JLab measurement of the ratio of the nucleon structure functions, F_2^n/F_2^p ,from electron DIS off ^{3}H and ^{3}He at large Bjorken *x* (MARATHON Experiment) *

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8th International Conference on New Frontiers in Physics, Kolymbari, August 27th, 2019

*Work supported by US NSF grant PHY-1714809 and DoE Contract DE-AC05-06OR23177

Deep Inelastic Scattering and Quark Parton Model

- Deep Inelastic Scattering:

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

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu}\left(1 + \frac{\nu^2}{Q^2}\right) - 1$$

$$\nu = E - E'$$

$$Q^2 = 4EE'\sin^2(\theta/2)$$

- Quark-Parton Model (QPM) interpretation in terms of quark probability distributions $q_i(x)$ (large Q^2 and ν):

$$F_1(x) = \frac{1}{2}\Sigma e_i^2 q_i(x) \qquad F_2(x) = x_i \Sigma e_i^2 q_i(x)$$

- Bjorken x: fraction of nucleon momentum carried by struck quark:

$$x = Q^2 / 2M\nu$$

F_2^n / F_2^p and d/u

- Assume isospin symmetry

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

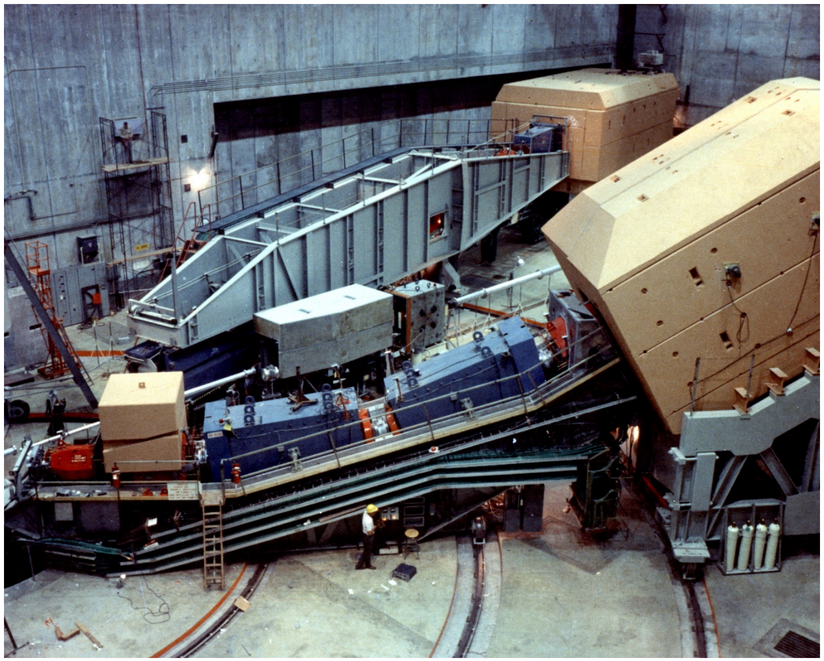
- Proton and neutron structure functions:

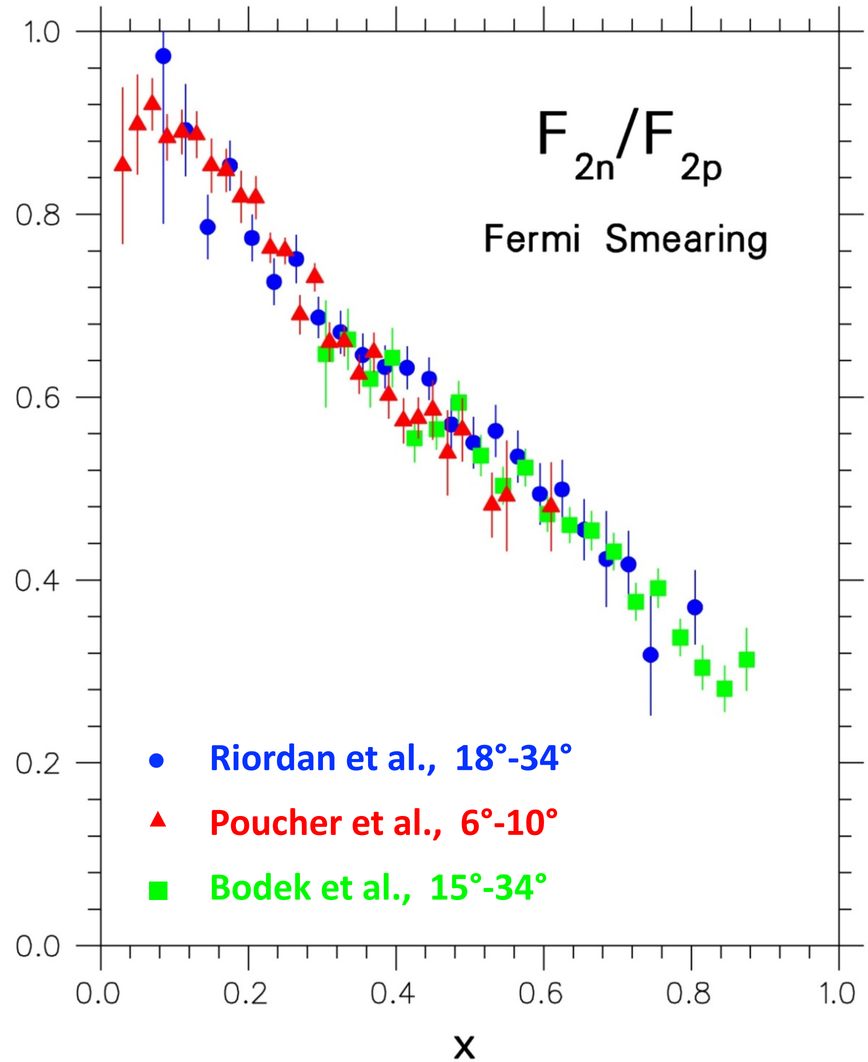
$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$
$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

- Nachtmann inequality

$$1/4 \leq F_2^n / F_2^p \leq 4$$

Early SLAC data





- SLAC, End Station A

- SLAC Measurements, End Station A,1968-1972
- F_2^n/F_2^p extracted from proton and deuterium deep inelastic data using Hamada-Johnston potential in a Fermi-smearing model.

SLAC/CERN Data Interpretation in QPM

- Nachtmann inequality satisfied
- For $x \rightarrow 0$: $F_2^n/F_2^p \rightarrow 1$: Sea quarks dominate with:

$$u + \overline{u} = d + \overline{d} = s + \overline{s}$$

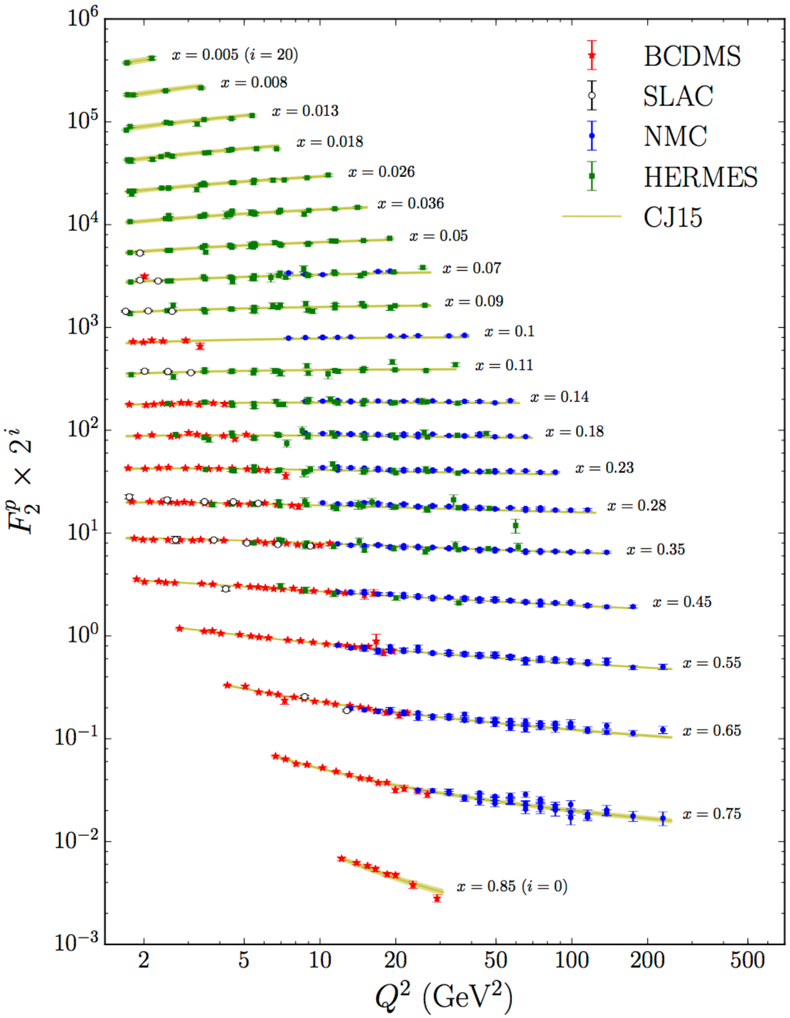
- For $x \rightarrow 1$: $F_2^n/F_2^p \rightarrow 1/4$: High momentum parton in proton (neutron) are up (down) quarks, and:

$$s + \overline{s} = 0$$

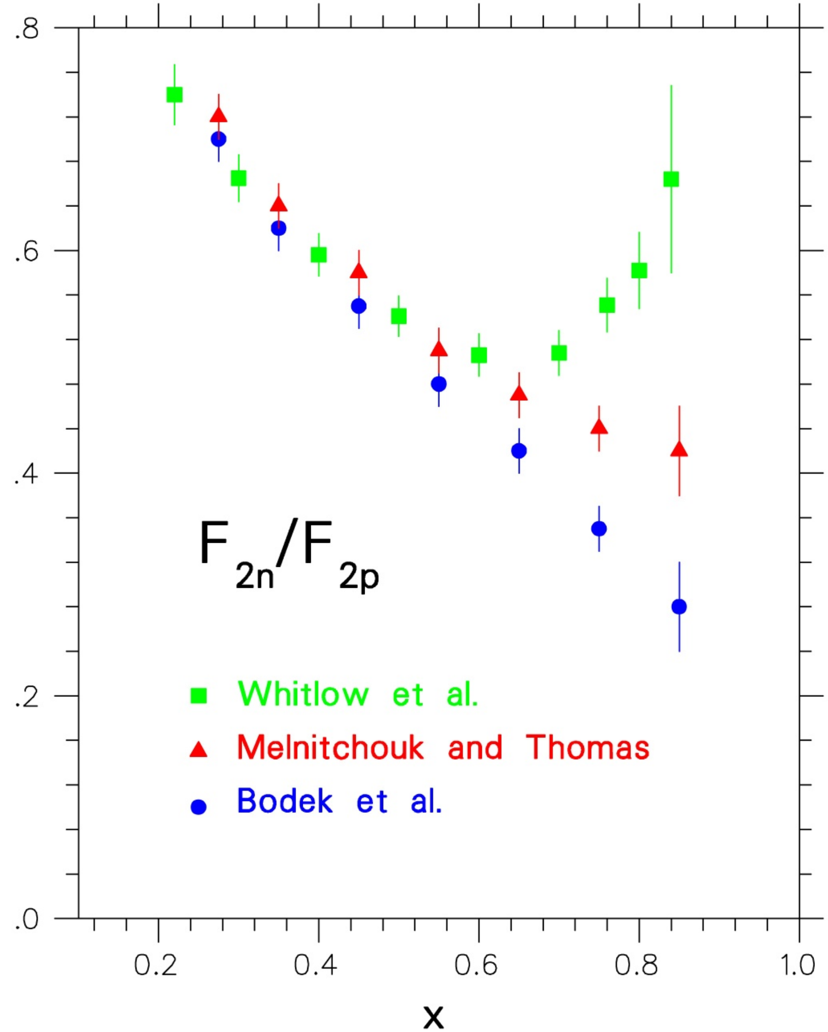
- For medium and high x, safe to assume that (with d and u denoting now quark plus antiquark distributions):

$$\frac{F_2^n}{F_2^p} = \frac{[1 + 4(d/u)]}{[4 + (d/u)]}$$

Half a century later

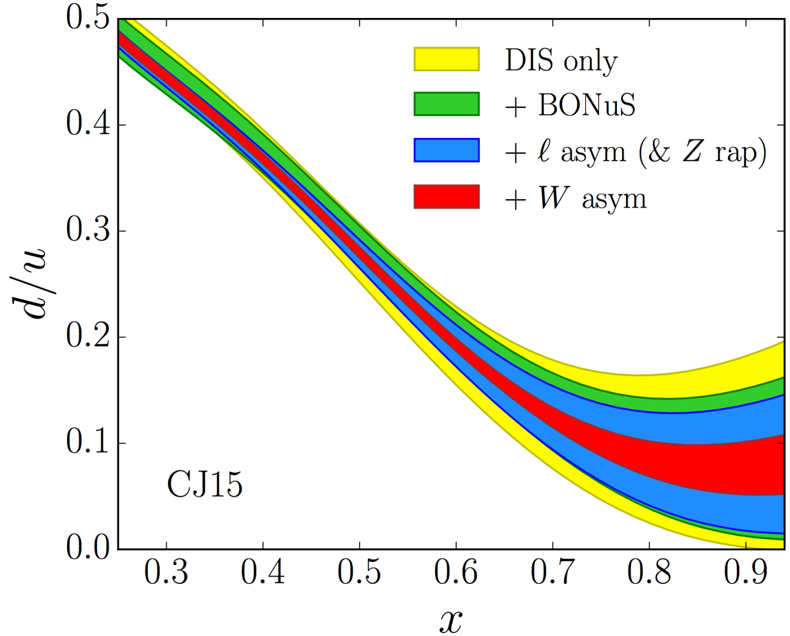


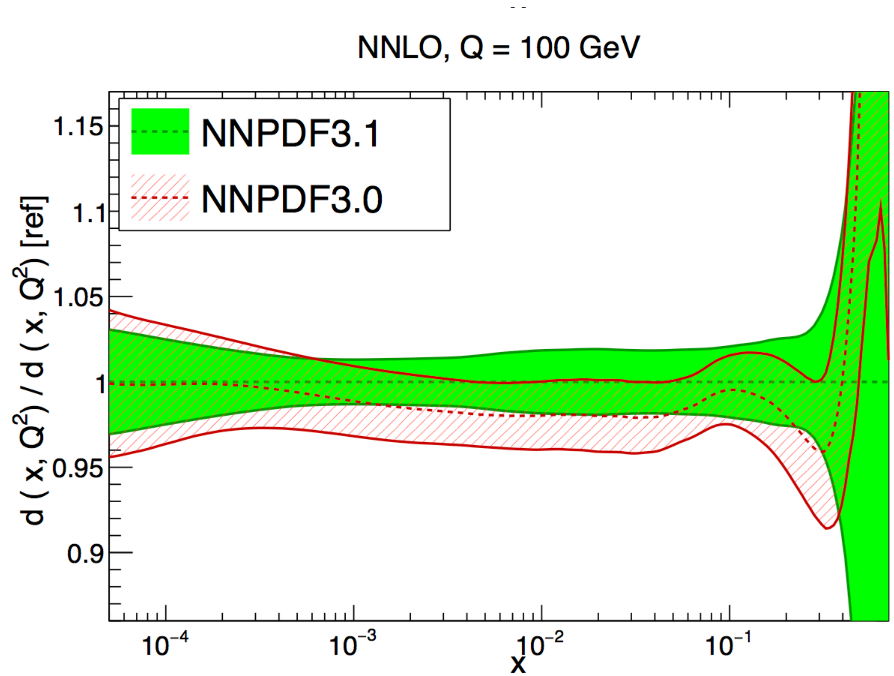
- F_2^p has been precisely measured



- F_2^n not well known at large x
- Data inconclusive due to uncertainties in deuterium nuclear corrections

F_2^n uncertains translates directly to uncertainty on d/u, d(x)...





- A. Accardi, L.T. Brady, W. Melnitchouk, J.F. Owens, N. Sato Phys. Rev. D **93** 114017 (2016)
- NNPDF Collaboration (Ball, Richard D. et al.) Eur. Phys. J. C77 (2017) no.10, 663

F_2^n/F_2^p from Theory

F_2^n/F_2^p, d/u ratios and A_1 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/Feynman	**1/4**	**0**	**1**	**1**
Quark Model/Isgur	**1/4**	**0**	**1**	**1**
Perturbative QCD	**3/7**	**1/5**	**1**	**1**
QCD Counting Rules	**3/7**	**1/5**	**1**	**1**

* R. J. Holt and C. D. Roberts, Rev. Mod. Phys. 82, 2991 (2010).

Extract F_2^n/F_2^p from A=3 nuclei

- Instead of dealing with the nuclear correction in deuterium, MARATHON proposed a new way to extract F_2^n/F_2^p from Tritium and Helium-3 DIS data by taking advantage of the mirror symmetry of the A=3 nuclei
- Define the EMC type ratio :

$$R_{3H} = \frac{F_2^{3H}}{2F_2^n + F_2^p} \quad R_{3He} = \frac{F_2^{3He}}{F_2^n + 2F_2^p}$$

- Super Ratio: $\mathfrak{R} = \frac{R_{3He}}{R_{3H}}$
- Solve for the nucleon F_2 ratio and calculate R^* (expected to be very close to unity) using a theory model:

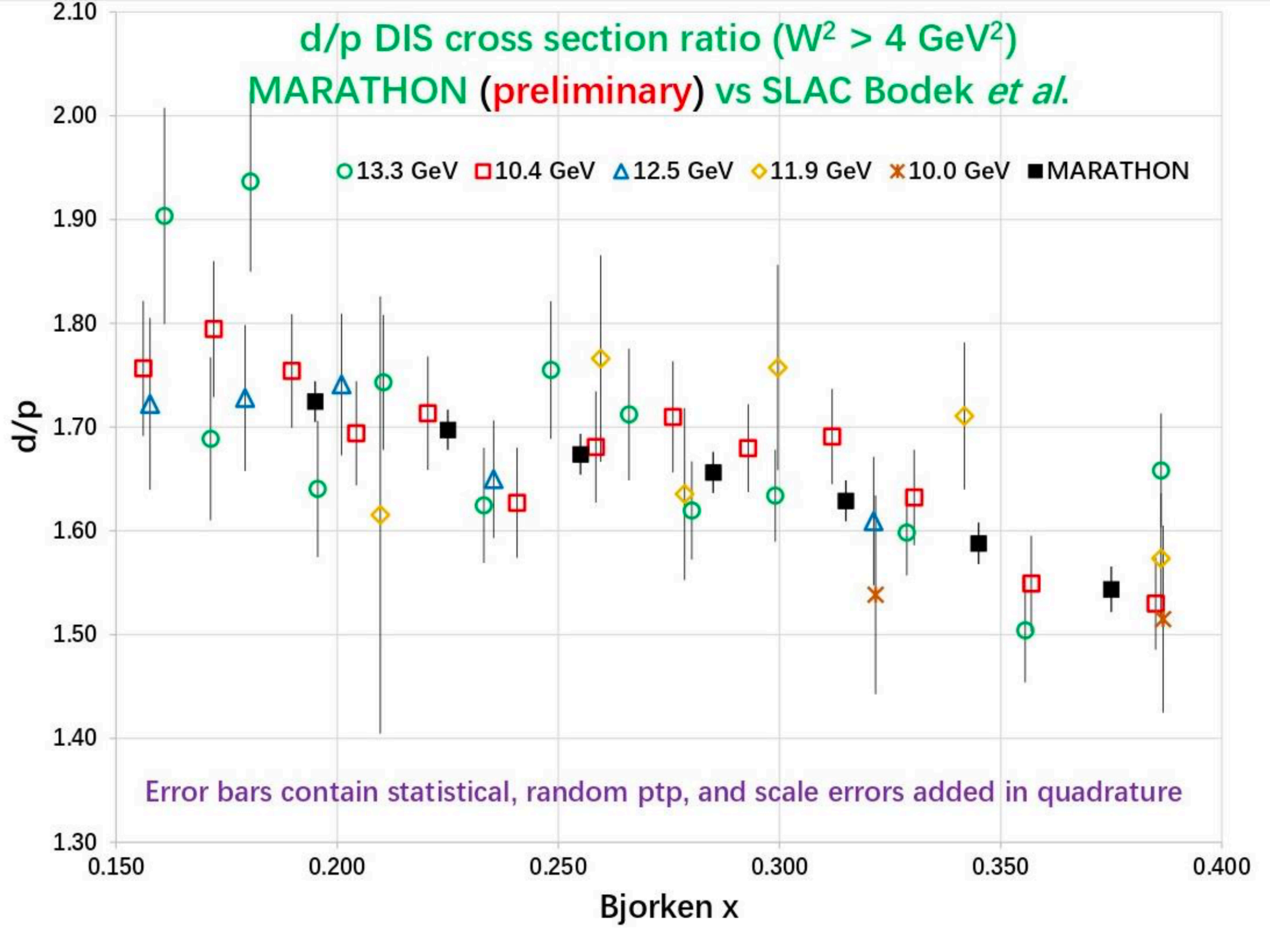
$$\frac{F_2^n}{F_2^p} = \frac{2\mathfrak{R} - F_2^{3He}/F_2^{3H}}{2(F_2^{3He}/F_2^{3H}) - \mathfrak{R}}$$

The JLab MARATHON Experiment

- MARATHON took data in the period January-April, 2018 at Jefferson Lab.
- 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 a10.6 GeV electron beam with 20μA beam current.
- The electron scattering angle varied between17 and 36deg.
- 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.

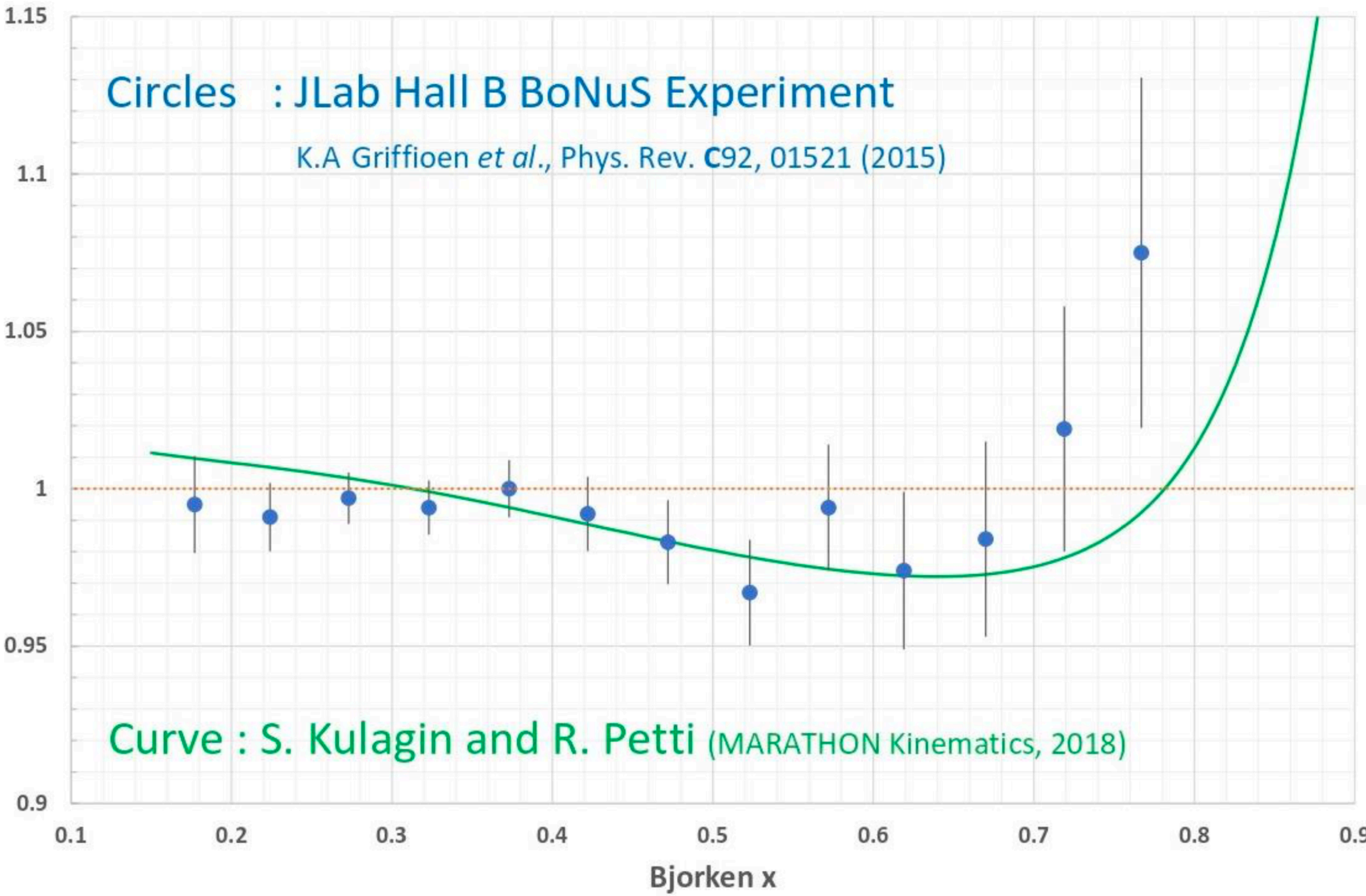
MARATHON $^2H/^1H$ DIS Calibration Data

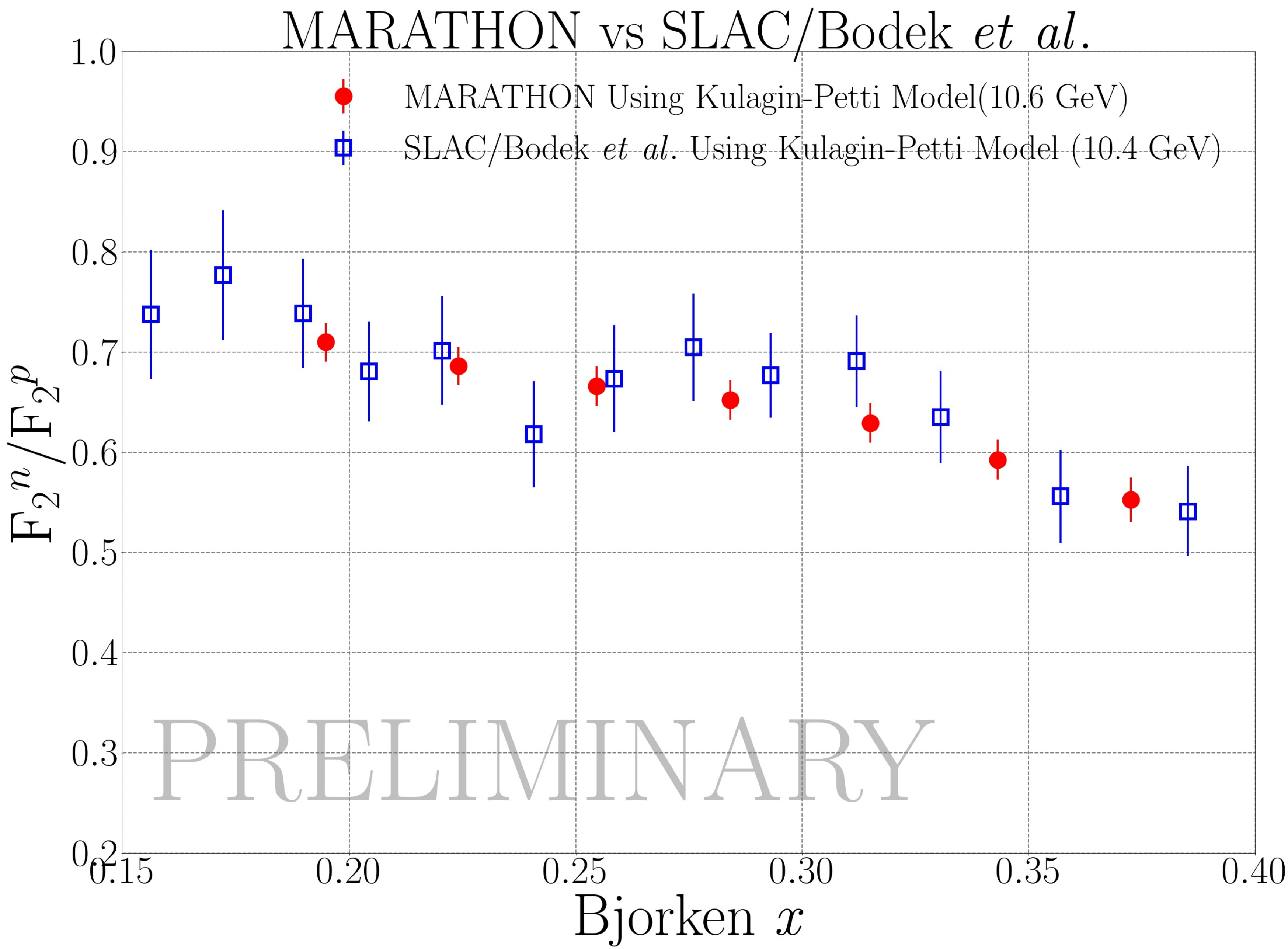
- MARATHON measured the ratio of d/p DIS yield at low Bjorken x values with *high precision*. The *accuracy* of the d/p results is essentially dominated by the gas target uncertainties.
- The d/p ratio data, are in excellent agreement with the SLAC benchmark data, taken at similar kinematics, by the SLAC/MIT Nobel prize winning group, with the 8 GeV/*c* Spectrometer.
- The MARATHON F_2^n/F_2^p calibration values have been determined from the ^1H and ^2H data using the standard formula $F_2^n/F_2^p = [(F_2^d/F_2^p)/R^*] - 1$, where R^* is the deuteron EMC-type ratio $R^* = F_2^d/[F_2^p + F_2^n]$, calculated from a theoretical model by S. Kulagin and R. Petti, which is, at low x, in very good agreement with data extracted from the JLab BoNuS experiment.
- The d/p F_2^n/F_2^p values in the vicinity of $x=0.3$ have been used to normalize the F_2^n/F_2^p obtained 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

EMC Effect - Deuteron - BoNuS -Kulagin&Petti

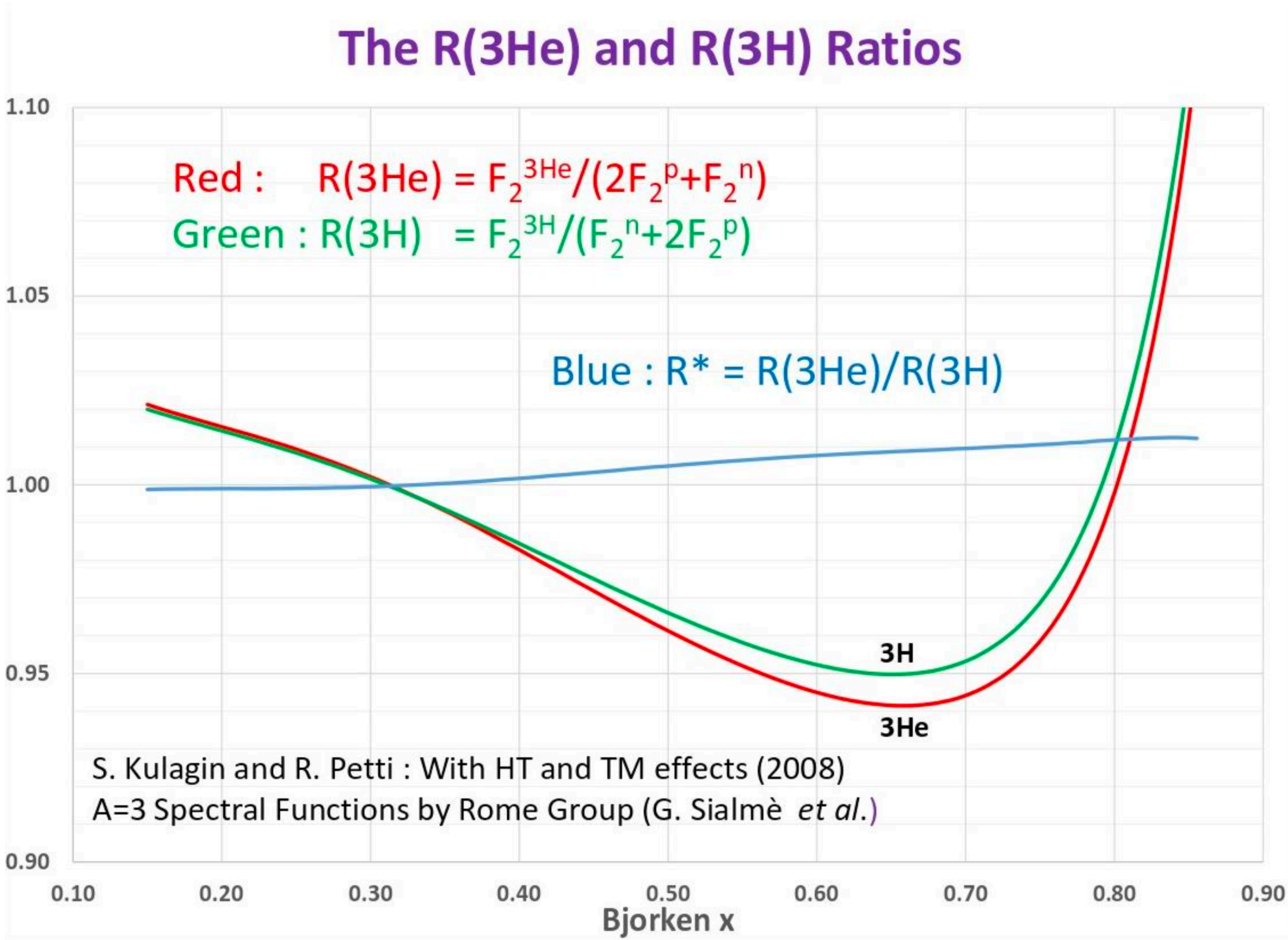


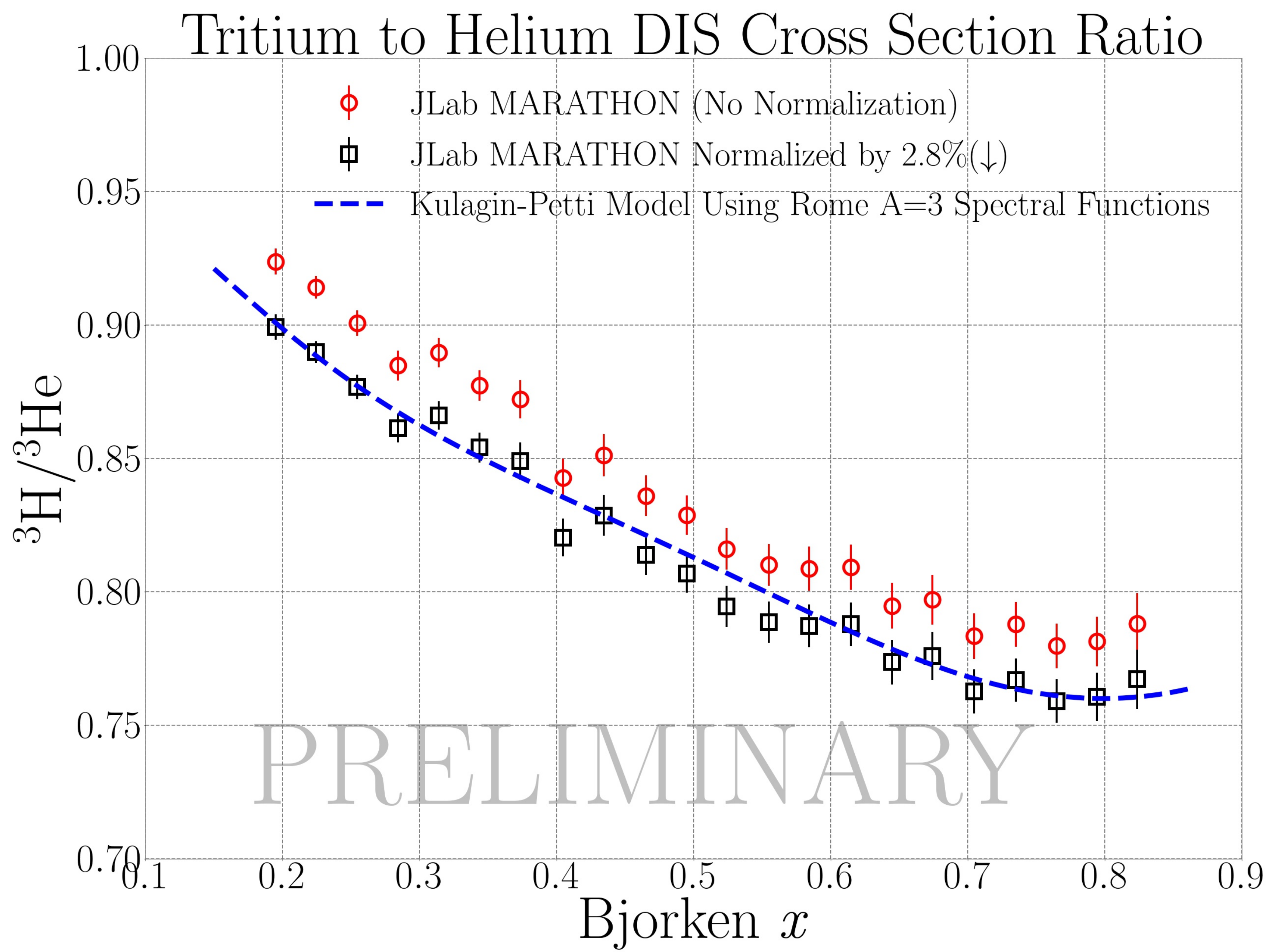


MARATHON vs SLAC/Bodek et al.
MARATHON Using Kulagin-Petti Model(10.6 GeV)
SLAC/Bodek et al. Using Kulagin-Petti Model (10.4 GeV)
F2n/F2p
Bjorken x
PRELIMINARY
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.15
0.20
0.25
0.30
0.35
0.40

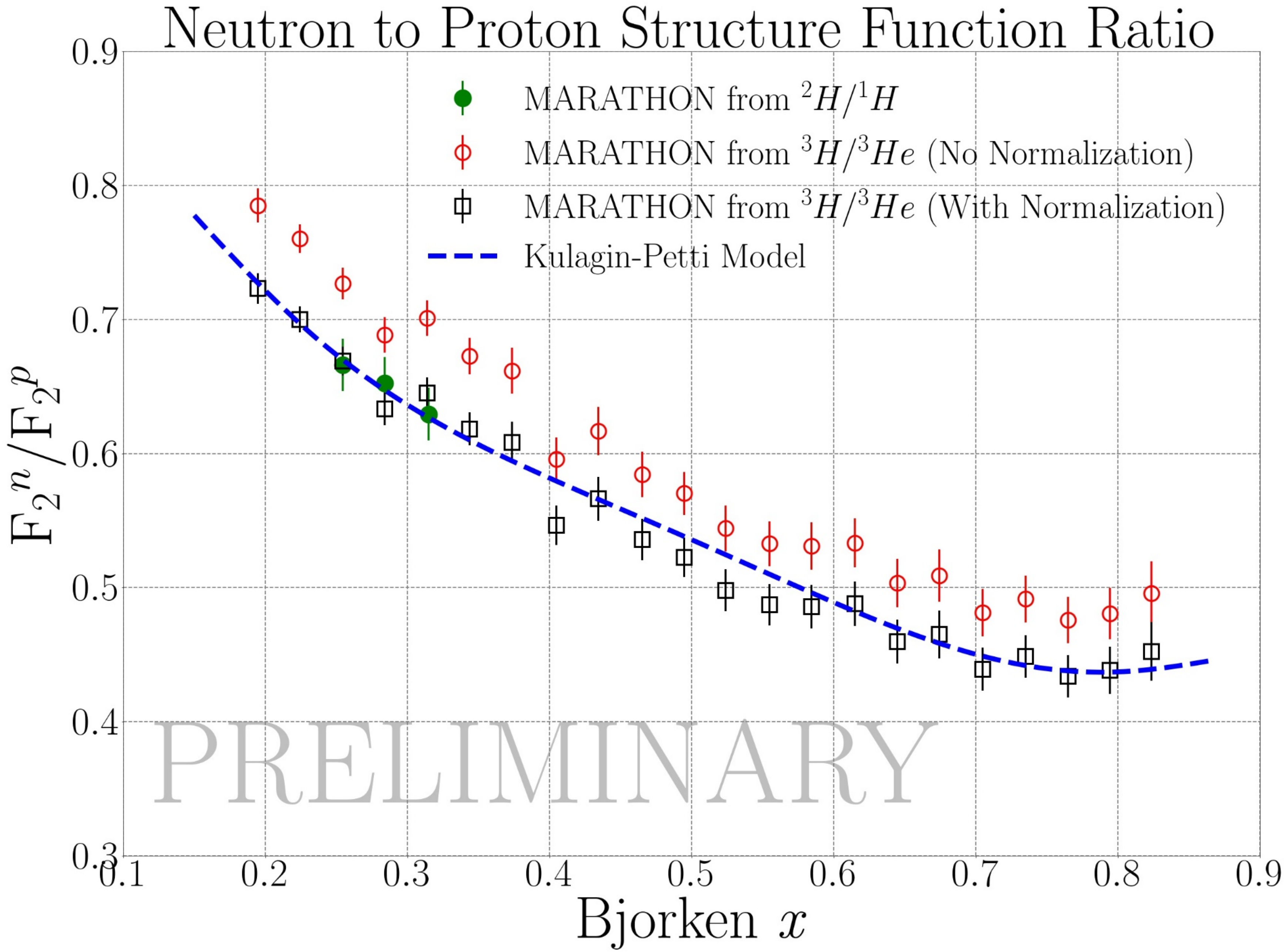
MARATHON $^3H/^3He$ DIS Data

- The super-ratio R^* model for ^{3}H and ^{3}He that was used (among several available models) was developed, for the actual MARATHON kinematics, by Kulagin and Petti in the summer of 2018, using 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 ^{3}H/^{3}He 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 ^{3}H/^{3}He ratio must be scaled down (normalized) by 2.8%.
- Note that the MARATHON measured values and the Kulagin-Petti F_2^n/F_2^p predicted values are in excellent agreement!

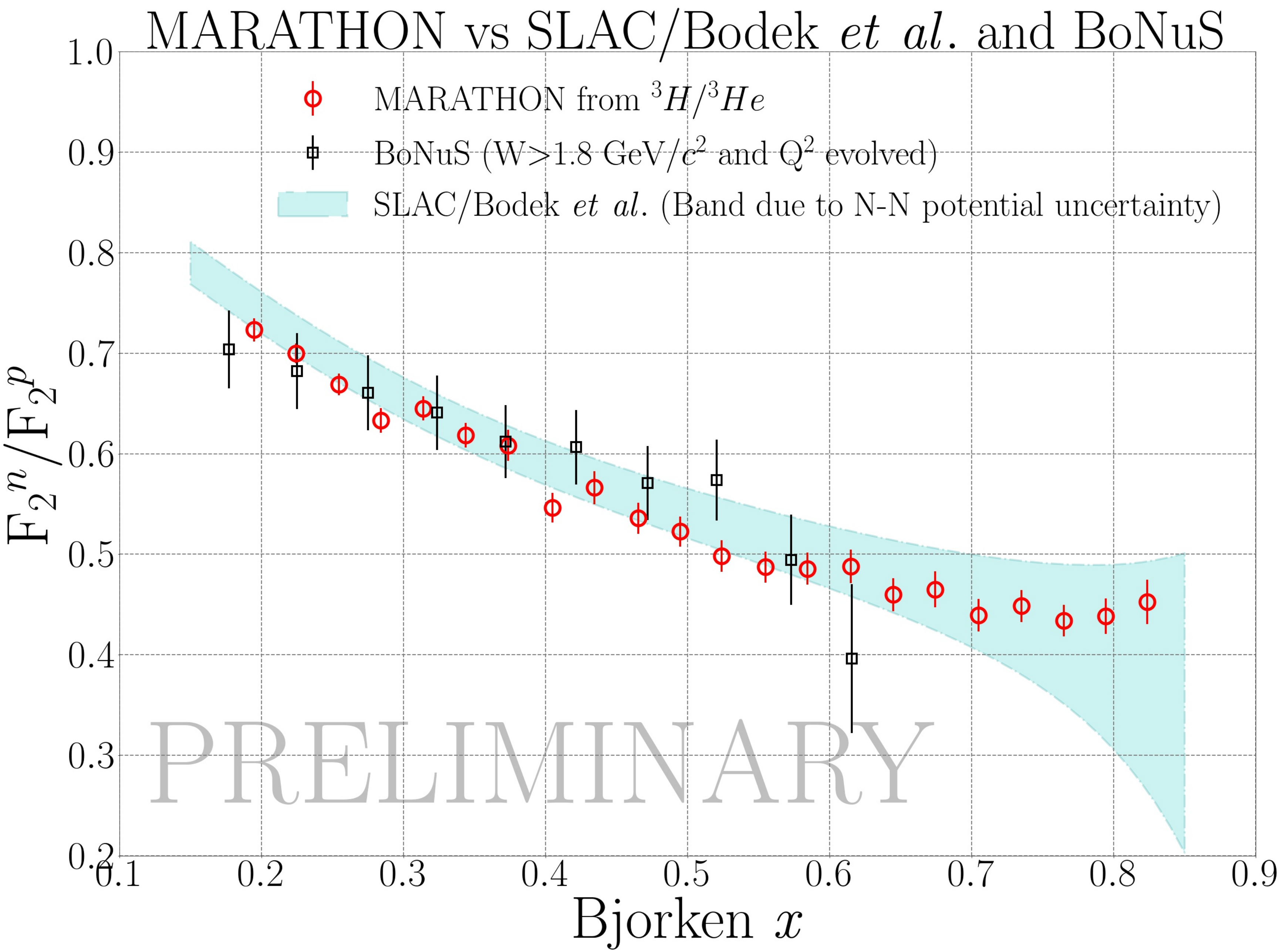

The R(3He) and R(3H) Ratios
Red : R(3He) = $F_2^{3He}/(2F_2^p+F_2^n)$
Green : R(3H) = $F_2^{3H}/(F_2^n+2F_2^p)$
Blue : R* = R(3He)/R(3H)
3H
3He
S. Kulagin and R. Petti : With HT and TM effects (2008)
A=3 Spectral Functions by Rome Group (G. Sialmè et al.)
1.10
1.05
1.00
0.95
0.90
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Bjorken x



Tritium to Helium DIS Cross Section Ratio
JLab MARATHON (No Normalization)
JLab MARATHON Normalized by 2.8%(↓)
Kulagin-Petti Model Using Rome A=3 Spectral Functions
^{3}H/^{3}He
Bjorken x
PRELIMINARY
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



Neutron to Proton Structure Function Ratio
MARATHON from $^2H/^1H$
MARATHON from $^3H/^3He$ (No Normalization)
MARATHON from $^3H/^3He$ (With Normalization)
Kulagin-Petti Model
PRELIMINARY
F_2^n/F_2^p
Bjorken x
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



MARATHON vs SLAC/Bodek et al. and BoNuS
MARATHON from $^3H/^3He$
BoNuS (W>1.8 GeV/c^2 and Q^2 evolved)
SLAC/Bodek et al. (Band due to N-N potential uncertainty)
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
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

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 from d/p DIS.
- There is no need to iterate the F_2^n/F_2^p extraction process, as the Kulagin and Petti input model agrees very well with the data!
- Next to be done is the extraction of LT (Leading Twist) F_2^n/F_2^p in order to determine the d/u ratio… Stay tuned …!
- Note: MARATHON has provided for the 1st time data for the EMC effect of ^{3}H, and new large-x and large-W^2 data for the EMC effect of ^{3}He. The isoscalarity correction factor uses the MARATHON F_2^n/F_2^p (following talks by M.Nycz and T.Hague).

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

Thanks

- Thanks to all fellow 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.

Thanks !