MINERvA experiment: Most Recent results and Future plans

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On behalf of MINERvA collaboration

WILLIAM & MARY
CHARTERED 1693

Symposium: Nucleon and nuclei structure from inclusive measurements

Main INjector ExpeRiment ν-A

A. MINERνA was/is an experiment dedicated to studying neutrino-nucleus interactions in the NuMI (Neutrinos at the Main Injector) beamline at Fermilab:
   1. High statistics neutrino and antineutrino data
   2. Neutrino energy range of ~1-50 GeV
   3. Array of nuclear targets (CH, Fe, Pb, C, H_2O, He) allow for study of nuclear effects
   4. Viability for various inclusive and exclusive final state measurements

B. Primary goal is to characterize neutrino interactions for oscillation experiments.

C. Identify the nuclear effects and test models.

D. MINERvA works to demonstrate key near detector techniques for oscillation experiments.

E. We want to probe neutrino interactions from "big" to "small" targets:
   Nucleus → Nucleons → Quarks

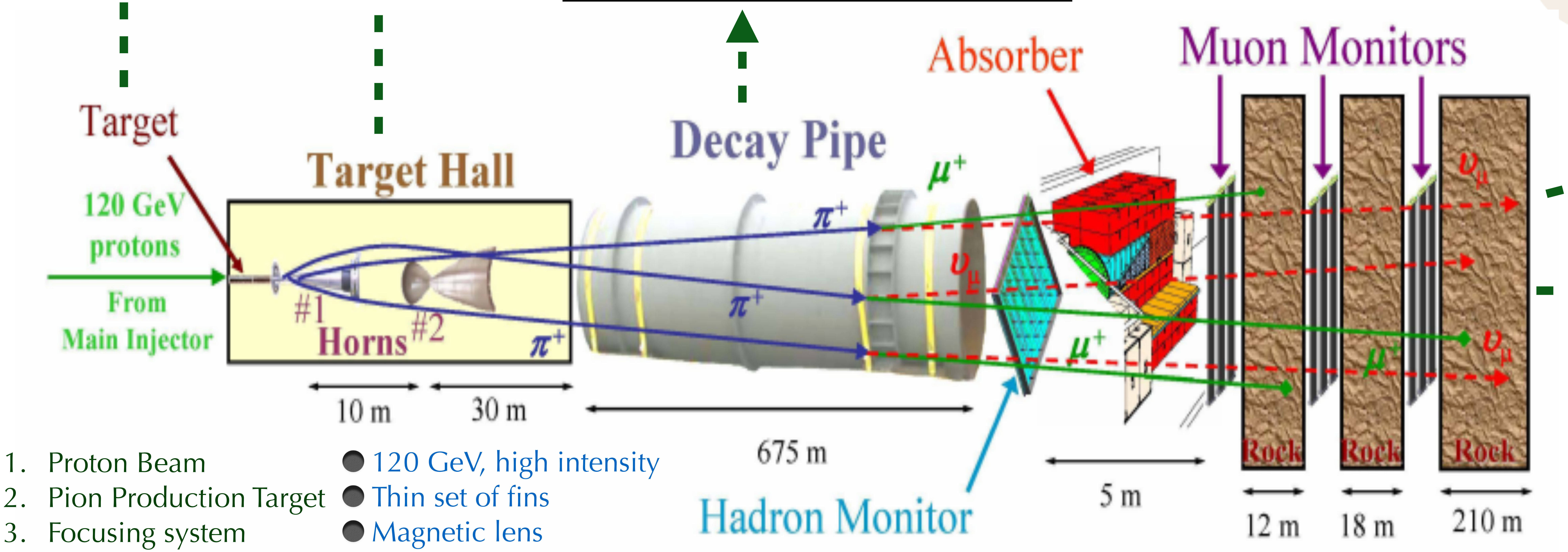
F. Unique overlap to DUNE flux.

NuMI (Neutrinos at Main Injector) Beamline

120 GeV protons strike a graphite target and hadronic cascade is created

Pions and kaons are focused by 2 magnetic horns

Pions and kaons decay



NOvA

MINERvA

MINOS

1. Proton Beam
2. Pion Production Target
3. Focusing system
4. Decay Region
5. Monitors, absorbors, sheildings

- 120 GeV, high intensity
- Thin set of fins
- Magnetic lens
- Tunnel, filled with helium
- Filter out the non-neutrinos

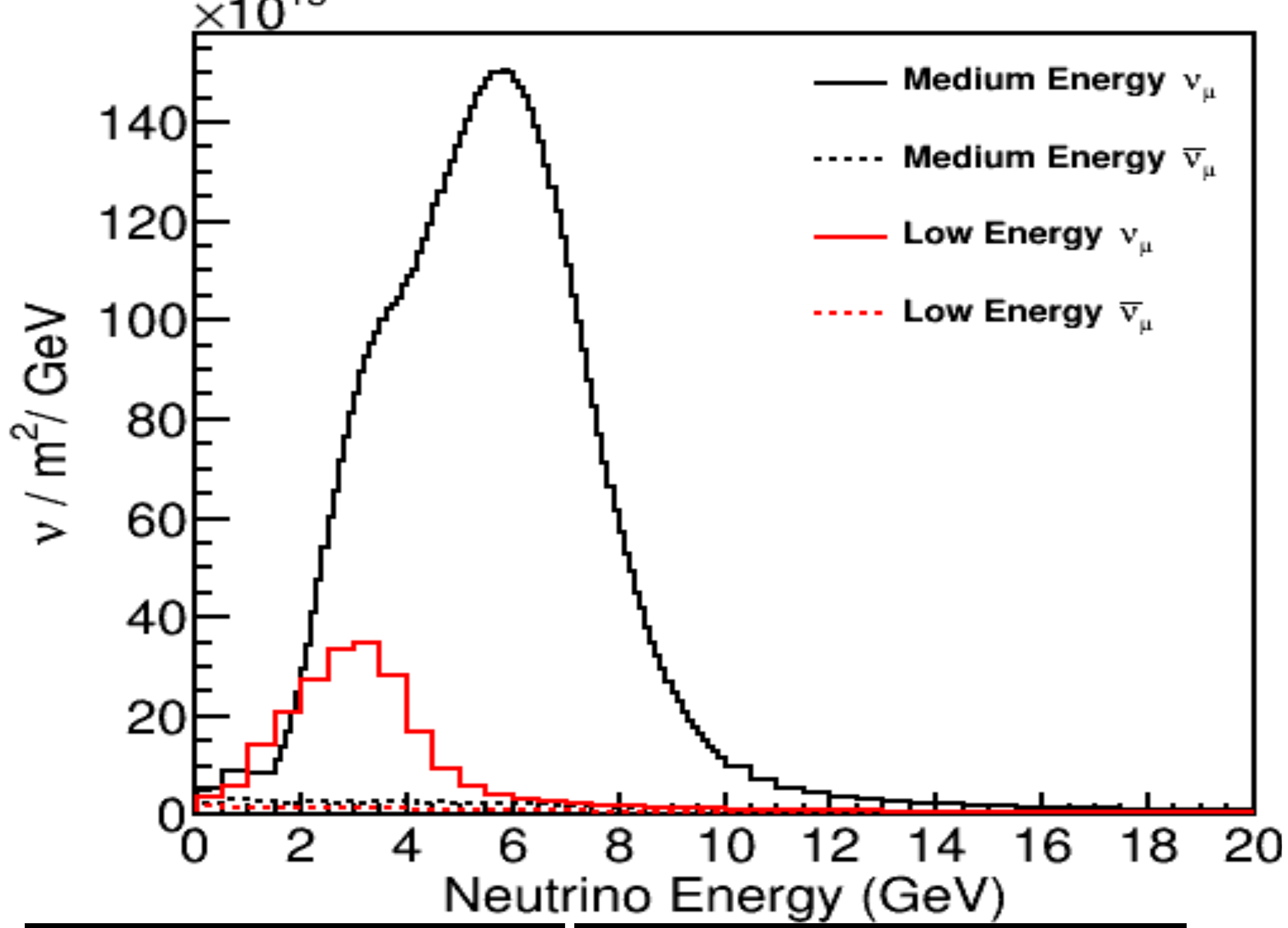
Note: A special thanks to Fermilab accelerator and computing division.

MINERvA Datasets history

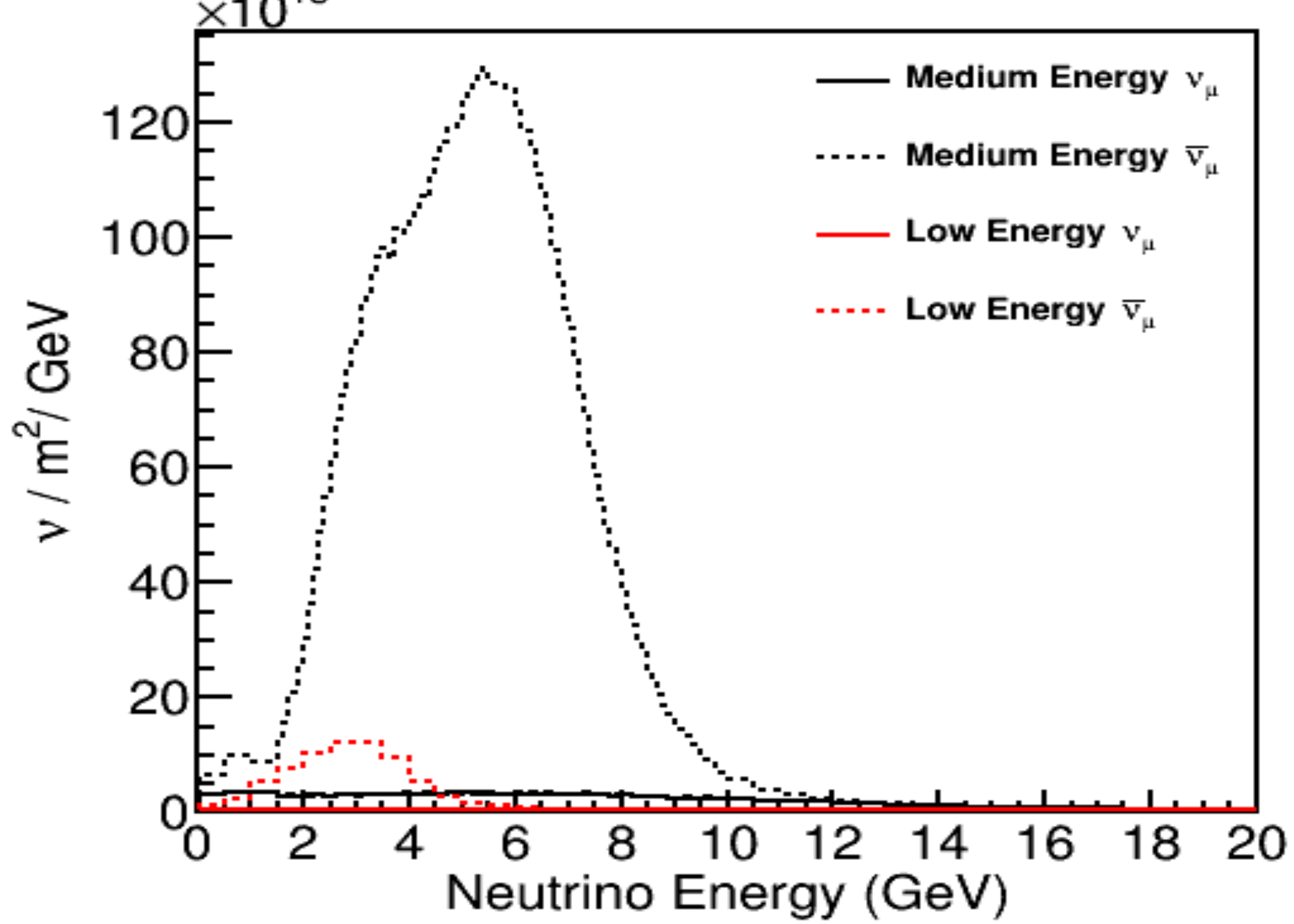
A. EOI: 2002, Construction Start: 2007, First Full Detector Data: 2009

B. Data-taking has been completed for both energy configurations → **<u>MINERvA has been decommissioned</u>**

Neutrino mode



Antineutrino mode



Low energy POT:

- ν: 4.0×10^{20}
- $\bar{\nu}$: 1.7×10^{20}

Medium energy POT:

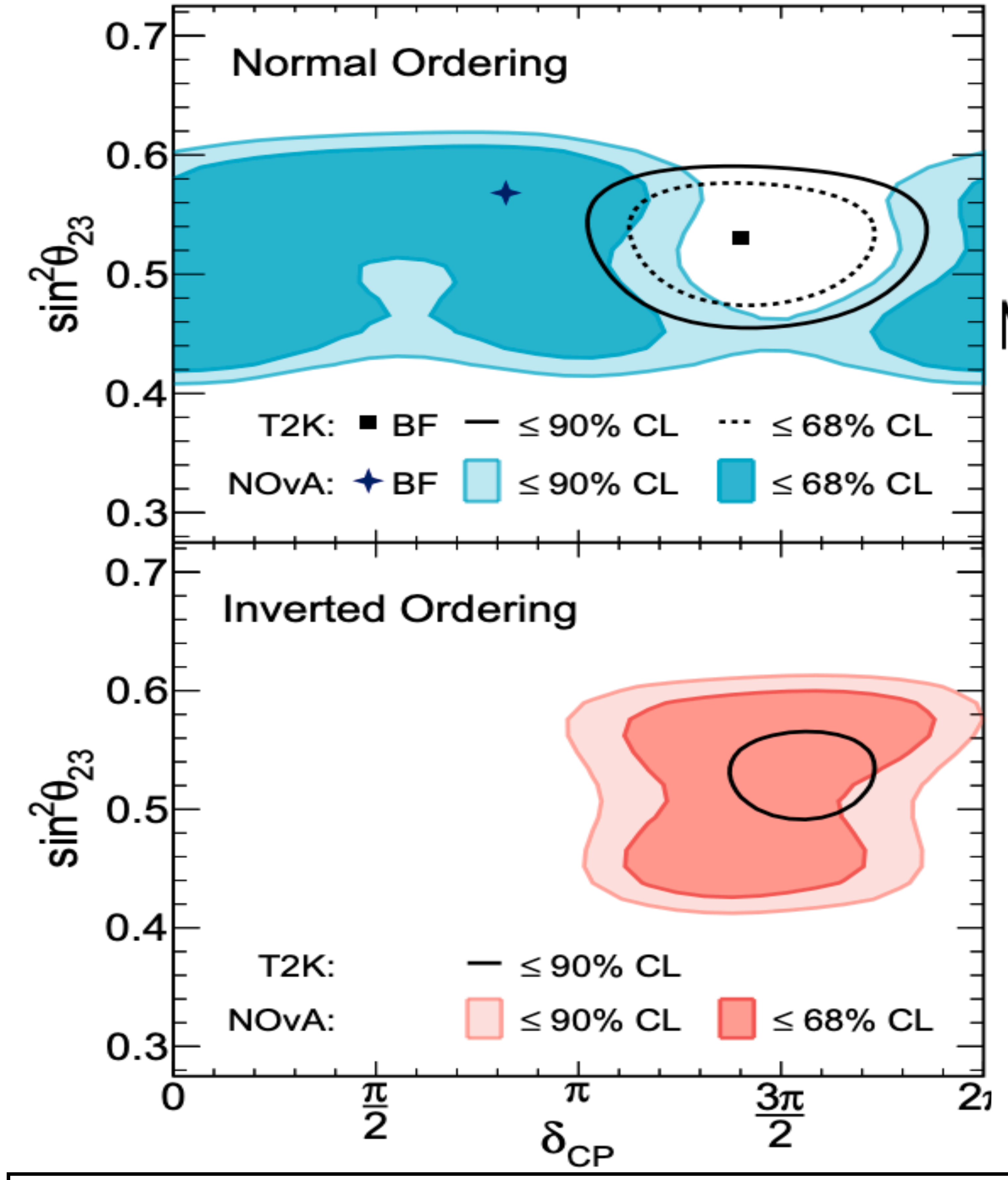
- ν: 12.1×10^{20}
- $\bar{\nu}$: 12.4×10^{20}

MINERvA operated in the NuMI beam line during the LE and ME eras from 2010 to 2019, in two beam modes: **neutrino** and **antineutrino**.

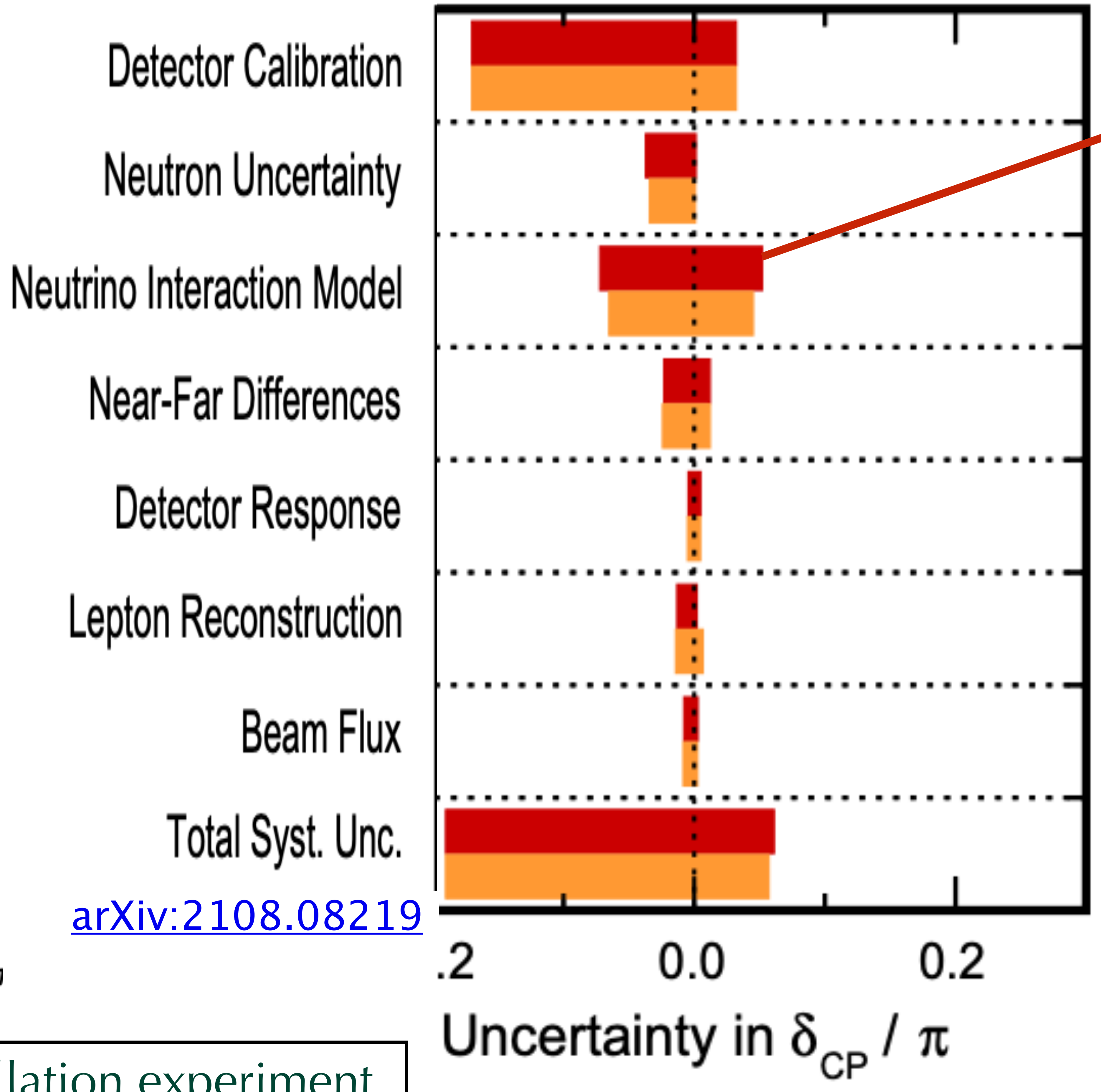
P.O.T: Protons on target, a proxy for number of neutrinos produced

Why MINERvA?

A. Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations
B. The Charge Parity (CP)-violating phase is least understood of all the neutrino oscillation parameters.
C. There is very a high uncertainty in the sensitivity of CP-violating phase in the recent measurements done by experiments like T2K, NOvA etc.



One of the recent result from NOvA oscillation experiment



arXiv:2108.08219

Interaction model uncertainty one of the biggest contributions to total uncertainty

Challenge: Neutrino interaction modelling is the one of the biggest systematics for the oscillation measurements.

MINERvA is working to ensure that oscillation experiments have a solid model and uncertainties to feed into their oscillation fits.

Why MINERvA?

Important for Oscillation experiment

Near Detector

Scattering Cross section

Transition Probability

$$\text{Event Rate: } N \propto \phi(E_\nu) \times \sigma(E_\nu) \times N_T \times P_{\nu_\mu -> \nu_e}$$

Energy dependent flux

Far Detector

Number of target particles

Convolution of cross section and nuclear medium effects

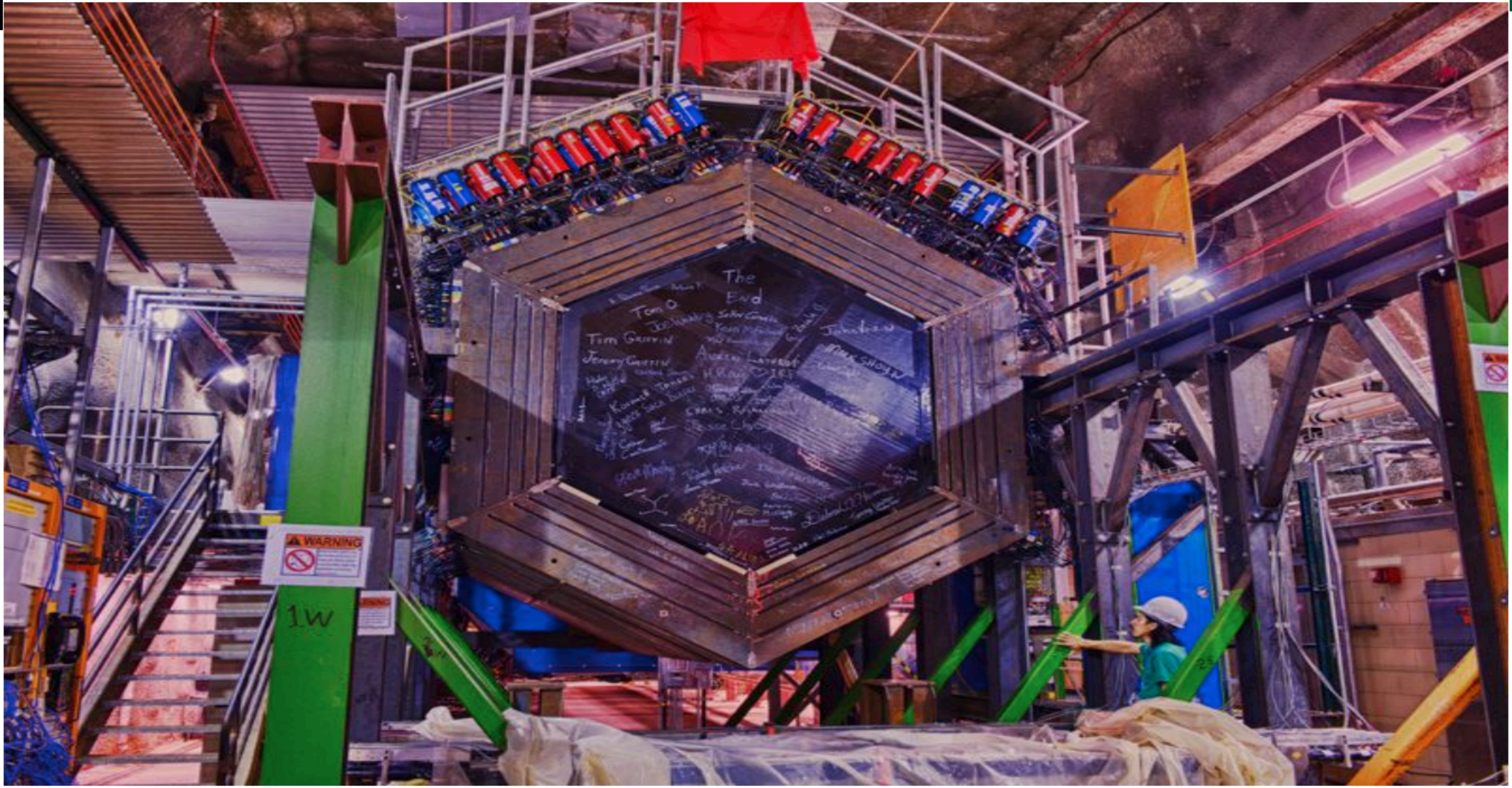
Oscillation experiments require:

- Flux predictions
- Models to relate observables and E_ν
- Precise cross sections of background and signal processes
- Understanding of Nuclear Medium Effects

MINERvA experiment was designed to:

A. understand and improve physics models
B. understand nuclear medium effects
C. improve flux predictions
D. relation between observables and E_ν
E. and many more….

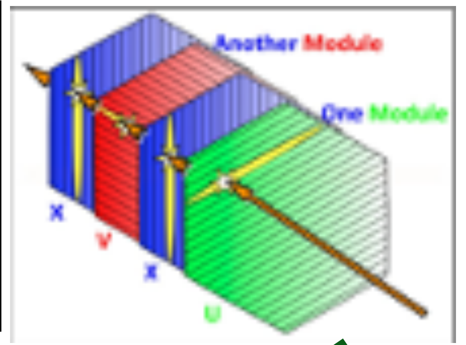
The MINERvA Experiment

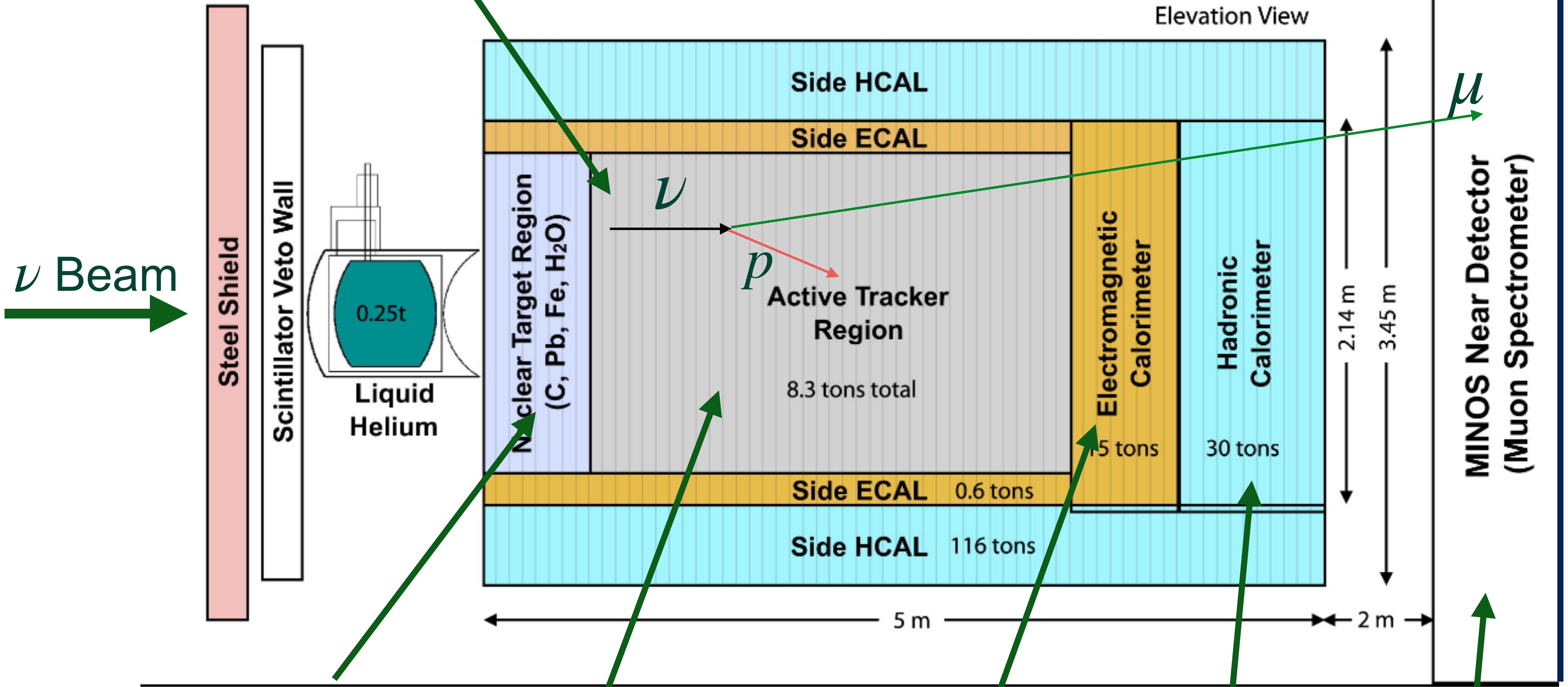


MINERvA Detector

- Was situated inside NuMI hall at Fermilab, upstream of MINOS ND
- Fully active scintillator tracker
- Embedded different nuclear targets like C, Fe, Pb, He, and H2O

Rotated planes of bars of scintillator allow for tracking





Passive Target Region

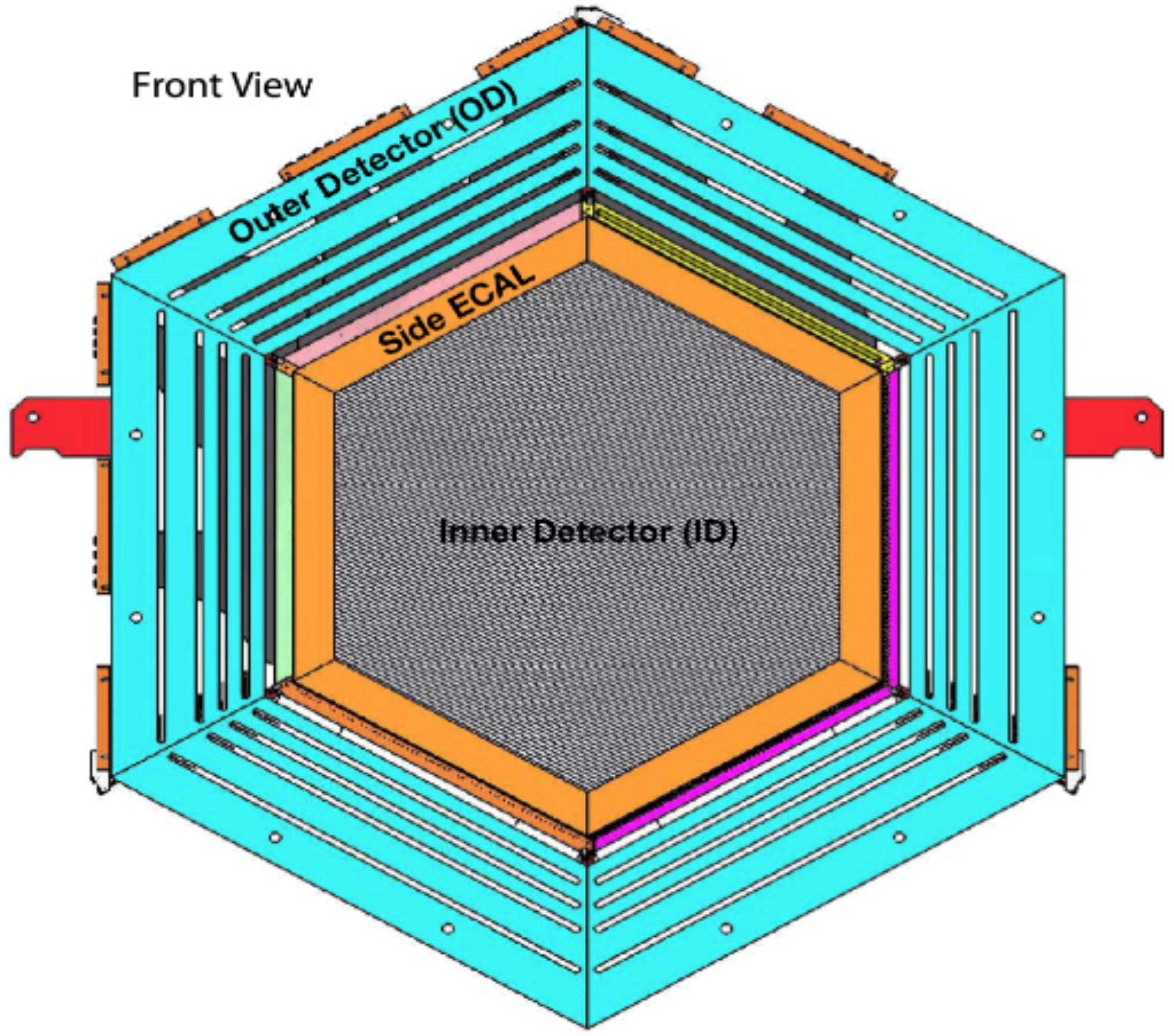
Hydrocarbon Fiducial Volume

Lead and Scintillators, stops EM activity

Iron and Scintillators, stops Hadronic activity

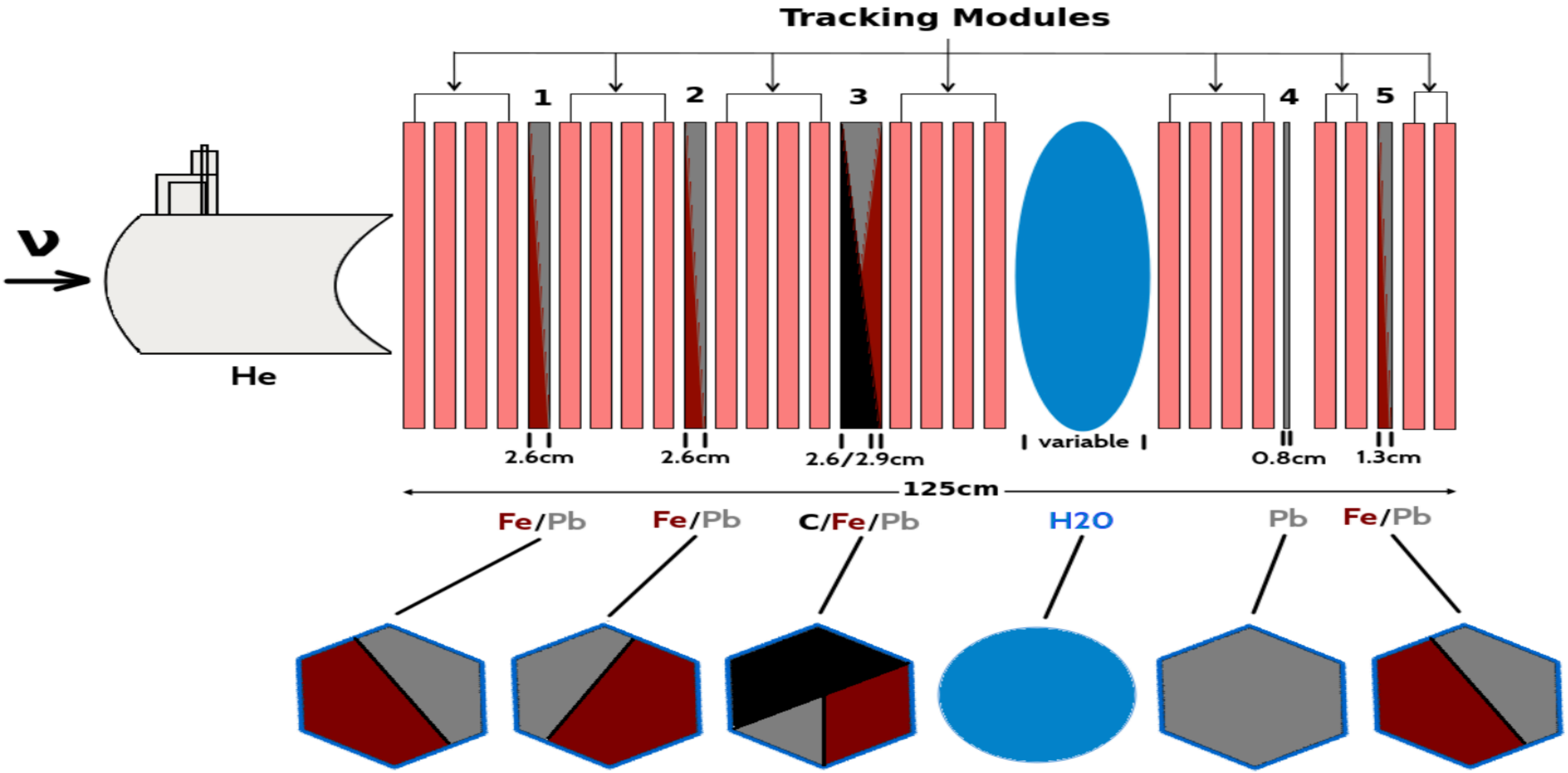
MINOS ND (magnetized) acts a a Muon spectrometer for MINERvA

Front View of the detector

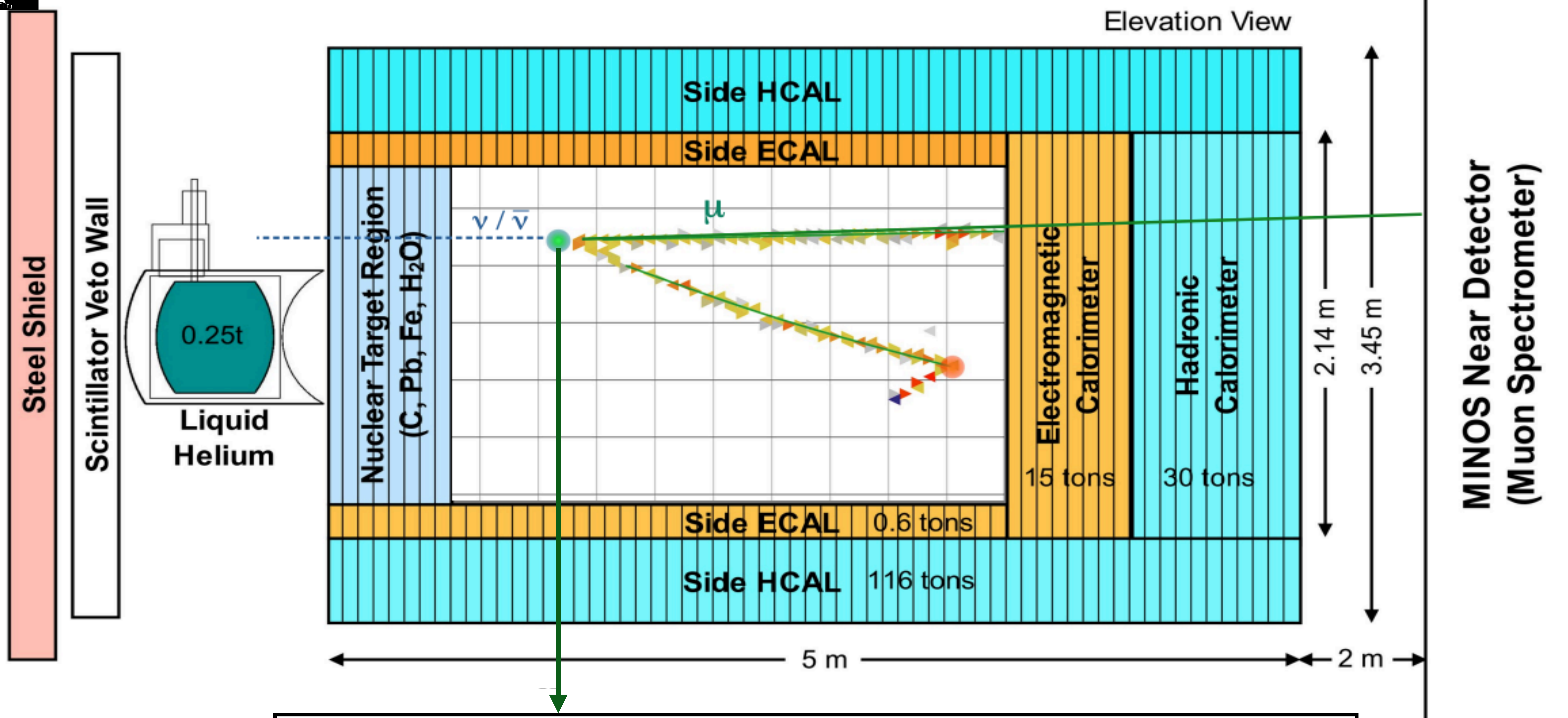


Charged particles pass through strips of scintillator. Light collected by fibers is measured by photomultiplier tubes.

Nuclear Target Region

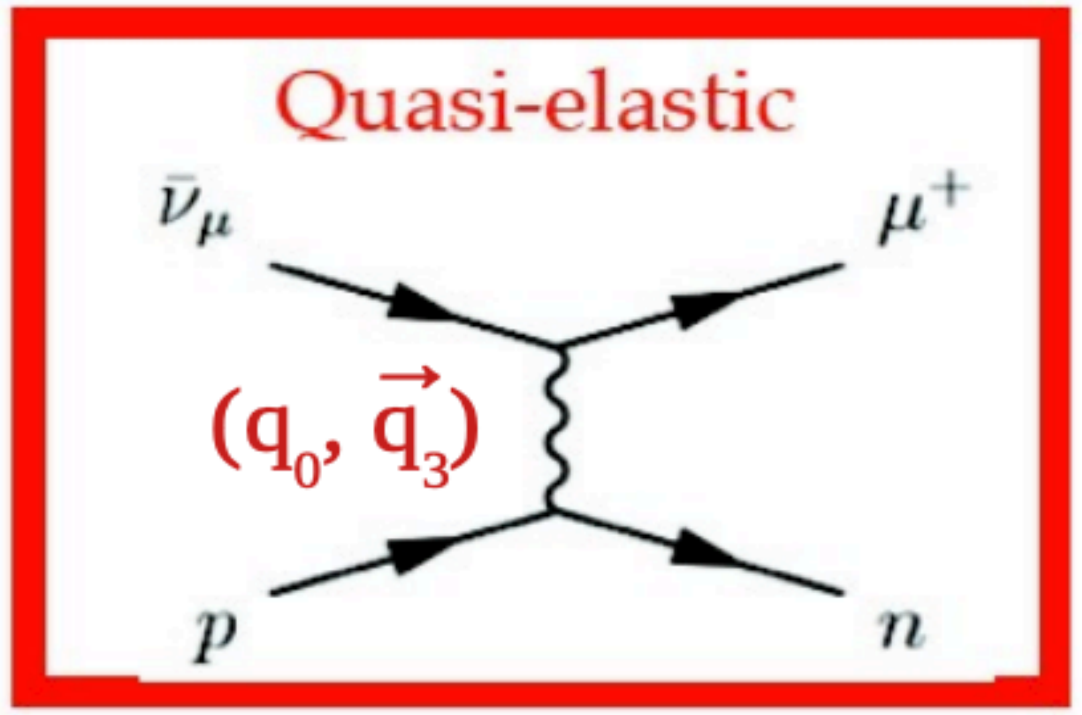


MINERvA (Main Injector Experiment for ν-A, US)

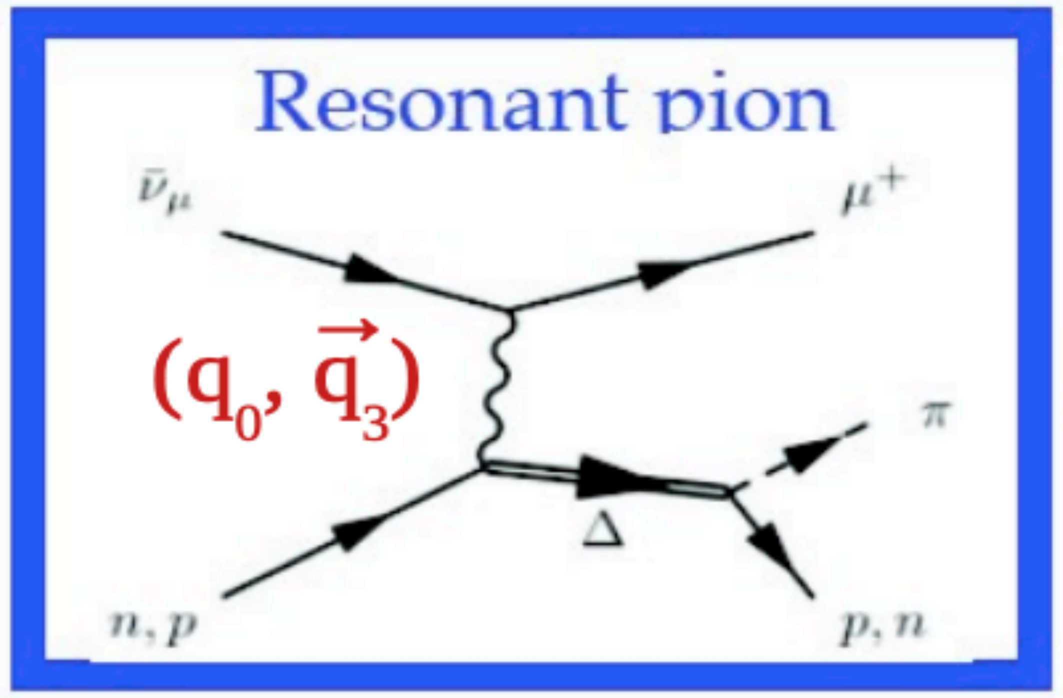


An actual neutrino/antineutrino interaction inside the fiducial volume producing a short track (hadron) and a long track (Muon)

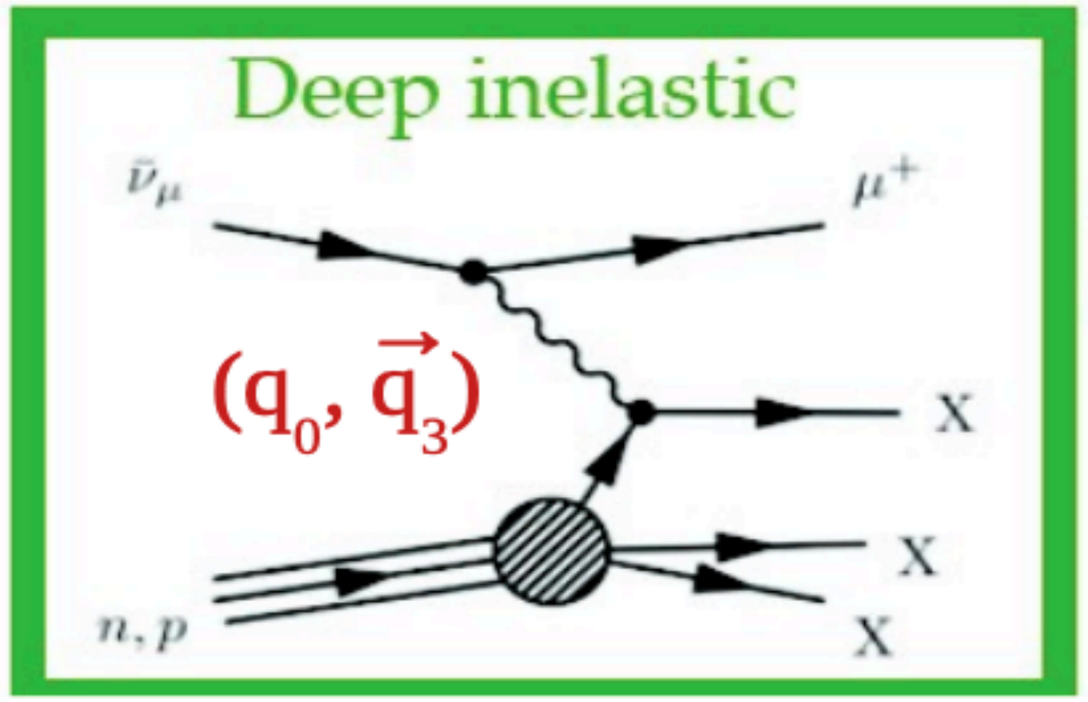
Different Neutrino Interactions in MINERvA



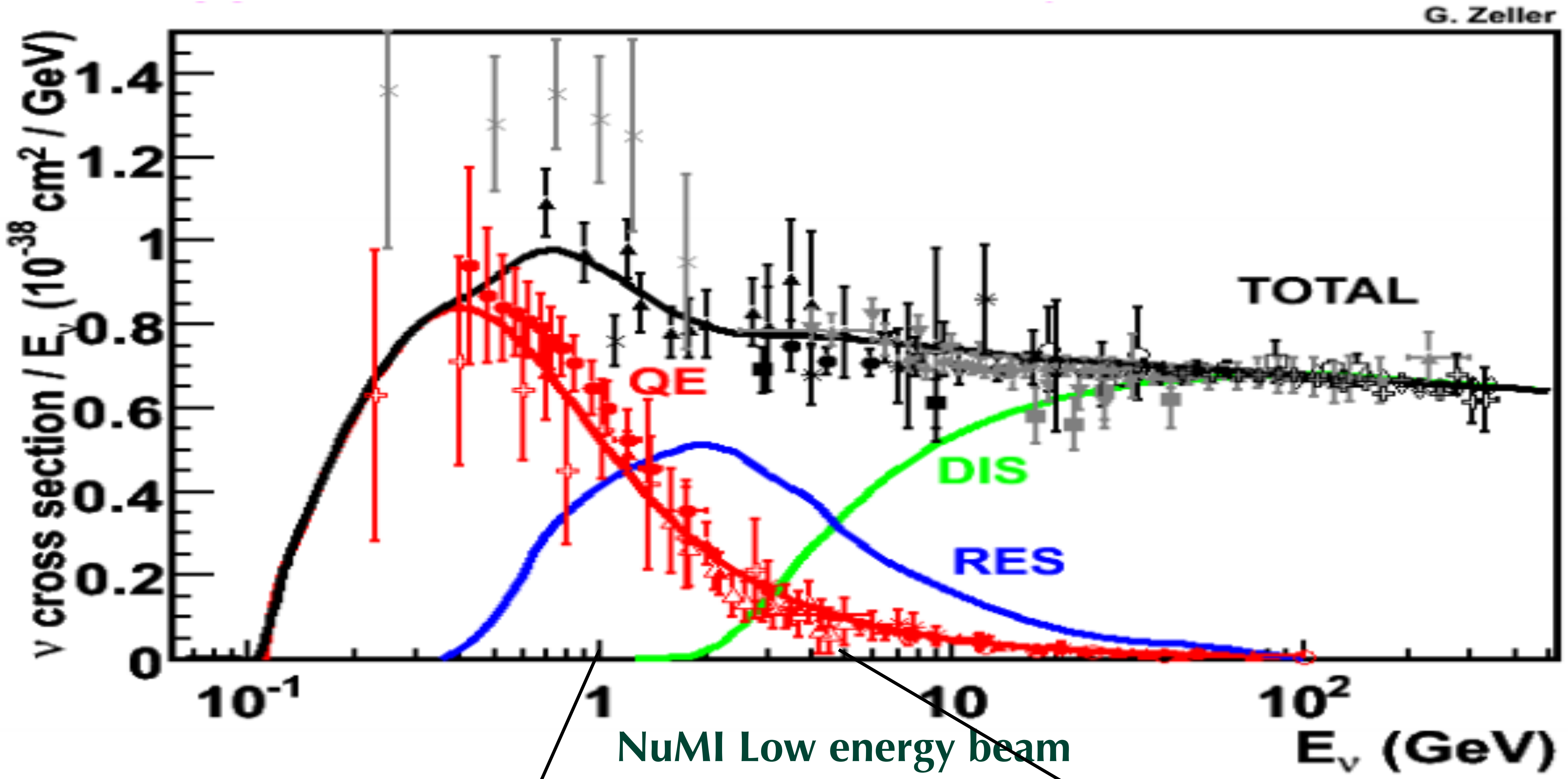
QE



RES



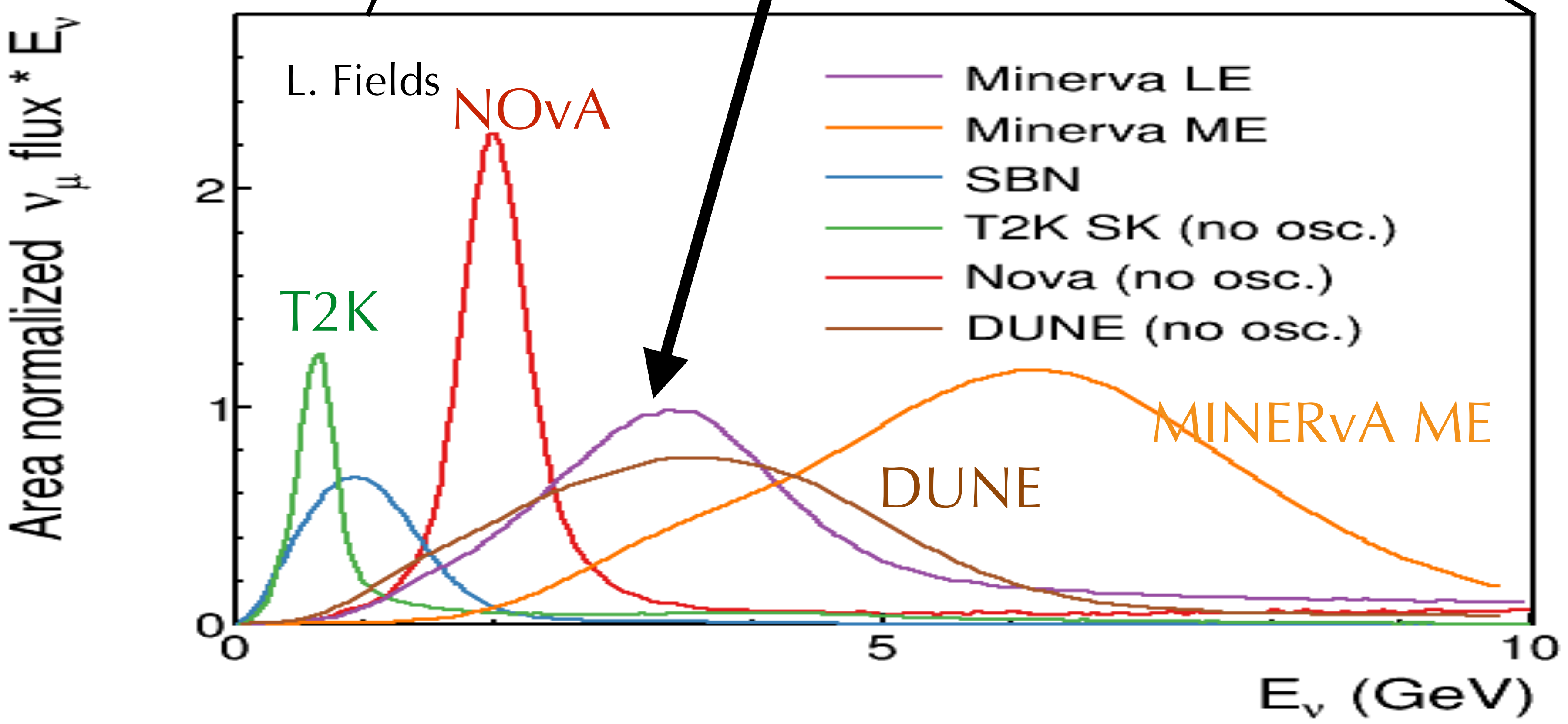
DIS



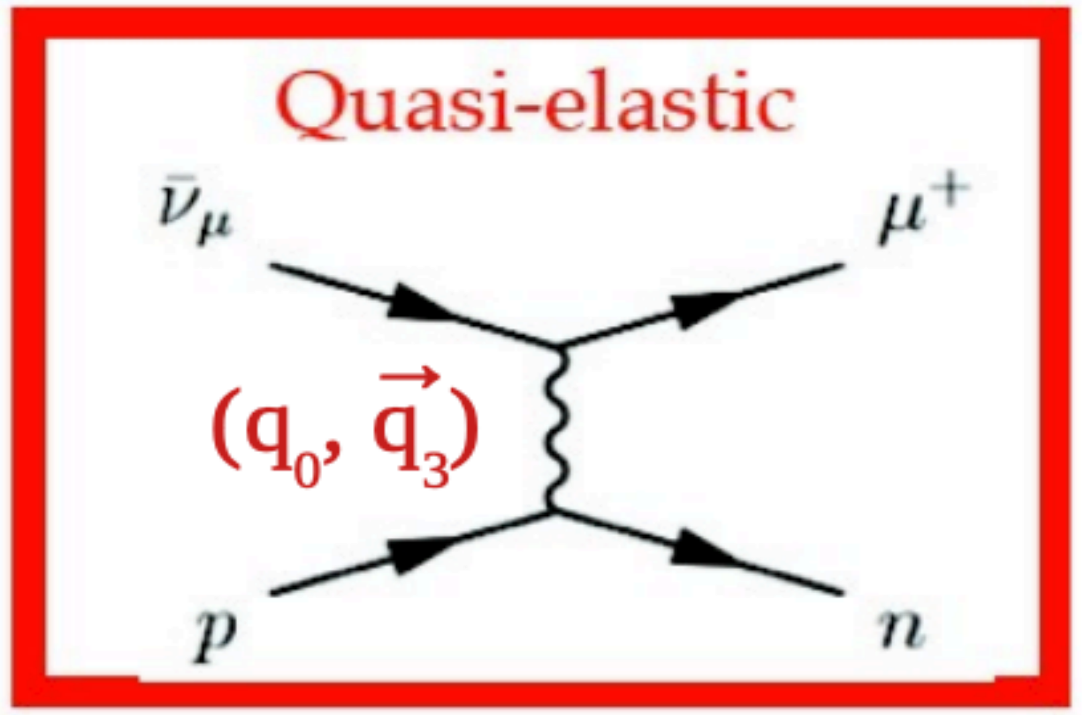
NuMI Low energy beam

$< E_\nu > \approx 3\ GeV$

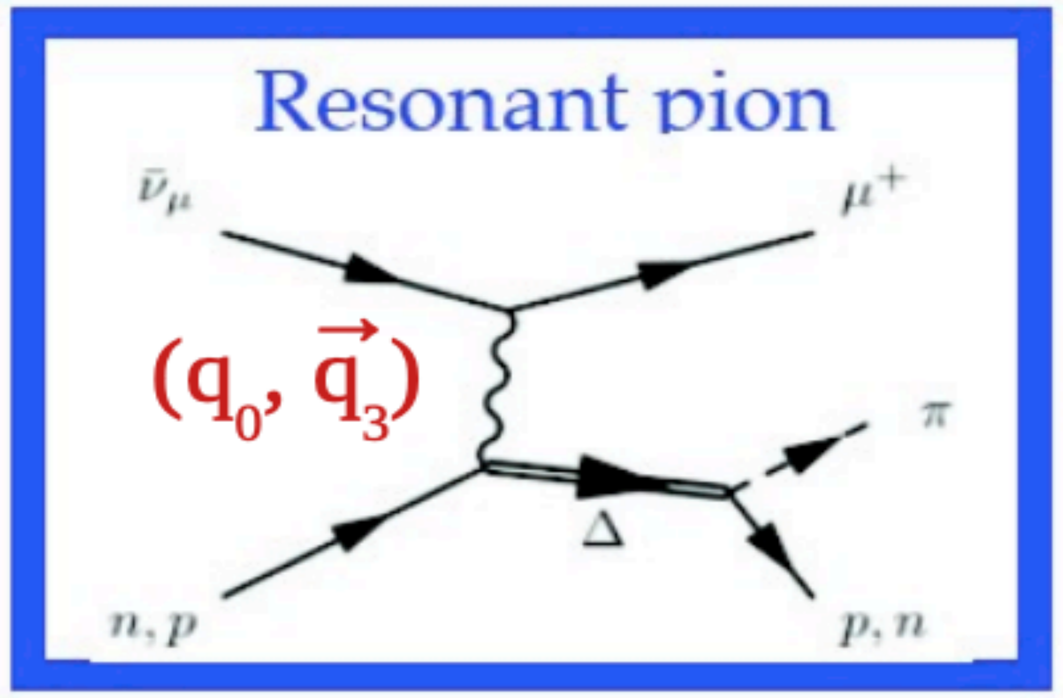
(MINERvA LE)



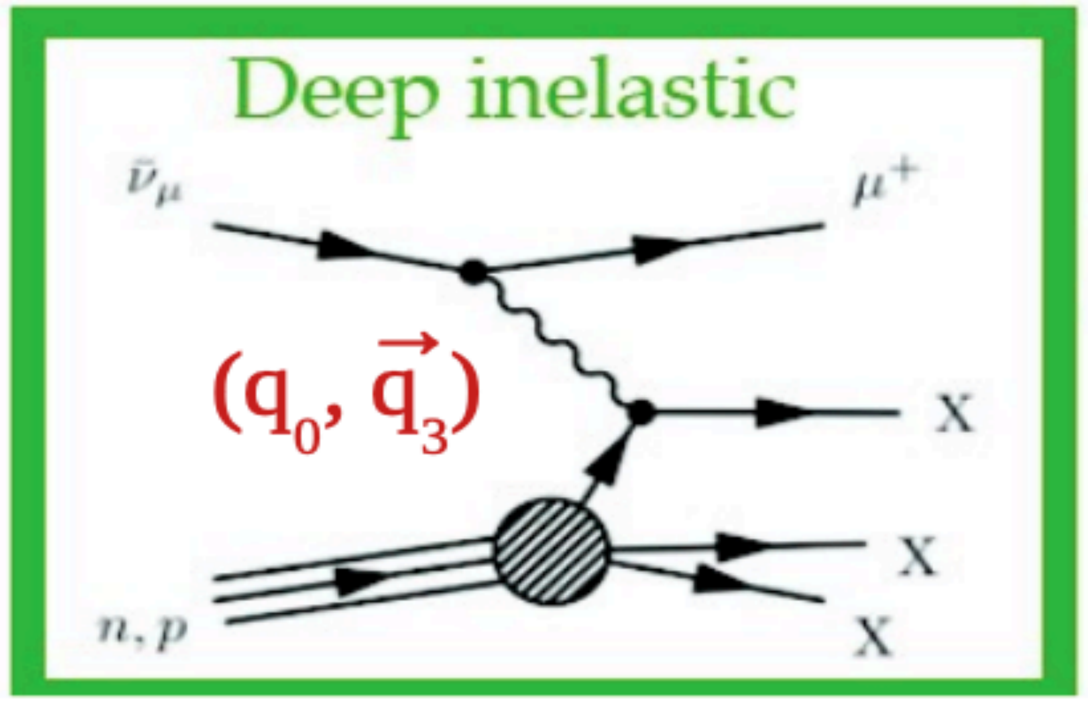
Different Neutrino Interactions in MINERvA



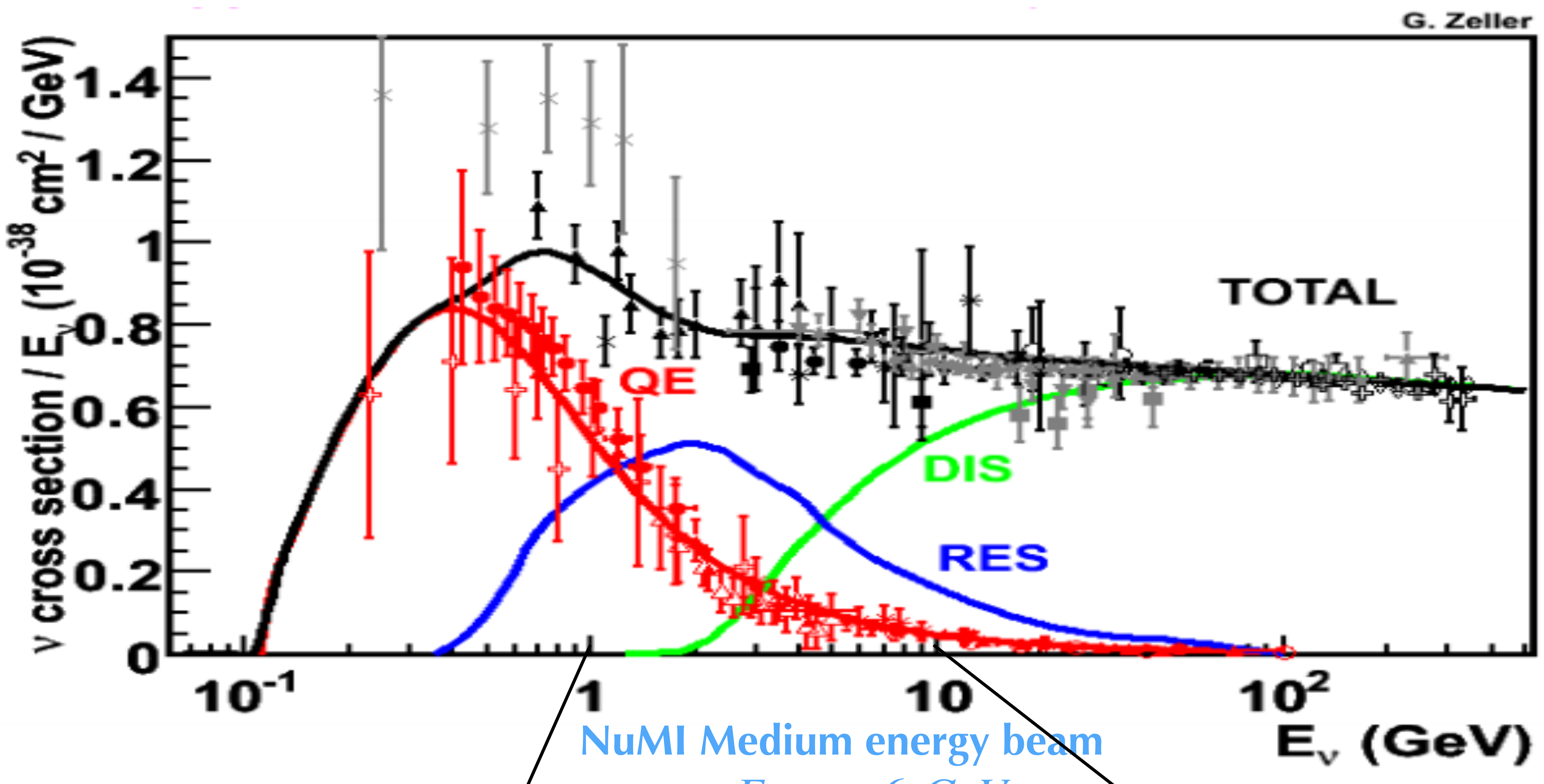
QE



RES



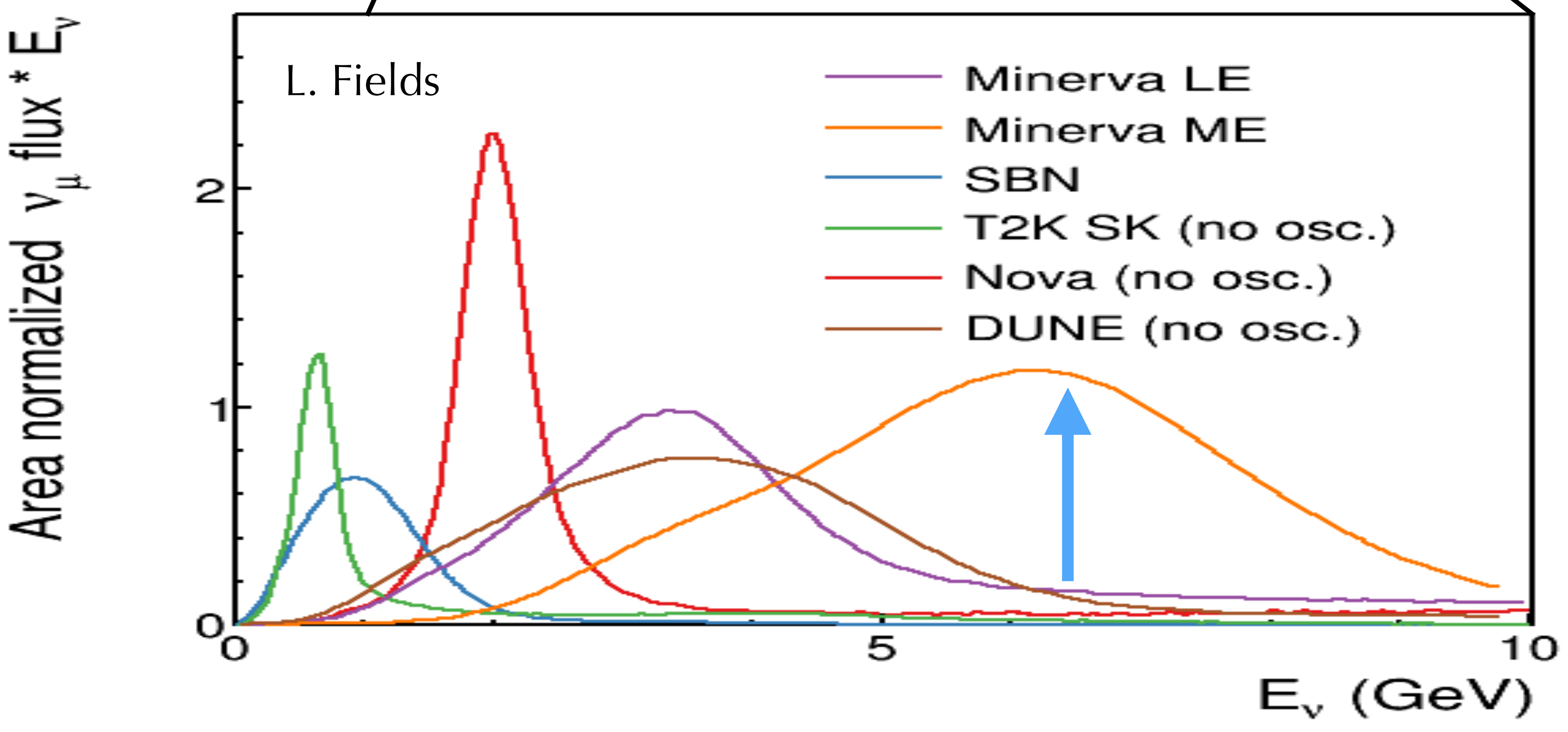
DIS



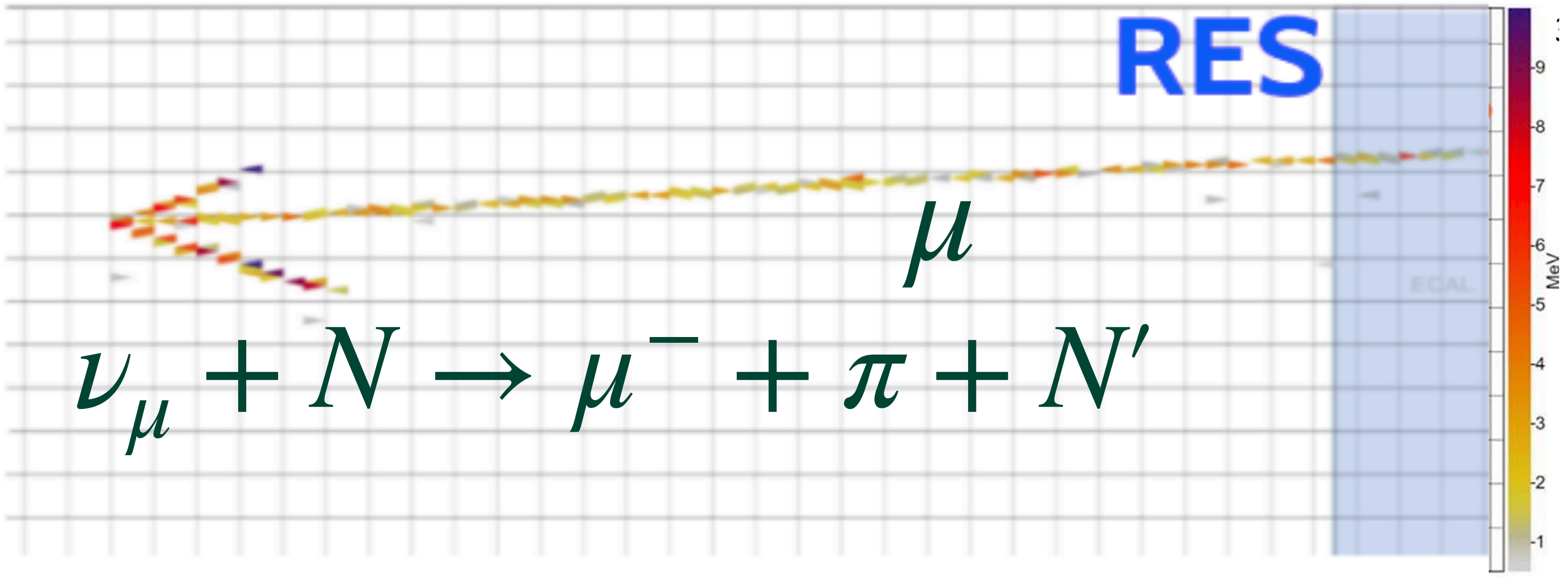
NuMI Medium energy beam

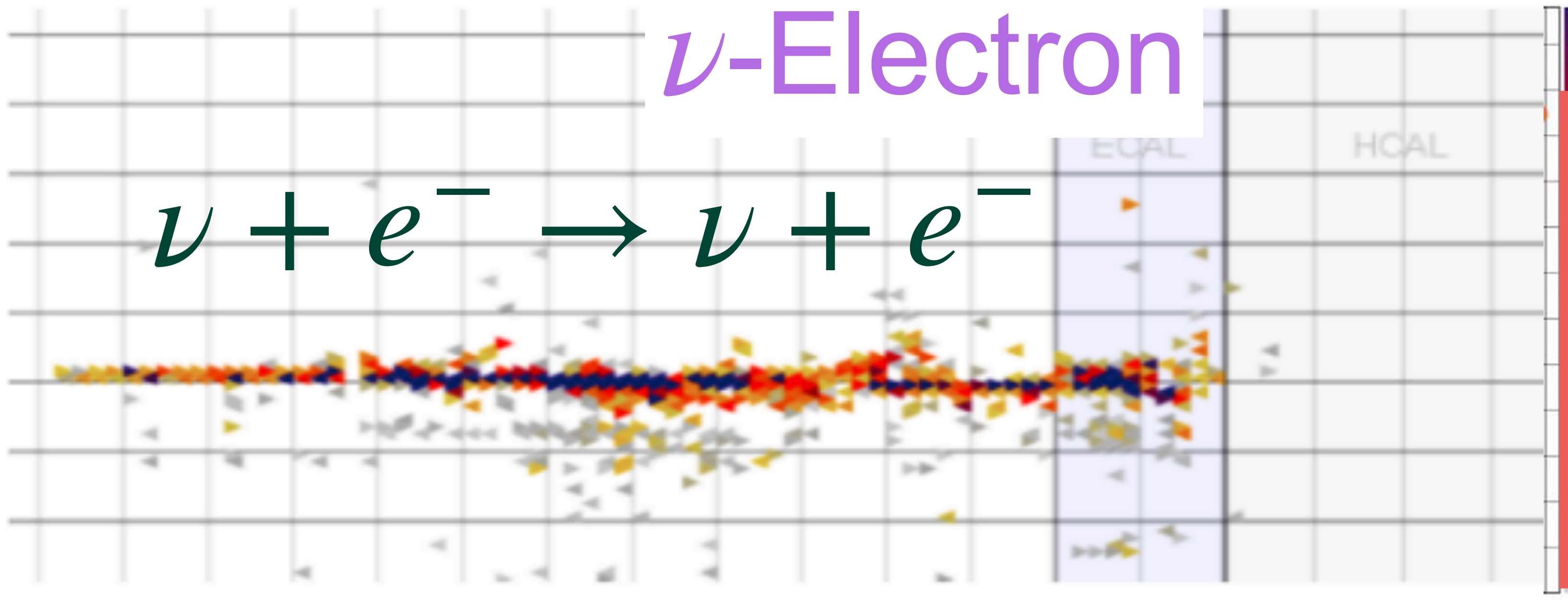
$< E_\nu > \approx 6\ GeV$

(MINERvA ME)

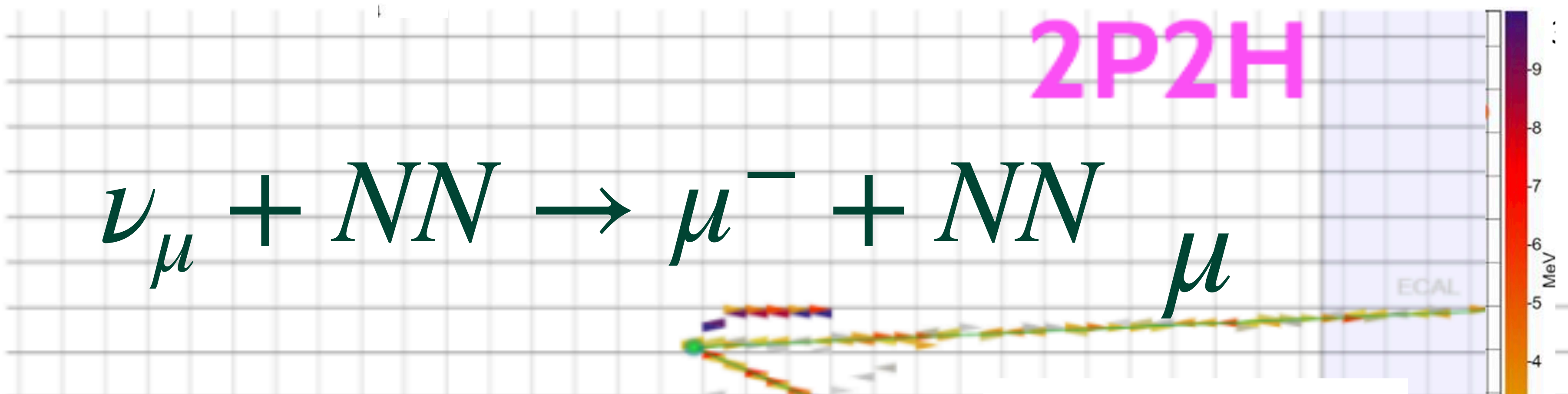


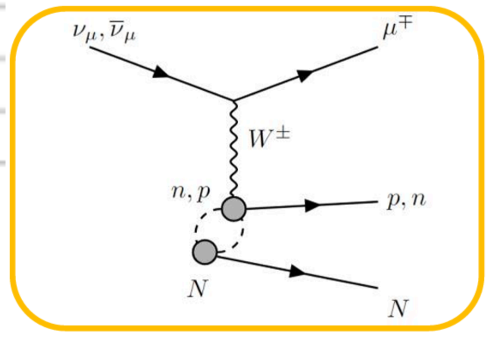
Different measurements at MINERvA



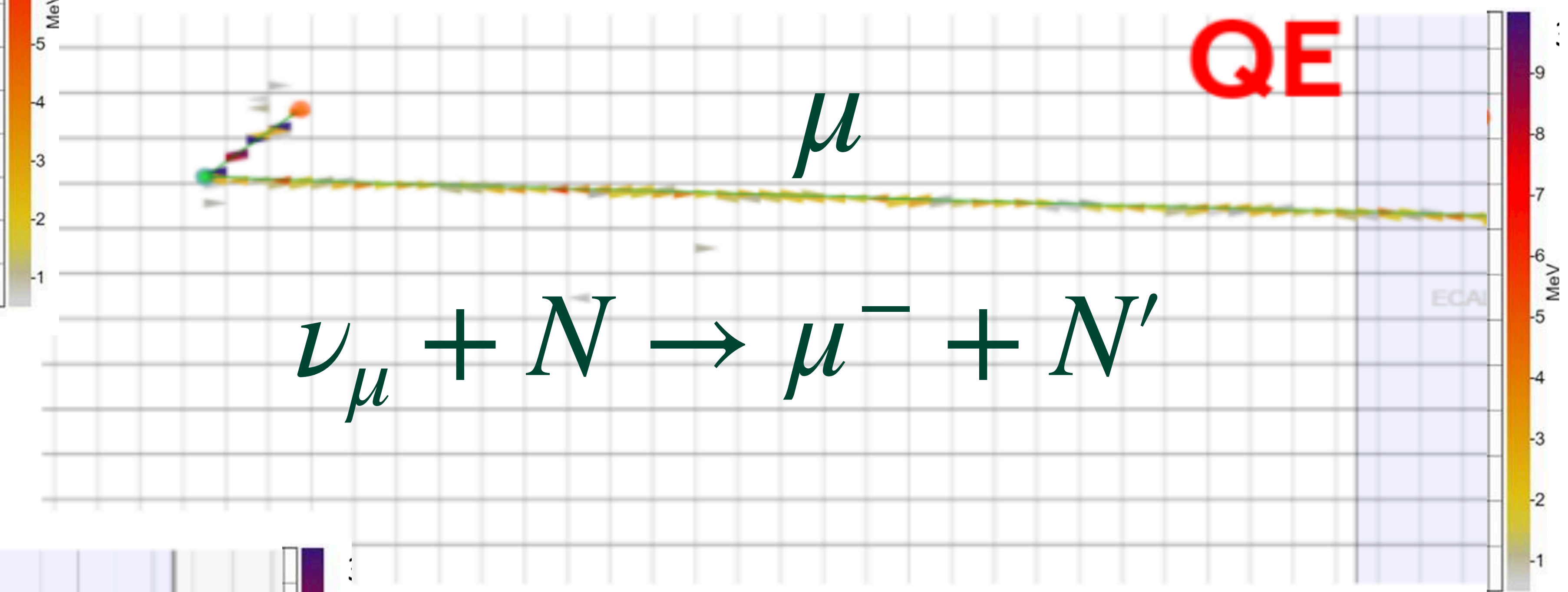


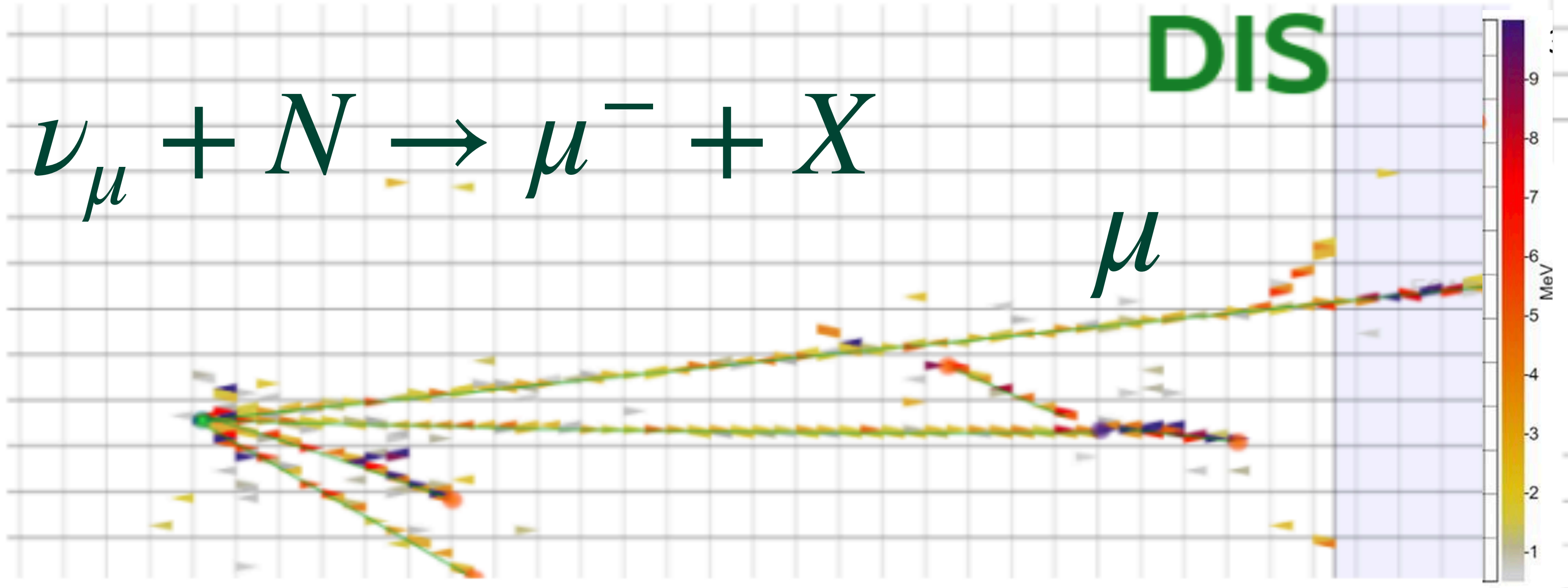
Muon traverses different regions of the detector and is identified in the MINOS spectrometer

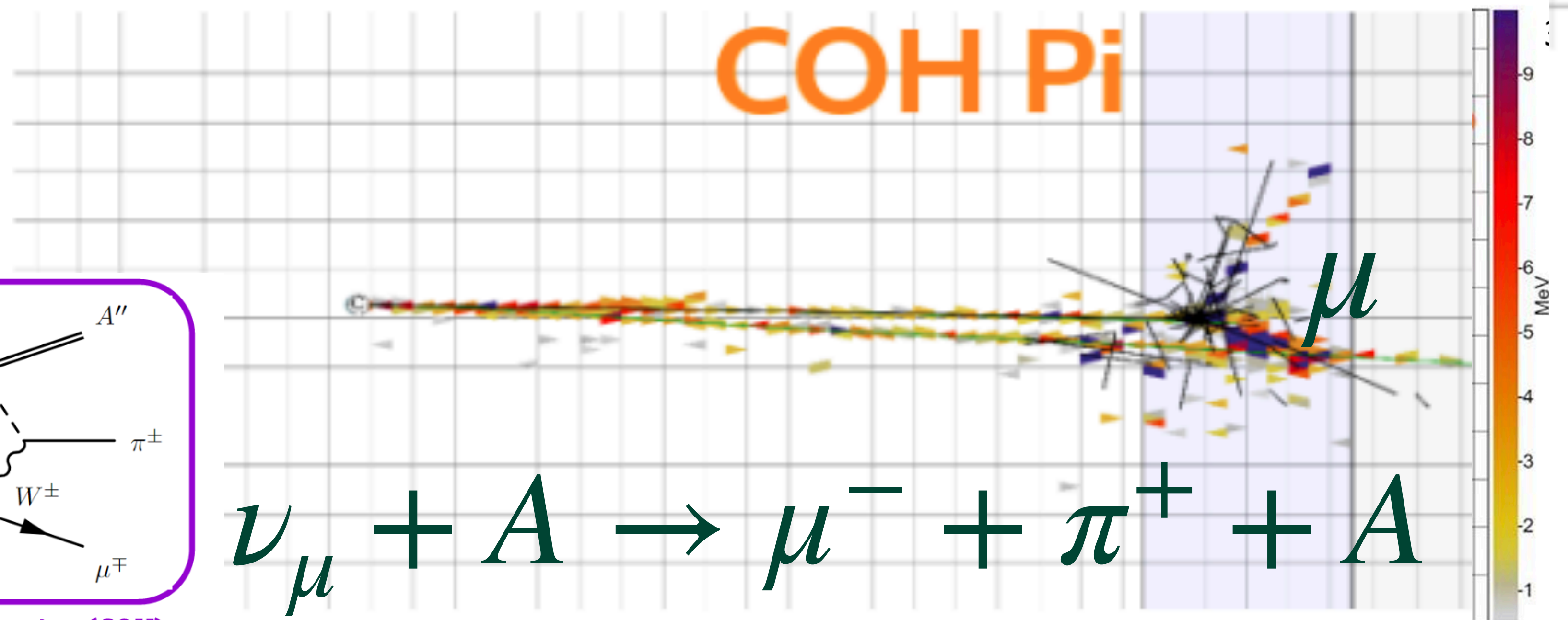


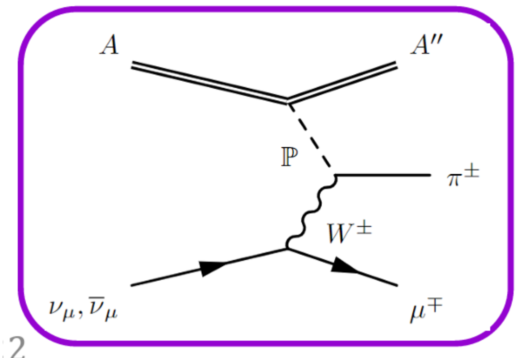


Multinucleon scattering (2p2h)









2 Coherent pion production (COH)

Neutrino Event Generators

GENIE: Nucl. Instrum. Meth. A614, 87 (2010)

A. Widely used by neutrino oscillation and cross section experiments
B. Comprehensive physics model and tools to support neutrino interaction simulation
C. MINERvA implements GENIE to generate simulations along with the local modifications to better explain data.
D. NonResonantPion (NRP), Random Phase Approximation (RPA) suppression and 2p2h enhancement is added to Default GENIE to have a better agreement with Data.

NuWRO: Nucl. Phys. Proc. Suppl. 229-232, 499 (2012)

A. Gives predictions for neutrino-nucleus interactions at neutrino energies between 0.1 and 100 GeV.

NEUT: Acta Phys. Polon. B 40, 2477 (2009)

A. Developed for Kamiokande
B. Updated continuously for Super-K
C. Gives background prediction to proton decay in Super-K.

GiBBU: Acta Phys.Polon.B40:2585-2592

A. For neutrino nucleus scattering with a focus on the FSI treatment.

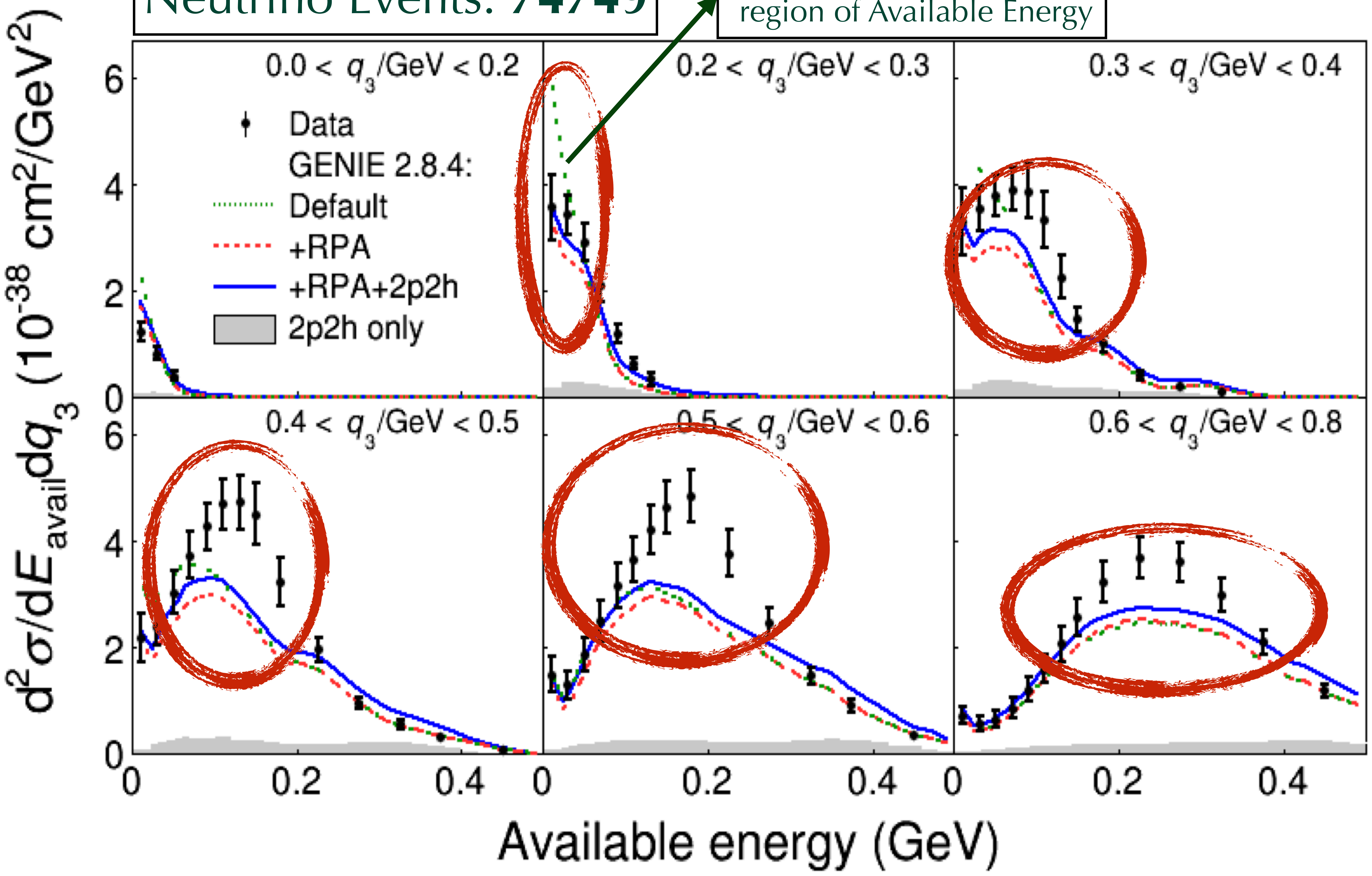
Neutrino-Carbon Interactions at Low three momentum transfer q_3

In Low Energy Era of NuMI beam, more than 30 physics publications

q_3: three momentum transfer

Neutrino Events: **74749**

RPA suppression has a significant effect in the low region of Available Energy



- **Signal Selection:**
  - Muon angle < 20^0
  - Muon Energy $E_\mu > 1.5$ GeV
  - $2 < E_\nu < 6$ GeV to span the neutrino flux spectrum

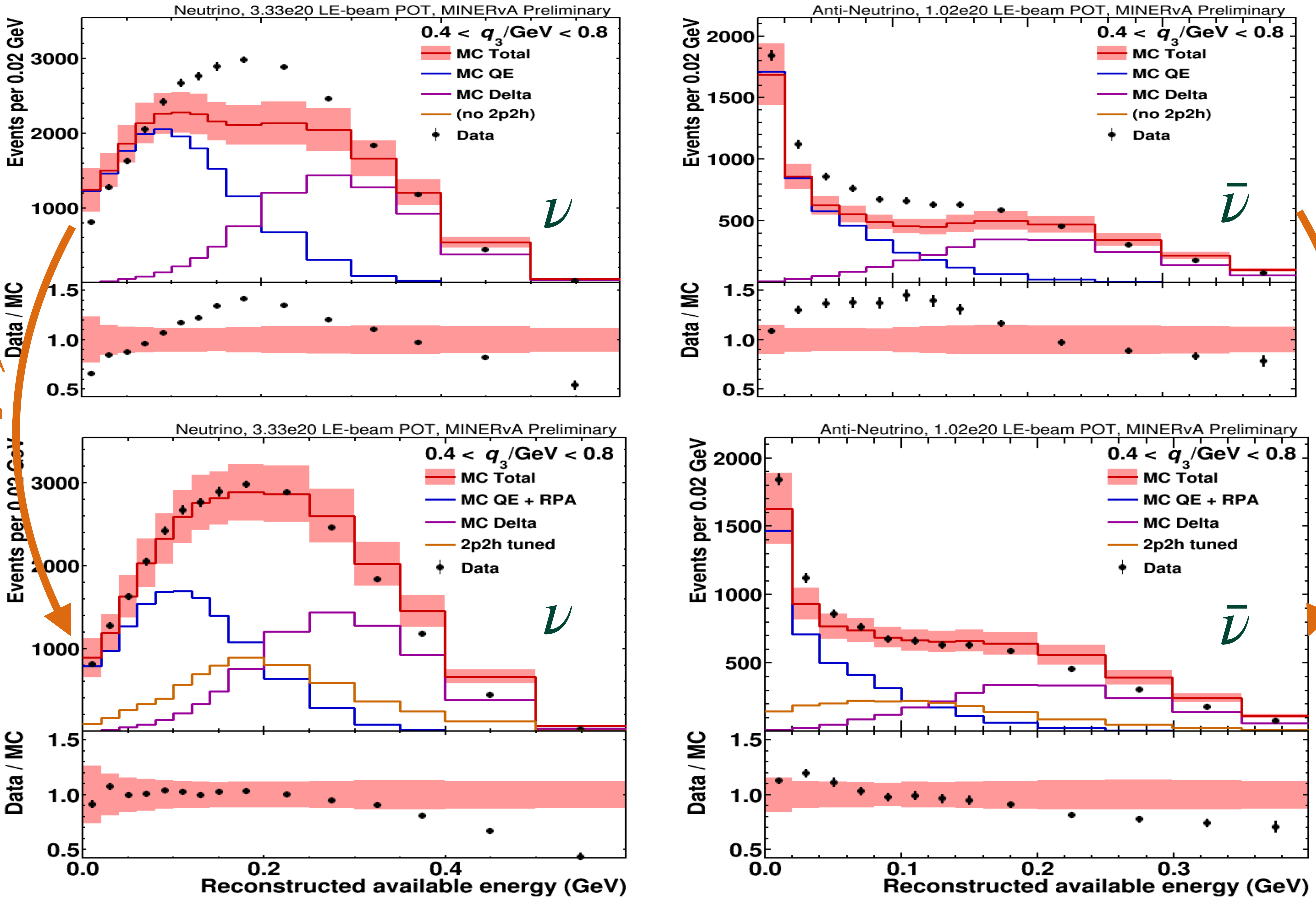
- Disagreements between data and Monte Carlo prediction seen in different analyses.
- Models treated the multi-nucleon environment as a group of non-interacting nucleons
- Default models don't agree with data. Modifications like adding RPA, 2p2h even didn't help much though they improved the result.
- MINERvA showed that models didn't have the complete picture, and the nuclear environment affects the produced final states in neutrino interactions.

Phys. Rev. Lett. 116, 071802 (2016)

E_{avail} = (Proton and $\pi^{\pm}$ K.E.) + (Energy of all particles except neutrons)

Neutrino Reactions on Hydrocarbons with Low q_3

We developed an empirical fit to account for the data-prediction disagreements based on our LE results and external data: **MINERvA Tune**.



MINERvA Tune based on fit using neutrino data.

Tune based on neutrino data applied to antineutrino analyses.

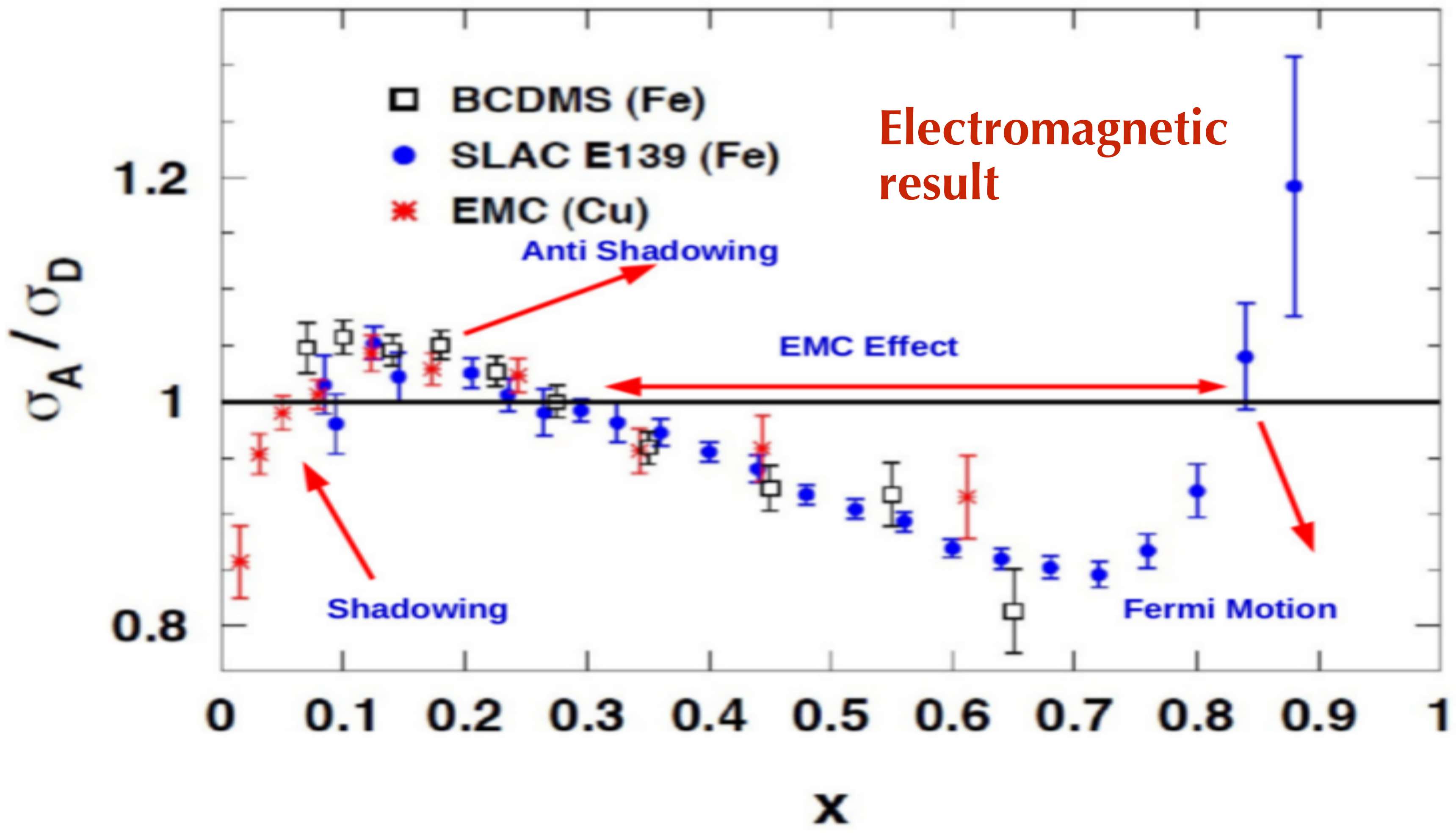
- Models were subject to tests on our neutrino data, and modified accordingly using alternative models and empirical fits to data.
- MINERvA Tune was developed investigating the fits that better agree with our data.
- Tune was complemented by measurements from other experiments.
- Additional tests were done with our antineutrino data, with good agreement.
- Our Tune set the foundation of one of the main goals of the ME physics program of MINERvA.
- The ME program would test this "LE" tune with greater statistics and a broader range of kinematics.

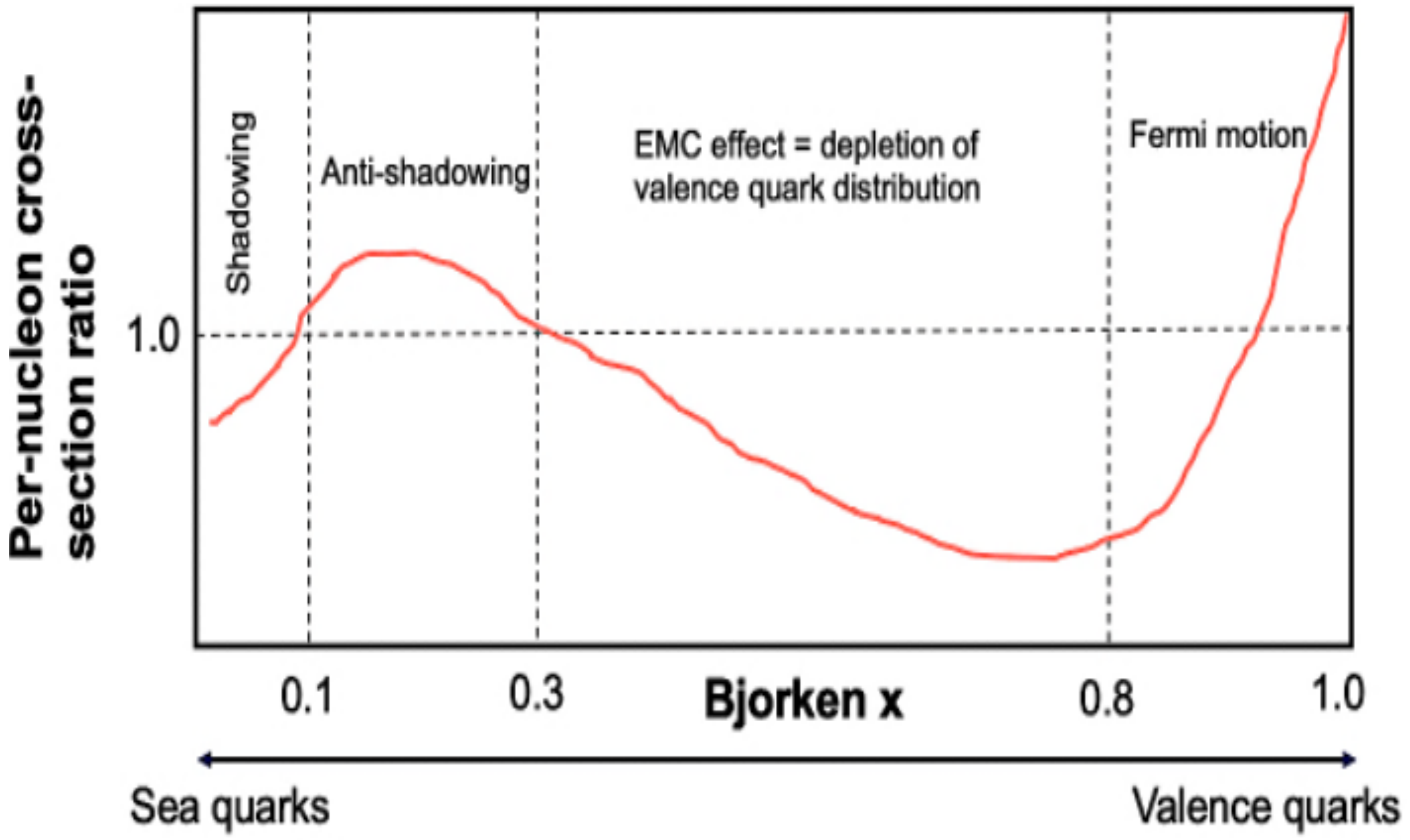
Phys. Rev. Lett. 120, 221805 (2018)

Neutrino Cross Sections on Nuclear Targets

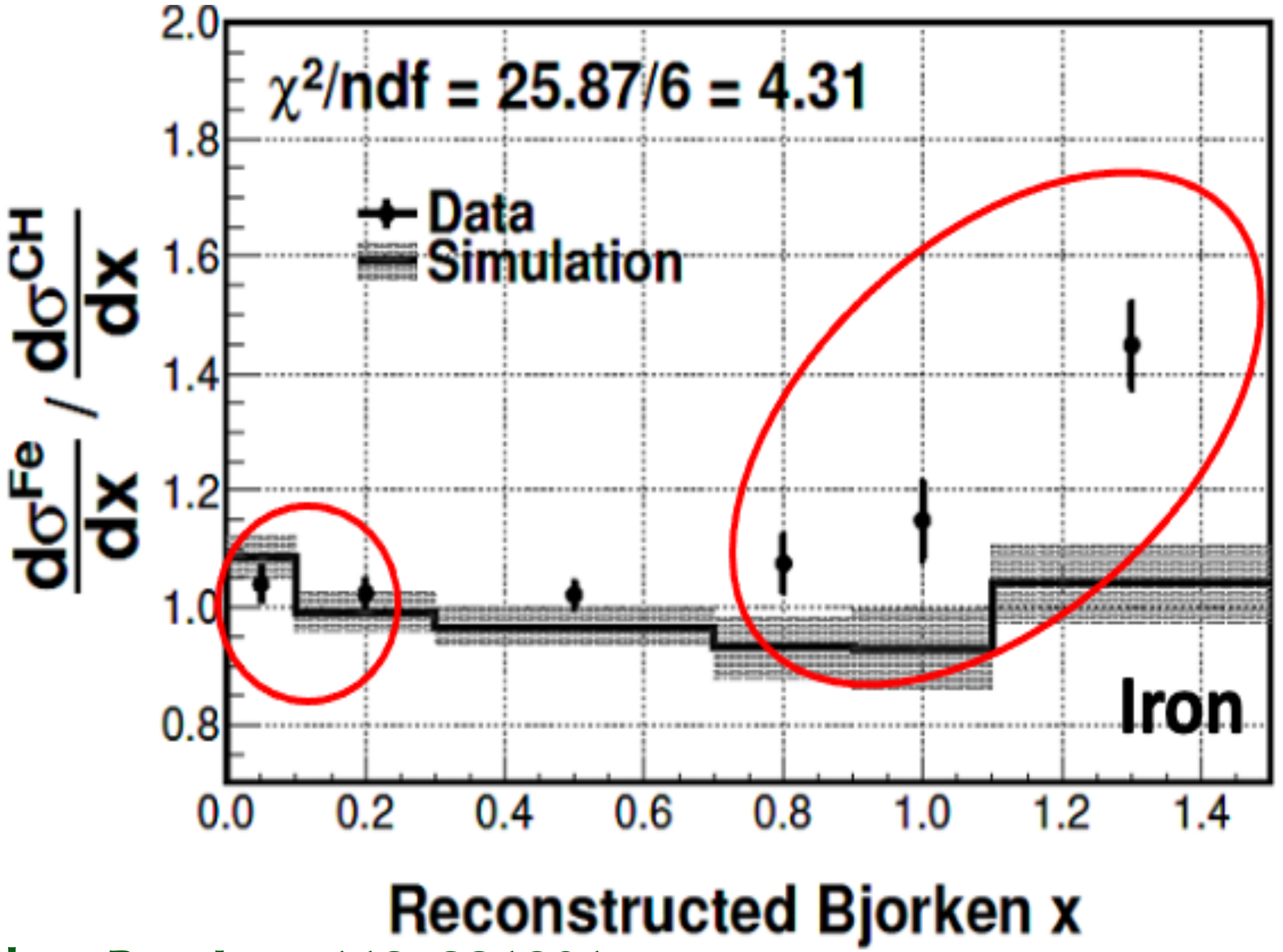
Nuclear Medium Effects

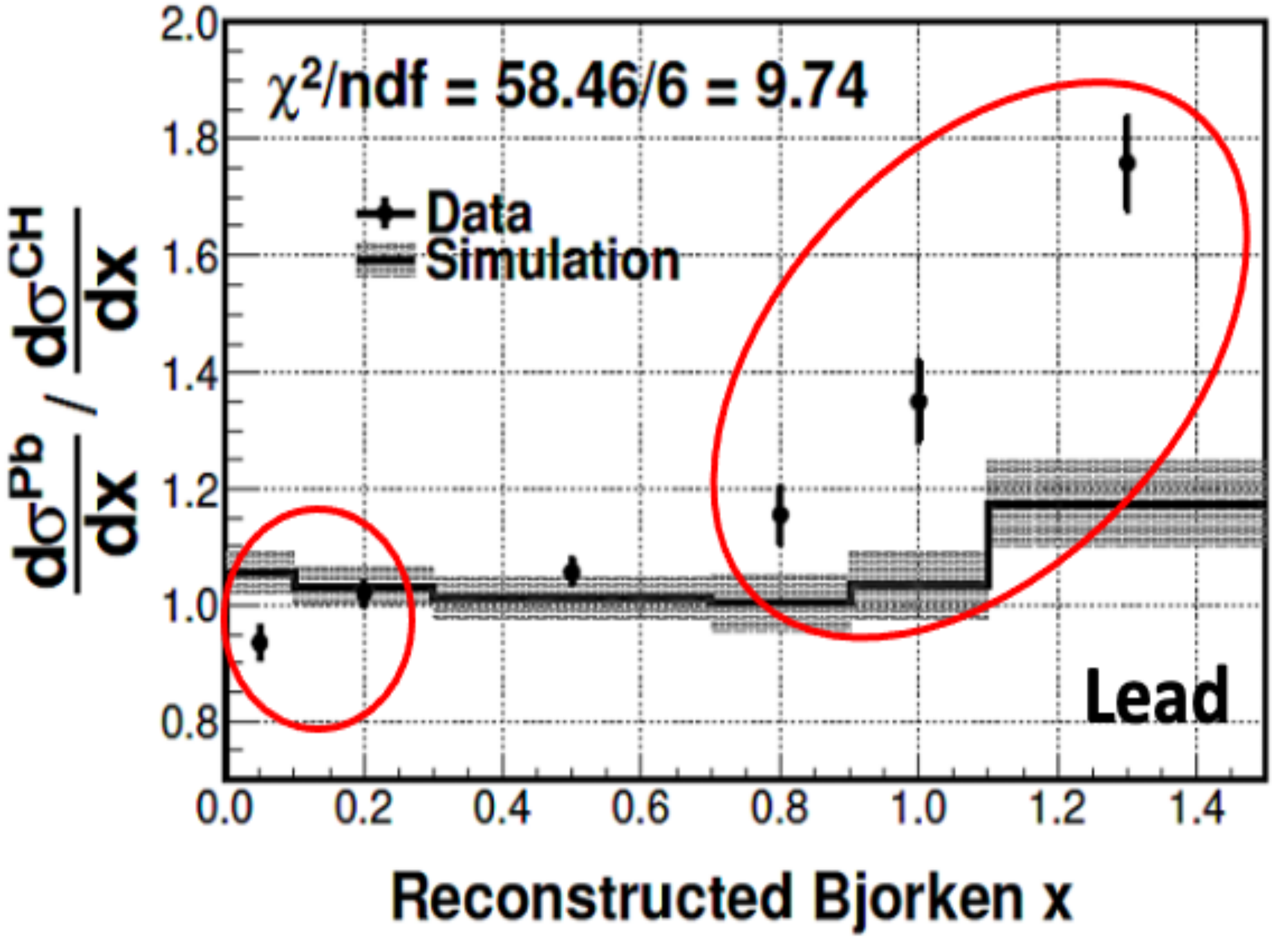
Phys. Rev. D 49, 4348





- Nucleons bound in a nucleus by the strong force – requires modifications compared to a free nucleon
- Modifications classified in terms of Bjorken x
  - Fraction of the nucleon's momentum carried away by the struck quark





Phys. Rev. Lett. 112, 231801

- **MINERvA low energy result:** Inclusive neutrino nuclear target to scintillator cross-section ratio
- Inclusive numbers: Fe 19024 events, Pb 23697 events

Physics Picture for the ME era

Expand our knowledge of cross-sections and the multi-nucleon environment, with an enhanced statistics.

Test different models with our data, allowing generators to improve predictions.

Improve neutrino flux model and constraints to reduce systematic uncertainties

Expand the reach of our physics results thanks to a larger energy regime.

Preserve MINERvA's data for the future and make it available once the collaboration ceases being active.

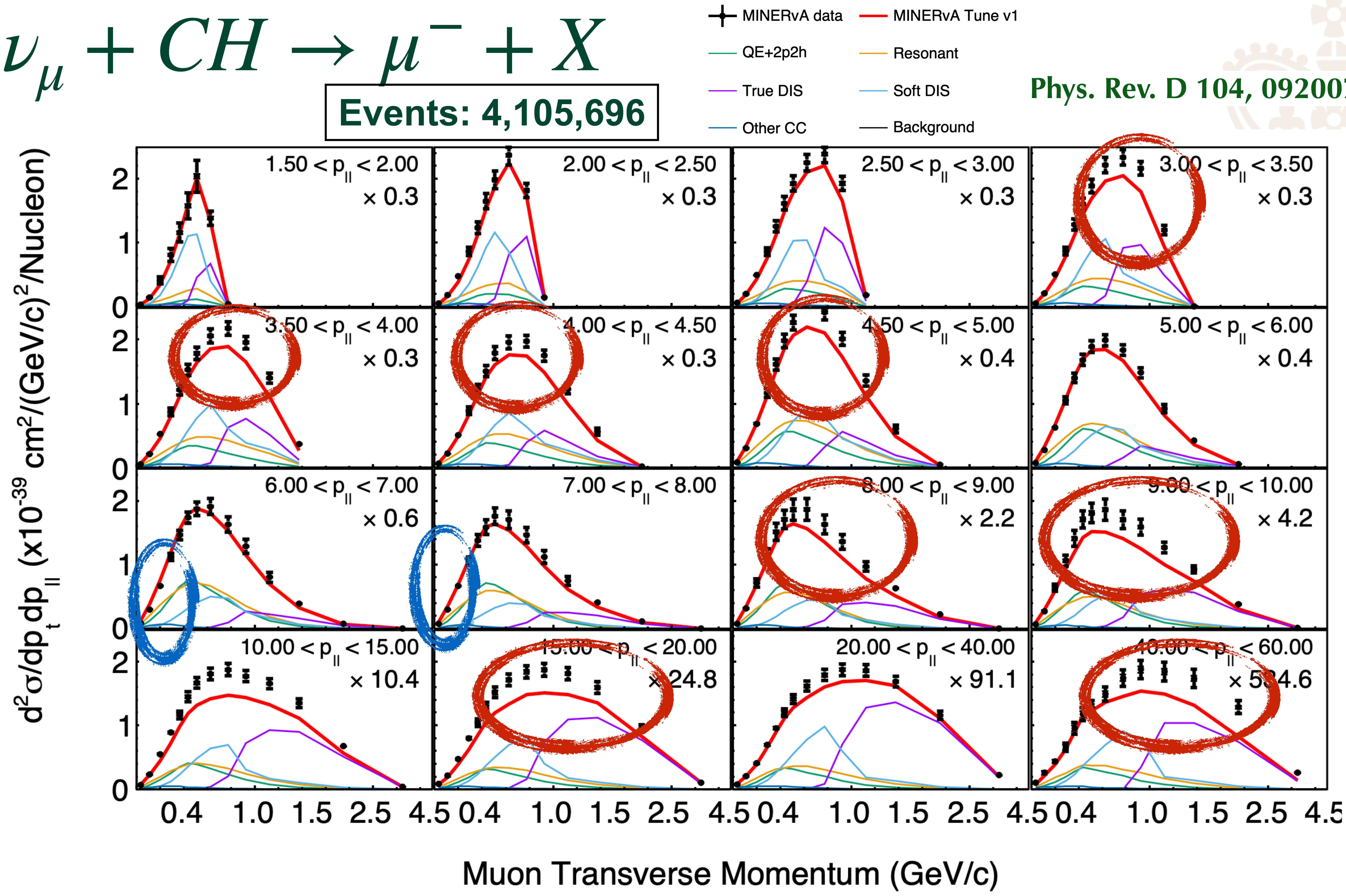
Neutrino inclusive cross-section in CH

$$\nu_\mu + CH \rightarrow \mu^- + X$$

Events: 4,105,696

Phys. Rev. D 104, 092007

- Signal with a muon angle with respect to neutrino beam < 20°.
- "Clean" analysis: Background prediction of 0.2%.
- Dominant systematics: flux with approximately 4%.
- A double differential measurement
  - A double differential measurement is better at kinematic separation.
- MINERvA Tune developed based on the LE data was tested on this analysis.
- Better agreement seen between data and the tuned prediction.

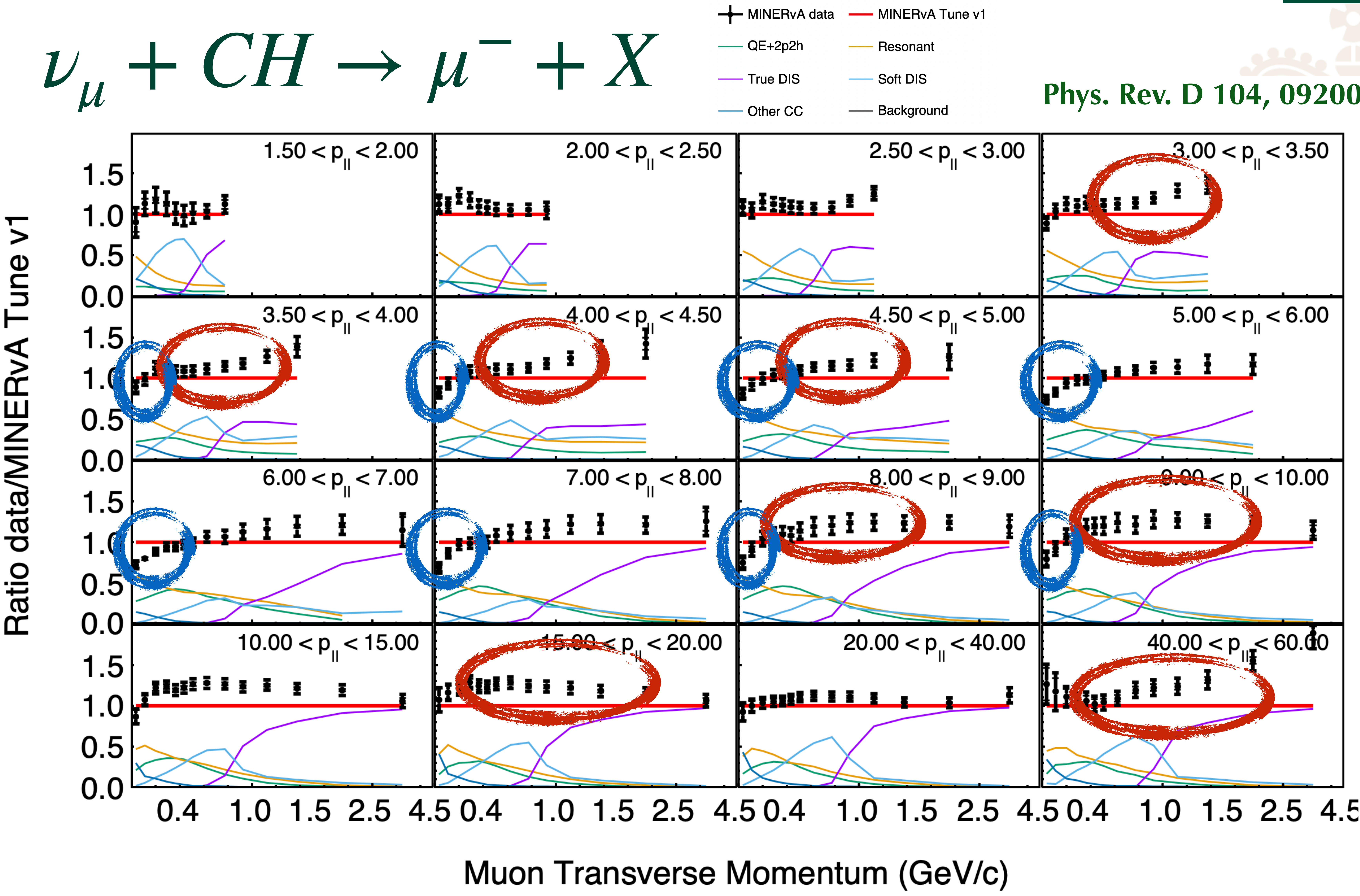


Neutrino inclusive cross-section in CH

- But agreement is not perfect yet:
  - ➡ **Underprediction** around the p_t peak for values of $p_{||} > 3$ GeV.
  - ➡ high pt region dominated by the "True DIS".
  - ➡ Poorly understood neutrino DIS nuclear effects could contribute to the underprediction in this region.
  - ➡ **Overprediction** for low values of p_t: dominant process is resonant pion production.
- Hard to differentiate the specific source of mismodeling:
  - All the underlying processes like QE, Soft DIS, True DIS, etc. contribute to the prediction in this region.
- Exclusive, semi-inclusive measurements required to investigate these complex regions.

$$\nu_\mu + CH \rightarrow \mu^- + X$$

Phys. Rev. D 104, 092007

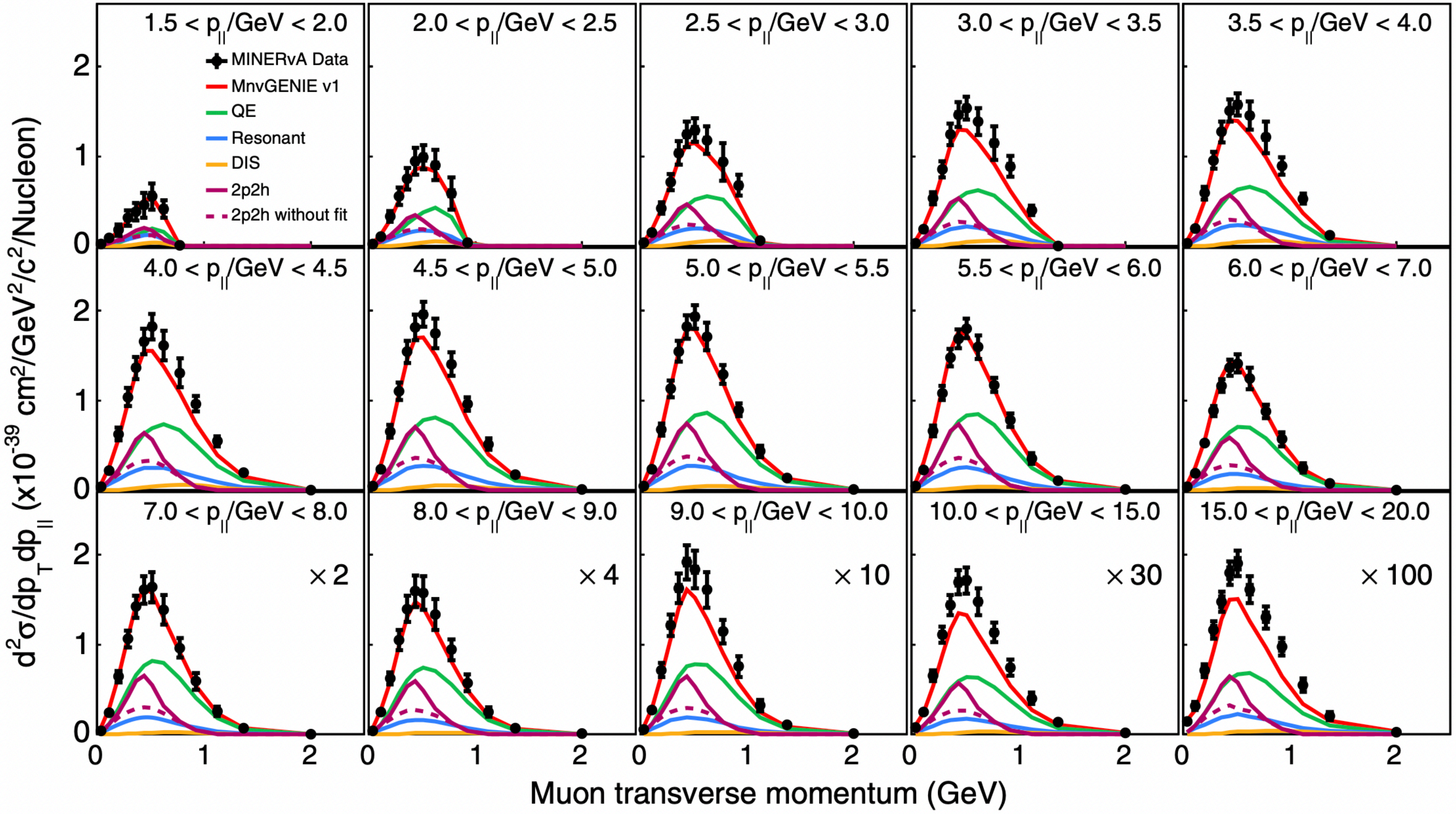


Quasi-elastic-like (QELike) neutrino cross-section in CH

$$\nu_\mu + CH \rightarrow \mu^- + N(p,n) + A'$$

Phys. Rev. Lett. 124, 121801 (2020)

- A 2D result of the QE-like measurement
- **Underprediction** in the $p_{||}$ bins above the spectral peak in range 3.0 to 5.0 GeV.
- **Overprediction** below the spectral peak from 5.5 to 8.0 GeV.
- We looked at the strength of models other than **quasi-elastic** in our measurements.
- Need to improve the **quasi-elastic model** as well, given the underpredictions in its dominant region.

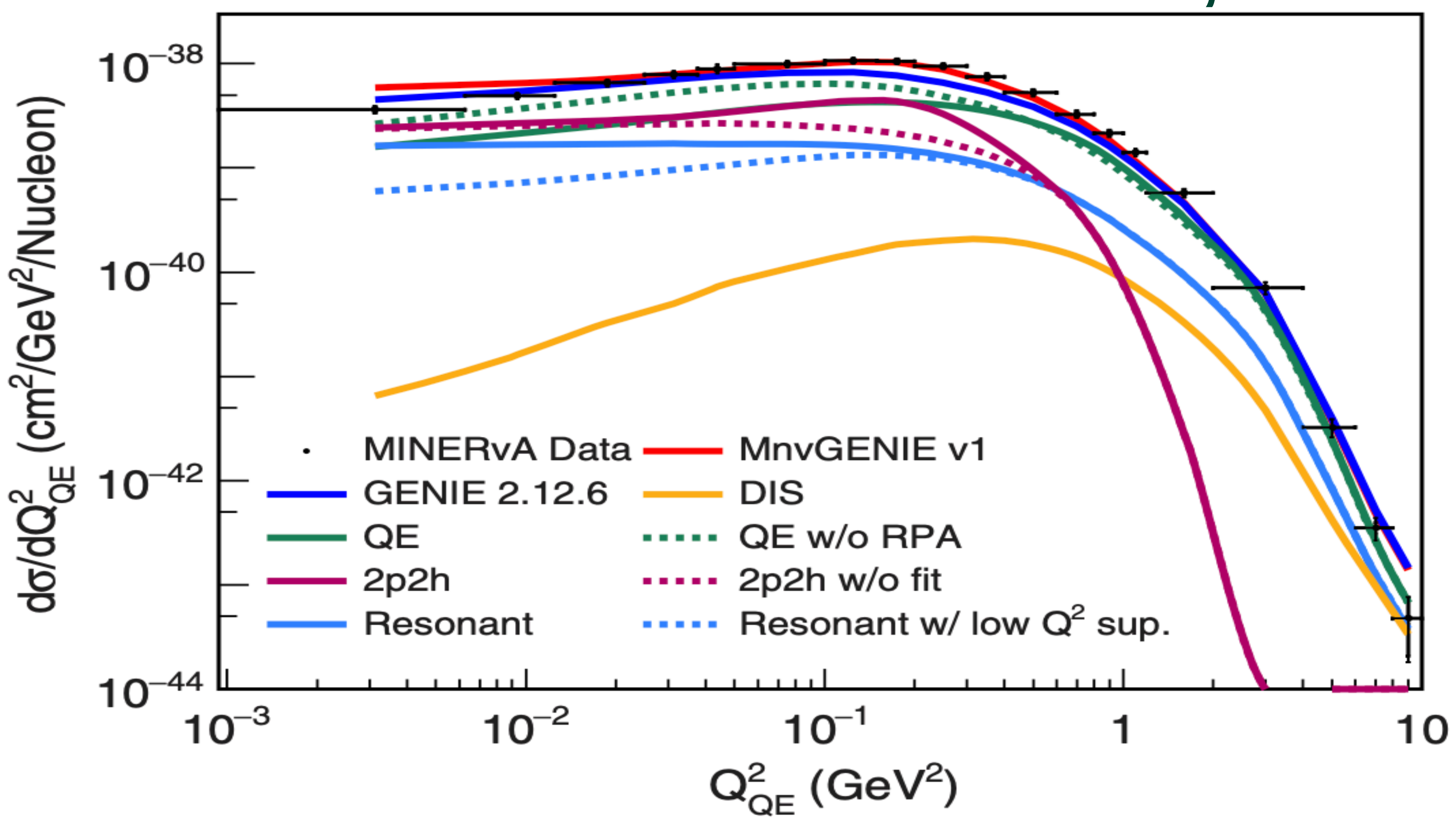


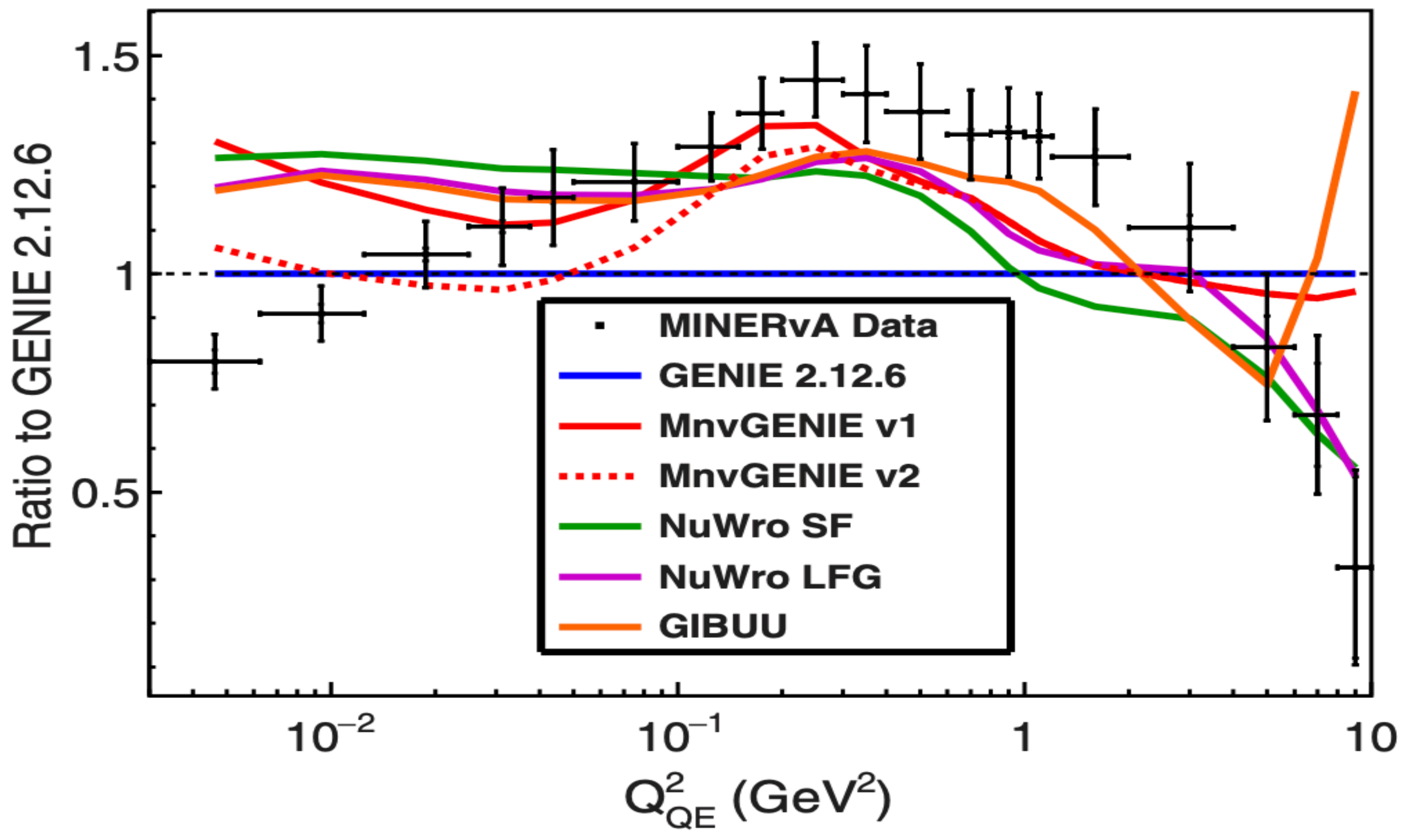
- World's largest Quasi Elastic Sample

CC QELike neutrino cross-section in CH

$$\nu_\mu + CH \rightarrow \mu^- + N(p,n) + A'$$

Phys. Rev. Lett. 124, 121801 (2020)





- Signal with a muon angle with respect to neutrino beam < 20°.
- Quasi-elastic-like:
  - ➡ Final-state: muon and any number of protons and/or neutrons.
  - ➡ No pions at all.
- Cross section reported as a function of $Q^2_{\rm QE}$
- $Q^2_{\rm QE}$: Transferred four-momentum squared under the quasi-elastic hypothesis:

$$Q^2_{QE} = 2E_\nu\,(E_\mu - p_{||}) - m_\mu^2$$

- **MINERvA Tune** greatly improves the agreement with the data compared to **out-of-the-box GENIE**.
- However, data in the high-Q2 region diverge from most predictions that are based on generators used by current oscillation experiments.
- There are no models that are even in approximate agreement over all ranges of Q2.

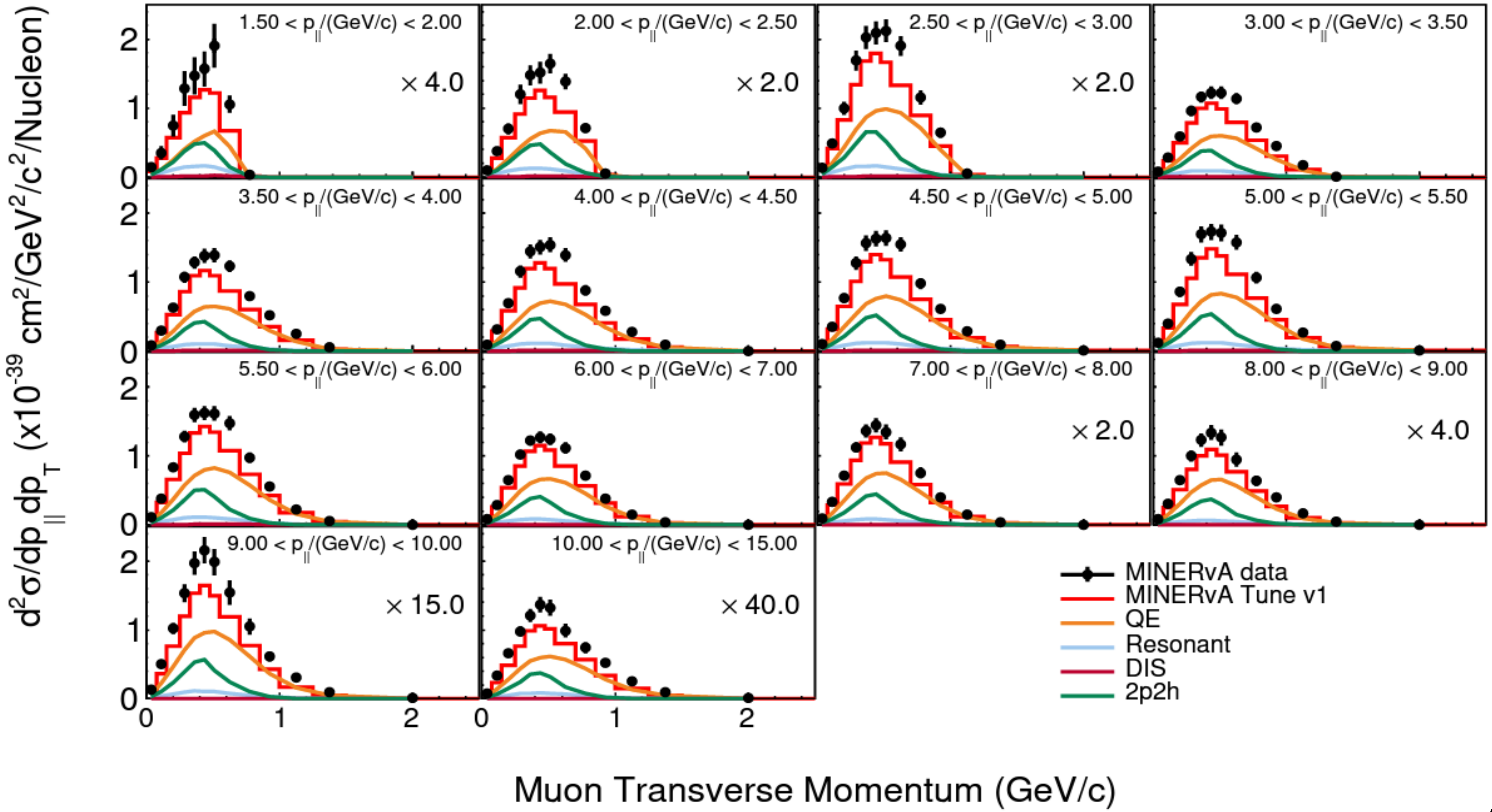
CC QELike Anti-neutrino cross-section in CH

A. Bashyal et. al.

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + N'$$

- Events: 635,592
- LE events: 14,839

- Double differential cross section in bins of muon momenta
- Signal definition:
  - ➡ One charged muon
  - ➡ No charged mesons.
  - ➡ Signal with a muon angle with respect to neutrino beam < 20°.
  - ➡ $1.5\ \mathrm{GeV/c} \leq p_{||} \leq 15\ \mathrm{GeV/c}$
- General disagreement between data and MC, especially at high muon p_T.
- p_T, momentum transfer, linked to Q^2. Dominated by QE.
- Model predicts that the cross section is dominated by pure 1p1h QE and 2p2h processes.
  - low p_T region dominated by QE and 2p2h processes
  - high p_T region dominated by QE processes only



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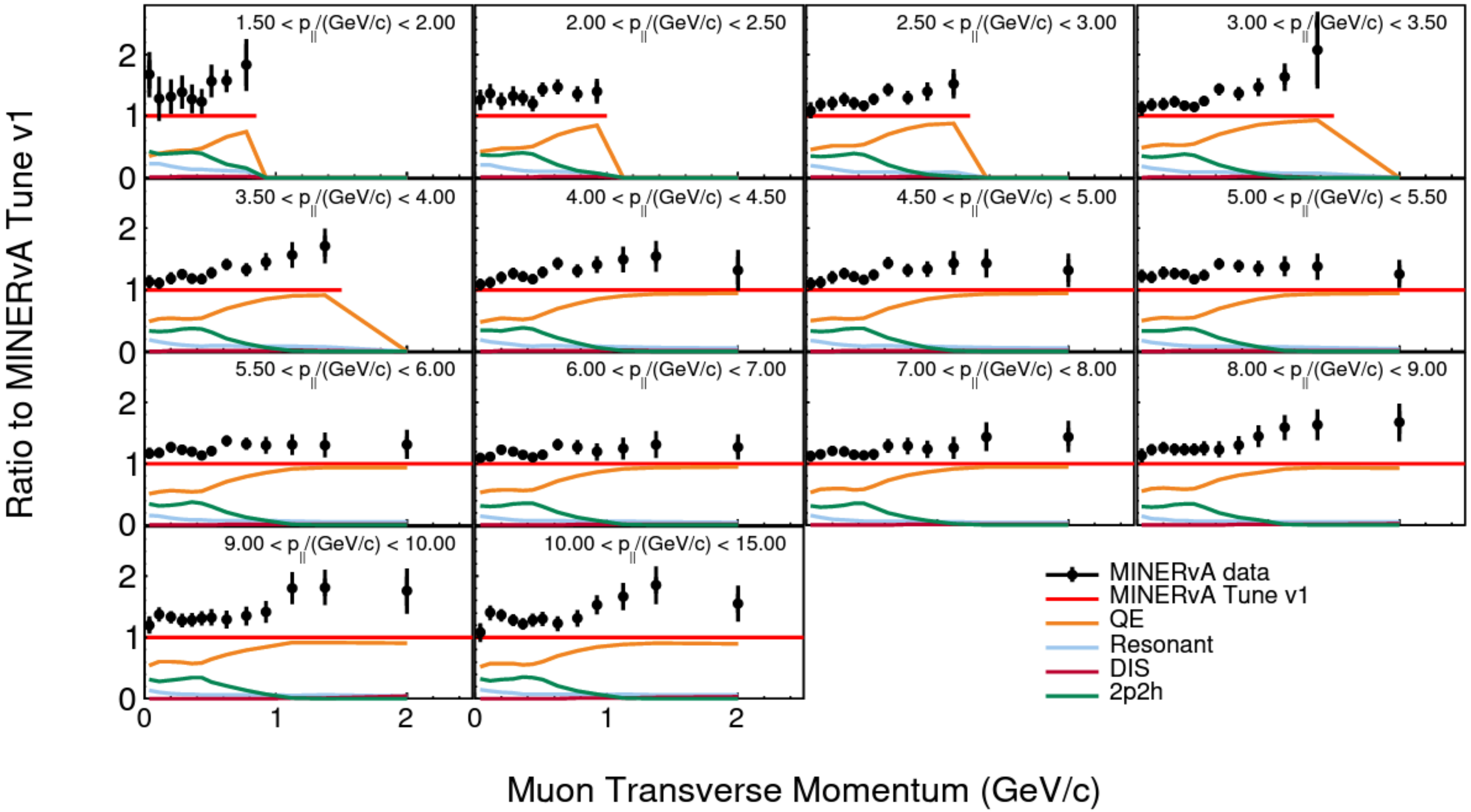
- General disagreement between data and MC, especially at high muon p_T.
- p_T, momentum transfer, linked to Q^2. Dominated by QE.
- Models fail to reproduce the high Q^2 behavior of the cross section.



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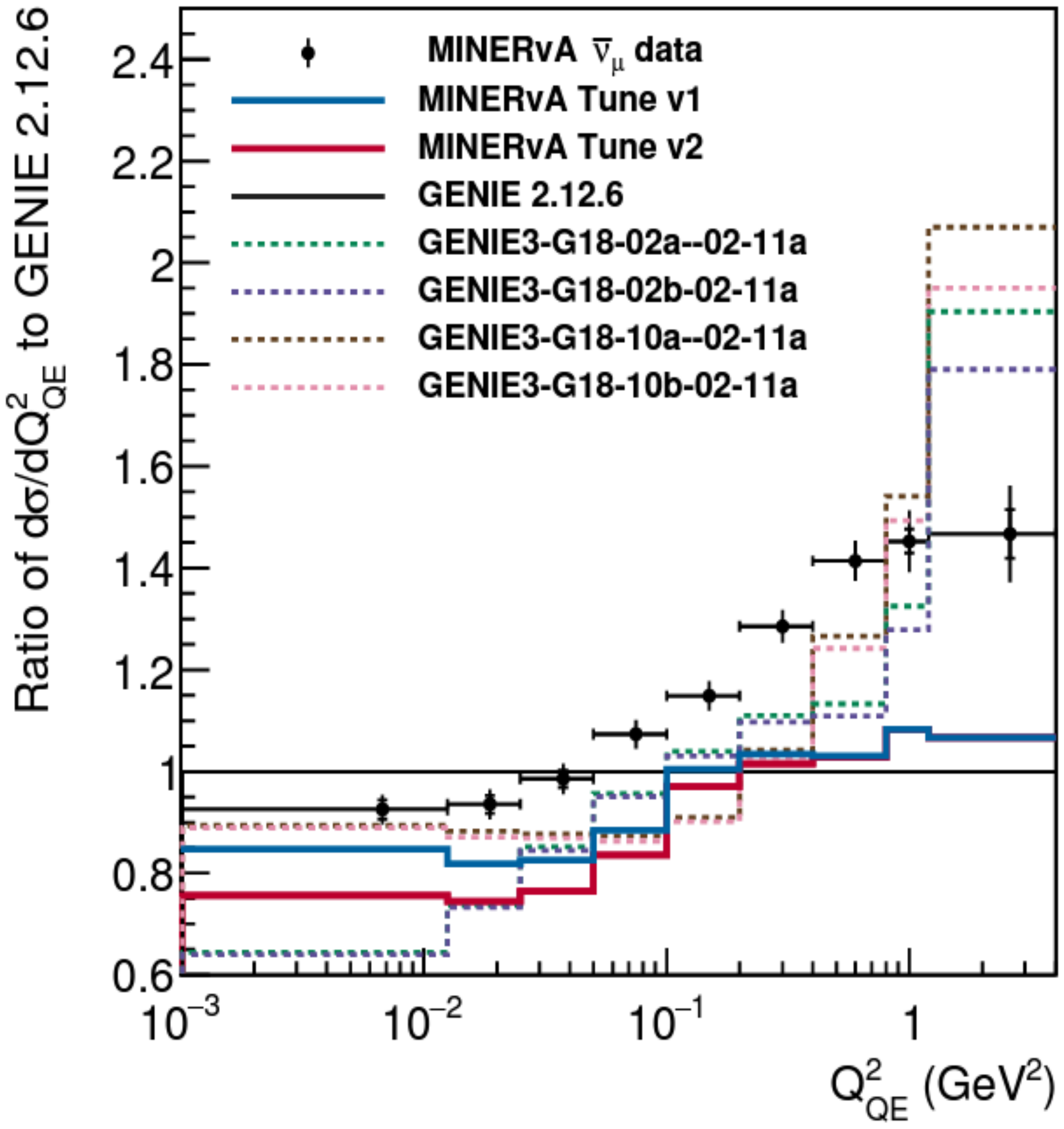
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + N'$$

A. Bashyal et. al.



- Signal with a muon angle with respect to antineutrino beam < 20°.
- Quasi-elastic-like:
  - ➡ Final-state: muon and any number of protons and/or neutrons.
- Cross section reported as a function of Q^2_{QE}

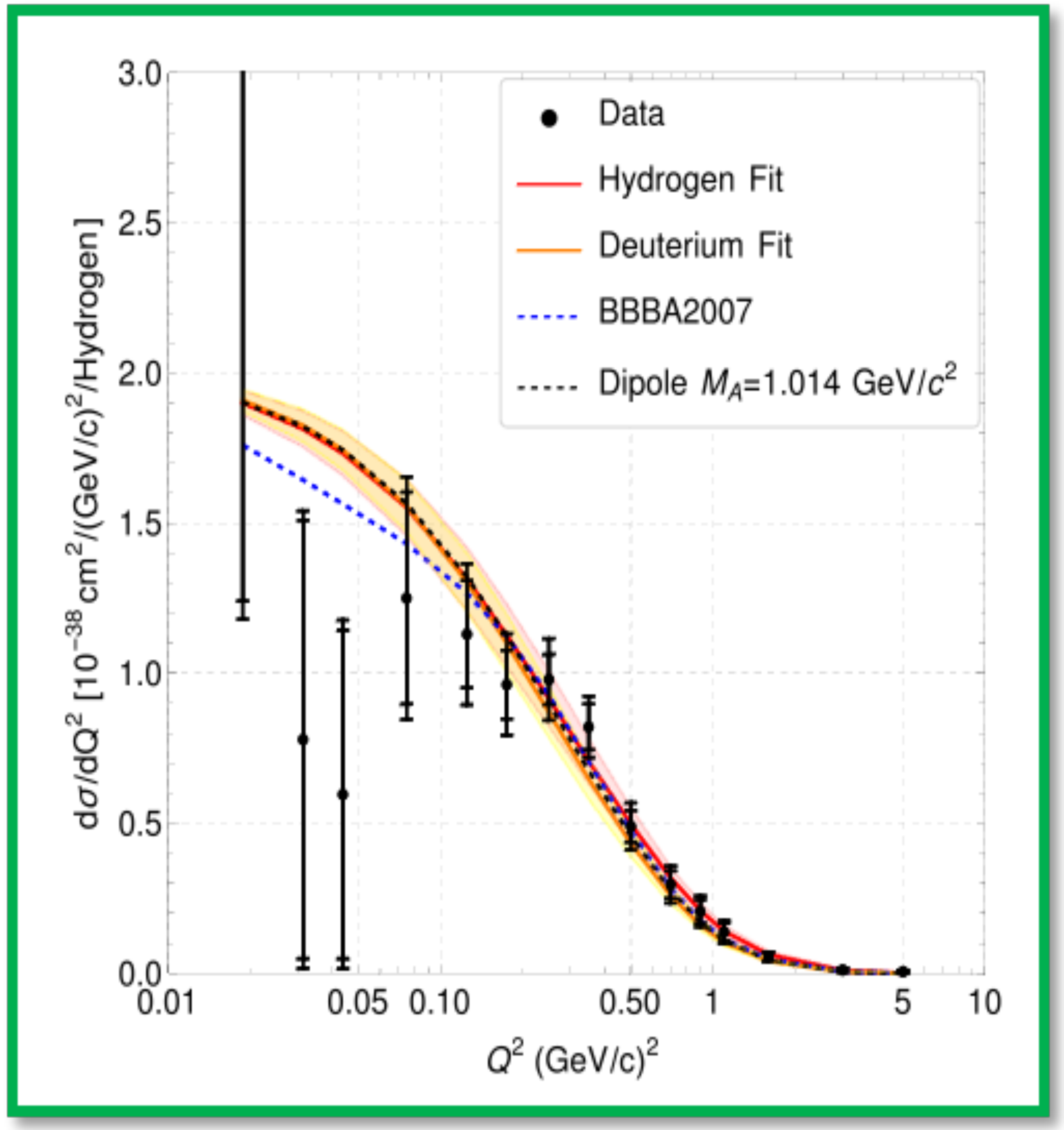
- Genie v3 appears to describe data better especially in high Q^2_{QE} region which is dominated by QE.
- MINERvA Tune v2 is MINERvA Tune v1 with the non-resonant pions suppressed in the low Q2 QE region.
- However, data across different Q2 regions diverge from most predictions that are based on generators used by current oscillation experiments.
- No models in approximate agreement over all ranges of Q2.
- Need to improve and have a proper model to understand different regions of Q2.

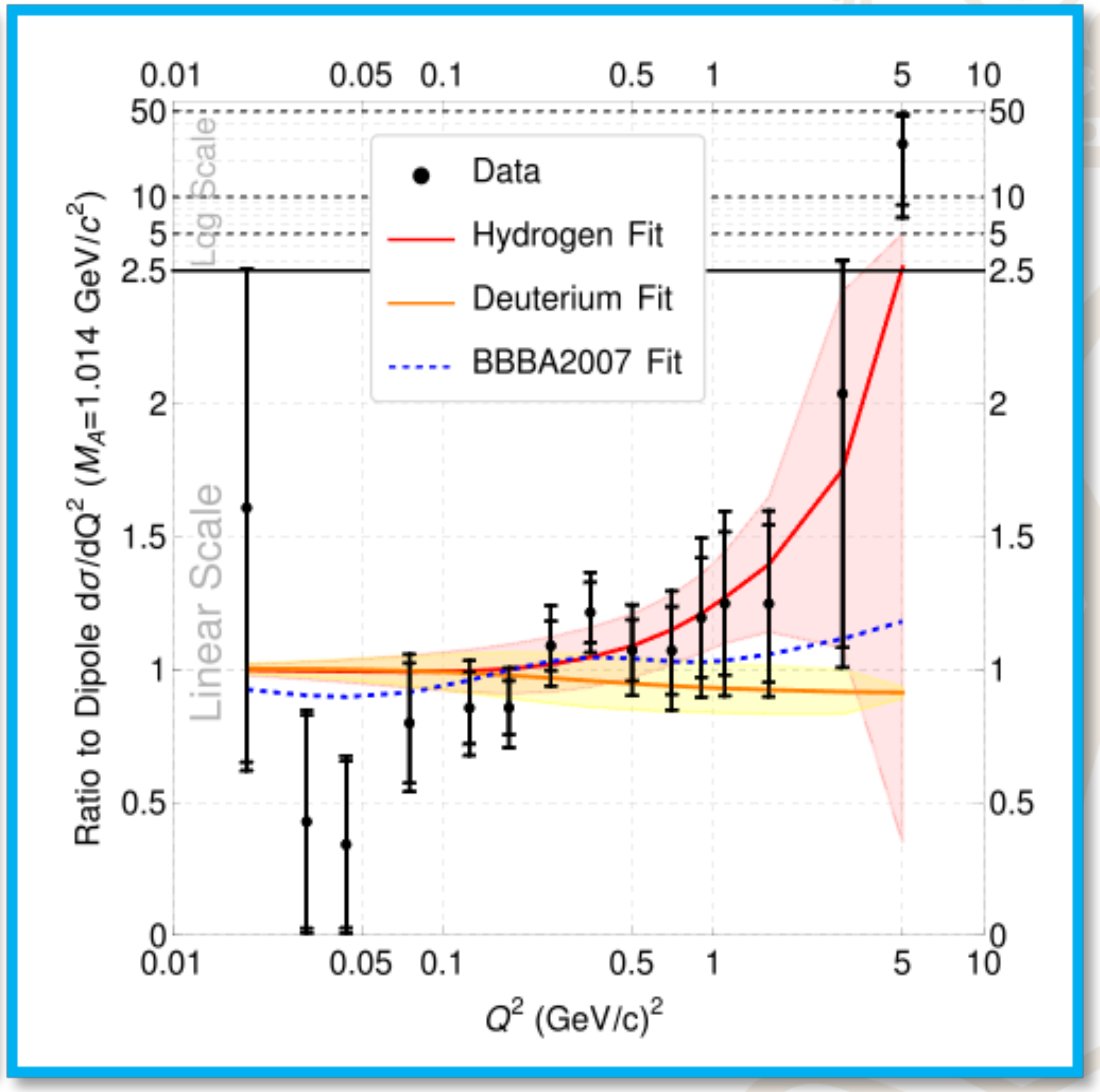
QELike Anti-neutrino scattering on free proton

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Nature, 614, 2023

- Scattering from weakly interacting neutrinos gives the opportunity to measure both vector and axial vector form factors of the nucleon,
- Provides an additional, complementary probe of the nucleonic structure.
- Reported first statistically significant measurement of elastic $\bar{\nu}p$ scatter cross section
  - ~5000 proton elastic scatters
- First F_A measurement for the last 30 years (to the best of our knowledge from literature).
- Fitted the cross section to export the Axial form factor and compared it with different models.
- This measurement will help in better understanding axial vector nucleon structure.



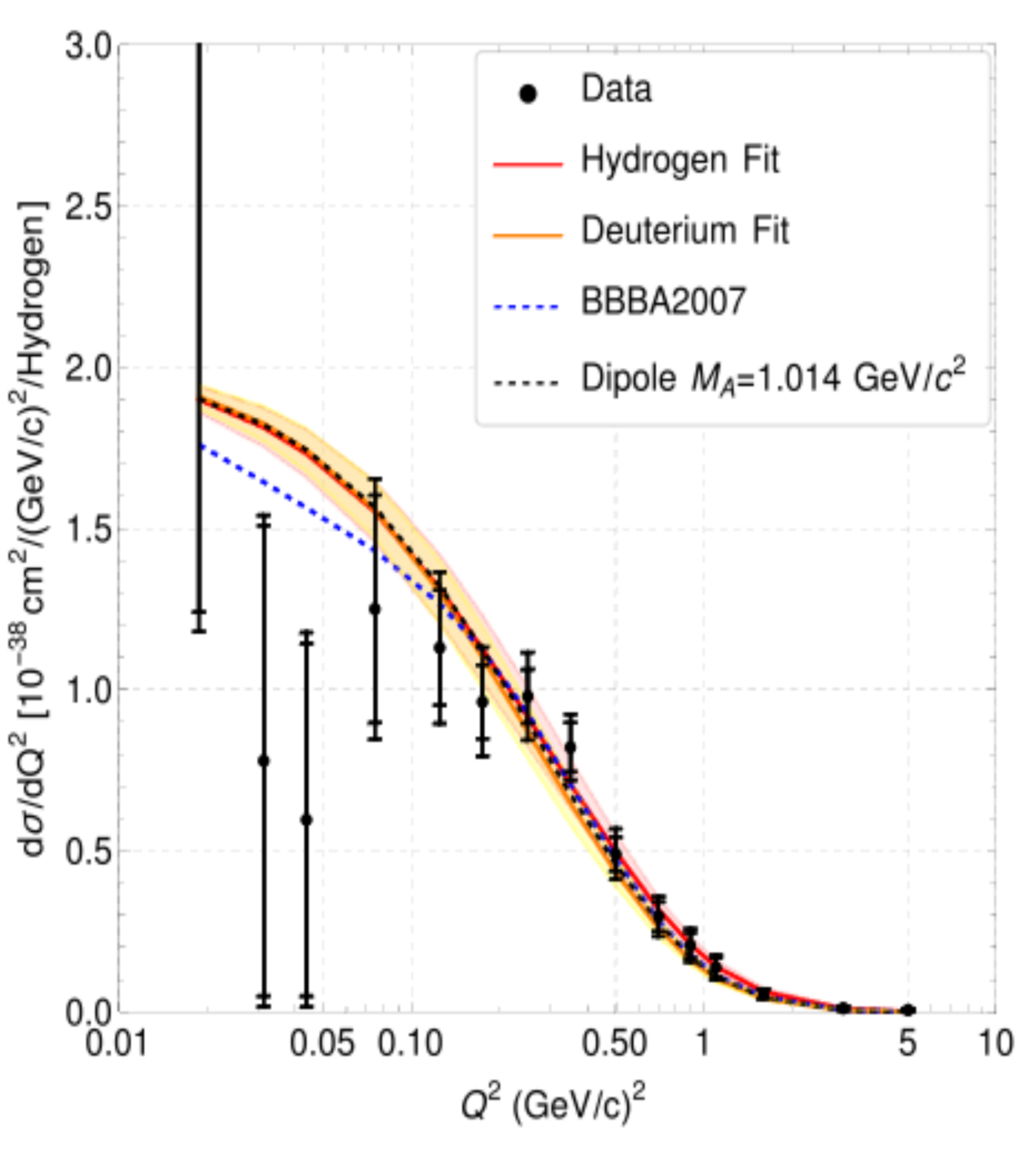


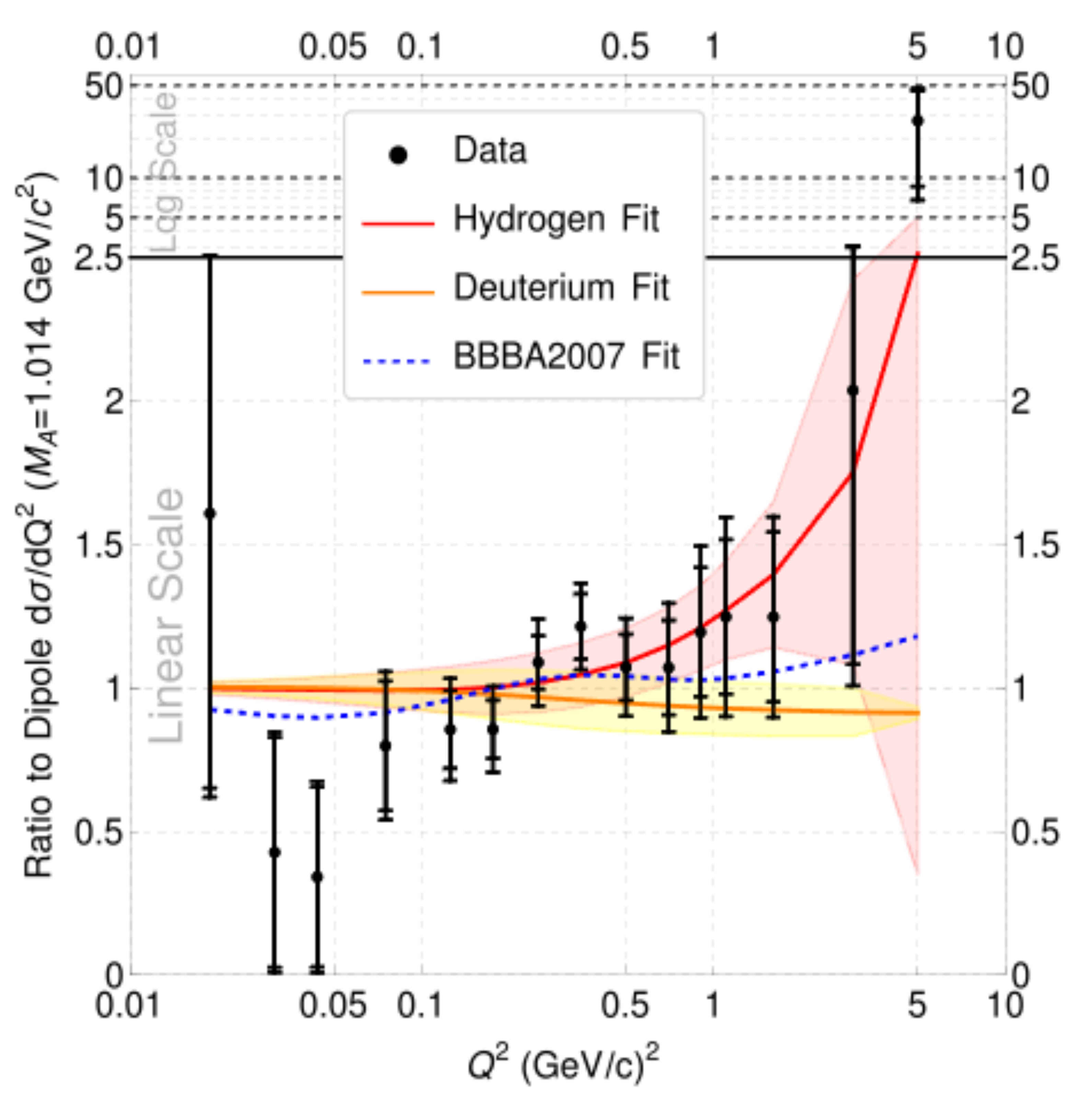
QELike Anti-neutrino scattering on free proton

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Nature, 614, 2023

- Comparison of our result (Hydrogen fit) with various models.
  - Deuterium scattering data in Bubble chamber
  - BBBA2007: Deuterium and pion electro-production data
  - Diople model:
    $$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$
    used in the neutrino generators
- Our measurement favors higher cross sections for higher Q^2
- This measurement will help in better understanding axial vector nucleon structure.





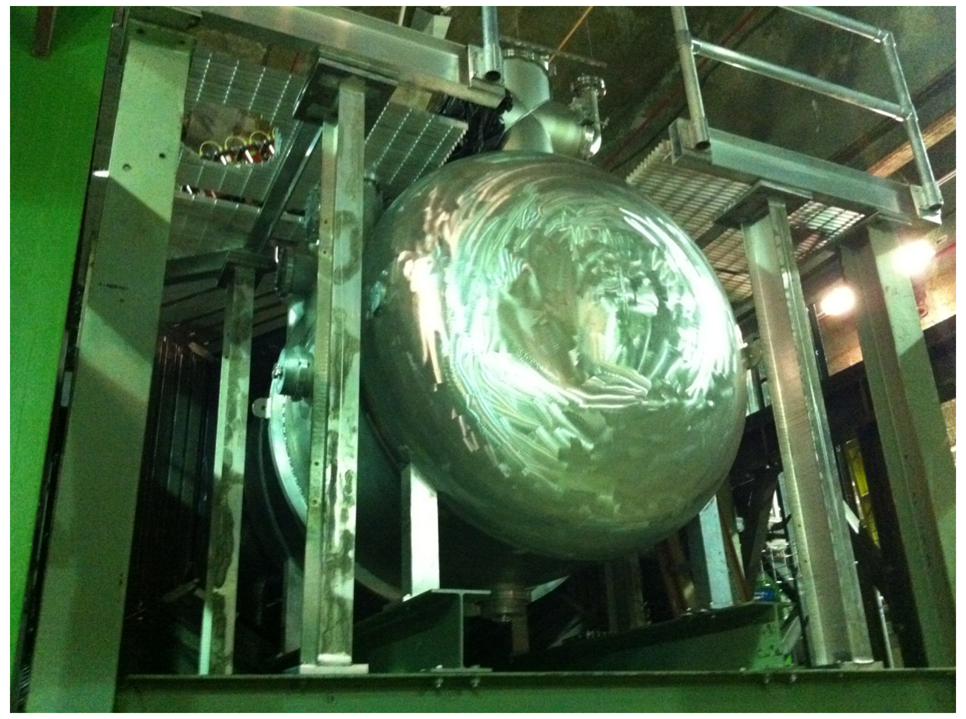
Extracted "proton radius" = $\sqrt{< r_A^2 >} = 0.73(0.17)\ fm$

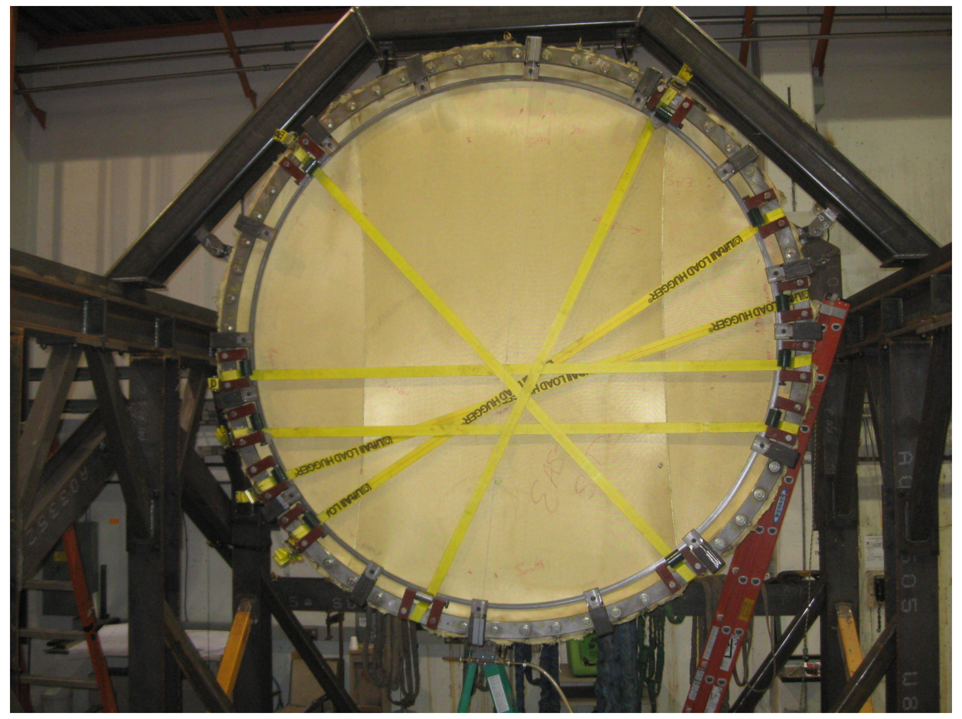
MINERvA future plans

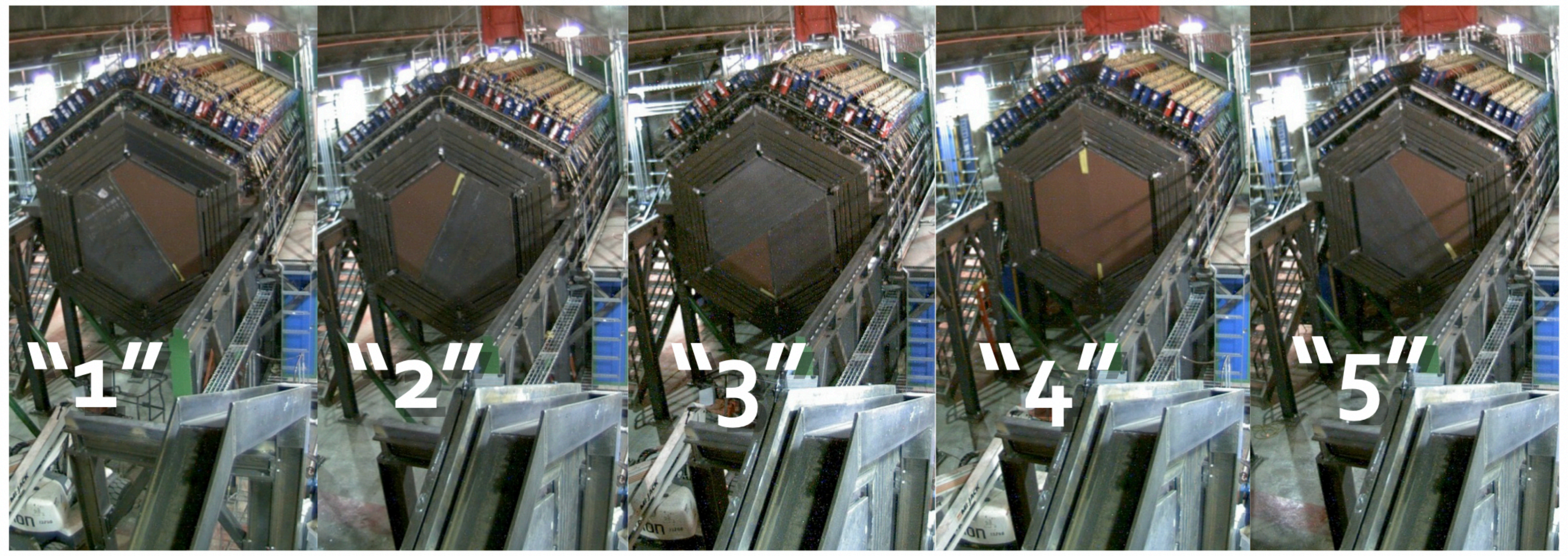
Physics analyses in-the-making

MINERvA never sleeps!

We are actively working on promising physics analyses in order to expand our understanding of the nuclear environment as well as exploring more energy regions.



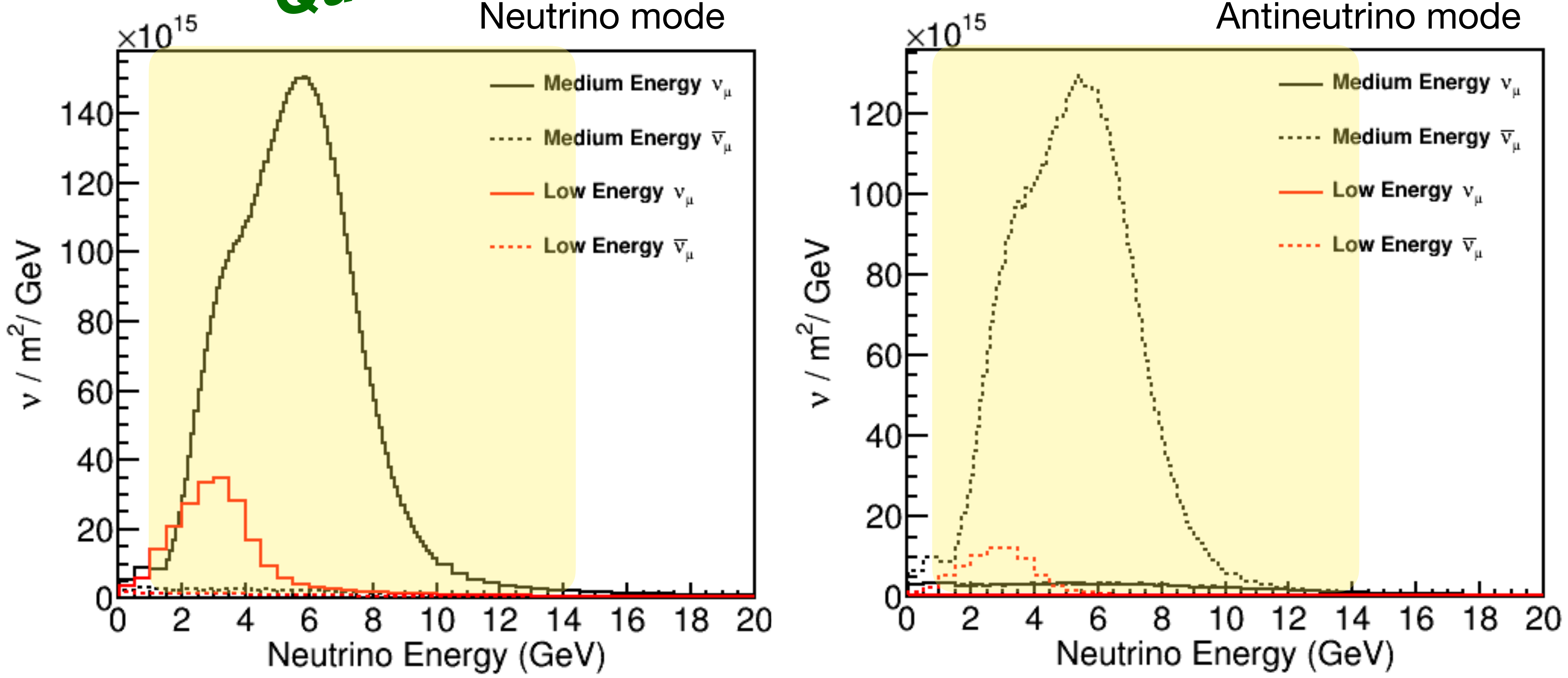




We have more targets to use!

Coherent MEC Resonant SIS

Quasi-elastic RES-DIS transition DIS



We have more channels to analyze!

Summary

A. MINERvA has pushed, and continues to push, the boundaries of the understanding of neutrino-nucleus interactions.

B. MINERvA provides ample statistics to investigate inclusive and exclusive final states of neutrino interactions across a variety of nuclear targets.

C. The efforts made by MINERvA are in great support of the goals to model and understand medium effects in a wide range of nuclear targets.

D. MINERvA has a huge amount of unique data, but is a very small collaboration. All of the physics that lies in the MINERvA data can't be extracted only by the present collaborators.

E. We started a dedicated effort in order to preserve collaboration's data to be used by new group members or people involved in other experiments like NOvA, DUNE, etc.

F. In the last couple of months, MINERvA has made a substantial progress:

    1. Reported cross-section measurements with enhanced statistics
    2. Interaction model comparisons with generators
    3. Published the free nucleon cross section and proton radius measurement in Nature.

G. Stay tuned for many more results from MINERvA.

MINERvA Recent Publications

- "Measurement of the axial vector form factor from antineutrino-proton scattering" **Nature, 614, 48-53 (2023)**.
- "Simultaneous measurement of νμ quasielastic-like cross sections on CH, C, water, Fe, and Pb as a function of muon kinematics at MINERvA" **Phys. Rev. Lett. 130, 161801 (2023)**
- "High-Statistics Measurement of Antineutrino Quasielastic-like scattering at Eν~ 6~GeV on a Hydrocarbon Target" **submitted for publication, [hep-ex]:2211.10402**
- "Neutrino-induced coherent π+ production in C, CH, Fe and Pb at ⟨Eν⟩~6 GeV" **Accepted in Phys. Rev. Lett (2023)**
- "Simultaneous measurement of νμ charged-current single π+ production in CH, C, H2O, Fe, and Pb targets in MINERvA" **submitted for publication, [hep-ex]:2209.07852**
- "Simultaneous measurement of proton and lepton kinematics in quasielastic-like νμ-hydrocarbon interactions from 2 to 20 GeV" **Phys.Rev.Lett. 129 (2022) 2, 021803**.
- "Improved constraint on the MINERvA medium energy neutrino flux using ν¯e−→ν¯e− data" **Phys.Rev.D 107 (2023).**
- "Simultaneous measurement of proton and lepton kinematics in quasielastic-like νμ-hydrocarbon interactions from 2 to 20 GeV" **Phys.Rev.Lett. 129 (2022)**
- "Vertex finding in neutrino-nucleus interaction: A Model Architecture Comparison" **Journal of Instrumentation 17 T08013 (2022)**
- "Measurement of inclusive charged-current muon neutrino scattering on hydrocarbon at ⟨Eν⟩~6 GeV with low three-momentum transfer" **Phys.Rev.D 106 (2022)**

Thank you for your attention!!

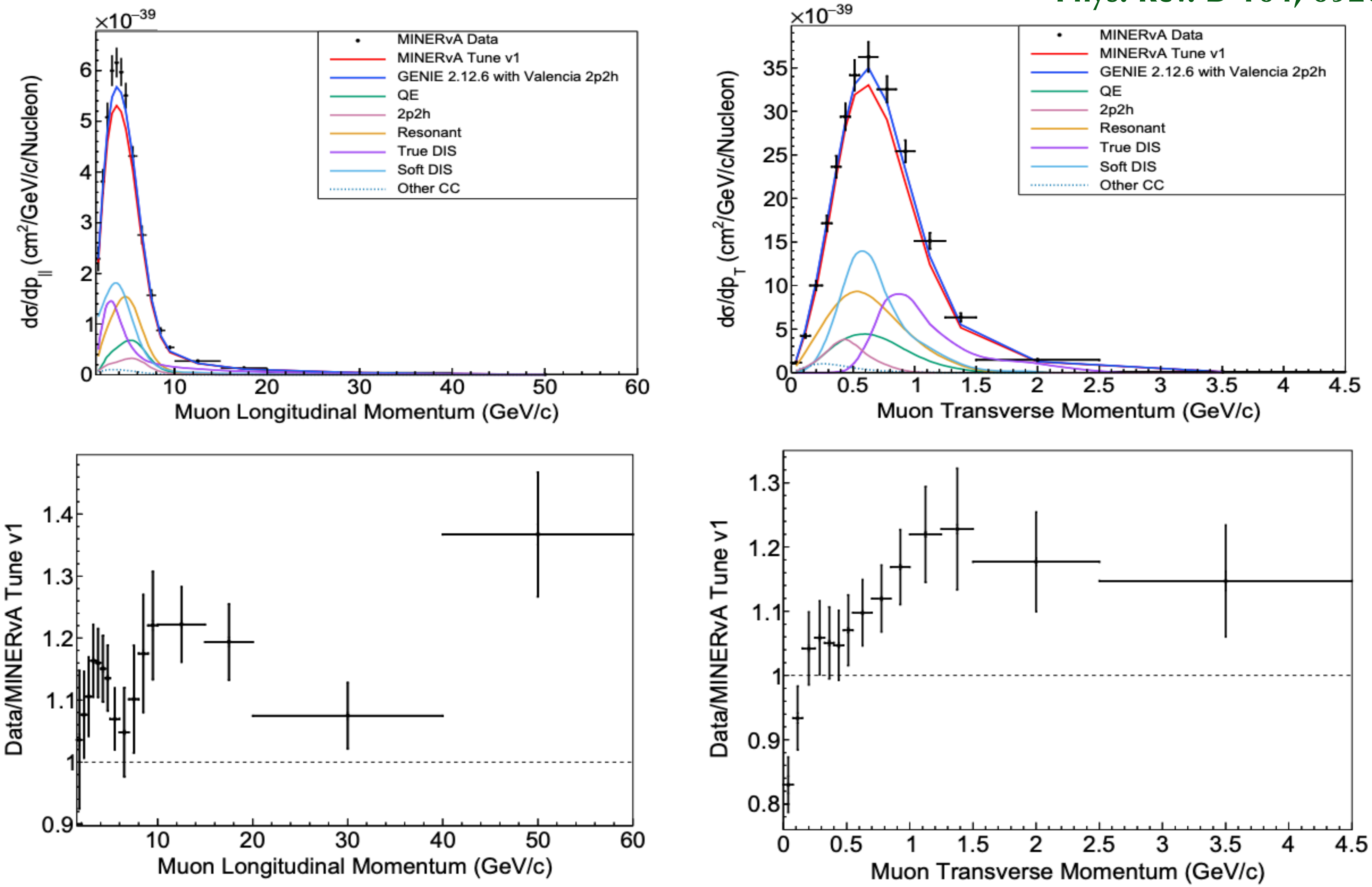
Back Up

Neutrino inclusive cross-section in CH

$$\nu_\mu + CH \rightarrow \mu^- + X$$

Phys. Rev. D 104, 092007

- Signal with a muon angle with respect to neutrino beam < 20°.
- "Clean" analysis: Background prediction of 0.2%.
- Dominant systematics: flux with approximately 4%.
- Single differential cross sections as a function of:
  - Muon p_t and $p_{||}$



CC QELike Anti-neutrino cross-section in CH

A. Bashyal et. al.

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + N'$$

Quantity	Variation ($\pm 1\sigma$ from CV)	Effect on cross section (%)
Angle reconstruction	± 1 mr	0 - 2
MINOS muon energy scale	± 1.0 %	2 - 6
GEANT Neutron	± 10 %	2 - 5
Flux	focusing and hadronic interaction parameters	5
GENIE Cross Section Models	GENIE cross section parameters	1-5
GENIE 2p2h	Low recoil fit parameters	1-3
Final State Interaction Model	GENIE FSI models parameters	1-3

TABLE I. Effect of input uncertainties on the cross section extraction for $d\sigma/dQ^2_{QE}$. Uncertainties which have significant effect on final cross section are listed. The $\pm 1\sigma$ is the shift of model parameters from their central values (CV).