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

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MENU 2019, Jun 6

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

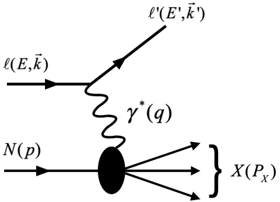
Blue-Boldfaced Names: Tritium Program postdoctoral associates

The JLab MARATHON Tritium Collaboration

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.

Inclusive Deep Inelastic Scattering (DIS)

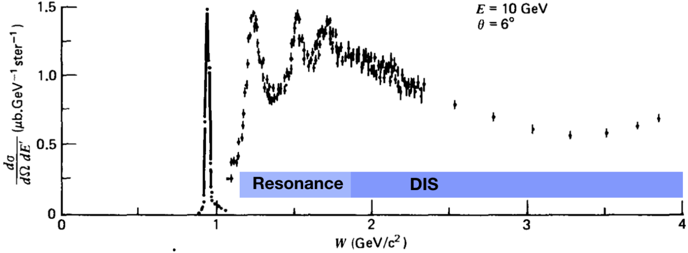


$$Q^2 = -q^2 = 4EE' \sin^2(\frac{\theta}{2})$$

$$\nu = E - E'$$

$$x = \frac{Q^2}{2M\nu} \quad \textbf{(Bjorken x)}$$

$$W^2 = (q+p)^2 = M^2 + Q^2(\frac{1}{x} - 1)$$



- **Inclusive:** only the scattered electron are detected;
- **DIS:** the scattering at large W^2 and large momentum transfer

Cross Section and Structure functions

- The cross section for inelastic electron-nucleon scattering is:

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2(E')^2}{Q^4} cos^2(\frac{\theta}{2})[\frac{F_2(\nu, Q^2)}{\nu} + \frac{2F_1(\nu, Q^2)}{M} tan^2(\frac{\theta}{2})]$$

$$F_1 = \frac{F_2(1 + Q^2/\nu^2)}{2x(1 + R)} \qquad \rightarrow \qquad \boldsymbol{\sigma \propto F_2}$$

The measurements of $R = \sigma_L/\sigma_T$ show almost no A dependence at high Q^2 and it's closed to 0.

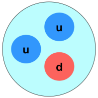
- Quark-Parton Model: the nucleon structure function is related to quark probability distributions $q_i(x)$, $(i = u, \overline{u}, d, \overline{d}, etc.)$

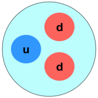
$$F_2(x) = x \sum_i e_i^2 q_i(x)$$

F_2^n/F_2^p and d/u

Quark-parton Model:

$$F_2^p(x) = x[(\frac{2}{3})^2(u^p + \overline{u}^p) + (-\frac{1}{3})^2(d^p + \overline{d}^p) + (-\frac{1}{3})^2(s^p + \overline{s}^p)]$$
$$F_2^n(x) = x[(\frac{2}{3})^2(u^n + \overline{u}^n) + (-\frac{1}{3})^2(d^n + \overline{d}^n) + (-\frac{1}{3})^2(s^p + \overline{s}^p)]$$





Assume isospin symmetry:

$$u^p(x) = d^n(x) \equiv u(x) \qquad u^n(x) = d^p(x) \equiv d(x)$$

And neglect the sea quarks distributions:

$$\frac{F_2^n}{F_2^p} = \frac{1 + 4\boldsymbol{d/u}}{4 + \boldsymbol{d/u}}$$

$x \to 1$ predictions	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Diquark Model/Feynman	1/4	0
Quark Model/Isgur	1/4	0
Perturbative QCD	3/7	1/5
QCD Counting Rules	3/7	1/5

F_2^n/F_2^p is one of the best methods to determine the d/u ratio.

PDFs and high energy physics

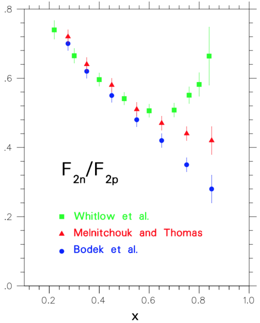
- The parton distribution functions (PDFs) in the valence region is the key to hadron physics;
- PDFs uncertainties limit the precision of high energy collider physics

A. Accardi et al. EPJC76, 471 (2016)

PDF sets	$\sigma(H)^{\text{NNLO}}$ (pb) nominal $\alpha_s(M_Z)$	$\sigma(H)^{\text{NNLO}}$ (pb) $\alpha_s(M_Z)=0.115$	$\sigma(H)^{\text{NNLO}}$ (pb) $\alpha_s(M_Z)=0.118$
ABM12 [2]	39.80 ± 0.84	41.62 ± 0.46	44.70 ± 0.50
CJ15 [1][a]	$42.45^{+0.43}_{-0.18}$	$39.48^{+0.40}_{-0.17}$	$42.45^{+0.43}_{-0.18}$
CT14 [3][b]	$42.33^{+1.43}_{-1.68}$	$39.41^{+1.33}_{-1.56}$ (40.10)	$42.33^{+1.43}_{-1.68}$
HERAPDF2.0 [4][c]	$42.62^{+0.35}_{-0.43}$	$39.68^{+0.32}_{-0.40}$ (40.88)	$42.62^{+0.35}_{-0.43}$
JR14 (dyn) [5]	38.01 ± 0.34	39.34 ± 0.22	42.25 ± 0.24
MMHT14 [6]	$42.36^{+0.56}_{-0.78}$	$39.43^{+0.53}_{-0.73}$ (40.48)	$42.36^{+0.56}_{-0.78}$
NNPDF3.0 [7]	42.59 ± 0.80	39.65 ± 0.74 (40.74 ± 0.88)	42.59 ± 0.80
PDF4LHC15 [8]	42.42 ± 0.78	39.49 ± 0.73	42.42 ± 0.78

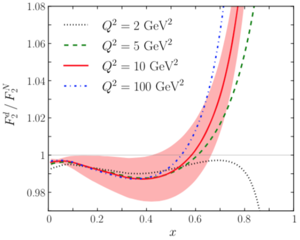
The predictions of Higgs cross section at NNLO in QCD depend largely (as large as 13%) on PDF paramterizations and running coupling.

Neutron structure function

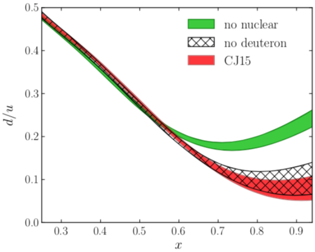


- F_2^p is measured up to 0.85 by electron/muon scattering on Hydrogen target;
- Since there is no free neutron target, inclusive DIS on deuteron is used to extract F_2^n for decades
- However, the nuclear corrections inside deuteron are model dependent.

$\leftarrow$ F_2^n/F_2^p extracted from SLAC d/p DIS data using different nuclear corrections



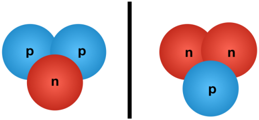
F_2^d/F_2^N computed from the CJ15 PDFs



Impact on d/u from CJ15 of removing the deuterium nuclear corrections

MARATHON

Perform inclusive DIS on mirror nuclei ${}^3H$, ${}^3He$



$$\frac{F_2^{{}^3H}}{F_2^{{}^3He}} = \frac{\sigma({}^3H)}{\sigma({}^3He)}$$

- ${}^3H$ and ${}^3He$ EMC type ratios:

$$R({}^3He) = \frac{F_2^{{}^3He}}{2F_2^p + F_2^n} \qquad R({}^3H) = \frac{F_2^{{}^3H}}{F_2^p + 2F_2^n}$$

define the "super-ratio" of EMC ratios in ${}^3H$ and ${}^3He$:

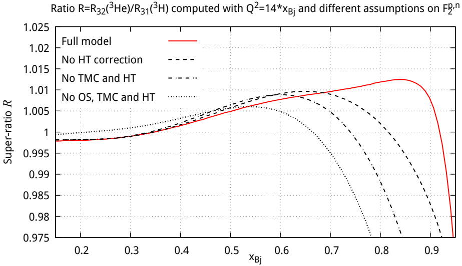
$$\mathcal{R} = \frac{R({}^3He)}{R({}^3H)}$$

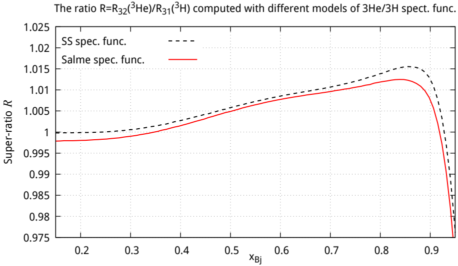
- Free neutron to proton structure functions:

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{{}^3He}/F_2^{{}^3H}}{2F_2^{{}^3He}/F_2^{{}^3H} - \mathcal{R}}$$

Super-ratio $\mathcal{R}$

- ^3H and ^3He are mirror nuclei. The nuclear corrections should be similar.
- $\mathcal{R}$ has been calculated in theory to deviate from 1 up to 2% by taking into account all possible effects

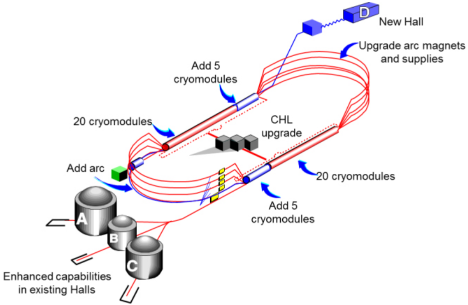




Super-ratio $\mathcal{R}$ calculated by S. Kulagin and R. Petti

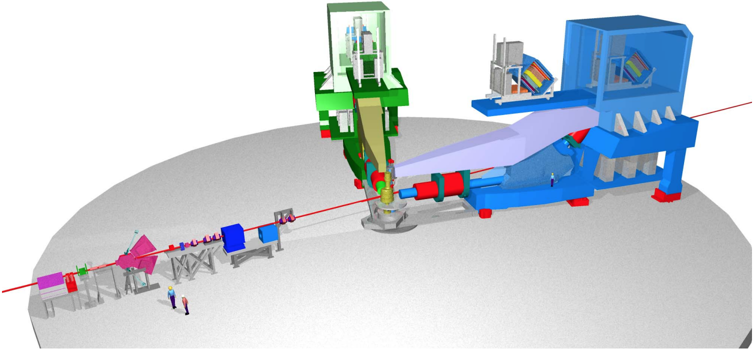
- The iterative procedure could eliminate the nucleon structure function dependence in the F_2^n/F_2^p extraction.

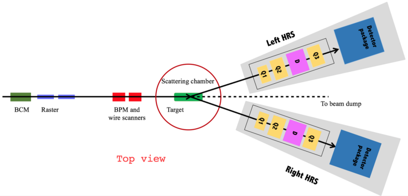
JLAB CEBAF 12 GeV



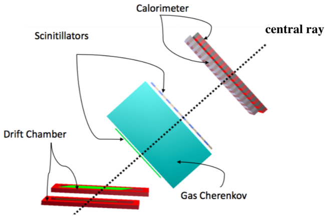
Newport News, VA, US

Hall A High Resolution Spectrometers (HRS)



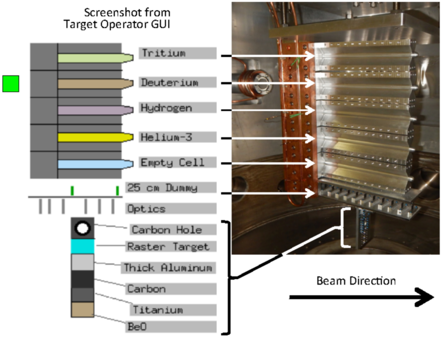


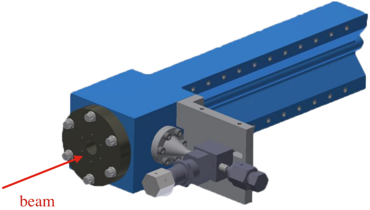
HRS top view



Detector package

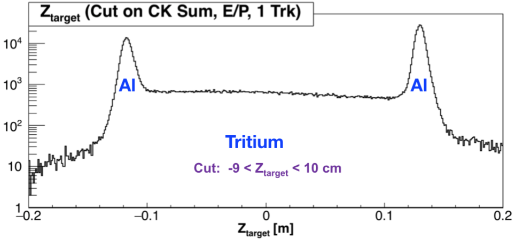
Targets





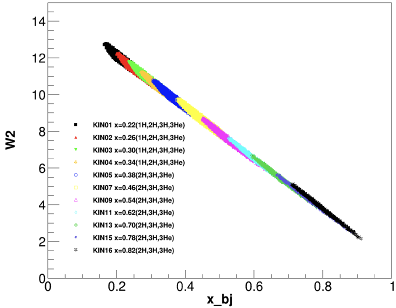
Tritium target

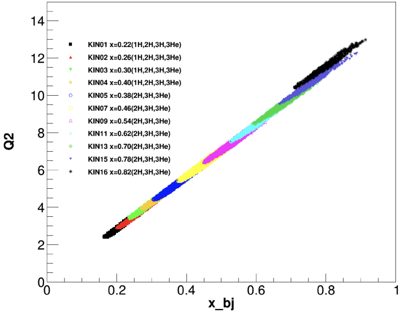
- Low activity ($\sim$ 1k Ci)
- Sealed cell
- 40K gas
- Beam current $\leq$ 22.5 uA



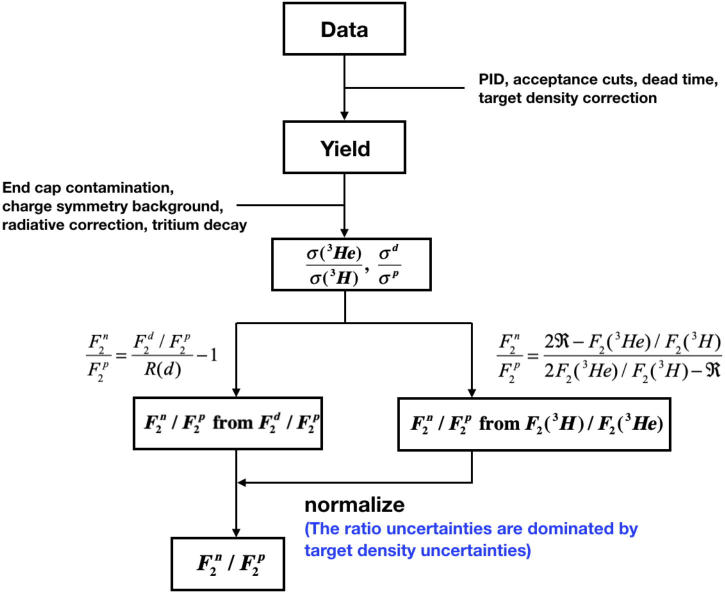
MARATHON Kinematics

- Experiment ran on January-April 2018;
- Beam energy 10.6 GeV;
- Average current $\sim$ 20 uA
- Scattering angle: 17 $^\circ$ - 36 $^\circ$
- Cover the Bjorken x range $0.19 < x < 0.83$
- Took DIS data on ^3H, ^3He, ^2D, ^1H

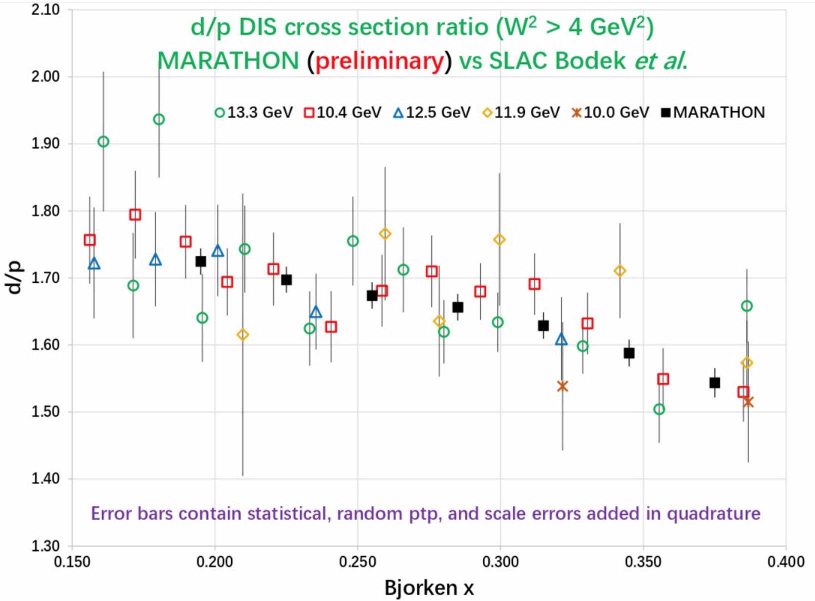




Data Analysis Procedure

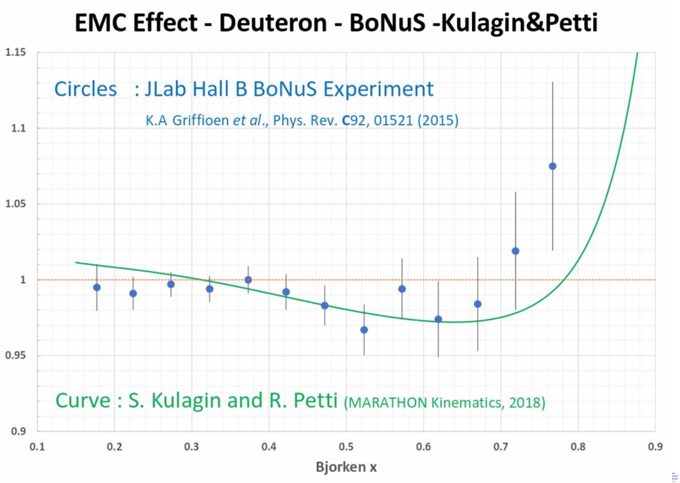


σ^d/σ^p from MARATHON

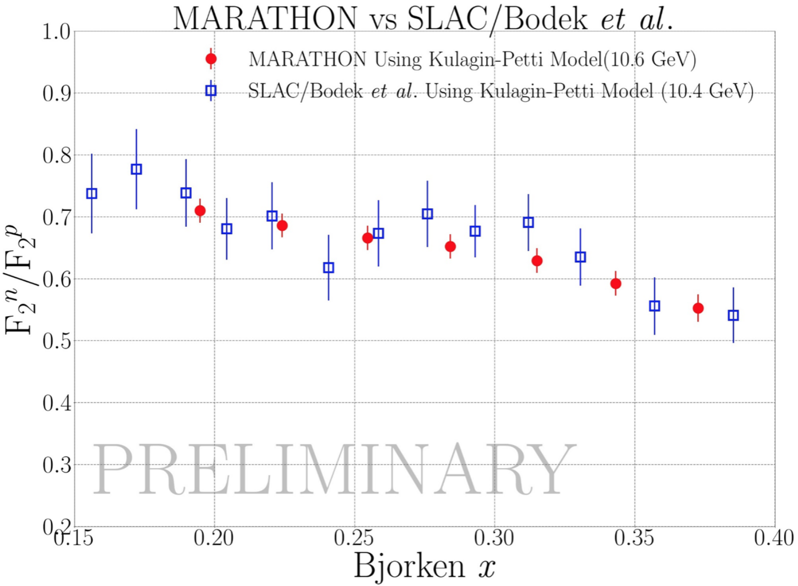


Deuteron EMC R(d)

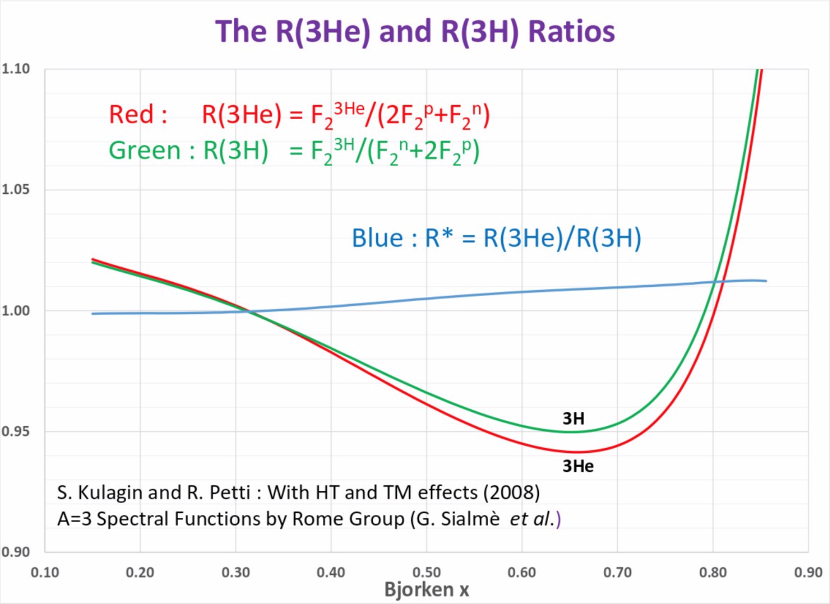
The comparison between the deuteron EMC $R(d) = \frac{F_2^d}{F_2^n + F_2^p}$ from K&P model and the BoNuS results



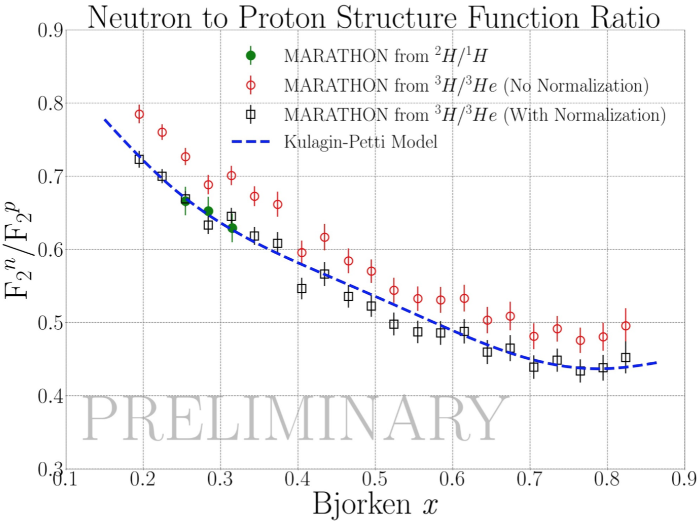
F_2^n/F_2^p extracted from σ^d/σ^p



Super-ratio $\mathcal{R}$

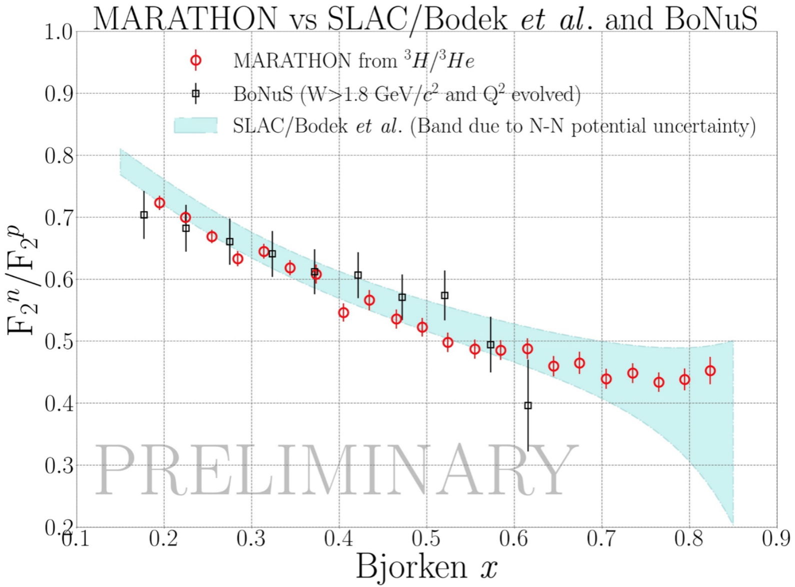


F_2^n/F_2^p extracted from $\sigma^{^3He}/\sigma^{^3H}$



In order to match the values of F_2^n/F_2^p from the two measurements in the vicinity of x=0.3, $F_2^{^3H}/F_2^{^3He}$ must be scaled down (normalized) by 2.7%.

F_2^n / F_2^p from MARATHON

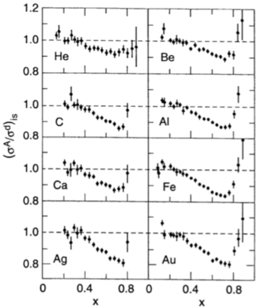


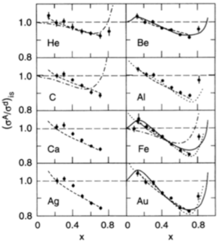
EMC effect

EMC effect: Nuclear structure function F_2 per nucleon is different than that of deuterium: large dependence on Bjorken x and mass A.
Possible explanations:

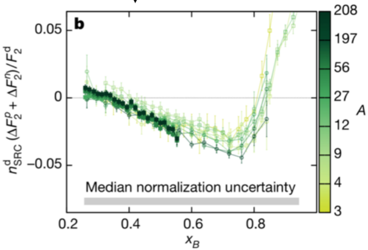
- Binding and x rescaling;
- Pion enhancement models;
- Quark confinement models;
- Short Range Correlations;

....



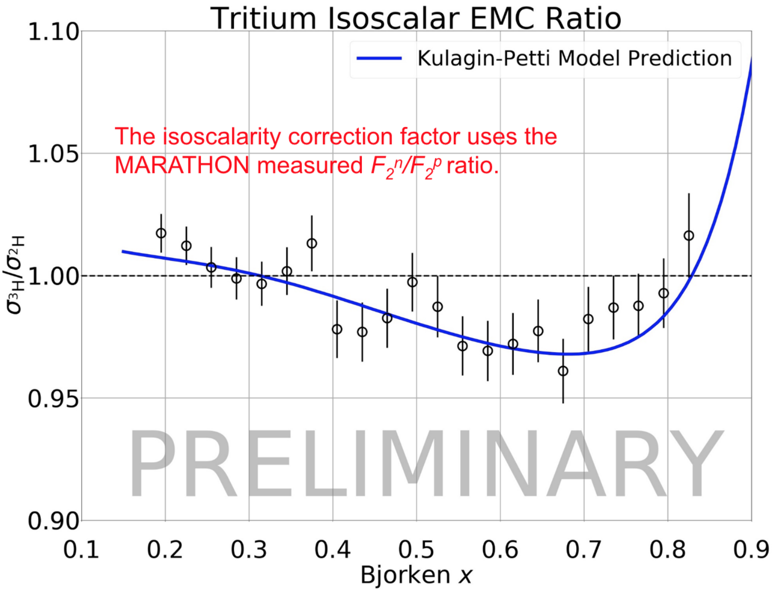


J. Gomez et al., Phys. Rev. D49, 4348-4372 (1994)

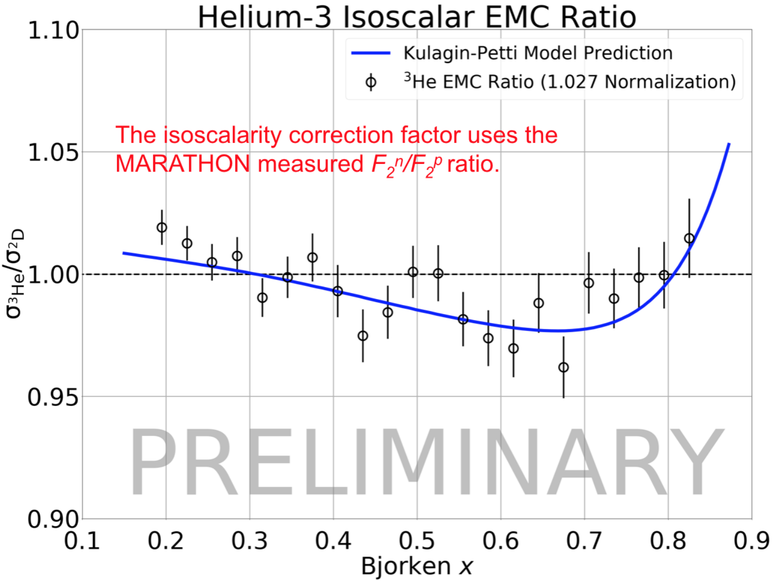


B. Schmookler et al., Nature 566, 354-358 (2019)

^3H EMC ratio


Tritium Isoscalar EMC Ratio
Kulagin-Petti Model Prediction
The isoscalarity correction factor uses the
MARATHON measured F_2^n/F_2^p ratio.
PRELIMINARY
$\sigma_{^3\mathrm{H}}/\sigma_{^2\mathrm{H}}$
1.10
1.05
1.00
0.95
0.90
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Bjorken x

^3He EMC ratio



Summary

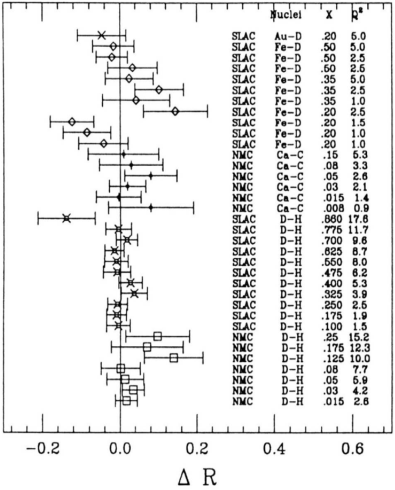
- The MARATHON d/p DIS measurements agree well with the seminal SLAC Bodek et al. measurements and provide an excellent normalization for the $^3H/^3He$ DIS data.
- MARATHON has provided high quality F_2^n/F_2^p data at medium and large x with much less theoretical uncertainties than the original SLAC data from d/p DIS.
- There may be no need to iterate our calculation, as the model used in the F_2^n/F_2^p extraction agrees very well with the data!
- Next to be done is the extraction of leading twist F_2^n/F_2^p in order to determine the d/u ratio.
- MARATHON provides the first ^3H EMC data and the new large-x and large-W^2 ^3He EMC data.
- The isoscalar $F_2^{^3H}/F_2^d$ and $F_2^{^3He}/F_2^d$ EMC ratio shapes are "similar", as expected, but with different "EMC effect slopes".

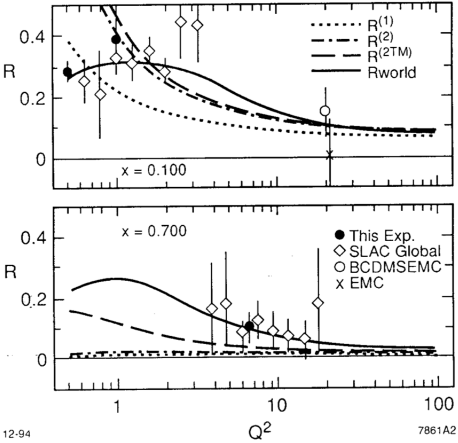
Thanks

- Thanks to the graduate students and postdocs for their hard work and dedication in preparing, running and analyzing the experiment
- Thanks to the Accelerator and Hall A Scientific and Technical Staff of JLab, and the Lab Management for their outstanding support of the MARATHON project.
- Special thanks to Roy Holt and David Meekins for making a reality, for (only) the third time in the US, a tritium target for electronuclear physics.
- Special thanks to Doug Higinbotham for managing the Tritium Program.
- Thanks to all theory colleagues who embraced the experiment since its inception and contributed to the development of the proposal and to the analysis of the experimental data.

backup

$R = \sigma_L / \sigma_T$



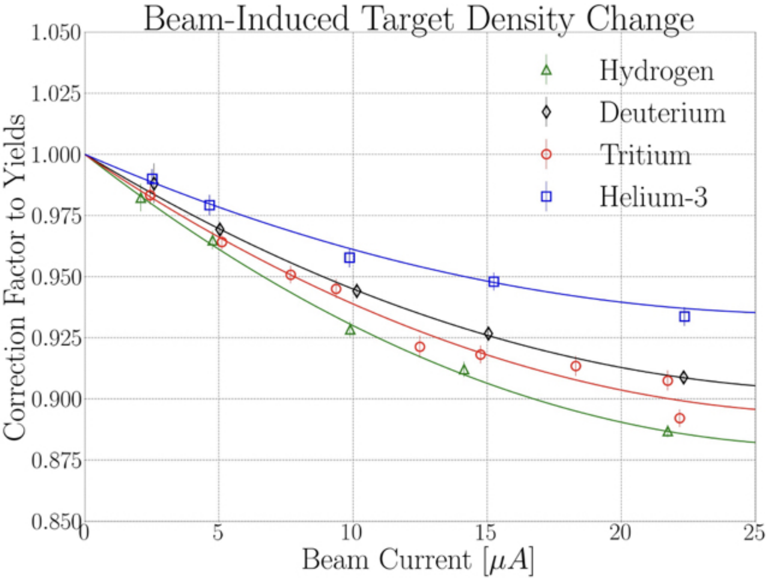


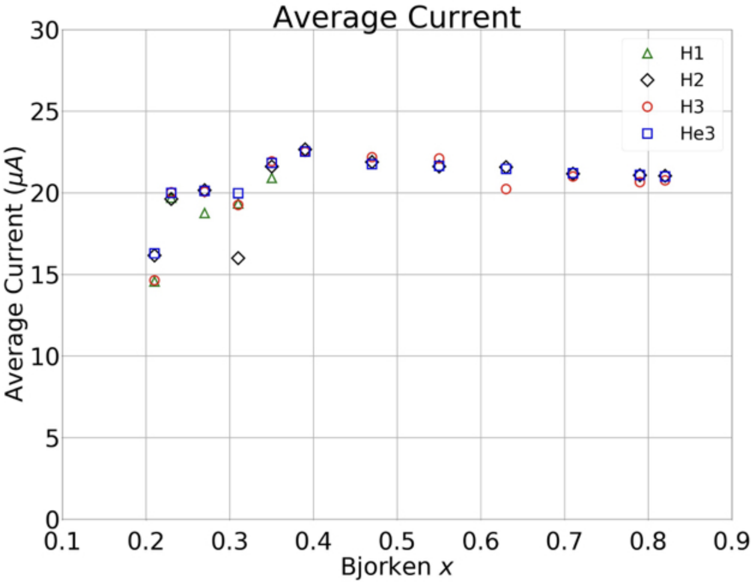
Isoscalar correction

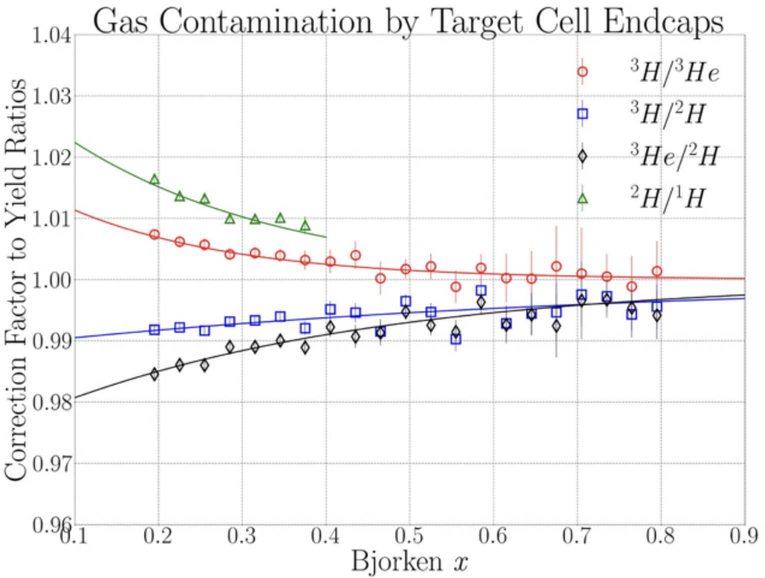
In order to compare the structure function for an average nucleon, must correct the ratio for the proton or neutron excess.

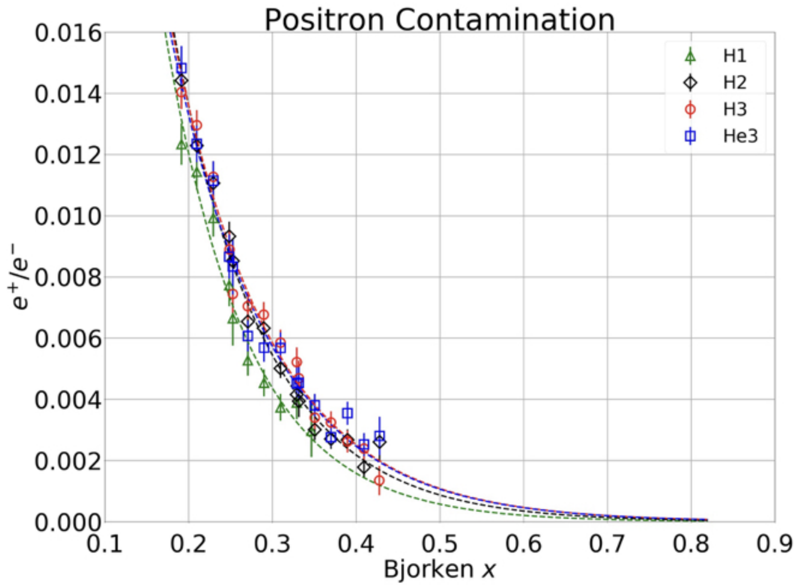
$$\left(\frac{\sigma^A}{\sigma^d}\right)_{iso} = \left(\frac{\sigma^A}{\sigma^d}\right)\frac{\frac{1}{2}(1 + F_2^n/F_2^p)}{\frac{1}{A}(Z + (A - Z)F_2^n/F_2^p)}$$

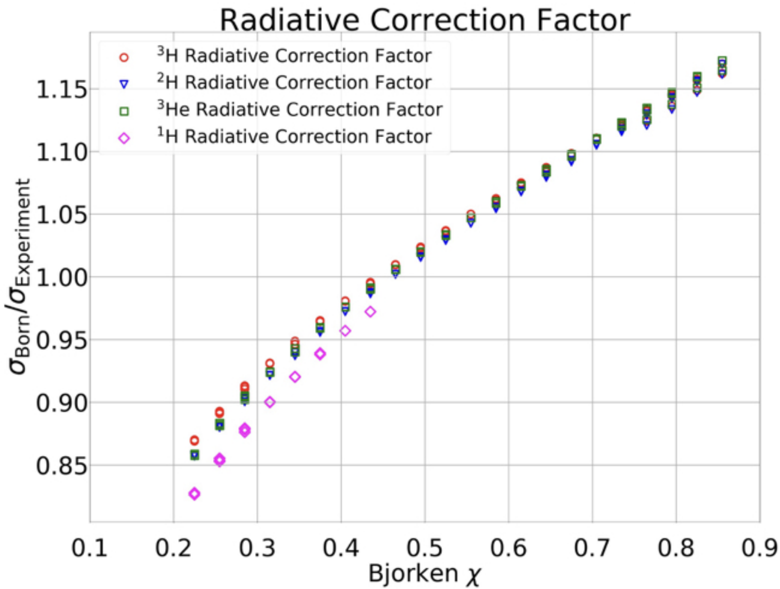
Computer Dead Time
Deadtime (%)
Bjorken x
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
H1
H2
H3
He3


Beam-Induced Target Density Change
Correction Factor to Yields
1.050
1.025
1.000
0.975
0.950
0.925
0.900
0.875
0.850
0
5
10
15
20
25
Beam Current [μA]
Hydrogen
Deuterium
Tritium
Helium-3

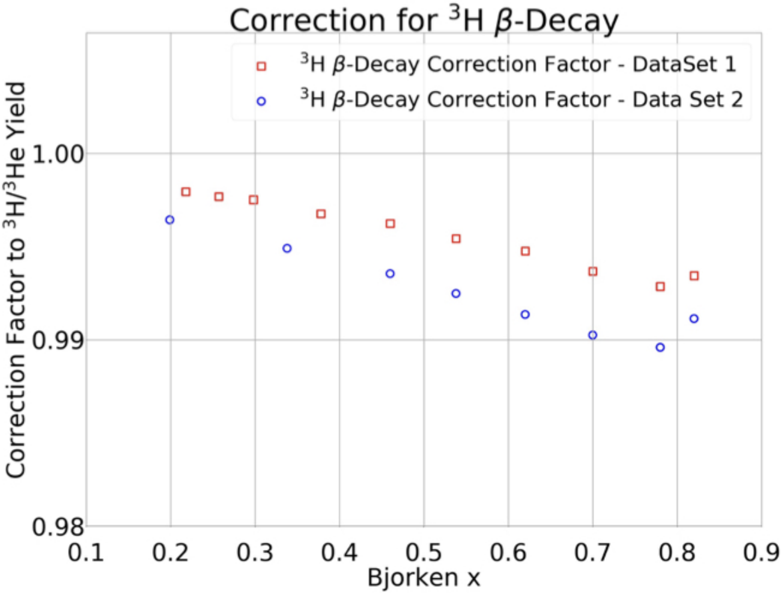

Average Current
Average Current (μA)
Bjorken x
H1
H2
H3
He3
0
5
10
15
20
25
30
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


Gas Contamination by Target Cell Endcaps
Correction Factor to Yield Ratios
Bjorken x
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$^3H/^3He$
$^3H/^2H$
$^3He/^2H$
$^2H/^1H$


Positron Contamination
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
e^+/e^-
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Bjorken x
H1
H2
H3
He3

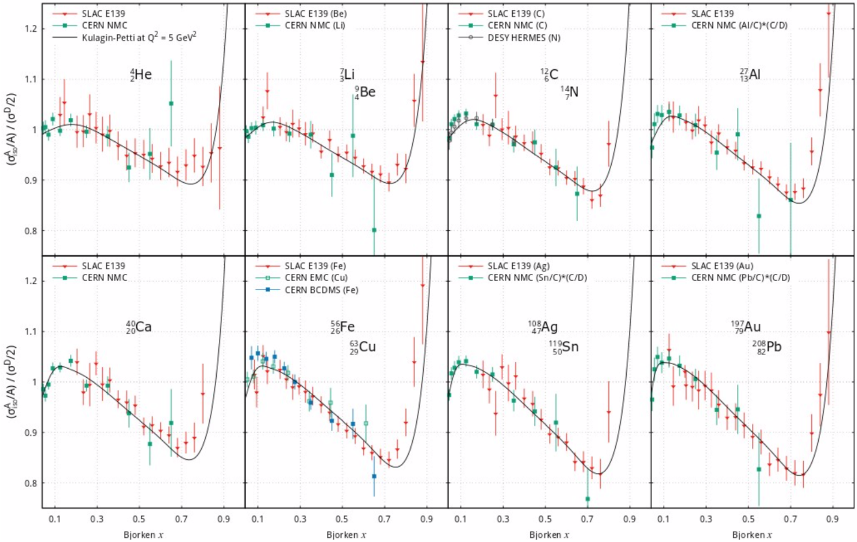

Radiative Correction Factor
^{3}H Radiative Correction Factor
^{2}H Radiative Correction Factor
^{3}He Radiative Correction Factor
^{1}H Radiative Correction Factor
$\sigma_{Born}/\sigma_{Experiment}$
Bjorken χ
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


Percentage of the Tritium Left
99.0
98.5
98.0
97.5
97.0
96.5
96.0
Tritium Fraction [%]
80
100
120
140
160
180
Time since Tritium Target Cell Filling [day]

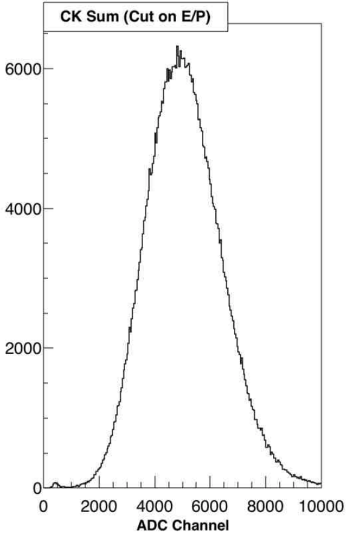


Correction for ^{3}H β-Decay
^{3}H β-Decay Correction Factor - DataSet 1
^{3}H β-Decay Correction Factor - Data Set 2
Correction Factor to ^{3}H/^{3}He Yield
1.00
0.99
0.98
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Bjorken x

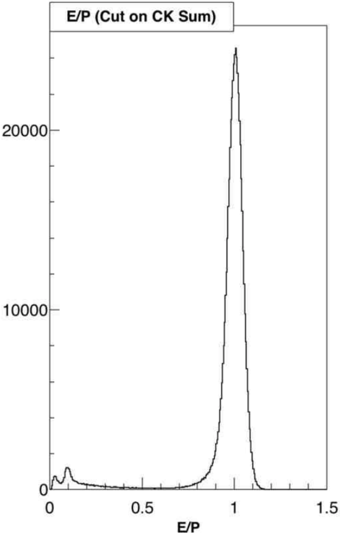
Compilation of EMC Effect Data by S. Kulagin and R. Petti SLAC E139-CERN



Electron Identification - MARATHON



Cherenkov Detector - Cut: Channel > 1500



Pb Glass Calorimeter - Cut: E/P > 0.7