Nuclear Dependence in Antineutrino Scattering at MINERvA, from A to Z

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Imperial HEP Seminar
February 20th, 2026

Nuclear Dependence in Antineutrino Scattering at MINERvA, from A to Z

(Well, from C to Pb really…)

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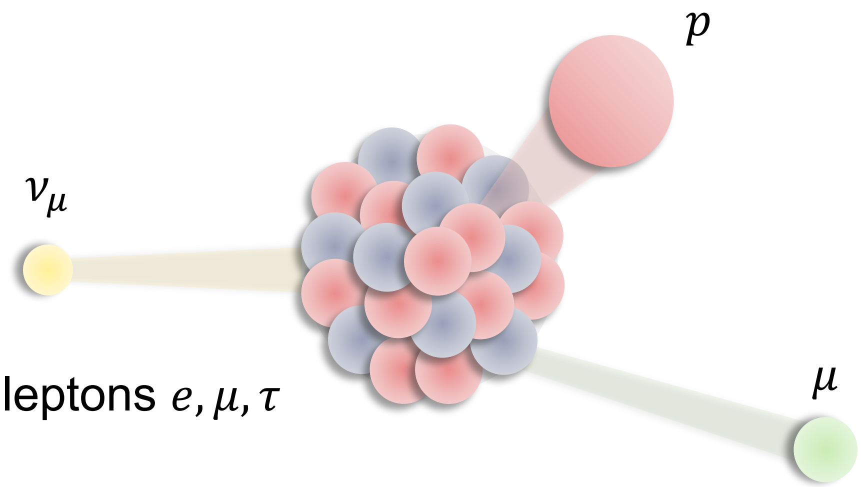
The Big Picture for Today

- Neutrinos 101 and detection/interaction challenges
- What is MINERvA and how it helps
- The measurement and what it tells us – my two cents

Neutrinos 101



- Neutrinos are neutral leptons which interact via weak interaction
- Can be detected only through particles they produce
- In charged-current interactions neutrinos ν_e, ν_μ, ν_τ produce their partner leptons e, μ, τ

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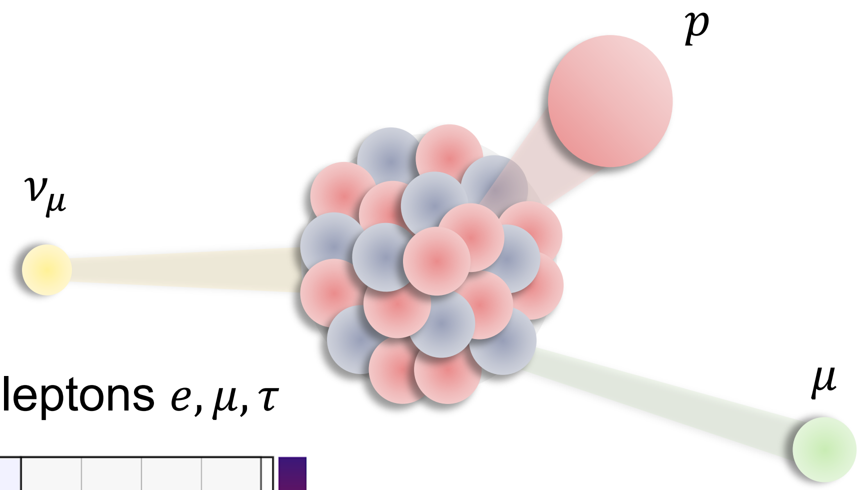
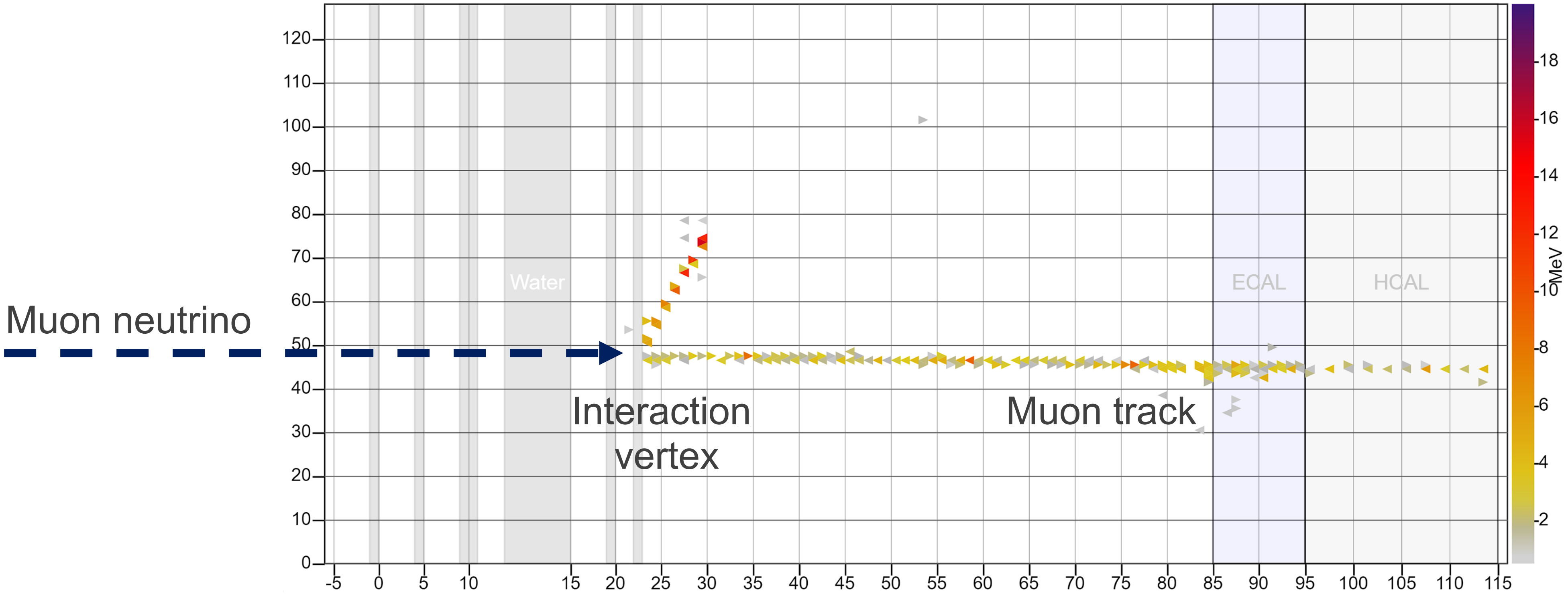
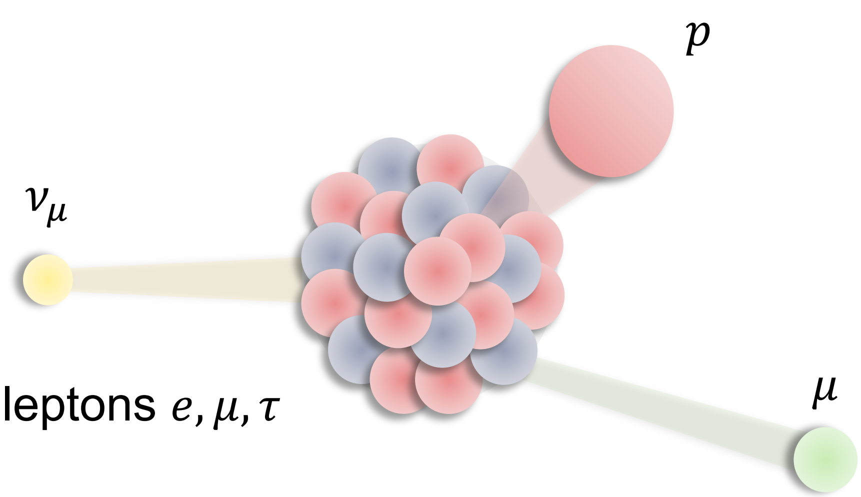




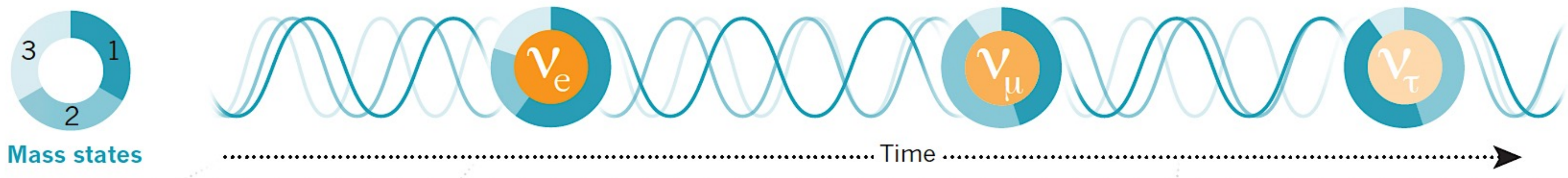
MINERvA event display

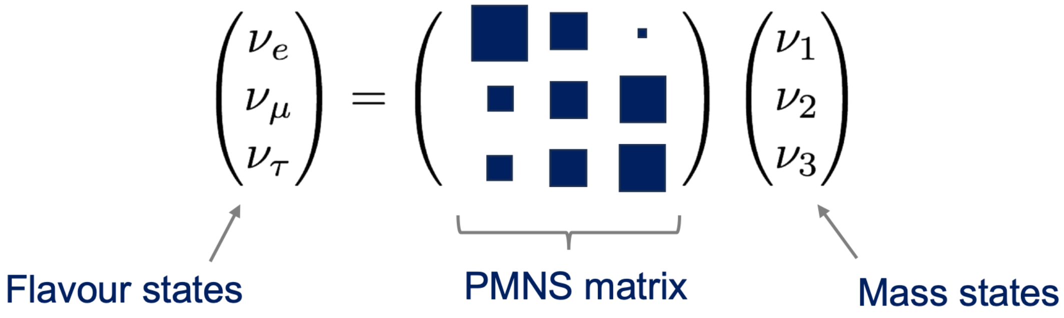
Neutrinos 101

- Neutrinos are neutral leptons which interact via weak interaction
- Can be detected only through particles they produce
- In charged-current interactions neutrinos ν_e, ν_μ, ν_τ produce their partner leptons e, μ, τ
- Massless until… neutrinos oscillate! Tool for discovery!



Graphic by Nigel Hawtin
2015 Springer Nature Open Access





Do neutrinos and **antineutrinos** oscillate differently? Is there CP violation in the neutrino sector?

Is it consistent with leptogenesis as an origin for the matter-antimatter asymmetry in the universe?

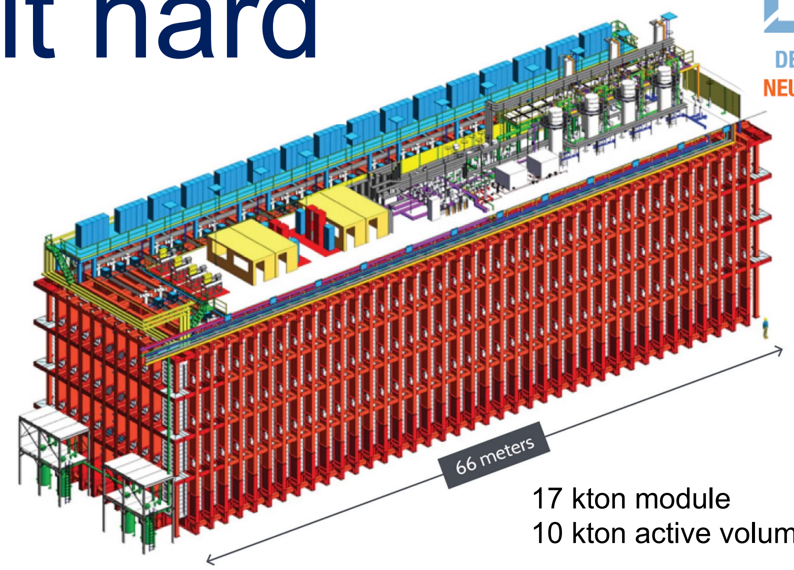
Here comes the challenge

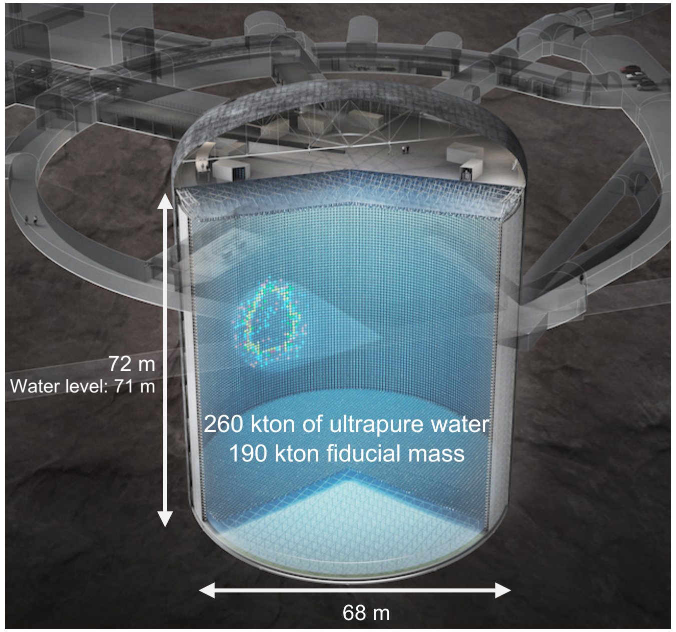
interaction

Detecting neutrinos: Why is it hard

- Neutrino interaction probability is small, $\sigma \sim 10^{-38}$ cm^2 (per nucleon)
  - GeV-scale neutrinos have ~ 1 in 10 billion chance to interact per meter of water equivalent
  - Typical strong cross-section $\sigma \sim 10^{-24}$ cm^2
- Not your usual detectors – must be huge and dense (and cheap)
  - Heavy nuclei to increase interaction probability
  - Need to consider the effect of the nuclear environment

DEEP UNDERGROUND NEUTRINO EXPERIMENT





Hyper-K

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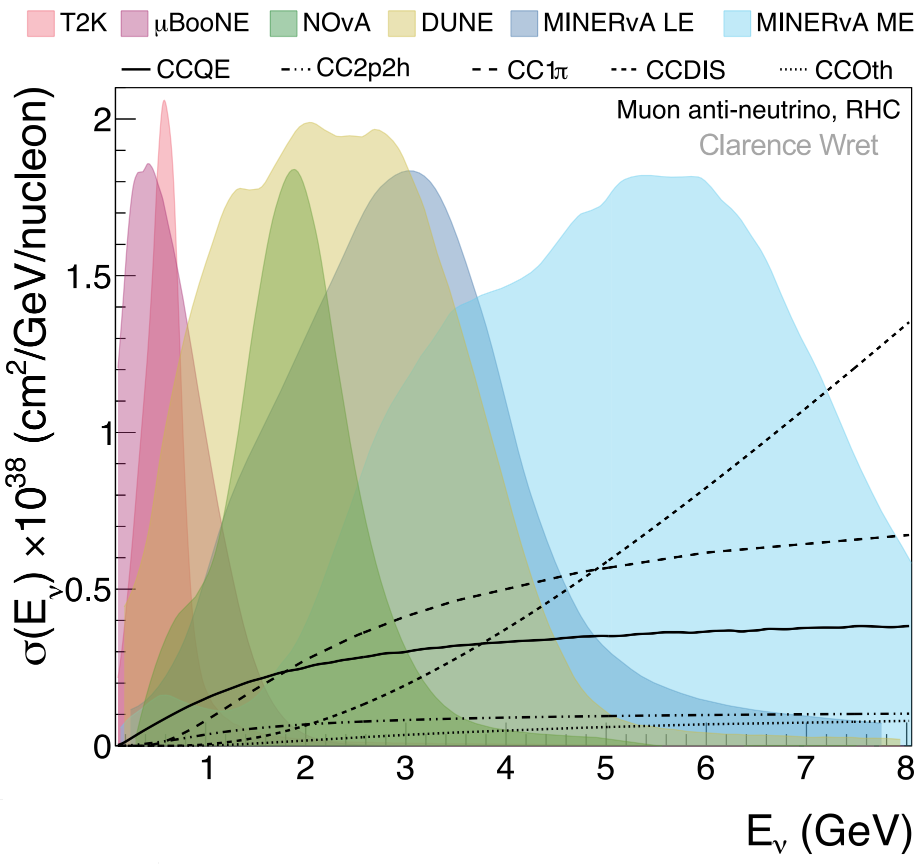
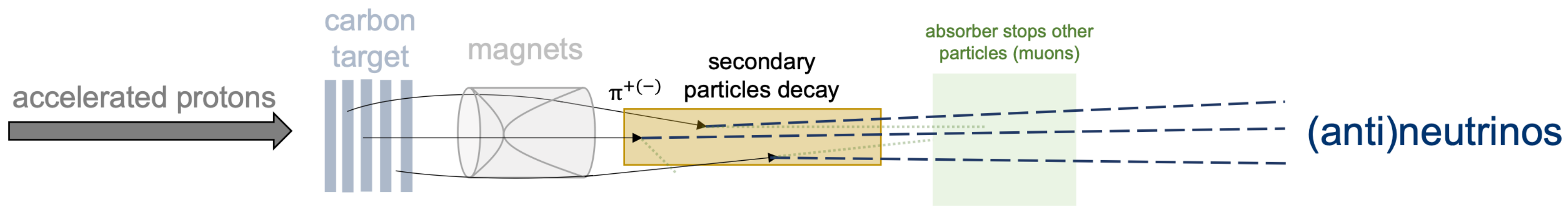
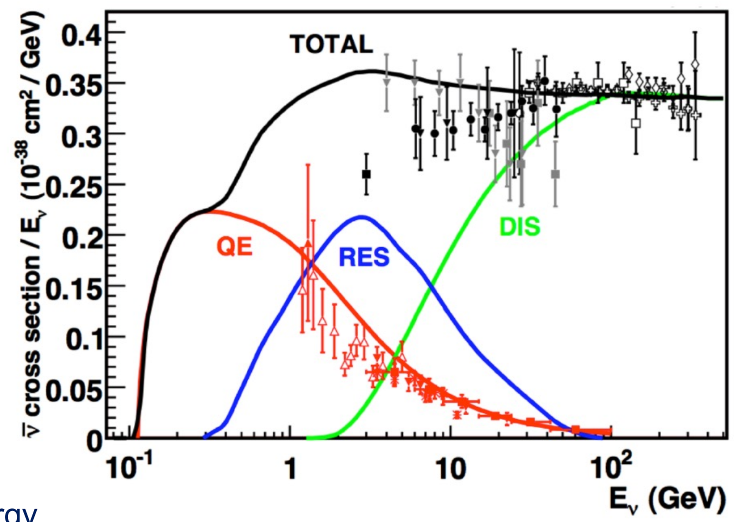
- Not your usual detectors – must be huge and dense (and cheap)
    - Heavy nuclei to increase interaction probability
    - Need to consider the effect of the nuclear environment
- Neutrino beams have broad spectrum, i.e., neutrino energy is not known
    - Requires detailed understanding of variety of neutrino interaction mechanisms and how they obscure energy reconstruction





Neutrino interactions

J. A. Formaggio and G. P. Zeller. Rev. Mod. Phys. 84, 1307 (2012).

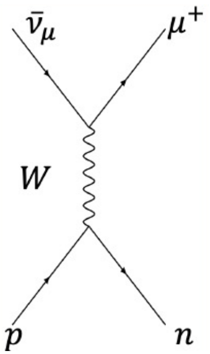


- Different processes contribute to the cross-section at different neutrino energies
- Not a simple transition, many overlapping interaction mechanisms

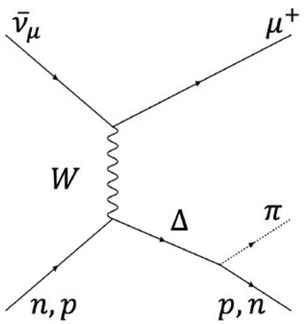
(anti)neutrino energy

complicated transition,
non-perturbative QCD!

quasi-elastic
scattering (QE)



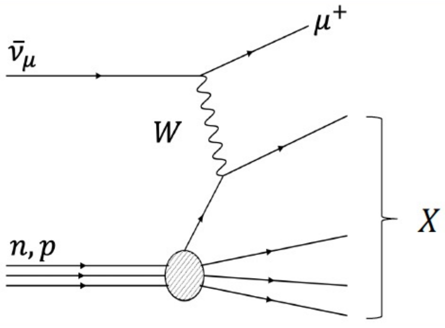
resonant pion
production (RES)



+ other pion producing processes
(coherent, non-resonant)

shallow inelastic
scattering*

deep inelastic scattering (DIS)



- What happens in between? Also, this still just on a free nucleon!

*First study by MINERvA:
A. Lozano, G. Silva, G. Caceres (MINERvA). arXiv:2503.20043 (2025)

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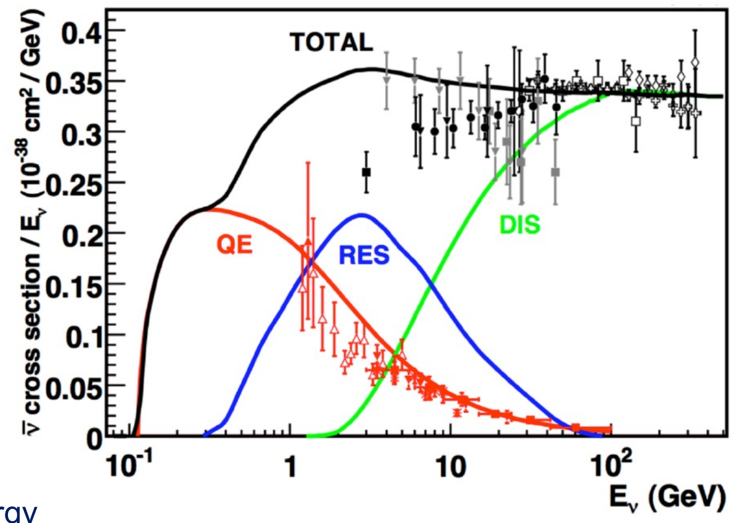

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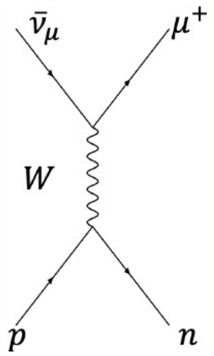

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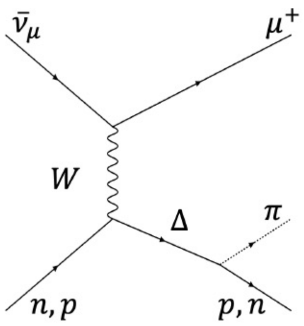

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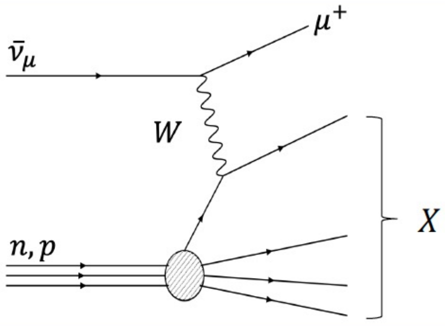

In an inclusive measurement, *all* reactions matter!

- What happens in between? Also, this still just on a free nucleon!

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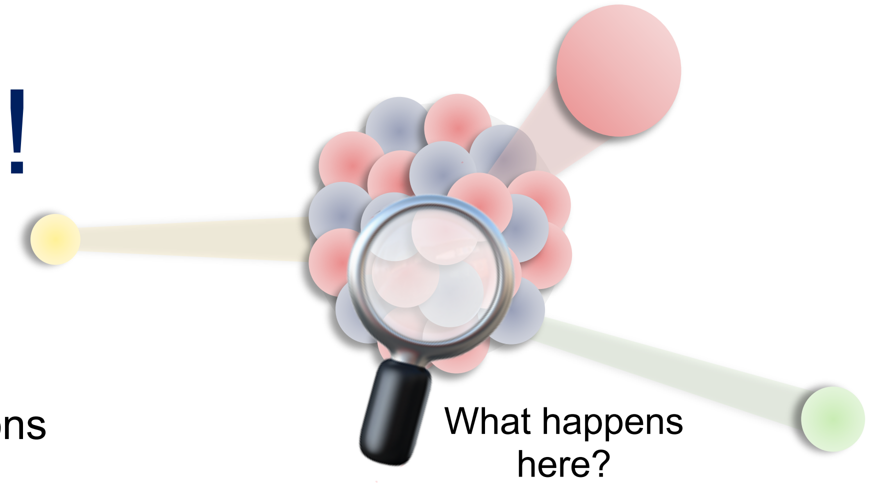
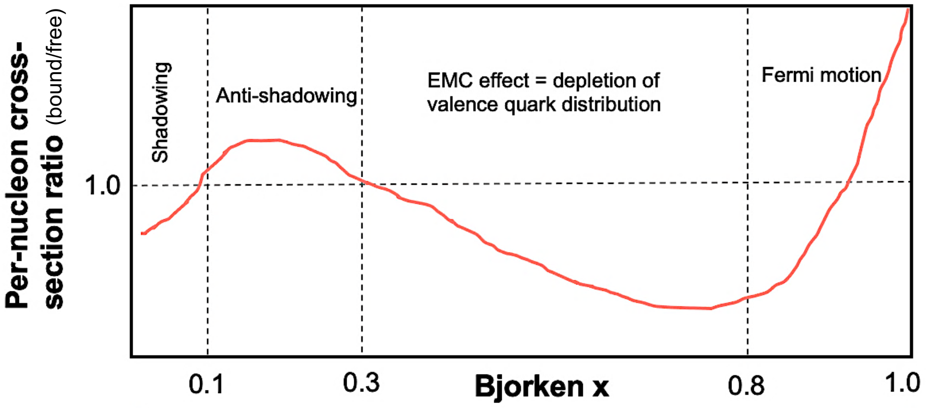
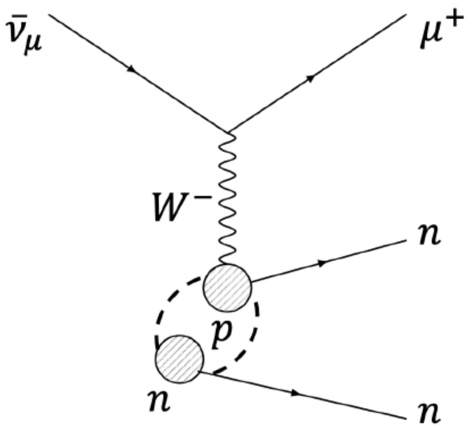
Neutrino interactions on nuclei!



- Nuclei are strongly interacting many-body quantum systems
- Need to consider the initial state state of the nucleus, nucleon-nucleon correlations
- Also need to understand what happens to the particles produced inside of the nucleus before they escape it and can be detected (final state interactions)
- All of this can lead to mis-reconstruction of (anti)neutrino energy

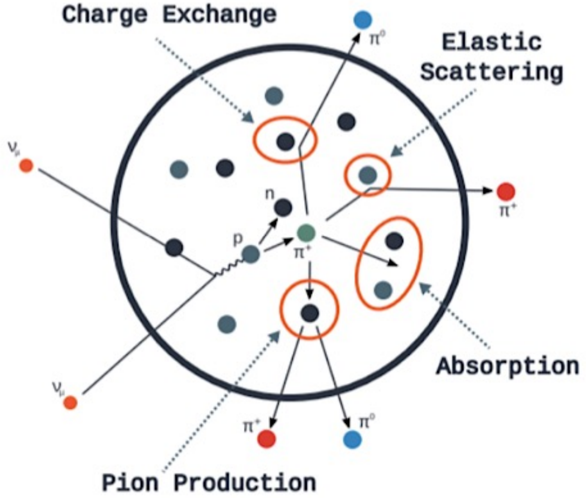


nuclear modifications to structure functions compared to a free nucleon (mainly a DIS effect)



multi-nucleon effects, i.e. 2-particle 2-hole interaction (2p2h)

T. Golan, NuSTEC (2015).

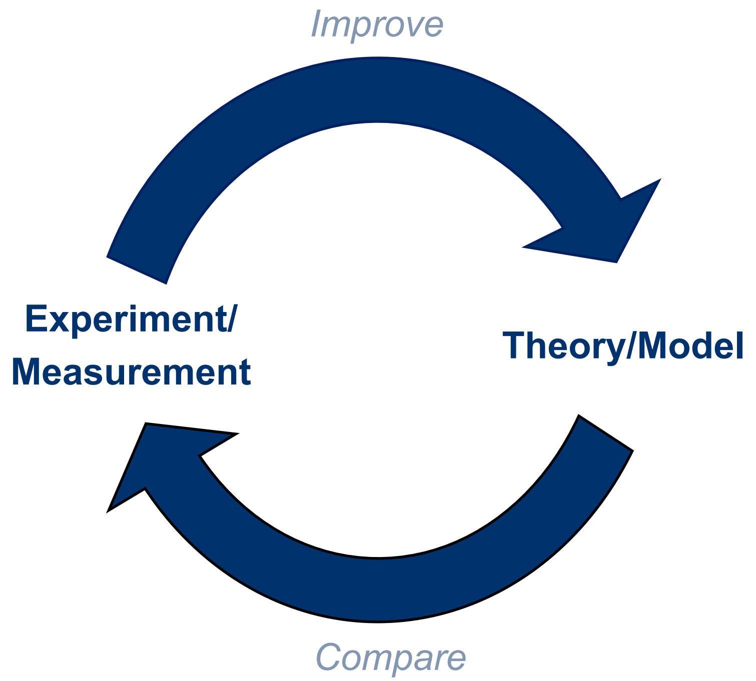


final state interactions (FSI)
(inclusive measurement mostly insensitive to FSI)

It’s complicated.

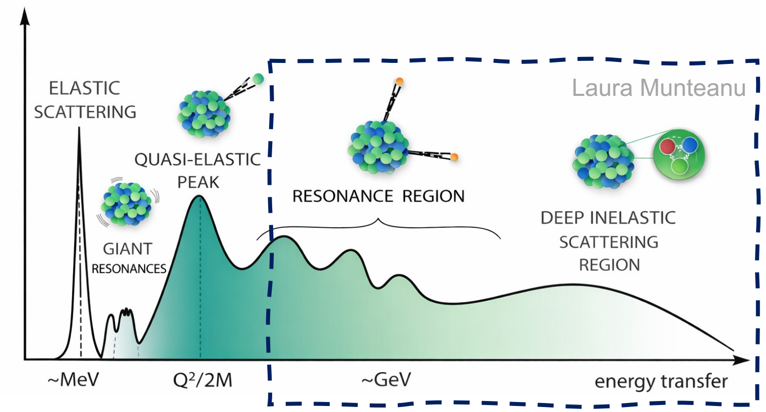
Nuclear model × Primary interaction × × Hadronisation × Final state interactions

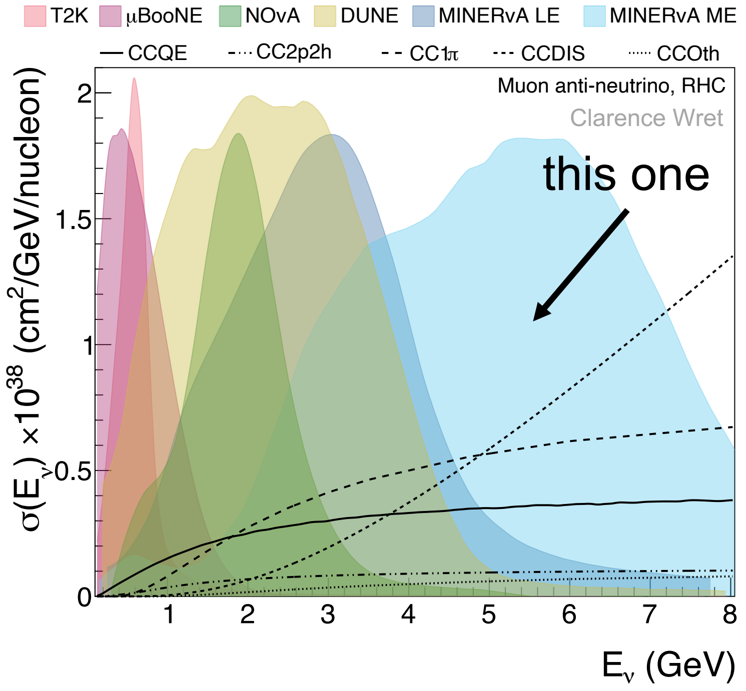
- Both theory and experiment are critical
- Theories/models typically use a factorisation approach, rely on necessary approximations, and may have limited phase space coverage or difficulties in describing the full final state
- Experiments are good at revealing model deficiencies but often struggle to pinpoint the source
    - Both inclusive and exclusive measurements are needed, ideally as a function of *A*
- Understanding neutrino-nucleus modelling is the leading systematic uncertainty in current oscillation measurements
    - Will limit future precision



Motivation for inclusive “higher-energy” antineutrinos vs A

- **“Higher-energy” regime:** excited nuclear resonances, bound states, neither fully perturbative nor fully non-perturbative
    - Both models and measurements limited, most experiments have low statistics in this regime, except MINERvA
    - Extremely relevant for DUNE (wide spectra with flux peak at 2.5 GeV)





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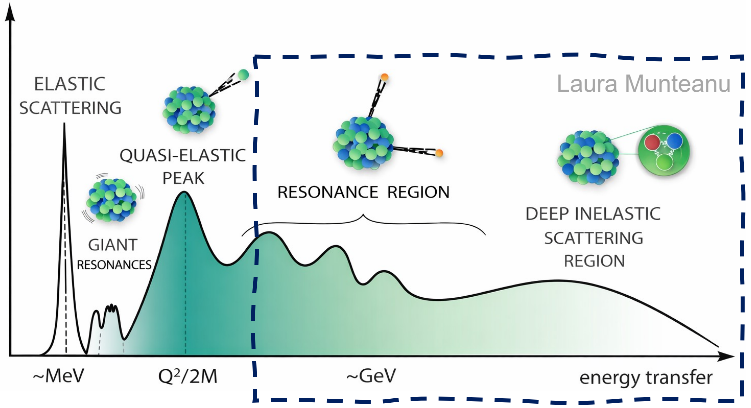
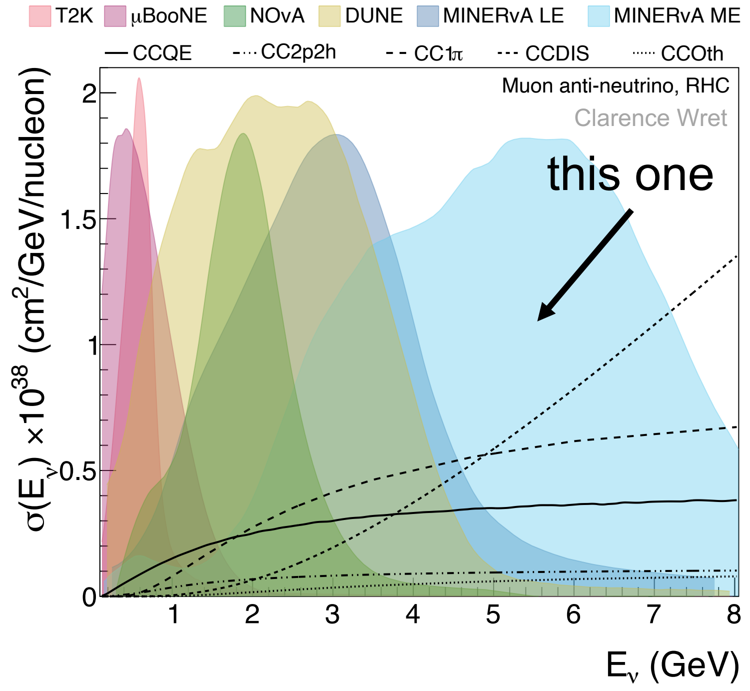
  - Smaller cross-section (~1/2 to 1/3 neutrino) → less data, longer exposure
  - Sensitive to different resonance channels, probes sea quark contributions





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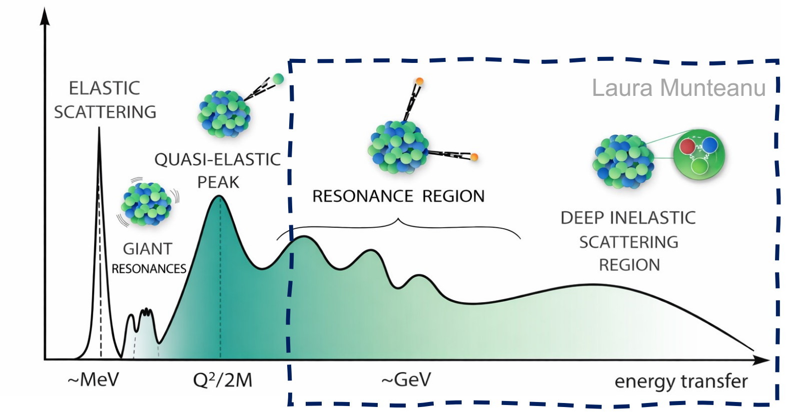
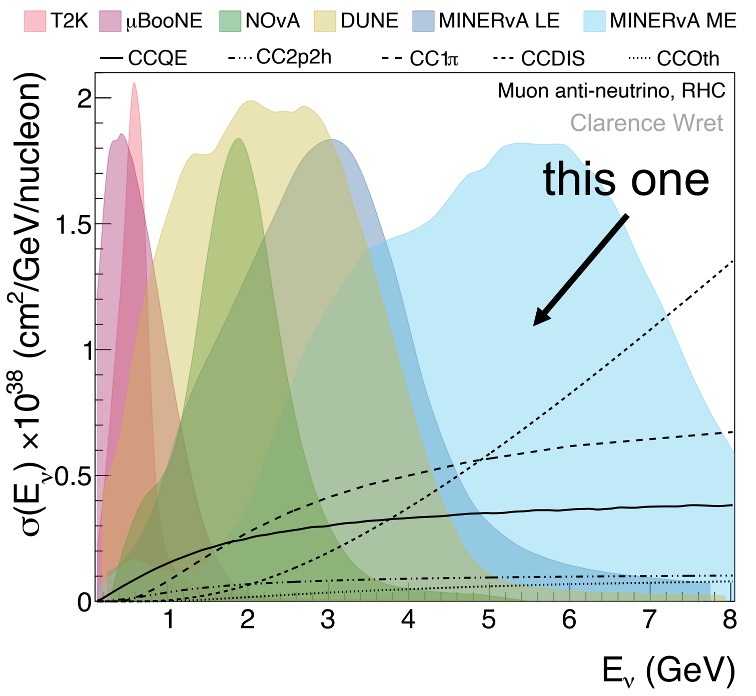
- **Inclusive measurement vs *A*:** tests how neutrino-nucleus event generators connect interaction regimes and treat nuclear effects over wide kinematic range





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Enter MINERvA

What is MINERvA?

Fresco of Minerva from Herculaneum (1st century AD)

Minerva. In Wikipedia, The Free Encyclopedia (20/02/2026)

Main INjector ExpeRiment for ν-A scattering

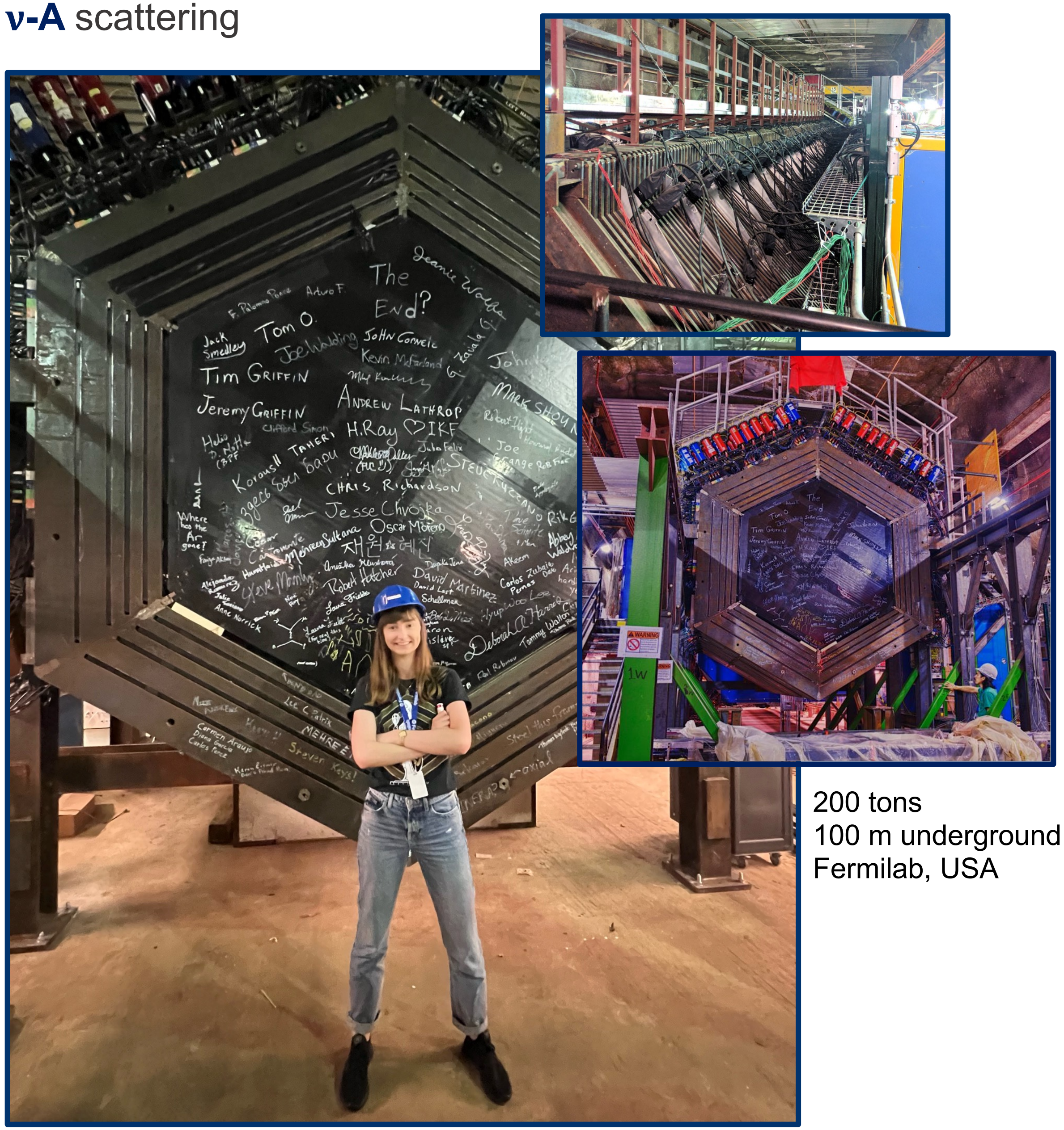
What is MINERvA?

- High-statistics cross-section experiment with different nuclear targets, which helps probe the structure of the nucleus and how it affects neutrino interactions
- 2009-2019 on axis in the NuMI beamline @Fermilab

Regime	Mode (POT) Neutrino-dominated	Mode (POT) Antineutrino-dominated
Low (LE) ~3 GeV	4.0×10^{20}	1.7×10^{20}
Medium (ME) ~6 GeV	10.6×10^{20}	11.2×10^{20} This measurement

POT: Protons on Target, proxy for number of neutrinos produced

- Actively analysing data! About 15 papers in the pipeline
- MINERvA Open Data product – all our data is now available to everybody!

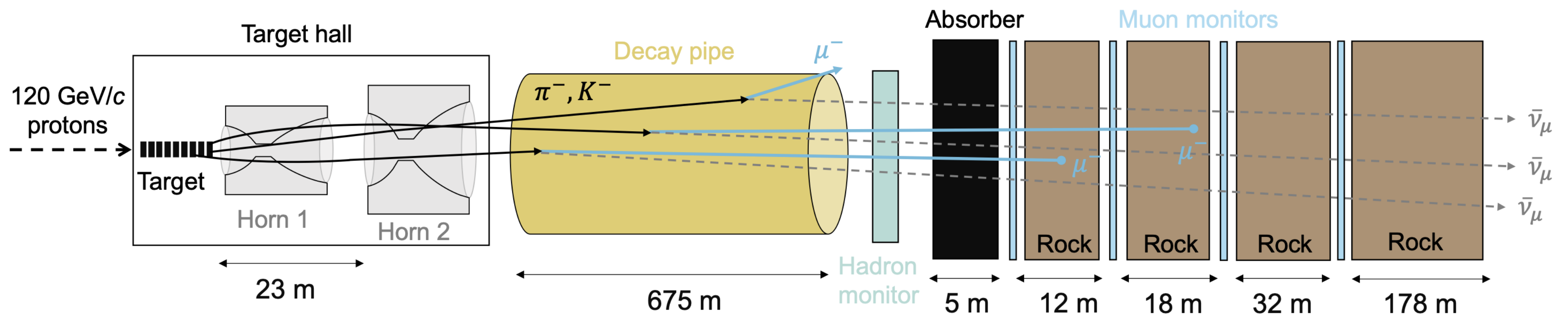


200 tons
100 m underground
Fermilab, USA

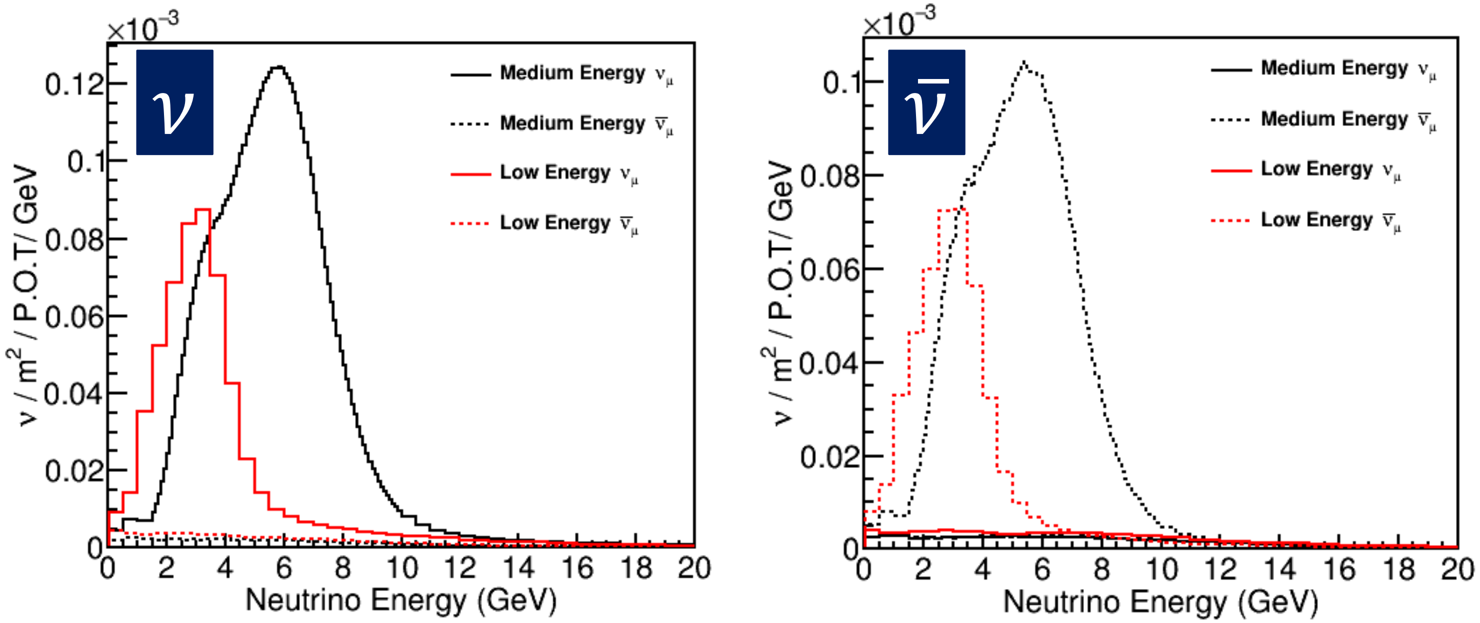
Decommissioned. Parts now serving DUNE near detector prototyping efforts!

NuMI beamline

Fermilab Accelerator Complex



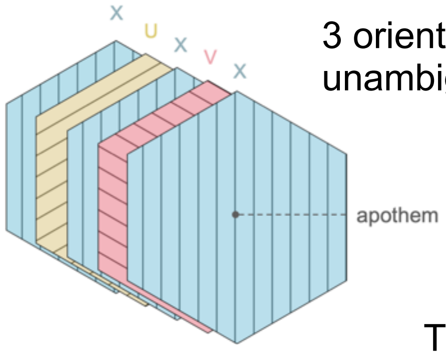
Flux at MINERvA



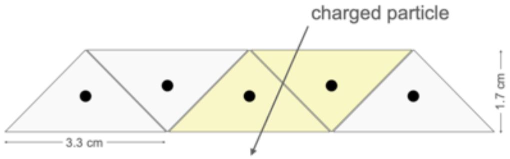
- Significant uncertainties in flux from hadron production and focusing
- Constrained with hadron production data and MINERvA's in-situ measurements of $\nu/\bar{\nu}$–e, inverse muon decay, and low-ν method (above 7.5 GeV)
  - E.g., in antineutrino-dominated beam, integrated uncertainty reduced from 7.8% to 4.7%

L. Zazueta (MINERvA). Phys. Rev. D 107, 012001 (2023).

MINERvA detector

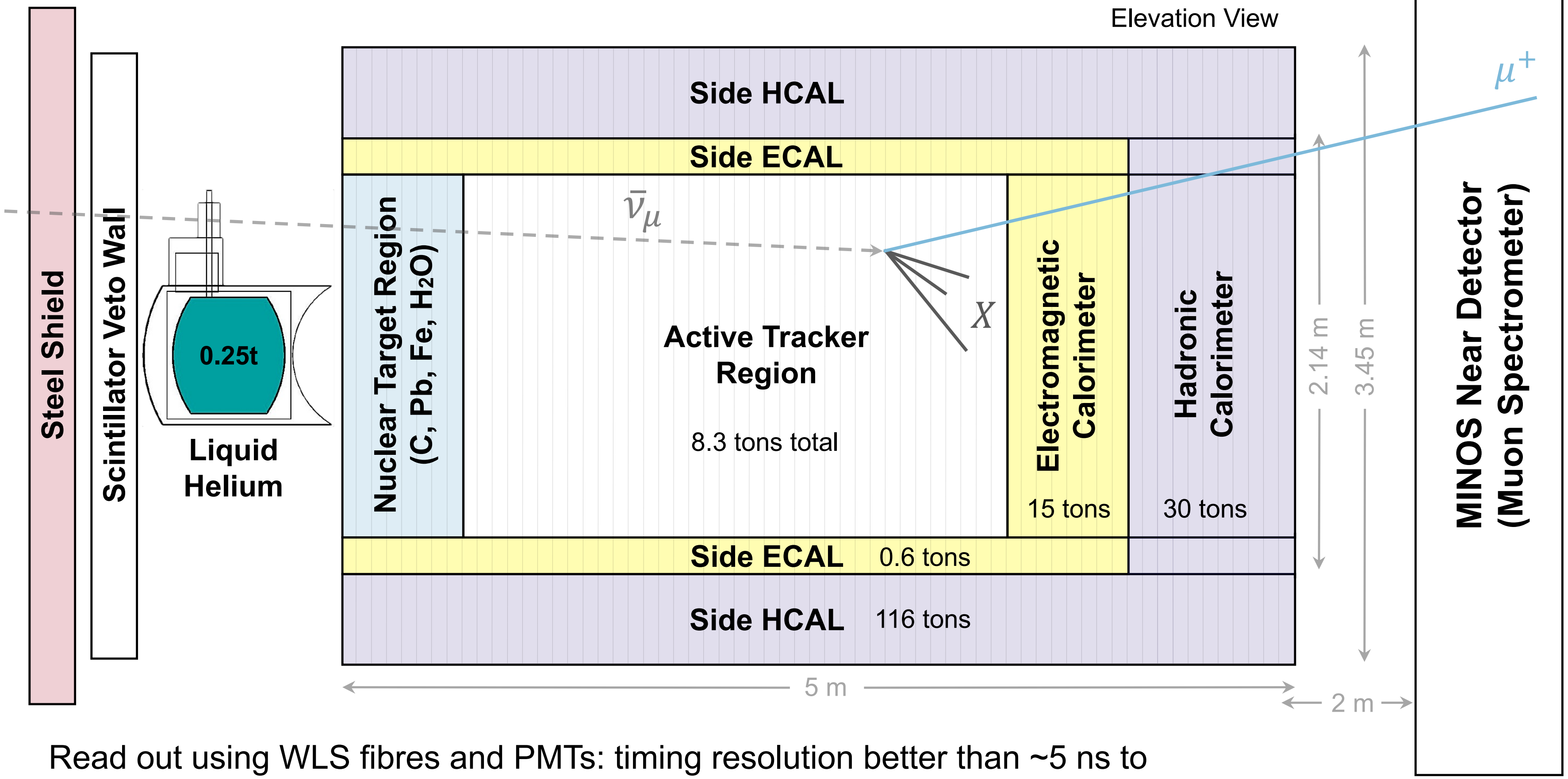


3 orientations of scintillator planes → unambiguous 3D track reconstruction



Triangular strips arranged to give a better position resolution

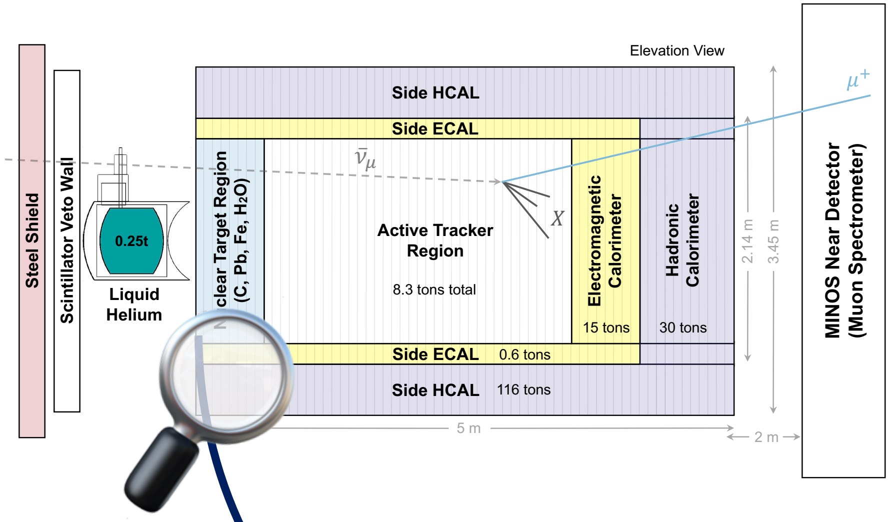
Main fiducial volume: active scintillator target made of hydrocarbon (CH), surrounded by calorimetry

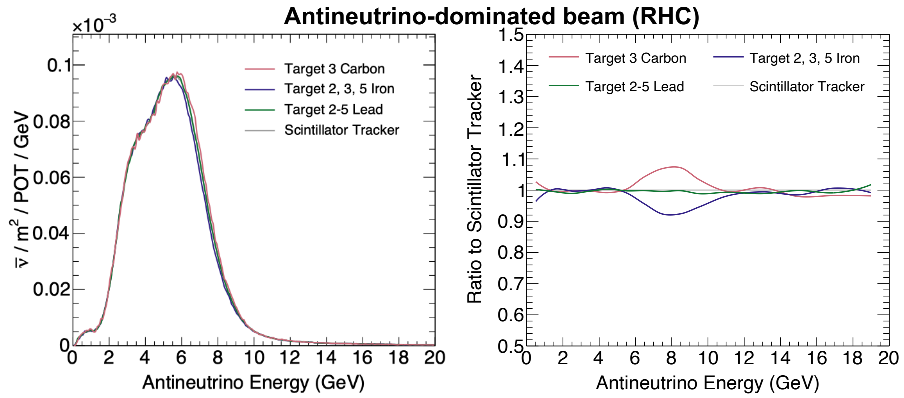


MINOS spectrometer: muon momentum and charge → phase space constraints

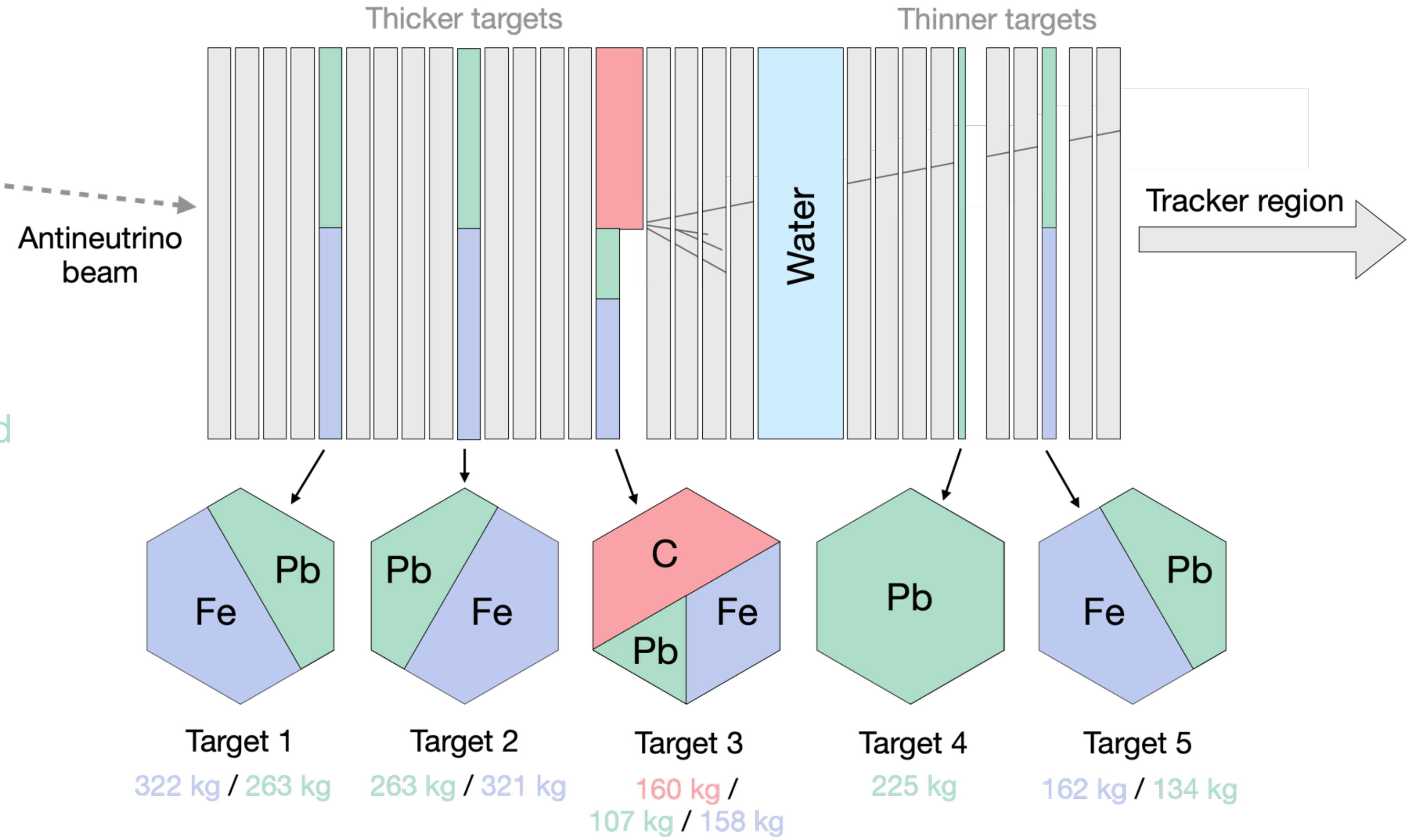
Read out using WLS fibres and PMTs: timing resolution better than ~5 ns to distinguish overlapping events within a single spill (< 10 μs)

Nuclear target region





Range of nuclei:
carbon, water, iron, and lead



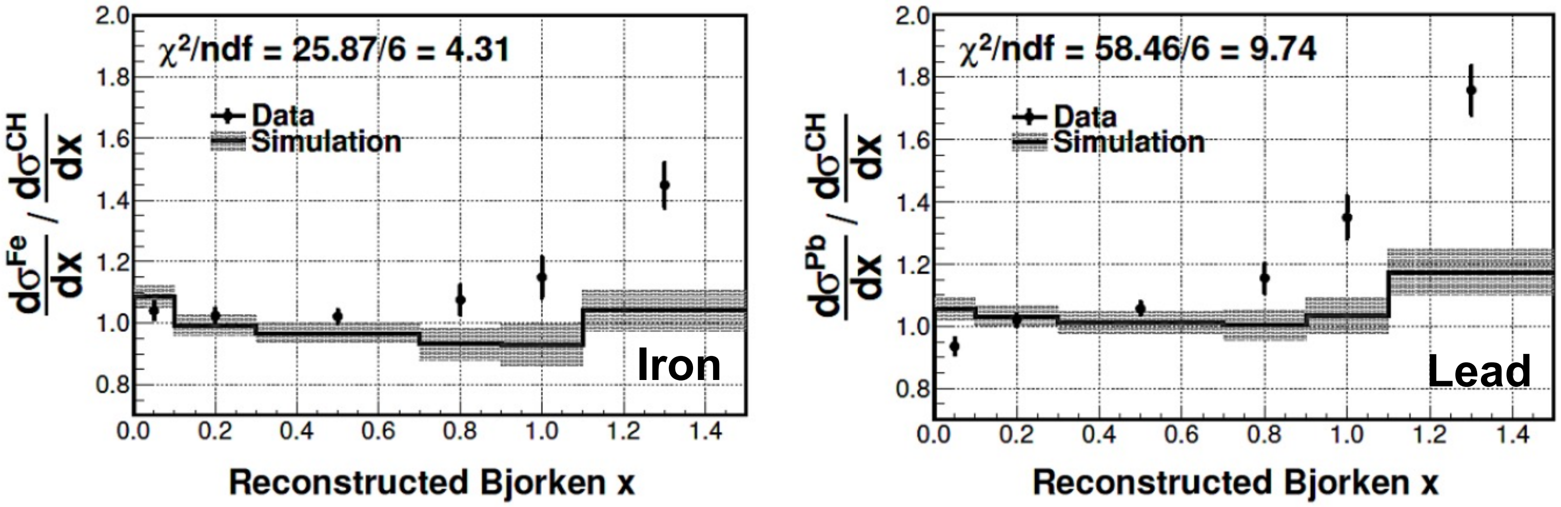
Solid targets interspersed by active scintillator planes (hydrocarbon)

MINERvA & inclusive measurement

Inclusive measurement in low energy beam

- In 2014, MINERvA measured **inclusive neutrino scattering** on carbon, iron, and lead, and reported cross-section ratios to hydrocarbon

B. Tice (MINERvA). Phys. Rev. Lett. 112, 231801 (2014).



$$x = \frac{Q^2}{2m_N E_{\text{had}}}$$

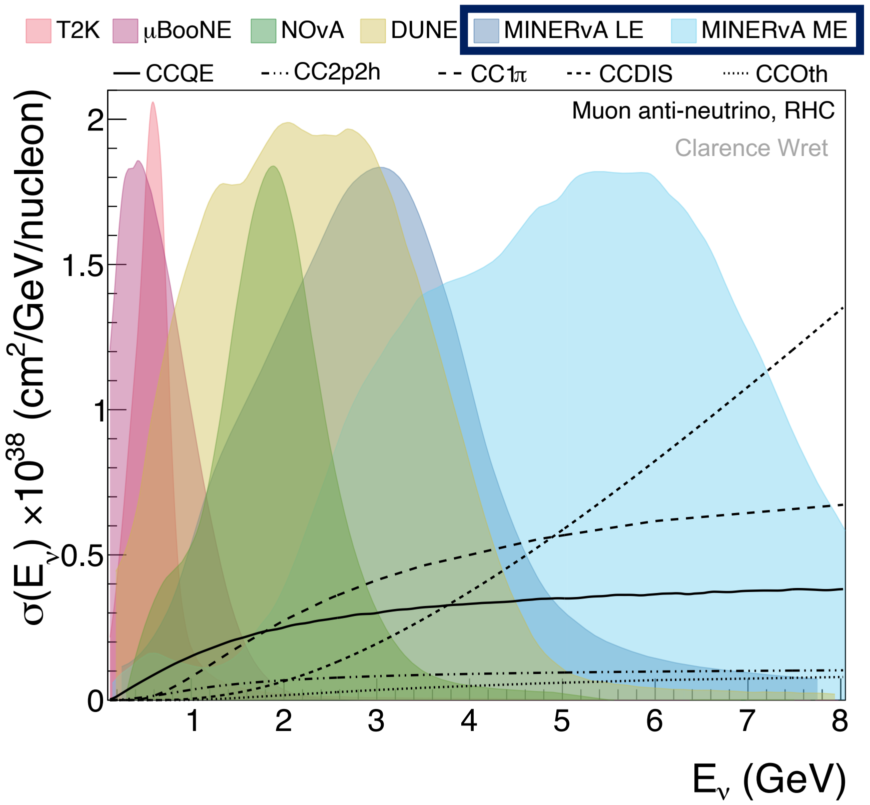
- Reported as a function of *reconstructed* Bjorken *x*
- Difficult to unfold, model dependence comes in through the hadronic system (even harder for antineutrinos)
- Relative depletion at low *x* and enhancement at large *x*

10+ years later, what has changed?

- Different energy regime (flux peak at 3.5 GeV vs at 6 GeV now) → different phase space and interaction-mechanism composition
- MINERvA collected large statistics of antineutrino scattering → dedicated antineutrino analysis possible!
  - 10× more events in the antineutrino analysis compared to low-energy neutrino analysis
- Better understanding of the detector and improved reconstruction techniques
  - Machine-learning used for vertex reconstruction using convolutional neural network results in increased selection purity and efficiency

F. Akbar (MINERvA). *JINST* 17 T08013 (2022).

- Significant progress in our understanding of neutrino-nucleus scattering, advancements in neutrino interaction models, and more awareness of model dependence when considering variables of interest



Event selection

Analysis finishing collaboration review — on arXiv soon!

In antineutrino mode:

$$\bar{\nu}_\mu + A \rightarrow \mu^+ + X$$

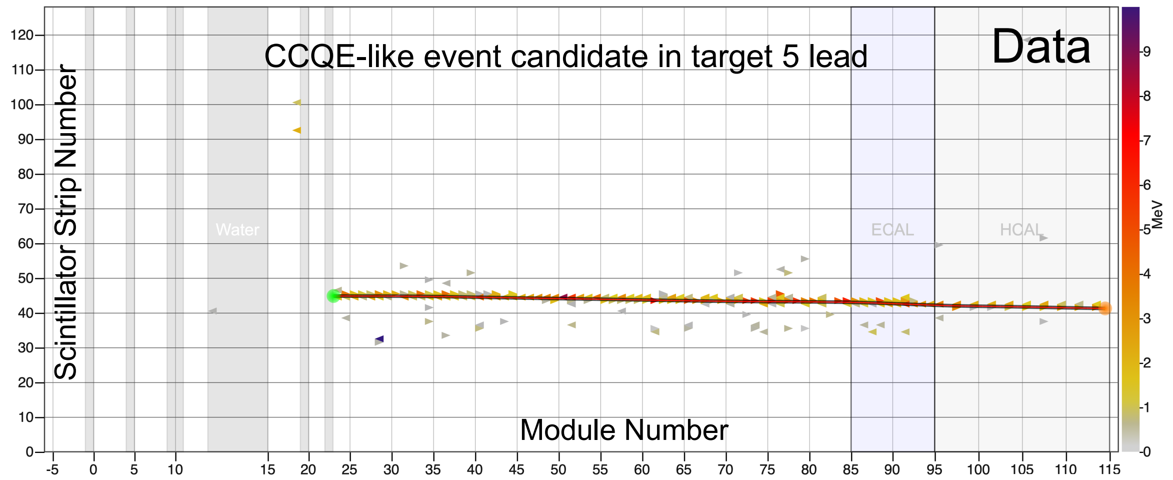
vertex in { hydrocarbon, carbon, iron, lead

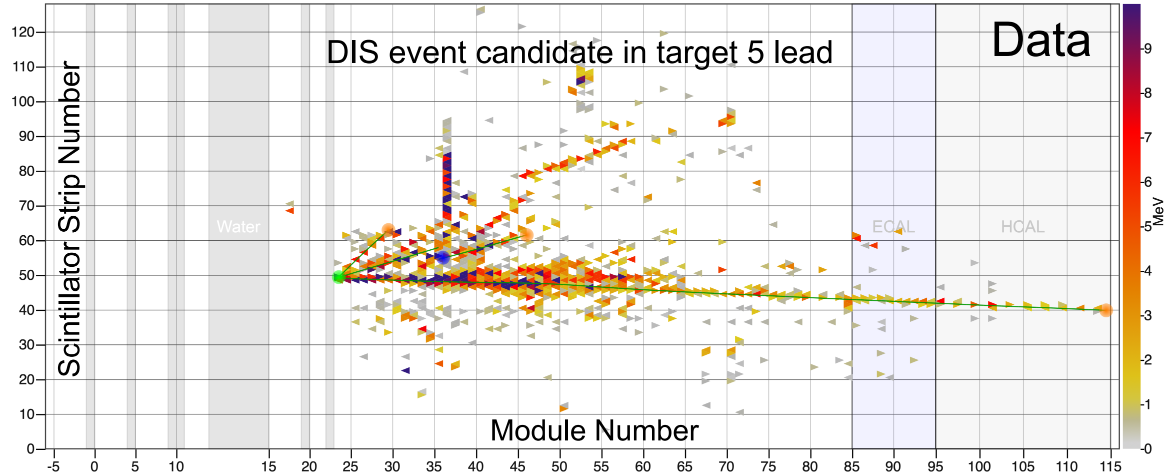
$\theta_{\mu^+} < 17°$
$2 < E_{\mu^+} < 20$ GeV } MINOS-matched antimuon

- Phase-space constraints due to measurement of antimuon momentum and charge in the spectrometer
- Inclusive = all final states

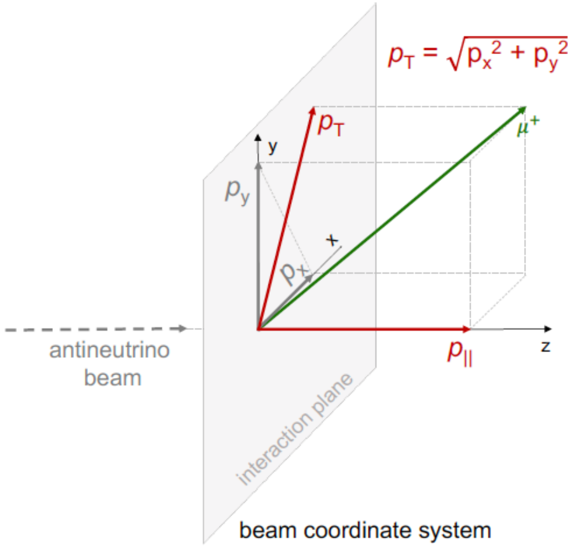
Target	Total Events
Carbon	63,956
Iron	192,694
Lead	225,313
Tracker	1,897,567

z-direction, towards MINOS spectrometer





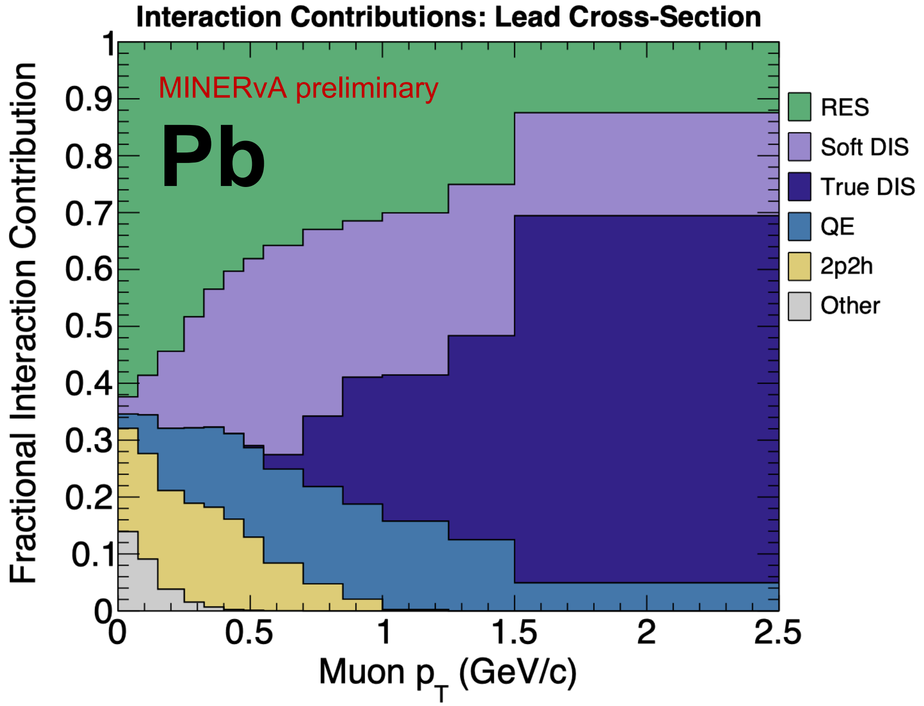
Variable of interest



- Muon kinematics only – no dependence on intranuclear re-scattering and containment
- Antimuon transverse momentum (p_T) – well reconstructed, minimises model dependence in unfolding
- Correlates with antimuon angle relative to the antineutrino beam
- Can be directly related to the four-momentum transfer squared

$$Q^2 \approx p_T^2(1 + \mathcal{O}\left(\frac{E_{\text{had}}}{E_\mu}\right)$$

- Separation power for different interaction types



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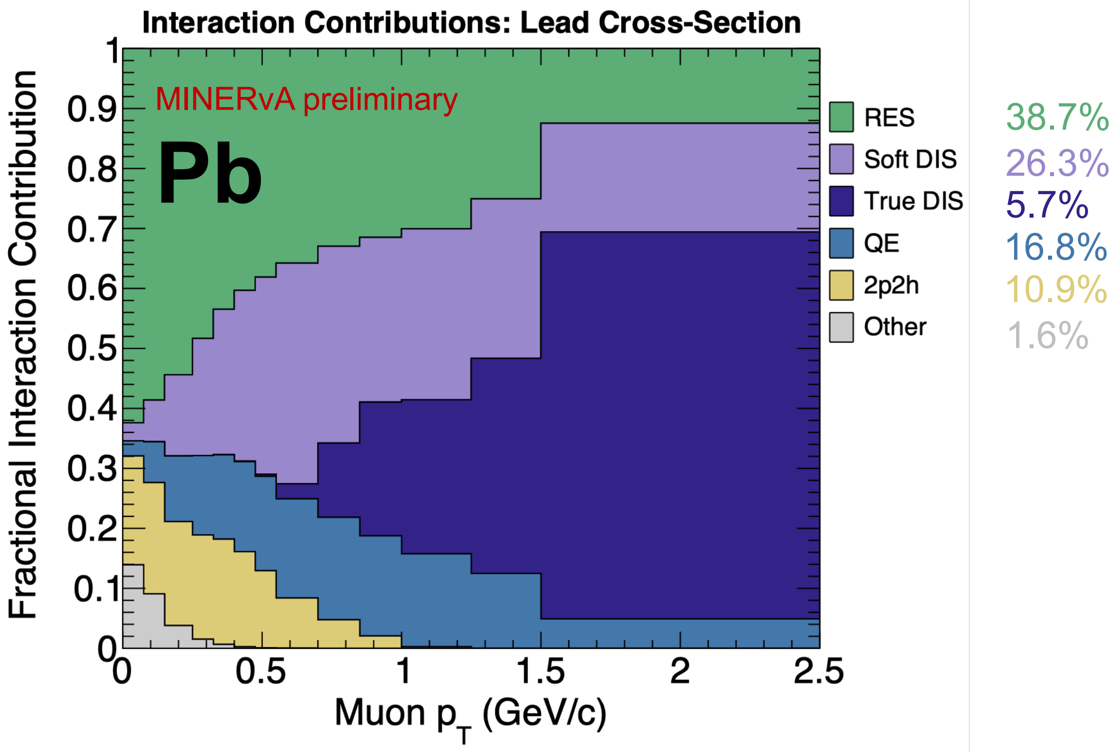
Some details of the underlying model

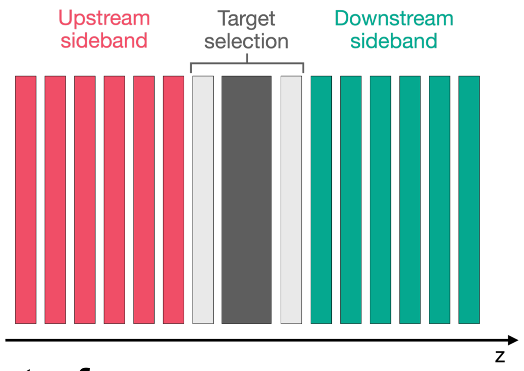
- Simulation prediction based on GENIE version 2.12.6, constrained by MINERvA neutrino measurements (QE, 2p2h, RES) and deuterium bubble chamber data*
  - This is so called MINERvA Tune v4.3.0
- GENIE DIS broken down into True DIS ($W > 2$ GeV/c^2 and $Q^2 > 1$ (GeV/c)^2) and Soft DIS (everything else)
  - Note GENIE DIS ≠ DIS defined by perturbative QCD ($Q^2 > 4$ (GeV/c)^2)
  - Soft DIS and True DIS correspond to soft shallow inelastic scattering (delta resonances, higher resonances, non-resonant processes) and multi-quark shallow inelastic scattering

A. Lozano, G. Silva, G. Caceres (MINERvA). arXiv:2503.20043 (2025)

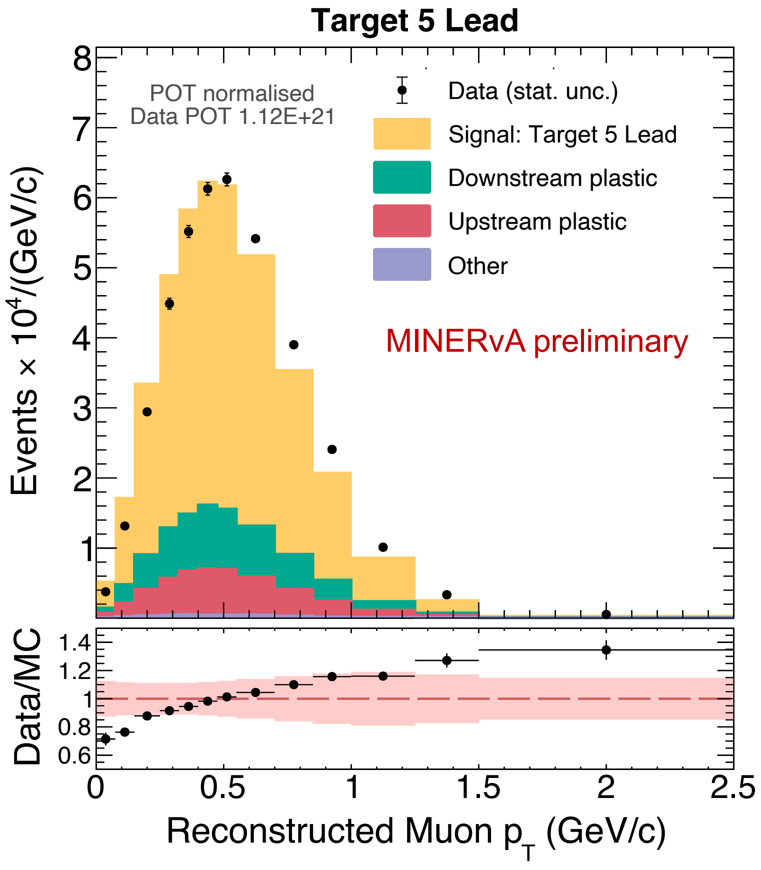


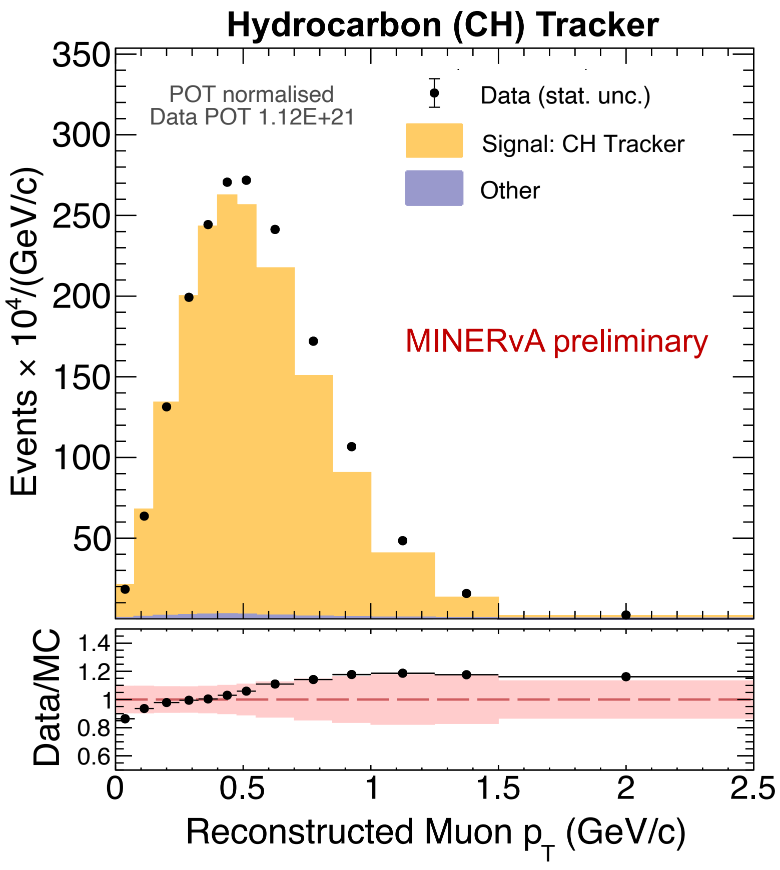
*P. Rodrigues, C. Wilkinson, & K. McFarland. Eur. Phys. J. C. 76, 474 (2016)

Background



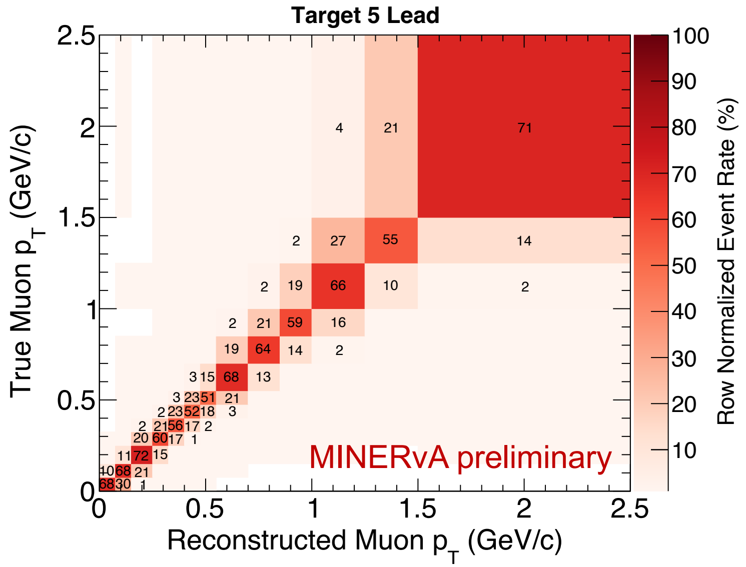
- ~70% purity across all targets and 99% in tracker
- In targets, plastic scintillator events from upstream/downstream constrained using data from surrounding scintillator planes → subtract constrained background





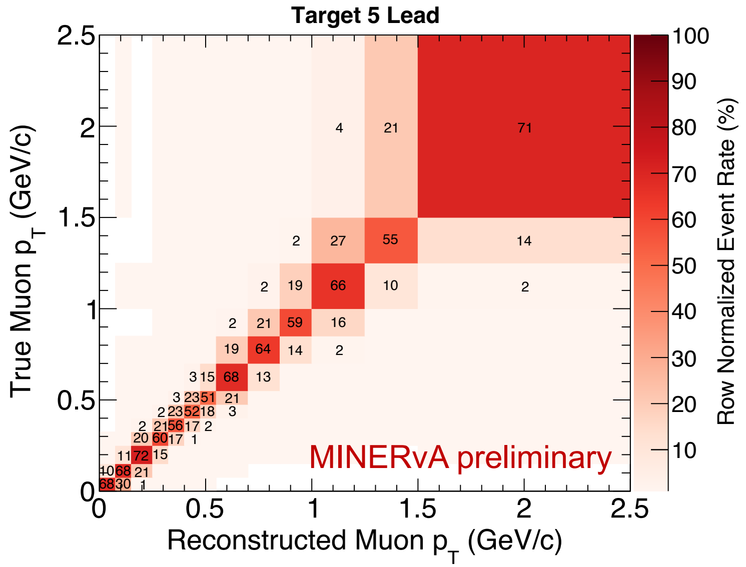
Unfolding, efficiency, and normalisation

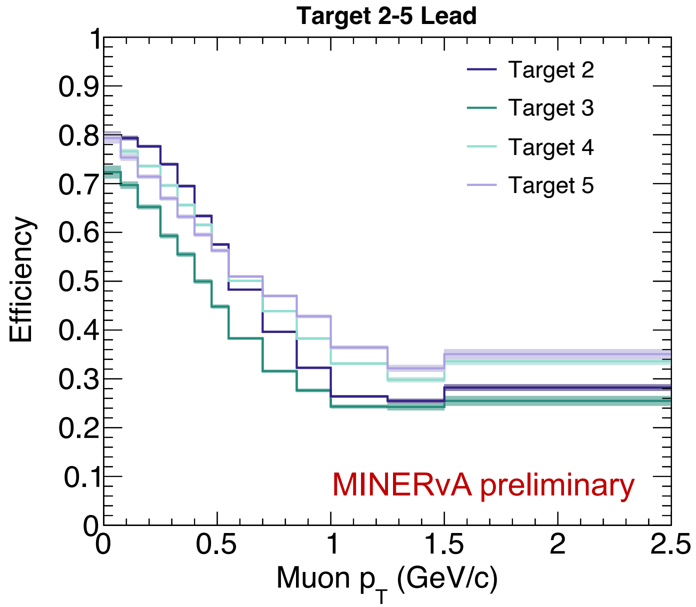
- Correct for smearing due to detector resolution and reconstruction
  - D'Agostini unfolding to true distribution with minimum iterations to account for possible physics variations

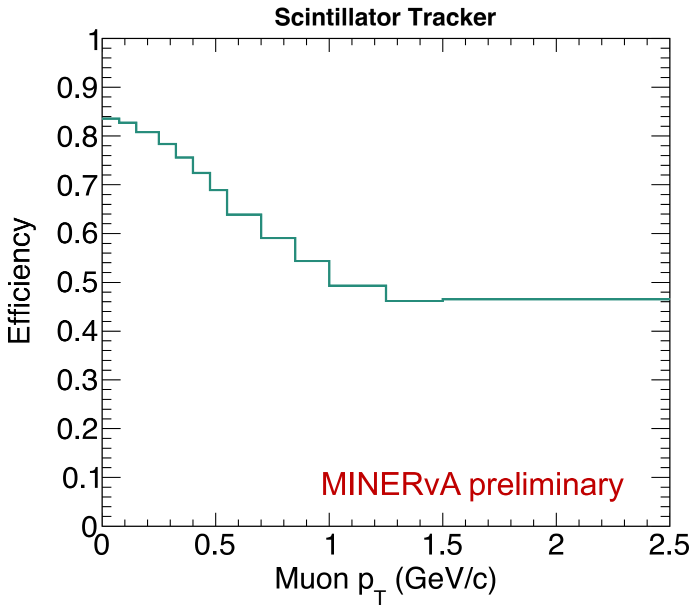


Unfolding, efficiency, and normalisation

- Correct for smearing due to detector resolution and reconstruction
  - D'Agostini unfolding to true distribution with minimum iterations to account for possible physics variations
- Efficiency/acceptance (decreases with p_T), integrated about 40–50% in targets and ~65% in tracker

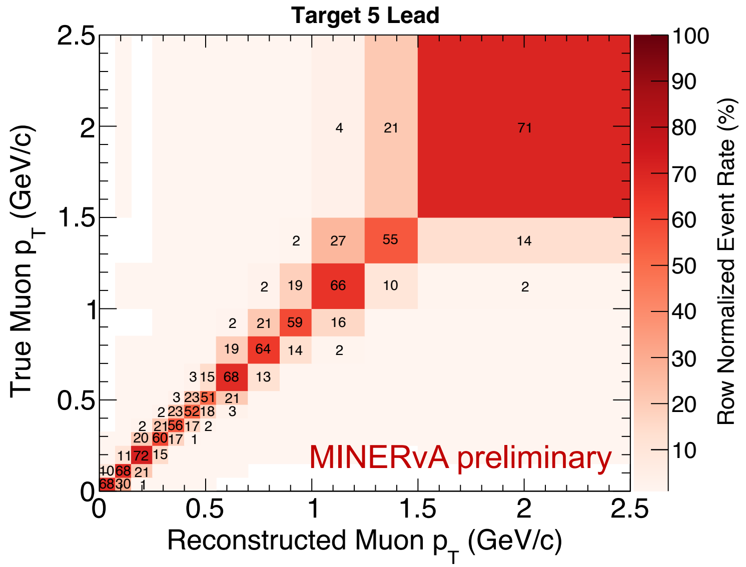


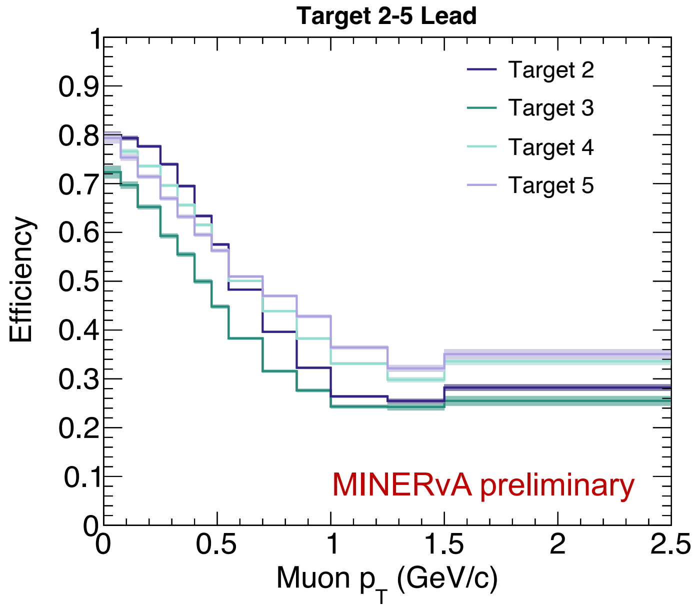


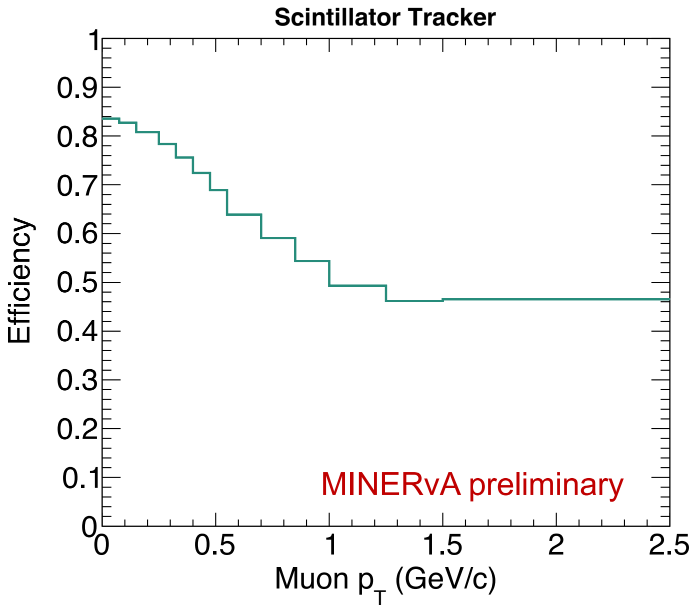


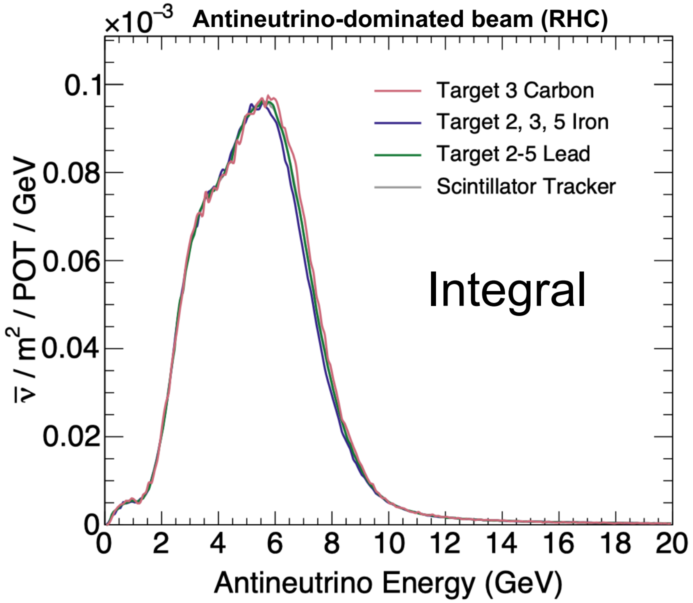
Unfolding, efficiency, and normalisation

- Correct for smearing due to detector resolution and reconstruction
  - D'Agostini unfolding to true distribution with minimum iterations to account for possible physics variations
- Efficiency/acceptance (decreases with p_T), integrated about 40–50% in targets and ~65% in tracker
- Normalise by flux, number of target nucleons, and bin width





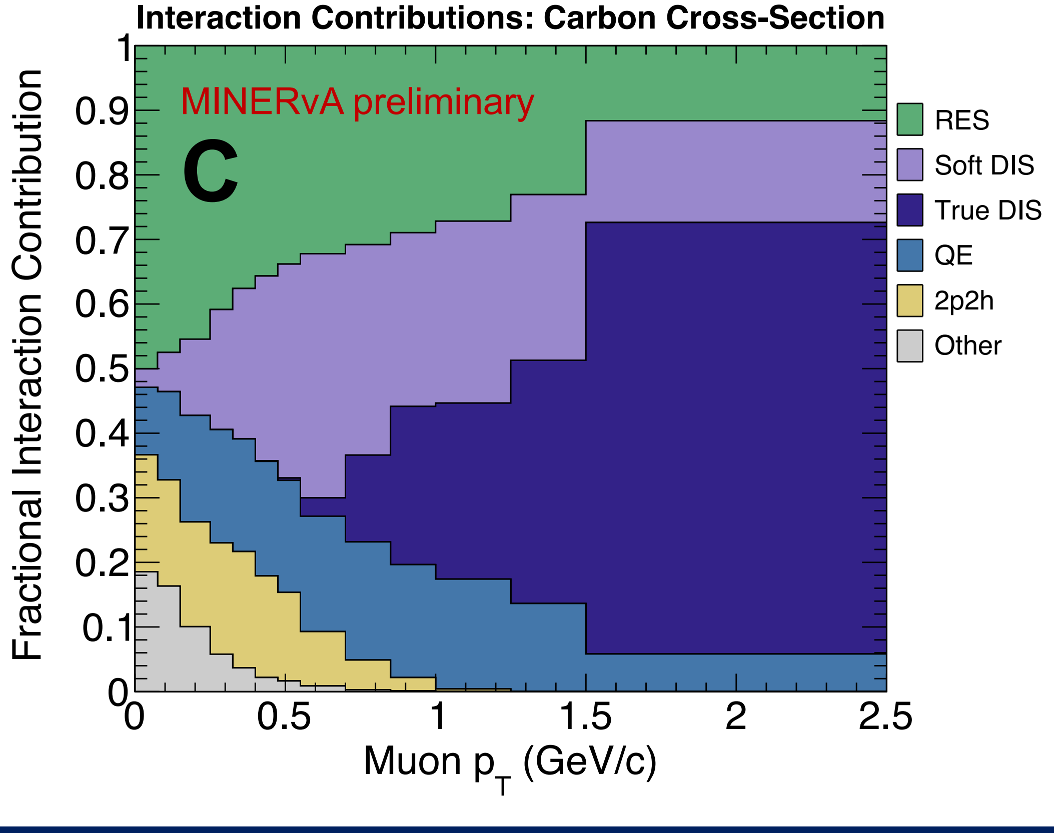


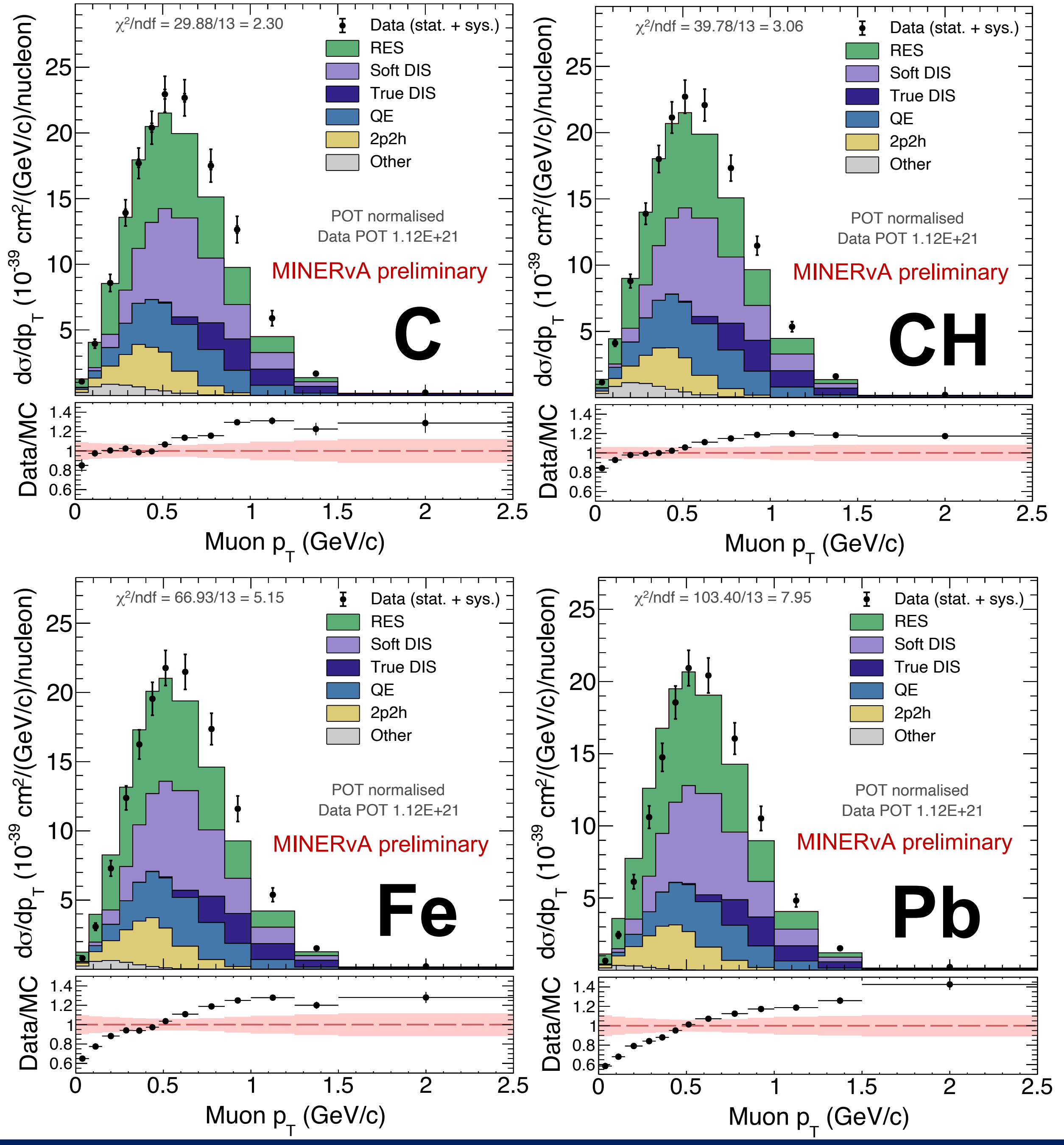


Results!

Cross-sections

- Some agreement in the peak of the distribution
- Underprediction at high p_T
- Overprediction at low p_T increasing with A



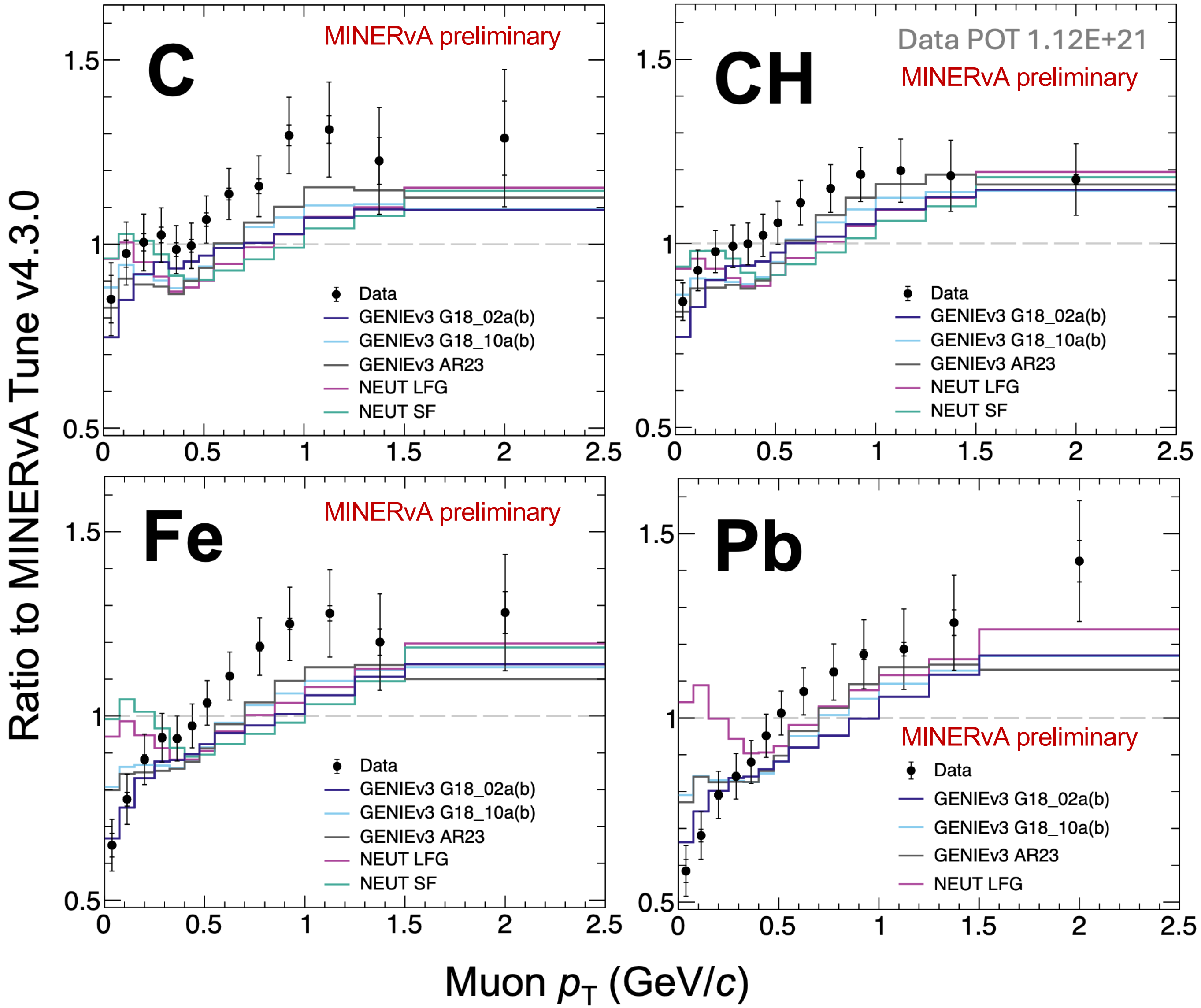


Can we learn more? Yes, we can

- Measured cross-section can be used to probe the robustness of different interaction models
- **Not going to discuss models in detail, but let’s focus on trends!**

Can we learn more? Yes, we can

- Measured cross-section can be used to probe the robustness of different interaction models
- **Not going to discuss models in detail, but let's focus on trends!**
- Compared to 5 GENIEv3 and 2 NEUT generator predictions using NUISANCE*
    - hA/hN (a/b) GENIE differences negligible
    - Not sensitive to FSI
- GENIE v3 AR23 (DUNE tune) yield lowest χ^2 (< 28 per 13 ndf for C and CH)

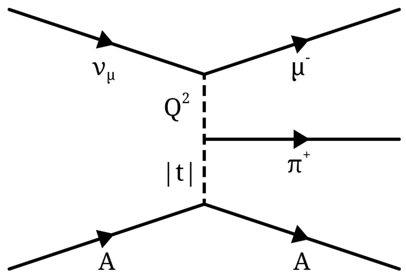


*P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et. al., JINST 12 P01016 (2017).

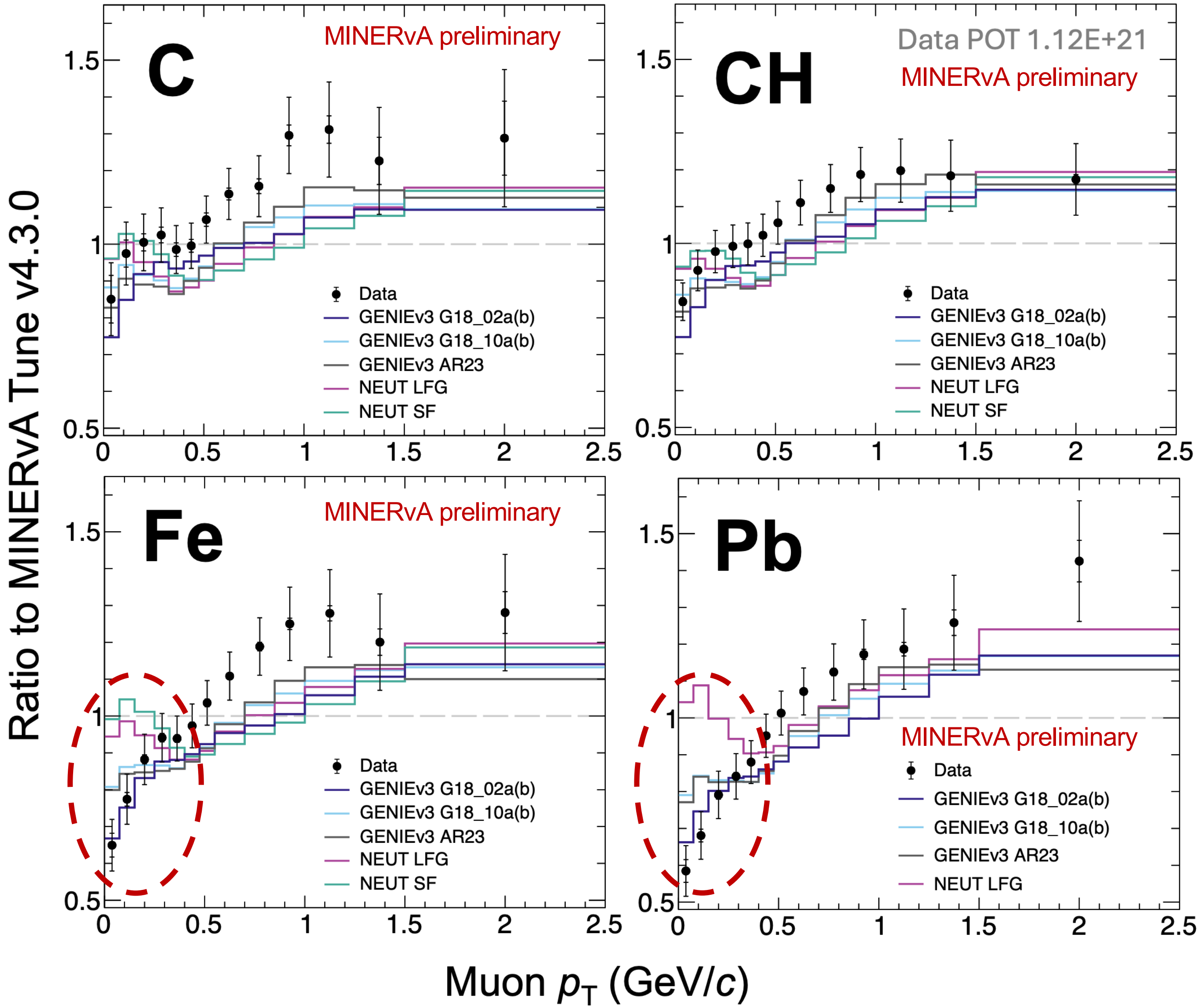
Note: NEUT version 5.4.1

Low-p_T

- GENIEv3 gives best low-p_T shape but more suppression needed for heavy targets
- Low-p_T in iron and lead: GENIEv3 vs NEUT differ
  - *A*-scaling differences in pion-producing processes
  - E.g., coherent cross-section in NEUT scales as ~*A* vs in GENIE as ~$A^{2/3}$



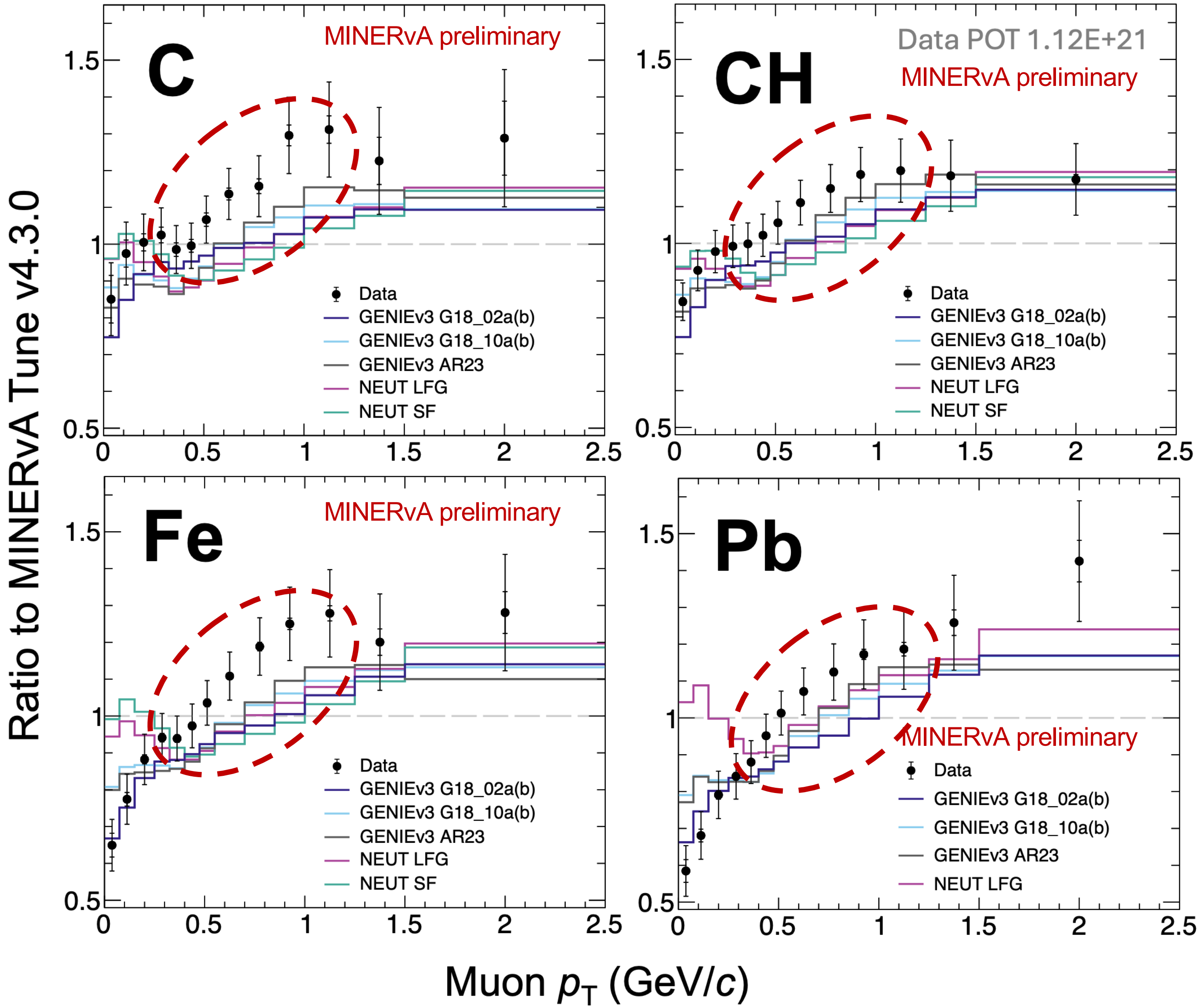
Coherent pion production



Note: NEUT version 5.4.1

Mid-p_T

- In p_T range ~0.4–1.0 GeV/*c* underprediction observed across all nuclei increasing with *A*



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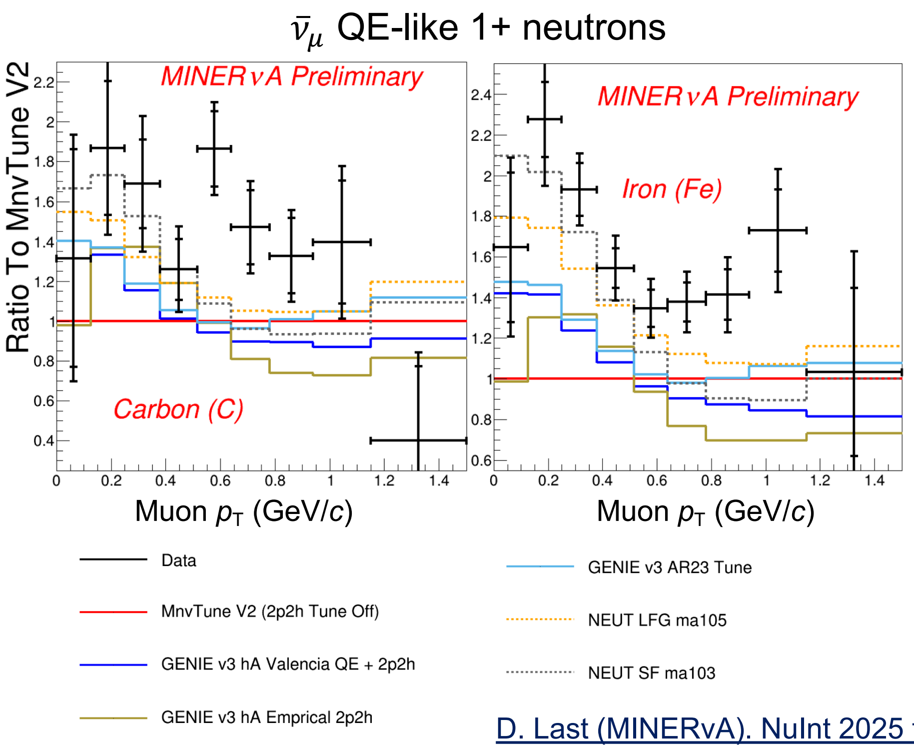
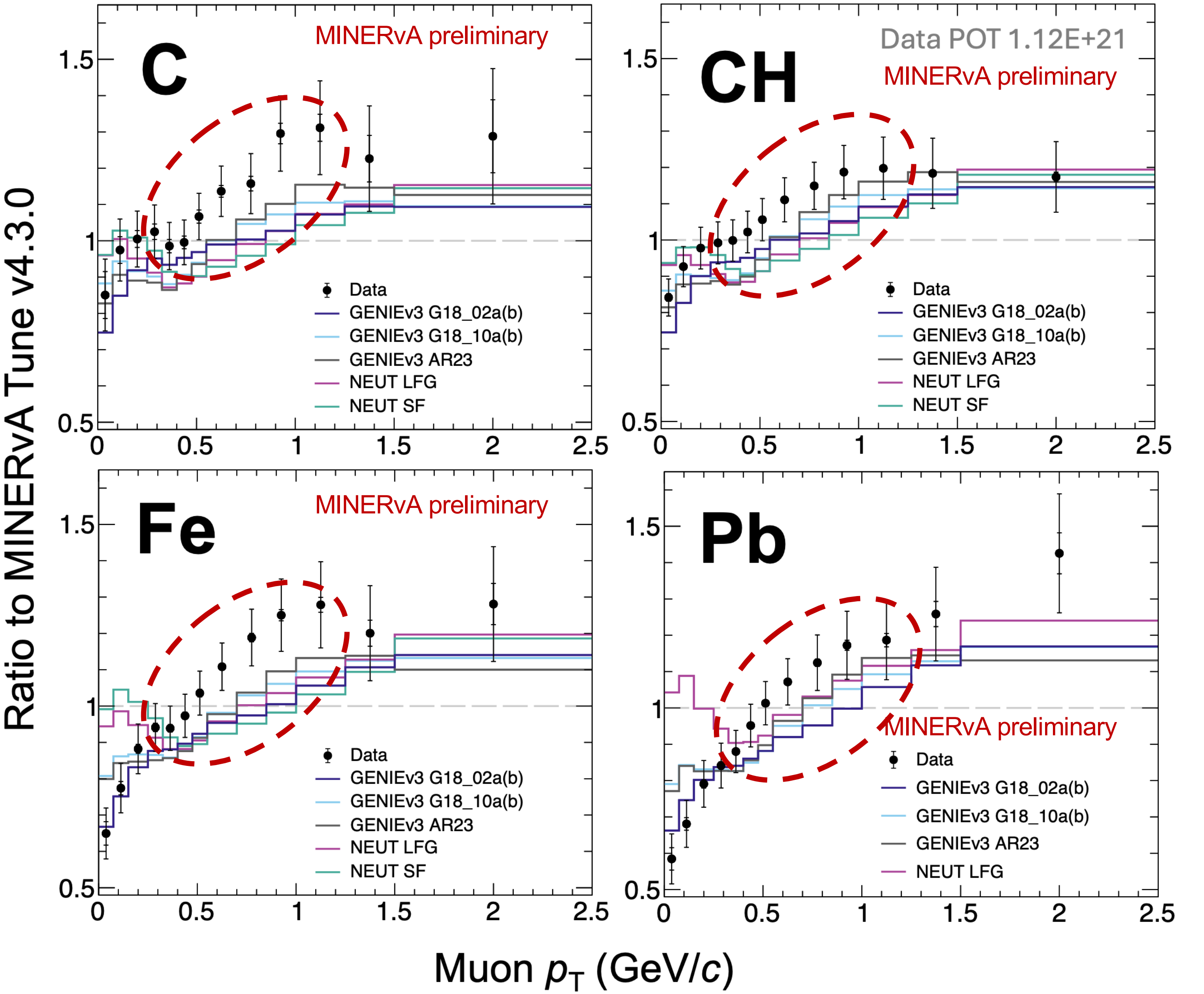


[D. Last (MINERvA). NuInt 2025 talk]



Note: NEUT version 5.4.1

Mid-p_T

- In p_T range ~0.4–1.0 GeV/*c* underprediction observed across all nuclei increasing with *A*
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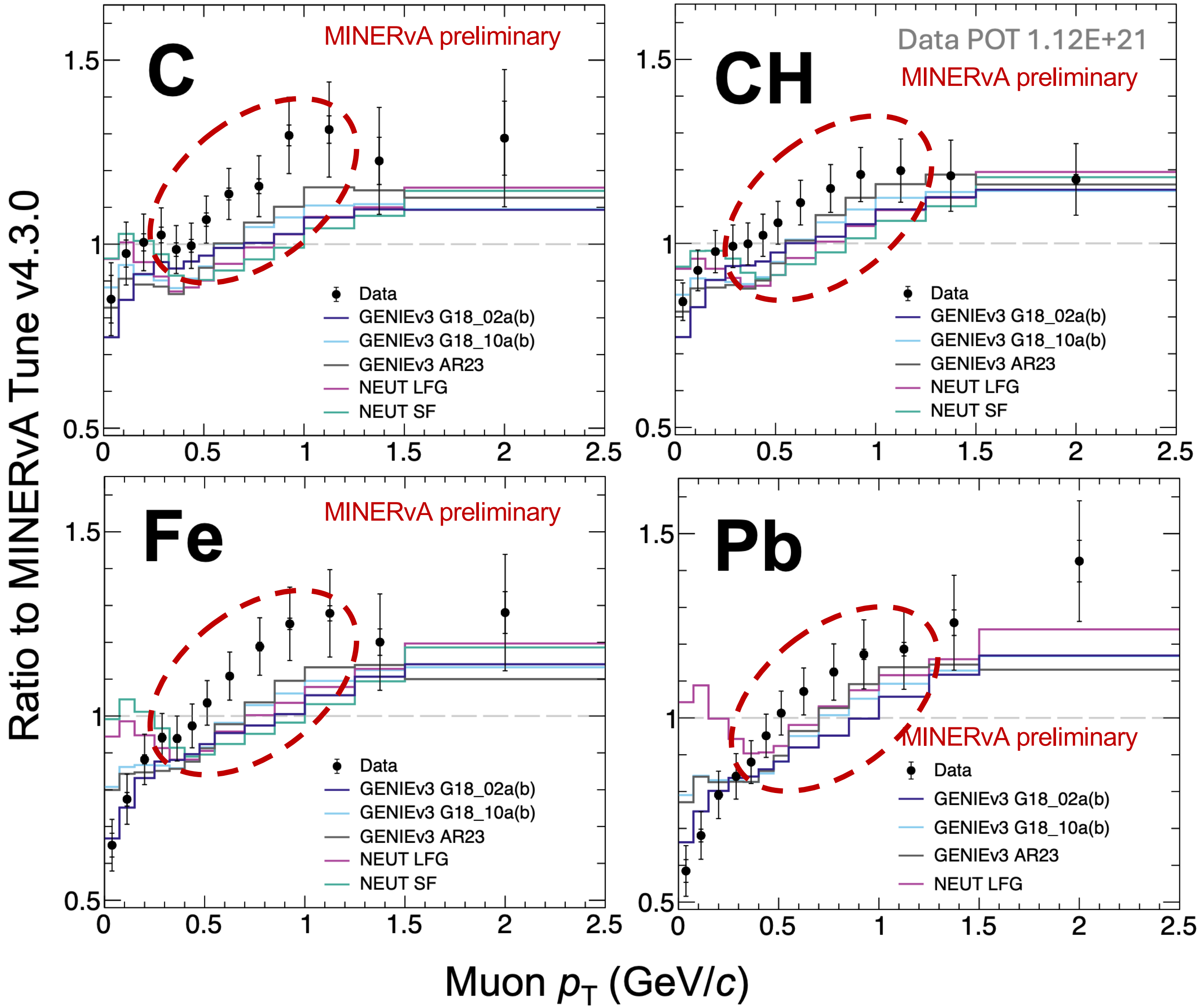

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Mid-p_T

- In p_T range ~0.4–1.0 GeV/c underprediction observed across all nuclei increasing with A
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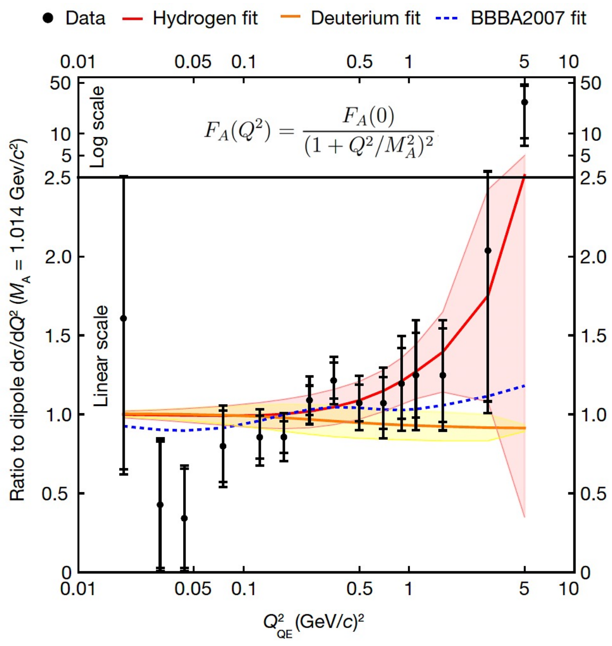
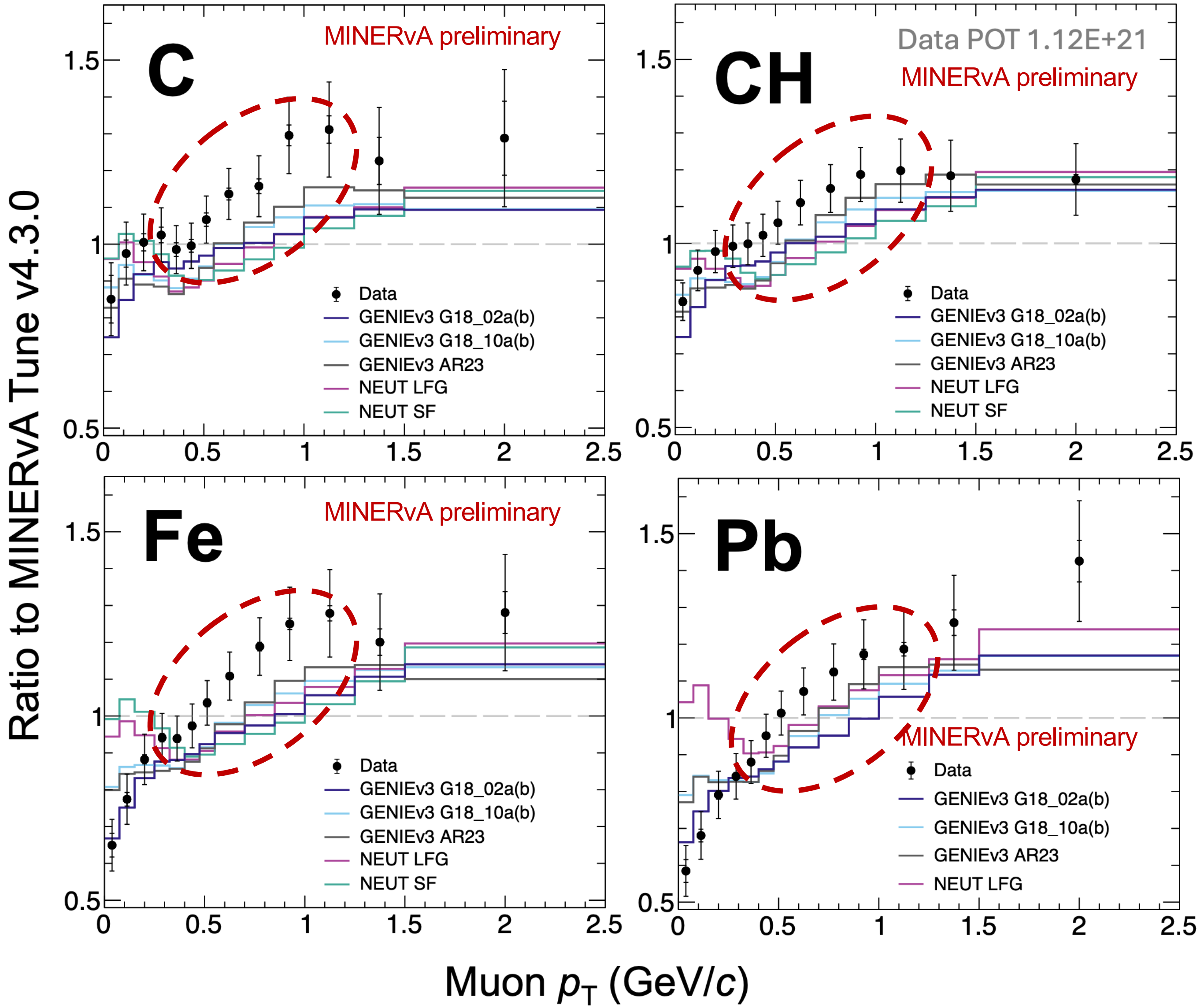
  - Related to the effect of dipole treatment of axial form factor (underprediction at higher Q^2)



T. Cai (MINERvA), Nature 614, 48–53 (2023)



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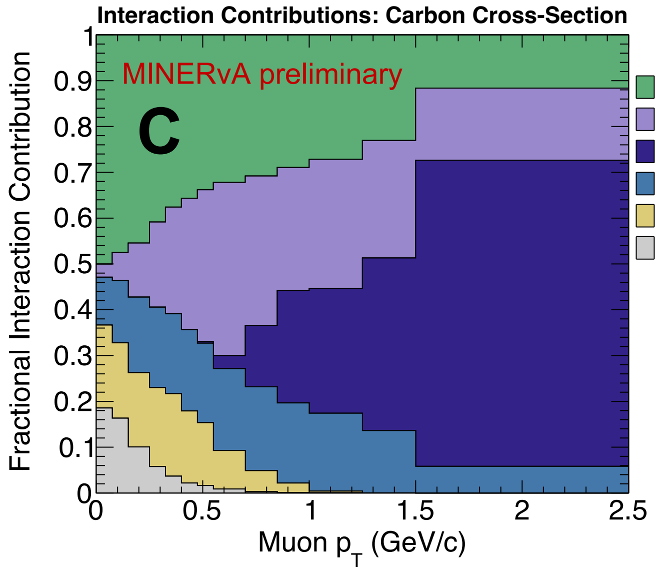
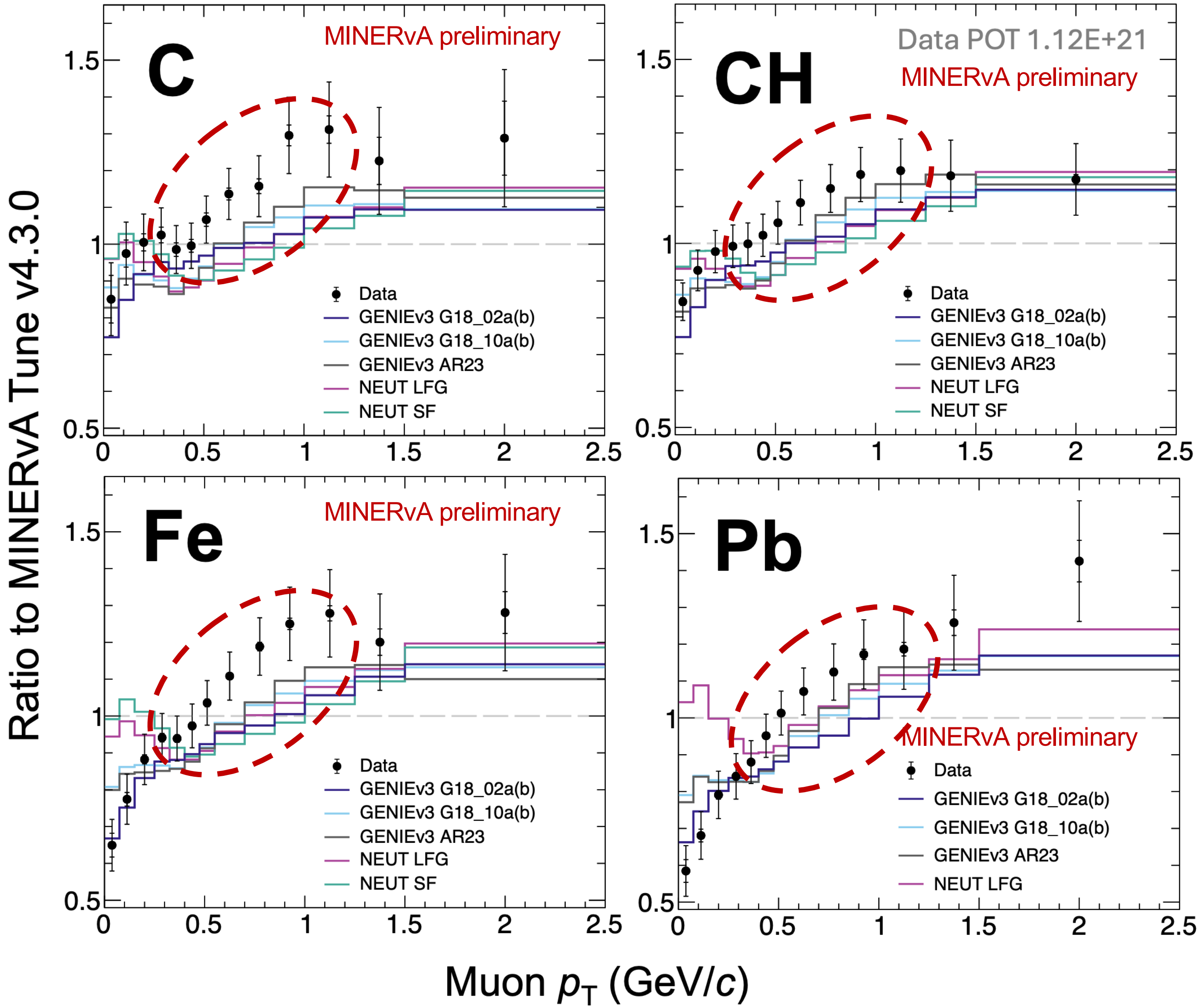
Mid-p_T

- In p_T range ~0.4–1.0 GeV/*c* underprediction observed across all nuclei increasing with *A*
    - Suggests partially from QE-like processes
    - Related to the effect of dipole treatment of axial form factor (underprediction at higher Q^2)
- But there are other processes too!
- Turns out resonant axial form factors just as wild

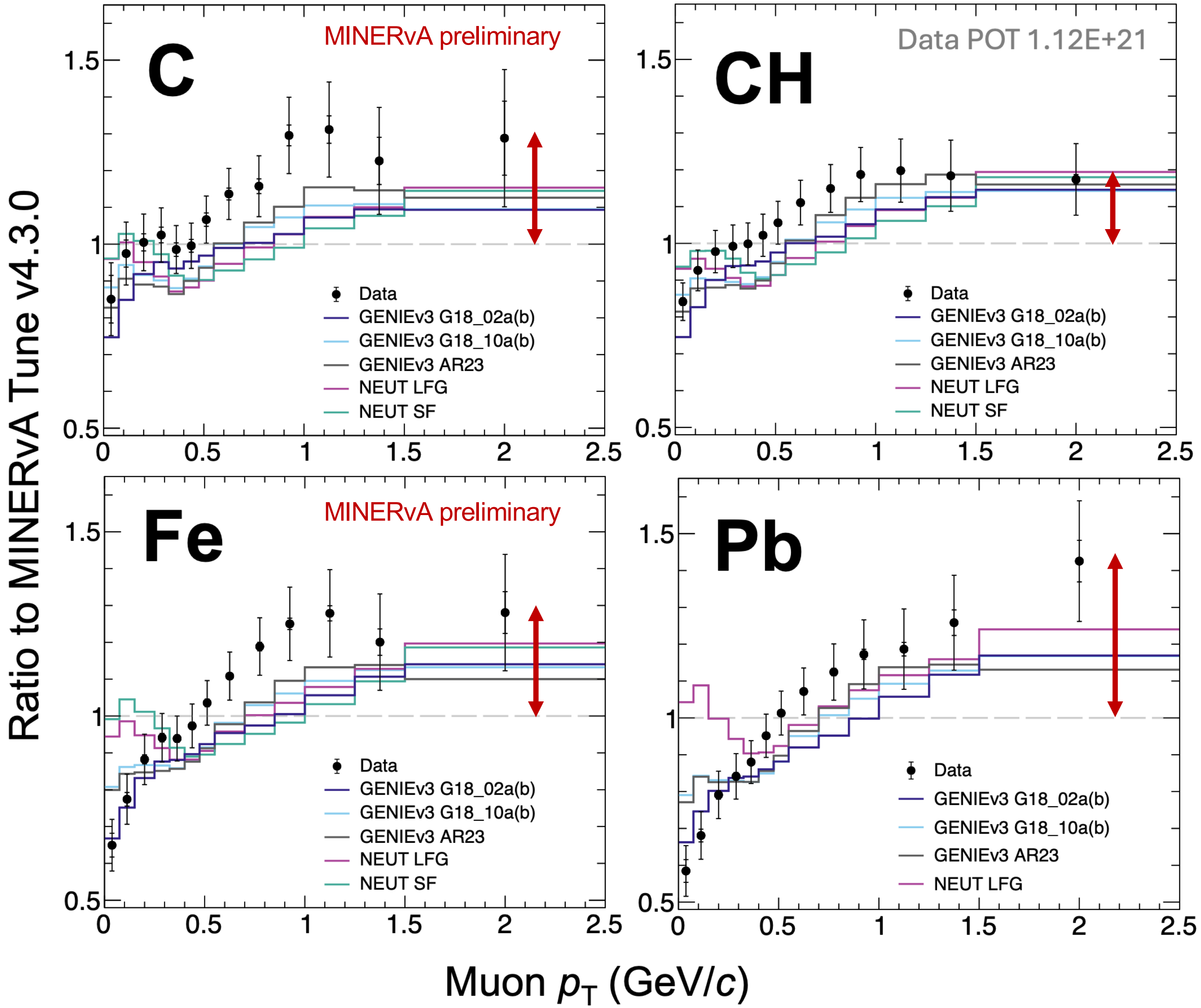




Note: NEUT version 5.4.1

(Mid- to) High-p_T

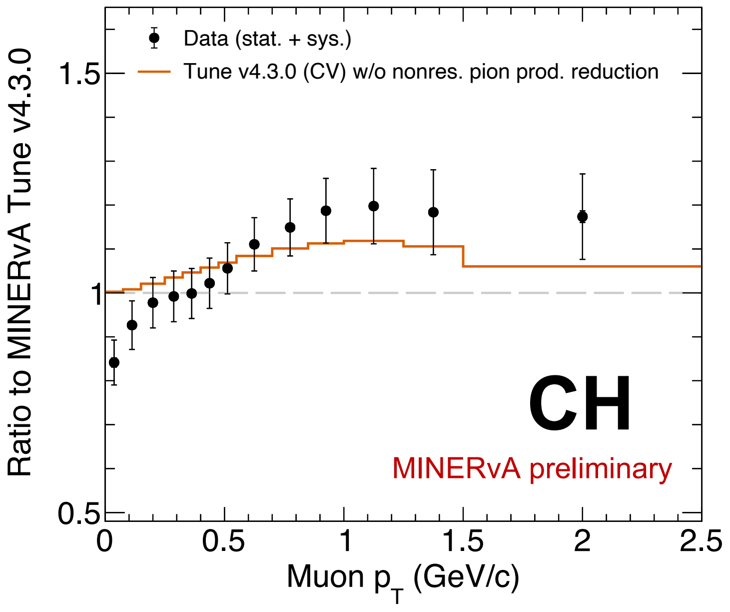
- (Mid- to) high-p_T region shows underprediction vs base model
  - High-p_T not tuned by MINERvA measurements

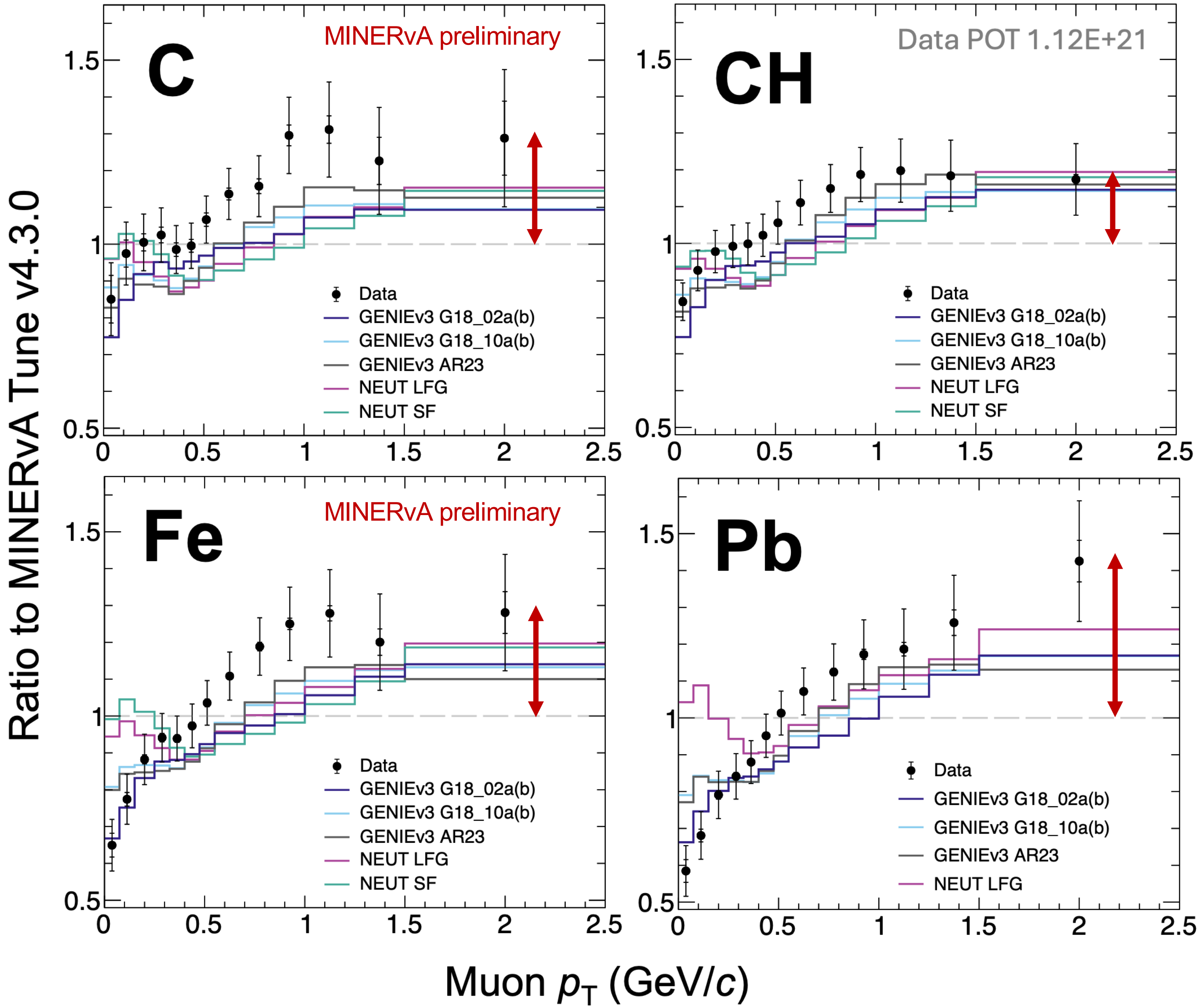


Note: NEUT version 5.4.1

(Mid- to) High-p_T

- (Mid- to) high-p_T region shows underprediction vs base model
  - High-p_T not tuned by MINERvA measurements
  - Non-resonant pion production is reduced based on deuterium data*, beyond the region where the data is relevant





*P. Rodrigues, C. Wilkinson, & K. McFarland. Eur. Phys. J. C. 76, 474 (2016)

Note: NEUT version 5.4.1

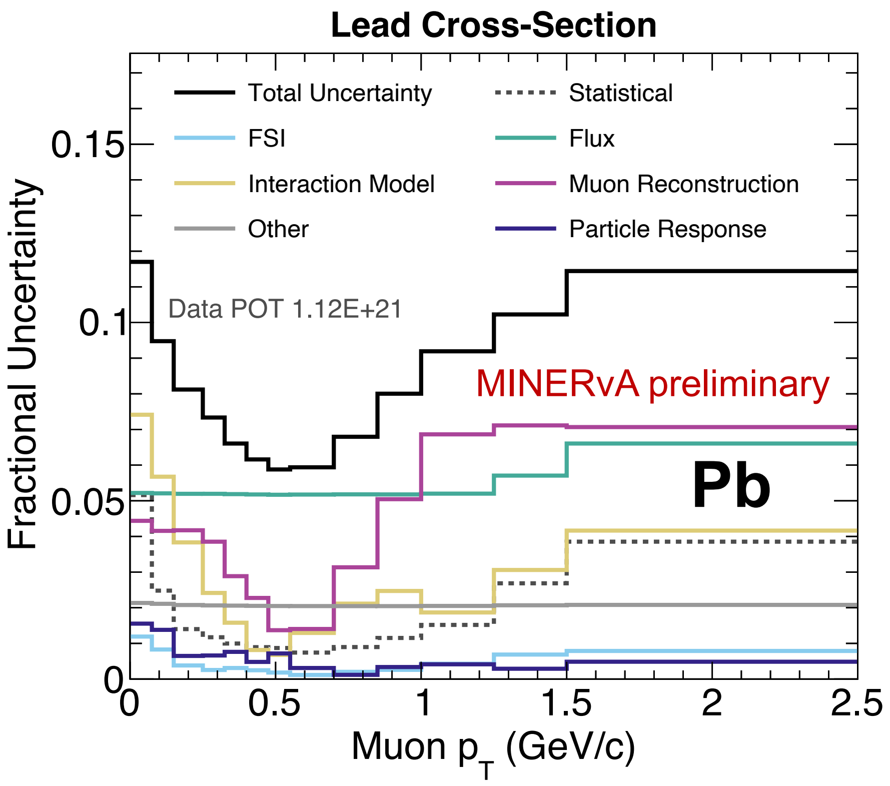
How (un)certain are we?

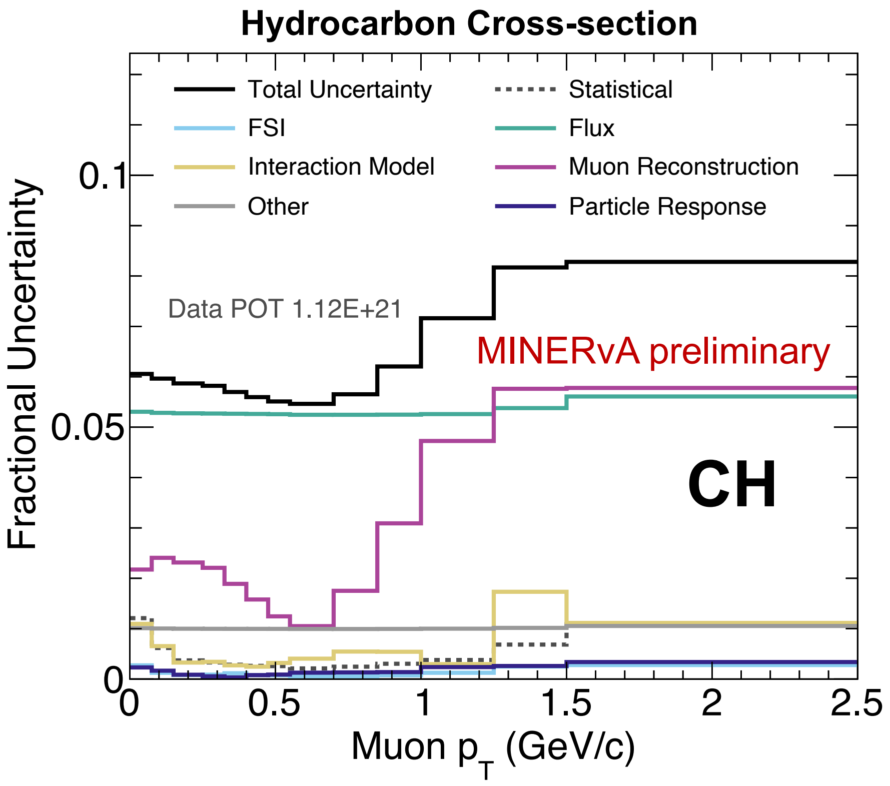
Evaluated in ‘universes’ by adjusting a parameter and modifying the central value simulation

~5–6% total uncertainty in the peak of the distribution, ~10% or less overall (targets), scintillator ~6%

Leading: flux & muon reconstruction

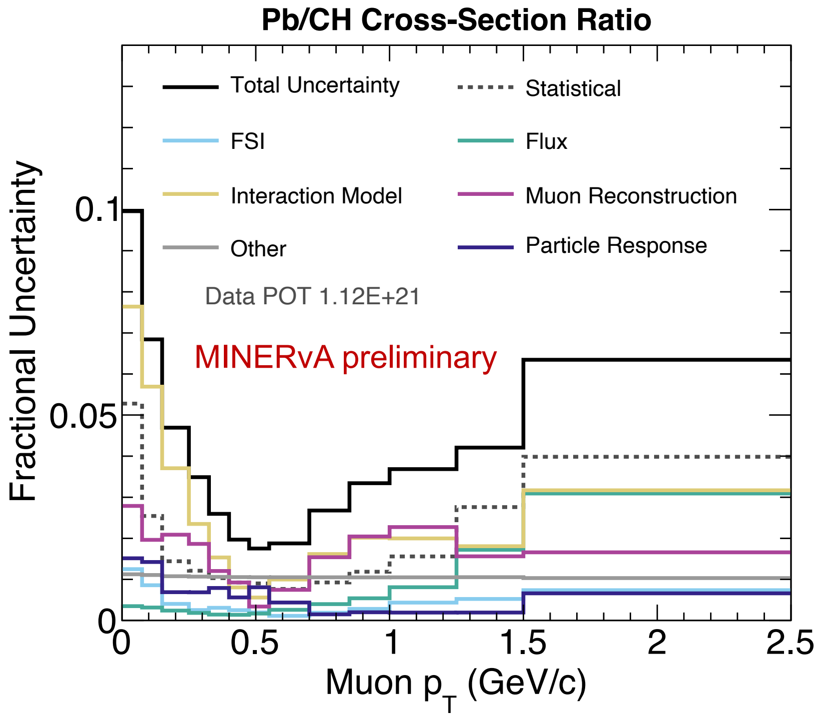
Interaction model: leading GENIE parameter MaRES + MINERvA tune reweights (conservative, especially targets)





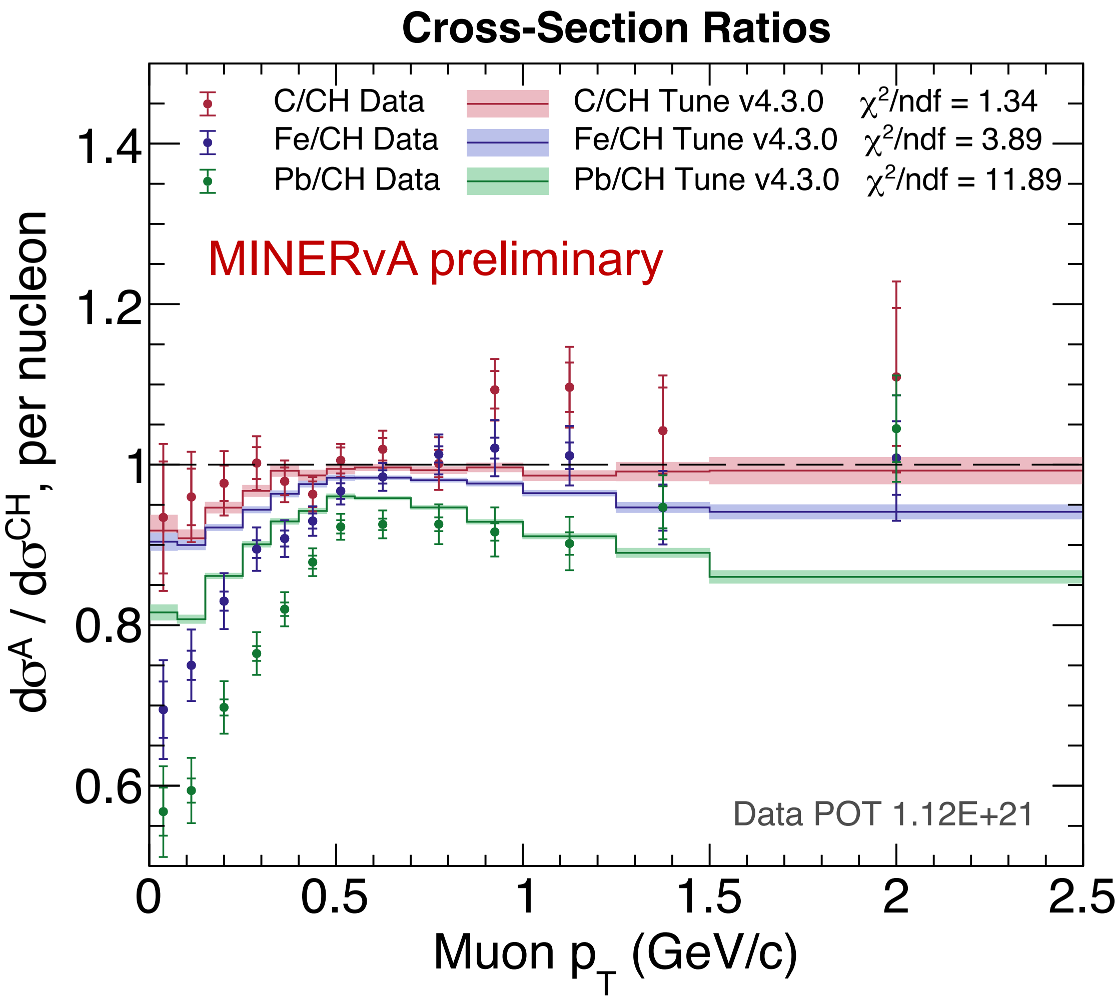
Even better, take a ratio

- Ratios to high-statistics scintillator
  - Cancellation of shared physics and systematics
  - $\lesssim$ 5% total uncertainty (~2% in the peak region)



Even better, take a ratio

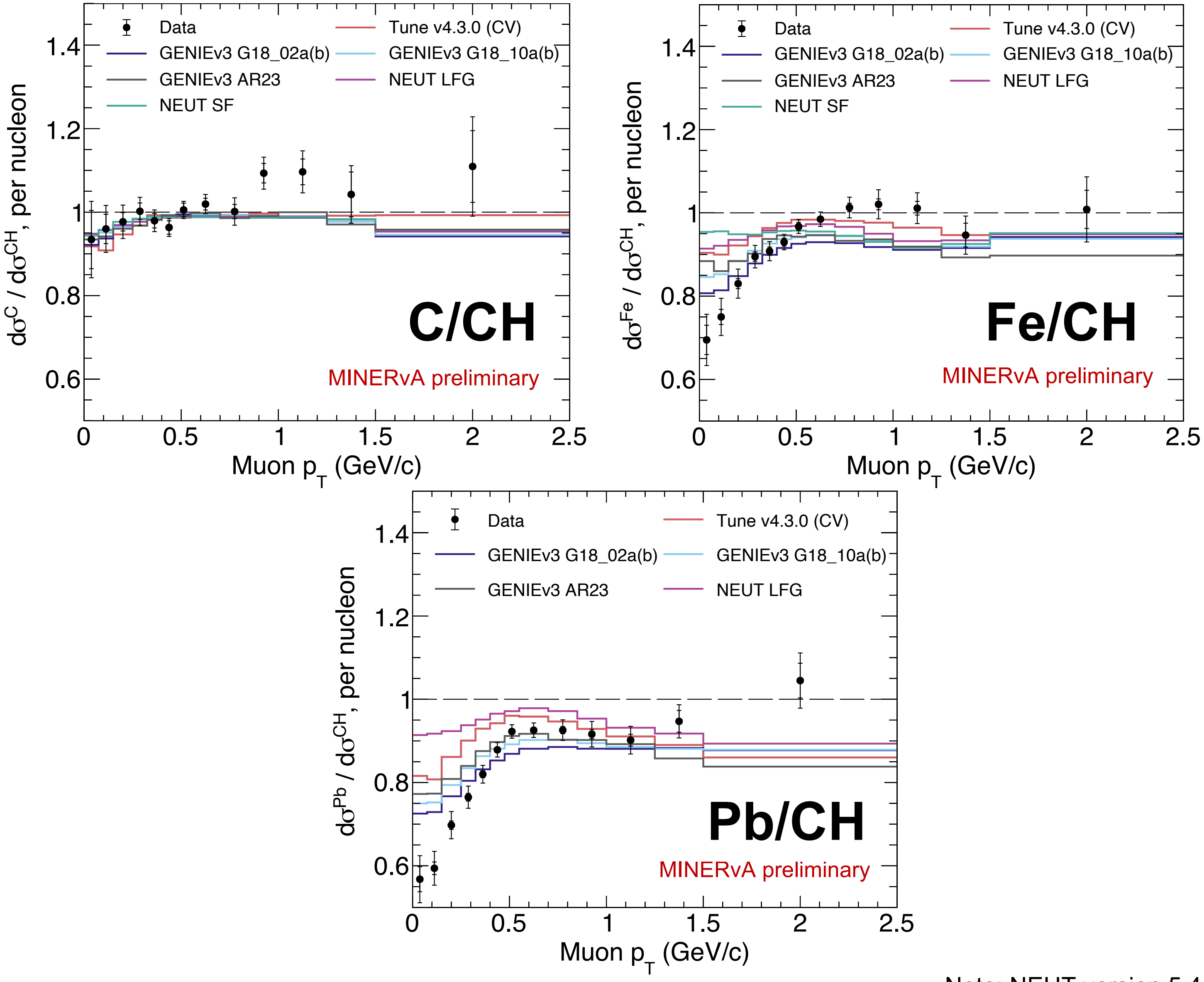
- Ratios to high-statistics scintillator
  - Cancellation of shared physics and systematics
  - $\lesssim$ 5% total uncertainty (~2% in the peak region)
  - More direct information about nuclear effects
- C/CH ratio as a 'cross-check' – expect well modelled and close to unity
  - Effect of diffractive scattering on H in CH at low p_T



Ratios vs models

Data POT 1.12E+21

- Statistical power to distinguish between different models – strong constraint on nuclear effects
- GENIE v3 AR23 (DUNE tune) yield lowest χ^2
- **Clear nuclear dependence in iron and lead, especially at low p_T, not reproduced by any generator**



Note: NEUT version 5.4.1

Ratios vs models

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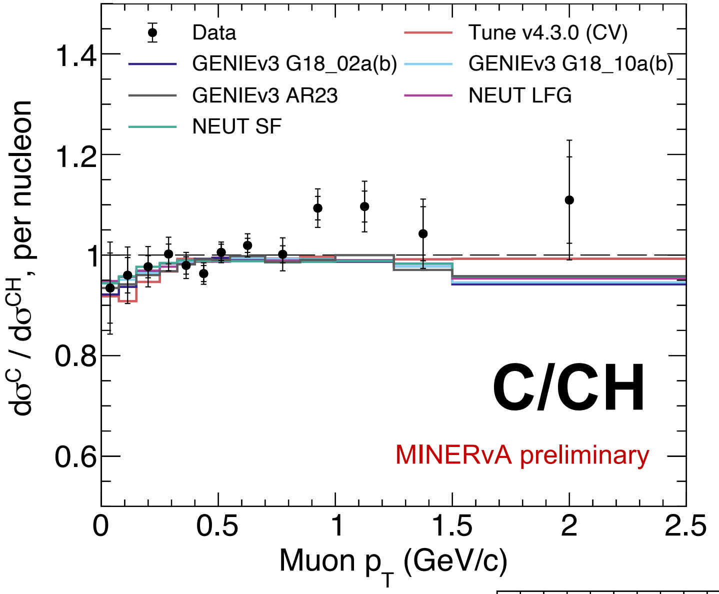
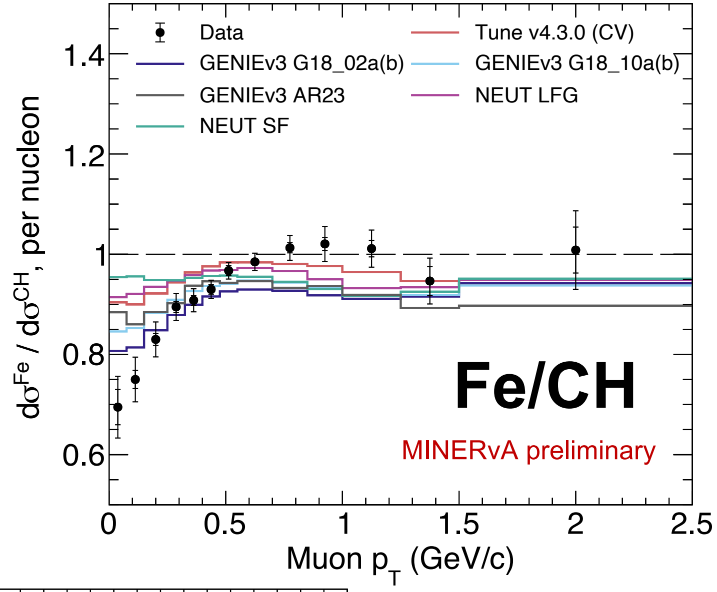
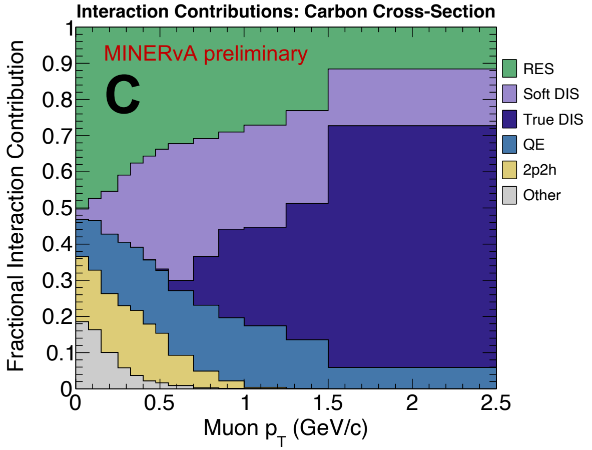
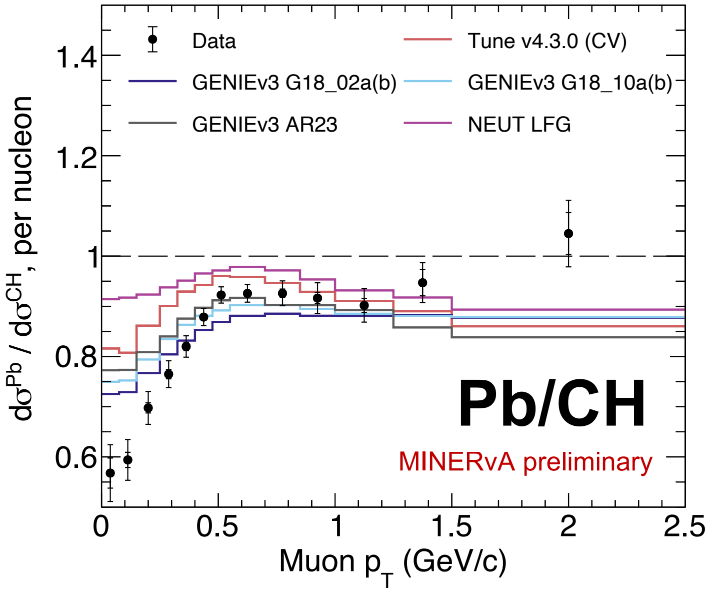
- Statistical power to distinguish between different models – strong constraint on nuclear effects
- GENIE v3 AR23 (DUNE tune) yield lowest χ^2
- **Clear nuclear dependence in iron and lead, especially at low p_T, not reproduced by any generator**
- Low p_T predicted resonance dominated – first peak at pion production in antineutrino beam
    - Stronger nuclear effects needed
- But many processes contribute!









Note: NEUT version 5.4.1

Conclusions

- Neutrino-nucleus interactions are challenging → both theory and measurements needed
- Inclusive measurements benchmark how models for different interaction mechanisms connect to build a comprehensive model
- MINERvA's measurements at average (anti)neutrino energy ~6 GeV provide crucial constraints for higher-energy interactions vs *A* where both measurements and theory are scarce (important for DUNE!)

Conclusions cont'ed

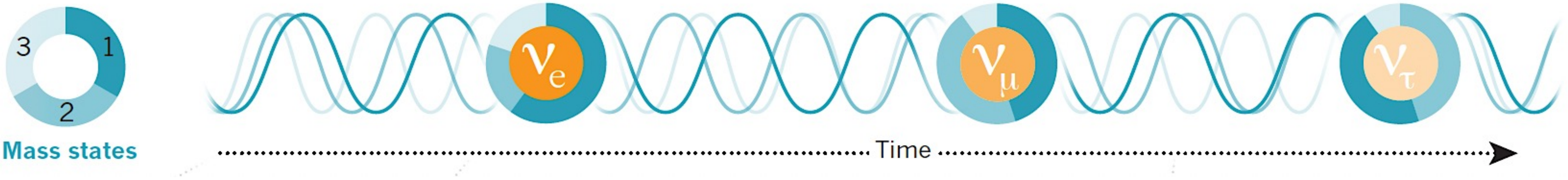
Analysis finishing collaboration review — on arXiv soon!

- For the first time, high-statistics antineutrino inclusive scattering has been measured simultaneously across C, CH, Fe, and Pb
  - C, Fe, and Pb cross-sections in p_T reported with a precision ~10% or less (~5% in the peak), and CH ~6%
  - C/CH, Fe/CH, Pb/CH cross-section ratios ~5% or less (~2% in the peak)
- Strong nuclear effects in Fe and Pb, particularly at low and high p_T not well reproduced by models
- By comparing to MINERvA's more exclusive antineutrino measurements
  - Low p_T: likely more suppression due to nuclear effects in resonance region needed
  - In p_T range ~0.4–0.8 GeV/*c*: indicates underprediction related to quasi-elastic and resonant axial form factors
- Multi-dimensional inclusive analyses and deep inelastic scattering measurements across various targets in the MINERvA pipeline will further clarify the observed trends

MINERvA collaboration

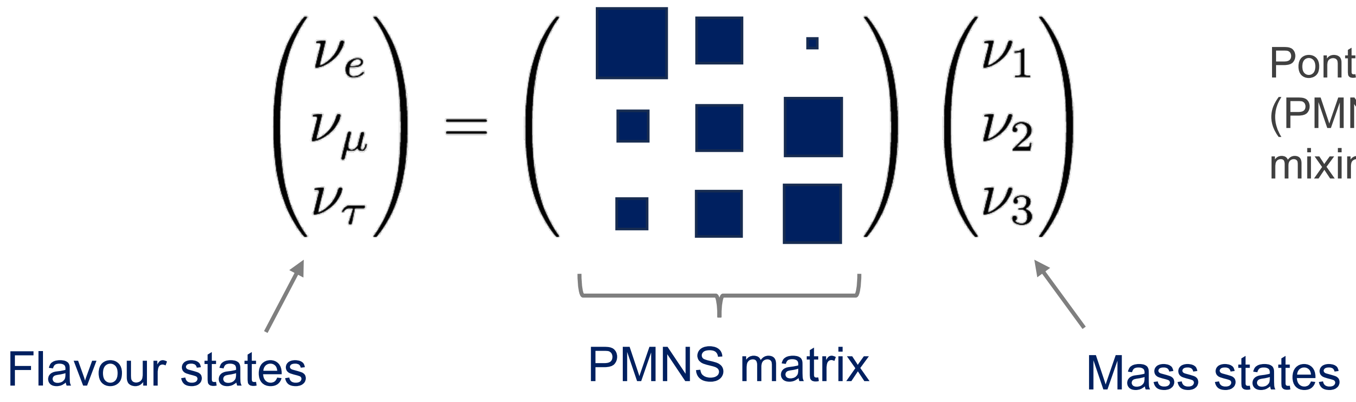
Back-up

But wait… Neutrinos oscillate



Graphic by Nigel Hawtin
2015 Springer Nature Open Access

- As a beam of neutrinos travels, some of them change their flavour
- Detected neutrinos flavours, ν_e, ν_μ, ν_τ, are a superposition of neutrino states with definite mass, ν_1, ν_2, ν_3

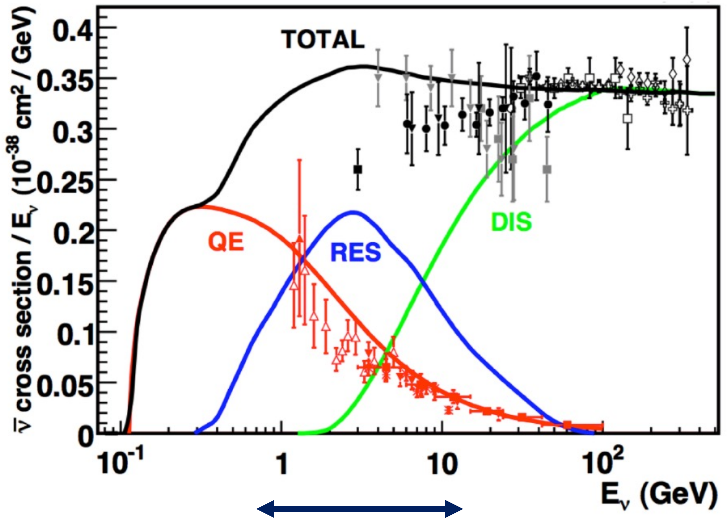


Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix parametrised by three mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and δ_{CP}

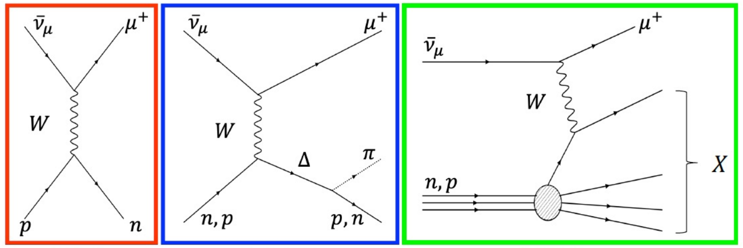
J. A. Formaggio and G. P. Zeller. Rev. Mod. Phys. 84, 1307 (2012).

(Anti)neutrino interactions

- Neutrino-nucleon interactions + effects of the nuclear medium
- Antineutrino scattering (W^-): $(u,c)/(\bar{d},\bar{s}) \rightarrow (d,s)/\ (\bar{u},\bar{c})$



MINERvA

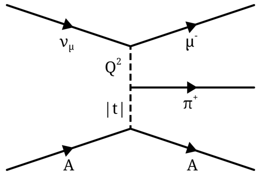


QE RES DIS

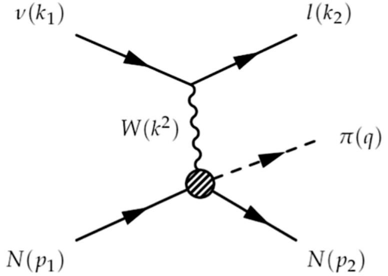
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^0 \rightarrow \mu^+ + p + \pi^-$

$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^0 \rightarrow \mu^+ + n + \pi^0$

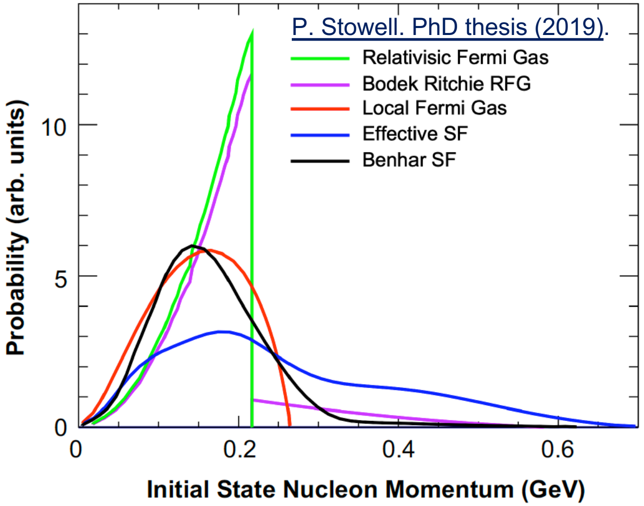
$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^- \rightarrow \mu^+ + n + \pi^-$

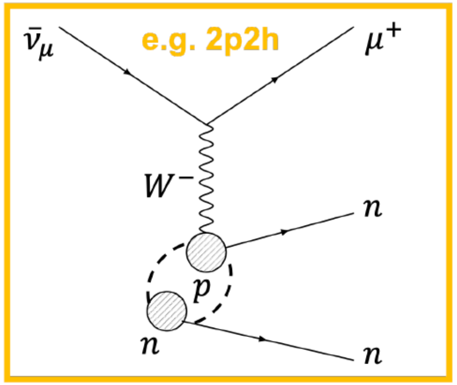


Coherent pion production

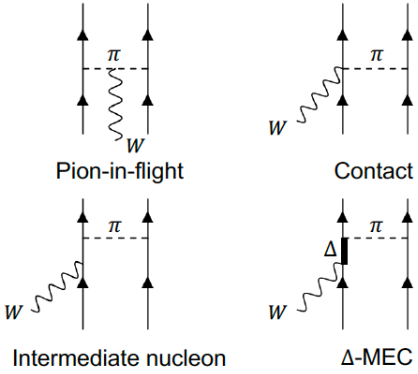


Non-resonant pion production



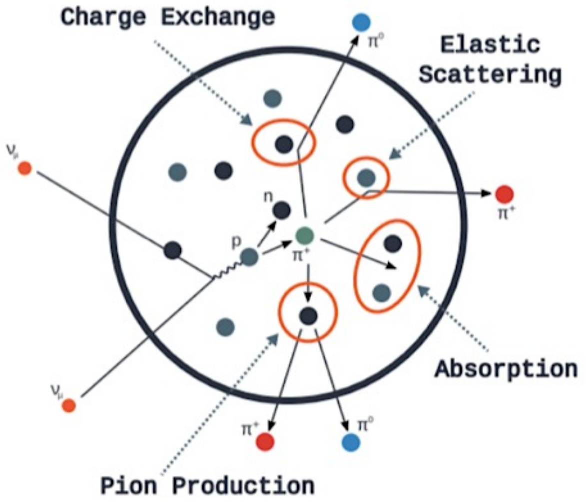


Multi-nucleon effects

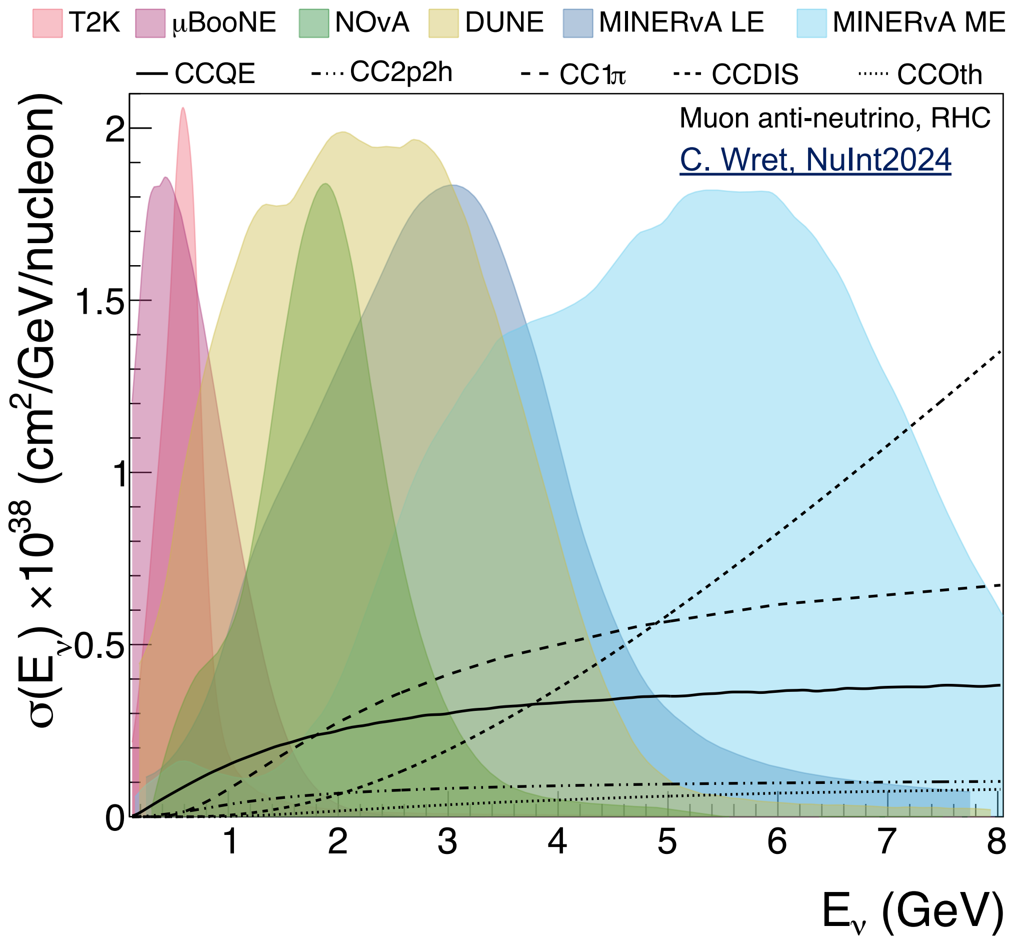


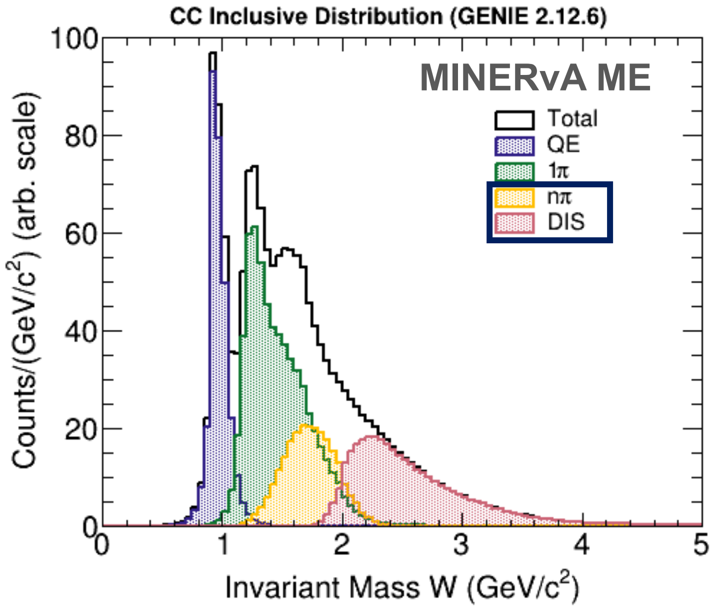
MEC at one-pion-exchange level

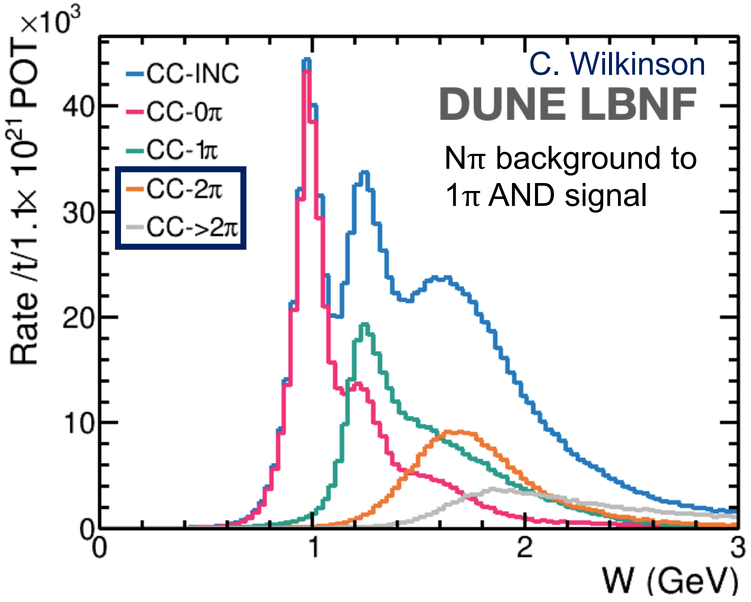
T. Golan, NuSTEC (2015).



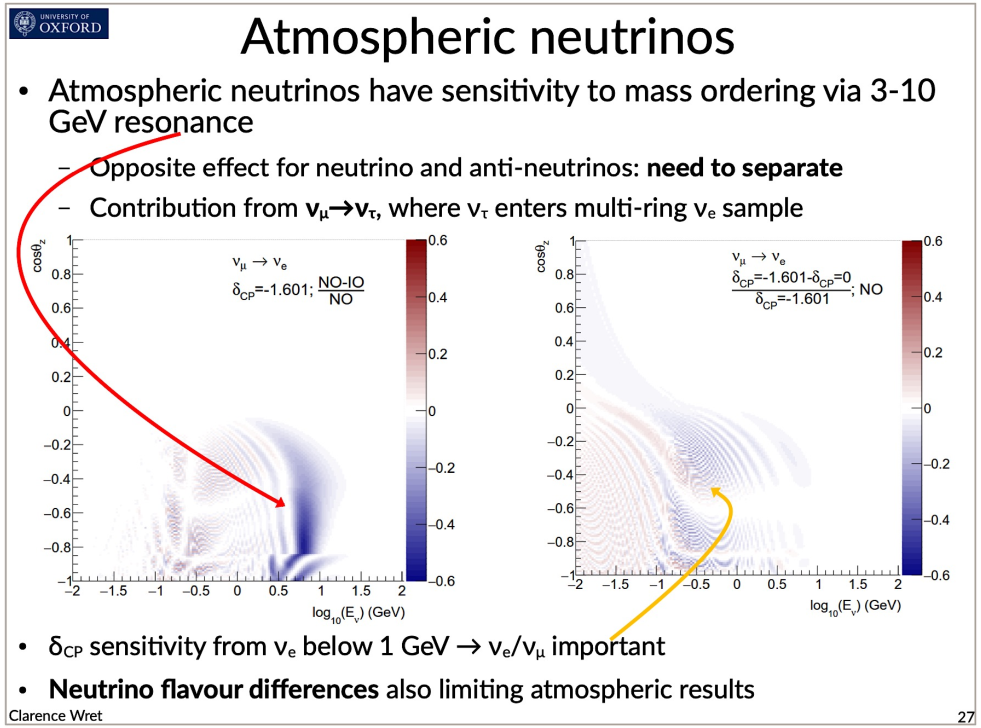
Why do we care?







C. Wret, NuInt 2024



Atmospheric neutrinos

- Atmospheric neutrinos have sensitivity to mass ordering via 3-10 GeV resonance
  - Opposite effect for neutrino and anti-neutrinos: **need to separate**
  - Contribution from $\nu_\mu \rightarrow \nu_\tau$, where ν_τ enters multi-ring ν_e sample
- δ_{CP} sensitivity from ν_e below 1 GeV → ν_e/ν_μ important
- **Neutrino flavour differences** also limiting atmospheric results

Clarence Wret 27

MINERvA resolution

- Spatial resolution ~3.0 mm
- Timing resolution ~3 ns
- Muon momentum resolution

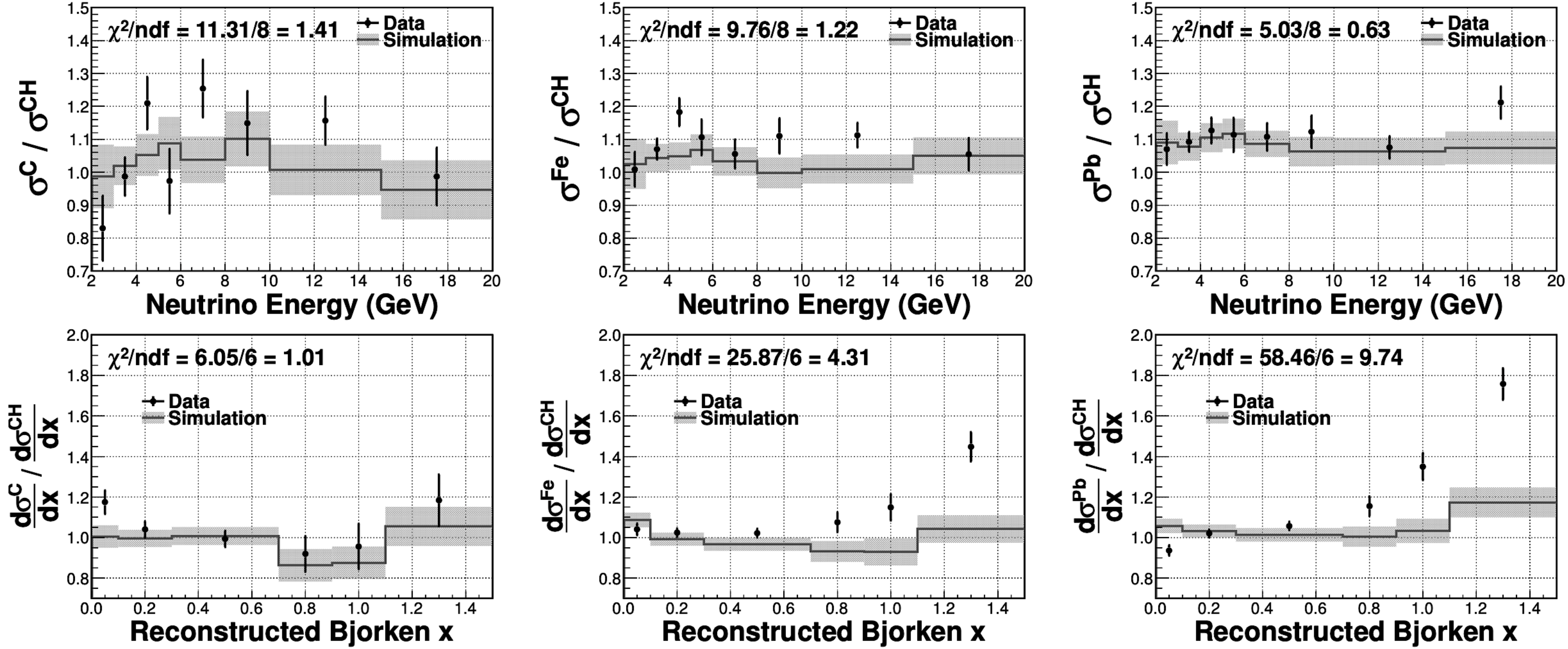
Momentum Range (GeV/c)	MINERvA Only	MINERvA + MINOS
< 2	6%	3.6%
2–6	6%	~5%
> 6	6%	7.9%

- Calorimetric energy resolution $\sigma/E = 0.134 \oplus 0.290/\sqrt{E}$

MINERvA. Nucl. Inst. and Meth. A743 130 (2014).

MINERvA LE inclusive neutrino measurement

5953 events in C, 19 024 in Fe, 23 967 in Pb, and 189 168 in CH

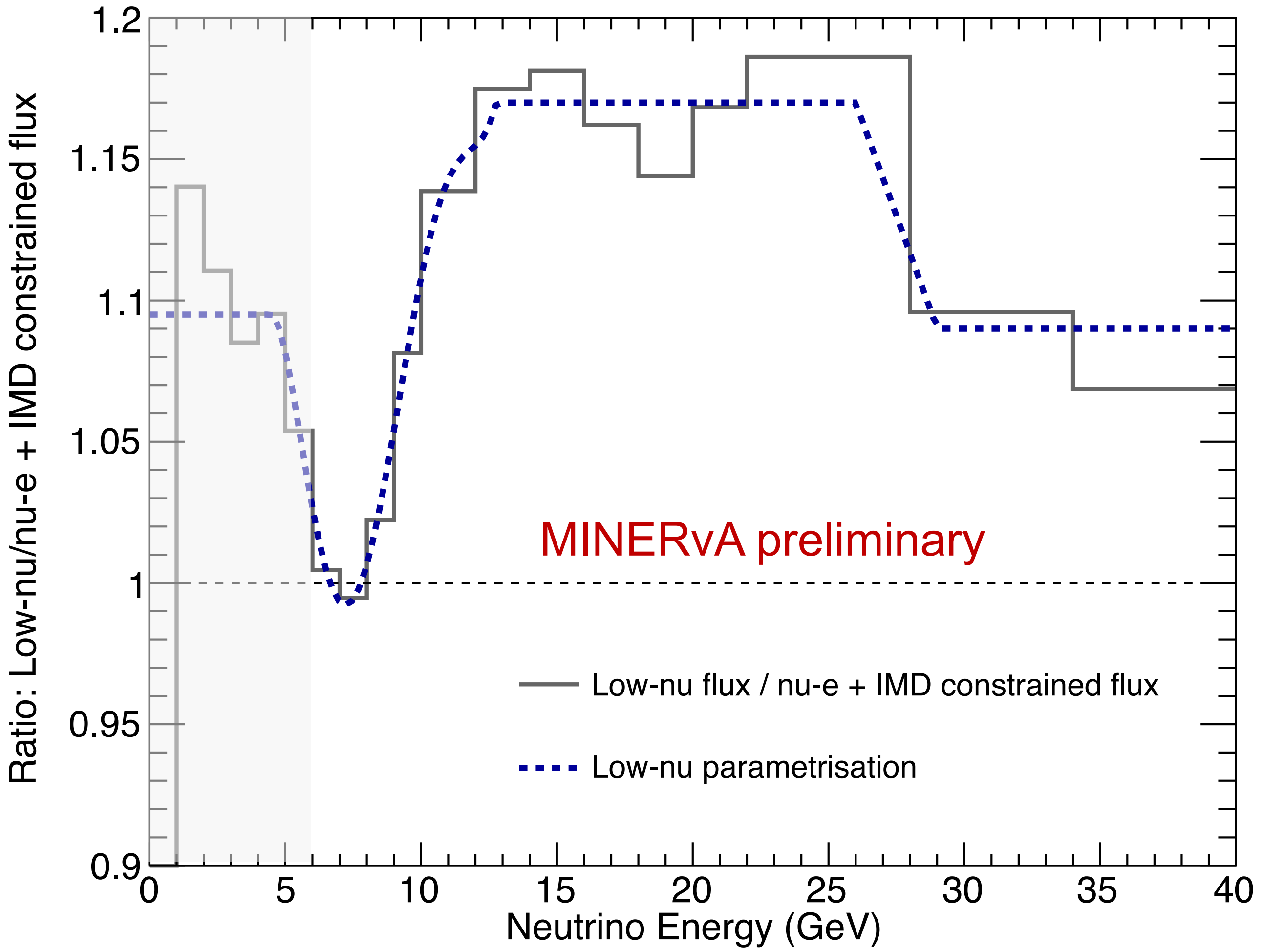


GENIE 2.6.2 prediction

B, Tice (MINERvA). Phys. Rev. Lett. 112, 231801 (2014)

IMPERIAL

Low-nu constraint



- Flux constrained by $\nu/\bar{\nu}$–e and IMD further constrained using parametrised reweight to MINERvA's low-nu measurement above 7.5 GeV
- **Low-nu technique:** Neutrino interactions with low-energy transfer to the nucleus such that the σ ~const. as a function of E_ν
- Fluxes agree at 7.5 GeV
- Above 7.5 GeV low-nu constraint provides stronger leverage than the $\nu/\bar{\nu}$–e constraint, increasing flux by up to 17% in the ~13–26 GeV region relative to the default prediction
- Ties our flux at 30 GeV to world-average cross section there

R. Fine, MINERvA Ph.D. thesis, University of Rochester (2020).

L. Zazueta (MINERvA). Phys. Rev. D 107, 012001 (2023).

Per nucleon cross-section on a particular nucleus

Differential cross-section in bin α for a given nucleus

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

- $\Sigma_j U_{j\alpha}$: **Unfolding matrix**
- $N_{data,j}$: **Selected events**
- $N^{bkgd}_{data,j}$: **Background prediction**
- E_α: **Efficiency**
- ΦT: **Integrated flux times the number of nucleons**
- Δx: **Bin width normalization**

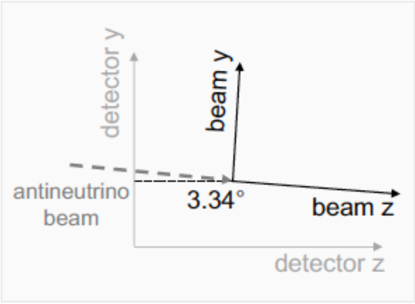
- j represents the reconstructed bin
- α represents the true bin
- x is the quantity we measure

Variables of interest

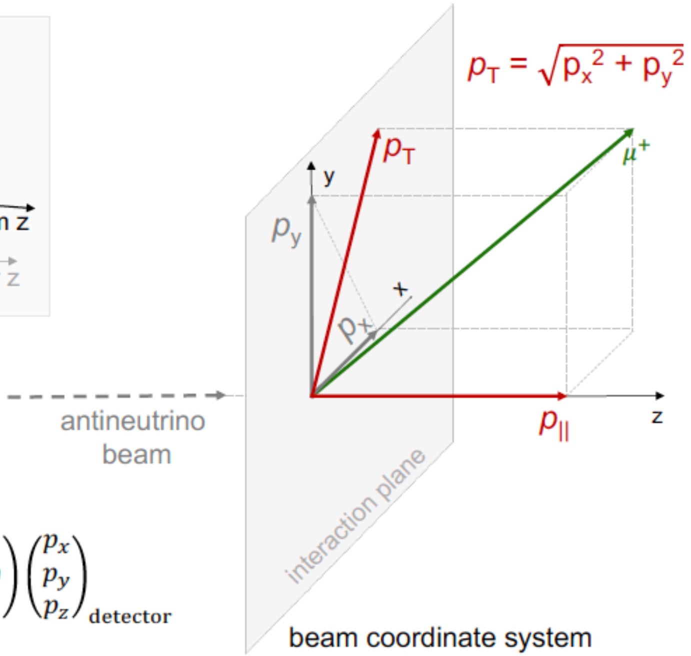
- p_T can be directly related to the four-momentum transfer squared

$$Q^2 \approx p_T^2 \left(1 + \mathcal{O}\left(\frac{E_{\text{recoil}}}{E_\mu}\right)\right)$$

- p_T also serves as a direct proxy to the antimuon angle relative to the antineutrino beam
- Bjorken x can be interpreted as the fraction of the nucleon momentum carried by the struck quark in a frame where the nucleon momentum is very large (and its mass can be therefore neglected)



detector-to-beam coordinate system



beam coordinate system

$$\begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}_{\text{beam}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}_{\text{detector}}$$

$$x = \frac{Q^2}{2p_N \cdot q} \overset{\text{lab}}{=} \frac{Q^2}{2m_N E_{\text{recoil}}}$$

where $Q^2 = -q^2 = -(p_{\bar{\nu}} - p_\mu)^2 = 2E_{\bar{\nu}}(E_\mu - |\mathbf{p}_\mu| \cos\theta_\mu) - m_\mu^2$

Variable	Bin edges													
p_T (GeV/c)	0.0	0.075	0.15	0.25	0.325	0.4	0.475	0.55	0.7	0.85	1.0	1.25	1.5	2.5
Bjorken x	0.001	0.05	0.1	0.2	0.4	1.0	2.2							

For Soft/True DIS invariant mass W separation:

$$W^2 = -Q^2 + 2E_{\text{recoil}} m_N + m_N^2$$

MINERvA tune v4.3.0

- Based on GENIE 2.12.6
  - QE – Llewellyn-Smith formalism with the vector form factors modeled using the BBBA05 model
  - RES and coherent – Rein-Sehgal model
  - DIS – a leading order model with the Bodek-Yang prescription
  - Nuclear environment – relativistic Fermi gas with additional Bodek-Ritchie high momentum tail
  - FSI – INTRANUKE-hA

- With modifications based on MINERvA and bubble chamber data:
  - Valencia RPA (modified for different materials) Phys. Rev. C **70**, 055503 (2004). arXiv:1705.02932 [hep-ex] (2017). Phys. Rev. C **80**, 065501 (2009).
  - LE low recoil fit Valencia 2p2h Phys. Rev. Lett. **116**, 071802 (2016). Phys. Rev. Lett. **120**, 221805 (2018).
  - 43% nominal non-resonant pion production and M_A^{RES}= 0.94 GeV/c^2, CCResNorm 1.15 based on reanalysis of deuterium bubble chamber data Eur. Phys. J. C. 76, 474 (2016)
  - ME coherent reweight $\mathcal{F}$(true π angle, true π KE) Phys. Rev. Lett. **131**, 051801 (2023).
  - Diffractive weight – normalisation of coherent events in scintillator increased by 43.7% Phys. Rev. D **85**, 073003 (2012).
  - ME nuCC1π^+ low Q^2 suppresion applied to π^- for $W < 1.4$ GeV/c^2 for all nuclei except hydrogen Phys. Rev. Lett. **131**, 011801 (2023).

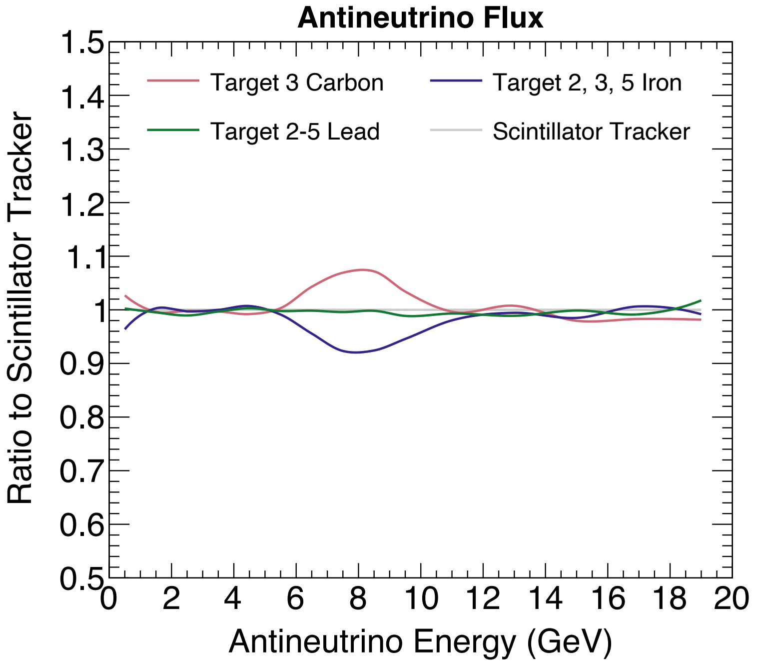
Note: v2 model has low Q^2 suppression based on LE MINERvA data Phys. Rev. D **100**, 072005 (2019).

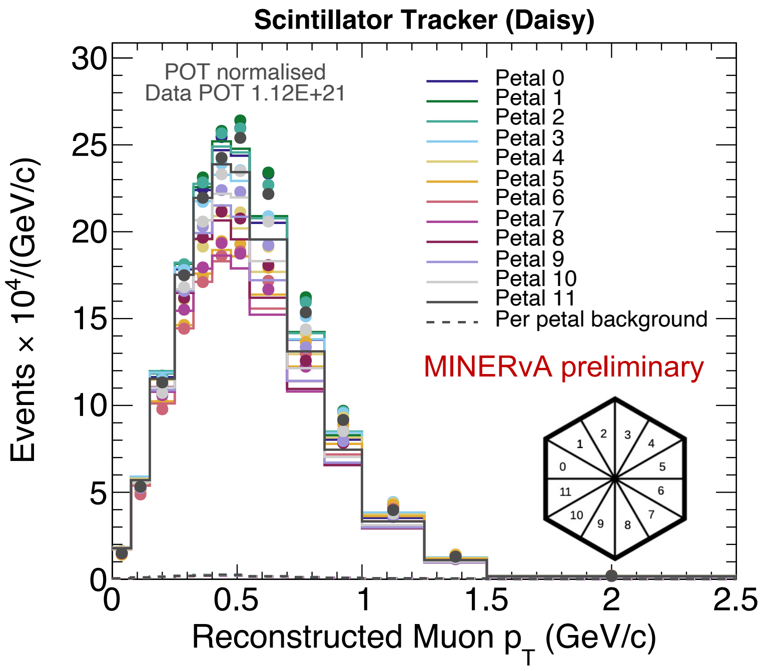
Target vs tracker flux – “daisy” technique

- NuMI beam pointed downwards → transverse center of the beam changes as a function of the longitudinal position
- Various nuclear targets are not symmetric with respect to the detector axis → each ‘sees’ a slightly different flux
- In cross-section ratios, use hydrocarbon flux ‘shadowing’ the nuclear target region
- *In practise:* match the target flux by taking a linear combination of the tracker fluxes extracted in 12 geometrical bins in *xy* (‘daisy’ bin)
    - Tracker analysis performed in the 12 geometrical bins with corrections to match individual target combinations applied after efficiency correction

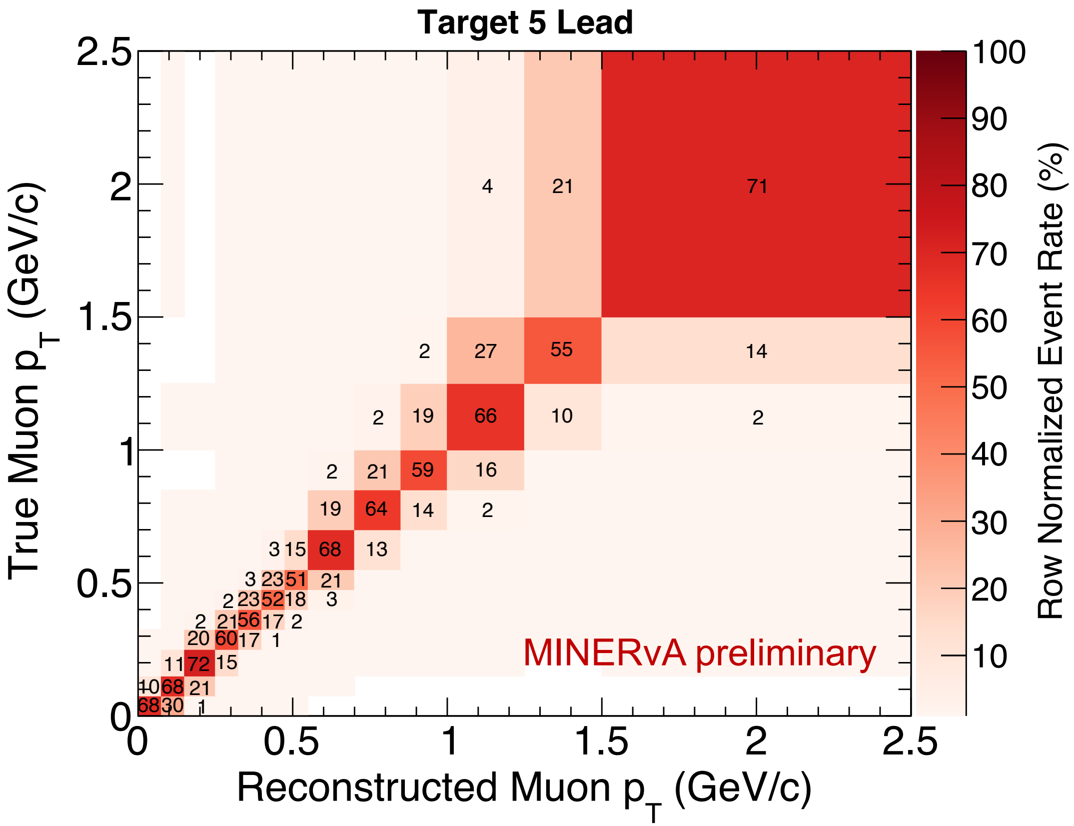
$$\chi^2_{reg} = \chi^2 + \lambda \left(\frac{N_i}{\sum N_i} \right) (p_i - 1)^2$$

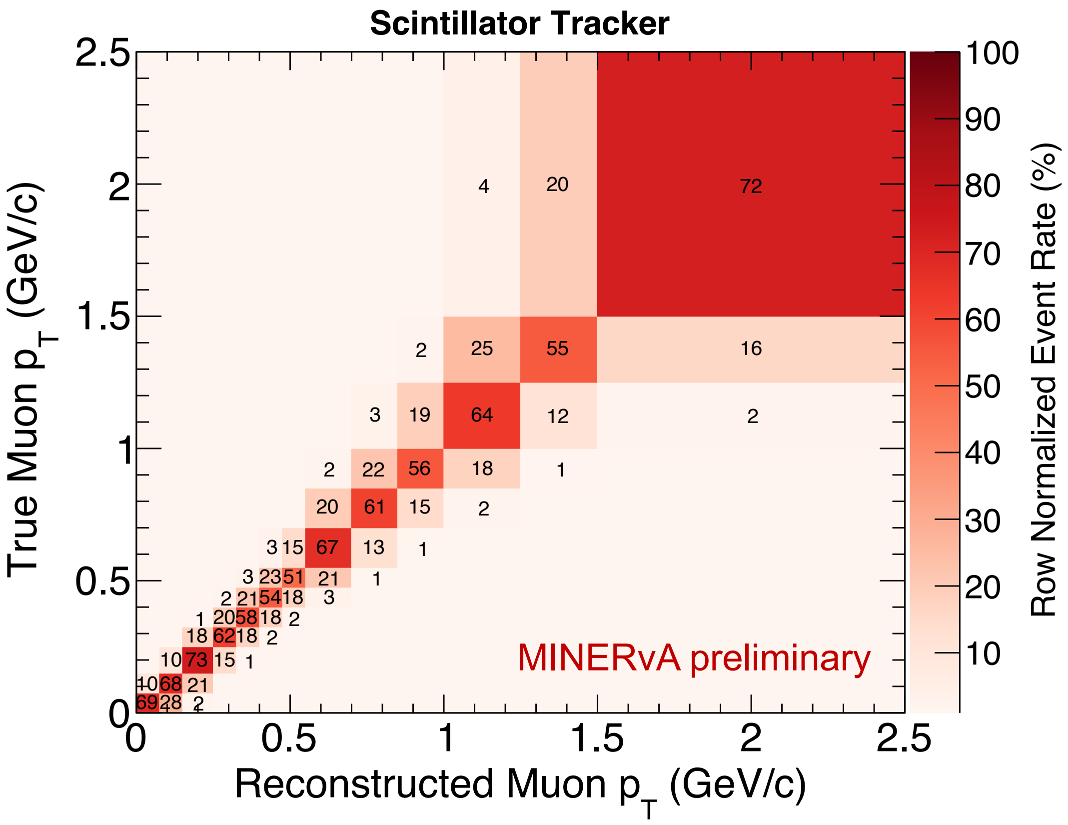
N_i : the number of events in a petal i
p_i : the scale factor of petal I
λ : regularization



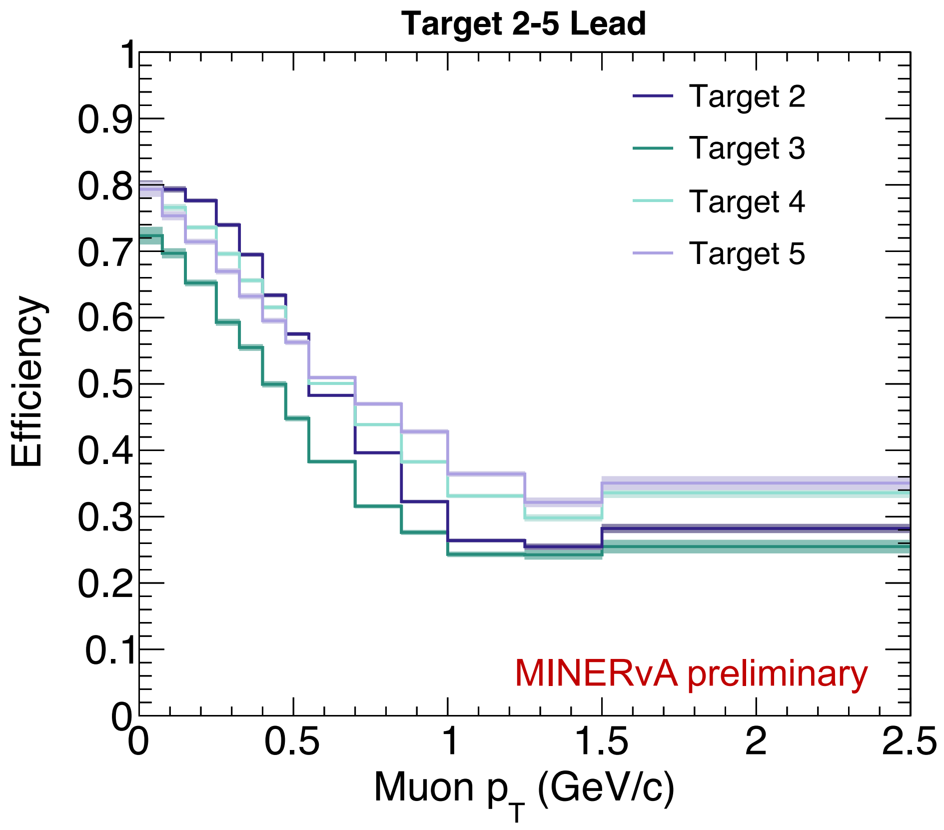


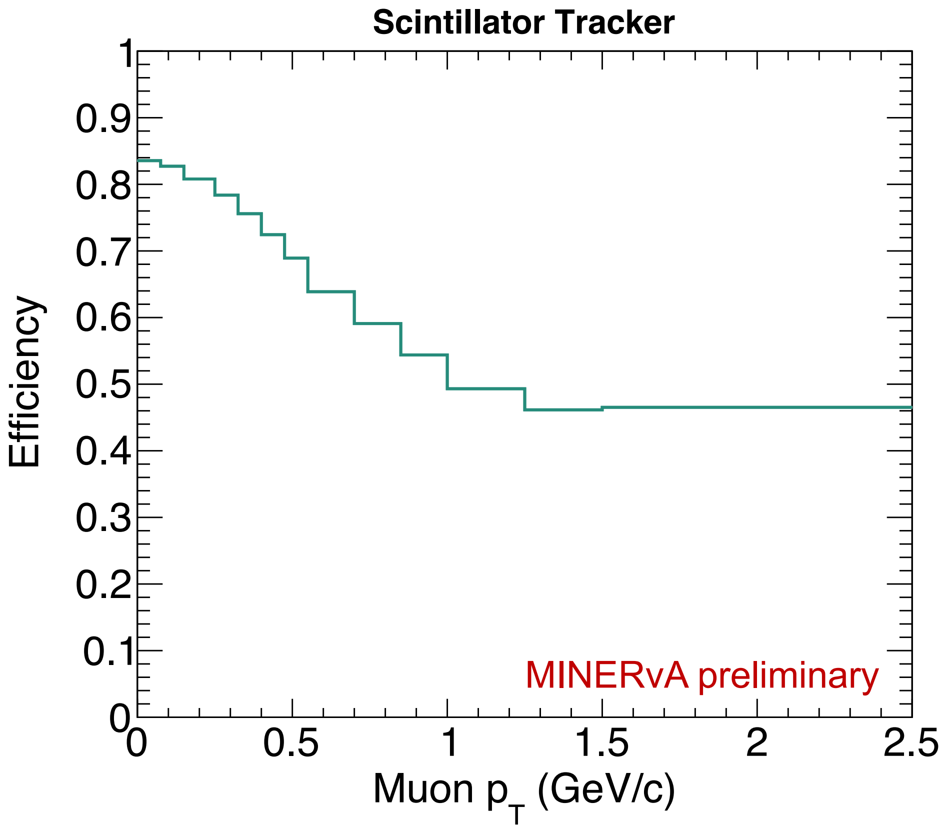
Migration


Target 5 Lead
True Muon p_T (GeV/c)
Reconstructed Muon p_T (GeV/c)
Row Normalized Event Rate (%)
MINERvA preliminary


Scintillator Tracker
True Muon p_T (GeV/c)
Reconstructed Muon p_T (GeV/c)
Row Normalized Event Rate (%)
MINERvA preliminary

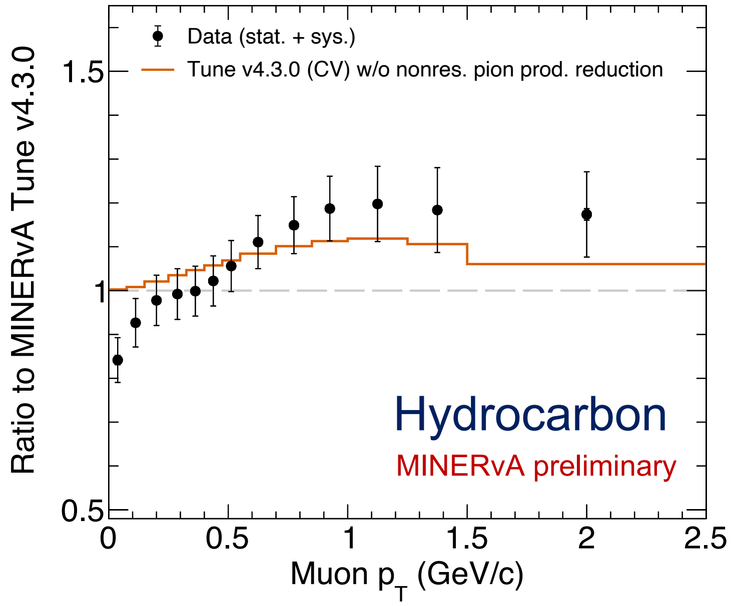
Efficiency

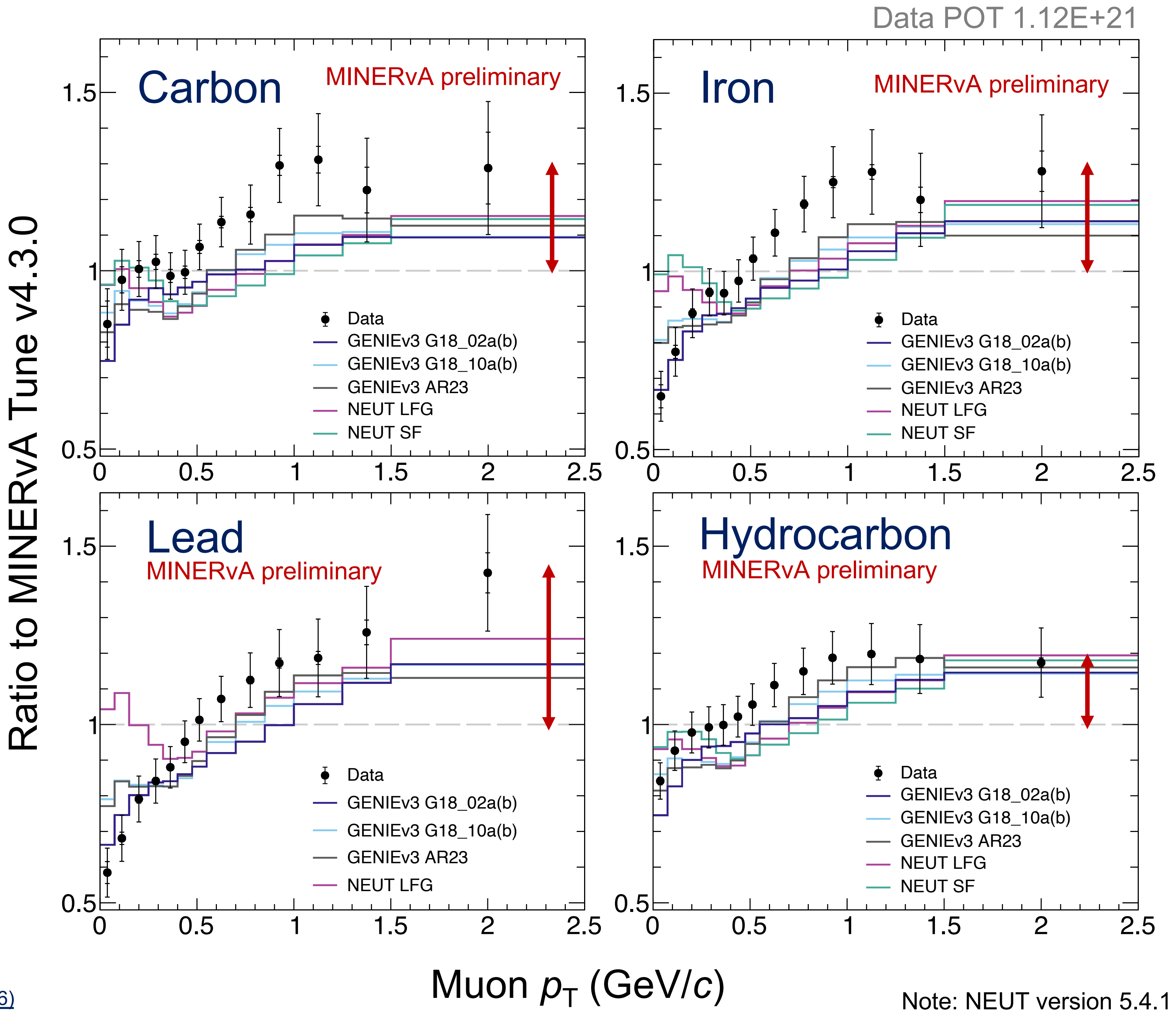

Target 2-5 Lead
Target 2
Target 3
Target 4
Target 5
Efficiency
Muon p_T (GeV/c)
MINERvA preliminary
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5
2
2.5


Scintillator Tracker
Efficiency
Muon p_T (GeV/c)
MINERvA preliminary
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5
2
2.5

(Mid- to) High-p_T

- (Mid- to) high-p_T region shows underprediction vs base model
  - High-p_T not tuned by any MINERvA measurements
  - Non-resonant pion production reduced based on deuterium data* also applied for W > 1.2 GeV/c² (beyond Δ region) and Q² > 1 (GeV/c)²





Note: NEUT version 5.4.1

*P. Rodrigues, C. Wilkinson, & K. McFarland. Eur. Phys. J. C. 76, 474 (2016)

Low-p_T (carbon)

NUISANCE to rescue

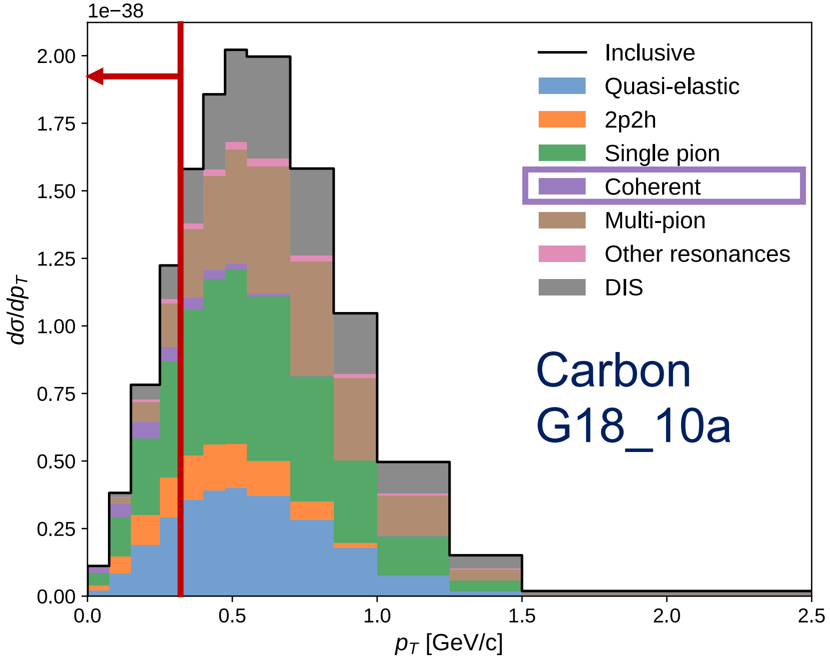
P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et. al., JINST 12 P01016 (2017).

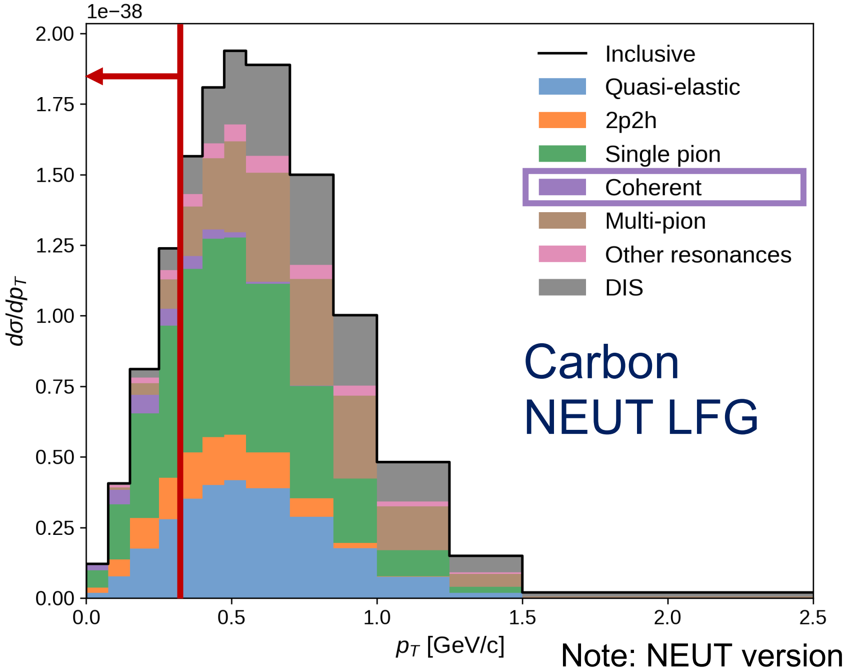
Carbon G18_10a

Subcategory	Bin 1	Bin 2	Bin 3	Bin 4
Quasi-elastic	2.73E-39 (18.34%)	1.52E-37 (22.38%)	1.90E-36 (24.29%)	9.22E-35 (23.83%)
2p2h	2.58E-39 (17.32%)	1.09E-37 (16.02%)	1.10E-36 (14.06%)	4.66E-35 (12.06%)
Single pion	6.14E-39 (41.27%)	2.62E-37 (38.53%)	2.84E-36 (36.31%)	1.36E-34 (35.04%)
Diffractive	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)
Coherent	2.34E-39 (15.72%)	8.34E-38 (12.28%)	6.01E-37 (7.69%)	1.74E-35 (4.50%)
Multi-pion	6.76E-40 (4.54%)	4.17E-38 (6.14%)	7.50E-37 (9.59%)	5.09E-35 (13.16%)
Other resonances	1.26E-40 (0.84%)	6.32E-39 (0.93%)	8.52E-38 (1.09%)	4.81E-36 (1.24%)
DIS	2.92E-40 (1.96%)	2.52E-38 (3.71%)	5.45E-37 (6.97%)	3.93E-35 (10.17%)

Carbon NEUT LFG

Subcategory	Bin 1	Bin 2	Bin 3	Bin 4
Quasi-elastic	2.44E-39 (15.06%)	1.36E-37 (18.81%)	1.76E-36 (21.68%)	8.83E-35 (22.57%)
2p2h	2.54E-39 (15.67%)	1.07E-37 (14.75%)	1.08E-36 (13.31%)	4.63E-35 (11.82%)
Single pion	8.22E-39 (50.77%)	3.49E-37 (48.17%)	3.70E-36 (45.62%)	1.70E-34 (43.49%)
Diffractive	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)
Coherent	2.53E-39 (15.64%)	8.98E-38 (12.41%)	6.51E-37 (8.02%)	1.89E-35 (4.83%)
Multi-pion	8.23E-41 (0.51%)	1.58E-38 (2.18%)	4.23E-37 (5.22%)	3.29E-35 (8.41%)
Other resonances	3.45E-40 (2.13%)	1.57E-38 (2.18%)	1.94E-37 (2.39%)	1.03E-35 (2.63%)
DIS	3.43E-41 (0.21%)	1.09E-38 (1.50%)	3.05E-37 (3.76%)	2.45E-35 (6.26%)





Note: NEUT version 5.4.1

Cross-sections vs models

Low-p_T (lead)

NUISANCE to rescue

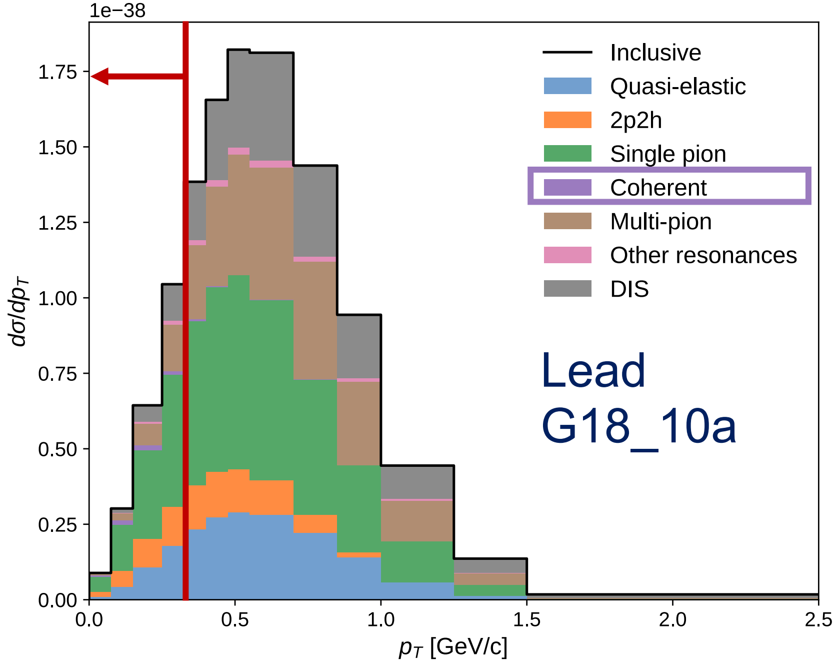
P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et. al., JINST 12 P01016 (2017),

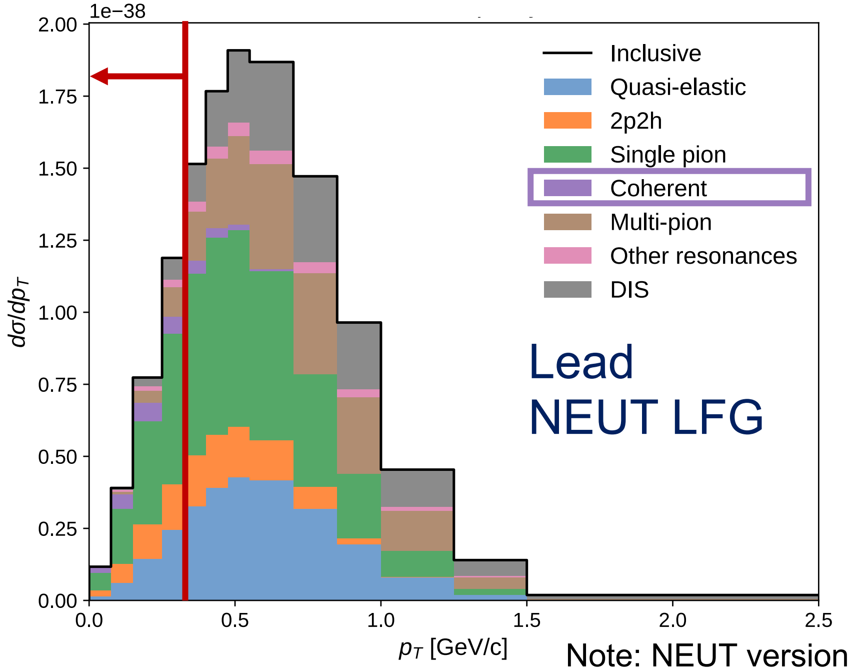
Lead
G18_10a

Subcategory	Bin 1	Bin 2	Bin 3	Bin 4
Quasi-elastic	1.37E-39 (11.54%)	7.66E-38 (14.25%)	1.07E-36 (16.55%)	5.64E-35 (17.07%)
2p2h	2.25E-39 (18.98%)	9.38E-38 (17.45%)	9.57E-37 (14.87%)	4.09E-35 (12.38%)
Single pion	6.46E-39 (54.59%)	2.73E-37 (50.76%)	2.94E-36 (45.65%)	1.38E-34 (41.90%)
Diffractive	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)
Coherent	7.46E-40 (6.31%)	2.41E-38 (4.48%)	1.50E-37 (2.33%)	3.59E-36 (1.09%)
Multi-pion	6.32E-40 (5.34%)	4.04E-38 (7.52%)	7.27E-37 (11.29%)	4.91E-35 (14.87%)
Other resonances	1.00E-40 (0.85%)	4.99E-39 (0.93%)	6.75E-38 (1.05%)	3.76E-36 (1.14%)
DIS	2.84E-40 (2.40%)	2.47E-38 (4.60%)	5.32E-37 (8.26%)	3.82E-35 (11.56%)

Lead
NEUT LFG

Subcategory	Bin 1	Bin 2	Bin 3	Bin 4
Quasi-elastic	1.93E-39 (12.38%)	1.09E-37 (15.69%)	1.45E-36 (18.78%)	7.73E-35 (20.57%)
2p2h	2.89E-39 (18.49%)	1.19E-37 (17.12%)	1.19E-36 (15.37%)	5.03E-35 (13.38%)
Single pion	7.89E-39 (50.53%)	3.38E-37 (48.67%)	3.57E-36 (46.17%)	1.65E-34 (43.97%)
Diffractive	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)	0.00E+00 (0.00%)
Coherent	2.51E-39 (16.09%)	8.97E-38 (12.93%)	6.50E-37 (8.40%)	1.86E-35 (4.95%)
Multi-pion	8.39E-41 (0.54%)	1.57E-38 (2.27%)	4.17E-37 (5.39%)	3.21E-35 (8.55%)
Other resonances	2.72E-40 (1.74%)	1.23E-38 (1.77%)	1.53E-37 (1.98%)	8.12E-36 (2.16%)
DIS	3.46E-41 (0.22%)	1.08E-38 (1.55%)	3.03E-37 (3.92%)	2.41E-35 (6.42%)

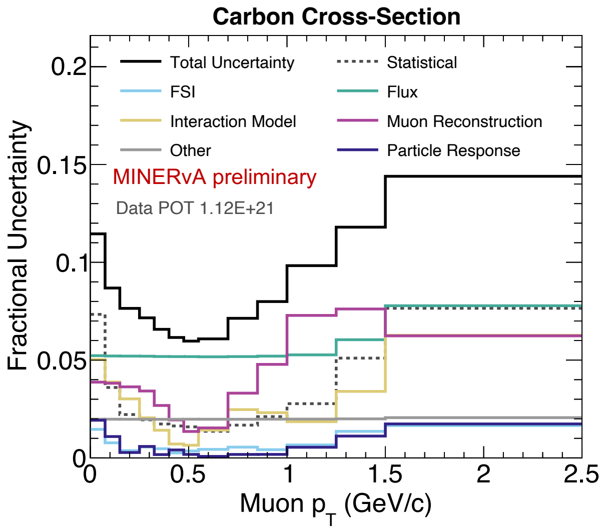


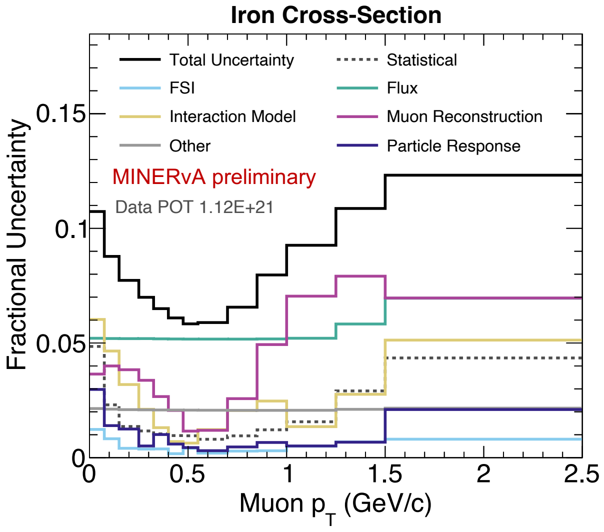


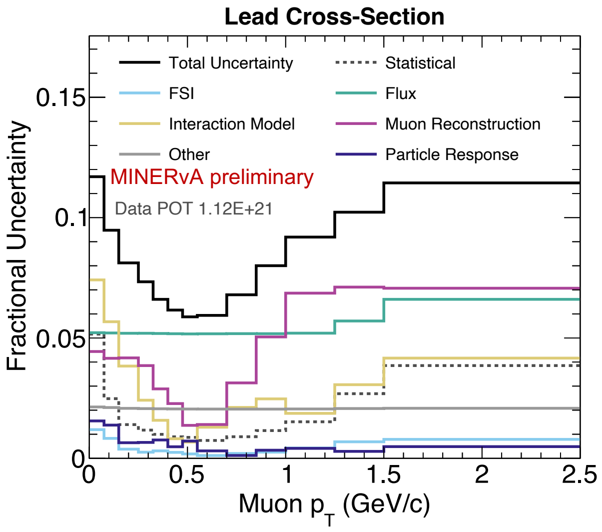
Note: NEUT version 5.4.1

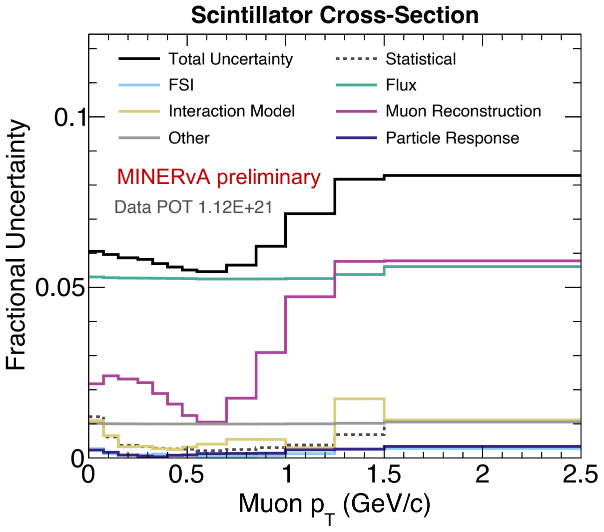
Cross-sections: fractional uncertainties

- Leading: flux & muon reconstruction
- Interaction model: GENIE parameters (leading MaRES) + MINERvA Tune reweights (conservative, especially targets)



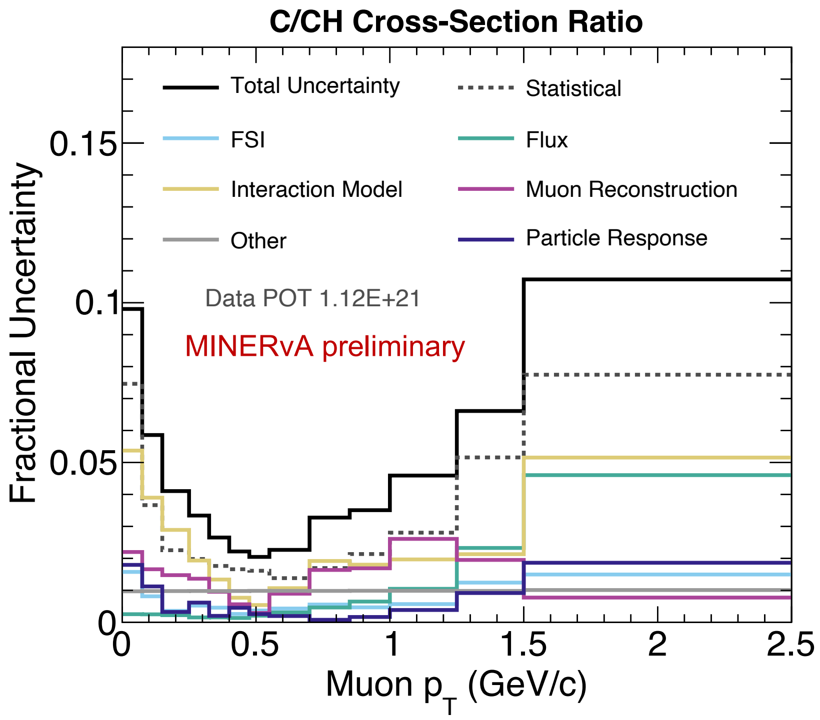


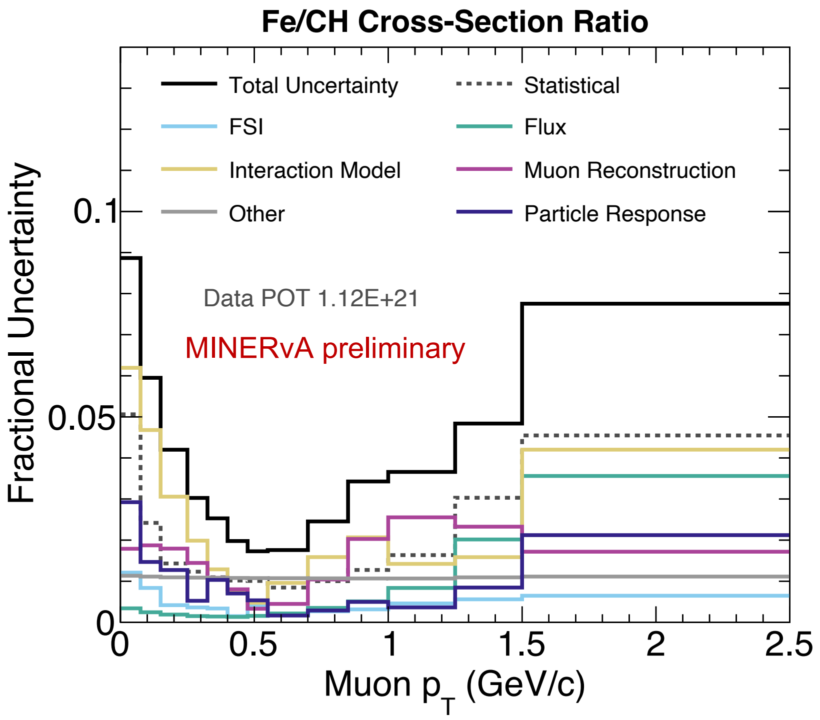


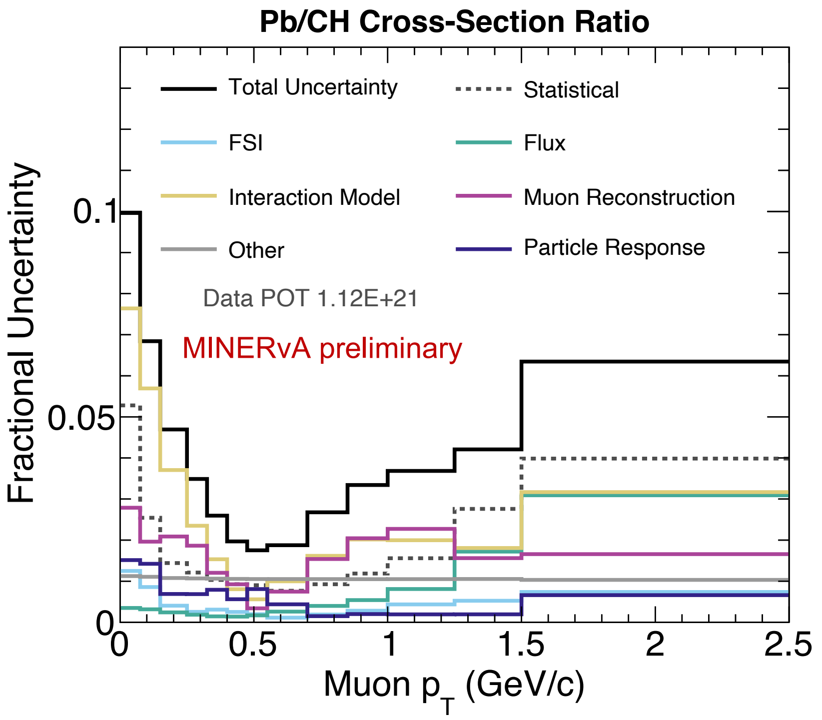


~5–6% total uncertainty in the peak of the distribution
~10% or less overall (targets), scintillator ~6%

Cross-section ratios: fractional uncertainties







~2% total uncertainty in the peak of the distribution
~5% or less overall

GENIE v3 models

GENIE Model Configuration Comparison

Feature / Model Component	G18_02a_02_11a (Legacy)	G18_10a_02_11a (Modern Default)	AR23_20i_00_000 (DUNE Baseline)
GENIE Version	v3.0.6+	v3.0.6+	v3.2.0+
Nuclear Model	Relativistic Fermi Gas (RFG) with Bodek–Ritchie tail	Valencia Local Fermi Gas (LFG) with spectral function	Valencia LFG with high-momentum tail (SRC approximation)
1p1h (Quasielastic) Model	Llewellyn-Smith with dipole form factors	Valencia with default form factors	Valencia with z-expansion form factors
2p2h (MEC) Model	Empirical MEC tuned to MiniBooNE	Valencia SuSAv2	Valencia SuSAv2 (tuning flexibility for DUNE systematics)
Resonant (RES) Model	Rein–Sehgal	Berger–Sehgal	Berger–Sehgal
Coherent (COH) Model	Rein–Sehgal	Berger–Sehgal	Berger–Sehgal
Final State Interactions (FSI)	hA2018	hA2018	hA2018 (default), but DUNE also studies hN, INCL++, Geant4
Deep Inelastic Scattering (DIS)	Bodek–Yang	Bodek–Yang	Bodek–Yang
Hadronization Model	AGKY/PYTHIA (default settings)	AGKY/PYTHIA (default)	AGKY with low-W tuning using bubble chamber data

RES: mainly affected by the Graczyk–Sobczyk form factors providing the necessary input for the axial and vector form factors.

G18_02 and G18_10 also include a tuning fitting scale factors for resonances, and 1 and 2-pion non-resonant pion production process. It also includes resonances up to W of 1.93 GeV/c^2 mixed with DIS model interactions, after which all events are from the DIS models.

NEUT 5.4.1

QE:

- **LFG:** *Nieves et al.* Local Fermi Gas
- **SF:** *Benhar et al.* Spectral Function

2p2h: *Nieves et al.*

RES: Rein-Sehgal model with Graczyk-Sobczyk form factors

COH: Berger-Sehgal

SIS and DIS: GRV98 PDF with Bodel-Yang correction, hadron multiplicity by Pythia v5.72 (W > 2 GeV) or a custom model (W < 2 GeV)

FSI: pion FSI *Salcedo et al.* cascade model, nucleon FSI based on *Bertini et al*. cascade model

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