

# Measurement of Anti- Neutrino Charged Current Elastic Scattering at MINERvA

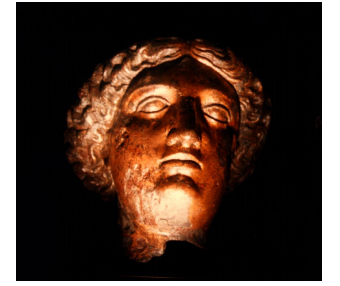
Kevin McFarland  
University of Rochester

29 June 2023

PREN/ $\mu$ ASTI @ Mainz (Remote)



# What is the purpose and scope of this measurement?



- We recently published (*Nature* 614, 48–53) a high statistics,  $\sim 5000$  event, measurement of the reaction  $\bar{\nu}_\mu p \rightarrow \mu^+ n$ , which we call “charged-current elastic scattering”.
- The previous world’s sample of such events were from hydrogen bubble chamber experiments in the 1980s, with 13 candidates.
- Our goal was to measure the (transition) axial form factor of the nucleon.

# Historical Analogue

- This is the neutrino equivalent of the Hofstadter *et al* proton structure experiment at Stanford's linac in the 1950s, which we've all seen in textbooks.

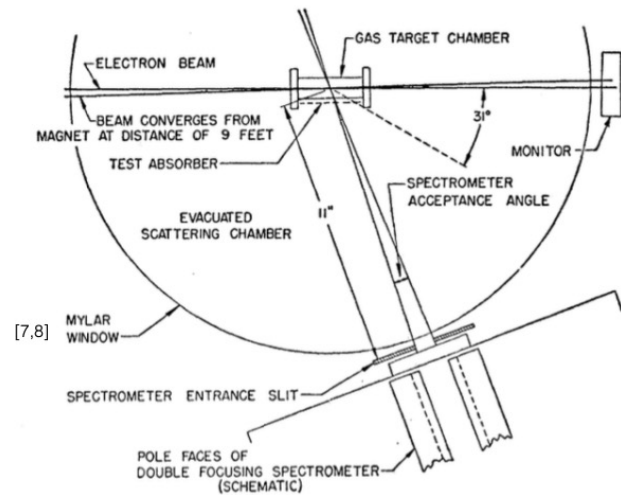
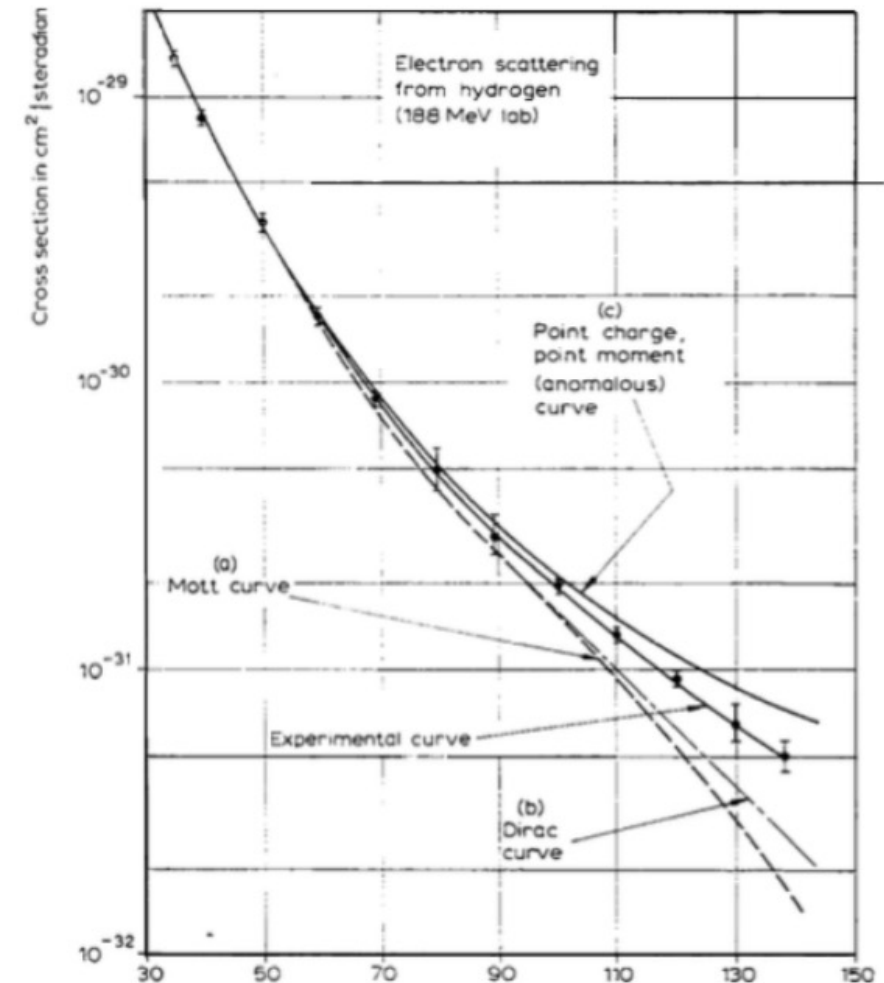
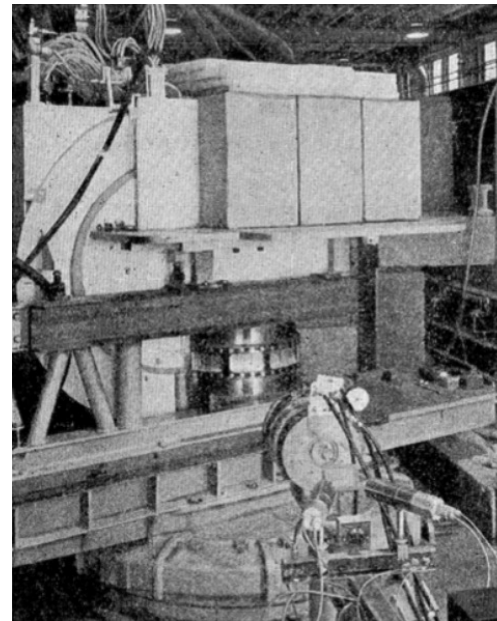


FIG. 17. Schematic diagram of scattering geometry employed with the gas target chamber.

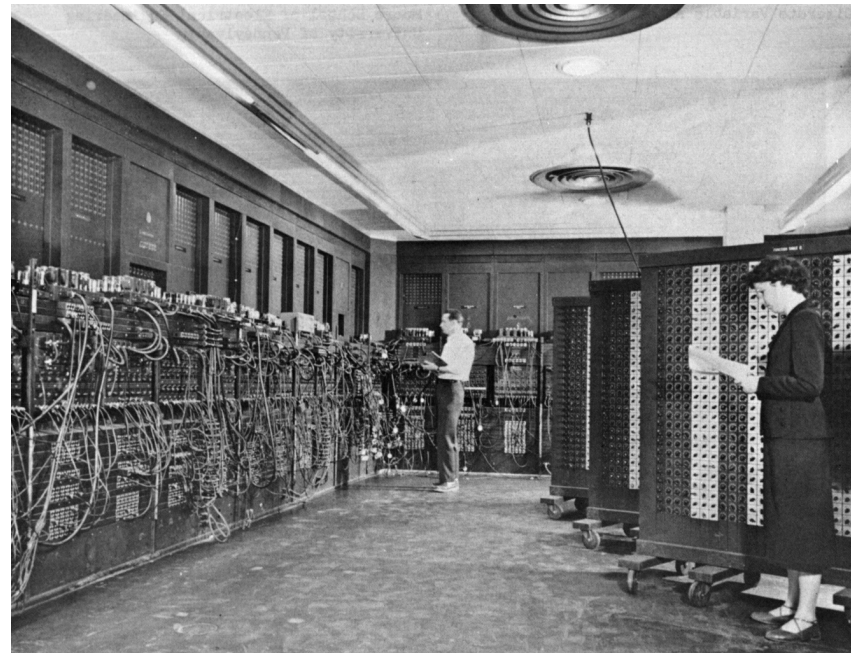


# Other things from the 1950s



1950's iPhone

1950's Laptop



1950's Economy Class Airplane Cabin

# The nucleon axial form factor ( $F_A$ )



- Like with the Hofstadter experiment in textbooks, the connection between the nucleon axial and the measurement requires some explanation.

$$\frac{d\sigma}{dQ^2} \left( \begin{array}{l} \nu n \rightarrow l^- p \\ \bar{\nu} p \rightarrow l^+ n \end{array} \right) = \frac{M^2 G_F^2 \cos^2 \theta_c}{8\pi E_\nu^2} \left[ A(Q^2) \mp B(Q^2) \frac{(s-u)}{M^2} + C(Q^2) \frac{(s-u)^2}{M^4} \right]$$

$$A(Q^2) = \frac{m^2 + Q^2}{4M^2} \left[ \left( 4 + \frac{Q^2}{M^2} \right) |F_A|^2 - \left( 4 - \frac{Q^2}{M^2} \right) |F_V^1|^2 + \frac{Q^2}{M^2} \left( 1 - \frac{Q^2}{4M^2} \right) |\xi F_V^2|^2 + \frac{4Q^2}{M^2} \text{Re} F_V^{1*} \xi F_V^2 + \mathcal{O} \left( \frac{m^2}{M^2} \right) \right],$$

$$B(Q^2) = \frac{Q^2}{M^2} \text{Re} F_A^* (F_V^1 + \xi F_V^2),$$

$$C(Q^2) = \frac{1}{4} \left( |F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2} |\xi F_V^2|^2 \right)$$

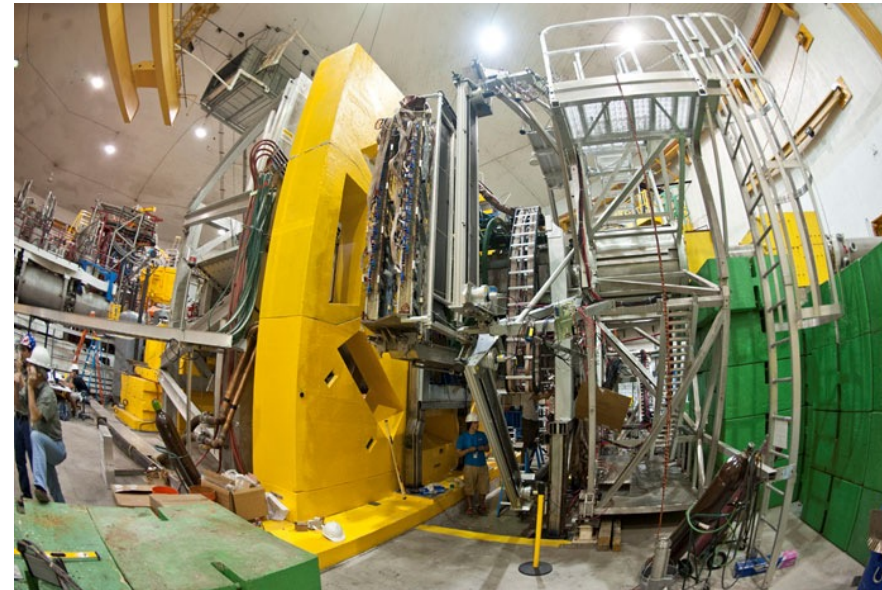
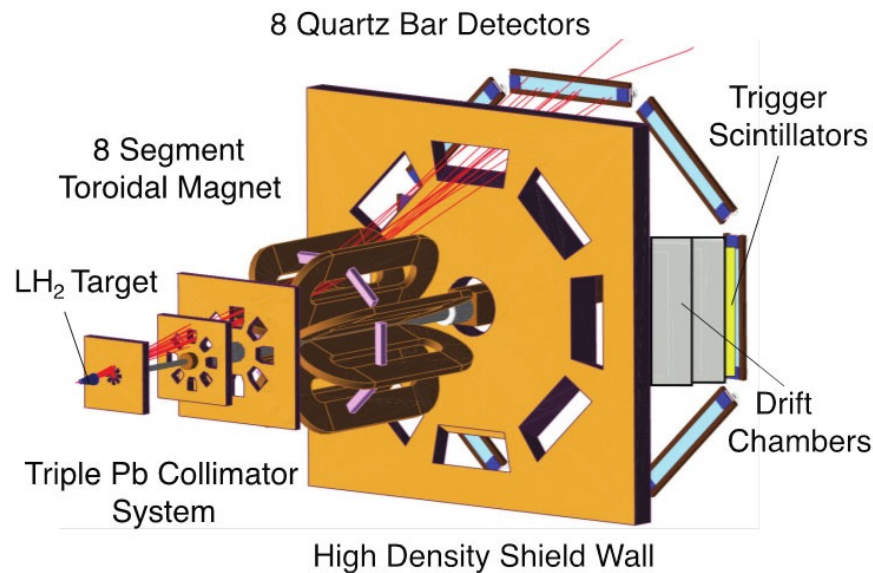
$F_V^1, \xi F_V^2$ : Electric and magnetic form factors. Measured in **charged lepton scattering experiments**, even at very high  $Q^2$ . A lot of data and well constrained!

$F_A$ : **Axial form factor**, accessible in **weak interactions**. Accessible through **neutrino scattering experiments**. Much less data from scattering, and all of that data relies on nuclear theory or QCD or both to interpret it.

# Neutrino Experiments are Hard



- For neutrino oscillation experiments, several % transition probabilities must be measured to few ‰ absolute precision...
  - The non-neutrino community just yawns. So what?



$$Q_{\text{weak}} A_{ep} = (-279 \pm 35 \pm 31) \times 10^{-9} \text{ Phys.Rev.Lett. 111 (2013) 141803}$$

# How Hard are They?



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- The problem is that neutrinos just don't interact, much.
- What is the mean free path of a 600 MeV neutrino from the T2K beam in the water target of the Super-Kamiokande detector?
  - A. diameter of the Earth
  - B. distance from Earth to Sun
  - C. distance from Earth to Neptune
  - D. distance between a US mega-tech company and the general good of humanity

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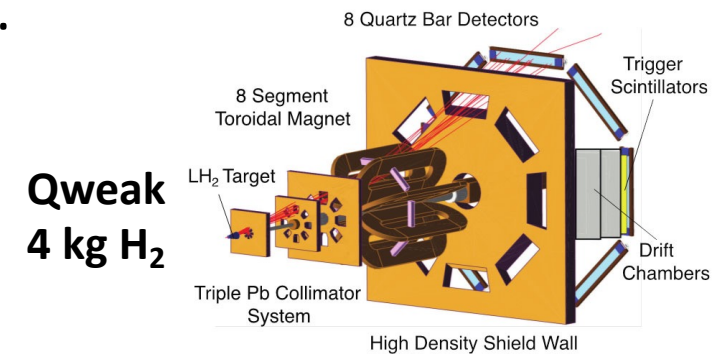
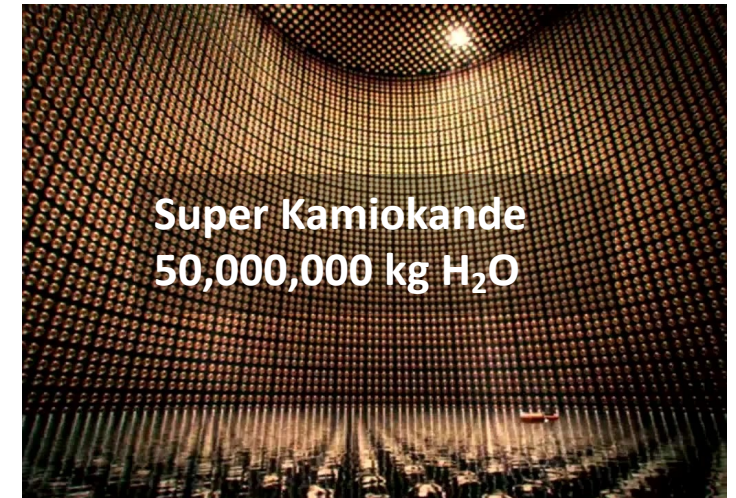
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- Another perspective: T2K has put  $\sim 10$  TJoule of relativistic protons on its production target, and observed  $\sim 10$  nJoule of particles from electron neutrino interactions in its far detector.



# What does this mean for a neutrino experiment?



- Several % transition probabilities, must be measured to few ‰ absolute precision...
- Therefore targets are different
  - Neutrino: “target”=“detector” since interactions occur uniformly throughout the target. Material must be cheap (nuclei). Requires trick photography to show the whole thing.
  - By contrast charged lepton scattering experiments have “find the target” pictures...



# What was MINERvA and what was our primary goal?



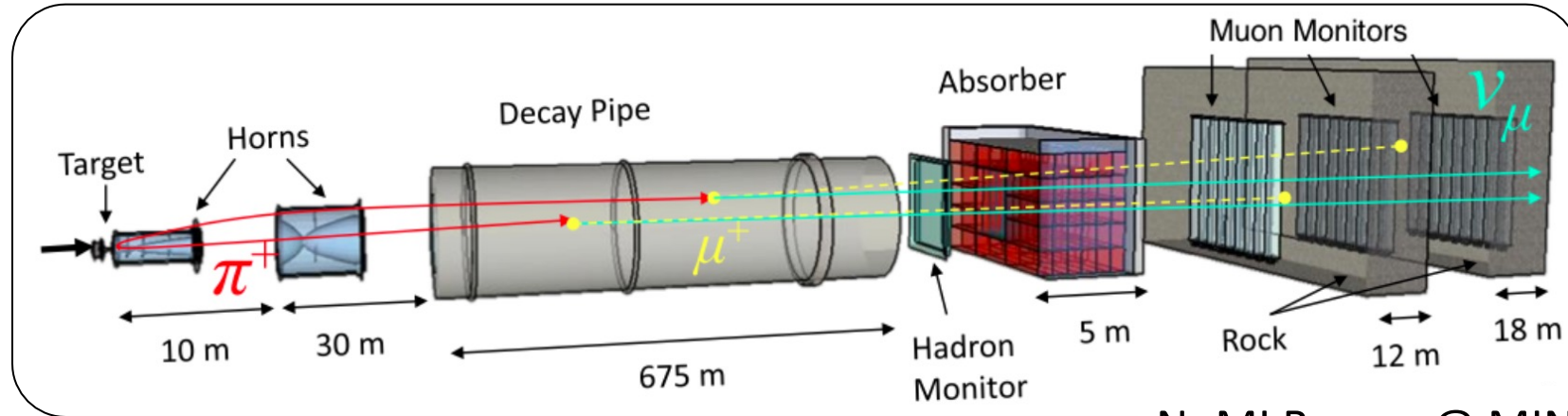
- MINERvA was a neutrino interaction experiment at Fermi National Accelerator Laboratory that ran from 2009-2019.
- It sat as close as possible to the world's highest intensity accelerator (GeV) beam, NuMI, which was built for neutrino oscillation measurements over a ~800km baseline.
- MINERvA's science goal was to measure a broad range of neutrino interactions on nuclei (cheap detectors!), primarily on carbon in our scintillator, but also helium, oxygen, iron, and lead, to help improve models of neutrino interactions used to infer energy in neutrino oscillation experiments.

# Did we achieve our goals?



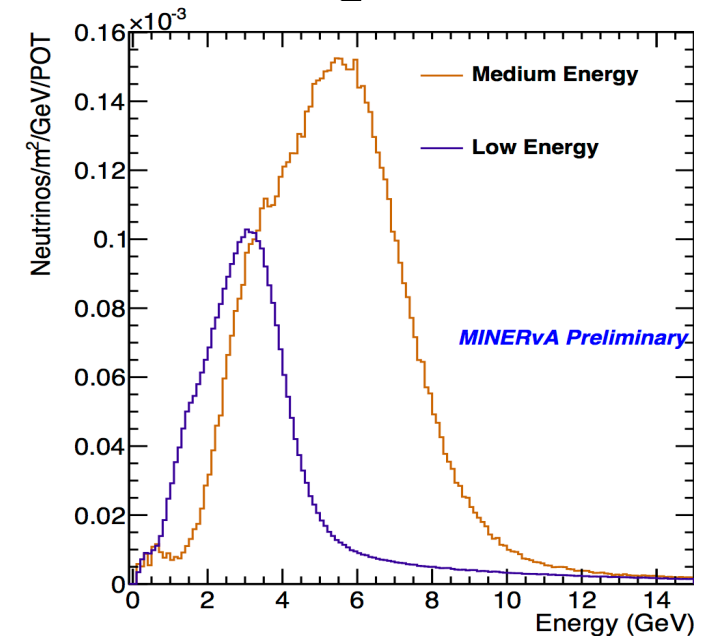
- Yes... and also are still “achieving” with the preserved data.
- Our data sets come from  $\sim 4\text{mC}$  of 120 GeV protons on our neutrino production target, resulting in a flux of  $\sim 10^{21}$  neutrinos and anti-neutrinos through the detector, and samples of  $\sim 10^7$  events.

# The NuMI Beam



- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions.
- Implies significant uncertainties in flux from hadron production and focusing.
- Constrain, where possible, with hadron production data.

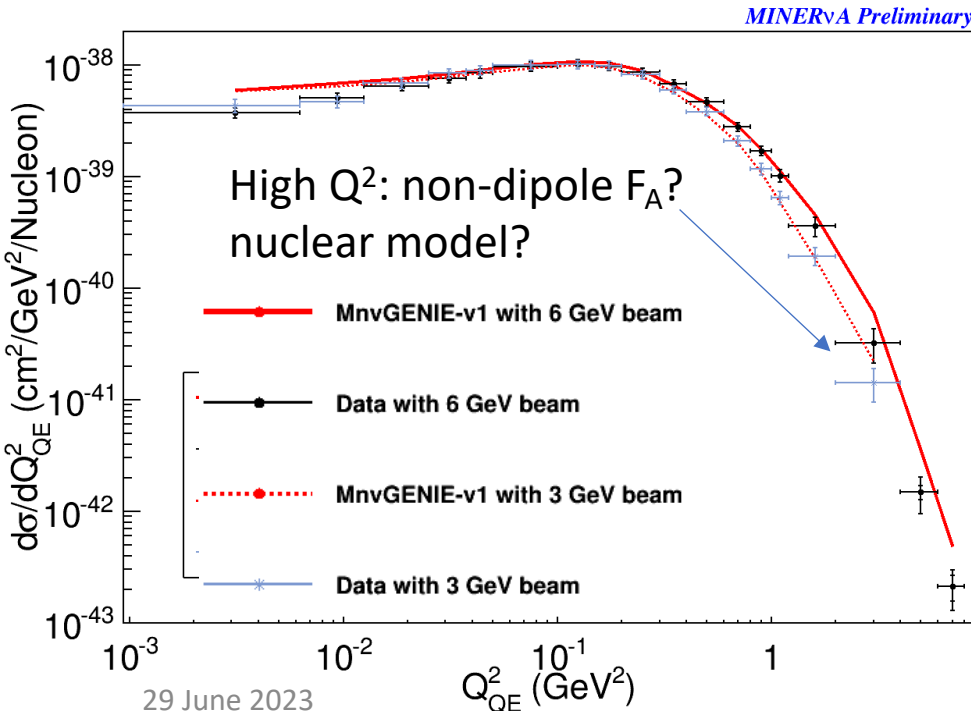
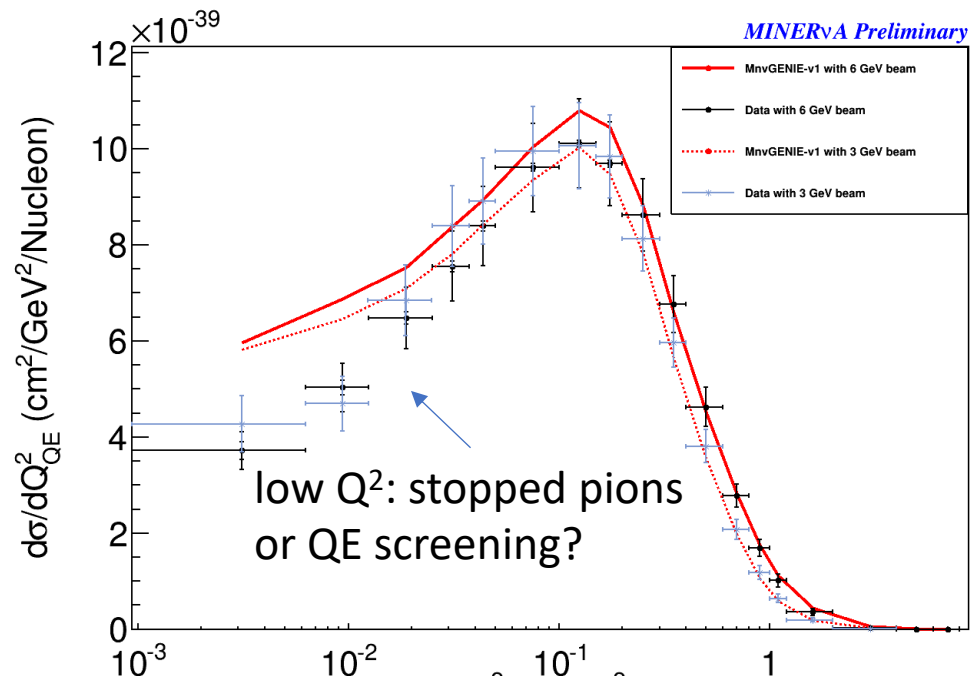
## NuMI Beams @ MINERvA



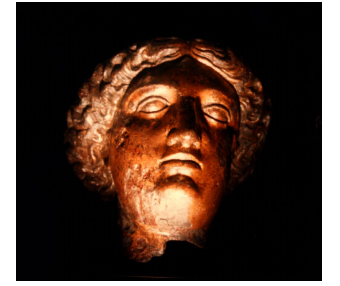
# Did we achieve our goals? (cont'd)



- Yes... and also are still “achieving” with the preserved data.
- Our data sets come from  $\sim 4\text{mC}$  of 120 GeV protons on our neutrino production target, resulting in a flux of  $\sim 10^{21}$  neutrinos and anti-neutrinos through the detector, and samples of  $\sim 10^7$  events.
- So for example, one major reaction we want to understand are “quasielastic like” ones,  $A(\bar{\nu}_\mu, \mu^+ n \dots)A'$  where the “...” allows for additional nucleons or fragments to be knocked out.
- These reactions make up a large fraction of the neutrino oscillation samples on nuclei, and the multi-nucleon knockout probability is large and poorly modeled.



$$A(\nu_\mu, \mu^- p \dots)A'$$

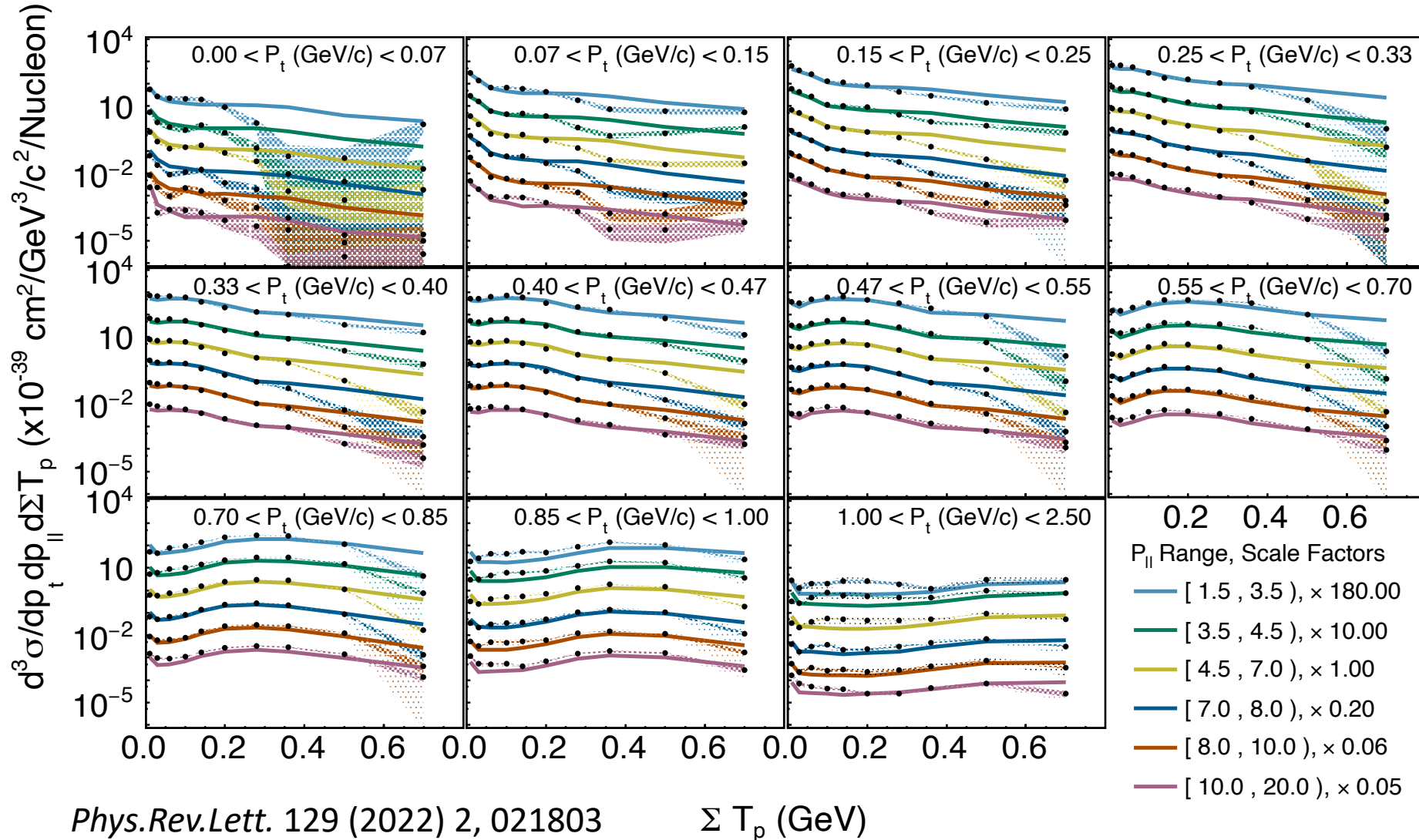


- Here is data on the neutrino analog from MINERvA, as a function inferred (from the final state)  $Q^2$  at two different beam energies,  $\langle E_\nu \rangle \sim 3$  and  $\langle E_\nu \rangle \sim 6$  GeV.
- Consistent physics trends noted.
  - Notably in discrepancies at low and high  $Q^2$ .
- But my primary points here are to show the astrophysics-like scale for the cross-section, to gloat about  $\propto 1/Q^4$ , and to note that this cross-section falls rapidly near  $Q^2 \sim 1 \text{ GeV}^2$  because the elastic form factors do so.

3 GeV from Phys. Rev. D 99, 012004 (2019),  
 6 GeV results Phys.Rev.Lett. 124 (2020) 12, 121801

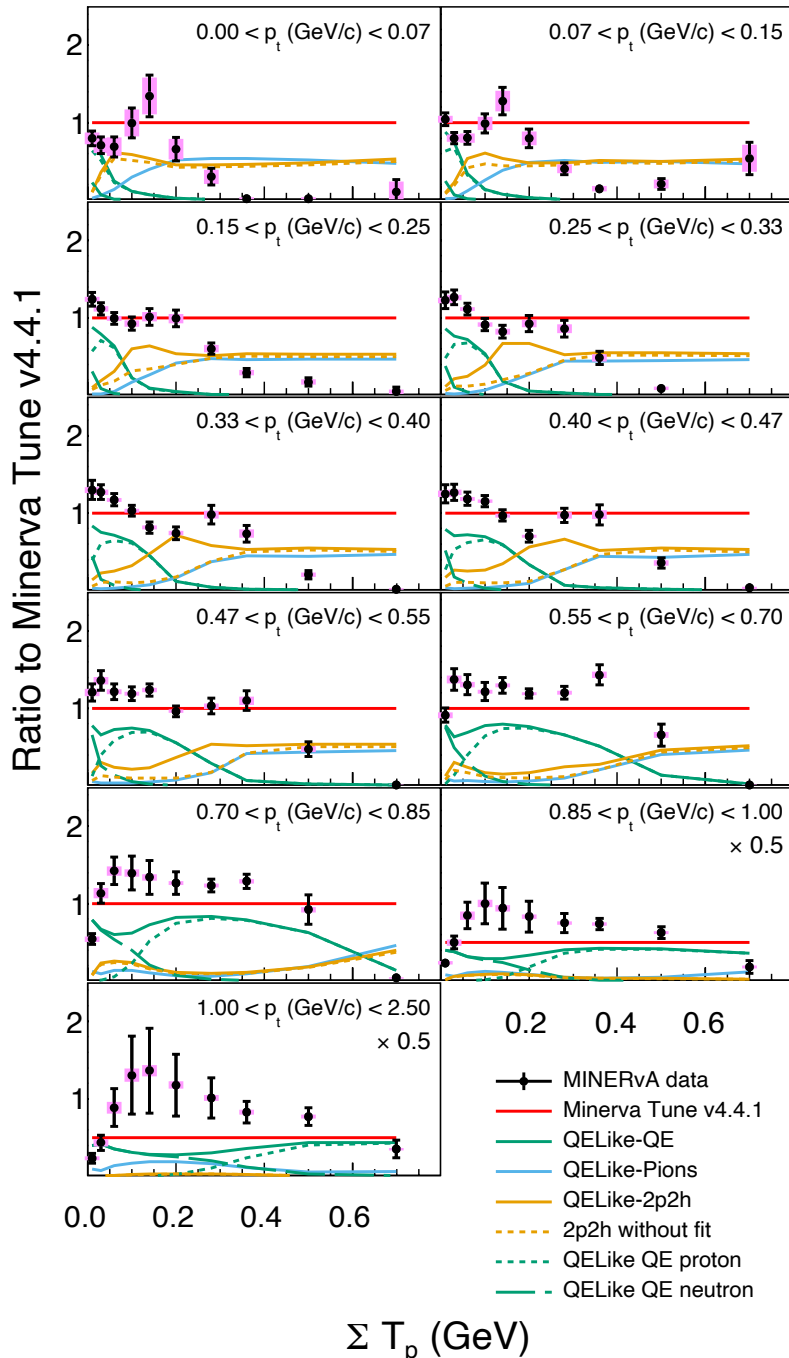


$$A(\nu_\mu, \mu^- p \dots) A' : d^3\sigma / d\Sigma T_p dp_T dp_{\parallel}$$



- Looks like a charged lepton scattering structure function experiment?
- The trends we see are independent of  $p_{\parallel}$ , suggesting they are not strongly energy dependent.
- In a single bin of  $p_{\parallel}$ ...

4.50 < P<sub>||</sub> (GeV/c) < 7.00



$$A(\nu_\mu, \mu^- p \dots) A' \Sigma T_p, p_T$$

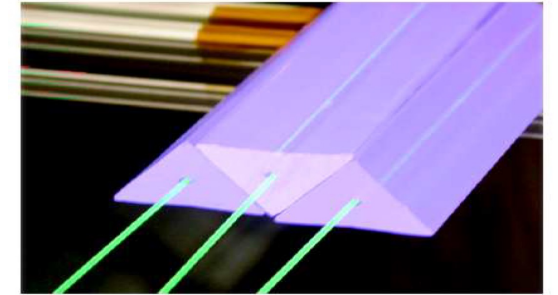
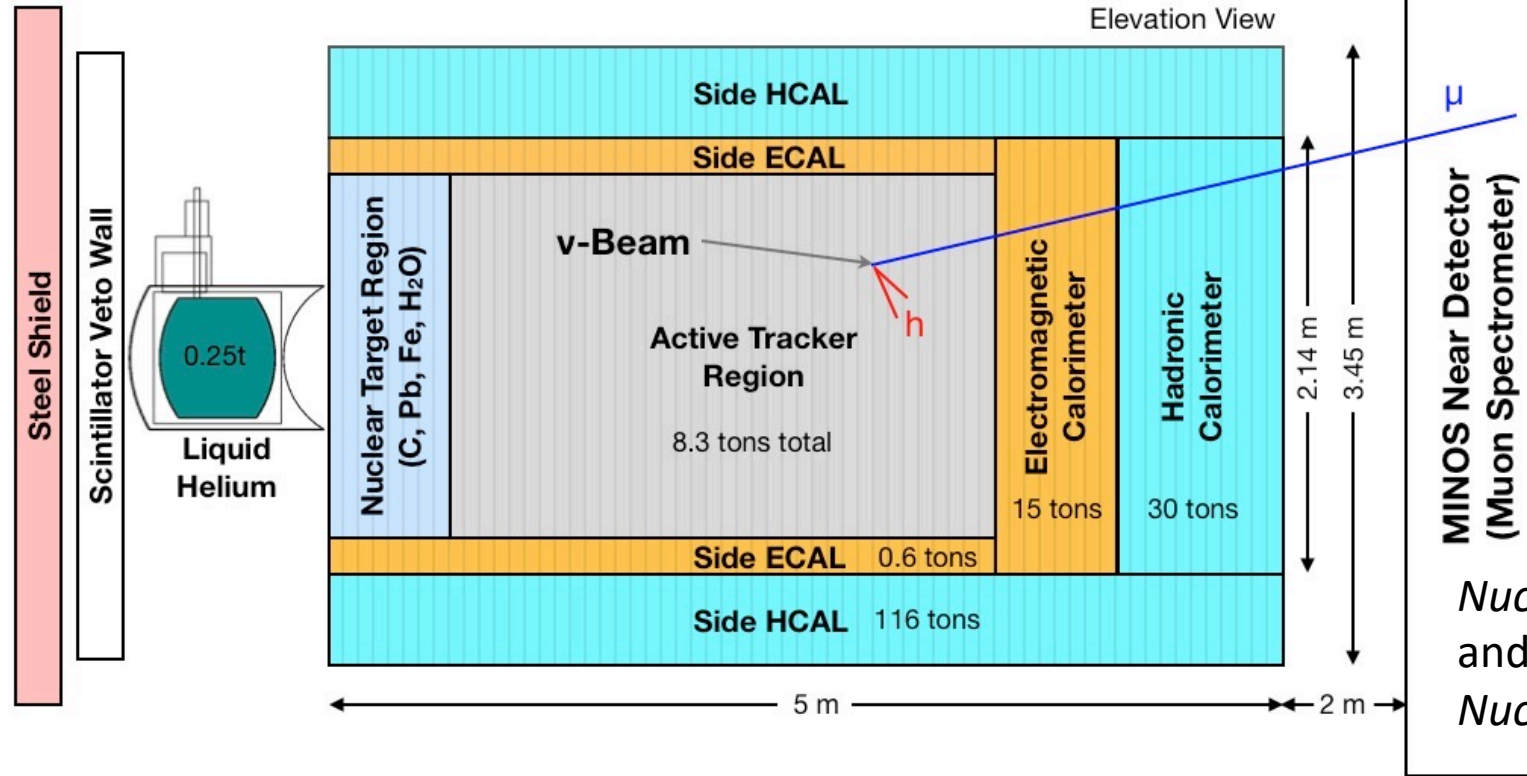
Phys.Rev.Lett. 129 (2022) 2, 021803



- The biggest discrepancy in cross-section, though not in the ratio, are the small deviations just above the QE peak, in the region we'd expect to be populated by multi-nucleon knockout (“2p2h”).
- Low  $p_T$  high  $\Sigma T_p$  events predicted by the model as 2p2h and stopped pions are almost completely absent in the data.
- Highest  $p_T$  low  $\Sigma T_p$  events, events where the leading proton's energy ends up as neutrons through final state interactions, are also very overpredicted.



# MINERvA's Detector



*Nucl.Instrum.Meth.A* 743 (2014) 130  
and beam test

*Nucl.Instrum.Meth.A* 789 (2015) 28

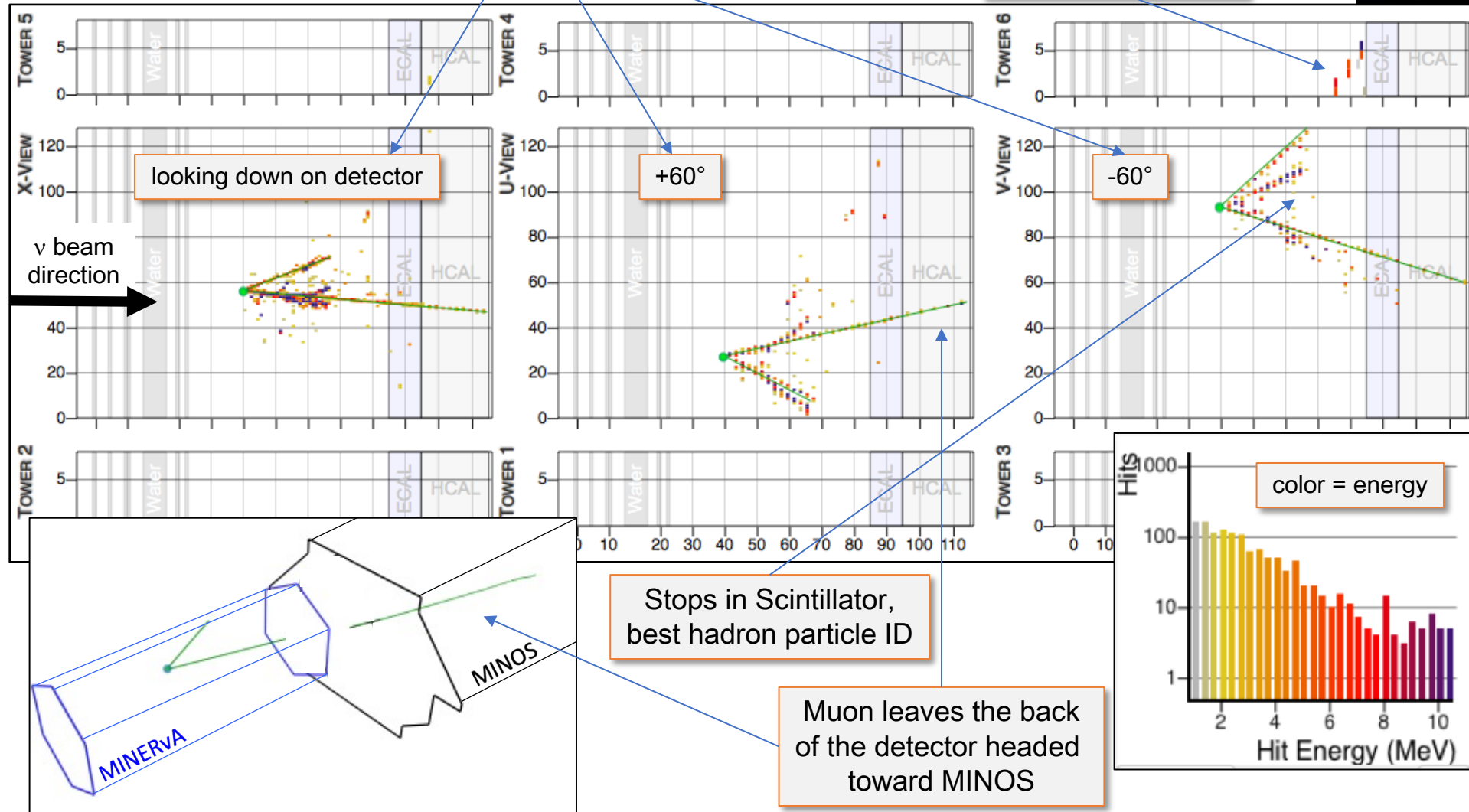
- Core of detector was an active scintillator strip target, surrounded by calorimetry.
- At MINERvA energies, most muons are forward and found in MINOS magnetic spectrometer.
- Passive targets interspersed with scintillator upstream.
- Detector is mostly in trash cans now, but some being recycled for DUNE tests!

# Events in MINERvA

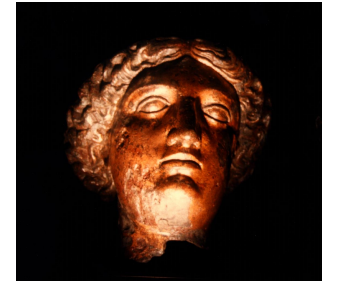


3 stereo views,  $X-U-V$ , shown separately

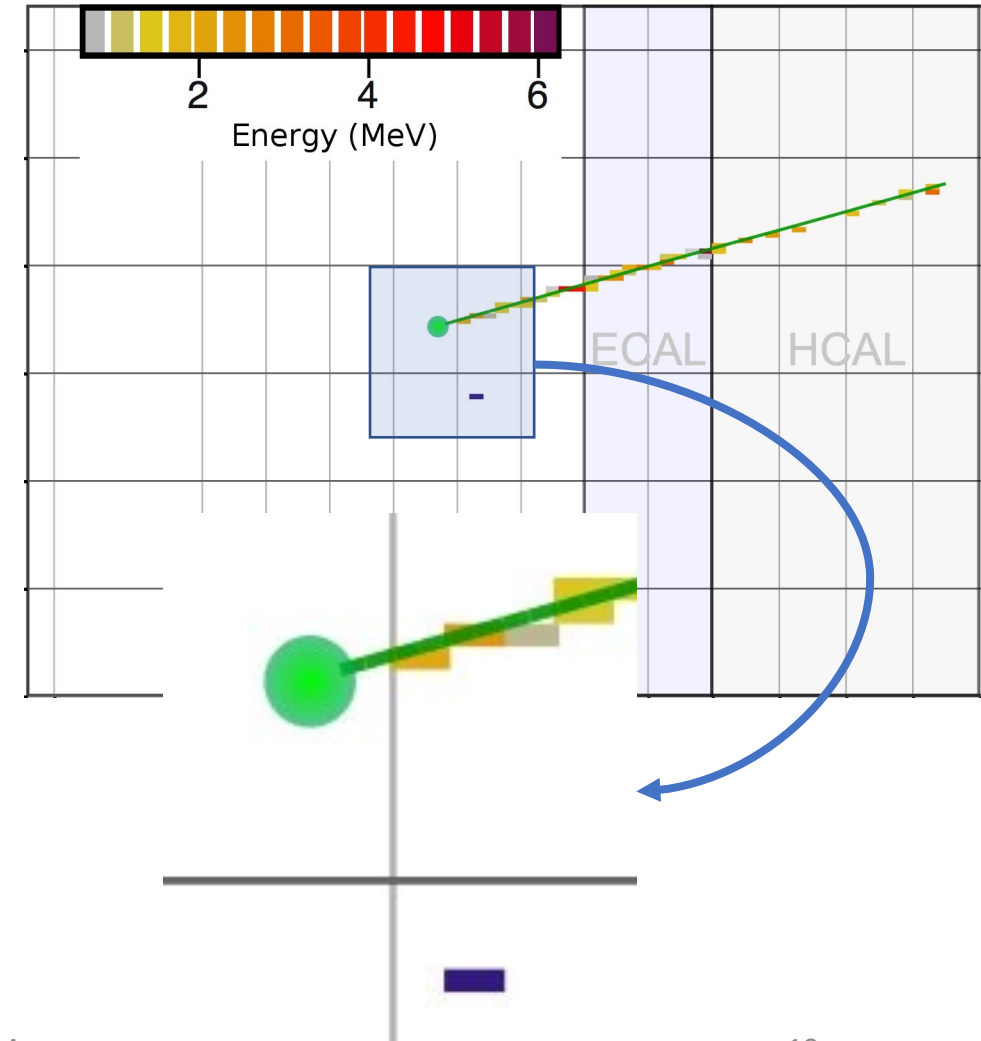
Particle leaves the inner detector, stops in outer iron calorimeter



# Detecting Charged Current Elastic Scattering in MINERvA



- Final state of  $\bar{\nu}_\mu p \rightarrow \mu^+ n$  in MINERvA is an energetic  $\mu^+$  and a (usually) much lower energy  $n$ .
- Neutrons in MINERvA are observed primarily by detecting the proton from  $^{12}\text{C}(n, np)^{11}\text{B}$  quasielastic scattering of neutrons, and other reactions producing protons.
- These measure the neutron direction well, but our timing is not good enough to measure energy by time of flight.



# Scattering on Free Protons?

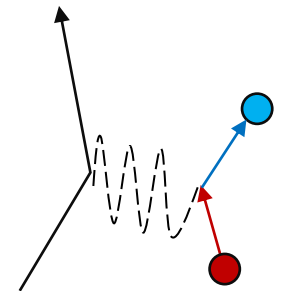
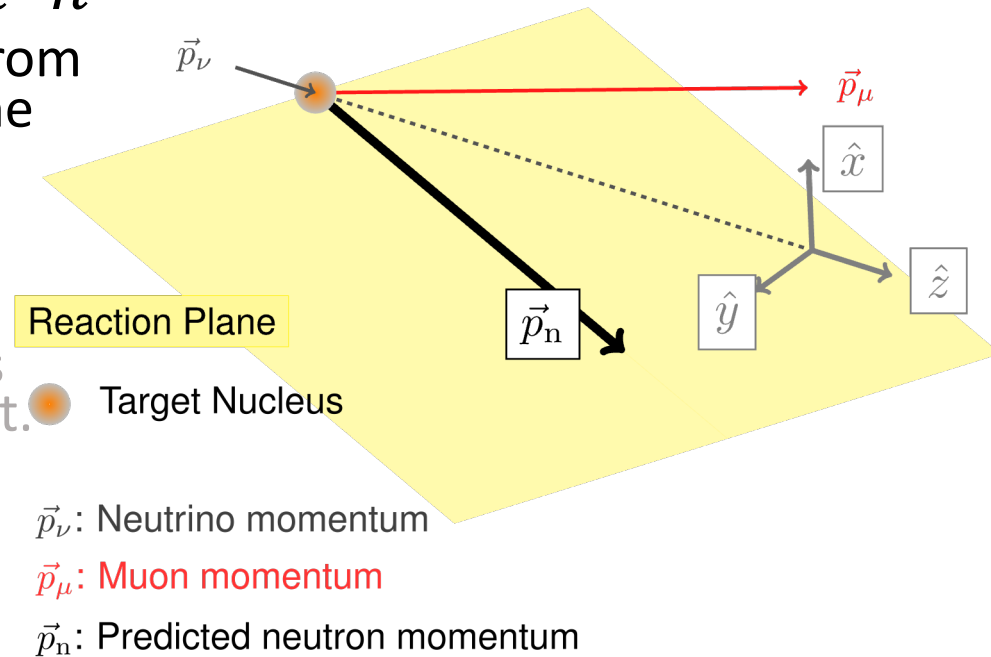


- You should now have enough knowledge about neutrinos and MINERvA to predict that this measurement wasn't done in a pure hydrogen target.
- MINERvA's scintillator is CH. In addition to charged-current elastic,  $\bar{\nu}_\mu p \rightarrow \mu^+ n$ , we also have backgrounds:
  - quasielastic anti-neutrino scattering on carbon,  $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ n)^{11}\text{B}$ ,
  - multi-nucleon knockout "2p2h",  $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ np)^{10}\text{Be}$  and  $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ nn)^{10}\text{B}$ ,
  - and inelastic reactions where baryon "resonances" produce a pion which is then absorbed in the nucleus.
- They may be separated if the neutron is detected, because the two body kinematics is completely determined by the energy and angle of the outgoing  $\mu^+$ .
- $A(\nu_\mu, \mu^- p \dots)A'$  is a background control sample to check what we predict under the hydrogen peak, since there are no free neutrons in our target.

# Signal and Background Separation

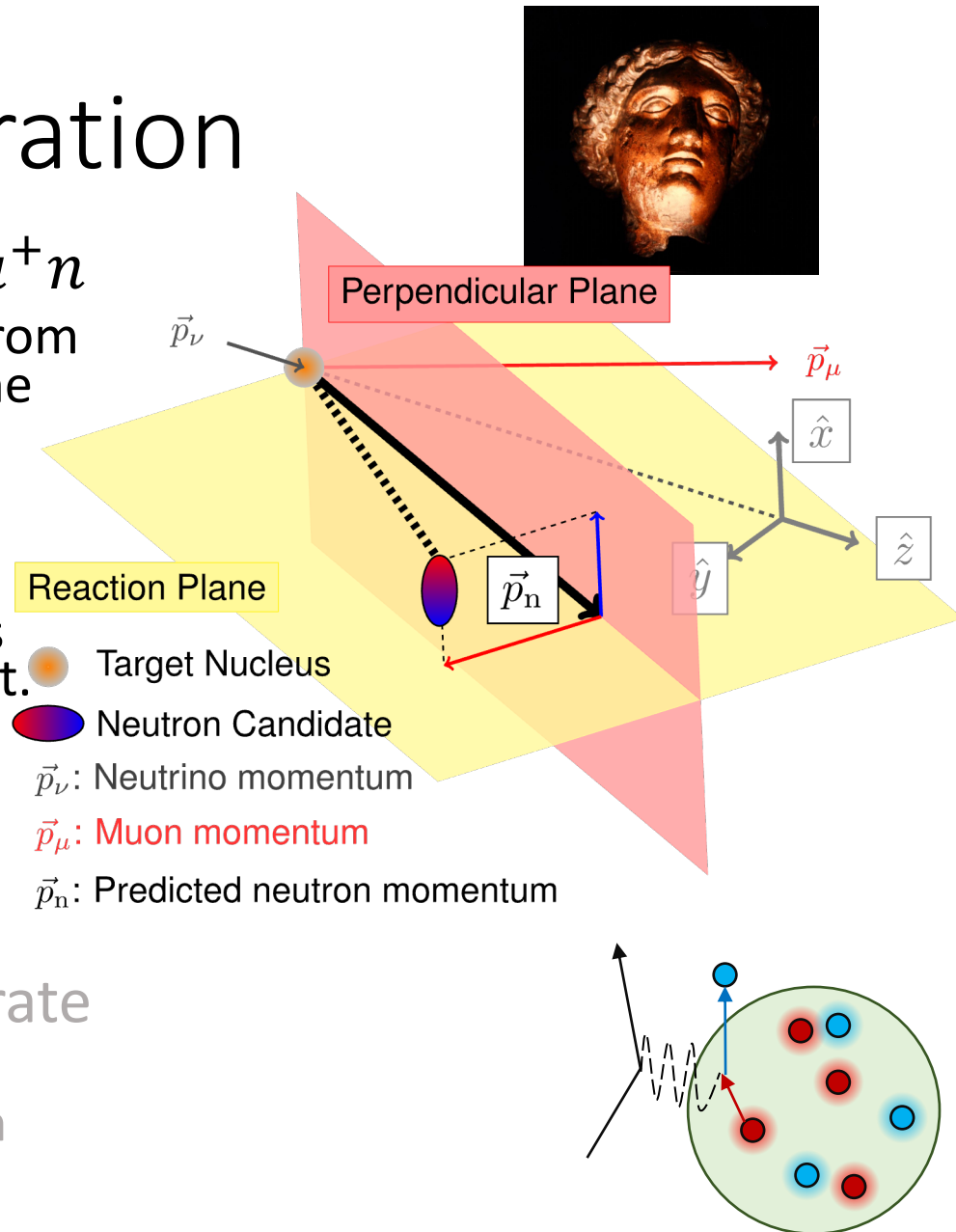


- Charged-current elastic on hydrogen:  $\bar{\nu}_\mu p \rightarrow \mu^+ n$ 
  - The outgoing neutron direction is fully predicted from the muon measurement, even without knowing the incoming neutrino energy.
- Largest background is  $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ n)^{11}\text{B}$ .
  - The outgoing direction is altered by the initial nucleon momentum and by final state interactions of the outgoing neutrons with the nuclear remnant.
- Other backgrounds, multi-nucleon knockout (“2p2h”) and inelastic processes
  - Systematic bias of the outgoing neutron direction in the reaction plane.
- Use the neutron directional deviation to separate different types of reactions.
  - Define  $\delta\theta_R$  and  $\delta\theta_P$  as the deviation in the reaction plane and perpendicular plane, respectively.



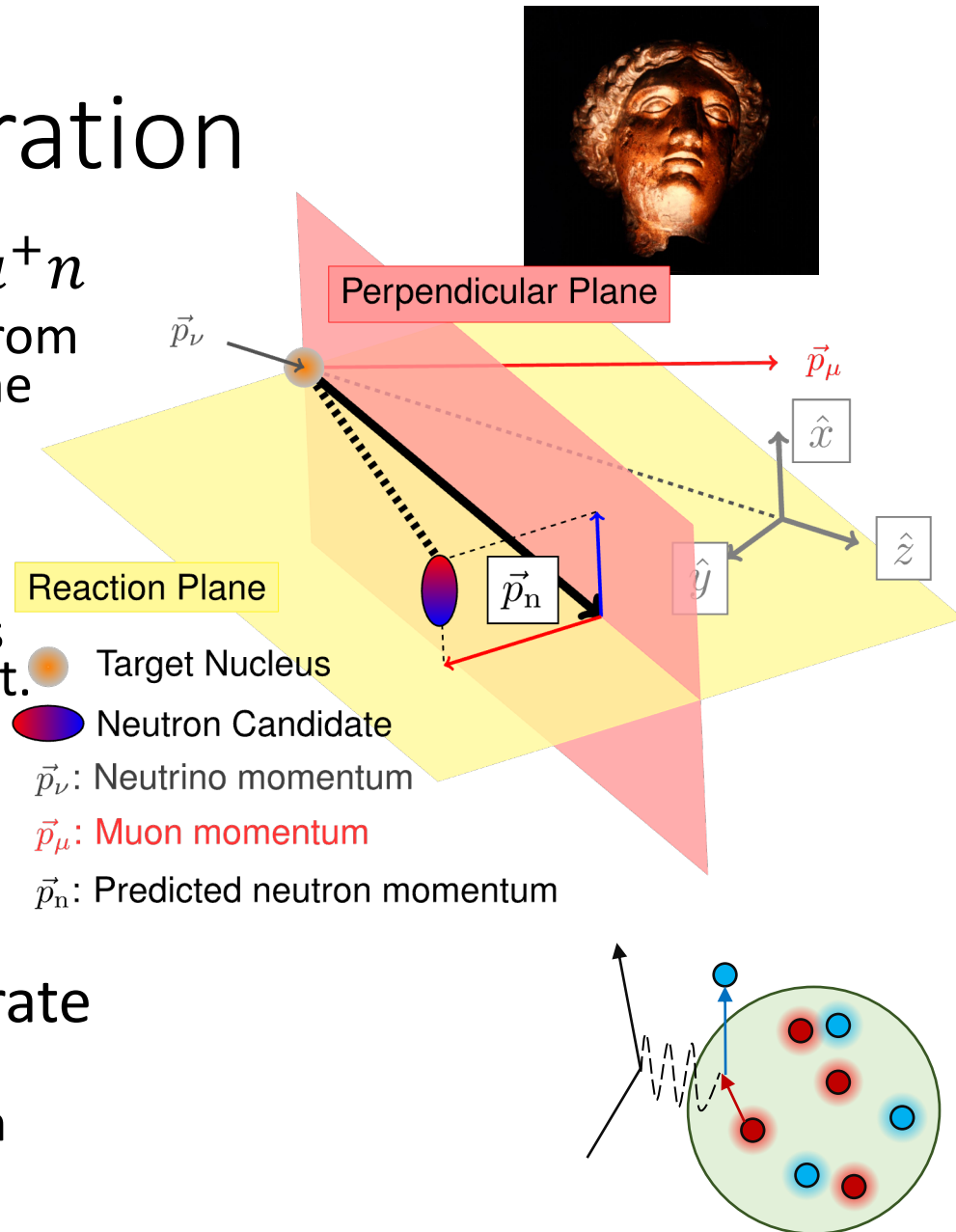
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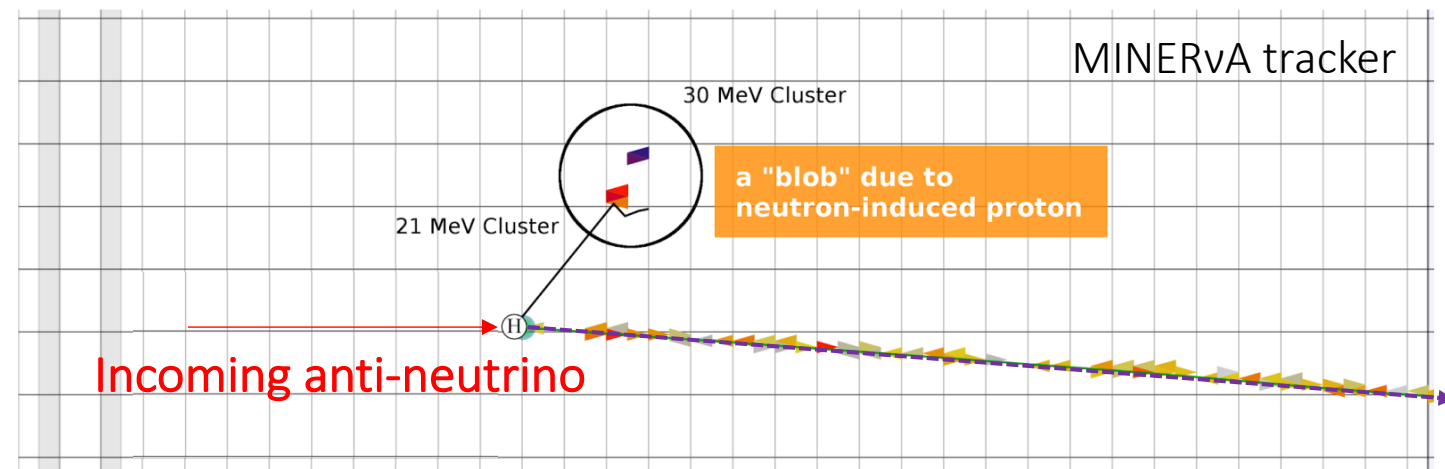
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# Selection and separation



- How do we select these events and what is the result?
  - No visible hadronic tracks (charged pions or protons)
  - Proton recoil from neutron must be 10 cm away from the muon axis ( $\delta$ -ray background)
  - Muon reconstructable in the detector:  $E_\mu [1.5; 20] \text{ GeV}$ ,  $\theta_{\mu\nu} < 20^\circ$

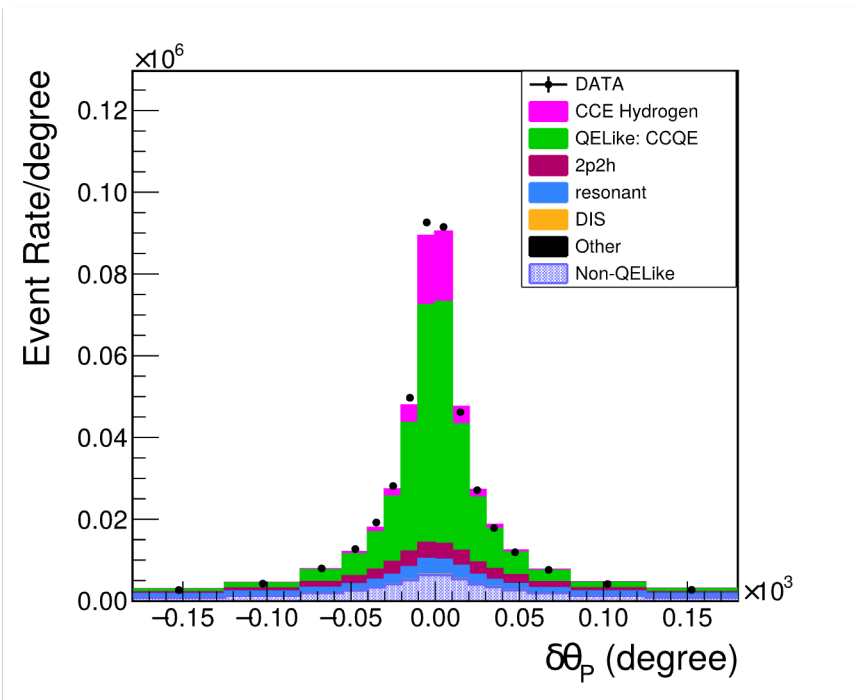




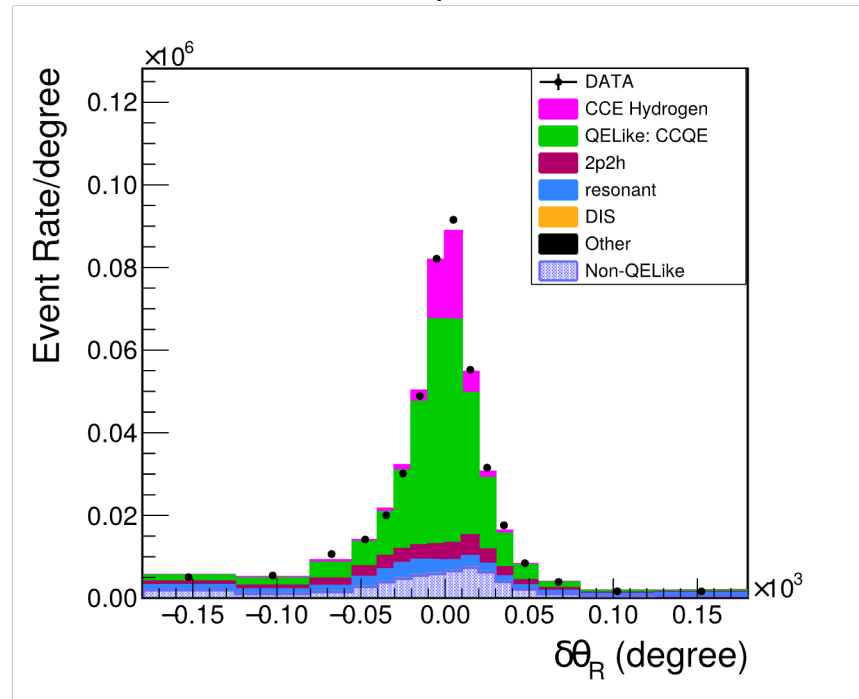
# Selection and separation (cont'd)



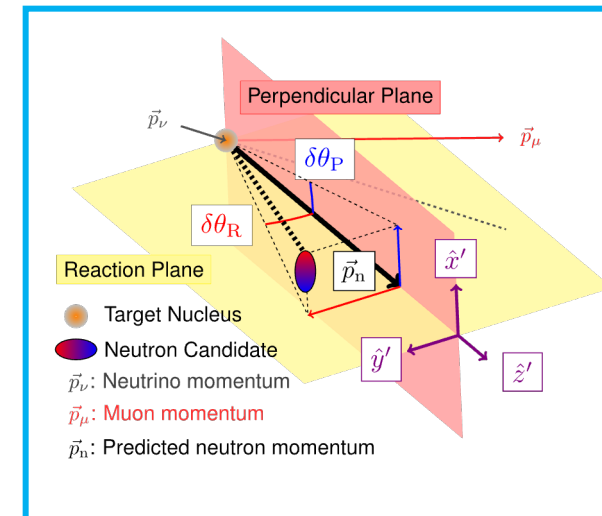
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29 June 2023



K. McFarland, Axial Form Factor @ MINERvA

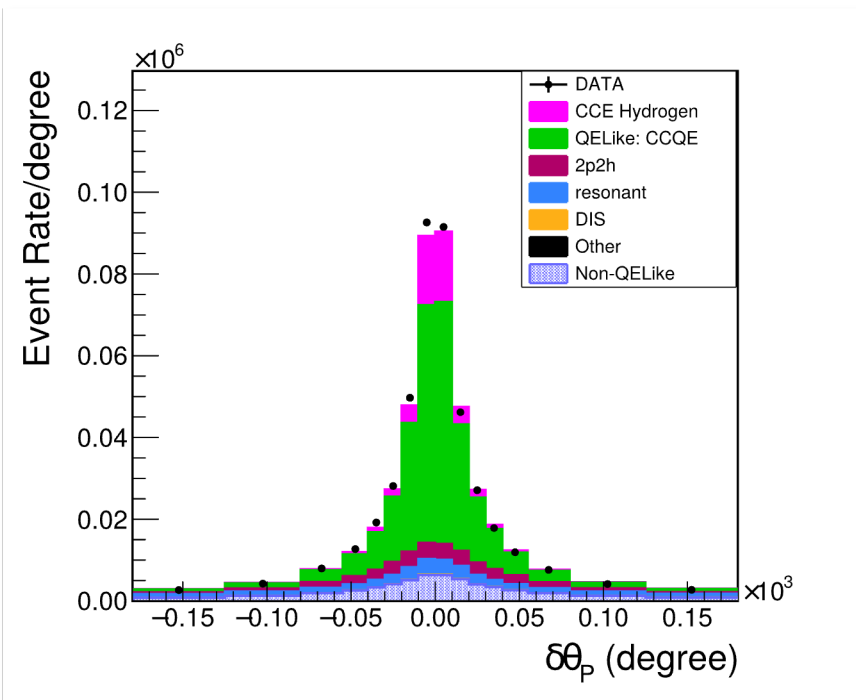


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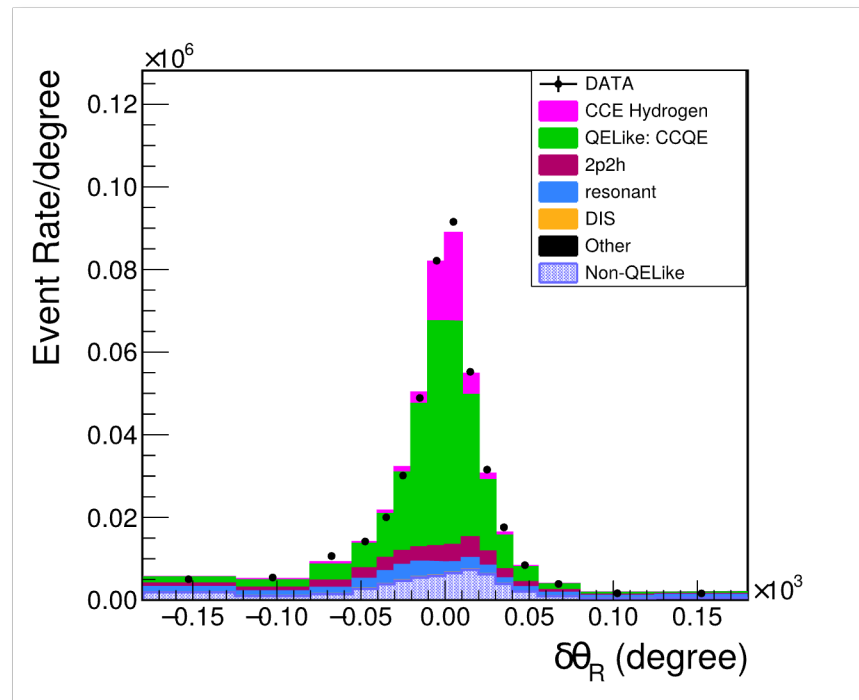
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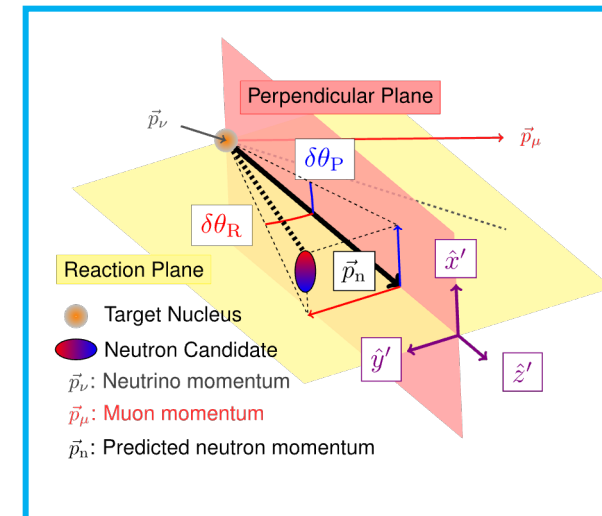
- This is not going to be a background free measurement.
- Simultaneous consideration of both deflection angles is helpful.
- Note non-quasielastic event bias in reaction plane.
  - Allows separation of quasielastic (symmetric) and non-QE backgrounds.



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K. McFarland, Axial Form Factor @ MINERvA



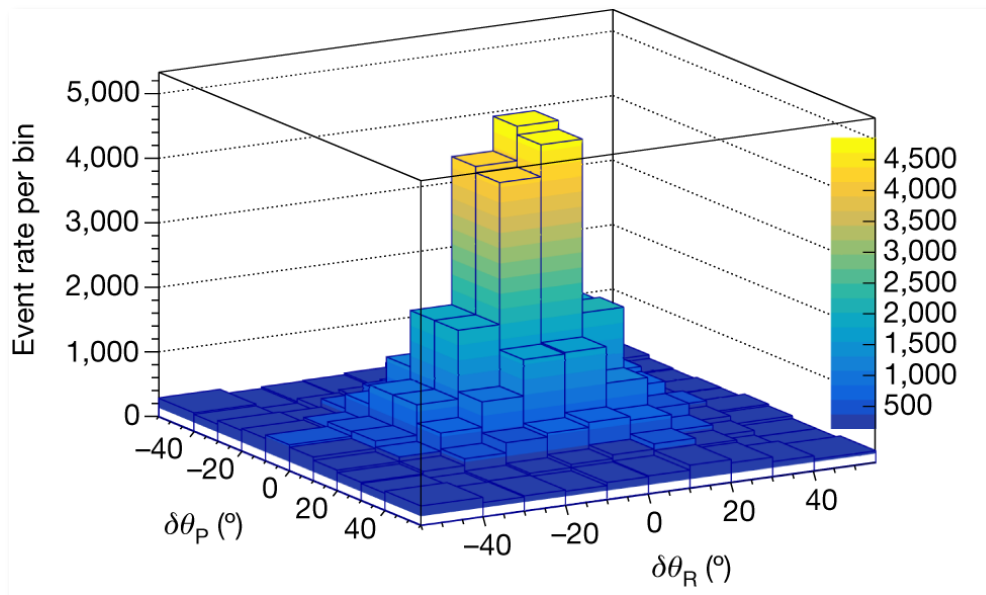
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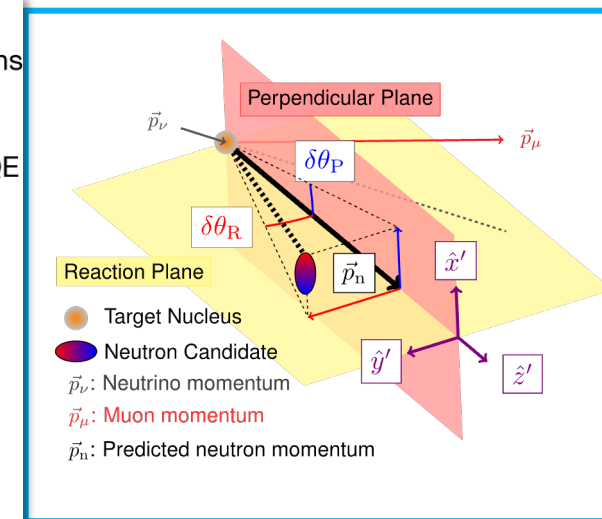
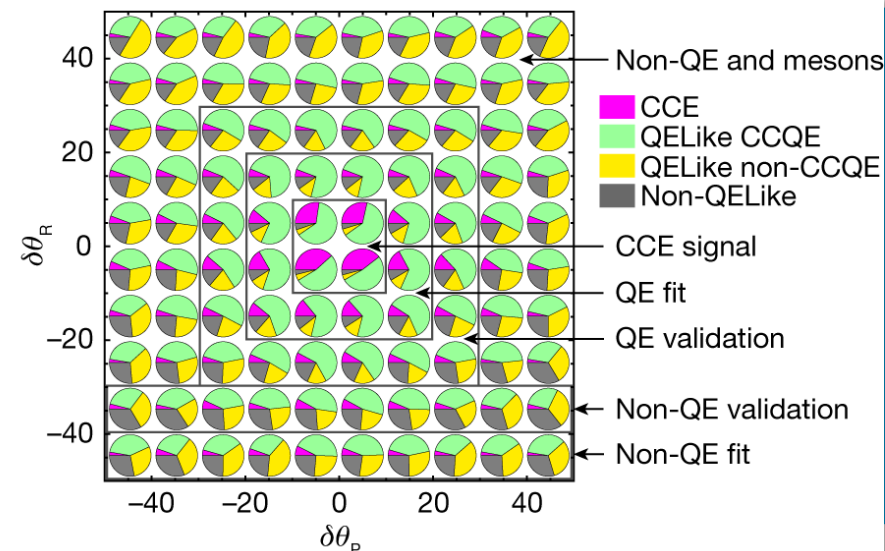
# Selection and separation (cont'd)

- Simultaneous consideration of both deflection angles is helpful
- Note non-quasielastic event bias in reaction plane.
  - Allows separation of quasielastic (symmetric) and non-QE backgrounds.
- Fit different background rates, as a function of  $Q^2$  from 2D regions.

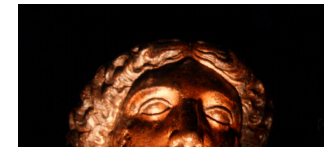
“2D” Total event rate



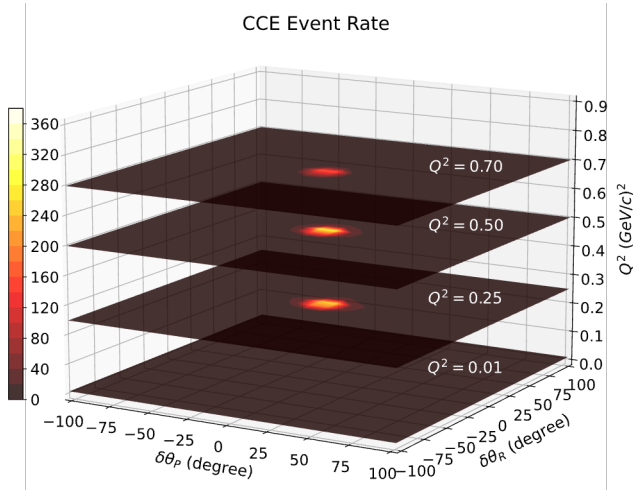
Fractions of rate predicted by model/simulation



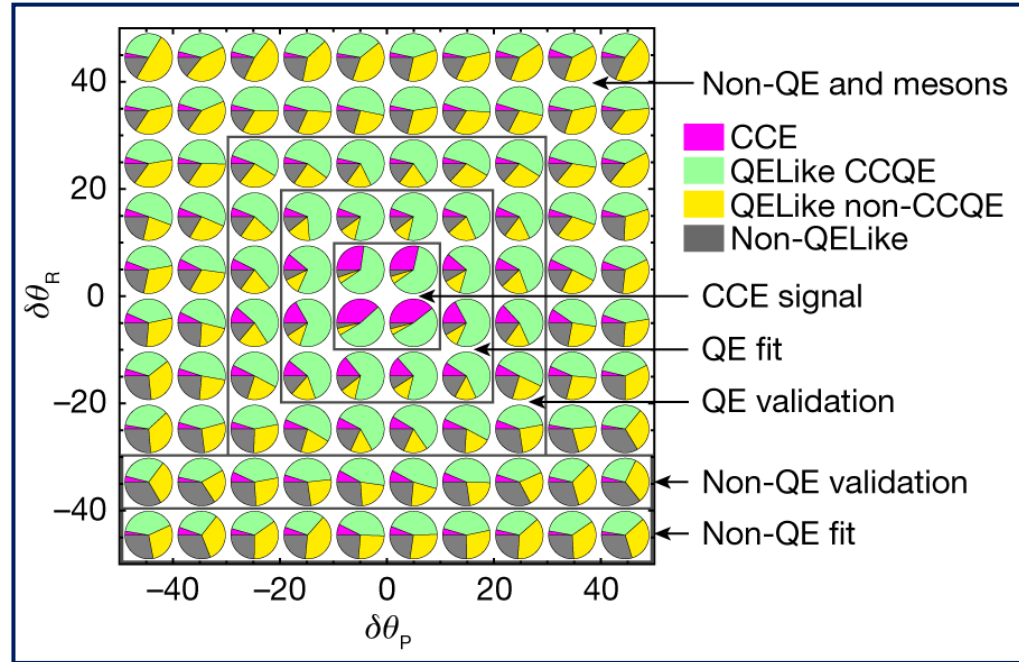
# Selection and separation (cont'd)



CCQE Event Rate

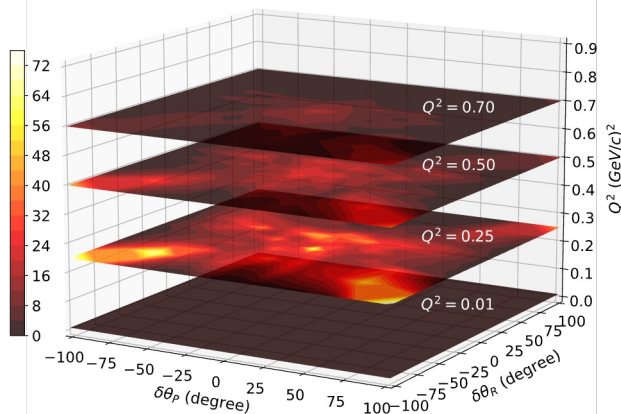


CCE Event Rate

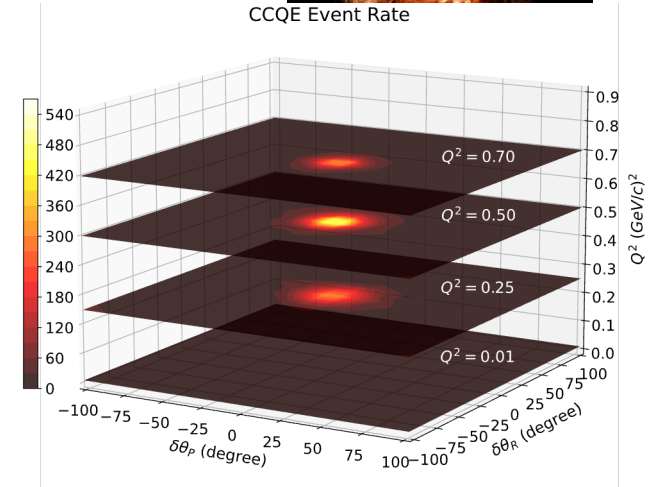


**SIGNAL: Elastic on H**

QELike 2p2h Event Rate

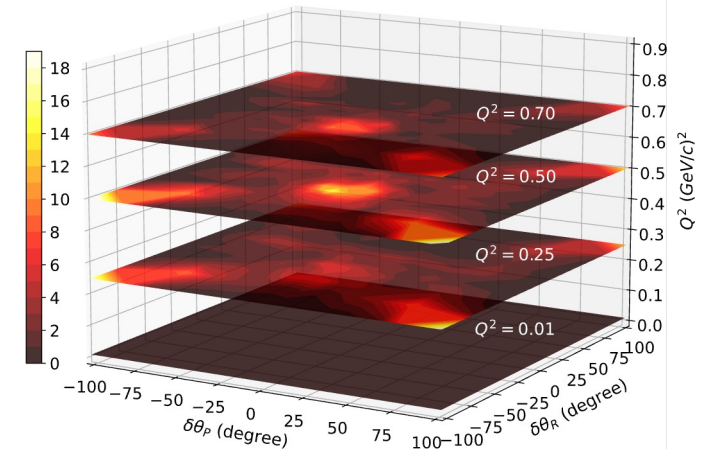


**Background: QELike 2p2h**



**Background: QELike CCQE (on C)**

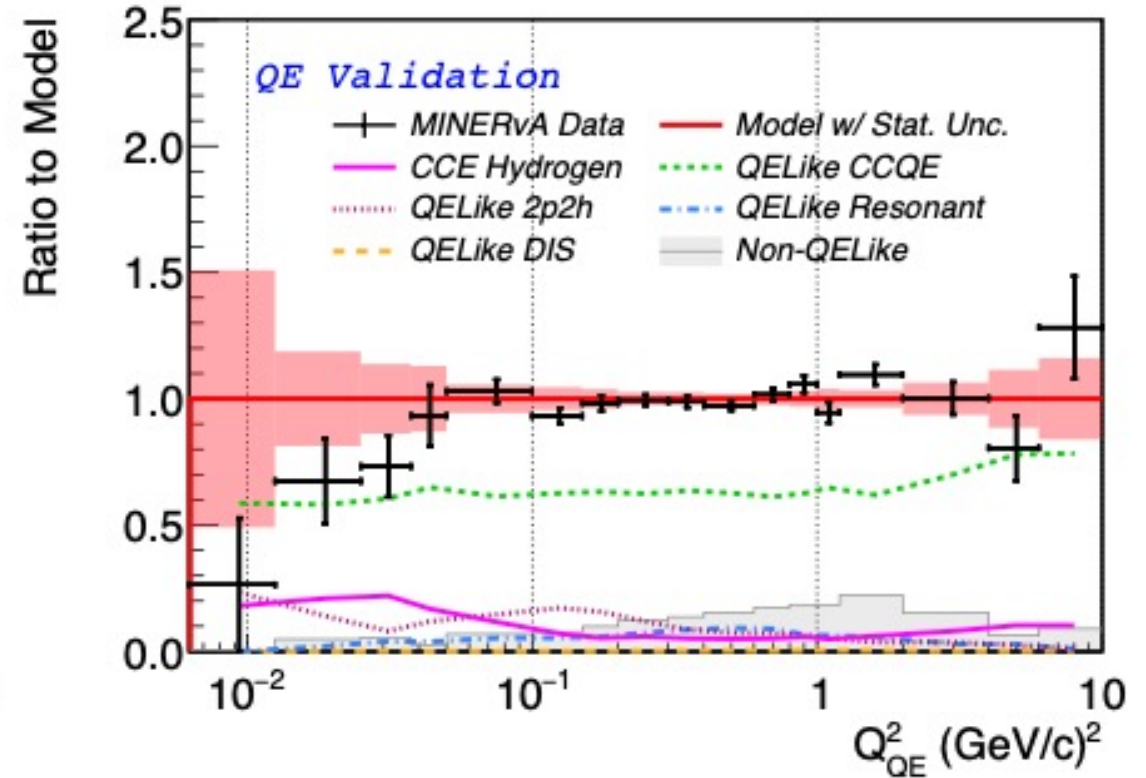
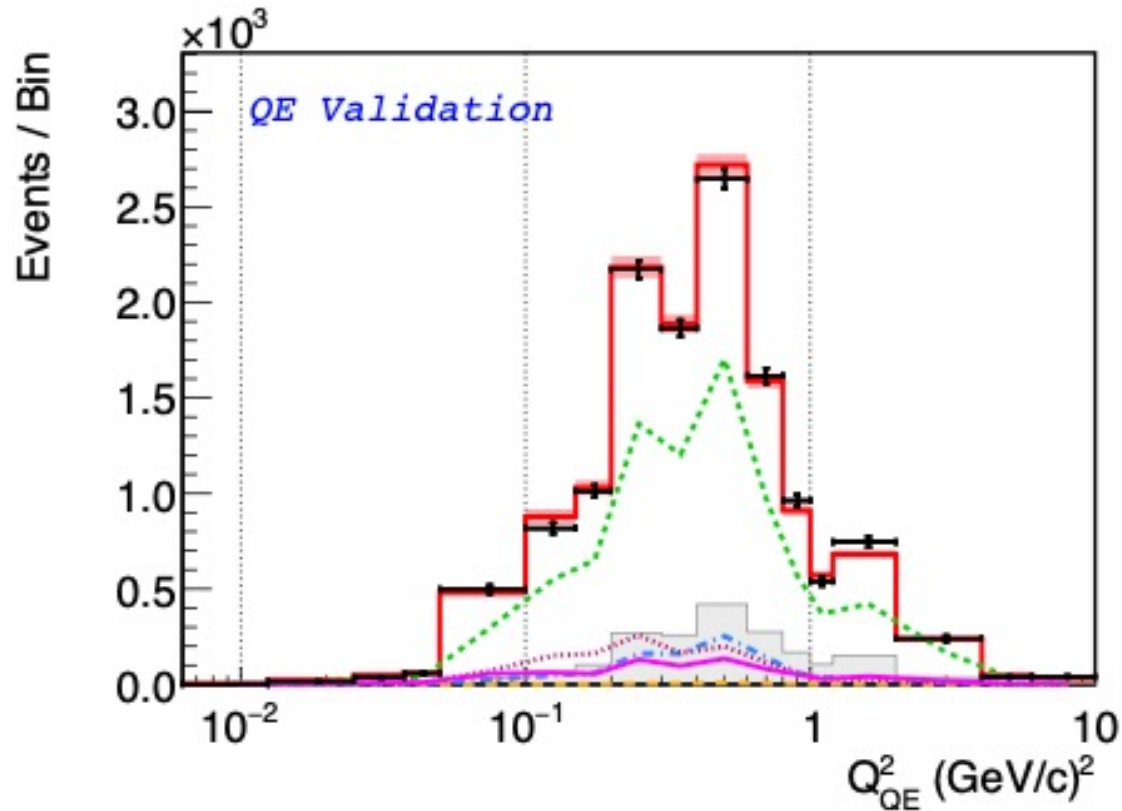
QELike Resonant Event Rate



**Background: QELike Resonant**

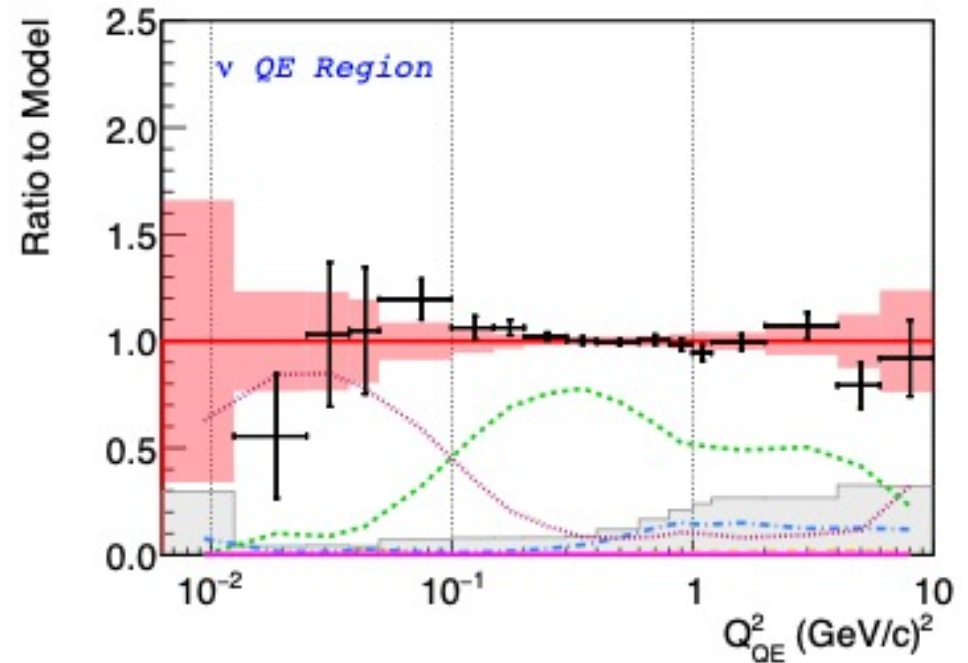
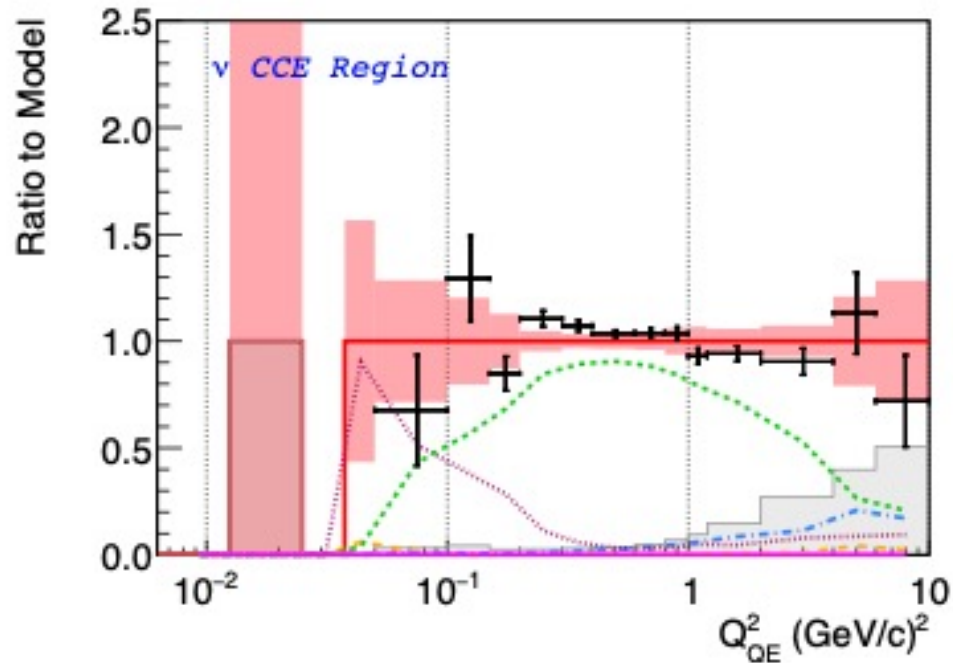
**Regions of the 2D angular distribution used to fit the backgrounds proportion in the signal region.**

# Sideband Sample Fits



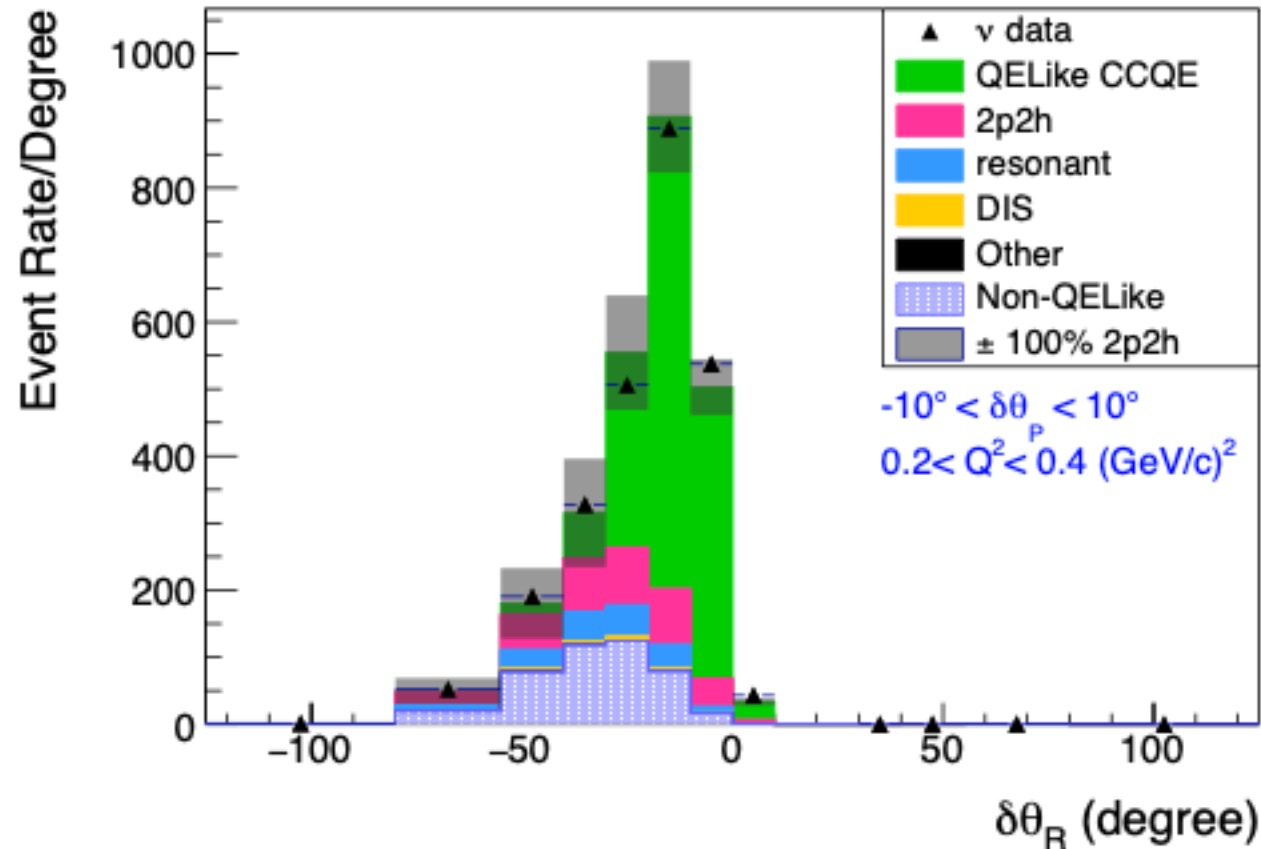
- CCQE is the dominant background. Small 2p2h, inelastic (absorbed), and Non-QELike contributions. The fitted model are well constrained by data.

# Control Sample, Neutrino Beam



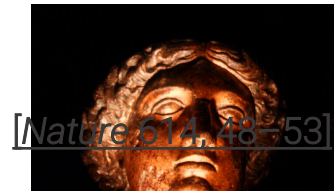
- We select events with trackable protons in a neutrino sample. Different final states and available kinematics. Apply same fitting mechanism. Data and MC mostly agree within uncertainty. Data and MC mostly agree. Disagreement can be explained by **2p2h** uncertainty (next slide).

# Control Sample, Neutrino Beam (cont'd)

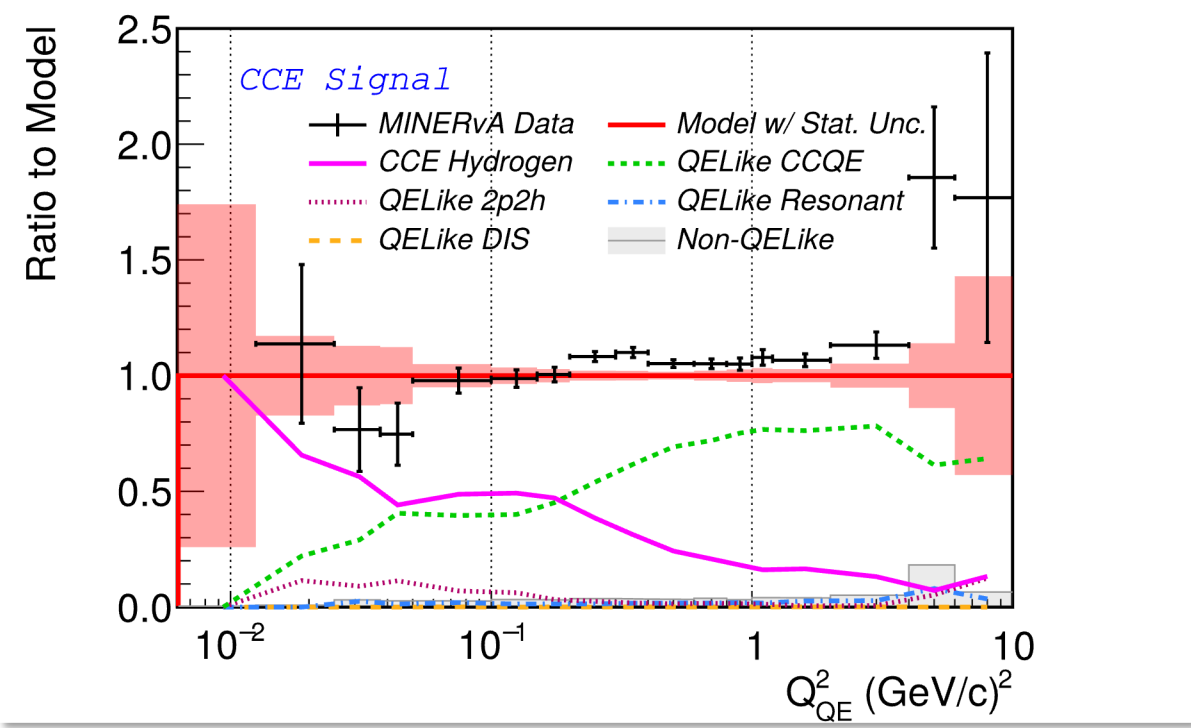
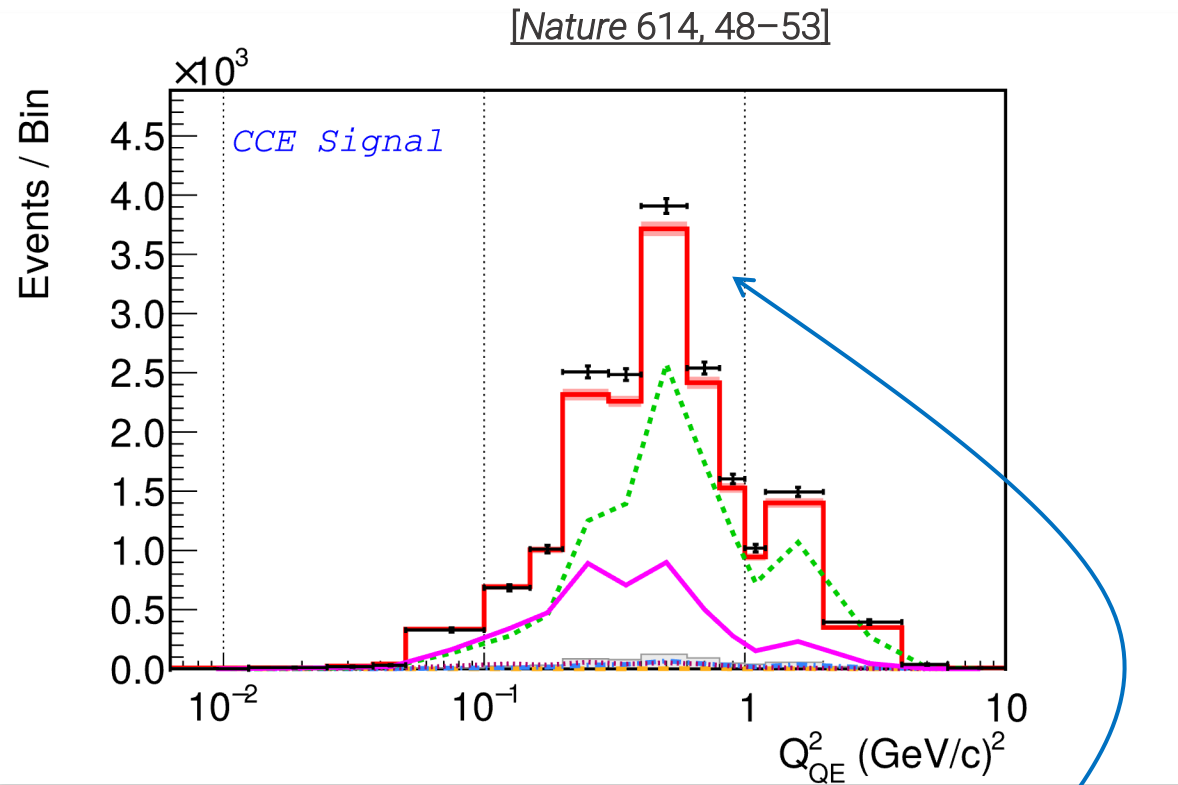


- A 100% 2p2h uncertainty covers the data-simulation difference seen here. In the  $\bar{\nu}$  mode a 100% 2p2h uncertainty is adequately covered by the total uncertainties.

# Cross-section Extraction



[Nature 614, 48-53]



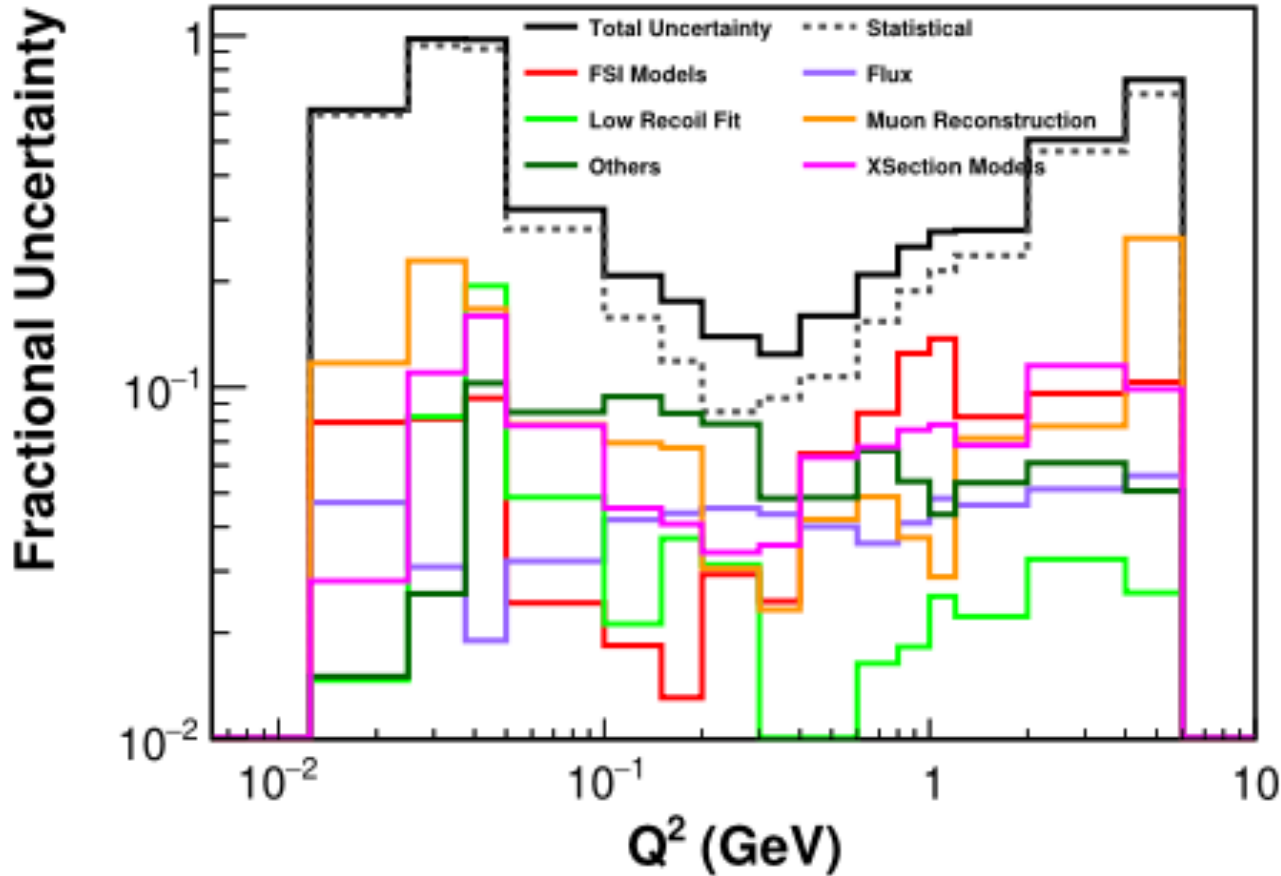
## Ingredients:

- 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

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



# Uncertainties in the 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.

# Extracting the Axial Form Factor



- The cross-section depends on the axial and vector form factors quadratically, and the result integrates over a range of neutrino energies.
- Bin-by-bin axial form factor cannot be extracted, but can fit the cross-section using a z-expansion formalism, as done in *Phys.Rev.D* 93 (2016) 11, 113015.
- $F_A(0)$  is constrained, and  $F_A(Q^2)$  required to fall as  $1/Q^4$  as  $Q^2 \rightarrow \infty$ .
- Regularization strength from data (L-curve).
- Can extra “axial radius” from this fit.

$$F_A(Q^2) = \sum_{k=0}^{k_{\max}} a_k z^k$$

$$z = \frac{\sqrt{t_{\text{cut}} + Q^2} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} + Q^2} + \sqrt{t_{\text{cut}} - t_0}}$$

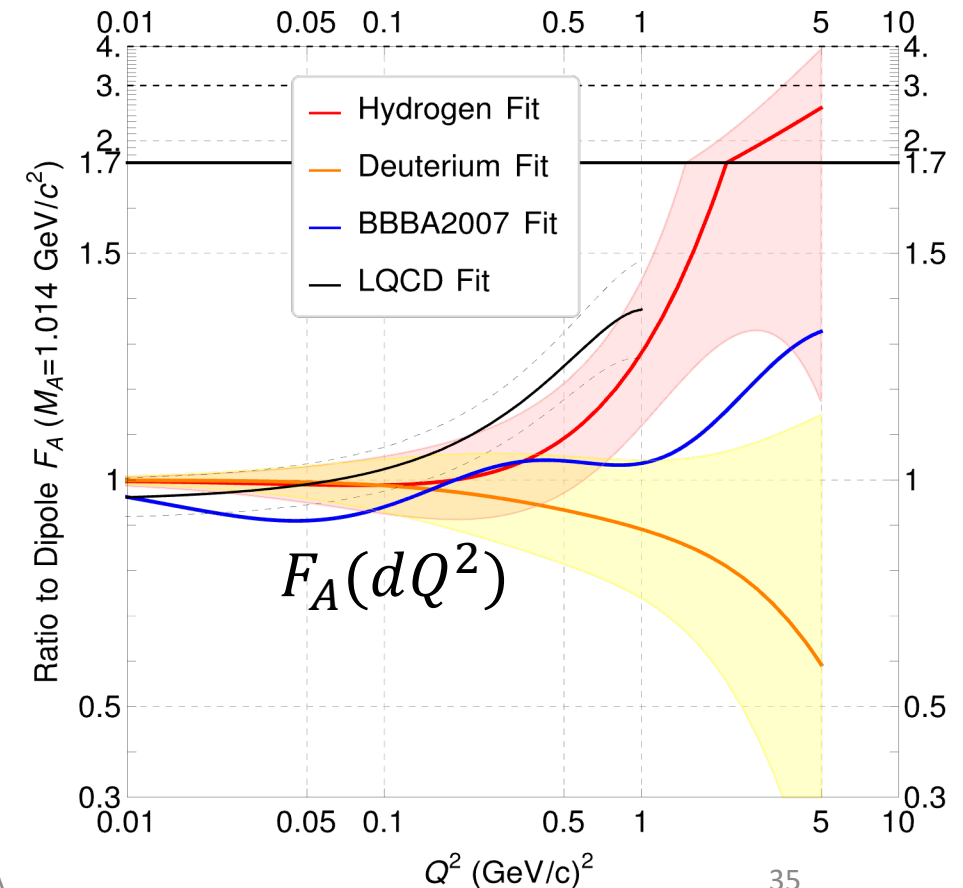
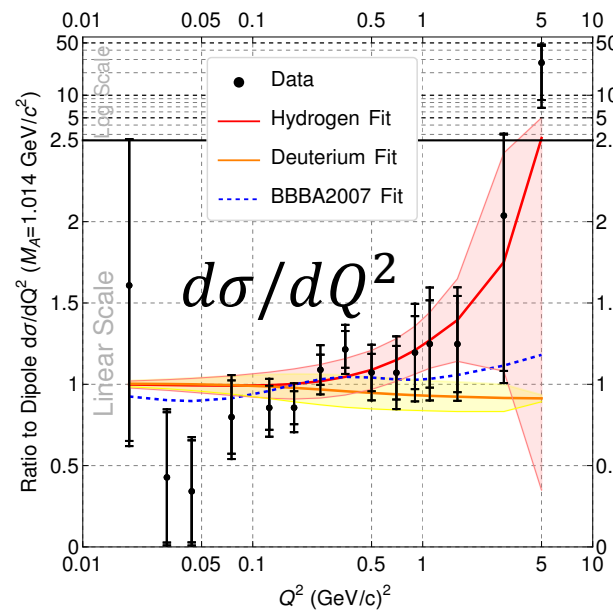
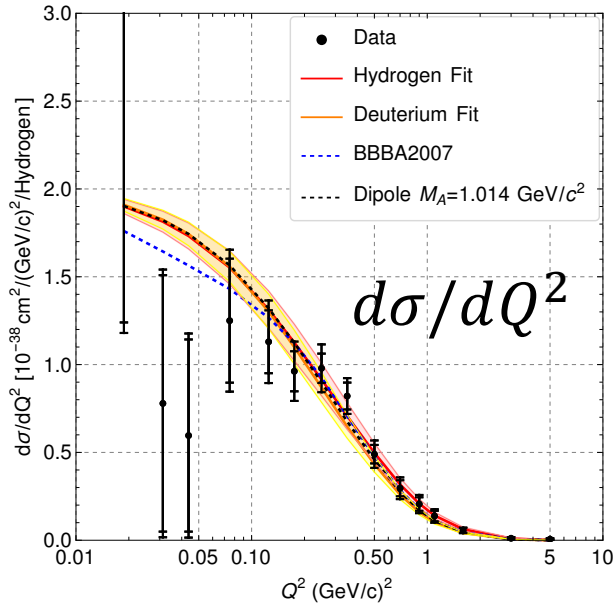
$$\sum_{k=n}^{\infty} k(k-1)\dots(k-n+1)a_k = 0, n \in (0, 1, 2, 3)$$

$$\chi^2 = \Delta X \cdot \text{cov}^{-1} \cdot \Delta X + \lambda \left[ \sum_{k=1}^5 \left( \frac{a_k}{5a_0} \right)^2 + \sum_{k=5}^{k_{\max}} \left( \frac{ka_k}{25a_0} \right)^2 \right]$$

# Free Nucleon Axial Form Factor



- We have  $\sim 5800$  such events on a background of  $\sim 12500$ .
- 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  $Q^2$ .



# Conclusion and Outlook

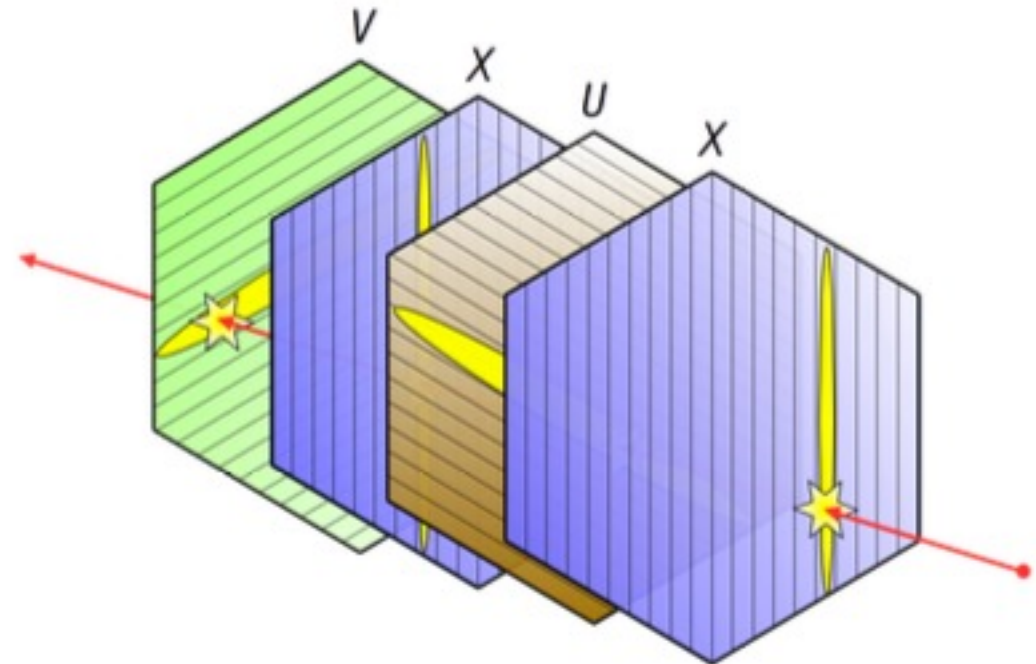
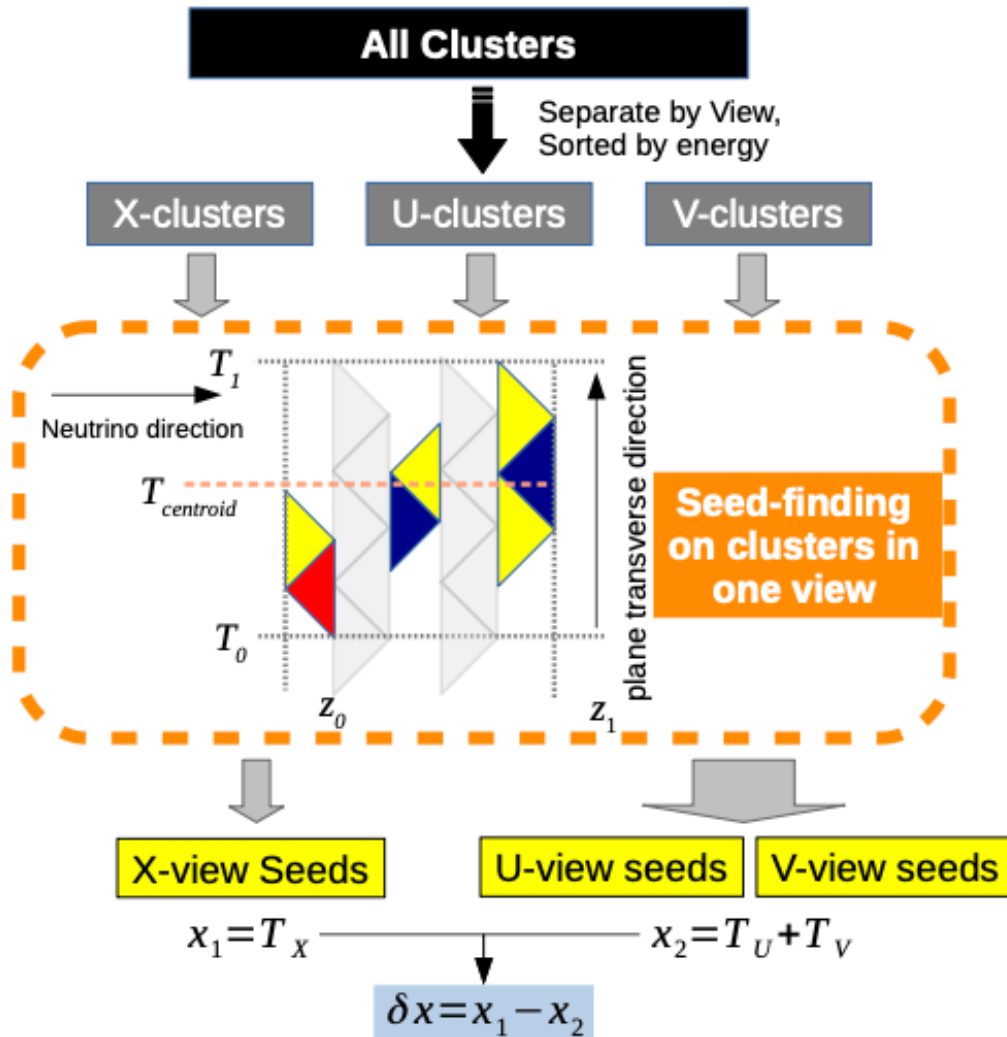


- With this result, still some work to do (in progress).
  - Incorporate radiative corrections (*Nature Commun.* 13 (2022) 1, 5286; *Phys.Rev.D* 106 (2022) 9, 093006) into the analysis.
  - Joint fits with neutrino-deuterium analysis (*Phys.Rev.D* 93 (2016) 11, 113015), including comprehensive analysis of compatibility.
- More neutrino measurements?
  - Not soon. Investigation of next generation neutrino beam experiments with CH/C targets and with H and D bubble chambers (DUNE).
- Theoretical interpretation of this form factor?
  - The data is in the record; have at it!



# Backup: Neutron Reconstruction

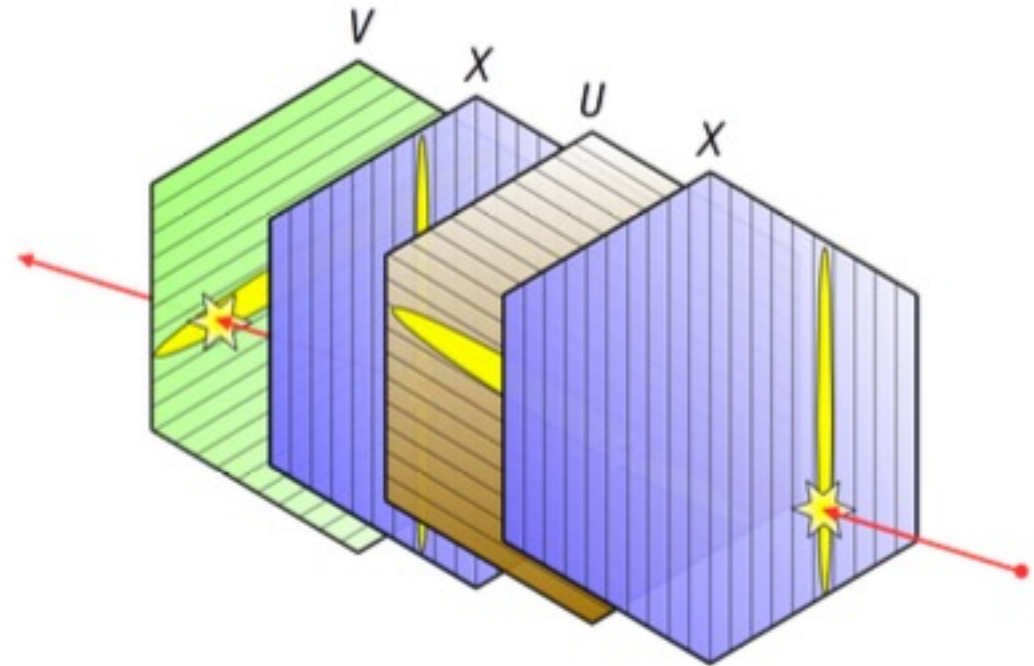
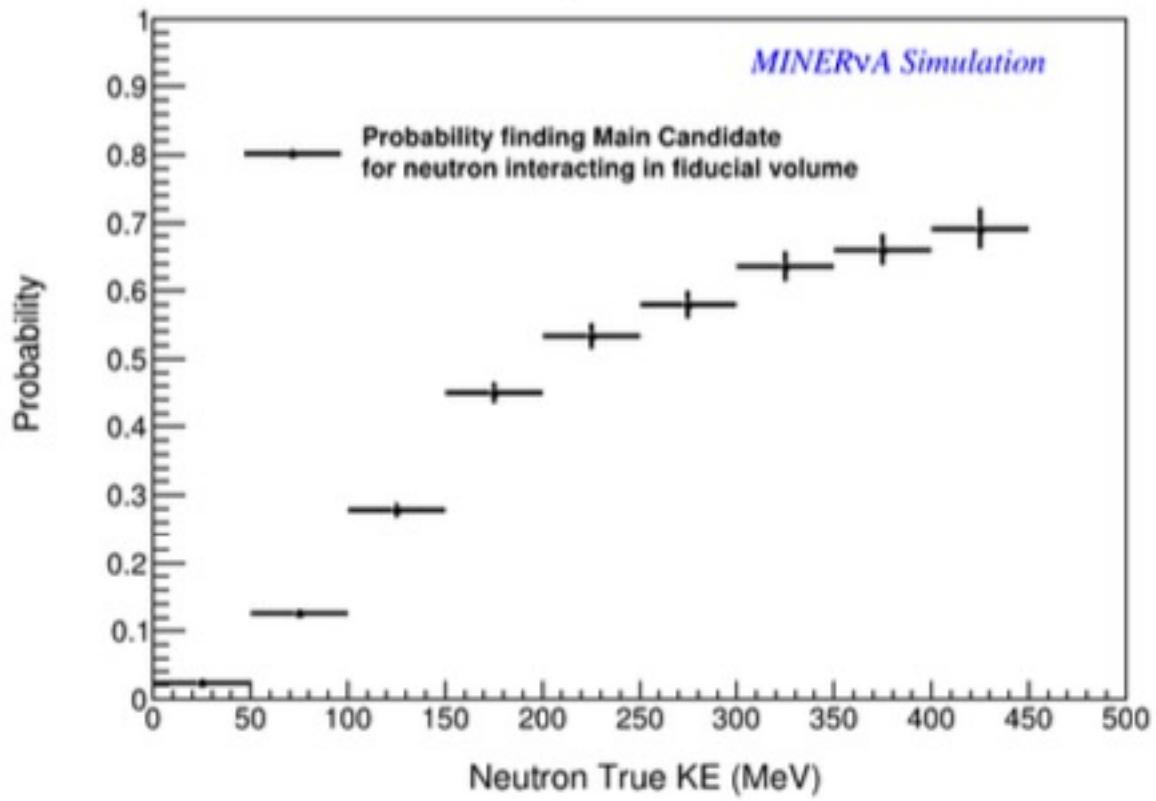
# Neutron “3D Blobs”

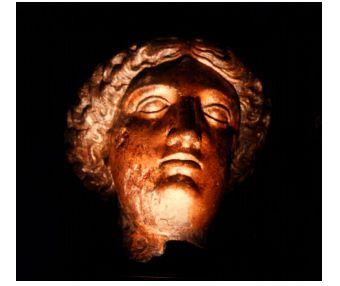


# Neutron "3D Blobs"



Probability for interacting neutron to have main candidate





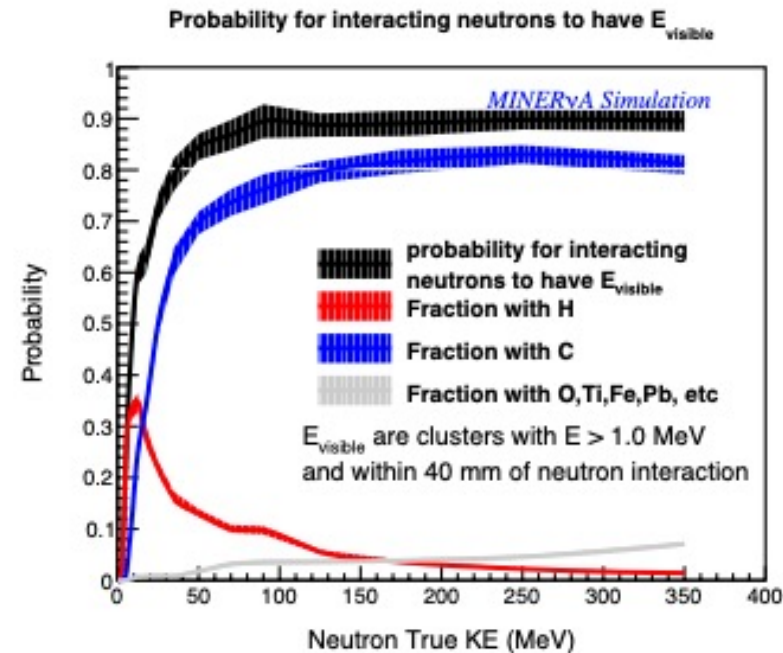
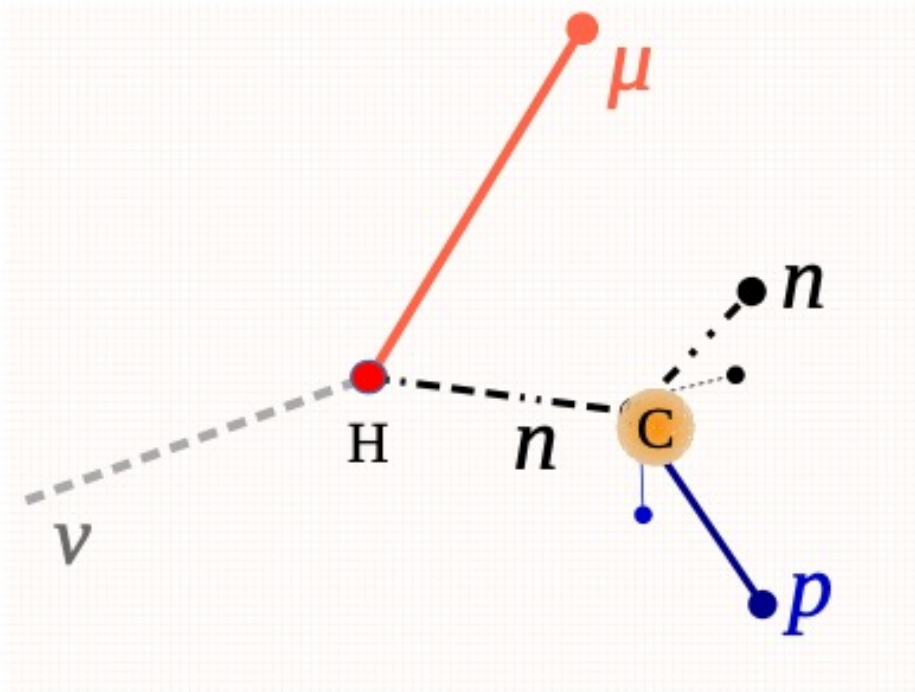
# Backup: Neutron Interactions



# Neutron Scintillator Reactions



Neutrons inside the detector interact with hydrogen or carbon to produce charged secondary particles.

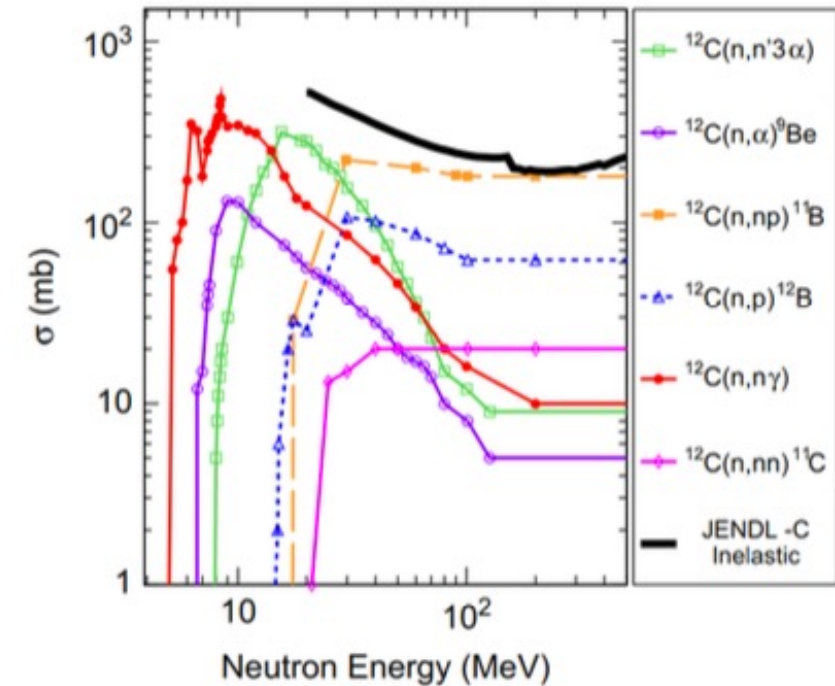


Most prompt neutron energy deposits due to knockout protons.

# MoNA Analysis



- The MoNA collaboration collected and modeled neutron cross section on CH.
  - $^{12}\text{C}(n, np)^{11}\text{B}$  is the dominant interaction channel
  - We tune each channel to the MoNA cross-section based on secondary daughter particles.



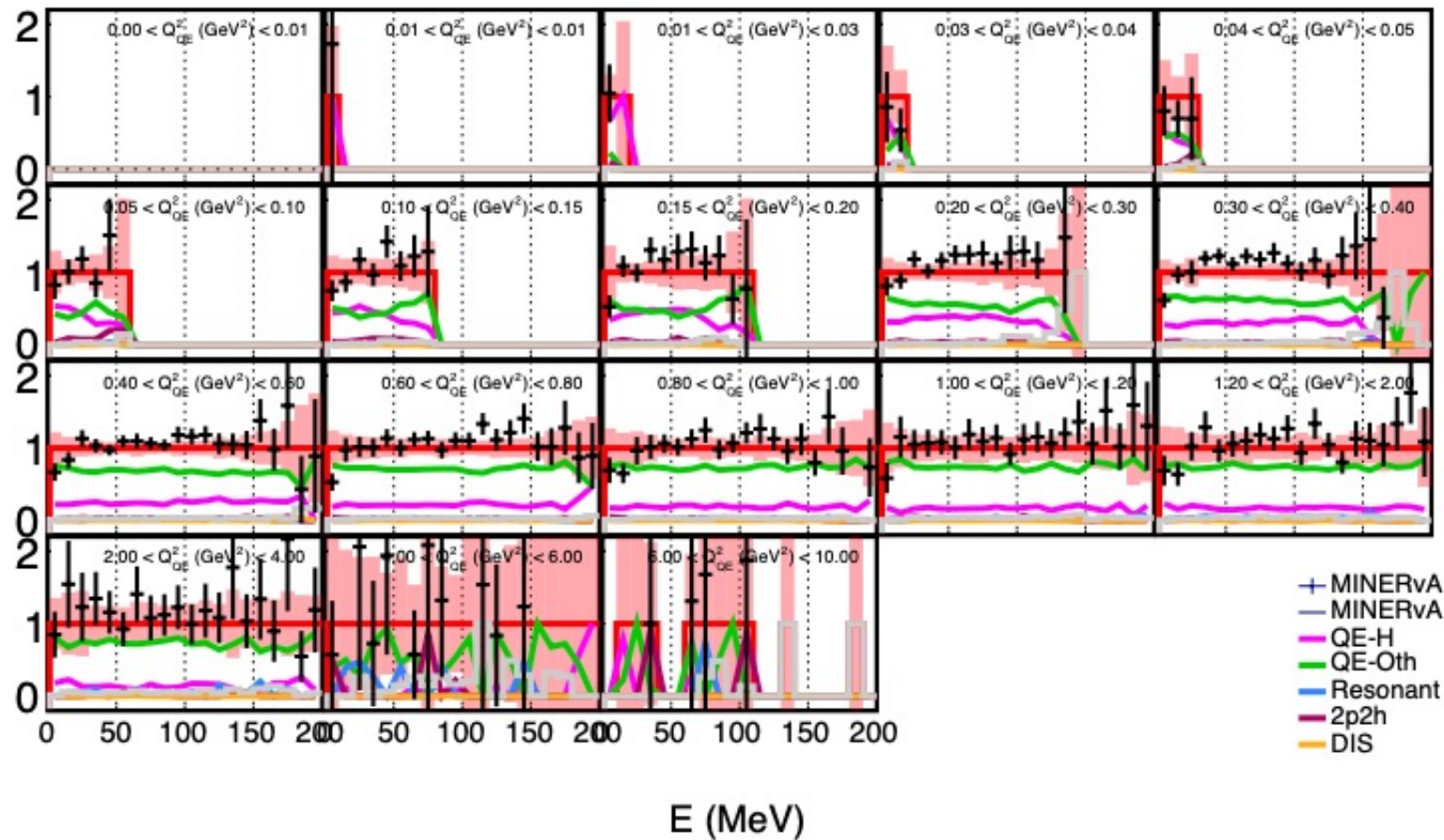
**Fig. 3.** Inelastic neutron-carbon reaction cross-sections are shown as a function of the incident neutron energy. MENATE\_R uses the six different discrete reaction channel cross-sections while the G4-Physics uses the total inelastic reaction cross-sections taken from the JENDL-HE library [37].

# “Nuisance” Distributions

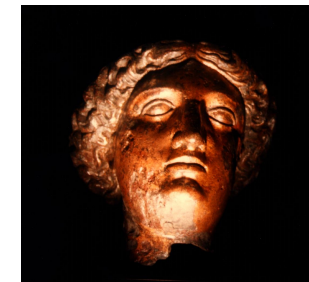


Neutron candidate energy distribution in reconstructed  $Q_{QE}^2$  bins.  
**Without MoNA.**

Ratio to MnvGENIE,  $\chi^2=288.39$ , DOF=360



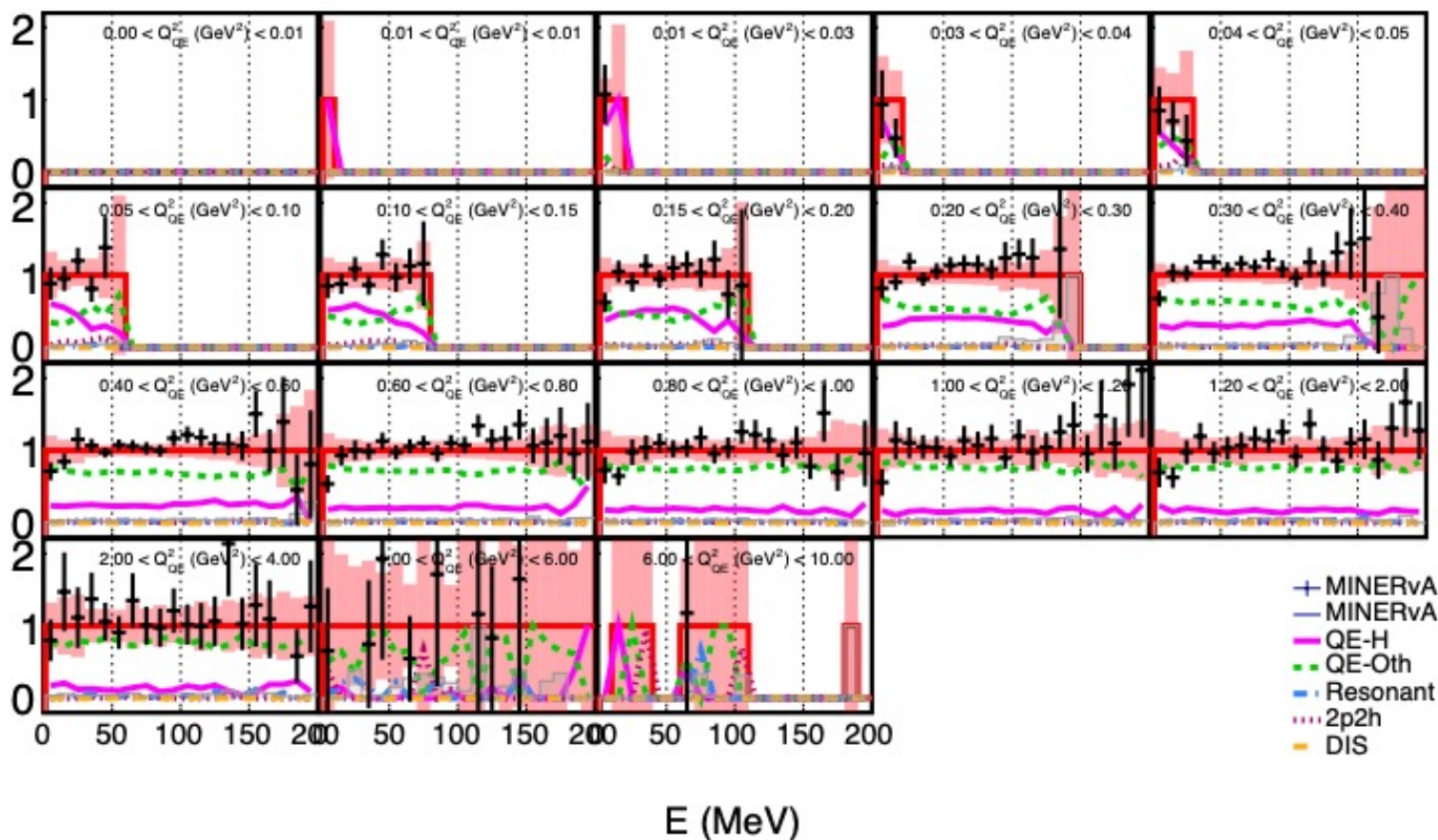
# “Nuisance” Distributions



Neutron candidate energy distribution in reconstructed  $Q_{QE}^2$  bins.

**With MoNA:** improved  $\chi^2$ .

Ratio to MnvGENIE,  $\chi^2=253.66$ , DOF=360





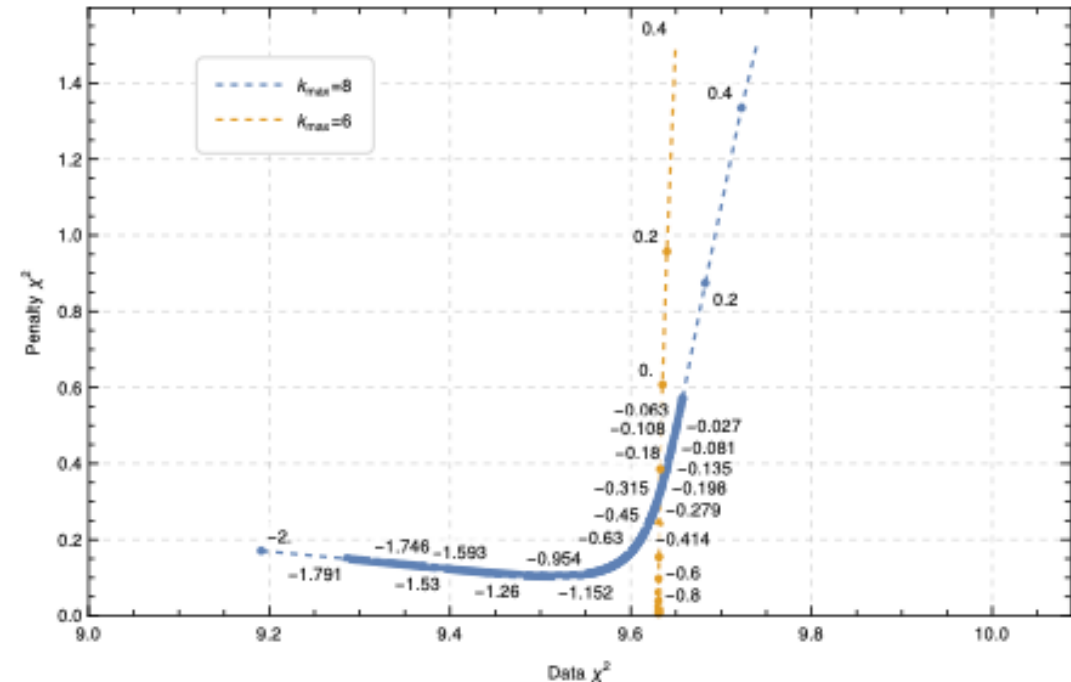
# Backup: Regularization L-curve

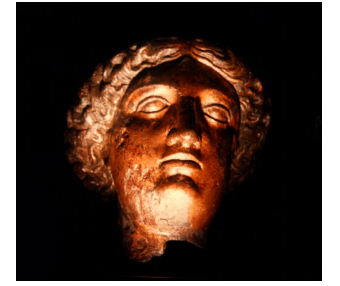
# Regularization strength



Central value fit:  $k_{\max} = 8, \lambda = 0.13$

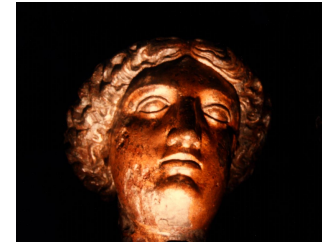
- Scan through large range of  $\lambda$
- Data  $\chi^2$  for  $k_{\max} = 8$  can be less than  $k_{\max} = 6$
- $\lambda$  chosen at point of maximum curvature.



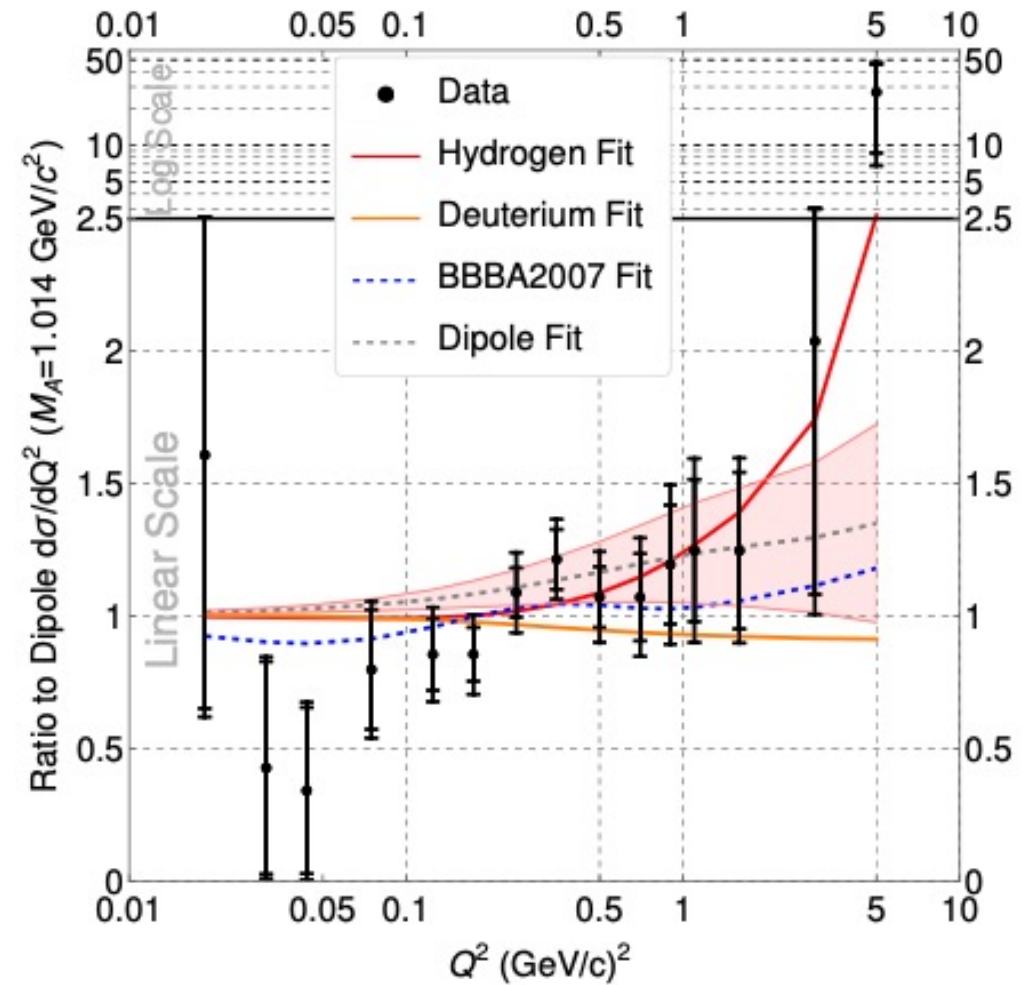


# Backup: Dipole Fit and Axial Radius

# Dipole Fit



- $M_A = 1.15(10)$  GeV
- Fit  $\chi^2 = 10.2$
- Comparable with z-expansion fit
  - ▶  $k_{\max} = 6$
  - ▶  $\lambda = 0$
  - ▶  $\chi^2 = 9.64$





# “Axial Radius” compared to LQCD calculations



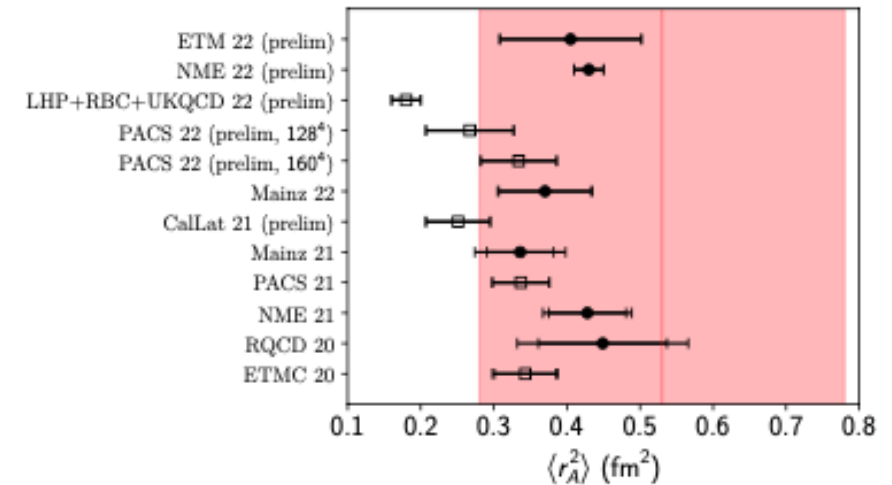
Favors larger  $F_A$  at higher  $Q^2$ .  
If fit with dipole,  $M_A \sim 1.15(10)$

Calculate proton radius from  $F_A$  for  $Q^2 \rightarrow 0$ .

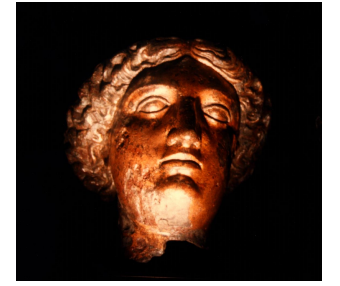
$$F_A(Q^2) = F_A(0) \left( 1 - \frac{\langle r_A^2 \rangle}{3!} Q^2 + \frac{\langle r_A^4 \rangle}{5!} Q^4 + \dots \right),$$

$$\frac{1}{F_A(0)} \frac{dF_A}{dQ^2} \Big|_{Q^2=0} = -\frac{1}{6} \langle r_A^2 \rangle$$

- $\langle r_A^2 \rangle = 0.53(25) \text{fm}^2$
- $\sqrt{\langle r_A^2 \rangle} = 0.73(17) \text{fm}$

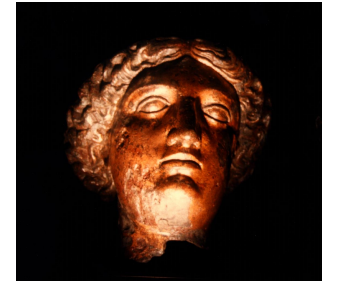


Filled circle: full error budget.  
Open square: incomplete.  
Red band: this result.  
Courtesy of Aaron Meyer.



# Backup: FNAL Thanks

# MINERvA owes a lot to Fermilab and partners at the Department of Energy



- MINERvA received a lot of encouragement and support in its formative phase.
  - Early R&D support from FNAL/PPD and DOE OHEP through the University of Rochester.
  - Fermilab's Project Support Office, particularly Ed Temple and Dean Hoffer.
  - Ted Lavine and Steve Webster, among many, at DOE for project oversight.
- Construction and Installation
  - Critical contributions from FNAL/PPD in engineering, technical, accounting, project oversight, and facilities staff.
- Operations and Analysis
  - Accelerator and beams.
  - FNAL/PPD->Neutrino Division staff for support of many construction subprojects
  - ES&H for finding ways for physicists & others to be safe working on our detector.
  - Children's center who gave us time to watch our detector.
  - Directorate support for Latin American and Indian collaborators.
  - Scientific Computing for proactive management of needed resources.
  - MINOS collaboration for operations help and analysis of muons in its near detector.

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Thank you!