Neutrino-Nucleus Interactions at MINERvA

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Imperial College London

LBNF/DUNE UK Project Meeting

3-4 July 2023, University of Bristol

What is MINERvA?

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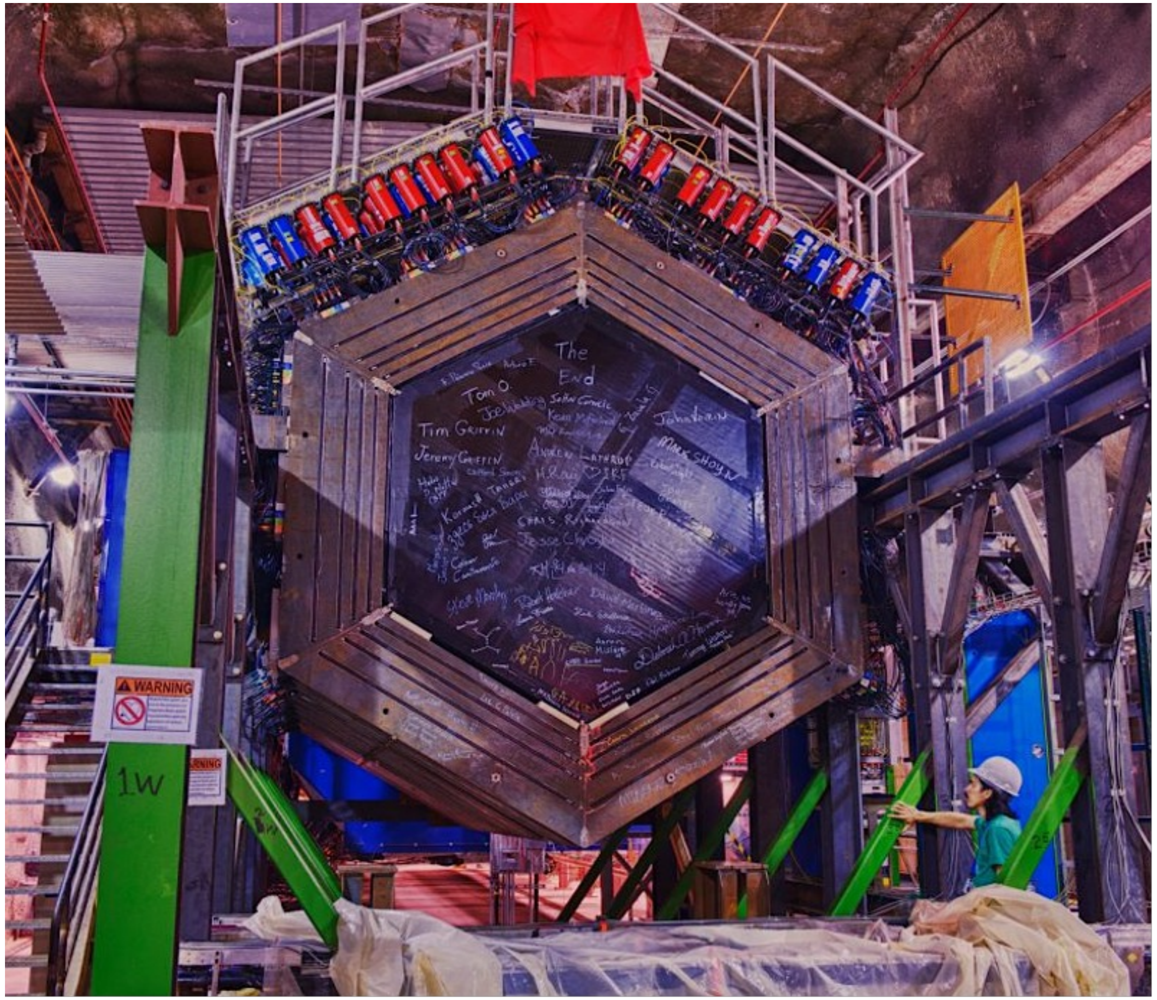

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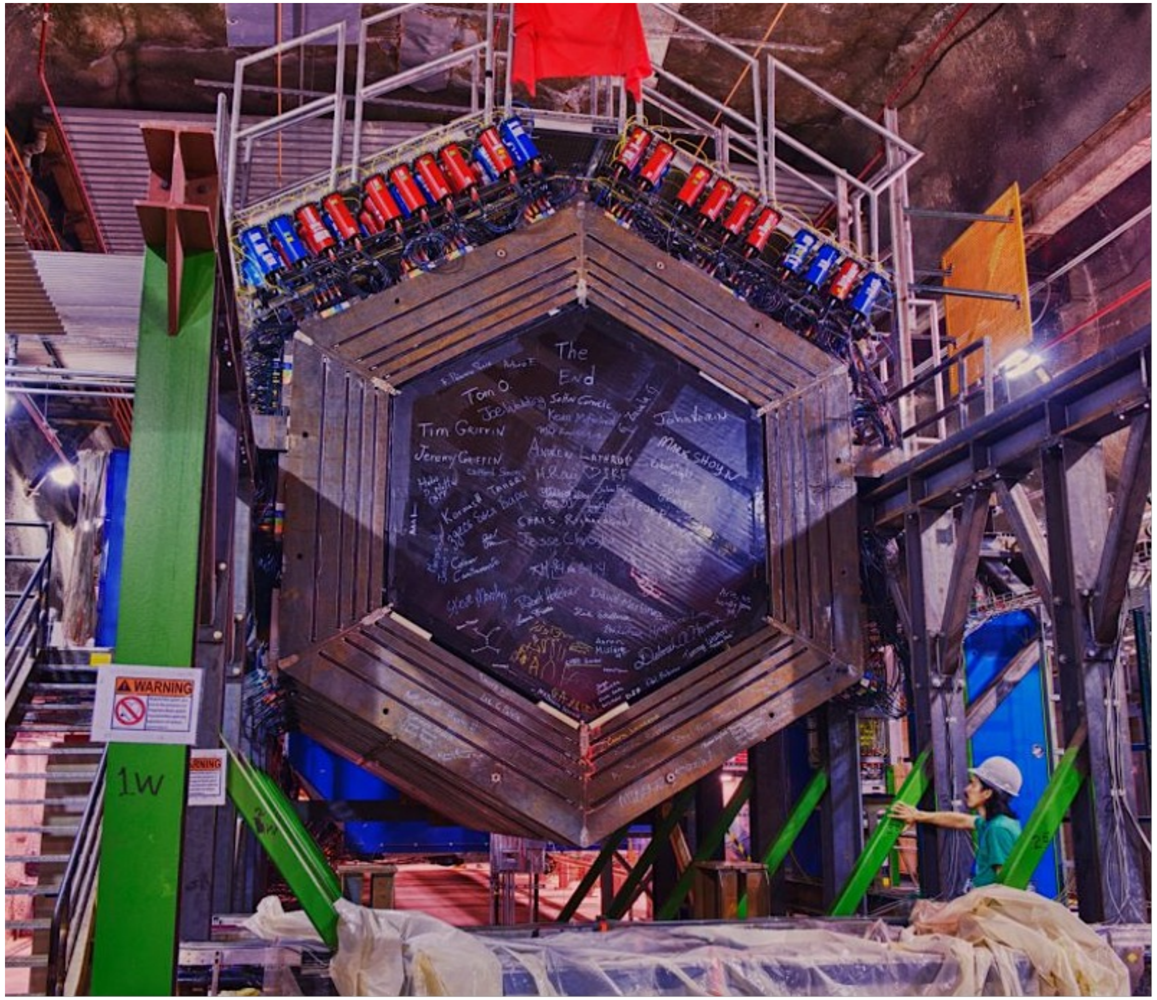

Main **IN**jector **E**xpe**R**iment for **ν-A** scattering

- High-statistics cross-section experiment **with different nuclear targets**

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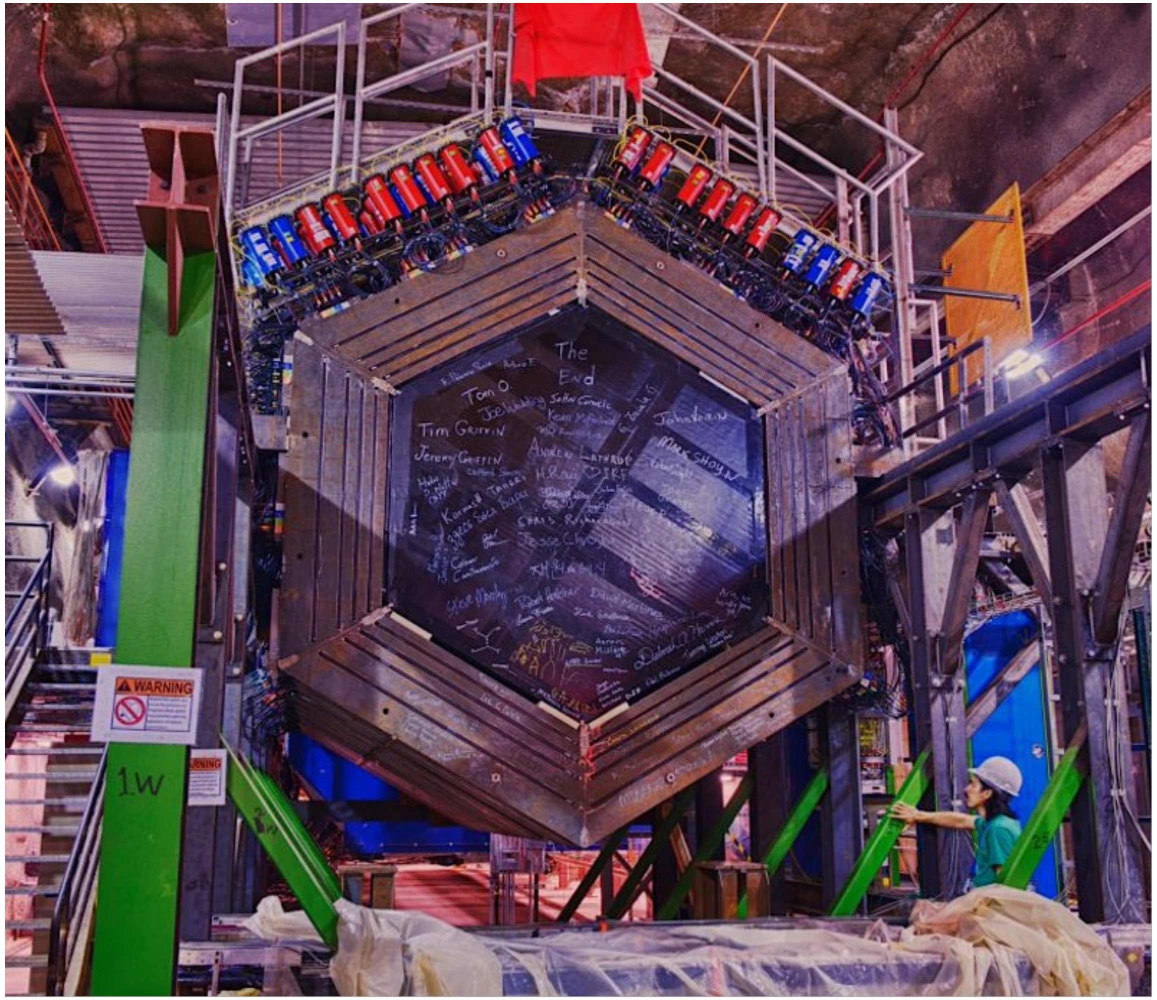

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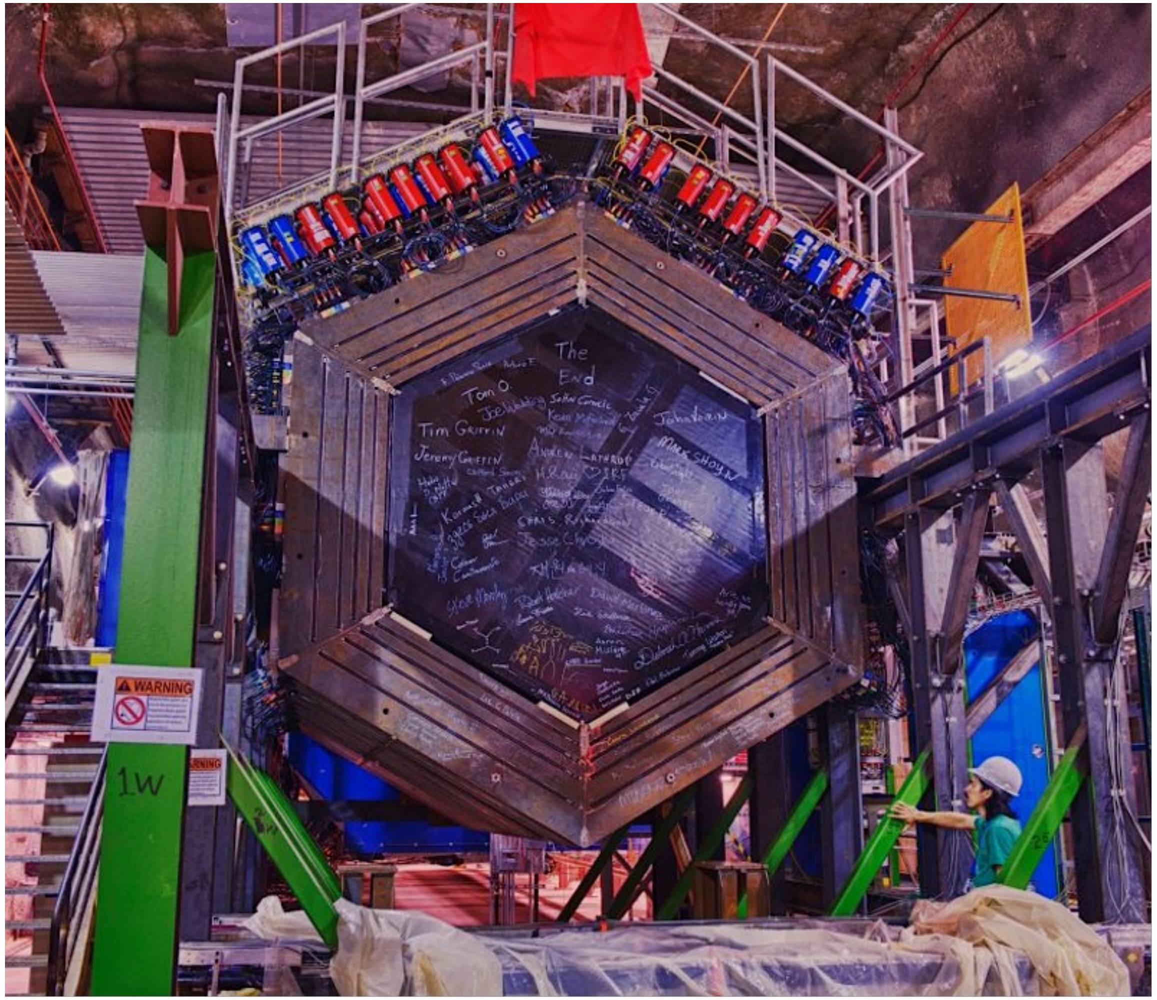

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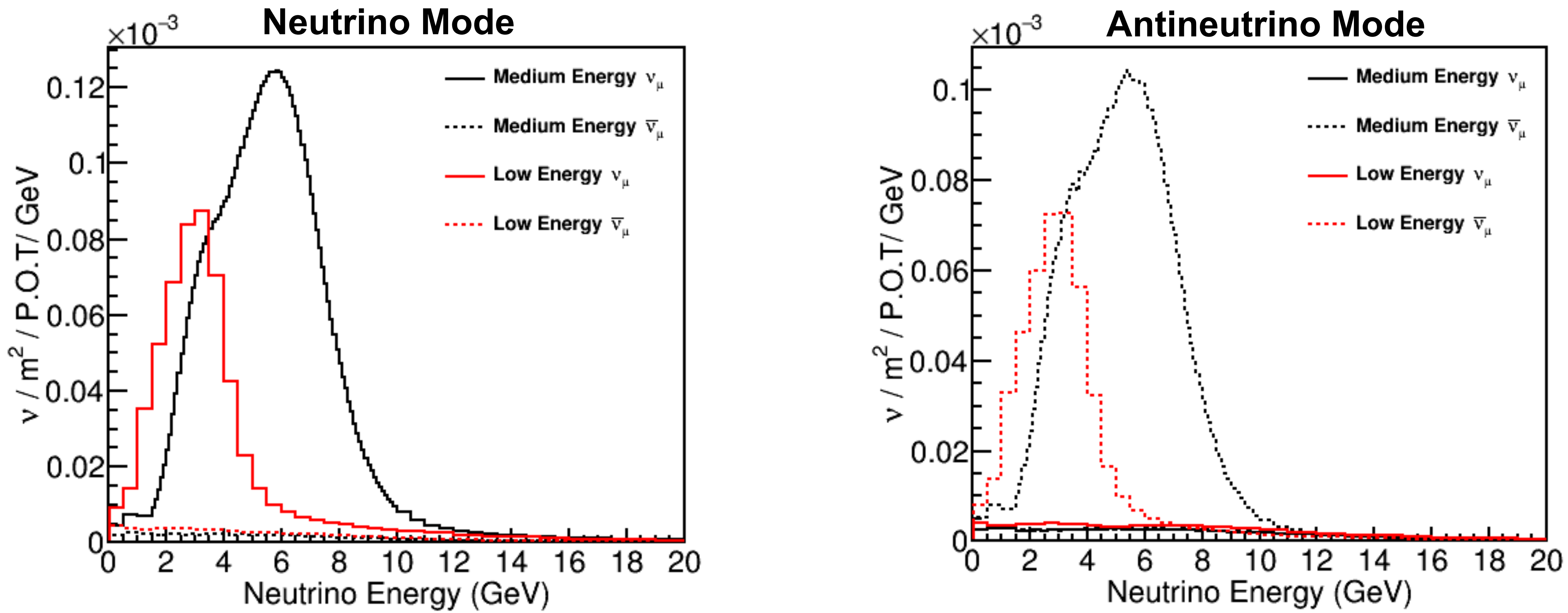
- High-statistics cross-section experiment **with different nuclear targets**
- 2009-2019 on axis in the NuMI beamline @Fermilab (~1 km away from beam target, ~100 m underground)
- 2 flux periods with 3 GeV (MINOS) and 6 GeV (NOvA) flux peak, both in $\nu/\bar{\nu}$

What is MINERvA?



Regime \ Mode	ν (POT)	ν̄ (POT)
Low (LE) ~ 3 GeV	4×10^{20}	1.7×10^{20}
Medium (ME) ~ 6 GeV	12.1×10^{20}	12.4×10^{20}

Main INjector ExpeRiment for ν-

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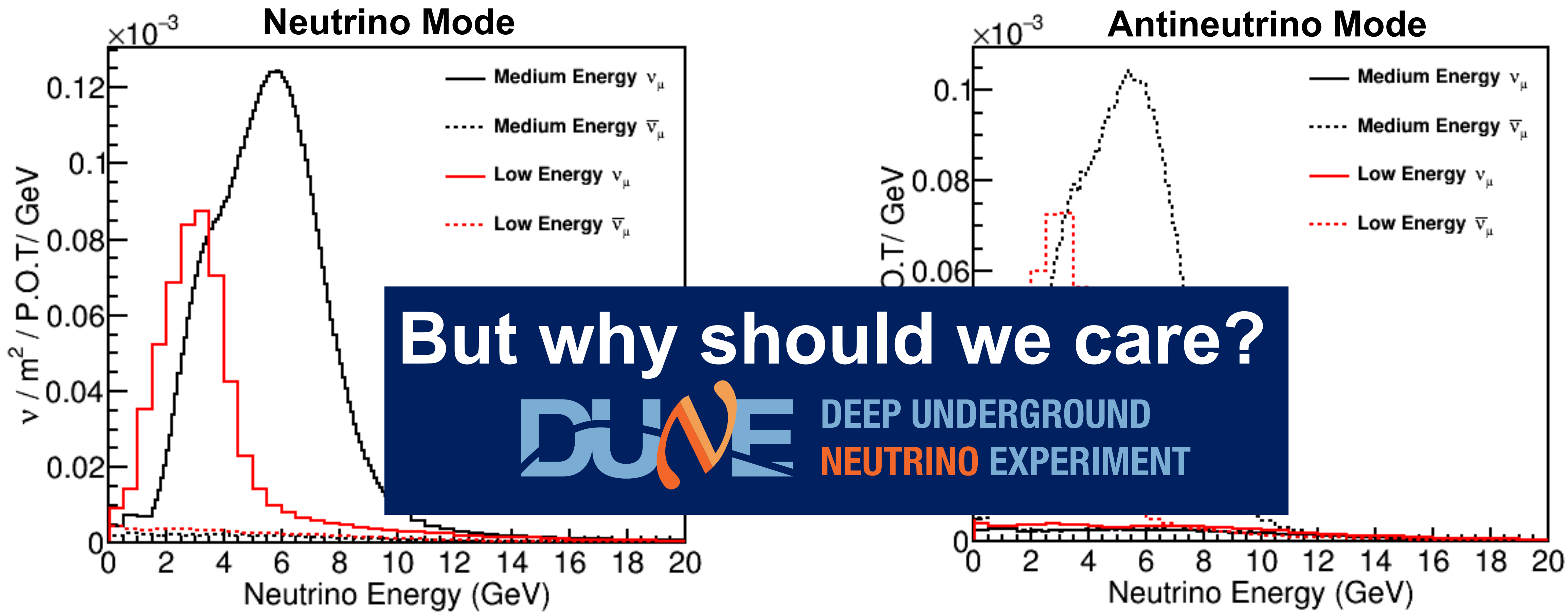

But why should we care?

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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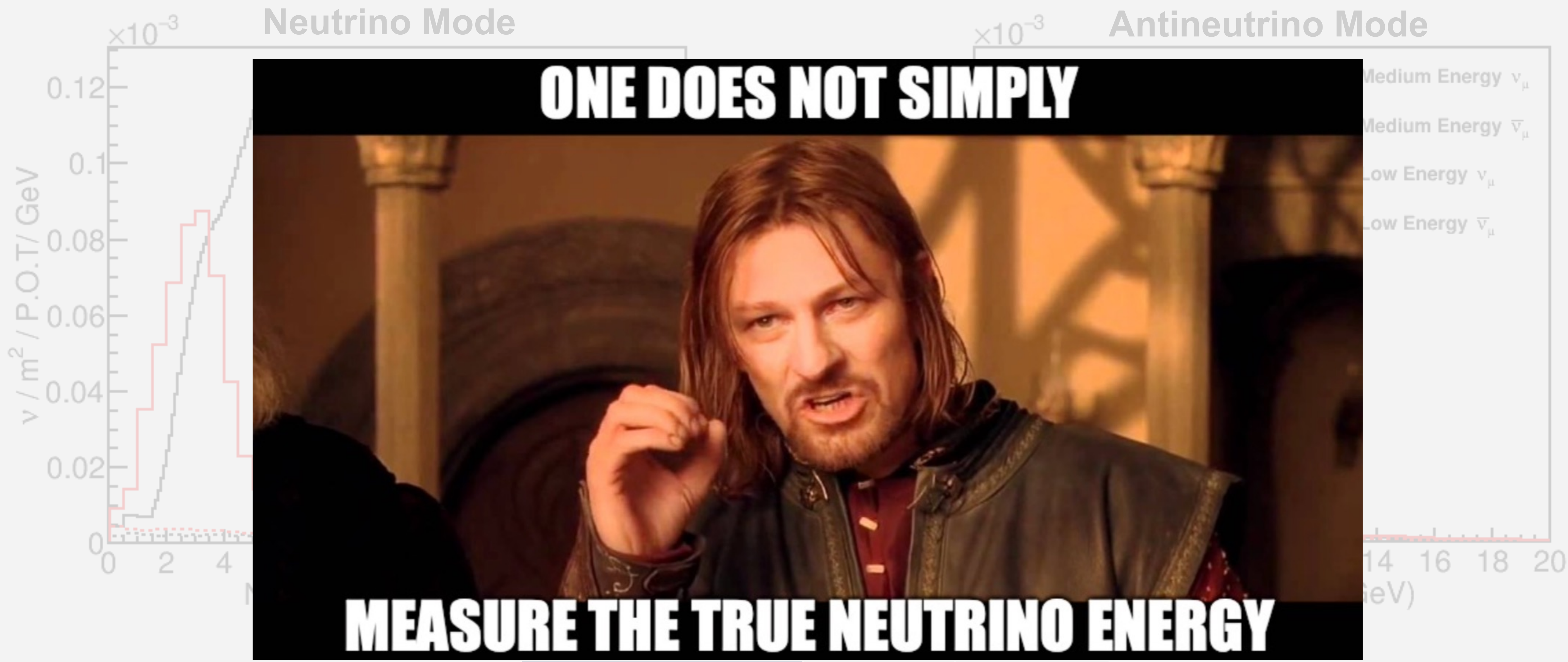
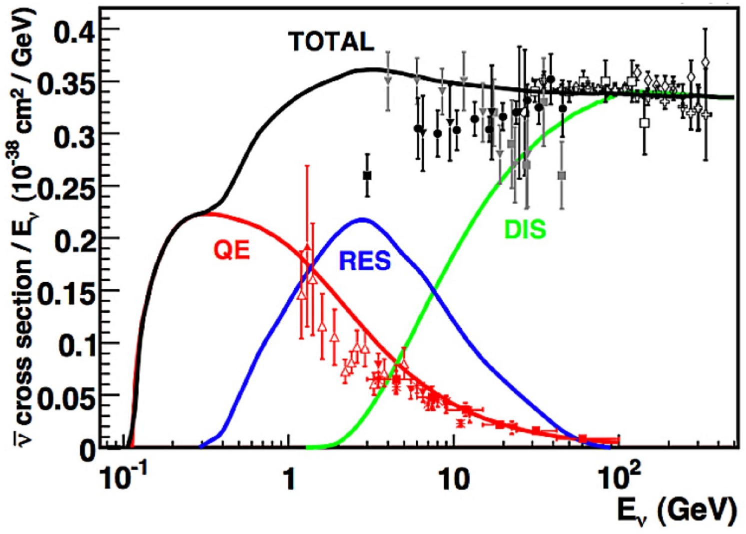


Low (LE) ~ 3.5 GeV	4×10^{20}	1.7×10^{20}
Medium (ME) ~ 6 GeV	12.1×10^{20}	12.4×10^{20}

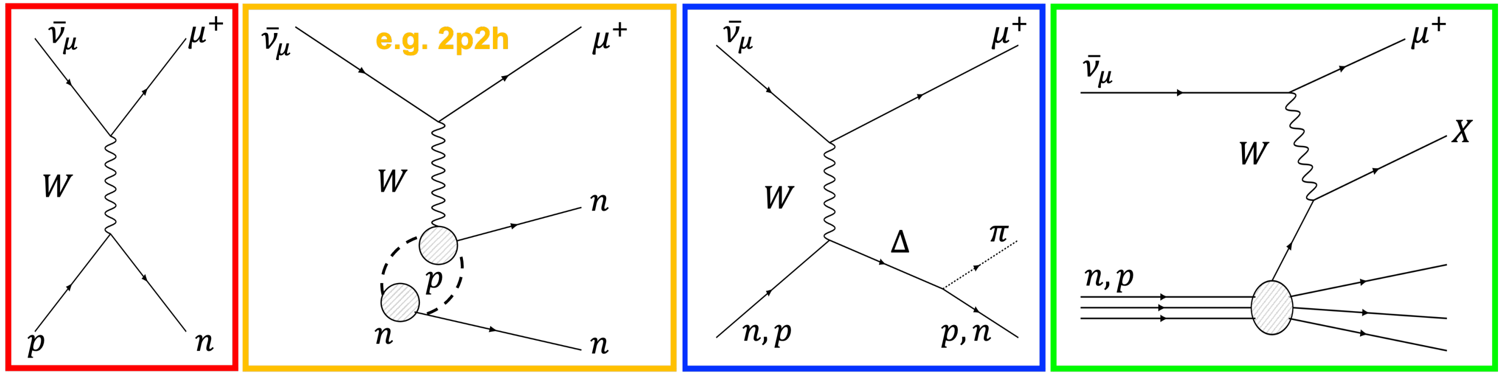
Main INjector ExpeRiment for ν-

Neutrino-Nucleus Interactions

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



- Oscillation experiments need **accurate measurements of true neutrino energy** (neutrino energy at initial neutrino nucleon interaction)
- **Different processes** contribute to the cross-section **at different neutrino energies**



QE

= quasi-elastic

Multi-nucleon effects

RES

= resonant pion production

DIS

= deep inelastic scattering

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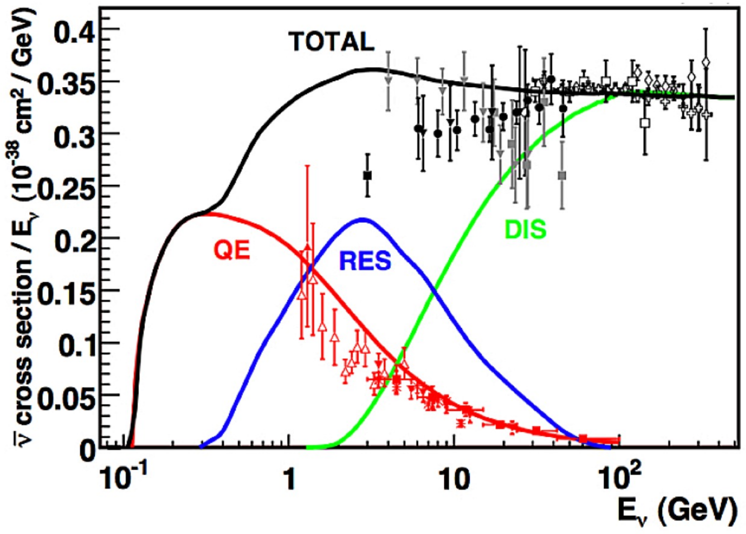
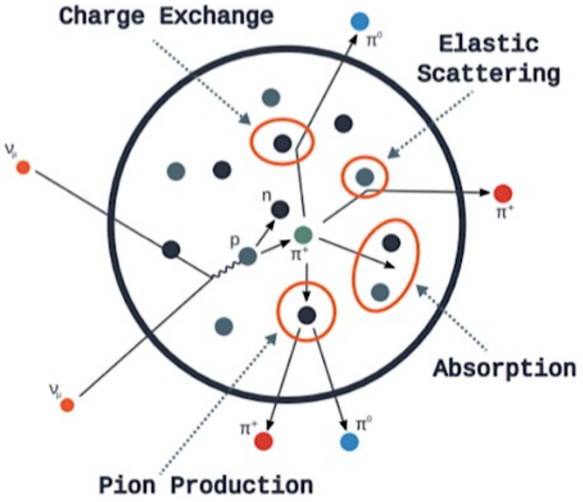
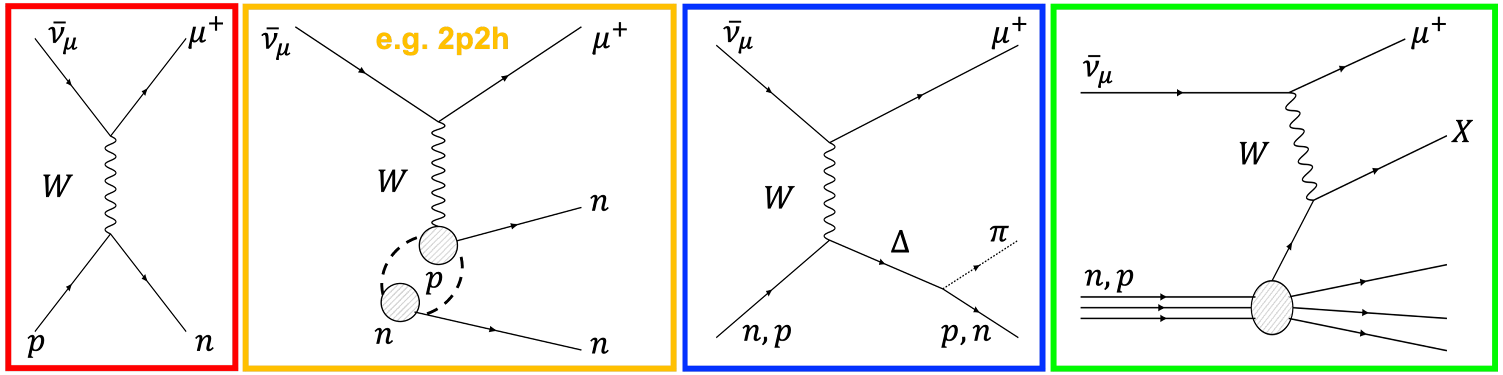


- Oscillation experiments need **accurate measurements of true neutrino energy** (neutrino energy at initial neutrino nucleon interaction)
- **Different processes** contribute to the cross-section **at different neutrino energies**
- **Nuclear effects** cause energy smearing and can modify final state particle kinematics

T. Golan, NuSTEC 2015





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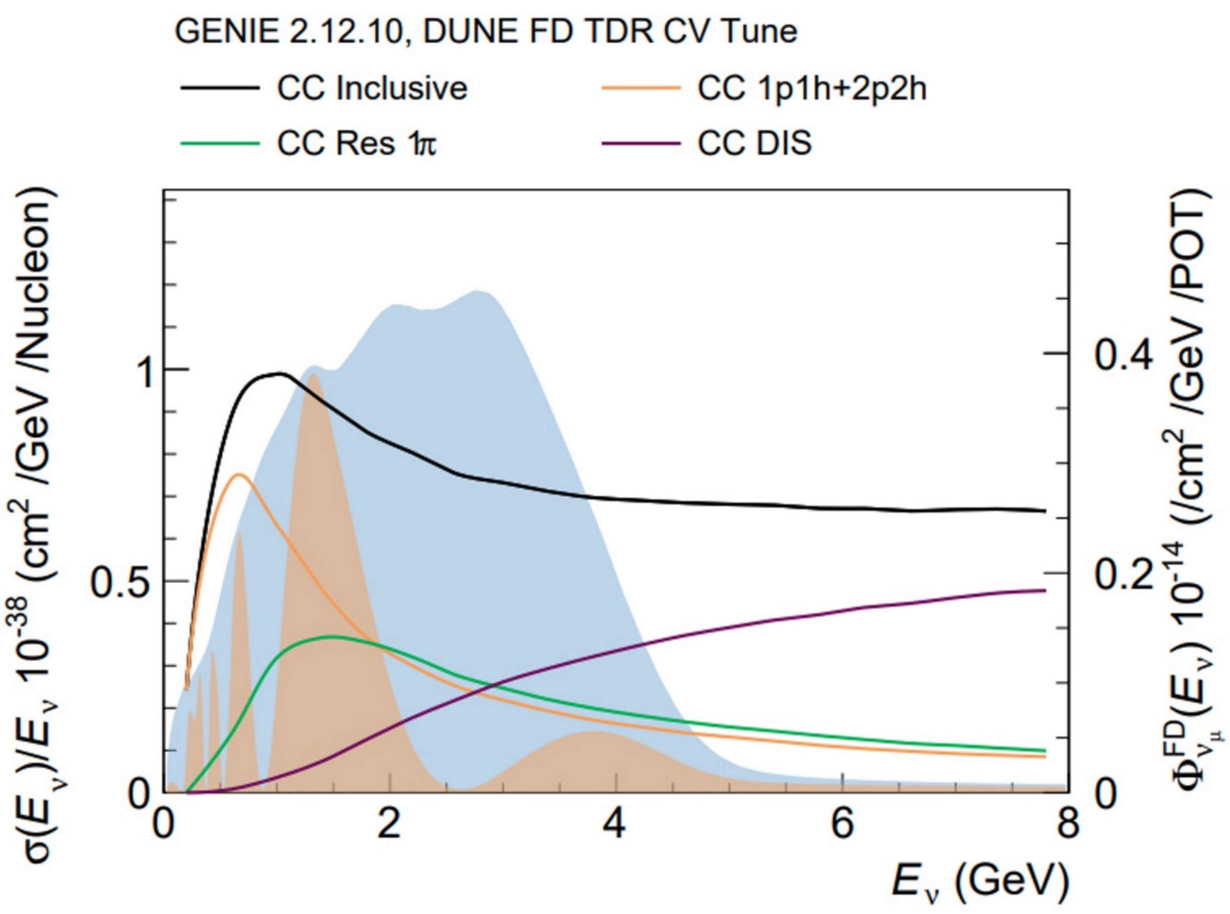
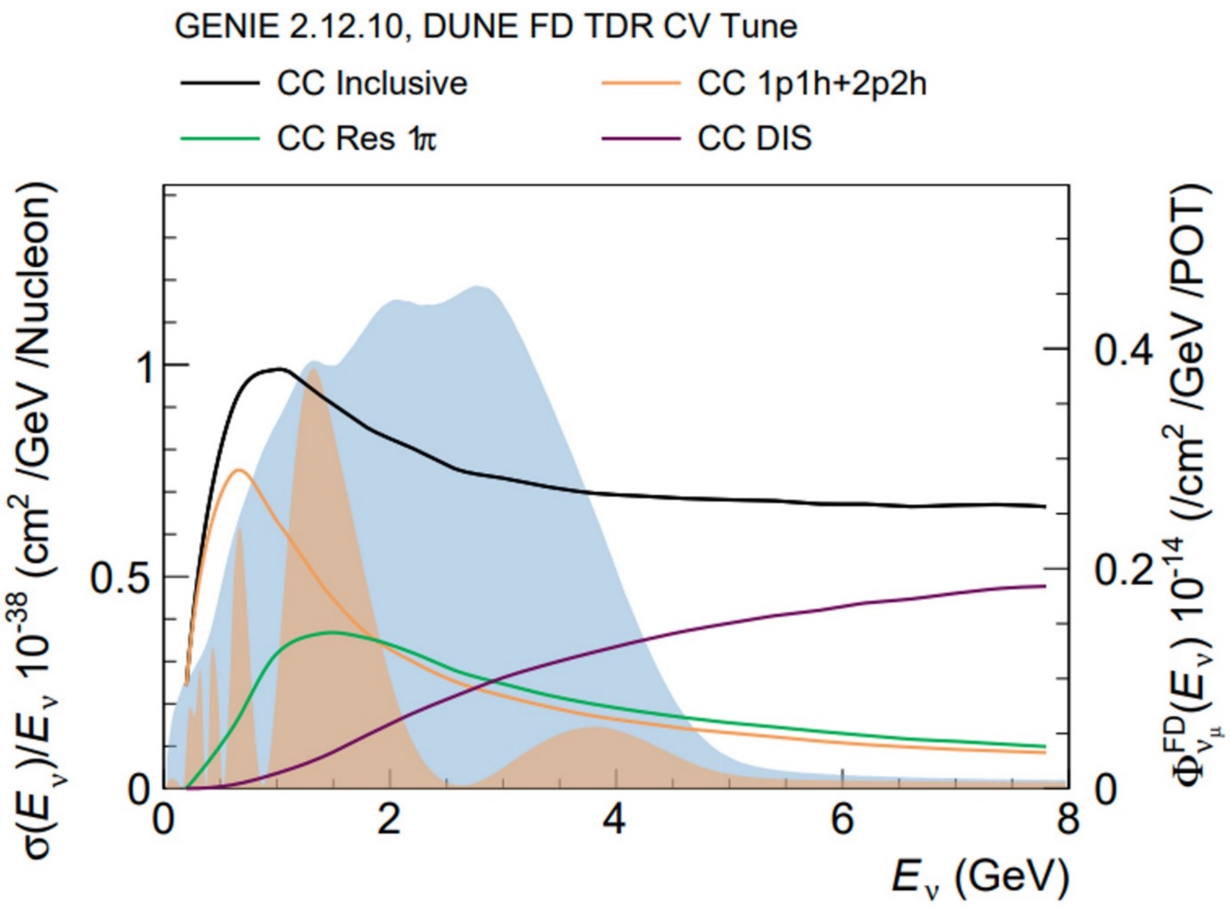
DUNE?

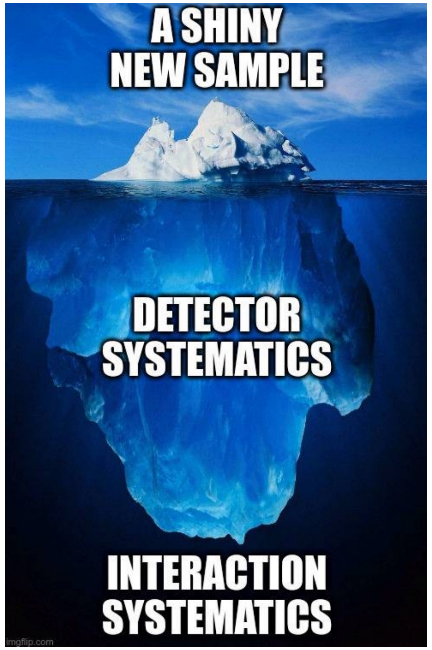


- **Massive statistics @ DUNE ND** ~100 million events/year on **argon**
- Complex region of phase space with **multiple interaction channels** and their **transition regions**: QE → RES → DIS

DUNE?



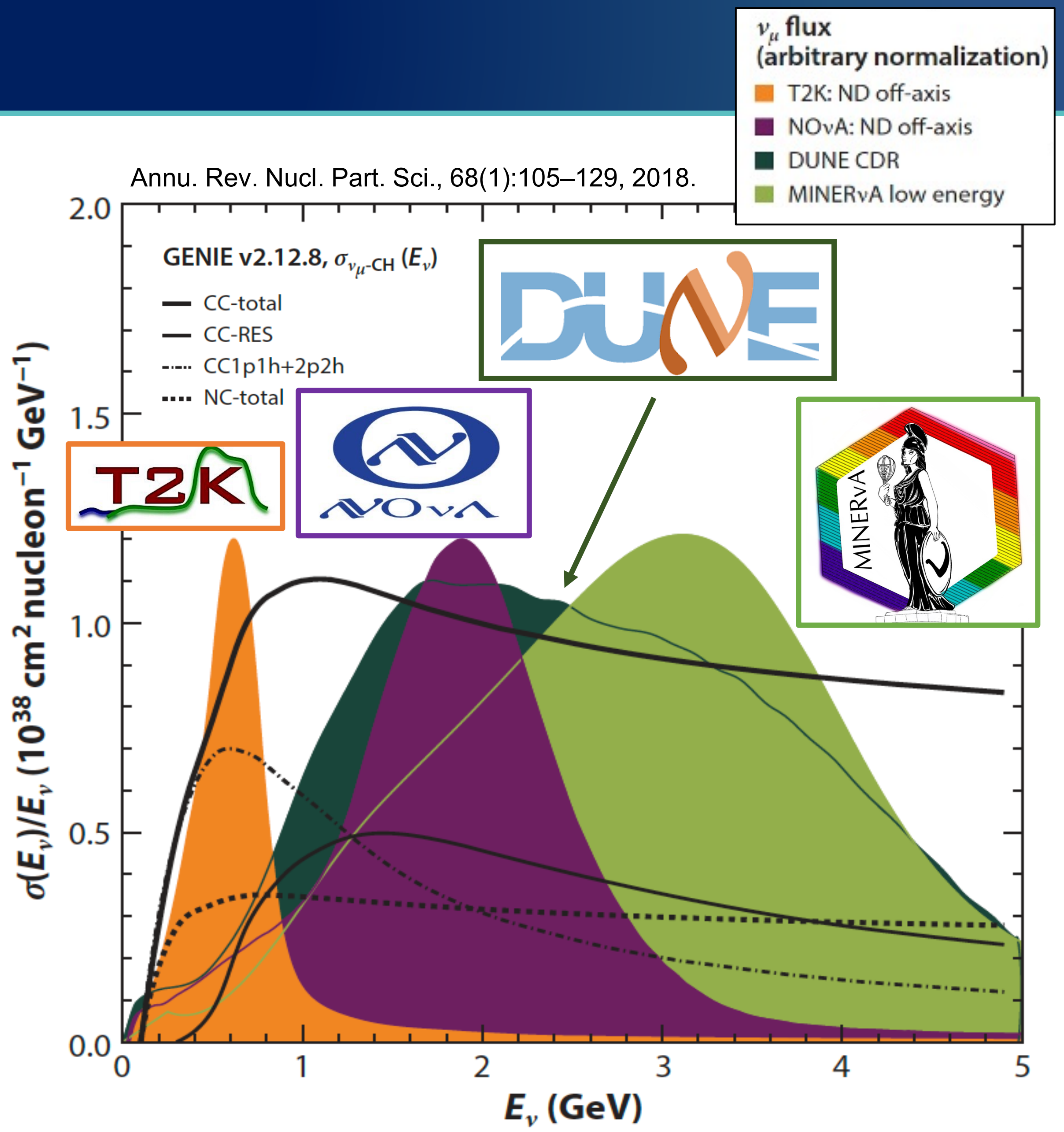
- **Massive statistics @ DUNE ND** ~100 million events/year on **argon**
- Complex region of phase space with **multiple interaction channels** and their **transition regions**: QE → RES → DIS
- Challenge for neutrino interaction models, **systematics limited!**



Enter MINERvA

- **DUNE** will have a large overlap with **MINERvA LE and ME datasets** (RES, DIS)

Annu. Rev. Nucl. Part. Sci., 68(1):105–129, 2018.



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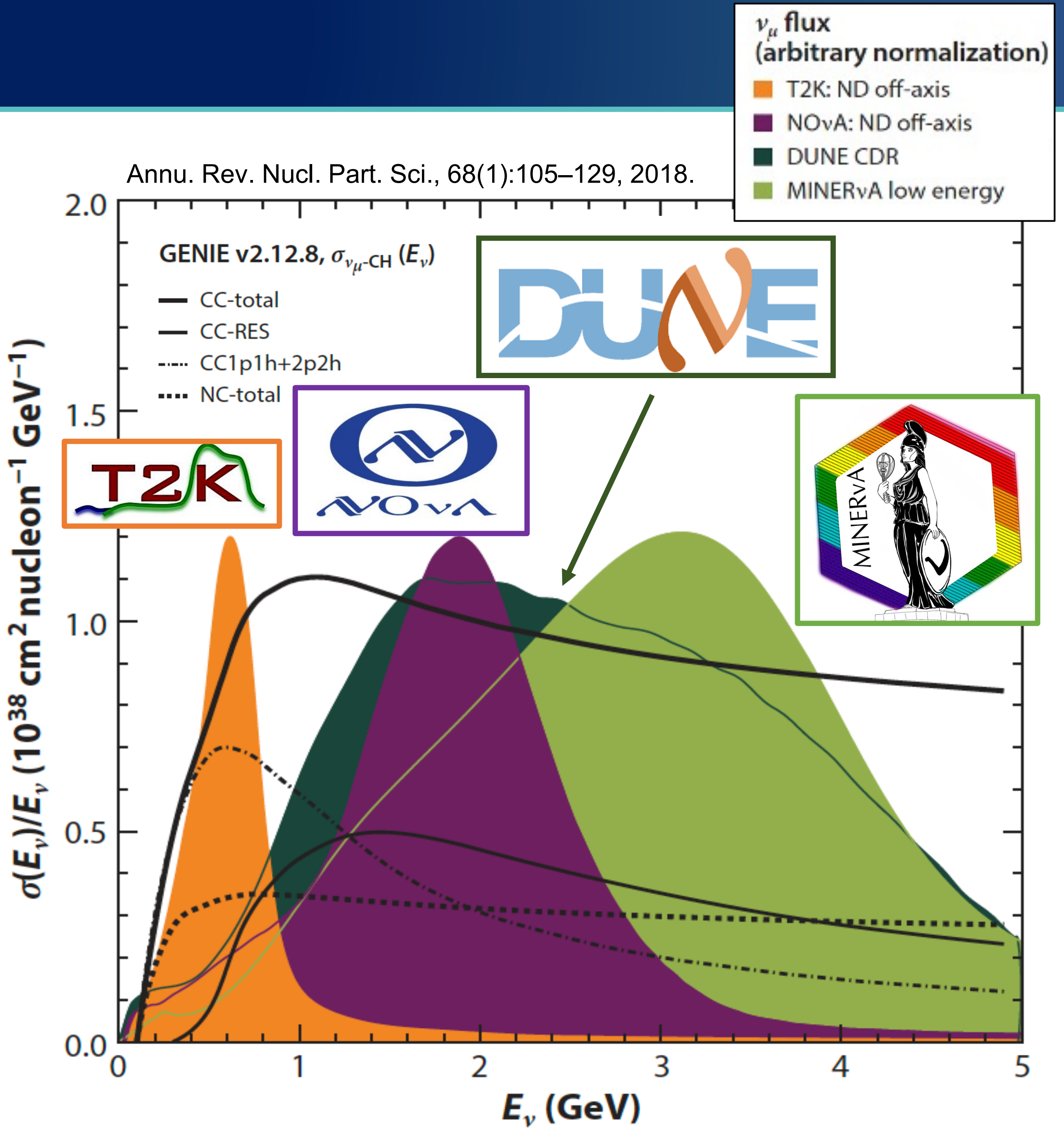

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- Measurements of interaction cross-sections at MINERvA can help to **refine neutrino interaction simulations for DUNE**

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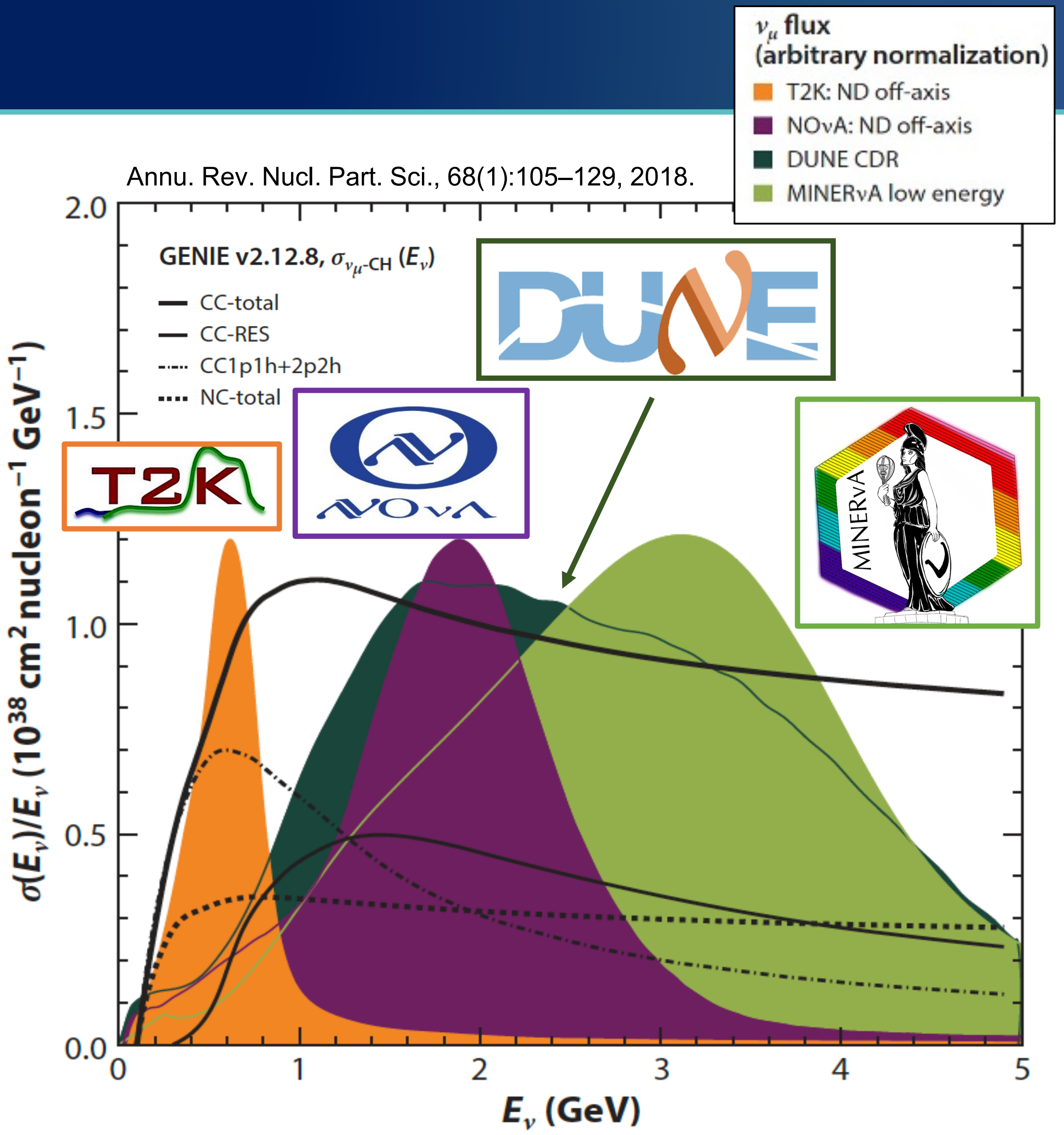
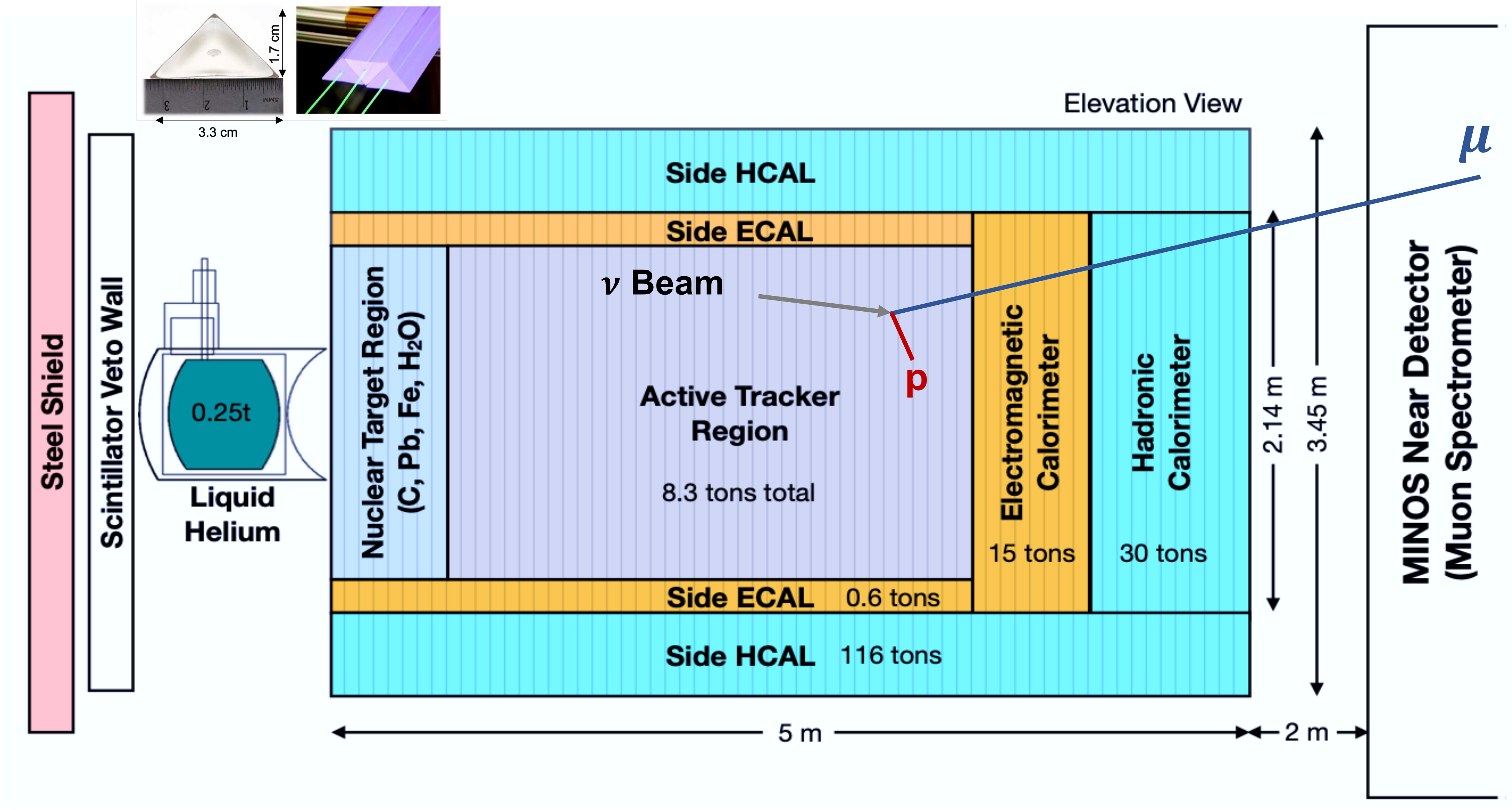
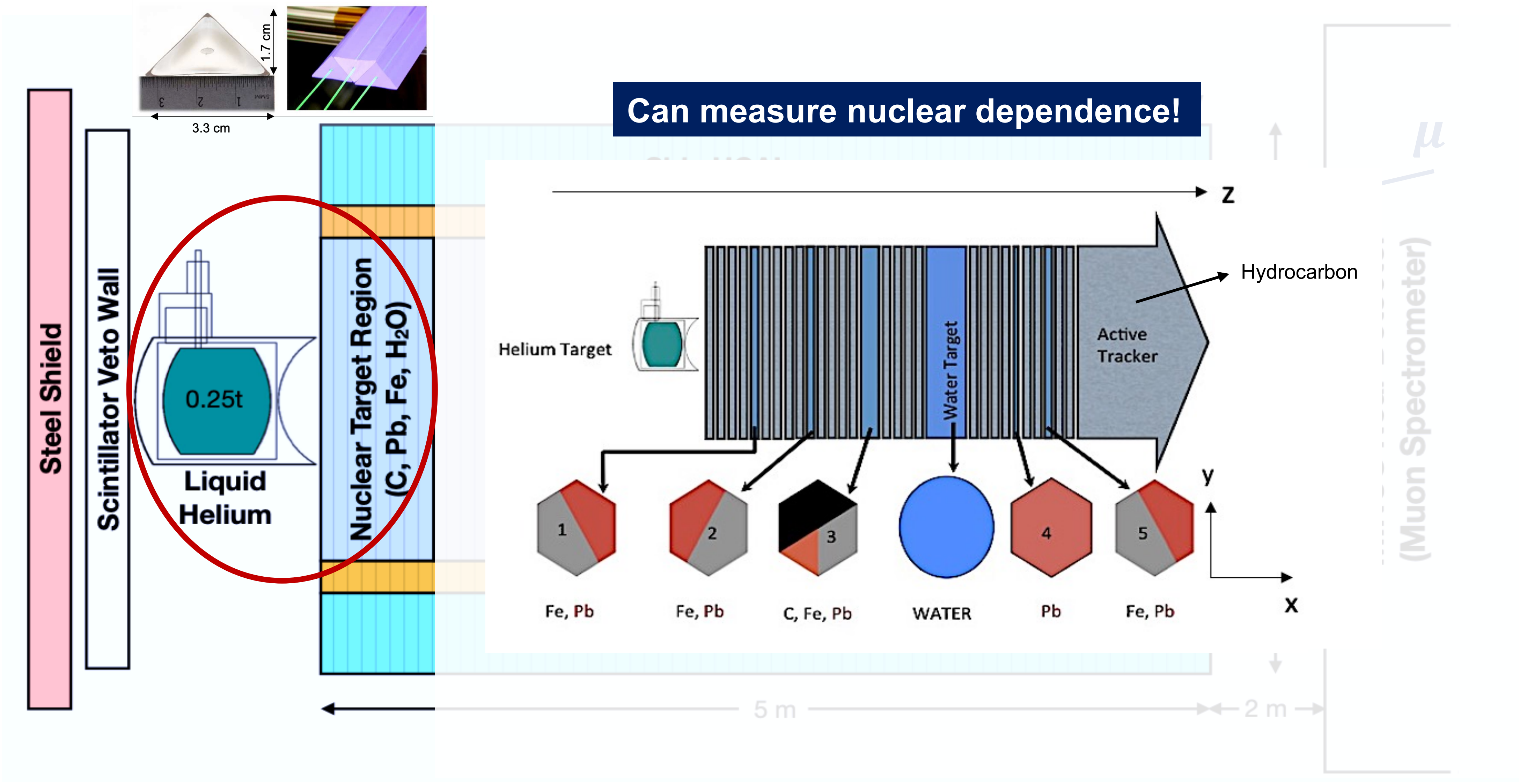


MINERvA Detector



Passive Target Region

Can measure nuclear dependence!



MINERvA's Latest Measurements Highlights

- Flux constraint using (anti)neutrino-electron scattering and inverse muon decay
- **A-dependence**
  - Neutrino CCQE-like
  - Neutrino CC1π^+
- Antineutrino CCQE on hydrogen

Cross-Section Measurement on a Particular Nucleus

Differential cross-section in bin α for a given nucleus

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

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

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

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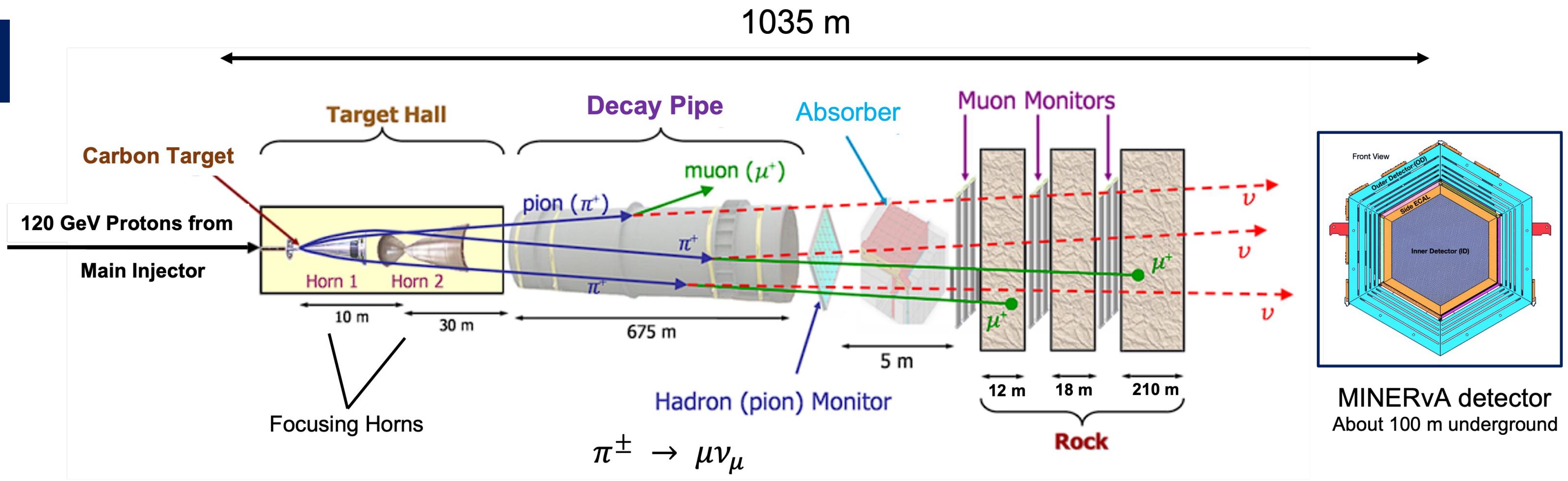
Improving Flux Constraint

NuMI beam



$$\pi^{\pm} \rightarrow \mu\nu_{\mu}$$

$$K^{\pm} \rightarrow \mu\nu_{\mu}$$

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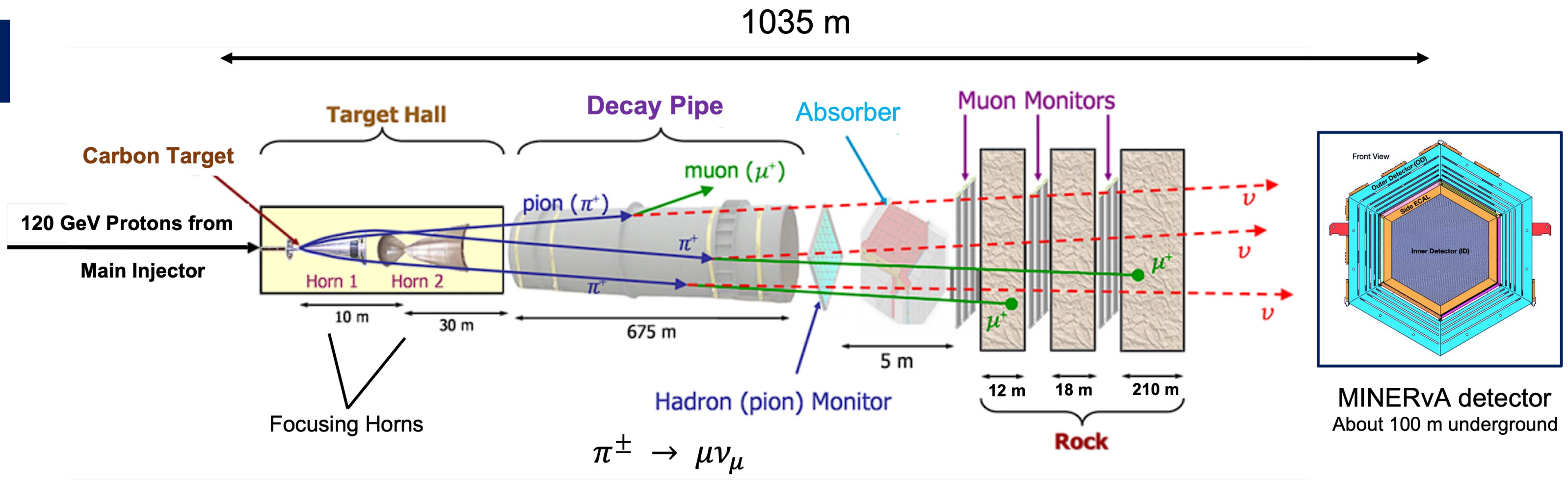

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- Flux is not known precisely → in-situ constraints

(Anti)Neutrino-Electron Elastic Scattering

$$\nu_{\mu} + e \rightarrow \nu_{\mu} + e$$

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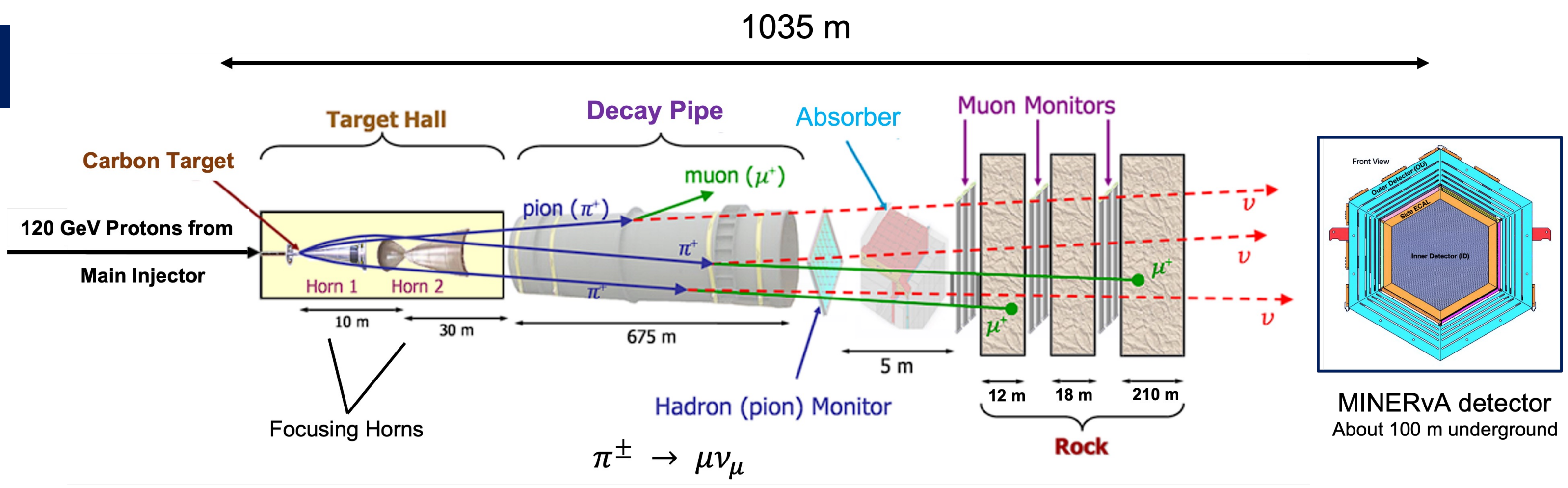

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Cross-section precisely predicted by electroweak theory

Normalization constraint (integrated flux)

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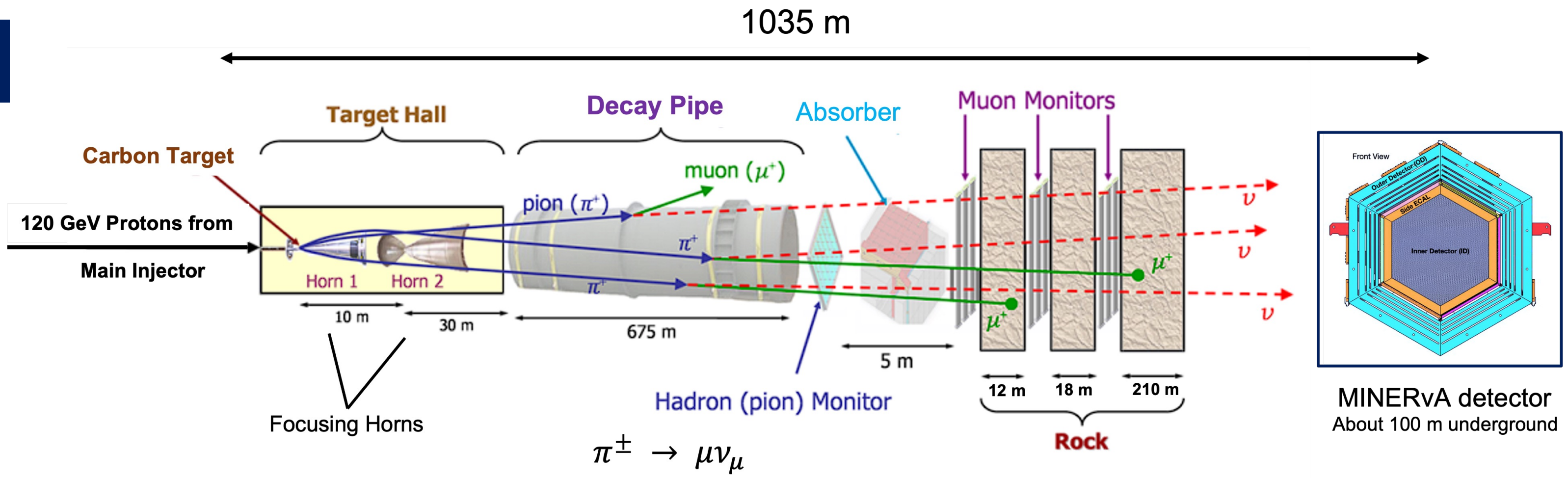

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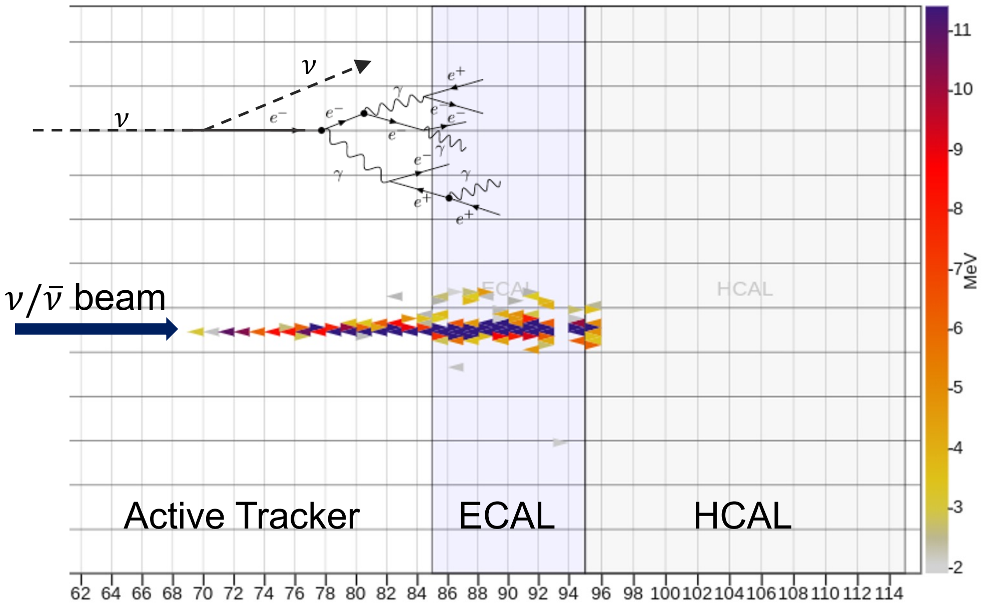

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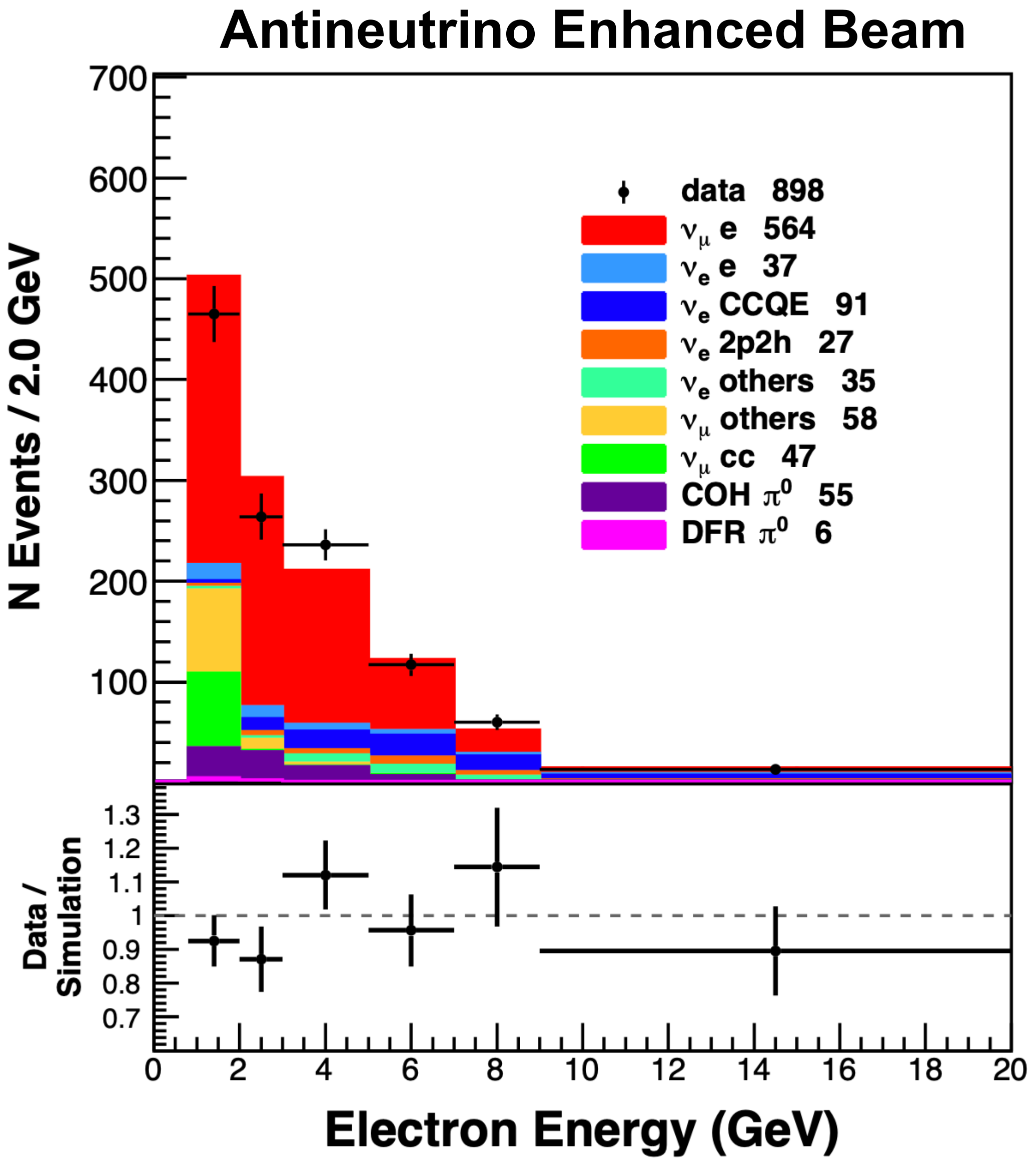

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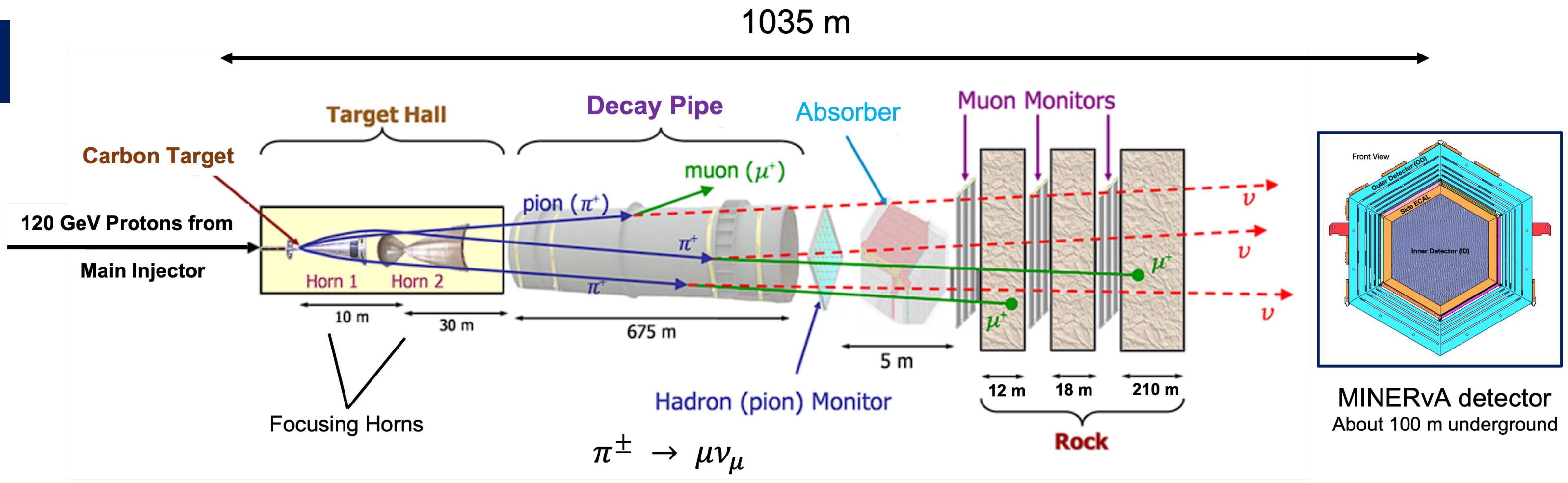

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Standard candle for flux
Cross-section precisely predicted by electroweak theory
Normalization constraint (integrated flux)

Inverse Muon Decay

$$\nu_\mu + e \rightarrow \nu_e + \mu^-$$

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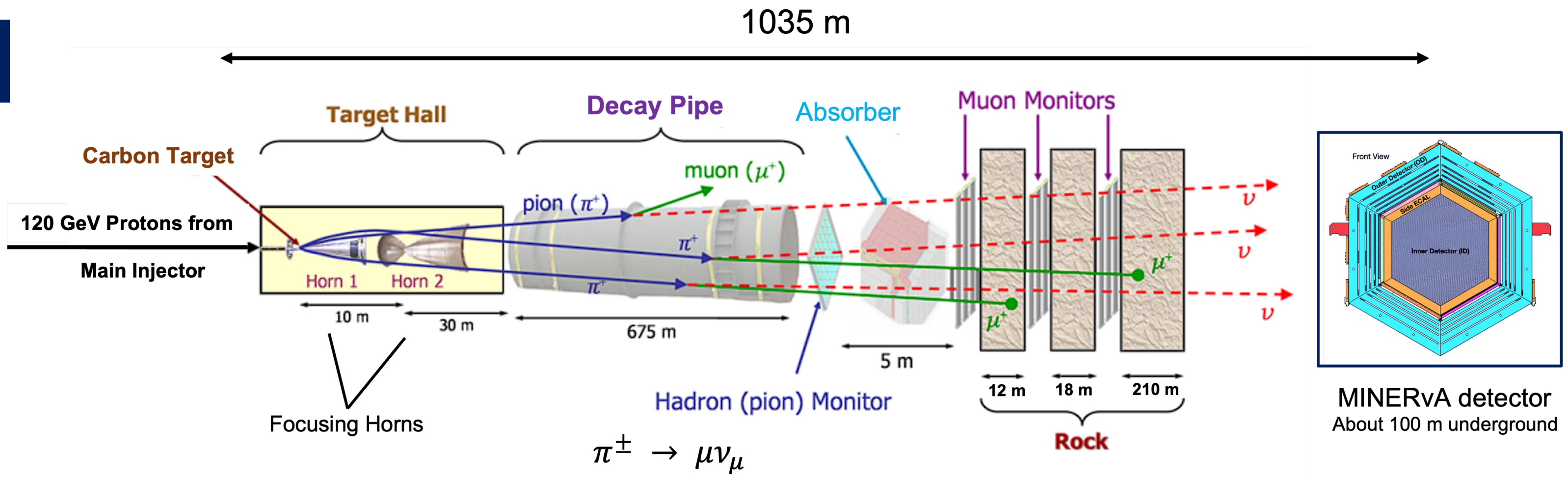

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$$\nu_{\mu} + e \rightarrow \nu_{e} + \mu^{-}$$

Threshold of ≈ 11 GeV with very forward going muon
Can constrain the high-energy part of the flux

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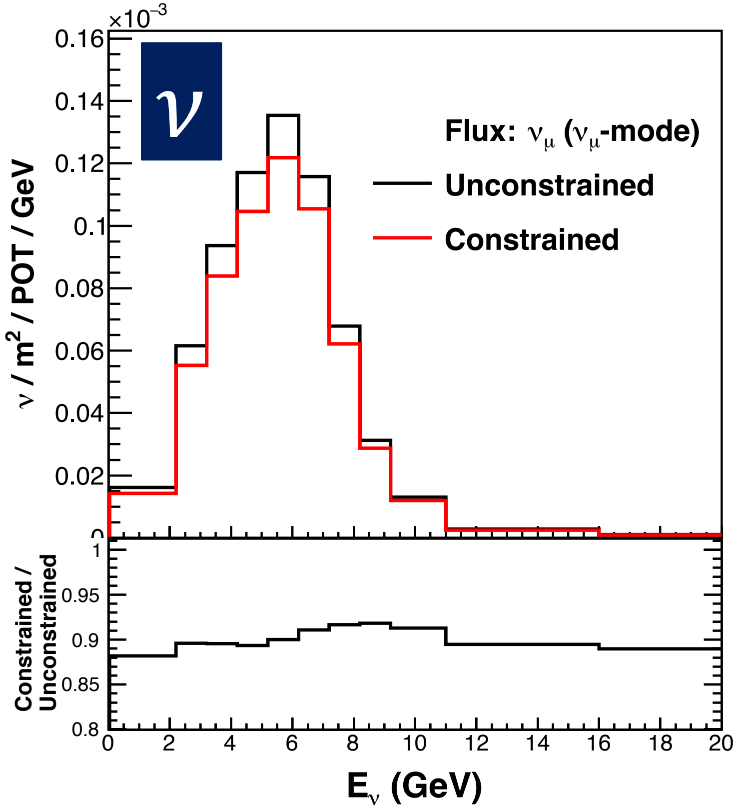
	$\bar{\nu}_\mu$-mode				ν_μ-mode			
	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
a priori	7.76	7.81	11.1	11.9	7.62	7.52	12.2	11.7
ν_μ-mode νe^-	6.11	5.81	6.30	8.50	3.90	3.94	8.37	8.68
$\bar{\nu}_\mu$-mode νe^-	4.92	4.98	8.07	9.19	5.88	5.68	8.36	8.64
combined νe^-	4.68	4.62	5.56	7.80	3.56	3.58	7.15	7.84
combined νe^- + 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%**



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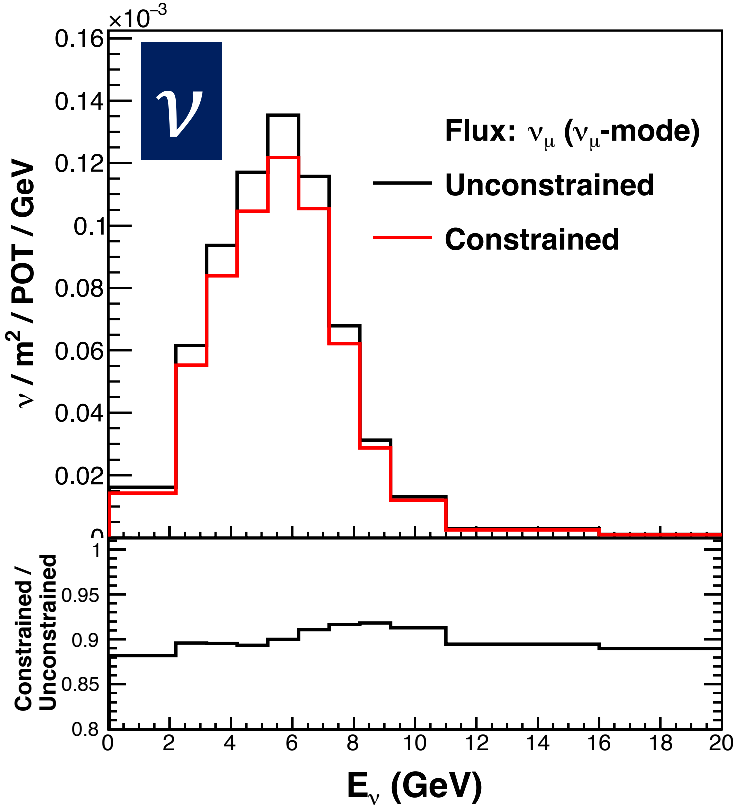
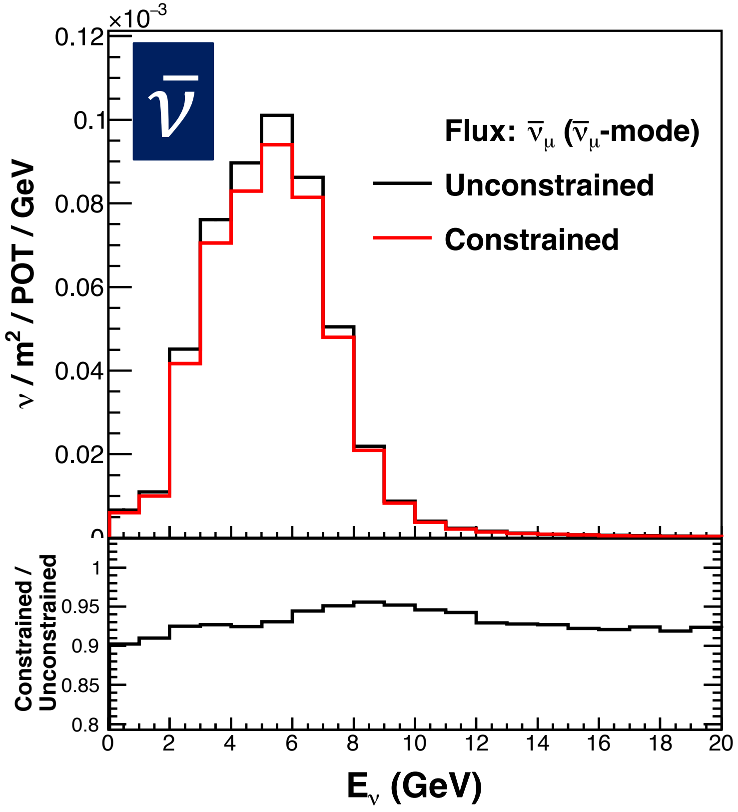
(Energy range integrated flux uncertainty)

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





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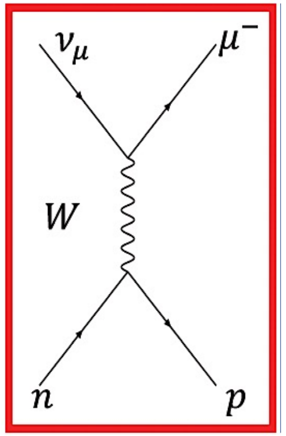
Nuclear Dependence with ν_μCC 0π

J. Kleykamp et al. Phys. Rev. Lett. **130**, 161801, 2023.



CCQE

What the detector sees vs what happens (2p2h/RES... + FSI)

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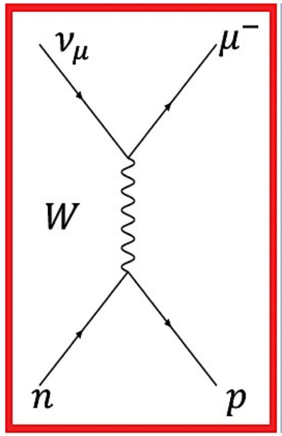

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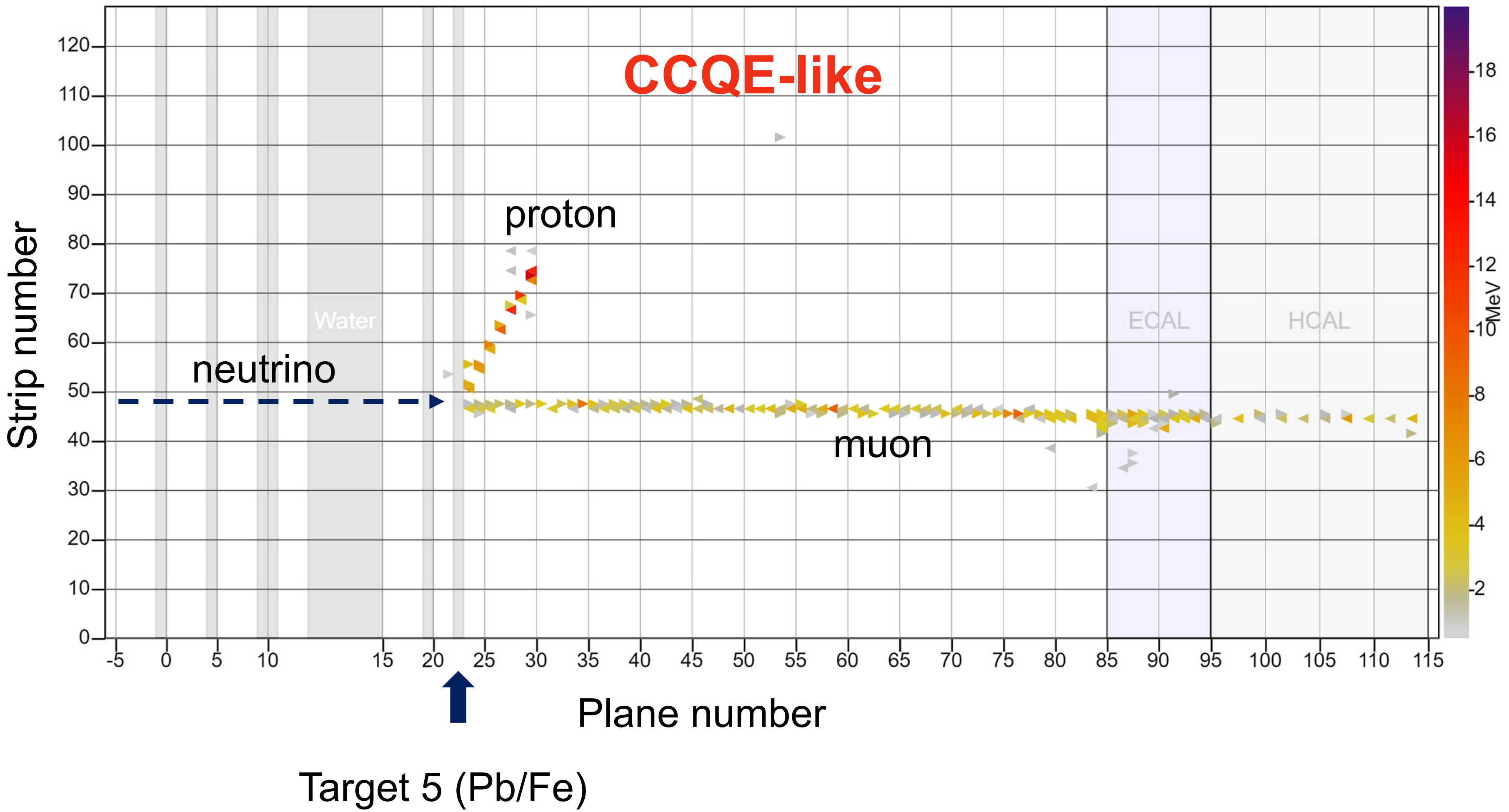

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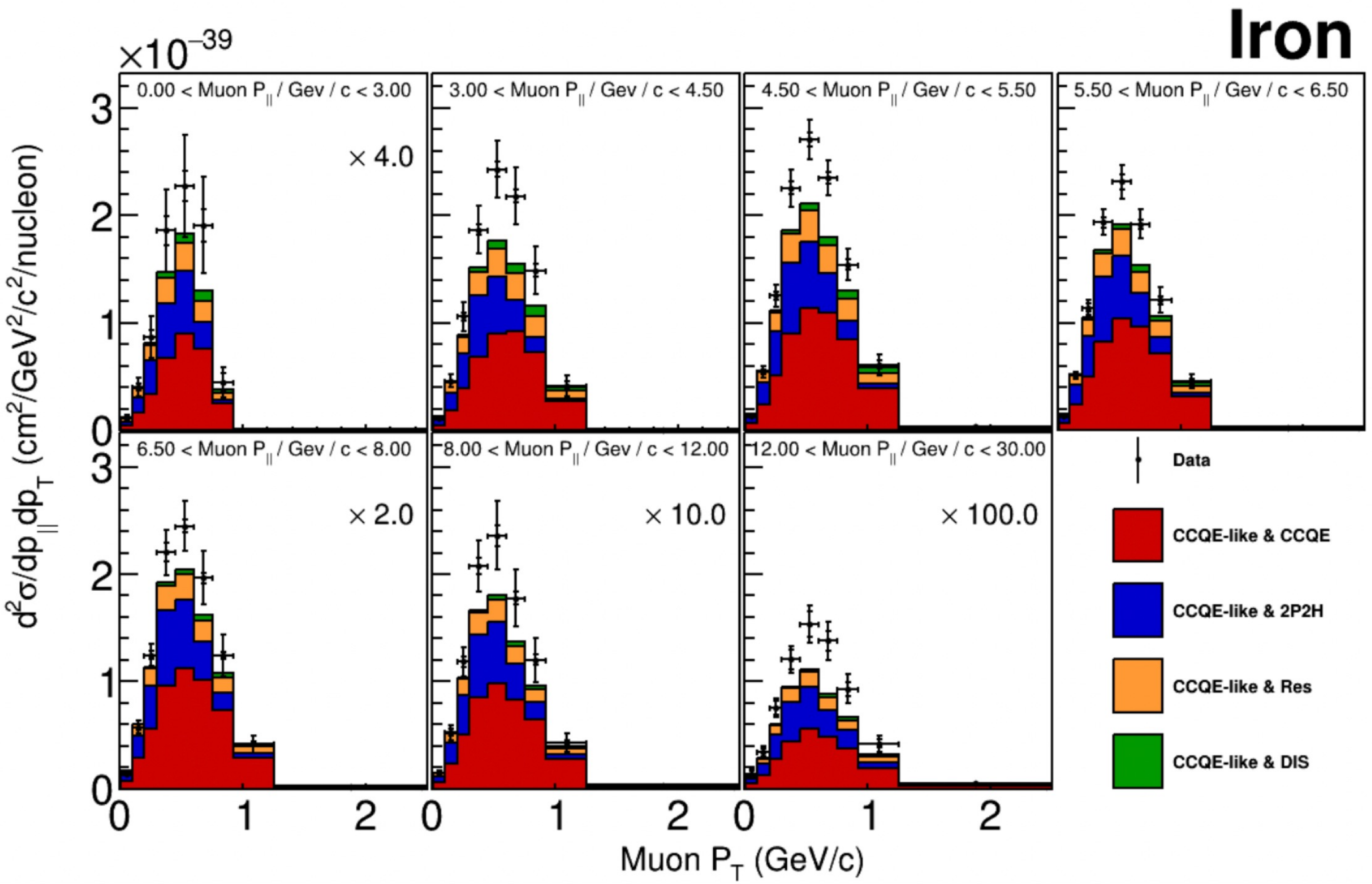

2D cross-section vs muon transverse momentum and longitudinal momentum

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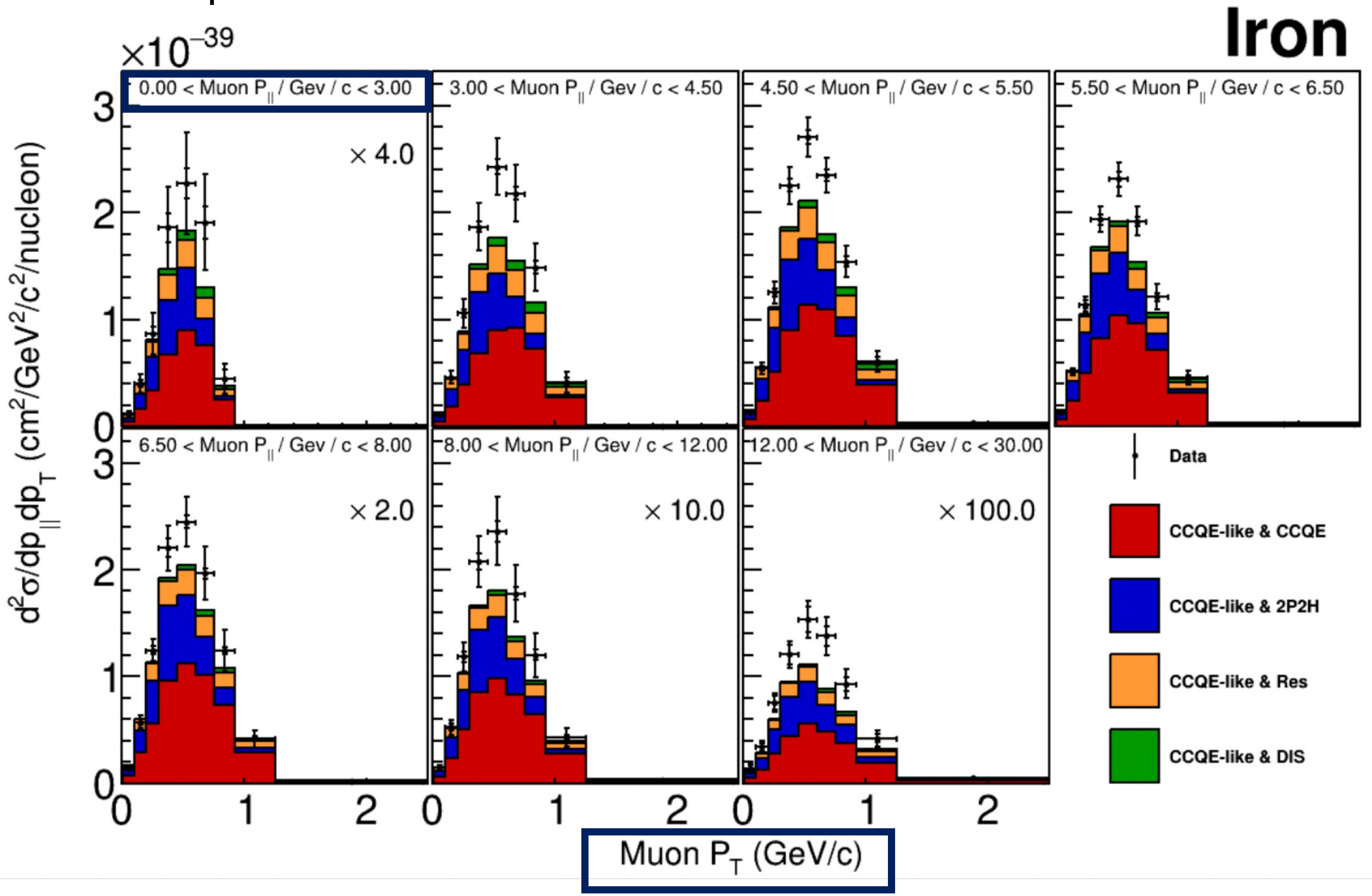
MINERvA tune to GENIE underpredicts the data on iron



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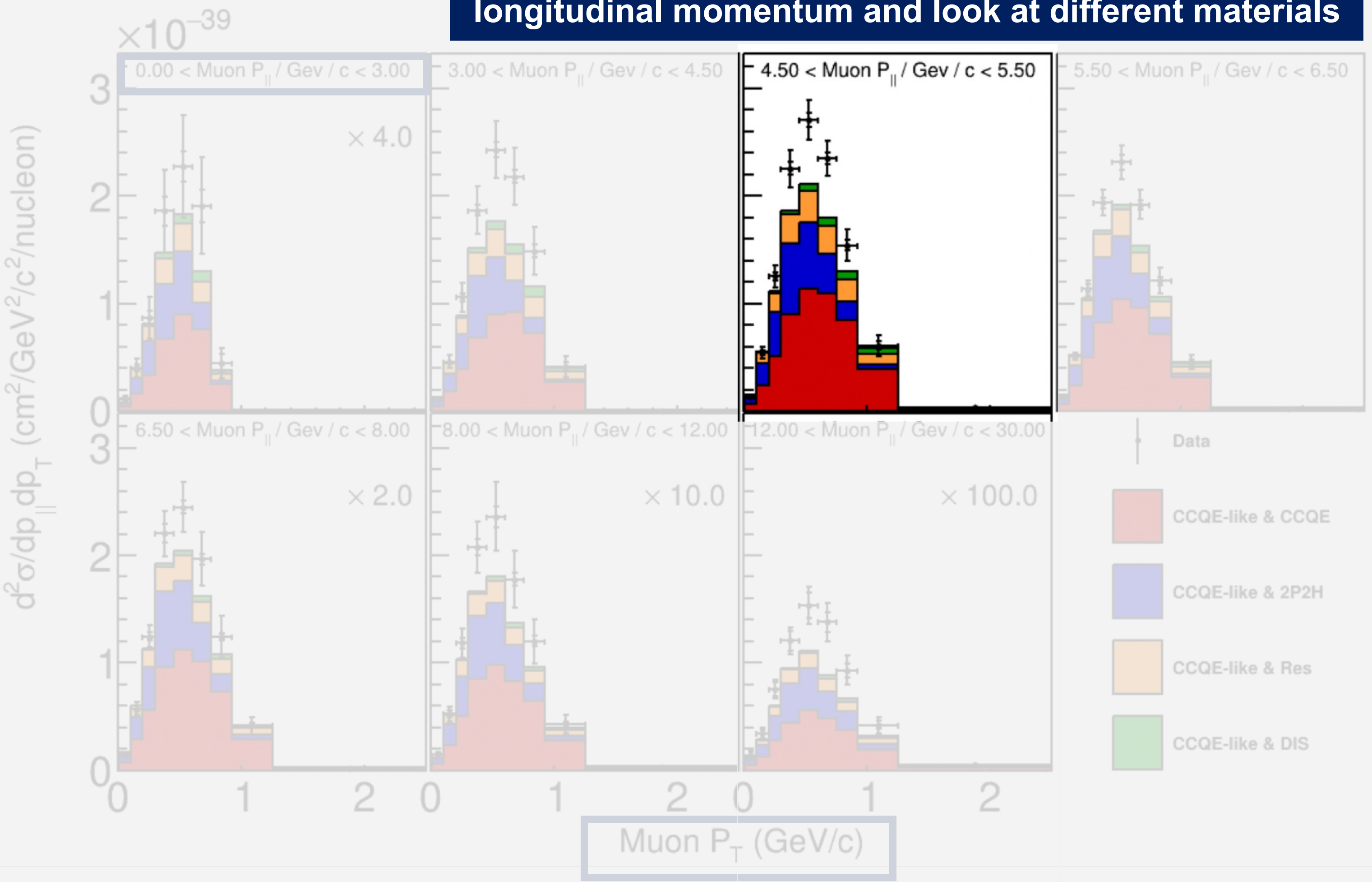
Zoom-in to the highest-statistics bin of muon longitudinal momentum and look at different materials



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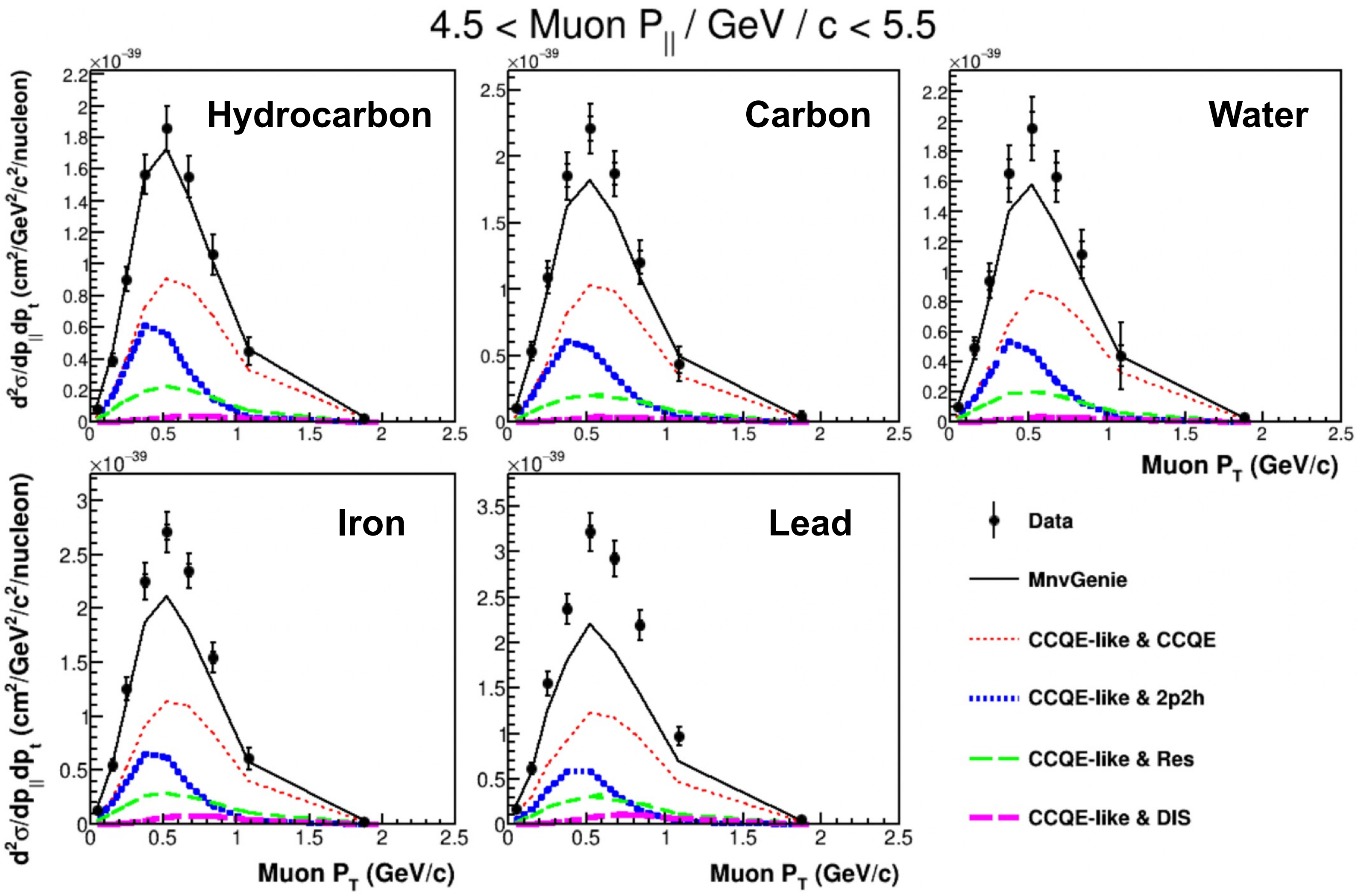

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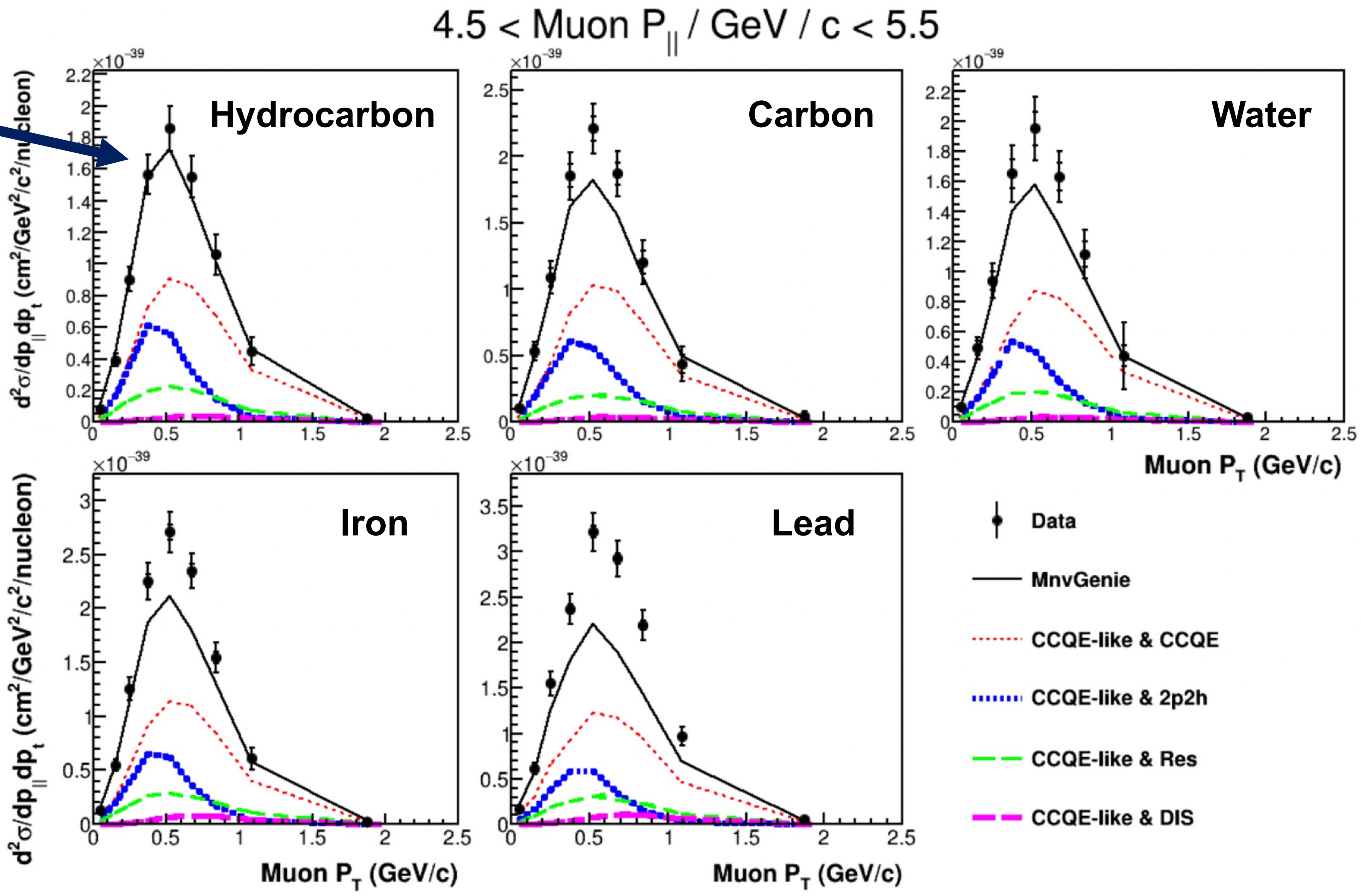
Model agrees with the data fairly well (tuned to scintillator)



Nuclear Dependence with ν_μCC 0π

J. Kleykamp et al. Phys. Rev. Lett. **130**, 161801, 2023.

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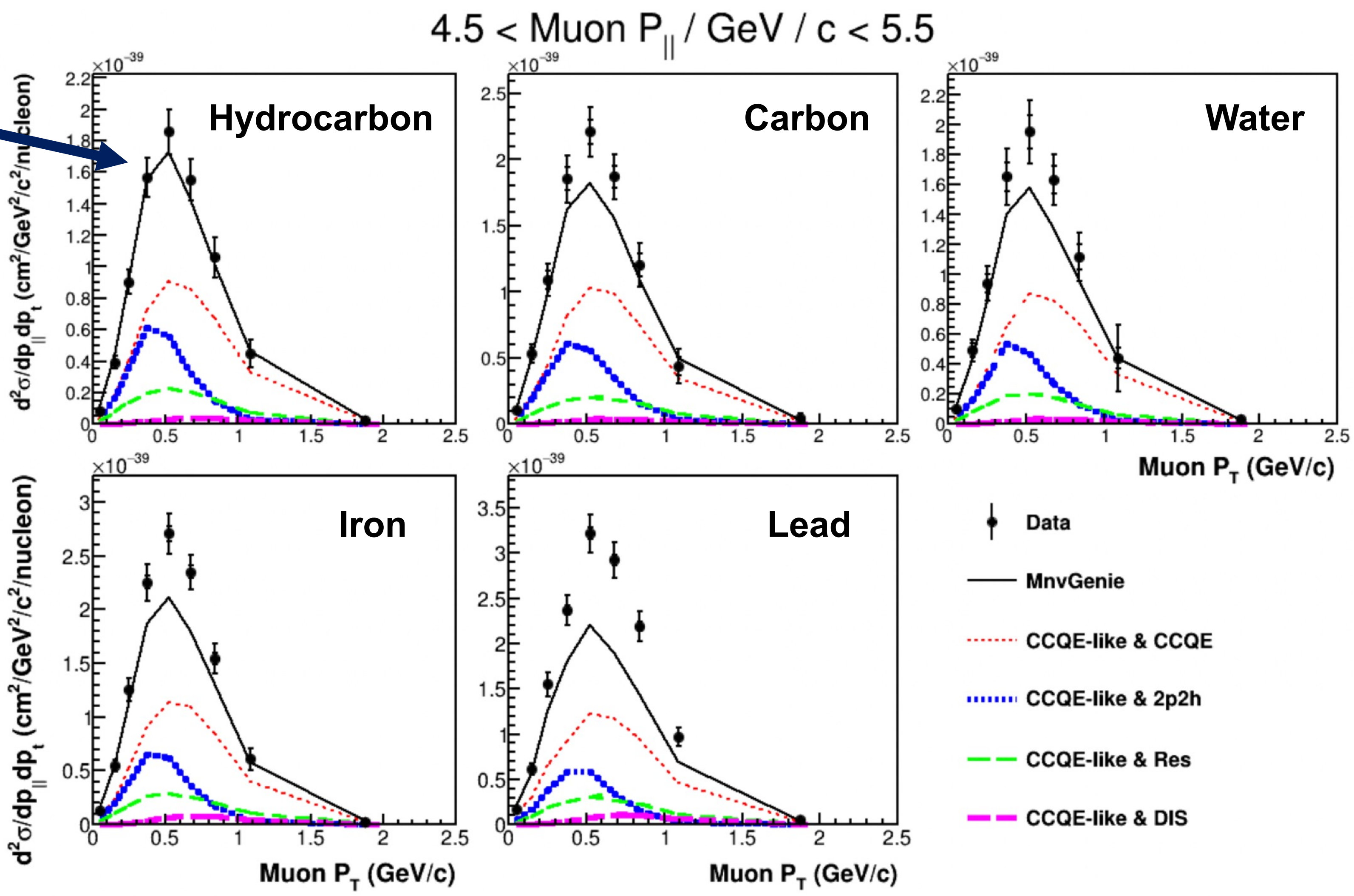

Underprediction increases with A

Nuclear Dependence with ν_μCC 0π

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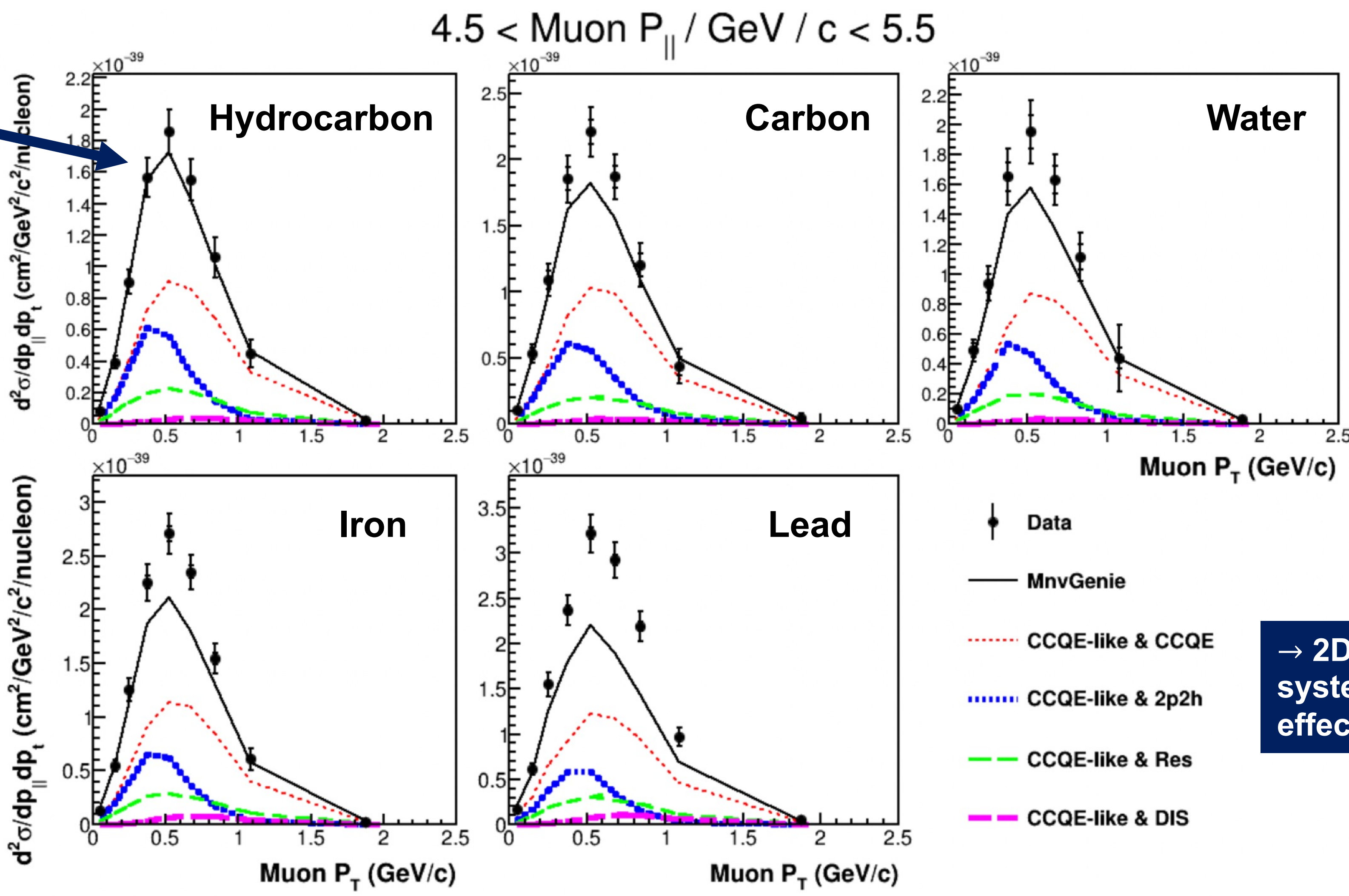

→ **2D ratios to cancel systematics (flux, detector effects)**

Underprediction increases with A

MINERvA's Latest Measurements Highlights

- ME flux constraint using (anti)neutrino-electron scattering and inverse muon decay
- **A-dependence**
  - Neutrino CCQE-like
  - **Neutrino CC1π^+**
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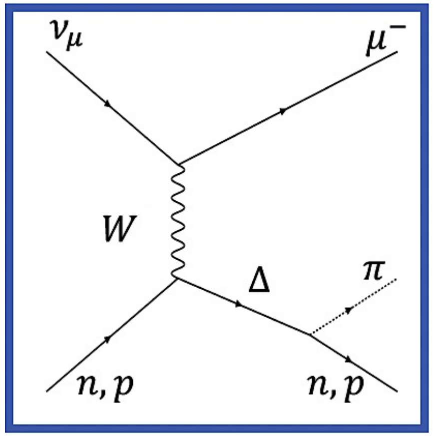
Nuclear Dependence with ν_μCC 1π

A. Bercellie et al. arXiv:2209.07852 [hep-ex].

How do we identify a charged pion in MINERvA?



RES

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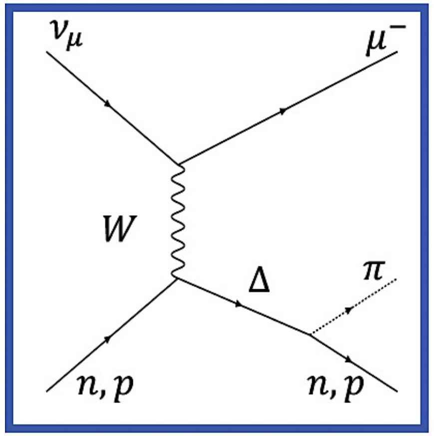
1. dE/dx



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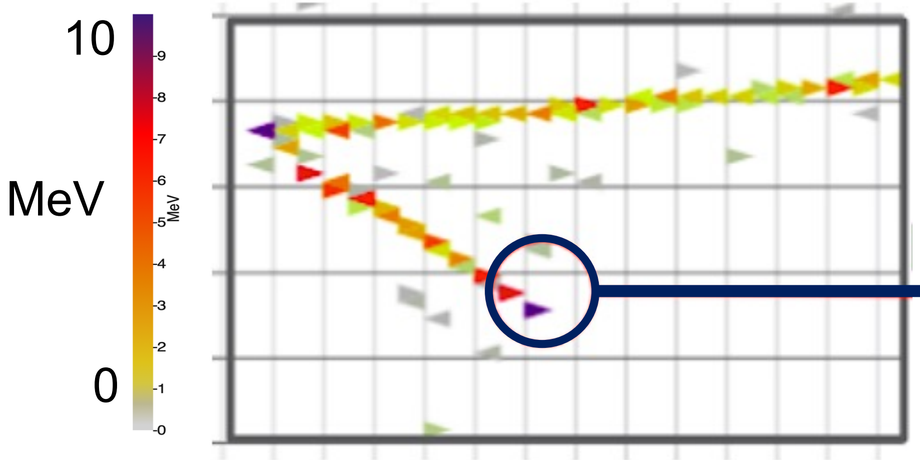

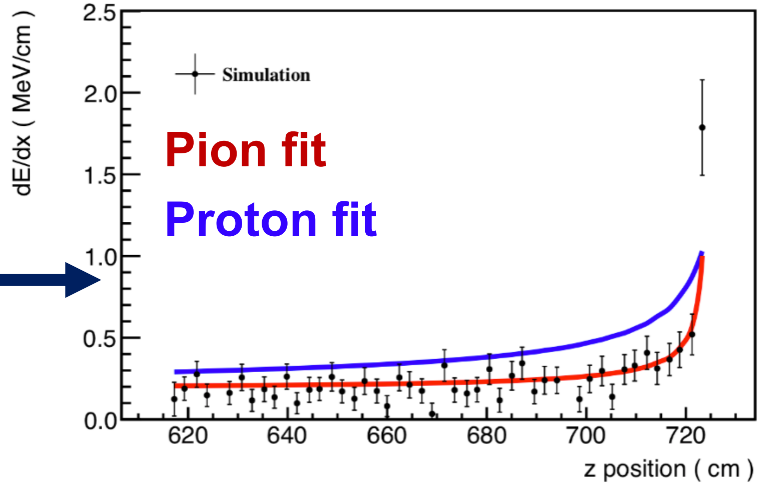

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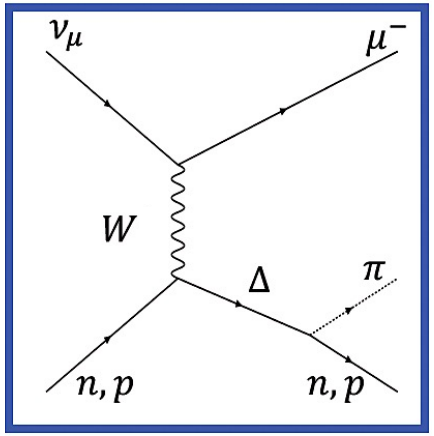

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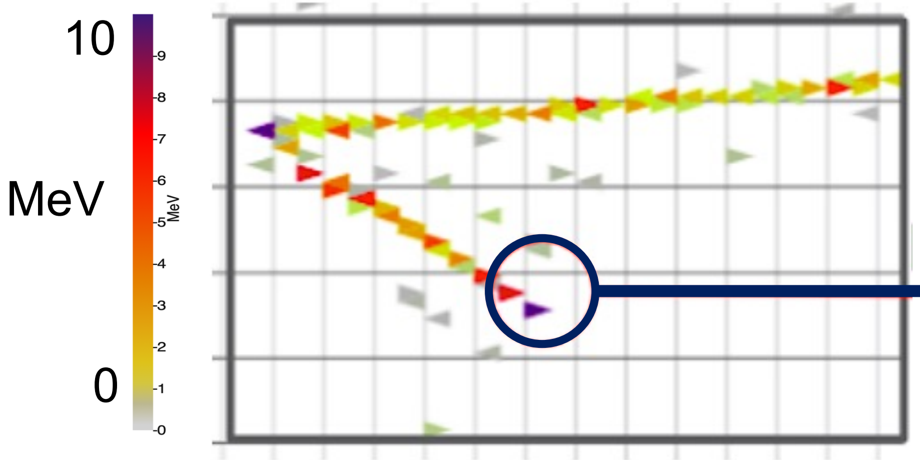
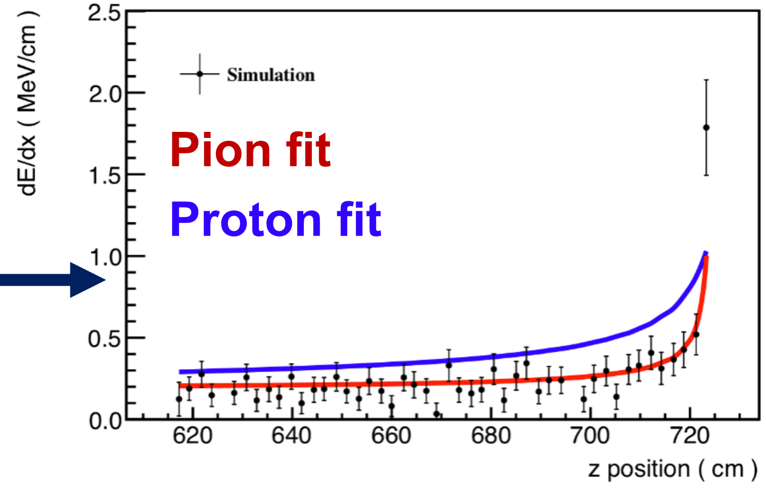
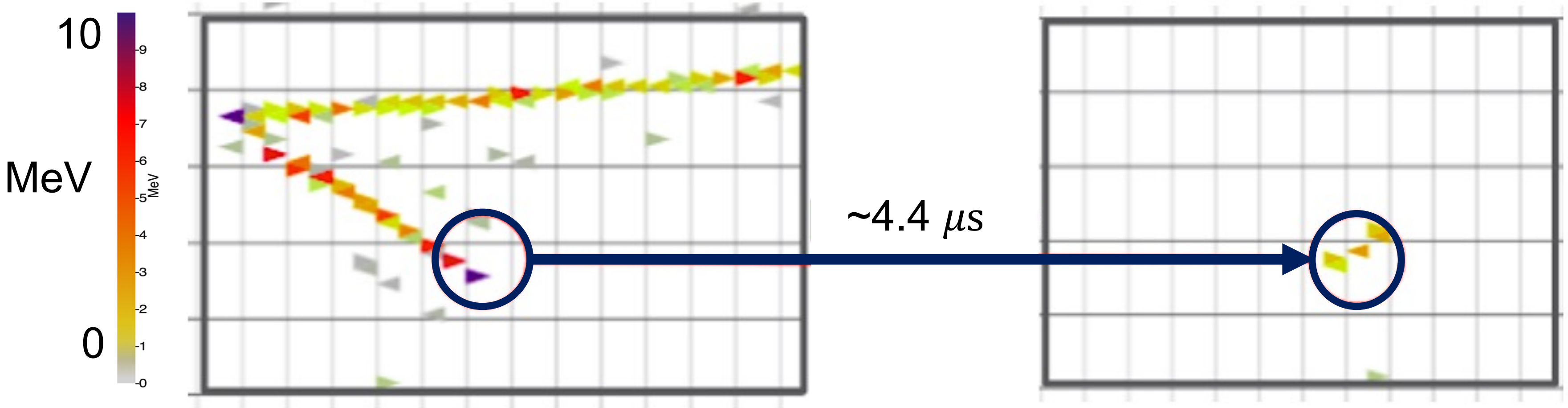




2. Michel electron tag
$\pi^+ \rightarrow \mu^+ \rightarrow e^-$



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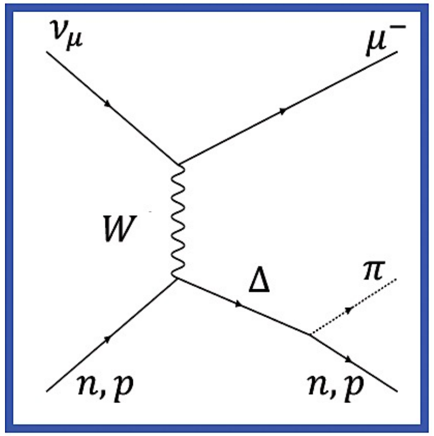

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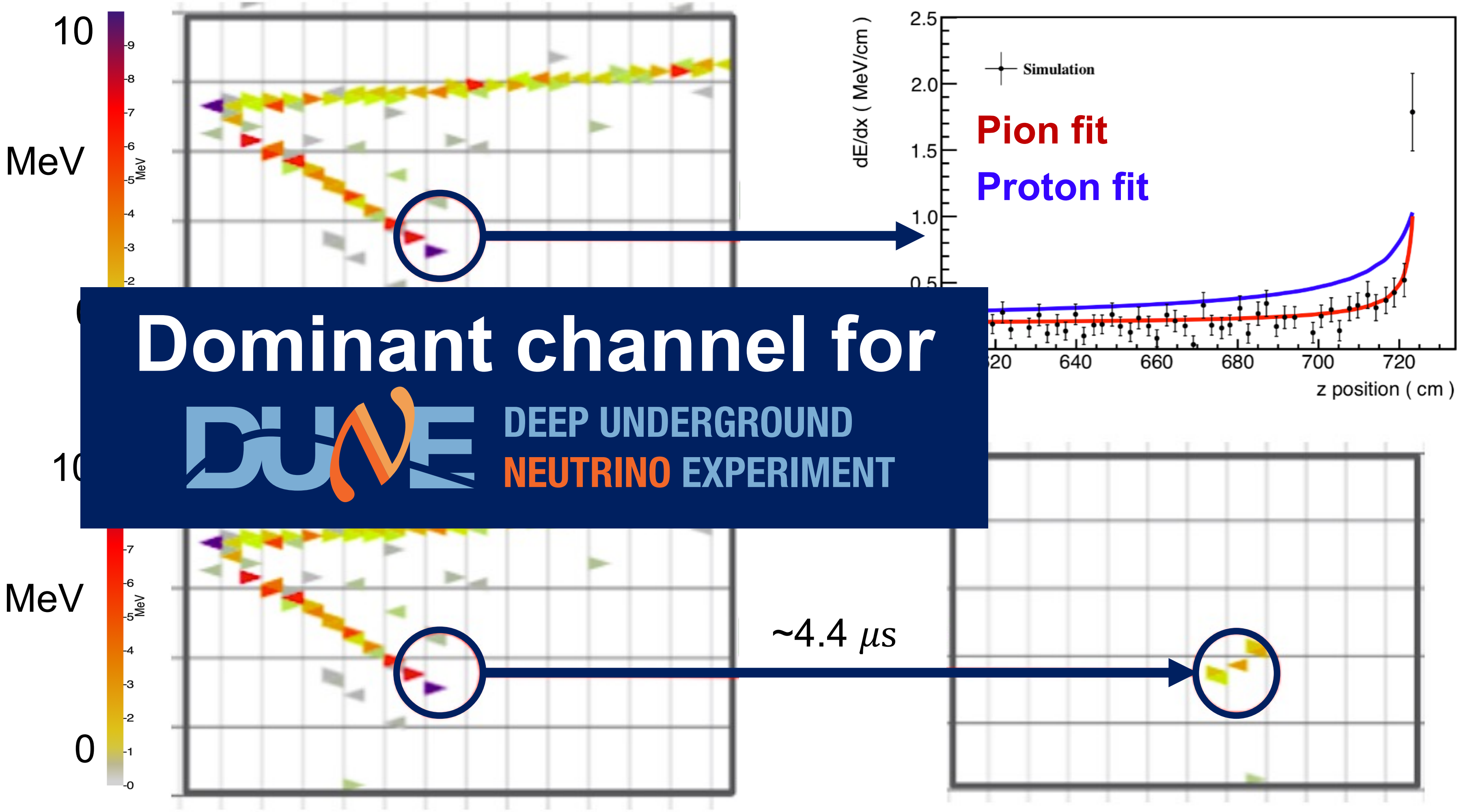
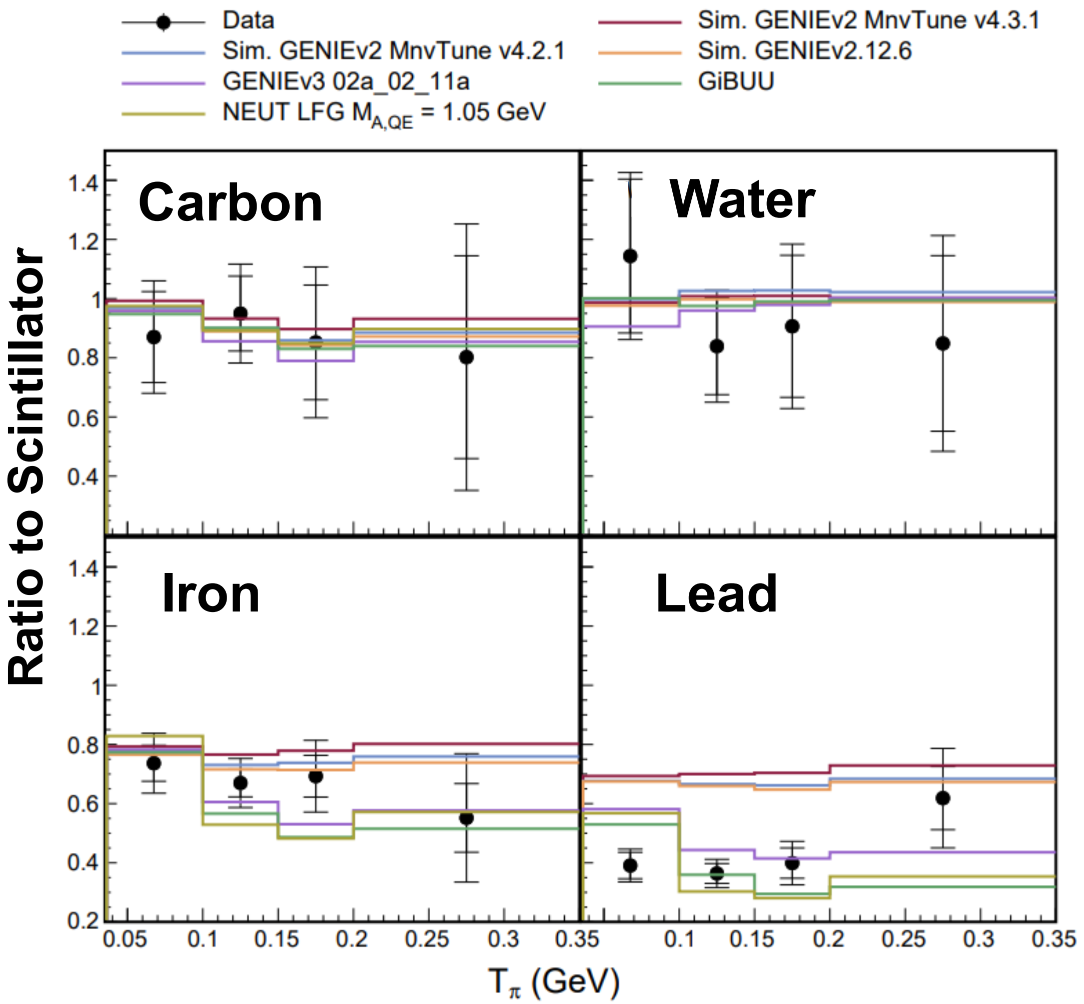


Dominant channel for DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Nuclear Dependence with ν_μCC 1π

Pion kinetic energy cross-section ratio



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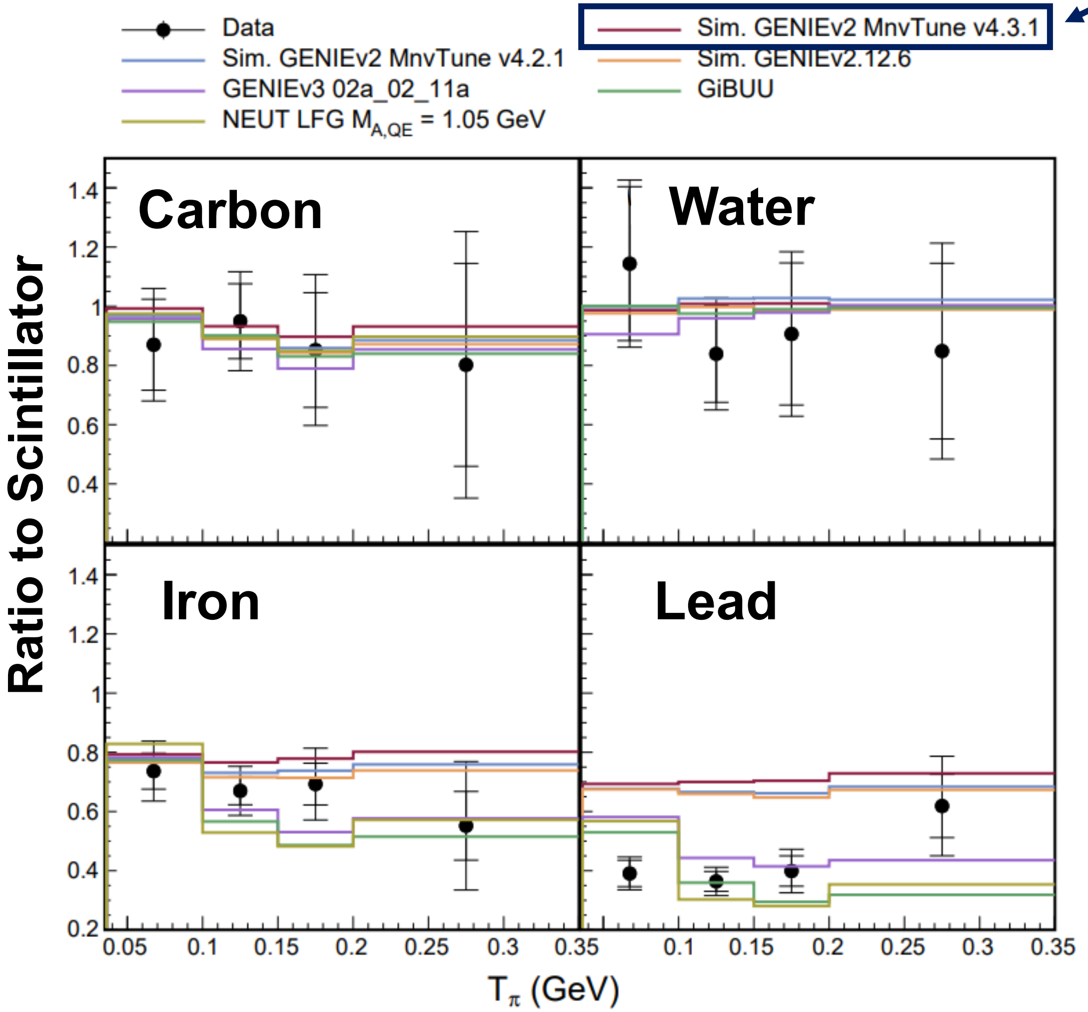
Pion kinetic energy cross-section ratio

Base CV



Carbon and water ratios consistent with unity (stats. limited)

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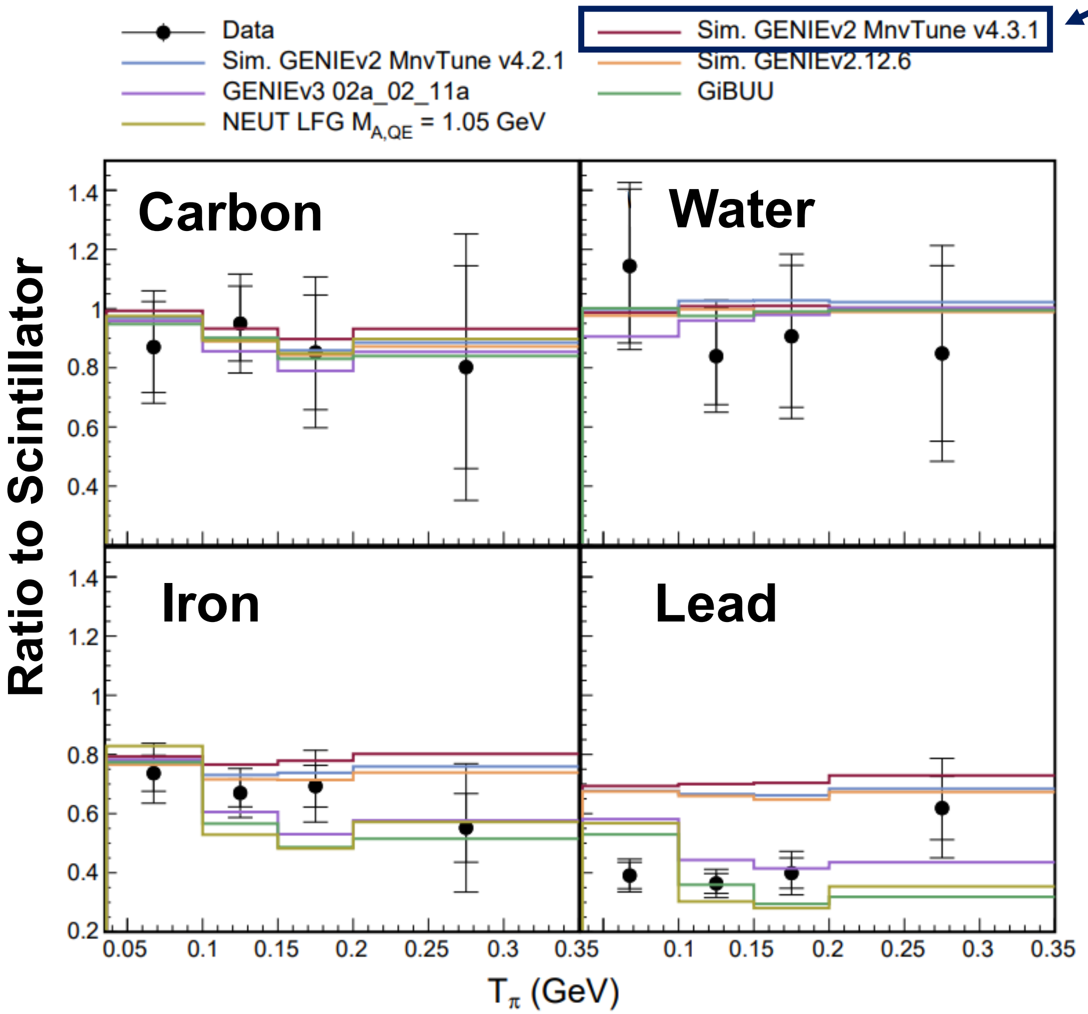

Carbon and water ratios consistent with unity (stats. limited)

Model overpredicts pions in heavy nuclei

- Opposite trend to CCQE-like discrepancy
- Pion absorption as a source of mismodelling?

MINERvA's Latest Measurements Highlights

- ME flux constraint using (anti)neutrino-electron scattering and inverse muon decay
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  - Neutrino CCQE-like
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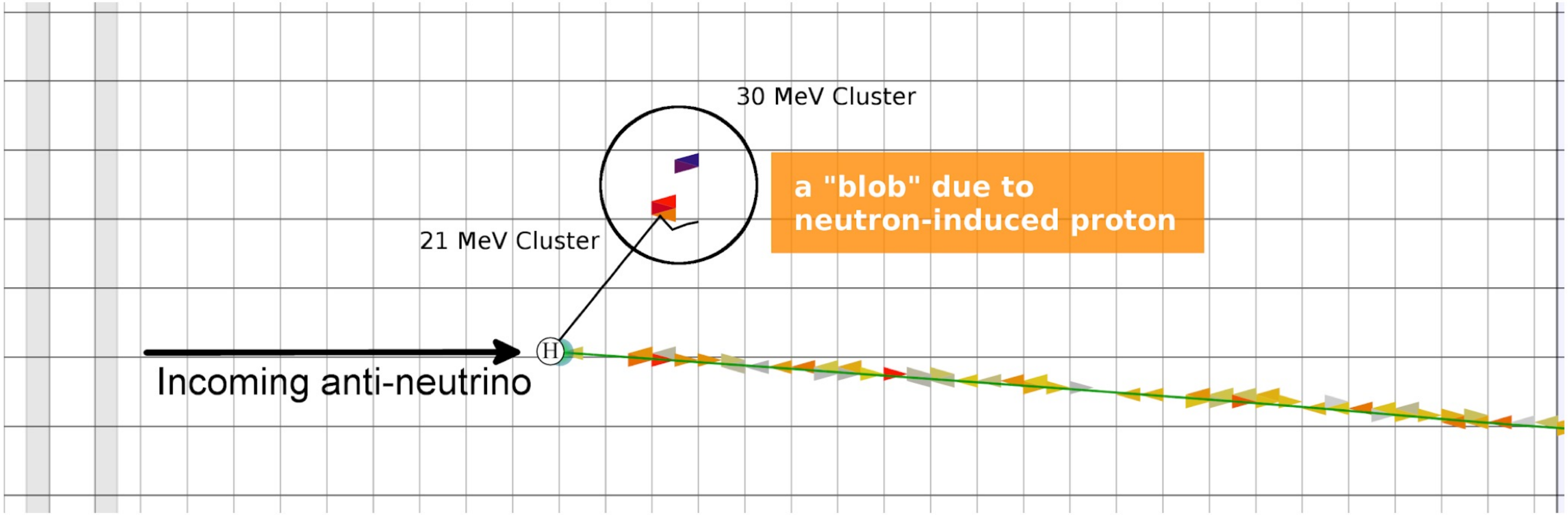
$\bar{\nu}_\mu$ CC 0π on Hydrogen

T. Cai et al. Nature, 614, 48-53, 2023.

- Measurement on a **free nucleon (no nuclear effects!)** – hydrogen in the CH tracker $\bar{\nu}_\mu H \rightarrow \mu^+ n$



Neutron undergoes secondary interactions to produce a visible proton

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T. Cai et al. Nature, 614, 48-53, 2023.

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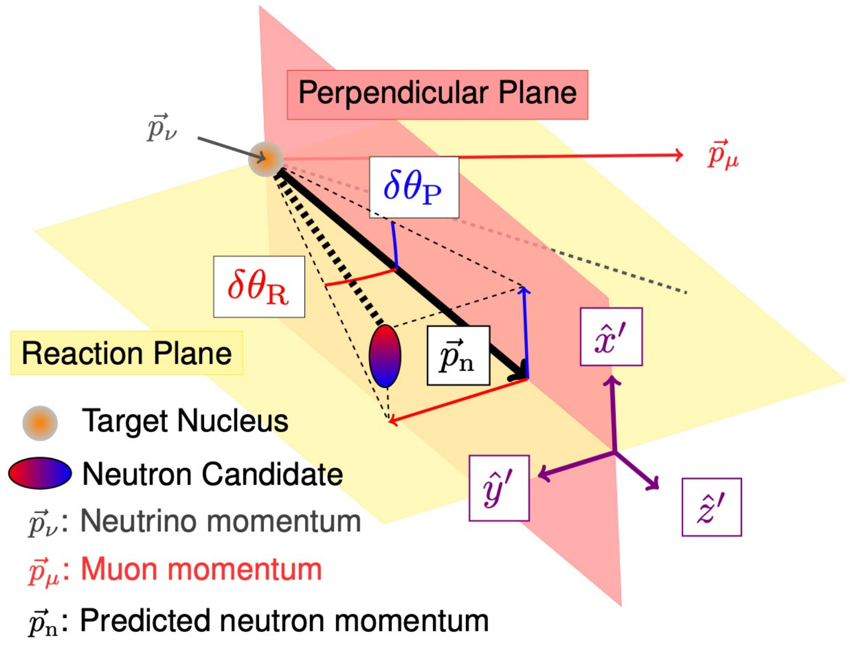

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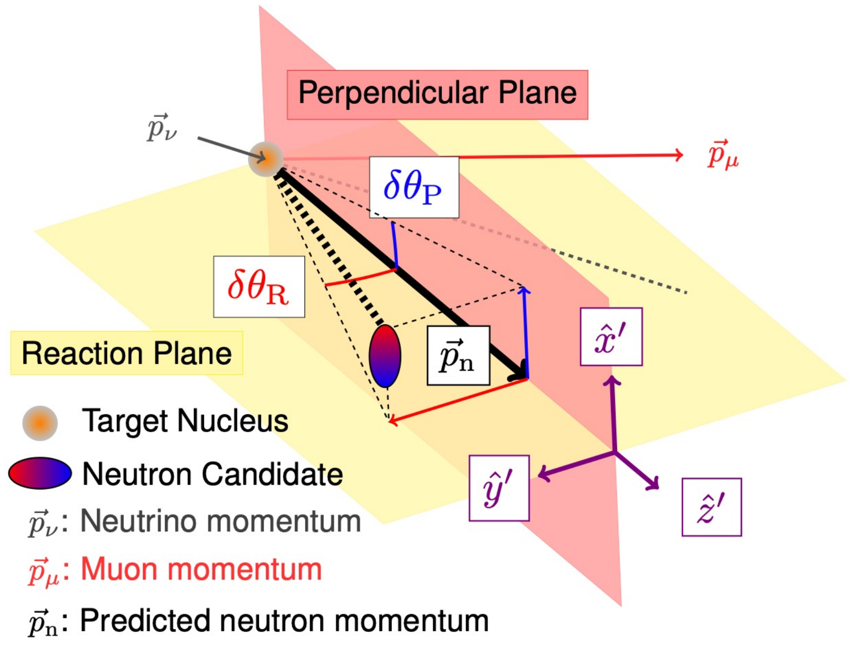
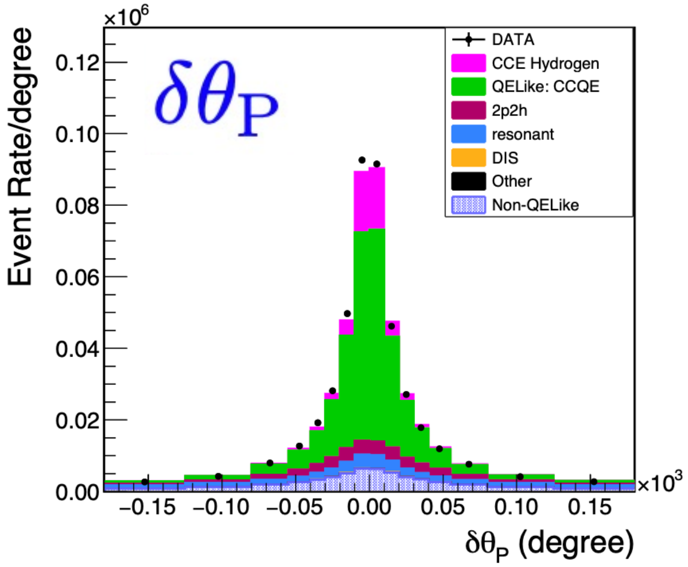
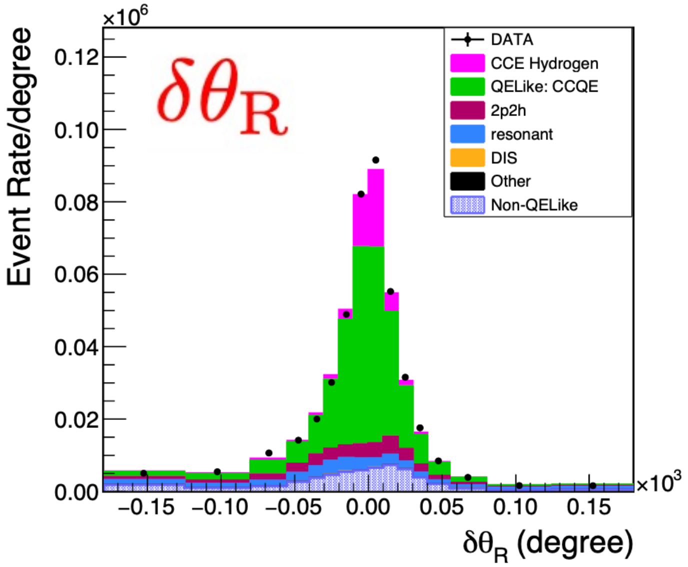


Centred (H) vs spread (C)





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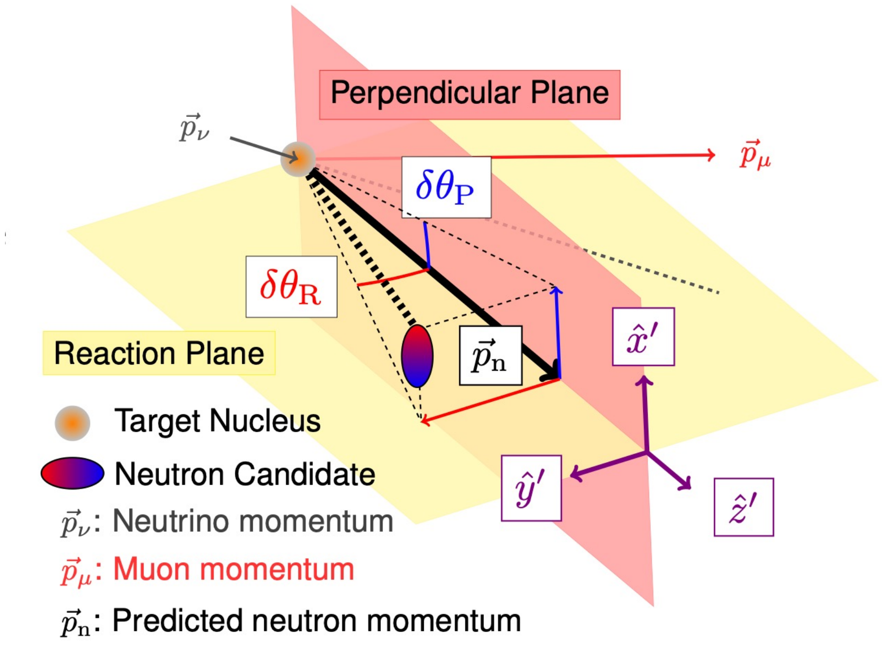

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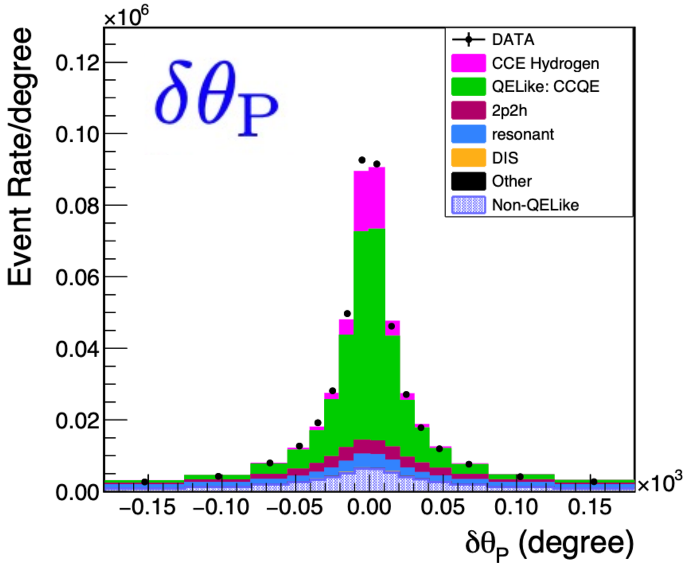
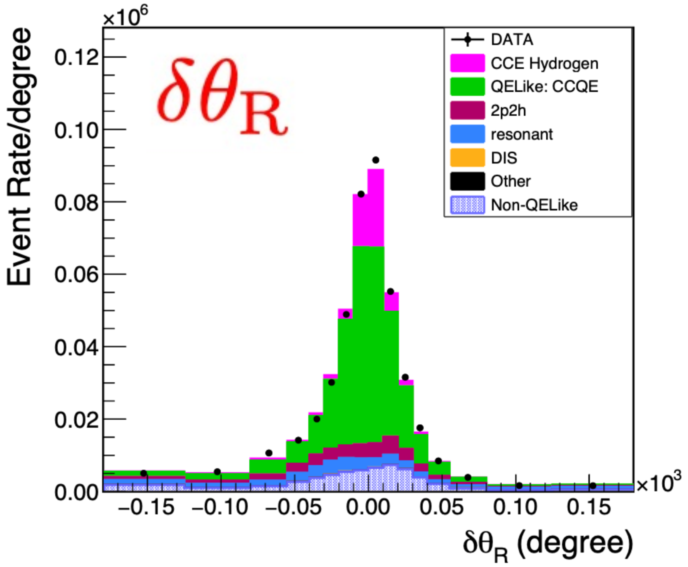
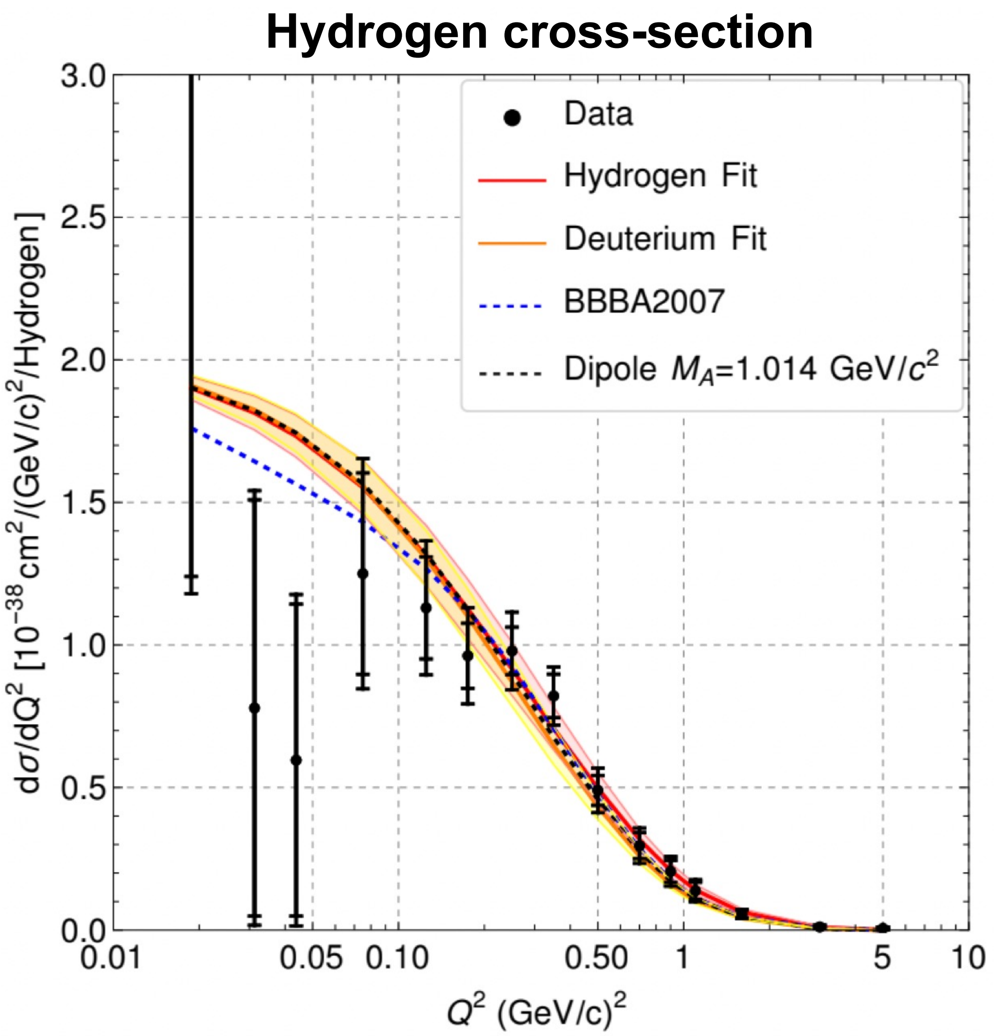




Tune in 2D and subtract carbon background using sidebands

$\bar{\nu}_\mu$ CC 0π on Hydrogen

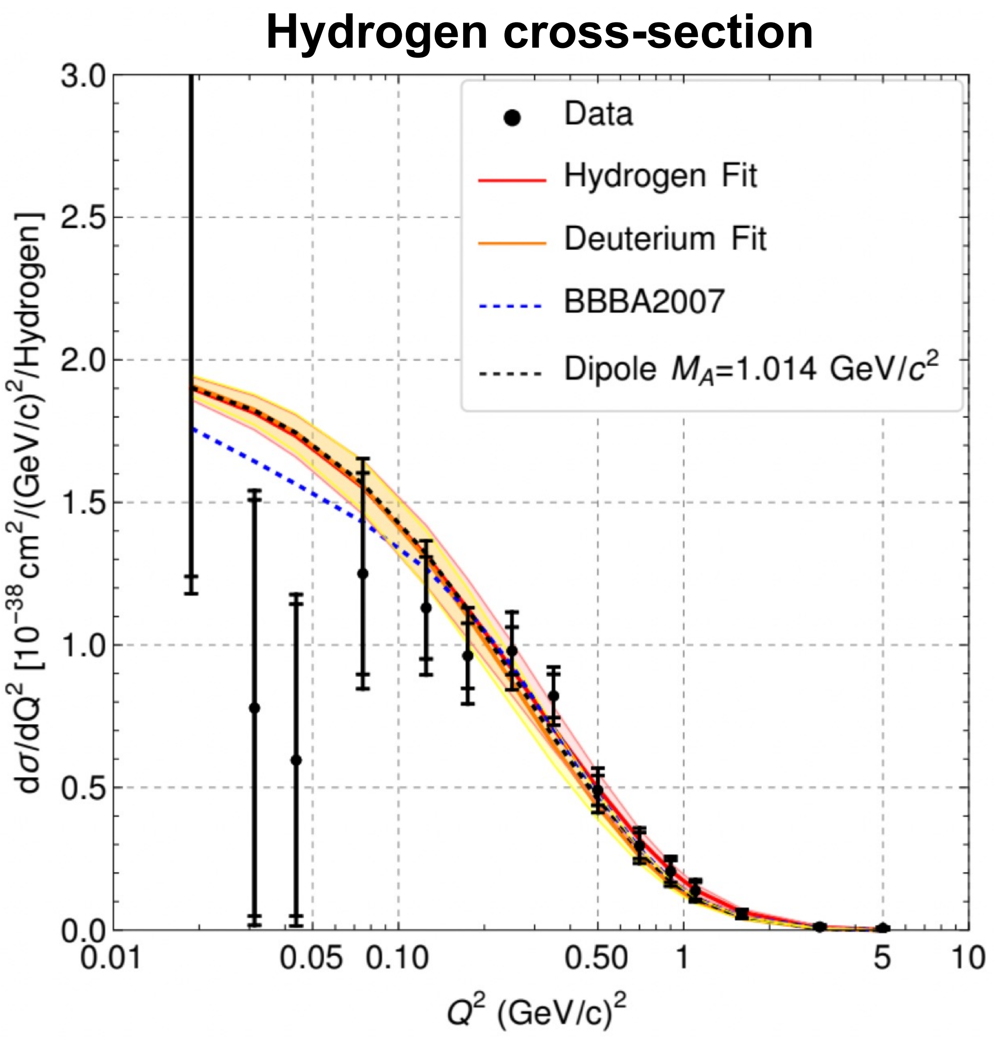
T. Cai et al. Nature, 614, 48-53, 2023.



More than 5000 hydrogen events!

$\bar{\nu}_\mu$ CC 0π on Hydrogen

T. Cai et al. Nature, 614, 48-53, 2023.



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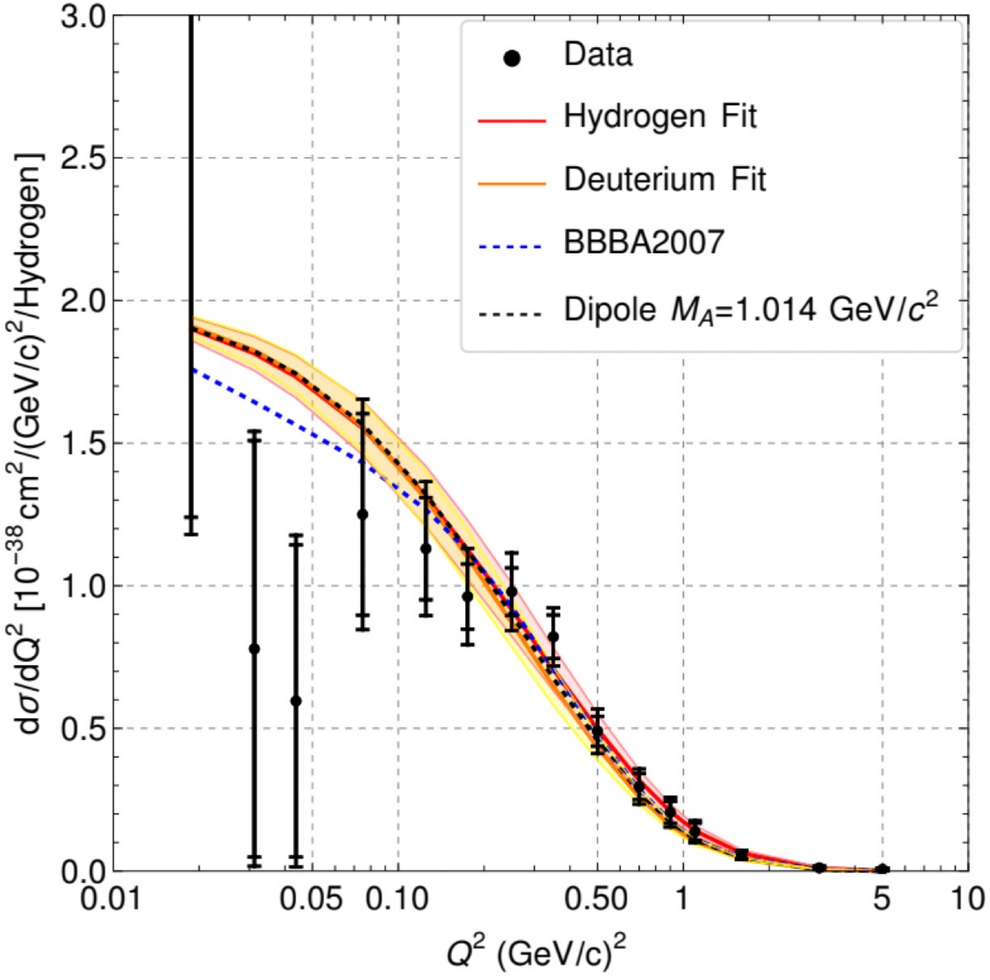
Fit cross-section to an Z-expansion axial form factor with BBBA2005 vector form factors

Axial form factor

$\bar{\nu}_\mu$ CC 0π on Hydrogen

T. Cai et al. Nature, 614, 48-53, 2023.

Hydrogen cross-section



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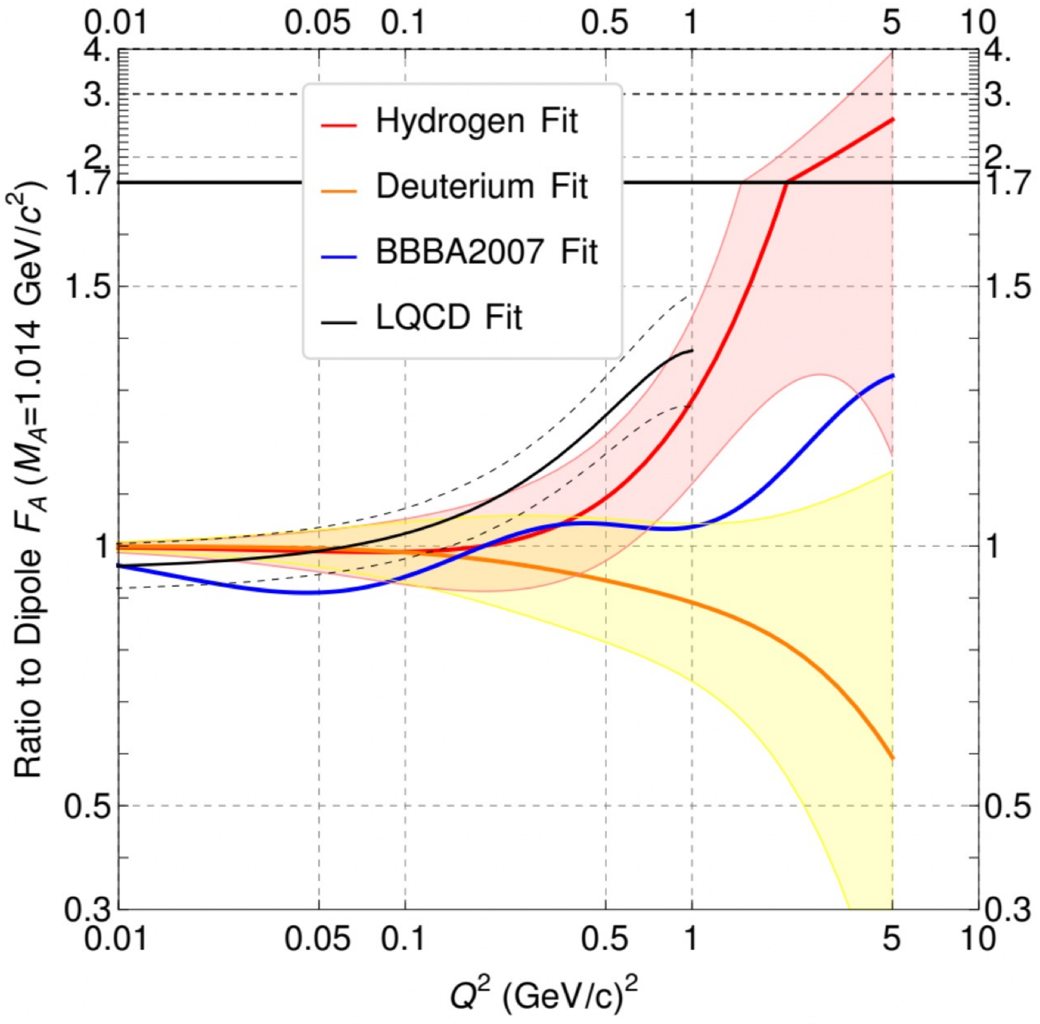
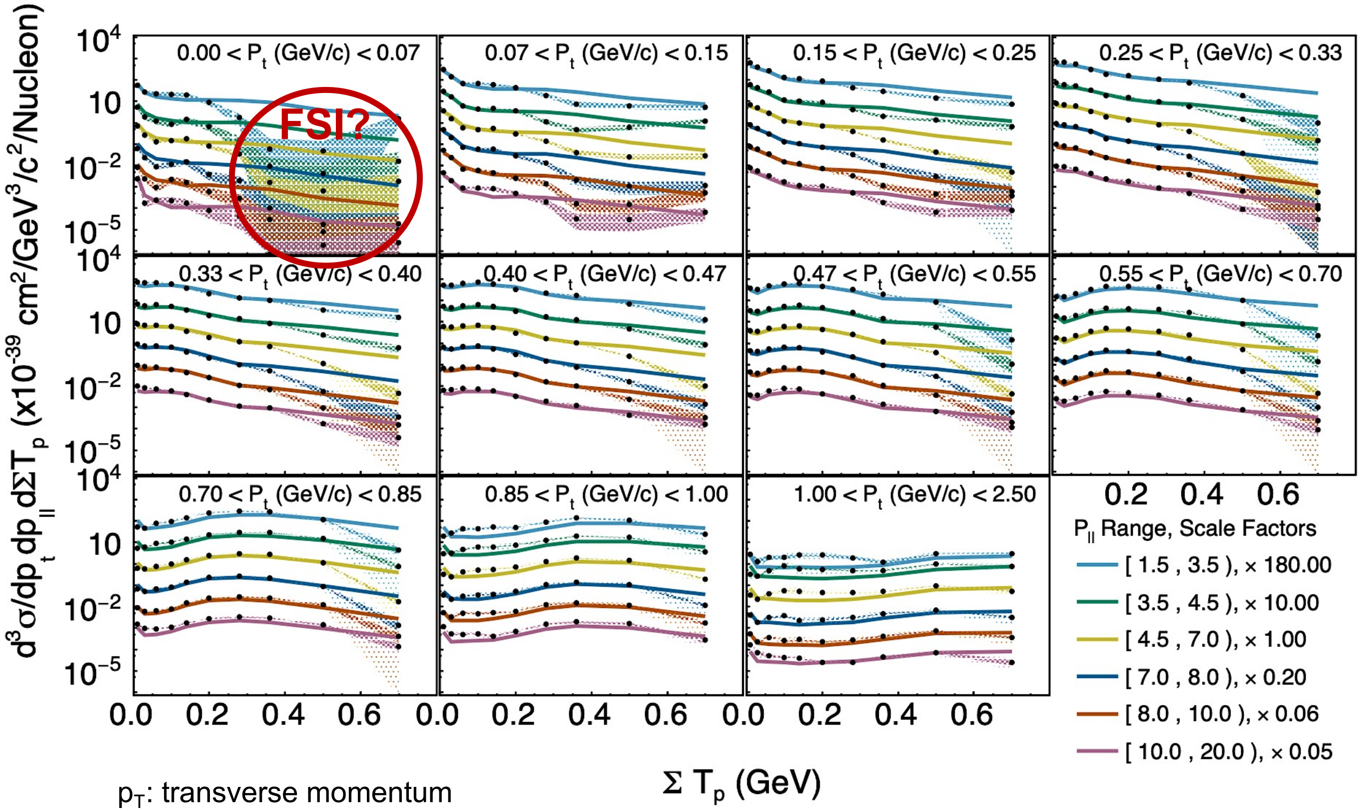
Axial form factor



And More!

D. Ruterbories et al. Phys. Rev. Lett. **129**, 021803, 2022.



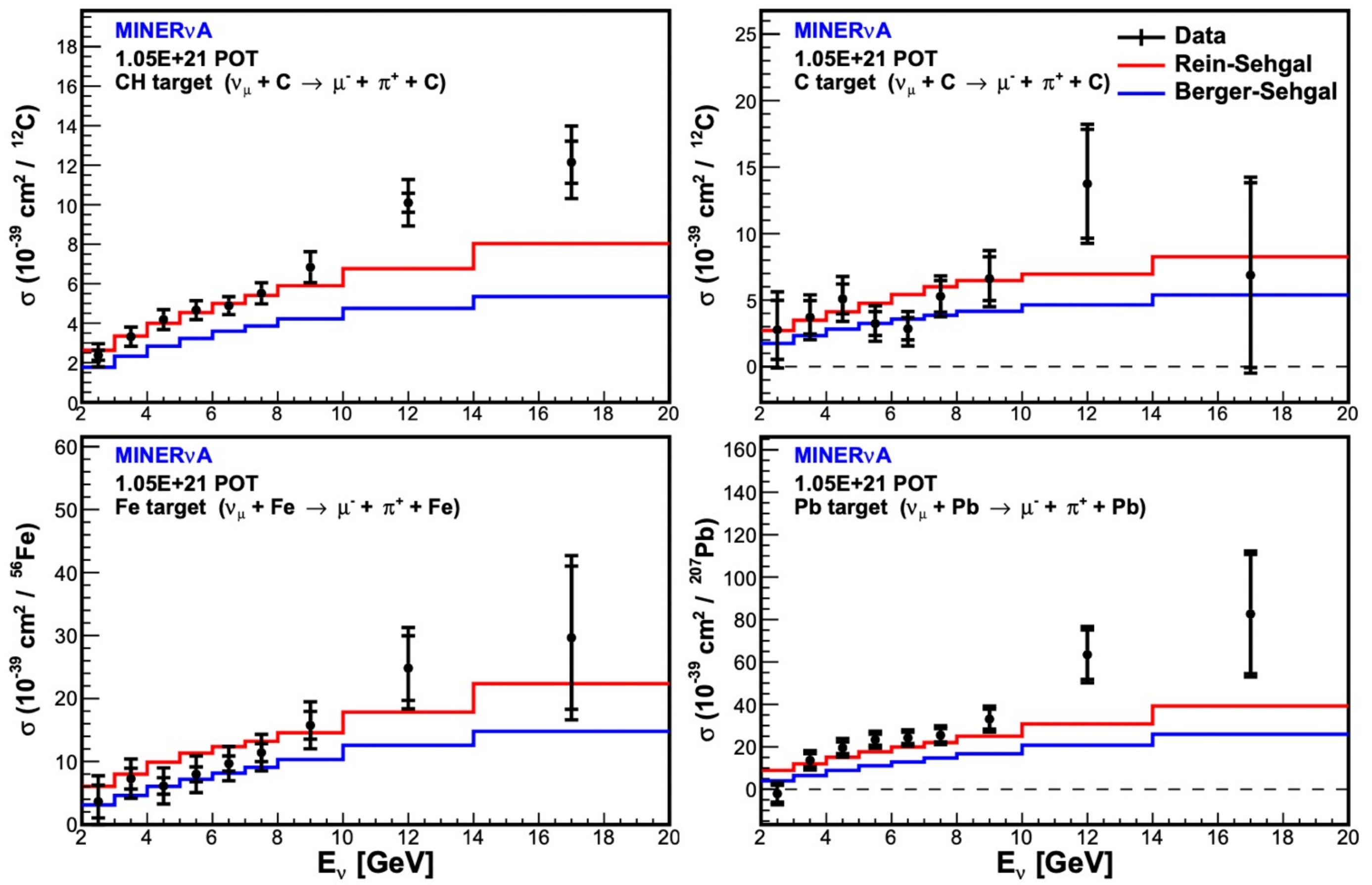
p_T: transverse momentum
$p_{||}$: longitudinal momentum
$\sum T_p$: sum of the kinetic energy of all protons

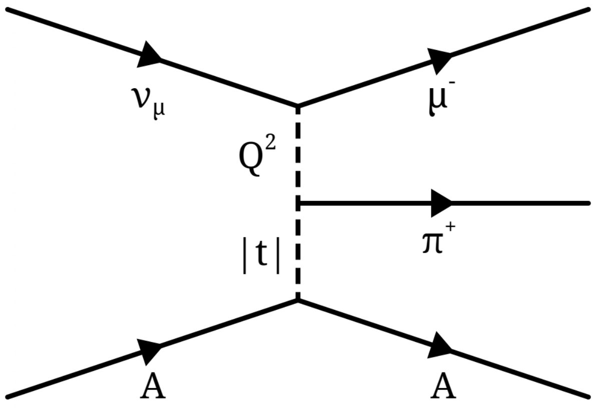
Simultaneous muon and hadron 3-dimension cross-sections for ν quasielastic-like scattering on hydrocarbon

And More!

M. A. Ramírez et al. arXiv:2210.01285 [hep-ex].

A-dependence in coherent pion production





p_T: transverse mome

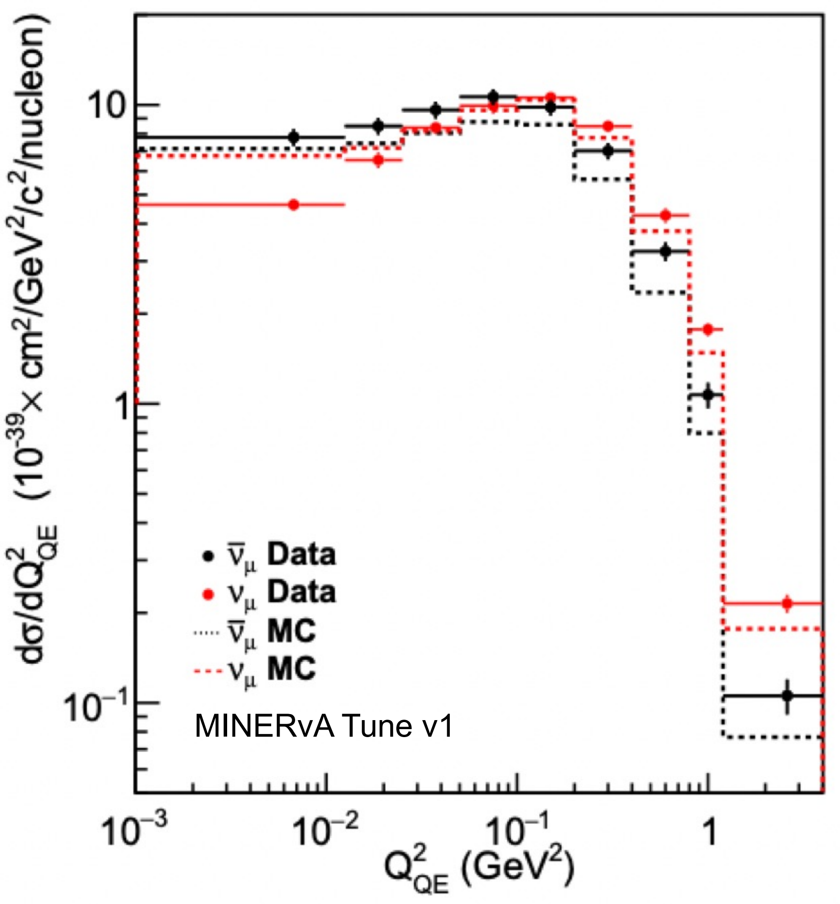
$p_{||}$: longitudinal mom

$\sum T_p$: sum of the kine

Simultan
cross-sections for ν quasielastic-like scattering on hydrocarbon

And More!

A. Bashyal et al. arXiv:2211.10402 [hep-ex].



High-statistics antineutrino quasielastic-like scattering on a hydrocarbon target

Coming Soon

- 3D CCQE vs transverse kinematic imbalance variables
- Neutron tagging, interaction with 2+ neutrons
- Electron neutrinos and antineutrinos
- Low recoil
- More charged pions
- Interactions on helium
- Inclusive, deep inelastic and shallow inelastic scattering

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Data preservation product to ensure more physics can be extracted from the data going into the DUNE era!

Analysis framework and data preservation tuples
Snowmass 2021 Contributed Paper

@MinervaExpt

UK Contribution

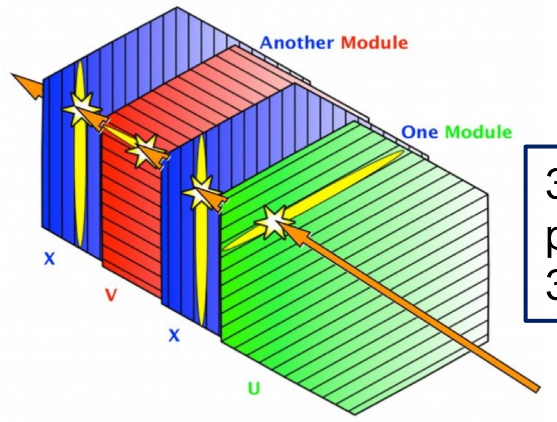
From X. Lu:

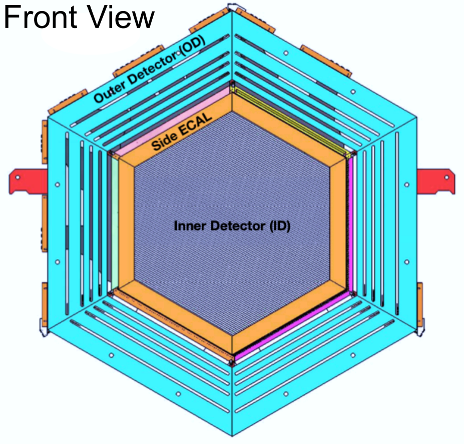
- Oxford 2016 (Lu, Wark, Weber), Imperial 2020 (Waldron, Wascko), Warwick 2021 (Boyd, Lu), QMUL 2022 (Waldron)
- **Funding sources:** ERF/UKRI, Marie Skłodowska-Curie/EU, University fundings
- **Activities:** Data analysis (neutrino interactions, BSM searches), data production and preservation
- **Leadership roles:** Analysis Coordinator 2020, Executive Committee Member 2020, Speakers Committee Member 2019, Neutrino Interaction Working Group Convener 2019, Reconstruction Working Group Convener 2018.
- **Publications with leading contributions:** Phys. Rev. D 102, 072007 (2020), Phys. Rev. D 101, 092001 (2020), and Phys. Rev. Lett. 121, 022504 (2018).

MINERvA planes repurposed for DUNE 2x2

Back-up

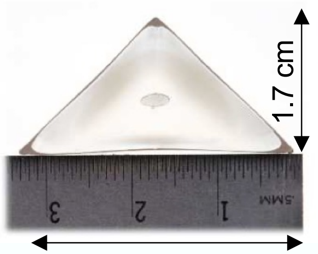
MINERvA Detector

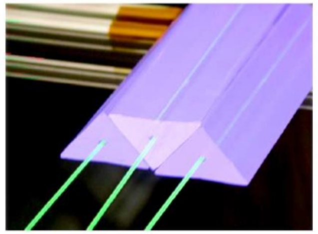




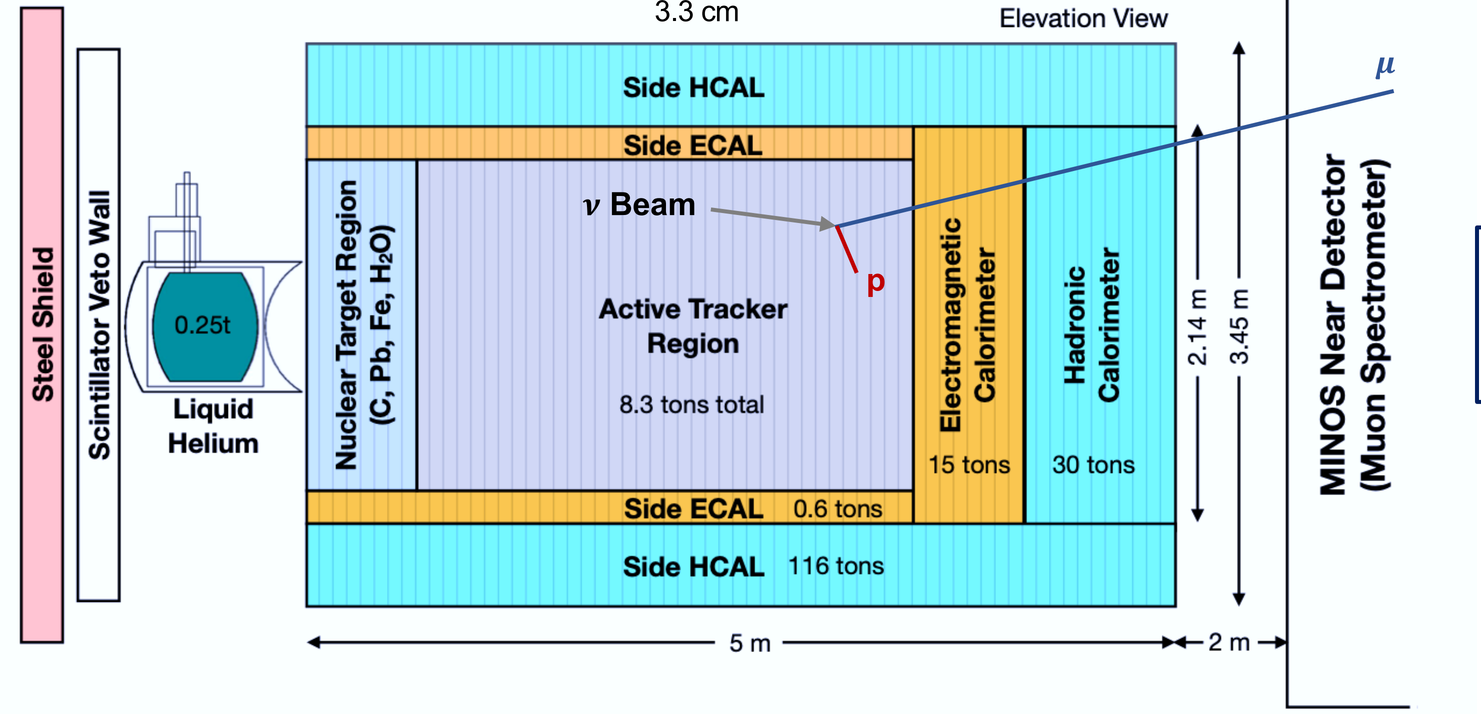
3 orientations of scintillator planes give unambiguous 3D track reconstruction.

Triangular strips arranged to give a better position resolution.





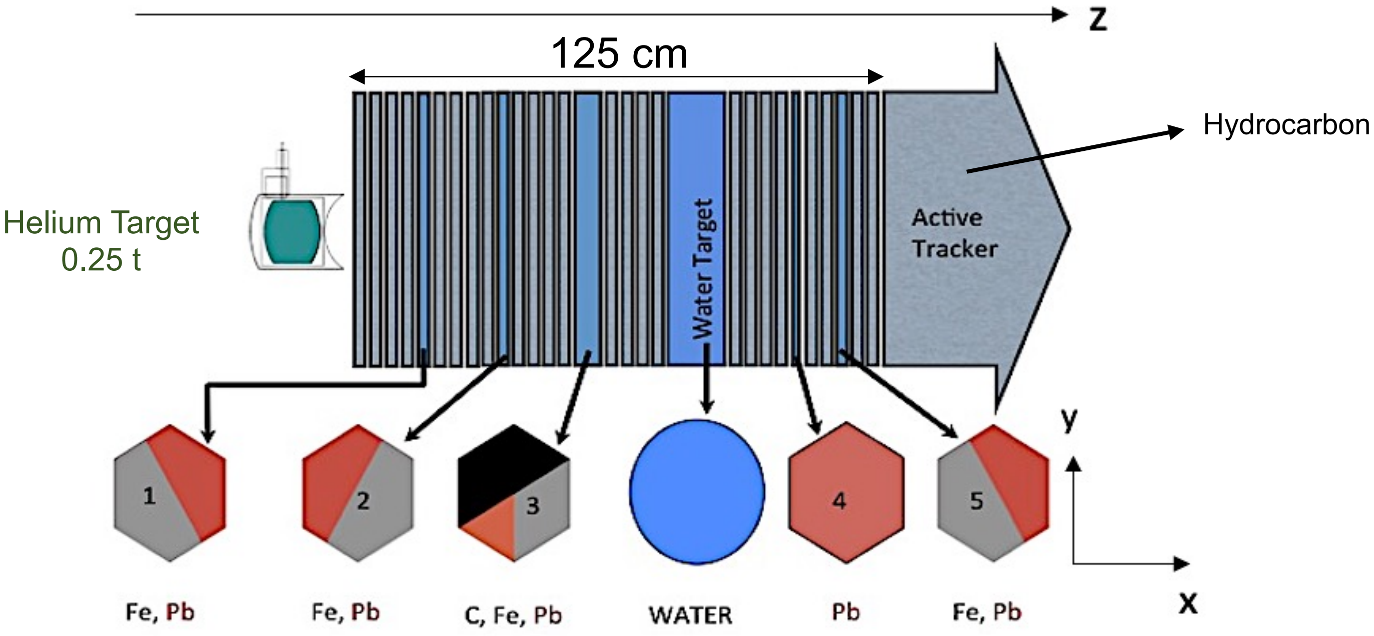
Read out using WLS fibres and PMTs: timing resolution better than ~5 ns to distinguish overlapping events within a single spill (< 10 μs).



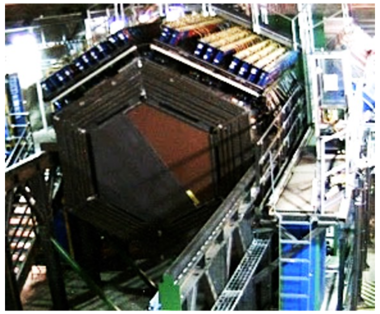
MINOS spectrometer: muon momentum and charge.

Passive Target Region

6 different nuclei
in 7 different targets

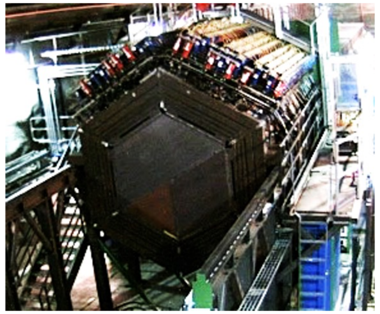


1 Fe / Pb
323 kg / 264 kg



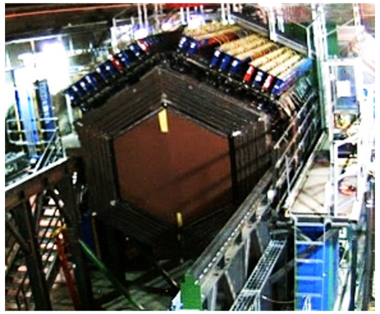
5 Fe / Pb
161 kg / 135 kg

2 Pb / Fe
266 kg / 323 kg



3 C / Fe / Pb
166 kg / 169 kg / 121 kg

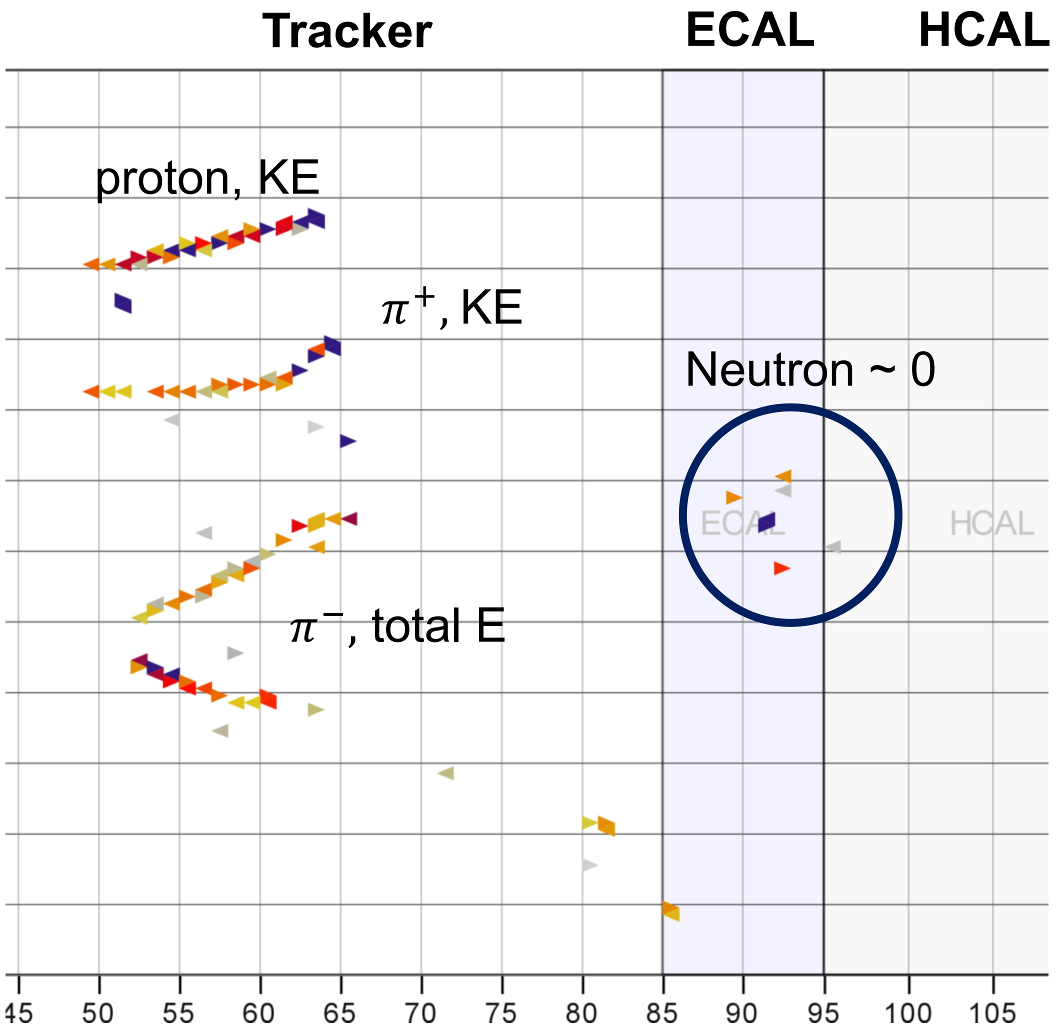
Distilled water
0.39 t



4 Pb
228 kg

Sensitivities to Final States

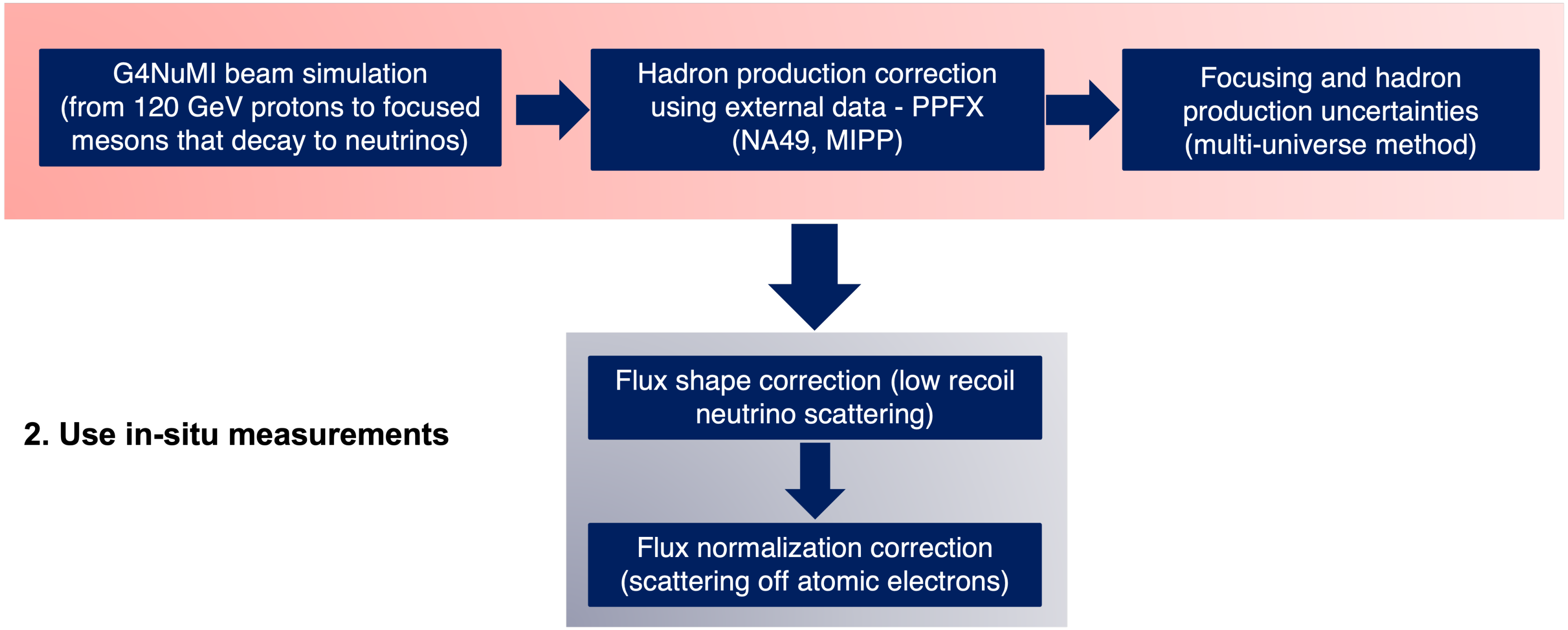
- Plastic scintillator sensitive to small energy deposits
- Hadronic recoils measured using calorimetry
- Tracking threshold (KE) for proton ~ 100 MeV
- Neutrons can deposit visible energies (albeit small) after recoil inside scintillator



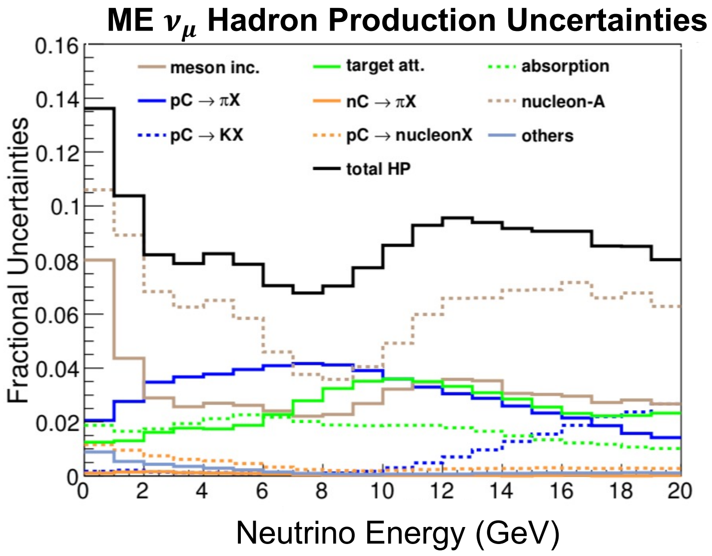
Flux Simulation & Uncertainties

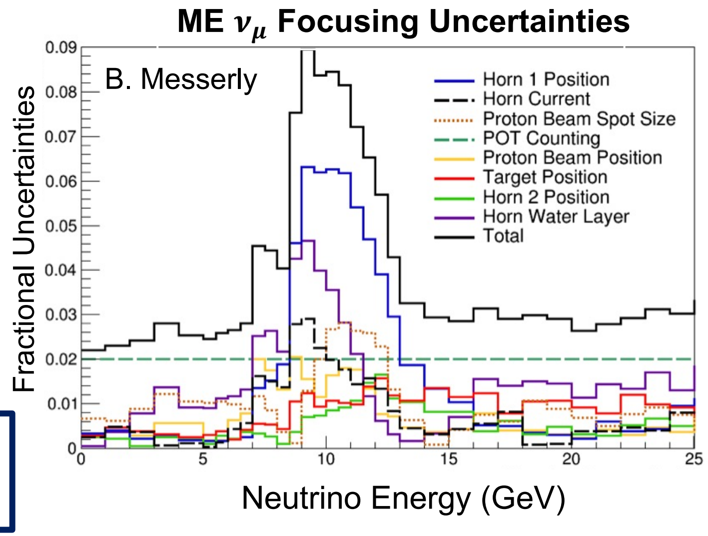
L. Aliaga et al. Phys. Rev. D 94, 092005 (2016).

1. Calculate and correct the a-priori flux



2. Use in-situ measurements





Small simulation inaccuracies have a big impact around the focusing peak!

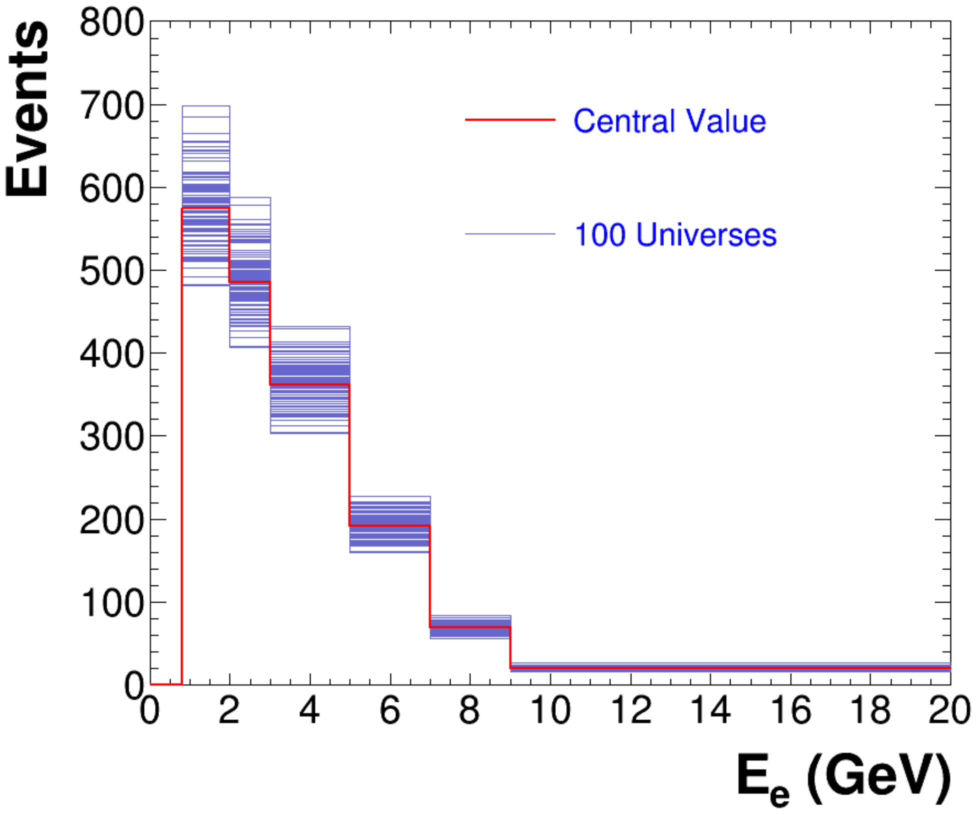
Flux Constraint Procedure

- Using Bayes' theorem

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

$P(M\vert N_{\nu e\rightarrow\nu e})$	new prediction (posterior) probability of the flux prediction given the electron spectra measurement)
$P(M)$	flux prediction in each universe/model (prior)
$P(N_{\nu e\rightarrow\nu e}\vert M)$	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)



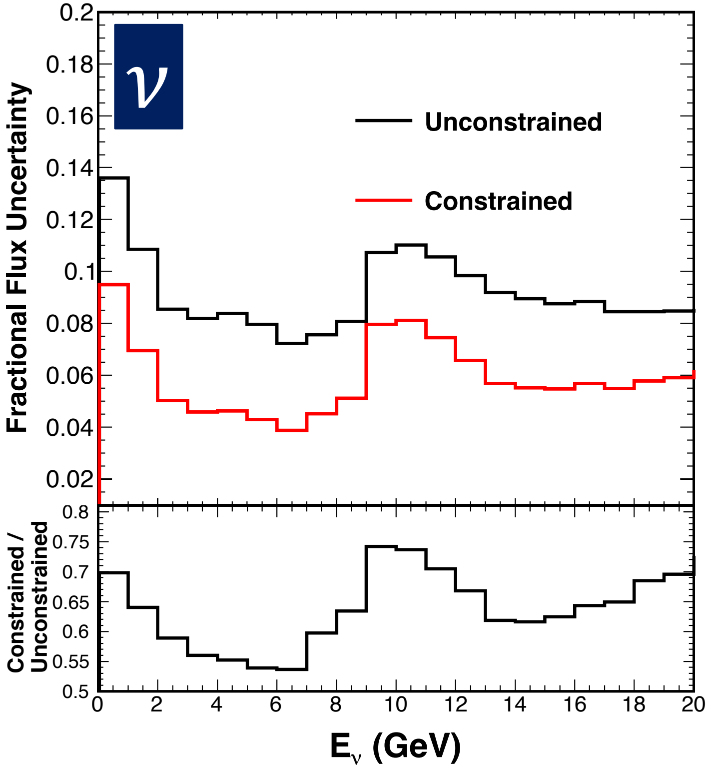
Neutrino Flux Constraint

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

- **Likelihood of the measurement** for each universe

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

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



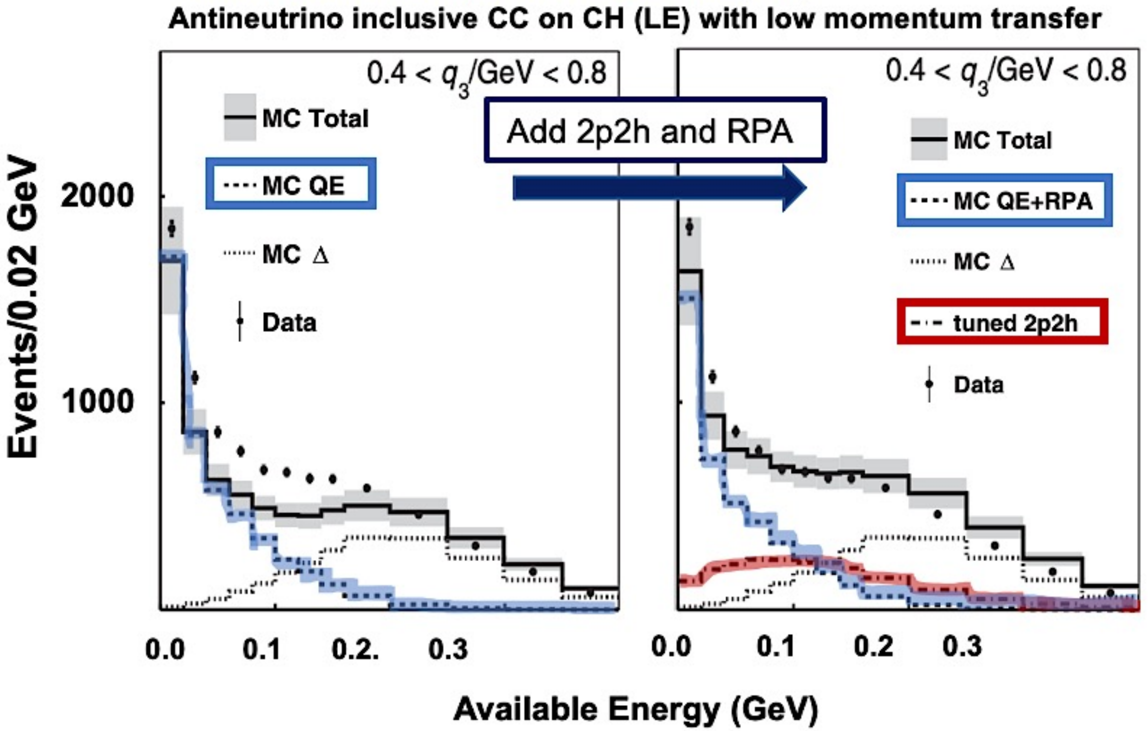
- Predictions from universes with poor data agreement are weighted down → **reduces uncertainty** (spread of the universes)
- **In neutrino mode, the neutrino flux uncertainty is reduced from 7.6% to 3.9% (integrated flux over the energy range)**

MINERvA Tune v1

P. A. Rodrigues et al. Phys. Rev. Lett. 116, 071802 (2016)
P. Rodrigues, C. Wilkinson, and K. McFarland, Eur. Phys. J. C**76**, 474 (2016).

- GENIE 2.12.6
  - QE – Llewellyn-Smith formalism with the vector form factors modeled using the BBBA05 model
  - RES – 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
- MINERvA modifications based on our data
  - Added RPA to better simulate QE
  - Added + enhanced Valencia 2p2h – increased by 50% over the nominal prediction (integrated over all phase space) based on low recoil fit
  - Non-resonant pion production reduced to 43%

Modified from MINERvA. Phys. Rev. Lett., 120, 221805 (2018).



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

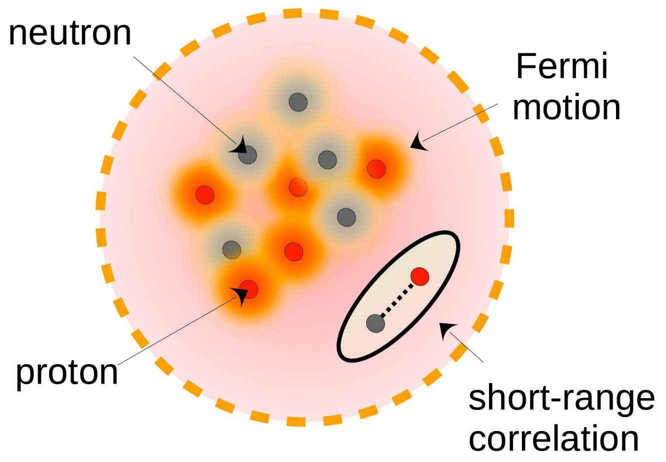
Z	Description
1	Bug fix of elastic FSI in pions and protons

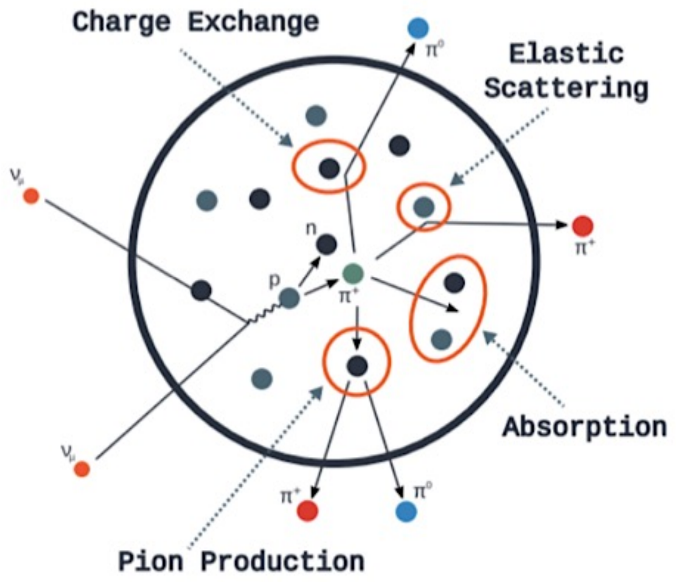
Neutrino-Nucleus Interactions

- Inseparable nucleon and nuclear effects unless scattering off of a free nucleon

- **Initial states:** Fermi motion, short-range correlation, binding energy, etc.
- **Final state interactions:** elastic, inelastic, charge-exchange, pion production, pion absorption, etc.

- Current and future neutrino oscillation experiments use relatively **heavy nuclei**: C, CH, H_2O, Ar
- Important to **study nuclear dependence**

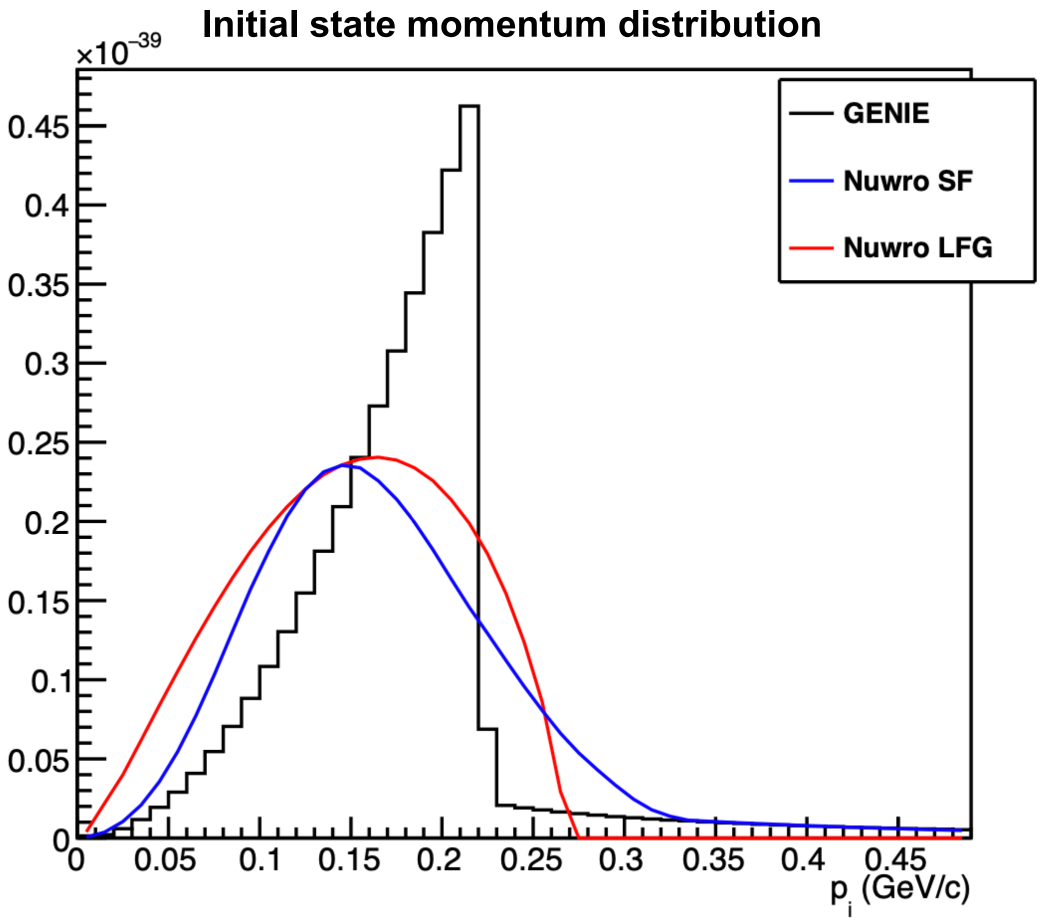




Nuclear Environment

- Relativistic Fermi Gas (RFG) vs Local Fermi Fas (LFG) vs Spectral Function (SF)

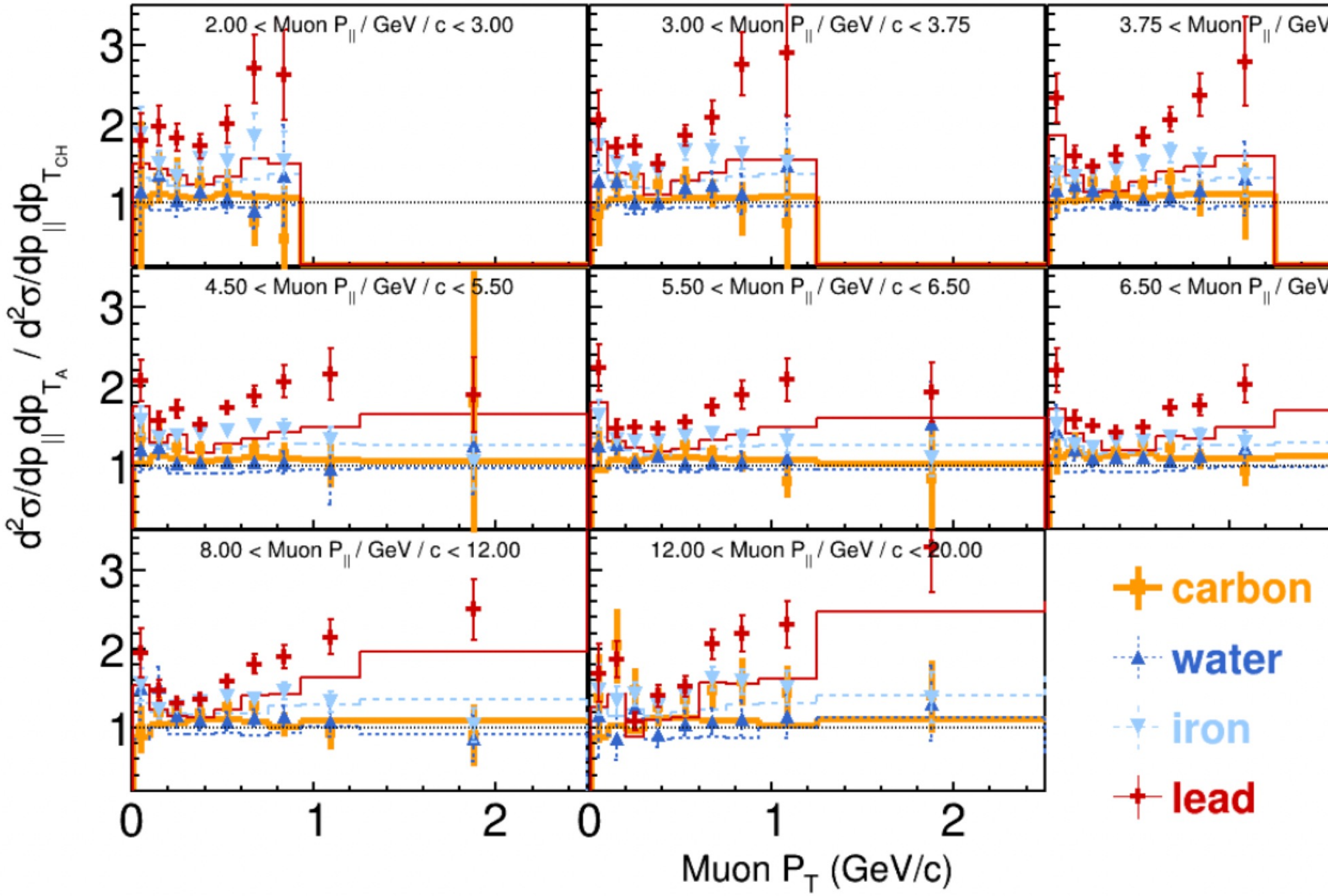
- **RFG:** non-interaction fermions in a potential well with fixed Fermi momentum
- GENIE RFG includes an additional tail
- **LFG:** Fermi gas with location dependent Fermi momentum
- **SF:** Nuclear shell model



Nuclear Dependence with ν_μCC 0π

Low vs high p_T (non-QE vs QE-like)
Overall QE-like A-scaling underpredicted

Cross-Section Ratios to CH

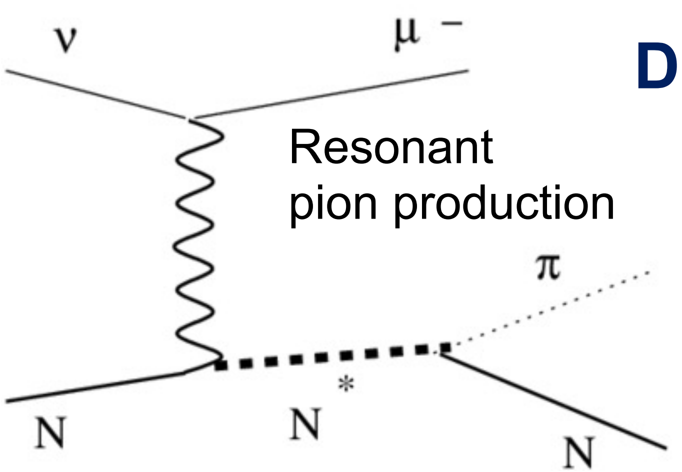


Ratios provide systematics cancellations (flux, detector effects)

How Do We Produce Single Pions?

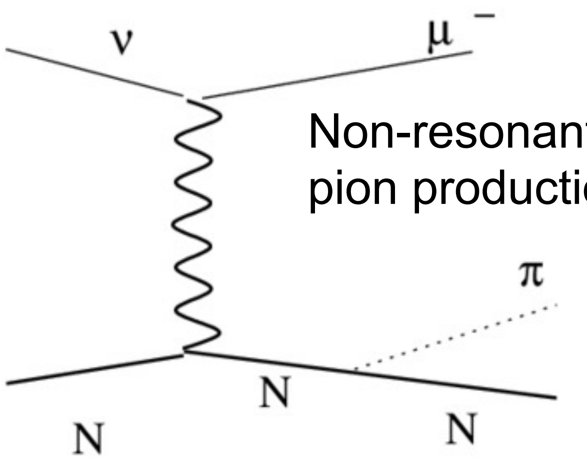
Kevin McFarland

- Many competing production mechanisms



Resonant
pion production

Dominant

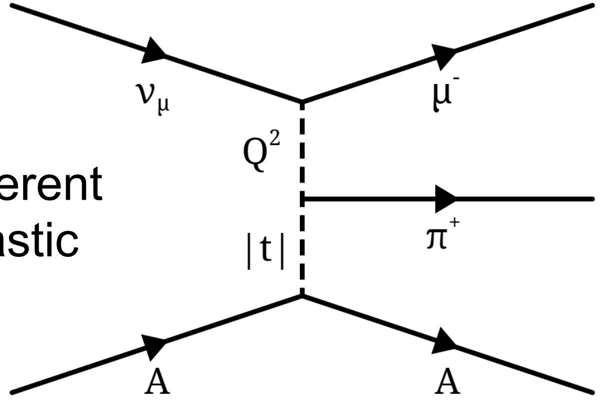


Non-resonant
pion production

Significant

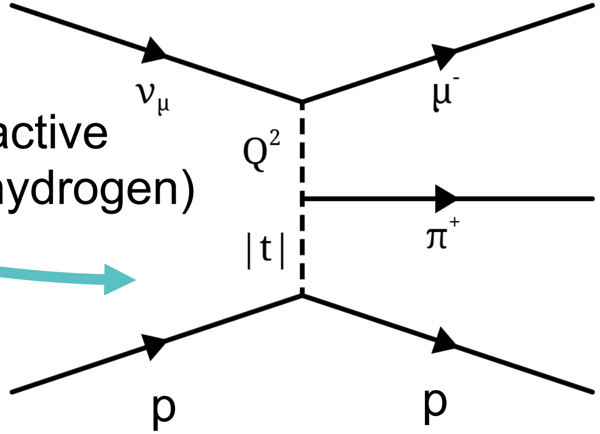
Interference may be large effect

Interference at low Q^2 on hydrogen



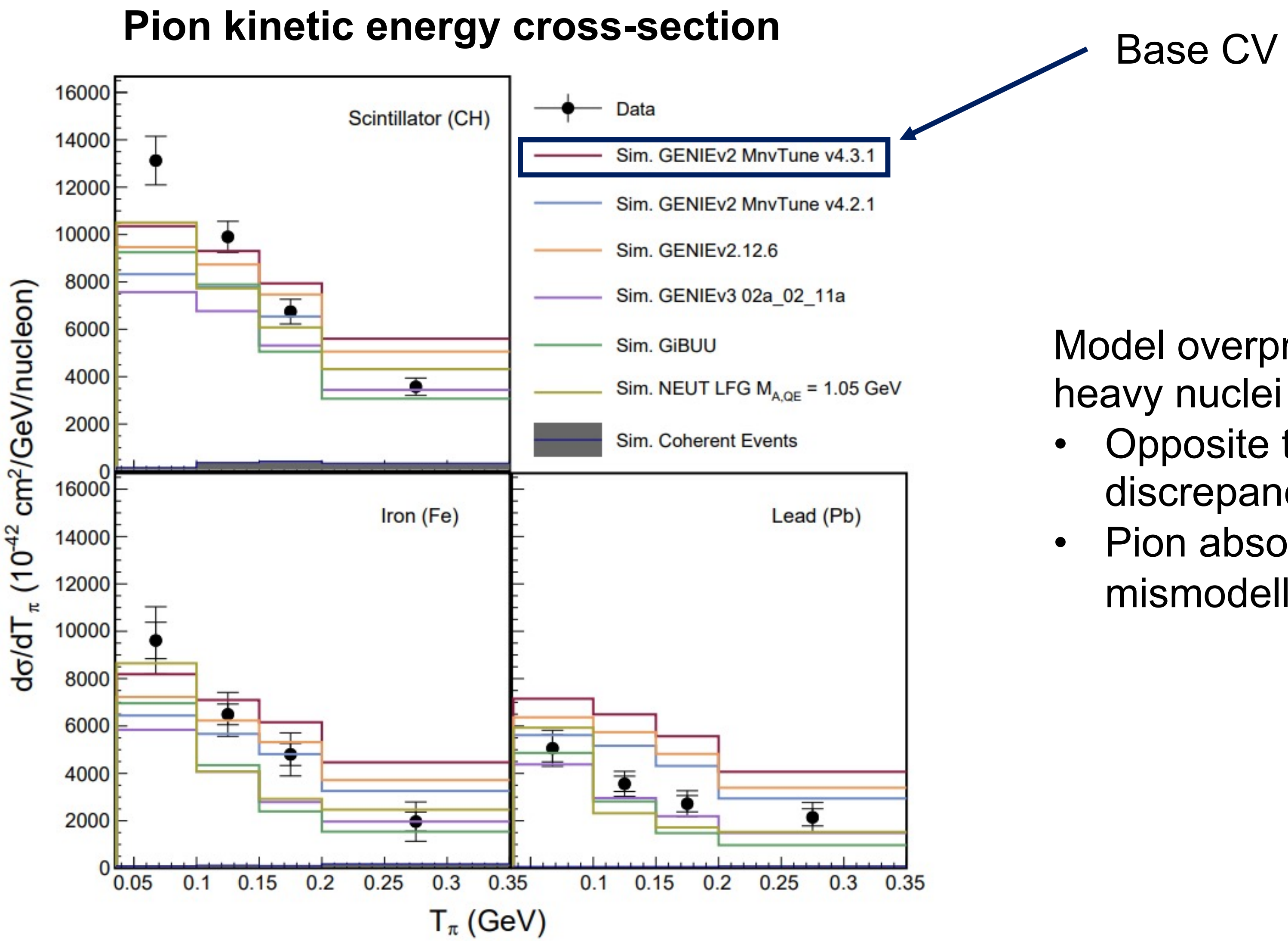
Coherent
inelastic

Sub-leading



Diffractive
(on hydrogen)

Nuclear Dependence with ν_μCC 1π

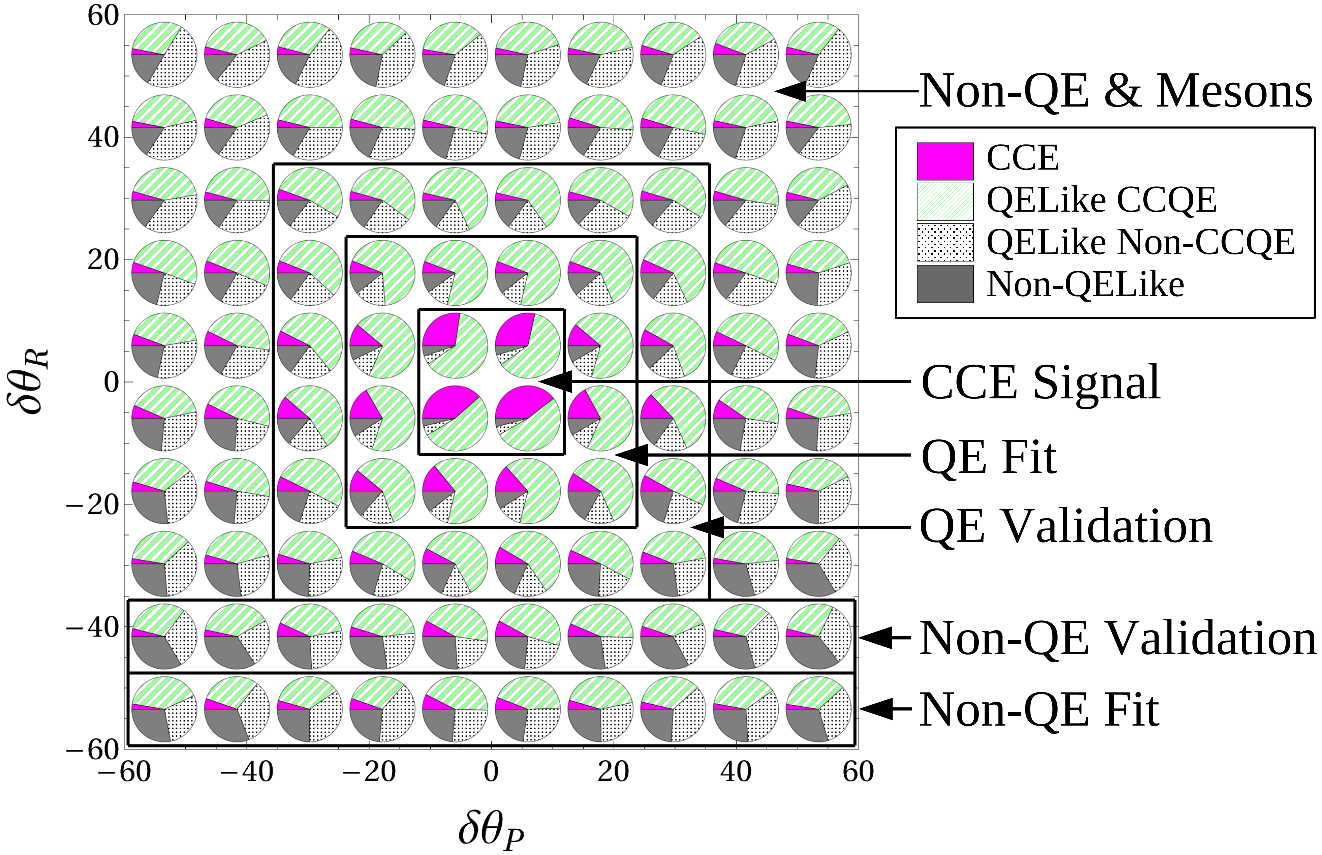


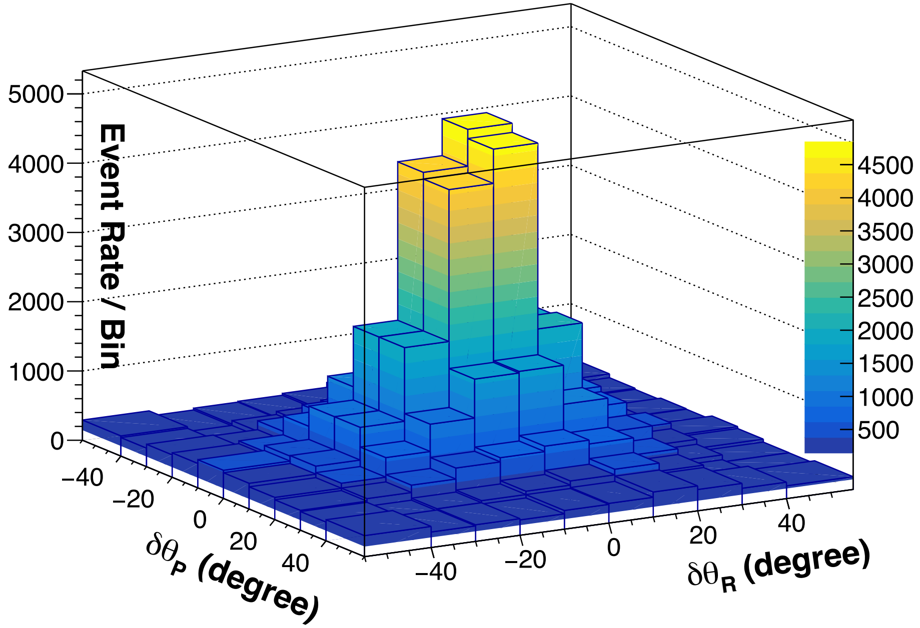
Model overpredicts pions in heavy nuclei

- Opposite trend to CCQE-like discrepancy
- Pion absorption as a source of mismodelling?

$\bar{\nu}_\mu$ CC 0π on Hydrogen

T. Cai et al. Nature, 614, 48-53, 2023.





Z Expansion

T. Cai et al. Nature, 614, 48-53, 2023.

Maps the 1D variable $t = -Q^2$ onto a unit circle bounded by $t_{cut} = 9m_\pi^2$, the threshold of three-pion production allowed by the axial current

$$F_{\mathrm{A}}(Q^2) = \sum_{k=0}^{k_{\max}} a_k z^k$$

$$z = \frac{\sqrt{t_{\mathrm{cut}} + Q^2} - \sqrt{t_{\mathrm{cut}} - t_0}}{\sqrt{t_{\mathrm{cut}} + Q^2} + \sqrt{t_{\mathrm{cut}} - t_0}}$$

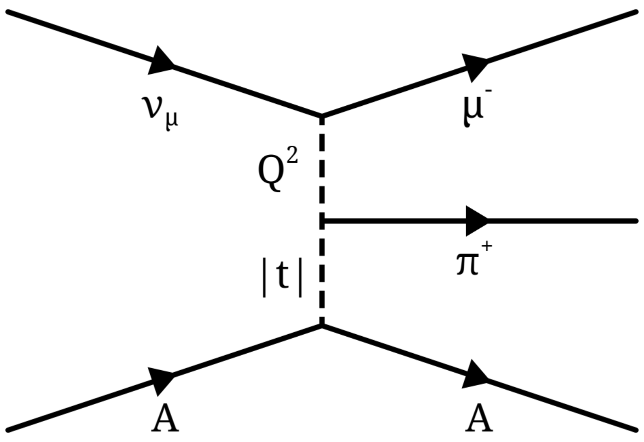
$$\sum_{k=n}^{\infty} k(k-1)\ldots(k-n+1)a_k = 0, n \in (0,1,2,3)$$

$$\chi^2 = \Delta X \cdot \mathrm{cov}^{-1} \cdot \Delta X + \lambda \left[\sum_{k=1}^{5} \left(\frac{a_k}{5a_0} \right)^2 + \sum_{k=5}^{k_{\max}} \left(\frac{k a_k}{25 a_0} \right)^2 \right]$$

$$\Delta X = \mathrm{data} - \mathrm{prediction}$$

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 $\nu A \rightarrow lA$, 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

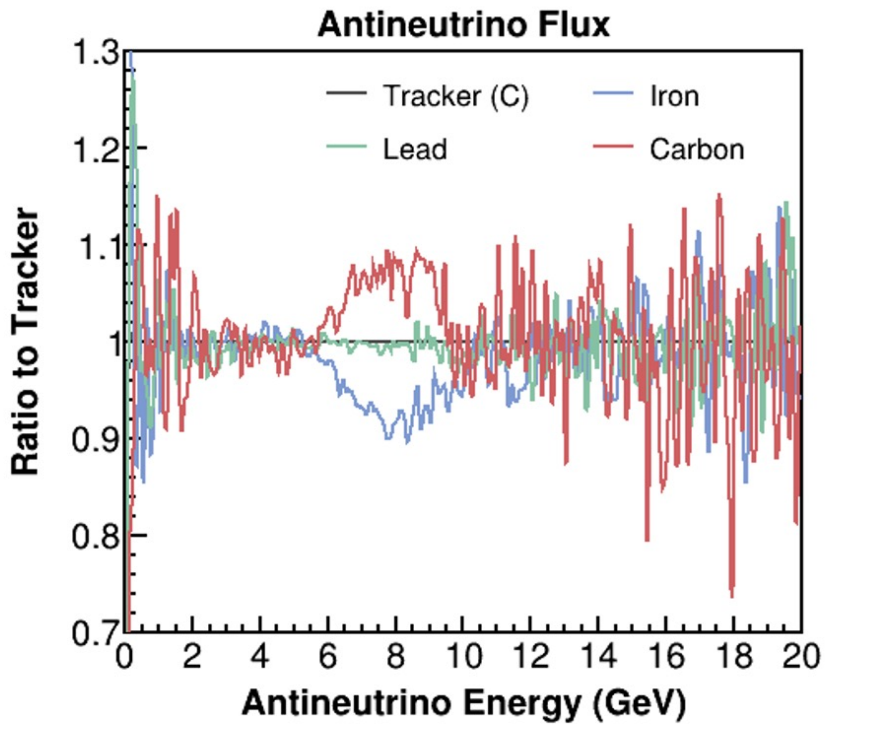


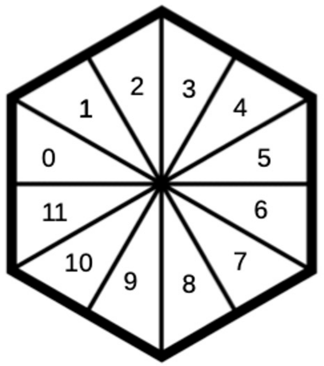
Coherence depends on the magnitude of the four-momentum transfer to the nucleus:

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

More info:
Alejandro Ramírez Delgado, W&C Seminar, June 10th, 2022

Behind The Scenes: 'Daisy' Tracker





- NuMI beam pointed downwards (3.34 deg) wrt the detector → transverse center of the beam changes as a function of the longitudinal position
- Difference in the flux shape + normalization in the nuclear targets compared to the tracker (problem for cross-section ratios)
- **'Daisy' concept:** Match the target flux by taking a linear combination of the tracker fluxes extracted in the 12 "daisy" petal bins