Tagging the EMC Effect with Slow and Fast Protons

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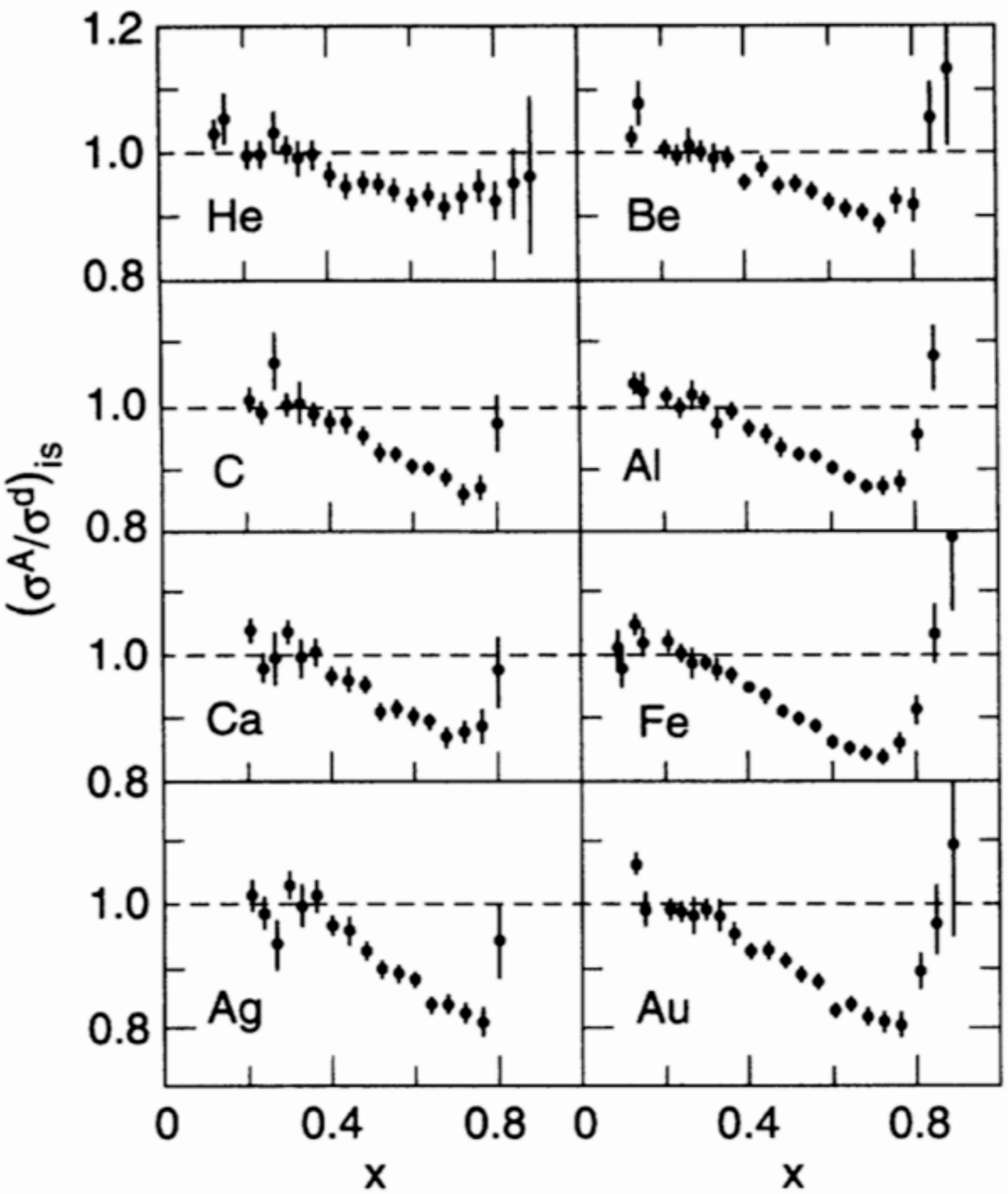
SLAC E139 EMC Effect Measurements

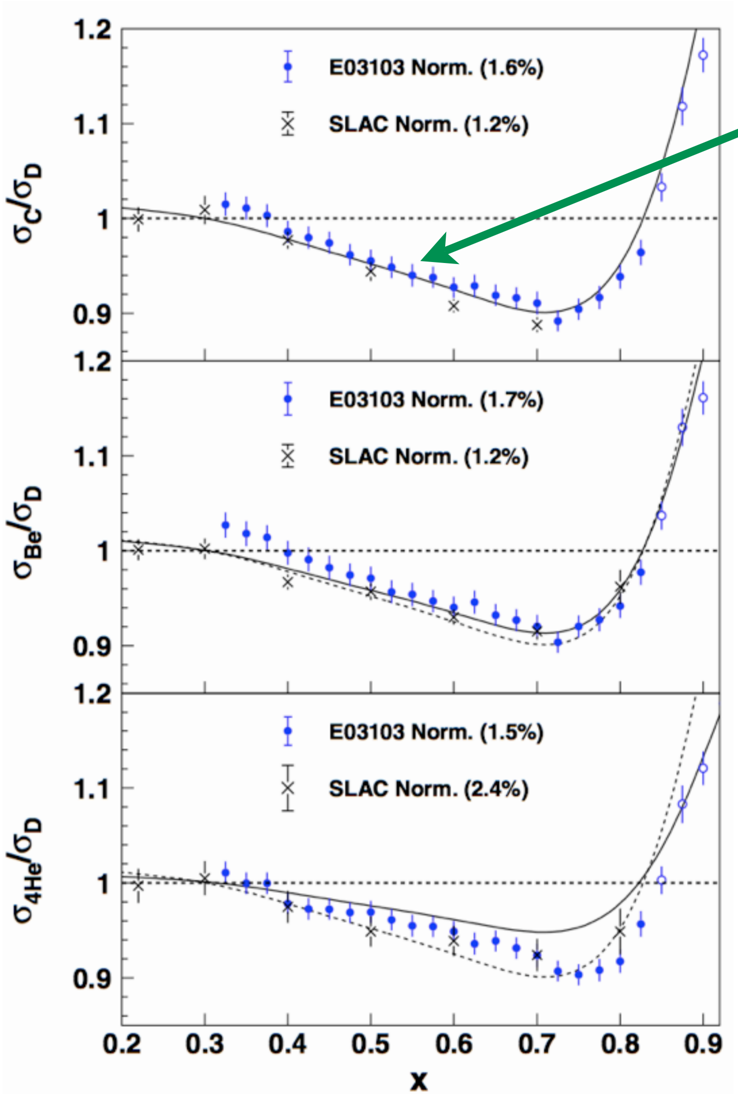


Gomez et al, PRC49(94)4348

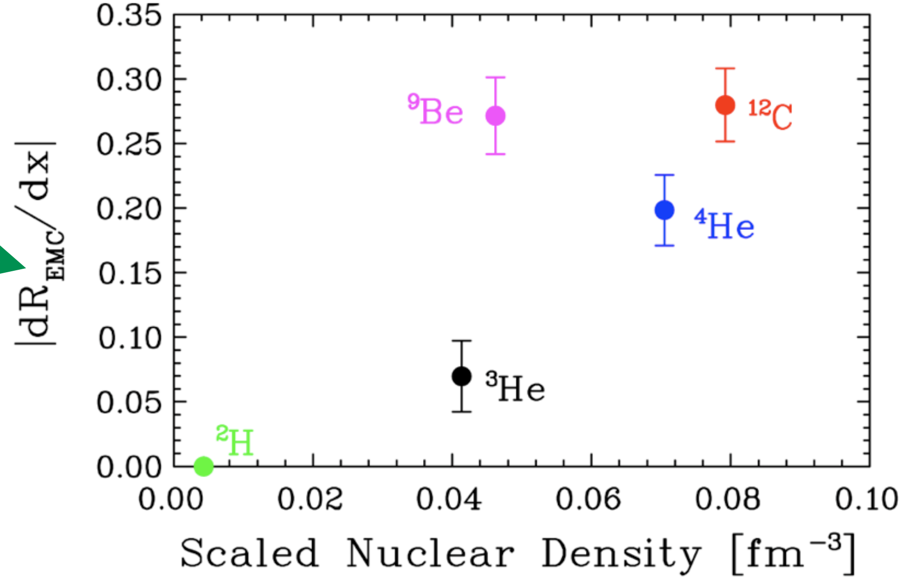
- European Muon Collaboration (EMC) discovered a reduced deep-inelastic cross section for 0.4<x<0.7 in nuclei compared to deuterium (Aubert et al., PLB**120**(83)275
- SLAC (see plot) showed the effect grows with A and depends almost linearly with x.
- Effect is still not understood, but the likely explanation is a modification of the bound nucleon structure function.

Recent EMC Effect Measurements

Seely et al, PRL103(09)202301



slope



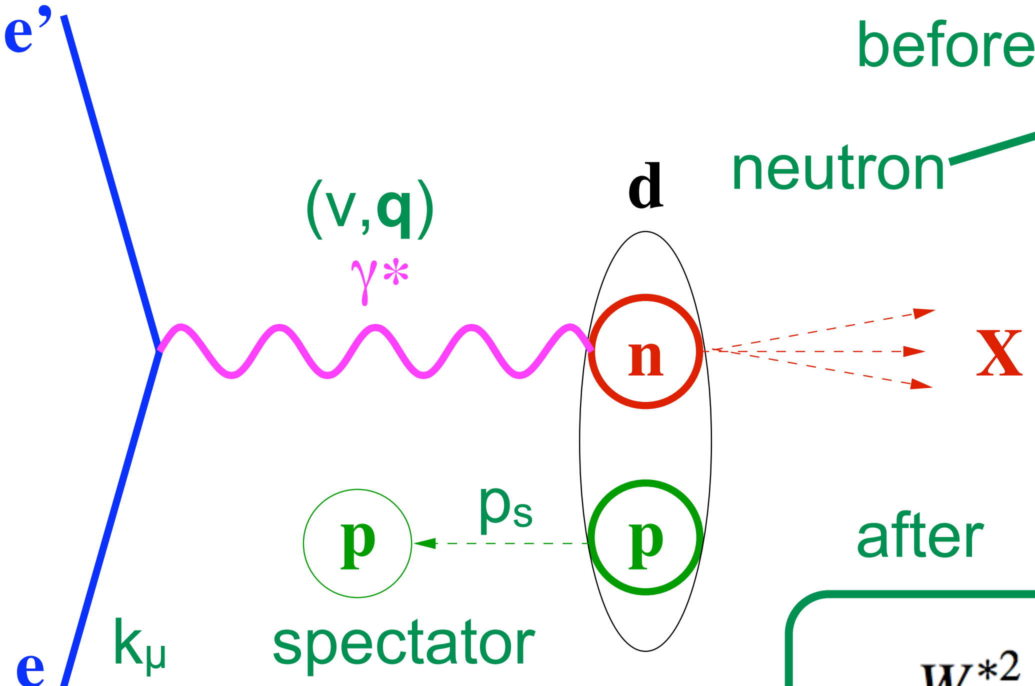
- Recent data from JLab are very precise.
- Slope with respect to x is used to characterize the strength of the effect
- ^{9}Be anomaly is used to argue for a local-density origin of the effect

A Tale of Two CLAS Experiments

- BoNuS
- Bound Nucleon Structure Experiment
- $d(e,e'p_s)X$ [(deep) inelastic]
- deuterium target, spectator proton
- $70 < p_s < 180$ MeV/c
- JLab Hall B CLAS with an RTPC
- search for F_2^n at high x

- DEEPS
- $d(e,e'p_s)X$ [deep inelastic]
- deuterium target, spectator proton
- $250 < p_s < 600$ MeV/c
- JLab Hall B CLAS
- search for $F_2^{n\{eff\}}$ for $0.3 < x < 0.7$

$d(e,e'p_s)X$



$$p_N^\mu = (M_d - E_s, -\vec{p}_s)$$

$$E_p + E_n = M_d$$

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

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

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

$$\alpha_s = \frac{E_s - p_{s_{||}}}{M_s} \qquad y^* = \frac{p_N^\mu q_\mu}{p_N^\mu k_\mu} \approx y$$

$$x^* = \frac{Q^2}{2p_N^\mu q^\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

- plane-wave impulse approximation
- backward-emitted p is spectator
- struck neutron is off-shell
- momenta are equal and opposite
- Lorentz invariants are corrected for initial neutron 4-momentum

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PWIA Spectator Formalism

Cross Section

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

Off-Shell F_2

Spectral Function

Nonrelativistic w.f.

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

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

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

Light Cone

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

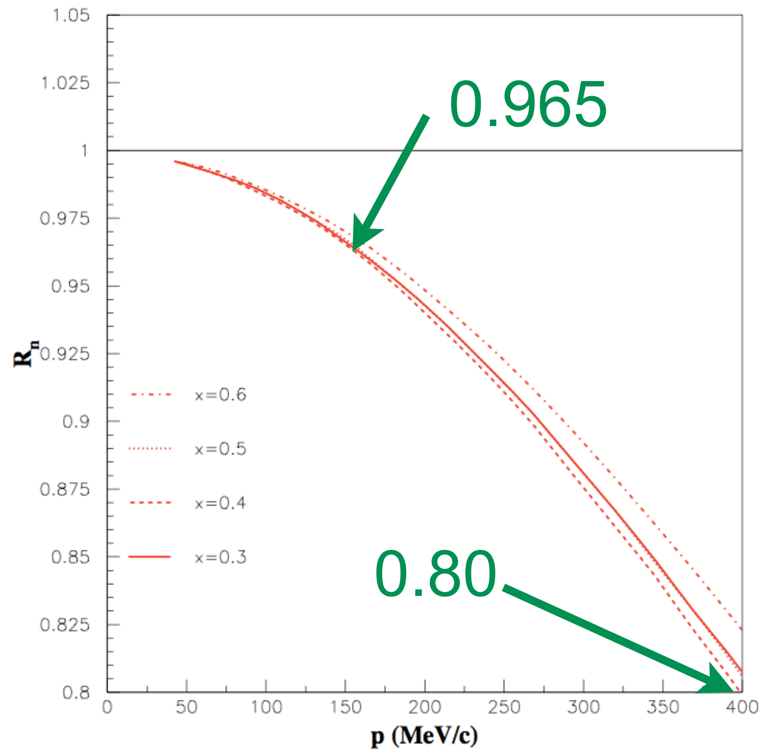
$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

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

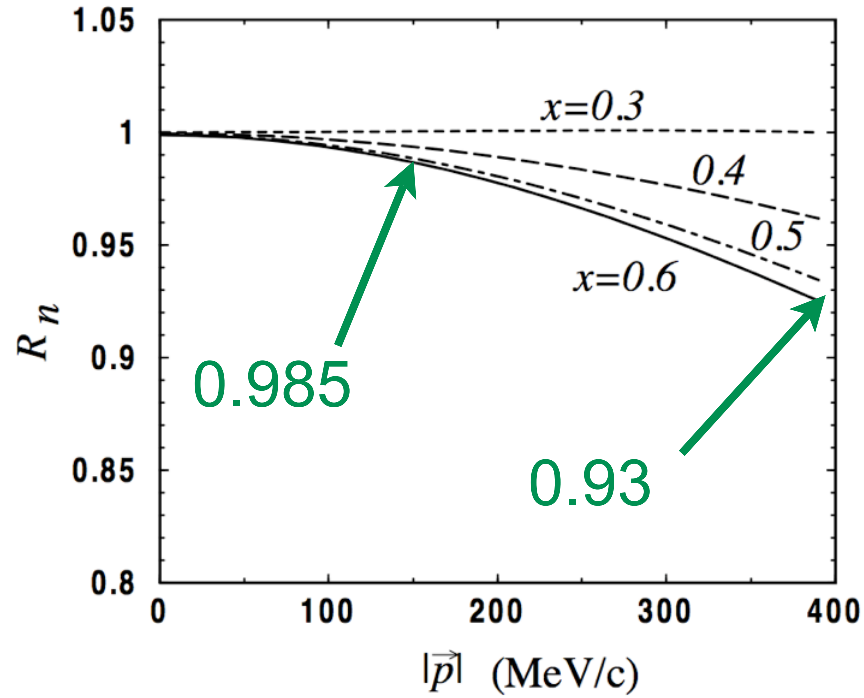
$$\int\int\int S^{\rm LC}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T = 1$$

Off-Shell Structure Functions

Liuti & Gross PLB356(95)157

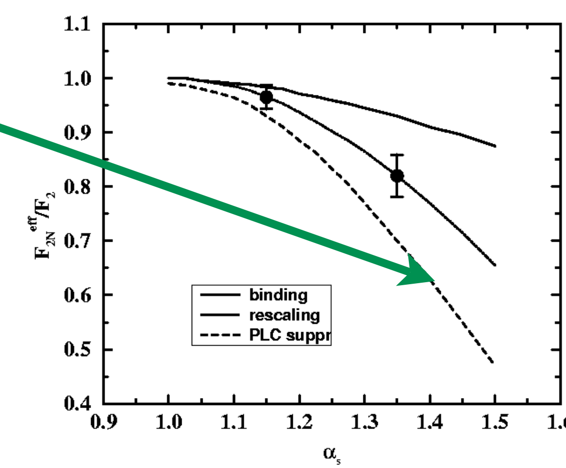


Melnitchouk et al, PLB335(94)11



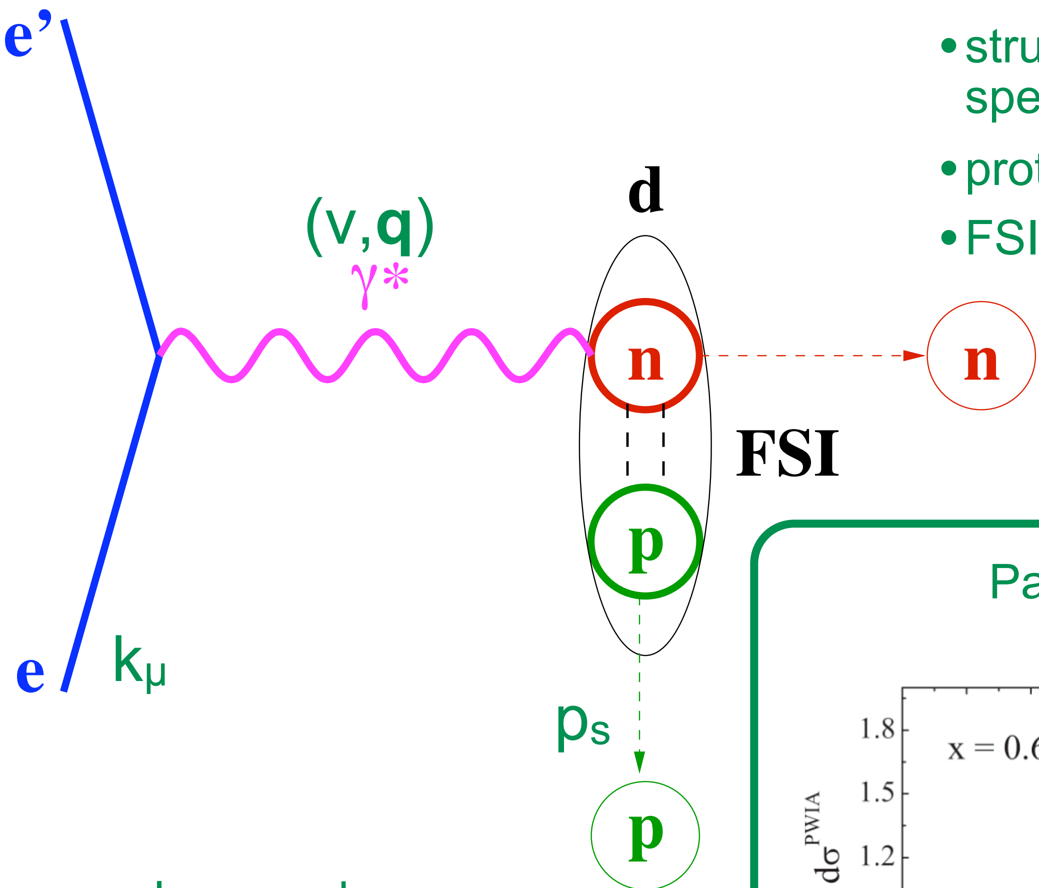
$$R_n \equiv (F_2^n)^{\mathrm{eff}} / (F_2^n)^{\mathrm{free}}$$

0.6



- R_n decreases with p_s or α
- at x*=0.5 and p_s=0.40 GeV/c, R_n deviates from 1 by 7-20% in these models
- at α=1.4 the deviation from unity could be 40%

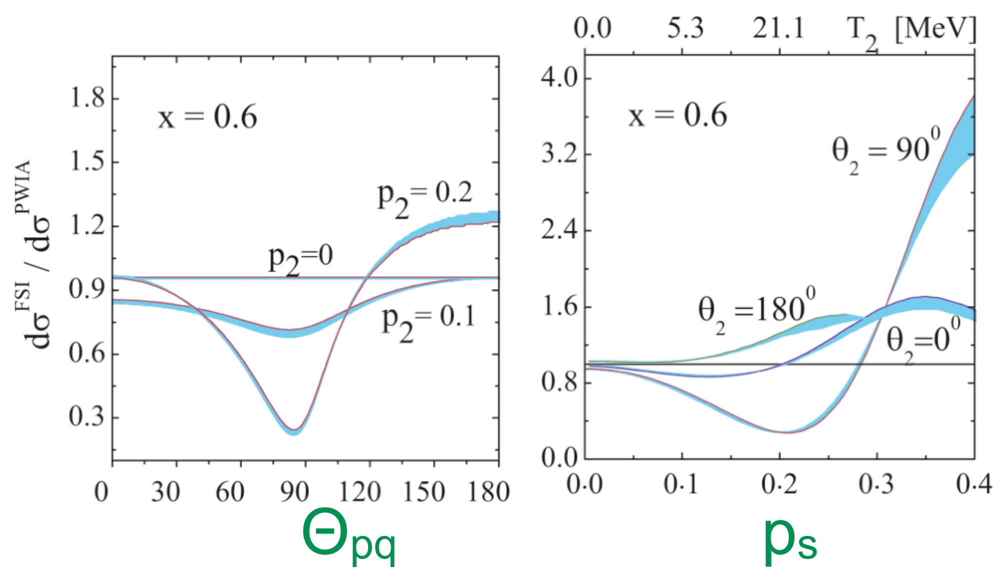
Final State Interactions



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

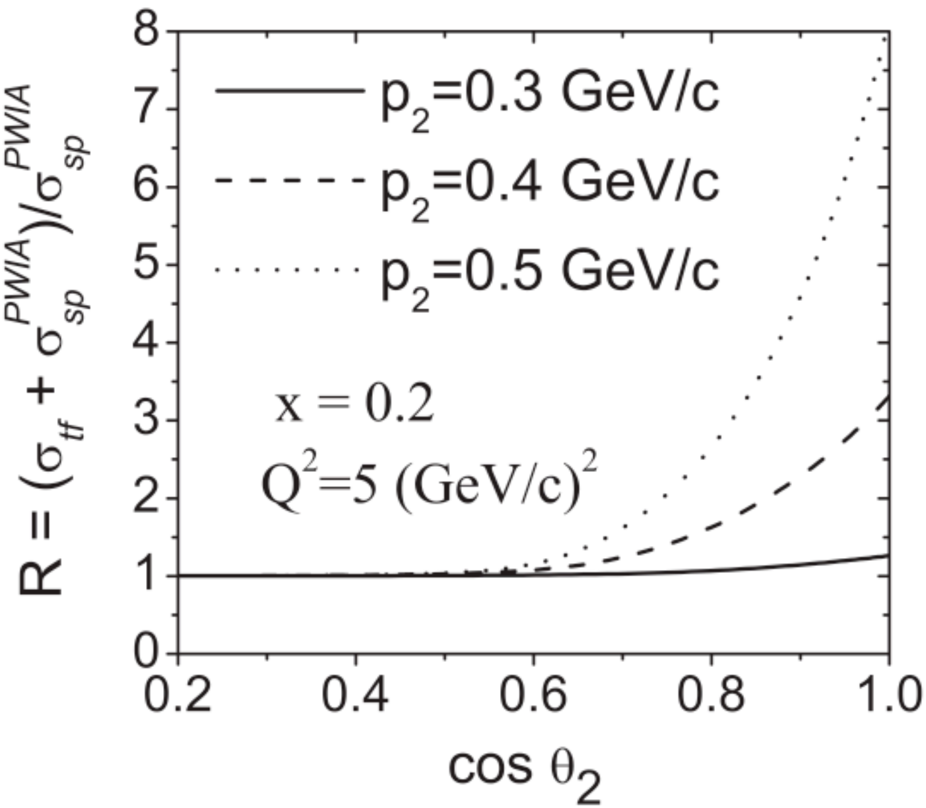
- several groups have calculated FSIs
- see e.g. posters by Wim Cosyn & Sabine Jeschonnek
- $\Theta_{pq} > 120^o$ minimizes FSIs

Palli et al, PRC80(09)054610



Target Fragmentation

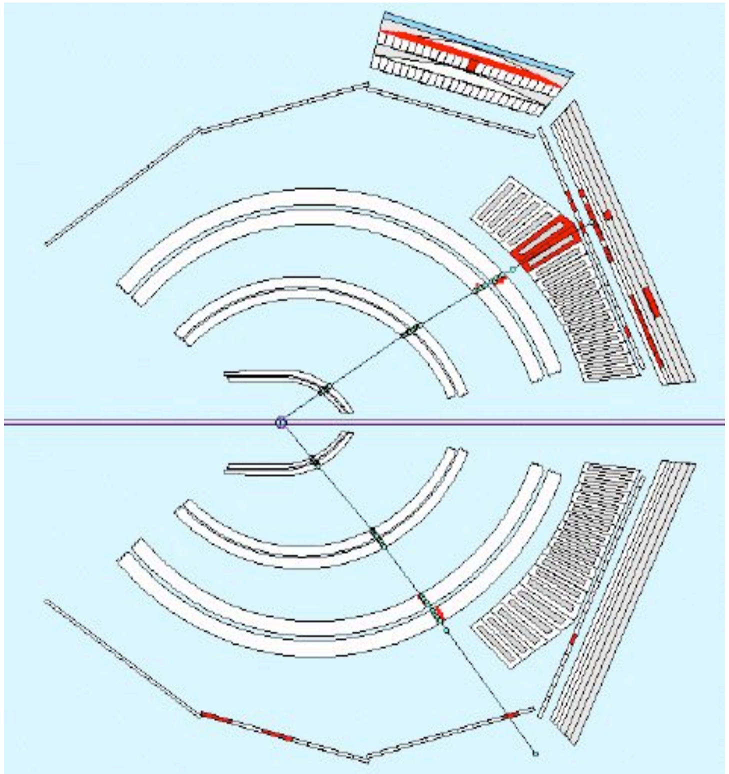
Palli et al, PRC80(09)054610



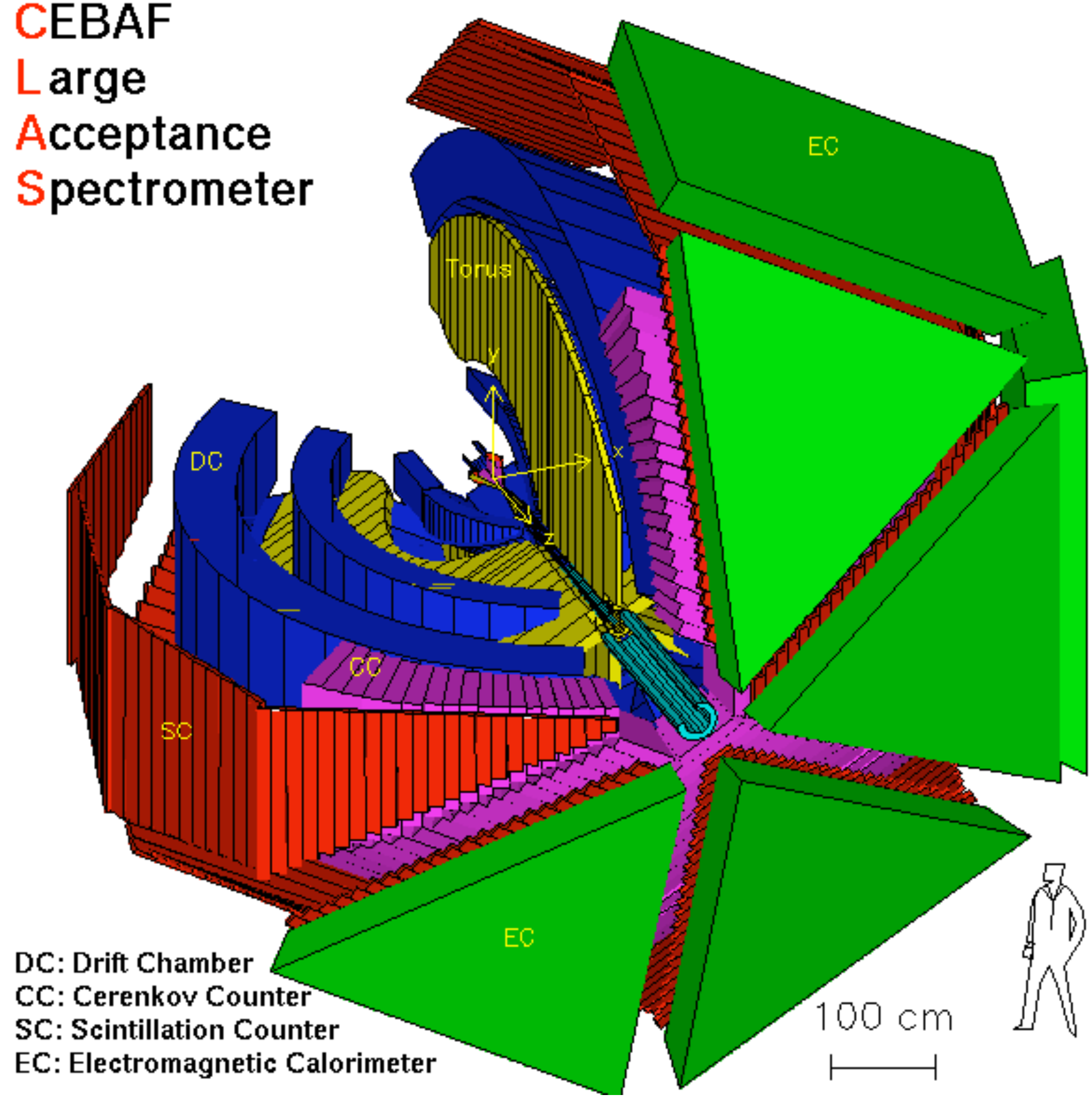
cos Θ_{pq}

- target fragmentation enhances the proton yield only at forward angles (cos Θ_{pq} >0.6)
- this can be ignored

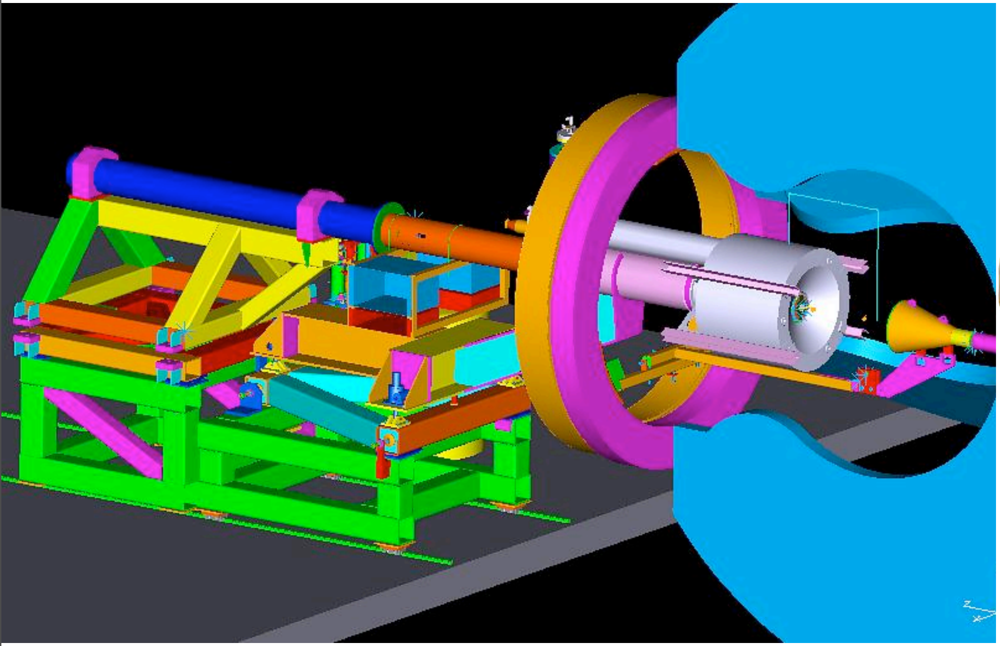
CLAS

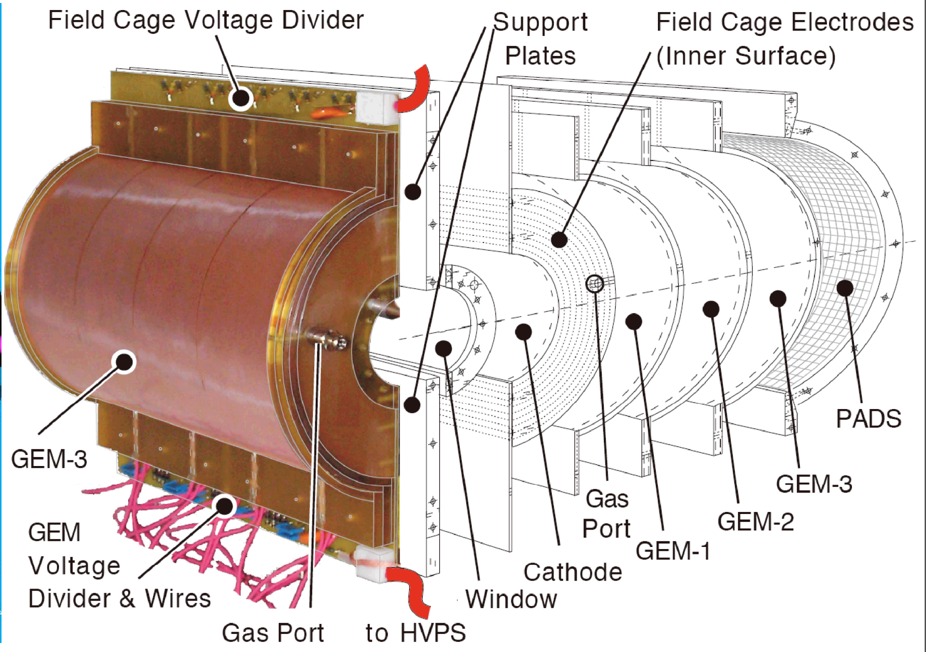


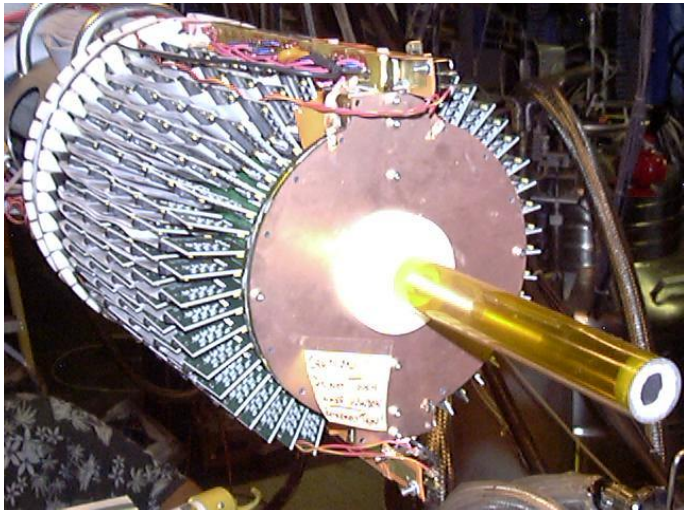
CEBAF
Large
Acceptance
Spectrometer



BoNuS Experiment

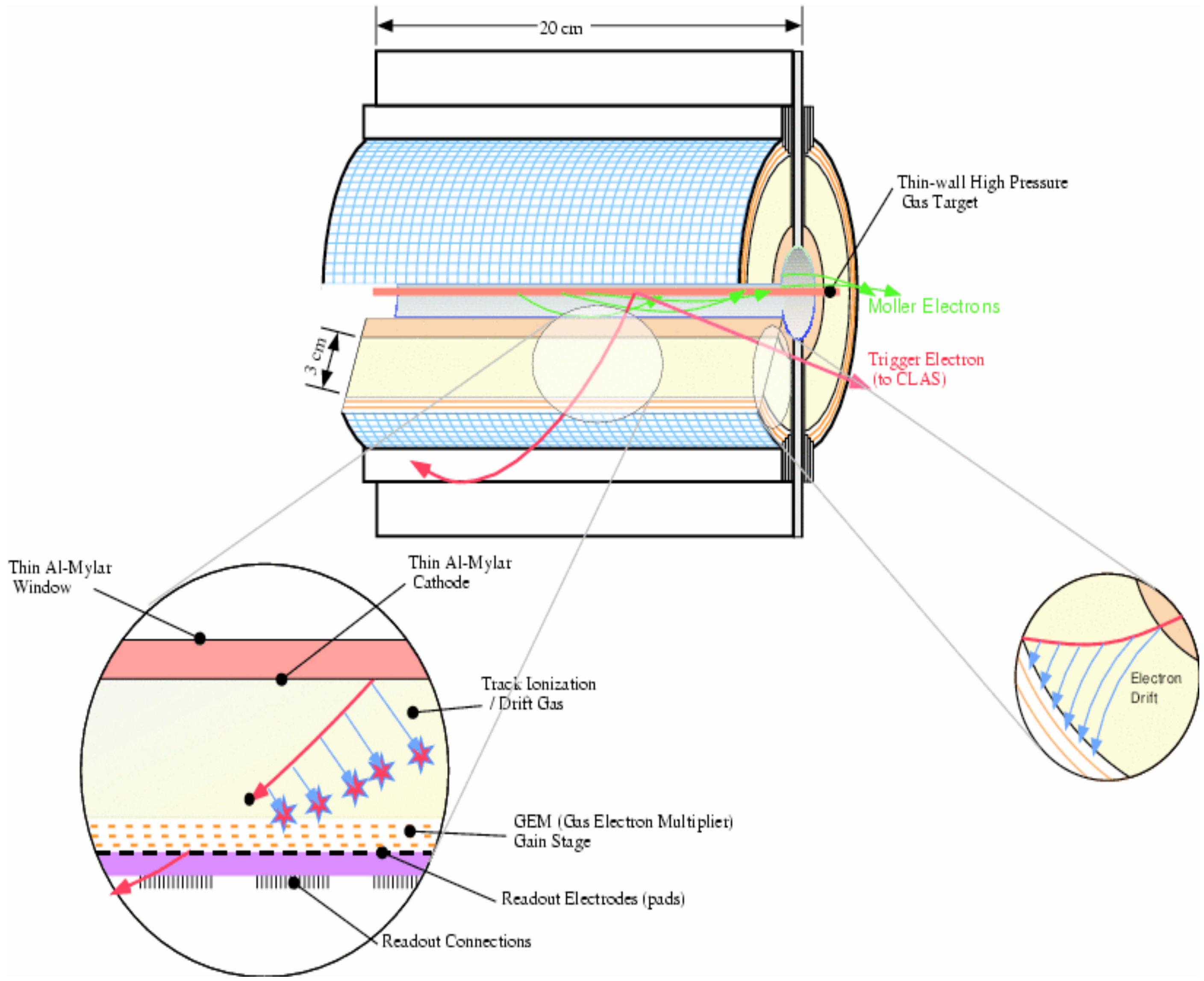






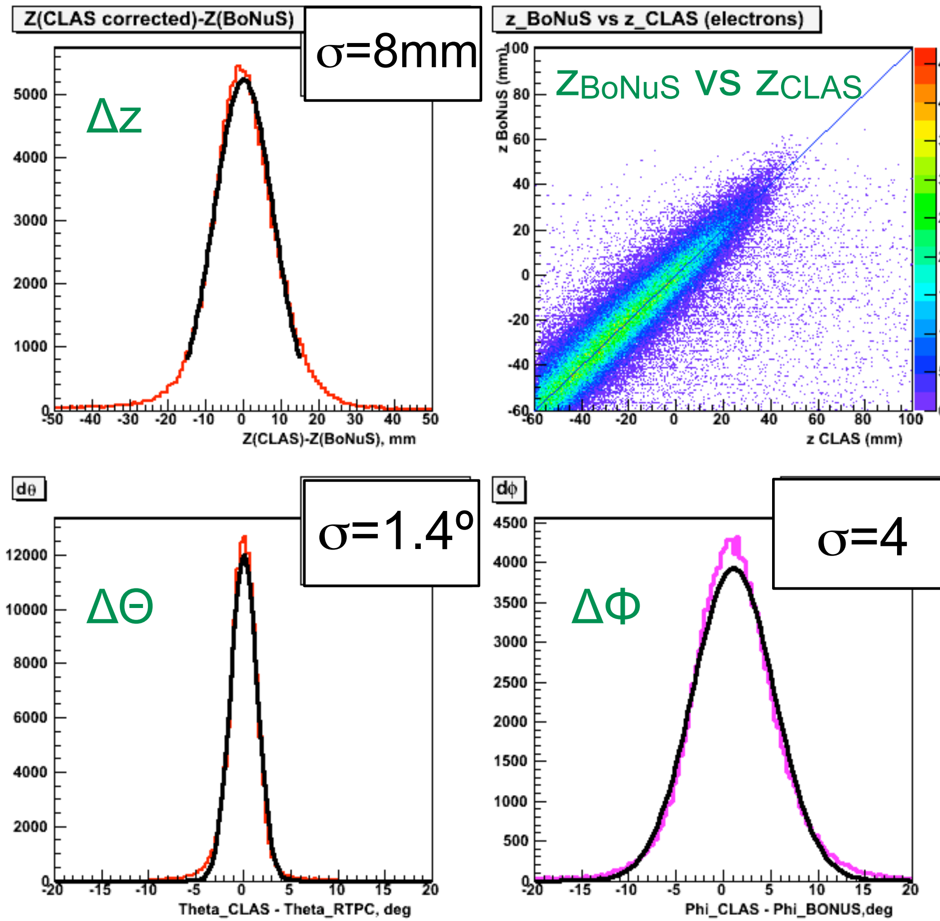
- Bound Nucleon Structure Experiment
- Hall B, JLab, CLAS
- $d(e,e'p_s)X$ with $0.07 < p_s < 0.15$ GeV/c
- E_{beam}=1.1, 2.1, 4.2, 5.3 GeV
- Radial time projection chamber for p_s
- Data taking in 2005

BoNuS Detector

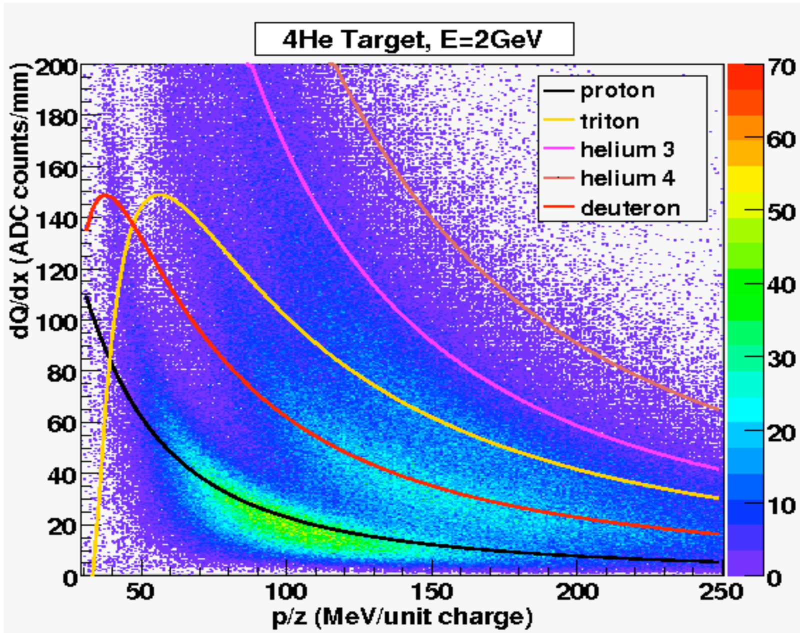


BoNuS RTPC Performance

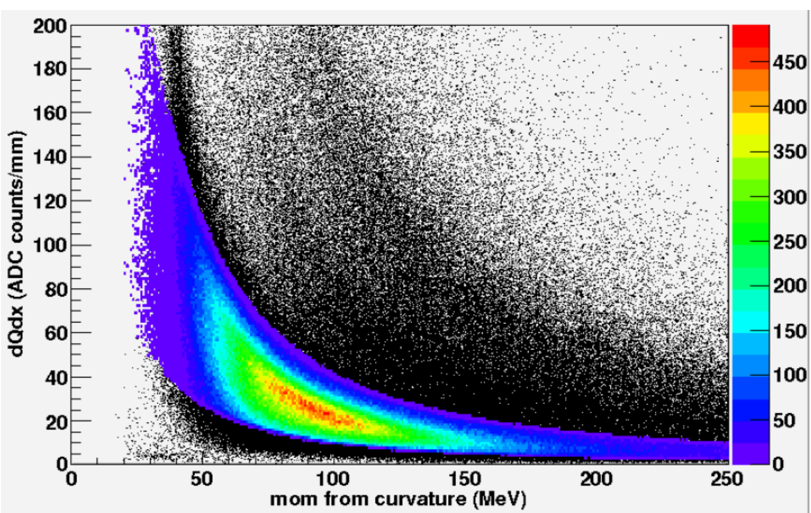
- upper left: dE/dx vs. p/Z for He target
- lower left: dE/dx vs. p for deuterium target
- below RTPC+CLAS resolution for common e^- events

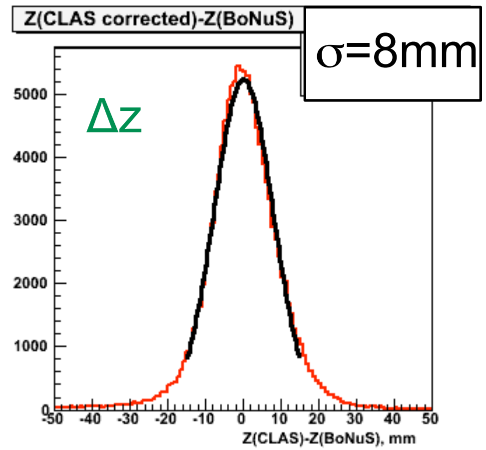


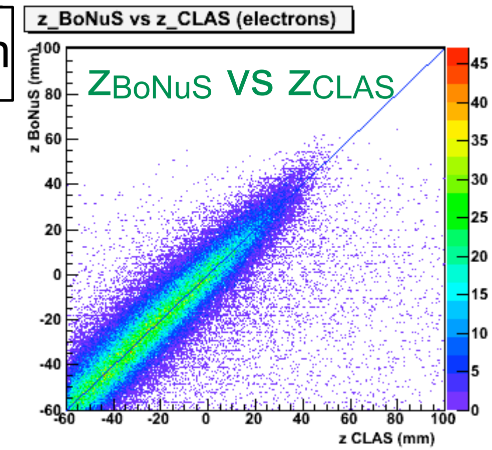
BoNuS RTPC Performance

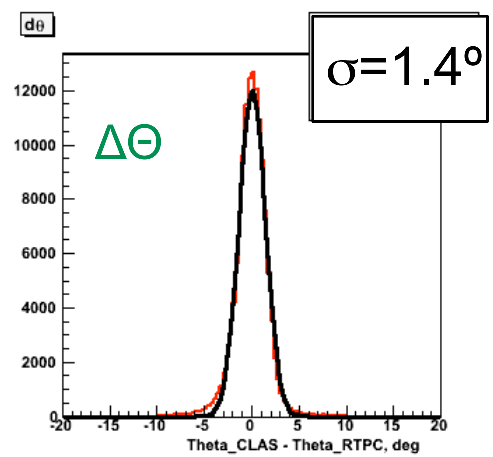


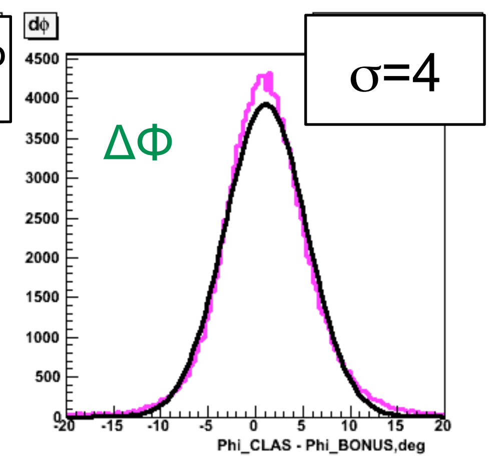
- upper left: dE/dx vs. p/Z for He target
- lower left: dE/dx vs. p for deuterium target
- below RTPC+CLAS resolution for common e⁻ events





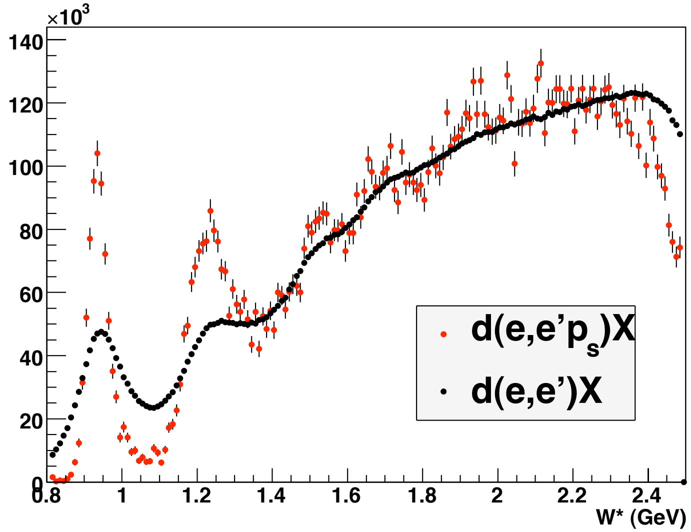


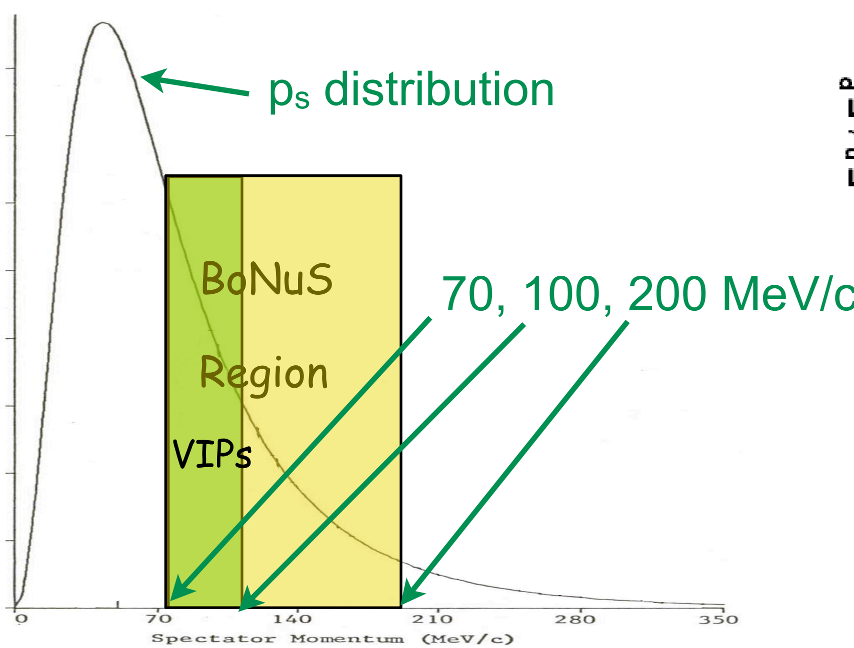


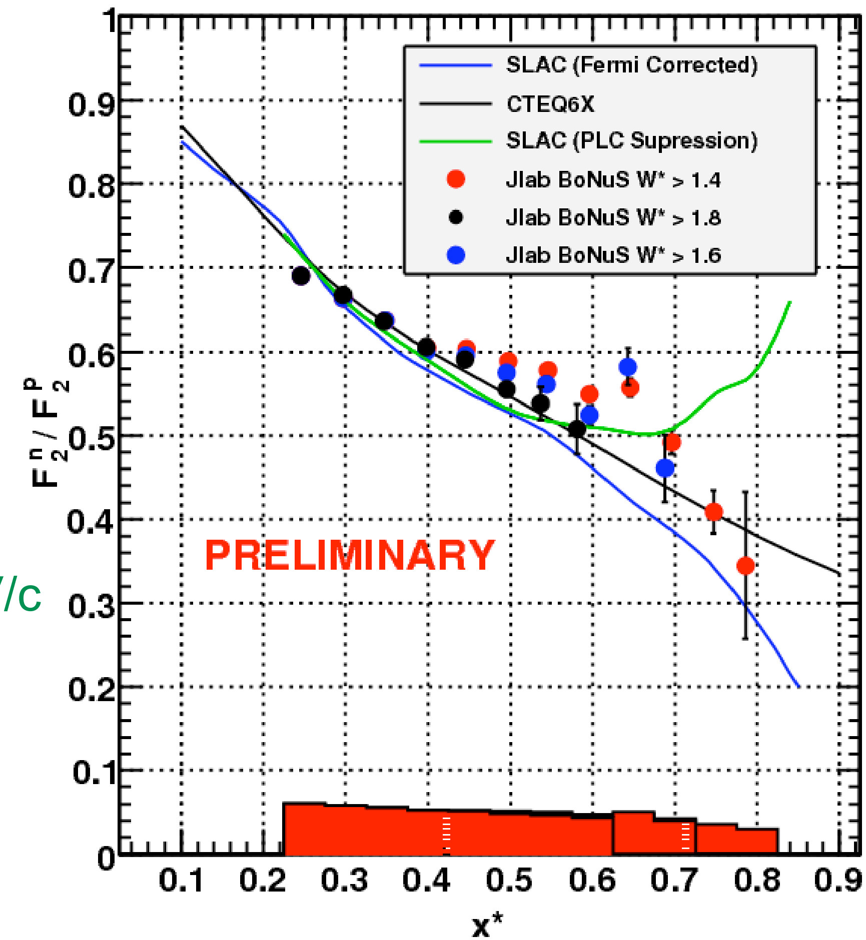


BoNuS Performance

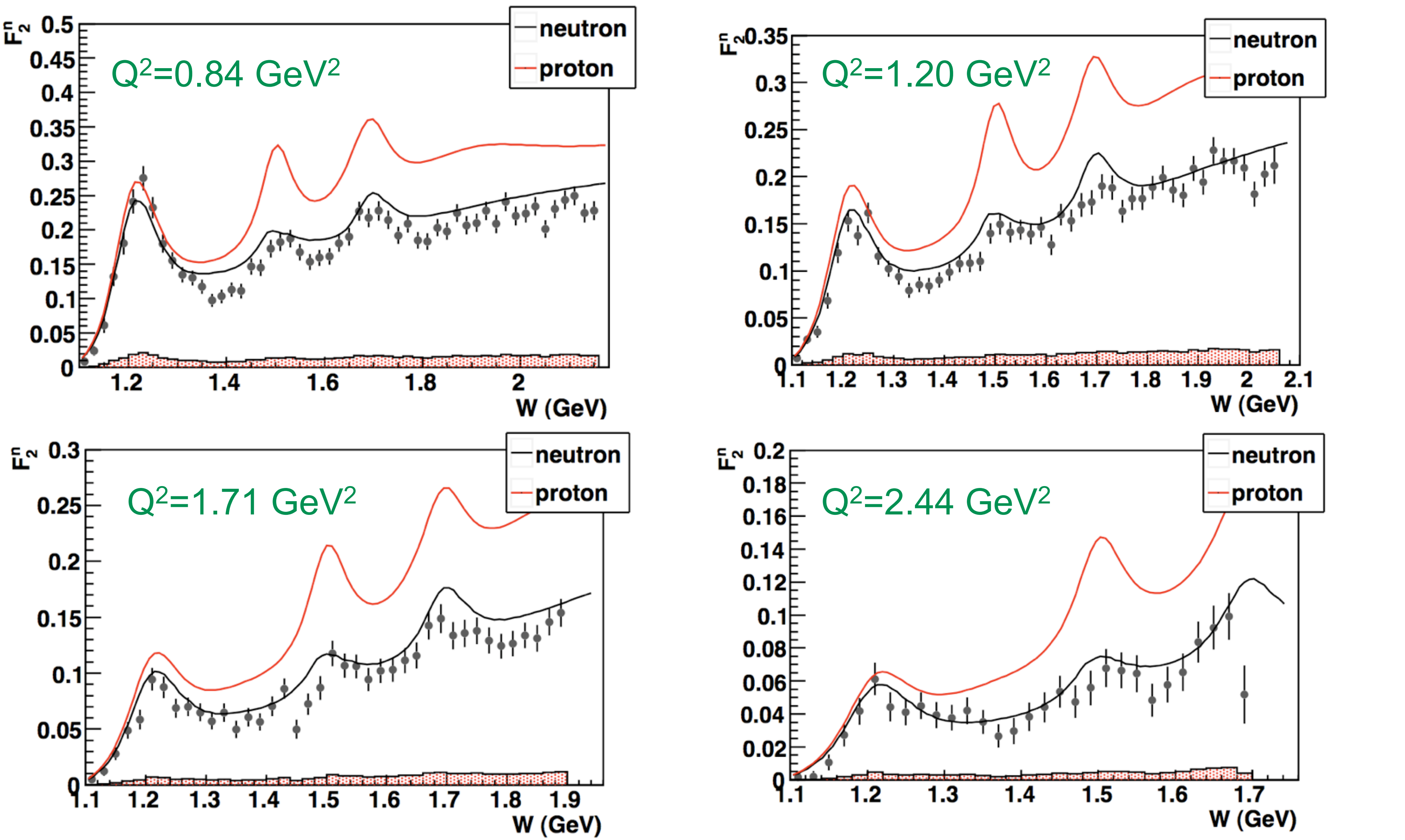
- Very Important Protons $70 < p_s < 100$ MeV/c
- Corrections make resonances stand out
- F_2^n/F_2^p is measured at high x*





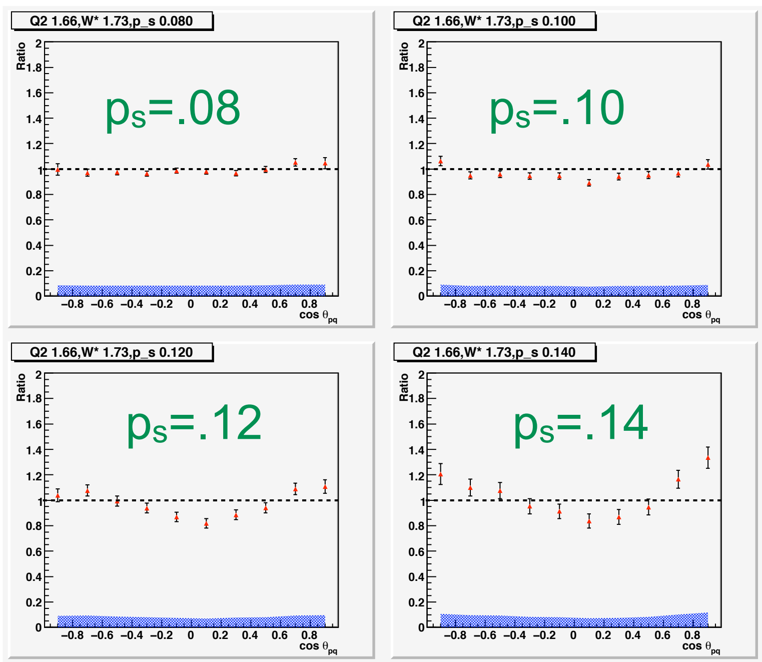


BoNuS F_2^n



4 of 16 spectra: $0.8 < Q^2 < 4.5$; E_{beam} = 4.2 & 5.3 GeV; Bosted/Christy world fits

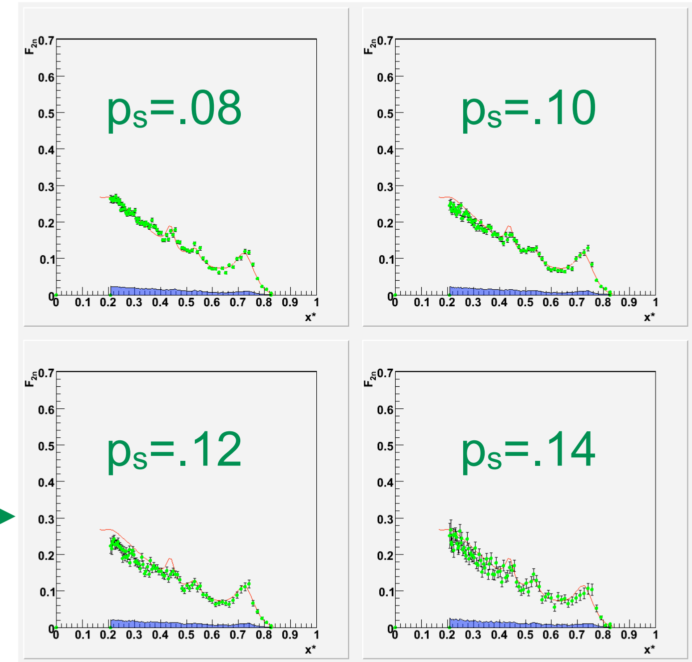
BoNuS Data



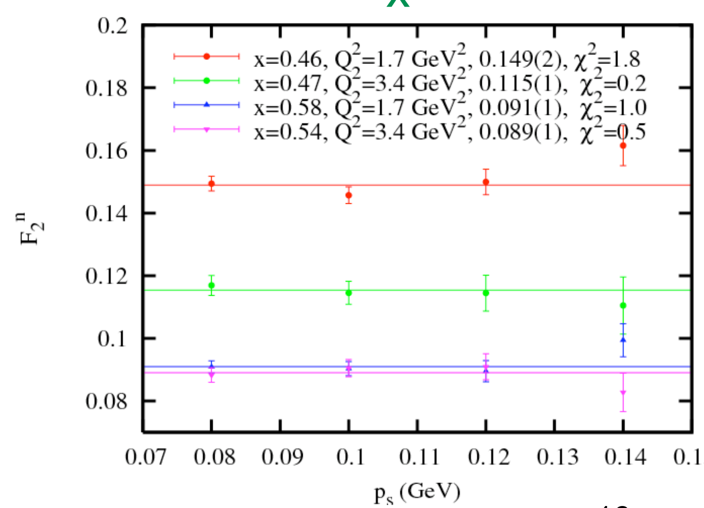
$\cos\theta_{pq}$

Data / PWIA ←

F_2^n →

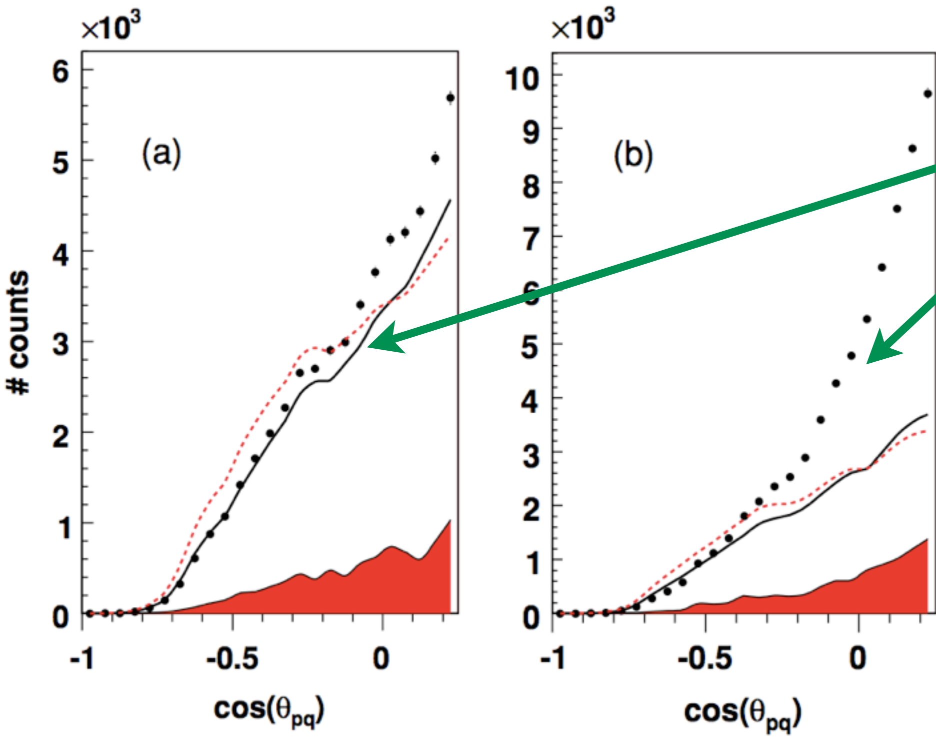


x*



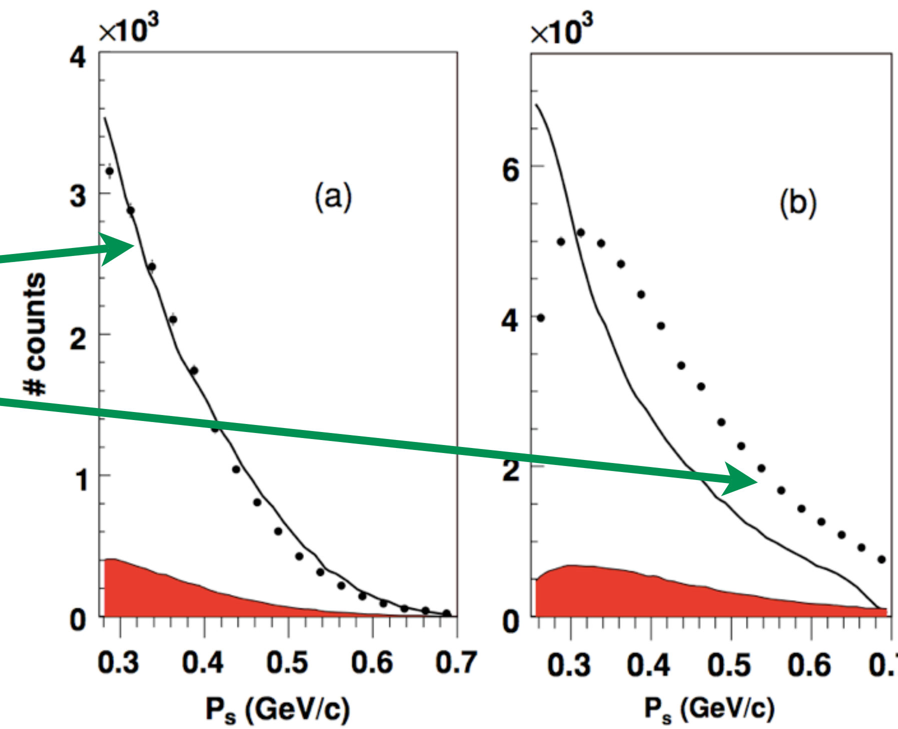
- FSIs start to appear for p_s >100 MeV/c
- F_2^n vs. x shows no p_s-dependence
- There is no observed off-shell modification of F_2^n for p_s<0.14 GeV/c

DEEPS Angular Distributions



Klimenko *et al.*, PRC**73**(06)035212

- (a) p_s = 0.28-0.32 GeV/c
- (b) p_s = 0.36-0.42 GeV/c
- (black line) PWIA w/ light cone w.f.
- (red dashed line) nonrelativistic w.f.
- Falloff is due to CLAS acceptance



- (a) -1 < cos Θ_{pq} < -0.3
- (b) -0.3 < cos Θ_{pq} < 0.3
- (black line) PWIA w/ light cone w.f.
- (red dashed line) nonrelativistic w.f.
- Θ_{pq} is the polar angle w.r.t. the **q**-vector

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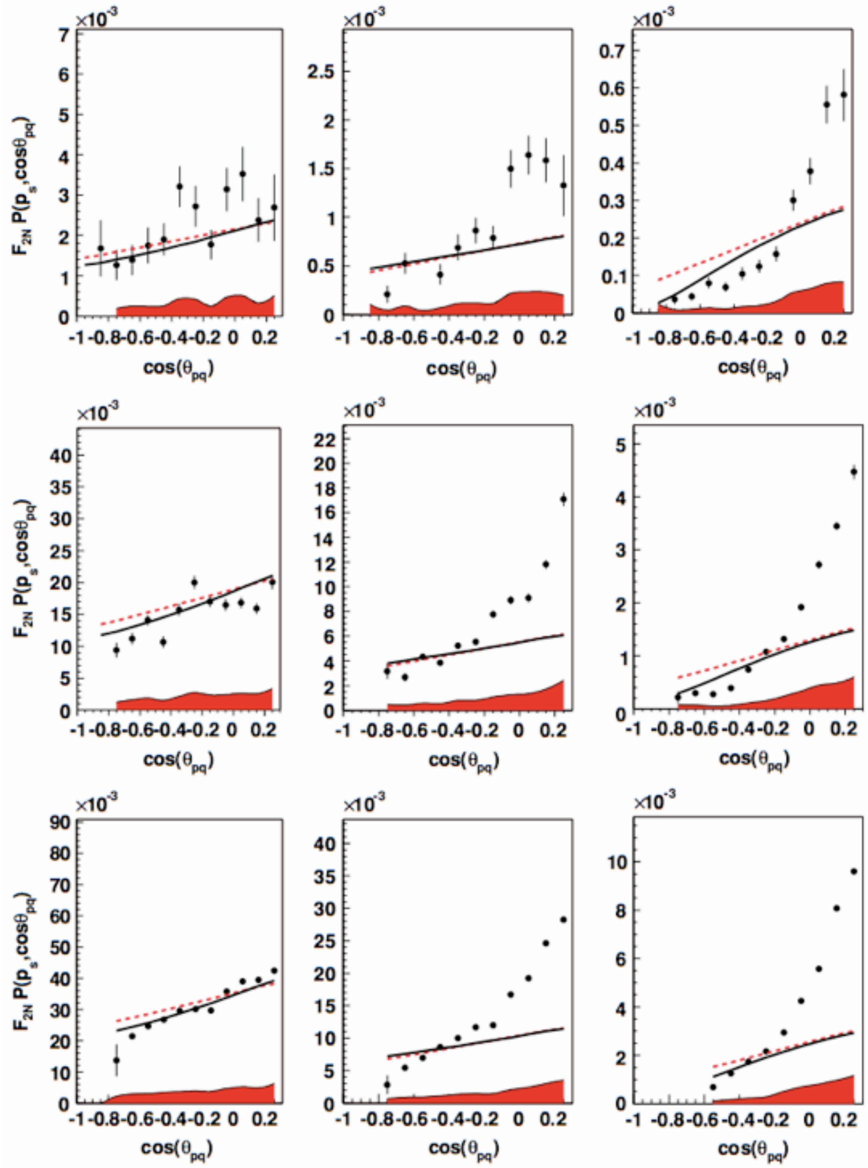
DEEPS $F_{2n} \times P(\vec{p}_s)$

W*=0.94

W*=1.50

W*=2.00

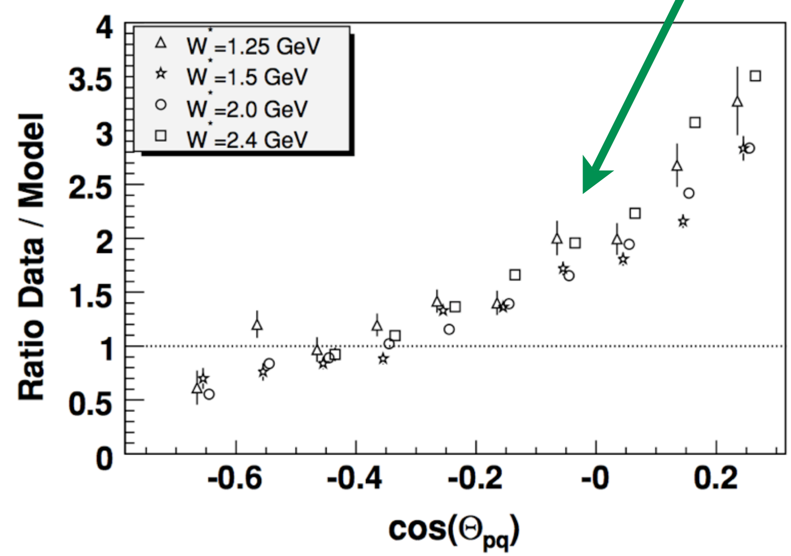


p_s=.30 p_s=.39 p_s=.56

Klimenko *et al.*, PRC**73**(06)035212

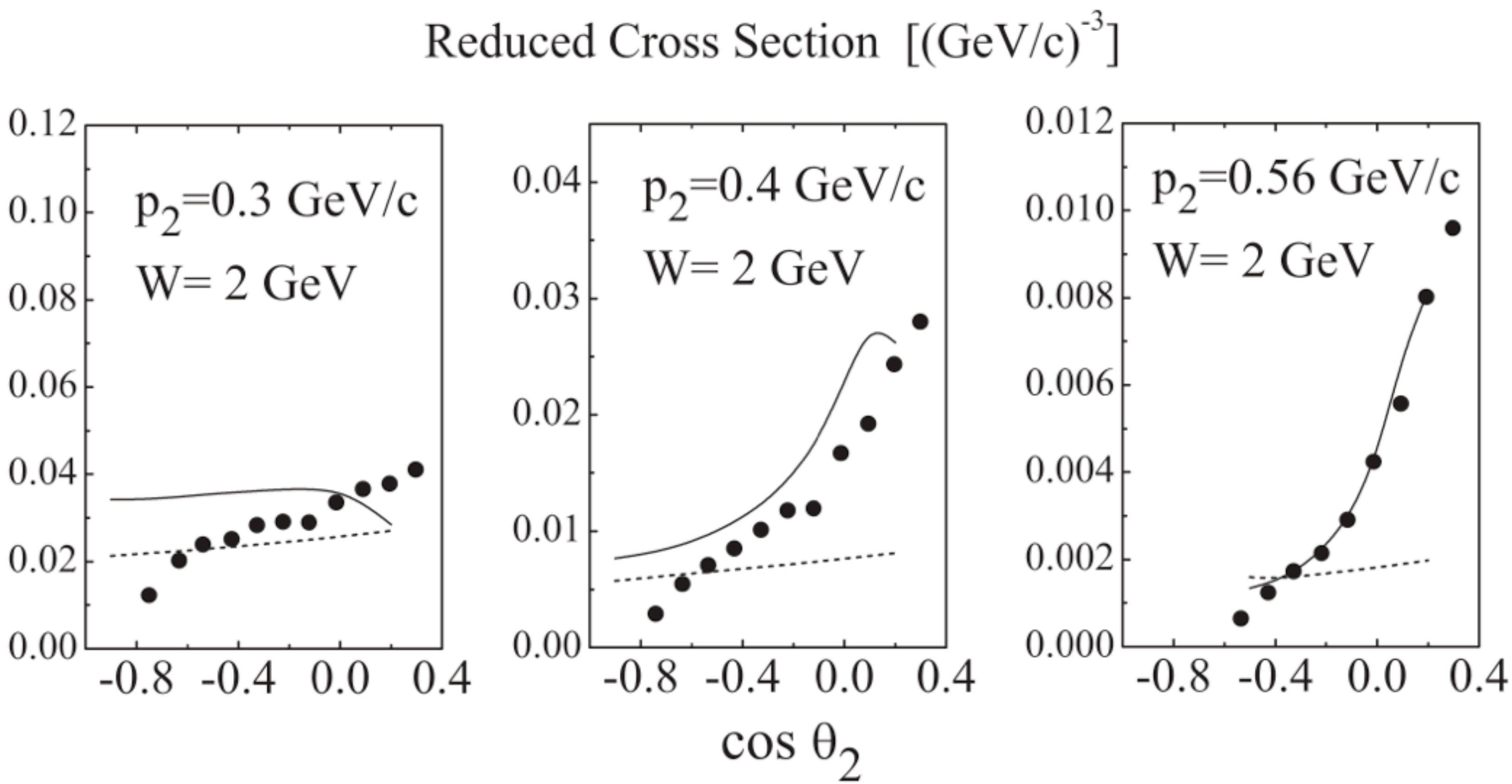
- (red dashed line) nonrelativistic w.f.
- (black line) light cone
- Θ_{pq} is the polar angle w.r.t. **q**

- Ratio of data to PWIA w/ light cone wf
- Ratio increases slightly with W*
- FSI at very backward angles?



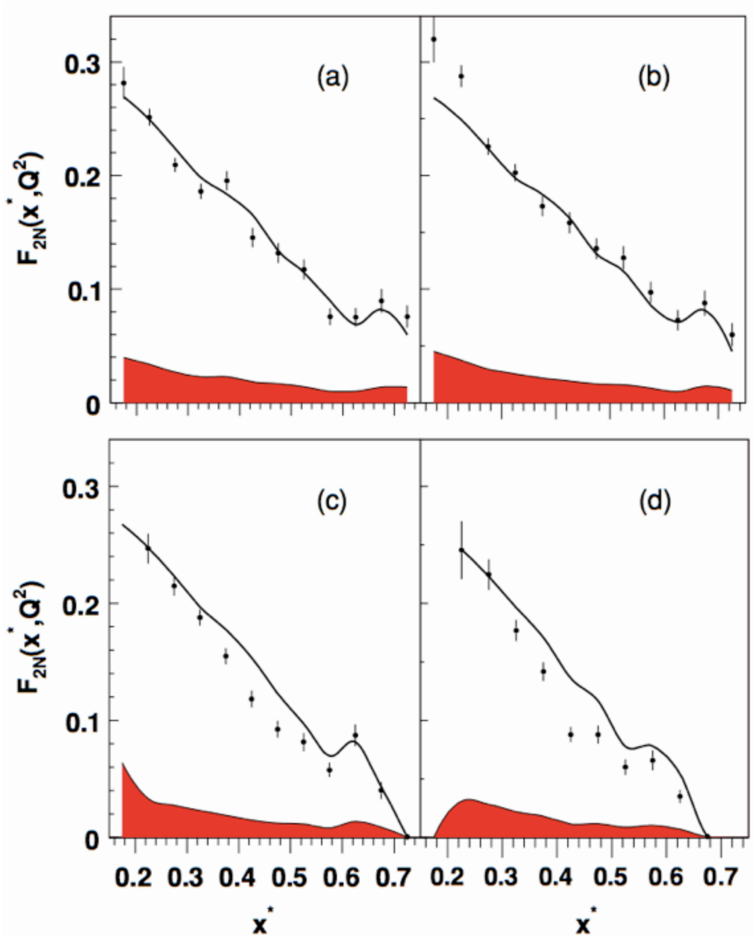
Calculations of FSI and Fragmentation

Palli et al, PRC80(09)054610



- A FSI model that works well for p_s=0.56 GeV/c misses the mark at p_s=0.4 and 0.3 GeV/c
- We see no discrepancy at p_s=0.56 from an off-shell F_2 for $\cos\Theta_{pq}$< -0.4
- Dotted lines show the PWIA expectation (i.e. no FSI, no modified F_2)

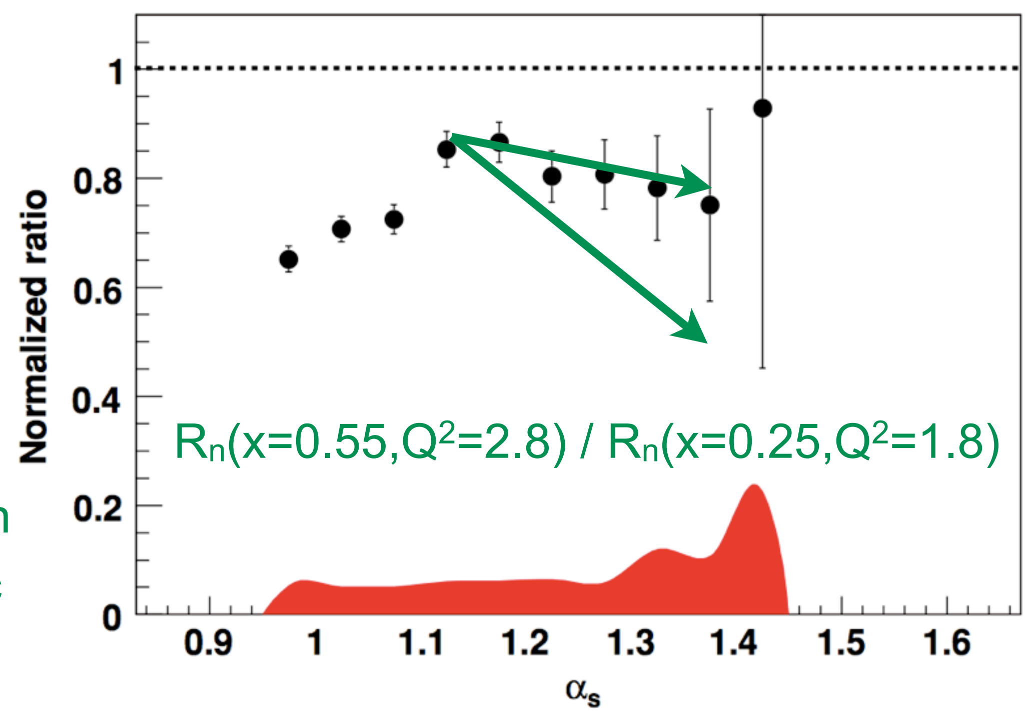
DEEPS $F_2^n(x^*,Q^2)$



- (black line) PWIA with light cone w.f.
- x^* is the corrected momentum fraction
- (a-d): p_s=0.30, 0.34, 0.46, 0.56 GeV/c
- at most a hint of p_s-dependence

Klimenko *et al.*, PRC**73**(06)035212

- Ratio of large to small EMC effect
- p_s dependence cancels in PWIA
- PWIA + off-shell predicts 1 at α_s=1
- FSI can upset norm
- No clear off-shell α_s-dependence



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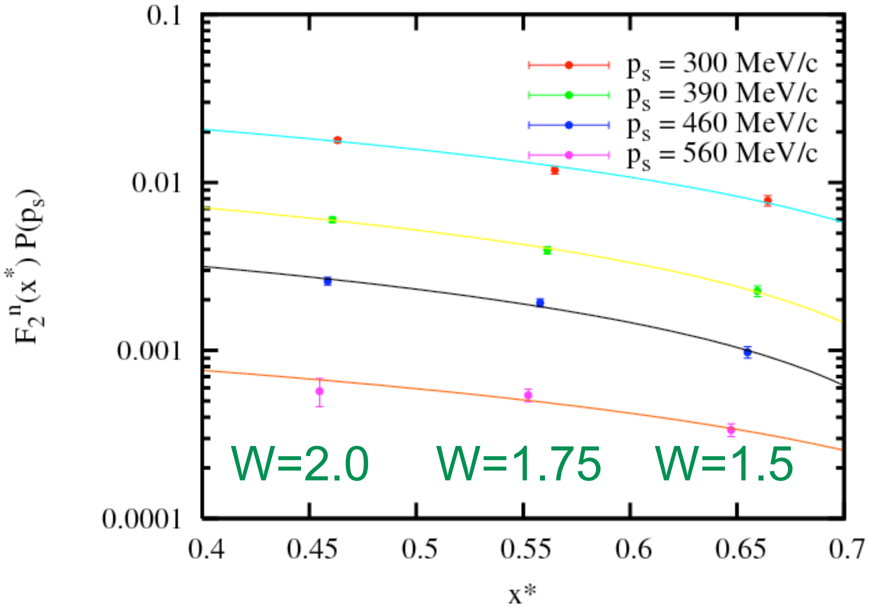
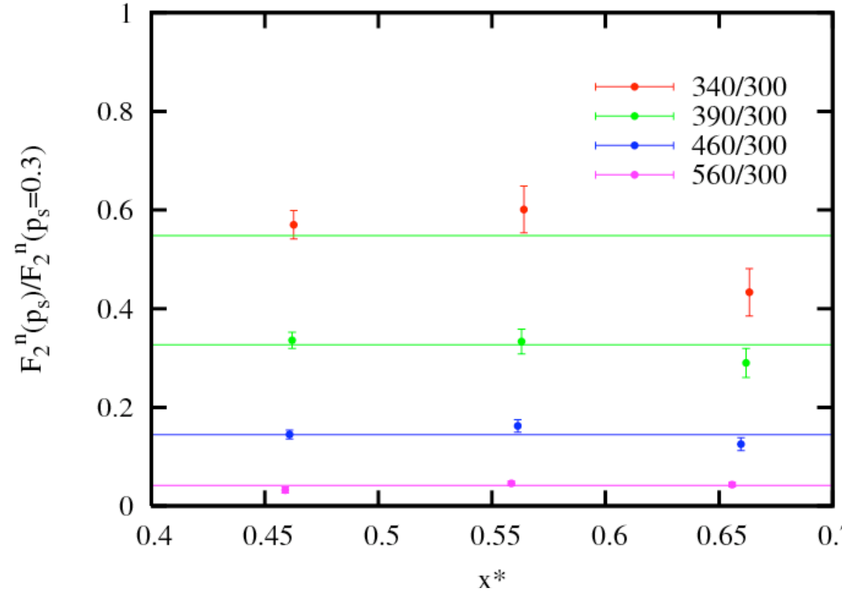
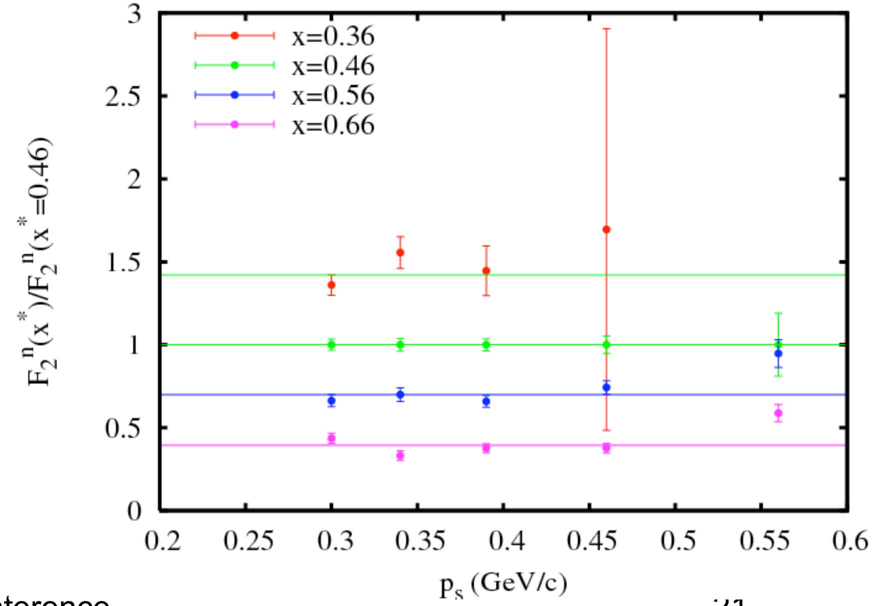
DEEPS $F_2^n(x^*,Q^2=2.8)$

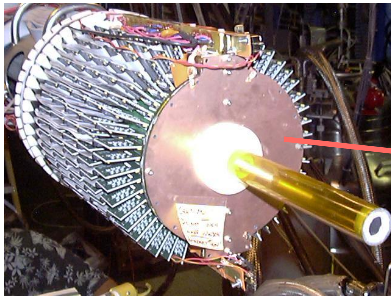


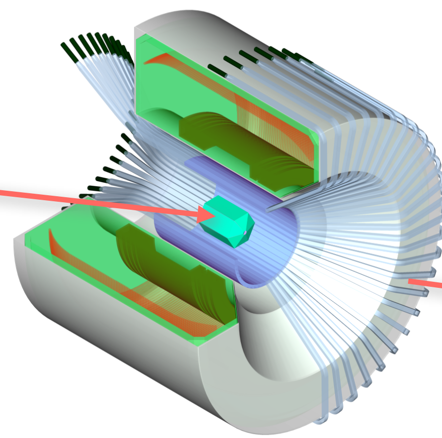


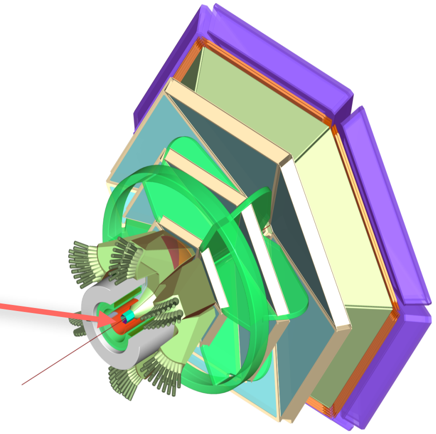


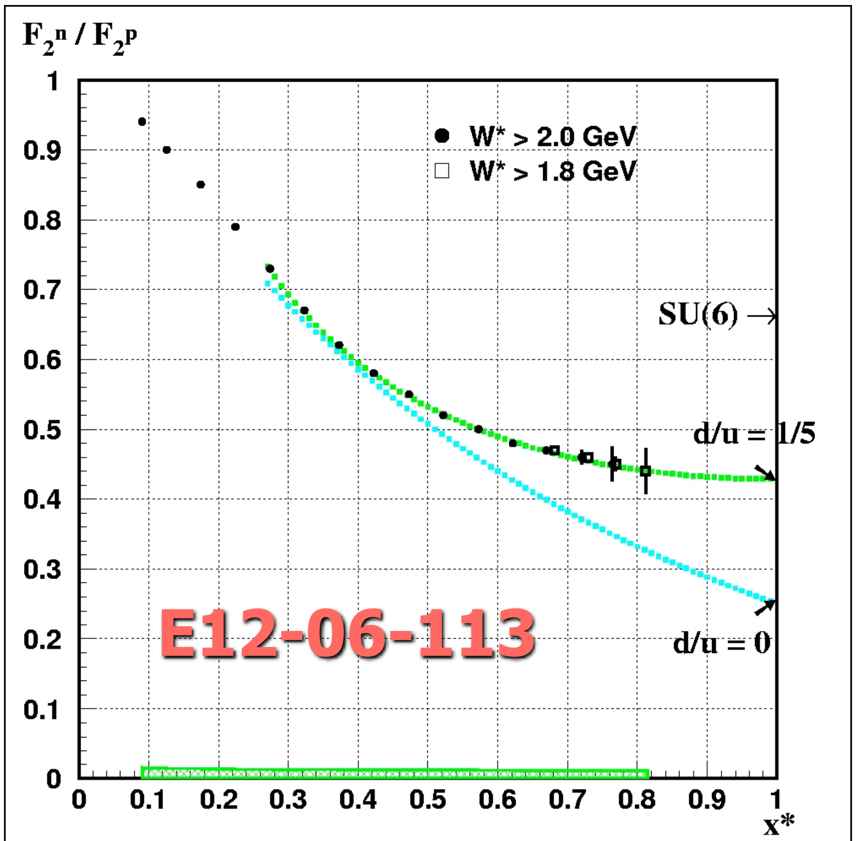
- pick -0.45 < cos < -0.3 where integrated data match PWIA
- above: $F_2(x^*)\,P(p_s)$
- top right: $F_2(x^*)\,P(p_s)$ / $F_2(x^*)\,P(300)$
- bottom right: $F_2(x^*)$ / $F_2(0.46)$
- no sign of off-shell F_2 vs. x^* (top right) or vs. p_s (bottom right)

BoNuS Plans for 12 GeV









Data taking:

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

DIS region:

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

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

Conclusions

- BoNuS:
  - we have measured F_2^n on a “free” neutron target
  - no effects from Fermi motion and the EMC
  - no evidence for off-shell structure for p_s<140 MeV/c
- DEEPS:
  - understanding FSIs is crucial to extract an off-shell F_2^n
  - data tend to favor models with a small off-shell F_2^n
- CLAS12:
  - new BoNuS proposal is conditionally approved
  - new DEEPS proposal is still a twinkle in our eyes