MINERvA's Recent Results and Data Preservation Effort

NDNN 2021

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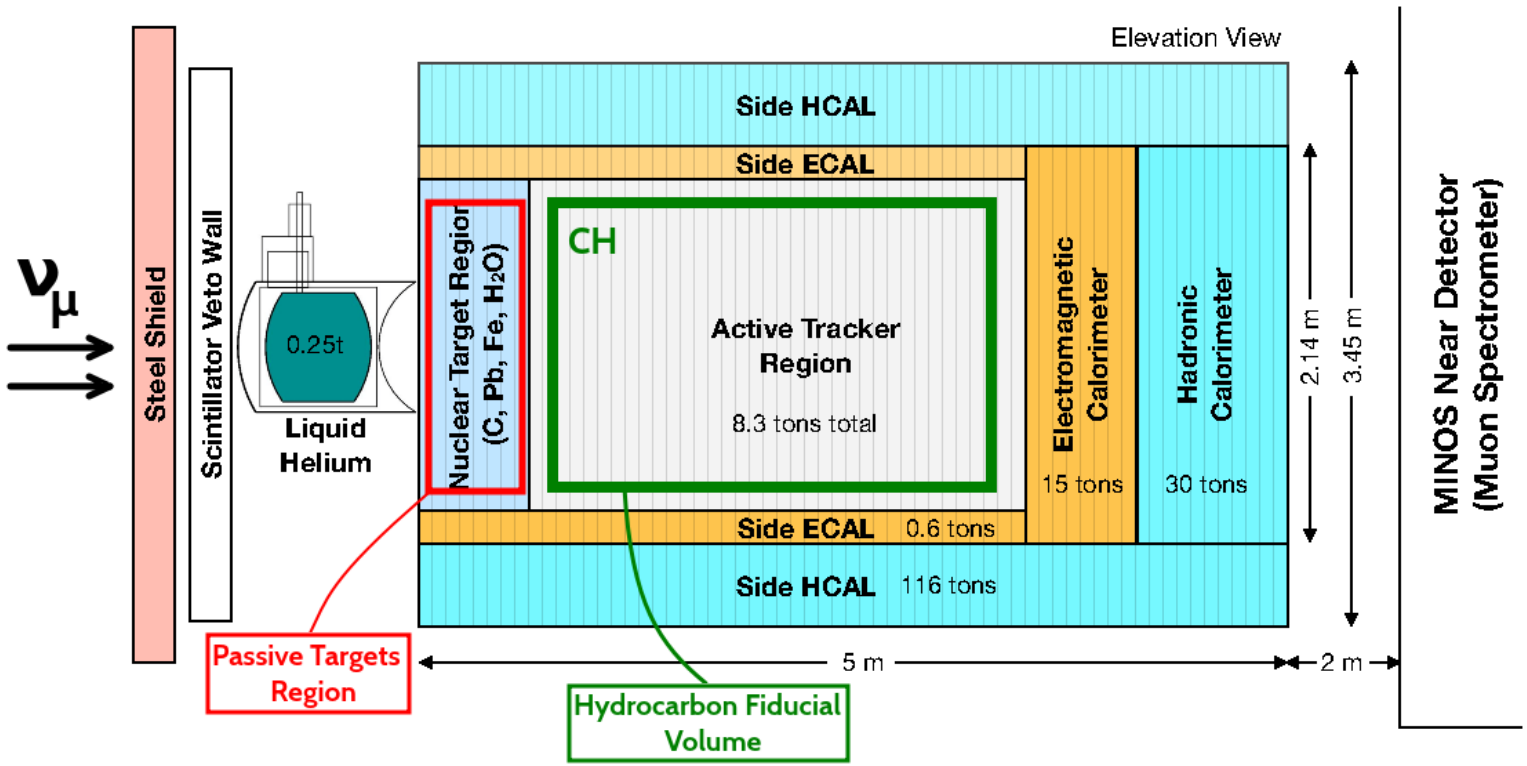
Outline

MINERvA Experiment in a Nutshell

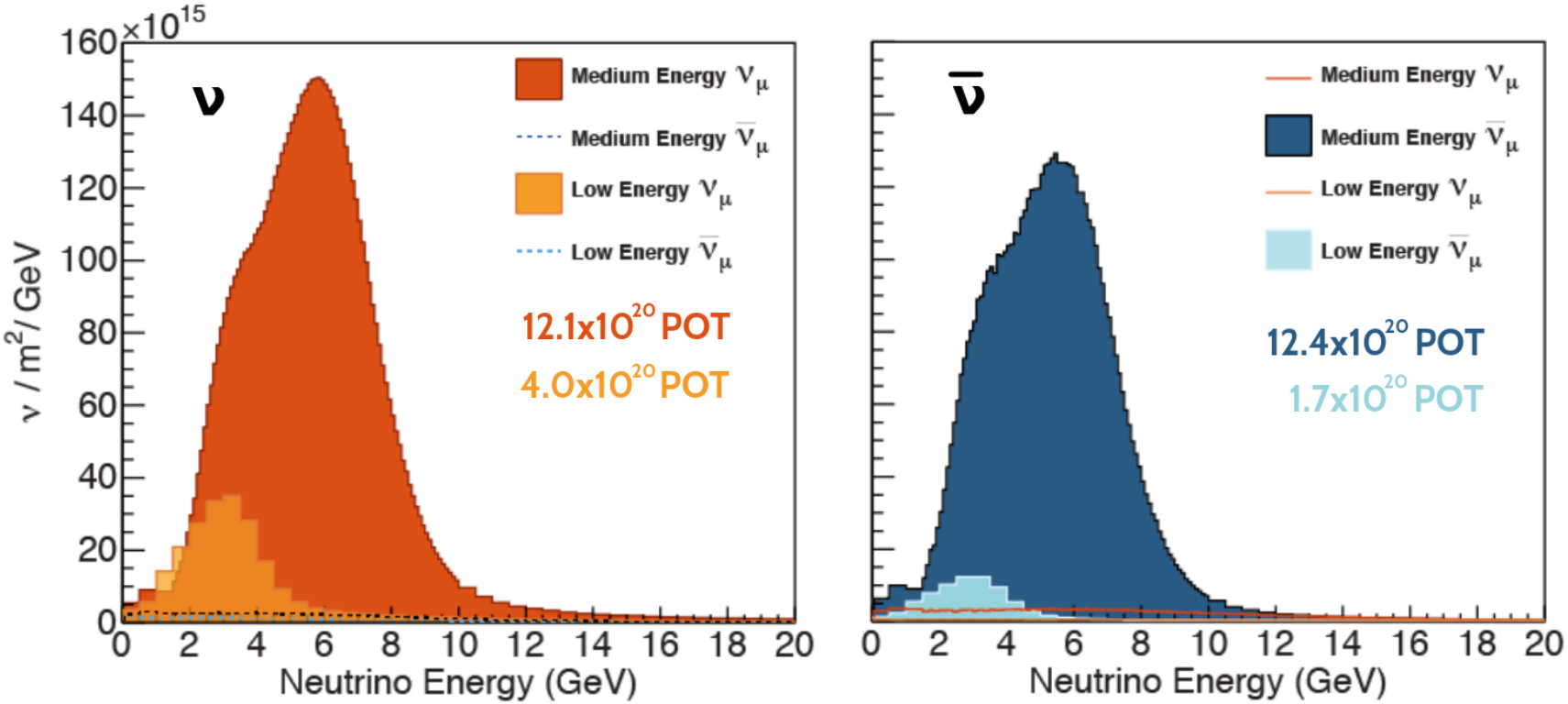
MINERvA Detector

- Located upstream of the MINOS ND, it consisted of an "inner" detector surrounded by calorimeters.
- The inner upstream "target" region with passive targets of different material.
- The inner downstream "tracker" region, with plastic scintillator.



MINERvA's Data

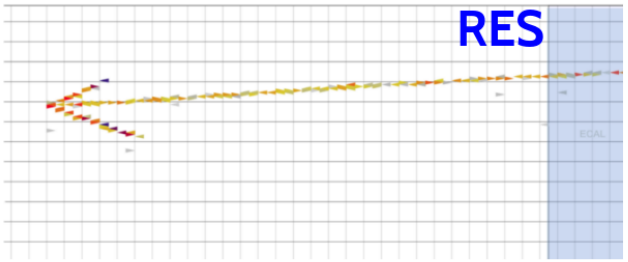
- ME/LE ratio of recorded events ~ 13 in ν_μ and ~ 40 in $\overline{\nu}_\mu$ mode.

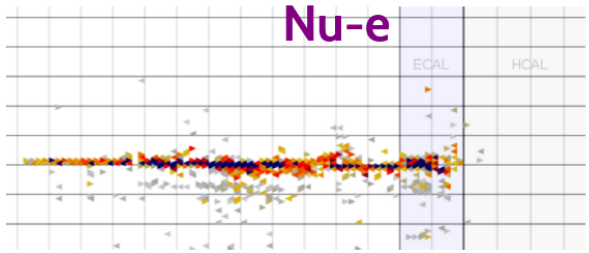


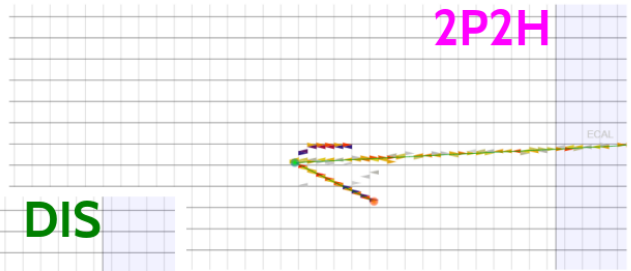
Thanks to Fermilab Accelerator Division for all the beam!

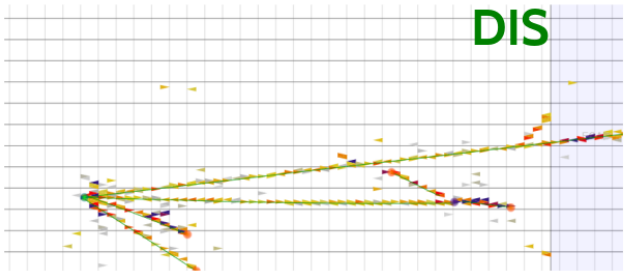
MINERvA's Catalogue

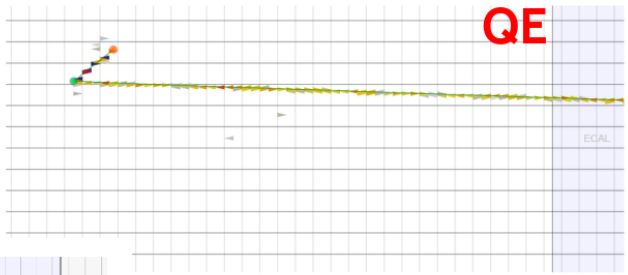
- 34 Publications: 22 ν_μ, 10 $\overline{\nu}_\mu$, 2 ν_e.
- The large ME sample, will:
  - Enable statistical limited channels.
  - Increase the precision of previous results.

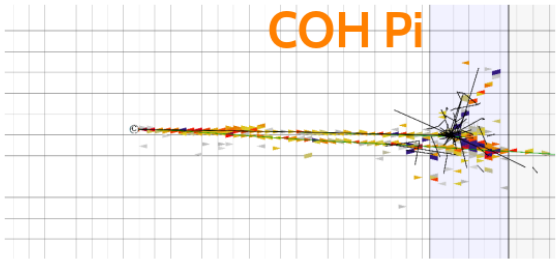








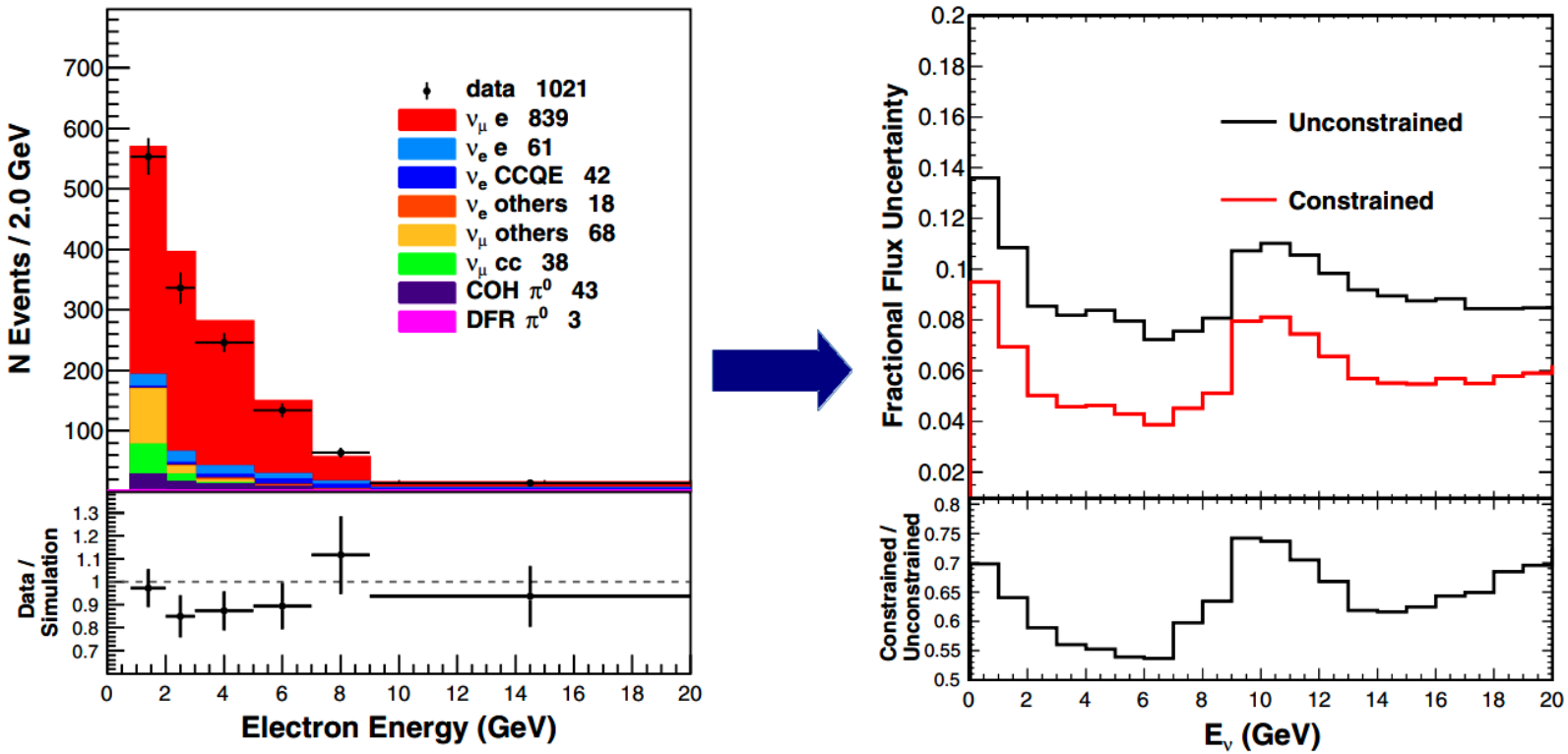




MINERvA Products - Flux Constraint

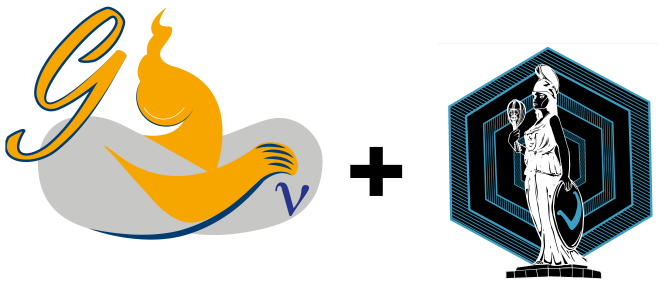
- Neutrino-electron scattering ME sample, was used to reduce the fractional uncertainty on the flux, from 7.6% to 3.9%.

PhysRevD.100.092001



MINERvA Products - MINERvA Tune v1

- GENIE 2.12.6 + The Following Additions:
- Nieves 2P2H model. Added 2P2H from electron scattering data.
- Valencia RPA for QE. Suppress QE events as a function of Q^2.
- ANL and BNL data used to suppress non-resonant pions.
- MINERvA's LE low recoil fit applied to 2P2H events.



ν_μ 3D CCQE in CH

CCQE Interactions

- Basic picture of CC QE: ν_μ interacts with nucleon, producing a muon and recoil nucleon of the proper charge.
- E_ν reconstruction with muon kinematics only (in principle).

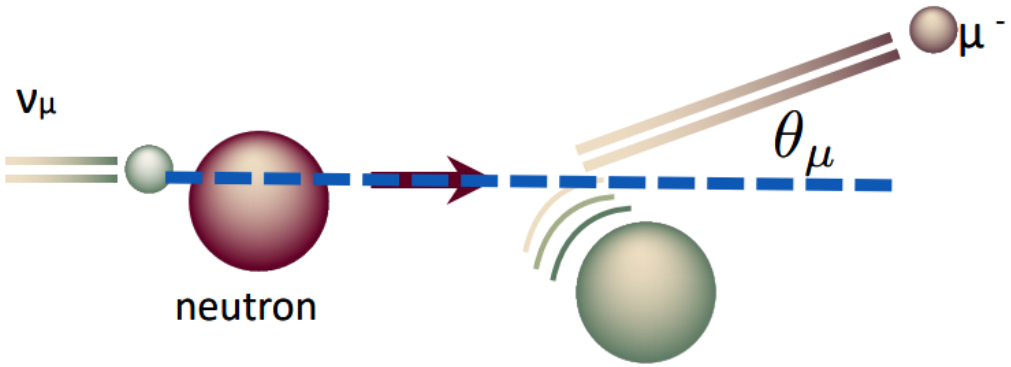


Figure by Cheryl Patrick

Motivation - ME ν_μ 3D CCQE

- Explore previously unavailable regions such as high Q^2_{QE}.
- This is possible with the fine slicing of the data, due to the ME high statistics.
- It's the first analysis of its kind in the few GeV region.

Signal Definition

- Any number of nucleons
- No mesons, or heavy baryons.
- Gammas < 10 MeV allowed (Deexcitation gammas)
- Muon angle with regards to the beam < 20 degrees

Initial and Final State Interactions

- The nuclear medium matters!
- CCQE 0π, defined "in terms of FSI particles."

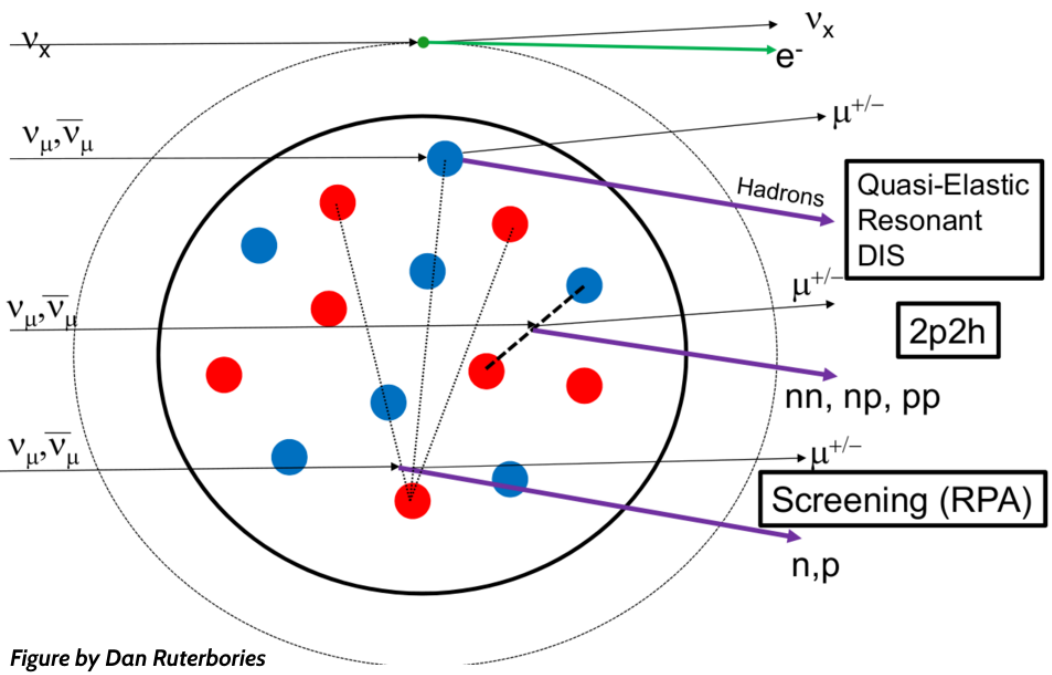


Figure by Dan Ruterbories

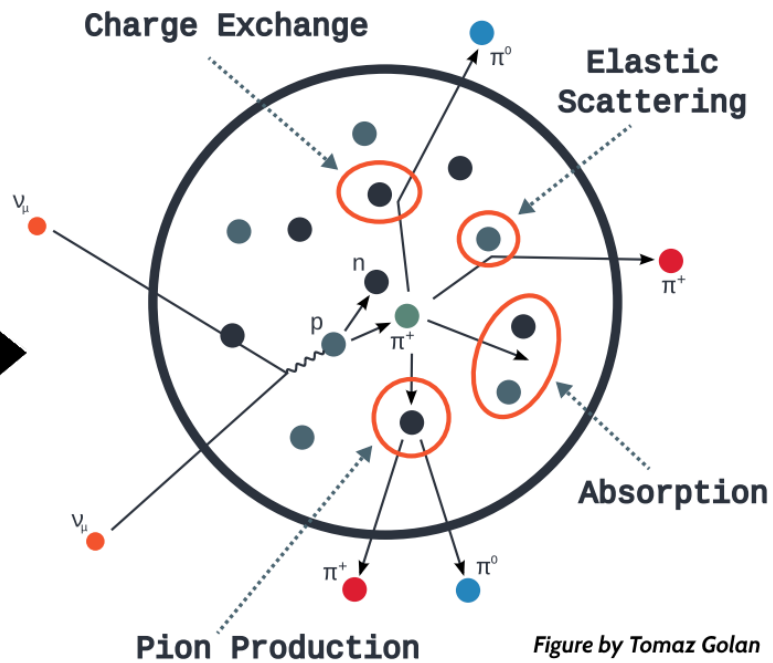
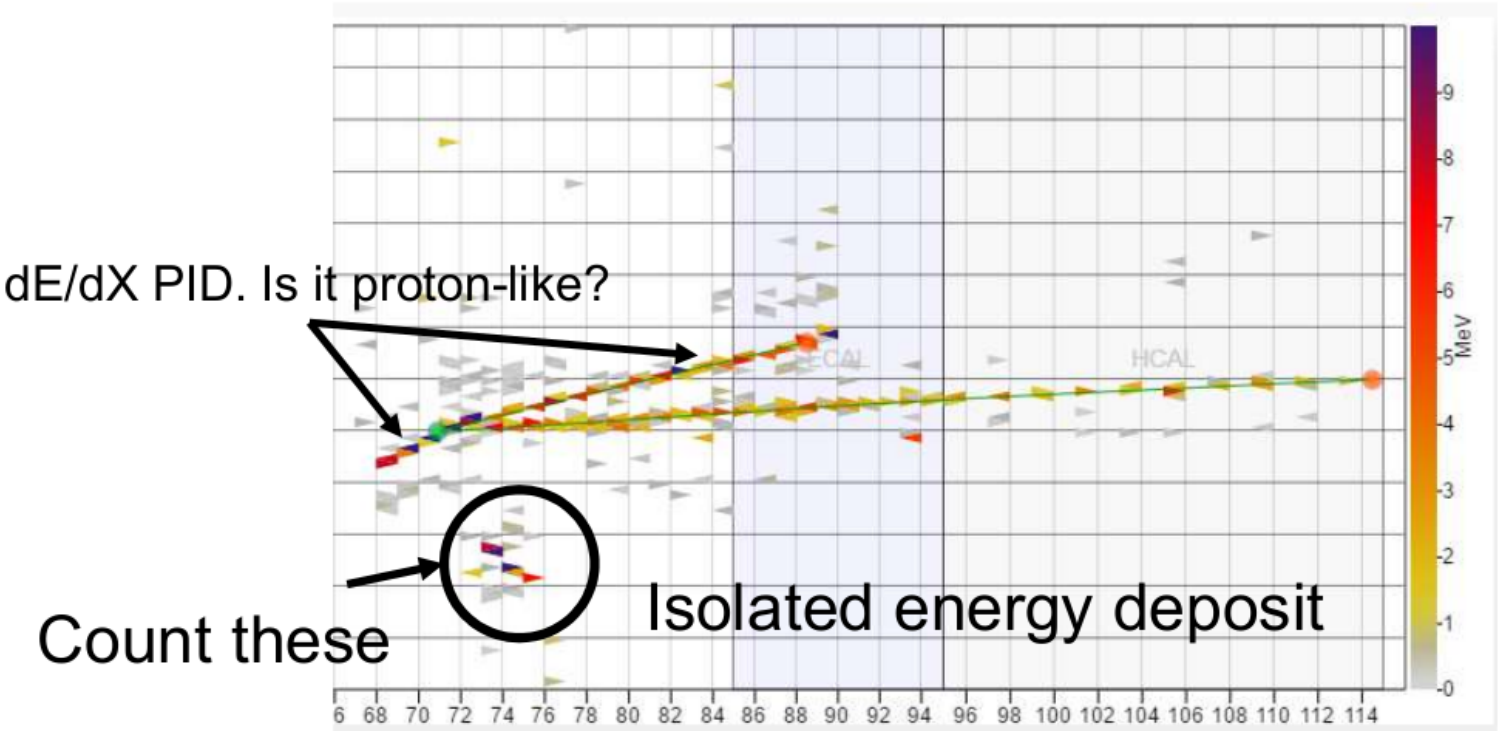


Figure by Tomaz Golan

Event Selection

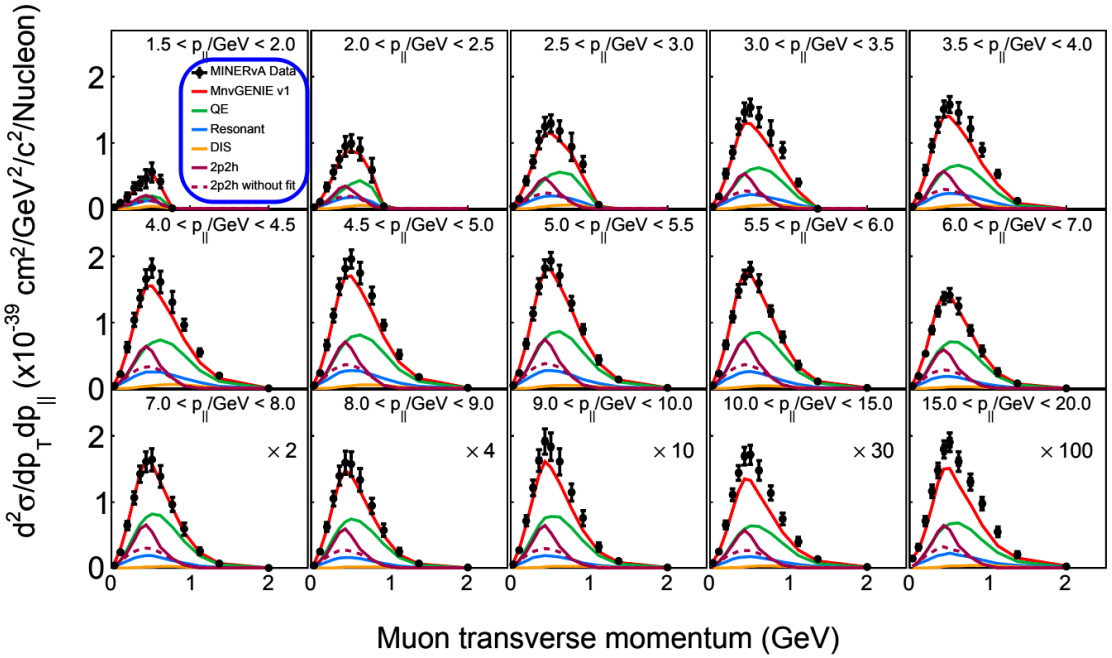
- PID-based selection of tracked particles
- Veto Michel electrons (reject pions).
- Set maximum number of isolated energy deposits.
- Set maximum extra recoil energy for un-tracked activity.
- Muon matched in the MINOS detector.

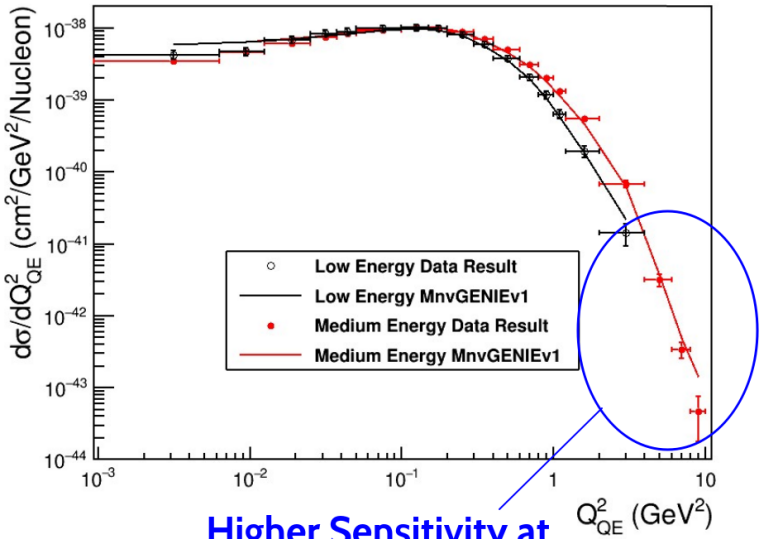


ME ν_μ 2D CCQE Results

- The ME 2D analysis showed improved sensitivity at high Q^2_{QE}

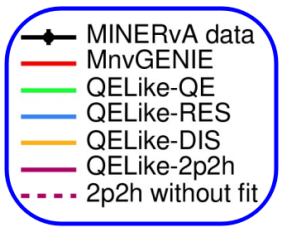
PhysRevLett.124.121801





Higher Sensitivity at High Q^2_{QE}

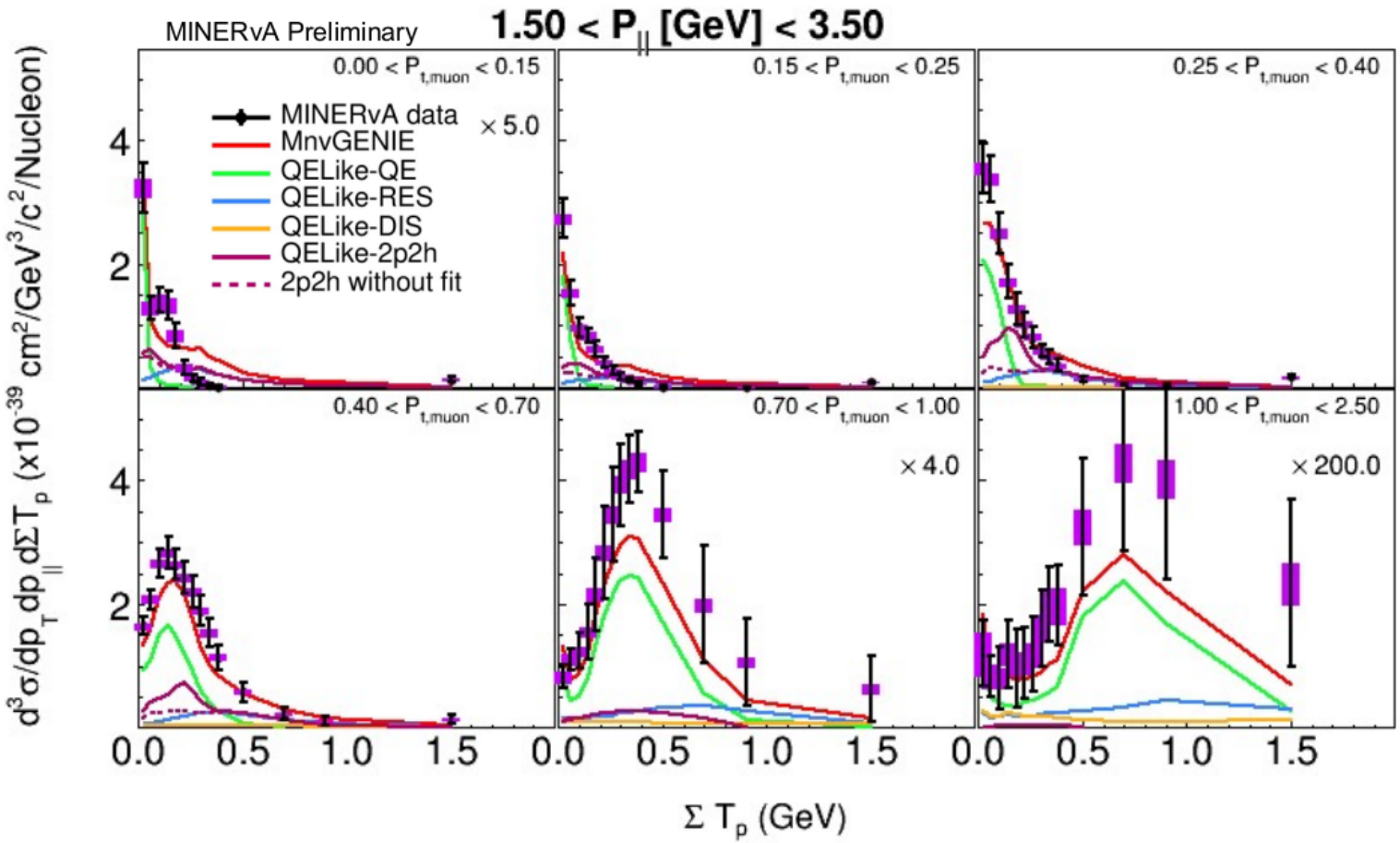
QE-Like Definition of Signal and Background



Which means Final State particles may be originated due to any of these processes, but they look like QE

ME ν_μ 3D CCQE Cross Section - Preliminary

The ME 3D analysis is going deeper by looking at $P_{||}$, P_t, plus $\sum T_p$ (hadronic visible energy).



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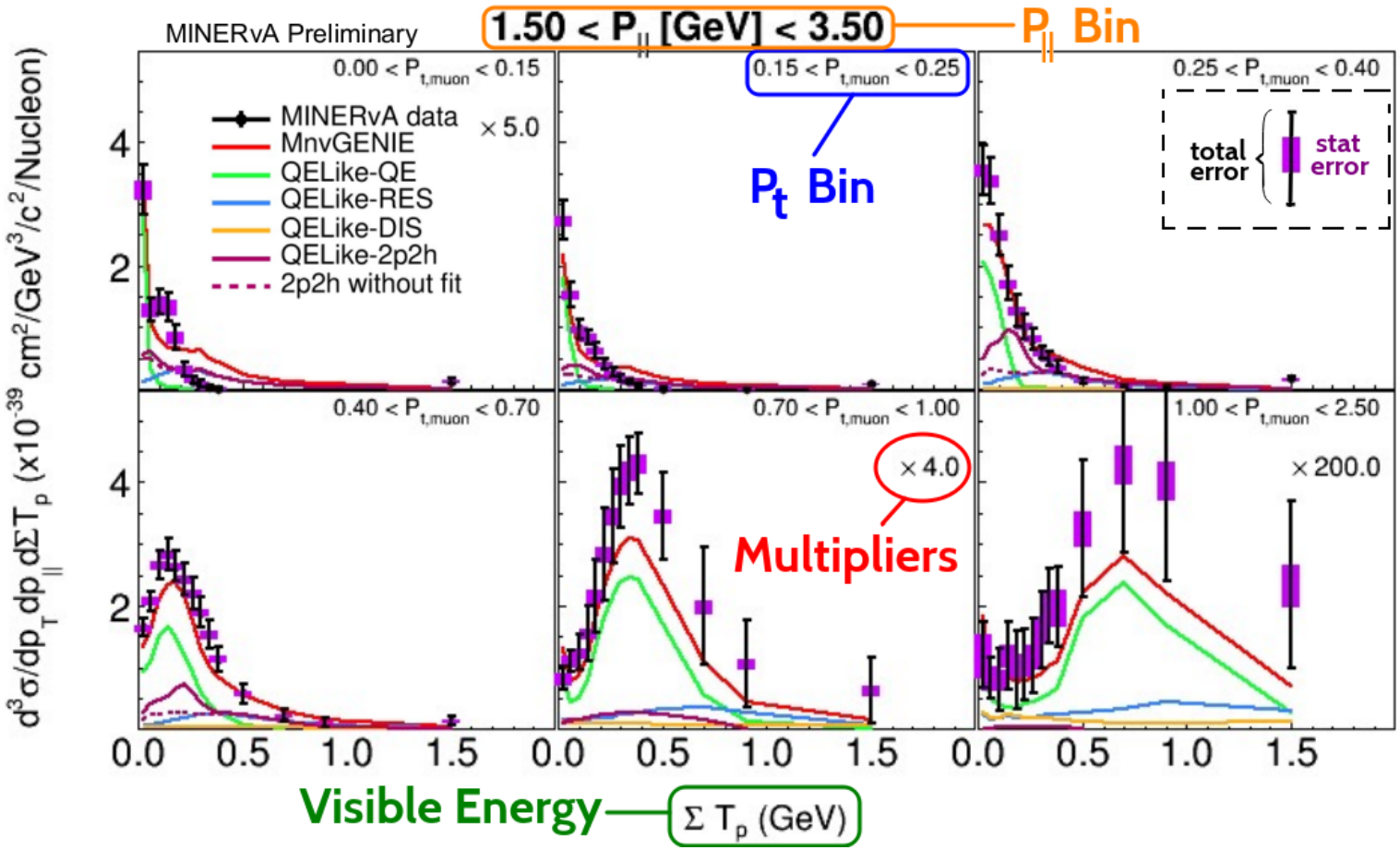

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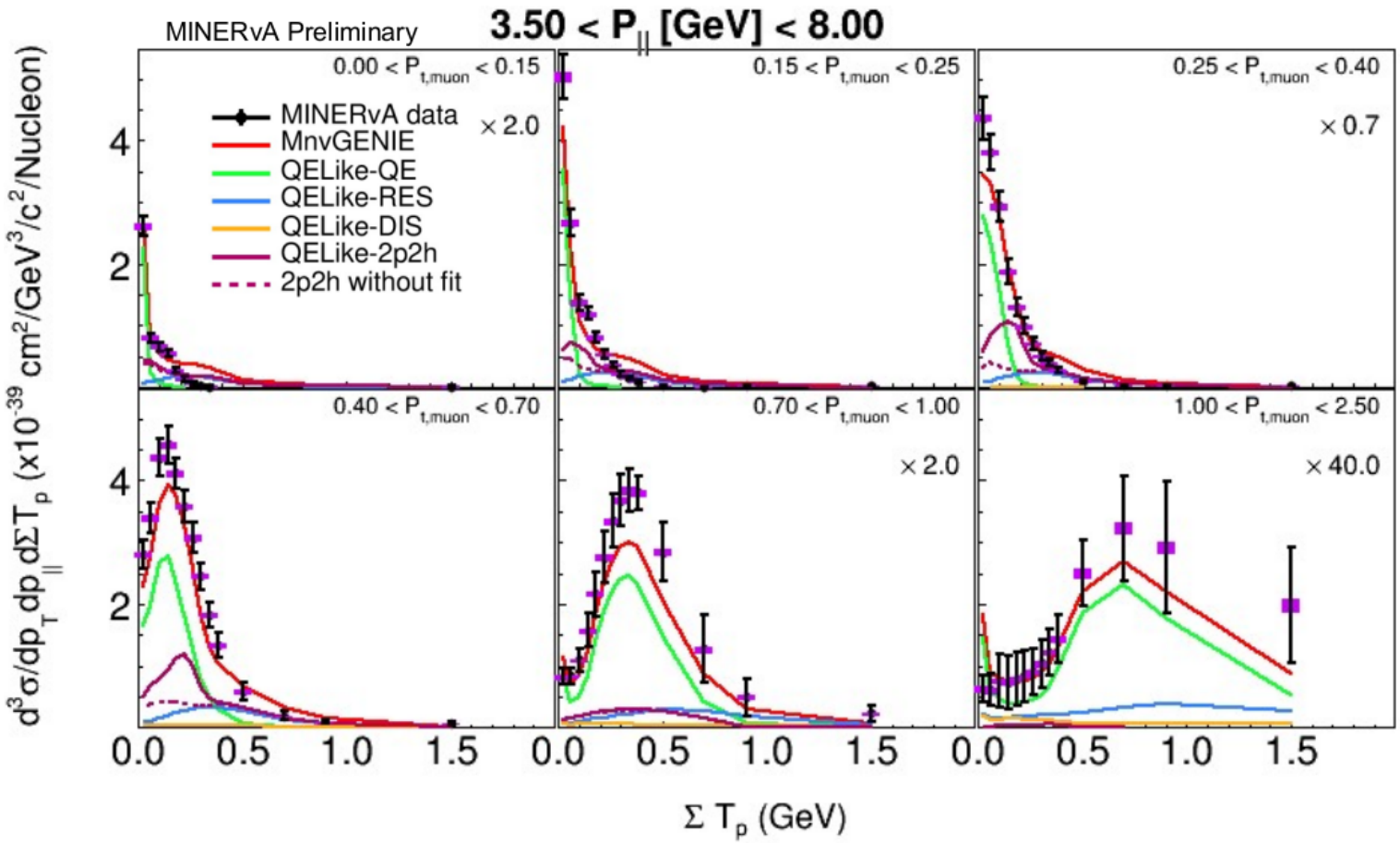

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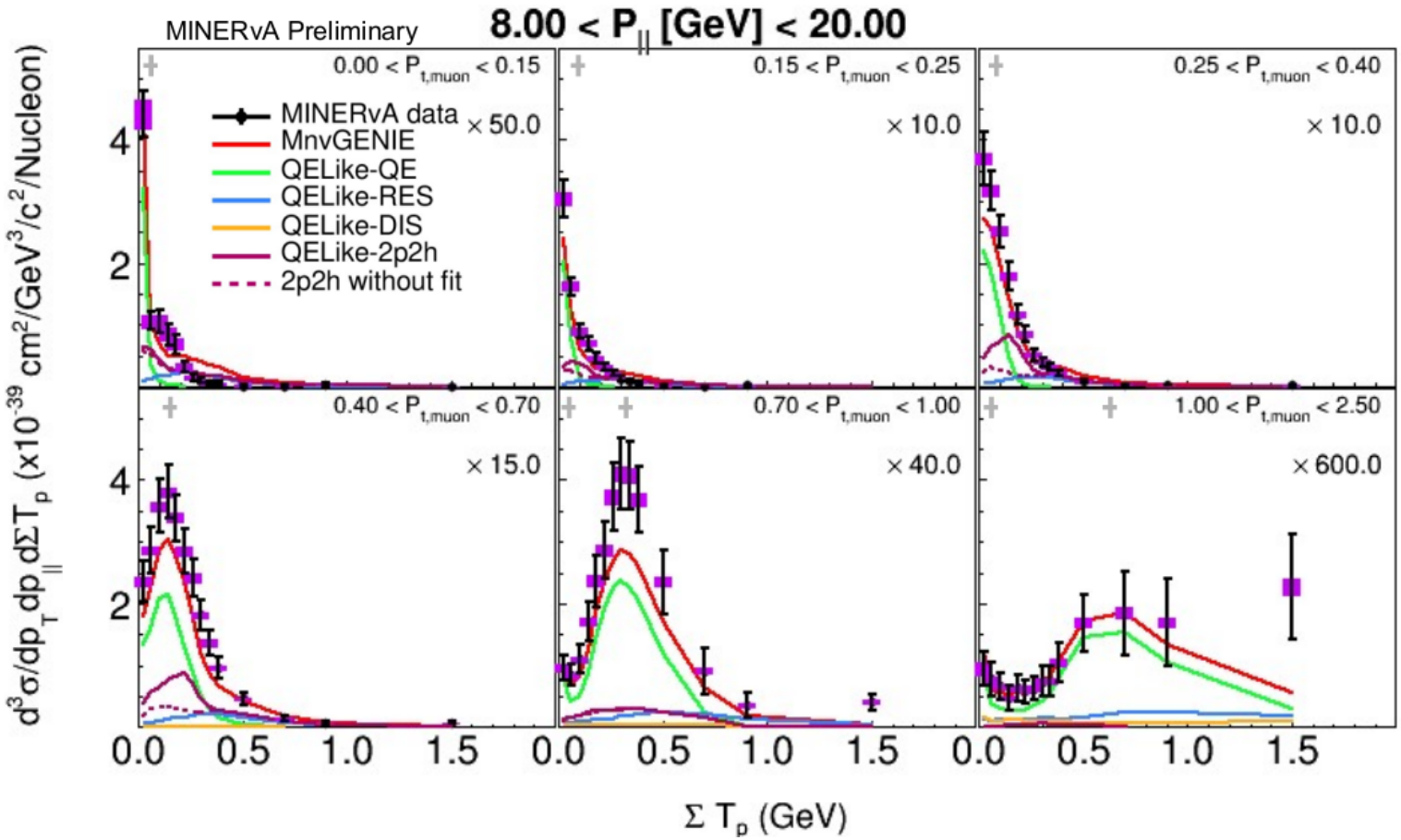
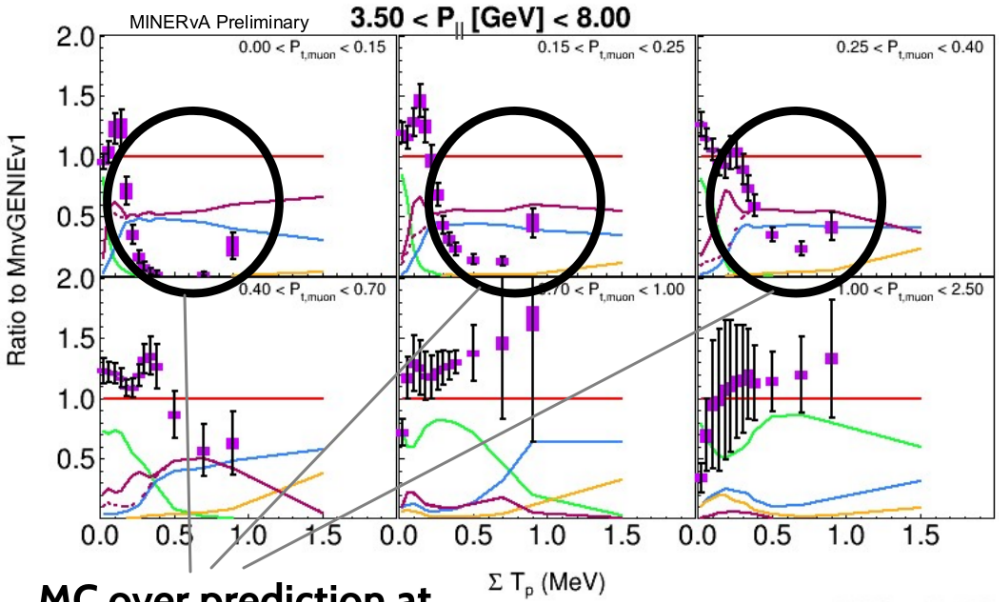
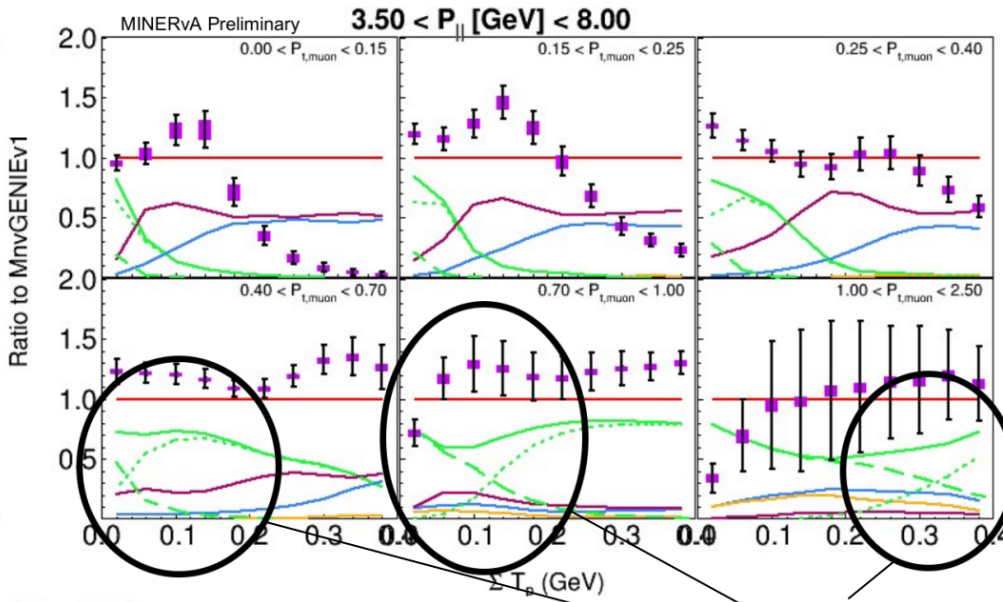


ME ν_μ 3D CCQE - Some Conclusions



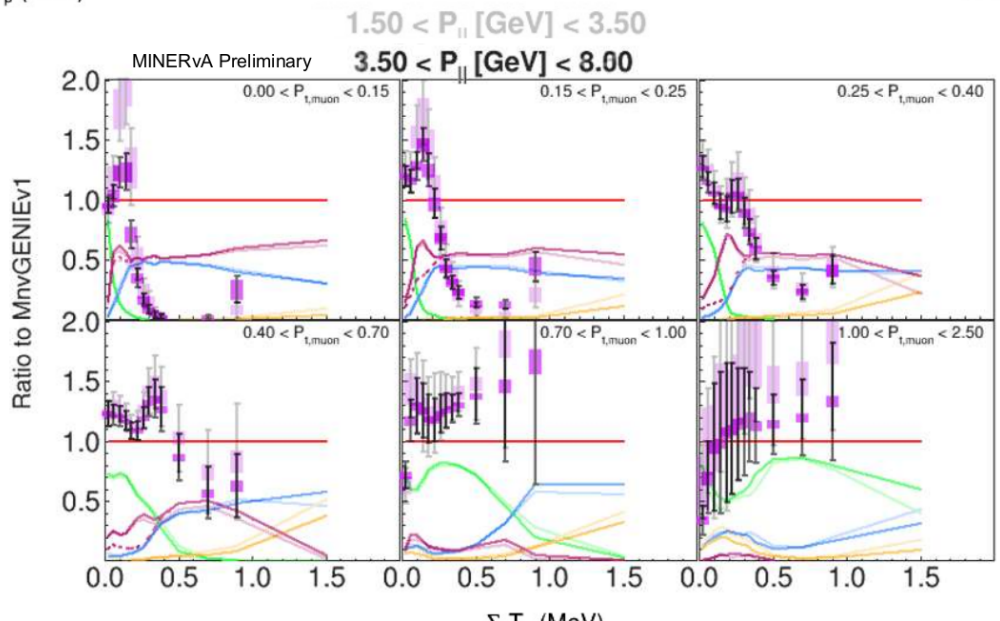


MC over prediction at low P_t, moderate ΣT_p

FSI probe

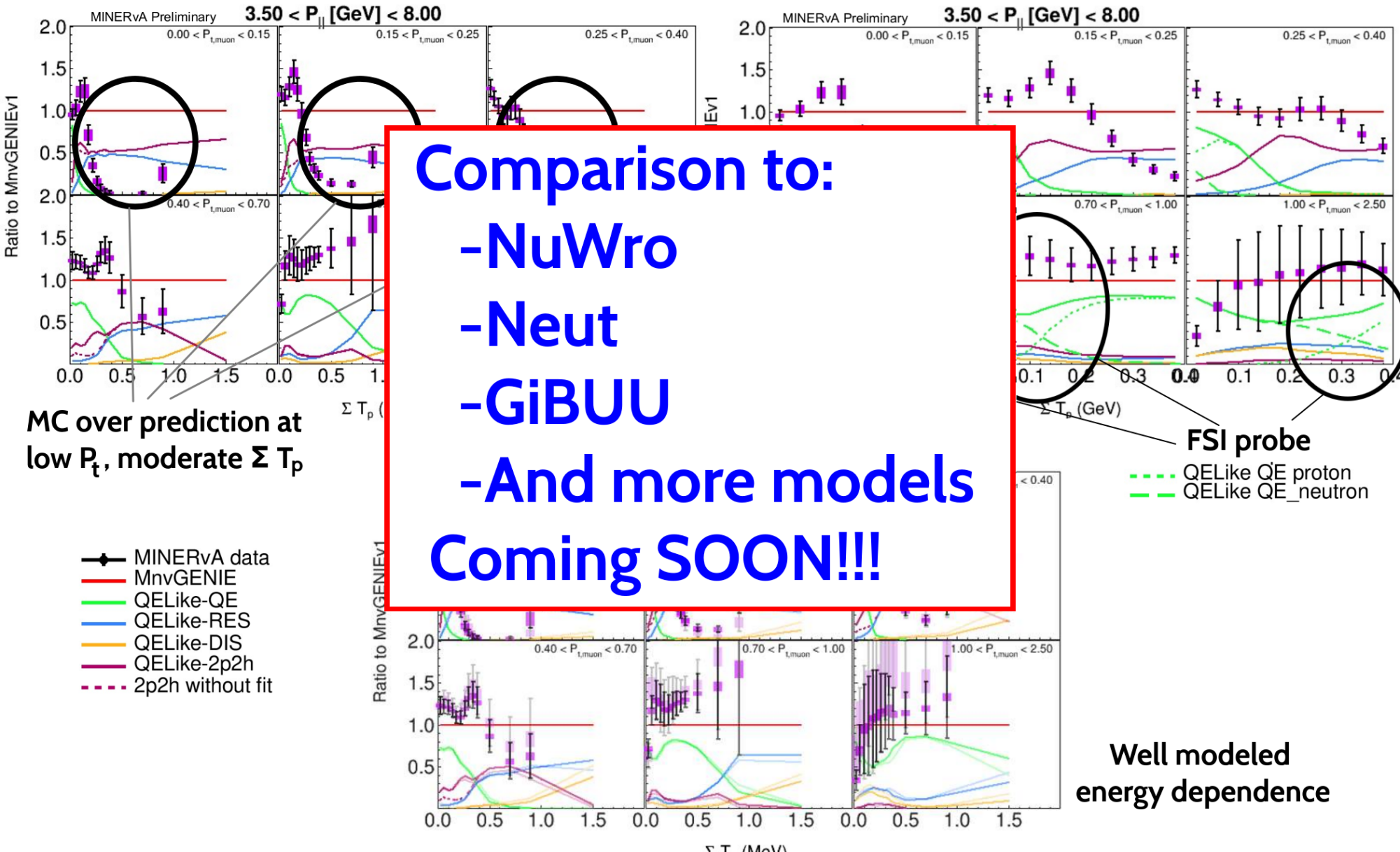
QELike QE proton
QELike QE_neutron

MINERvA data
MnvGENIE
QELike-QE
QELike-RES
QELike-DIS
QELike-2p2h
2p2h without fit



Well modeled energy dependence

ME ν_μ 3D CCQE - Some Conclusions



MC over prediction at low P_t, moderate ΣT_p

Comparison to:
- **NuWro**
- **Neut**
- **GiBUU**
- **And more models**

Coming SOON!!!

FSI probe

Well modeled energy dependence

$\overline{\nu}_\mu$ 2D CCQE in CH

Motivation - ME $\overline{\nu}_\mu$ 2D CCQE

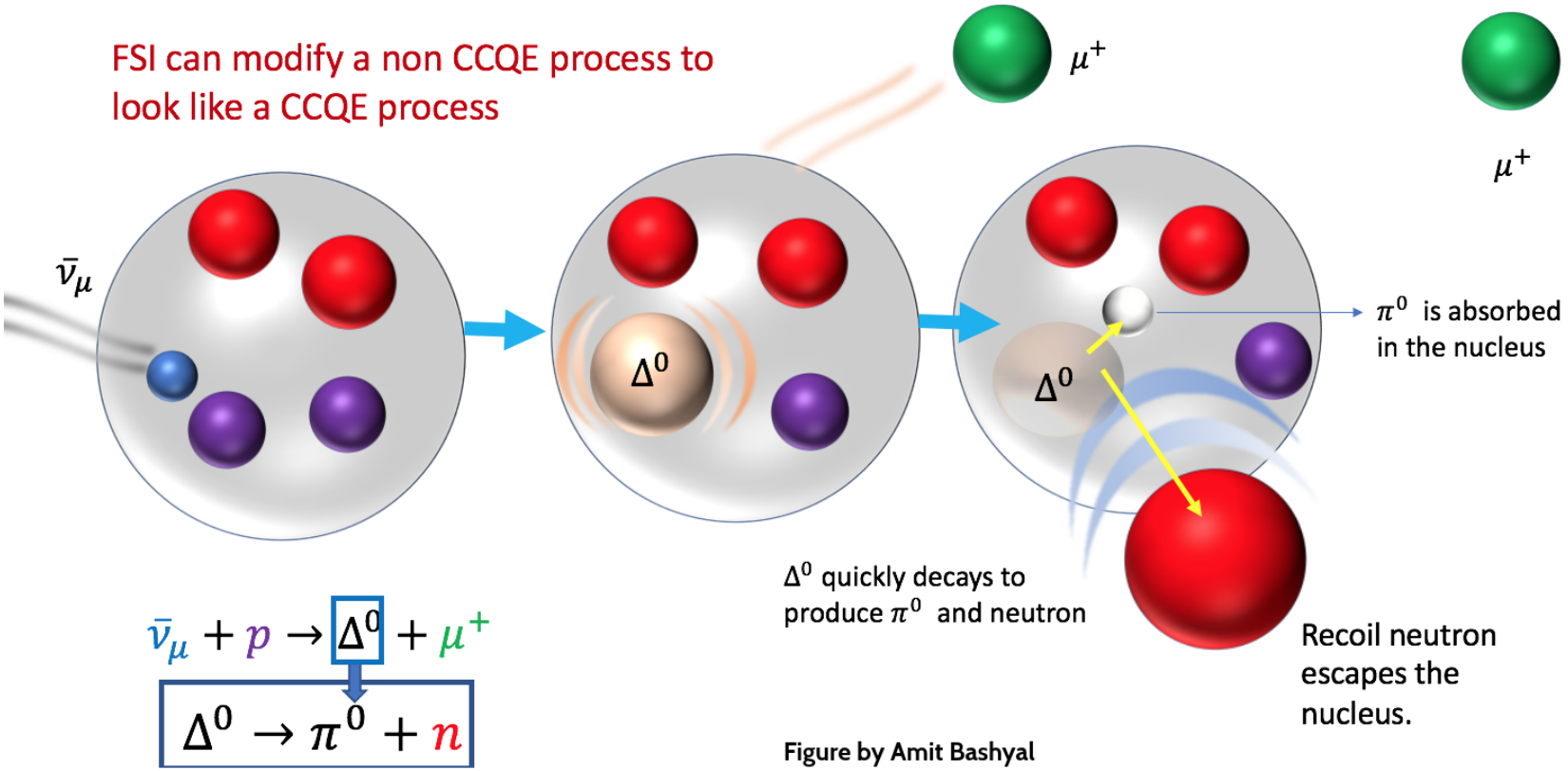
- Complement of the 2D LE anti-neutrino, and the 2D ME neutrino results.
- Important probe at high Q^2_{QE}, where models fail to describe the data.

Signal Definition

- Any number of nucleons.
- No mesons, or heavy baryons.
- Gammas < 10 MeV allowed (Deexcitation gammas).
- Muon angle with regards to the beam < 20 degrees.
- Proton kinetic energy > 120 MeV.

Initial and Final State Interactions

Remember, the nuclear medium matters!



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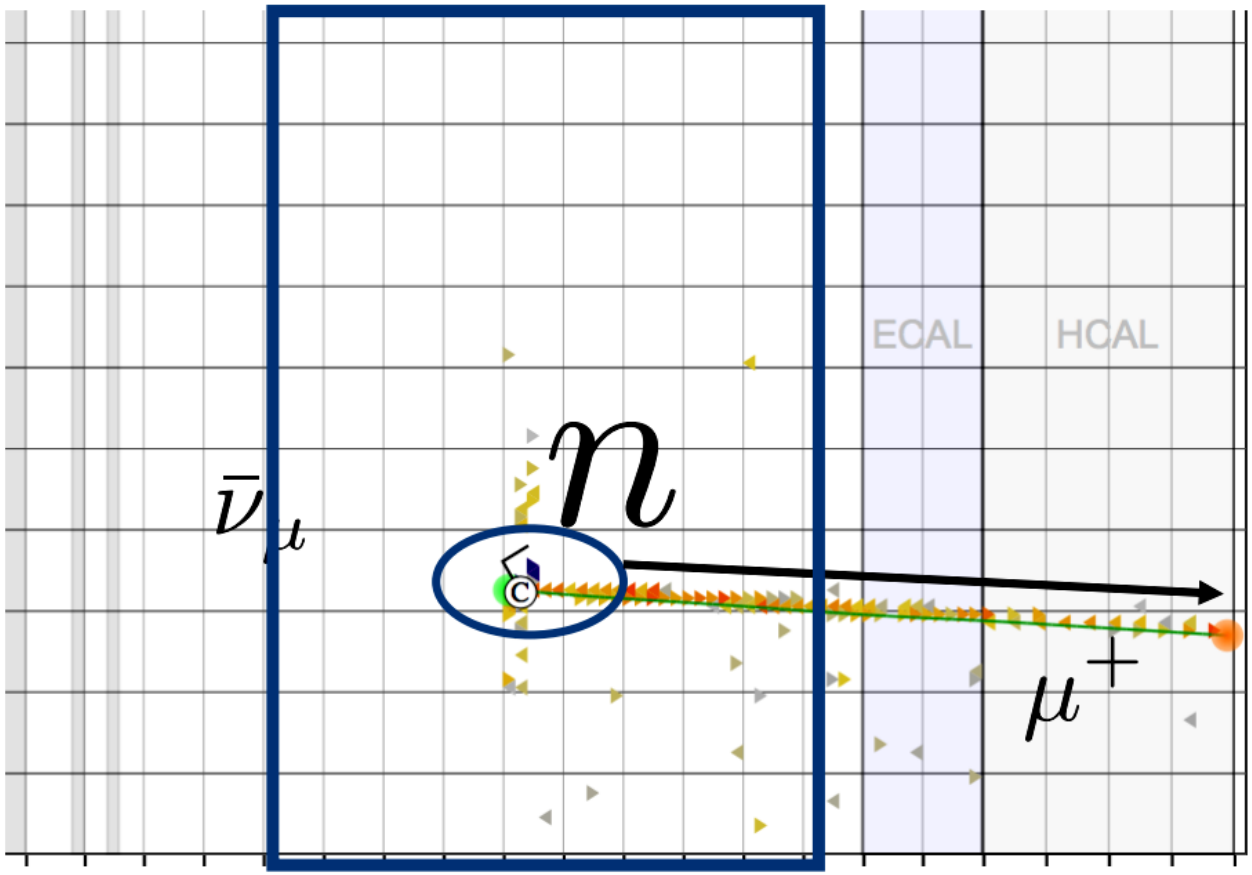
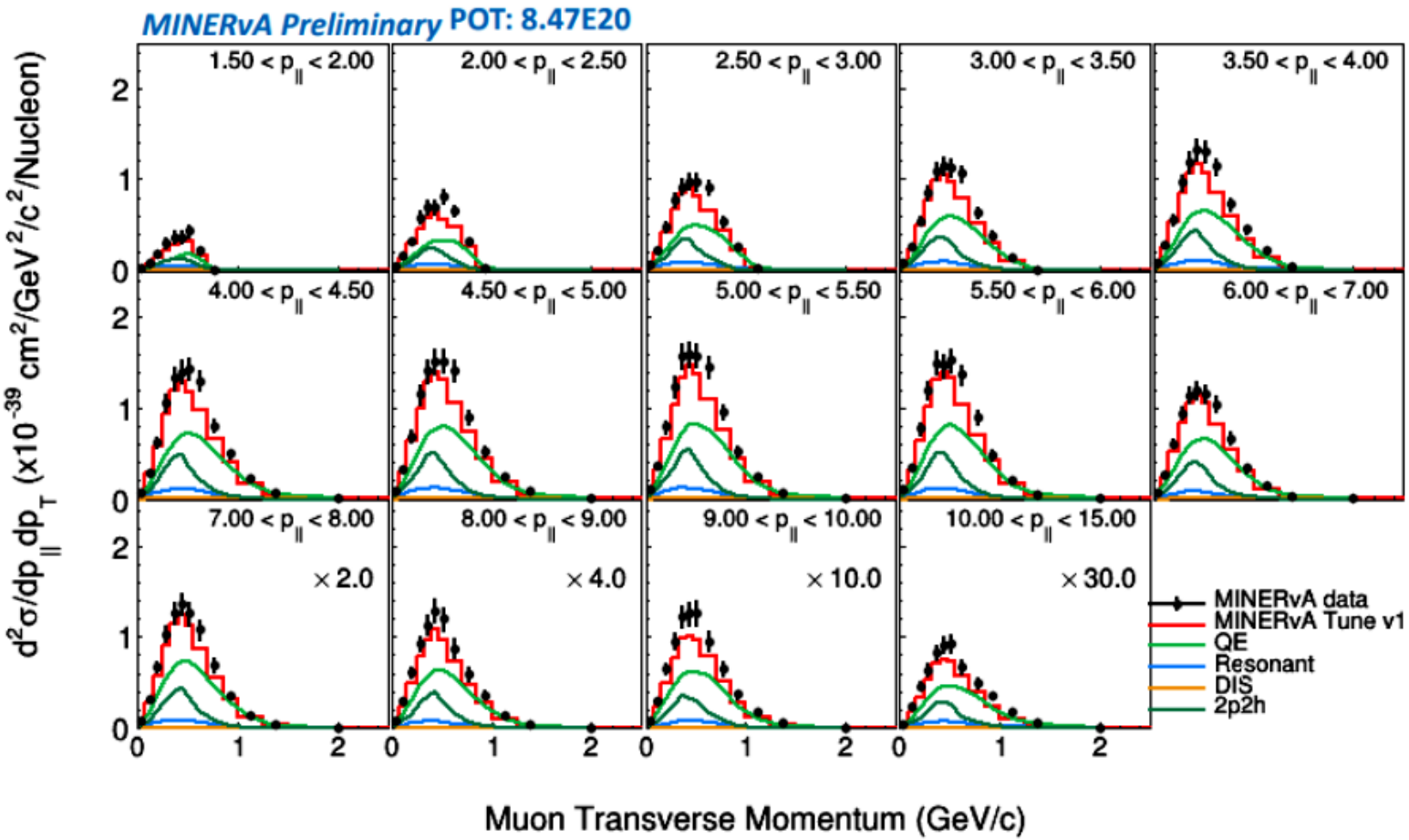


ME $\overline{\nu}_\mu$ 2D CCQE Cross Section - Preliminary

NEW!!!



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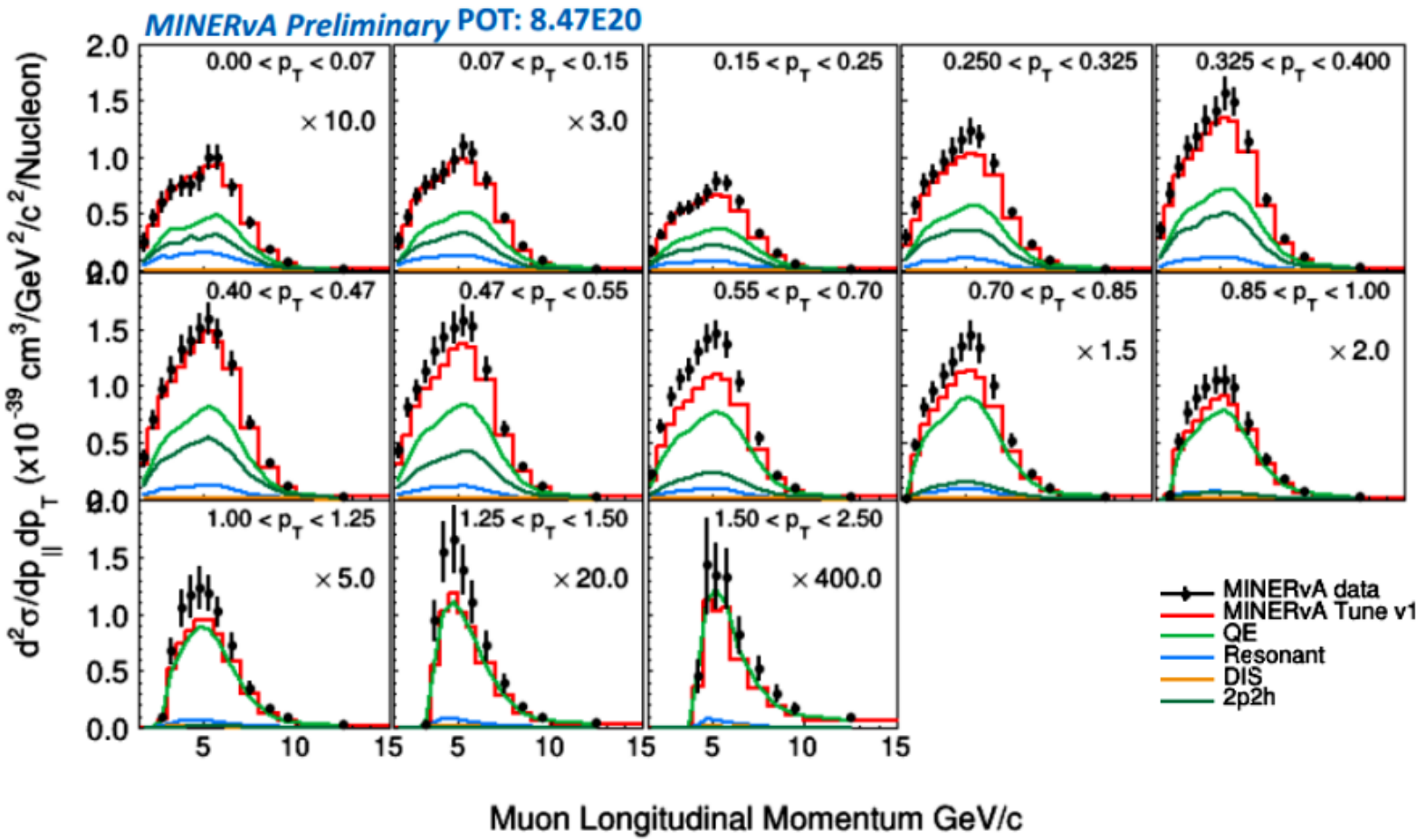

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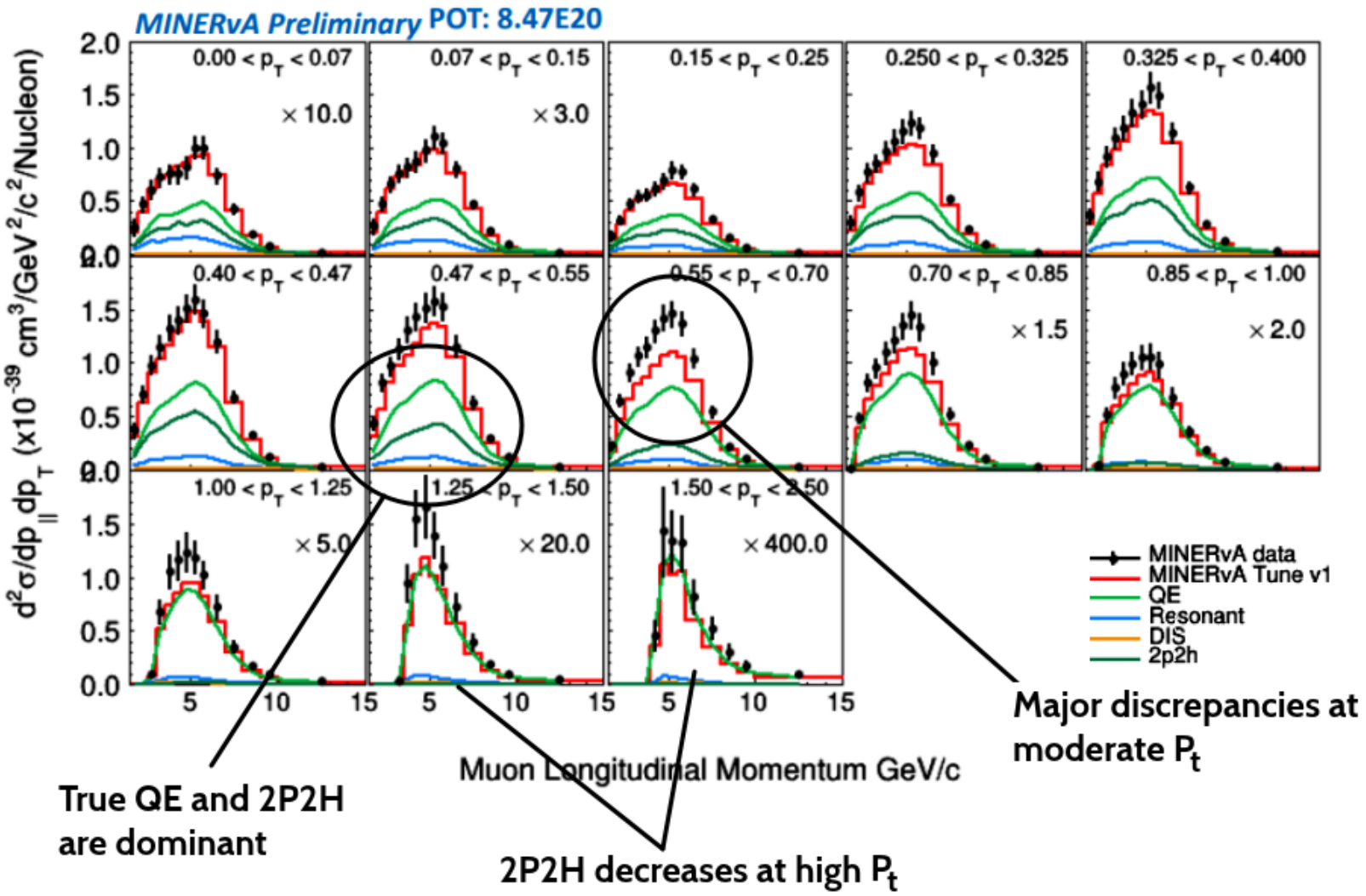

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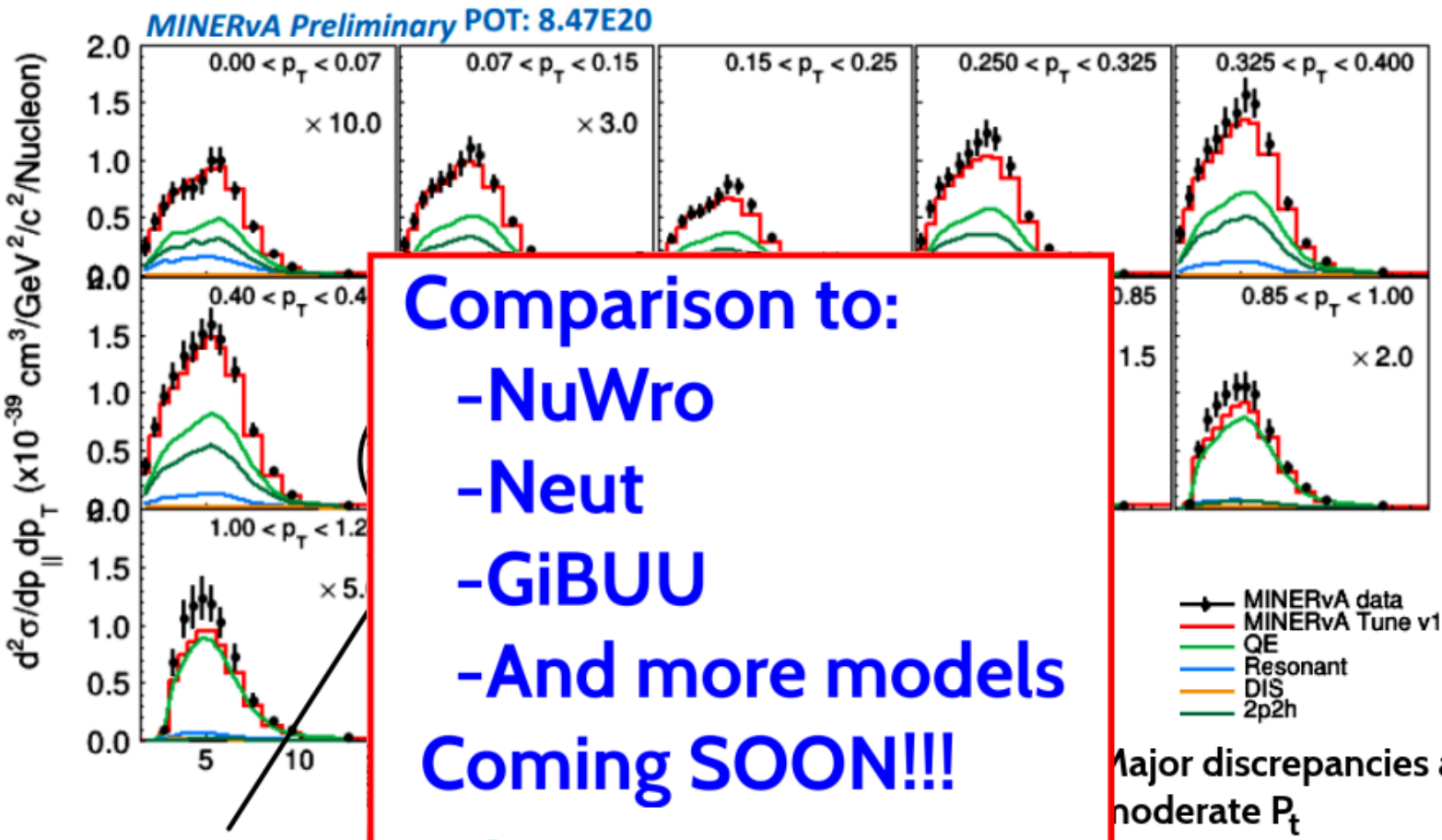


Comparison to:

- -NuWro
- -Neut
- -GiBUU
- -And more models

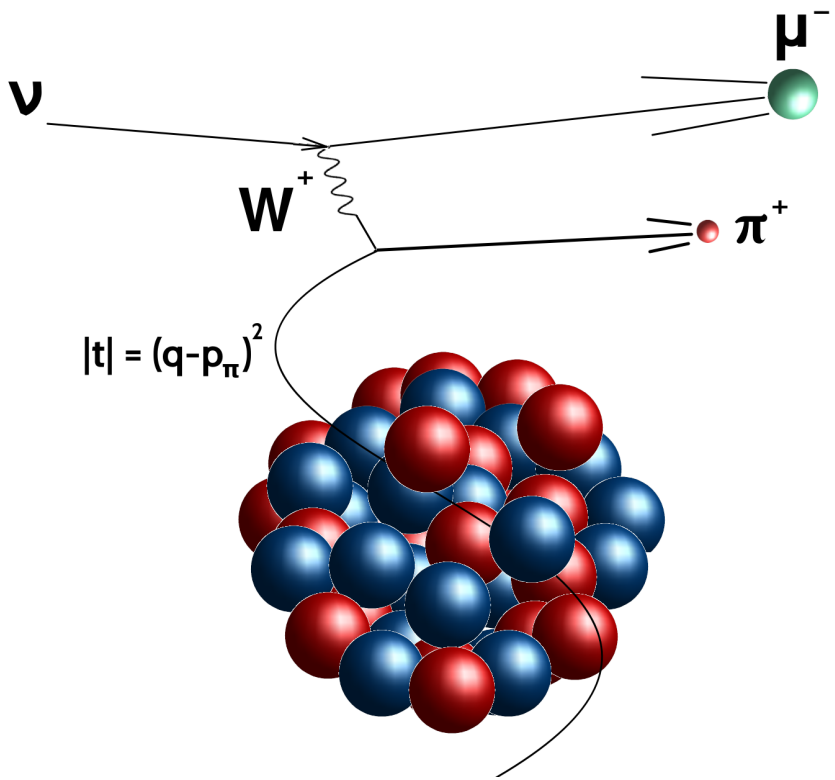
Coming SOON!!!

Plus cross sections in Q^2 and E_ν

ν_μ CC Coherent π^+ in C, CH, Fe and Pb

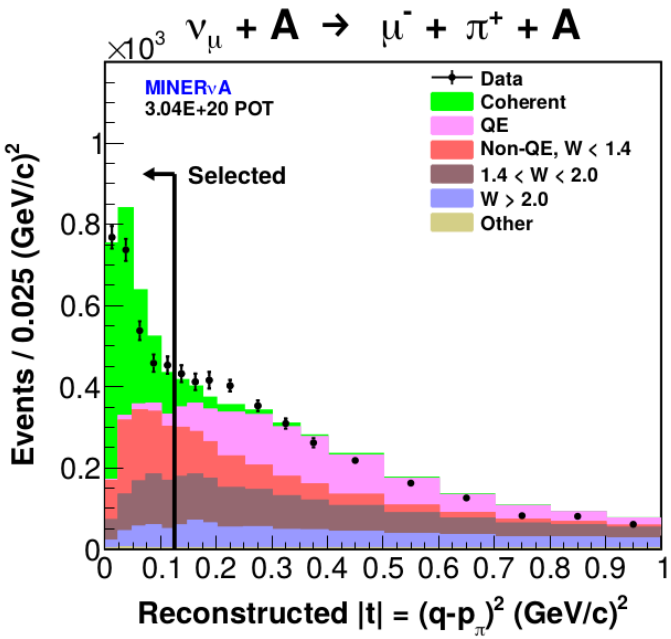
Coherent Interactions

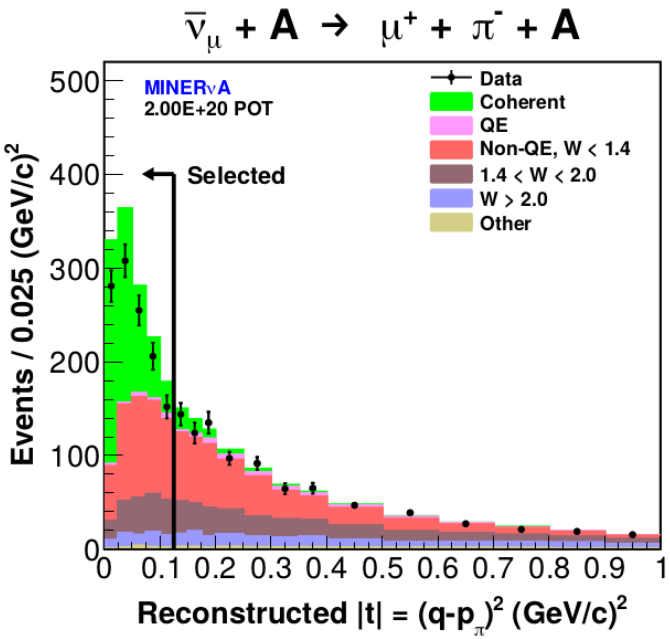
- Characterized by a low momentum transferred to the nucleus $|t|$, which is left in its ground state
- Phenomenology according to PCAC Models. MINERvA uses the one by Rein and Sehgal.



Low Energy CC Coherent Puzzle Solved by MINERvA

- Previously unobserved in the CC channel at lower energies.
- MINERvA observed the interaction by fully containing the pion, and looking at $|t|$ instead of Q^2.



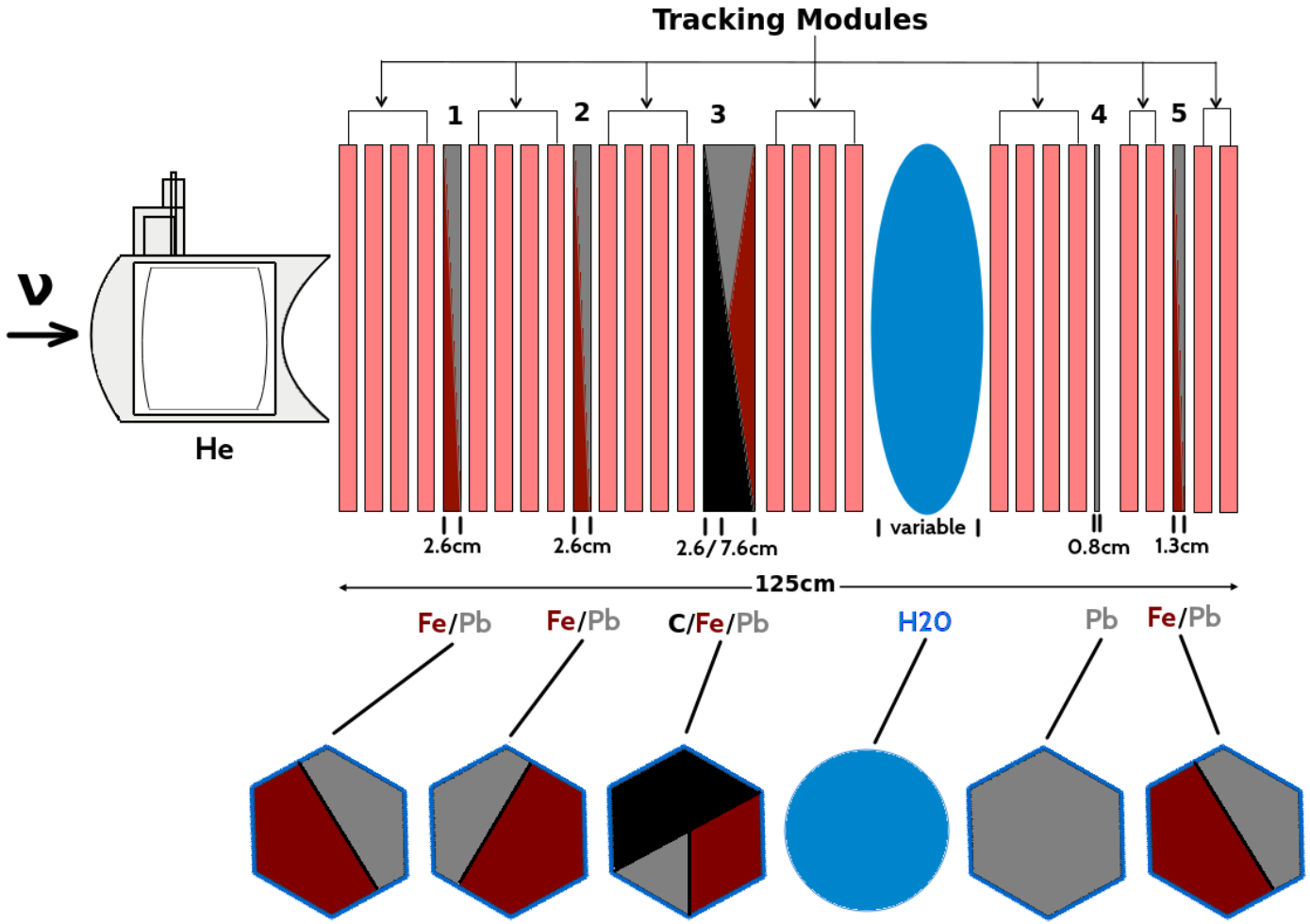


Motivation - ME ν_μ CC COH π^+

- ME complement of the LE CH analysis.
- Look at the interaction in heavier nuclei like Iron and Lead.
- Perform a simultaneous measurement in different materials, for exploring the A-Scaling of the interaction.

The Target Region

- He, H_2O, C, Fe and Pb targets for A-dependence studies.
- Position and thickness are for energy and areal acceptance purposes.

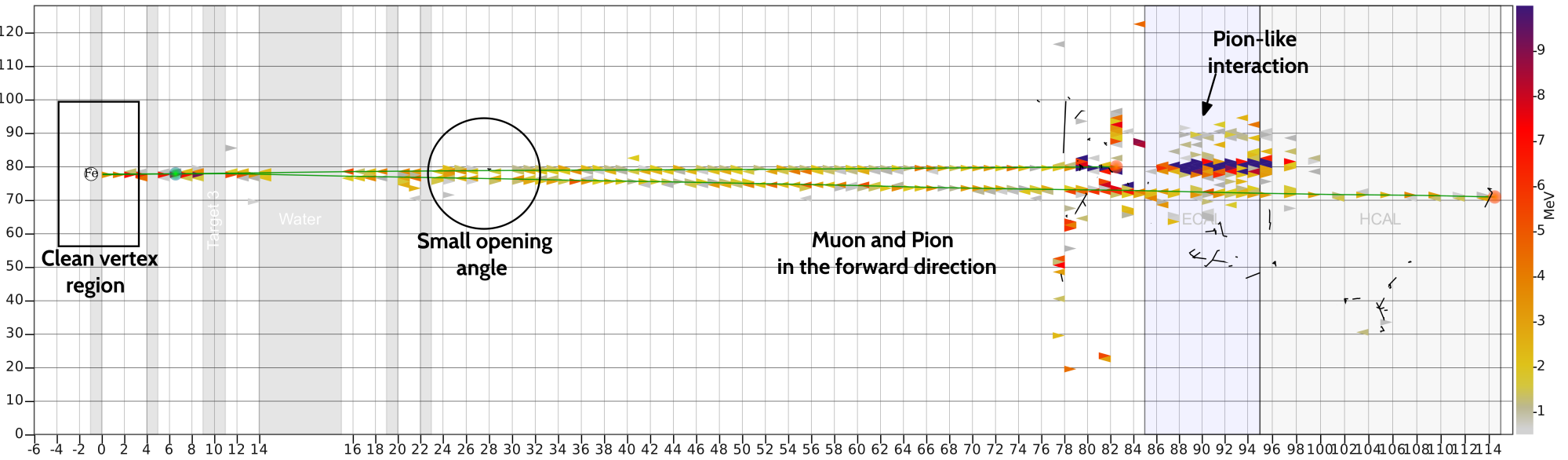


Signal Definition

- Negative muon and positive pion originated from the same vertex.
- No other particles created in the interaction vertex.
- Muon reconstructed in the MINOS detector.

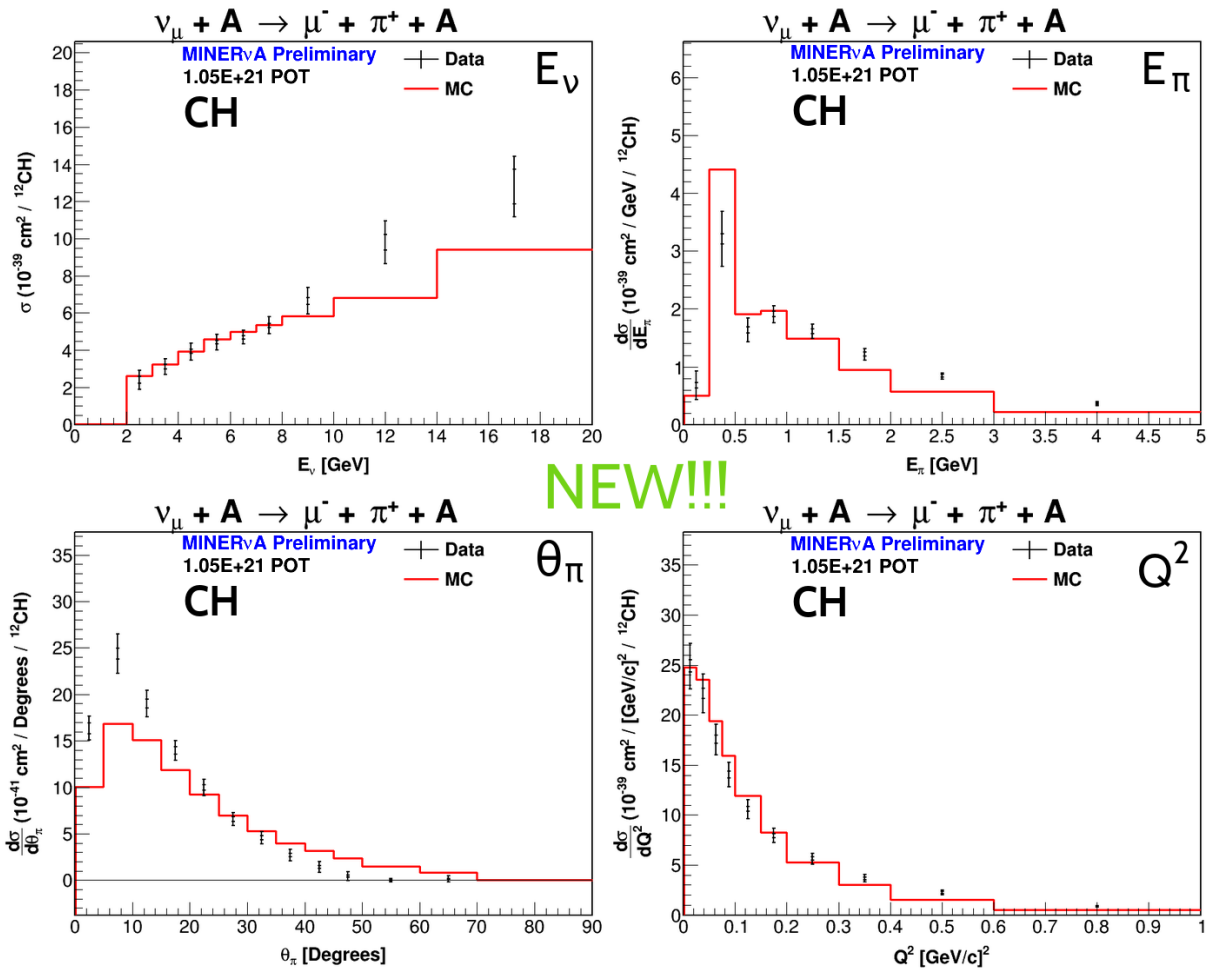
Event Selection

- Low vertex energy.
- Pion-like PID.
- Low momentum transferred to the nucleus.
- Muon reconstructed in the MINOS detector.



ME ν_μ CC COH π^+ - Preliminary

- Preliminary cross section in the CH "tracker" target.
- Consistency with LE analysis.
- ME analysis has not included diffractive contribution.



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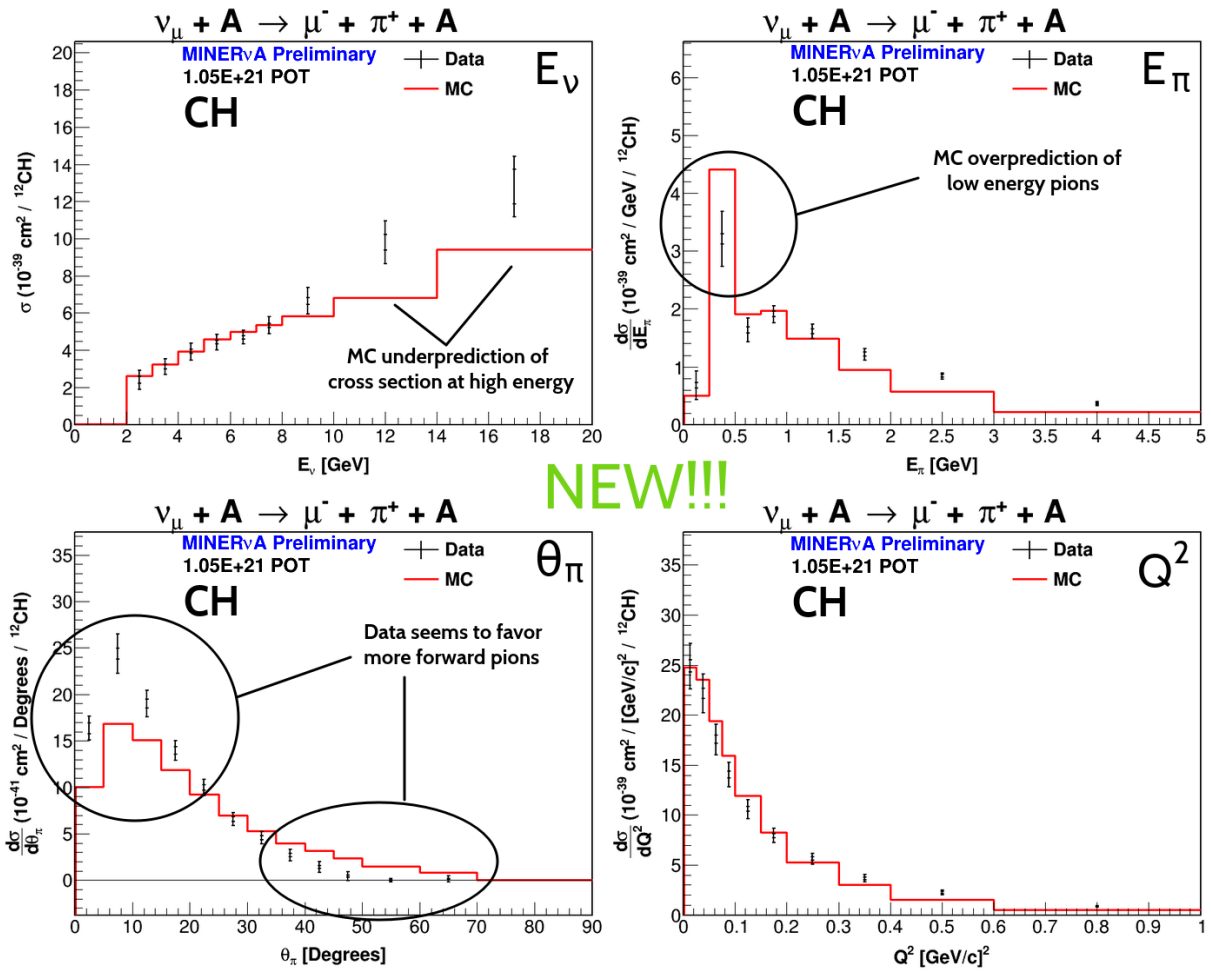
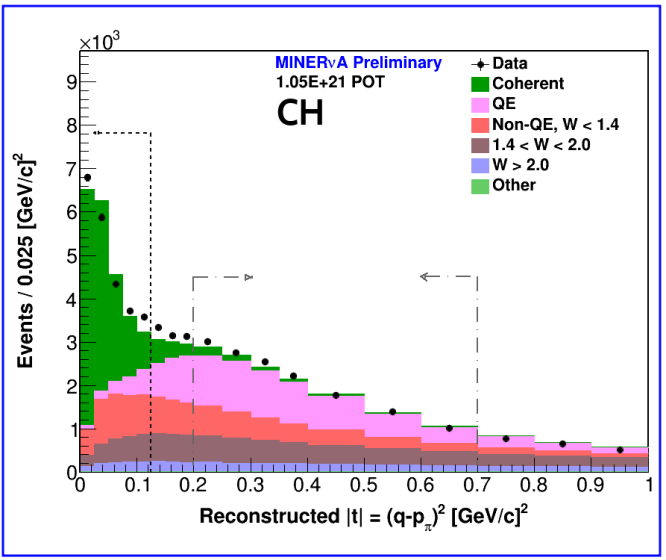
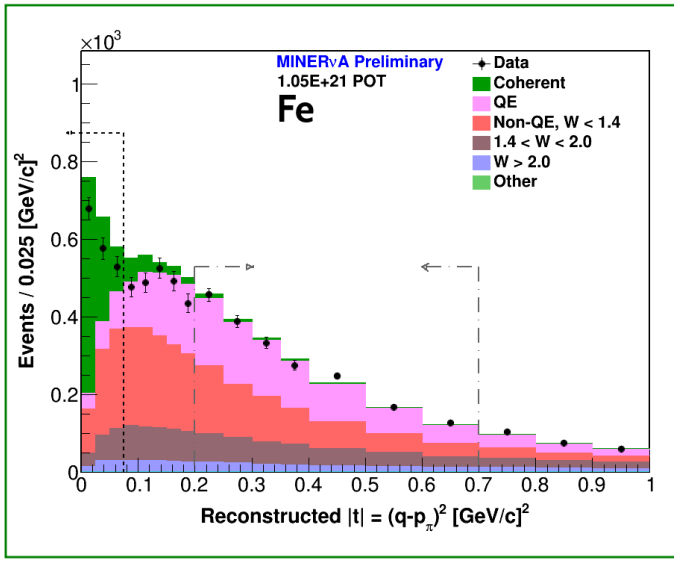


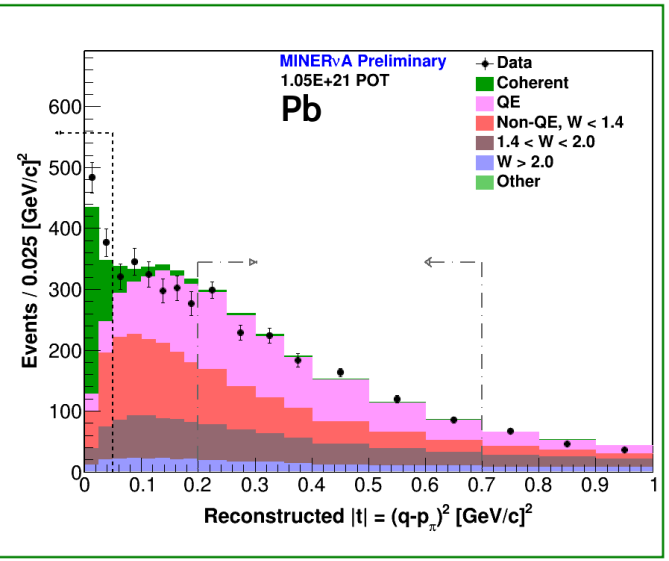
Momentum Transfer to the Nucleus $|t|$ - Preliminary

- Strong indication of CC COH π^+ in Iron and Lead, for the first time.
- CH sample is the largest statistical sample of the interaction.
- A sample from a "pure" carbon target, is also under study.

NEW!!!







High Statistical Sample

Low |t| Peak Consistent With Coherent Pi$^+$ in Fe and Pb

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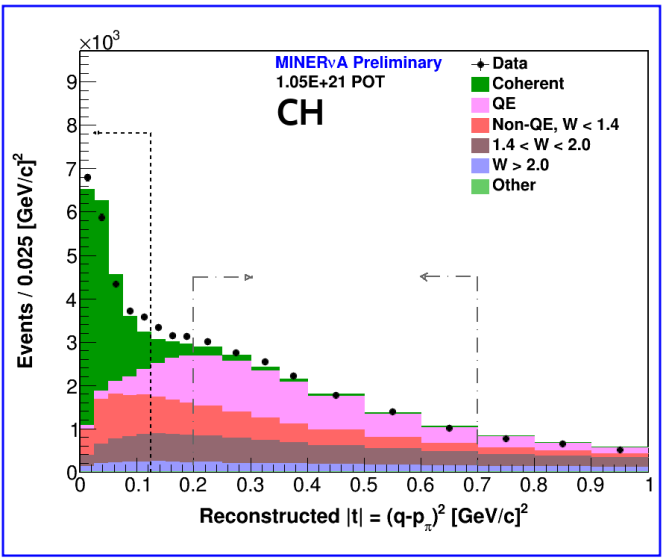

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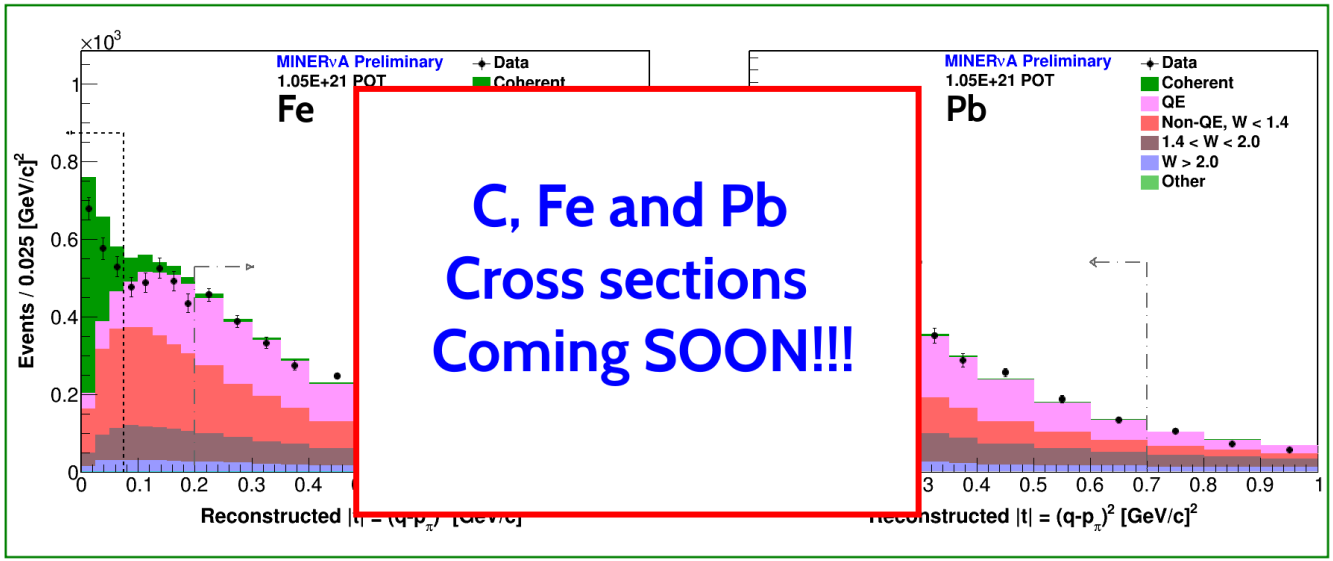


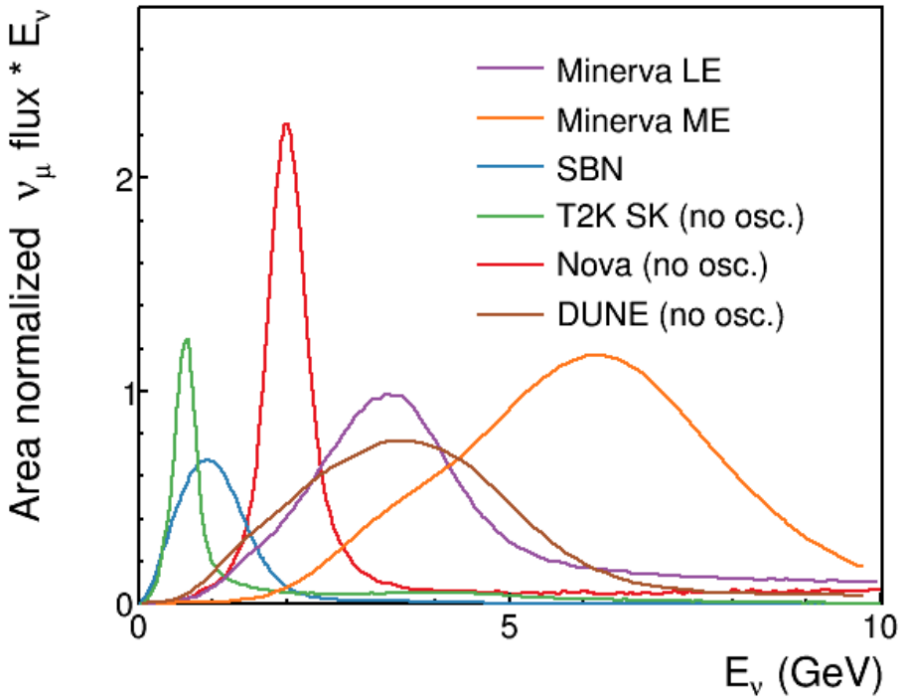
C, Fe and Pb Cross sections Coming SOON!!!

Low |t| Peak Consistent With Coherent Pi$^+$ in Fe and Pb

Data Preservation Effort

MINERvA's Data Relevance

- Relevant both theoretical and experimentally, particularly for DUNE.
- Although due to its high statistics, energy range, in both ν_μ and $\overline{\nu}_\mu$ modes, it isn't hard to envision many other applications.
- Of special importance is the data simultaneously taken in different materials: H, He, C, O, Fe and Pb.



MINERvA's Data and Analysis Infrastructure for the Future

- Good old data needs to be revisited as models evolve.
- However, our ability to access it, might go from challenging to impossible.
- Ideally every experiment's data would be accessible in the future.
- MINERvA has started doing it, why don't you all follow?

What a Future User Will Need From Us

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- Access to "Data" (Recorded and Simulated).
- A Data Analysis Infrastructure.

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What We Will Deliver

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- Access to "Data" (Recorded and Simulated).
- A Data Analysis Infrastructure.

What We Will Deliver

- Access to "Data" in the form of a single ROOT tuple, with low- and high-level reconstructed objects.
- A MINERvA Analysis Toolkit "MAT".
  - Infrastructure for producing new, and already published results.
  - It includes the parallel treatment of systematic uncertainties.
  - All, using data from the ROOT tuple.
- Plus a paper! https://arxiv.org/abs/2009.04548

Final Goal

- Deliver a state-of-the-art infrastructure to analyze all this data

	POT ($\times 10^{20}$)		ν_μ Interactions		Publications	
	LE	**ME**	**LE**	**ME**	**LE**	**ME**
ν_μ	4.0	12.1	$\gtrsim$ 300k	$\gtrsim$ 4M	22	2 + ??
$\overline{\nu}_\mu$	1.7	12.4	$\gtrsim$ 50k	$\gtrsim$ 2M	10	??

So users can:

- Reproduce MINERvA published result.
- Produce new results!

Conclusions

- MINERvA's ME Effort is getting closer to produce a lot of interesting results.
  - Reproducing LE results with higher statistics and precision.
  - Including brand new results!
- The CCQE analyses have taken the lead in the ME era, with one published result, and two more coming soon.
- More exclusive channels have been enabled, specially in the "target region", also due to the increase in statistics, and are getting closer to completion, such as the CC Coherent π^+.
- Not happy with all that, MINERvA has started developing an infrastructure to make all its results and data, available for the physics community! ;D

Backup

QE Kinematics

- Free nucleons at rest.

$$E_{\nu,QE} = \frac{M_p^2 - (M_n - E_b)^2 - M_\mu^2 + 2(M_n - E_b)E_\mu}{2(M_n - E_b - E_\mu + P_\mu \cos(\theta_\mu))}$$

$$Q^2_{QE} = 2E_{\mu,QE}\left(E_\nu - P_\mu \cos\left(\theta_\mu\right)\right) - M_\mu^2$$

- E_ν, E_μ and E_b, are the neutrino, muon and binding energy, respectively.
- M_x represents the particle "x" mass.

CC COH Kinematics

- Considering the nucleus at rest, and the energy transfer to it, negligible, the neutrino energy is expressed like:

$$E_\nu \simeq E_\mu + E_\pi$$

- With that assumption, $|t| = |(p_\nu - p_l - p_\pi)^2|$ can be expressed in terms of the μ and π kinematics like:

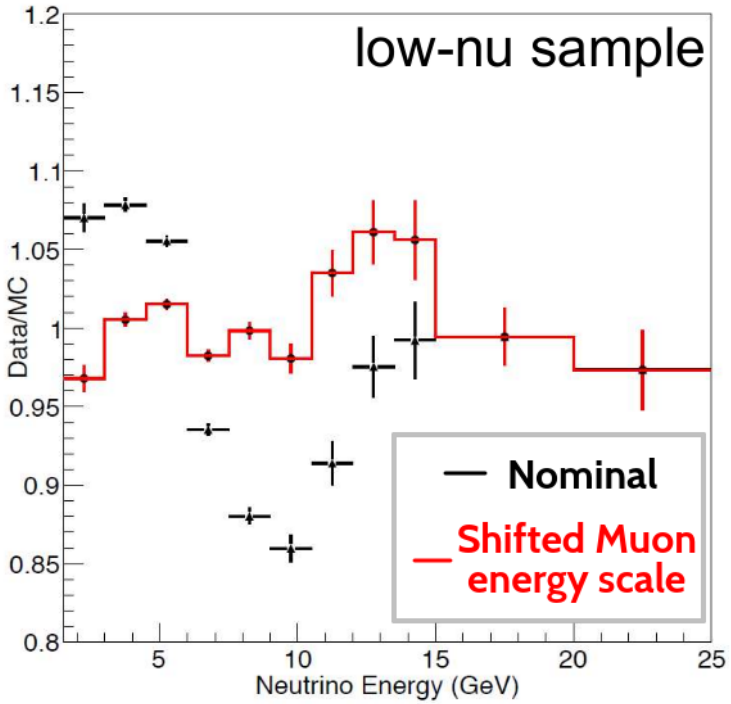
$$|t| \simeq \left(\sum_{i=l,\pi} p_T^i \right)^2 + \left(\sum_{i=l,\pi} (E^i - p_L^i) \right)^2$$

- Which after deploying the algebra is written like:

$$\begin{aligned} |t| \simeq |&2\left(E_\mu + E_\pi\right)\left(E_\mu - p_\mu \cos\theta_{\nu\mu}\right) - m_\mu^2 \\ &- 2\left(E_\pi^2 - \left(E_\mu + E_\pi\right) p_\pi \cos\theta_{\nu\pi} + p_\mu p_\pi \cos\theta_{\mu\pi}\right) + m_\pi^2| \end{aligned}$$

"A Priori" ME Flux Prediction

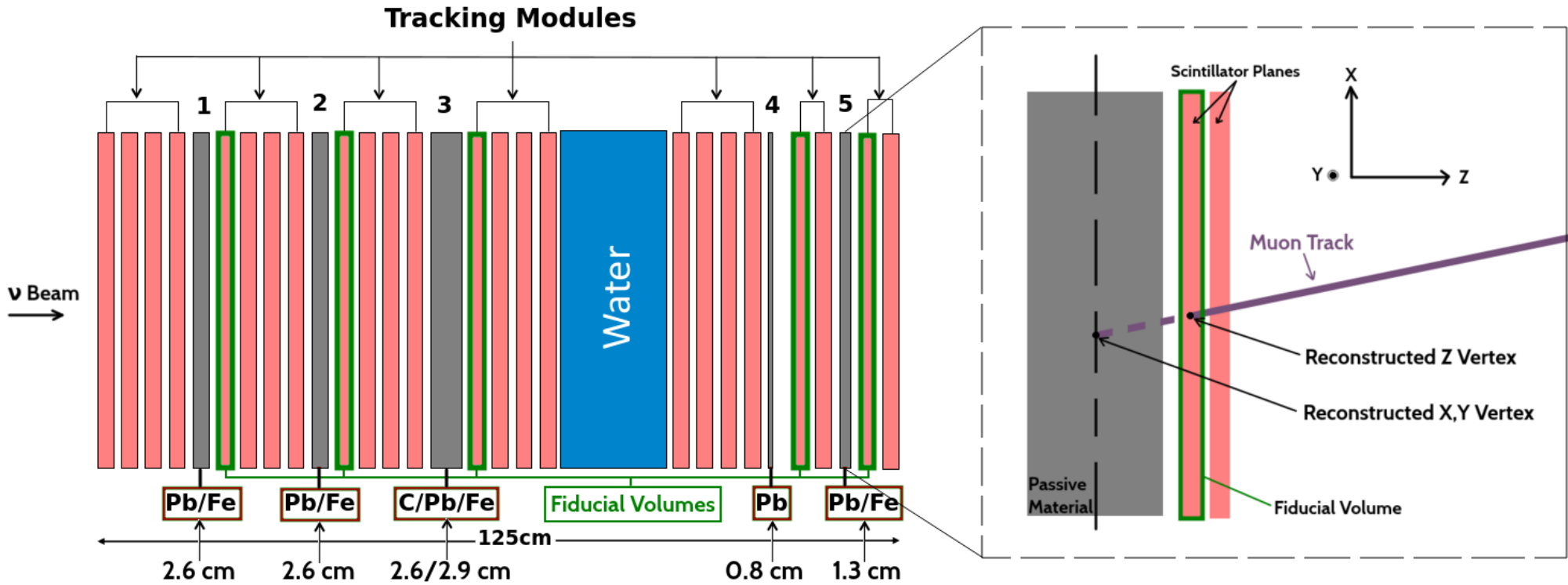
- From fits "with" and "without" constrained beam parameters, it was determined the muon energy scale was shifted by 3.6% (1.8σ).



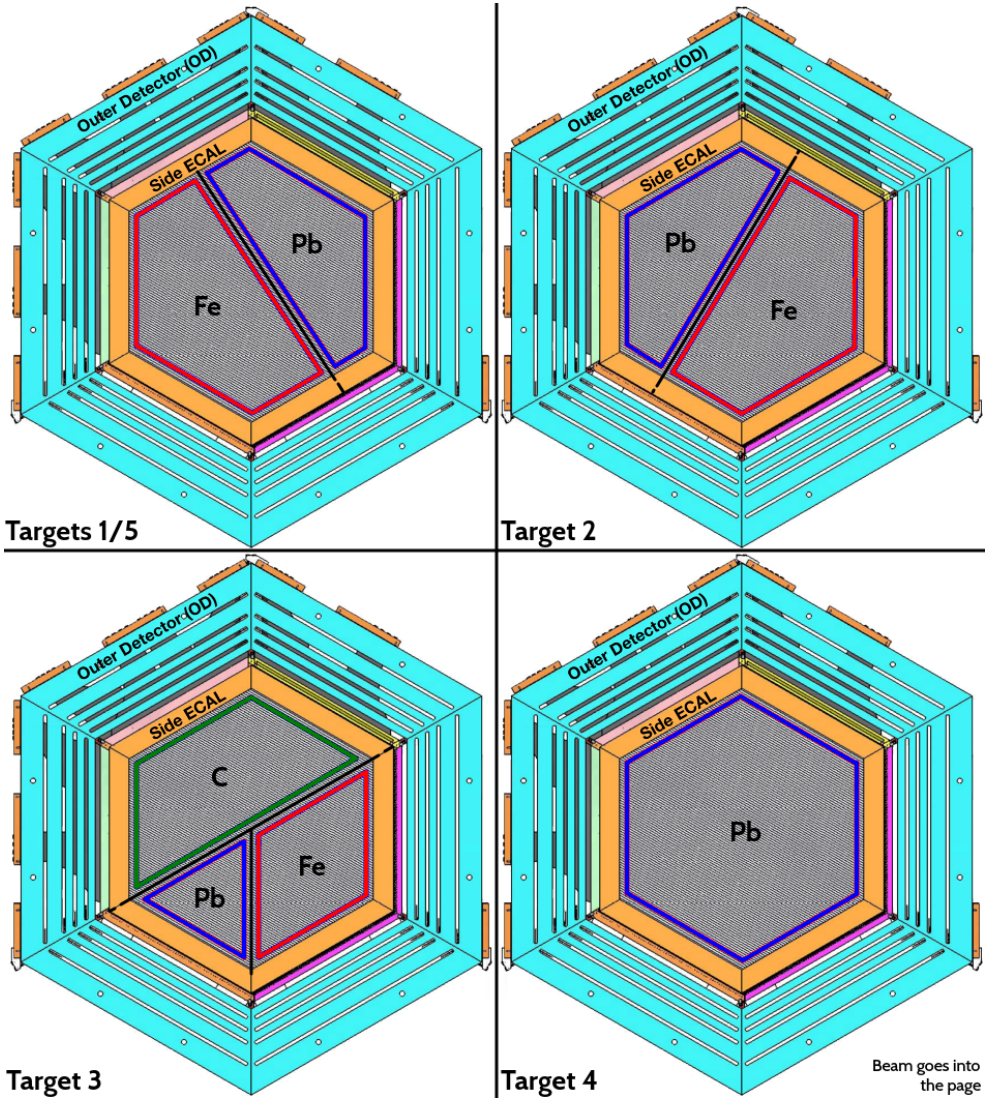
Leading Systematics

- ν_μ 3D CCQE, and $\overline{\nu}_\mu$ 2D CCQE
  - Flux
  - Muon Energy Scale
  - Cross Section Model: Uncertainty on the QE axial mass / FSI Models.
- ν_μ CC COH π^+
  - Muon Energy
  - Flux
  - Cross Section Model: FSI Models.

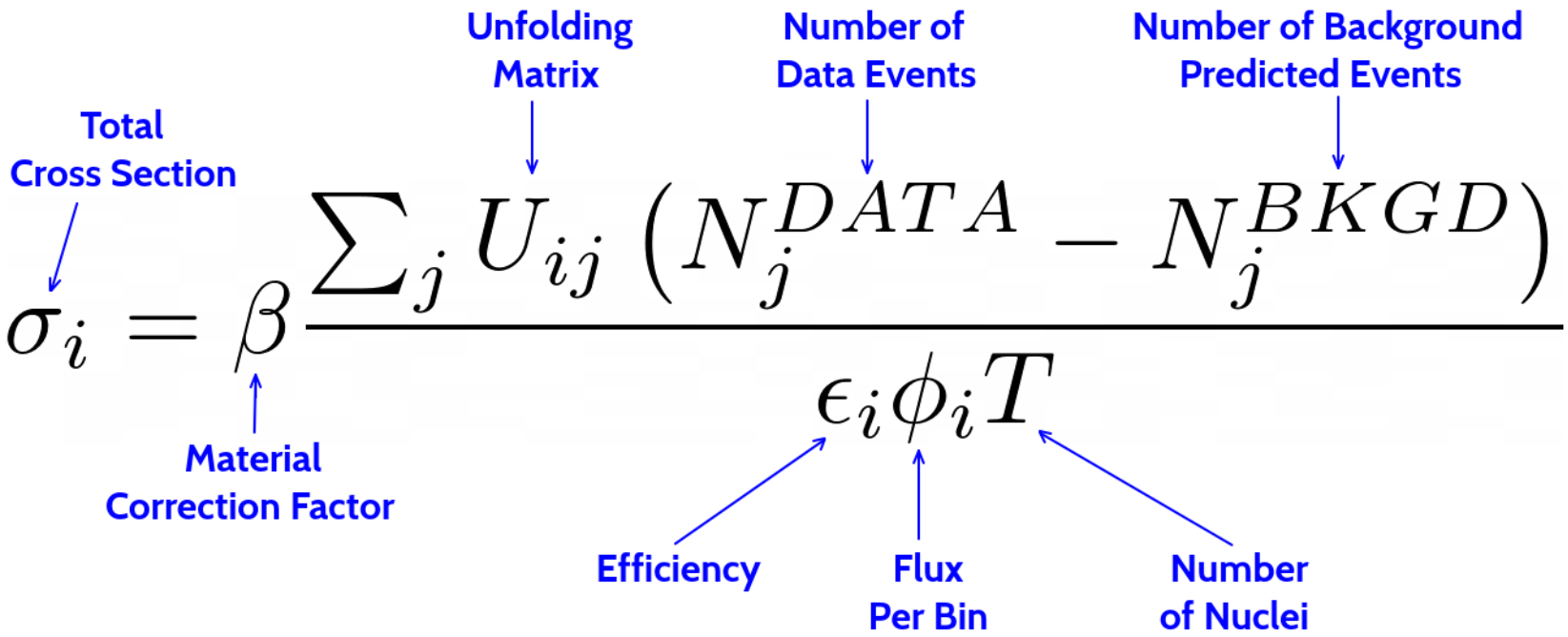
Fiducial Volume for the CC COH π^+ in the Passive Materials



Front View of Passive Materials

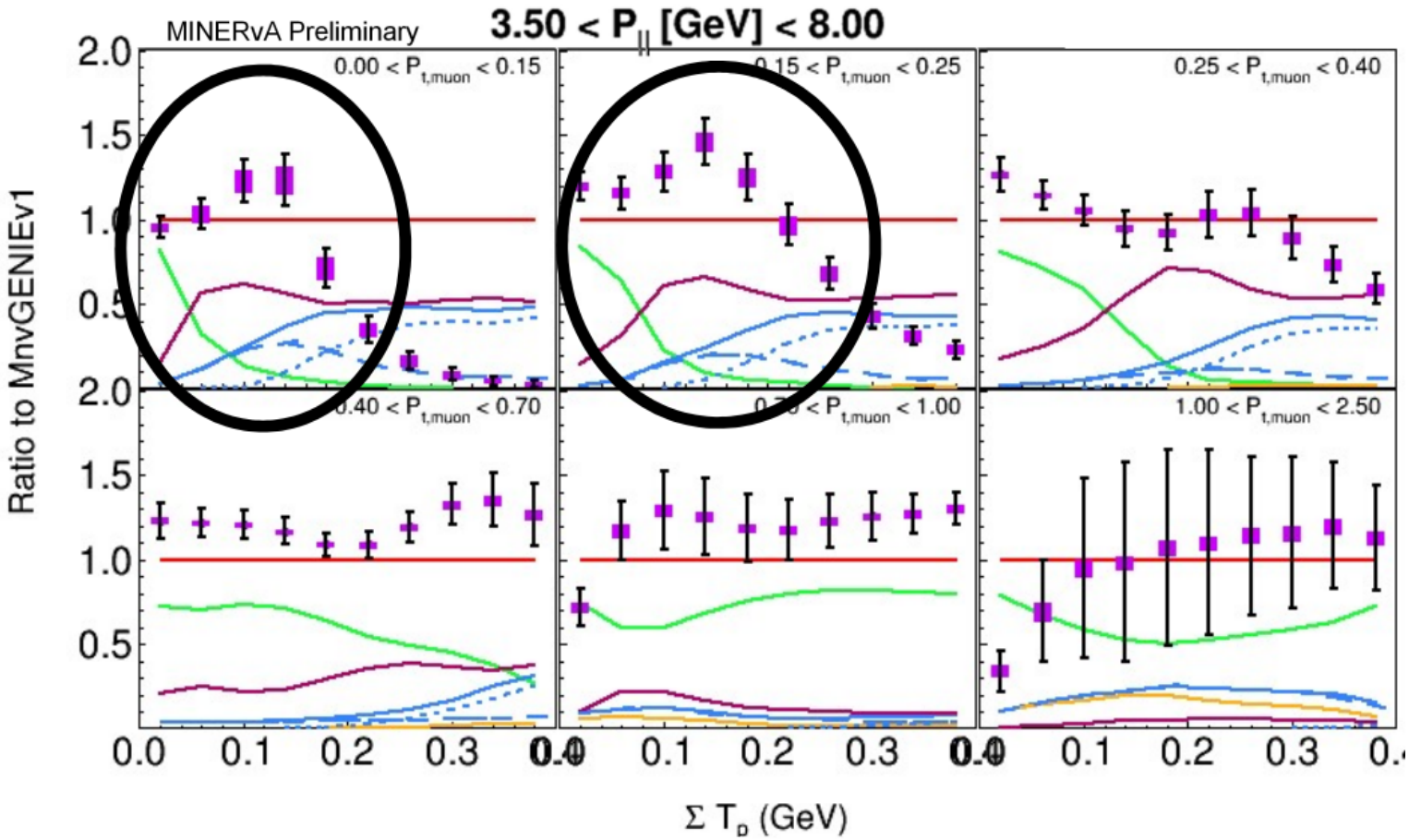


Cross Section Extraction Formula



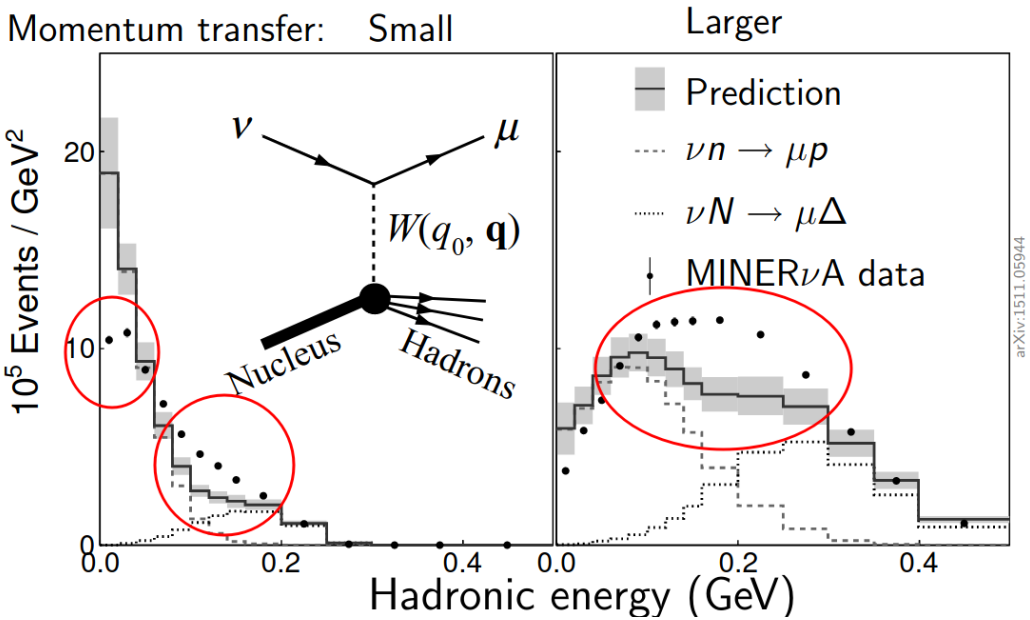
FSI in Resonance Background - ν_μ 3D CCQE

- Neutron-Proton separation in the RES background contribution



Low Recoil and its Fit

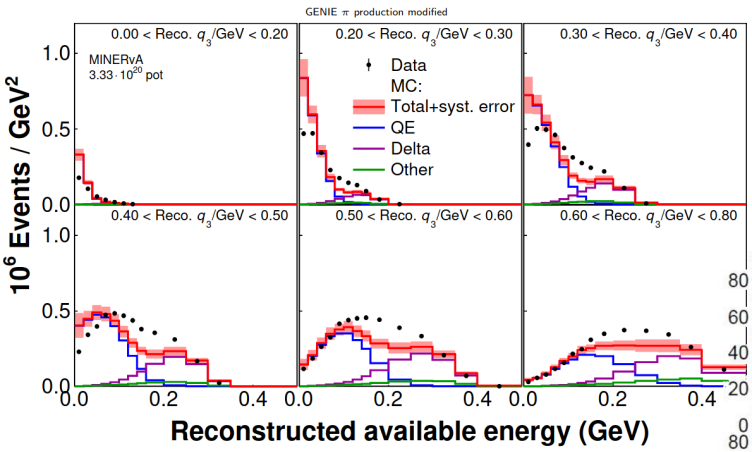
- A low-recoil inclusive sample saw important differences at both, low and large momentum transfer.



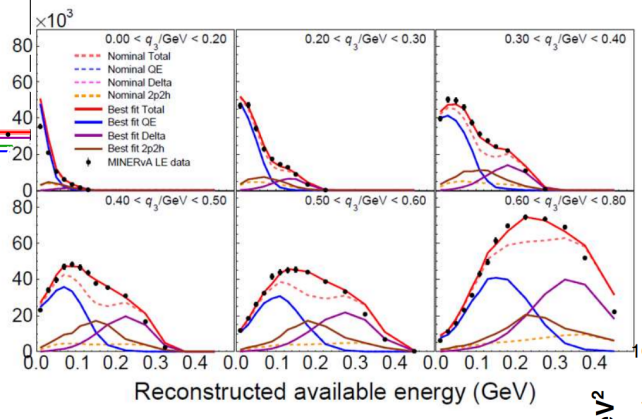
- The LE analysis showed improvements implementing RPA and 2P2H contributions, but tensions remained.
- An empirical fit obtained from that analysis has been successful in describing new data.

Low Recoil and its Fit (Continued)

- The ME analysis is implementing this fit, plus new techniques to study this, using many more statistics.



LE result



LE-based fit

ME in progress