Measurement of Anti-Neutrino Charged Current Elastic Scattering at MINERvA

Kevin McFarland
University of Rochester

22 August 2023

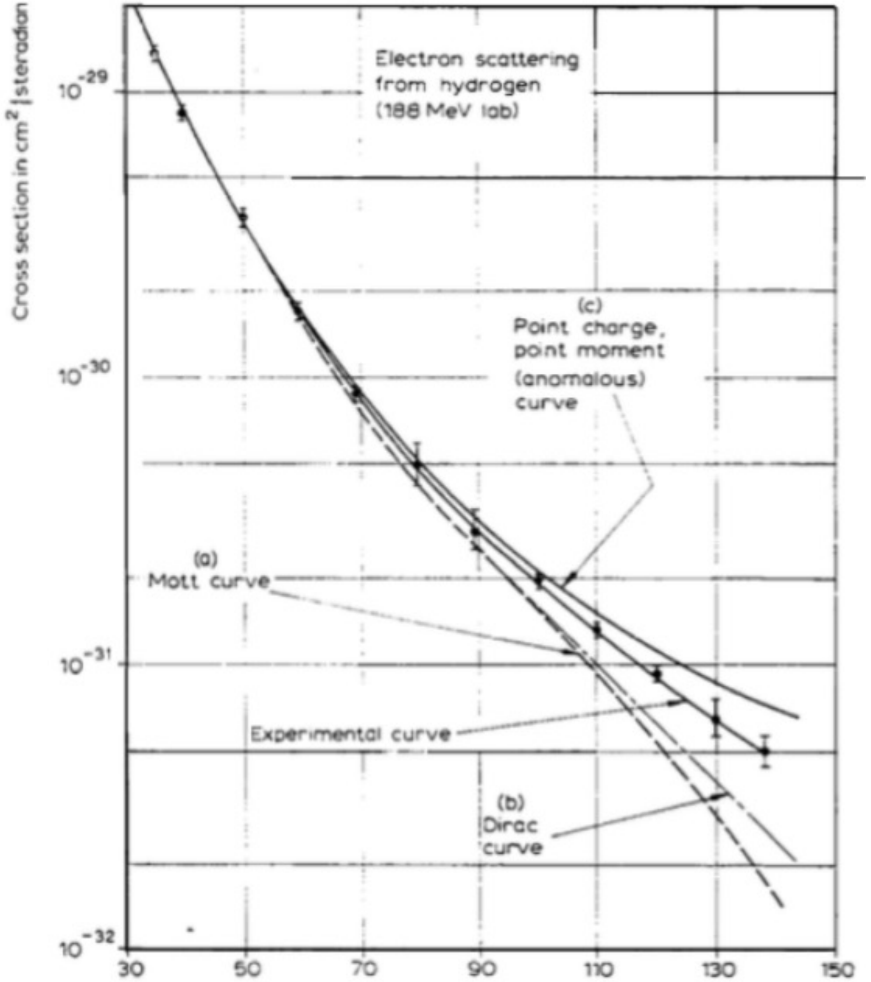
NuFact @ SNU

What is the purpose and scope of this measurement?

- MINERvA recently published (*Nature* 614, 48–53) a high statistics, ~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.



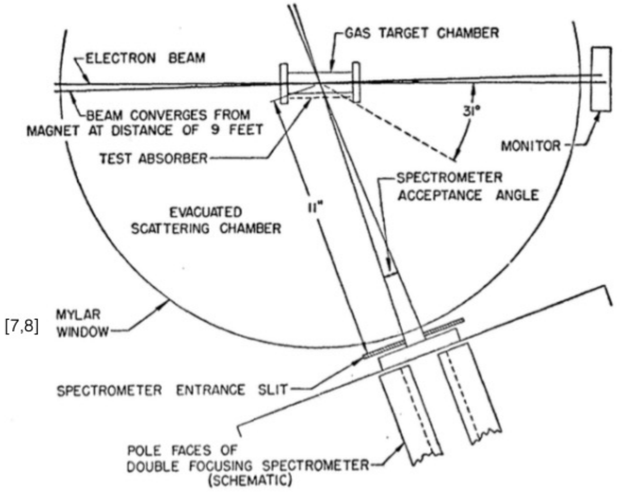
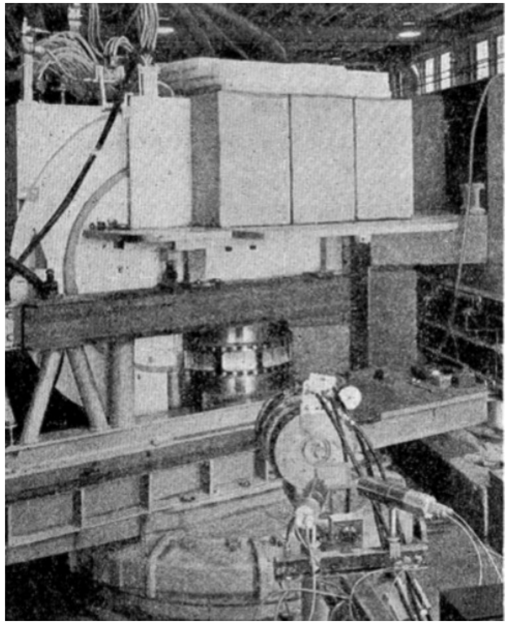


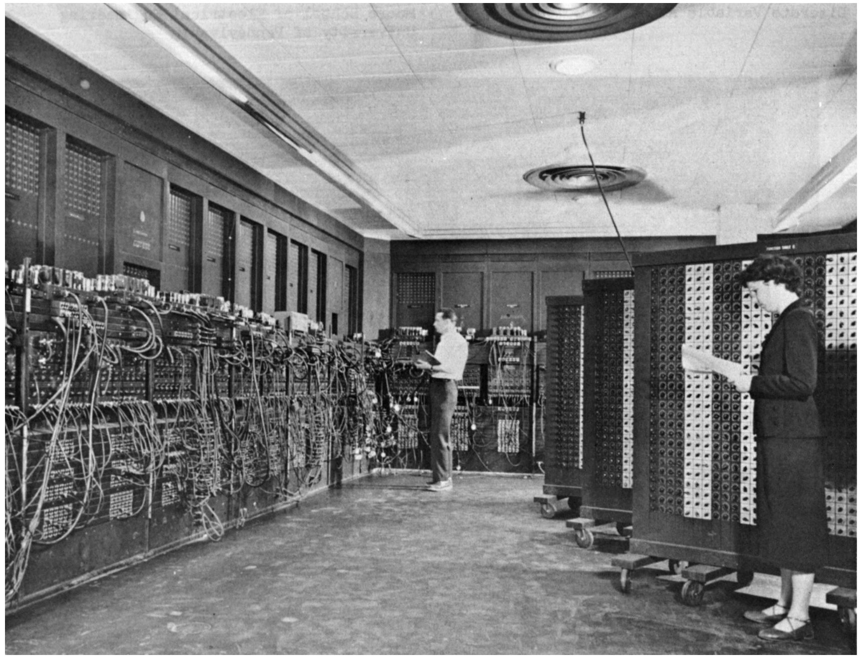
FIG. 17. Schematic diagram of scattering geometry employed with the gas target chamber.



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.

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

$$\begin{aligned}
A(Q^2) = \frac{m^2+Q^2}{4M^2}\Bigg[&\left(4+\frac{Q^2}{M^2}\right)|\boldsymbol{F}_{\mathrm{A}}|^2 - \left(4-\frac{Q^2}{M^2}\right)|\boldsymbol{F}_{\mathrm{V}}^{\mathbf{1}}|^2 \\
&+ \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\boldsymbol{\xi F}_{\mathrm{V}}^{\mathbf{2}}|^2 + \frac{4Q^2}{M^2}\mathrm{Re}\,\boldsymbol{F}_{\mathrm{V}}^{\mathbf{1}*}\boldsymbol{\xi F}_{\mathrm{V}}^{\mathbf{2}} + \mathcal{O}\left(\frac{m^2}{M^2}\right)\Bigg],\\
B(Q^2) = {}&\frac{Q^2}{M^2}\mathrm{Re}\,\boldsymbol{F}_{\mathrm{A}}^{*}(\boldsymbol{F}_{\mathrm{V}}^{\mathbf{1}} + \boldsymbol{\xi F}_{\mathrm{V}}^{\mathbf{2}}),\\
C(Q^2) = {}&\frac{1}{4}\left(|\boldsymbol{F}_{\mathrm{A}}|^2 + |\boldsymbol{F}_{\mathrm{V}}^{\mathbf{1}}|^2 + \frac{Q^2}{4M^2}|\boldsymbol{\xi F}_{\mathrm{V}}^{\mathbf{2}}|^2\right)
\end{aligned}$$

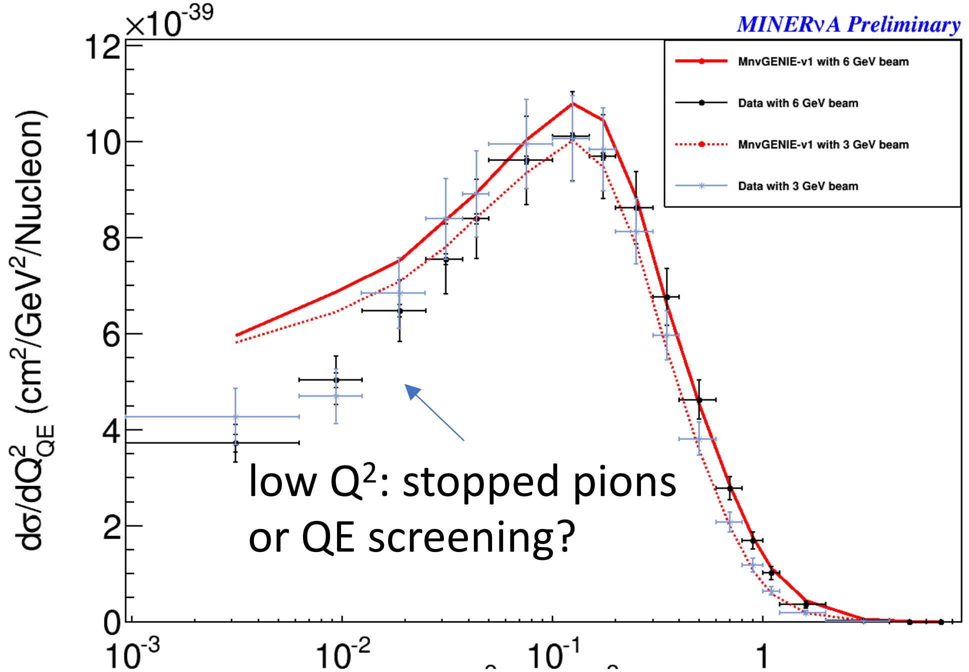
$\boldsymbol{F_V^1}$, $\boldsymbol{\xi F_V^2}$: **Electric and magnetic form factors**. Measured in **charged lepton scattering experiments,** even at very high Q^2. A lot of data and well constrained!

$\boldsymbol{F_A}$: **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.

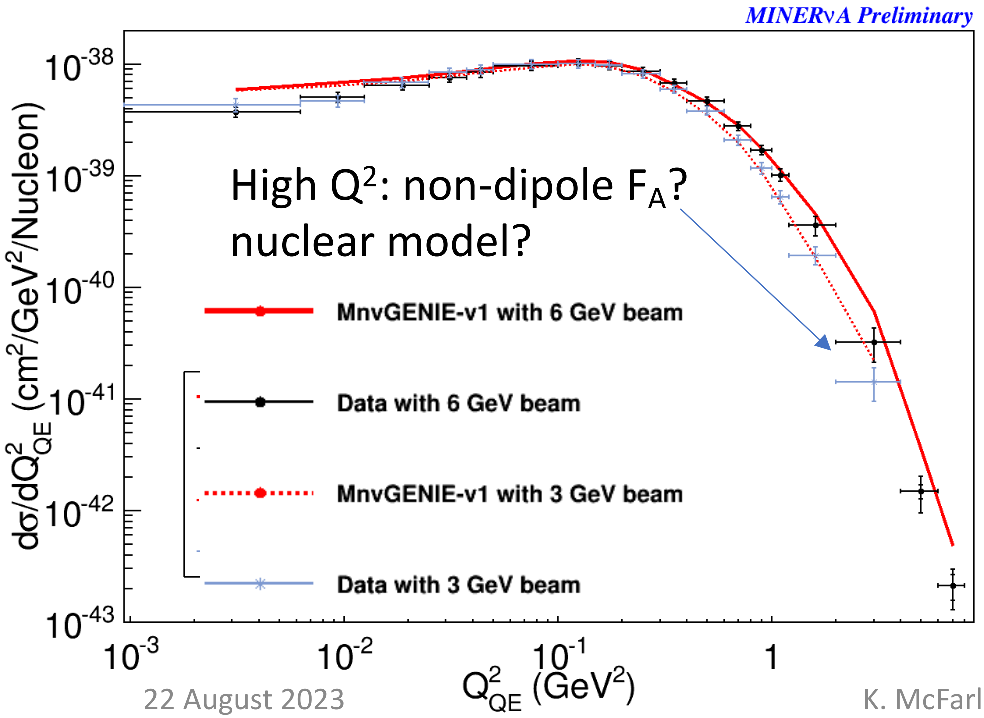
Context: MINERvA and Quasielastic Scattering

- A large portion of MINERvA’s physics program has concentrated on quasielastic scattering, meaning the “charged current elastic scattering” but from a target embedded in a nucleus.
- So instead of $\bar{\nu}_\mu p \rightarrow \mu^+ n$, a.k.a. $p\left(\bar{\nu}_\mu, \mu^+\right)n$, have $A(\bar{\nu}_\mu, \mu^+ n \ldots)A'$
- These measurements convolve nucleon structure with nuclear effects from the embedding, including
  - Initial state momentum and energy of the struck nucleon.
  - Collective effects in the hard scattering (RPA screening, 2p2h, etc.)
  - Rescattering of hadrons in the nucleus (FSI).
- And we mostly focus on nuclear effects.

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



low Q^2: stopped pions or QE screening?

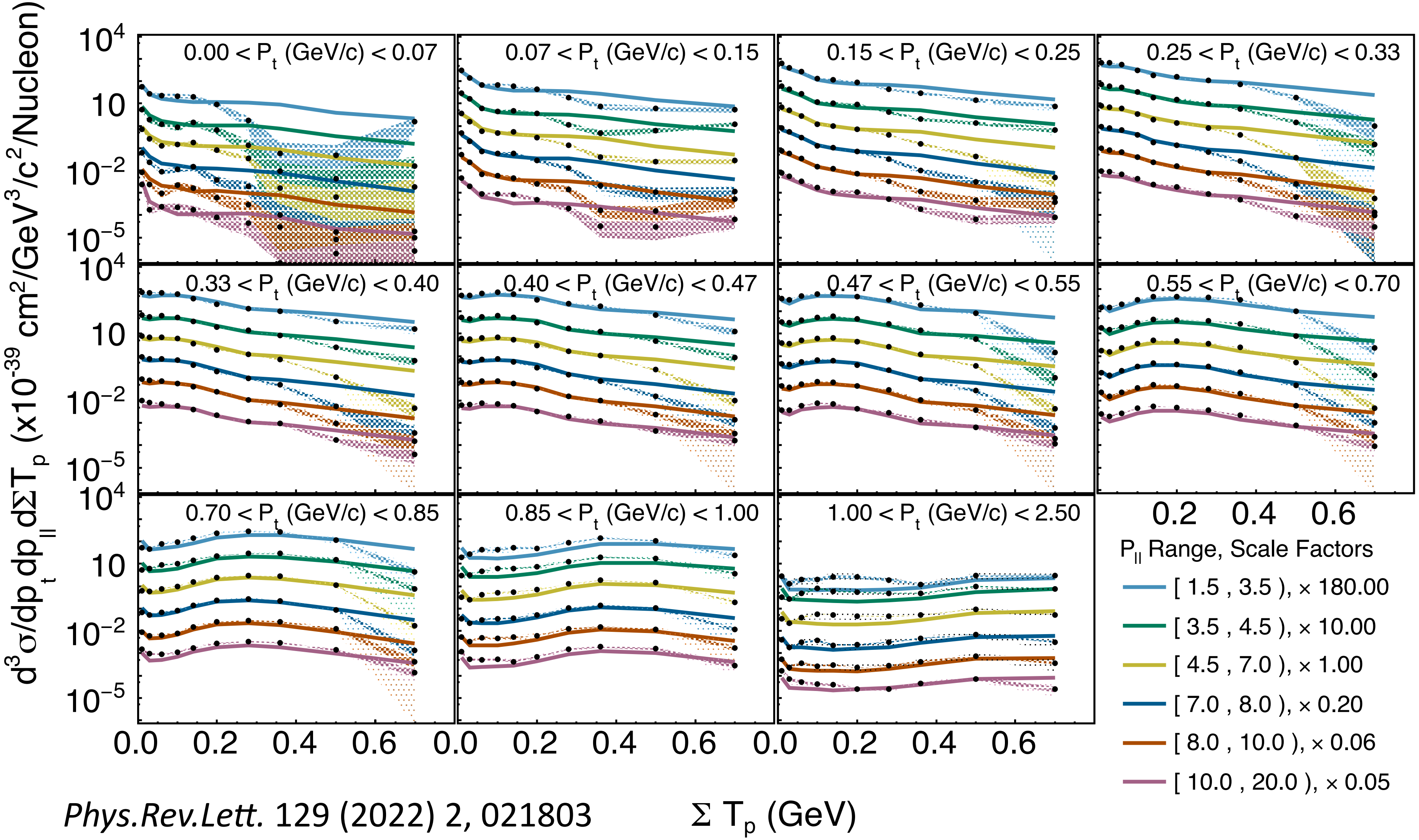


High Q^2: non-dipole F_A? nuclear model?

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

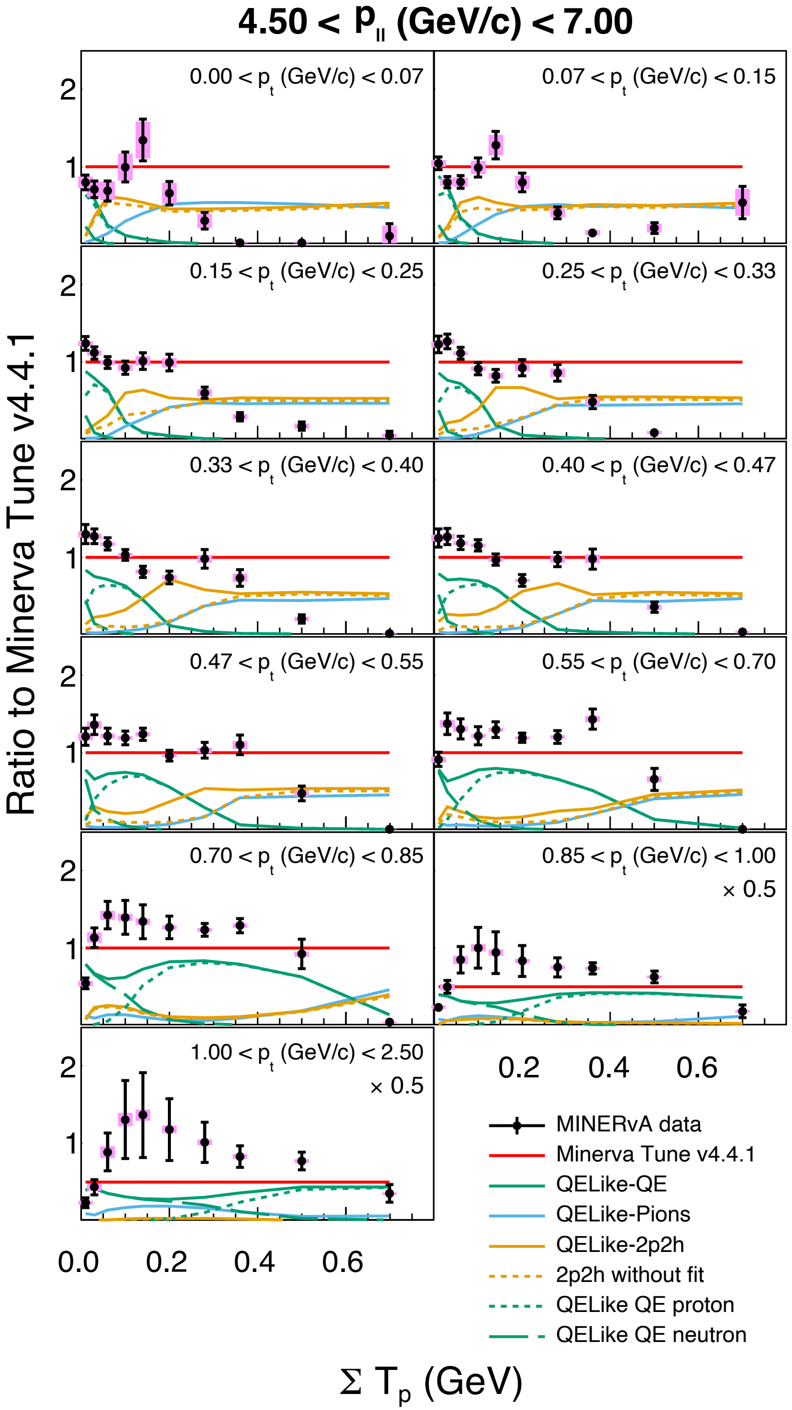
3 GeV from Phys. Rev. D 99, 012004 (2019),
6 GeV results Phys.Rev.Lett. 124 (2020) 12, 121801

$A(\nu_\mu, \mu^- p \ldots)A'$: $d^3\sigma/d\Sigma T_p \mathrm{d}p_T \mathrm{d}p_\parallel$



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

- 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 $p_\parallel$…



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

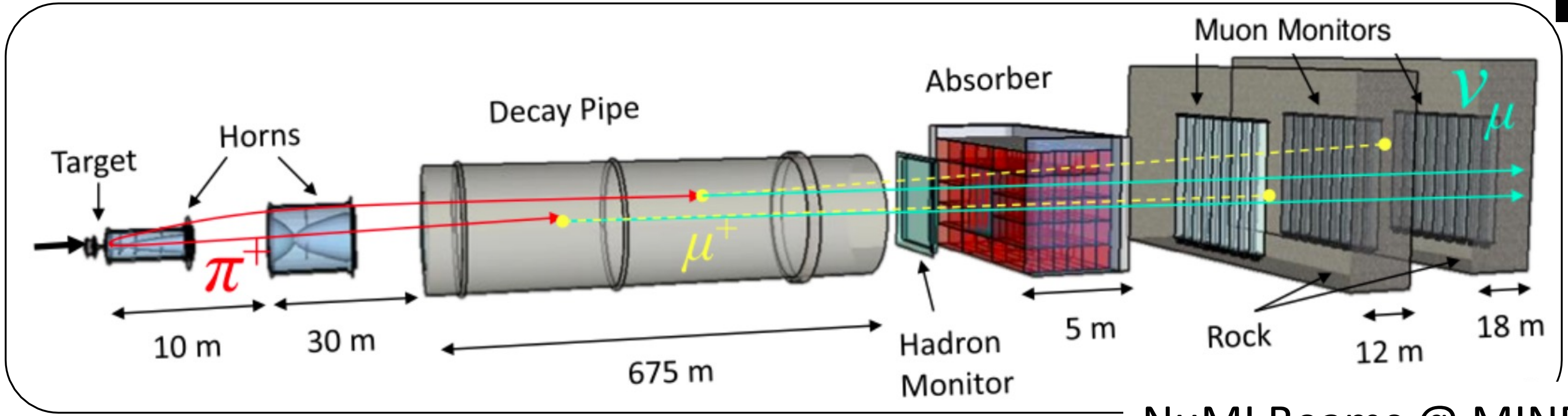
Phys.Rev.Lett. 129 (2022) 2, 021803

- 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 ΣT_p events predicted by the model as 2p2h and stopped pions are almost completely absent in the data.
- Highest p_T low ΣT_p events, events where the leading proton's energy ends up as neutrons through final state interactions, are also very overpredicted.

MINERvA, Repurposed for Neutrino-Nucleon Scattering

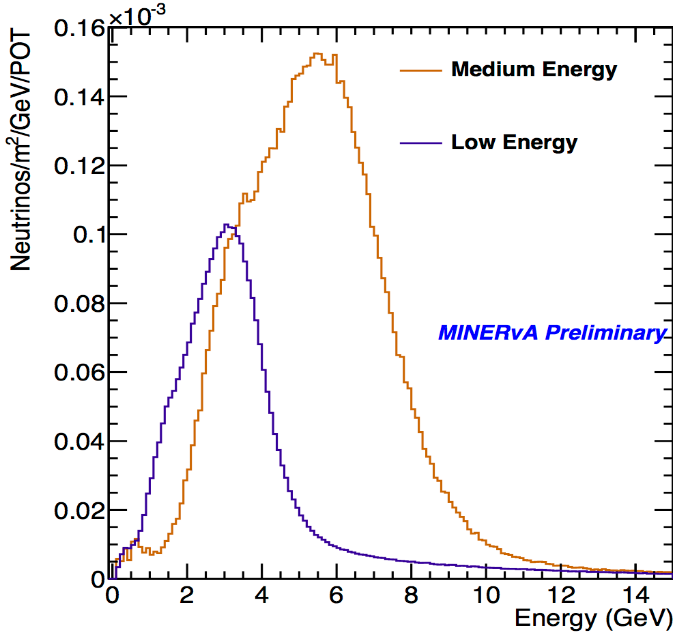
- We’ve demonstrated that MINERvA probes physics of scattering on nuclei.
- How does MINERvA then extract a sample of $\bar{\nu}_\mu p \rightarrow \mu^+ n$ from scattering on free protons?
- The technique is:
  1. Measure $\mu^+ + n$ final state on CH target.
  2. Kinematically separate elastic on H from quasielastic on C and subtract it.
  3. Use the same approach with the $\mu^- + p$ from the neutrino beam as a control sample to validate the technique.
  4. Correct efficiency for detecting neutrons in MINERvA using external n+CH scattering data.
- And from this cross-section, we extract the nucleon elastic form factor.

The NuMI Beam

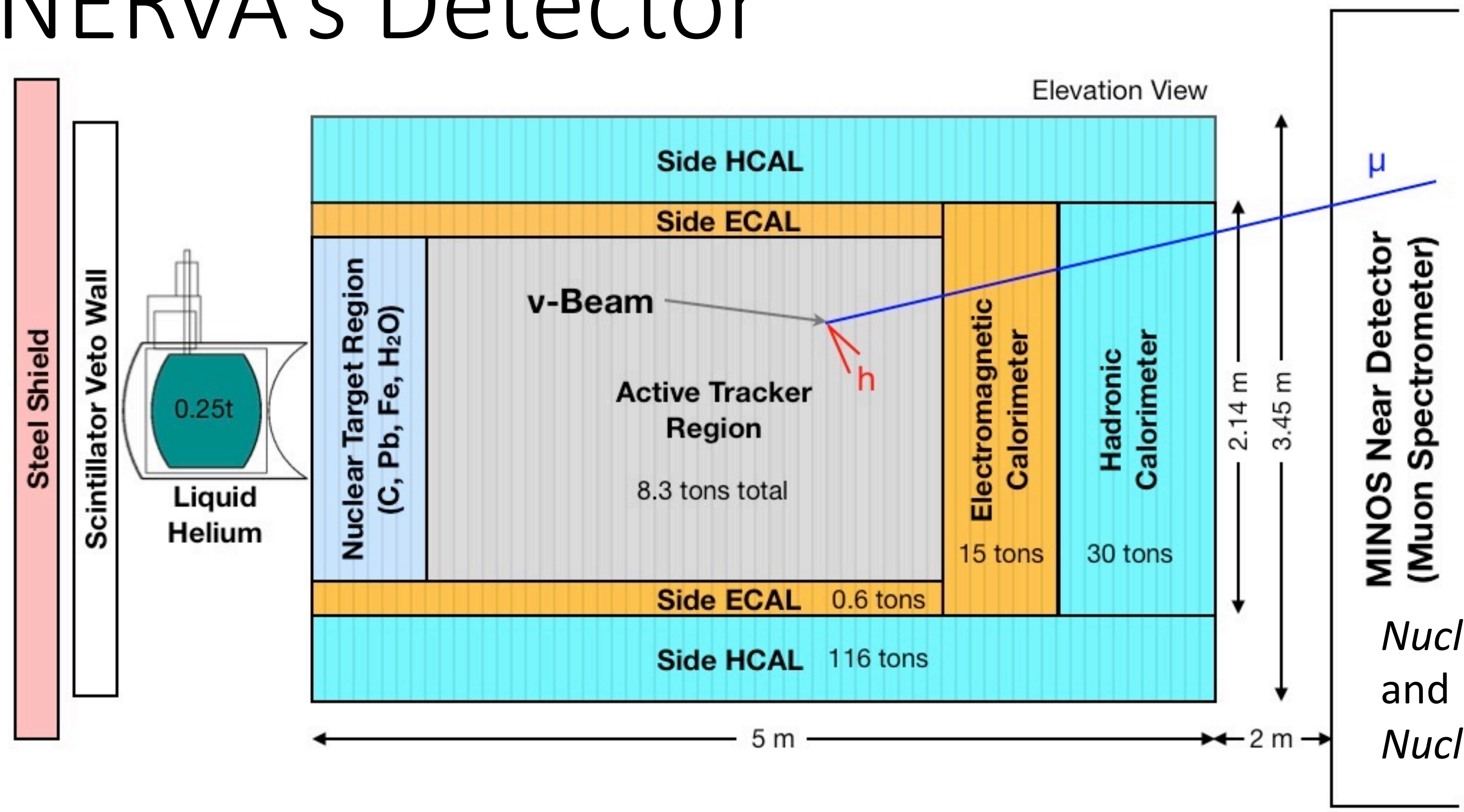


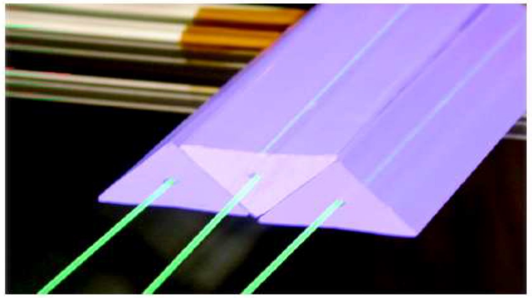
- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions.
- Implies significant uncertainties in flux from hadron production and focusing.
- Constrain, where possible, with hadron production data and in situ neutrino data ($\nu e \rightarrow \nu e$).

NuMI Beams @ MINERvA



MINERvA’s Detector



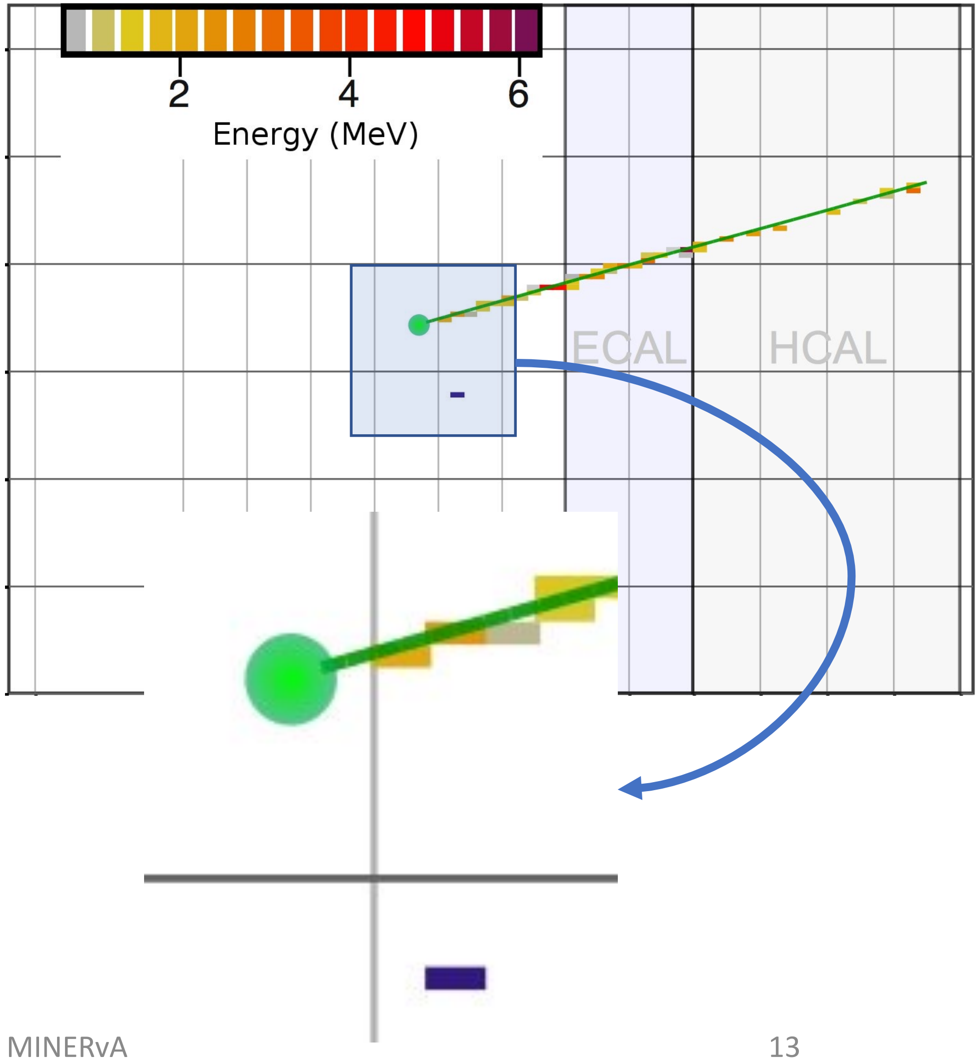


Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

- 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 has been recycled for DUNE tests.

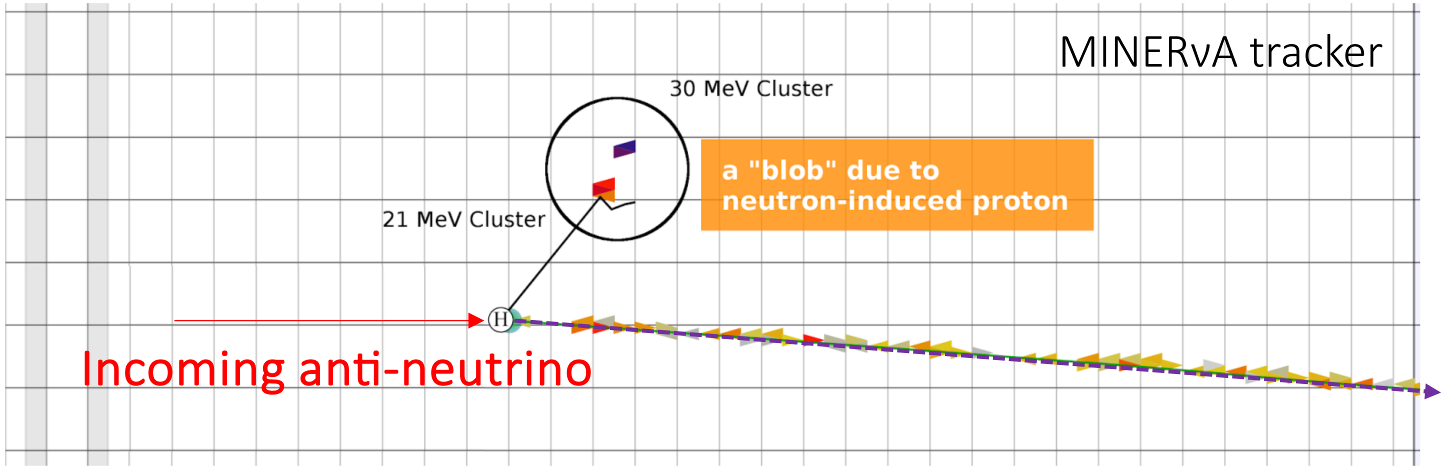
Detecting Charged Current Elastic Scattering in MINERvA

- Final state of $\bar{\nu}_\mu p \rightarrow \mu^+ n$ in MINERvA is an energetic μ^+ and a (usually) much lower energy n.
- Neutrons in MINERvA are observed primarily by detecting the proton from $^{12}C(n,np)^{11}B$ 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.



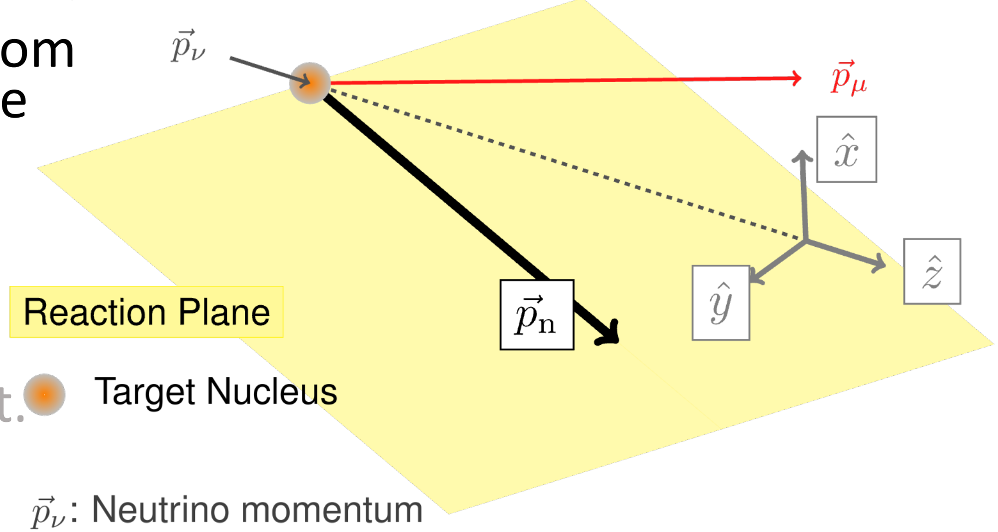
Selection of CCE Events

- No visible hadronic tracks from charged pions or protons.
- Proton recoil from neutron must be 10 cm away from the muon axis, to remove δ-ray background.
- Muon reconstructable in the detector: E_{μ} [1.5; 20] GeV, $\theta_{\mu\nu} < 20°$

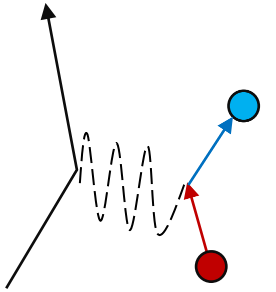


Signal and Background Separation

- 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 ${}^{12}C\left(\bar{\nu}_\mu, \mu^+ n\right){}^{11}B$.
  - 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.

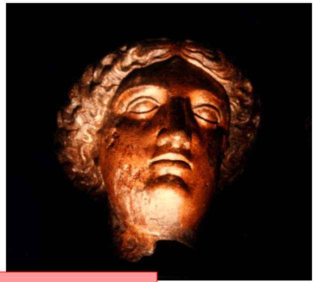


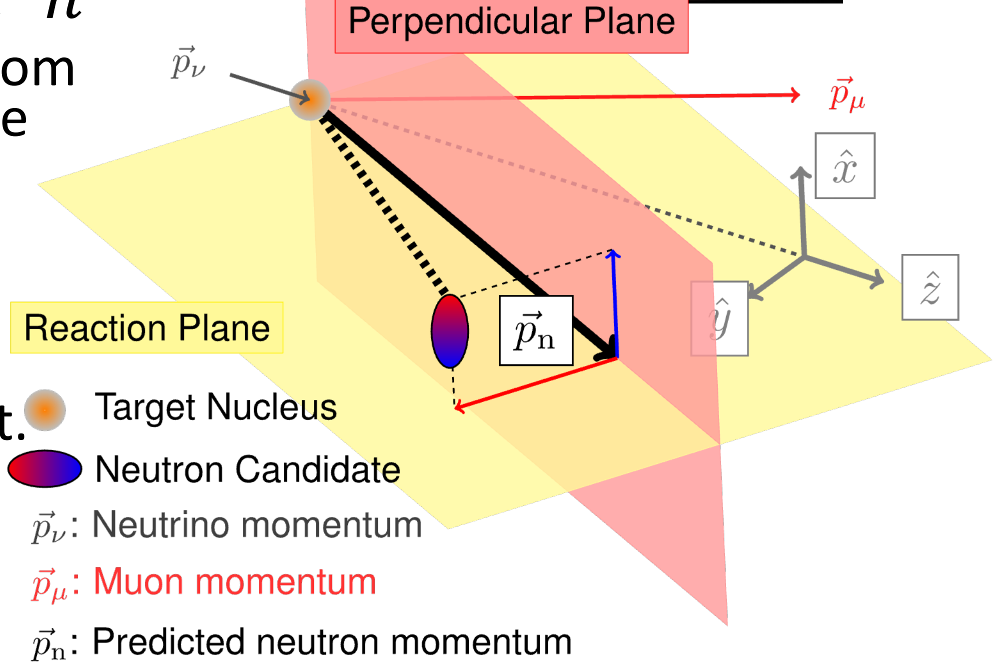
$\vec{p}_\nu$: Neutrino momentum
$\vec{p}_\mu$: Muon momentum
$\vec{p}_\mathrm{n}$: Predicted neutron momentum



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 ${}^{12}C\left(\bar{\nu}_\mu, \mu^+ n\right){}^{11}B$.
  - 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.





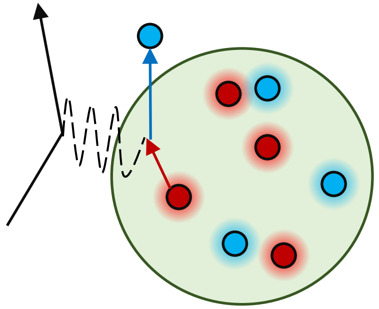
● Target Nucleus

⬮ Neutron Candidate

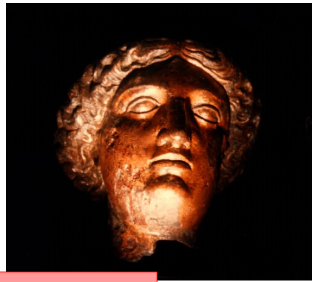
$\vec{p}_\nu$: Neutrino momentum

$\vec{p}_\mu$: Muon momentum

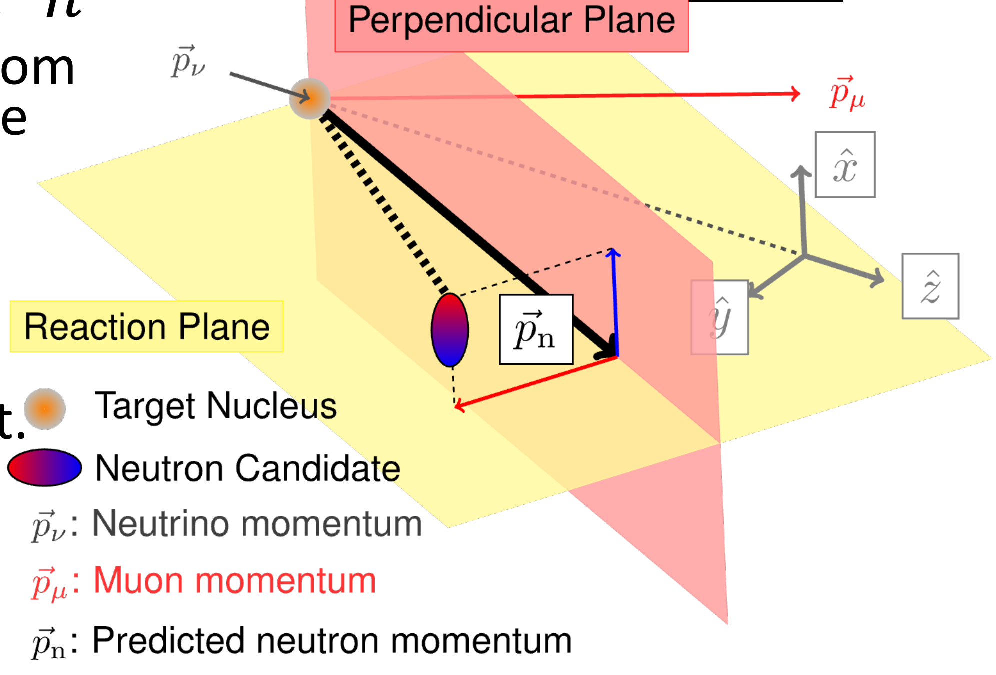
$\vec{p}_\mathrm{n}$: Predicted neutron momentum

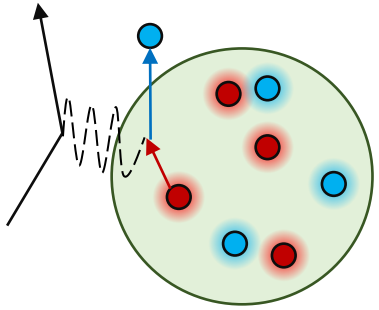


Signal and Background Separation



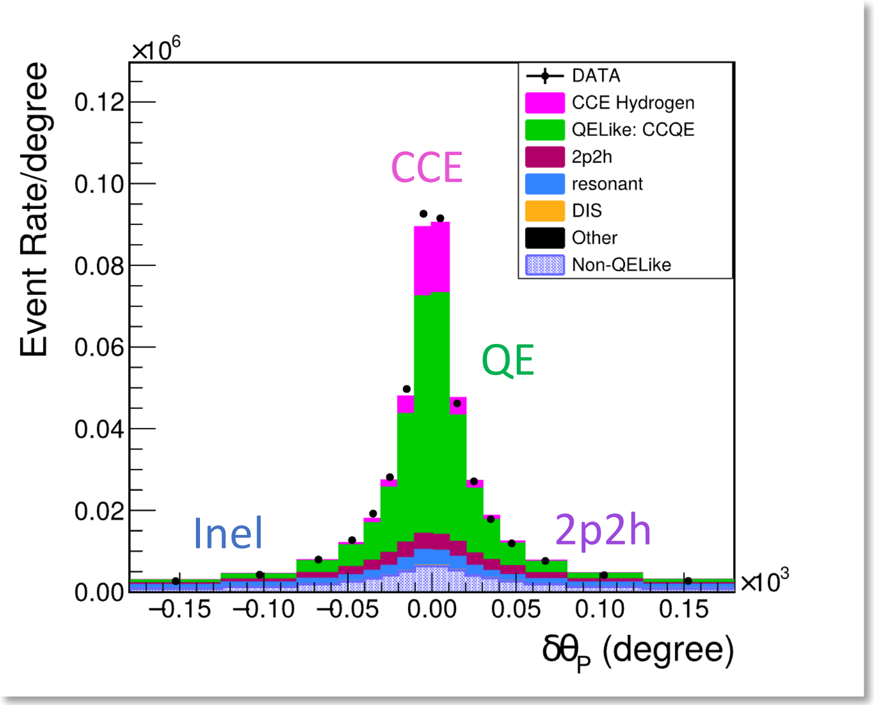
- Charged-current elastic on hydrogen: $\bar{\nu}_\mu p \rightarrow \mu^+ n$
  - The outgoing neutron direction is fully predicted from the muon measurement, even without knowing the incoming neutrino energy.
- Largest background is ${}^{12}C\left(\bar{\nu}_\mu, \mu^+ n\right){}^{11}B$.
  - The outgoing 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.

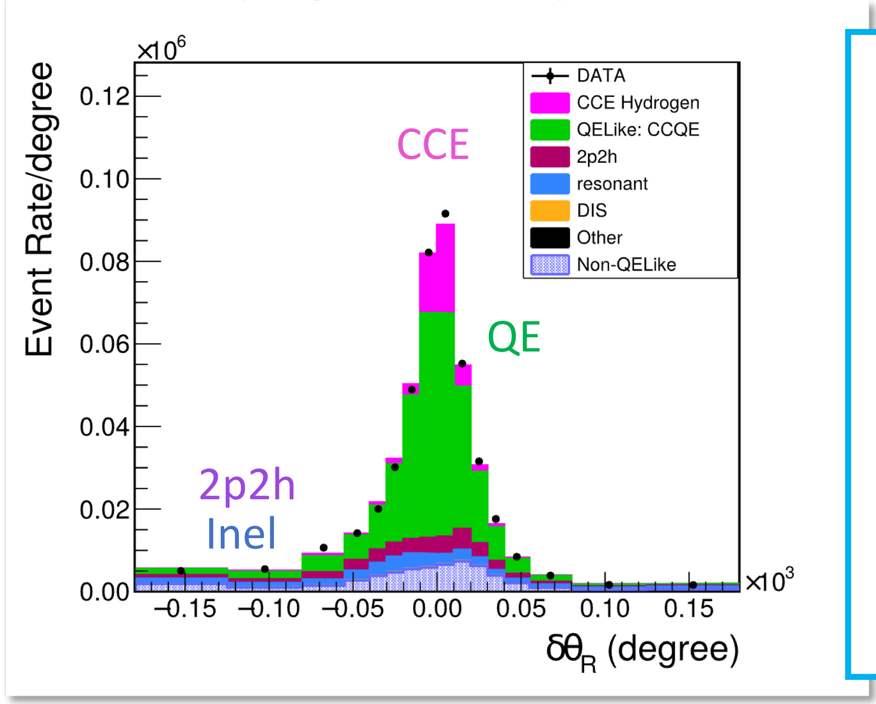


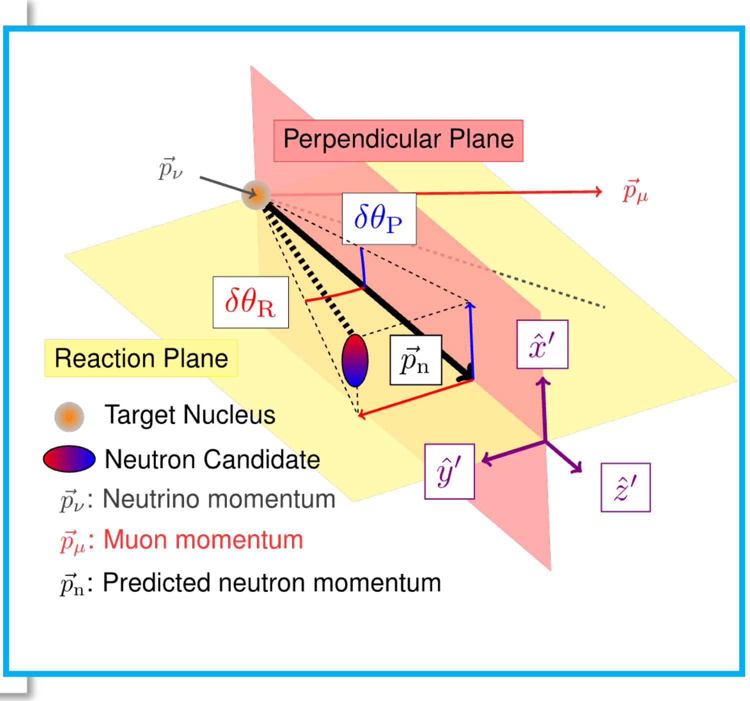


Signal & Background Separation (cont'd)

- 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.



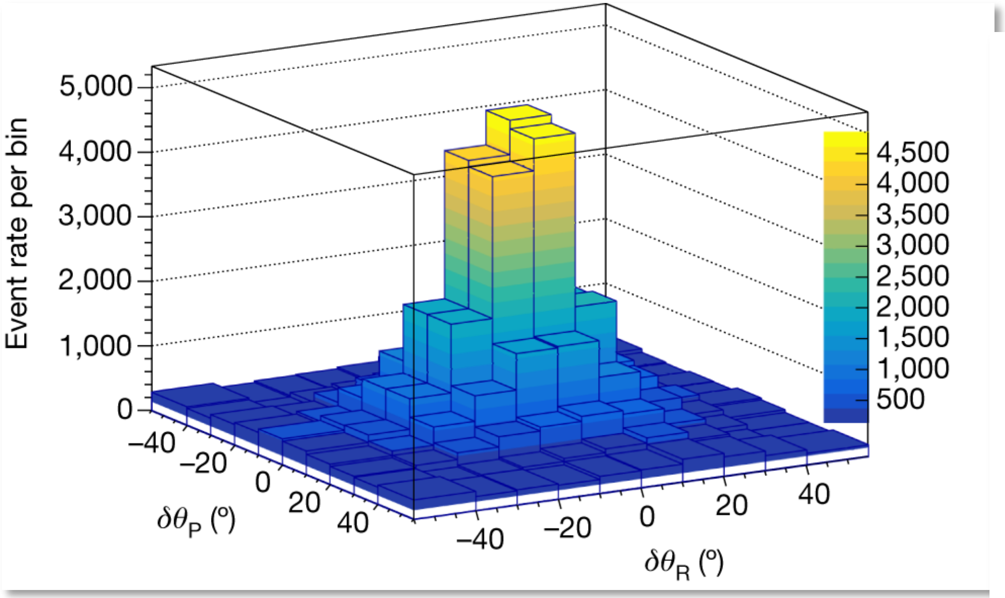




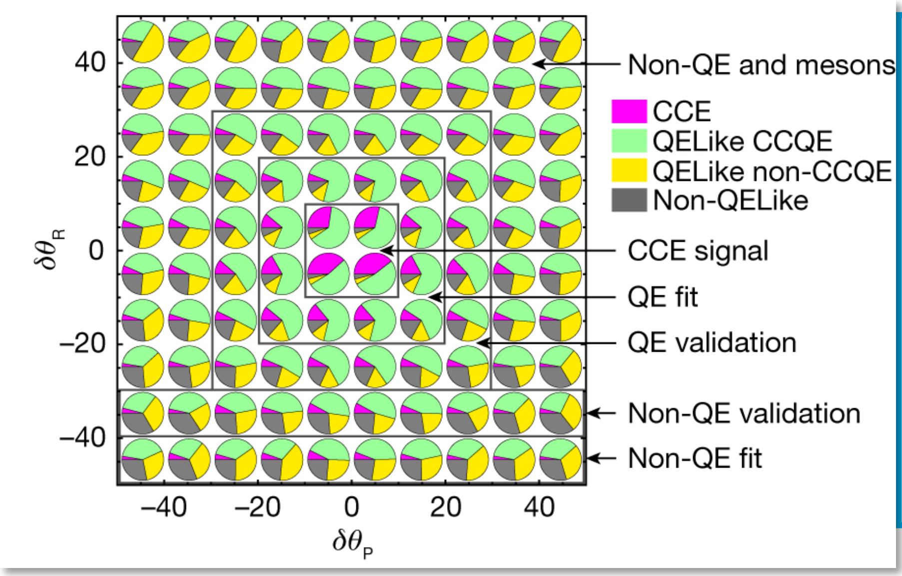
Signal & Background Separation (cont’d)

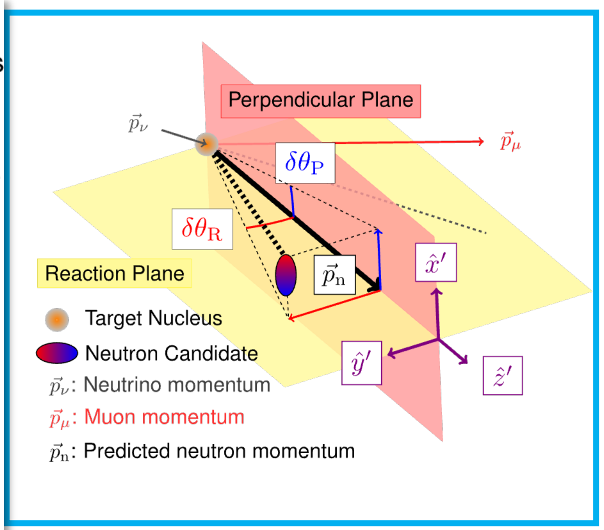
- Simultaneous consideration of both deflection angles helps.
- Note non-quasielastic event bias in reaction plane.
  - Allows separation of quasielastic (~symmetric) and non-QE backgrounds.
- Fit different background rates, as a function of Q^2 from 2D regions.

“2D” Total event rate

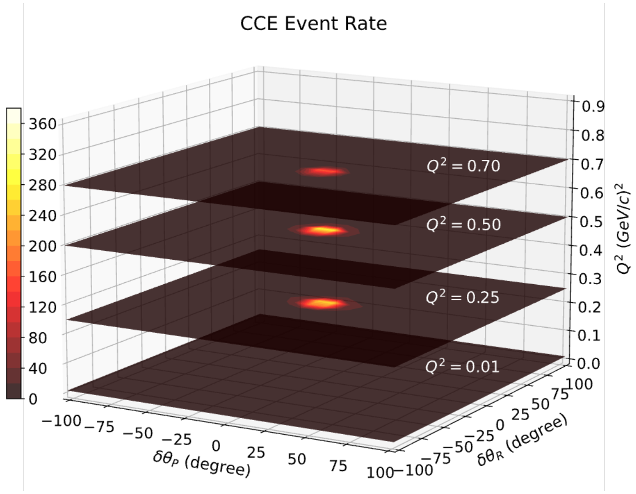


Fractions of rate predicted by model/simulation

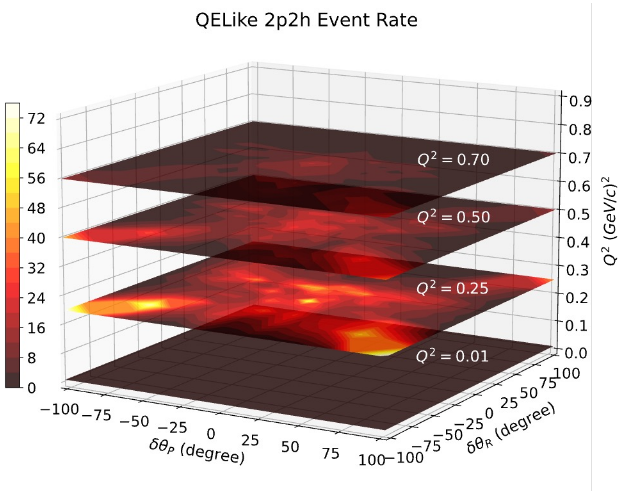




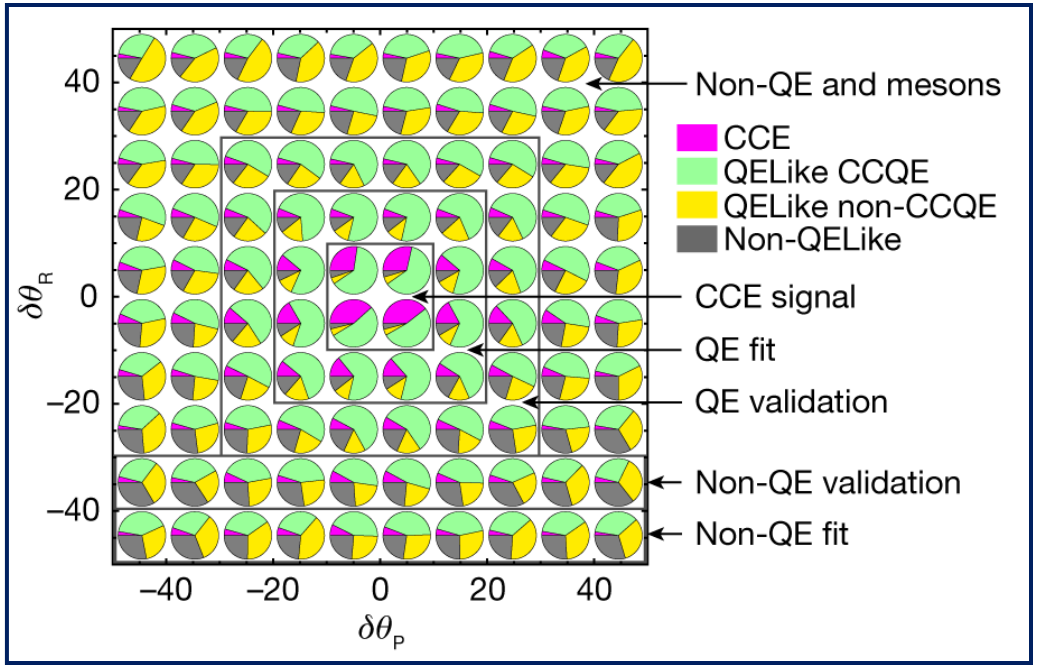
Signal & Background Separation (cont'd)

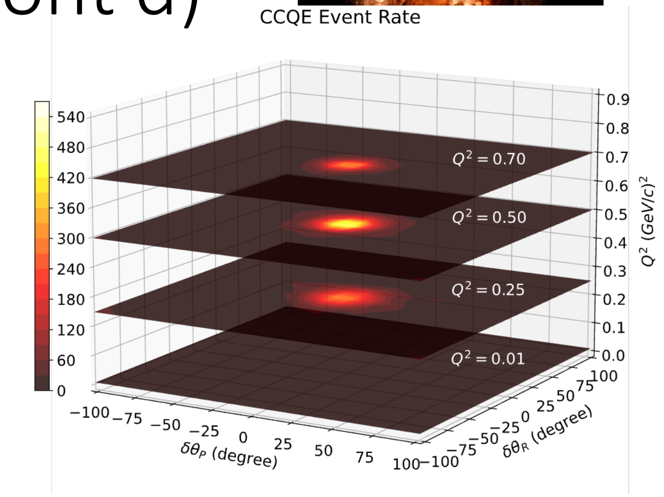


SIGNAL: Elastic on H

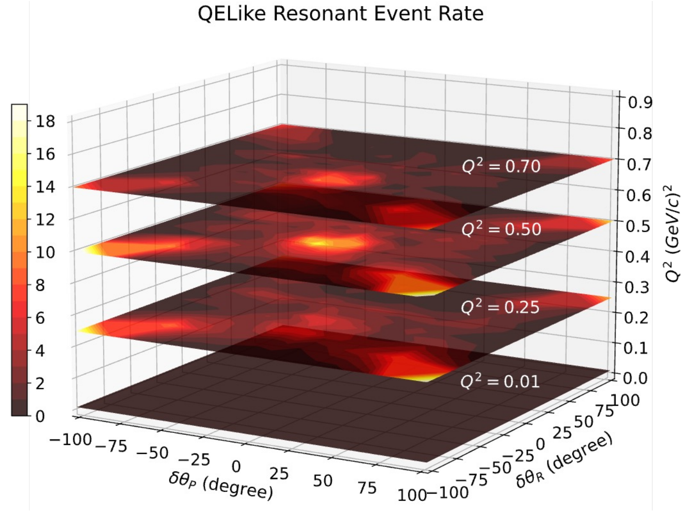


Background: QELike 2p2h





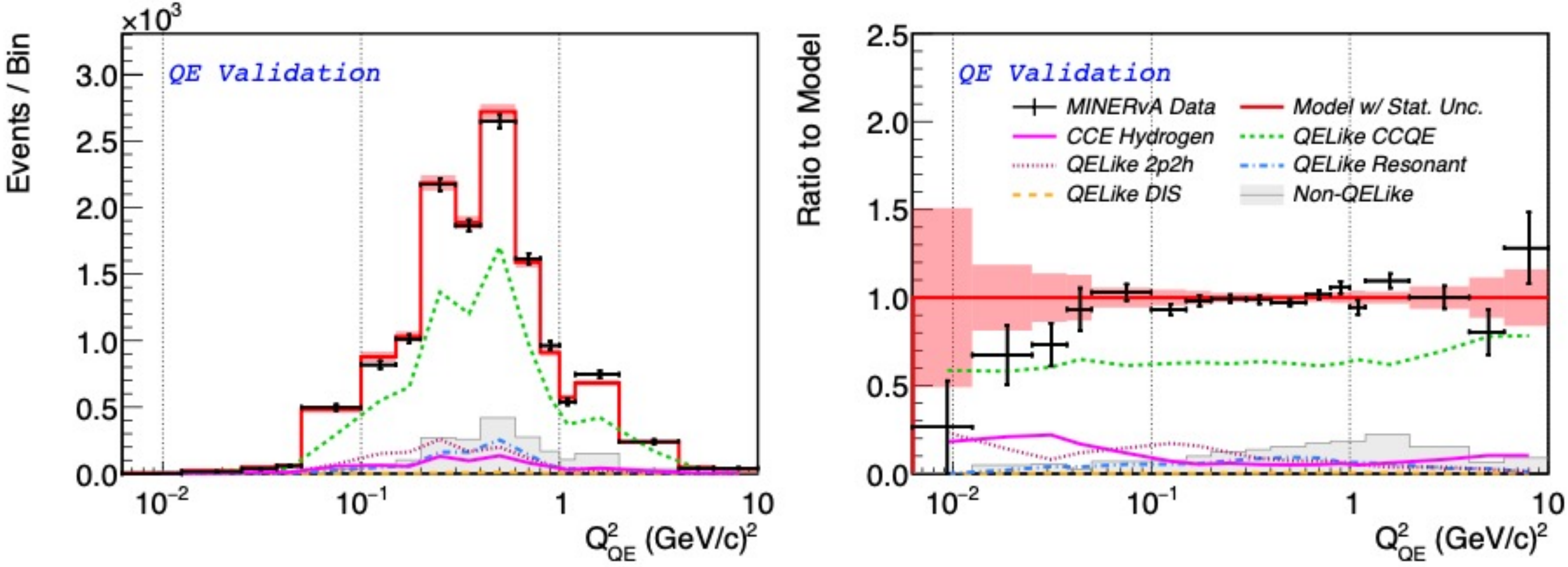
Background: QELike CCQE (on C)



Background: QELike Resonant

The 2D angular distribution is divided up into different **regions** which are **used to extrapolate the background** events predicted **in the signal region**.

Results of Background Sideband Fits in QE "Validation" Region

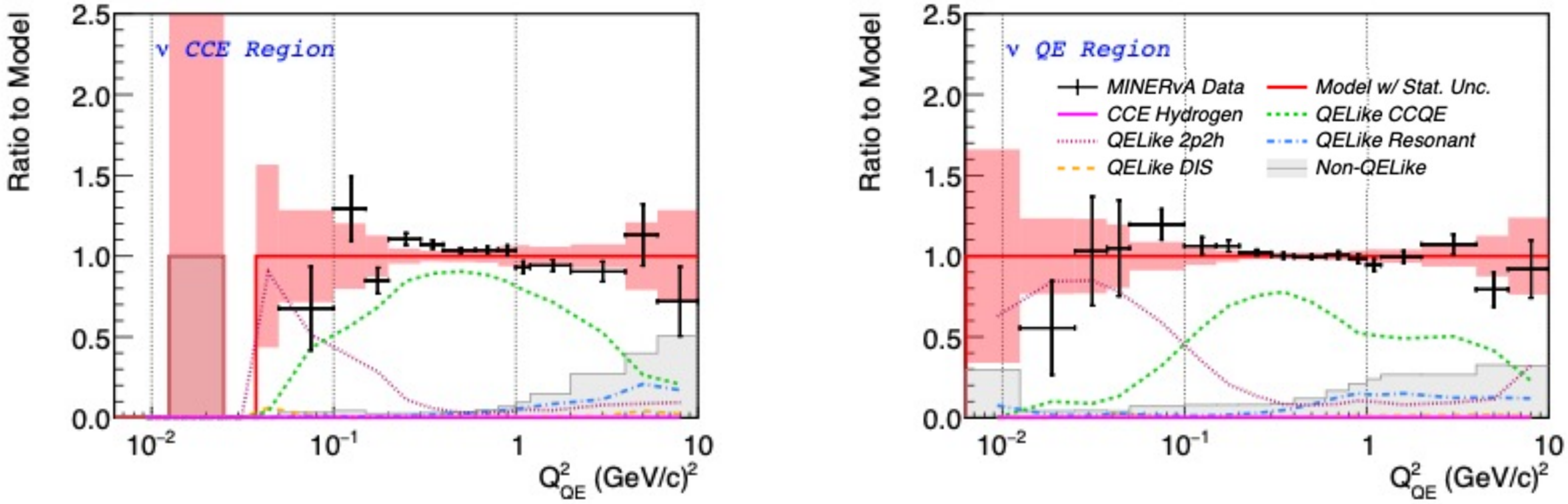


CCQE is dominant in this region. Small 2p2h, inelastic QE-like, and Non-QELike contributions. The fitted model, constrained by data, fits this region well.

Same Technique, applied to Control Sample of Neutrino Beam

Analog of signal region, but without free protons

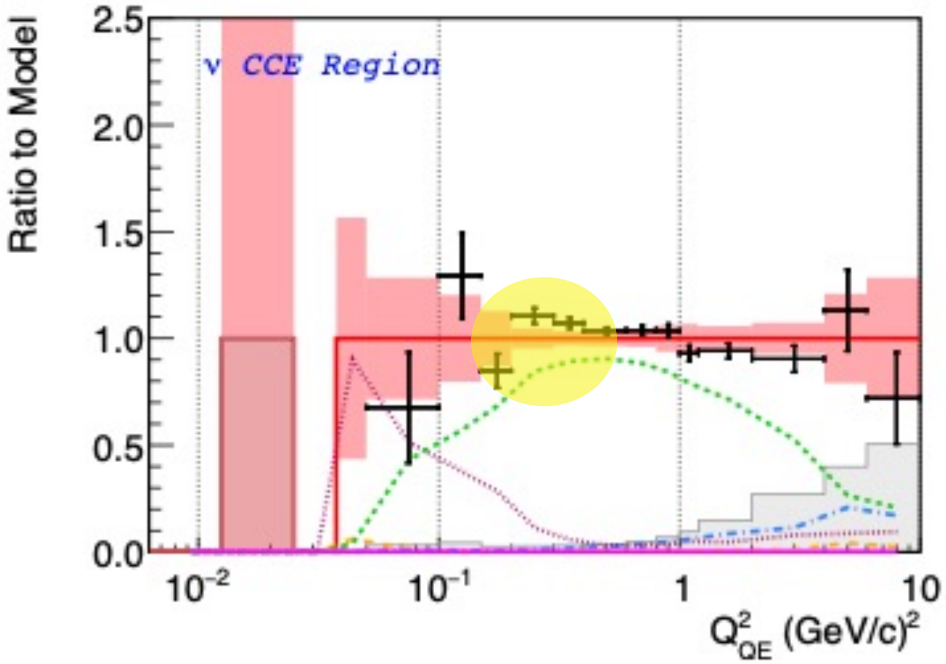
Quasielastic region



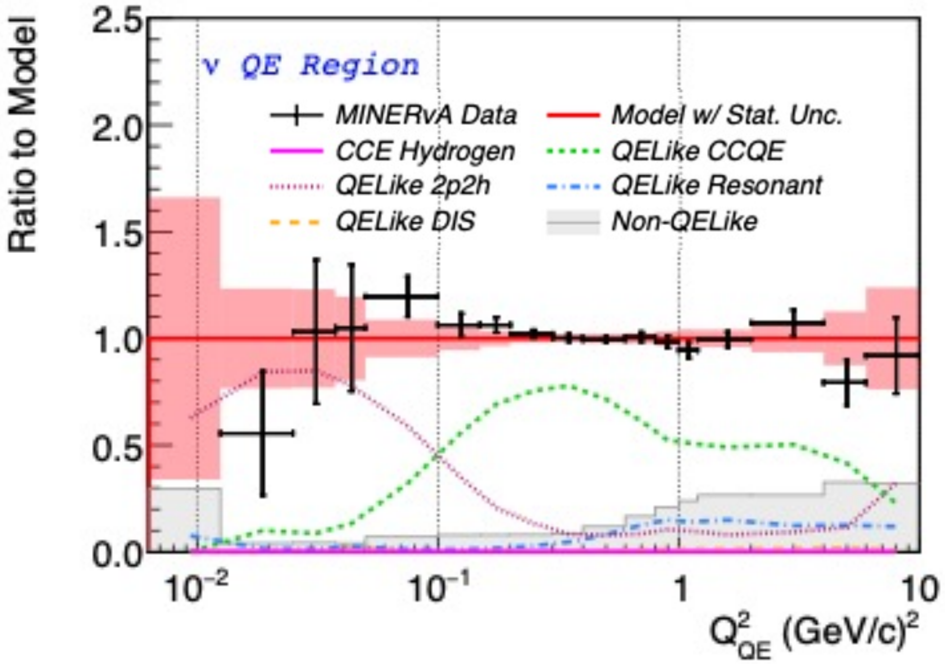
We select events with trackable protons in a neutrino sample. No CCE signal. Different final states and available kinematics. Apply same fitting mechanism.

Same Technique, applied to Control Sample of Neutrino Beam

Analog of signal region, but without free protons



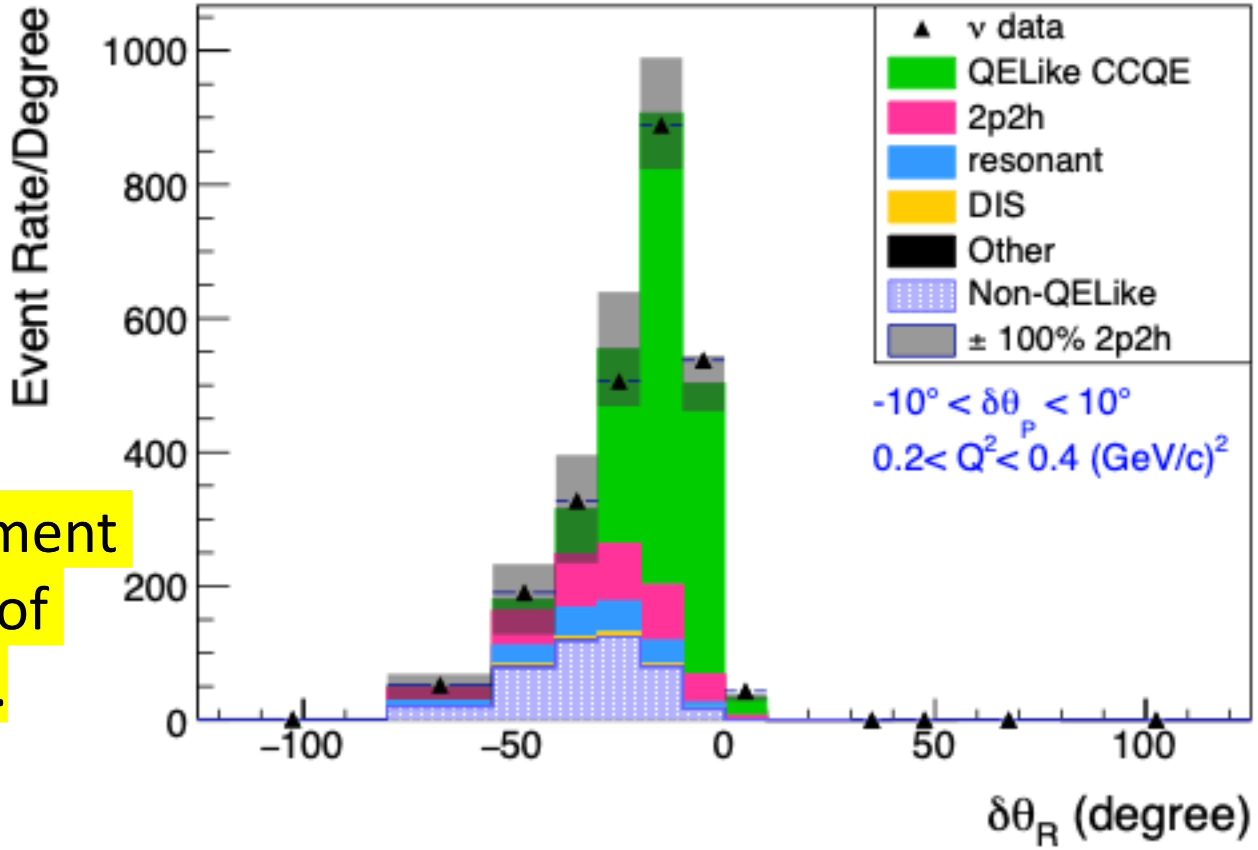
Quasielastic region



We select events with trackable protons in a neutrino sample. No CCE signal. Different final states and available kinematics. Apply same fitting mechanism.

Data and MC mostly agree within uncertainty. Small low Q^2 disagreement is consistent with 2p2h uncertainty that is more important in neutrino sample.

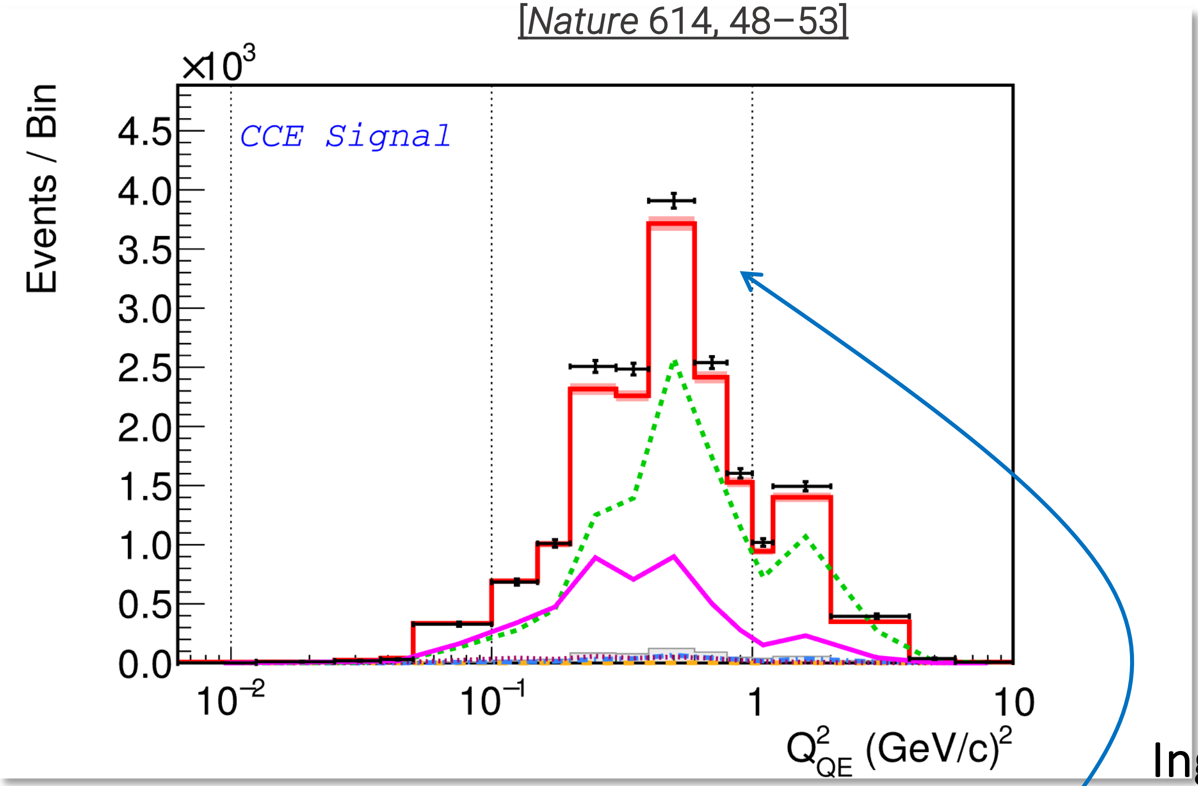
Control Sample, Neutrino Beam (cont'd)



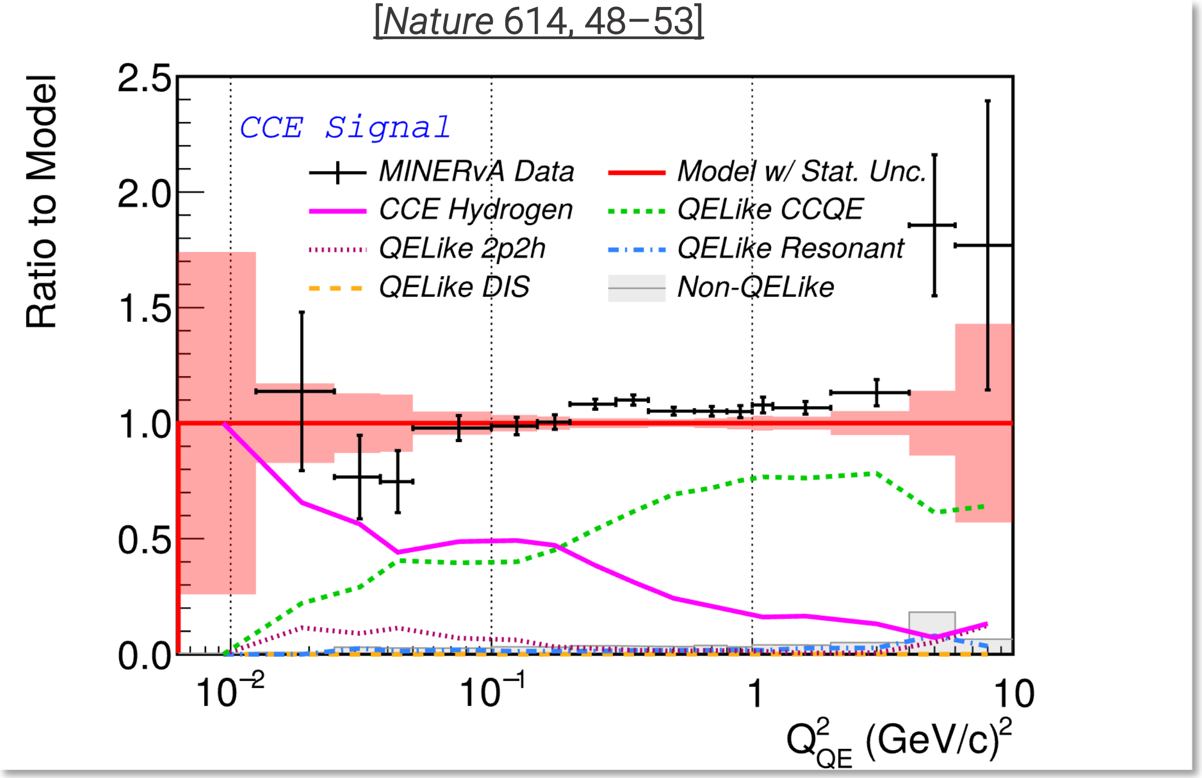
The low Q^2 disagreement shown as a function of reaction plane angle.

Our systematic uncertainties for the CCE (anti-neutrino beam) due to interaction model in the background subtraction are larger than a 100% 2p2h uncertainty would be. The gray band here shows the size of an equivalent uncertainty in 2p2h in the control sample.

Cross-section Extraction



[Nature 614, 48–53]



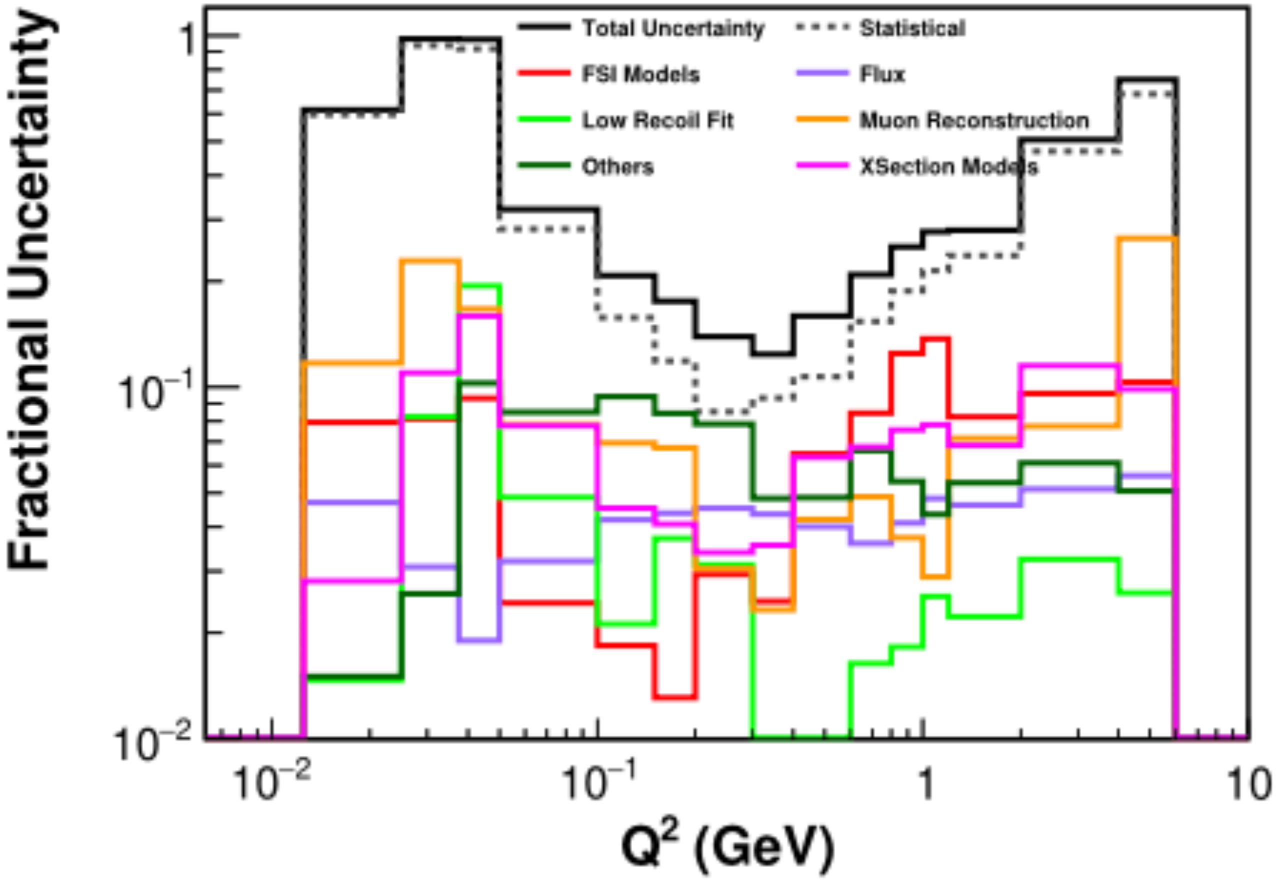
[Nature 614, 48–53]

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

Ingredients:

- Unfolding matrix and efficiency from Simulation (tuned on data, of course)
- 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

Uncertainties in the Cross-Sections



Dominated by statistical uncertainty.

Model systematic uncertainties from residuals of constrained background subtraction.

Neutron interaction uncertainties dominate the "other" category.

Muon reconstruction (Q^2 measurement) is also noticeable.

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. Therefore, Bin-by-bin axial form factor cannot be extracted
- Fit $F_A(Q^2)$ to 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).
- Use BBBA05 form factors by default.

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

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

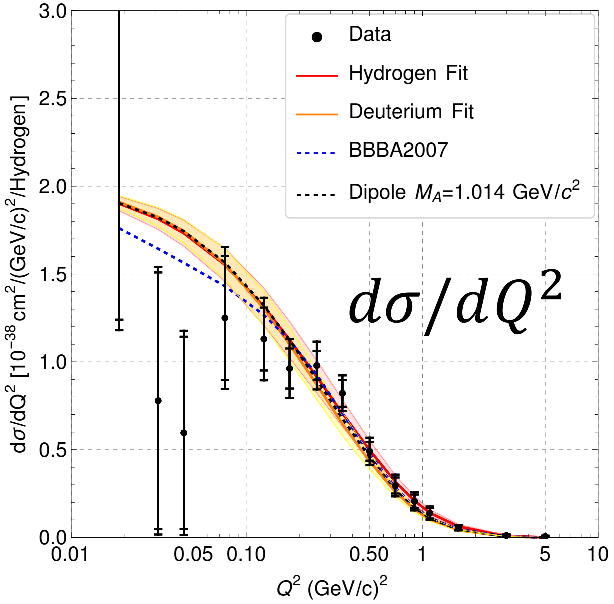
$$\sum_{k=n}^{\infty} k(k-1)\ldots(k-n+1)a_k = 0, n \in (0,1,2,3)$$

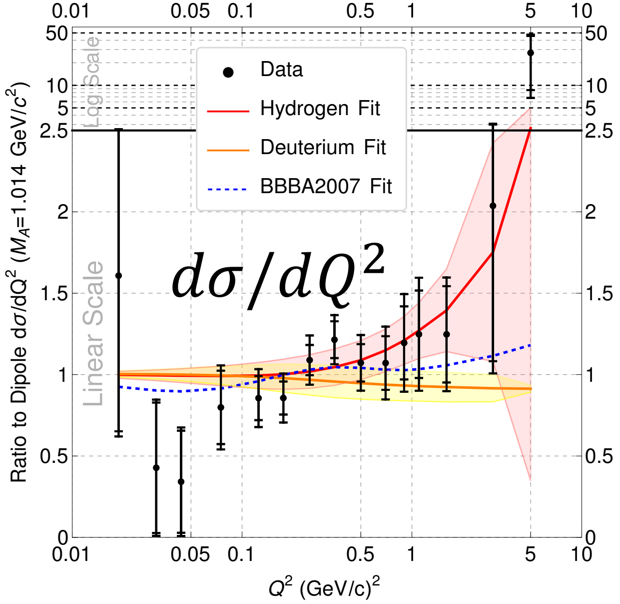
$$\chi^2 = \Delta X \cdot \mathrm{cov}^{-1} \cdot \Delta X + \lambda\left[\sum_{k=1}^{5}\left(\frac{a_k}{5a_0}\right)^2 + \sum_{k=5}^{k_{\mathrm{max}}}\left(\frac{ka_k}{25a_0}\right)^2\right]$$

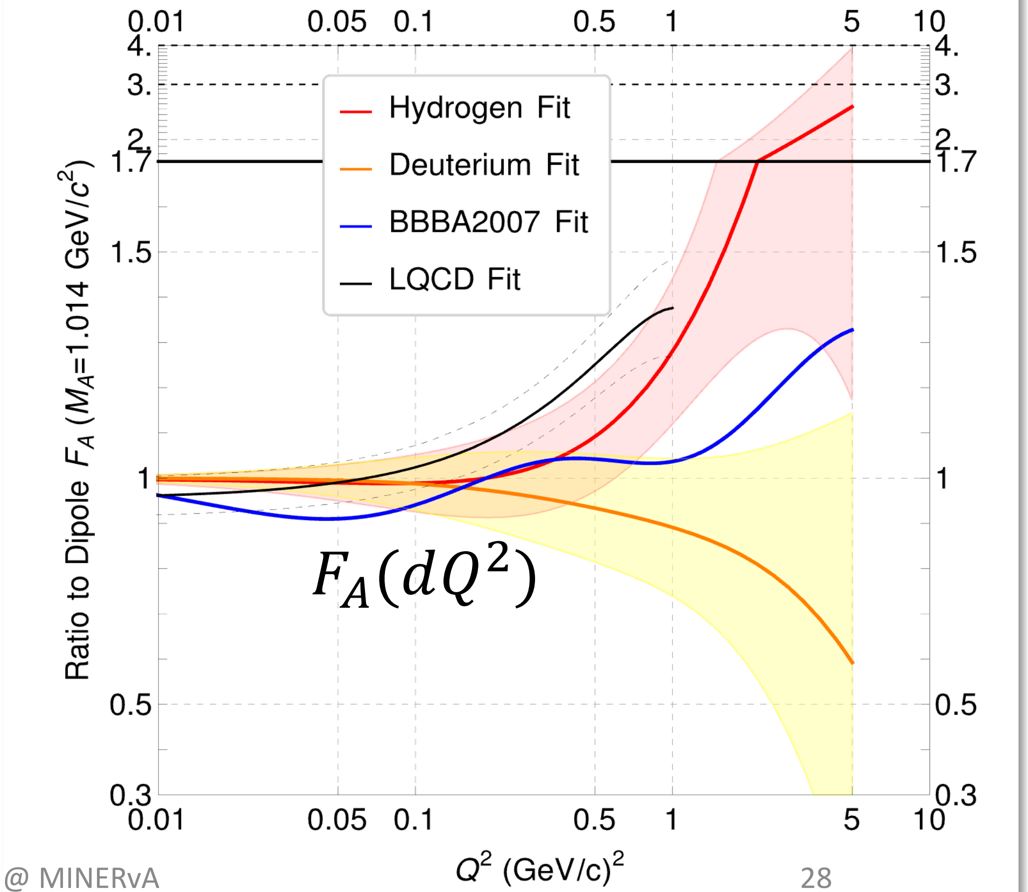
BBBA05 is R. Bradford et al., Nuclear Physics B, Proceedings Supplements 159 (2006) 127–132, doi:https://doi.org/10.1016/j.nuclphysbps.2006.08.028.

Free Nucleon Axial Form Factor

- We have ~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.

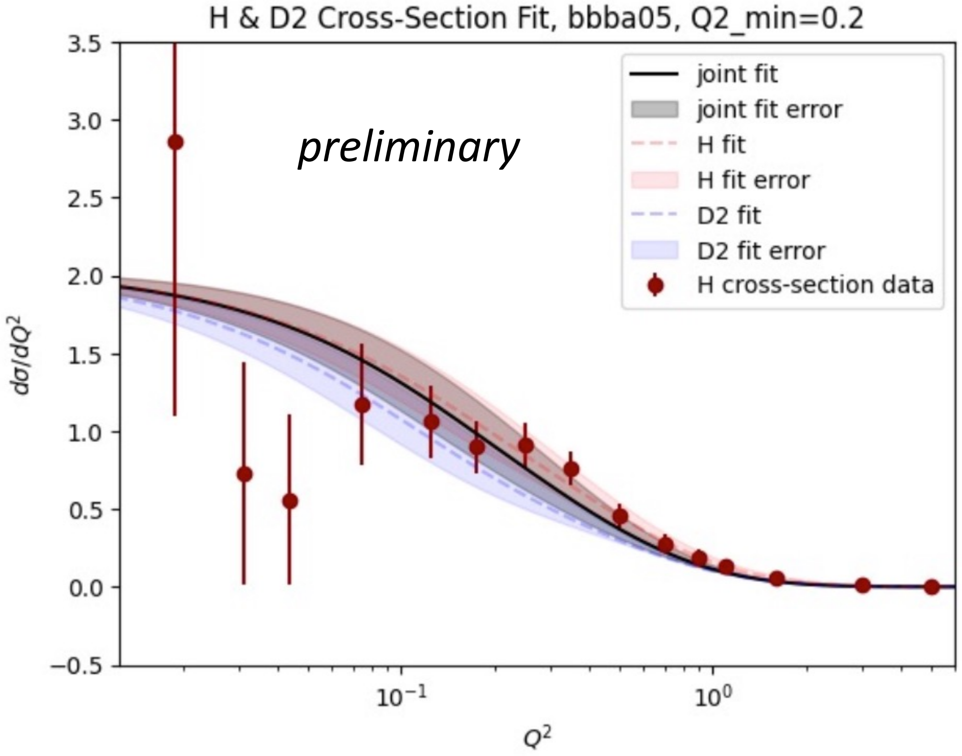






Compatible with D_2 Data? Mmmmmaybe?

- We have some progress on joint fits with neutrino-deuterium analysis (*Phys.Rev.D* 93 (2016) 11, 113015), including comprehensive analysis of compatibility.
  - Note that compatibility depends on the choice of vector form factors, since vector-axial vector interference flips sign.
  - We see that compatibility also depends strongly on how low in Q^2 we use the D_2 data, which might suggest low Q^2 nuclear effects?
- With BBBA05 vector form factors and $Q^2 > 0.2$ GeV^2, $\delta\chi^2 \sim 5.5$, or p-value of ~2%.

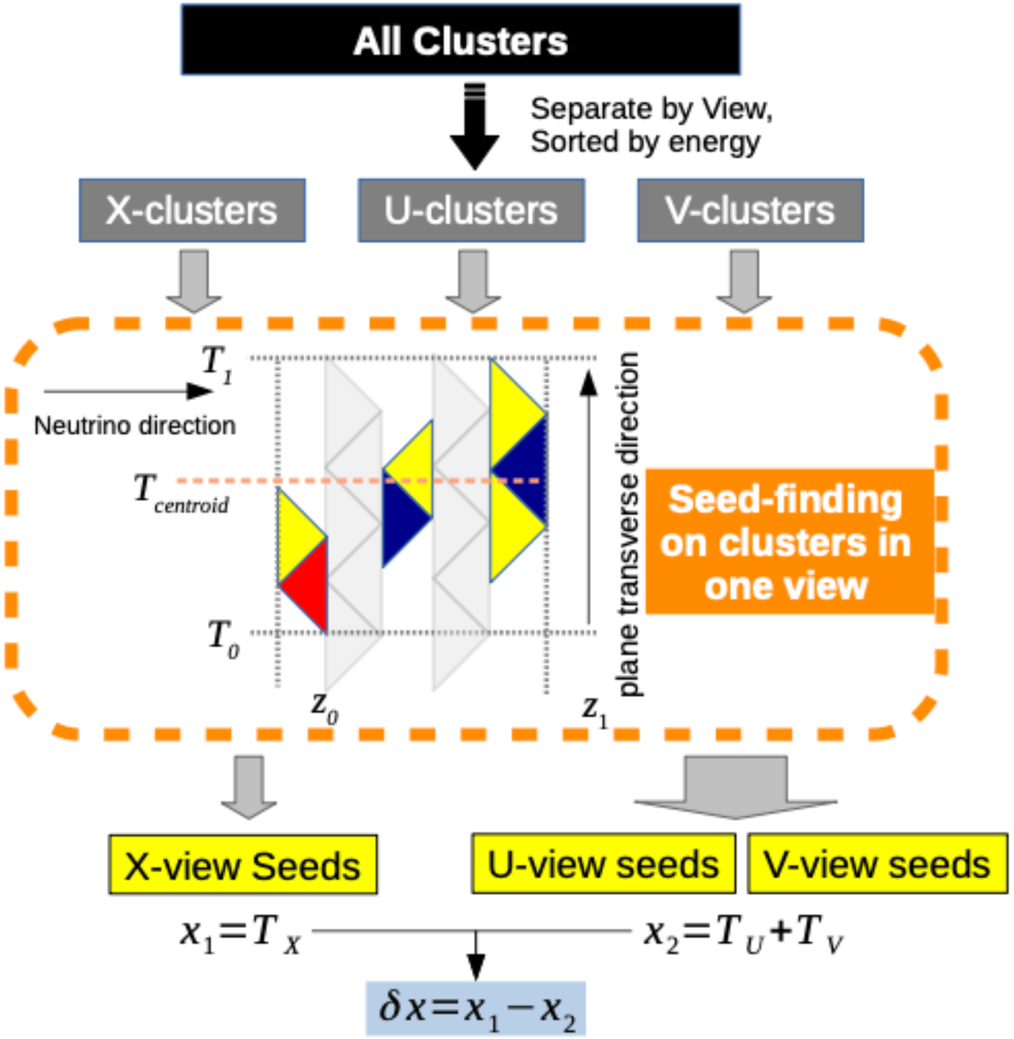


Conclusion and Outlook

- With this result, still some work to do (in progress).
  - Incorporate radiative corrections (O. Tomalak *et al.*, *Nature Commun.* 13 (2022) 1, 5286; *Phys.Rev.D* 106 (2022) 9, 093006).
  - Complete joint fits with neutrino-deuterium results, including more comprehensive analysis of compatibility.
- More neutrino measurements?
  - Not soon. But there is active planning 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”



All Clusters

Separate by View,
Sorted by energy

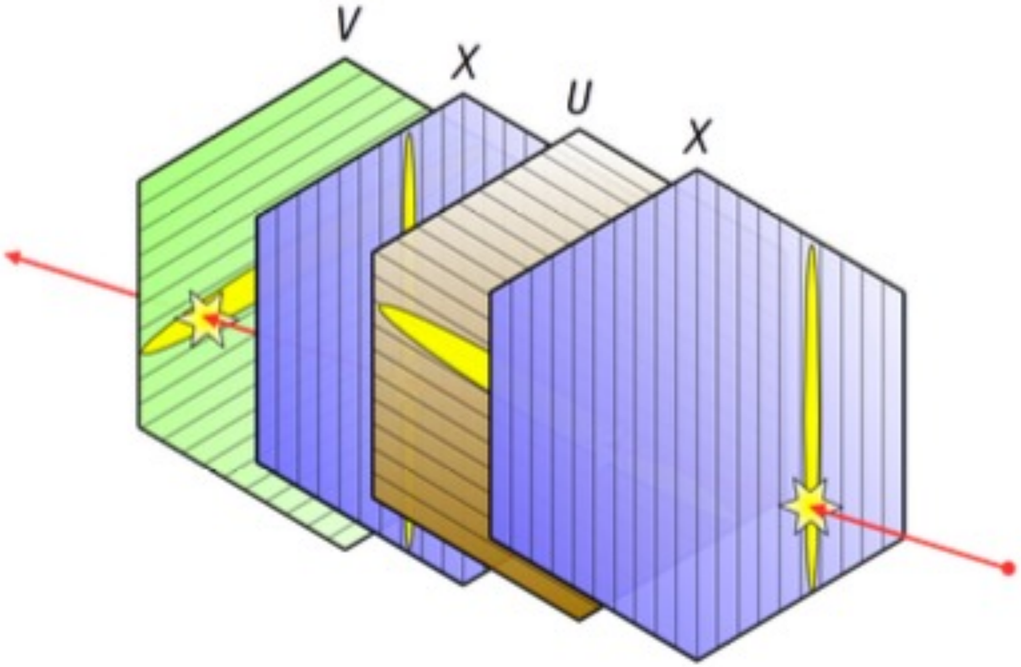
X-clusters **U-clusters** **V-clusters**

Seed-finding on clusters in one view

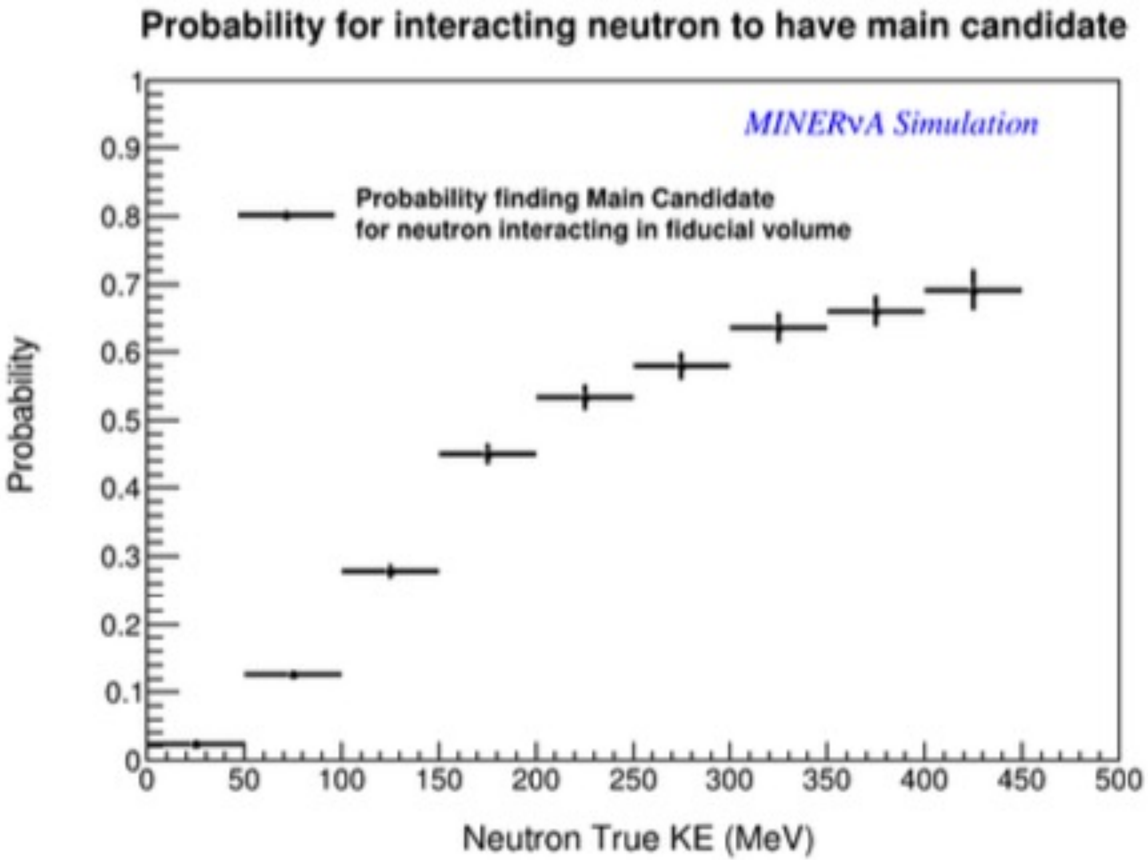
X-view Seeds **U-view seeds** **V-view seeds**

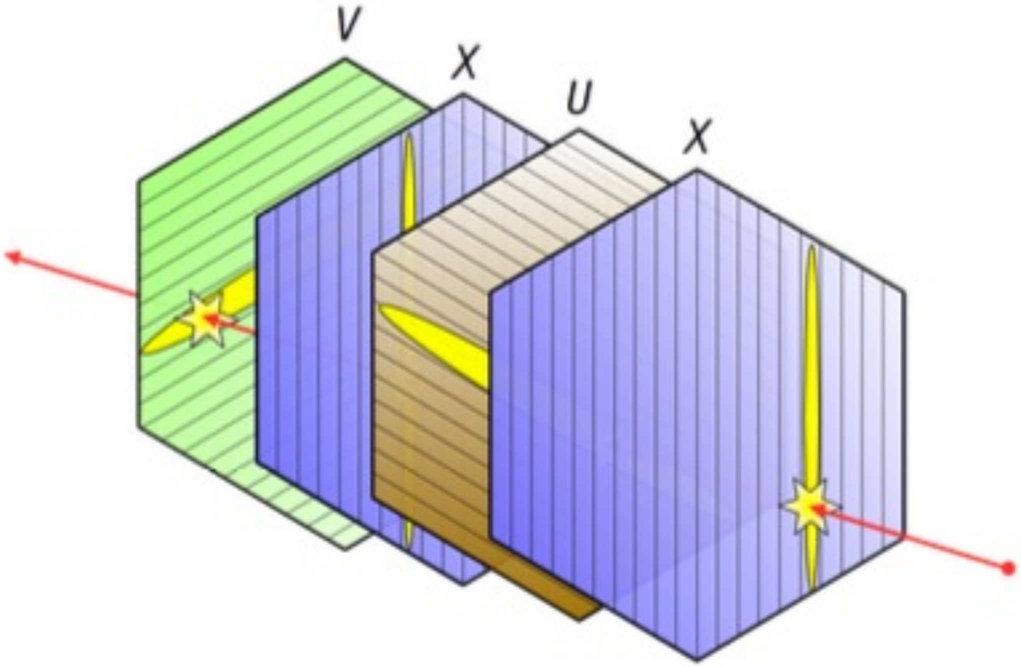
$x_1 = T_X$ $x_2 = T_U + T_V$

$\delta x = x_1 - x_2$



Neutron "3D Blobs"

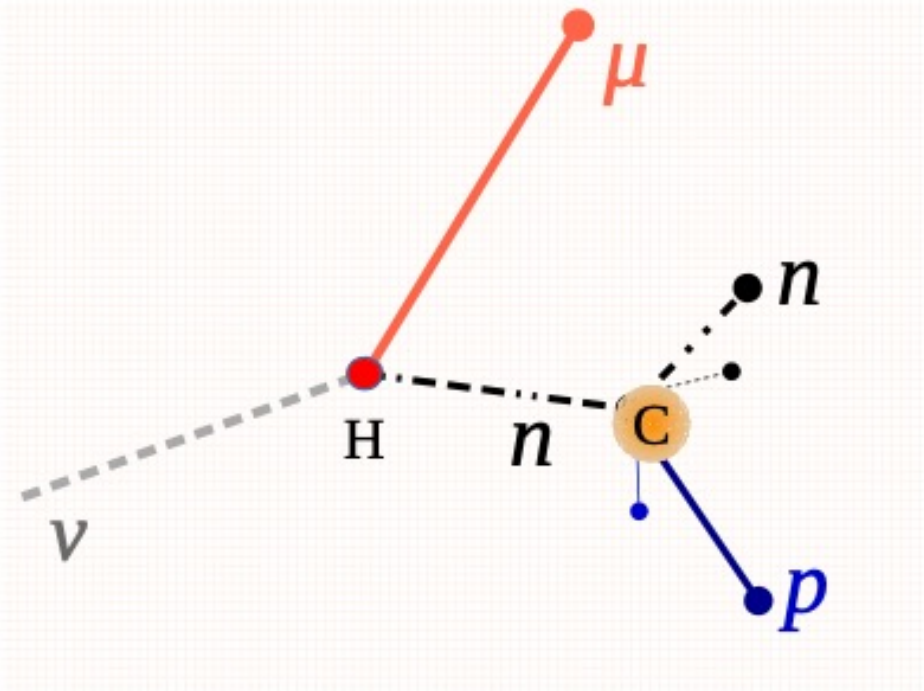


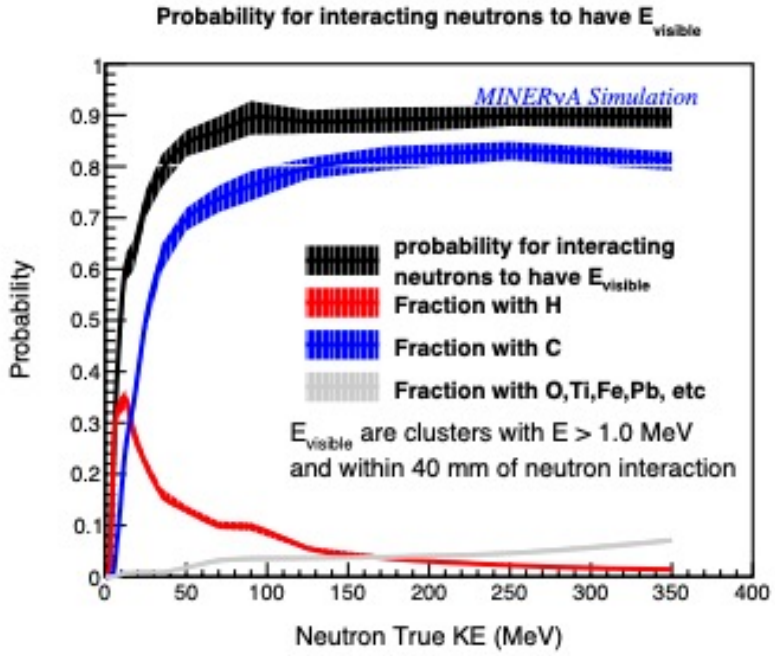


Backup: Neutron Interactions

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.
- $^{12}C(n,np)^{11}B$ is the dominant interaction channel
- We tune each channel to the MoNA cross-section based on secondary daughter particles.

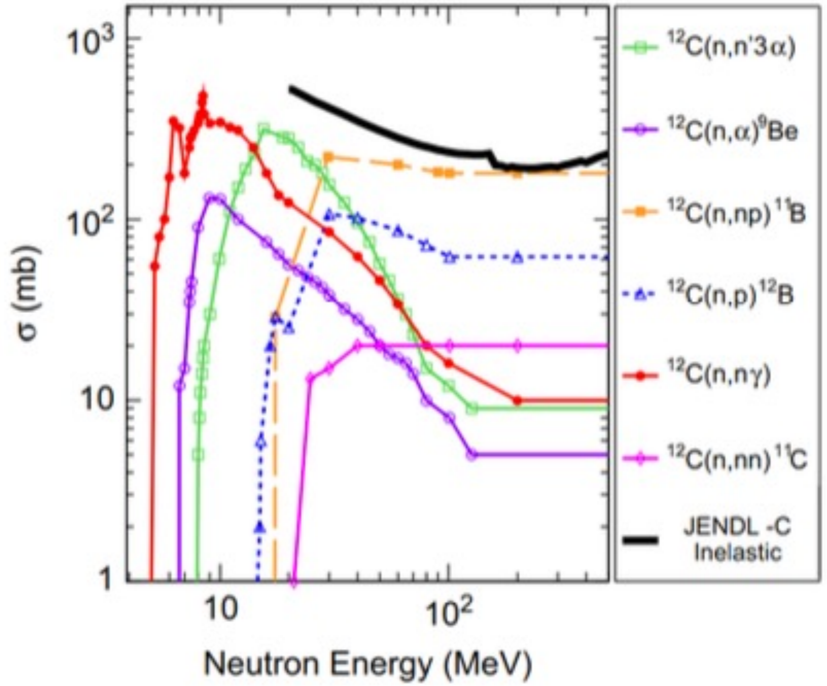
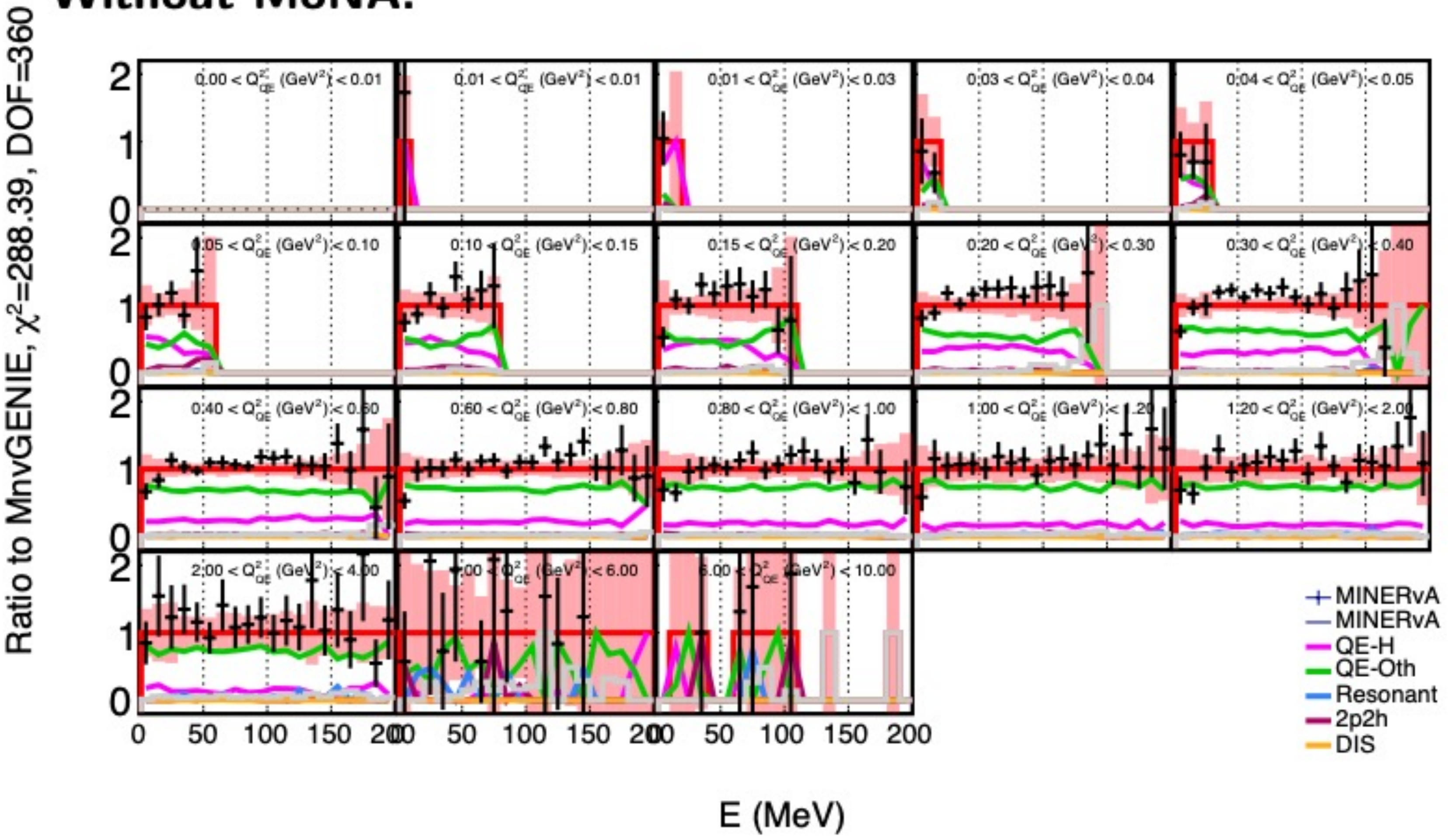


Fig. 3. Inelastic neutron–carbon reaction cross-sections are shown as a function of the incident neutron energy. MENATE_R uses the six different discrete reaction channel cross-sections while the G4-Physics uses the total inelastic reaction cross-sections taken from the JENDL-HE library [37].

“Nuisance” Distributions

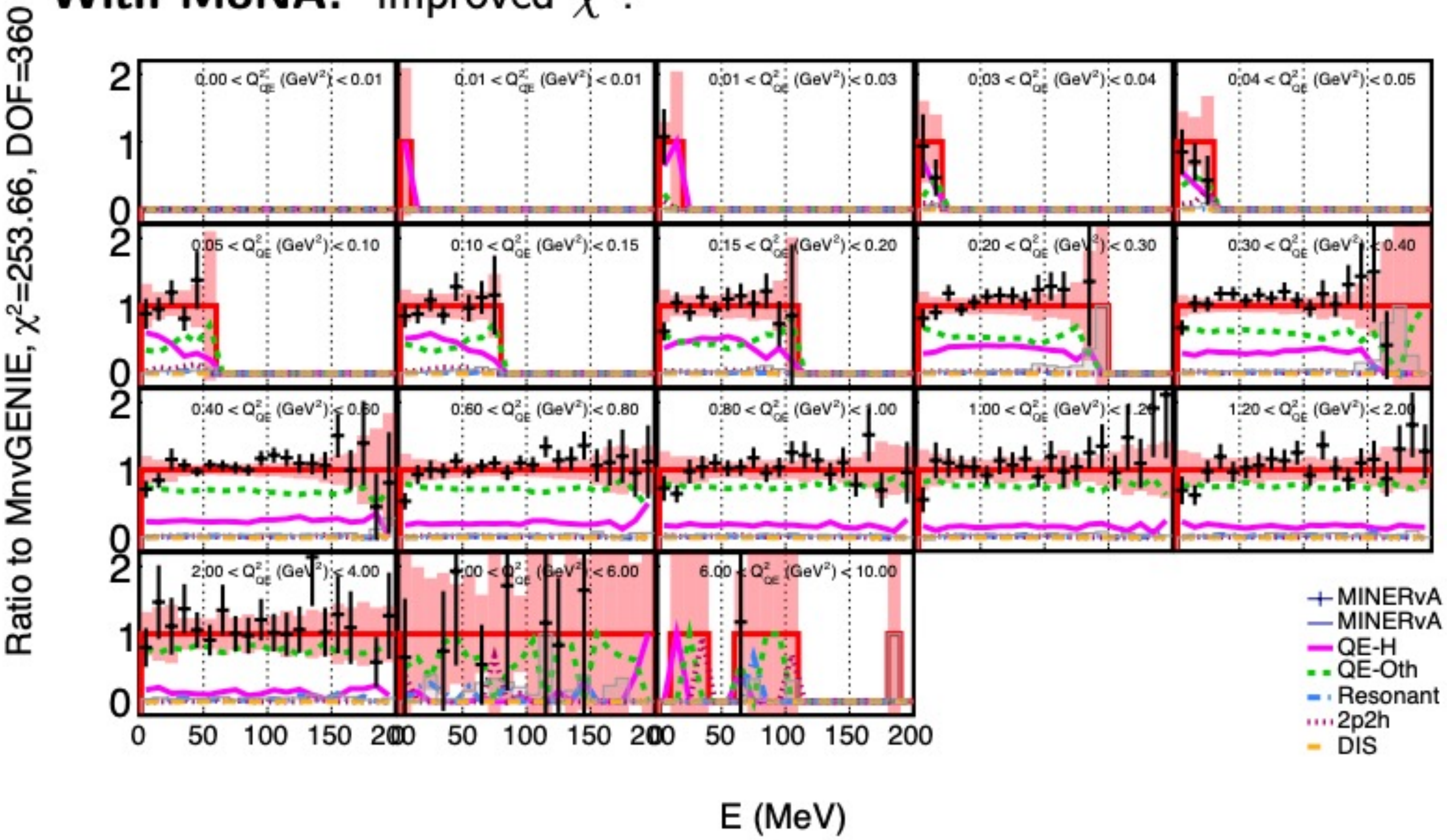
Neutron candidate energy distribution in reconstructed Q^2_{QE} bins. **Without MoNA.**



“Nuisance” Distributions

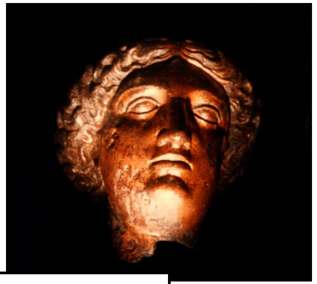
Neutron candidate energy distribution in reconstructed Q^2_{QE} bins.

With MoNA: improved χ^2.



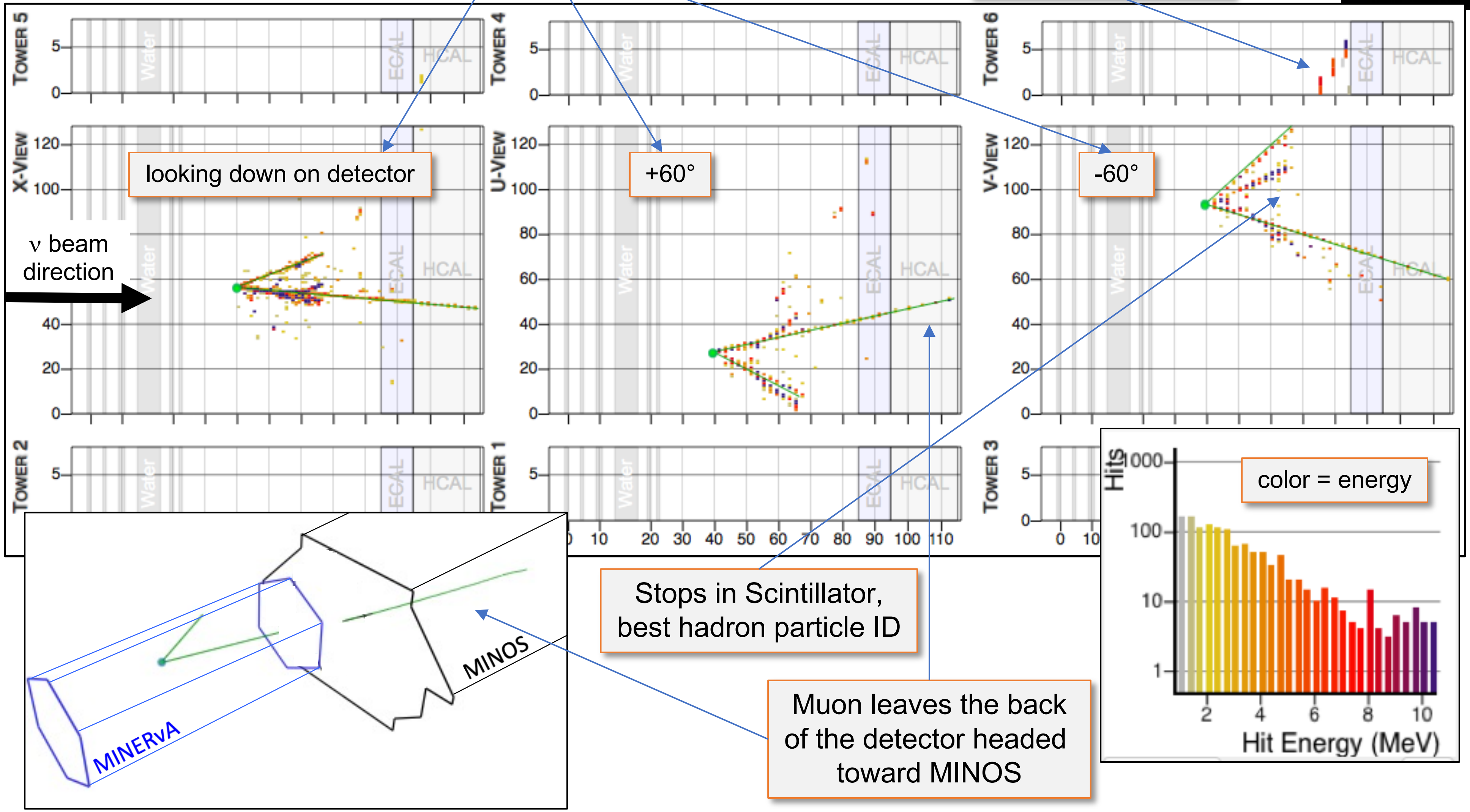
Backup: More Event Display

Events in MINERvA



3 stereo views, X—U —V , shown separately

Particle leaves the inner detector, stops in outer iron calorimeter



looking down on detector

+60°

-60°

ν beam direction

color = energy

Stops in Scintillator, best hadron particle ID

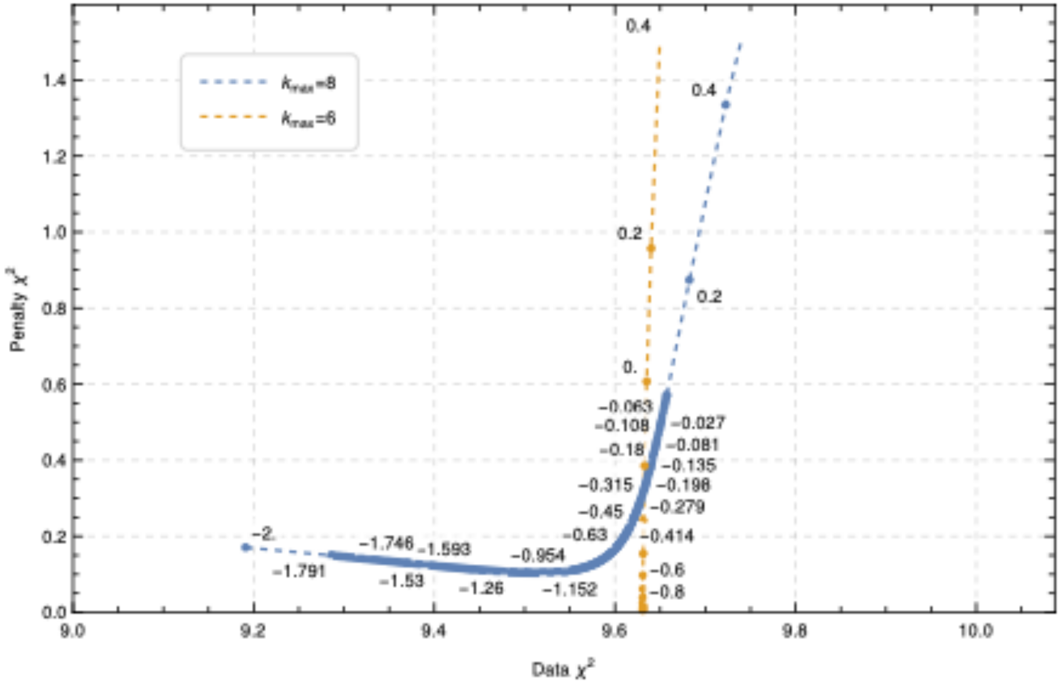
Muon leaves the back of the detector headed toward MINOS

Backup: Regularization L-curve

Regularization strength

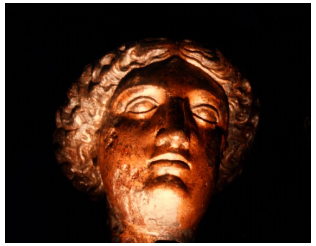
Central value fit: $k_{\max} = 8, \lambda = 0.13$

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

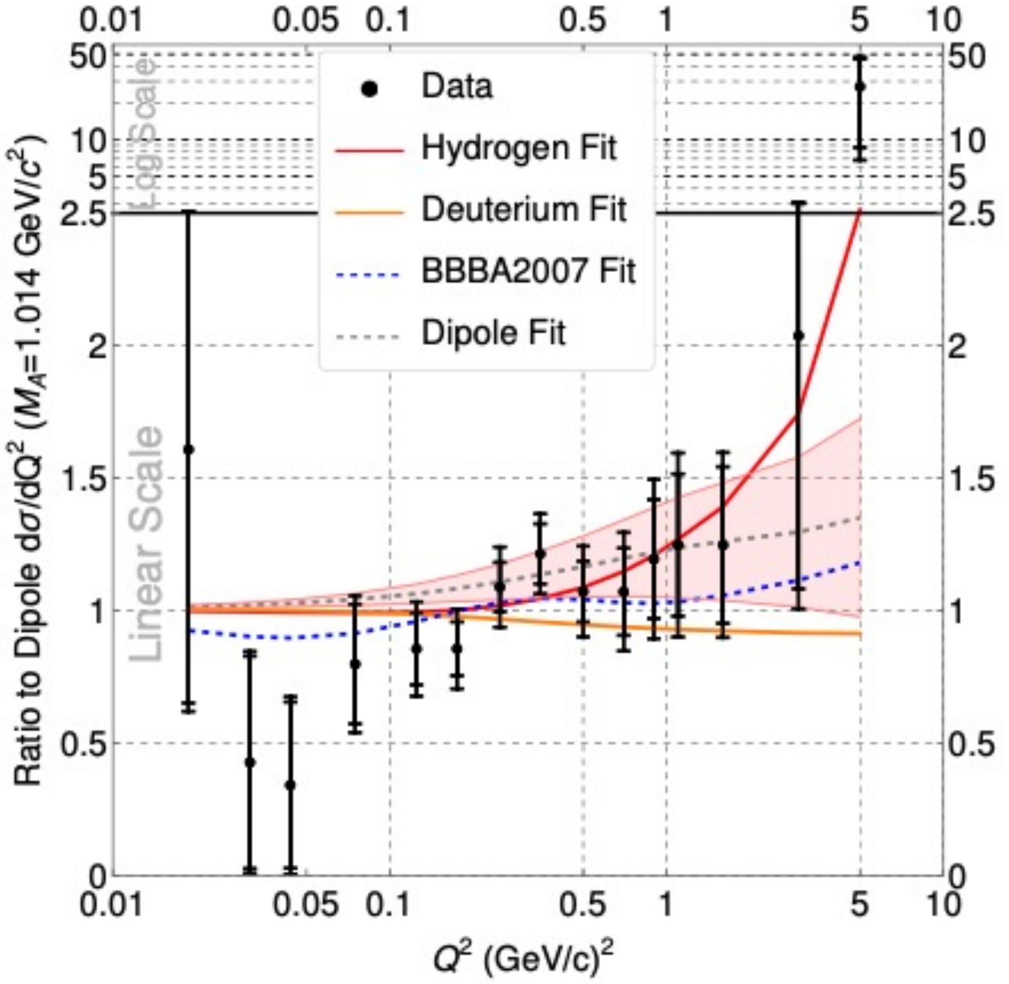


Backup: Dipole Fit and Axial Radius

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

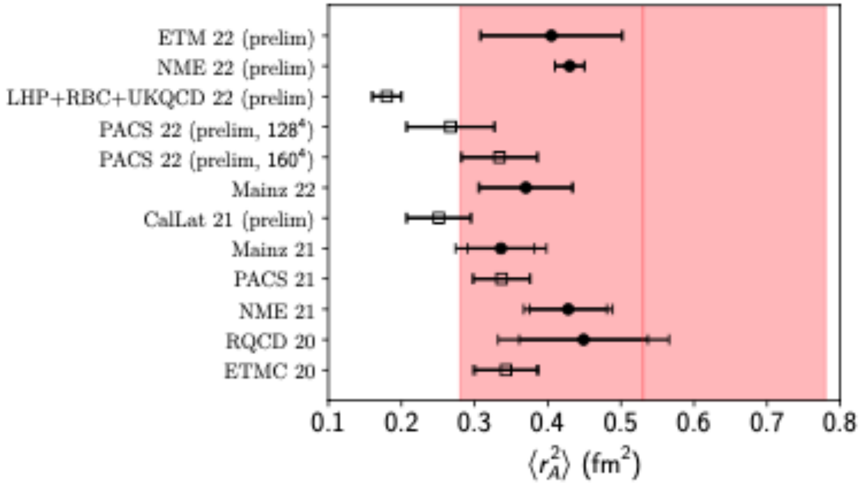
Favors larger F_{A} at higher Q^2.
If fit with dipole, $M_A \sim 1.15(10)$

Calculate proton radius from F_{A} for $Q^2 \to 0$.

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

$$\frac{1}{F_{\mathrm{A}}(0)}\frac{\mathrm{d}F_{\mathrm{A}}}{\mathrm{d}Q^2}\bigg|_{Q^2=0} = -\frac{1}{6}\langle {r_A}^2\rangle$$

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



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

Backup: For those who don’t know MINERvA

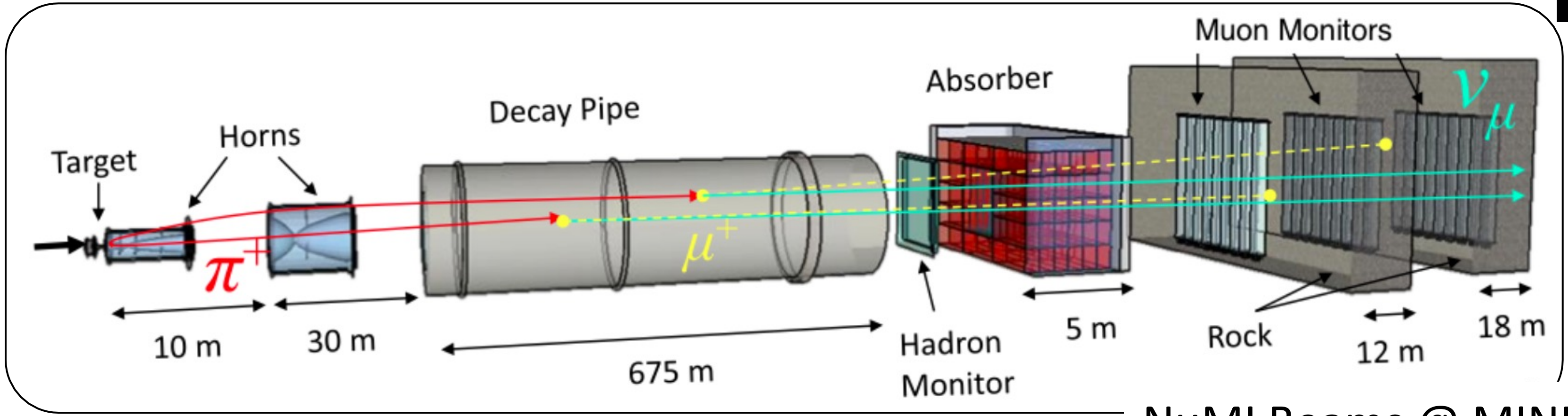
What was MINERvA and what was our primary goal?

- 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?

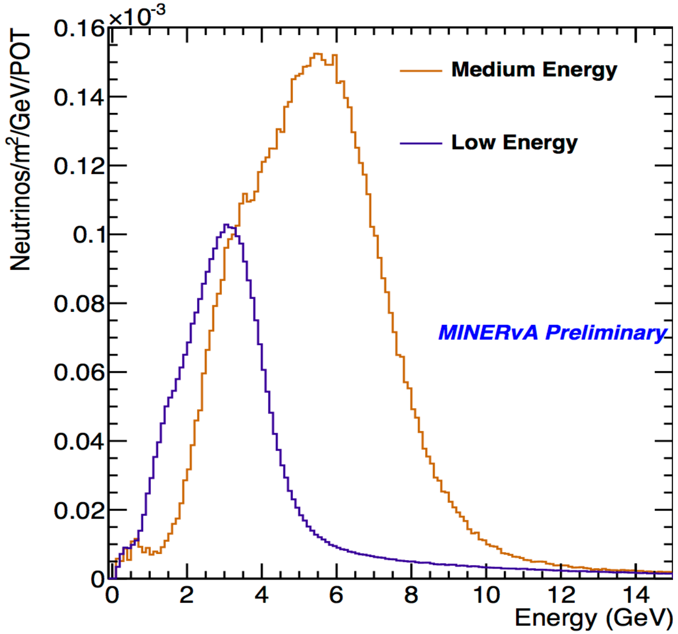
- Yes… and also are still “achieving” with the preserved data.
- Our data sets come from ~4mC of 120 GeV protons on our neutrino production target, resulting in a flux of ~10^{21} neutrinos and anti-neutrinos through the detector, and samples of ~10^{7} events.

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 ~4mC of 120 GeV protons on our neutrino production target, resulting in a flux of ~10^{21} neutrinos and anti-neutrinos through the detector, and samples of ~10^{7} events.

- So for example, one major reaction we want to understand are “quasielastic like” ones, $A(\bar{\nu}_\mu, \mu^+ n \ldots)A'$ 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 larg and poorly modeled.

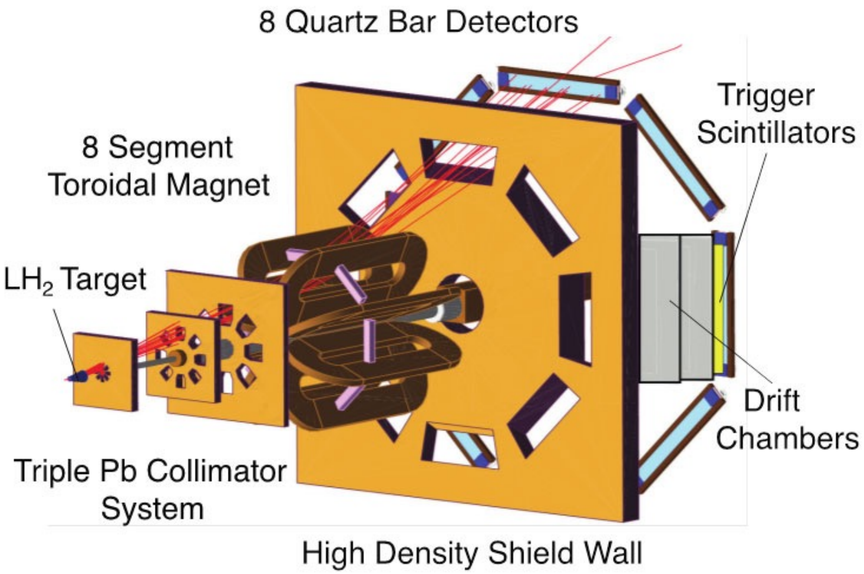
Scattering on Free Protons?

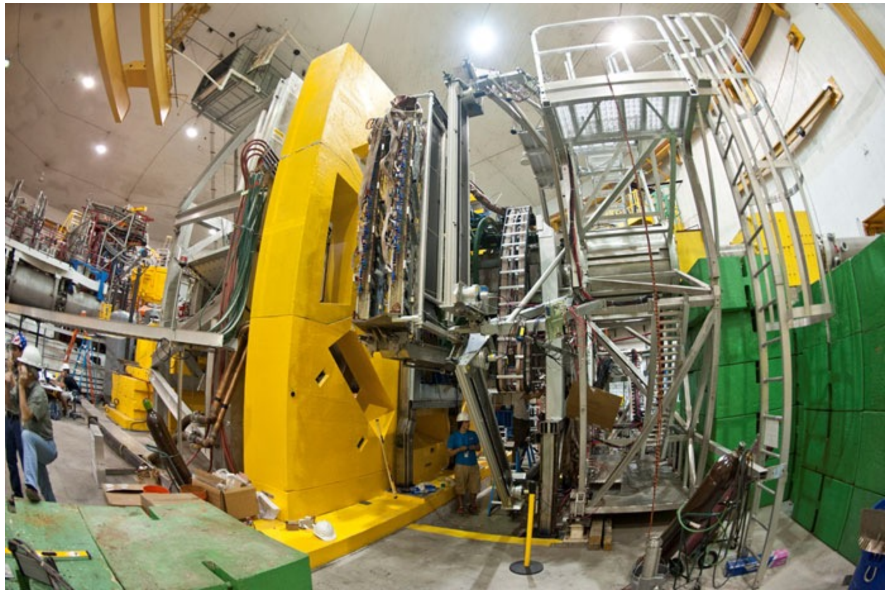
- You should now have enough knowledge about neutrinos and MINERvA to predict that this measurement wasn't done in a pure hydrogen target.
- MINERvA's scintillator is CH. In addition to charged-current elastic, $\bar{\nu}_\mu p \rightarrow \mu^+ n$, we also have backgrounds:
  - quasielastic anti-neutrino scattering on carbon, ${}^{12}C\left(\bar{\nu}_\mu, \mu^+ n\right){}^{11}B$,
  - multi-nucleon knockout "2p2h", ${}^{12}C\left(\bar{\nu}_\mu, \mu^+ np\right){}^{10}Be$ and ${}^{12}C\left(\bar{\nu}_\mu, \mu^+ nn\right){}^{10}B$,
  - 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 μ^+.
- $A(\nu_\mu, \mu^- p \ldots)A'$ is a background control sample to check what we predict under the hydrogen peak, since there are no free neutrons in our target.

Backup: For the Electron Scattering Community

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?





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

How Hard are They?

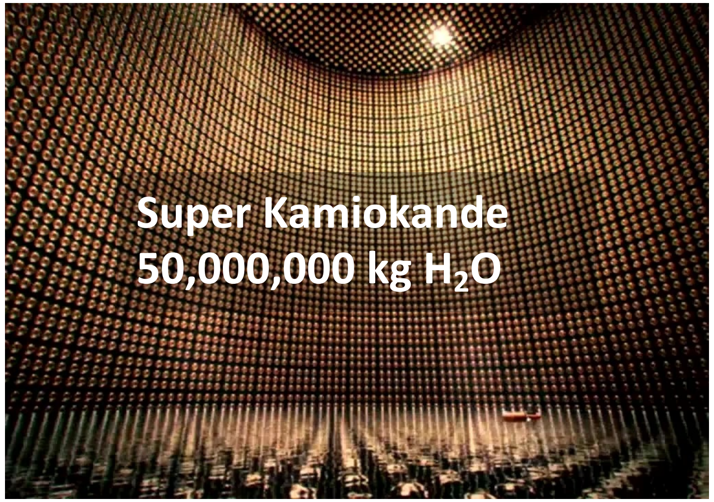
- For neutrino oscillation experiments, several % transition probabilities must be measured to few ‰ absolute precision…
  - The non-neutrino community just yawns. So what?
- The problem is that neutrinos just don’t interact, much.
- What is the mean free path of a 600 MeV neutrino from the T2K beam 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

How Hard are They?

- For neutrino oscillation experiments, several % transition probabilities must be measured to few ‰ absolute precision…
  - The non-neutrino community just yawns. So what?
- 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
- Another perspective: T2K has put ~10 TJoule of relativistic protons on its production target, and observed ~10 nJoule of particles from electron neutrino interactions in its far detector.

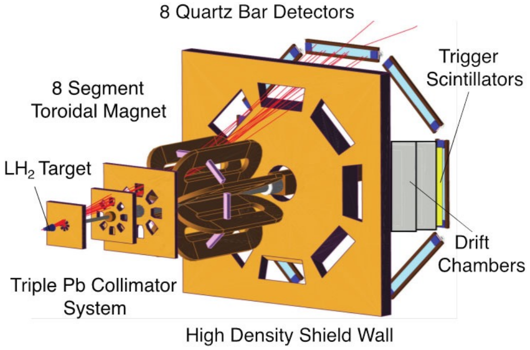
What does this mean for a neutrino experiment?

- 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…

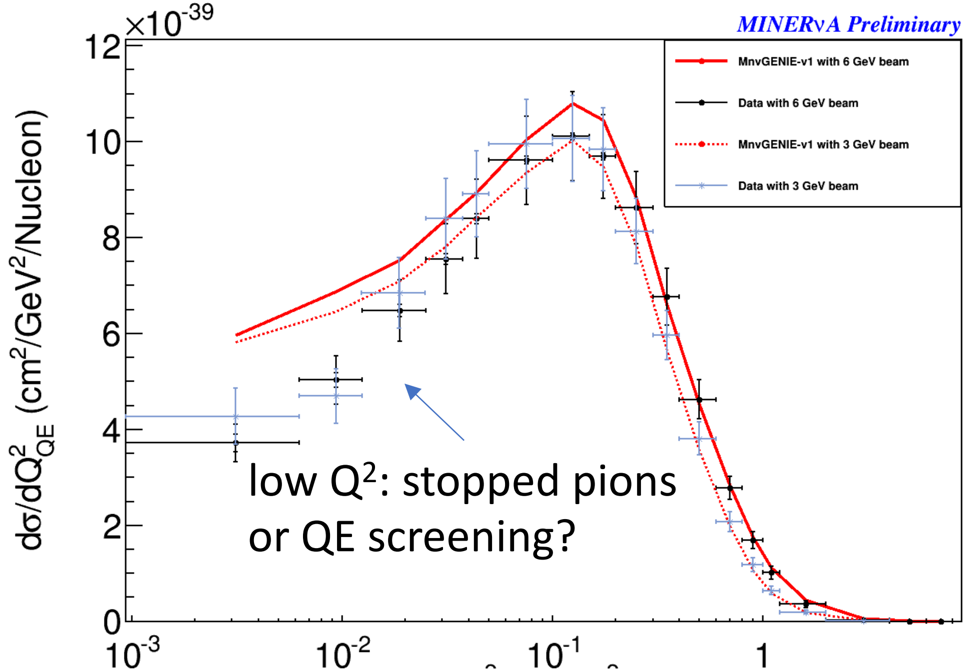


Super Kamiokande
50,000,000 kg H_2O

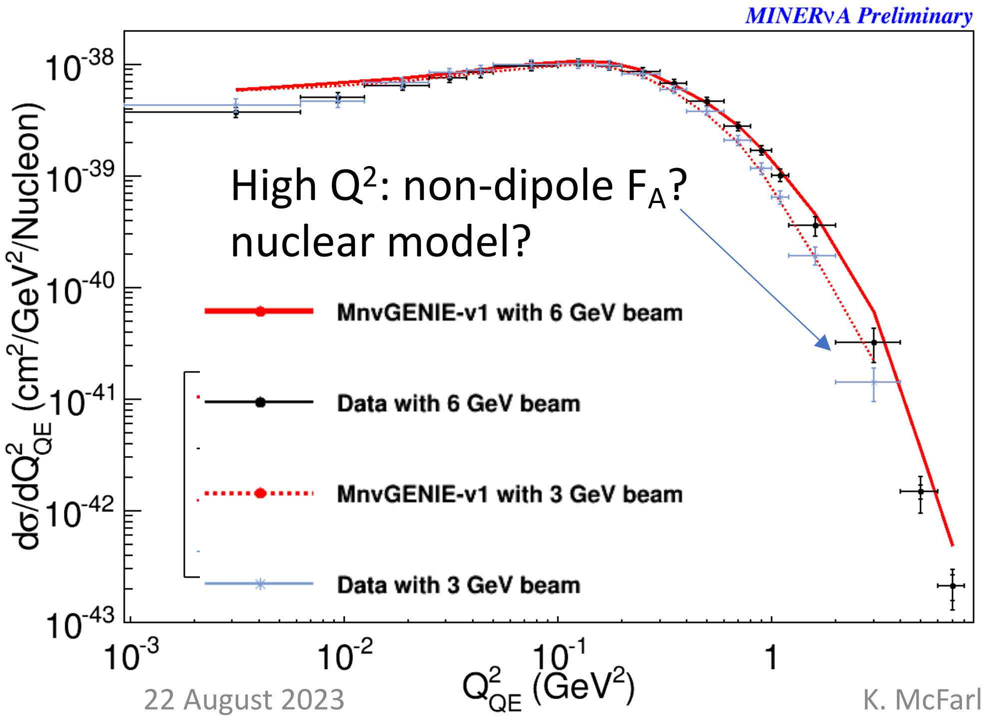
Qweak
4 kg H_2



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



low Q^2: stopped pions or QE screening?



High Q^2: non-dipole F_A? nuclear model?

- Here is data on the neutrino analog from MINERvA, as a function inferred (from the final state) Q^2 at two different beam energies, $\langle E_\nu \rangle$~3 and $\langle E_\nu \rangle$~ 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 no $\propto 1/Q^4$, and to note that this cross-section falls rapidly near Q^2~1 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

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.

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.

Thank you!