The Neutrino's View of the Nucleus: New Results from MINERvA

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Fermilab

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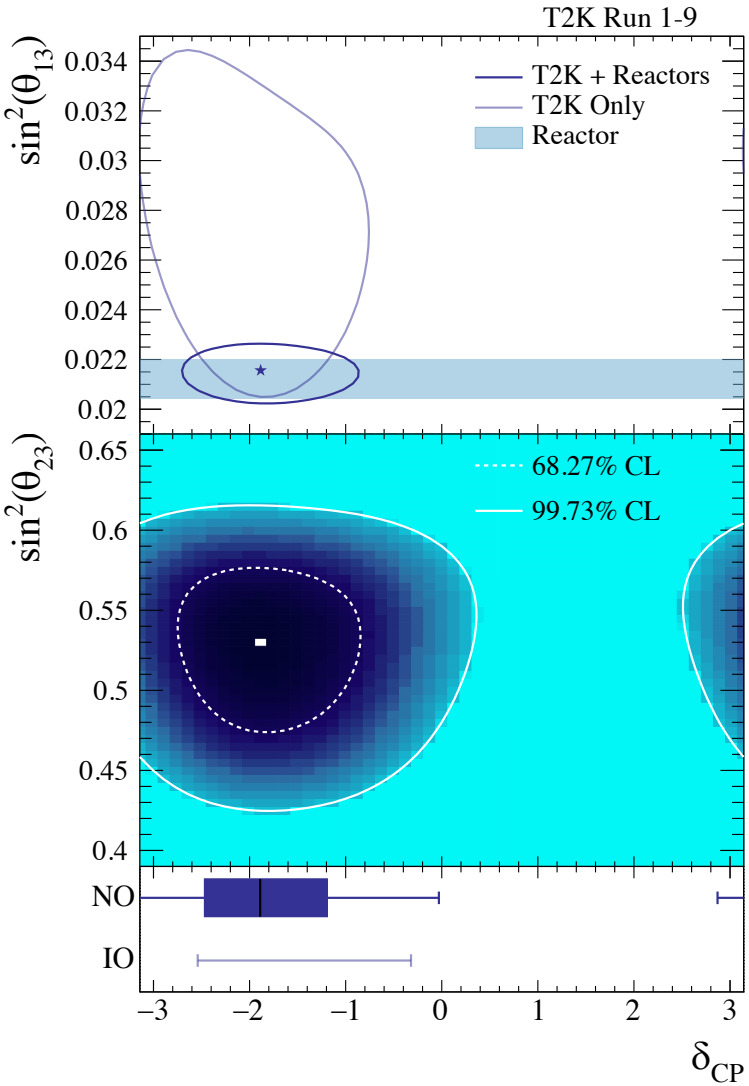
NEUTRINO 2020

XXIX INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS

Why MINERvA ?

Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations



Nature **580,** 339–344 (2020). arXiv:1910.03887

Challenge: Neutrino interaction modelling is 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

Convolution of cross section and nuclear effects

Near detector

Event Rate: $N(x) = \phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times P_{\nu_{\mu \to \nu_e}}$

Far detector

Oscillation experiments requires:

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

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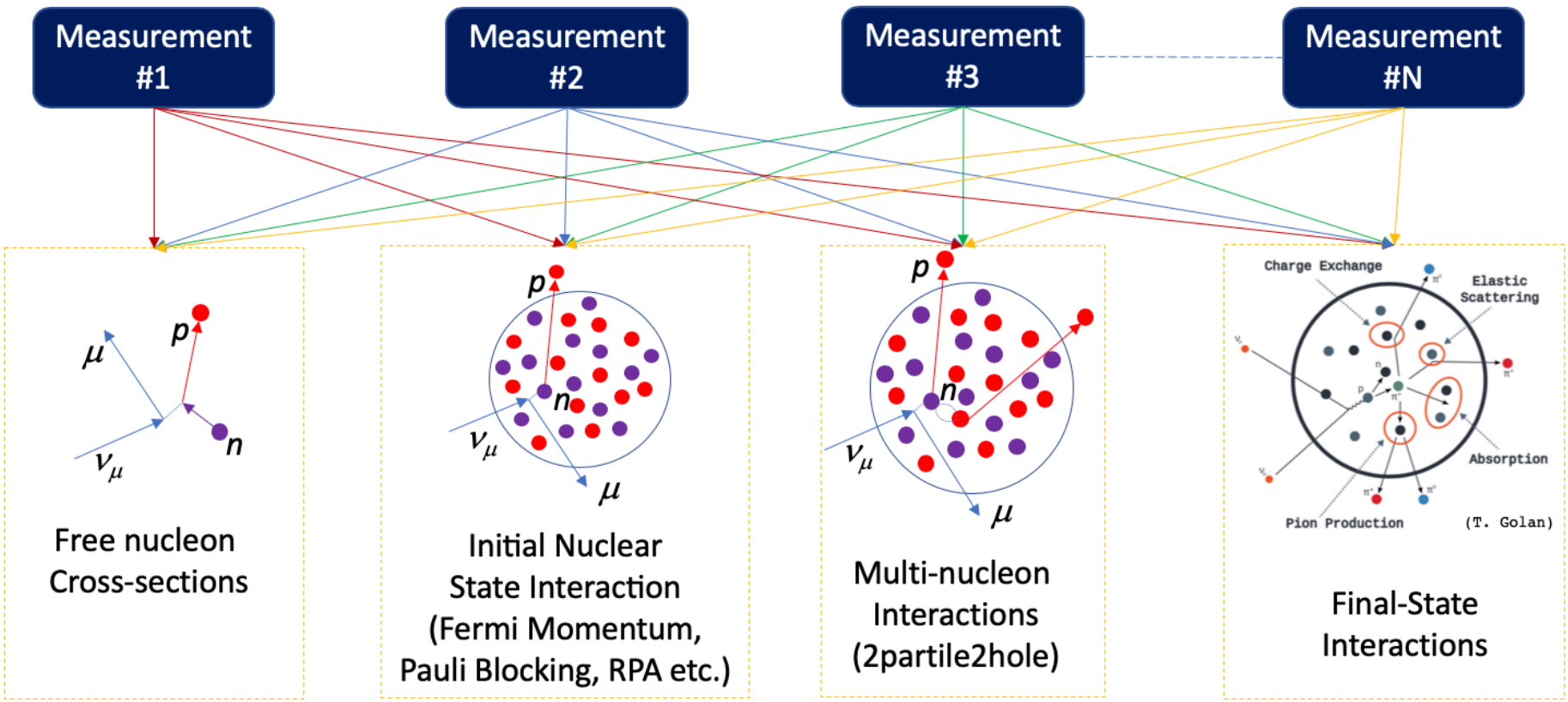
- Nuclear Effects

MINERvA was designed to improve physics models

Nuclear Effects : Challenge

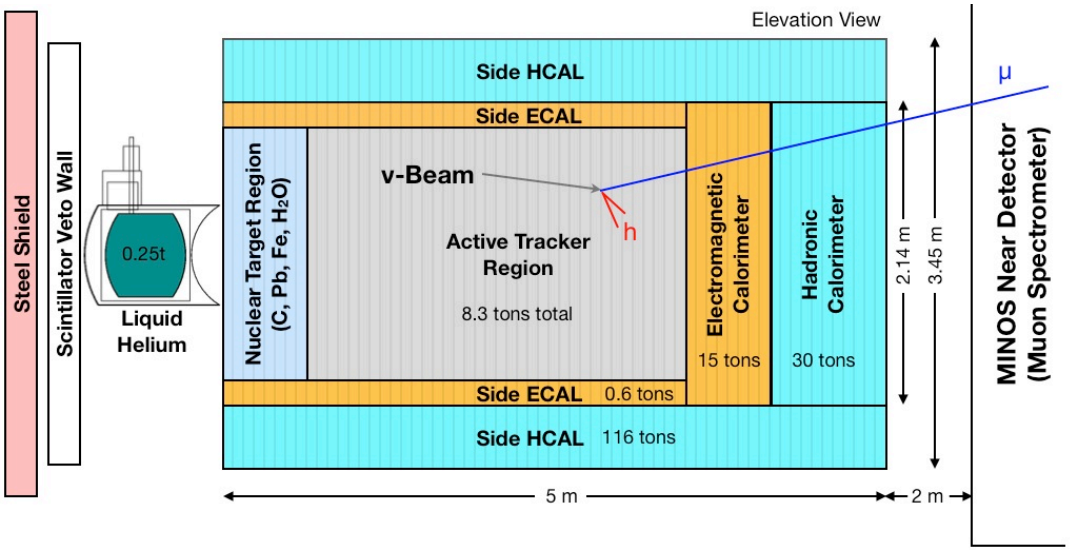


Welcome to MINERvA Land!

https://nypost.com/2015/07/18/is-this-the-most-dangerous-roller-coaster-in-america/

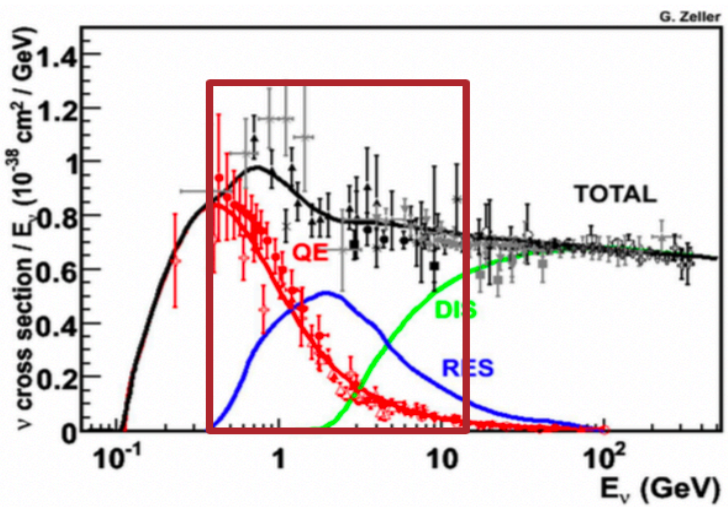
MINERvA Experiment

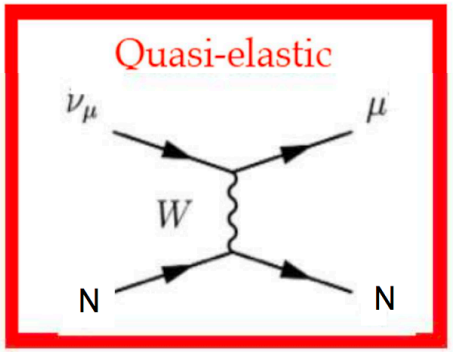
- MINERvA is a dedicated neutrino scattering experiment in the NuMI beamline at Fermilab.
- Primary goal is to characterize neutrino interactions for oscillation experiments.
- Identify the nuclear effects and test models.
- Unique overlap to DUNE flux
- Demonstrate techniques for oscillation experiments.

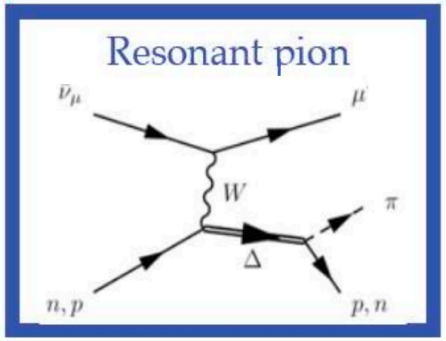


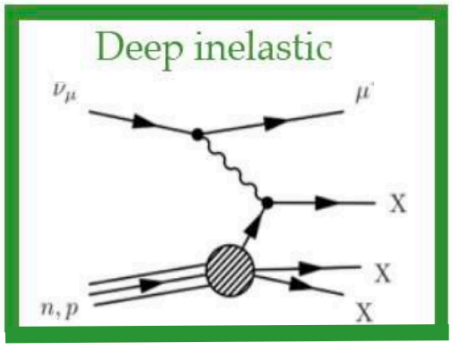
- Detector has a large "active tracker" of segmented solid scintillator
- Upstream of the MINERvA tracker is a region of He, C, H_2O, Fe, and Pb targets.
- Downstream and side by HCAL and ECAL.
- MINOS to track the muons.

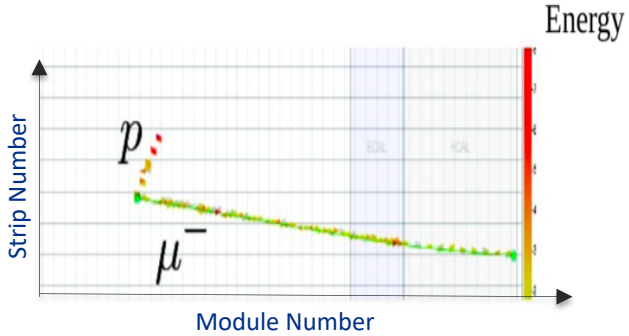
Interaction channels that MINERvA measure

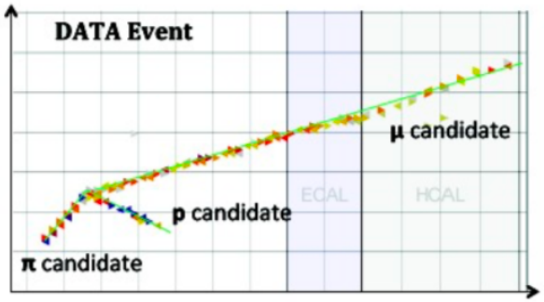


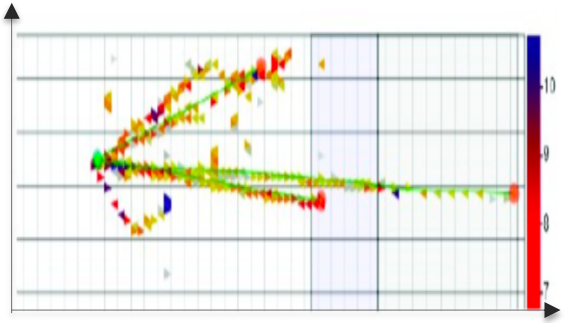




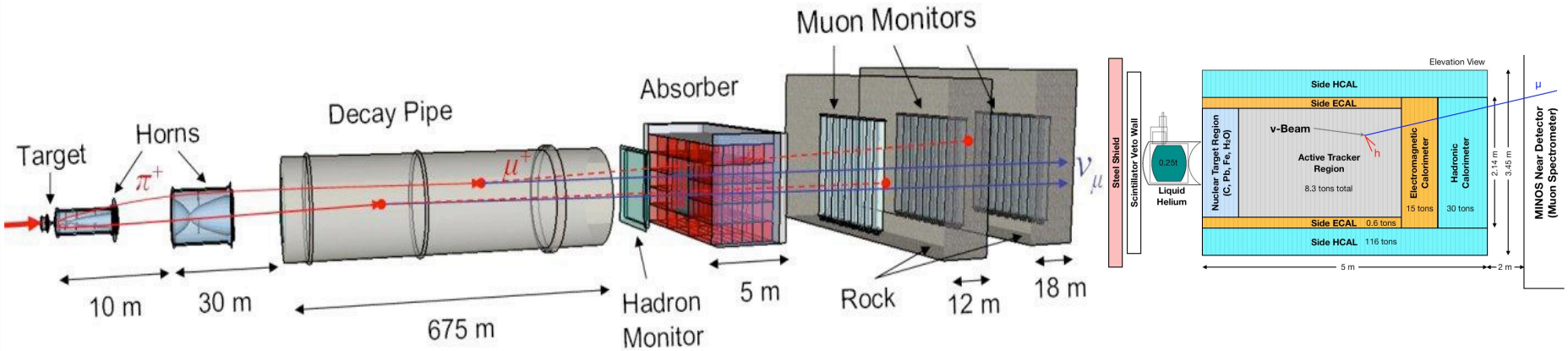




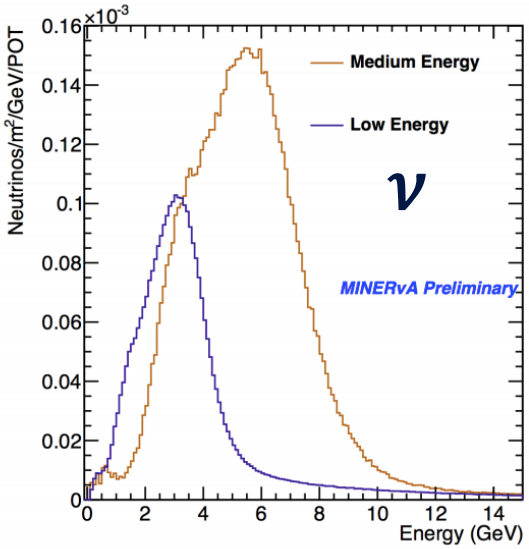


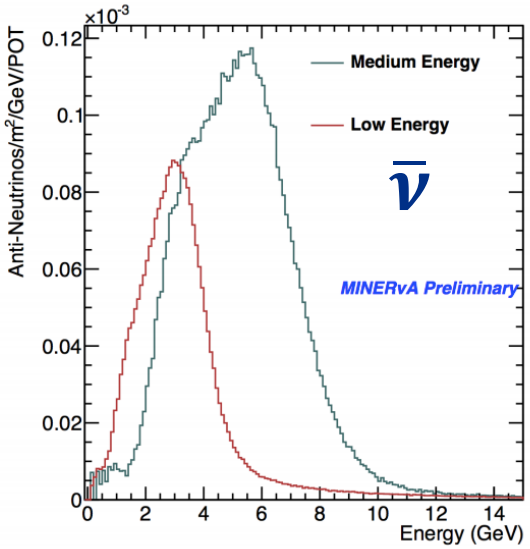


MINERvA Medium and Low Energy



- Target/horn spacing can be varied to produce different energy spectra.
- MINERvA has collected large datasets in both the "Low Energy (LE)" and "Medium Energy (ME)" configurations
- $POT_{ME} \approx 4\ POT_{LE}$





MINERvA Publications

Published since Neutrino-2018:

- "High-statistics measurement of neutrino **quasi-elastic-like scattering at ~ 6 GeV** on a hydrocarbon target", Phys. Rev. Lett. 124, 121801 (2020
- "**Nuclear binding energy and transverse momentum imbalance** in neutrino-nucleus reaction", Phys. Rev. D 101, 092001 (2020)
- "Constraint of the MINERvA Medium Energy **Neutrino Flux using Neutrino-Electron Elastic Scattering**", Phys. Rev. D 100, 9 (2019)
- "Measurement of **$\bar{\nu}_\mu$ charged-current single π^- production** on hydrocarbon in the few-GeV region using MINERvA", Phys. Rev. D 100, 5 (2019)
- "**Tuning the GENIE Pion Production** Model with MINERvA Data", Phys.Rev. D 100, 7 (2019)
- "**Neutron measurements** from anti-neutrino hydrocarbon reactions", Phys. Rev. D 100, 052002 (2019)
- "Measurement of **Quasielastic-Like Neutrino Scattering at $\langle E_\nu \rangle \sim 3.5$ GeV** on a Hydrocarbon Target", Phys. Rev. D 99, 012004 (2019)
- "Reducing model bias in a **deep learning classifier** using domain adversarial neural networks in the MINERvA experiment", Journal of Instrumentation, Vol. 13 (2018)
- "Measurement of **final-state correlations in neutrino muon-proton mesonless production** on hydrocarbon at $\langle E_\nu \rangle = 3$ GeV", Phys. Rev. Lett. 121, 022504 (2018)

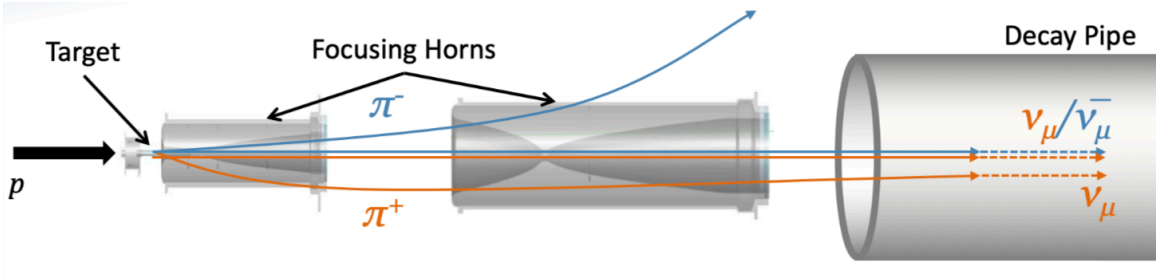
Submitted:

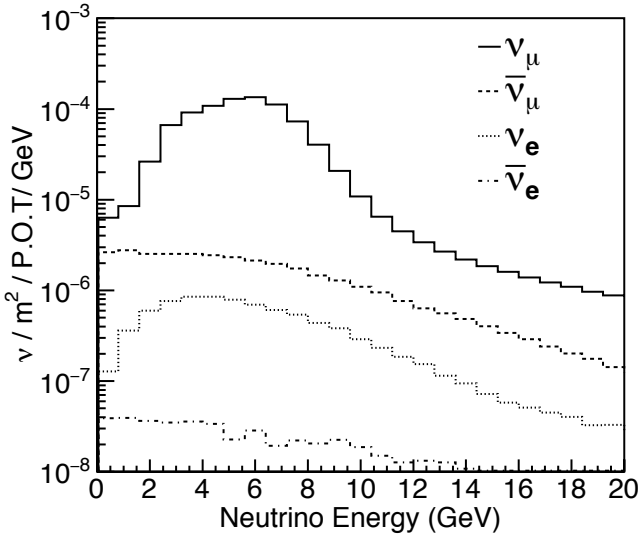
- "Double-Differential Inclusive Charged-Current ν_μ Cross Sections on Hydrocarbon in MINERvA at $\langle E_\nu \rangle \sim 3.5$ GeV", arXiv:2002.12496.
- "Probing Nuclear Effects with Neutrino-induced Charged-Current Neutral Pion Production" arXiv:2002.05812

All MINERvA publications:

- **https://minerva.fnal.gov/recent-minerva-results/**

NuMI Flux

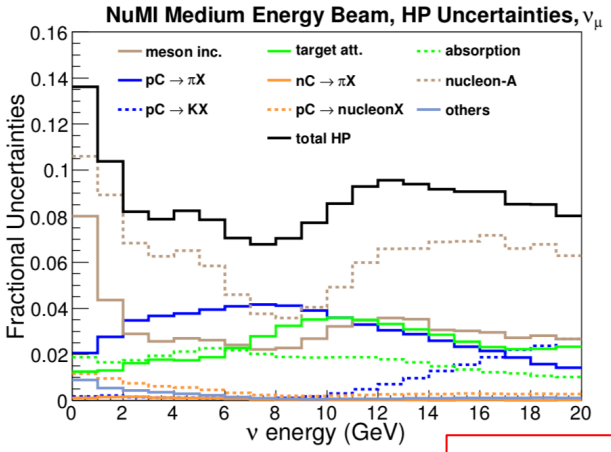


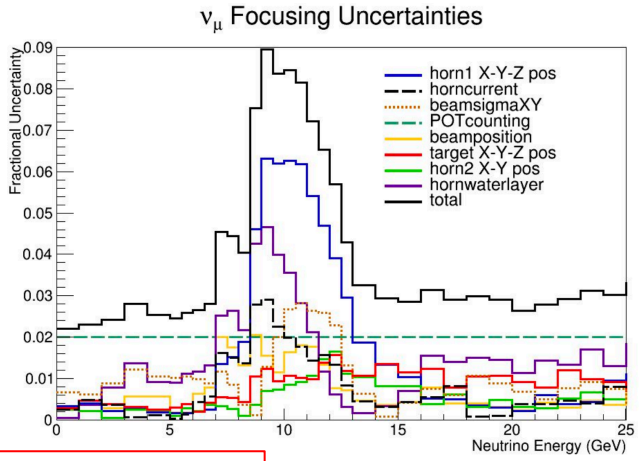


Flux is simulated via GEANT4 and flux predictions are corrected using the available external hadron production data.

Uncertainties on Flux:

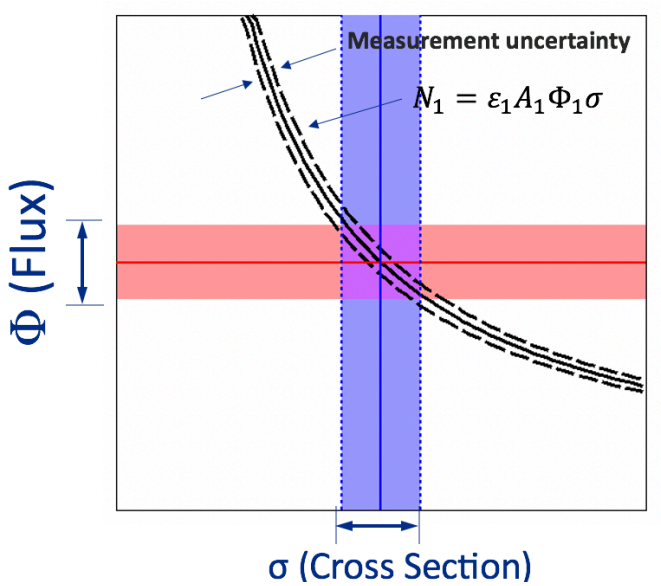
- Hadron Production
- Focusing

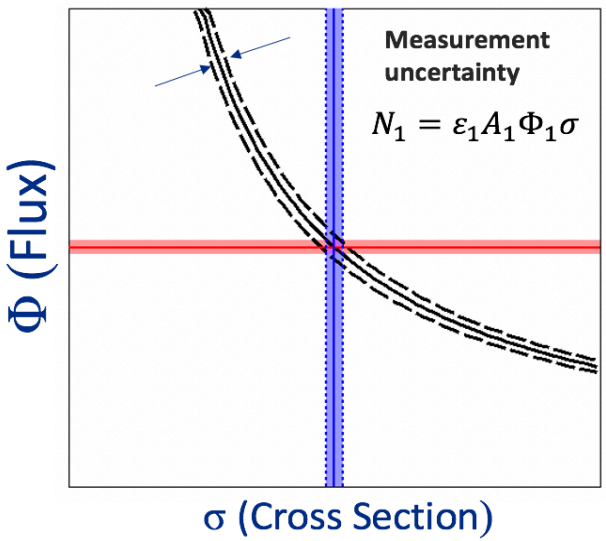


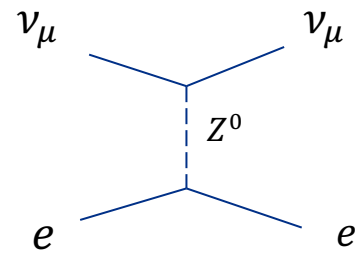


Phys. Rev. D 94, 092005 (2016)

In Situ Measurements : $\nu - e$ Scattering





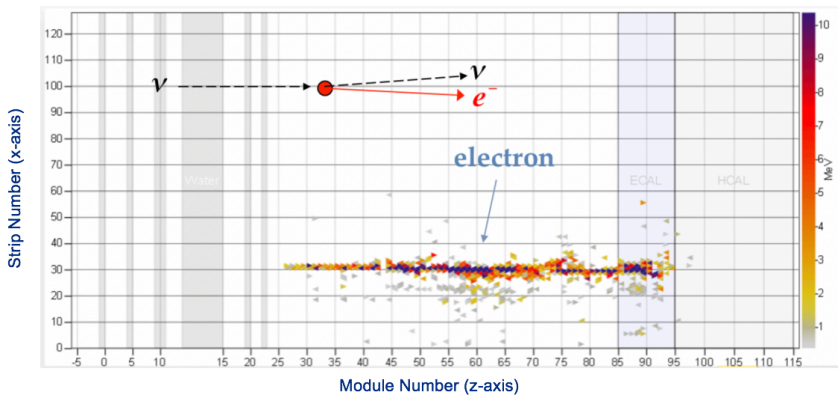


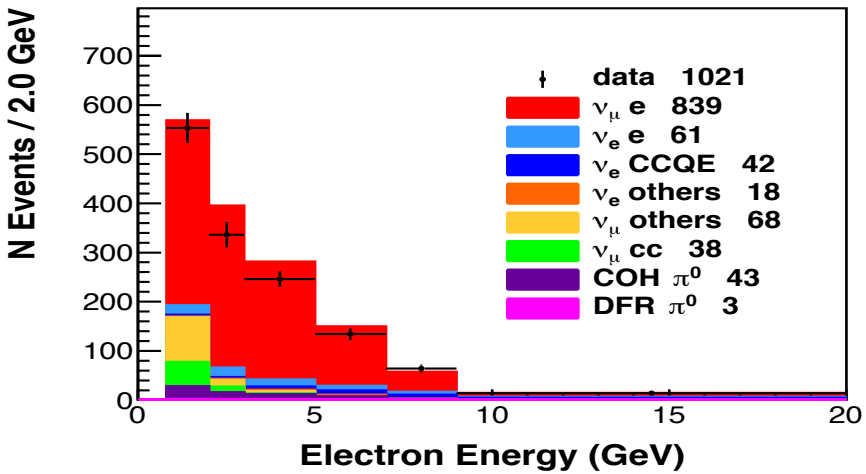
- Well understood cross-section by standard electroweak scattering theory.
- Discrepancies between data and Monte Carlo predictions will be due to mis-modeling of the flux distribution.
- The final-state distribution of electron energies can be used to constrain the overall normalization.

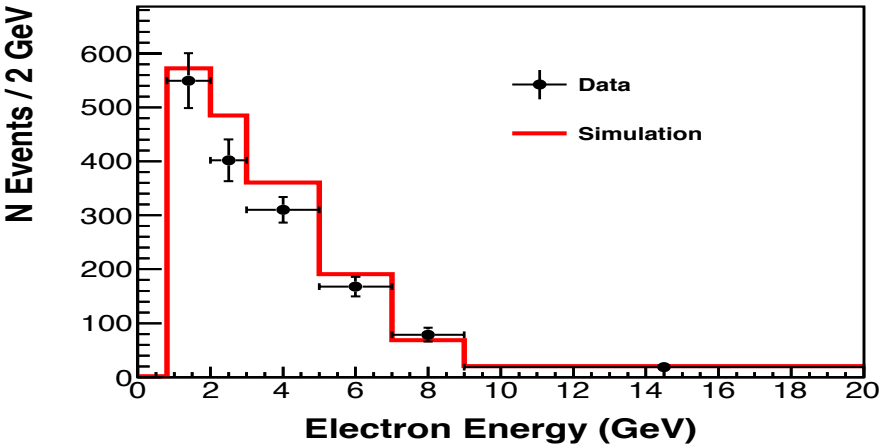
In Situ Measurements : ν – e Scattering

Experimental signature is a very forward single electron state.

Caveat: Statistically limited due to very small cross section



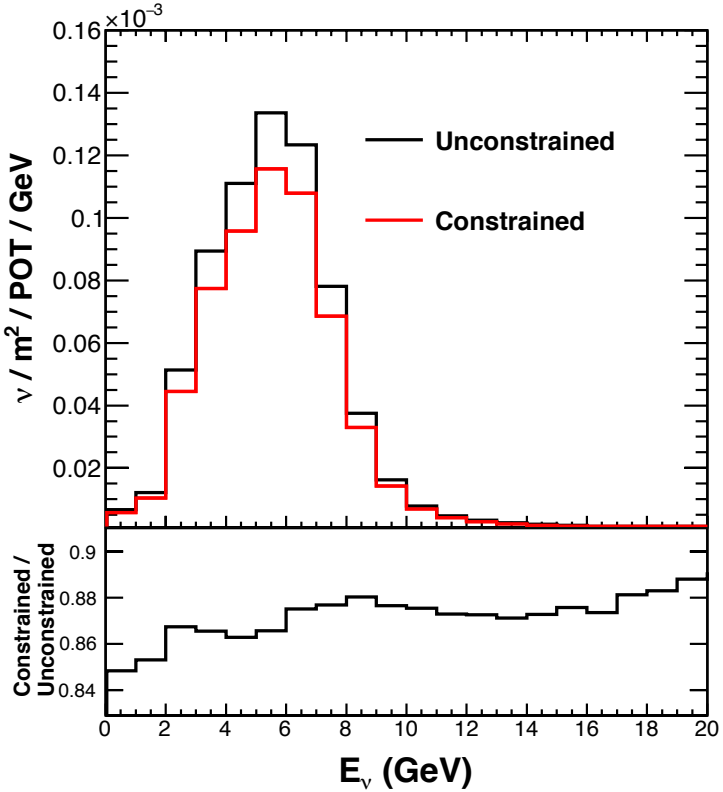


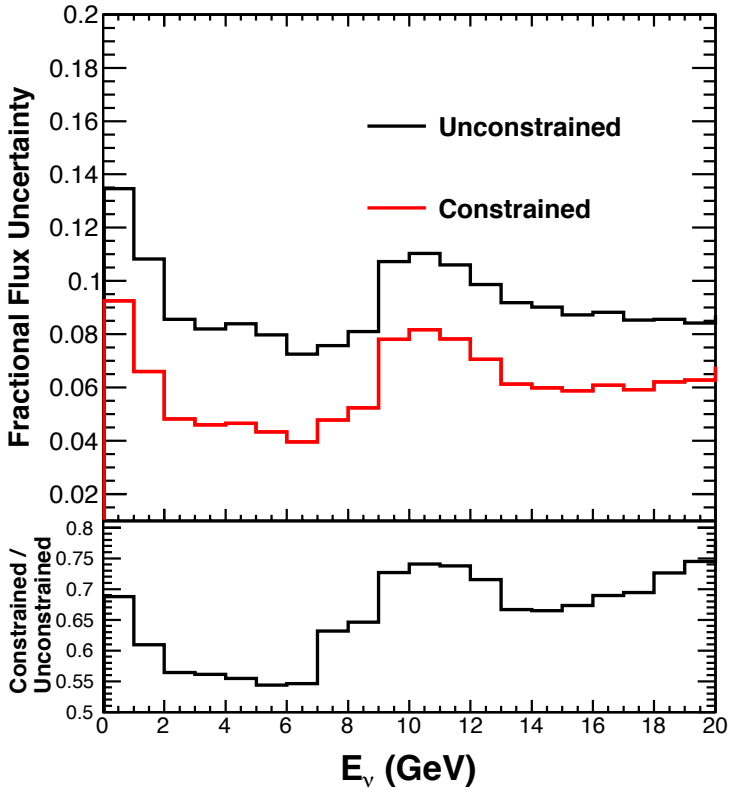


chi2 based likelihood between the observed and predicted electron spectra.

Flux and Fractional Uncertainty

Phys. Rev. D 100, 092001 (2019)





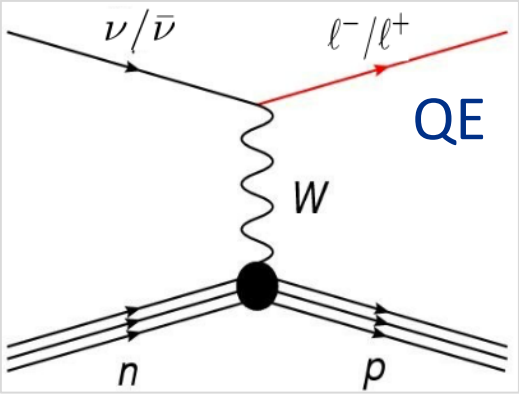
ν_μ flux in bins of neutrino energy before(black) and after(red) constraint is reduced by ~ 10 %

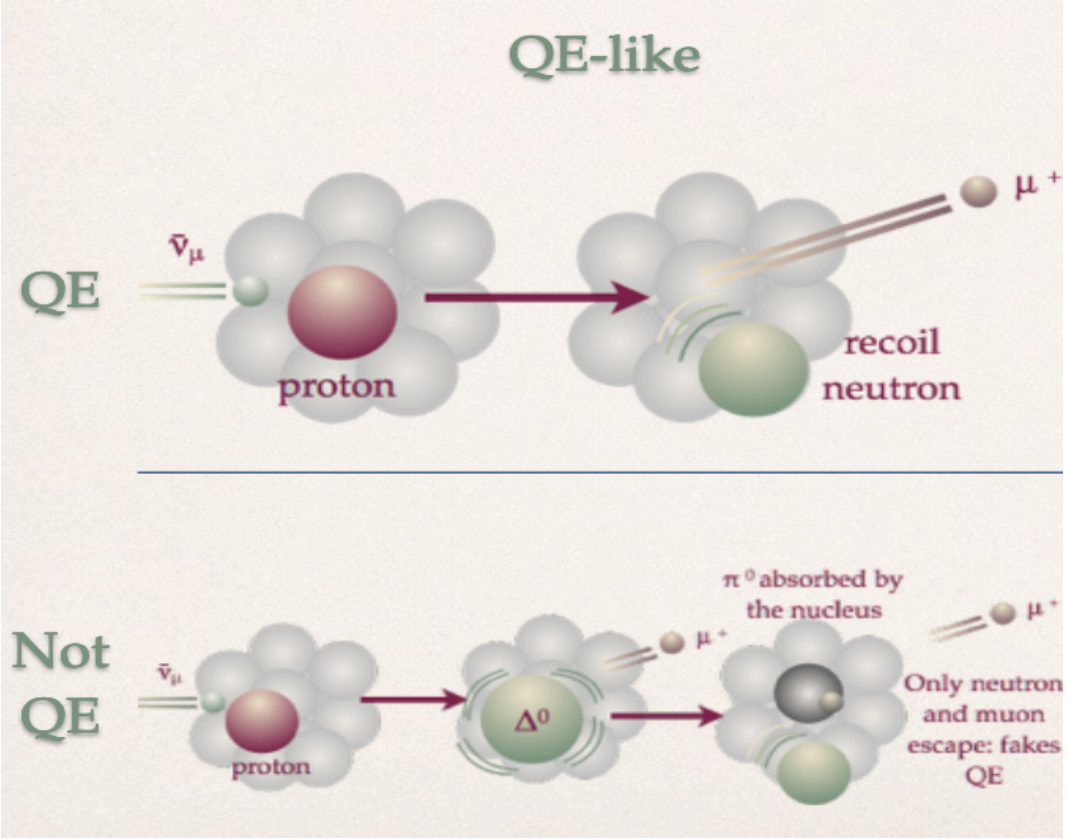
The flux uncertainty is reduced from 7.6 % to 3.9 % .

Let's talk about the first medium energy paper using this nu-e constraint.

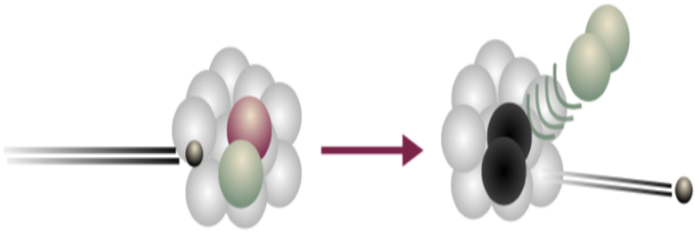
Muon neutrino QE-like Scattering

A non-QE event will appear to be QE if its products interact undergo final state interactions to produce a single outgoing proton.

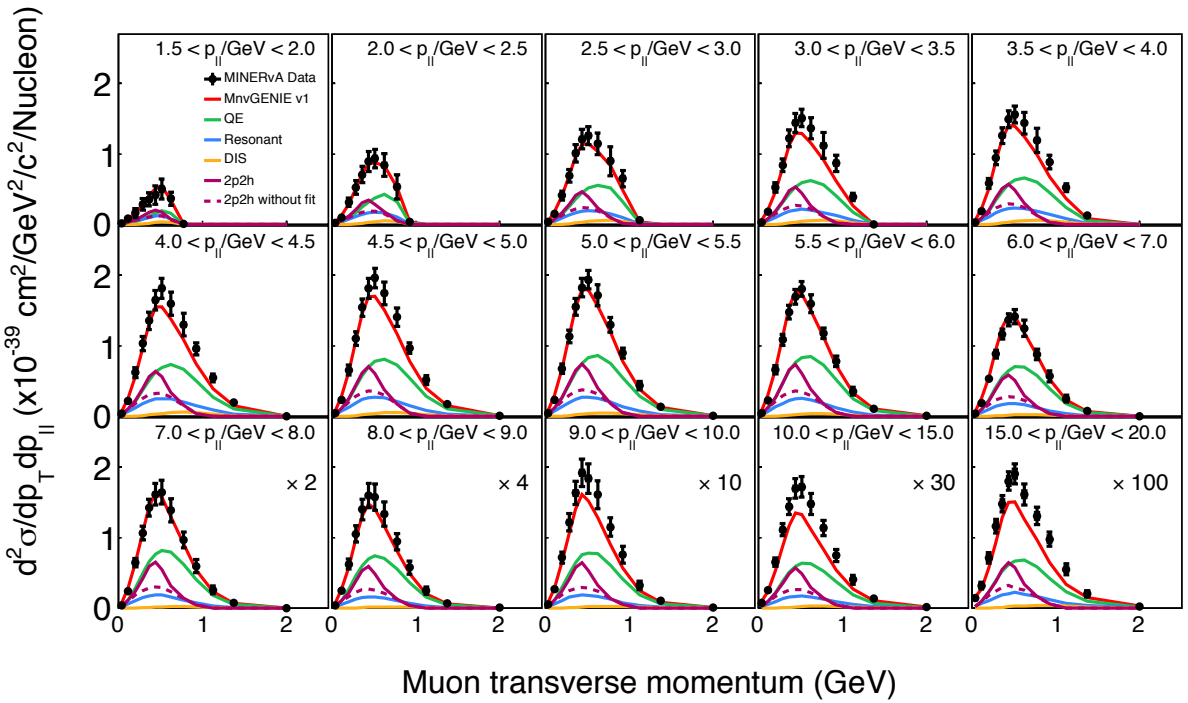




Multi-nucleon interactions
2 particle 2hole(2p2h)



Muon Neutrino QE-like Scattering



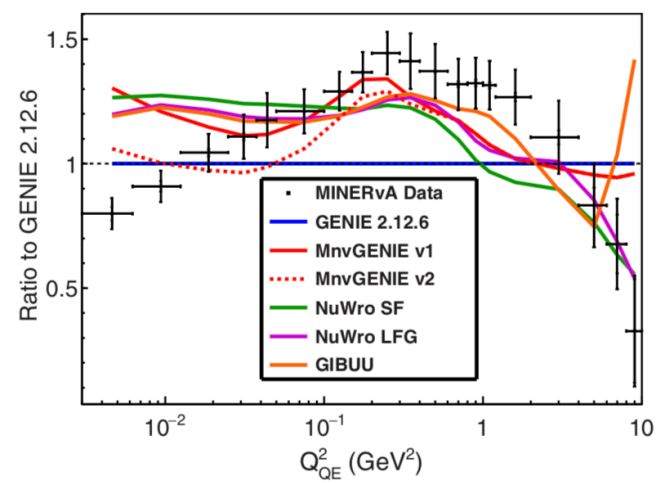
First ME cross section result

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

High statistics measurement in dimensions of muon transverse and longitudinal momentum

CCQE and 2p2h comprise the dominant spectral components

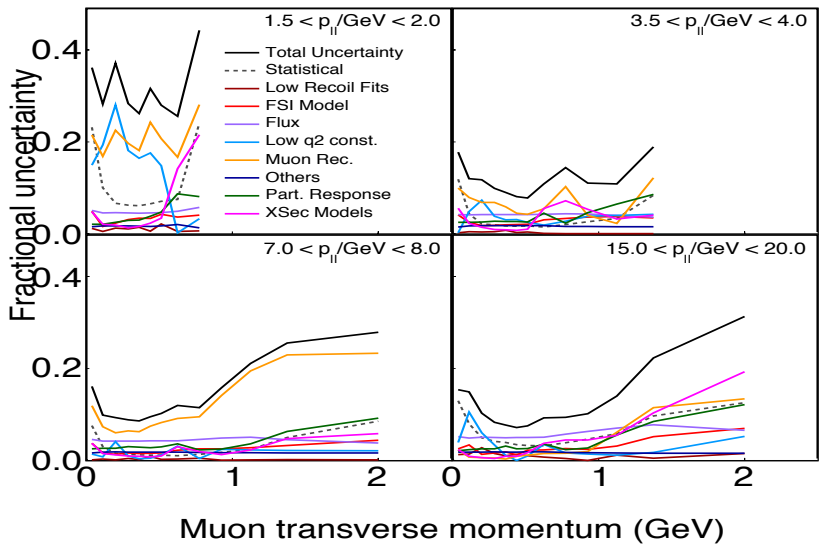
No model has the right shape at low Q^2



MnvGENIE v1 : RPA + 2p2h + non-resonant pion production
MnvGENIE v2 : MnvGENIE v1 + lowQ^2 resonant suppression.

MINERvA's tune

Muon Neutrino QE-like Scattering

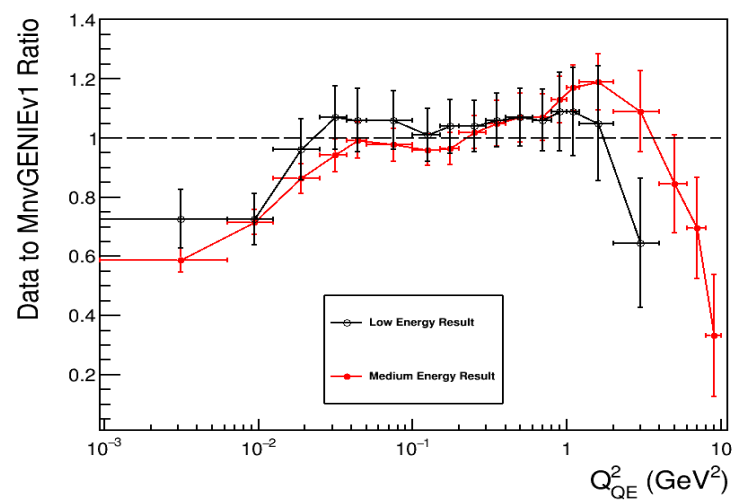


- Flux error is constrained to ~ 3.9% by internal nu-e measurement.
- Muon reconstruction uncertainties are a leading systematic and are dominated by uncertainty in the energy scale in MINOS.

See Andrew Olivier Poster at ID 487

- Same discrepancies are seen in both datasets
- New data goes to much high Q^2, and the high Q^2 data will provide constraint on the axial form factor.

See Amit Bashyal Poster at ID 194



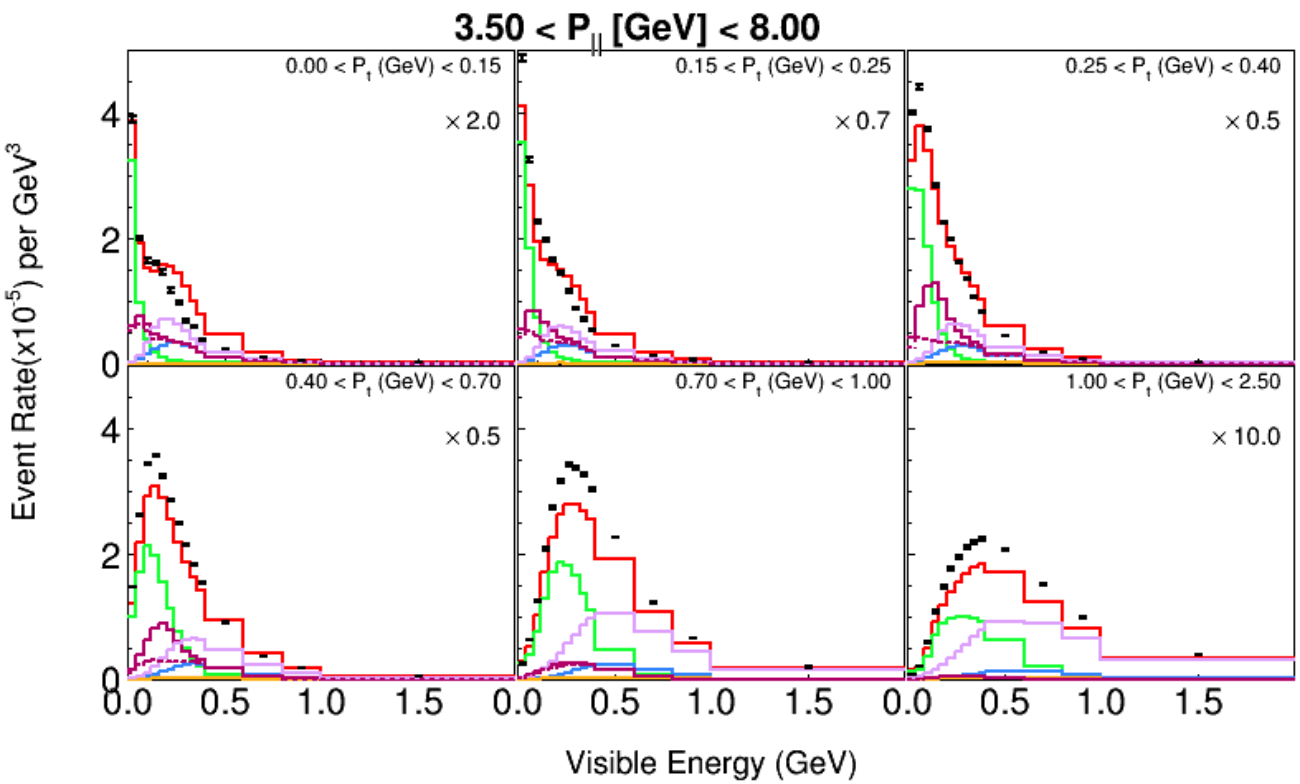
Future : Generation 3D CCQE-Like

Medium energy : Improved sensitivity at high Q^2
Explore regions at low Q^2.

MINERvA look at the visible energy $E_{available} = \Sigma T_{proton}$

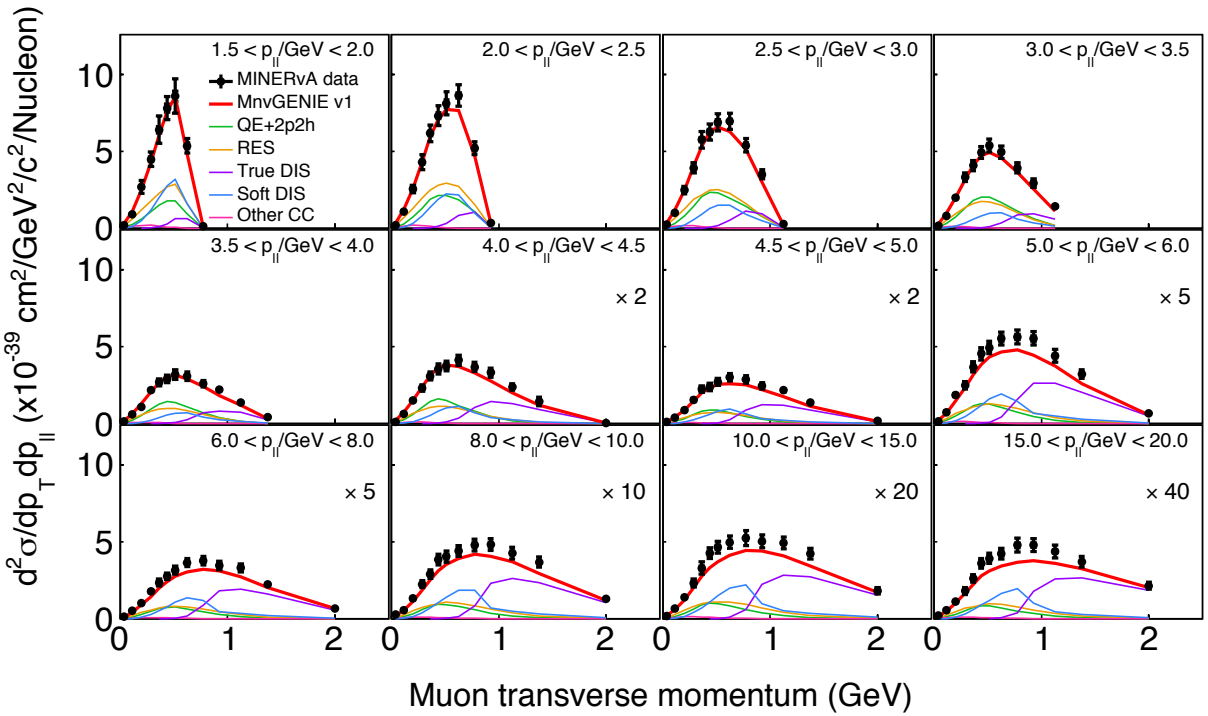
Different way of looking at the leptonic–hadronic 4–momentum sharing.

JETP Seminar by Dan Ruterbories (Oct 25 2019)



Panel = Bin of $P_{||,\mu}$
Cell = Bin of $P_{t,\mu}$
Bins = Bins of Recoil

Muon neutrino CC Inclusive



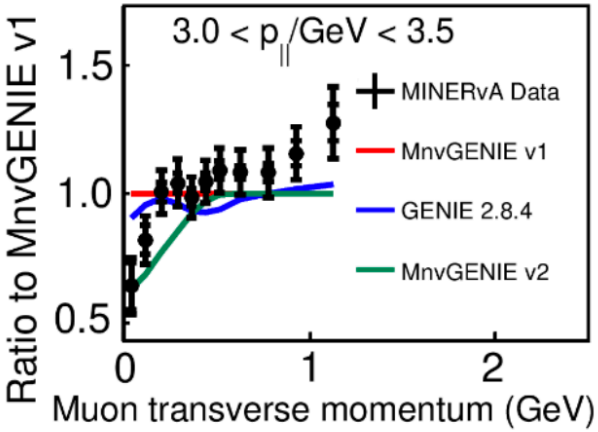
MINERvA's tune

MnvGENIE v1: RPA + 2p2h + non-resonant pion production

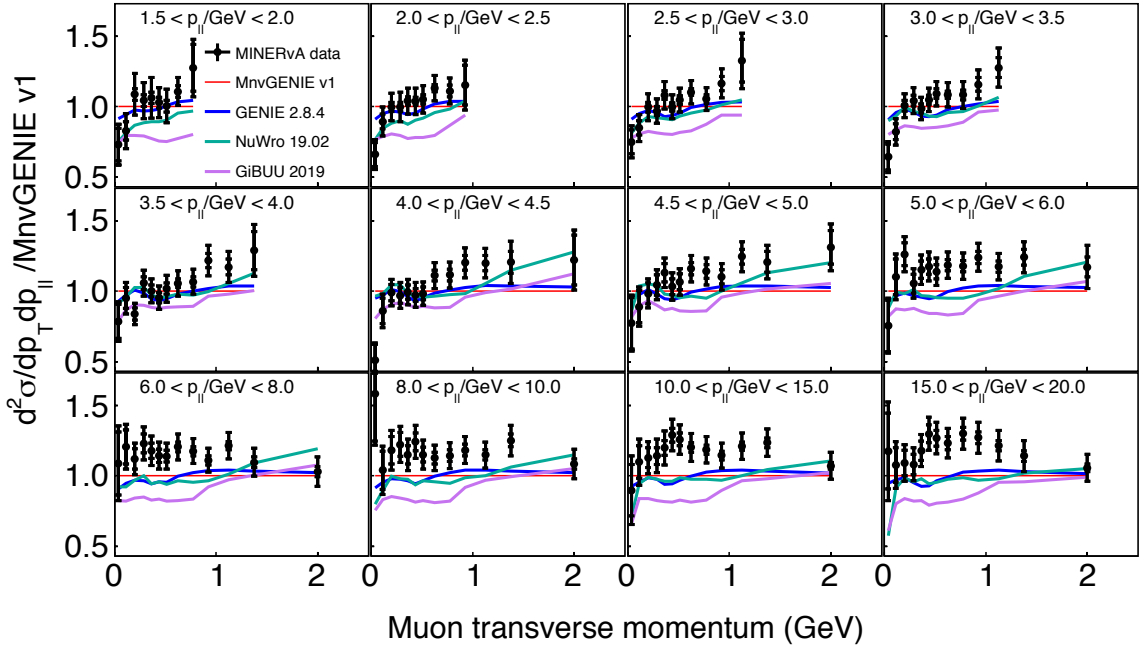
MnvGENIE v2: MnvGENIE v1 + lowQ^2 resonant suppression.

Discrepancy seen between the models in the whole phase space .

Low Q^2 resonance suppression improves the prediction at low p_T but degrades it at high p_T .

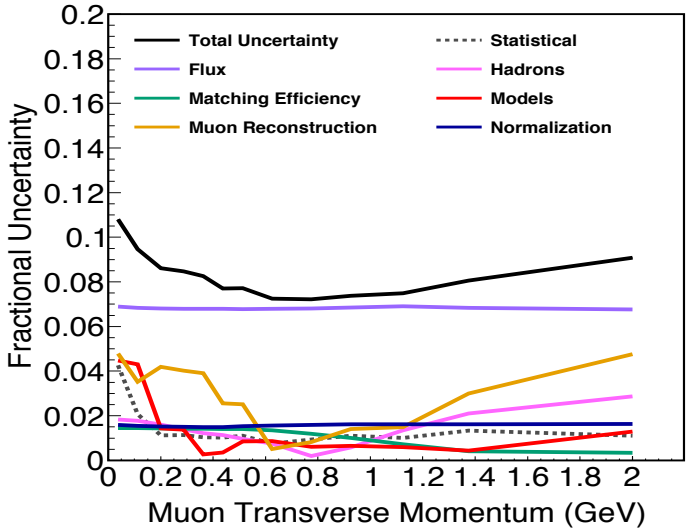


Muon neutrino CC Inclusive



GENIE 2.8.4, GIBUU 2019, and NuWro 19.02 underpredict the cross sections in mid p_T and at high p_{II}.

None of these models have good agreement with the data throughout the full phase space.

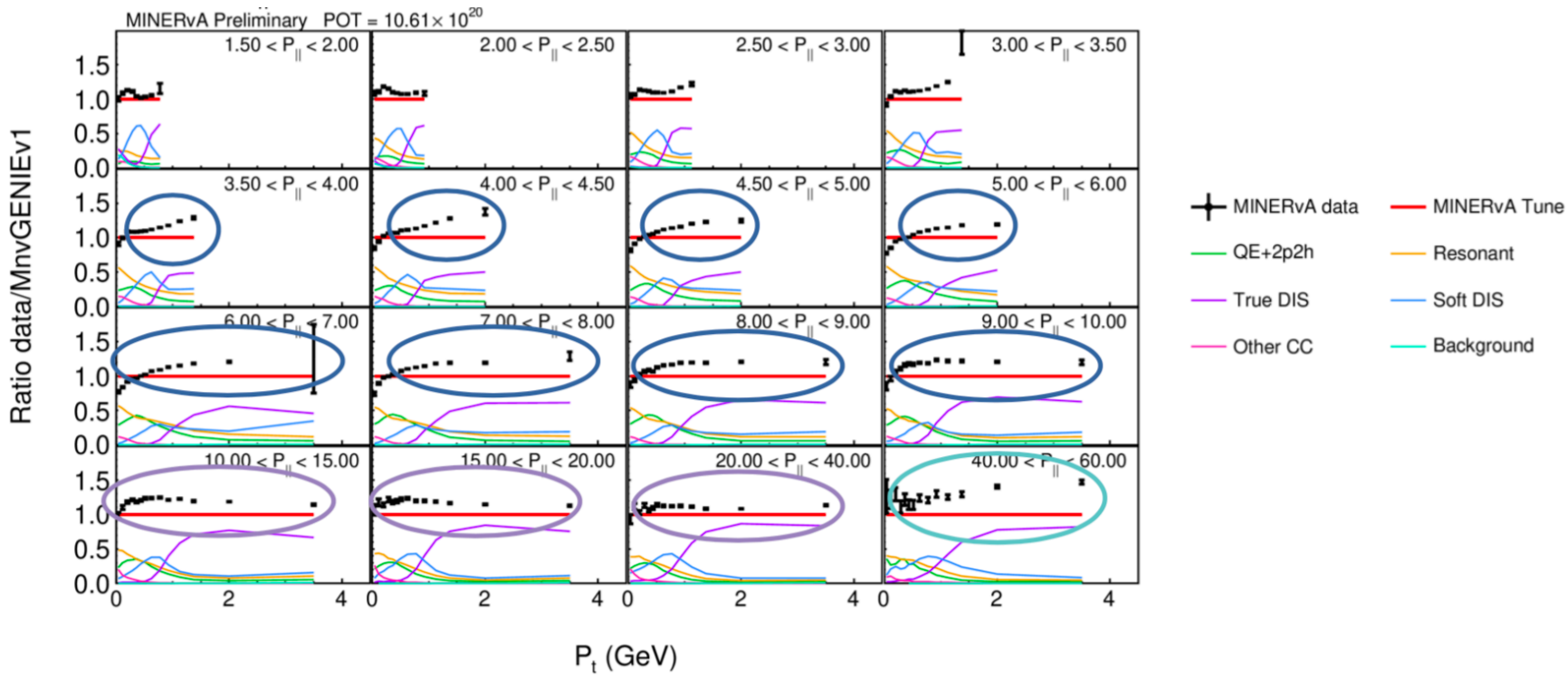


Flux is the dominant uncertainty ~ 7%

See Amy Filkins's Poster at ID 64

Medium Energy Inclusive Analysis Preview

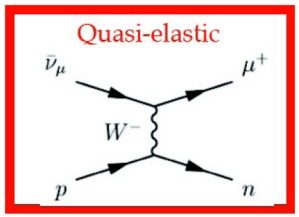
Will have smaller uncertainties – Flux ~4-5% .
Better kinematic coverage – 4 new $p_{||}$ bins, 1 new p_T bin



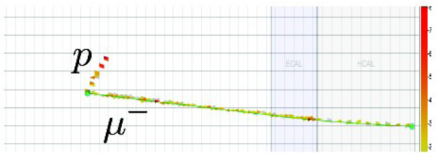
The event rate have consistent underprediction of data at high p_T and high $p_{||}$

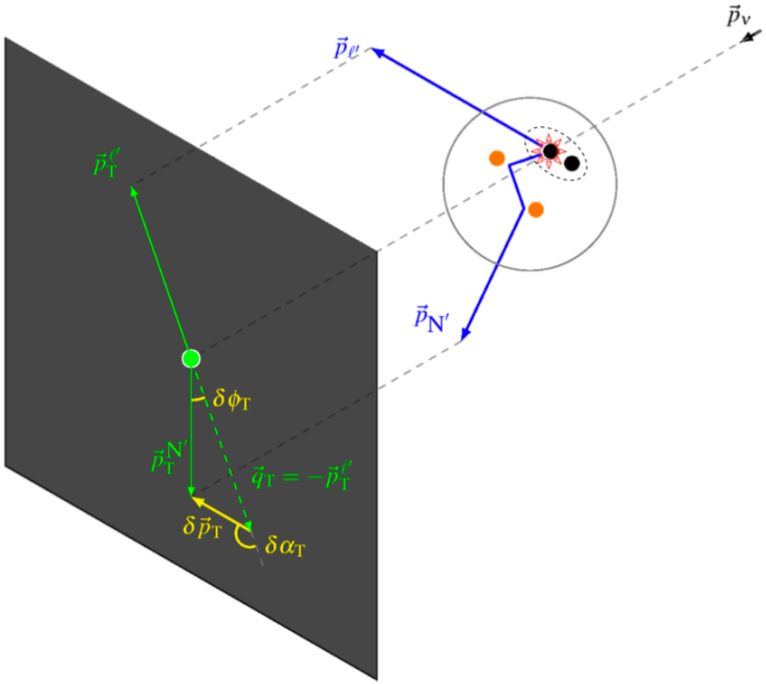
Nuclear Effects : Transverse Kinematic Imbalance

One very useful probe is the transverse imbalance of the leading proton and the lepton in charged current QE mesonless production.



QE





Transverse: $0 = \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'} - \delta\vec{p}_{\mathrm{T}}$

Longitudinal: $E_\nu = p_{\mathrm{L}}^{\ell'} + p_{\mathrm{L}}^{\mathrm{N}'} - \delta p_{\mathrm{L}}$

New variable: $p_{\mathrm{n}} \equiv \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$

Assume exclusive μ-p-A final states

$$E_\nu + m_{\mathrm{A}} = E_{\ell'} + E_{\mathrm{N}'} + E_{\mathrm{A}'}$$

$$E_{\mathrm{A}'} = \sqrt{m_{\mathrm{A}'}^2 + p_{\mathrm{n}}^2}$$

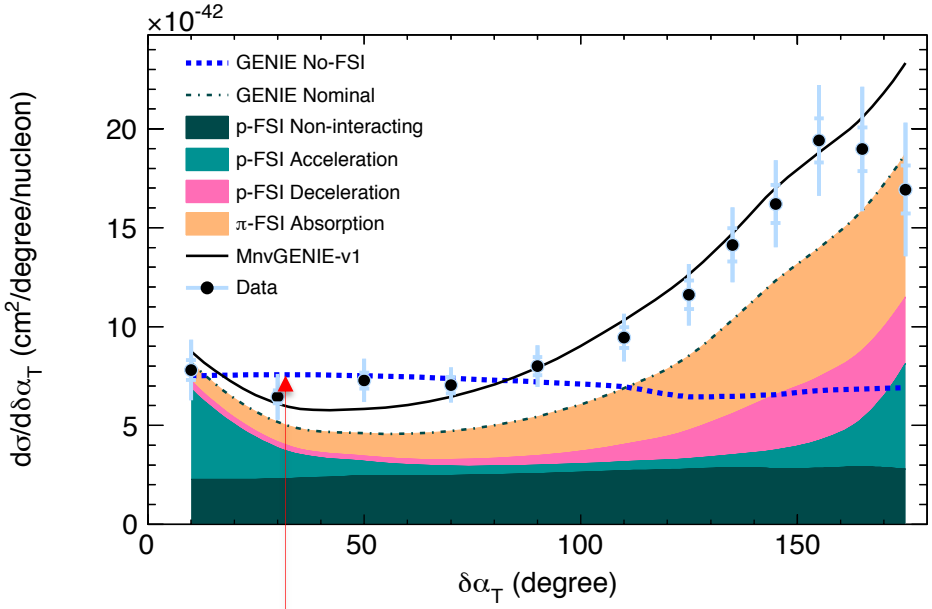
In absence of nuclear effect i.e. static nucleon target it is balanced.

Phys. Rev. C 94, 015503

If energy of recoiling nucleus is known, can reconstruct momentum of target nucleon.

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

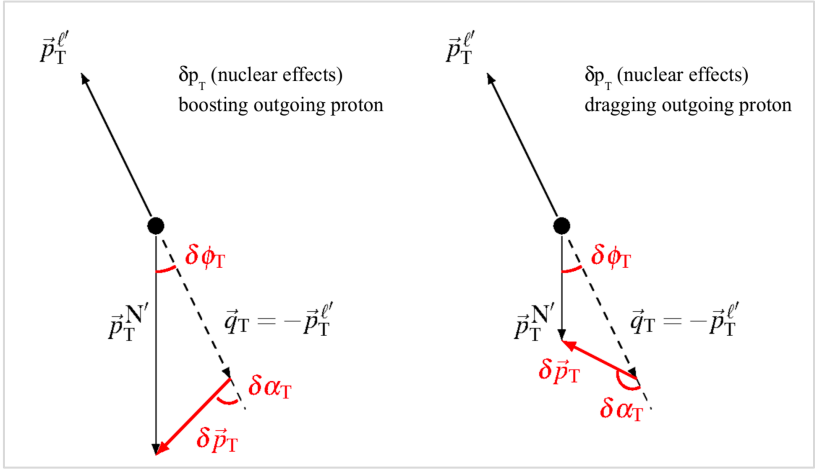
Transverse Kinematic Imbalance



$\delta\alpha_T$ is Fermi motion direction → isotropic
– GENIE No-FSI ⟹ $\delta\alpha_t$ is flat

Proton FSI:

- Non-interacting (no change of energy and direction of the proton)
- Pion FSI: FSI in which pion is absorbed.



Deceleration at large $\delta\alpha_T$

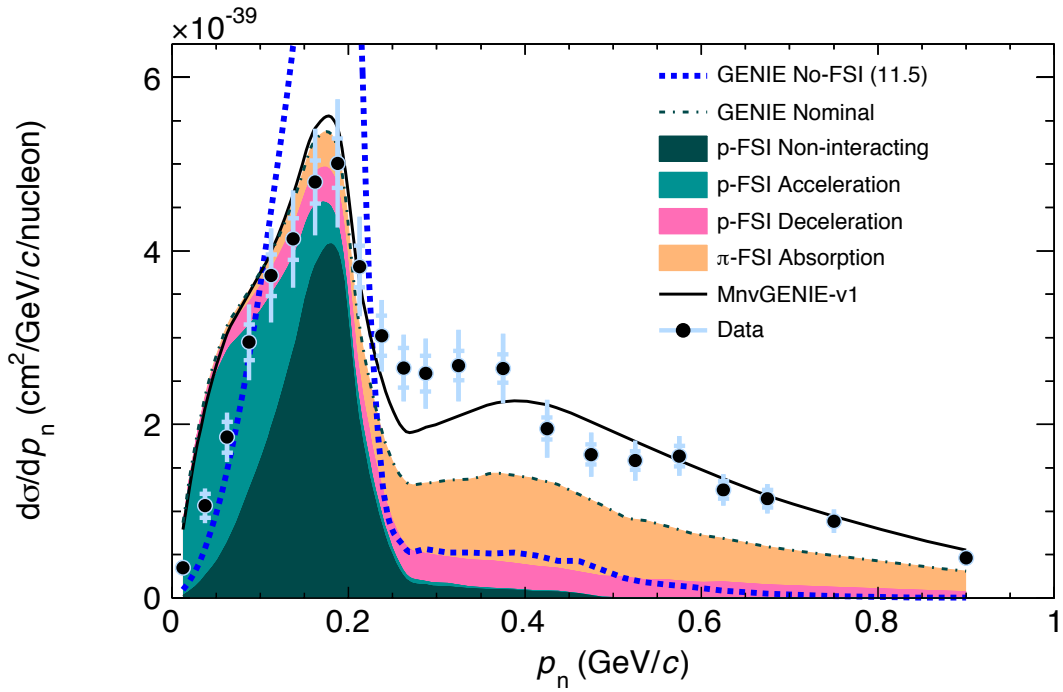
Only acceleration can enter small $\delta\alpha_T$

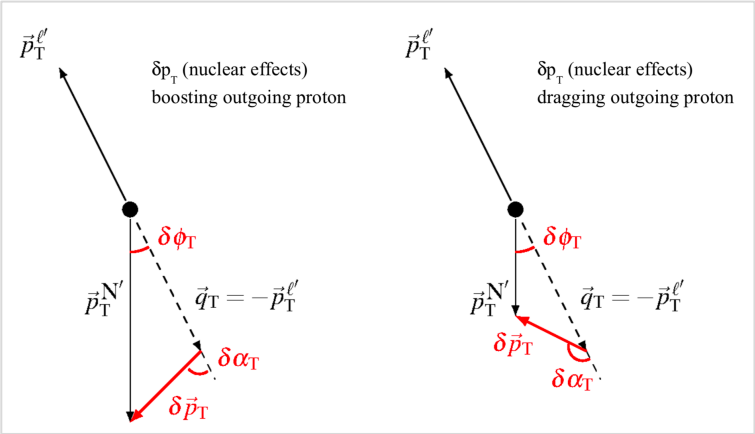
Baseline for all non-Fermi motion effects. Complementary to p_n

Phys. Rev. Lett. 121, 022504 (2018)

Transverse Kinematic Imbalance

Phys. Rev. C 99, 055504





Accelerating proton due to nuclear effects strongly distort QE peak.

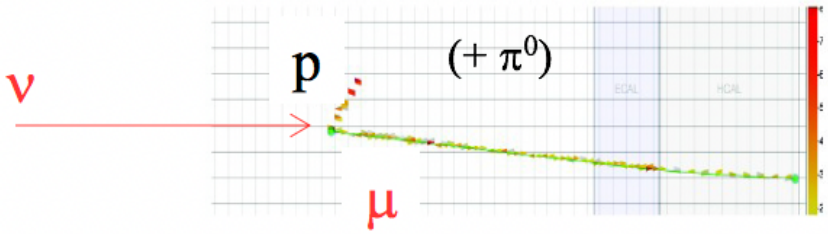
Fermi Gas model prediction

p_n is Fermi motion magnitude → "QE peak"

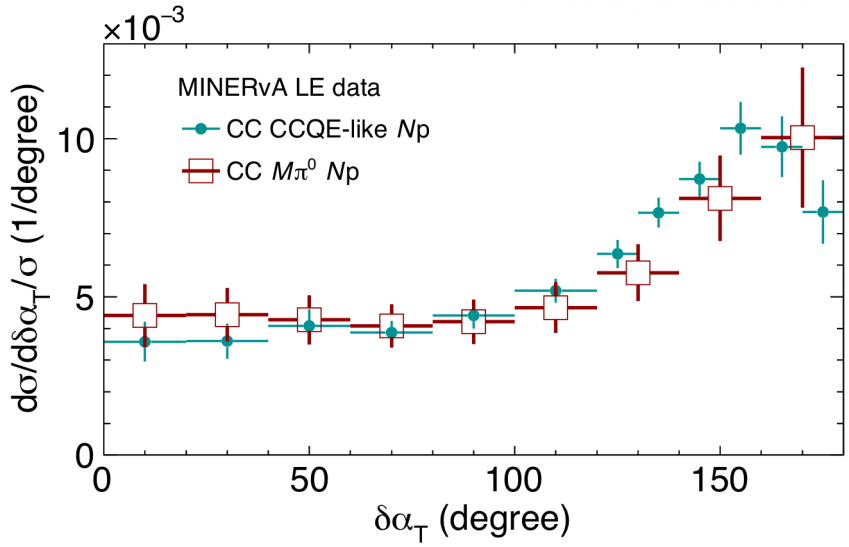
QE peak dominated by CCQE without FSI
Direct constraint of Fermi motion

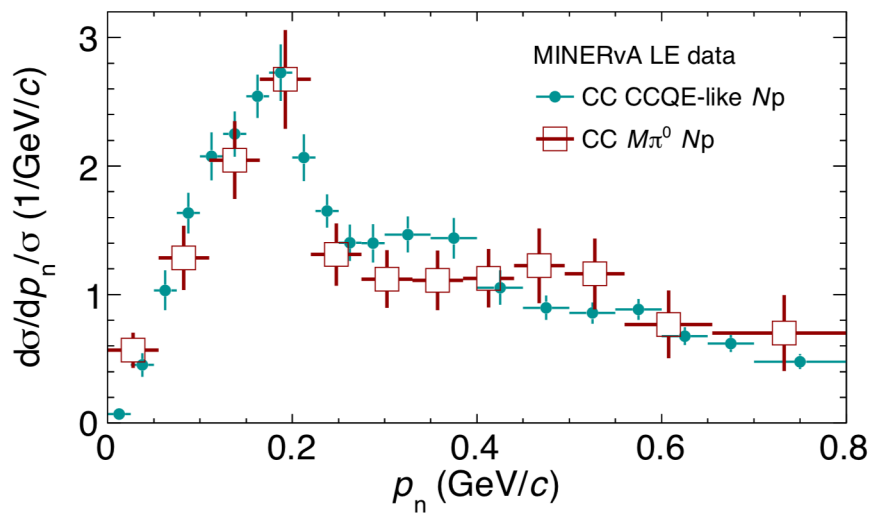
GENIE describes the tail reasonably well due to large contribution from 2p2h tuned to MINERvA inclusive measurements

TKI in neutral pion production



arXiv:2002.05812



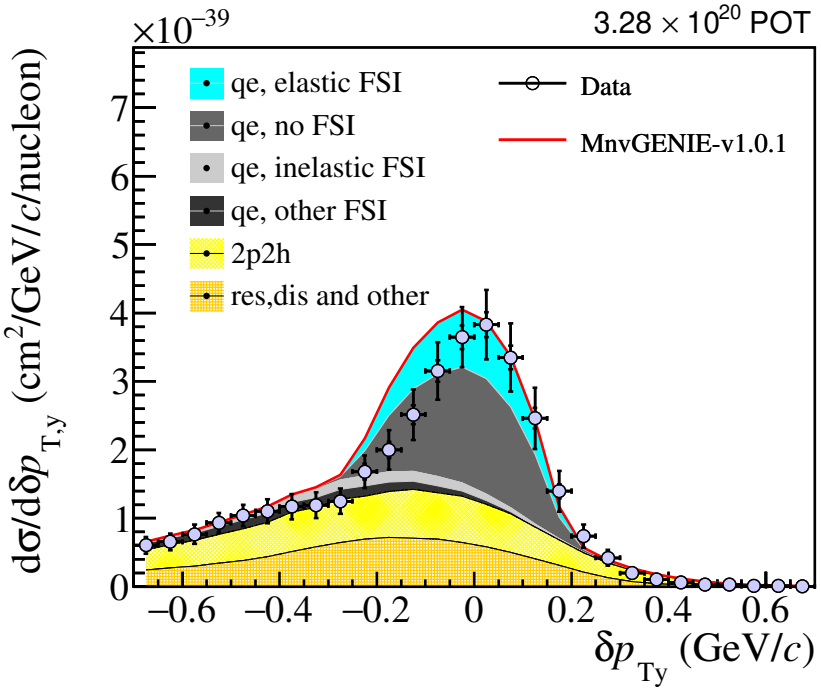


Very different underlying mechanism

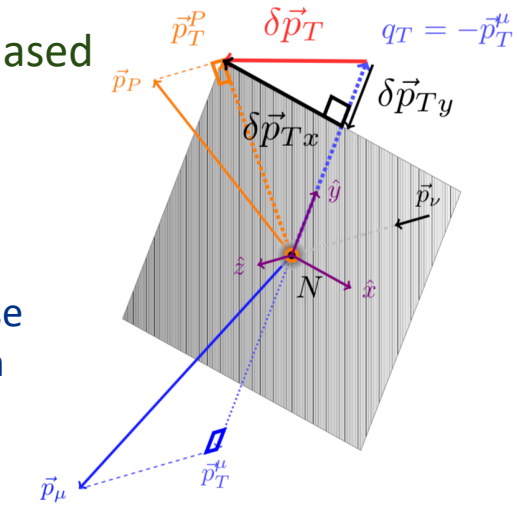
- Fermi motion peak is expected to be universal.
- Consistency in $\delta\alpha_T$ trending and p_n tail.

Nuclear Binding Energy

Projection of transverse balance into the reaction plane is directly biased by energy required to remove nucleon from nucleus.



$\delta p_{Ty} > 0$: Proton has gained momentum along transverse muon momentum direction



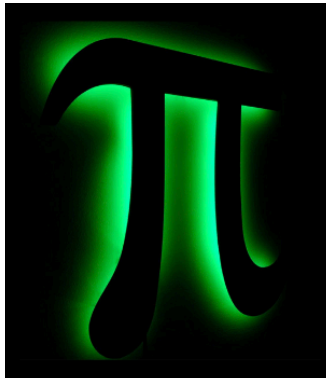
- The δp_{Ty} predictions is wider than the data in the peak region.
- A shift in the interaction energy changes the position of the QE peak along the y-direction which shows the sensitivity to the interaction energy.

High statistics measurement in dimensions of muon transverse momentum.

Phys. Rev. D 101, 092001 (2020)
Eur. Phys. J. C. (2019) 79: 293

See Deepika Jena Poster at ID 535

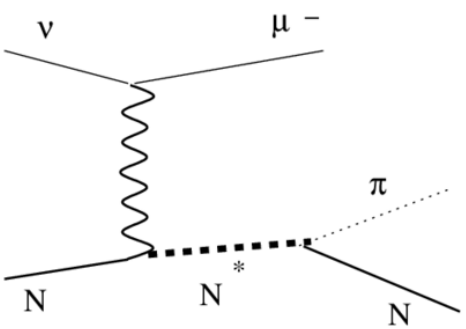
Pions at MINERvA

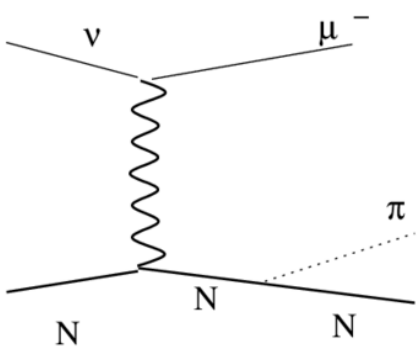


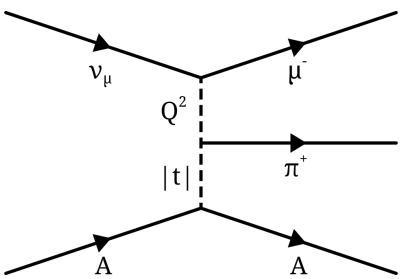
Single Pion Production

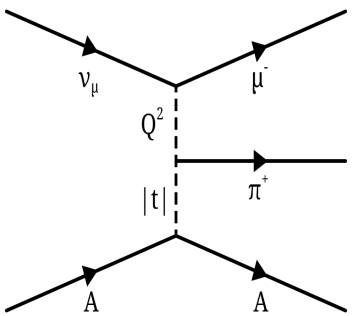
Various Production Mechanisms

Resonant pion production	Non-resonant pion production	Coherent inelastic	Diffractive (on hydrogen)









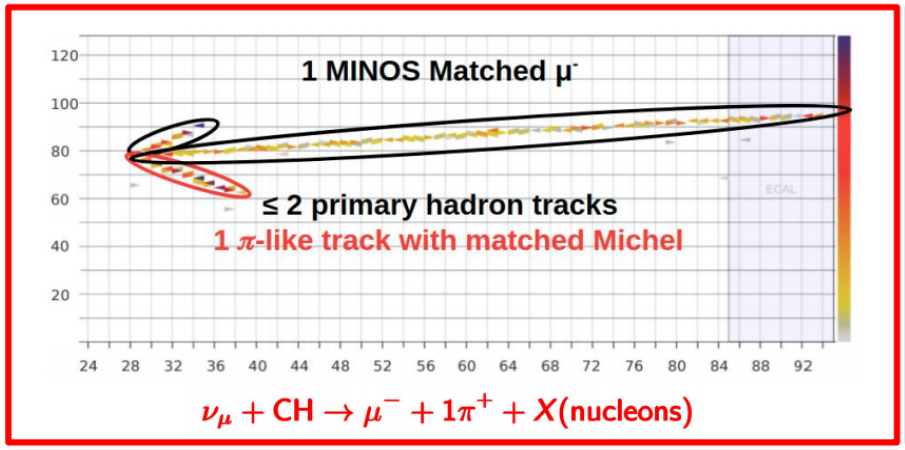
Dominant

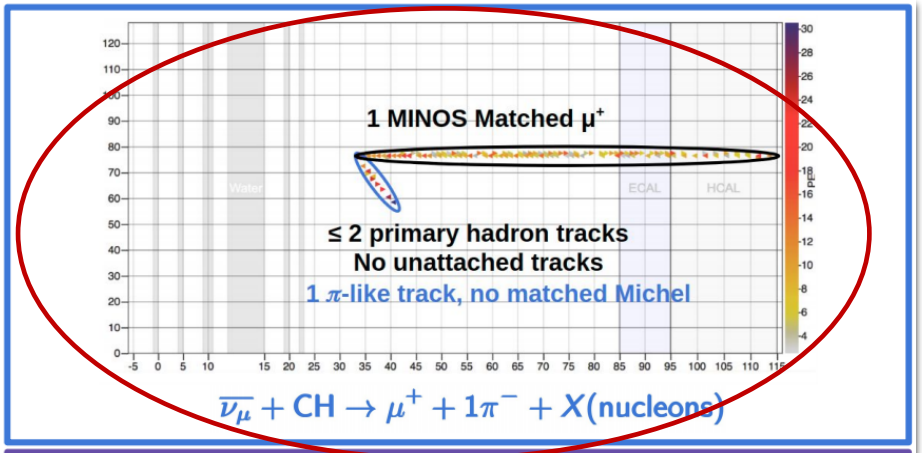
Significant

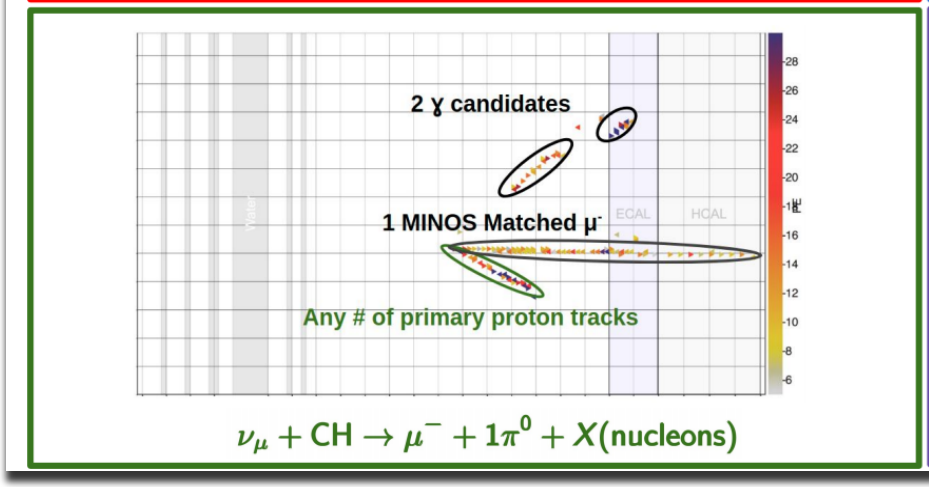
Sub-leading

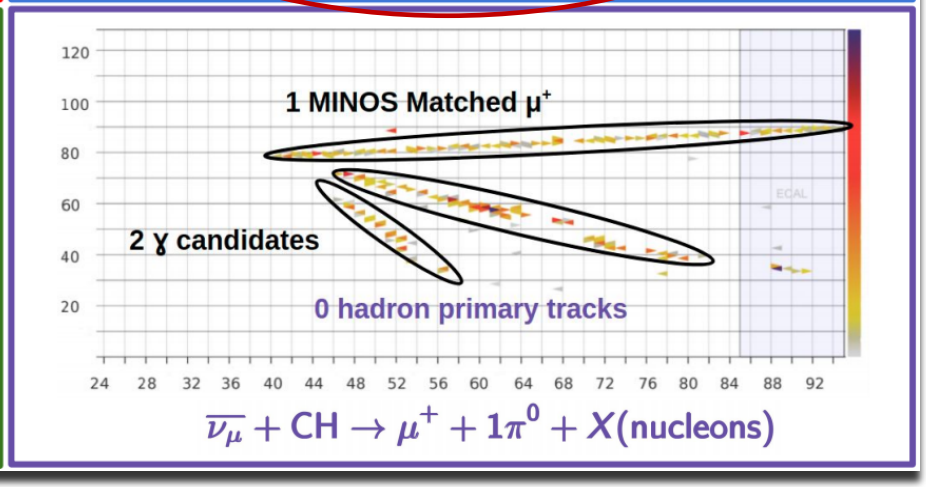
Pions at MINERvA

MINERvA's four LE pion measurements







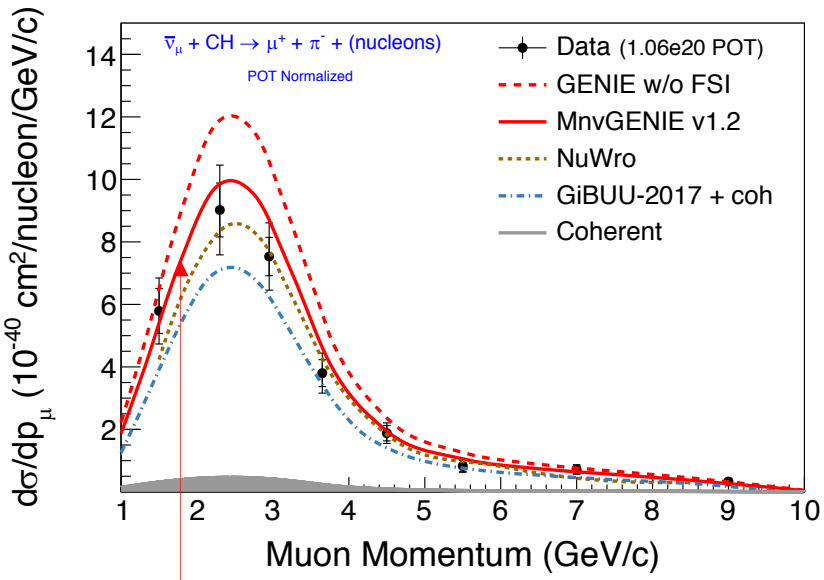


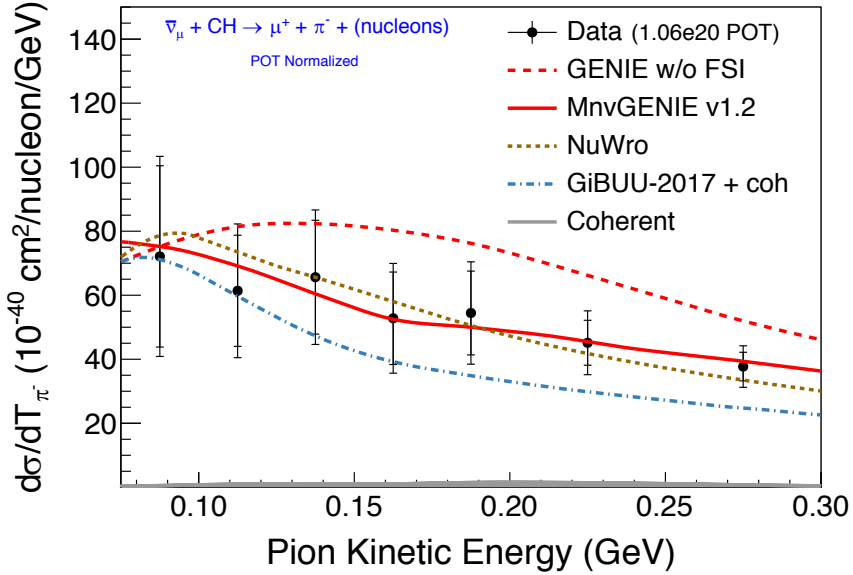
See Mehreen Sultana Poster at ID 217

$\bar{\nu}_\mu$ CC single π^- production

$\bar{\nu}_\mu + \{n, p\}_{HC} \rightarrow \mu^+ + \pi^- +$ nucleon(s)

Phys. Rev. D 100, 052008 (2019)



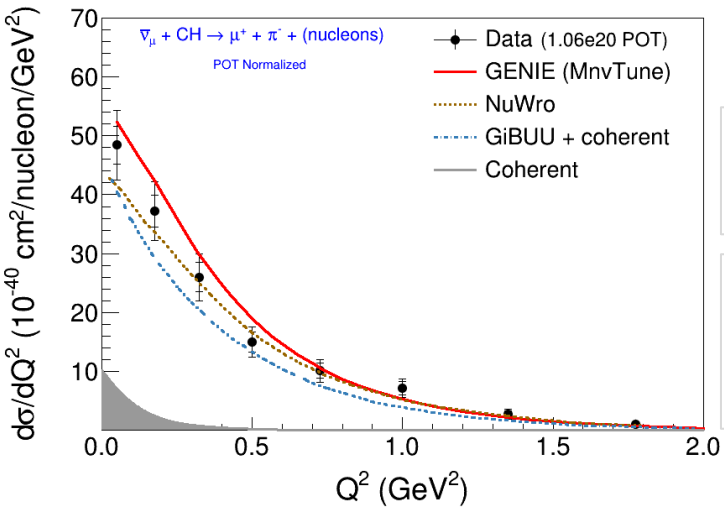


- Reflects the strength of pion FSI in carbon (π^- absorption).
- With FSI included still overpredicts the data.
- Final State model dominated by $\Delta^-(1232)$ production

Test Models : Generators get the shape but struggles with the absolute rate.

Minerva tune does well with predicting the shape of pion KE distributions in MINERvA CC(π^-) data.

Four Momentum Transfer Q^2

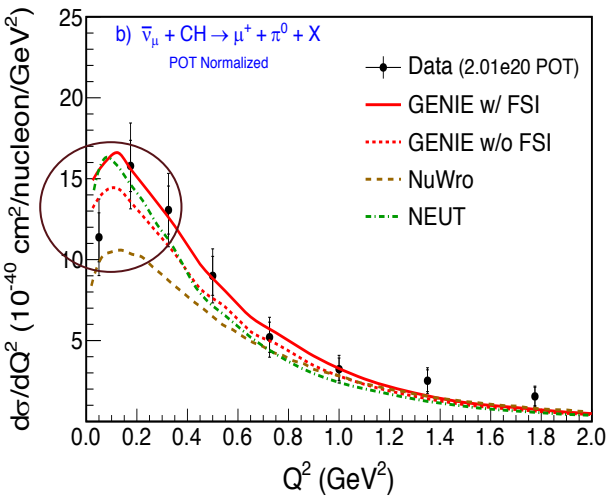


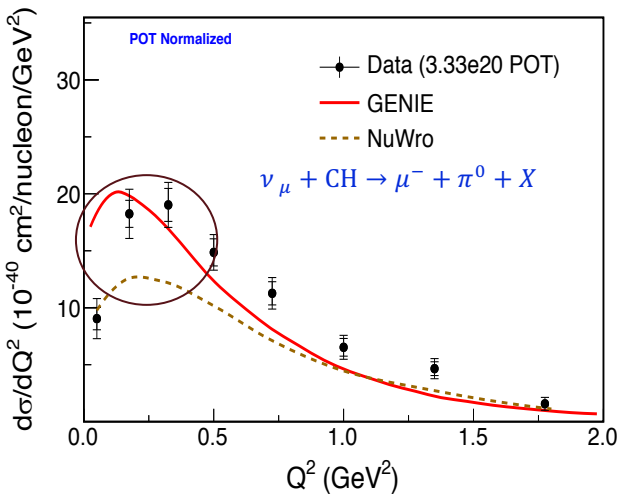
$$Q^2 = 2E_\nu(E_\nu - p_\mu \cos\theta_{\mu\nu}) - m_\mu^2$$

Note the contribution of coherent $\bar{\nu}_\mu$-CC(π^-) at $Q^2 < 0.4$ GeV^2 (est. based on MINERvA meas'ment)

No indication in signal channel of low-Q^2 suppression The absence of a turnover differentiates the signal channel of neutral and charged pions.

CC diffractive pion production should be present.



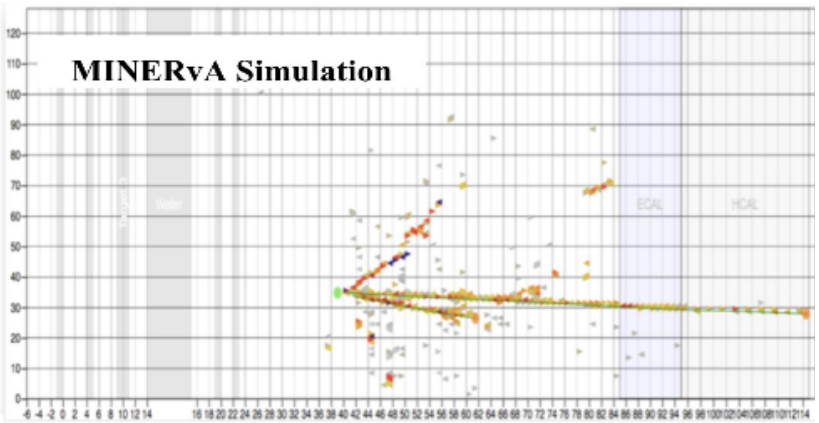


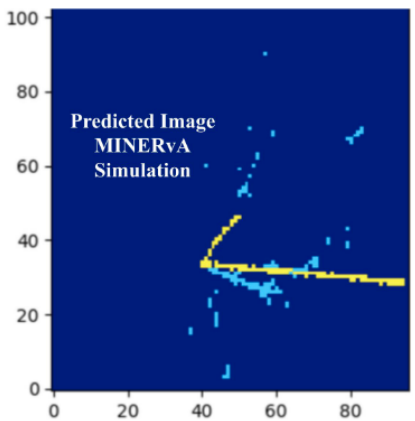
Similar evidence in Pion tune results. Pion production model in GENIE is compared to four MINERvA charged current pion production measurements using **NUISANCE**

Phys. Rev. D 100, 072005 (2019)

Interface : MINERvA and Machine Learning

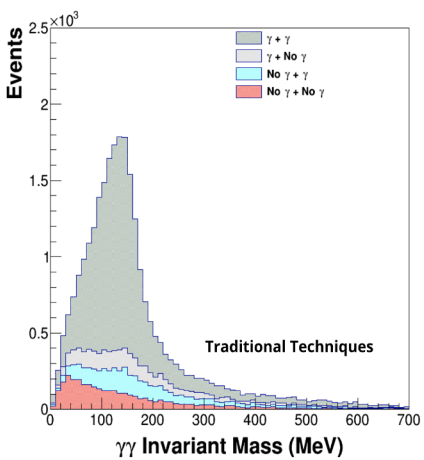
Along the way, we've developed a deep learning method for reconstructing location of neutrino interaction.

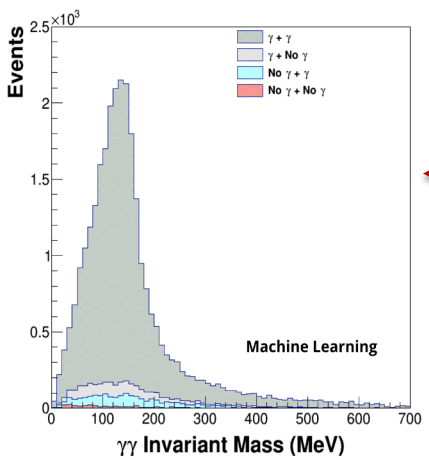




Difficult to distinguish between neutral and charged pions

ML approach via semantic segmentation method

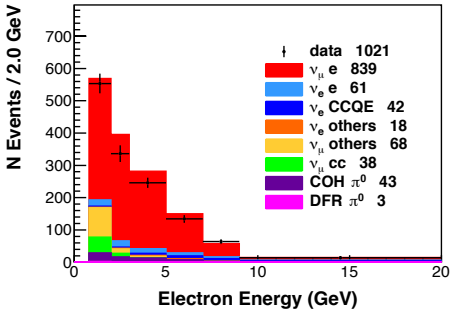


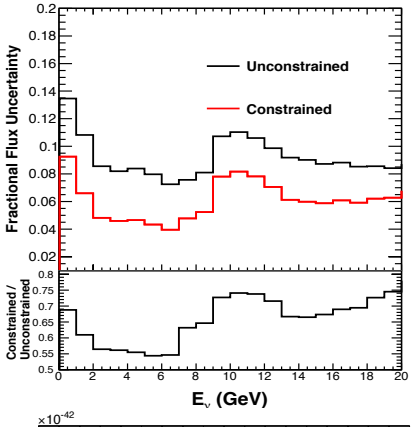


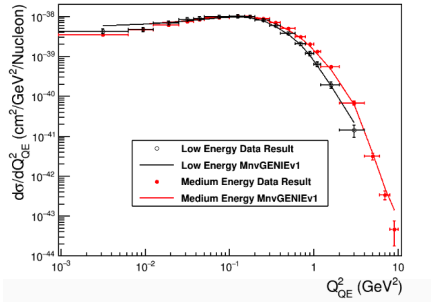
ML technique improves the purity!

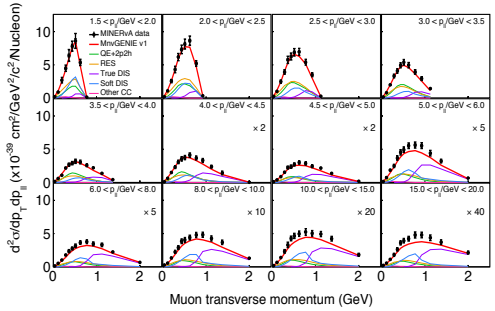
See Barbara Yaeggy Poster at ID 237

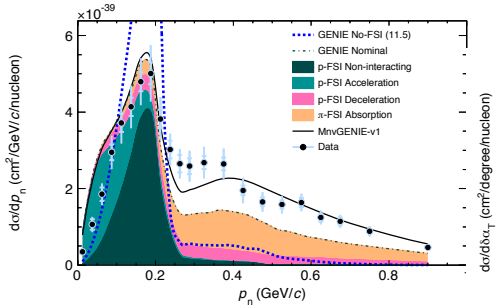
MINERvA provides a broad range of neutrino-nucleus cross sections !

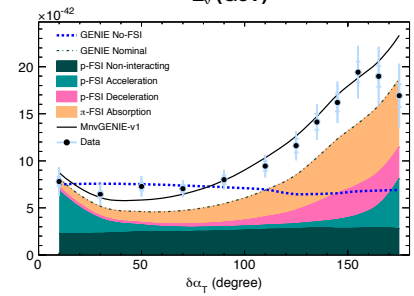


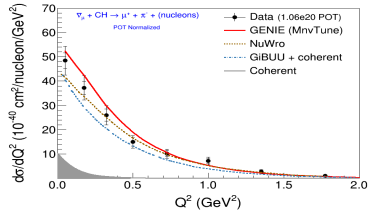


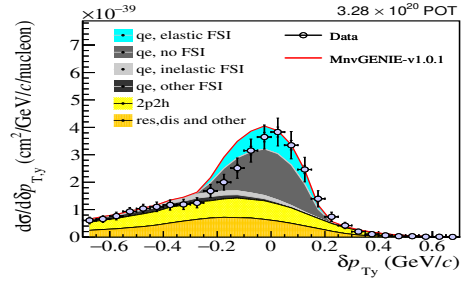


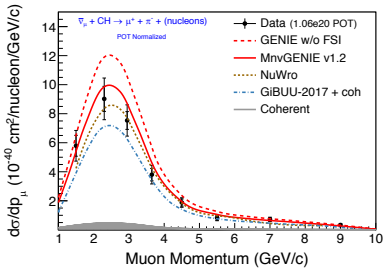


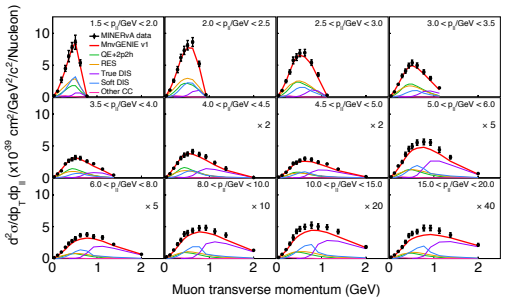


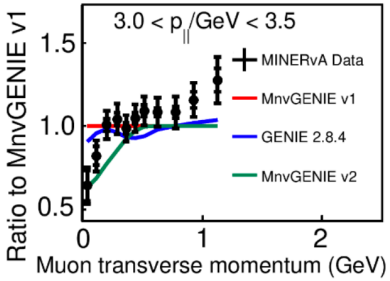


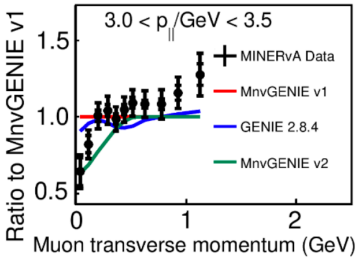


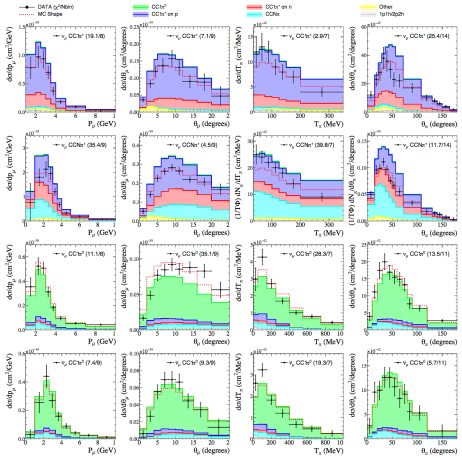






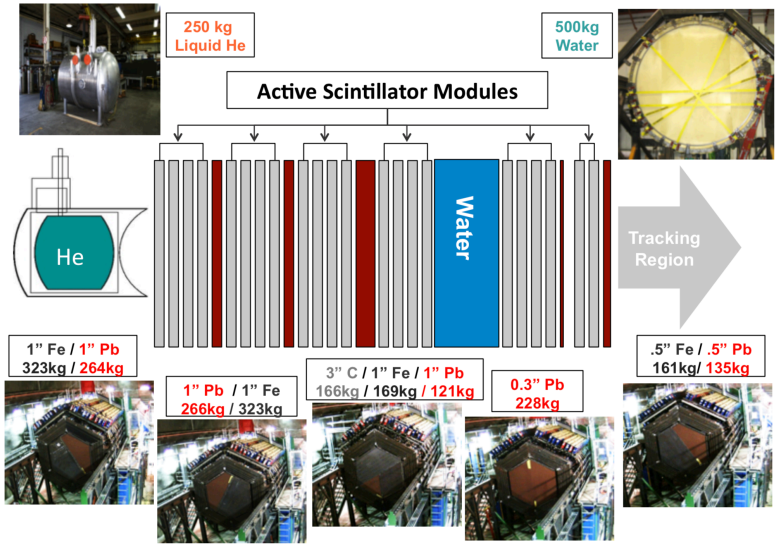






Conclusion and Future Plans

- MINERvA is also studying the ratio of neutrino interactions on different nuclei using solid nuclear targets.



- 3D measurements for CCQE and Transverse kinematic imbalance variables.

- Lower Flux Uncertainties, expect new MINERvA tunes.

- Low recoil analyses – muon and electron neutrino and anti-neutrino as well as neutrons.

- MINERVA is working up with releasing & preserving data to allow the future analyses of oscillation experiments.

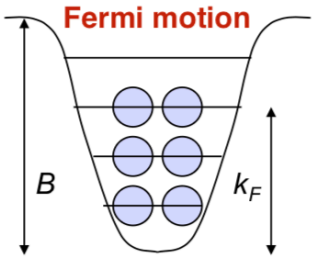
Thank You!

BACKUP

Nuclear Effects

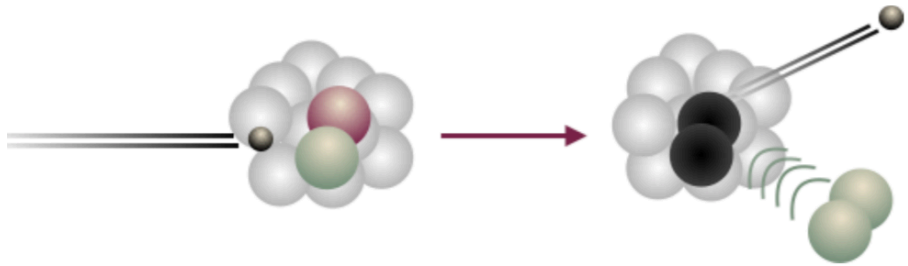
- Fermi motion: In a nucleus, the target nucleon has a momentum. Modeled as Fermi gas that fills up all available state until some Fermi momentum
- Pauli blocking: Pauli exclusion principle ensures that states cannot occupy states that are already filled
- Multi nucleon interactions
- Final state interactions

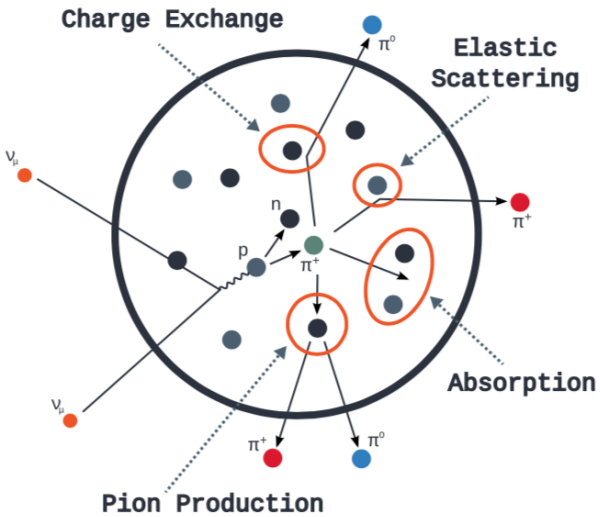
Fermi motion



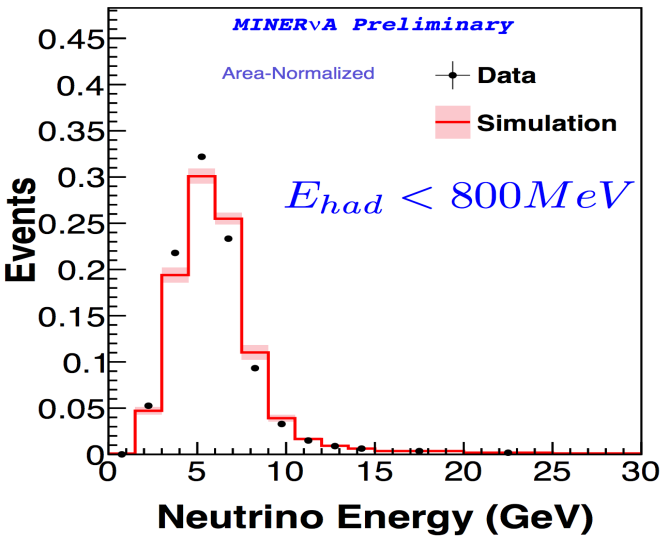
Final State Interactions (FSI)

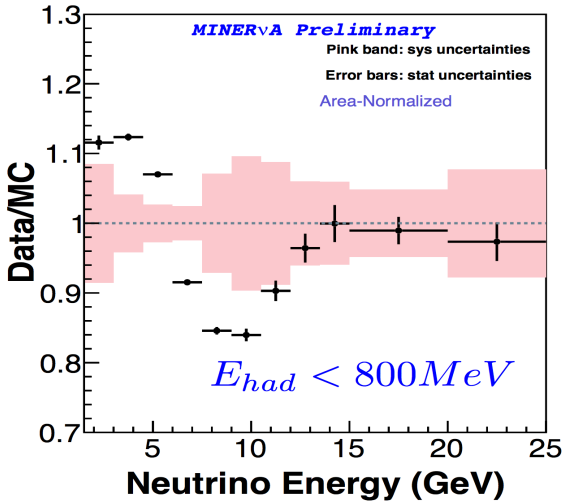
Multi nucleon interactions





Slowdown: 6 GeV Flux Puzzle





low recoil events

systematic band at right includes flux and GENIE's (unconstrained) estimate of low recoil cross section.

normalization uncertainties not shown

- Results of fits to low recoil flux measurement in different regions of the detector give two equally valid solutions.

muon energy scale needs to be pulled by 1.8σ.

target position in z or horn currents far out of measured tolerance.

Surprisingly, this indicates NuMI's focusing peak is *a priori* more precise than our detector calibration!

So far, we consider the full range of both solutions as uncertainties.

Fermilab

Cross-section estimation:

Events Selection
(Selected data)

Migration between true and
reconstructed quantities

Background Selection
(Constrained background)

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

Bin width

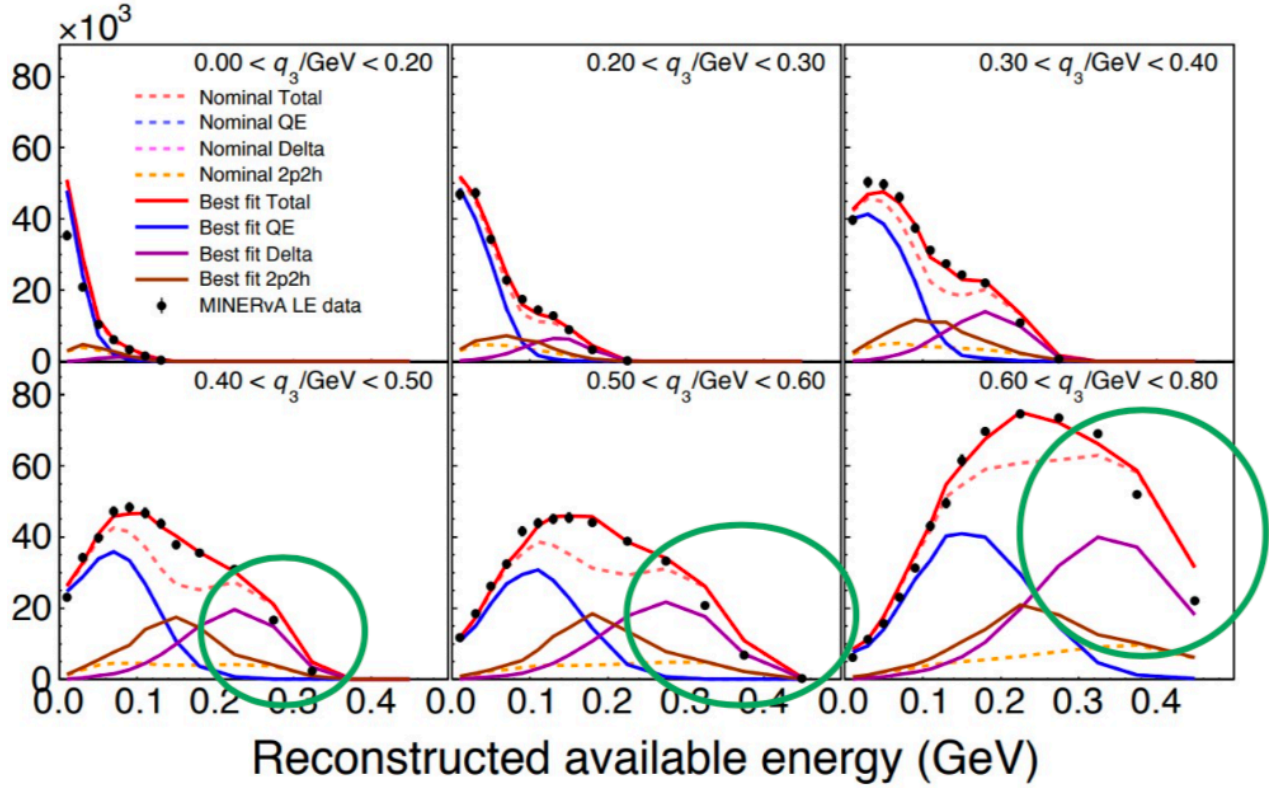
Cross-section

Selection
acceptance

Integrated flux and
number of targets
in detector volume

Muon neutrino CC Inclusive

Adding multi-nucleon events(2p2h and RPA) gives some agreement but still some gaps are there.



Enhancement of 2p2h fills the dip region

However, there are still regions were the tune is not perfect at high available energy