MINERvA's Axial FF Measurement

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Overview

- MINERvA finished a 10 year run at Fermilab in 2019 with an unprecedentedly large dataset.
- One of the the initial goals of MINERvA was to measure the axial vector form factor, only accessible in weak interactions.
- While F_A is important it it's own right, neutrino oscillation experiments have to reconstruct the neutrino energy from neutrino nucleus collisions.
  - Messy, messy.
  - A solid understanding of neutrino nucleon scattering is a necessary input
- Also, neutrino experiments would really benefit from a standard candle cross-section
  - Well, $\nu e^- \rightarrow \nu e^-$ & $\nu_\mu e^- \rightarrow \nu_e \mu^-$ but the cross-sections are small and you can't get E_ν easily.

Formalism - dσ/dQ^2

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

$$\begin{aligned}
A(Q^2) &= \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)\boxed{|F_{\mathrm{A}}|^2} - \left(4-\frac{Q^2}{M^2}\right)|F_{\mathrm{V}}^1|^2\right.\\
&\quad \left. + \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\xi F_{\mathrm{V}}^2|^2 + \frac{4Q^2}{M^2}\mathrm{Re}F_{\mathrm{V}}^{1*}\xi F_{\mathrm{V}}^2 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right],\\
B(Q^2) &= \frac{Q^2}{M^2}\boxed{\mathrm{Re}F_{\mathrm{A}}^*}(F_{\mathrm{V}}^1+\xi F_{\mathrm{V}}^2),\\
C(Q^2) &= \frac{1}{4}\left(\boxed{|F_{\mathrm{A}}|^2} + |F_{\mathrm{V}}^1|^2 + \frac{Q^2}{4M^2}|\xi F_{\mathrm{V}}^2|^2\right)
\end{aligned} \tag{5}$$

- Vector form factors $F_V^1(Q^2)$ and $F_V^2(Q^2)$ measured and parameterized by you all.
- $\boxed{F_A^1(Q^2)}$ only appears in weak interactions which give neutrinos a chance to measure it.

Measurement concept

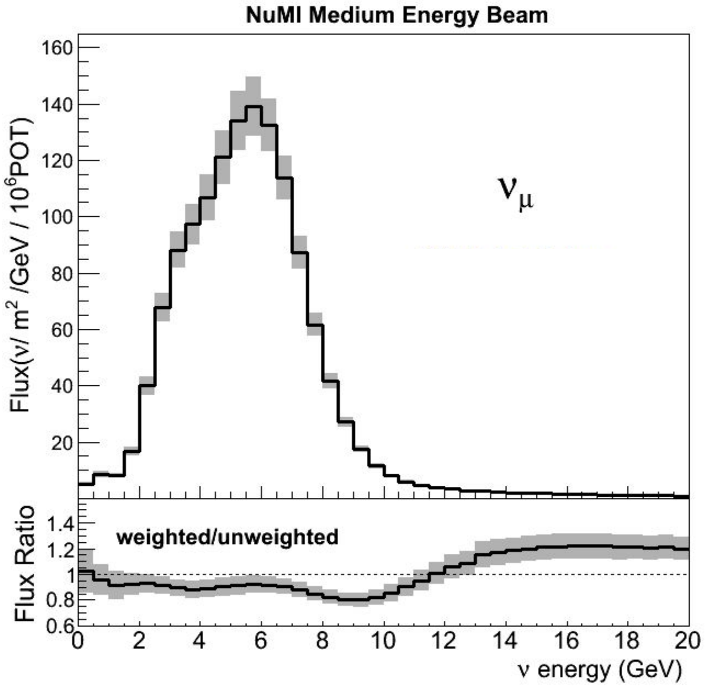
- In MINERvA neutrinos interact on plastic scintillator, CH
- The nucleons in carbon are bound and are therefore moving targets (Fermi motion, etc).
- The free protons in hydrogen are at rest.
- Elastic scattering $\bar{\nu}_\mu p \to \mu^+ n$ is a 2-body problem.
- We don't know the energy of each incoming neutrino but we do know its direction and we can measure $(p_{\mu,} \theta_\mu)$.
- This is enough to completely constrain the system
  - namely, momentum must be conserved in the reaction plane and perpendicular to it.
  - not true for interactions on C or inelastic interactions.
- We'll use this to select a sample enriched in elastic events with sidebands that can be used to constrain backgrounds in the signal region.

Main Reference

T. Cai et al., The MINERvA Collaboration, Nature 614 (2023) 7946, 48-53

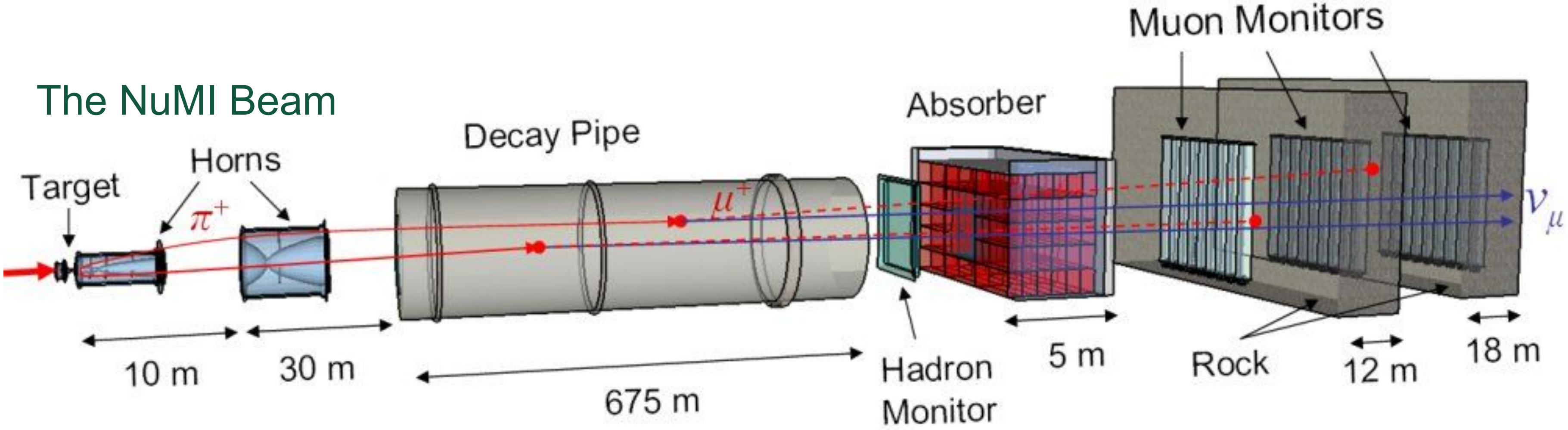
What was MINERvA?

- MINERvA was a dedicated neutrino interaction experiment that ran in the NuMI beam at Fermilab from 2009-2019.
- Two beam configurations:
    - Low Energy ~<3 GeV>
    - Medium Energy ~<6 GeV>
- Goal was to measure inclusive and exclusive scattering off of a wide range of nuclei (Pb/Fe/C/O/He)
- Collected ~10^7 neutrino interactions

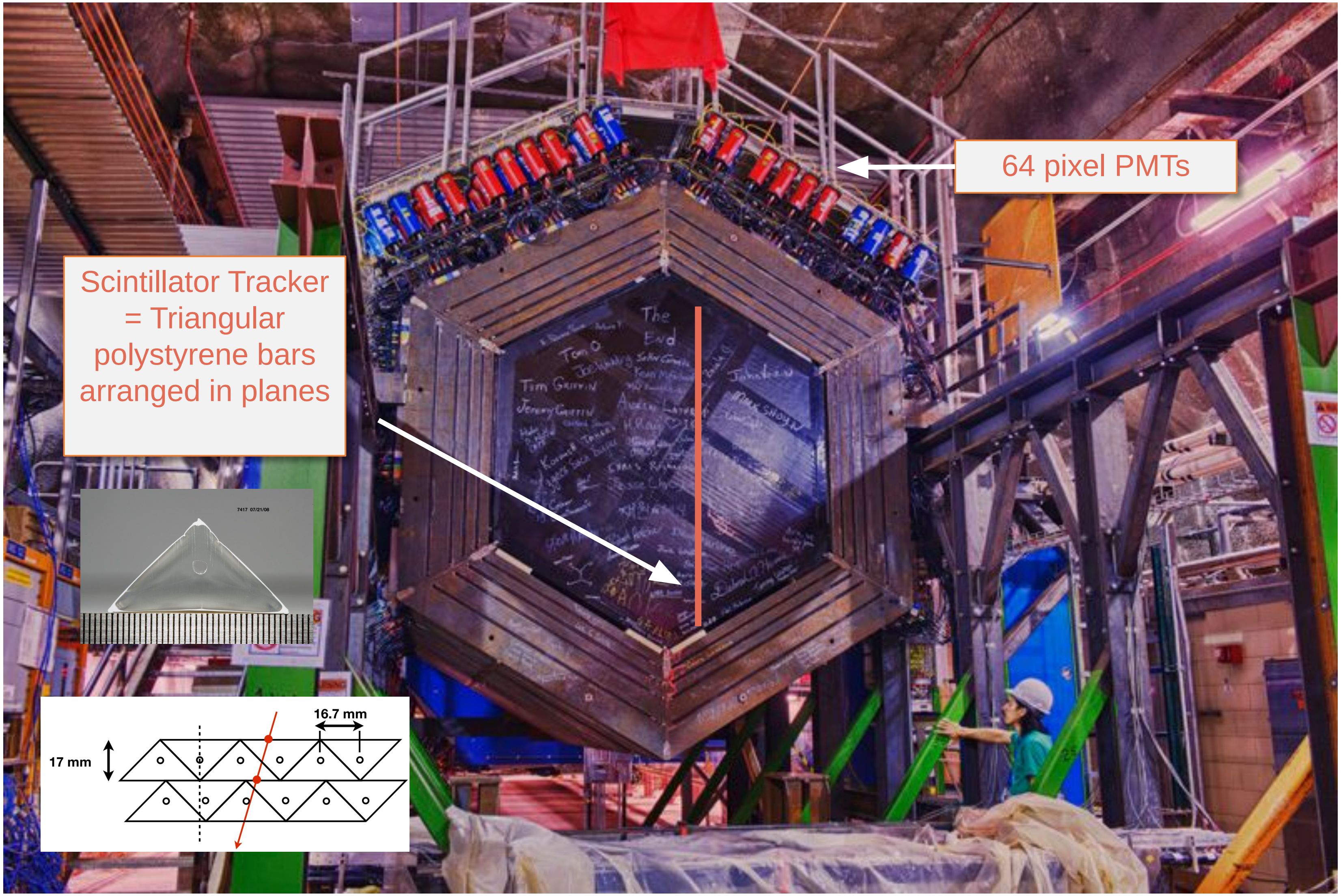


flux correction

The NuMI Beam



The MINERvA Experiment

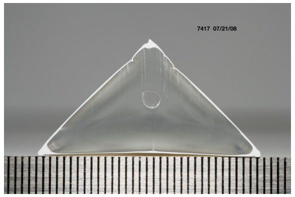


64 pixel PMTs

Scintillator Tracker = Triangular polystyrene bars arranged in planes

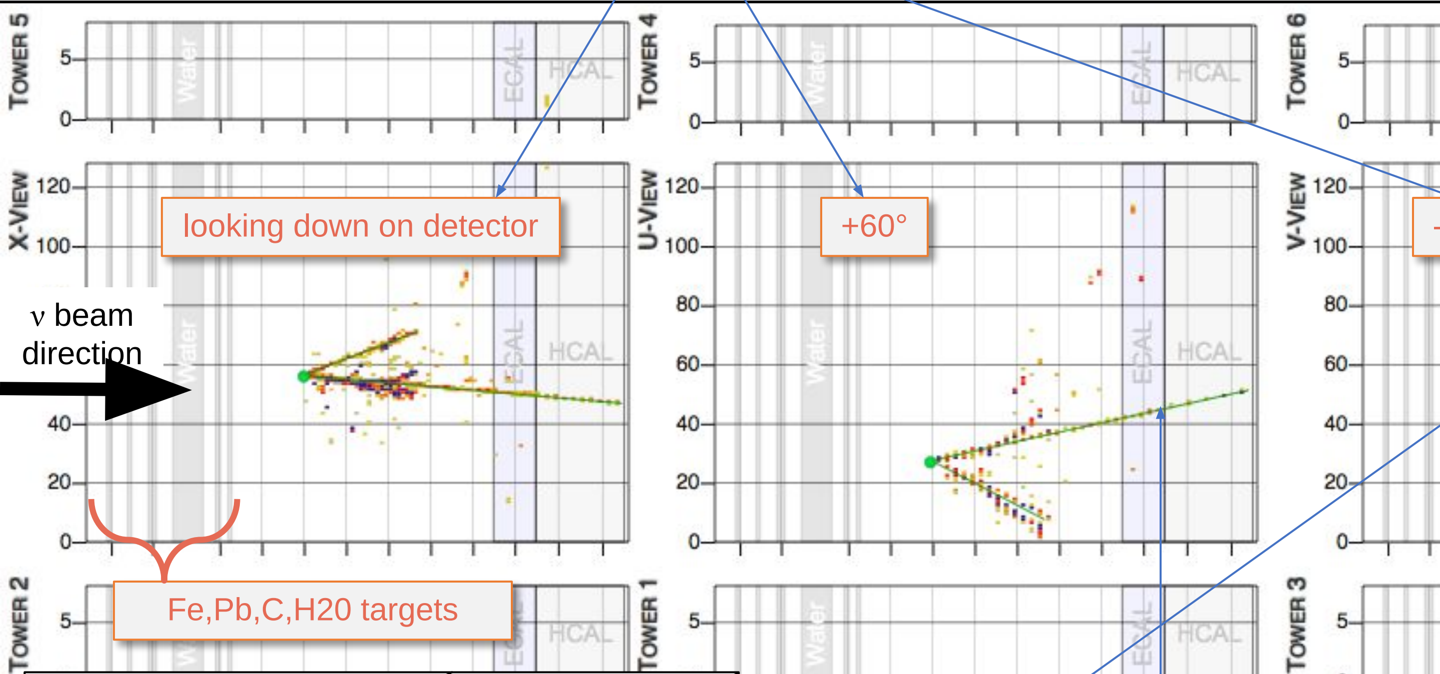
An event in MINERvA's scintillator tracker

Triangular polystyrene bars



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

Particle leaves the inner detector, stops in outer iron calorimeter



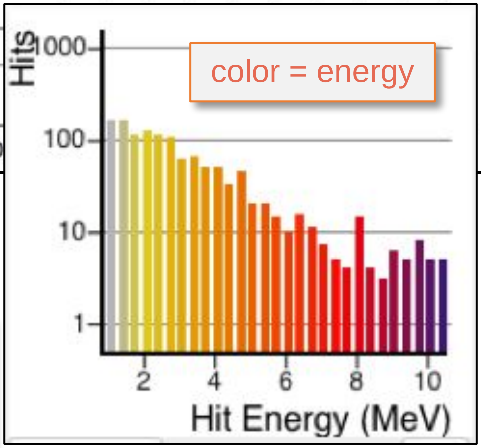
looking down on detector

+60°

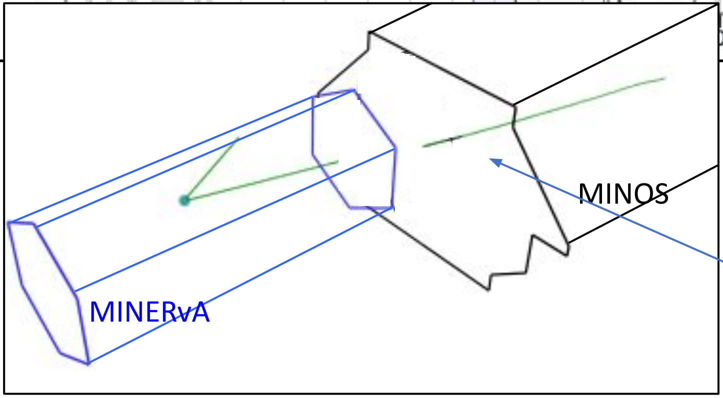
-60°

ν beam direction

Fe,Pb,C,H20 targets



color = energy



Stops in Scintillator, best hadron particle ID

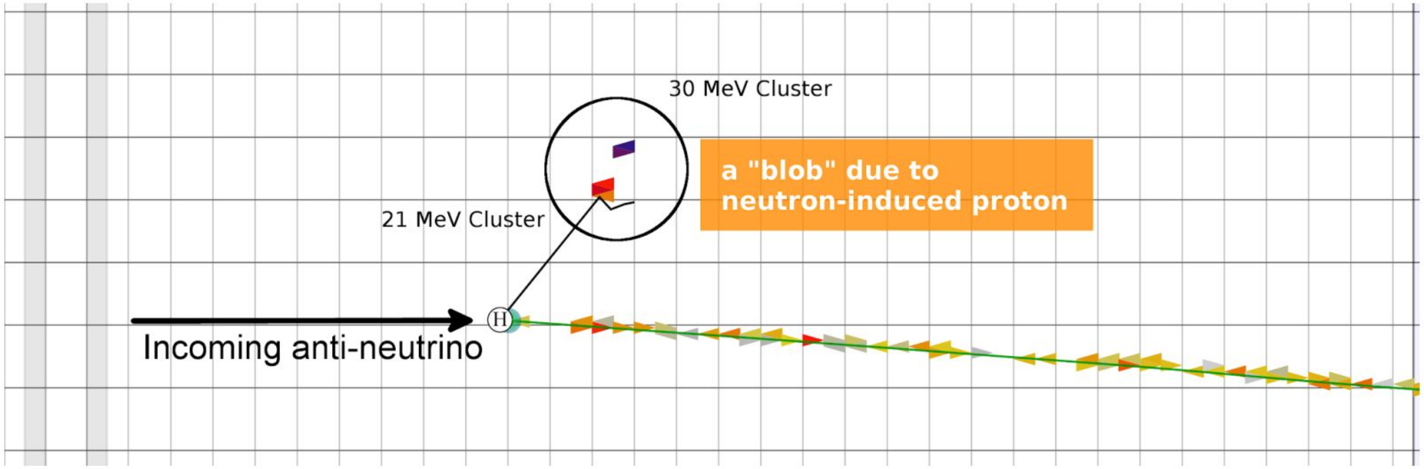
Muon leaves the back of the detector headed toward magnetized spectrometer (a.k.a. MINOS Near Detecor)

Event selection

- We are looking for $\bar{\nu}_\mu p \rightarrow \mu^+ n$ ("elastic scattering")
- Backgrounds:
  - Primary: same process but on a proton bound in C ("quasi-elastic")
  - Multi-nucleon emission & inelastic (i.e., pion production) events that produce isolated blobs but not much other activity
- E_ν and Q^2 are reconstructed from the muon arm assuming a target at rest:

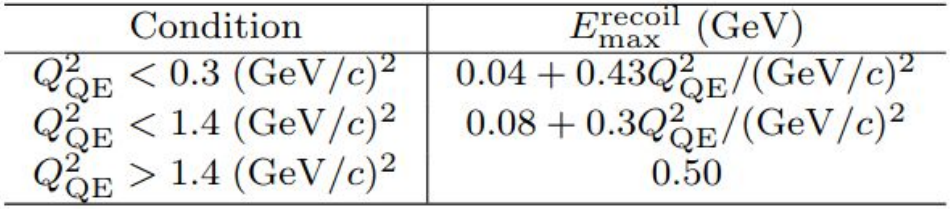
$$E_{\bar{\nu}} = \frac{M_\mathrm{n}^2 - M_\mathrm{p}^2 - m_\mu^2 + 2M_\mathrm{p}E_\mu}{2(M_\mathrm{p} - E_\mu + p_\mu \cos\theta_\mu)},$$

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



Event selection

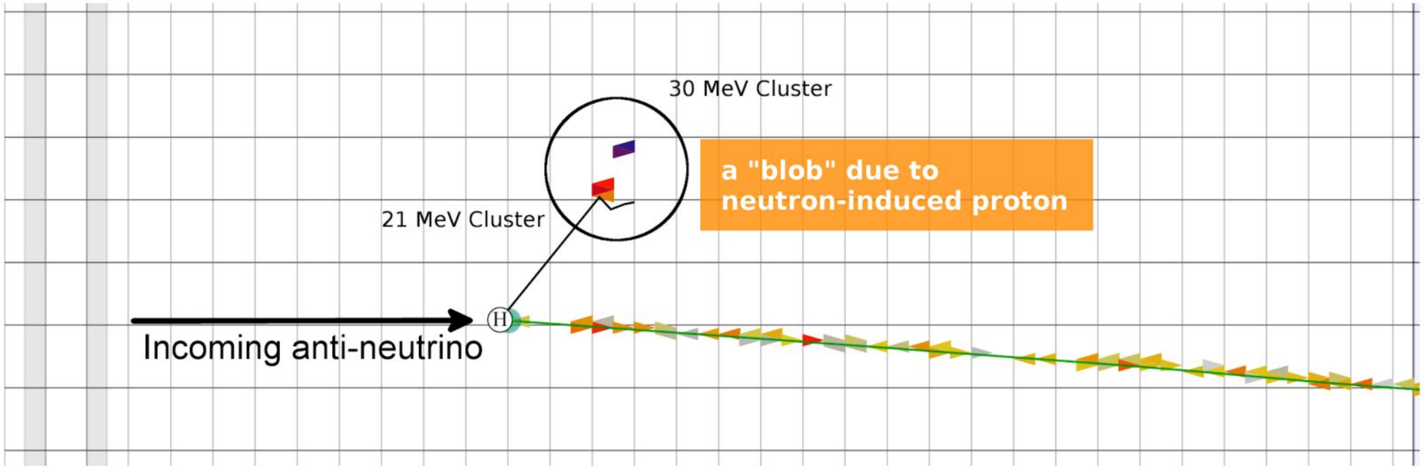
- Require:
  - μ^+ track starting in the scintillator tracker and reconstructed in MINOS with $\Theta_\mu < 20°$ and $1.5 < p_\mu < 20$ GeV/c
  - No other tracks from protons or pions at the vertex
  - Isolated blob or proton-like track 20 cm or more from the vertex. No other significant blobs are allowed.
  - Because recoil energy=$q_0 = Q^2/2m_n$ we require that the energy not associated with the muon is less than a Q^2 dependent threshold



Condition	$E_{\text{max}}^{\text{recoil}}$ (GeV)
$Q^2_{\text{QE}} < 0.3\ (\text{GeV}/c)^2$	$0.04 + 0.43 Q^2_{\text{QE}}/(\text{GeV}/c)^2$
$Q^2_{\text{QE}} < 1.4\ (\text{GeV}/c)^2$	$0.08 + 0.3 Q^2_{\text{QE}}/(\text{GeV}/c)^2$
$Q^2_{\text{QE}} > 1.4\ (\text{GeV}/c)^2$	0.50

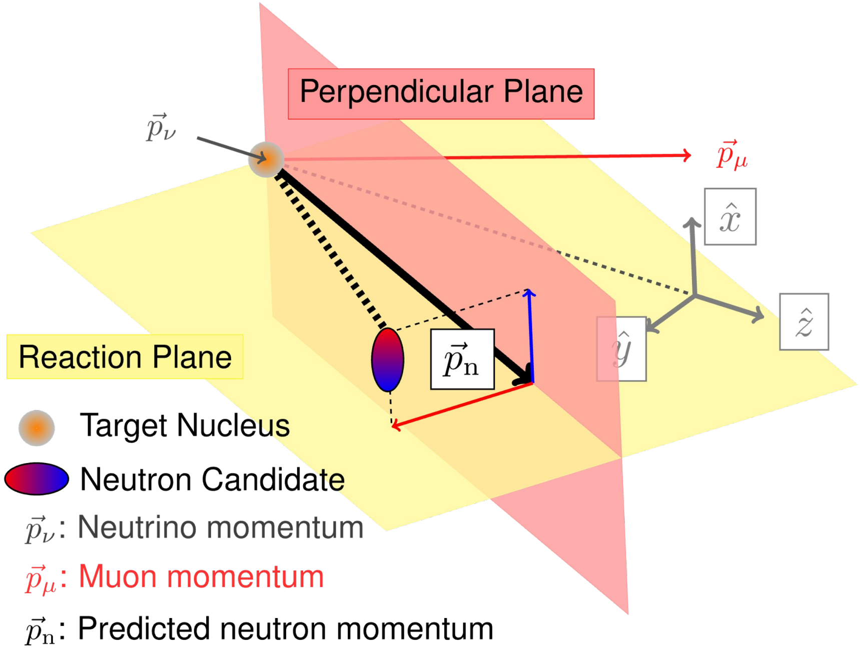
→ 170 MeV

→ 500 MeV

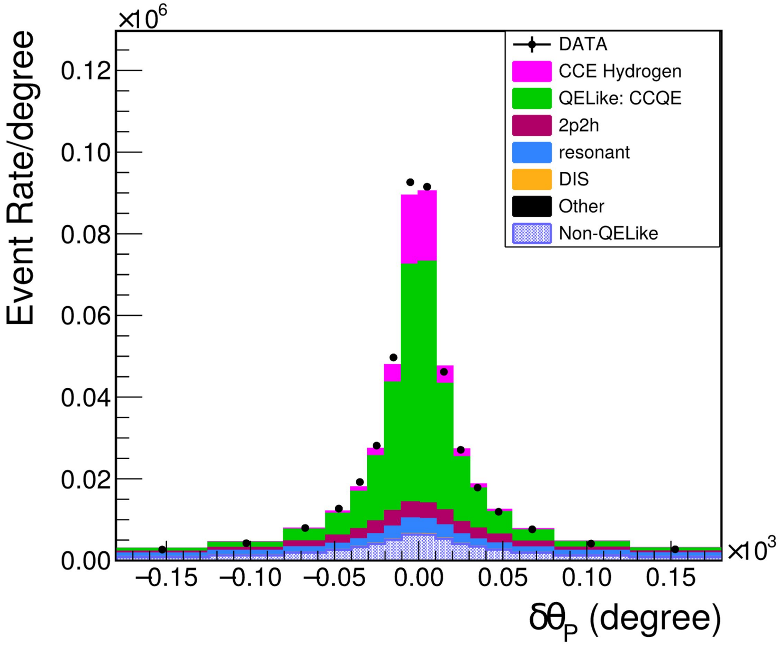


Signal vs Background

- When scattering on a free proton the direction of the neutron is predicted from the muon kinematics.
- Not the case for bound protons due to to initial state interactions (e.g., Fermi motion) and and final state interactions (neutron rescattering).
- Other backgrounds are from multi-nucleon scattering (2p2h) and inelastic processes.
- We separate signal from background using the difference between the observed neutron angle and what would be expected for scattering off a free proton: $\delta\theta_R$ and $\delta\theta_P$



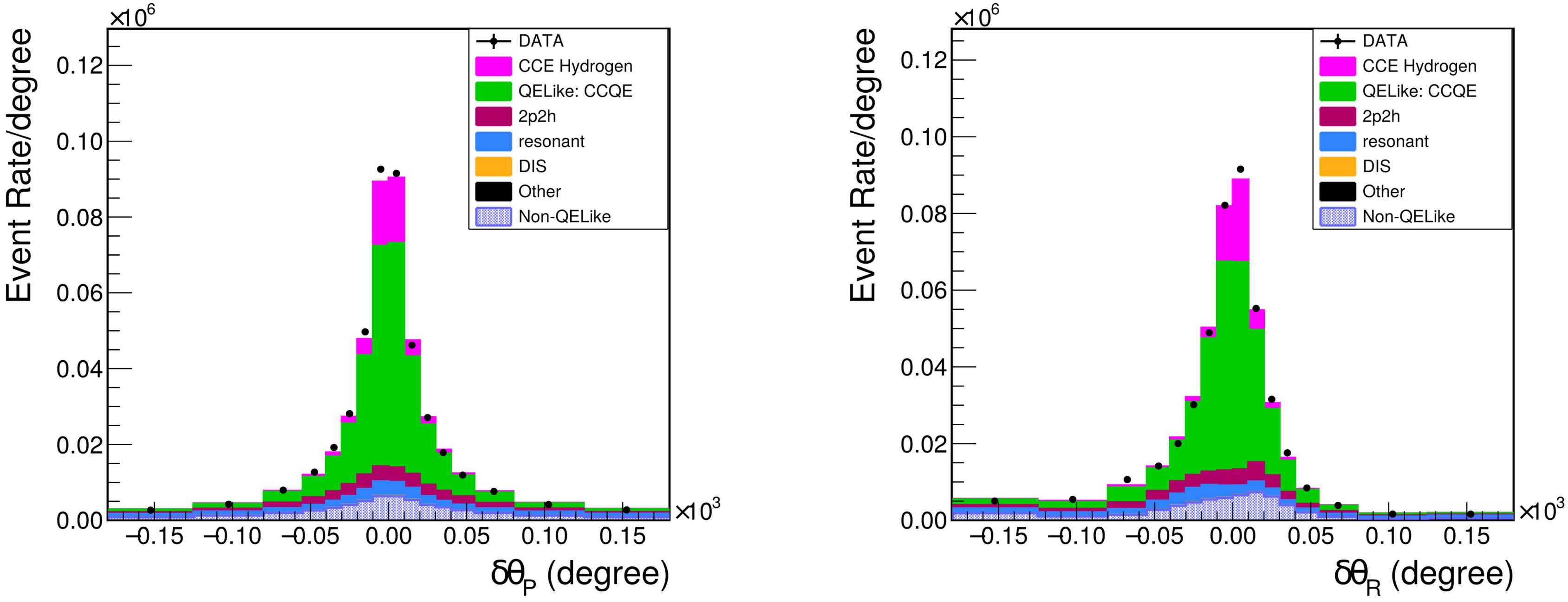
$\delta\theta_P$ and $\delta\theta_R$ distributions



Event categories

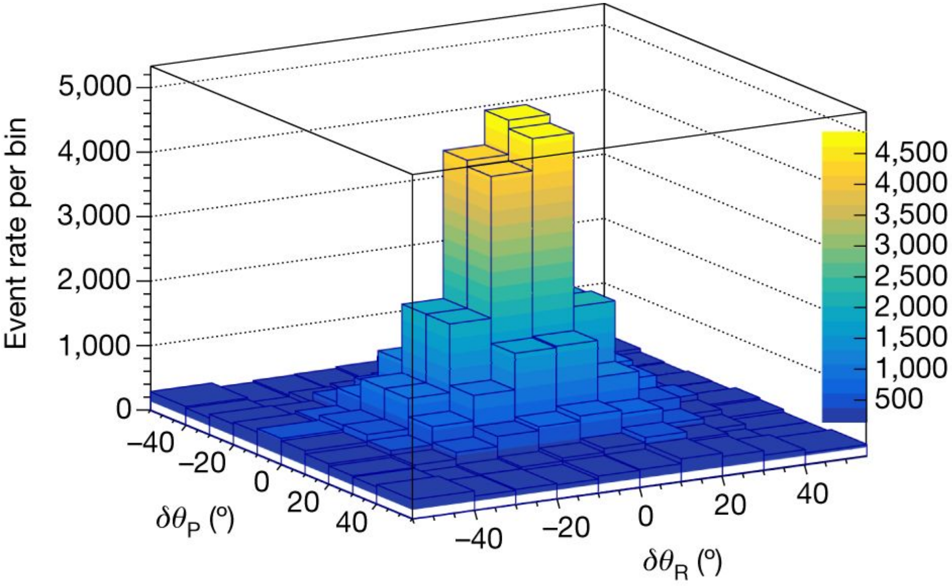
- Based (mostly) on particles in the final state according to MC truth
- CCE=signal $\bar{\nu}_\mu p \rightarrow \mu^+ n$
- QELike:
  - only μ^+ and nucleons in final state
  - reconstructed proton tracks must have $T_p < 150$ MeV
- QELike backgrounds:
  - CCQE=quasi-elastic
  - 2p2h=multi-nucleon
  - resonant+DIS=inelastic
- Non-QELike:
  - events with other particles in the final state or those with $T_p > 150$ MeV

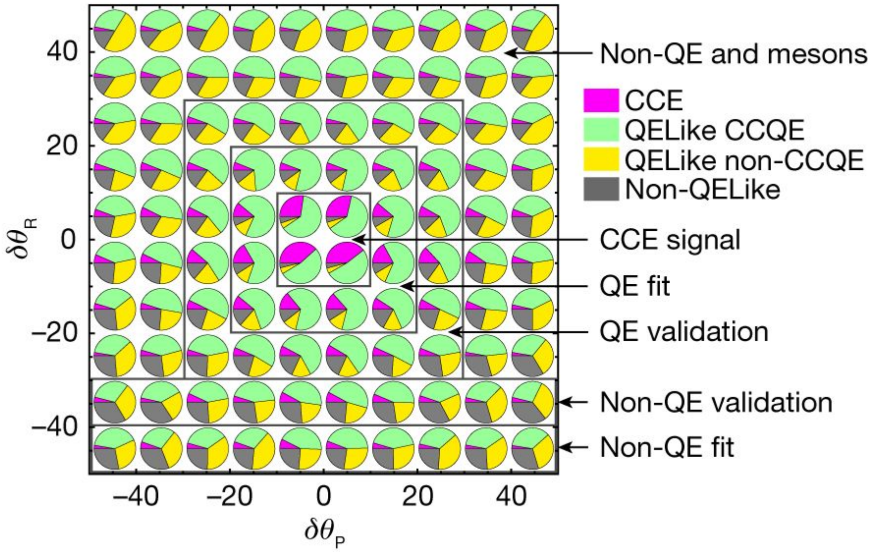
$\delta\theta_P$ and $\delta\theta_R$ distributions



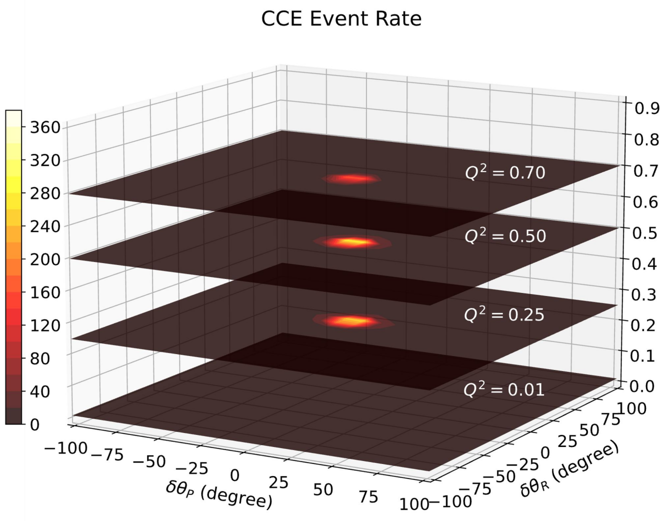
- Signal concentrated around $\delta\theta_P$ & $\delta\theta_R$=0°
- Symmetry in $\delta\theta_P$
- Asymmetry for backgrounds in $\delta\theta_R$

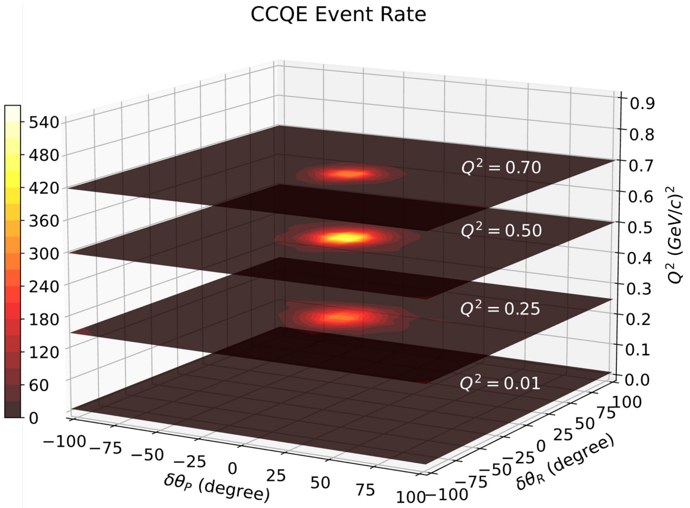
$\delta\theta_P$ and $\delta\theta_R$ distributions: in two dimensions



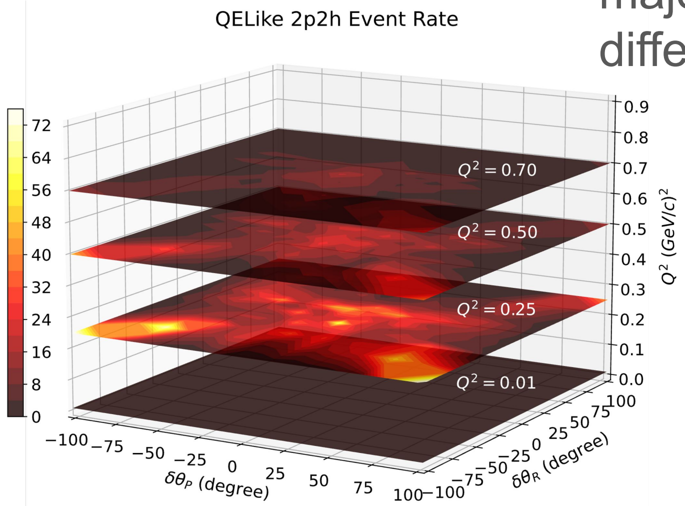


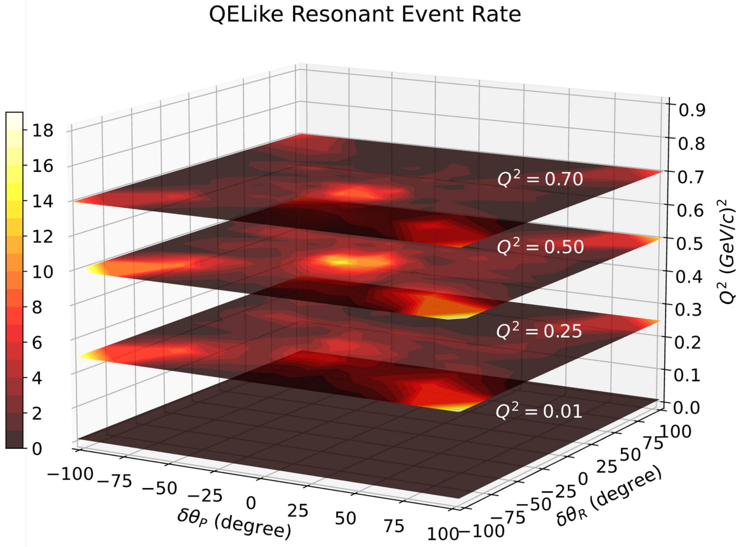
$\delta\theta_P$ and $\delta\theta_R$ distributions: in three dimensions


CCE Event Rate

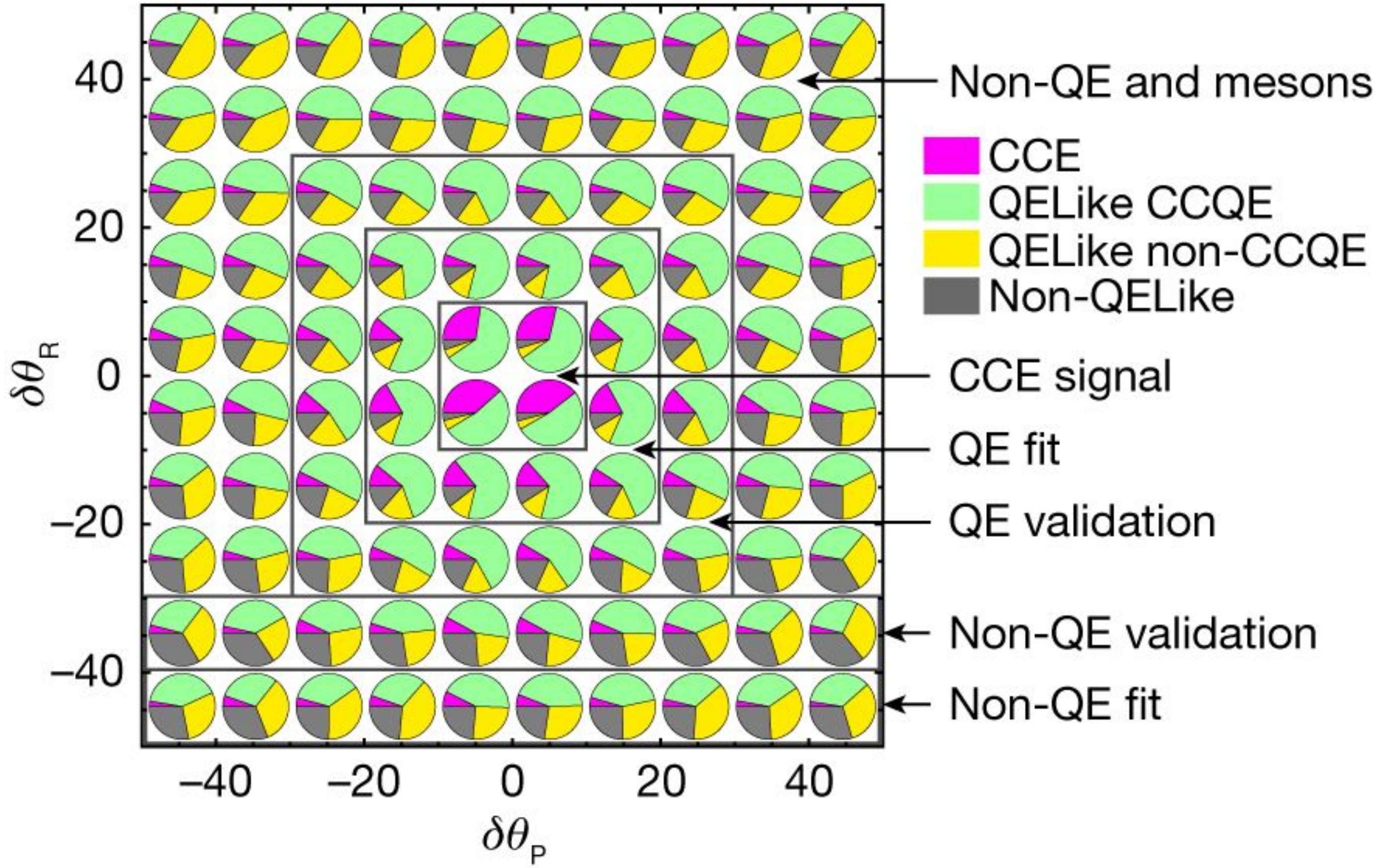

CCQE Event Rate

Heat maps of signal and major backgrounds at different Q^2


QELike 2p2h Event Rate

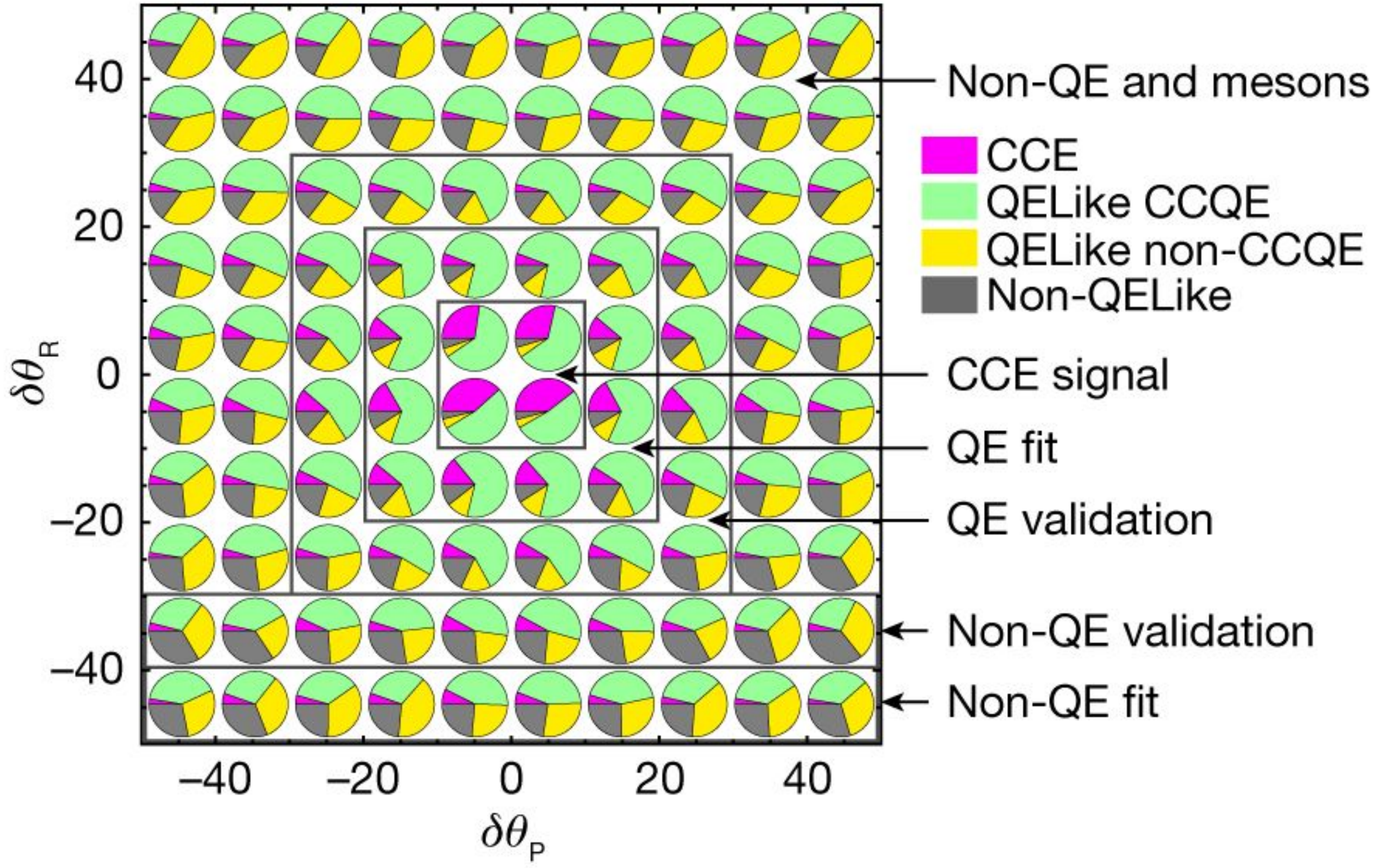

QELike Resonant Event Rate

Background constraint via sidebands



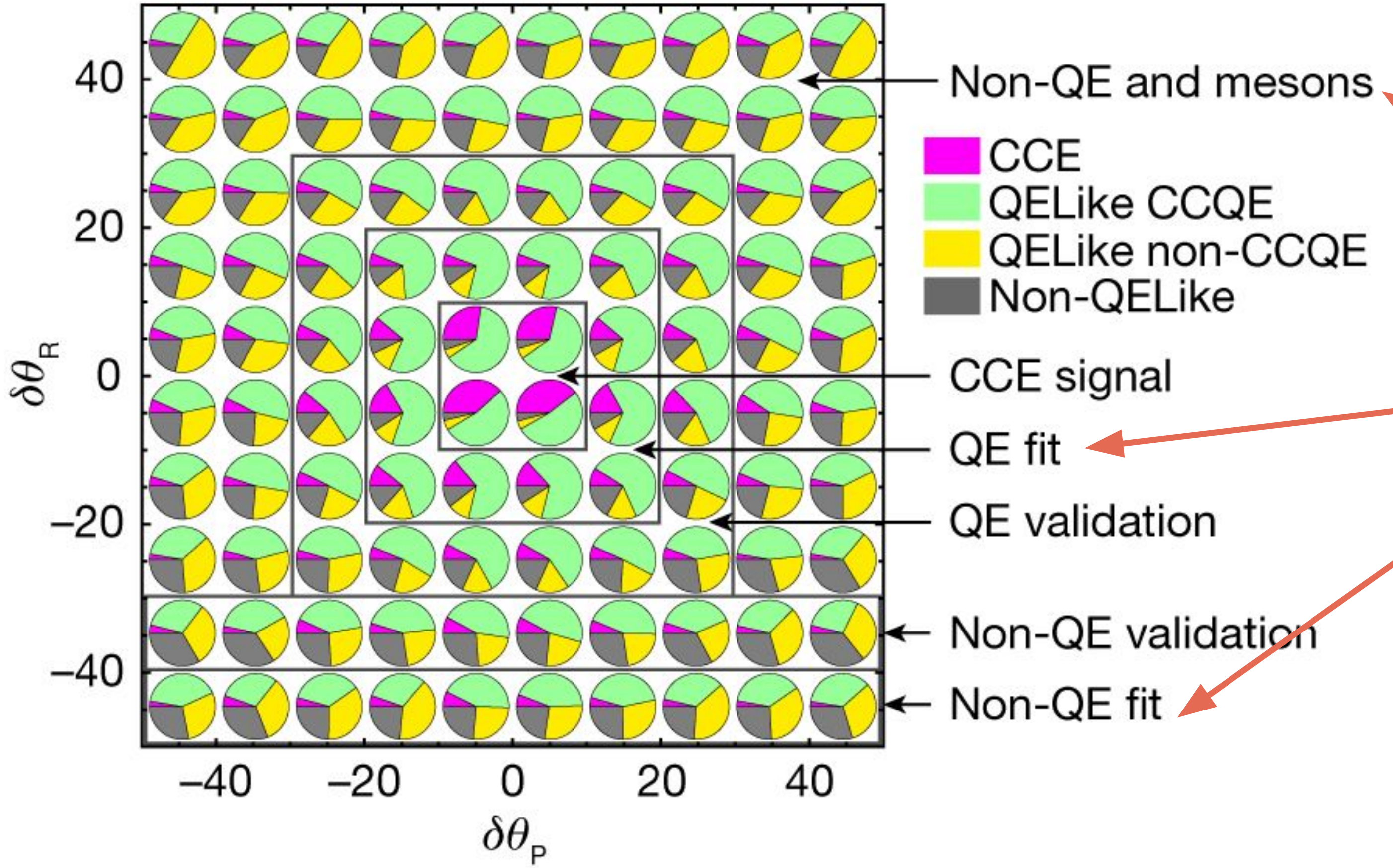
- The events are divided into two samples:
  - those that pass the full event selection (“single-blob”)
  - those that fail because they have more than one significant blob (“multi-blob”)
  - This latter sample is enriched in Non-QELike events

Background constraint via sidebands



- QE-like CCQE and non-QE are fit in different regions of the ($\delta\theta_P$,$\delta\theta_R$) plane
- The results are tested in the validation regions.
- The fit is done in bins of Q^2 with each bin weighted up or down. A regularization term is added to the χ^2 to ensure smoothness.

Background constraint via sidebands



Fit regions

- In each Q2 bin a weight is fit for each of these categories:
  - CCQE, 2p2h, “resonant” (π absorbed in target nucleus)
  - Non-QELike
- The fit is done using both the single and multi-blob samples separately taking the events from the fit regions above

Fit validation

The results of the fit in the validation regions

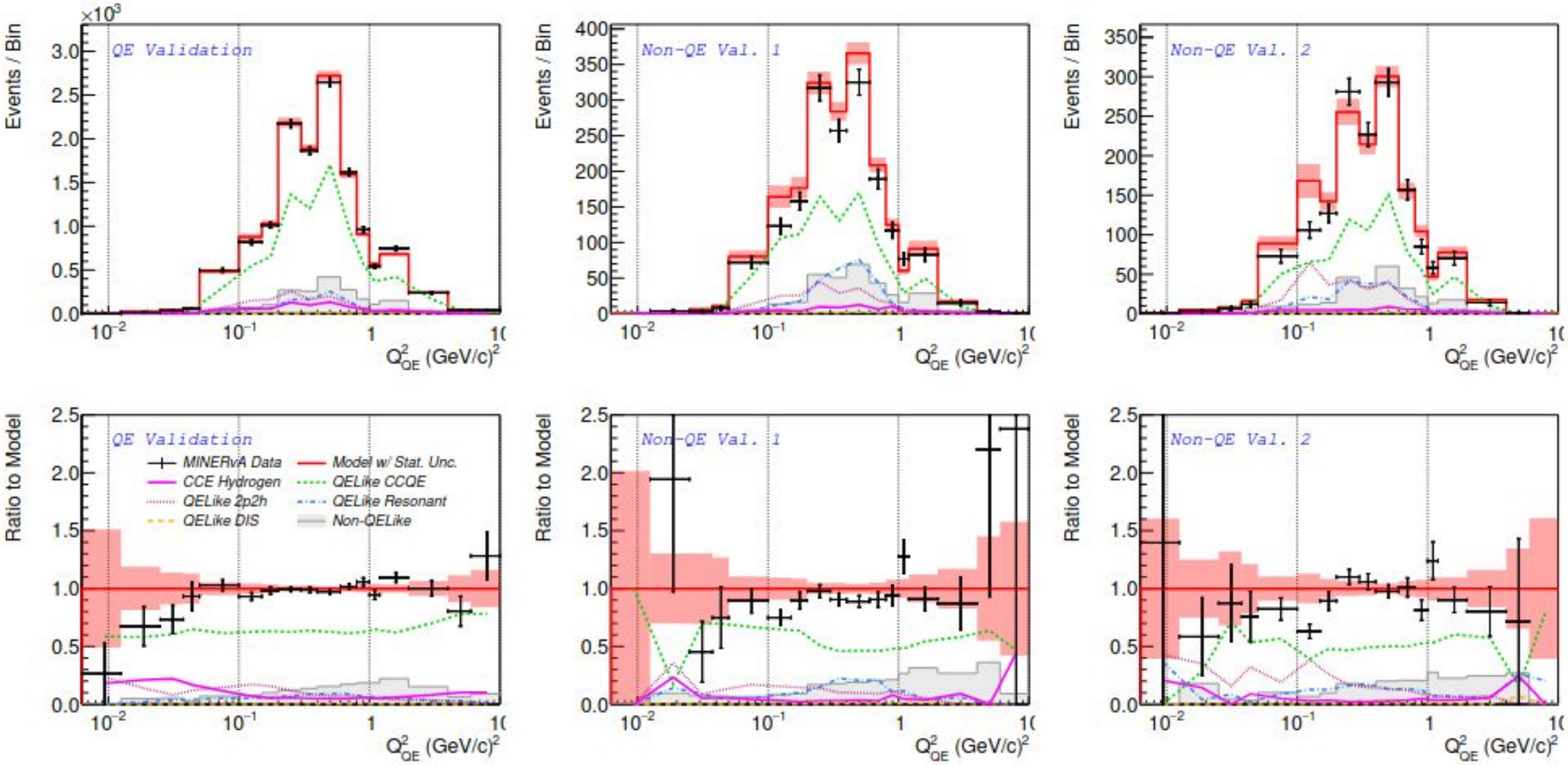
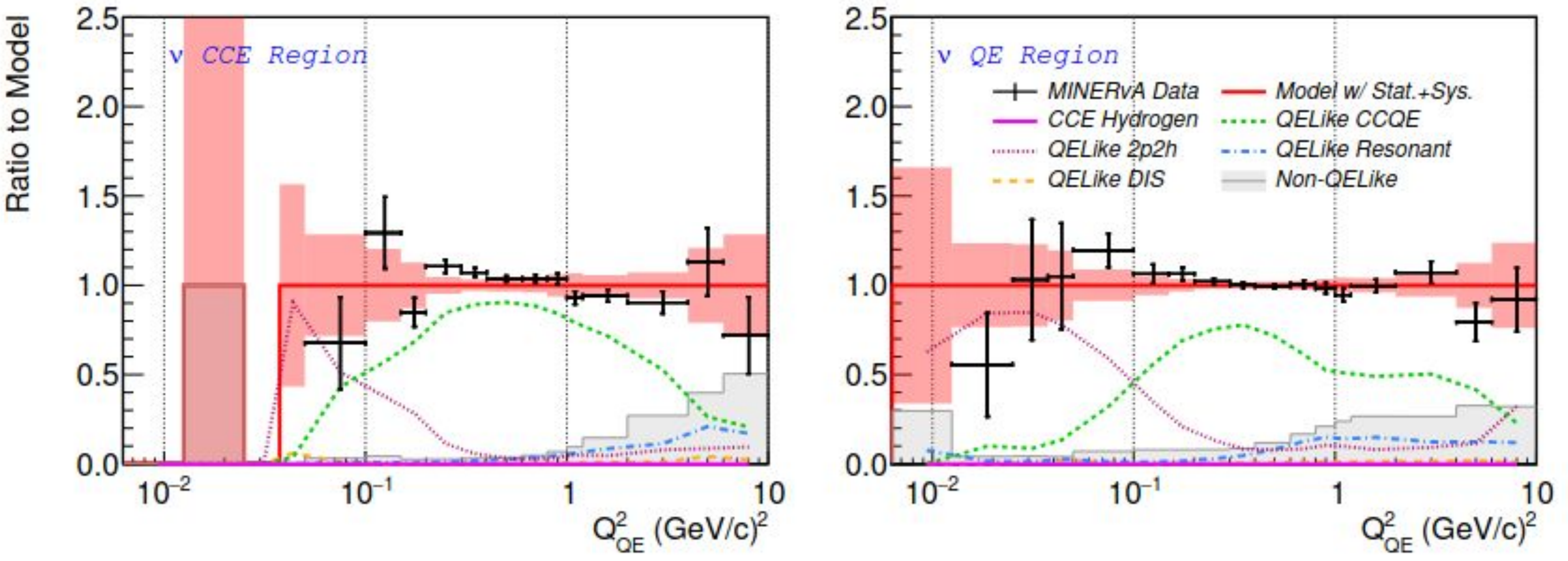


Fig. 8 Post-fit event rate and ratio in the validation regions. The "Non-QE validation" region is shown separated into two sub-regions. "Non-QE Val. 1" spans $|\delta\theta_P| < 20^\circ$, "Non-QE Val. 2" occupies $20^\circ < |\delta\theta_P| < 55^\circ$. The vertical error bars around the data points and the error band around the model prediction account for 1 standard deviation due to statistical uncertainty. The CCE signal and the regions used in the background fits are shown in Fig. 2 and 3, respectively.

Validation using the ν_μ sample

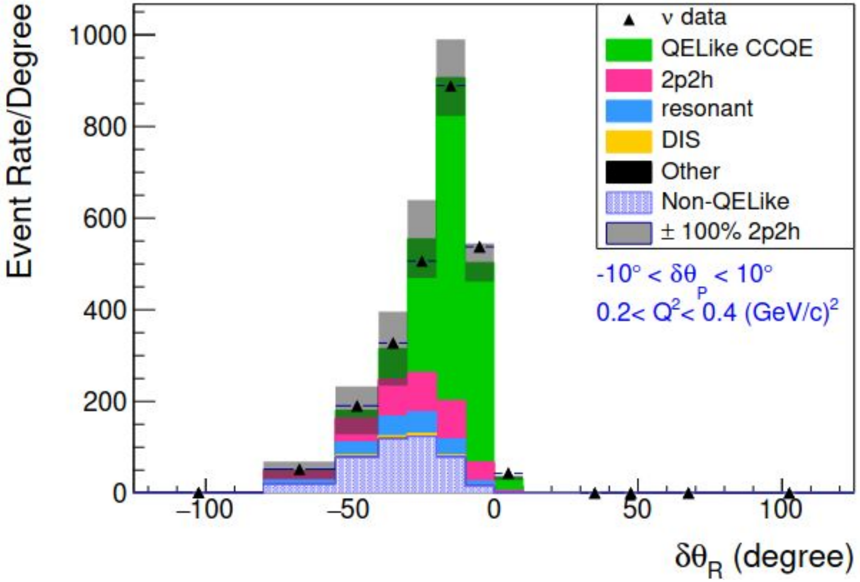
- The data here were from an anti-neutrino dominated beam
- We also have data from a neutrino dominated beam and the analogous process with a μ- and a proton in the f.s.
  - But, there is no elastic signal!
  - So we can look to see how well the signal region in the $(\delta\theta_P,\delta\theta_R)$ plane is modeled!
- We use events with a tracked proton from the vertex to predict where the neutron would have gone.
- With this we can repeat the background constraint exercise.

Validation using the ν_μ sample



- Generally good agreement.
- Small discrepancy between 0.2 and 0.4 GeV^2
- This can be accounted for by a 100% increase in the 2p2h rate

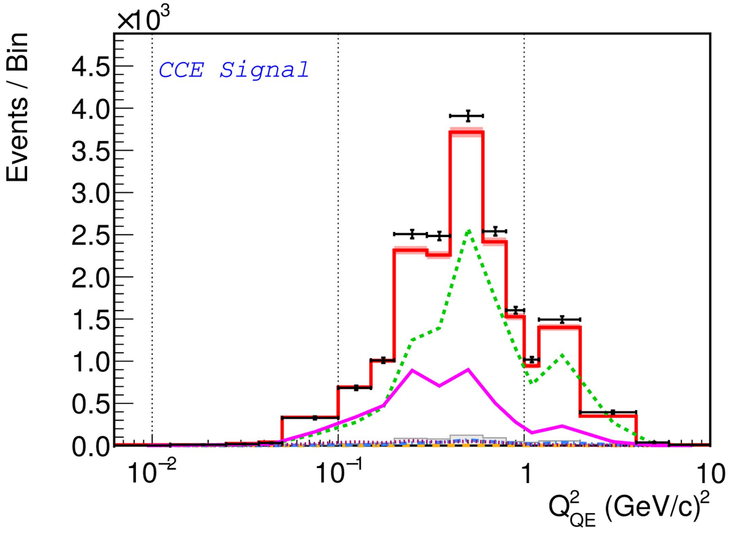
Validation using the ν_μ sample

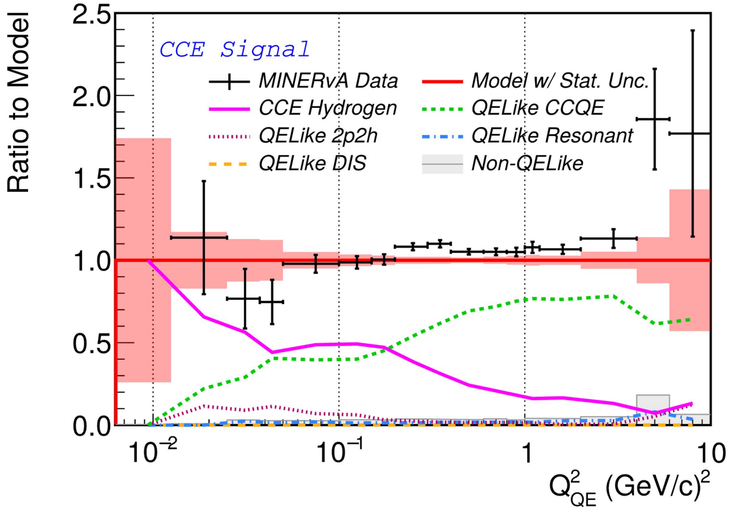


- The elastic signal region is just the central two bins.
- The gray band indicates +/- 100% 2p2h (pink)

Getting to a cross-section

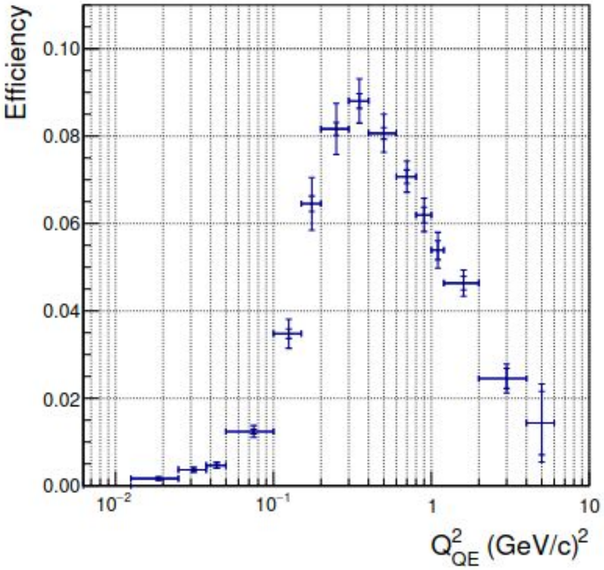
- The observable is events per Q^2 bin in the signal region (+/- $|\delta\theta_{P,R}| < 10°$)
- After constraint the backgrounds are subtracted from the event sample in the signal region





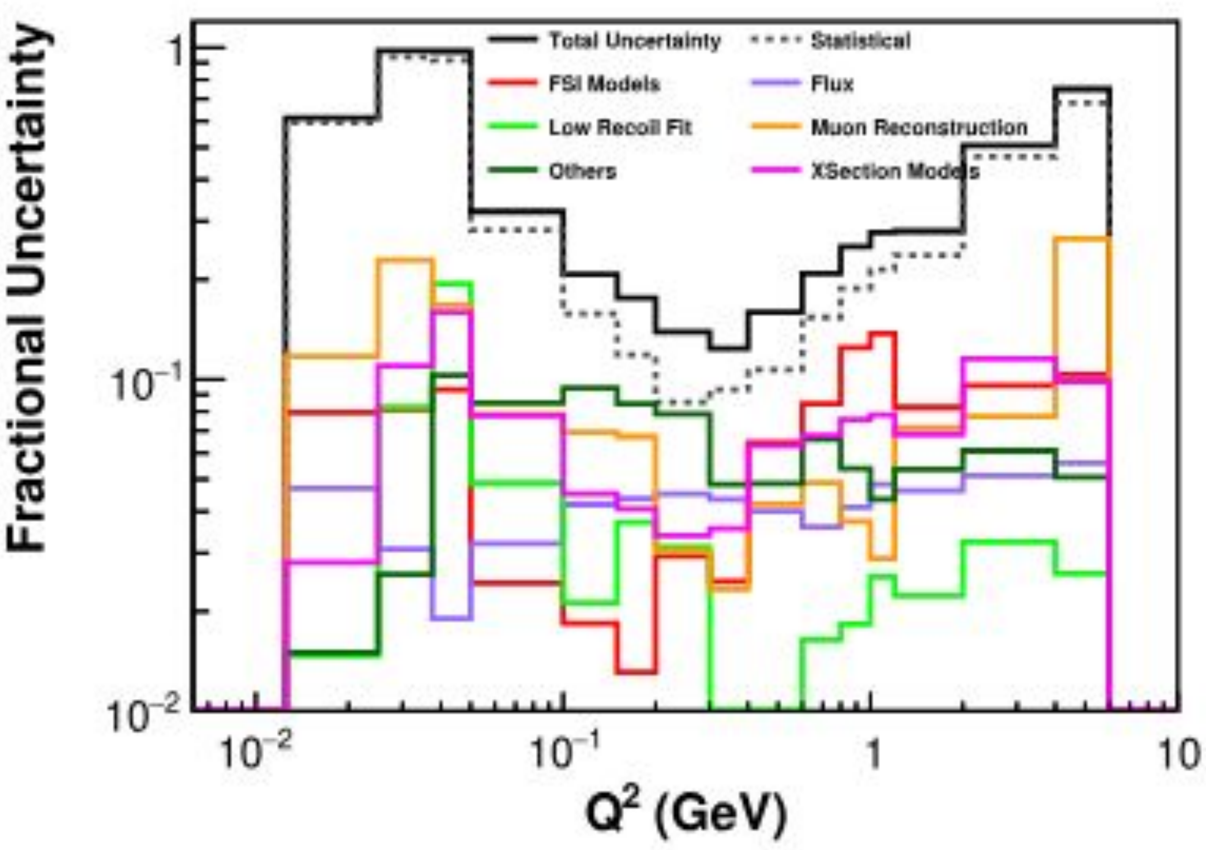
Getting to a cross-section

- The observable is events per Q^2 bin in the signal region (+/- $|\delta\theta_{P,R}| < 10°$)
- After constraint the backgrounds are subtracted from the event sample in the signal region
- The distribution is then unfolded using the d'Agostini method
- An efficiency correction is applied
- The predicted neutrino flux and target mass are incorporated to produce a cross-section



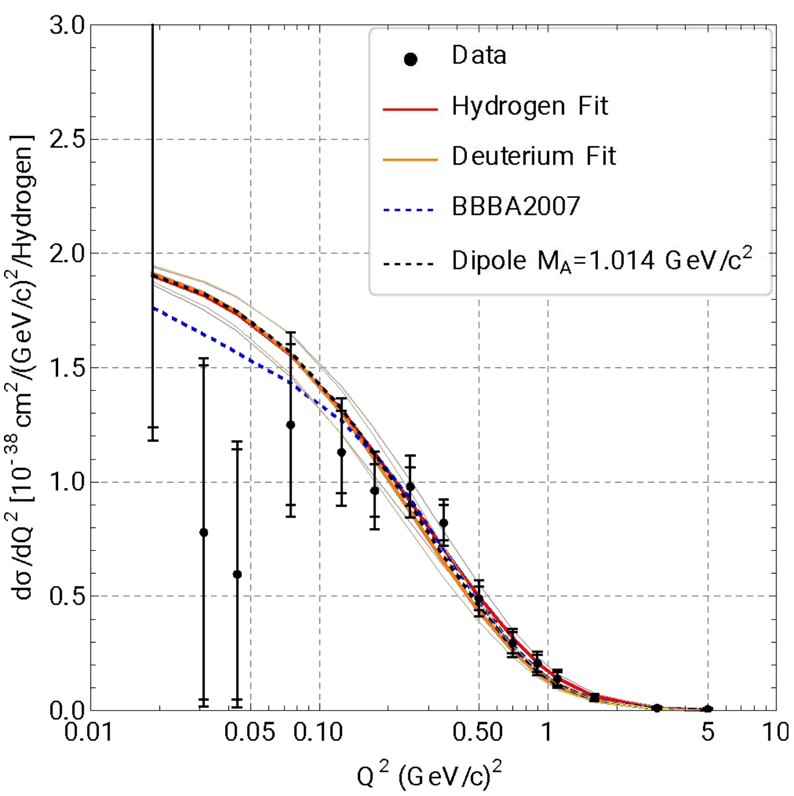
Systematics

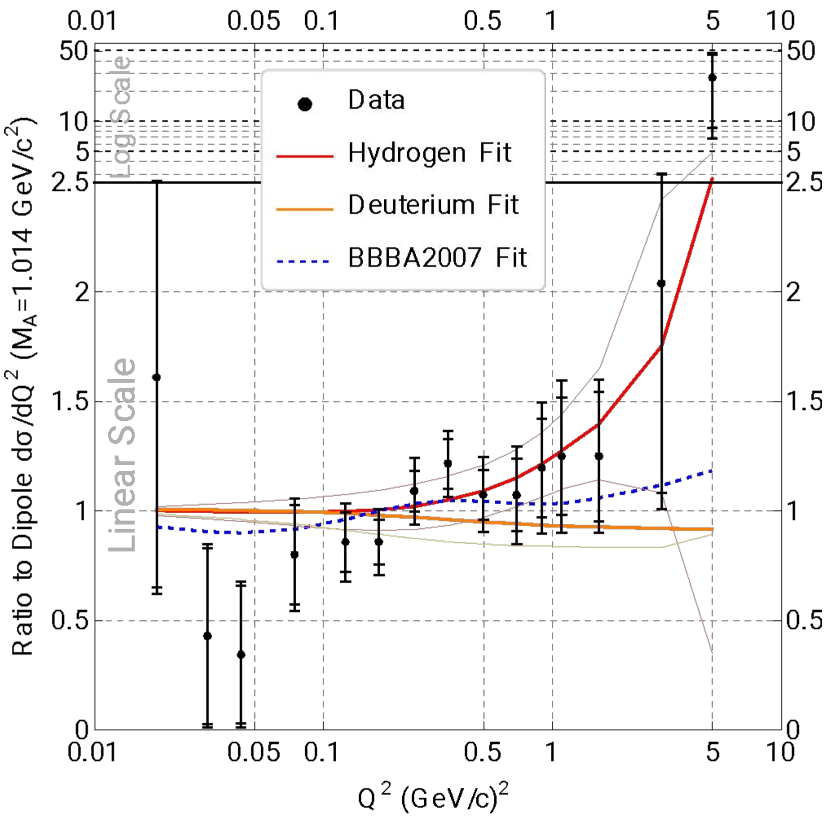
- Systematics are incorporated by redoing the entire analysis with one or more uncertain parameters in the MC shifted. There are several 10s of these.
- This produces a new result.
- After doing this for all uncertain parameters the variance in the result gives the uncertainty.



- Secondary neutron interactions: 4.8%
- CCQE normalization: 4.5%
- μ energy scale: 4.2% (MINOS), 3.1%(MINERvA)
- Flux: 3.9%
- neutron FSI: 3%
- 2p2h: 2.3%

Result: $d\sigma/dQ^2$





- The H (this work) and D fits use the z-expansion formalism as in Meyer et al, Phys Rev D 93 (2016) 11, 113015
- BBBA 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.

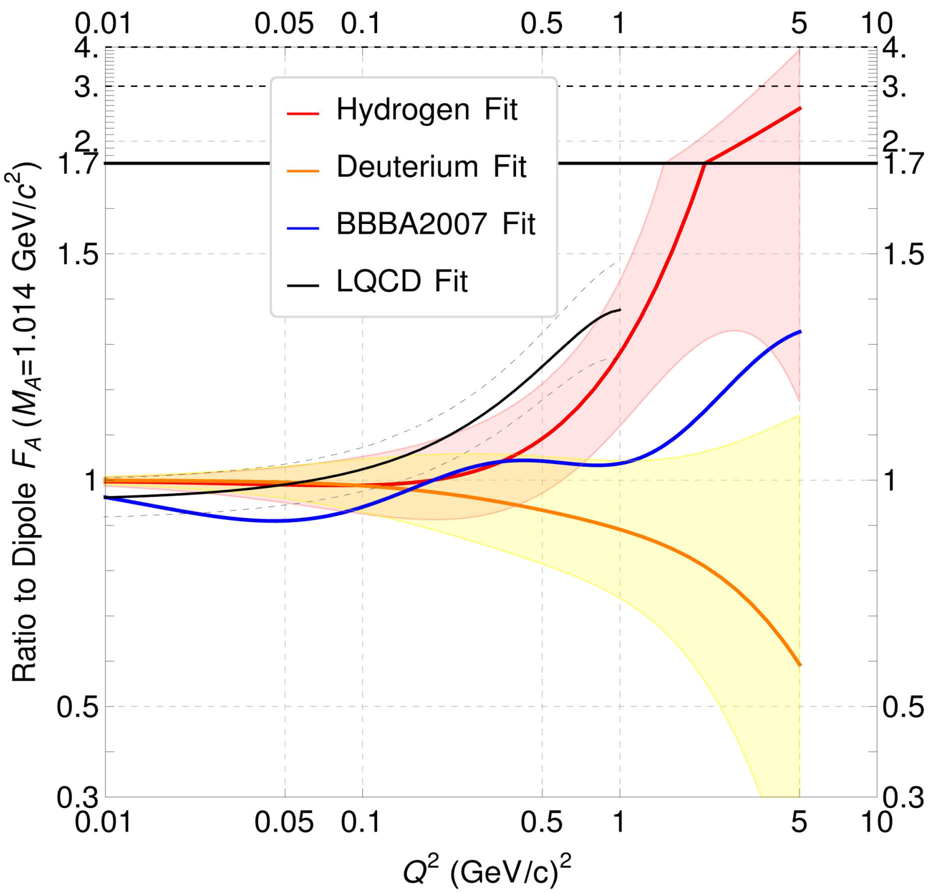
Result: $F_A(Q^2)$

z-expansion

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

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

- k_{max}=8 here and t_0=-750 MeV
- $t_{cut} = 9m_\pi^2$
- The chi-square includes a regularization term that penalizes higher order a_k terms to prevent overfitting
- There is a sum-rule that makes only k_{max}-4 of the a_k free
- $F_A(0)$=-1.2723 from beta decay



$$F_{\mathrm{A}}(Q^2) = F_{\mathrm{A}}(0)\left(1 - \frac{\langle r_A^2\rangle}{3!}Q^2 + \frac{\langle r_A^4\rangle}{5!}Q^4 + \dots\right) \longrightarrow r_A \equiv \sqrt{\langle {r_A}^2\rangle} = 0.73(17)\ \mathrm{fm}$$

Summary

- A major goal of MINERvA was to measure $F_A(Q^2)$
- Thanks to the large dataset enabled by the powerful NuMI beam we were eventually able to collect 5580 signal events with a data constrained background of 12500 events.
- Roughly 10% uncertainties on the ratio to dipole in the range $0.1 < Q^2 < 1.0$ GeV^2 dominated by statistics but systematics starting to become noticeable.
- No new data for a while. The DUNE near detector complex's SAND detector may be able to do a similar measurement (i.e., kinematics selection) and there are proposals for H and D targets or bubble chambers or gas TPCS with (some) H in them.
- Data release at https://minerva.fnal.gov/data-release-page/

Questions?

Some colors

Spirit Gold

Patina

Colonial Yellow

Vine

College Sky

Weathered Brick

Moss

College Woods

Slate

Griffin Green

Wren Twilight