



Experimental Results at Large x from JLab

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Nucleon Structure at High Bjorken x

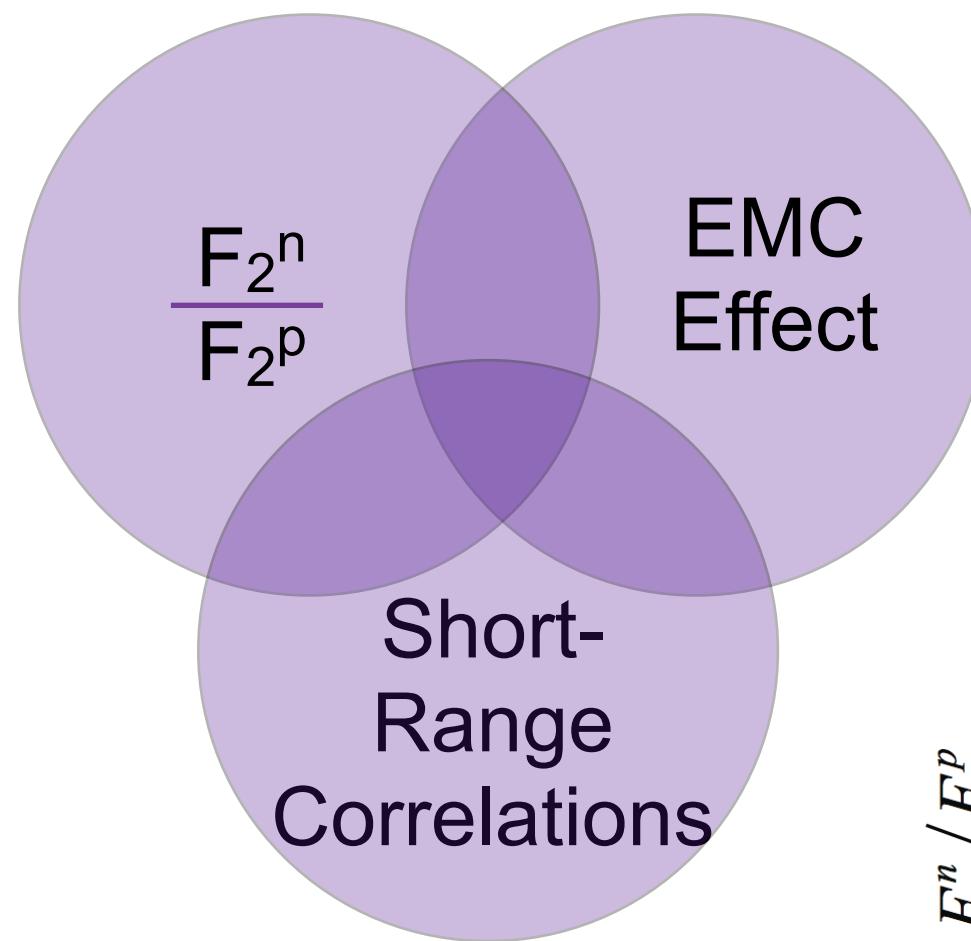
Laboratori Nazionali di Frascati

Frascati, Italy

17-21 November 2014

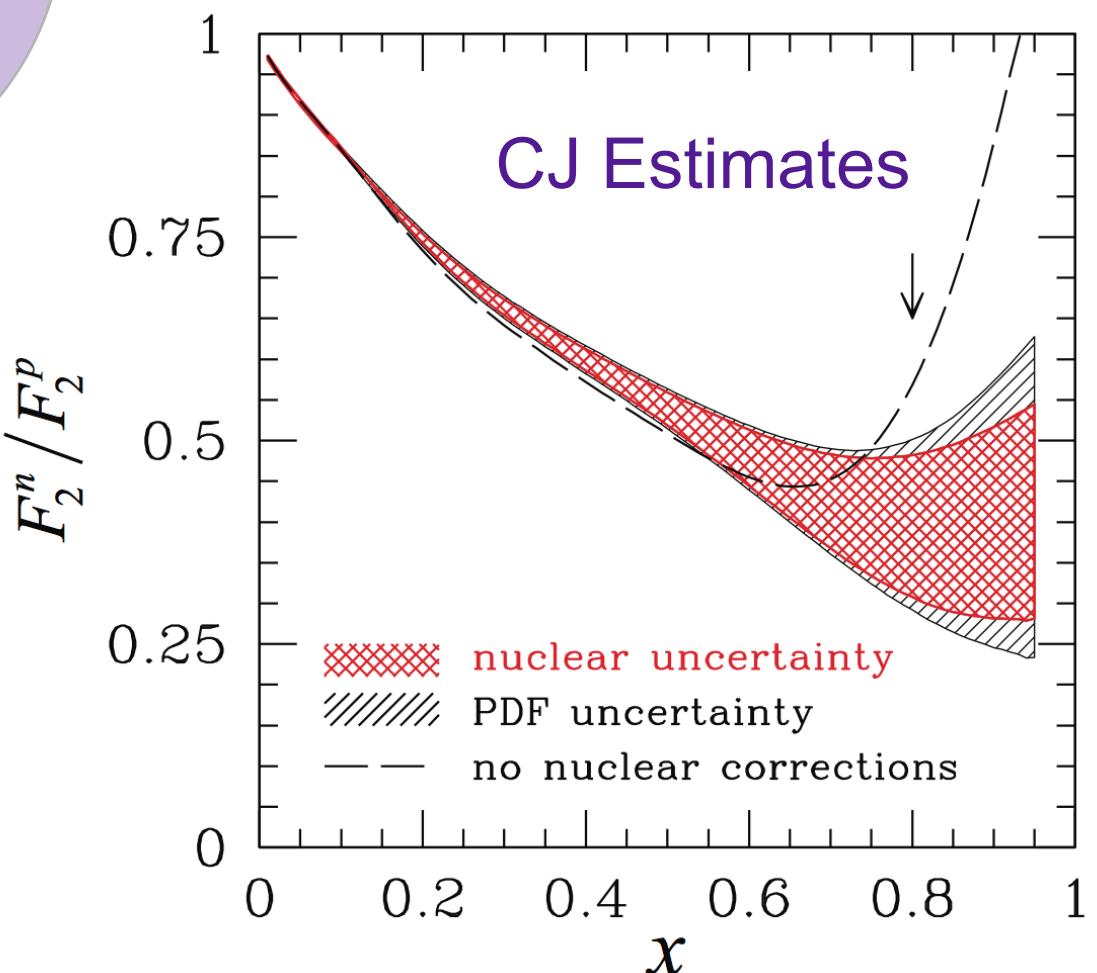


Uncertainty at High x



Understanding the neutron
requires understanding the
nucleus

F_2^n is poorly
known at high x
because neutrons can
only be studied within nuclei



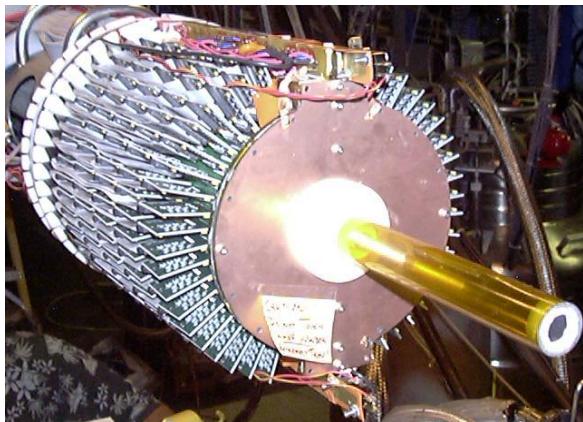


- Bound Nucleon Structure Experiment
- $d(e,e'p_s)X$ [(deep) inelastic]
- Deuterium target, spectator proton
- $70 < p_s < 150$ MeV/c
- JLab Hall B CLAS with an RTPC
- Measure F_2^n at high x

Fenker, NIM A **592** (2008) 273– 286

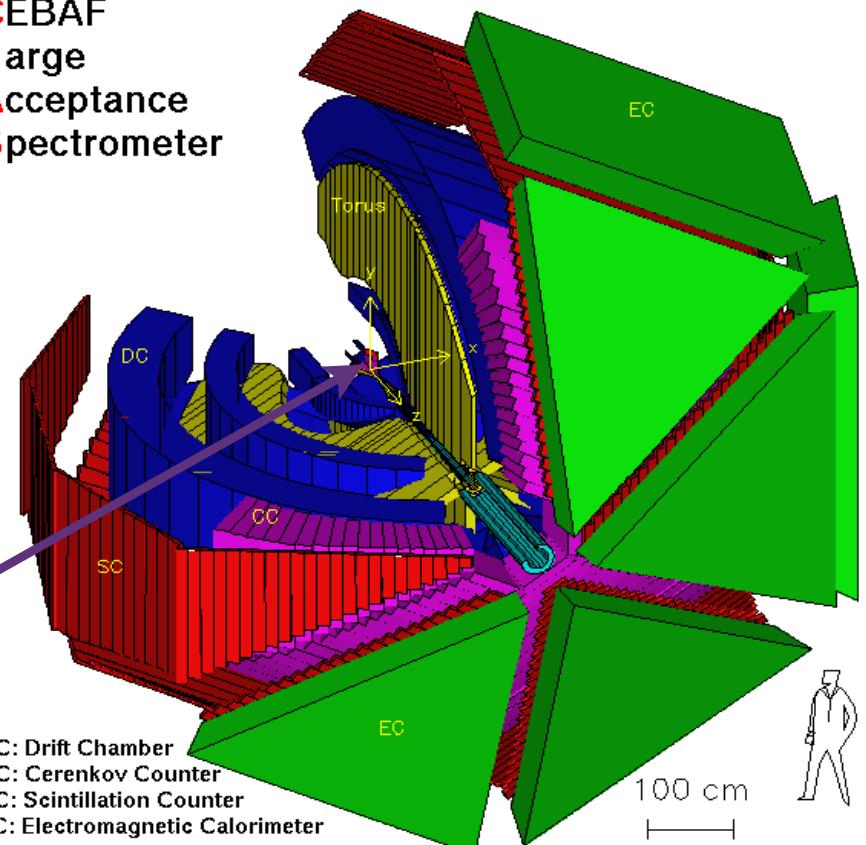
Baillie, PRL **108**, 142001 (2012)

Tkachenko Phys. Rev. C **89**, 045206 (2014)

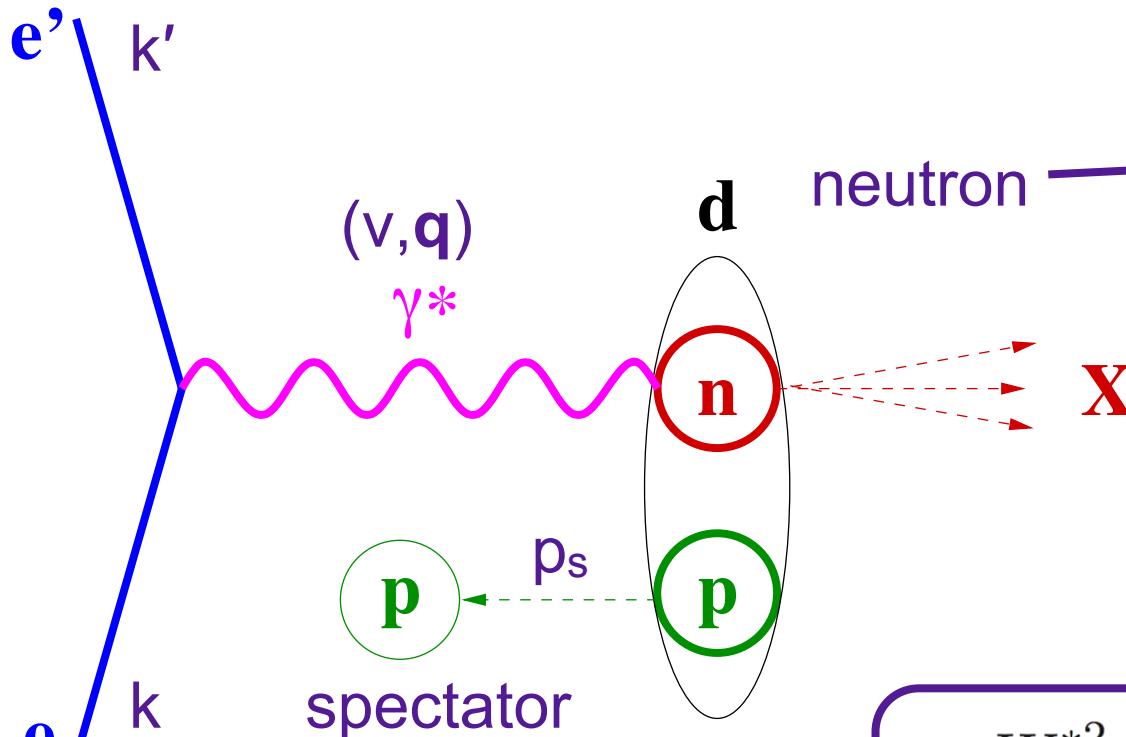


N.Baillie, S. Tkachenko,
W. Melnitchouk, K. Griffioen,
S. Kuhn, C. Keppel, M.E. Christy,
H. Fenker, J. Zhang, S. Bültmann

CEBAF
Large
Acceptance
Spectrometer



DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter



before

$$p_n = (M_d - E_s, -\vec{p}_s)$$

$$M_d = E_n + E_s$$

$$E_n = M_d - \sqrt{M_s^2 + p_s^2}$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^2$$

after

$$W^{*2} \approx M^{*2} - Q^2 + 2M_s\nu(2 - \alpha_s)$$

$$\alpha_s = \frac{E_s - p_{s\parallel}}{M_s}$$

$$x^* = \frac{Q^2}{2p_n \cdot q} \approx \frac{Q^2}{2M_s\nu(2 - \alpha_s)} = \frac{x}{2 - \alpha_s}$$

- Plane-wave impulse approximation
- Backward-emitted p is a spectator
- Struck neutron is off-shell
- \mathbf{p}_s and \mathbf{p}_n are equal and opposite
- Lorentz invariants are corrected for initial neutron 4-momentum



$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{\text{EM}}^2}{x^* Q^4} \left[\frac{y^{-2}}{2(1+R)} + (1-y) \right. \\ \left. + \frac{M^{*2} x^{*2} y^{-2}}{Q^2} \frac{1-R}{1+R} \right] F_2(x^*, \alpha_s, p_T, Q^2) \\ \times S(\alpha_s, p_T) \frac{d\alpha_s}{\alpha_s} d^2 p_T,$$

Cross Section

Off-Shell F_2

$R = \sigma_L / \sigma_T$

Light Cone

Spectral Function

Nonrelativistic w.f.

$$P(\vec{p}_s) = J |\psi_{\text{NR}}(p_s)|^2$$

$$J = 1 + \frac{p_{s||}}{E_n} = \frac{(2 - \alpha_s) M_d}{2(M_d - E_s)}$$

$$S(\alpha_s, p_T) \frac{d\alpha_s}{\alpha_s} d^2 p_T = P(\vec{p}_s) d^3 p_s$$

$$S^{\text{LC}}(\alpha_s, p_T) \frac{d\alpha_s}{\alpha_s} d^2 p_T = |\psi_{\text{NR}}(|\vec{k}|^2)|^2 d^3 k$$

$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2 - \alpha_s)} - M^2} \quad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

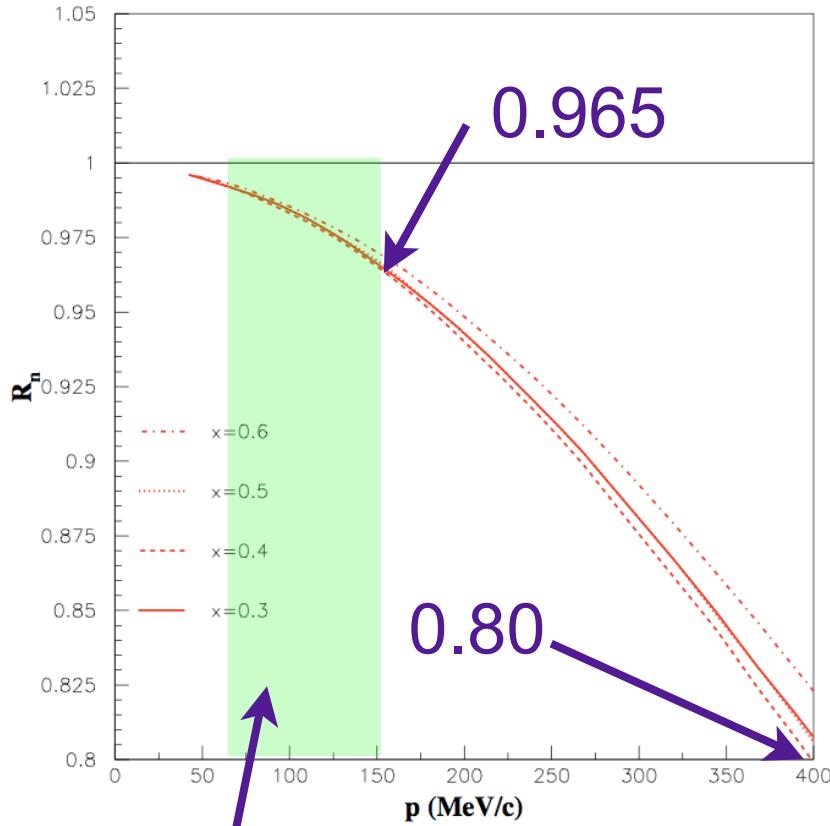
$$k_0 = \sqrt{M^2 + \vec{k}^2}$$

$$\vec{p}_T = \vec{k}_T$$

$$\int \int \int S^{\text{LC}}(\alpha_s, p_T) \frac{d\alpha_s}{\alpha_s} d^2 p_T = 1$$



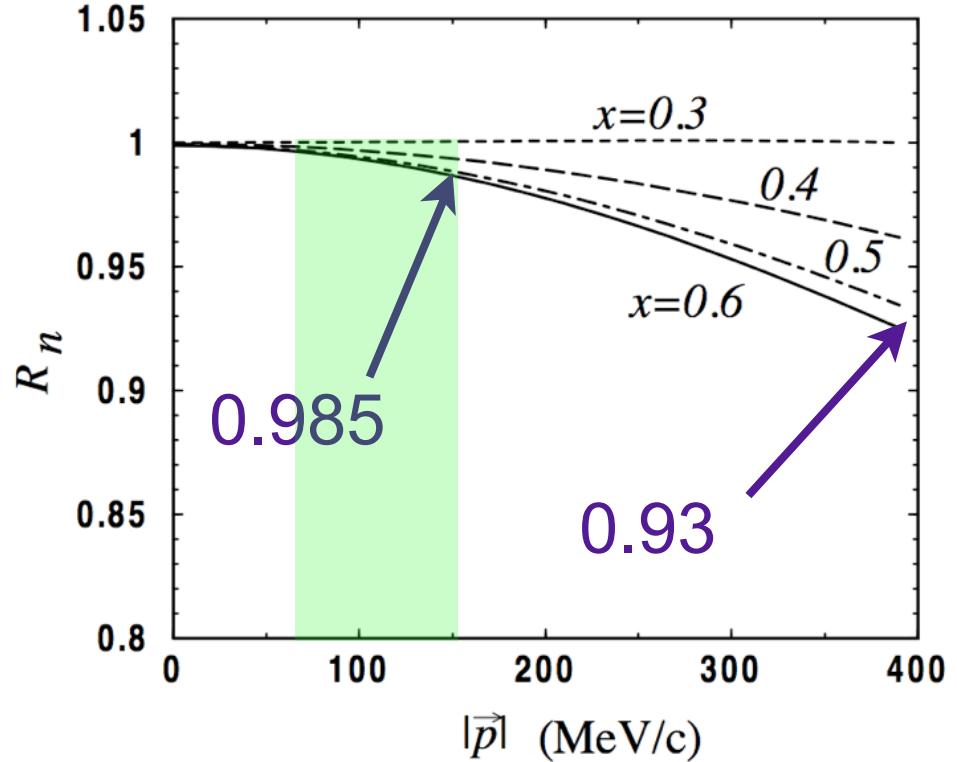
Liuti & Gross PLB356(95)157



$$R_n \equiv (F_2^n)^{\text{eff}} / (F_2^n)^{\text{free}}$$

BoNuS p_s
detection range

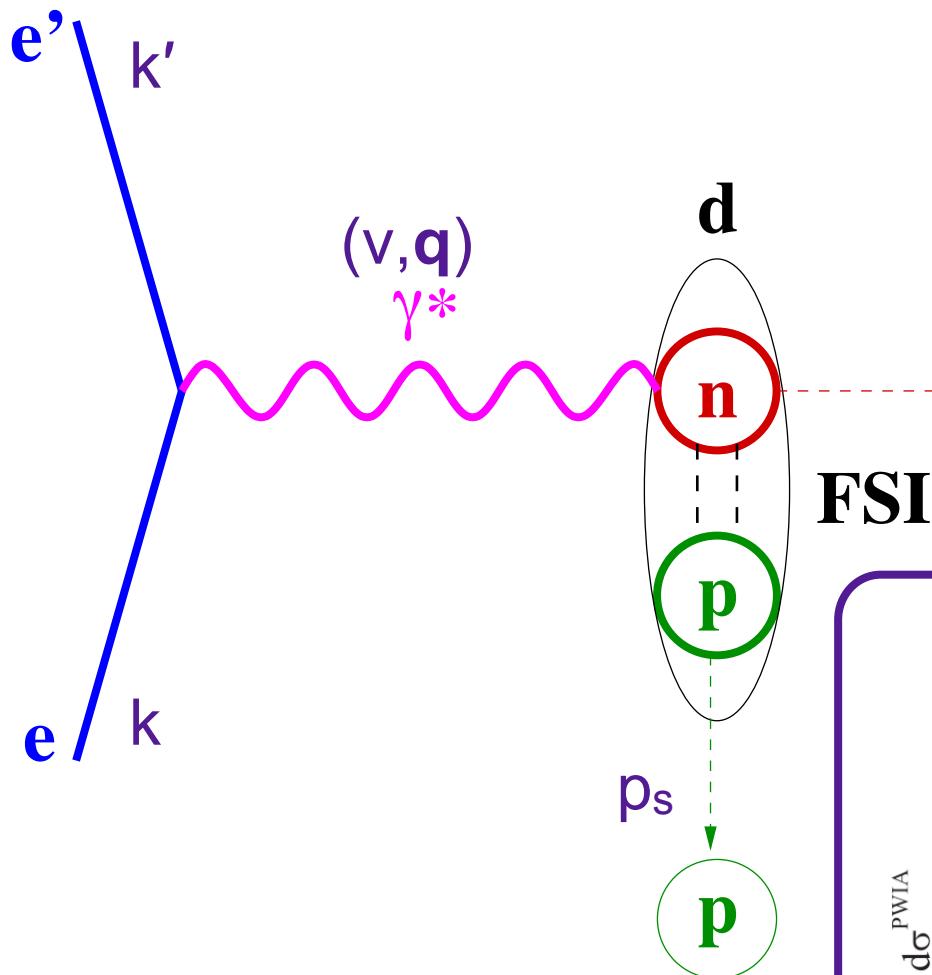
Melnitchouk *et al.*, PLB335(94)11



- R_n decreases with p_s or α_s
- At $x^*=0.5$ and $p_s=400$ MeV/c, R_n deviates from unity by 7-20% in these models

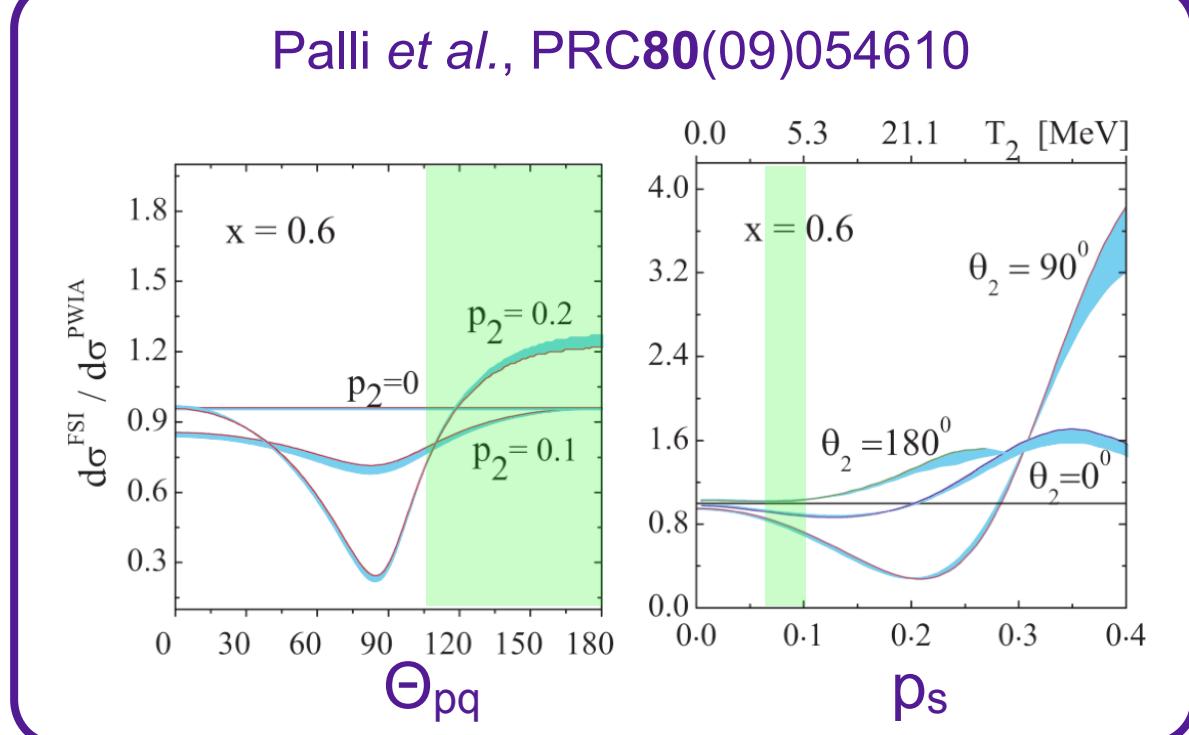


Final State Interactions



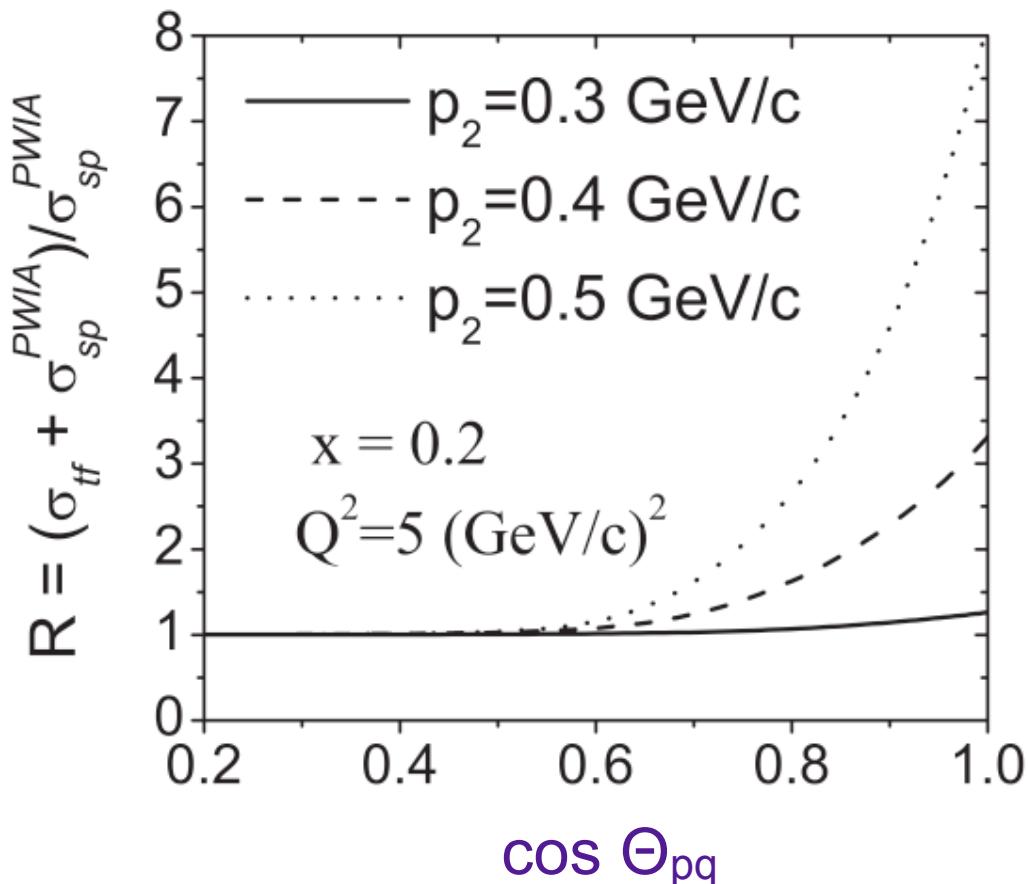
- Several groups have calculated FSIs
- $\Theta_{pq} > 110^\circ$ and $p_s < 100 \text{ MeV}/c$ greatly reduces FSIs

- Struck neutron can interact with the spectator proton
- Proton momentum is enhanced
- FSIs are small at low p_s and large Θ_{pq}





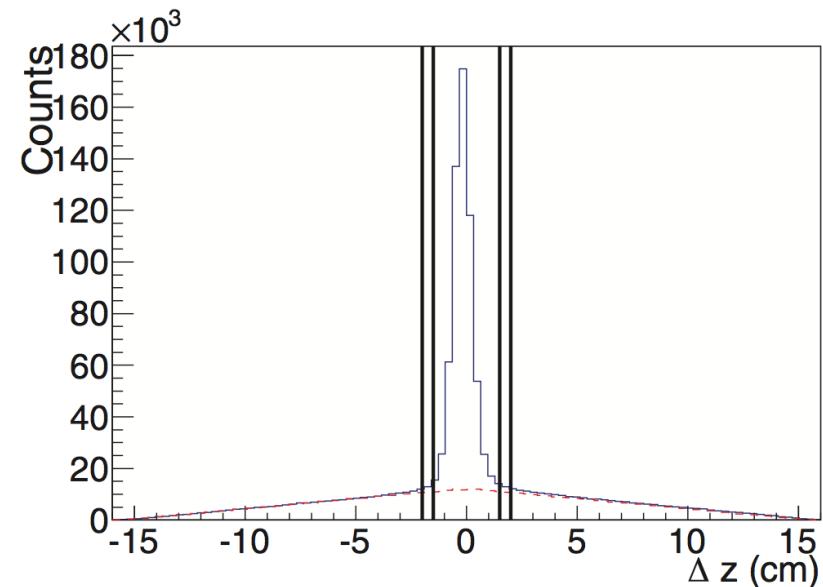
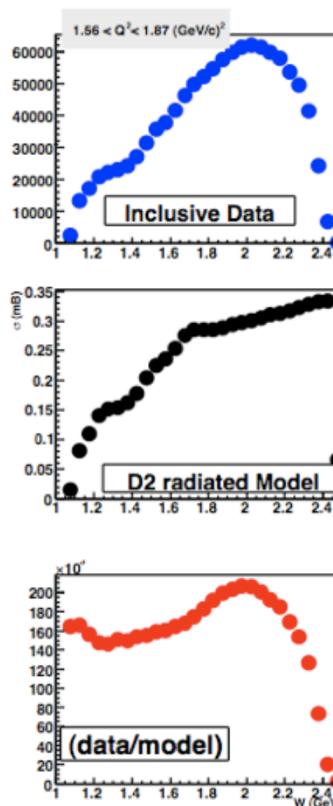
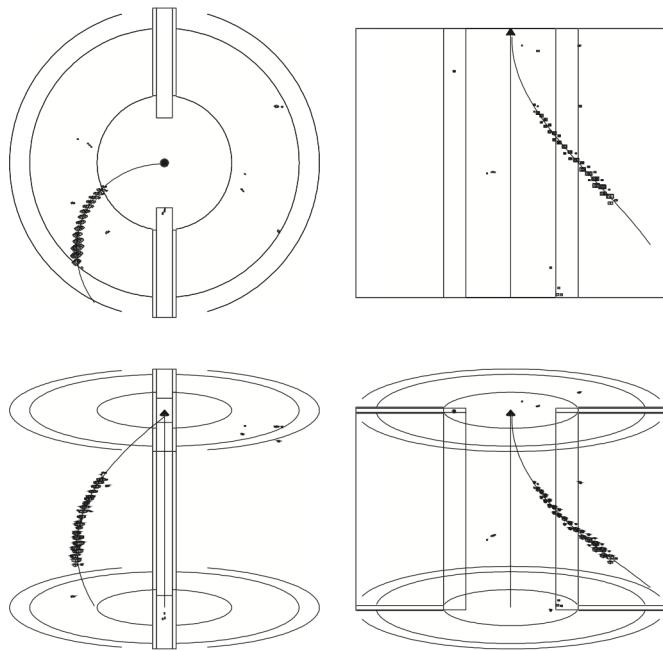
Palli *et al.*, PRC**80**(09)054610



- Target fragmentation enhances the proton yield only at forward angles ($\cos \Theta_{pq} > 0.6$)
- This can be ignored



Experimental Details

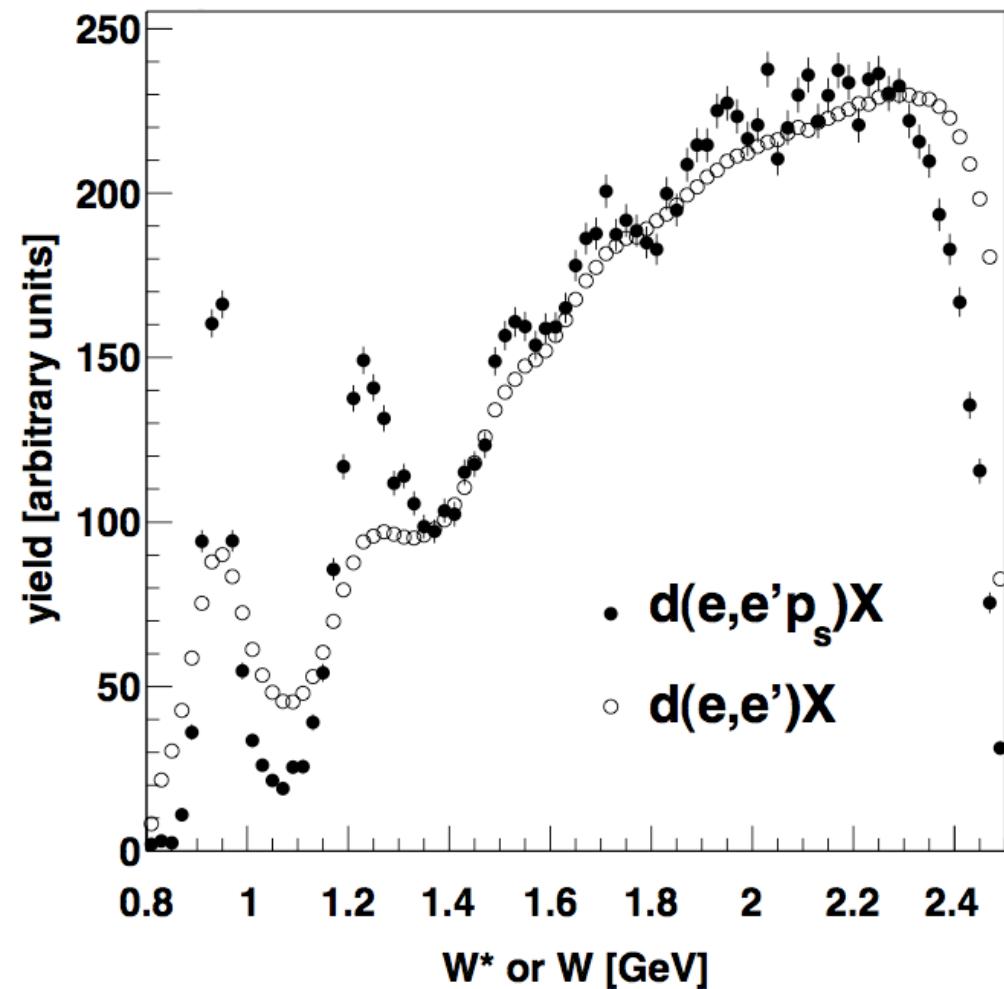
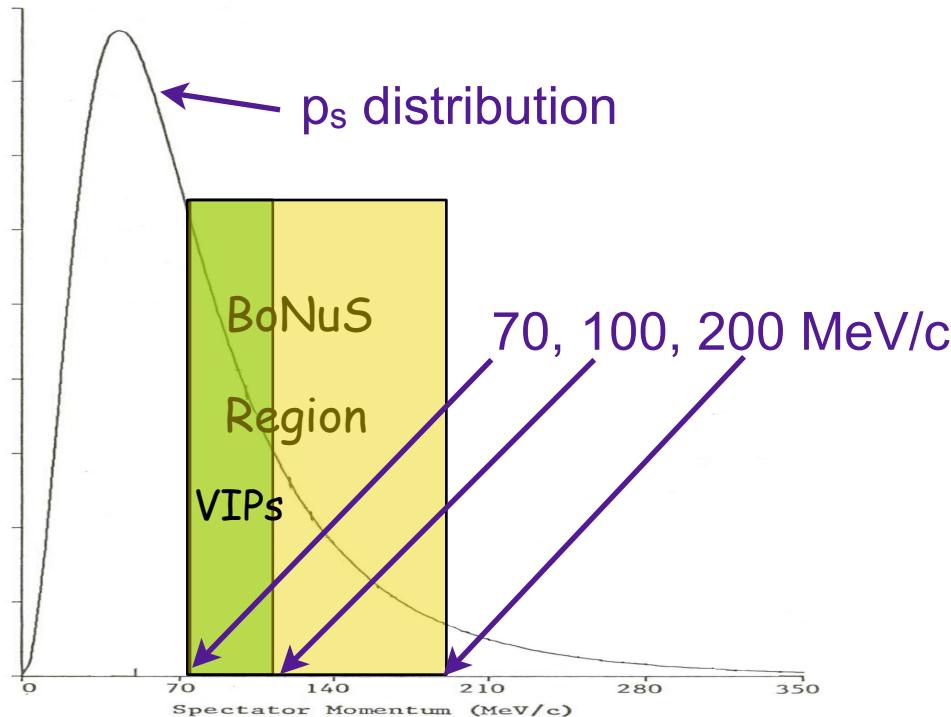


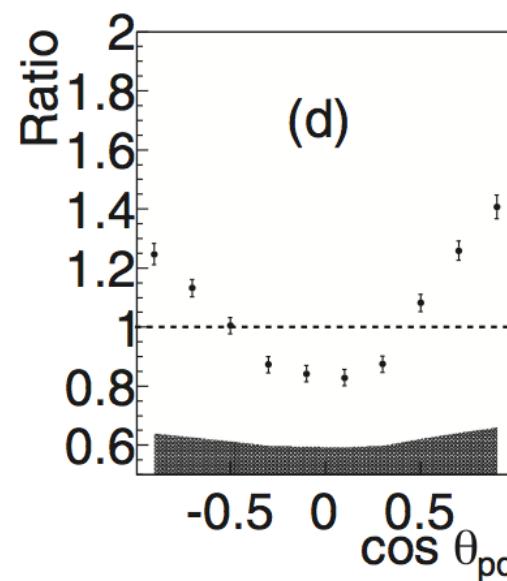
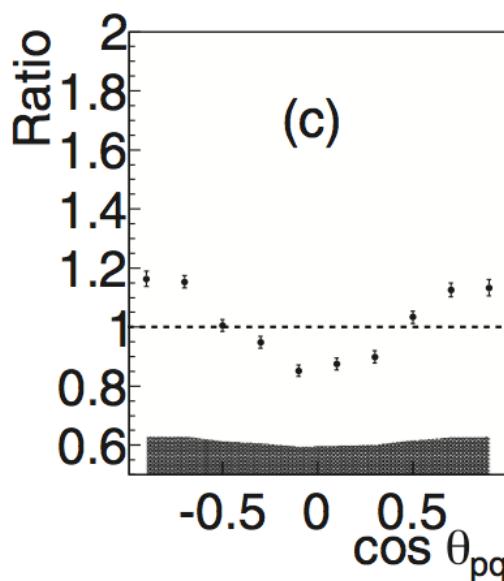
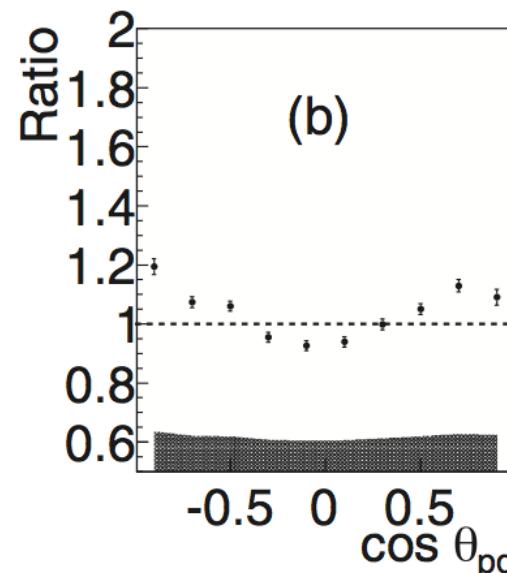
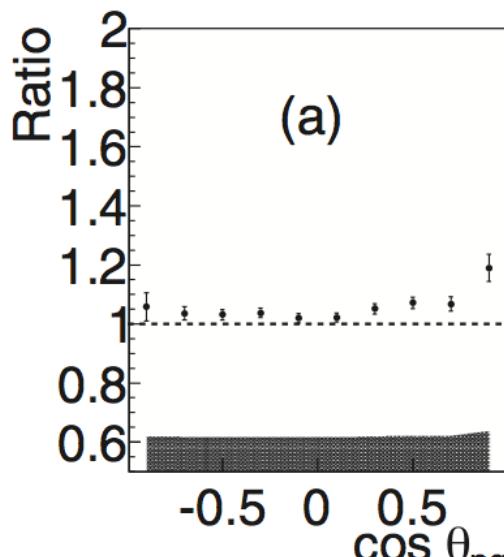
Determine:

- p_s from helical tracks in time projection chamber
- acceptance from ratio of eD counts to world fit
- accidentals from relative distance along beam line of proton and electron



- Very Important Protons $70 < p_s < 100 \text{ MeV}/c$
- VIPs are 17% of the p_s distribution
- Corrections make resonances stand out
- F_2^n/F_2^p can be measured at high x^*

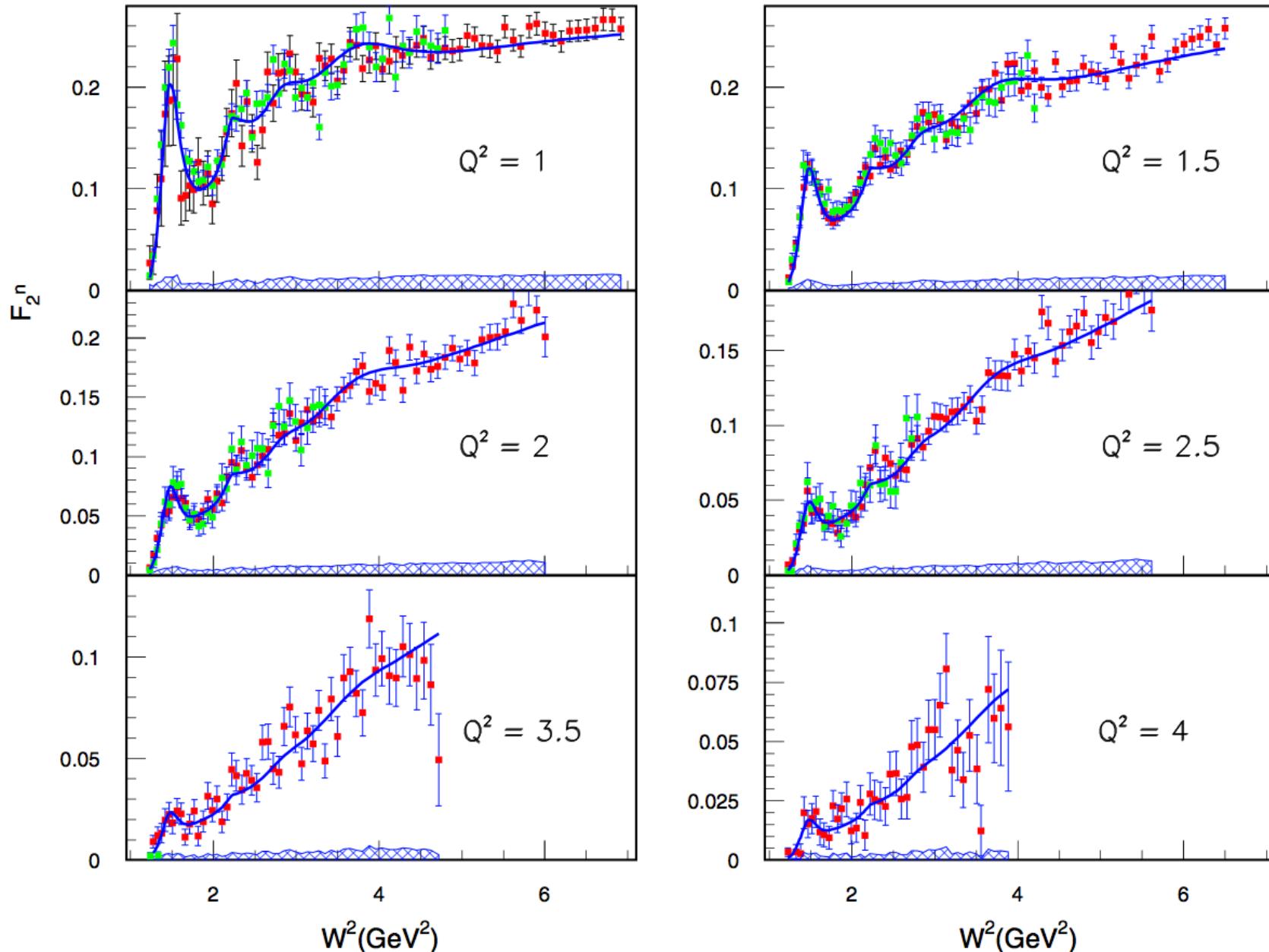


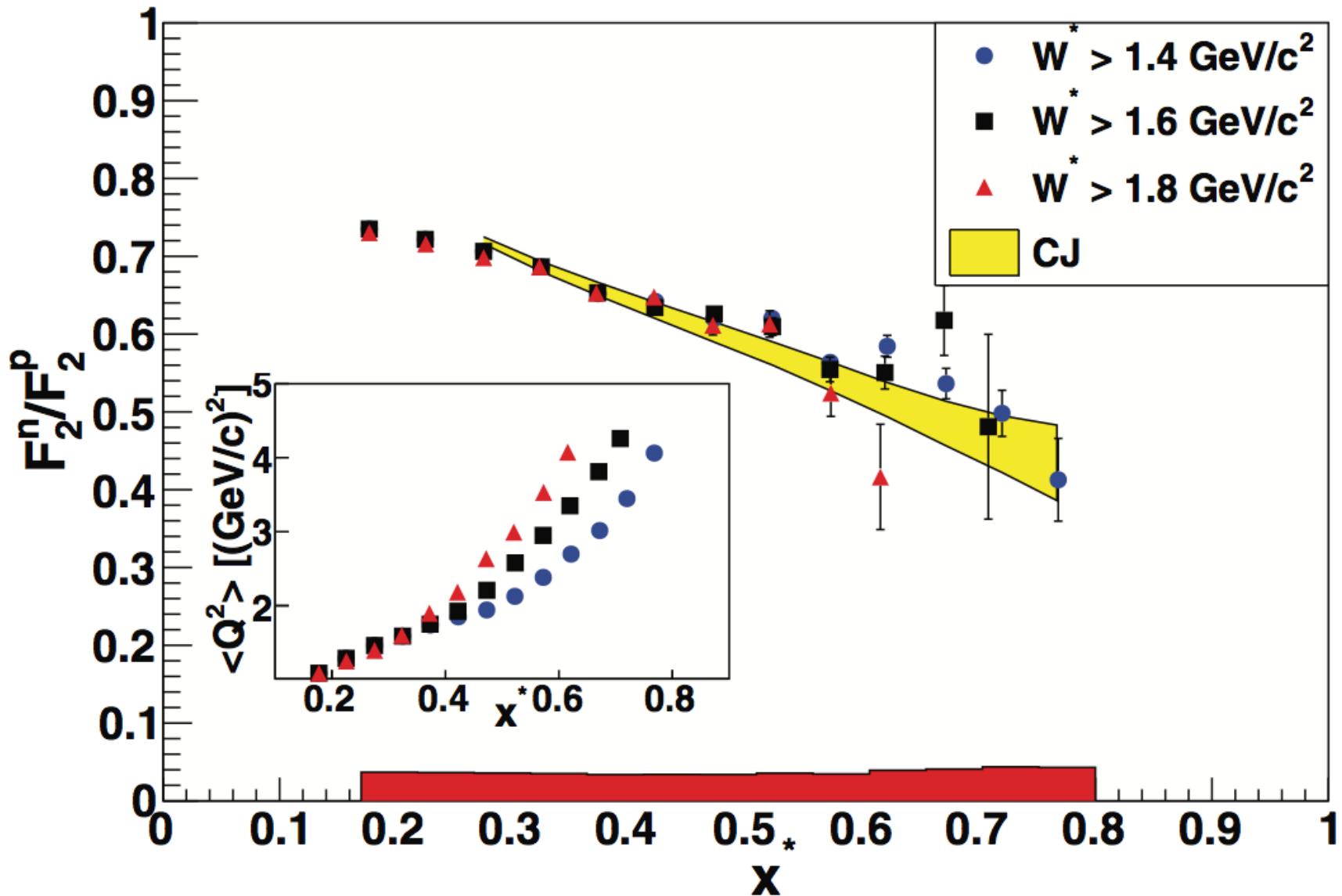


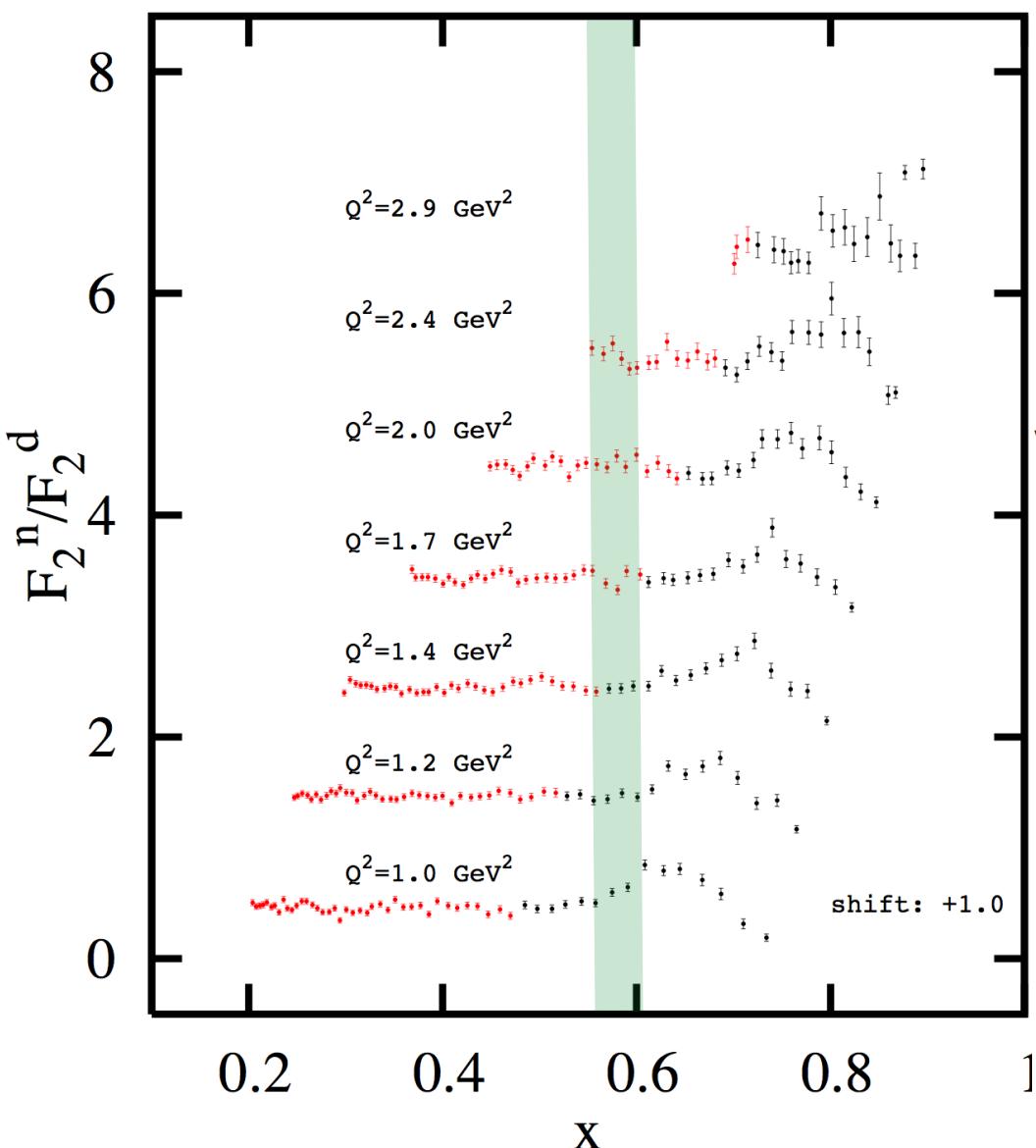
- Data Yield / PWIA MC
- $1.85 < W < 2.2$ GeV
- $p_s =$
 - (a) 70-85,
 - (b) 85-100,
 - (c) 100-120,
 - (d) 120-150 MeV/c
- Deviations from unity imply FSIs and off-shell effects
- F_2^n comes ONLY from left-hand side of top two plots.



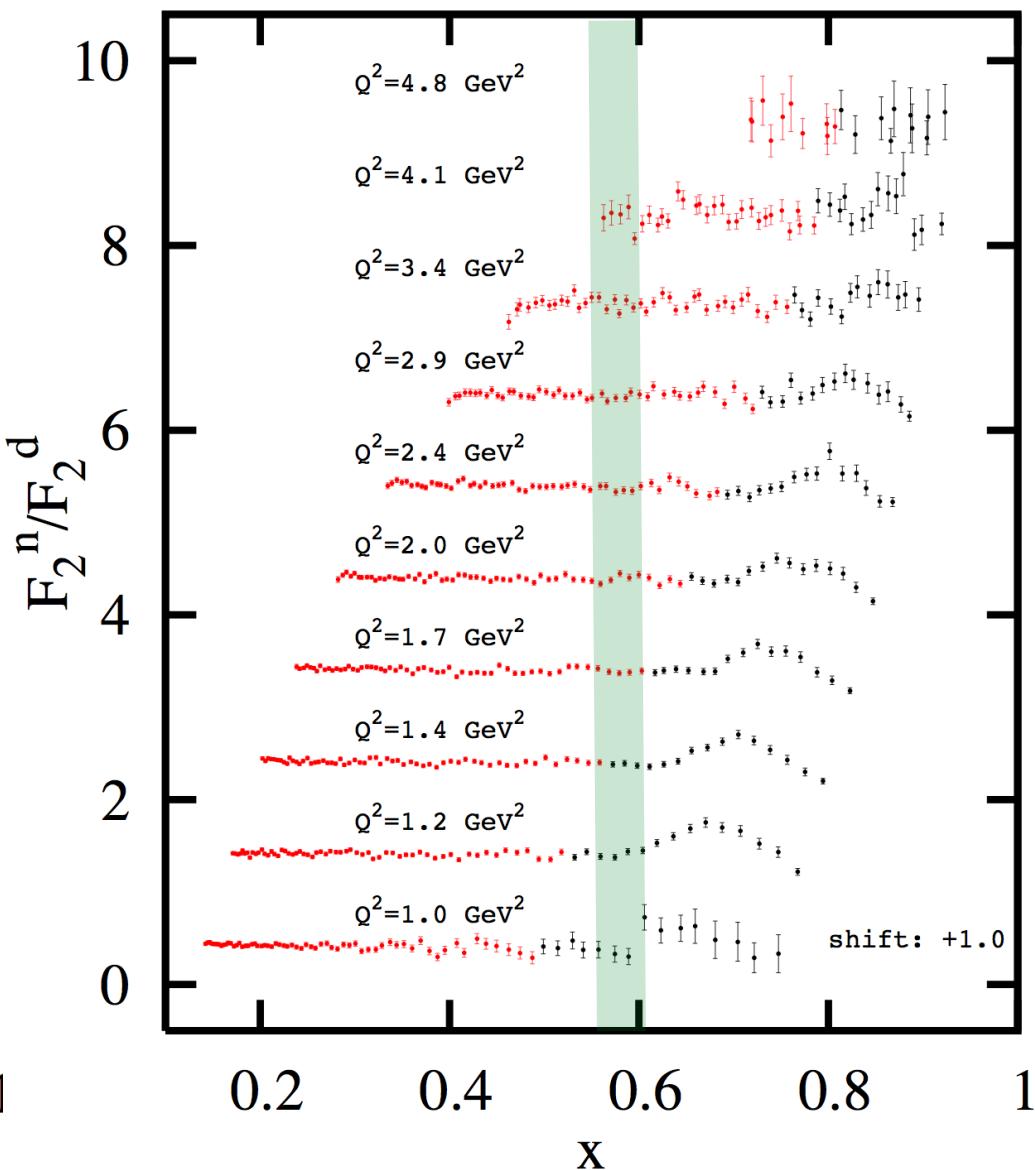
Curve: Kalantarians/Christy global fit before BoNuS







4.22 GeV



5.26 GeV



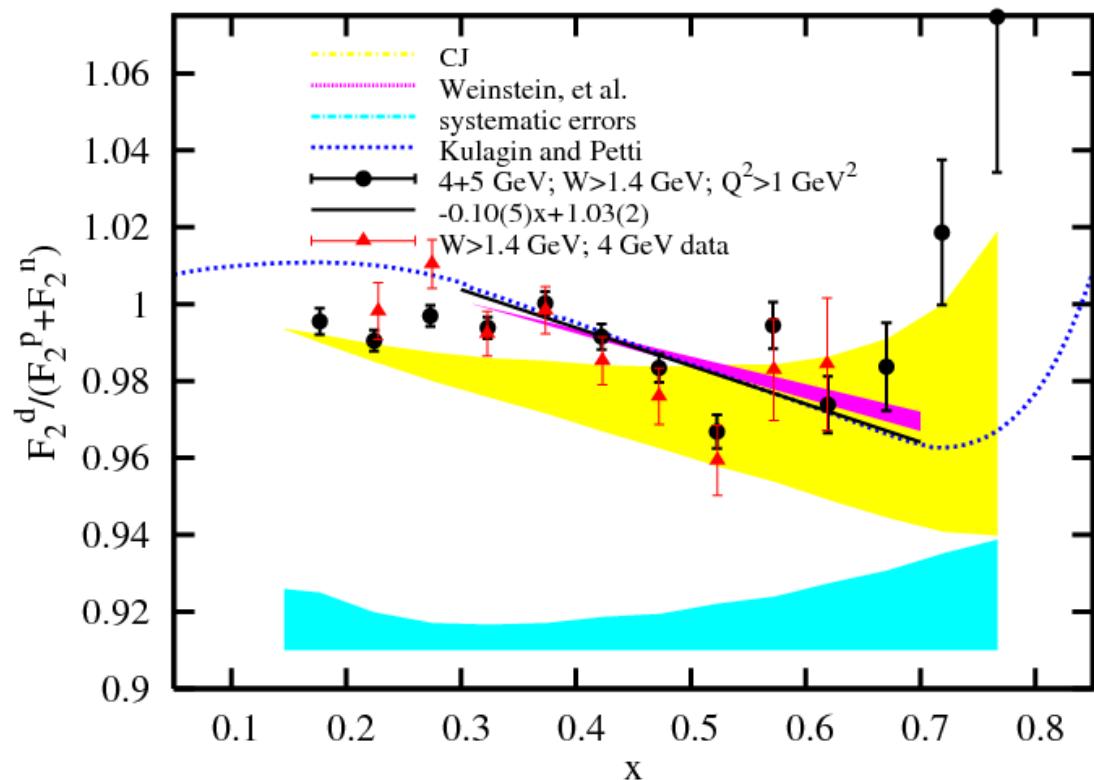
Ratios

$$r(W, Q^2) = \frac{F_2^n}{F_2^d} + \frac{F_2^p}{F_2^d}$$

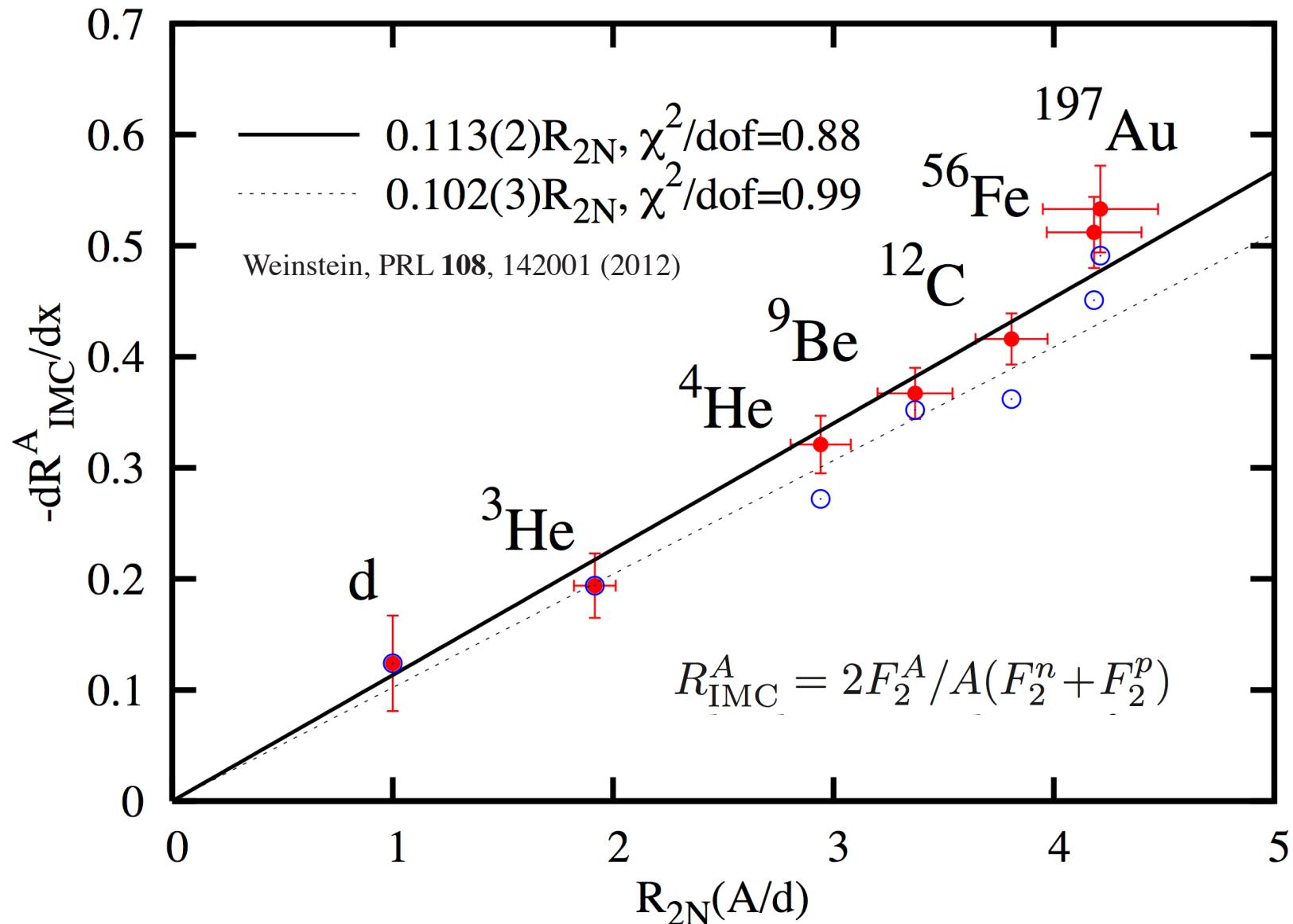
x

From BoNuS data

From global fits

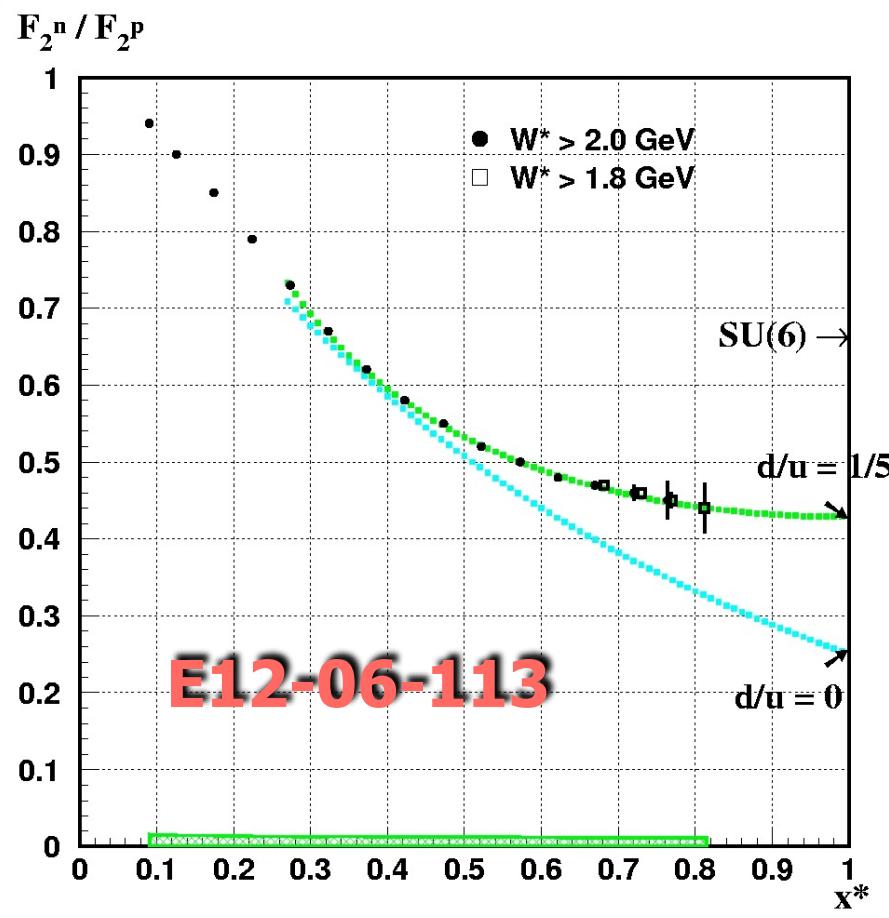
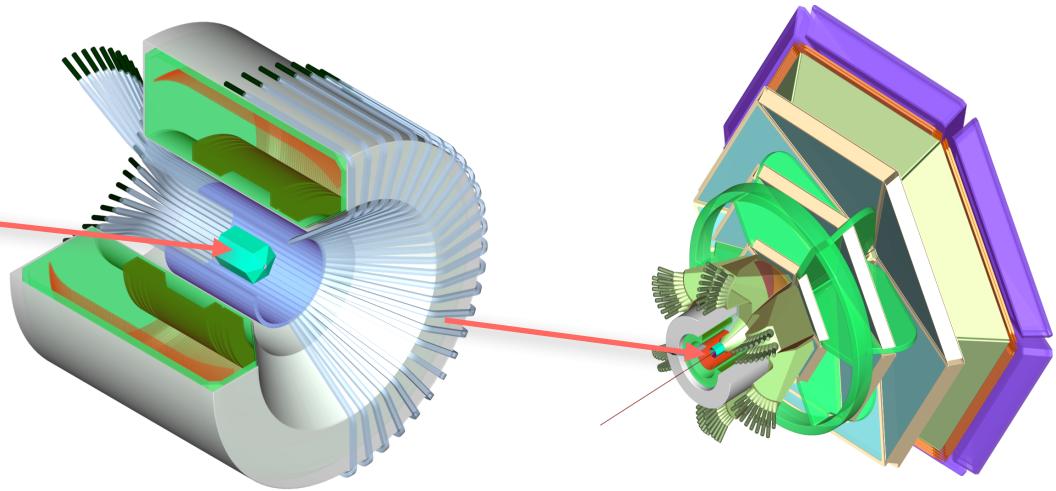
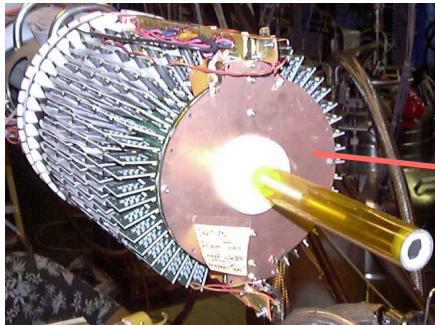


$$\frac{dR_E^d}{dx} = -0.079 \pm 0.006 \quad \text{Weinstein SRC}$$
$$0.35 < x < 0.7 \quad -0.13 \pm 0.05 \quad \text{BoNuS}$$





BoNuS Plans for 12 GeV



Data taking:

- 35 days on D_2
- 5 days on H_2
- $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$

DIS region:

- $Q^2 > 1 \text{ GeV}^2$
- $W^* > 2 \text{ GeV}$
- $p_s < 100 \text{ MeV}/c$
- $\theta_{pq} > 110^\circ$
- $x^*_{\max} = 0.80$

$W^* > 1.8 \text{ GeV}: x^*_{\max} = 0.83$

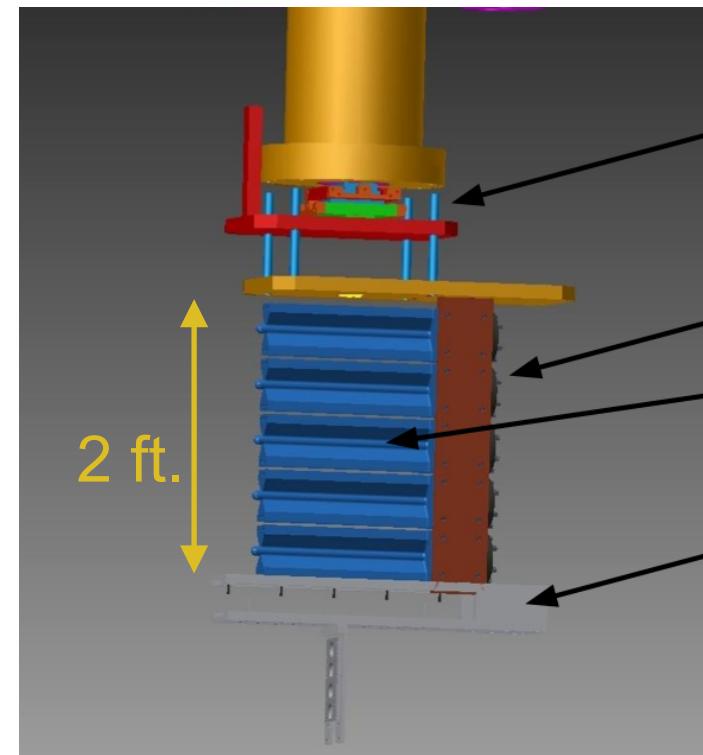
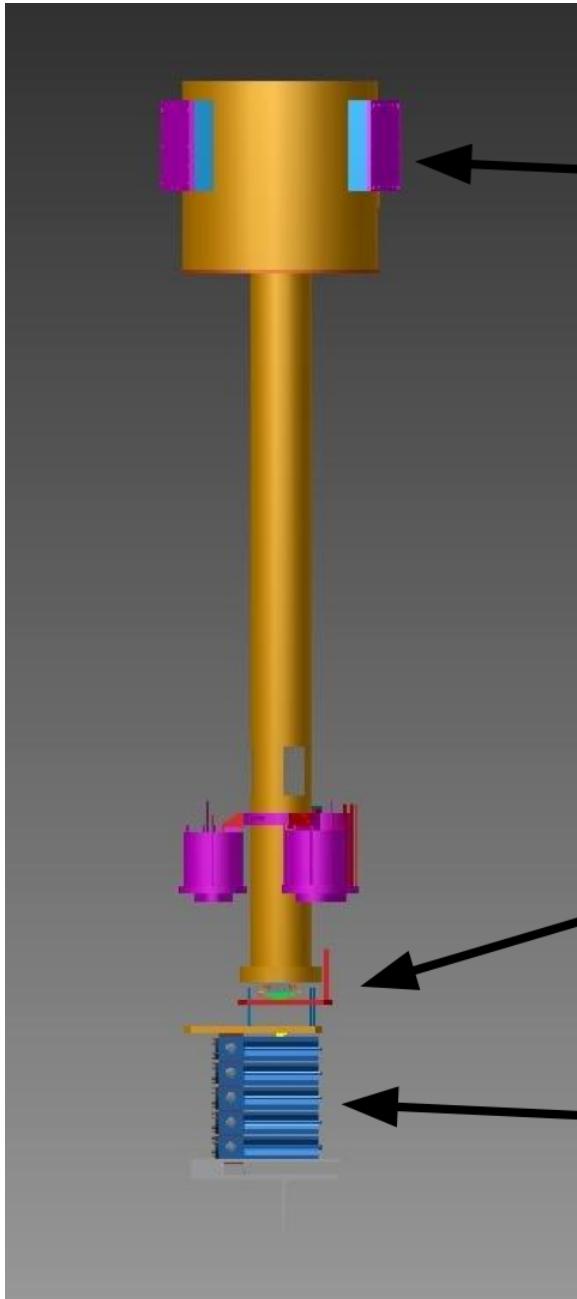


Related Experiments in Hall A

- E12-10-103 **Marathon**
G. Petratos,* J. Annand, J. Gomez , R. Holt, R. Ransome
 - Measurement of F_2^n/F_2^p at high x
- E12-11-112 **$x>1$ SRCs**
P. Solvignon-Slifer* J. Arrington, D. Day, D. Higinbotham
 - Measurement of short-range correlations in t, ${}^3\text{He}$
- E12-14-009 **Triton Charge Radius**
L. Myers,* J. Arrington, D. Higinbotham
 - Measurement of t/ ${}^3\text{He}$ at low Q^2 to obtain charge radius
- E12-14-011 **Proton momentum via (e,e'p)**
L. Weinstein,* W. Boeglin, O. Chen, S. Gilad
 - Measurements of proton momenta in t and ${}^3\text{He}$



Hall A Tritium Target



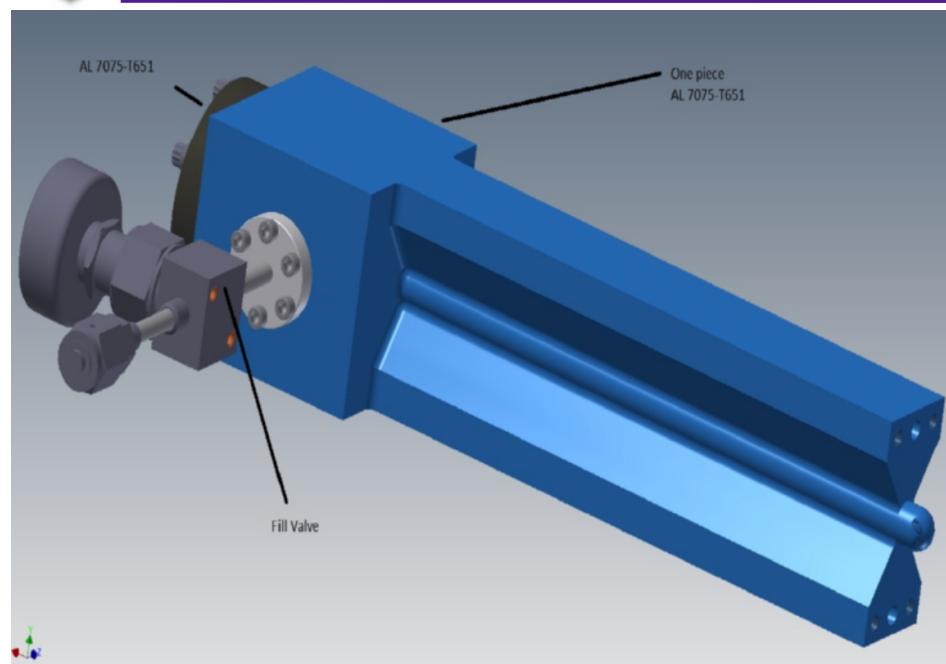
Positioning
system

Target
Stack

- T_2 , D_2 , H_2 , 3He , MT targets
- 15 K LHe cooling
- 1 kCi; 0.084 g/cm²; 25 μ A; 200 psi
- Windows: 0.01 in; Walls: 0.018 in



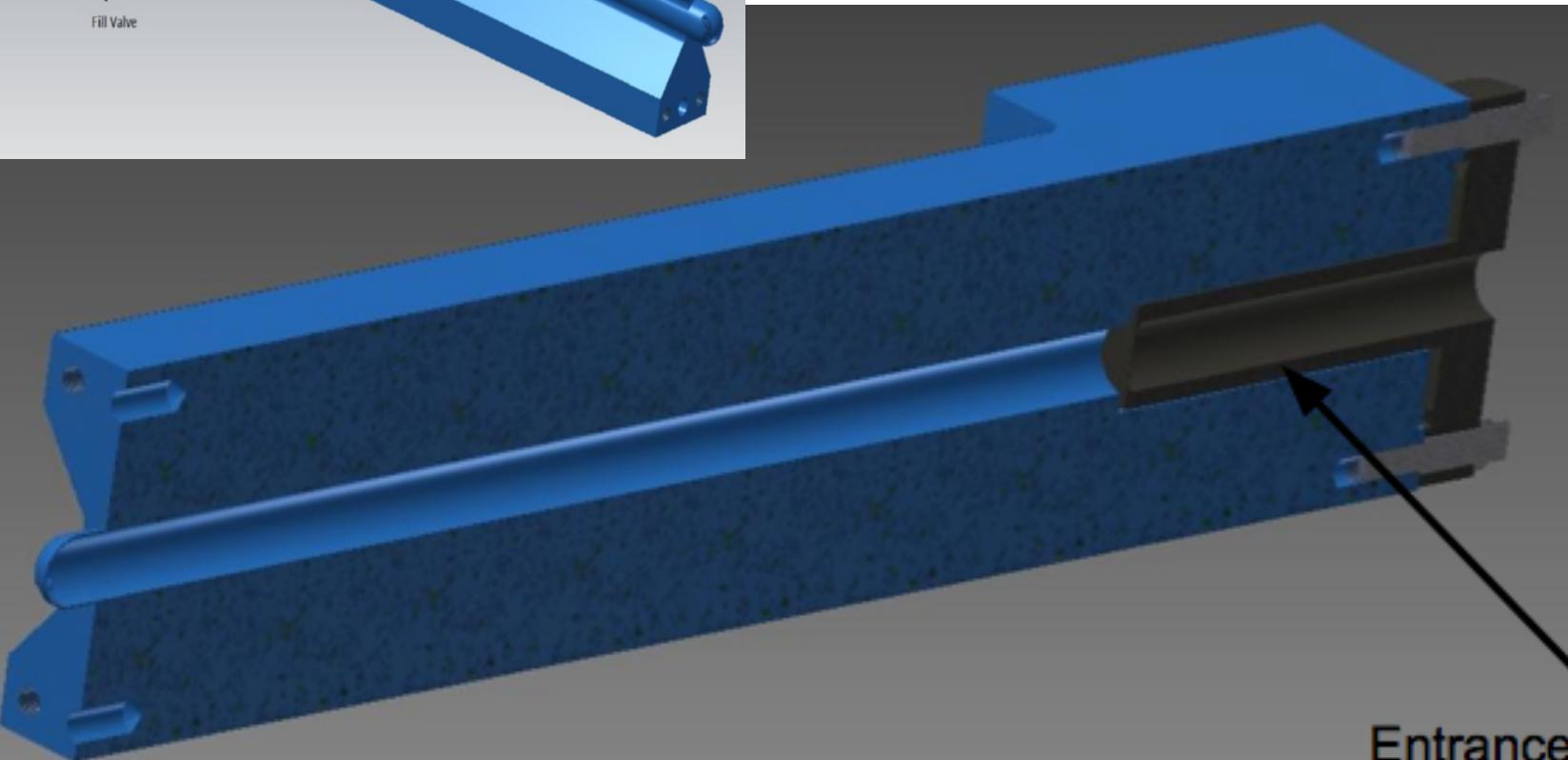
Hall A Tritium Target Cell



25 cm long

1.25 cm diameter

AI-2219



Entrance window



- E12-10-103

Marathon

Petratos,*J. Annand, J. Gomez ,R. Holt, R. Ransome

EMC Ratios

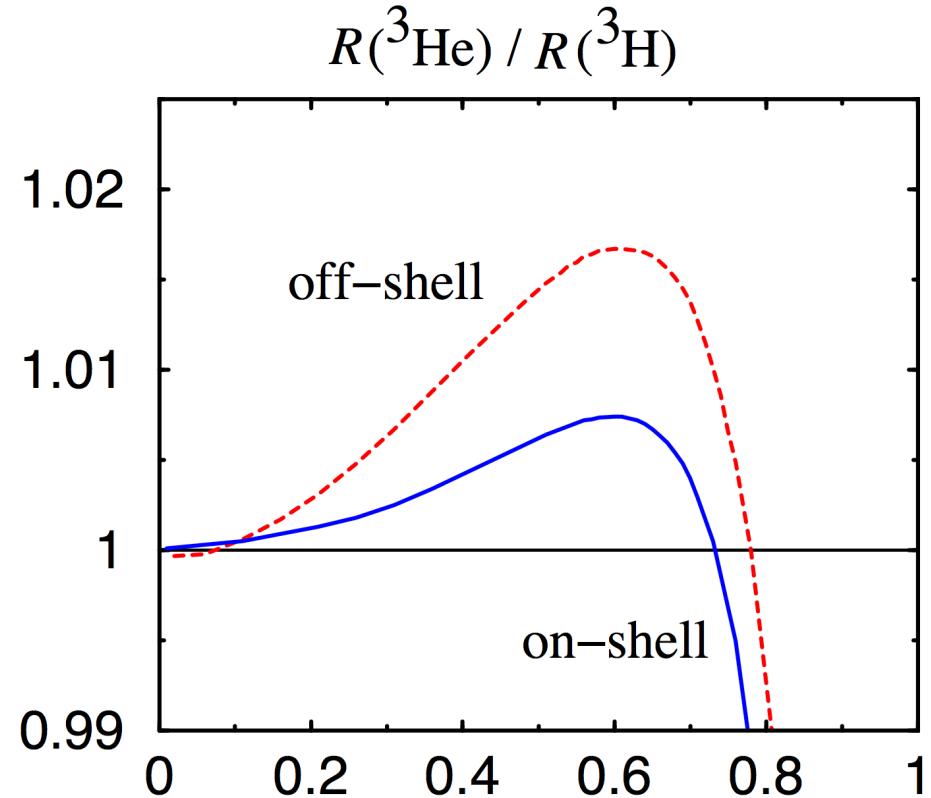
$$R(^3\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n}$$

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

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

≈ unity

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





- E12-10-103 **Marathon**

Petratos,*J. Annand, J. Gomez ,R. Holt, R. Ransome

EMC Ratios

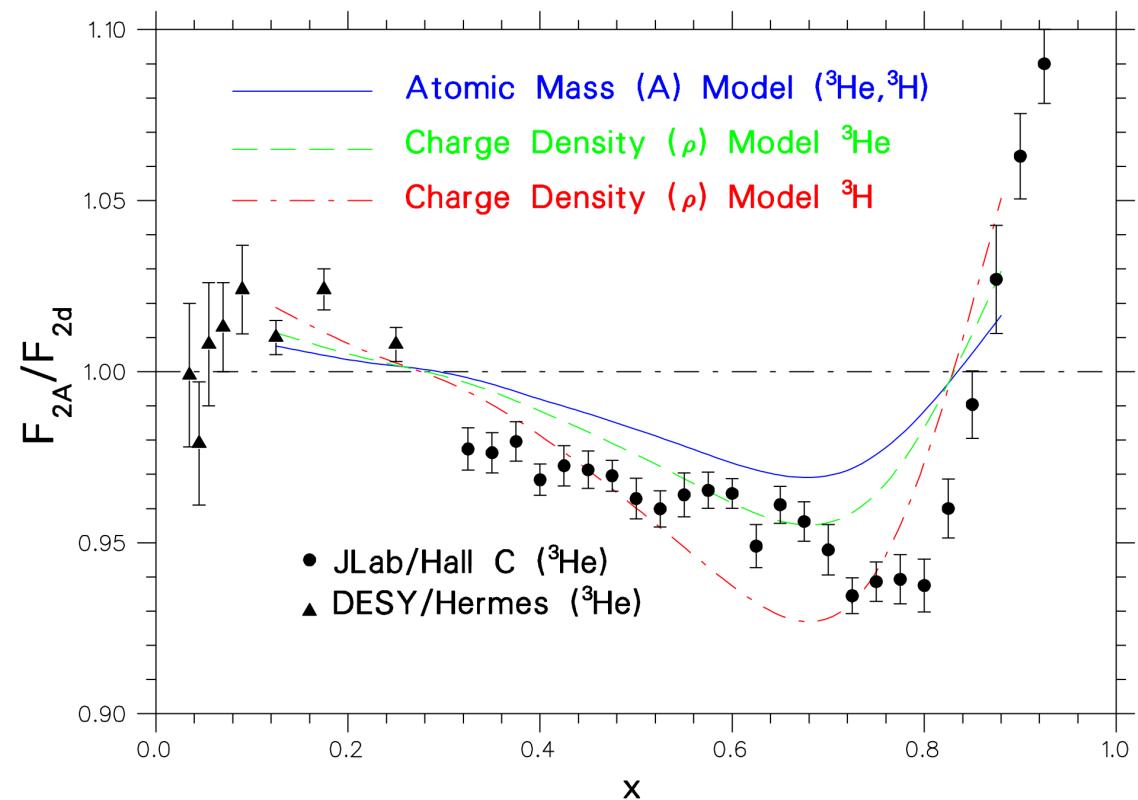
$$R(^3\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n}$$

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

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

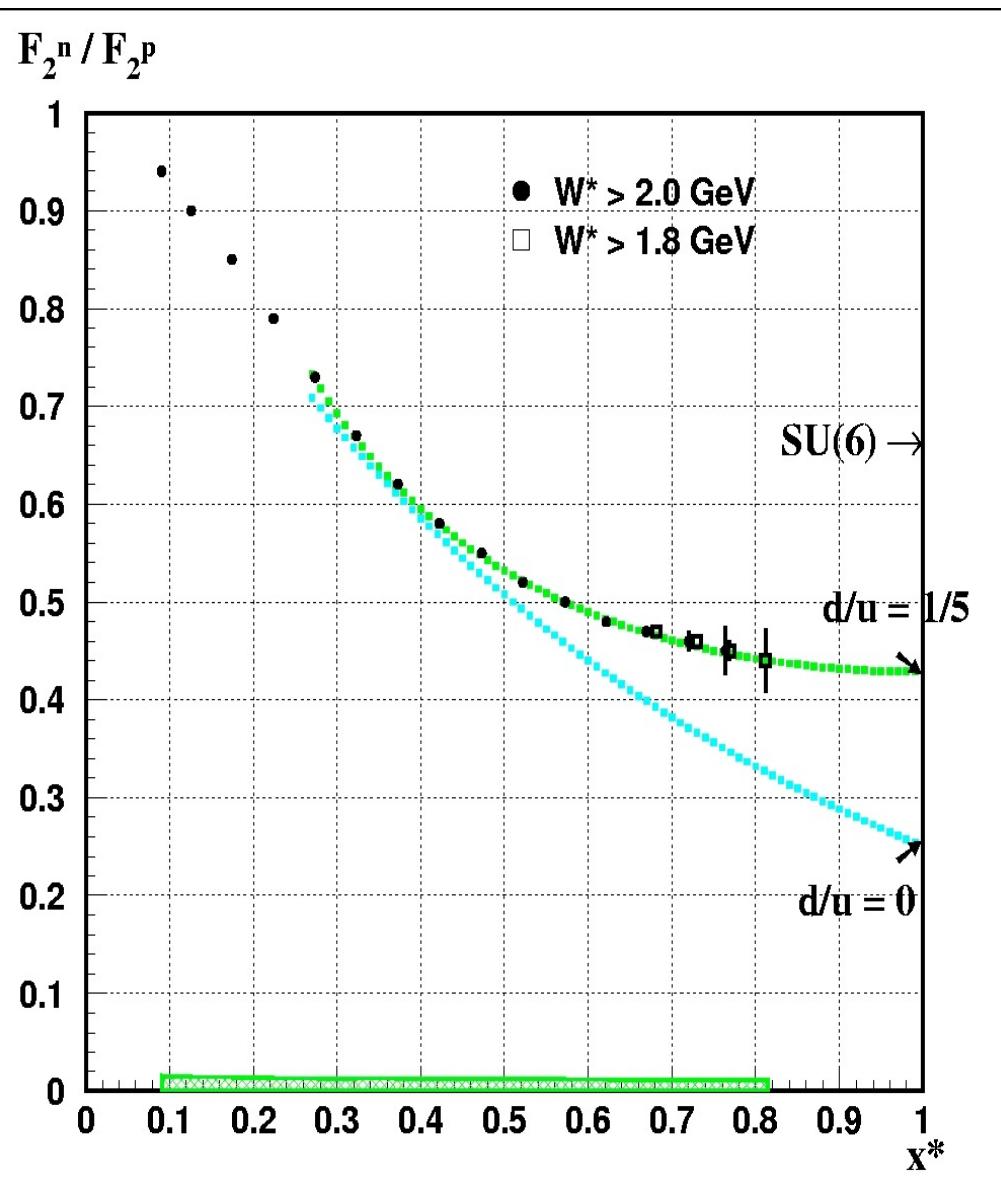
≈ unity

Compare EMC effect for t and ${}^3\text{He}$



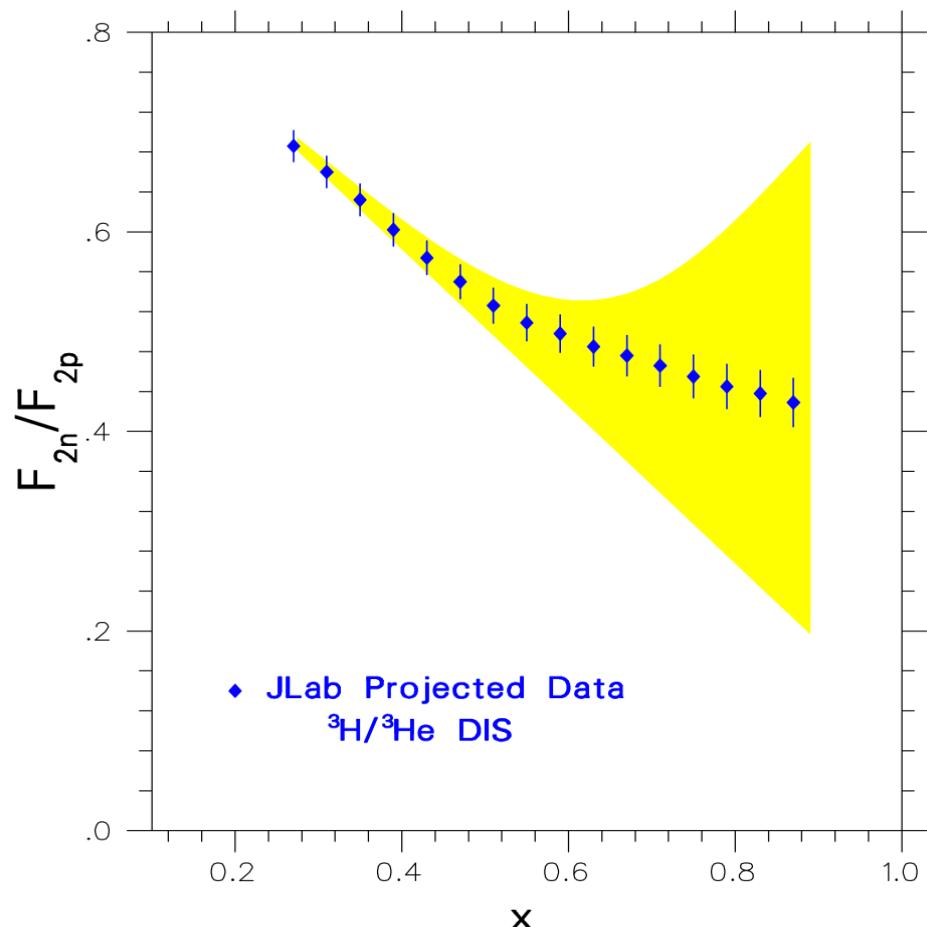


BoNuS



The two experiments
on the same scale

MARATHON

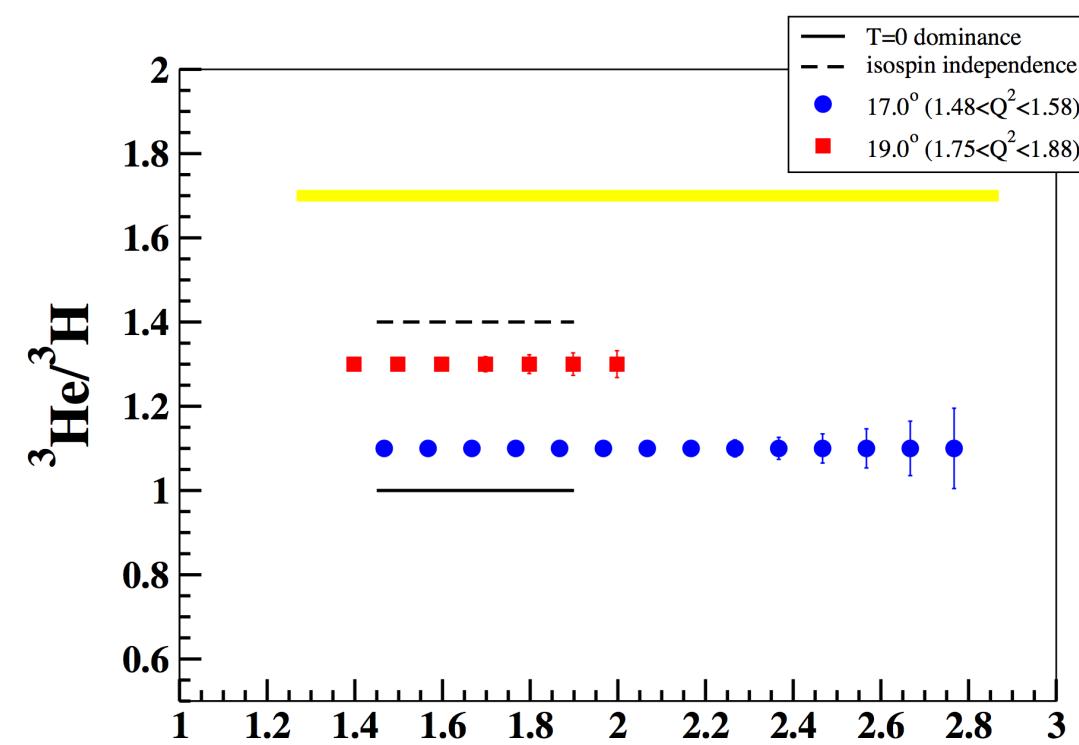




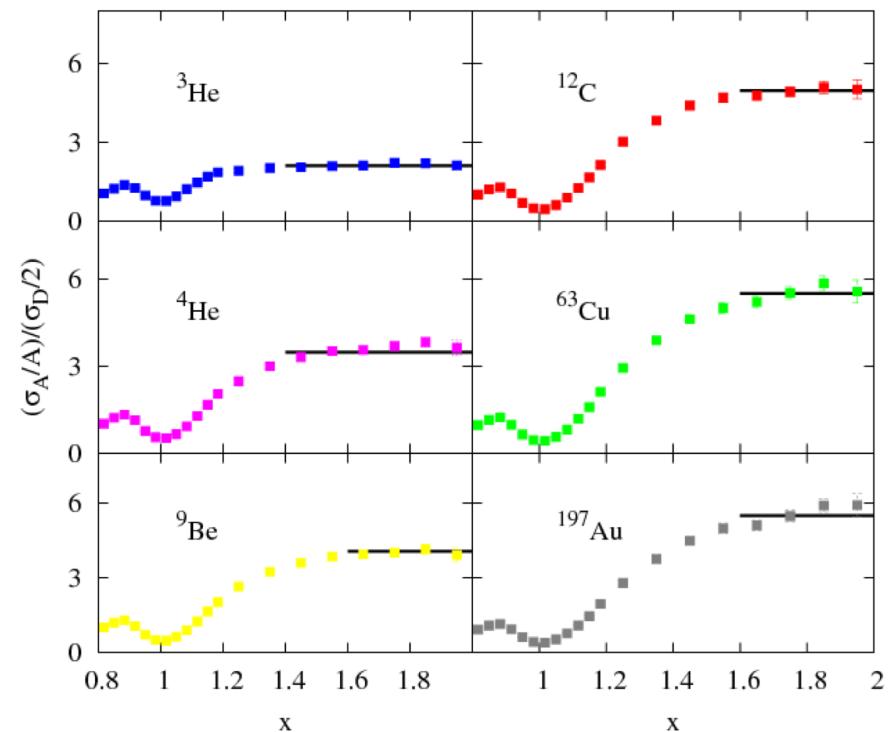
Short Range Correlations

- E12-11-112 $x > 1$ SRCs

P. Solvignon-Slifer*, J. Arrington, D. Day, D. Higinbotham



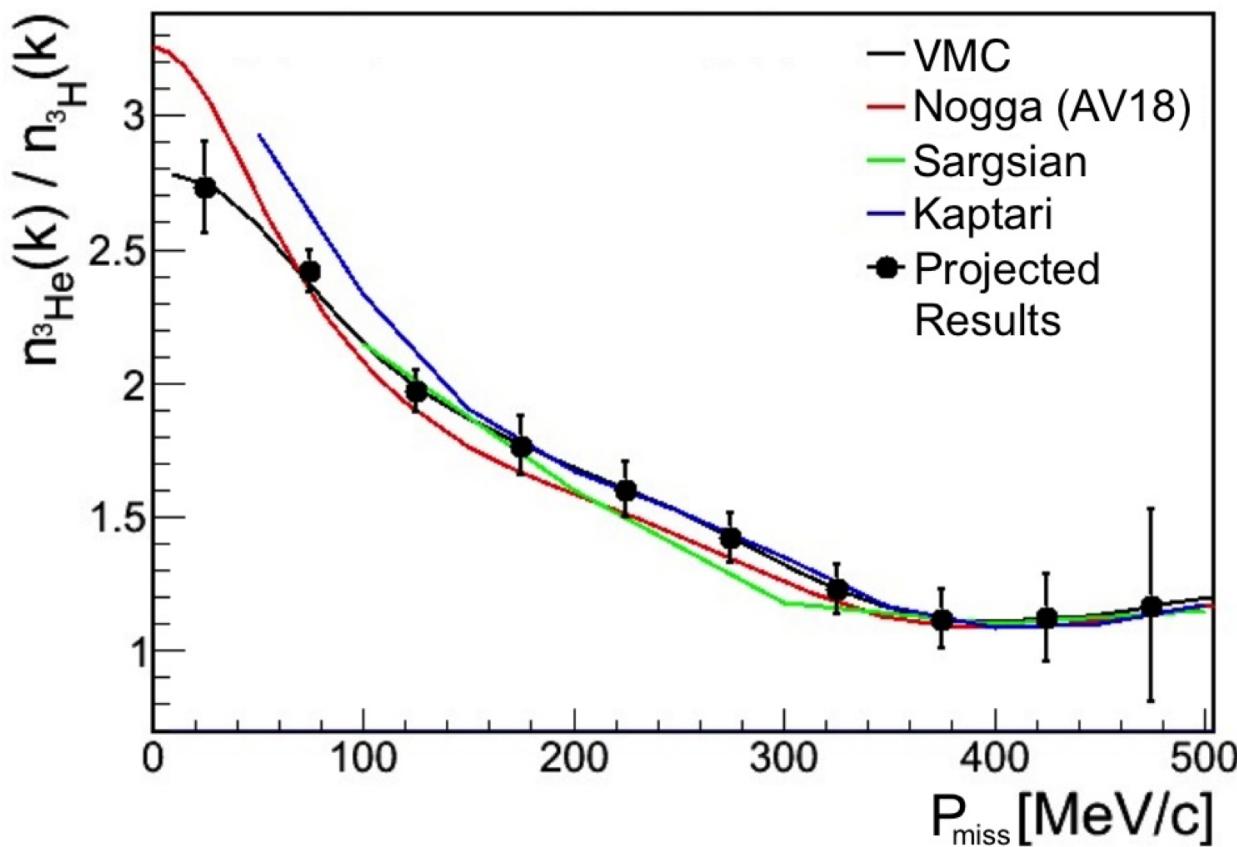
N. Fomin et al., Phys. Rev. Lett. 108, 092502 (2012)



Look for short-range correlations
at $x > 1$ in the ratio ${}^3\text{He}/t$



- E12-14-011 **Proton momentum via (e,e'p)**
L. Weinstein,* W. Boeglin, O. Chen, S. Gilad



Compare momentum distributions for protons when they are a majority vs. a minority in an A=3 system.



Elastic Scattering

$$\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \left[G_E^2 + \frac{\tau}{\varepsilon} G_M^2 \right] (1 + \tau)^{-1}$$

$$\tau = Q^2/4M^2 \text{ and } \varepsilon^{-1} = \{1 + 2(1 + \tau) \tan^2 \theta / 2\}$$

$$\langle r_{rms}^2 \rangle_{^3\text{He}} - \langle r_{rms}^2 \rangle_{^3\text{H}} \approx (0.20 \pm 0.03) \text{ fm}$$

- E12-14-009 **Triton Form Factor**
Myers,* J. Arrington, D. Higinbotham

$$\langle r_E^2 \rangle = -6 \left. \frac{dG_E}{dQ^2} \right|_{Q=0}$$

	Theory	(e,e')	(p,p')	Atomic Measurements
¹ H	—	0.895(18)	—	0.883(14)
² H	2.14(1)	2.128(11)	—	2.145(6)
³ H	1.77(1)	1.755(86)	—	
³ He	1.97(1)	1.959(30)	—	1.9506(14)
⁴ He	1.68(1)	1.676(8)	1.71(3)	1.673(1)
⁶ He	2.06(1)	—	2.03(11)	2.054(14)

Ratio (to 2%)
of t/³He
measures the
difference in t
and ³He radii



Conclusions

- The BoNuS Experiment provides a good way to extract F_2^n at high x
- F_2^n/F_2^p behaves at high x similar to the CJ high- x fits but with tighter constraints on the values.
- BoNuS shows a sizable EMC effect for the deuteron
- BoNuS will be extended to 12 GeV CLAS running.
- Plans for a tritium target at JLab make several new experiments possible that compare ${}^3\text{He}$ and tritium
- MARATHON will determine F_2^n/F_2^p with different systematic errors from nuclear physics
- Both MARATHON & BoNuS are essential because of their different dependences on nuclear physics