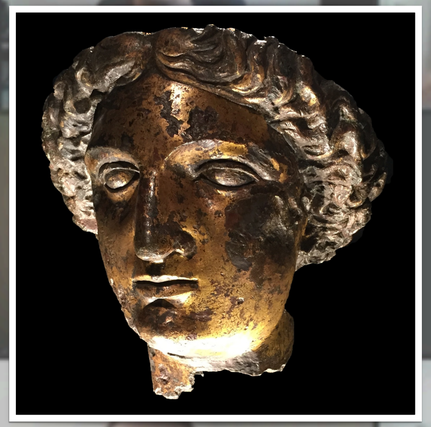
MINERvA experiment

Most recent results and future plans



Gonzalo Díaz

on behalf of the MINERvA collaboration

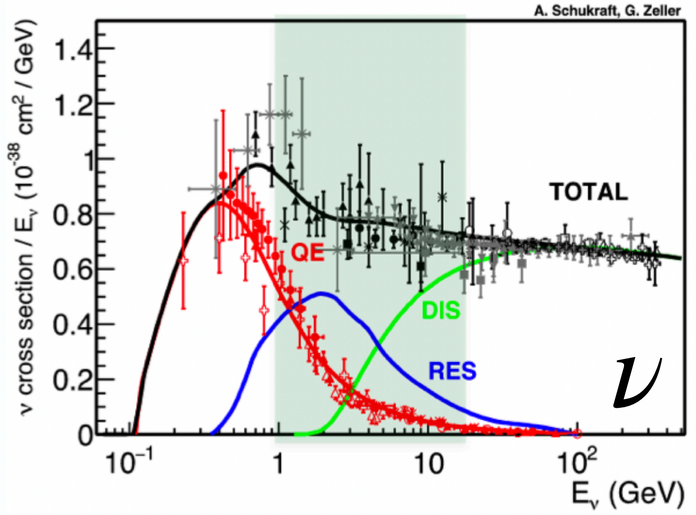
Fermilab Users Meeting
August 5th, 2021

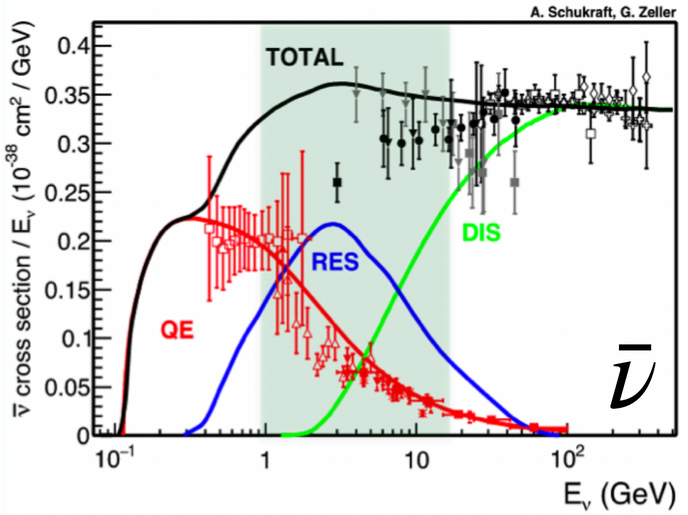
Main INjector ExpeRiment ν-A

MINERvA is a dedicated neutrino-nucleus cross-section experiment.

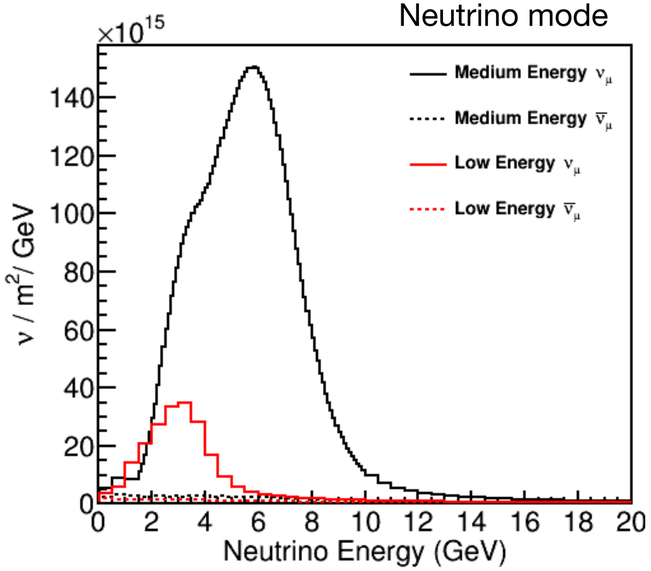
Interested in the neutrino energy regime of 1 to 50 GeV.

We want to probe neutrino interactions from “big” to “small” targets:
Nucleus → Nucleons → Quarks

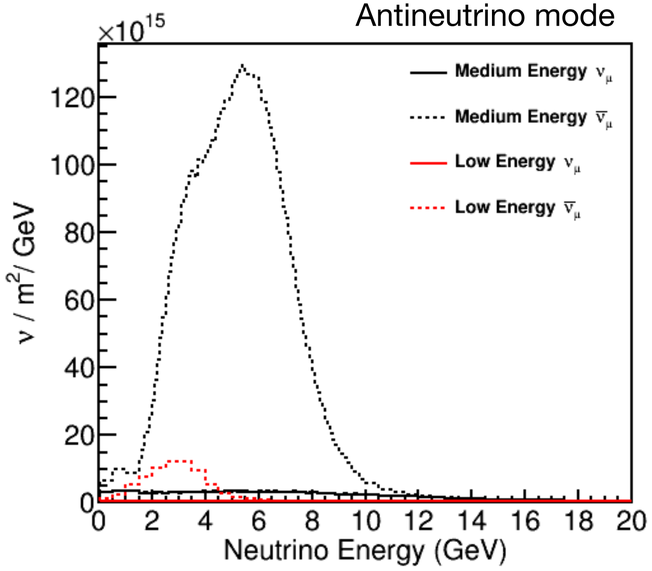




Neutrino mode



Antineutrino mode



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

Low energy POT:

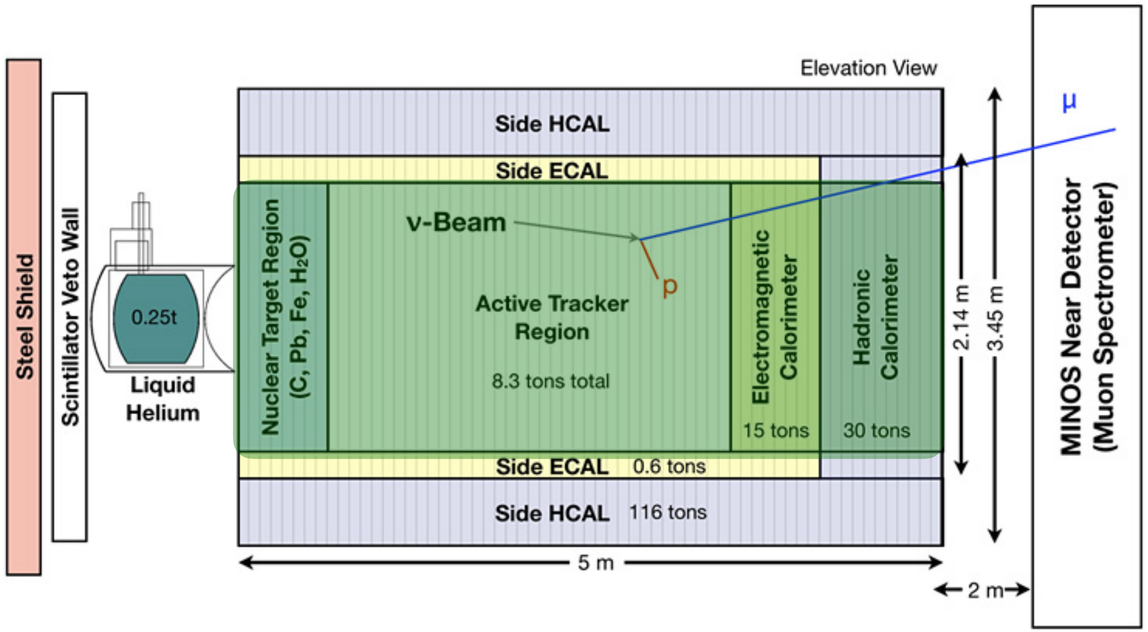
- ν: 4.0×10^{20}
- $\bar{\nu}$: 1.7×10^{20}

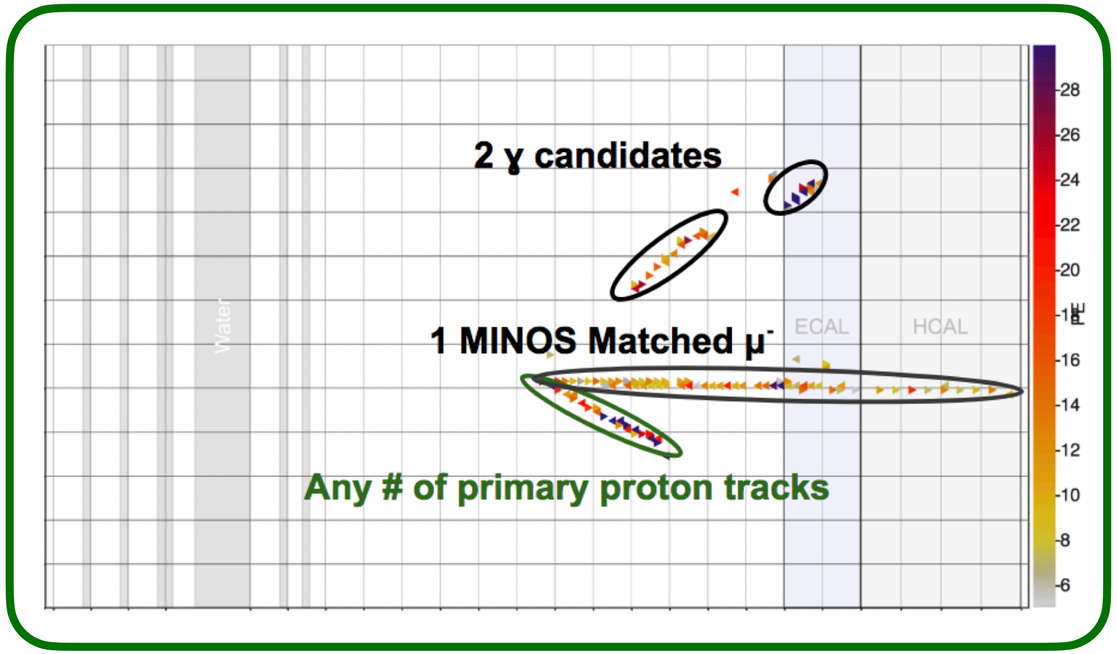
Medium energy POT:

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

MINERvA detector

Composed of segmented hydrocarbon scintillator, fully instrumented.

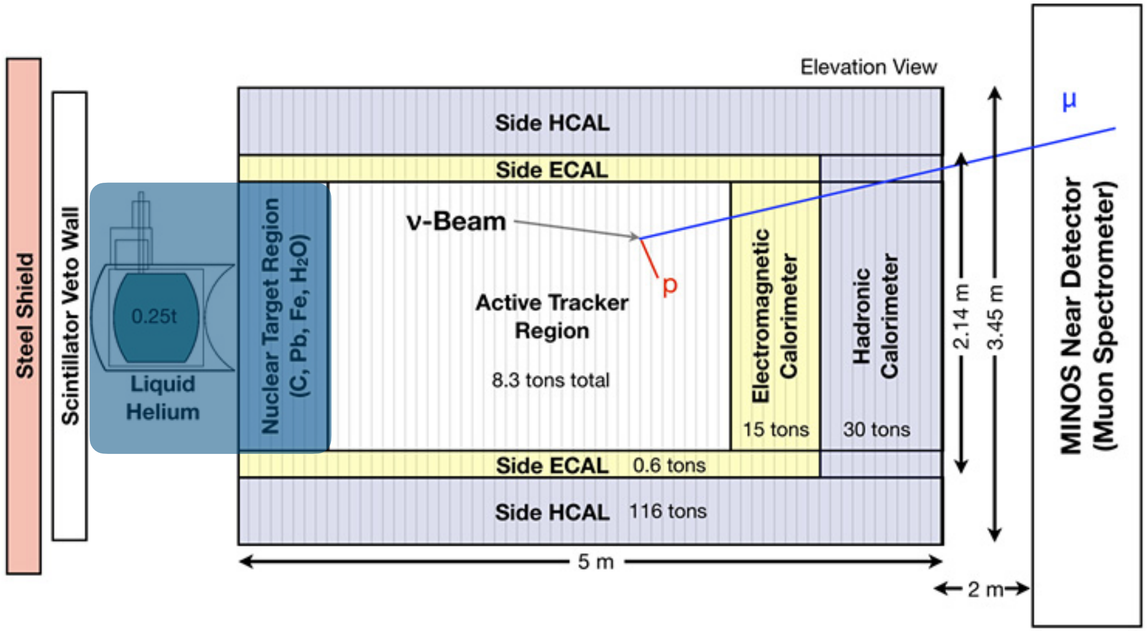


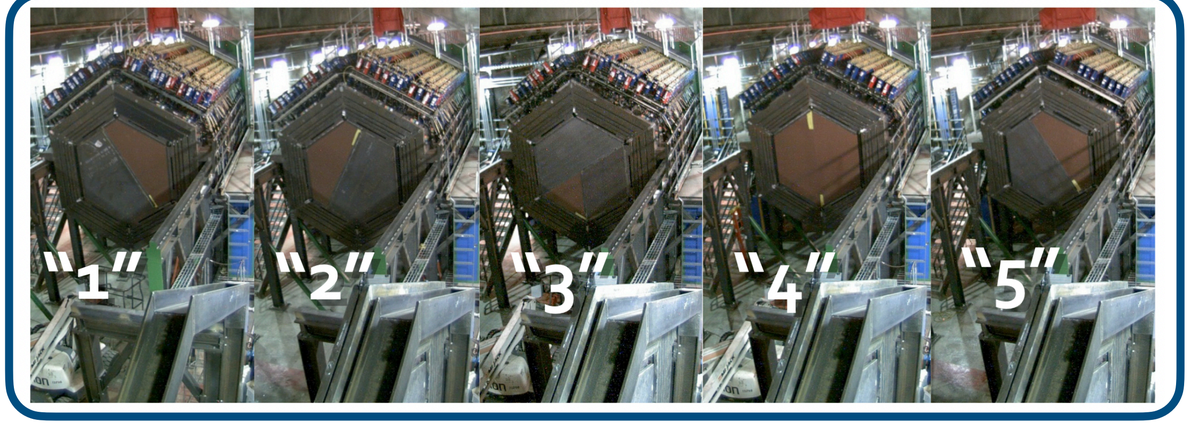


Active material designed to track energy signature of charged particles.

MINERvA detector

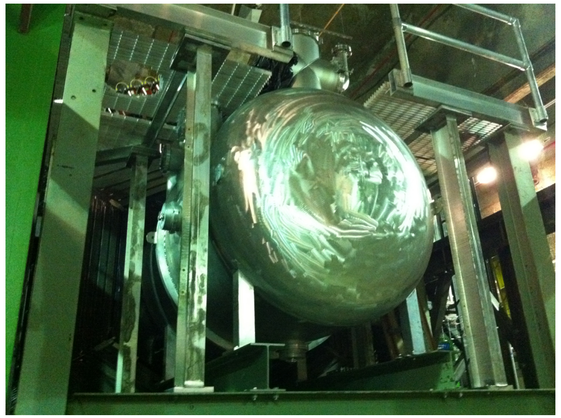
Composed of segmented hydrocarbon scintillator, fully instrumented.





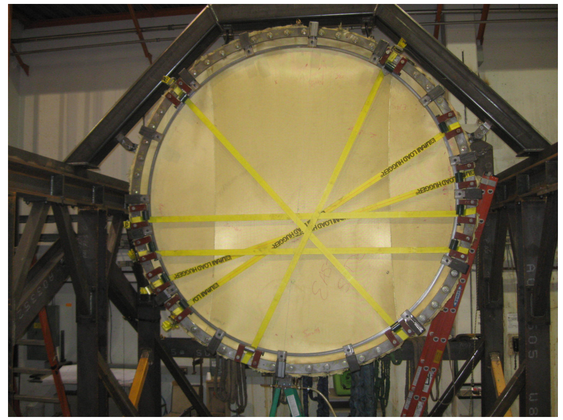
Heavy nuclear targets: Pb, Fe and C

Passive nuclear targets at the front designed for the study of A-dependent cross-section measurements.



Water target

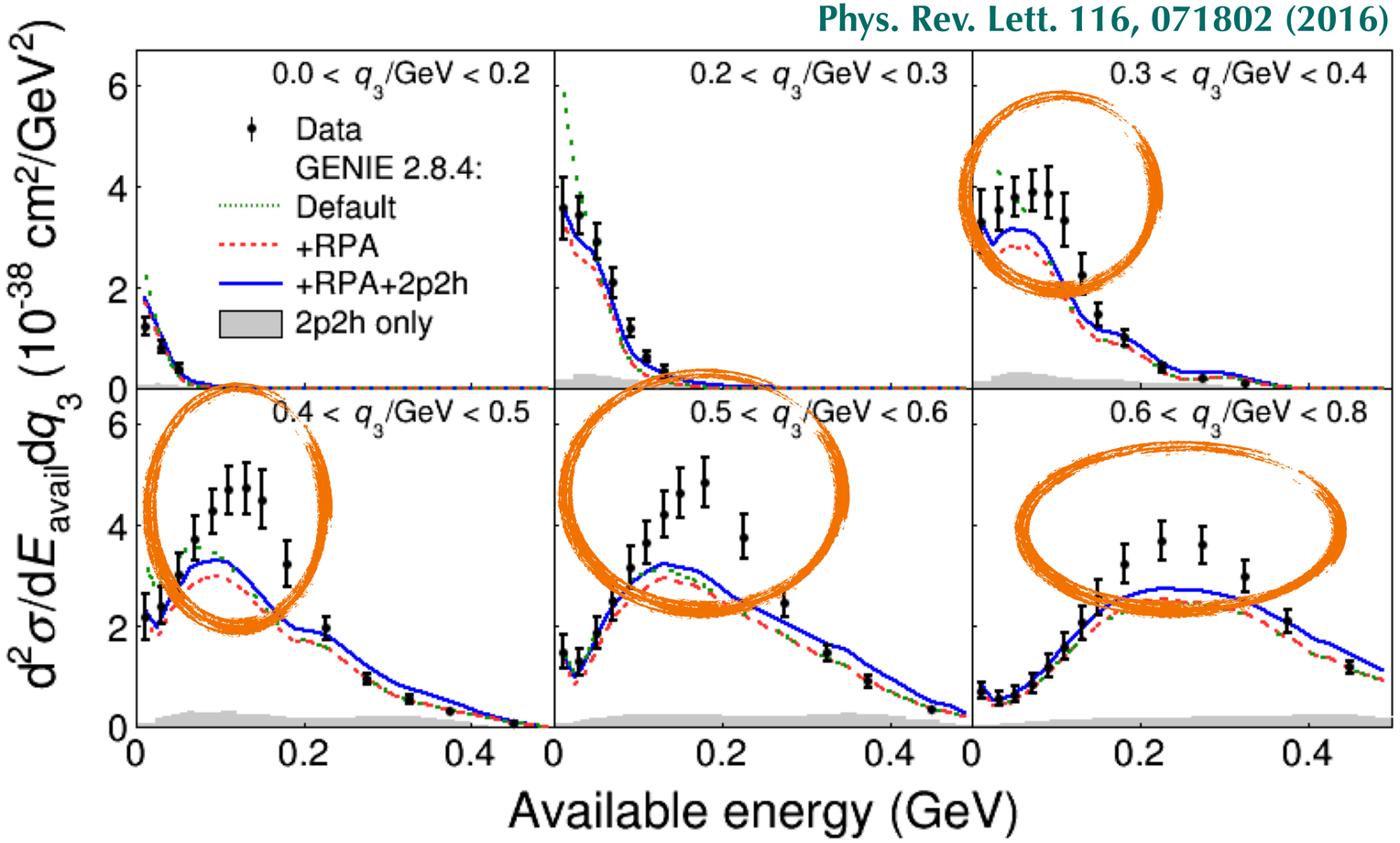
Liquid helium target



MINERvA in the LE era

More than 30 physics publications

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

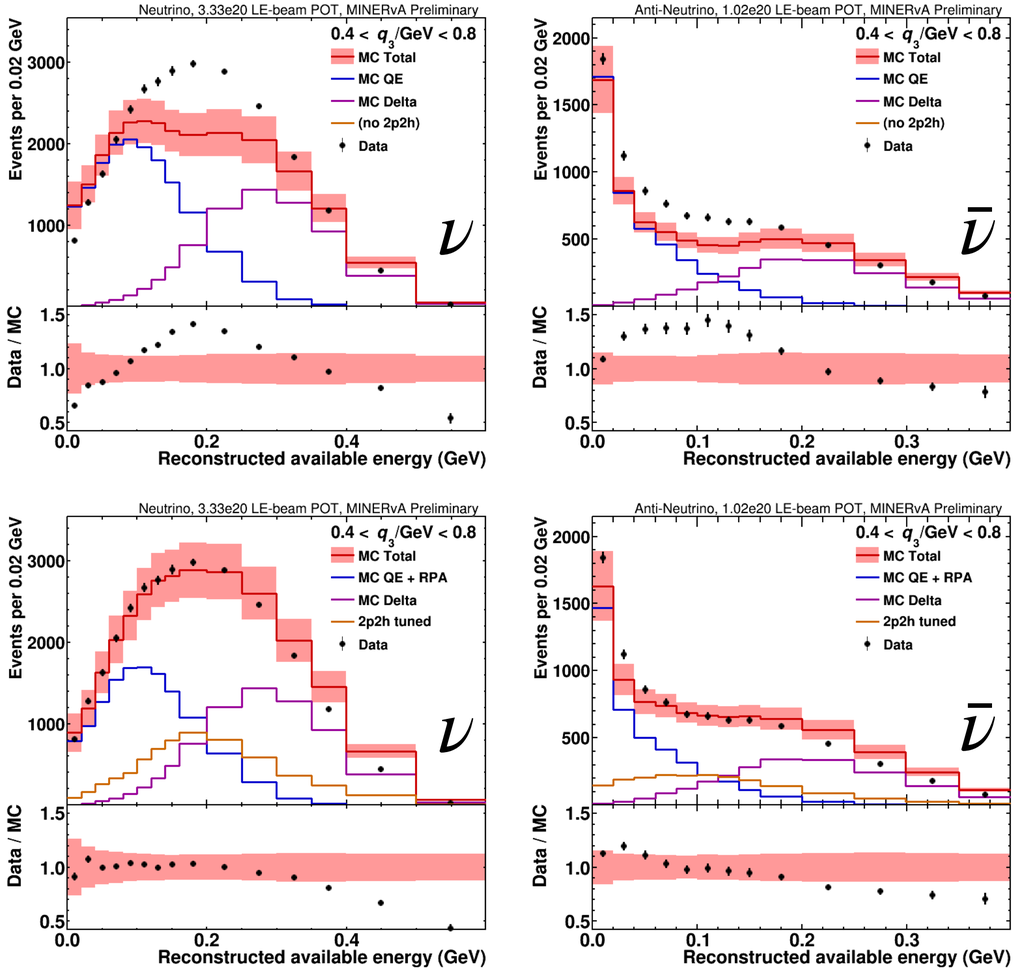


- Our measurements exhibited disagreements between data and Monte Carlo prediction in different analyses.
- Models treated the multi-nucleon environment as a group of non-interacting nucleons
- Different from what the data describes.
- MINERvA showed that models didn't have the complete picture, and the nuclear environment affects what gets produced in neutrino interactions.

MINERvA in the LE era

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.

- Prediction models were subject to tests on our neutrino data, and modified accordingly using additional models.
- 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.

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

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, and improve predictions for generators.

Improve neutrino flux model and constraints to reduce systematic uncertainties.

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

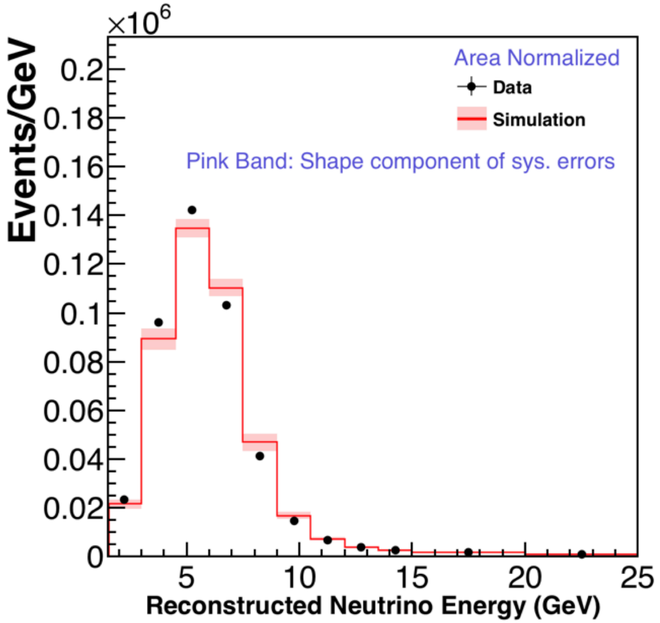
Preserve MINERvA's data for the future and make it available once the collaboration ceases being active.

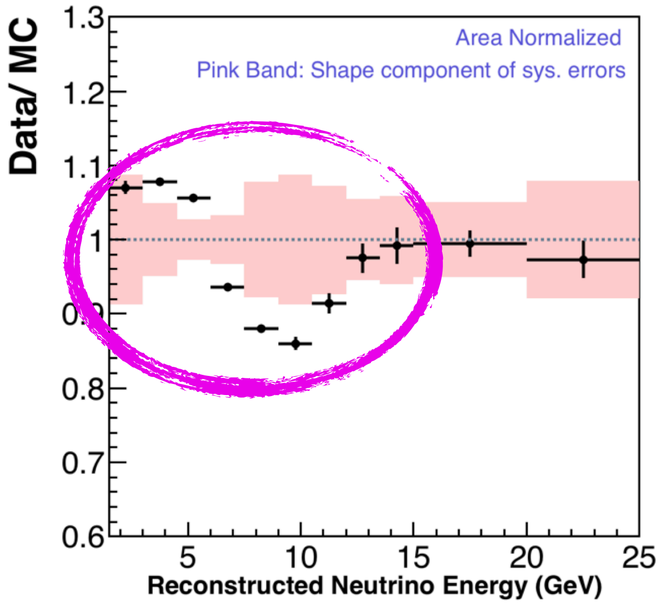
Most recent MINERvA results

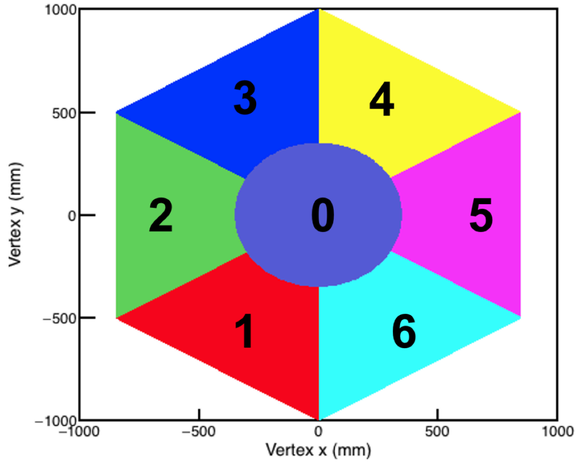
Flux and muon energy scale in low-E_{had} events

arXiv: 2104.05769

- We observed a data-MC discrepancy in area-normalized reconstructed E_ν for events with hadronic energy < 800 MeV.
- Discrepancy could be caused by parameters that are allowed to vary in our simulation.
- Dominant uncertainties in that region: **neutrino beam alignment parameters** and **muon energy scale**.



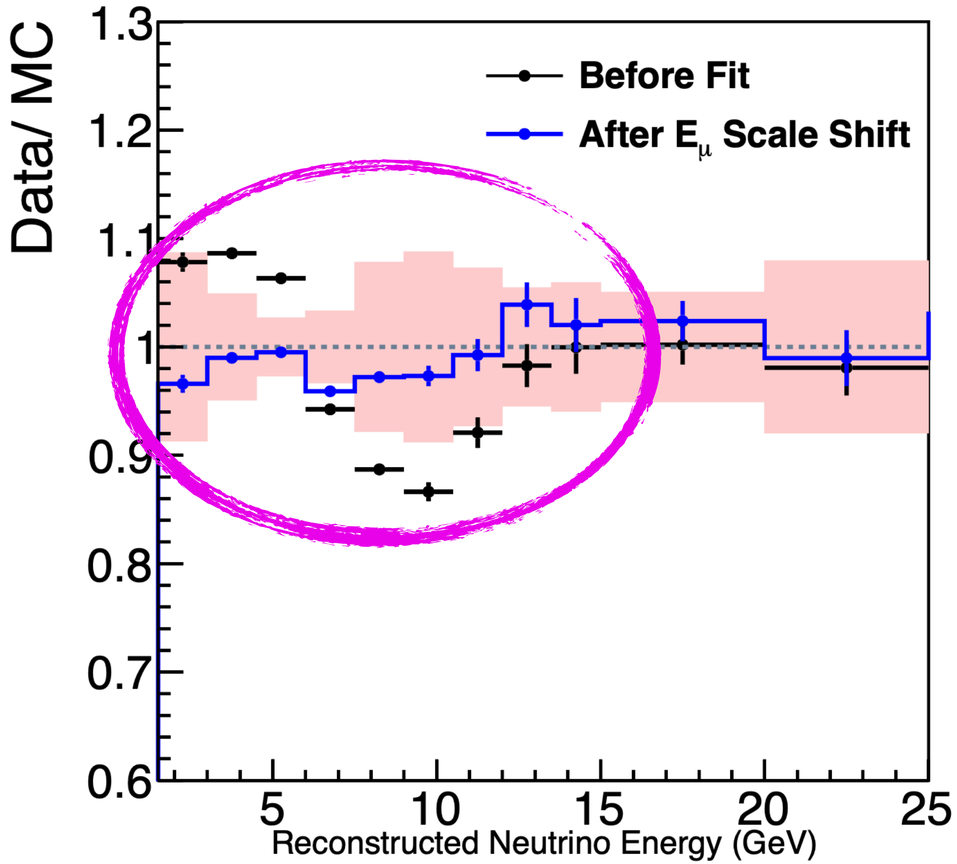




- Proposed a data-MC χ^2 minimization fit on reconstructed E_ν.
- Beam alignment and muon energy scale as parameters to vary in the fit.
- Detector was treated separated by regions: different alignment uncertainties would manifest differently depending on the region.
- χ^2 fit was done simultaneously across all regions.

Flux and muon energy scale in low-E_{had} events

arXiv: 2104.05769



- Fit results showed that discrepancy is consistent with a **muon energy scale shift of 3.6%**.
- Uncertainty in the muon energy scale from the fit is 1%.
- No shifts on the beam alignment parameters were needed.

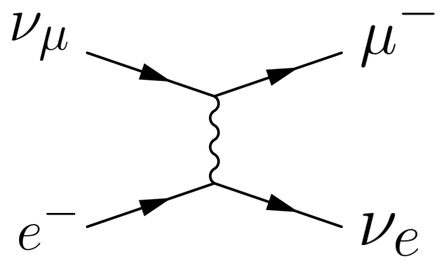
This result helped to improve the estimation of the muon energy scale that we use for our ME results.

Flux constraint with inverse muon decay

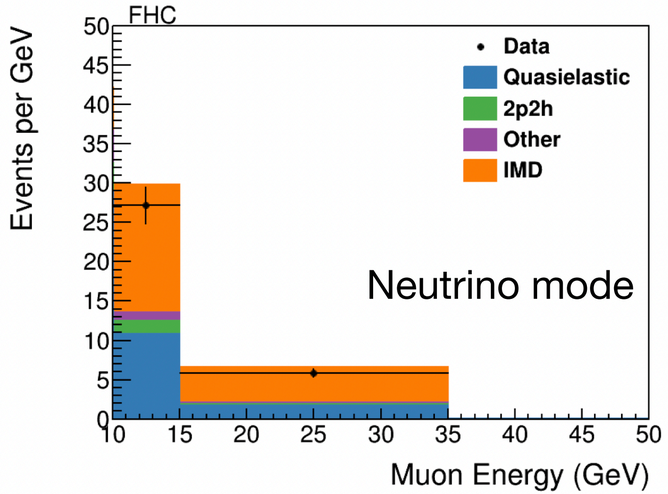
arXiv: 2107.01059

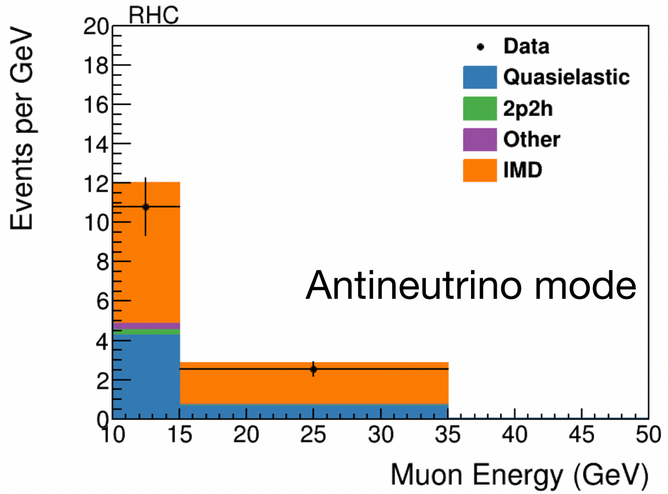
- In the last Users Meeting, we talked about $\nu + e \rightarrow \nu + e$ scattering to constrain the neutrino flux.
- **Inverse muon decay (IMD)**: Alternative ν-e scattering interaction.
- Cross-section ~100 times smaller than quasi-elastic processes.
- Minimum energy threshold determined by:

$$E_{\min} = \frac{m_\mu^2 - m_e^2}{2\, m_e} \approx 11\,\mathrm{GeV}$$



Another **standard candle** to constrain our flux.



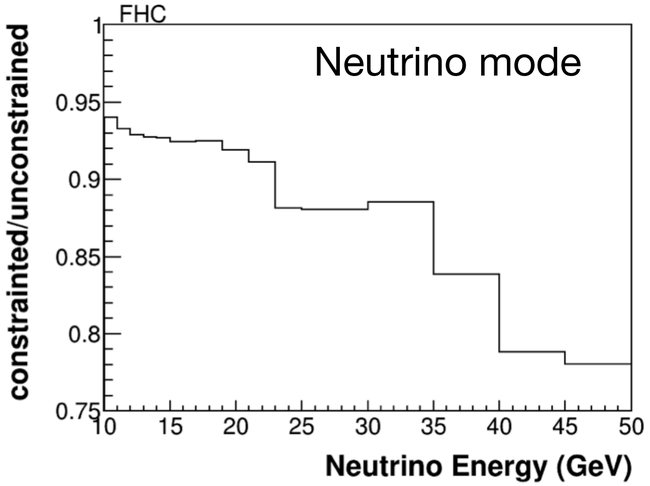


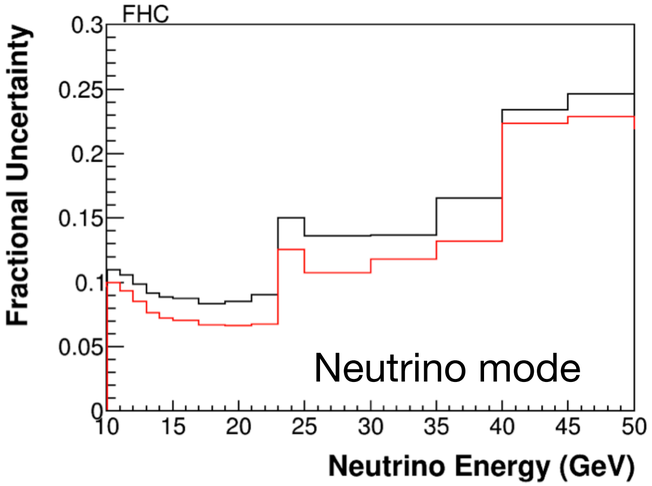
- Sensitive to the high-energy tail of the flux: dominated by neutrinos coming from pions not focused.
- MINERvA's ME high statistics allows to measure a good IMD event rate.

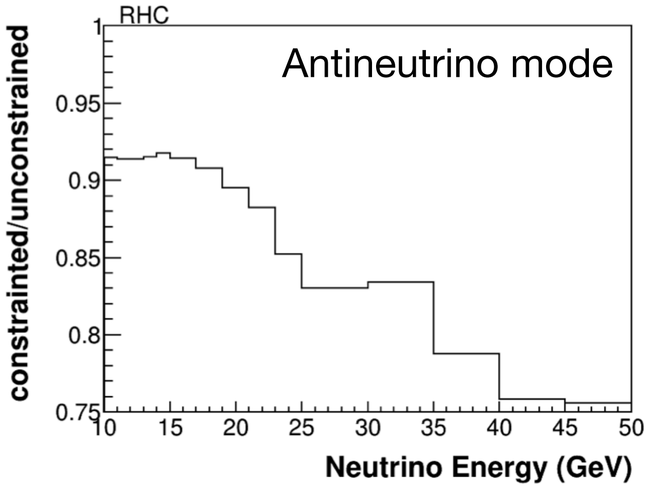
Flux constraint with inverse muon decay

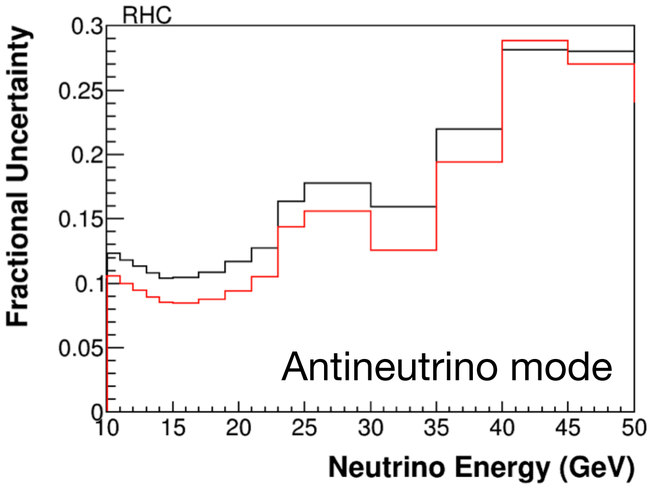
arXiv: 2107.01059

- The analysis was performed in terms of an event rate for both beam polarities, with total uncertainties:
  - ➡ Neutrino mode: **127 ± 16.1**
  - ➡ Antineutrino mode: **56 ± 20.3**
- Uncertainties are statistically-dominated.
- Flux was constrained comparing event rates of different flux models with our data.
- Constraint lowers the flux by 10% and reduces the uncertainty.
- **Unique analysis:** First neutrino flux constraint in the regime of 11 and 50 GeV.







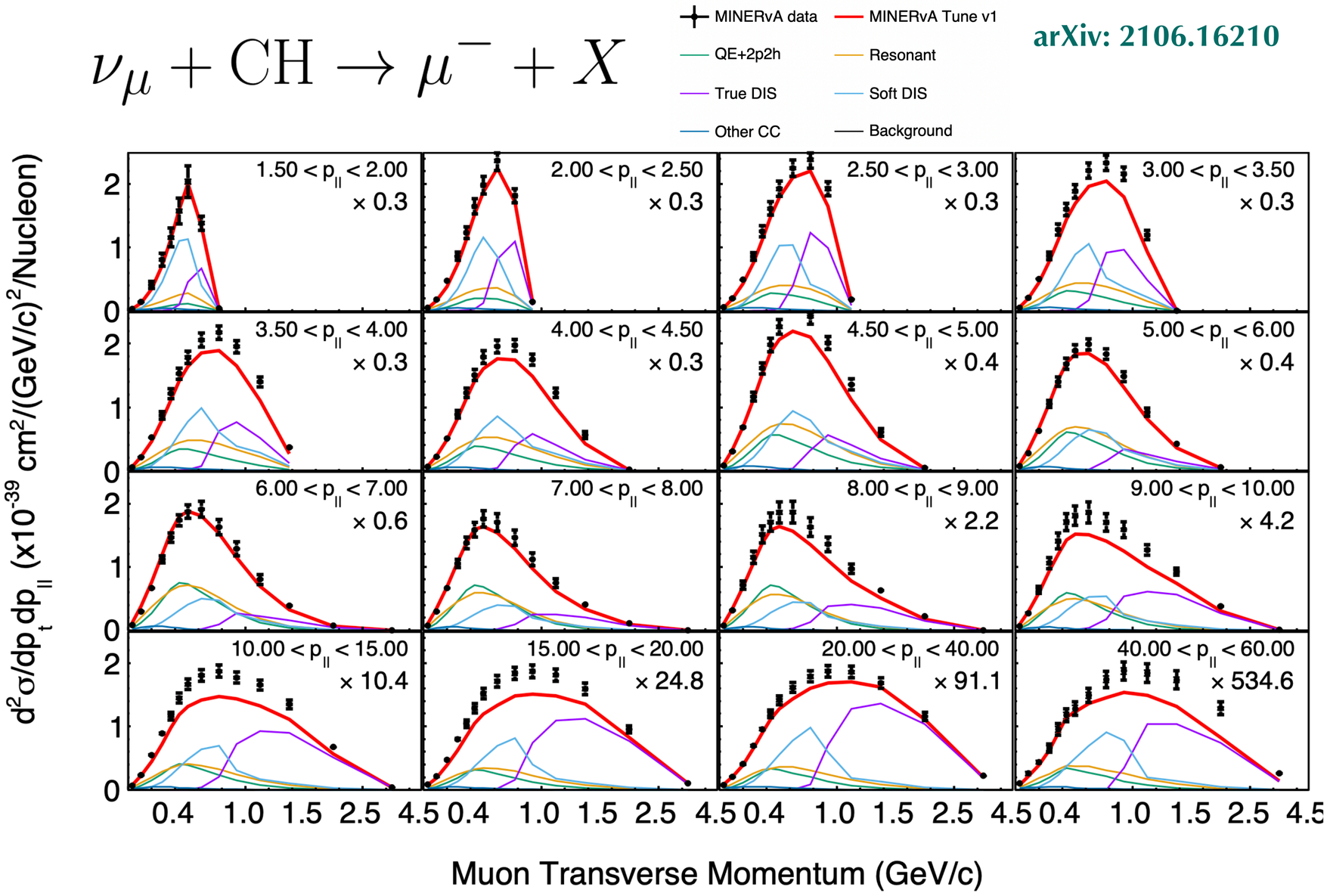


Neutrino inclusive cross-section in CH

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + X$$

arXiv: 2106.16210

- Signal with a muon angle with respect to neutrino beam < 20°.
- "Clean" analysis: 64% of efficiency and background prediction of 0.2%.
- Results reported as function of muon kinematics:
  - ➡ Transverse momentum: p_t
  - ➡ Longitudinal momentum: $p_{||}$
- Simulation w/constrained flux, and cross-section models from MINERvA Tune.
- Dominant systematics: flux with approximately 4%.

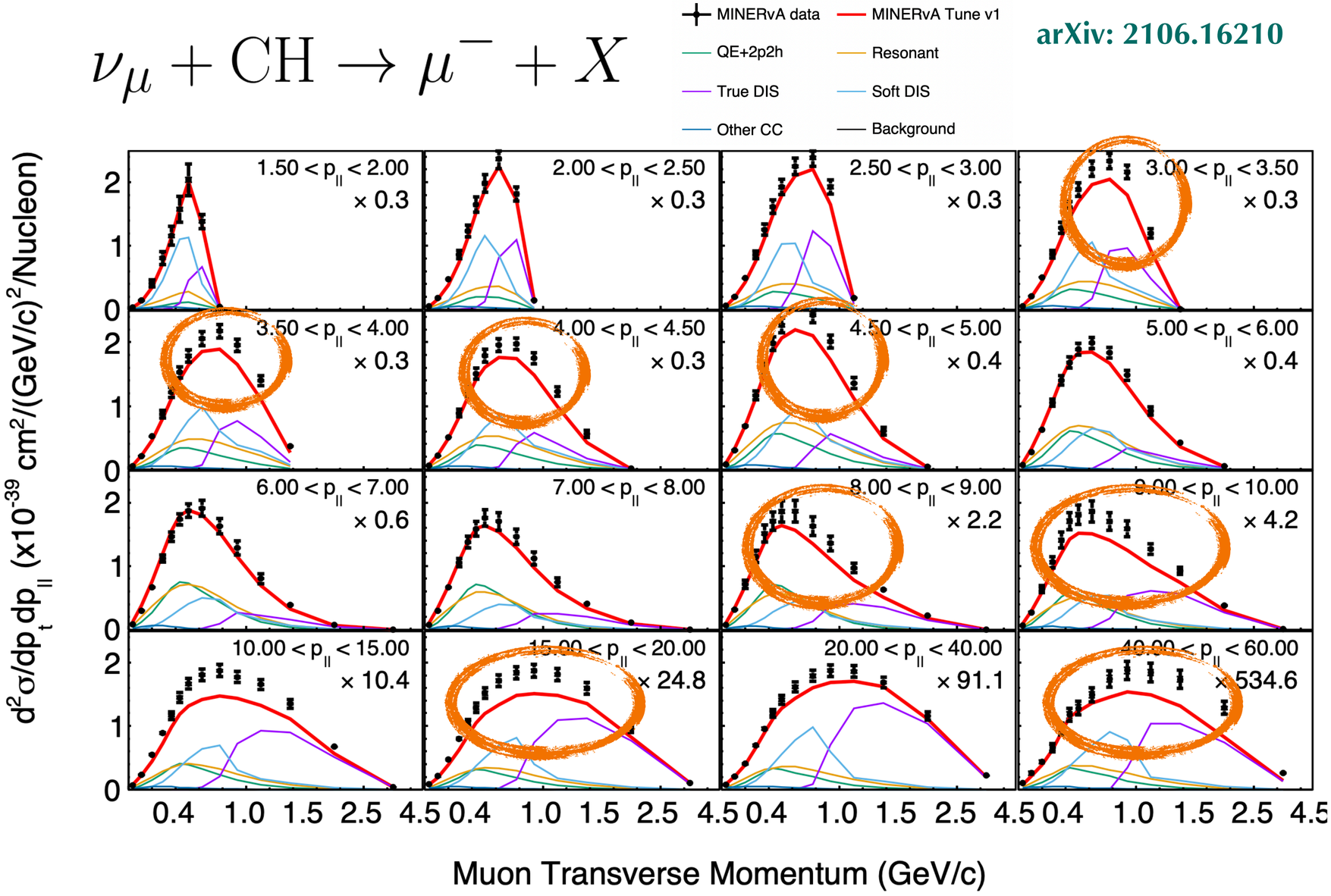


Neutrino inclusive cross-section in CH

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + X$$

arXiv: 2106.16210

- MINERvA Tune developed based on the LE data was tested on this analysis.
- Better agreement seen between data and the tuned prediction.
- But agreement is not perfect yet:
  - ➡ **Underprediction** around the p_t peak for values of $p_{||} > 3$ GeV.
  - ➡ **Overprediction** for low values of p_t.



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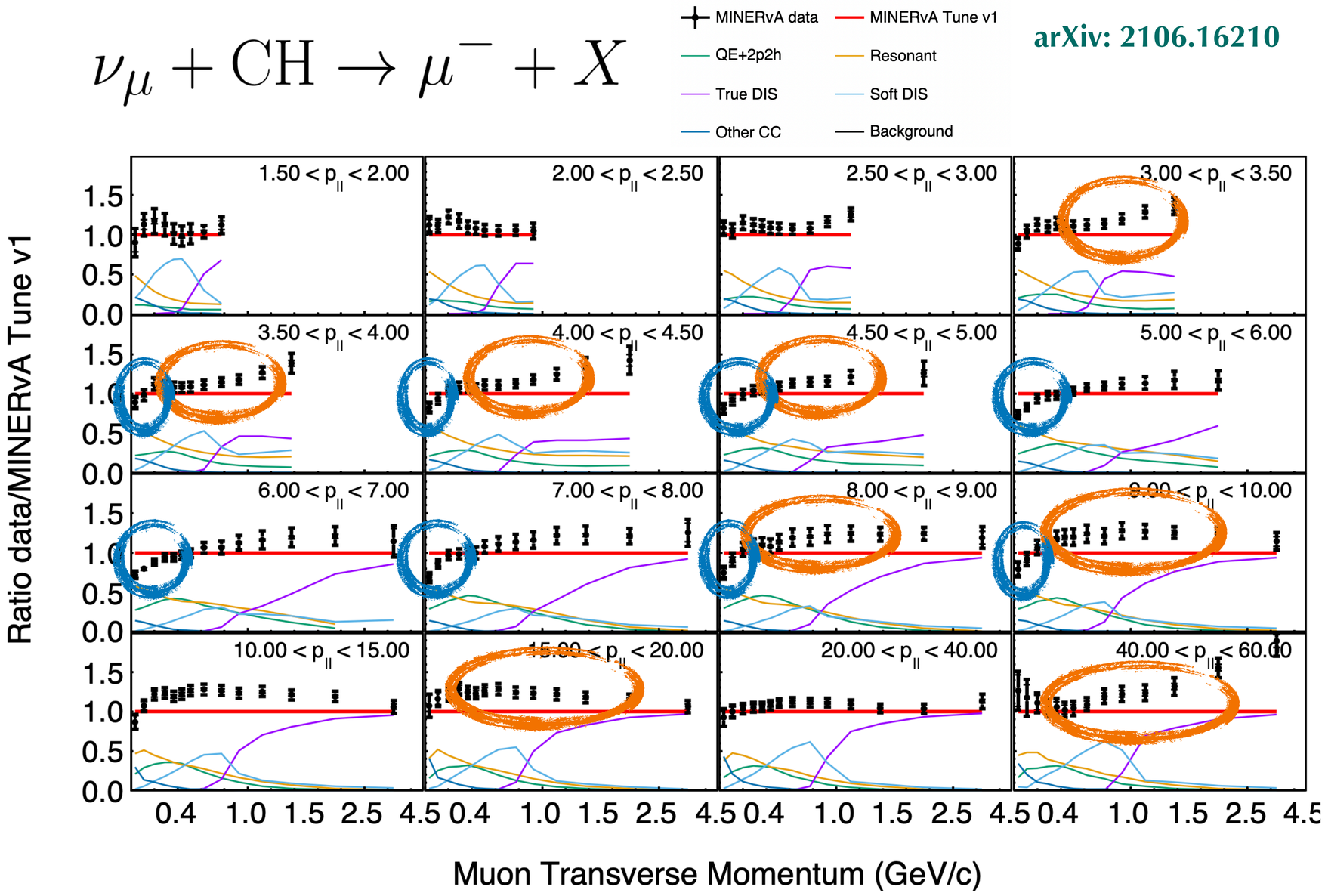
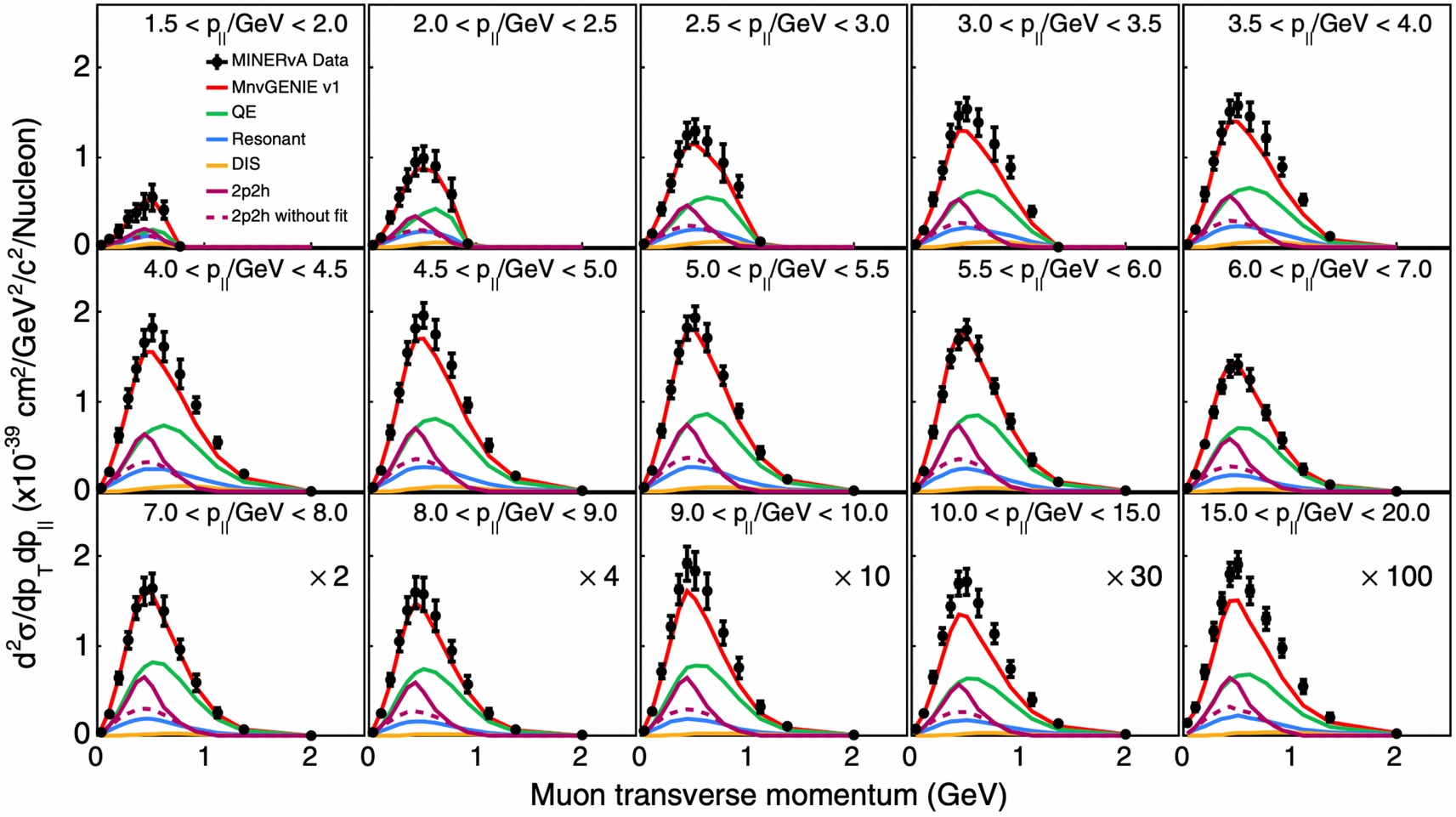


Quasi-elastic-like cross-section in CH

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + N(p,n) + \mathrm{A}' \quad [\text{No pions}]$$

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

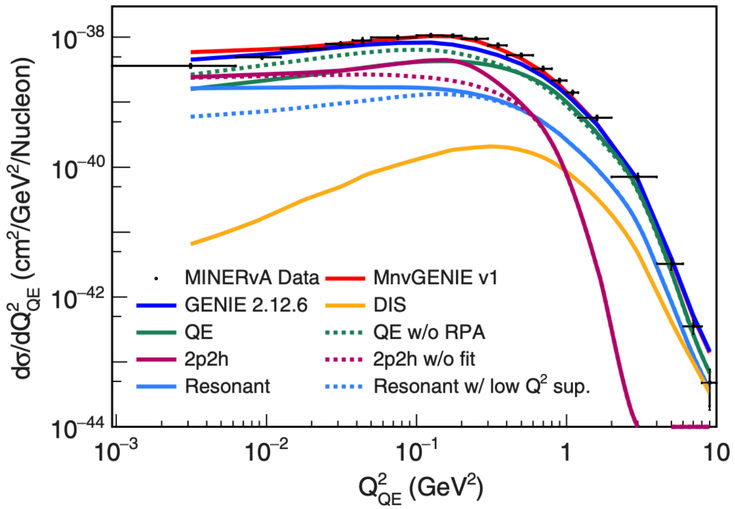
- Quasi-elastic-like:
  - ➡ Final-state: muon and any number of protons and/or neutrons.
  - ➡ No pions at all.
- **One of the most important interaction channels for oscillation experiments.**
- Simulation w/constrained flux, and cross-section models from MINERvA Tune.
- Dominant systematics: muon energy scale.
- We looked at the strength of models other than **quasi-elastic** in our measurements.
- Contribution from other models shows evidence of nuclear effects.
- Need to improve the **quasi-elastic model** as well, given the underpredictions in its dominant region.

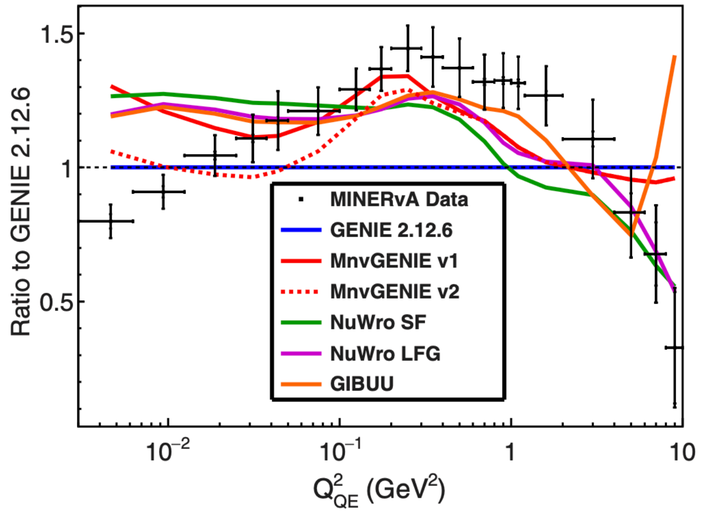


CC quasi-elastic-like cross-section in CH

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + N(p,n) + \mathrm{A}' \quad [\text{No pions}]$$

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





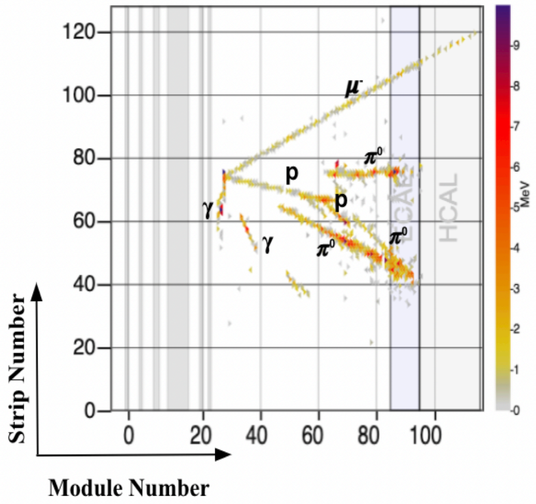
- Additional method to report the same physics result with a different observable.
- Q^2_{QE}: Transferred four-momentum squared under the quasi-elastic hypothesis:

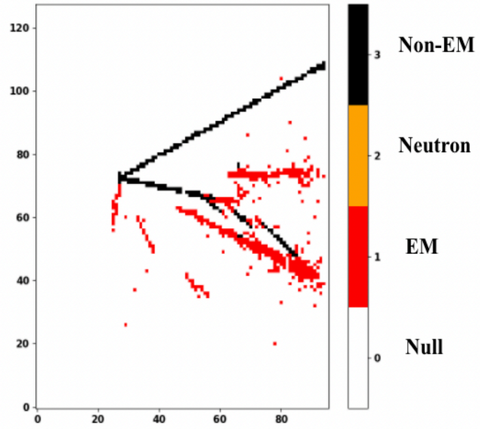
$$Q^2_{\mathrm{QE}} = 2\,E_\nu\left(E_\mu - p_{||}\right) - m^2_\mu$$

- Capability of measure cross-section over 3 orders of magnitude.
- **MINERvA Tune** greatly improves the agreement with the data compared to **out-of-the-box GENIE**.
- However, no models seem to describe accurately regions of very low- and high-Q^2 yet.

Machine Learning for π^0 reconstruction

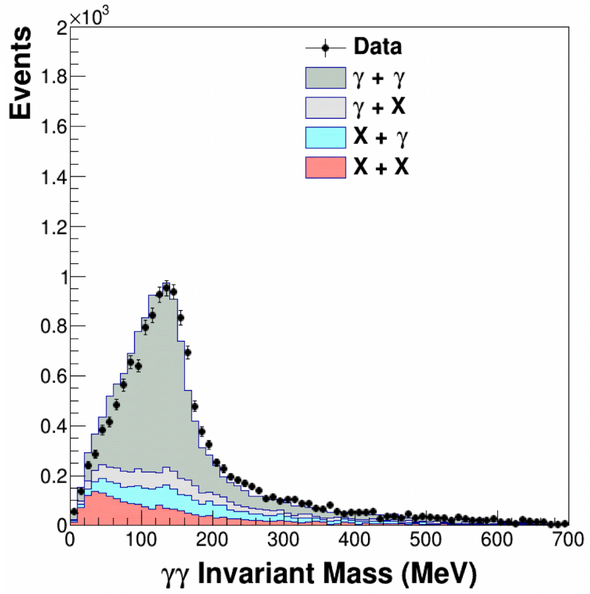
JINST 16 P07060 (2021)



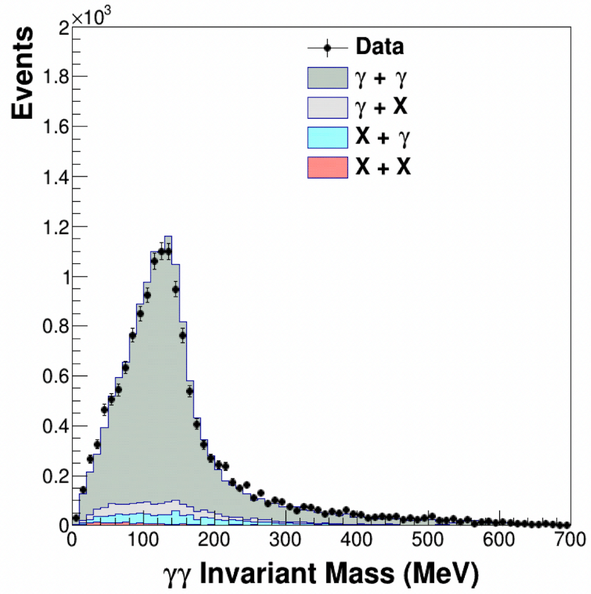


- Machine Learning technique to improve $\pi^0 \rightarrow \gamma\gamma$ reconstruction in fully instrumented regions of our detector: **Image Segmentation**.
- Algorithm is fed with a training MC sample, and then tested with a different MC sample as well as data.

- This technique helps to isolate EM showers as an extension of our reconstruction method.
- From tests with π^0 invariant mass peak (60 to 200 MeV): reconstructed efficiency increased from 70.7% to 89.3%.



(a) Baseline reconstruction



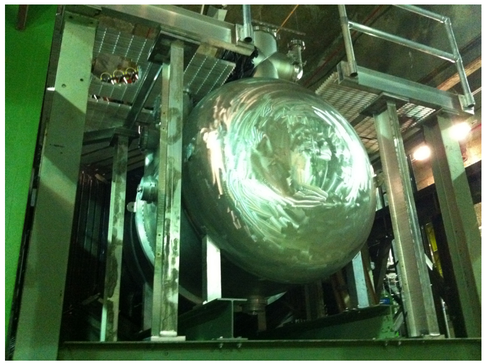
(b) Machine learning reconstruction

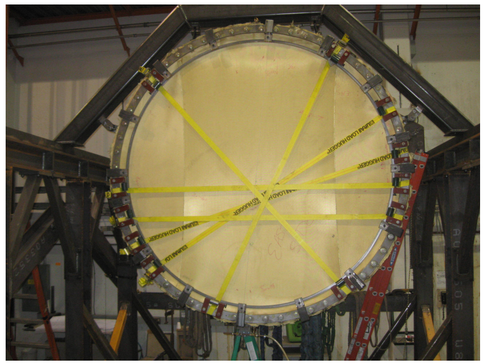
MINERvA future plans

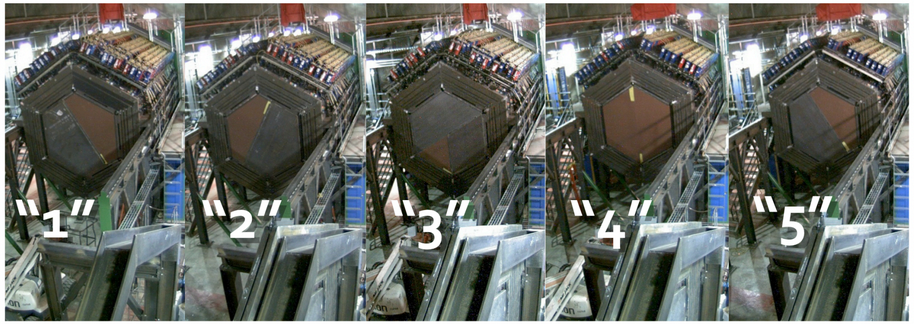
Physics analyses in-the-making

MINERvA never sleeps! *(Sometimes literally…)*

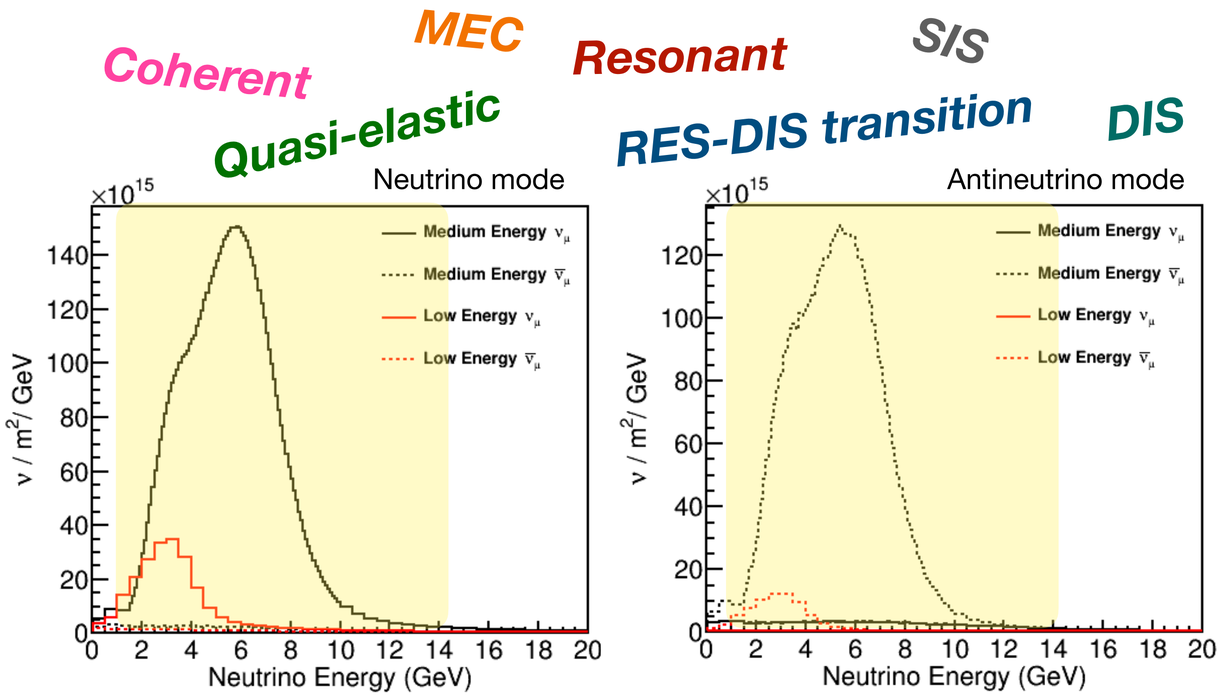
We are actively working on promising physics analyses in order to expand our understanding of the nuclear environment as well as exploring more energy regions.







We have more targets to use!



We have more channels to analyze!

MINERvA Data Preservation project

arXiv: 2103.08677

MINERvA has a huge amount of unique data, but we are a small group. All of the physics that lies in our data can't be extracted only by us.

Because of that, we started a dedicated effort in order to preserve our collaboration's data so it remains usable for the extension of the DUNE era.

The Data Preservation project is based on:

- **Master AnaTuple:** A unified ROOT file that contains low- and high-level reconstruction objects used to reproduce MINERvA's results.
- **MINERvA Analysis Toolkit (MAT):** A framework with functionalities that allow straightforward cross-section extractions centralized across an experiment.

Our goal: Allow the neutrino community not only to reproduce MINERvA's results, but also provide the basis for new analyses.

Current status: MAT is in constant development within MINERvA, and preliminary versions are being tested by SBN collaborators.

Summary

In the past months, MINERvA has made much progress:

- Cross-section reports using the ME data using and an enhanced statistics compared to the previous results.
- Different interaction model comparisons with generators.
- Comprehensive constraint of the neutrino flux using standard candles.
- Novel techniques to improve particle reconstruction and energy scale.

But the fun doesn't end there… There are many interesting analyses in mature stage that will be unveiled within the next months.

And we are dedicated to keep MINERvA data alive and usable by the entire community in the future.

Stay tuned for new exciting results soon.

Thank you for your attention!