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

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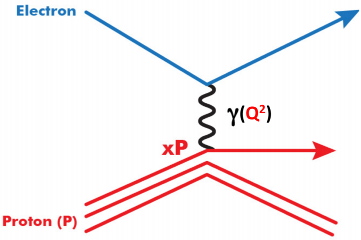
Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory.

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**.

Outline

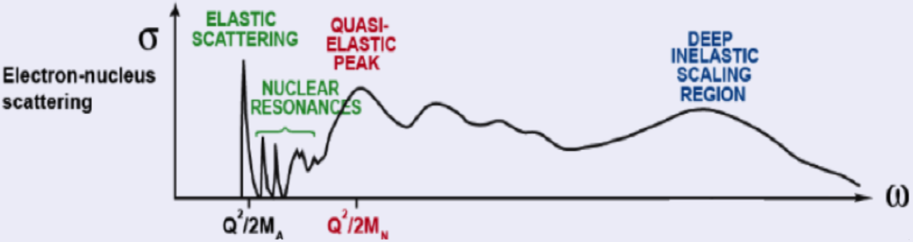
- Deep Inelastic Scattering
- The EMC Effect
- The MARATHON Experiment
- Data Analysis
- EMC Effect of A=3

Deep Inelastic Scattering (DIS)

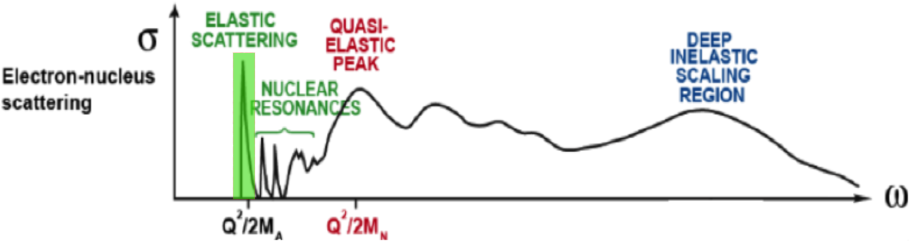


- $Q^2 \equiv 4EE' sin^2 \frac{\theta}{2}$
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $\nu \equiv$ E-E$'$
- $W^2 = 2M\nu + M^2 - Q^2$
- $W^2 > 4 \rightarrow$ DIS

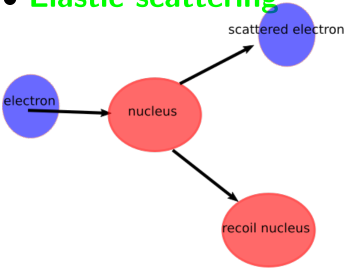
DIS ??????

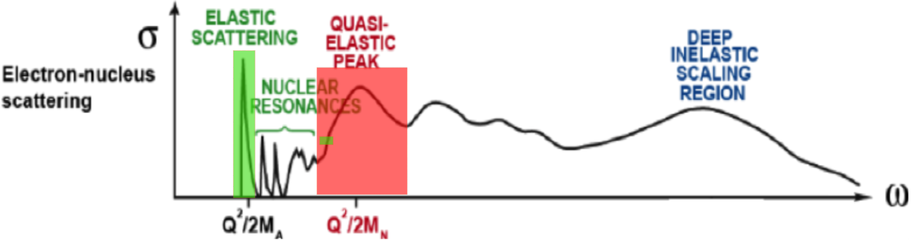


Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].



- **Elastic scattering**





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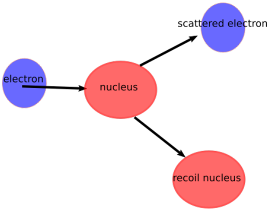
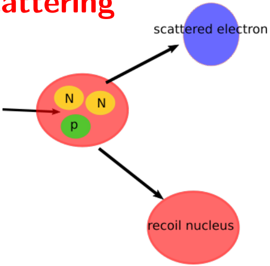
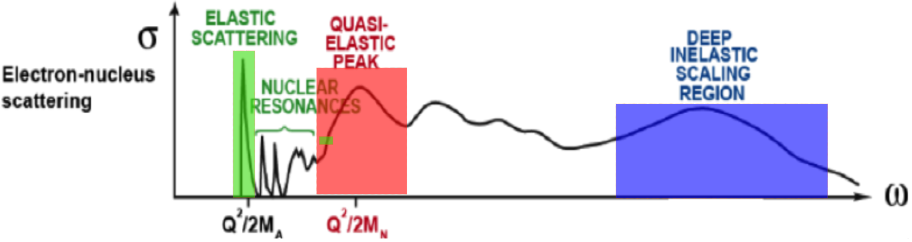
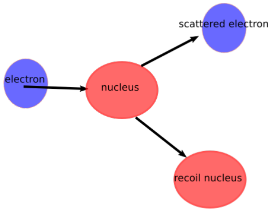


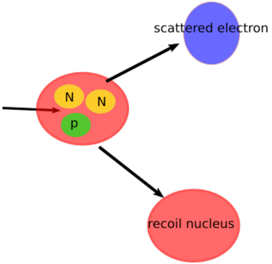
- **Quaiselastic scattering**

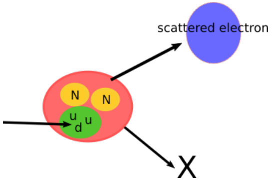




- **Elastic scattering**
- **Quaiselastic scattering**
- **DIS**





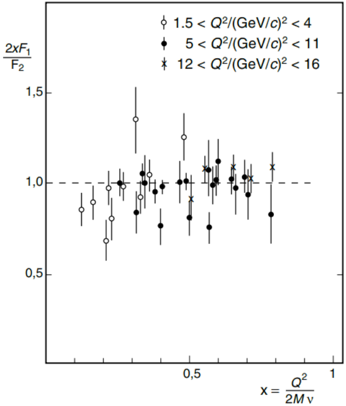


Why DIS?

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

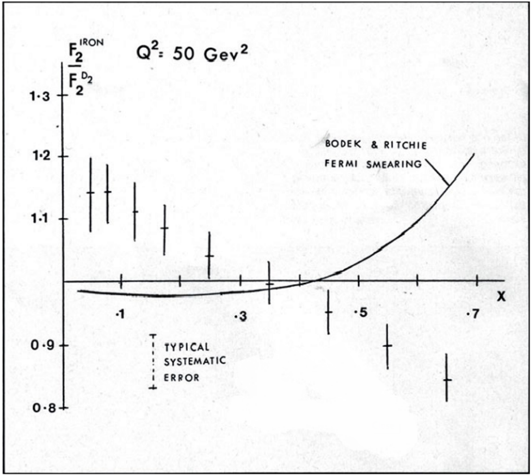
Quark parton model

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



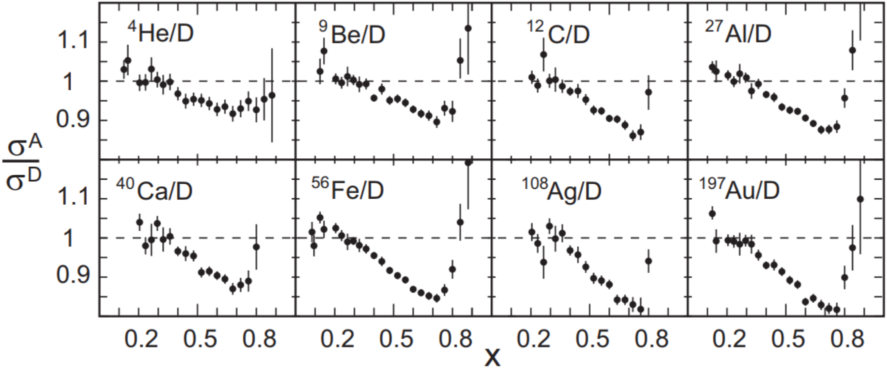
[Aubert, J.J. et al. 1981]

European Muon Collaboration

- X = fraction of momentum carried by quark
- Expected Unity at low x
  - Binding < momentum transfer
  - Free Nucleons
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$
- Unexpected Relative Decrease
- Missing high-momentum quarks in A>2
- EMC Effect ≡ structure of the A/D Ratio

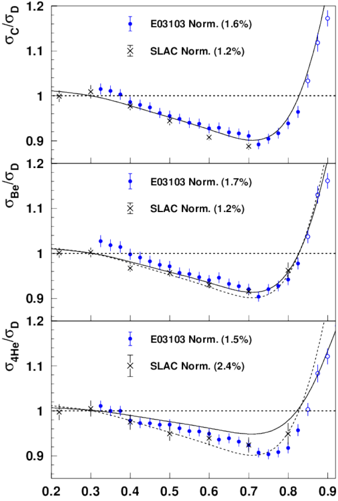
EMC Effect

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



EMC Effect

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



- Studied for last 30+ years
- CERN, SLAC, HERMES, BCDMS, and JLab
- 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

EMC Effect

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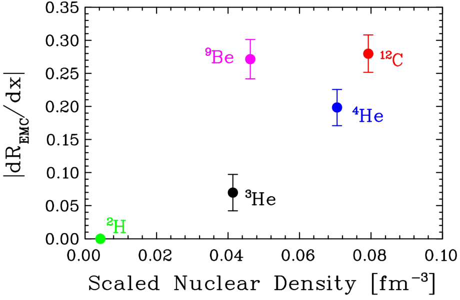

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- sensitivity to "local" effects

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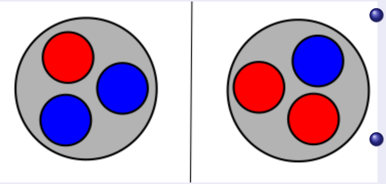
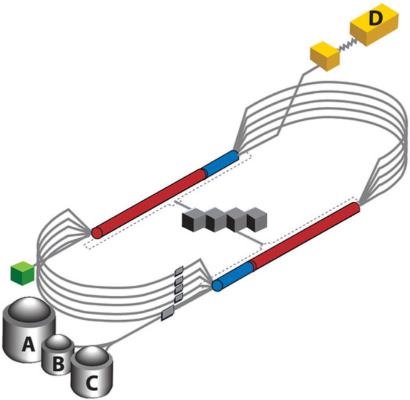
MARATHON

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 MirrOr 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.



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

MARATHON's proposal

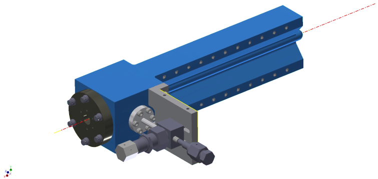
- 11 GeV Beam
- Bigbite spectrometer
- Hall A's high resolution spectrometers (HRS)
- Tritium

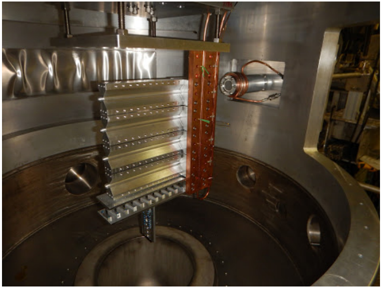
Uses of Tritium

Tritium Target Cell

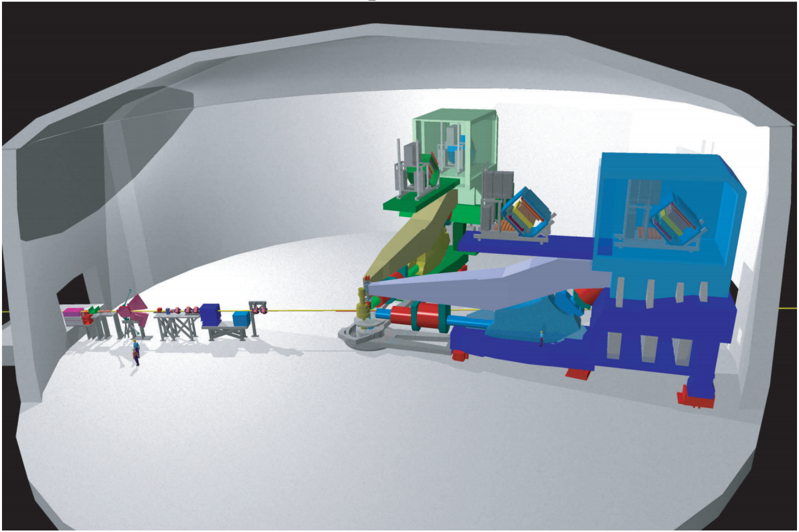
First tritium target at JLab

- 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

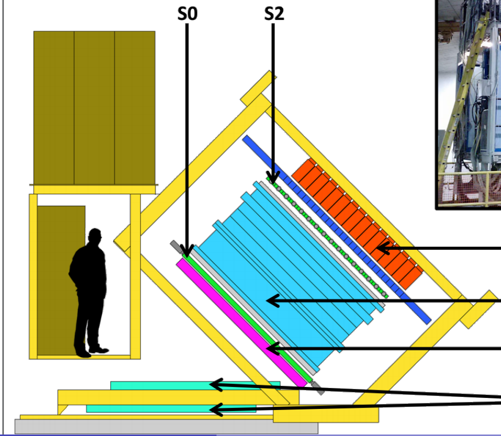




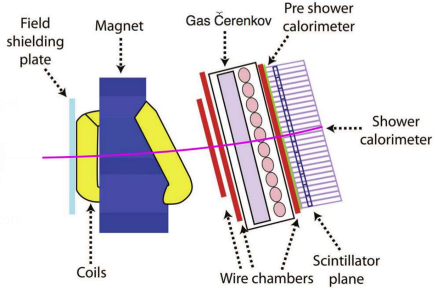
Hall A



High Resolution Spectrometers (HRSs)



Bigbite Spectrometer



Large Acceptance Spectrometer

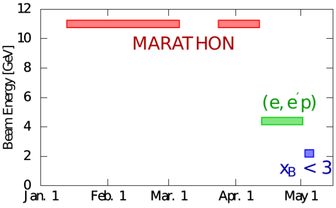
- Solid angle = 96 mrad
- Large Momentum Acceptance: > 500 MeV/c

My contributions in preparing Bigbite

- Constructing the data acquisition system
- PMT performance studies
- Designing trigger logic
- Ensuring consistent and dependable HV power

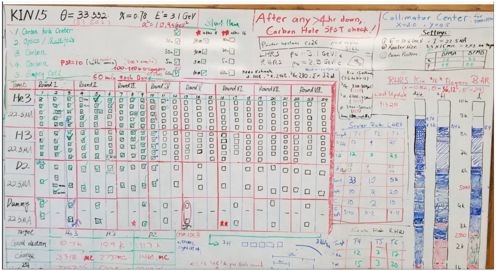
Removed from then run plan for safety and logistical concerns

The Run Period

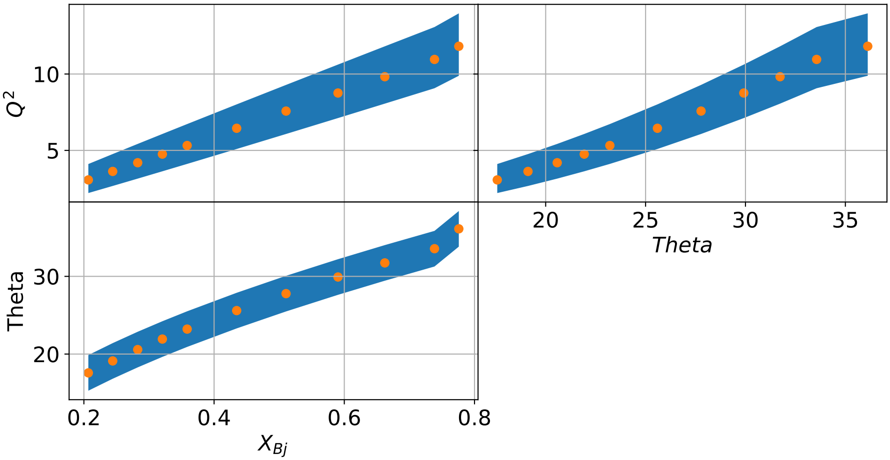


Rey Torres

- 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 Theta. 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

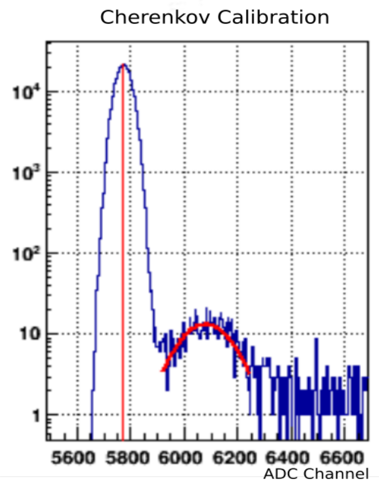
- Calorimeters, Scintillators, and **Cherenkov**

TDC calibration

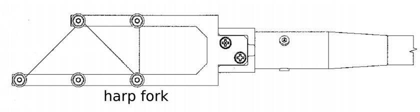
- Scintillators and VDC

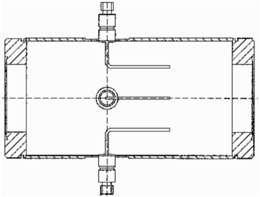
Detector calibrations

- Beam Current Monitors
- **Beam Position Monitors**



Beam Position Monitor(BPM) Calibration



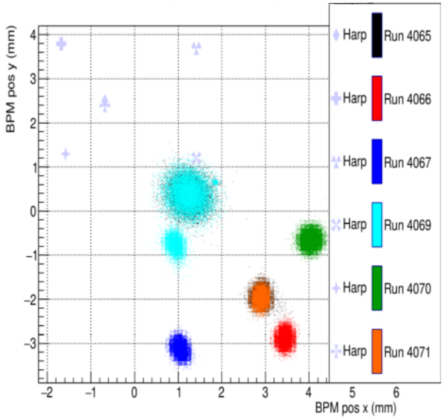


Intrusive absolute position measurement

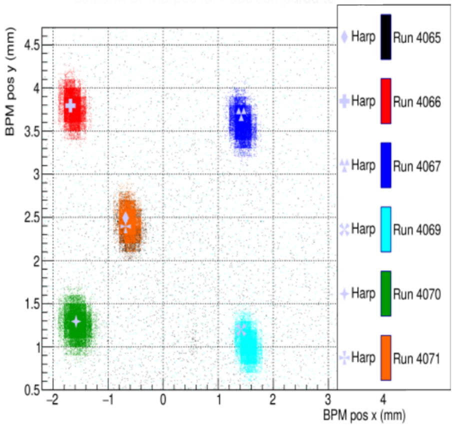
Relative position measurement

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

Beam position from BPM and harp for a collection of runs



Before Calibration



After Calibration

Experimentally Measured Cross Section

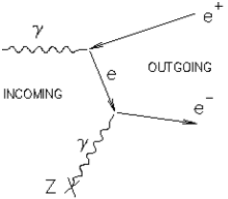
$$\frac{d\sigma}{dE'd\Omega} = \frac{(N - BG)}{L \cdot \epsilon \cdot \Delta E' \Delta\Omega \cdot A(E', \theta)}$$

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

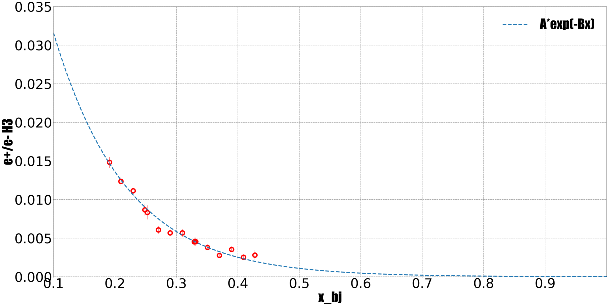
Charge Symmetric Background

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

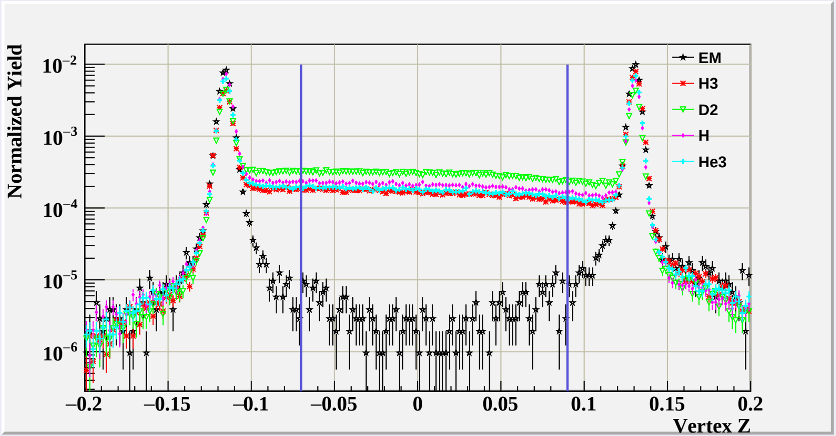
Pair Production



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

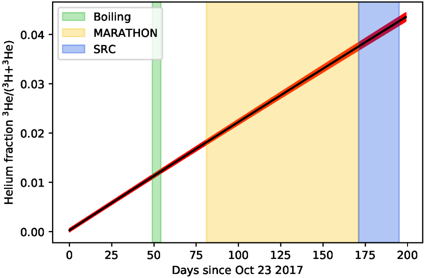
$^3H \rightarrow ^3He$

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

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

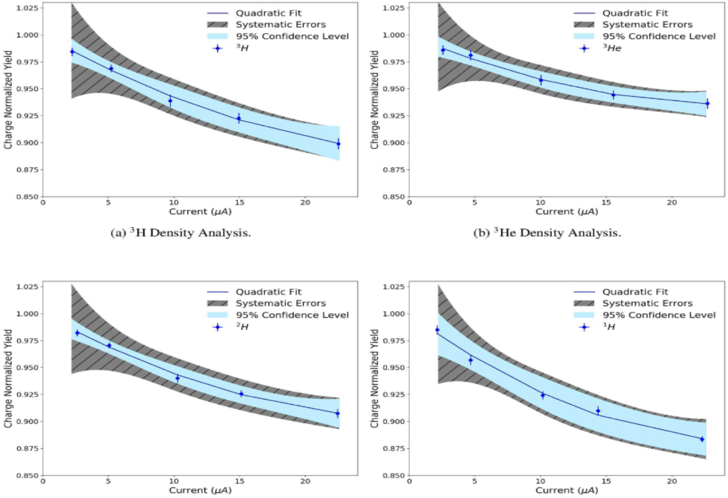
$$\sigma_{^3H} = \left(\frac{\sigma_{tot}}{\sigma_{^3He}}\right)\left(\frac{1}{1-c}\right) - \left(\frac{1}{1-c}\right)$$

Beta Decay Helium Fraction



Tyler Kutz

Density Fluctuations



(a) ^{3}H Density Analysis. (b) ^{3}He Density Analysis.

(c) ^{2}H Density Analysis. (d) ^{1}H Density Analysis.

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

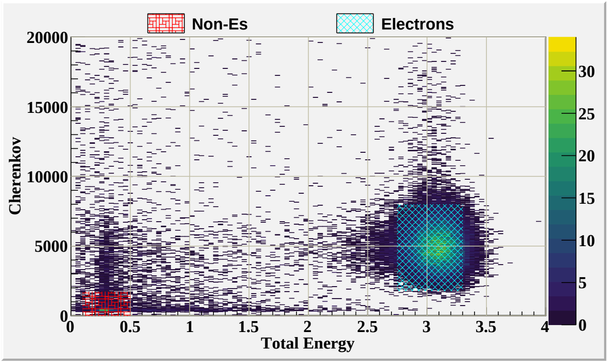
Efficiencies (ϵ)

- Particle Identification(PID)
  - Cherenkov
  - Calorimeters
- Trigger
  - Scintillators
- Tracking
  - Vertical Drift Chambers(VDCs)
- Electronic Deadtime

Calculating efficiencies

- Use well defined sampling
- 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

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

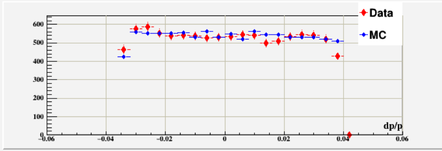
- $(\Delta E' \Delta \Omega)_{Data} = (\Delta E' \Delta \Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

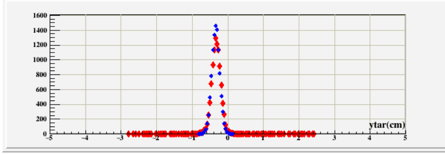
$$\sigma_{Data} = \sigma_{model} \cdot \frac{Y_{Data}}{Y_{MC}}$$

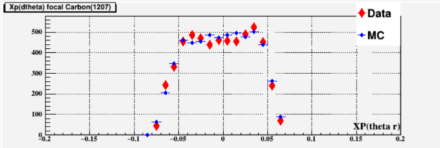
Monte Carlo

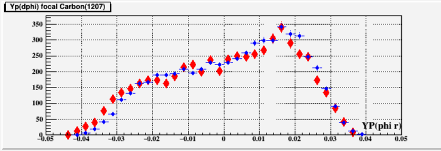
- Generate events → Pass through Magnetic apertures
- Tune Simulation offsets to match detector response
- Use model to weight events
  - Deep Inelastic and resonance region from Ari Bodek Fit from E139

[A. Bodek and U.K. Yang, 2002]









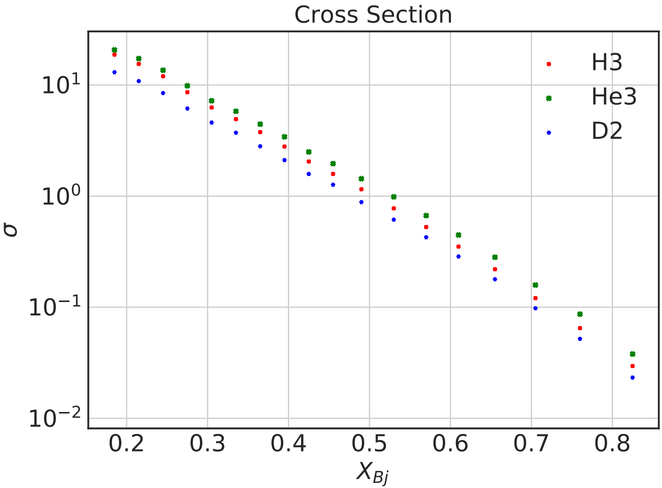
Result

Deep Inelastic Cross Section

Cross Section Ratios

EMC Effect

DIS Cross Section



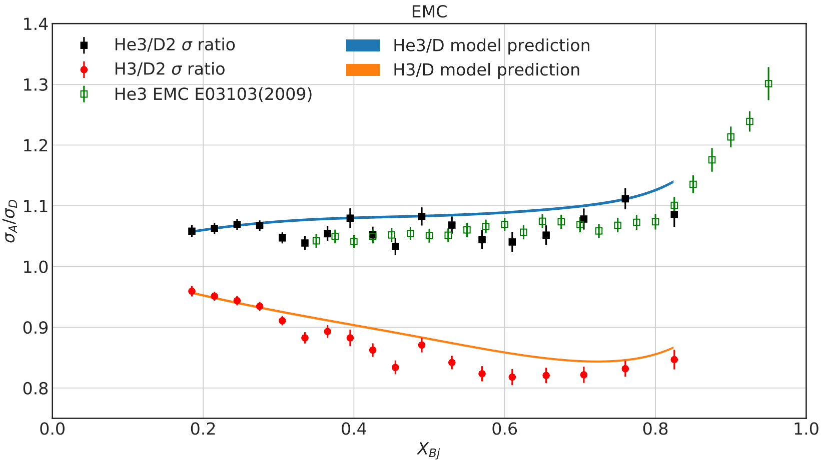
Normalization uncertainty due to target thickness uncertainty
He3 - 1.12% • H3 - 0.97% • D - 0.56%

Relative Error Contributions in % for Cross Section for a selection of bins

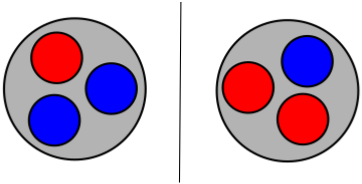
x bin	**0.215**	**0.455**	**0.705**
Statistical Error	0.512	0.889	1.106
Positron Correction Error	0.036	0.016	0.005
Efficiency Error*	0.665	1.477	2.951
Density Correction Error	0.002	0.002	0.002
Monte Carlo Error	0.193	0.217	0.209
Total Error	0.95	1.931	3.316

* Contains contributions from PID, tracking, trigger, and livetime

Per Nucleon Cross Section Ratio



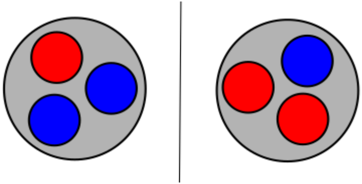
Isoscalar Corrections



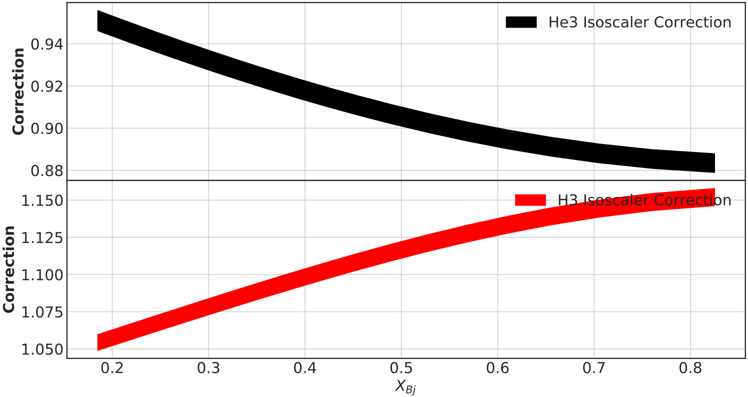
- Correct for the unpaired nucleon in the A/D ratio.

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

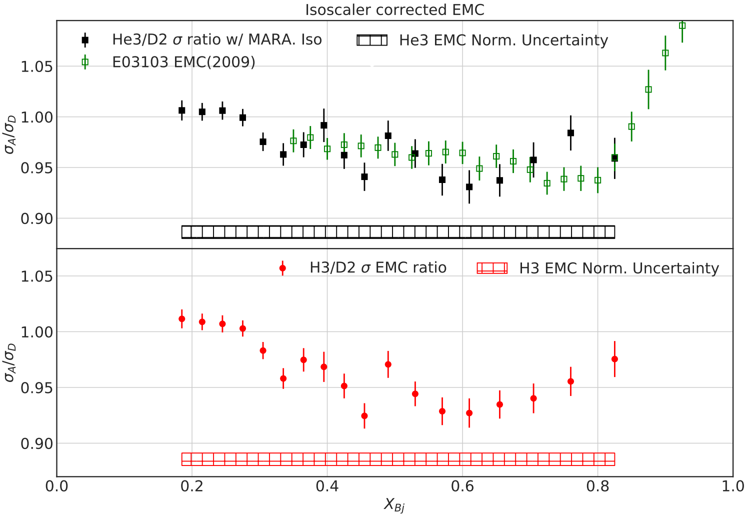
Isoscalar Corrections



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



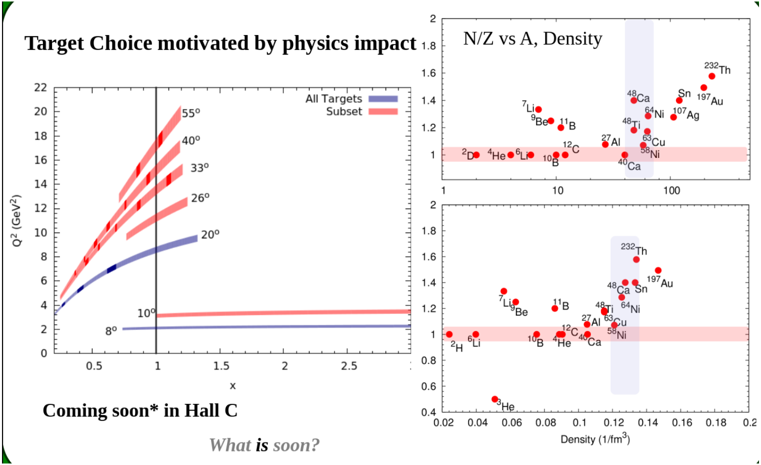
EMC Effect


Isoscaler corrected EMC
He3/D2 σ ratio w/ MARA. Iso
E03103 EMC(2009)
He3 EMC Norm. Uncertainty
H3/D2 σ EMC ratio
H3 EMC Norm. Uncertainty
σA/σD
1.05
1.00
0.95
0.90
0.0
0.2
0.4
0.6
0.8
1.0
XBj

Future Plans

- Model dependence on cross section extraction
- 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

Detailed Studies of the nuclear dependence of F2 in light nuclei [E12-100-008: J. Arrington, A Daniel, NF, D. Gaskell]

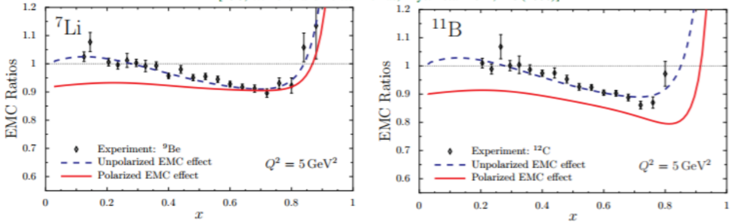


Slide credit Nadia Fomin

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 7Li

Slide credit Nadia Fomin

Summary

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

Special Thanks

- Nadia Fomin and Douglas Higinbotham
- The Tritium Students
- DOE and JSA
- Rex Tayloe for the invite.

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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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