The EMC Effect for Tritium and Helium-3 from MARATHON

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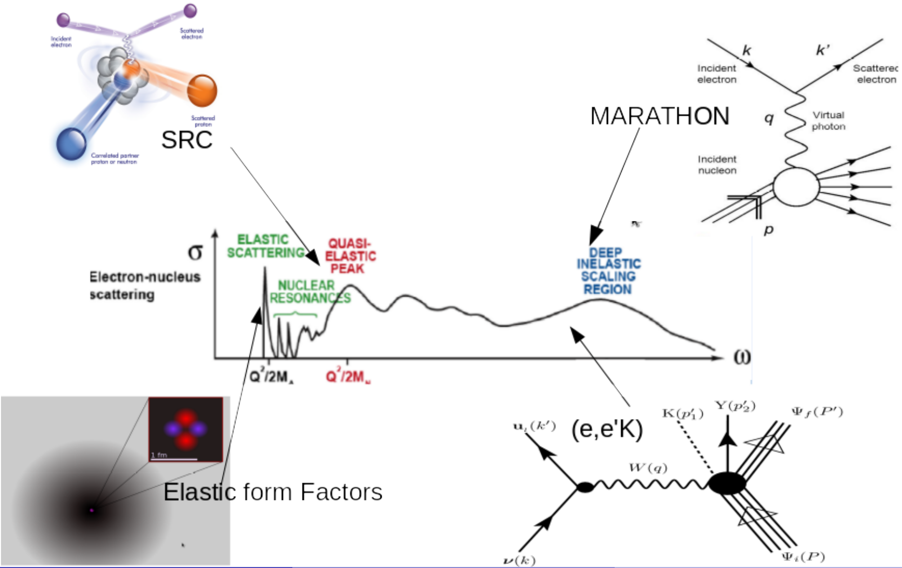
Outline

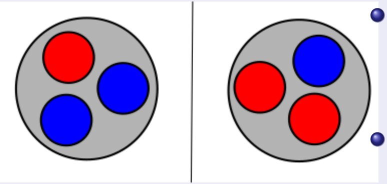
- Introduction
  - MARATHON
  - EMC
  - Deep Inelastic Scattering
- The Experiment
- Data Analysis
- EMC Effect of A=3

Tritium Experiments



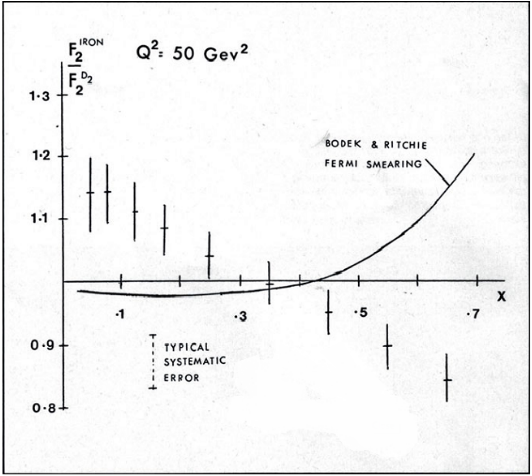
MARATHON

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 EMC Effect

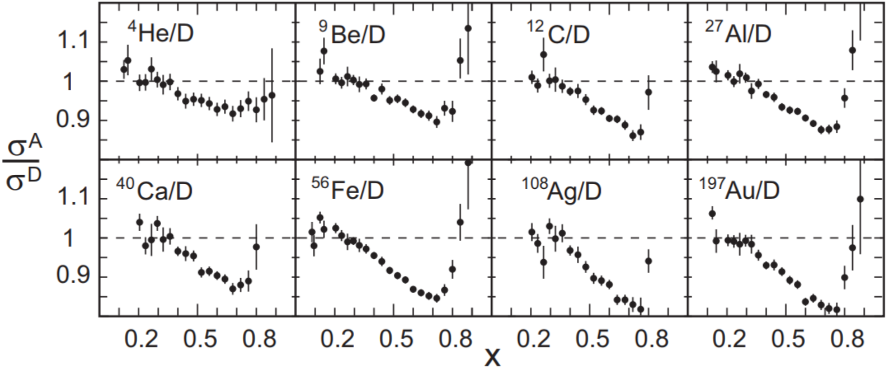


European Muon Collaboration

- Expected Unity $\rightarrow$ Binding $<$ interaction
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$
- Unexpected Relative Decrease
- EMC Effect $\equiv$ structure of the A/D Ratio

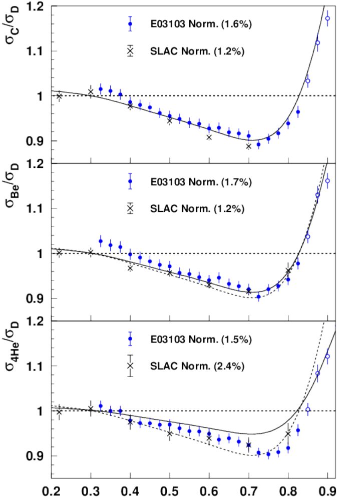
EMC Effect

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



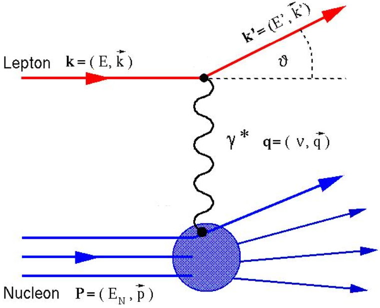
EMC Effect

JLab experiment E03103
[J.Seely, A. Daniel et al, 2013]



- Studied for last 30+ years
- CERN, SLAC, HERMES, BCDMS, and JLab
- Slope of A/D Ratios from 0.3 - 0.7 in x
- $\approx$ log dependence in A
- Models have difficulty matching data for all criteria

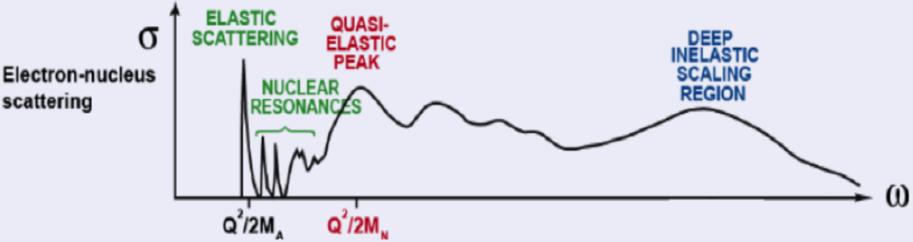
Deep Inelastic Scattering (DIS)



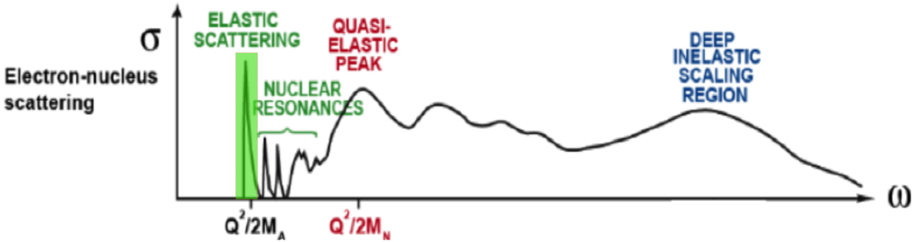
- $Q^2 \equiv 4EE'sin^2\frac{\theta}{2}$
- ν or $\omega \equiv$ E-E′
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $W^2 = 2M\nu + M^2 - Q^2$
- $W^2 > M^2 \rightarrow$ Inelastic Scattering

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

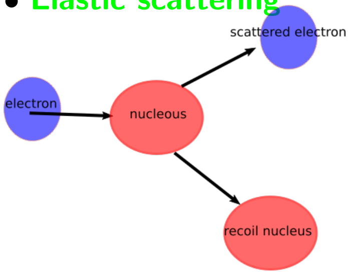
DIS ??????

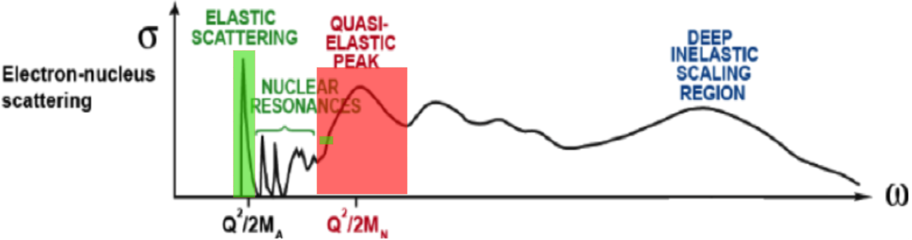


[G. T. Garvey, et al., 2015].

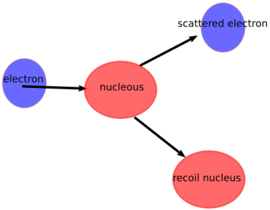


- **Elastic scattering**

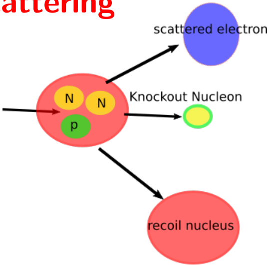


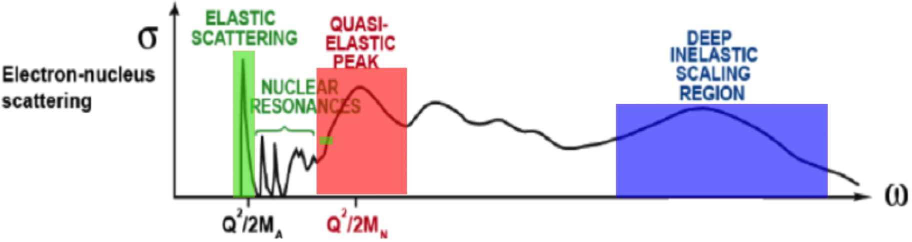


- **Elastic scattering**

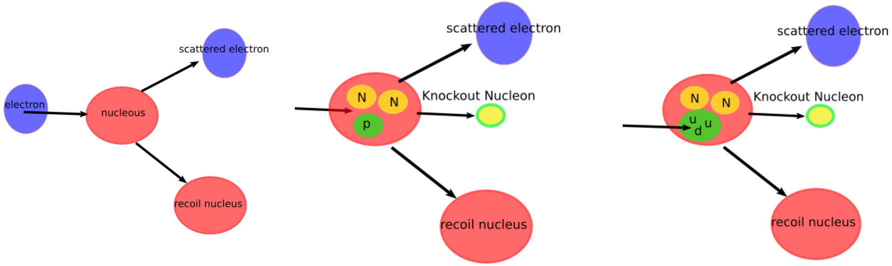


- **Quaiselastic scattering**

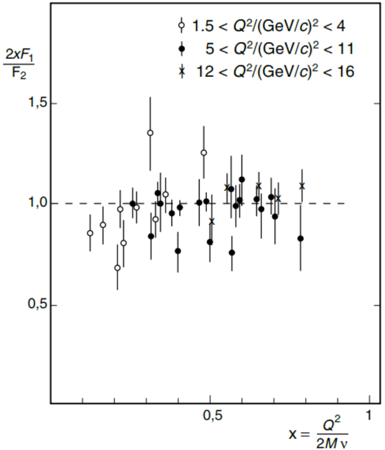




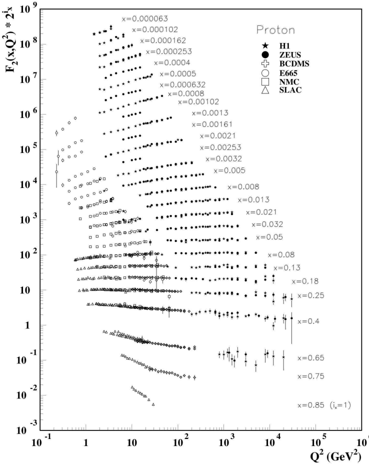
- Elastic scattering
- Quaiselastic scattering
- DIS



Why DIS?

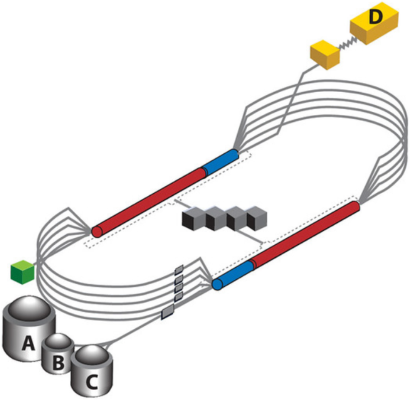


Ratio of $2x \cdot F_1(x)$ and $F_2(x)$ vs. x [?].



Measurements of the proton structure function $F_2(x, Q^2)$ for different x settings[?] .

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

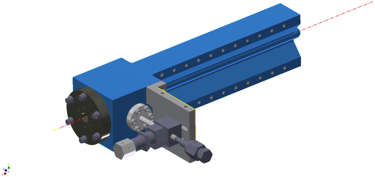
MARATHON planned to use

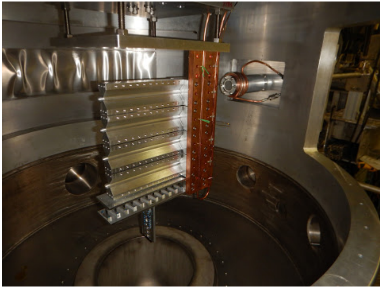
- 11 GeV Beam
- 22.5 μA current
- Hall A's spectrometers and Big Bite Spectrometer

Tritium Target Cell

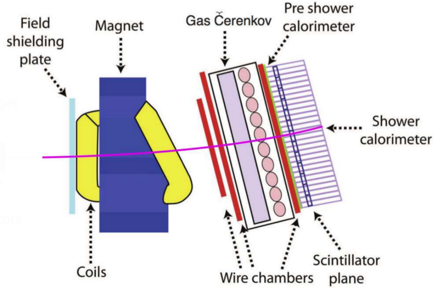
First tritium target at JLab

- 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





The Big Bite Spectrometer



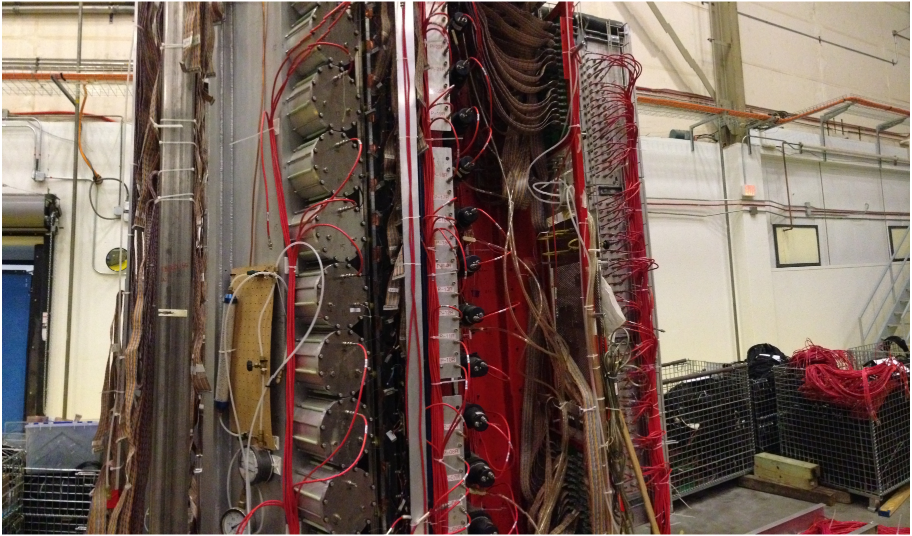
Large Acceptance Spectrometer

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

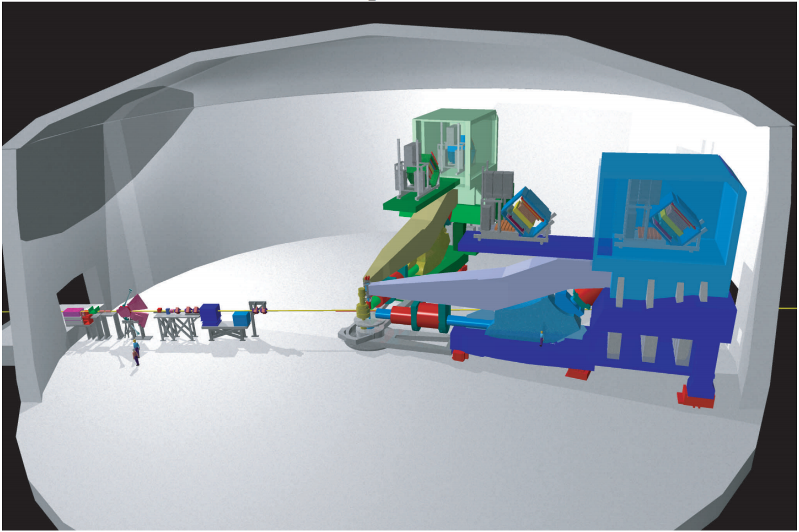
Preparing Big Bite

- Refurbishing signal electronics and cables
- Testing then repairing or replacing PMTs
- Building front end electronics and coincidence trigger logic
- Testing High voltage power sources and providing power to the detectors

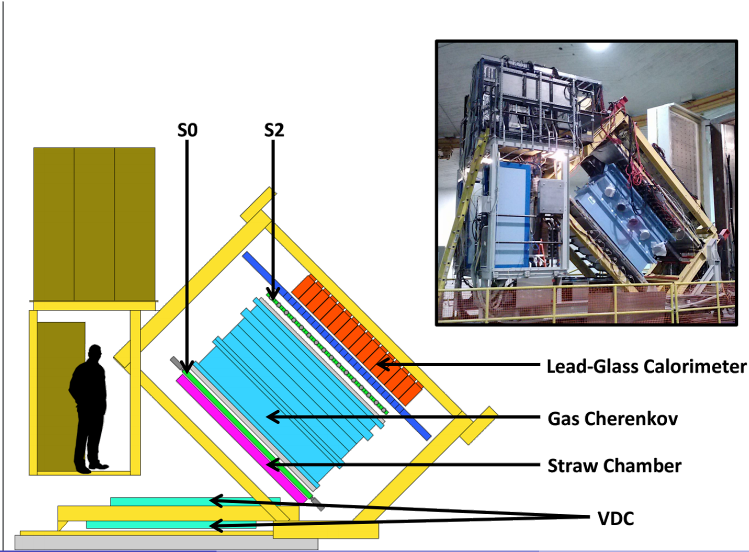
The Big Bite Spectrometer



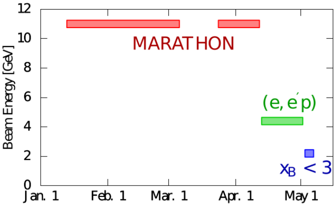
Hall A



High Resolution Spectrometers (HRSs)

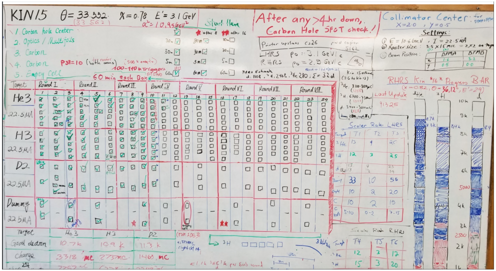


The Run Period

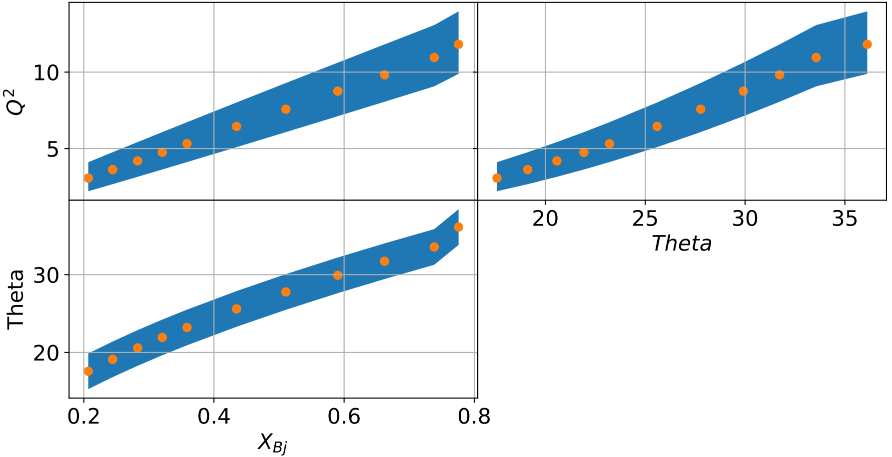


Rey Torres

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



Kinematic Coverage



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

Preparing Data for Analysis

Calibration

ADC calibration

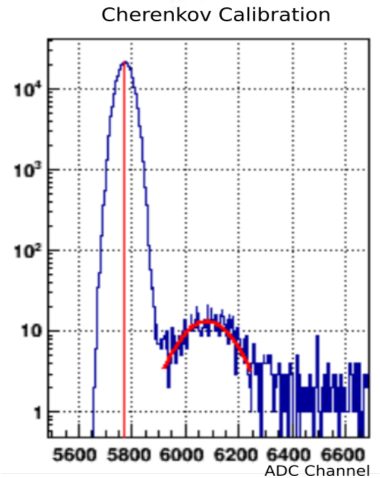
- Calorimeters, Scintillators, and Cherenkov

TDC calibration

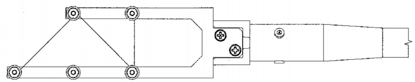
- Scintillators and VDC

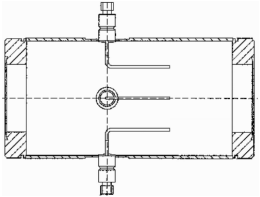
Detector calibrations

- BPMs, BCMS, Optics



Beam Position Monitor(BPM) Calibration



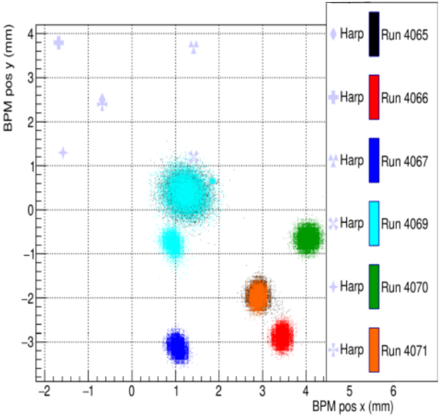


Intrusive absolute position measurement

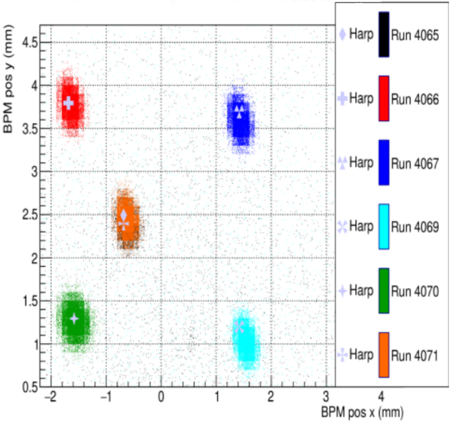
Relative position measurement

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

Beam position from BPM and harp for a collection of runs



Before Calibration



After Calibration

Experimentally Measured Cross Section

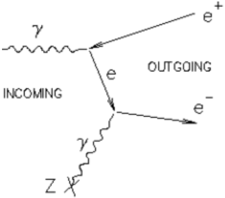
$$\frac{d\sigma}{dE'd\Omega} = \frac{(N - BG)}{L \cdot \epsilon \cdot \Delta E'\Delta\Omega \cdot A(E', \theta)}$$

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

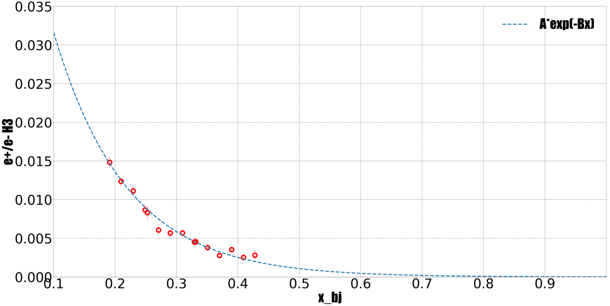
Charge Symmetric Background

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

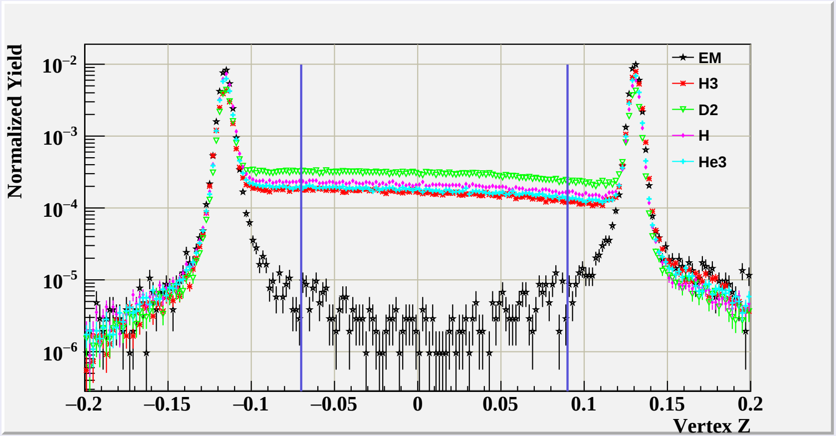
Pair Production



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

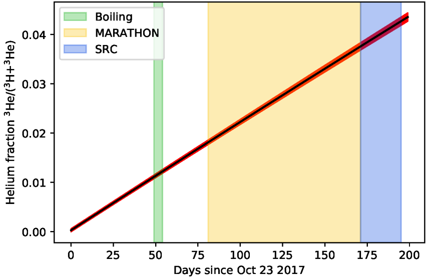
$^3H \rightarrow ^3He$

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

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

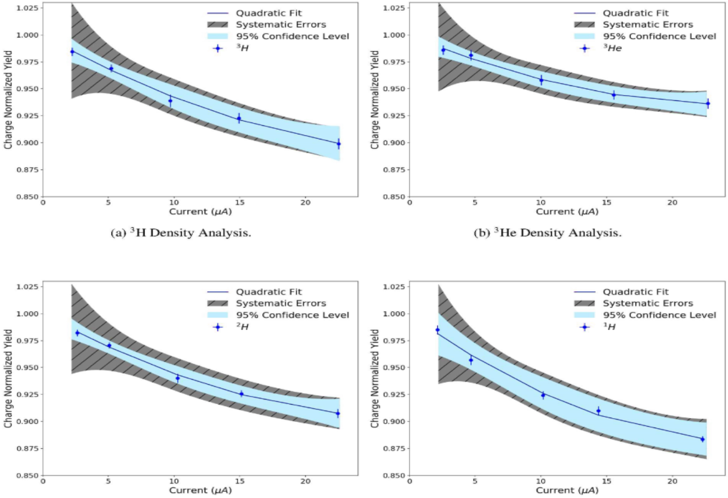
$$\sigma_{^3H} = \left(\frac{\sigma_{tot}}{\sigma_{^3He}}\right)\left(\frac{1}{1-c}\right) - \left(\frac{1}{1-c}\right)$$

Beta Decay Helium Fraction



Tyler Kutz

Density Fluctuations



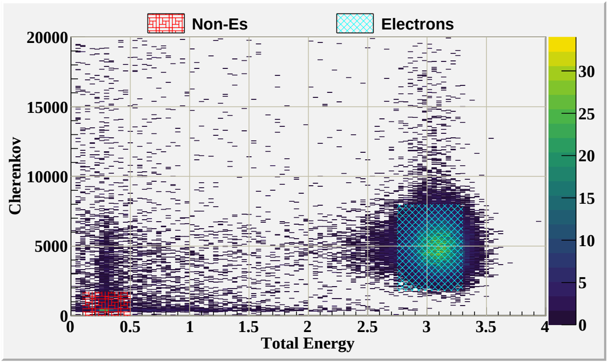
(a) ^{3}H Density Analysis. (b) ^{3}He Density Analysis. (c) ^{2}H Density Analysis. (d) ^{1}H Density Analysis.

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

Efficiencies (ϵ)

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

Particle ID Efficiency



- Use well defined samples
- Apply PID cuts and count
- PID efficiency $\approx 98\%$ for all kinematics

Monte Carlo Ratio Method

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

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

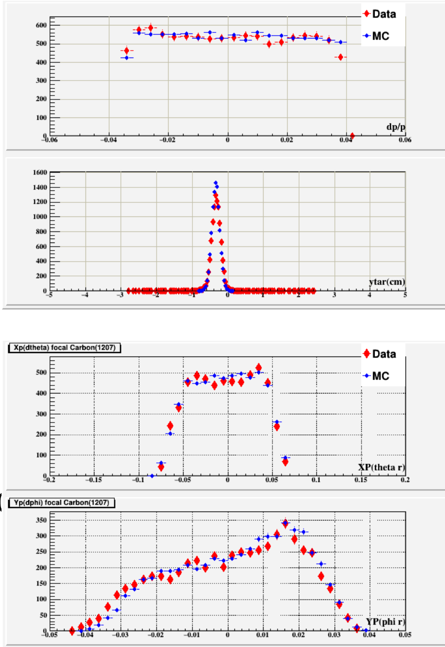
Use a Monte Carlo simulation

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

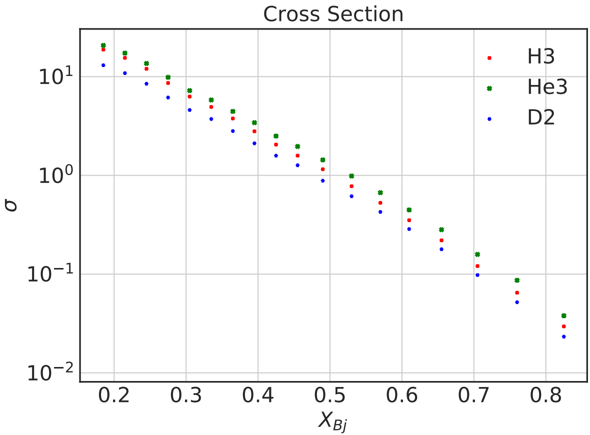
$$\sigma_{Data} = \sigma_{model} \cdot \frac{Y_{Data}}{Y_{MC}}$$

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, 20



DIS Cross Section



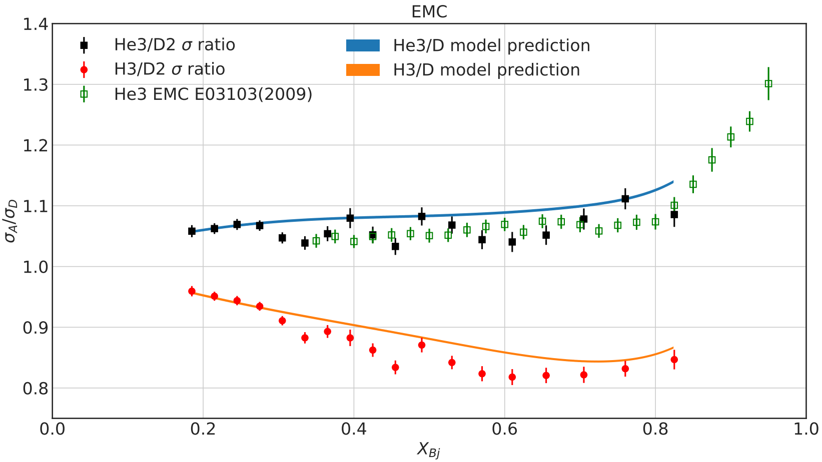
Normalization uncertainty due to target thickness uncertainty
He3 - 1.12% • H3 - 0.97% • D - 0.56%

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

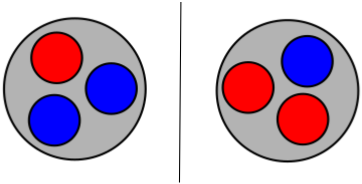
X bin	0.215	0.455	0.705
Statistical Error	0.512	0.889	1.106
Positron Correction Error	0.036	0.016	0.005
Efficiency Error*	0.665	1.477	2.951
Density Correction Error	0.002	0.002	0.002
Monte Carlo Error	0.193	0.217	0.209
Total Error	0.95	1.931	3.316

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

Per Nucleon Cross Section Ratio



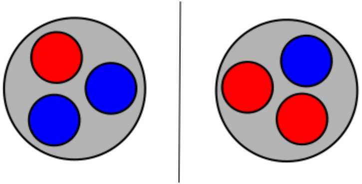
Isoscalar Corrections



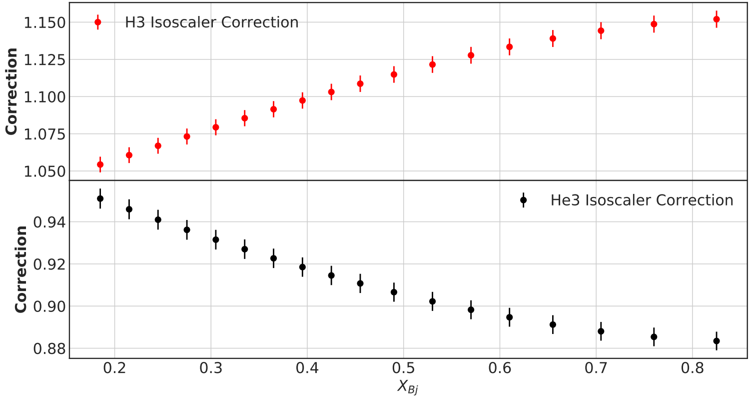
- Correct for the unpaired nucleon in the A/D ratio.

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

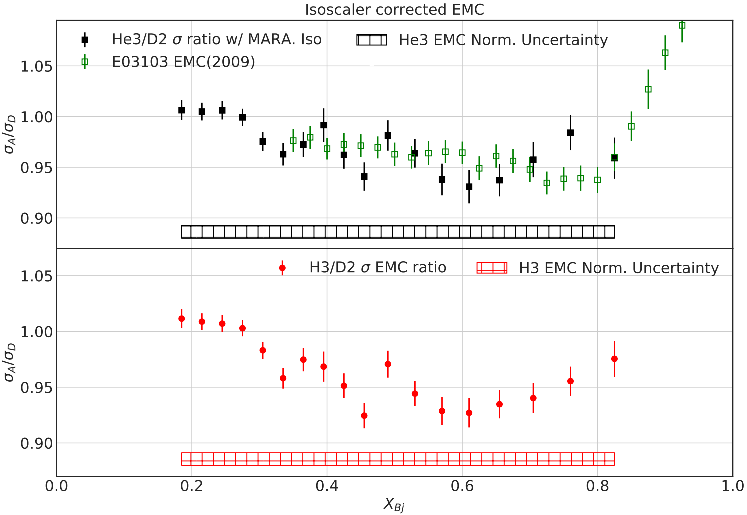
Isoscalar Corrections



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



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
- Model Dependence on Isoscalar correction
- Determine EMC effect for Tritium and Helium-3

The JLab MARATHON Tritium Collaboration

D. Abrams, H. Albataineh, **S. Alsalmi**, D. Androic, K. Aniol, W. Armstrong, J. Arrington, H. Atac, T. Averett, C. Ayerbe Gayoso, X. Bai, **J. Bane***, **S. Barcus**, A. Beck, V. Bellini, H. Bhatt, D. Bhetuwal, D. Biswas, D. Blyth, W. Boeglin, D. Bulumulla, A. Camsonne, **M. Carmignotto**, **J. Castellanos**, J-P. Chen, C. Ciofi degli Atti, E. O. Cohen, S. Covrig, K. Craycraft, **R. Cruz-Torres**, B. Dongwi, M. Duer, B. Duran, D. Dutta, N. Fomin, E. Fuchey, C. Gal, T. N. Gautam, S. Gilad, K. Gnanvo, T. Gogami, J. Gomez, C. Gu, A. Habarakada, **T. Hague***, O. Hansen, M. Hattawy, **F. Hauenstein**, O. Hen, D. W. Higinbotham, R. Holt, E. Hughes, C. Hyde, H. Ibrahim, S. Jian, S. Joosten, A. Karki, B. Karki, A. T. Katramatou, C. Keppel, M. Khachatryan, V. Khachatryan, A. Khanal, D. King, P. King, I. Korover, S. A. Kulagin, **T. Kutz***, N. Lashley-Colthirst, G. Laskaris, **S. Li**, W. Li, **H. Liu***, S. Liuti, N. Liyanage, D. Lonardoni, R. Machleidt, L.E. Marcucci, P. Markowitz, **E. McClellan**, D. Meekins, W. Melnitchouk, S. Mey-Tal Beck, Z-E. Meziani, R. Michaels, M. Mihovilovič, V. Nelyubin, **D. Nguyen**, N. Nuruzzaman, **M. Nycz***, R. Obrecht, M. Olson, L. Ou, V. Owen, E. Pace, **B. Pandey**, V. Pandey, A. Papadopoulou, M. Paolone, S. Park, M. Patsyuk, S. Paul, G. G. Petratos, R. Petti, E. Piasetzky, R. Pomatsalyuk, S. Premathilake, A. J. R. Puckett, V. Punjabi, R. Ransome, M. N. H. Rashad, P. E. Reimer, S. Riordan, J. Roche, F. Sammarruca, G. Salmè, **N. Santiesteban**, B. Sawatzky, J. Segal, E. P. Segarra, B. Schmookler, A. Schmidt, S. Scopetta, A. Shahinyan, S. Širca, N. Sparveris, **T. Su***, R. Suleiman, H. Szumila-Vance, A. S. Tadepalli, L. Tang, W. Tireman, F. Tortorici, G. Urciuoli, M. Viviani, L. B. Weinstein, B. Wojtsekhowski, S. Wood, **Z. H. Ye**, Z. Y. Ye, and J. Zhang.

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

Forty Five Institutions (in no particular order): University of Virginia; Texas A & M University; Kent State University; University of Zagreb; California State University, Los Angeles; Argonne National Laboratory; Temple University; The College of William and Mary; University of Tennessee; Massachusetts Institute of Technology; INFN Sezione di Catania; INFN Sezione di Roma, INFN Sezione di Pisa; Mississippi State University; Hampton University; Florida International University; Old Dominion University; Jefferson Lab; University of Perugia; Tel Aviv University; University of Connecticut; Tohoku University; Columbia University; Cairo University; Ohio University; Stony Brook, State University of New York; Syracuse University; Nuclear Research Center-Negev, Beer-Sheva; Institute for Nuclear Research of the Russian Academy of Sciences; University of New Hampshire; University of Regina; Columbia University; Facility for Rare Isotope Beams, Michigan State University; Los Alamos National Laboratory; University of Idaho; University of Pisa; Jožef Stefan Institute, University of Ljubljana; Johannes Gutenberg-Universität Mainz; Saint Norbert College; Center for Neutrino Physics, Virginia Tech; University of South Carolina; Kharkov Institute of Physics and Technology; Norfolk State University; Rutgers University; Artem Alikhanian National Laboratory; Tel Aviv University; Northern Michigan University; University of Illinois, Chicago.

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References I

A. Bodek and U.K. Yang
Nuclear Physics B, Procc. Suppl. 112 (2002) 70-76

Garvey, G. T. et. al.
Phys. Rept., 580 (2015) 1-45

J. Gomez et al.
Phys. Rev D 49 (1994) 4348

Douglas Higinbotham (2013)
The EMC effect still puzzles after 30 years. *Cern Courier* April 2013.

K. Nakamura et. al.
Review of Particle Physics, 37 (2010)

S.N.Santiestebana et. al
Nucl. Instrum. Meth. A 940 (2019) 351-358

J.Seely, A. Daniel et al
Phys. Rev. Lett. 103, 202301 (2009).