Imperial College London

MINERνA in 10 Minutes

Anežka KLUSTOVÁ

a.klustova20@imperial.ac.uk

On behalf of MINERvA Collaboration

FERMILAB-SLIDES-22-080-V

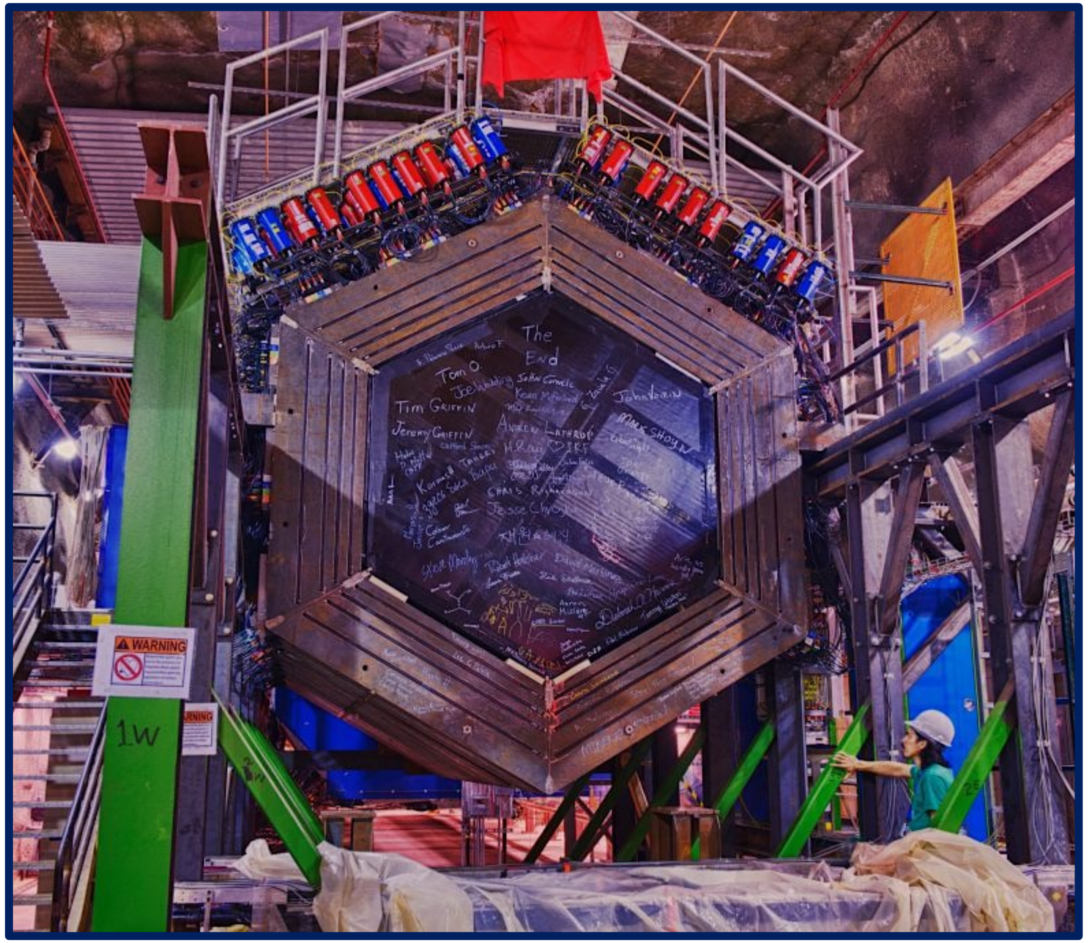
New Perspectives, Fermilab

June 21st, 2022

What is MINERvA?

Imperial College London

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



- The only currently active neutrino cross-section experiment with high-statistics, controlled systematics, different nuclear targets, and access to the DIS region
- 2009-2019 on axis in the NuMI beamline at Fermilab
- 2 flux periods with 3.5 and 6 GeV flux peak, both in $\nu/\bar{\nu}$

Regime \ Mode	ν (POT)	$\bar{\nu}$ (POT)
Low (LE) ~ 3.5 GeV	4×10^{20}	1.7×10^{20}
Medium (ME) ~ 6 GeV	12.1×10^{20}	12.4×10^{20}

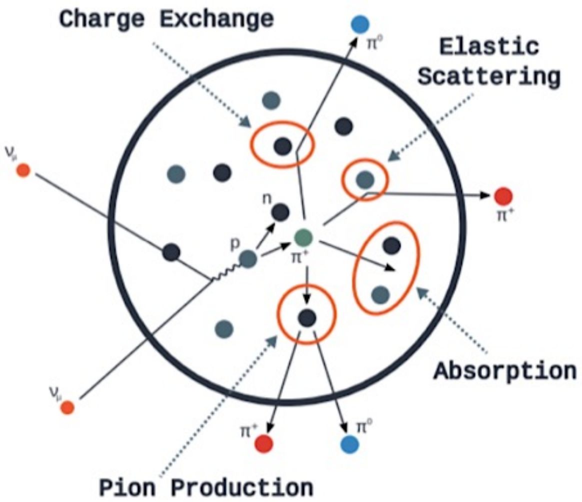
- MINERvA achieved extremely low flux uncertainties constrained using $\nu(\bar{\nu})$-electron scattering and inverse muon decay
    - 3.3% in ν mode, 4.7% in $\bar{\nu}$ mode

Note: POT = protons on target, proxy for the number of neutrinos produced

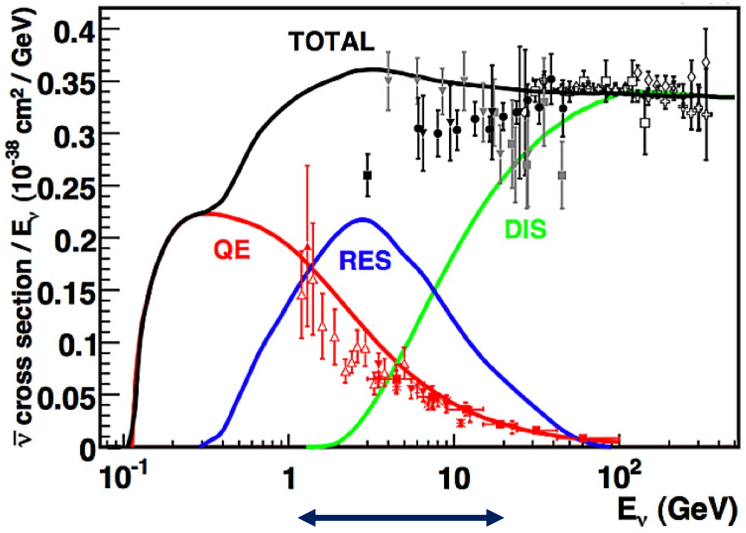
Neutrino Oscillation & Neutrino-Nucleus Interactions

- Oscillation experiments need precise measurements of neutrino energy, but reconstruction depends on the neutrino interaction mode
- Different processes contribute to the cross-section at different neutrino energies
- Measurements of interaction cross-sections are useful for tuning neutrino interaction simulations
- Current and future neutrino oscillation experiments use relatively heavy nuclei: C/CH, H_2O, Ar
- Not well understood nuclear effects cause energy smearing and can modify final-state particle kinematics, complex *A*-dependence

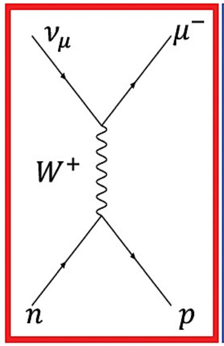
T. Golan, NuSTEC 2015



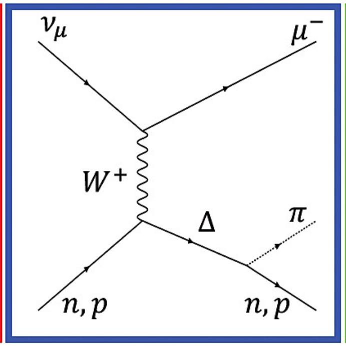
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012).



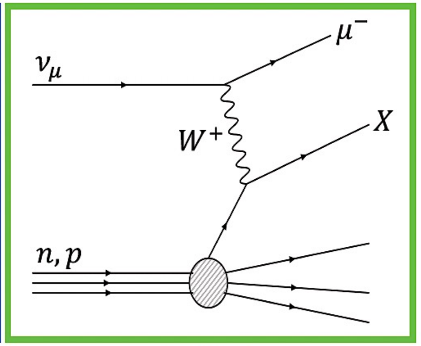
MINERvA



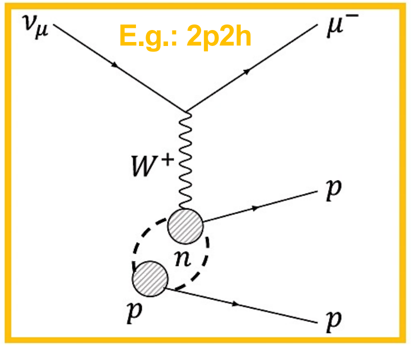
QE



RES

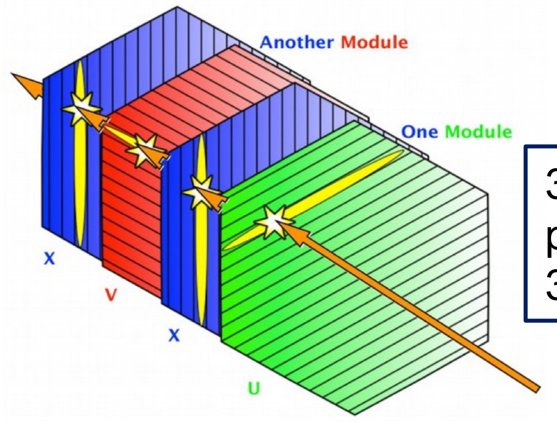


DIS

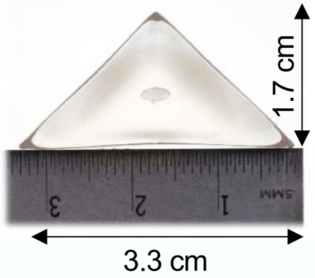


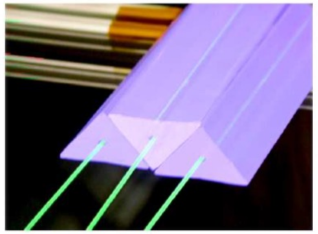
Multi-nucleon effects

MINERvA Detector



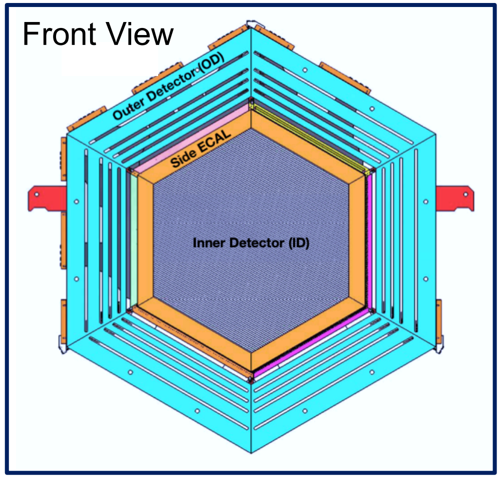
Triangular strips arranged to give a better position resolution.

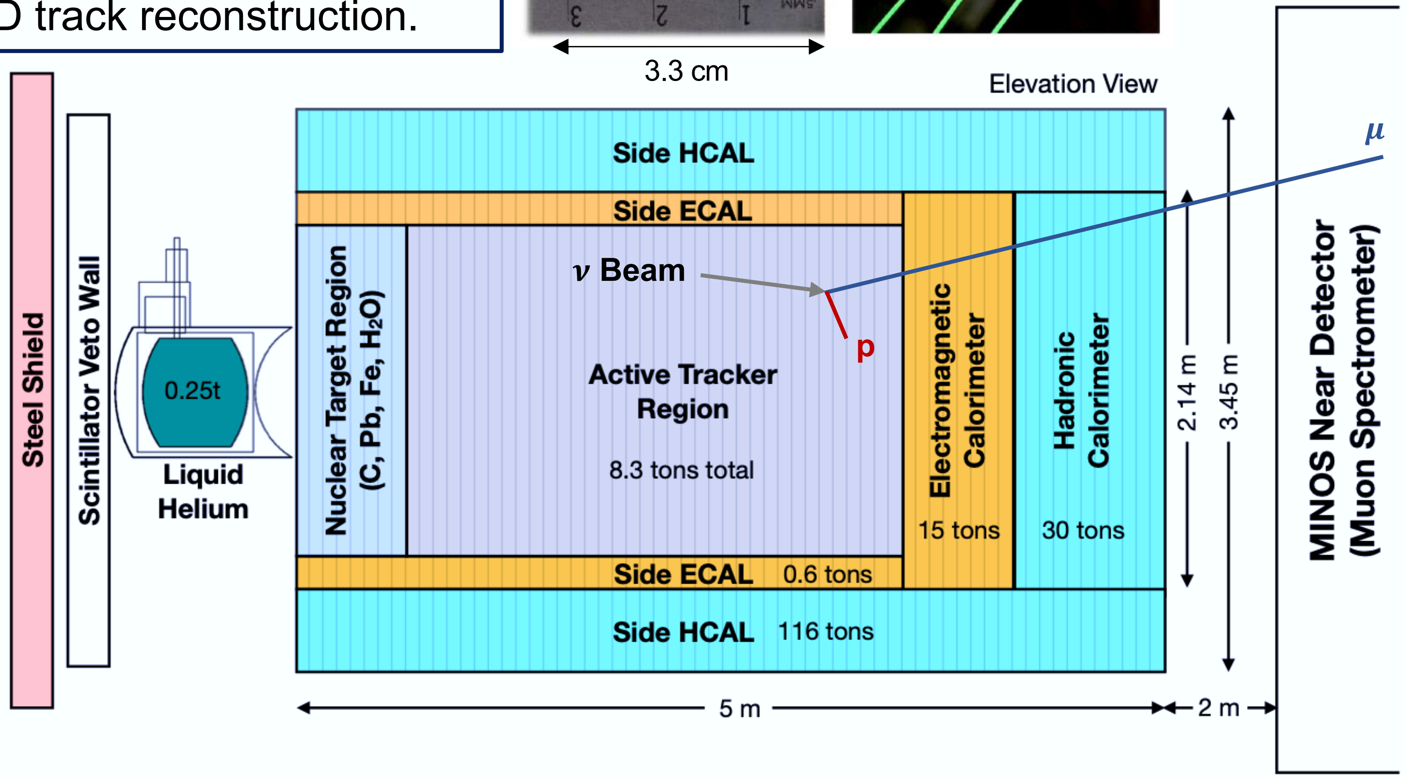




Read out using WLS fibres and PMTs: timing resolution better than ~5 ns to distinguish overlapping events within a single spill (< 10 μs).

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



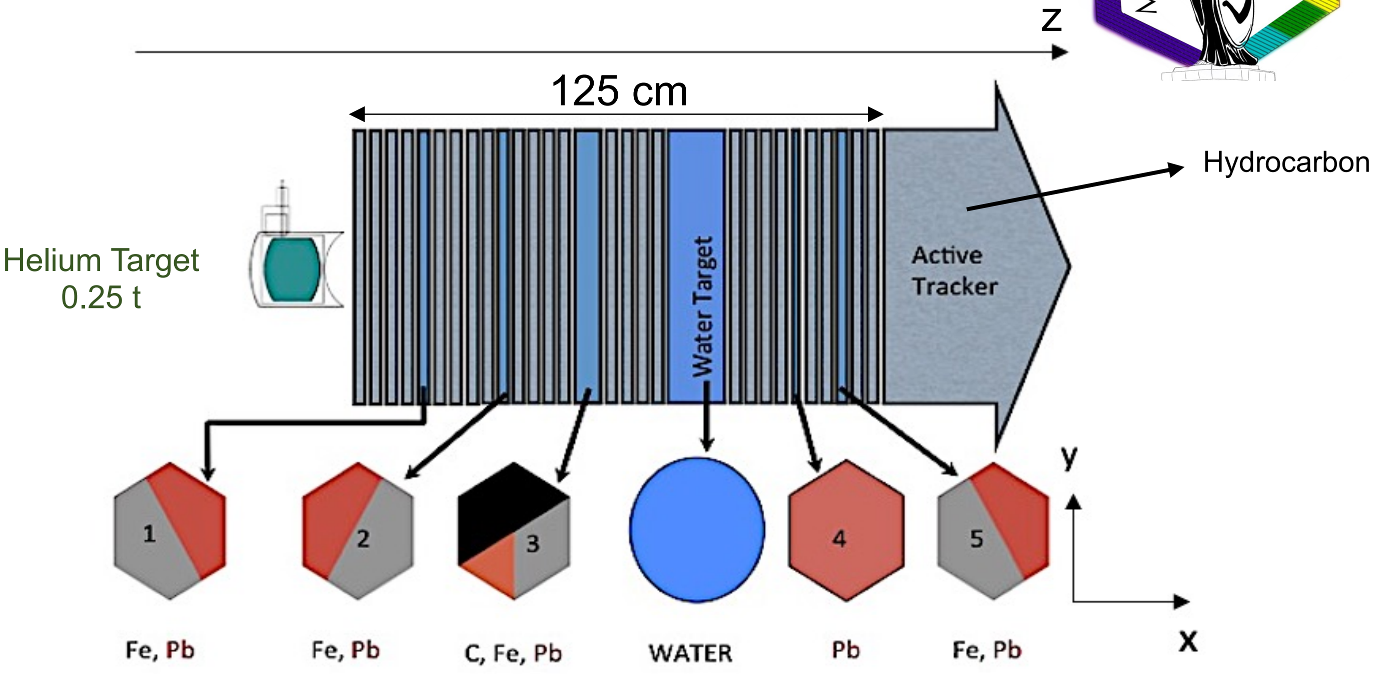


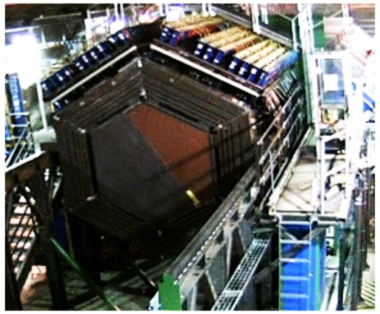
MINOS spectrometer: muon momentum and charge.

MINERvA Detector

Imperial College London

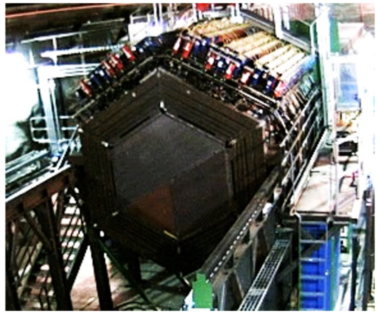
6 different nuclei
in 7 different targets

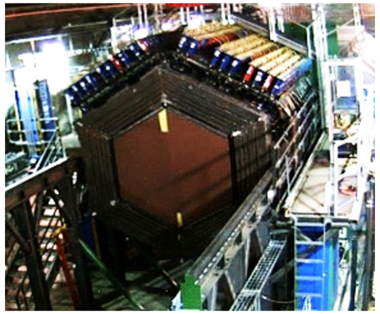




5 Fe / Pb
161 kg / 135 kg

1 Fe / Pb
323 kg / 264 kg





4 Pb
228 kg

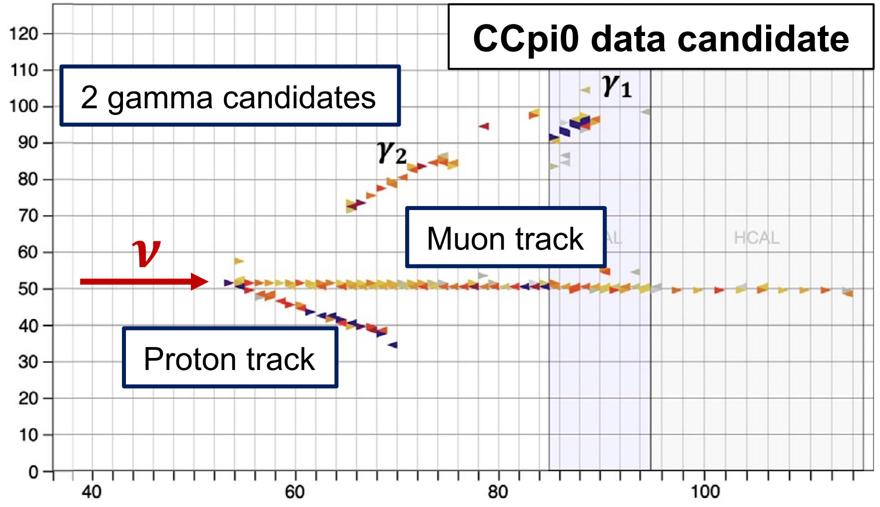
2 Pb / Fe
266 kg / 323 kg

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

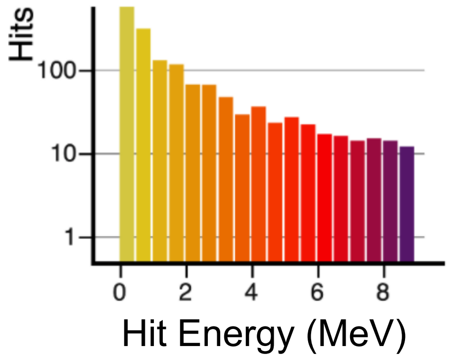
Distilled water
0.39 t

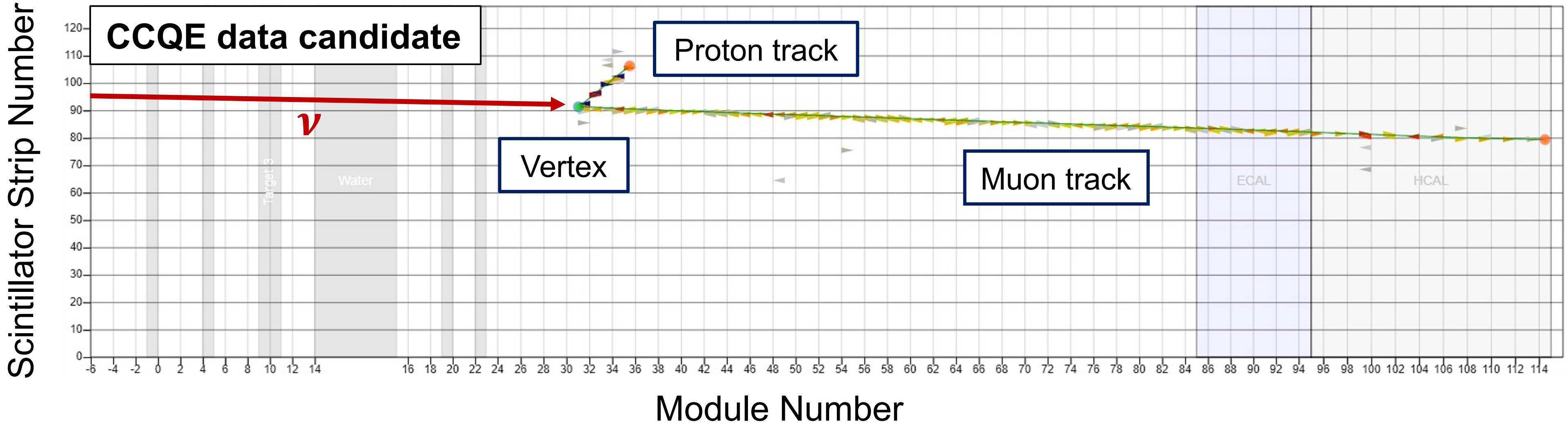
How does MINERvA see?

Imperial College London



- Neutrino energy determined from the final state particles
- Active layers allow for the selection of exclusive final states
- Colour of the track = deposited energy



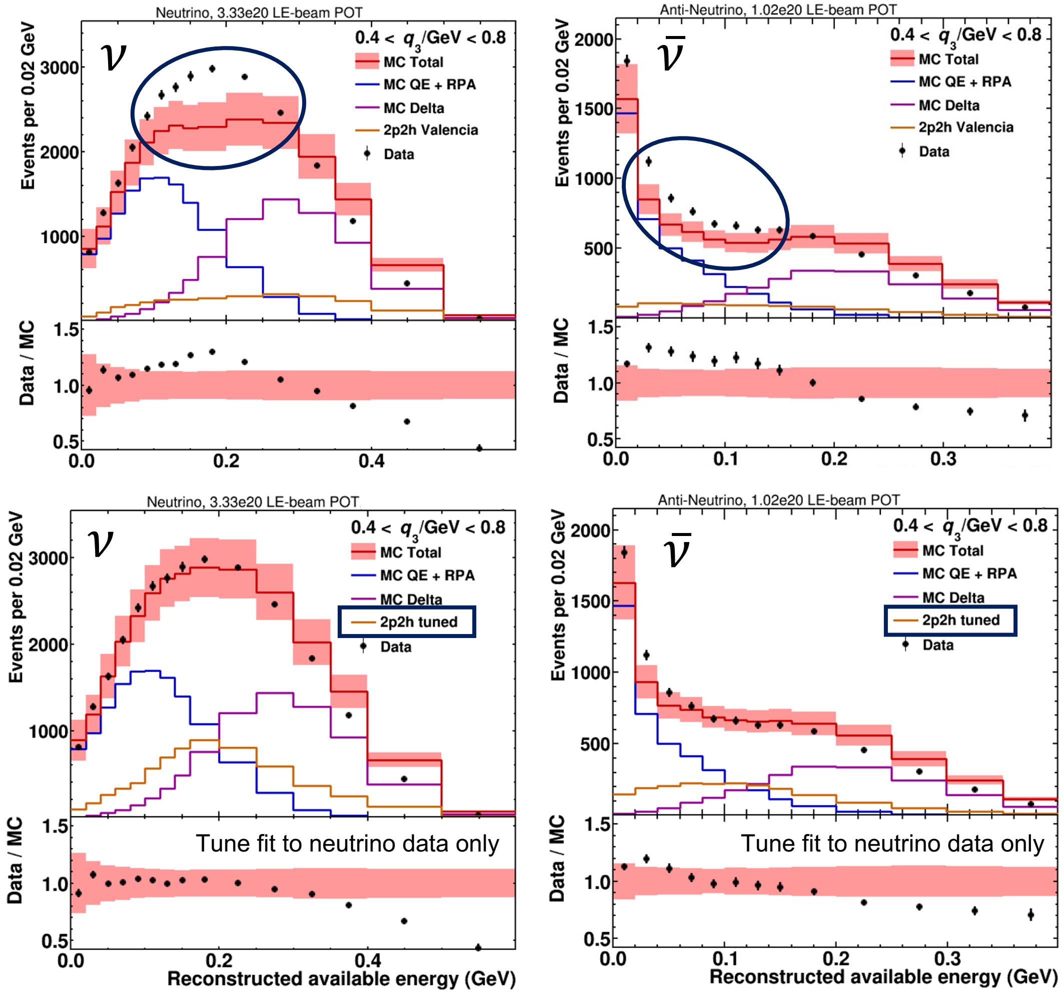


Past Accomplishments

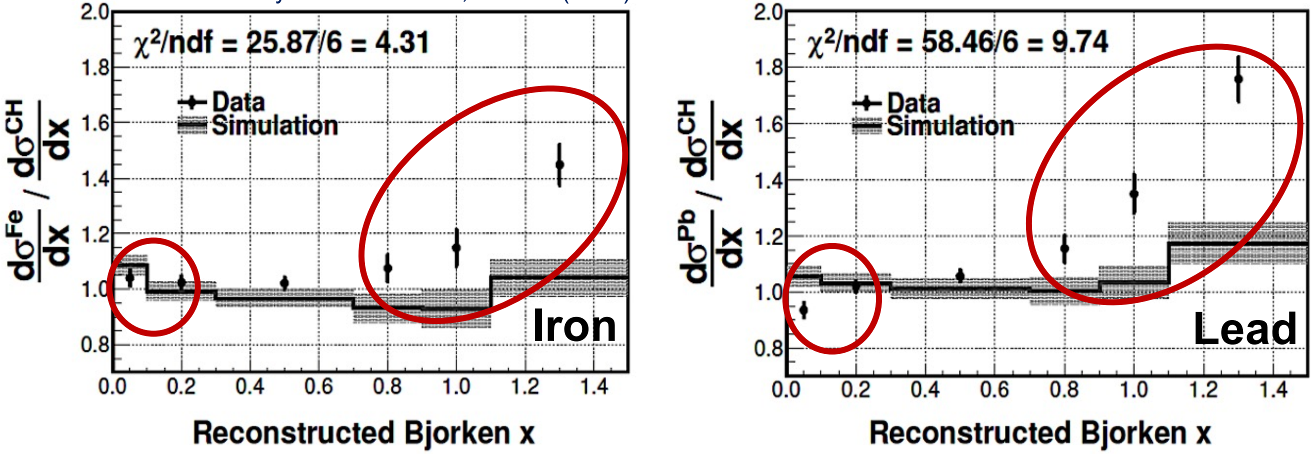
Imperial College London

- Many inclusive and exclusive channel measurements for both $\nu/\bar{\nu}$ quantifying different effects of the nucleus neutrino scattering (LE: 32 publications, ME: 4 publications)
- LE low recoil analysis attributed data excess to the experimental evidence for strong multinucleon effect
- First ever EMC-style measurement of nuclear dependence with multiple nuclear targets in the same beam and detector in LE

P. Rodrigues et al. Phys. Rev. Lett. 116, 071802 (2016).
R. Gran et al. Phys. Rev. Lett. 120, 221805.



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



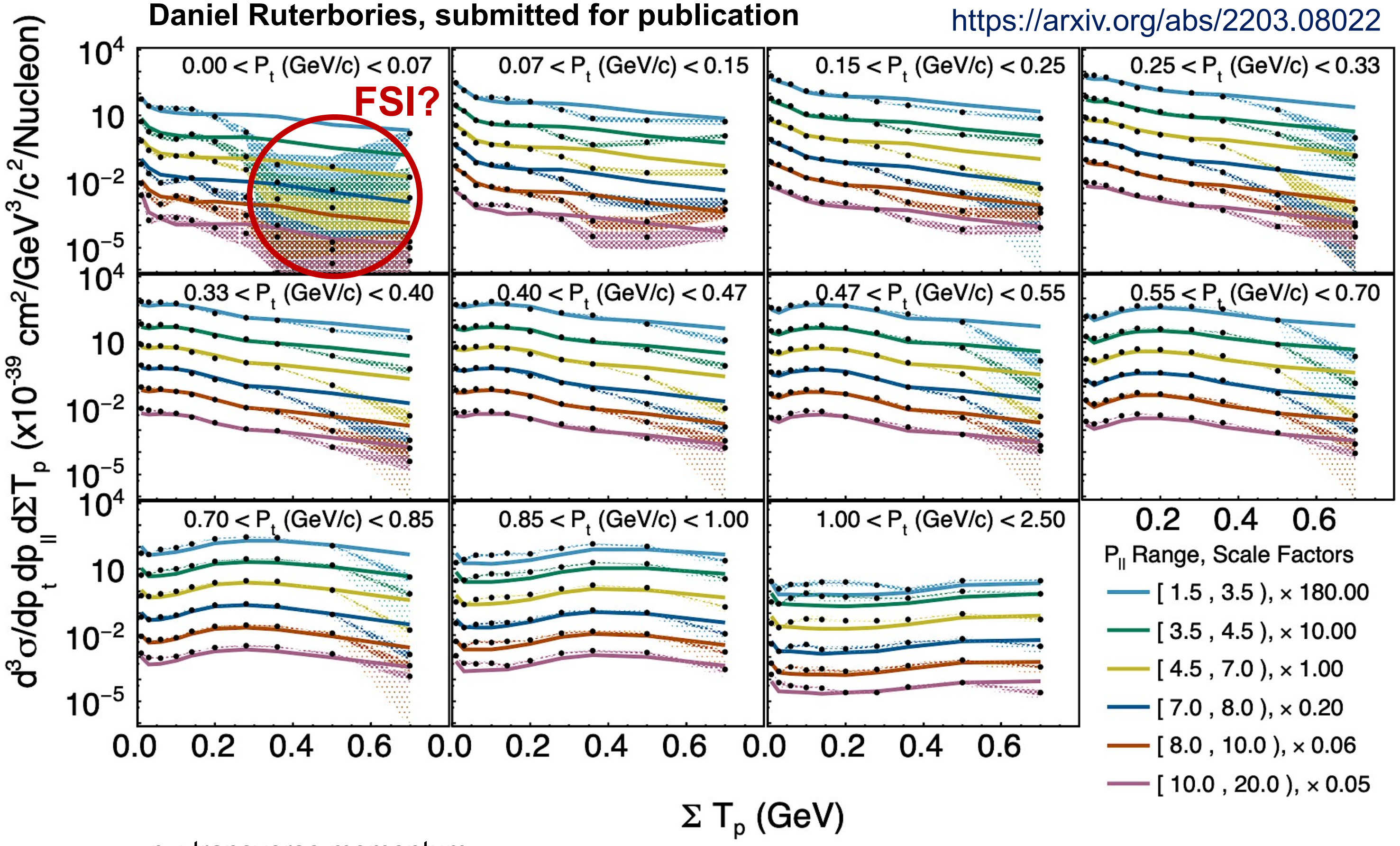
Current MINERvA Physics Programme

Imperial College London

- Analysing data from medium energy
- Many inclusive and exclusive channel measurements for both $\nu/\bar{\nu}$ in progress
- 2 new exciting results recently submitted for publication!
  - Simultaneous muon and hadron 3-dimensional cross sections for ν quasielastic-like scattering on hydrocarbon
  - First measurement of the nucleon axial form factor F_A in antineutrino scattering from hydrogen

Daniel Ruterbories, submitted for publication

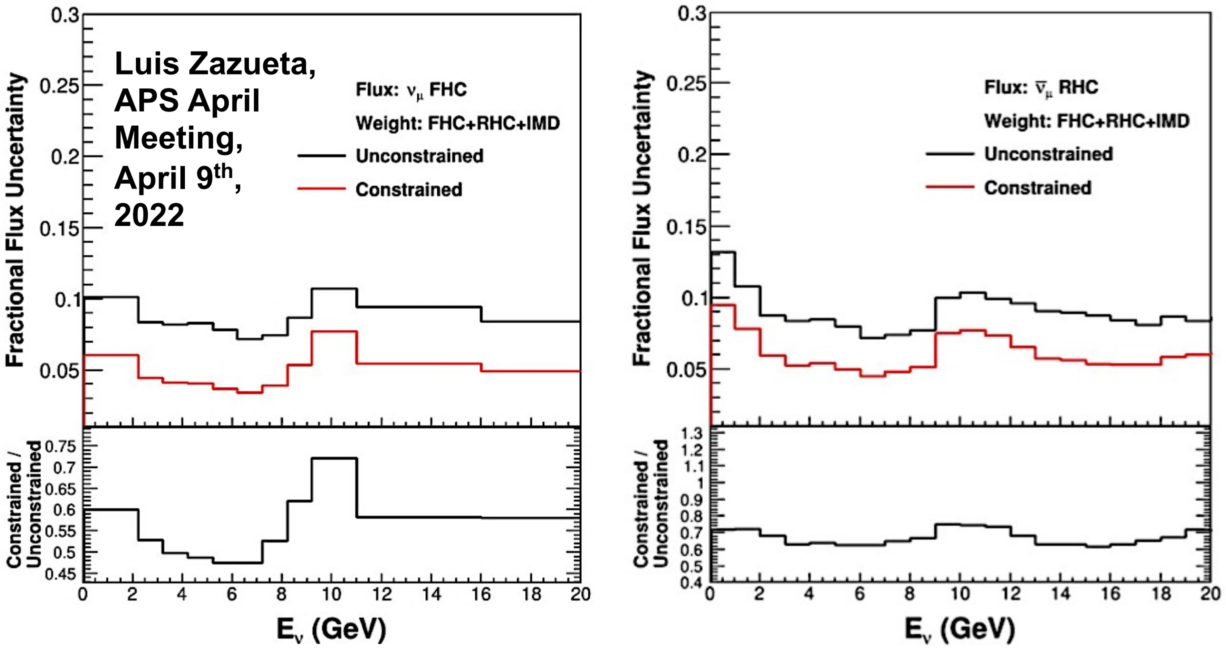
https://arxiv.org/abs/2203.08022



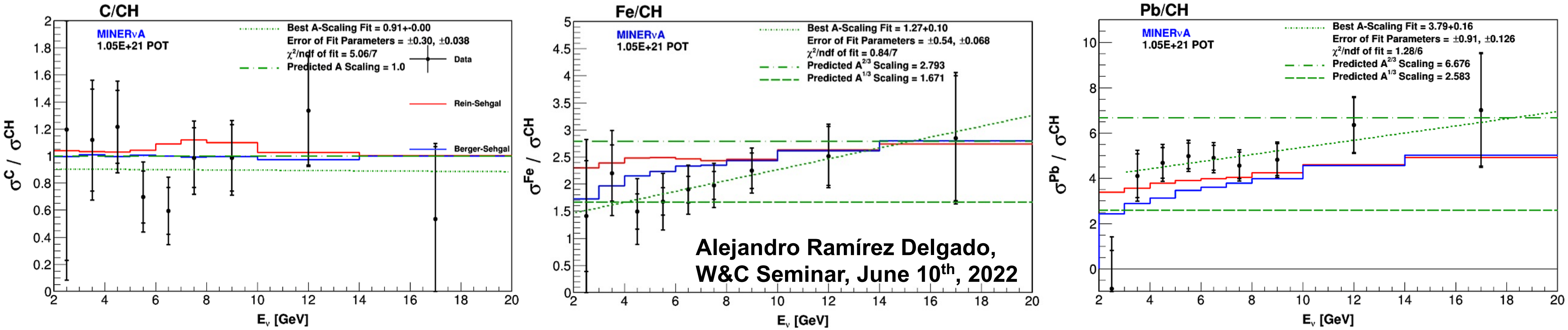
p_T: transverse momentum
$p_{||}$: longitudinal momentum
$\sum T_p$: sum of the kinetic energy of all protons

Current MINERvA Physics Programme

- Hitting the press soon:
  - Flux constraint using $\nu(\bar{\nu})$-electron scattering and inverse muon decay
  - Nuclear target analyses (pion production, QE-like), TKI imbalance
- Data preservation effort to ensure more physics can be extracted from the data



First direct measurement of nuclear dependence of coherent pion production by neutrinos



Outlook & Summary

- MINERvA illuminates the interaction of (anti)neutrinos with bound nucleons in the nuclear environment
- Constrained cross-section modelling is a critical input to oscillation experiments
- MINERvA has been the leading cross-section experiment since 2013 (first publication) with 36 publications in total and counting!
- More results from MINERvA's medium energy incoming
    - More statistics, observables and nuclear dependence measurements
- Future: data available to public (data preservation effort)

Funded by an Imperial College London President's PhD Scholarship.

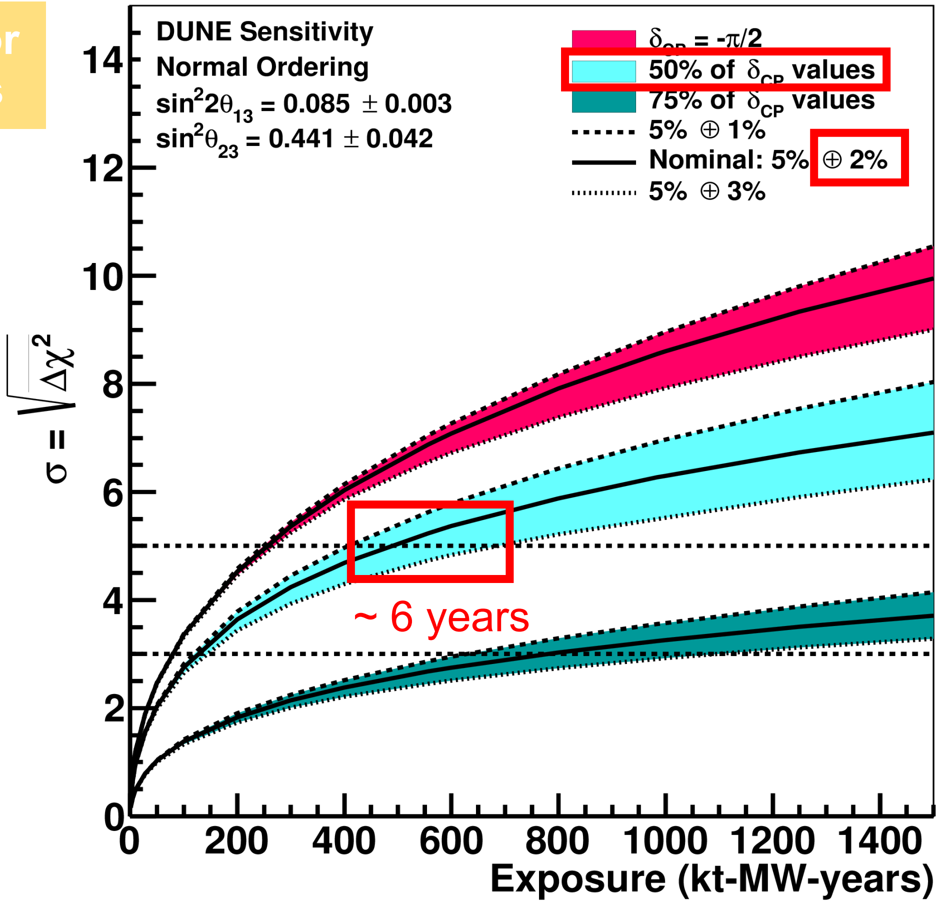
Back-up

Neutrino Oscillation Measurements

 # Far Detector Events = **Flux** **Oscillation Probability** **Cross-section** **Detector Effects**

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

Nature **580**, 339–344 (2020).



What is a Cross-section?

Imperial College London

"Cross Section is the "effective" area subtended by the target particle to an incident beam. It is numerically equal to the reaction rate (N) per target particle (T) per unit incident flux (Φ)."

D. H. Perkins, Introduction to High Energy Physics

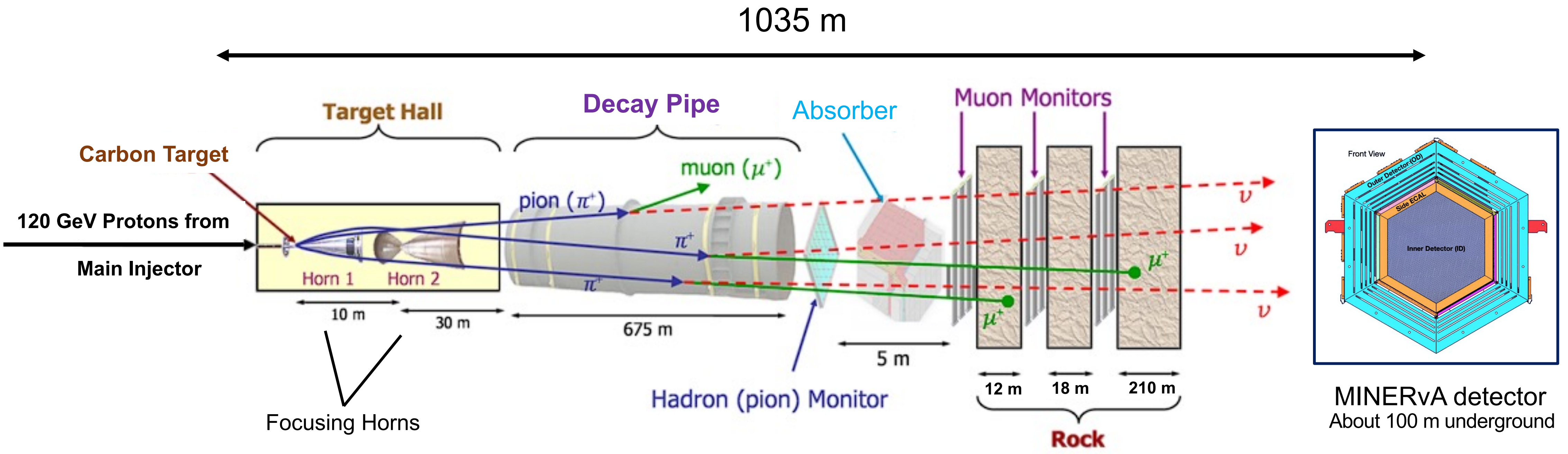
$$\sigma_i = \frac{\Sigma_j U_{ij}(N_{data,j} - N^{bkg}_{data,j})}{\epsilon_i \phi_i T}$$

- σ_i: Total cross-section
- U_{ij}: Unfolding matrix
- $N_{data,j}$: Number of data events
- $N^{bkg}_{data,j}$: Number of background predicted events
- ϵ_i: Efficiency
- ϕ_i: Flux per bin
- T: Number of nuclei

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\Sigma_j U_{ij}(N_{data,j} - N^{bkg}_{data,j})}{\epsilon_i \Phi T (\Delta x)}$$

- Φ: Flux integral between 2 and 120 GeV
- (Δx): Bin width normalization

NuMI Beamline



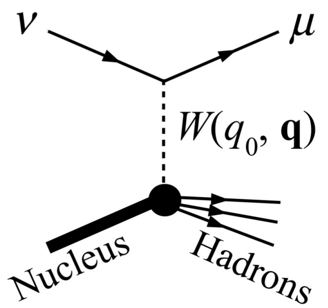
$$\pi^\pm \rightarrow \mu\nu_\mu$$
$$K^\pm \rightarrow \mu\nu_\mu$$

Definitions of Variables

Low Recoil Analysis

- Three-momentum transfer

$$q_3 = \sqrt{Q^2 + q_0^2} \quad \text{where} \quad Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_\mu\right) - M_\mu^2 \quad \text{and} \quad E_\nu = E_\mu + q_0$$



- Available energy as energy transfer proxy (no neutrons included)

$$q_0 \sim E_{avail} = \sum T_p + \sum T_{\pi^\pm} + \sum E_{K^\pm} + \sum E_{e^\pm} + \sum E_{\pi^0} + \sum E_\gamma$$

Bjorken x

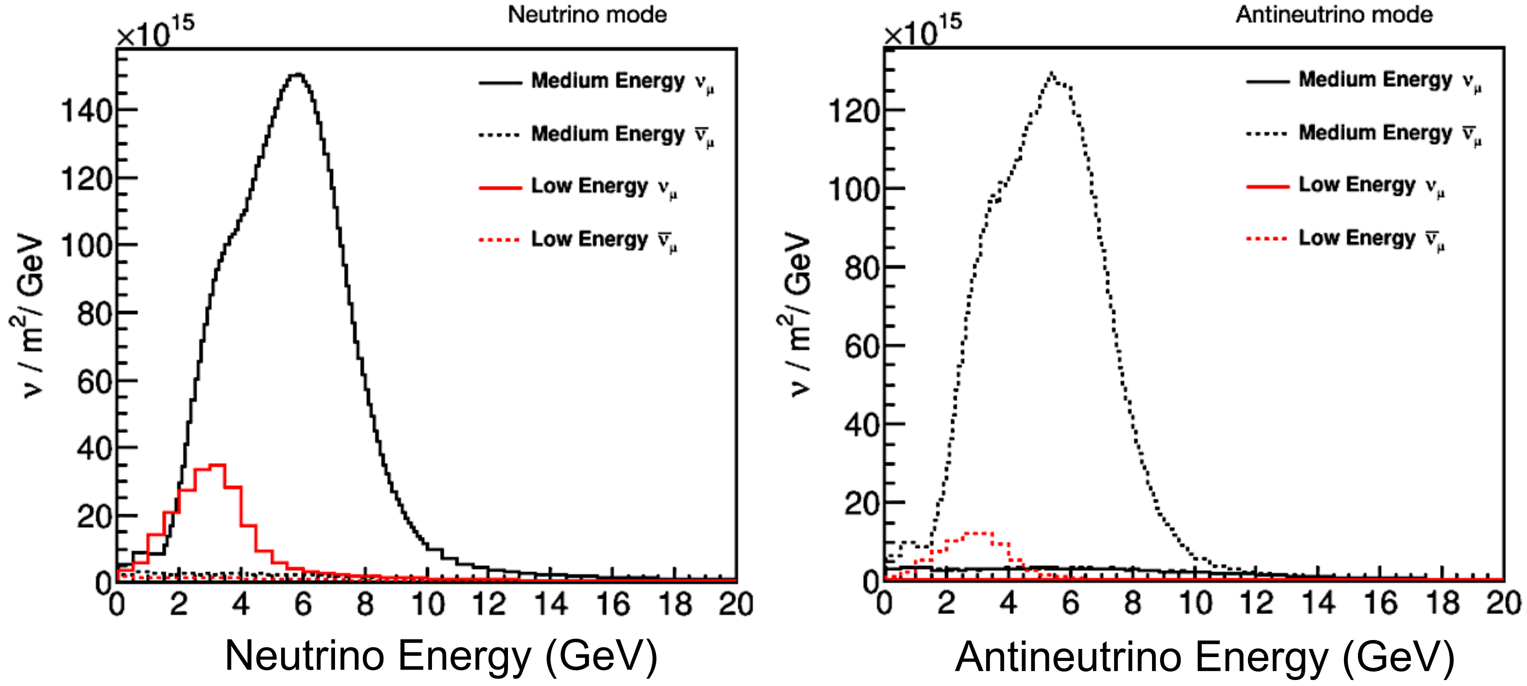
- Fraction of the nucleon’s momentum carried away by the struck quark

$$x = Q^2/2M_N(E_\nu - E_\mu)$$

Flux

Flux $\Phi\ (E_\nu)$ is the number of neutrino produced by the accelerator per cm^2, per bin of energy for a given number of protons on target.

- A-priori flux accounts for focusing and hadron production uncertainties
  - Corrected for hadron production to constrain with external hadron production data
- In-situ measurements are used to apply an additional constraint from the neutrino-electron scattering events and inverse muon decay (IMD)



Flux Constraint

Imperial College London

- Standard candle: neutrino electron scattering – cross-section well understood by standard electroweak scattering theory
- Discrepancies between data and MC predictions → due to mismodeling of the flux distribution

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

Posterior probability distribution can be reconstructed by weighting prior universes by likelihood.

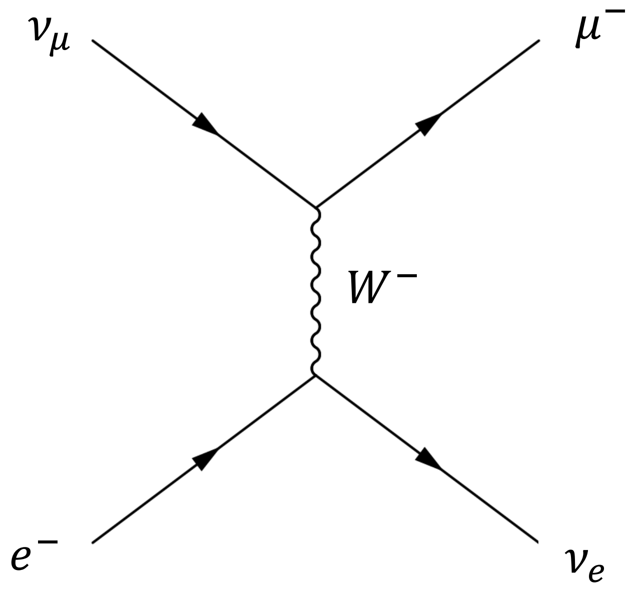
Predicted electron energy spectrum for each universe (model) in which we propagate the flux uncertainties.

Likelihood of data given model.

Inverse Muon Decay (IMD)

https://arxiv.org/abs/2107.01059

- Cross-section can be predicted with very small uncertainties
- Threshold of ≈ 11 GeV (indistinguishable process $\bar{\nu}_e\, e^- \rightarrow \mu^- \bar{\nu}_\mu$ unimportant in MINERvA due to threshold)
- Can constrain the high-energy part of the flux in the NuMI neutrino beam

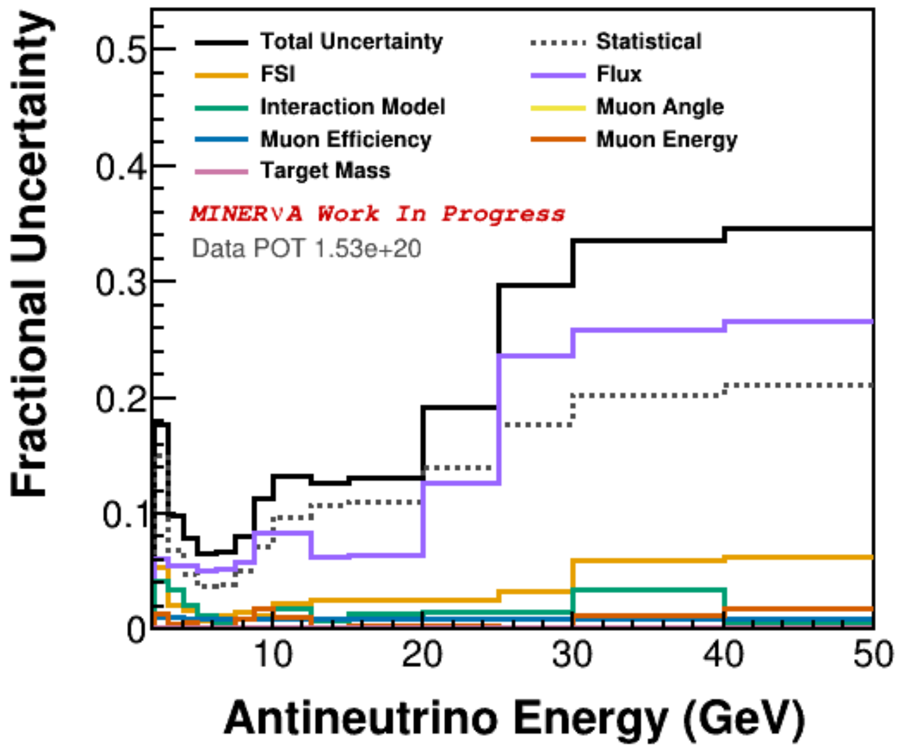


Systematic Uncertainties

An Error Analysis Toolkit for Binned Counting Experiments. EPJ Web of Conferences **251**, 03046 (2021). https://doi.org/10.1051/epjconf/202125103046

- Handled by MINERvA Analysis Toolkit (MAT), a utility for centralizing the handling of systematic universes
- Evaluated by re-extracting the event rate/cross-section using modified simulations
  - Size of each related to the uncertainty in each source
  - Multidimensional histogram container class MnvHnD (@MinervaExpt on GitHub)

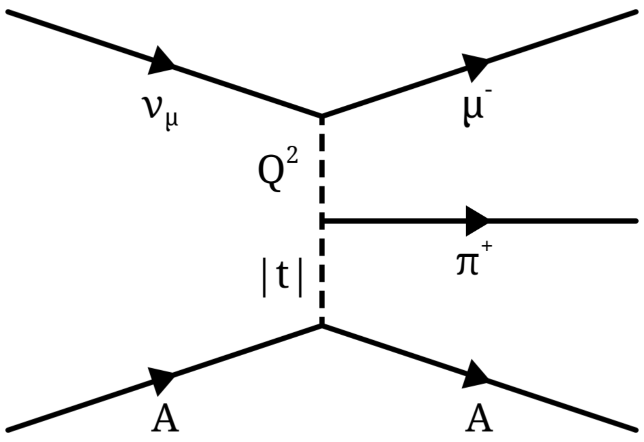
Example of data cross-section uncertainty in inclusive analysis in target 3 iron



Equivalent to 1/8 of total data POT and 1/4 of target 2-5 iron mass.

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 $\nu A \to l\pi A$ to elastic $\nu A \to lA$, 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 $\pi A \to \pi A$ 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