MARATHON Experiment Update*

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

Makis Petratos

For the JLab Hall A MARATHON Tritium Collaboration

Summer 2020 JLab Hall A/C Collaboration Meeting

July 16-17 2020, Newport News, VA

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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

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.

Deep Inelastic Scattering and Quark Parton Model

- Cross Section – Nucleon structure functions F_1 and F_2:

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

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu} \left(1 + \frac{\nu^2}{Q^2} \right) - 1 \qquad \nu = E - E' \qquad Q^2 = 4EE' \sin^2(\theta/2)$$

- Quark-Parton Model (QPM) interpretation in terms of quark probability distributions $q_i(x)$ (large Q^2 and ν, with the Bjorken scaling x variable being finite):

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) \qquad F_2(x) = x \sum_i e_i^2 q_i(x) \qquad x = Q^2 / 2M\nu$$

- Since R is the same for all nuclei, the cross section ratio of two nuclei is equal to the ratio of their F_2 structure functions.

F_2^n/F_2^p in the Quark Parton Model

- Assume isospin symmetry:

$$u^p(x) \equiv d^n(x) \equiv u(x) \qquad \bar{u}^p(x) \equiv \bar{d}^n(x) \equiv \bar{u}(x)$$

$$d^p(x) \equiv u^n(x) \equiv d(x) \qquad \bar{d}^p(x) \equiv \bar{u}^n(x) \equiv \bar{d}(x)$$

$$s^p(x) \equiv s^n(x) \equiv s(x) \qquad \bar{s}^p(x) \equiv \bar{s}^n(x) \equiv \bar{s}(x)$$

- Proton and neutron structure functions:

$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

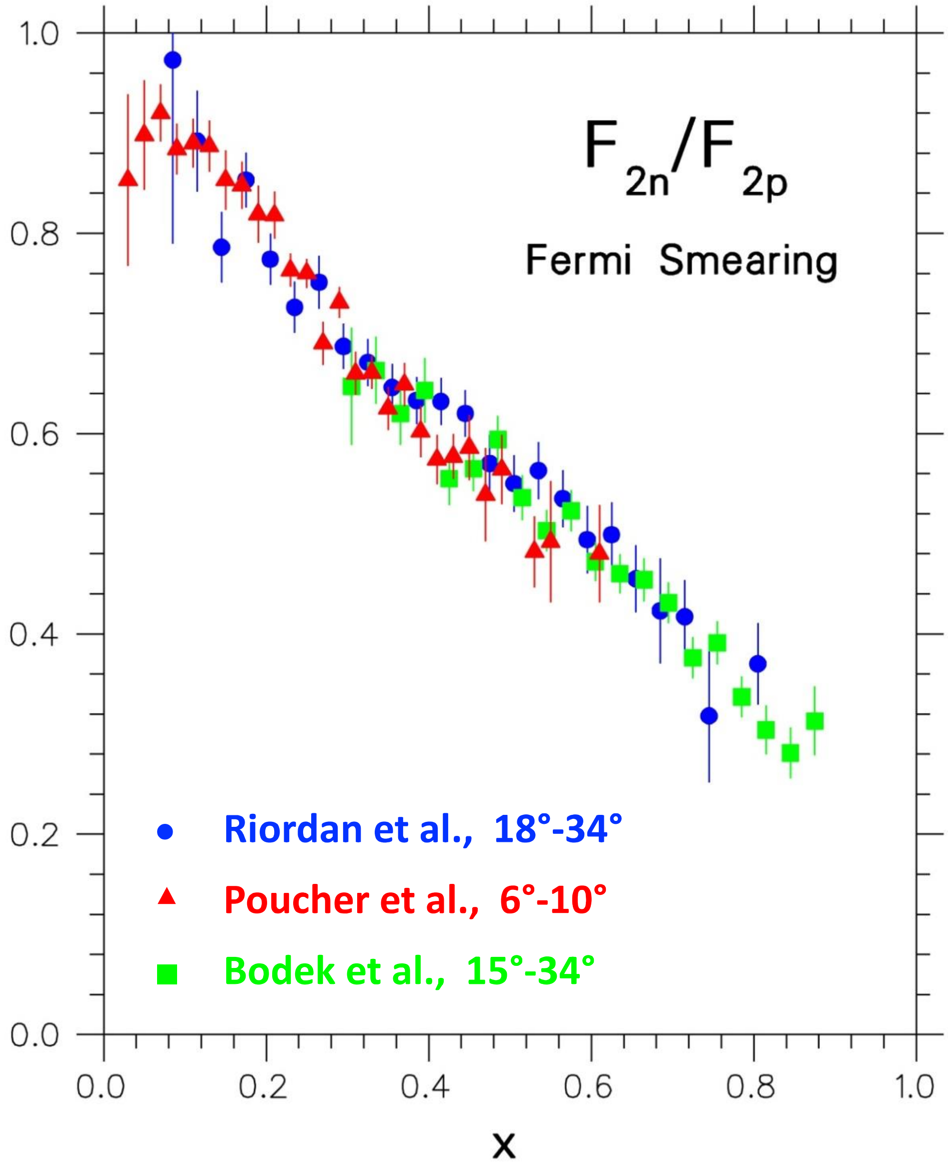
$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

- Nachtmann inequality: $1/4 \le F_2^n / F_2^p \le 4$

SLAC Measurements

End Station A, 1968-1972

Friedman, Kendal, Taylor, Nobel 1990



F_2^n/F_2^p extracted from proton and deuterium deep inelastic data using the Hamada-Johnston potential in a Fermi-smearing model.

Data in disagreement with *SU(6)* prediction of 2/3=0.67!

Data in agreement with the diquark model of Feynman and others.

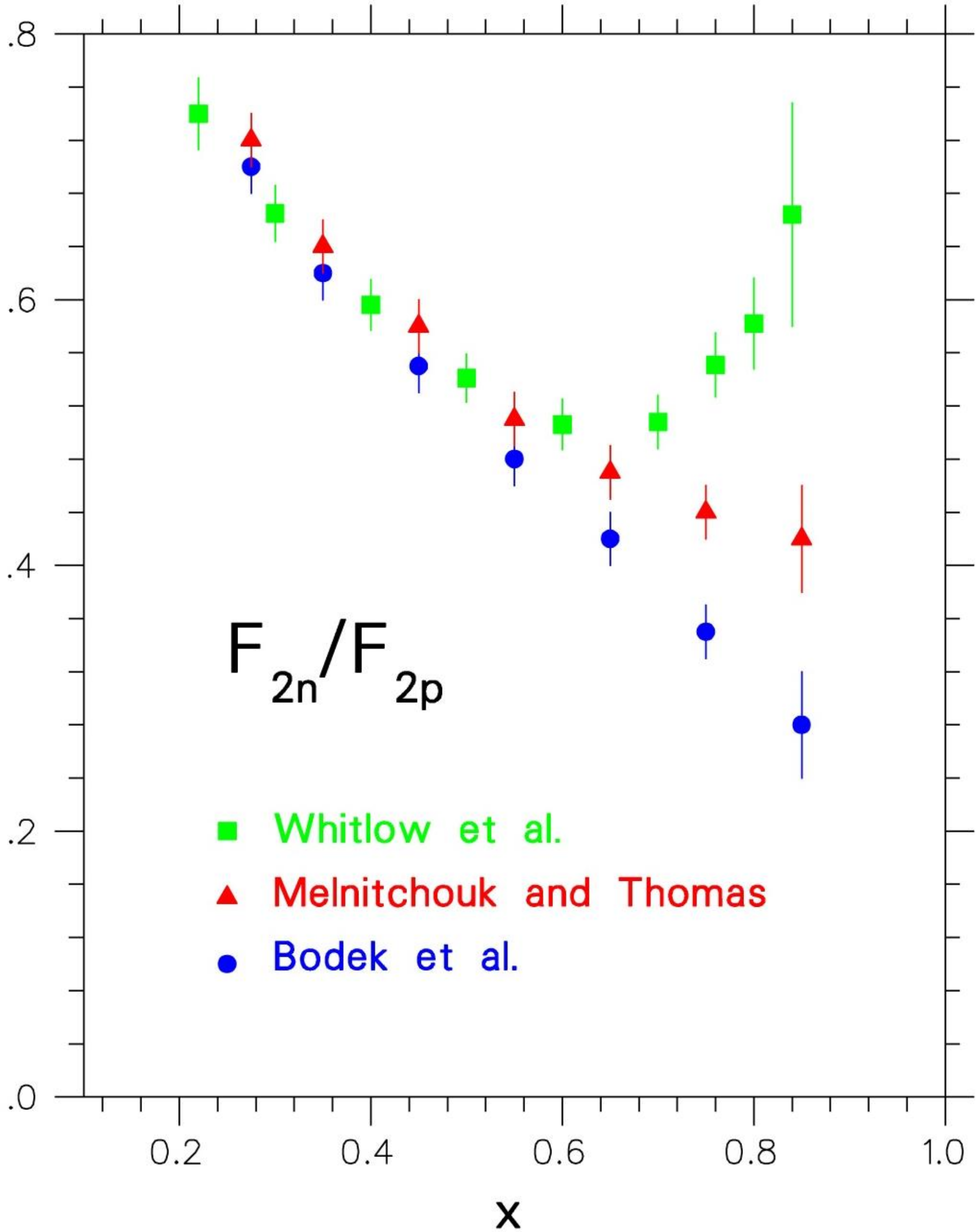
F_2^n/F_2^p is bounded, between 1/4 and 4, as predicted (by the Nachtmann inequality).

At low x, see quarks dominate with the 3 u, d, and s quark distributions being equal.

High momentum quarks in the proton (neutron) are up (down) quarks.

Then, the d/u ratio can be extracted at medium and high x from F_2^n/F_2^p

Nucleon F_2 Ratio Extraction Revisited



SLAC DIS Data

Whitlow (1992): Assumes EMC effect in deuteron (Frankfurt and Strikman data-based Density Model)

Melnitchouk &Thomas (1996): Relativistic convolution model with empirical binding effects

Bodek (1992): Non-relativistic Fermi smearing model with Paris N-N potential. Note: at large *x* there is significant dependence on the N-N potential used (Paris, Bonn, Argonne, etc.)

Nucleon F_2 Ratio Extraction from ^{3}He/^{3}H

- Form the "Super-Ratio" of EMC-type ratios for A=3 mirror nuclei:

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

- Solve above equations for the $A=3$ F_2 structure function ratio:

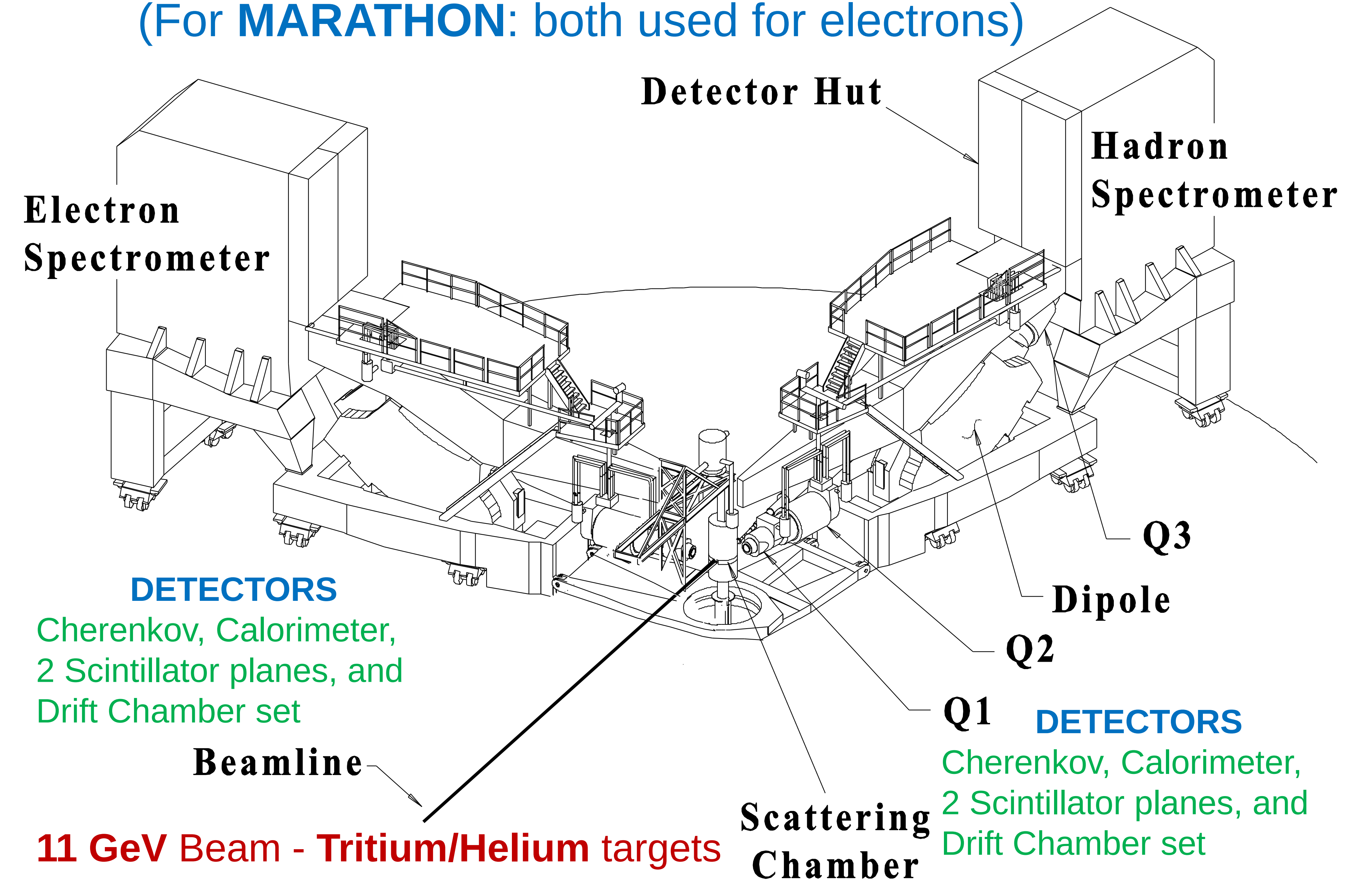
$$\frac{\sigma^{^3He}}{\sigma^{^3H}} = \frac{F_2^{^3He}}{F_2^{^3H}} = R^* \frac{2F_2^p + F_2^n}{F_2^p + 2F_2^n}$$

- Solve for the nucleon F_2 ratio and calculate it, using R^* from a reliable theoretical/phenomenological model (value of R^* is very close to unity with small uncertainty), and the measured $A=3$ DIS cross section ratio:

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

JLab Hall A High Resolution Spectrometers

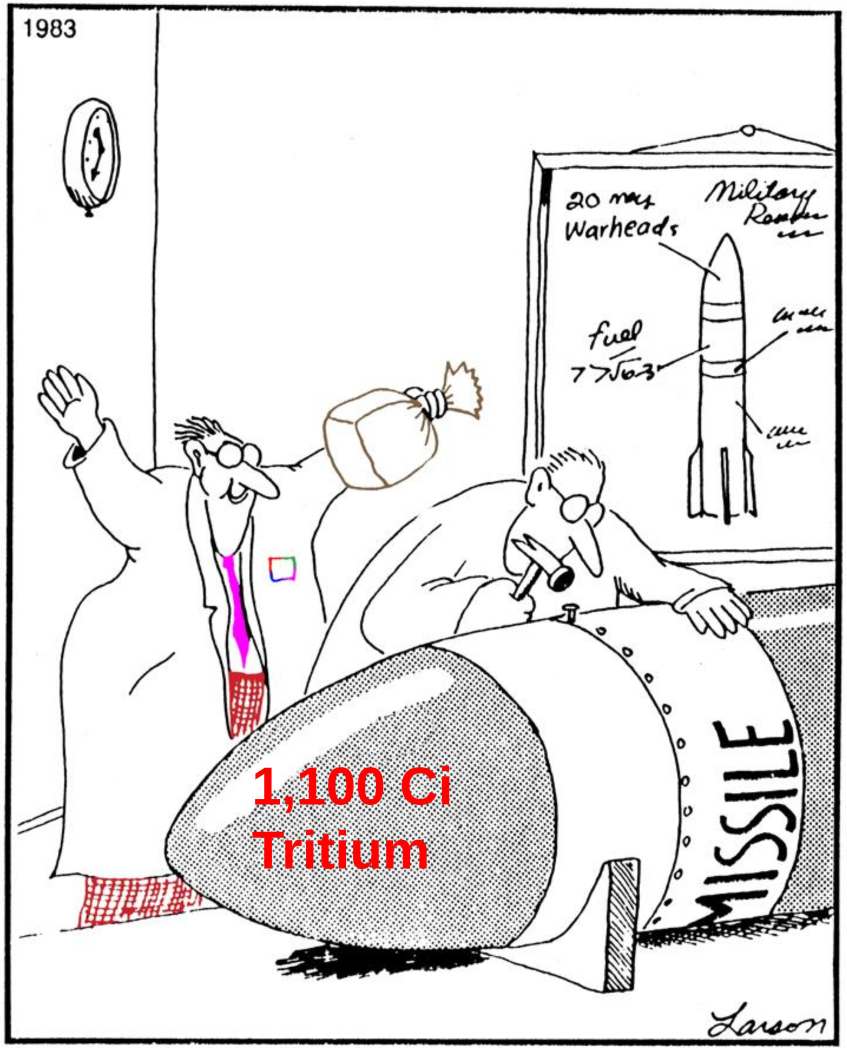
(For **MARATHON**: both used for electrons)



The JLab MARATHON Experiment

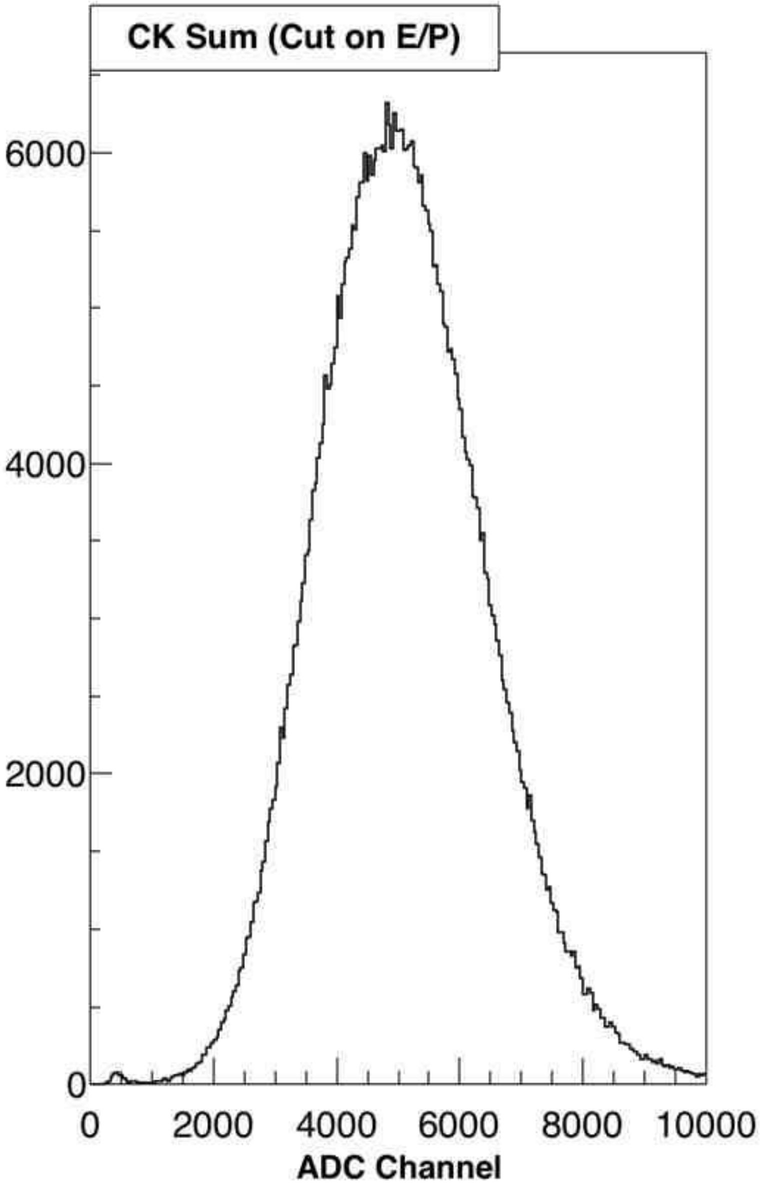
- MARATHON took data in the period January-April 2018.
- It used the 2 High Resolution Spectrometers (HRS) of Hall A and a cryogenic high pressure gas target system of **3H, 3He, 2H, and 1H** (25 cm long cells of 1.25 cm diameter).
- It used a 10.6 GeV electron beam with 20 μA beam current.
- The electron scattering angle varied between 17 and 36 deg.
- The scattered electron momentum was fixed at 3.1 GeV/*c* for the Left-HRS and at 2.9 GeV/*c* for the Right-HRS.
- **MARATHON covered the Bjorken *x* range $0.19 < x < 0.83$ with $3 < Q^2 < 12$ (GeV/*c*)^2 and $1.8 < W < 3.5$ GeV/*c*^{2}.**
- Scattered electrons in each HRS were identified using a gas threshold Cherenkov detector and a lead-glass calorimeter. Their tracks were measured with a drift chamber set.

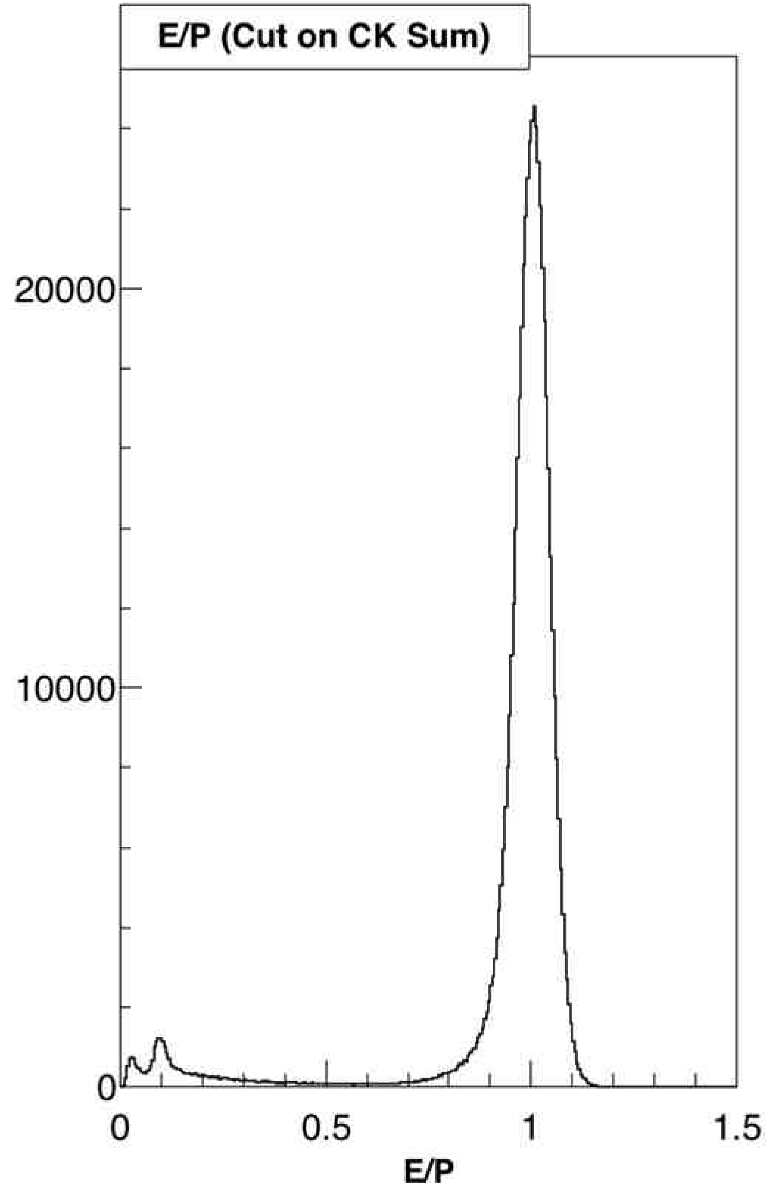
The 3H, 2H, 1H, 3He High Pressure Gas Cells Target Ladder Structure



Tritium cell was filled at the Tritium Handling Facility of Savannah River National Laboratory (1,100 Curies).

Electron Identification - MARATHON

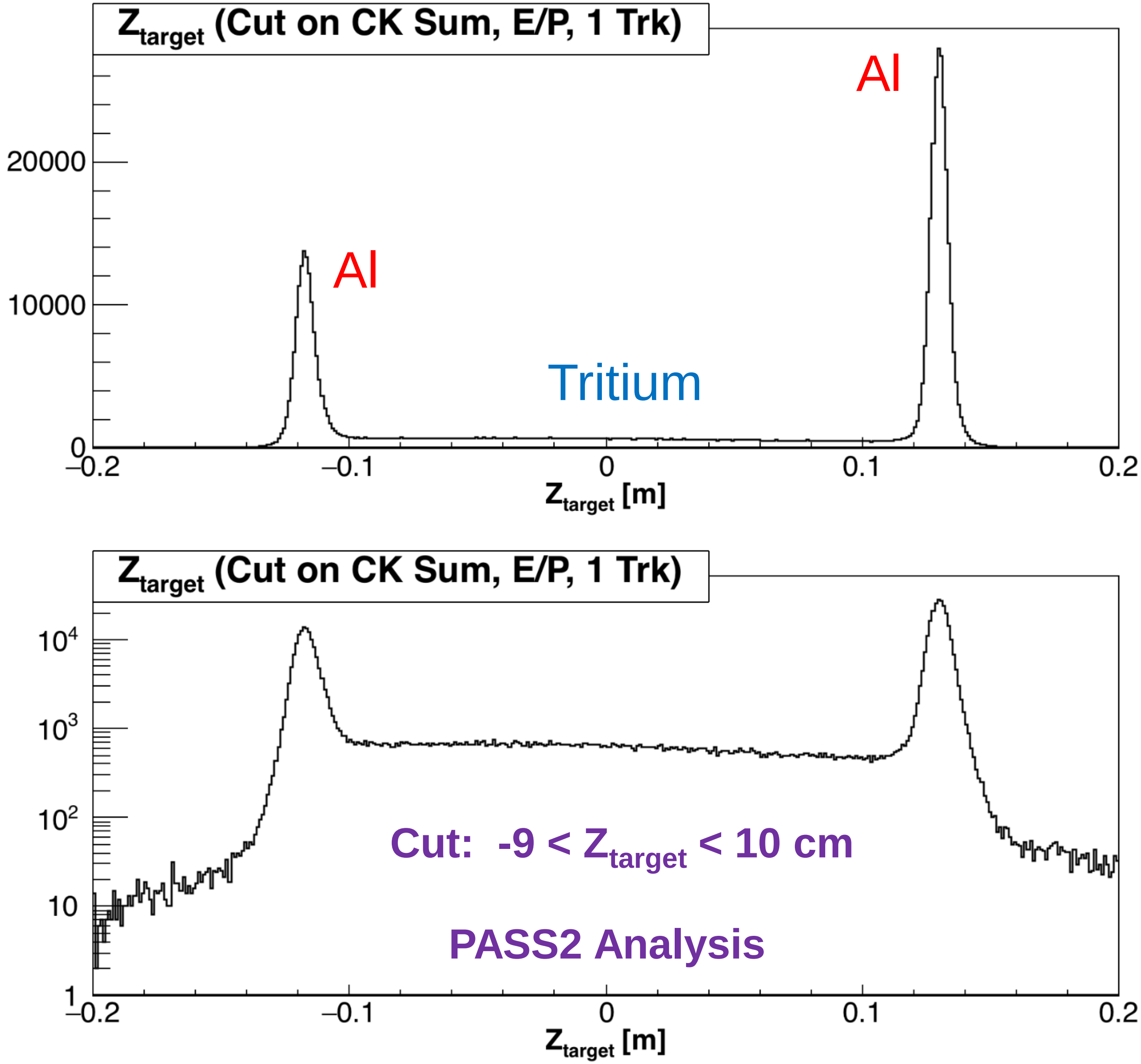




Cherenkov Detector - Cut: Channel > 1500

Pb Glass Calorimeter - Cut: E/P > 0.7

Reconstructed Origin of Electrons at Target



Event rate was dominated by electrons originating from the target cell endcaps!

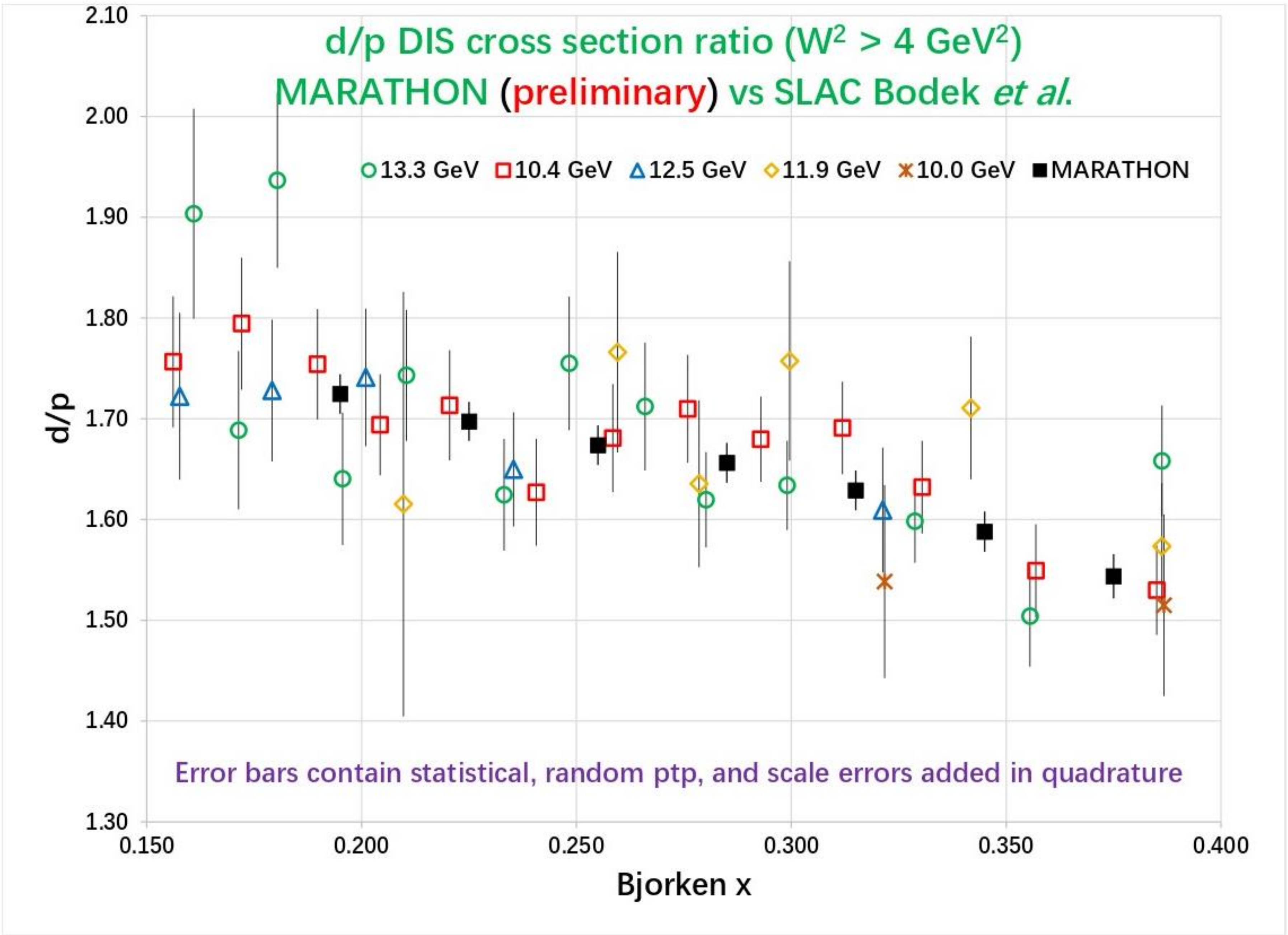
MARATHON ANALYSIS

- MARATHON yields (# of electrons per incident charge and per target density) have been calculated applying reasonable cuts on the Cherenkov ADC, calorimeter/tracking E/P, and HRS acceptance, for 1-track events. Reasonable variations in cut values do not change, beyond the few tenths of percent level, the ratios of yields. Corrections made:

1. Computer dead time correction
2. Beam-induced target density correction
3. Radiative correction
4. Coulomb correction
5. Ionization energy loss correction
6. Subtraction of electron events from pair symmetric processes
7. Bin-centering correction (negligible to ratios, of order $<10^{-3}$)
8. Correction for the conversion of tritium to helium
9. Correction for events originating from the target cell endcaps

MARATHON 2H/1H DIS Calibration Data

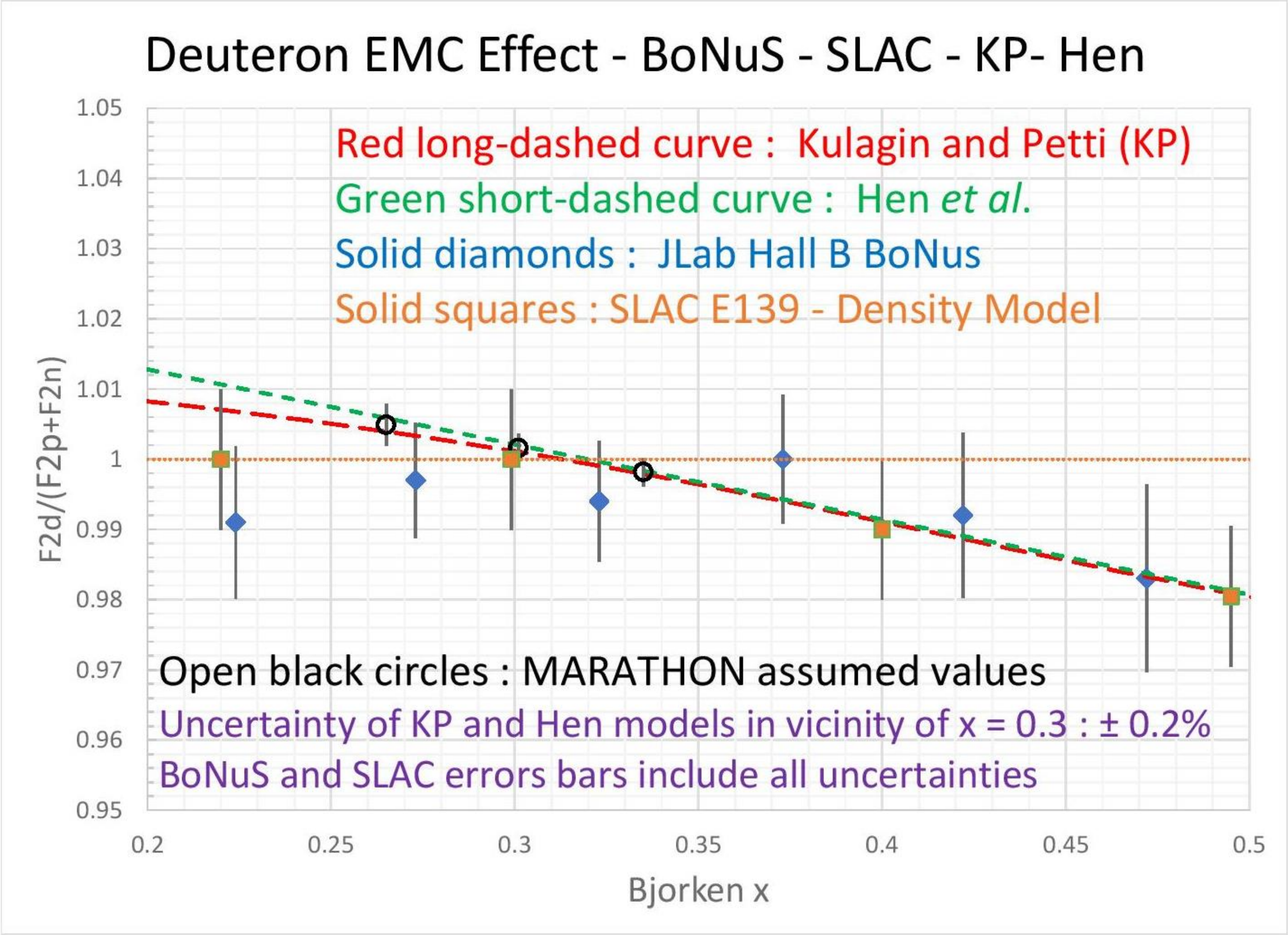
- MARATHON measured the ratio of d/p DIS yield at low *x* values (around *x=0.3)* with *high precision*. The *accuracy* of the d/p results is dominated by the gas target uncertainties (~0.5%).
- The d/p ratio data, are in excellent agreement with the SLAC benchmark data, taken at similar kinematics, by the SLAC/MIT group, with the 8 GeV/*c* Spectrometer.
- The F_2^n/F_2^p calibration values have been determined from the 2H and 1H data using $F_2^n/F_2^p = [(F_2^d/F_2^p)/R^*]-1$, where R^* is the deuteron EMC-type ratio $R^* = F_2^d/(F_2^n + F_2^p)$, calculated from the average of **two data-driven models by Kulagin and Petti, and by Segarra *et al.***, which are, at low *x*, in very good agreement with data from JLab BoNuS and SLAC E139 expts.
- The d/p-extracted F_2^n/F_2^p values in the vicinity of $x = 0.3$ have been used to normalize F_2^n/F_2^p from the 3H/3He ratio data.

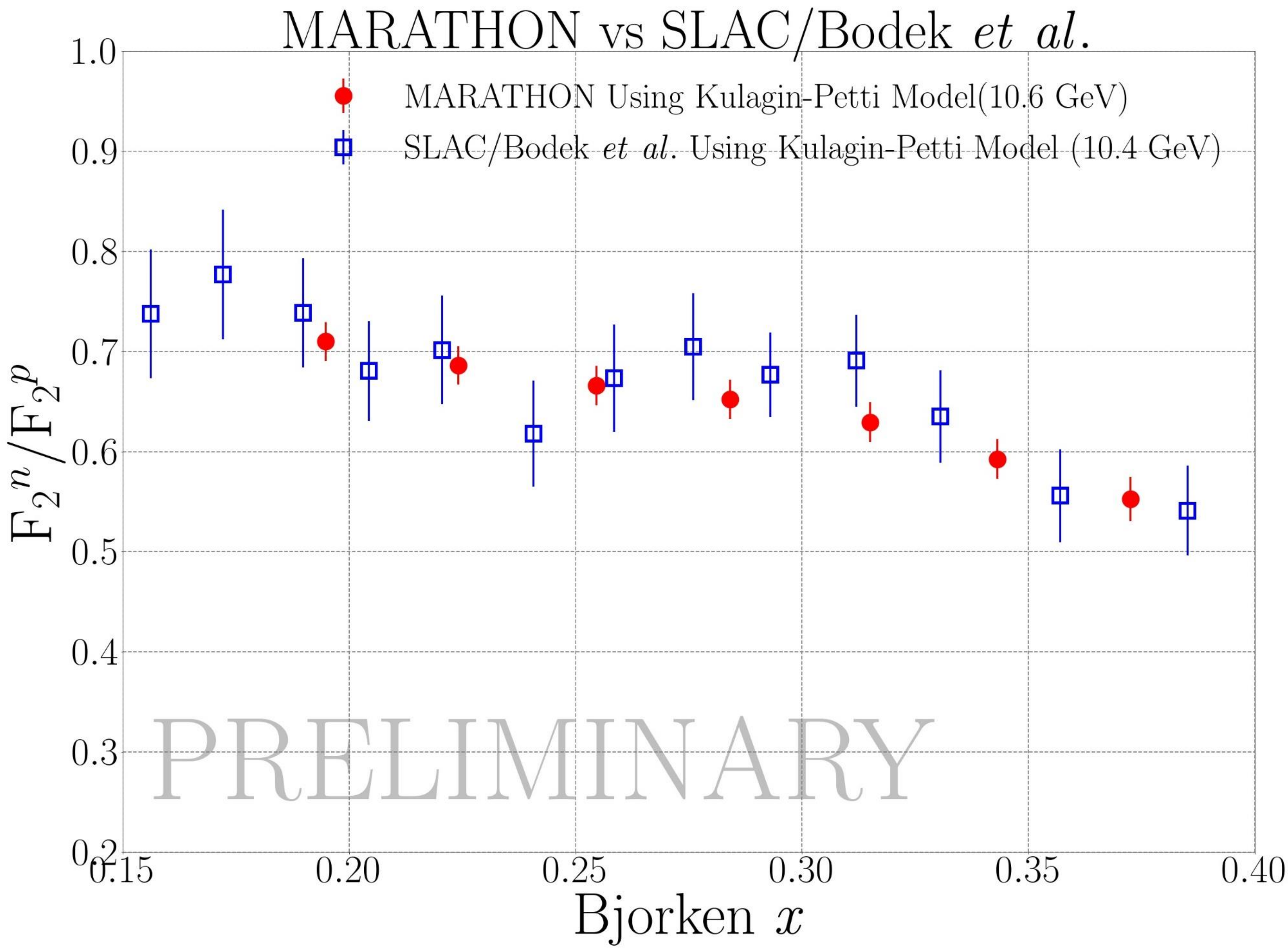


d/p DIS cross section ratio (W^2 > 4 GeV^2)
MARATHON (preliminary) vs SLAC Bodek *et al.*
13.3 GeV
10.4 GeV
12.5 GeV
11.9 GeV
10.0 GeV
MARATHON
Error bars contain statistical, random ptp, and scale errors added in quadrature
d/p
Bjorken x
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
0.150
0.200
0.250
0.300
0.350
0.400

From F2d/F2p to F2n/F2p

$$F2n/F2p=[(F2d/F2p)/R^*]-1 \quad R^*=F2d/(F2p+F2n)$$

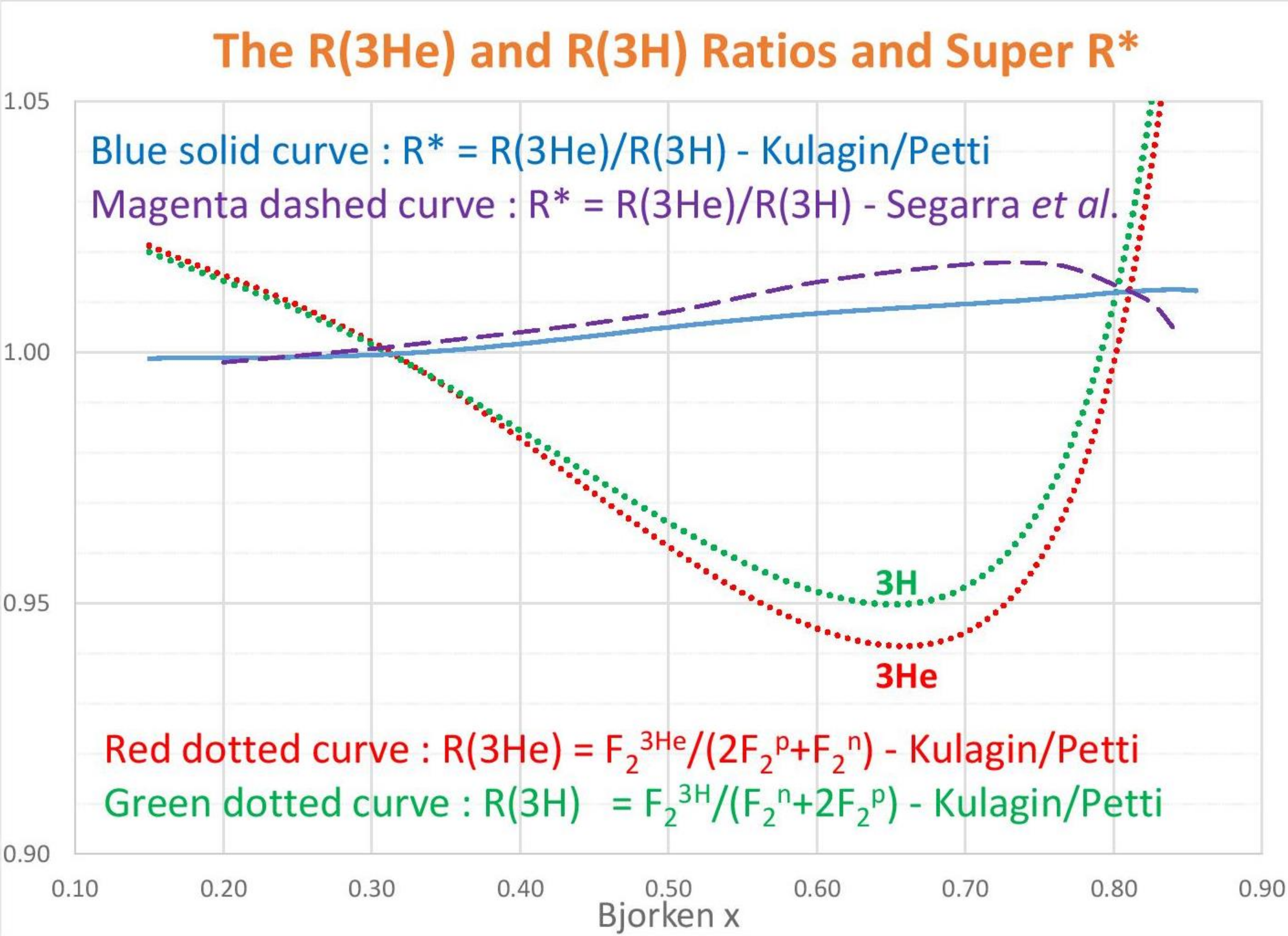




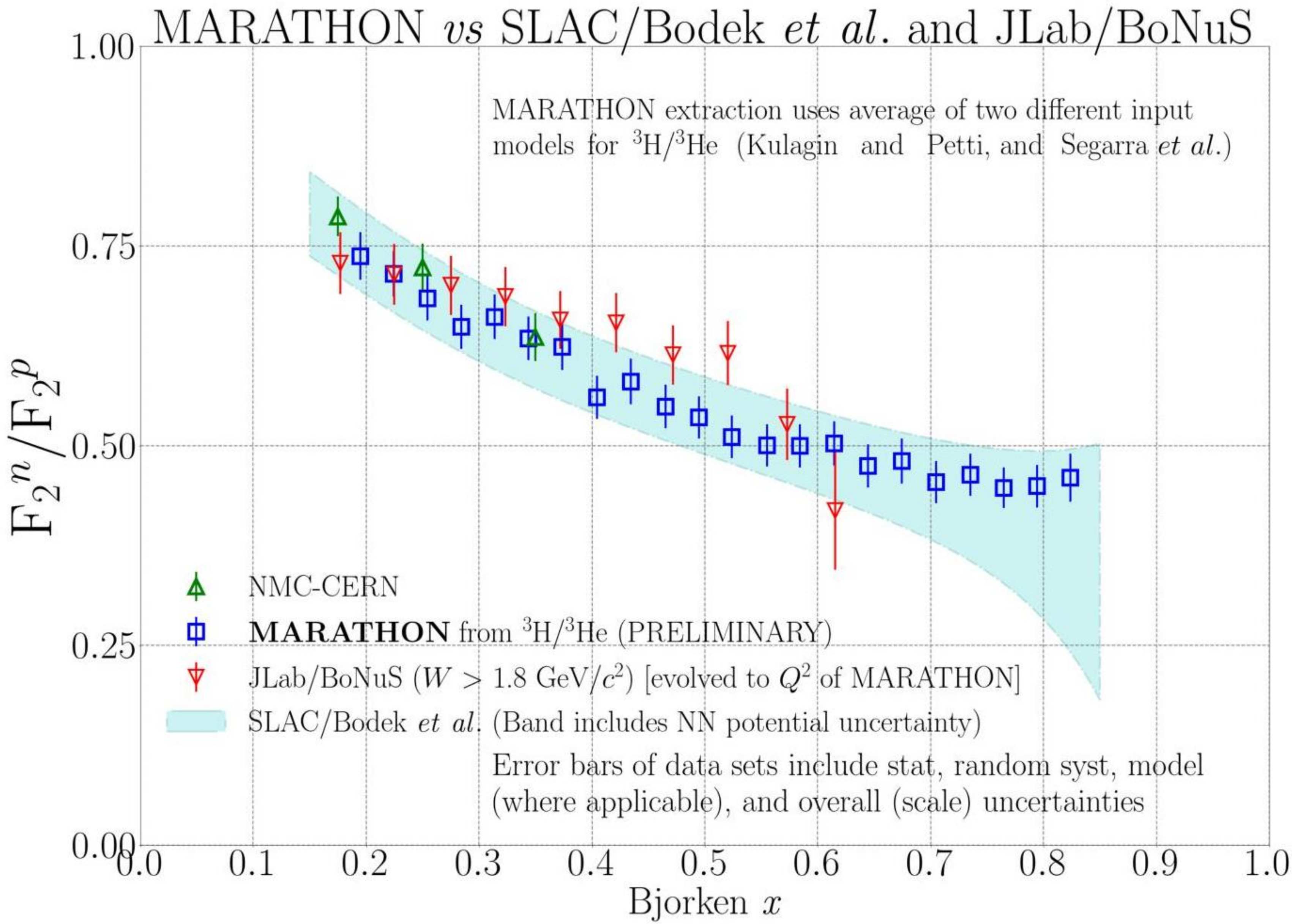
MARATHON vs SLAC/Bodek et al.
MARATHON Using Kulagin-Petti Model(10.6 GeV)
SLAC/Bodek et al. Using Kulagin-Petti Model (10.4 GeV)
F_2^n/F_2^p
Bjorken x
PRELIMINARY
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.15
0.20
0.25
0.30
0.35
0.40

MARATHON 3H/3He DIS Data

- For the EMC-type **super-ratio *R**** model of 3H and 3He, MARATHON used the **average of two models**, which are data-driven: i) by **Segarra *et al*.** which explores the relationship of the EMC effect with x > 1 plateaus, and ii) by **Kulagin and Petti**, which uses the *A = 3* spectral functions by the Rome group (E. Pace, G. Salmè *et al*.).
- F_2^n/F_2^p as calculated from the measured 3H/3He ratio was compared to F_2^n/F_2^p as calculated from the measured d/p MARATHON ratio. In order to match the values of the two measurements in the vicinity of $x = 0.3$, **the 3H/3He ratio must be scaled down (normalized) by 2.7%**.
- Note that the MARATHON data and in good agreement with the 3He/3H values calculated from the above two models.


The R(3He) and R(3H) Ratios and Super R*
Blue solid curve : R* = R(3He)/R(3H) - Kulagin/Petti
Magenta dashed curve : R* = R(3He)/R(3H) - Segarra et al.
3H
3He
Red dotted curve : R(3He) = $F_2^{3He}/(2F_2^p+F_2^n)$ - Kulagin/Petti
Green dotted curve : R(3H) = $F_2^{3H}/(F_2^n+2F_2^p)$ - Kulagin/Petti
1.05
1.00
0.95
0.90
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Bjorken x

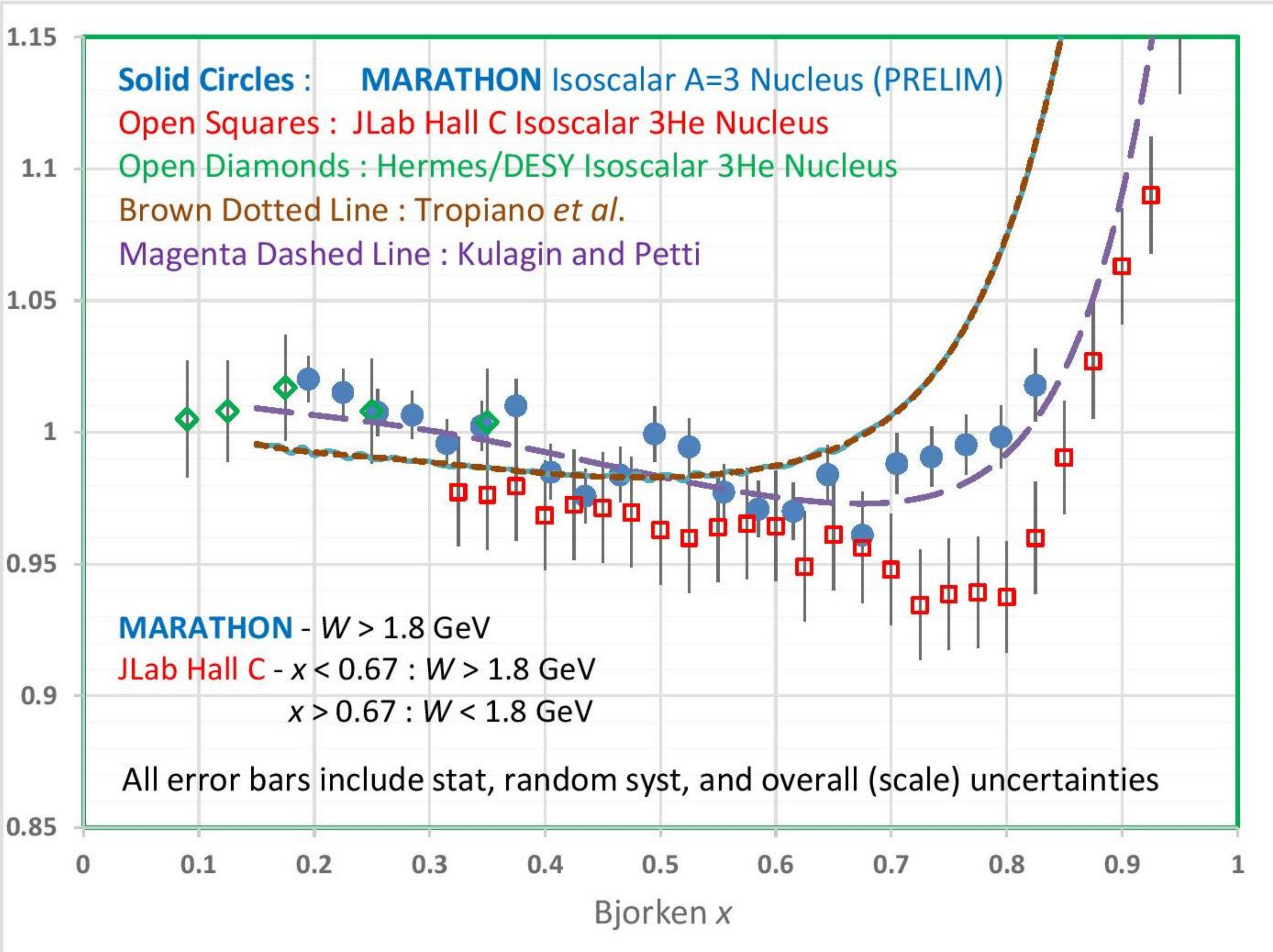
MARATHON **Preliminary** F2n/F2p Results



Isoscalar EMC Effect of A=3 Nucleus

EMC_iso (A=3) = (h/d+t/d)/2 = (h/t+1)/(t/d)/2

[h = σ(3He)/3, t = σ(3H)/3, d = σ(2H)/2]



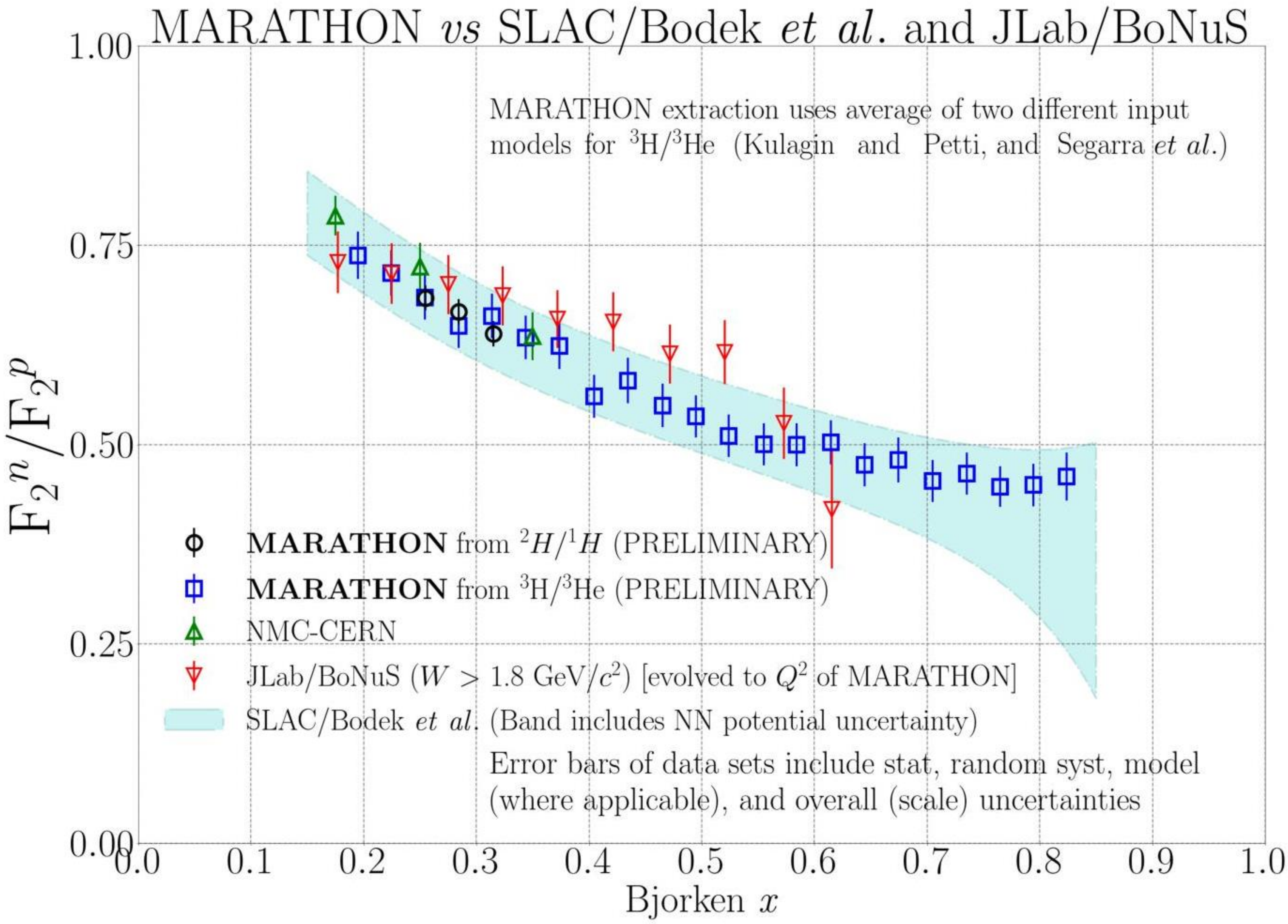
Summary

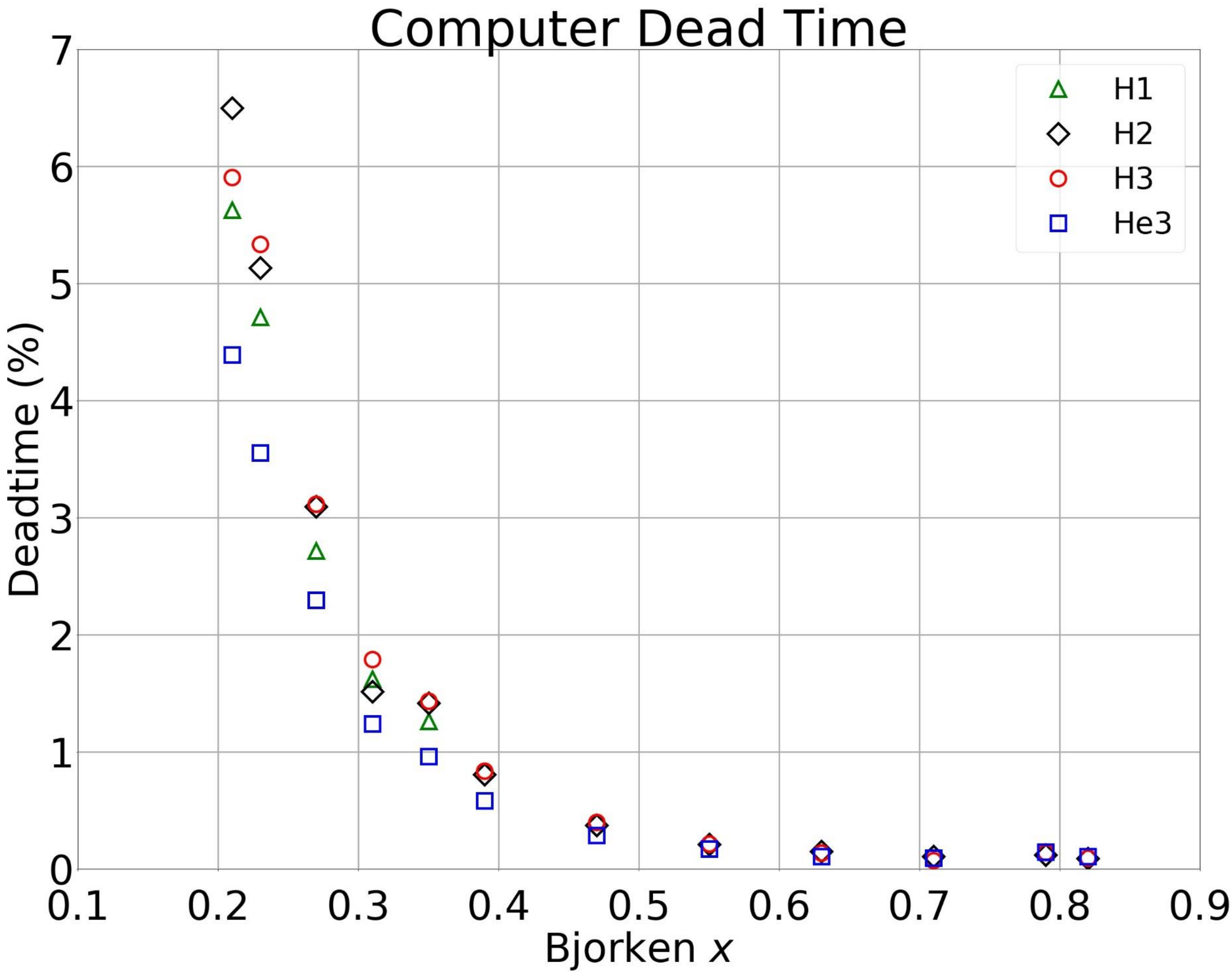
- The MARATHON d/p DIS measurements agree very well with the seminal SLAC Bodek *et al*. measurements and provide an excellent normalization for the 3H/3He DIS data.
- MARATHON has provided high quality F_2^n/F_2^p data at medium and large values of Bjorken x that are free of the deuteron structure uncertainties present in the SLAC data extracted from d/p DIS.
- The F_2^n/F_2^p results are in good agreement with the old NMC (in the vicinity of x = 0.3) and SLAC data, and the recent JLab Hall B BoNuS data, albeit with much smaller uncertainties.
- MARATHON has also provided a high quality measurement of the isoscalar EMC effect of the $A=3$ nucleus (a nucleus made up of 1.5 proton and 1.5 neutron).
- A paper is being prepared in parallel to a PASS3 analysis…

Thanks

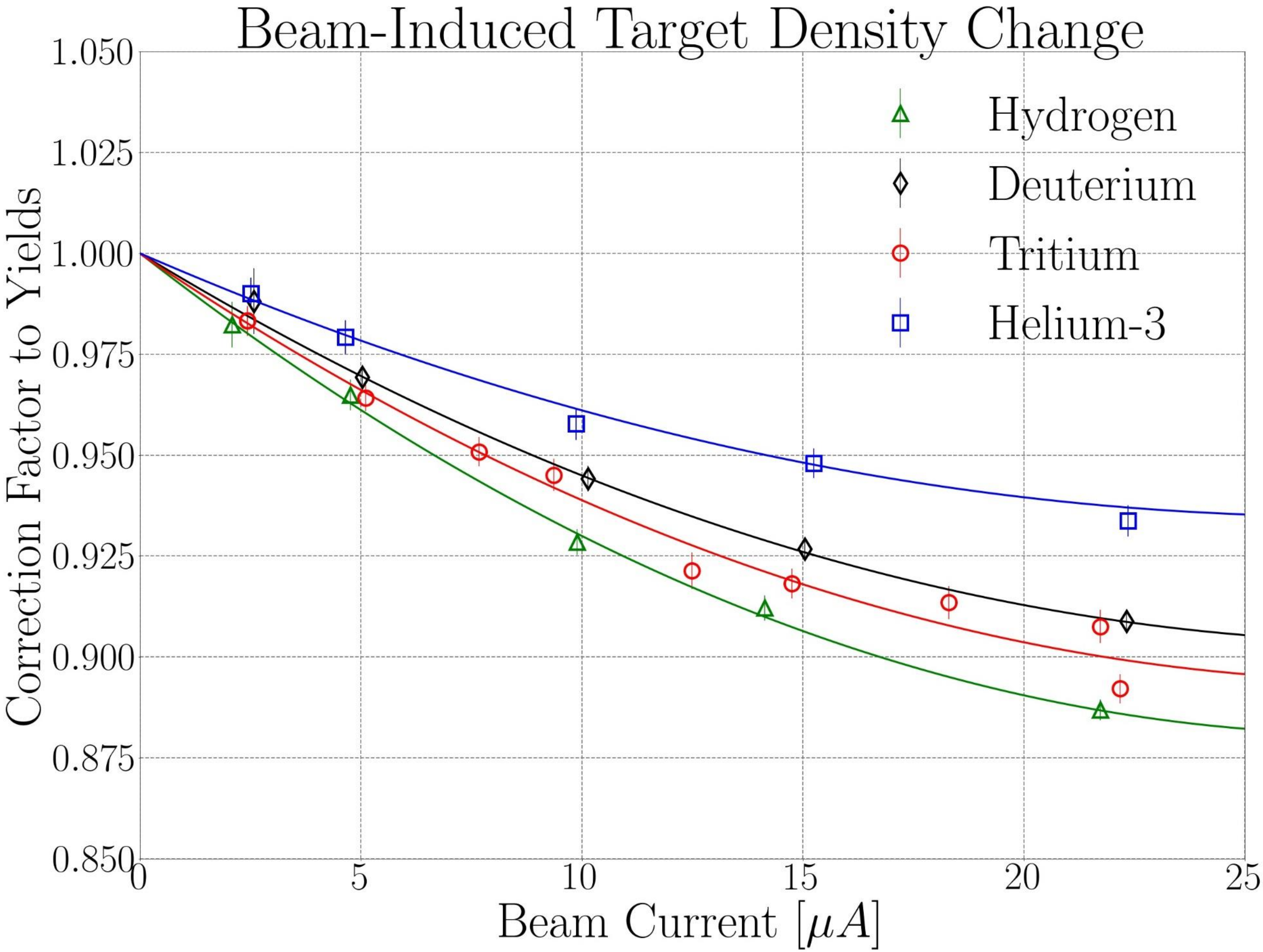
- Thanks to the graduate students and postdocs for their hard work and dedication in preparing, running and analyzing the experiment.
- Thanks to the Accelerator and Hall A Scientific and Technical Staff of JLab, and the Lab Management for their outstanding support of the MARATHON project.
- Special 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.

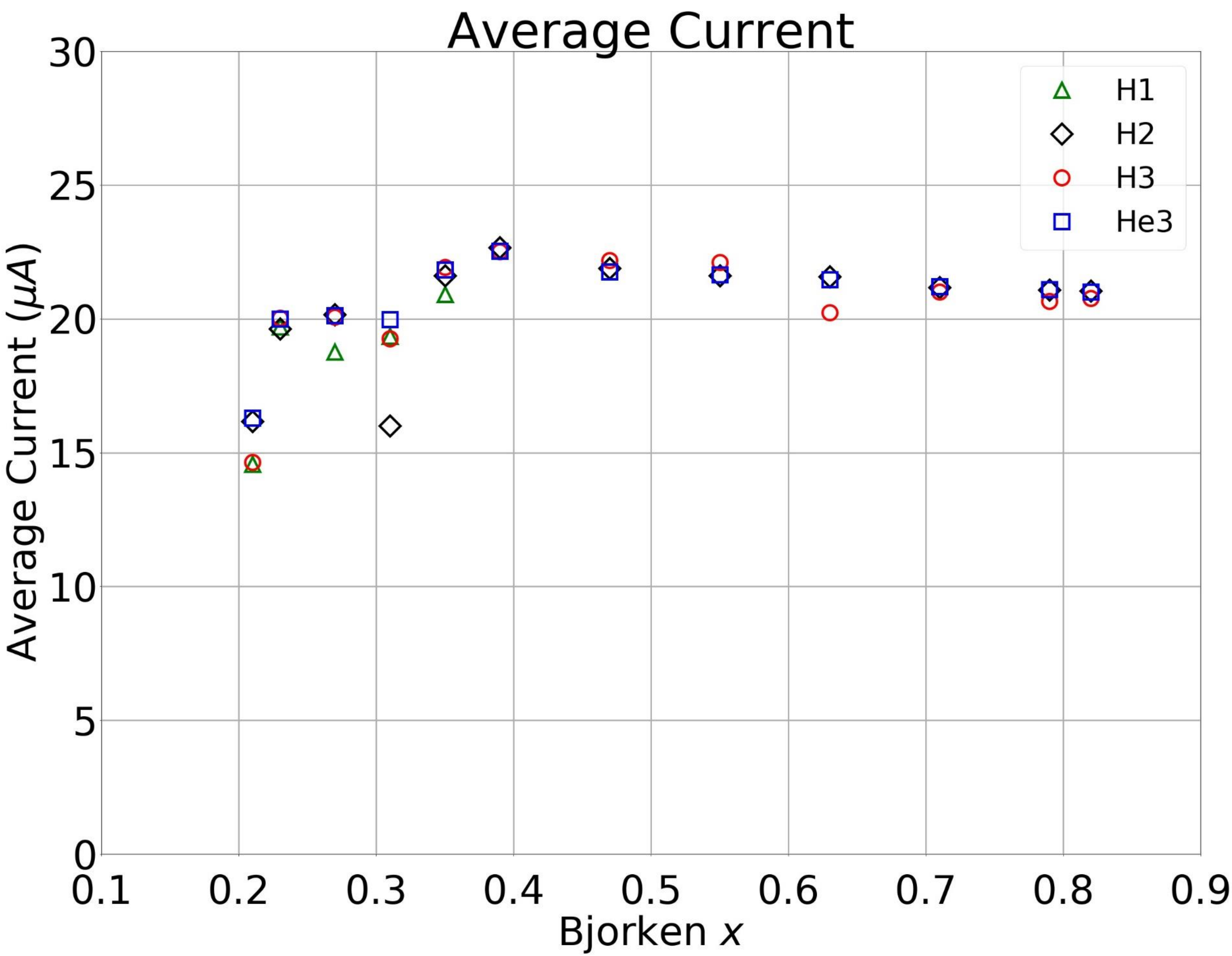
MARATHON **Preliminary** F2n/F2p Results



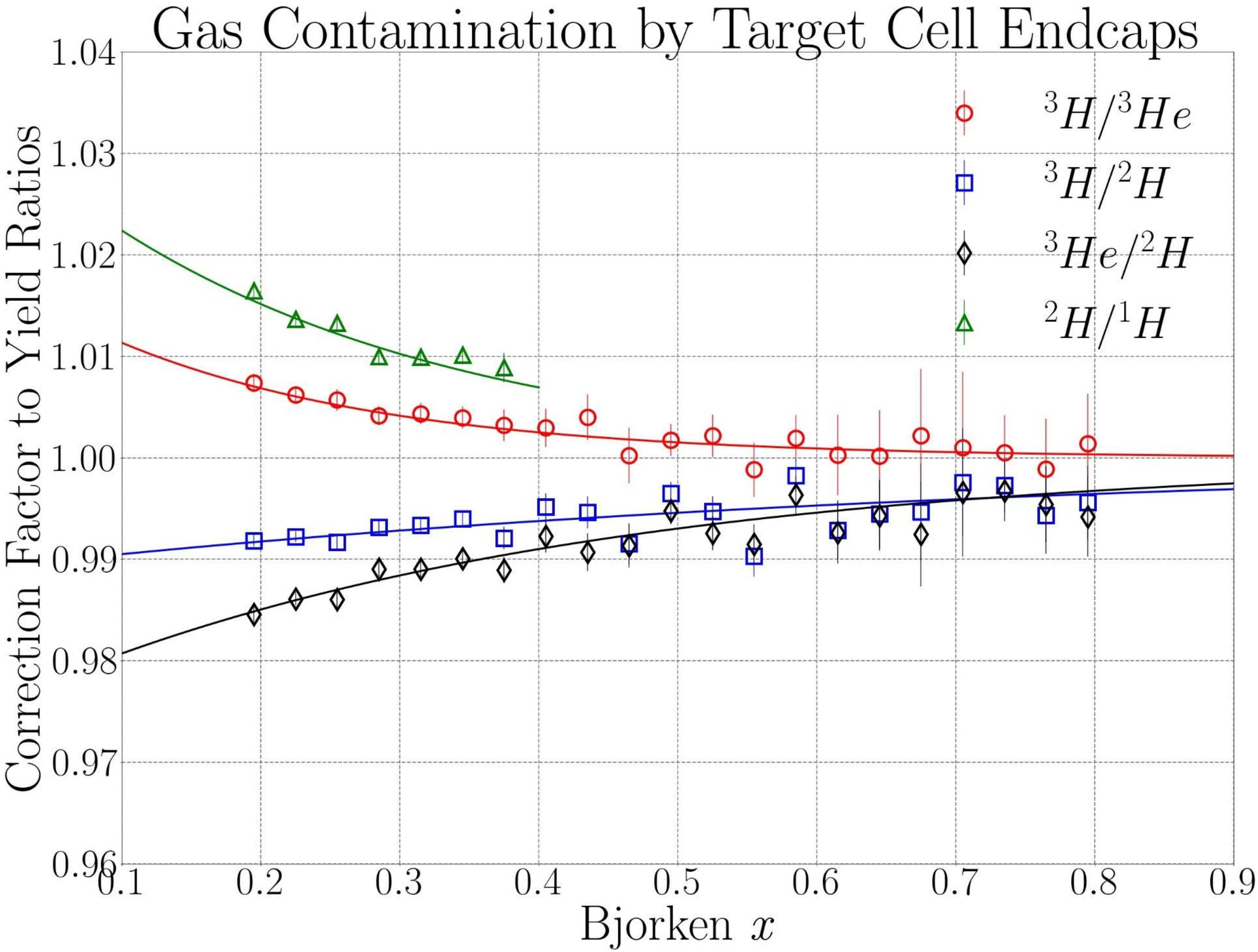


Computer Dead Time
Deadtime (%)
Bjorken x
H1
H2
H3
He3
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

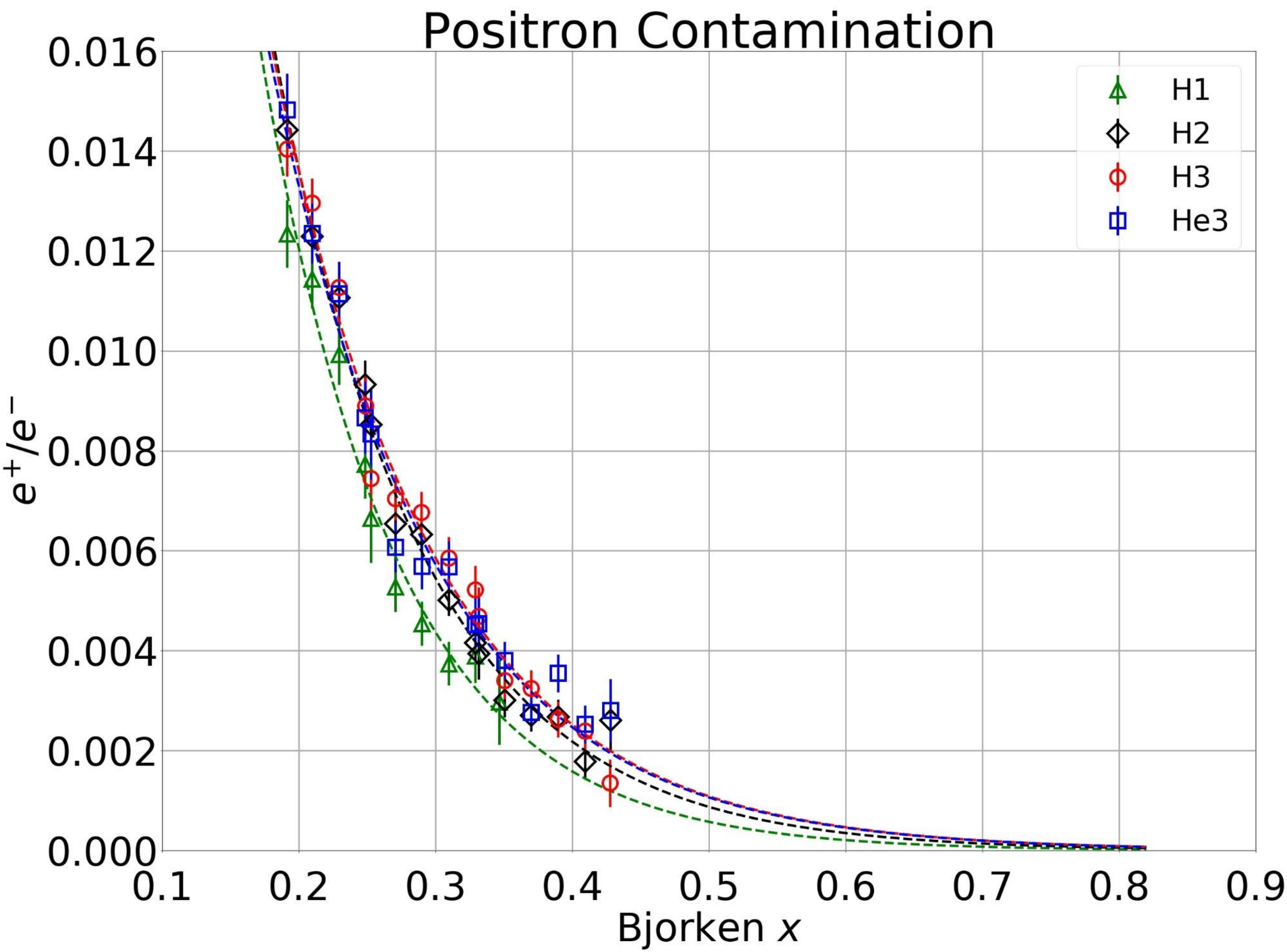

Beam-Induced Target Density Change
Correction Factor to Yields
Beam Current [μA]
1.050
1.025
1.000
0.975
0.950
0.925
0.900
0.875
0.850
0
5
10
15
20
25
Hydrogen
Deuterium
Tritium
Helium-3



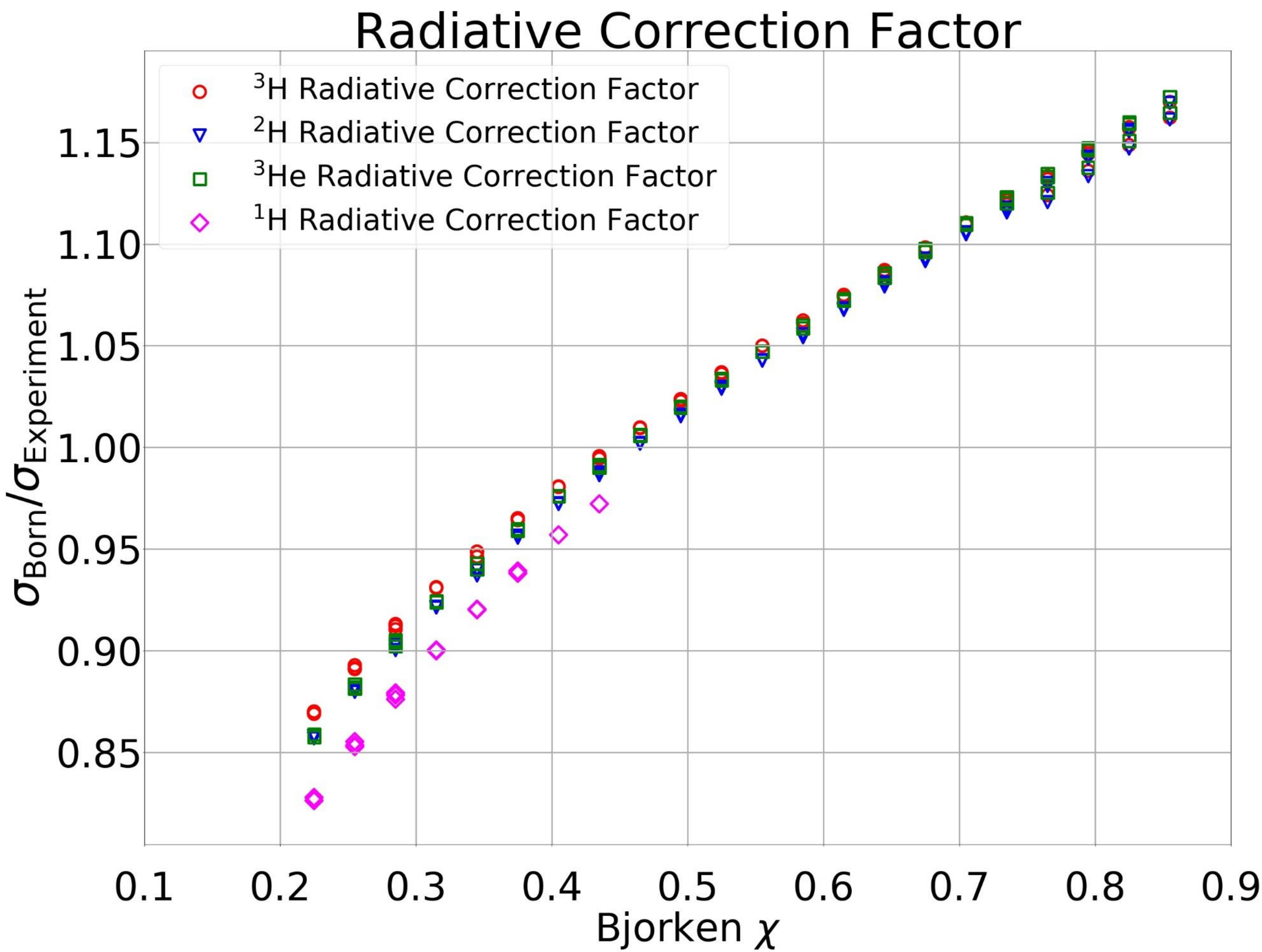
Average Current
Average Current (μA)
Bjorken x
H1
H2
H3
He3
0
5
10
15
20
25
30
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



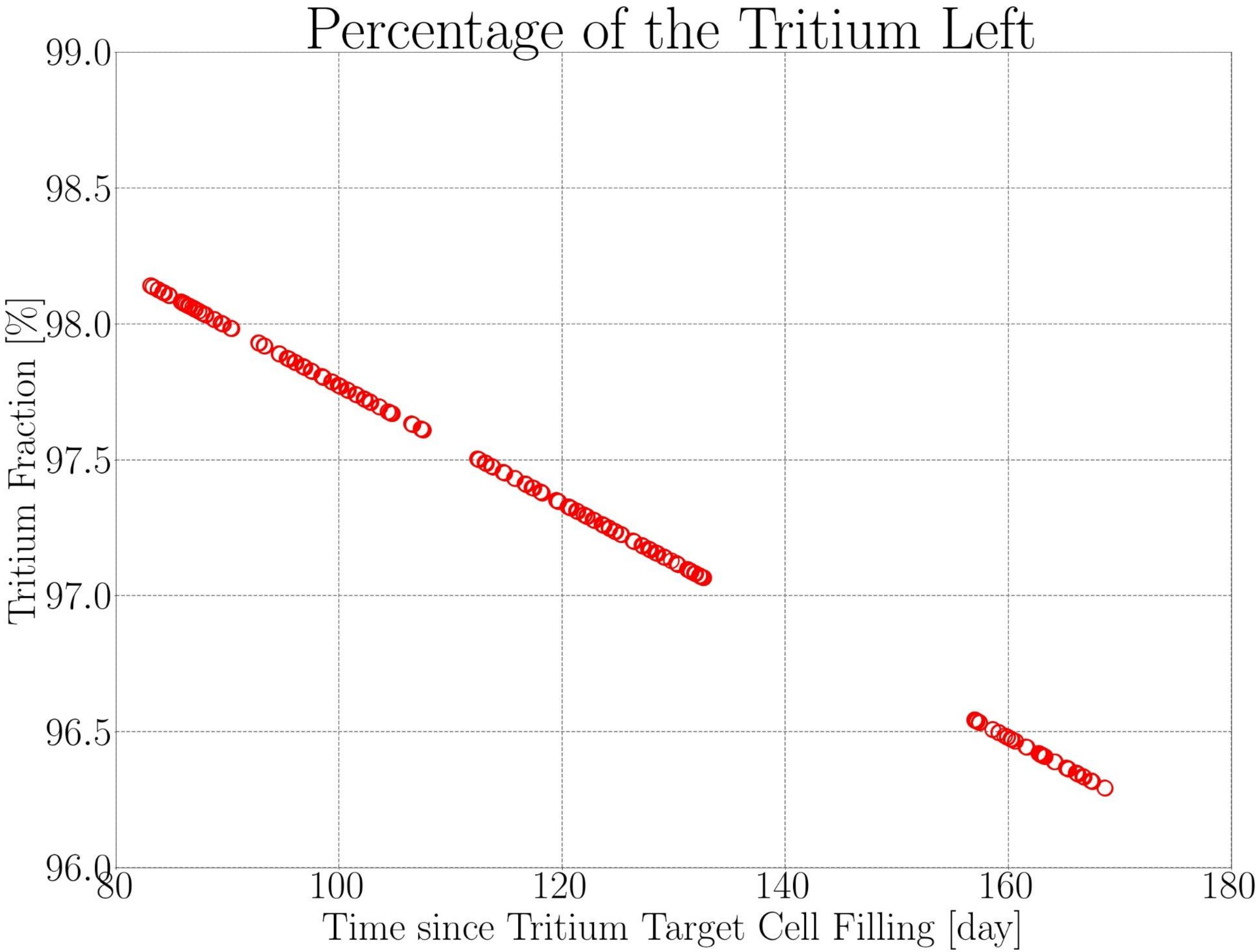
Gas Contamination by Target Cell Endcaps
Correction Factor to Yield Ratios
Bjorken x
$^3H/^3He$
$^3H/^2H$
$^3He/^2H$
$^2H/^1H$
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

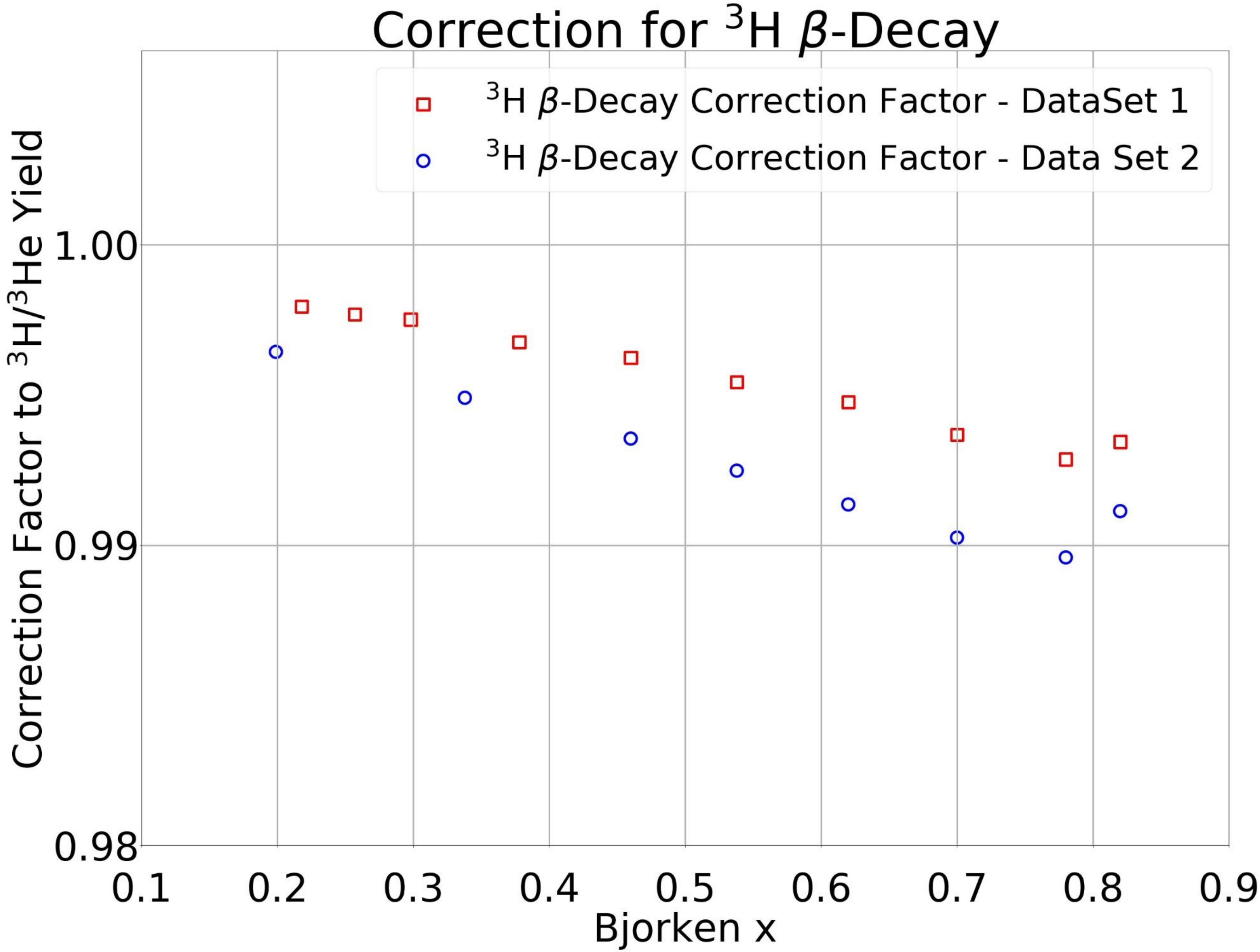


Positron Contamination
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
e^+/e^-
Bjorken x
H1
H2
H3
He3



Radiative Correction Factor
^{3}H Radiative Correction Factor
^{2}H Radiative Correction Factor
^{3}He Radiative Correction Factor
^{1}H Radiative Correction Factor
$\sigma_{\mathrm{Born}}/\sigma_{\mathrm{Experiment}}$
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
Bjorken χ


Percentage of the Tritium Left
99.0
98.5
98.0
97.5
97.0
96.5
96.0
80
100
120
140
160
180
Tritium Fraction [%]
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

F_2^n/ F_2^n, d/u Ratios and A_1 Limits for $x \rightarrow 1$

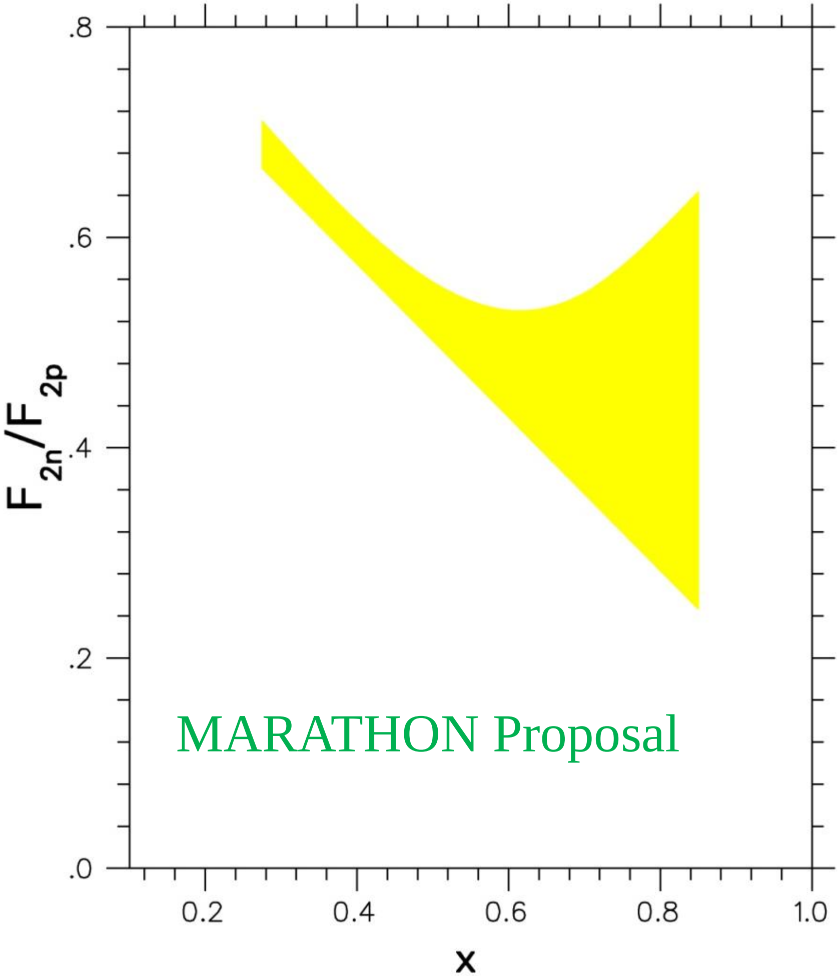
	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
Quark Counting Rules	3/7	1/5	1	1

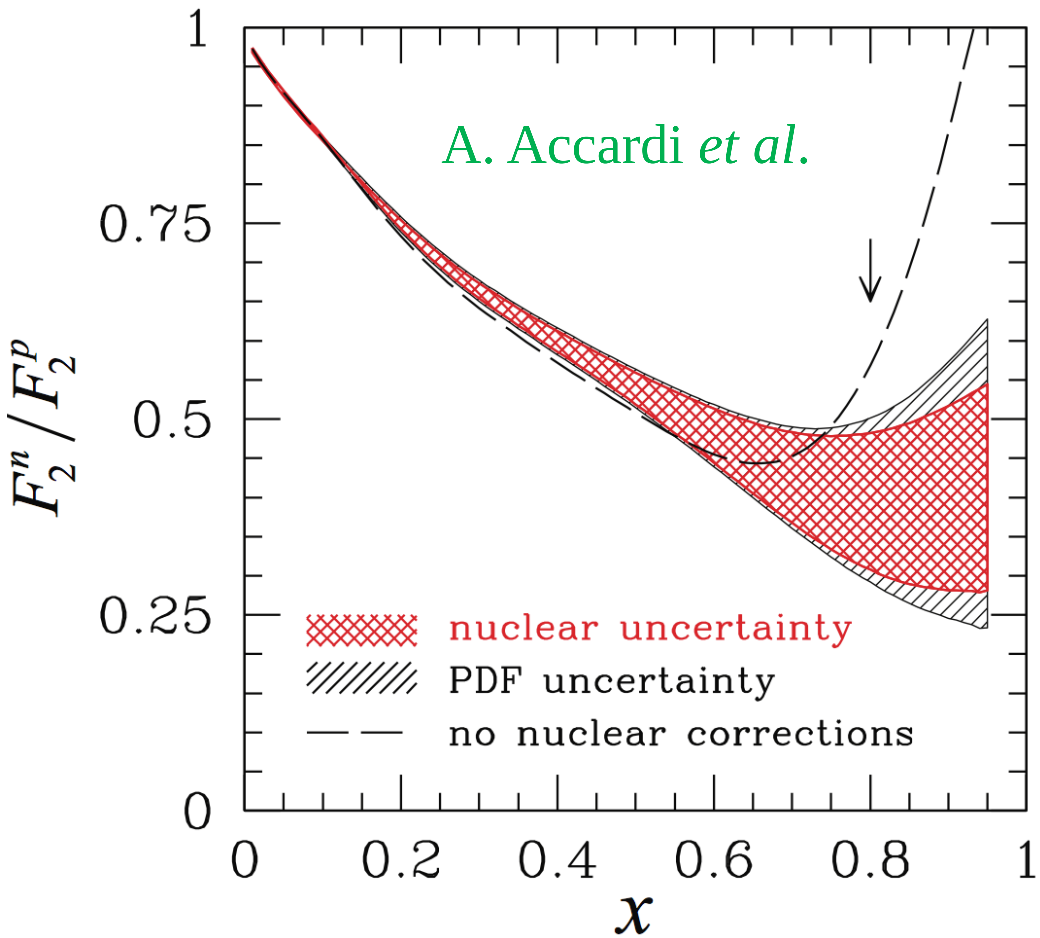
A_1: Asymmetry measured with polarized electrons and nucleons. Equal in QPM to probability that the quark spins are aligned with the nucleon spin.

A_1^p, A_1^n: Extensive experimental programs at CERN, SLAC, DESY and JLab (6 GeV and 12 GeV Programs)

MARATHON Motivation

MARATHON Proposal motivation for remeasuring the F_2^n/F_2^p ratio with another method (for example using 3H/3He DIS) was justified by several other works.





JLab Program Advisory Committee: "[MARATHON] is one of the flagship experiments driving the original scientific case for the 12 GeV energy upgrade of JLab".