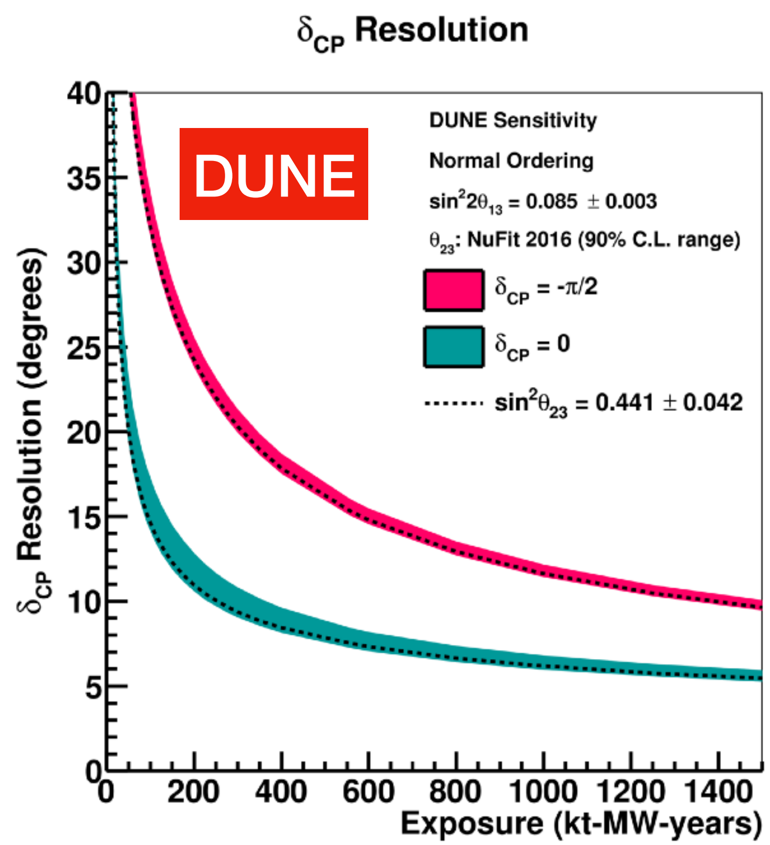
# Recent results from MINERvA

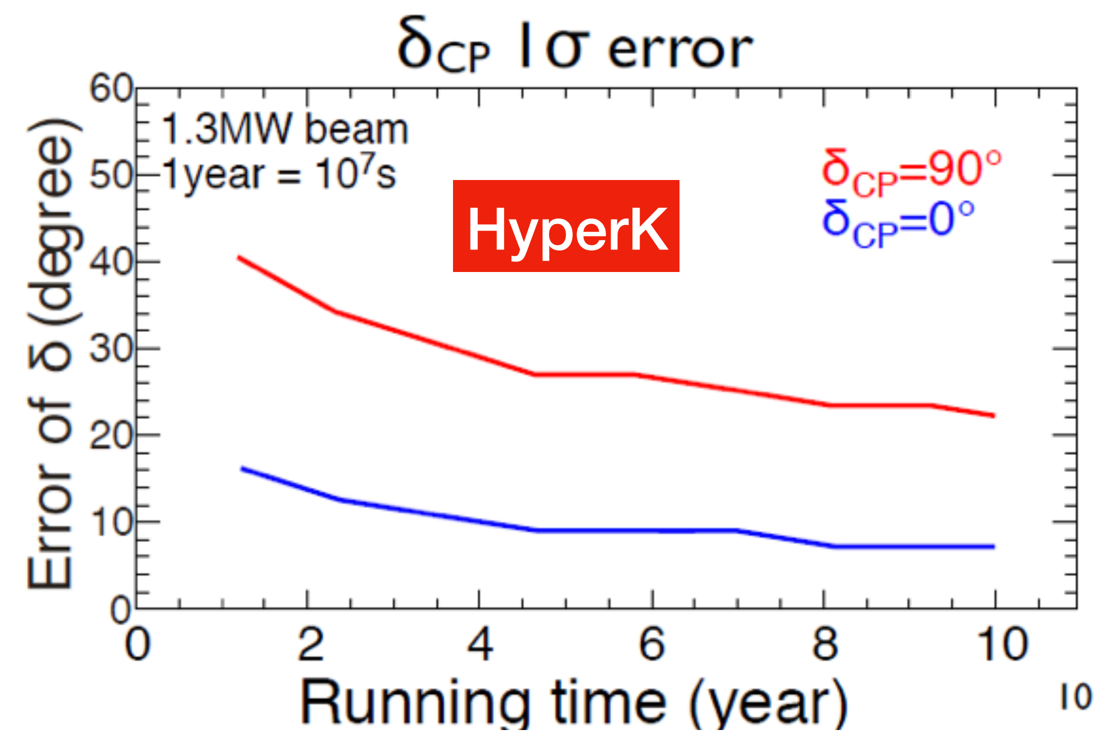

Jorge Chaves
University of Pennsylvania
on behalf of the MINERvA collaboration


**NOW 2018**
**September 10-15, 2018**

# Cross section measurements as inputs to oscillation experiments




50 kT-MW-years corresponds to a year data-taking at 1.2 MW and 40 kT




- We are now in the era of precision measurements.
  - Future experiments expect to constrain their uncertainties to a few %.
  - Uncertainties include flux and nuclear models.
- MINERvA measurements will help with both of these.

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# NuMI beam

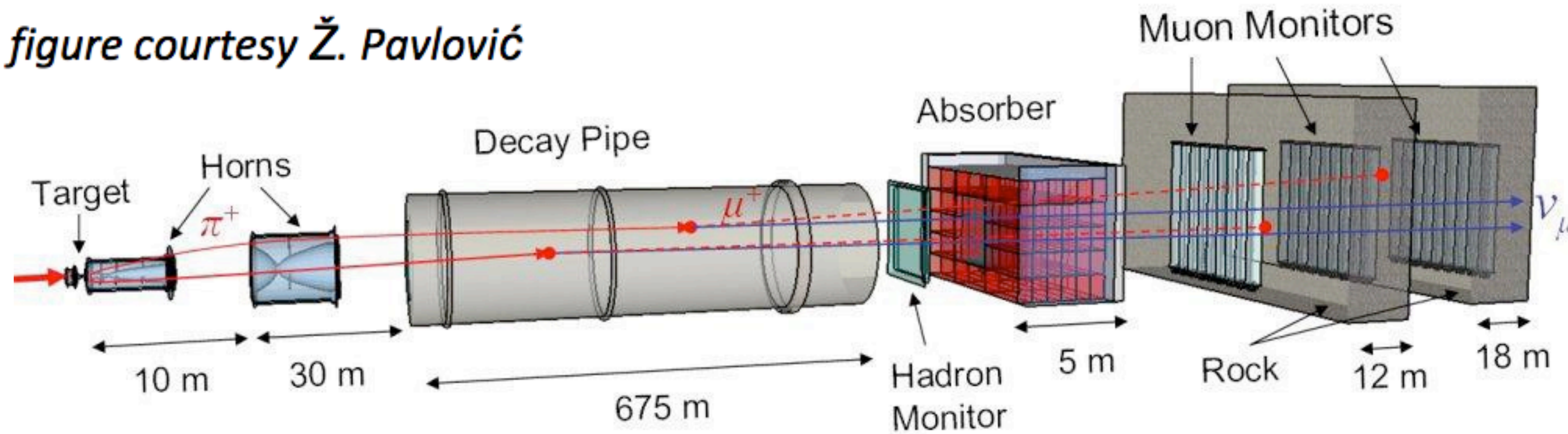
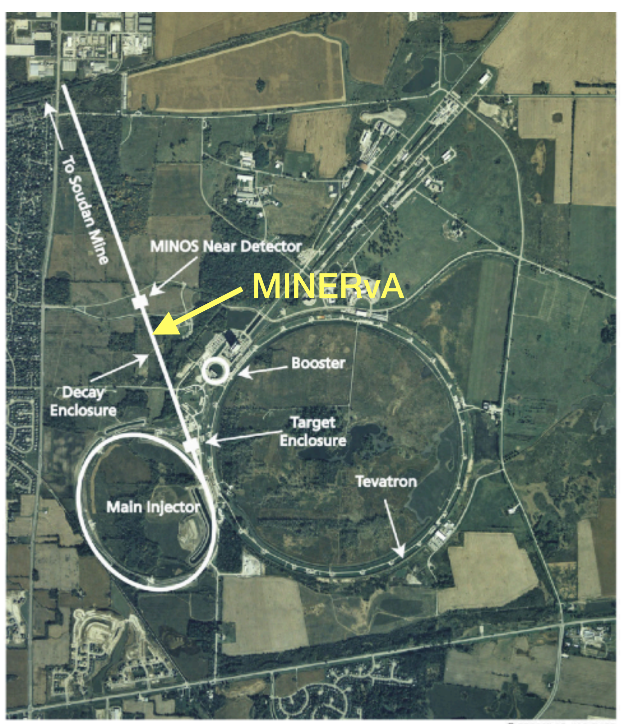
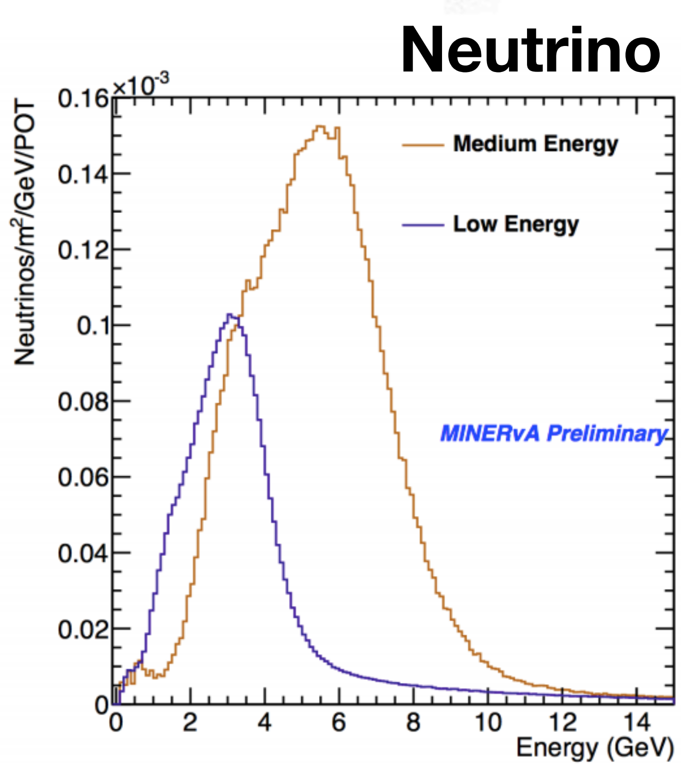


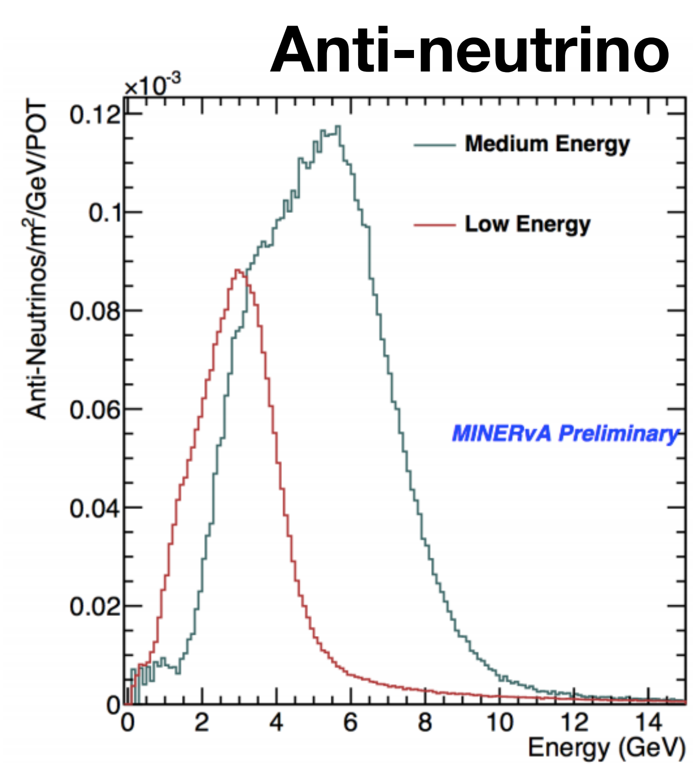
figure courtesy Ž. Pavlović
Muon Monitors
Absorber
Decay Pipe
Horns
Target
$\pi^+$
$\mu^+$
$\nu_\mu$
10 m
30 m
675 m
Hadron Monitor
5 m
Rock
12 m
18 m

To Soudan Mine
MINOS Near Detector
MINERvA
Booster
Decay Enclosure
Target Enclosure
Tevatron
Main Injector

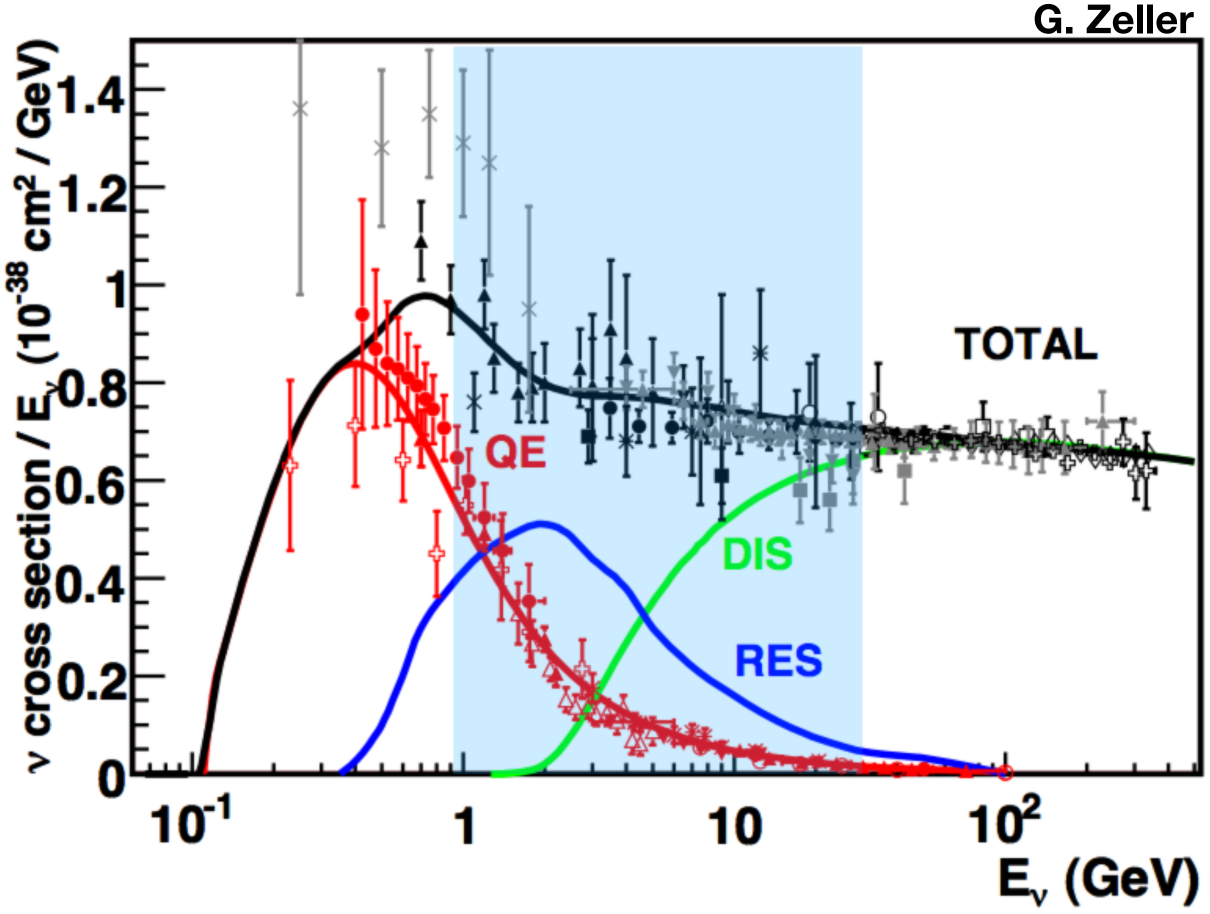
Neutrino
Neutrinos/m²/GeV/POT
×10⁻³
Medium Energy
Low Energy
MINERvA Preliminary
Energy (GeV)

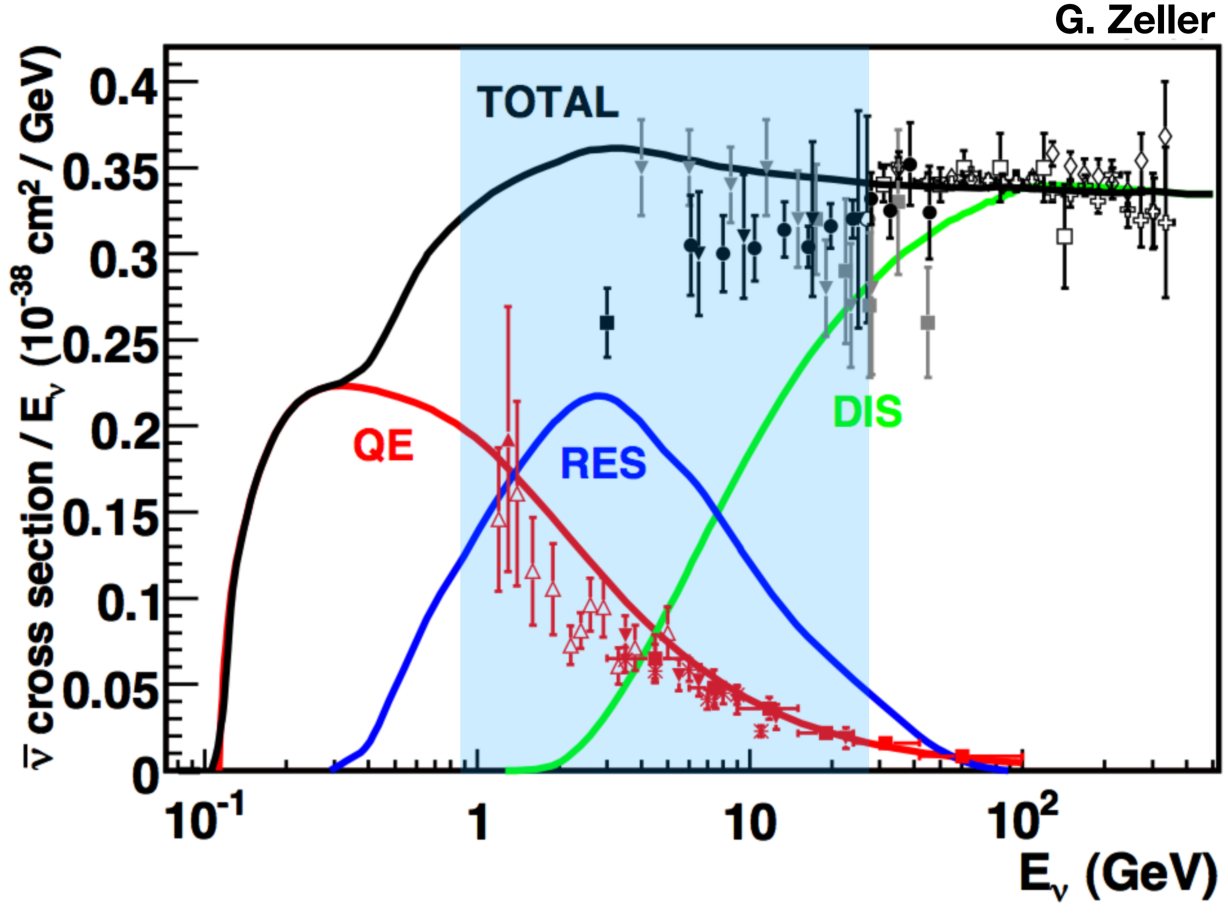



Anti-neutrino
Anti-Neutrinos/m²/GeV/POT
×10⁻³
Medium Energy
Low Energy
MINERvA Preliminary
Energy (GeV)

# Physics in MINERvA

- The beam energy available to MINERvA provides a broad range of physics processes.
- Approach is to study final state topologies.

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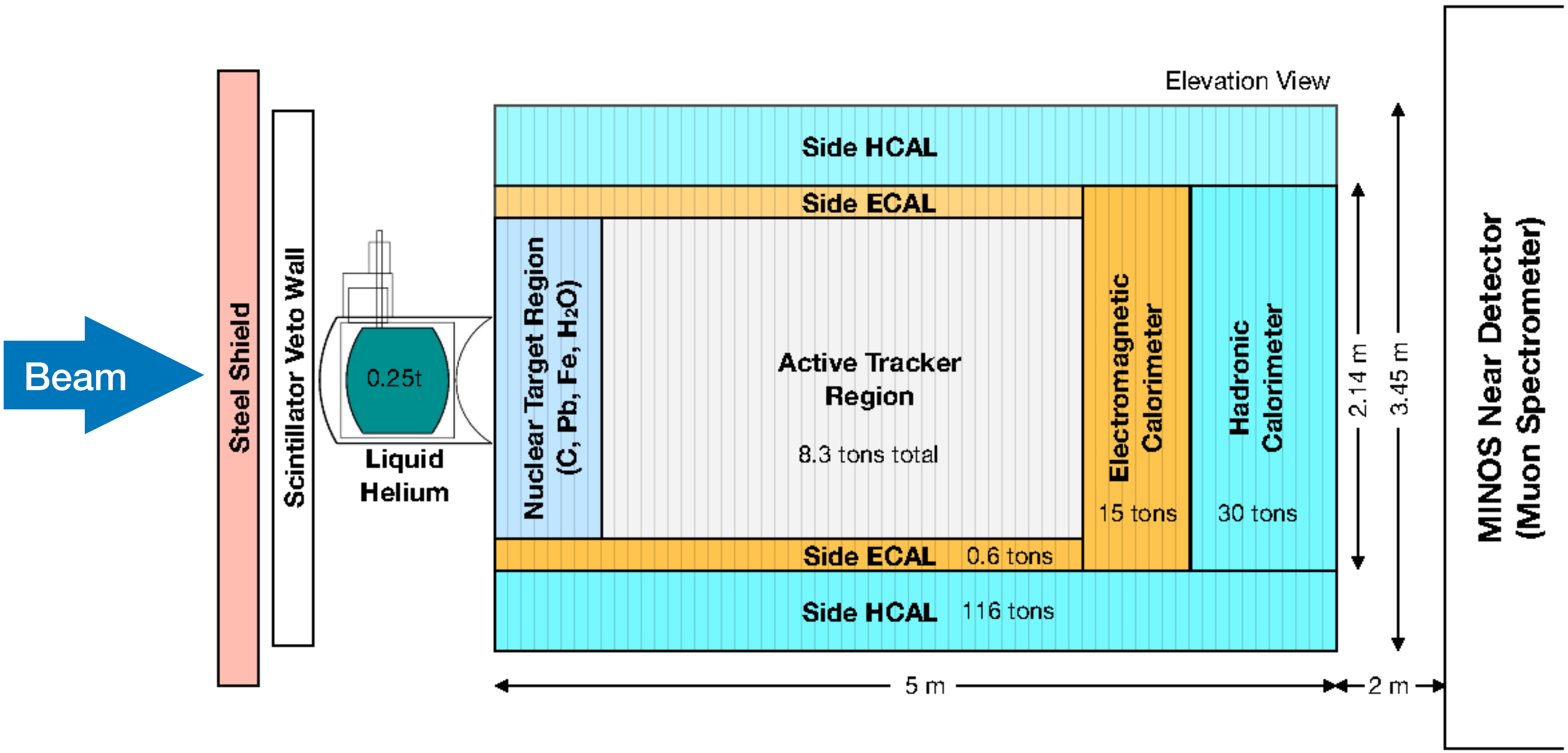
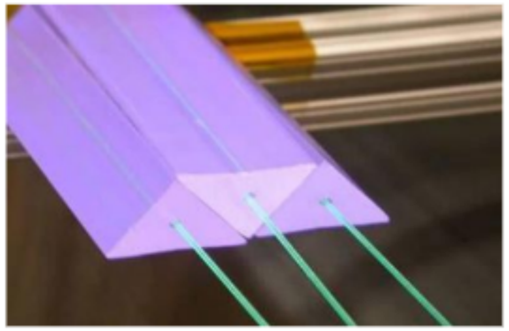
# MINERvA detector




- High granularity, fully active scintillator detector.
- Scintillator planes along beam line are arranged at an offset to provide full 3D position.
- Multiple nuclear targets taking data simultaneously.



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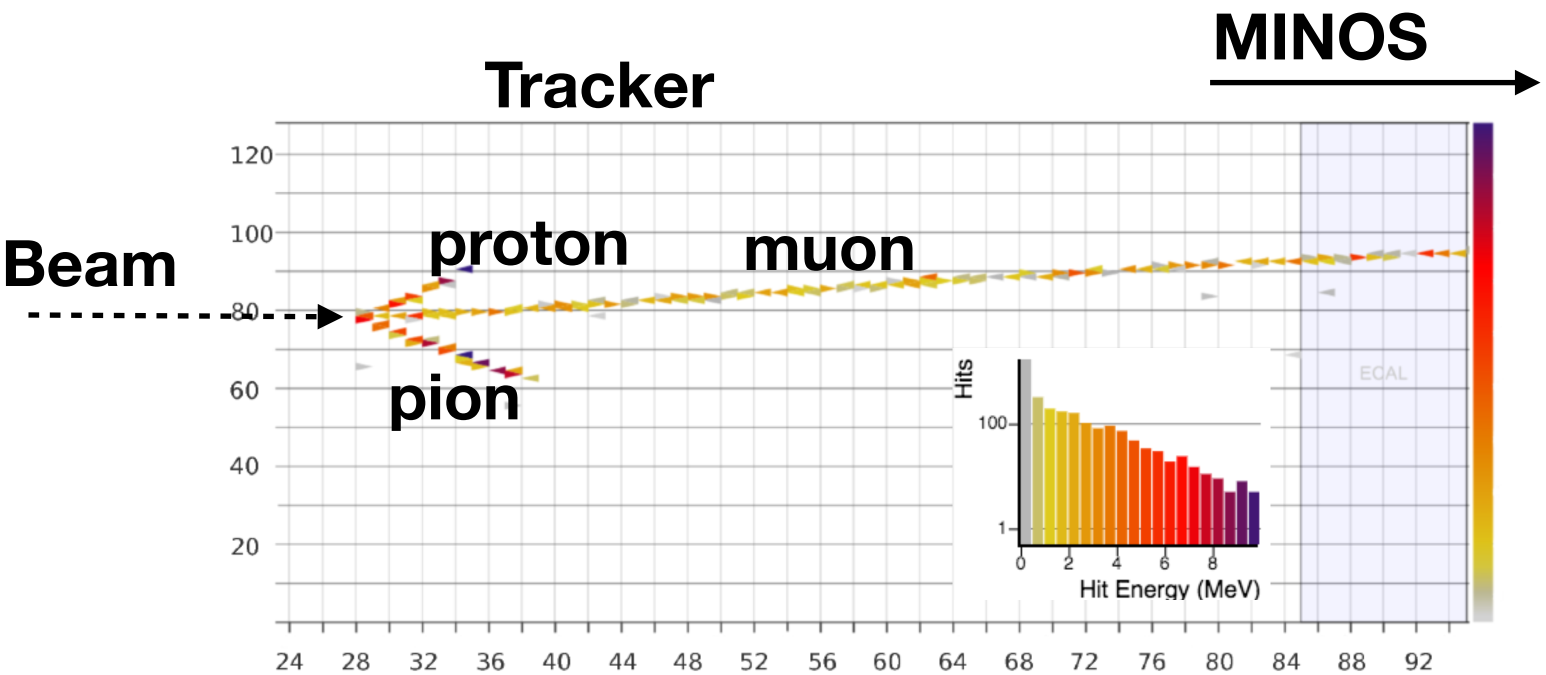
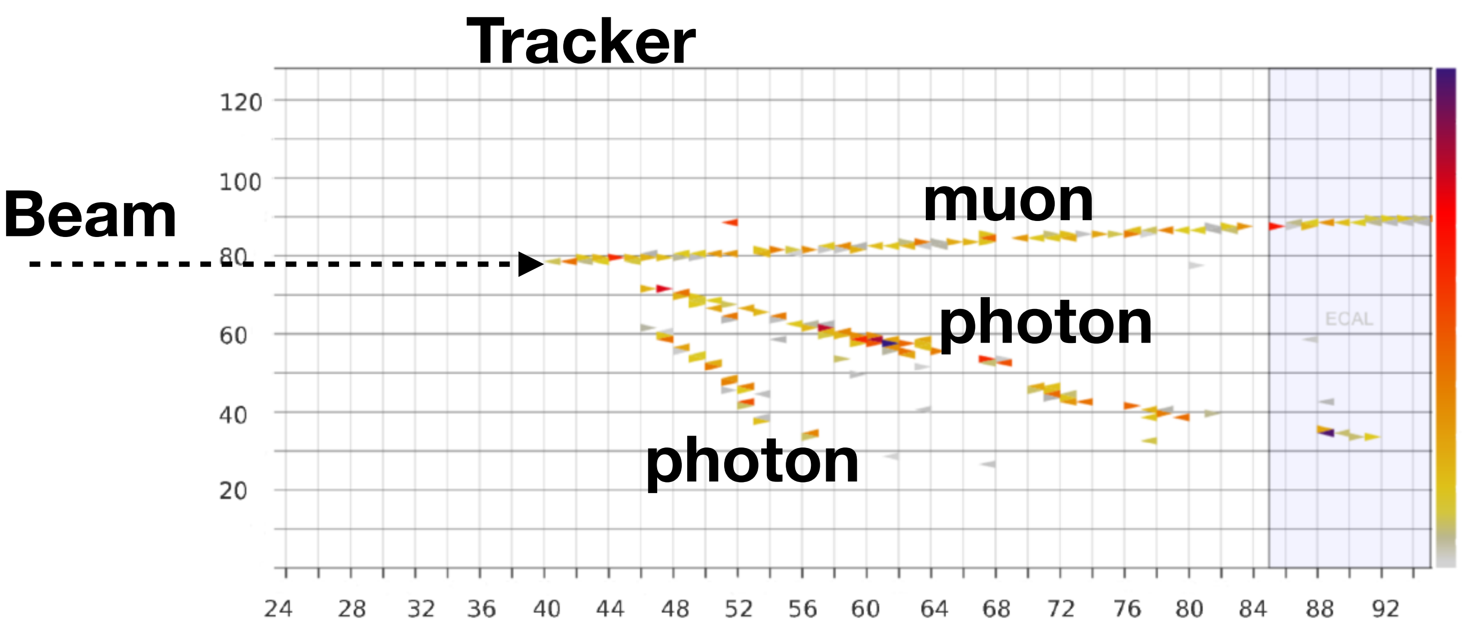
# Events in MINERvA




Neutrino data event of the $\nu_\mu$-CC($\pi^+$).
The event is a candidate for the final state
$\mu^-\pi^+p$




Antineutrino data event and candidate for the final state
$\mu^+\pi^0n$

# Nuclear effects

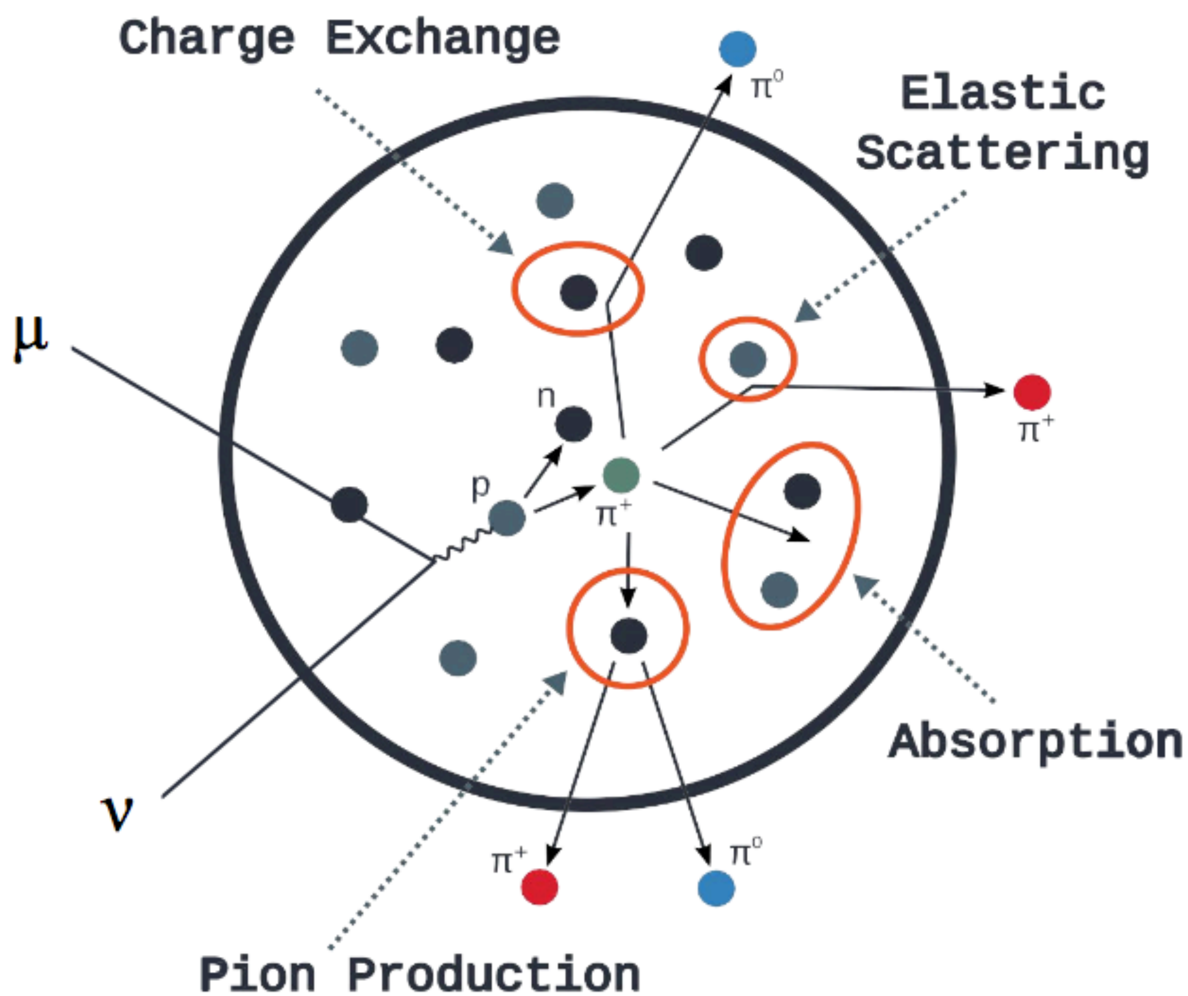



**Illustration by Tomasz Golan**

- Neutrinos interact with the nucleus in multiple ways:
  - Quasi-elastic scattering.
  - Resonance production.
  - Deep inelastic scattering.

# Nuclear effects

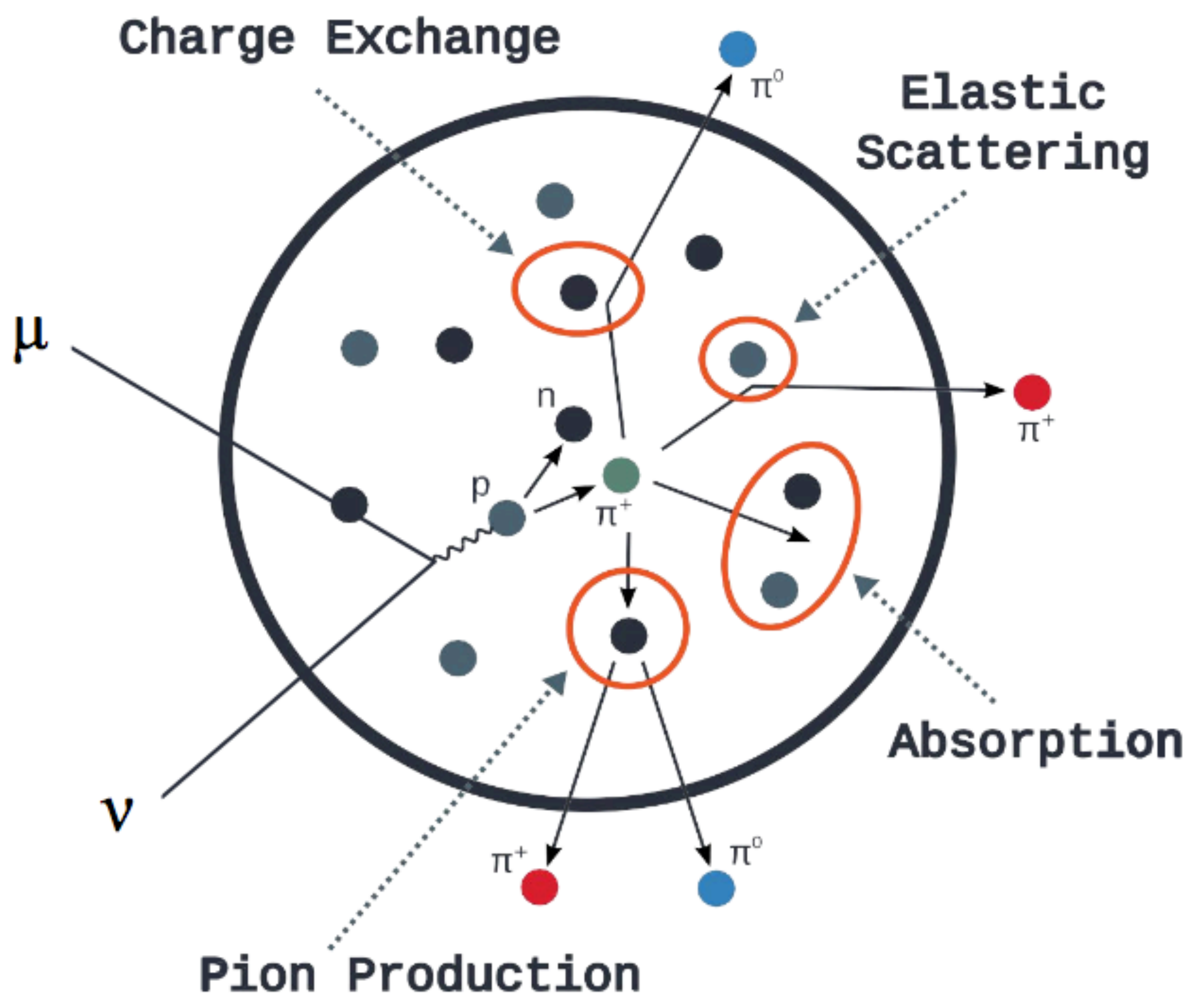
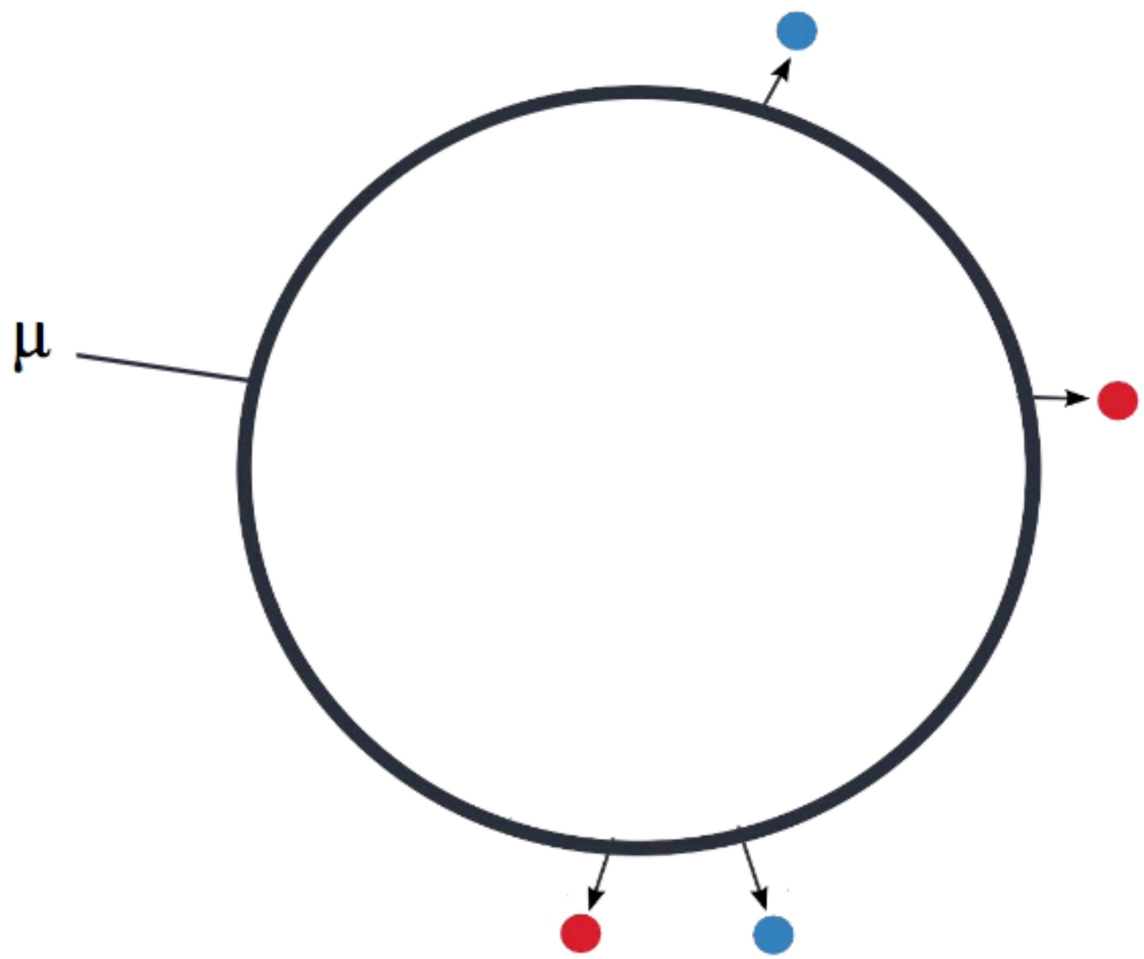



**Illustration by Tomasz Golan**

- Neutrinos interact with the nucleus in multiple ways:
  - Quasi-elastic scattering.
  - Resonance production.
  - Deep inelastic scattering.
  - Neutrino-electron scattering.
  - Screening.
  - Multi-nucleon correlations (2p2h).
  - Final state interactions.
  - …

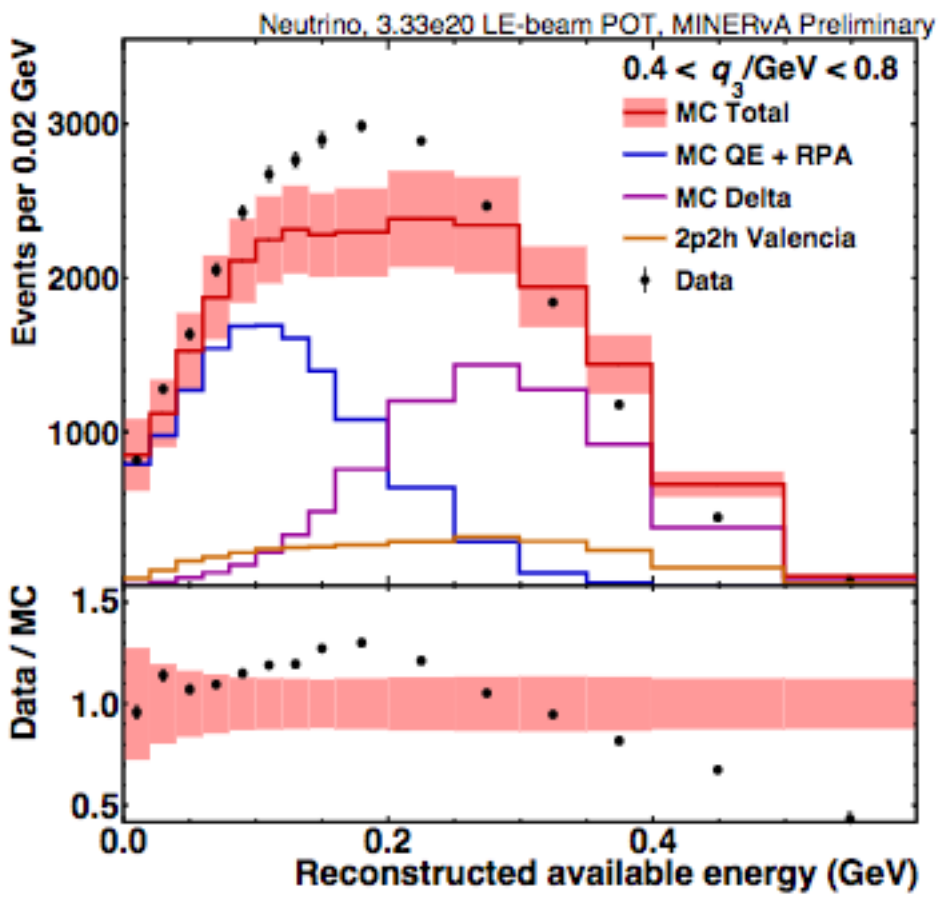
# Nuclear effects



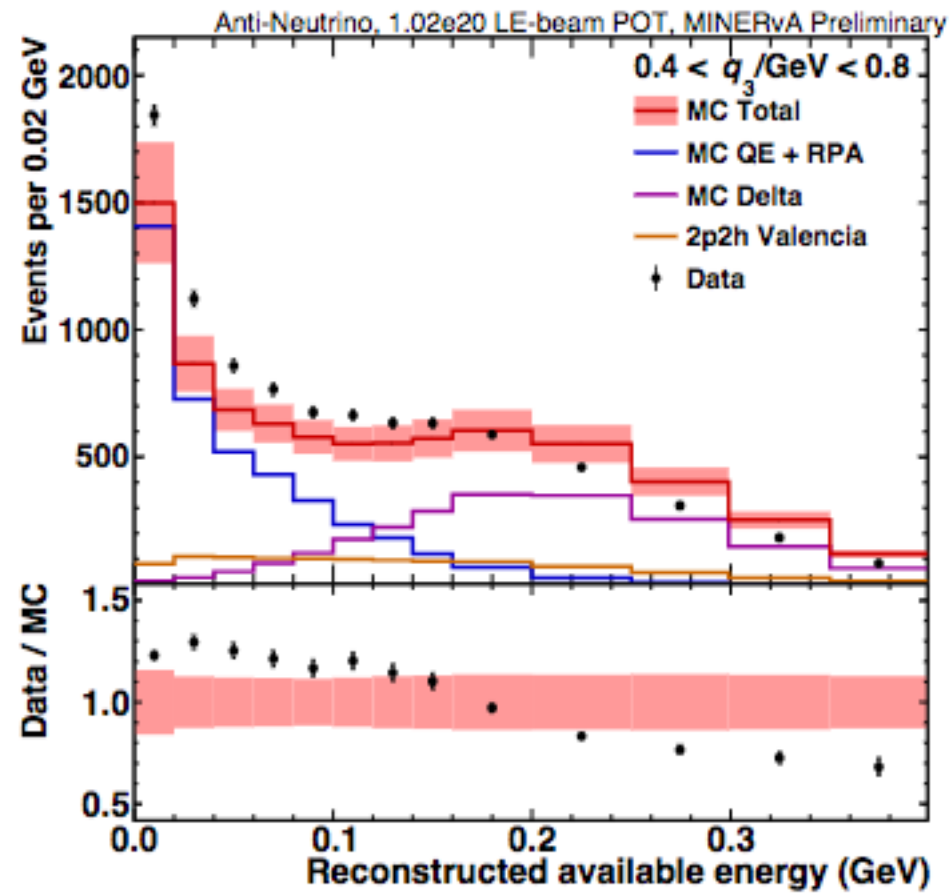

- What we actually see in the detector.
- We need to infer from the final state topology about the neutrino-nucleus interactions.

# Inclusive scattering

**Neutrino**



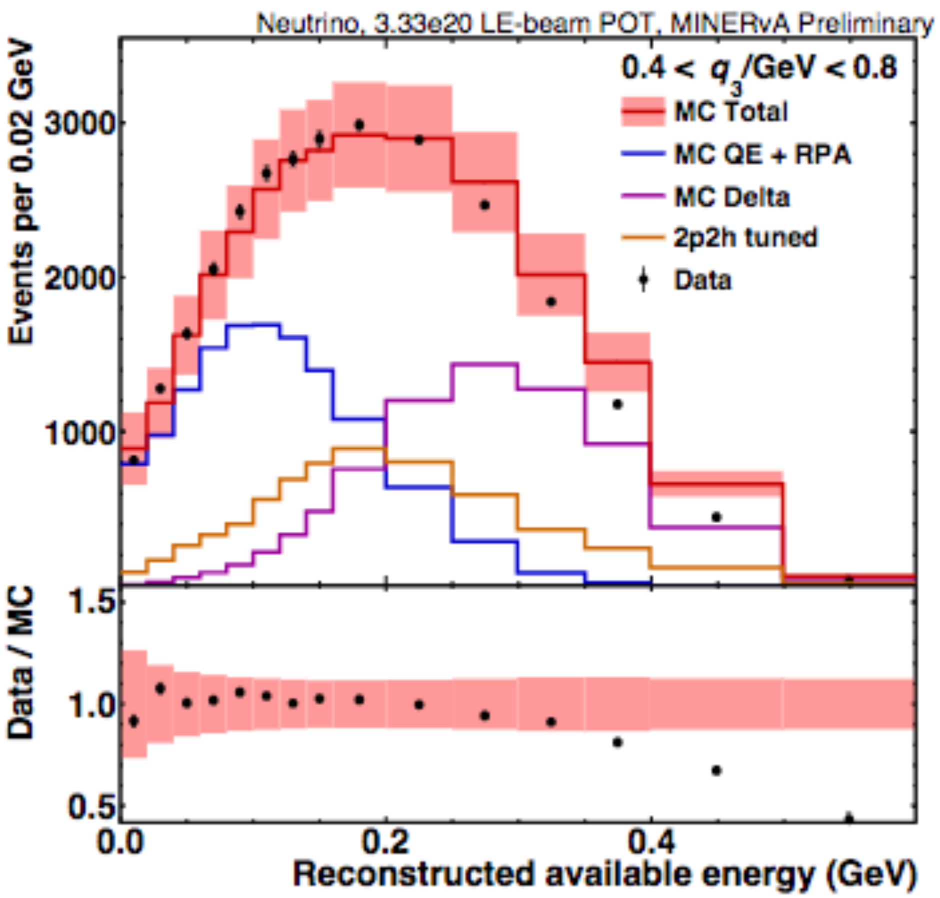

**Anti-neutrino**



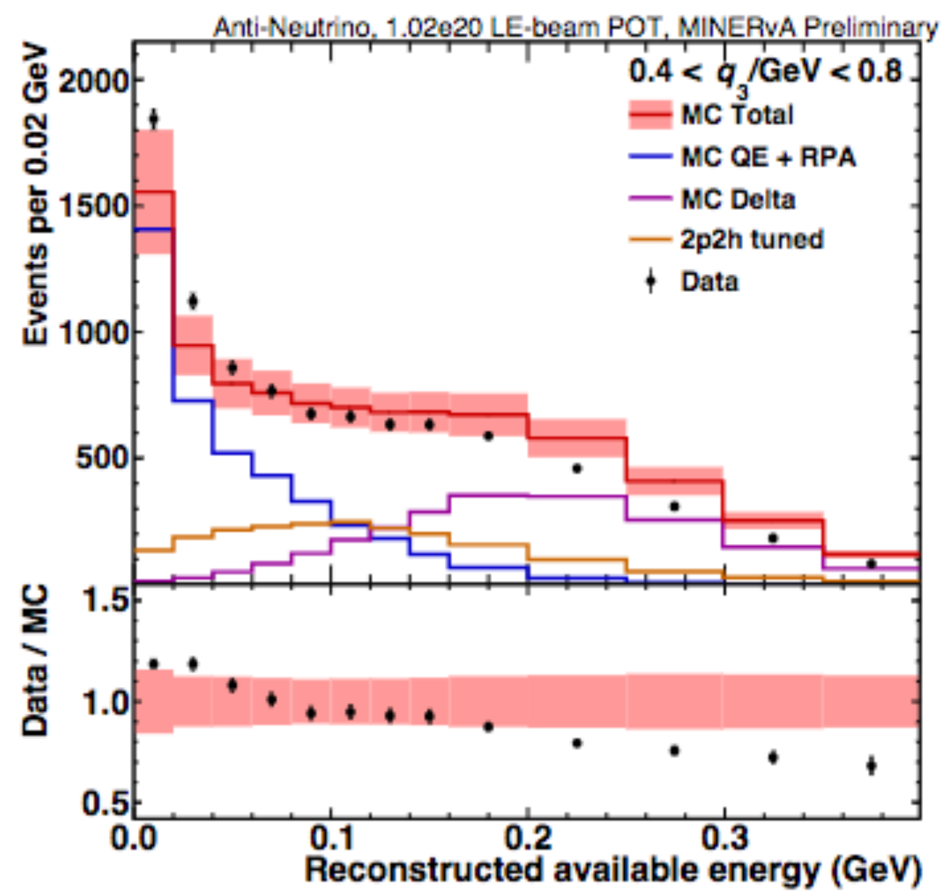

- Monte Carlo = GENIE 2.8.4 + RPA + 2p2h Valencia model
- Even with the above modifications to GENIE, there are still large disagreements

# MINERvA 2p2h tune

## Neutrino

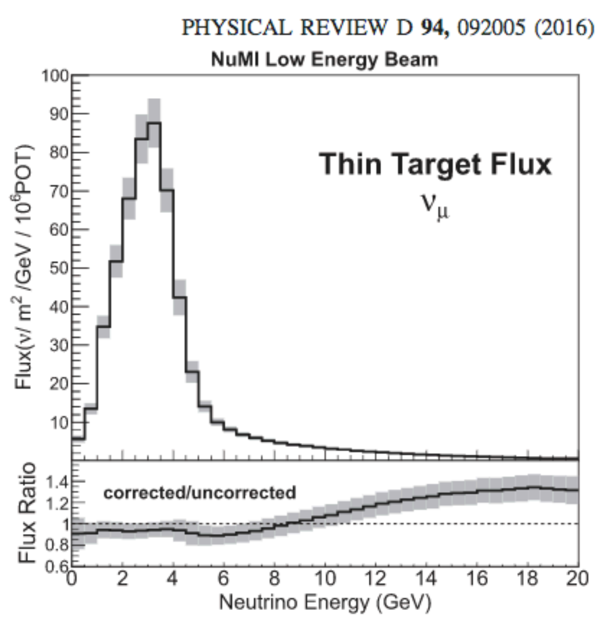


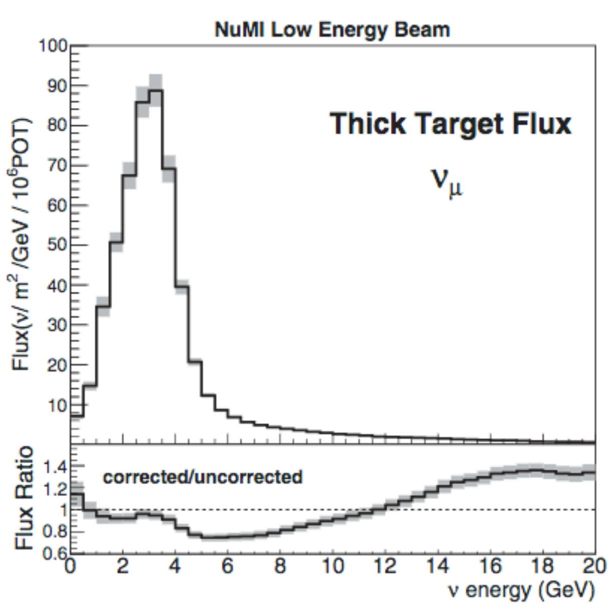

## Anti-neutrino




- Strength of 2p2h contribution is empirically enhanced in the neutrino channel.
  - Simple Gaussian 2D weight fit for 2p2h contribution.
- The antineutrino channel also sees much better agreement.
  - No reason to expect this, but points to an underlying issue with the 2p2h model in GENIE.

# Flux predictions

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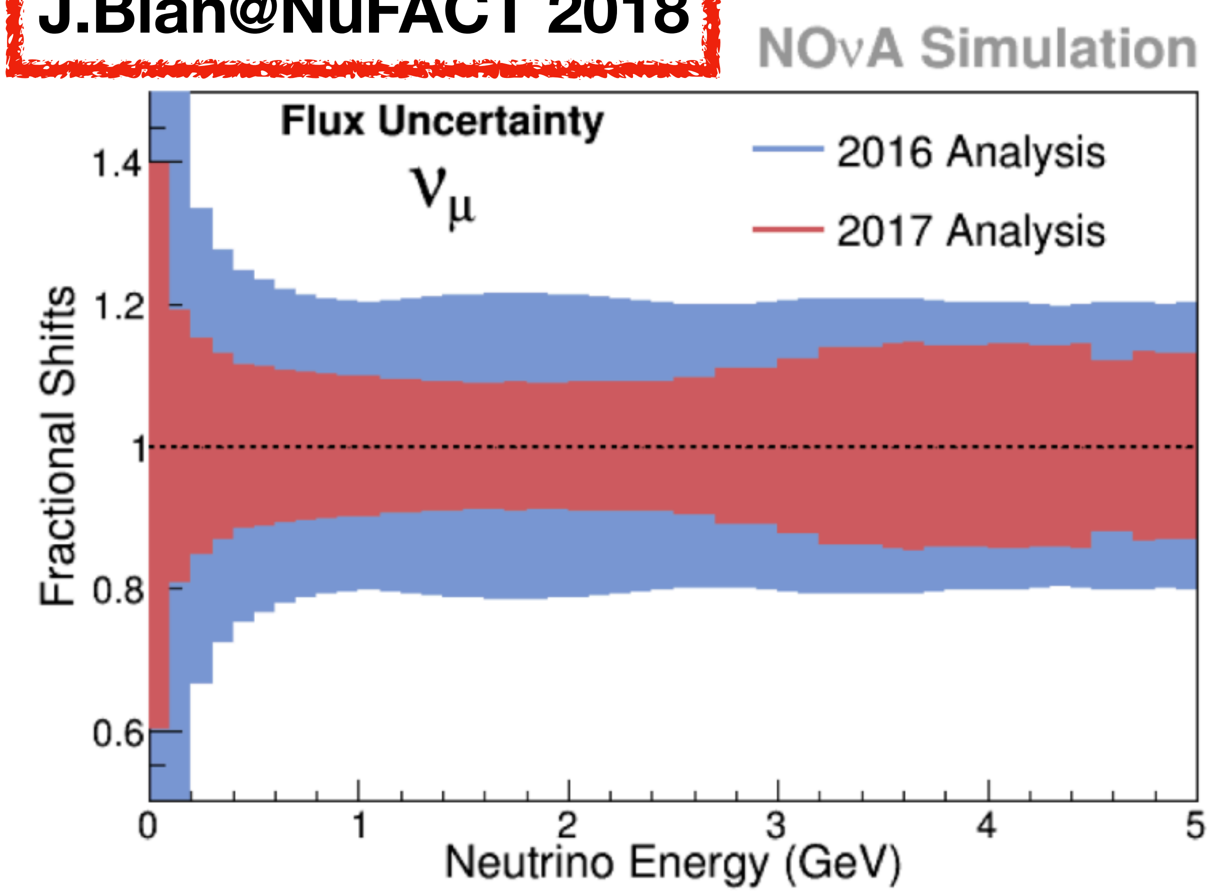
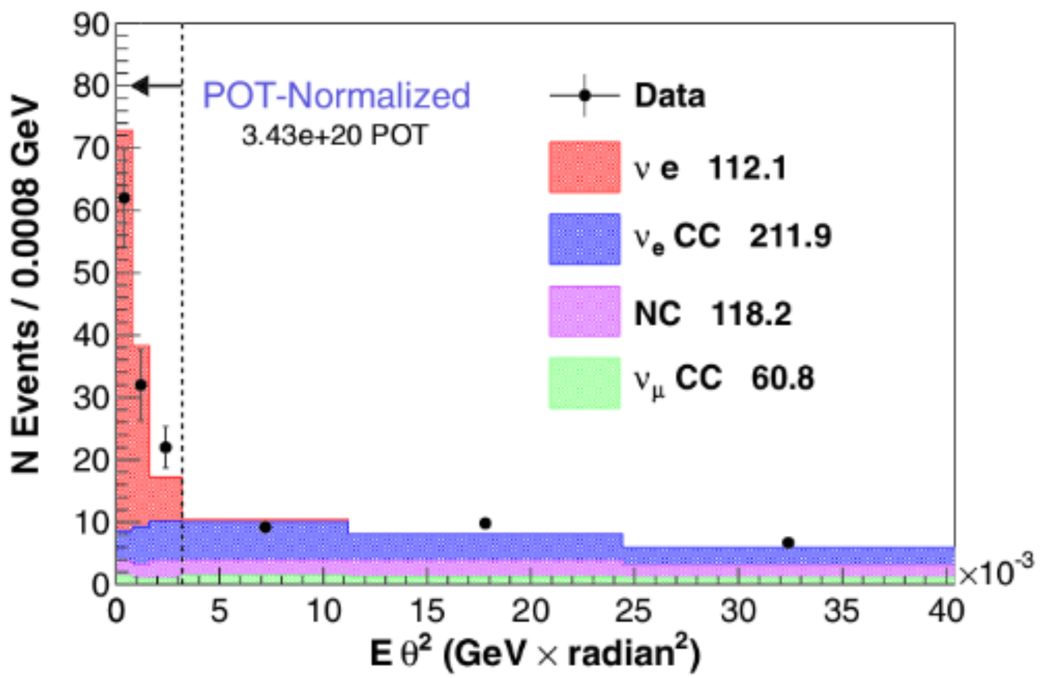


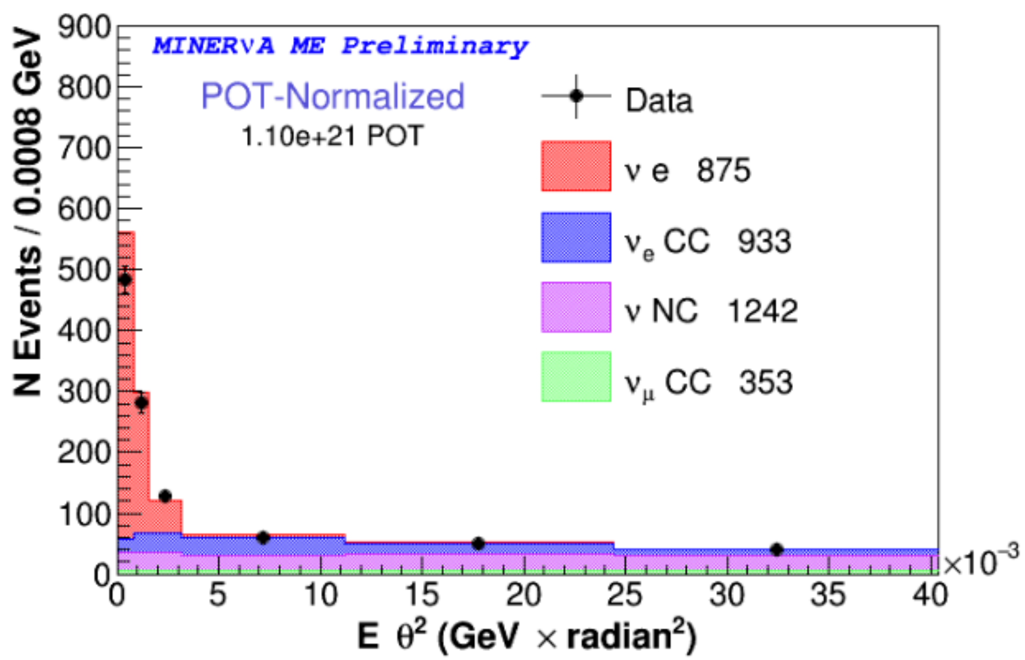

- Package to Predict Flux (PPFX) is available for other experiments (NOvA, MicroBooNE, SBND).
- MINERvA flux predictions has helped in NOvA analyses to significantly reduce systematics.

# Flux studies: Low to medium energy

**Low Energy: Phys. Rev. D 93, 112007**




**Medium Energy: Work in progress**




- Electron-neutrino scattering
- Flux constraint analysis done in LE.
    - Uncertainties dominated by statistical unc.
- Much larger sample in ME.
- Analysis is currently finishing up systematics.
- Flux uncertainty reduced from 8% to 6% in the focusing peak.

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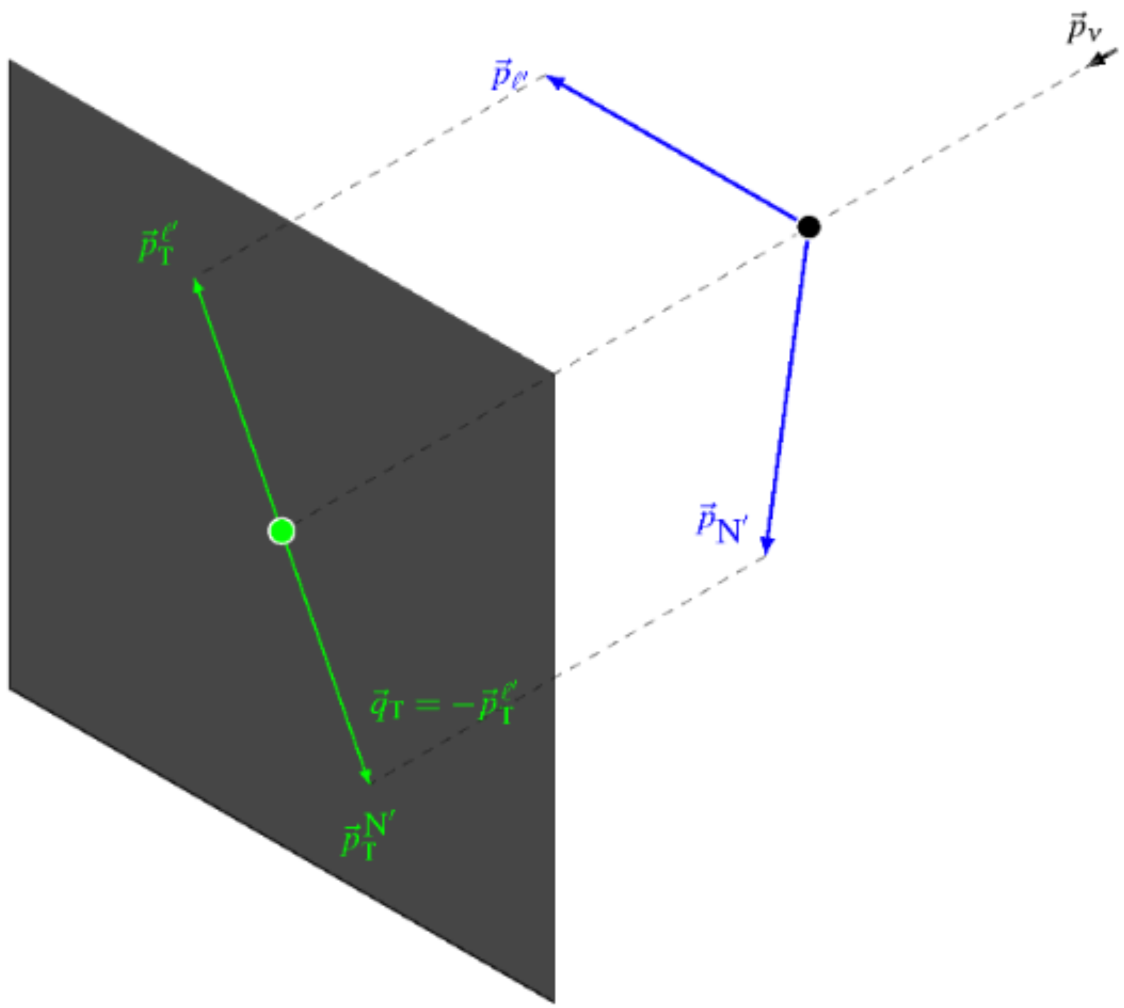
# Transverse kinematic imbalances

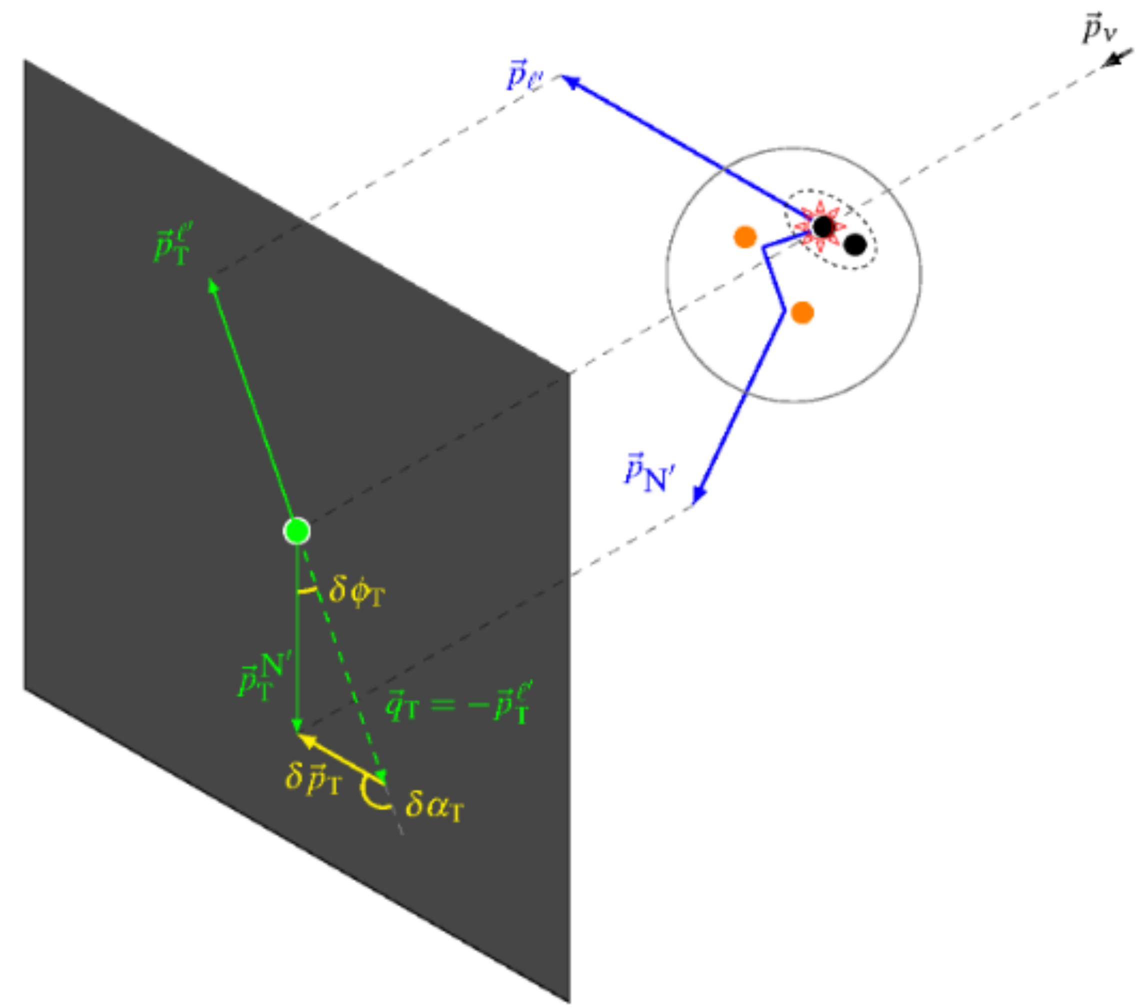
*– Bonus entertainment: Neutrino Shadow Play*

$$\delta \vec{p}_{\rm T} = \vec{p}_{\rm T}^{\rm N} - \Delta \vec{p}_{\rm T}$$

Convolution of Fermi motion and **Intra-nuclear Momentum Transfer** (**IMT**) due to FSI, resonance production, 2p2h etc.




Stationary nucleon target



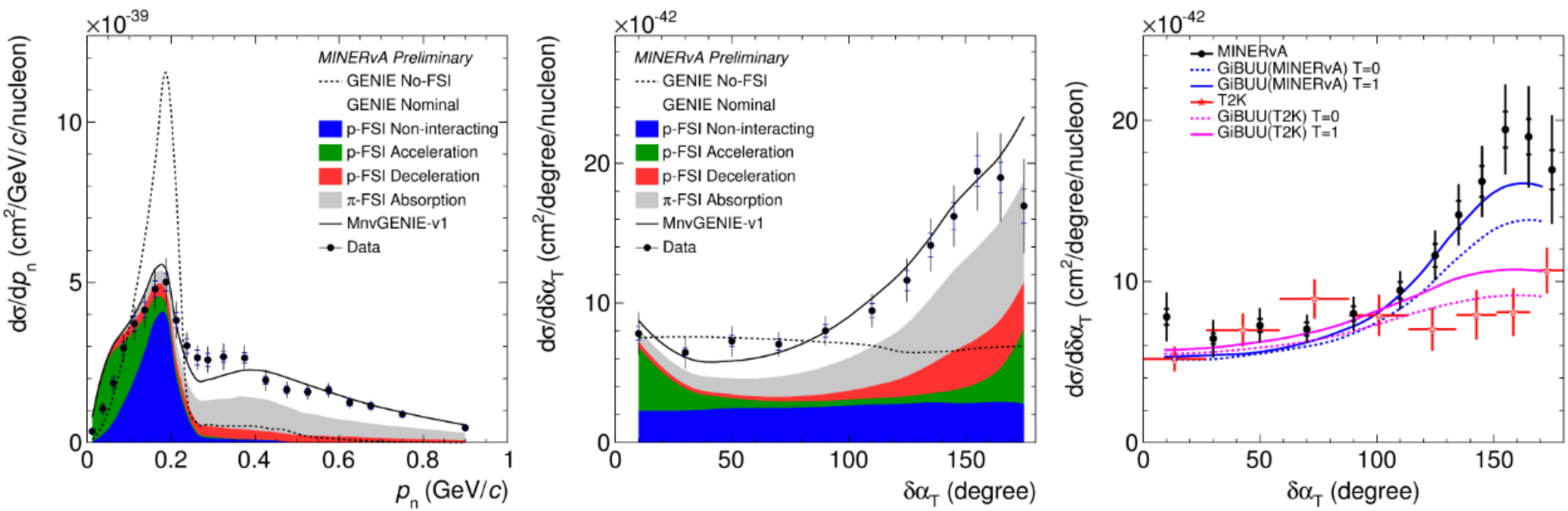

Nuclear target

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

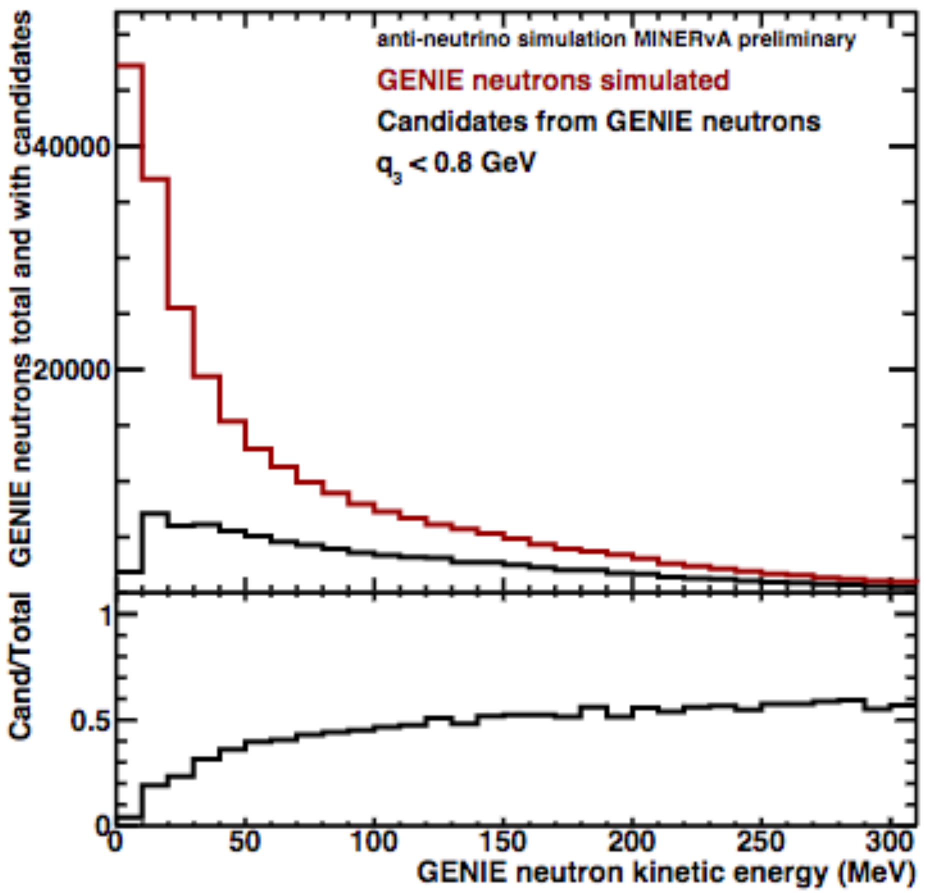
**Very nice Wine&Cheese at FNAL: http://theory.fnal.gov/events/event/new-results-from-minerva/**

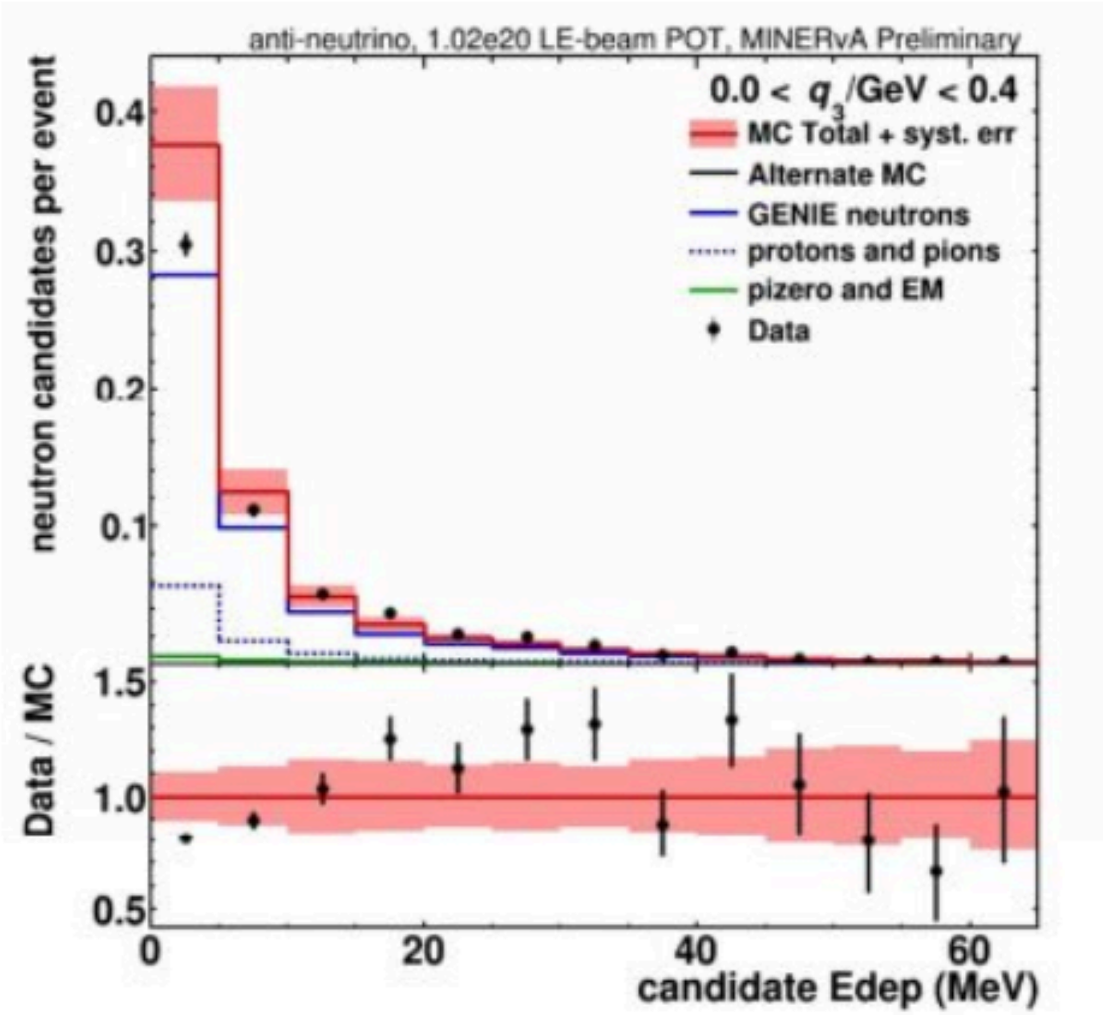
# Nuclear effects diagnostics using proton-muon correlation

- Data/MC comparisons highlight effects of mis-modeling by generators.
- Transverse variables provide an additional handle on nuclear effects: Fermi motion, 2p2h, FSI.



# Future results: Neutron counting

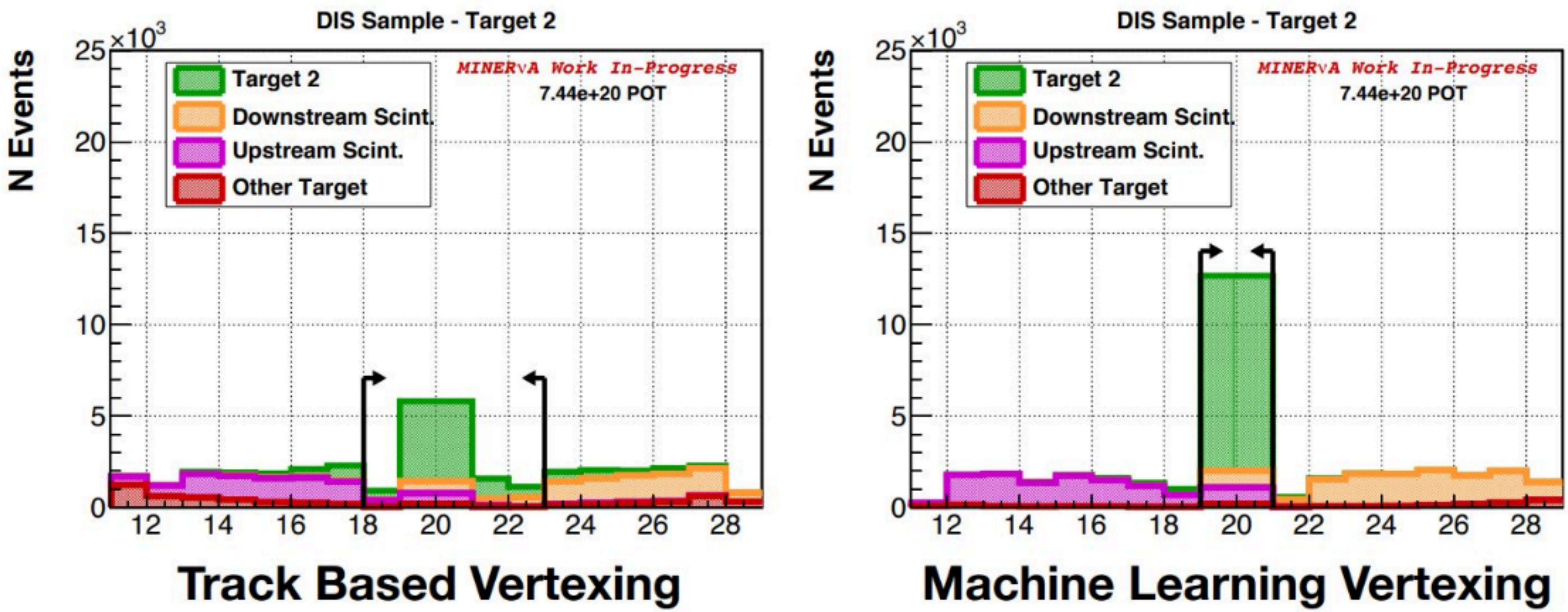



- Antineutrino low recoil sample.
- Start by counting neutron candidates and measure positions and energy deposited.
- Working on understanding neutrons in MINERvA

**Publication in preparation**

# Future results:
# Machine Learning for vertex ID




- New tools from ML can help our vertex finding in DIS events.
- Some vertices easily seen by human eye are missed by reconstruction algorithm. Image processing in ML enhance vertex finding algorithm.

**arXiv:1808.08332**

# Selected MINERvA publications

- “Measurement of final-state correlations in neutrino muon-proton mesonless production on hydrocarbon at ⟨Eν⟩ = 3 GeV” Phys. Rev. Lett. 121, 022504 (2018)
- “Antineutrino charged Current charged-current reactions on scintillator with low momentum transfer” 10.1103/PhysRevLett.120.221805
- “Measurement of the muon anti-neutrino double-differential cross section for quasi-elastic scattering on hydrocarbon at~Eν~3.5 GeV” Phys. Rev. D 97, 052002 (2018)
- “Measurement of Total and Differential Cross Sections of Neutrino and Antineutrino Coherent π± Production on Carbon” Phys. Rev. D 97, 032014, (2018)
- “Measurement of νμ charged-current single π0 production on hydrocarbon in the few-GeV region using MINERvA” Phys. Rev. D 96, 072003 (2017)
- “Direct Measurement of Nuclear Dependence of Charged Current Quasielastic-like Neutrino Interactions using MINERvA” Phys. Rev. Lett. 119, 082001 (2017)
- “Measurement of the antineutrino to neutrino charged-current interaction cross section ratio on carbon” Phys. Rev. D 95, 072009 (2017)
- “Measurement of neutral-current K+ production by neutrinos using MINERvA” Phys. Rev. Lett. 199, 011802 (2017)
- “Measurements of the Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low-ν Flux Method” Phys. Rev. D 94, 112007 (2016)
- “Neutrino Flux Predictions for the NuMI Beam” Phys. Rev. D 94, 092005 (2016)
- “First evidence of coherent K+ meson production in neutrino-nucleus scattering” Phys. Rev. Lett. 117, 061802 (2016)
- “Measurement of K+ production in charged-current νμ interactions” Phys. Rev. D 94, 012002 (2016)
- “Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA” Phys. Rev. D 94, 052005 (2016).
- “Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon” Phys. Rev. Lett. 117, 111801 (2016)
- “Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering” Phys. Rev. D 93, 112007 (2016)
- “Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA” Phys. Rev. D 93, 071101 (2016).
- •“Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer” Phys. Rev. Lett. 116, 071802 (2016).
- “Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Eν of 3.6 GeV” Phys. Rev. Lett 116, 081802 (2016).
- “Single neutral pion production by charged-current anti-νμ interactions on hydrocarbon at average Eν of 3.6 GeV” Phys. Lett. B749 130-136 (2015).
- “Measurement of muon plus proton final states in νμ interactions on Hydrocarbon at average Eν of 4.2 GeV” Phys. Rev. D91, 071301 (2015).
- “MINERvA neutrino detector response measured with test beam data” Nucl. Inst. Meth. A789, pp 28-42 (2015).
- “Measurement of Coherent Production of π± in Neutrino and Anti-Neutrino Beams on Carbon from Eν of 1.5 to 20 GeV” Phys. Rev. Lett. 113, 261802 (2014).
- “Charged Pion Production in νμ interactions on Hydrocarbon at average Eν of 4.0 GeV” Phys. Rev. D92, 092008 (2015).

# Summary and outlook

- MINERvA physics program is helping oscillation experiments to get a handle on systematics.
  - Empirical generator tunes might be a clue into deeper understanding of neutrino-nucleus interactions.
  - Flux prediction and systematics constraints.
  - Nuclear models studied using transverse variables.
- Medium energy results are in the works and coming soon.

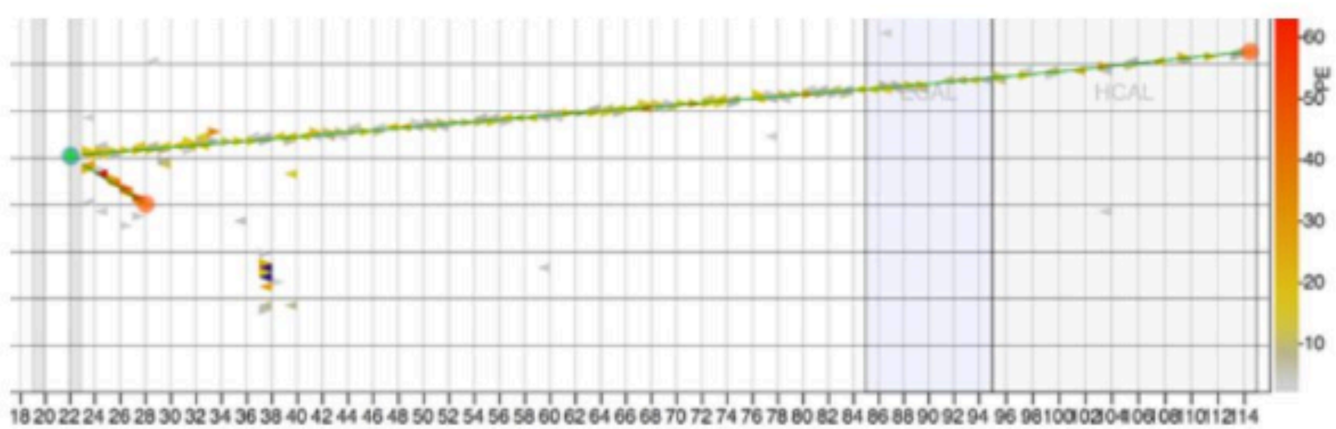
# THANK YOU!

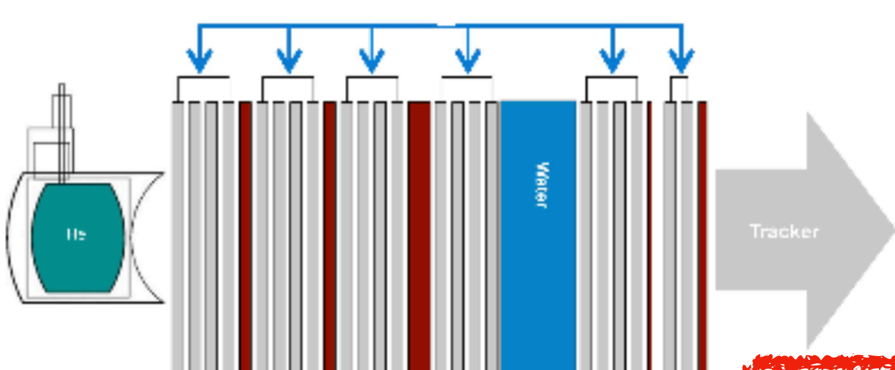
# BACKUP

# FSI Effects in the passive targets

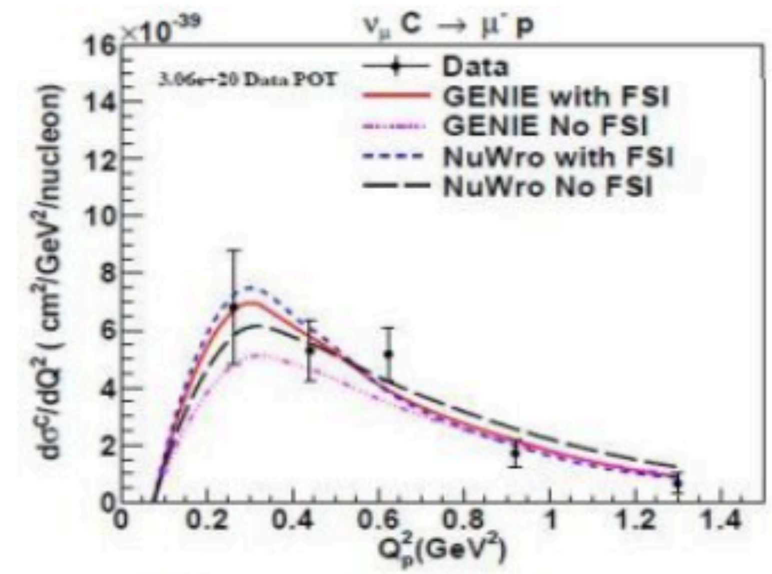
Analyses require a proton track to be well reconstructed

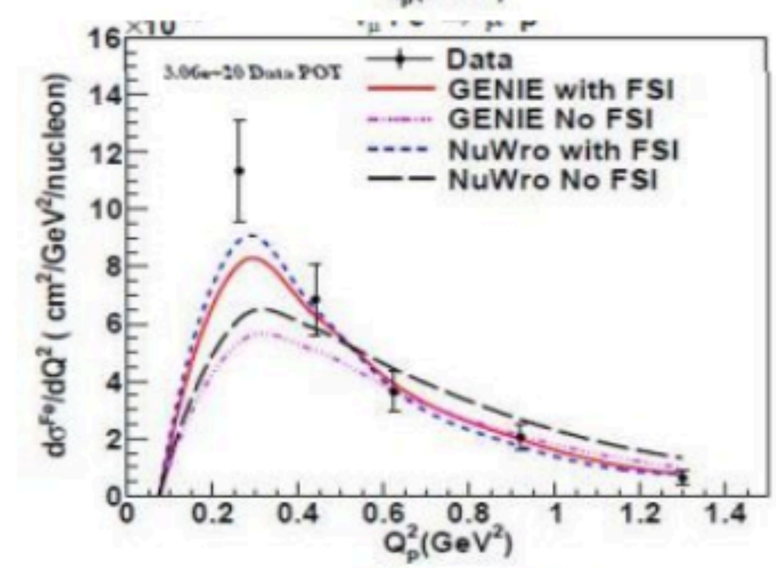
Uses passive targets, tracking determines target

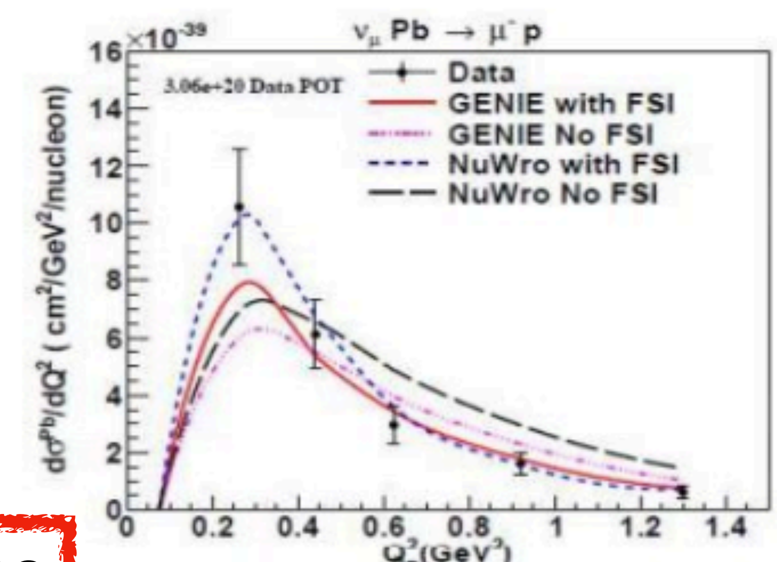



Phys. Rev. Lett. 119, 082001 (2017)



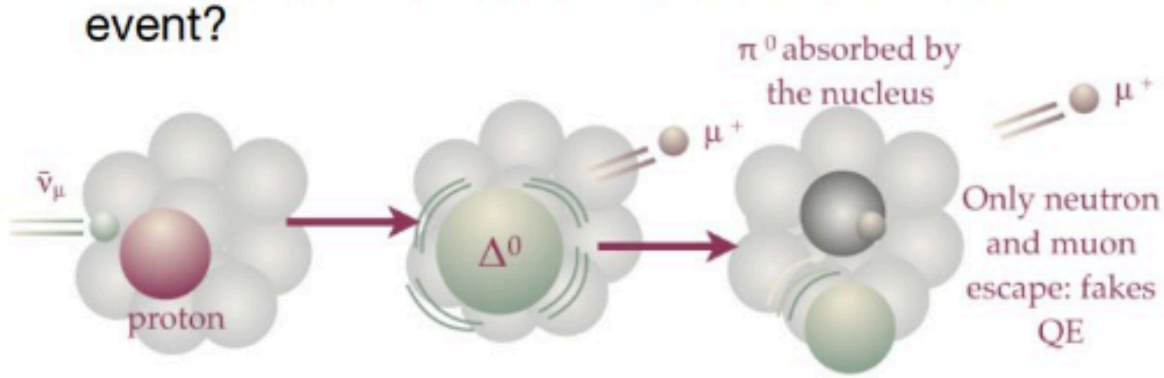



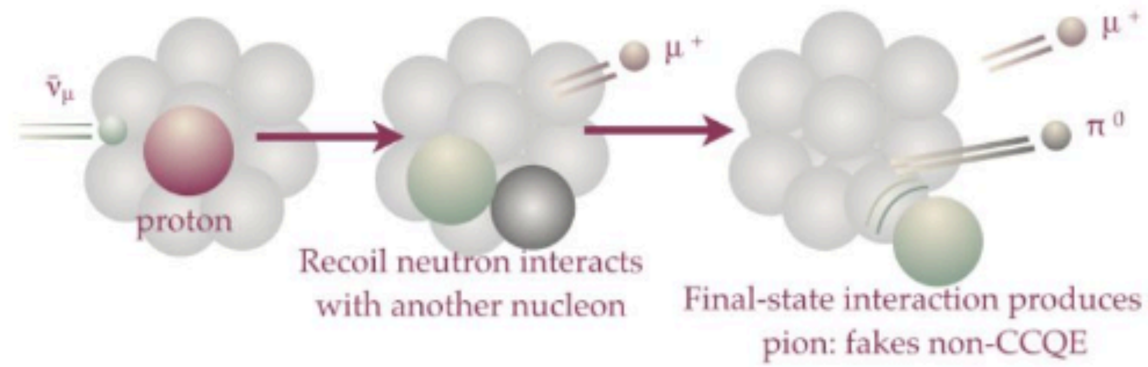

**M.Carneiro@NuFACT 2018**

We know that a true CCQE event produces a muon and single nucleon, but what about…?

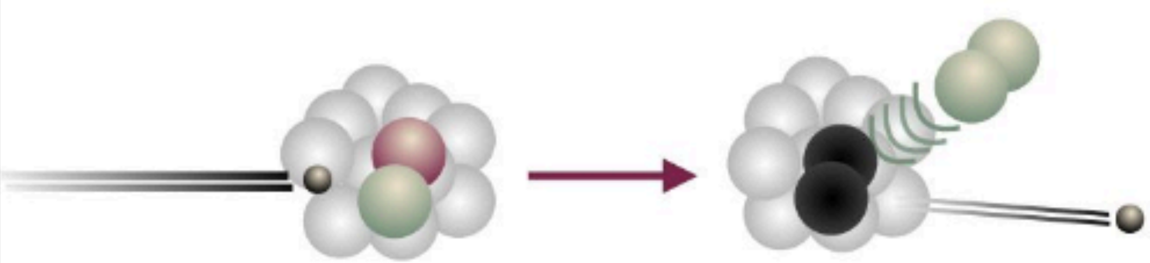
Resonant events where pion is absorbed in FSI, leaving a final state identical to a CCQE event?



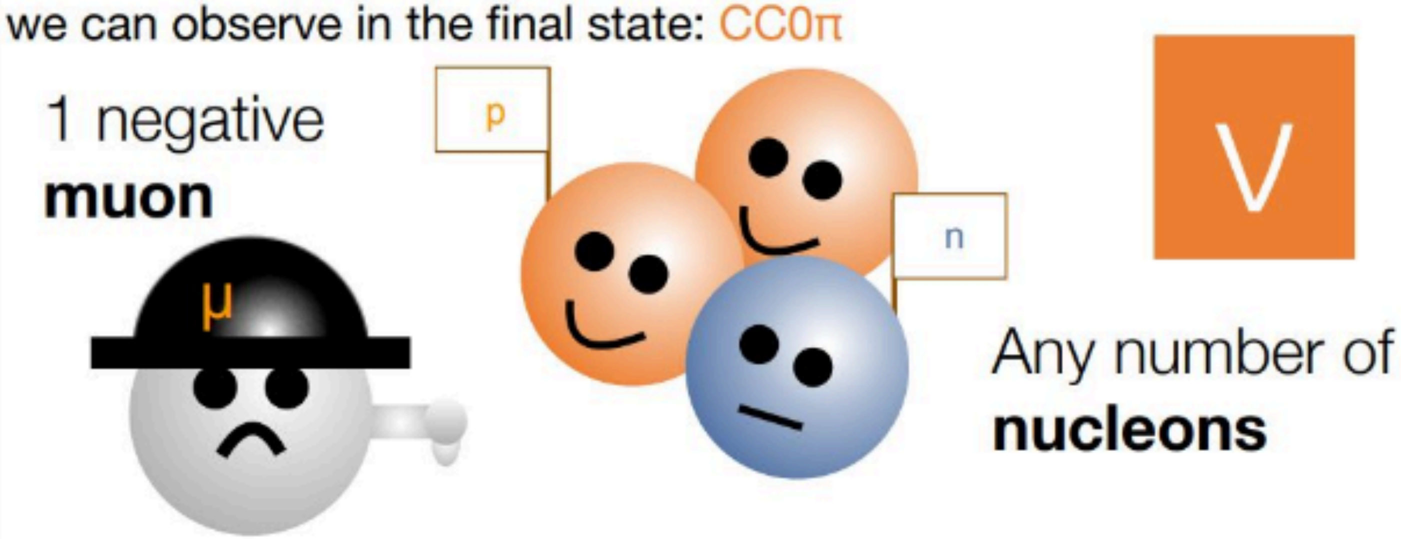

CCQE events where FSI produces pions in the final state?




2p2h events with CCQE scattering from a correlated pair of nucleons?



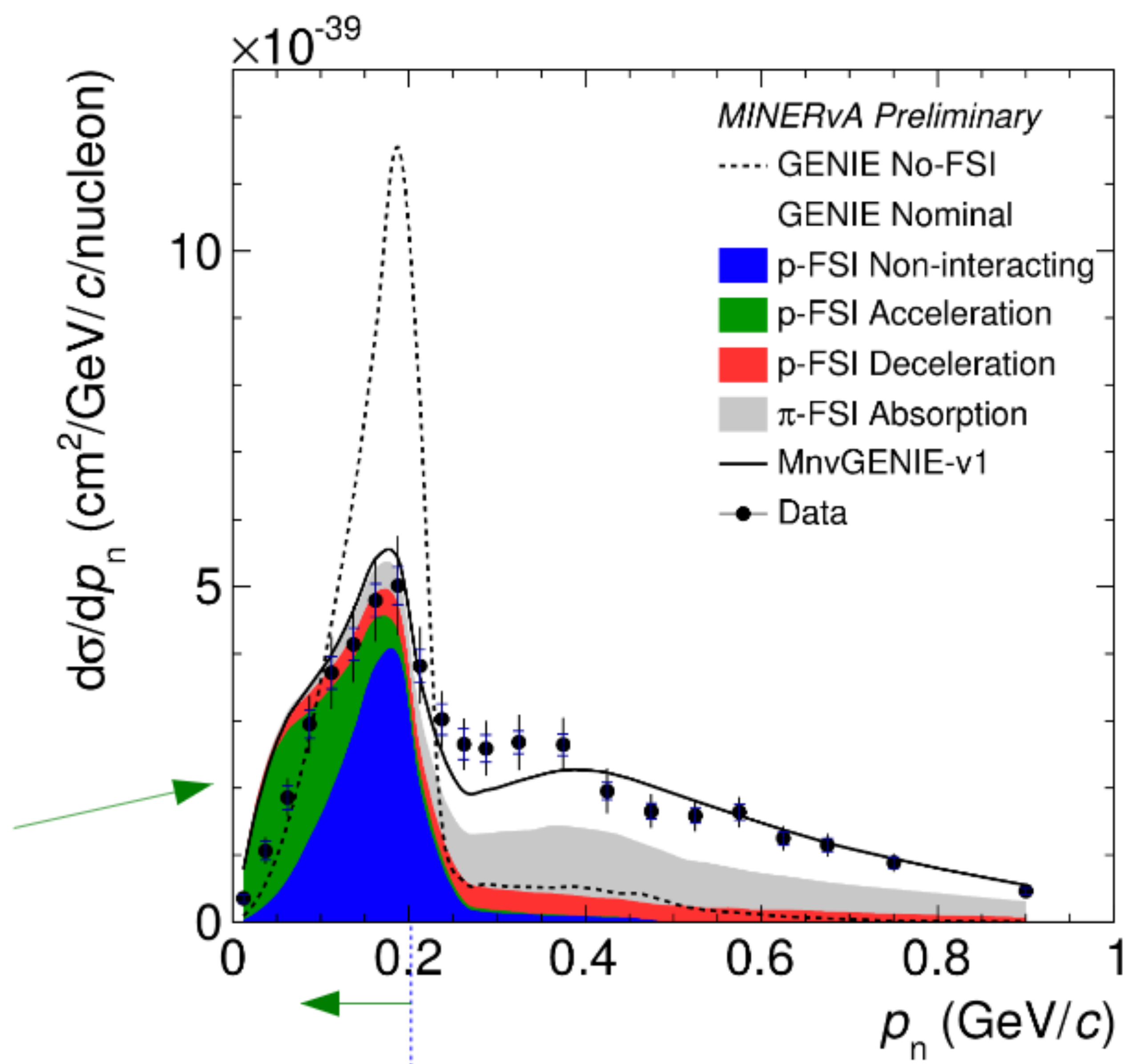
To reduce model dependence, and follow the lead of other experiments, we choose a signal definition that is based on what we can observe in the final state: CC0π



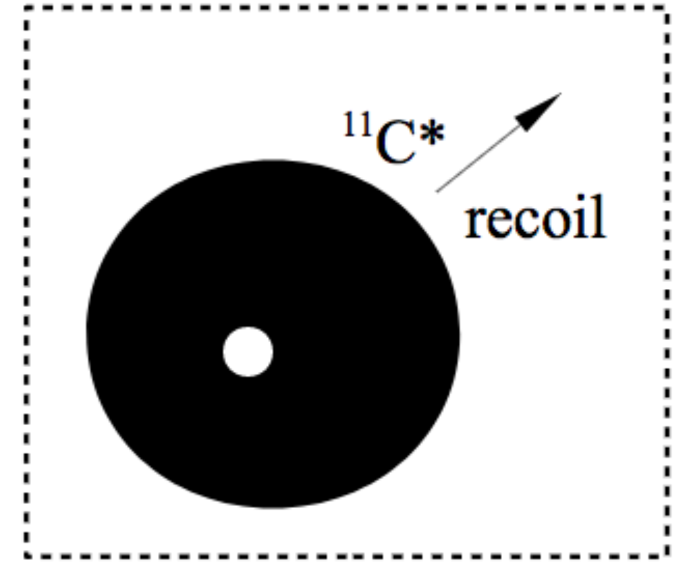

Signal definition for neutrino "QE-like"

# Nuclear Effect Diagnostics

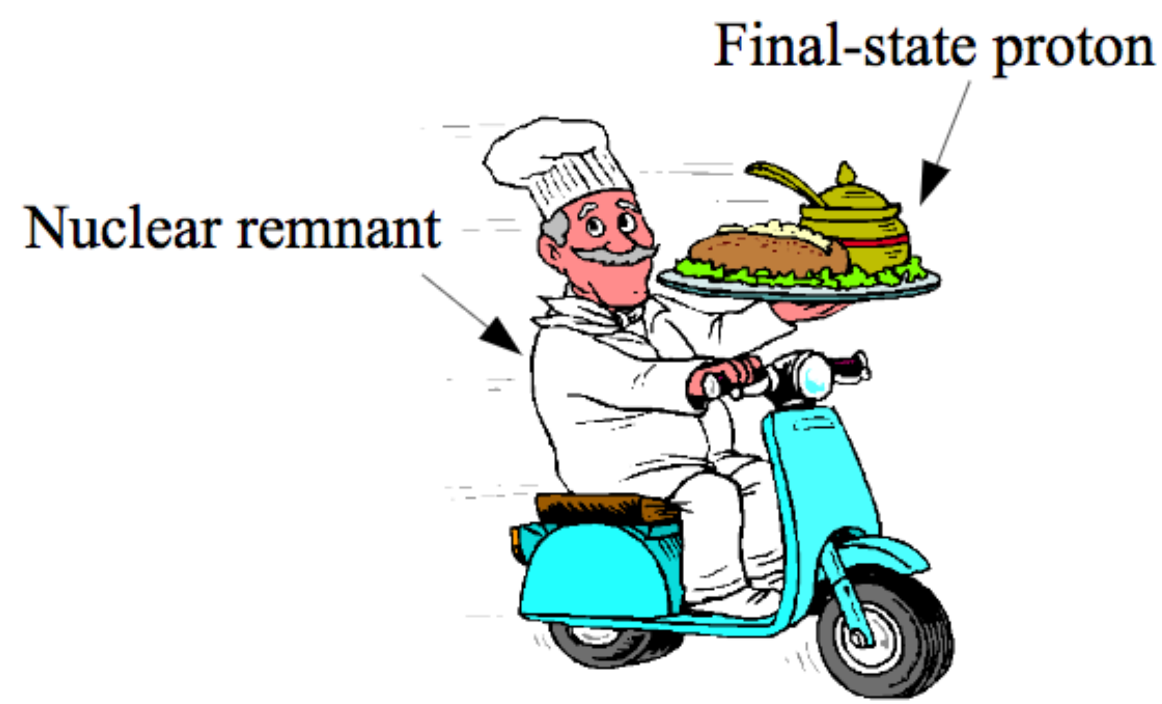
- Initial state
- Final state




In **elastic** FSI (GENIE hA model)
accelerating proton = decelerating nuclear remnant
→ $p_n$ decreases → left of FM peak




**<u>Dual interpretation</u>** of $p_n$:
recoil momentum of the nuclear remnant (final-state)




http://www.animatedimages.org/img-animated-scooter-image-0040-161427.htm