Preliminary Results of Jefferson Lab MARATHON Experiment*

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

J. Gomez

For the Jefferson Lab Hall A Tritium Collaboration

Strong QCD

from Hadron Structure Experiments Workshop

Jefferson Lab, Nov. 9, 2019

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JLab MARATHON Tritium Collaboration

Thesis students:

MARATHON: J. Bane, T. Hague, T. Kutz, H. Liu, M. Nycz, T. Su

T-group: S. Ansalmi, S. Barcus, J. Castellanos, R. Cruz-Torres, S. Li, D. Nguyen, B. Pandey, N. Santiesteban

Postdoctoral Associates:

M. Carmignotto, F. Hauenstein, E. McClellan, Z.H. Ye.

Collaboration:

140+ members

Long time coming … a workshop on experiments with Tritium at JLab took place Sept. 1999

Many thanks to all the above students and postdocs
this talk is only possible because of their hard work

Deep Inelastic Scattering and Quark Parton Model

Cross Section – Nucleon structure functions F_1 and F_2:

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

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

$$\nu = E - E'$$

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

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

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

Bjorken *x*: fraction of nucleon momentum carried by struck quark: $x = Q^2 / 2M\nu$

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

Assume isospin symmetry:

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

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

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

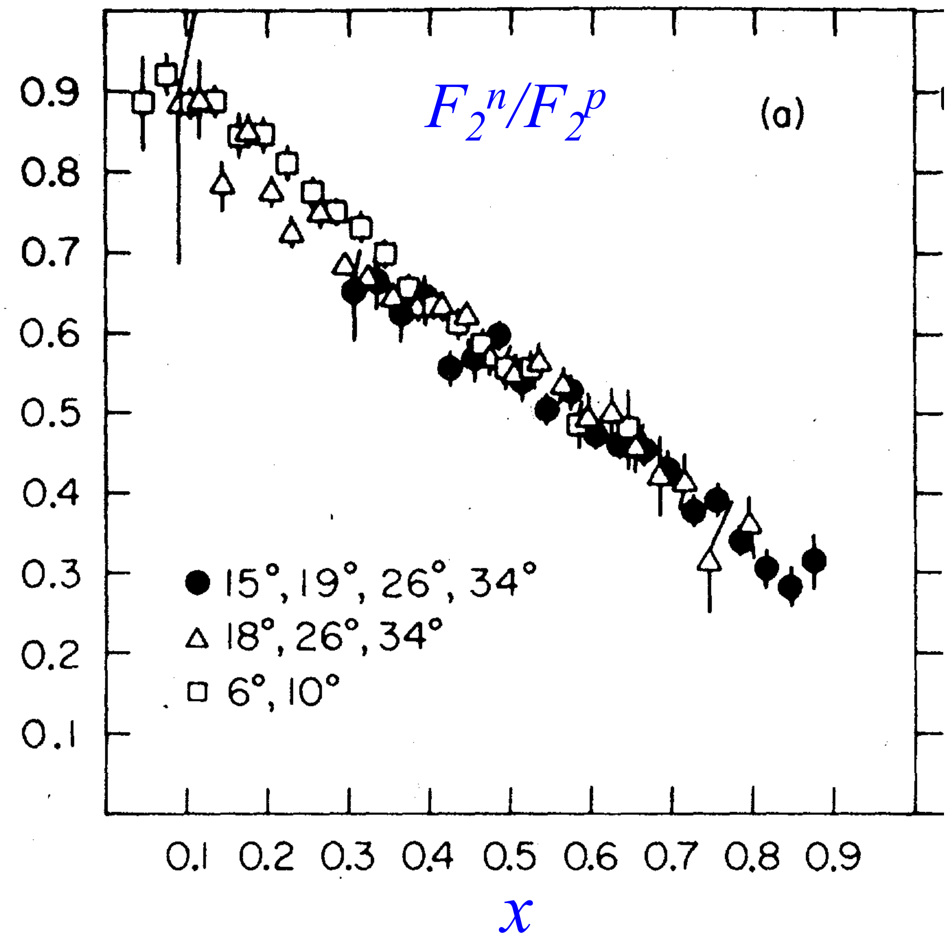
Proton and neutron structure functions:

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

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

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

F_2^n/F_2^p from 70's SLAC data



A. Bodek, et al., Phys Rev D**20**, 1471 (1979)

A nuclear correction model is needed to extract the "free" neutron xsec out of deuterium – most used,

- Atwood & West, PRD 7, 773 (1973)
- Bodek, PRD 8, 2331 (1973)
- Frankfurt & Strikman, PLB 76, 333 (1978)
- Frankfurt & Strikman, Phys. Rep. 76, 215 (1981)

Similar results: *~constant 1-2% in the range $x \leq 0.6$, changing fast for larger x ("Fermi Smearing")*

Results,
≠ *SU(6)* prediction of 2/3
≈ diquark model

SLAC/CERN Data Interpretation in QPM

Nachtmann inequality satisfied: $1/4 \leq F_2^n / F_2^p \leq 4$

For $x \to 0$: $F_2^n/F_2^p \to 1$: Sea quarks dominate and,

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

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

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

For medium and high x,

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

d,u = quark +anti-quark dist.

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

	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
DiquarkModel/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)

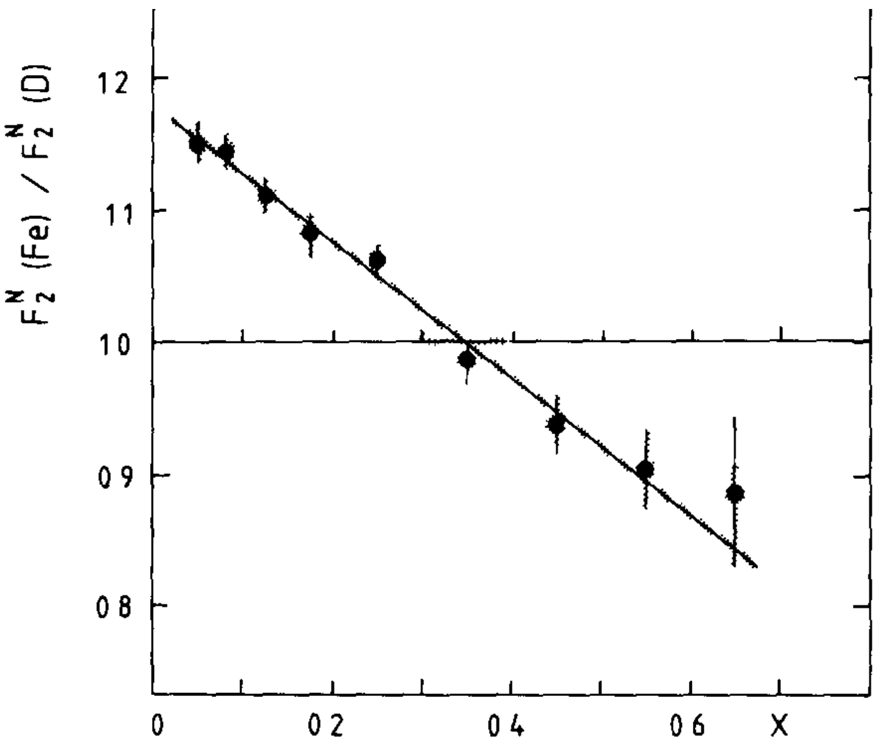
The 80's and Nuclear Effects in DIS

Expected $A\mathscr{F}_2^{\{A,Z\}} \sim ZF_2^p + (A-Z)F_2^n$

or $\mathscr{F}_2^{\{A,Z\}} \rightarrow$ isoscalar xfrm $\rightarrow \mathscr{F}_2^{\{A,A/2\}} \simeq \mathscr{F}_2^{\{2,1\}}$

Measured *the EMC effect*

J. Aubert et al., Phys. Lett. **B**123, 275 (1983)



- Many nuclei measured since then.
- Q^2 independent effect.
- Effects grows from light to heavy nuclei.
- Enhancement seen by EMC for x < 0.3 not reproduced by other experiments.
- Many proposed explanations – some shown unlikely but many more remain.
- Naïve parameterizations of the effect used so far – e.g. A, ρ(A) ("average" nuclear density), nucleon overlap, …
- BUT - in all cases, extrapolating to a (proton + "free" neutron) gives an EMC ratio ≠ 1

➔➔ *not all nuclear effects are accounted for by usual methods of extracting the "free" neutron struct. funct.*

[Frankfurt & Strikman, Phys. Rep. 160, 235 (1988)]

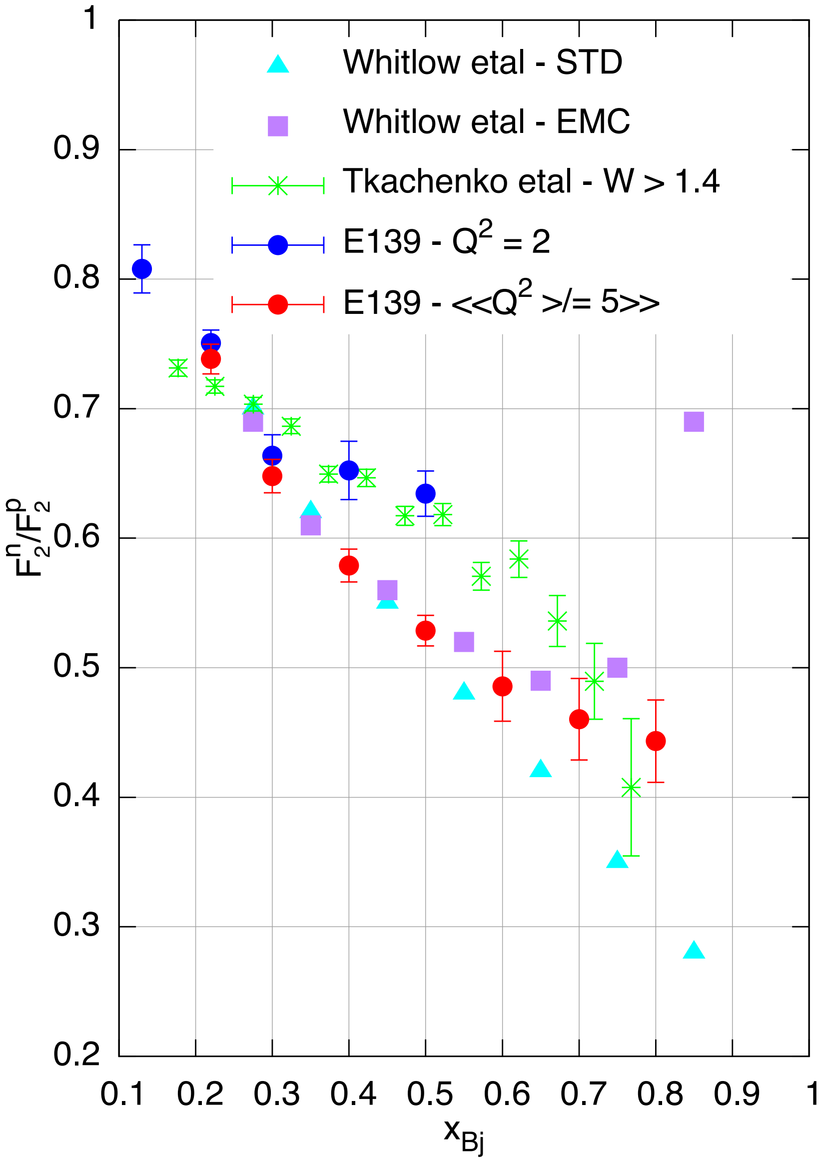
Quest for the "missing" nuclear effects - the 90's to now

- Can we calculate the "missing" nuclear effects? – not in the 90's although recent works seem to be closer to such feat.

- Can we account "phenomenologically" for those effects? – worth a try, e.g. Frankfurt & Strikman, Phys. Rep. 160, 235 (1988).

- Can we go around this problem by using other techniques with different assumptions? – yes, probably the best known proposals at JLab are,
  - BoNuS (Barely off-shell Nucleon Structure) – extracts F_2^n by tagging spectator protons in semi-inclusive electron scattering from the deuteron. See, for example, N. Baillie et. al., PRL **108,** 142001 (2012) for theory refs. concerning this technique and results from a 2005 run in Hall B. A similar experiment, with higher incident beam energy, is scheduled in CLAS12 for next year.
  - Tritium-^{3}He comparison ←← *discussed later*
  - Parity violation in DIS off hydrogen – measure the proton *d/u* quark momentum distributions without nuclear corrections. *See JLab proposal PR12-10-007*

F_2^n/F_2^p – an spaghetti of results



- Whitlow et. al., Phys. Lett. B **282**, 475 (1991)
  - STD = deuterium corrections as in Frankfurt & Strikman, Phys. Rep. 76, 215 (1981)
  - EMC = "Missing" deuterium corrections as in Frankfurt & Strikman, Phys. Rep. 160, 235 (1988)
- Tkachenko et. al., Phys. Rev. C **89**, 045206 (2014)
- SLAC E139
  - Uses xsec for A=2-197, $2 \leq Q^2 \leq 15$
  - Assume n & p affected equally by nuclear effects
  - Parametrize xsections in terms of a nuclear effect variable – e.g. "nuclear density", "nucleon overlap" …
  - Use Whitlow etal global parametrization of proton structure function.
  - At each x, Q^2, a fit to all available xsections yields intercept ("free" F_2^n/F_2^p) and slope

F_2^n/F_2^p from ^3H and ^3He comparison

- Nuclear physics commonly refers to 3H and 3He as "mirror" nuclei – i.e. their wavefunctions are similar

- Are they similar enough that nuclear effects could be made to cancel leaving us with a "free" neutron & proton?

- Let,

$$Q(^3H) = \frac{F_2^{\{3,1\}}}{F_2^p + 2F_2^n}; \quad Q(^3He) = \frac{F_2^{\{3,2\}}}{2F_2^p + F_2^n}; \quad Q_r = \frac{Q(^3He)}{Q(^3H)}$$

  where

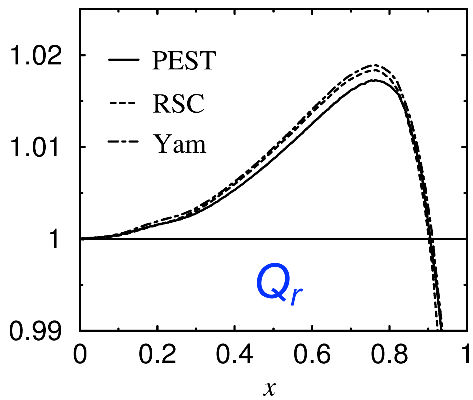
  $F_2^{\{3,1\}}$ & $F_2^{\{3,2\}}$ = exp. measured struct. funct. for ^{3}H and ^{3}He respectively

  F_2^p & F_2^n = free proton and neutron struct. funct.

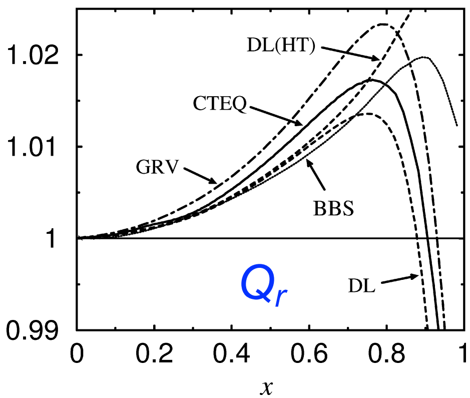
  Q_r is then a measure of how different are nuclear effects between the two nuclei

- Some theoretical work on understanding Q_r
  - Afnan et al. Phys. Lett. B **493**, 36 (2000)
  - Pace et al. Phys. Rev. C **64**, 055203 (2001)
  - Sargasian et al. Phys Rev C **66**, 024001 (2002)
  - Afnan et al. Phys. Rev. C **68**, 035201 (2003)

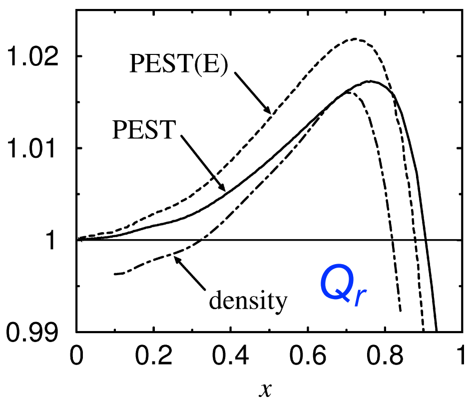
F_2^n/F_2^p from ^3H and ^3He comparison (II)



Sensitivity to potential chosen (F_2^N from CTEQ@10 GeV)
PEST = separable approx. to Paris potential.
RSC = Reid Soft Core
Yam = Yamaguchi (with 7% $^3S_1$ & $^3D_1$ waves)



Sensitivity to chosen nucleon structure function parametrization (PEST wavefunction)
GRV = Gluck, Reya, Vogt
BBS = Brodsky, Burkardt, Schmidt
DL = Donnachie, Landshoff (HT = with higher twist)



Other sensitivity tests (F_2^N from CTEQ@10 GeV)
PEST(E) = binding energy modifications
density = expectation using nuclear density parametrization of EMC effect for A=3.

➔➔ Q_r is close to unity with a spread of up to 1% for $x \leq \sim 0.85$

F_2^n/F_2^p from ^3H and ^3He comparison (III)

- Inverting expressions,

$$\frac{F_2^n}{F_2^p} = \frac{2Q_r - \left[F_2^{\{3,2\}}/F_2^{\{3,1\}}\right]}{2\left[F_2^{\{3,2\}}/F_2^{\{3,1\}}\right] - Q_r}$$

$F_2^{\{A,Z\}}$ comes from experiment

Q_r comes from theory

- DIS structure functions and cross sections related by,

$$\frac{F_2^{\{3,2\}}}{F_2^{\{3,1\}}} = \frac{\sigma^{\{3,2\}}}{\sigma^{\{3,1\}}} \frac{\left(1+\epsilon R^{\{3,1\}}\right)}{\left(1+\epsilon R^{\{3,2\}}\right)} \frac{\left(1+R^{\{3,2\}}\right)}{\left(1+R^{\{3,1\}}\right)}$$

with $\epsilon = \left[1 + 2(1+\nu^2/Q^2)\tan^2(\theta/2)\right]^{-1}$

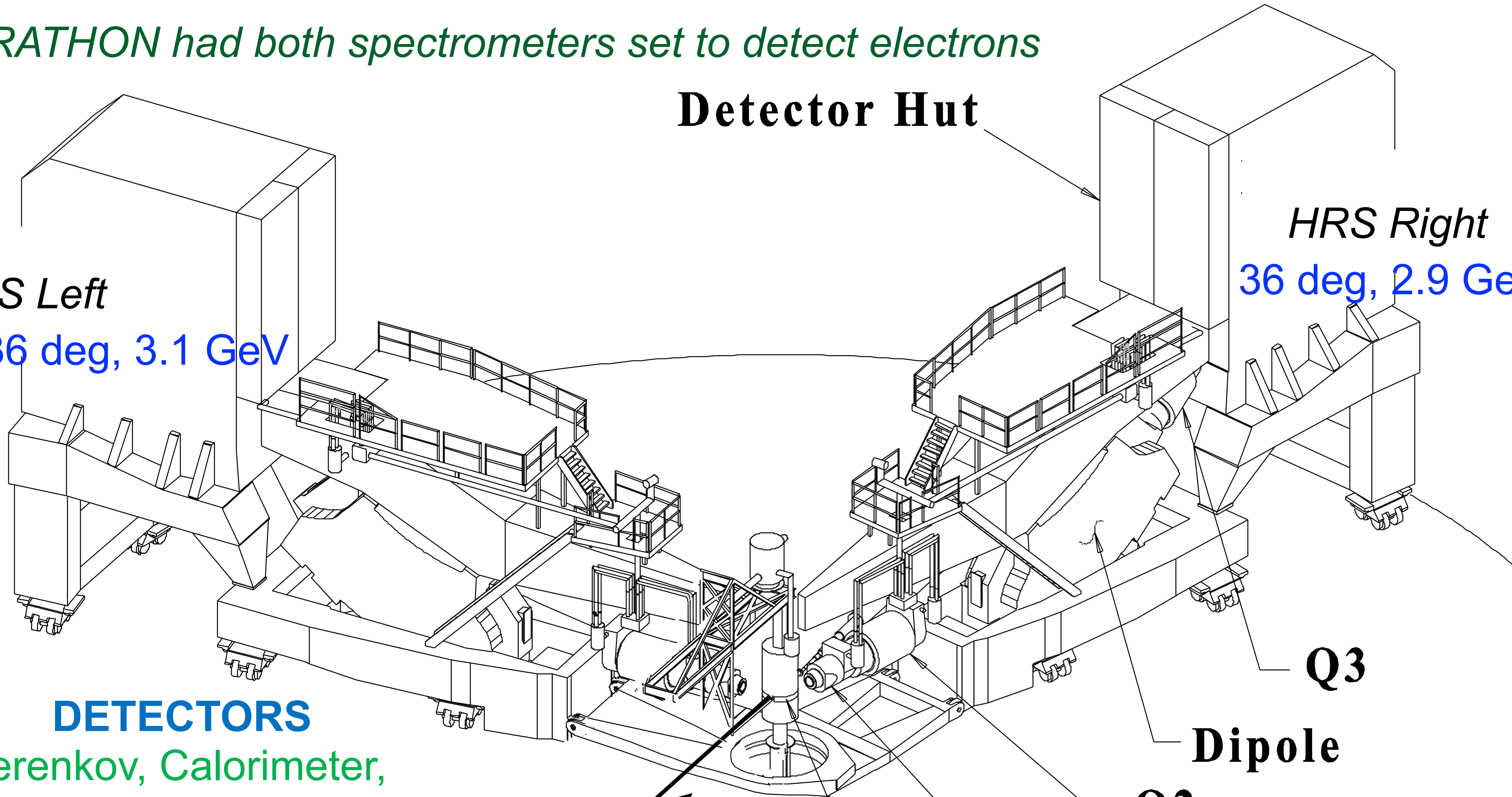
- *R* appears to be A independent - Tao et al, Z. Phys. C **70**, 387 (1996)

$$F_2^{\{3,2\}}/F_2^{\{3,1\}} = \sigma^{\{3,2\}}/\sigma^{\{3,1\}}$$

➔➔ $$\frac{F_2^n}{F_2^p} = \frac{2Q_r - \left[\sigma^{\{3,2\}}/\sigma^{\{3,1\}}\right]}{2\left[\sigma^{\{3,2\}}/\sigma^{\{3,1\}}\right] - Q_r}$$

JLab Hall A High Resolution Spectrometers (HRS)

MARATHON had both spectrometers set to detect electrons



HRS Left

17-36 deg, 3.1 GeV

HRS Right

36 deg, 2.9 GeV

DETECTORS

Cherenkov, Calorimeter,
2 Scintillator planes, and
Drift Chamber set

DETECTORS

Cherenkov, Calorimeter,
2 Scintillator planes, and
Drift Chamber set

Kin. coverture

$0.19 \leq x \leq 0.83$

$3 \leq Q^2\ (GeV/c)^2 \leq 12$

$1.8 \leq W\ (GeV/c)^2 \leq 3.5$

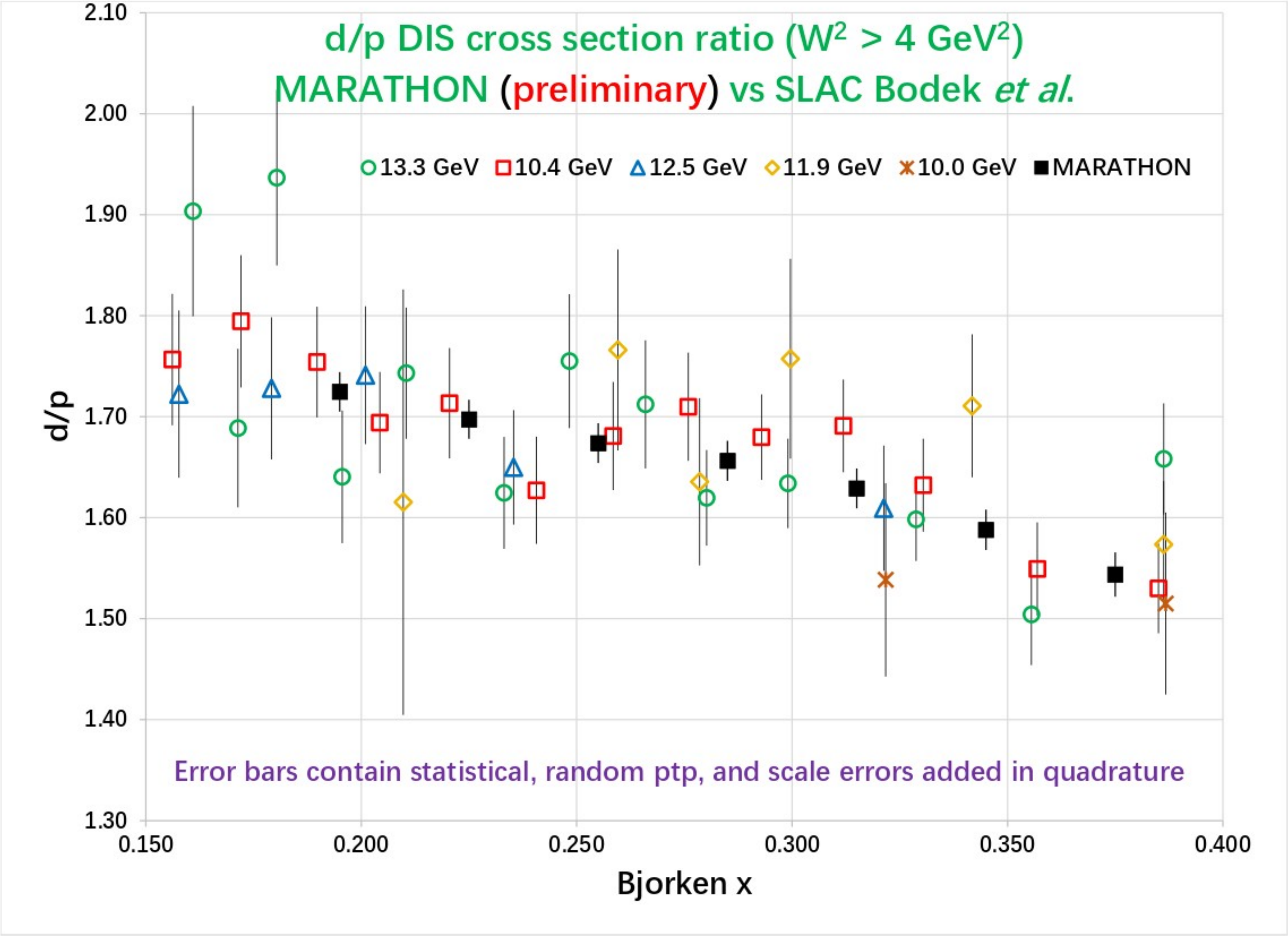
The target system

- Closed, high pressure gas cells.
- Single block Aluminum 7075 (no seams), 250 mm long, 12.7 mm inside diam. with 0.457, 0.254 & 0.279 mm thick side, entrance and exit walls.
- Cells of ^{3}H, ^{1}H, ^{2}H & ^{3}He at 200, 500, 500,& 500 psia and 40K – densities 0.00363 (^{3}H), 0.00425 (^{3}He) and 0.00568 (^{2}H) g/cm^3
- Beam current limited to ~20 uA with a minimum beam raster of 2X2 mm2

-----Tritium target -----

- Filled at the Tritium Handling Facility At Savanah River (1,100 Curies) – **on loan to JLab**
- (special) FedEx transport to/from JLab. Held in a different vessel until time to put it into target chamber.
- Number of reviews and requirements were **mind-numbing** – None of the ^{3}H exp. would have been possible without the effort of Dave Meekins (proj. manager) and Roy Holt.

Consistency check – measured $^2H/^1H$ vs existing data



What's next ....

- Check for potential systematic errors in normalization (e.g. target thickness) by *requiring that $^2H/^1H$, $^3H/^2H$ and $^3He/^2H$ yield the same value of F_2^n/F_2^p at $x = 0.3$, where we have ^1H data and nuclear corrections appear to be small*

➔ we need the equivalent of the theoretical super-ratio Q_r of $^3H/^3He$ mentioned earlier but now for the above ratios in the region around x = 0.3.

- We relay on the work by Kulagin and Petti and the Rome group (Pace, Salme) for those theoretical super-ratios. See, for example,

  Pace *et al*., Phys. Rev. C **64**, 055203 (2001)

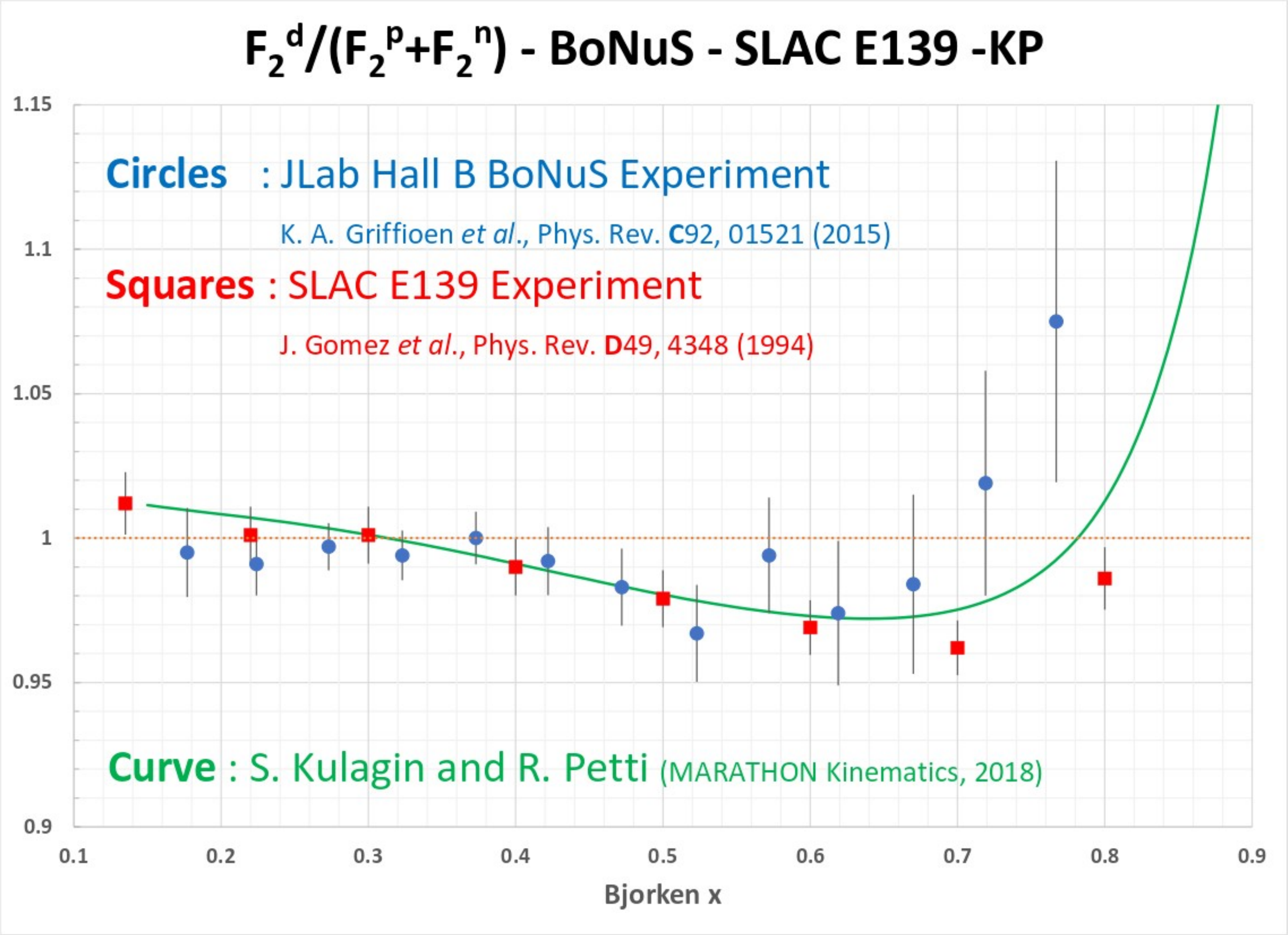
  Kulagin and Petti, Phys. Rev. C **82**, 054614 (2010)

  ➔ Example, for $^2H/^1H$,

  $$F_2^n/F_2^p = (F_2^d/F_2^p)_{exp} / Q_r - 1;$$

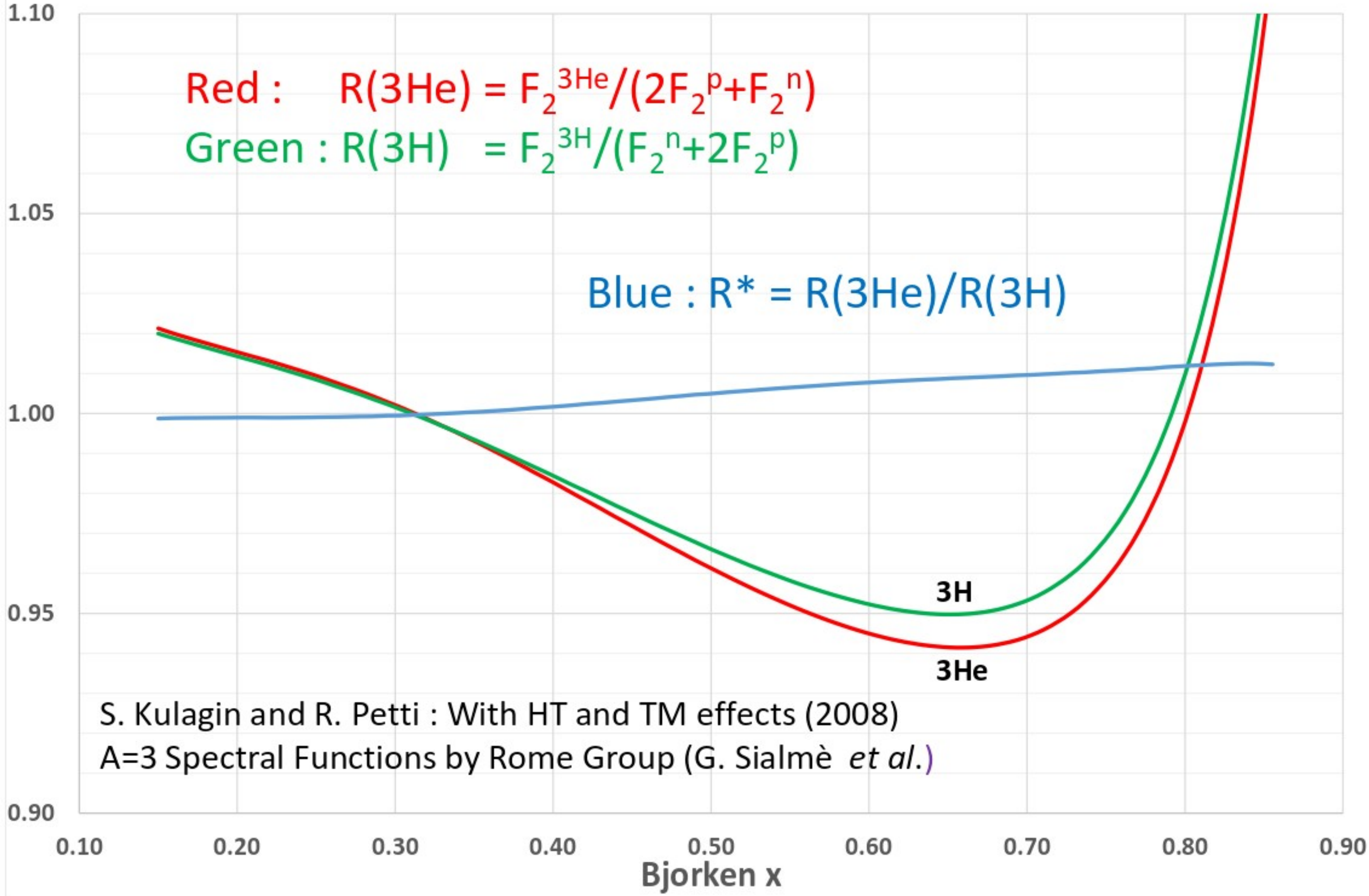
  with Q_r = green curve (next slide) in the x ~ 0.3 neighborhood

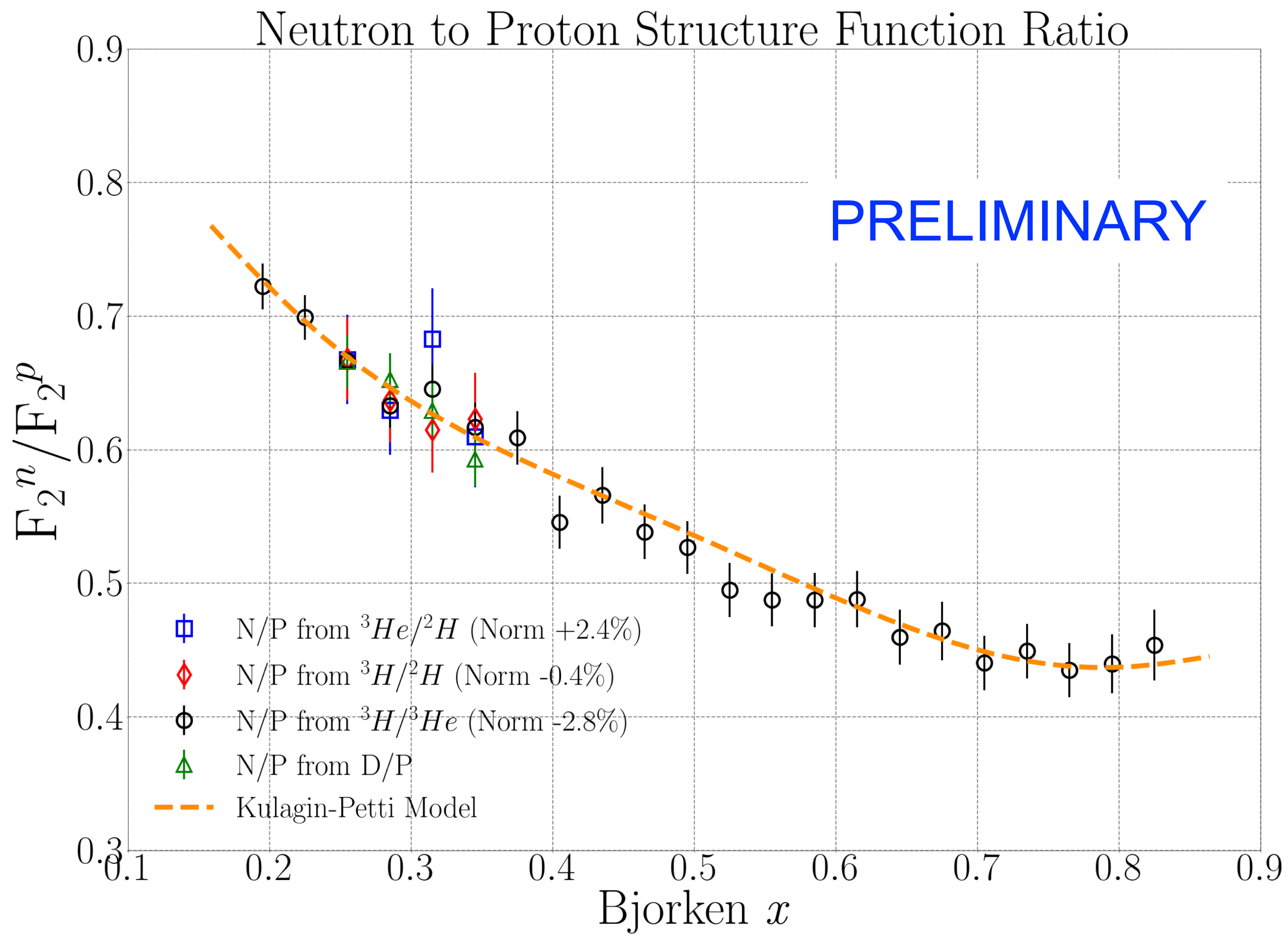
- Find, that at $x = 0.3$, F_2^n/F_2^p *from*
  - $^2H/^1H$ is consistent with world data
  - $^3H/^2H$ needs to be scaled by -0.4%
  - $^3He/^2H$ needs to be scaled by +2.4%
  - ➔➔ $^3H/^3He$ needs to be scaled by -2.8%



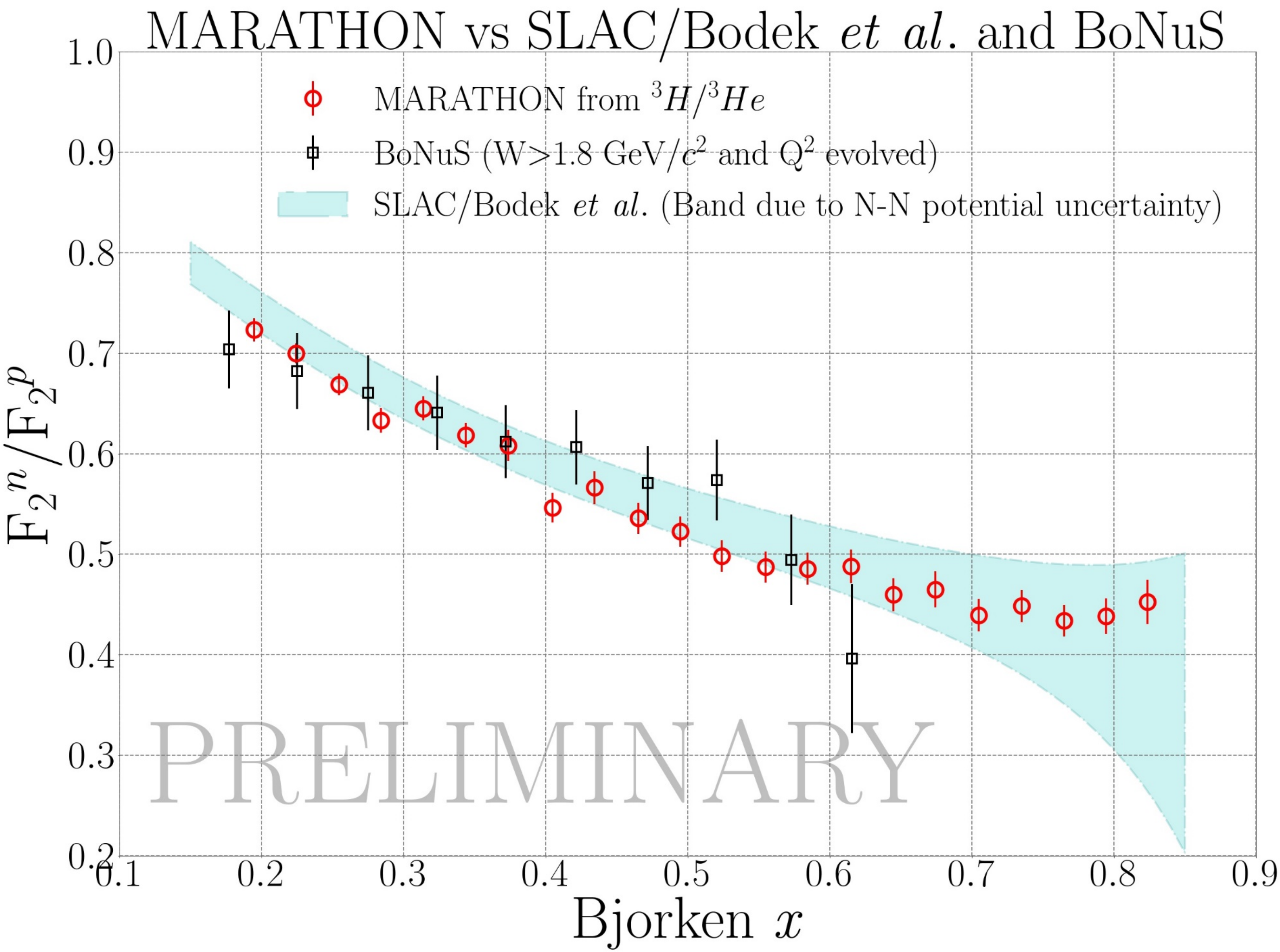
F2d/(F2p+F2n) - BoNuS - SLAC E139 -KP
Circles : JLab Hall B BoNuS Experiment
K. A. Griffioen et al., Phys. Rev. C92, 01521 (2015)
Squares : SLAC E139 Experiment
J. Gomez et al., Phys. Rev. D49, 4348 (1994)
Curve : S. Kulagin and R. Petti (MARATHON Kinematics, 2018)
1.15
1.1
1.05
1
0.95
0.9
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Bjorken x

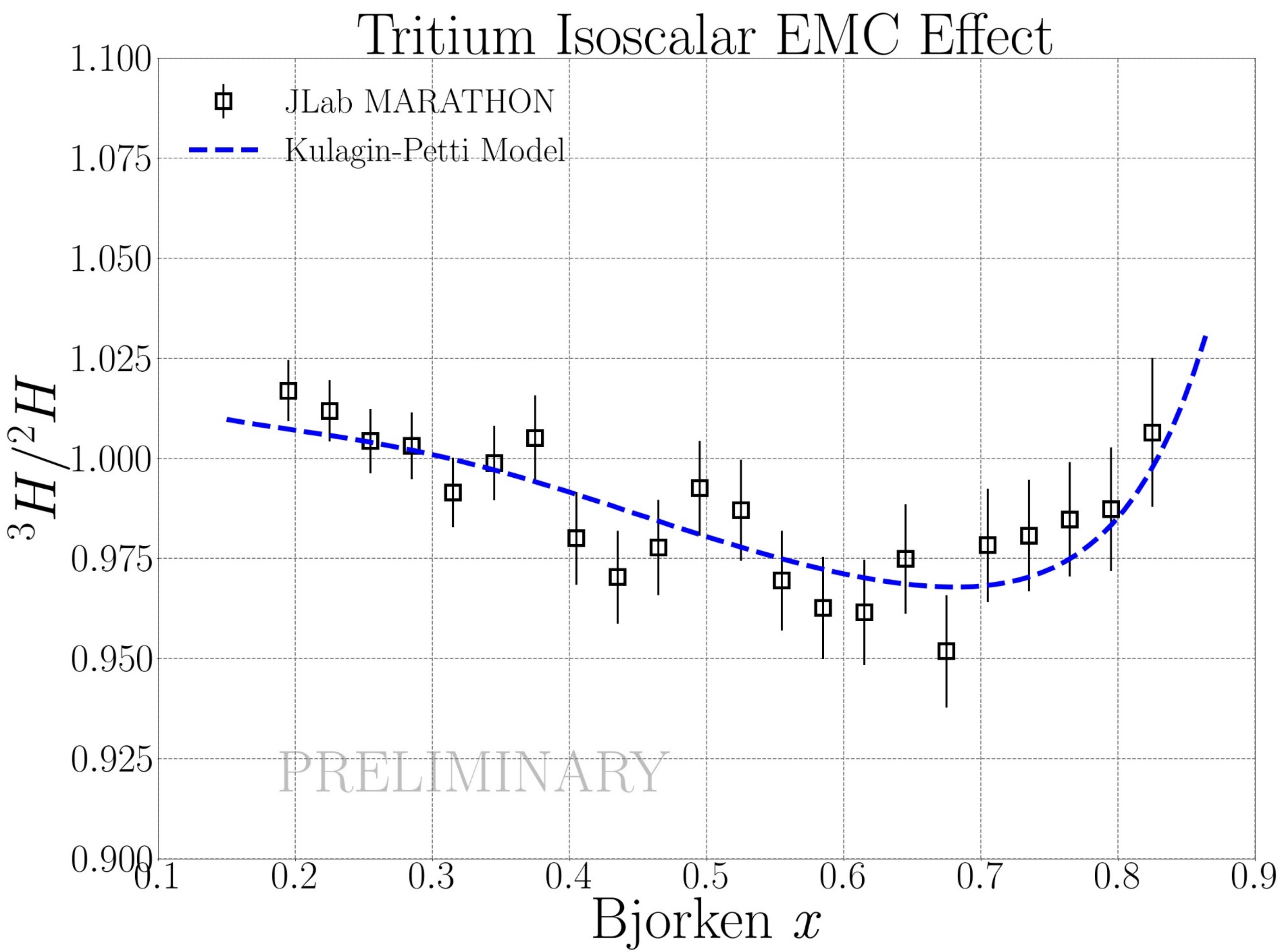
The R(3He) and R(3H) Ratios



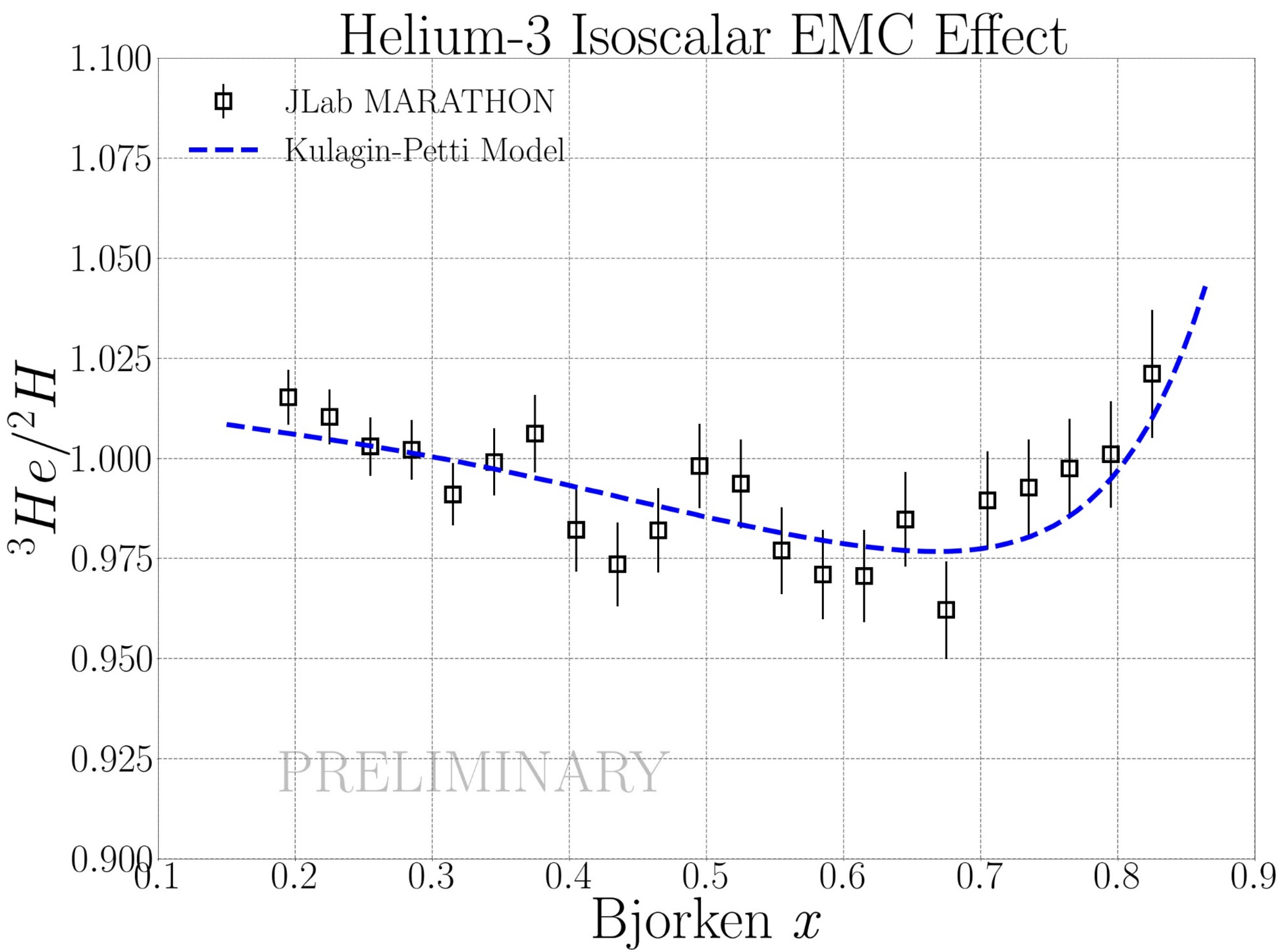


Neutron to Proton Structure Function Ratio
PRELIMINARY
F_2^n/F_2^p
Bjorken x
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
N/P from $^3He/^2H$ (Norm +2.4%)
N/P from $^3H/^2H$ (Norm -0.4%)
N/P from $^3H/^3He$ (Norm -2.8%)
N/P from D/P
Kulagin-Petti Model


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
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
PRELIMINARY

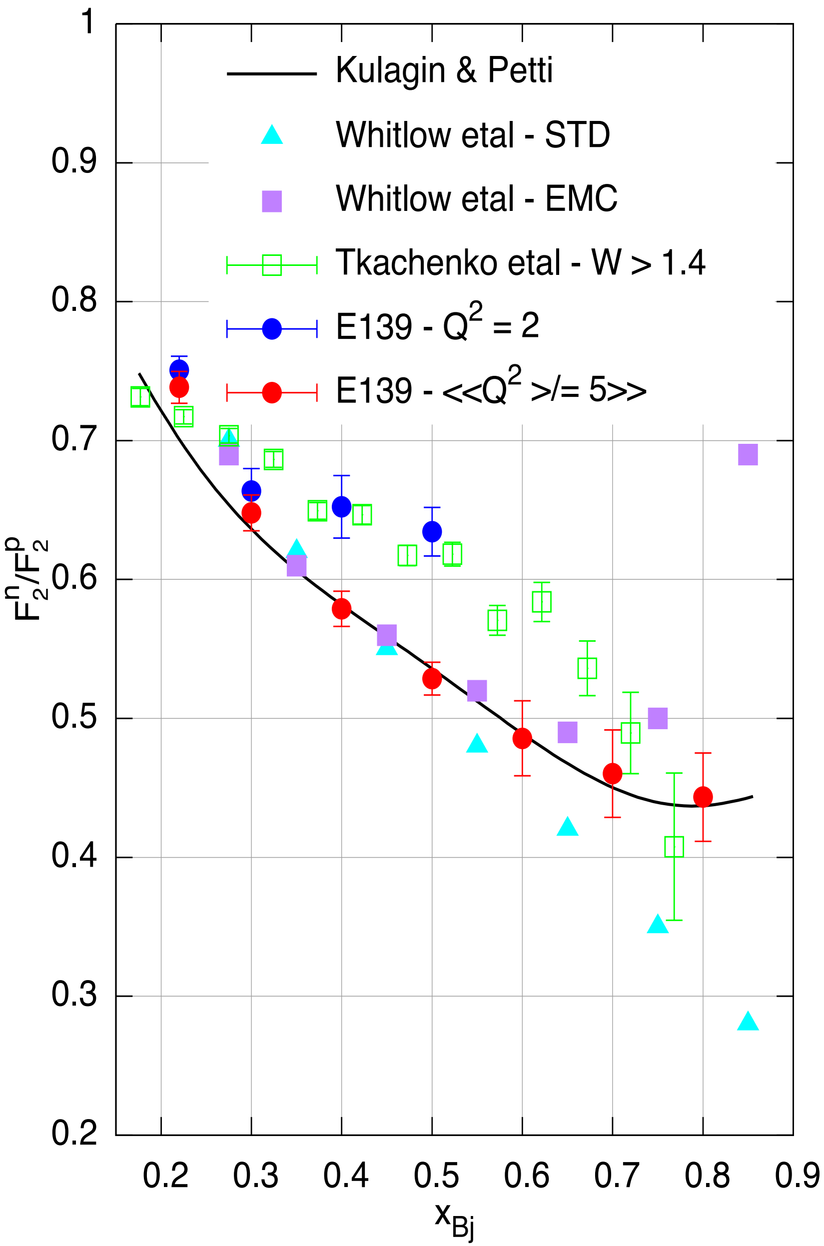


Tritium Isoscalar EMC Effect
JLab MARATHON
Kulagin-Petti Model
PRELIMINARY
$^3H/^2H$
Bjorken x
1.100
1.075
1.050
1.025
1.000
0.975
0.950
0.925
0.900
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



Helium-3 Isoscalar EMC Effect
JLab MARATHON
Kulagin-Petti Model
PRELIMINARY
$^3He/^2H$
Bjorken x
1.100
1.075
1.050
1.025
1.000
0.975
0.950
0.925
0.900
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

More n/p comparisons …. & a bit of a summary



- Yes, looks like there are unaccounted nuclear effects in the early extractions of the “free” *n/p* ratio
- Tempting to say that *n/p* extrapolates to neighborhood of 3/7 BUT …… too many things can happen between *x* = 0.8-1
- Looking forward to the upcoming BoNus results

THANKS for your time