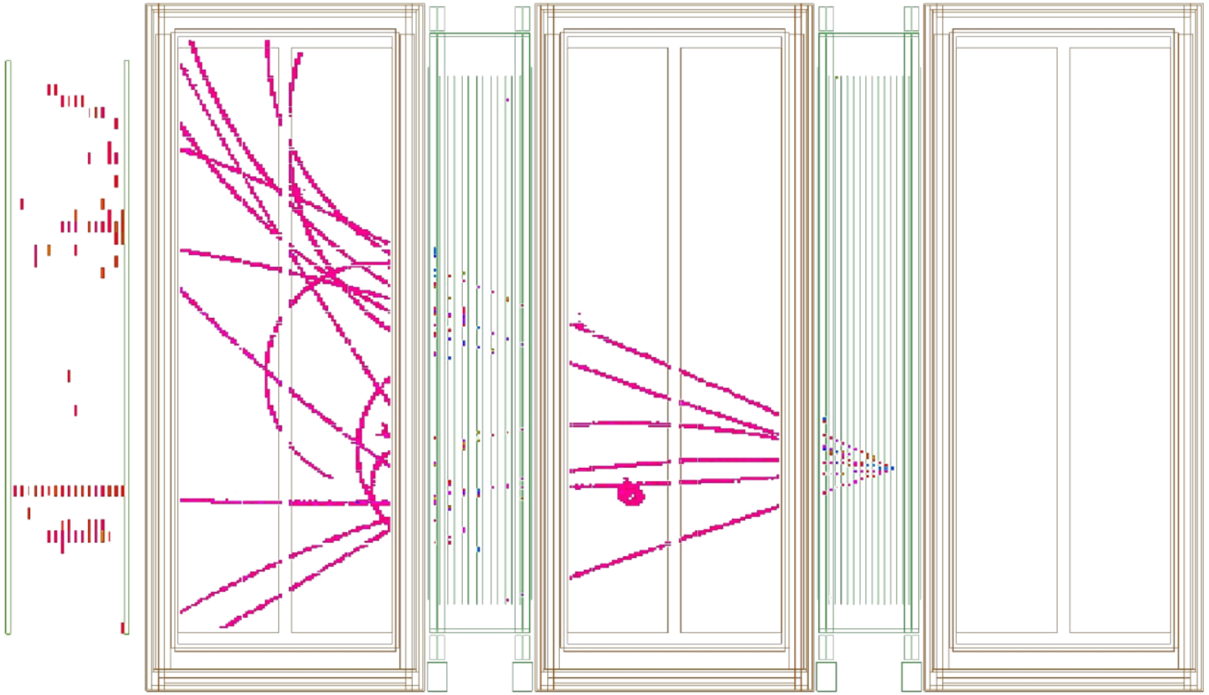
Time Projection Chambers (TPC):

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

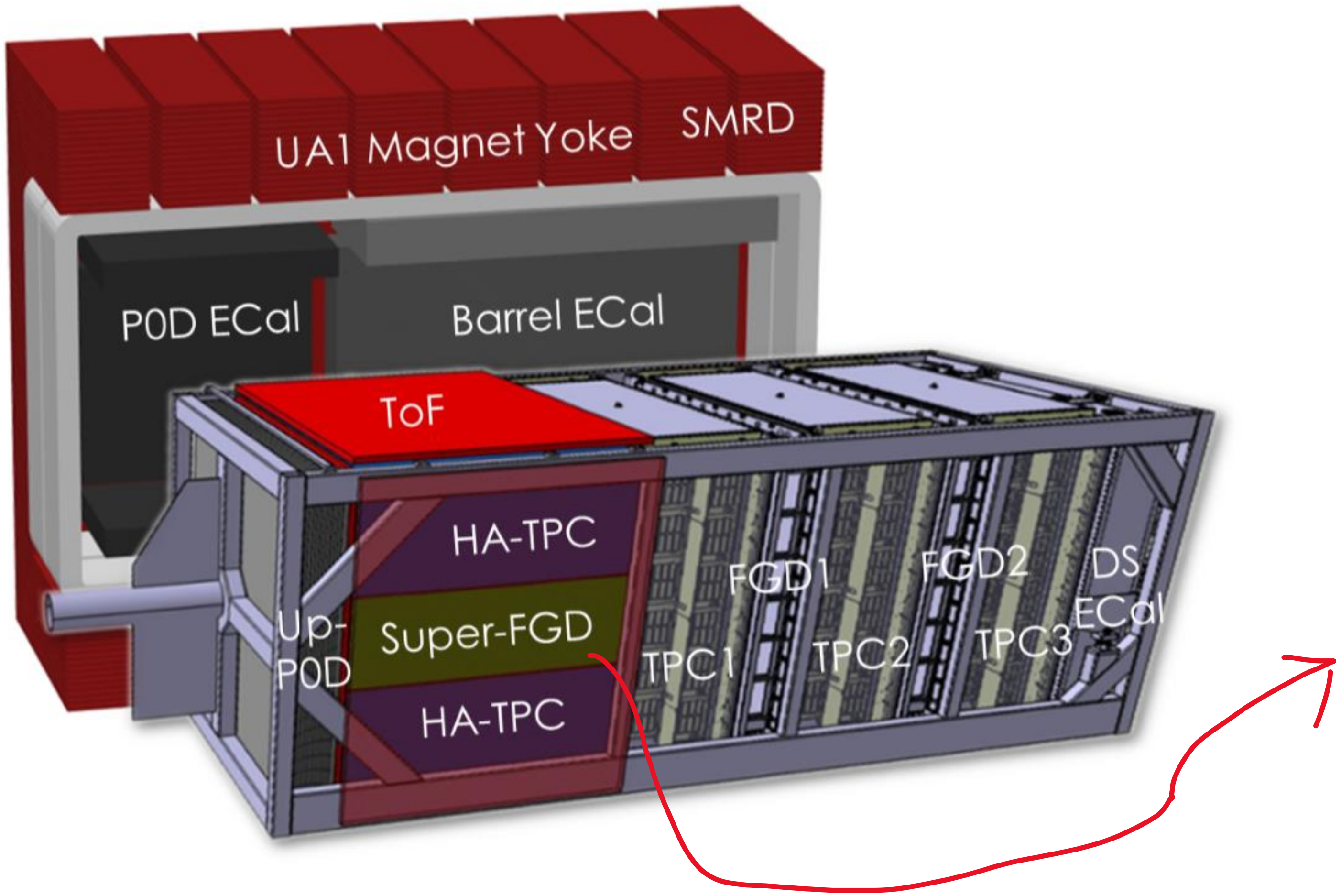
Fine-Grained Detectors (FGD 1 & 2):

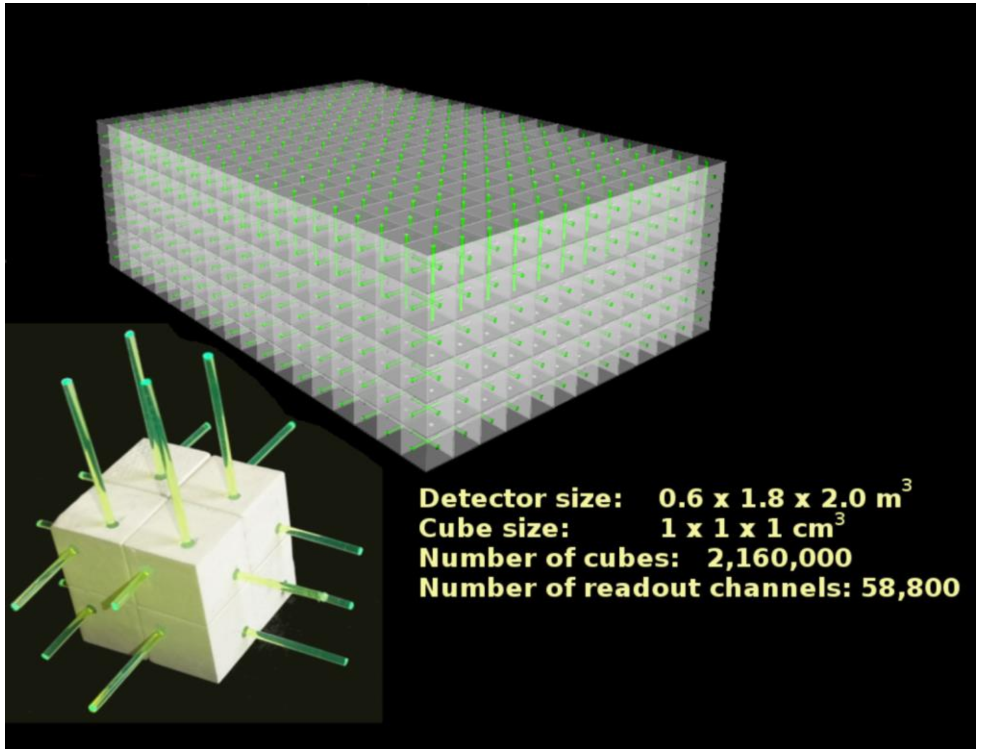
- CH scintillator tracker
- Target for ν
- FGD2 contains water





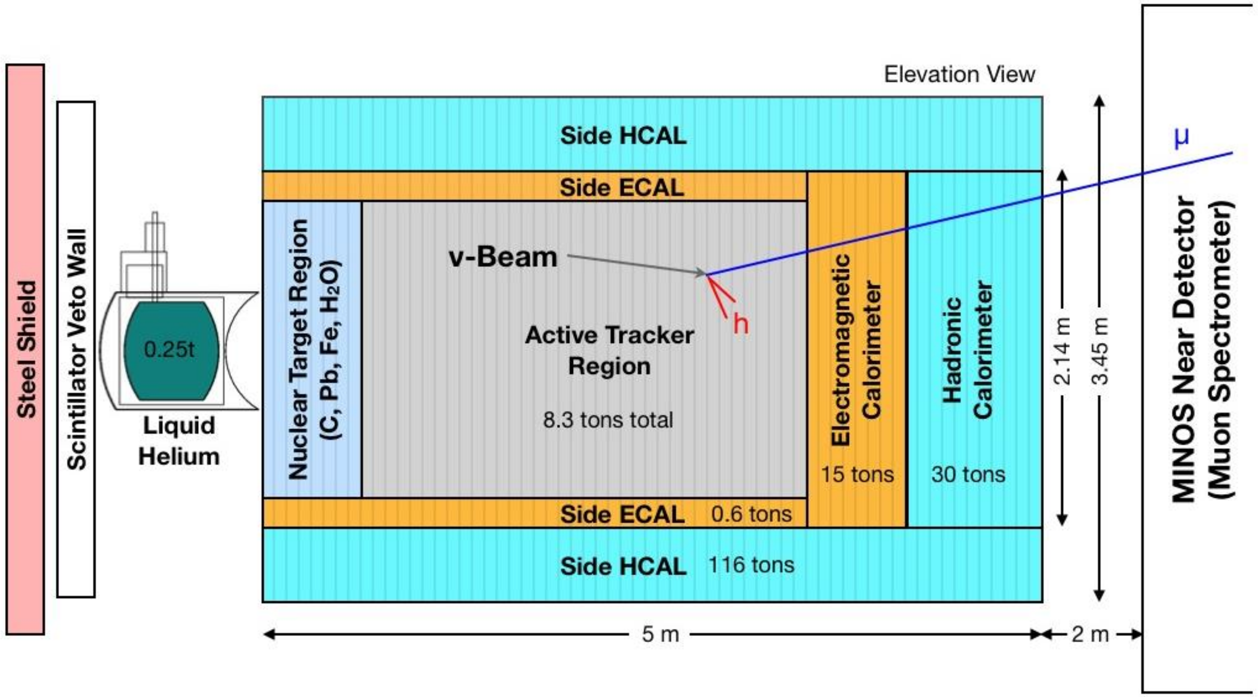
Upgrade to original T2K Near Detector

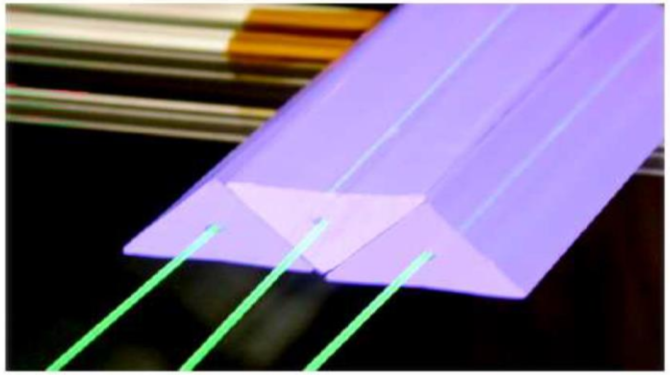




Detector size: 0.6 x 1.8 x 2.0 m^3
Cube size: 1 x 1 x 1 cm^3
Number of cubes: 2,160,000
Number of readout channels: 58,800

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.

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

Quick word about units

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

- What are the units of the different components?
  - N: number of events, unitless
  - σ: cross section, area per target (for neutrinos, usually x10^{-38} cm^2)
  - Φ: flux, Neutrinos per unit area (for near detector location, cm^{-2})
    - example: NOvA reports*: 87ν_μ/cm^2/10^{10} POT or for 10^{20} POT, 10^{12} ν/cm^2
  - ε: efficiency, unitless
  - M: ”mass” must be “number of targets” : recall this is 6.023x10^{23} if your detector weighed 1 gram

*Phys.Rev.D 107 (2023) 11, 112008

How to measure a cross section

- From the equation: $\mathrm{N}(x_{true}) = \frac{d\sigma(E_\nu, x_{true})}{dx_{true}} \Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M$

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

U written this way is a “smearing” step that translates from the true quantity to a reconstructed quantity

Solving for ${}^{d\sigma}/_{dx}$

$$\frac{d\sigma(E_\nu, x_{true})}{dx_{true}} = \frac{\mathrm{N}(x_{measured})\, U^{-1}(x_{measured}, x_{true})}{\Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M}$$

- And in real life, there are backgrounds: not every event you select is going to be the signal process you are looking for!
- Integrate over the entire flux to find:

$$\frac{d\sigma(x_{true})}{dx_{true}} = \frac{(\mathrm{N}(x_{measured}) - B)U^{-1}(x_{measured}, x_{true})}{\int \Phi_\nu\, \epsilon(x_{true})M\Delta x_{true}}$$

Measuring Cross Sections: Simplify notation

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

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

- Deconstruct this piece by piece, from the easiest to the most complicated:

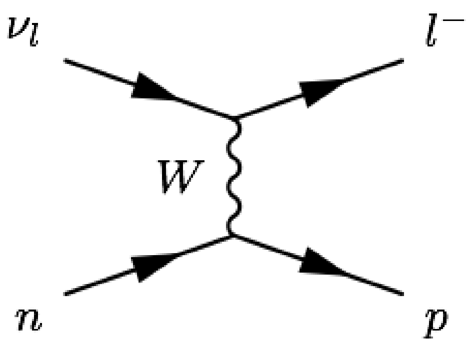
$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\,U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

- $B(x_m)$: These are the backgrounds that are still in the event sample even after you make all your cuts.
- $\mathrm{B}(x_m) = M \sum {U^{mt}}^{-1} \frac{d\sigma_B(E_\nu, x_{true})}{dx_{true}} \Phi_\nu(E_\nu)\epsilon_B(x_{true}, E_\nu)$
- You could predict what this background is from your simulation, but that prediction may have a large uncertainty!
  - Background Process Cross Section uncertainties (have to sum over all processes!)
  - Flux uncertainties (have to Sum over all fluxes!)
  - Have to smear back: is that smearing matrix the same for all backgrounds?

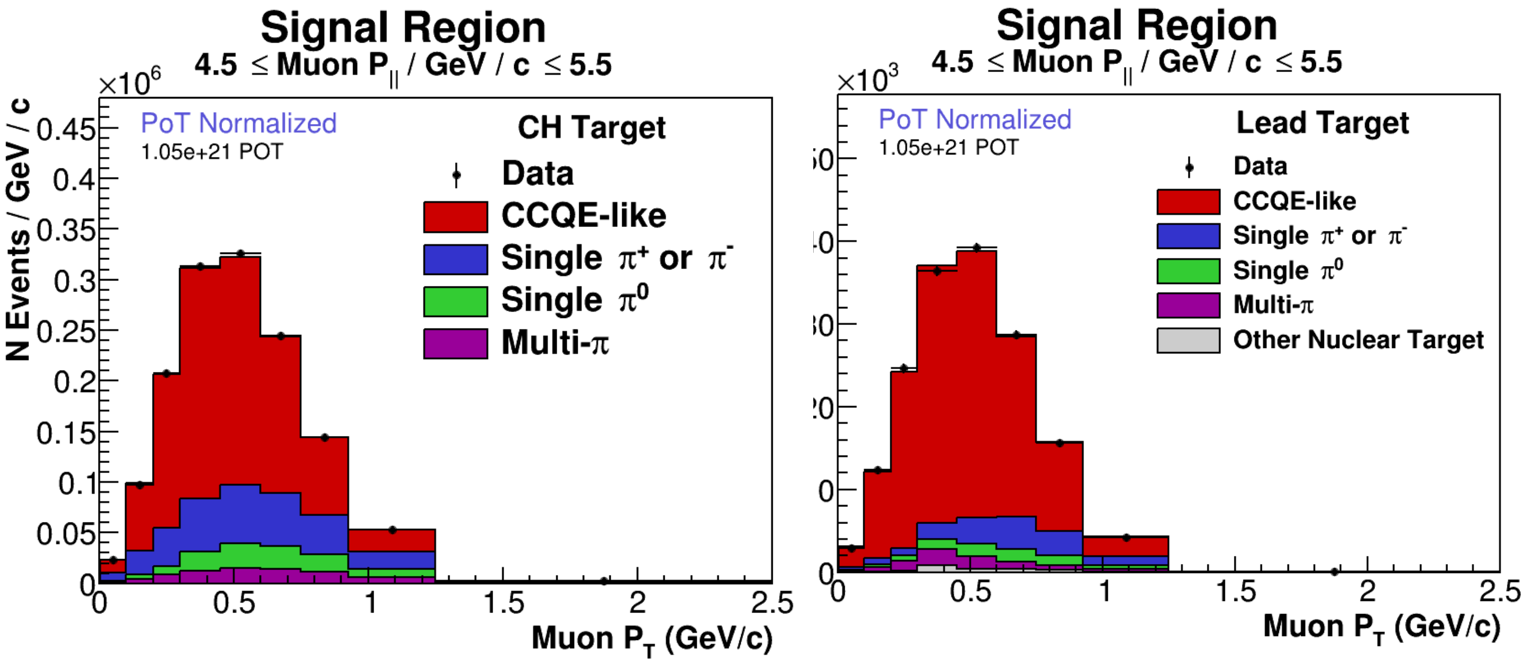
Signal

Background

Using data to predict B(x_m)



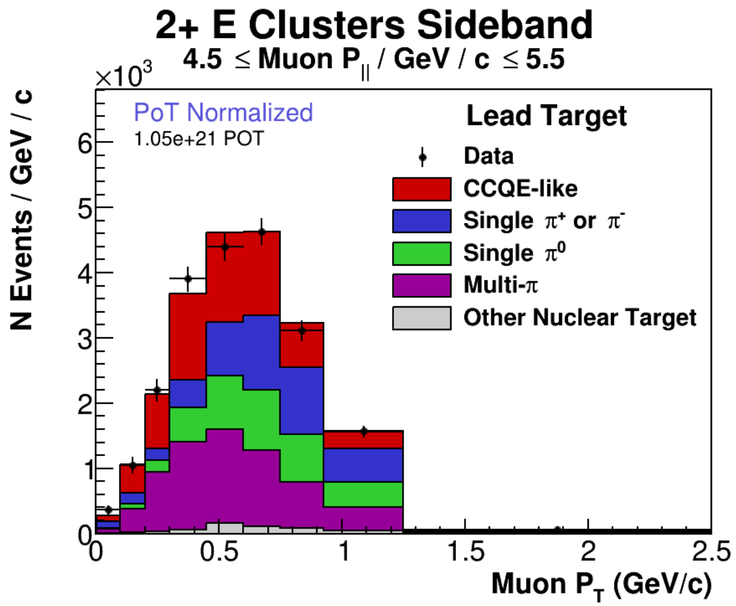
- Quasi-elastic neutrino scattering should have an easily-identifiable signature: one muon and one proton
- Example from MINERvA: if you only require a muon (p>1.5GeV/c)
- and NO other energy deposits far from the nucleus, no Michel electron, here are the backgrounds:

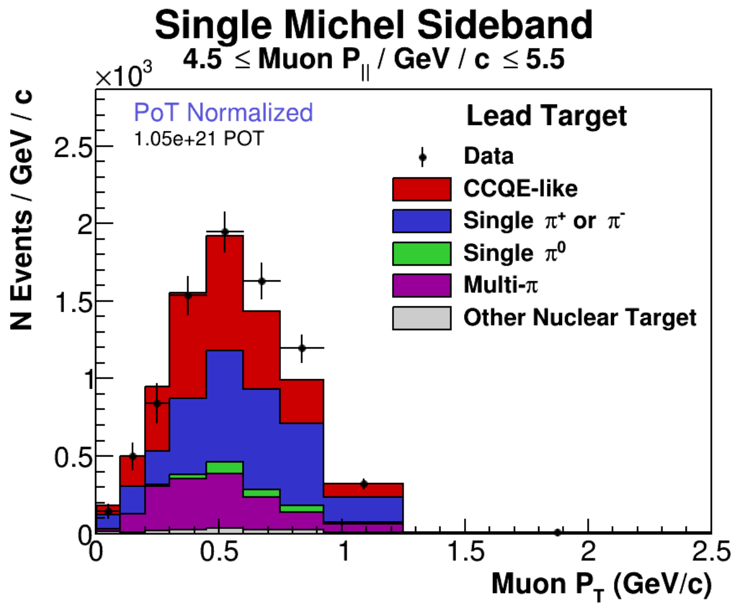


Phys.Rev.Lett. 130 (2023) 16, 161801

Using Data to predict $B(x_m)$

- Remember: the CCQE process is probably the best known neutrino-nucleus process, how could you trust your simulation to tell you the background levels?
- Solution: Use the data itself, but try to isolate each background by looking at the events you REMOVED from the signal process
- How to find events with π^+?
- How to find events with π^0?
- Remember, red is signal: can't always find event samples that have all one background, or no signal events in them…





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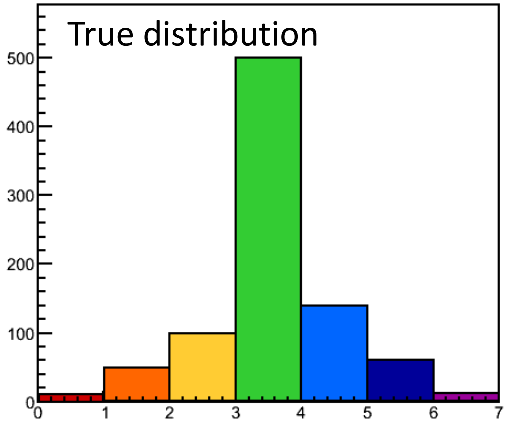
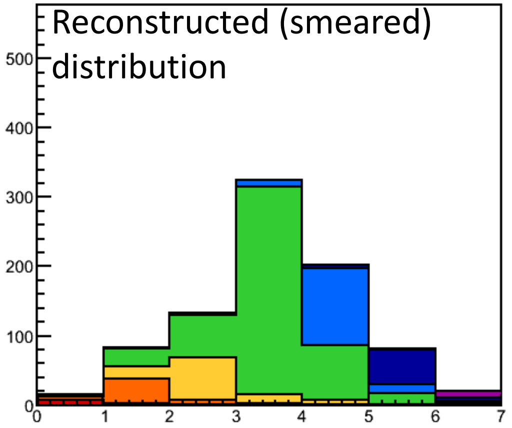
$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

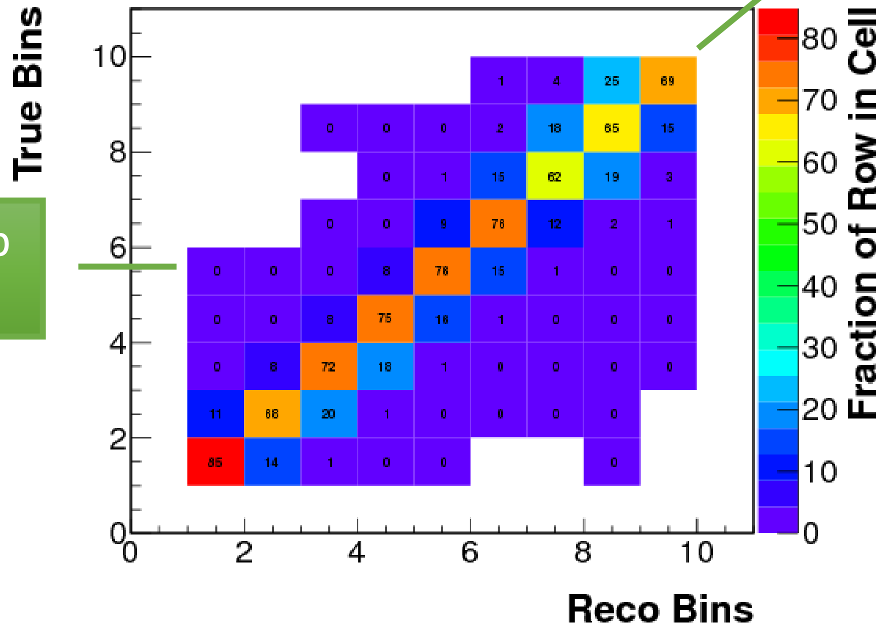
- U_{mt}: This is the "unsmearing matrix" that takes you from the measured variable to the true variable
- We want to know, if an event is observed in bin m, what bin did it really happen in?
- In other words, what's the probability that an event observed in bin m (measured) actually occurred in bin t (true)?
- We can use our Monte Carlo to form a migration matrix indicating what fraction of events generated in each true bin α were observed in each reconstructed bin j
- If the detector has good resolution, the matrix should be close to diagonal





Graphics courtesy C. Patrick

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



Each row adds up to 100%

Diagonal corresponds to events reconstructed in the right bin

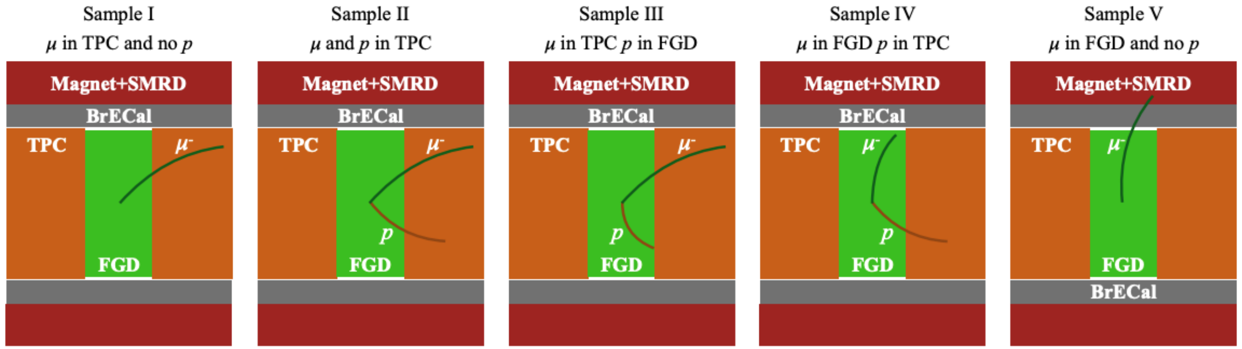
"Migration Matrix"

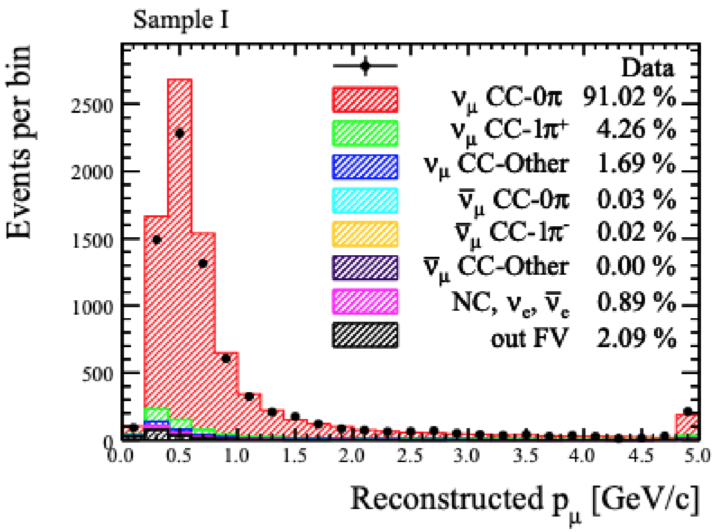
- To get the unsmearing matrix U_{tm}, you have to invert the migration matrix
- …in theory. In practice, it often gives poor results and we often need to use a more sophisticated method

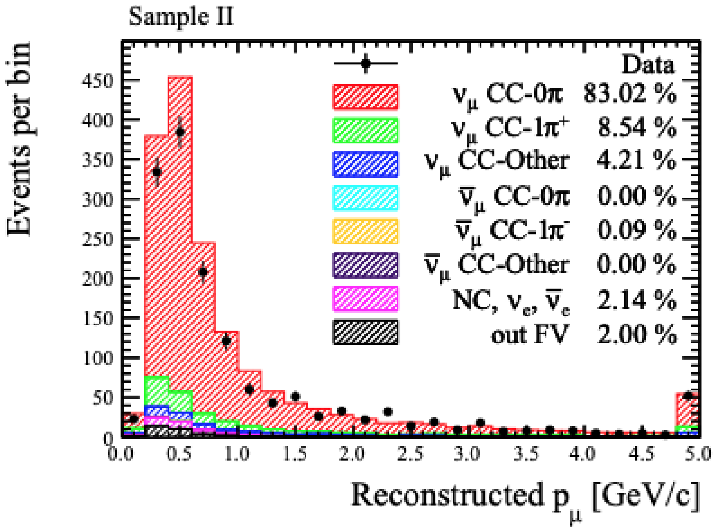
Graphics courtesy C. Patrick

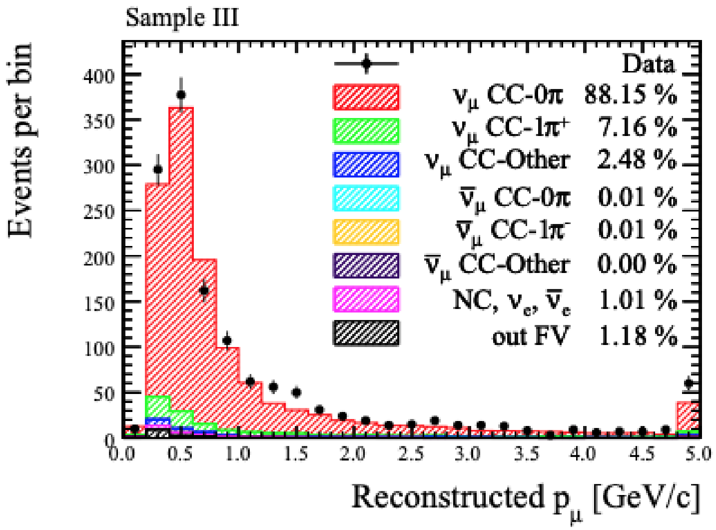
T2K: Letting U_{mt} vary

- T2K: Showing 3 out of 5 samples
- "CC0π" Analysis for ν_μ
- Try to get as many μ as possible!









•*Phys.Rev.D* 101 (2020) 11, 112001

T2K: Letting U_{mt} vary

Likelihood:

$$\chi^2 \approx -2\log\mathcal{L} = -2\log\mathcal{L}_{\text{stat}} - 2\log\mathcal{L}_{\text{syst}}$$

statistic term (Barlow-Beeston)

$$2\sum_{j}^{\text{reco bins}}\left(\beta_j N_j^{\text{MC}} - N_j^{\text{obs}} + N_j^{\text{obs}}\log\frac{N^{\text{obs}_j}}{\beta_j N_j^{\text{MC}}} + \frac{\beta_j^2 - 1}{2\sigma_j^2}\right)$$

Where:

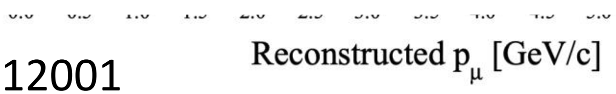
systematic term

$$(\vec{p} - \vec{p}_{\text{prior}})\mathbf{V}_{\text{syst}}^{-1}(\vec{p} - \vec{p}_{\text{prior}})$$

Cross-Section **Flux** **Detector**

Event prediction (as a function of models parameters):

$$N_j^{\text{MC}} = \sum_{i}^{\text{true bins}}\left(c_i w_{ij}^{\text{sig}}(\vec{p})N_{ij}^{\text{sig}} + w_{ij}^{\text{bkg}}(\vec{p})N_{ij}^{\text{bkg}}\right)$$



- *Jesus-Valls, NuINT 2022, and Phys.Rev.D* 101 (2020) 11, 112001

T2K: Letting U_{mt} vary

- In order to incorporate systematic uncertainties on cross section model, T2K parameterizes the uncertainties and then lets them float in a fit that incorporates not only the signal region but also two control samples

Likelihood: $\chi^2 \approx -2\log\mathcal{L} = -2\log\mathcal{L}_{\text{stat}} - 2\log\mathcal{L}_{\text{syst}}$

statistic term (Barlow-Beeston)

$$2\sum_{j}^{\text{reco bins}}\left(\beta_j N_j^{\text{MC}} - N_j^{\text{obs}} + N_j^{\text{obs}}\log\frac{N^{\text{obs}_j}}{\beta_j N_j^{\text{MC}}} + \frac{\beta_j^2-1}{2\sigma_j^2}\right)$$

Where:

$$\beta_j = \frac{1}{2}\left(-(N_j^{\text{MC}}\sigma_j^2 - 1) + \sqrt{(N_j^{\text{MC}}\sigma_j^2-1)^2 + 4N_j^{\text{MC}}\sigma_j^2}\right)$$

systematic term

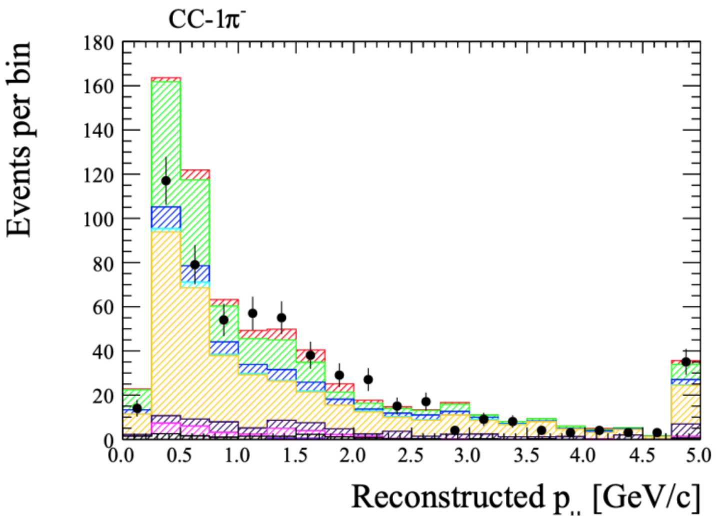
$$(\vec{p}-\vec{p}_{\text{prior}})\mathbf{V}_{\text{syst}}^{-1}(\vec{p}-\vec{p}_{\text{prior}})$$

Cross-Section **Flux** **Detector**

Example:

Event prediction (as a function of models parameters):

$$N_j^{\text{MC}} = \sum_{i}^{\text{true bins}}\left(c_i w_{ij}^{\text{sig}}(\vec{p})N_{ij}^{\text{sig}} + w_{ij}^{\text{bkg}}(\vec{p})N_{ij}^{\text{bkg}}\right)$$



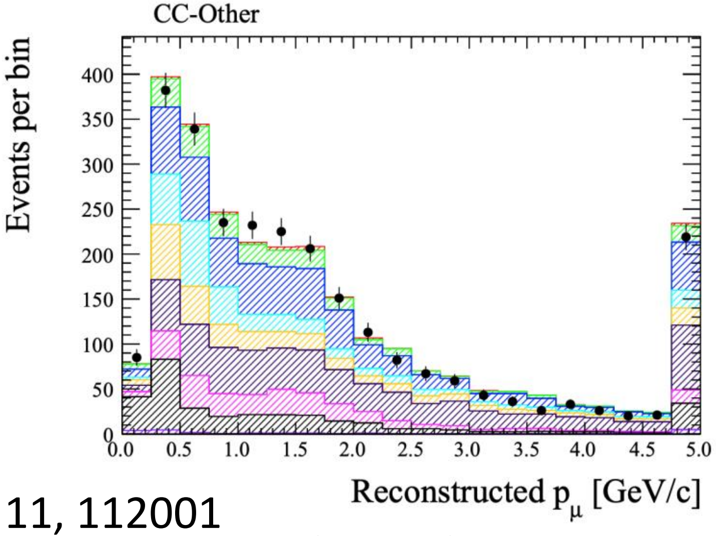


TABLE II. Prior values and errors of the cross section model parameters used in this analysis.

Parameter	Prior	Error
M_A^{QE} (GeV/c^2)	1.2	0.3
p_F^C (MeV/c)	217	30
E_B^C (MeV)	25	9
2p2h ν	1	1
2p2h $\bar{\nu}$	1	1
C_A^5 (GeV/c^2)	1.01	0.12
M_A^{Res} (GeV/c^2)	0.95	0.15
$I_{1/2}$	1.3	0.2
DIS Multiple pion	0.0	0.4
CC Coherent on C	1.0	1.0
CC-1π $E_\nu < 2.5$ GeV	1.0	0.5
CC-1π $E_{\bar{\nu}} < 2.5$ GeV	1.0	1.0
CC-1π $E_\nu > 2.5$ GeV	1.0	0.5
CC-1π $E_{\bar{\nu}} > 2.5$ GeV	1.0	1.0
CC Multile π	1.0	0.5
CC-DIS ν	1.0	0.035
CC-DIS $\bar{\nu}$	1.0	0.065
NC Coherent	1.0	0.3
NC Other	1.0	0.3
Pion production	0.0	0.5
Pion absorption	0.0	0.41
Pion quasi-elastic int. for $p_\pi < 500$ MeV/c	0.0	0.41
Pion quasi-elastic int. for $p_\pi > 400$ MeV/c	0.0	0.34
Pion charge exchange for $p_\pi < 500$ MeV/c	0.0	0.57
Pion charge exchange for $p_\pi > 400$ MeV/c	0.0	0.28

•*Jesus-Valls, NuINT 2022, and Phys.Rev.D* 101 (2020) 11, 112001

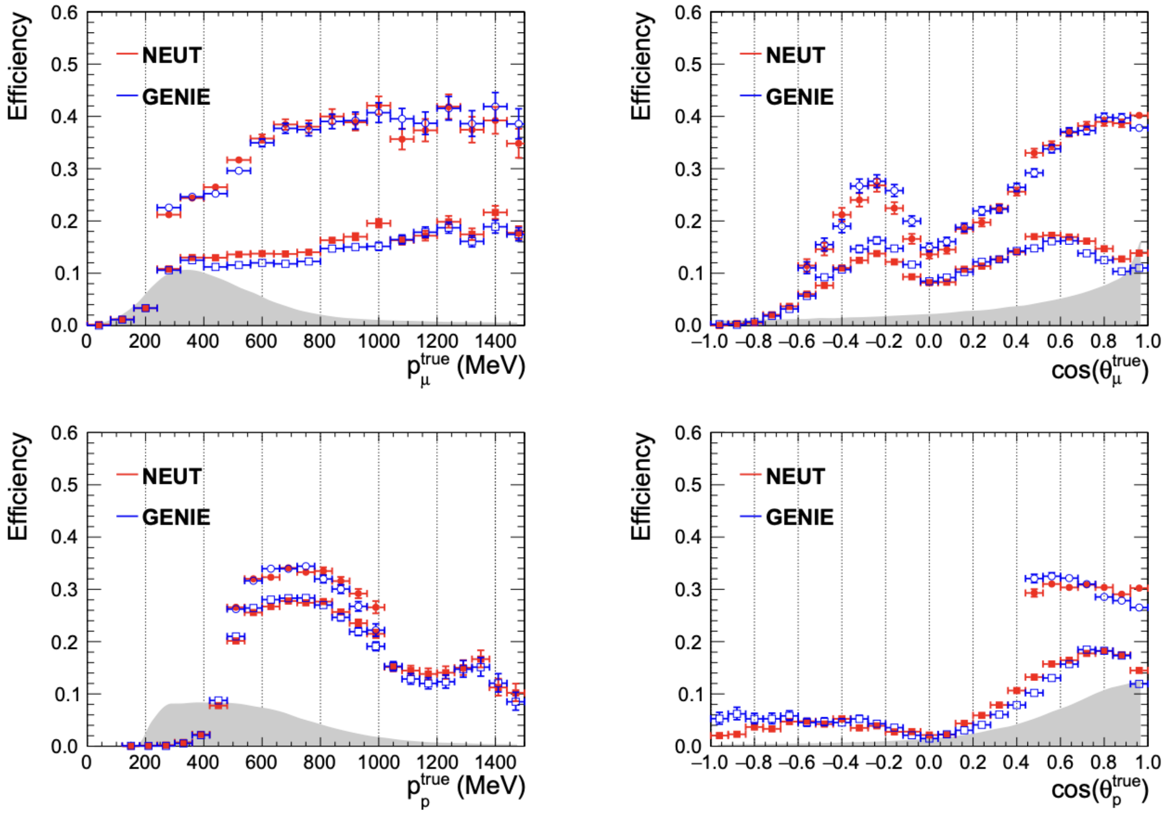
$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\,U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

- Φ_ν: Flux [neutrinos/cm^2]
- Usually the cross section is reported assuming you've integrated over all neutrino energies: so Φ really means
- $\Phi_\nu = \frac{\int dE_\nu \Phi_\nu(E_\nu)}{\int dE_\nu}$
- For the rare cases where neutrino energy is measurable

Total Cross Section: $$\sigma(E_\nu) = \frac{(\mathrm{N}(E_\nu) - B(E_\nu))\,U_{mt}}{\Phi_\nu(E_\nu)\epsilon(E_\nu)M}$$

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

- $\epsilon(x_t)$: Efficiency [unitless]
- The fraction of signal events that you retain after making all the analysis cuts to remove your backgrounds
- In truth, this efficiency may depend not only on but also on neutrino energy, and remember you're integrating over the flux
- $\epsilon(x_t) = \frac{\int \epsilon(x_t, E_\nu)\Phi_\nu dE_\nu}{\int \Phi_\nu dE_\nu}$

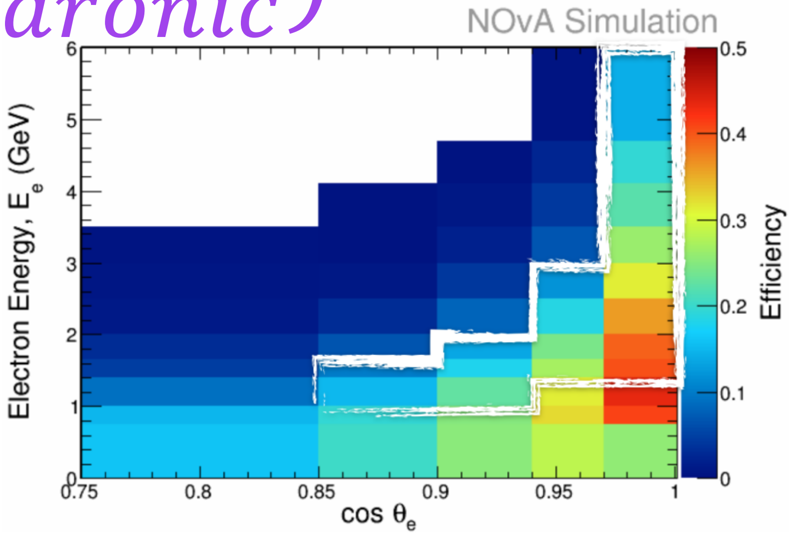


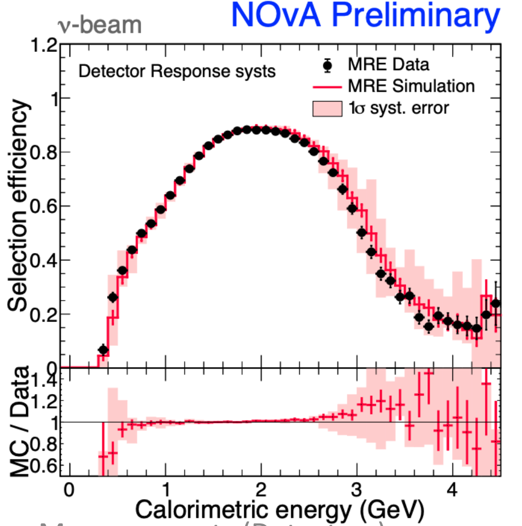
One way to check: Compare efficiencies from different generators

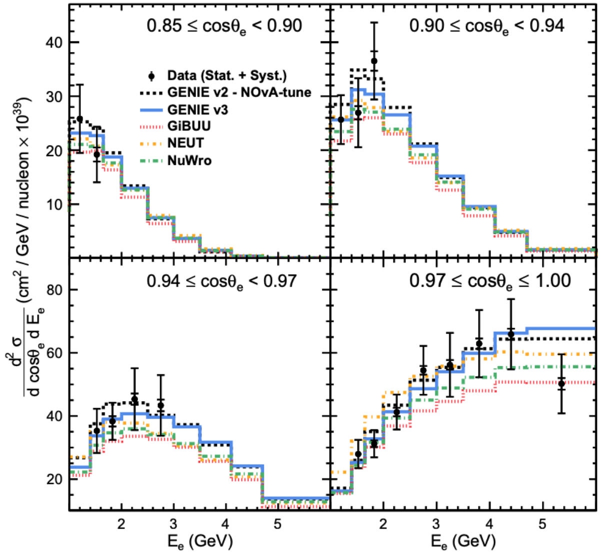
- (Ref: T2K, *Phys.Rev.D* 98 (2018) 3, 032003)

NOvA: Using Data to test $\epsilon(E_{hadronic})$

- NOvA has produced first double differential cross section for electron neutrino charged current inclusive scattering
- Use Boosted Decision Tree to identify electrons
- How do they know that they model the efficiency of the BDT correctly given uncertainties in hadron energy? Use the Data! Can you guess how?
- "Muon Removal" Technique: remove muon from ν_μCC data events, add electron at same angle and energy, then measure efficiency, and compare to the efficiency for original simulation.



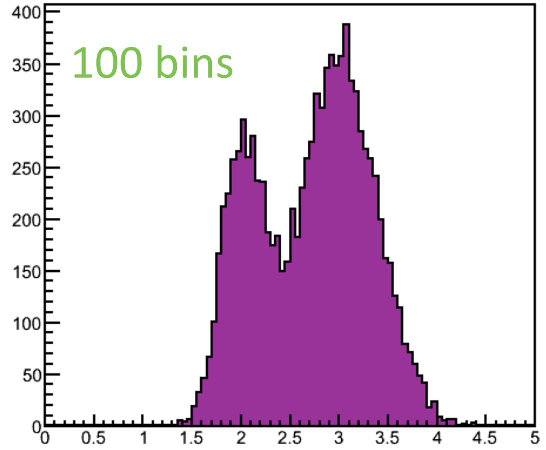


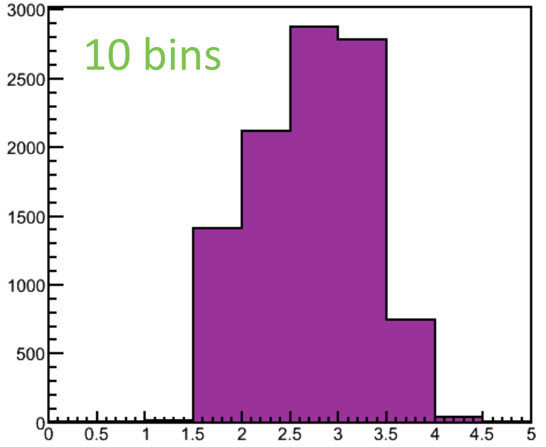


Phys.Rev.Lett. 130 (2023) 5, 051802

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

- Δx: Bin width [units of whatever x is]
- How wide should this bin width be?
- The more bins you have, easier to distinguish features of the distribution
- The more bins you have, the worse the statistics are in each bin
- BUT…Depends on your resolution: if you can't measure something to better than δ , you shouldn't pick bins that are $\delta/10$!





Graphics courtesy C. Patrick

Break, now that we've discussed every term in

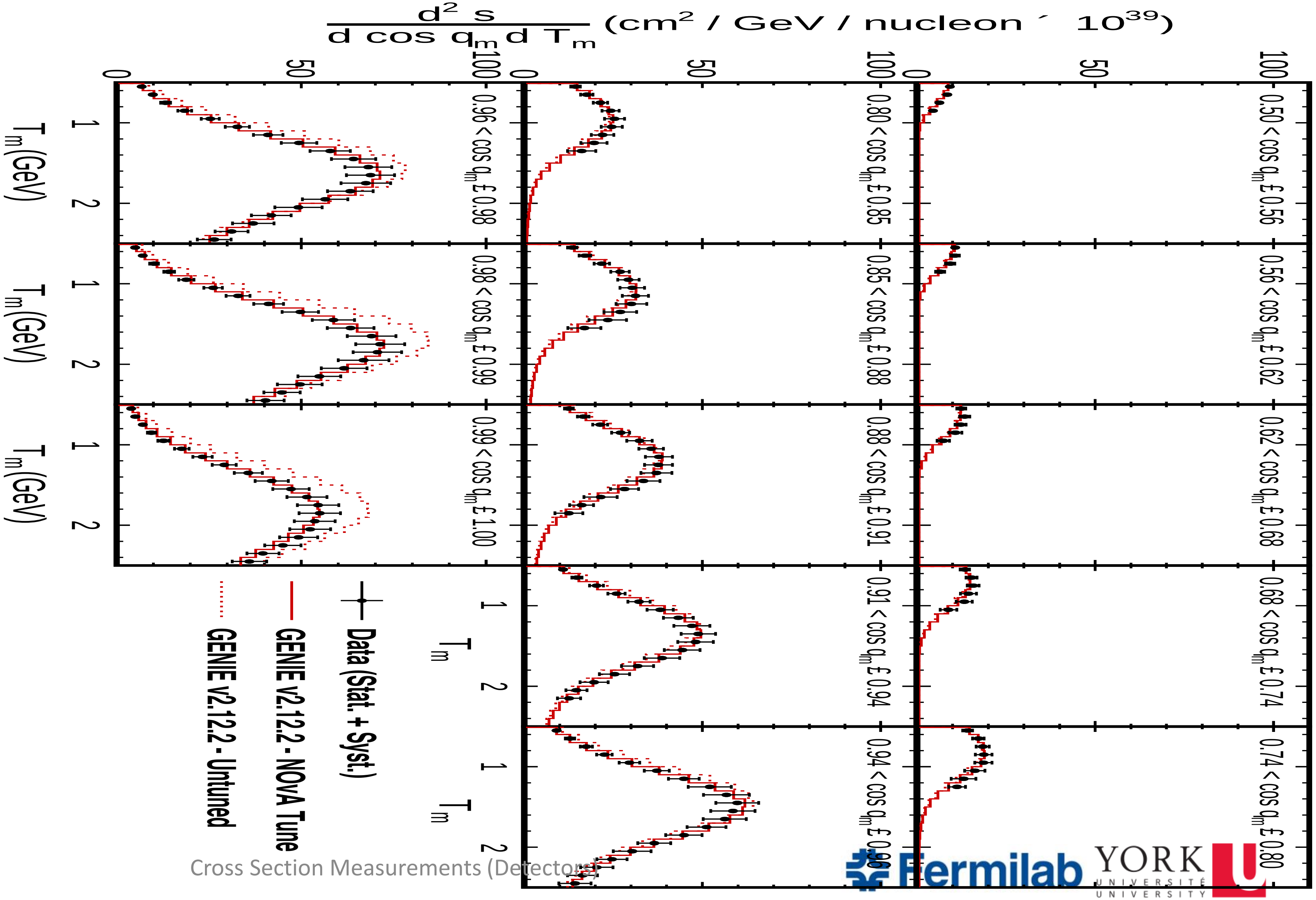
$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\ U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

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?
  - 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
- Easiest Observables to measure: Muon Kinetic Energy (T) and angle (θ) w/rt Neutrino beam

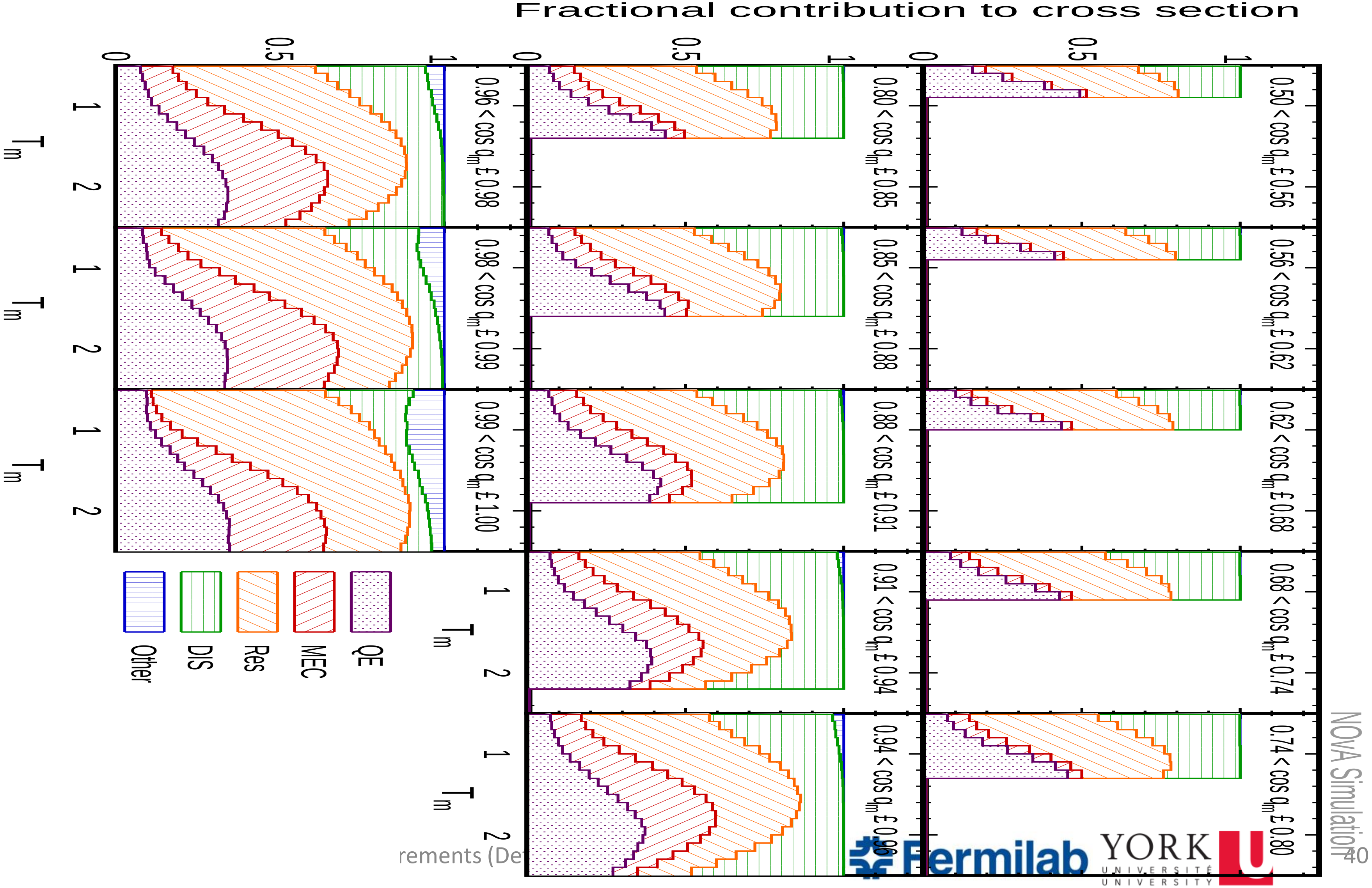
One example of Inclusive Cross Section Result

- 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

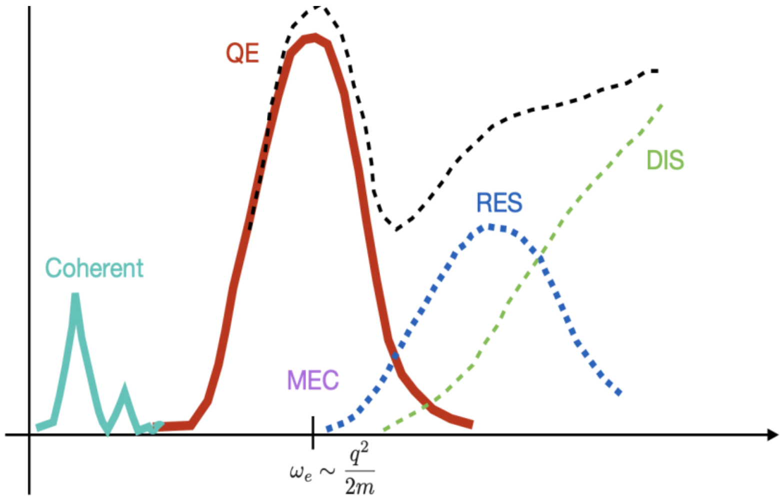
- Let’s say you have measured the following quantities:
  - Final lepton charge and momentum 3-vector: can determine p_{lep}, E_{lep}, θ_{lep}
  - Total hadronic energy

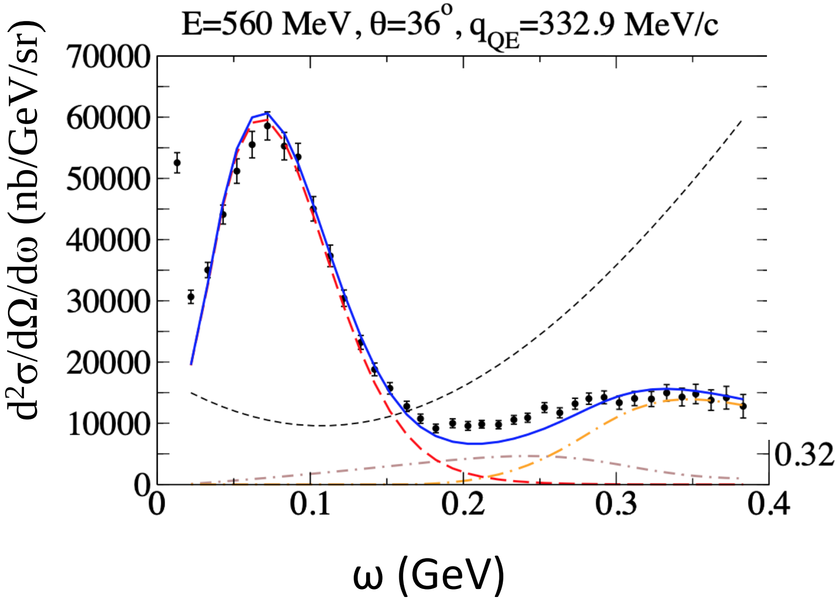
    (**pretend** you can see all of it, even the neutron energy) E_{had}
- Can define a few quantities:
  - Estimated Neutrino Energy $E_\nu = E_{lep} + E_{had}$
  - Estimated Momentum Transfer (squared) to the nucleus:

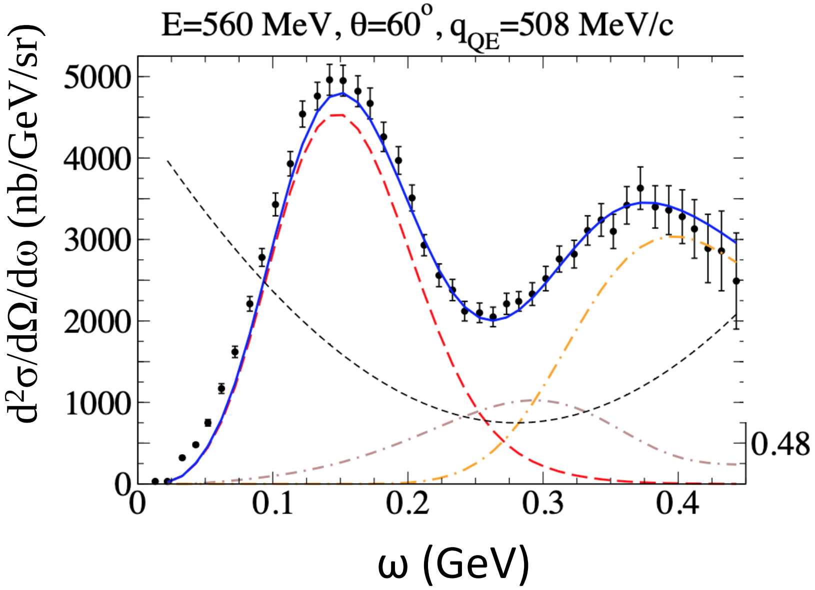
    (remember, W is virtual) $-q^2=Q^2 = 2\,E_\nu(E_\mu - p_\mu \cos\,\theta_\mu) - M_\mu^{\,2}$
  - Estimated Energy transferred to the nucleus = $\omega = E_{had}$
  - 3-momentum transferred to the nucleus: $Q^2+\omega^2=q_3^{\,2}$

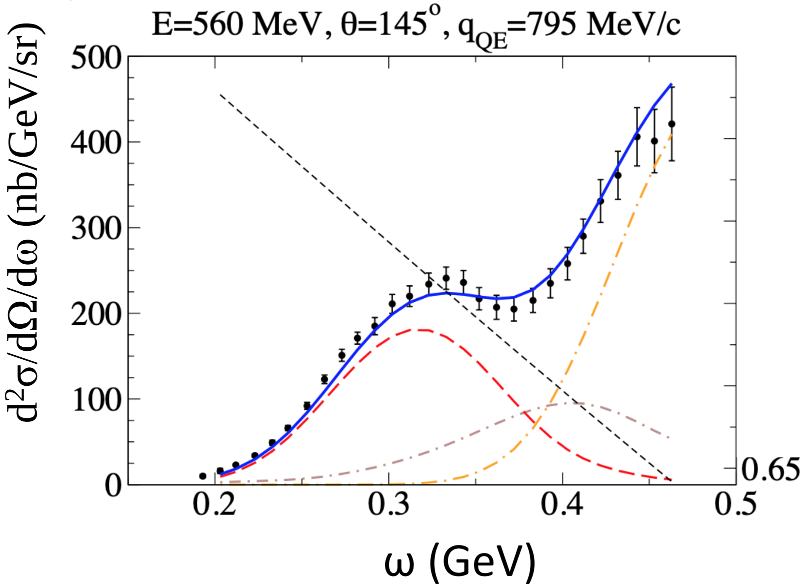
Neutrino Observables w/hadrons & leptons

- Remember this picture 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’







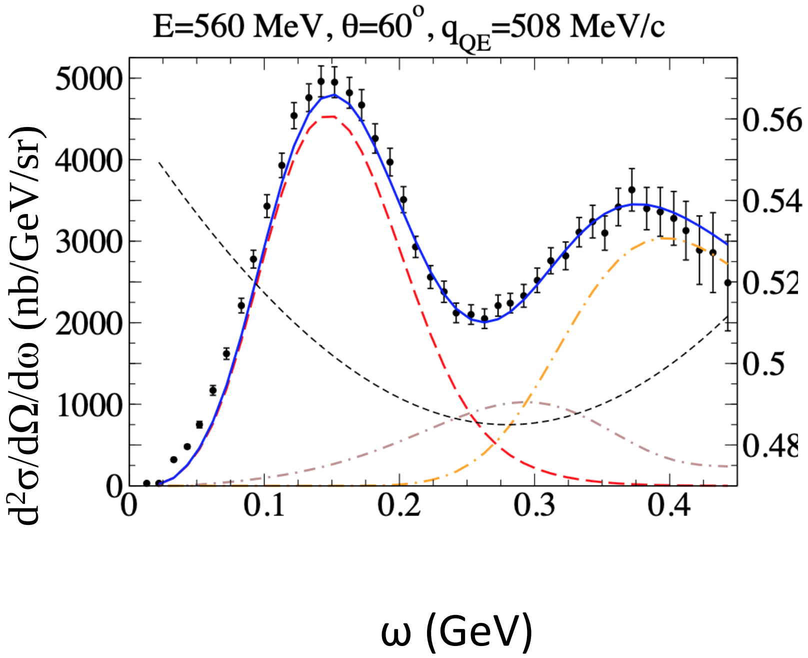


Phys. Rev. D 94, 013012 (2016)

Neutrino Observables w/hadrons & leptons

- Translating this picture to Neutrino Scattering

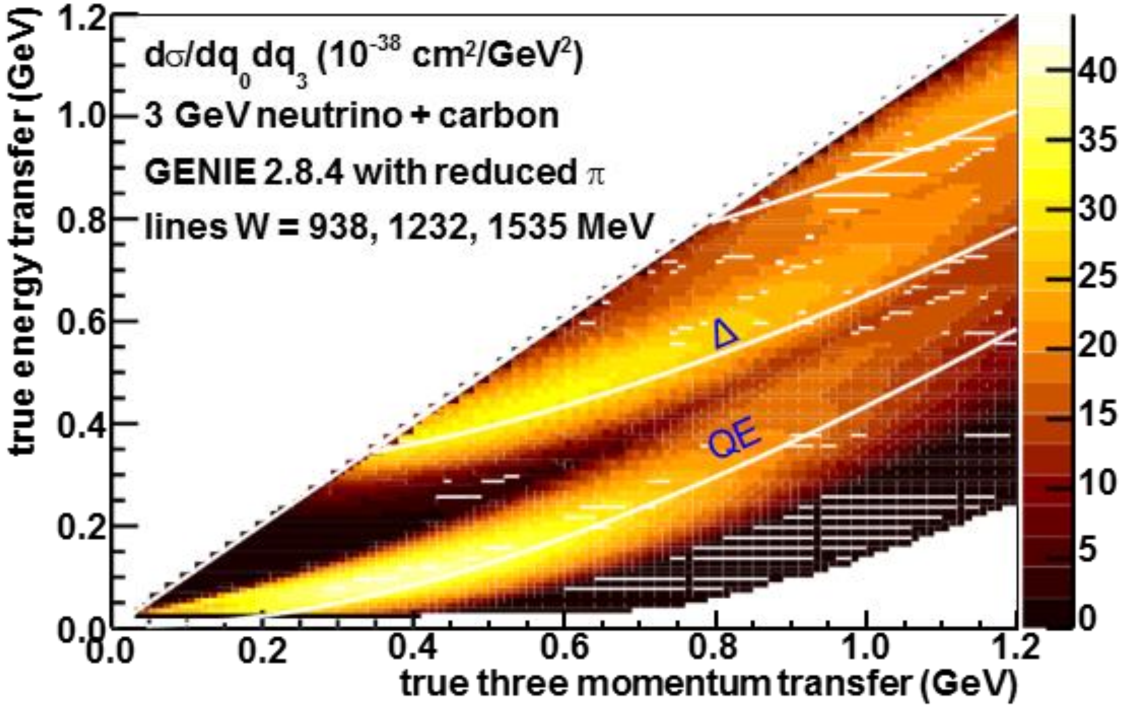
Graphics courtesy R. Gran



Phys. Rev. D 94, 013012 (2016)

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

For neutrinos:
True Energy transfer: ω
True 3-momentum transfer: $Q^2+\omega^2=q_3^2$



Proxy for True Energy transfer to Hadronic system: "Available Energy" (answer to HW#4)

- 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

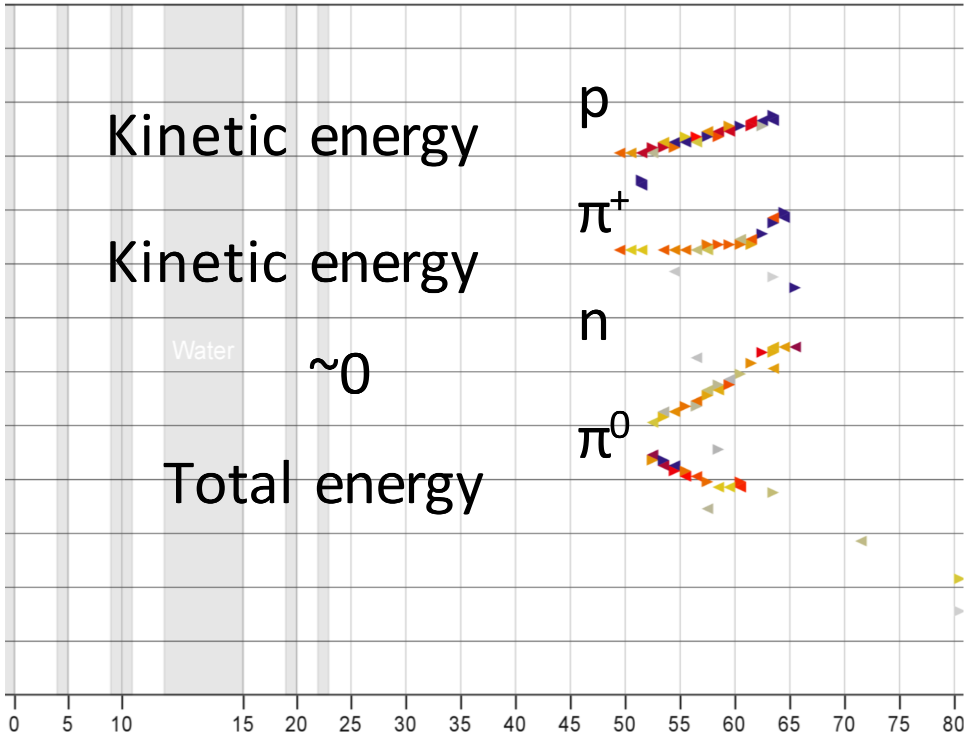


Figure courtesy P. Rodrigues

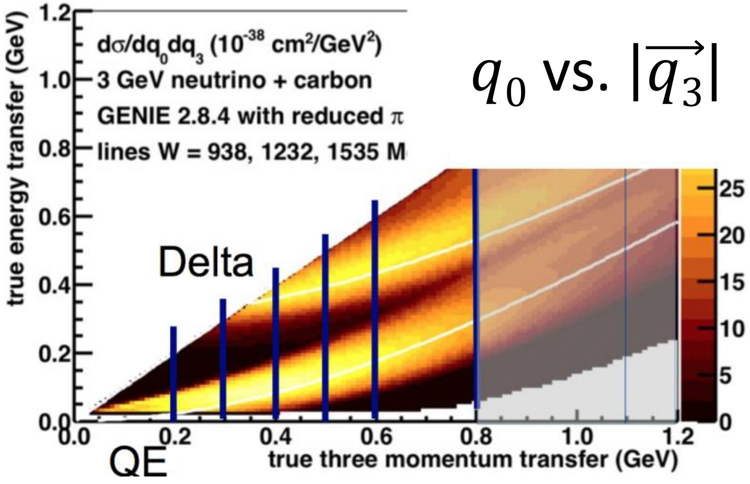
Example from MINERvA at right,
3.3cm plastic granularity
Similar in spirit to ~3cm wire pitch Liquid Argon (but different density, Z)

Phys. Rev. D 94, 013012 (2016)

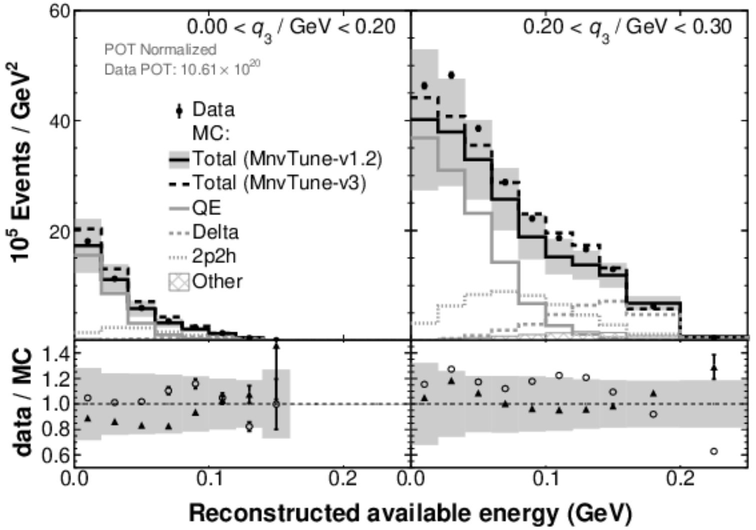
What does the Data Look like in this space?

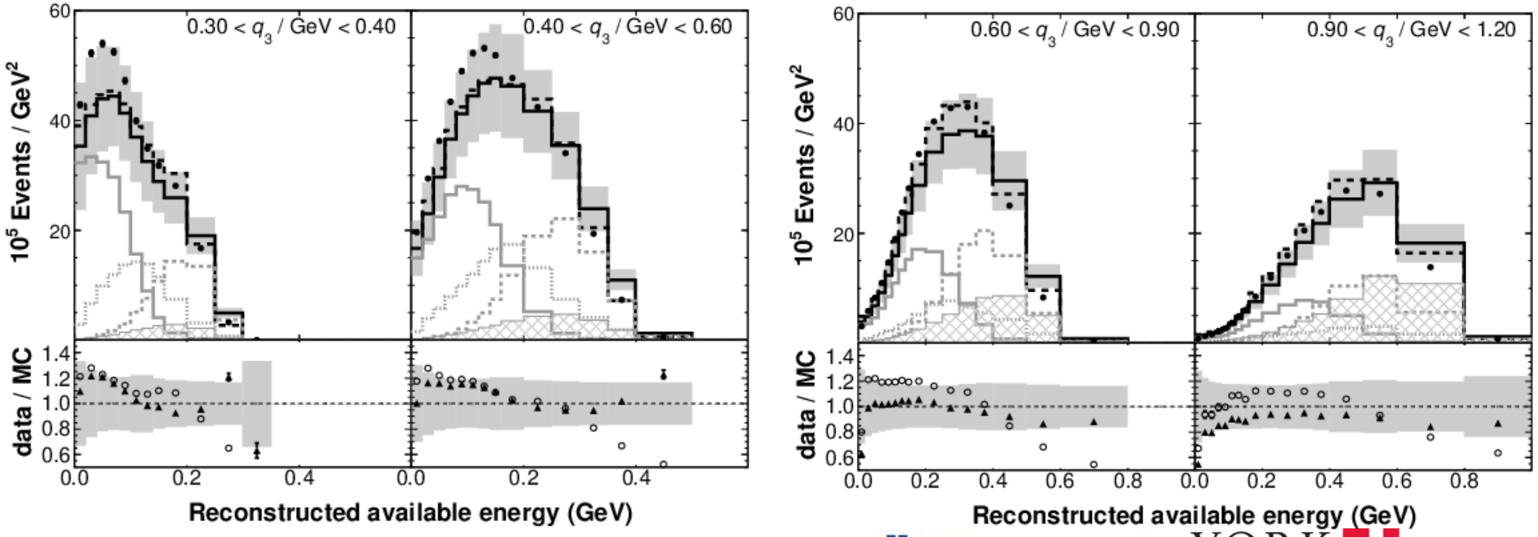
- Look at inclusive sample of events as function of energy AND momentum transferred
- Showing event distributions, but cross sections were extracted
- Cross sections were also extracted from these distributions
- Available Energy: “visible” energy in scintillator
- Unfolding this was tricky!

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



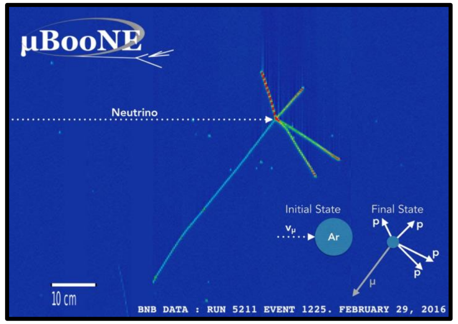
q_0 vs. $|\overrightarrow{q_3}|$

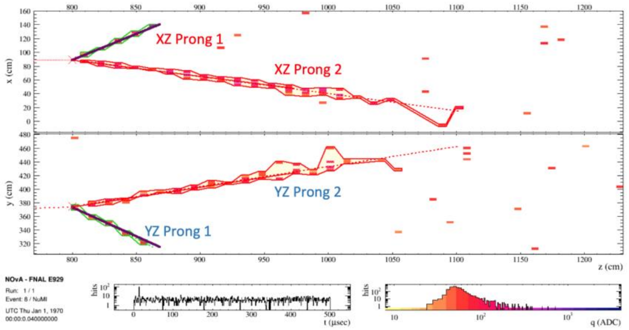


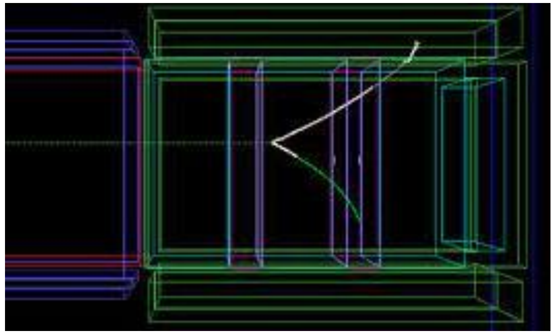


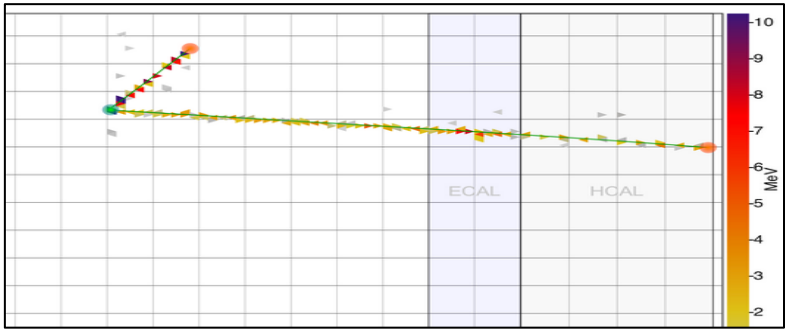
From Inclusive to Exclusive

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



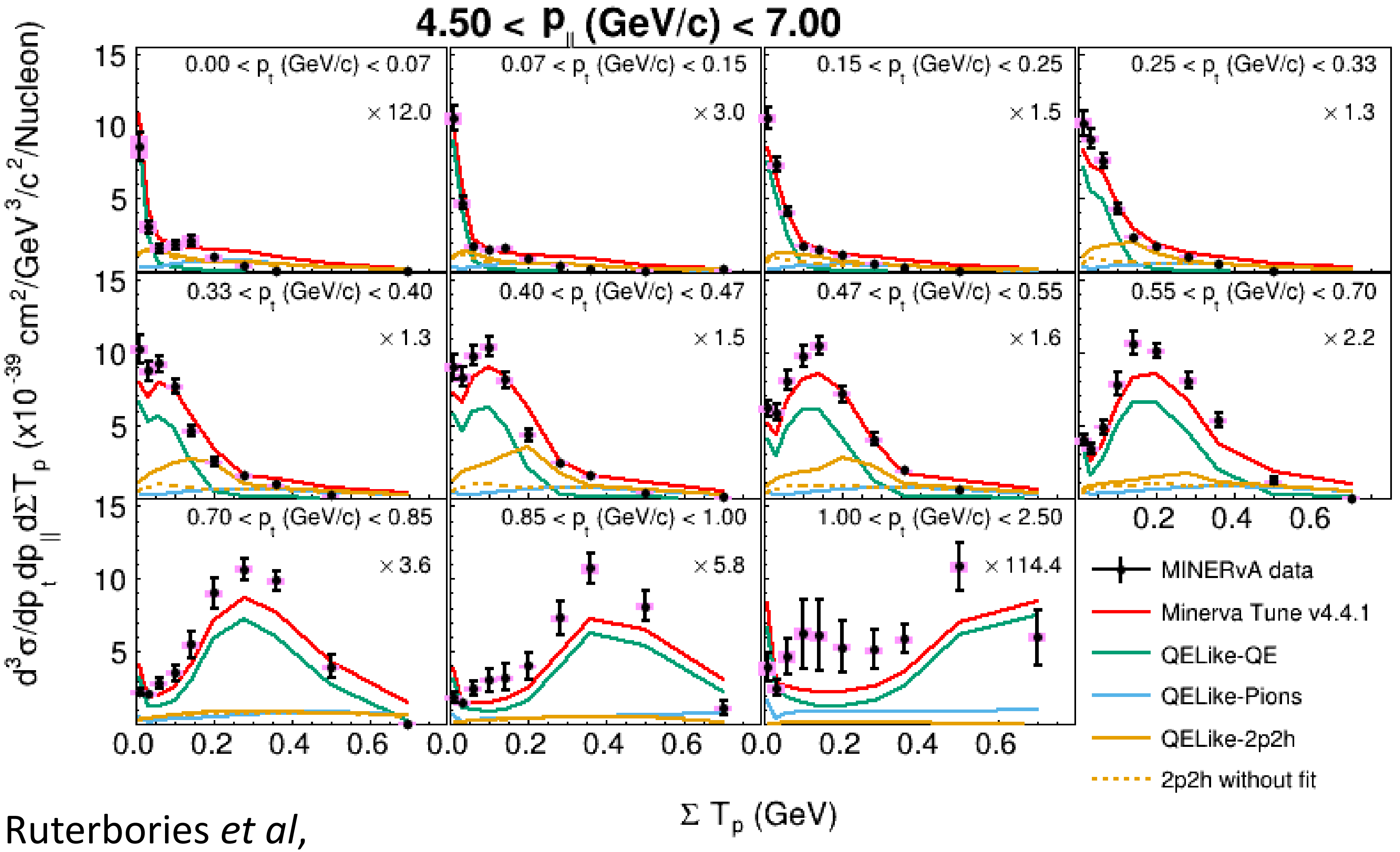






- How would you isolate events that are quasielastic?
  - Require one lepton (of the correct charge if possible)
  - Do you require a proton track? Or do you only require NO pion tracks?
  - What about Michel Electrons: what if you didn't see a pion track but you saw a tiny em-like shower right near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

New vocabulary: Quasielastic-like

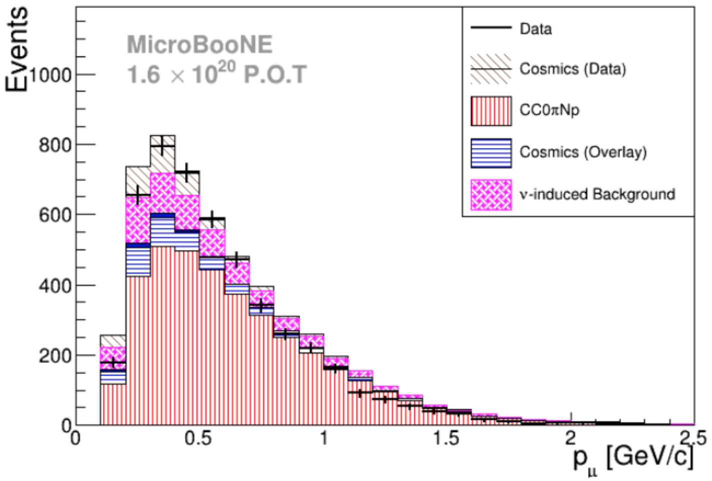


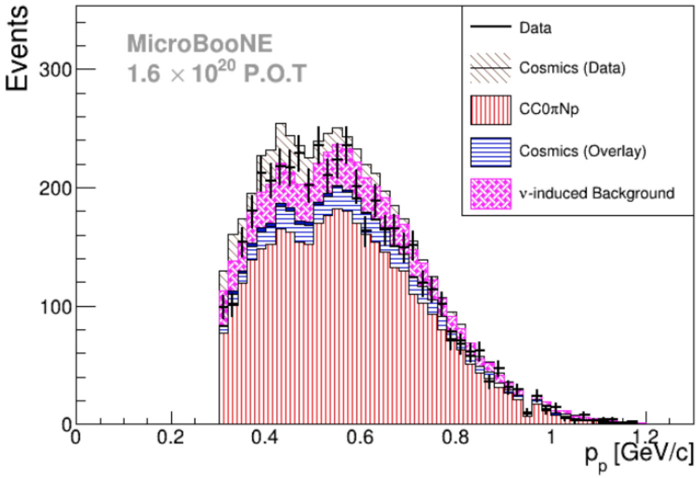
- After subtracting backgrounds, MINERvA has enough statistics to bin QE-like events along 3 axes: muon kinematics AND hadron energy
- Many processes contribute to "CC0$\boldsymbol{\pi}$"
  - CCQE
  - 2p2h
  - Resonance+π absorption
  - DIS
- Lots of discrepancies with the model

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

Different Detectors will have different cuts

- MicroBooNE example: ν_μ CC0π Cross section
- Event with muon and proton candidate
- Leading Muon candidate has p>100MeV/c
- Leading Proton candidate has p<1.2GeV/c
    - Proton candidate has to be shorter than muon candidate

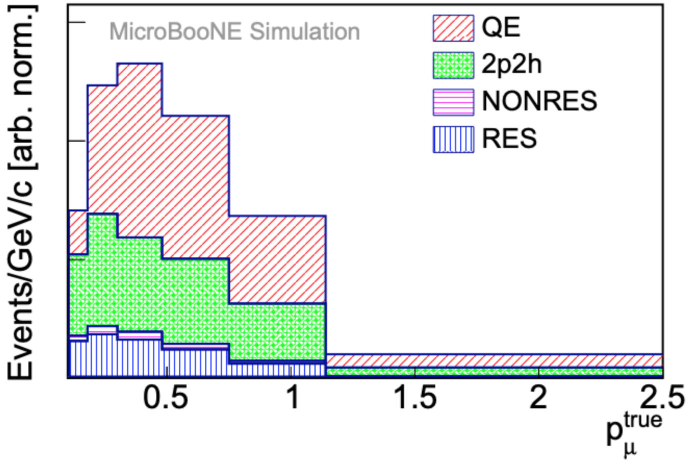


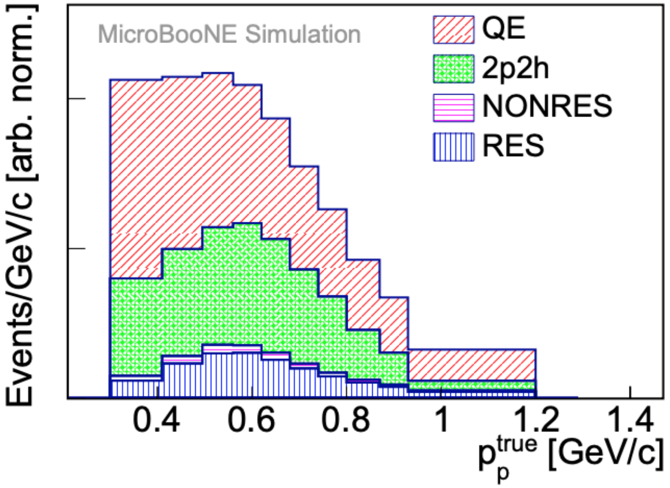


•*Phys.Rev.D* 102 (2020) 11, 112013

CCQE versus “CCQE-like” versus “CC0π”

- Since so many other processes can look like a CCQE event even if you have a perfect detector, we have defined a new term
- How would you make a CCQE-like event that is not CCQE?
- Example from MicroBooNE: breakdown of signal events after background subtraction:



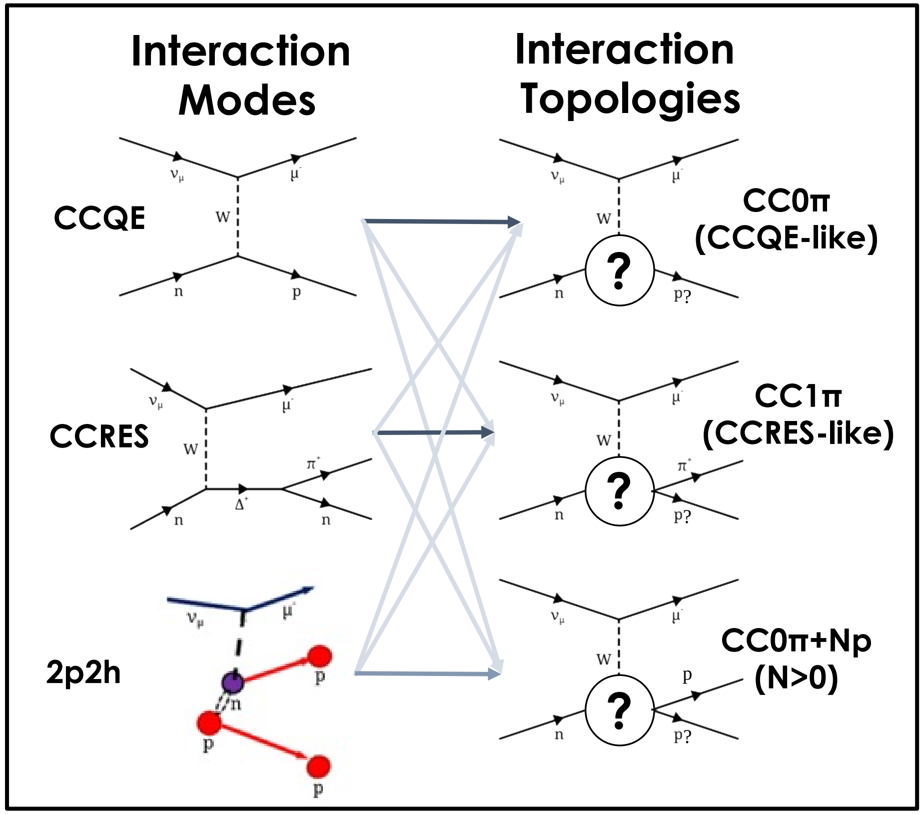


•*Phys.Rev.D* 102 (2020) 11, 112013

Have to map on to Cross Section 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



S. Dolan, INSS 23

QE-like processes and Unfolding Neutrino Energy

- Solution to Homework #3: QE assumption, solve for Neutrino Energy

$$\mathbb{P}_\nu + \mathbb{P}_n = \mathbb{P}_p + \mathbb{P}_\ell$$

4-vector equation

$$\mathbb{P}_\nu - \mathbb{P}_\ell = \mathbb{P}_p - \mathbb{P}_n$$

$$m_\nu^2 + m_\ell^2 - 2(E_\nu E_\ell - p_\nu p_\ell \cos\theta) = m_p^2 + m_n^2 - 2(E_p E_n - p_p p_n \cos\theta_n)$$

$$m_\ell^2 - 2E_\nu(E_\ell - p_\ell \cos\theta) = m_p^2 + m_n^2 - 2E_p m_n$$

$$E_p = E_\nu + m_n - E_\ell$$

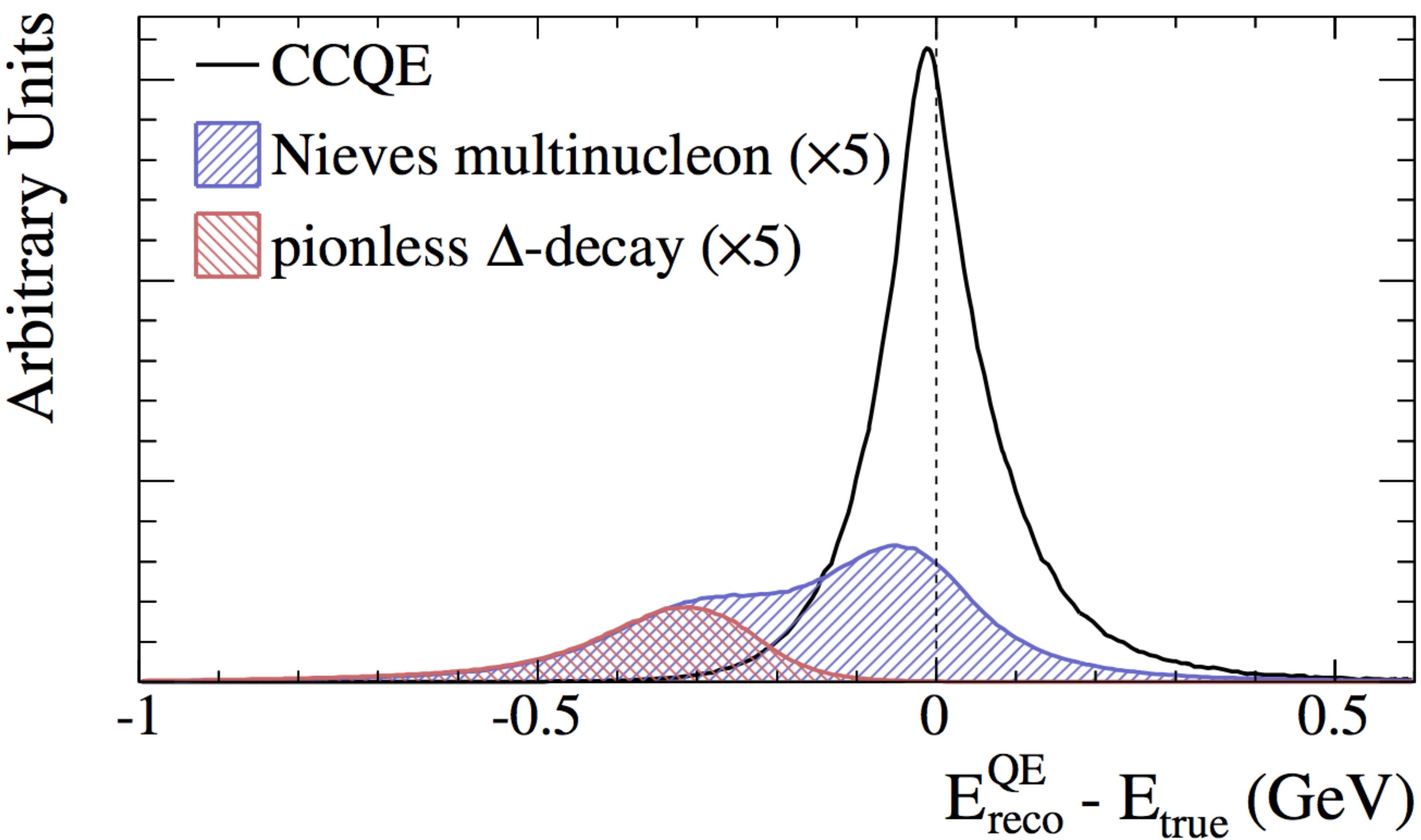
$$m_\ell^2 - 2E_\nu(E_\ell - p_\ell \cos\theta) = m_p^2 + m_n^2 - 2m_n(E_\nu + m_n - E_\ell)$$

$$2m_n E_\nu - 2E_\nu(E_\ell - p_\ell \cos\theta) = m_p^2 + m_n^2 - m_\ell^2 - 2m_n^2 + 2m_n E_\ell$$

$$\boxed{E_\nu = \frac{m_p^2 - m_n^2 - m_\ell^2 + 2m_n E_\ell}{2(m_n + p_\ell \cos\theta - E_\ell)}}$$

What if you were to unfold to Neutrino Energy?

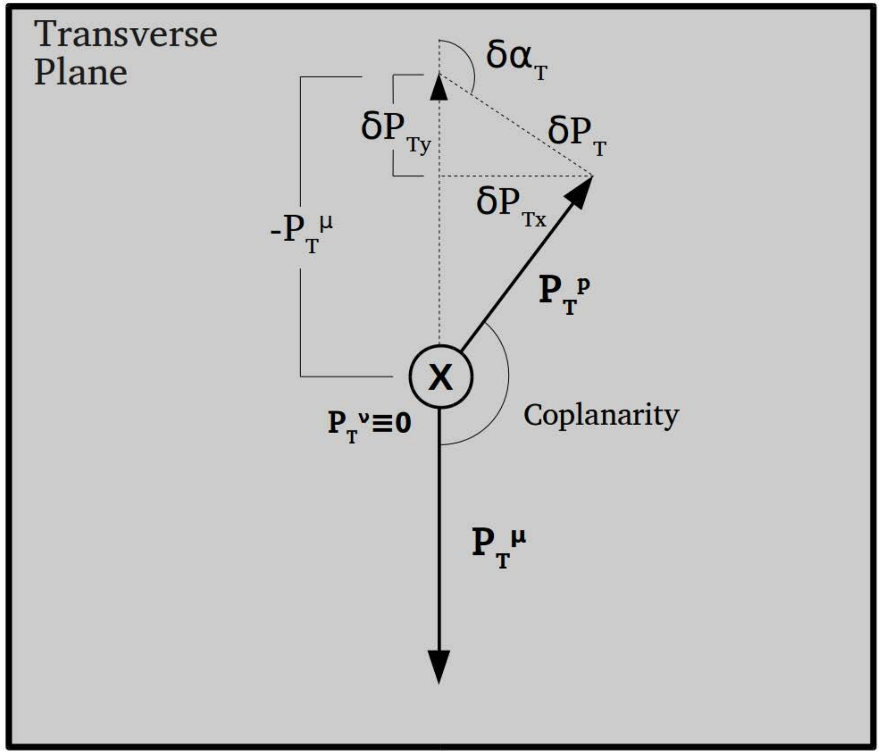
- The energy resolution you get using this formula (or ANY FORMULA) depends on what you assume about the events that pass all your cuts
- Plot at right is for T2K, one of their earliest oscillation papers
- *Phys.Rev.Lett.* 112 (2014) 18



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

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



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

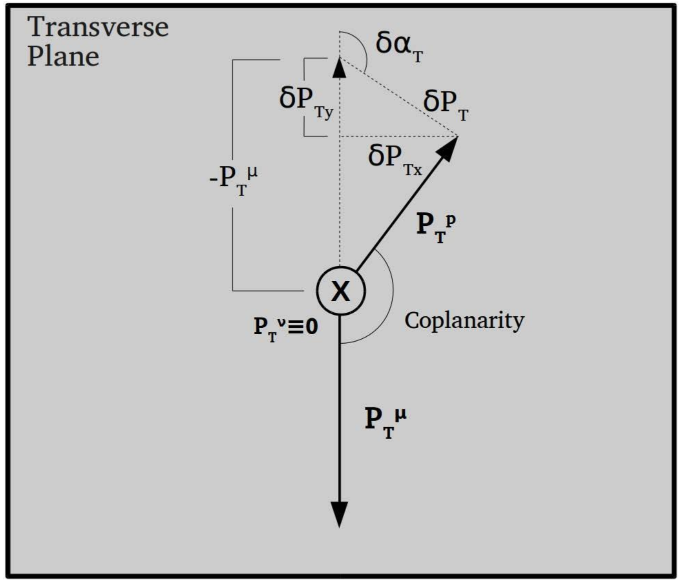
$$\delta\alpha_T = \arccos\left(-\frac{\mathbf{p}_T^\mu \cdot \delta\mathbf{p}_T}{p_T^\mu \delta p_T}\right),$$

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

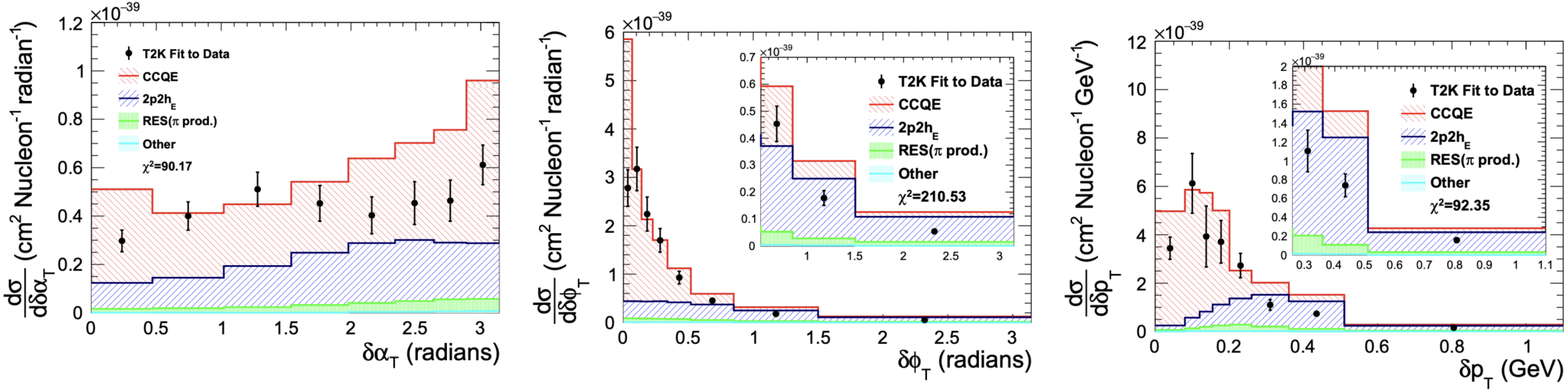
$$P_n \equiv \sqrt{\delta {P_T}^2 + \delta {P_L}^2}$$

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

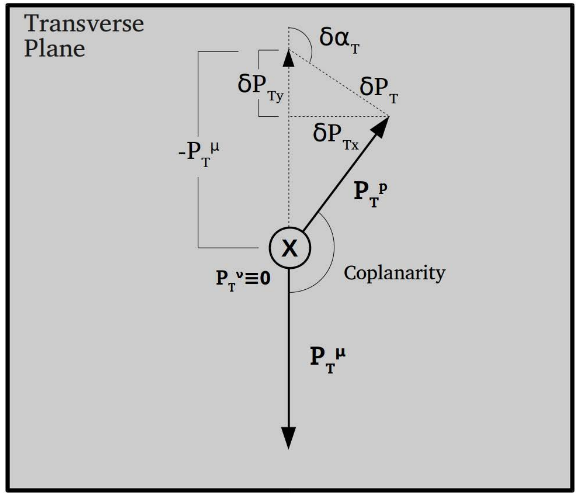
New Neutrino Observables: Transverse Kinematic Imbalance (TKI)



- 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)

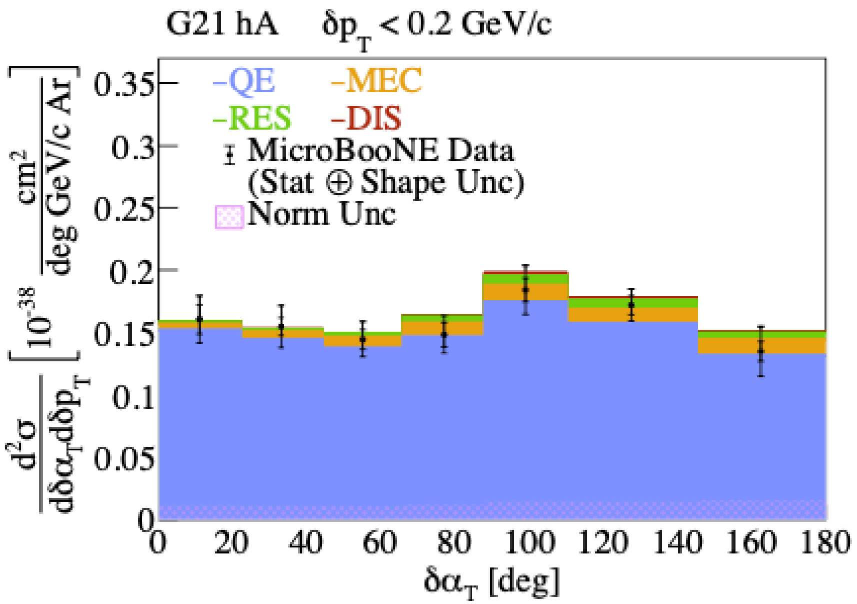


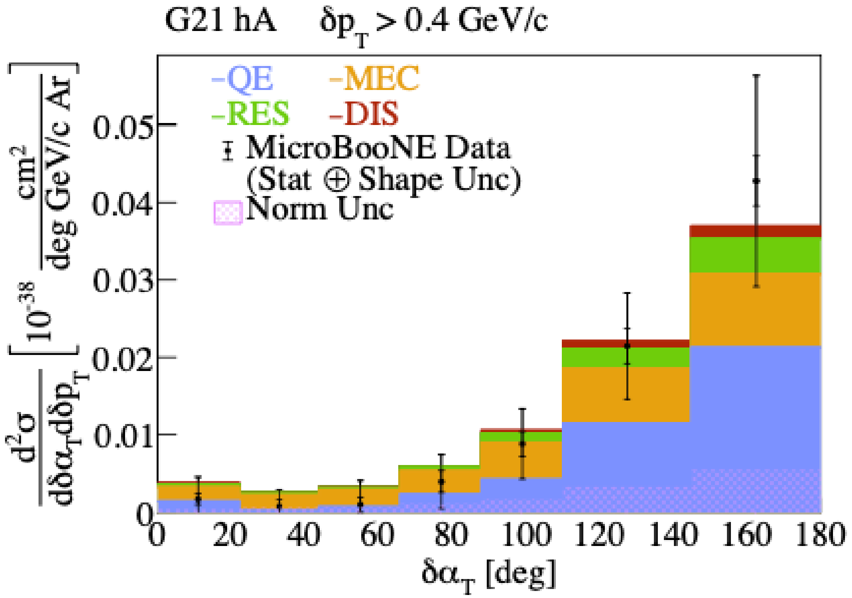
MicroBooNE: Looking at TKI in 2 dimensions



- MicroBooNE split these distributions up into “QE-rich” samples and “everything else” samples
- Plus: Another tool of the trade: “Fake Data Studies”
  - Put in different interaction models see if your procedure extracts predictions from the new model or the one in your unfolding matrix

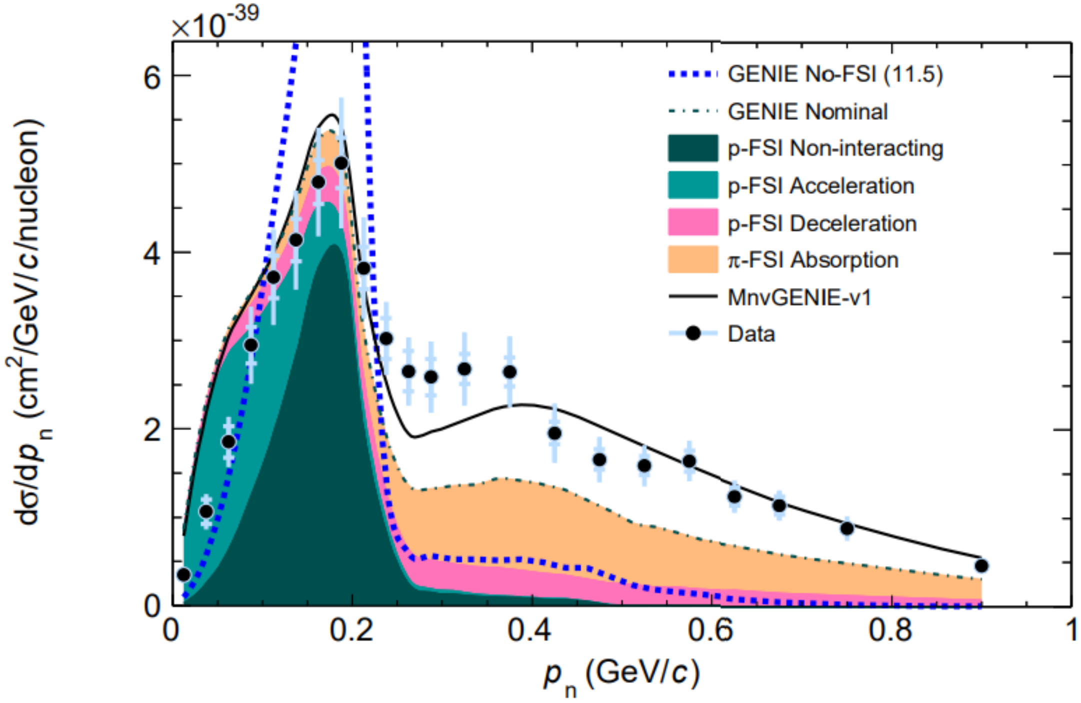
Phys.Rev.D 108 (2023) 5, 053002

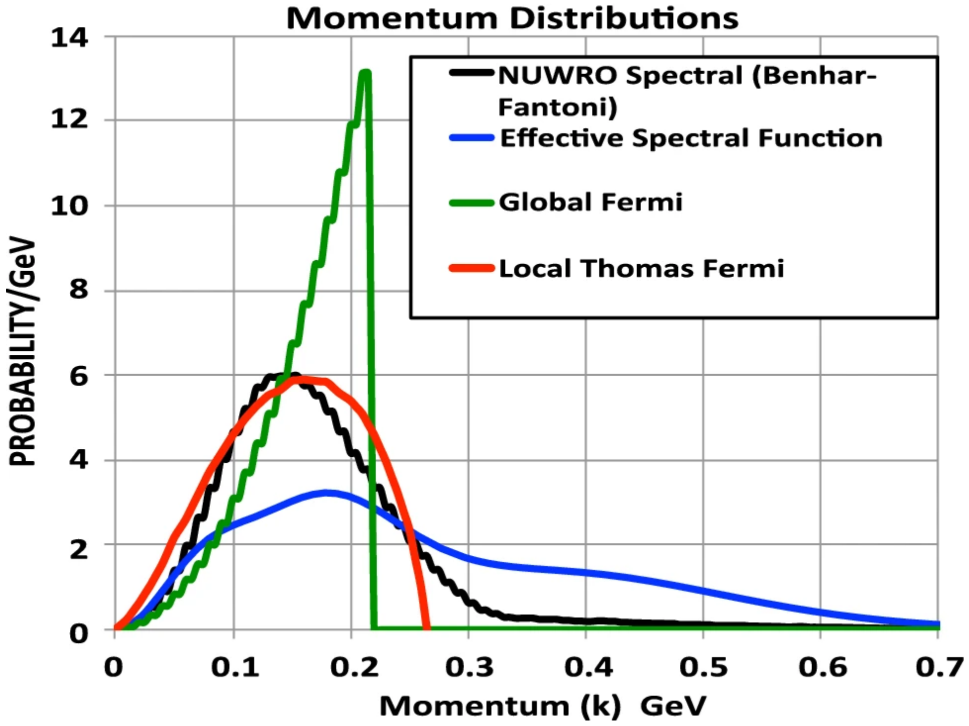




”Initial Nucleon Momentum” as observable?

- Another “transverse kinematic imbalance variable”: if you assume conservation of momentum for events with a final state proton and muon, can calculate the initial nucleon momentum





MINERvA Phys. Rev. Lett. 121, 022504 (2018)

Challenges

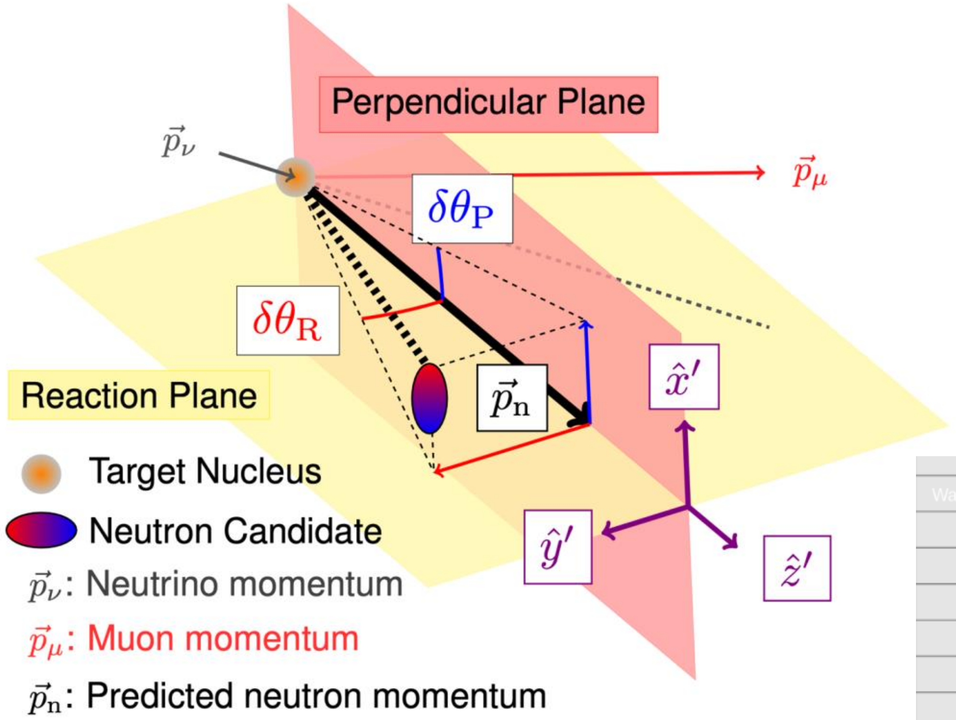
- Goal: make measurements that can constrain models

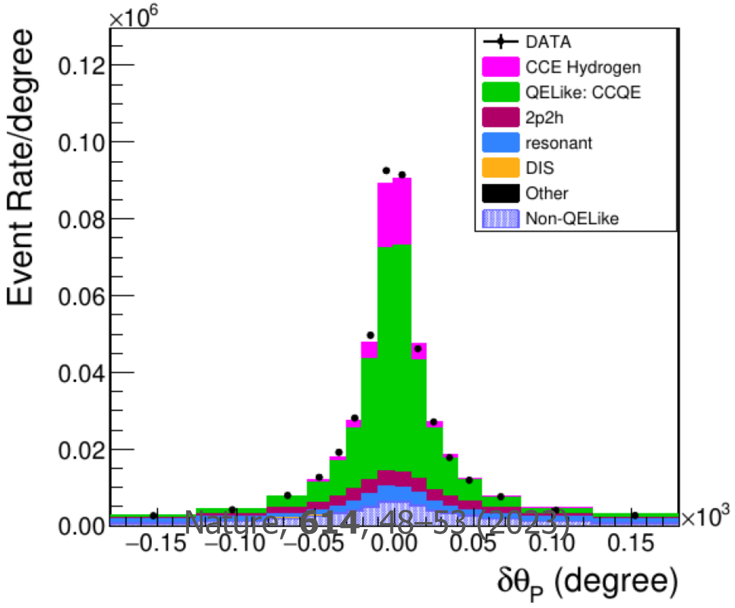
- Why is this difficult?
  - Given the flux, you never know precisely what neutrino energy you have for any one event
  - Given the analysis cuts to isolate the signal you are trying to find, the detector limitations mean you may have backgrounds in your sample
  - Given detector limitations you never know precisely what energy you missed from neutrons
  - If that’s not bad enough, there’s also the fact that nuclear effects can make one process look like another even if your detector was perfect

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

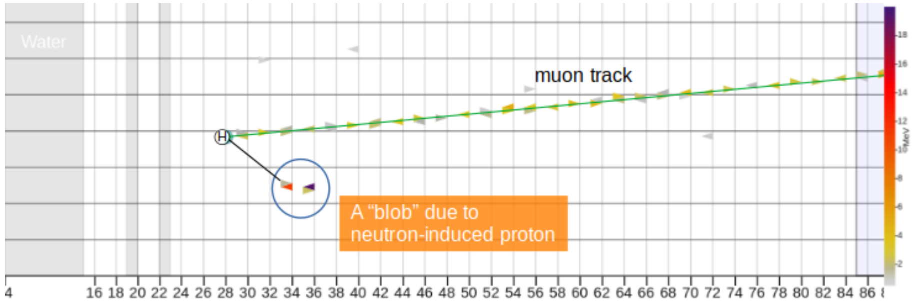
Using what you’ve learned to see H by itself

- 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!

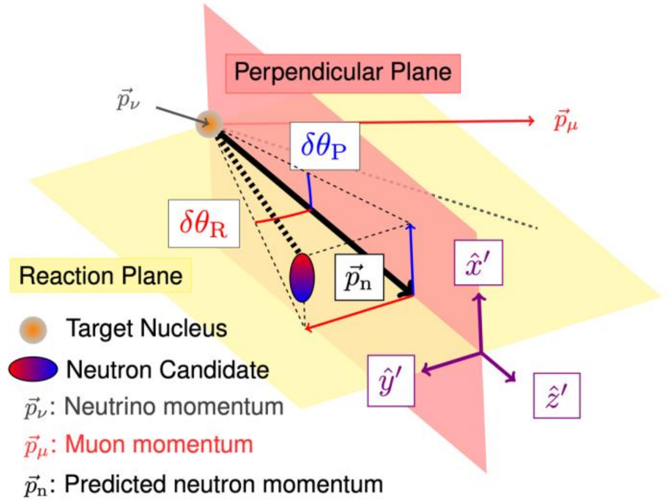


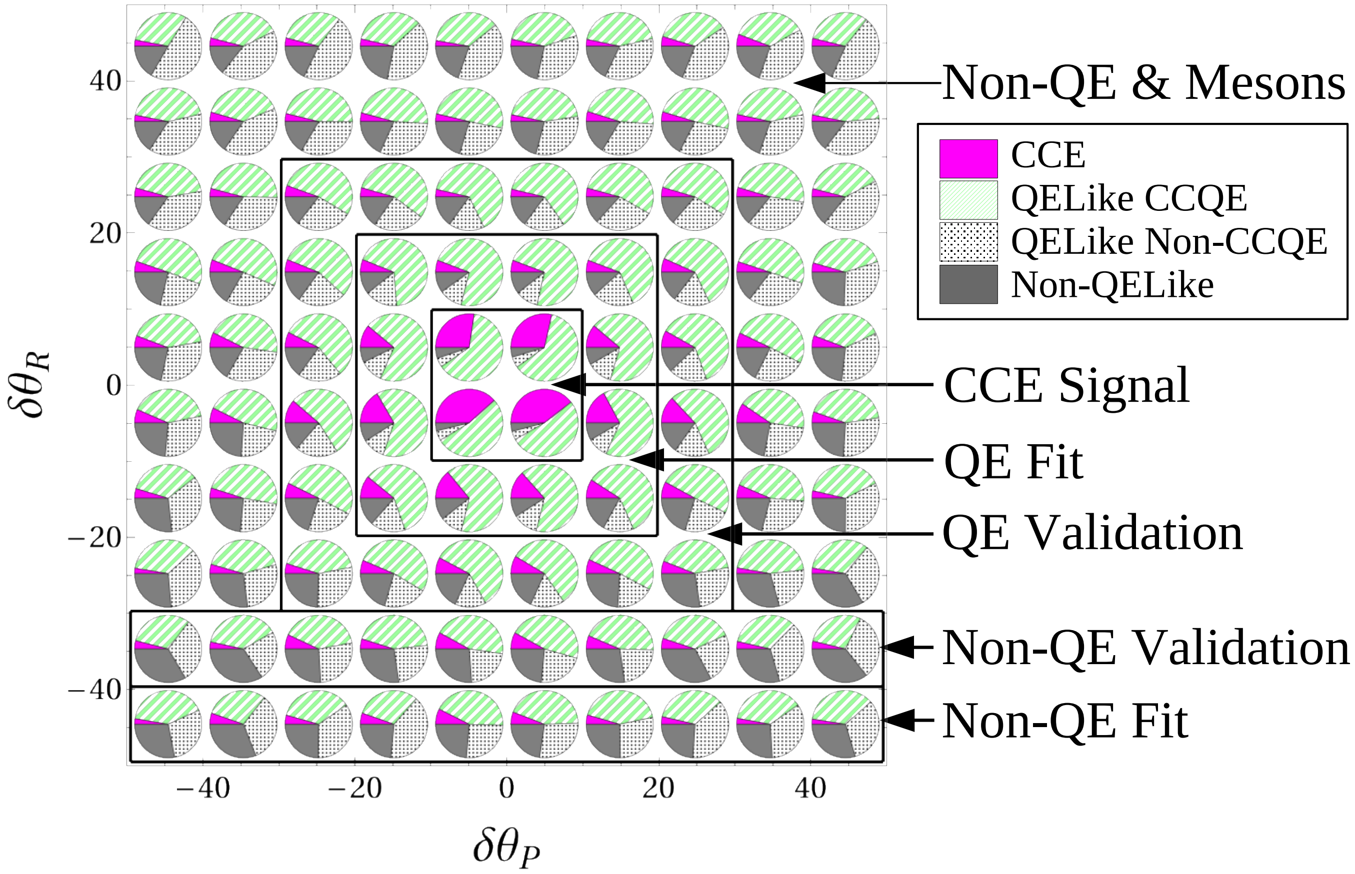


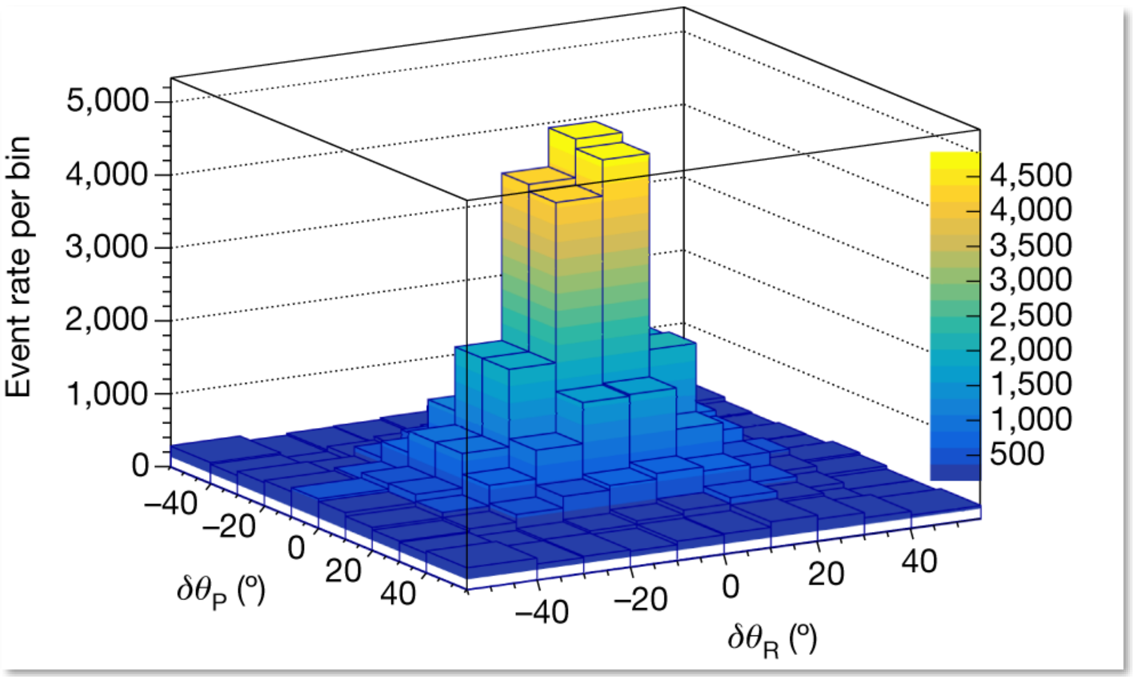
Nature, **614**, 48–53 (2023)



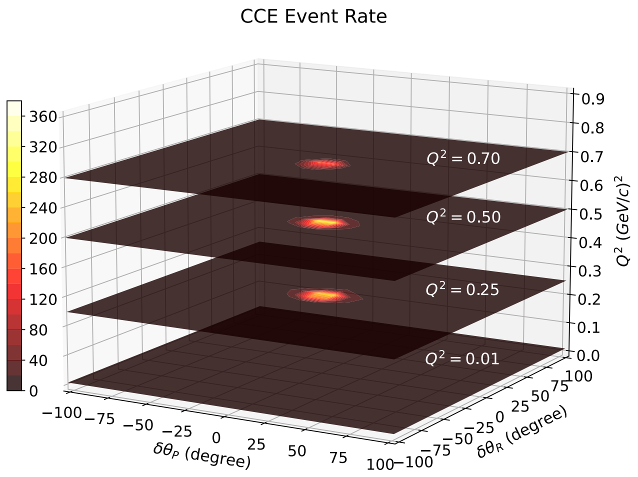
When life gives you lemons…
make lemon meringue pie



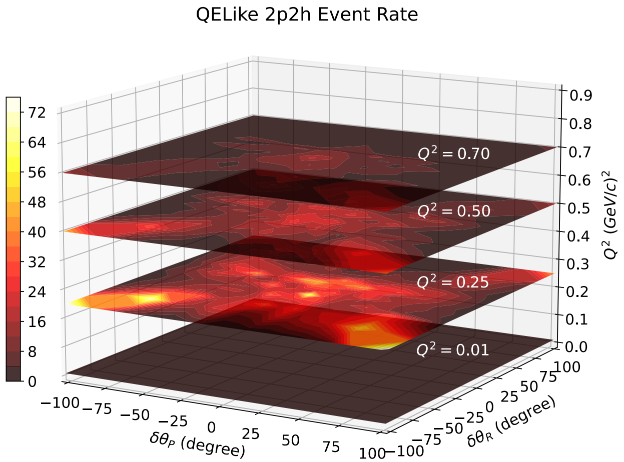




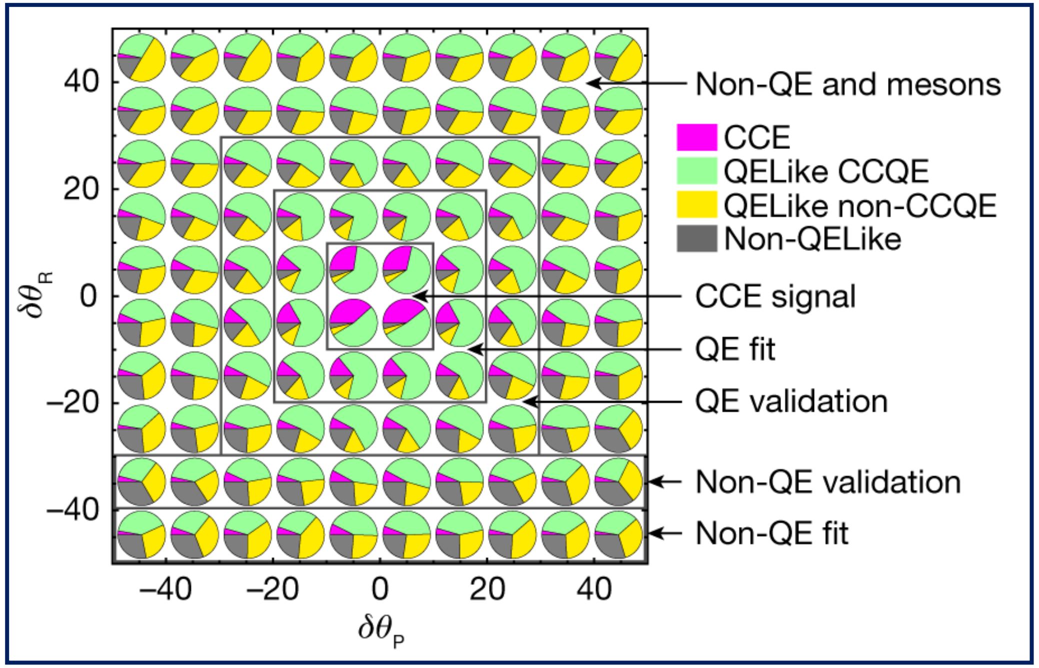
Different Reactions populate different regions



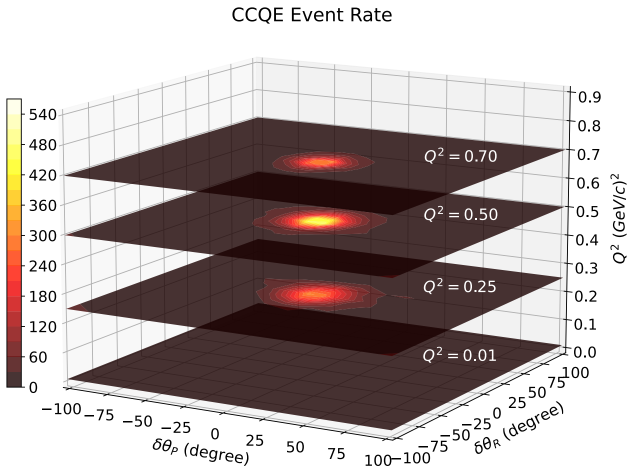
SIGNAL: Elastic on H



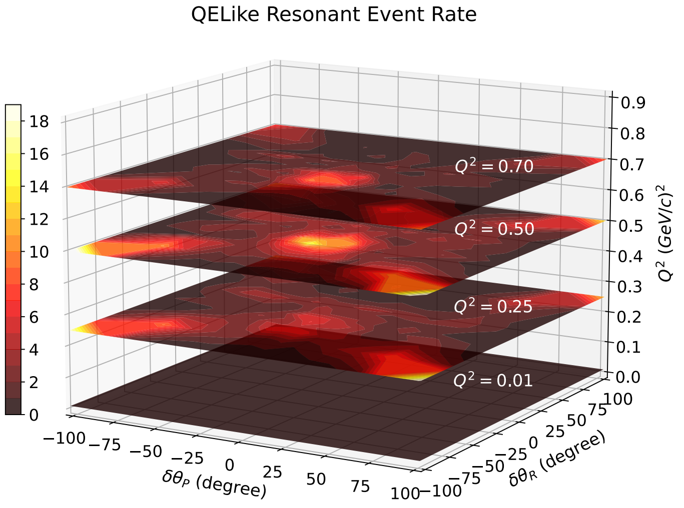
Background: QELike 2p2h



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

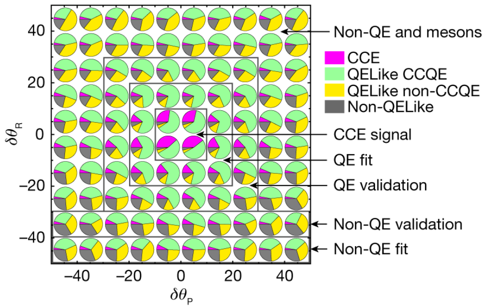


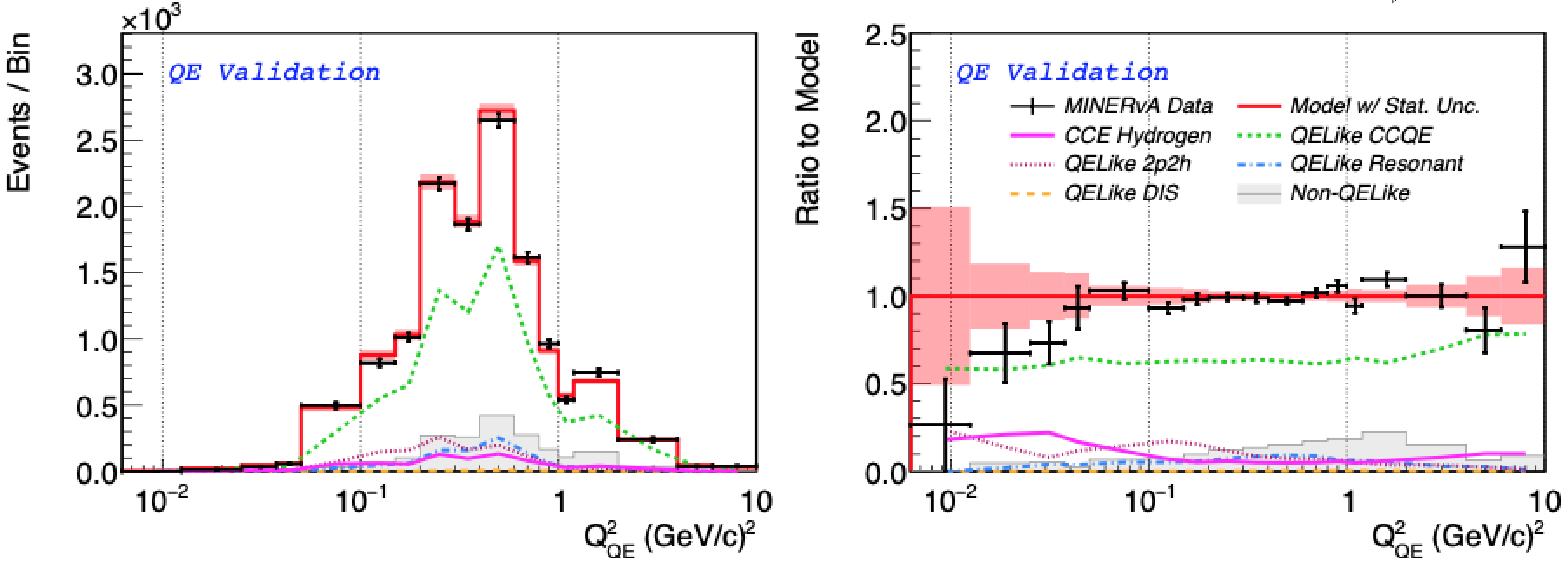
Background: QELike CCQE (on C)



Background: QELike Resonant

Validating the Background Prediction

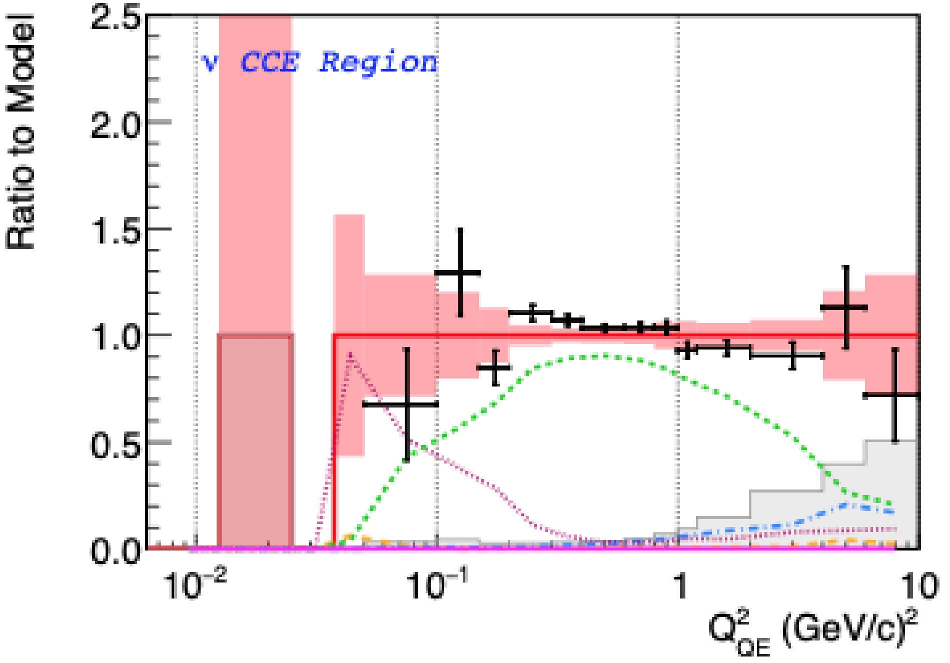


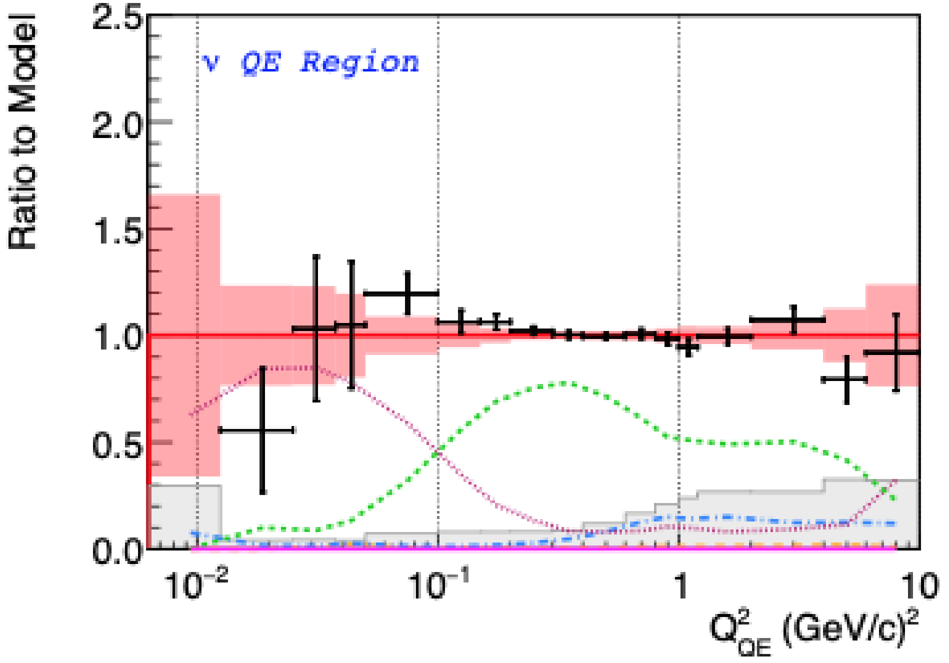


- CCQE is the dominant background. Small 2p2h, inelastic (absorbed), and Non-QELike contributions. The fitted model are well constrained by data.

Another test: Neutrino Beam

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



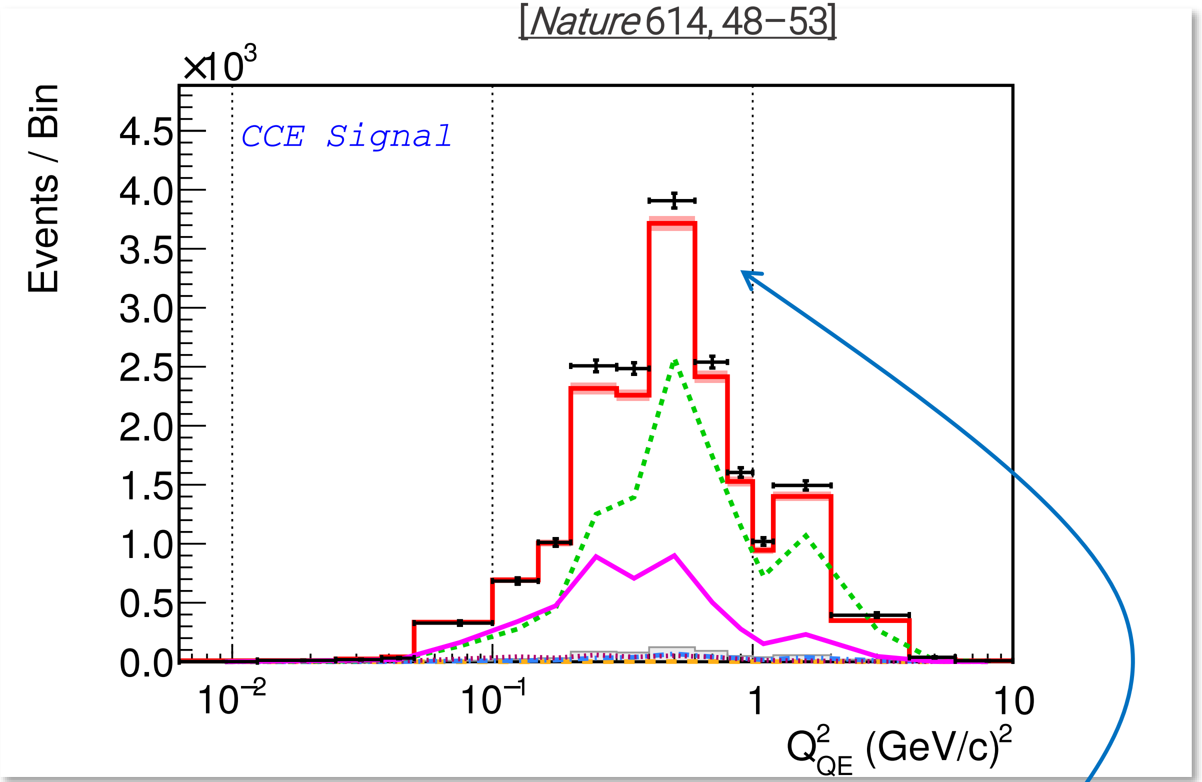


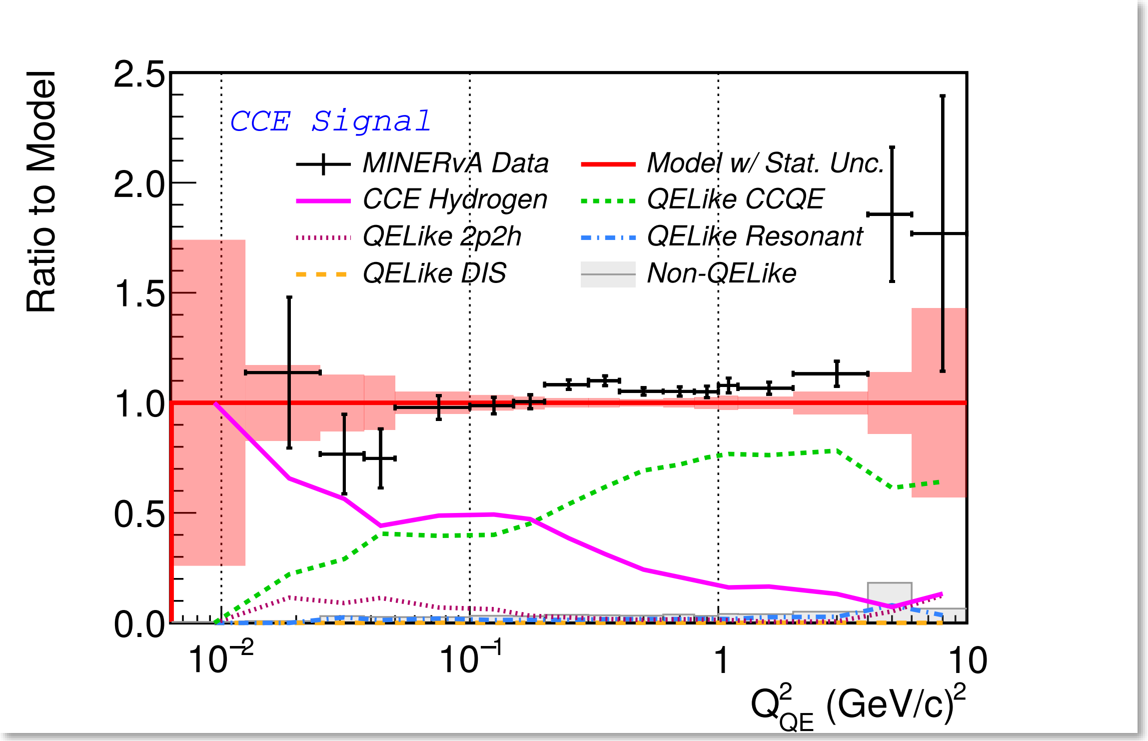
- Recipe: select events with trackable protons in a neutrino sample. Different final states and available kinematics. Apply same fitting mechanism. Data and MC mostly agree within uncertainty. Data and MC mostly agree. Disagreement can be explained by 2p2h uncertainty.

Cross-section Extraction

[*Nature* 614, 48–53]

[*Nature* 614, 48–53]





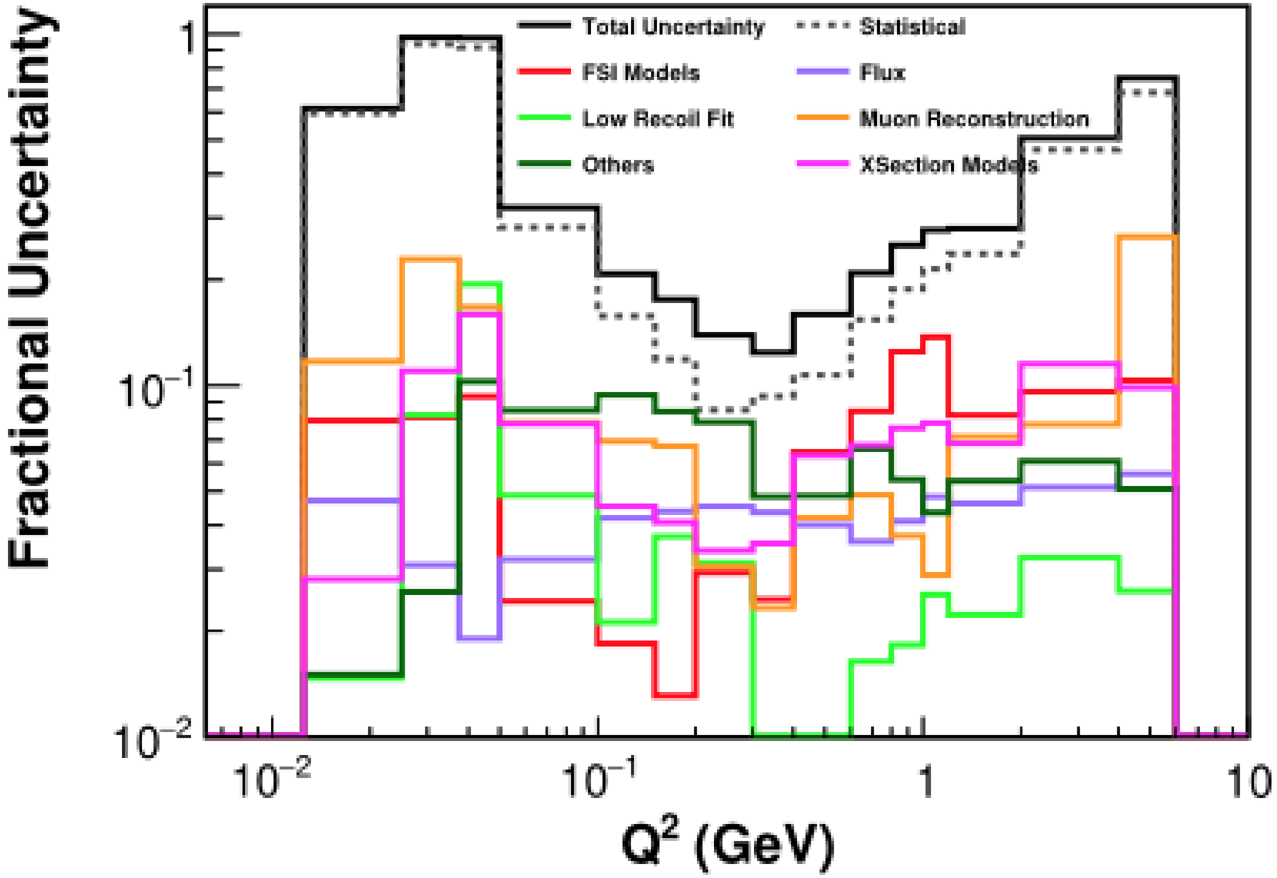
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_i = \frac{\sum_j U_{ji}\left(N_j^{\mathrm{data}} - N_j^{\mathrm{bkg-pred}}\right)}{\Phi N_H \epsilon_i (\Delta Q^2)_i}$$

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

NuFact23

Uncertainties in the Axial Form Factor Cross-Sections



- Dominated by statistical uncertainty after the background subtraction.

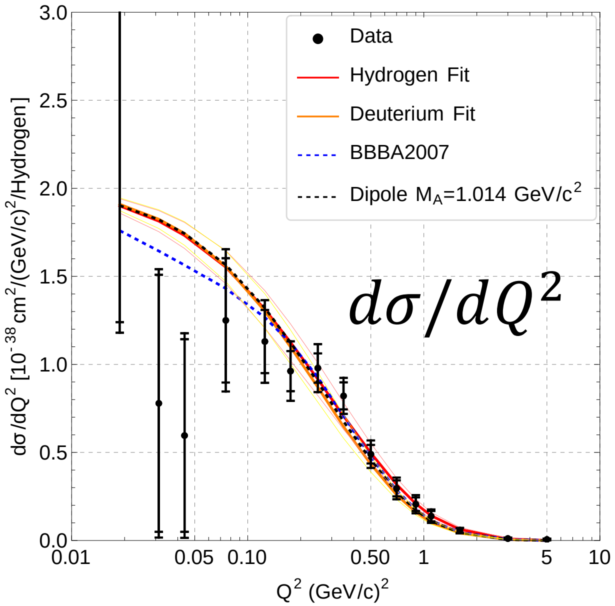
  Systematic uncertainties from residuals of background subtraction

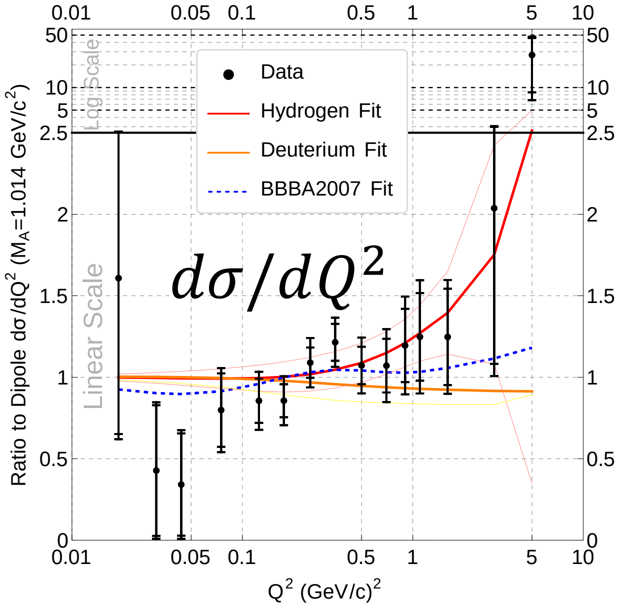
  Particle responses in the "other" category, dominated by neutron systematics.

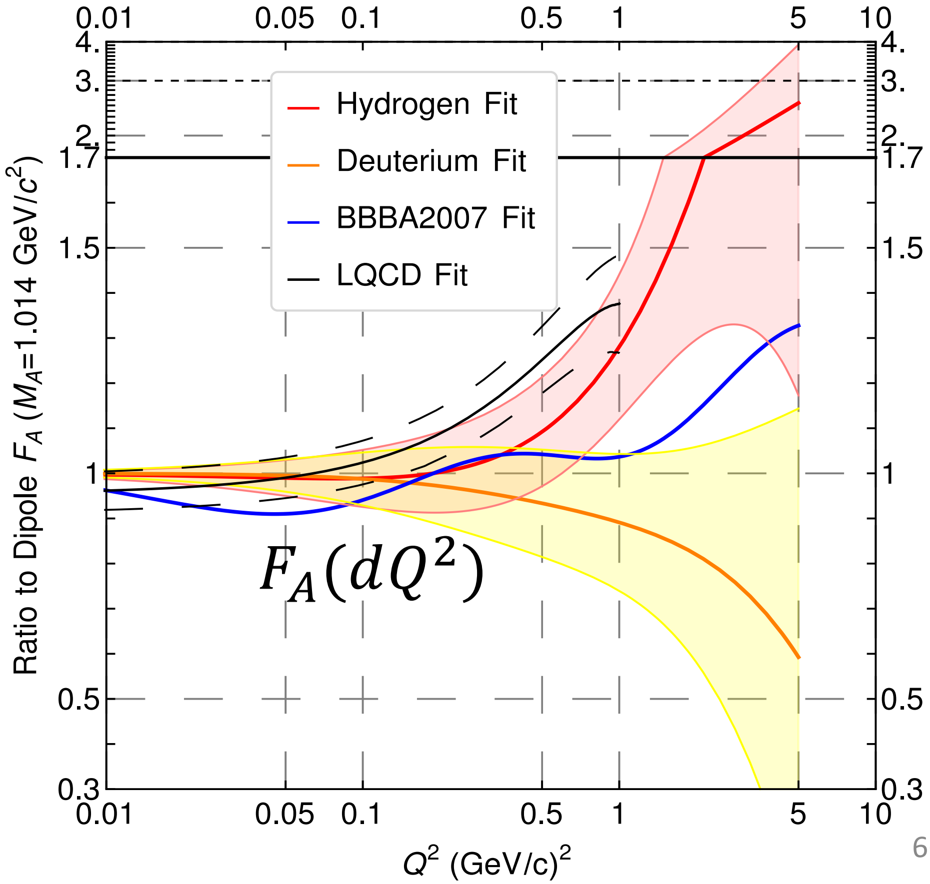
Always
ask
to see
uncertainties!

Free Nucleon Axial Form Factor

- MINERvA found ~5800 such events on a background of ~12500.
- Shape is not a great fit to a dipole at high Q^2.
- LQCD prediction at high Q^2 is close to this result, but maybe not at moderate Q^2.







How to summarize this field?

- Want to cover “current cross sections” but…
- Consider the various combinations: 6x4x5x6

Interaction
Inclusive Scattering
CC 0 π Production
CC 1π^+ Production
CC 1π^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 (x_m)
Lepton Kinematics
Q^2
q_0 vs q_3
Proton Kinematics
Pion Kinematics
Transverse Kinematic Imbalance variables (many)
“Neutrino Energy”

Number of Dimensions
1
2
3

Summary of This Lecture

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

- So many interactions, so little time!
- Measuring Cross Sections all use the same formula
- Challenges with making a robust measurement
  - Flux
  - Detector
  - Cross section
- Clever ideas of new observables and ways to reduce backgrounds are yours to discover!
- All the tricks we've figured out to isolate different effects in Quasielastic interactins, we have to figure out for pion production!

Backup Slides

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

- M: ”Mass” [nucleons] Sounds easy, right?
- Cross sections are usually reported “per nucleon” so…

- BUT, it depends on what cross section you are trying to measure: are you trying to measure something “per nucleon”?

- What if you are measuring something that (in principle) only happens on neutrons? (i.e. $\nu_\mu + n \rightarrow \mu^- + p$)
- What if you are measuring something that (in principle) only happens on protons? (i.e. $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$)

Full Disclosure on calculating "M"

- For Liquid Argon detector, it's very pure so you can be sure the nucleus that is struck is Ar
- For Water, at least at Super-K or Hyper-K those detectors are very pure H_2O
- But scintillator-based detectors may not always
  be all CH or CH_2:
  for example NOvA:

Element	Mass [kg]	Nucleon Count	Mass Fraction
H	3814.5	2.28×10^{30}	0.108
C	23650	1.41×10^{31}	0.667
O	1050	6.30×10^{29}	0.030
Cl	5690	3.40×10^{30}	0.161
Ti	1140	6.81×10^{29}	0.032
Other	95	5.7×10^{28}	0.003

•*Phys.Rev.D* 107 (2023) 11, 112008

NOvA Image: https://doi.org/10.1016/j.nuclphysb.2016.04.027

Observables in Quasielastic Interactions

- If you have a quasielastic interaction, *and* the initial nucleon is at rest, you can estimate the neutrino energy and momentum transfer from the lepton kinematics ALONE
- This is how T2K makes its (most precise) oscillation measurements!
  - Require ONLY one lepton in the final state
  - Require conservation of energy and momentum
- You may hear from Stephen and Luke why this is a problem, but it’s still an observable
- Just don’t call it true energy if you are scattering off a big nucleus!

$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2,$$