Some Lessons from MINERvA

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SBN-Theory Workshop
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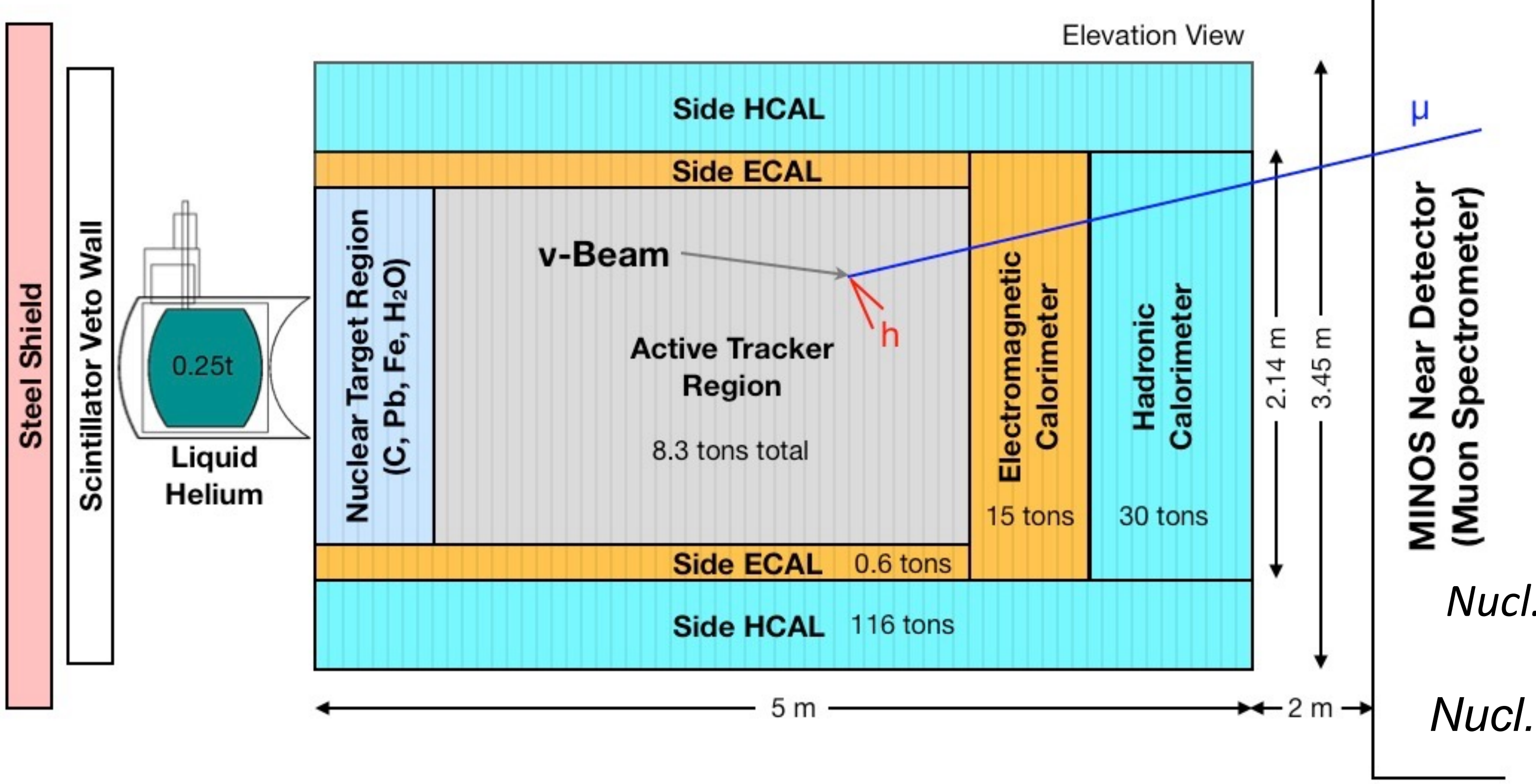
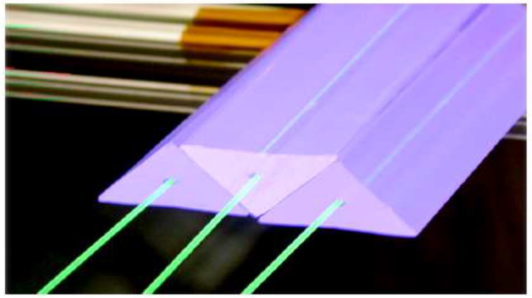
What was MINERvA and what was our primary goal?

- 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 interferometry measurements over a ~800km baseline.
- MINERvA's science goal was to measure a broad range of neutrino interactions on nuclei (big, 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.
- One *signature*: overwhelming statistics, at least for a neutrino experiment.
- Another *signature*: neutrino, electron scattering, and theory community as part of the collaboration from its inception.

MINERvA's Detector

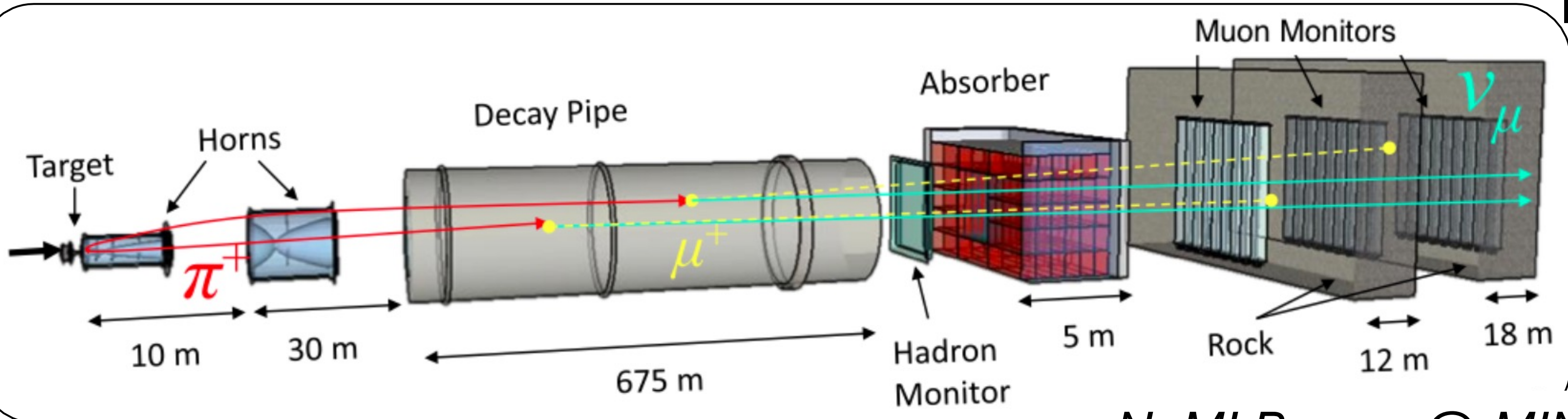




Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

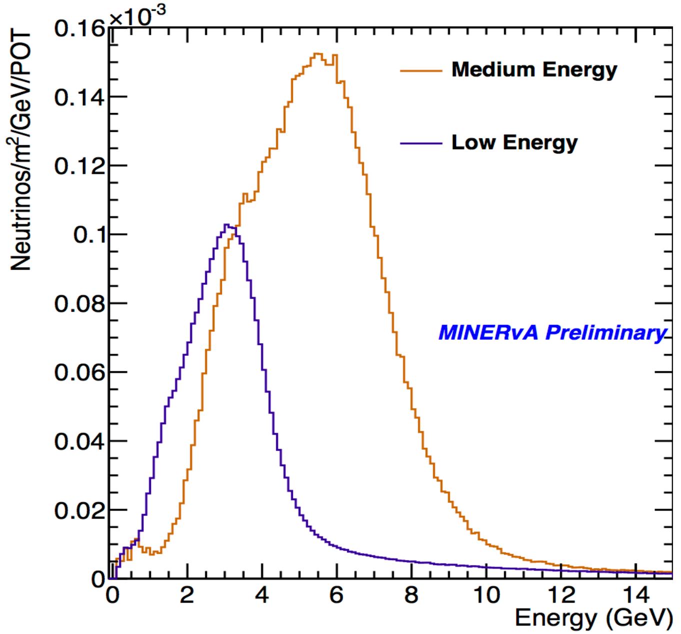
- Core of detector was an active scintillator strip target, surrounded by calorimetry.
- At MINERvA energies, most muons are forward and found in MINOS magnetic spectrometer.
- Passive targets interspersed with scintillator upstream.
- Detector is mostly in trash cans now, but some has been recycled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

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



Some lessons from MINERvA

1. Experiments take a long time. Things change.
2. “Simple” reactions are surprisingly complex, if you look.
3. Medium to large nuclei are all just “nuclei”, to first order.
4. Sub-leading processes are rich, if you have statistics.
5. You can do more than you think you can. Sometimes.
6. Momento mori.

Lesson One: Experiments take a long time, and things change around them.

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

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"

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Implications of the Neutrino History

Atmospheric neutrino oscillations at Super-K

 

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

 

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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.

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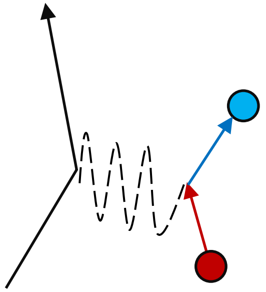
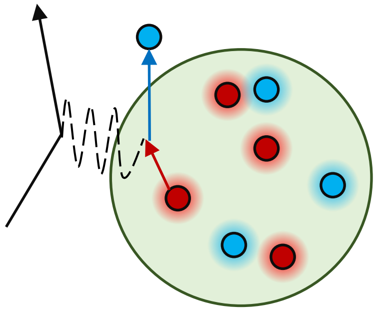
Lesson Two:
Even “Simple” Reactions are Hard, if you look.

MINERvA and Quasielastic Scattering

- MINERvA's targets are primarily nuclei, and the main active target is polystyrene scintillator (CH).
- Most of the "least inelastic" reactions from this target that are quasielastic scattering, meaning the "charged current elastic scattering" but from a target embedded in a nucleus.
- So charged current elastic is,
  $\bar{\nu}_\mu p \rightarrow \mu^+ n$, a.k.a. $p\left(\bar{\nu}_\mu, \mu^+\right)n$,

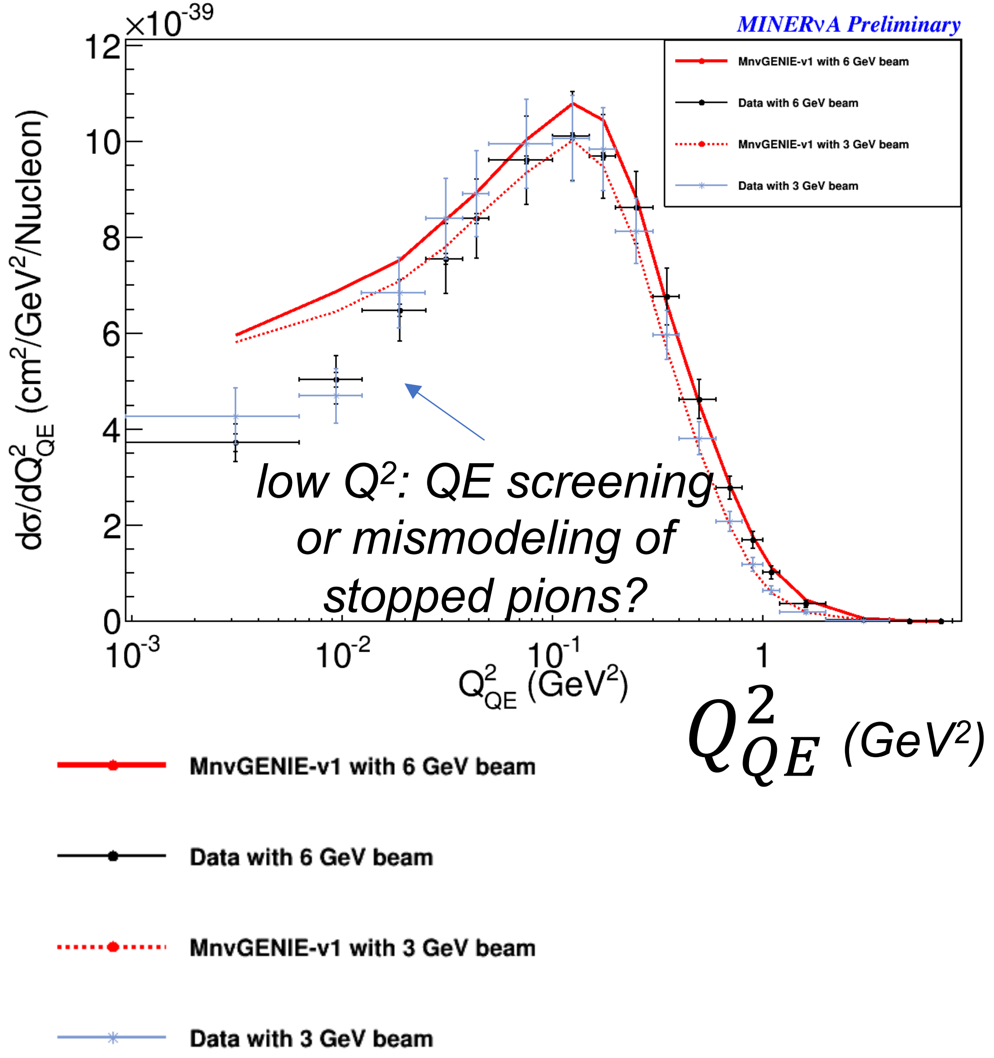


  but quasielastic means we look at $A(\bar{\nu}_\mu, \mu^+ n \ldots)A'$.



- These measurements convolve nucleon structure with nuclear effects.
- MINERvA's main focus was nuclear effects.

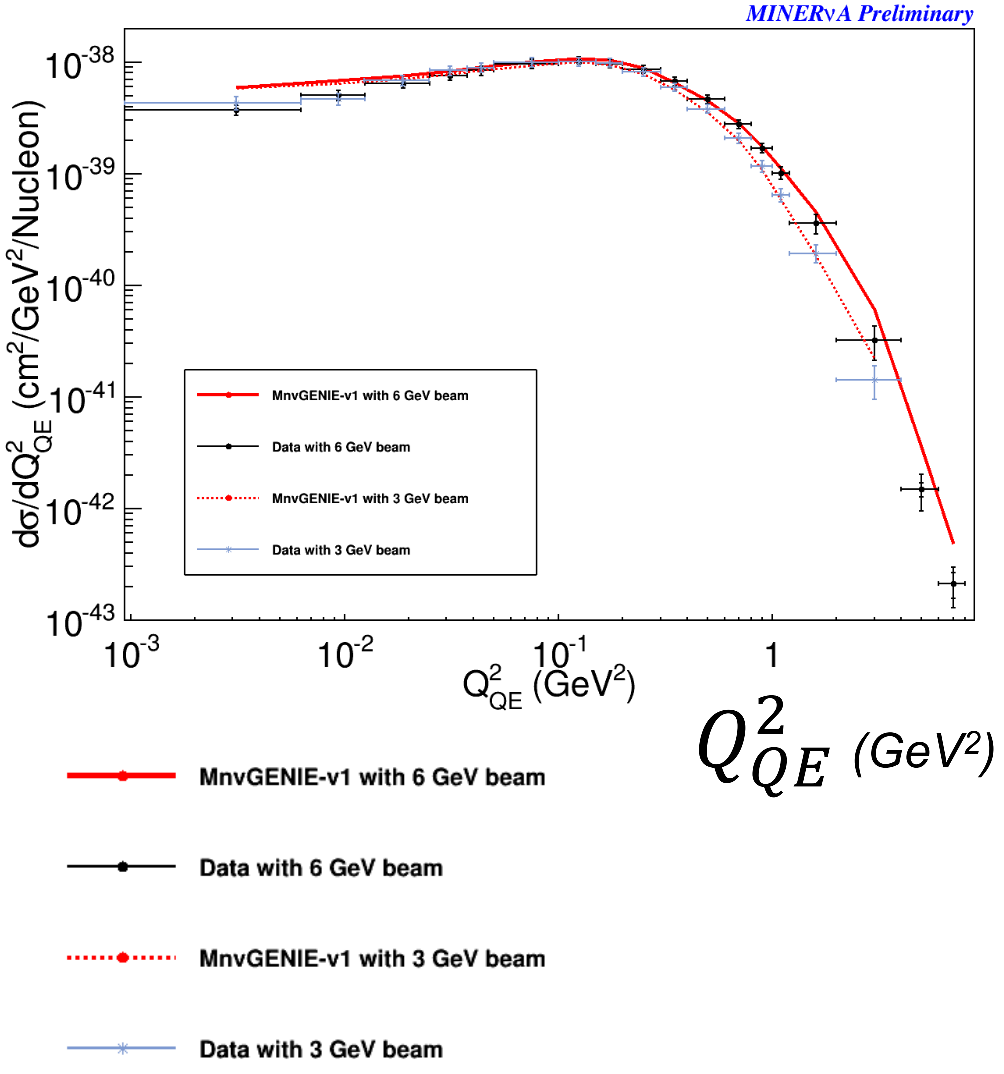
Quasielastic Results: $A(\nu_\mu, \mu^- p \ldots)A'$



- 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

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



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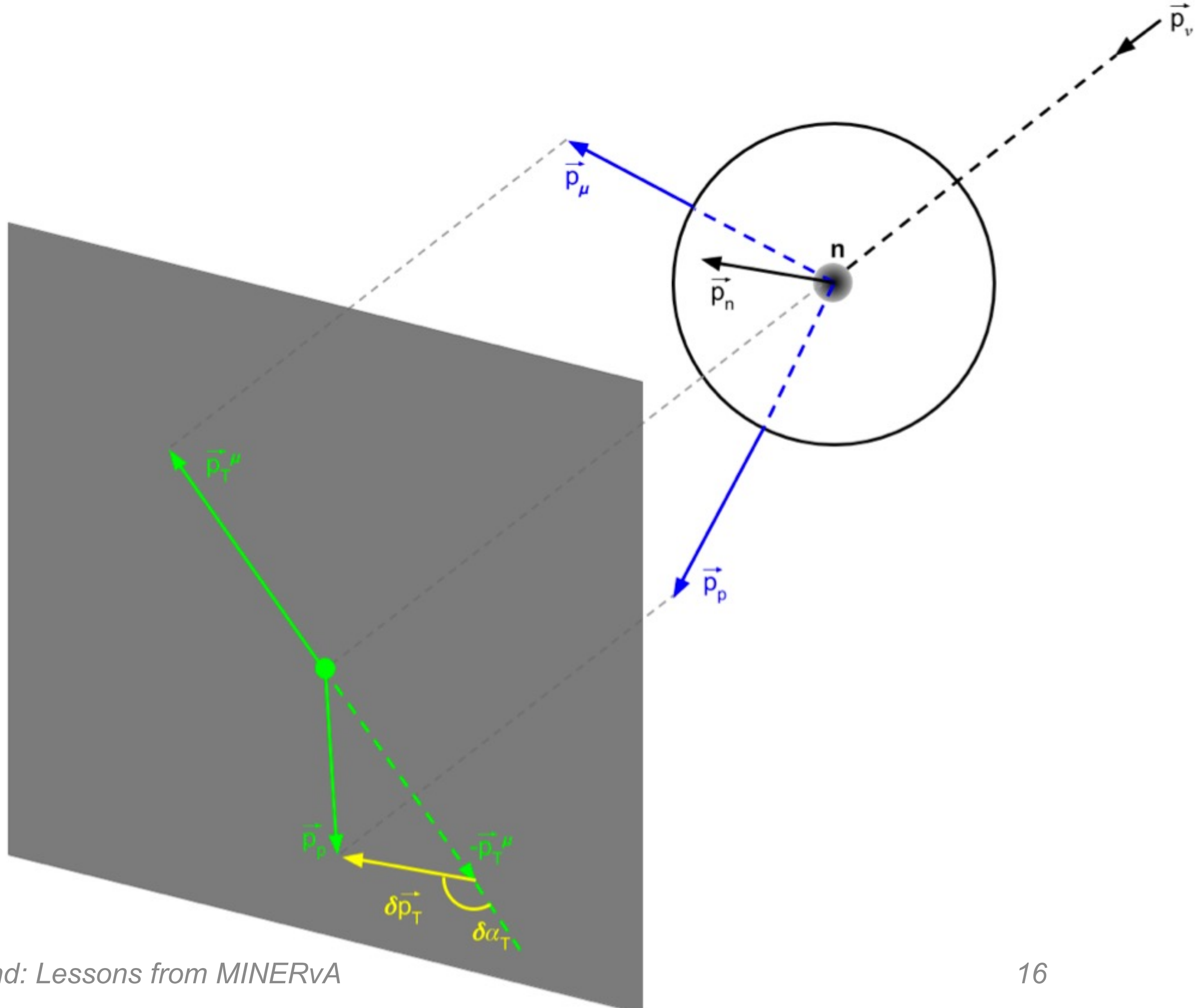
Lepton-Hadron Correlations

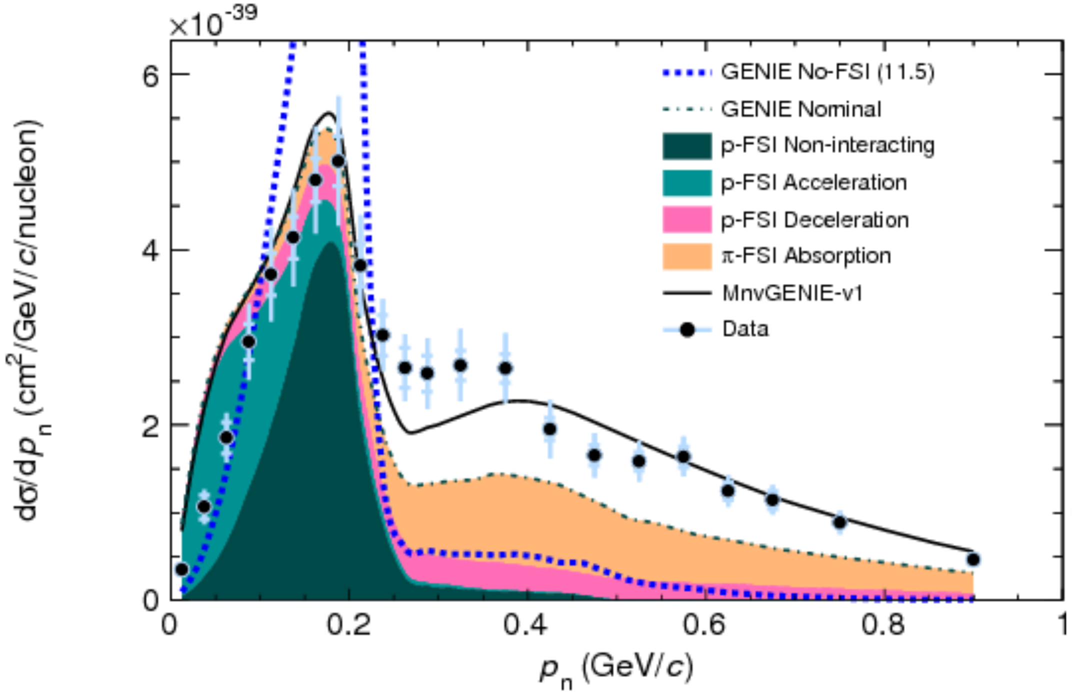
Transverse Balance in CC0π

- One very useful probe is the transverse balance of the leading proton and the lepton in CC0π events.
- In the absence of nuclear effects and extra particles in the final state, they are balanced.
- If energy of recoiling nucleus is known, can reconstruct momentum of target nucleon.

J. Sobczyk and A. Furmanski, Phys.Rev. C95 065501 (2017)

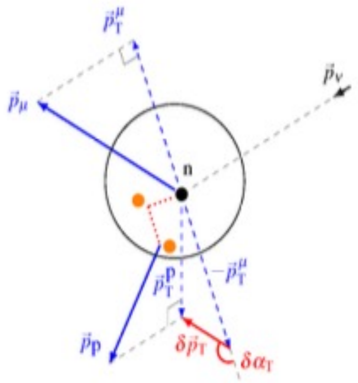


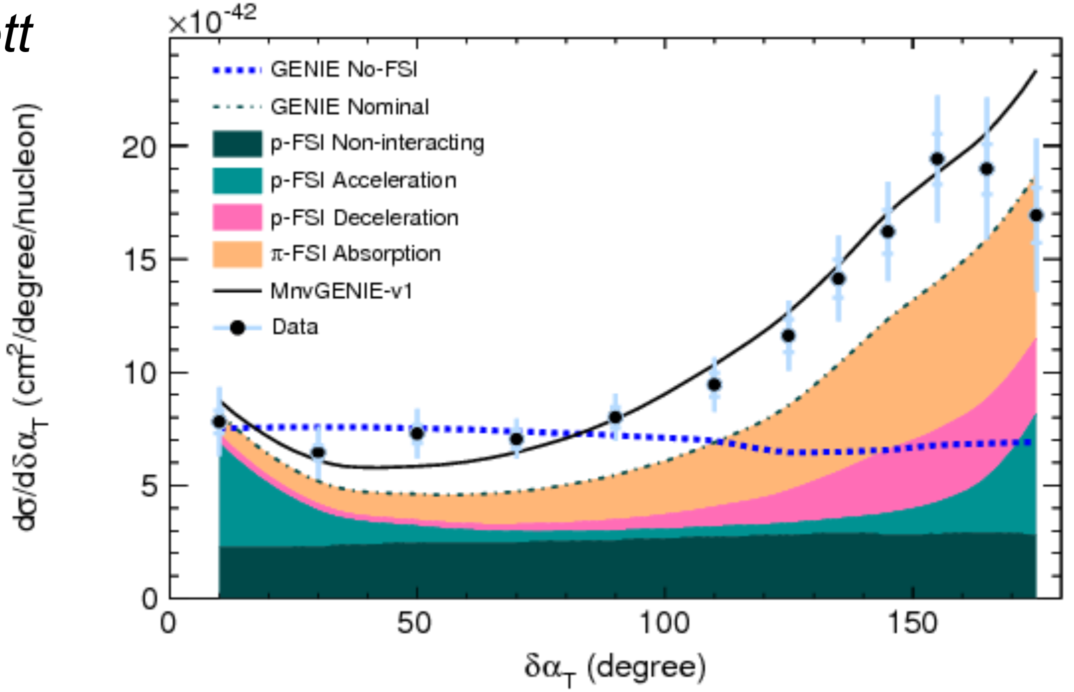
Initial State and Final State in CC0π



Neutron momentum under exclusive μp hypothesis

Phys. Rev. Lett 121 022504 (2018)





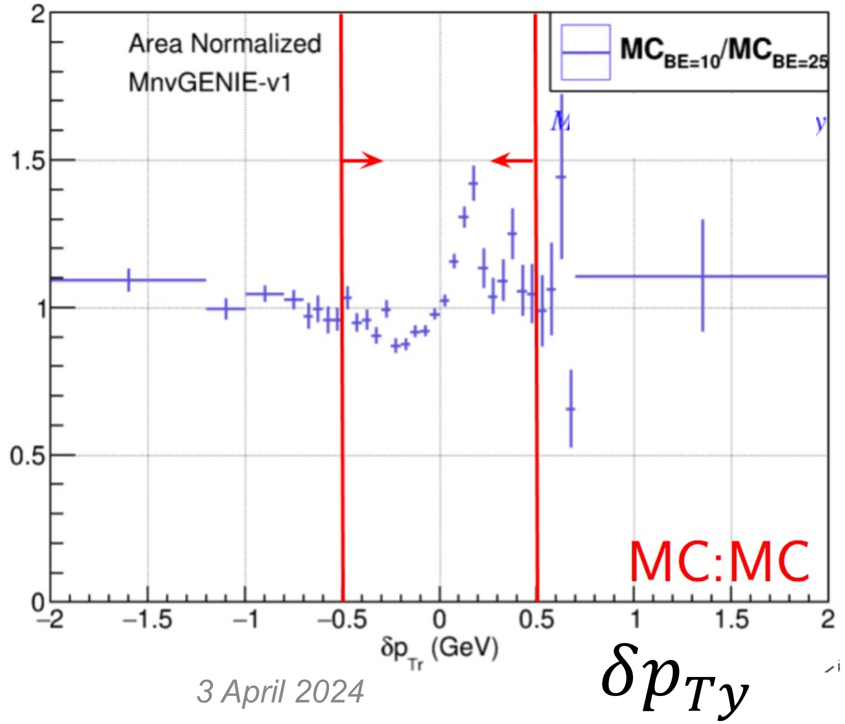
Missing p_T direction (decelerating process is 180^o)

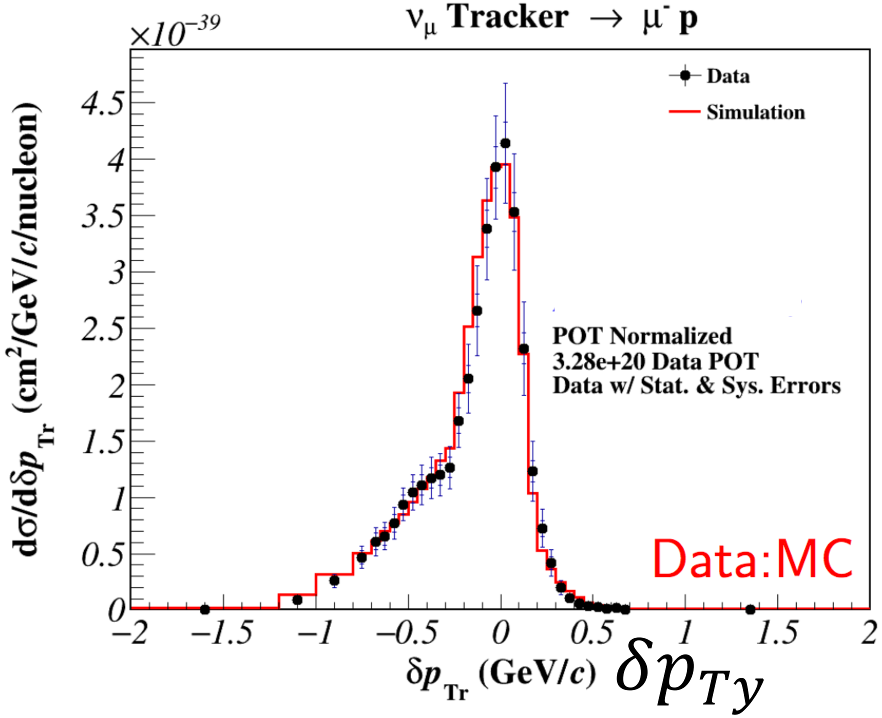
- MINERvA 2p2h tune helps! But by studying reconstructed neutron momentum and transverse variables in CC0π events, we have evidence for deficiencies in the initial and final state models (and tune?).

Transverse Variables and Nuclear Potentials

- Transverse balance projected into the reaction plane, δp_{Ty}, is biased by the nuclear binding potential.

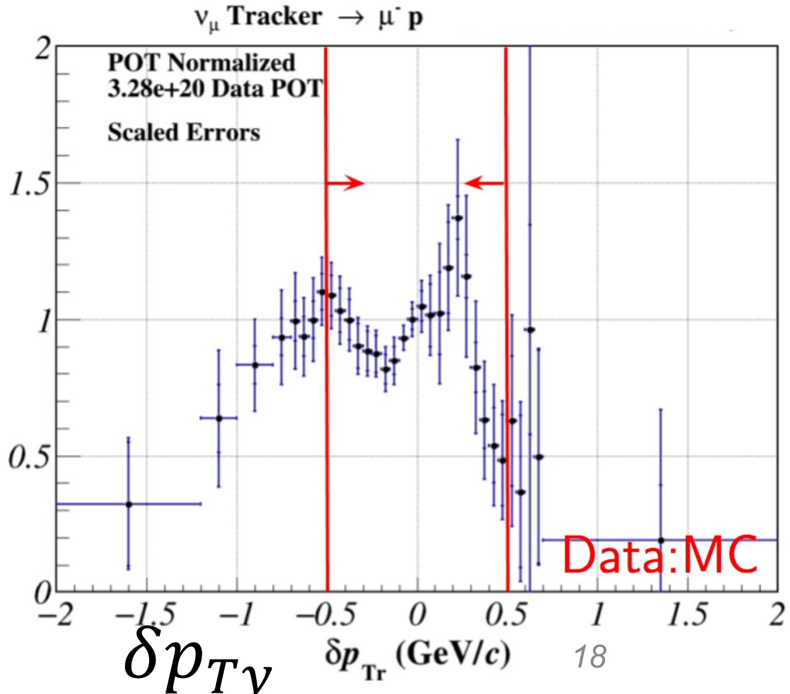
Peak shift from default binding energy to correction proposed by Bodek and Cai in Eur. Phys. J. C. (2019) 79: 293.



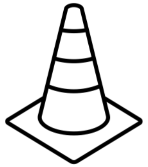


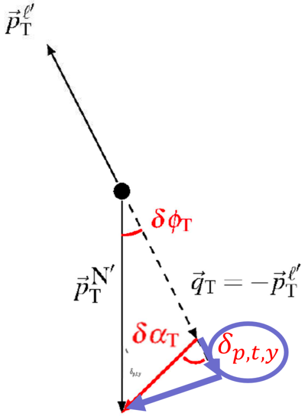
As it turns out, there is a similar shift near the peak. (Features in tail also.)

Phys.Rev.D 101 (2020) 9, 092001



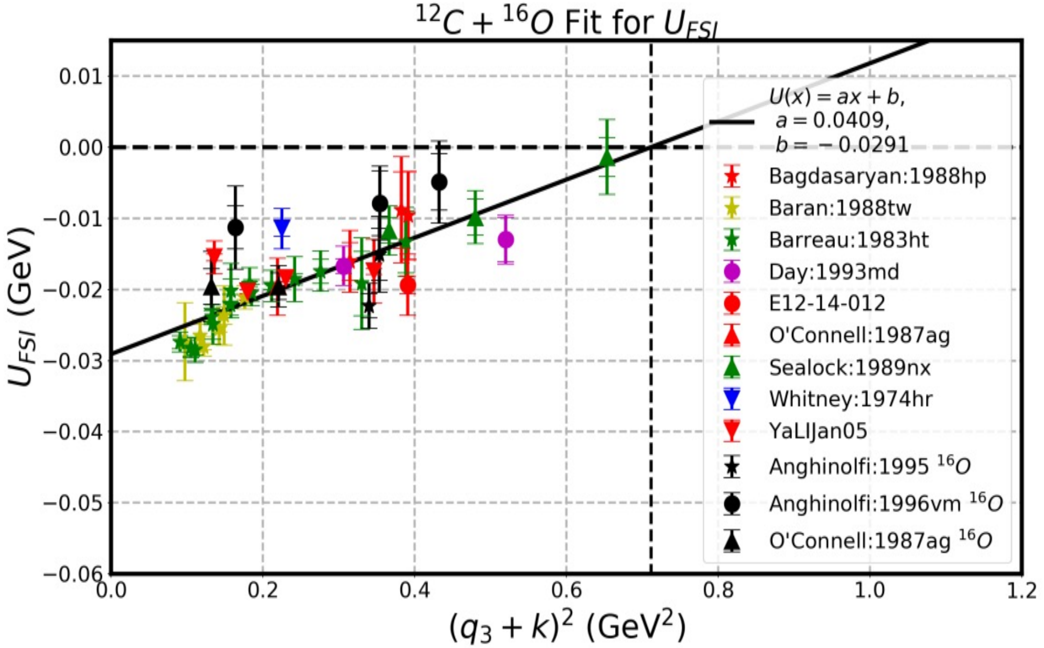
Transverse variables, full MINERvA statistics





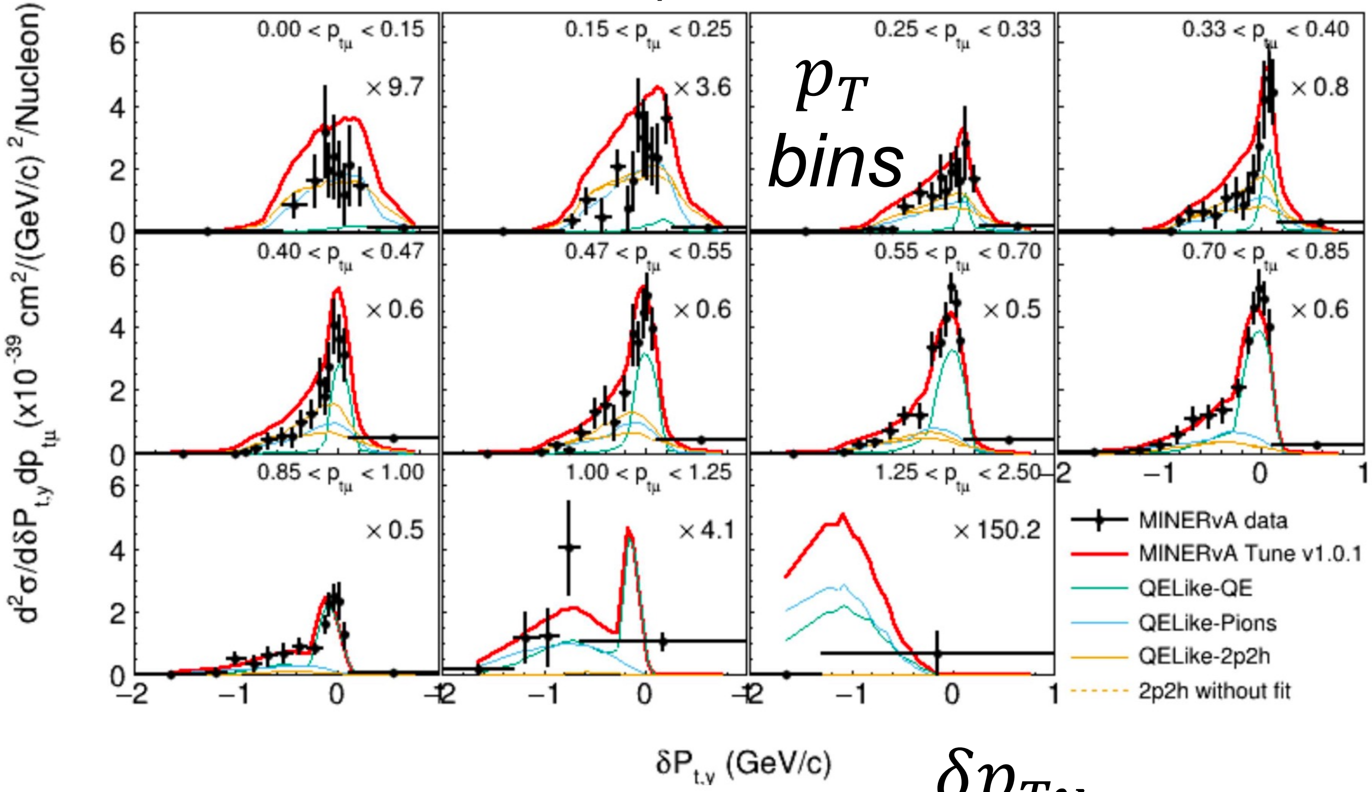
in reaction plane, sensitive to Fermi motion and (bias) from removal energy

$\delta_{p,t,y}$



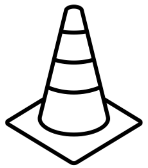
Summary of optical potential from electron scattering
A. Bodek and T. Cai, Eur. Phys. J. C. (2019) 79: 293

all processes



δp_{Ty}

Transverse variables, full MINERvA statistics



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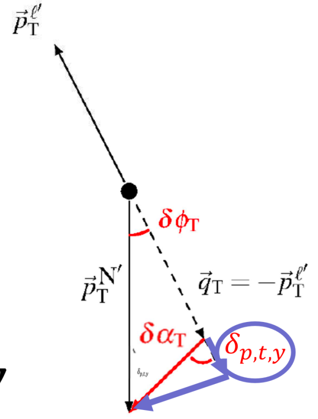

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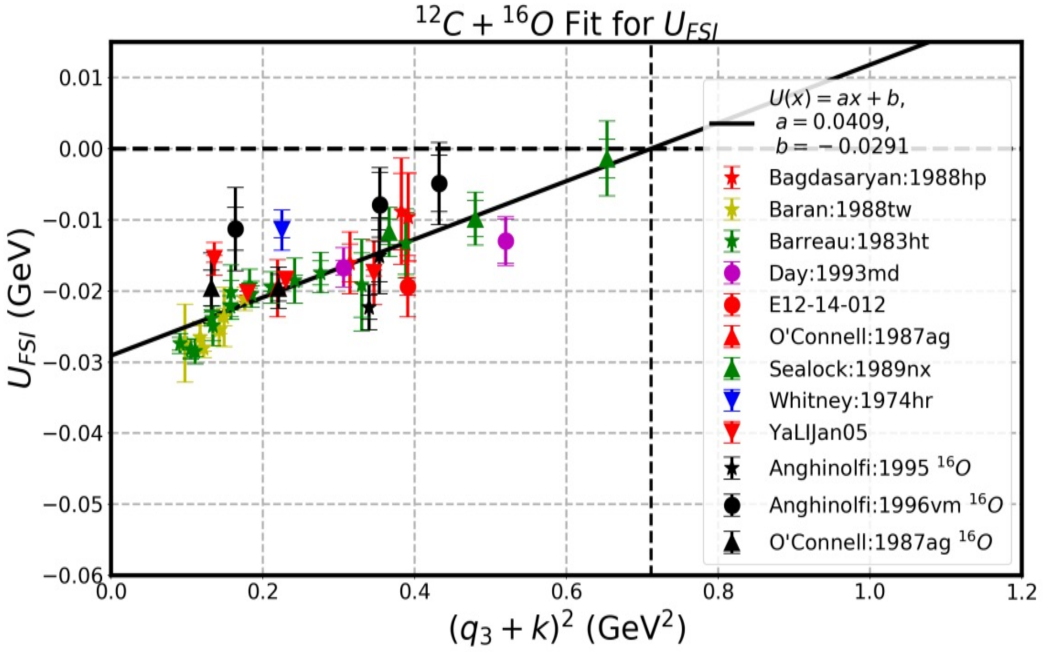
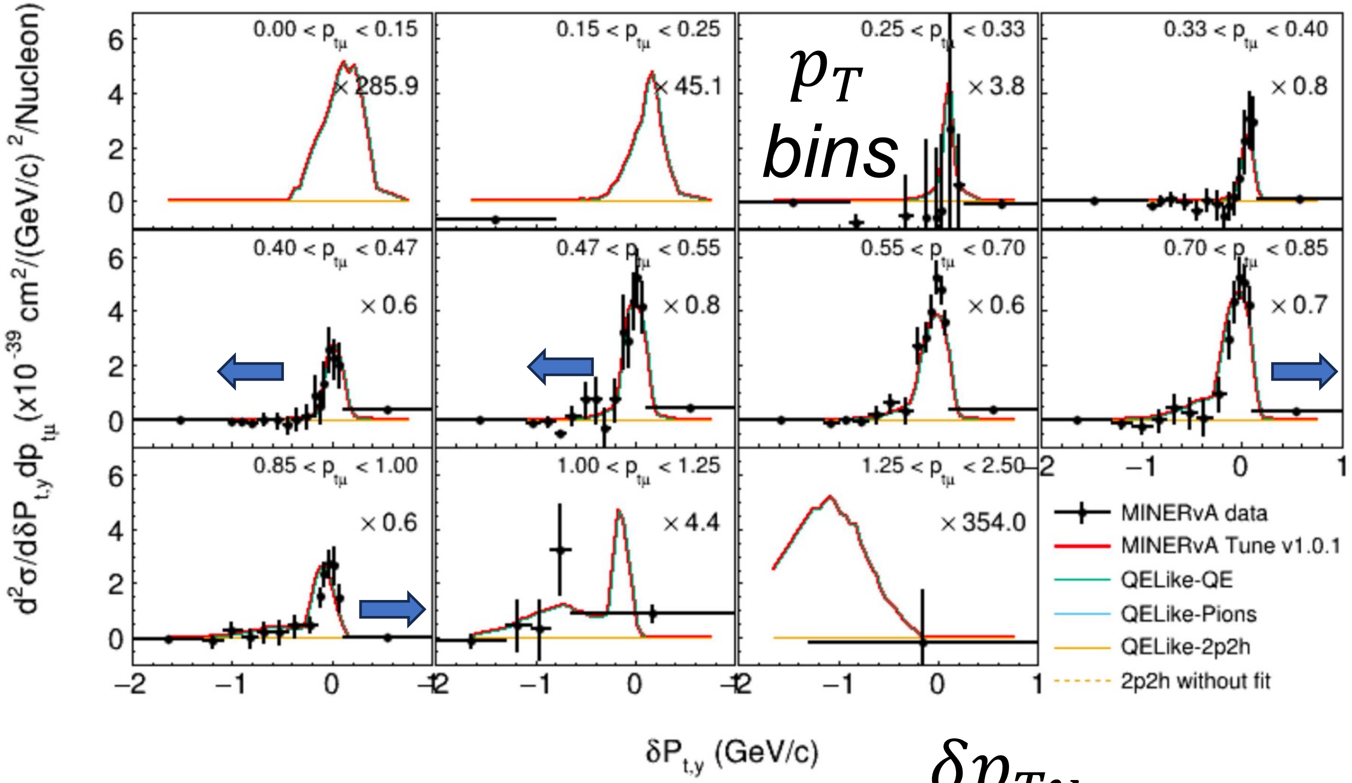


Summary of optical potential from electron scattering
A. Bodek and T. Cai, Eur. Phys. J. C. (2019) 79: 293

quasielastic, after other processes subtracted

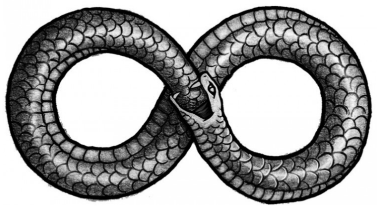


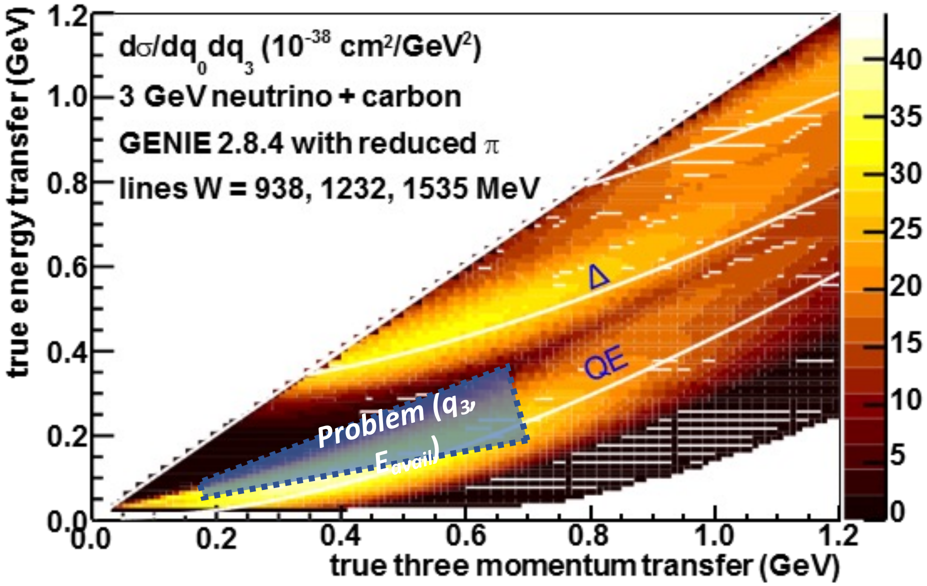
δp_{Ty}

Visible Energy

Visible energy in CC0π

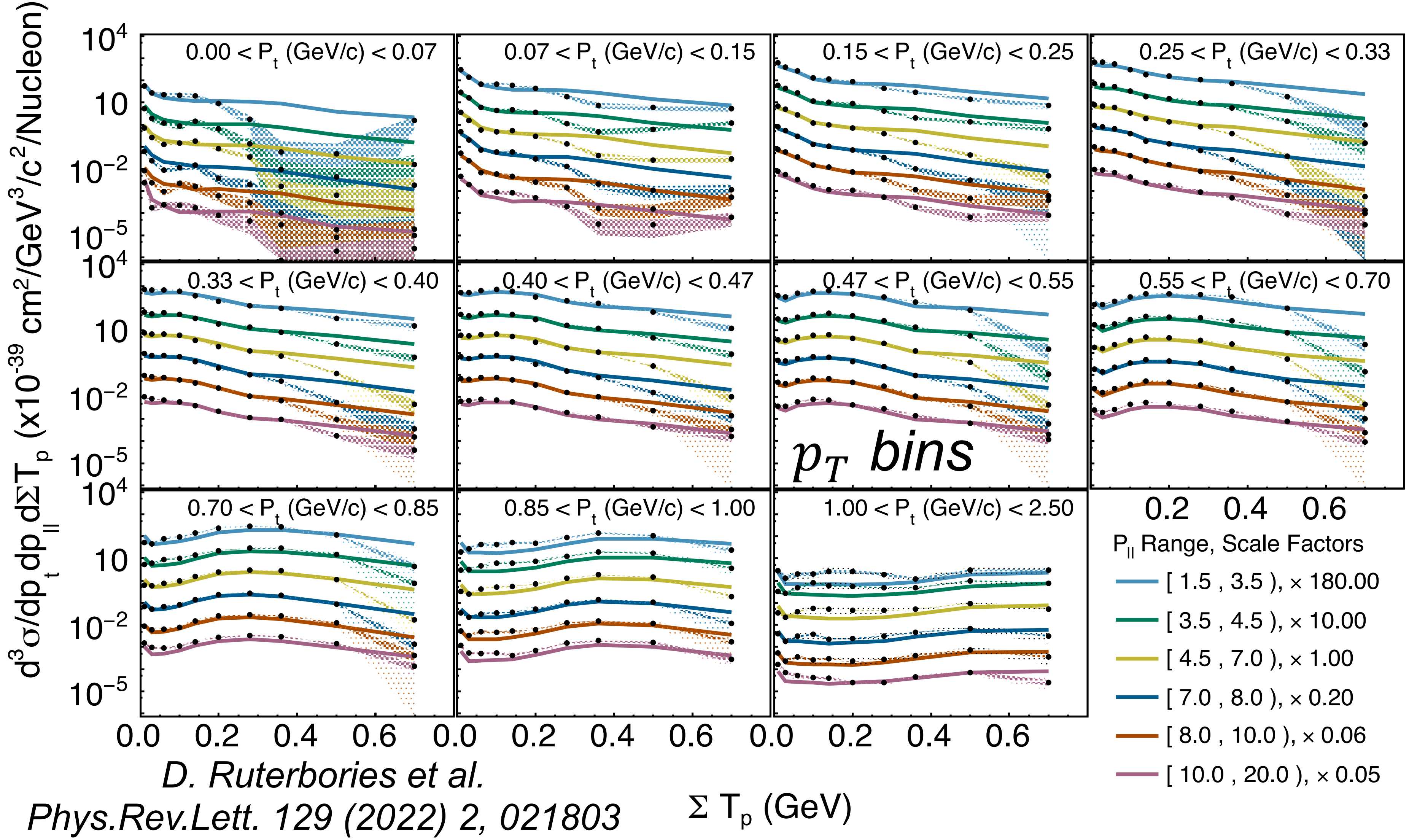
- It's possible to look explicitly at the subset of the inclusive sample in which we measured $E_{\text{avail}} \approx q_0 - \Sigma T_n - \Sigma m_{\pi^\pm}$.
- For the CC0π subsample,
$$E_{\text{avail}} = \Sigma T_p = q_0 - \Sigma T_n$$
- To divide the data up in this variable simultaneously with lepton variables, we used the higher statistics 6 GeV CC0π.





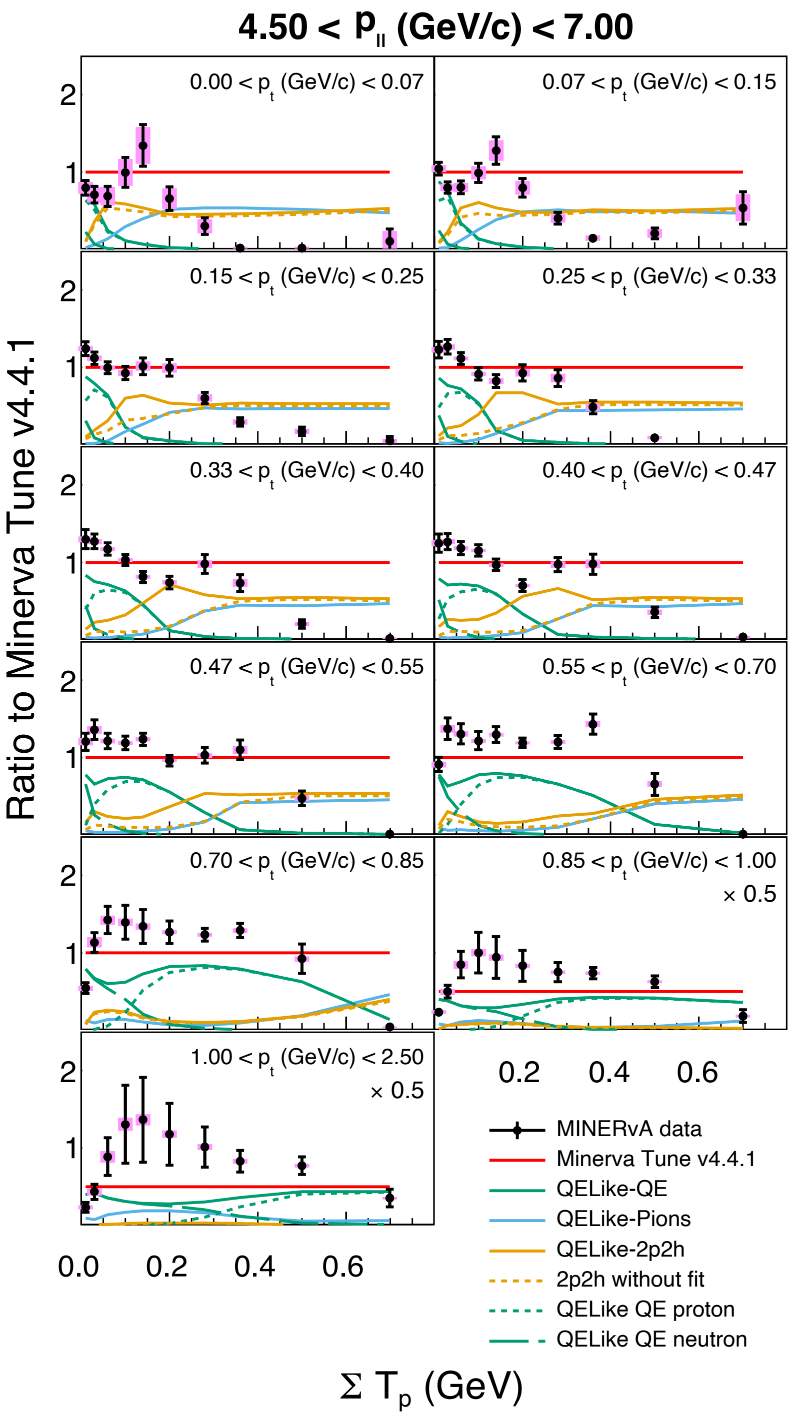
$$E_{\text{avail}} \approx q_0 - \Sigma T_n - \Sigma m_{\pi^\pm}.$$

Results: CC0$\boldsymbol{\pi}$ ΣT_p, p_T, $p_\parallel$



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

- *Lots to see here.*
- *The trends we see are independent of $p_\parallel$, suggesting they are not strongly energy dependent.*
- *Easier to break it down in a single bin of $p_\parallel$*



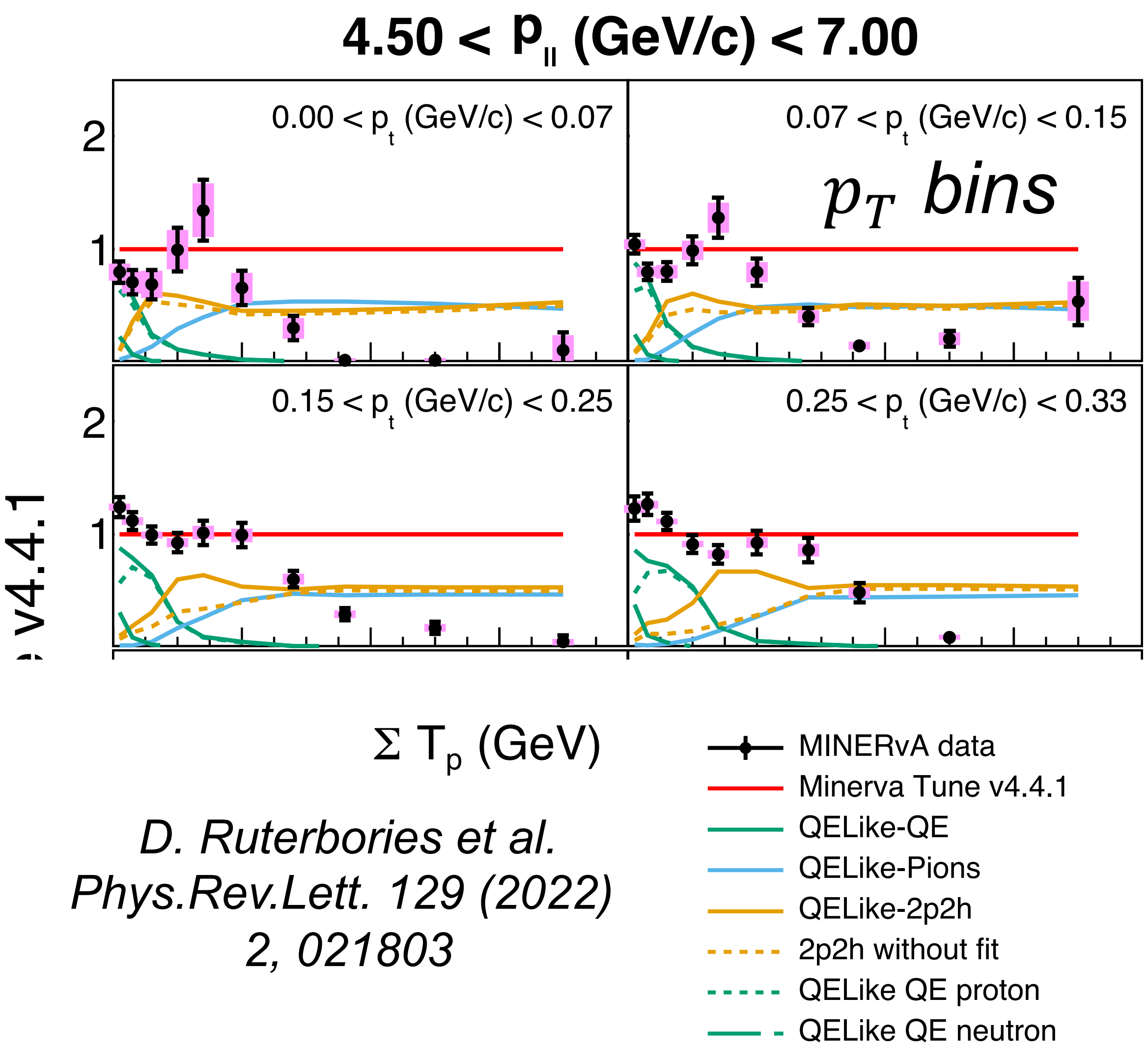
Results: CC0$\boldsymbol{\pi}$ ΣT_p, p_T, $p_{\|}$

p_T *bins*

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

- The biggest change in cross-section, though not in the ratio, are the small deviations just above the QE peak. Maybe MINERvA's tune was affected by non- CC0$\boldsymbol{\pi}$ events? Or…?
- 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.

Results: CC0$\boldsymbol{\pi}$ ΣT_p, p_T, $p_{\parallel}$



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

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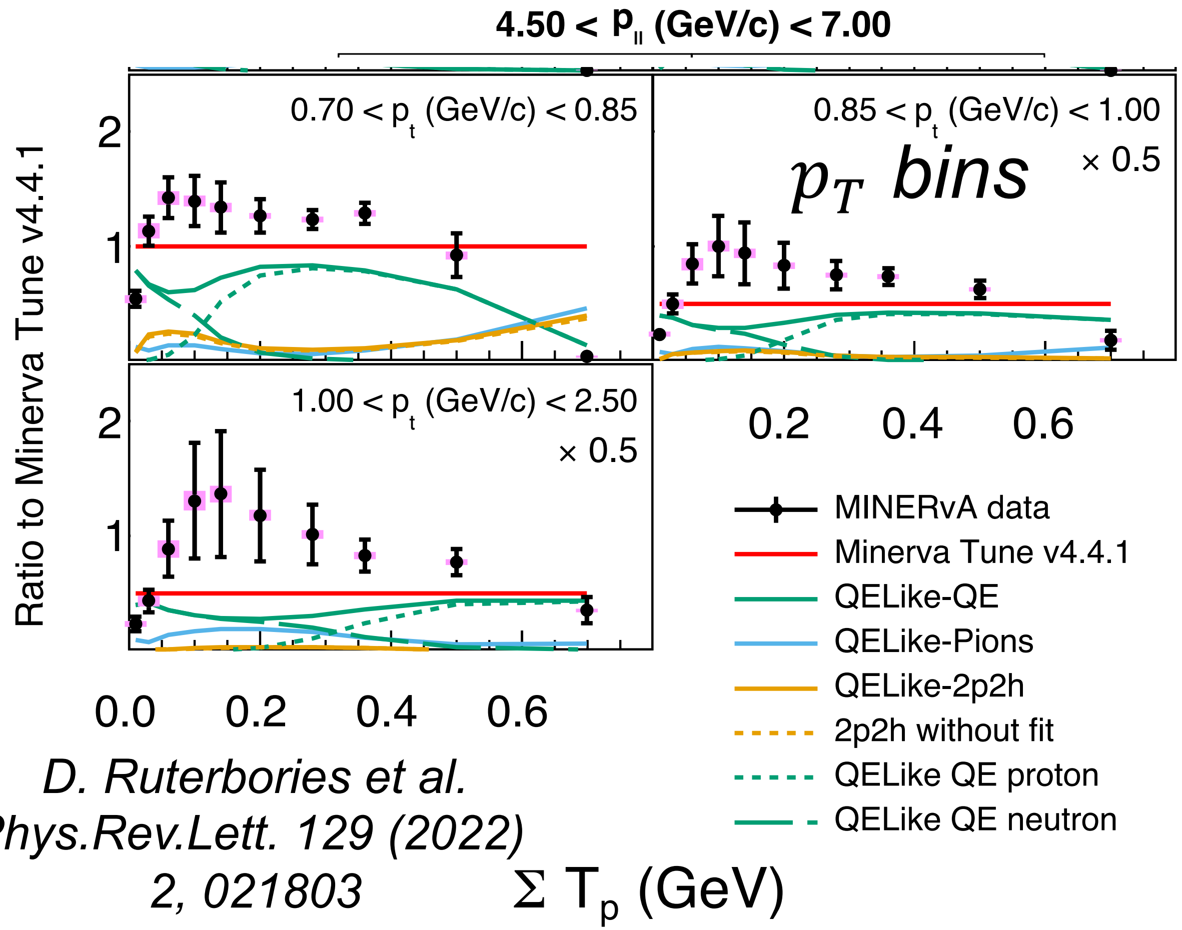

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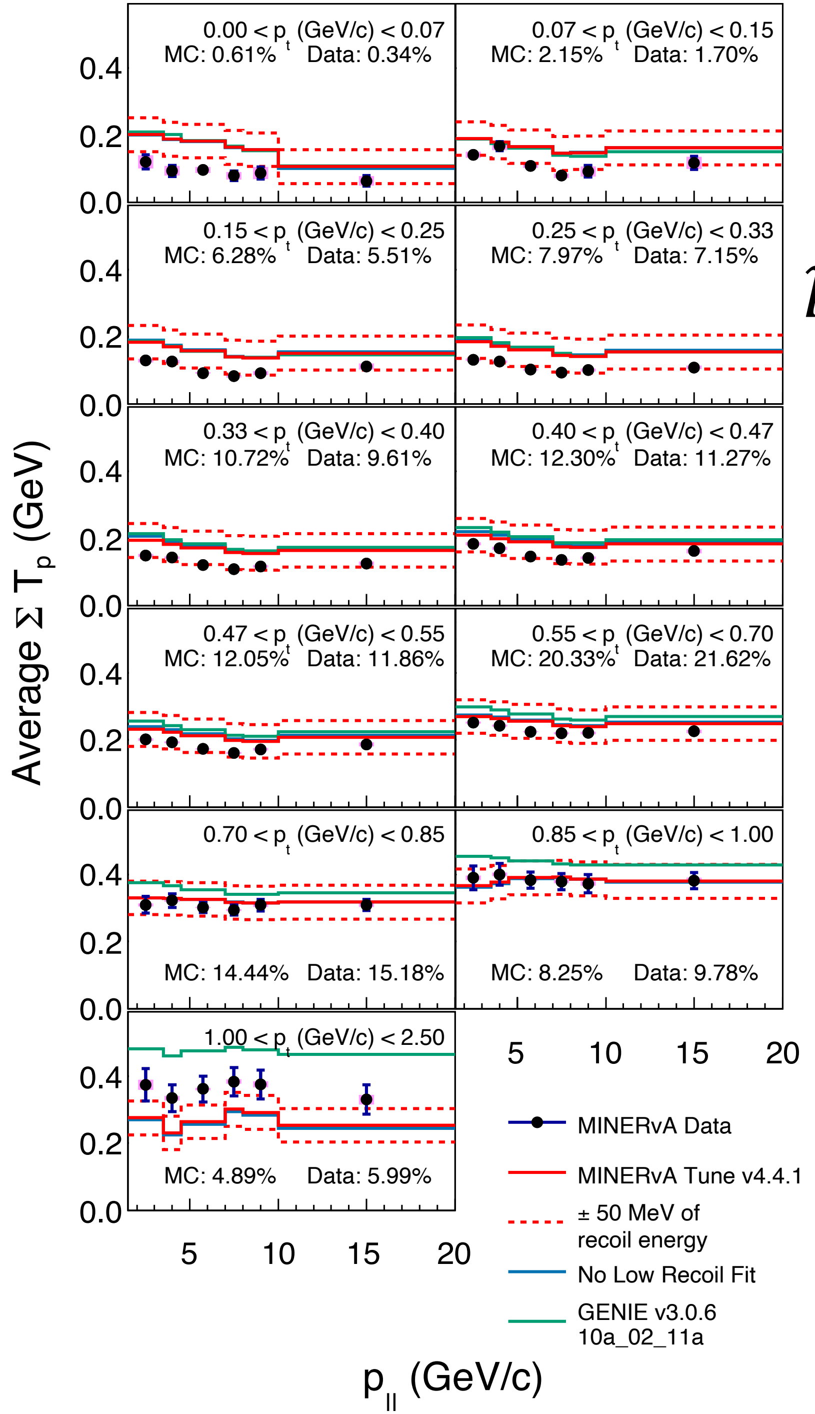
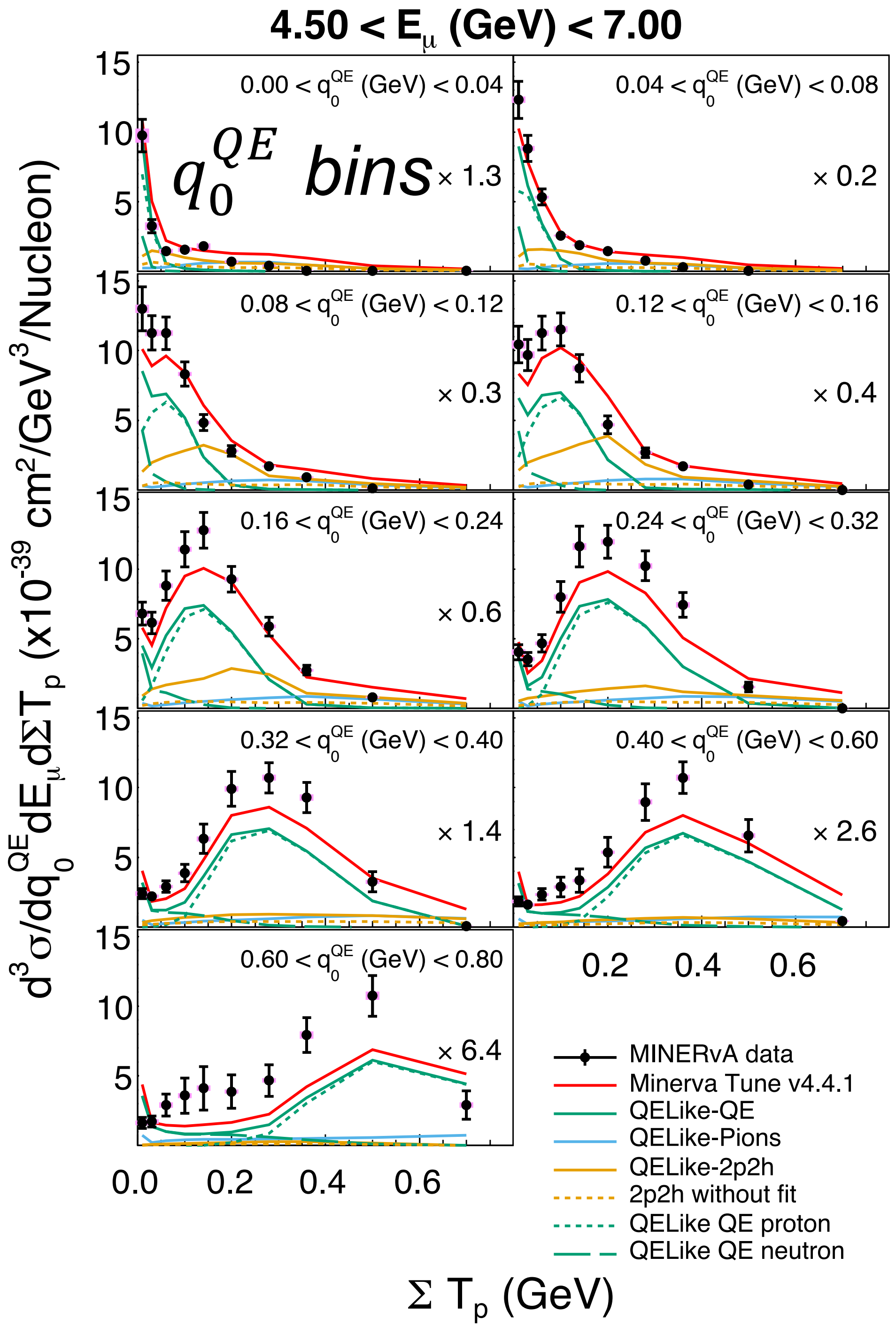
Another visualization of $\text{CC0}\boldsymbol{\pi}\ \Sigma T_p, p_T, p_{\|}$



p_T bins

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

- The first and second discrepancies are the biggest and potentially most important effects in cross-sections: large parts of the rate shows up at a given p_T with a different recoil than expected.
- Problem for interferometry experiments?
  - In T2K (and future Hyper-K) p_T is used to measure the recoiling energy by two body quasielastic kinematics.
  - In NOvA and DUNE, the visible recoil is measured. And SBN can do both.
  - Apparently, these two won't agree.
- Recoil is 50 MeV too high, until high Q^2. No model we checked sees anything like this discrepancy.



Another visualization of CC0$\boldsymbol{\pi}$ $\Sigma T_p, p_T, p_\parallel$

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

- Problem for oscillation experiments?
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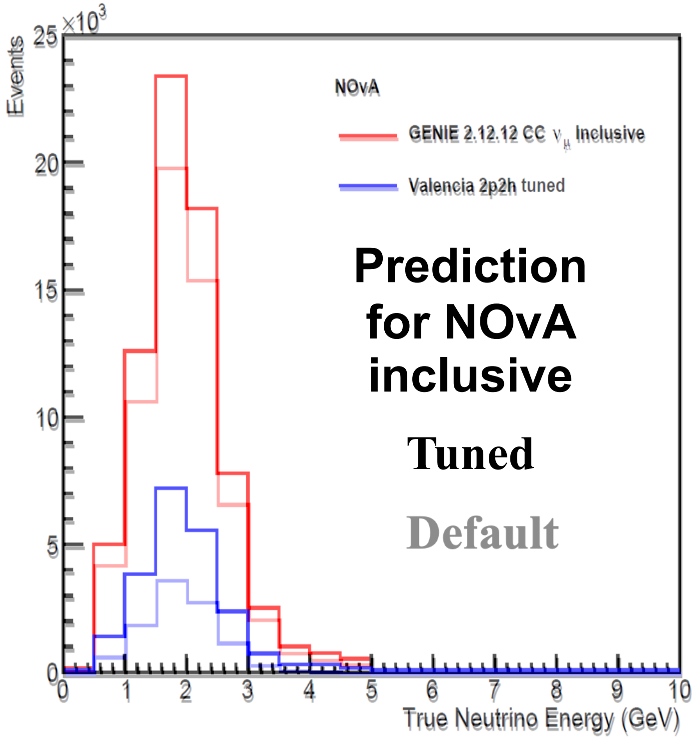
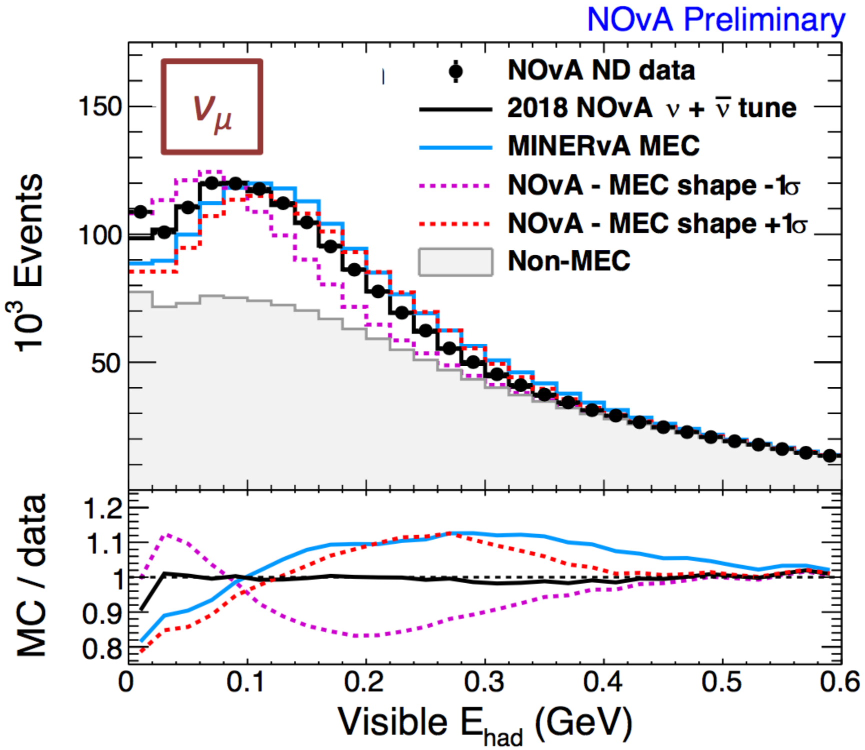
  - In NOvA and DUNE, the visible recoil is measured. And SBN can do both.
  - Apparently, these two won't agree.
- We can actually directly compare the two types of energy measures: recoil in bins of q_0^{QE}.
- Agreement with the model is, as expected, poor.
  - Peaks are missed at low p_T.
  - High side tail is overestimated and low side is underestimated.

Implications for NOvA and DUNE





- Beam energy ~ 2 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Signifiicant change in inclusive energy spectrum at NOvA energy

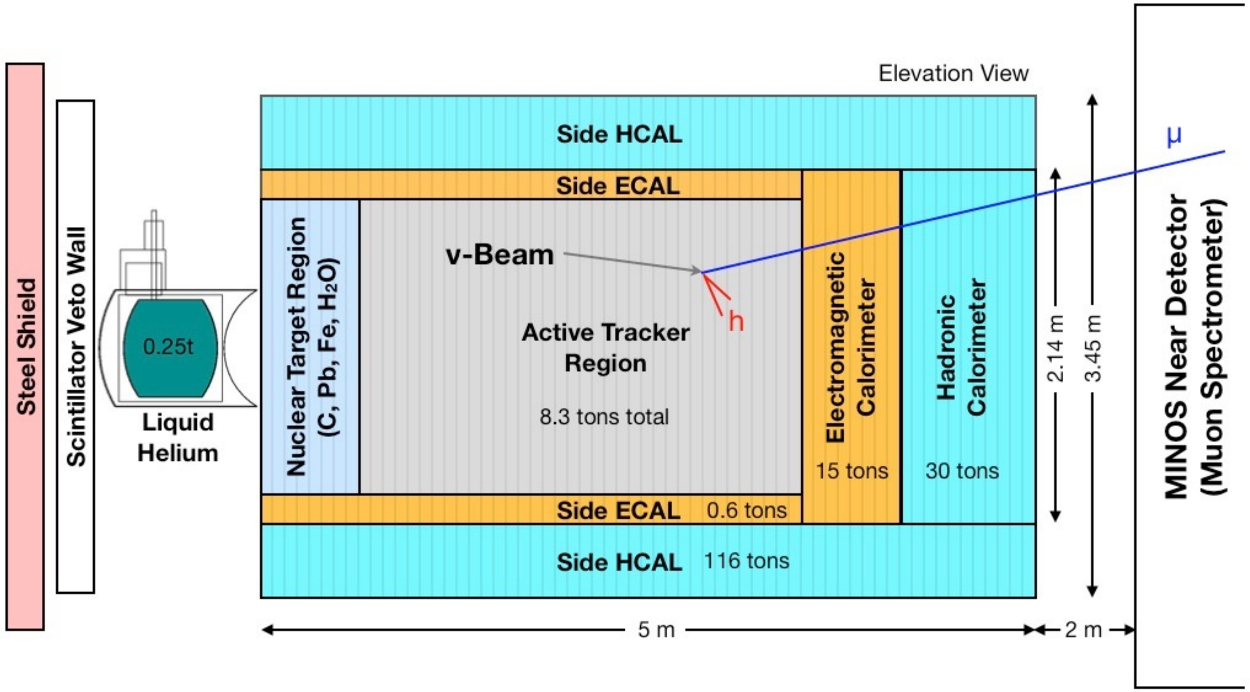
Alex Himmel, JETP Seminar, June 2018

- As noted, NOvA follows MINERvA's "inclusive" E_{avail} technique to tune.
- Within the limits of what is probed, it seems effective.
- But our recent data suggests that the part of the model being tuned won't have its recoil well modeled by the tune.

Lesson Three:
The leading order nuclear effect is that all nuclei are nuclei.

MINERvA's Passive Targets and CC0π

- *Evolution of scattering with nuclear size is are largely unmeasured experimentally.*
- *However, there is theoretical guidance that tells us what to look for.*

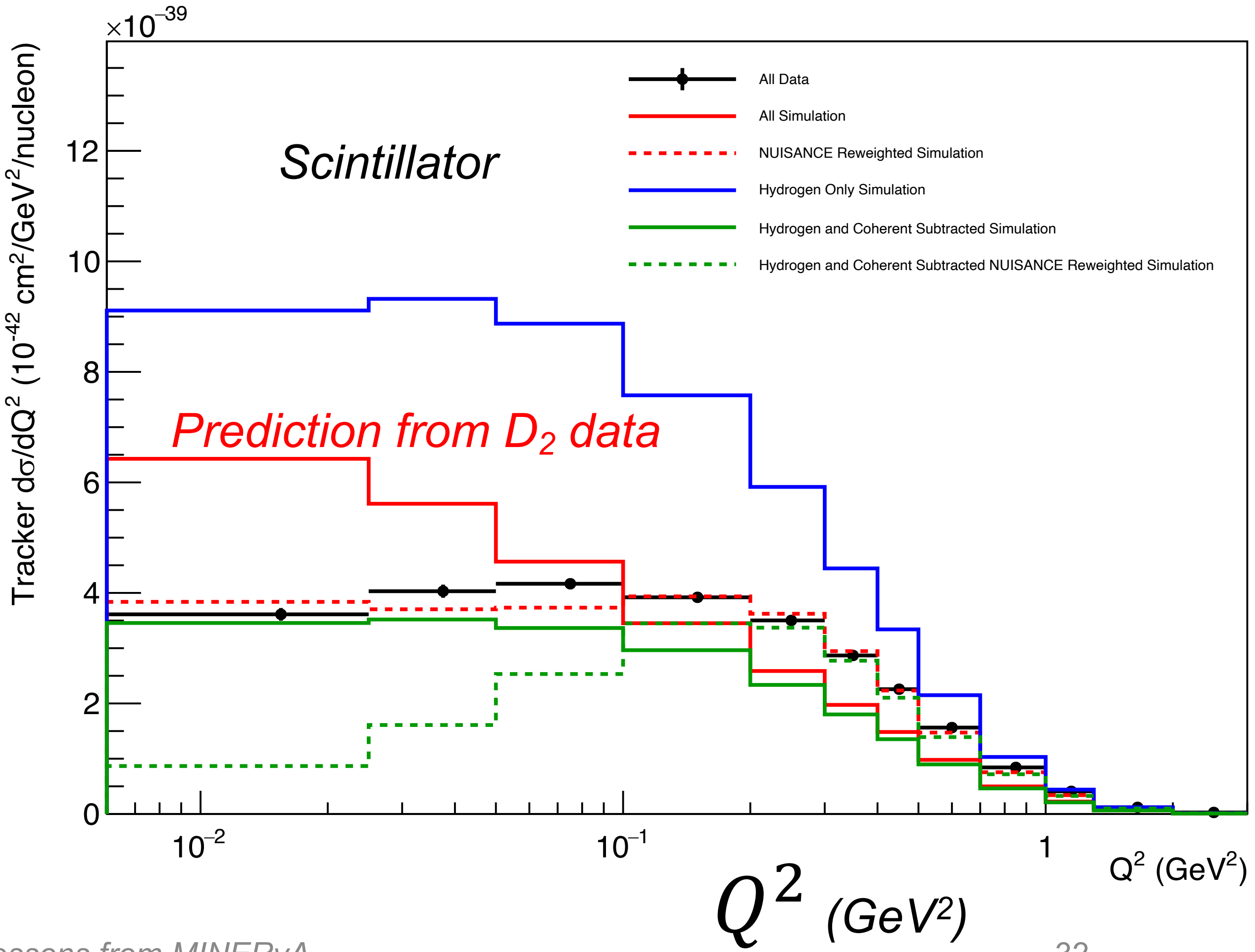


- Upstream of the MINERvA tracker is a region of He, C, H_2O, Fe, and Pb targets.
  - Masses of 0.25-0.8 ton, so statistics limited.
- First results from 3 GeV beam were very limited for CC0π and essentially impossible for any other exclusive or semi-inclusive state.
- But the 6 GeV data set offers more than an order of magnitude more statistics…

$\nu 1\pi^+$ and $\nu 1\pi^0$ on nuclear targets

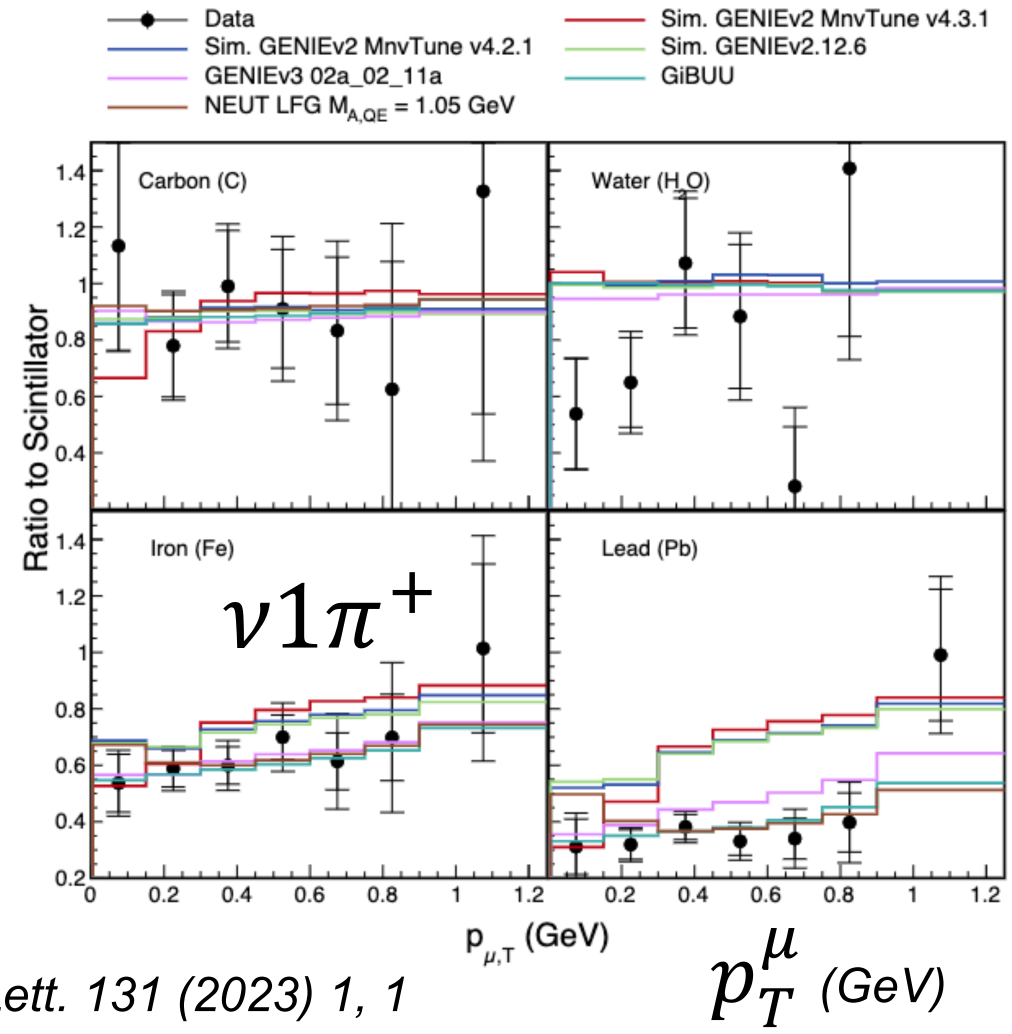
- Basic message. Low Q^2 suppression in the scintillator (and enhancement at high Q^2) is definitely present in data.
- We tune coherent pion production to match our coherent results, and nuclear suppression to match these results on scintillator.

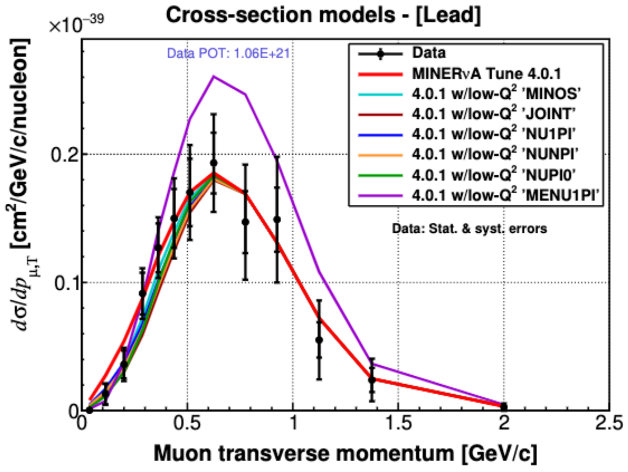
A. Bercellie et al, Phys.Rev.Lett. 131 (2023) 1, 1



$\nu 1\pi^+$ and $\nu 1\pi^0$ on nuclear targets

- Altered shape in Q^2 appears universal!
- But rates are far from prediction and suppressed in heavier targets.





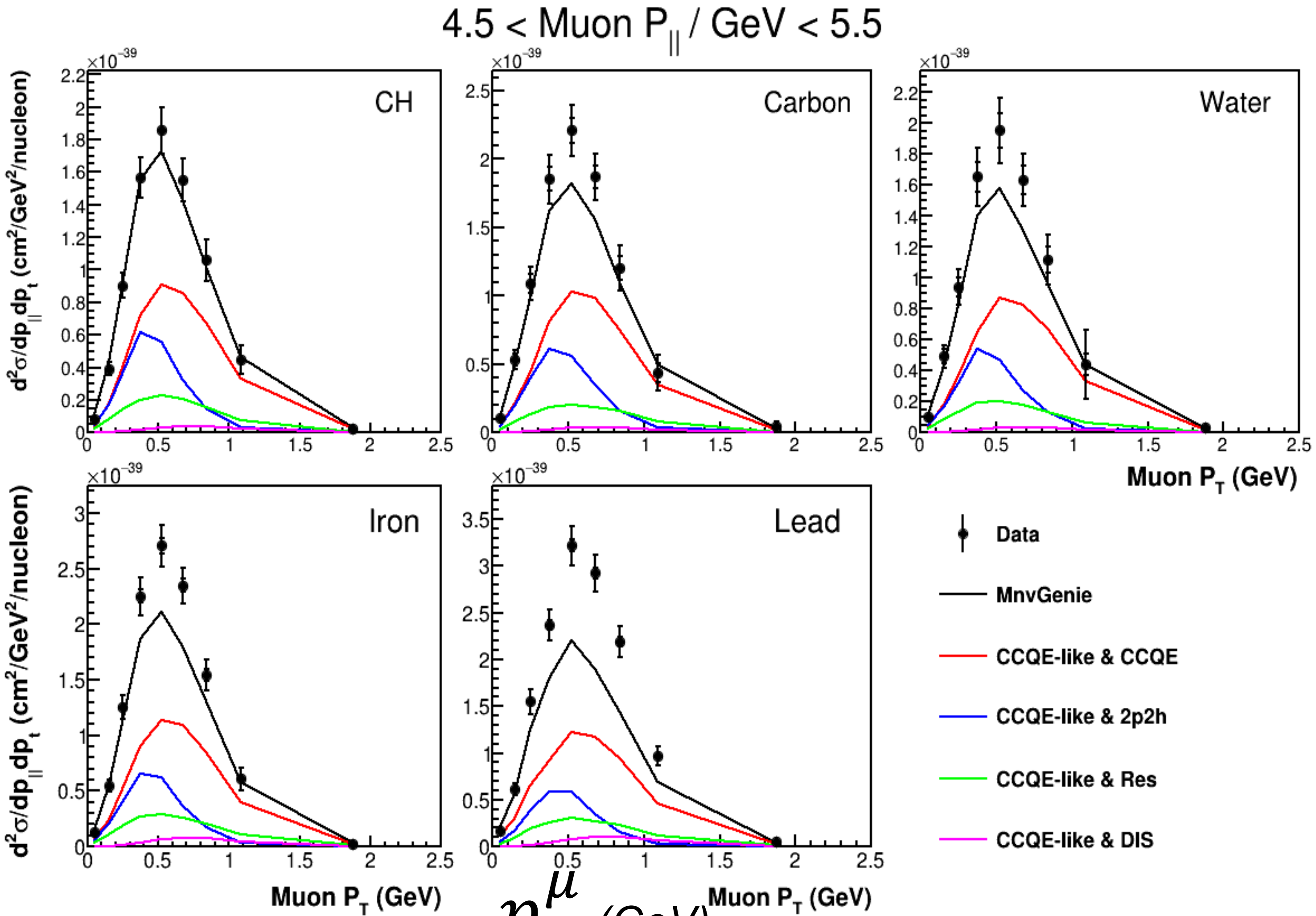
$\nu 1\pi^0$

A. Bercellie et al, Phys.Rev.Lett. 131 (2023) 1, 1

6 GeV CC0π Lepton Kinematics on targets

J. Kleykamp et al., *Phys.Rev.Lett. 130 (2023) 16, 161801*

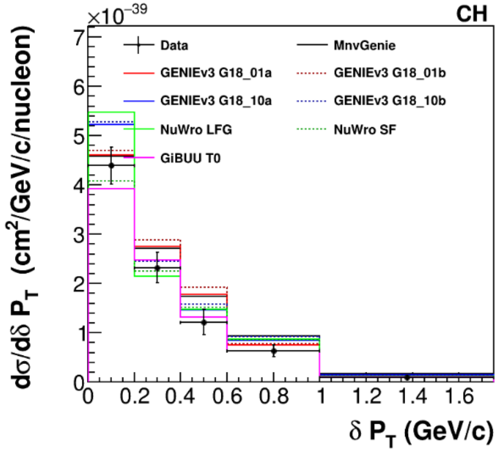
- There is a large predicted cross-section in the more neutron rich targets; but within this model that prediction doesn't explain the changes.
- Overpredicted processes (stopped pions) on proton? 2p2h scaling with A?
- Progress might rely on more information… like proton-lepton correlations…

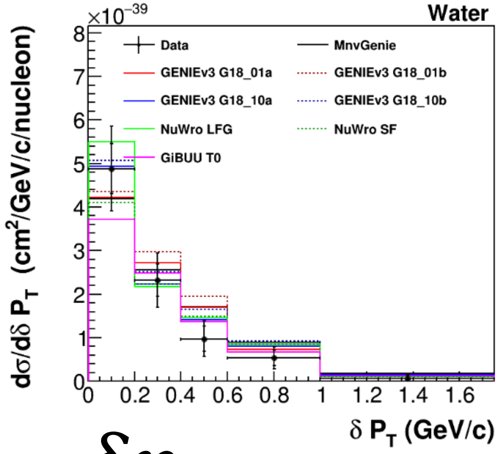


p_T^{μ} (GeV)

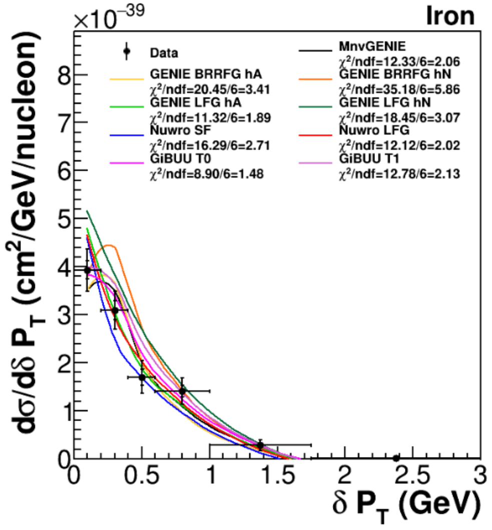
6 GeV CC0π Transverse Kinematic Imbalance in Targets

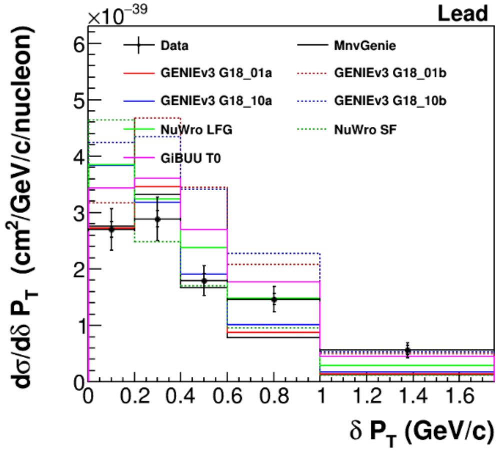
- A paper on proton-lepton correlations is in progress, to appear soon.
- Models vary wildly in how they predict A scaling of non-QE processes/FSI.





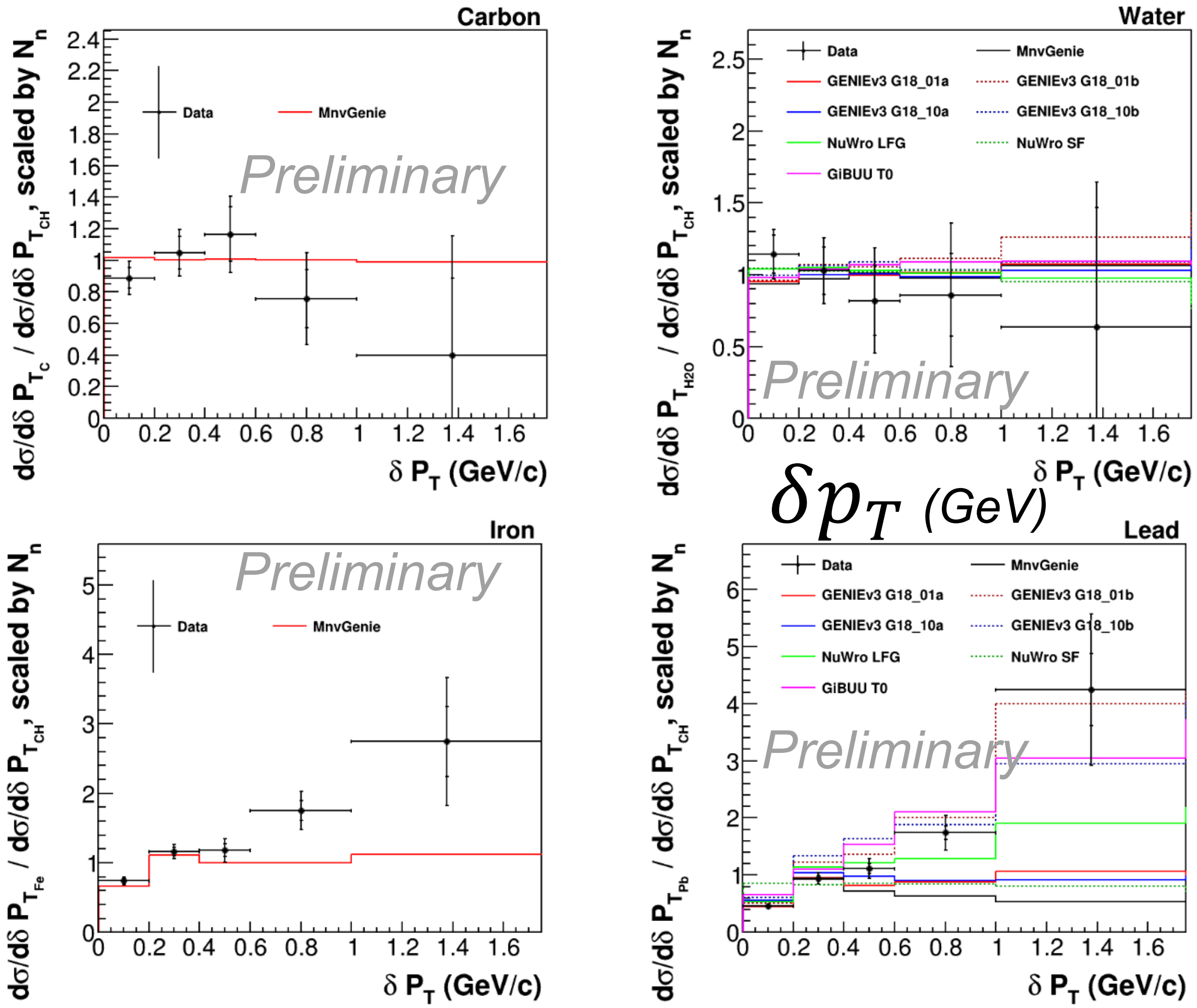
δp_T (GeV)





6 GeV CC0π Transverse Kinematic Imbalance in Targets

- A paper on proton-lepton correlations is in progress, to appear soon.
- Models vary wildly in how they predict A scaling of non-QE processes/FSI.
- Ratios to scintillator are also included, to help give more insight into A scaling.
- But the QE peak region seems universal.

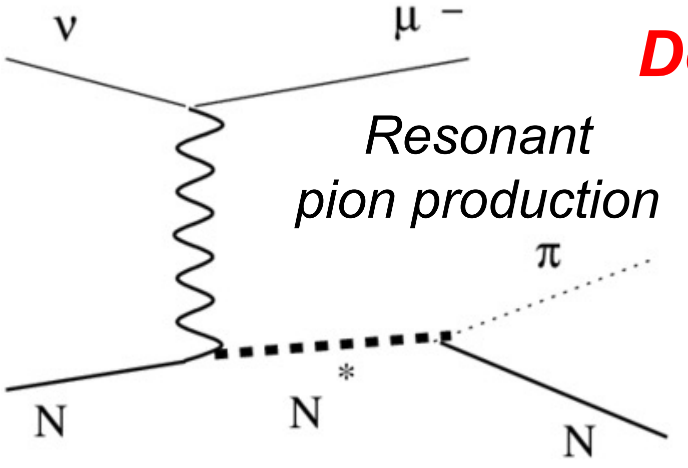


Lesson Four: Sub-leading Processes give rich physics, if you have the statistics.

How do we produce single pions?

(Let us count the ways.)

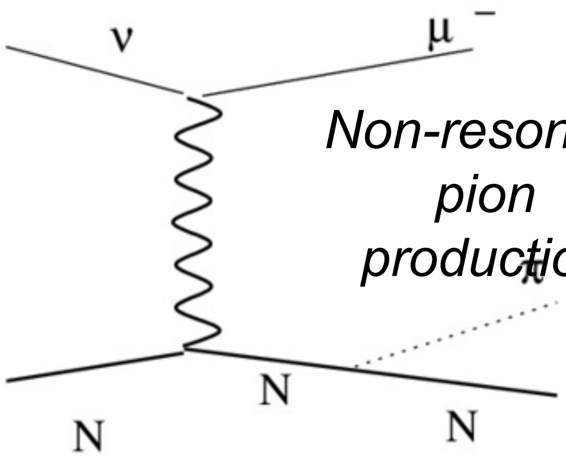
- Many competing production mechanisms.



Dominant

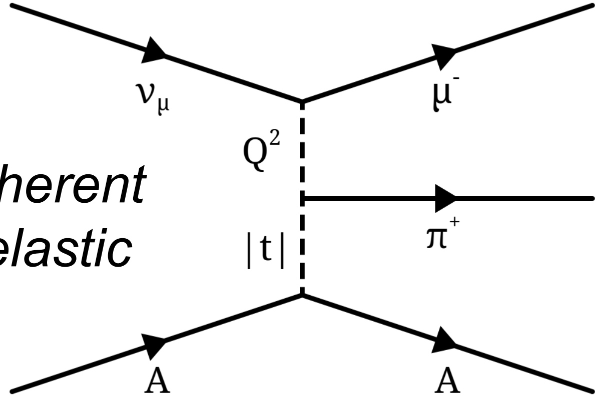
Resonant pion production

Interference may be large effect



Non-resonant pion production

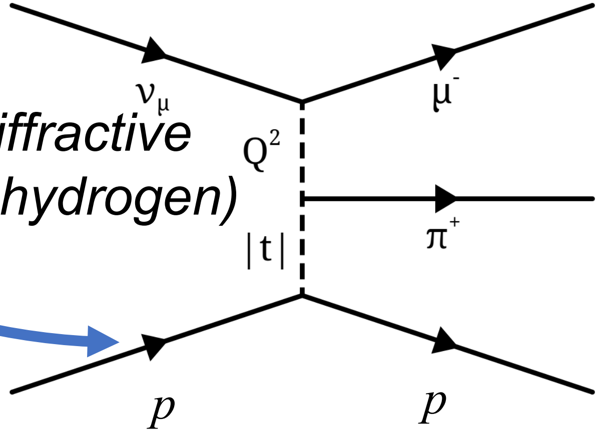
Significant



Coherent inelastic

Sub-leading

Interference at low Q^2 on hydrogen

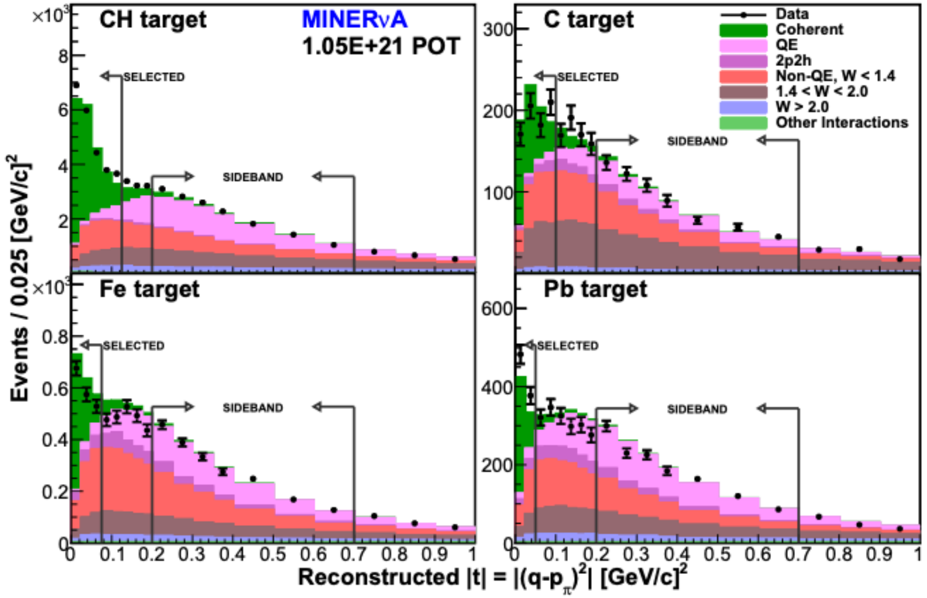


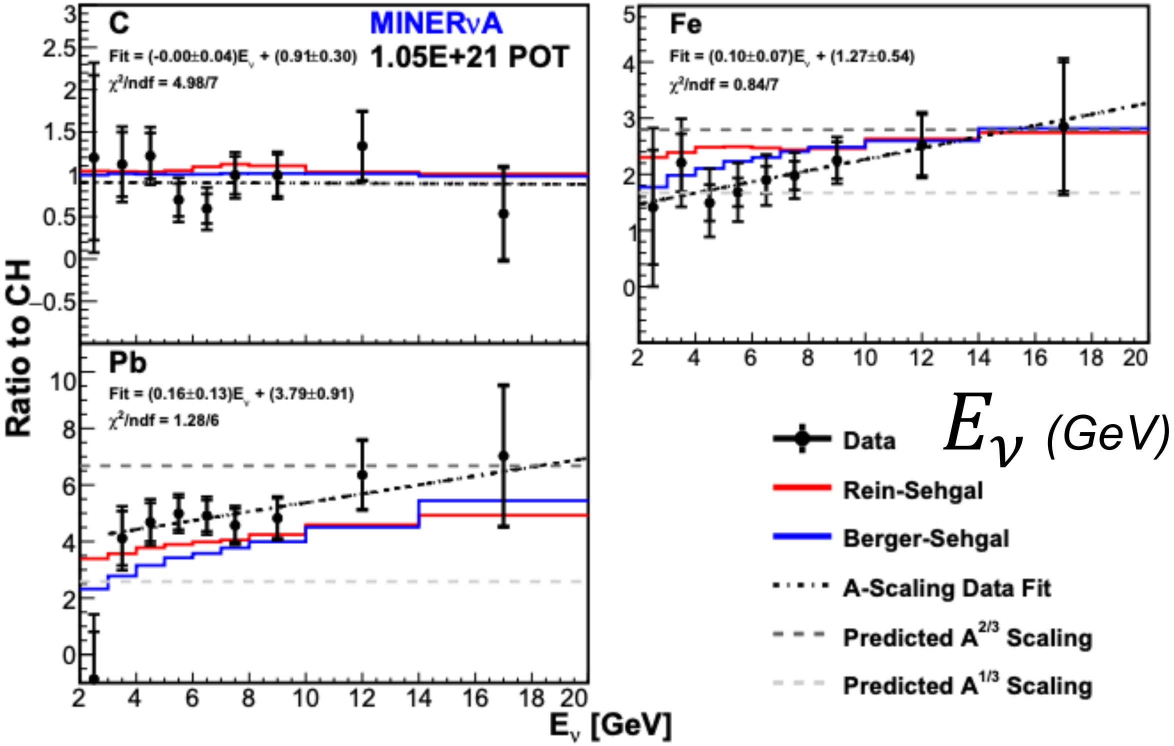
Diffractive (on hydrogen)

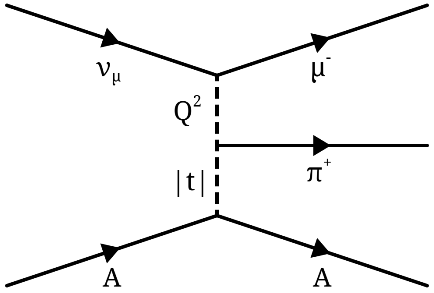
Coherent π^+ production on MINERvA's passive targets, Fe, Pb

Phys.Rev.Lett. 131 (2023) 5, 051801

- Study the coherent inelastic process on different targets.
- Short version is that A scaling is not radically wrong, nor correct in detail.



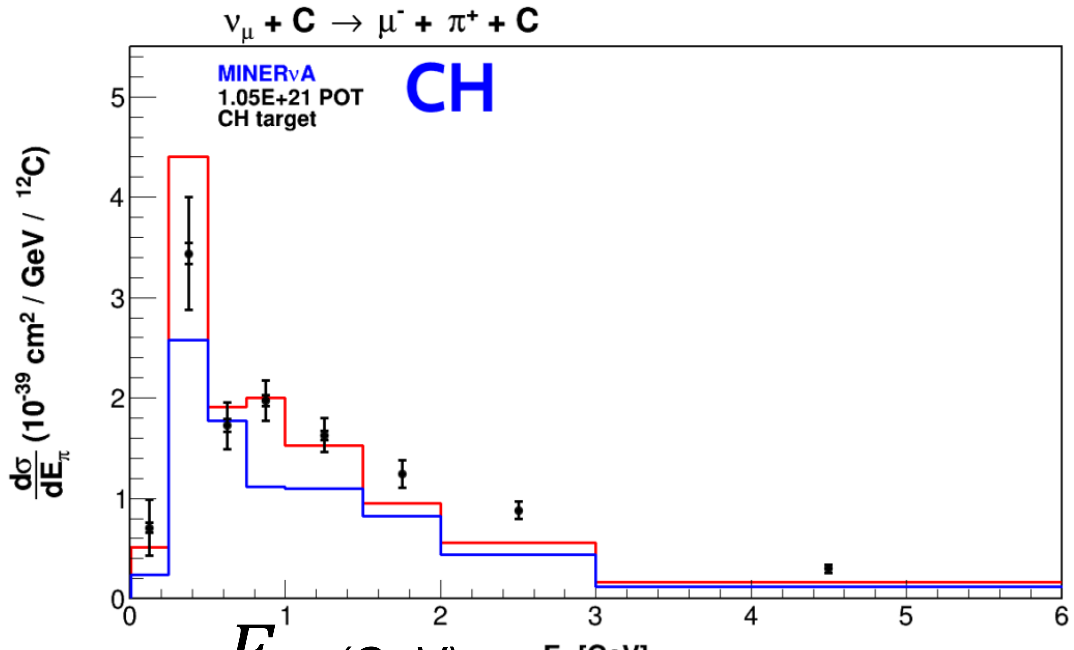




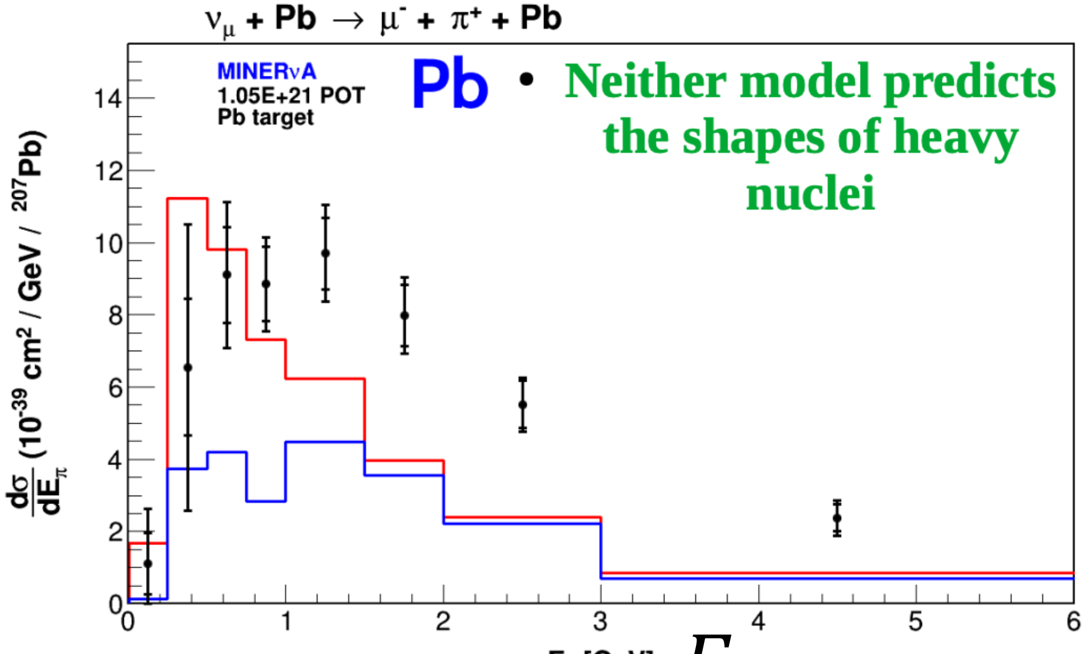
Coherent π^+ production on MINERvA's passive targets, Fe, Pb

Phys.Rev.Lett. 131 (2023) 5, 051801

- Short version is that A scaling is not radically wrong, nor correct in detail. Slightly longer version is that the pion energy distribution prediction is wrong, more so in heavy nuclei. and causes the problem with the naïve A-scaling.



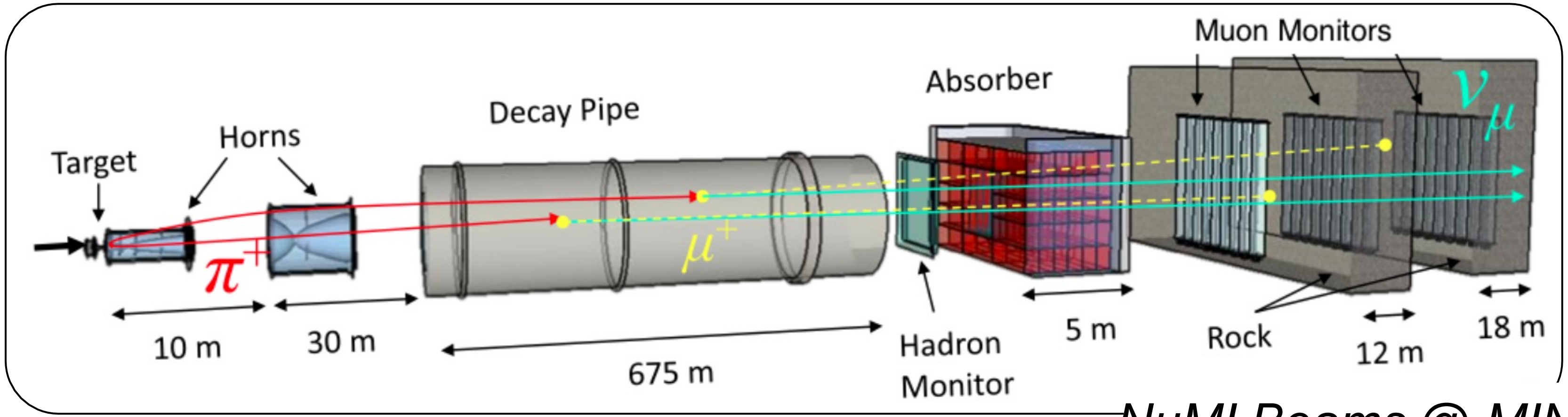
E_π (GeV)



E_π (GeV)

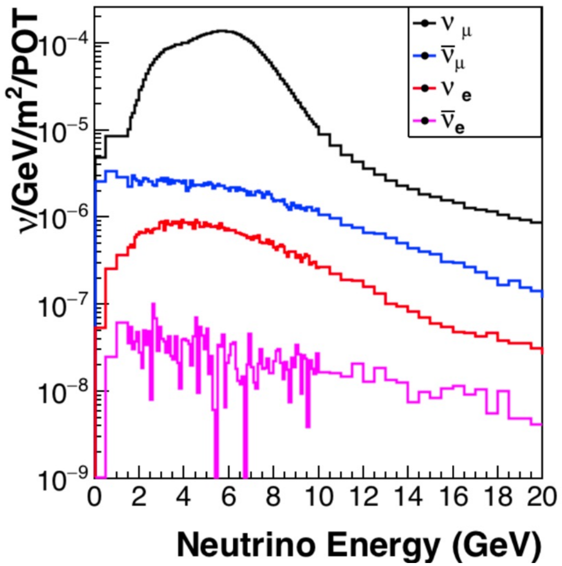
Electron Neutrinos!

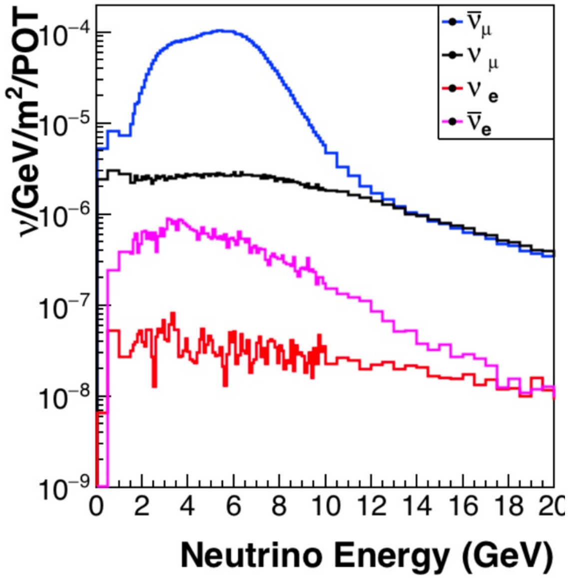
The NuMI Beam



- NuMI is a "conventional" neutrino beam, with most neutrinos produced from focused pions.
- Pions decay mostly to muons, but weak decays involving electrons come from daughter muons, kaons, and so forth.
- ~1% contribution of the beam.

NuMI Beams @ MINERvA

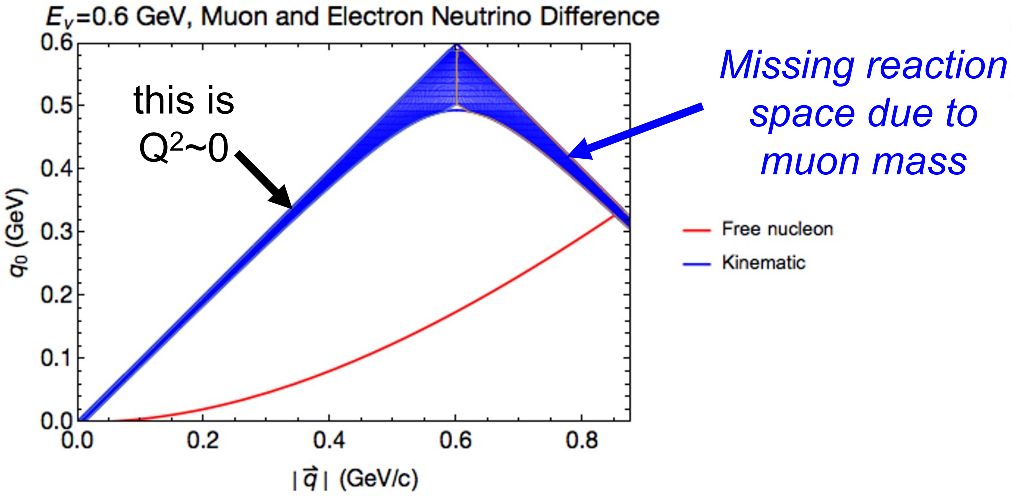




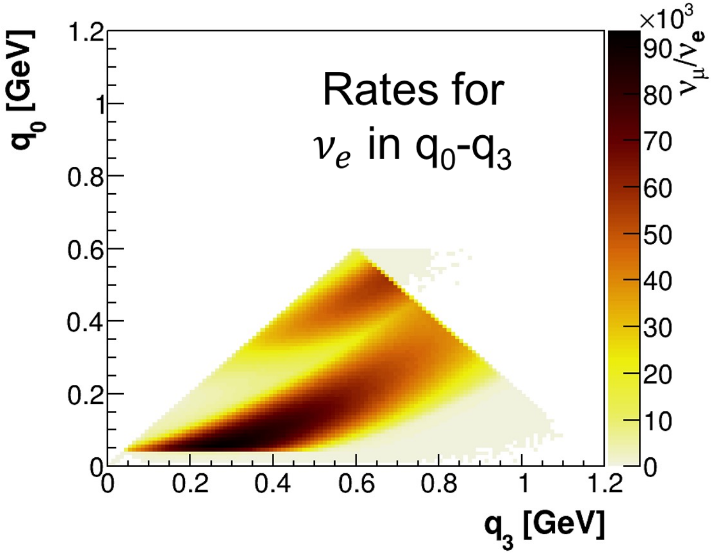
The ν_e Problem

- By necessity, our ν_μ rich beams have few ν_e in them to allow us to study any difference between ν_μ and ν_e interactions.
- Therefore, we infer ν_e interactions from studies of ν_μ
- But what we study can't give us the whole picture.
- Phase space (below), radiative corrections, etc.

Radiative corrections: O. Tomalak et al, Nature Commun. 13 (2022) 1, 5286 and Phys.Rev.D 106 (2022) 9, 093006

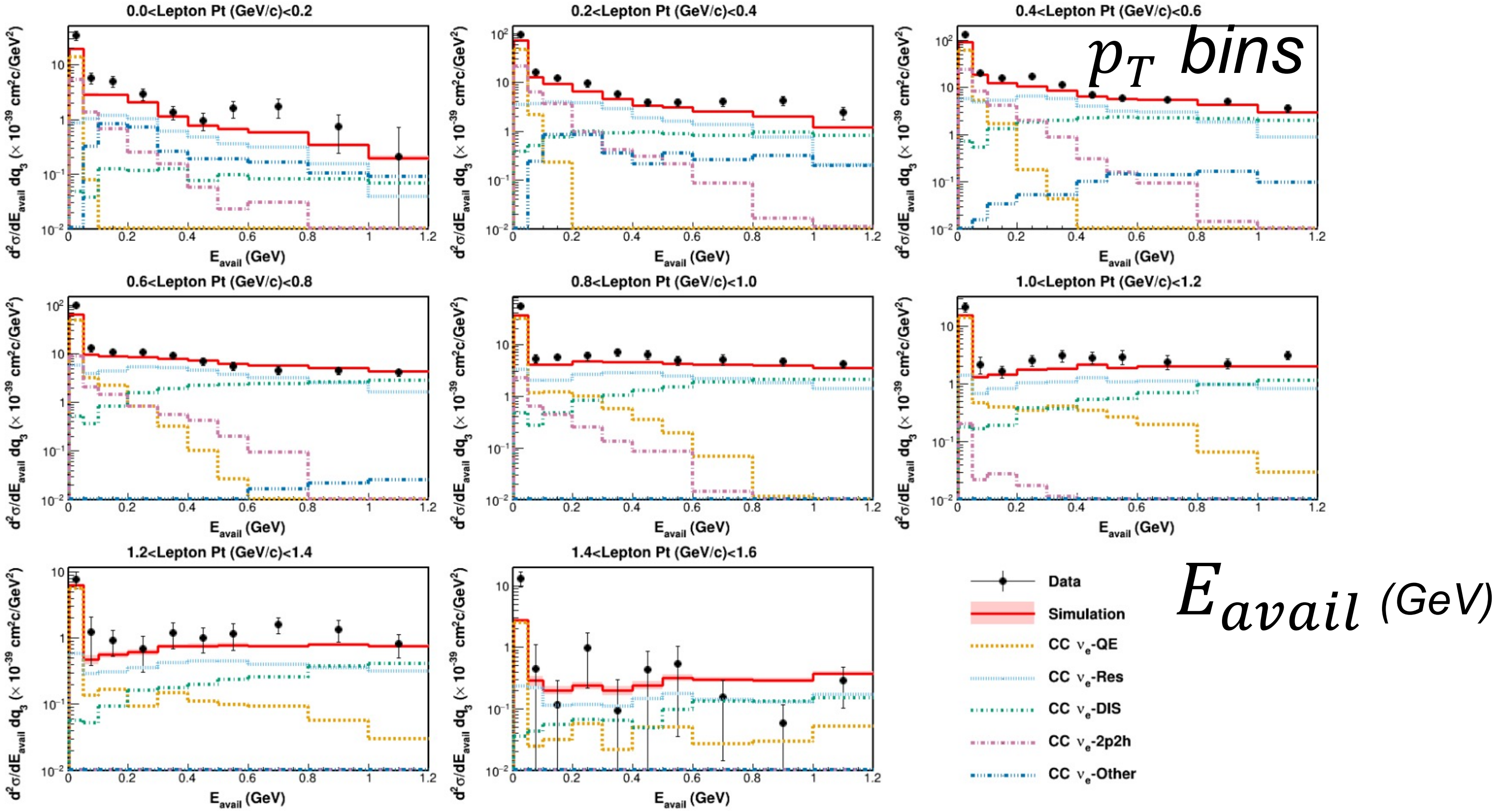


3-momentum transfer



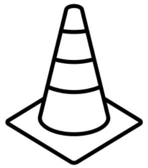
Preview: Electron Neutrinos

- MINERvA has 10s of thousands of *electron* neutrinos.
- Can measure cross-sections of neutrinos and anti-neutrinos at low visible energy.



anti-neutrinos

Preview: Electron Neutrinos



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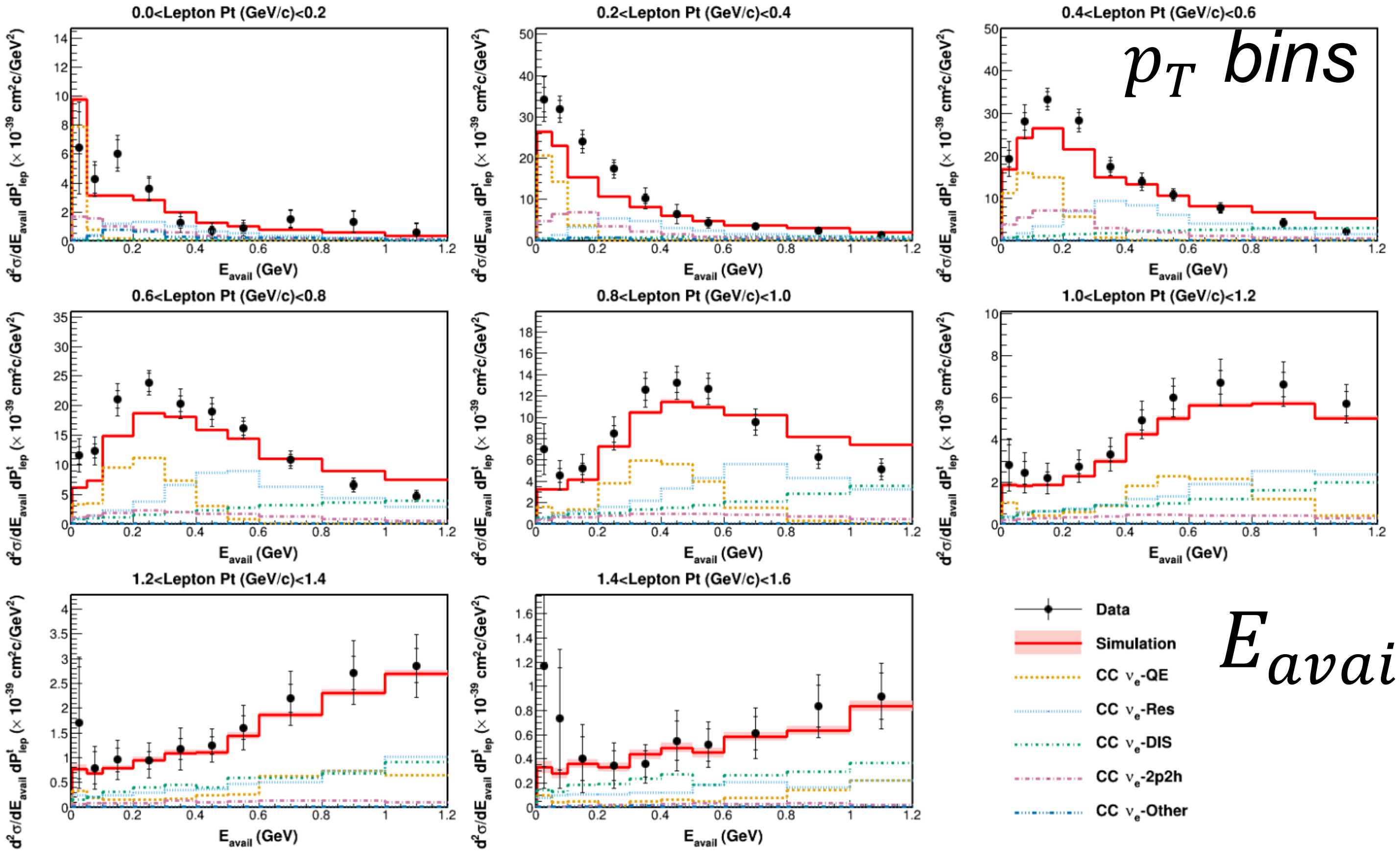


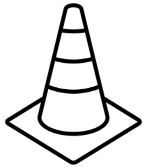
neutrinos

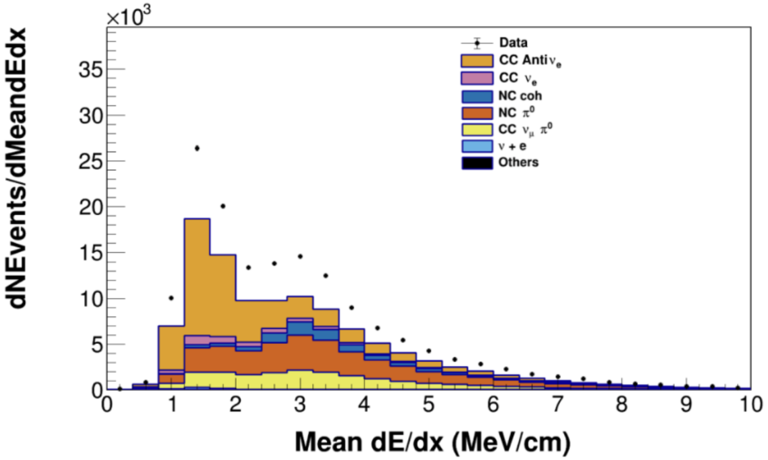
E_{avail} *(GeV)*

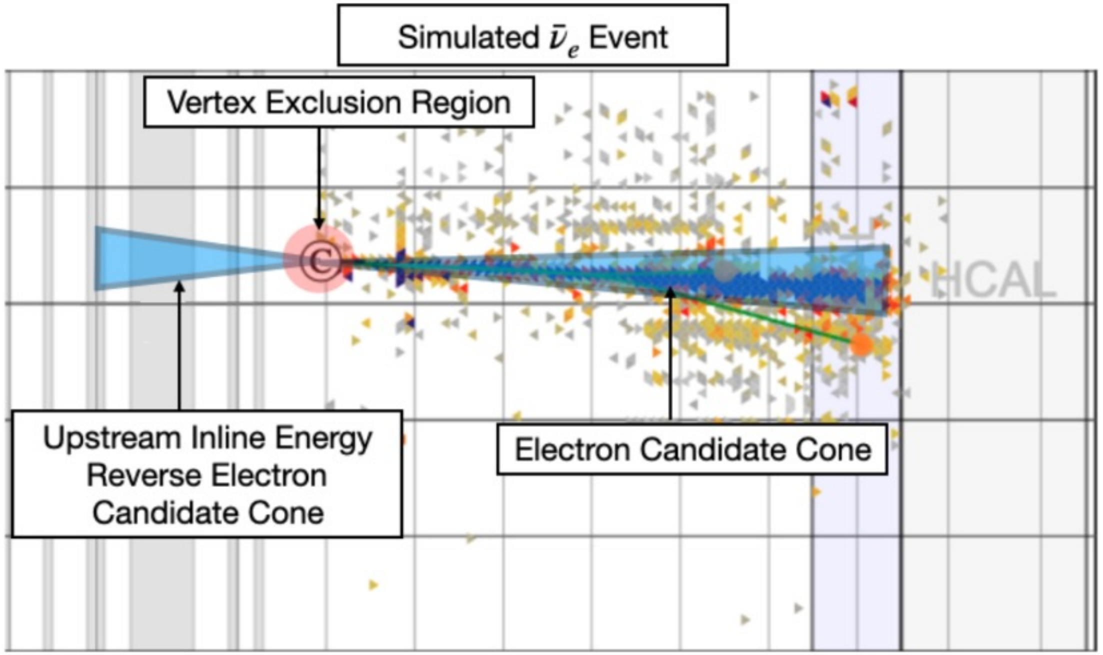
Lesson Five:
You can do (some) things you didn't think you could

Preview: High Energy Diffractive π^0
(Coherent inelastic on protons)

- At high energies, above 1.5 GeV, we can cleanly separate coherent and diffractive neutral pion production from backgrounds.
- *They look like electron neutrinos (how we found them) with high dE/dx at the electron start.*
- *Diffractive events have a visible recoiling proton upstream.*

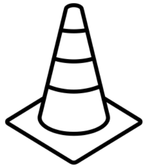


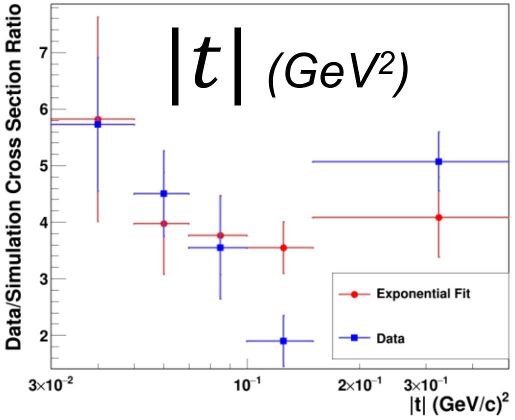


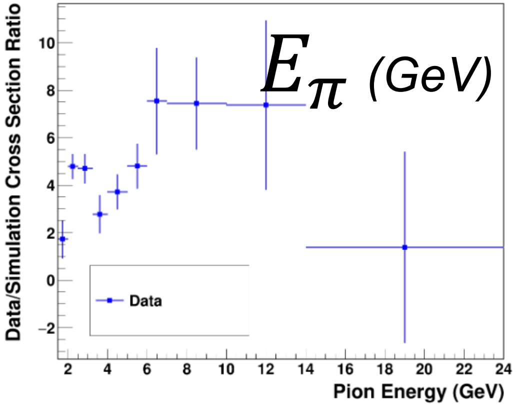


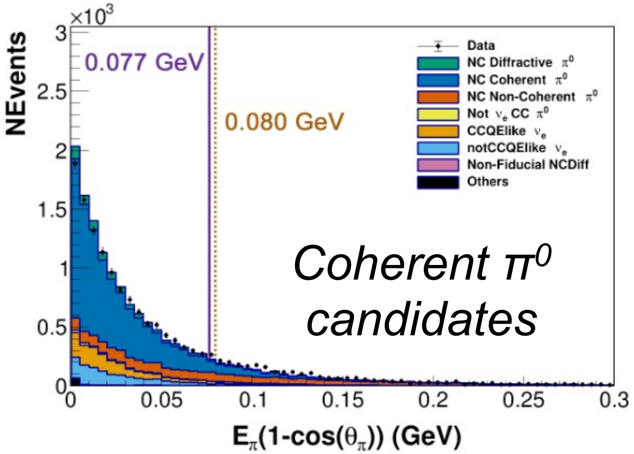
Preview: High Energy Diffractive π^0
(Coherent inelastic on protons)

- Prediction in GENIE Rein model is dramatically underpredicts rate.
- Bonus: we can look at the $E_\pi(1-\cos\theta)$ distribution, which is predicted from kinematics and size of target to be small, $\sim\frac{1}{R}$.
    - All previous measurements of coherent process had assumed this, and used it to select the process.

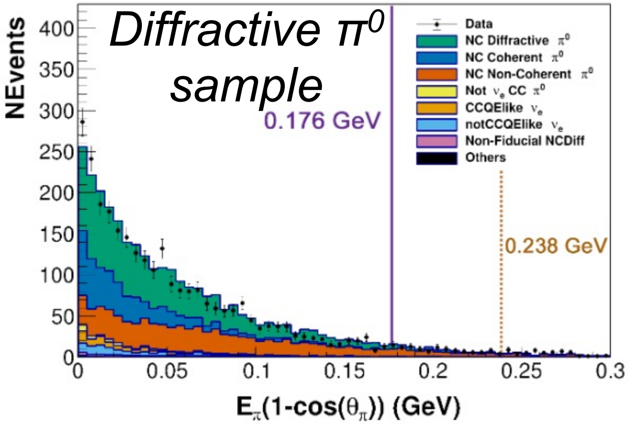








(a) Coherent π^0 production



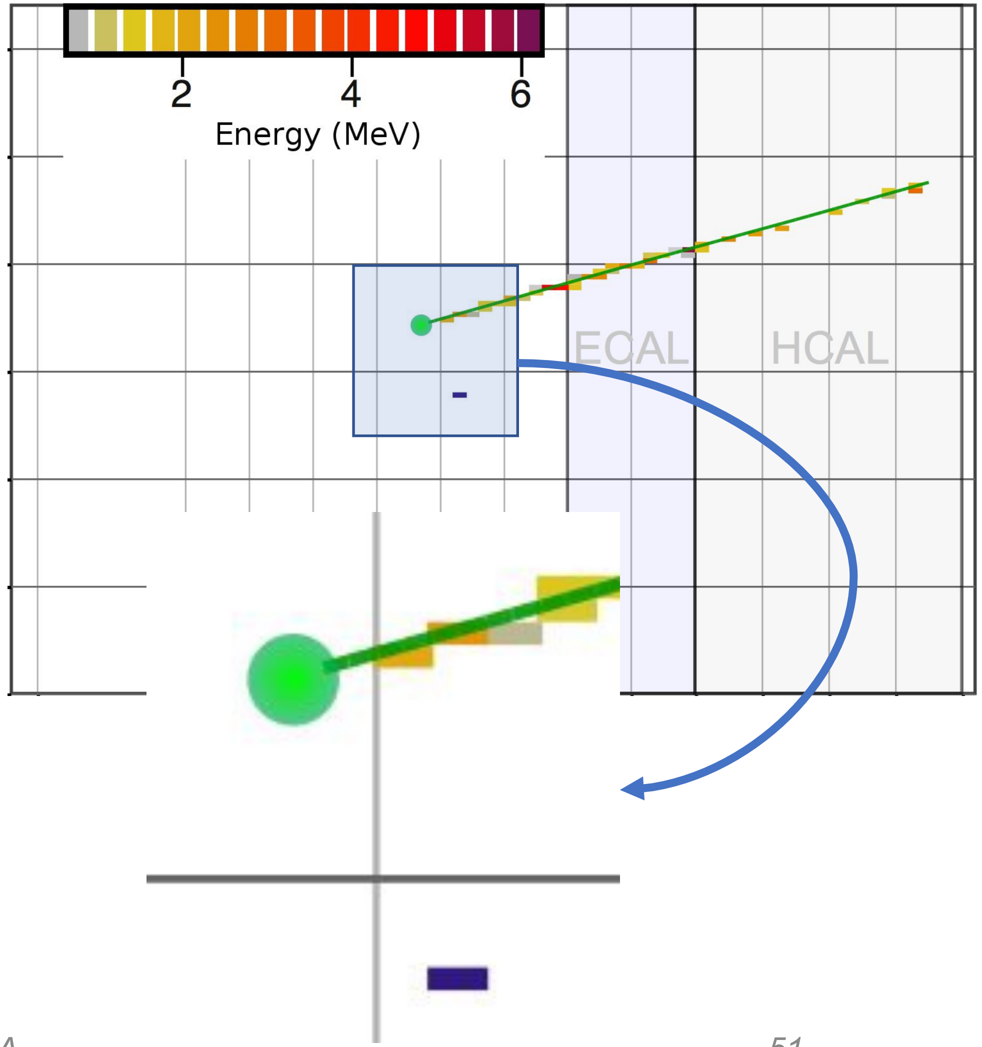
Hmm… that’s a cross-section on hydrogen, isn’t it?

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.

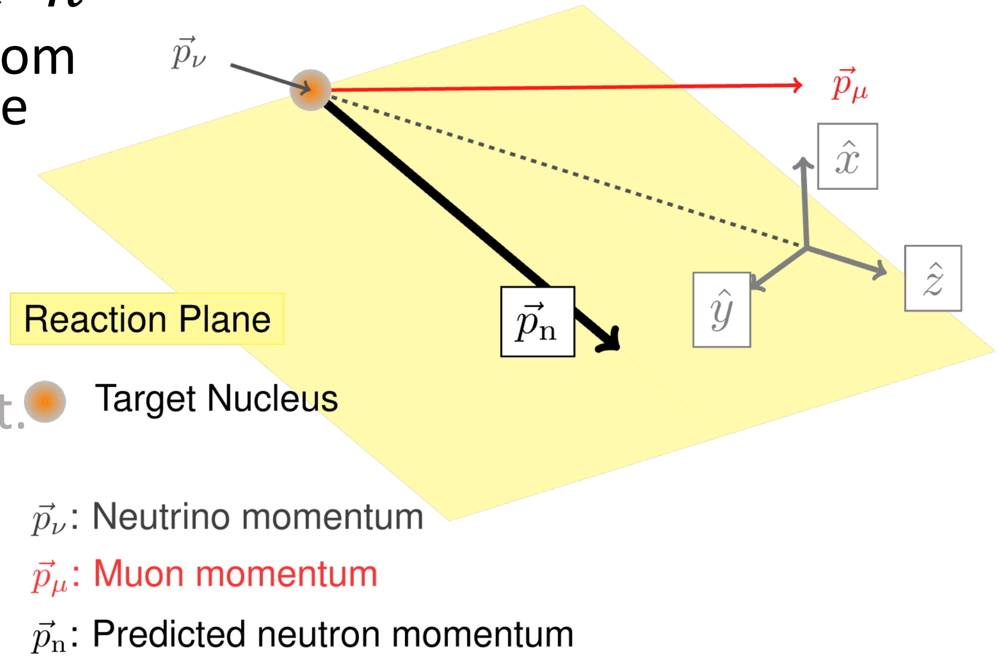
Detecting Charged Current Elastic Scattering in MINERvA

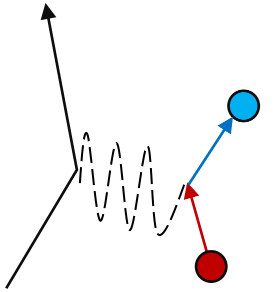
- Final state of $\bar{\nu}_\mu p \rightarrow \mu^+ n$ in MINERvA is an energetic μ^+ and a (usually) much lower energy n.
- Neutrons don't directly leave signals in scintillator as they pass through.
- Neutrons in MINERvA are observed primarily by detecting the proton from ${}^{12}C(n,np){}^{11}B$ quasielastic 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.



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.





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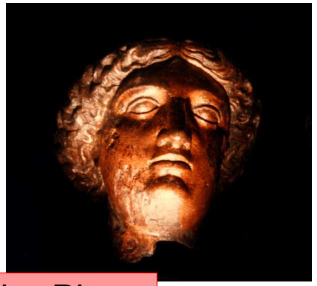

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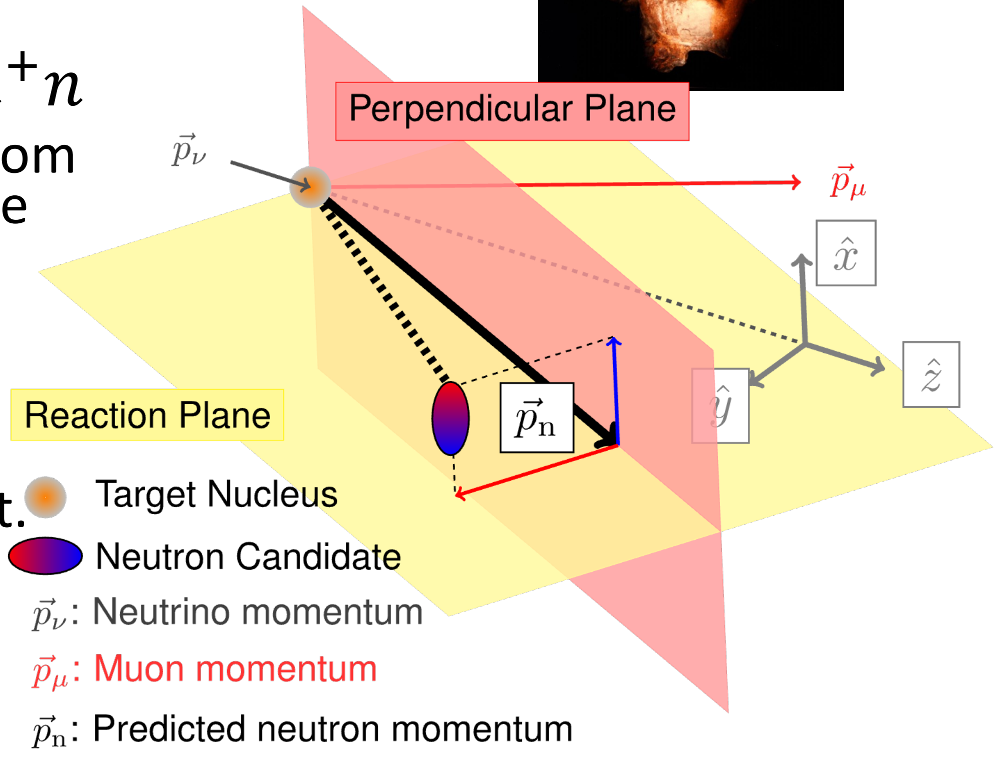

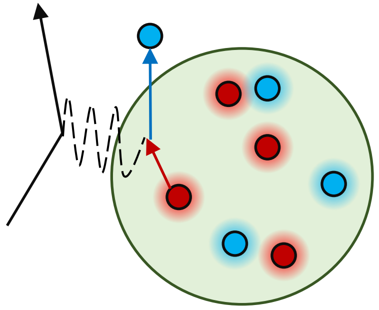

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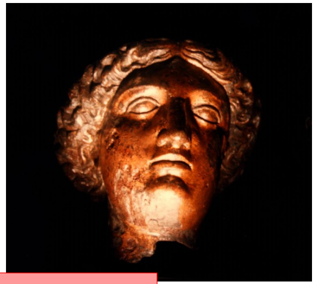

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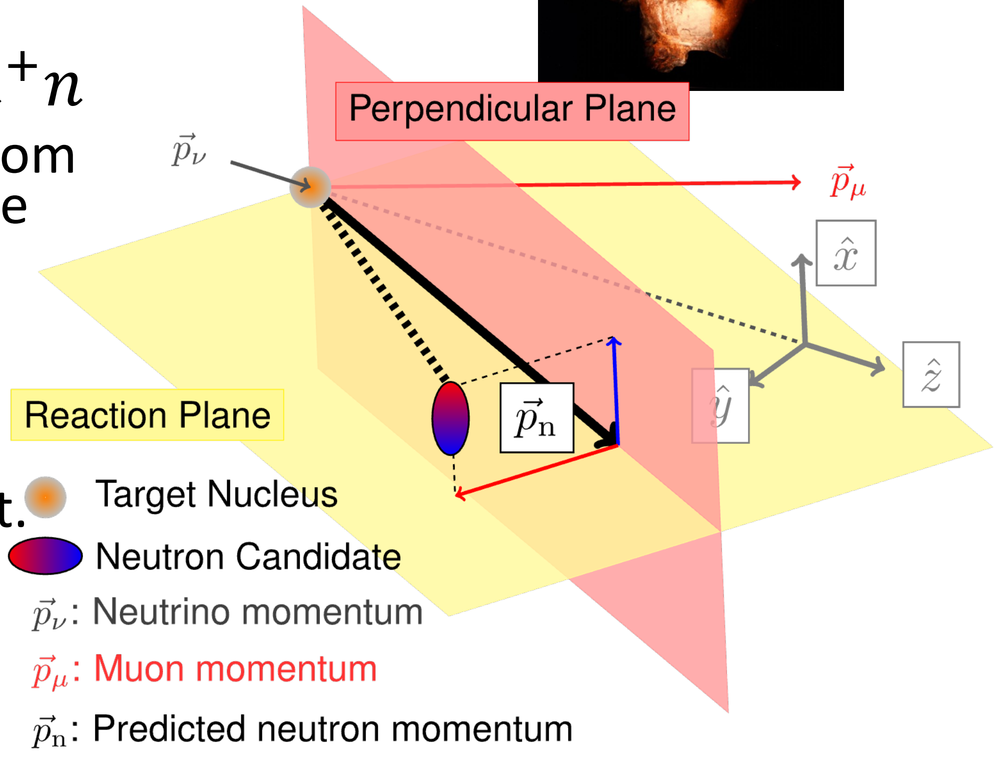
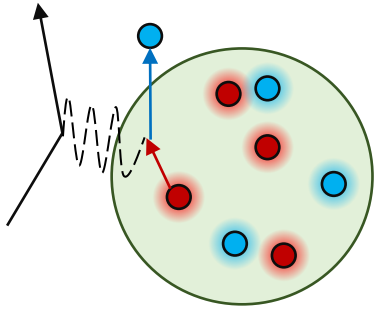
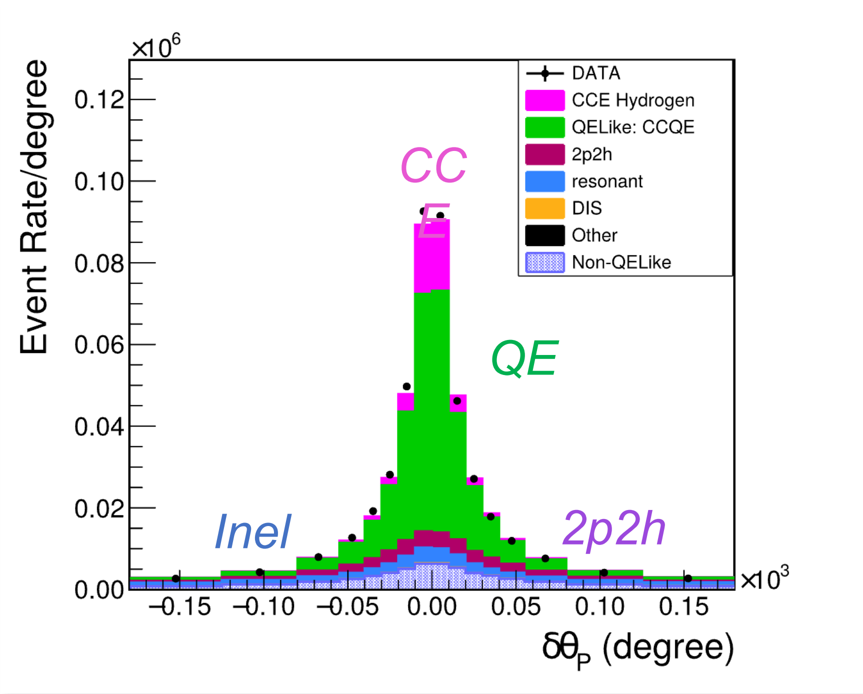
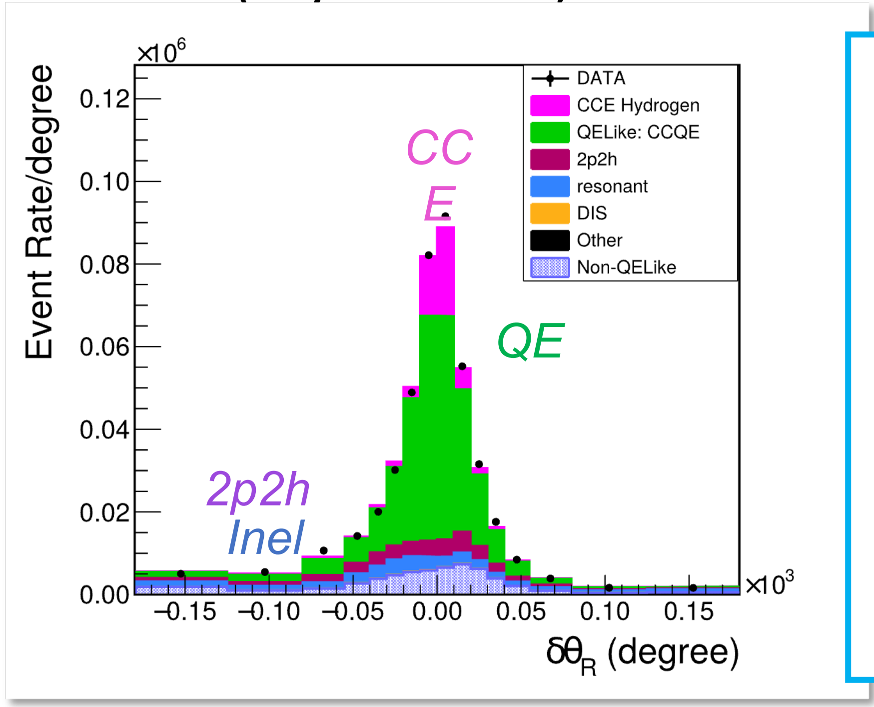


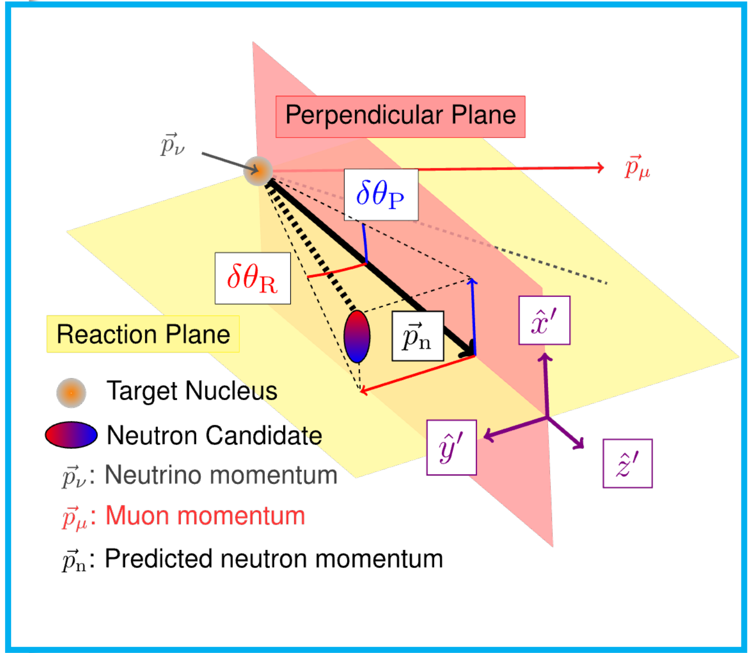


Signal & Background Separation (cont'd)

- 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.



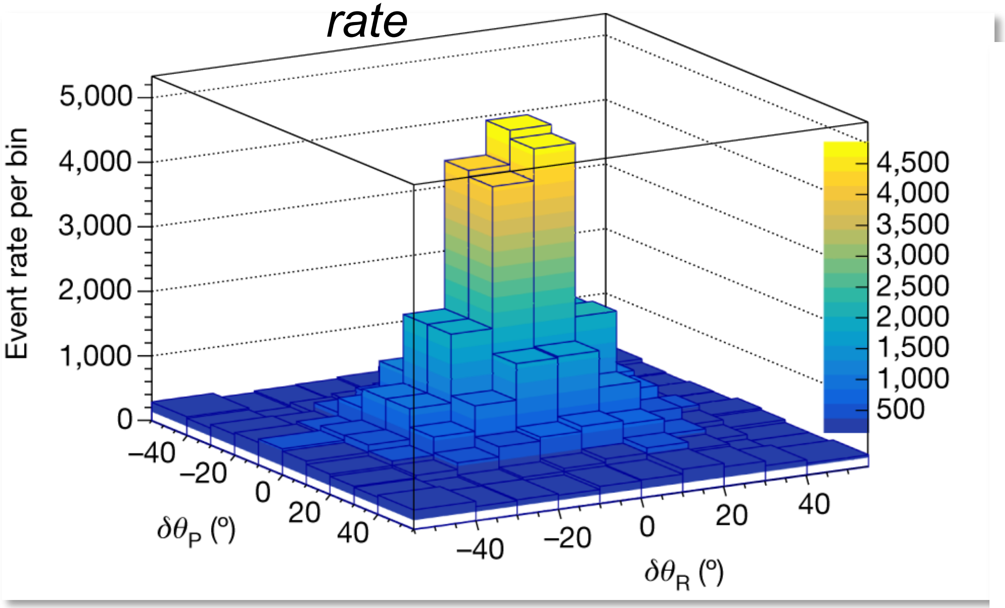




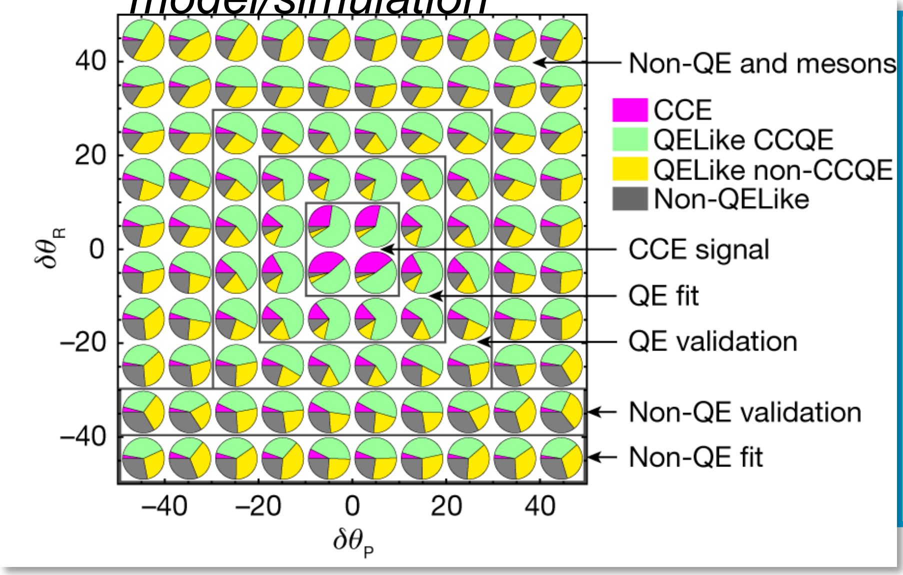
Signal & Background Separation (cont’d)

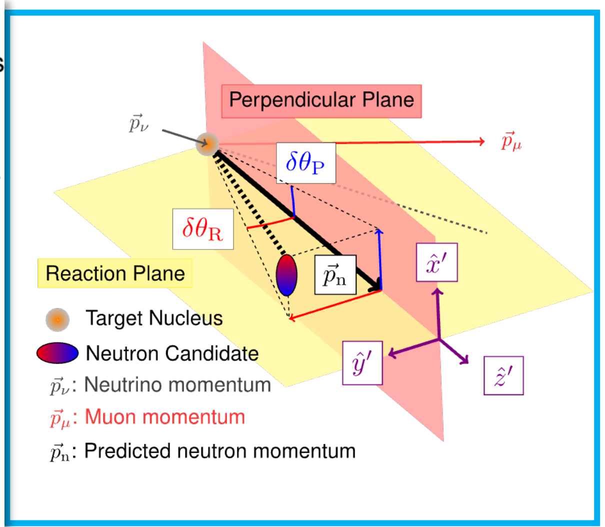
1. Fit different background rates, as a function of Q^2 from different regions of scattering angle deviation.
2. Check that other regions, not used in fit, are well predicted.
3. Use those results to predict the, now constrained, backgrounds.

“2D” Total event rate

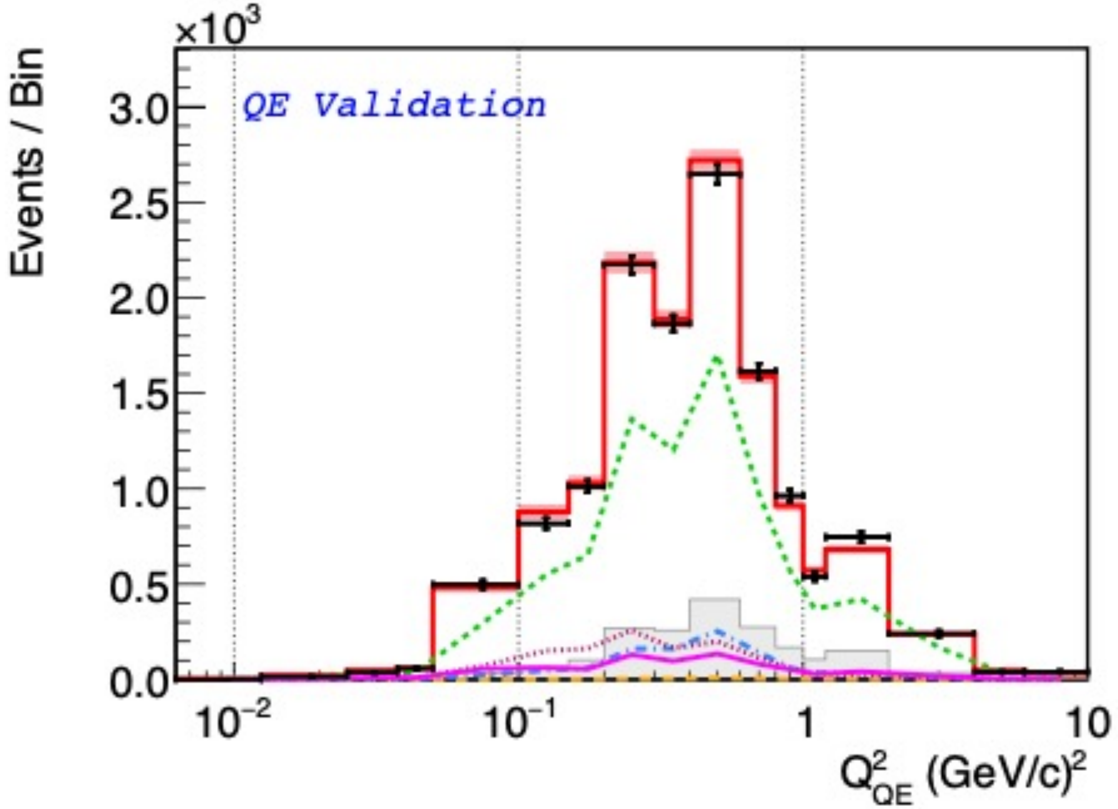


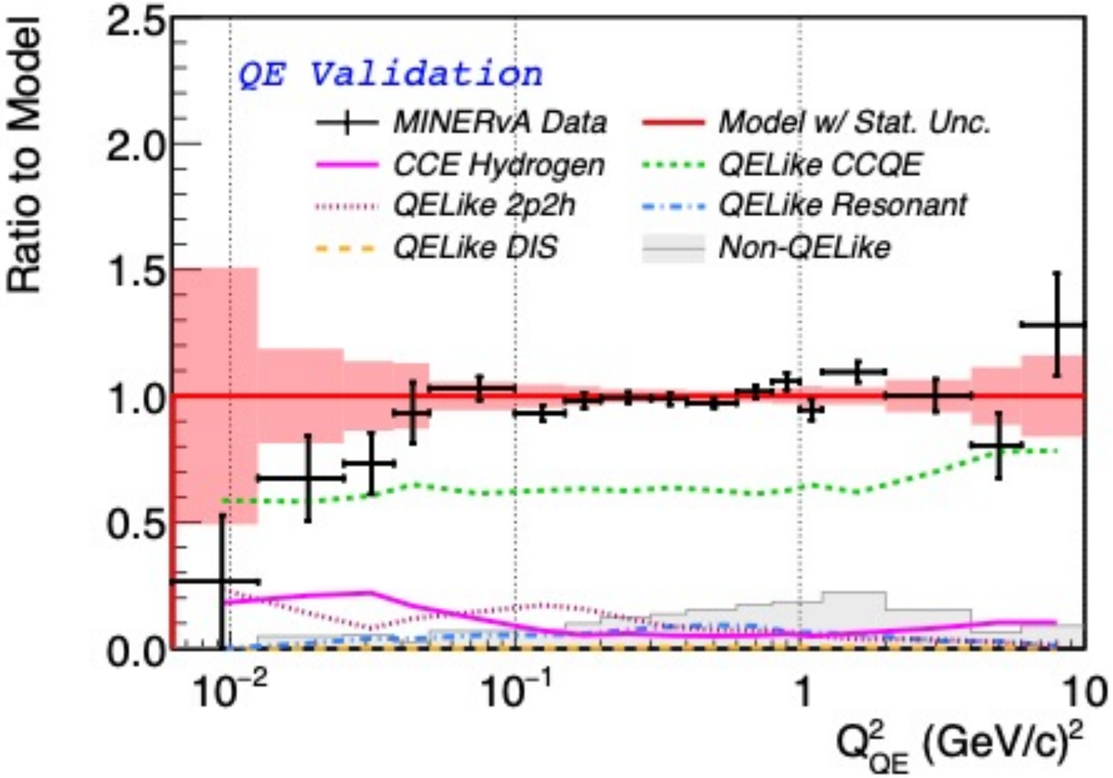
Fractions of rate predicted by model/simulation





Results of Background Sideband Fits in QE "Validation" Region

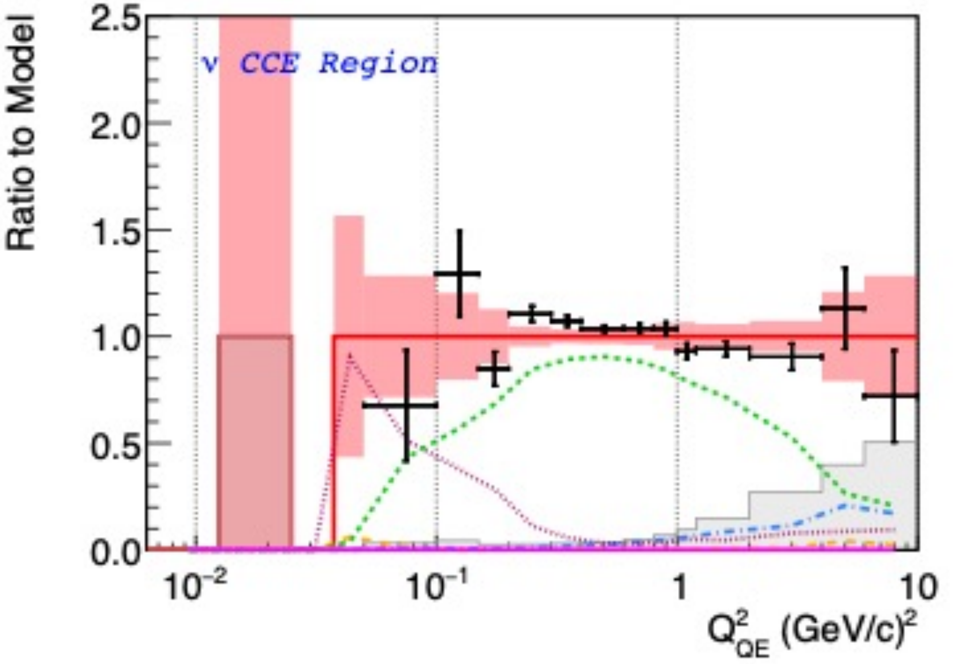




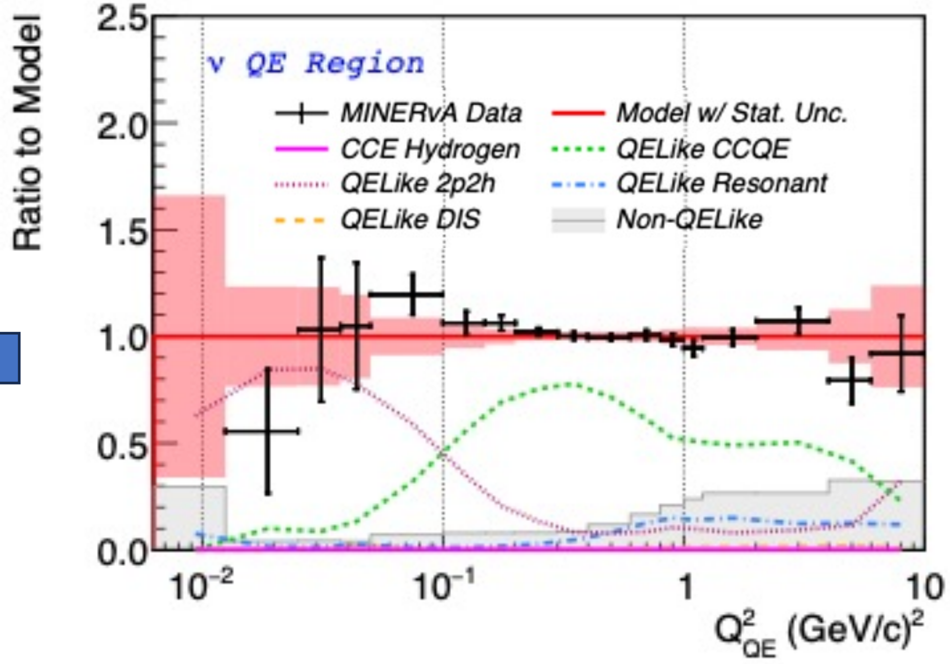
CCQE is dominant in this region. Small 2p2h, inelastic QE-like, and Non-QELike contributions. The fitted model, constrained by data, fits this region well.

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

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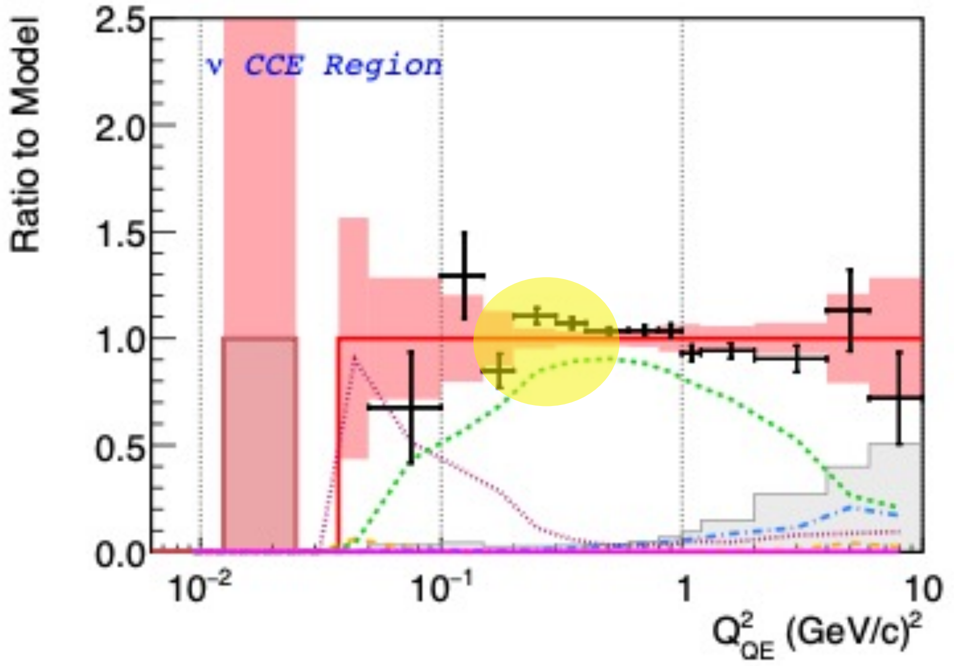
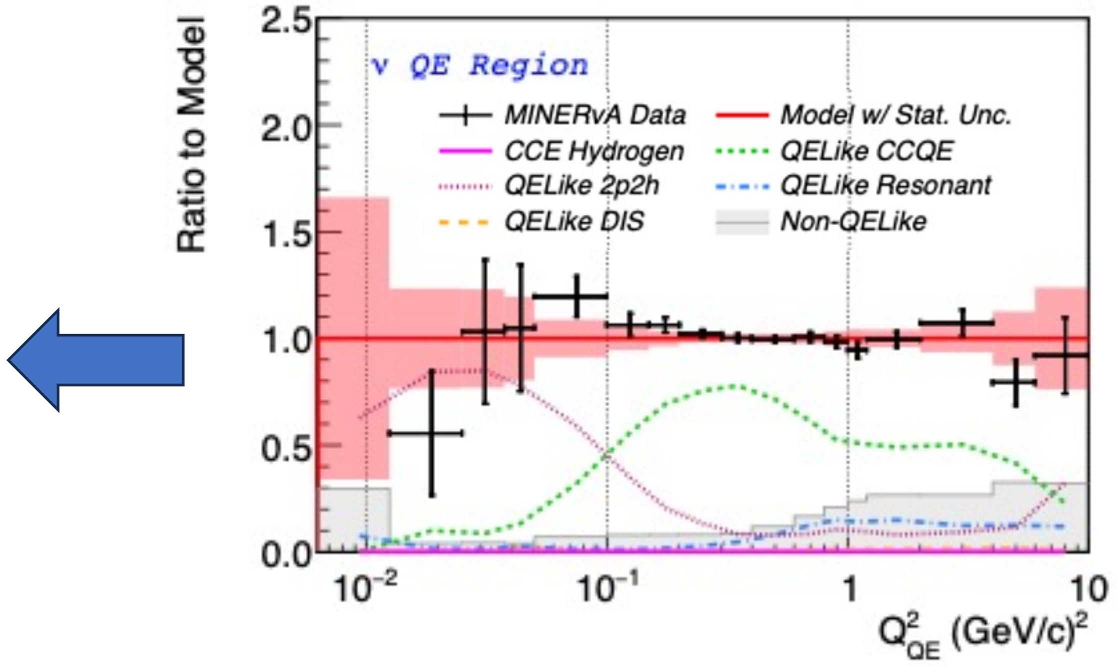


Quasielastic region

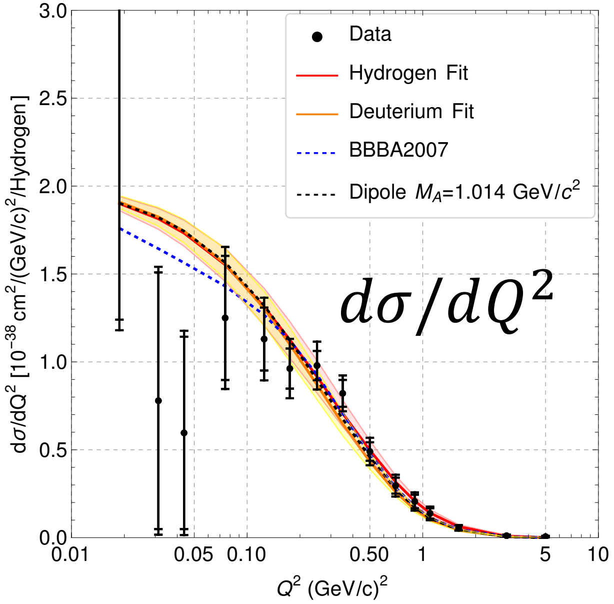


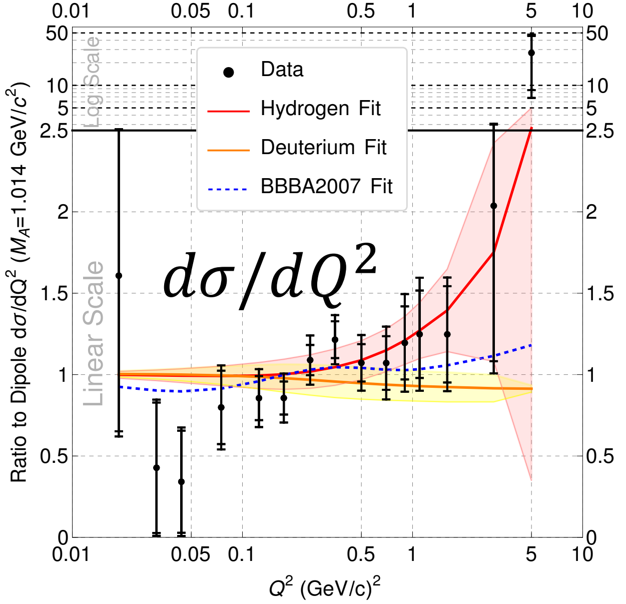
We select events with trackable protons in a neutrino sample. No CCE signal. Different final states and available kinematics. Apply same fitting mechanism.

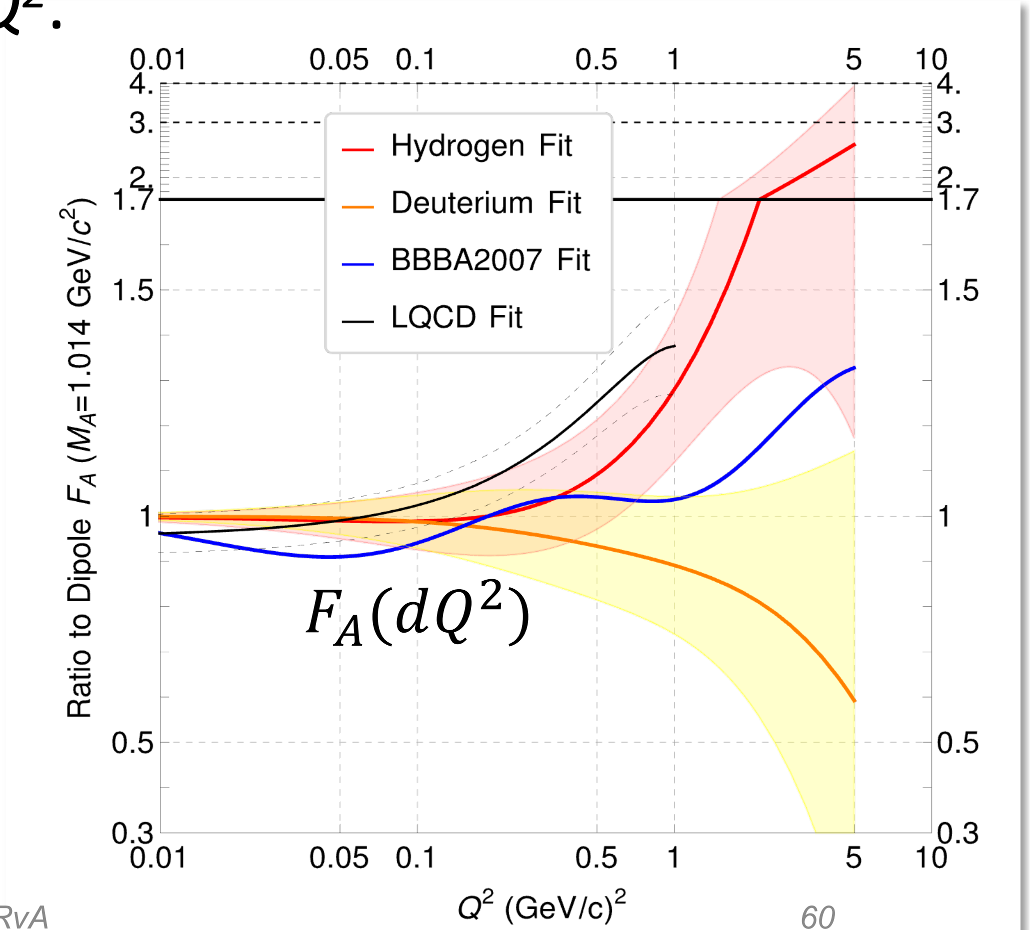
Data and MC mostly agree within uncertainty. Small low Q^2 disagreement is consistent with 2p2h uncertainty that is more important in neutrino sample.

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.

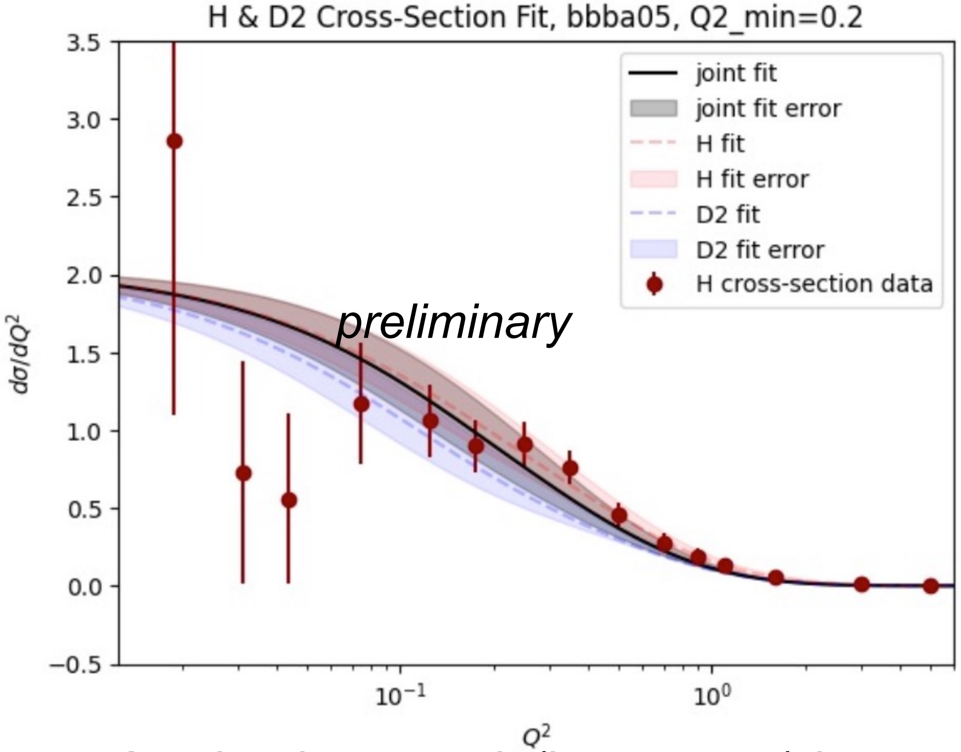






Compatible with D_2 Data? Mmmmmaybe?

- 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, $\delta\chi^2$~5.5, or p-value of ~2%.



Another homework (in progress) is to incorporate radiative corrections (O. Tomalak et al., Nature Commun. 13 (2022) 1, 5286; *Phys.Rev.D* 106 (2022) 9, 093006).

Lesson Last:
Momento Mori

Data Preservation

- MINERvA is largely a hobby for continuing participants, with the exception of a small number of finishing Ph.D. students.
- Interesting questions remain in our datasets, many of which were “late breaking” developments or driven by outside work.
  - Could the axial form factor dataset be increased?
  - Are there combinations of existing analyses that should be done, e.g., electron neutrino TKI in $A(\nu_e, e^- p \ldots)A'$ sample?
  - Are there hints of non-standard interactions that would be revealed if we looked at other variables in “interesting” samples, e.g., our electron neutrinos or our high energy EM shower plus “nothing” events.

Data Preservation (cont'd)

- MINERvA has a "data preservation" project that will conclude, one way or another, when FNAL shuts off access to SL7 at the end of June.
- In brief, it is a set of n-tuples of the results of our standard reconstructions for every event, and a set of macros to allow an analyzer to efficiently interpret that data, focused on the measurement of a cross-section, but not limited to that goal.

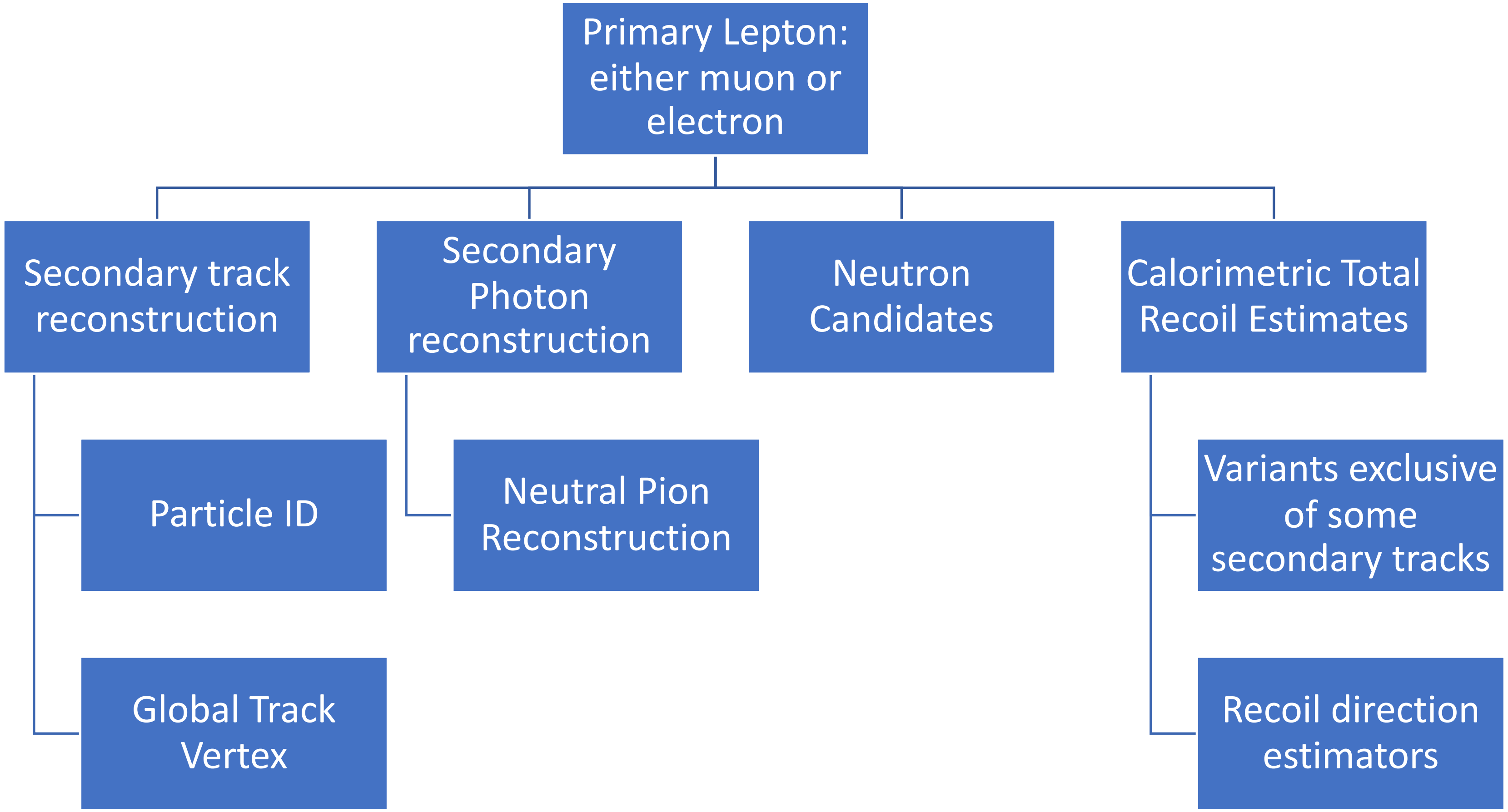
Tuples with reconstructed objects
- Data
- Simulation, ~4x data

→ **Event Loop Macros**

→ **Interpretation Macros:**
- background subtraction from sidebands
- unfolding and efficiency
- flux and target counting

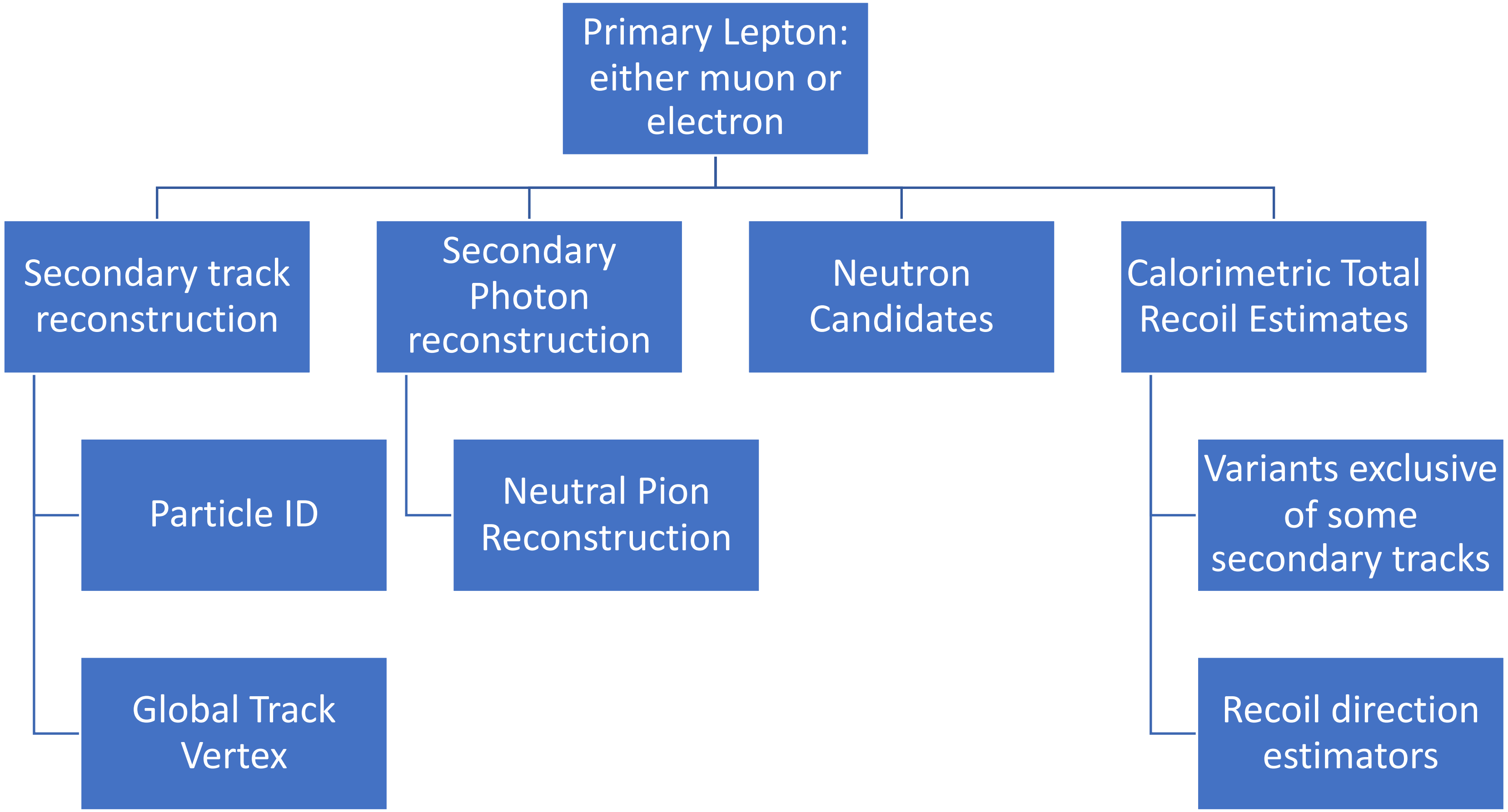
Data Preservation (cont’d)

- What is in the reconstruction?



Data Preservation (cont'd)

- What is in the reconstruction?



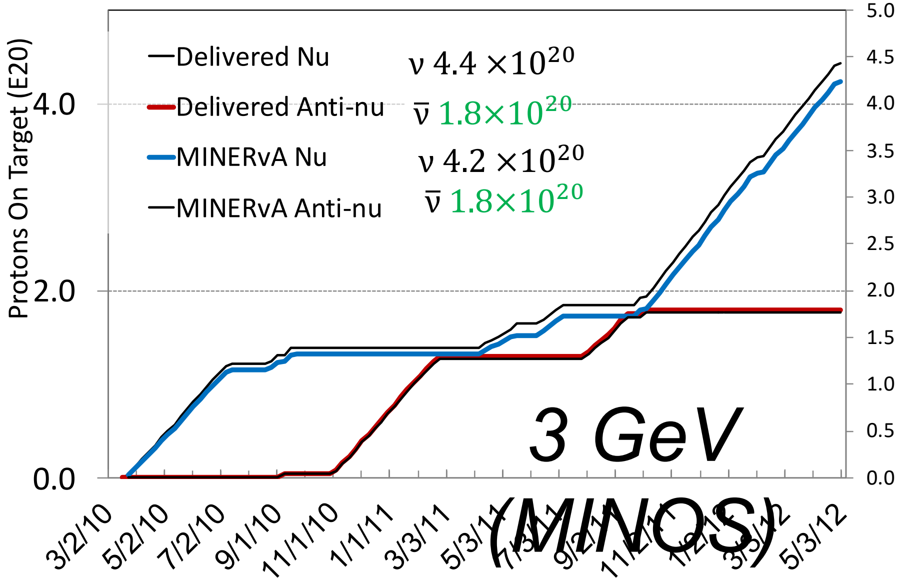
- MINERvA neophytes may encounter difficulties.
- Data will be available to all, but collaboration with recovering MINERv-ites may be wise and isalways welcome.

End of Lesson Plan

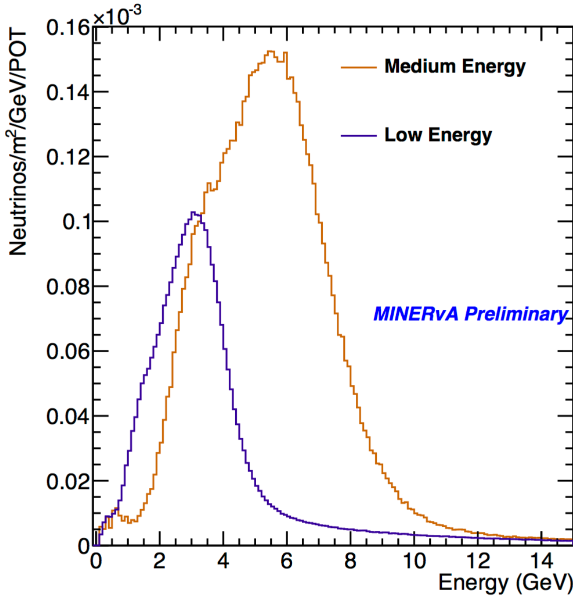
Backup: Beam

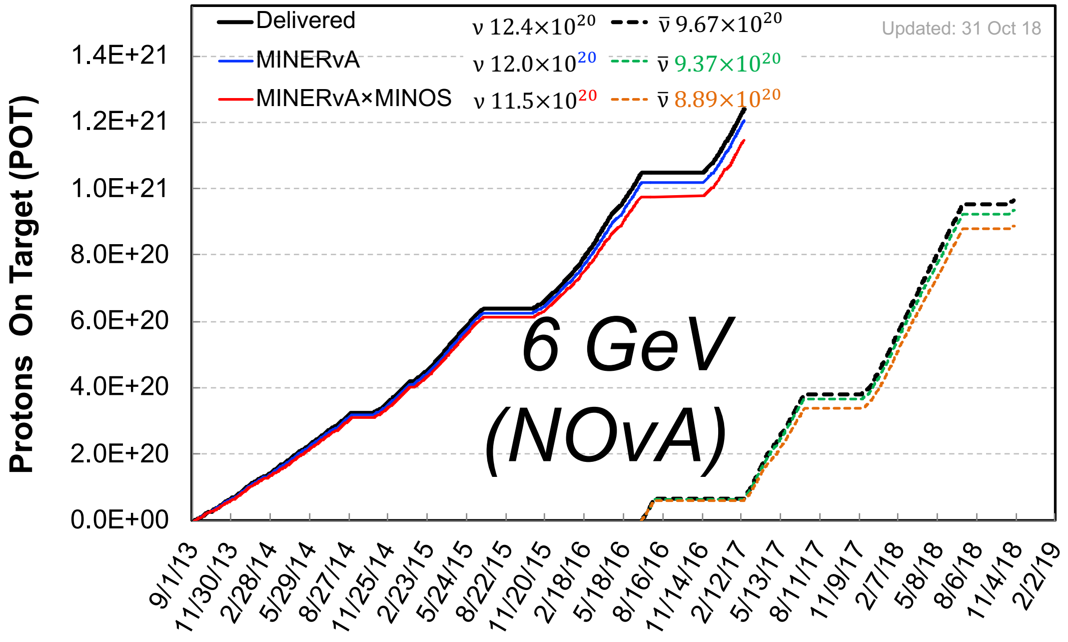
MINERvA thrived on the outstanding beam delivered to MINOS and to NOvA

- Kudos to the accelerator division and the NuMI beam group.



Day in the Low (3GeV) Energy Run



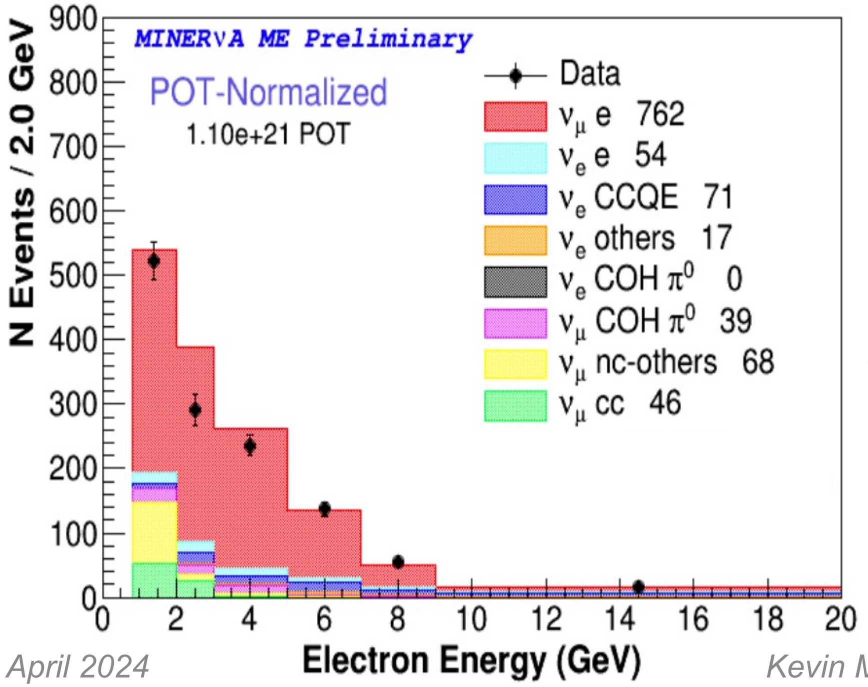


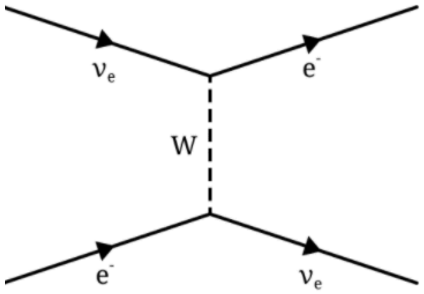
Day in the Medium (6GeV) Energy Run

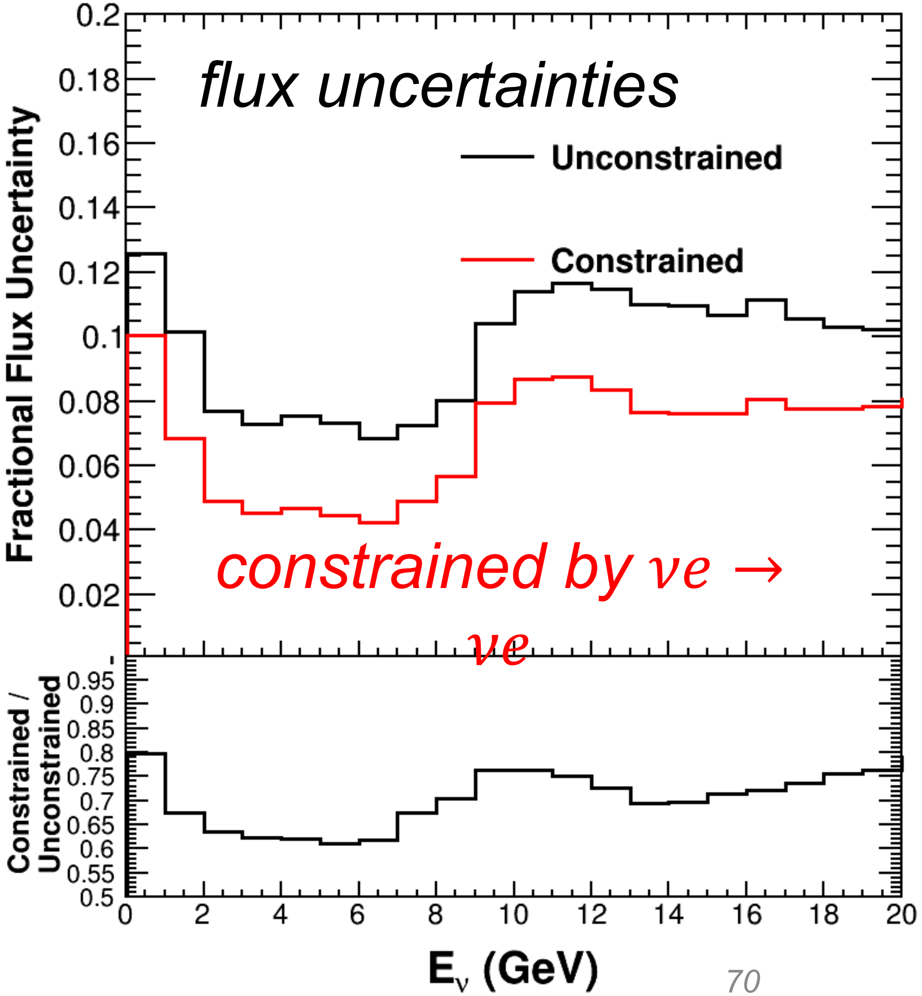
Flux from Neutrino-Electron Scattering

Phys.Rev.D 100 (2019) 9, 092001; *Phys.Rev.D 104 (2021) 9, 092010*

- Neutrino-electron elastic scattering is a standard candle for neutrino interactions.
- Using this reaction in 3 GeV and 6 GeV neutrino and anti-neutrino beams, with inverse muon decay, flux uncertainties are ~4%, which is pretty good by neutrino standards.



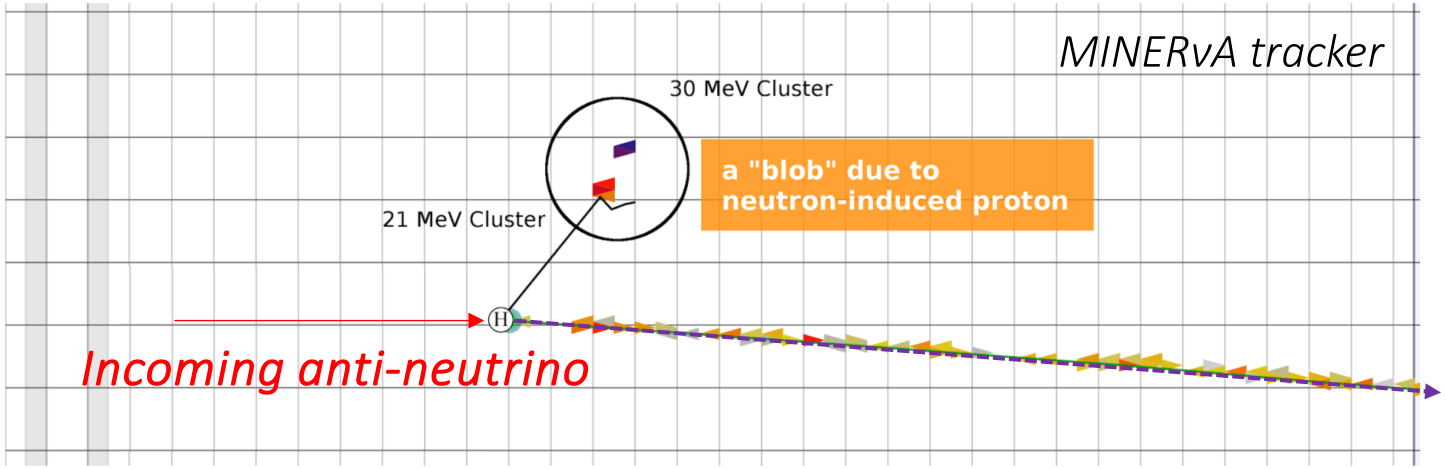




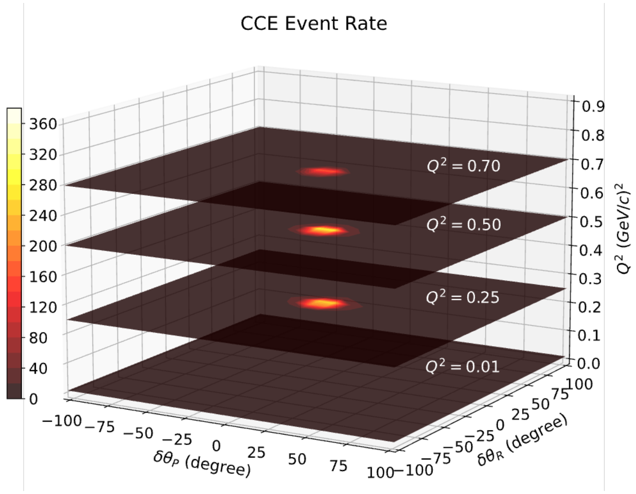
Backup: More Details of H CCE

Selection of CCE Events

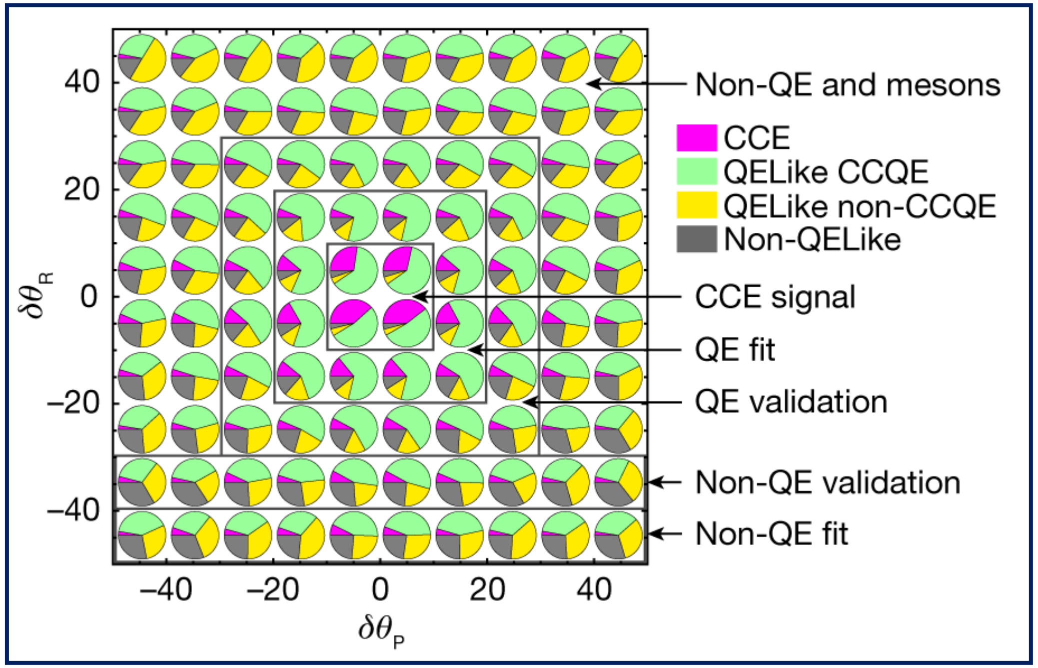
- No visible hadronic tracks from charged pions or protons.
- Proton recoil from neutron must be 10 cm away from the muon axis, to remove δ-ray background.
- Muon reconstructable in the detector: E_μ [1.5; 20] GeV, $\theta_{\mu\nu} < 20°$

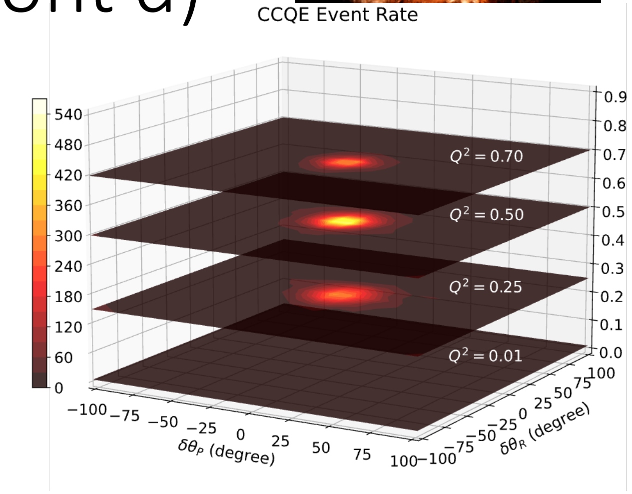


Signal & Background Separation (cont'd)

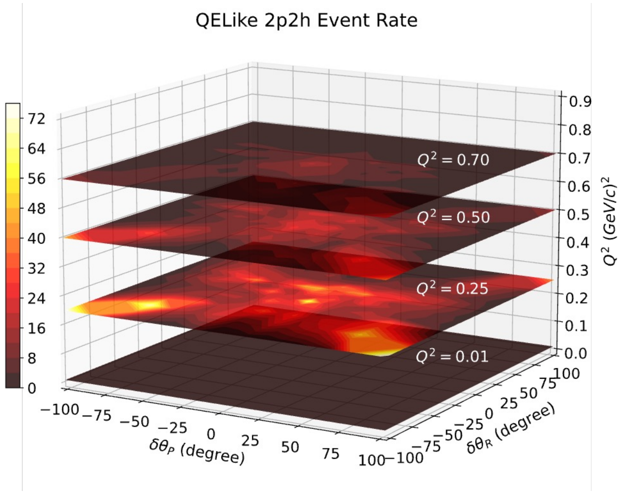


SIGNAL: Elastic on H

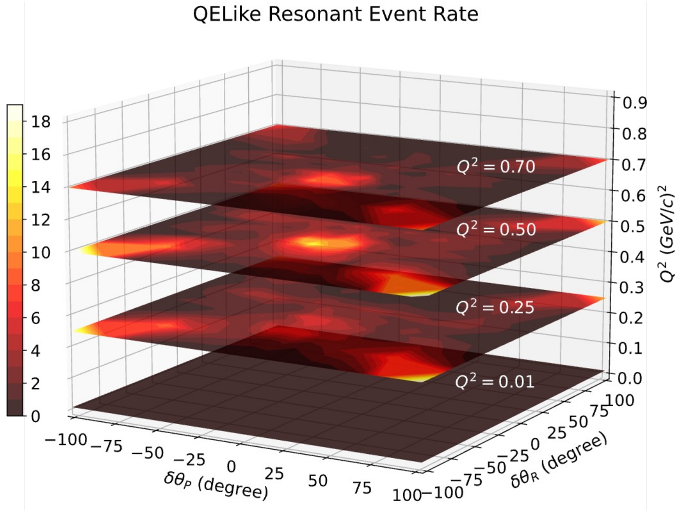




Background: QELike CCQE (on C)



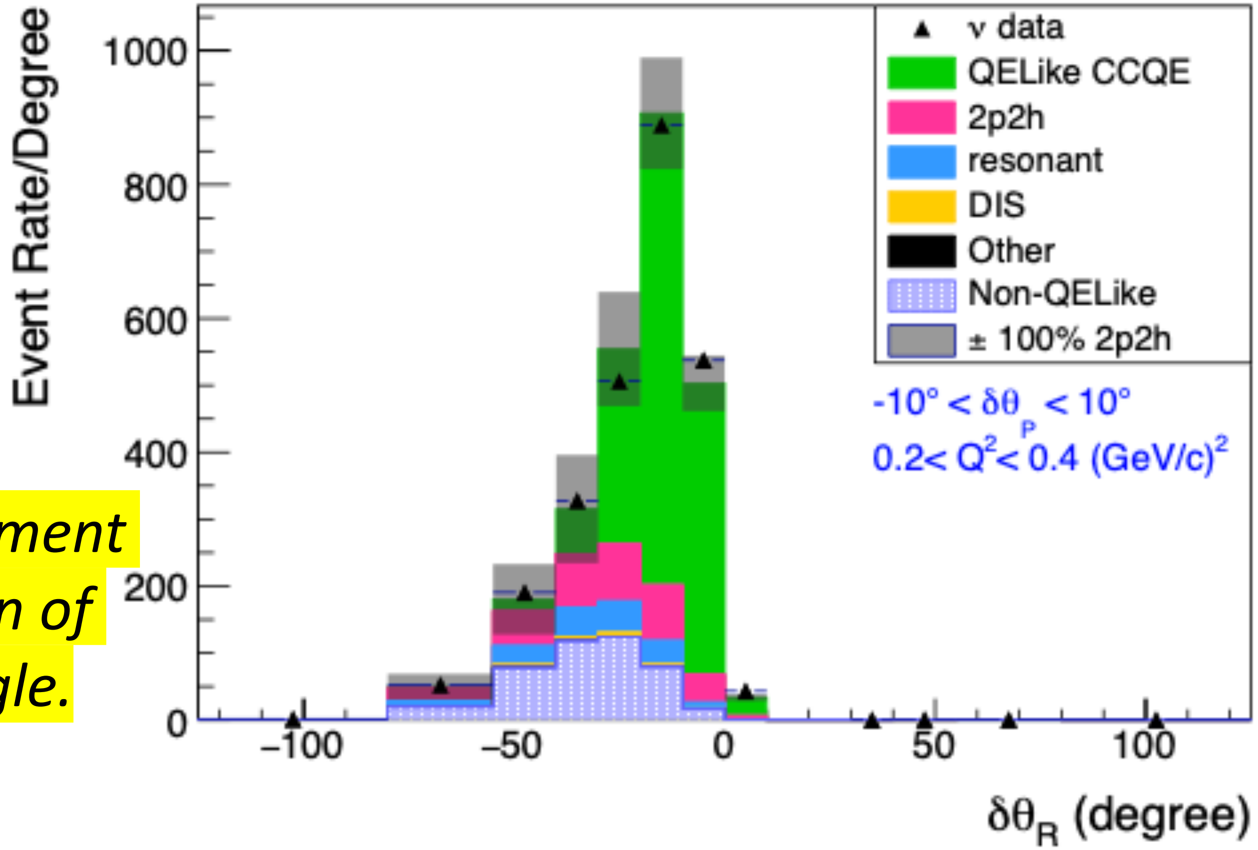
Background: QELike 2p2h



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****.*

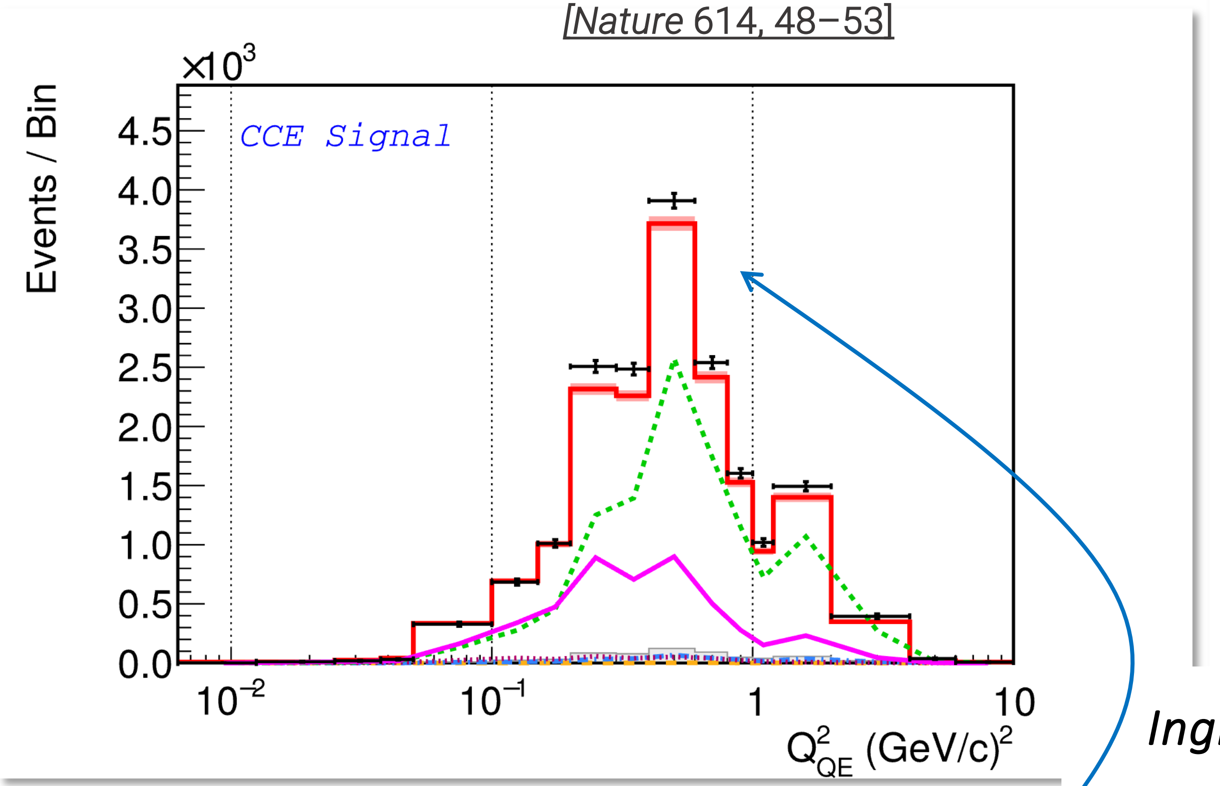
Control Sample, Neutrino Beam (cont'd)

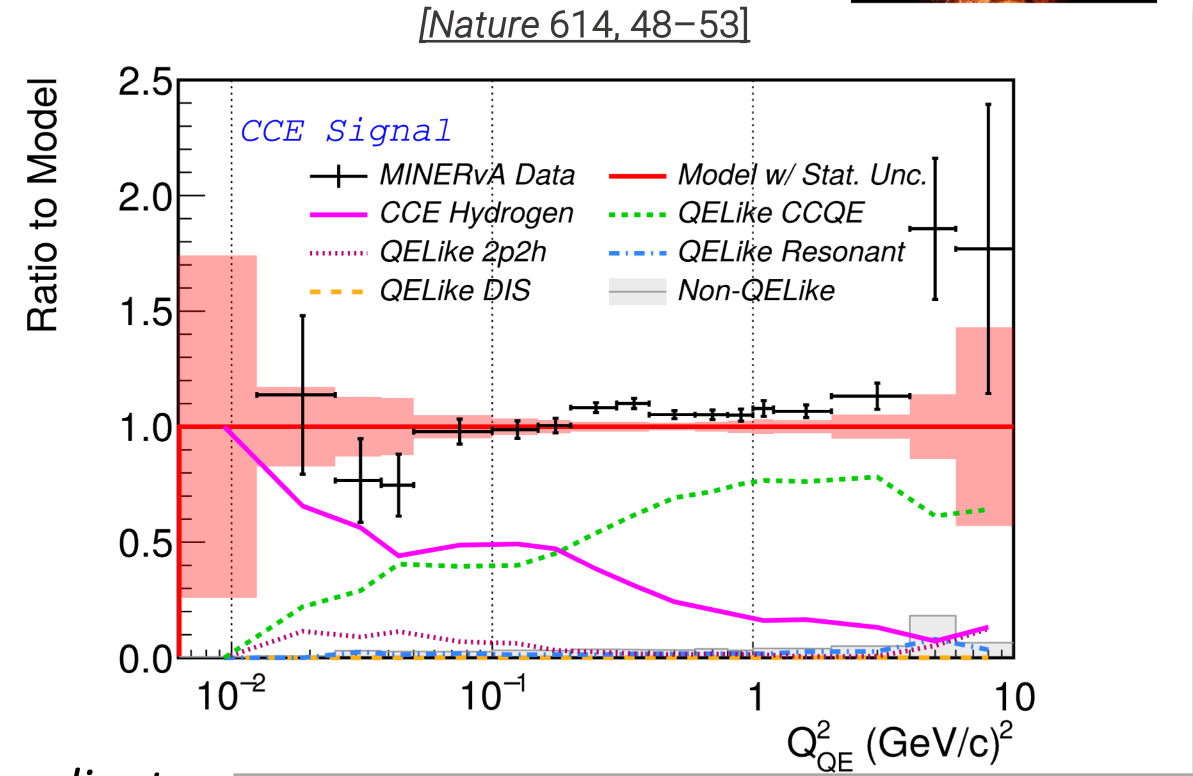


The low Q^2 disagreement shown as a function of reaction plane angle.

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



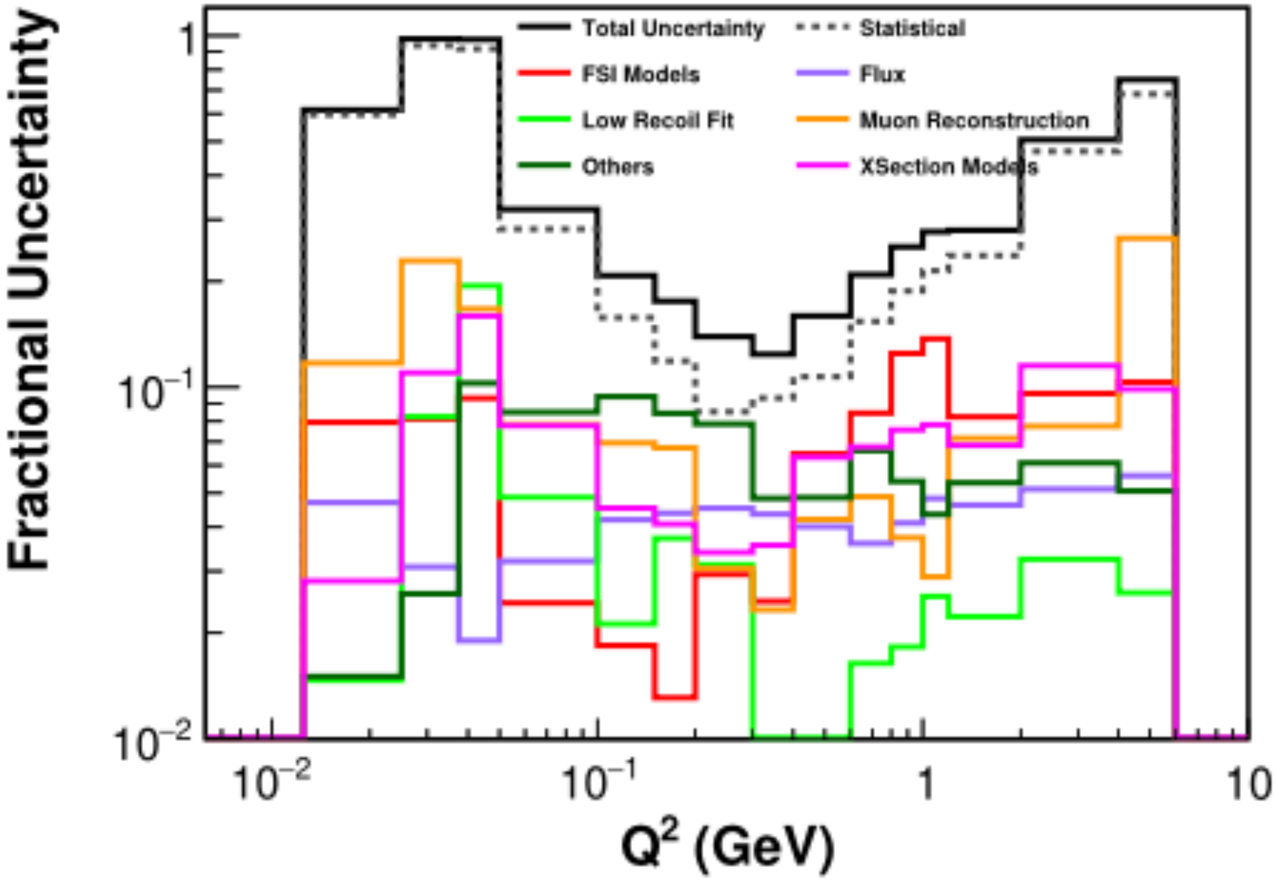


$$\left(\frac{d\sigma}{dQ^2}\right)_i = \frac{\sum_j U_{ji}\left(N_j^{\text{data}} - N_j^{\text{bkg-pred}}\right)}{\Phi N_H \epsilon_i (\Delta Q^2)_i}$$

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.*

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 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.

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

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

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

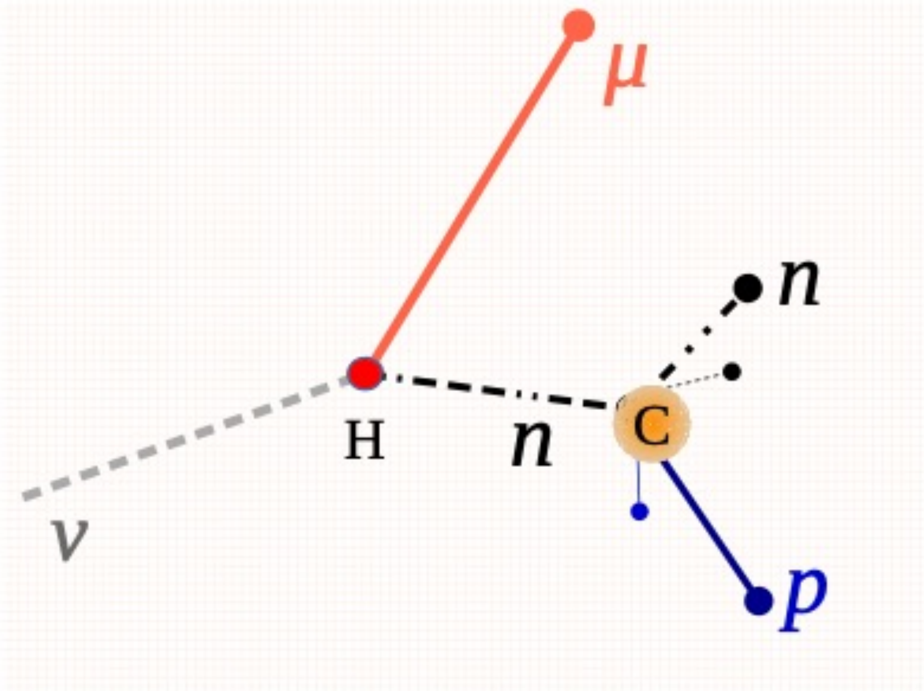
$$\chi^2 = \Delta X \cdot \mathrm{cov}^{-1} \cdot \Delta X + \lambda \left[\sum_{k=1}^{5} \left(\frac{a_k}{5a_0} \right)^2 + \sum_{k=5}^{k_{\max}} \left(\frac{k a_k}{25 a_0} \right)^2 \right]$$

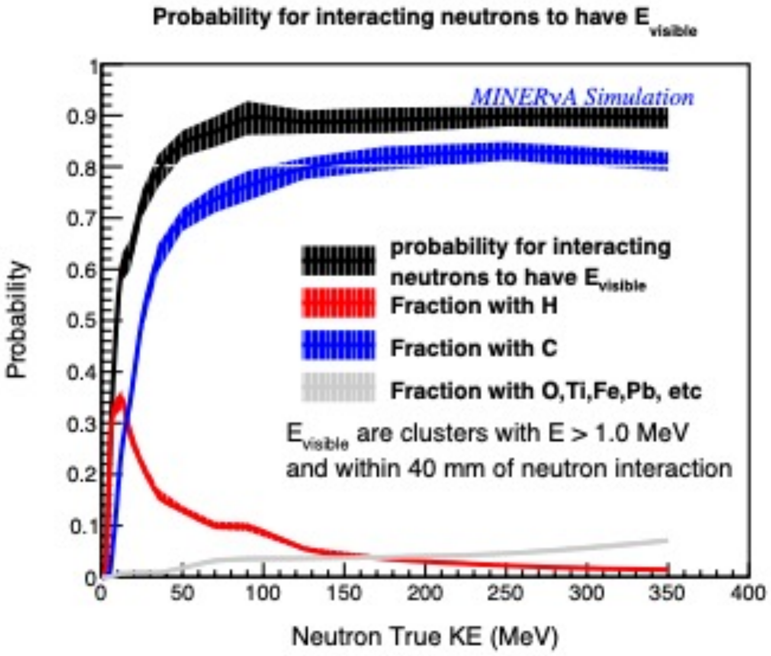
BBBA05 is R. Bradford et al., Nuclear Physics B, Proceedings Supplements 159 (2006) 127–132, doi:https://doi.org/10.1016/j.nuclphysbps.2006.08.028.

Backup: 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.*

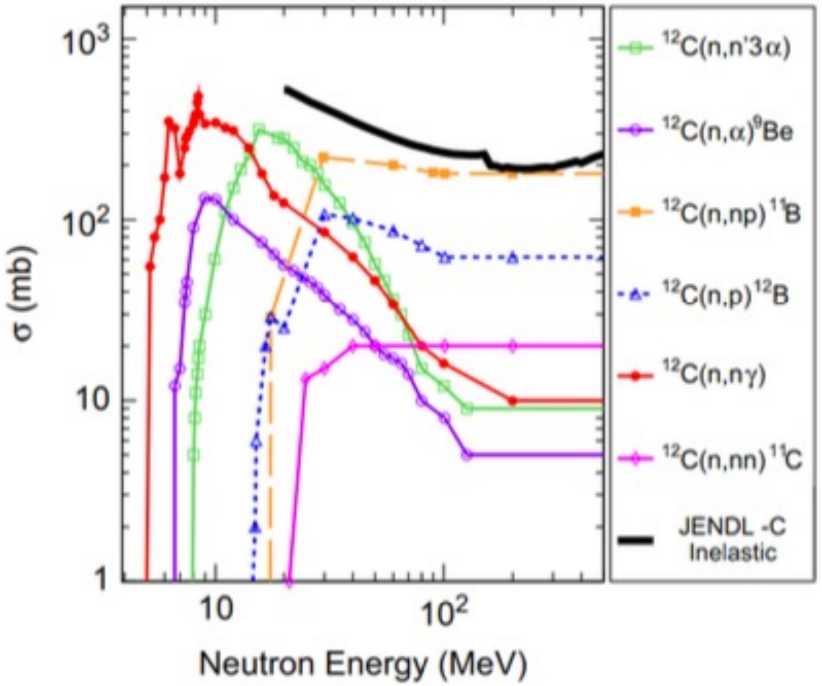
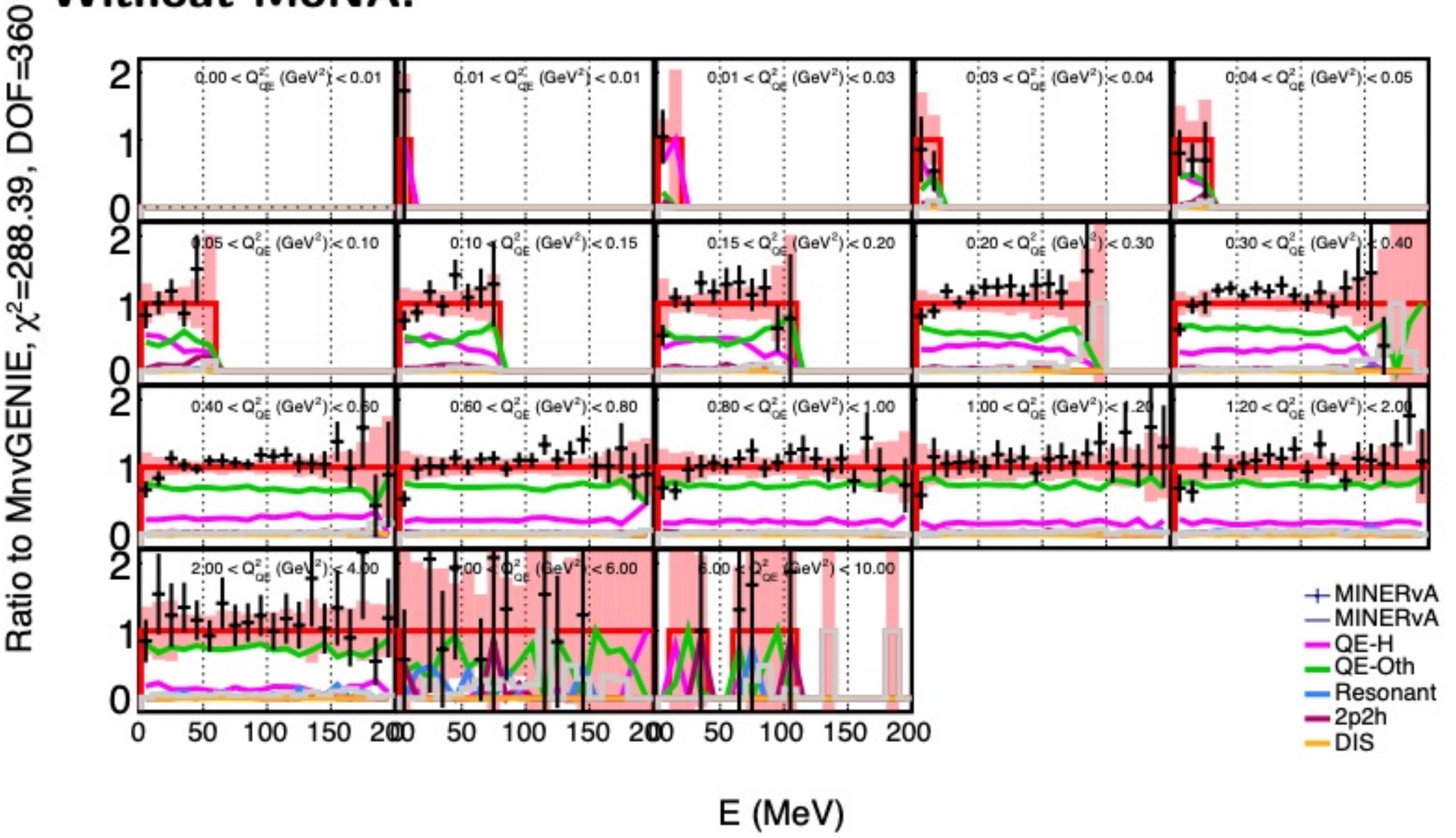


Fig. 3. Inelastic neutron–carbon reaction cross-sections are shown as a function of the incident neutron energy. MENATE_R uses the six different discrete reaction channel cross-sections while the G4-Physics uses the total inelastic reaction cross-sections taken from the JENDL-HE library [37].

“Nuisance” Distributions

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

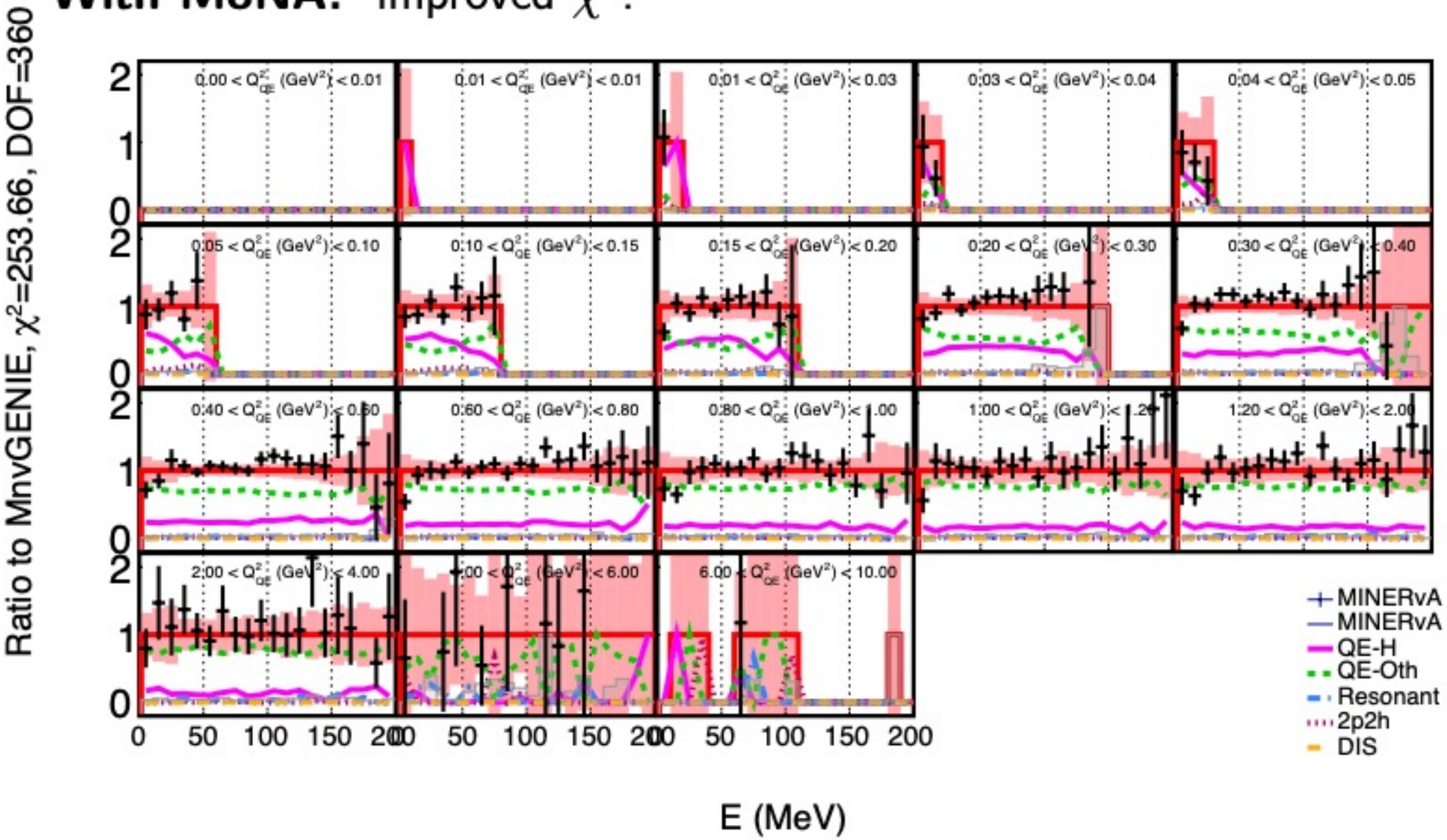
Without MoNA.



“Nuisance” Distributions

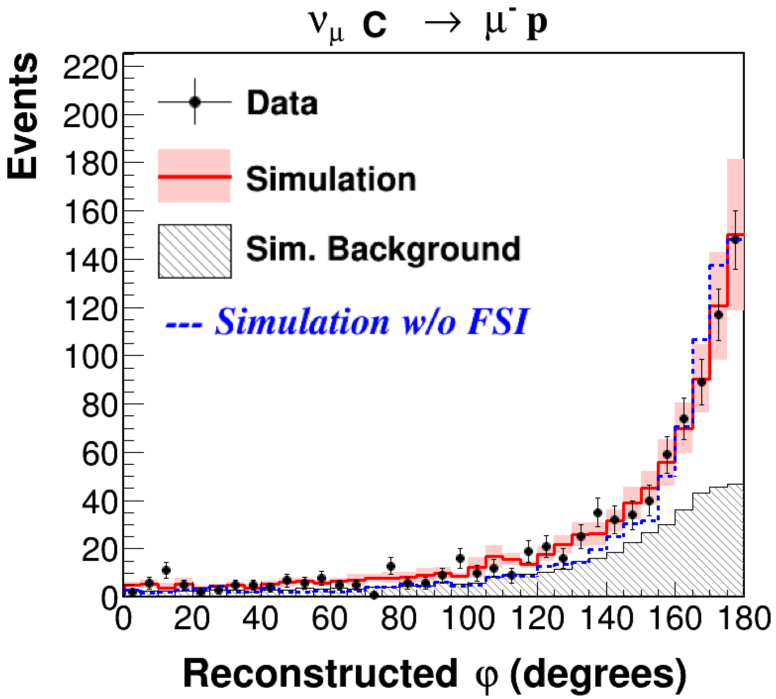
Neutron candidate energy distribution in reconstructed Q^2_{QE} bins.

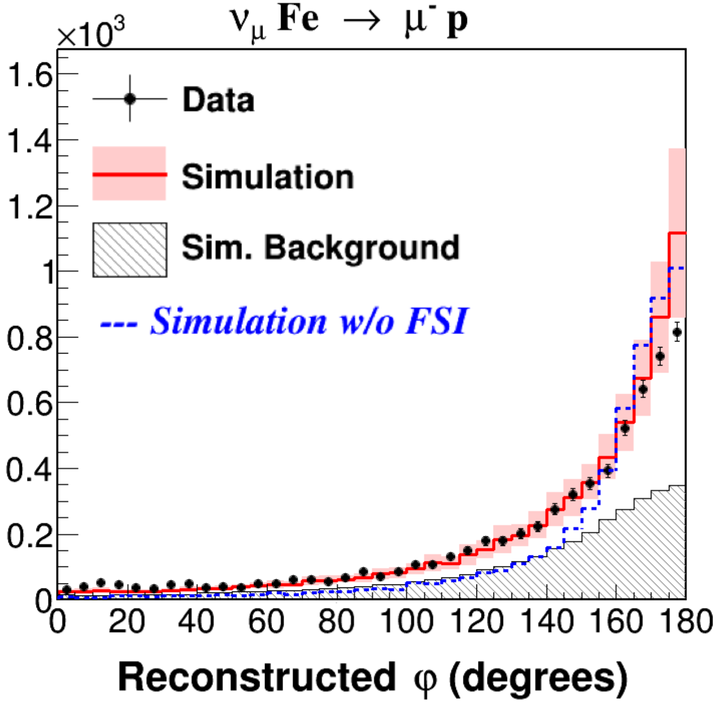
With MoNA: improved χ^2.



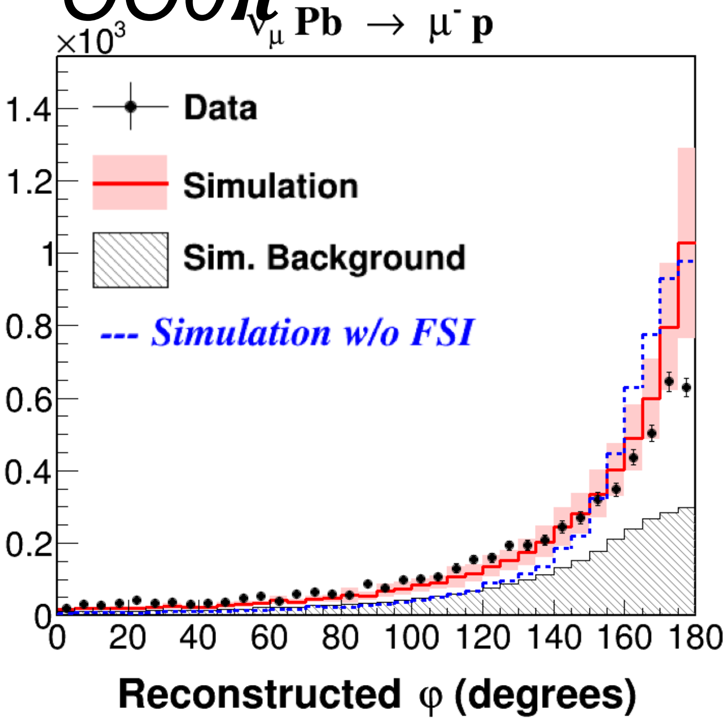
Backup: Older CC0$\boldsymbol{\pi}$ on other Targets

MINERvA's Passive Targets and CC0$\boldsymbol{\pi}$





3 GeV CC0$\boldsymbol{\pi}$

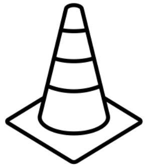


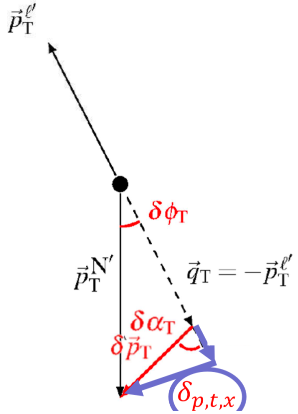
- Acoplanarity of C, Fe, and Pb targets in proton and muon CC0$\boldsymbol{\pi}$ events.
- Unsimulated migration away from planar peak with increasing A: C→[Arg(on)] → Fe → Pb.

Phys.Rev.Lett. 119 (2017) 082001

Backup: More TKI ME Preview

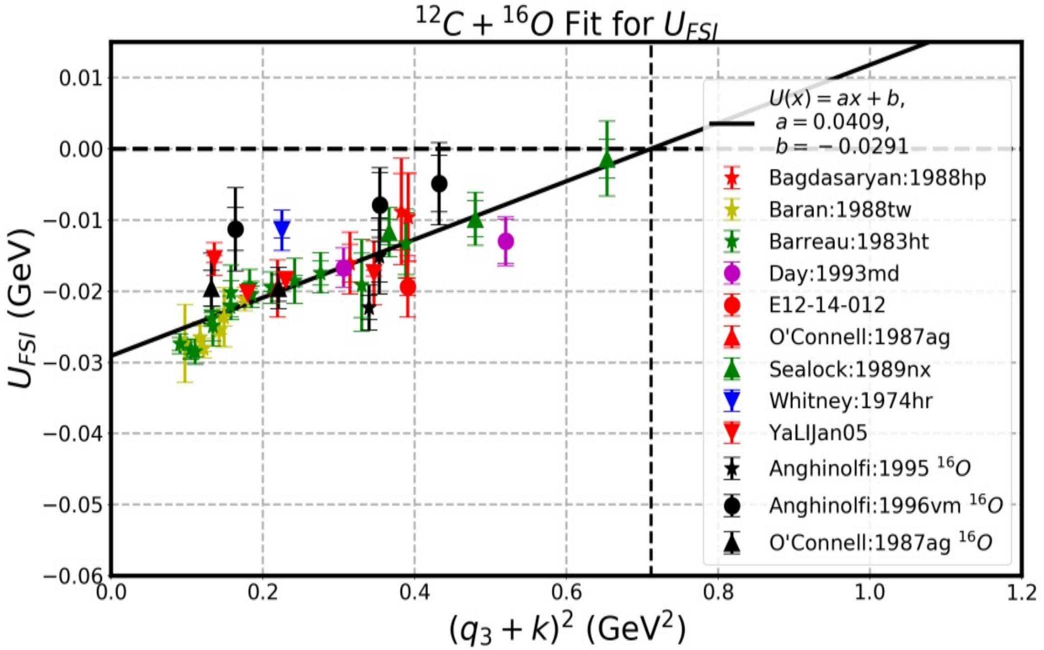
Transverse variables, full MINERvA statistics





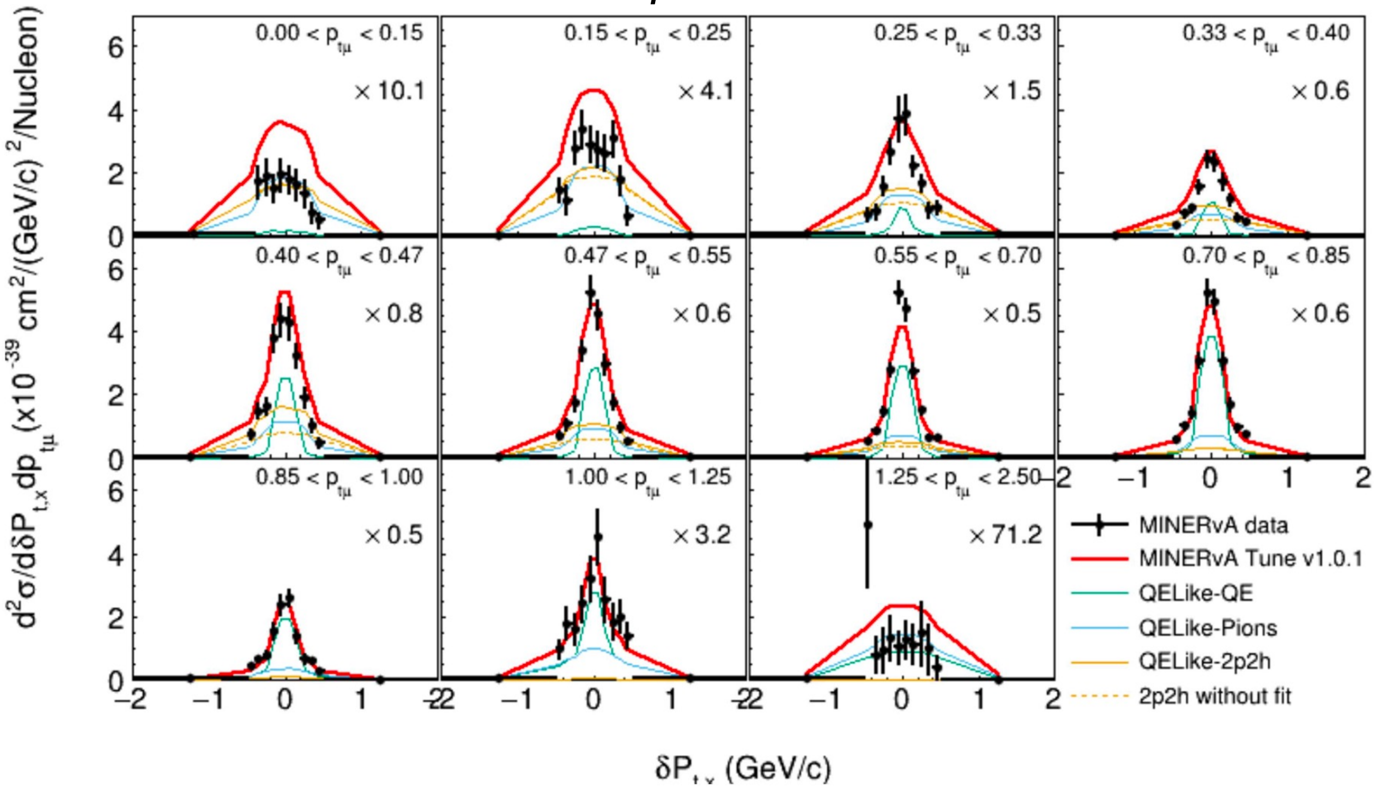
out of reaction plane, sensitive to Fermi motion only

$\delta_{p,t,x}$



Summary of optical potential from electron scattering
A. Bodek and T. Cai, Eur. Phys. J. C. (2019) 79: 293

all processes

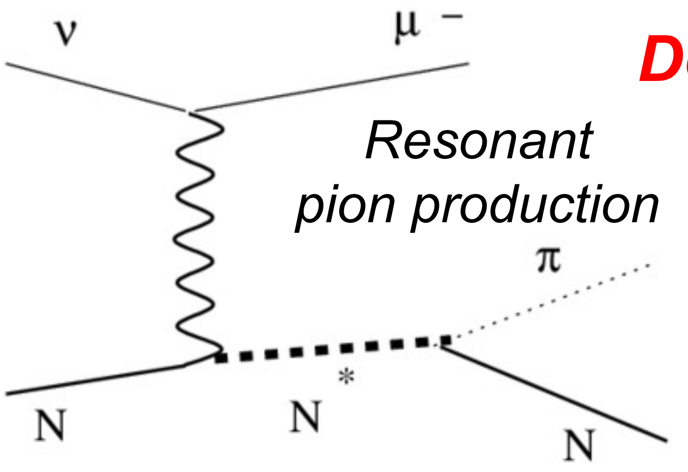


Backup: More on CC1π Reactions

How do we produce single pions?

(Let us count the ways.)

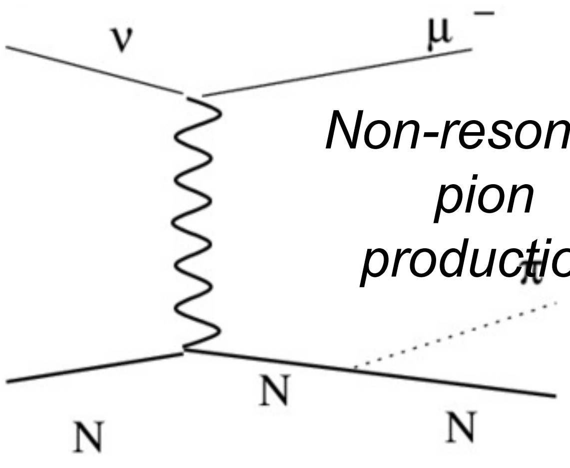
- Many competing production mechanisms.



Dominant

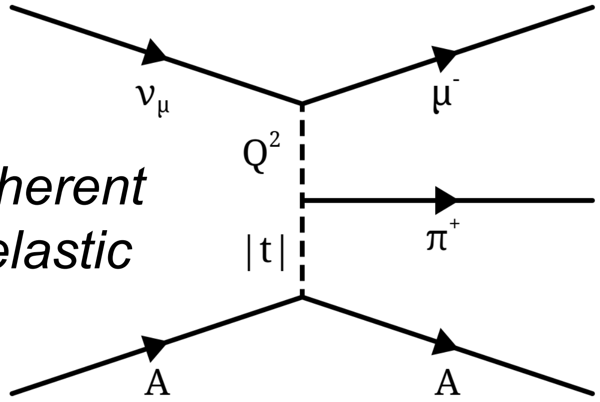
Resonant pion production

Interference may be large effect



Non-resonant pion production

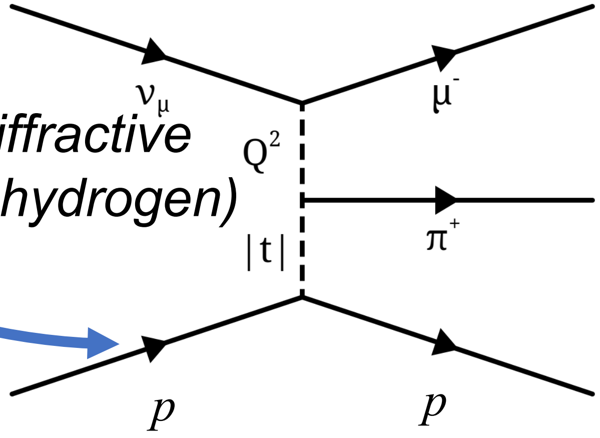
Significant



Coherent inelastic

Sub-leading

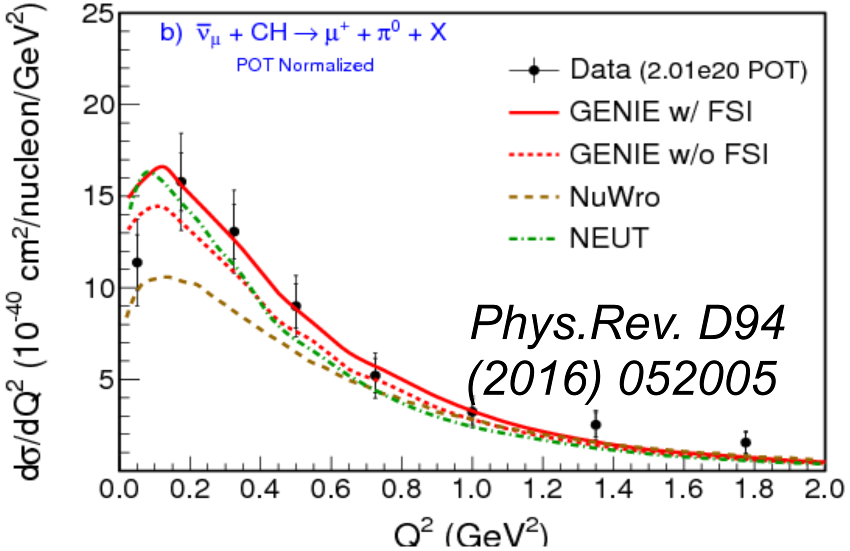
Interference at low Q^2 on hydrogen

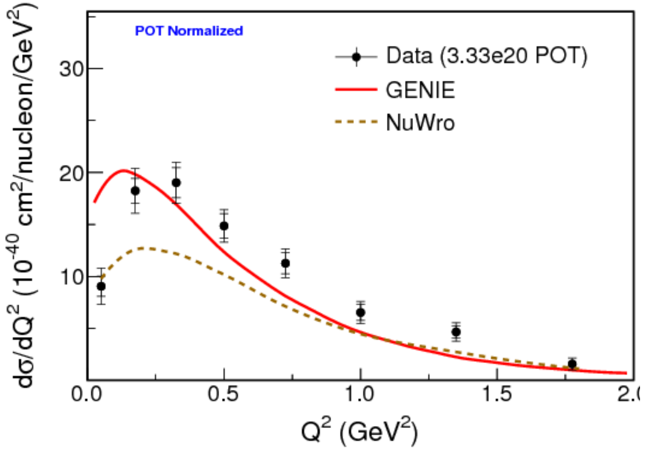


Diffractive (on hydrogen)

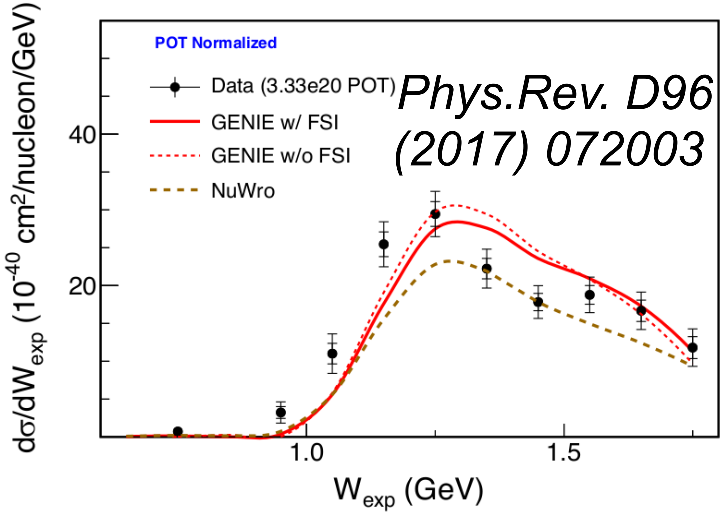
Incoherent pion production observations

- MINERvA sees a strong deficit of pion production at low Q^2 in several channels.
  - MINOS has also seen a low Q^2 suppression in "resonance region".
- MINERvA also sees a shift in the pion spectra to slightly lower values, which look to be consistent with a shift in the Δ(1232) peak.
  - Maybe resonant-non resonant interference that is absent from model?

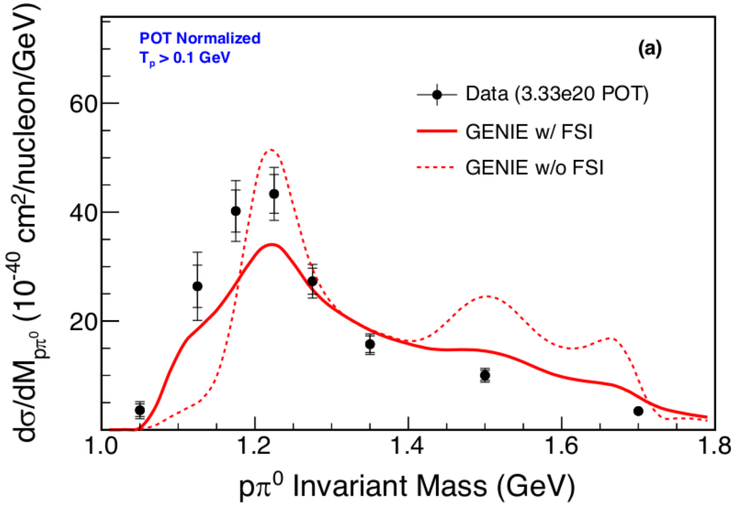




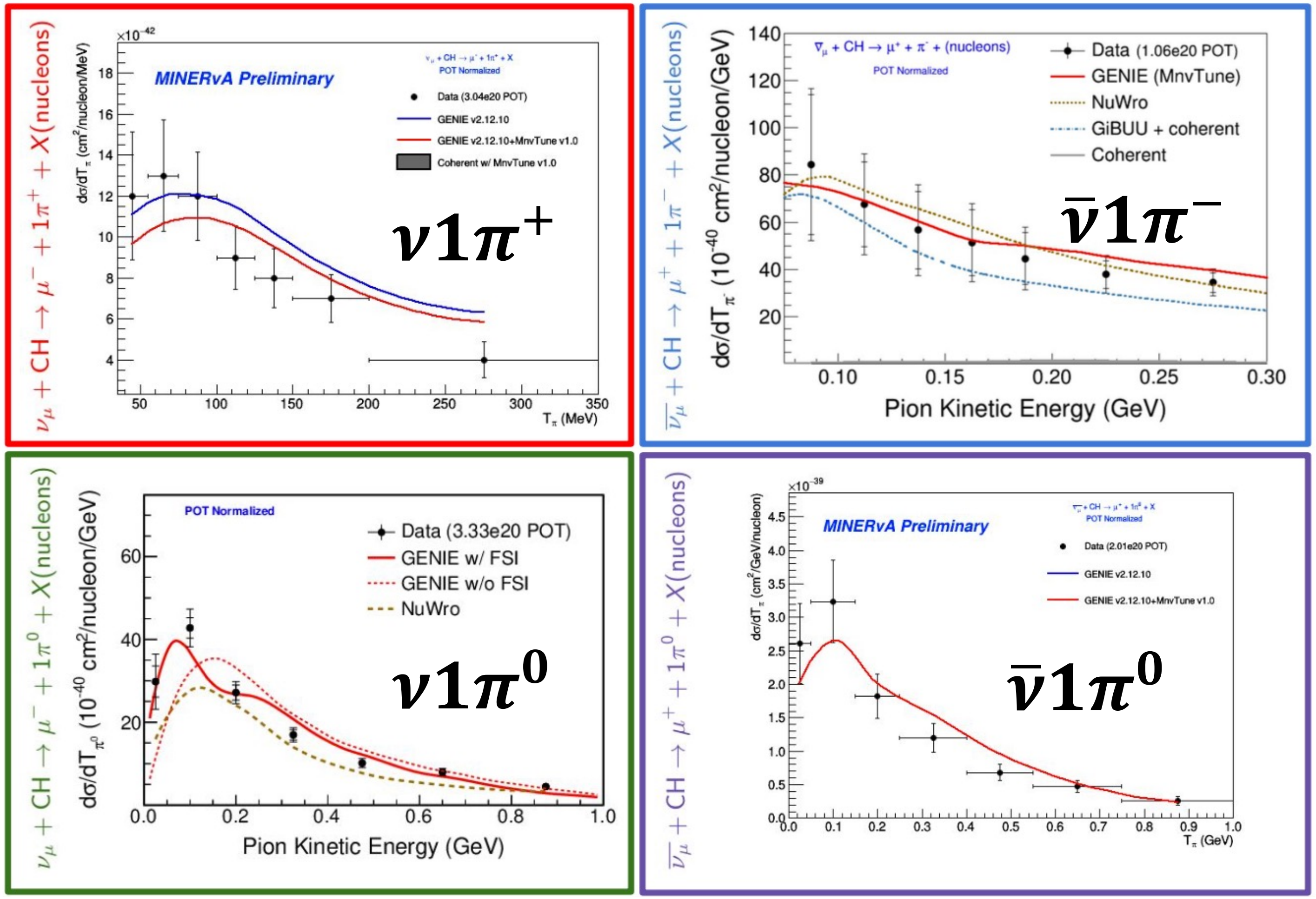
$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$



Invariant Mass calculated with proton and π^0 4-momenta



MINERvA's Four Charged-Current Single Pion Channels: T_π

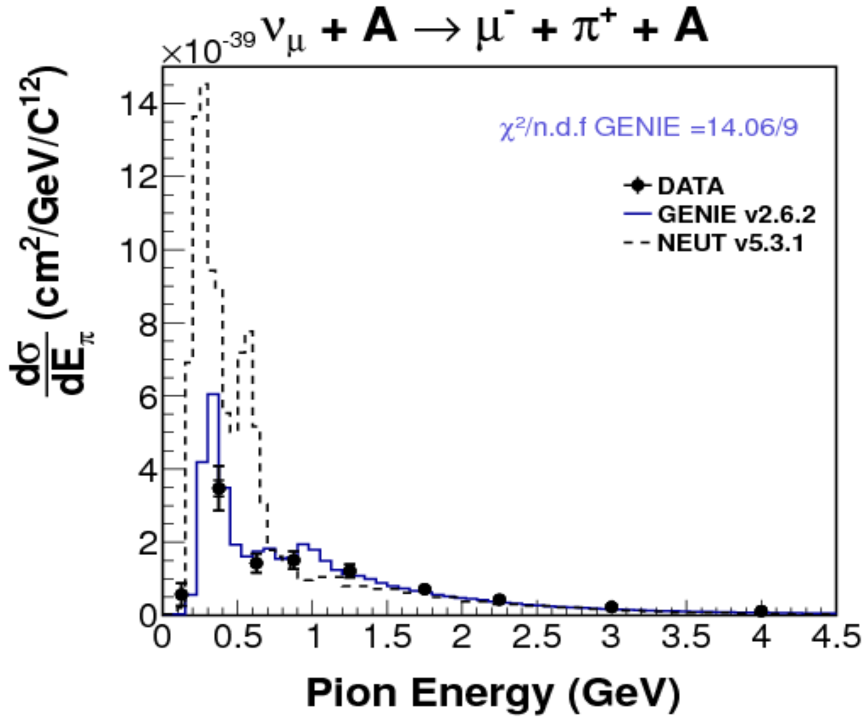


Pion Kinetic Energy (GeV)

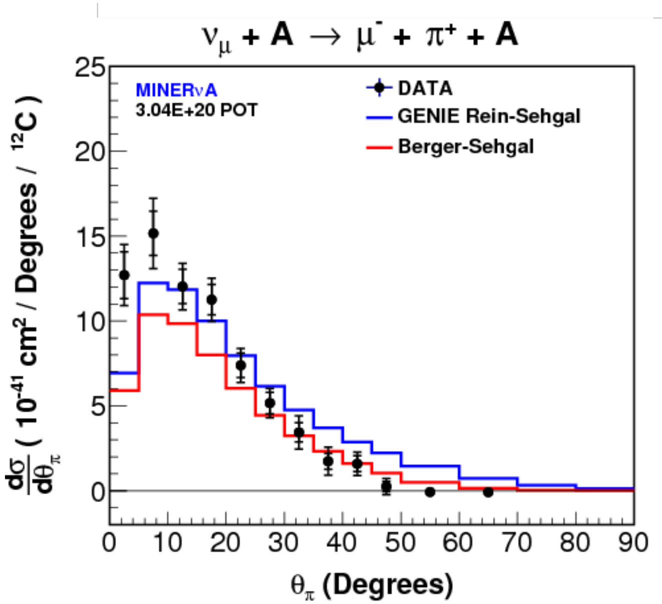
- Generally adequate description from MINERvA tuned GENIE 2.12.x
- Some tendency for more strength at lower energies
- Maybe consistent with shift of Δ? Maybe consistent with FSI alteration?

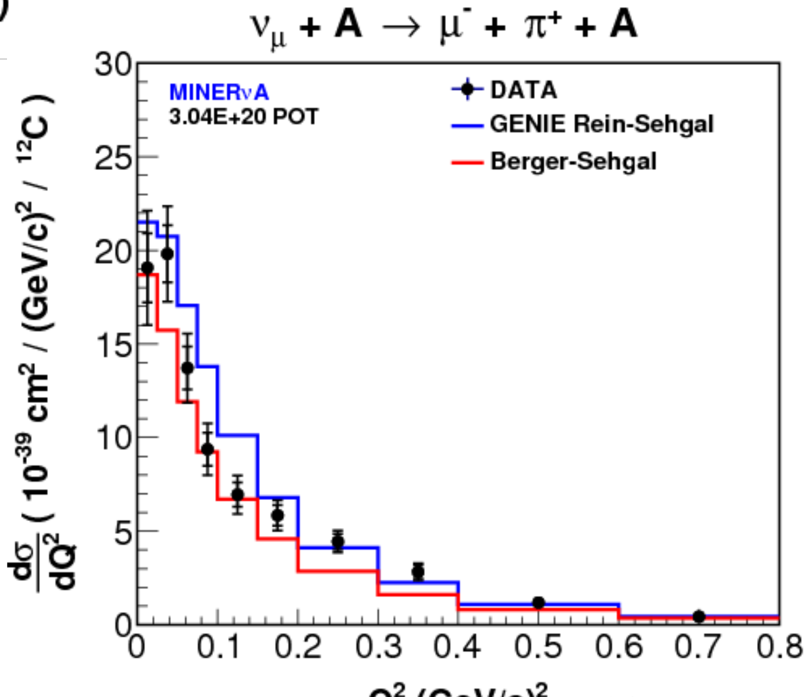
Coherent pion production

- Our coherent pion production results show some preference for Berger-Sehgal rather than GENIE's Rein-Sehgal prediction.
    - NEUT R-S prediction was poor at low pion energy.
    - T2K fixed this after MINERvA's results.



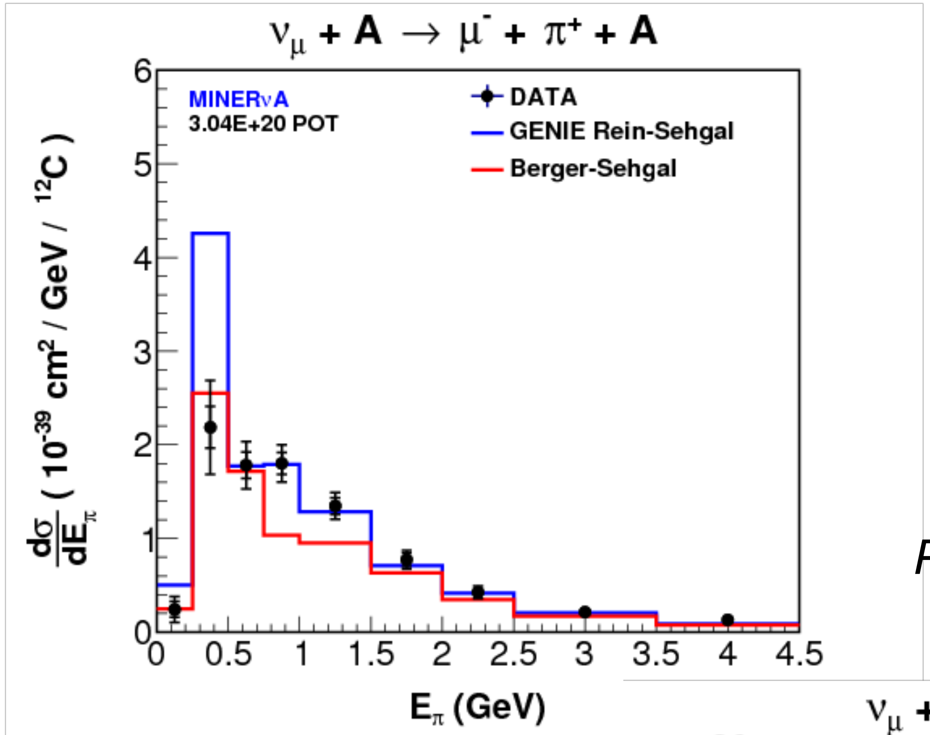
Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802



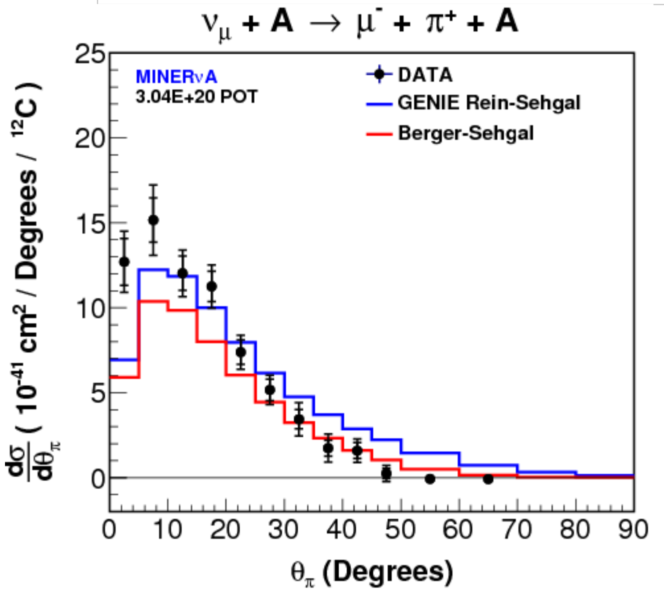


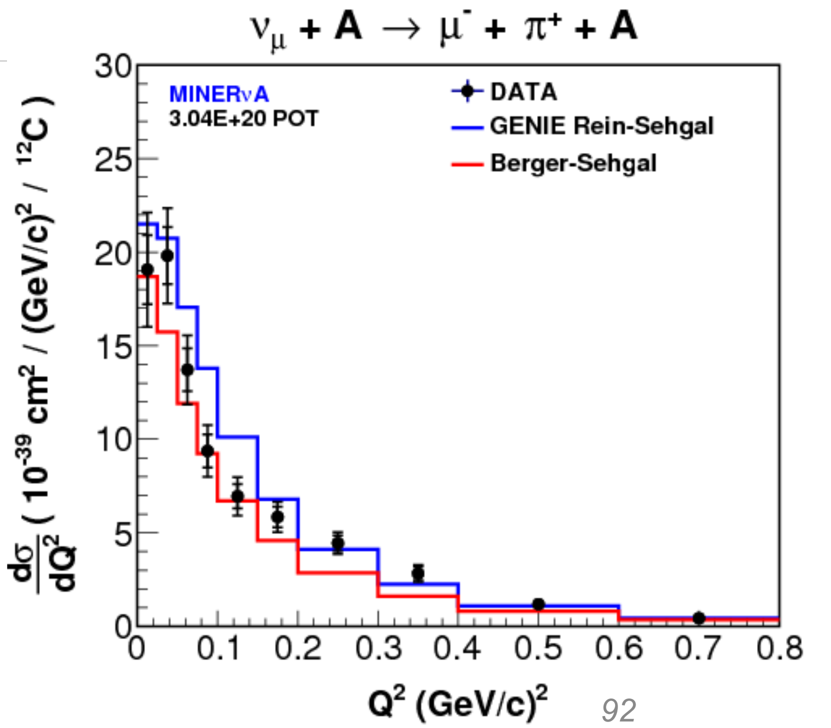
Coherent pion production

- Our coherent pion production results show some preference for Berger-Sehgal rather than GENIE's Rein-Sehgal prediction.
- Berger-Sehgal has been implemented in GENIE.
- MINERvA adds tunes in comparison to pion production with a coherent component.

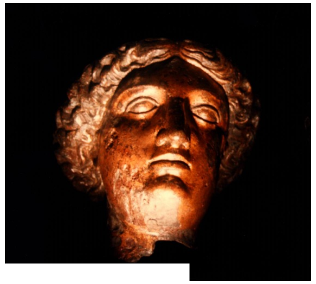


Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802

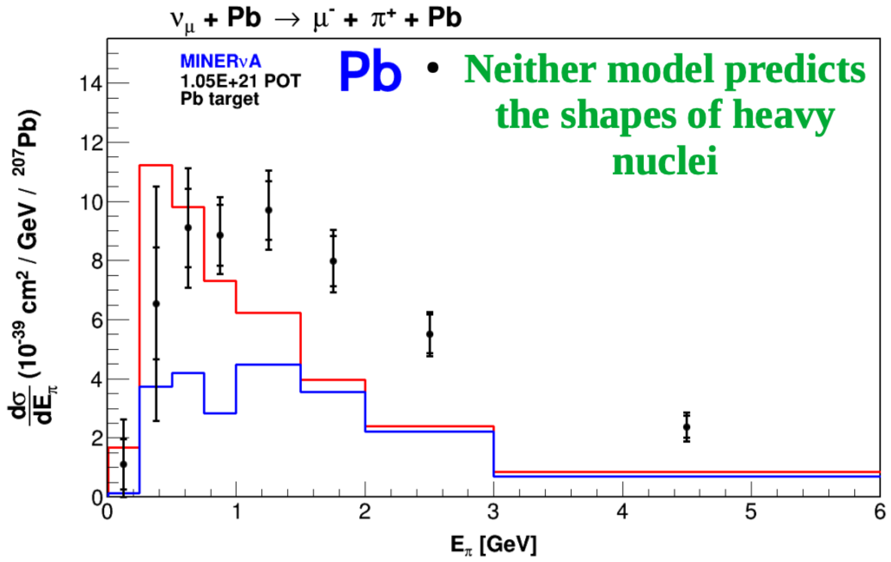


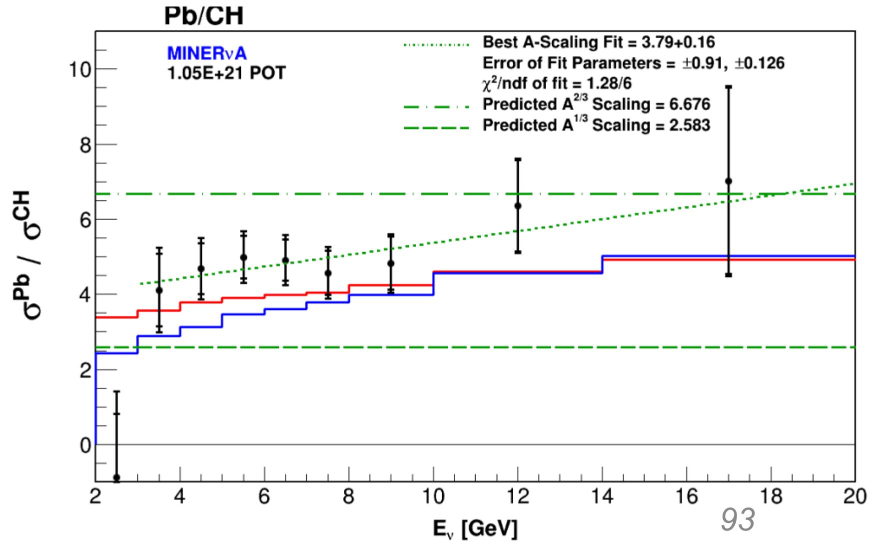


Coherent pion production on MINERvA's other targets, Fe, Pb



- Short version is that A scaling is not radically wrong, nor correct in detail.
- Scaling seems to be modestly different at low and high pion energies, which is a feature also see in models.
-

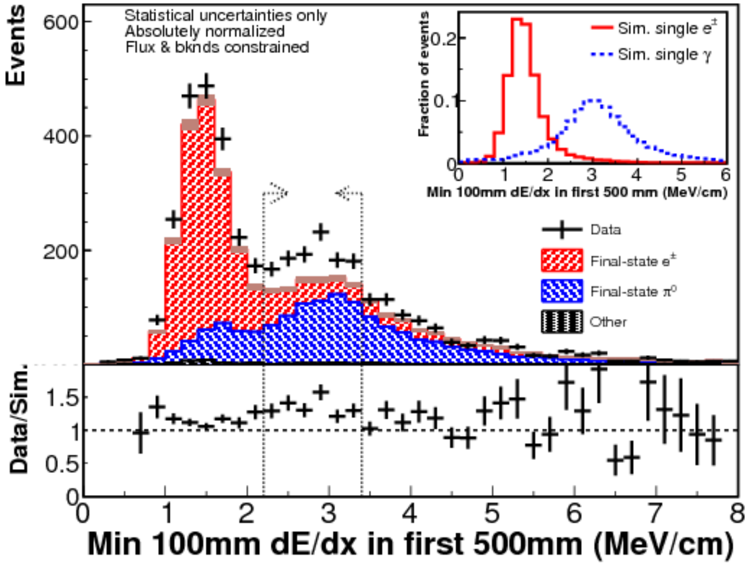


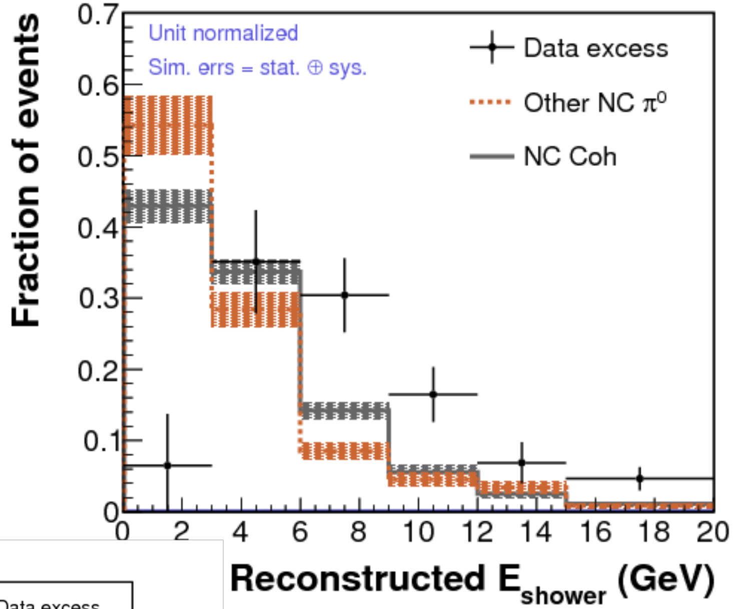


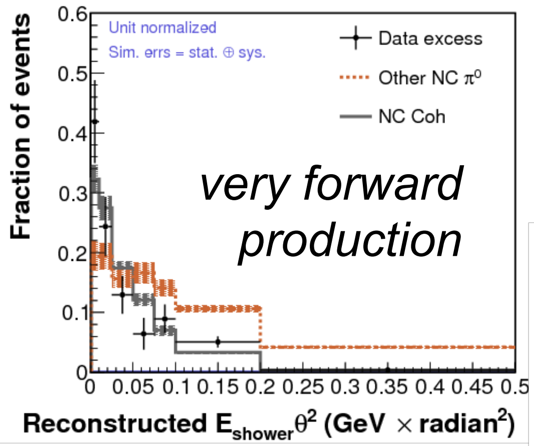
M.A. Ramírez et al, Phys.Rev.Lett. 131 (2023) 5, 051801

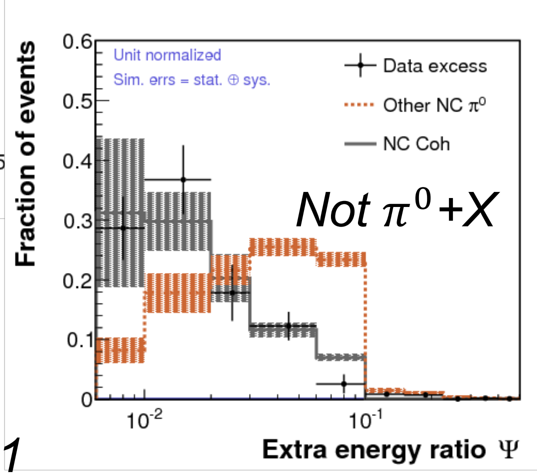
High energy diffractive (?) π^0

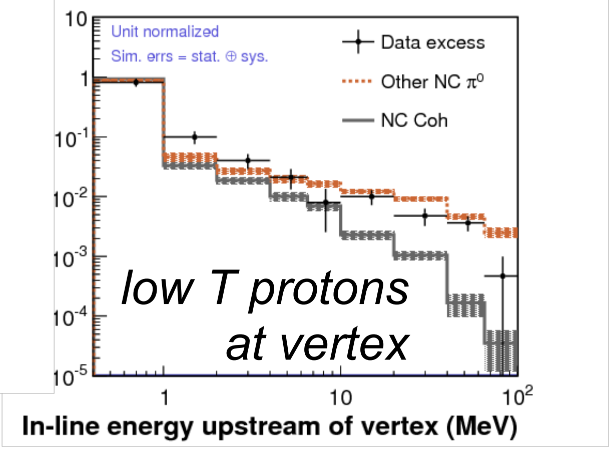
- Our electron neutrino analyses found excess events with dE/dx near the “electron” vertex consistent with photons.
- Most consistent with high energy diffractive π^0 production missing in GENIE.
- Important to add “by hand” for all electron neutrino analyses.
- No model describes this! Sorry.











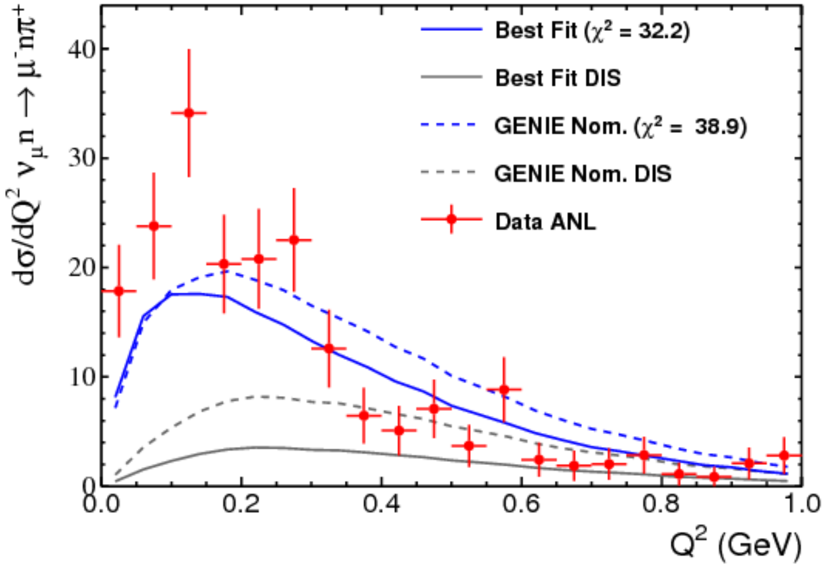
Phys.Rev.Lett. 117 (2016) 111801

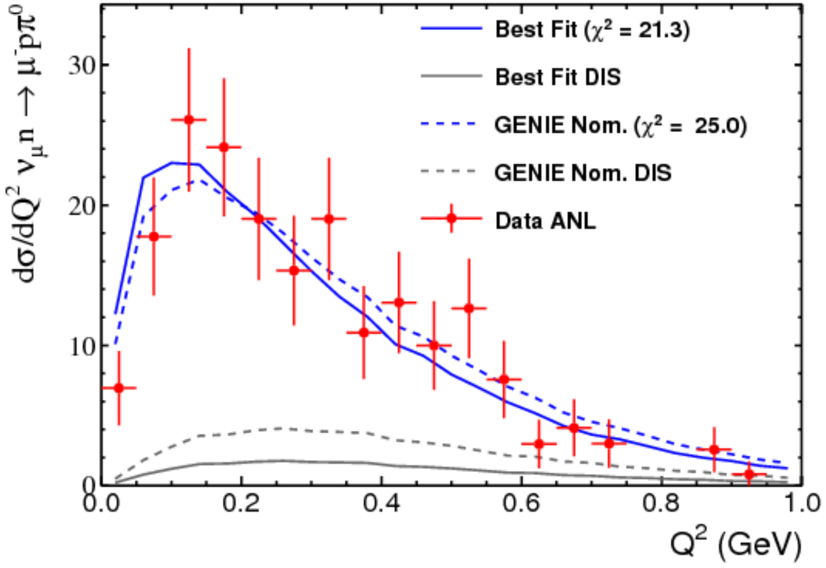
Deuterium Tune

- Results taken from analysis of ANL/BNL pion production data
- Largest change is reduction of non-resonant pion production.
- But without interference in the model, this is a bandaid.

C. Wilkinson, P. Rodrigues, KSM, Eur.Phys.J. C76 (2016) 474.

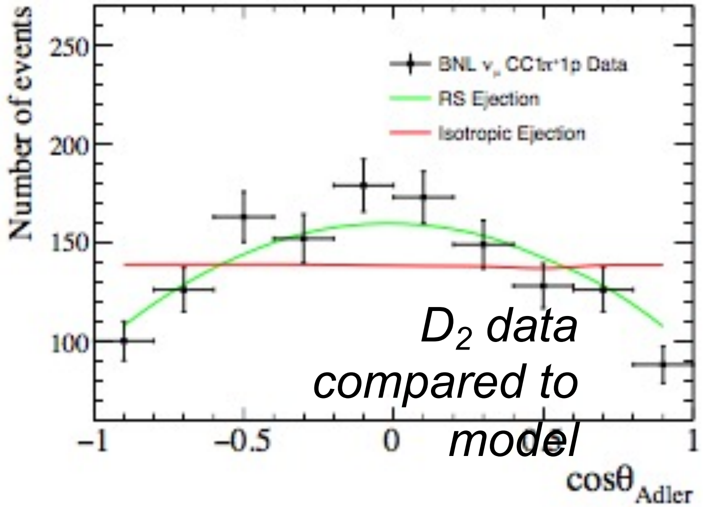
Model	GENIE default	ANL/BNL Tune
M_A^{RES} [GeV]	1.12 ± 0.22	0.94 ± 0.05
NormRES [%]	100 ± 20	115 ± 30
NonRES1π [%]	100 ± 50	43 ± 4

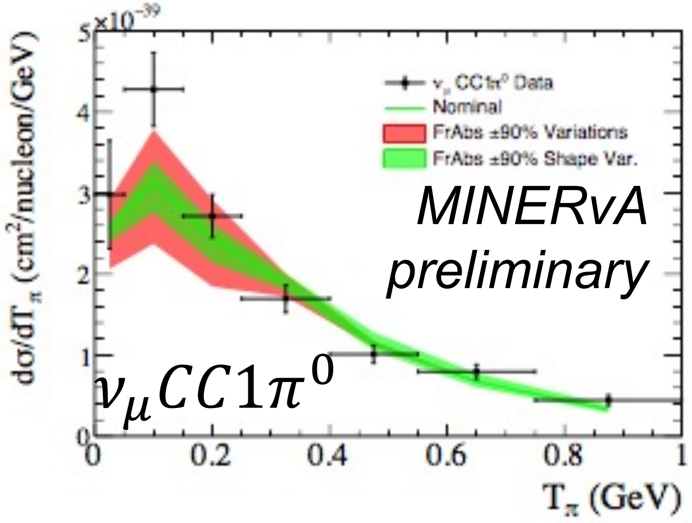


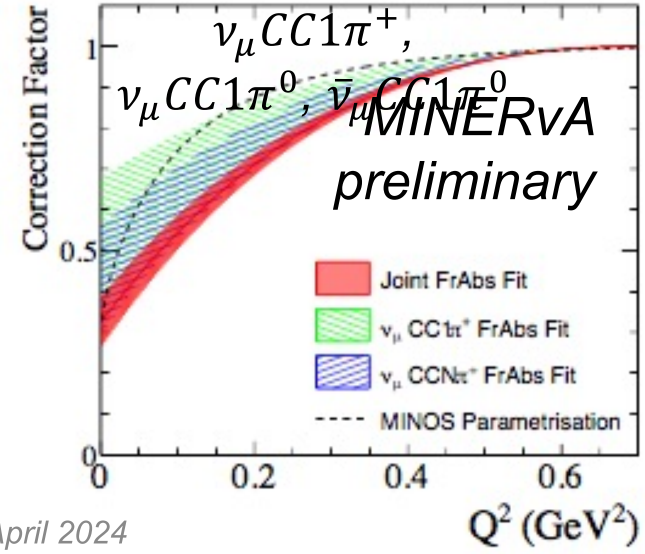


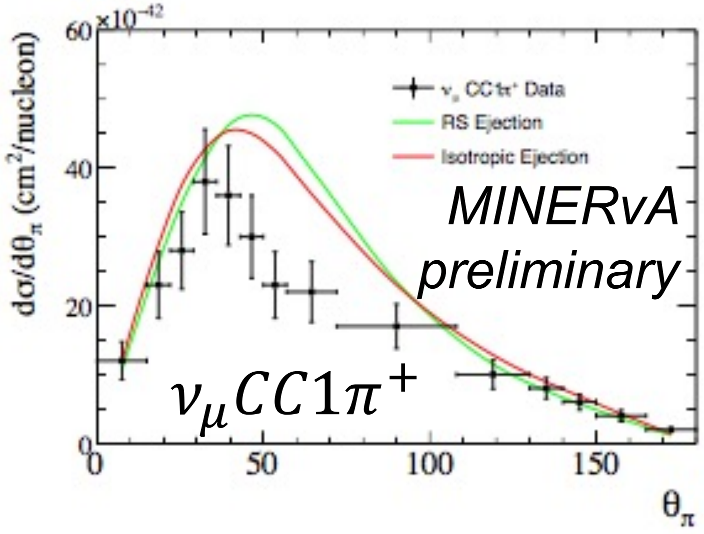
Pion tune results

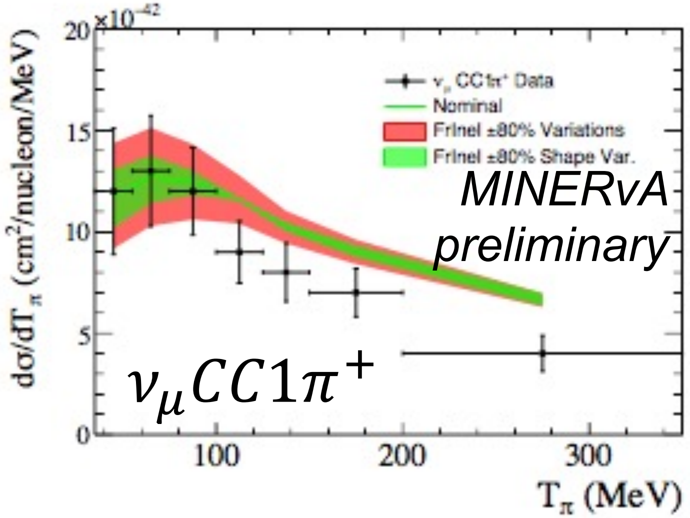
1. Form factor and non-resonant terms are not strongly pulled.
2. Strong FSI pulls are preferred, but hard to tell which.
3. Carbon data favors isotropic emission, which perhaps says more about FSI than emission.
4. Low Q^2 suppression is strongly preferred.



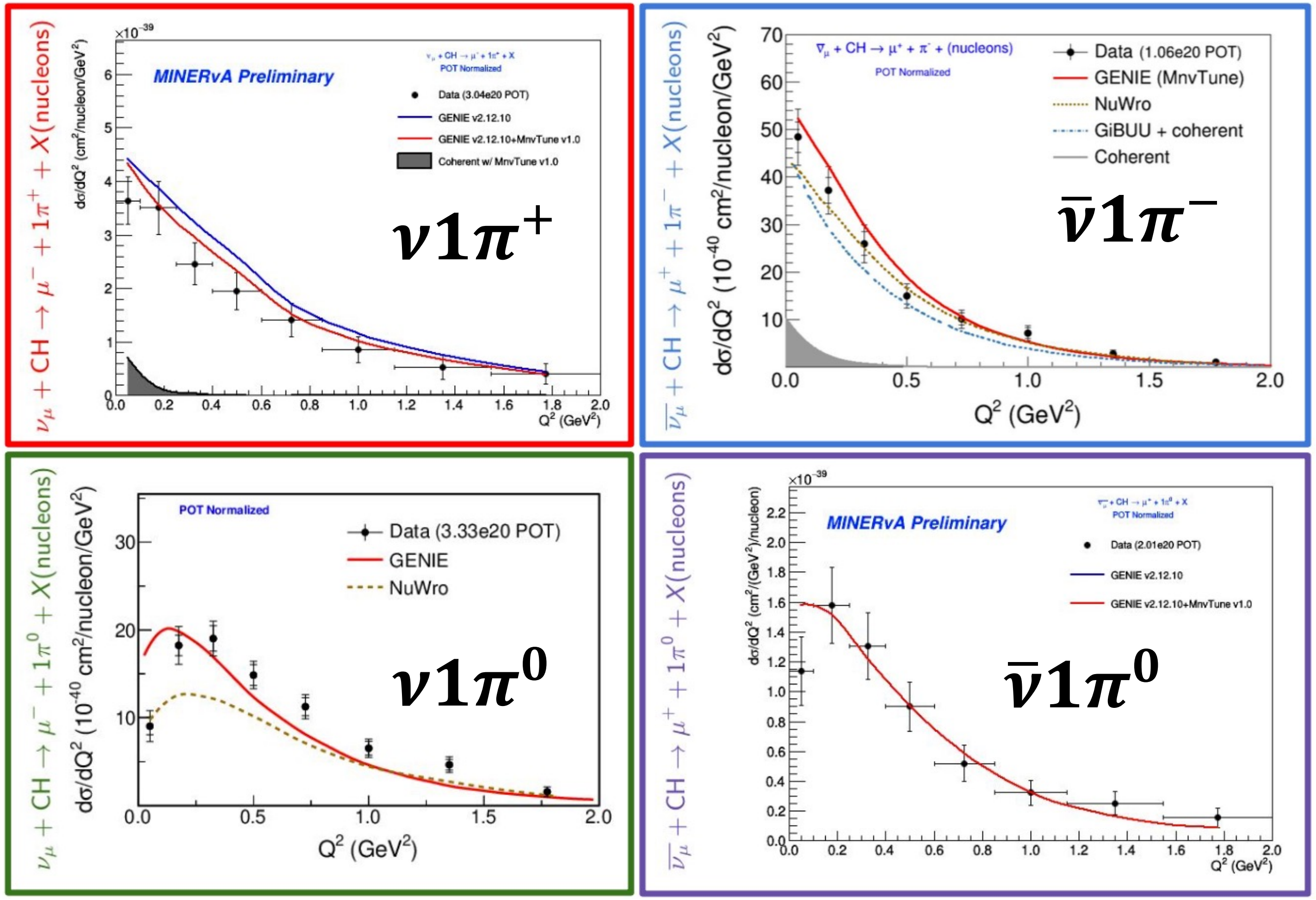








MINERvA's Four Charged-Current Single Pion Channels: Q^2

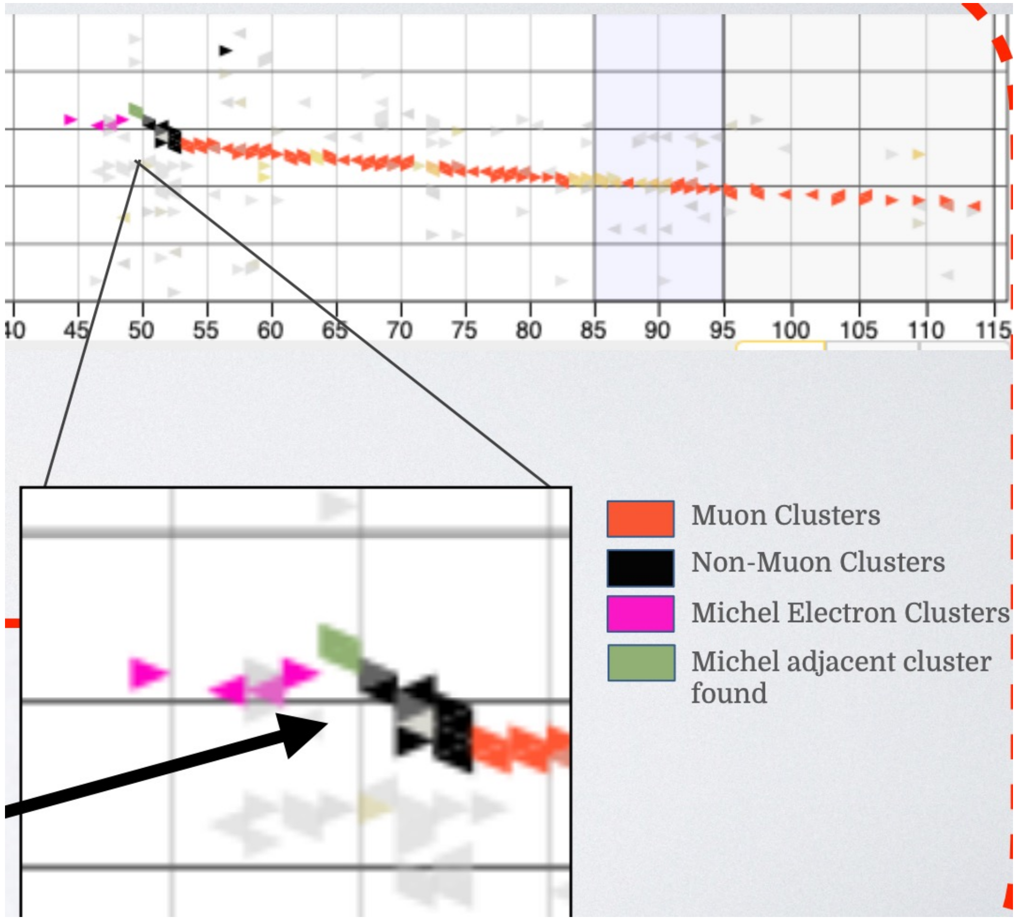


$$Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_{\mu\nu}\right) - m_\mu^2$$
(GeV^2/c^2)

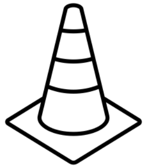
- Neutral pion production shows strong low Q^2 suppression
- Unknown nuclear effect?
- Charged pion final states have a coherent contribution included, but diffractive production from hydrogen in MINERvA unsimulated.

Backup: Preview of Trackless CC1π^+

Preview: Trackless (zero-threshold) π^+



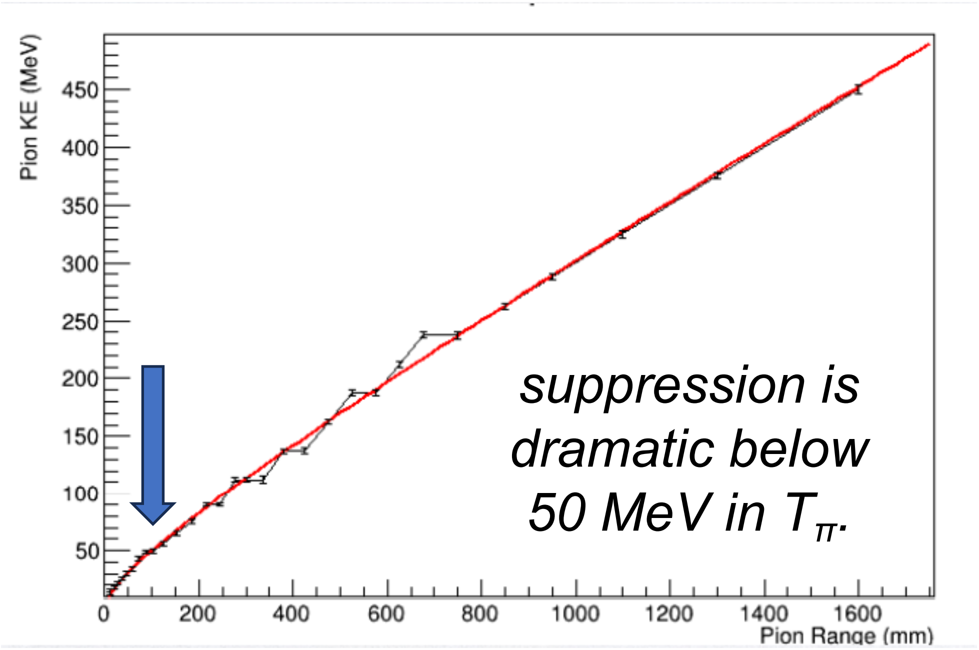
- Technique is to find a Michel later in time and match to prompt (in time with the interaction) energy in the detector.



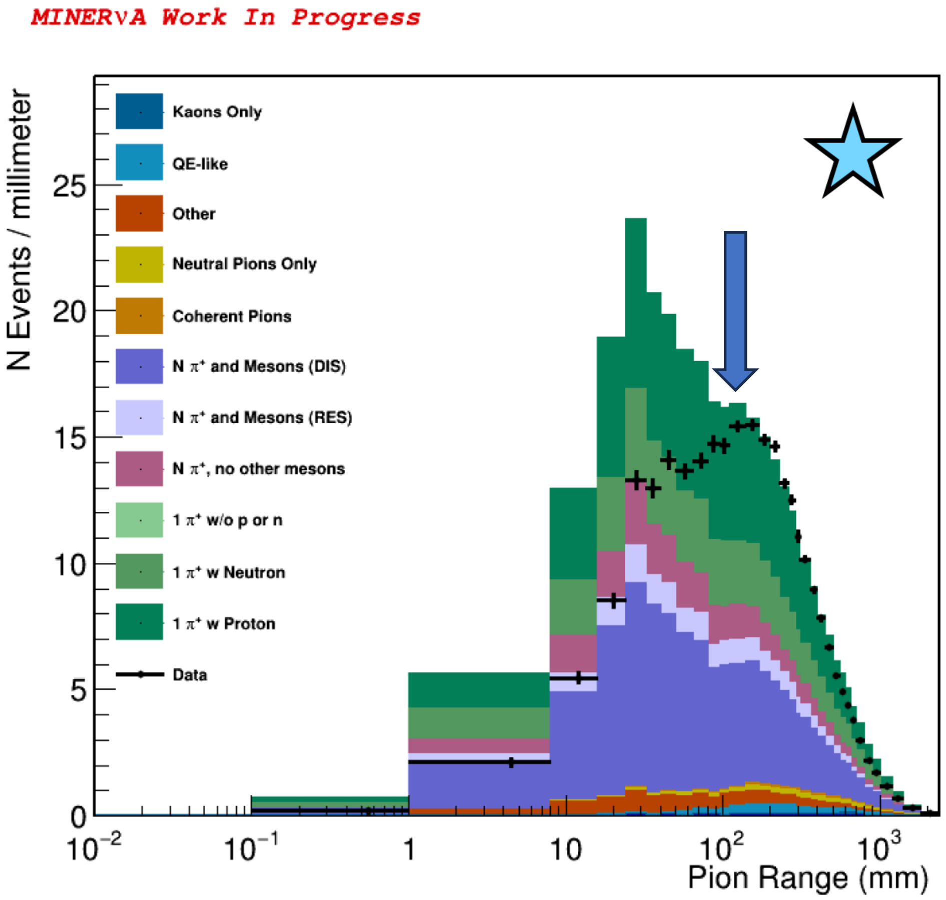
- Allows access to π^+ reconstruction without tracking, so can go down to zero kinetic energy.
- Reconstruct energy by range.

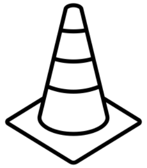
Preview: Trackless (zero-threshold) π^+

- First observation… sub-tracking threshold pions are very poorly modeled.

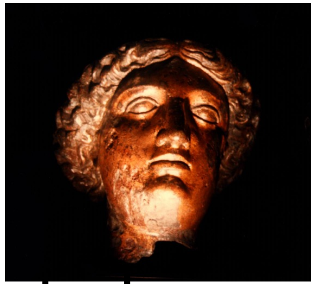


suppression is dramatic below 50 MeV in T_π.

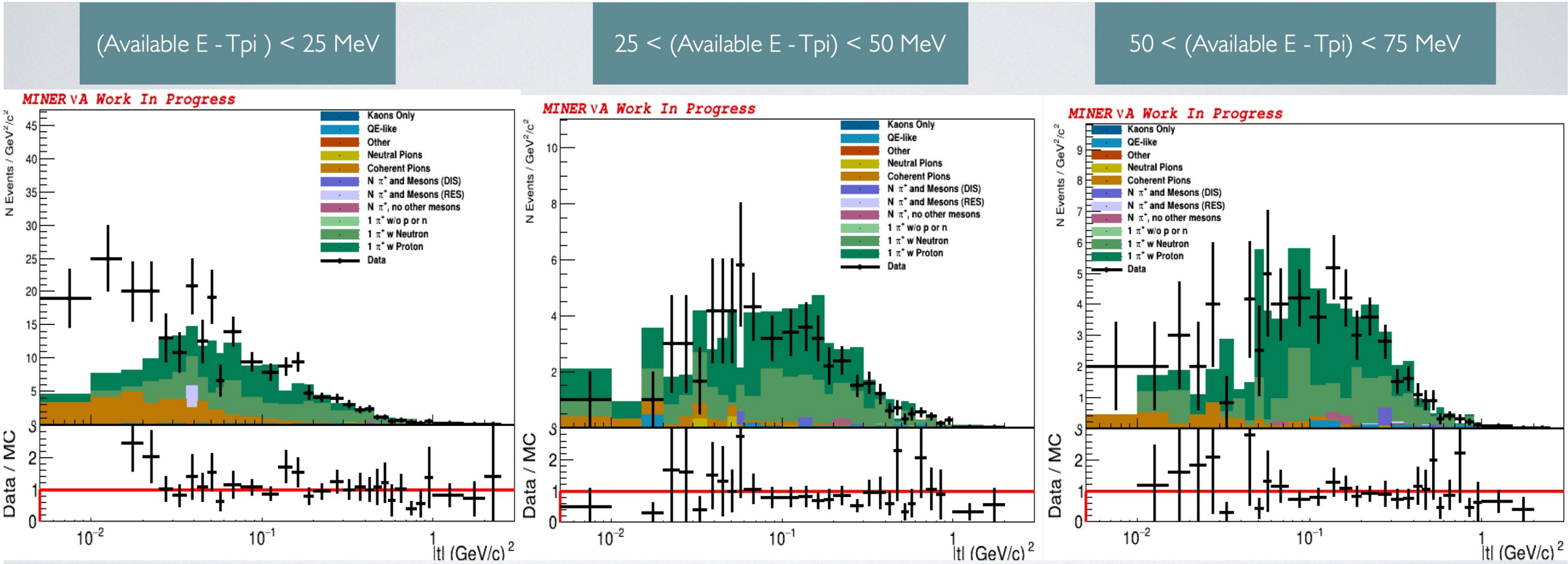




Preview: Trackless (zero-threshold) π^+

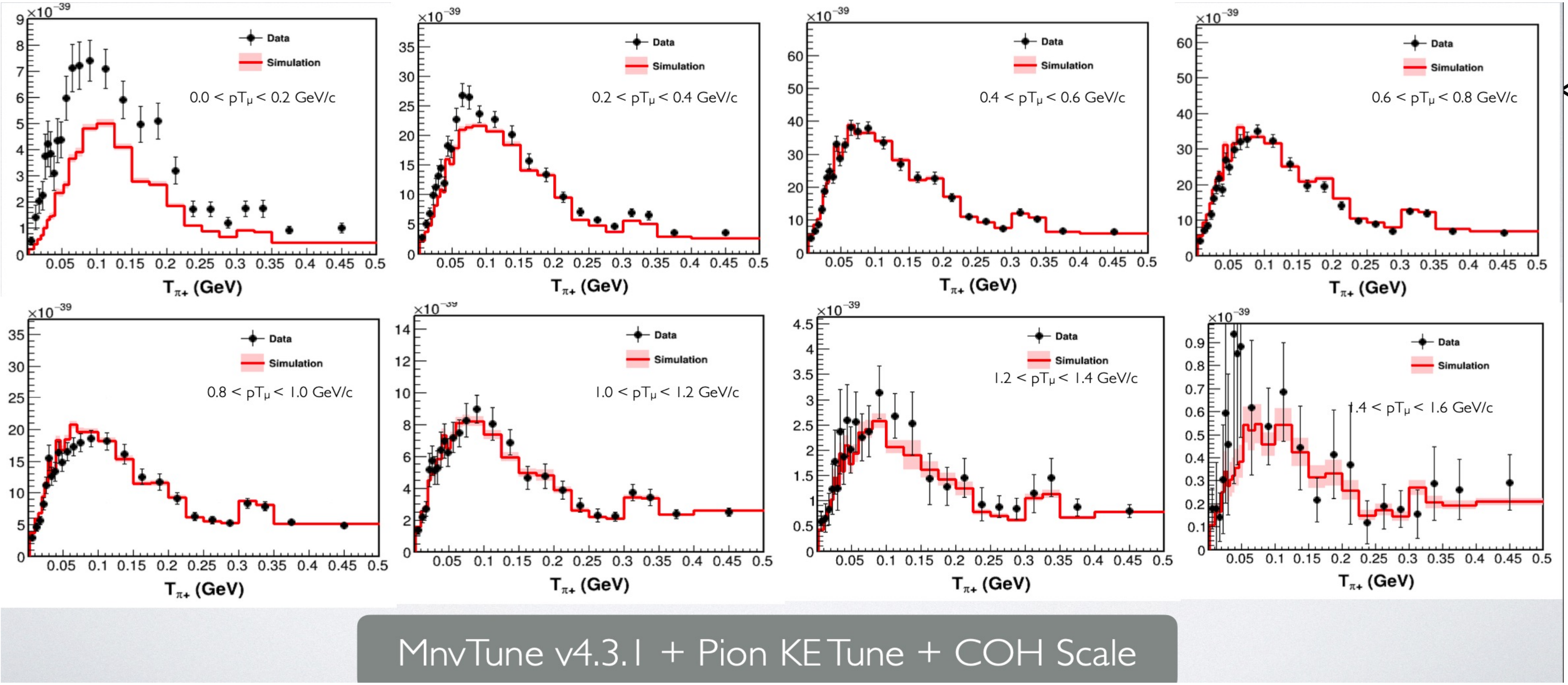


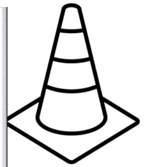
- Second observation… low energy coherent π^+ are underpredicted.
- “Available E-Tpi” means energy in event except π^+ and lepton.



Preview: Trackless (zero-threshold) π^+

- This is ~2/3 of our data. Cross-sections in pion and other "available" energy. (Reference model is tuned already…)





Preview: Trackless (zero-threshold) π^+

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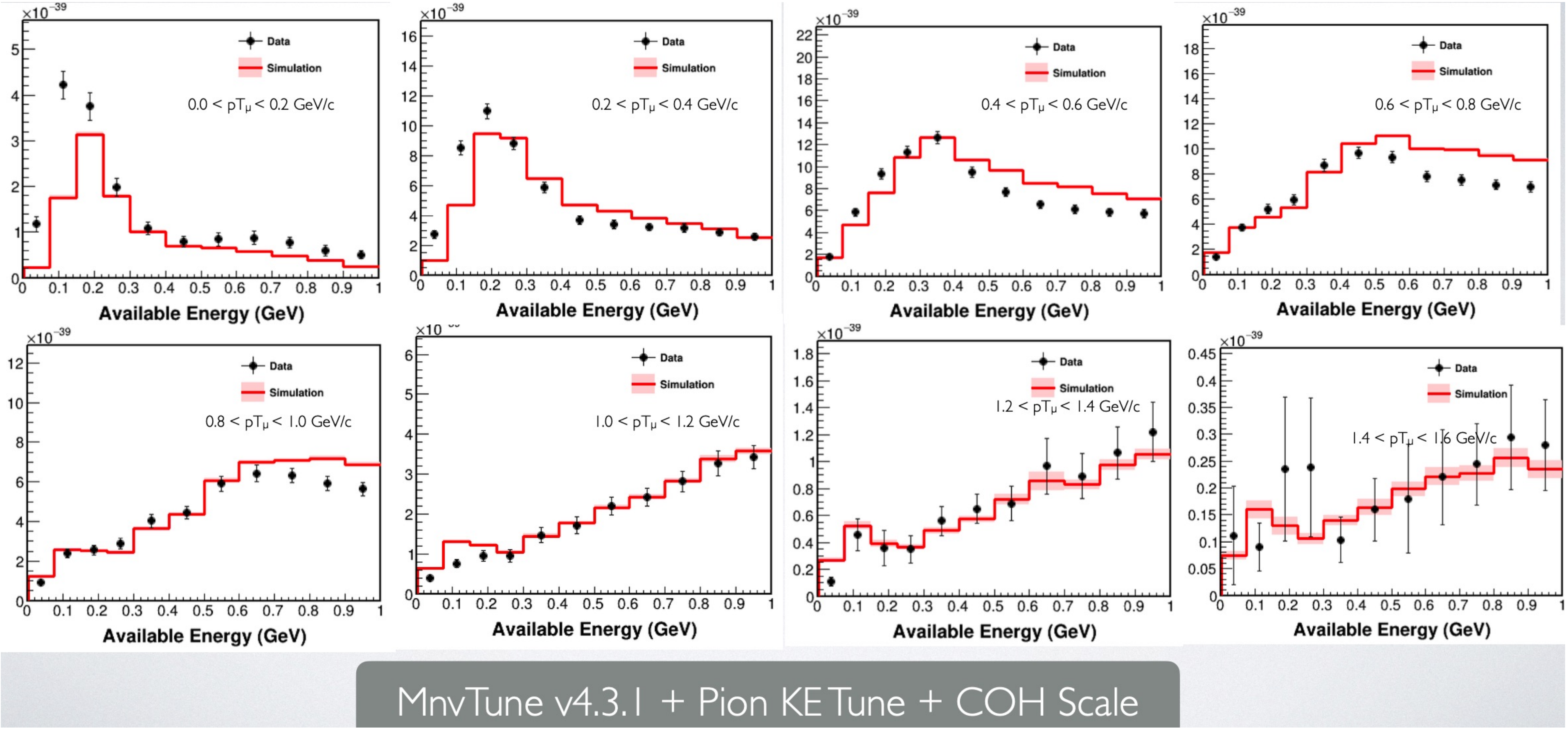
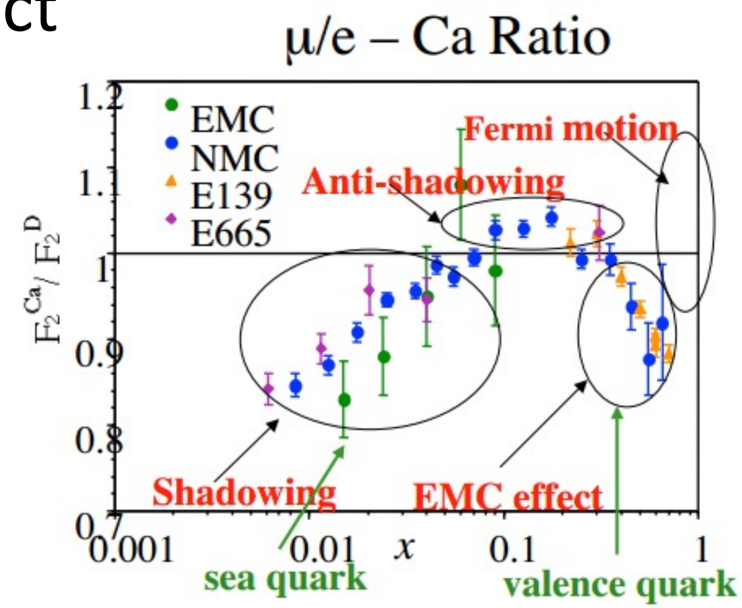


Backup: Other Reactions

- EMC in Neutrinos
- Electron neutrino cross-sections for comparison to muon neutrino

Another Goal: Nuclear Effects in DIS

- In Deep Inelastic kinematic regime, there are a variety of effects observed in charged lepton scattering: shadowing at low x, Fermi Motion at high x and the "EMC effect"
- Viable models exist for the former two, and related phenomena have been observed.
  - Interesting to test with neutrinos as well.
- BUT, the "EMC effect" region has one data set, charged lepton DIS, on a variety of nuclei.
- Difficult to distinguish models: the "Every Model's Cool" problem.
- No neutrino data on these ratios prior to MINERvA.



CERN COURIER

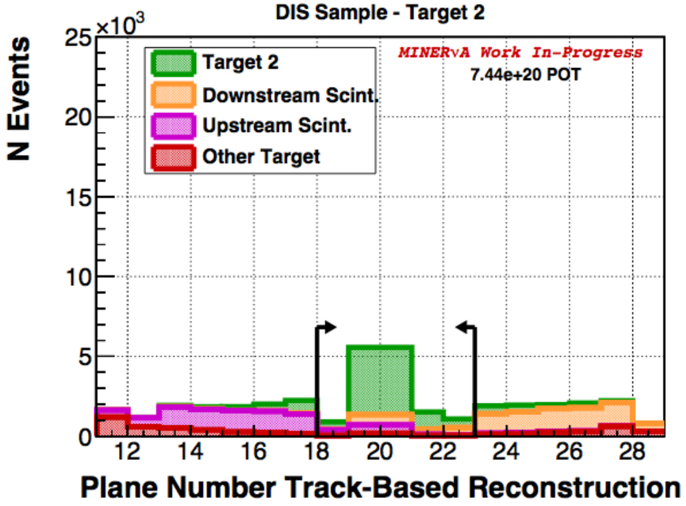
Apr 26, 2013

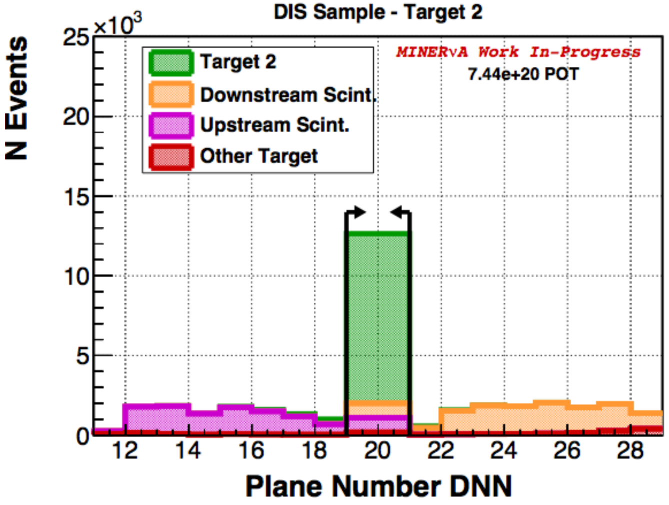
The EMC effect still puzzles after 30 years

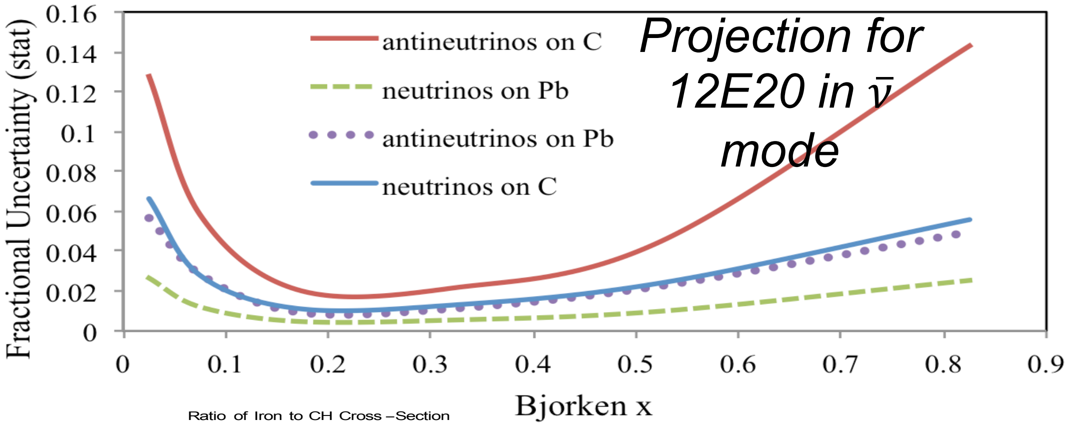
Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

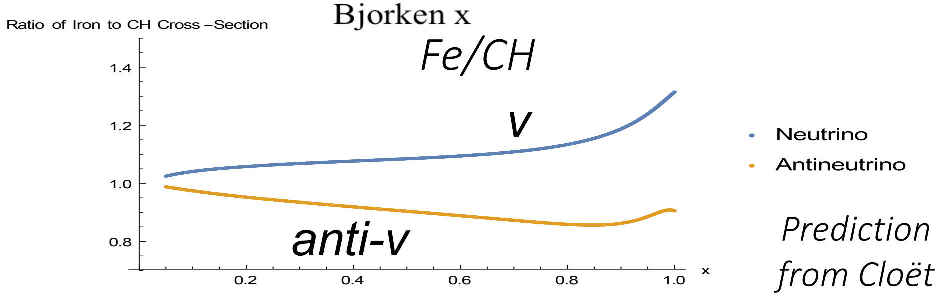
6 GeV DIS Ratios in Targets

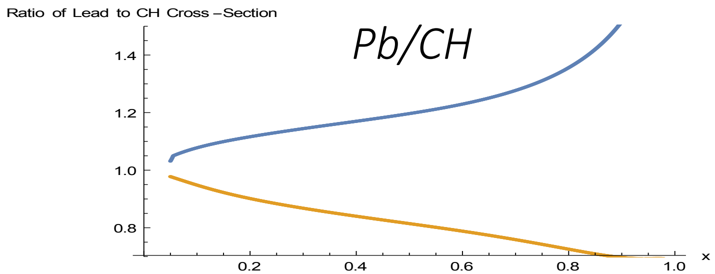
- Models for EMC effect typically predict different effects in neutrino and antineutrino scattering
- Completion of MINERvA's run allows "ν-EMC" ratio measurement vs. quark momentum fraction at ~5% precision for Fe and Pb









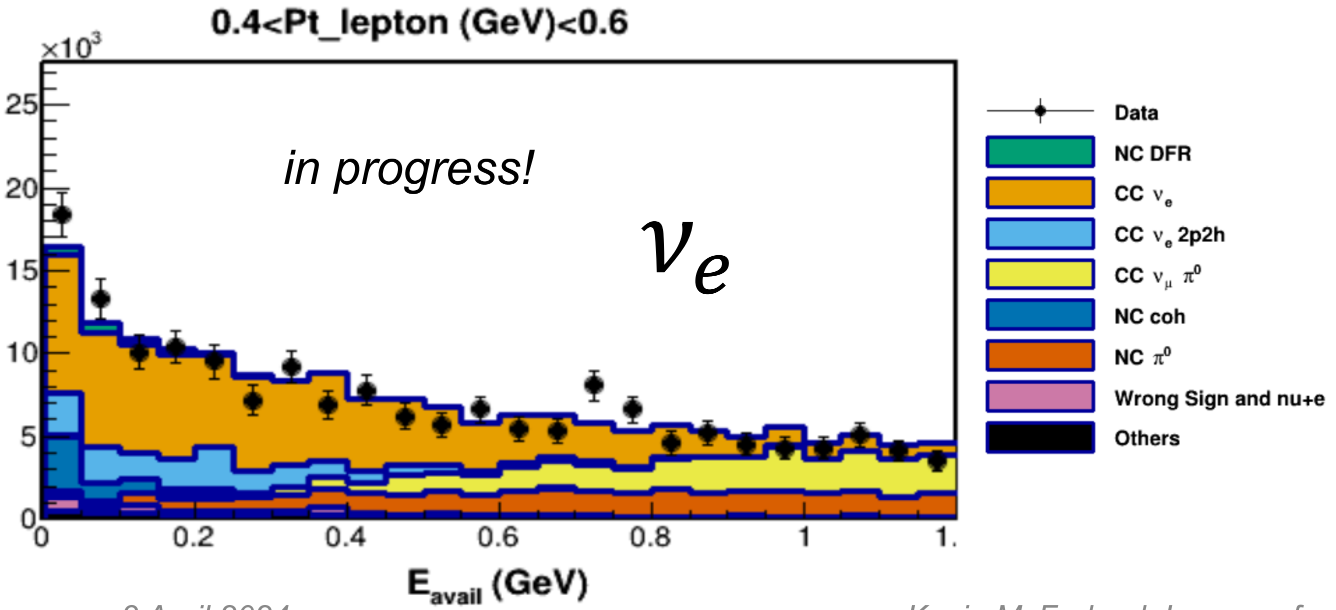


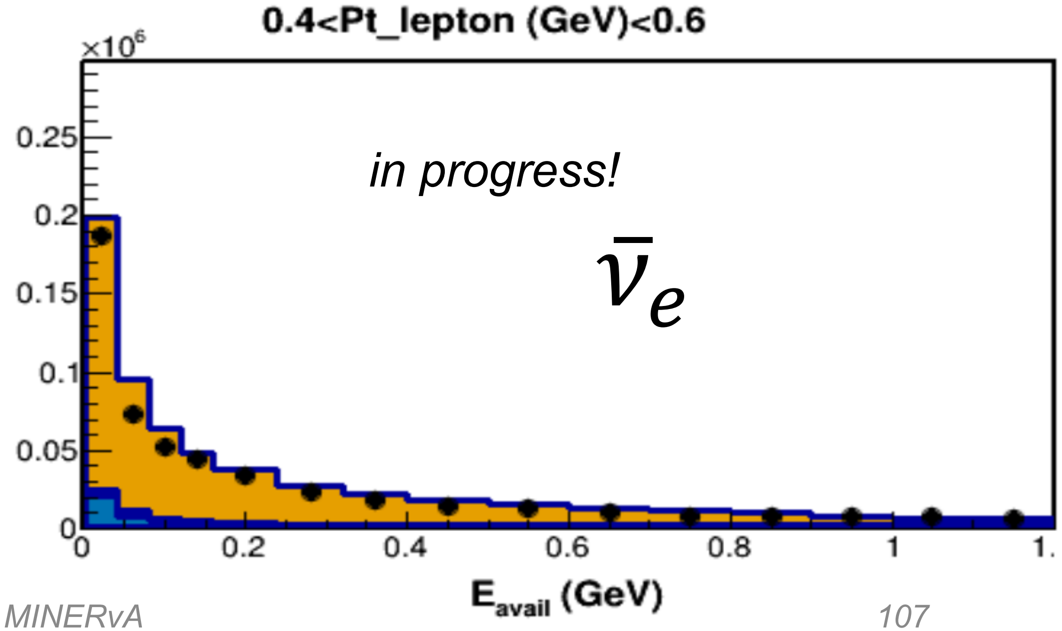
Prediction from Cloët model described in PRL 109, 182301

- *Along the way, we've developed a deep learning method for reconstructing location of neutrino interaction.*
- *Uses "domain adversarial" networks that learn to ignore model dependent features. (See JINST 13 (2018) 11, P11020)*

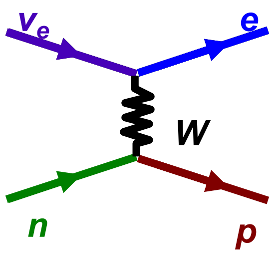
Electron Neutrino Interactions

- Eneutrinos are only 1% of our beam. But we have a lot of neutrinos!
- Unfortunately, there is nothing here that I can show (yet) you at cross-section level. ~January 2024. But I can tease the sizes of the samples.
- Output will be be an E_{avail} differential cross section in lepton p_T (or converted to three momentum transfer with some model dependence. And a direct comparison to muon neutrinos and anti-neutrinos.



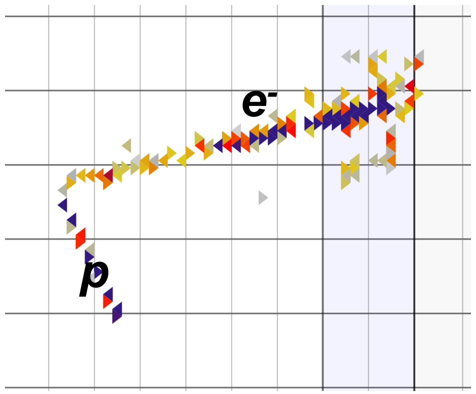


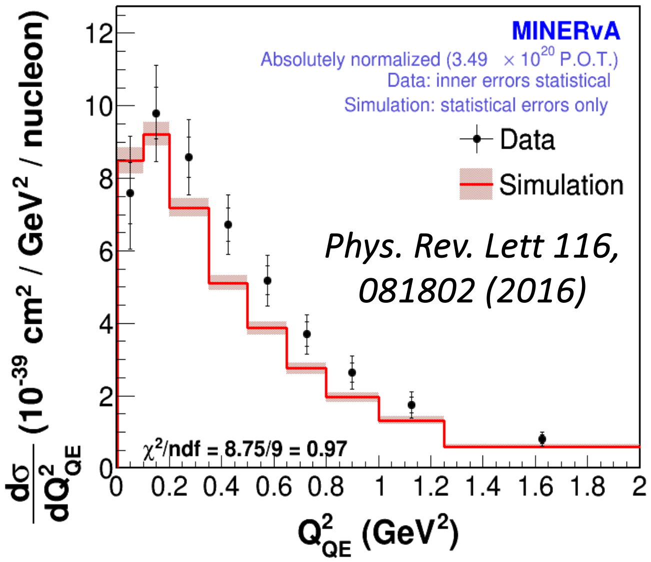
3 GeV ν_e CCQE

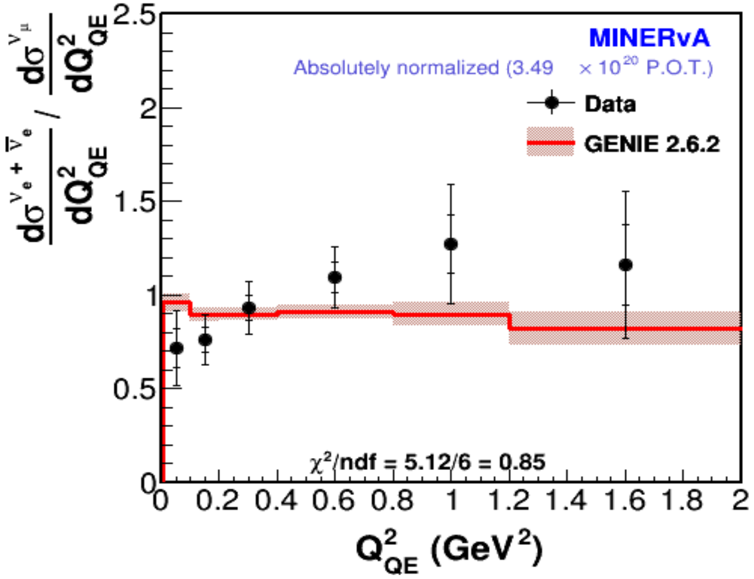


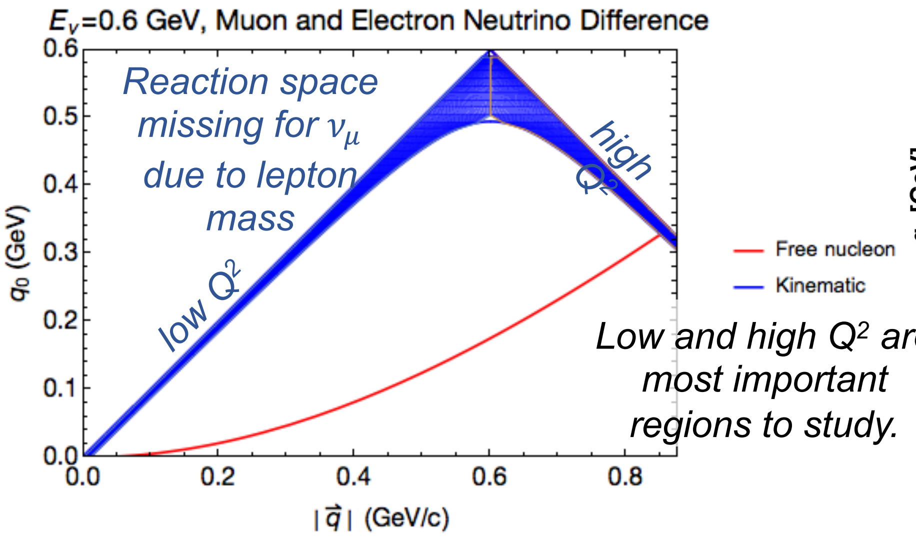
We all assume fundamental coupling is universal, but know nuclear effects are not!

- *ν_e CCQE is oscillation signal for T2K and MiniBooNE, but there is almost no data.*

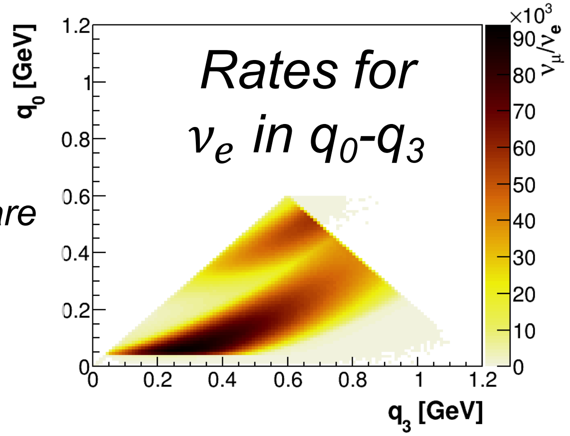








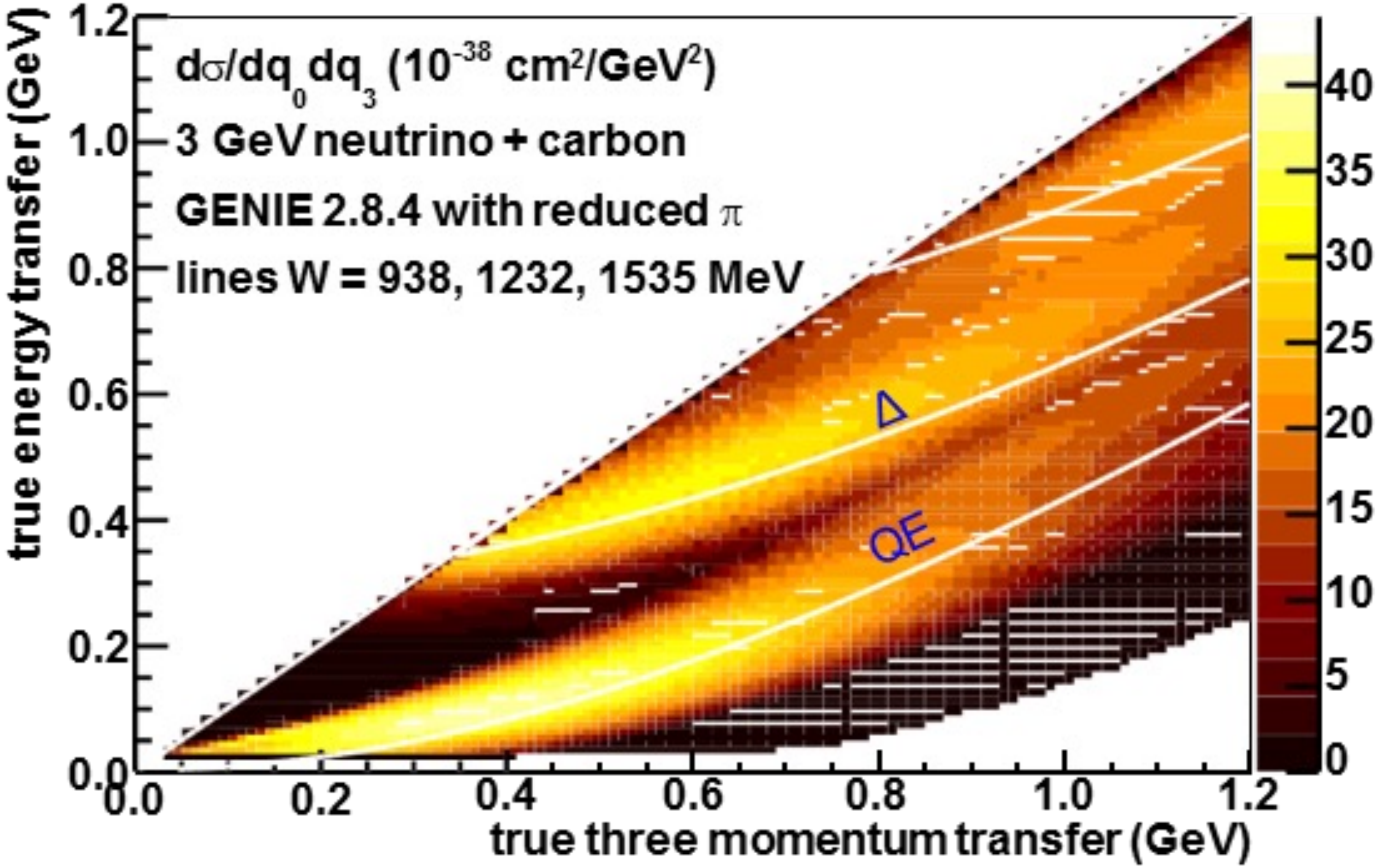
Low and high Q^2 are most important regions to study.



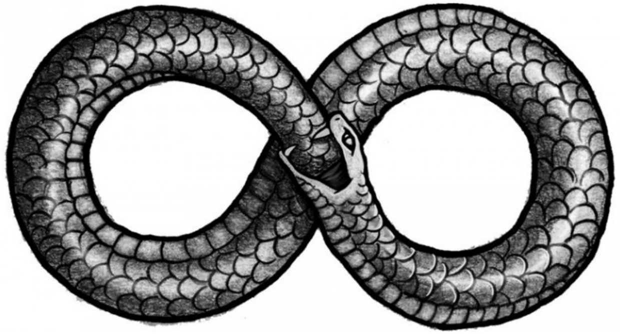
- *This result probes low Q^2.*
- *Measured cross sections and ν_e/ν_μ ratio consistent with GENIE model @ 1σ (~10-20% uncertainties)*
  - *Need better for DUNE.*

Backup: “MINERvA” 2p2h Tune

If we had a monochromatic neutrino beam, like electron scattering…



To do this in neutrino scattering, we have to use the final state observed energy since we don't know incoming neutrino energy.



Since we don't know neutrino energy…

- Must determine neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.

- *MINERvA uses calorimetry for all but the final state lepton*
  - *Don't measure energy transfer, q_0, but a related quantity dependent on the details of the final state, "available energy"*

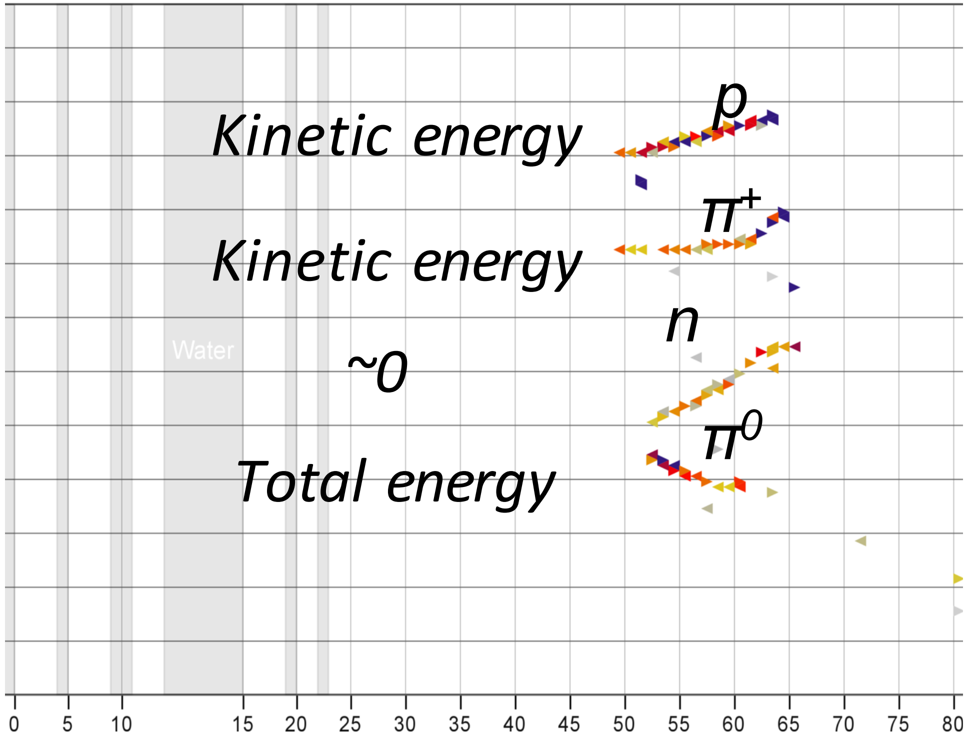
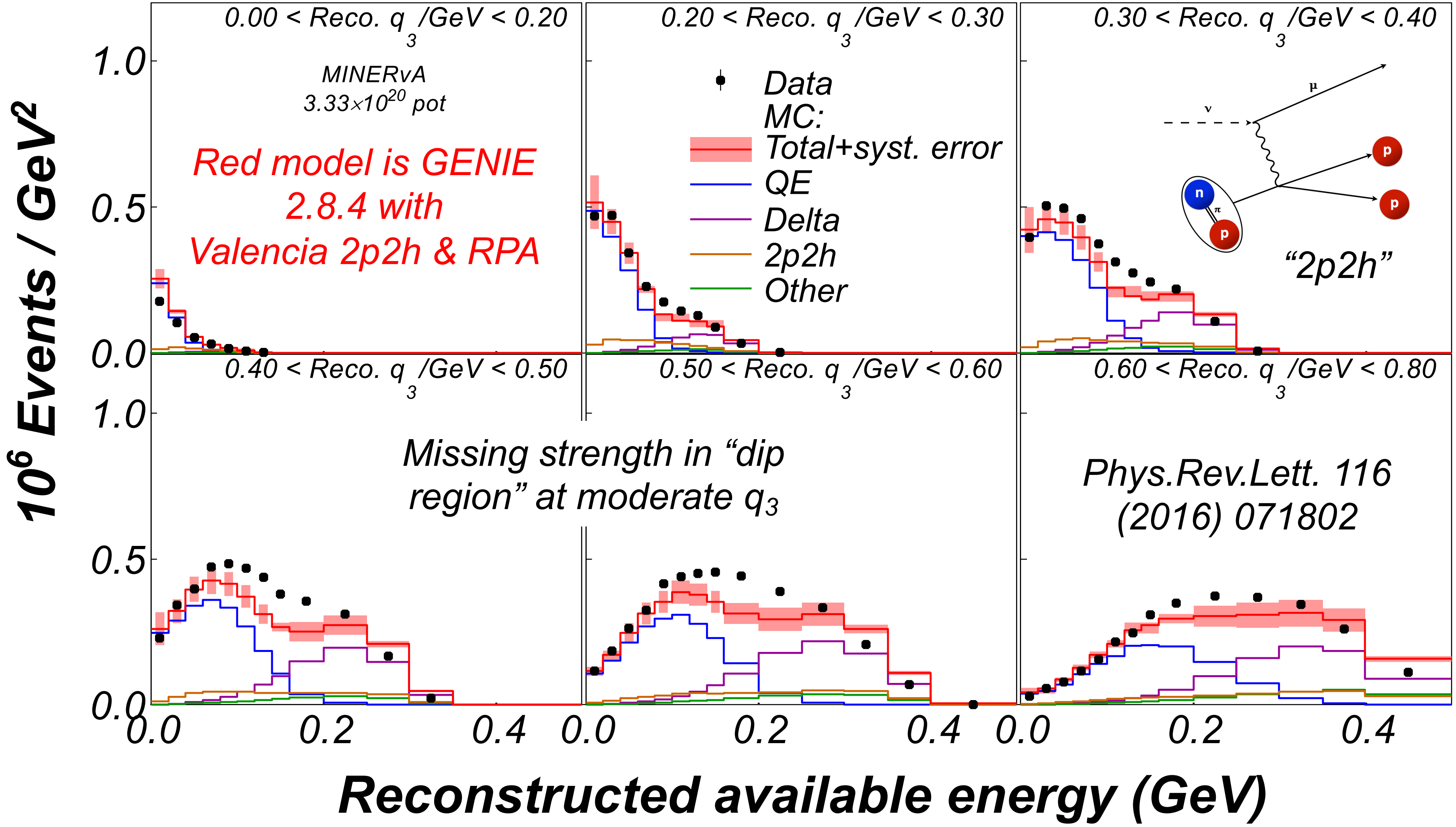


Figure courtesy P. Rodrigues

$$E_{avail} \equiv (\text{Proton and } \pi^{\pm}\ KE) + (E \text{ of other particles except neutrons})$$

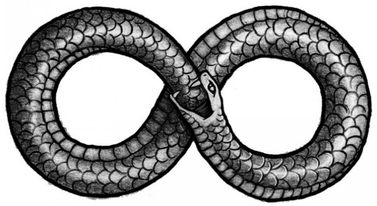
Missing moderate $|q_3|$ "Dip Region"



- Nieves 2p2h & RPA model added to GENIE prediction used by MINERvA.
- But it doesn't provide enough strength at moderate $|q_3|$.

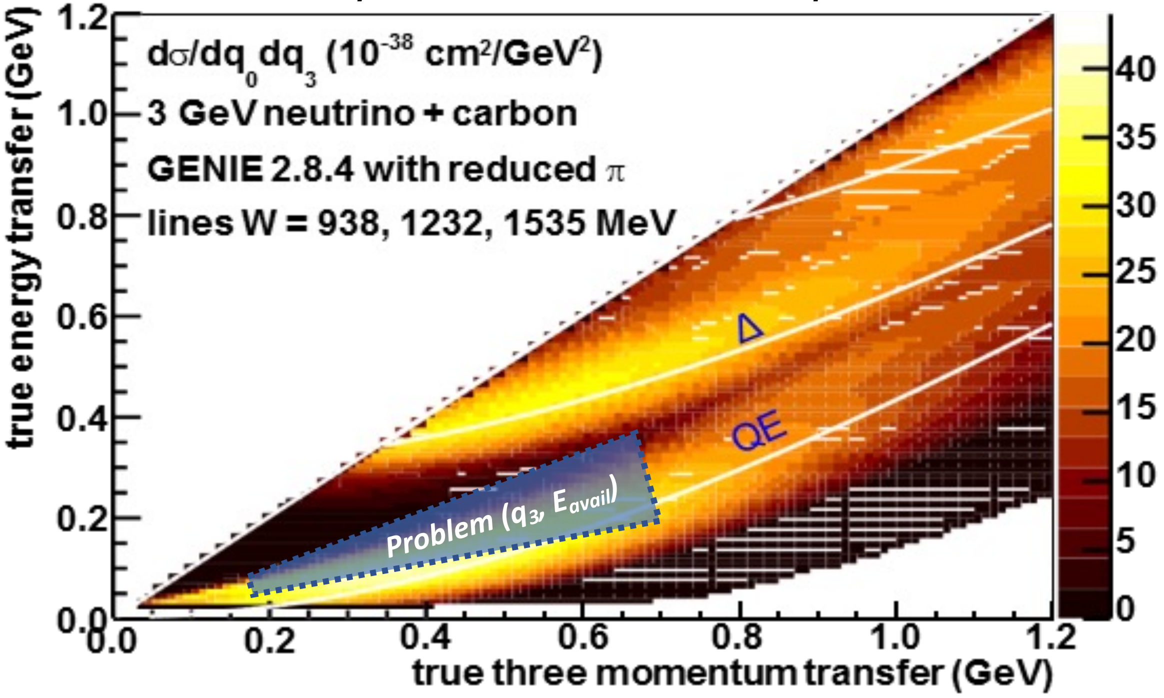
What can we do to fix it?

- The problem of course is that we don't cleanly separate the processes, and the process choice affects the final state measurement of the final state.



- But in this kinematic region, there are only so many possible contributing processes.

Quasielastic (single nucleon knockout) and 2p2h (multi-nucleon knockout) are the dominant processes where the problem lies.

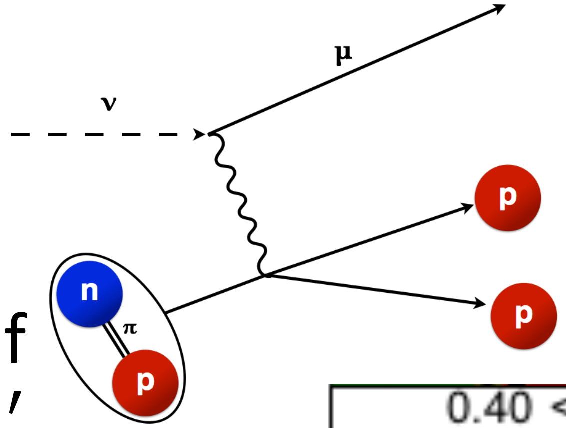


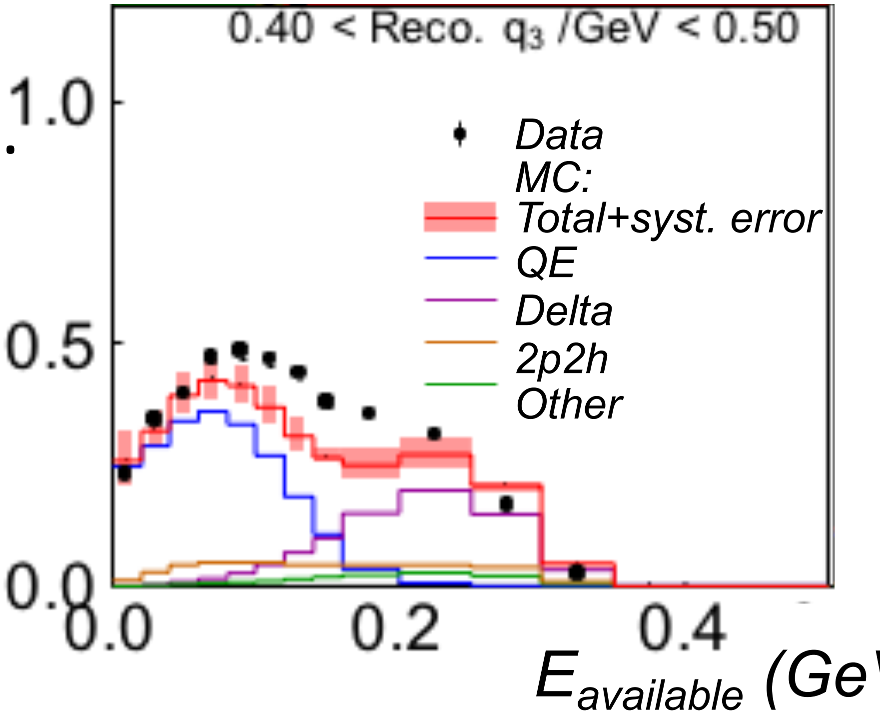
$$E_{\text{avail}} \approx q_0 - \Sigma T_n - \Sigma m_{\pi^\pm}.$$

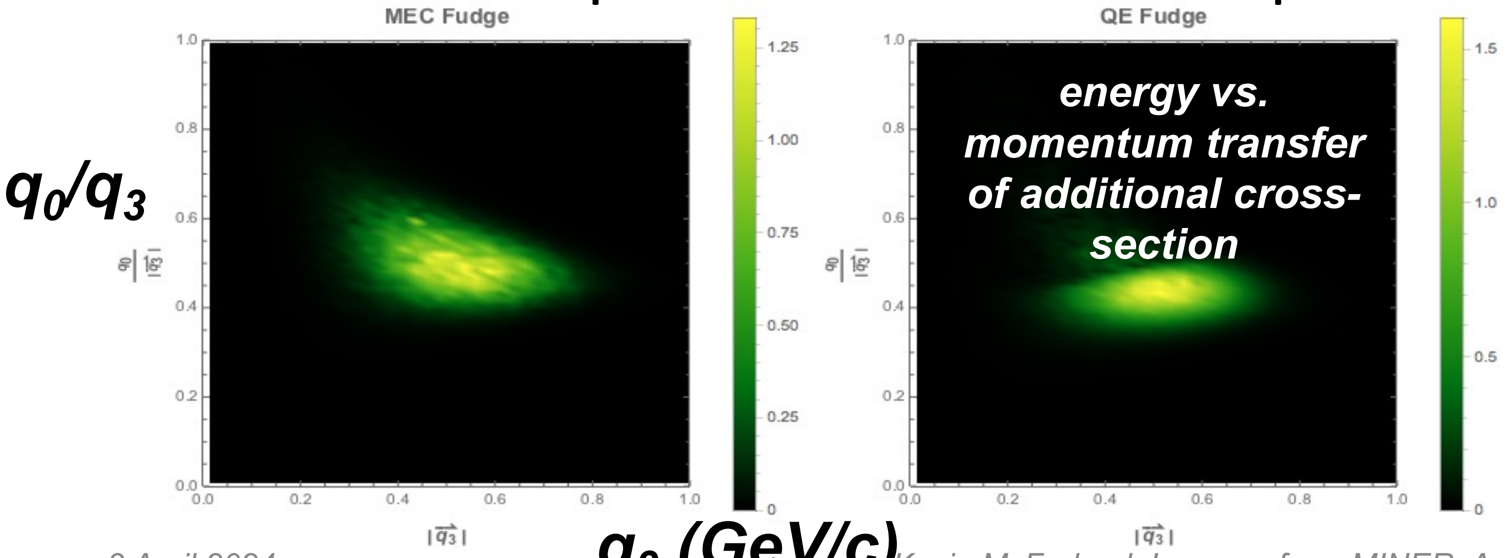
need ~200 MeV to migrate from Δ

What to Fix?

- MINERvA's low recoil data identifies missing strength, but it doesn't identify if $\nu_\mu A(n) \to \mu^- p A'$ or $\nu_\mu A(nn) \to \mu^- pn A'$ or $\nu_\mu A(np) \to \mu^- pp A'$ is the most likely source.
  - Different choices mean different $E_{\text{avail}}(q_0)$.
- Default tune augments ratio of 2p2h nn/np initial state as per Nieves' model of 2p2h.







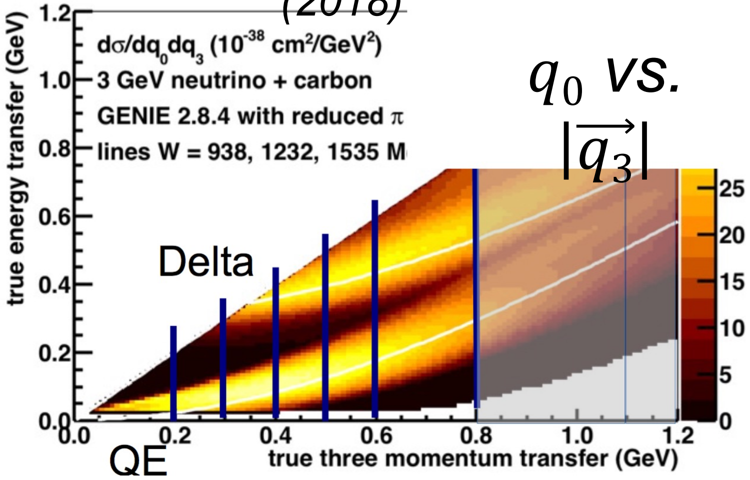
Does this lead to a descriptive Quasielastic-like (CC0π) Model?

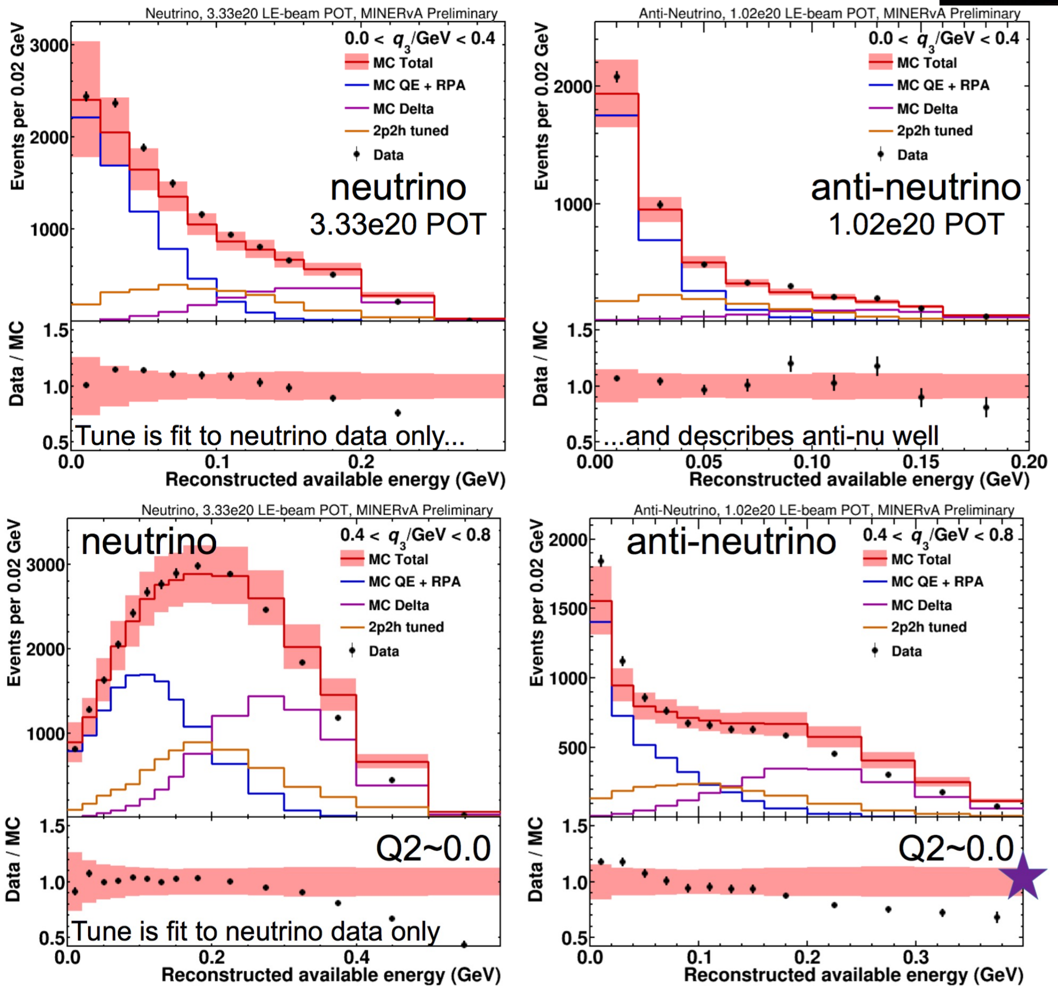
- Data that confirms or refutes the model
- Implications

MINERvA ν_μ and anti-ν_μ "low q"

- Low recoil "Inclusive" ν_μ cc interactions in antineutrinos

Phys. Rev. Lett. 116, 071802 (2016) and Phys. Rev. Lett. 120, 221805 (2018)



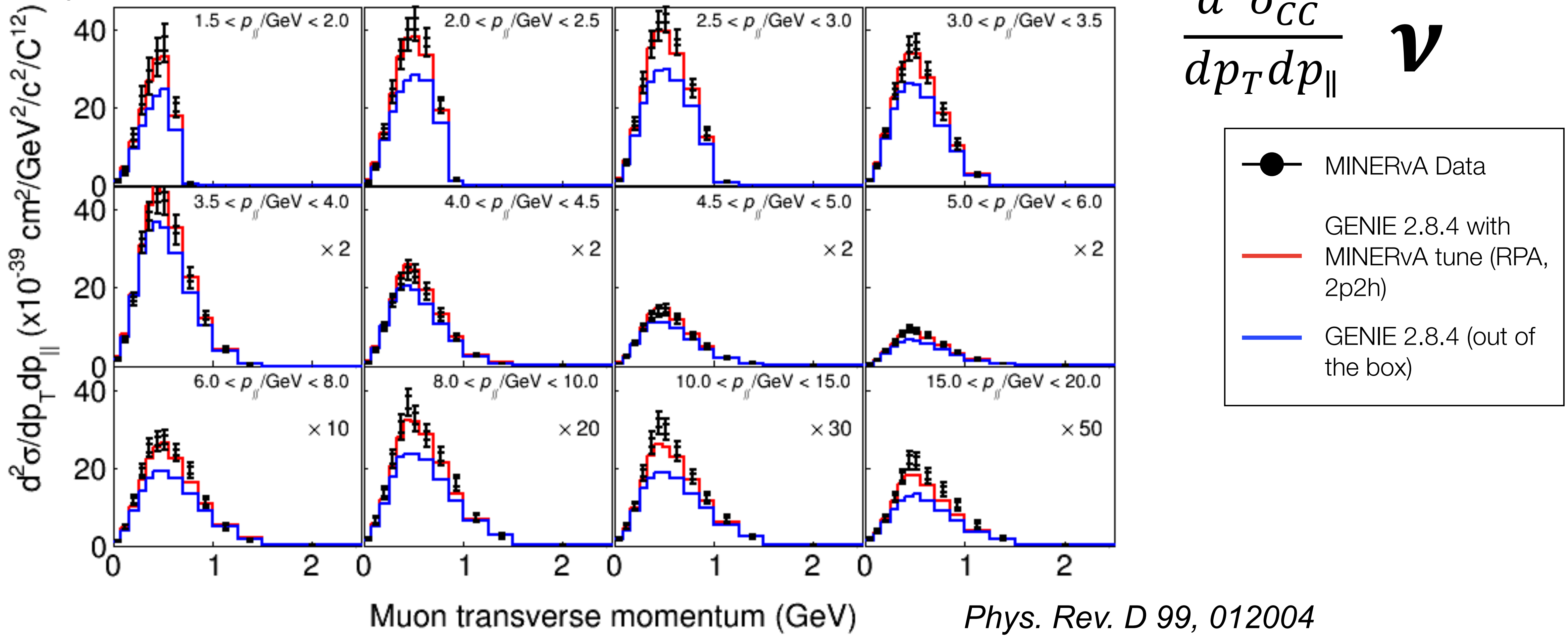


- *Tune model (extra 1p1h or 2p2h) to fill in dip region between QE & Δ.*
- *This tune from neutrino data also agrees with antineutrino data!*
- *Remaining problem is low Q^2 region, consistent with pion production.*

MINERvA $\boldsymbol{\nu}$ pionless events (CC0$\boldsymbol{\pi}$)

- What if we take tune to inclusive data and feed it back to predict muon distributions in an exclusive channel?

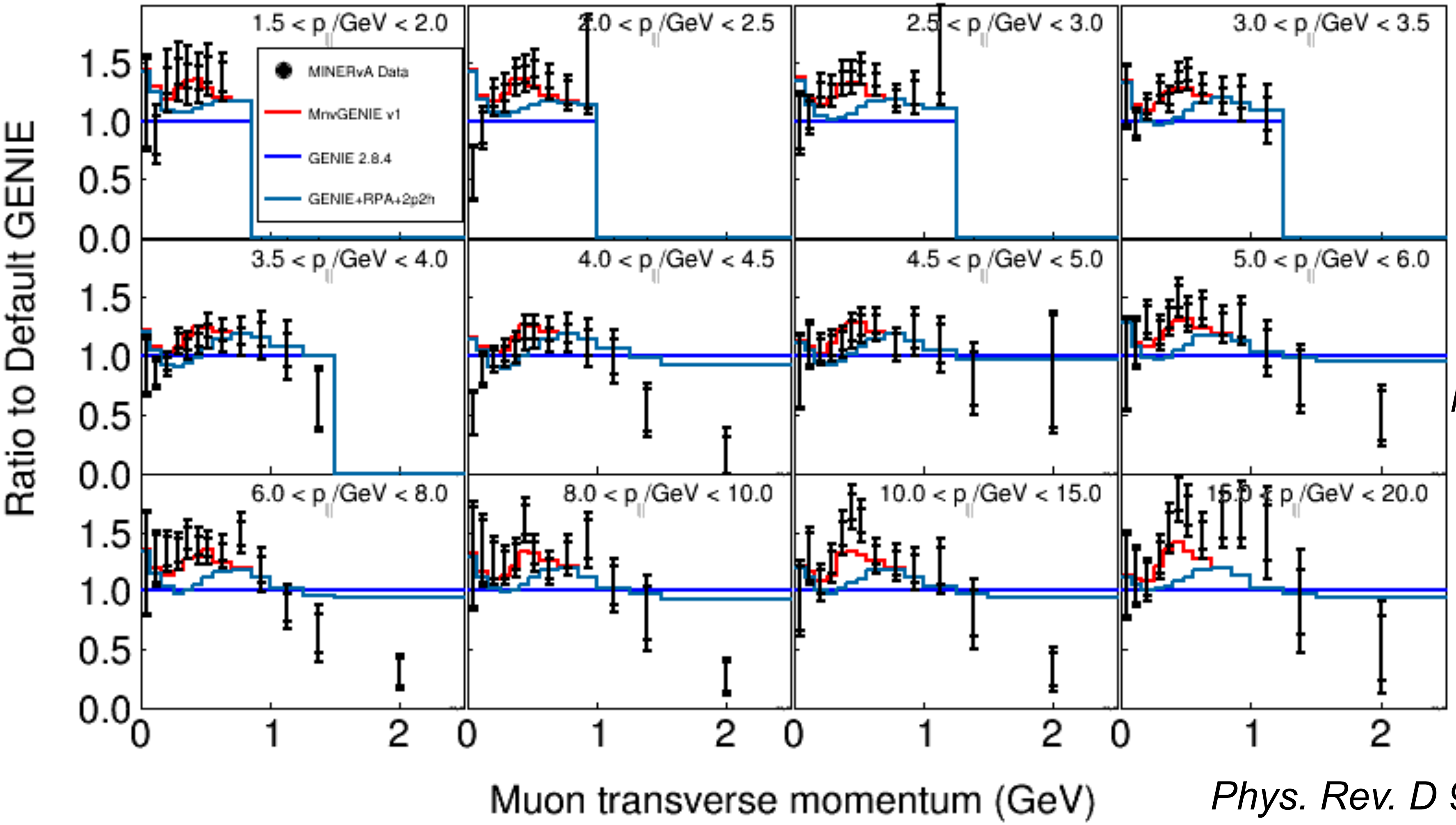
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_{\|}} \quad \boldsymbol{\nu}$$



Phys. Rev. D 99, 012004 (2019)

MINERvA $\boldsymbol{\nu}$ pionless events (CC0$\boldsymbol{\pi}$)

- Tuned vs untuned in an exclusive channel



$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_\parallel} \quad \boldsymbol{\nu}$$

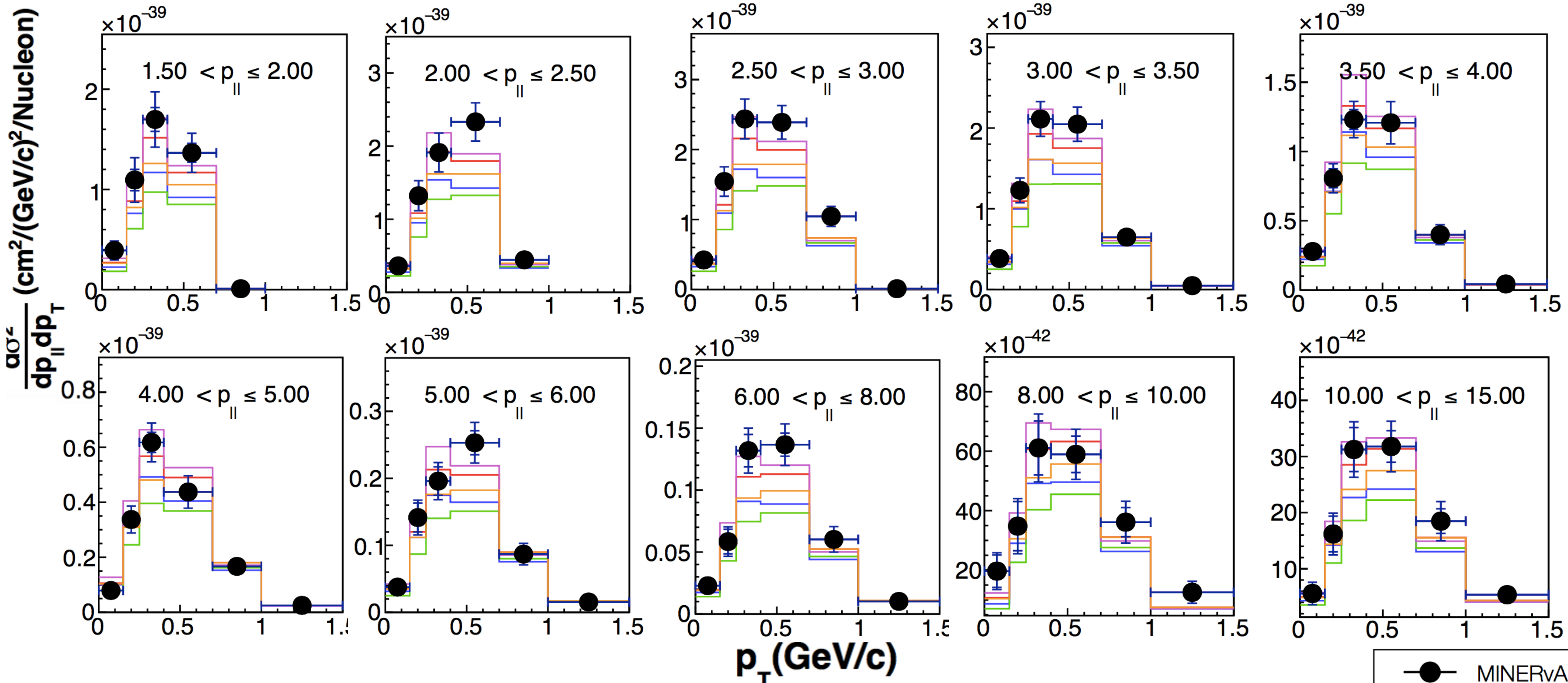
- MINERvA Data
- MnvGENIE v1
- GENIE 2.8.4
- GENIE+RPA+2p2h

MINERvA's tune

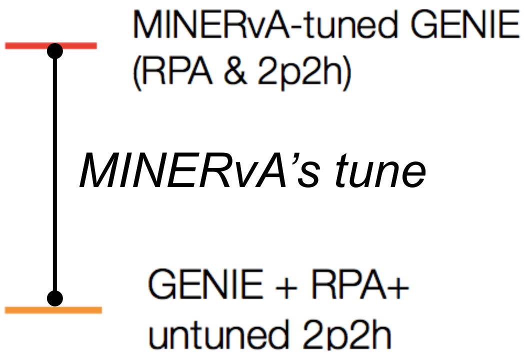
Phys. Rev. D 99, 012004 (2019)

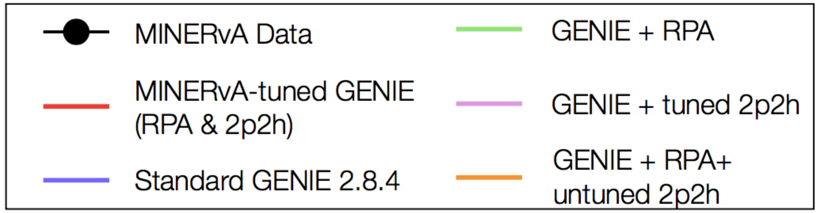
MINERvA $\bar{\nu}$ pionless events (CC0π)

- What if we take tune to inclusive data and feed it back to predict muon distributions in a different exclusive channel?



$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T\,dp_{\parallel}} \qquad \bar{\nu}$$

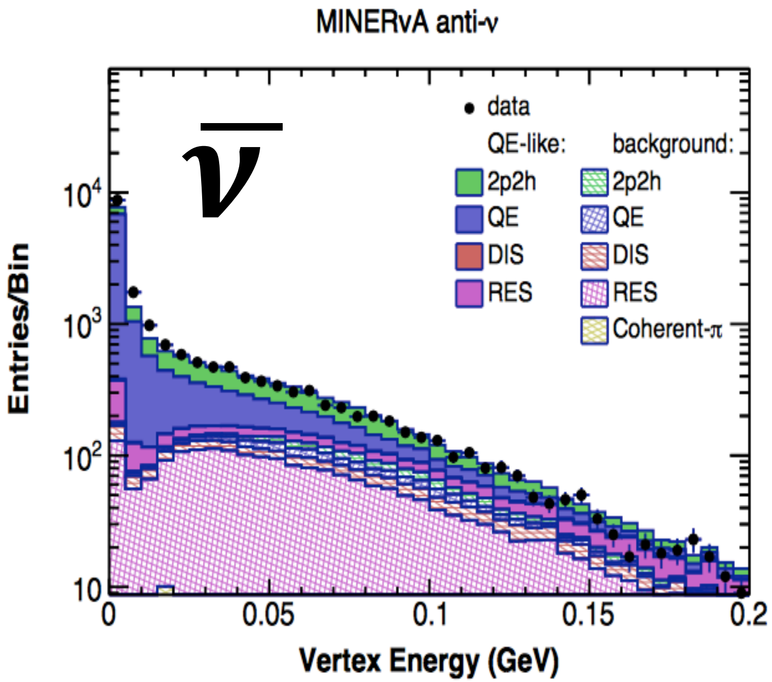


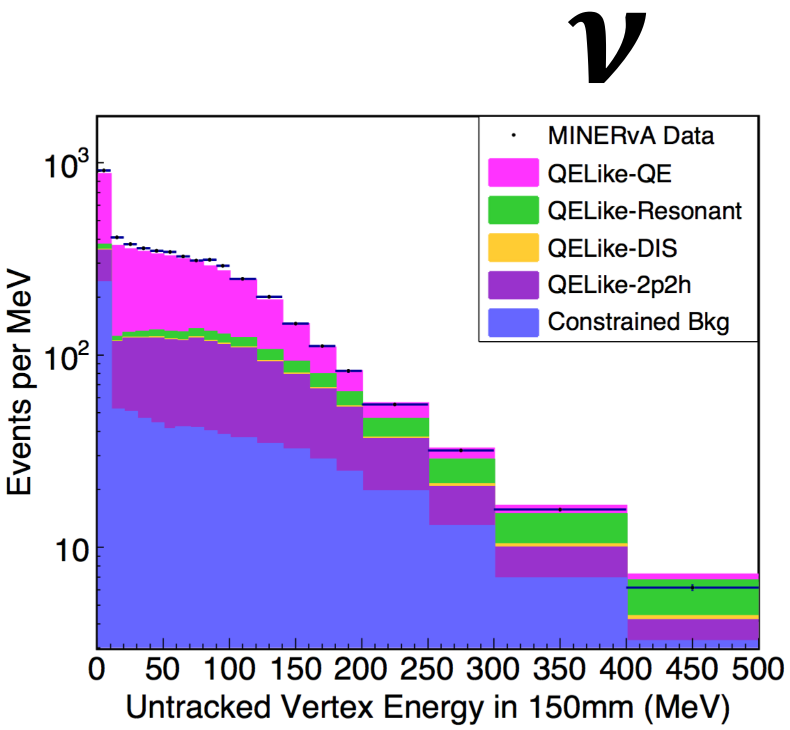


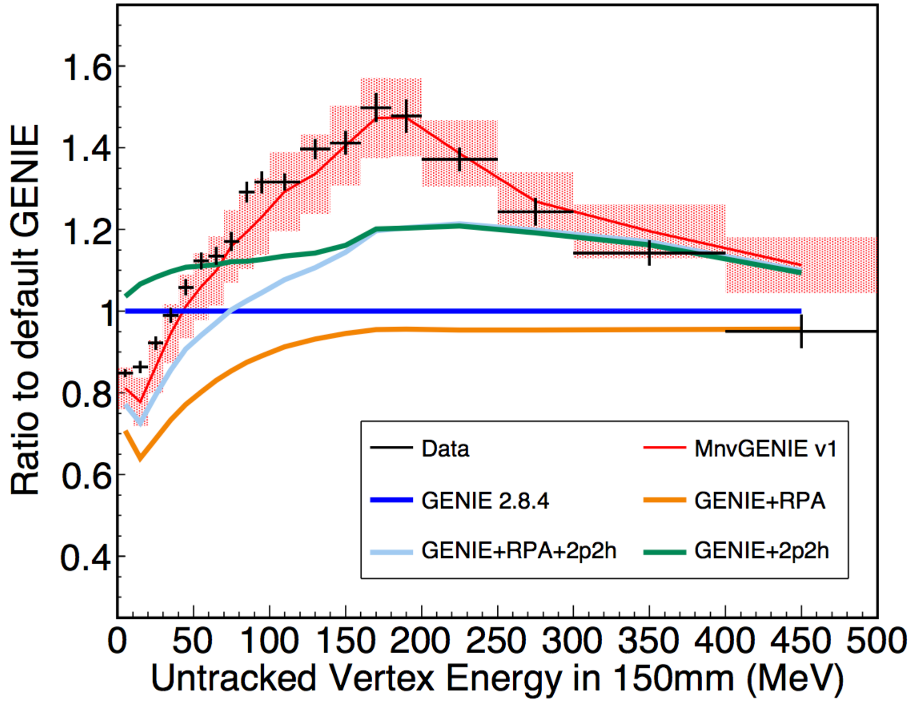
Phys.Rev. D97 052002 (2018)

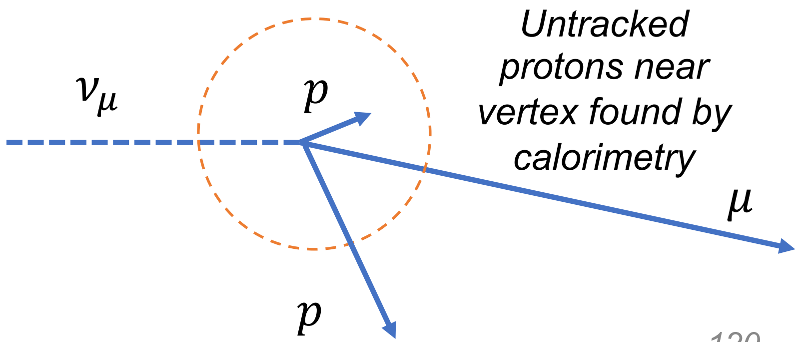
Low energy protons in CC0$\boldsymbol{\pi}$ events

- Does this tune get details right, like energy from protons below tracking threshold ("vertex energy")?





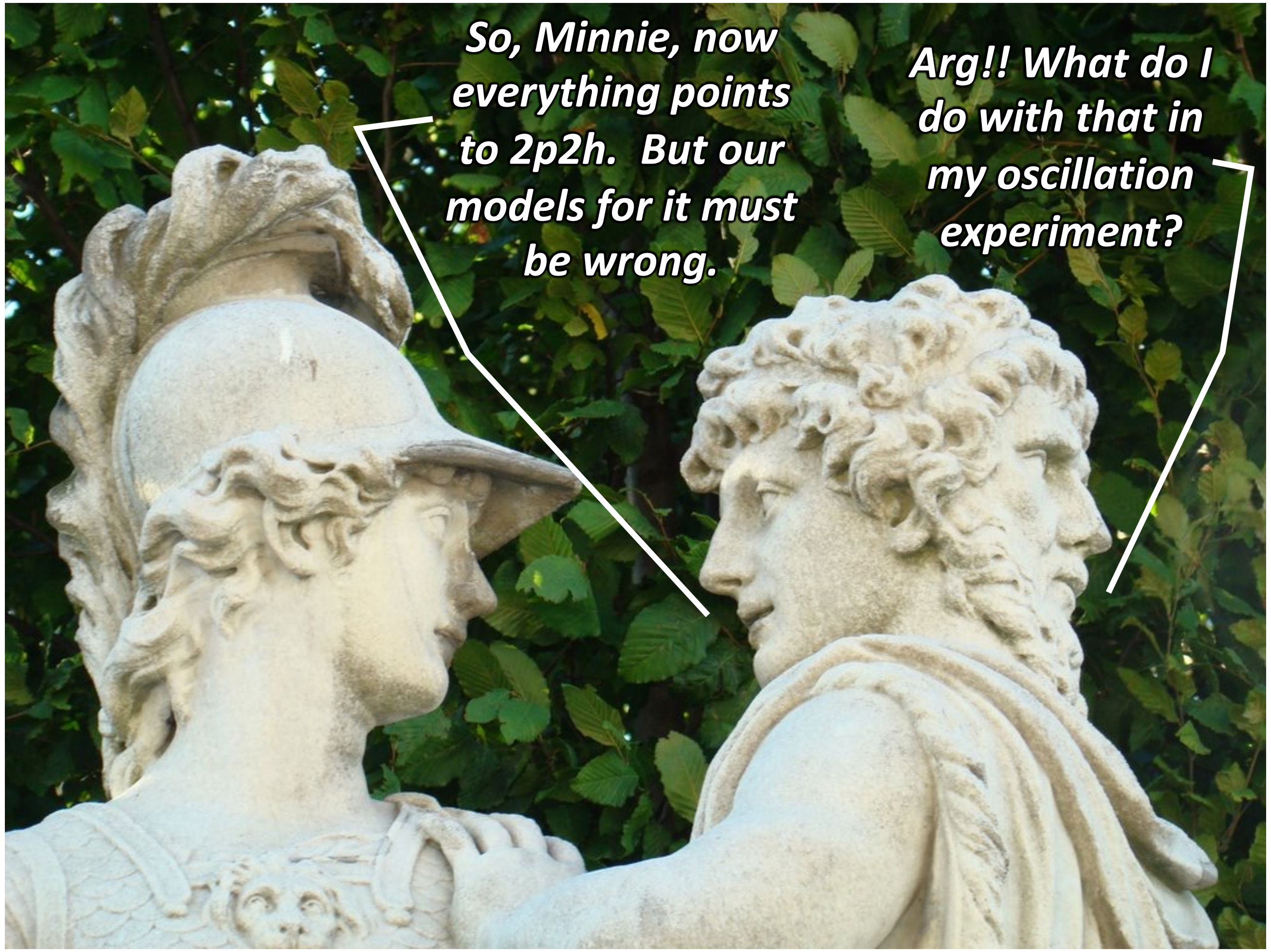




Phys.Rev. D97 (2018), 052002 and Phys. Rev. D 99, 012004 (2019)

Backup: Almost Elastic Tune and T2K Energy Dependence

CC0$\boldsymbol{\pi}$ Model Tune

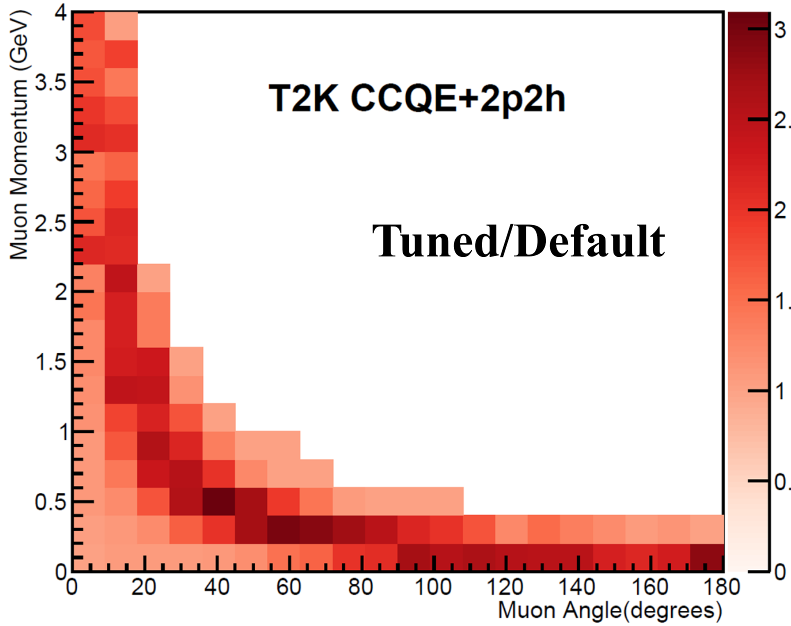


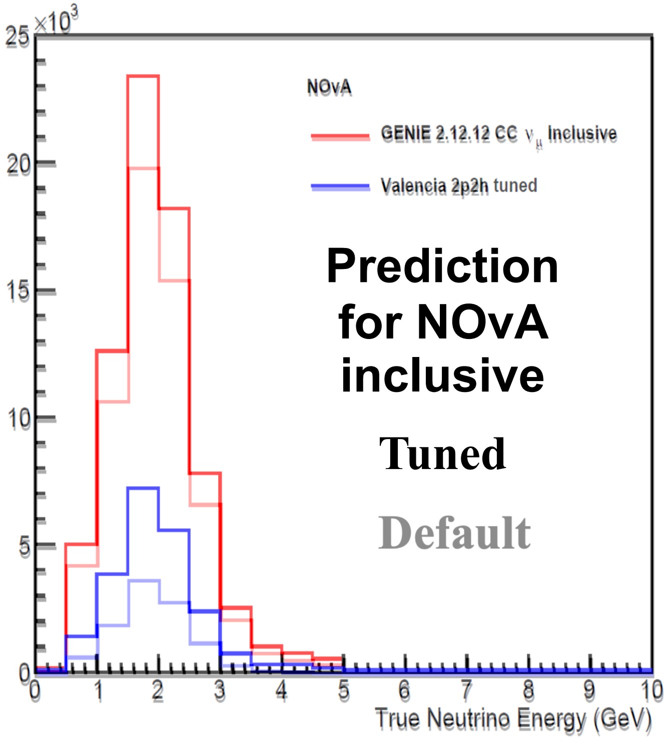
- For these "least inelastic" events, MINERvA has found a tuned model which explains:
  - Lepton energy-momentum distributions
  - Details of nucleon recoil
- Not theoretically motivated (=magic?), but identifies particular energy-momentum transfer.

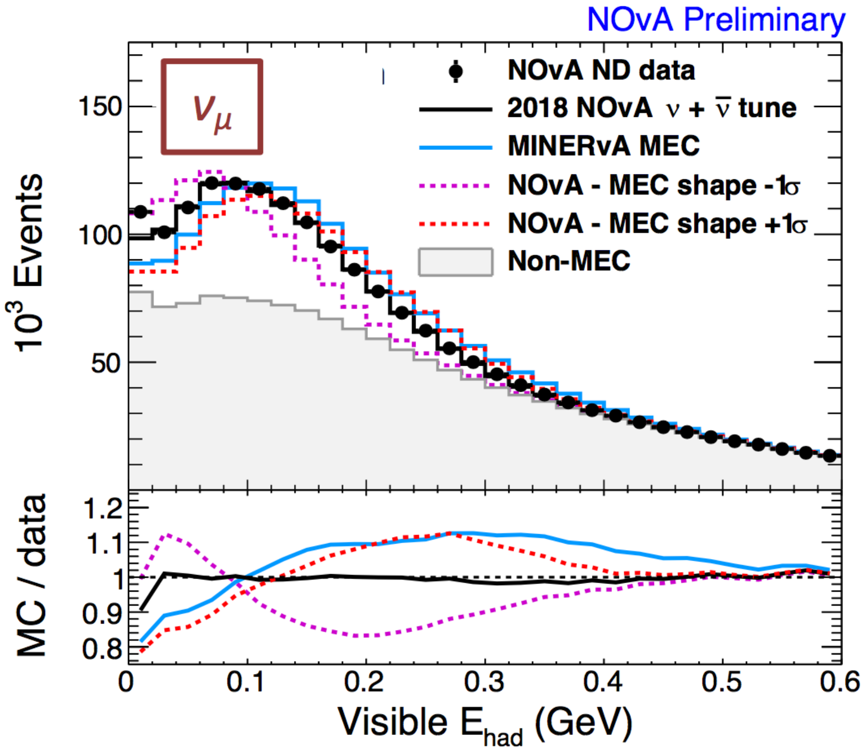
- NOvA uses this technique on its own near detector data for its oscillation analysis to tune 2p2h. ✔
- Can MINERvA's tune be applied to T2K, SBN/MicroBooNE energies?

Implications for NOvA and T2K

Event rate ratio: Tuned/Default





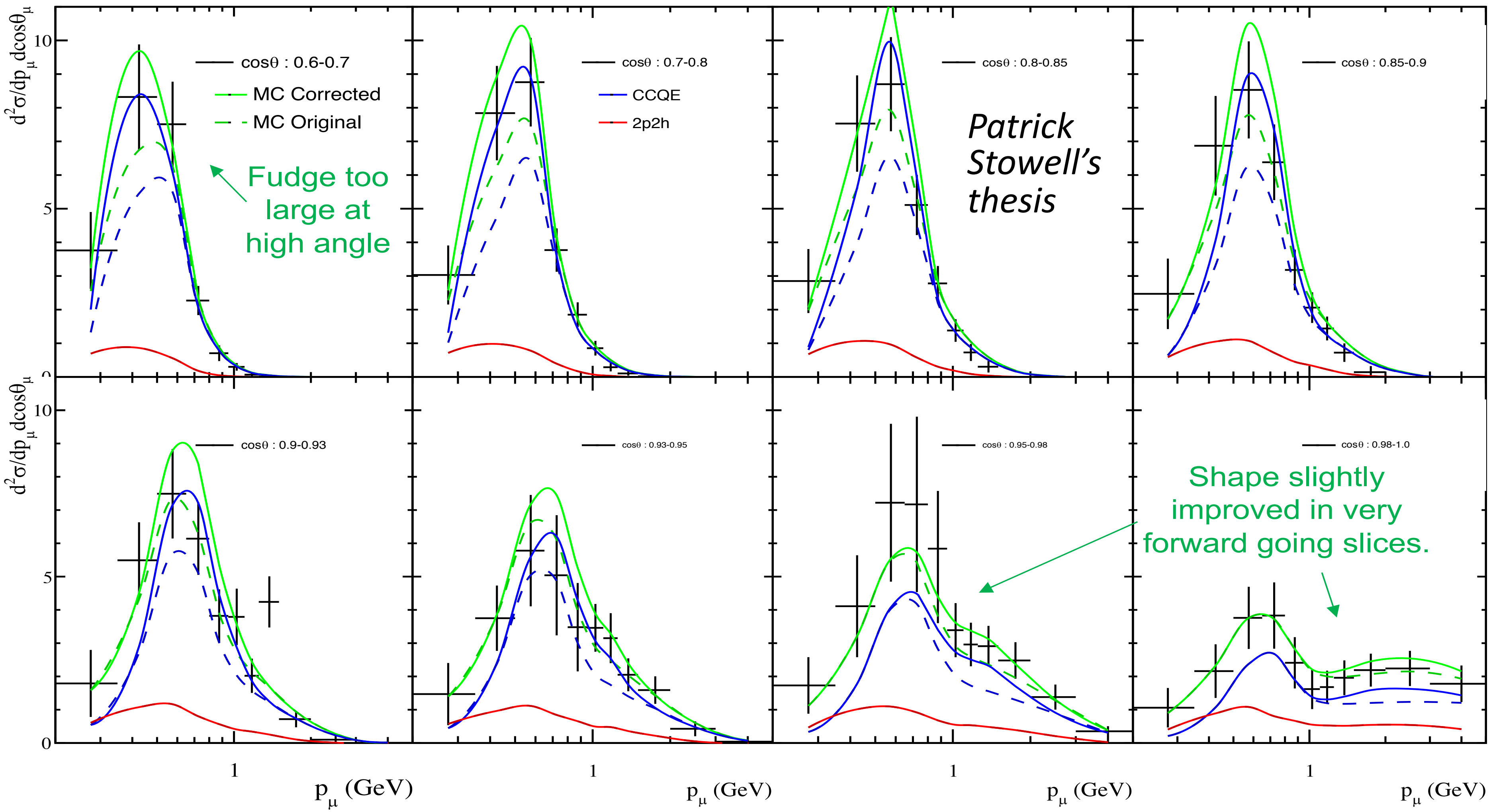


- Beam energy ~ 0.6 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible impact in CCQE-like full phase space at T2K energy, especially at high angle

Alex Himmel, JETP Seminar, June 2018

- Beam energy ~ 2 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible change in inclusive energy spectrum at NOvA energy

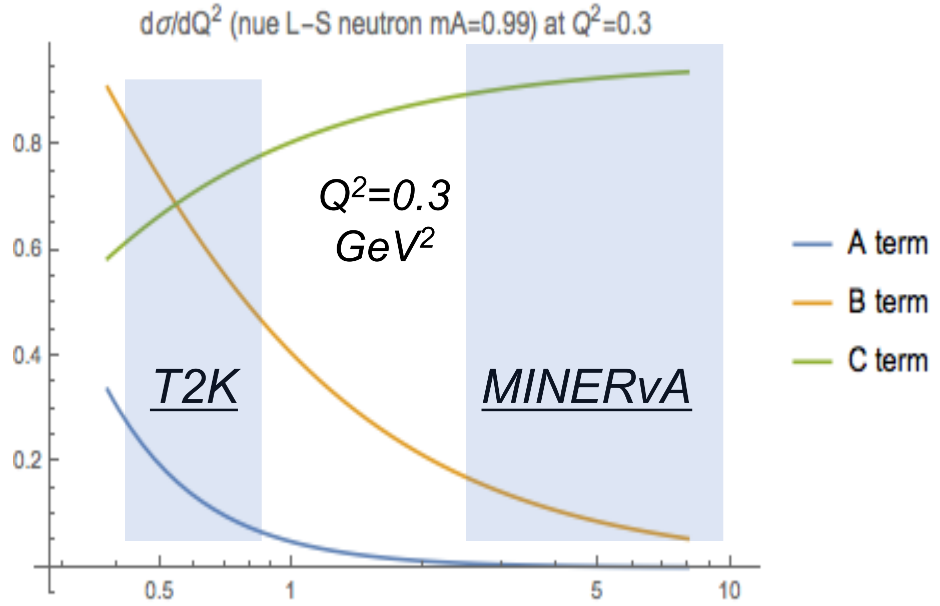
Apply to T2K CC0π… too much tune!



MINERvA tune, compared to data from Phys. Rev. D93, 112012 (2016)

Could the "MINERvA tune" be Energy Dependent?

- At MINERvA energies, should we expect any? Not much.



E_ν (GeV)

CCE on free neutrons

- *What are the A, B, C terms?*

- It turns out that there is a general form for energy dependence in exclusive and inclusive reactions on nucleons:

$$E_\nu^2 \frac{d\sigma}{dQ^2 d\nu} = \breve{A} + \breve{B}E_\nu + \breve{C}E_\nu^2$$

  - *This holds for QE, 2p2h, etc.*

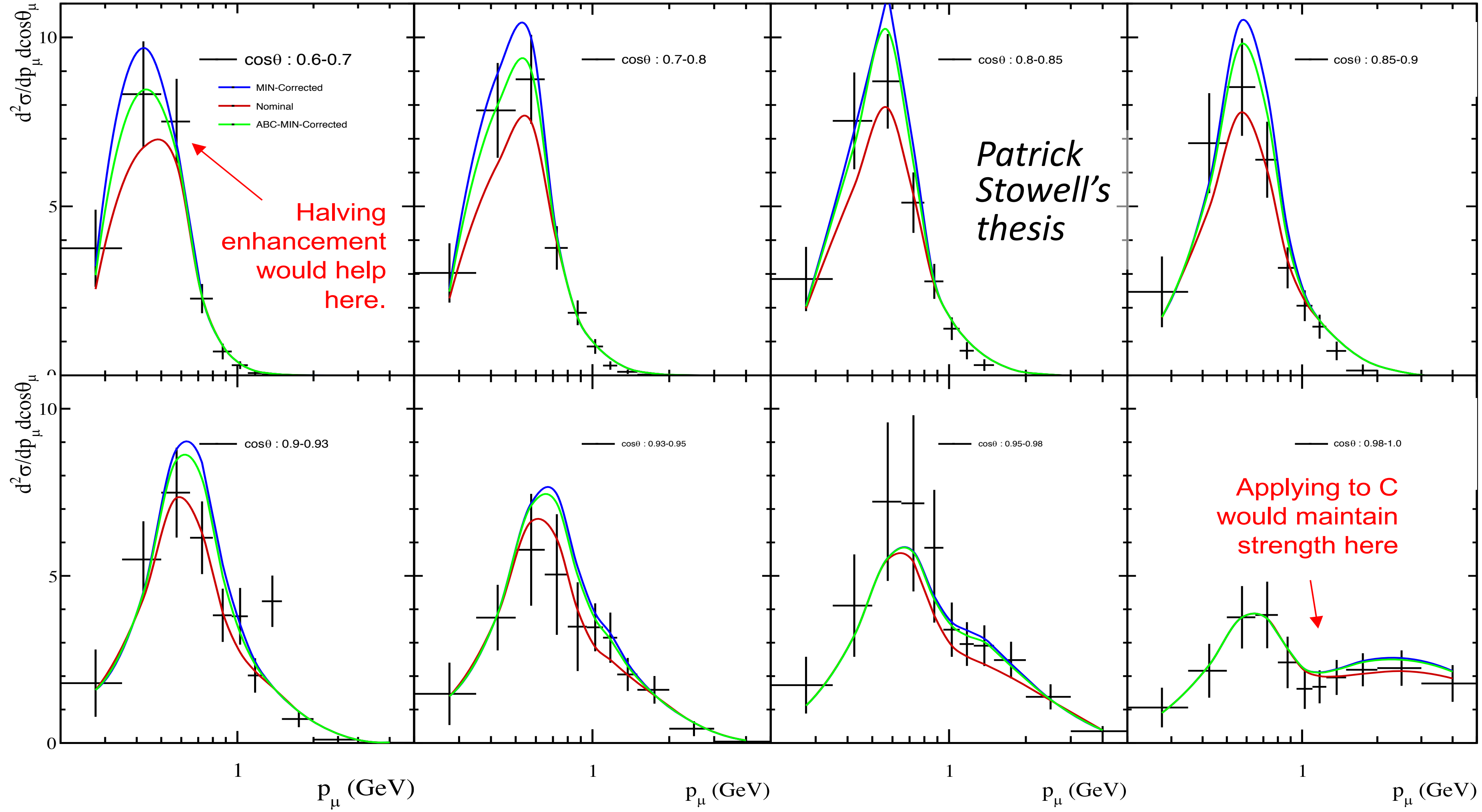
An expansion similar to eq. (2.5) holds for $\sum\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

$$\overline{\sum}\sum m_{\mu\nu} \quad \overline{\sum}\sum W^{\mu\nu} = A + B\,k\cdot P + C(k\cdot P)^2 \,, \qquad (2.7)$$

a quadratic polynomial in the laboratory energy $E_\nu = k\cdot P/M$ whose coefficients A, B and C depend on ν, q^2, and the reaction in question [L14, P2], It follows that if the interaction is of the current-current form *then* $E_\nu^2\, \mathrm{d}^2\sigma/\mathrm{d}q^2\,\mathrm{d}\nu$ *is a quadratic polynomical in* E_ν (cf. eqs. (2.10) and (2.11)) and therefore *only three combinations of structure functions are obtained if the final lepton polarization is not observed*. An alternative way to obtain the same result is to note that

C.H. Llewellyn Smith, Phys. Rep. 3 261-379 (1972), p. 280

Apply to T2K C term for CC0π



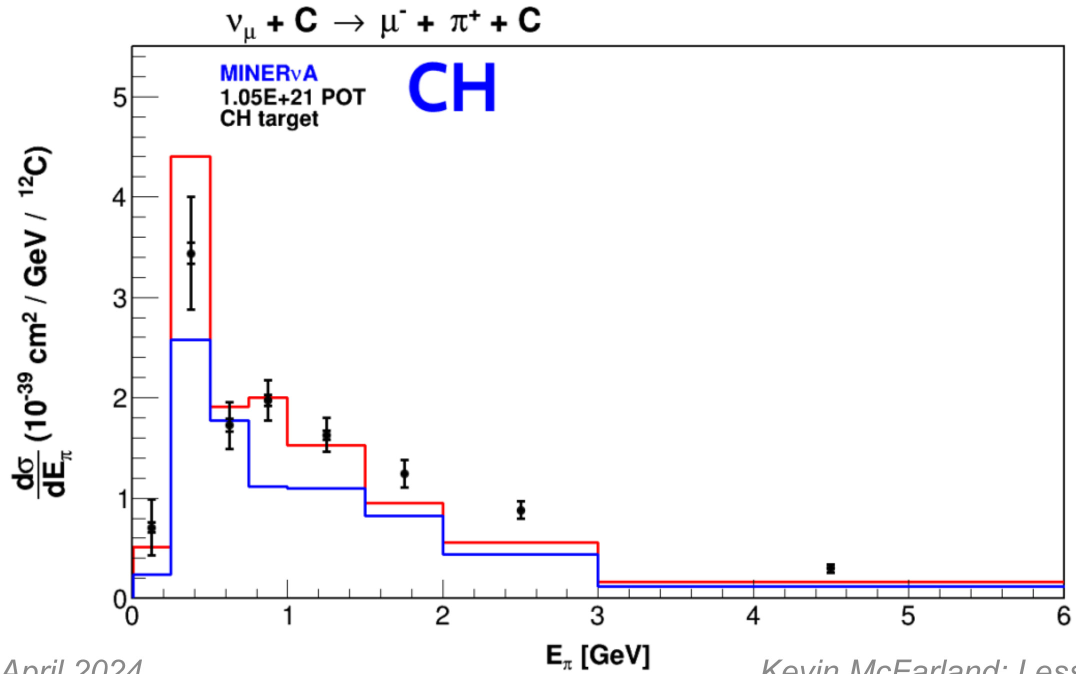
Scaled MINERvA tune, compared to data from Phys. Rev. D93, 112012 (2016)

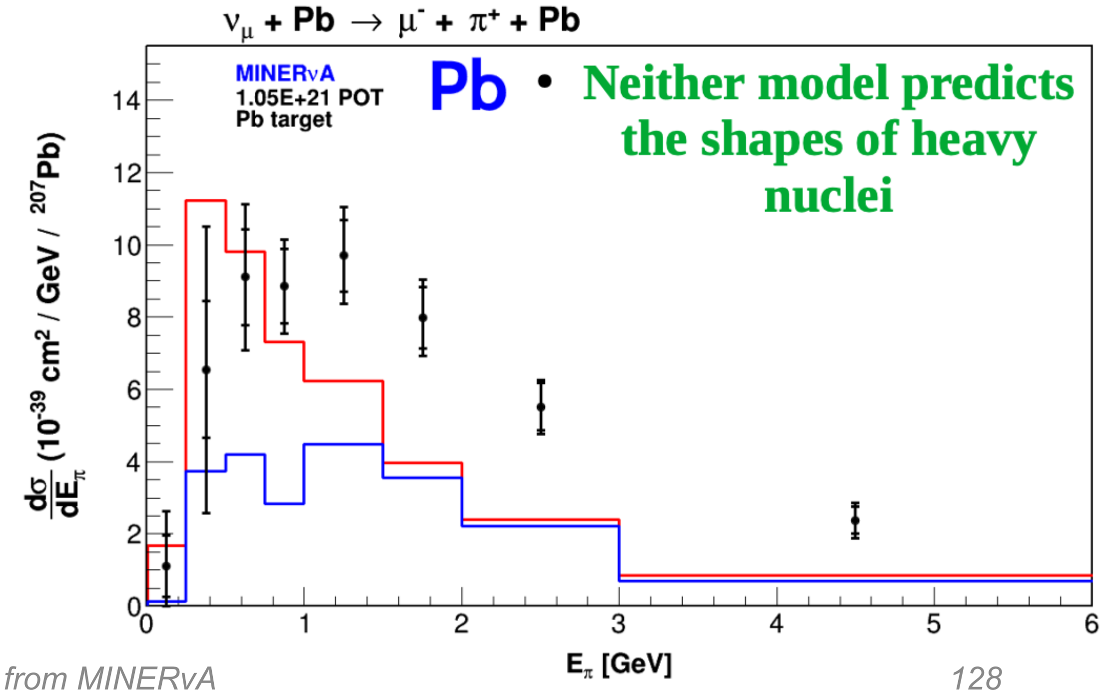
- Applying to the C term, as though this were the standard 1p1h interaction, get better agreement.
- However, without a model, we don't know energy dependence of this missing strength.

Backup: More Coherent on Pb

Coherent pion production on MINERvA's other targets, Fe, Pb

- Sneak peak! Short version is that A scaling is not radically wrong, nor correct in detail. Slightly longer version, I think, is that the pion energy distribution prediction is wrong, more so in heavy nuclei. and causes the problem with the naïve A-scaling.





- **Neither model predicts the shapes of heavy nuclei**

Backup: Pion Selection

Pion Selection and Kinematics

$E_\nu = E_\mu + E_H$ (E_H determined calorimetrically)

- Reconstructed $E_\nu \in [1.5, 10]$ GeV
- $1\pi^+$: $W < 1.4$ GeV
- $N\pi^+$: $W < 1.8$ GeV

$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$$

$E_\nu = E_\mu + E_H$ (E_H determined calorimetrically)

- Reconstructed $E_\nu \in [1.5, 10]$ GeV

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$$

$E_\nu = E_\mu + E_{\pi^0} + \Sigma T_p + E_{vtx} + E_{extra}$

- Reconstructed $E_\nu \in [1.5, 20]$ GeV
- Invariant π^0 mass $\in [60, 200]$ MeV/c^2

$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$$

$E_\nu = E_\mu + E_H$ (E_H determined calorimetrically)

- Reconstructed $E_\nu \in [1.5, 10]$ GeV
- Invariant π^0 mass $\in [75, 195]$ MeV/c^2
- $W < 1.8$ GeV

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$$

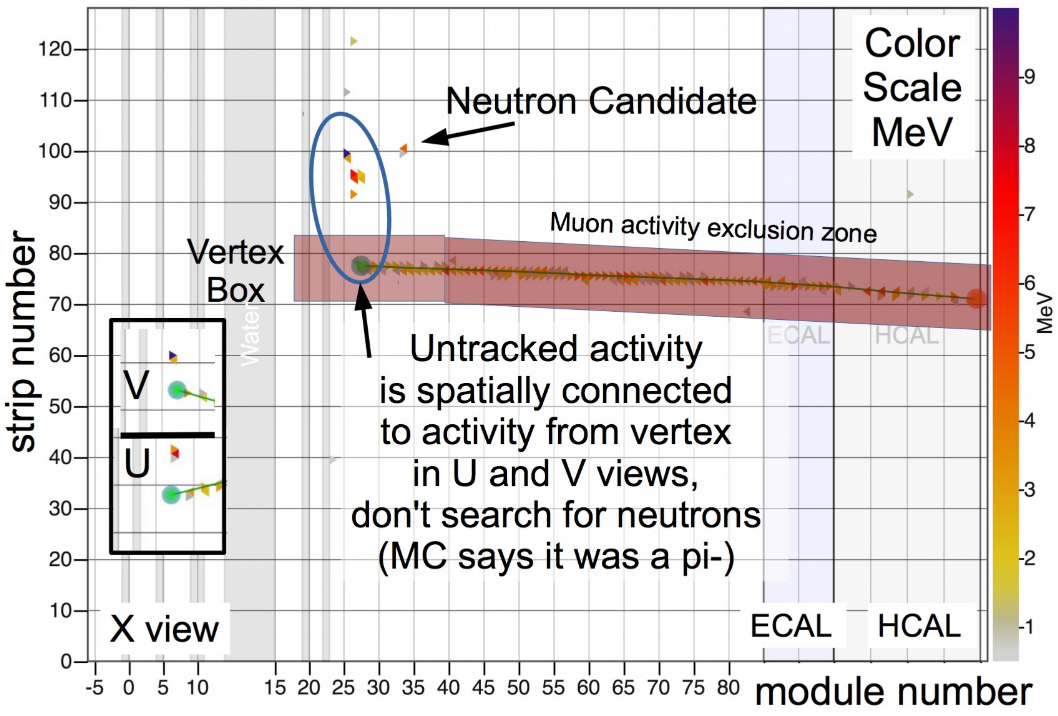
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

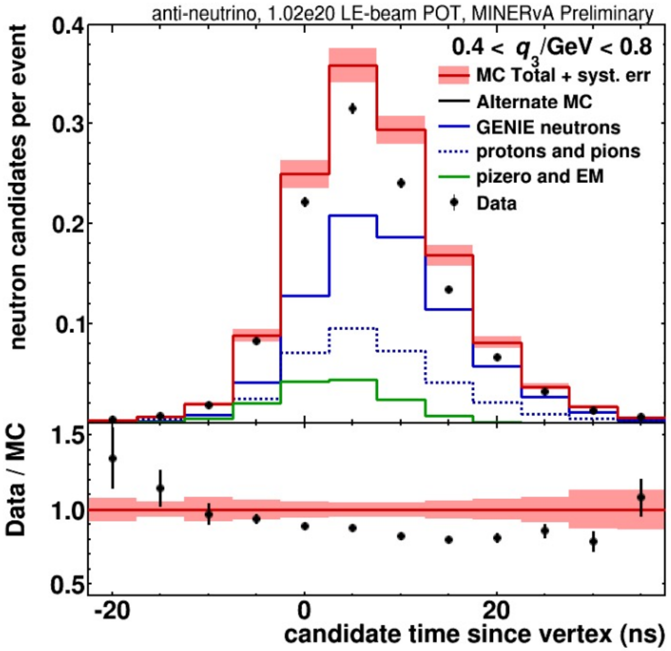
$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \ (m_N = \text{nucleon mass})$$

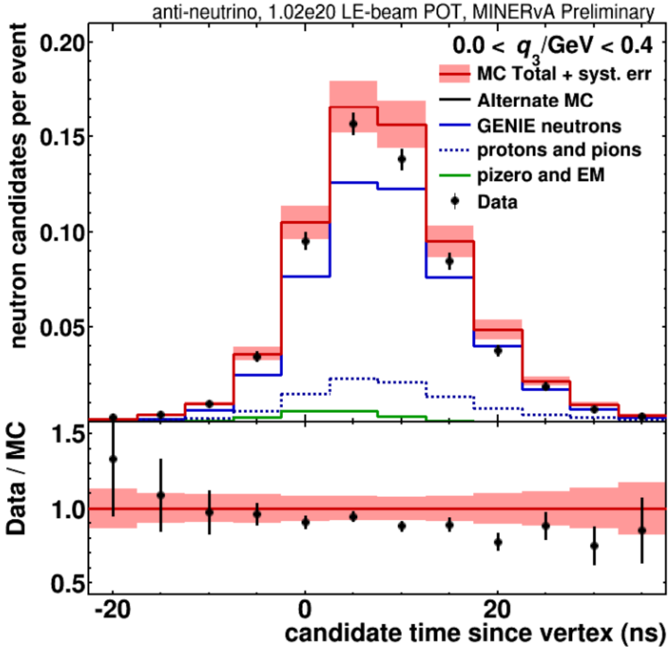
Backup: Neutrons

Neutron Production in Low Recoil $\bar{\nu}$

- Finally, we can look at the numbers of neutrons as a function of momentum transfer.



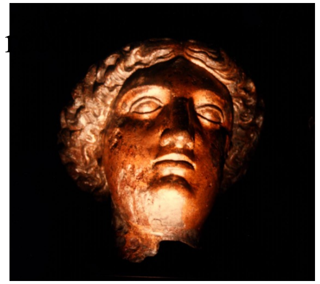


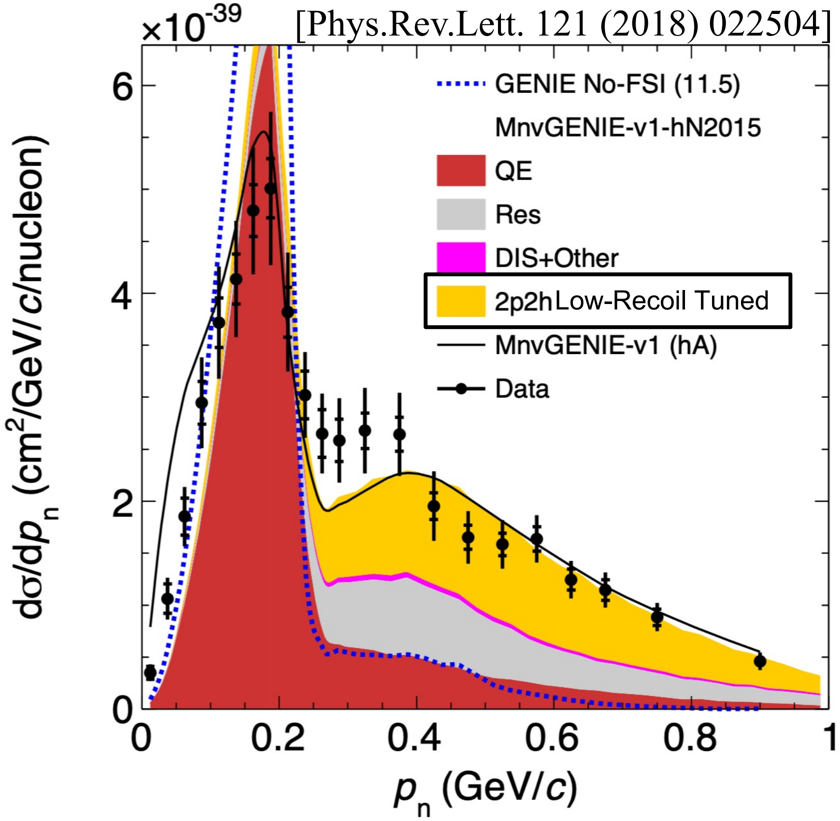


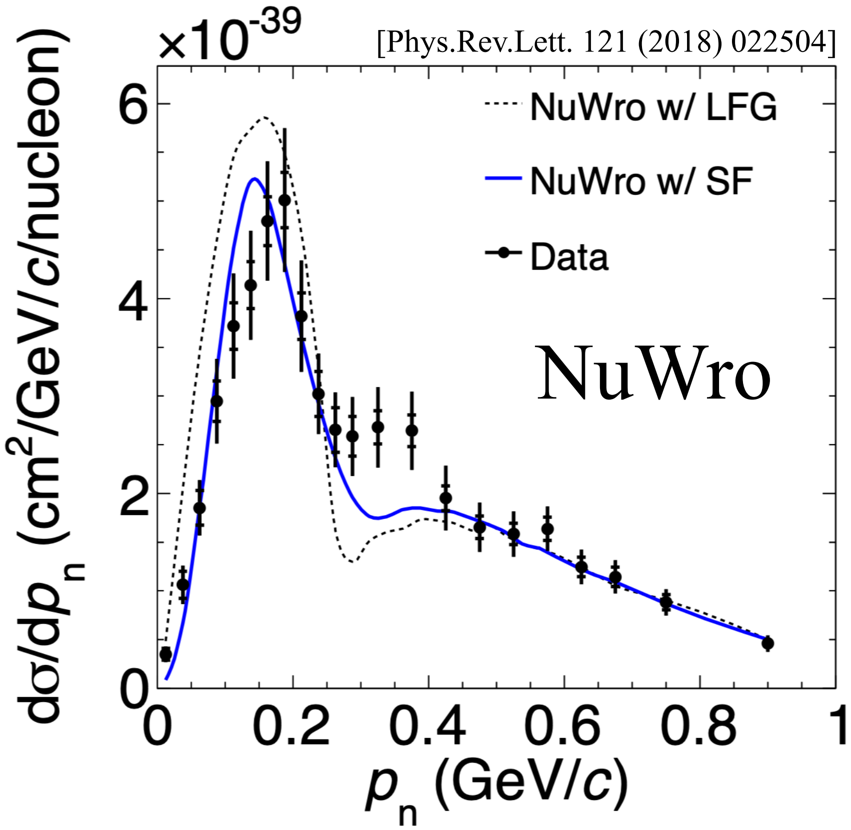
- Agreement is not as pretty. See excess of low momentum candidates at high time.
- Likely neutron interaction model or low energy neutron production.

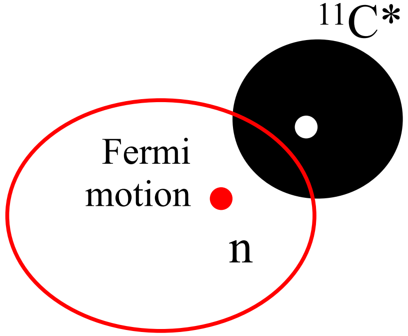
Backup: Tranverse Balance and Models

“Neutron momentum” from transverse kinematic balance







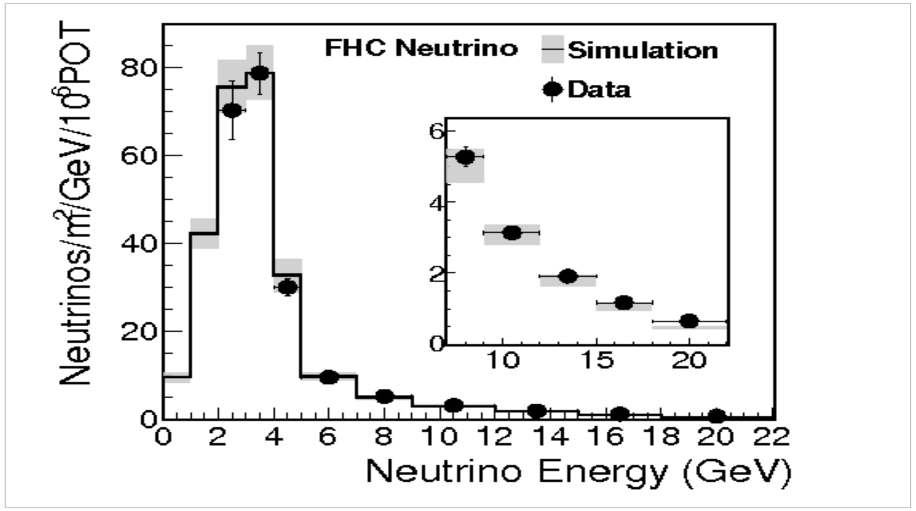


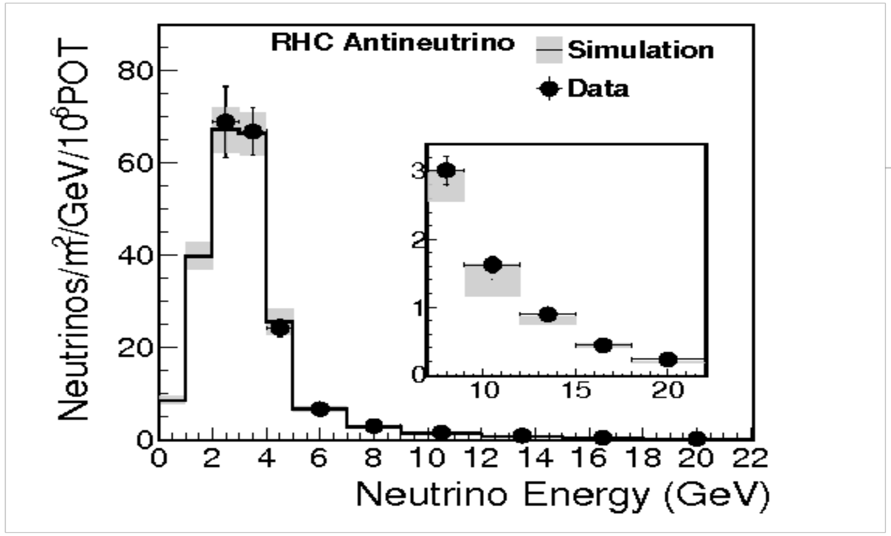
Global Fermi Gas with Bodek-Ritchie tail Local Fermi Gas Spectral Function

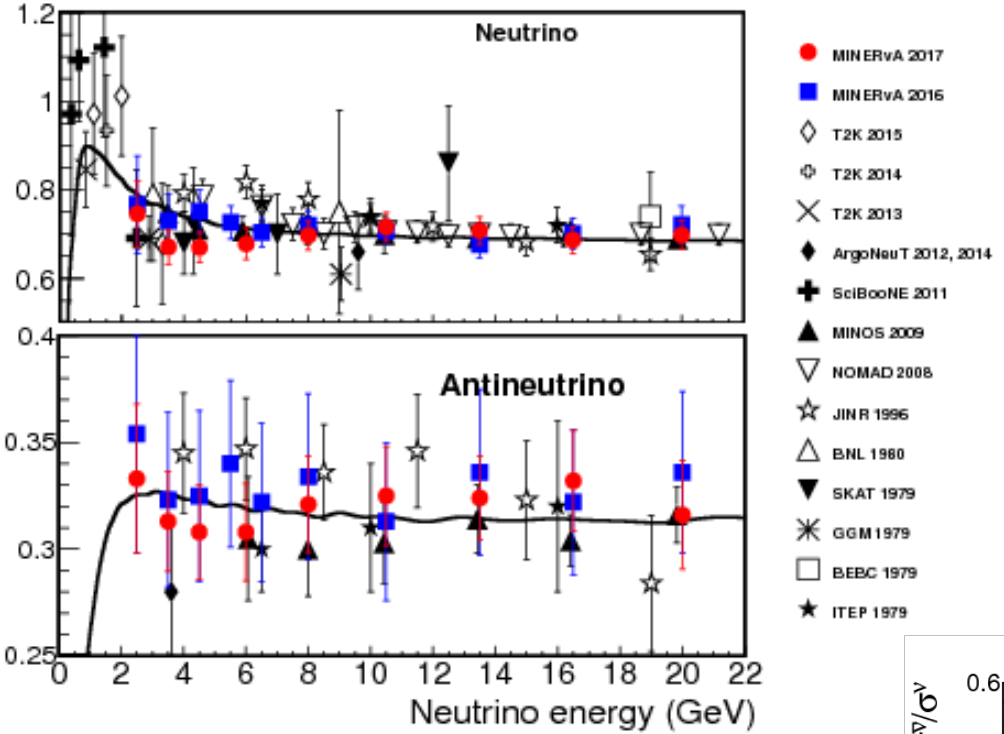
- Base Model depends on 1p1h and Short Range Correlation (SRC) modeling
- Critical to separate QE and RES to reduce Base-Model-dependence

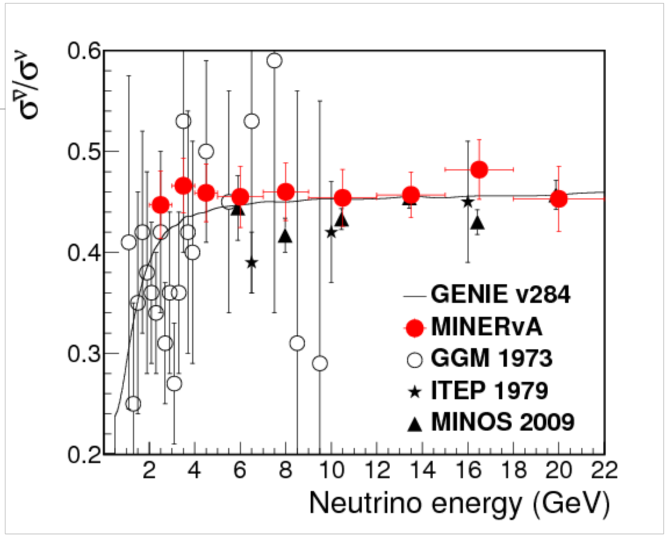
Backup: Neutrino CC Inclusive Cross Sections

Low nu technique to measure total Cross Section





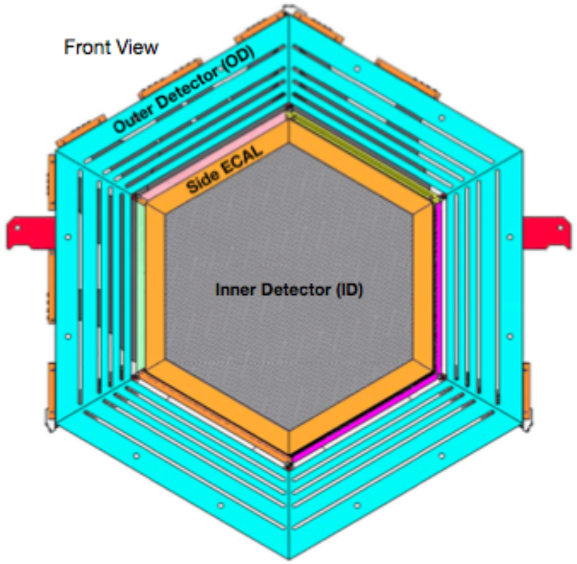




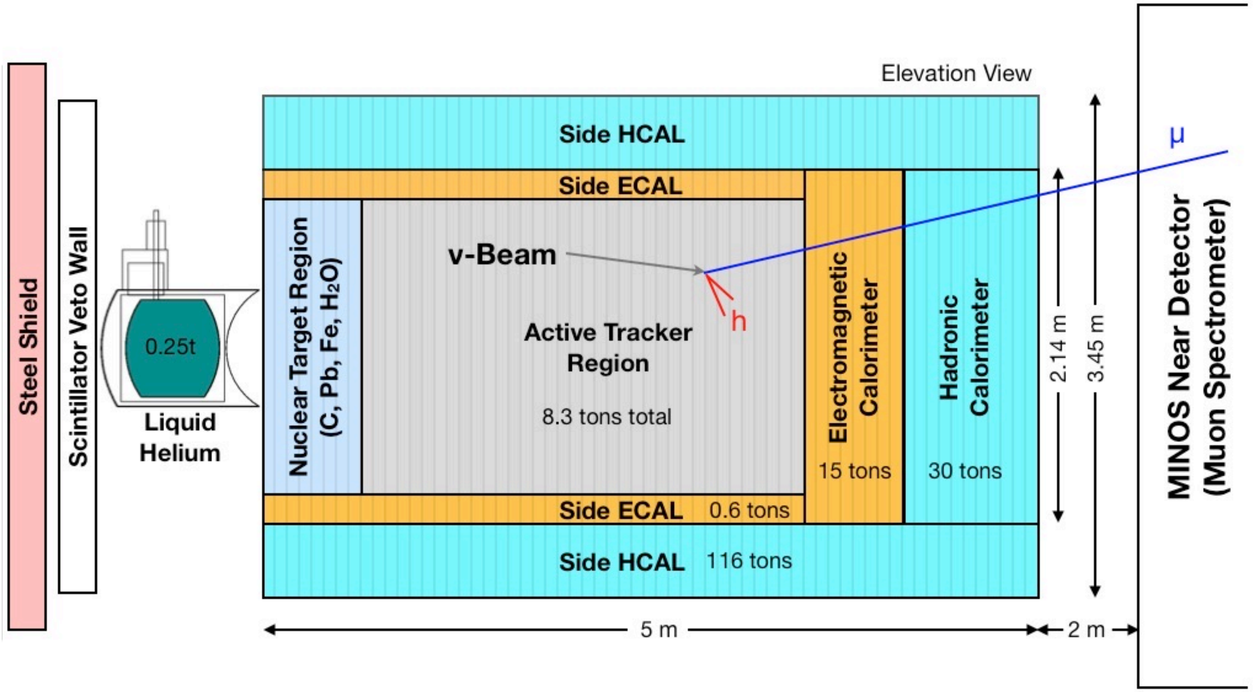
Phys.Rev. D94 (2016) no.11, 112007 and Phys.Rev. D95 (2017) no.7, 072009

Backup: Detector

Detector



3 orientations
0°, +60°, −60°

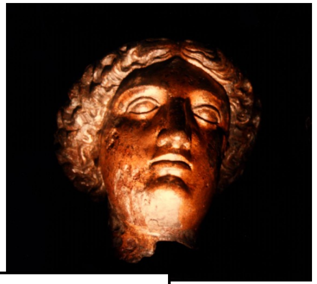


*Detector comprised of **120 "modules"** stacked along the beam direction*

*Central region is **finely segmented scintillator tracker***

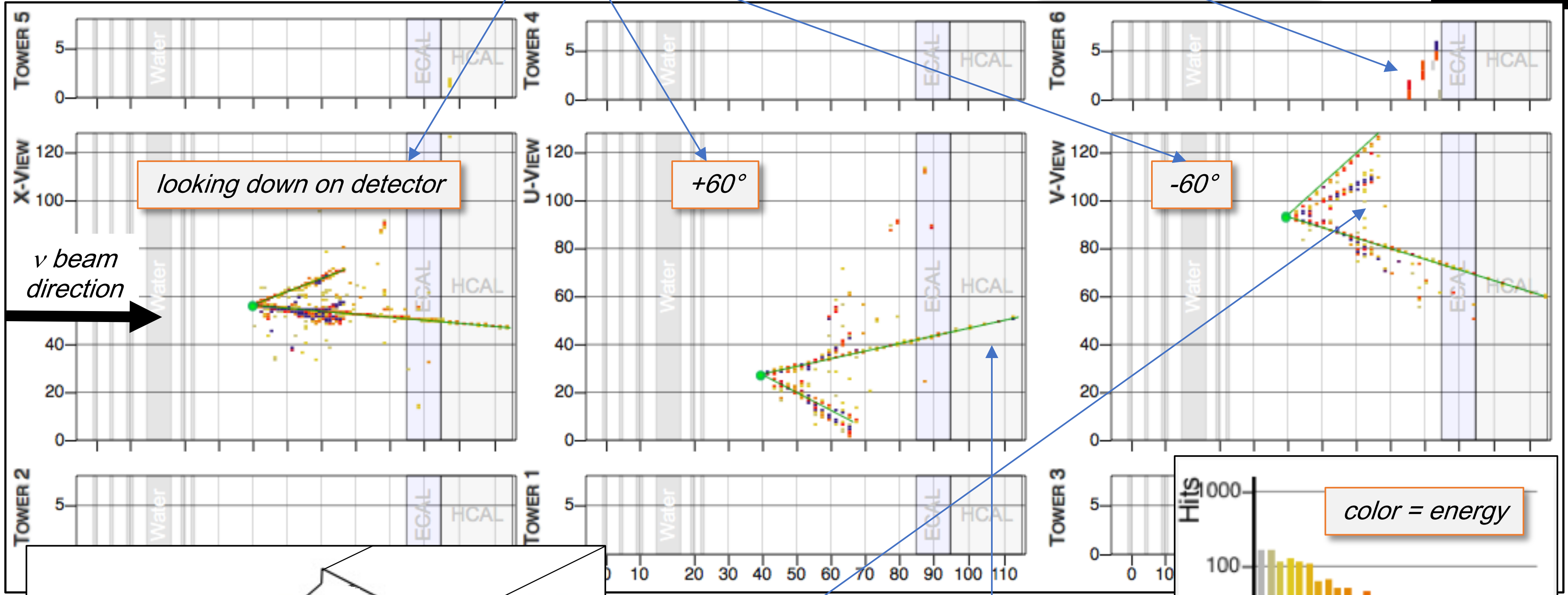
~32k plastic scintillator strip channels total

Events in MINERvA



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

Particle leaves the inner detector, stops in outer iron calorimeter

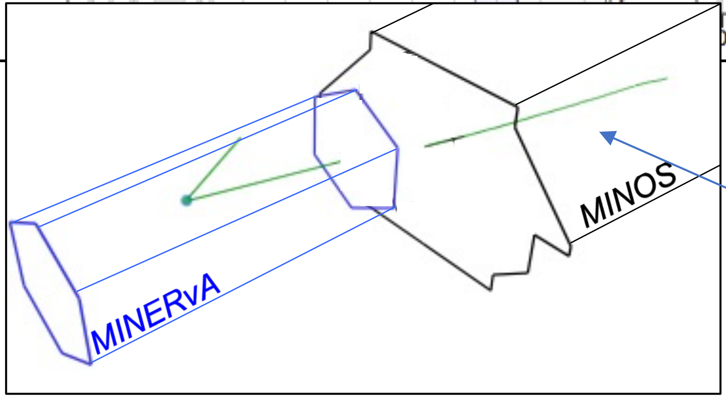


looking down on detector

+60°

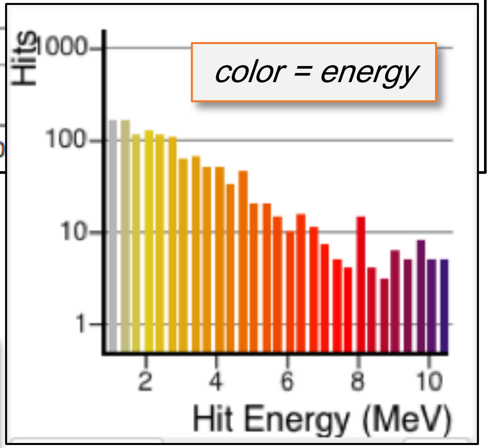
-60°

ν beam direction



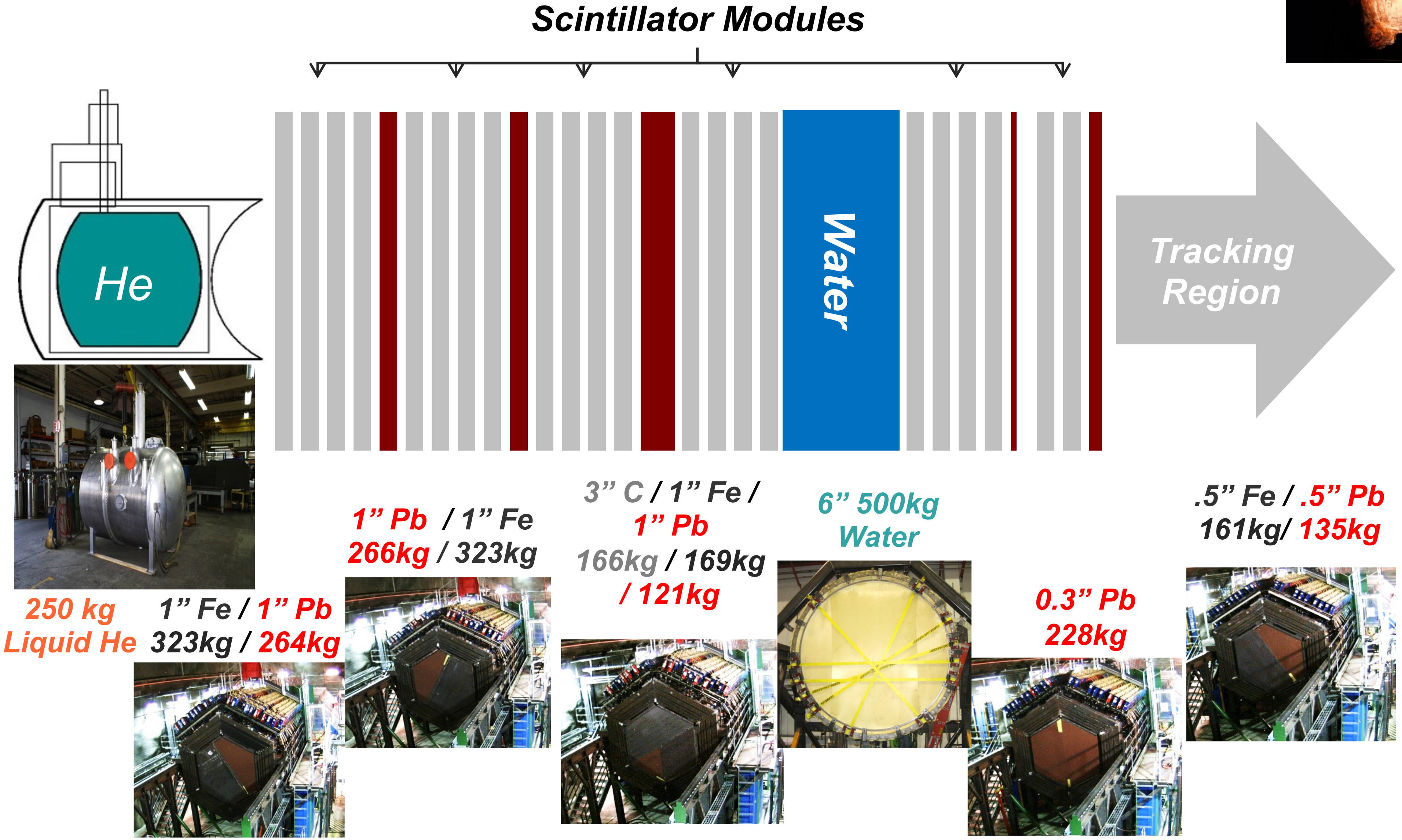
Stops in Scintillator, best hadron particle ID

Muon leaves the back of the detector headed toward MINOS

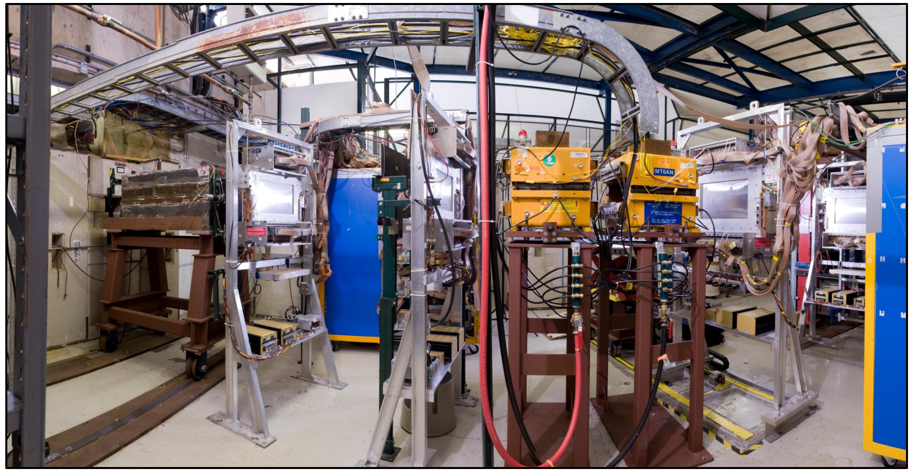


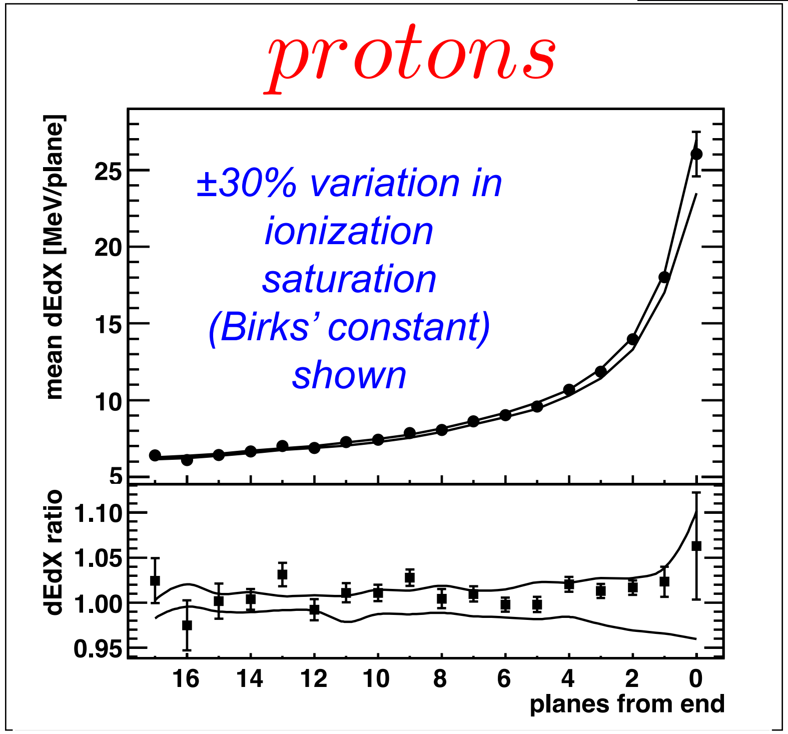
color = energy

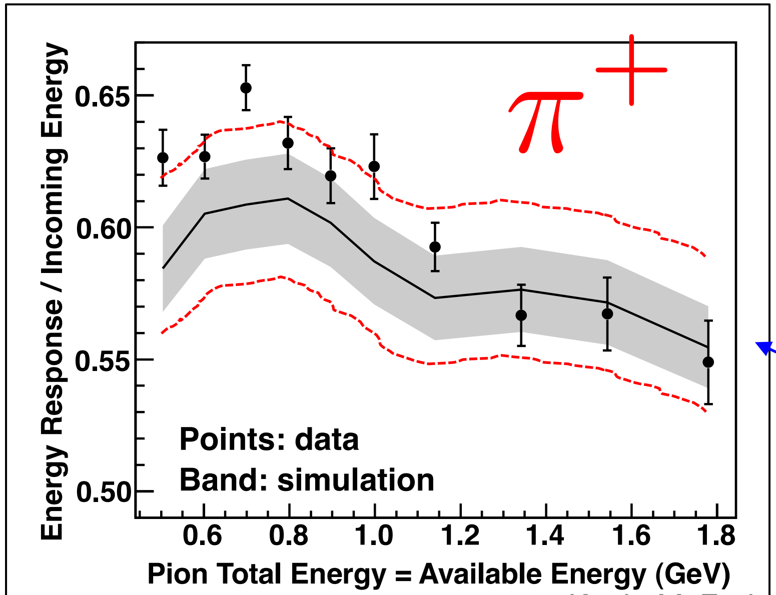
Passive Nuclear Targets



Hadron Testbeam







high-energy charged pion response uncertainty ≈ 5% (before tuning hadron interactions in detector)