

The EMC Effect for Tritium and Helium-3 from JLab's MARATHON Experiment using DIS.

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Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory.

Jefferson Lab's unique and exciting mission is to expand humankind's knowledge of the universe by **studying the fundamental building blocks of matter** within the nucleus: subatomic particles known as **quarks and gluons**.

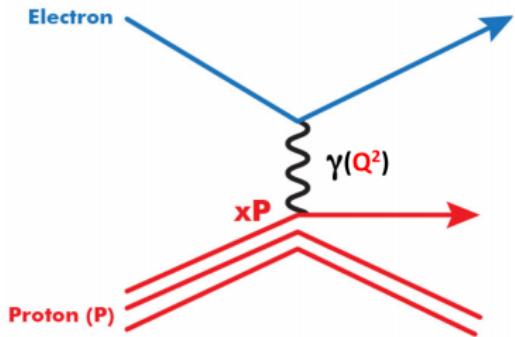


More than 1,500 nuclear physicists worldwide come to Jefferson Lab to conduct and collaborate on research.

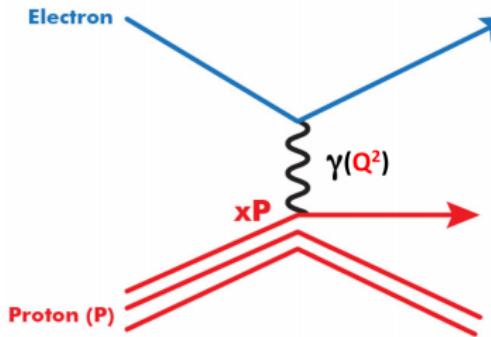
Outline

- Deep Inelastic Scattering
- The EMC Effect
- The MARATHON Experiment
- Data Analysis
- EMC Effect of $A=3$

Deep Inelastic Scattering (DIS)

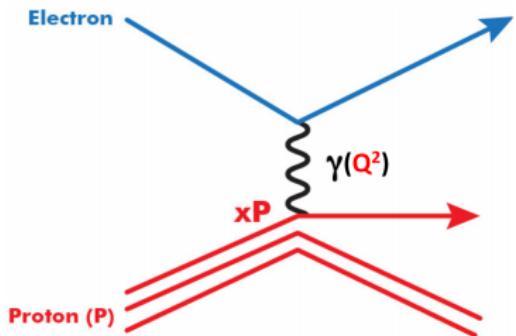


Deep Inelastic Scattering (DIS)



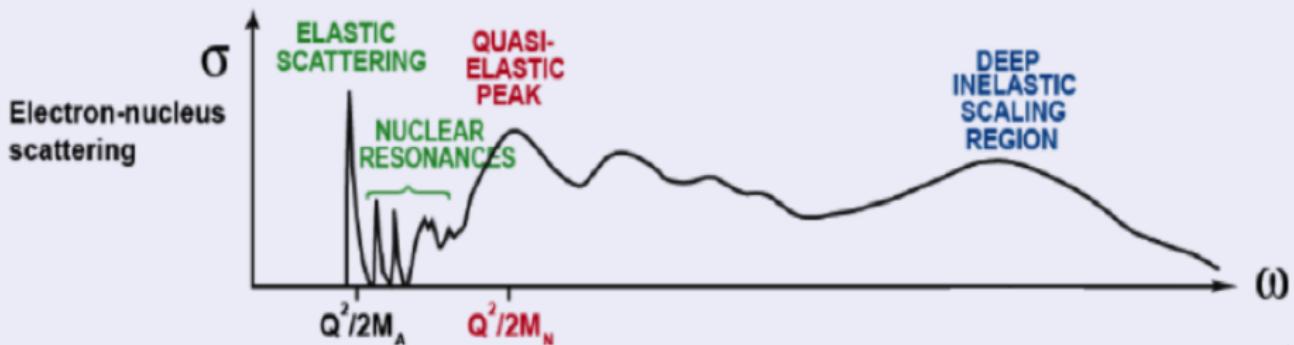
- $Q^2 \equiv 4EE' \sin^2 \frac{\theta}{2}$
- $\nu \equiv E - E'$

Deep Inelastic Scattering (DIS)

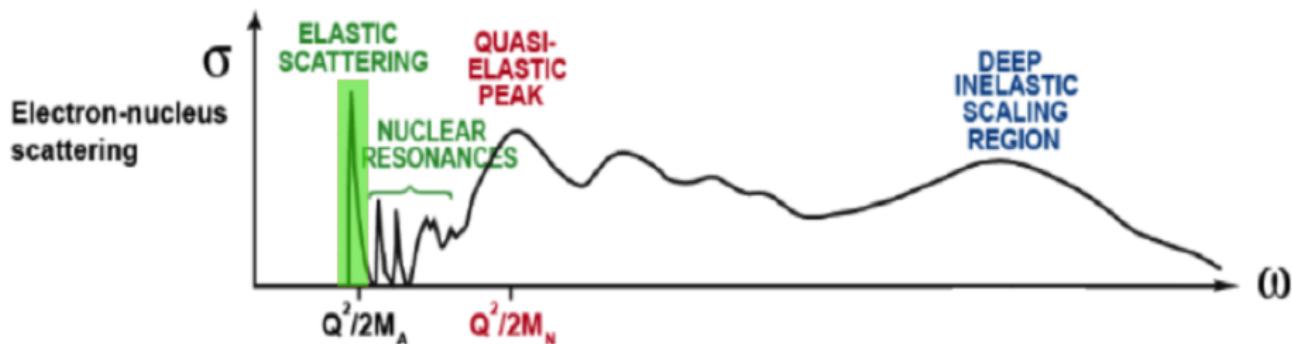


- $Q^2 \equiv 4EE' \sin^2 \frac{\theta}{2}$
- $\nu \equiv E - E'$
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $W^2 = 2M\nu + M^2 - Q^2$
- $W^2 > 4 \rightarrow \text{DIS}$

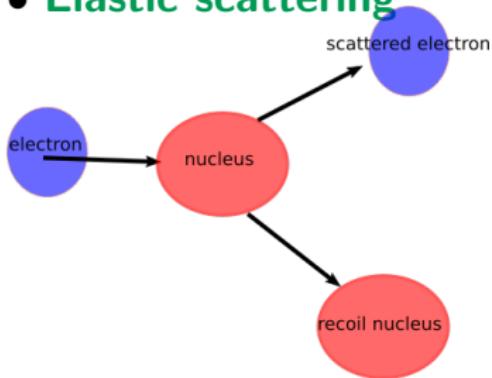
DIS ??????

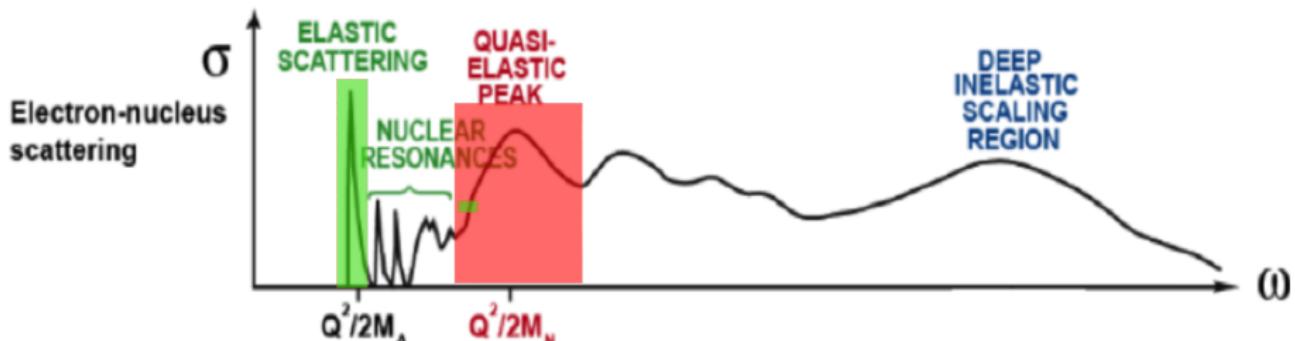


Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].

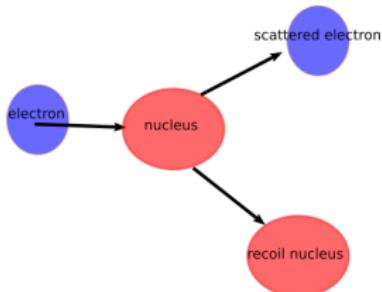


- Elastic scattering

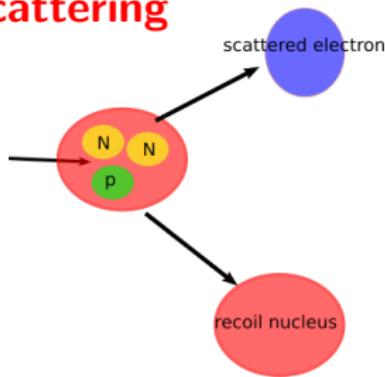


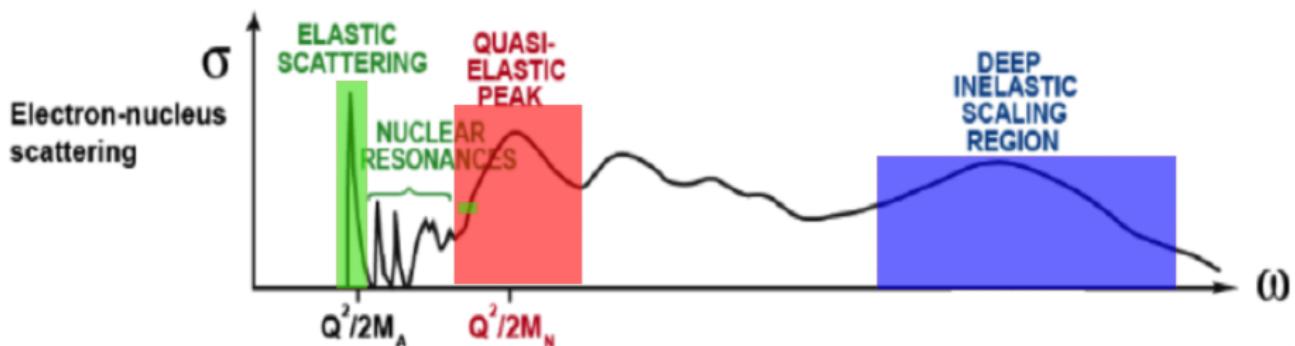


- Elastic scattering



- Quasielastic scattering

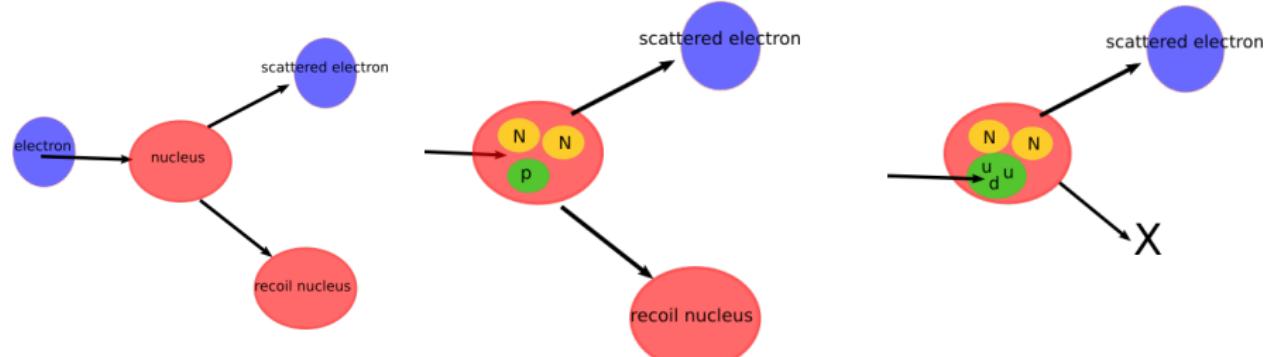




- **Elastic scattering**

- **Quaiselastic scattering**

- **DIS**

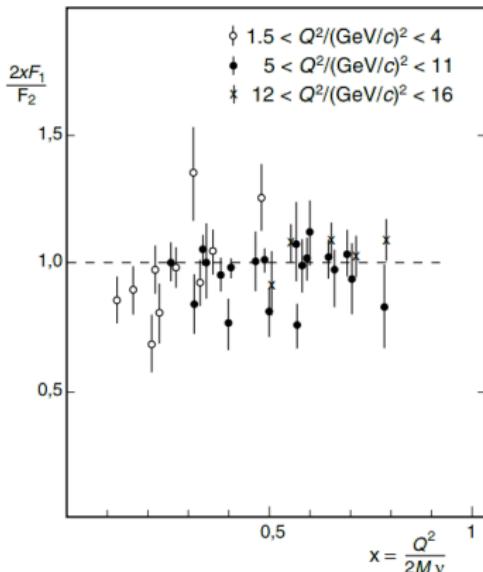


Why DIS?

$$\sigma_{eN} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)} \left[\frac{F_2(x)}{\nu} \cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(x)}{M} \sin^2\left(\frac{\theta}{2}\right) \right]$$

Quark parton model

- $F_2(x) = x \cdot \sum_i z_i^2 f_i(x)$
- $F_1(x) = 1/2 \cdot \sum_i z_i^2 f_i(x)$
- **Spin 1/2 quarks**
 $F_2(x) = F_1(x) \cdot 2x$

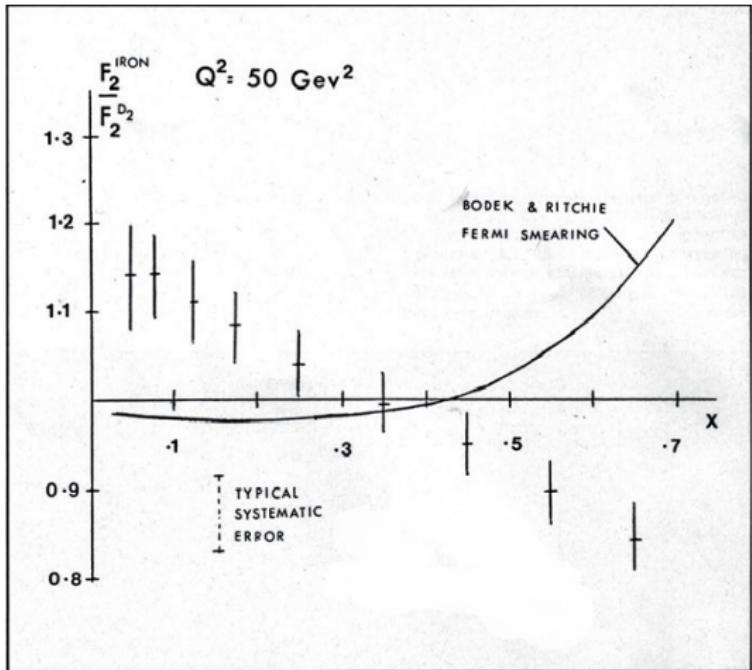


Ratio of $2x \cdot F_1(x)$ and $F_2(x)$ vs. x .
[Povh, 1995]

The EMC Effect

European Muon Collaboration

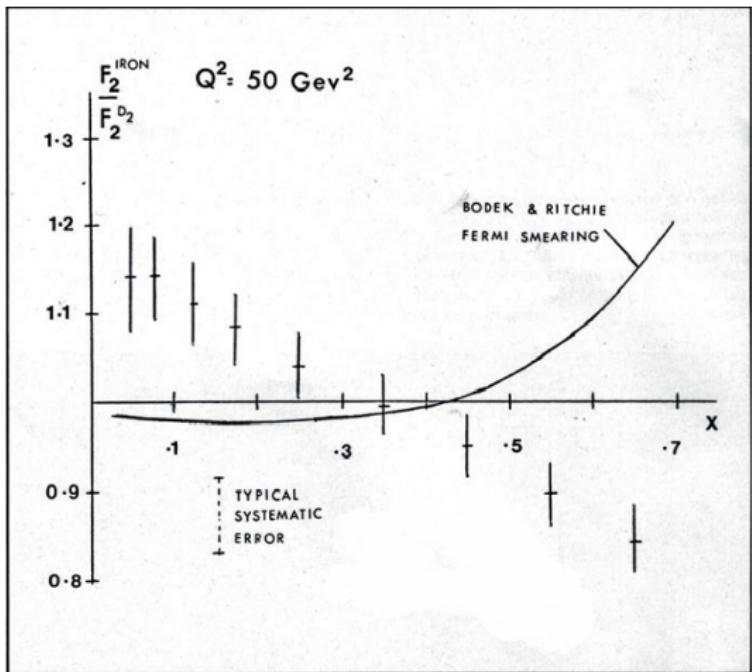
- X = fraction of momentum carried by quark



[Aubert, J.J. et al. 1981]

The EMC Effect

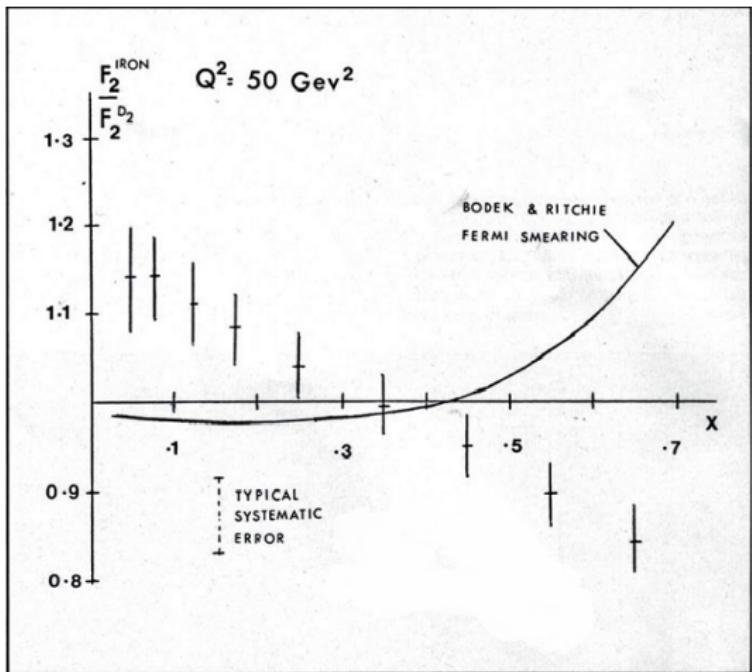
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[Aubert, J.J. et al. 1981]

The EMC Effect

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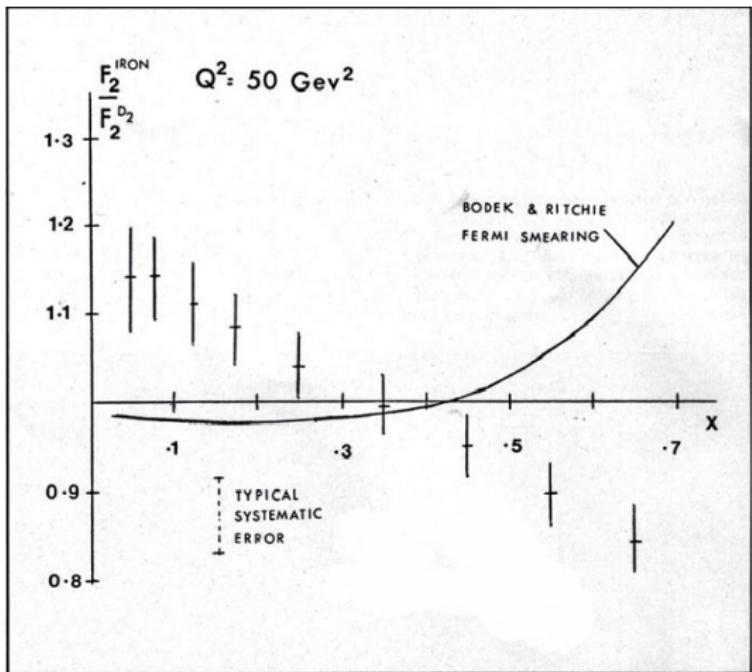


[Aubert, J.J. et al. 1981]

- X = fraction of momentum carried by quark
- Expected Unity at low x
 - ▶ Binding < momentum transfer
 - ▶ Free Nucleons
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$

The EMC Effect

European Muon Collaboration

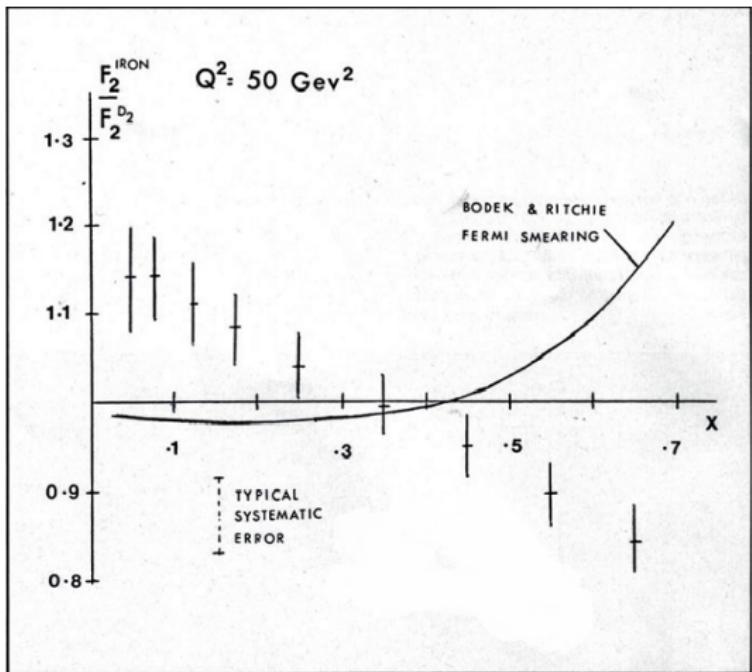


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- Unexpected Relative Decrease
- Missing high-momentum quarks in $A > 2$

The EMC Effect

European Muon Collaboration

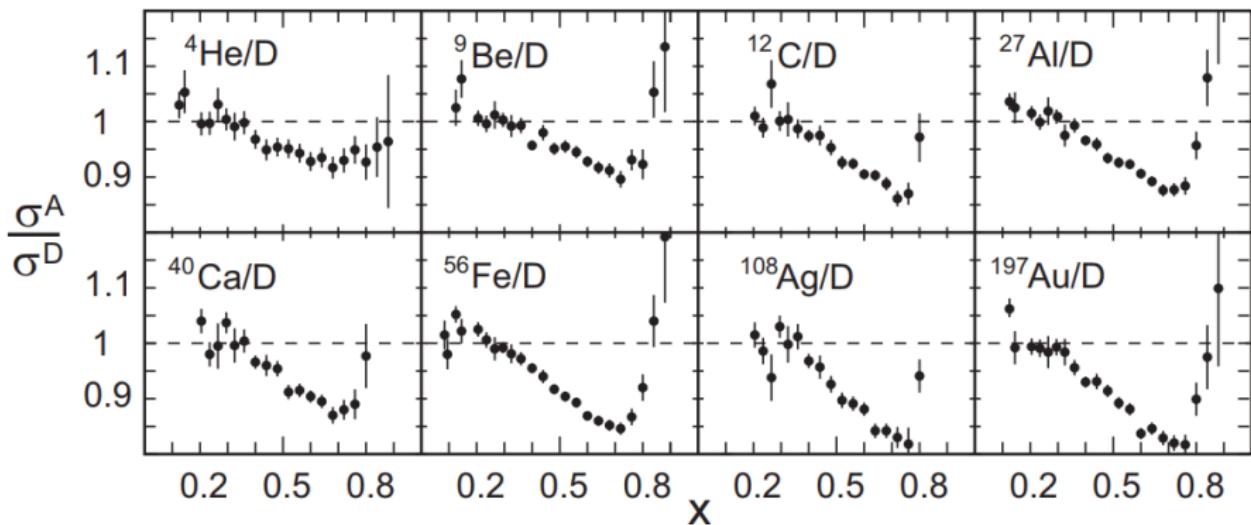


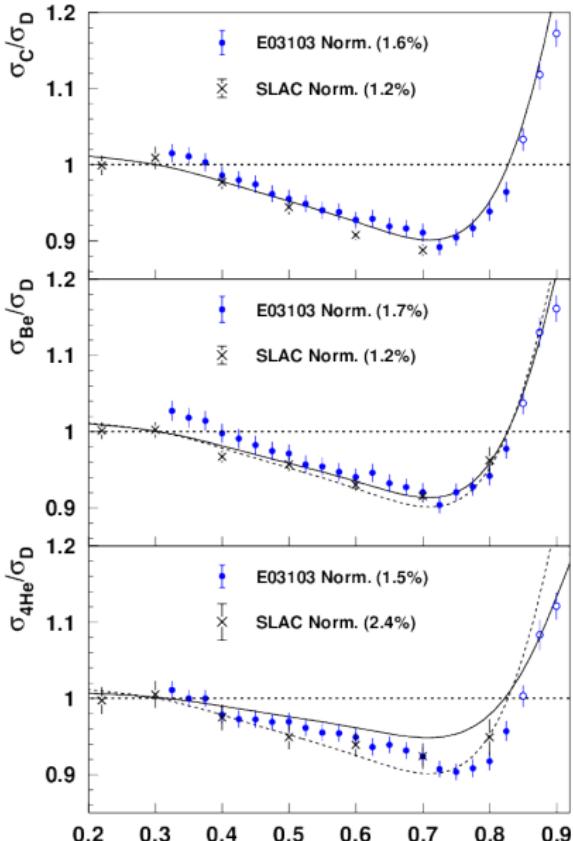
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- Unexpected Relative Decrease
- Missing high-momentum quarks in $A > 2$
- EMC Effect \equiv structure of the A/D Ratio

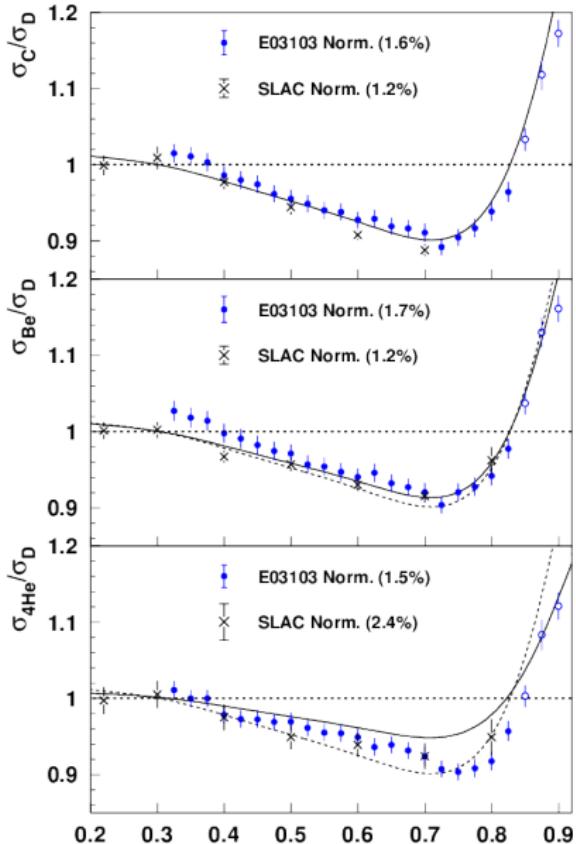
The EMC Effect

SLAC experiment E139 [J. Gomez et al., 1994] .





- JLab experiment E03103
[J.Seely, A. Daniel et al, 2009]

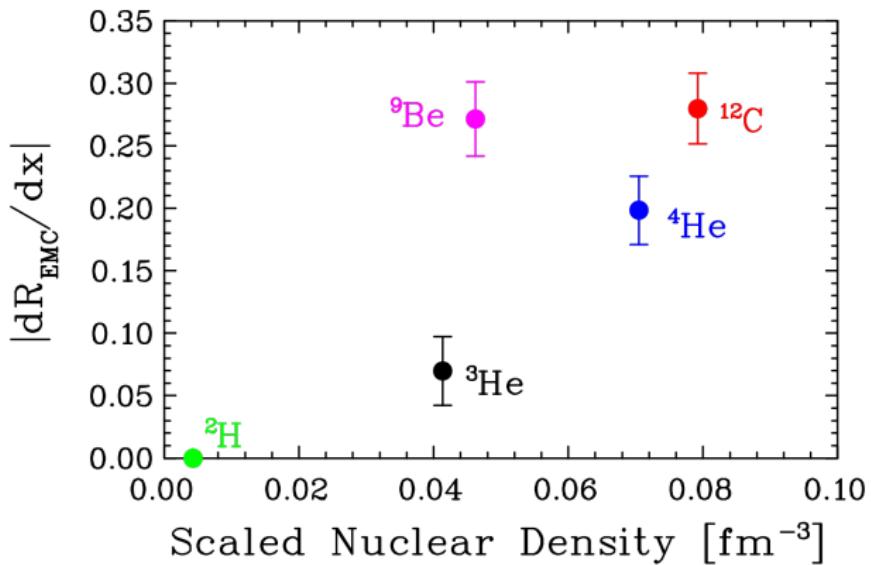


- JLab experiment E03103 [J.Seely, A. Daniel et al, 2009]
- CERN, SLAC, HERMES, BCDMS, and JLab
- Quantized by slope of A/D ratios from 0.3 - 0.7 in x
- Models have difficulty matching data for all criteria
- $\approx \log$ dependence in A

The EMC Effect

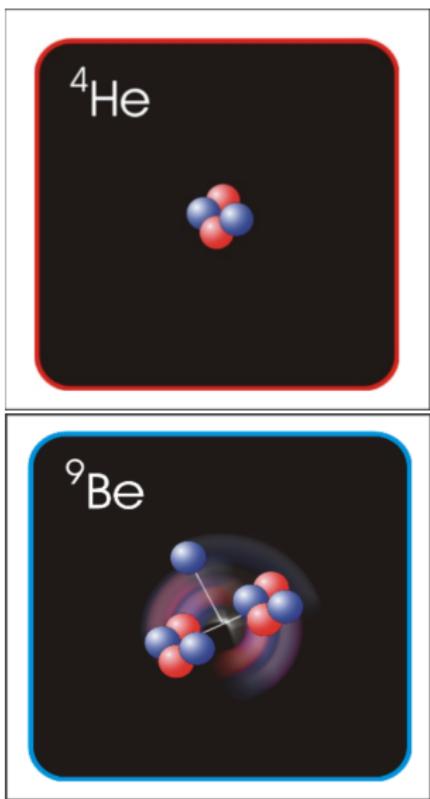
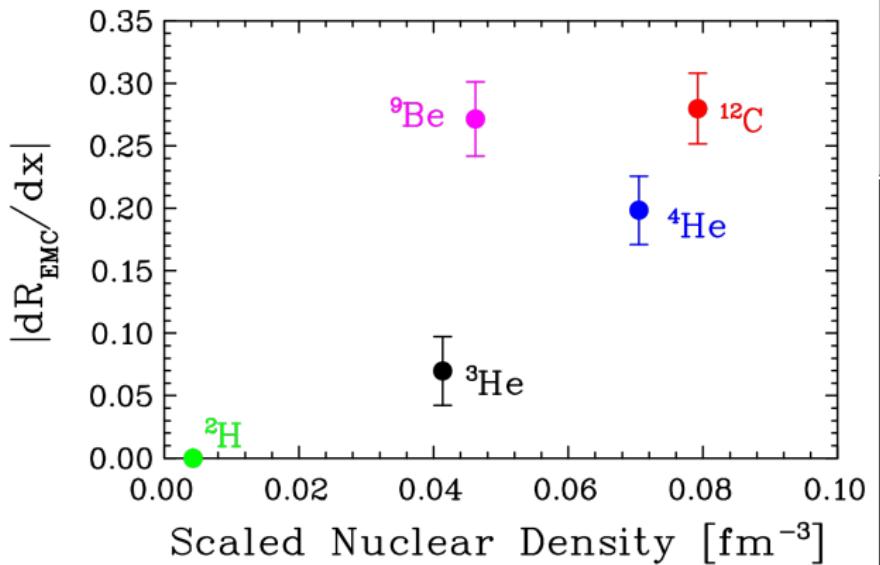
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The EMC Effect

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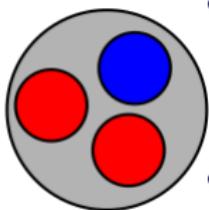
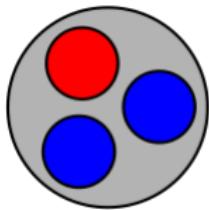


The EMC puzzle

- 3+ decades of study
- Every Model is Cool(EMC)
- Dependence on A
- Driven by local density

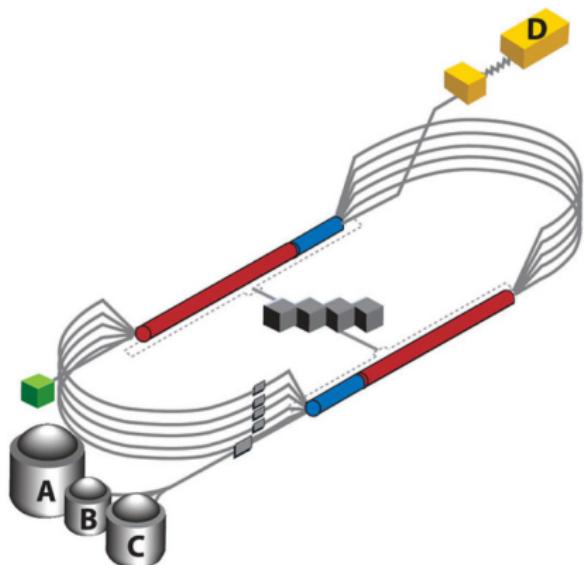
MARATHON

MeAsurement of F_2^n/F_2^p , d/u RAtios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering off the Tritium and Helium MirOr Nuclei.



- Lightest and simplest mirror system
 - ▶ Number of protons in 3H = neutrons in 3He
- Differences in the nuclear effects are small

The Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson Accelerator Facility.



- ≈ 2.2 GeV per revolution
- 12 GeV for Hall D
- Superconducting RF cavities
- RF separators split the beam to each Hall

MARATHON's proposal

- 11 GeV Beam
- Hall A's high resolution spectrometers (HRS)
- Tritium

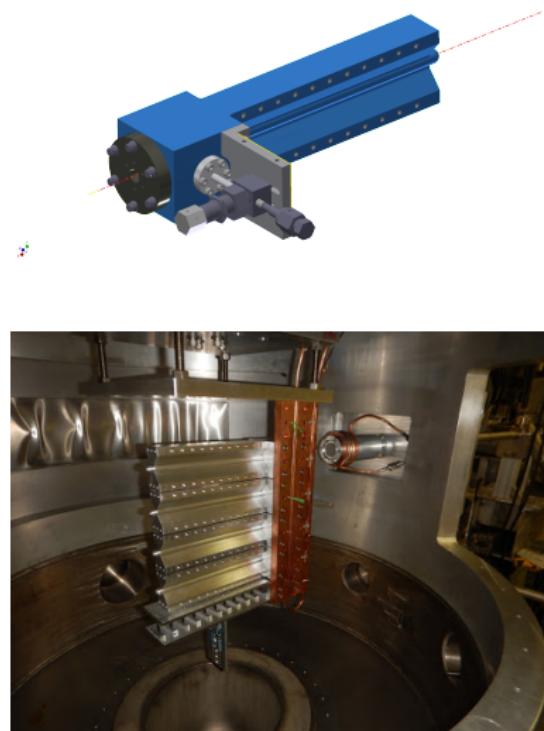
Uses of Tritium



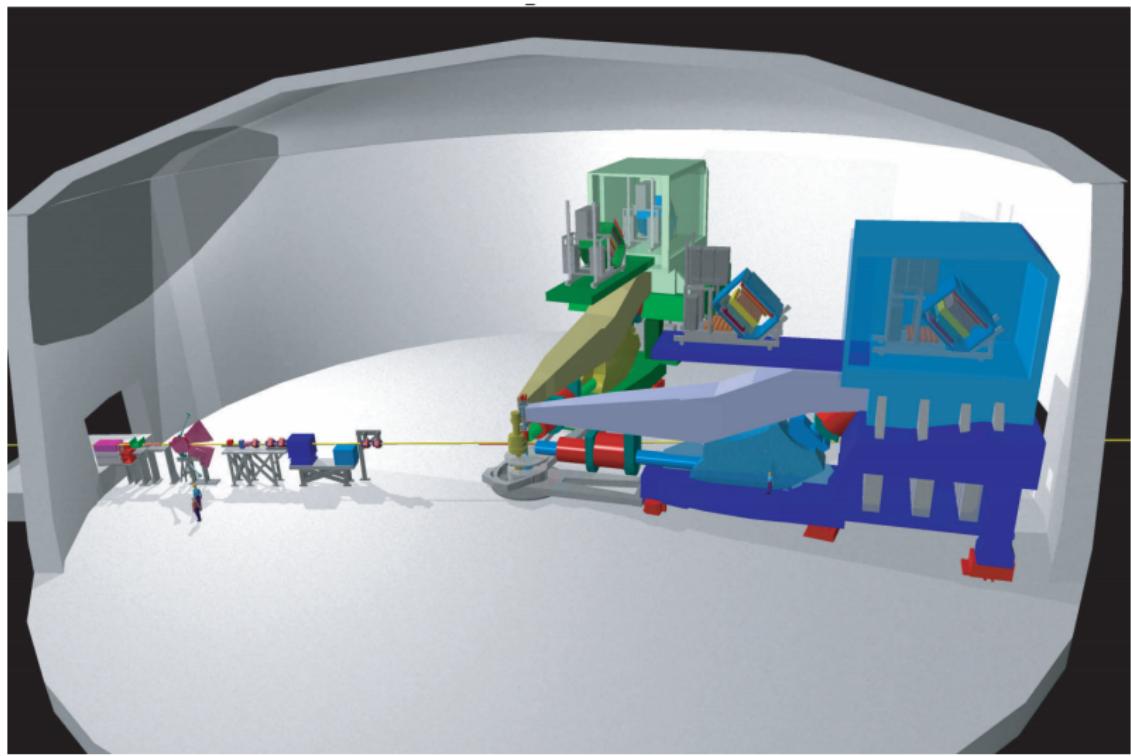
Tritium Target Cell

First tritium target at JLab

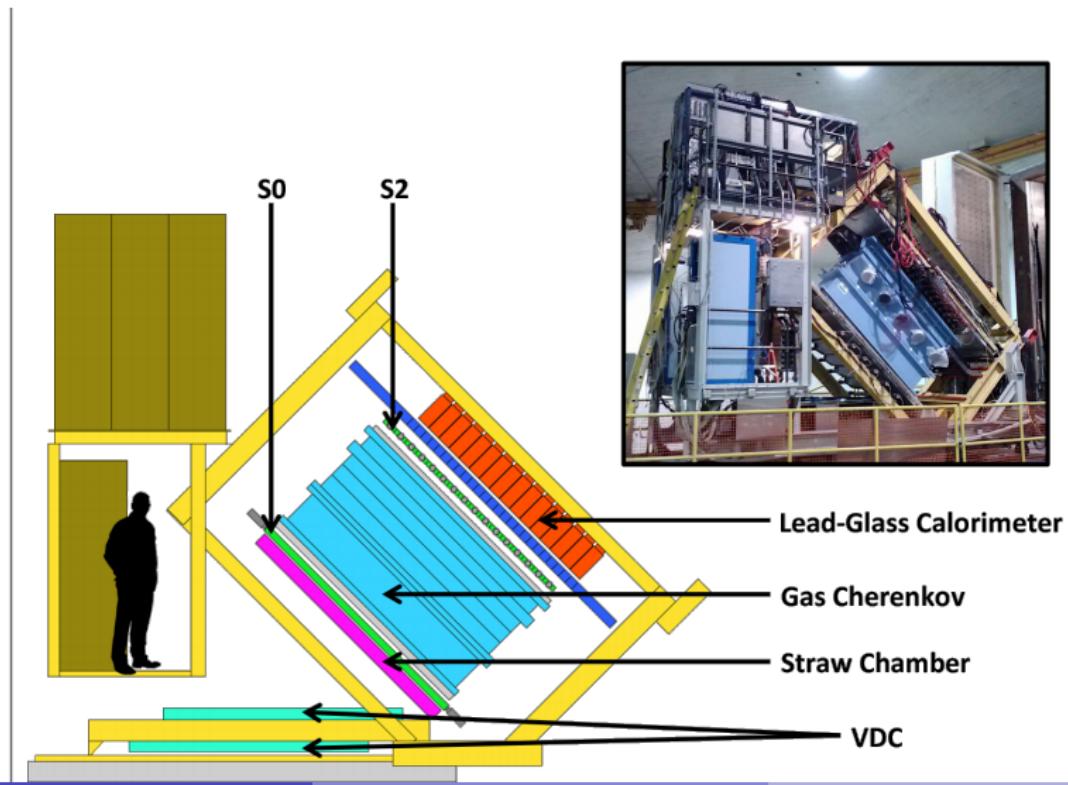
- Thin Al entrance and exit windows 0.01 inches
- 1090Ci of Tritium (0.1 g)
- 25 cm long
- Tritium Cell was filled in Savannah River
- 40 kelvin Helium is used to cool an attached heat sink



Hall A

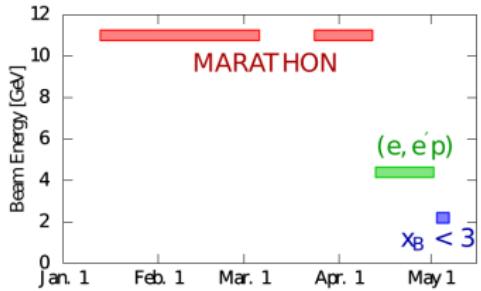


High Resolution Spectrometers (HRSs)



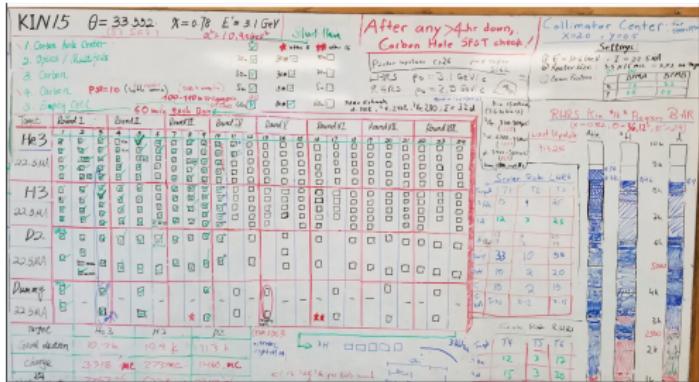


The Run Period

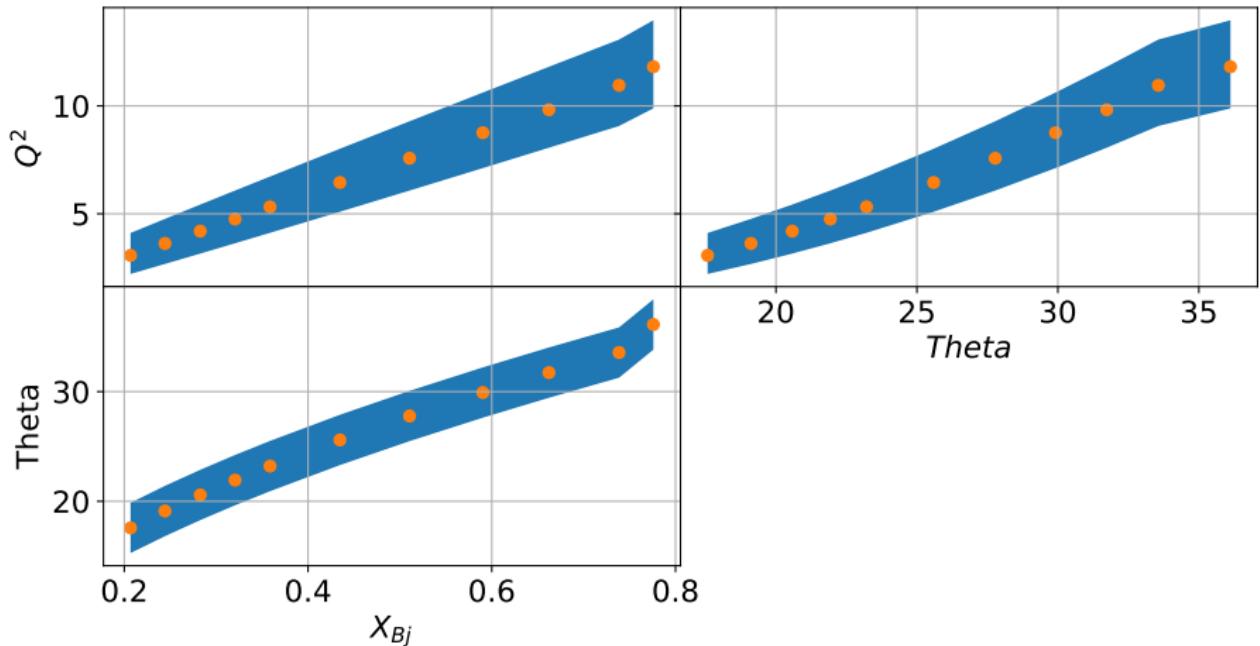


Rey Torres

- Ran from January 11th to April 12th of 2018.
- Gaseous targets - Tritium, Deuterium, Helium-3, and Hydrogen
- Rotated through targets to achieve equal statistics and reduce the impact of systematic uncertainties



Kinematic Coverage



Kinematic coverage between Q^2 , x , and Θ . The band around the points represents the approximate spectrometer acceptance in the y axis.



Path to The EMC Effect

- Calibrate detectors to receive meaningful data
- Determine the yield, efficiency and background
- Calculate the cross sections and ratios
- Extract the corrected EMC effect!

Preparing Data for Analysis

Calibration

ADC calibration

- Calorimeters, Scintillators, and Cherenkov

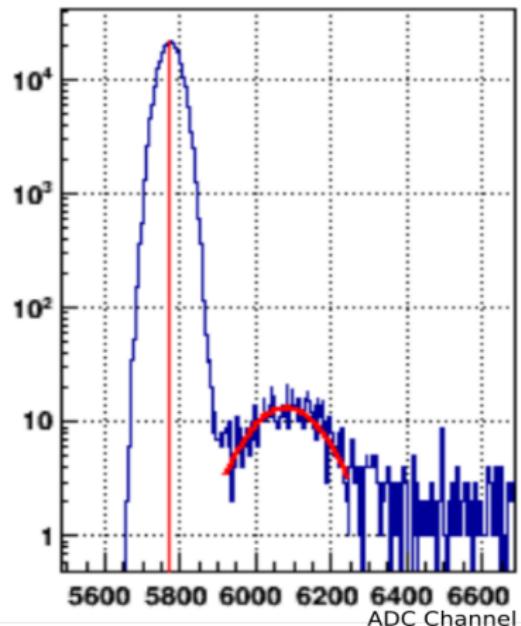
TDC calibration

- Scintillators and VDC

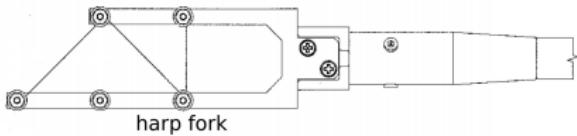
Detector calibrations

- Beam Current Monitors
- Beam Position Monitors

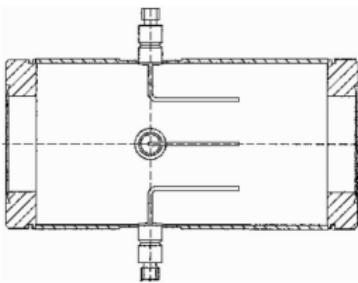
Cherenkov Calibration



Beam Position Monitor(BPM) Calibration



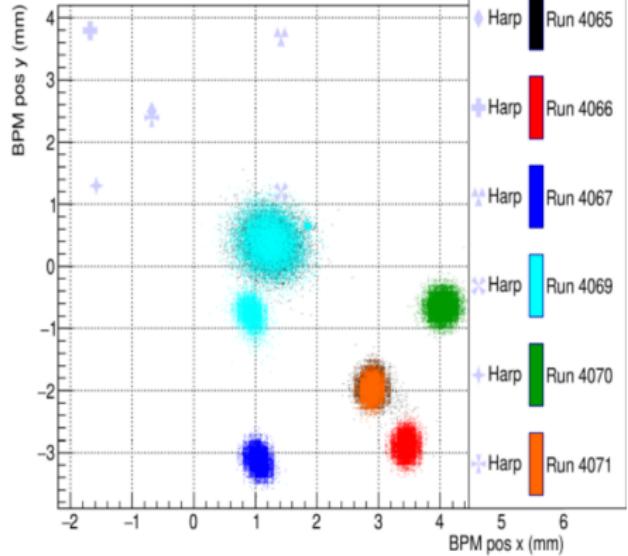
Intrusive absolute position measurement



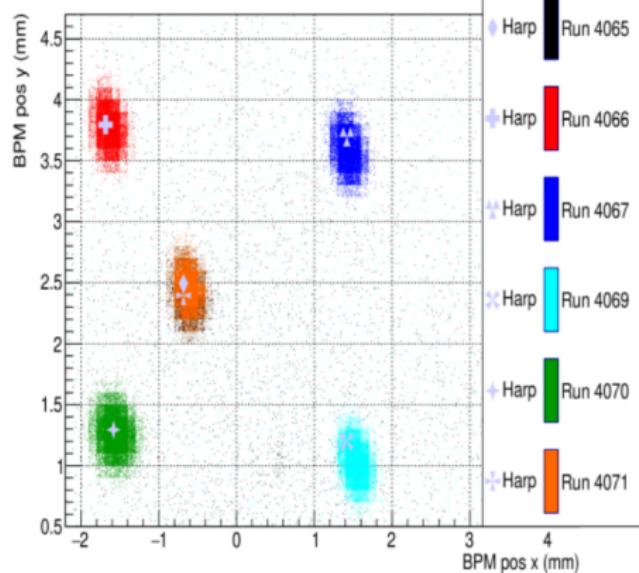
Relative position measurement

$$\begin{pmatrix} X_{position} \\ Y_{position} \end{pmatrix} = \begin{pmatrix} C(0, 0) & C(0, 1) \\ C(0, 0) & C(0, 1) \end{pmatrix} * \begin{pmatrix} X_{BPM} \\ Y_{BPM} \end{pmatrix} + \begin{pmatrix} X_{offset} \\ Y_{offset} \end{pmatrix}$$

Beam position from BPM and harp for a collection of runs



Before Calibration



After Calibration

Experimentally Measured Cross Section

$$\frac{d\sigma}{dE'd\Omega} = \frac{(N - BG)}{L \cdot \epsilon \cdot \Delta E' \Delta \Omega \cdot A(E', \theta)}$$



- N = Number of electrons
- BG = Background
- L = Luminosity
 - ▶ Density Correction
- ϵ = Efficiency
- $\Delta E' \Delta \Omega$ = Bin Size
- $A(E', \theta)$ = Acceptance probability

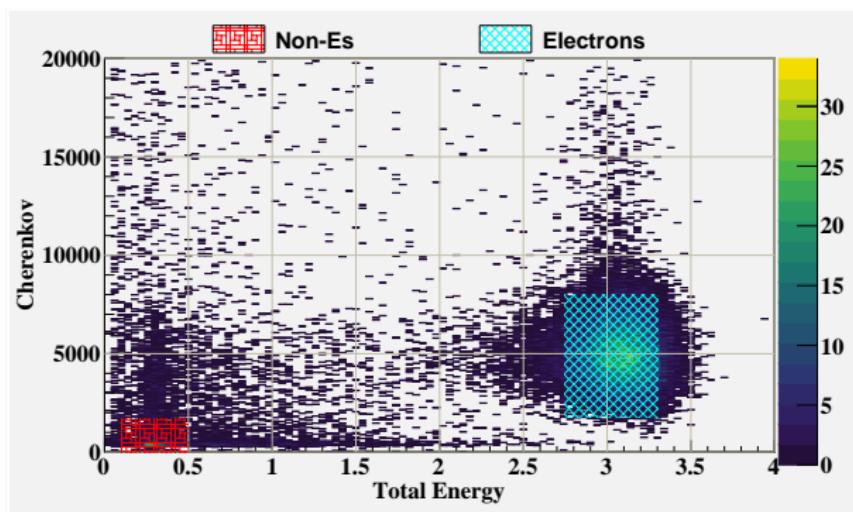
Efficiencies (ϵ)

- Particle Identification(PID)
 - ▶ Cherenkov
 - ▶ Calorimeters
- Trigger
 - ▶ Scintillators & cherenkov
 - ▶ $\approx 99\%$
- Tracking
 - ▶ Vertical Drift Chambers(VDCs)
 - ▶ $\approx 98\%$
- Electronic Deadtime
 - ▶ $\approx 96\%-99\%$

Calculating efficiencies

- Use well defined sample
- Determine good event samples with cuts
- # of events to fail the criteria \rightarrow inefficiency

Particle ID Efficiency

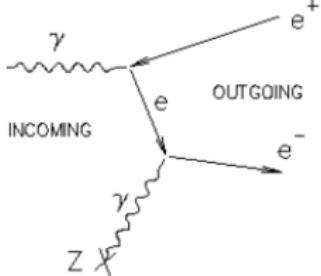


- Total energy absorber for electrons
- Cherenkov's pion threshold is $>$ momentum setting
- PID efficiency $\approx 98\%$ for all kinematics

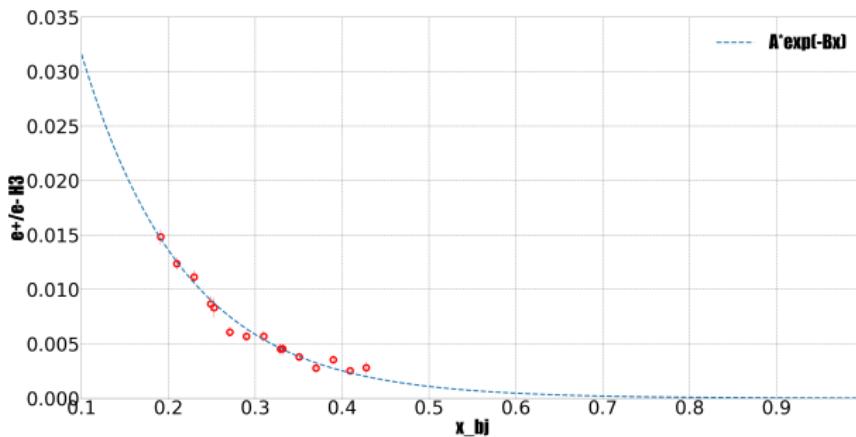
Charge Symmetric Background

- γ decay into an e^+e^- pairs
- Pair produced e^- by detecting e^+
- Extraction based on fit to Exponential function

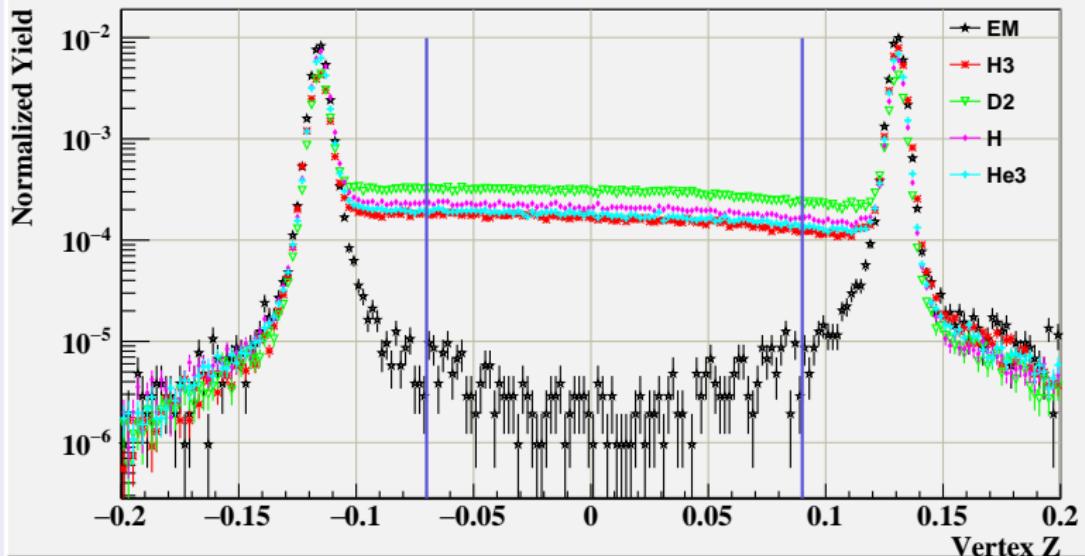
Pair Production



Tritium positron contamination. Credit: Tong Su



Aluminum Endcap Background



- Extract ratio of the normalized yield from the gas cell to that of the empty cell

3H Decay

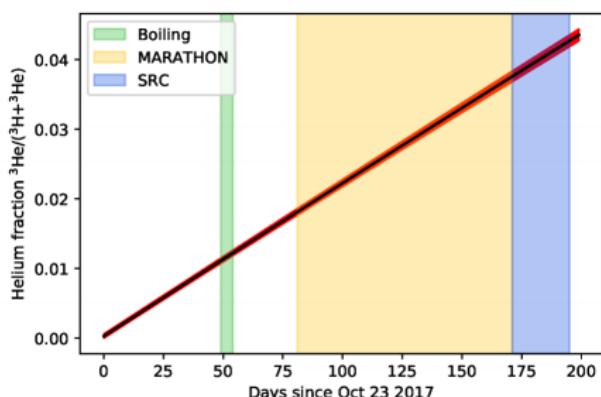


$$\tau(^3H) = 4500 \pm 8\text{ days}$$

$$c = \frac{\eta_{^3He}}{\eta_{tot}}$$

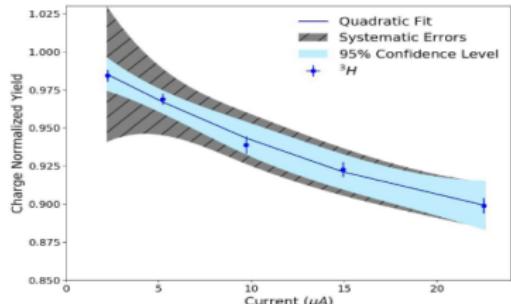
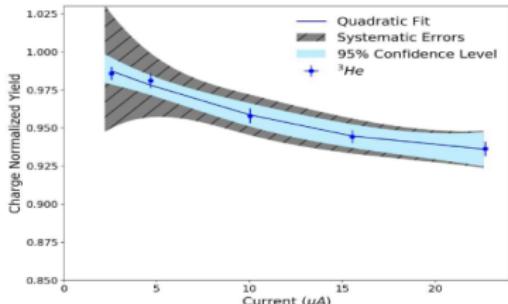
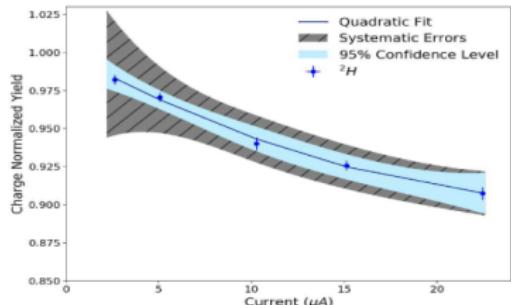
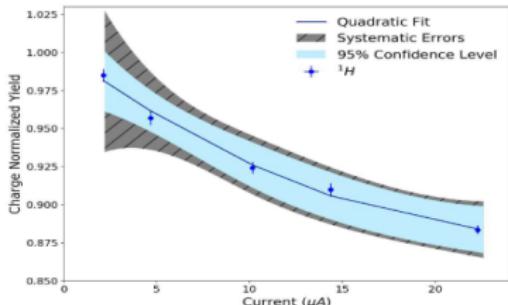
$$\sigma_{^3H} = \left(\frac{\sigma_{tot}}{\sigma_{^3He}} \right) \left(\frac{1}{1 - c} \right) - \left(\frac{1}{1 - c} \right)$$

Beta Decay Helium Fraction



Tyler Kutz

Density Fluctuations

(a) ${}^3\text{H}$ Density Analysis.(b) ${}^3\text{He}$ Density Analysis.(c) ${}^2\text{H}$ Density Analysis.(d) ${}^1\text{H}$ Density Analysis.

[S.N.Santiesteban et. al (2019)]

Monte Carlo Ratio Method

$$Y_{MC}(E', \theta) = L \cdot \sigma^{model} \cdot (\Delta E' \Delta \Omega) \cdot A(E', \theta)$$

$$\sigma_{data} = \frac{Y_{data}(E', \theta)}{L \cdot (\Delta E' \Delta \Omega) \cdot A(E', \theta)}$$

Use a Monte Carlo simulation

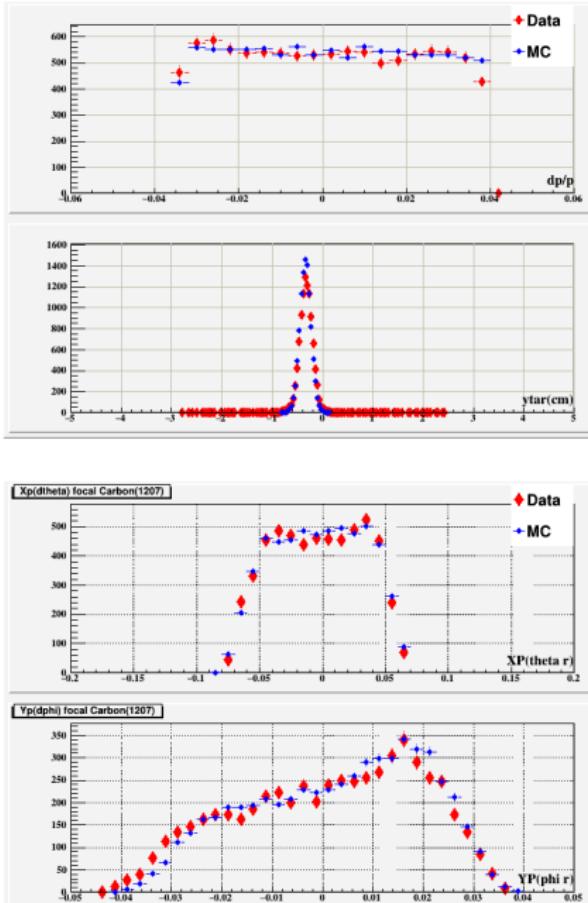
- $(\Delta E' \Delta \Omega)_{Data} = (\Delta E' \Delta \Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

$$\sigma_{Data} = \sigma_{model} \cdot \frac{Y_{Data}}{Y_{MC}}$$

Monte Carlo

- Generate events → Pass through Magnetic apertures
- Tune Simulation offsets to match detector response
- Use model to weight events
 - ▶ Deep Inelastic and resonance region from Ari Bodek Fit from E139
 - ▶ Full Mo and Tsai radiative correction

[A. Bodek and U.K. Yang, 2002]
[L.W. Mo and Y.S. Tsai, 1969]



Result

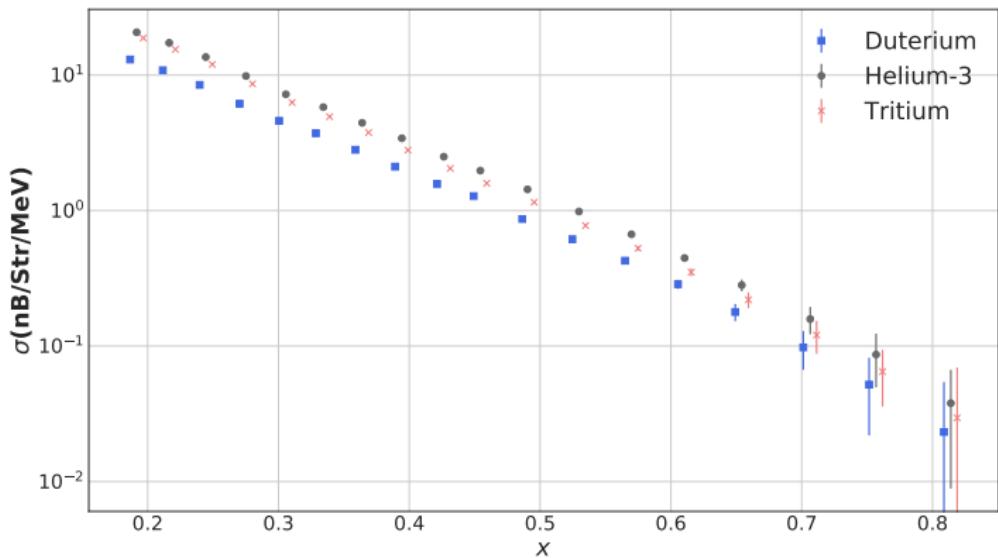
Deep Inelastic Cross Section

10.6 GeV Beam, $W^2 > 3.5$

Cross Section Ratios

EMC Effect

DIS Cross Section



Normalization uncertainty due to target thickness uncertainty
 ${}^3\text{He} - 1.12\% \bullet {}^3\text{H} - 0.97\% \bullet \text{D} - 0.56\%$

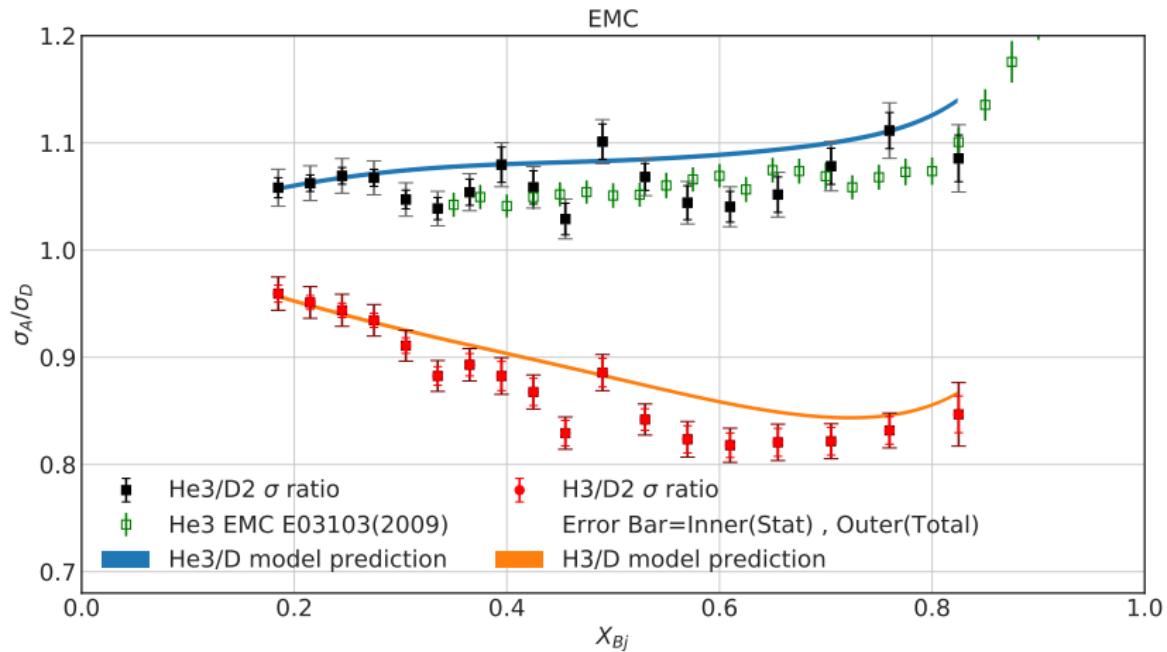
Relative Error Contributions for Cross Section for a selection of bins.

Xbjc	0.185	0.305	0.49	0.57	0.705	0.825
Yield Error	0.01	0.01	0.014	0.015	0.014	0.016
Stat Err*	0.0062	0.0053	0.0097	0.0106	0.011	0.0143
End Cap*	0.007	0.007	0.007	0.007	0.0070	0.007
Eff Err*	0.004	0.0051	0.0075	0.0071	0.0041	0.0032
MC&Model	0.015	0.015	0.013	0.014	0.028	0.026
Resolution**	0.015	0.011	0.006	0.004	0.007	0.02
Model Err**	0.002	0.01	0.011	0.011	0.027	0.018
Total Error	0.018	0.018	0.019	0.021	0.031	0.031

* Part of the error in the yield calculation

** Part of the error in Monte Carlo and Cross section model calculation.

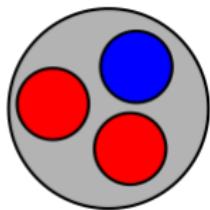
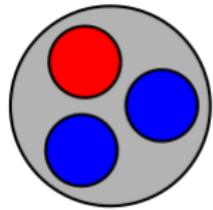
Per Nucleon Cross Section Ratio



MARATHON results compared with E03103

[J.Seely, A. Daniel et al, 2009] and the A/D ratios from a DIS scattering model from Arie Bodek model [A. Bodek and U.K. Yang, 2002].

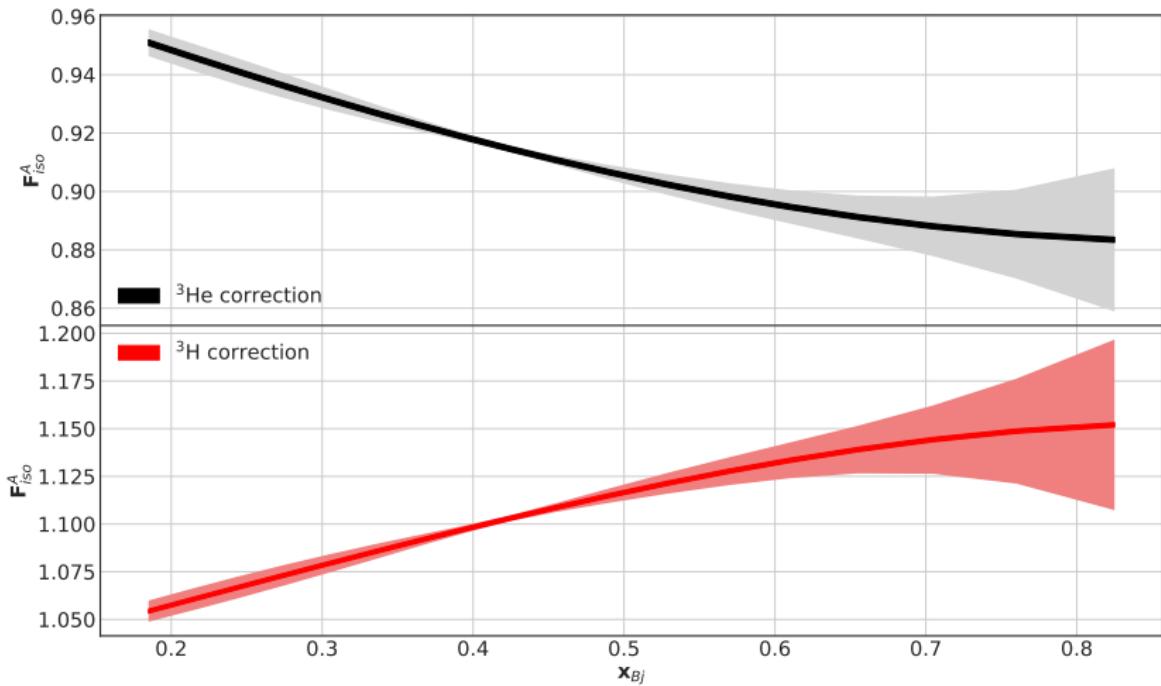
Isoscalar Corrections



- Correct for the unpaired nucleon in the A/D ratio.

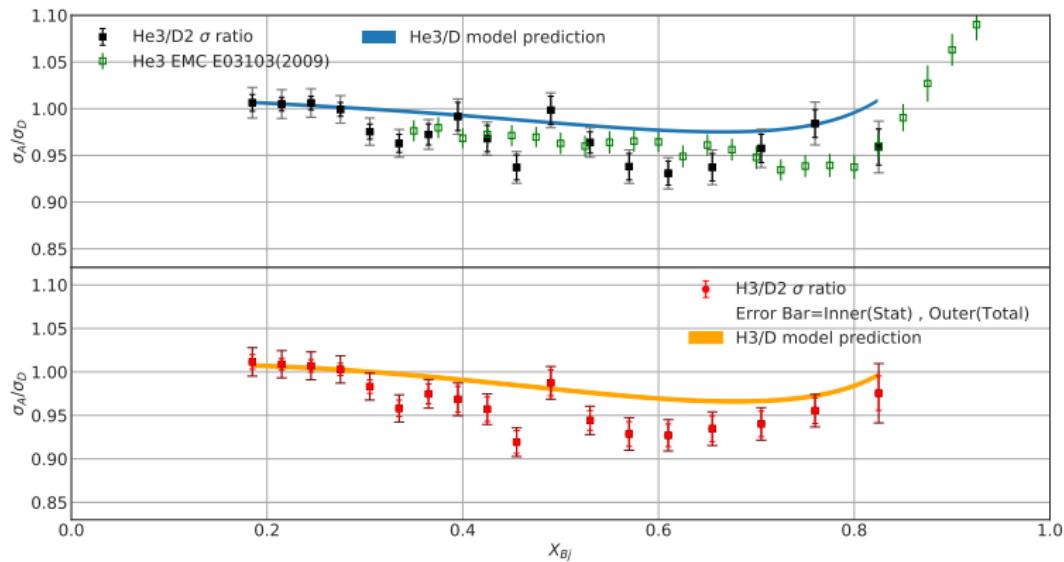
$$F_{Iso}^A = \frac{\left(0.5 * (1.0 + \frac{F_2^n}{F_2^p})\right)}{\left(\frac{1}{A} \cdot (Z + (A - Z) \cdot \frac{F_2^n}{F_2^p})\right)}$$

Isoscalar Corrections



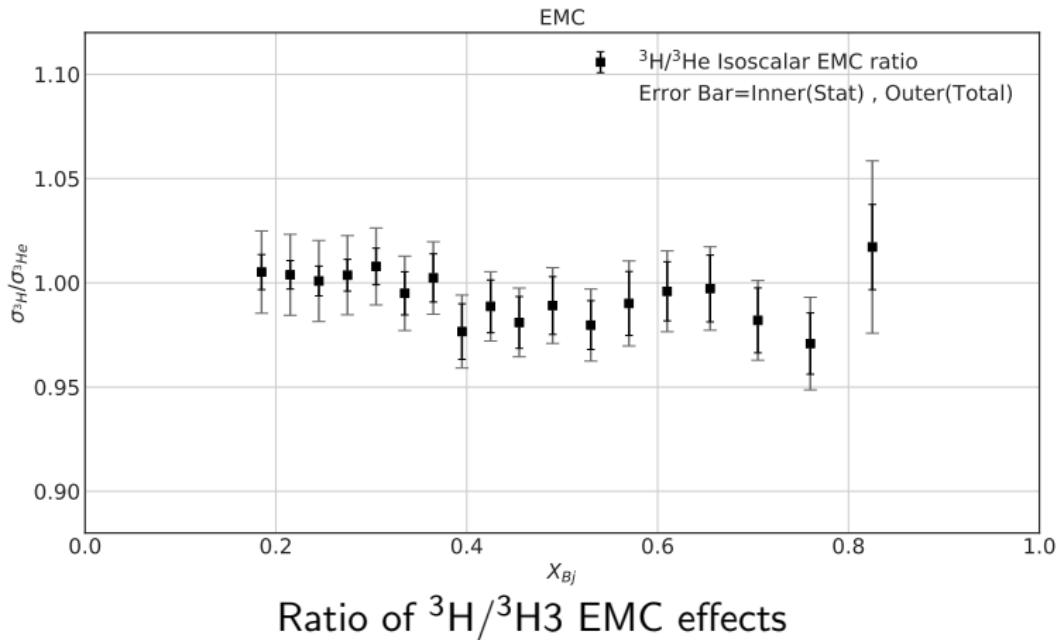
Isoscalar correction factor for both ${}^3\text{He}$ and ${}^3\text{H}$. Model dependent calculation, error is calculated via comparing different models for $\frac{F_2^n}{F_2^p}$.

- My EMC results for He3 in black • H3 in red
- Previous Jlab He3 in green



MARATHON results compared with E03103

[J.Seely, A. Daniel et al, 2009] and the EMC ratios from a DIS scattering model from Arie Bodek model [A. Bodek and U.K. Yang, 2002].



Conclusion

- Used DIS to extract inclusive cross section for ${}^3\text{H}$, ${}^3\text{H}3$, and D
- Study the edge of the HRS acceptance for a long target
- Model Dependence on Isoscalar correction
- Determine the magnitude of the EMC effect for Tritium and Helium-3

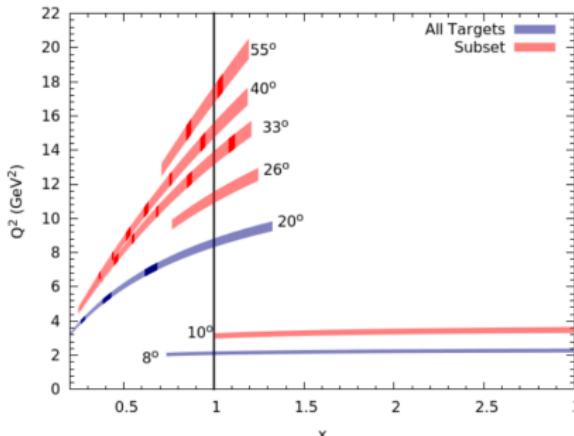
Understanding the effect of neutron/proton excess on the
EMC Effect



Detailed Studies of the nuclear dependence of F2 in light nuclei

[E12-100-008: J. Arrington, A Daniel, NF, D. Gaskell]

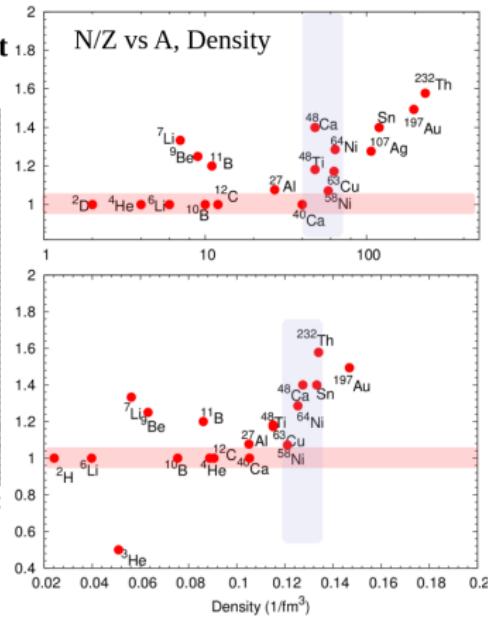
Target Choice motivated by physics impact



Coming soon* in Hall C

What is soon?

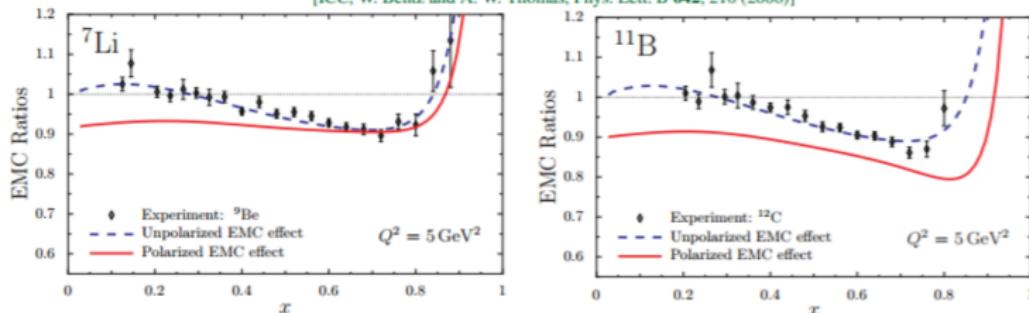
Slide credit Nadia Fomin



The EMC effect in spin structure functions

[E12-14-001: Will Brooks and Sebastian Kuhn]

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



- A polarized EMC effect arises because in-medium quarks are more relativistic
 - Lower components of quark wave functions are enhanced
 - Quark Spin is converted to orbital angular momentum
- Spin Dependent cross-section is suppressed by $1/A$
- Experiment to measure spin structure functions of ${}^7\text{Li}$

Slide credit Nadia Fomin

Summary

- DIS - probe the quarks
- The puzzling EMC Effect - decrease in high momentum quarks $A > 2$
- Used JLab's 12GeV electron beam & Hall A's HRS
- Use the ${}^3\text{He}$ & ${}^3\text{H}$ EMC Effect to add a puzzle piece to the EMC puzzle.

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The JLab MARATHON Tritium Collaboration

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More than 140 Collaborators

Red-Boldfaced Names: Tritium Program grad students; **starred:** MARATHON Ph.D. students

Blue-Boldfaced Names: Tritium Program postdoctoral associates



The JLab MARATHON Tritium Collaboration

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Twelve Countries: Armenia, Canada, Croatia, Egypt, Germany, Israel, Italy, Japan, Russia, Slovenia, Ukraine, United States.



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