Measuring the Structure of Protons with Accelerator Neutrinos at MINERvA

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This talk is based on *Nature*, 614, 48-53, “Measurement of the axial vector form factor from antineutrino–proton scattering”.

It is the scientific work of the MINERvA Collaboration.

Key contributors to this analysis:
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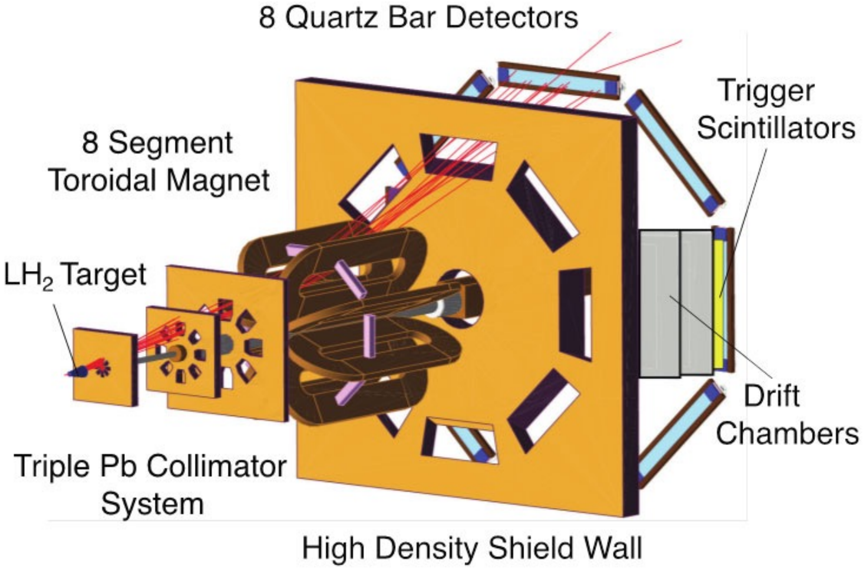
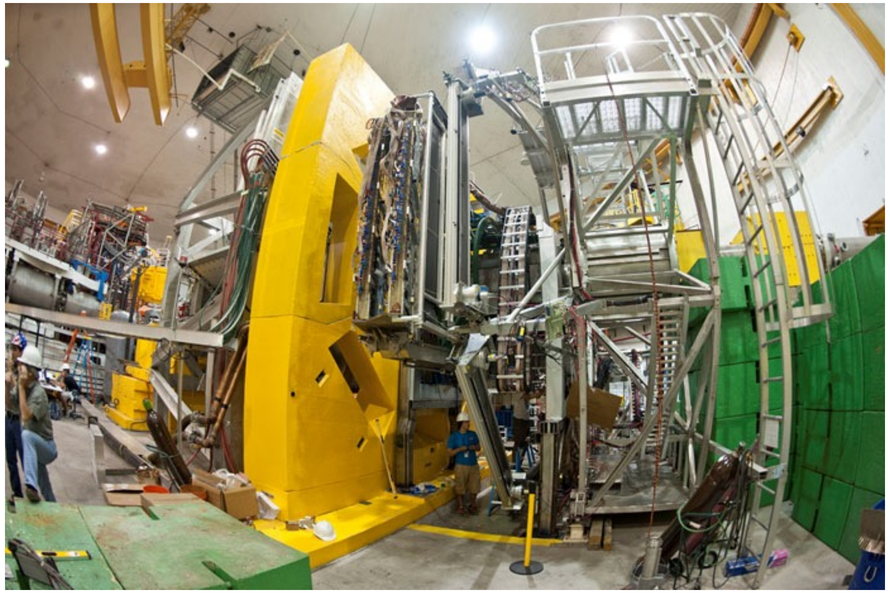
Arie Bodek, KSM

(NuMI Magnetic Horn, Photo Credit: Reidar Hahn)

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?





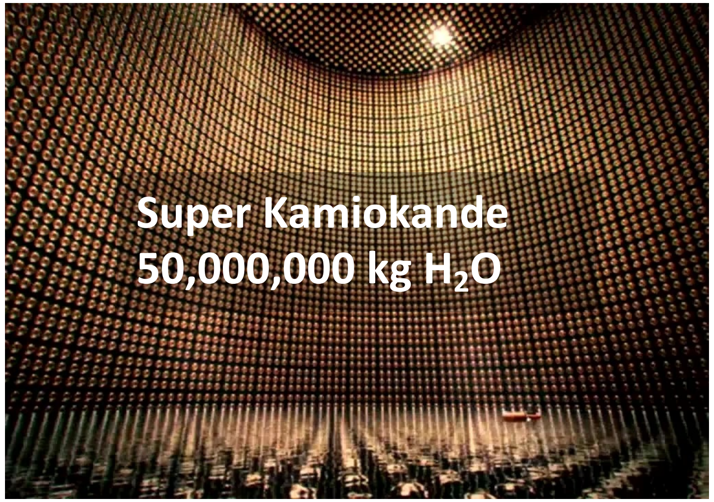
Qweak $A_{ep} = (-279 \pm 35 \pm 31)\times 10^{-9}$ Phys.Rev.Lett. 111 (2013) 141803

How Hard are They?

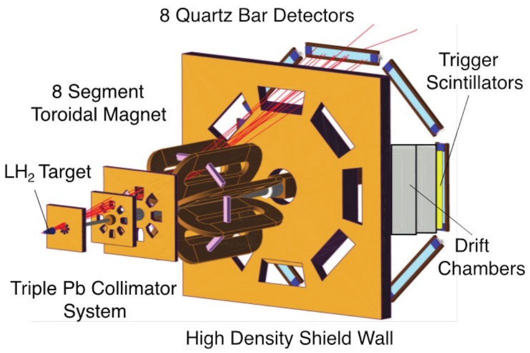
- For neutrino oscillation experiments, several % transition probabilities must be measured to few ‰ absolute precision…
  - The non-neutrino community just yawns. So what?
- The problem is that neutrinos just don't interact, much.
  - For example, the mean free path of a 600 MeV neutrino from the T2K beam in the water of the Super-Kamiokande is the distance from Earth to Neptune.
  - Another metric: 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.
- So neutrino experiments need enormous beam power and very large detectors to succeed. Think Megawatts of high energy proton beam power and significant fractions of a Megaton of 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…



Qweak
4 kg H_2



The MINERvA Experiment

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.

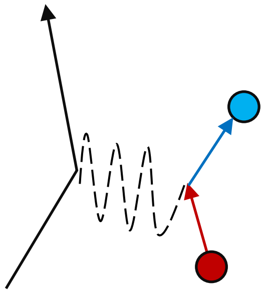
Did we achieve our goals?

- 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.

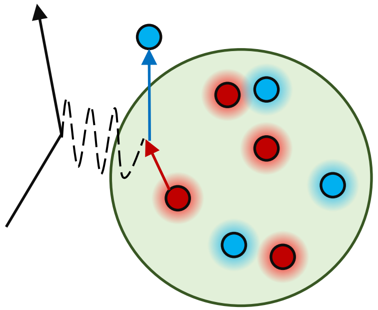
- So for example, one major reaction we want to understand are “quasielastic like” ones, $A(\bar{\nu}_{\mu}, \mu^{+} n \ldots)A'$ where the “…” allows for additional nucleons or fragments to be knocked out.
- These reactions make up a large fraction of the neutrino oscillation samples on nuclei, and the multi-nucleon knockout probability is larg and poorly modeled.

An aside: 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 today's star reaction, $\bar{\nu}_\mu p \to \mu^+ n$, a.k.a. $p\left(\bar{\nu}_\mu, \mu^+\right)n$,



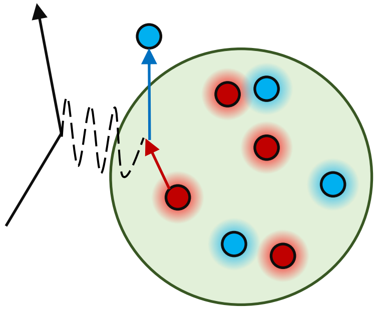
  quasielastic means we look at $A(\bar{\nu}_\mu, \mu^+ n \ldots)A'$.



- These measurements convolve nucleon structure with nuclear effects.
- And we mostly focus on nuclear effects.

An aside: MINERvA and Quasielastic Scattering (cont'd)

- What are the nuclear effects in quasielastic scattering?
  - 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)



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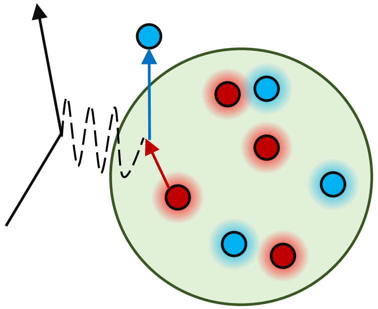

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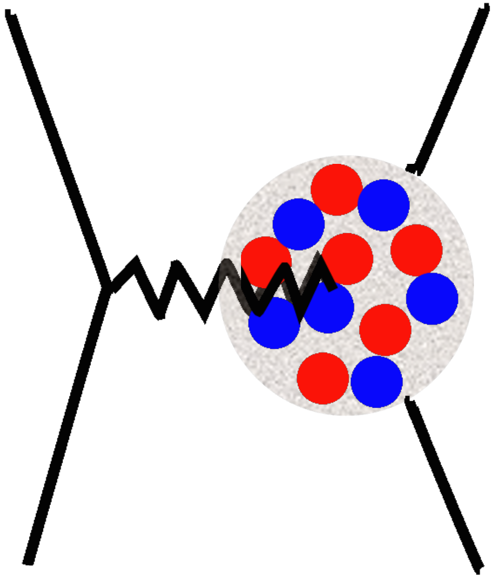
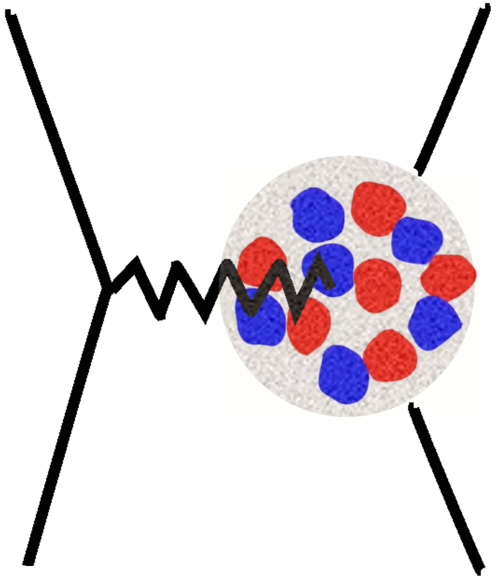


Nucleons are in nucleus are confined to a space of ~10^{-15}m.

By the uncertainty principle, they must have a spread in momentum, ~a few 100 MeV!



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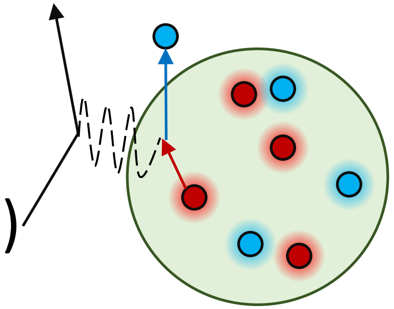
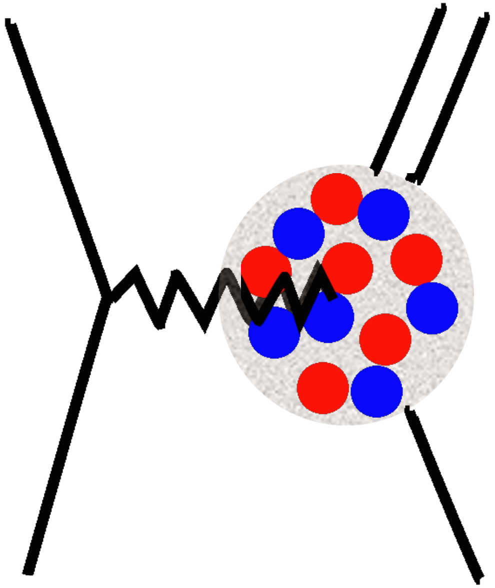
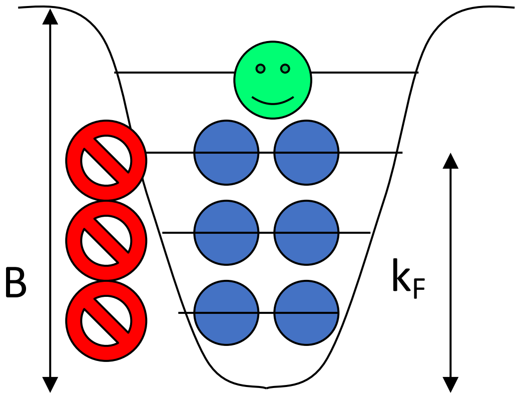




Can knock two nucleons out instead of one! This is referred to as a "two particle two hole" process ("2p2h").

"Pauli blocking". Only so many nucleons can live in each state in the nucleus, so low momentum struck nucleons must be in a higher state.



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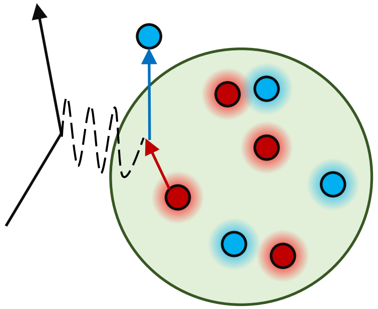
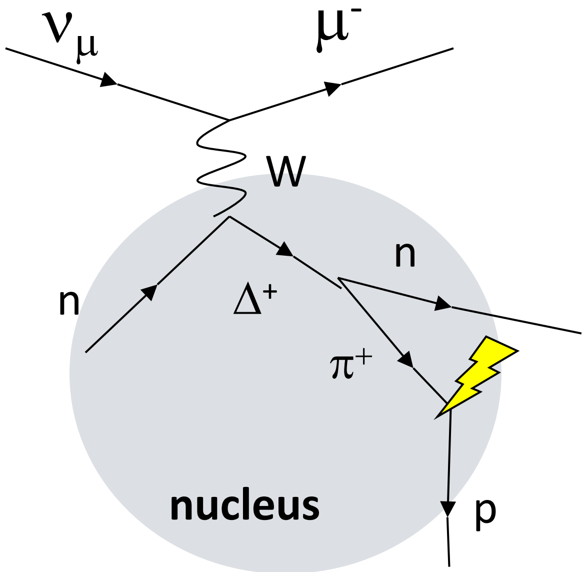


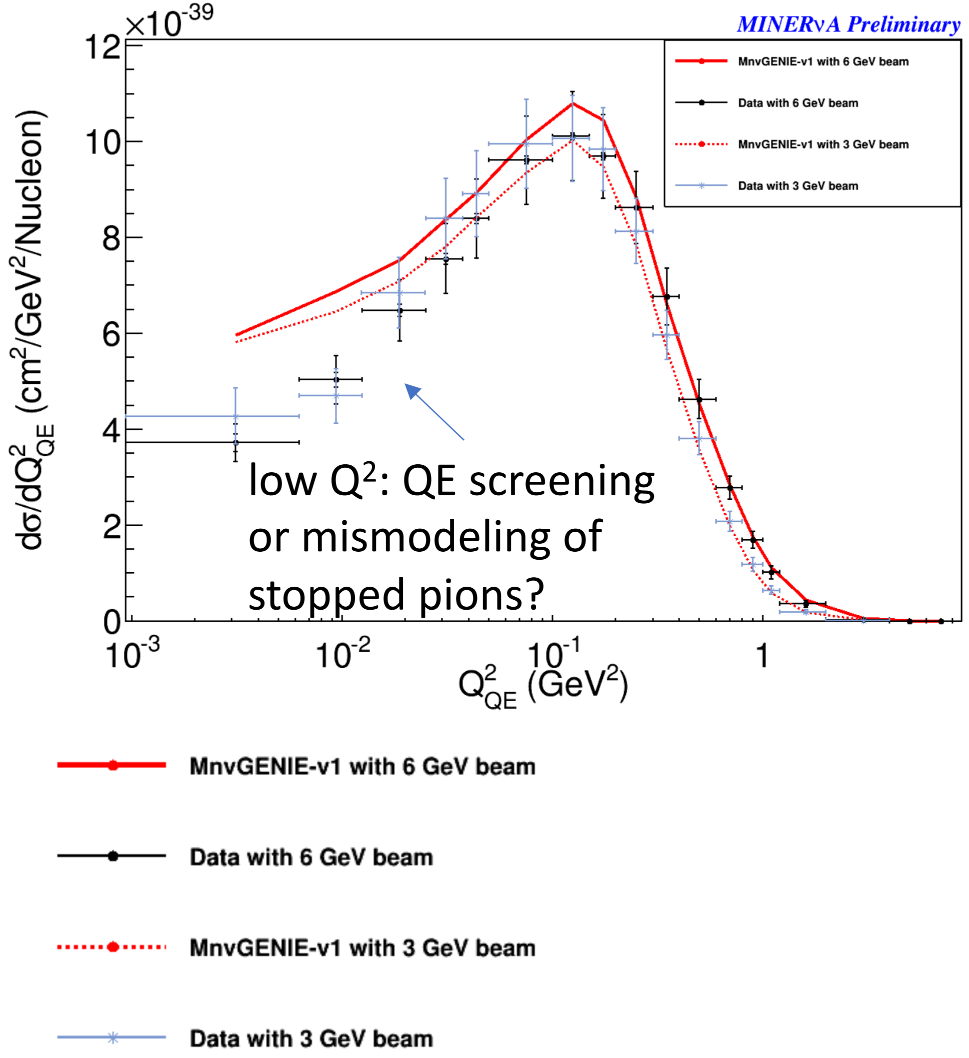
This process isn't quasielastic at all! The struck neutron is excited into a Δ baryon, which decays into nucleon+pion.

But the pion reinteracts in the nucleus and its energy knocks out another proton.

This is NOT rare. The "strong interactions" between nucleons, pions, and the nucleus are really strong!



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



- Data from MINERvA, as a function inferred (from the final state) of Q^2 at two different beam energies, $\langle E_\nu \rangle$~3 and $\langle E_\nu \rangle$~ 6 GeV.
  - Consistent physics trends observed.
- The process on free nucleons should be flat at low Q^2; it's not because of nuclear screening due to low wavelength of probe.
- The rate falls off at high Q^2 not because of nuclear effects, but because the nucleon if hit with that much momentum and energy will tend to break apart.
- I also want to brag about the astrophysics-like scale for a neutrino cross-section.

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

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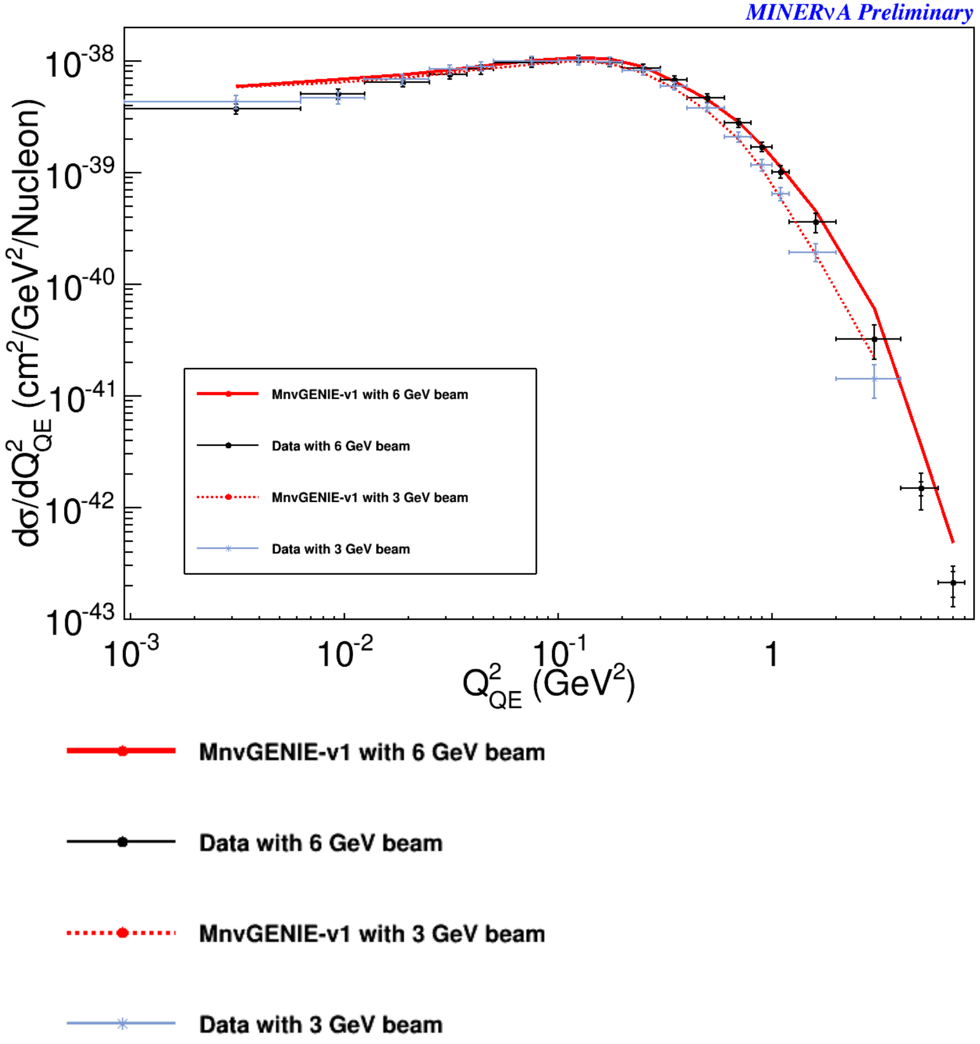

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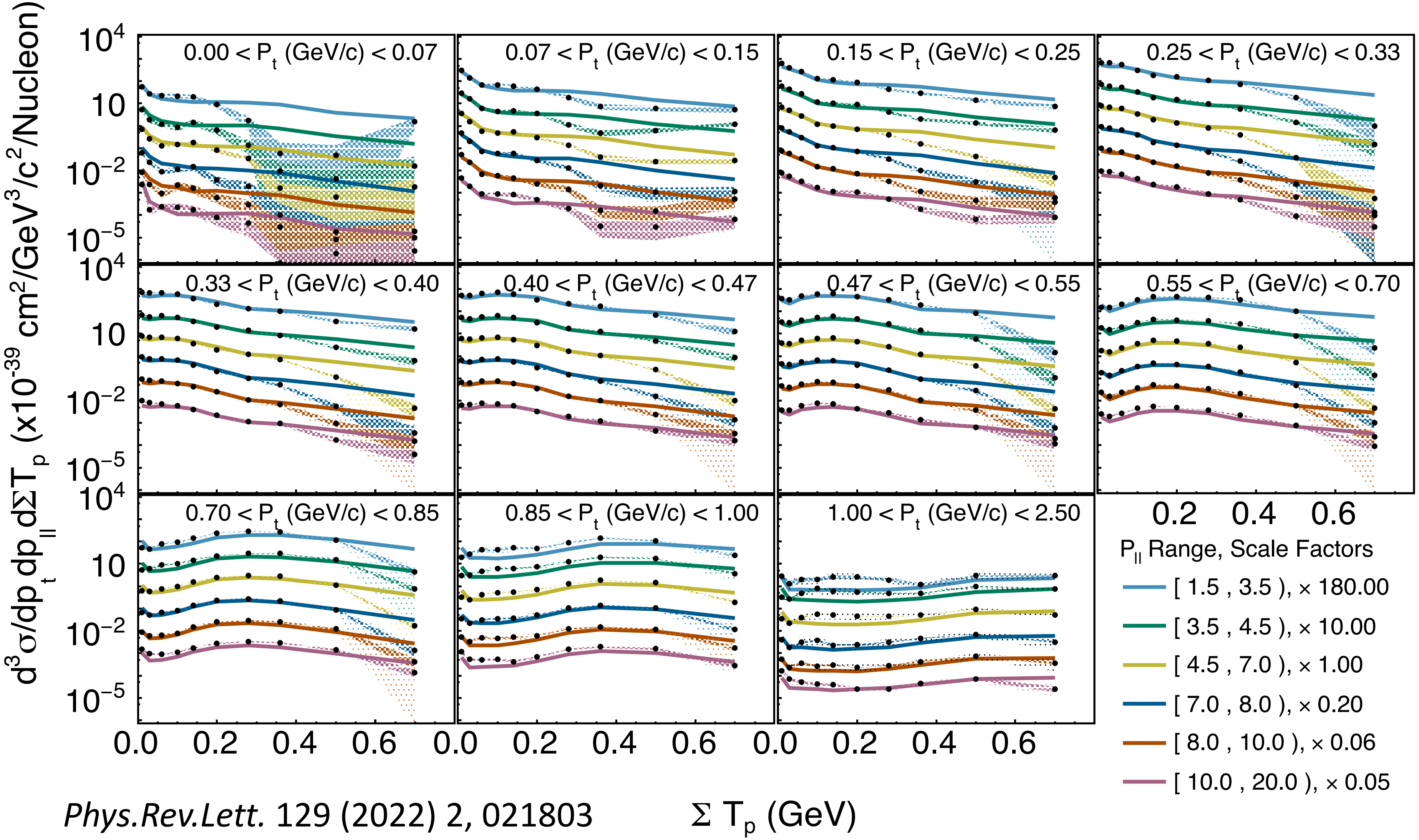
$A(\nu_\mu, \mu^- p \dots)A': d^3\sigma/d\Sigma T_p \mathrm{d}p_T \mathrm{d}p_\parallel$



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

- Looks like a charged lepton scattering structure function experiment? But it's neutrinos!
- Lines… $p_\parallel$ show consistent behavior, suggesting they are not strongly neutrino energy dependent.
- In a single bin of $p_\parallel$…

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

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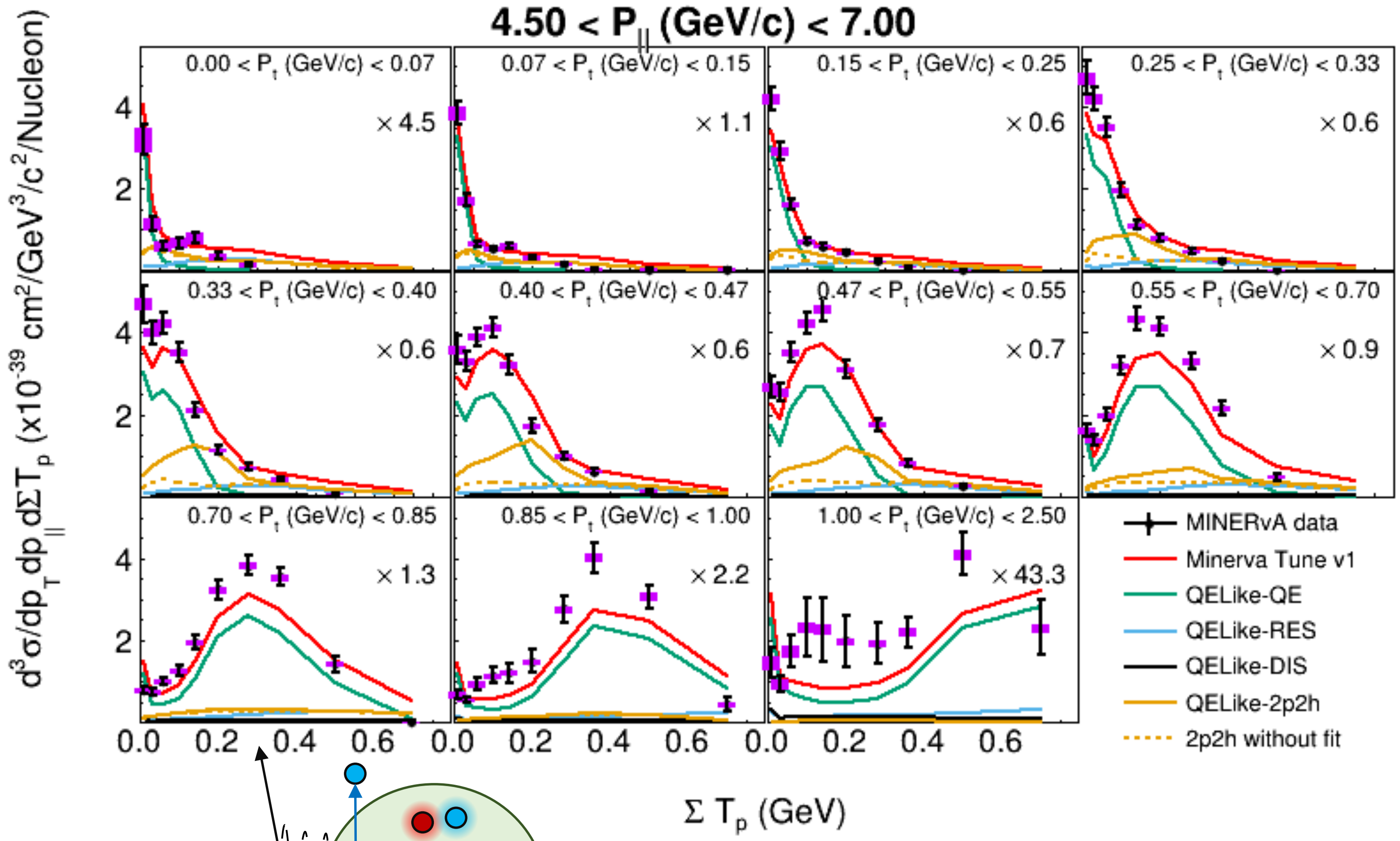
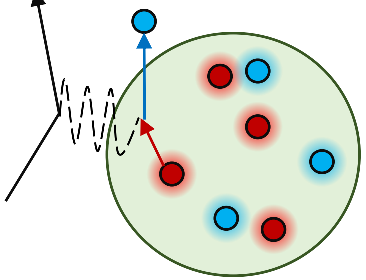
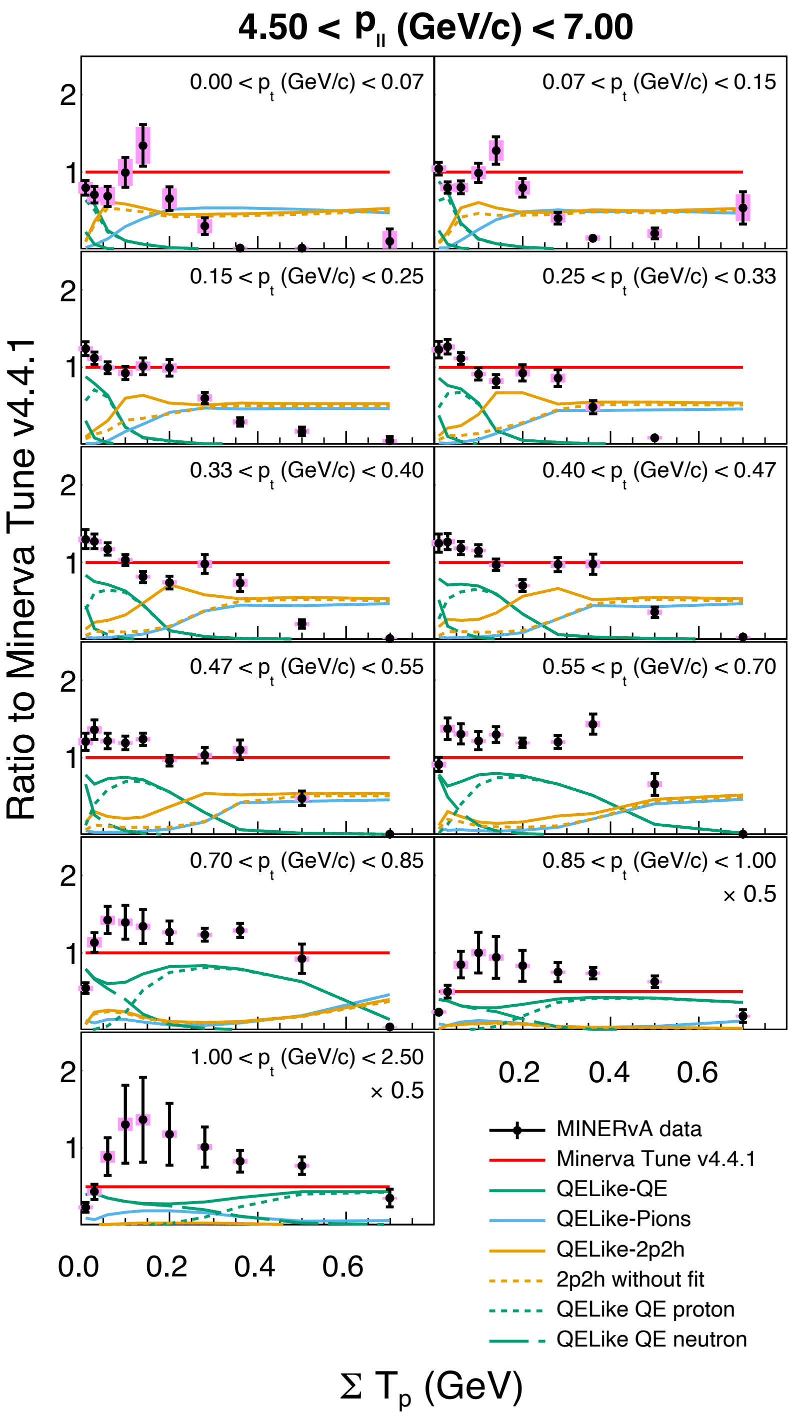




- If we were scattering on free nucleons, each of these plots, which represents on momentum of the muon, would be a delta-function, broadened by the width of the bin.
- There is a peak, but the nuclear processes broaden it out and add new reactions.



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

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

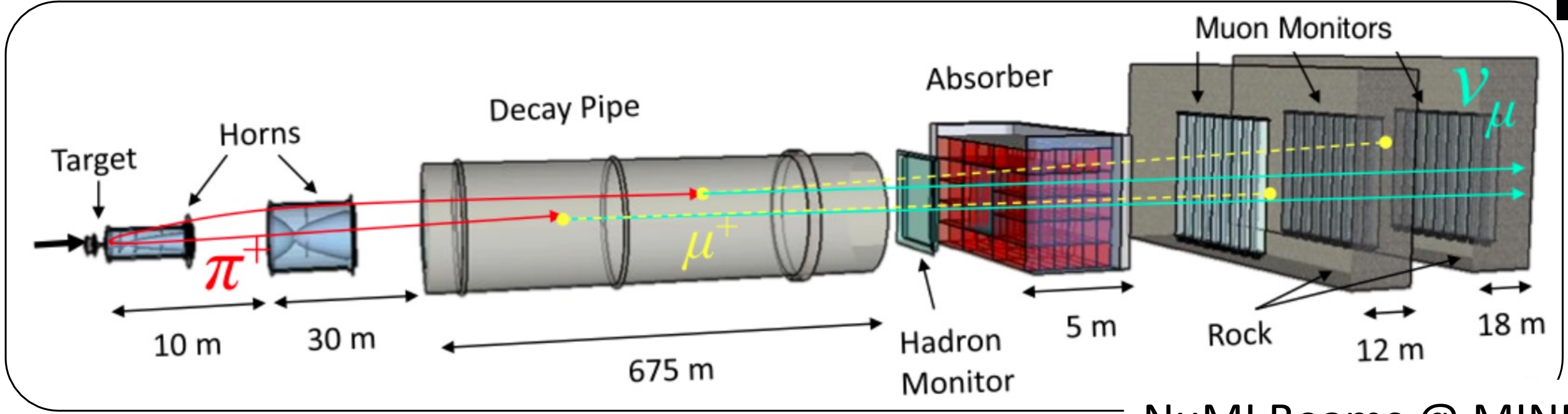
- The biggest discrepancy in cross-section, though not in the ratio, are the small deviations just above the QE peak, in the region we'd expect to be populated by multi-nucleon knockout ("2p2h").
- Low p_T high ΣT_p events predicted by the model as 2p2h and stopped pions are almost completely absent 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 and Free Nucleon Scattering

MINERvA, Repurposed for Neutrino-Nucleon Scattering

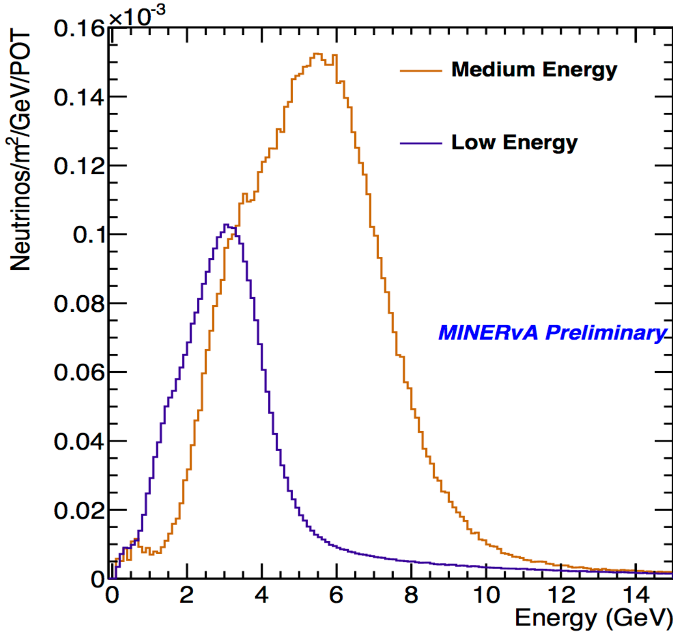
- We've demonstrated that MINERvA probes physics of scattering on nuclei.
- How does MINERvA then extract a sample of $\bar{\nu}_\mu p \to \mu^+ n$ from scattering on free protons?
- The technique is:
  1. Measure $\mu^+ + n$ final state on CH target.
  2. Kinematically separate elastic on H from quasielastic on C and subtract it.
  3. Use the same approach with the $\mu^- + p$ from the neutrino beam $\nu_\mu n \to \mu^- p$ as a control sample (no free neutrons!) 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

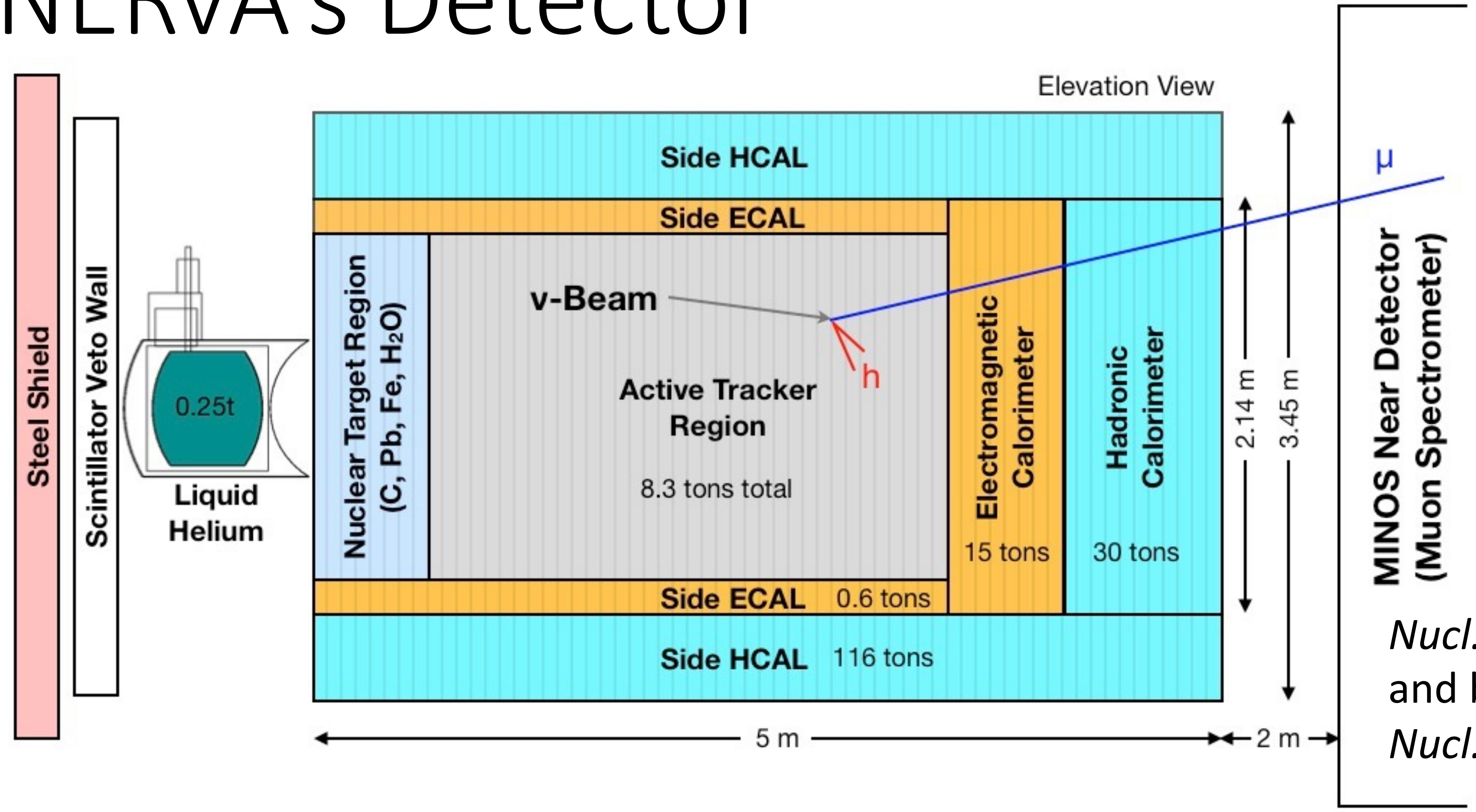


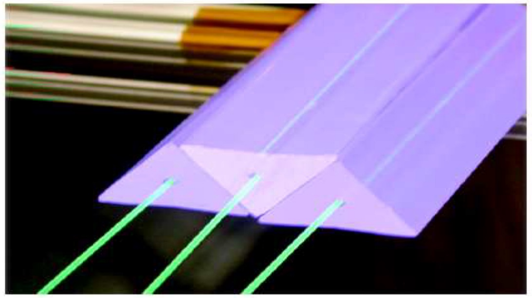
- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions.
- Implies significant uncertainties in flux from hadron production and focusing.
- Constrain, where possible, with hadron production data and in situ neutrino data ($\nu e \rightarrow \nu e$).

NuMI Beams @ MINERvA



MINERvA's Detector



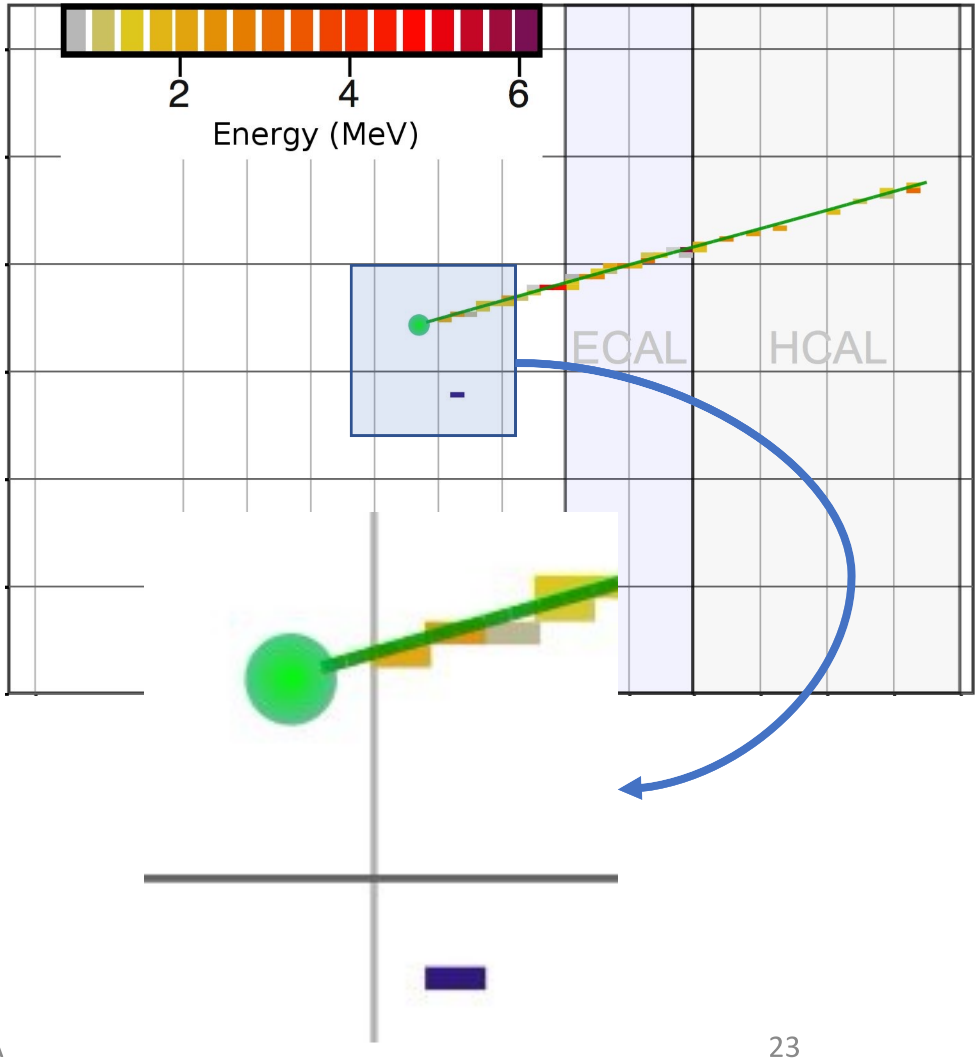


Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

- 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.

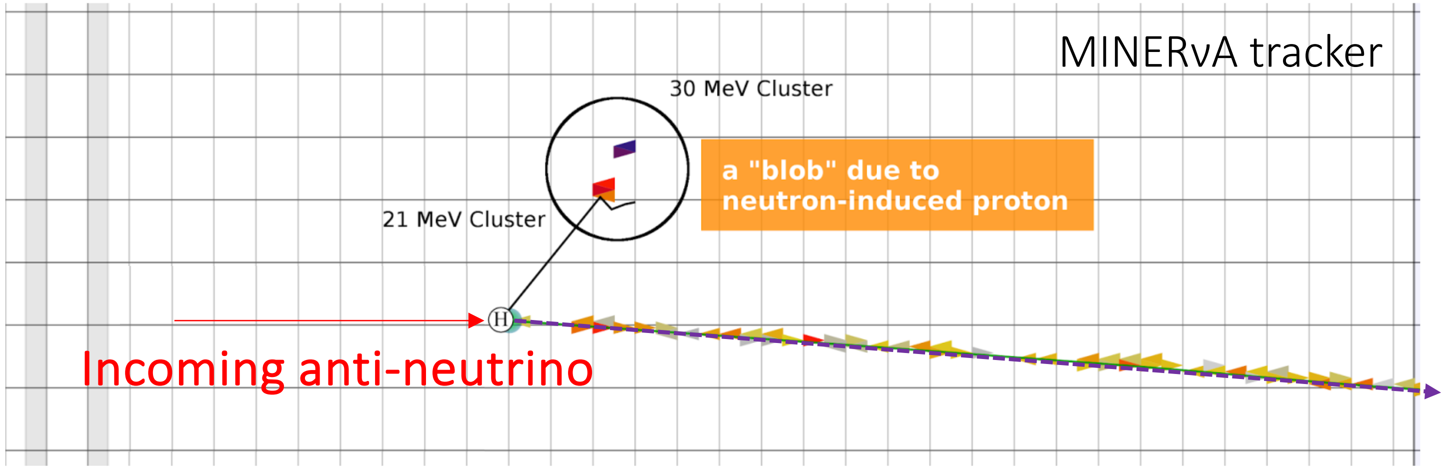
Detecting Charged Current Elastic Scattering in MINERvA

- Final state of $\bar{\nu}_\mu p \rightarrow \mu^+ n$ in MINERvA is an energetic μ^+ and a (usually) much lower energy n.
- Neutrons don't directly leave signals in scintillator as they pass through.
- 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.



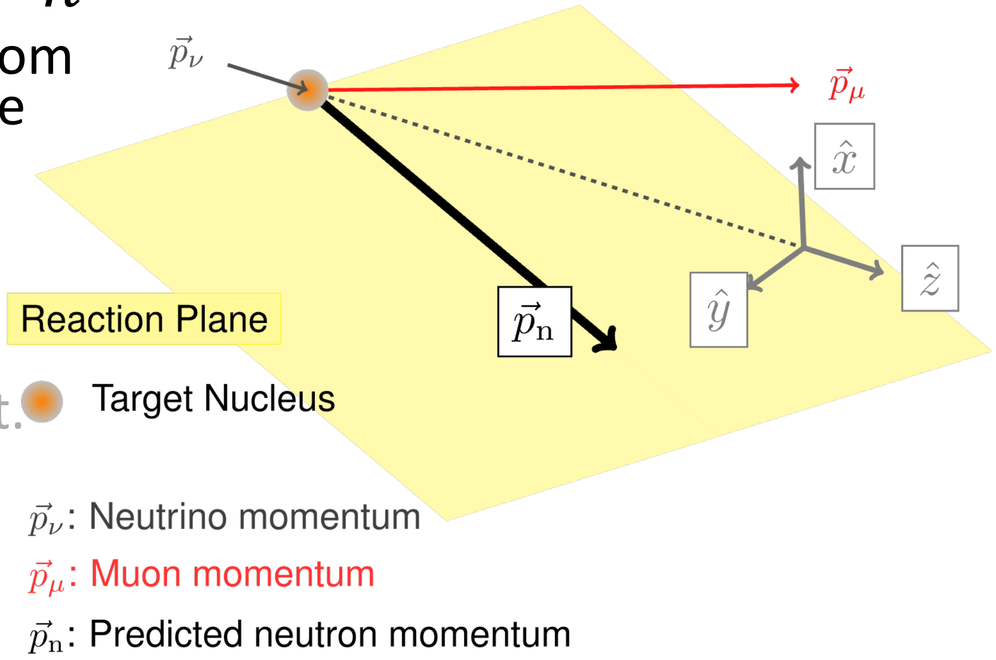
Selection of CCE Events

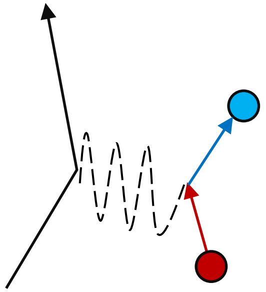
- No visible hadronic tracks from charged pions or protons.
- Proton recoil from neutron must be 10 cm away from the muon axis, to remove δ-ray background.
- Muon reconstructable in the detector: E_μ [1.5; 20] GeV, $\theta_{\mu\nu} < 20°$



Signal and Background Separation

- Charged-current elastic on hydrogen: $\bar{\nu}_\mu p \to \mu^+ n$
  - 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.





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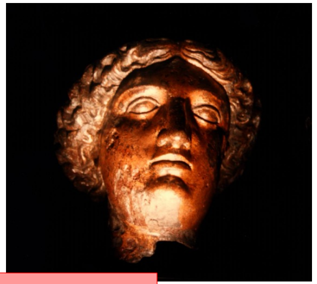

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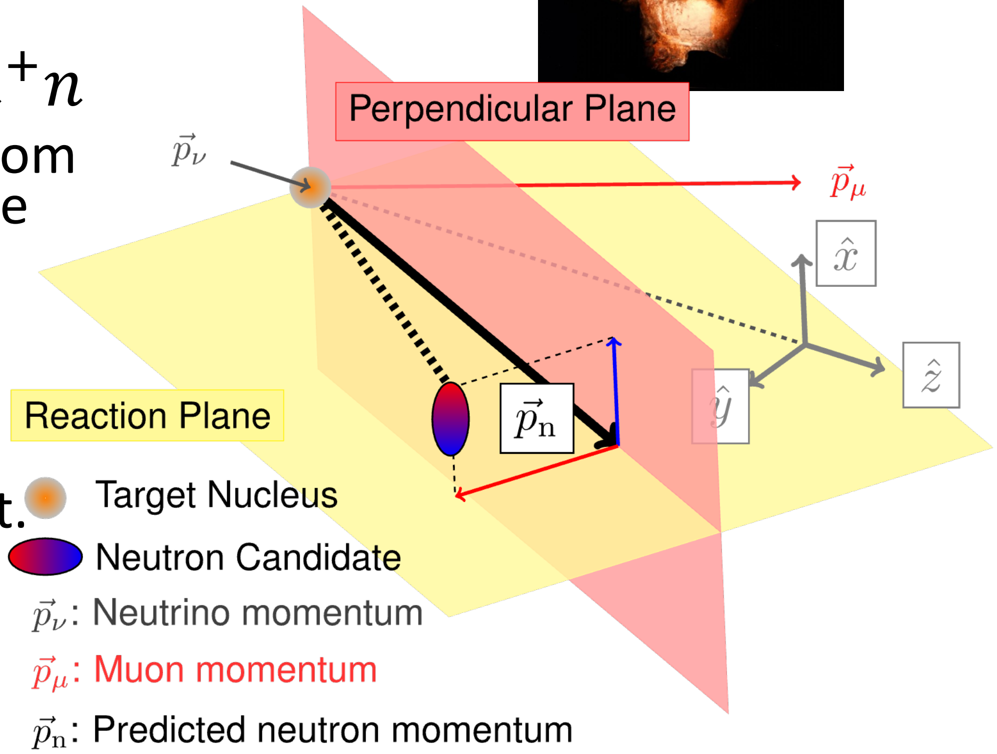

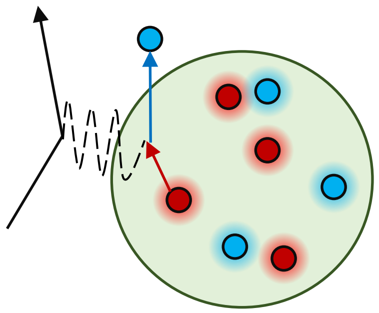

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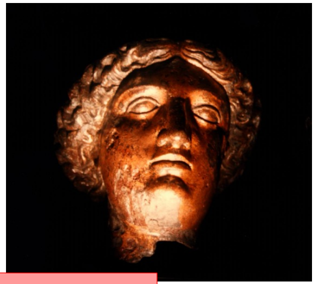

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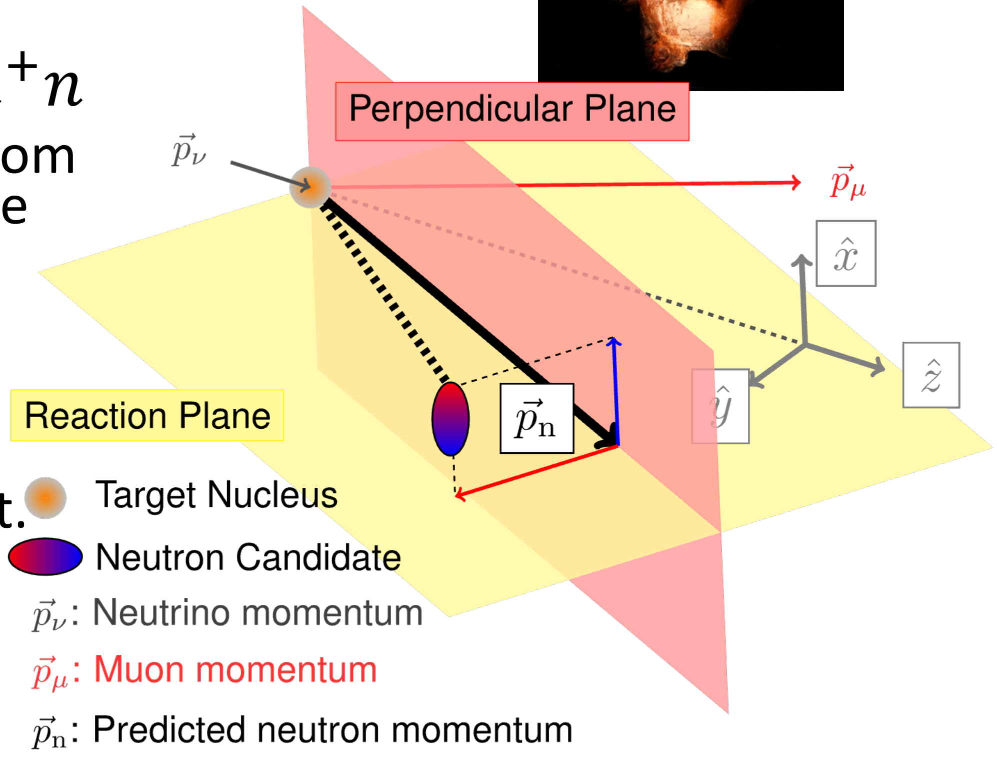
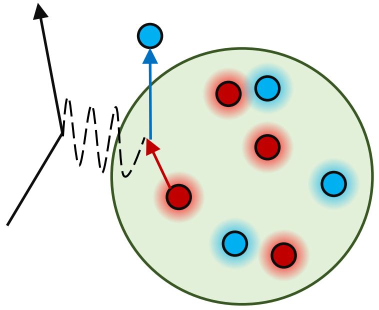
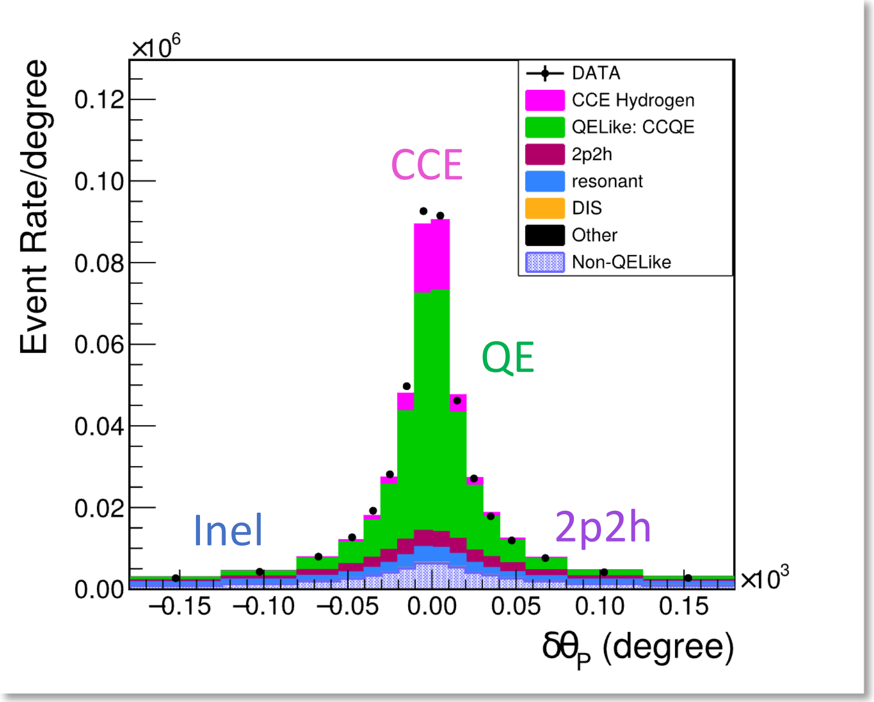
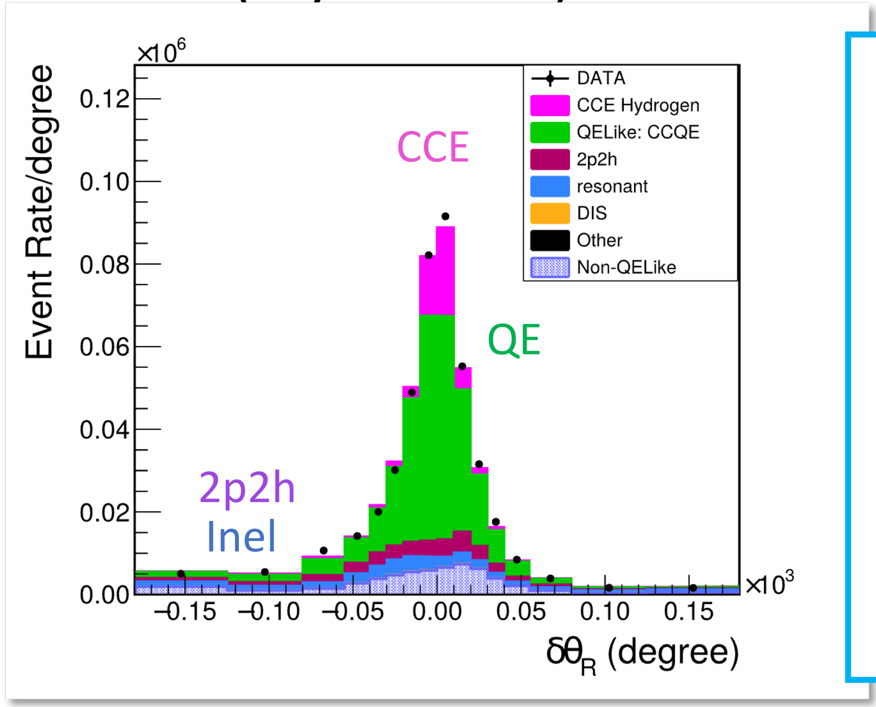


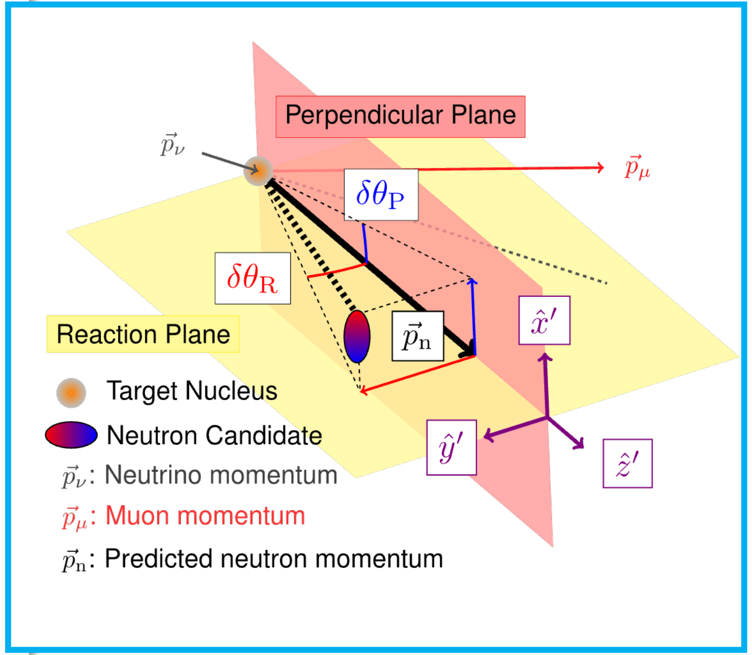


Signal & Background Separation (cont'd)

- 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.



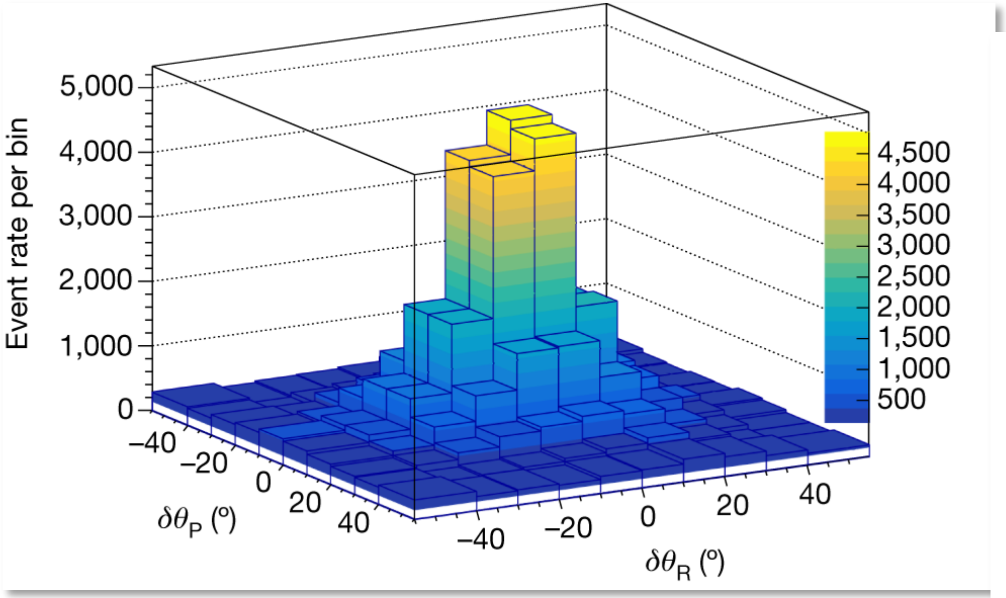




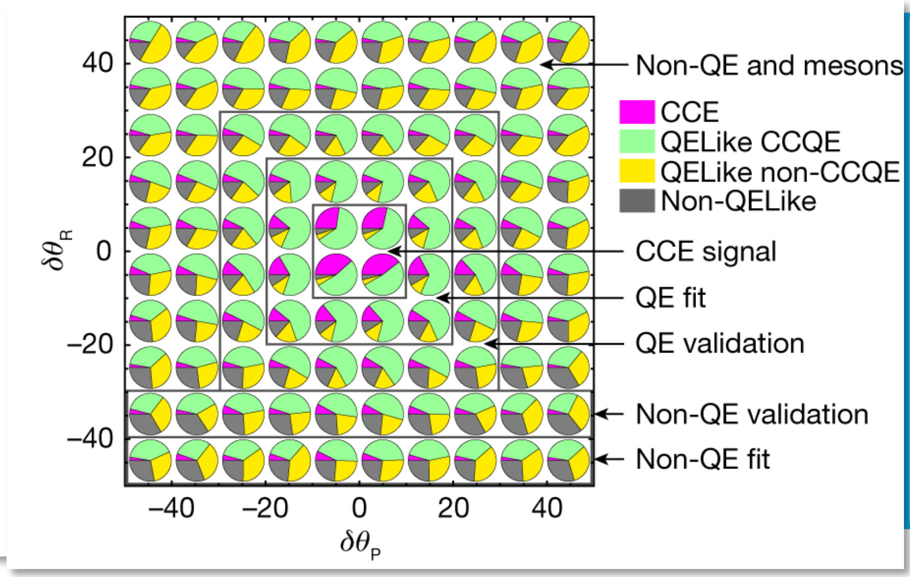
Signal & Background Separation (cont'd)

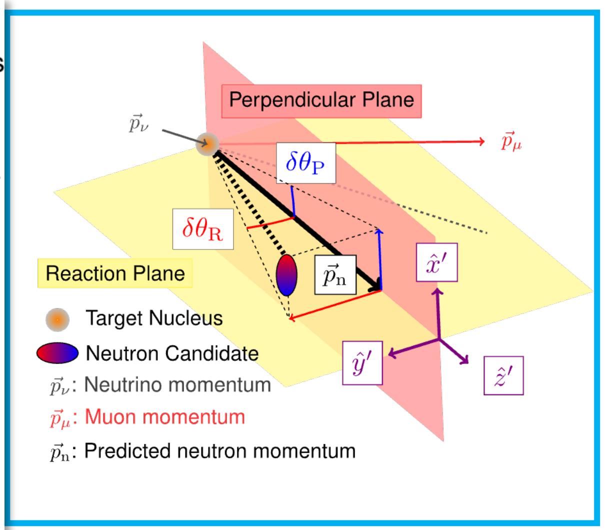
1. Fit different background rates, as a function of Q^2 from different regions of scattering angle deviation.
2. Check that other regions, not used in fit, are well predicted.
3. Use those results to predict the, now constrained, backgrounds.

"2D" Total event rate

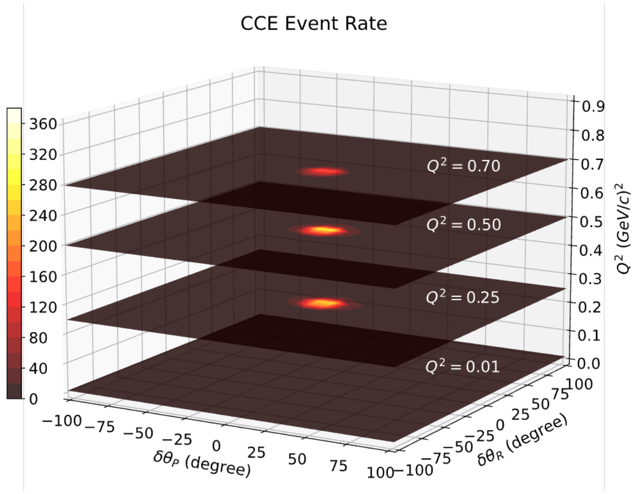


Fractions of rate predicted by model/simulation

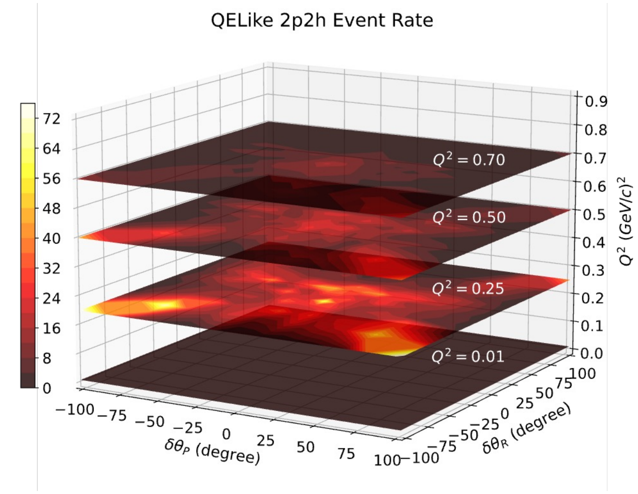




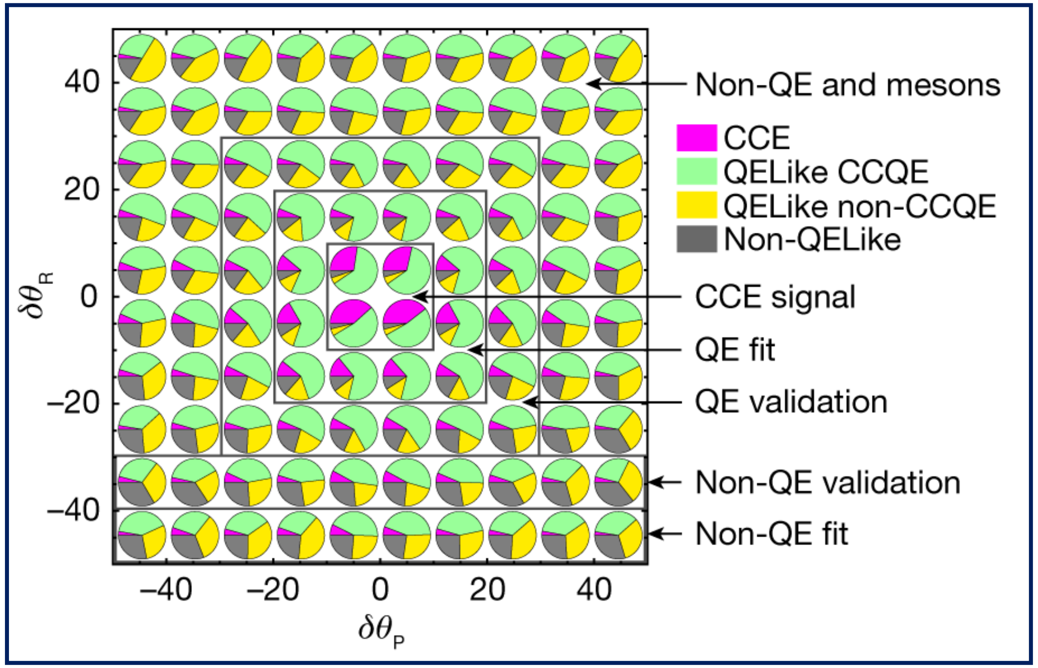
Signal & Background Separation (cont'd)



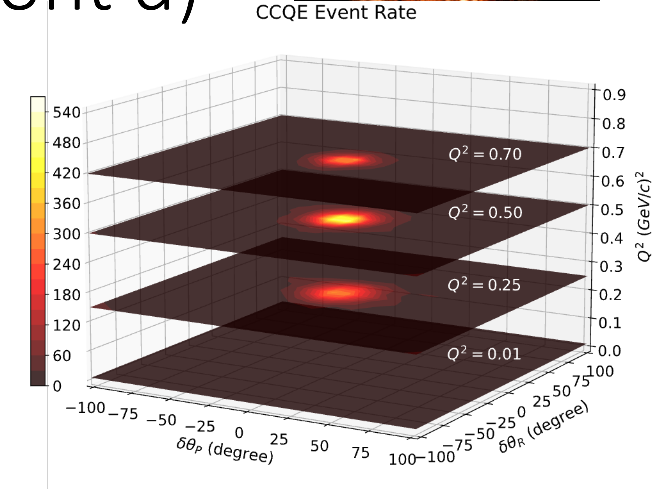
SIGNAL: Elastic on H



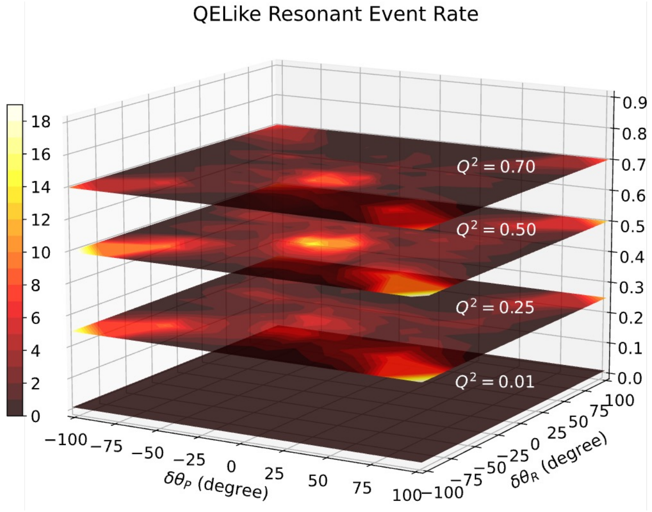
Background: QELike 2p2h



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

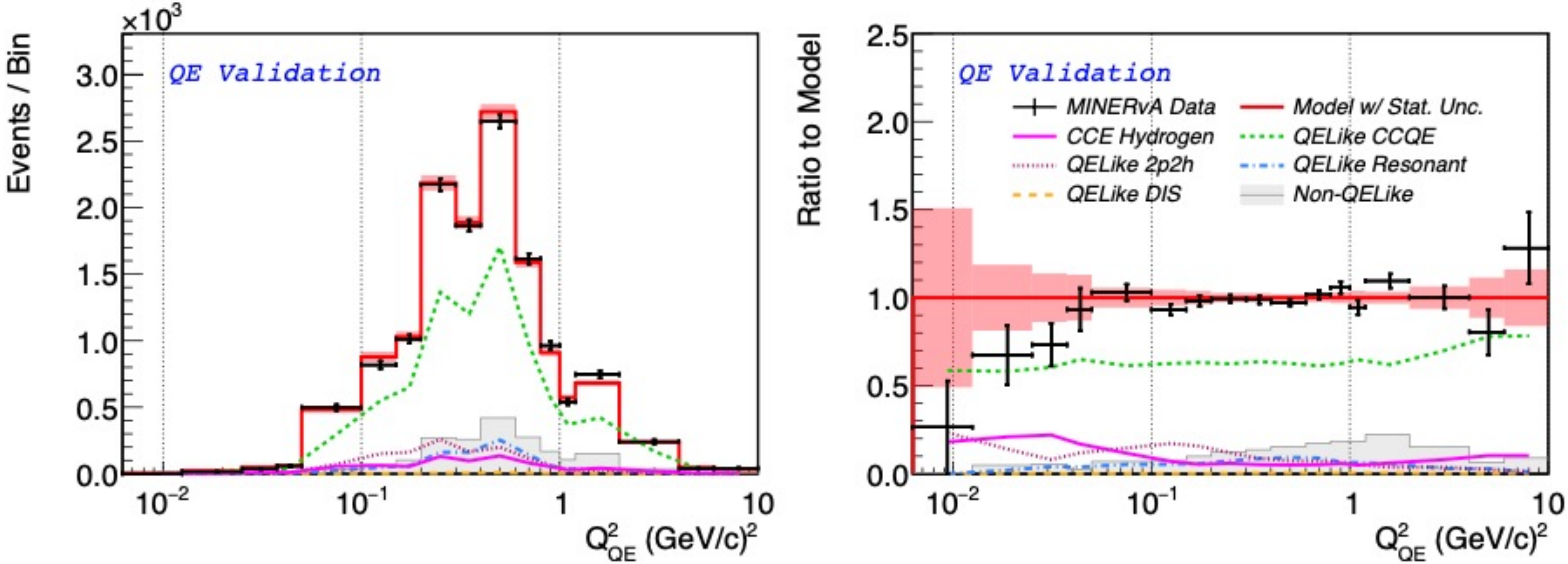


Background: QELike CCQE (on C)



Background: QELike Resonant

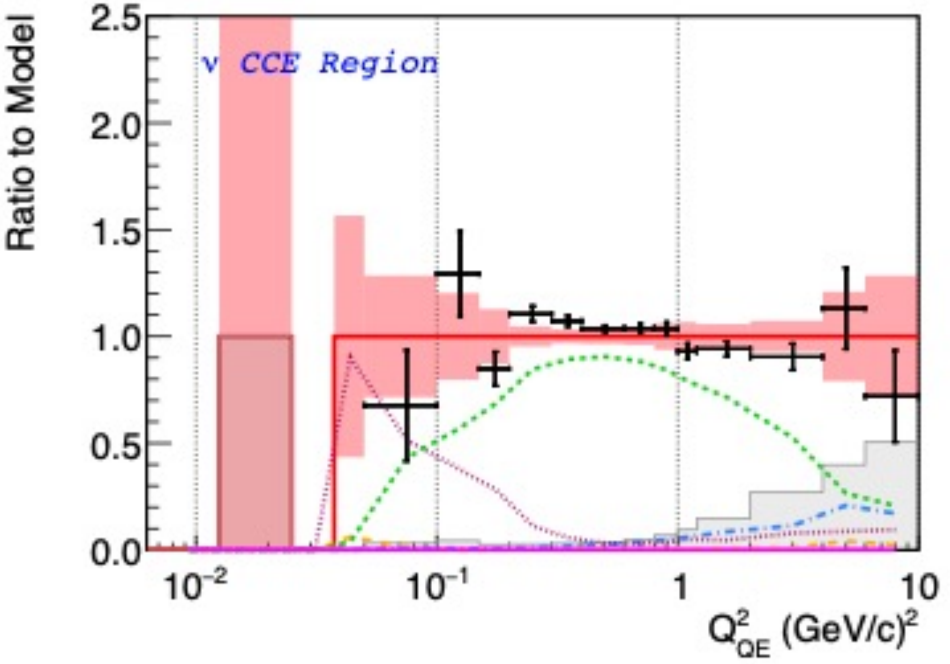
Results of Background Sideband Fits in QE “Validation” Region



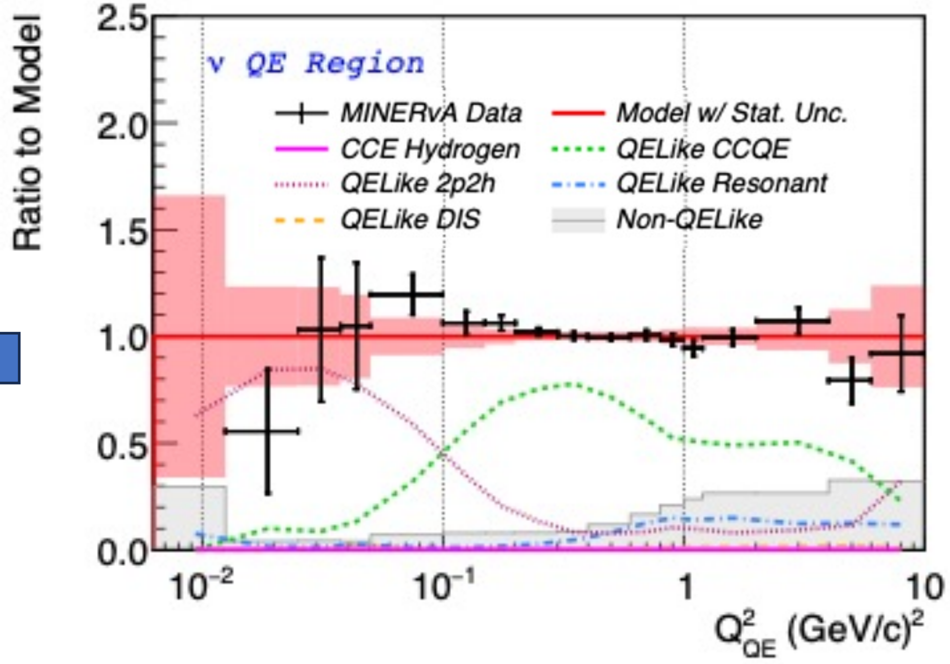
CCQE is dominant in this region. Small 2p2h, inelastic QE-like, and Non-QELike contributions. The fitted model, constrained by data, fits this region well.

Same Technique, applied to Control Sample of Neutrino Beam

Analog of signal region, but without free protons



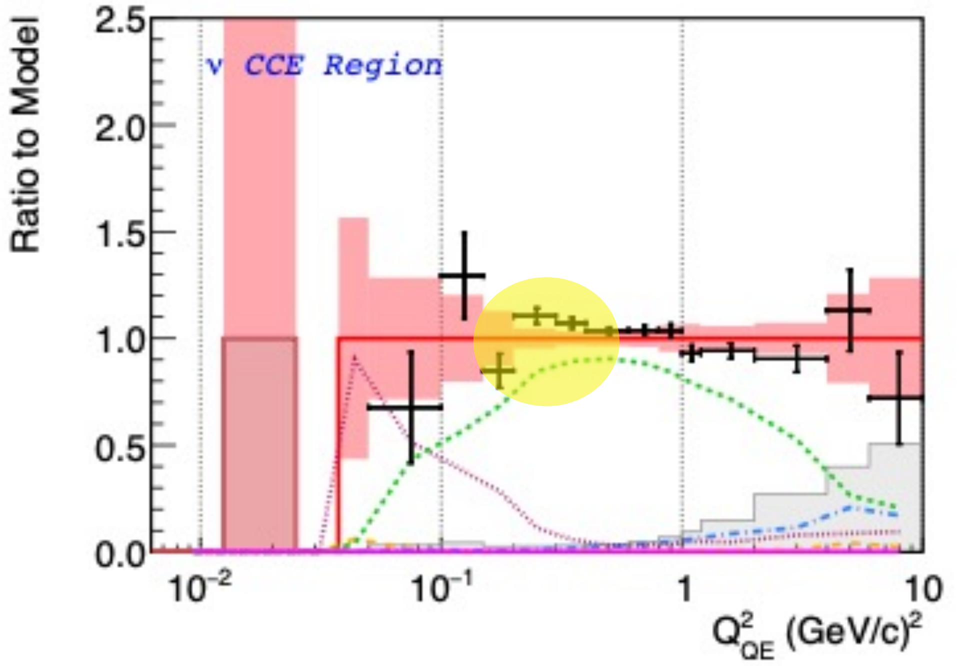
Quasielastic region



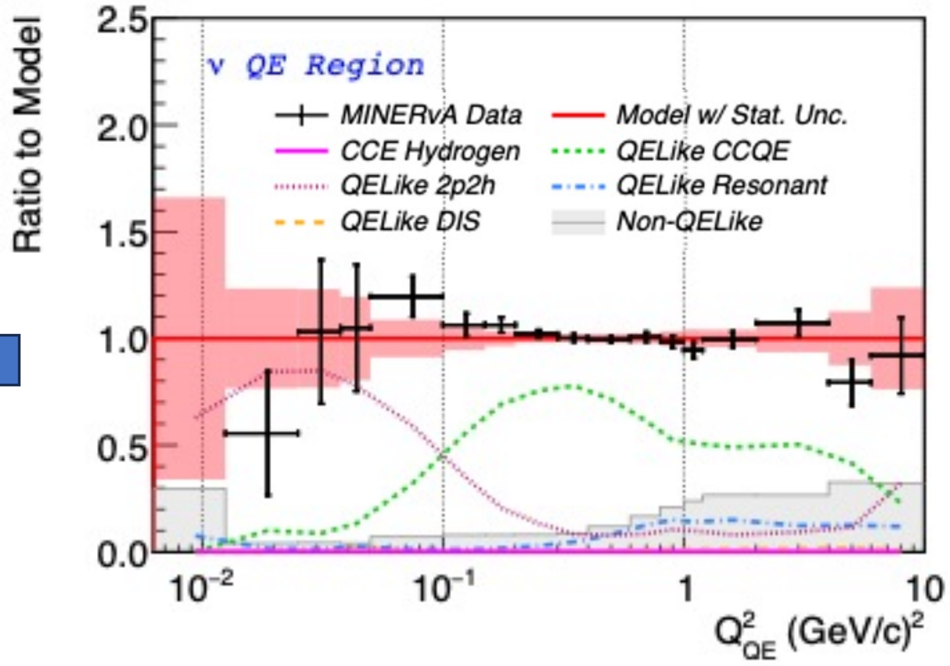
We select events with trackable protons in a neutrino sample. No CCE signal. Different final states and available kinematics. Apply same fitting mechanism.

Same Technique, applied to Control Sample of Neutrino Beam

Analog of signal region, but without free protons



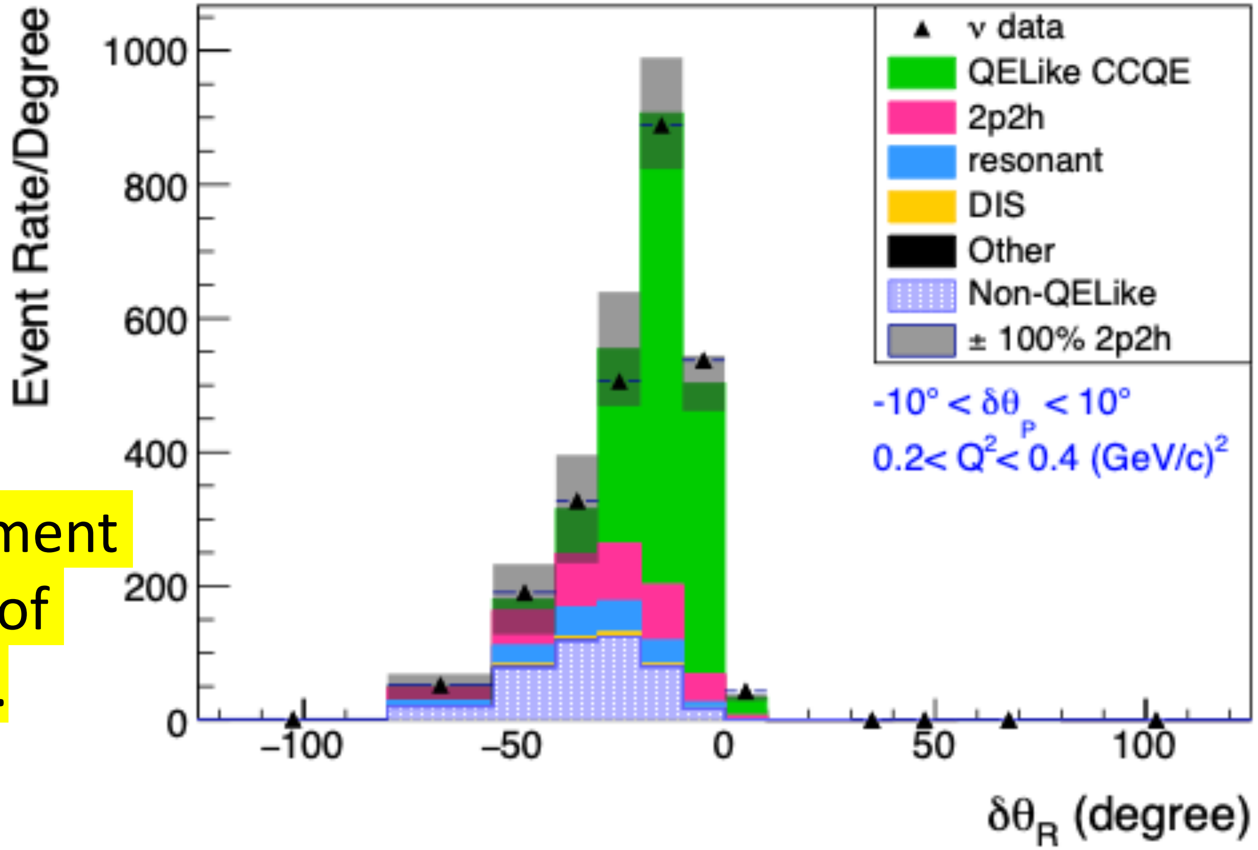
Quasielastic region



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.

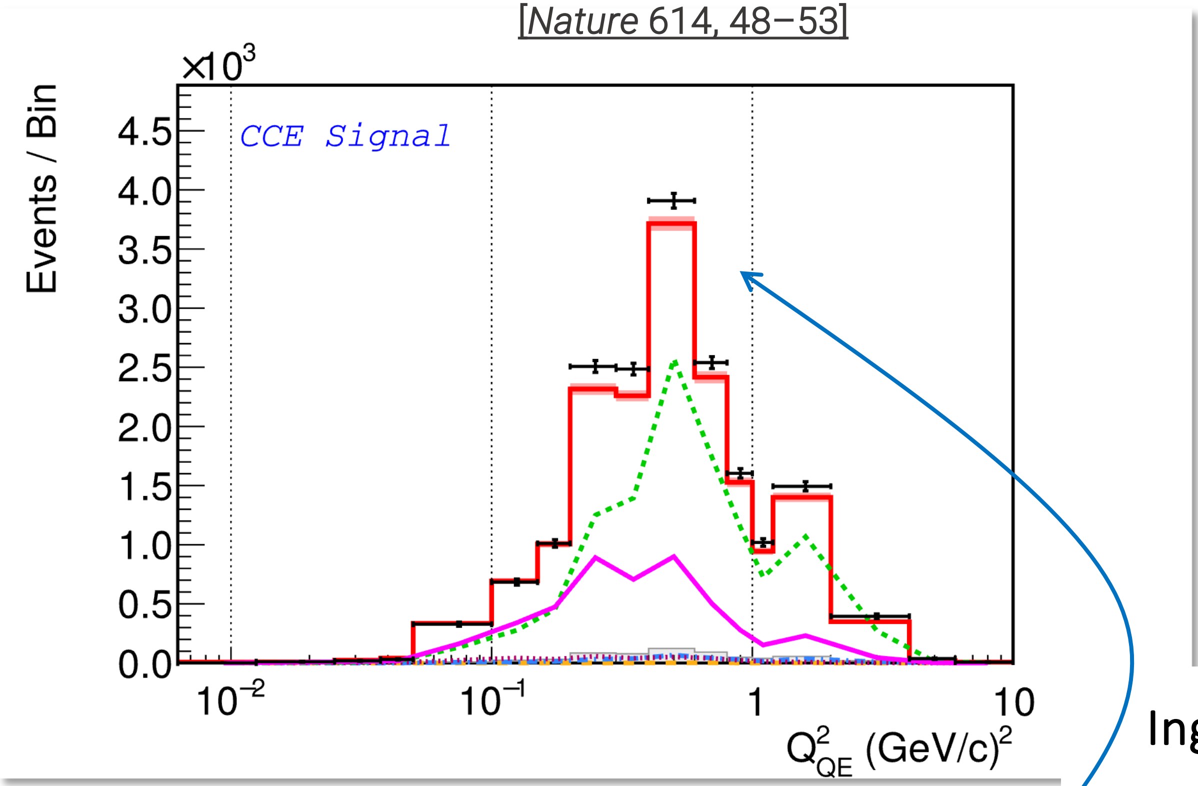
Control Sample, Neutrino Beam (cont'd)

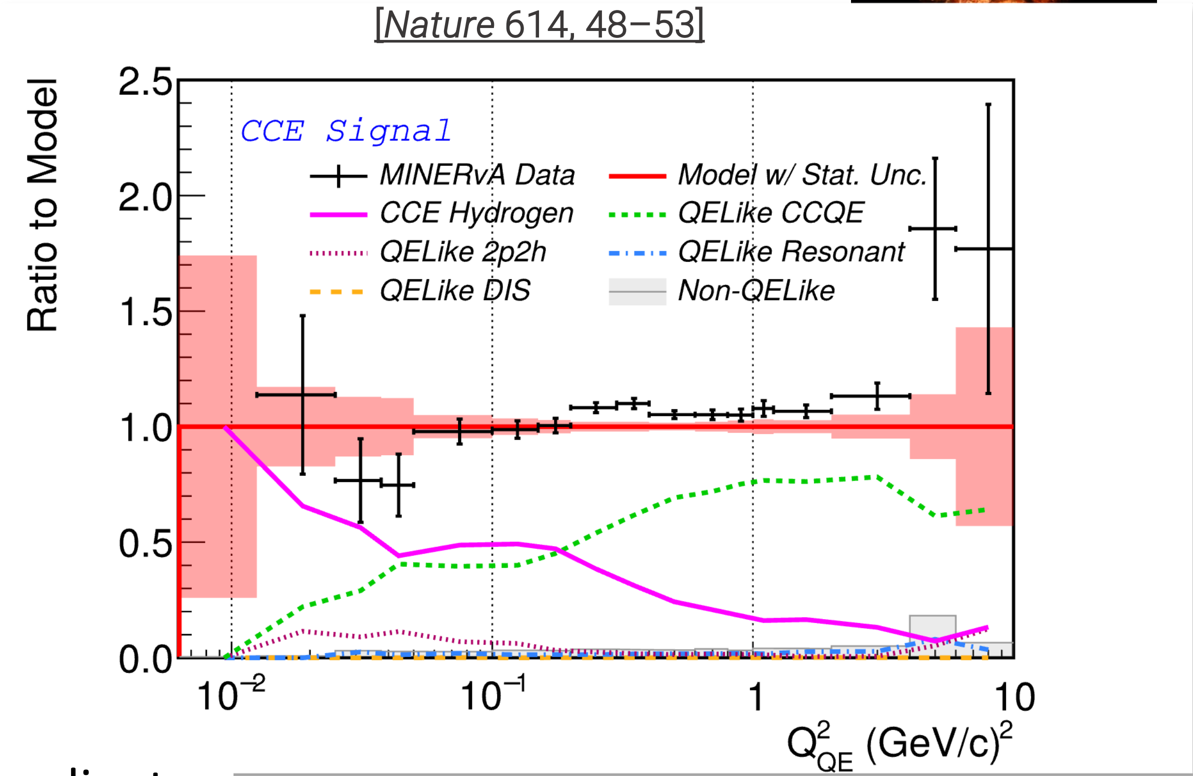


The low Q^2 disagreement shown as a function of reaction plane angle.

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





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

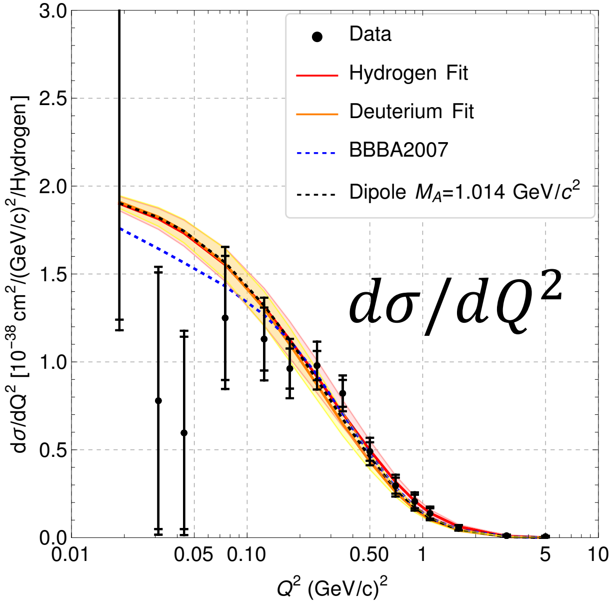
Ingredients:

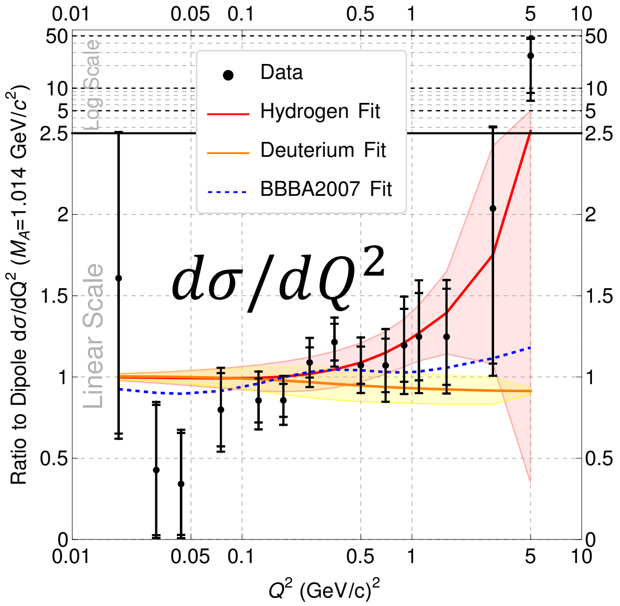
- **Measured signal** from data – predicted background
- Unfolding matrix and efficiency from Simulation (tuned on data, of course)
- Flux from models and data measurements ($\nu e \rightarrow \nu e$)
- Number of Hydrogen targets from the detector assay.

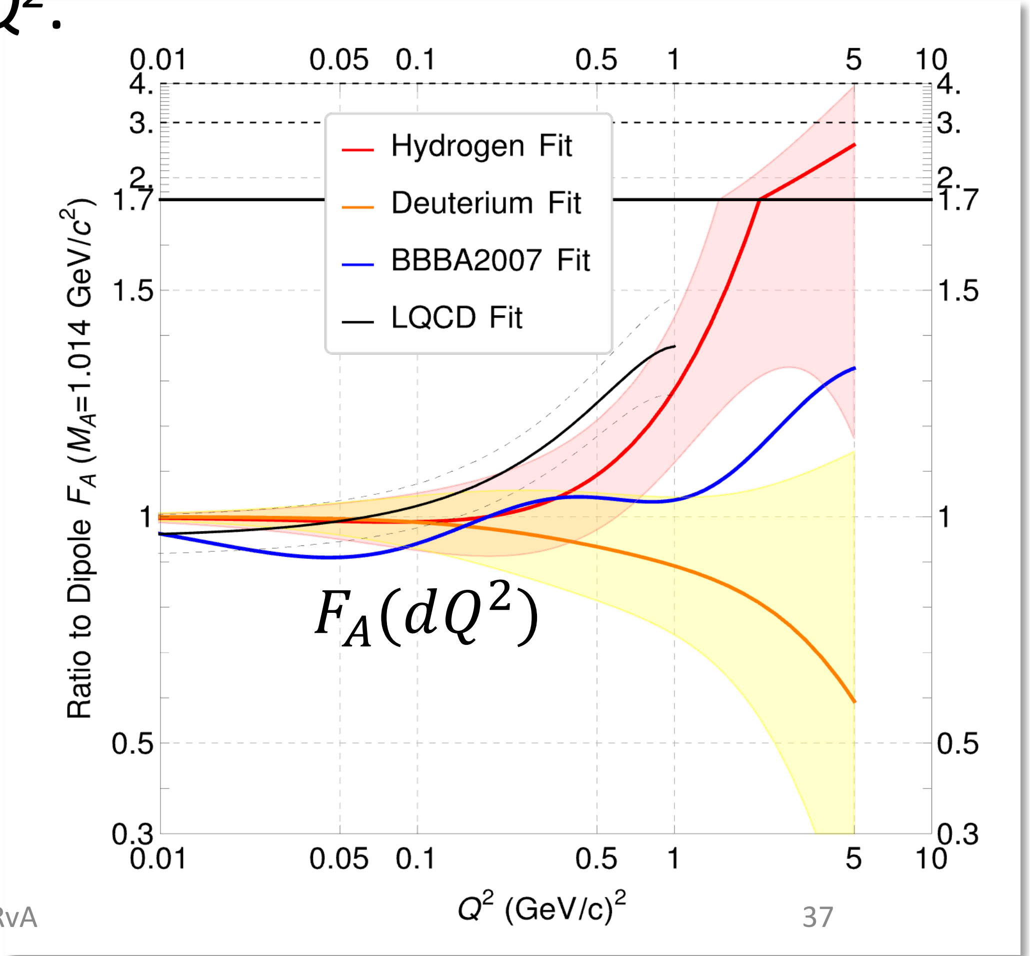
And so…?

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.





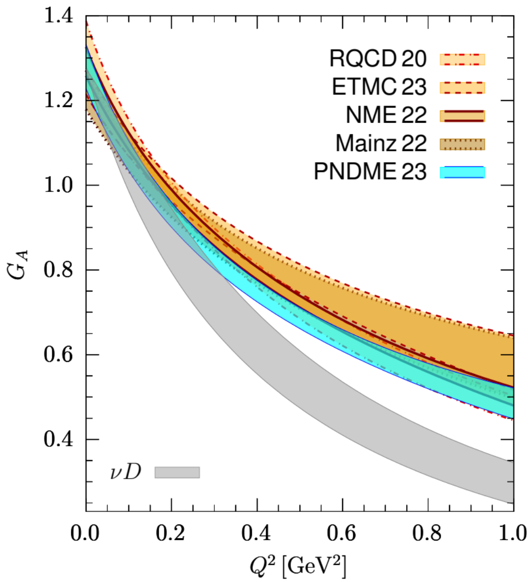


Compatible with Lattice QCD?

Isovector axial & pseudoscalar FFs

Isovector axial & pseudoscalar FFs studied by many LQCD collabs

- Consensus between different LQCD calculations/collaborations



- Combined~10% uncertainties for $0 \leq Q^2 \leq 1\mathrm{GeV}^2$
- Consistent with experimental results from MINERνA
- Tension with older ν-deuterium bubble chamber scattering data
- Dipole fit ansatz insufficient

[Compilation from Gupta 2401.16614]

Lattice QCD: PNDME 2305.11330 (2023), RQCD 1911.13150 (2019), ETMC 2309.05774 (2023), NME 2103.05599 (2021), Mainz 2207.03440 (2022)

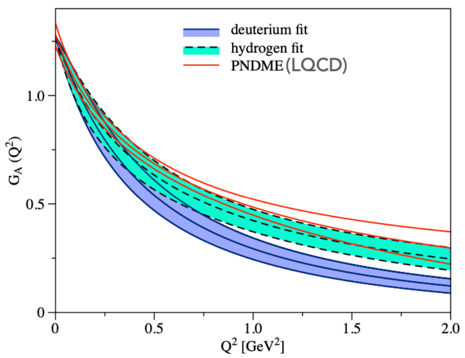
νD fit: Taken from 1603.03048 (2016)

Lattice QCD compared with MINERνA

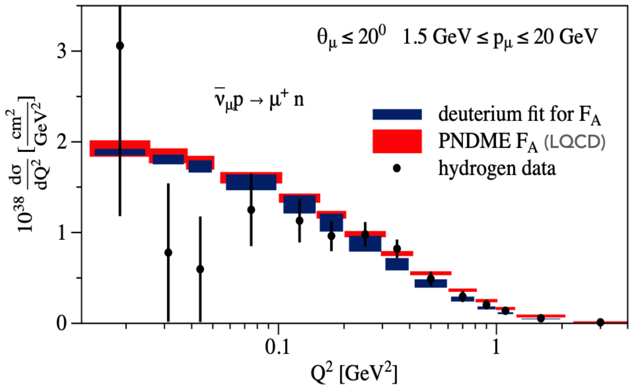
Isovector axial & pseudoscalar FFs studied by many LQCD collabs

- Consensus between different LQCD calculations/collaborations
- Consistent with experimental results from MINERνA antineutrino-hydrogen data

Axial FF



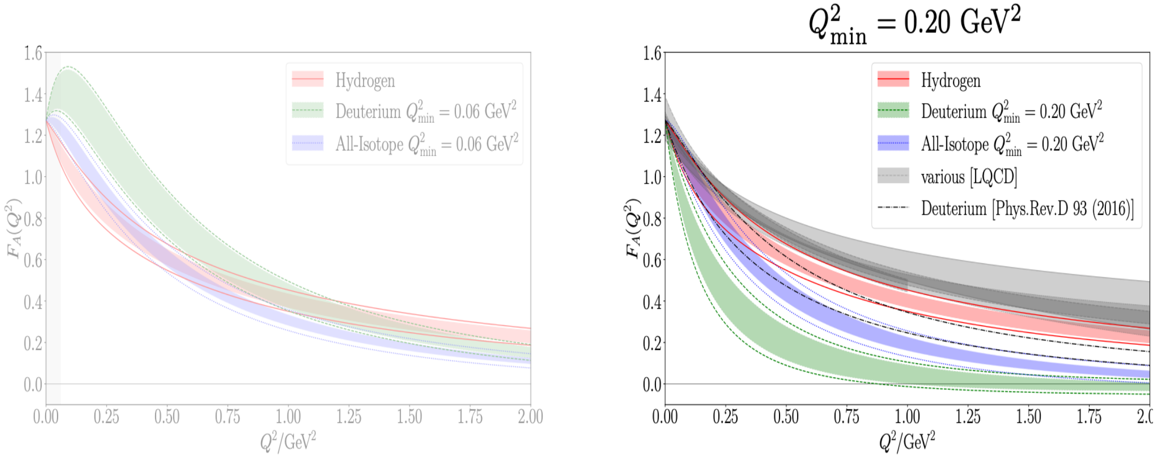
Antineutrino-nucleon charged current elastic differential cross-section



[Tomalak, Gupta, Bhattacharya, 2307.14920 (2023)]

Compatible with D_2 Data? Mmmmmaybe?

- We (MINERvA plus Aaron Meyer, LLNL) have some progress on joint fits with neutrino-deuterium analysis (*Phys.Rev.D* 93 (2016) 11, 113015), including comprehensive analysis of compatibility.
- This comparison has serious limitations.
  - The D_2 data has major flaws, such as fluxes unknown at the ~15% level (c.f., MINERvA ~4%), a baked in nuclear model with a kinematic fit, etc.
  - Our work has concluded that the interpretation of the D_2 strongly depends on fit choices, such as regularization.
  - Compatibility depends on vector form factors, since vector-axial vector interference flips sign in neutrino vs. antineutrino.
- Maybe the answer is that we should "retire" the long-serving D_2 data.



preliminary, Aaron Meyer @ NuINT April 2024

Tension in fits:

$$\Delta\chi^2 = \chi^2_{\text{H+D}} - \chi^2_{\text{D}} - \chi^2_{\text{H}} \approx 8.8 \implies \Delta\chi^2 \ / \ 1 \text{ DoF yields } p\text{-Value} \approx 3.0 \times 10^{-3}$$

Test compatibility by fixing axial parameters (marginalize deuterium nuisance parameters):

	$\{a_k\}_{\text{D}}$	p_{D}	$\{a_k\}_{\text{H}}$	p_{H}
$\chi^2_{\text{D}}/\text{DoF}_{\text{D}}$	94.9/94	0.45	167.7/96	8.3×10^{-6}
$\chi^2_{\text{H}}/\text{DoF}_{\text{H}}$	23.3/15	0.08	10.0/13	0.69

Deuterium is incompatible with hydrogen, LQCD

Aaron S. Meyer Section: Combined Hydrogen–Deuterium Fits

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 the joint analysis with neutrino-deuterium results, including finalizing the pessimistic conclusions of the last slide.
- 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; please enjoy.

Backup: Axial Form Factor Extraction

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 factors 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 $Q^2 \to \infty$.
- Regularization strength from data (L-curve).
- Use BBBA05 form factors by default.

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

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

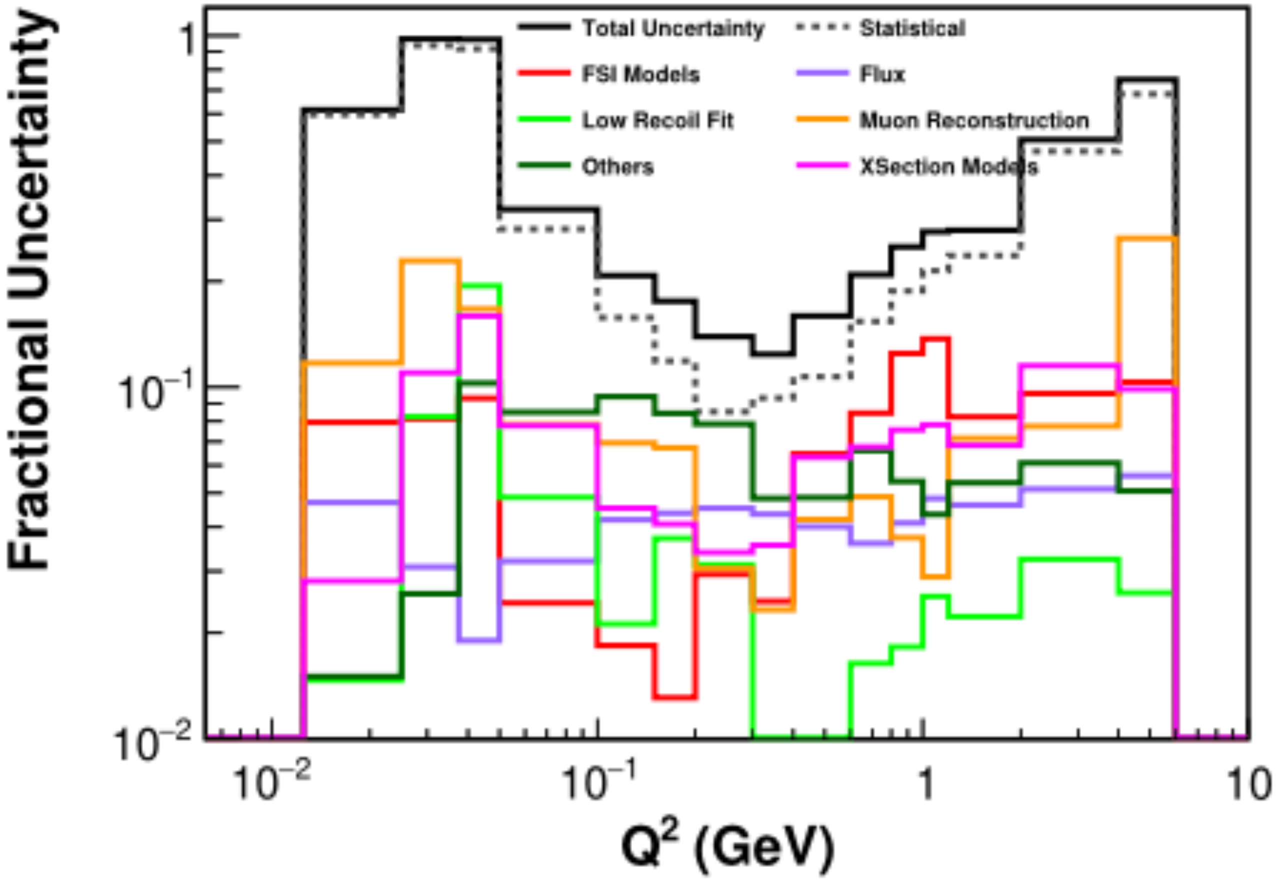
$$\sum_{k=n}^{\infty} k(k-1)\ldots(k-n+1)a_k = 0, n \in (0,1,2,3)$$

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

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.

Backup: Uncertainty Summary

Uncertainties in the Cross-Sections



Dominated by statistical uncertainty.

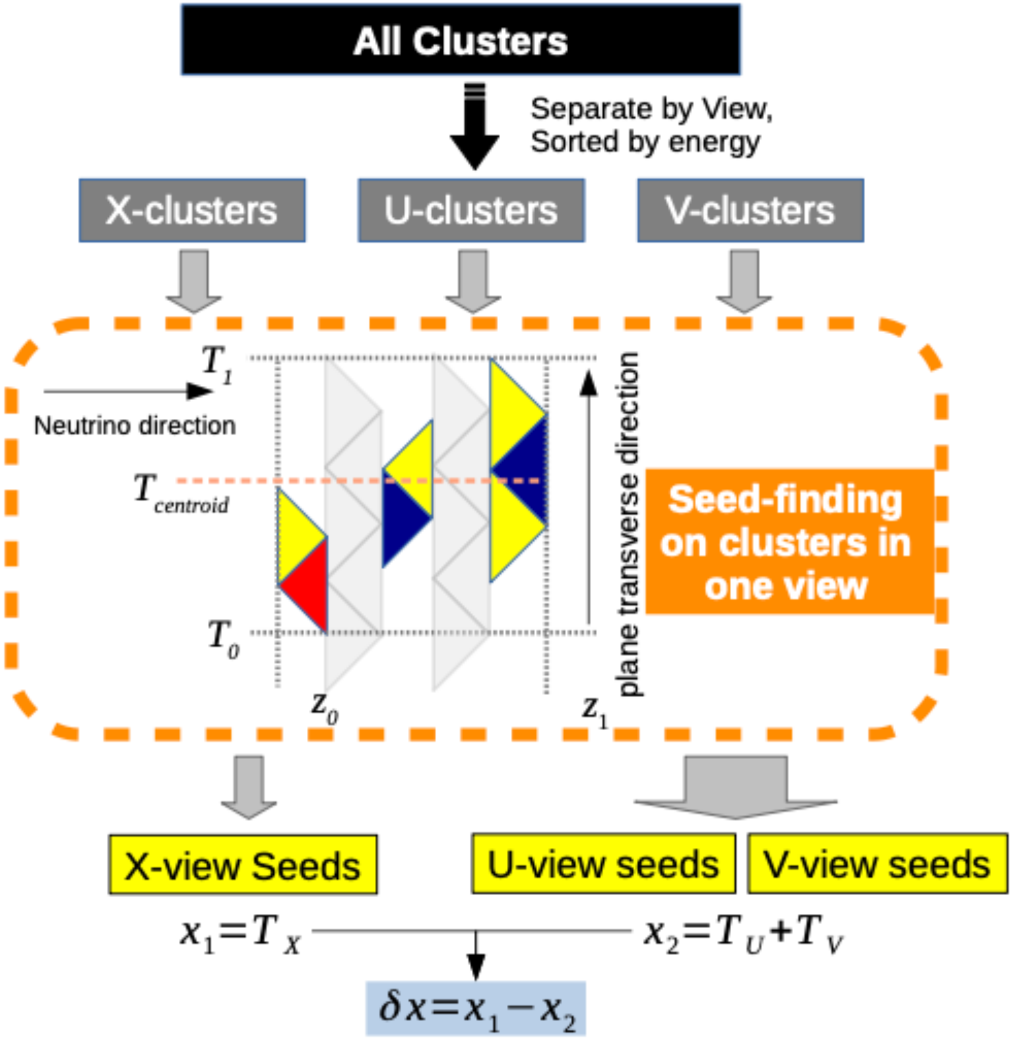
Model systematic uncertainties from residuals of constrained background subtraction.

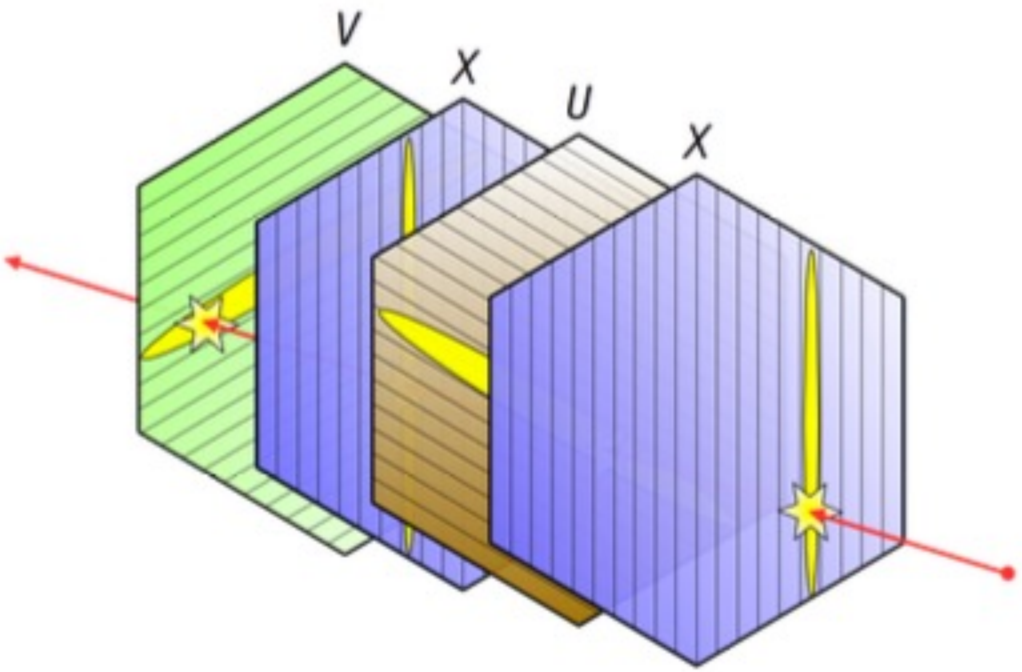
Neutron interaction uncertainties dominate the “other” category.

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

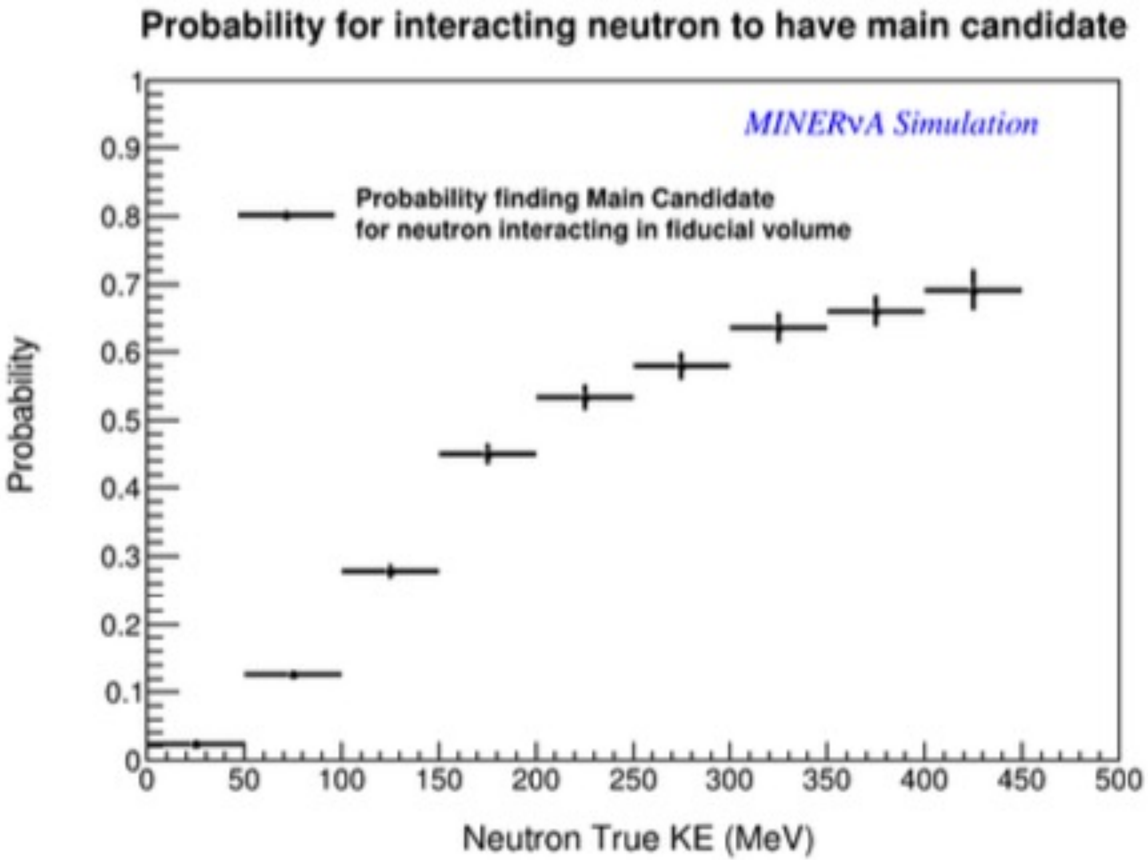
Backup: Neutron Reconstruction

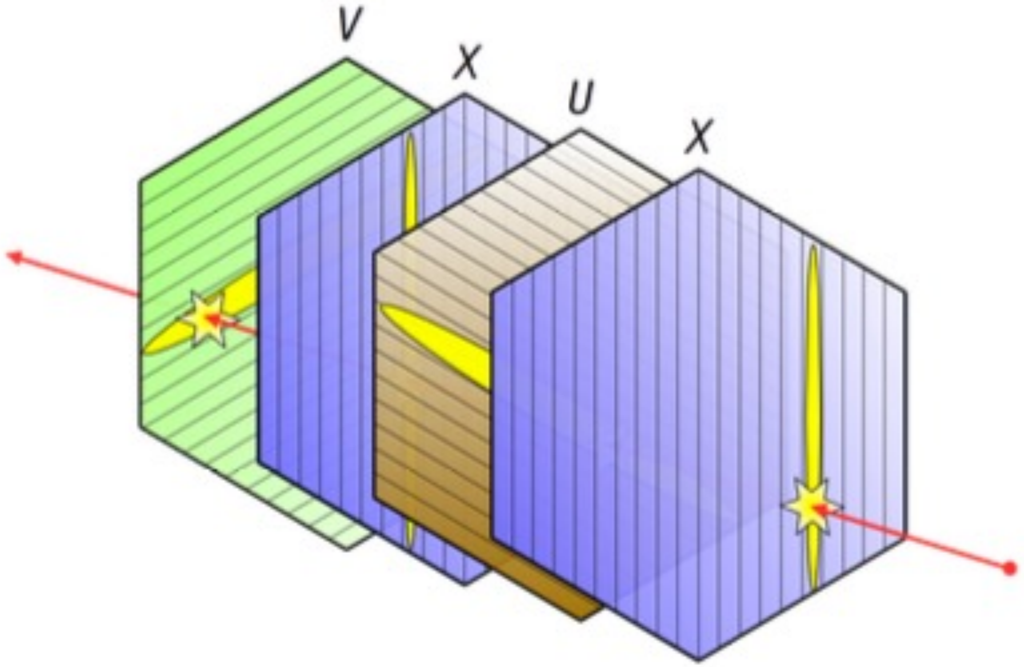
Neutron “3D Blobs”





Neutron “3D Blobs”

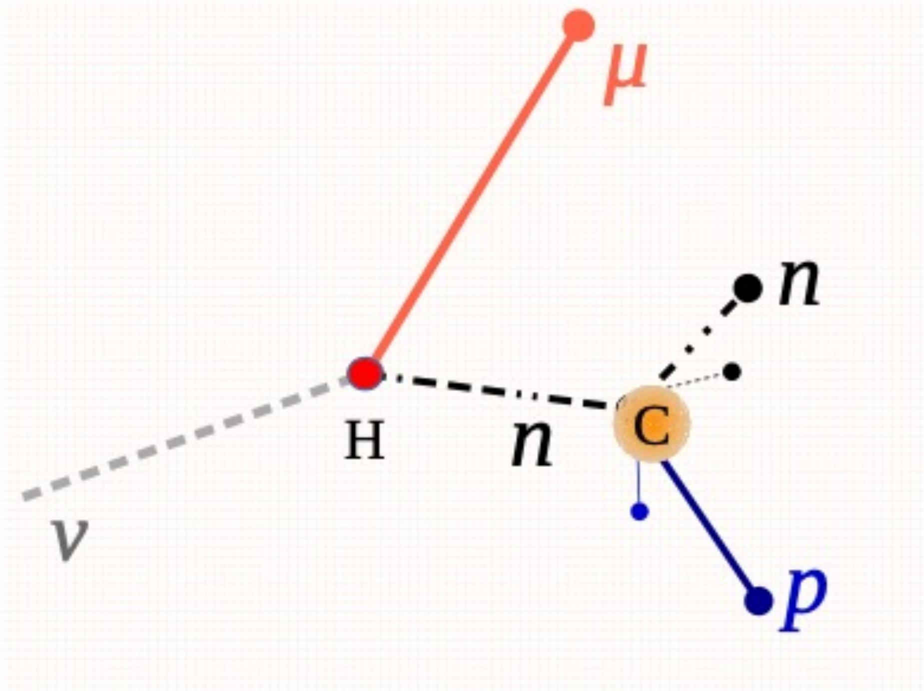


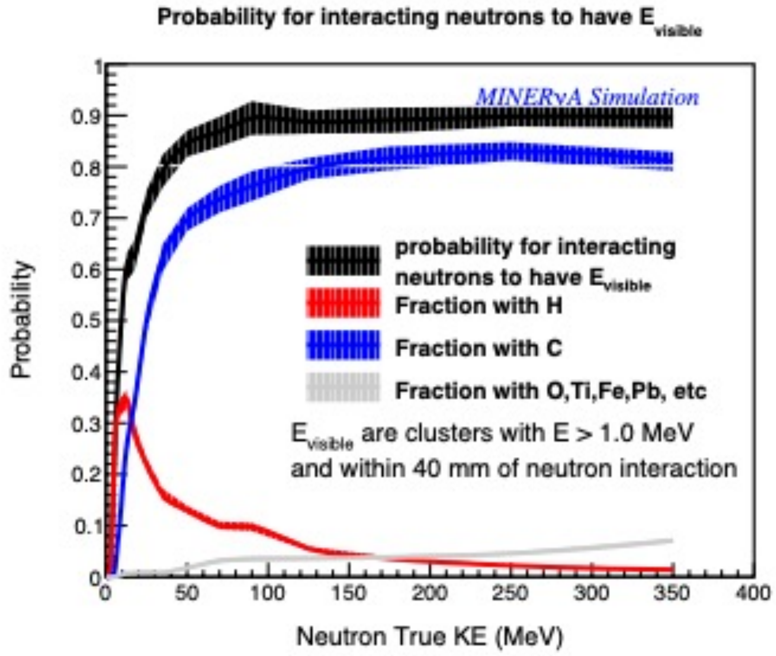


Backup: Neutron Interactions

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.

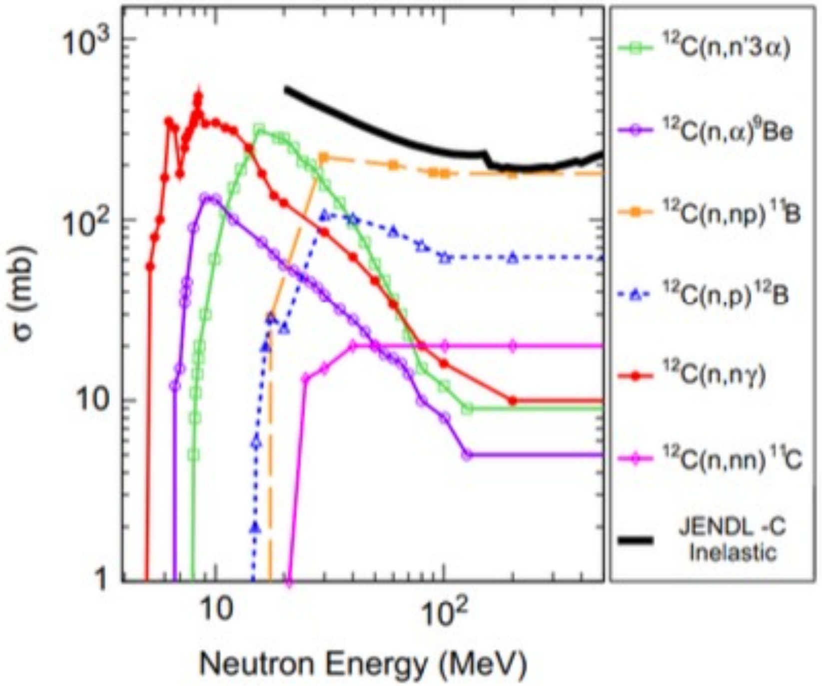
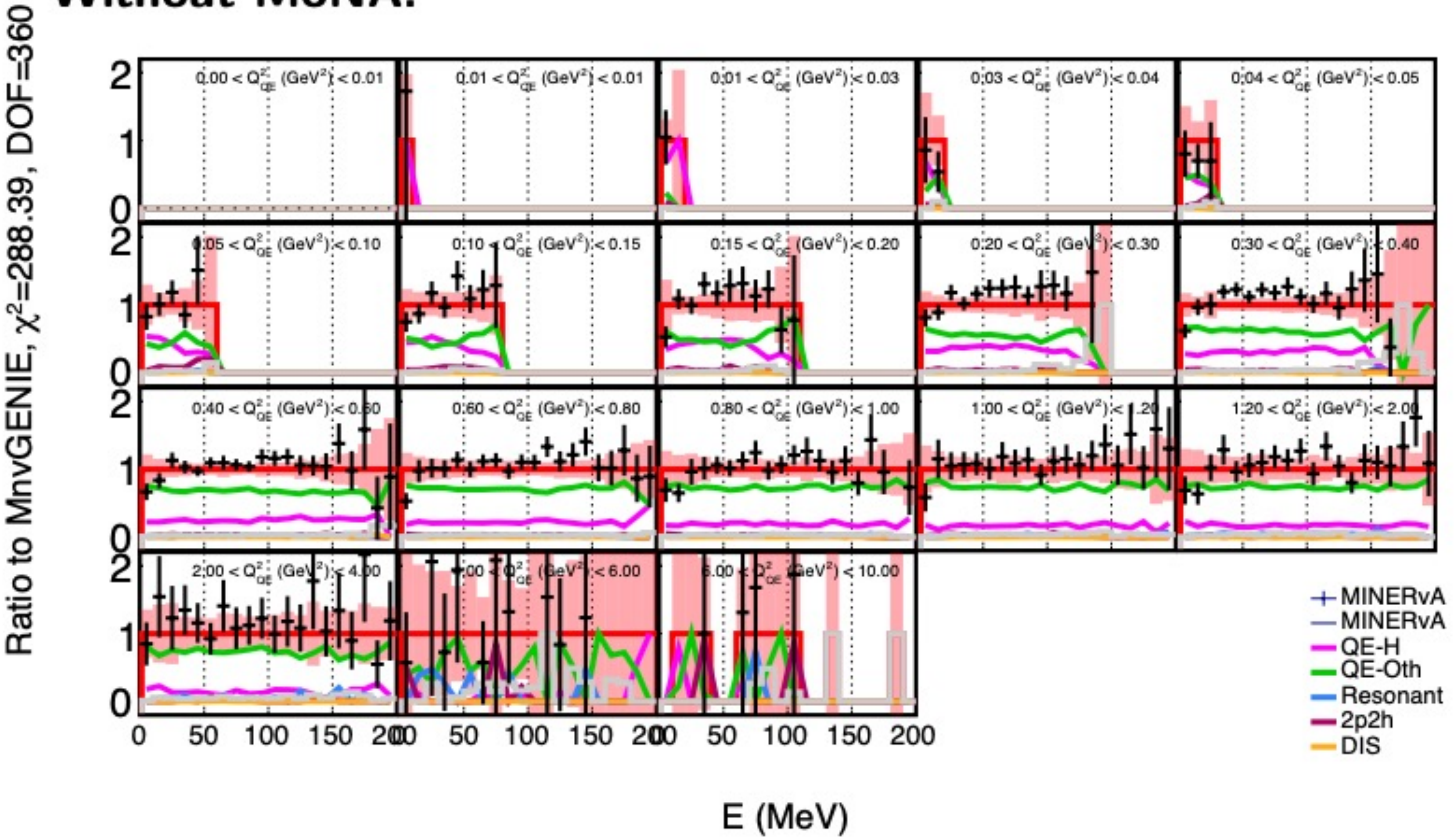


Fig. 3. Inelastic neutron–carbon reaction cross-sections are shown as a function of the incident neutron energy. MENATE_R uses the six different discrete reaction channel cross-sections while the G4-Physics uses the total inelastic reaction cross-sections taken from the JENDL-HE library [37].

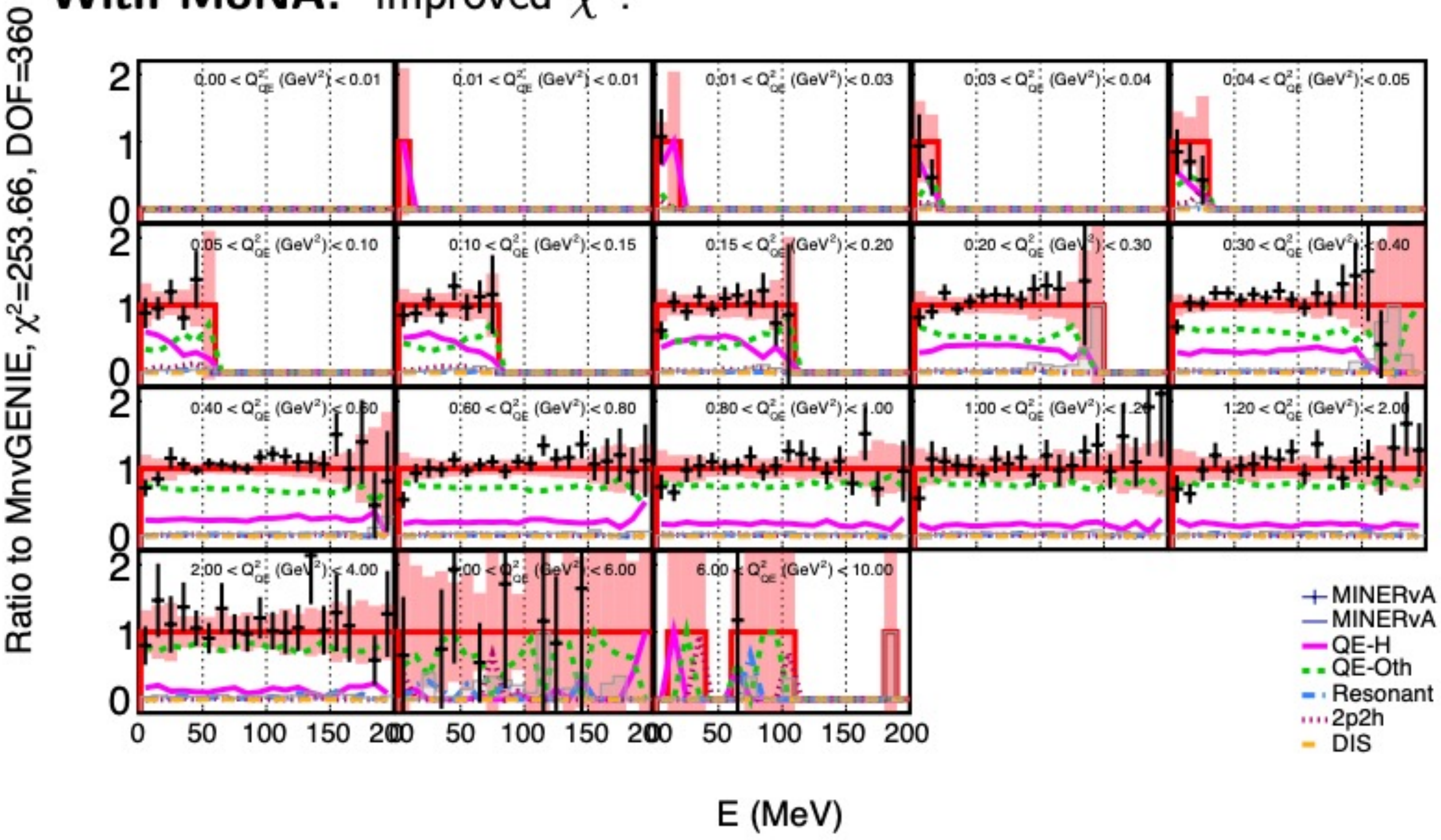
“Nuisance” Distributions

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.

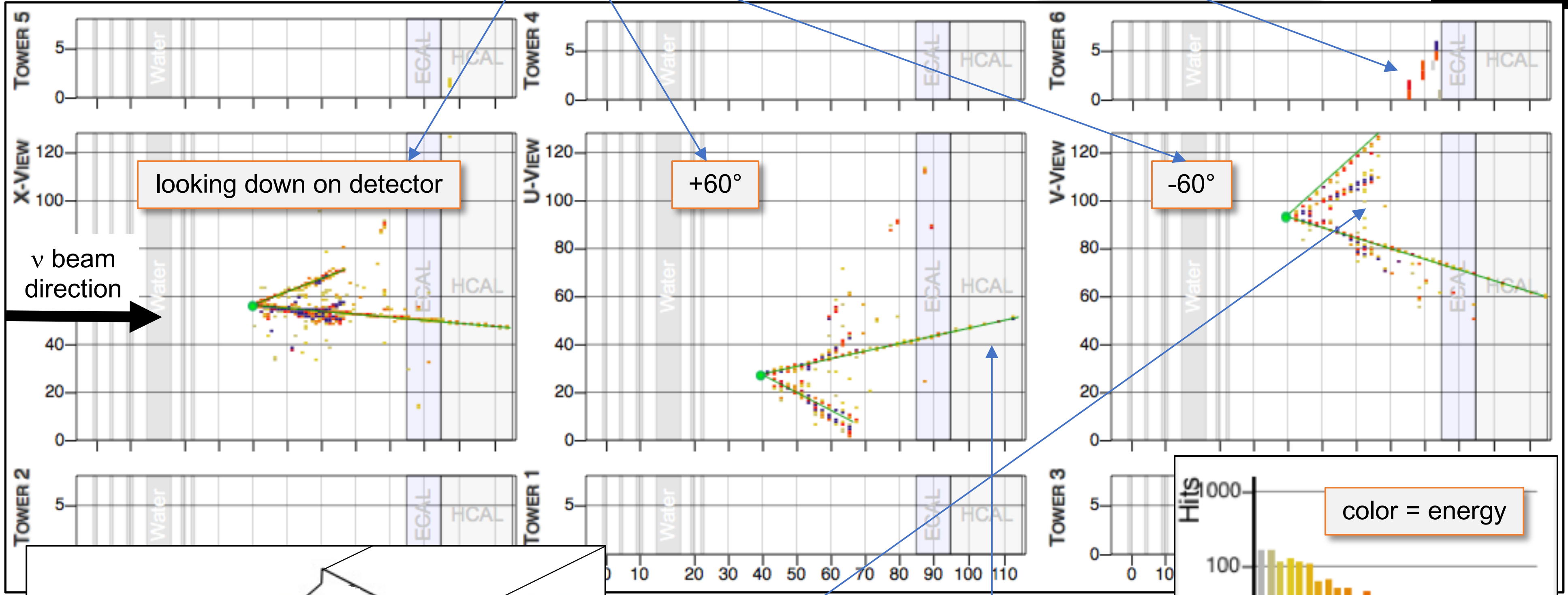


Backup: More Event Display

Events in MINERvA

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

Particle leaves the inner detector, stops in outer iron calorimeter

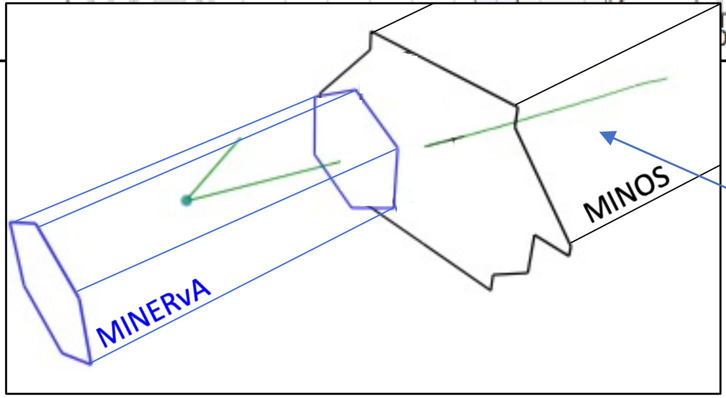


looking down on detector

+60°

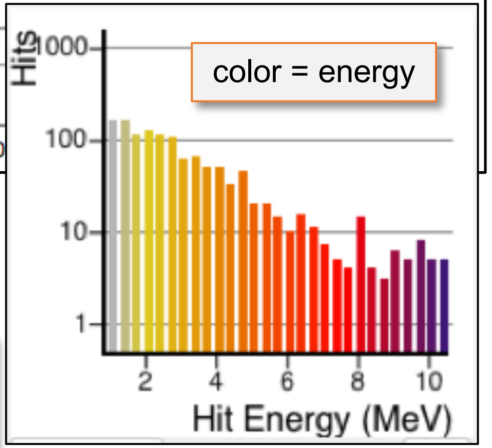
-60°

ν beam direction



Stops in Scintillator, best hadron particle ID

Muon leaves the back of the detector headed toward MINOS



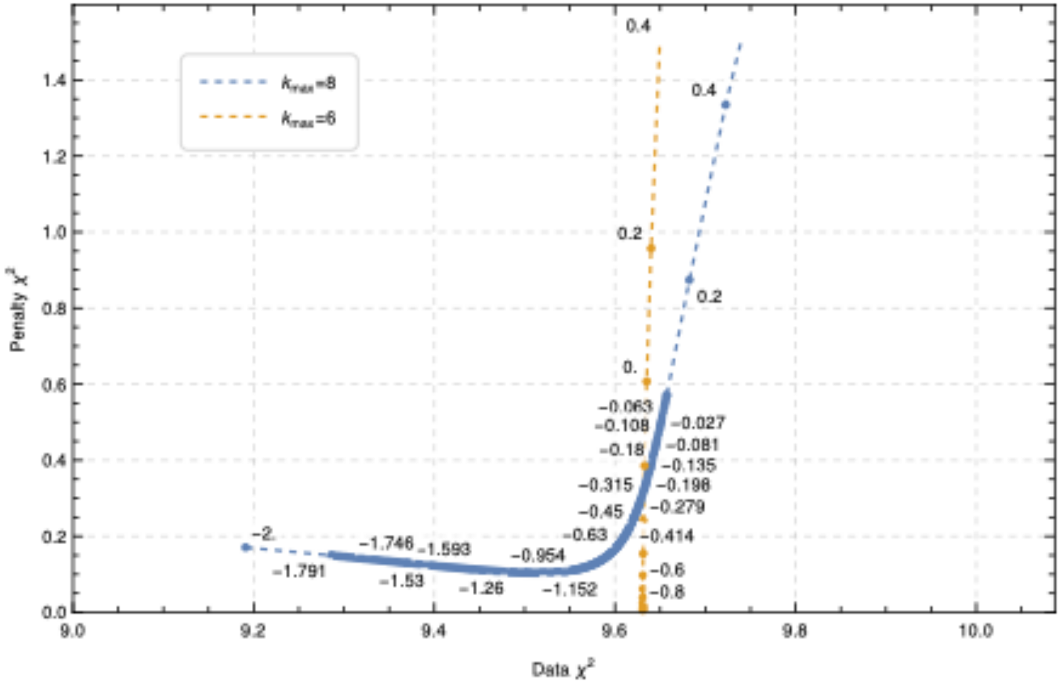
color = energy

Backup: Regularization L-curve

Regularization strength

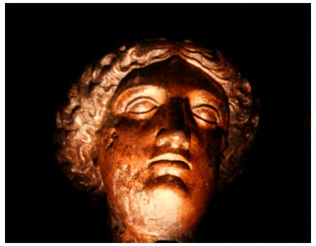
Central value fit: $k_{\max} = 8, \lambda = 0.13$

- 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.

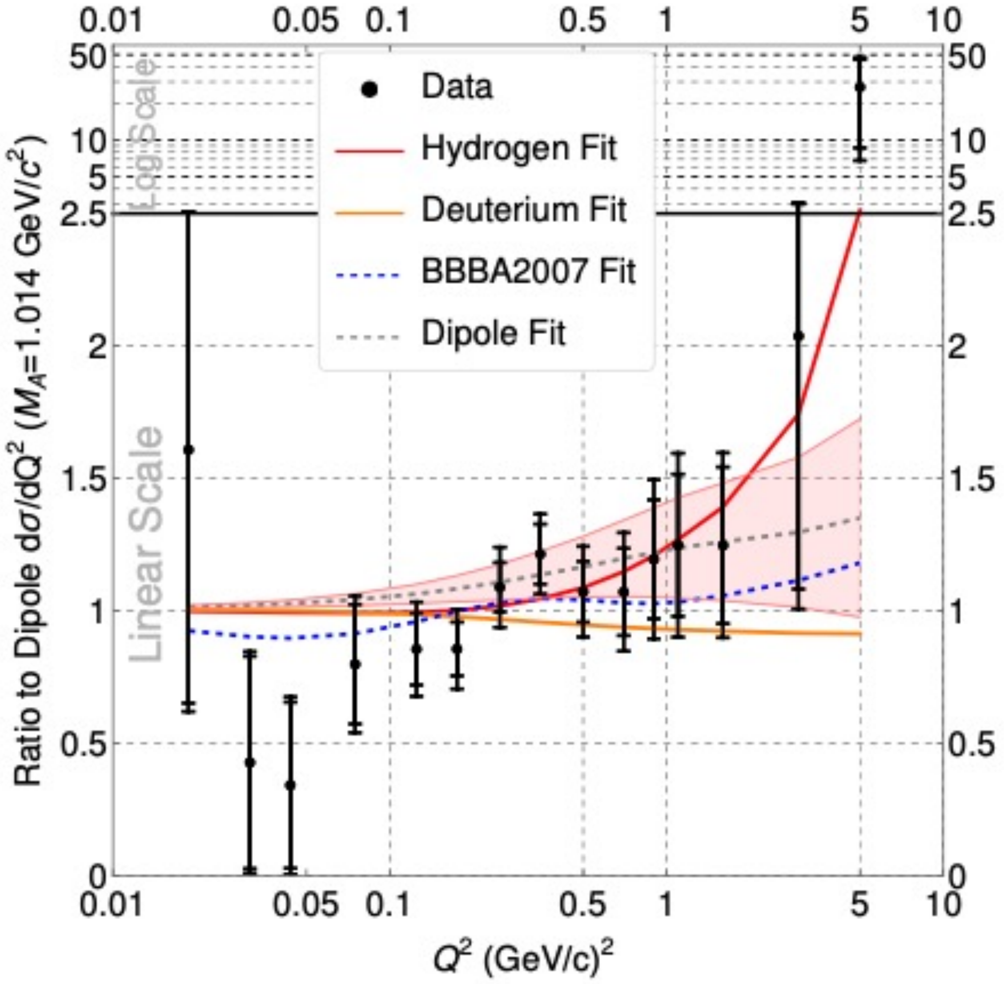


Backup: Dipole Fit and Axial Radius

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

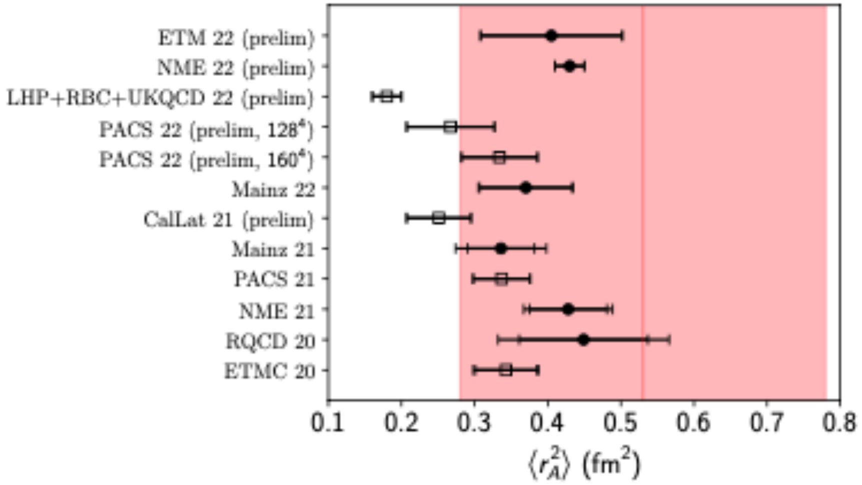
Favors larger F_{A} at higher Q^2.
If fit with dipole, $M_A \sim 1.15(10)$

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

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

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

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



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

Backup: MINERvA Timescale

The Long History of MINERvA

2002

MINERvA EOI
Scintillator tracker and passive targets, NuMI

2007

Construction Start
Begin fiber, scintillator production.

2010

First Data-taking
Low Energy (MINOS), Mar’10 – Mar’12

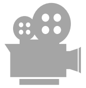
2012

1st Interact. Papers
CCQE in neutrino and antineutrino.

2017

First “tunes”
$CC0\pi/1\pi$ tunes. Coh π resolved.

2019



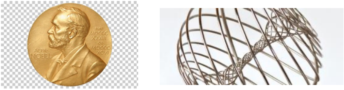
And… scene
Med Energy (NOvA) Oct ‘13-Feb ‘19

2022

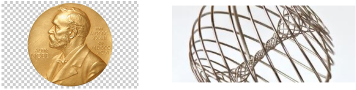
Med Eng Papers
Peak of publishing.

The Long History of MINERvA

Precise $\Delta m^2_{\odot}$ at SNO and KAMLAND



Atmospheric neutrino oscillations at Super-K



MINOS begins; first precise Δm^2_{23}

T2K 6 ν_e Events

Reactor θ_{13}

NOvA $\overline{\nu_e}$ Appearance

T2K δ_{CP} "Indication"

2002 — 2007 — 2010 — 2012 — 2017 — 2019 — 2022

MINERvA EOI
Scintillator tracker and passive targets, NuMI

Construction Start
Begin fiber, scintillator production.

First Data-taking
Low Energy (MINOS), Mar'10 – Mar'12

1st Interact. Papers
CCQE in neutrino and antineutrino.

First "tunes"
CC0π/1π tunes. Coh π resolved.

And… scene
Med Energy (NOvA) Oct '13-Feb '19

Med Eng Papers
Peak of publishing.

Implications of the Neutrino History

Atmospheric neutrino oscillations at Super-K

Precise $\Delta m^2_\odot$ at SNO and KAMLAND

MINOS begins; first precise Δm^2_{23}

T2K 6 ν_e Events

Reactor θ_{13}

NOvA $\overline{\nu_e}$ Appearance

T2K δ_{CP} "Indication"

2002 — 2007 — 2010 — 2012 — 2017 — 2019 — 2022

Neutrino Oscillations at GeV Accelerator Experiments

Sub-leading effects from solar oscillations possible

Δm^2_{23} well enough known to tune narrowband beam experiments

Large θ_{13}! Therefore, CP phase, δ, accessible in these experiments

Justification for DUNE and Hyper-K

Other Long Histories and MINERvA

Elizabeth McFarland-Porter

Crane School of Music ('21), now an elementary school music teacher in suburban DC.

2002

MINERvA EOI
Scintillator tracker and passive targets, NuMI

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Construction Start
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First Data-taking
Low Energy (MINOS), Mar'10 – Mar'12

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$CC0\pi/1\pi$ tunes. Coh π resolved.

2019

And... scene
Med Energy (NOvA) Oct '13-Feb '19

2022

Med Eng Papers
Peak of publishing.

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.
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Thank you!

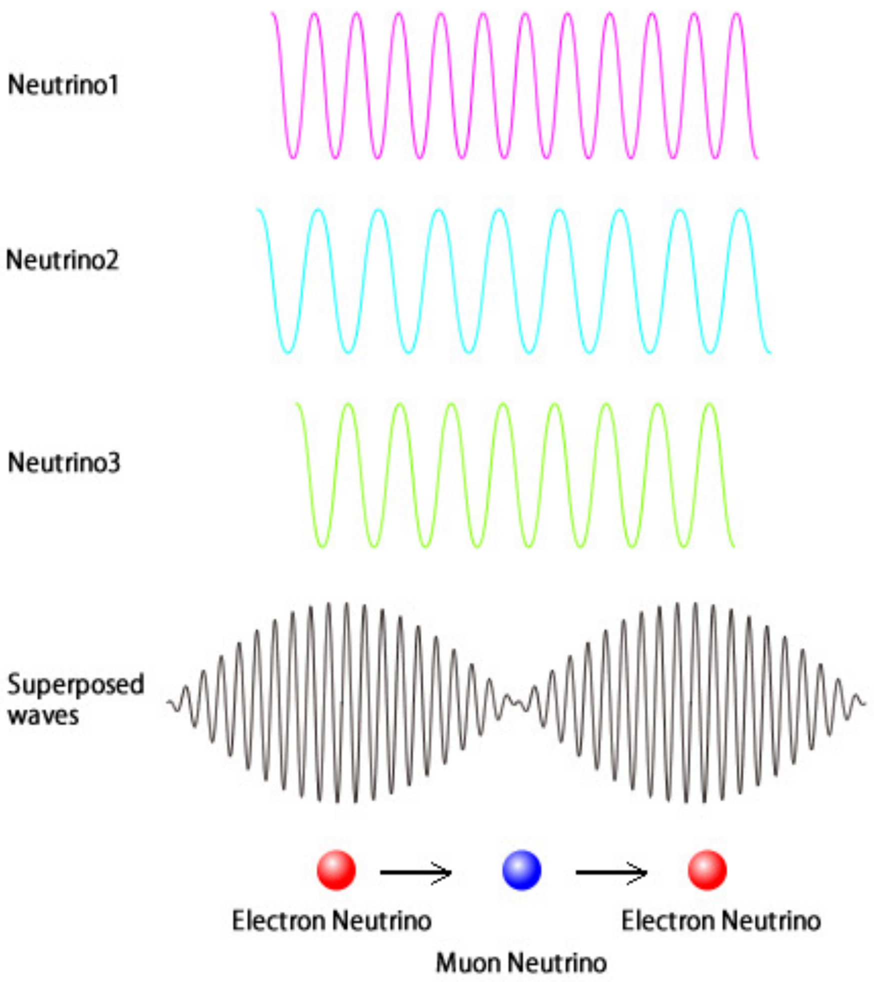
Why Neutrinos at Accelerators?

Why? Neutrino Interferometry

- Future neutrino accelerator experiments because we want to study neutrino interferometry, or "flavor oscillations".
- When we produce a neutrino and an electron in beta decay, the neutrino is a coherent superposition of three different neutrinos of different masses.

$$\nu_{\text{flavor}} = \sum_{\text{mass eigenstates, } i} U_{\text{flavor},i}\,\nu_i$$

ν_1
ν_2
ν_3



Why? Neutrino Interferometry (cont'd)

- For a neutrino of fixed momentum, then each mass eigenstate will have a different energy.

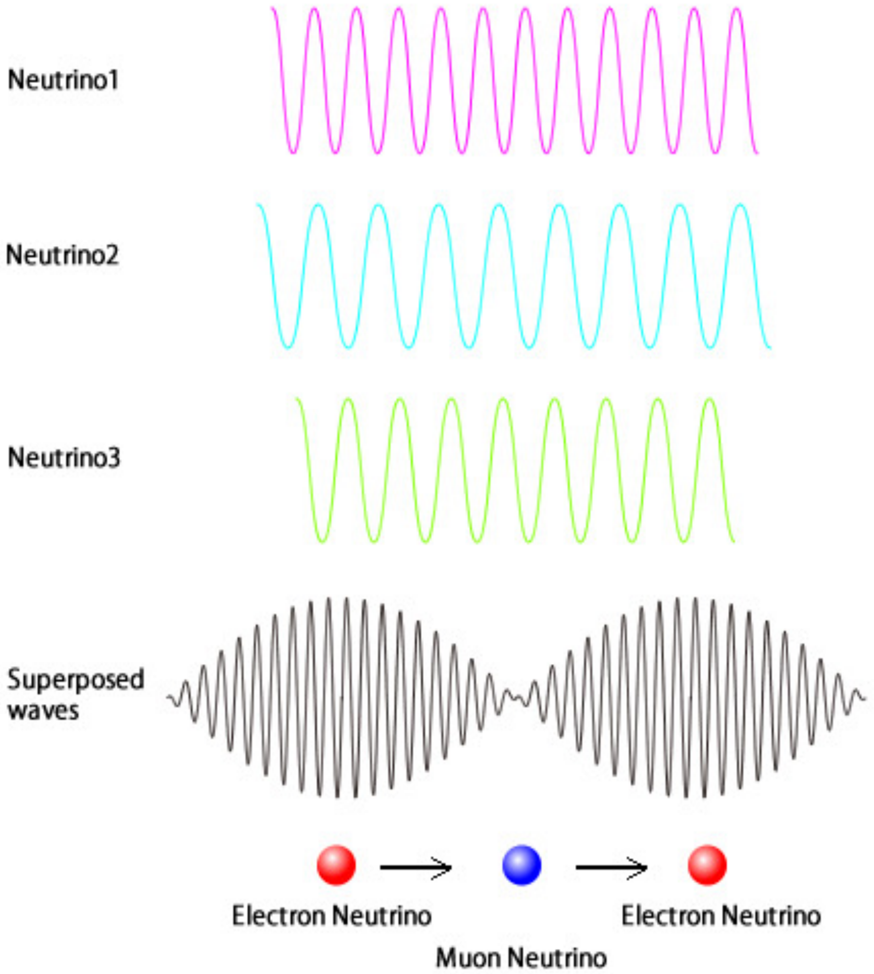
$$E_i = \sqrt{p^2 + m_i^2} \approx p\left(1 + \frac{m_i^2}{2p^2}\right)$$

- Therefore, the wavefunction of each mass eigenstate has a different phase evolution.

$$H|\psi(\tau)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(\tau)\rangle \Longrightarrow |\psi(\tau)\rangle \sim e^{-iE\tau/\hbar}$$

- The phase evolution at different rates leads to different flavor probabilities as the neutrinos propagate through space.

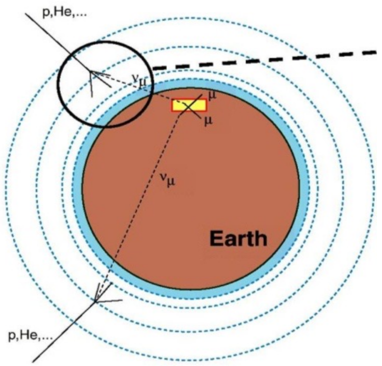
$$i(E_i - E_j)\frac{\tau}{h} \approx i(m_i^2 - m_j^2)\frac{Lc}{2ph}$$

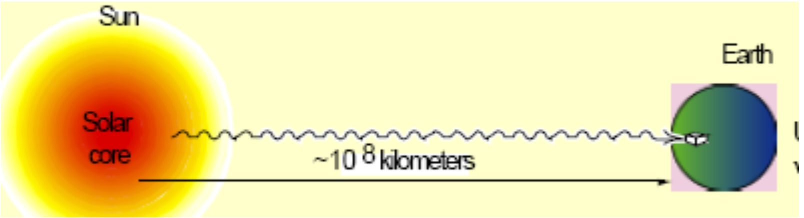


What We Know about Masses and Mixings

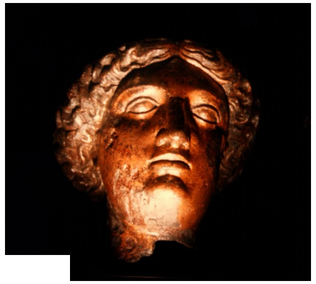
- Neutrino flavor oscillations were discovered with neutrinos from astrophysical sources, not in human made neutrino beams!
- We are lucky that $E_{atm\ \nu}/R_{earth} < \Delta m_{atm}^2 < E_{atm\ \nu}/h_{atm}$

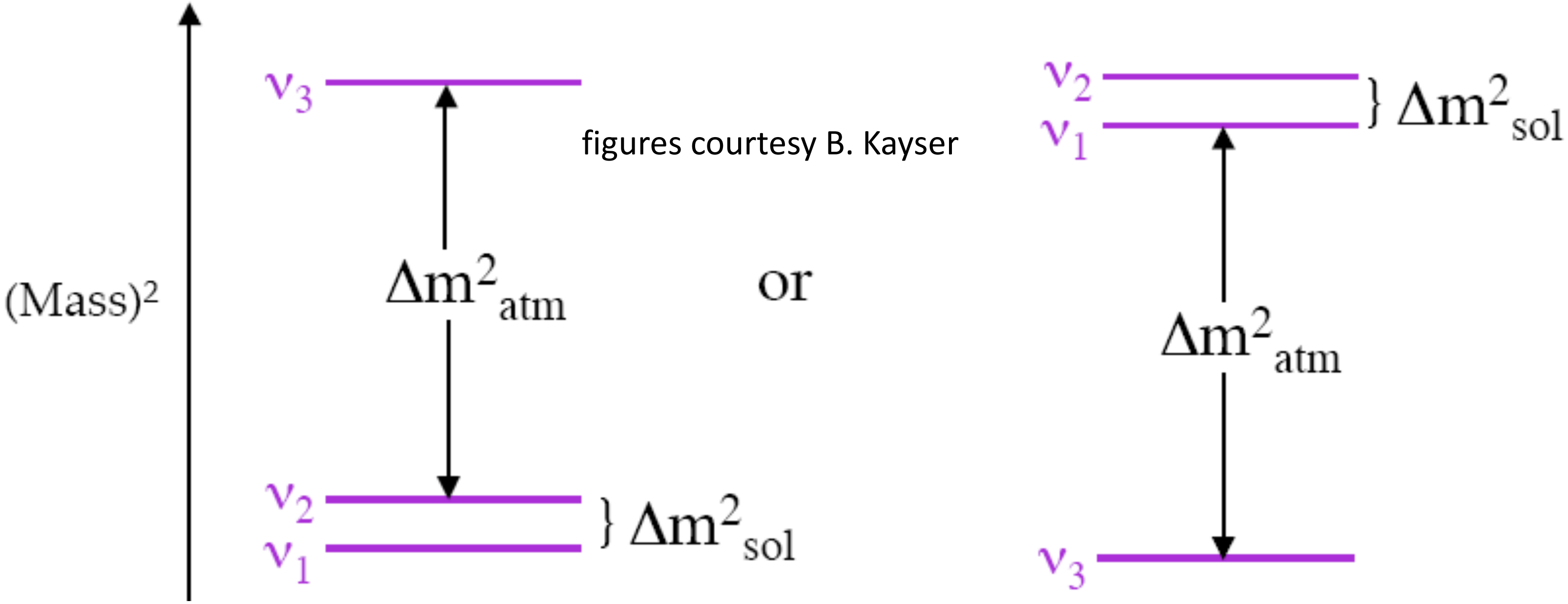
  and that the solar density profile and Δm_{sol}^2 are well-matched.





Two Interference Signatures and Three Neutrinos





$\Delta m_{sol}^2 \rightarrow \Delta m_{12}^2 \approx 8\text{x}10^{-5}\text{eV}^2$ $\Delta m_{atm}^2 \rightarrow \Delta m_{23}^2 \approx 2.5\text{x}10^{-3}\text{eV}^2$

- Interferometry has told us the differences in m², but nothing about the ordering (which sometimes, not to my taste, is called "hierarchy")
- The electron neutrino potential as neutrinos pass through electron containing material *("matter effects") can resolve this.*

Three Generation Mixing

- As noted by Kobayashi and Maskawa in the quarks, a third generation of mixing admits the possibility of a complex phase → CP violation

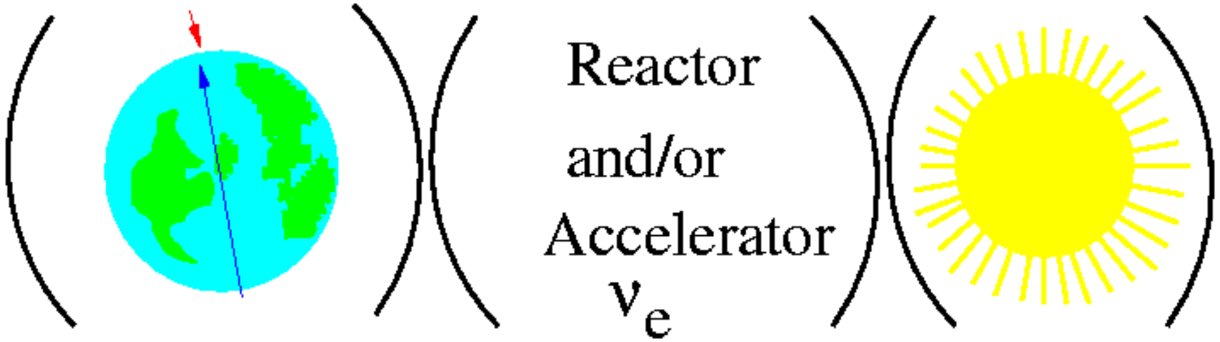
(blue-yellow ~even split) (small green in 3) (blue-green 1-2 difference)

$$\begin{pmatrix} \upsilon_e \\ \upsilon_\mu \\ \upsilon_\tau \end{pmatrix} = U \begin{pmatrix} \upsilon_1 \\ \upsilon_2 \\ \upsilon_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = cos\theta_{ij}$$
$$s_{ij} = sin\theta_{ij}$$

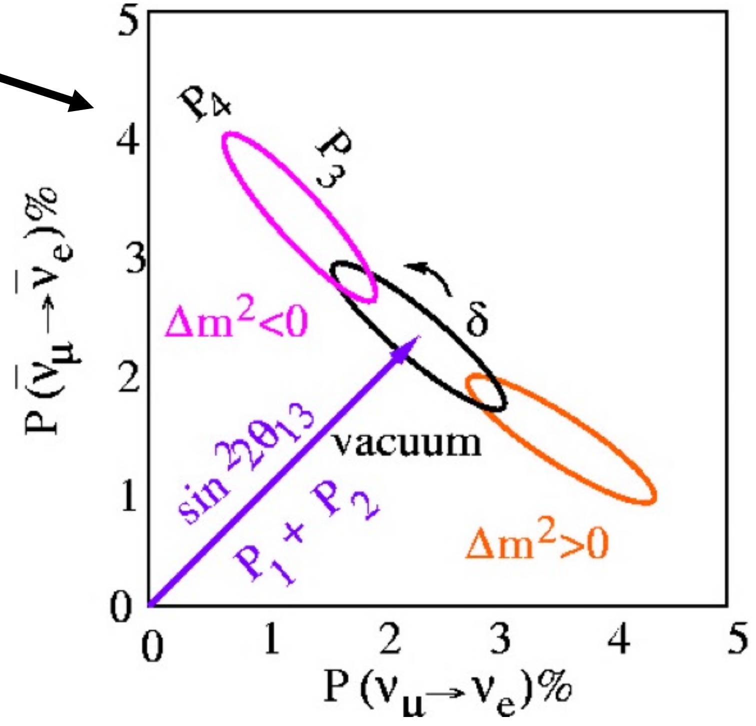
U=



Observable Effects due to this Interference

- "CP violation" (interference term) and matter effects lead to a complicated mix…
- Simplest case:
  first interference maximum, appearance of electron neutrinos and anti-neutrinos.
- CP violation gives ellipse; matter effects shift the ellipse in a precision long-baseline accelerator experiment.

Minakata & Nunokawa
JHEP 2001



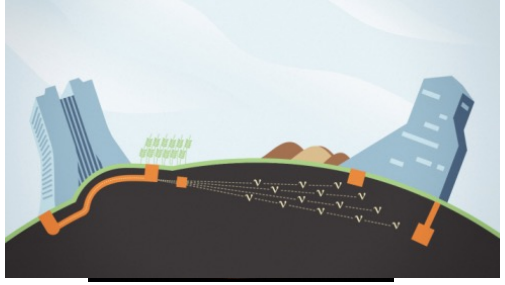
Precision Neutrino Interferometry

- Neutrino interferometry is a tool for discovery.

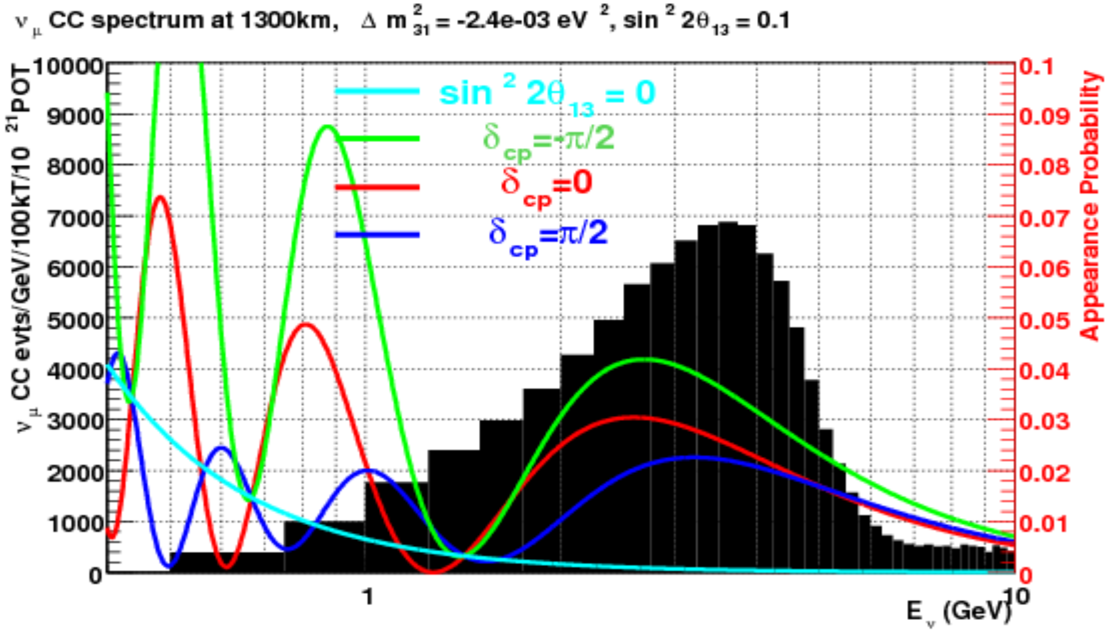
- Is there CP violation in neutrino mixing? And is it consistent with leptogenesis as an origin for the matter-antimatter asymmetry in the universe?
- Is there a symmetry to the pattern of masses or mixings?
- Are there other hidden neutrinos visible only in interferometry?

- Answers to all of these probems require us to make precise measurements of neutrino flavor transitions.

Future Neutrino Experiments: DUNE

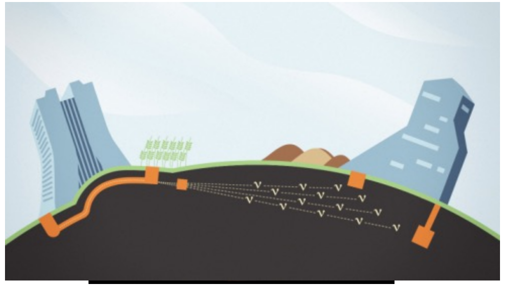


- Happy coincidence of location of Sanford lab (the former Homestake mine where neutrino emission from the sun was discovered!) and locations of high power multi-GeV proton sources the right distance away.

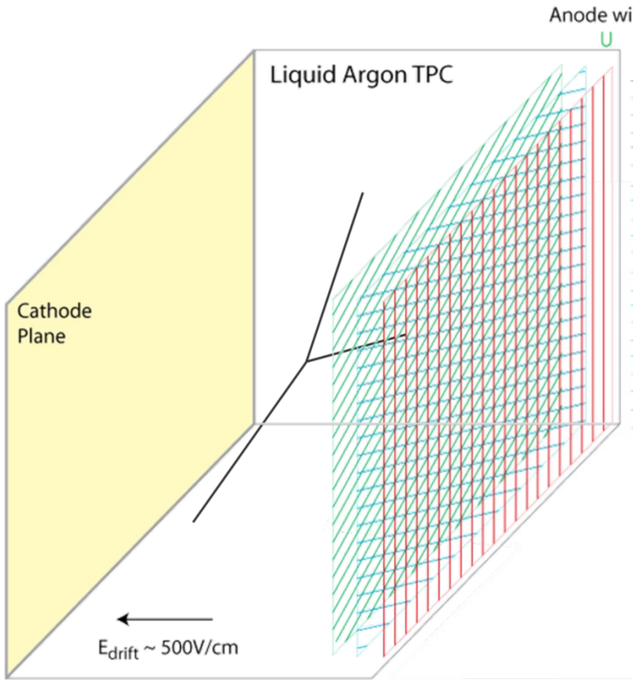


- The transitions most directly sensitive to CP asymmetry result in electron neutrino and anti-neutrino appearance from a dominantly muon neutrino beam.

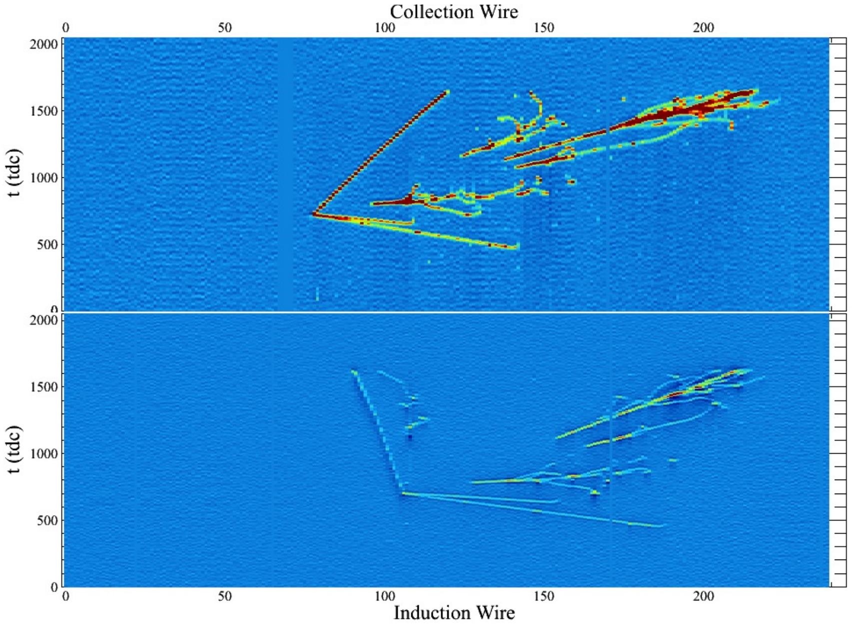
DUNE: Large but Capable Detectors



- Number of interactions is proportional to detector mass, so detector must be large
- If the detector more efficiently finds signal (more reactions) and more efficiently reject backgrounds, capabilities matter also! Enter Liquified Argon Time Projection Chambers.

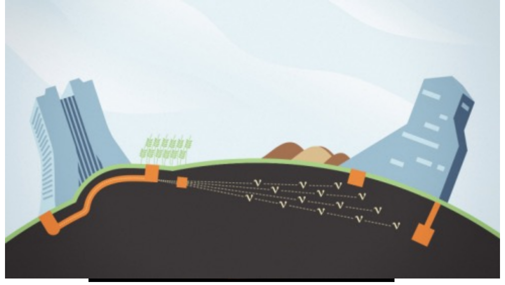


Drift and collect ionization e⁻ in liquid argon (~2 e⁻ per µm). Try to identify all particles in the event by their ionization or interactions.

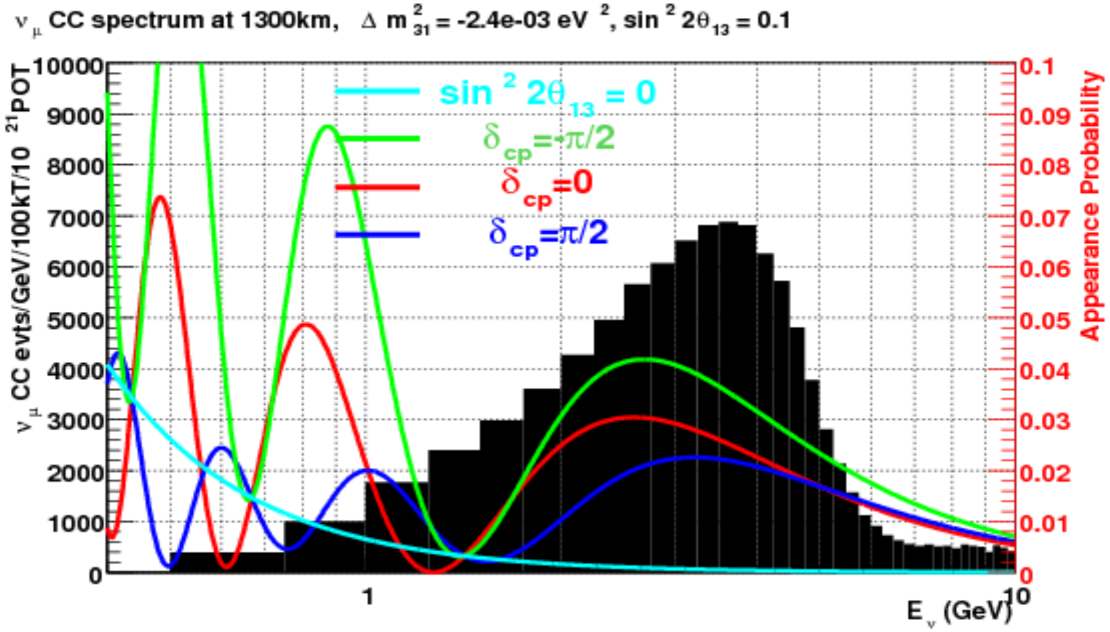


Neutrino Interaction in ArgoNeuT Detector

Precision Interferometry and DUNE



- The rate of neutrino flavor transition and the spectrum of those neutrinos that transition help to extract parameters related to neutrino oscillation.



- The rate of neutrino flavor transition and the spectrum of those neutrinos, particularly in that transition to electron neutrinos are used to extract parameters related to neutrino oscillation.