

The EMC Effect in A=3 Nuclei.

Jason Bane

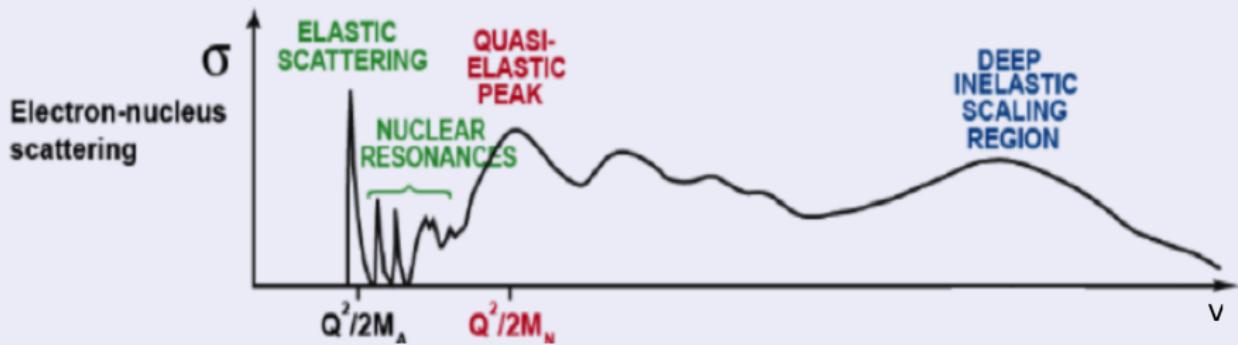
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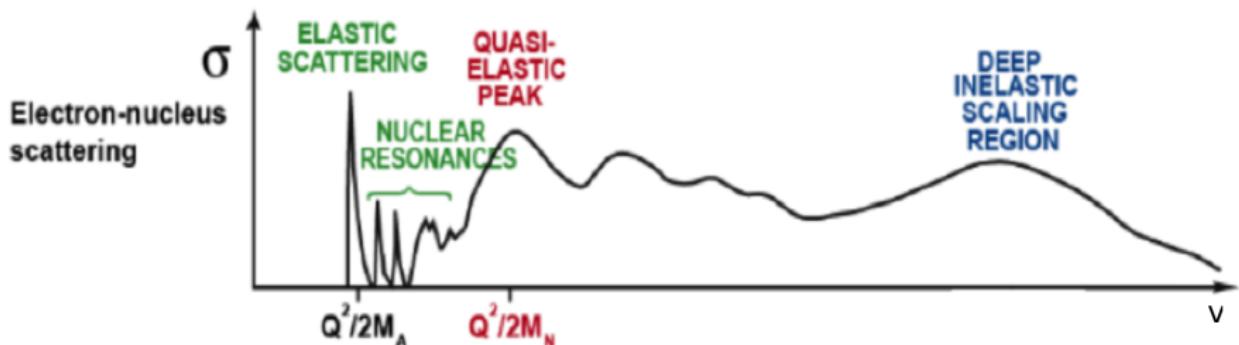
Outline

- ① Deep Inelastic Scattering
- ② The EMC Effect
- ③ The MARATHON Experiment
- ④ Data Analysis
- ⑤ EMC Effect of $A=3$

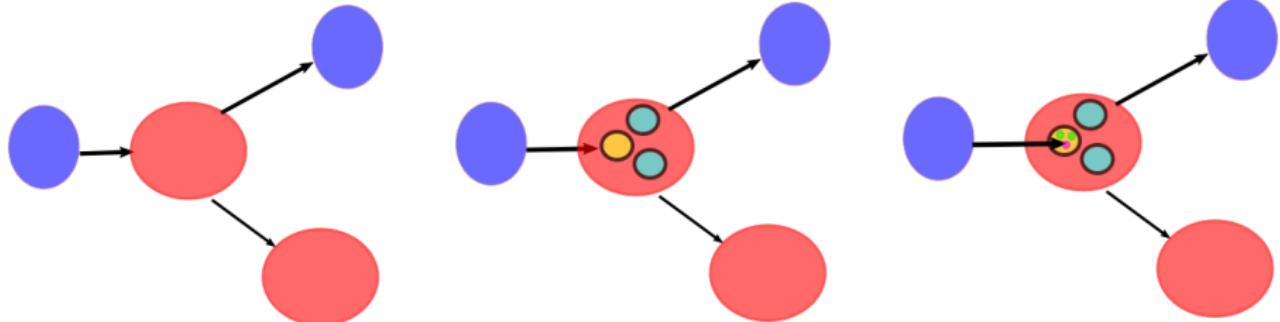
Deep Inelastic Scattering(DIS) ??????



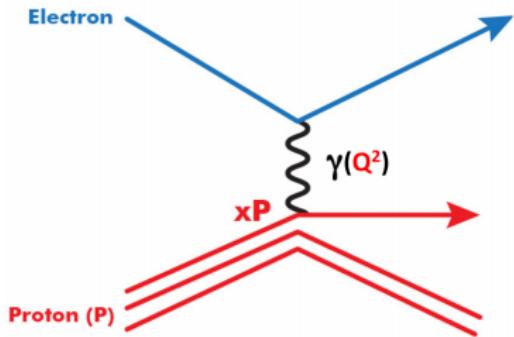
Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].



- Elastic scattering
- Quasielastic
- DIS

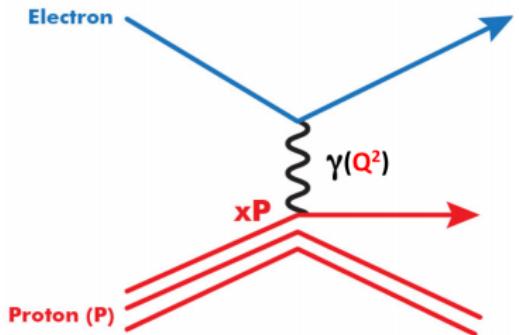


Deep Inelastic Scattering (DIS)



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

Deep Inelastic Scattering (DIS)



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

Why DIS?

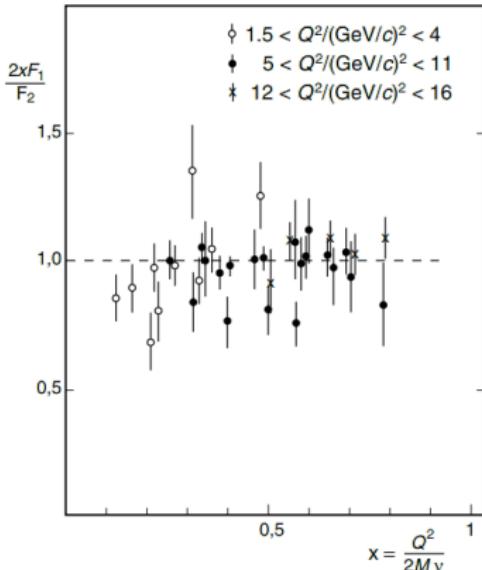
$$\sigma_{eN} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)} \left[\frac{F_2(x)}{\nu} \cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(x)}{M} \sin^2\left(\frac{\theta}{2}\right) \right]$$

Quark parton model

In the Bjorken limit where
 (Q^2/ν) is fixed

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

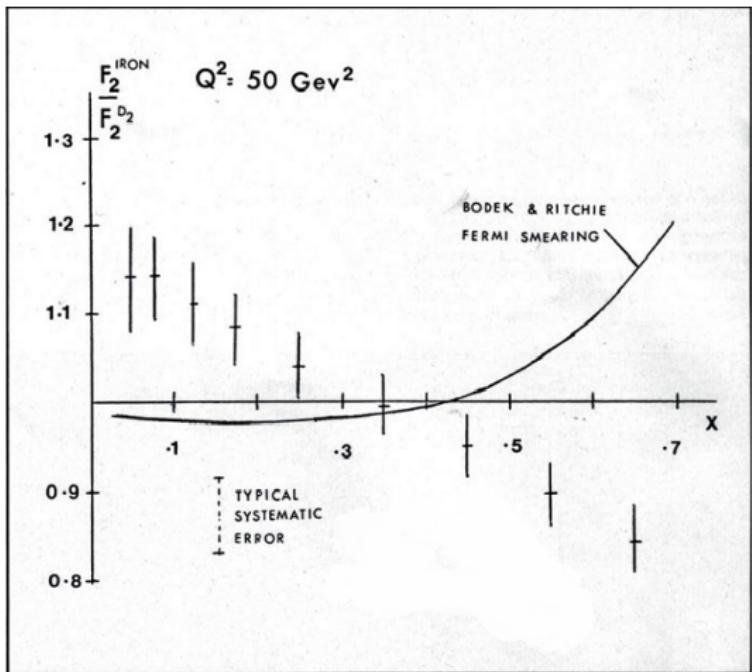
$$F_2(x) = F_1(x) \cdot 2x$$



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

The EMC Effect

European Muon Collaboration

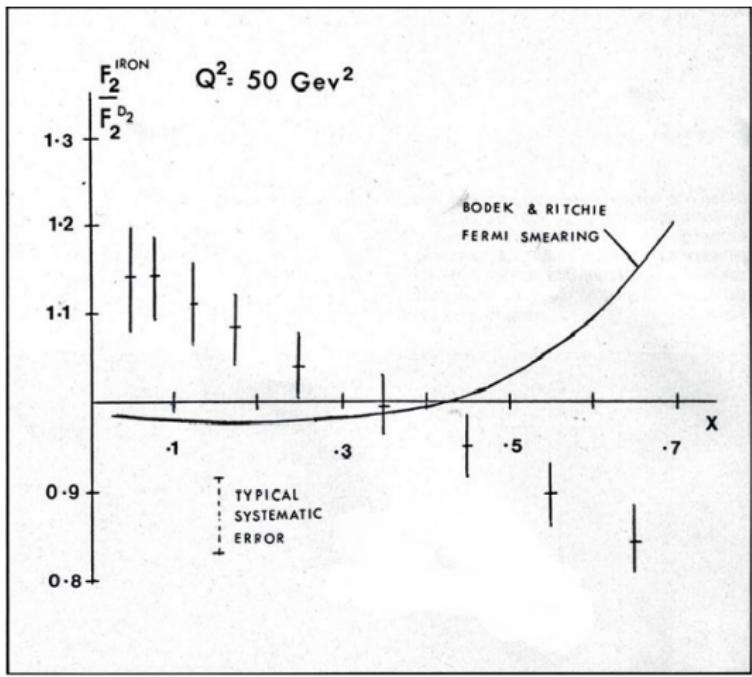


[J.J. Aubert, et al. 1981]

The EMC Effect

European Muon Collaboration

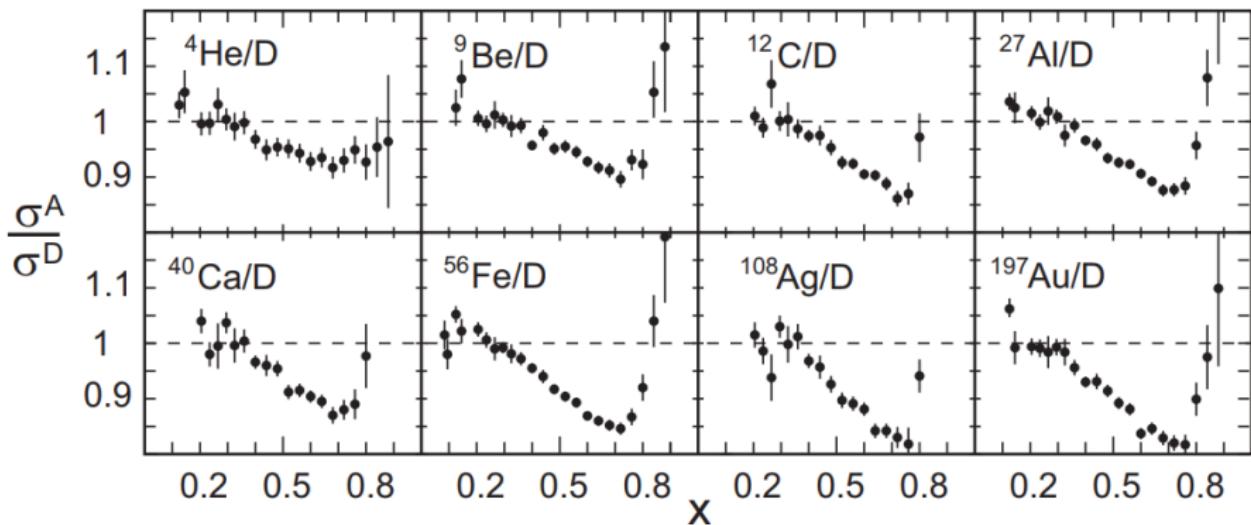
- Expected Unity at low x
 - ▶ Binding < momentum transfer
 - ▶ Free Nucleons
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$
- Isoscalar corrections
- Unexpected Relative Decrease
- Missing high-momentum quarks in $A > 2$
- EMC Effect \equiv structure of the A/D Ratio

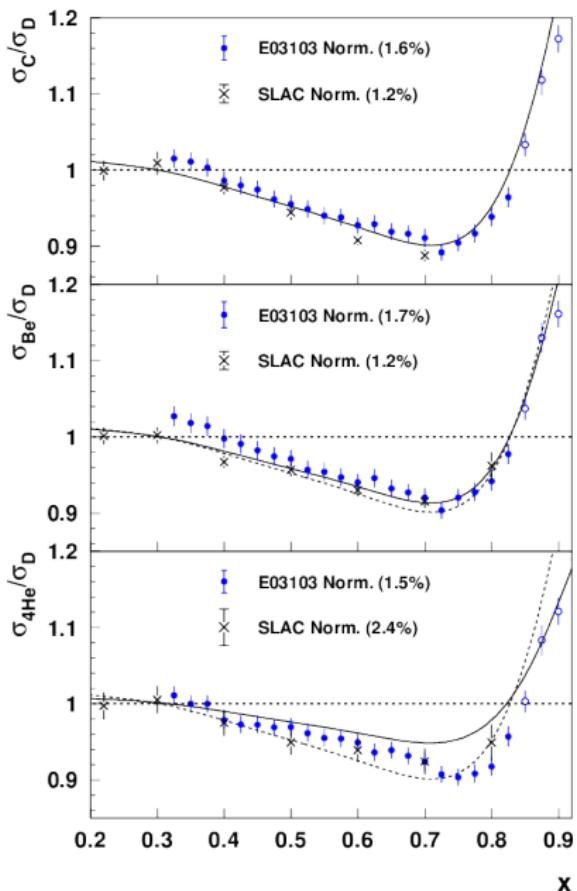


[J.J. Aubert, et al. 1981]

The EMC Effect

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



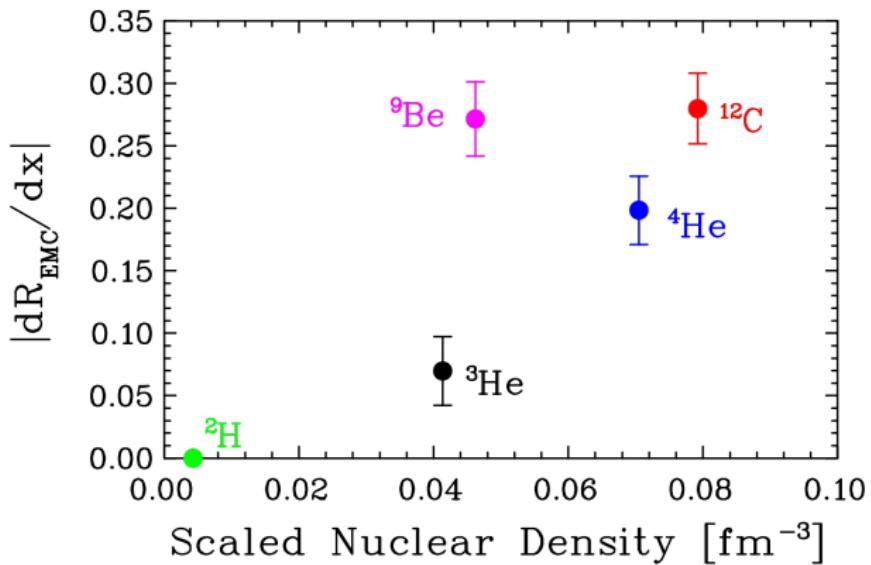


- JLab experiment E03103 [J.Seely, A. Daniel et al, 2009]
- CERN, SLAC, HERMES, BCDMS, and JLab
- Quantized by slope of A/D ratios from 0.3 - 0.7 in x
- Corrections for non-isoscalar nuclei
- Models have difficulty matching data for all criteria
- $\approx \log$ dependence in A

The EMC Effect

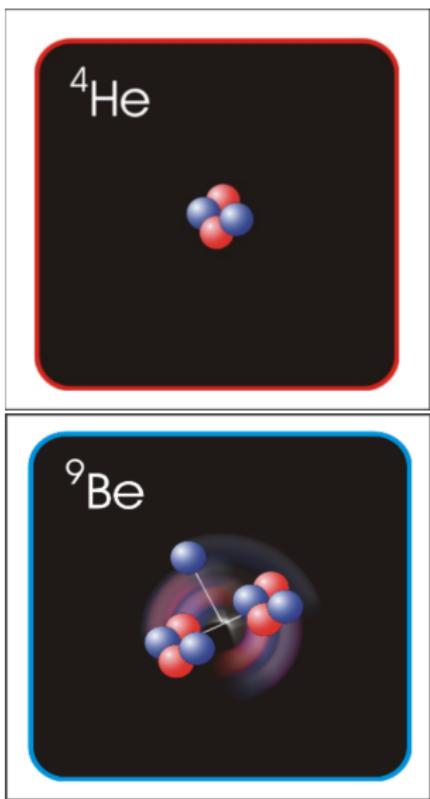
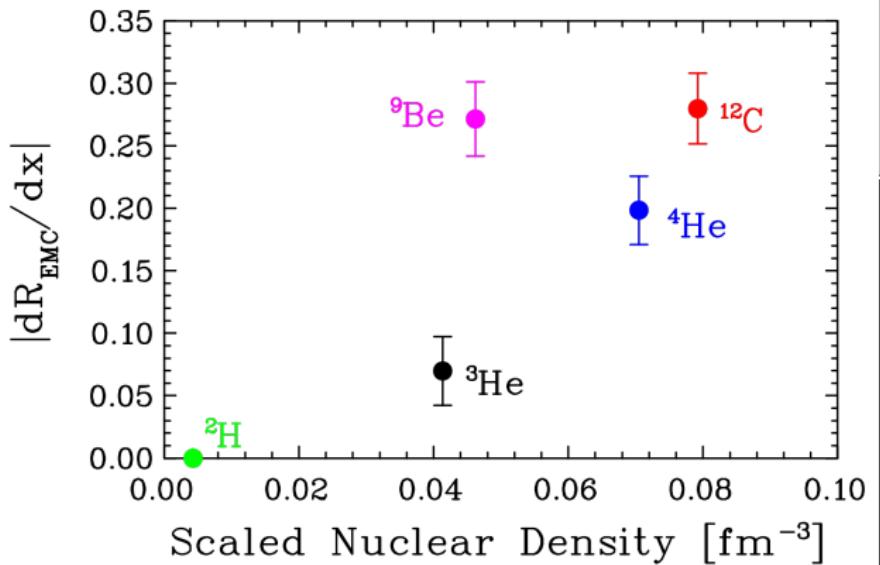
JLab experiment E03103

[J.Seely, A. Daniel et al, 2009]



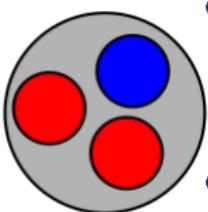
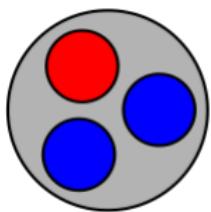
The EMC Effect

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



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
- Can help determine the validity of the isoscalar correction procedure.
- Are we using the correct method of correcting the non-isoscalar nuclei?



The JLab 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. Mihovilović, 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. Pettit, 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. Sirca, 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. Wojtsekowski, 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

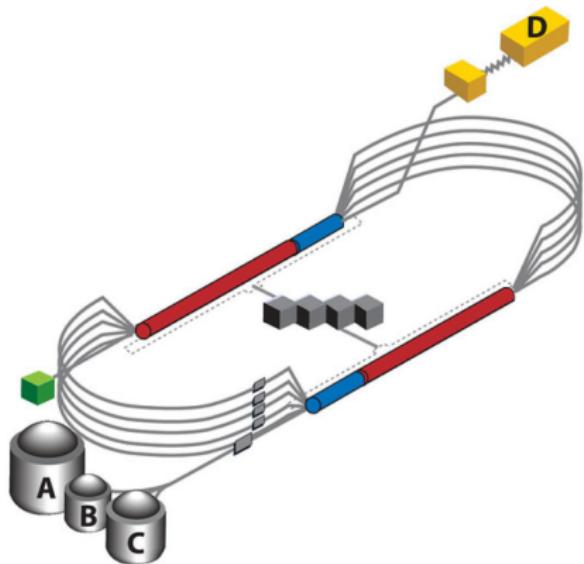


The JLab Tritium Collaboration

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.

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

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

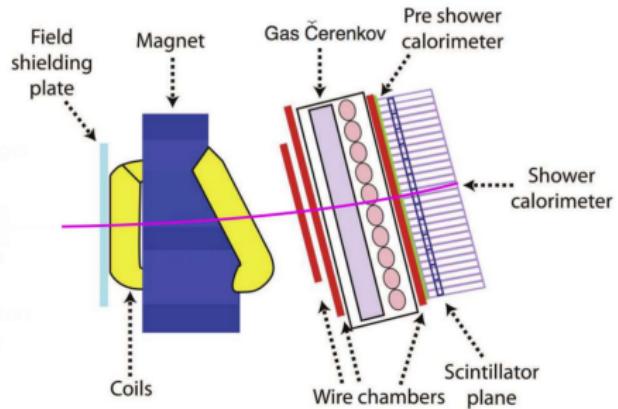


- ≈ 2.2 GeV per revolution
- 12 GeV for Hall D
- Superconducting RF cavities
- RF separators split the beam to each Hall

MARATHON's proposal

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

Bigbite Spectrometer



Large Acceptance Spectrometer

- Solid angle = 96 mrad
- Large Momentum Acceptance: $> 500 \text{ MeV}/c$

My contributions in preparing Bigbite

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

Removed from the run plan for safety and logistical concerns

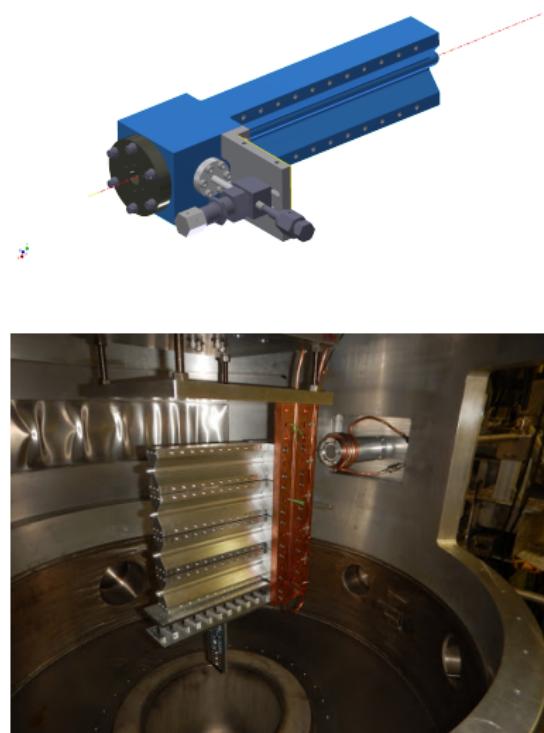
Uses of Tritium



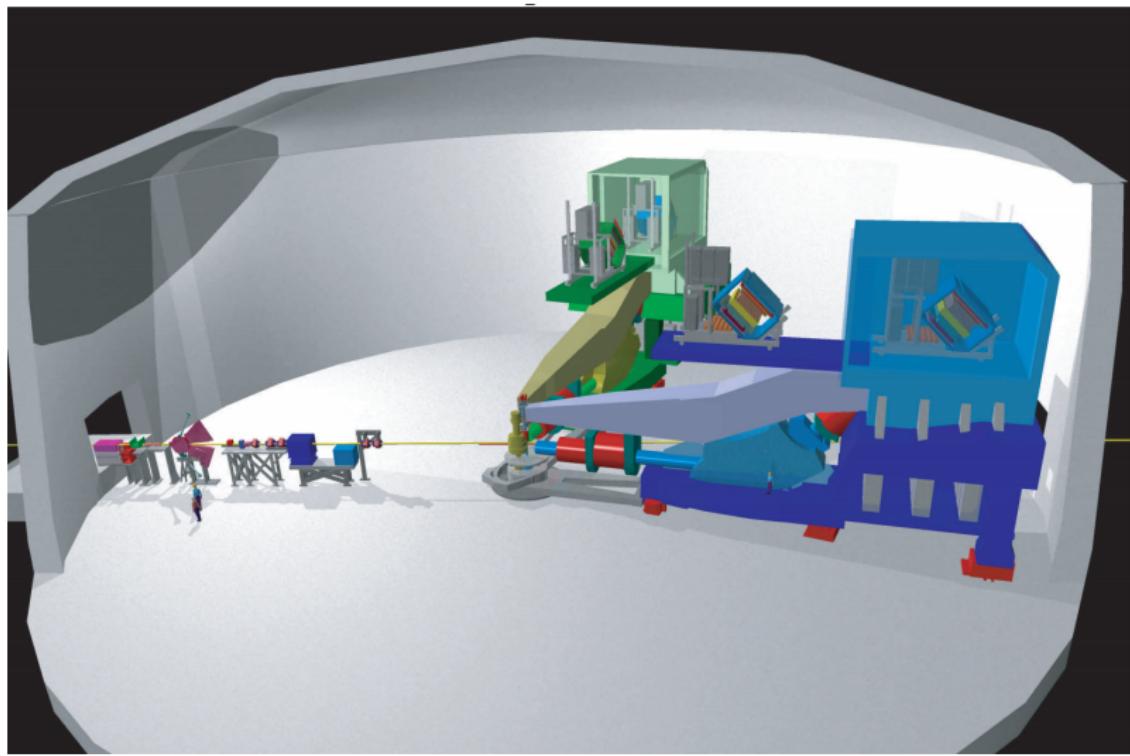
Tritium Target Cell

First tritium target at JLab

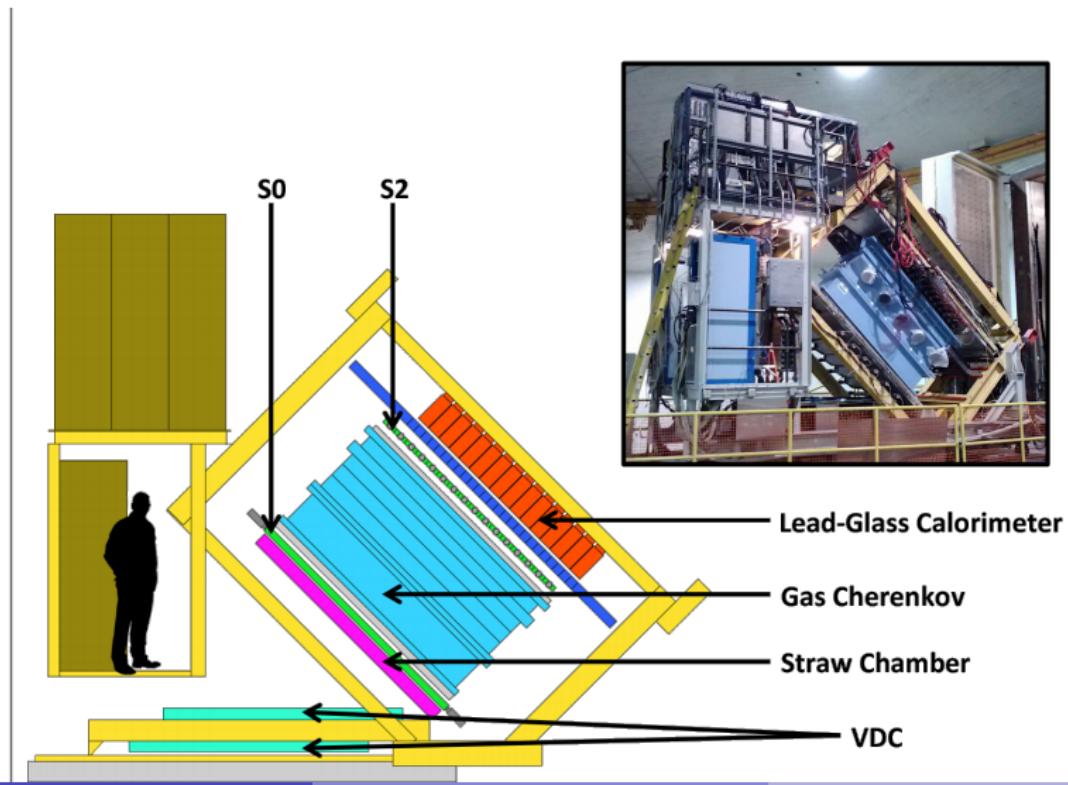
- Thin Al entrance and exit windows 0.01 inches
- 1090Ci of Tritium (0.1 g)
- 25 cm long
- Tritium Cell was filled in Savannah River
- 40 kelvin Helium is used to cool an attached heat sink



Hall A

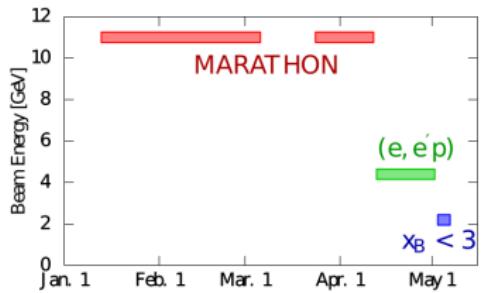


High Resolution Spectrometers (HRSs)



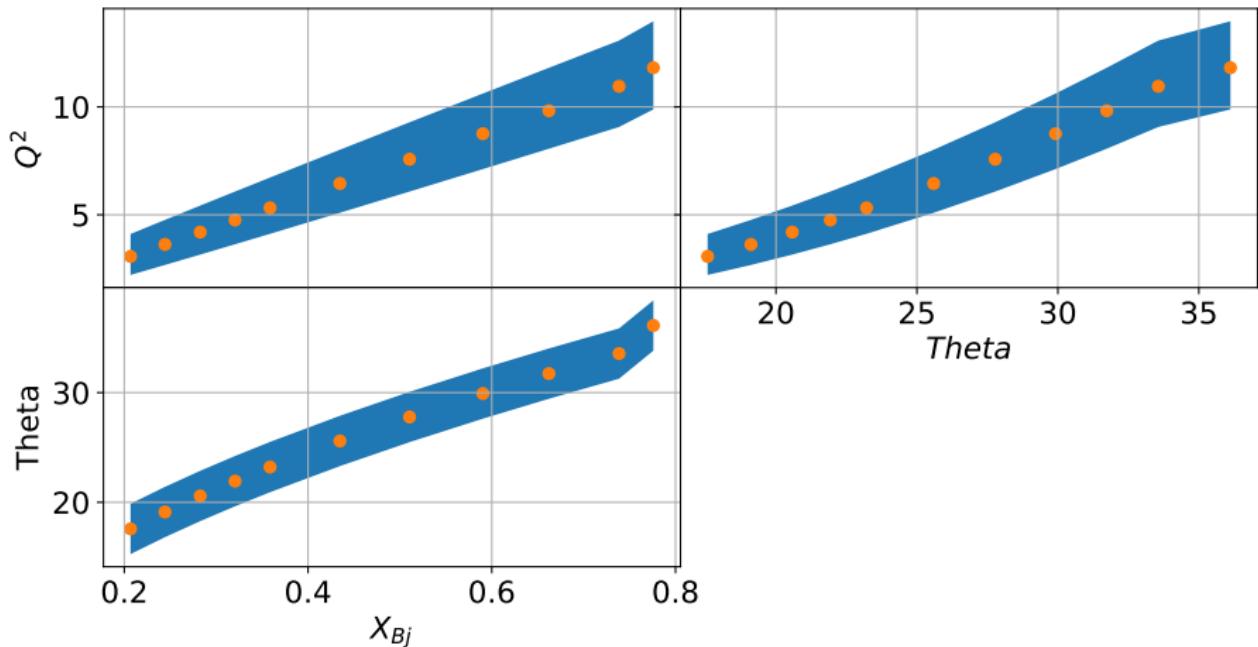


The Run Period



Rey Torres

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

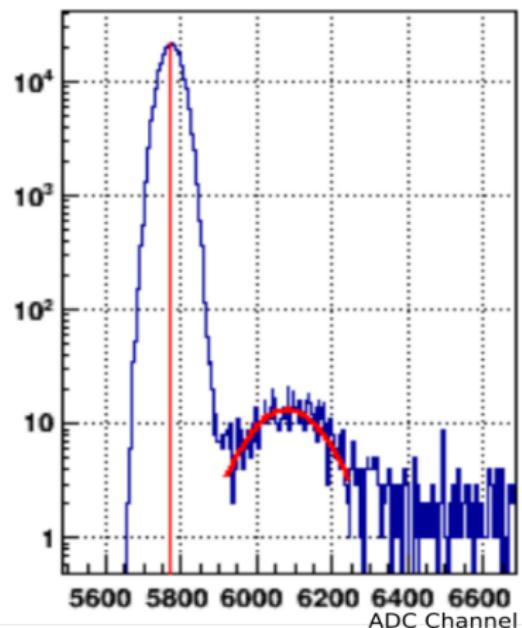
TDC calibration

- Scintillators and VDC

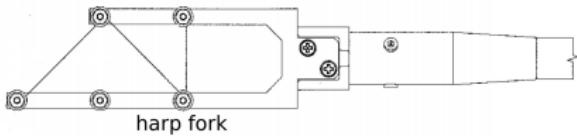
Detector calibrations

- Beam Current Monitors
- Beam Position Monitors

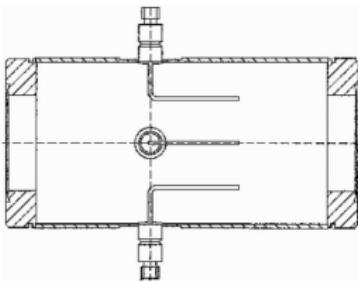
Cherenkov Calibration



Beam Position Monitor(BPM) Calibration



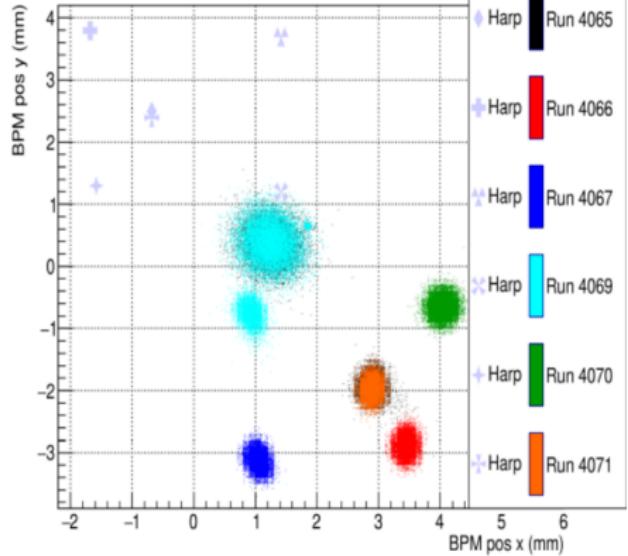
Intrusive absolute position measurement



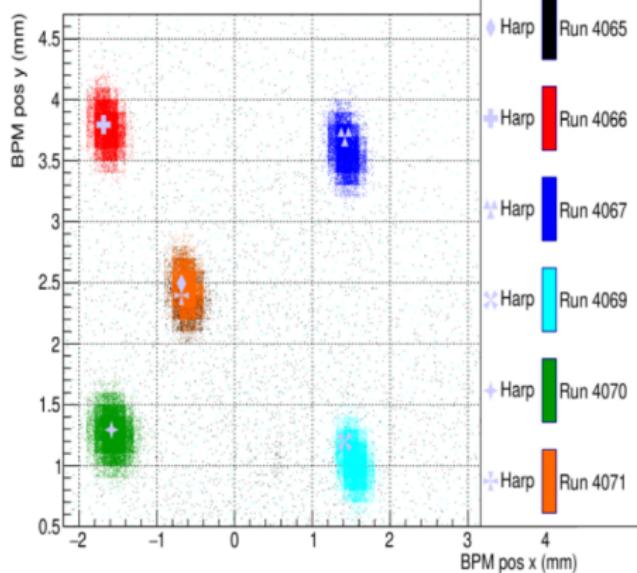
Relative position measurement

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

Beam position from BPM and harp for a collection of runs



Before Calibration



After Calibration

Experimentally Measured Cross Section



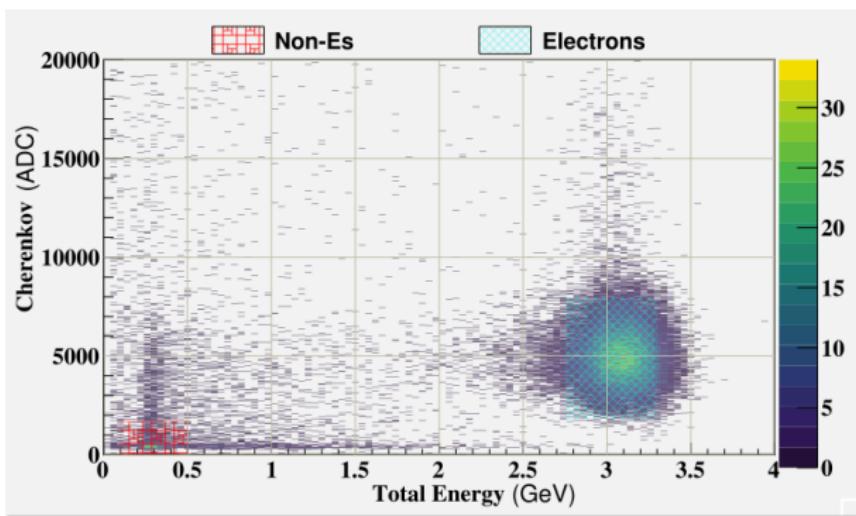
- N = Number of electrons
- BG = Background
- L = Luminosity
 - ▶ Density Correction
- ϵ = Efficiency
- $\Delta E' \Delta \Omega$ = Bin Size
- $A(E', \theta)$ = Acceptance probability

Efficiencies (ϵ)

Calculating efficiencies

- Use well defined samples from separate system(s)
 - ▶ Testing cherenkov use calorimeters
 - ▶ Testing VDC use scintillators.
- Determine good event samples with cuts
- # of events which fail the criteria → inefficiency
- Particle Identification(PID)
 - ▶ Cherenkov
 - ▶ Calorimeters
- Trigger
 - ▶ Scintillators & cherenkov
 - ▶ $\approx 99\%$
- Tracking
 - ▶ Vertical Drift Chambers(VDCs)
 - ▶ $\approx 98\%$
- Electronic Lifetime
 - ▶ $\approx 96\%-99\%$

Particle ID Efficiency

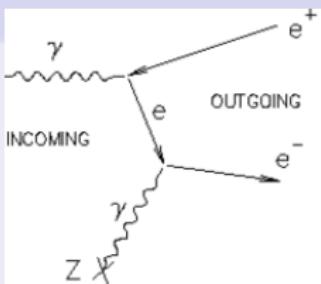


- Total energy absorber for electrons
- Cherenkov's pion threshold is $>$ momentum setting
- PID efficiency $\approx 98\%$ for all kinematics

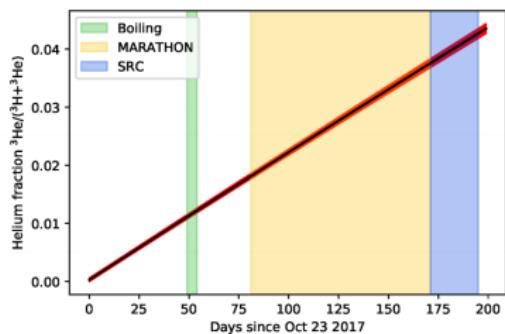
Background Subtraction

Pair Production

- γ decay into an e^+e^- pairs
- Fit use to extrapolate correction



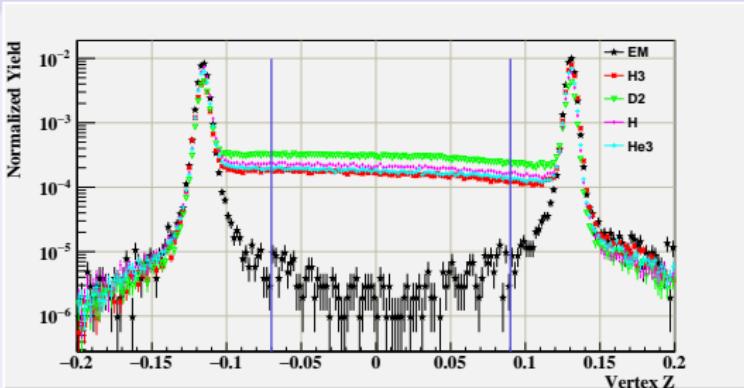
Beta Decay



- ${}^3\text{H}$ beta decays into ${}^3\text{He}$
- Time depended correction

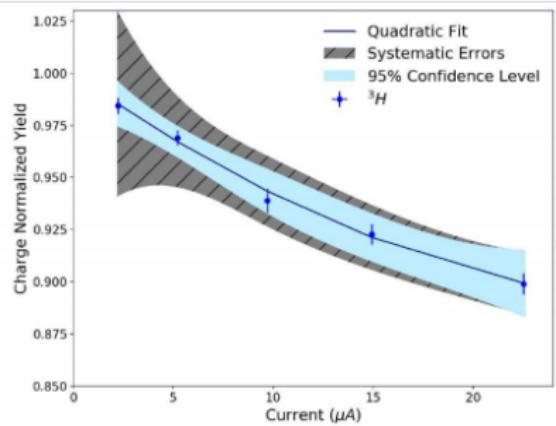
Tyler Kutz

EndCap Subtraction



Density Correction

- Local density fluctuations due to beam heating
- S.N. Santiesteban, J. Bane, et. al *Nucl. Instrum. Meth. A* 940 (2019) 351-358



Monte Carlo Ratio Method

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

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

Monte Carlo simulation :

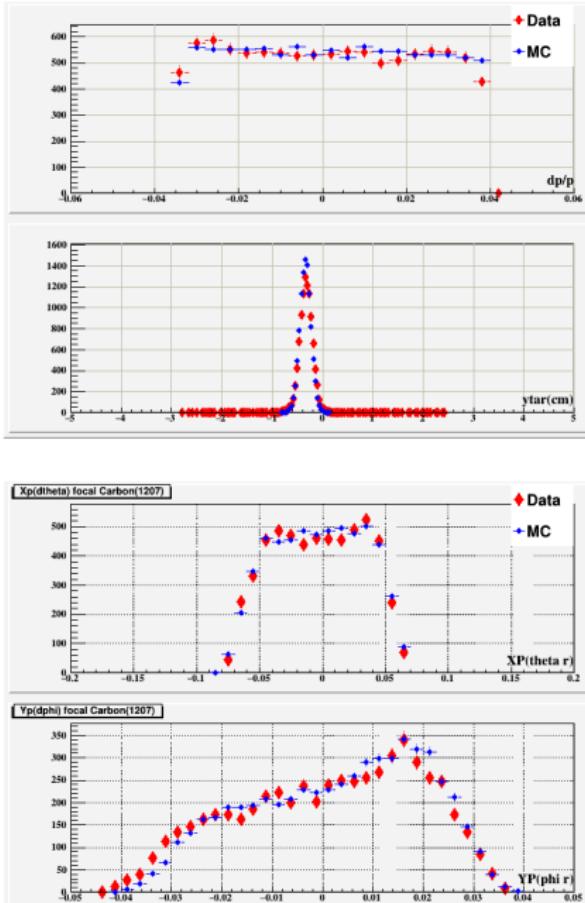
- $(\Delta E' \Delta \Omega)_{Data} = (\Delta E' \Delta \Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

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

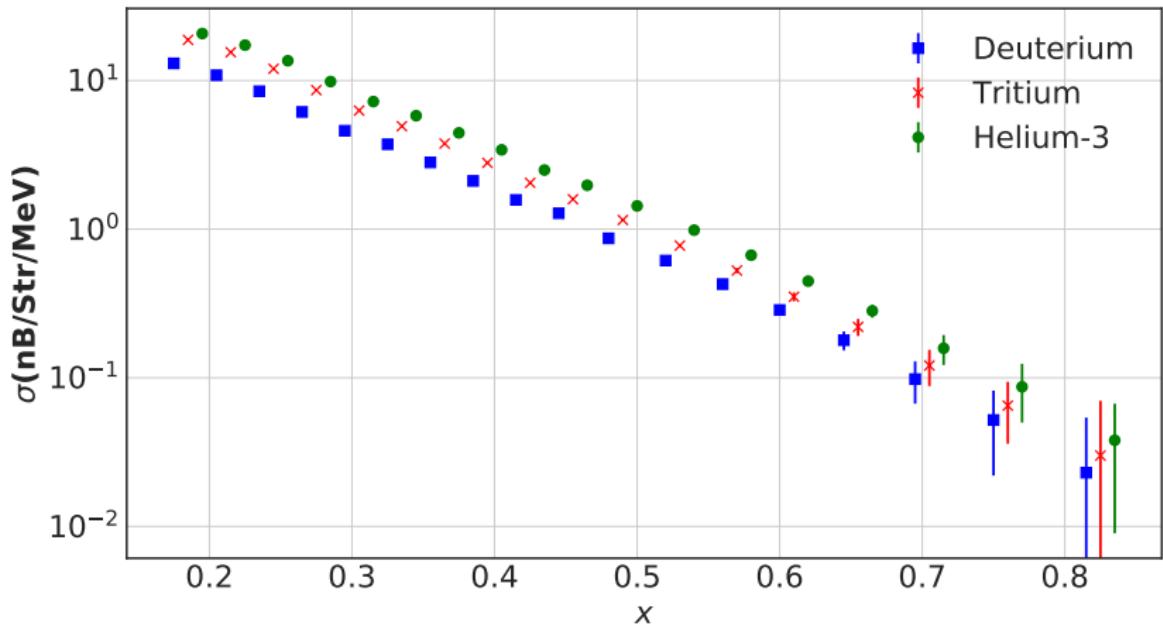
Monte Carlo

- 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]



DIS Cross Section



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

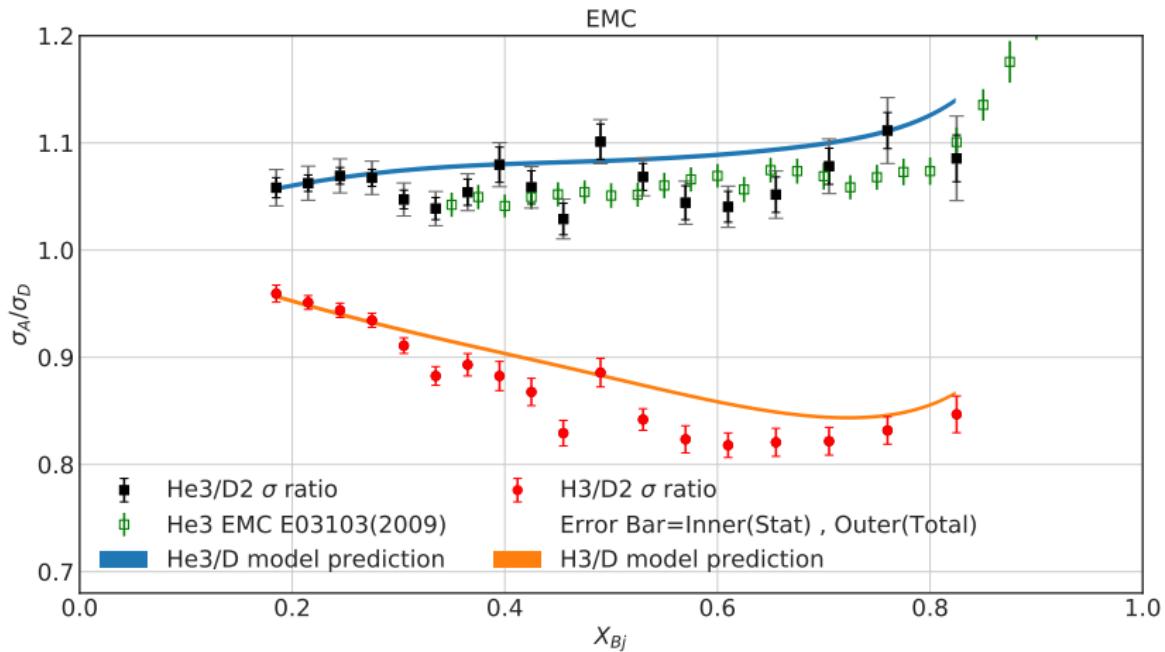
Relative uncertainty contributions for the cross section ${}^3\text{H}$.

Xbjc	0.185	0.305	0.49	0.57	0.705	0.825
Yield	0.01	0.0107	0.0149	0.0151	0.0141	0.0163
Stat *	0.0055	0.0059	0.01	0.0111	0.0113	0.0143
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Efficiency *	0.004	0.0051	0.0083	0.0071	0.0041	0.0032
MC&Model	0.016	0.014	0.013	0.016	0.03	0.037
Resolution**	0.015	0.011	0.005	0.001	0.007	0.018
Model**	0.006	0.009	0.012	0.016	0.029	0.032
Total	0.019	0.018	0.02	0.022	0.033	0.04

* Largest contributors to the uncertainty in the yield calculation

** Largest contributors to the uncertainty in Monte Carlo and Cross section model calculation.

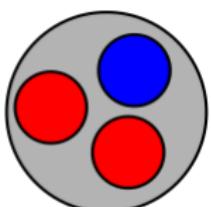
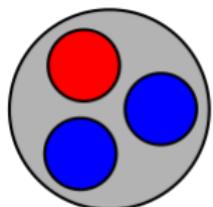
Per Nucleon Cross Section Ratio



MARATHON results compared with E03103

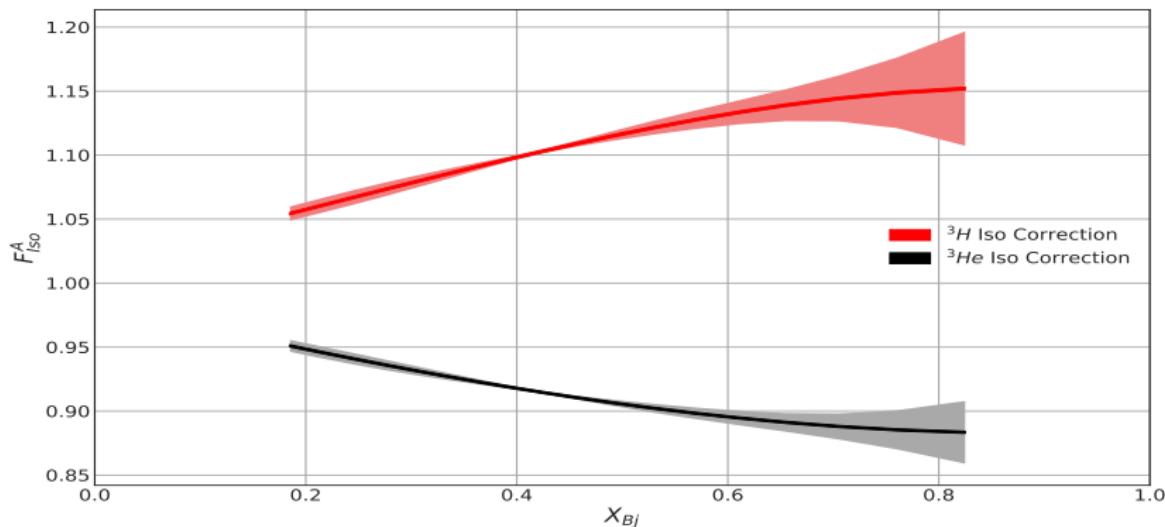
[J.Seely, A. Daniel et al, 2009] and the A/D ratios from a DIS scattering model from Arie Bodek model [A. Bodek and U.K. Yang, 2002].

Isoscalar Corrections

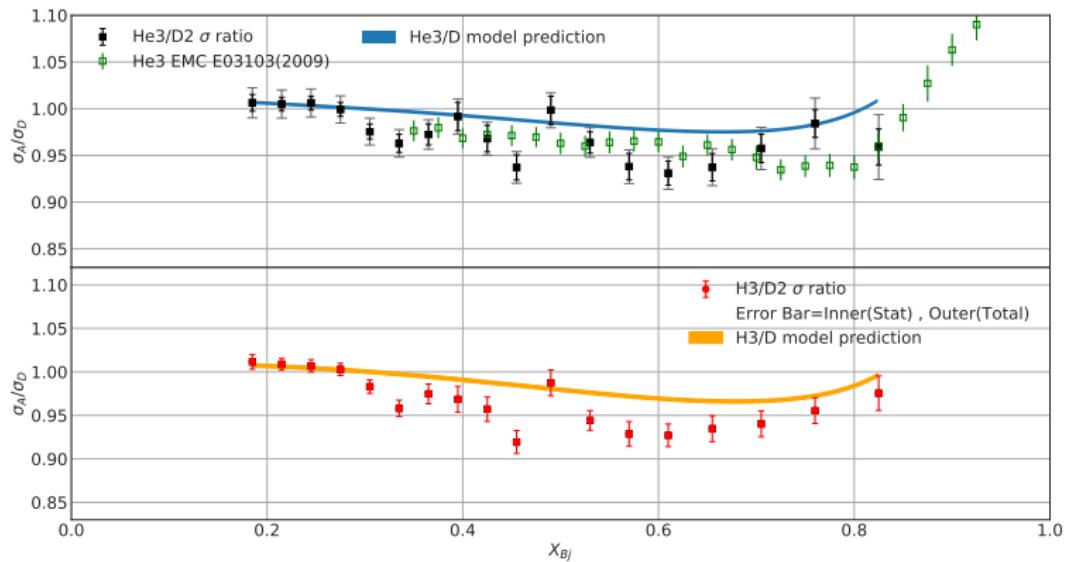


- Correct for the unpaired nucleon in the A/D ratio.

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



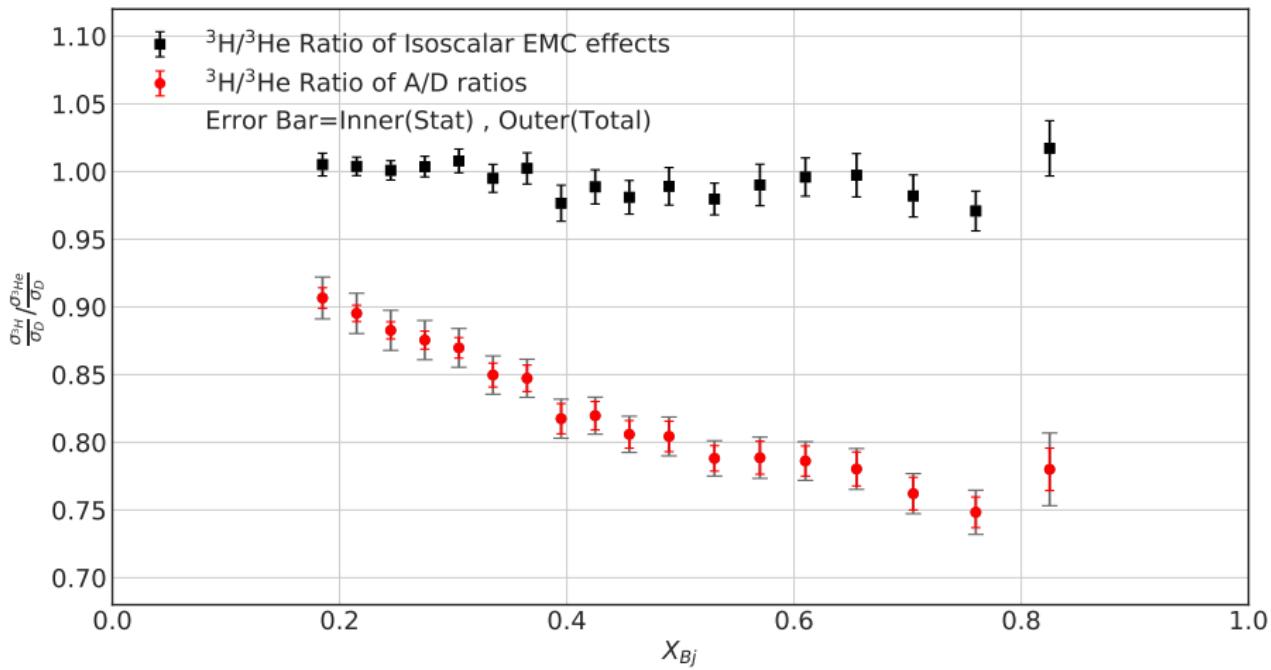
- My EMC results for He3 in black • H3 in red
- Previous Jlab He3 in green



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].

Ratio of $^3\text{H}/^3\text{He}$ EMC effects



Ratio of EMC effects.

Summary

- Used DIS to extract inclusive cross section for ${}^3\text{H}$, ${}^3\text{He}$, and D
- Looked at the A/D ratio for both ${}^3\text{H}$ and ${}^3\text{He}$
- Compared the EMC effects of the two, A=3 nuclei.
 - ▶ See no difference for Isoscalar EMC effects within analysis accuracy



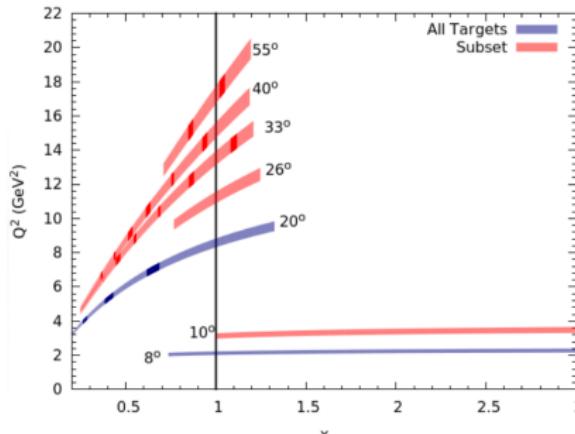
Special Thanks

- The Tritium Students
- JLab staff and technicians
- Nadia Fomin and Douglas Higinbotham
- DOE and JSA(Jefferson Science Associates)
- CMRU for allowing me the opportunity to present.

Detailed Studies of the nuclear dependence of F2 in light nuclei

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

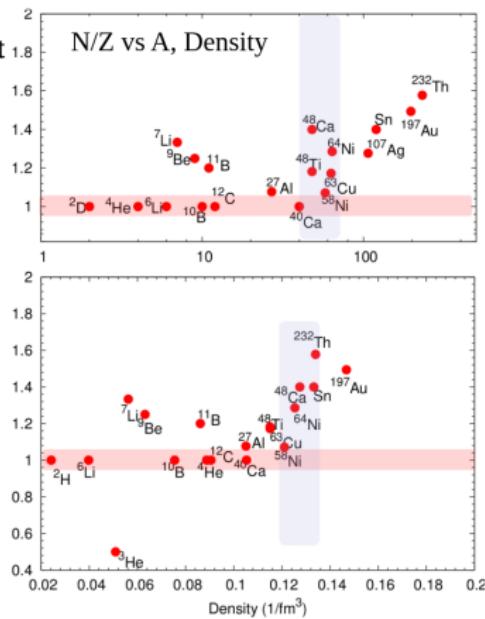
Target Choice motivated by physics impact



Coming soon* in Hall C

What is soon?

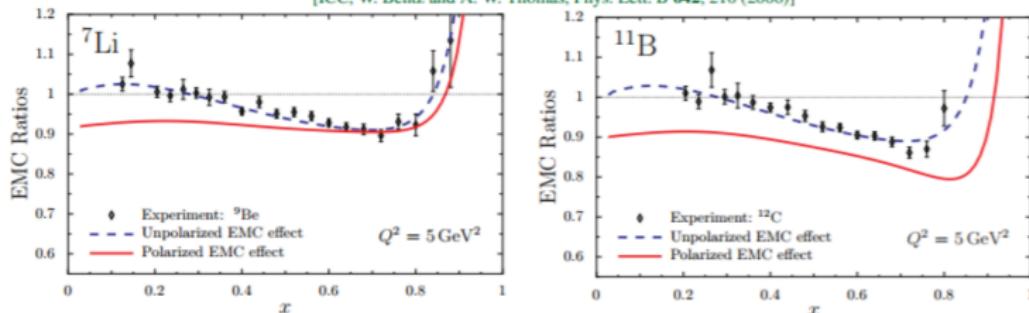
Slide credit Nadia Fomin



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 ${}^7\text{Li}$

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Backup Slides

Relative Error Contributions for the Cross Section ${}^3\text{He}$.

Xbjc	0.185	0.305	0.49	0.57	0.705	0.825
Yield Error	0.0104	0.011	0.0147	0.0149	0.0139	0.0161
Stat Error*	0.0063	0.0064	0.0098	0.0108	0.0111	0.0141
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Eff Error*	0.004	0.0051	0.0083	0.0071	0.0041	0.0031
MC&Model	0.016	0.017	0.012	0.013	0.033	0.024
Resolution**	0.015	0.012	0.006	0.002	0.007	0.018
Model**	0.005	0.013	0.01	0.013	0.032	0.016
Total Error	0.019	0.02	0.019	0.02	0.036	0.029

* Largest contributors to the error in the yield calculation

** Largest contributors to the error in Monte Carlo and Cross section model calculation.

Relative Error Contributions for the Cross Section D.

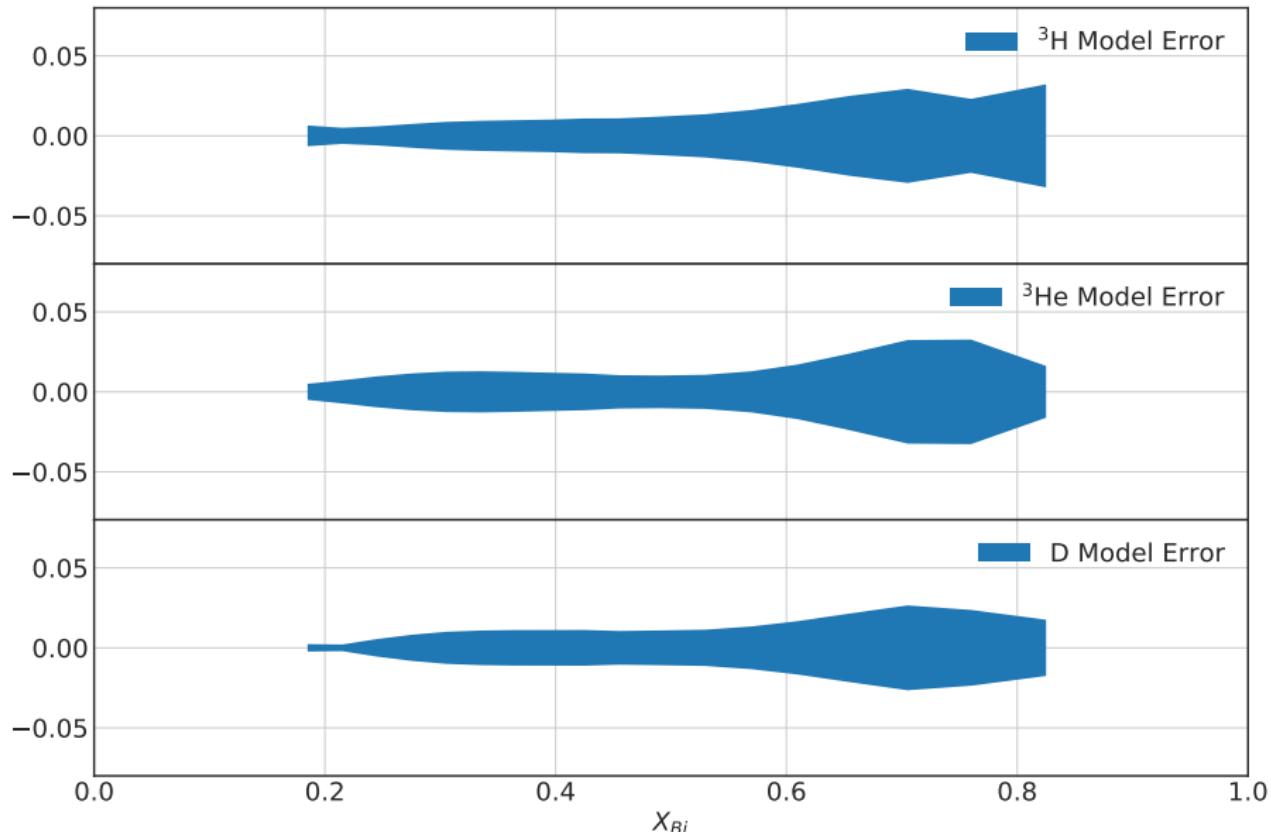
Xbjc	0.185	0.305	0.49	0.57	0.705	0.825
Yield Error	0.0104	0.0104	0.0159	0.0148	0.0139	0.0164
Stat Error*	0.0062	0.0053	0.0113	0.0106	0.011	0.0143
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Eff Error*	0.004	0.0051	0.0081	0.0071	0.0041	0.0032
MC&Model	0.015	0.015	0.013	0.014	0.028	0.026
Resolution**	0.015	0.011	0.006	0.002	0.007	0.02
Model**	0.002	0.01	0.011	0.013	0.027	0.018
Total Error	0.018	0.018	0.021	0.02	0.031	0.031

* Largest contributors to the error in the yield calculation

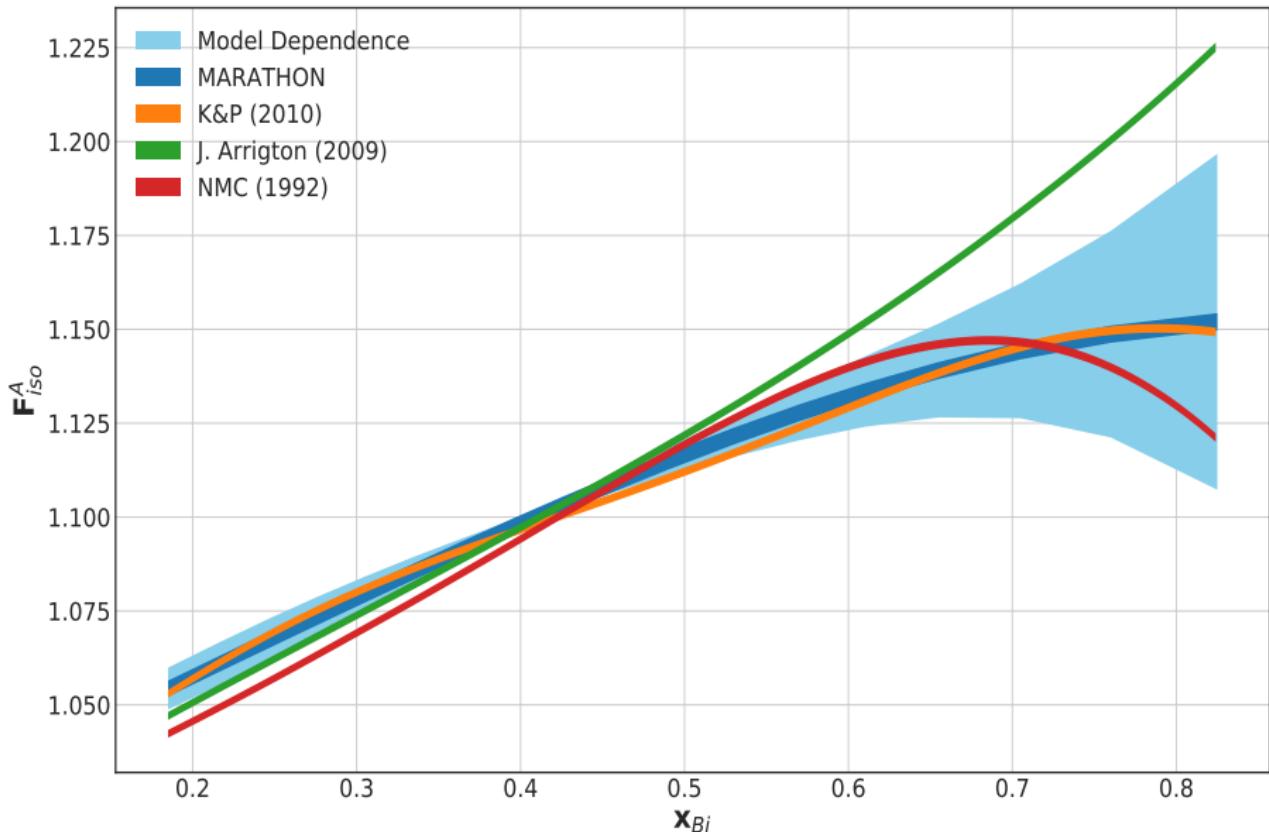
** Largest contributors to the error in Monte Carlo and Cross section model calculation.



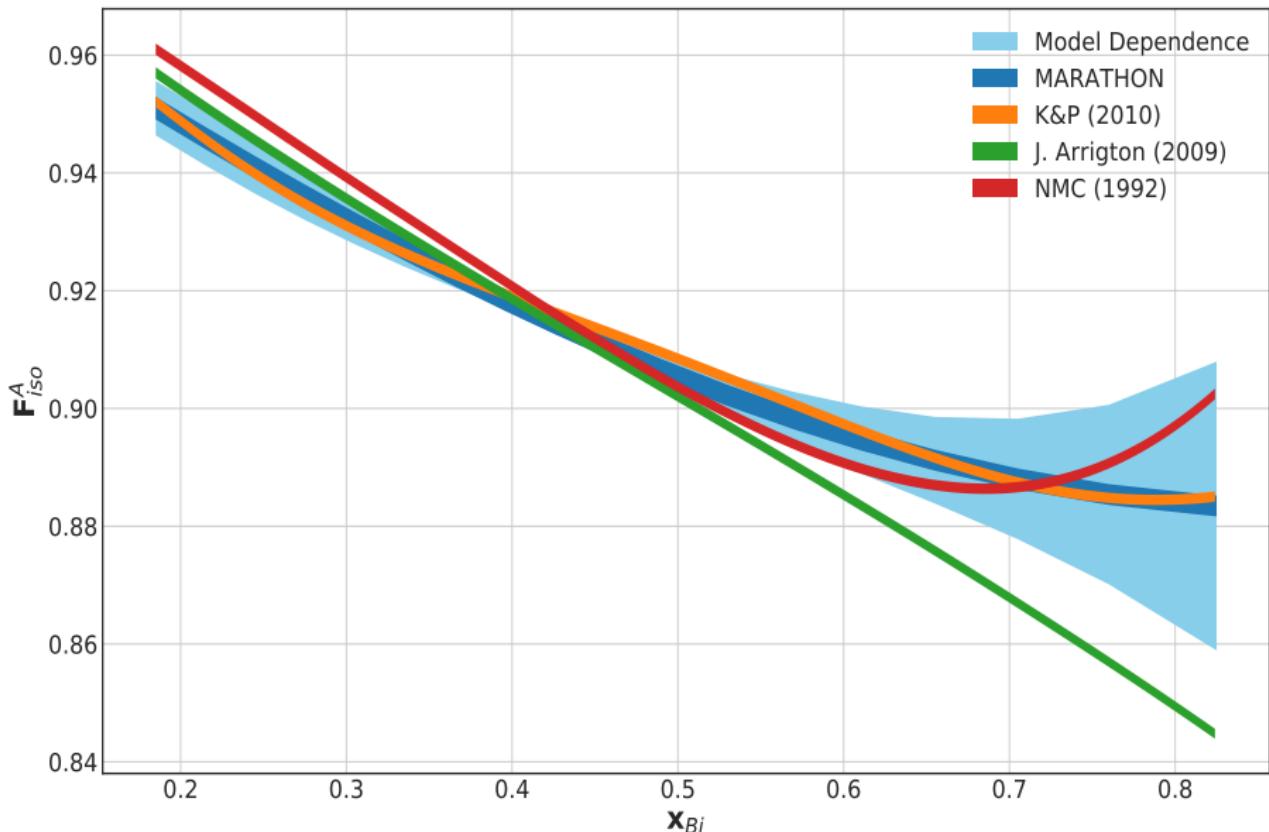
Model Cross Section Error



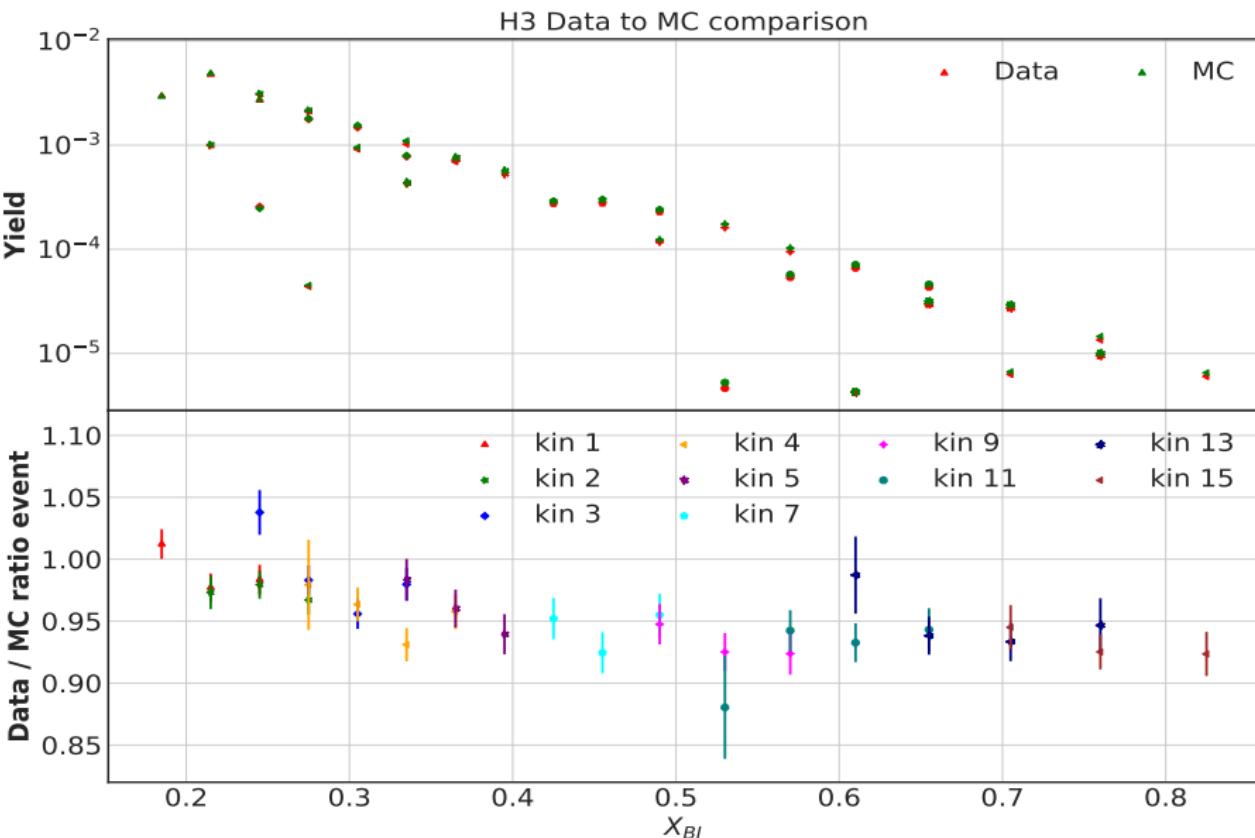
Isoscalar Correction Error for ${}^3\text{H}$



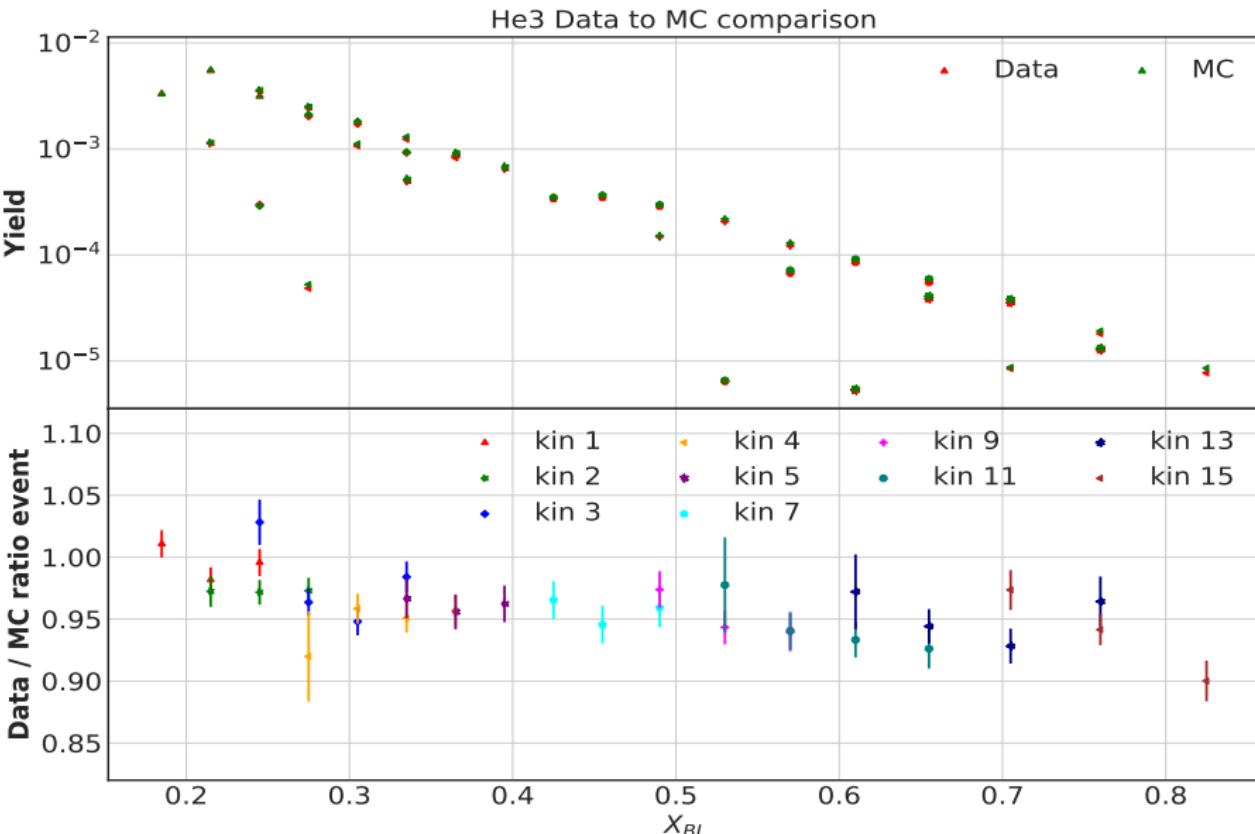
Isoscalar Correction Error for ${}^3\text{He}$



Yield & MC ratio ${}^3\text{H}$



Yield & MC ratio ^3He



Yield & MC ratio D

D2 Data to MC comparison

