The Neutron Structure Functions from BoNuS using CLAS

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Elba XII Workshop

Electron-Nucleus Scattering XII

Marciana Marina, Isola d'Elba, Italy

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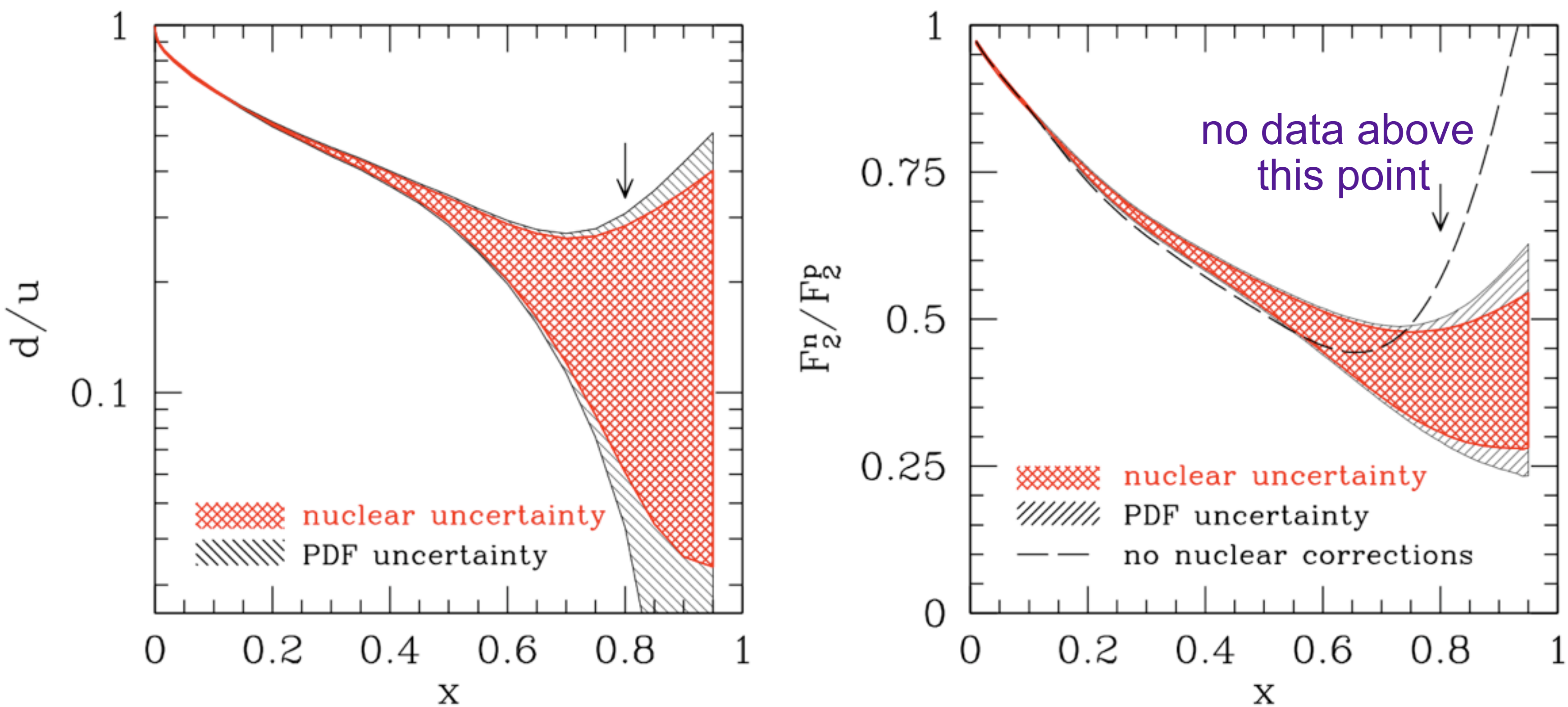
The Problem

- There is no free ~~lunch~~ neutron target
- Nuclear uncertainties inhibit extracting F_2^n from d(e,e′)X at large x
- We need to measure the neutron free of nuclear effects

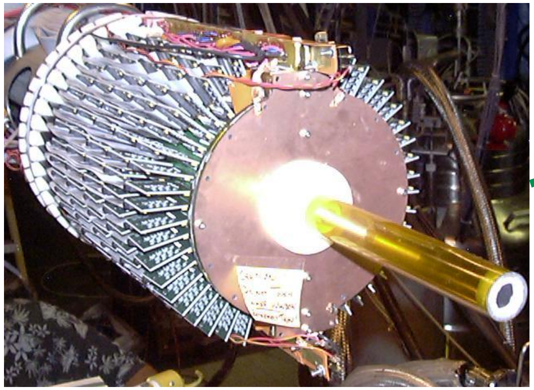


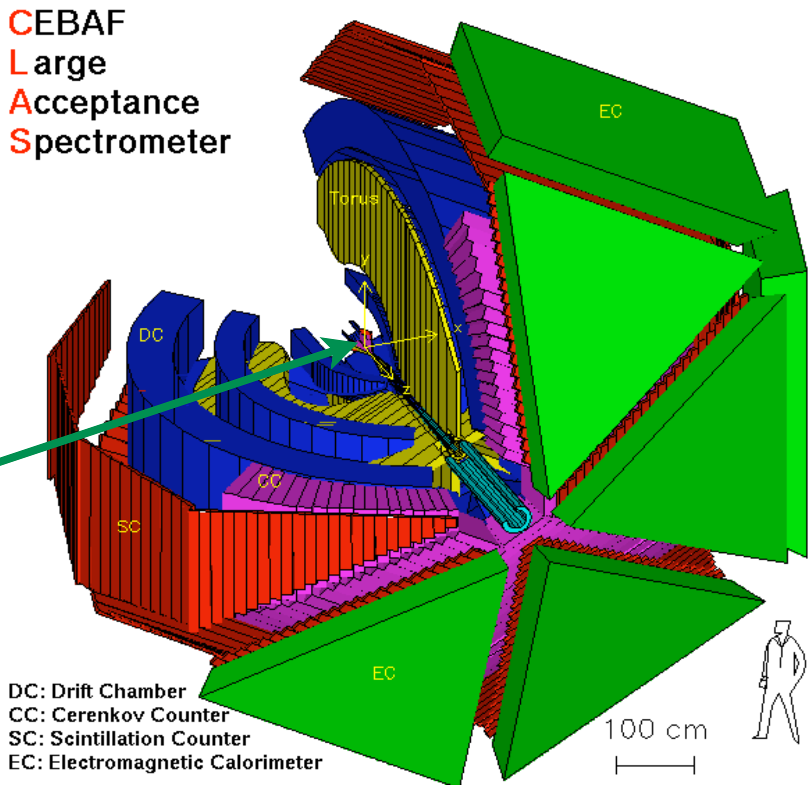
Accardi, AIP Conf. Proc. **1374**(11)383

A Solution: CLAS with RTPC

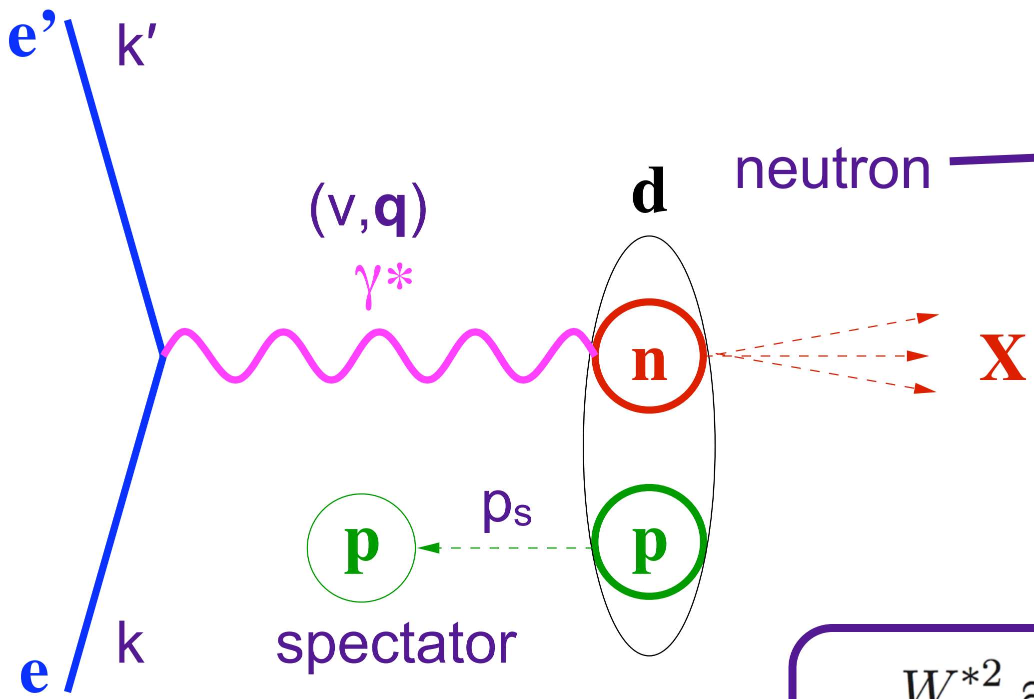
- Bound Nucleon Structure Experiment
- $d(e,e'p_s)X$ [(deep) inelastic]
- Deuterium target, spectator proton
- $70 < p_s < 150$ MeV/c
- JLab Hall B CLAS with an RTPC
- Measure F_2^n at high x

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





d(e,e'p$_s$)X



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

$$W^{*2} \approx M^{*2} - Q^2 + 2M_s\nu(2 - \alpha_s)$$
$$\alpha_s = \frac{E_s - p_{s\|}}{M_s}$$
$$x^* = \frac{Q^2}{2p_n \cdot q} \approx \frac{Q^2}{2M_s\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

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

PWIA Spectator Formalism

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

$$\times S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T,$$

Cross Section

Off-Shell F_2

$R=\sigma_L/\sigma_T$

Light Cone

Spectral Function

Nonrelativistic w.f.

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

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

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

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

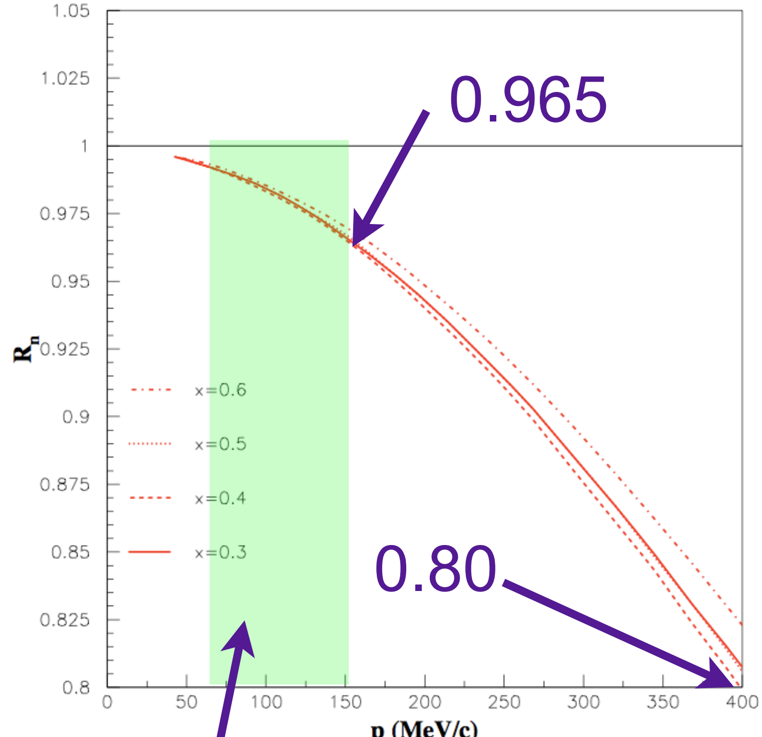
$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

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

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

Off-Shell Structure Functions

Liuti & Gross PLB**356**(95)157

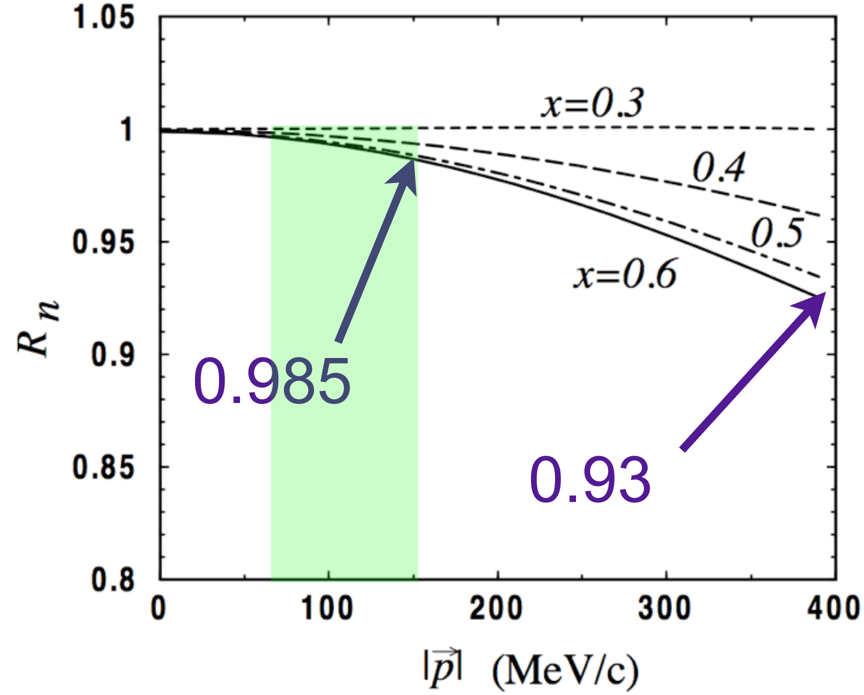


$$R_n \equiv (F_2^n)^{\text{eff}} / (F_2^n)^{\text{free}}$$

BoNuS p_s

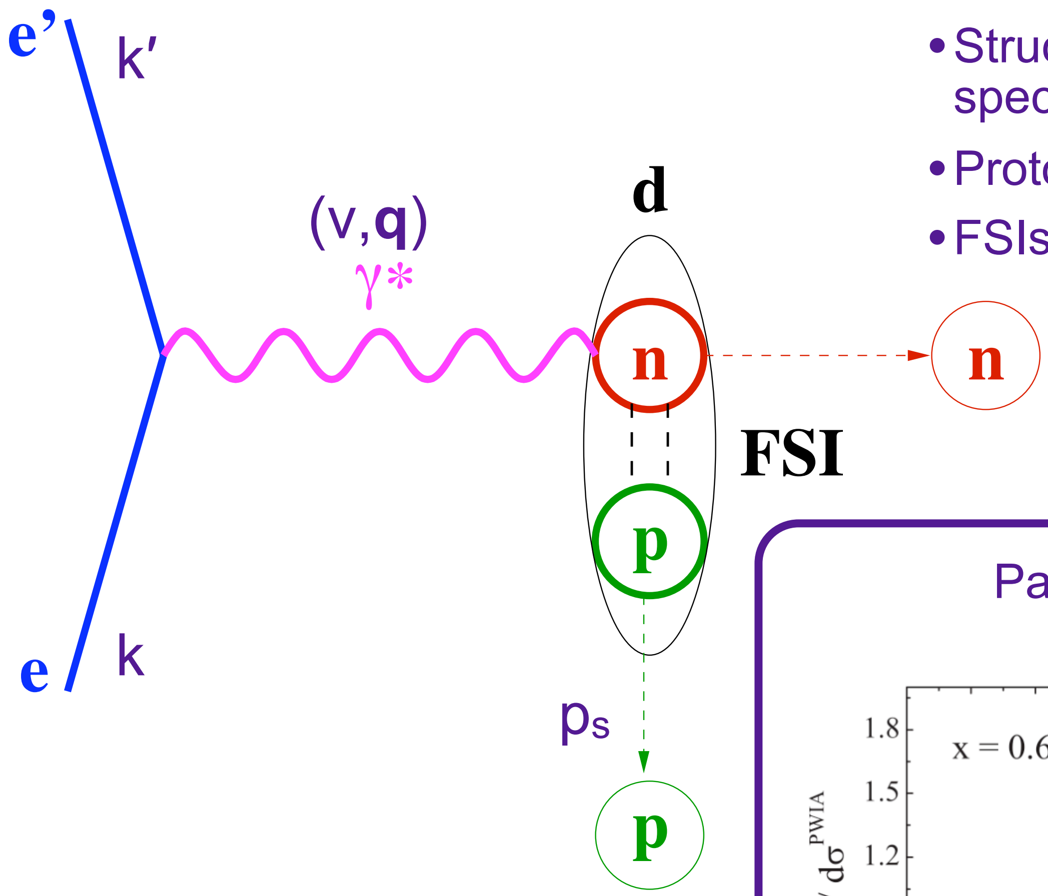
detection range

Melnitchouk *et al.*, PLB**335**(94)11



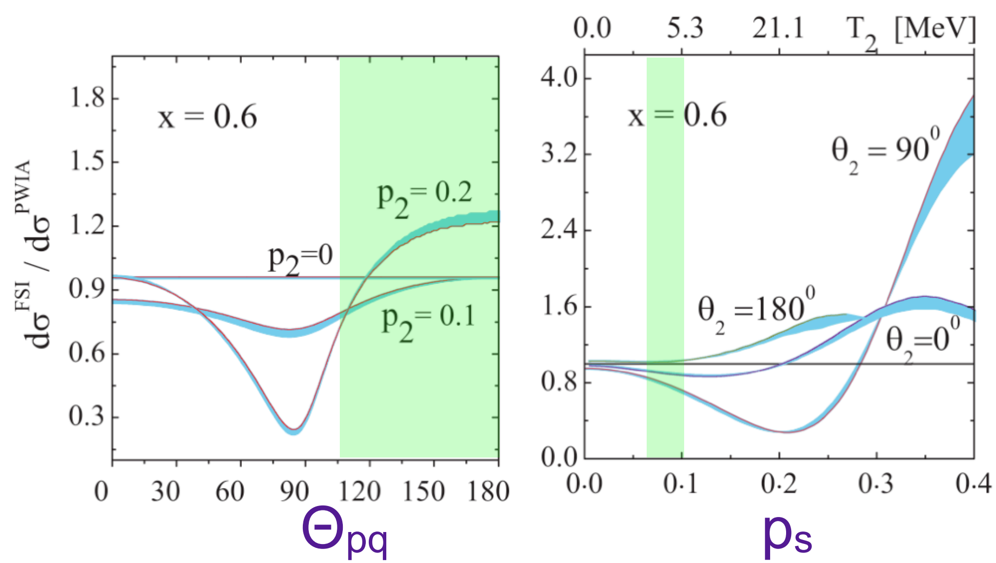
- R_n decreases with p_s or α_s
- At x*=0.5 and p_s=400 MeV/c, R_n deviates from unity by 7-20% in these models

Final State Interactions



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

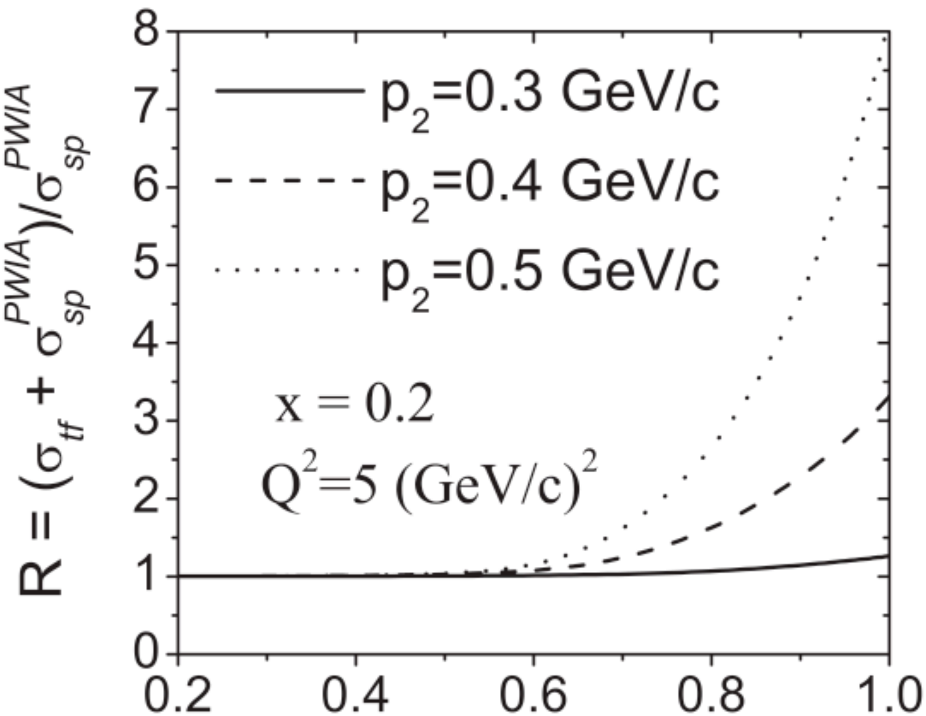
Palli *et al.*, PRC**80**(09)054610



- Several groups have calculated FSIs
- Θ_{pq} > 110° and p_s<100 MeV/c greatly reduces FSIs

Target Fragmentation

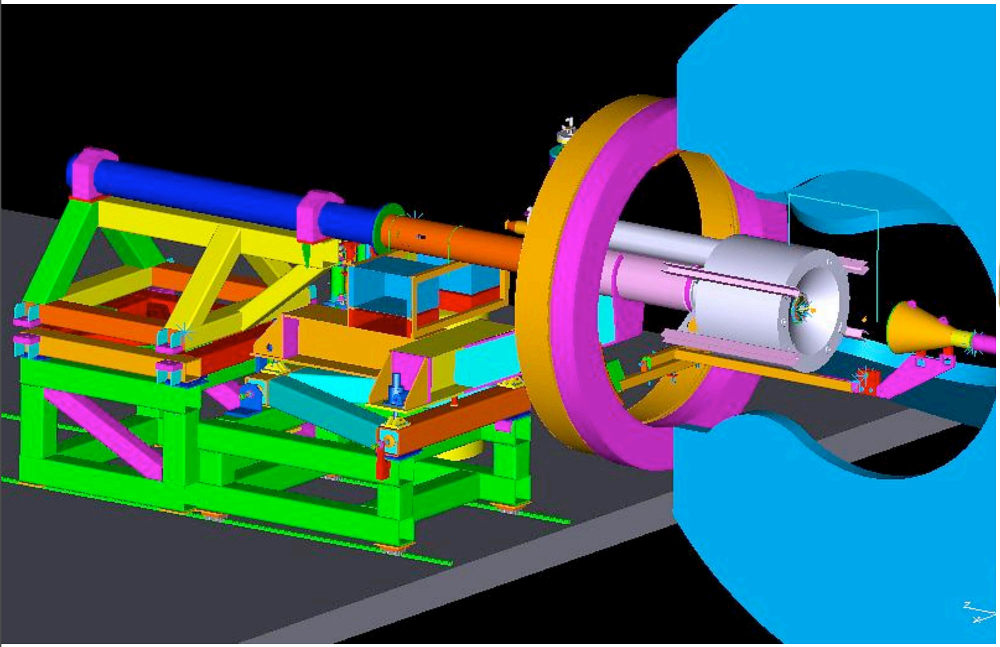
Palli *et al.*, PRC**80**(09)054610

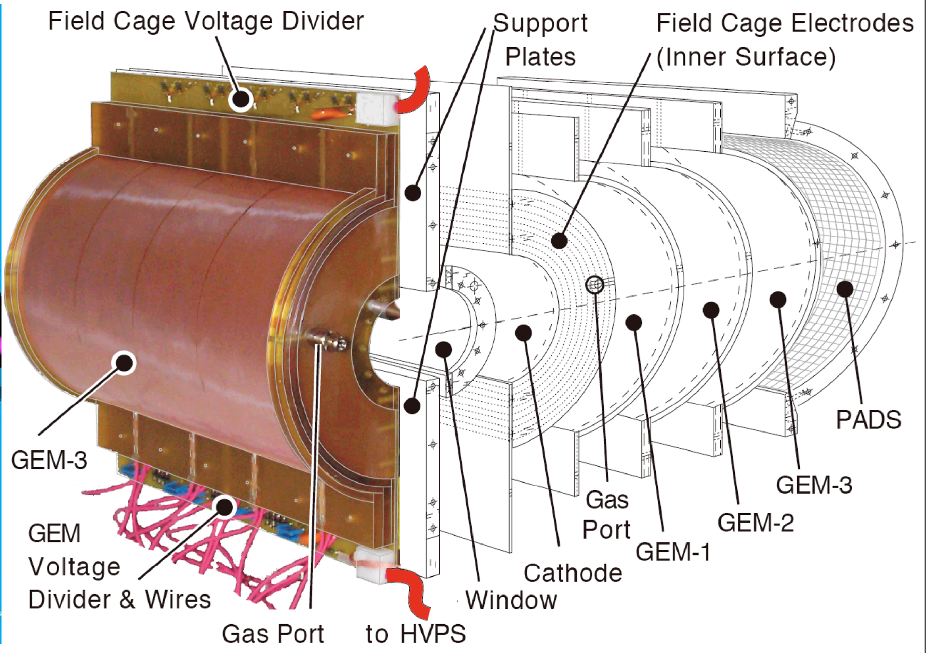


cos Θ_{pq}

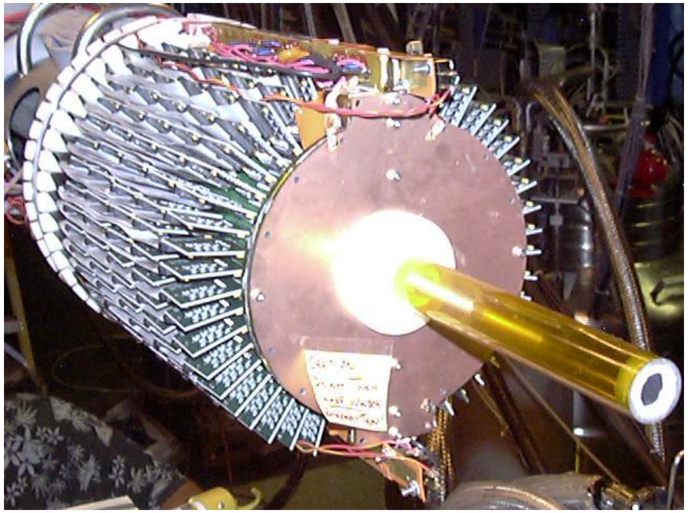
- Target fragmentation enhances the proton yield only at forward angles (cos Θ_{pq} >0.6)
- This can be ignored

BoNuS Experiment

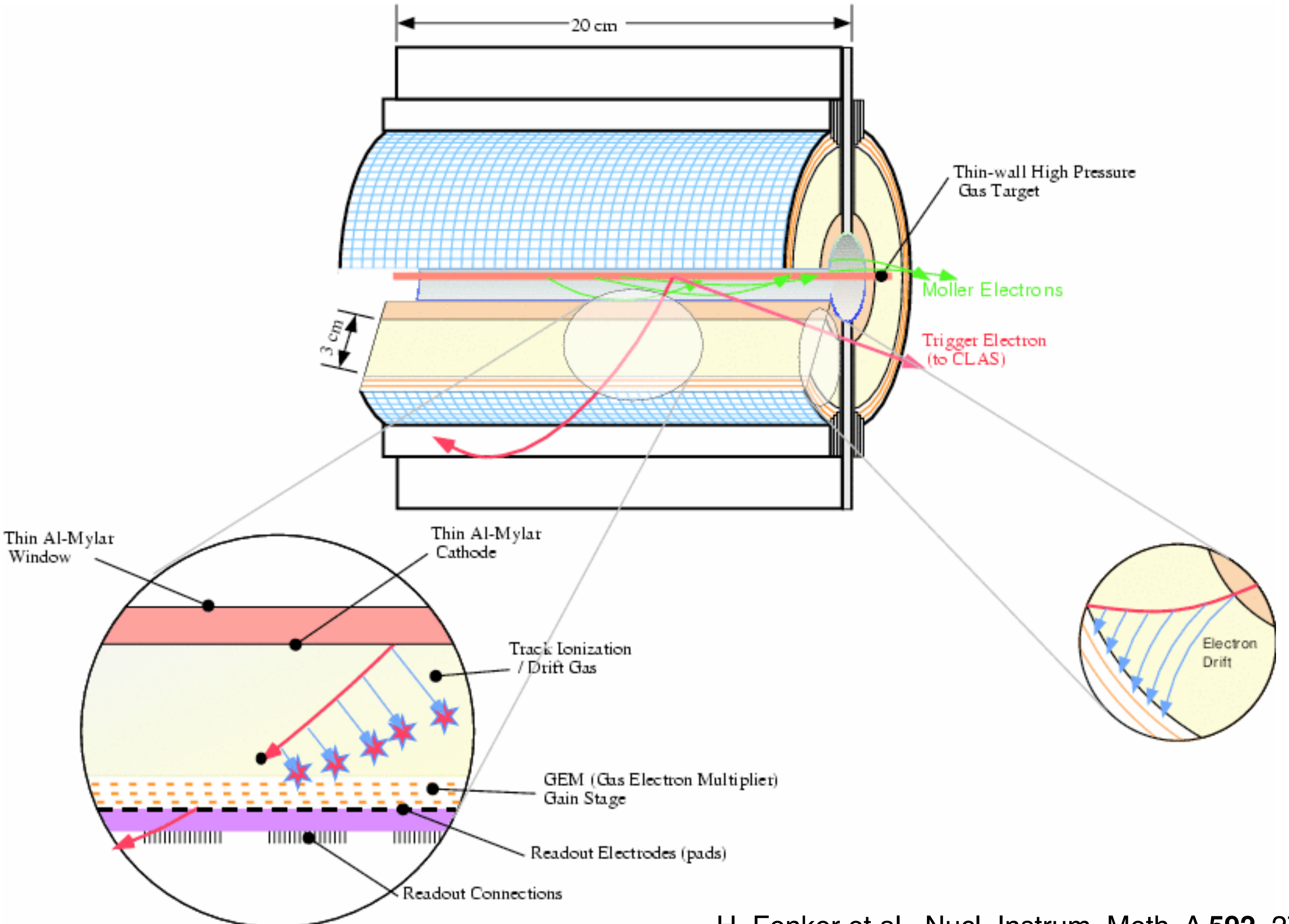




- Bound Nucleon Structure Experiment
- Hall B, JLab, CLAS
- $d(e,e'p_s)X$ with $70 < p_s < 150$ MeV/c
- E_{beam}=1.1, 2.1, 4.2, 5.3 GeV
- Radial time projection chamber for p_s
- Data taking in 2005

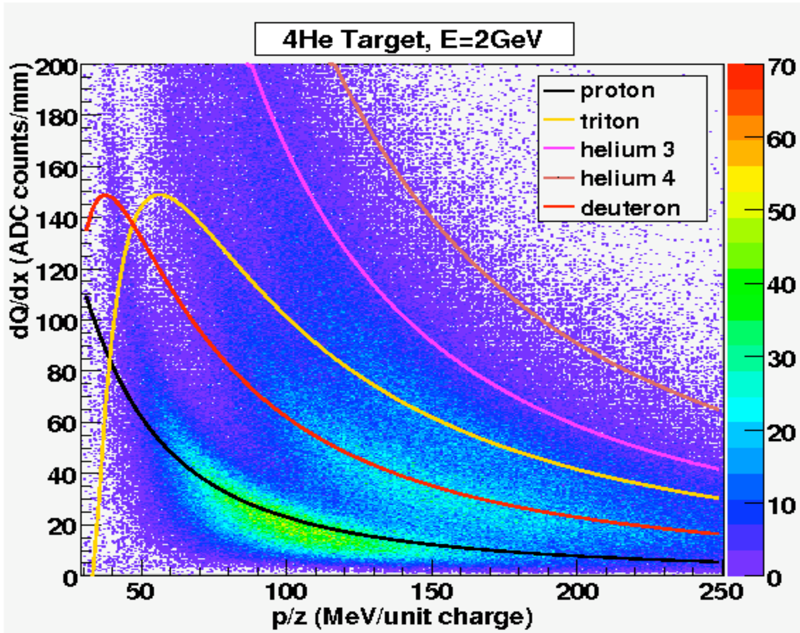


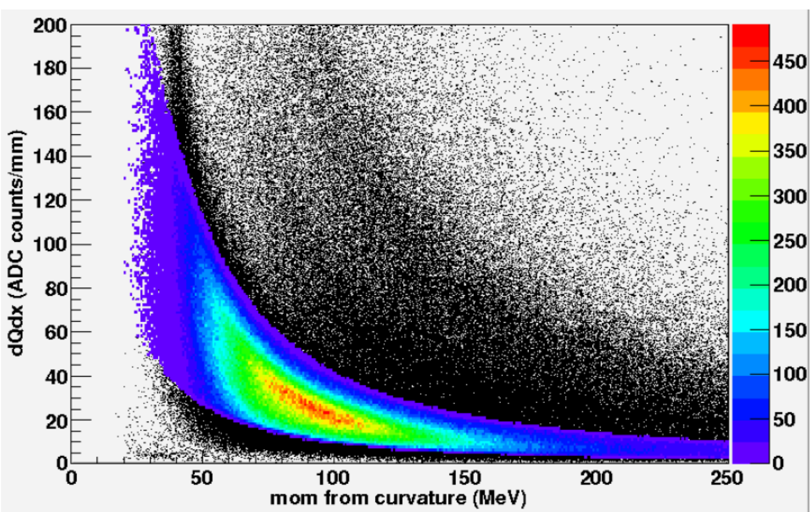
BoNuS Detector



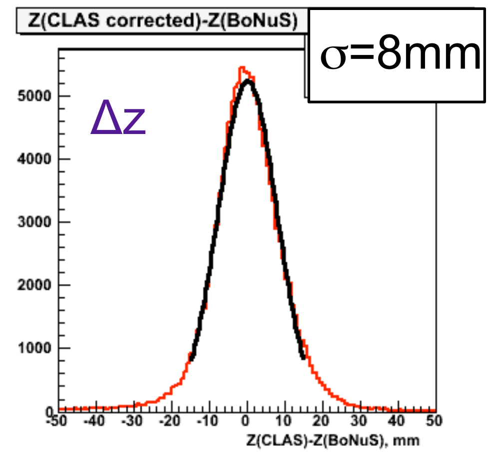
H. Fenker et al., Nucl. Instrum. Meth. A **592**, 273 (2008)

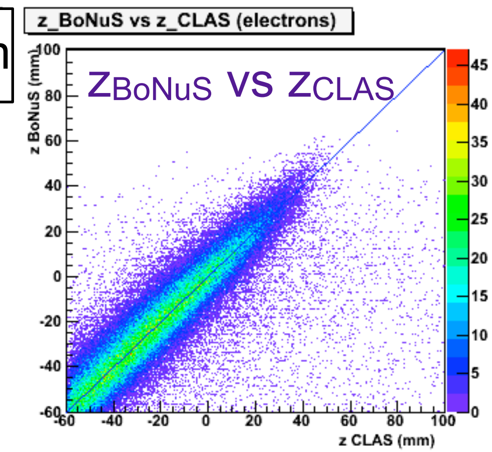
BoNuS RTPC Performance

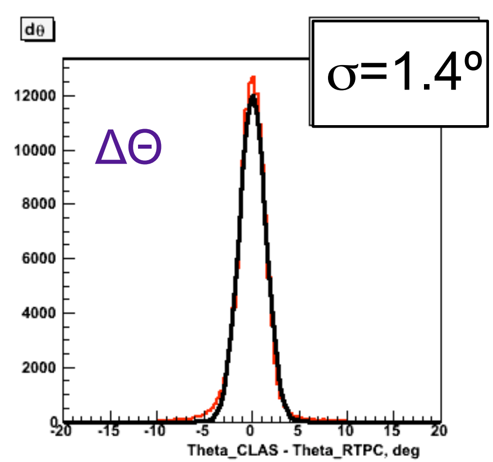


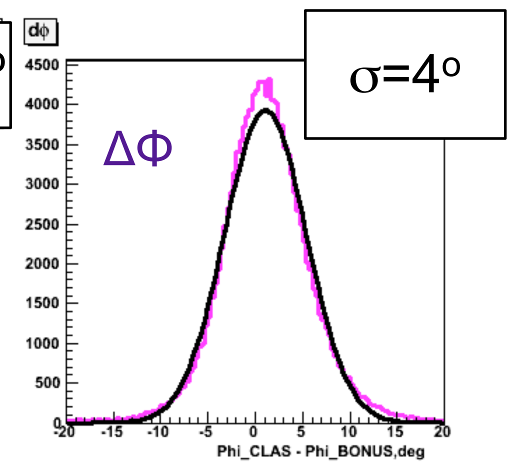


- Upper left: dE/dx vs. p/Z for He target
- Lower left: dE/dx vs. p for deuterium target
- Below RTPC+CLAS resolution for common e^- events



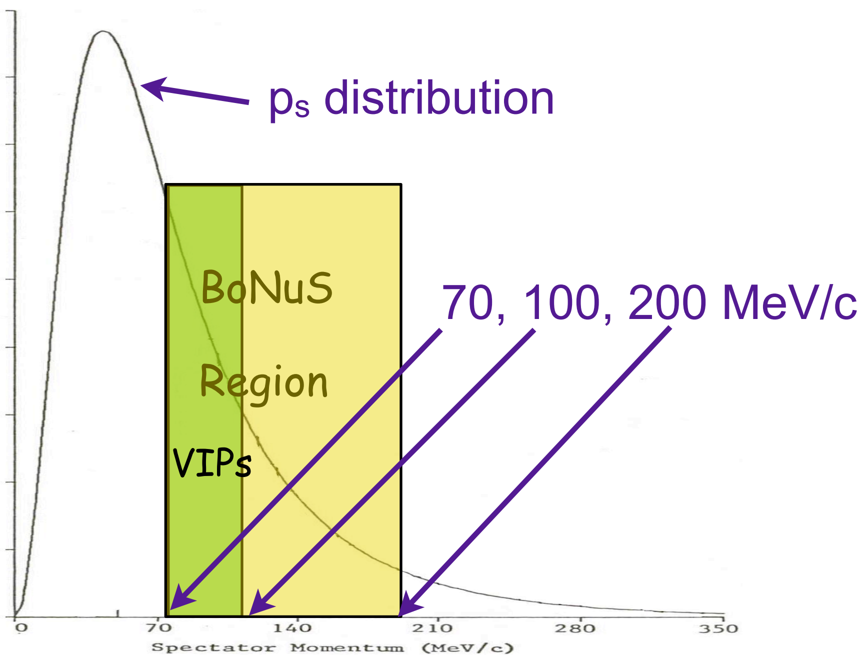


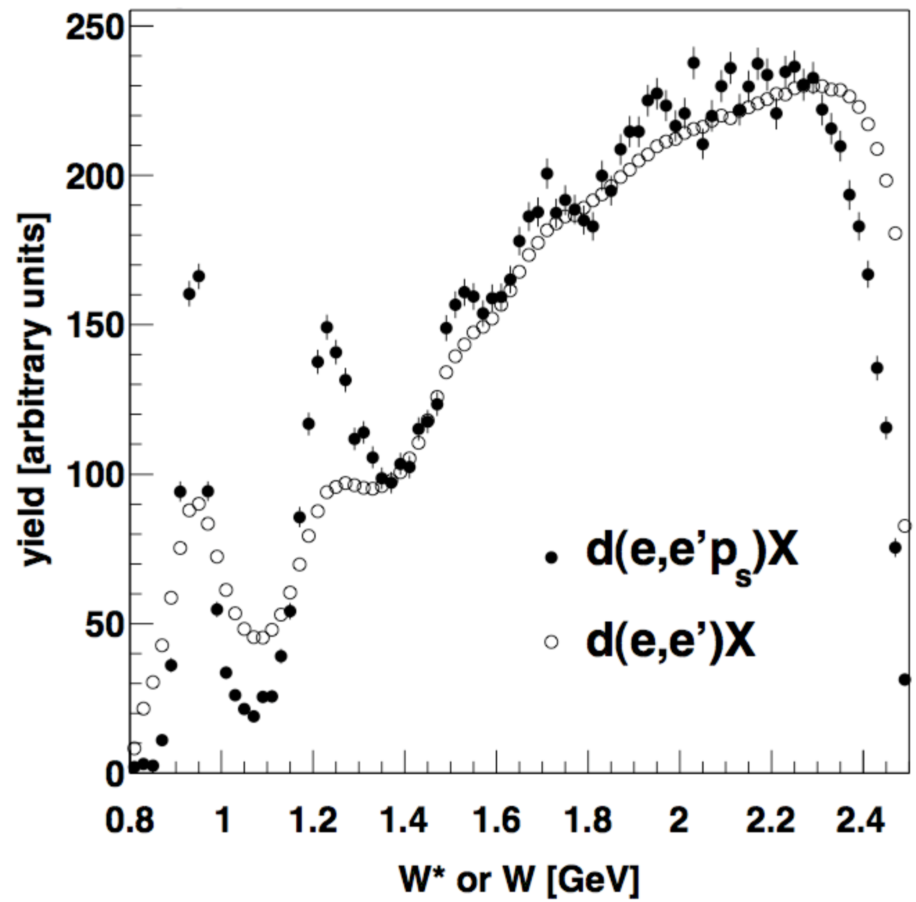




BoNuS Kinematic Correction

- Very Important Protons $70<p_s<100$ 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*

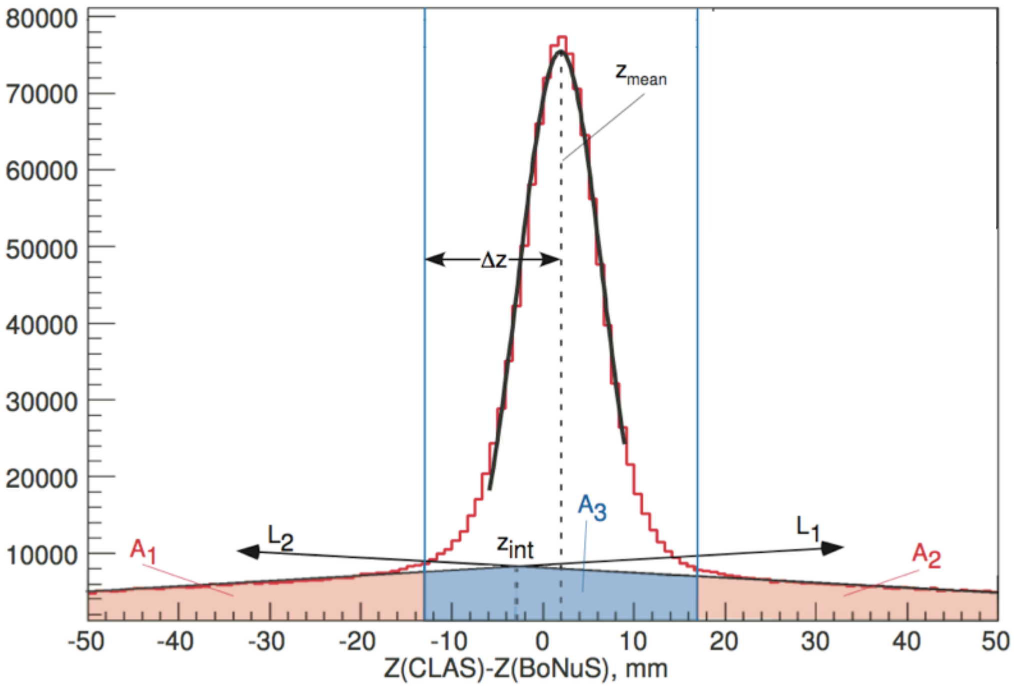




Two Analysis Methods

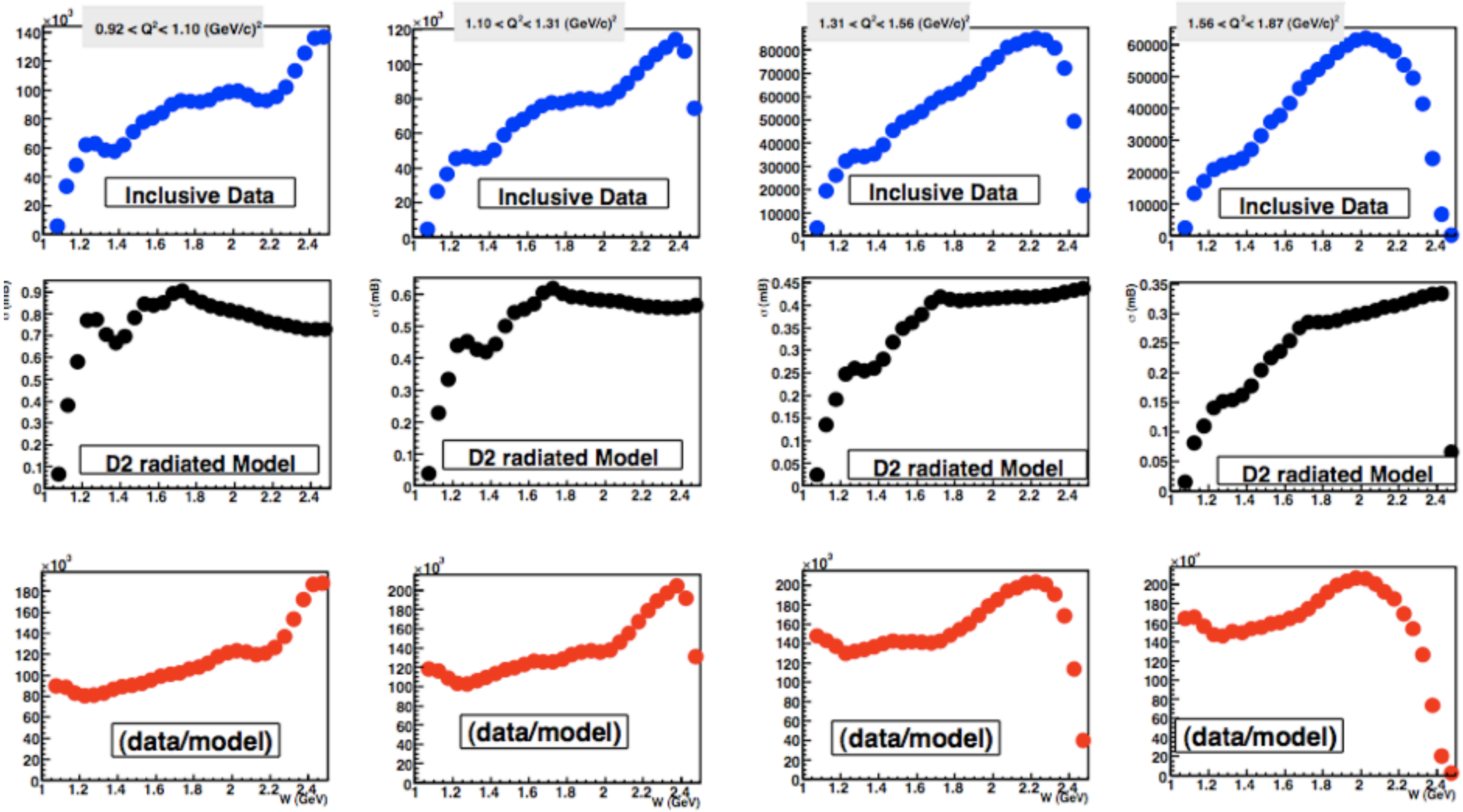
- The Ratio Method
  - ⋆ measure tagged counts divided by inclusive counts
  - ⋆ correct this ratio for backgrounds
  - ⋆ one scale factor gives F_2^n/F_2^d
- The Monte Carlo Method
  - ⋆ measure tagged counts
  - ⋆ divide by spectator model Monte Carlo results
  - ⋆ multiply by F_2^n used in the model
- The two methods have different systematic errors, but give very similar results.

Accidental Backgrounds



- Z is the position along the beam direction
- Tracking of the electron gives Z(CLAS)
- Tracking of the spectator proton gives Z(BoNuS)
- ΔZ=Z(CLAS)-Z(BoNuS) shows a coincidence peak and a triangular background
- Fits to the triangular background allows us to measure backgrounds underneath the peak
- Blue area = R_{bg} x Pink area
- R_{bg} is independent of kinematics

CLAS Detection Efficiency



- Top Row: Raw inclusive *ed* scattering in CLAS [vs. W, 4 plots in Q^2]
- Middle Row: Inclusive *ed* radiated cross sections from world data fit (Bosted)
- Bottom Row: Relative efficiency ε (*i.e.* Top Row / Middle Row)

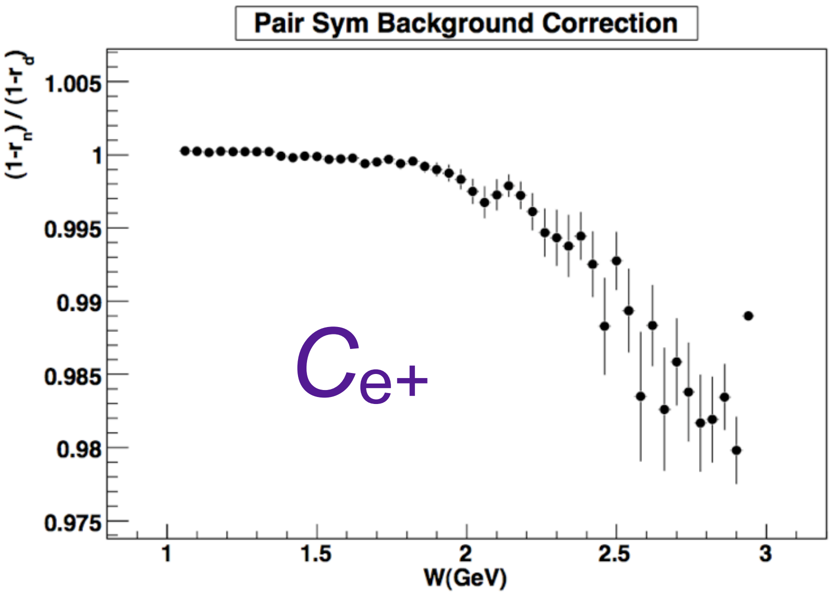
F_2^n/F_2^d from Tagged/Untagged Events

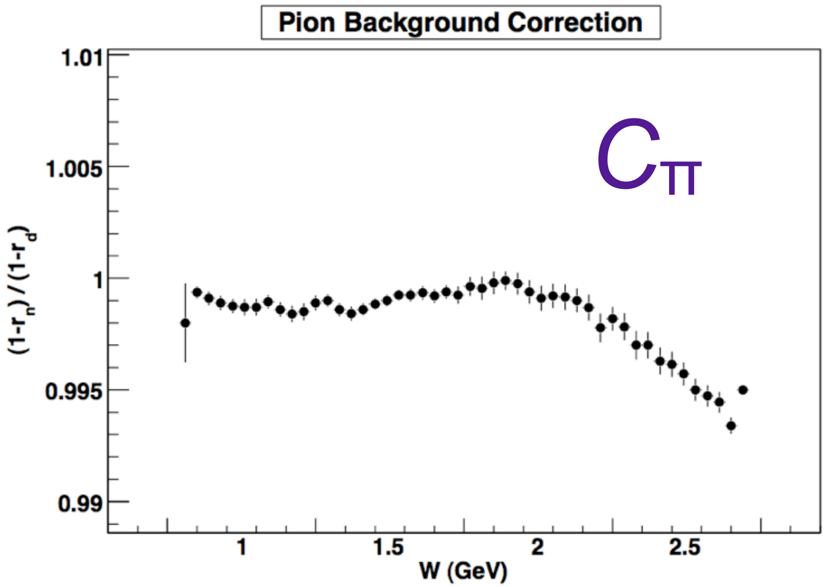
$$R_{corr} = \frac{\displaystyle\sum_{i=1}^{N_{tag}(W^*,Q^2)} \frac{1}{\epsilon_i(W,Q^2)} - R_{bg} \sum_{j=1}^{N_{bg}(W^*,Q^2)} \frac{1}{\epsilon_j(W,Q^2)}}{\displaystyle\sum_{k=1}^{N_{untag}(W,Q^2)} \frac{1}{\epsilon_k(W,Q^2)}}$$

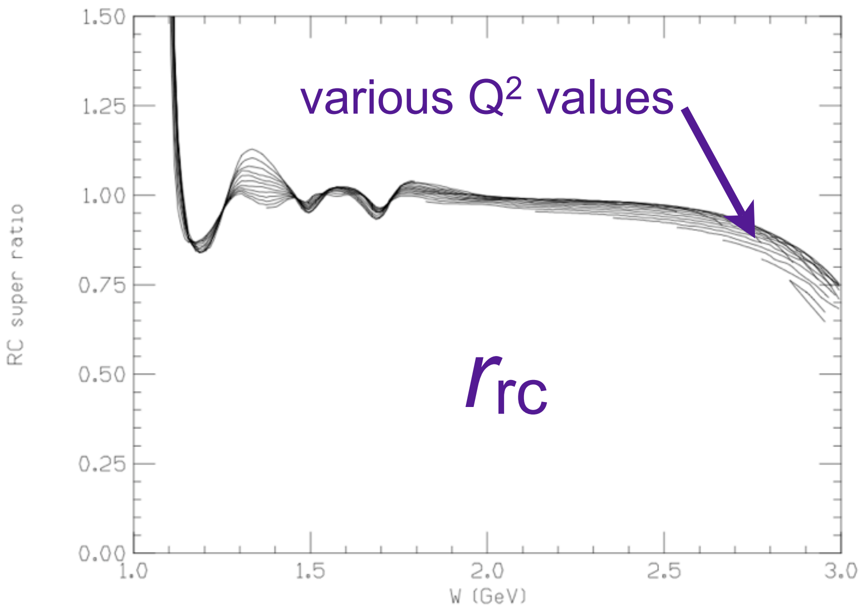
$$\boxed{\frac{F_2^n}{F_2^d} = (R_{corr})(C_{e+})(C_{\pi})(r_{rc})(n)}$$

- R_{corr} is the tagged to untagged ratio corrected for CLAS efficiency and accidentals
- C_{e+} and C_{π} are corrections for pair-symmetric and π^- backgrounds
- r_{rc} is the radiative correction
- n is an overall normalization constant that ensures agreement with world data at x=0.3

Corrections C_{e+}, C_{p-}, and r_{rc}

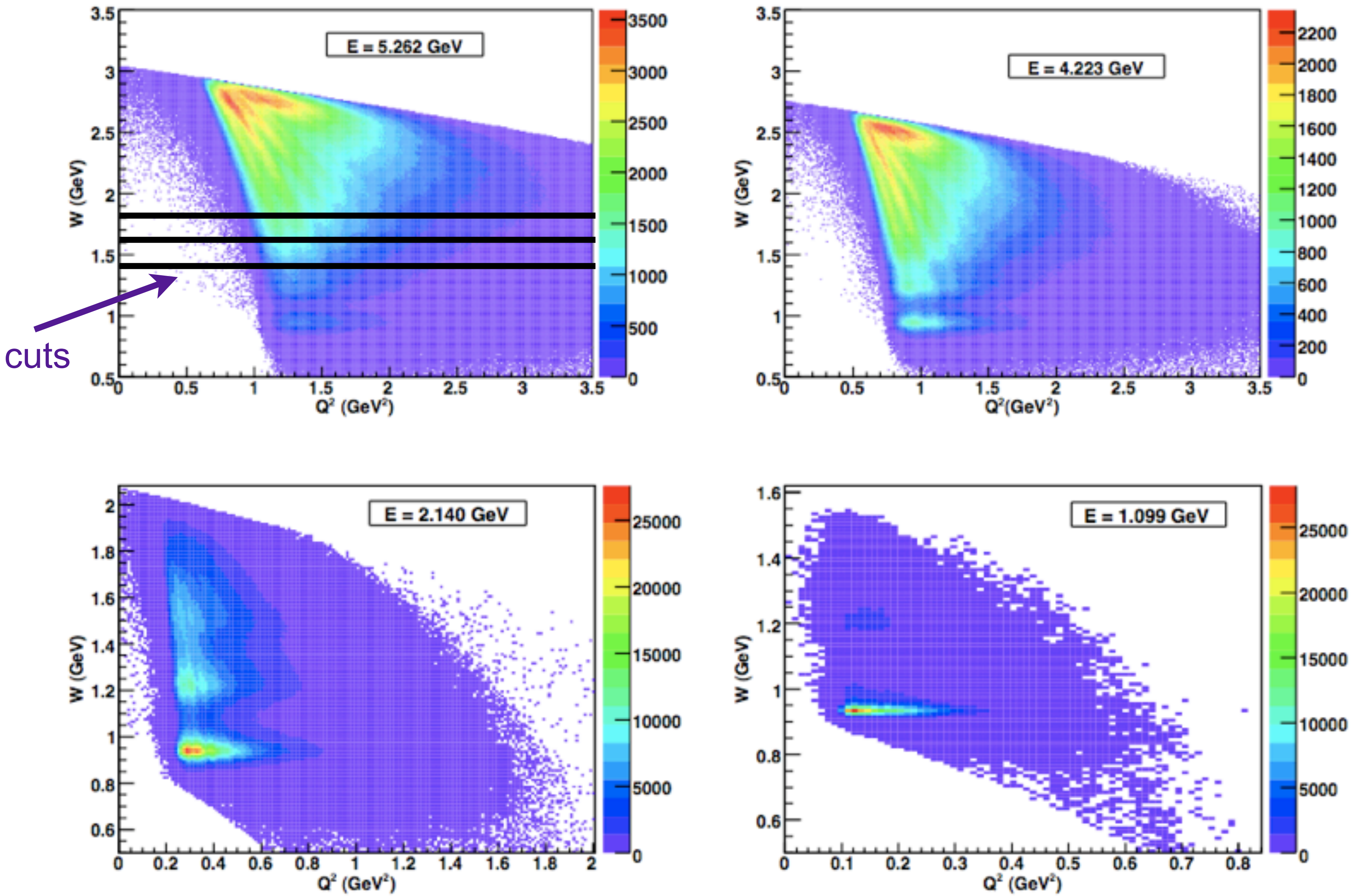




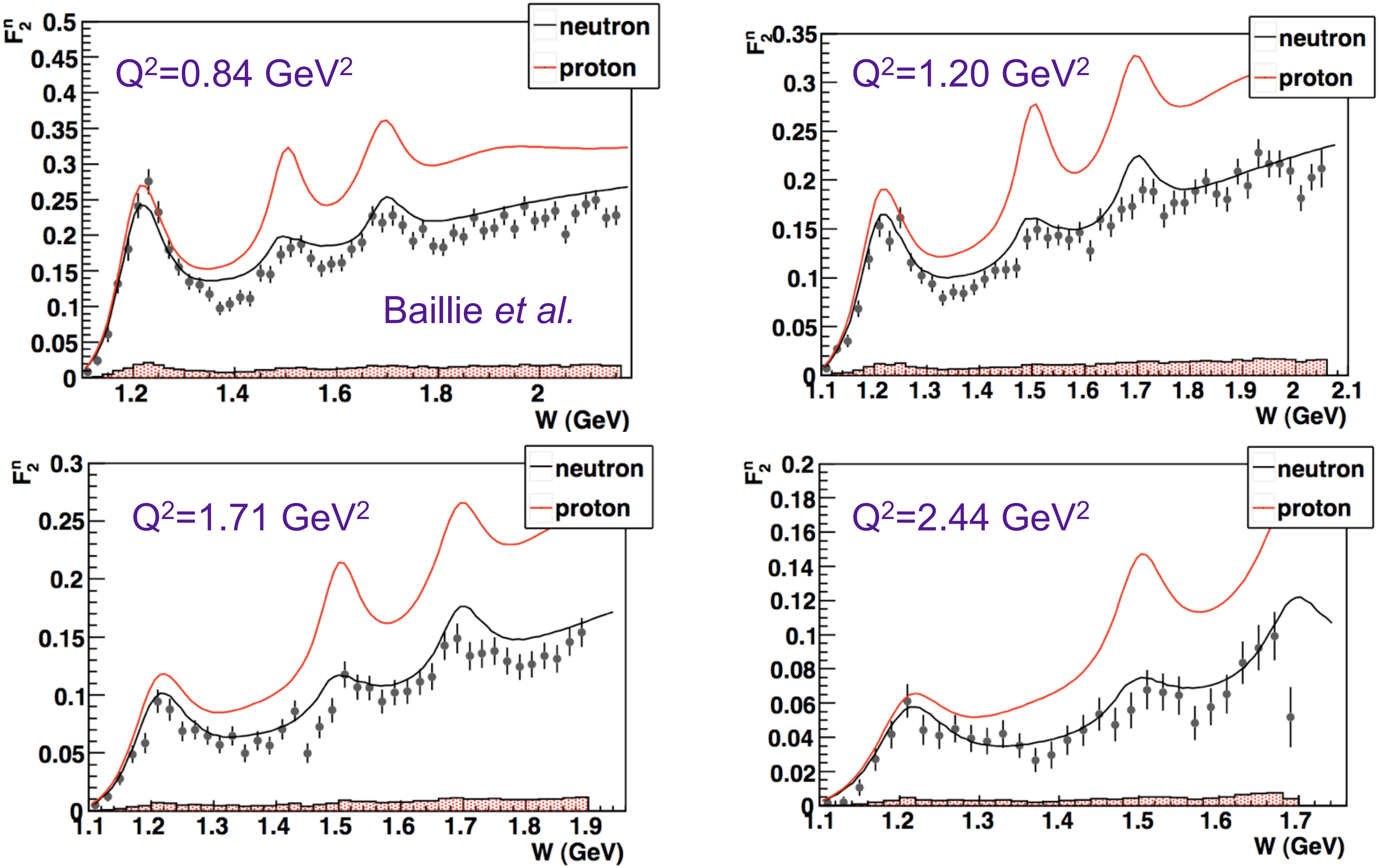


- C_{e+} correction < 2 %
- C_{π} correction < 1/2 %
- r_{rc} correction < 10% in the region 1.2<W<2.7 GeV
- $1/n = 0.02535 \pm 3.37\%$

Kinematic Coverage



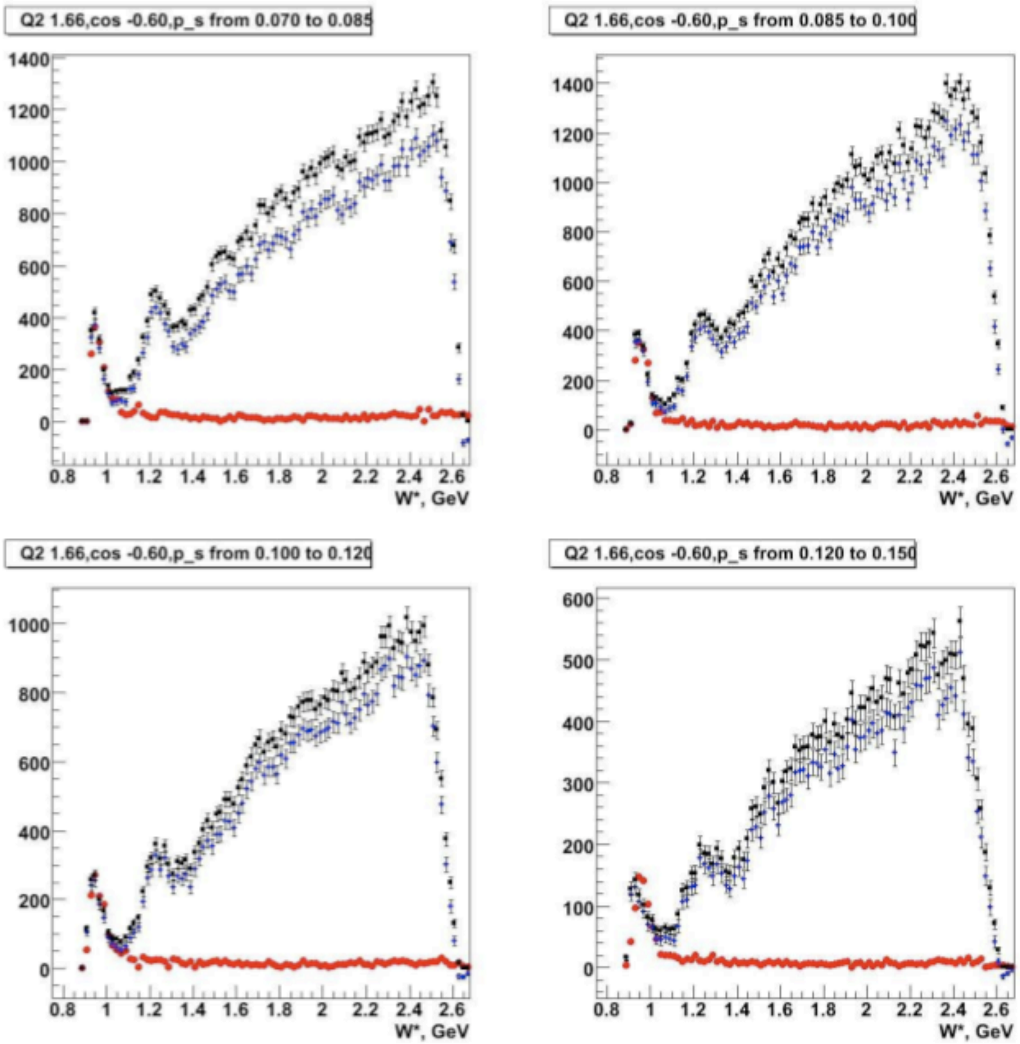
BoNuS F_2^n



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

Monte Carlo Method

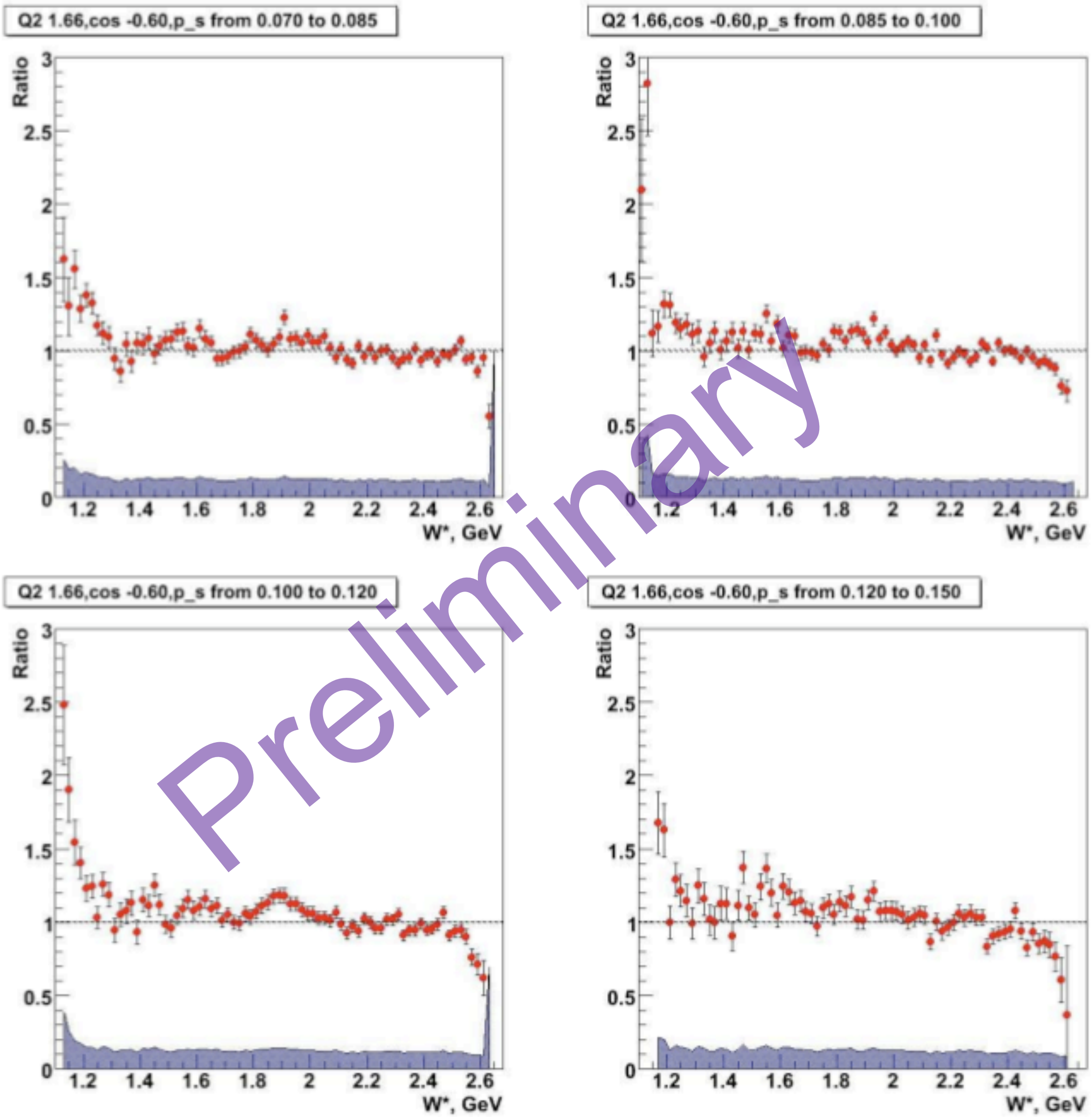
$$R(data/MC) = \frac{F_{2n}^{eff}(W^*, Q^2, \vec{p_s})}{F_{2n}^{model}(W, Q^2)}$$



Left: Black=raw tagged data; blue=accidental subtracted data; red=elastic and radiative tail

Tkachenko *et al.*

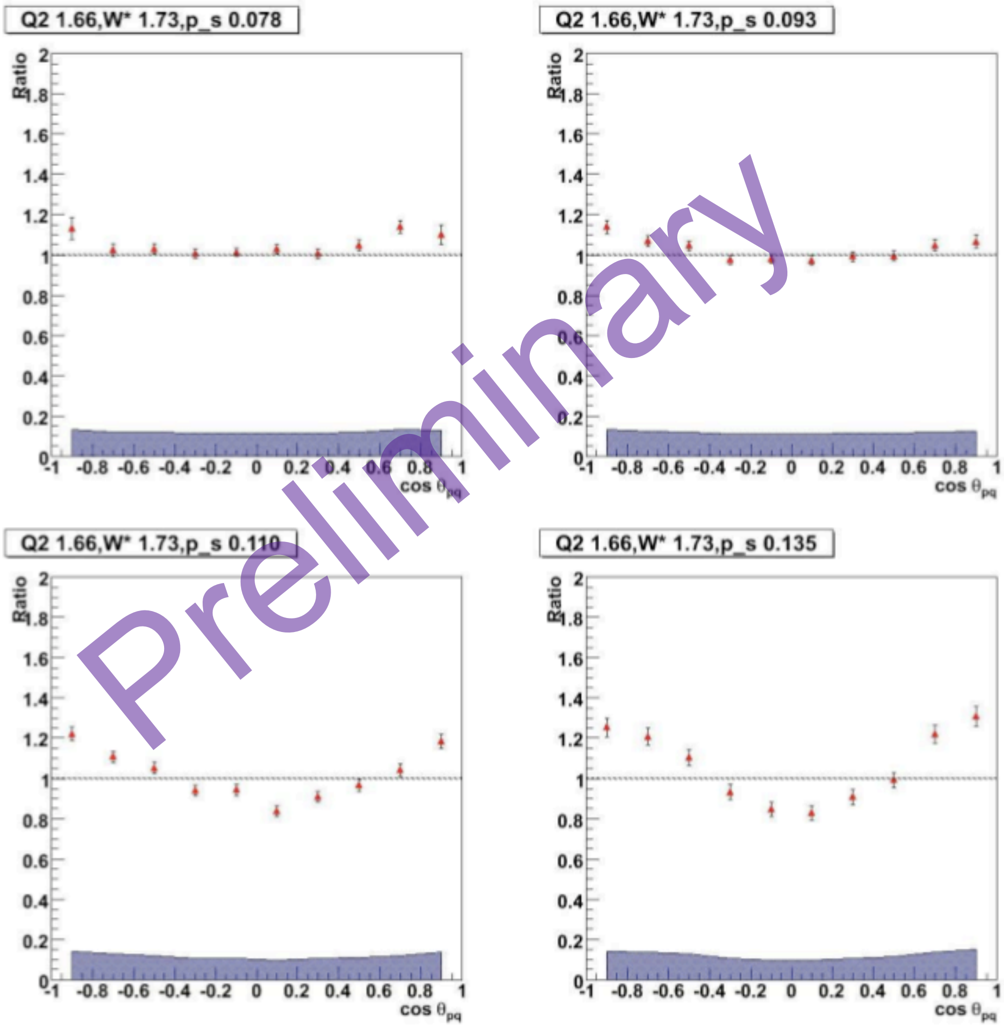
Data / MC vs W* for Different p_s



- Deviations from unity at low W* comes from difficulties of getting the model right for the resonances
- Generally the ratio is close to unity
- Perhaps some effects at high p_s

Tkachenko *et al.*

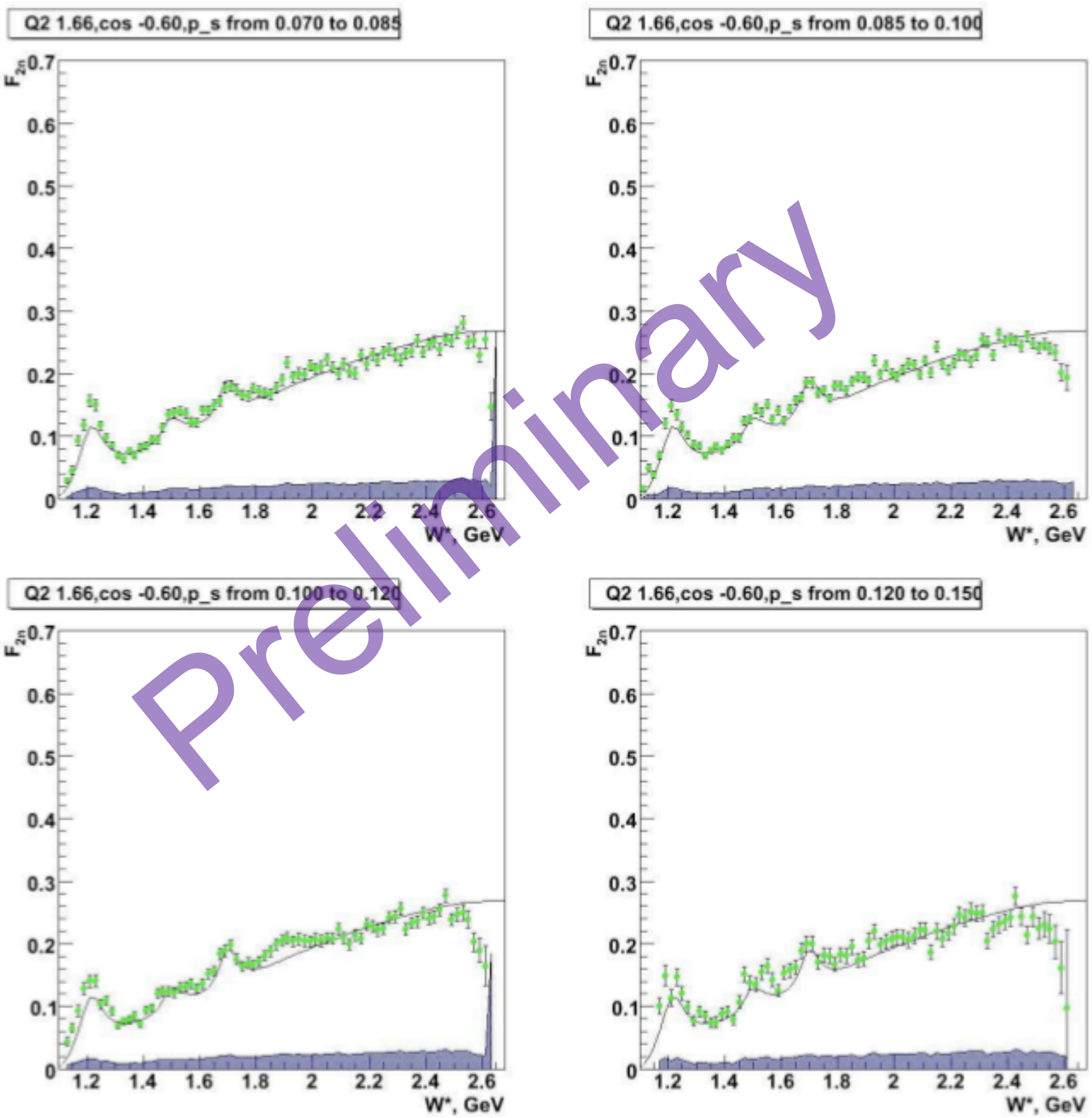
cosθ distributions / MC



- At low p_s the data agree with the spectator model quite well
- At higher p_s the distributions deviate significantly from unity, indicating that VIP particles should have p_s<100 MeV/c

Tkachenko *et al.*

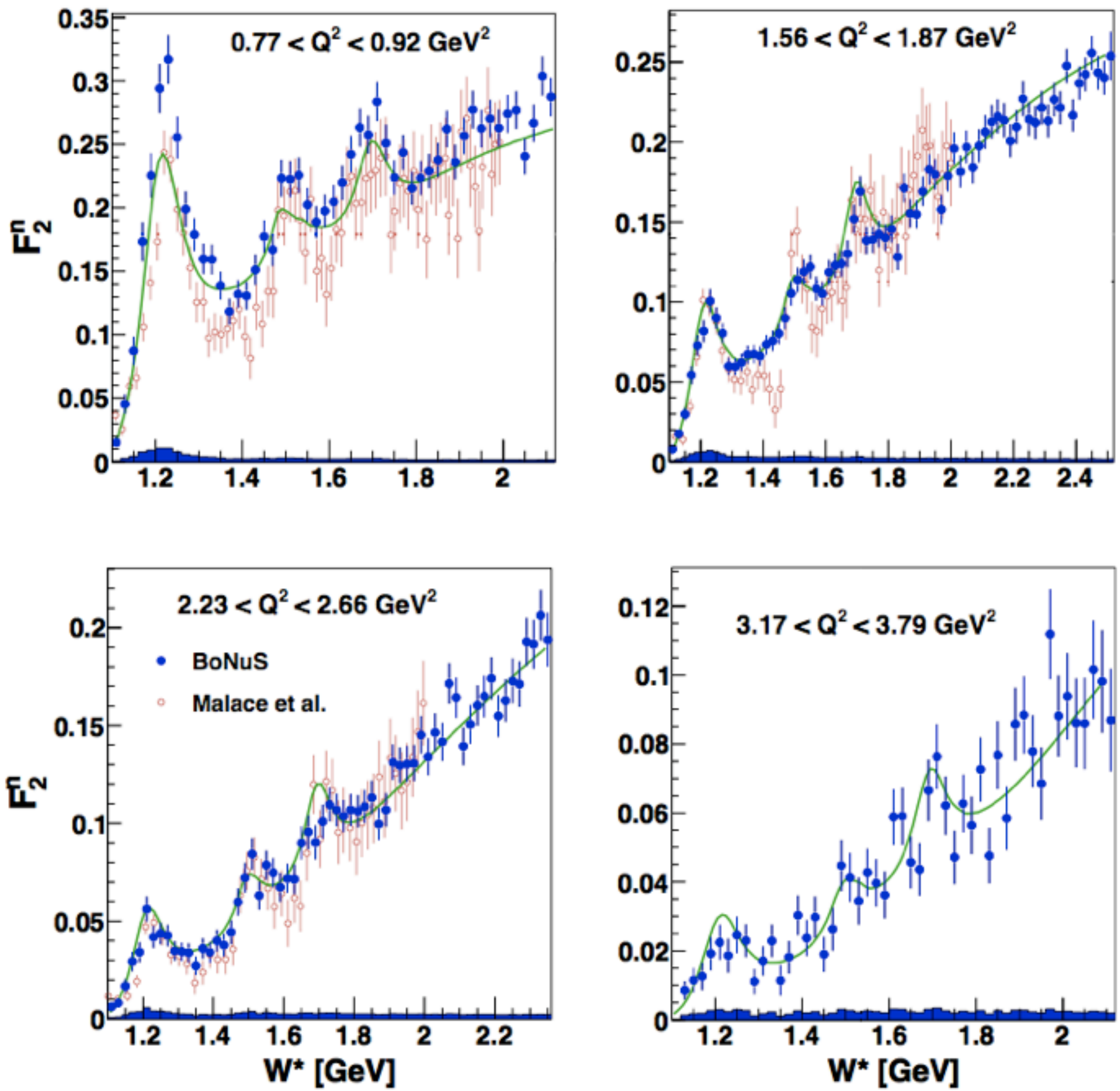
F_2^n for various p_s



- Data show resonance peaks.
- Data agree quite well with resonance model of world data
- Dependence on spectator momentum is slight

Tkachenko *et al.*

Final Data

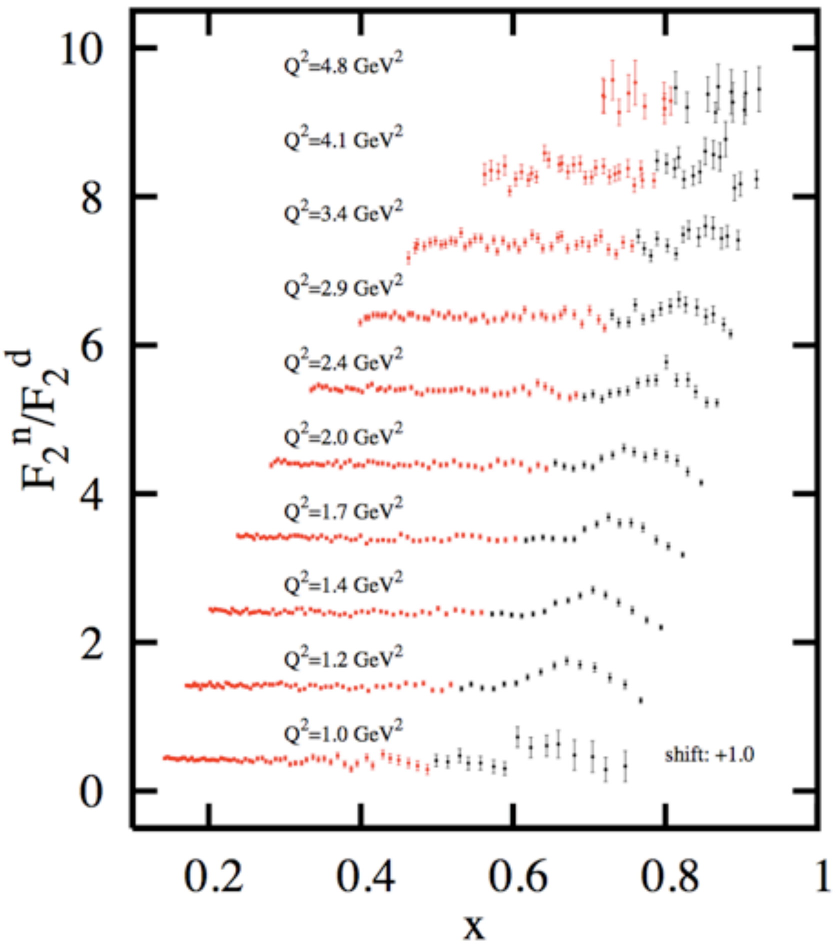


Various data compared to a state of the art nuclear physics extraction of neutron structure functions from deuterium (red points, Malace, et al.)

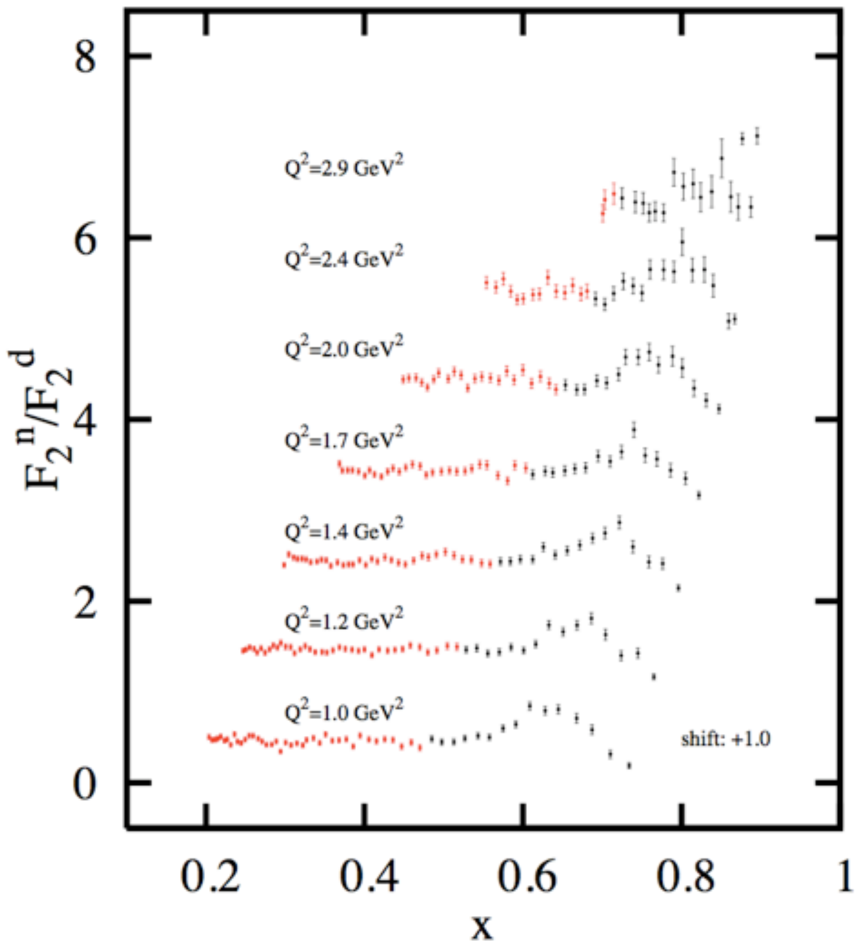
Baillie *et al.*,PRL **108**(12)142001

F_2^n/F_2^d

5 GeV Data

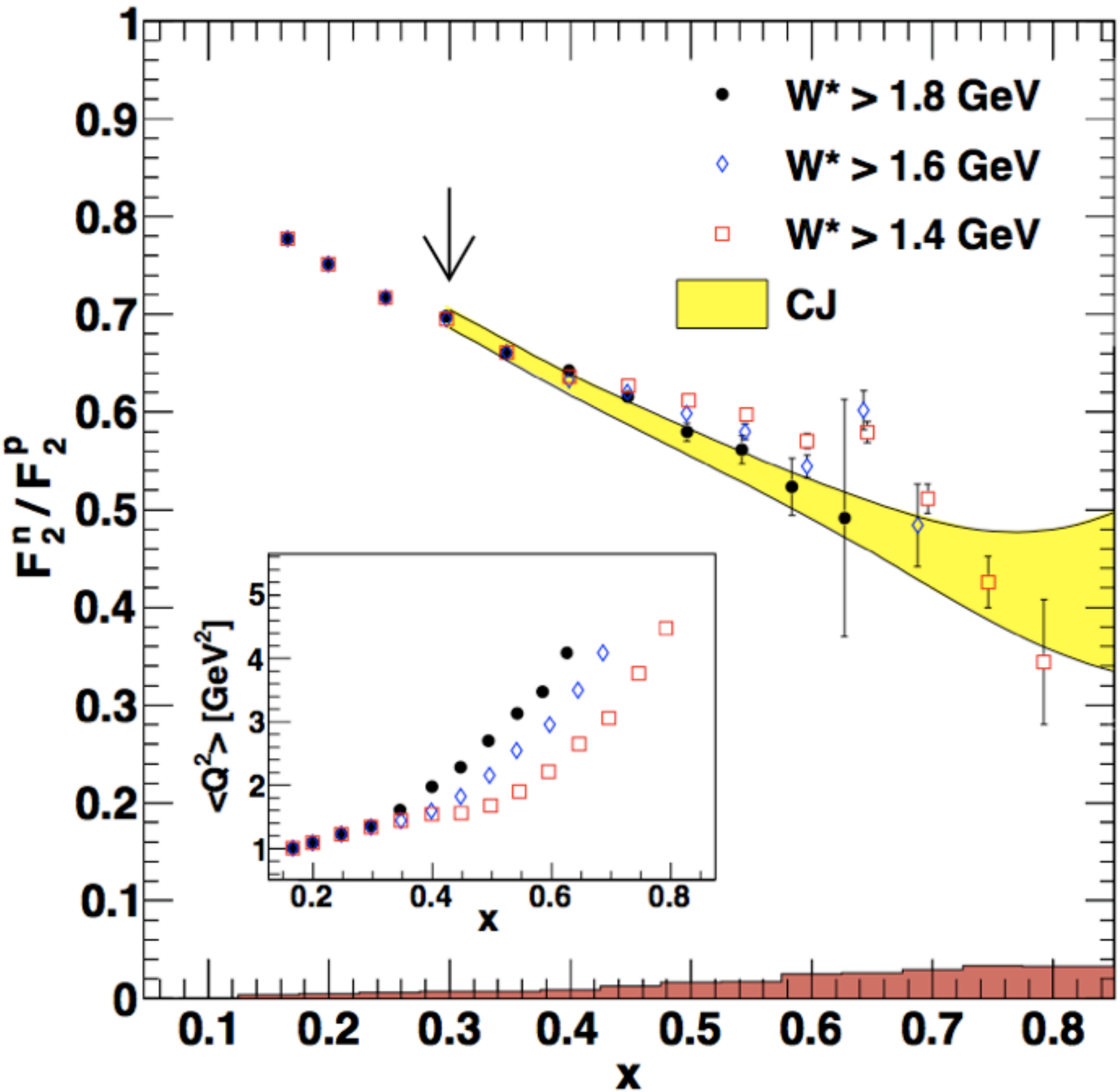


4 GeV Data



BoNuS primary results: n/d structure function ratios for $Q^2>1$ GeV^2

BoNuS F_2^n/F_2^p



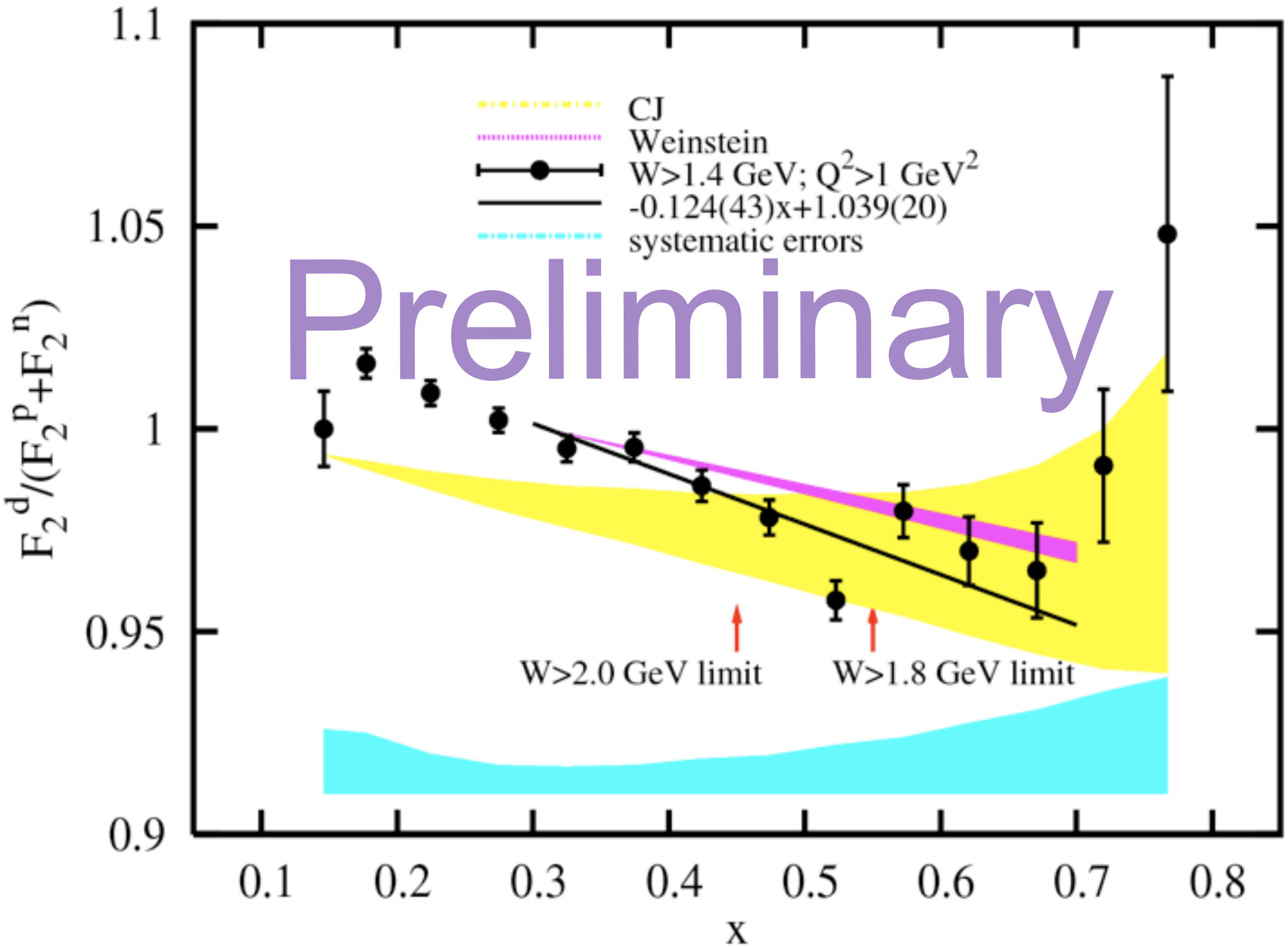
- F_2^n/F_2^p = $(F_2^n/F_2^d)_{exp}(F_2^d/F_2^p)_{world}$ Bosted/Christy fits: PRC**77**(08)065206, PRC**81**(10)055213
- Curves are CJ error bands [Accardi, *et al.*, PRD **84**(11)014008]
- CJ cuts off at low x because Q^2 is too low
- Lower cuts in W* yield higher x values but the inclusion of resonance contributions.
- Results are consistent with CJ trends at high x.

Baillie *et al.*,PRL **108**(12)142001

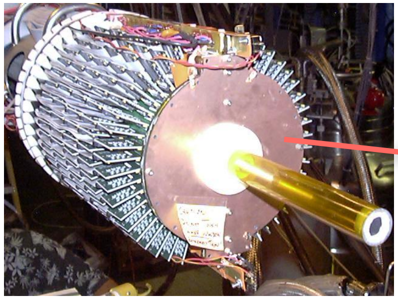
EMC Effect

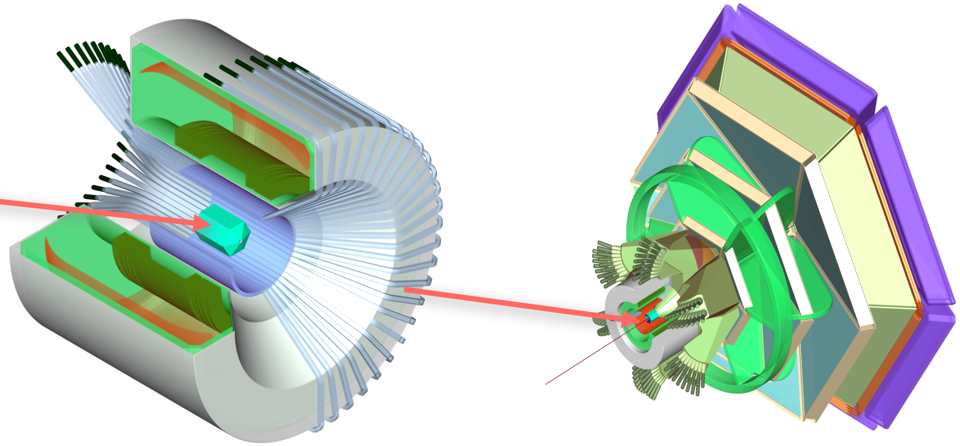
EMC ratio for the deuteron: $[(F_2^n/F_2^d)_{exp} + (F_2^p/F_2^d)_{world}]^{-1}$

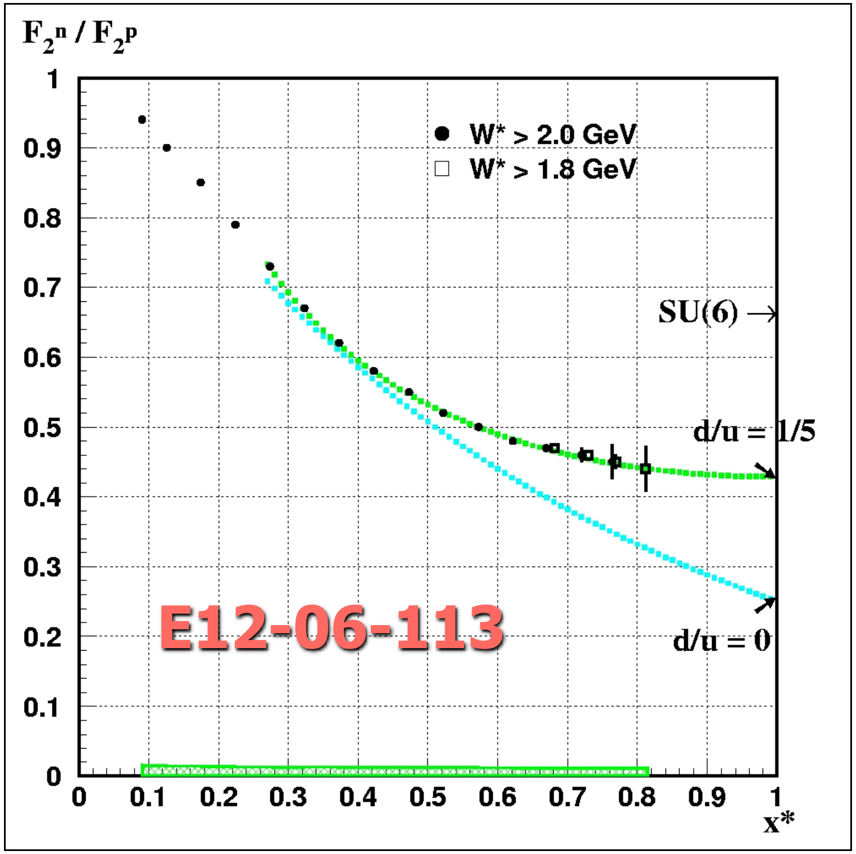
Normalization: unity at x = 0.31 (the world EMC average for nuclei)



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: $x^*_{max} = 0.83$

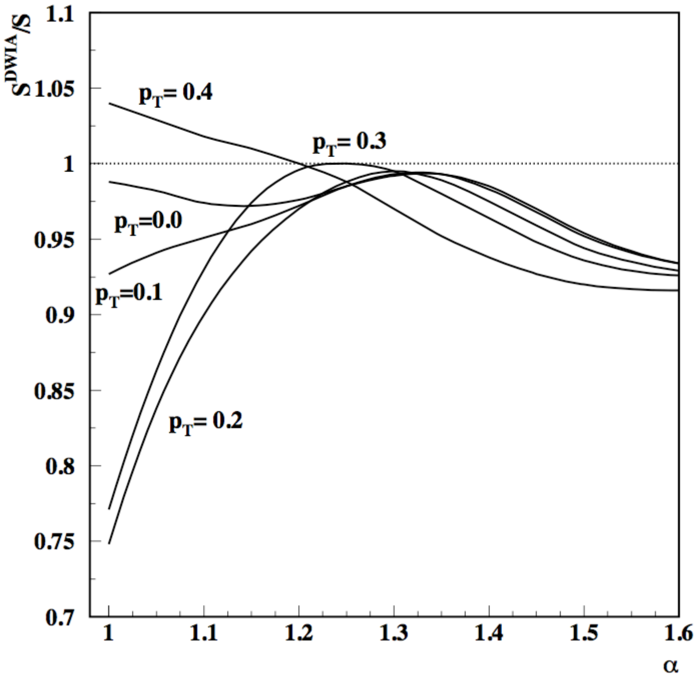
Conclusions

- BoNuS has measured F_2^n on a "free" neutron target
- Virtually no effects from Fermi motion and final-state interactions
- No evidence for off-shell structure for p_s<100 MeV/c
- F_2^n/F_2^p behaves at high x much like CJ high-x fits
- F_2^n resonance data will significantly improve the world's data set, which up to now came from d with nuclear corrections
- In the works: a long paper with details of the off-shell study (S. Tkachenko), a paper on $D(e,e'\pi^- p_s p)$ (J. Zhang), and a paper on the deuteron EMC effect.

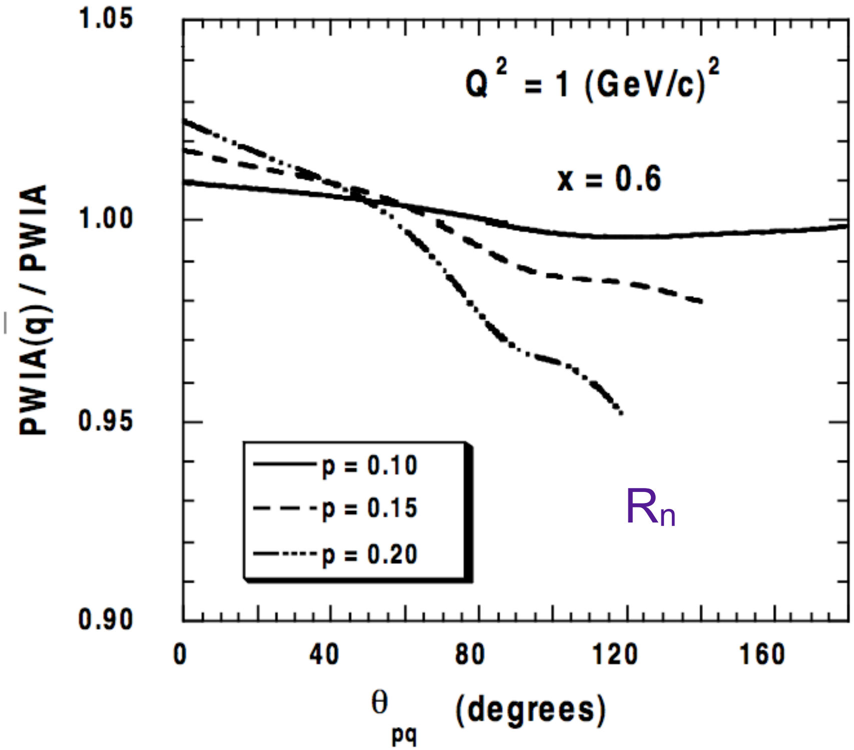
END

Spectral Functions

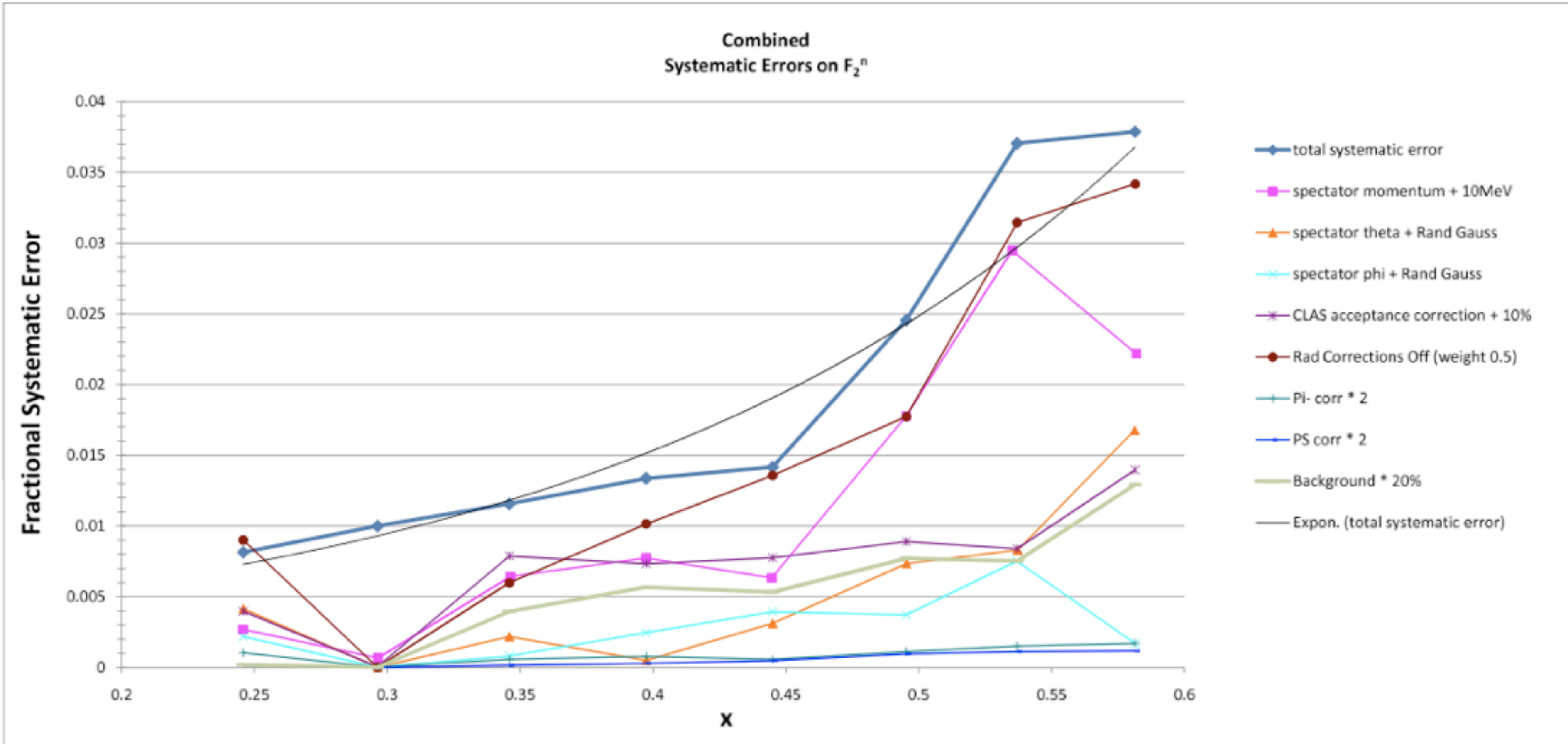
Melnitchouk *et al.*, ZPA**359**(97)99



Heller & Thomas, PRC**41**(90)2756



Systematic Errors



- Full analysis of F_2^n is done after shifting or broadening various quantities
- $\Delta F_2^n = 0$ at $x=0.3$ where normalization takes place (total value there is interpolated)
- Blue line, all changes are made at once; total error rises from 1% to 4% vs x.

Ratio and MC Method Comparison