First high statistics measurement of Deep Inelastic Scattering Cross Sections on Iron, Lead, Carbon, and hydrocarbons (CH) with MINERvA

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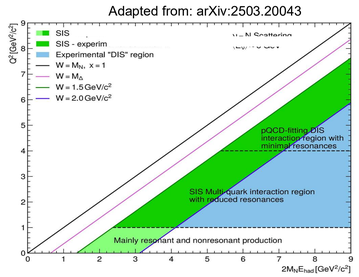
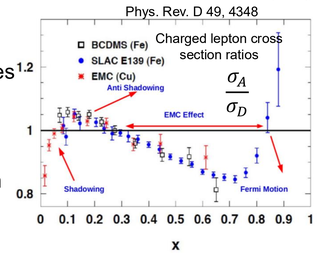
1. Physics Motivation

A poorly understood and critical kinematic regime:
Precise modeling of neutrino CC cross sections in the few-GeV, higher-W, low-to-moderate Q² regime is critical for current and future oscillation experiments. Nuclear medium effects and mostly unexplored partonic dynamics significantly impact observed final states.



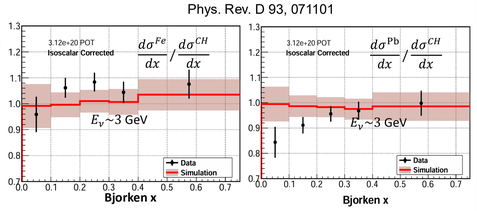
Nuclear Medium effects at MINERvA:

- EMC study using the $\nu/\bar{\nu}$ with nuclear targets C, Fe, Pb.
- **Low Energy** (~3 GeV) stat. limited: 3450 DIS events.
- **Medium energy** (~6 GeV) results with better precision:
  - MINERvA uniquely positioned to provide data vs A, enabling extrapolation to DUNE's argon target.
  - Higher energy opening more phase space to explore processes including Shallow Inelastic (SIS) & Deep Inelastic Scattering.
  - Improved vertex reconstructed with deep convolutional neural net.
  - Improved neutrino flux determination (PPFX, neutrino-electron scattering, low nu).



Why Bjorken x: $X = \dfrac{Q^2}{2M_N E_{had}}$

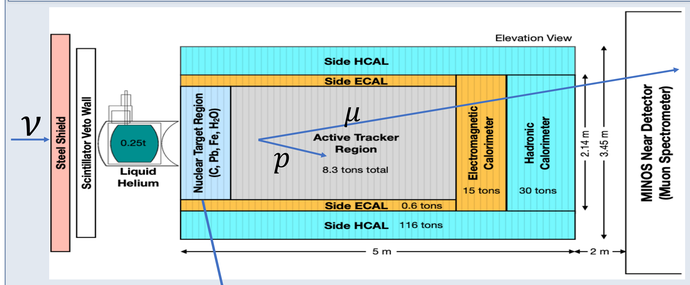
- Fraction of the nucleon's momentum carried by the struck parton (quark).
- In **DIS** at high energies, structure functions depend primarily on x.
- Used to map the parton distribution functions inside nucleons and nuclei.

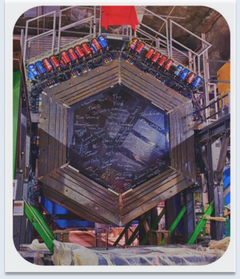


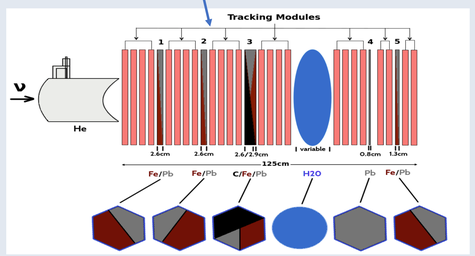
2. The MINERvA Experiment

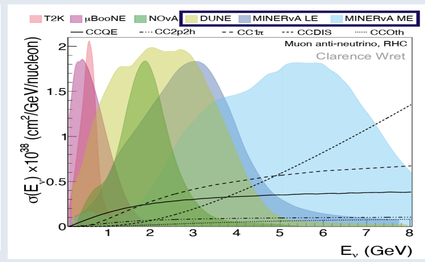
MINERvA detector, Fermilab

- Precision neutrino–nucleus scattering measurements with high-statistics data samples.
- Nuclear targets: C, Fe, Pb, and CH (Scintillator region).
- Fine-grained CH scintillator tracker serving as the active detector region.
- Muon momentum and charge determined using the MINOS near detector.









3. Event Selection

Signal: $Q^2 > 1$ GeV², $W > 2$ GeV (experimentally defined DIS)

$$\nu_\mu(\bar{\nu}_\mu) + A \rightarrow \mu^-(\mu^+) + X$$

C, Fe, Pb, CH

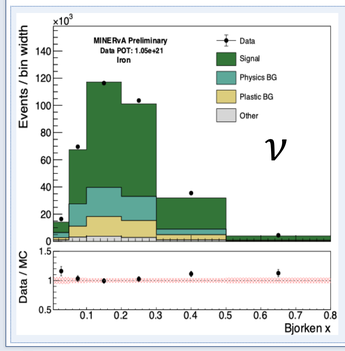
$2\ GeV \leq E_\mu \leq 40\ GeV$
$\theta_\mu < 17^0$
Q^2 & W cuts

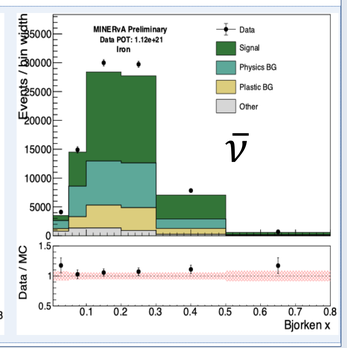
Two types of Backgrounds:

- Plastic scintillator:
  - Events that come from plastic scintillator surrounding the nuclear targets
- Physics:
  - Low W "transition" events
  - Low Q^2 "continuum" events

ν & $\bar{\nu}$ events in the medium energy

C: 12k	C: 3k
Fe: 34k	Fe: 8k
Pb: 40k	Pb: 9k
CH: 254k	CH: 66k

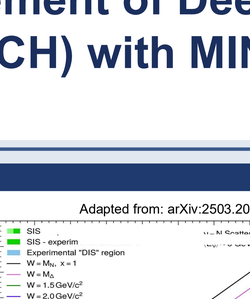


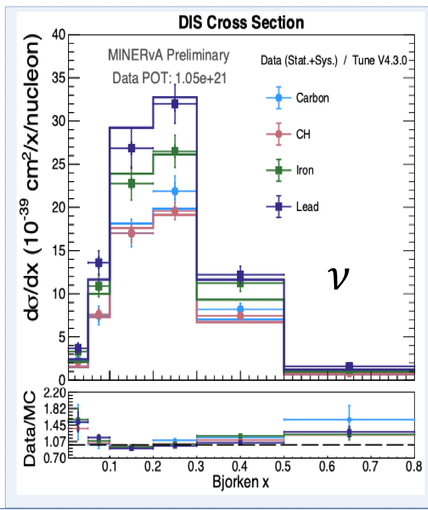


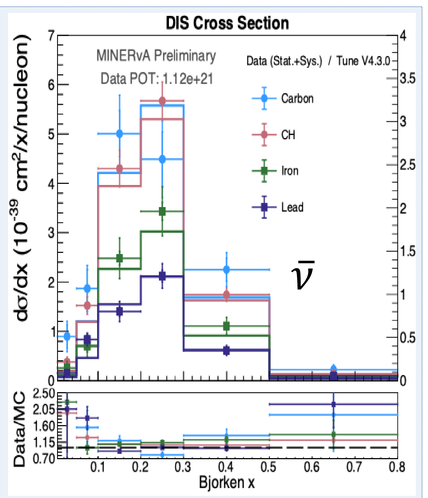
4. CC High-W Cross-Section Measurements

First high W charged current (CC) measurements ($Q^2 > 1$ GeV², $W > 2$ GeV) on C, Fe, Pb & CH:

- MINERvA Tune V4.3.0: GENIE 2.12.6 with local modifications based on MINERvA and bubble chamber chamber data:
  - Valencia RPA, Valencia 2p2h enhanced based on our low-recoil data, Non-Resonant Pion production, etc.
- Per-nucleon cross sections as a function of Neutrino Energy and Bjorken x
- Model under-predicts the data, especially in low and high of x.
- Consistent shape in Bjorken x across all nuclear targets and in both neutrino and antineutrinos.



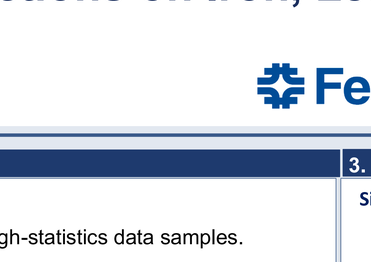


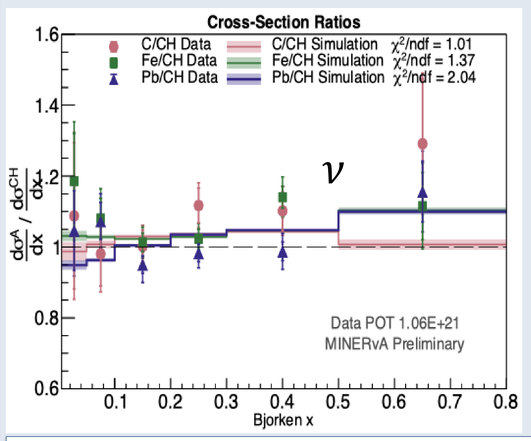


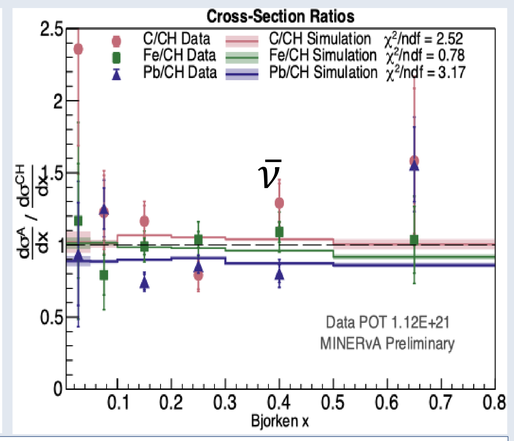
5. Nuclear Cross-Section Ratios A/CH

Ratios: $\dfrac{d\sigma^A}{dx} / \dfrac{d\sigma^{CH}}{dx}$

- C/CH ratios expected to be close to unity: used as a sanity check
  - Good agreement within the uncertainties.
- Data in agreement with simulation within the uncertainties.
- Data shows minimal Fe/Pb variation beyond predicted neutron excess effects.





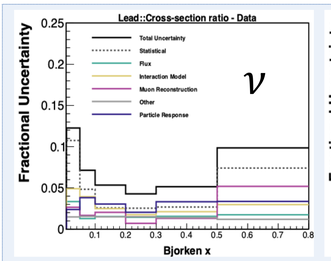


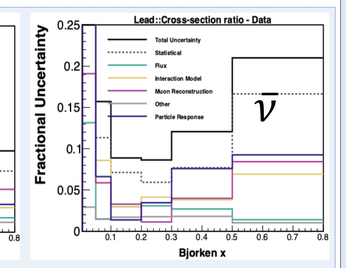
- **Note**: EMC study is with the charged lepton cross section and the current study is via weak interaction.

6. Systematic Uncertainties

Fractional uncertainty on Pb cross section vs. Bjorken x:

- Cancellation of correlated systematics
  - Direct insight into nuclear effects
- Statistics is one of the dominant uncertainties especially in antineutrinos.





7. Summary & Conclusions

- MINERvA's high precision CC cross-section measurements ($Q^2 > 1$ GeV², $W > 2$ GeV) on C, Fe, Pb and CH.
- Nuclear dependence measured as a function of Bjorken-x.
- Results relevant to DUNE, probing neutrino interactions in a similar energy range and on nuclear targets (C, Fe, Pb) that bracket argon in atomic mass.
- Improved nuclear and low-Q^2 descriptions needed in neutrino interaction generators.
- MINERvA has opened its data for the community, so, anyone with the right tools can do a full data analysis.

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