

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

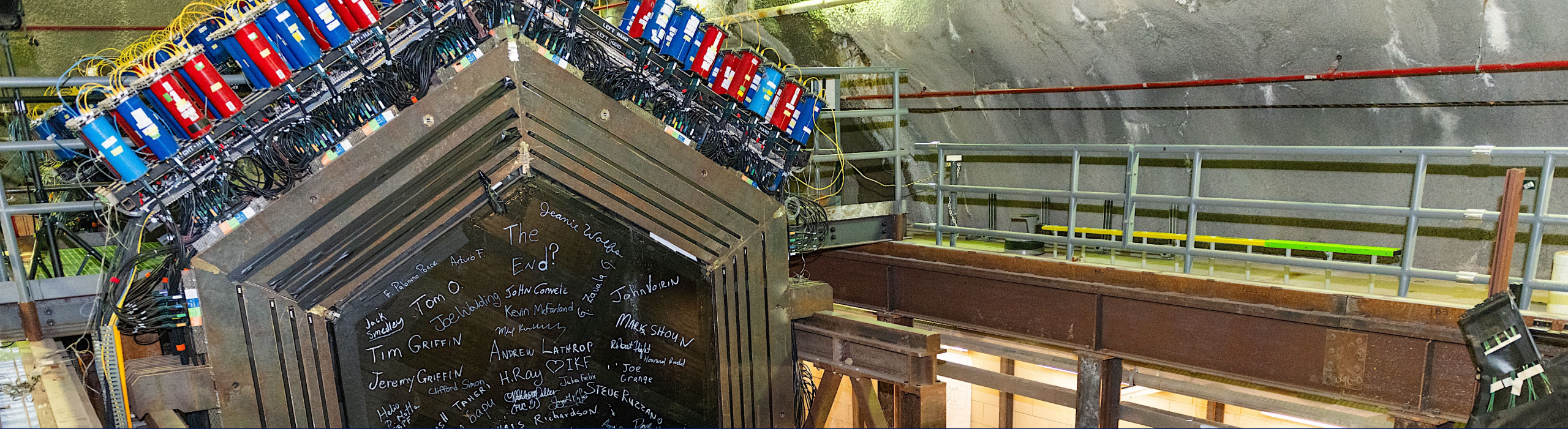
Anežka Klustová

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IMPERIAL

PPRC Seminar
Queen Mary University of London
March 25th, 2026



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(Well, from C to Pb really...)

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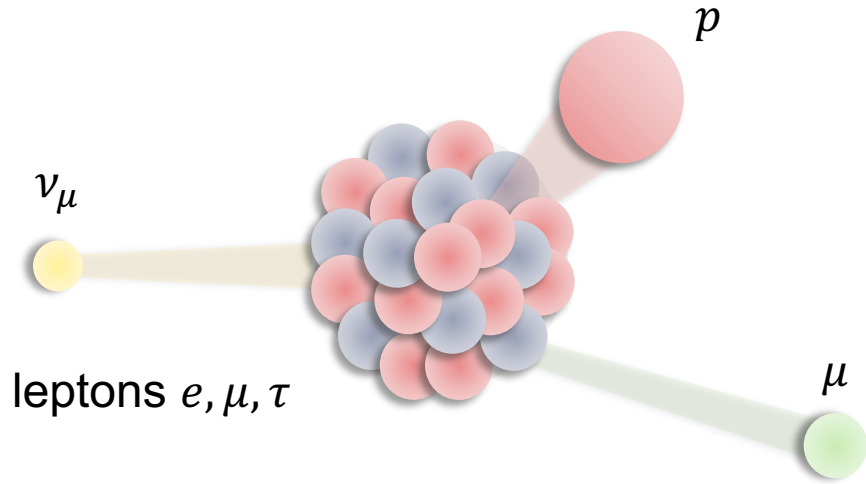
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Today's story

1. Neutrinos 101 & the challenge of neutrino–nucleus scattering
2. How MINERvA enables precision measurements
3. Measurement of inclusive antineutrino scattering across nuclei

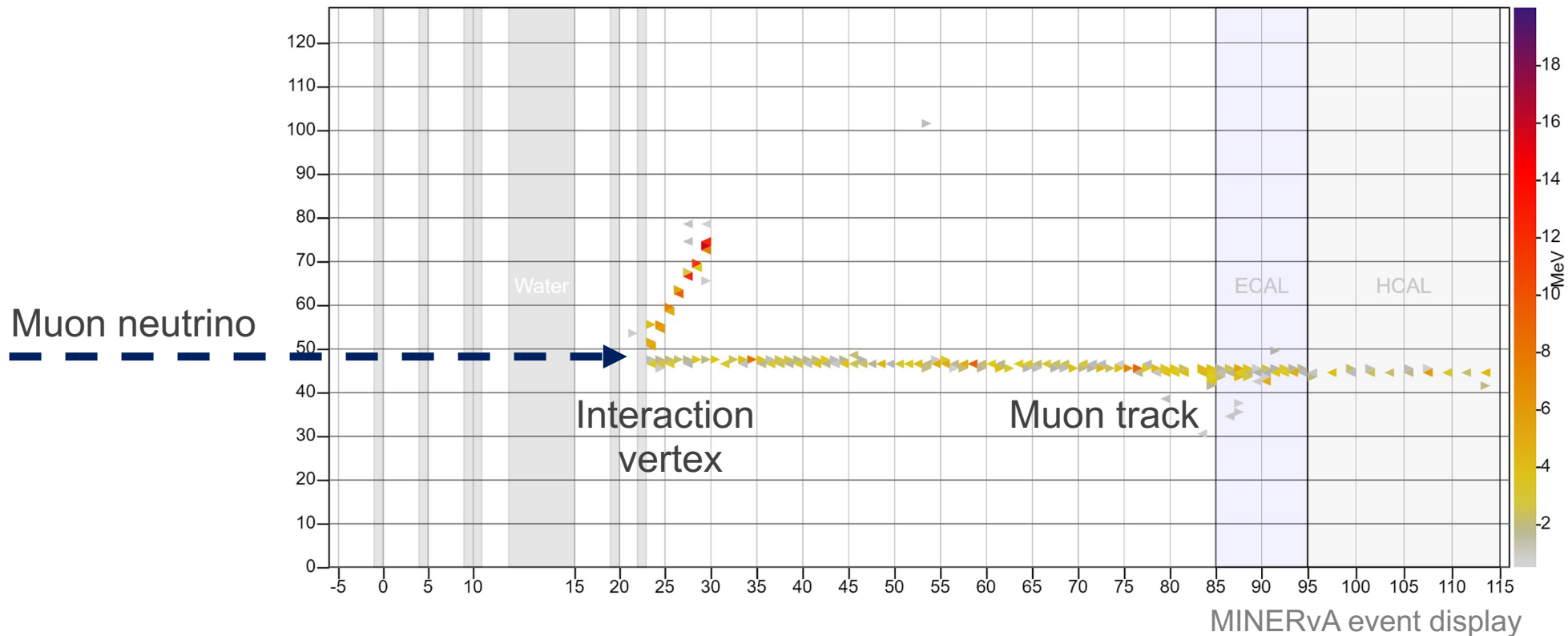
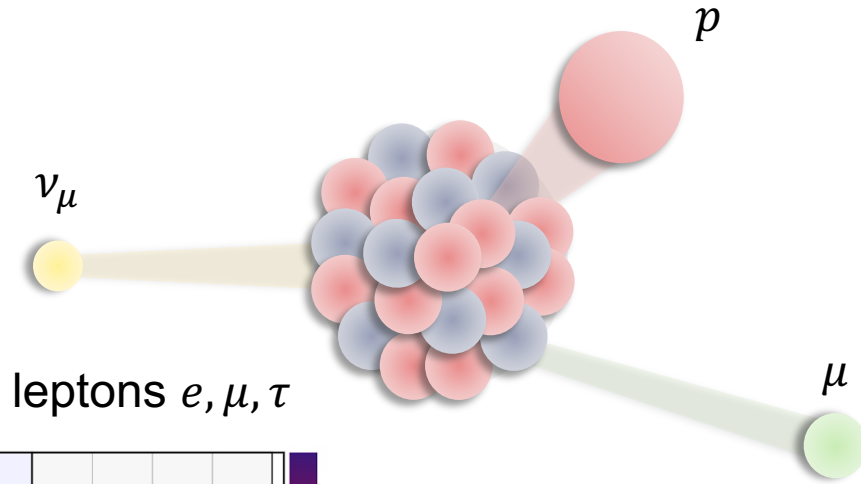
Neutrinos 101

- Neutral leptons that interact via the weak interaction
- Observed through the particles they produce
- In charged-current interactions neutrinos ν_e, ν_μ, ν_τ produce their partner leptons e, μ, τ



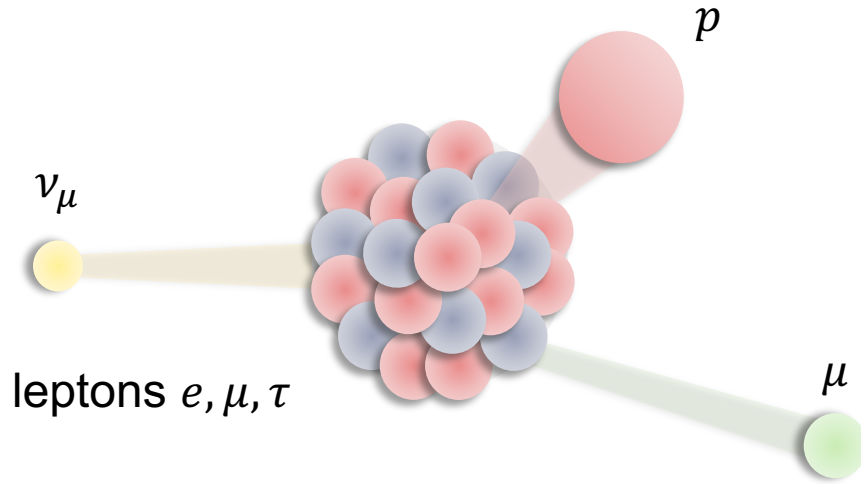
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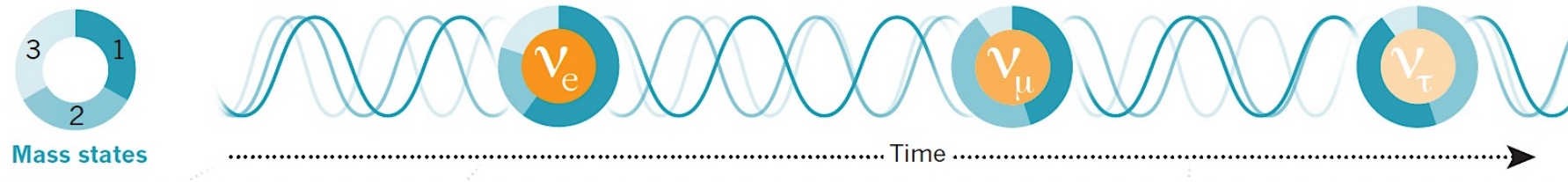


Neutrinos 101

- Neutral leptons that interact via the weak interaction
- Observed through the particles they produce
- In charged-current interactions neutrinos ν_e, ν_μ, ν_τ produce their partner leptons e, μ, τ
- Thought massless, but neutrino oscillations proved non-zero mass



Graphic by Nigel Hawtin
2015 Springer Nature Open Access



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour states PMNS matrix Mass states

💡 Do neutrinos and **antineutrinos** oscillate differently, i.e., is there CP violation in the neutrino sector?

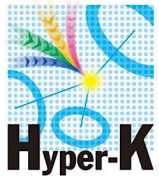
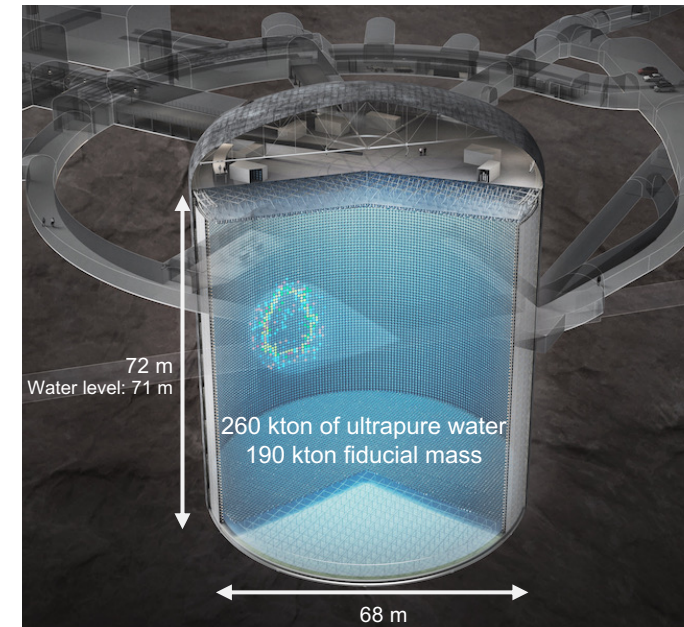
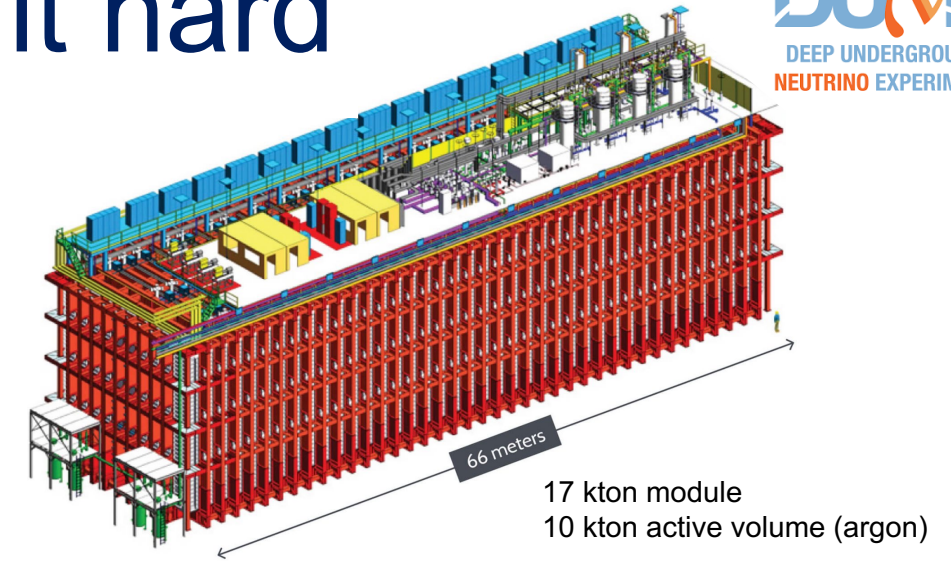
💡 Is it consistent with leptogenesis as an origin for the matter-antimatter asymmetry in the universe?

Here comes the challenge

interaction

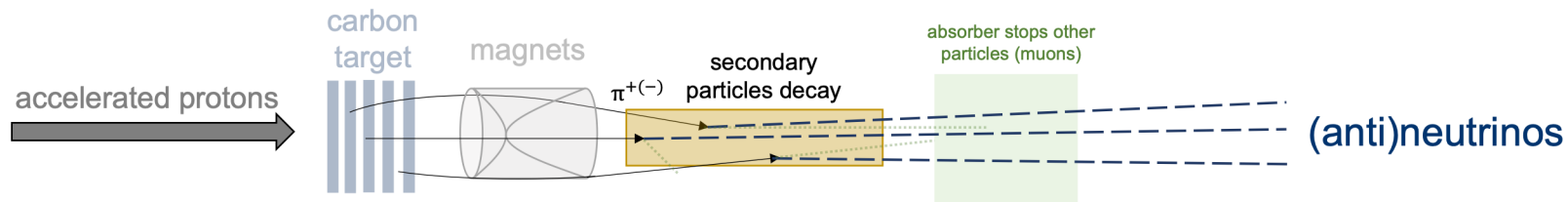
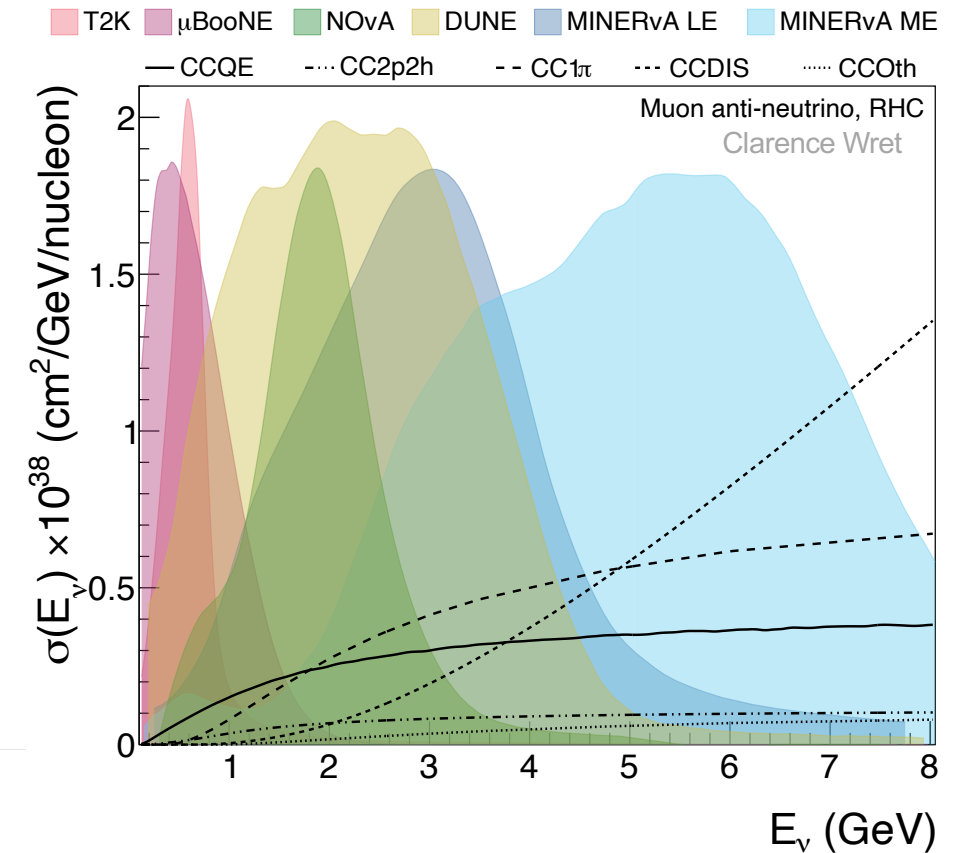
Detecting neutrinos: Why is it hard

- Neutrino interaction probability is small, $\sigma \sim 10^{-38} \text{ cm}^2$ per nucleon
 - GeV-scale neutrinos have ~ 1 in 10 billion chance to interact per metre of water equivalent
 - Typical strong cross-section $\sigma \sim 10^{-24} \text{ cm}^2$
- Detector requirements: huge, dense, and inexpensive
 - Heavy nuclei to increase interaction probability
 - Need to consider the effect of the nuclear environment



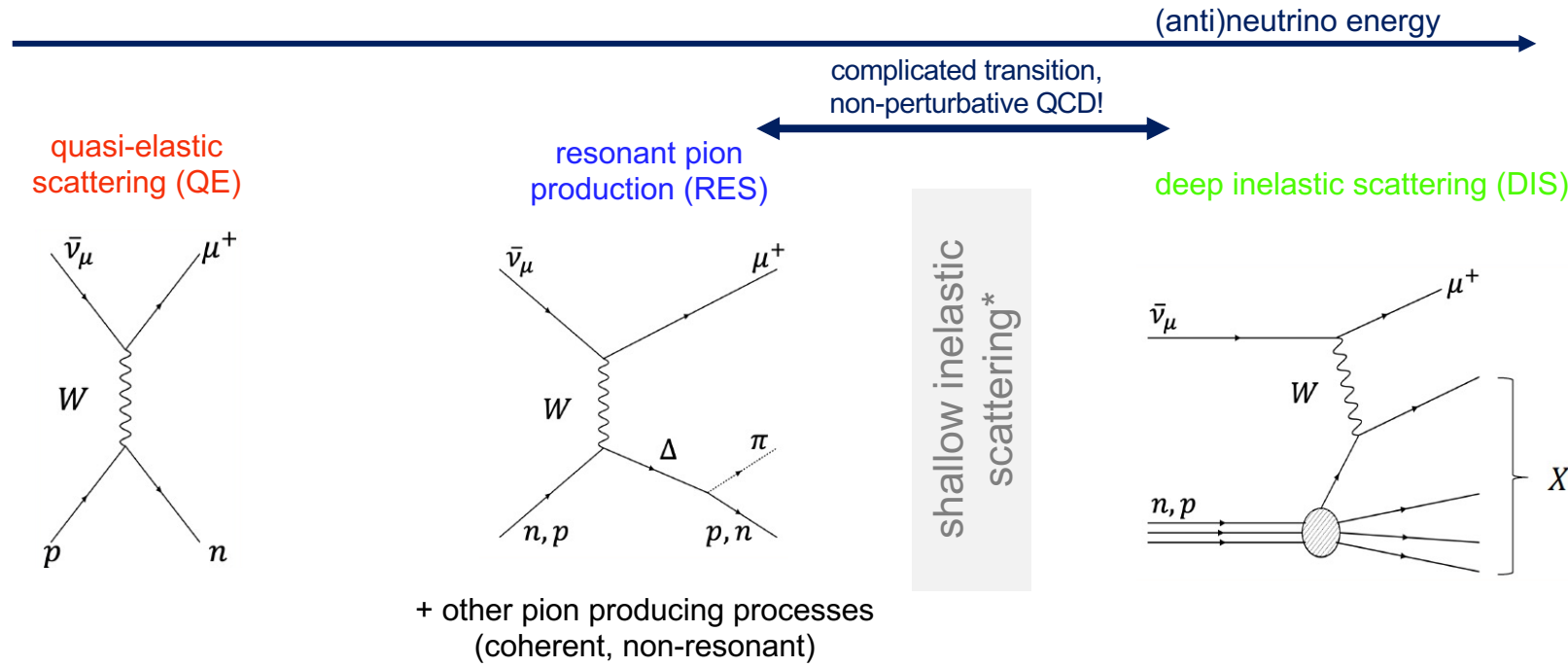
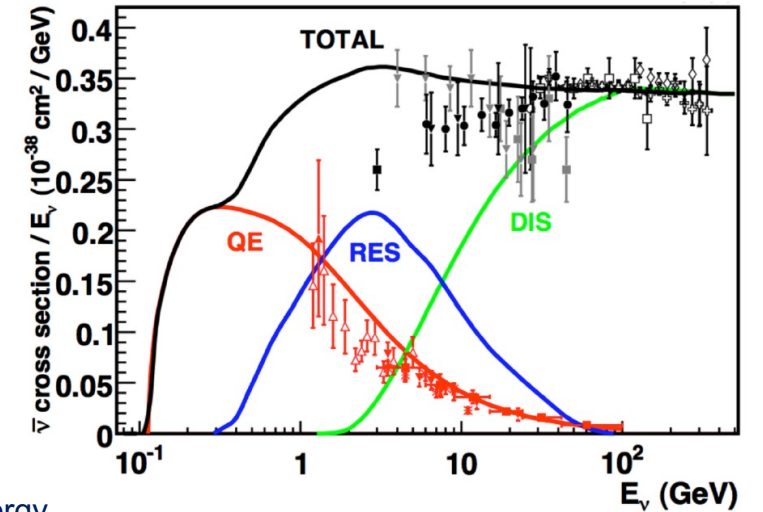
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- Neutrino beams have wide energy spread
 - Requires detailed understanding of different neutrino interaction mechanisms and how they obscure energy reconstruction



Neutrino interactions

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

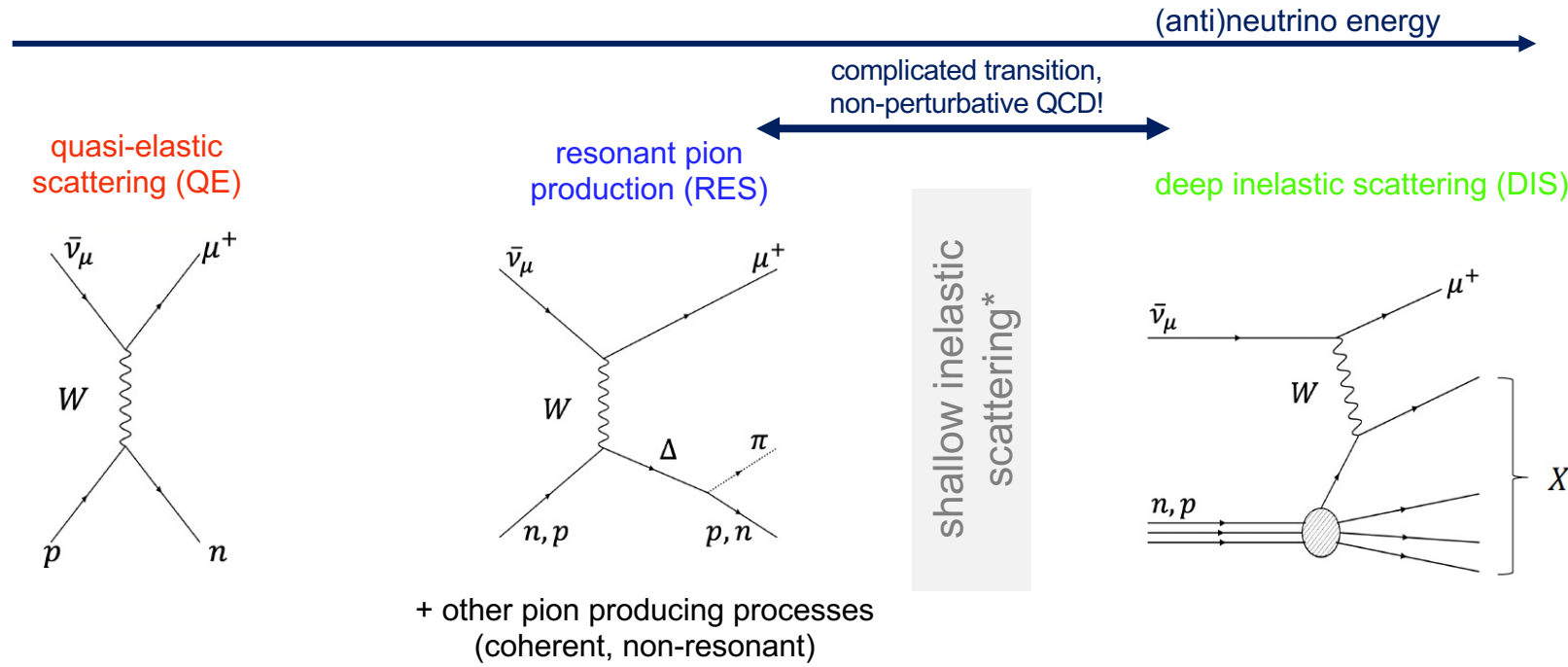
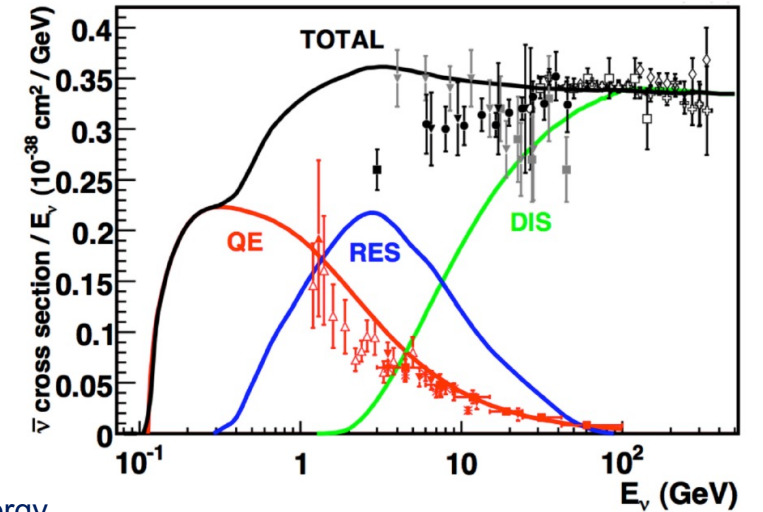


- What happens in between? Also, this is still just for a *free nucleon*

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

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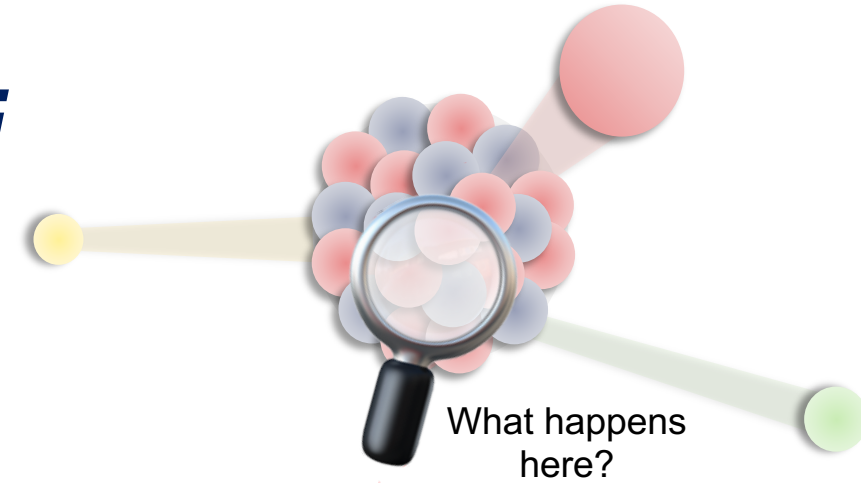


In an inclusive measurement, *all* reactions matter!

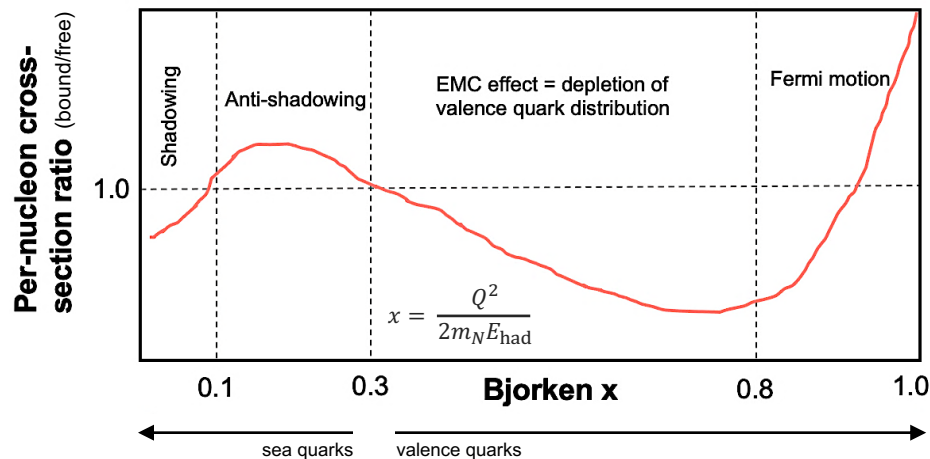
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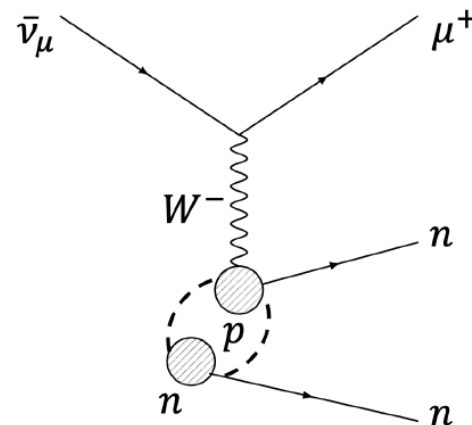
Neutrino interactions on *nuclei*



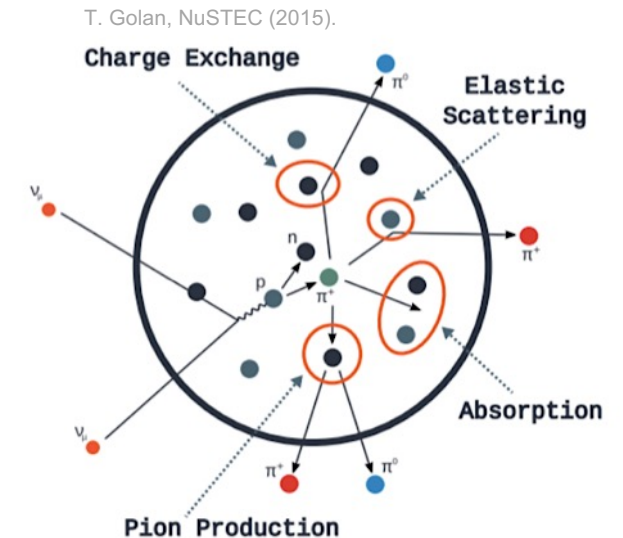
- Need to consider the initial state of the nucleus, nucleon-nucleon correlations
- Final-state interactions: what happens to particles before escaping the nucleus
- **All of this can lead to mis-reconstruction of (anti)neutrino energy**



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)

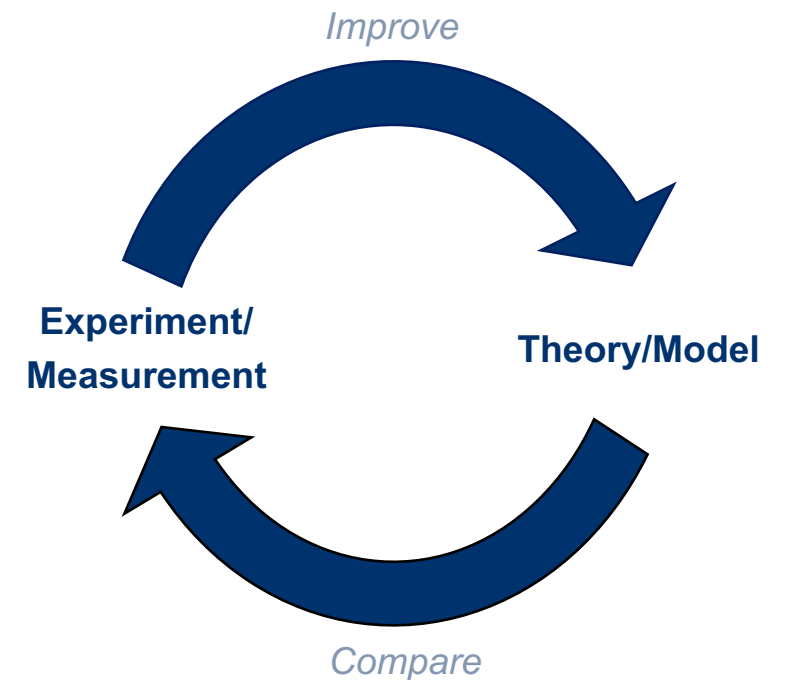


final-state interactions (FSI)

Inclusive measurement mostly insensitive to FSI!

It's complicated

- Neutrino-nucleus modelling is the leading systematic uncertainty in current oscillation measurements and **will limit future precision**
- Both theory and experiment are critical
- **Theories/models:** use factorisation, necessary approximations, limited phase-space, may struggle with full final state
- **Experiments:** reveal model deficiencies but often cannot pinpoint the source
 - Need inclusive and exclusive measurements, ideally as a function of A



[C.Andreopoulos et al., Nucl.Instrum.Meth.A614 \(2010\) 87-104](#)
[Y. Hayato, L. Pickering. Eur.Phys.J.ST 230 \(2021\) 24, 4469-4481](#)

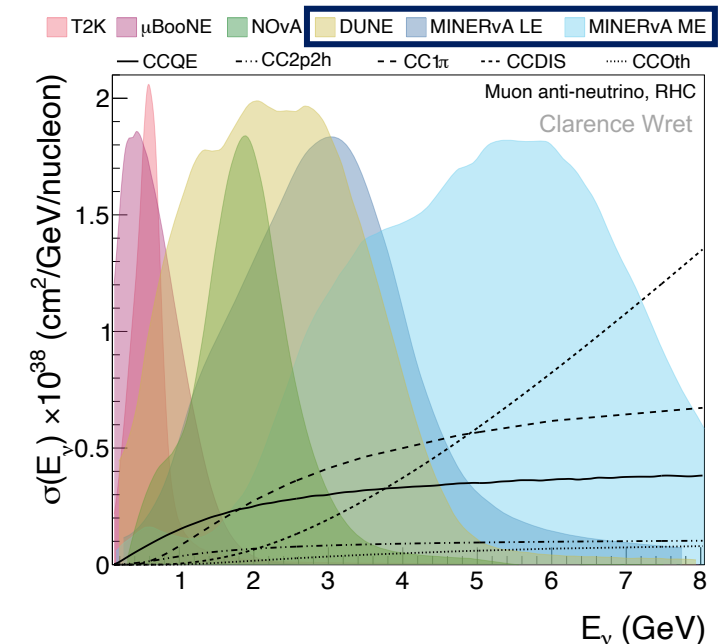
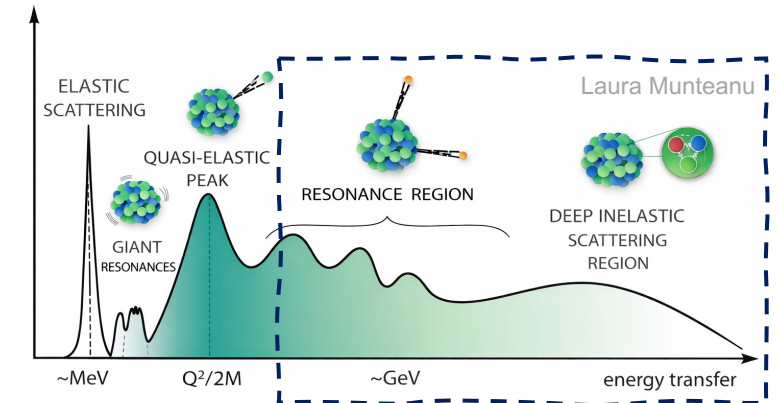
Nuclear model × Primary interaction ×
× Hadronisation × Final state interactions

Why study antineutrinos vs A at “higher energy”?

- **Antineutrinos:** CP violation searches require neutrino vs antineutrino comparison
 - Smaller cross-section ($\sim 1/2$ to $1/3$ neutrino) \rightarrow less data, longer exposure
 - Sensitive to different resonance channels, probes sea quark contributions

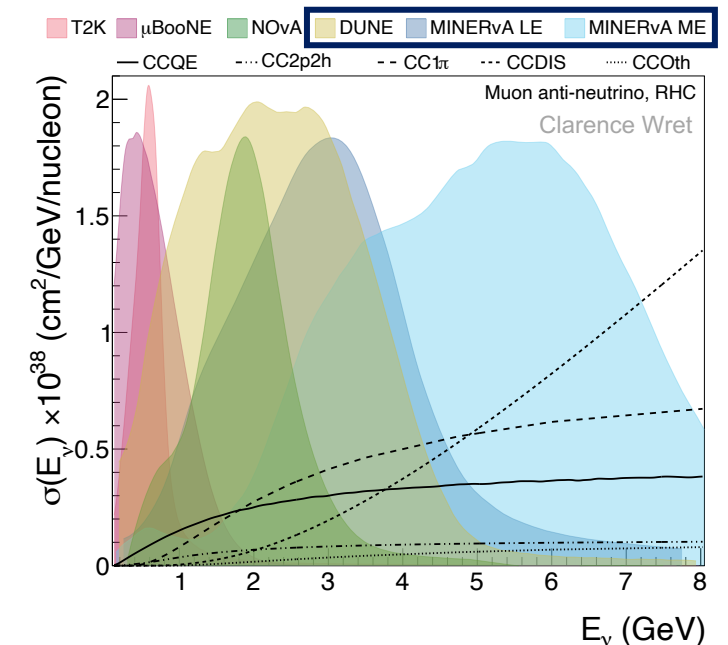
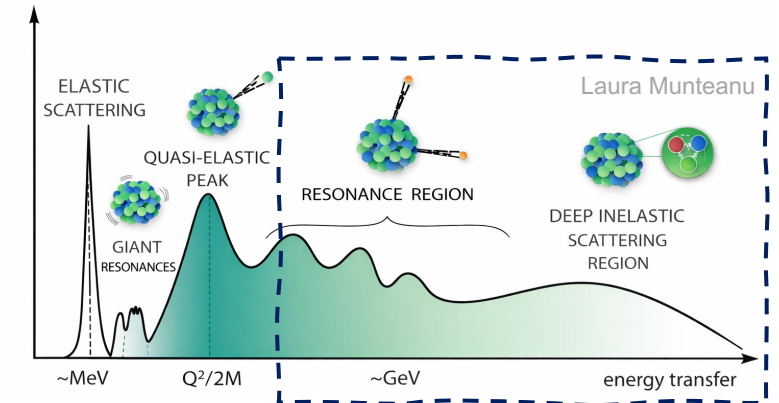
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- **“Higher-energy” regime:** DUNE’s wide spectrum, with flux peak at 2.5 GeV
 - RES \rightarrow DIS transition region poorly understood, both models and measurements limited
 - MINERvA uniquely positioned to provide data vs A , enabling extrapolation to DUNE’s argon target



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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



Enter MINERvA

What is MINERvA?

Fresco of Minerva from Herculaneum (1st century AD)



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

What is MINERvA?

- High-statistics neutrino cross-section experiment on different nuclei to probe nuclear effects
- 2009-2019 on axis in the NuMI beamline @Fermilab

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

Regime	Mode (POT)	
	Neutrino-dominated	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



200 tons
100 m underground
 ~ 1 km from neutrino production point

Decommissioned. Parts now used for DUNE near detector prototype!

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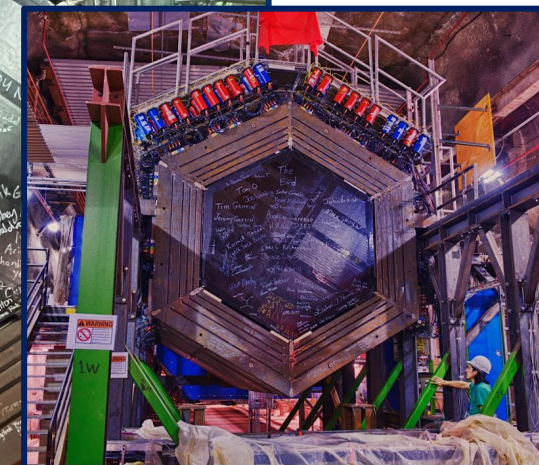
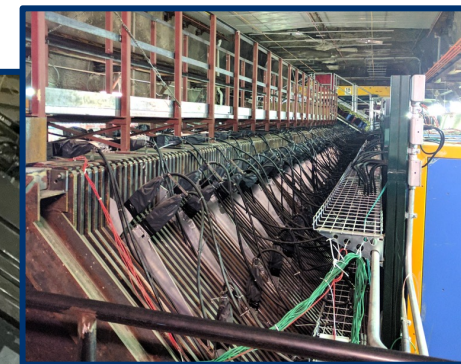
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This measurement

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

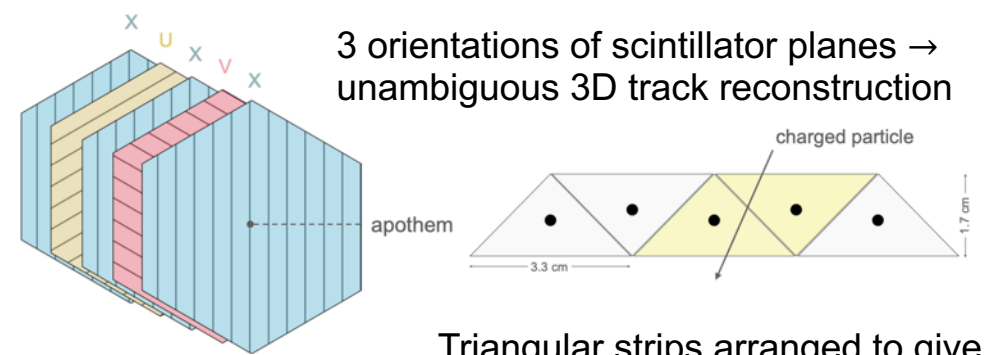


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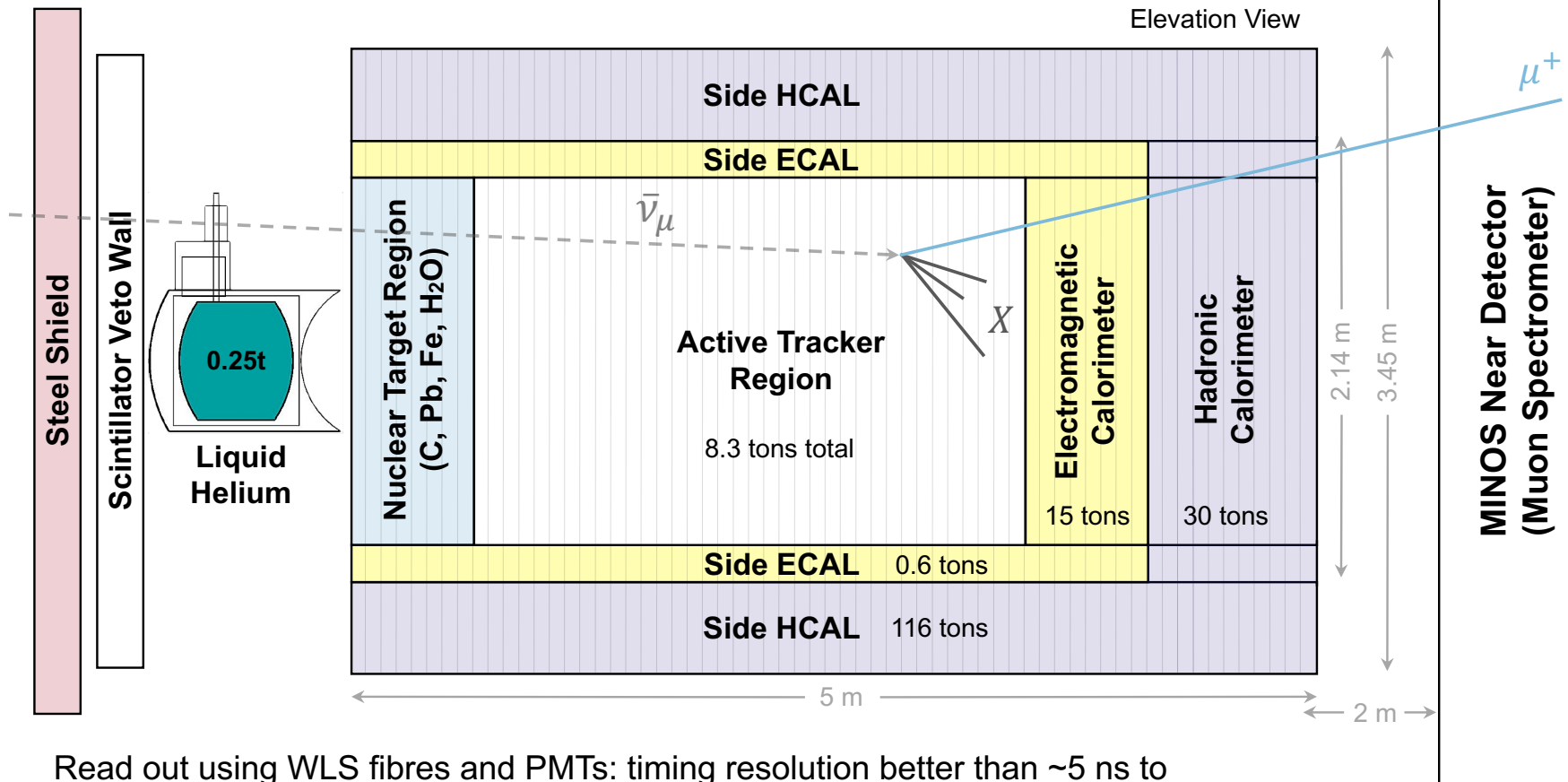
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MINERvA detector

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



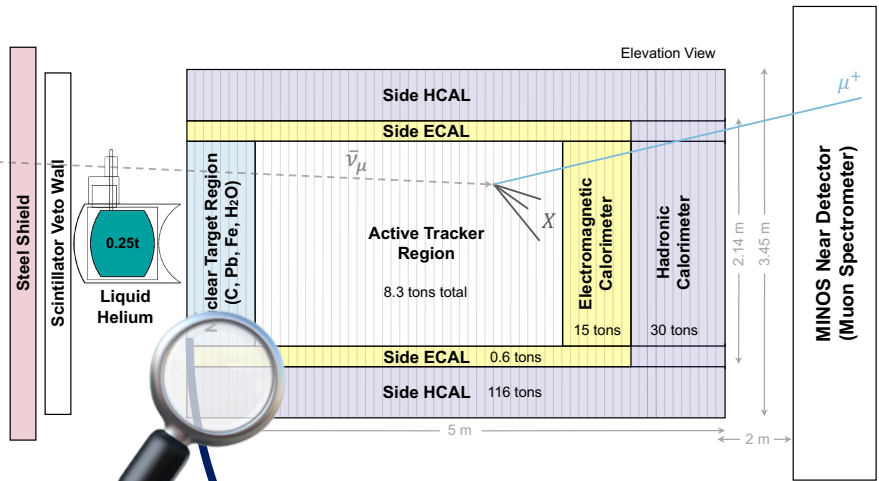
Triangular strips arranged to give a better position resolution



MINOS spectrometer: muon momentum and charge → phase space constraints

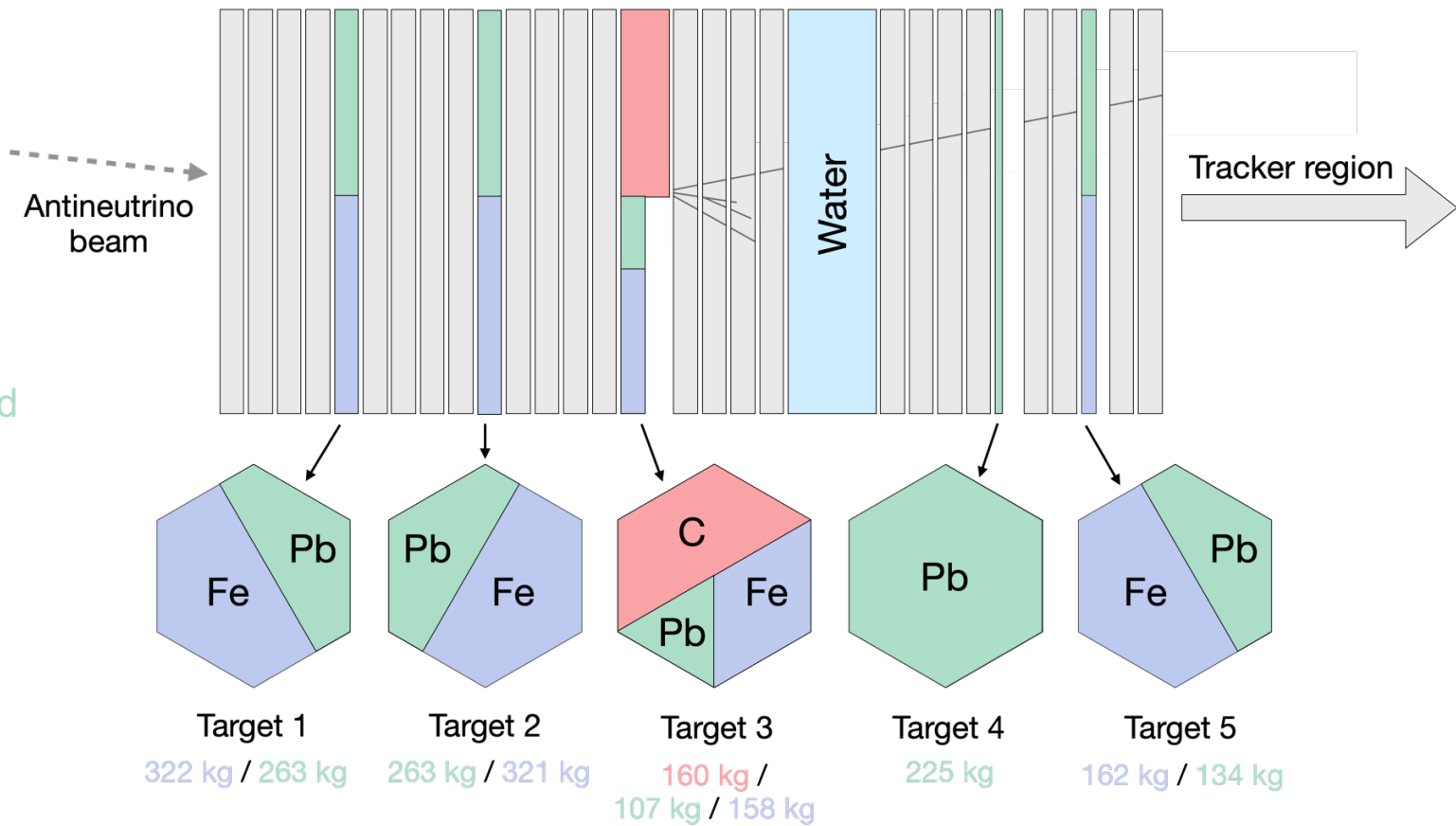
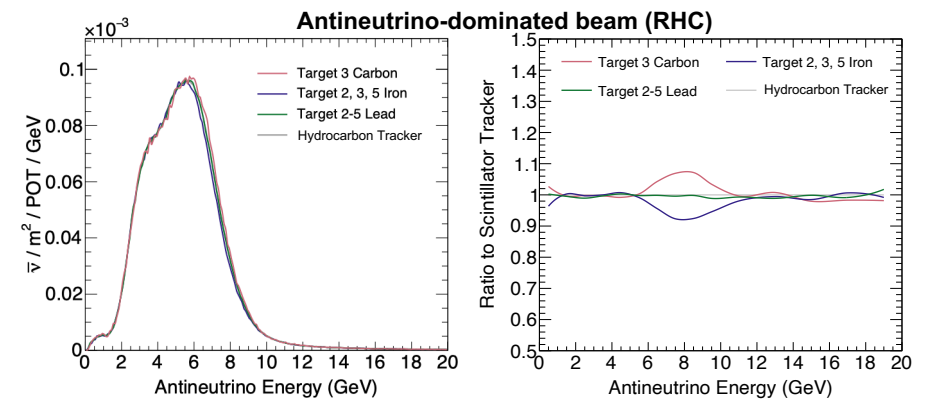
Read out using WLS fibres and PMTs: timing resolution better than ~5 ns to distinguish overlapping events within a single spill (< 10 μ s)

Nuclear target region

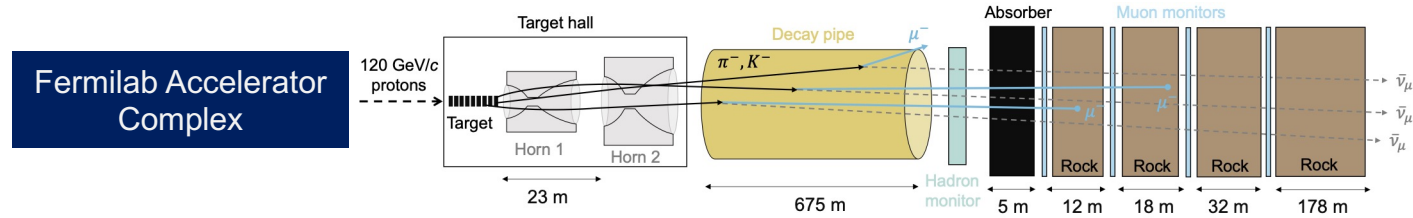


Range of nuclei:
carbon, water, iron, and lead

Interspersed by active scintillator planes (hydrocarbon)

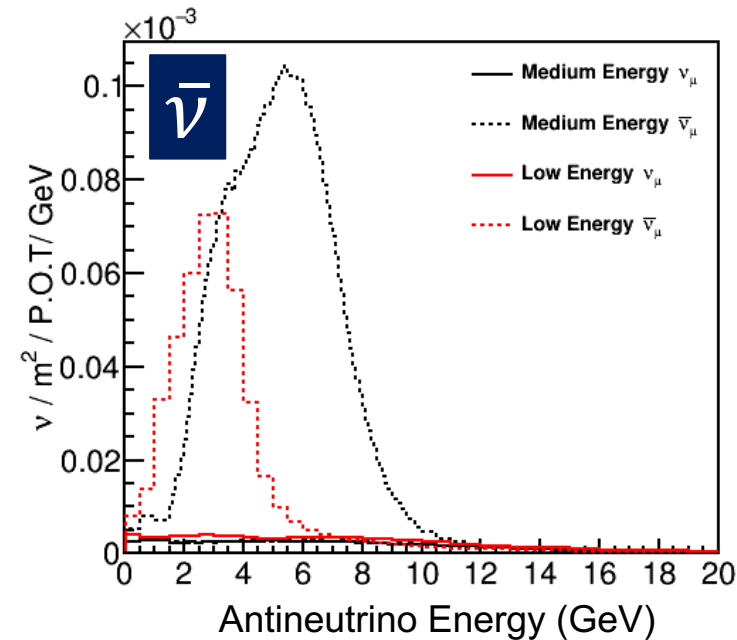
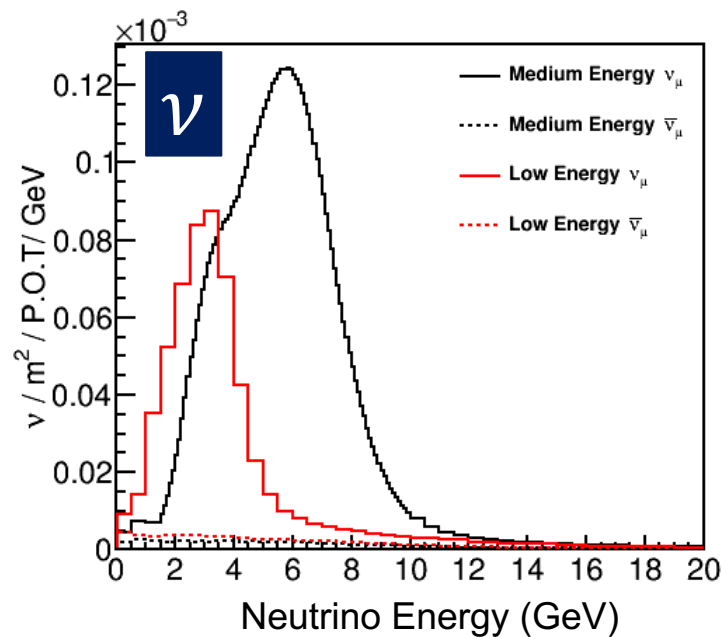


Flux at MINERvA



- Antineutrinos from Neutrinos at the Main INjector (NuMI) beamline
- Significant uncertainties from hadron production and focusing
- MINERvA constrains flux using hadron production data and *in situ* measurements
 - $\nu/\bar{\nu}$ -e, inverse muon decay, and using interactions with low energy transfer to the nucleus
- **In antineutrino mode, integrated uncertainty reduced from 7.8% to 4.7%**

[L. Zazueta \(MINERvA\). Phys. Rev. D 107, 012001 \(2023\).](#)

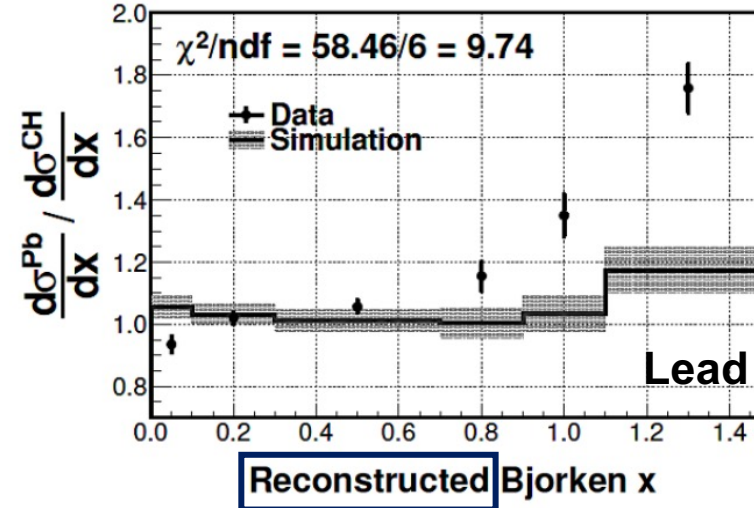
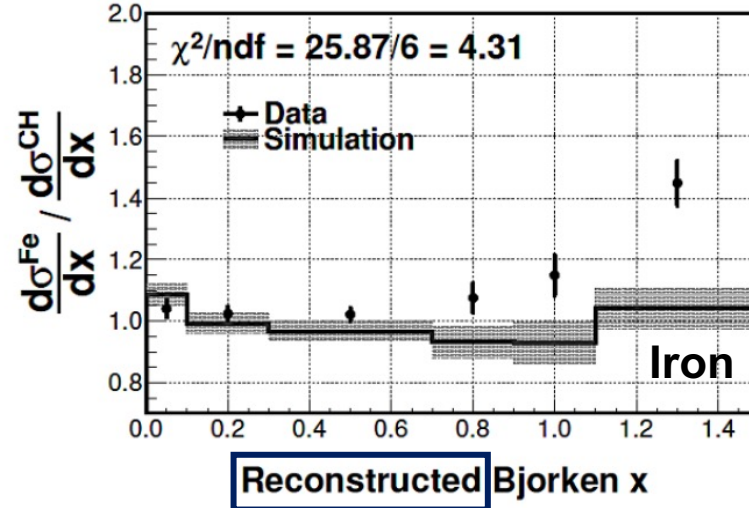


MINERvA & inclusive measurement

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 \(2014\).](#)

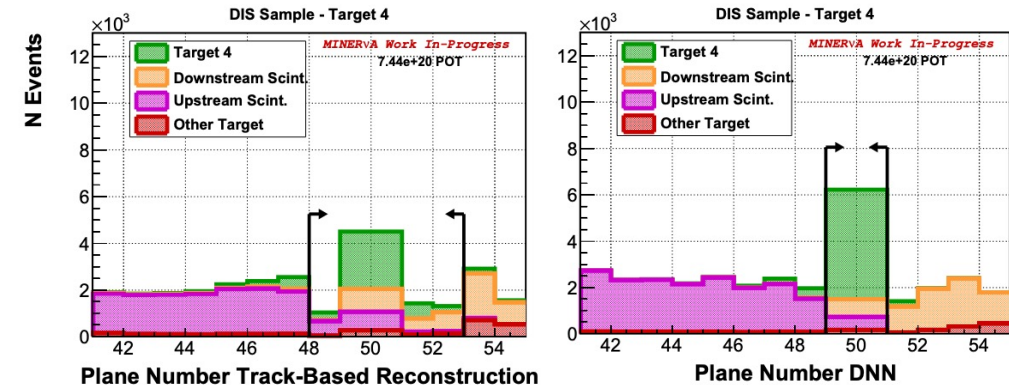
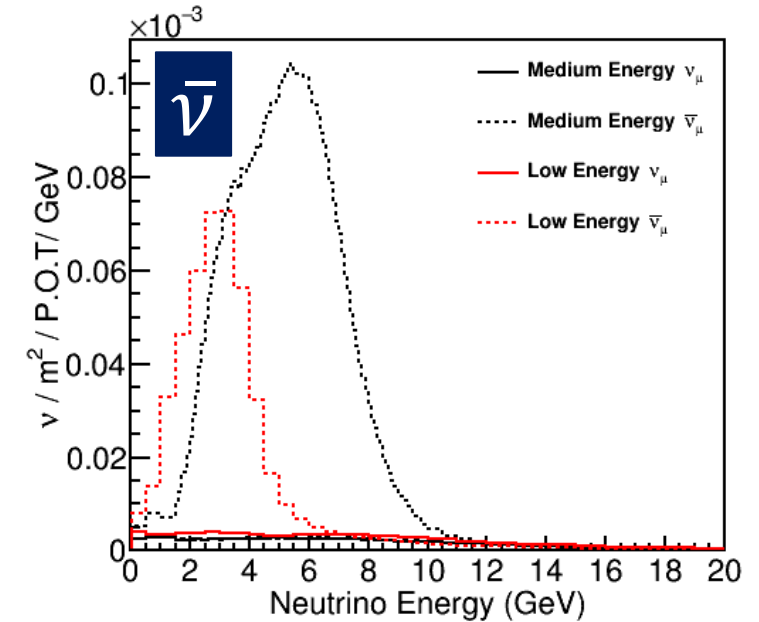


$$x = \frac{Q^2}{2m_N E_{\text{had}}}$$

- 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 of progress!

- 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 detector understanding and improved reconstruction techniques
 - Machine-learning vertex reconstruction with convolutional neural network results in increased selection purity and efficiency
- As a community, progress in understanding of neutrino-nucleus scattering, improved interaction models, and awareness of model dependence



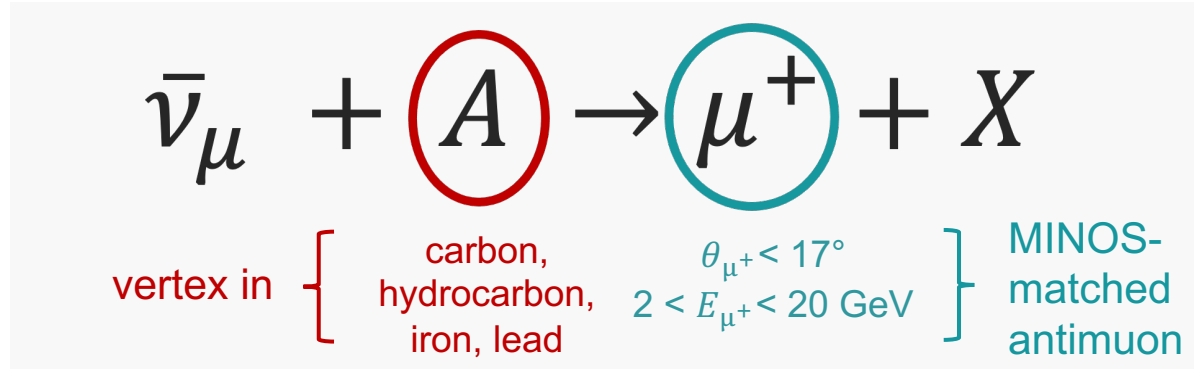
(a) Track-based vertex finding.

(b) DCNN-based vertex finding.

[F. Akbar \(MINERvA\), JINST 17 T08013 \(2022\).](#)

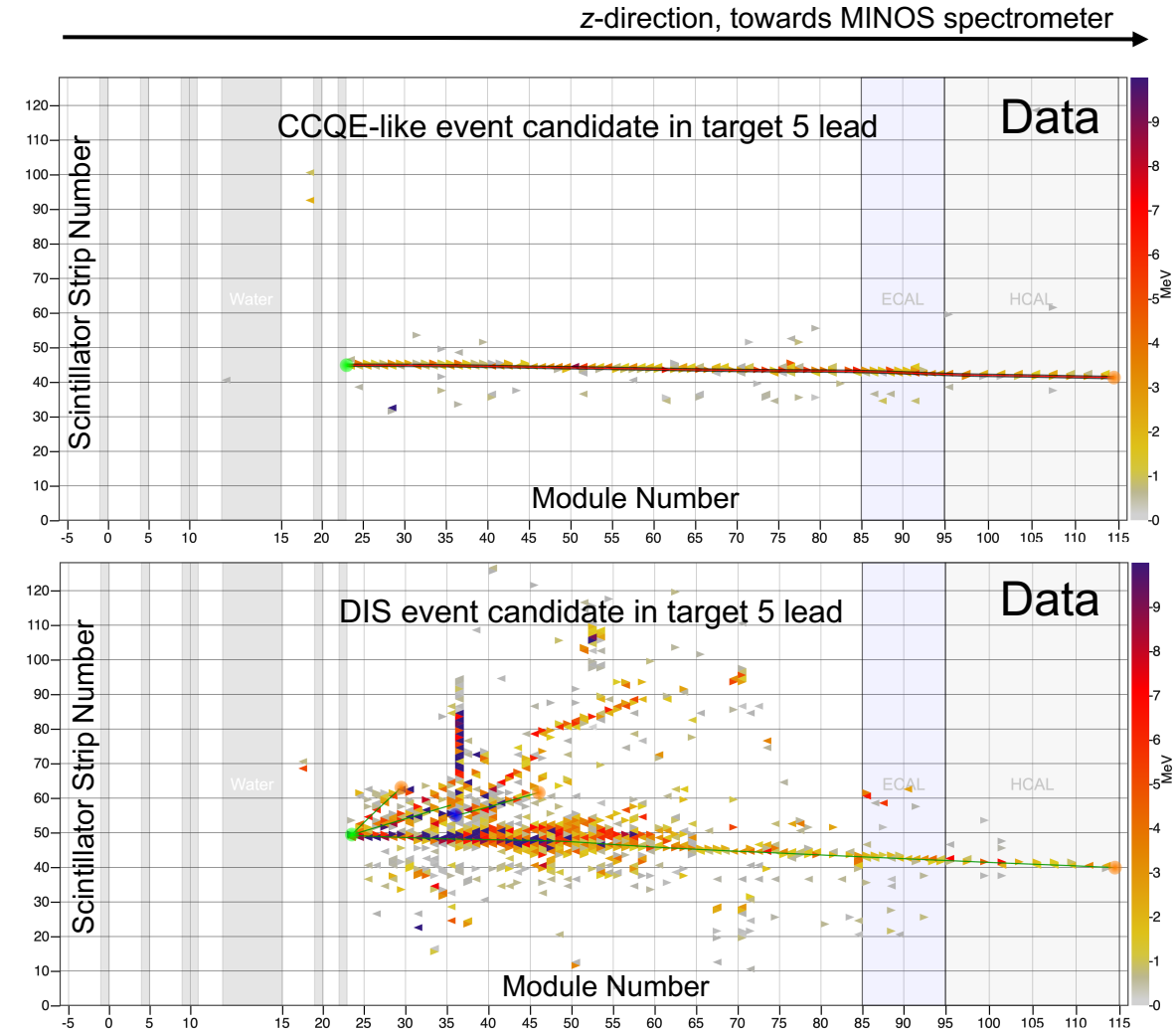
Signal definition

In antineutrino mode:



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

Target	Total Events
C	63,956
CH	1,897,567
Fe	192,694
Pb	225,313

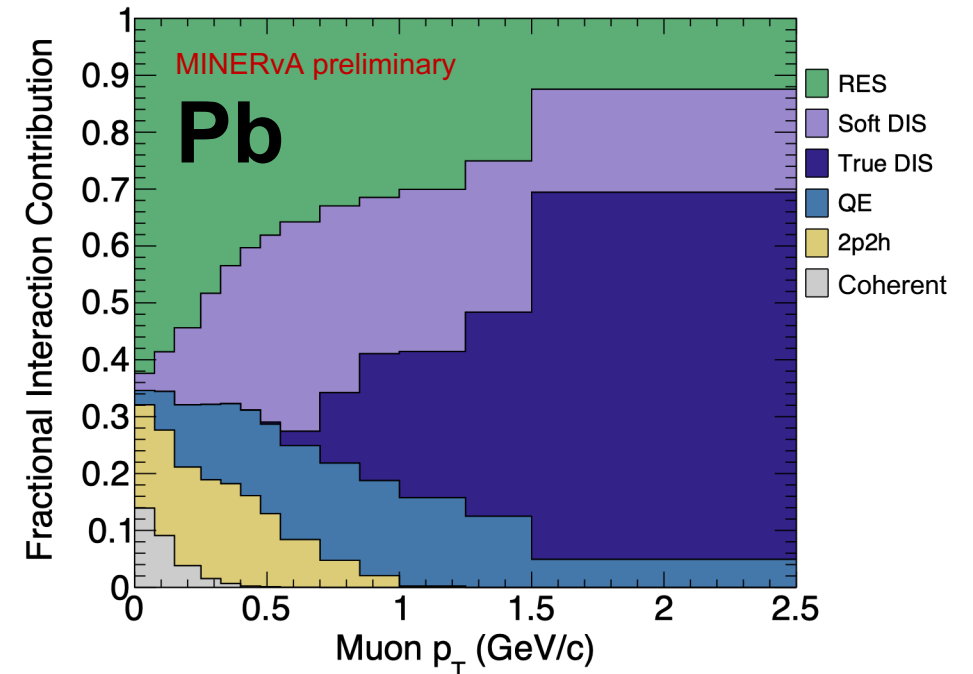
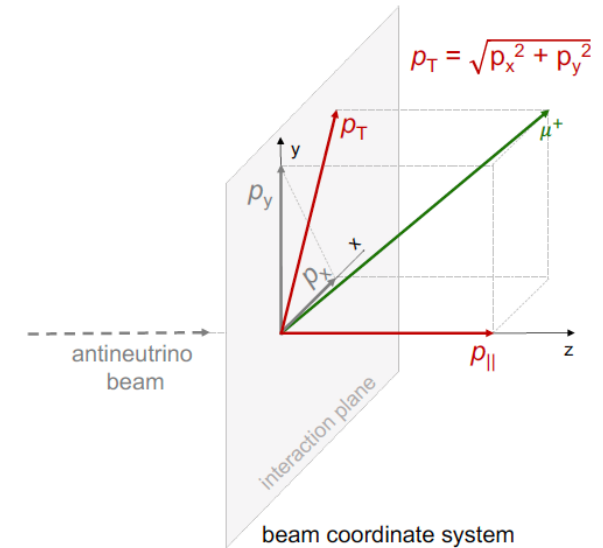


Variable of interest

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

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

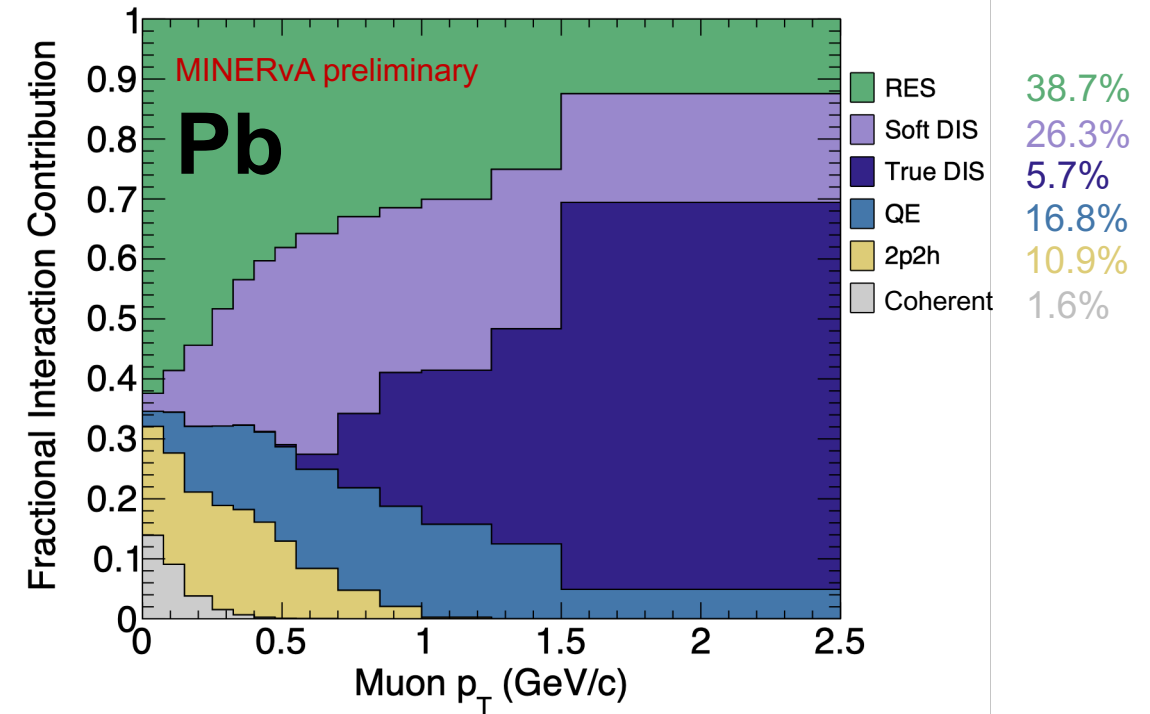
- Separation power for different interaction types



Baseline model prediction

- 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](#)
- **Dominated by RES and RES → DIS transition**
 - First peek at single pion production in antineutrino mode

Compared to MINERvA's $CC1\pi^+$ vs A measurement: [A. Bercellie \(MINERvA\). Phys.Rev.Lett. 131, 011801 \(2023\).](#)



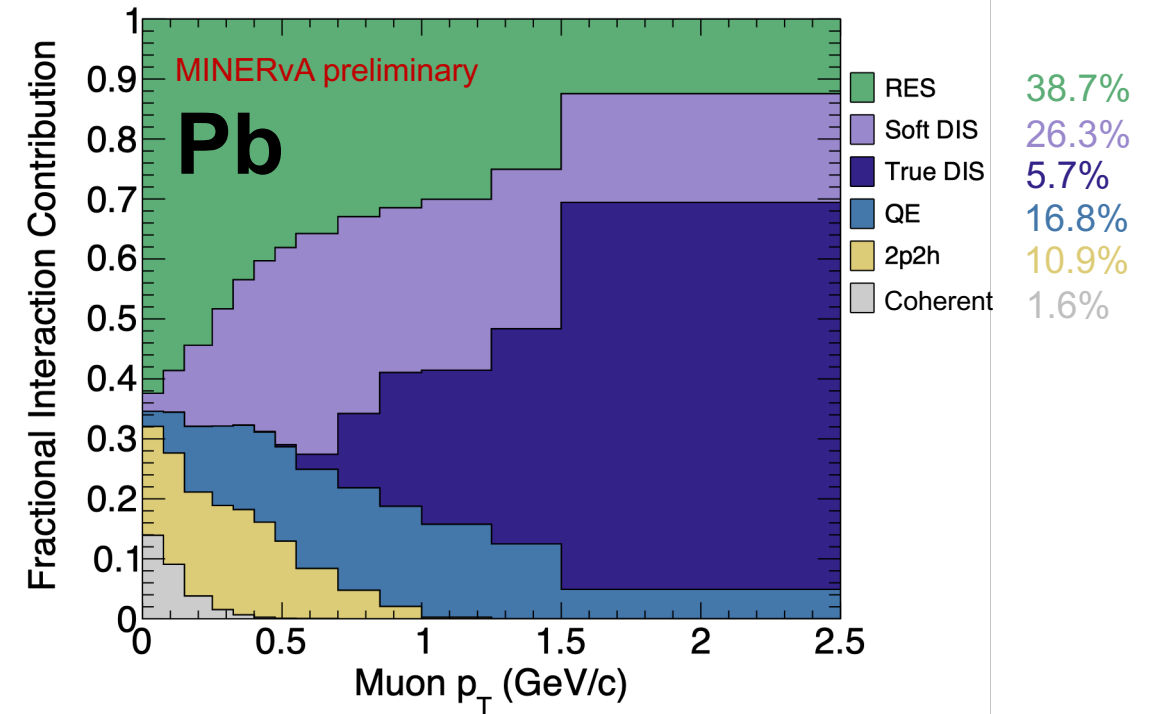
*P. Rodrigues, C. Wilkinson, & K. McFarland. Eur. Phys. J. C. 76, 474 (2016)

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- Note GENIE DIS \neq DIS defined by perturbative QCD ($Q^2 > 4$ (GeV/c)²)
 - GENIE DIS broken down into **True DIS** ($W > 2$ GeV/c ² and $Q^2 > 1$ (GeV/c)²) and **Soft DIS** (everything else)
 - **Soft DIS** and **True DIS** mostly correspond to soft and multiquark shallow inelastic scattering, respectively

MINERvA's SIS measurement: [A. Lozano, G. Silva, G. Caceres \(MINERvA\), arXiv:2503.20043 \(2025\)](#)

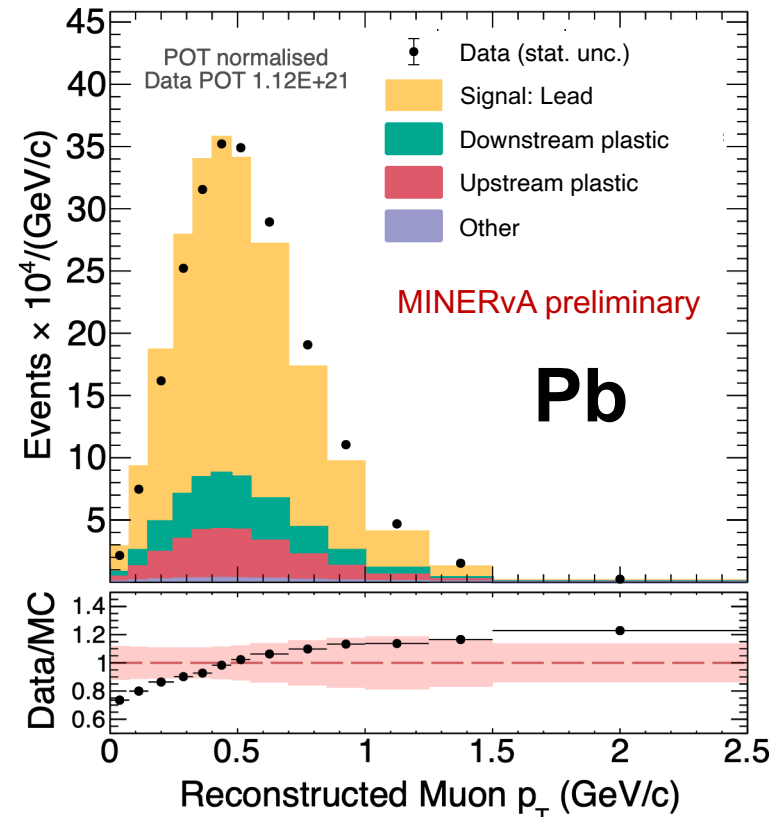
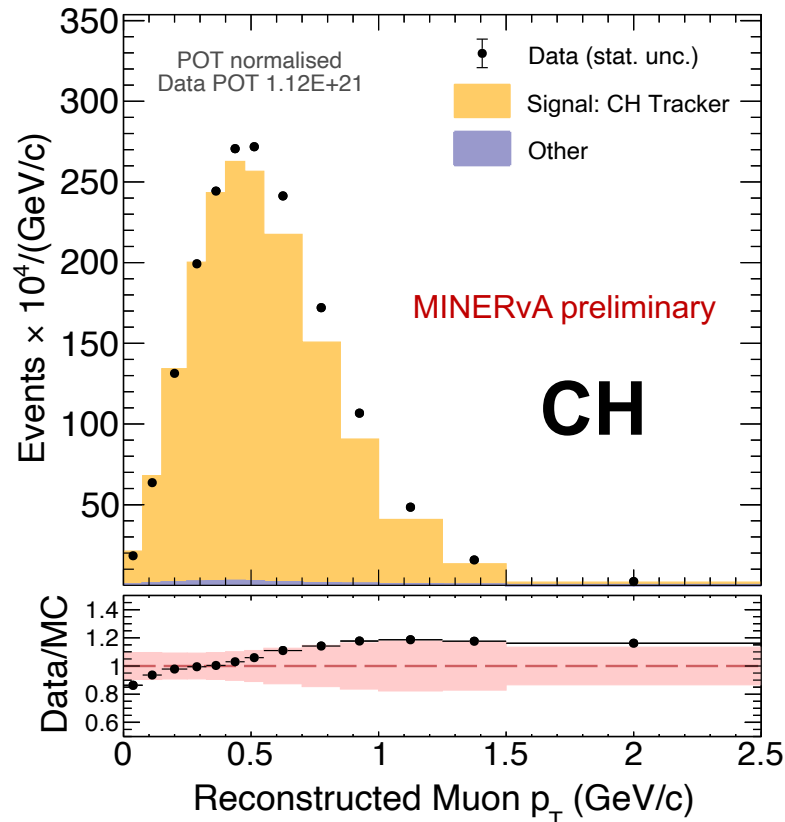
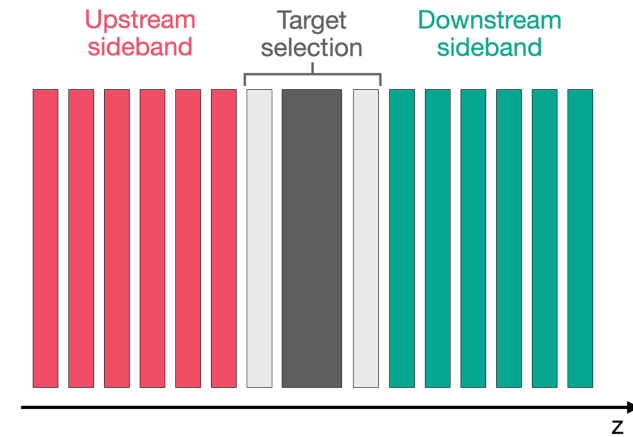
*P. Rodrigues, C. Wilkinson, & K. McFarland. Eur. Phys. J. C. 76, 474 (2016)



Q^2 : how hard the scattering is
 W : mass of the hadronic system produced in the interaction

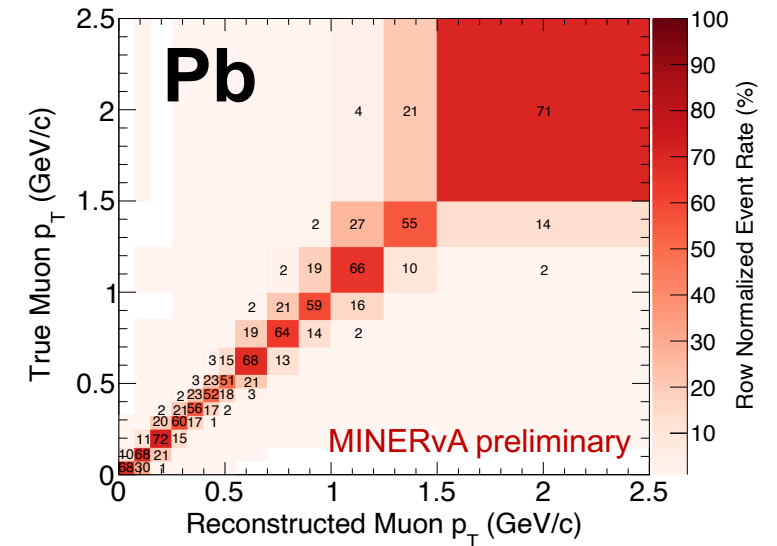
Selected distributions

- 99% purity in CH tracker, ~70% purity across C, Fe, and Pb targets
- In nuclear target region, plastic scintillator events from upstream/downstream constrained using data from surrounding scintillator planes → subtract constrained background



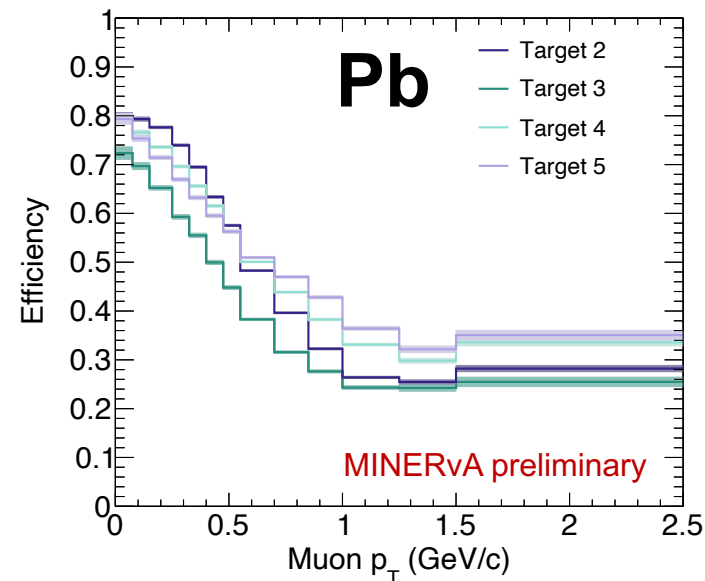
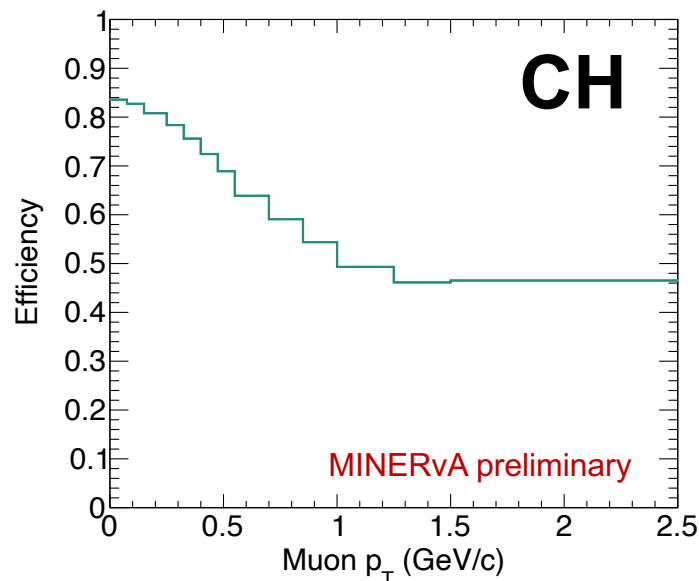
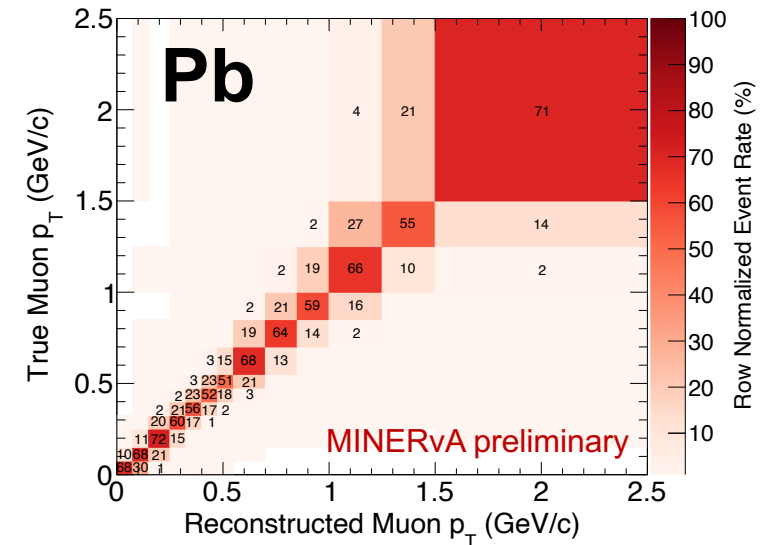
Unfolding, efficiency, and normalisation

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



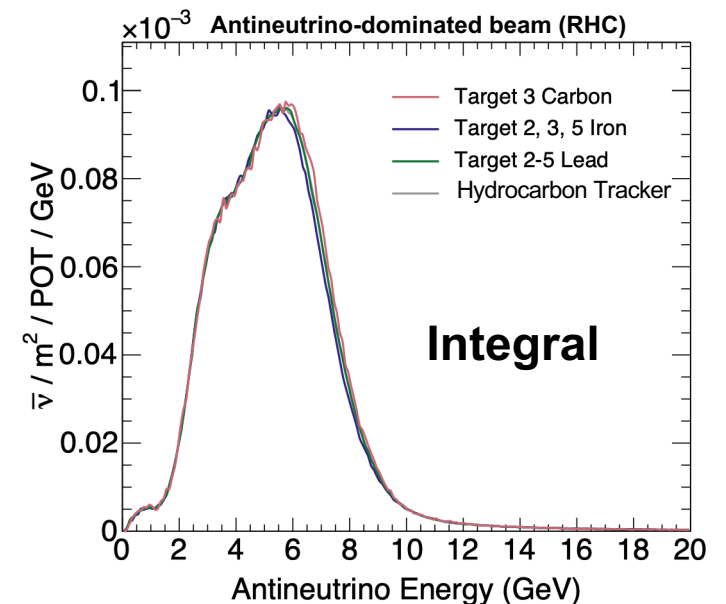
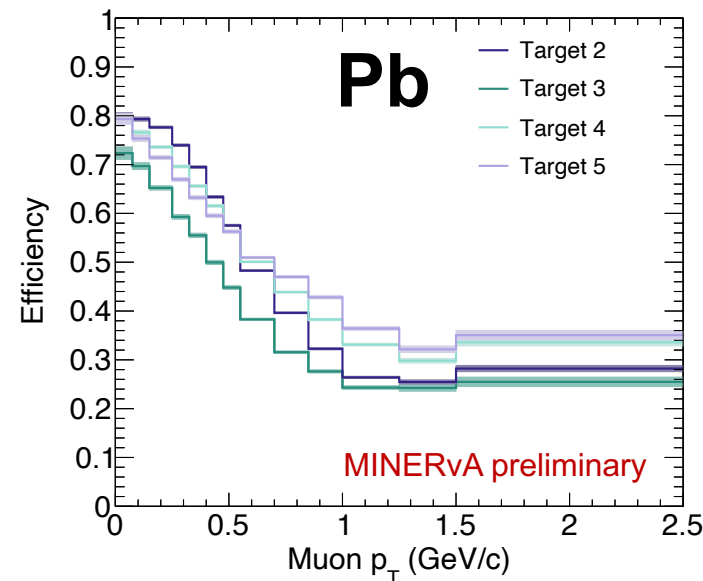
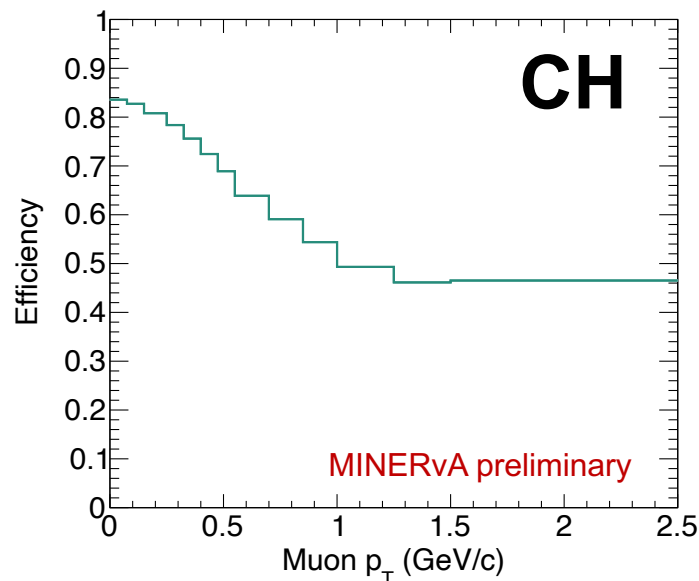
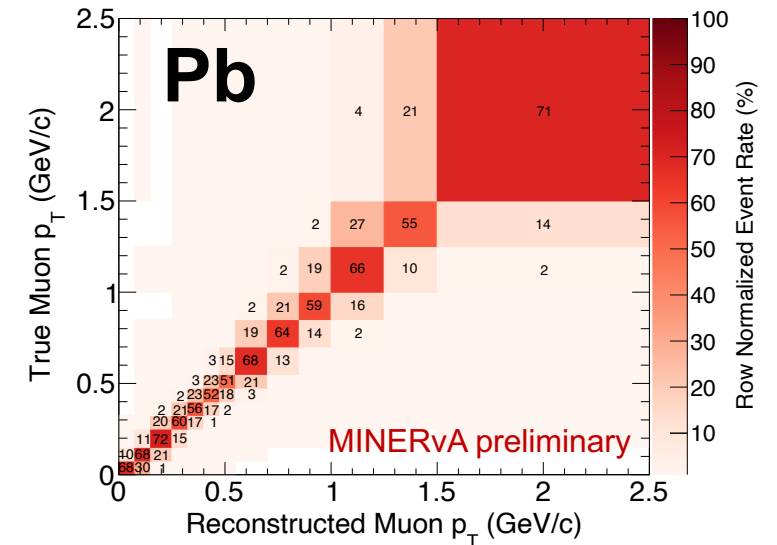
Unfolding, efficiency, and normalisation

- Correct for smearing due to detector resolution and reconstruction
 - D'Agostini iterative unfolding to true distribution with minimum iterations chosen to account for possible physics variations
- Efficiency/acceptance (decreases with p_T), integrated $\sim 65\%$ in the hydrocarbon tracker and about 40–50% in the nuclear target region



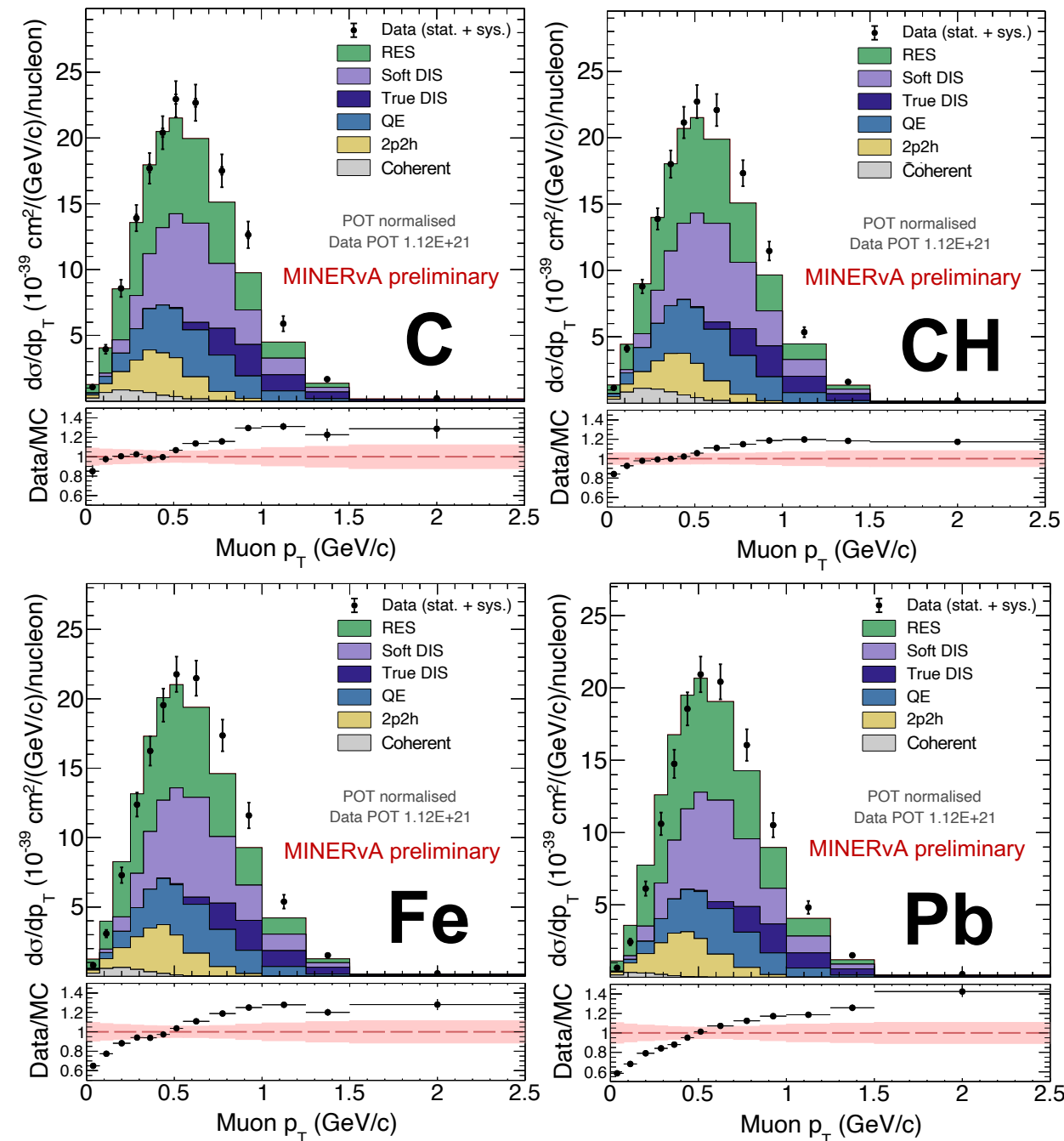
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 - D'Agostini iterative unfolding to true distribution with minimum iterations chosen to account for possible physics variations
- Efficiency/acceptance (decreases with p_T), integrated $\sim 65\%$ in the hydrocarbon tracker and about 40–50% in the nuclear target region
- Normalise by flux integral, number of target nucleons, and bin width



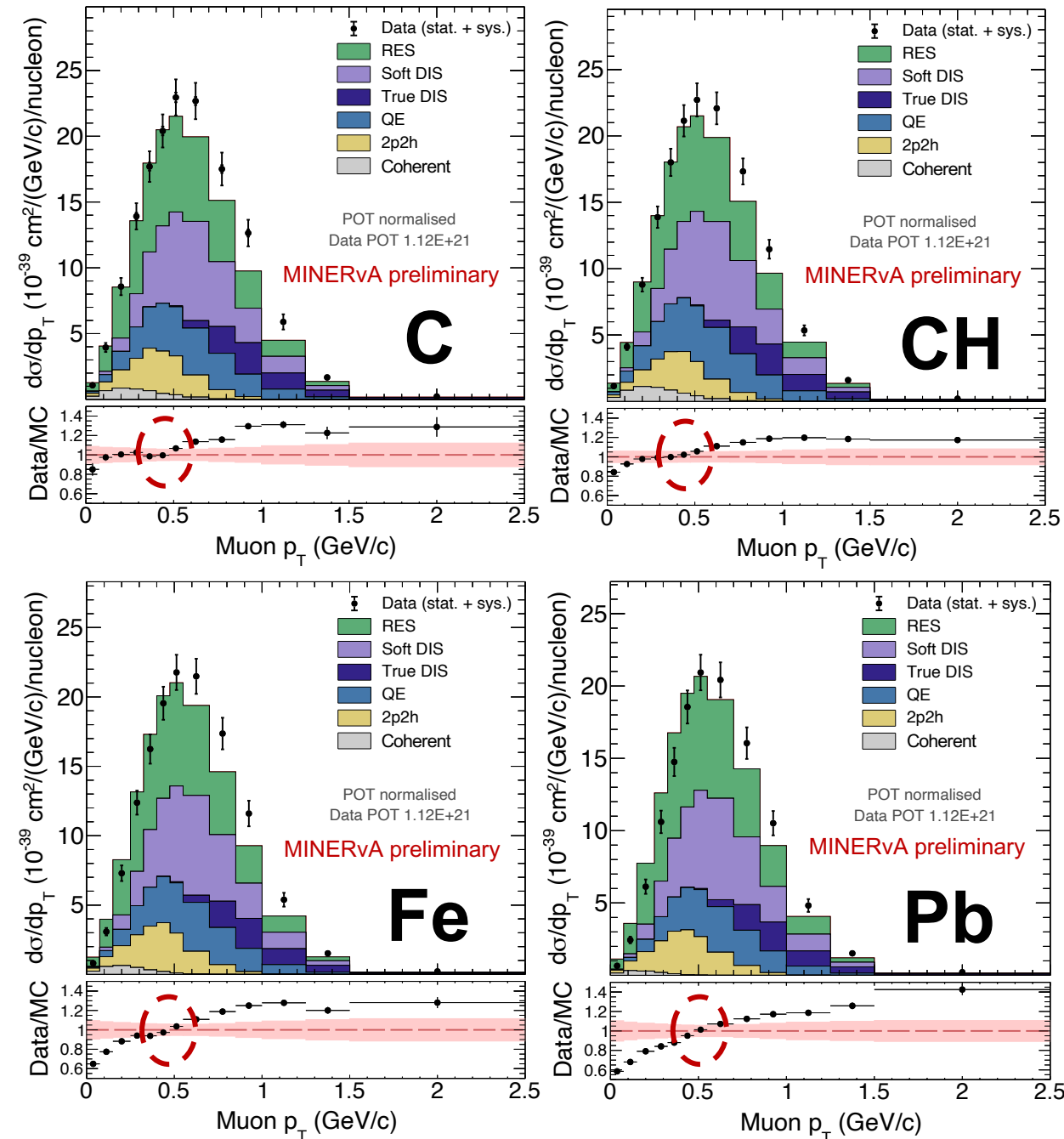
Results!

Cross-sections



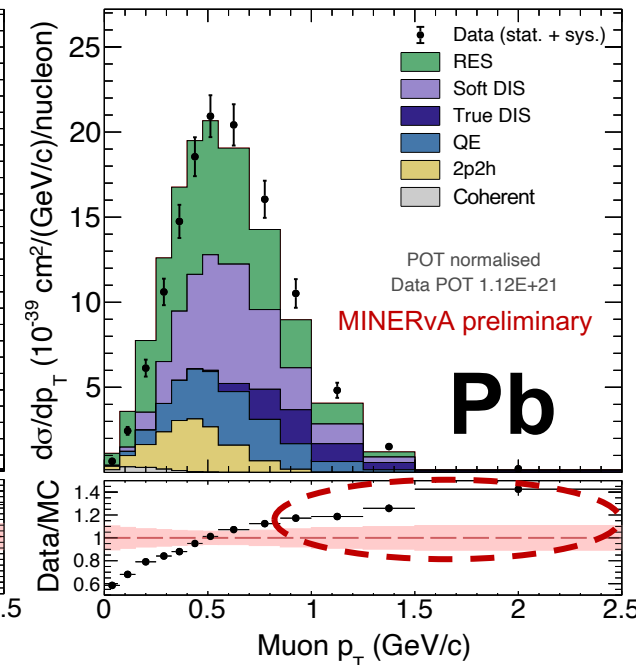
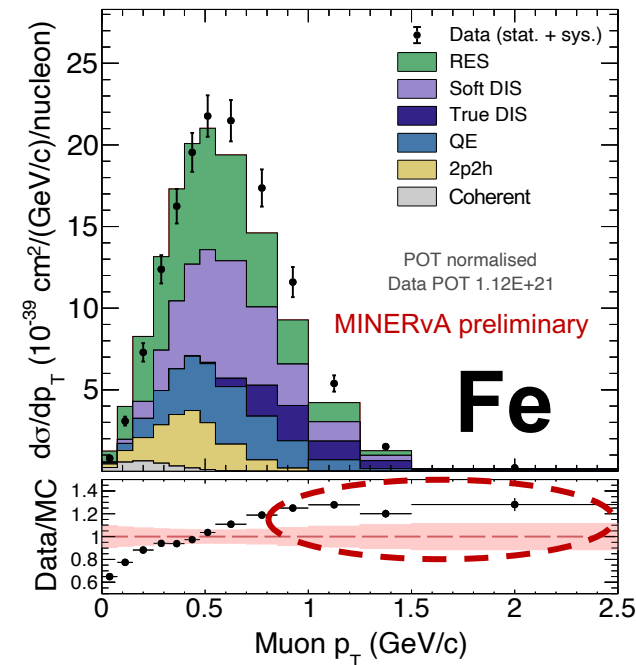
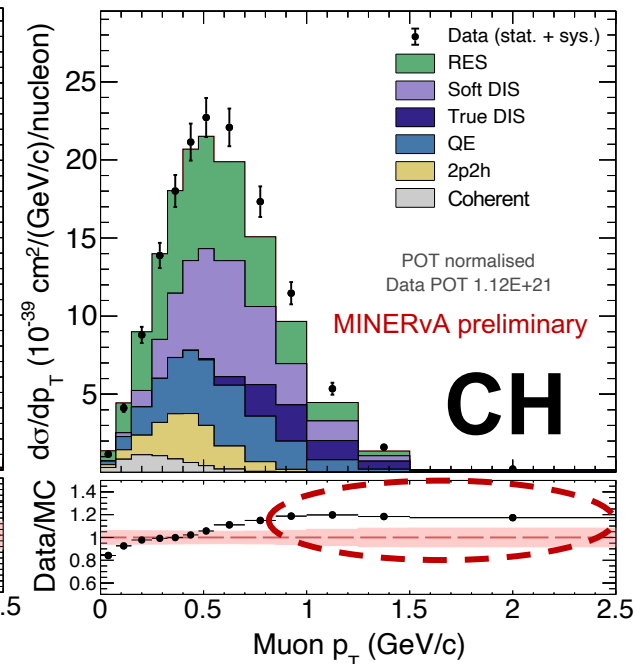
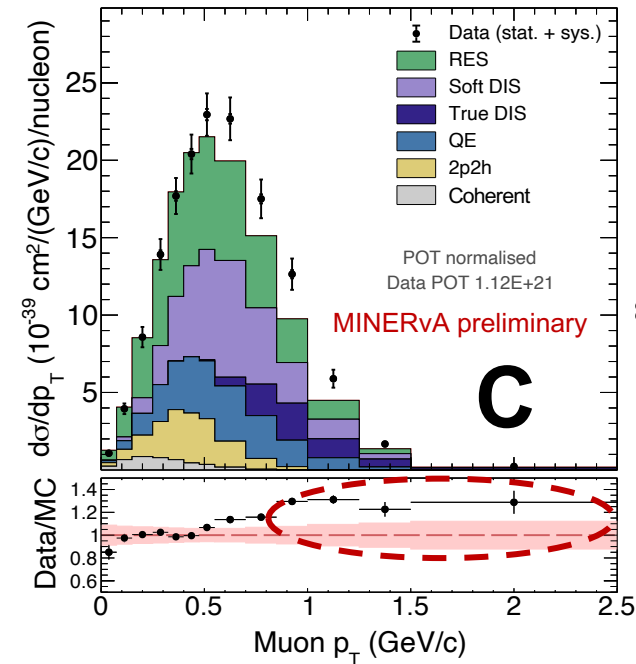
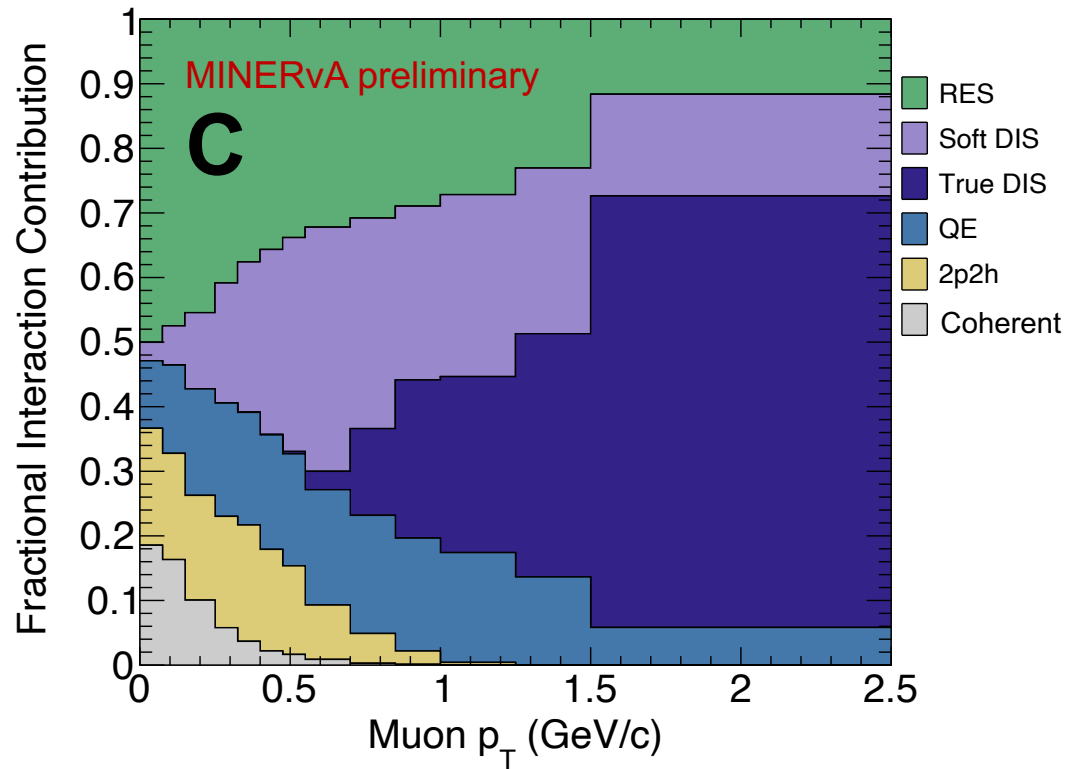
Cross-sections

- Some agreement in the peak of the distribution



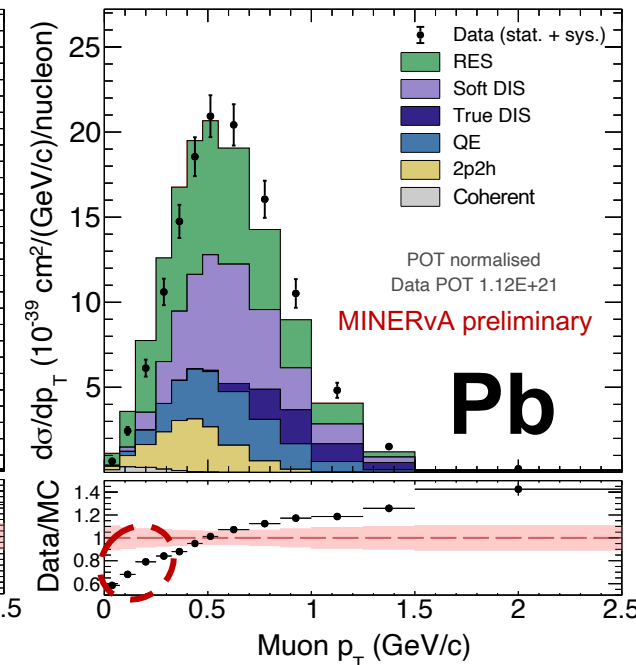
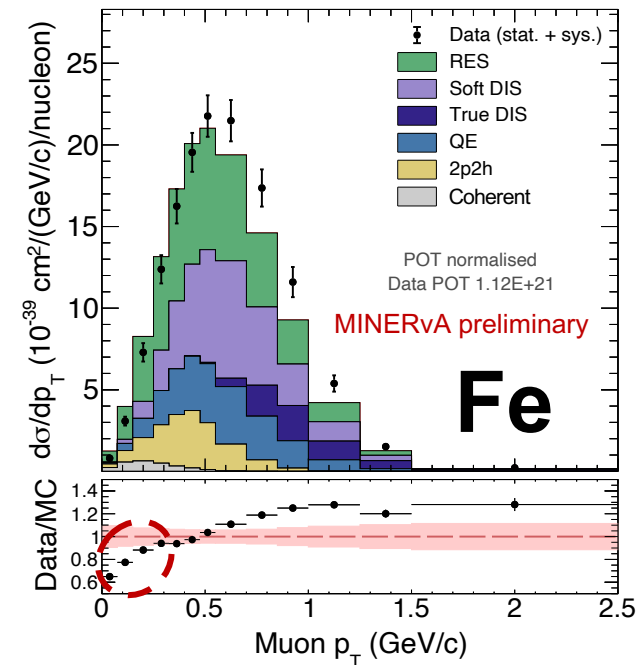
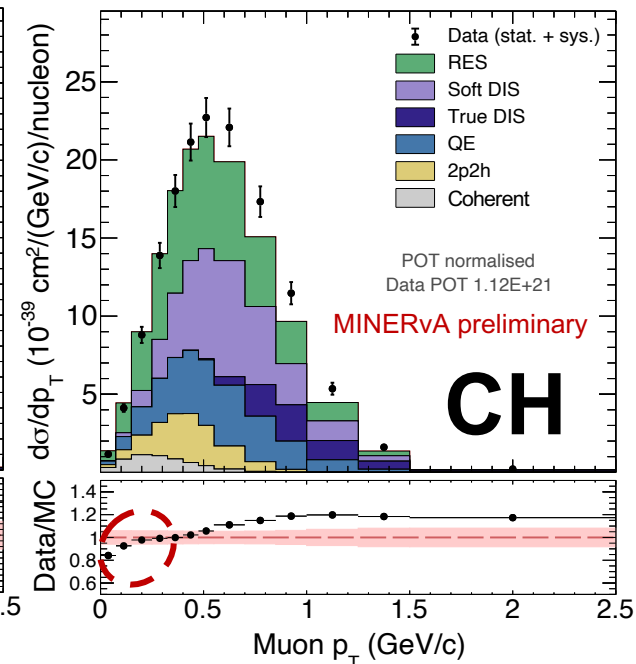
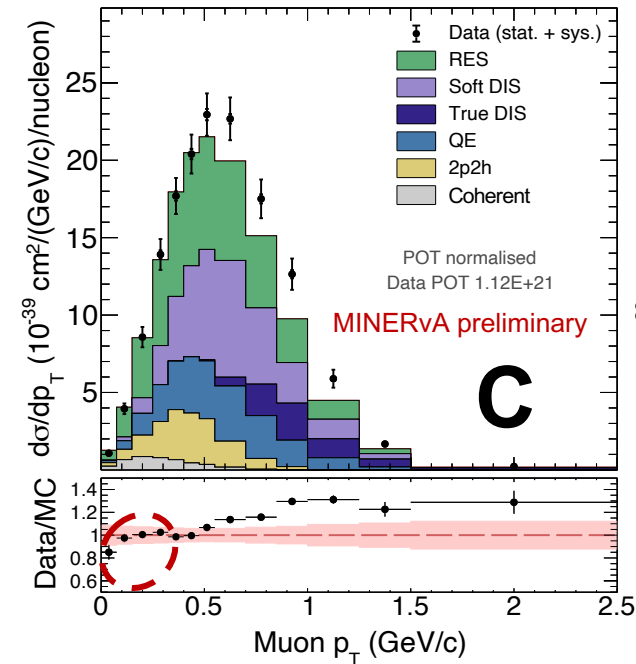
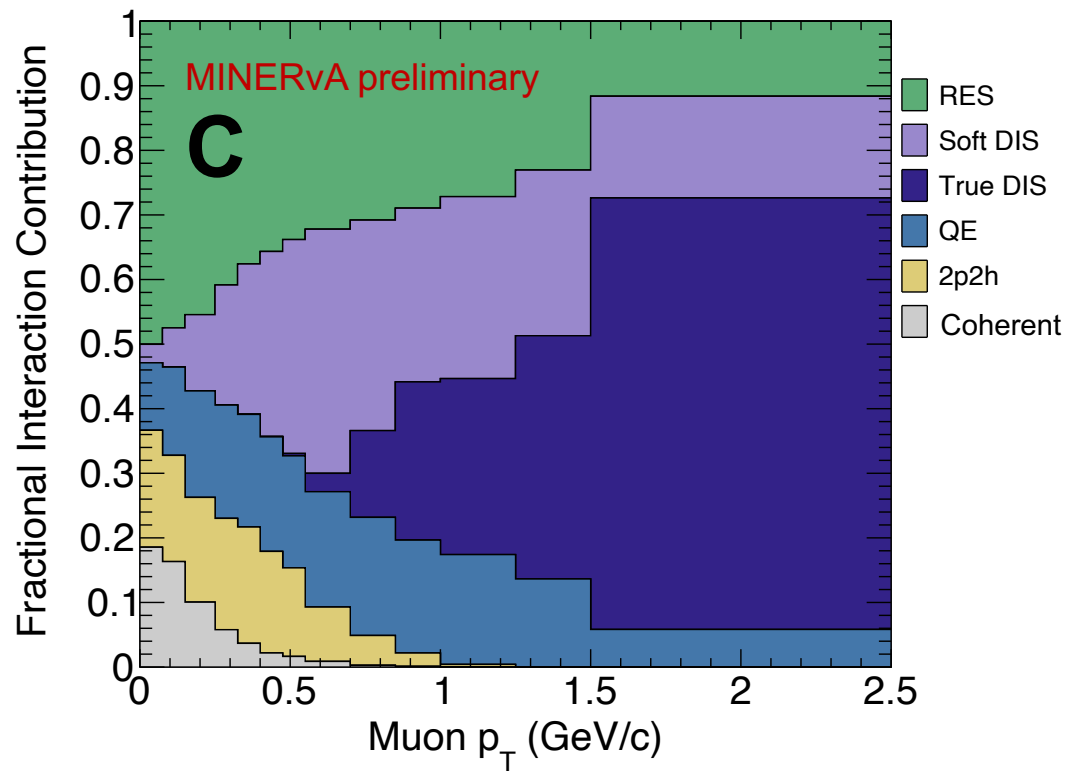
Cross-sections

- Some agreement in the peak of the distribution
- Underprediction at higher p_T



Cross-sections

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

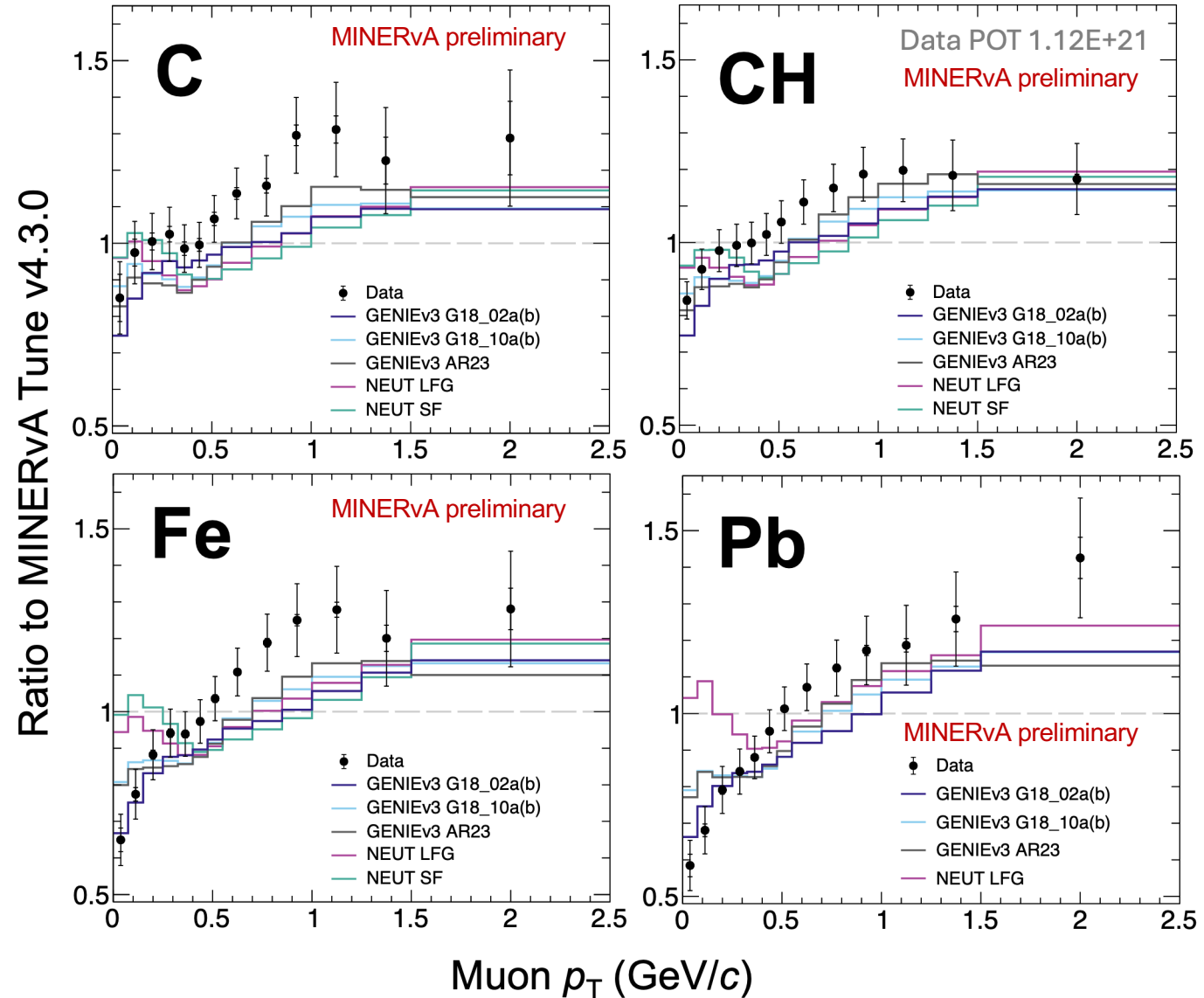


Can we learn more?

- Test robustness of different interaction models
- **Not going to discuss models in detail, but let's focus on trends!**

Can we learn more?

- Test robustness of different interaction models
- **Not going to discuss models in detail, but let's focus on trends!**
- 5 GENIEv3 and 2 NEUT generator predictions using NUISANCE*
 - Not sensitive to FSI \rightarrow hA/hN (a/b) GENIE differences negligible
- GENIEv3 AR23 (DUNE tune) yields lowest χ^2 with < 28 per 13 ndf for C and CH

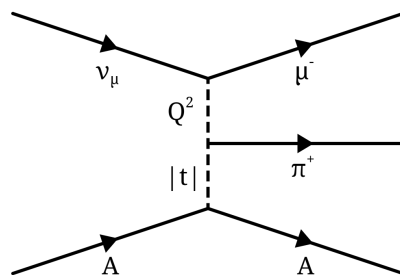


*P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et. al., JINST 12 P01016 (2017).

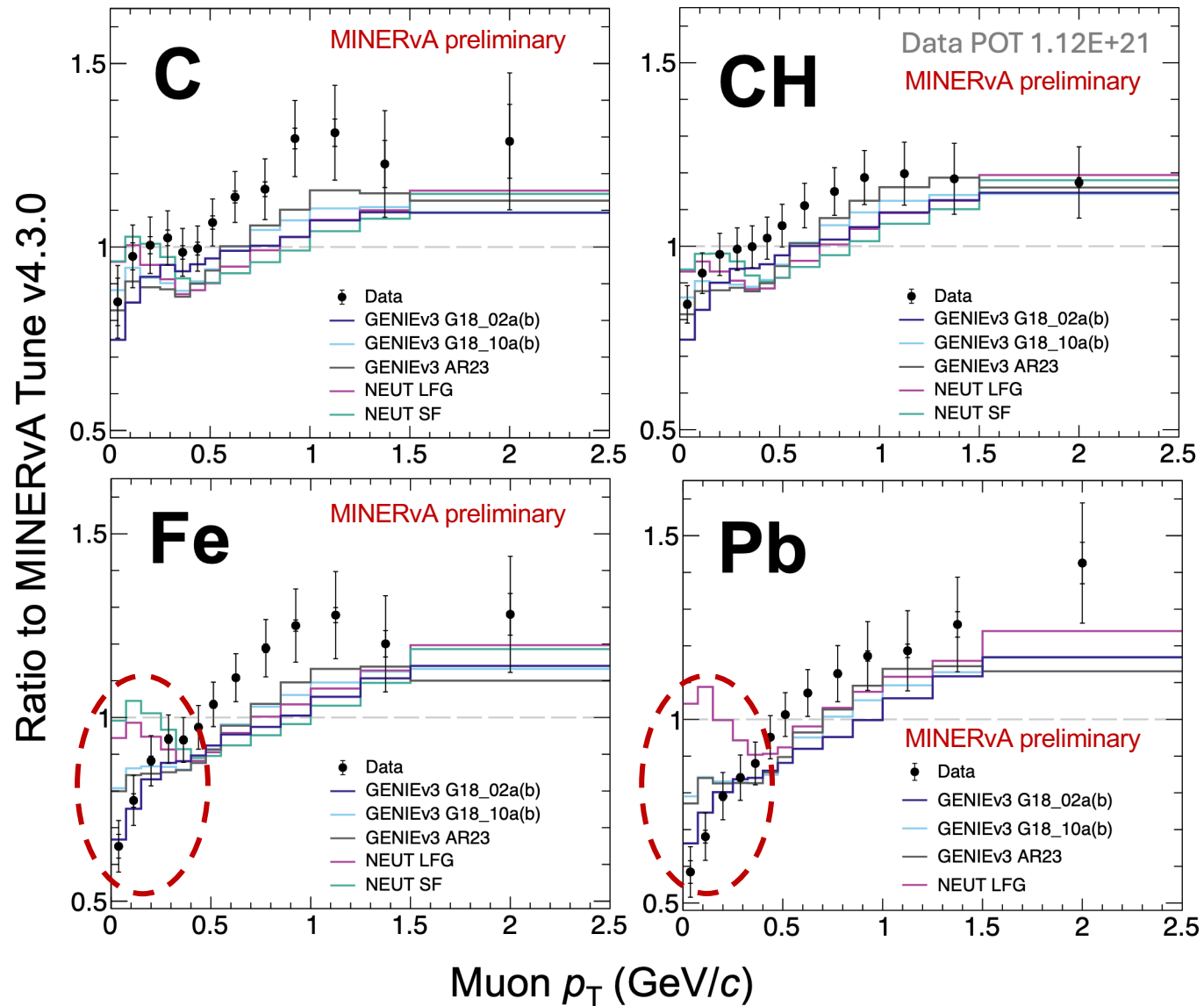
Note: NEUT version 5.4.1

Low- p_T

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



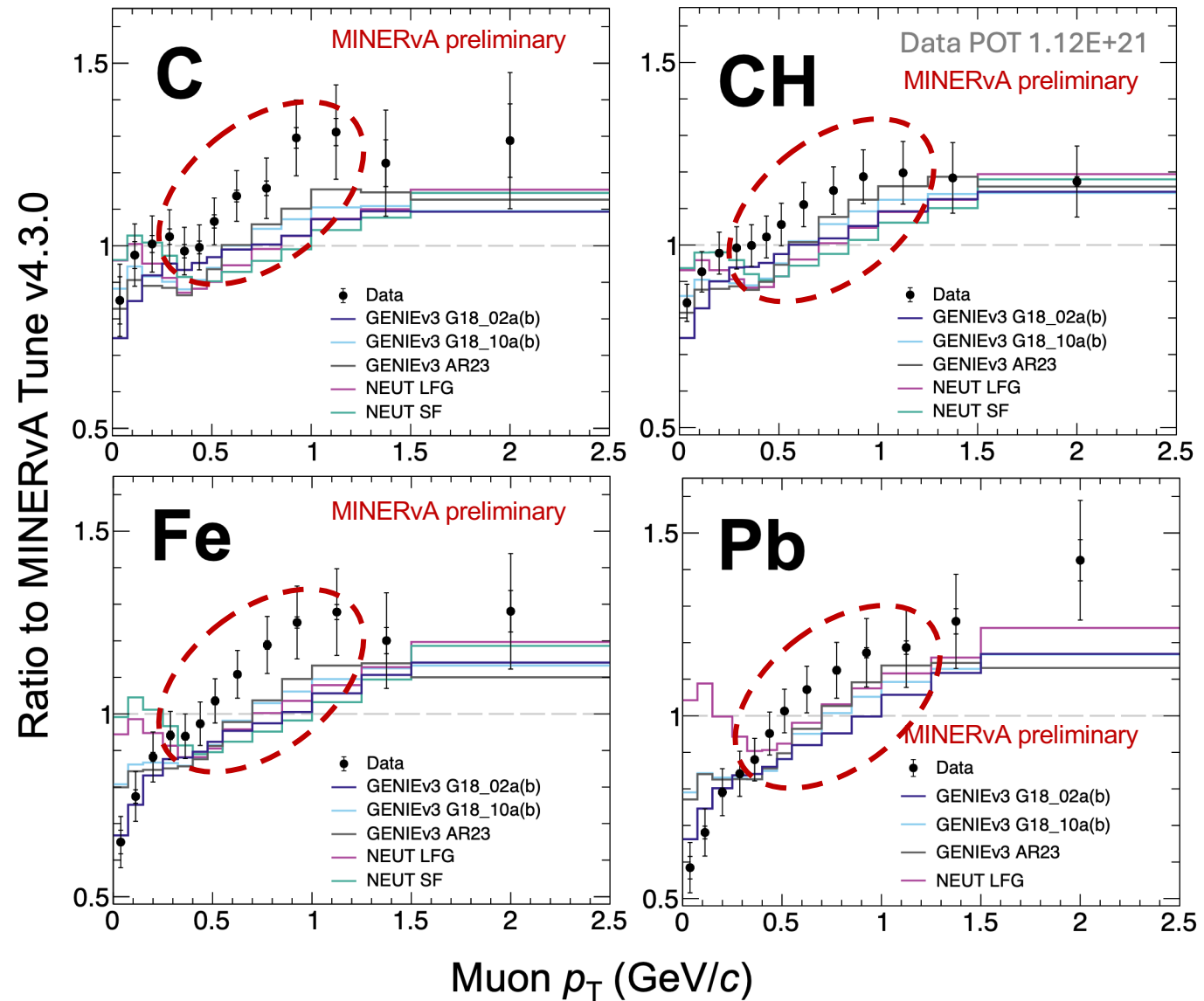
Coherent pion production



Note: NEUT version 5.4.1

Mid- p_T

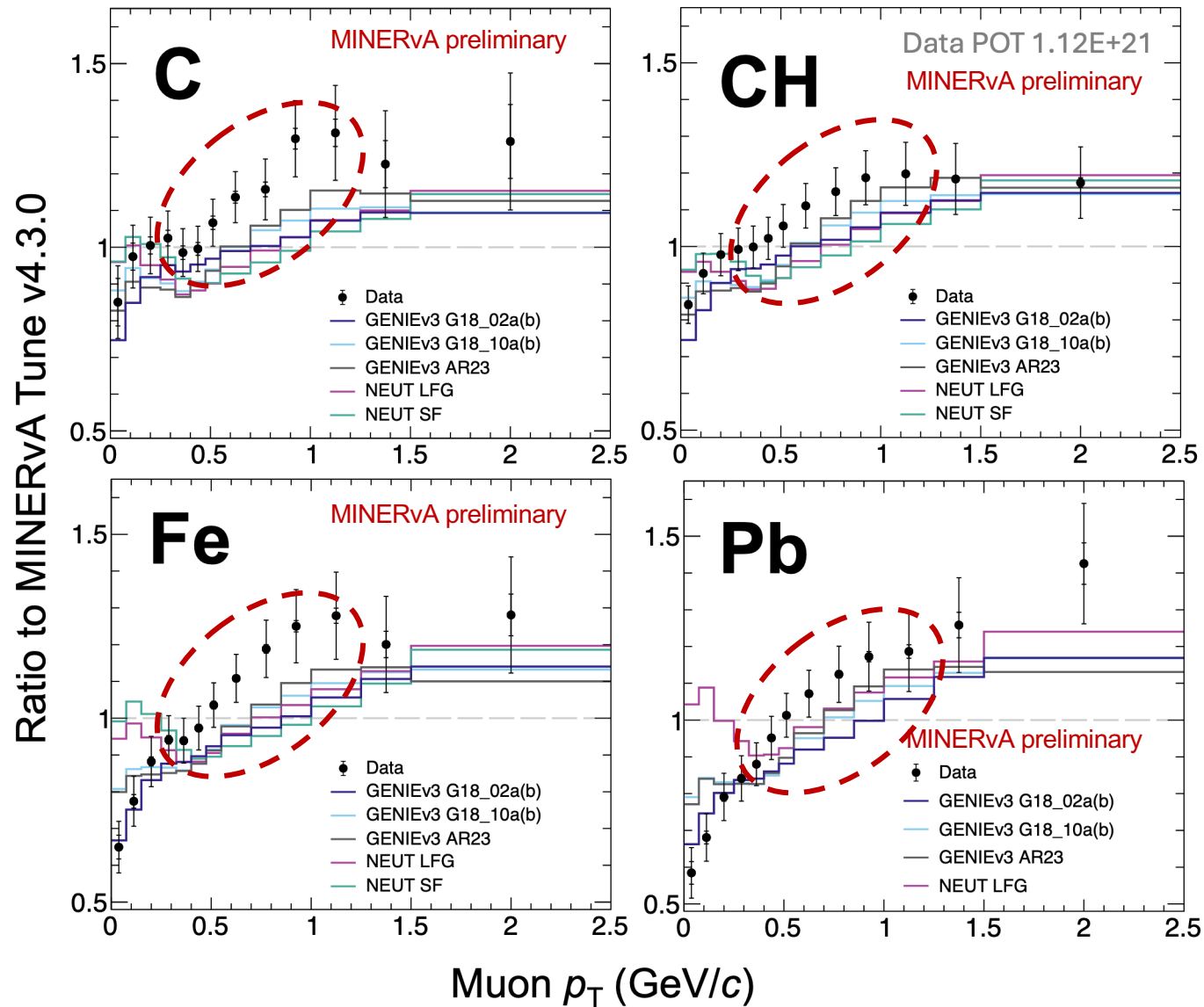
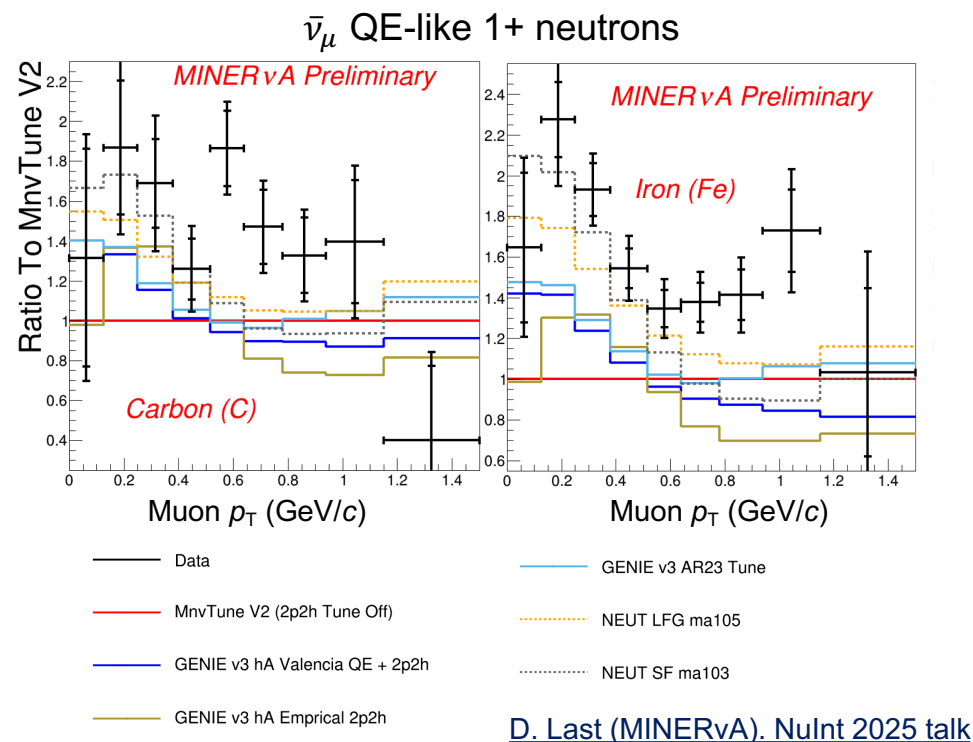
- In p_T range $\sim 0.4\text{--}1.0$ GeV/c underprediction observed across all nuclei



Note: NEUT version 5.4.1

Mid- p_T

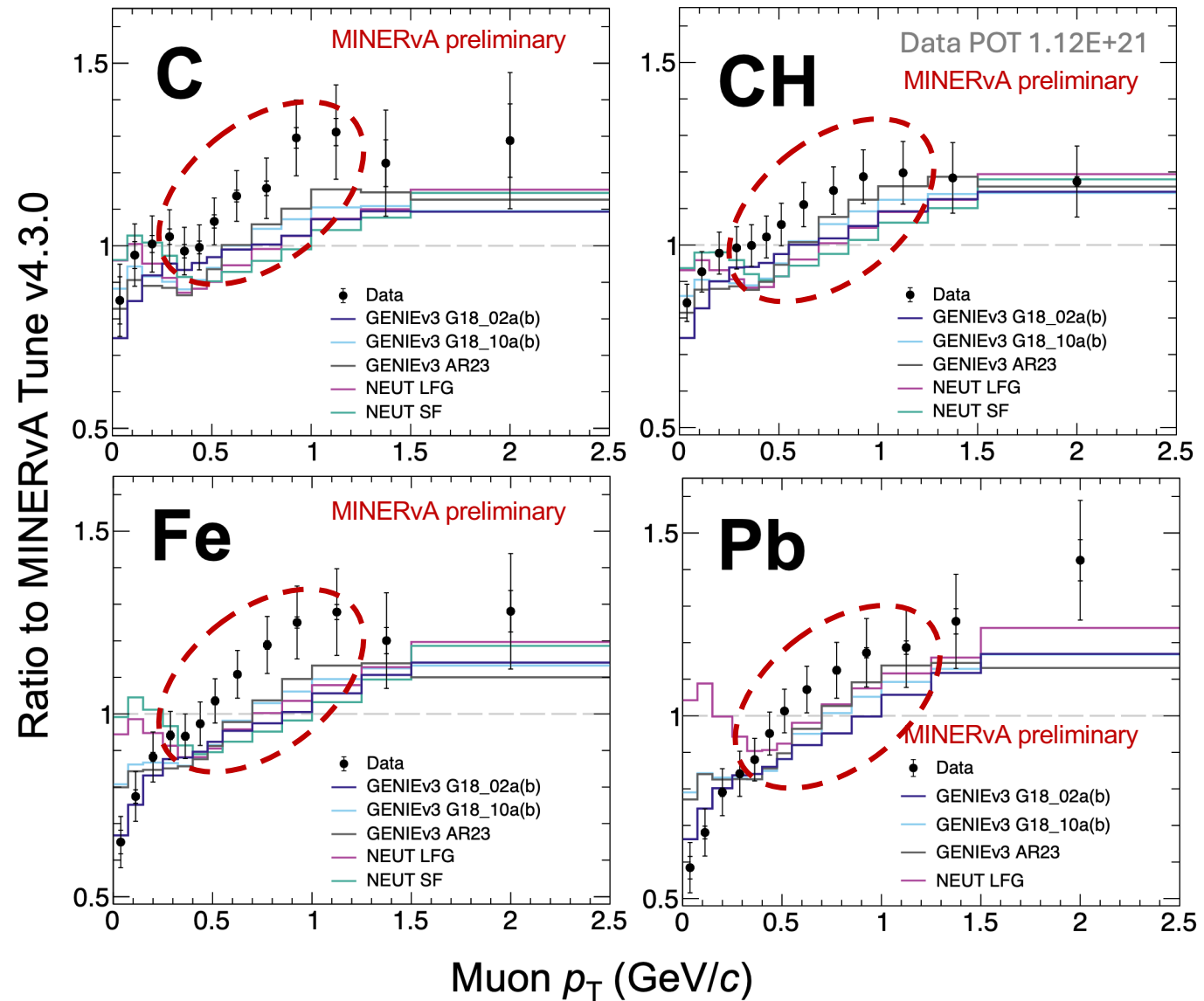
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Mid- p_T

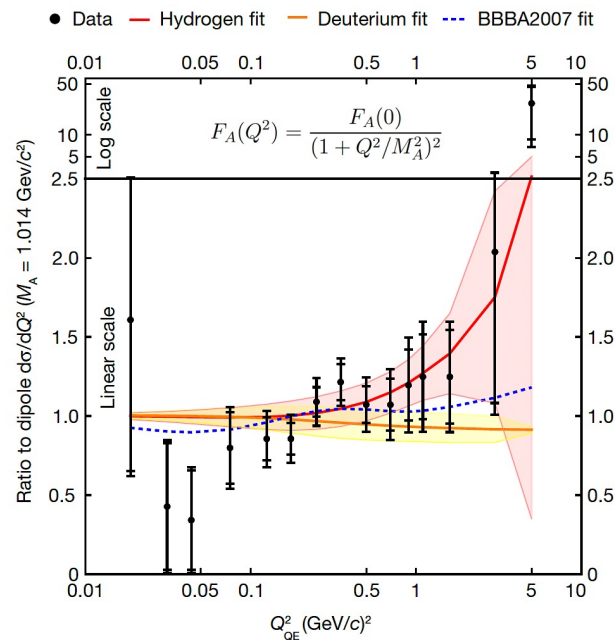
- In p_T range $\sim 0.4\text{--}1.0$ GeV/c underprediction observed across all nuclei
 - Suggests partially from QE-like processes



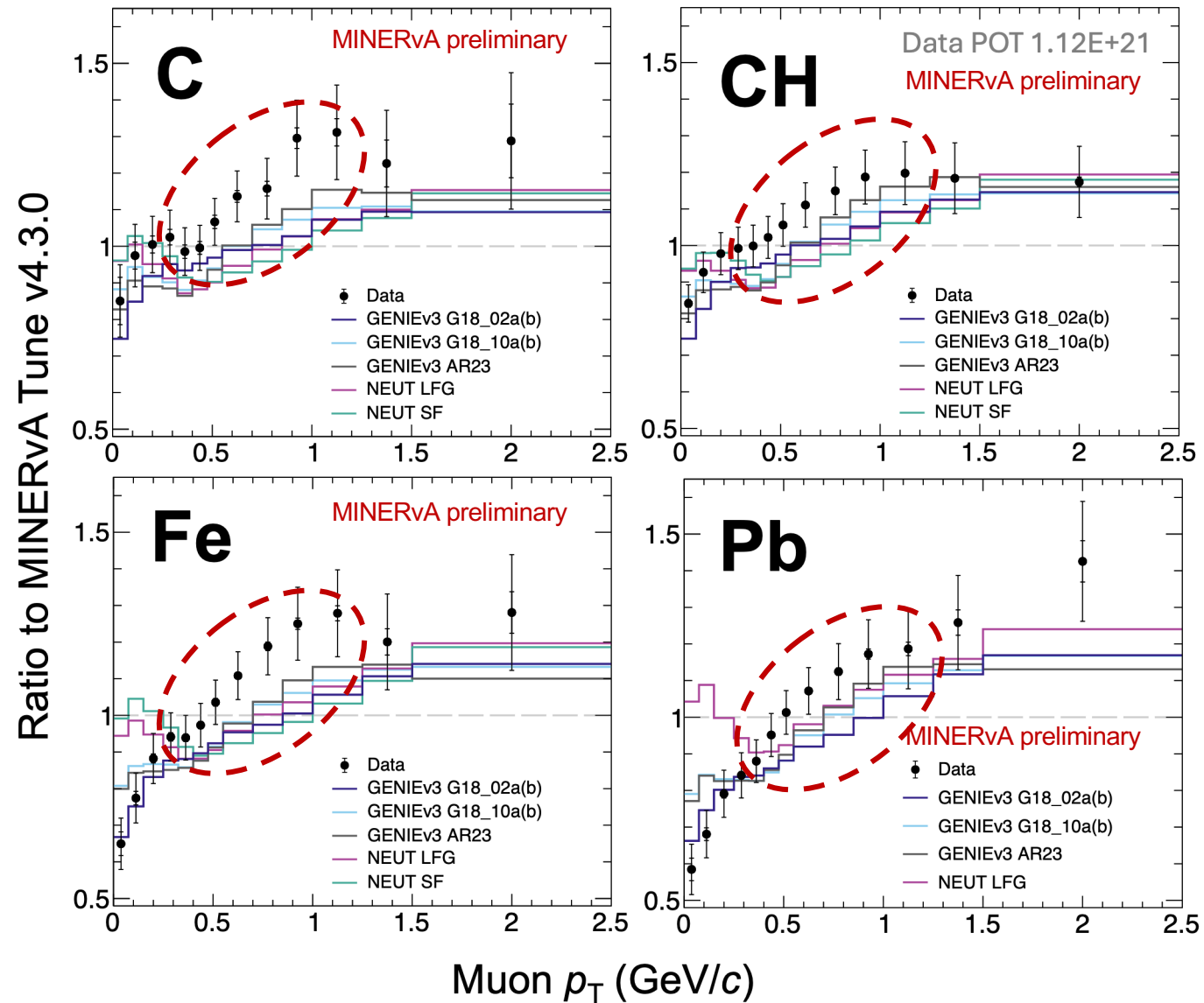
Note: NEUT version 5.4.1

Mid- p_T

- In p_T range $\sim 0.4\text{--}1.0$ GeV/c underprediction observed across all nuclei
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 - Related to the effect of dipole treatment of axial form factor (underprediction at higher Q^2)



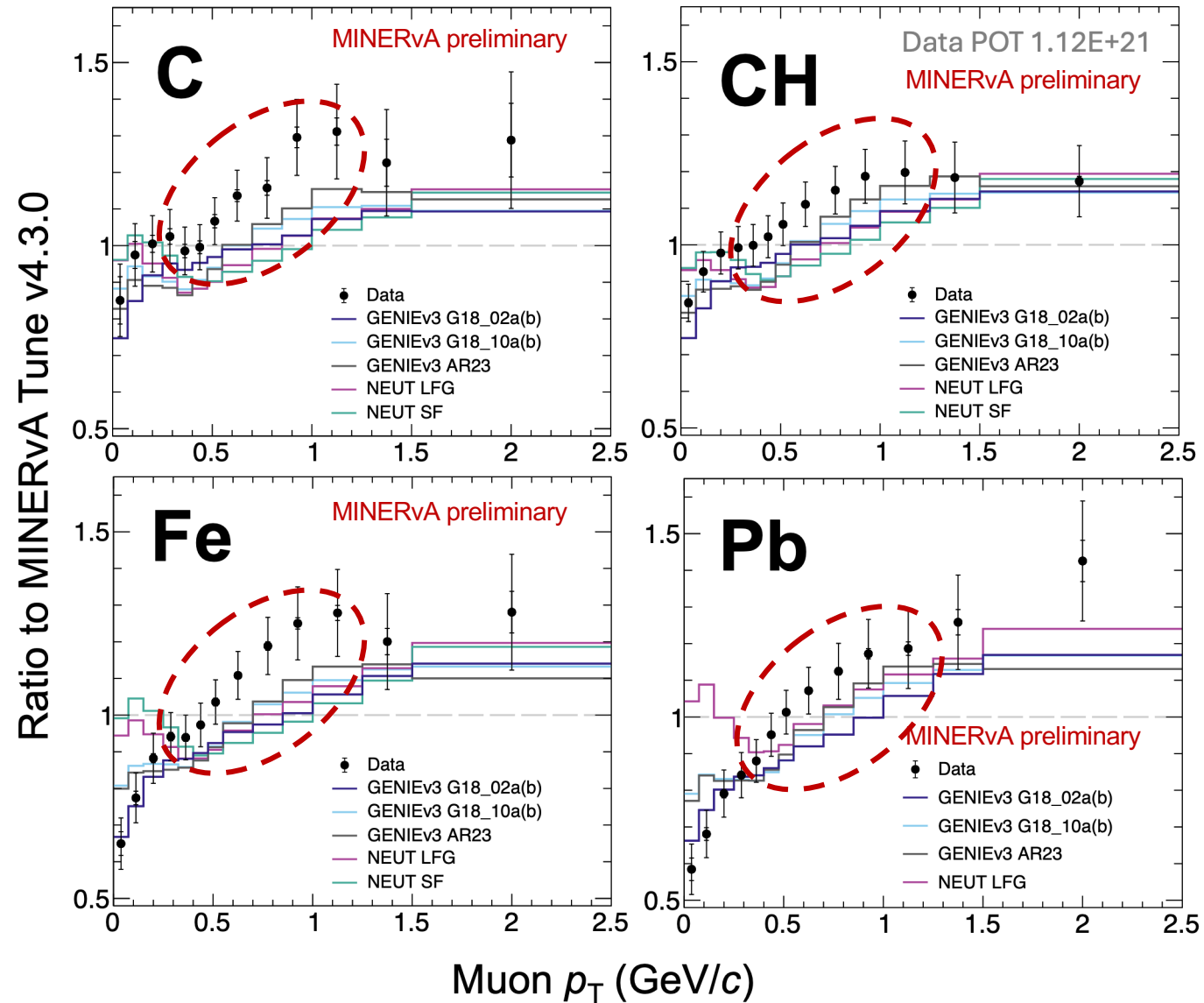
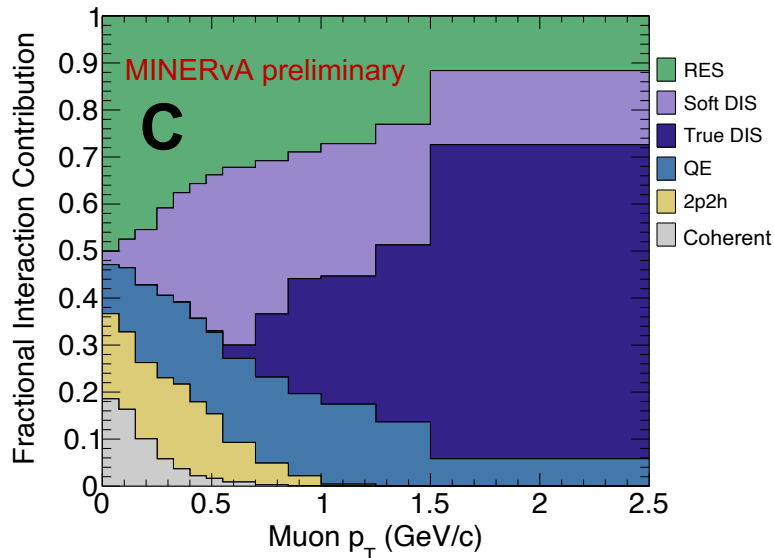
T. Cai (MINERvA), Nature 614, 48–53 (2023)



Note: NEUT version 5.4.1

Mid- p_T

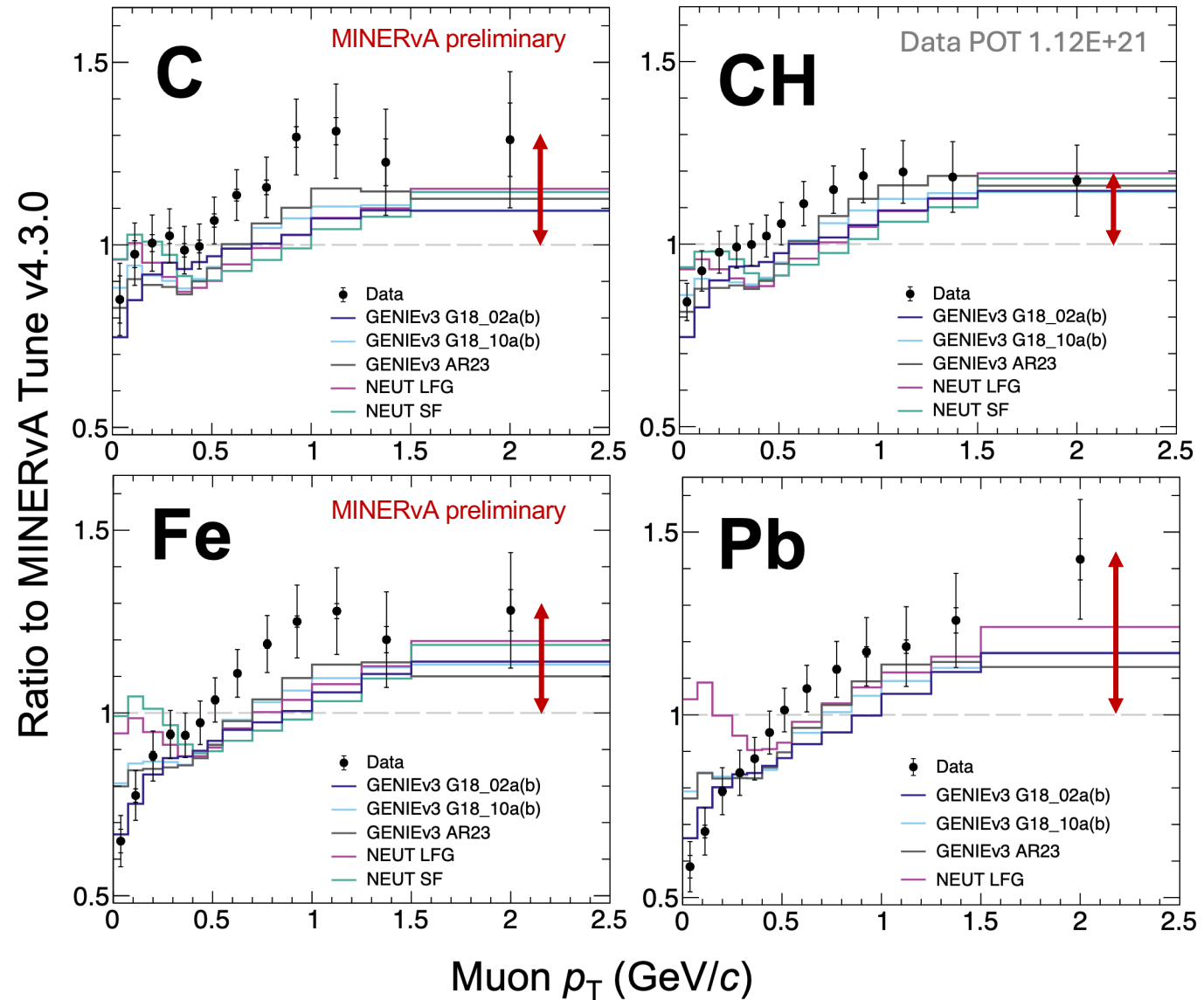
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 - Suggests partially from QE-like processes
 - Related to the effect of dipole treatment of axial form factor (underprediction at higher Q^2)
- **But there are other processes too!**
- Resonant axial form factor just as uncertain



Note: NEUT version 5.4.1

High- p_T

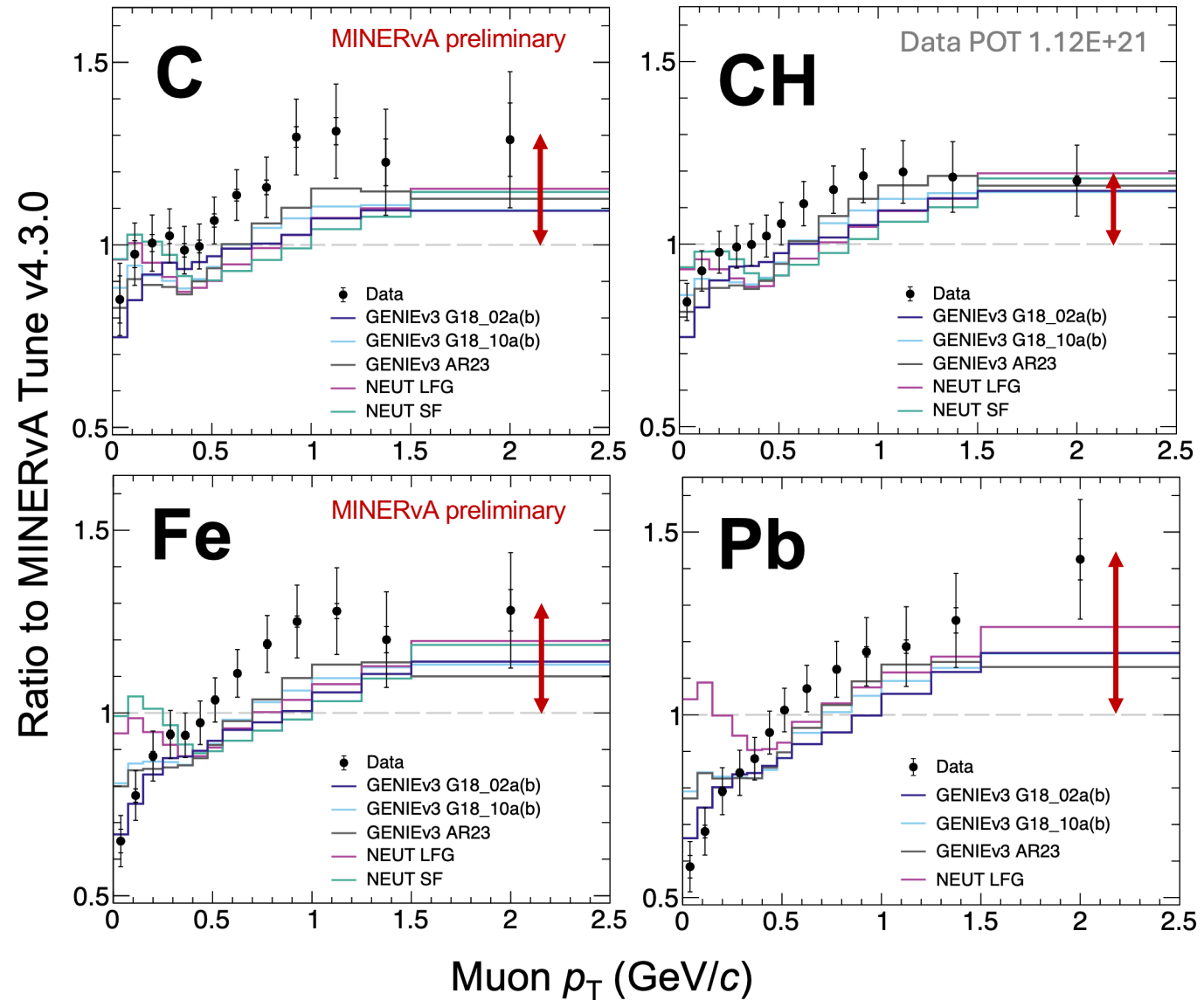
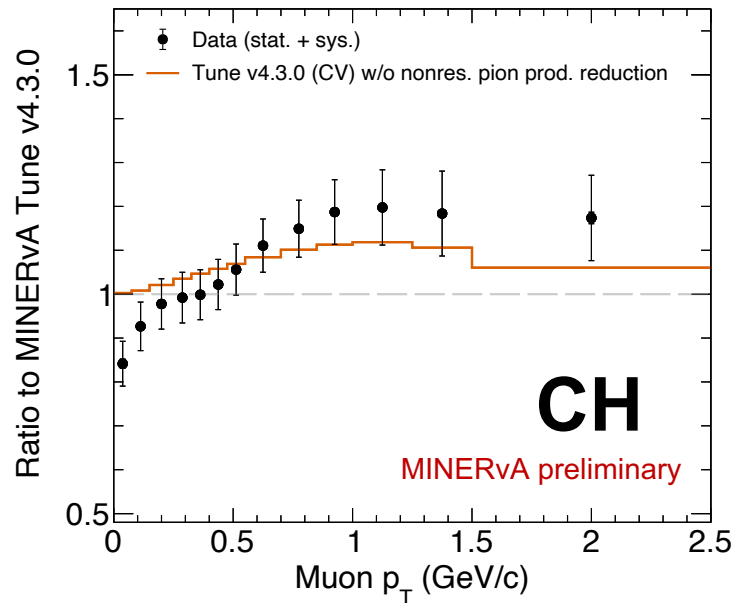
- (Mid- to) high- p_T region shows underprediction vs base model
 - High- p_T not tuned by MINERvA measurements



Note: NEUT version 5.4.1

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 reduced based on deuterium data*, beyond the region where the data are directly applicable

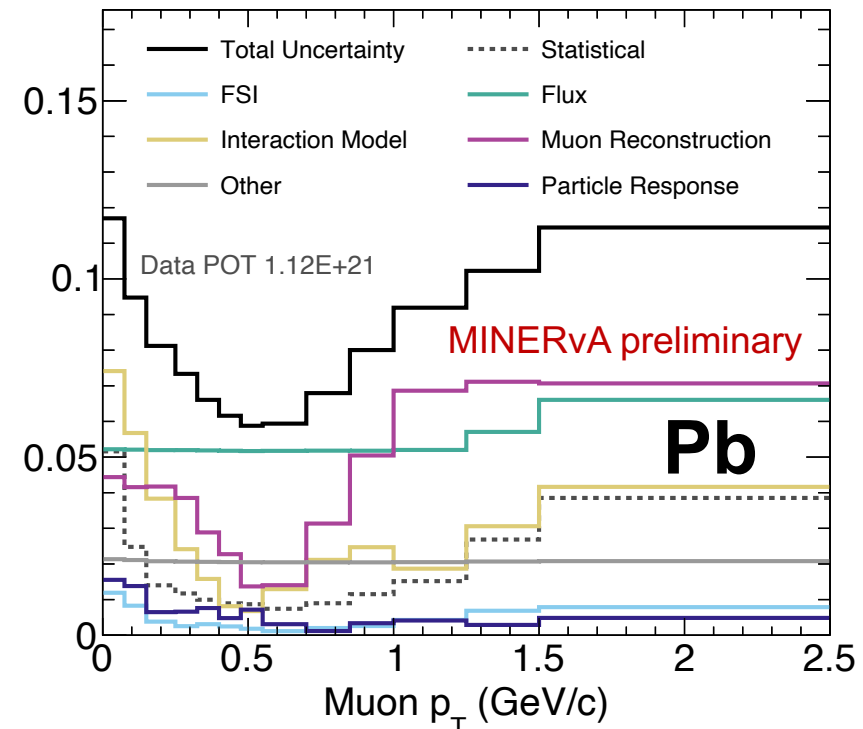
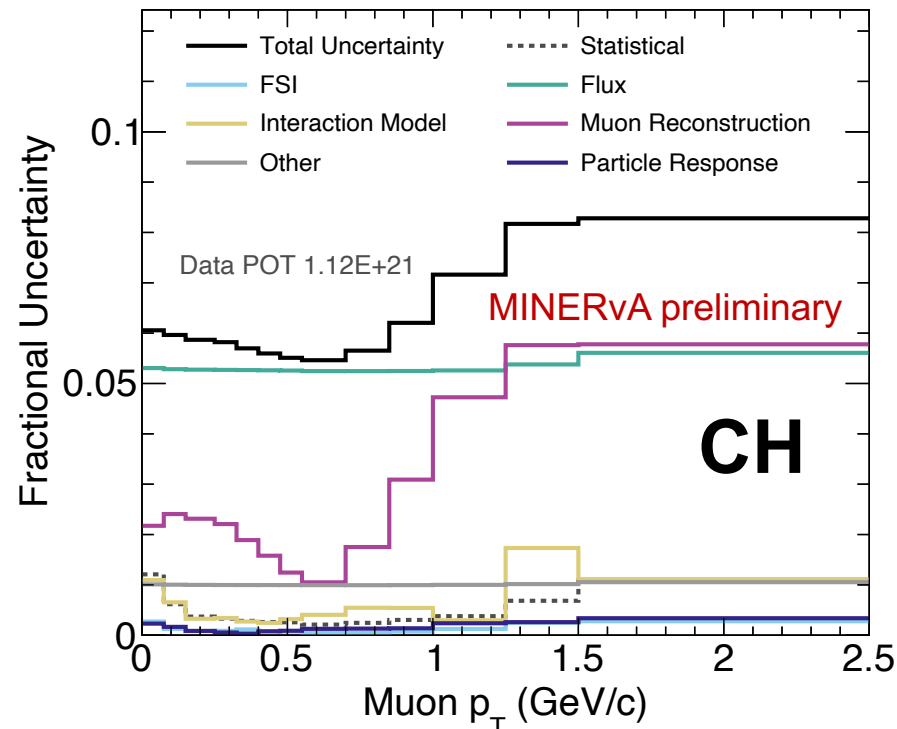


*P. Rodrigues, C. Wilkinson, & K. McFarland. Eur. Phys. J. C. 76, 474 (2016)

Note: NEUT version 5.4.1

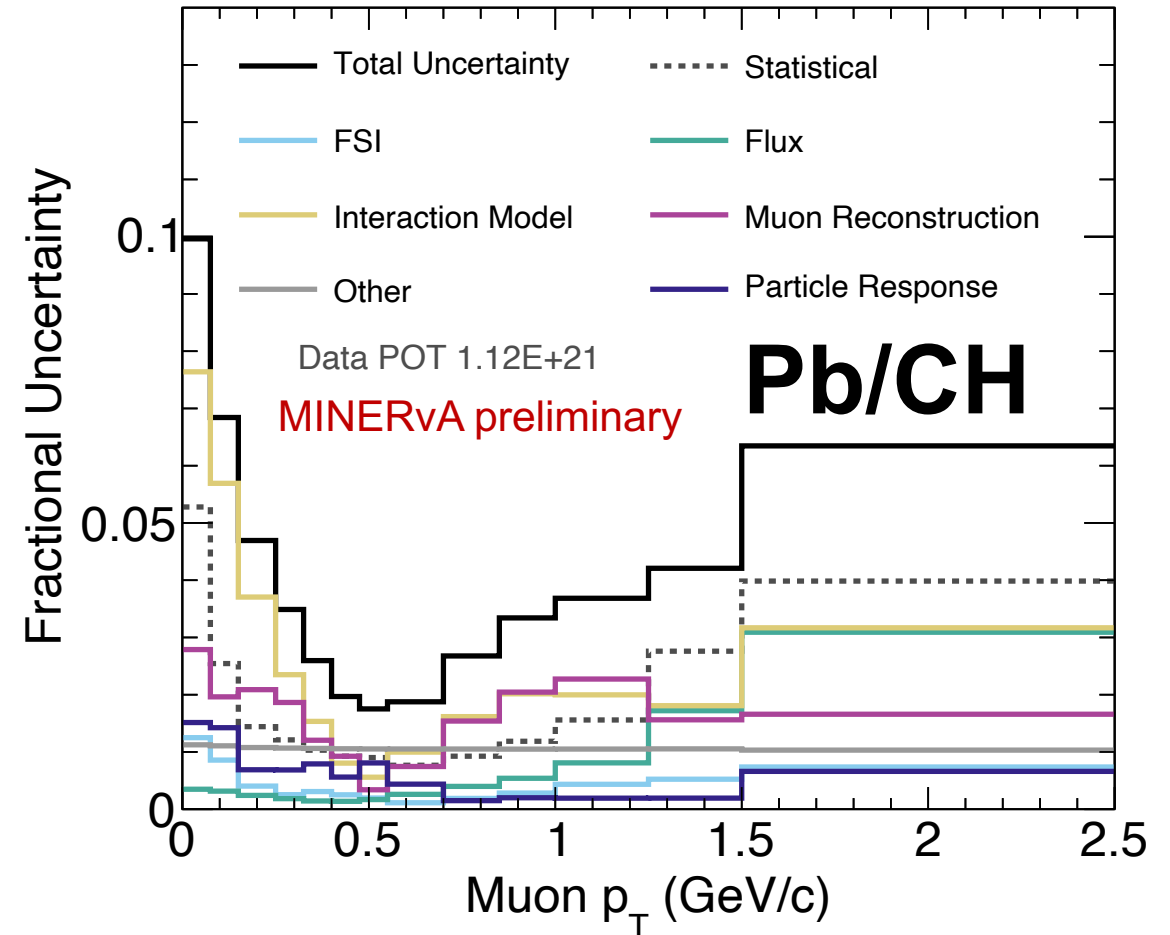
Systematic uncertainties

- Evaluated by varying parameters within their uncertainties and re-extracting cross-section in “universes”
- **5–6% total uncertainty in the peak of the distribution, ~6% CH, ~10% or less overall for C, Fe, Pb**
 - Leading: flux & muon reconstruction
 - **Interaction model**: leading GENIE parameter M_A^{RES} + conservative MINERvA tune reweights



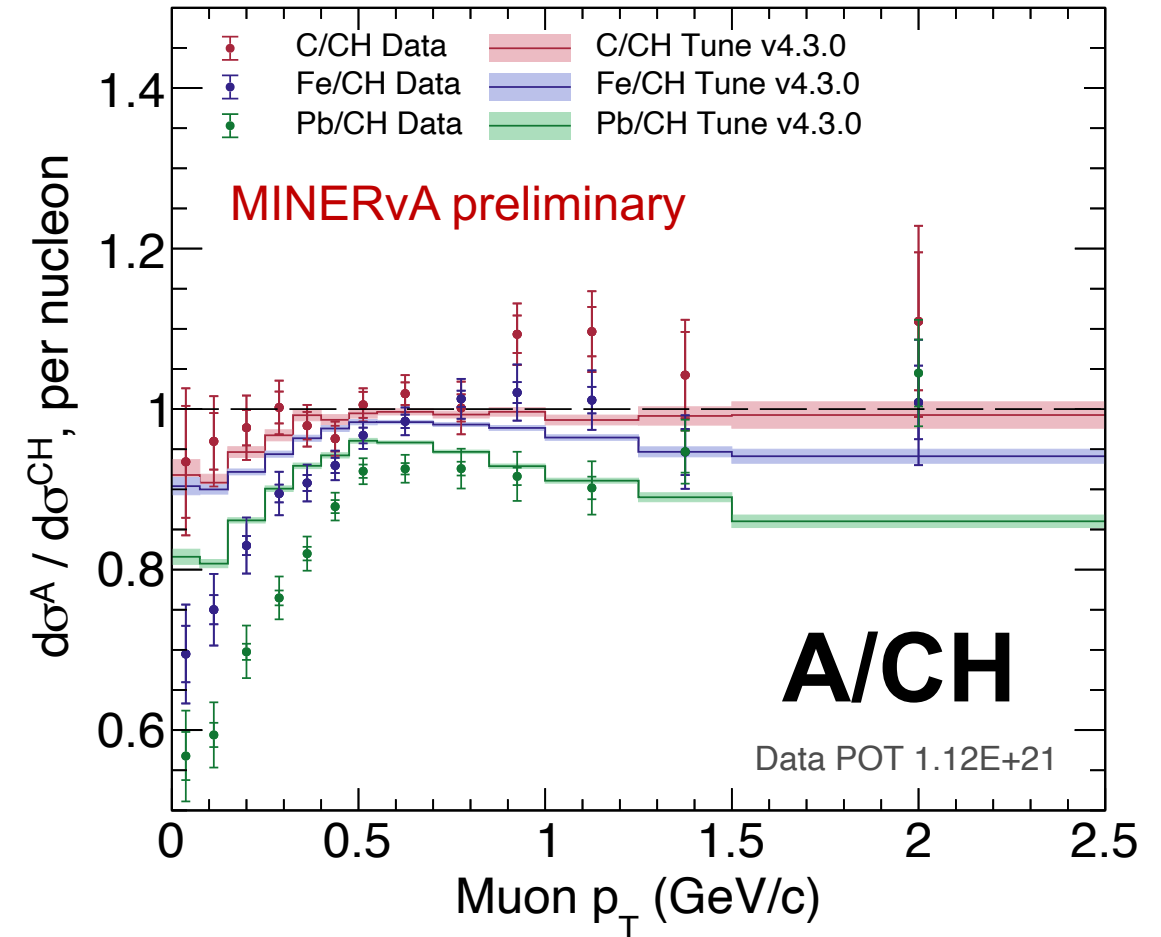
Even better, take a ratio

- Ratios to high-statistics hydrocarbon sample
 - Cancellation of shared physics and systematics
 - $\leq 5\%$ total uncertainty ($\sim 2\%$ in the peak region)



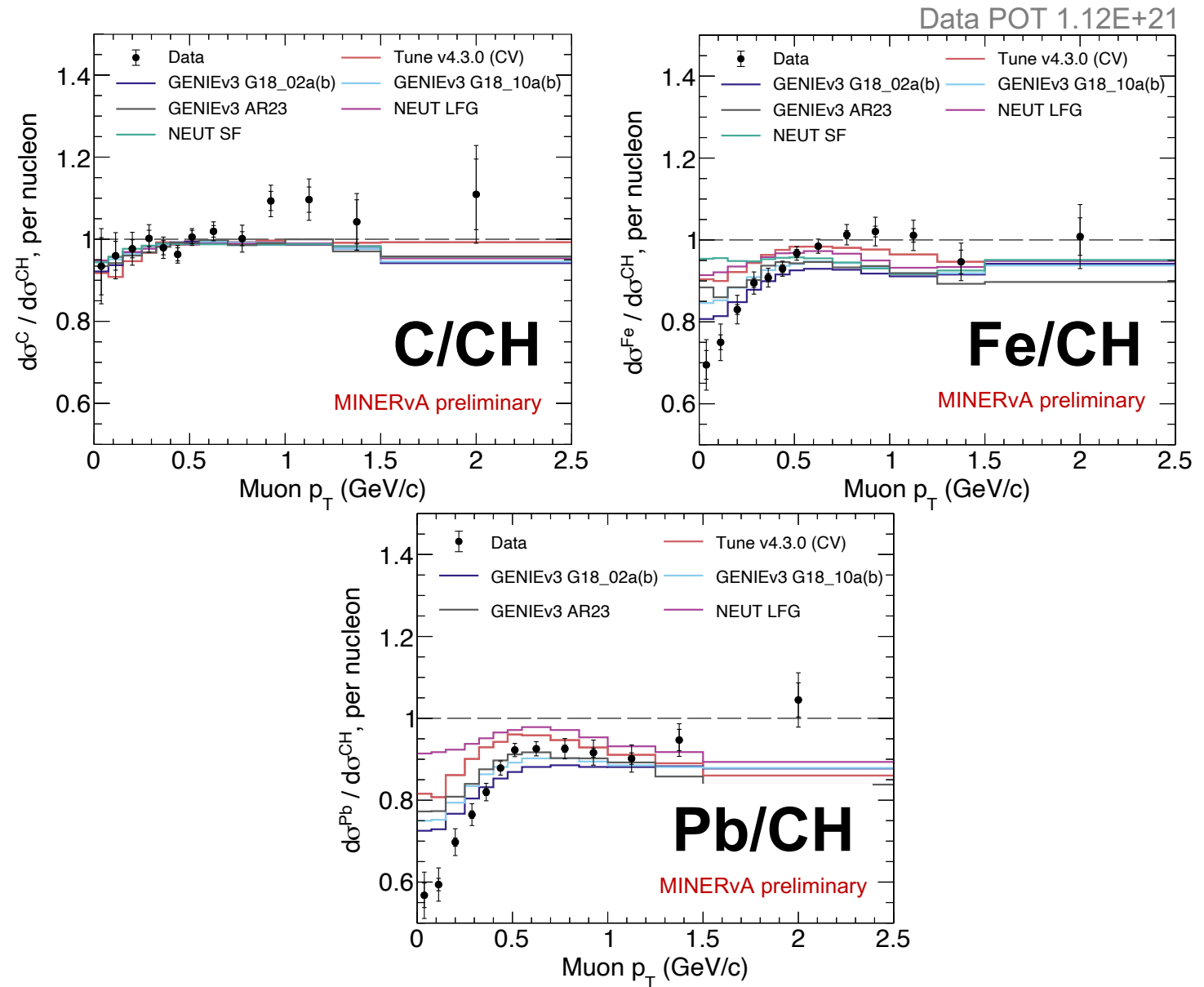
Even better, take a ratio

- Ratios to high-statistics hydrocarbon sample
 - Cancellation of shared physics and systematics
 - $\leq 5\%$ total uncertainty ($\sim 2\%$ 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
- **Clear A -dependent low- p_T suppression in iron and lead**



Ratios vs models

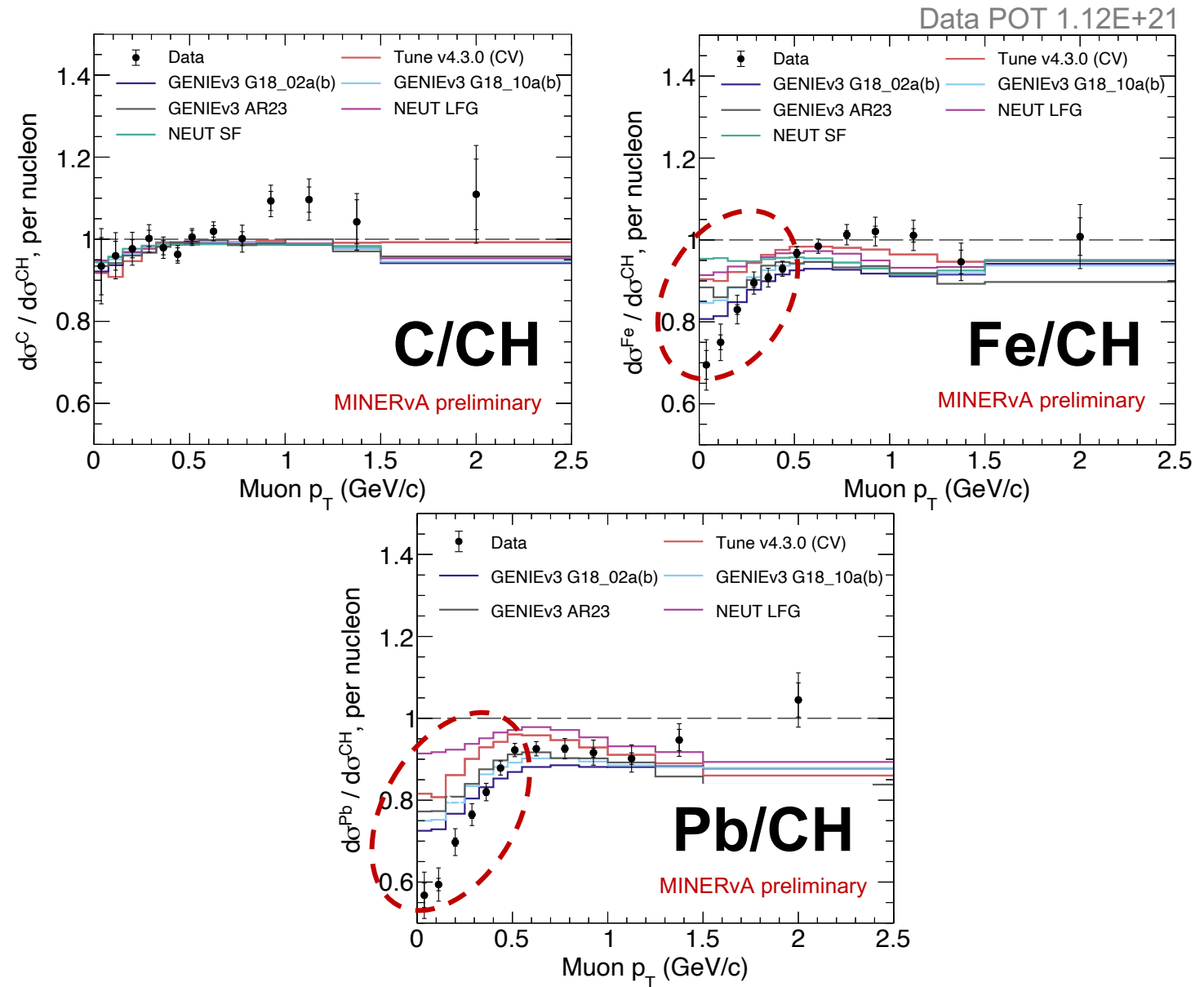
- Statistical power to distinguish between different models – strong constraint on nuclear effects
- GENIEv3 AR23 (DUNE tune) has lowest χ^2



Note: NEUT version 5.4.1

Ratios vs models

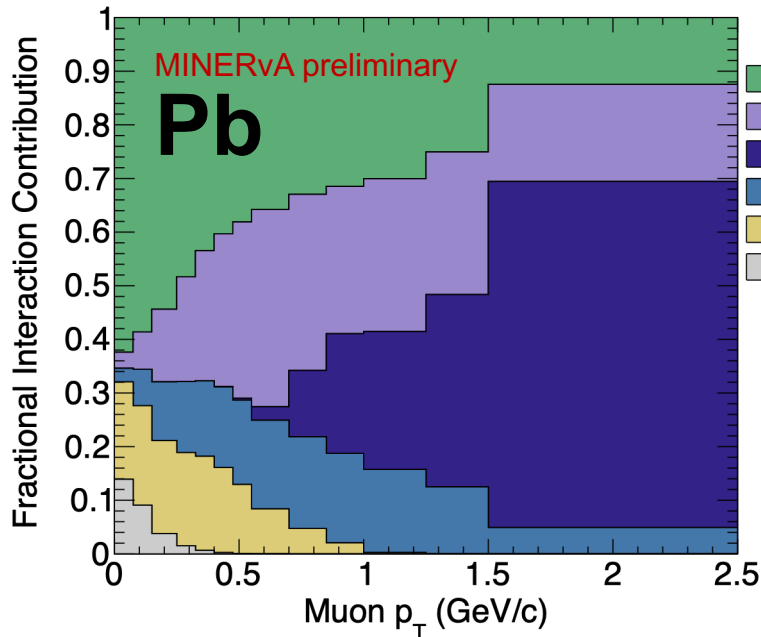
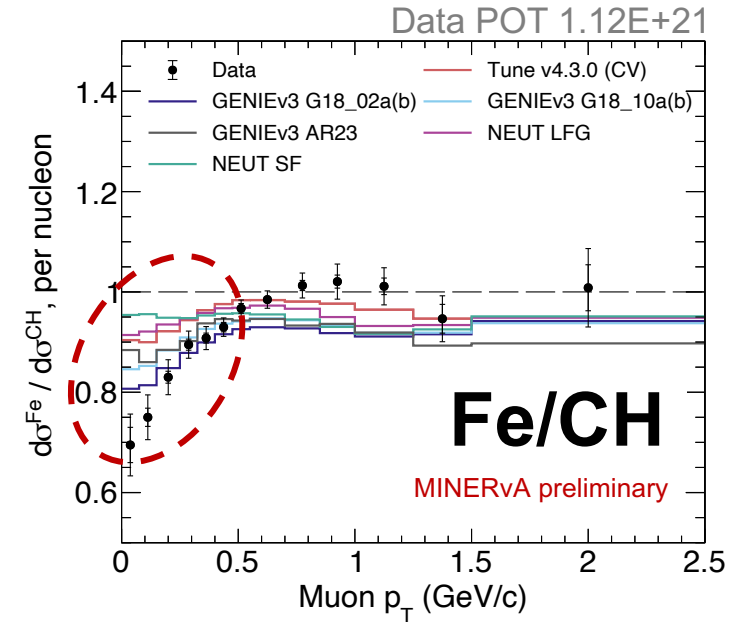
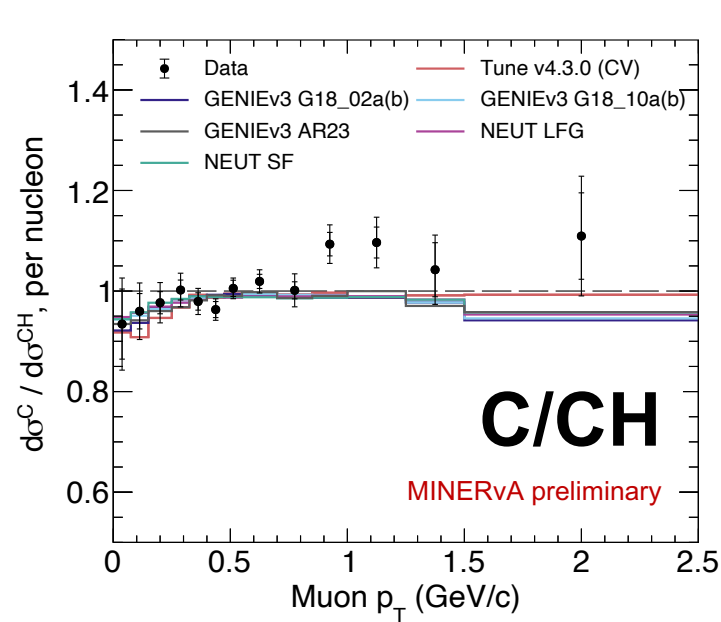
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- **Low p_T nuclear dependence not reproduced by any of the generator predictions**



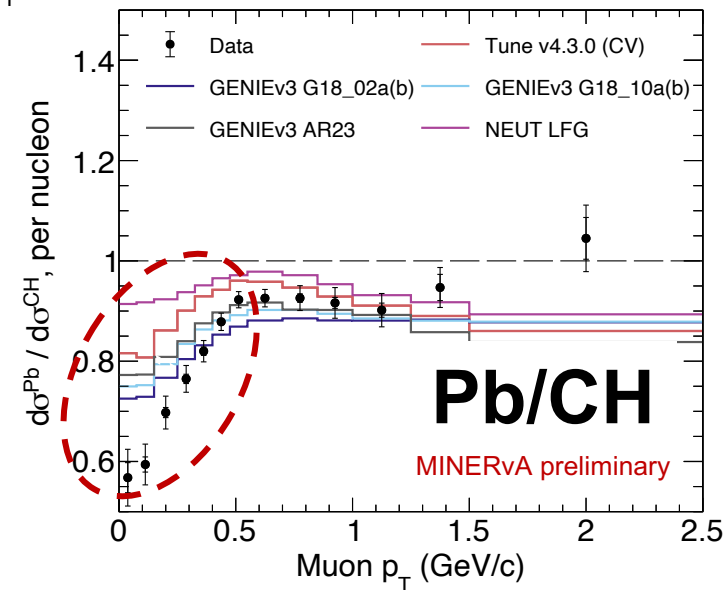
Note: NEUT version 5.4.1

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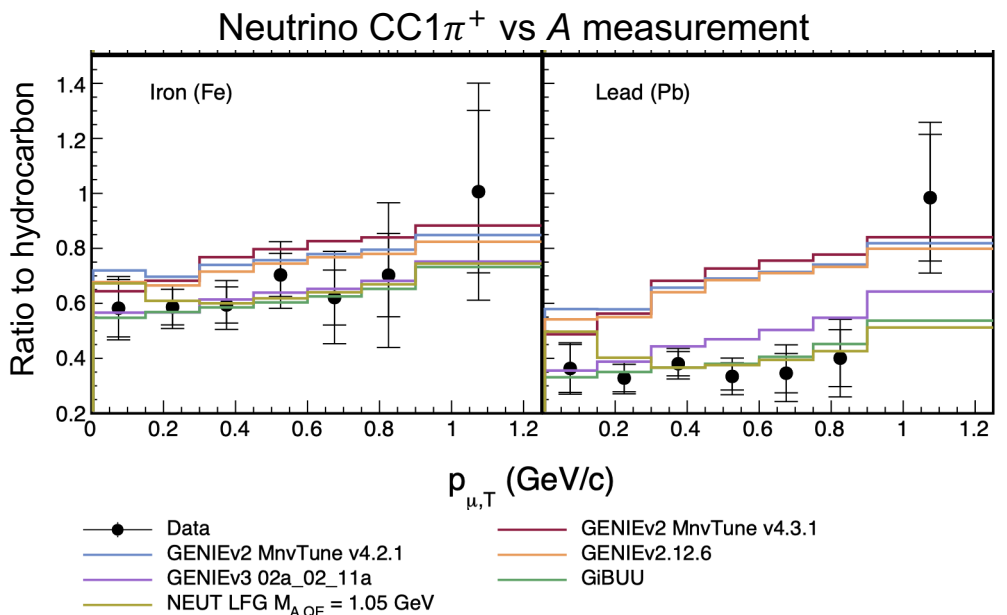
RES-dominated: need for stronger nuclear effects in resonance region?



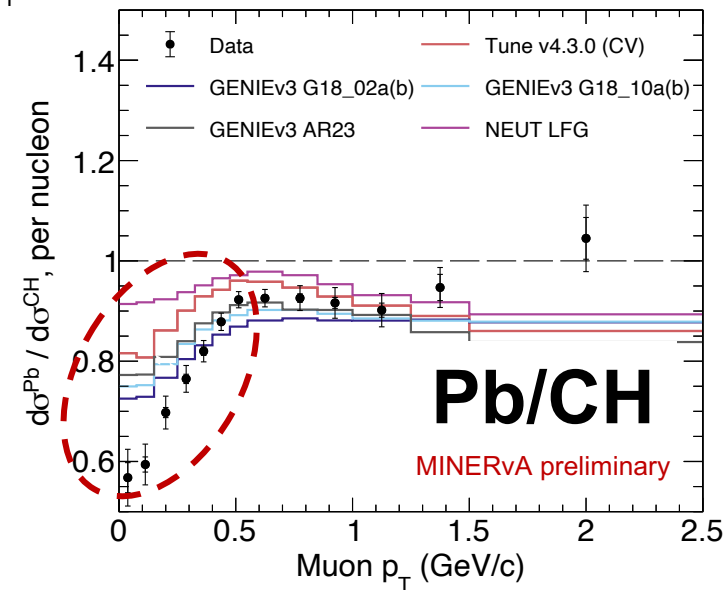
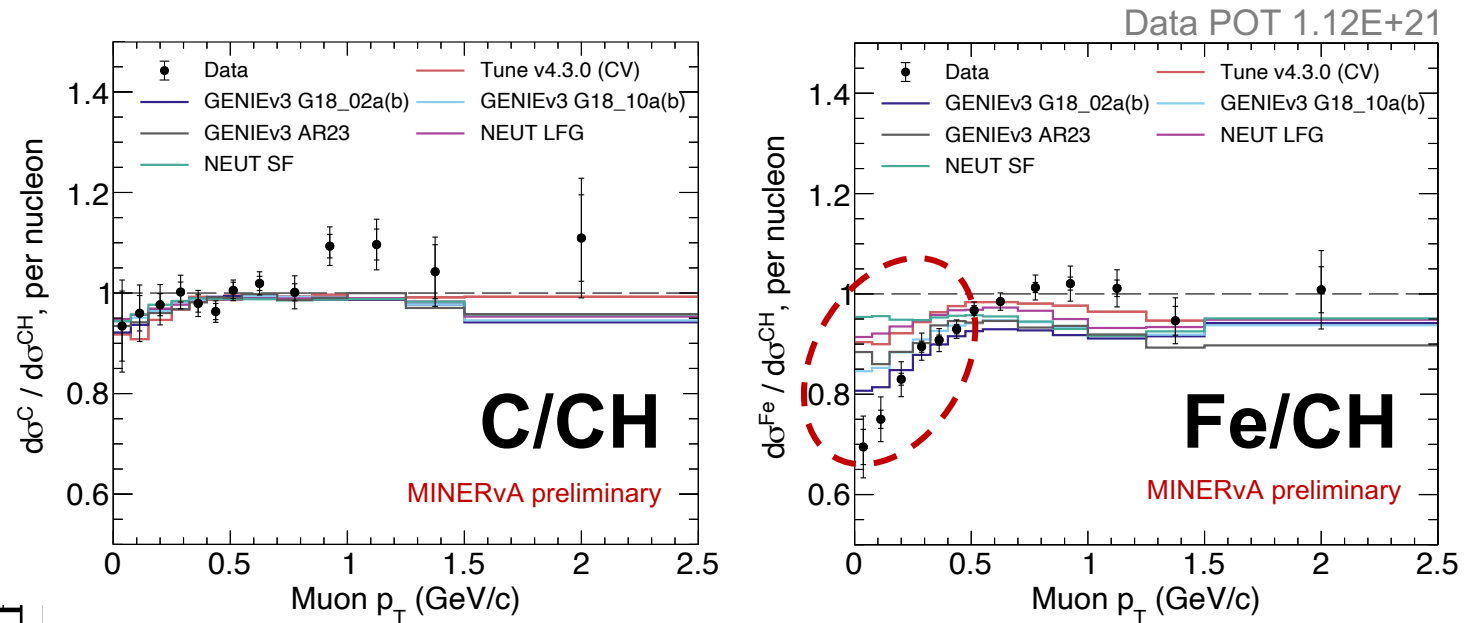
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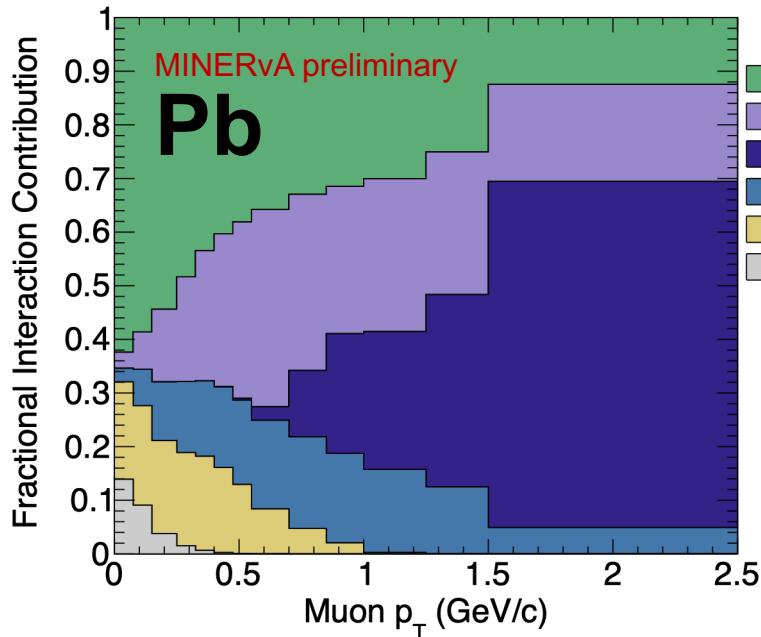
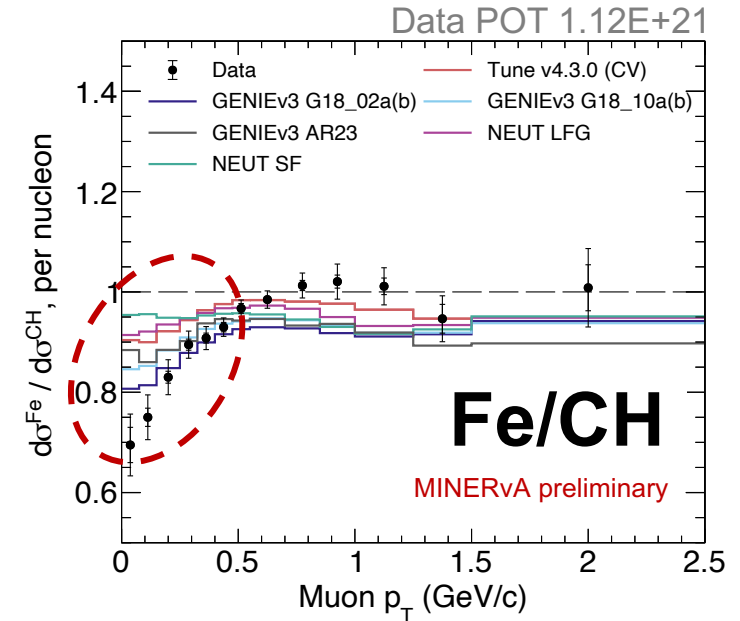
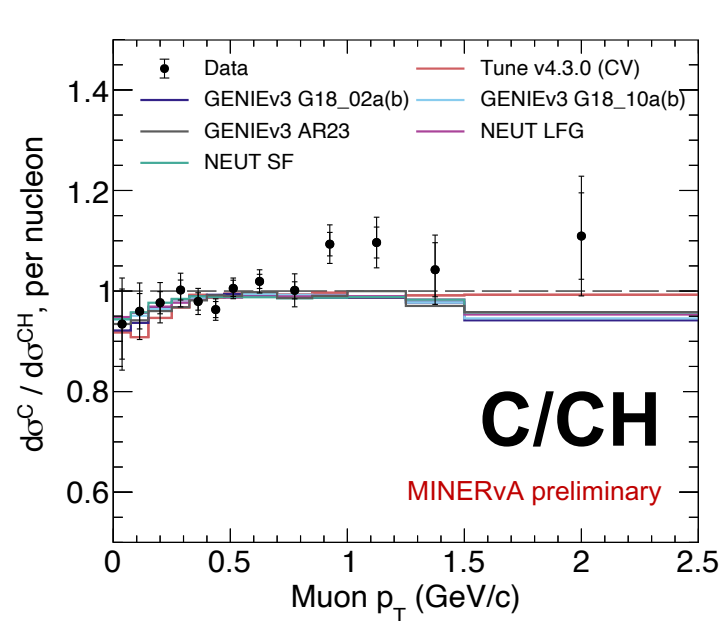
[A. Bercellie \(MINERvA\). Phys.Rev.Lett. 131, 011801 \(2023\).](#)



Note: NEUT version 5.4.1

Ratios vs models

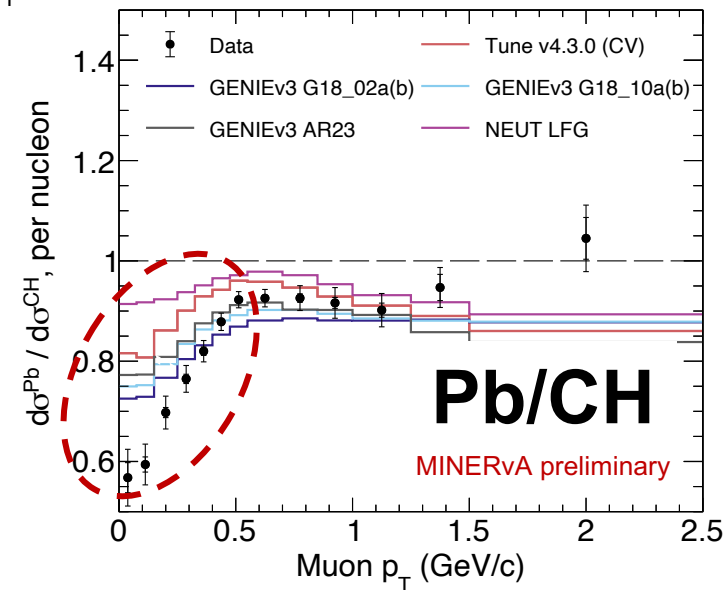
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- **Low p_T nuclear dependence not reproduced by any of the generator predictions**



RES-dominated: need for stronger nuclear effects in resonance region?

Antineutrino mode
Other processes contribute too!

Strong mystery indication



Note: NEUT version 5.4.1

Conclusions I



- 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 II

- **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 $\sim 10\%$ or less ($\sim 5\%$ in the peak), and CH $\sim 6\%$
 - C/CH, Fe/CH, Pb/CH cross-section ratios $\sim 5\%$ or less ($\sim 2\%$ in the peak)
- **Strong nuclear effects in Fe and Pb, particularly at low and high p_T not reproduced by models**
- By comparing to MINERvA's more exclusive measurements
 - Low p_T : likely more suppression due to nuclear effects in resonance region needed
 - In p_T range $\sim 0.4\text{--}1.0$ 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

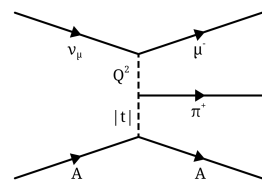
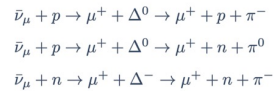
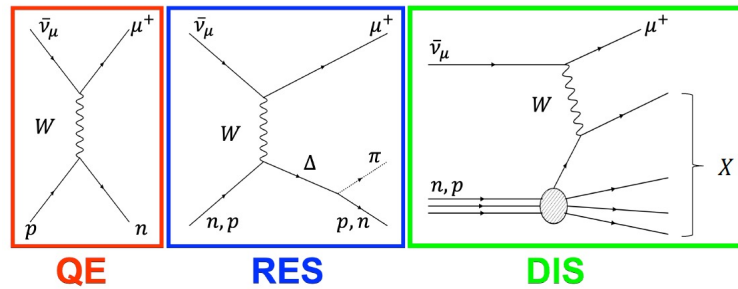
On arXiv soon!



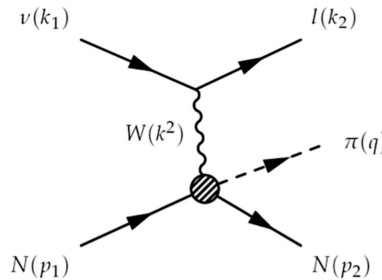
Back-up

(Anti)neutrino interactions

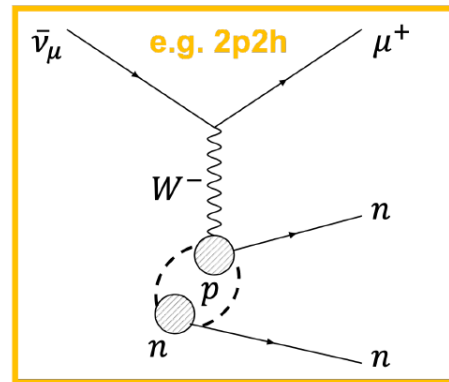
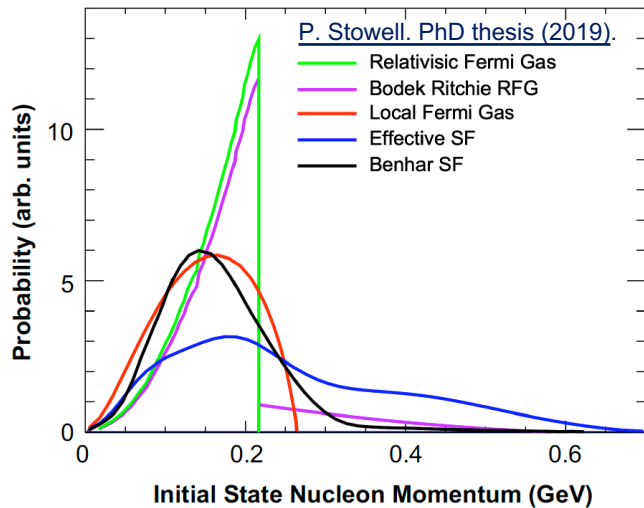
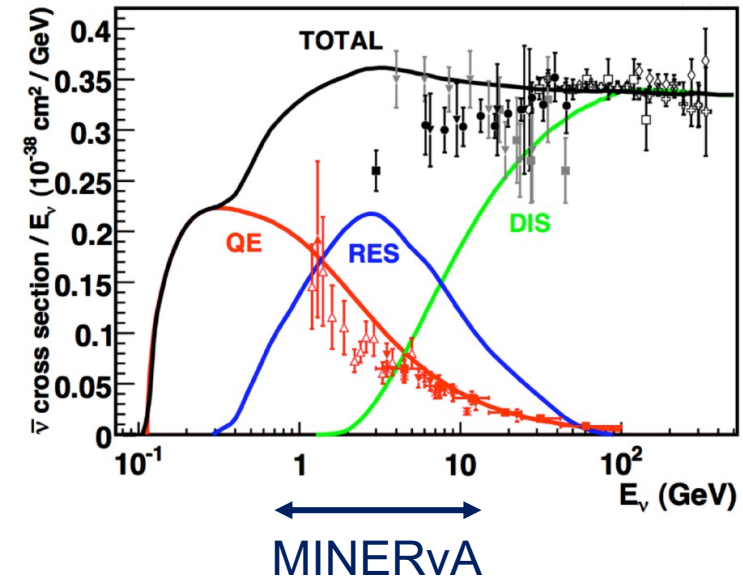
- Neutrino-nucleon interactions + effects of the nuclear medium
- Antineutrino scattering (W^-): $(u, c)/(\bar{d}, \bar{s}) \rightarrow (d, s)/(\bar{u}, \bar{c})$



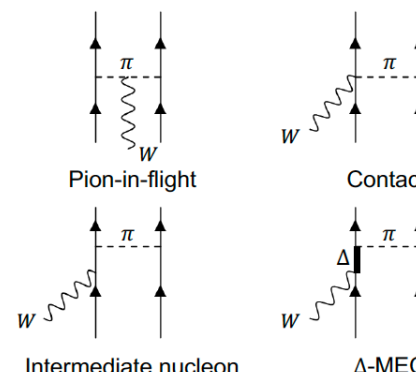
Coherent pion production



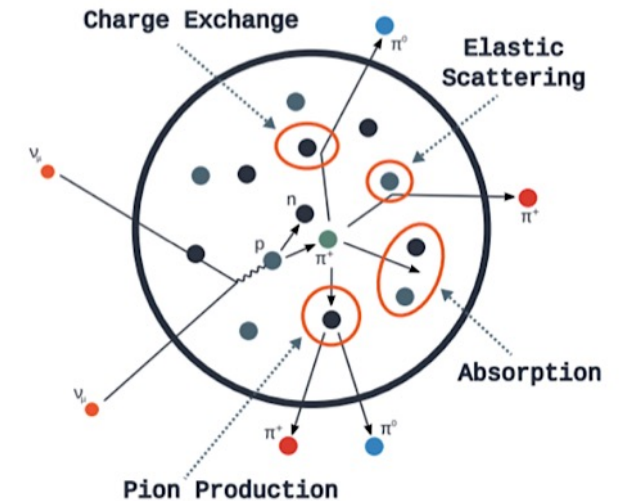
Non-resonant pion production



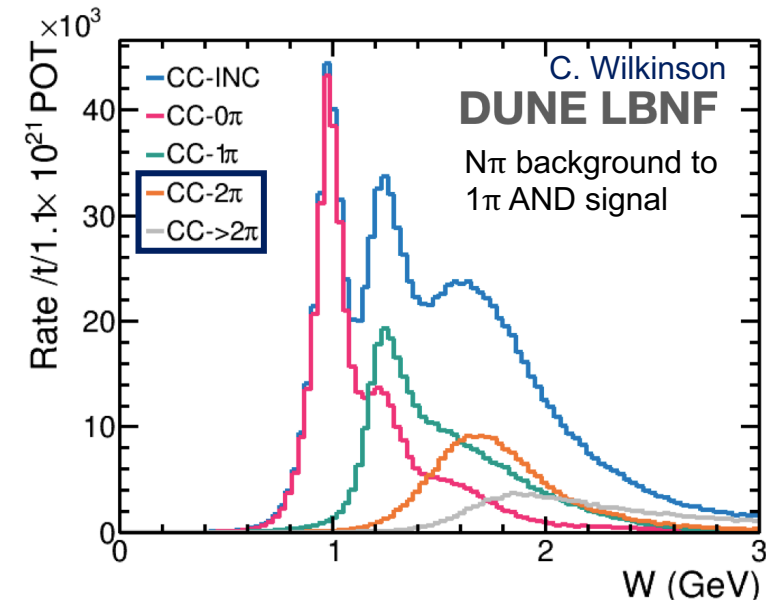
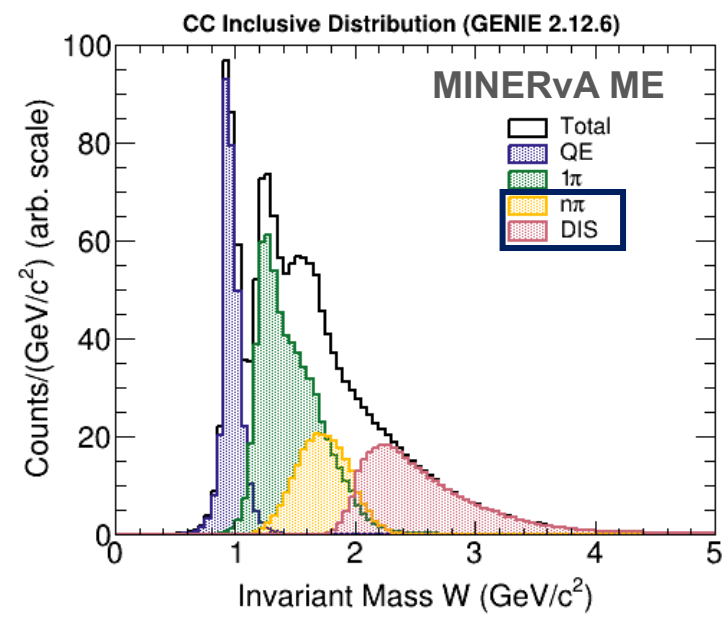
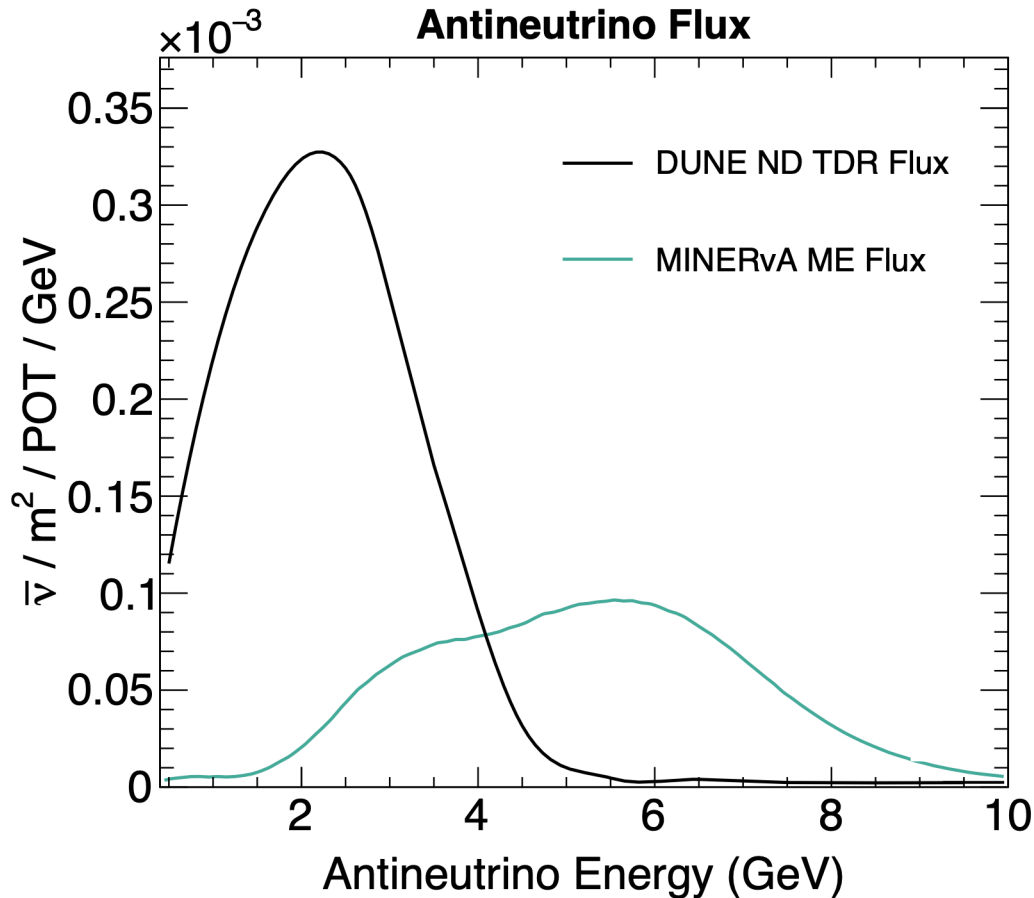
Multi-nucleon effects



T. Golan, NuSTEC (2015).

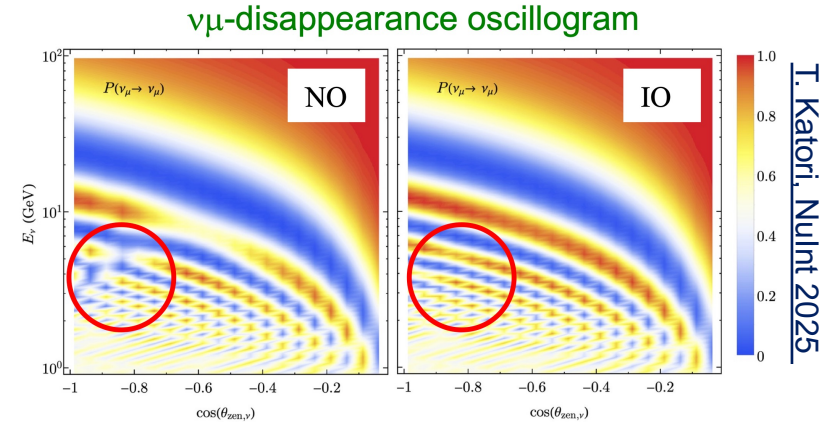


Why do we care?



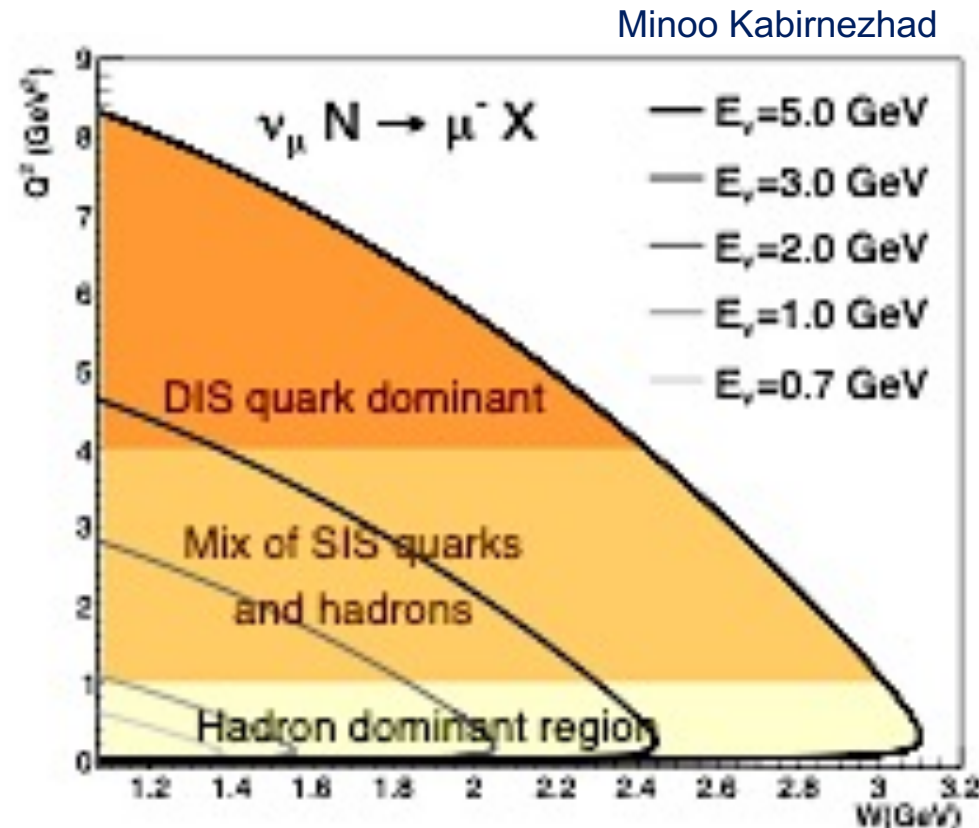
Also, atmospheric neutrinos have sensitivity to mass ordering via 3-10 GeV MSW resonance

- Opposite effect for neutrinos vs antineutrinos – need to be separated
- Contribution from $\nu_\mu \rightarrow \nu_\tau$, where ν_τ may enter ν_e multi-ring sample
- Need good final state hadron simulation



Shallow inelastic scattering (SIS)

- Accelerator-based neutrino experiments around 1-10 GeV not quite DIS yet, defined by perturbative QCD ($Q^2 > 4 \text{ (GeV}/c)^2$)
- SIS: non-resonant meson production and non-perturbative multi-quark meson production, generally not well defined



MINERvA resolution

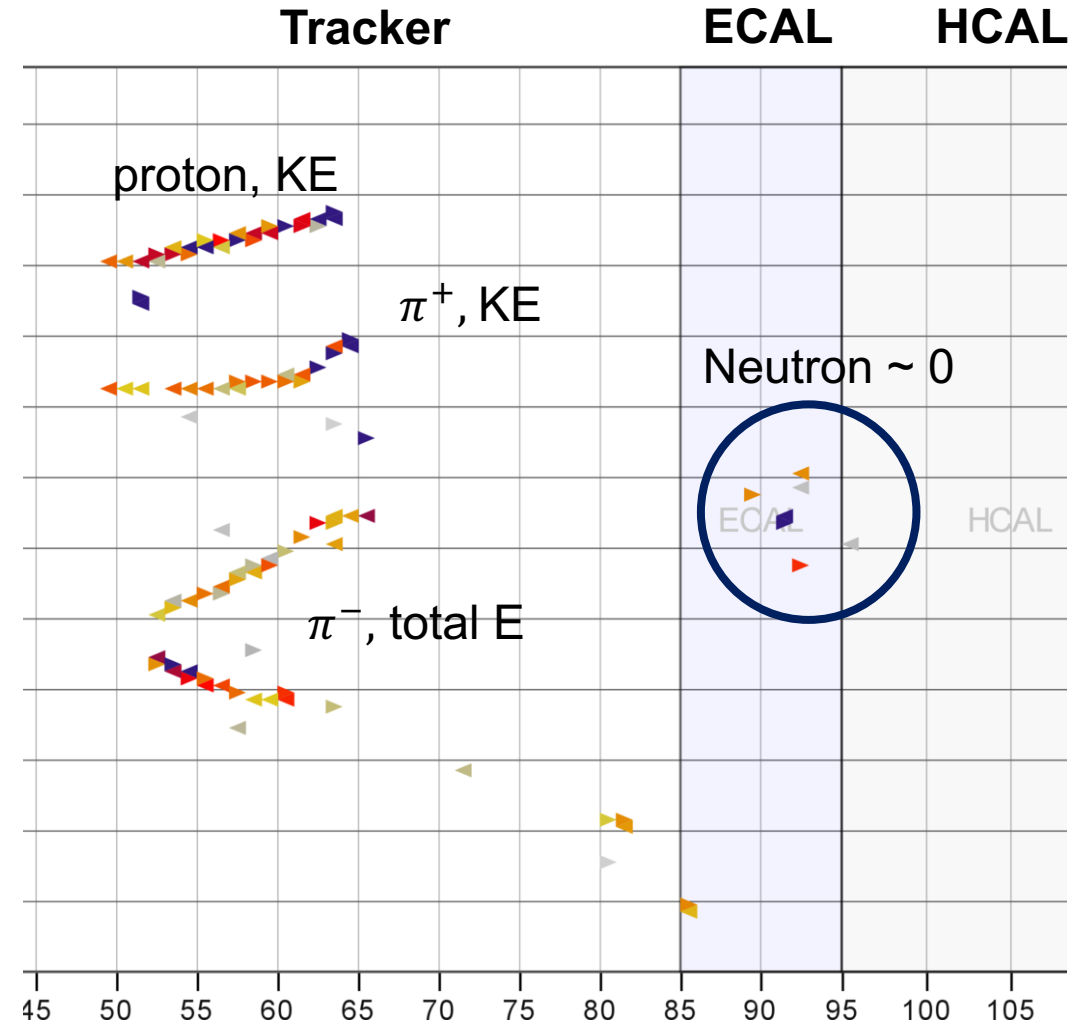
- Spatial resolution ~3.0 mm
- Timing resolution ~3 ns
- Muon momentum resolution

Momentum range (GeV/c)	MINERvA only	MINERvA + MINOS
< 2	6%	3.6%
2-6	6%	~5%
>6	6%	7.9%

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

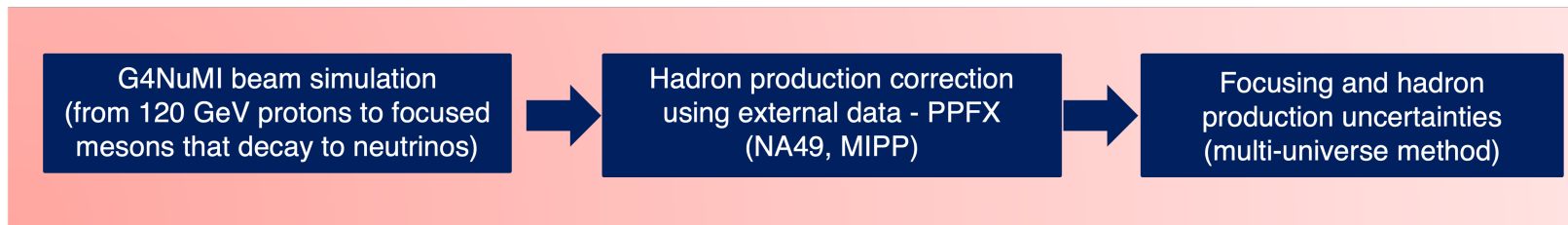
Sensitivities to final states

- Plastic scintillator sensitive to small energy deposits
- Hadronic recoils measured using calorimetry
- Tracking threshold (KE) for proton ~ 100 MeV
- Neutrons can deposit visible energies (albeit small) after recoil inside scintillator

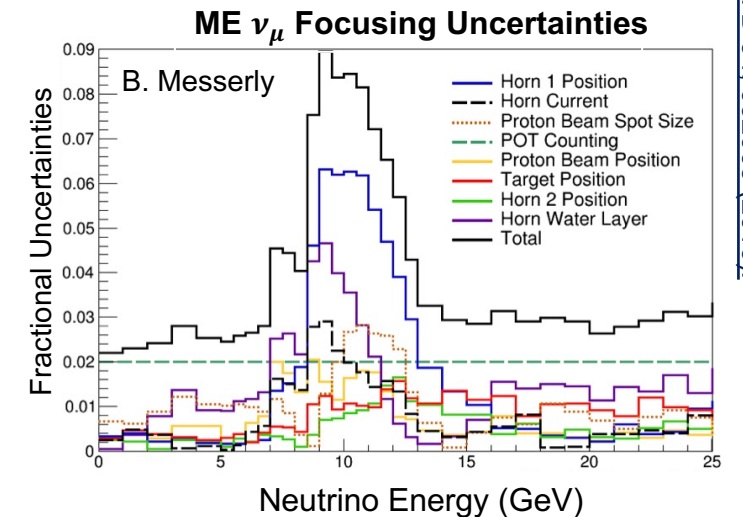
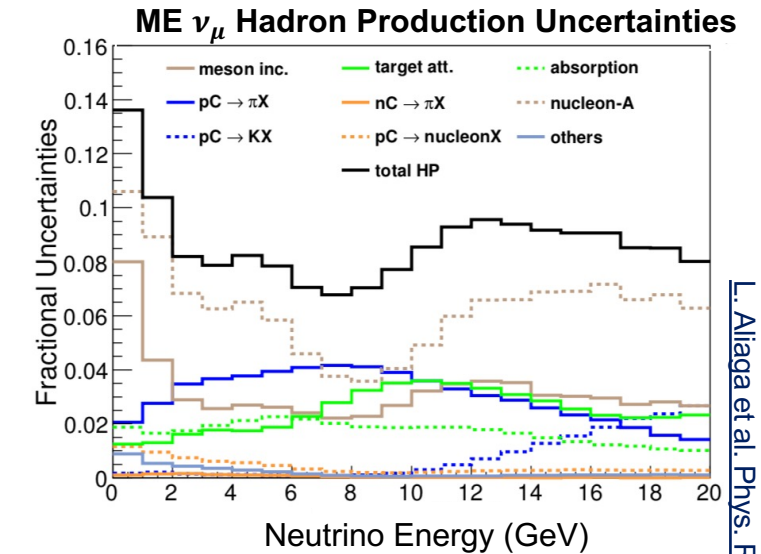
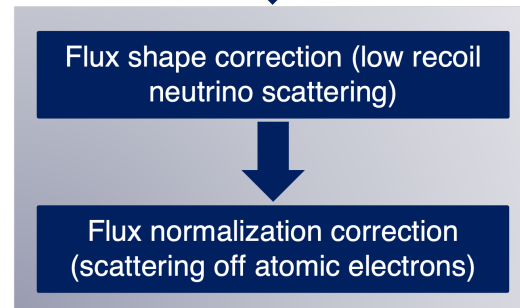


Flux simulation and uncertainties

1. Calculate and correct the a-priori flux



2. Use in-situ measurements



L. Aliaga et al. Phys. Rev. D 94, 092005 (2016).

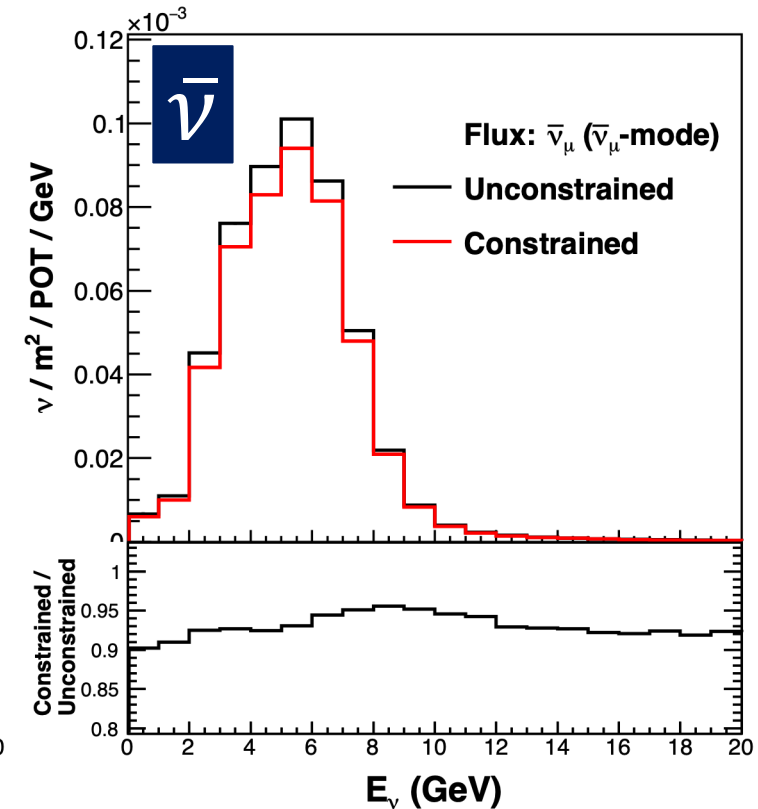
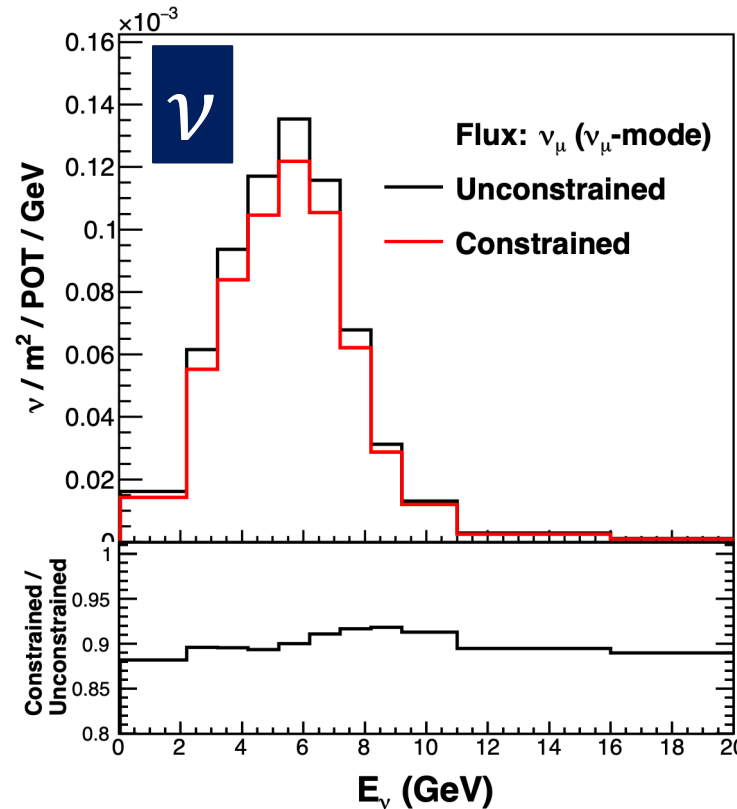
Flux constraint

E. Valencia et al. Phys. Rev. D **100**, 092001, 2019.
 D. Ruterbories et al. Phys. Rev. D **104**, 092010, 2021.
 L. Zazueta et al. Phys. Rev. D **107**, 012001, 2023.

	$\bar{\nu}_\mu$ -mode				ν_μ -mode			
	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
<i>a priori</i>	7.76	7.81	11.1	11.9	7.62	7.52	12.2	11.7
ν_μ -mode νe^-	6.11	5.81	6.30	8.50	3.90	3.94	8.37	8.68
$\bar{\nu}_\mu$ -mode νe^-	4.92	4.98	8.07	9.19	5.88	5.68	8.36	8.64
combined νe^-	4.68	4.62	5.56	7.80	3.56	3.58	7.15	7.84
combined $\nu e^- + \text{IMD}$	4.66	4.56	5.20	6.08	3.27	3.22	6.98	7.54

(Energy range integrated flux uncertainty)

- Flux uncertainty in ν mode reduced from **7.6% to 3.3%**
- In $\bar{\nu}$ mode from **7.8% to 4.7%**
- Used in MINERvA analyses!



Flux constraint procedure

- Using Bayes' theorem

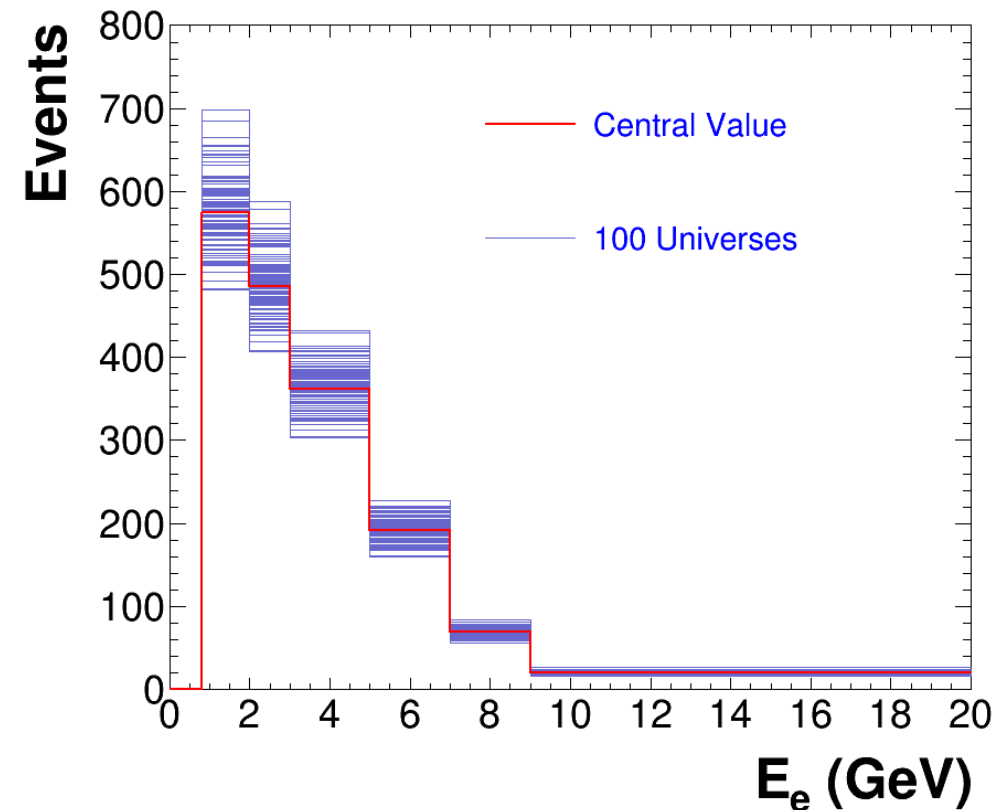
$$P(M|N_{\nu e \rightarrow \nu e}) \propto P(M) P(N_{\nu e \rightarrow \nu e}|M)$$

$P(M|N_{\nu e \rightarrow \nu e})$ new prediction (posterior) probability of the flux prediction given the electron spectra measurement)

$P(M)$ flux prediction in each universe/model (prior)

$P(N_{\nu e \rightarrow \nu e}|M)$ likelihood of the electron spectra measurement given the a-priori model

- A-priori flux uncertainty estimated using **multiverse method**
 - Ensemble of flux predictions by varying flux parameters within their uncertainties (hadron production, beam alignment)



Neutrino flux constraint

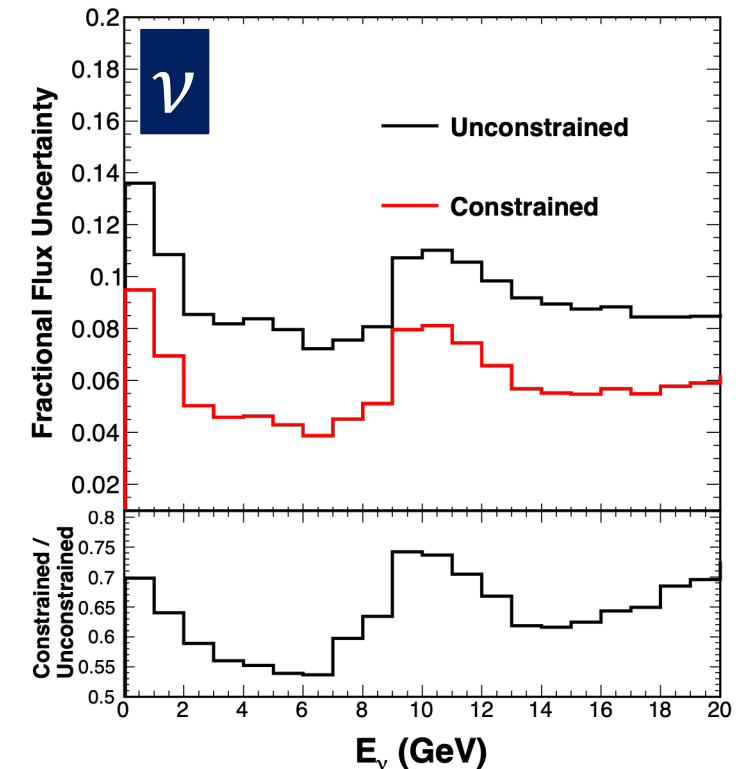
E. Valencia et al. Phys. Rev. D **100**, 092001, 2019.

- Likelihood of the measurement for each universe

$$P(N_{\nu e \rightarrow \nu e} | M) = \frac{1}{(2\pi)^{K/2}} \frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}} e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T \Sigma_{\mathbf{N}}^{-1} (\mathbf{N}-\mathbf{M})}$$

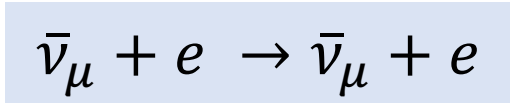
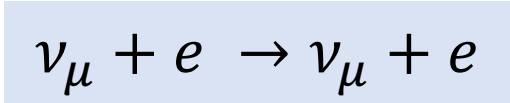
N	vector containing the bin content of the measured energy spectrum of given process
M	same as N but for the MC prediction
Σ_N	covariance matrix of the uncertainties of N
K	number of the bins of the spectrum

- Predictions from universes with poor data agreement are weighted down → **reduces uncertainty** (spread of the universes)
- **In neutrino mode, the neutrino flux uncertainty is reduced from 7.6% to 3.9% (integrated flux over the energy range)**

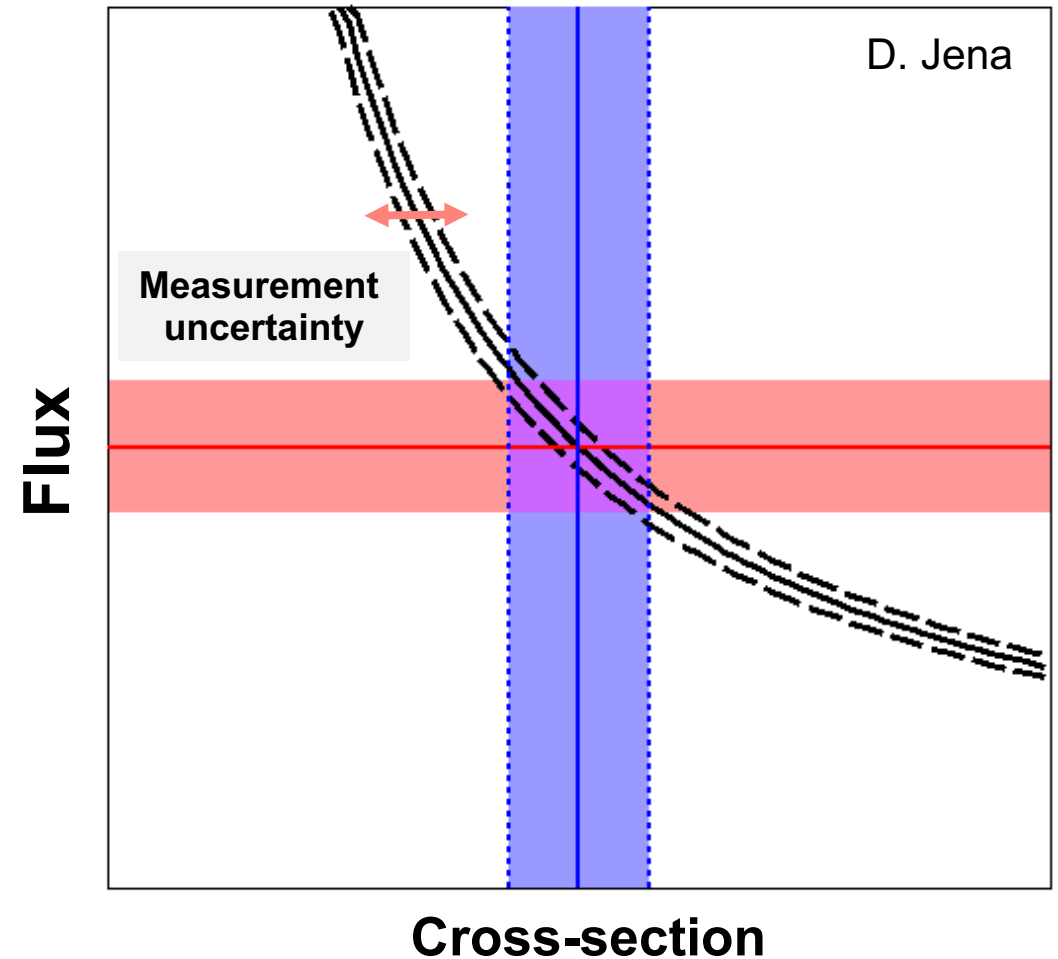


(Anti)Neutrino-electron elastic scattering

- MINERvA uses the **standard candle for flux estimate** – (anti)neutrino-electron elastic scattering **BOTH in anti/neutrino beam in medium energy**



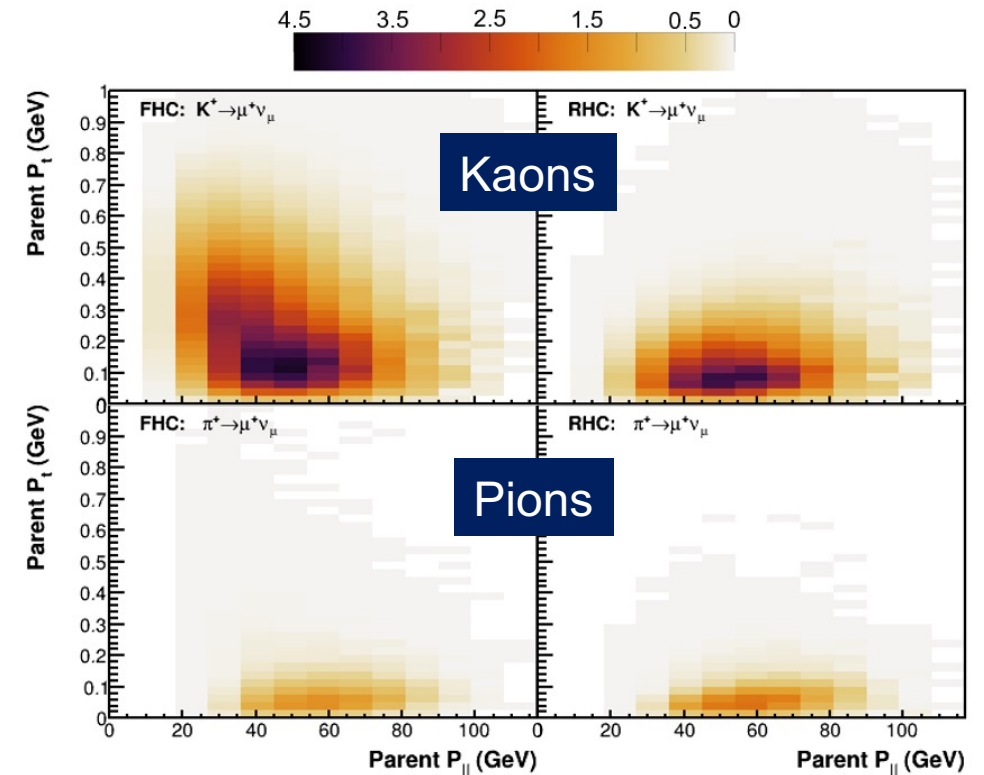
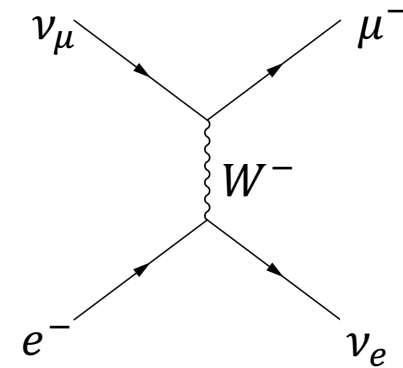
- Cross-section **precisely predicted** by the standard electroweak scattering theory
- **Limited statistics**: three orders of magnitude smaller than neutrino-nucleus cross-section
- Final state distribution of electron energies – **constraint on integrated flux** (improvement in normalization uncertainty)



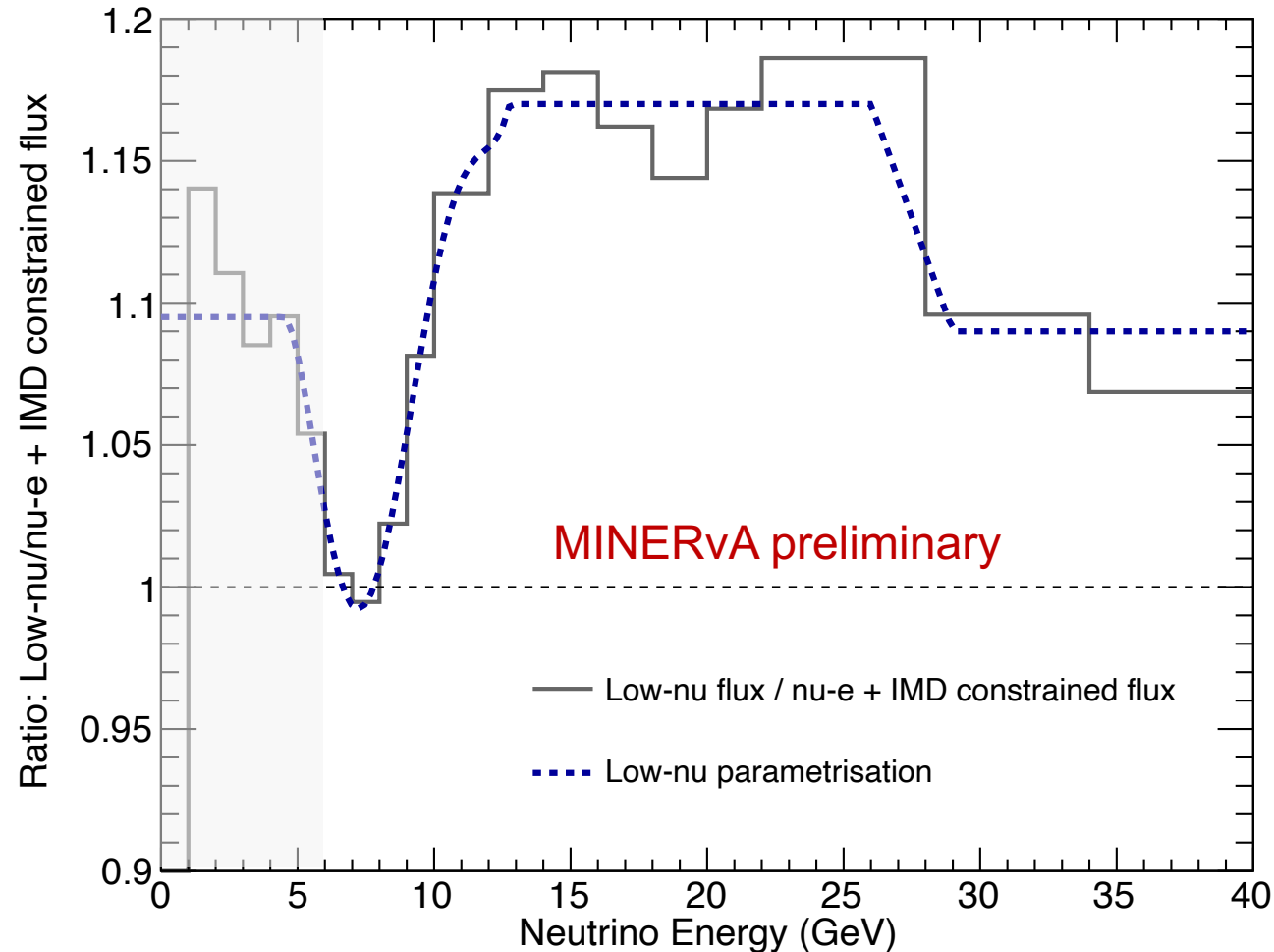
$$\text{Cross-section} = \frac{\# \text{ of events}}{\text{Acceptance} \times \text{efficiency} \times \text{Flux}}$$

Inverse muon decay

- Cross-section can be predicted with very small uncertainties
- **Threshold of ≈ 11 GeV with very forward going muon**
 - Indistinguishable process $\bar{\nu}_e e^- \rightarrow \mu^- \bar{\nu}_\mu$ unimportant in MINERvA due to threshold
- Neutrinos from underfocused or unfocused K^+ and π^+
- Can **constrain the high-energy part of the flux** in the NuMI neutrino beam



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 $\sigma \sim \text{const.}$ as a function of $E_\nu \rightarrow$ **effect on shape**

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{\nu}{E_\nu} [F_2 + xF_3] + \frac{\nu}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{\nu^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} + xF_3 \right] \right) dx$$

- 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 \(2020\).](#)

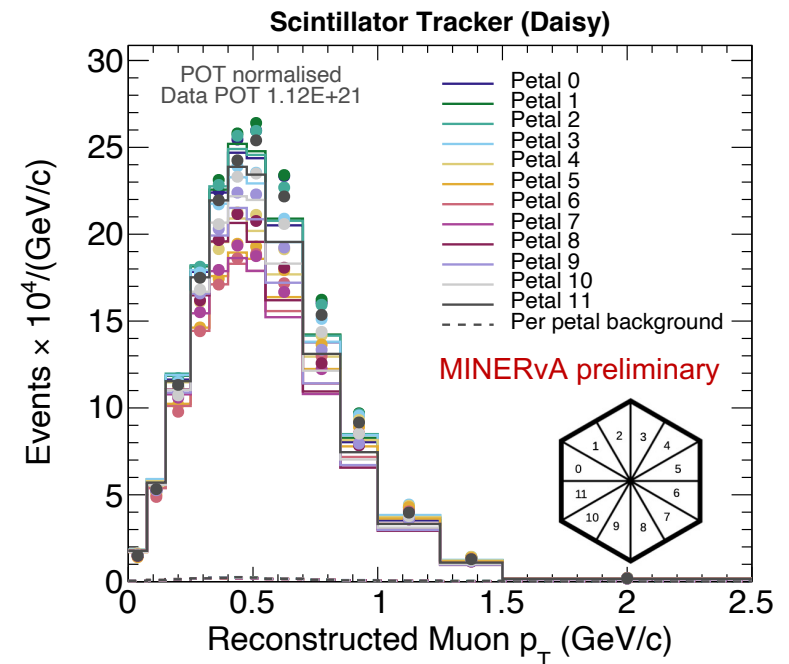
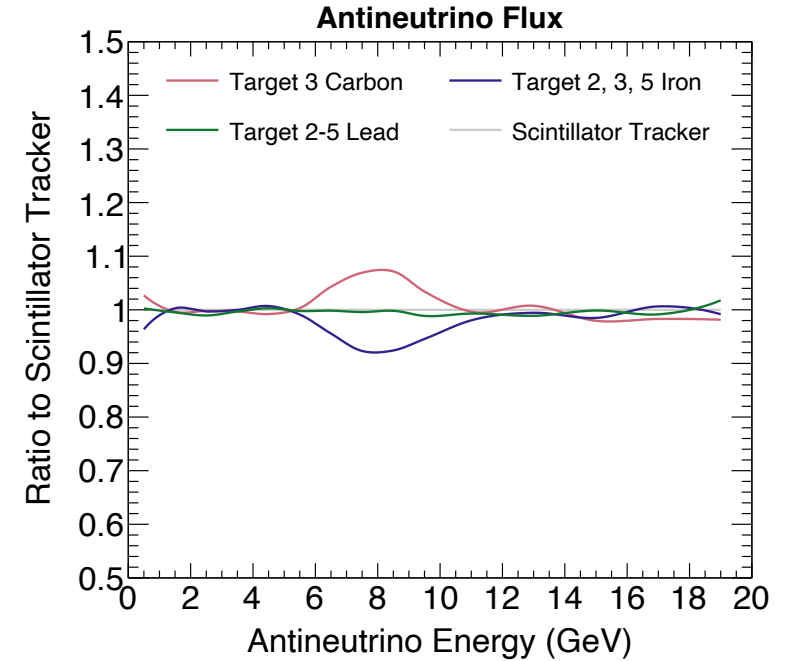
[L. Zazueta \(MINERvA\). Phys. Rev. D 107, 012001 \(2023\).](#)

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

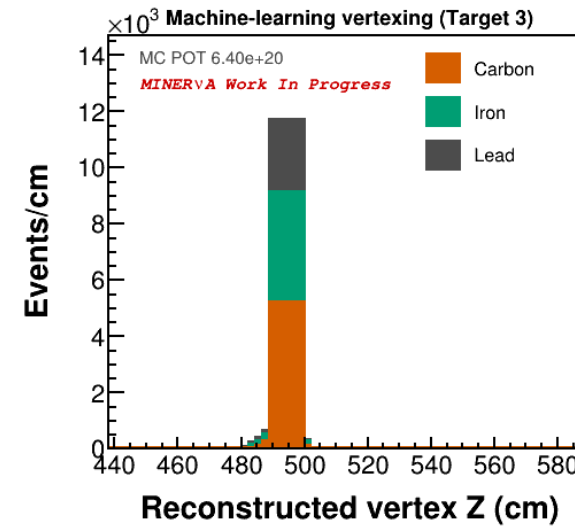
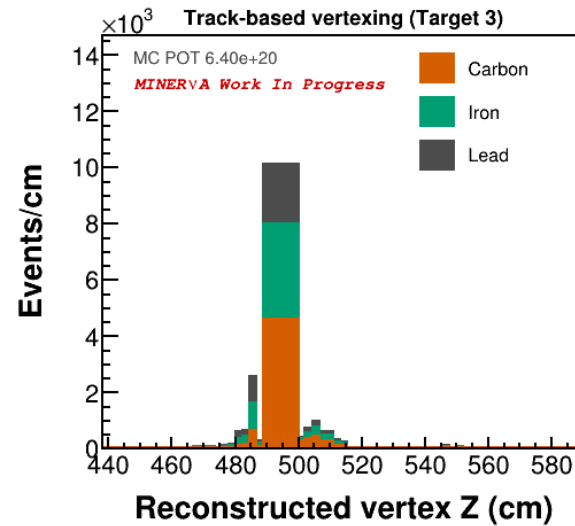
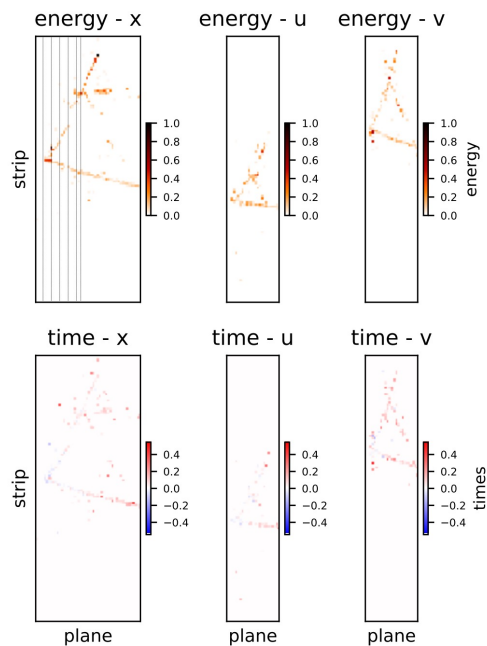
$$\chi_{reg}^2 = \chi^2 + \lambda \left(\frac{N_i}{\sum N_i} \right) (p_i - 1)^2$$

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

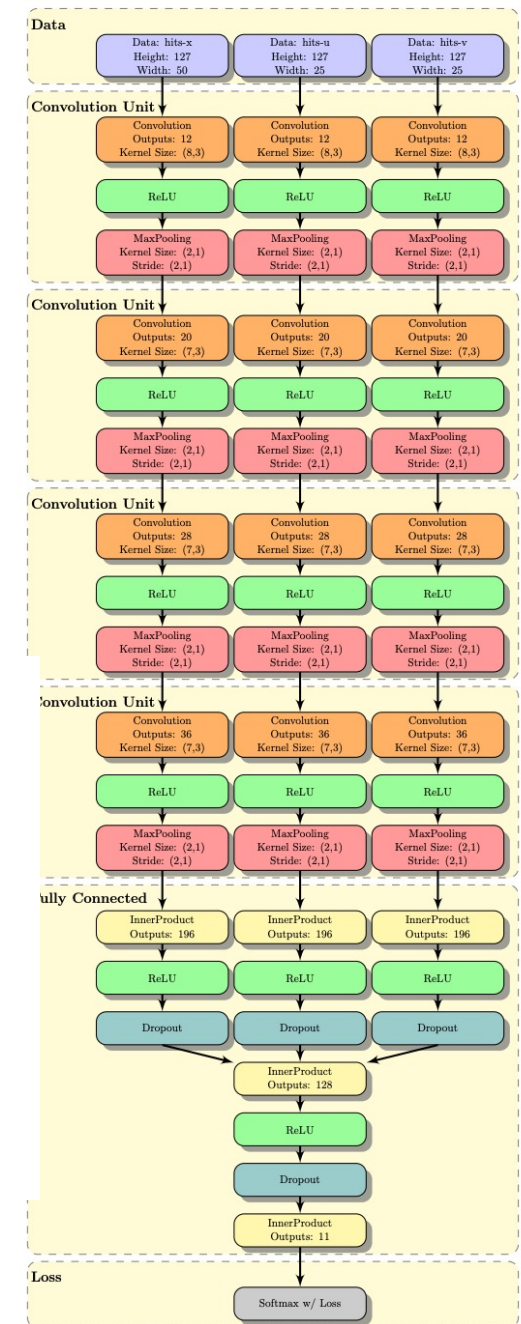


Machine-learning vertex reconstruction

- Energy deposits and timing in XUV views converted to hdf5 images
- Deep convolutional neural net (DCNN) in TensorFlow
- Increase of selection purity and efficiency

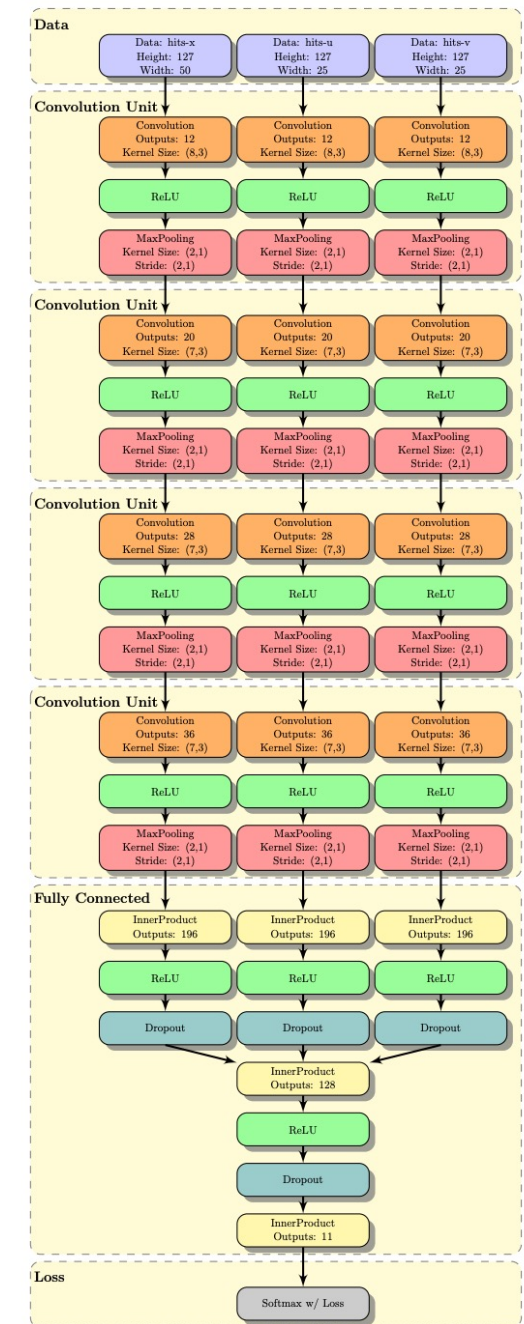
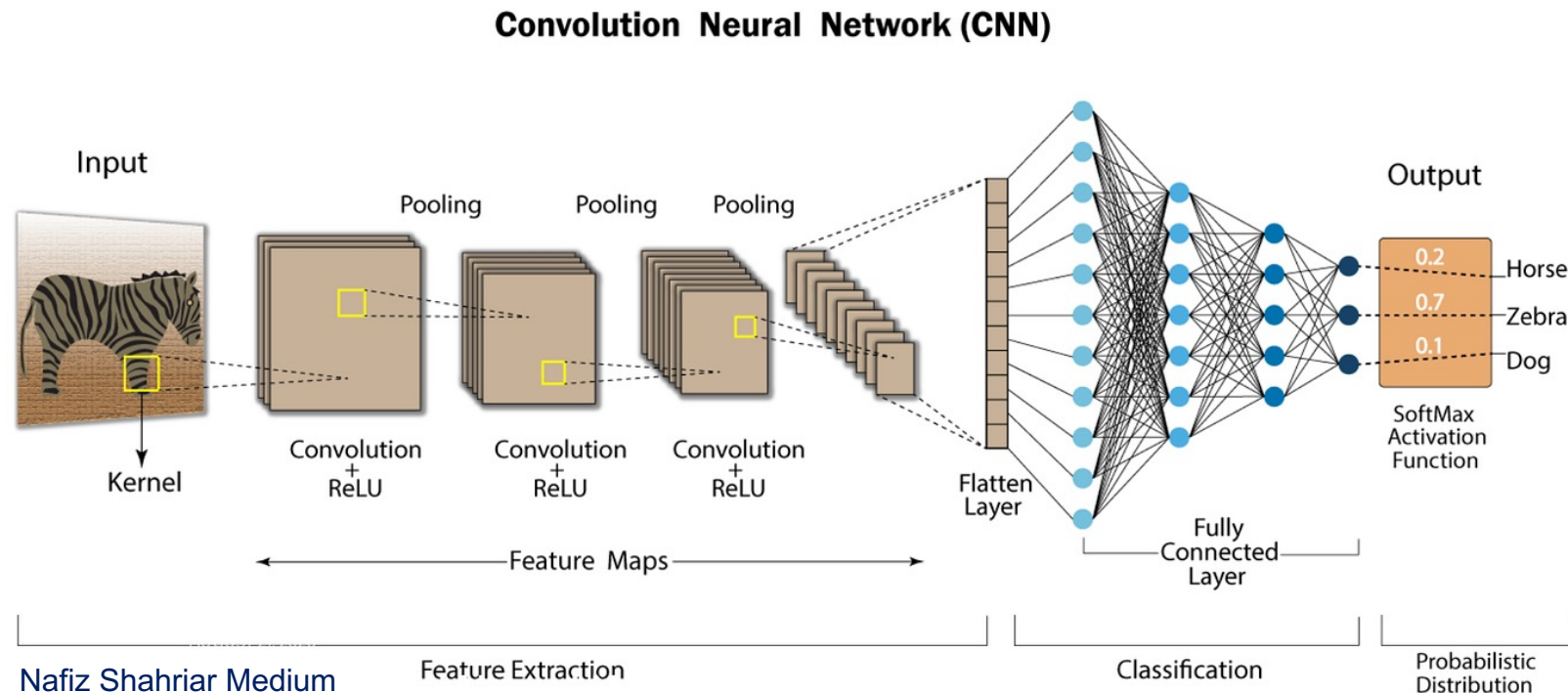


[F. Akbar \(MINERvA\). JINST 17 T08013 \(2022\).](#)
[G.N. Perdue \(MINERvA\). JINST 13 P11020 \(2018\)](#)



Machine-learning vertex reconstruction

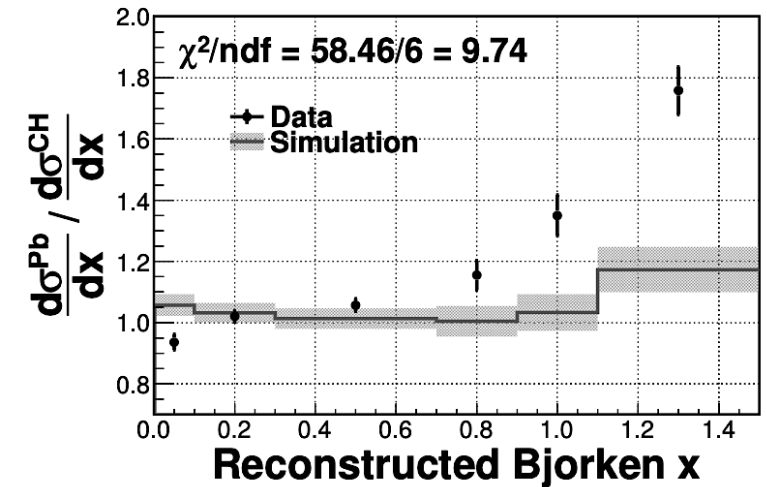
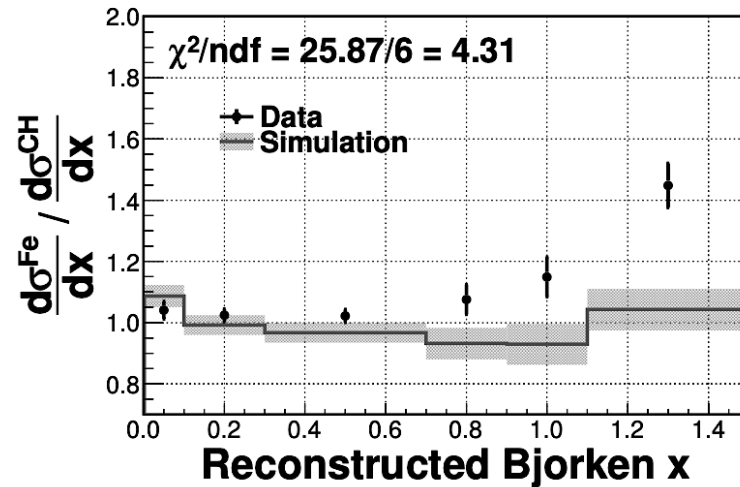
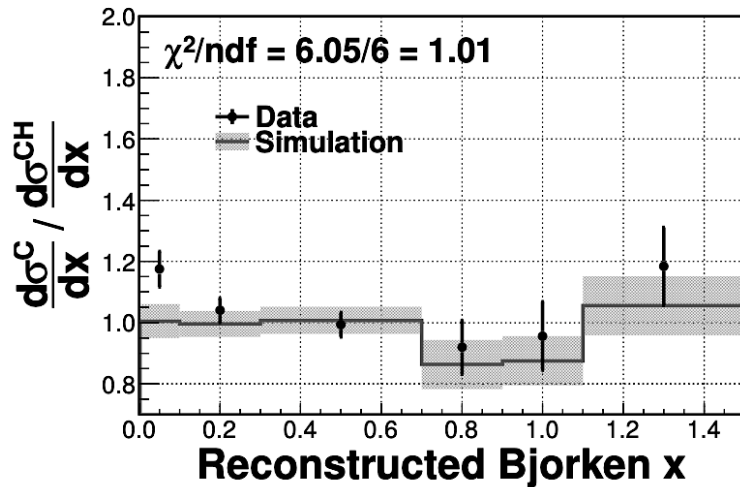
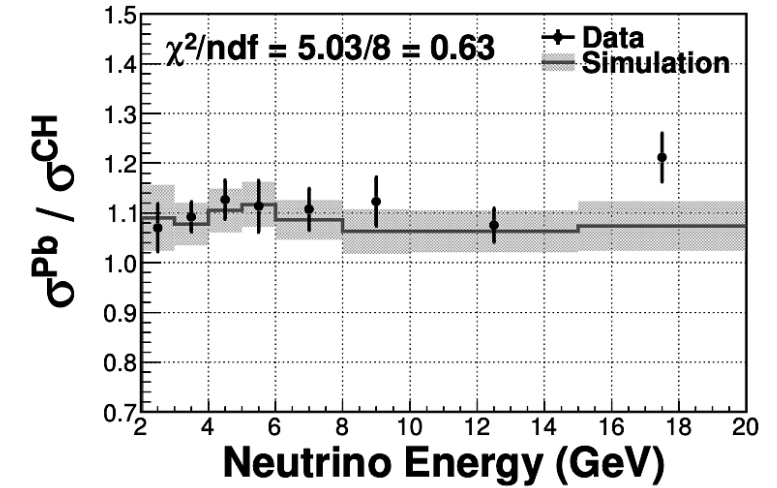
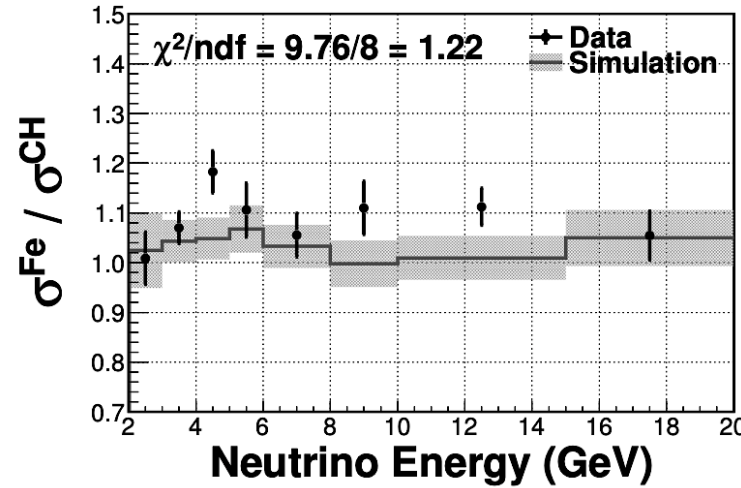
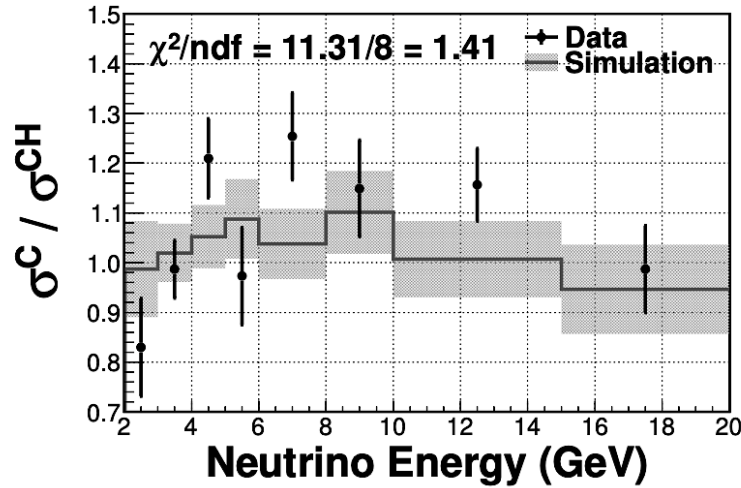
- Convolution: apply kernel to extract/identify specific features
- ReLU: non-linear activation layer allows to learn more complex representation of the input data
- Max pooling: reduces spatial dimensions of the feature (reduces computational complexity)
- Fully connected layer: combine features learned from convolution + pooling



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 \(2014\)](#)

Per nucleon cross-section on a particular nucleus

Differential cross-section in bin α for a given nucleus

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

Unfolding matrix Selected events Background prediction

Efficiency Integrated flux times the number of nucleons Bin width normalization

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

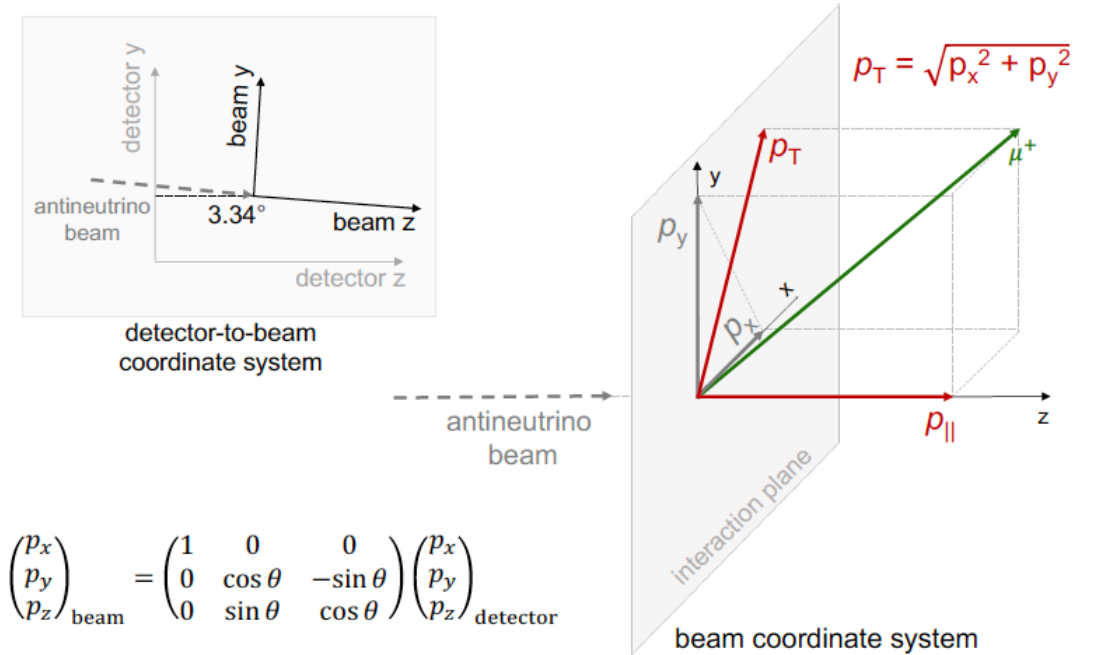
Variables of interest

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

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

- p_T also correlates with 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)



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

$$x = \frac{Q^2}{2p_N \cdot q} \stackrel{\text{lab}}{=} \frac{Q^2}{2m_N E_{\text{had}}} \quad 0 \leq x \leq \frac{M_A}{m_N} \sim A$$

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

For Soft/True DIS invariant mass W separation:

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

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								

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 $M_A^{\text{RES}} = 0.94 \text{ GeV}/c^2$, CCRNorm 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 nuCC1 π^+ low Q^2 suppression applied to π^- for $W < 1.4 \text{ GeV}/c^2$ 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 \(2019\)](#).

MINERvA tunes

vX.Y.Z

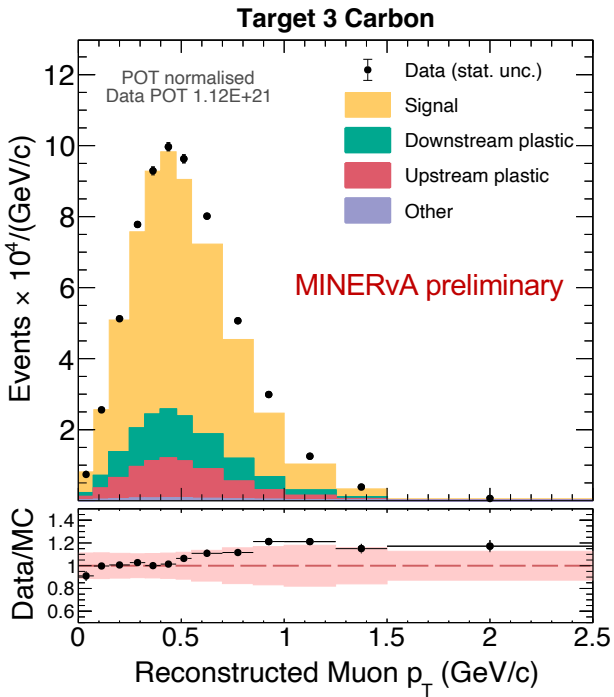
X	Description
1	the original tune. Valencia RPA applied to QE (RFG), non-resonant pion production reduction, low recoil fit (LE) applied to Valencia 2p2h
2	Same as 1 but includes the Stowell et. al (MINERvA) GENIE pion tune low Q2 suppression
3	Replace Valencia 2p2h with SuSA 2p2h, non-resonant pion production reduction, QE is still RFG with RPA correction from Valencia but has enhanced Bodek-Ritchie tail, removal of 25 MeV from Eavail in pion events with protons in the final state
4	Same as 1 but includes the full pion bubble chamber fit, CCNormRes increased to 1.15 (from 1) and MaRES set to 0.94. Also includes full treatment of the correlations between MaRES and CCNormRes in the fit

Y	Description
1	Normalization change of coherent pion production Epi
2	Normalization change of coherent pion production using the angle and E pi distributions (ME)
3	A. Bercellie low Q2 pion production suppression (see docDB 30137) and normalization of coherent pion production using the angle and E pi distributions (ME)
4	Replace dipole form of the axial form factor of QE with the Meyer et. al. z-expansion
5	Replace QE RFG nuclear model with NuWro SF

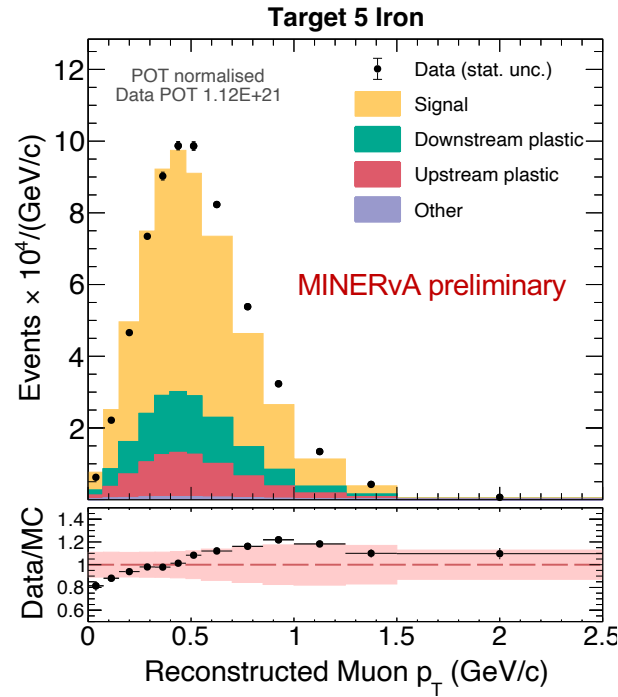
Z	Description
1	Bug fix of elastic FSI in pions and protons

Event selection: background breakdown

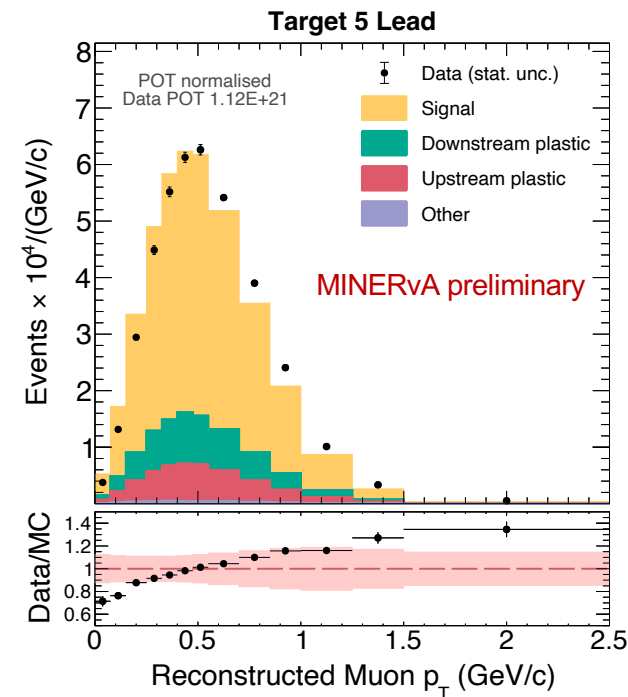
Roughly 70% purity in targets, 99% purity in tracker



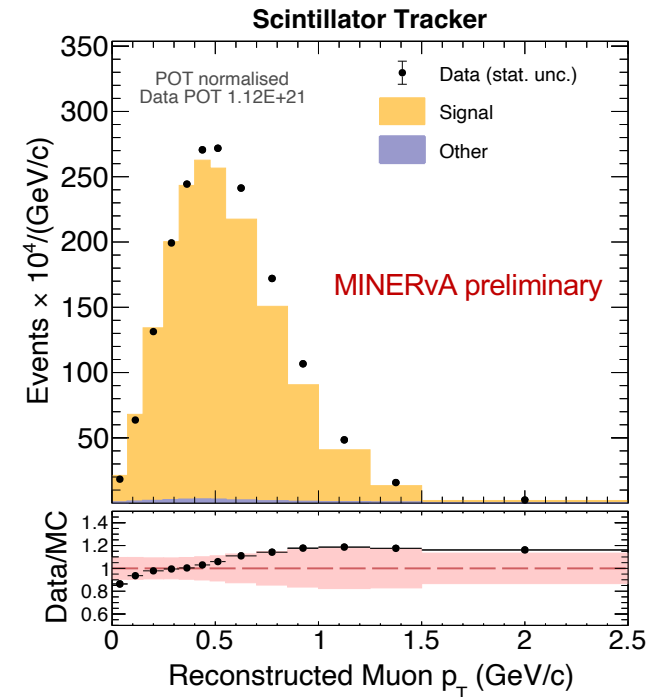
Signal	73.4%
DS plastic	14.1%
US plastic	11.5%
Other	1.0%



Signal	68.3%
DS plastic	17.8%
US plastic	12.9%
Other	1.0%



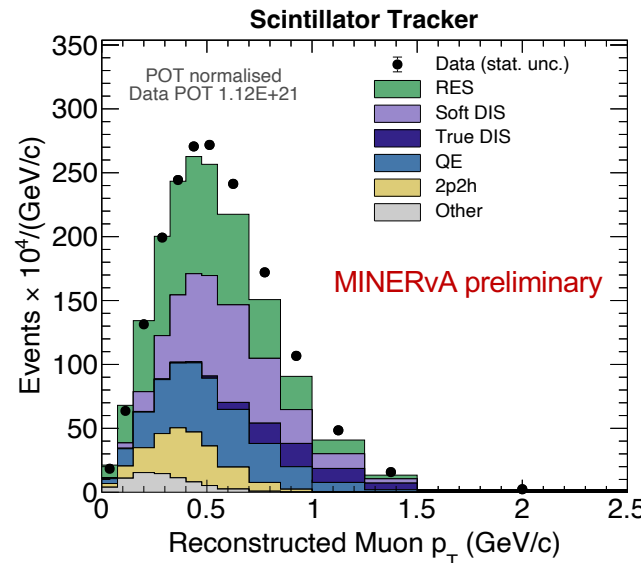
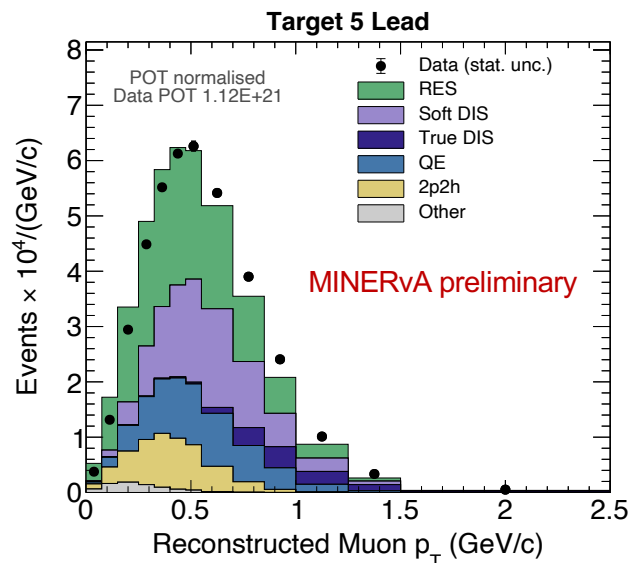
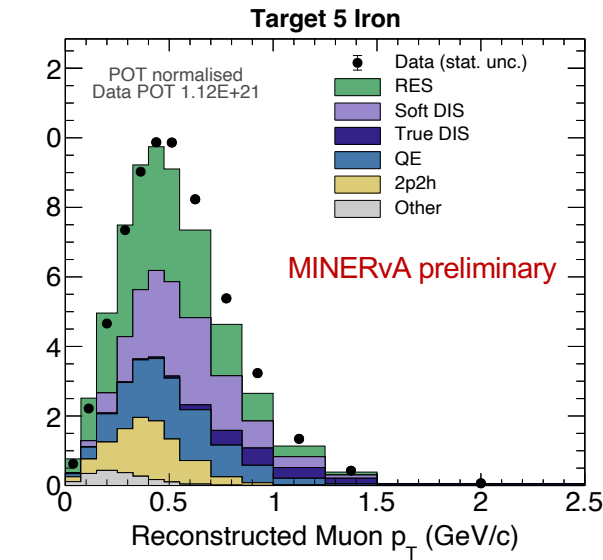
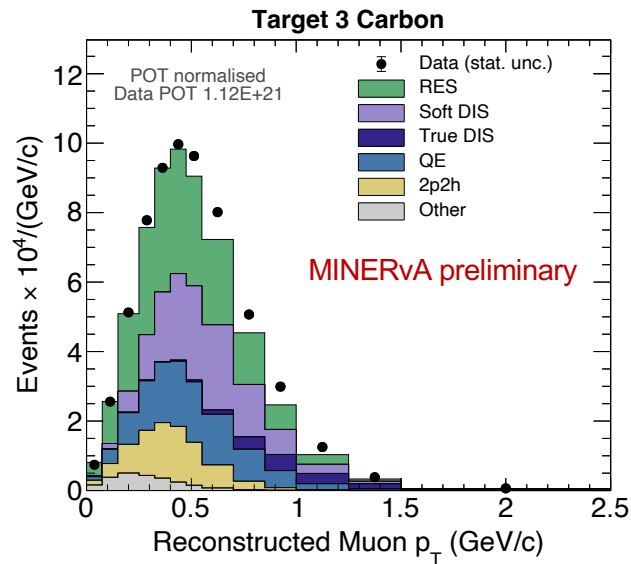
Signal	73.9%
DS plastic	14.3%
US plastic	10.8%
Other	1.0%



Signal	98.9%
Other	1.1%

(Out of this 0.3% wrong sign)

Event selection: interaction type stacked



Carbon:

RES:	35.8%
Soft DIS:	25.3%
True DIS:	5.0%
QE:	18.9%
2p2h:	11.8%
Other:	3.2%

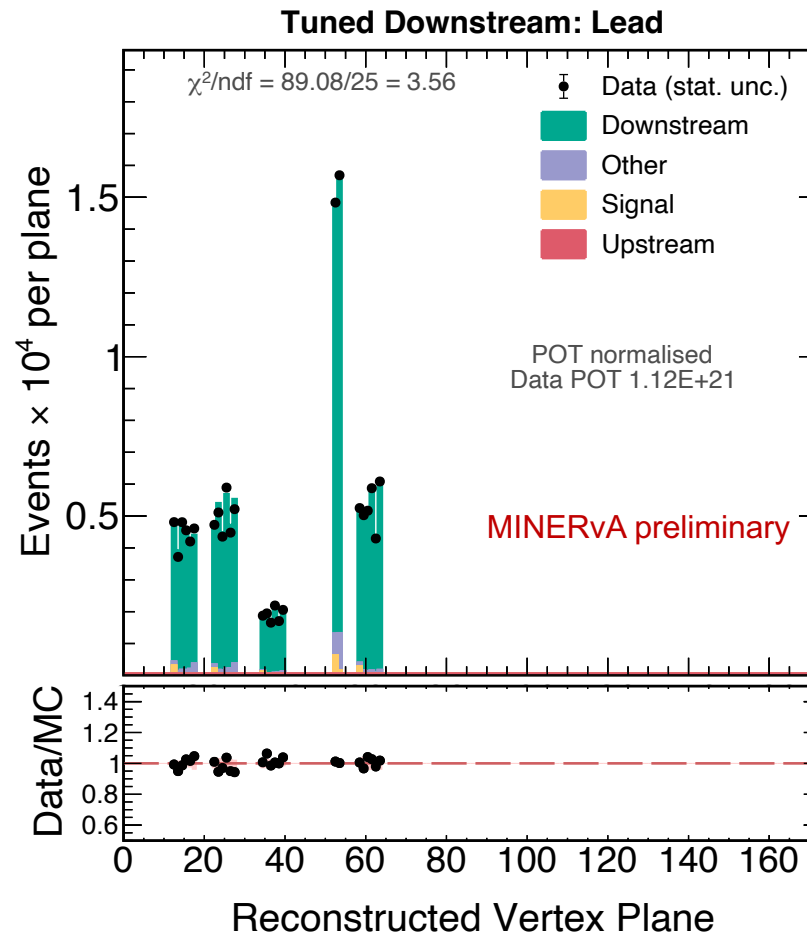
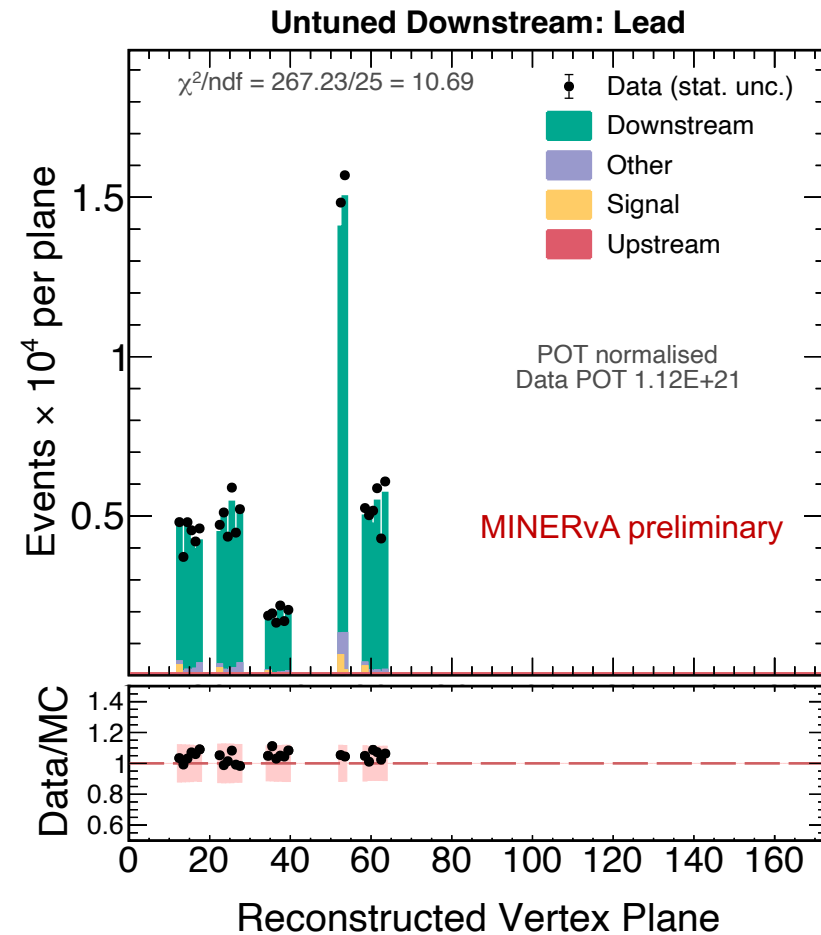
Similar in other targets within ~1-2%,
more contributions from RES, Soft
DIS, and True DIS in heavier targets

Other corresponds to
coherent/diffractive scattering

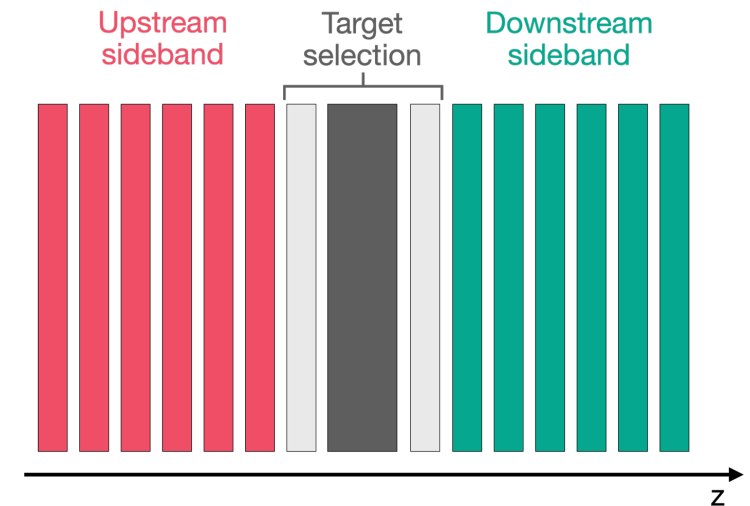
Background tuning

TABLE III. Background scale factors with statistical and systematic uncertainties.

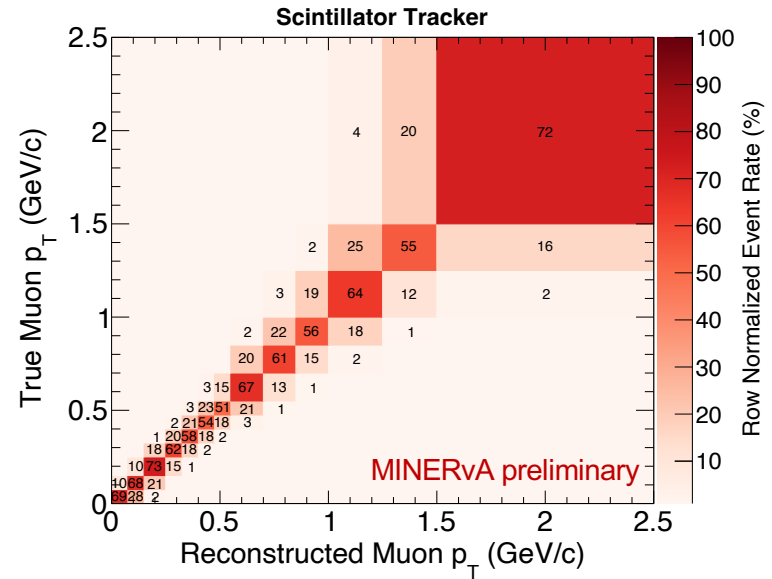
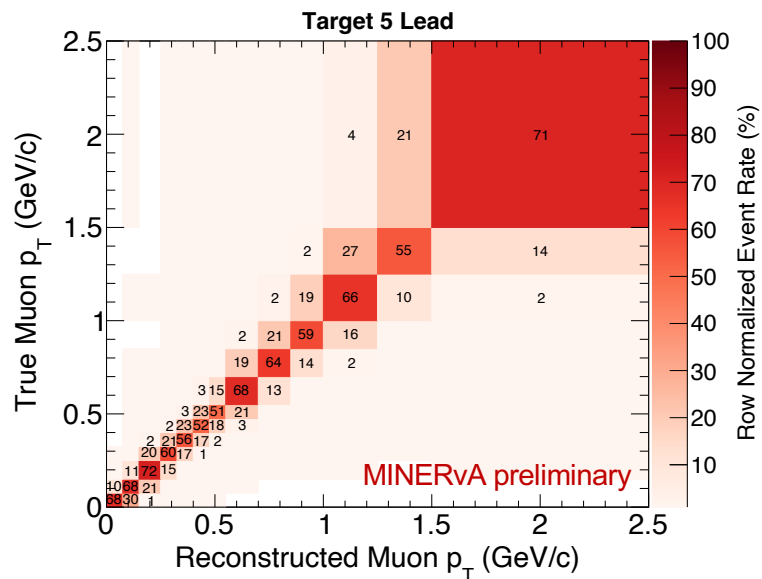
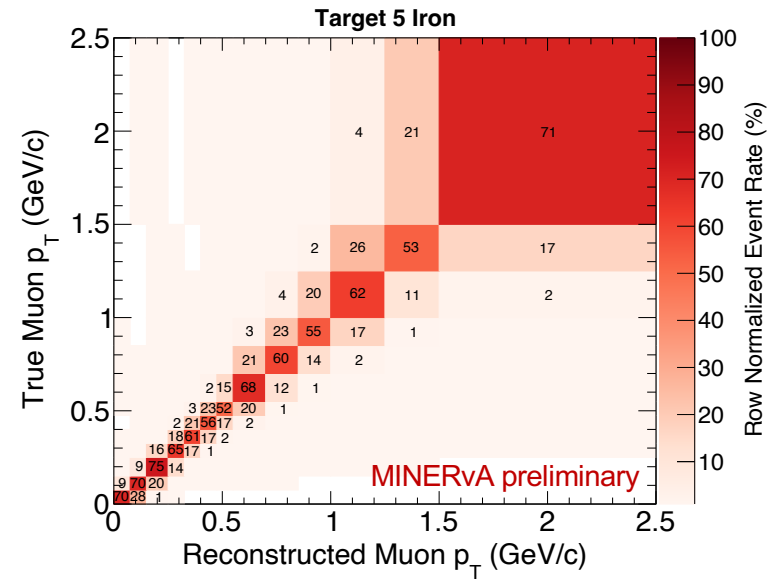
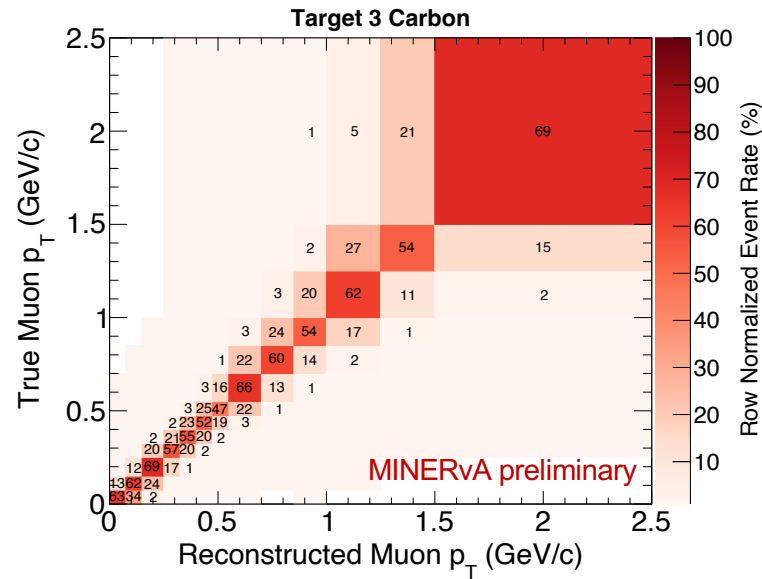
Material	Upstream (US)	Downstream (DS)
Carbon	$1.029 \pm 0.005 \pm 0.133$	$1.036 \pm 0.005 \pm 0.127$
Iron	$1.065 \pm 0.004 \pm 0.133$	$1.061 \pm 0.003 \pm 0.125$
Lead	$1.069 \pm 0.003 \pm 0.137$	$1.046 \pm 0.003 \pm 0.128$



- Single scale factor from simultaneous χ^2 minimisation of data (stat) and MC (total) in planeDNN
- Applied in signal region (with its stat+sys error)



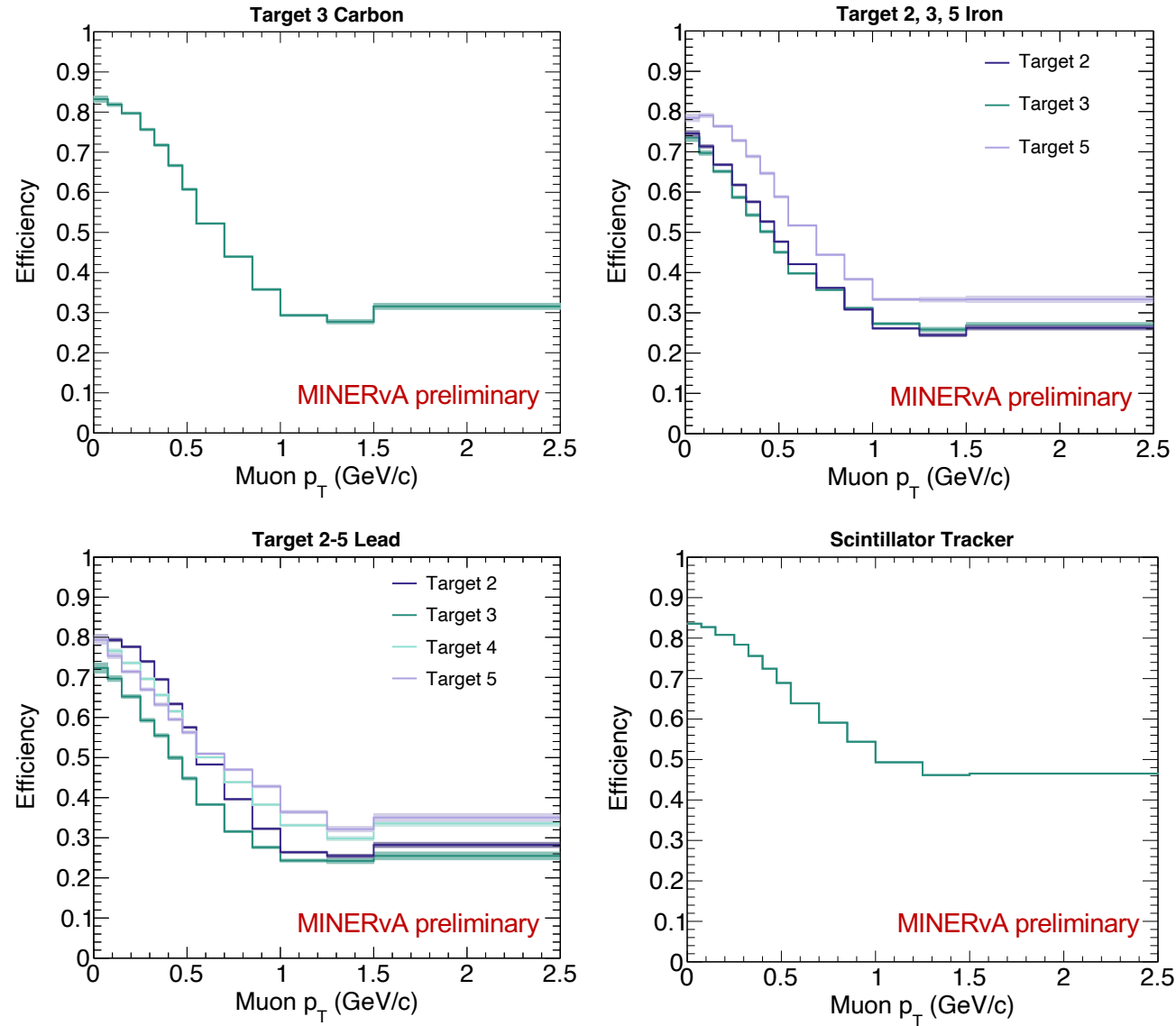
Migration matrices



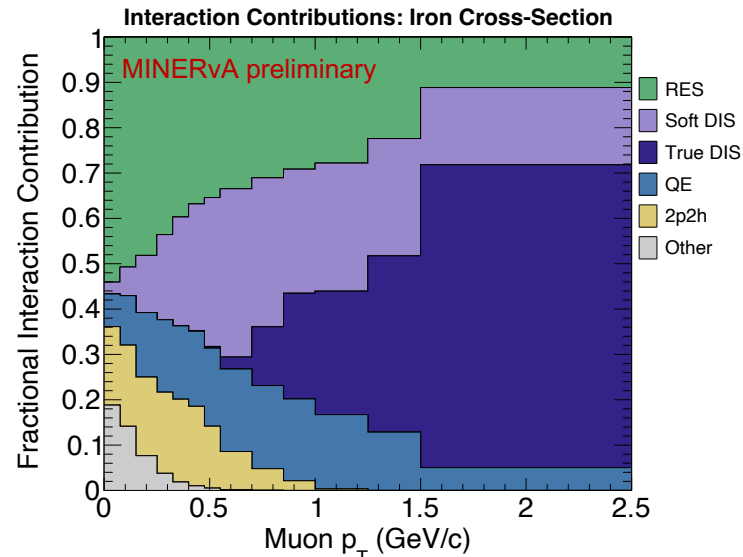
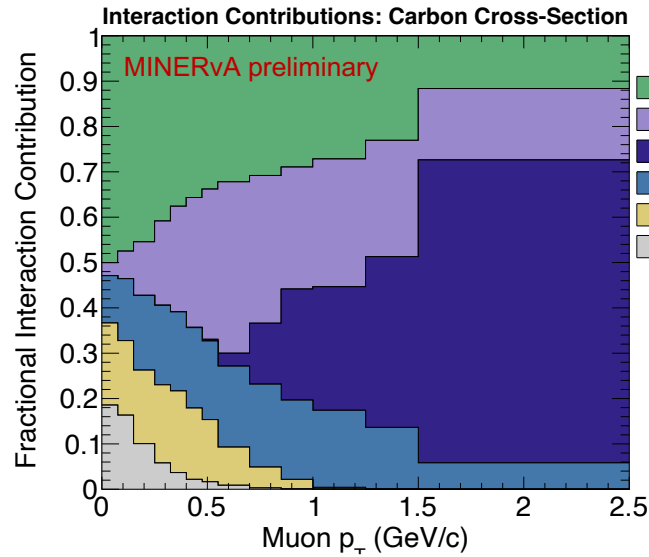
Efficiency

$$E_{\alpha} = \frac{\text{true reconstructed signal events}}{\text{all signal events}}$$

Integrated efficiency for targets ~40-50%
Integrated efficiency for tracker ~65%

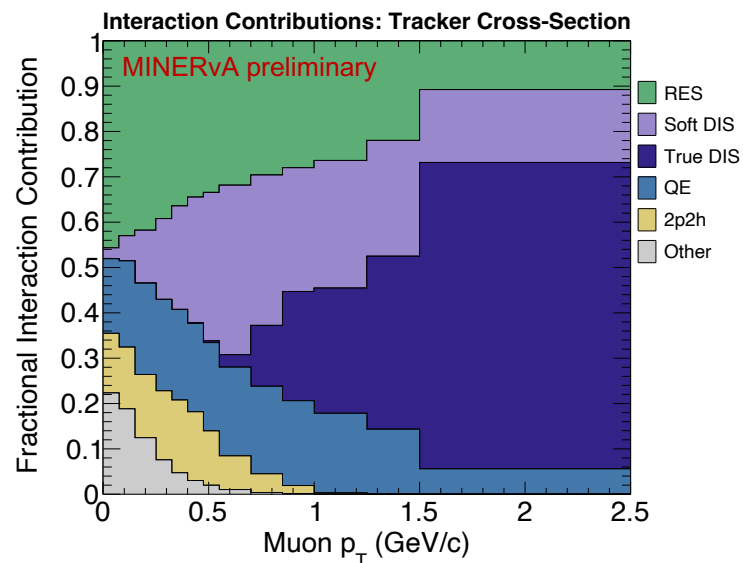
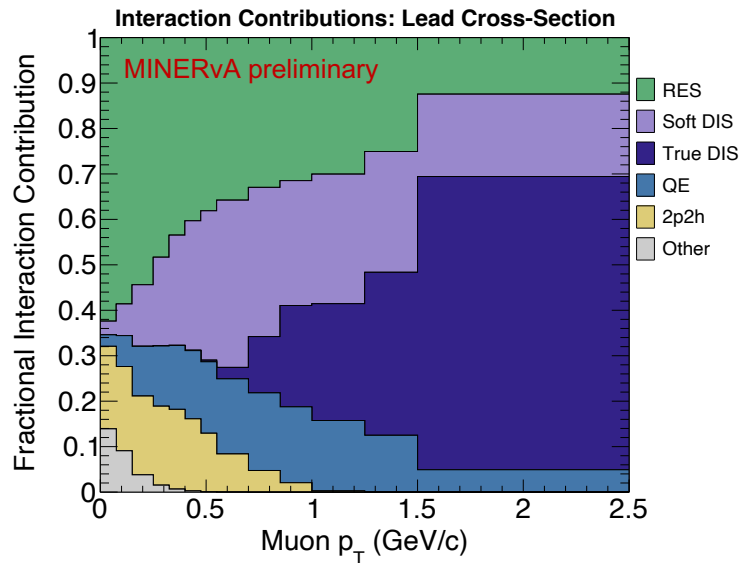


Cross-sections: fractional int. contributions



Carbon:

RES:	35.3%
Soft DIS:	27.3%
True DIS:	5.0%
QE:	17.3%
2p2h:	12.0%
Other:	3.1%

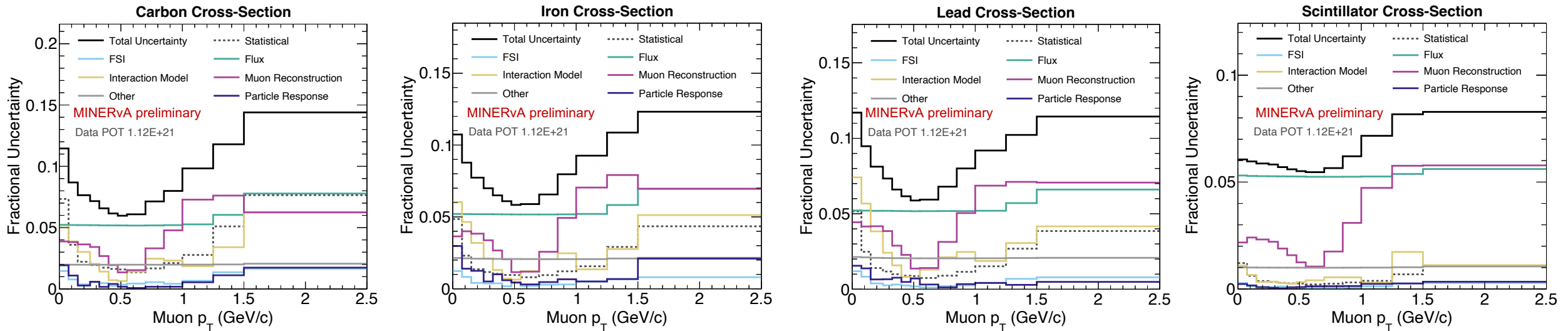


Similar in other targets within ~1-2%, more contributions from RES, Soft DIS, and True DIS in heavier targets

Other corresponds to coherent/diffractive scattering

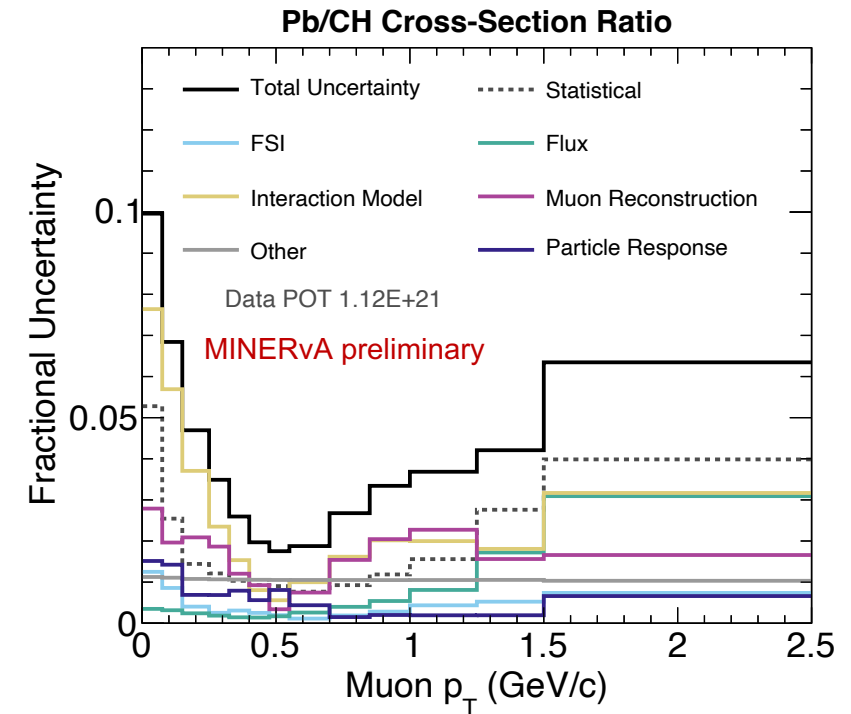
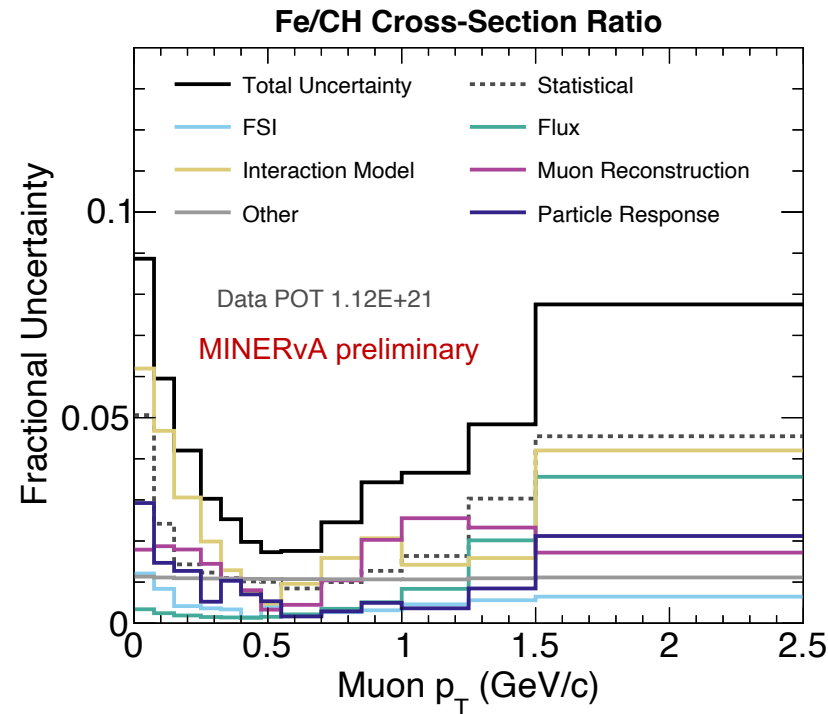
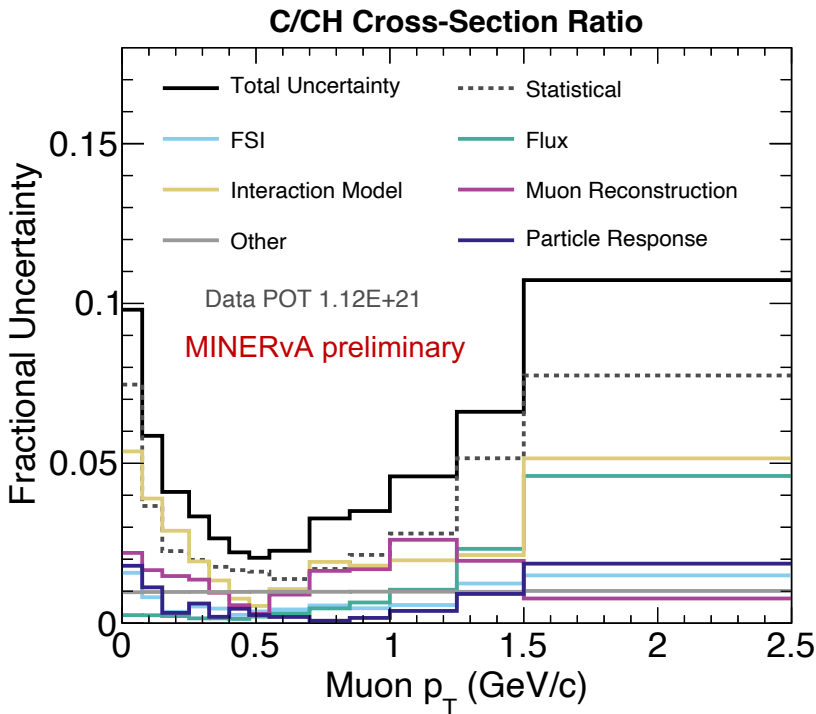
Cross-sections: fractional uncertainties

- 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

Generator / Tune	Version	Nuclear Model	QE Model	2p2h Model	Resonance / Pion Production	DIS & Hadronisation	FSI	Additional Notes
GENIE v3 G18 02a	v3.0.6	Rel. Fermi Gas (Bodek–Ritchie)	Llewellyn-Smith	Empirical 2p2h	Tuned Berger–Sehgal; resonances up to $W=1.93$ GeV	Bodek–Yang + AGKY/PYTHIA	hA2018	Includes resonance tune
GENIE v3 G18 02b	v3.0.6	Same as 02a	Same as 02a	Same as 02a	Same as 02a	Same as 02a	hN	Differences negligible vs hA
GENIE v3 G18 10a	v3.0.6	Valencia LFG + RPA	Valencia QE (RPA)	Valencia 2p2h	Same as 02a	Same as 02a	hA2018	
GENIE v3 G18 10b	v3.0.6	Same as 10a	Same as 10a	Same as 10a	Same as 10a	Same as 10a	hN	Differences negligible vs hA
GENIE v3 AR23 (DUNE tune)	v3.0.6	Extended ground state (based on 10a)	z-expansion form factors	SuSAv2	Same base as 10a	Same base as 10a	Same as 10a	Includes nuclear de-excitation γ (C, Ar)

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



[Y. Hayato, L. Pickering. *Eur.Phys.J.ST* 230 \(2021\) 24, 4469-4481](#)

QE:

LFG: *Nieves et al.* Local Fermi Gas

SF: *Benhar et al.* Spectral Function

2p2h: *Nieves et al.*

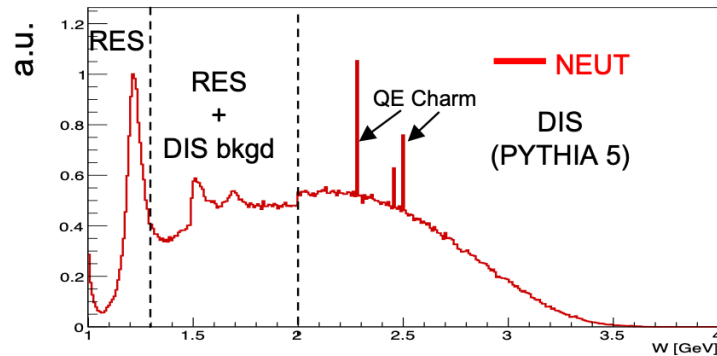
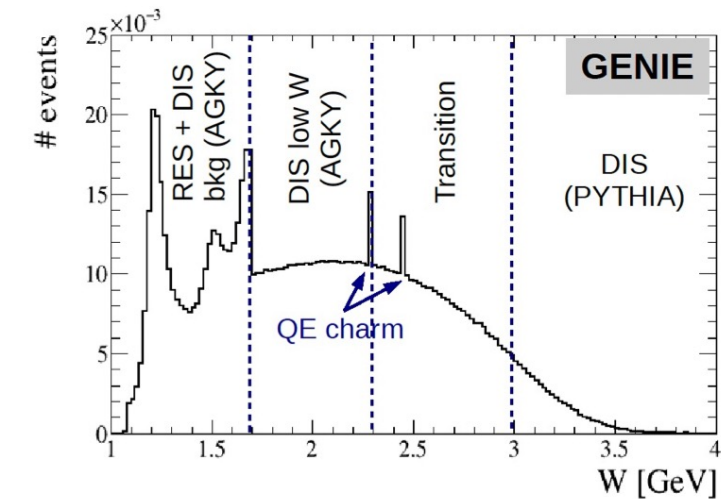
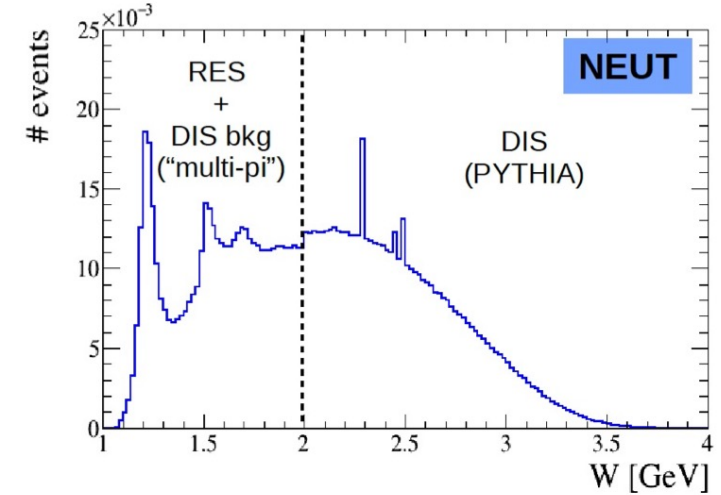
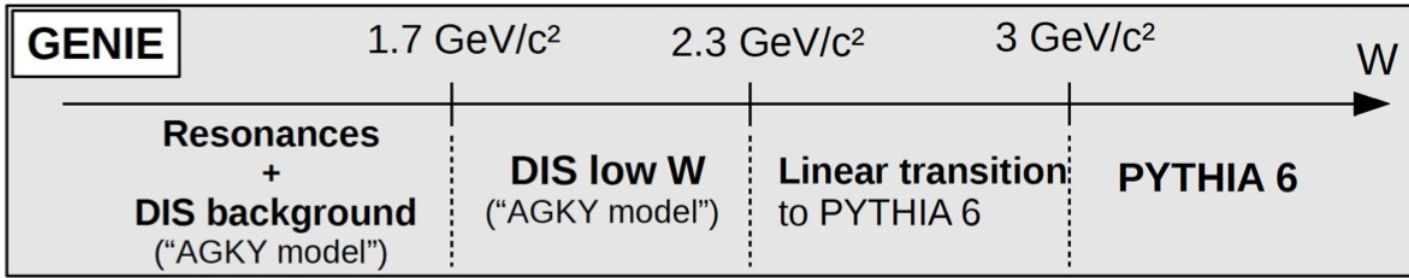
RES: Rein-Sehgal model with Graczyk-Sobczyk form factors

COH: Berger-Sehgal

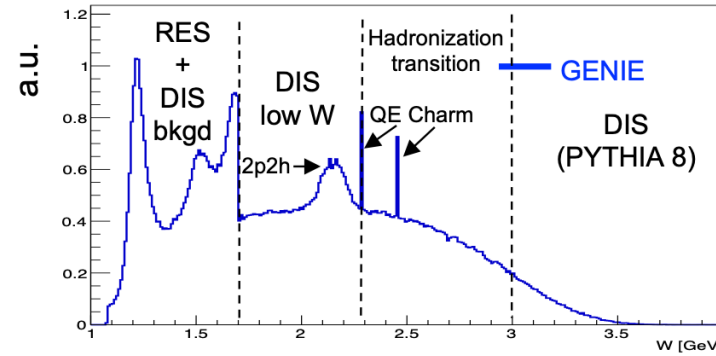
SIS and DIS: GRV98 PDF with Bodel-Yang correction, hadron multiplicity by Pythia v5.72 ($W > 2$ GeV) or a custom model ($W < 2$ GeV)

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

RES → DIS transition in generators

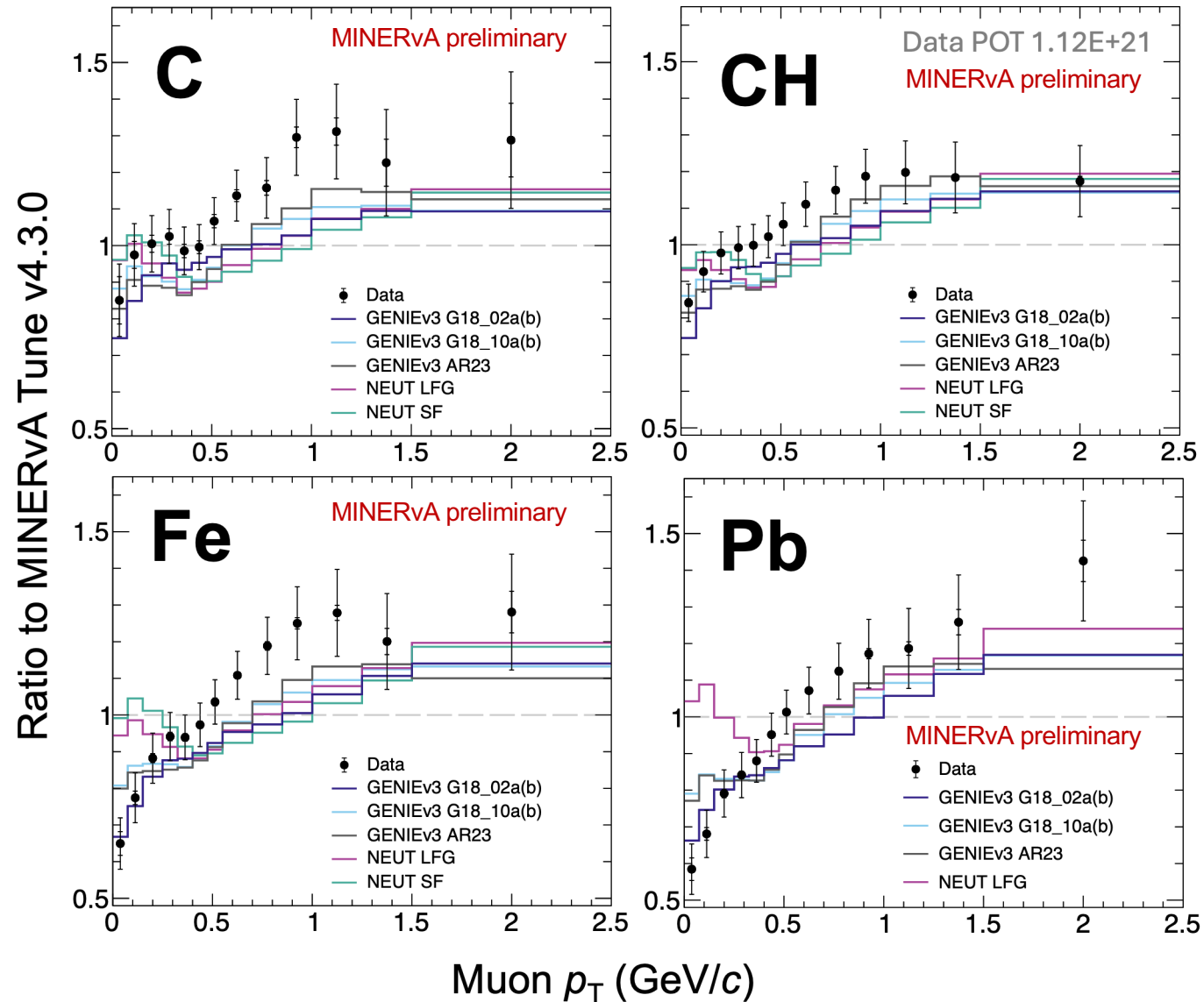


NEUT v5.6.4.3
GENIE v3.06.00, G18_01a

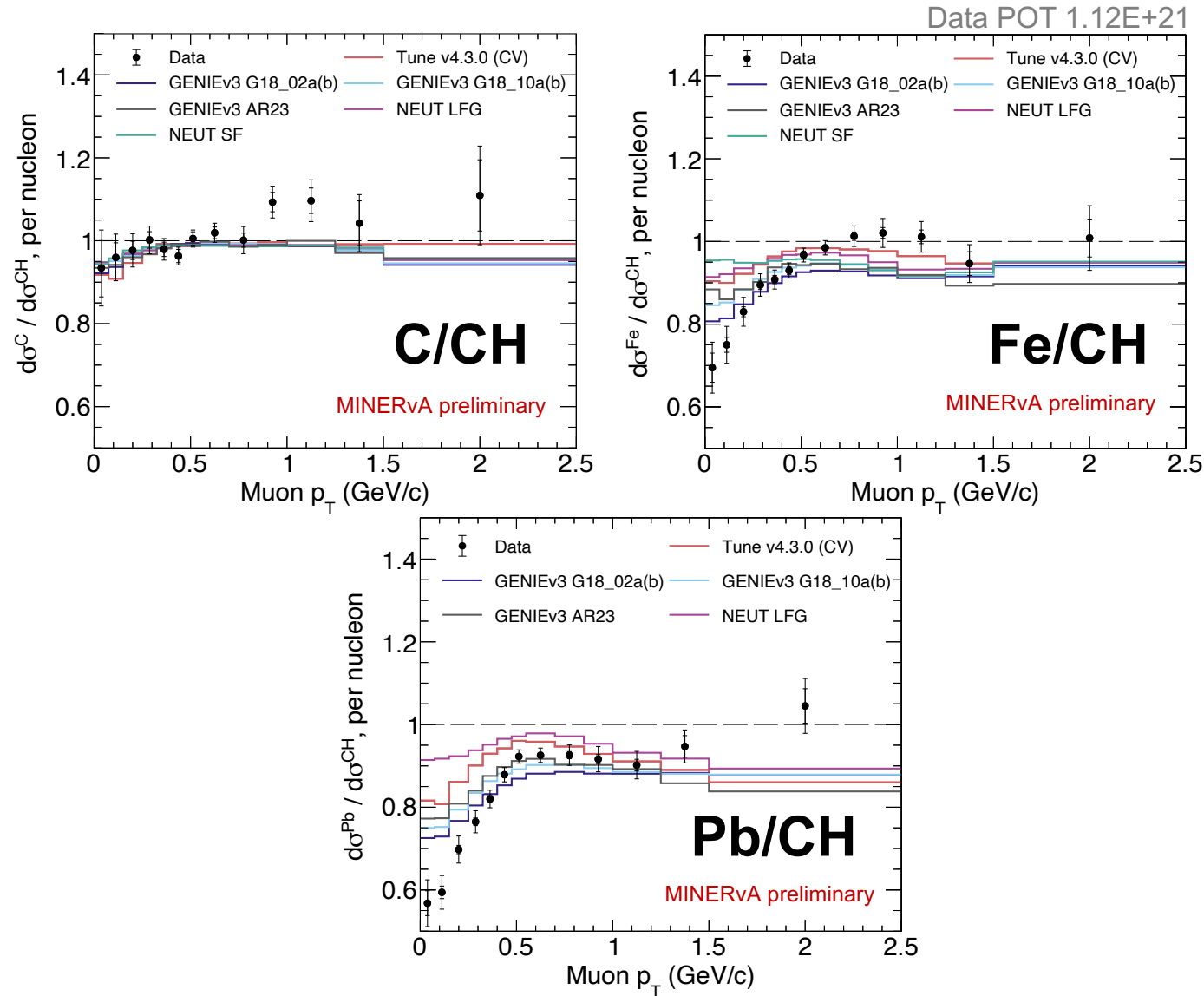


NEUT 5.4.0
GENIE 2.12.10

Model comparison cross-sections



Model comparison cross-section ratios



Low- p_T (carbon) NUISANCE to rescue

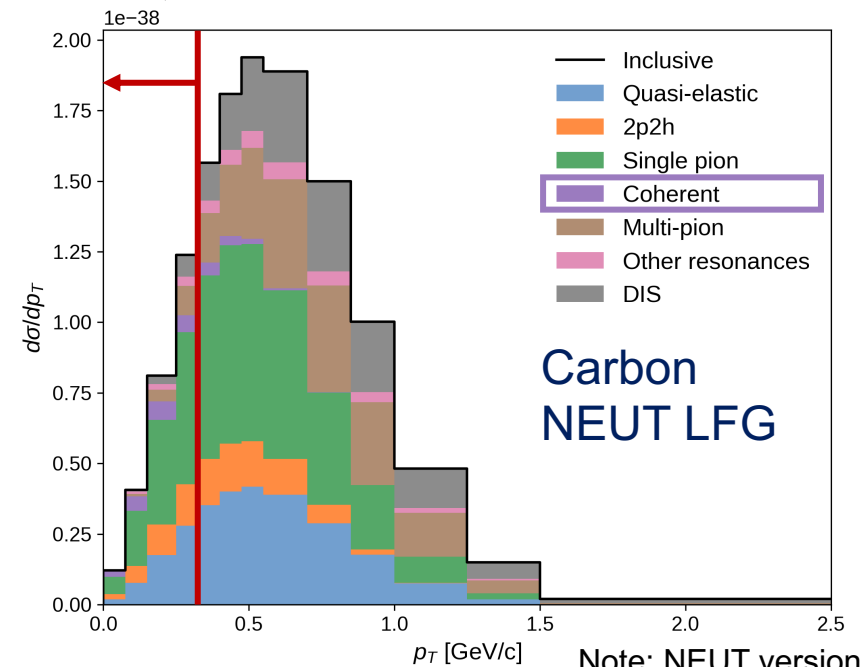
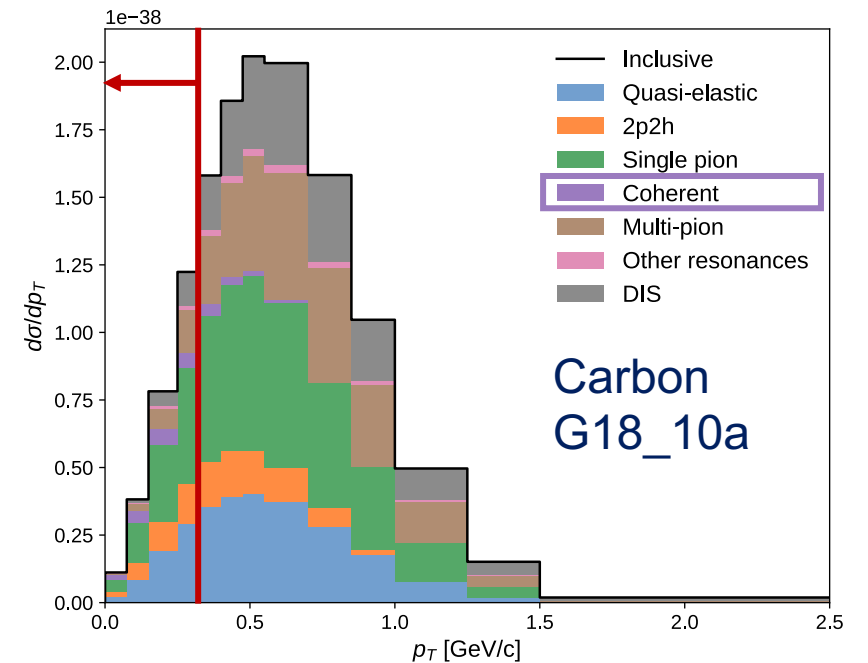
P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et. al.,
[JINST 12 P01016 \(2017\)](#),

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%)
Diffraction	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%)
Diffraction	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

Low- p_T (lead) NUISANCE to rescue

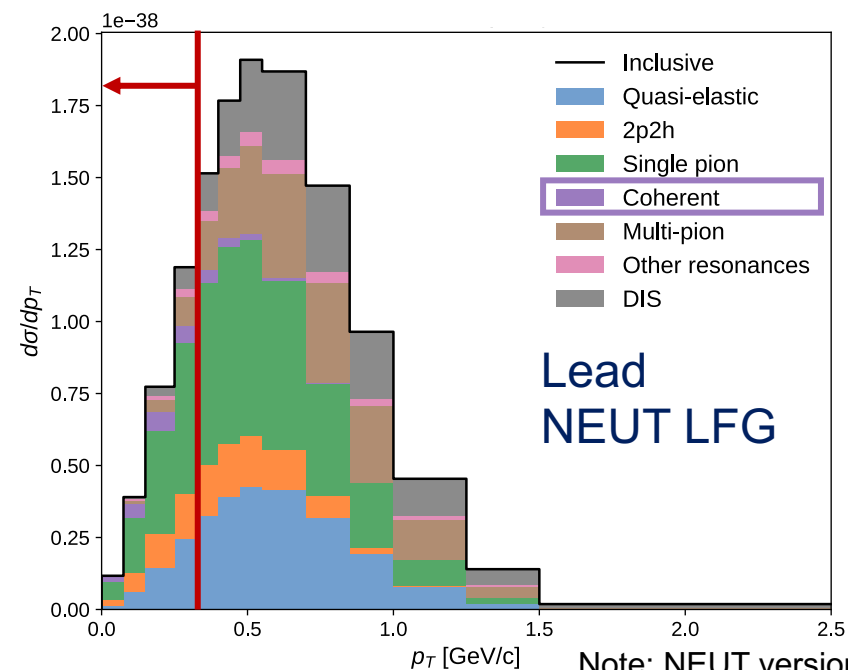
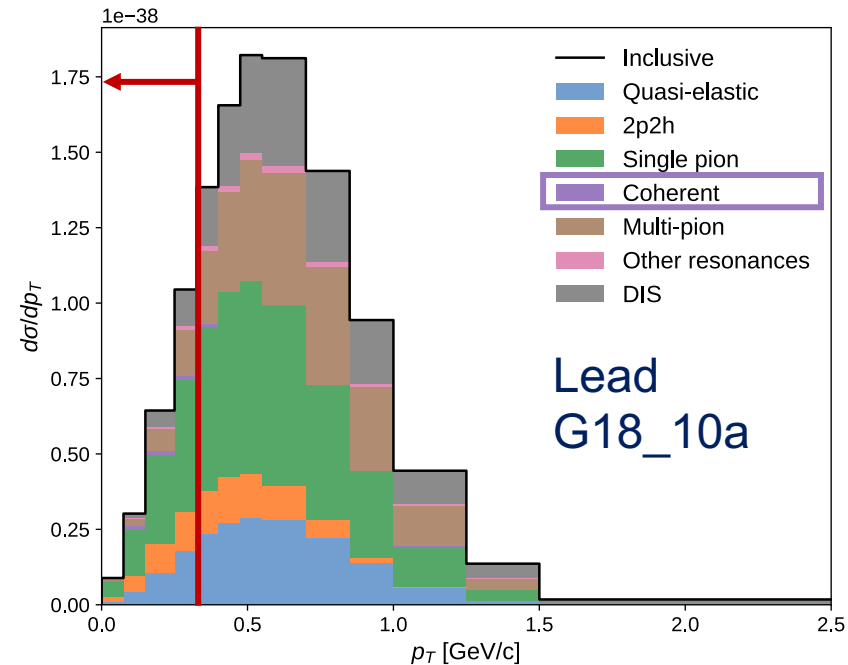
P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et al.,
[JINST 12 P01016 \(2017\)](#)

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%)
Diffraction	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%)

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%)
Diffraction	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%)

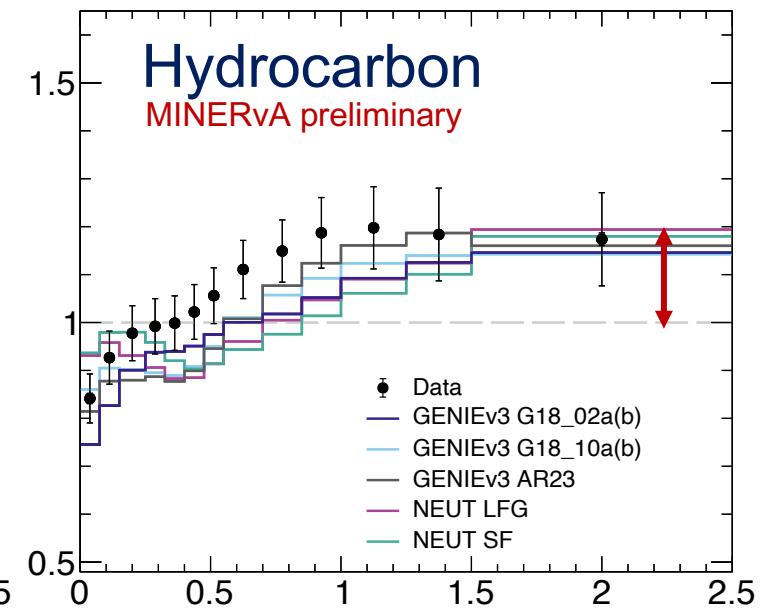
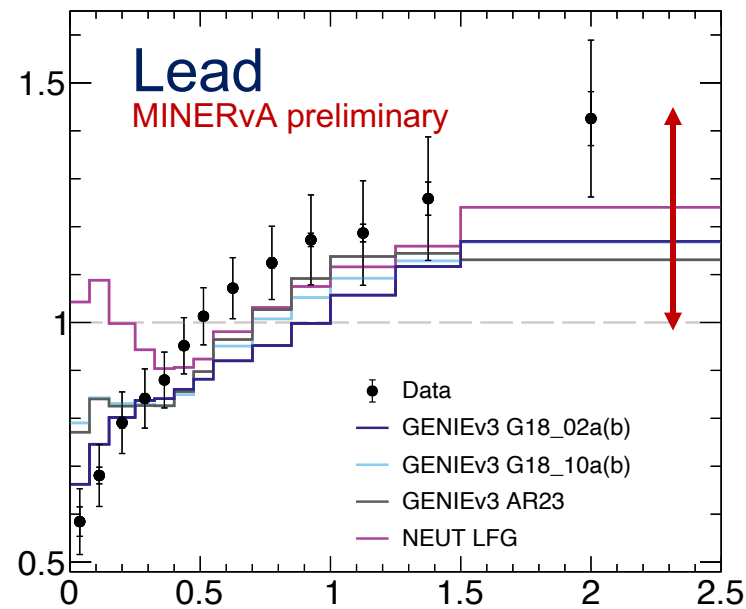
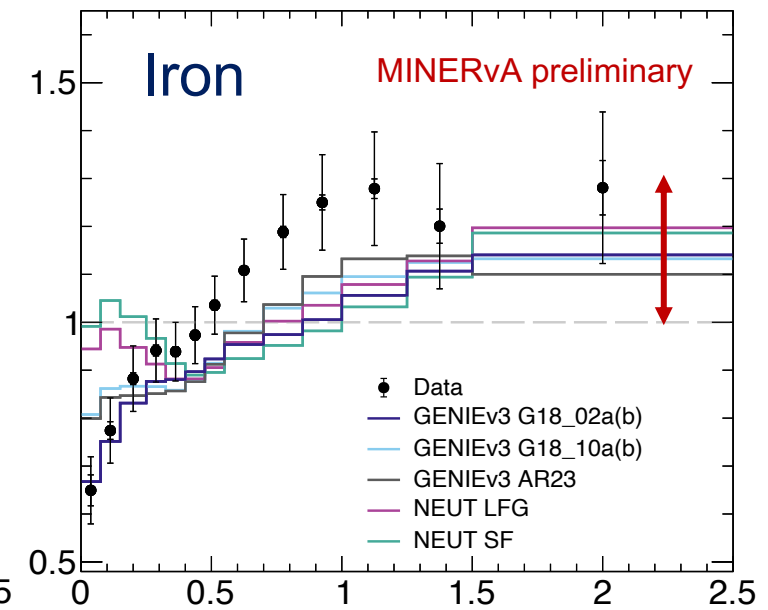
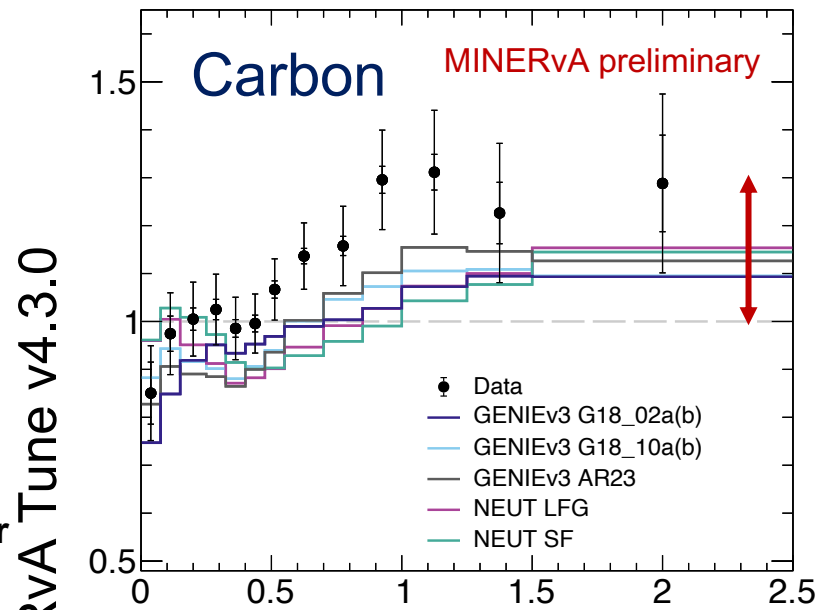
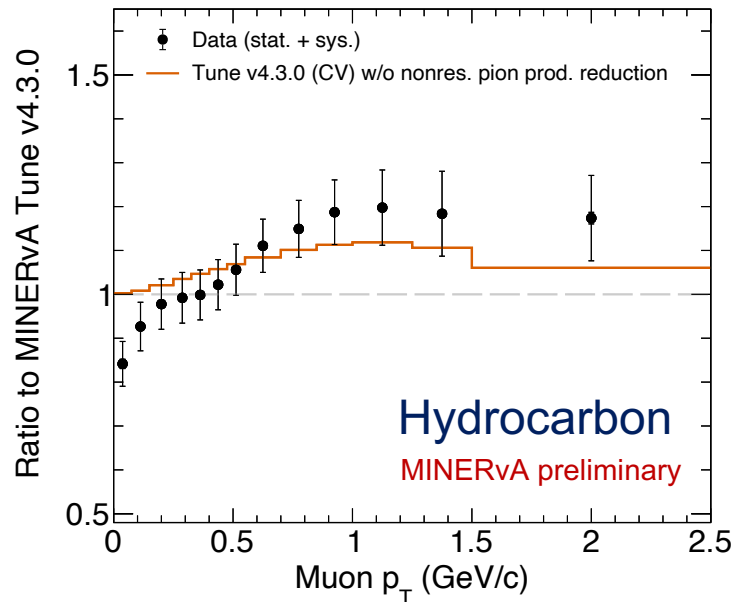
Lead
NEUT LFG



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 any MINERvA measurements
 - Non-resonant pion production reduced based on deuterium data* also applied for $W > 1.2 \text{ GeV}/c^2$ (beyond Δ region) and $Q^2 > 1 (\text{GeV}/c)^2$**



Muon p_T (GeV/c)

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

Note: NEUT version 5.4.1

$\bar{\nu}_\mu$ QE-like 1+ neutrons vs A

Primary Muon Requirement

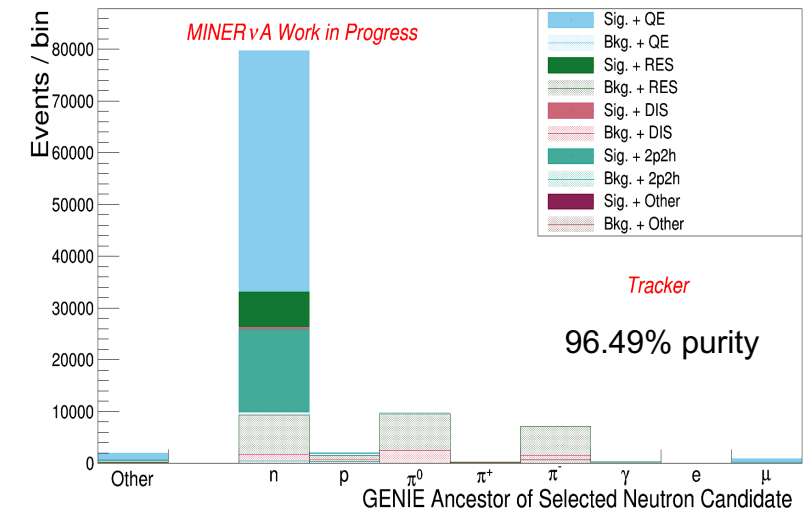
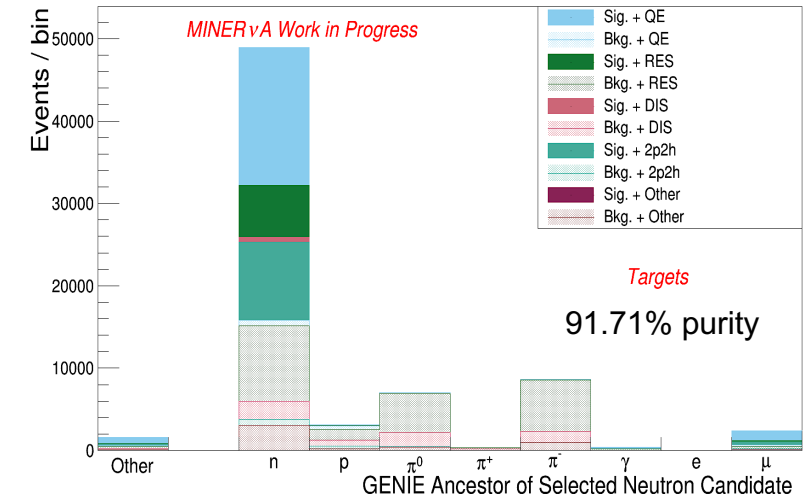
- Exactly one positive muon
- Angle to beam $< 17^\circ$
- Momentum range: $1.5 \text{ GeV}/c < p_\mu < 20 \text{ GeV}/c$

Final State (CCQE-Like)

- Zero mesons
- Allowed additional particles (X):
- Neutrons
- Untrackable protons ($T_{\text{kin}} < 120 \text{ MeV}$)
- Photons ($E < 10 \text{ MeV}$)

Neutron Requirement

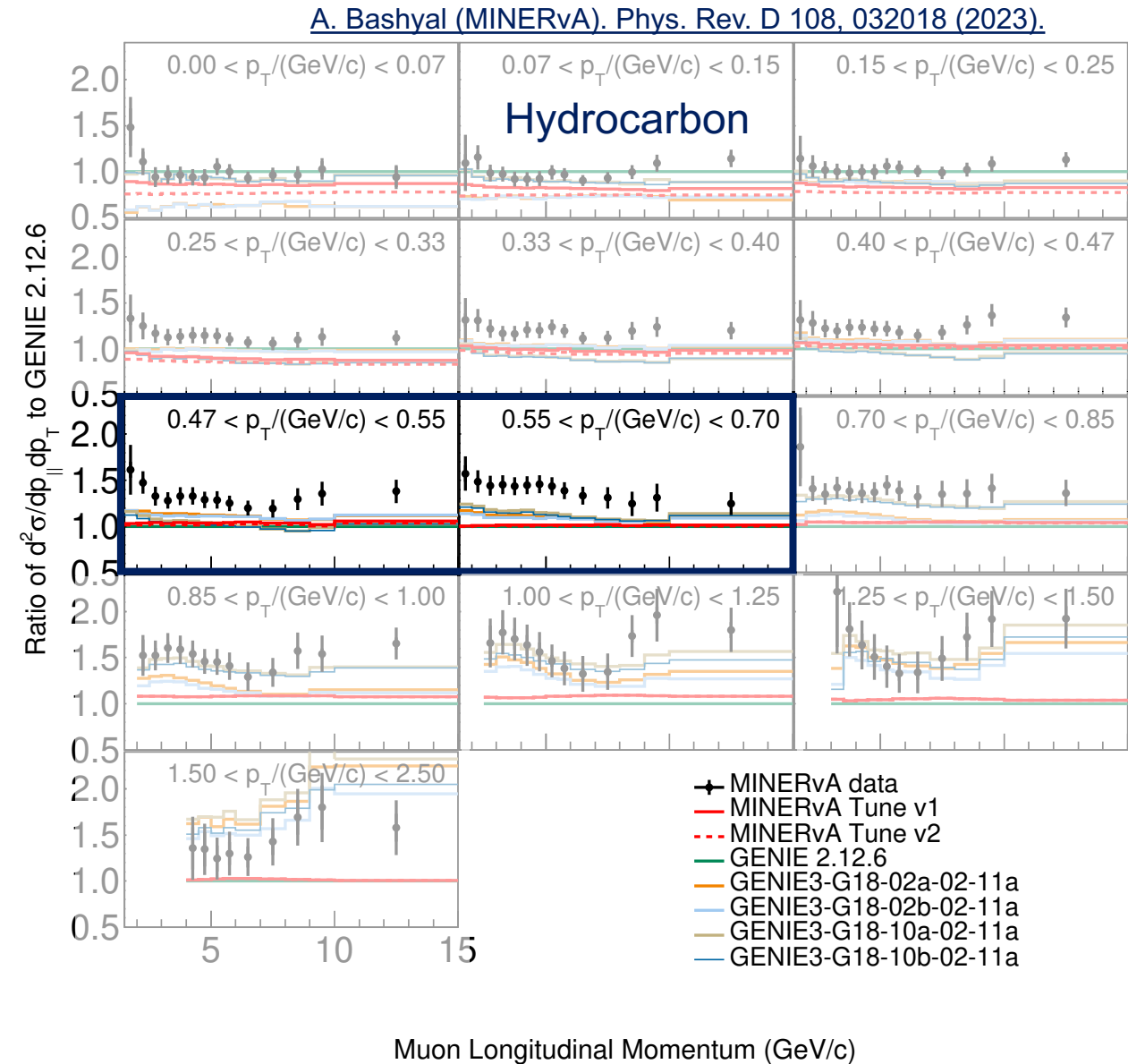
- ≥ 1 neutron present
- Highest-energy (“lead”) neutron must have $T_{\text{kin}} > 10 \text{ MeV}$



D. Last (MINERvA). NuInt 2025 talk

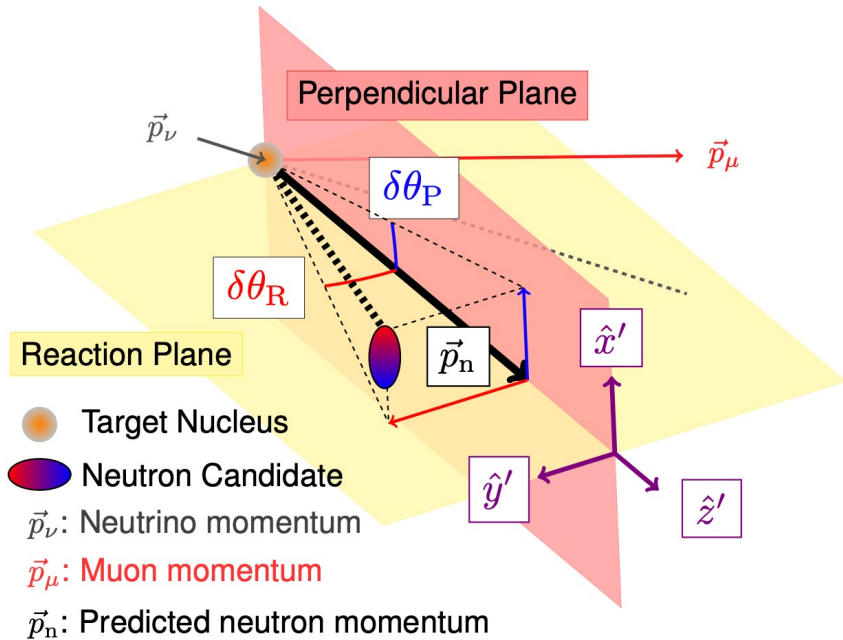
2D $\bar{\nu}_\mu$ QE-like on CH

- Also consistent with QE-like 2D analysis on CH only
- $\sim 0.4\text{--}0.8$ GeV/c underprediction
 - QE, 2p2h, and some RES predicted contribution

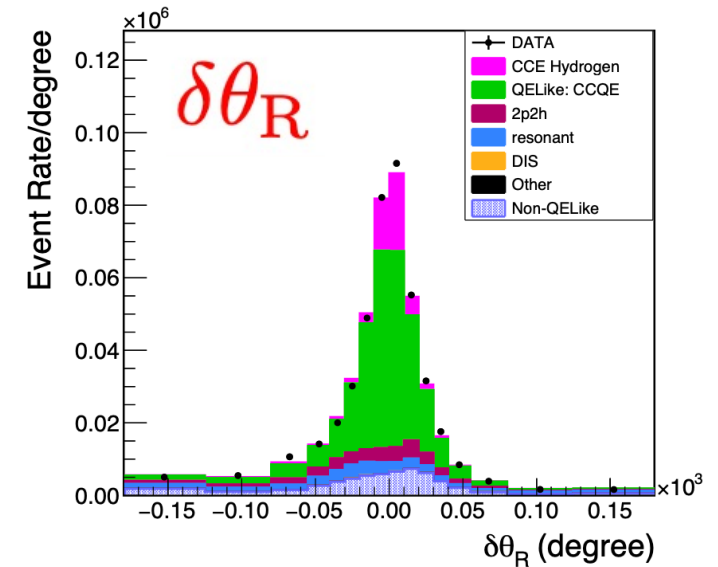
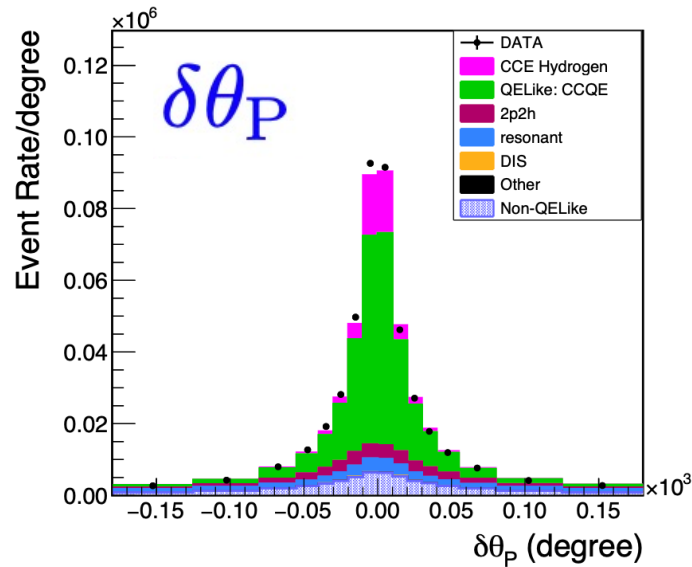


$\bar{\nu}_\mu$ CC 0π on H

- Measurement on a **free nucleon (no nuclear effects!)** – hydrogen in the CH tracker $\bar{\nu}_\mu H \rightarrow \mu^+ n$
- Neutron deviation from scattering on a free nucleon vs carbon (transverse kinematic imbalance)
- Neutron deviation can be captured using angular variables



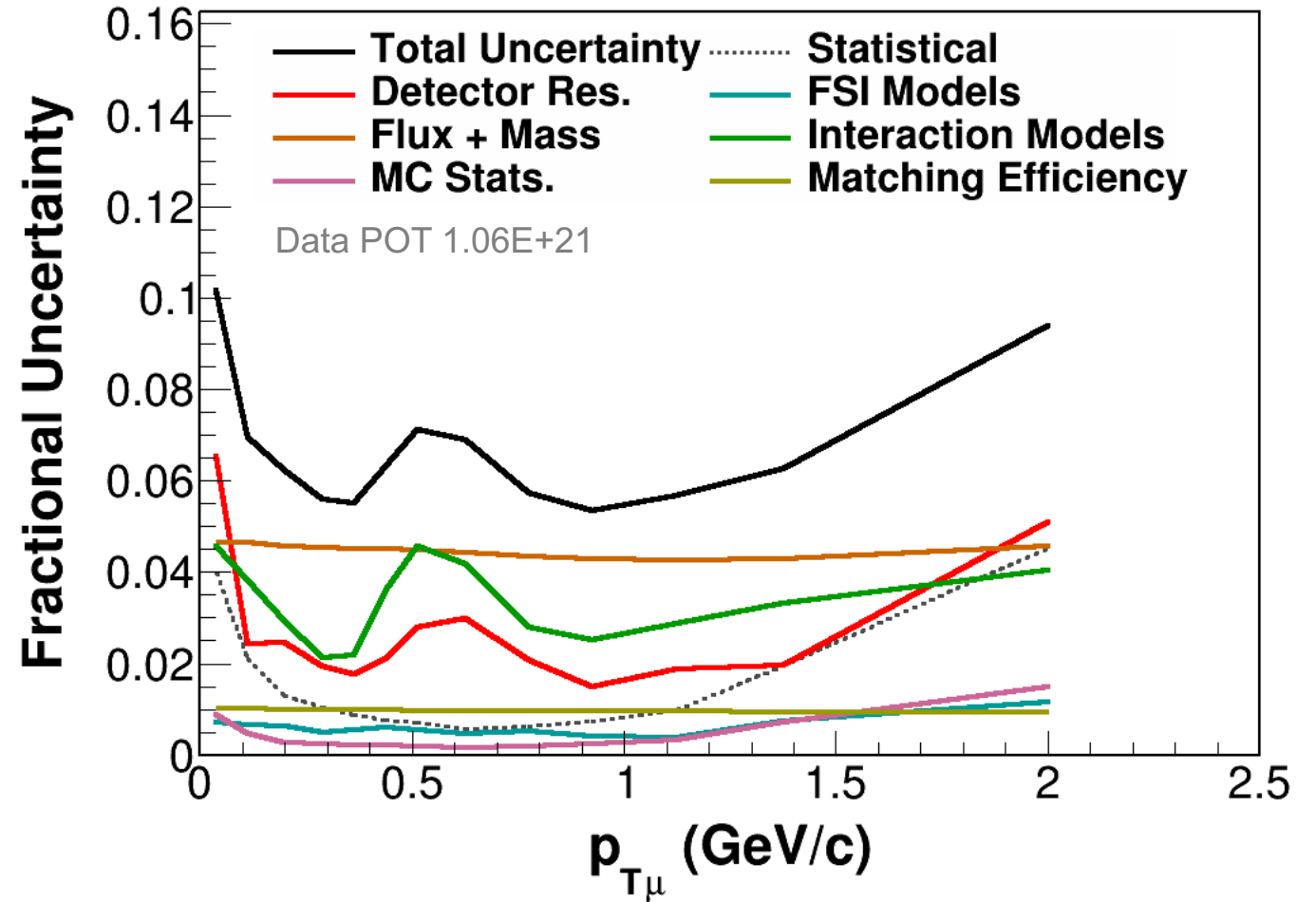
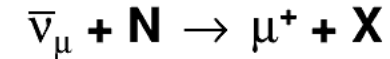
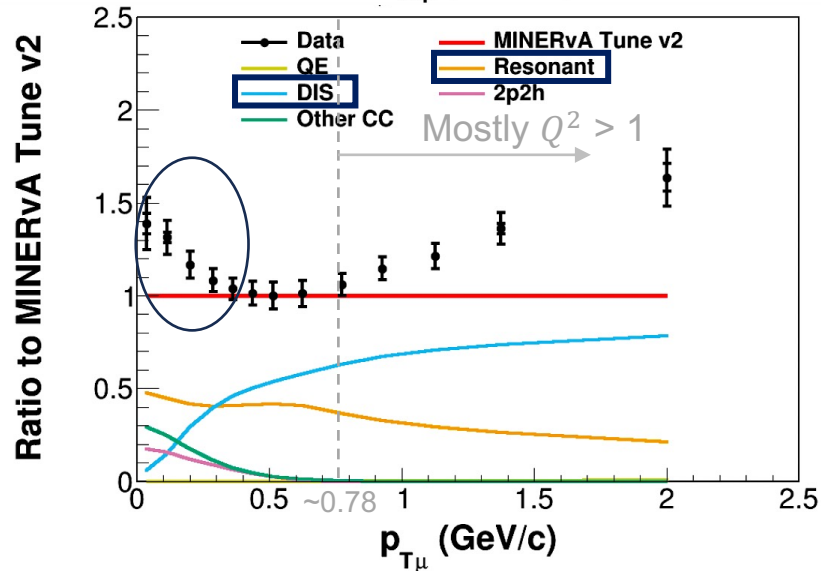
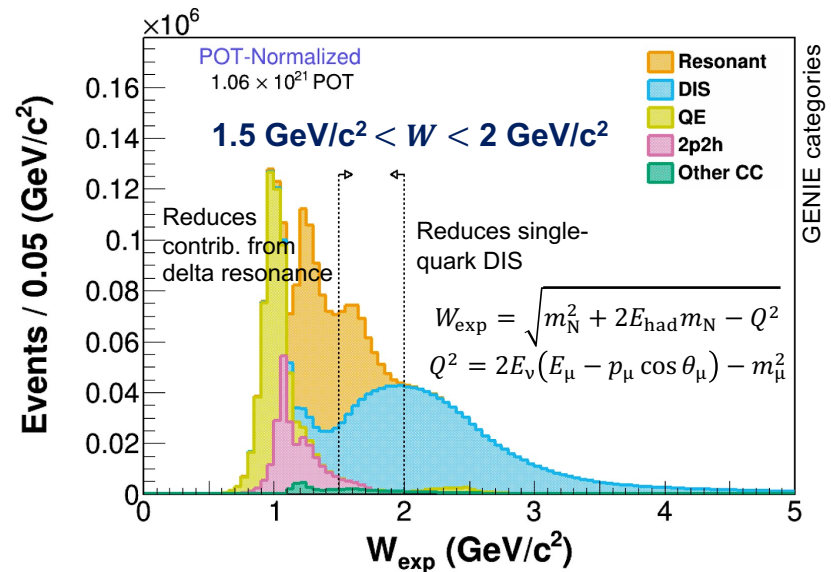
Centred (H) vs spread (C)



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

$\bar{\nu}_\mu$ SIS on CH

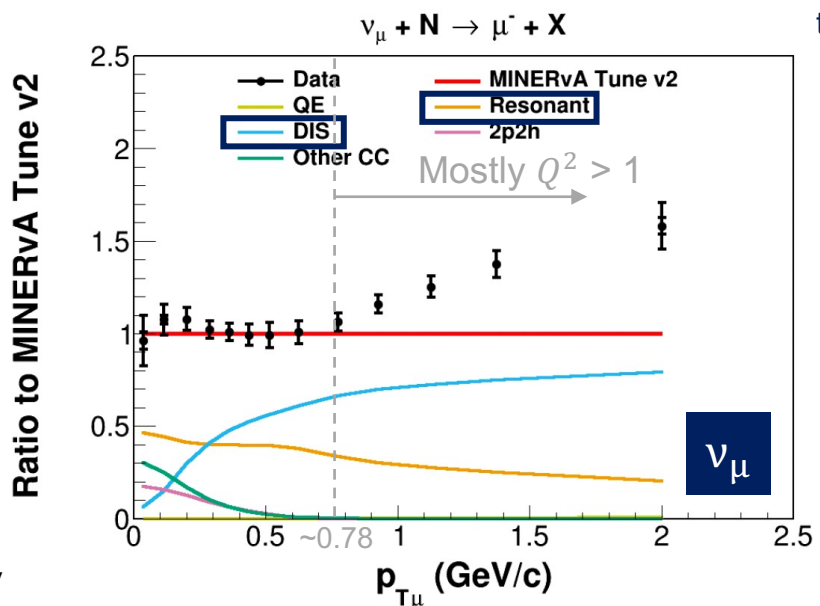
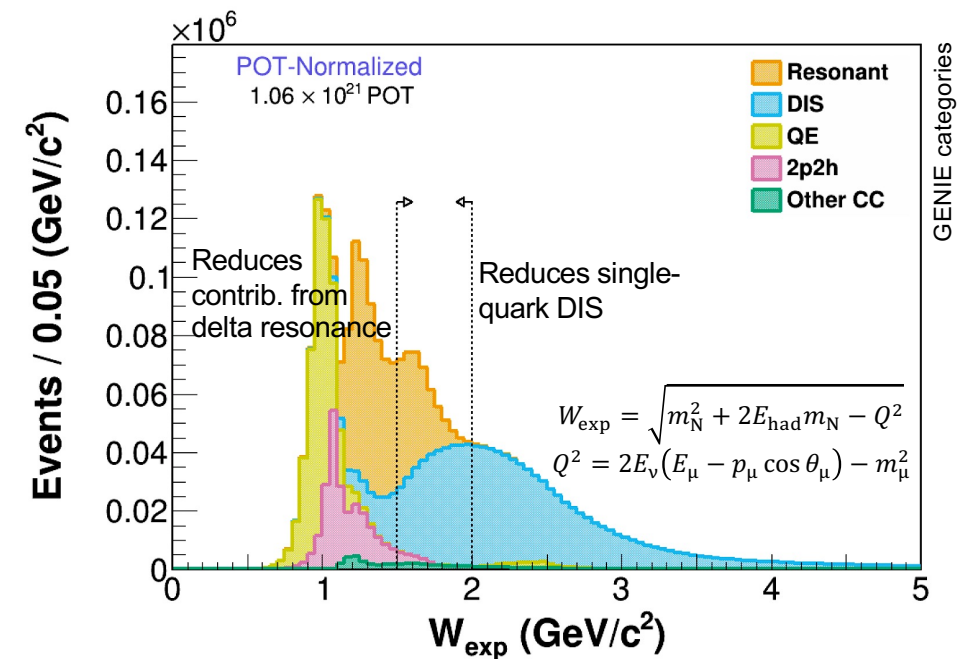
Based on 364,082 selected antineutrino events in data.



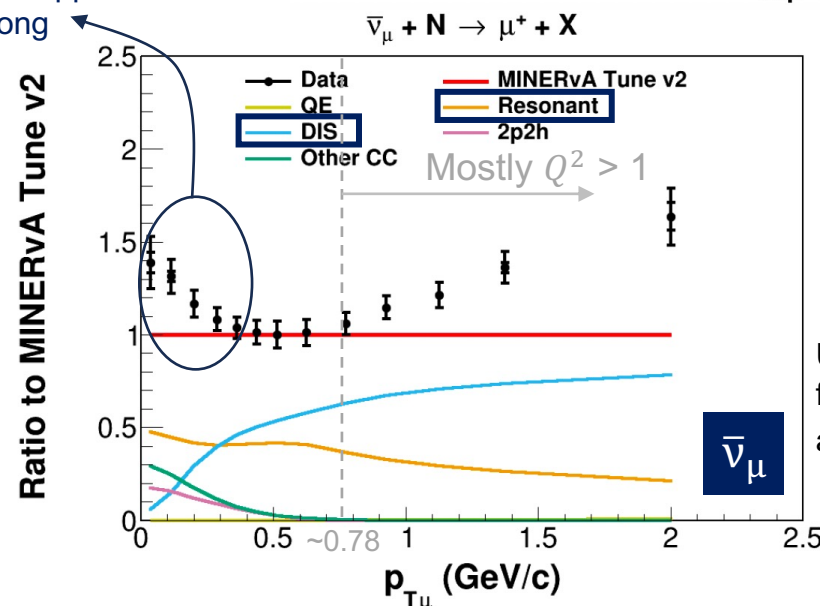
A. Lozano, G. Silva, G. Caceres (MINERvA).
 Submitted for publication. arXiv:2503.20043 (2025).

MINERvA's SIS measurement

- 1D neutrino and antineutrino cross-sections reported in (anti)muon momentum variables and variables sensitive to the hadronic system
- Calorimetric reconstruction of visible recoil energy with model-dependent correction for invisible energy
- QE, resonant, and higher W DIS background constraint in sideband regions via simultaneous shape+normalisation fit to data



Low Q^2 suppression too strong



High $p_{T\mu}$ underprediction, shape not quite right (true SIS region with $Q^2 > 1$)

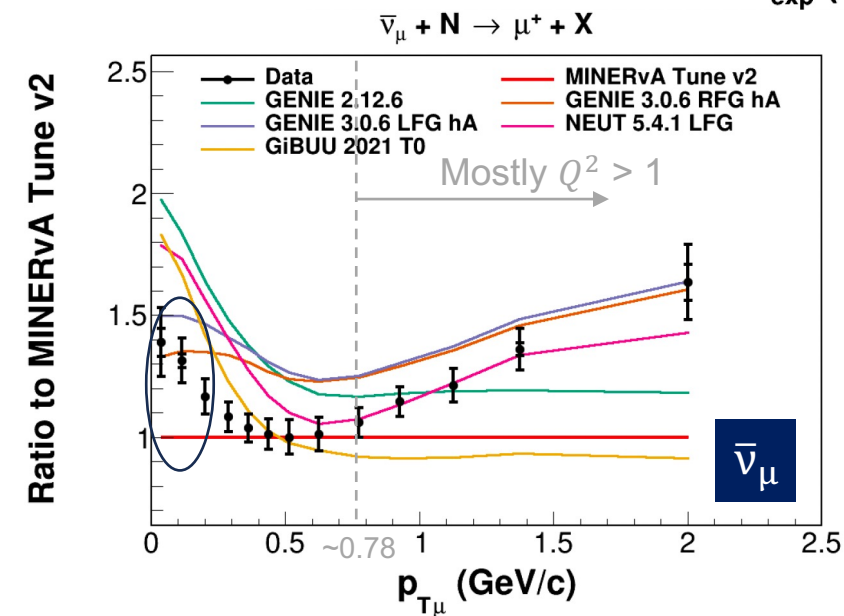
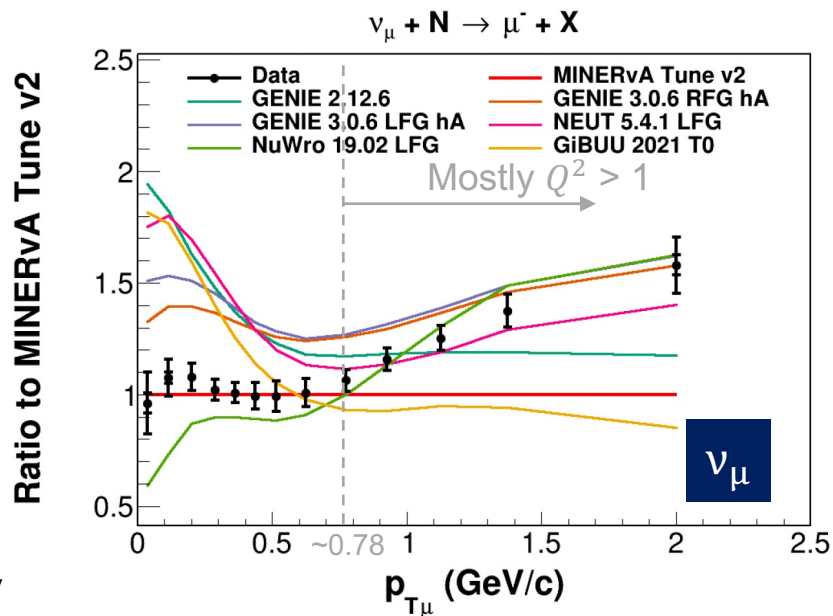
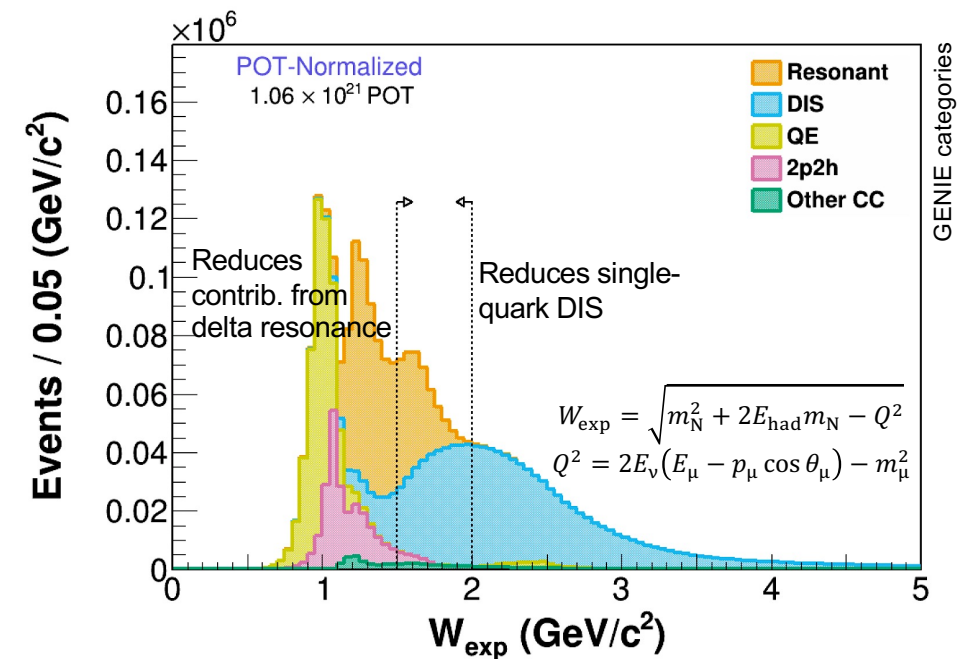
Uncertainties dominated by flux, interaction model ($M_{A/V}^{RES}$), and detector response

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

ME datasets
 $2 \text{ GeV} < E_\mu < 20 \text{ GeV}$

MINERvA's SIS measurement

- None of them describe data well across the full kinematic region
- At low $p_{T\mu}$ **central value** does pretty well
- At high $p_{T\mu}$ **GENIE3** gets shape right, **NuWro** and **NEUT** fit well
- Other variables, dedicated $Q^2 > 1 \text{ GeV}^2$ analysis for multi-quark component of SIS, full systematics info in the publication



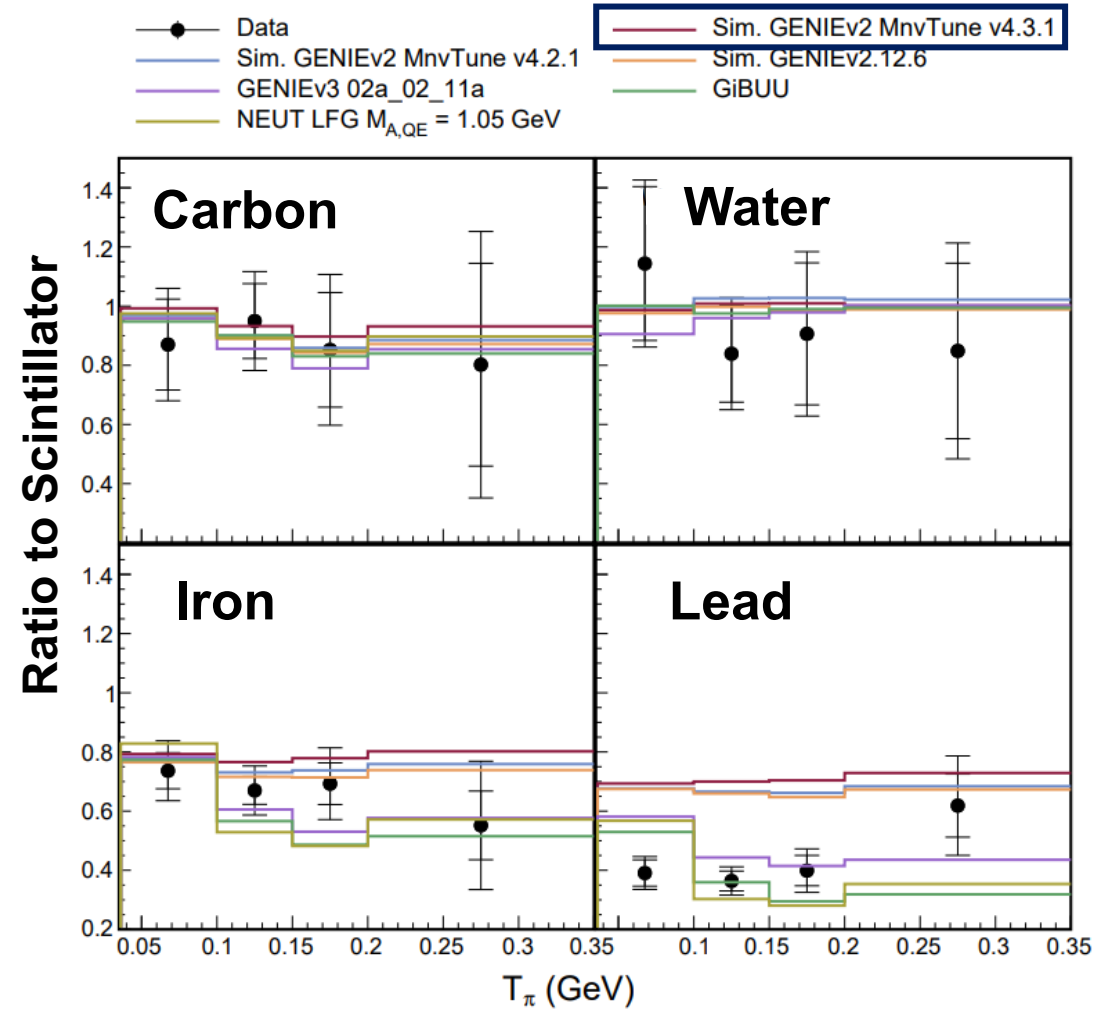
$$Q^2 \approx p_T^2 \left(1 + \mathcal{O} \left(\frac{E_{\text{recoil}}}{E_\mu} \right) \right)$$

ME datasets
 $2 \text{ GeV} < E_\mu < 20 \text{ GeV}$

ν_{μ} CC $1\pi^+$ vs A

- Muon and pion candidate
- Any number of baryons in final state – $W < 1.4 \text{ GeV}/c^2$ to enhance interactions producing Δ resonances
- Muon angle less than 13 degrees
- Muon momentum between 1.5-20 GeV
- Pion kinetic energy between 35-350 MeV

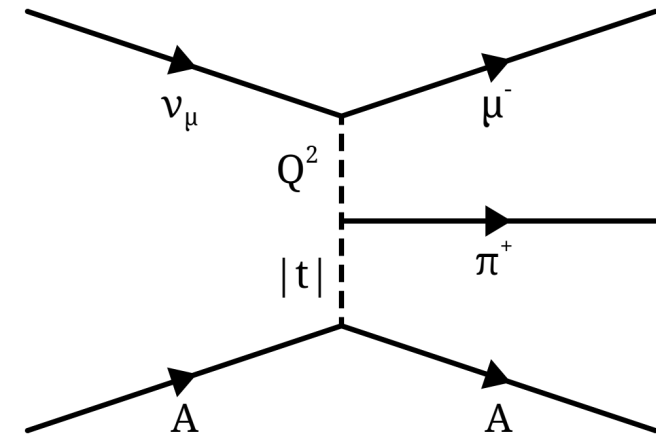
Pion kinetic energy cross-section ratio



[A. Bercellie \(MINERvA\). Phys.Rev.Lett. 131, 011801 \(2023\).](#)

Coherent pion production

- Occurs in both CC and NC
- All nucleons react in phase, no nuclear break-up with nuclear recoil undetected producing forward lepton and forward pion
- Pion scatters coherently off the nucleus
- Not well understood
 - W/Z exchange in the presence of a nucleus, boson fluctuates to a π meson
 - Coherent addition of all neutrino-nucleon interactions, delta resonance is the main process contributing
- Rein-Sehgal Model: [Ann. Phys. 133, 79-153 \(1981\)](#)
 - Relates inelastic $\nu A \rightarrow l \pi A$ to elastic $\nu A \rightarrow l A$, assumes ν and l are parallel for $Q^2 = 0$, neglects lepton mass
 - Pion-nucleus scattering modelled using pion-nucleon data
- Berger-Sehgal: [Phys.Rev. D79, 053003 \(2009\)](#).
 - Uses π -carbon data for the $\pi A \rightarrow \pi A$ scattering, includes lepton mass



Coherence depends on the magnitude of the four-momentum transfer to the nucleus:

$$|t| = |(p_\nu - p_l - p_\pi)^2|$$

[M. A. Ramírez \(MINERvA\). Phys. Rev. Lett. 131, 051801 \(2023\).](#)

“Measurements of the cross-section ratios of Fe and Pb relative to CH reveal the effective A scaling to increase from an approximate $A^{1/3}$ scaling at few GeV to an $A^{2/3}$ scaling for $E_\nu > 10$ GeV.”