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The Bound Nucleon Structure Experiment (BoNuS) at CLAS

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Paris, France

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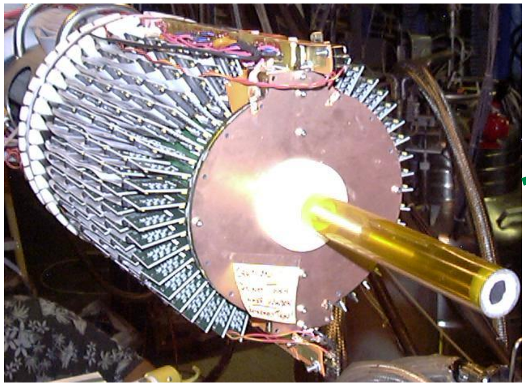
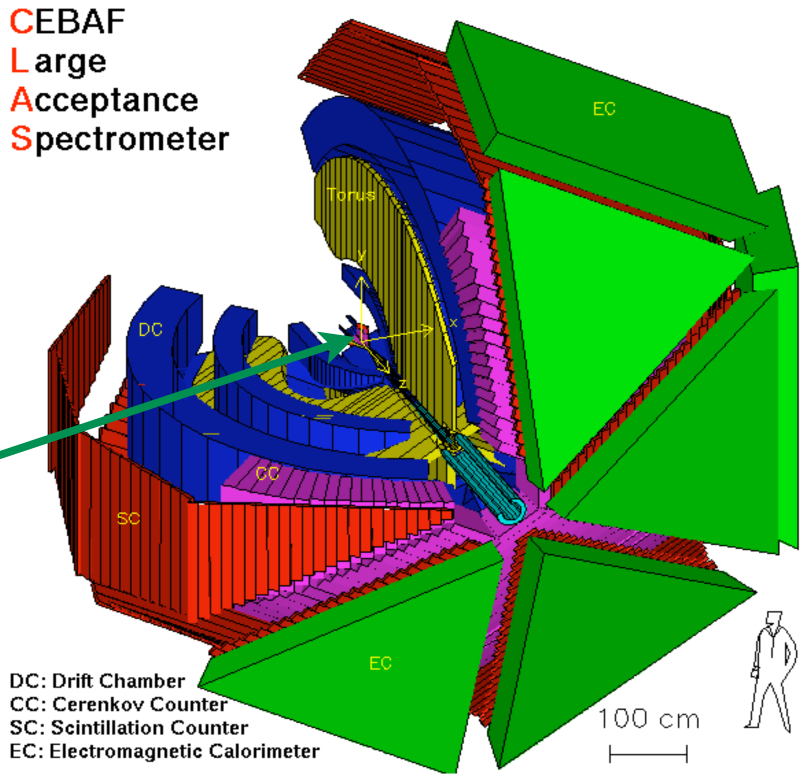
A CLAS Experiment with RTPC

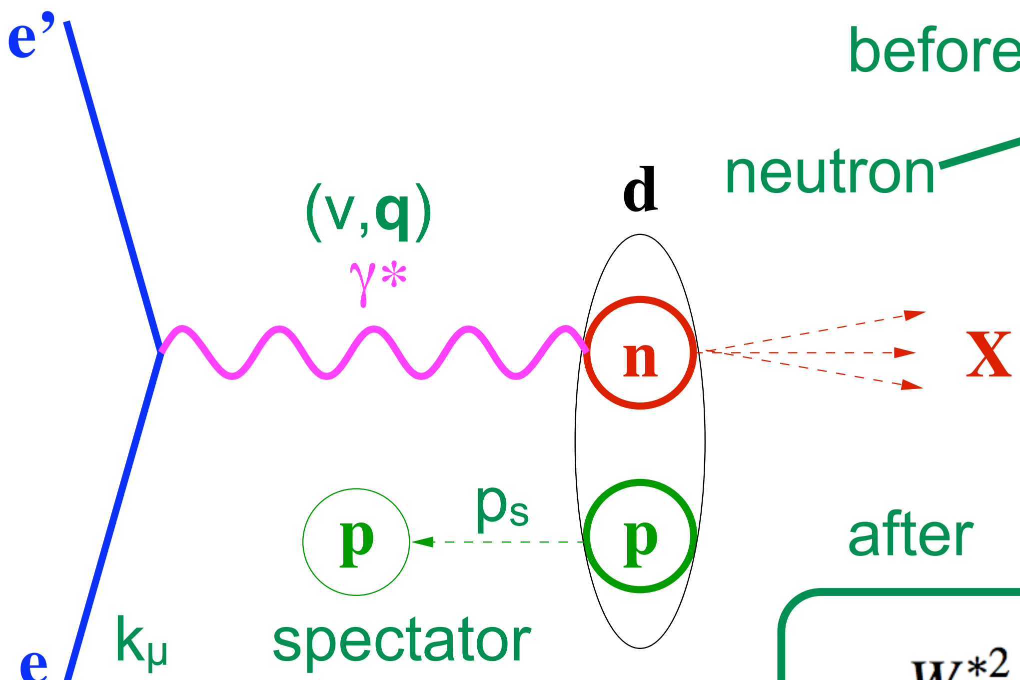
- BoNuS
- Bound Nucleon Structure Experiment
- $d(e,e'p_s)X$ [(deep) inelastic]
- deuterium target, spectator proton
- $70 < p_s < 180$ MeV/c
- JLab Hall B CLAS with an RTPC
- search for F_2^n at high x

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

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

$$E_p + E_n = M_d$$

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

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

after

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

$$\alpha_s = \frac{E_s - p_{s_{||}}}{M_s}$$

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

- 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

PWIA Spectator Formalism

Cross Section

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

Off-Shell F_2

R= L/ T

Spectral Function

Nonrelativistic w.f.

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

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

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

Light Cone

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

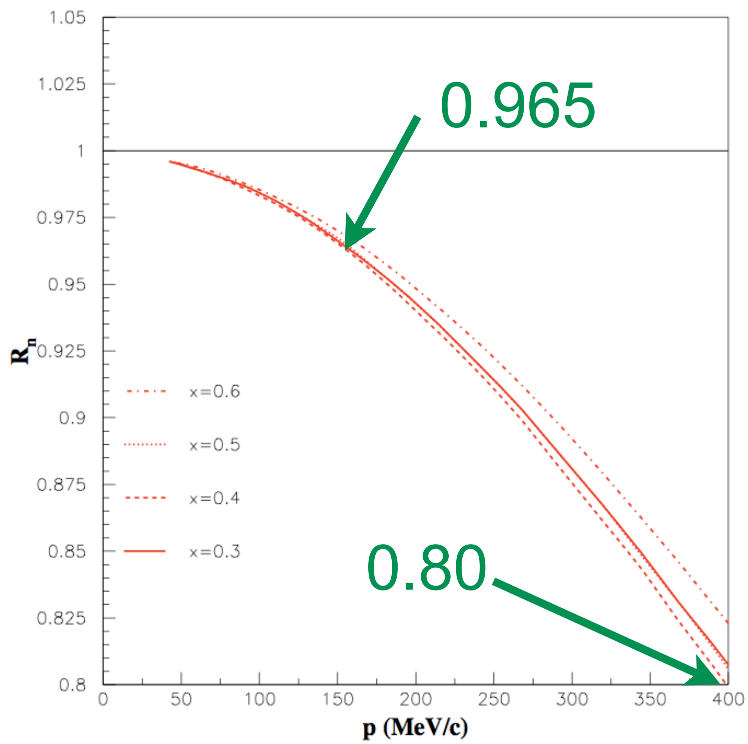
$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

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

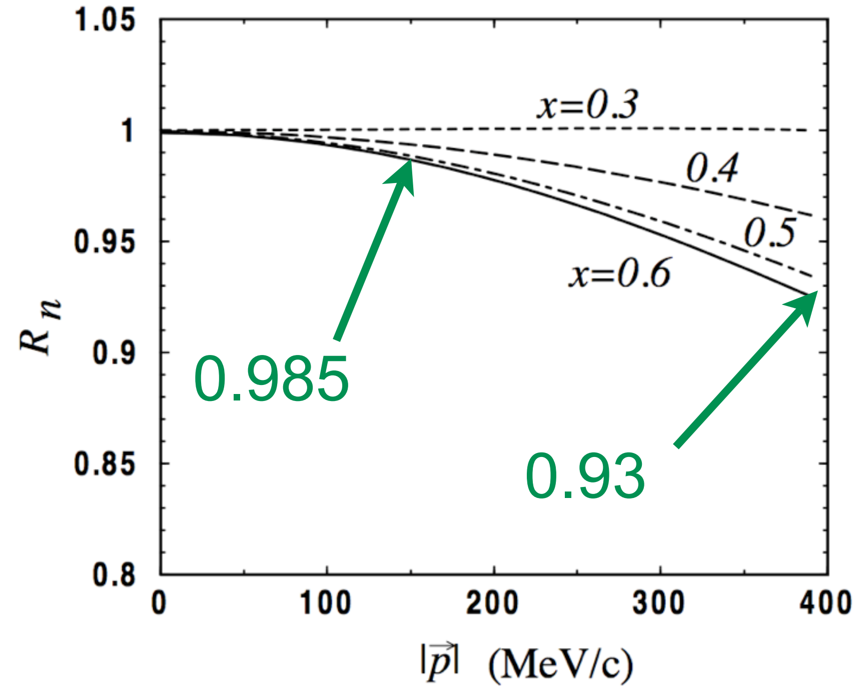
$$\int\int\int S^{\mathrm{LC}}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s} d^2 p_T = 1$$

Off-Shell Structure Functions

Liuti & Gross PLB356(95)157

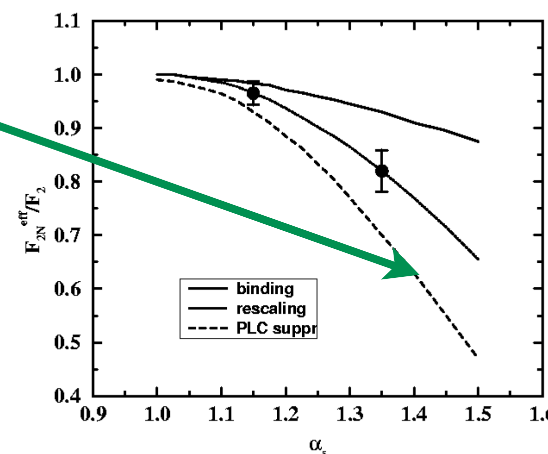


Melnitchouk et al, PLB335(94)11



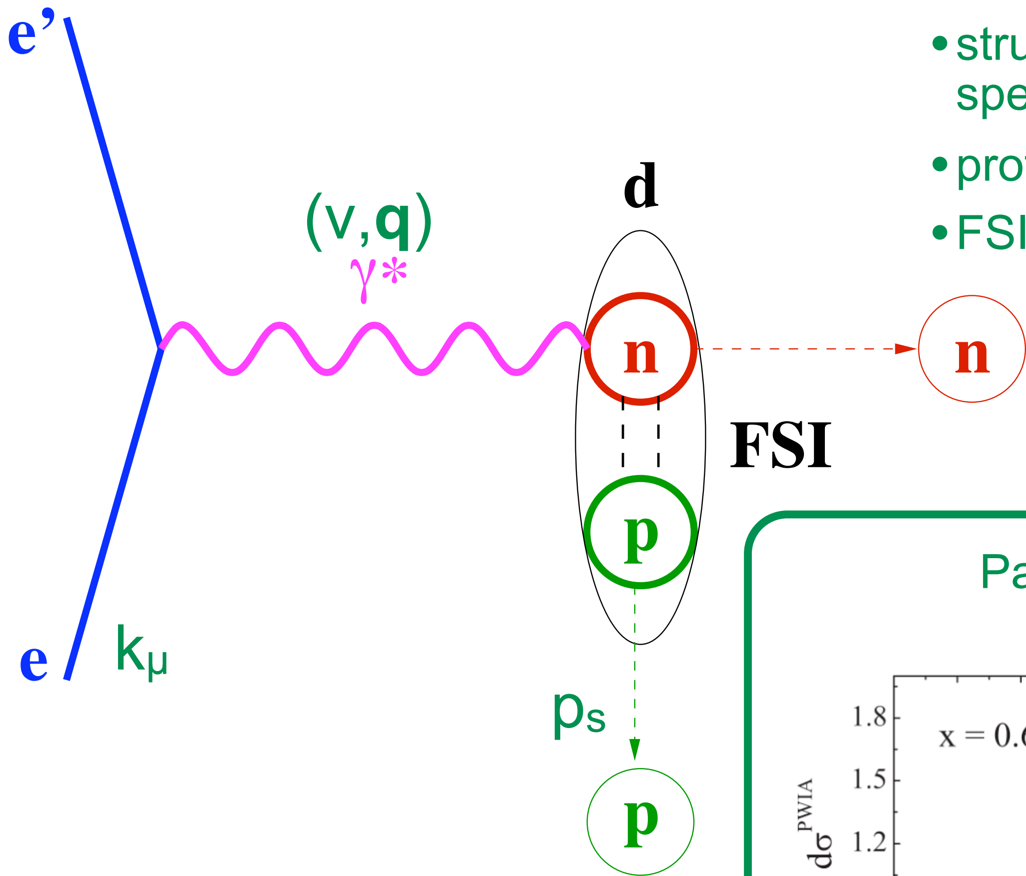
$$R_n \equiv (F_2^n)^{\mathrm{eff}} / (F_2^n)^{\mathrm{free}}$$

0.6



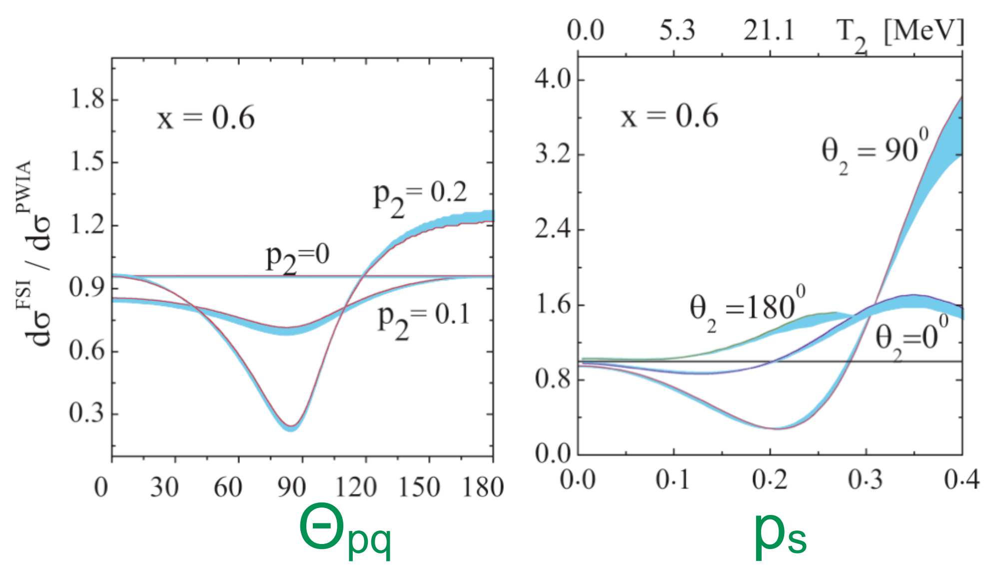
- R_n decreases with p_s or α
- at $x^*=0.5$ and $p_s=0.40$ GeV/c, R_n deviates from 1 by 7-20% in these models
- at α=1.4 the deviation from unity could be 40%

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}

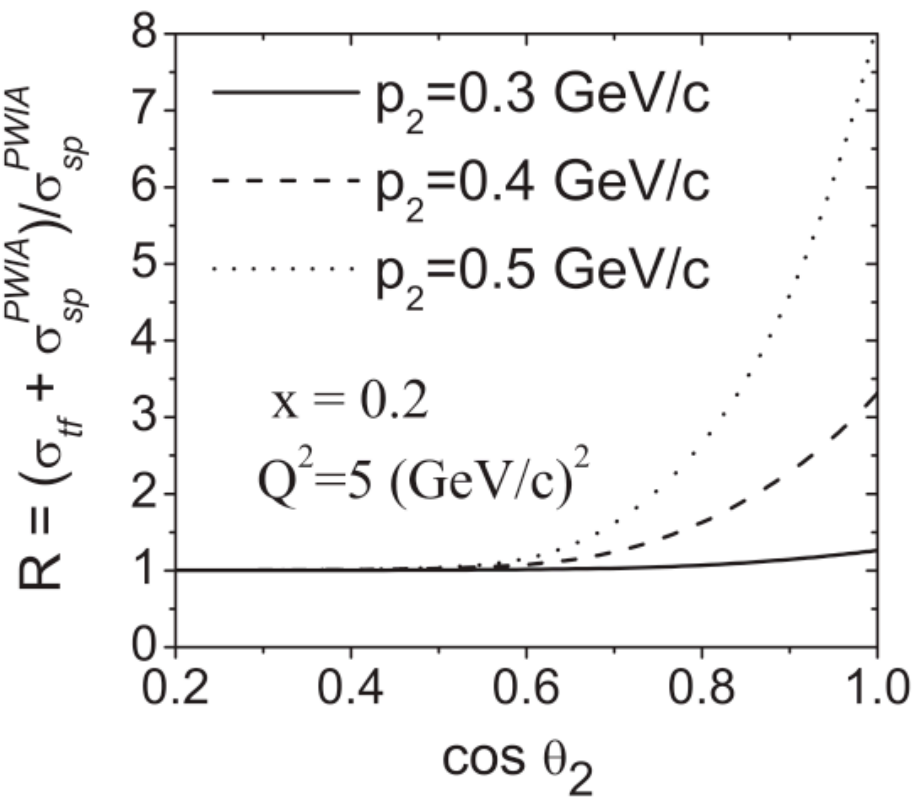
Palli et al, PRC80(09)054610



- several groups have calculated FSIs
- $\Theta_{pq} > 120^o$ minimizes FSIs

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

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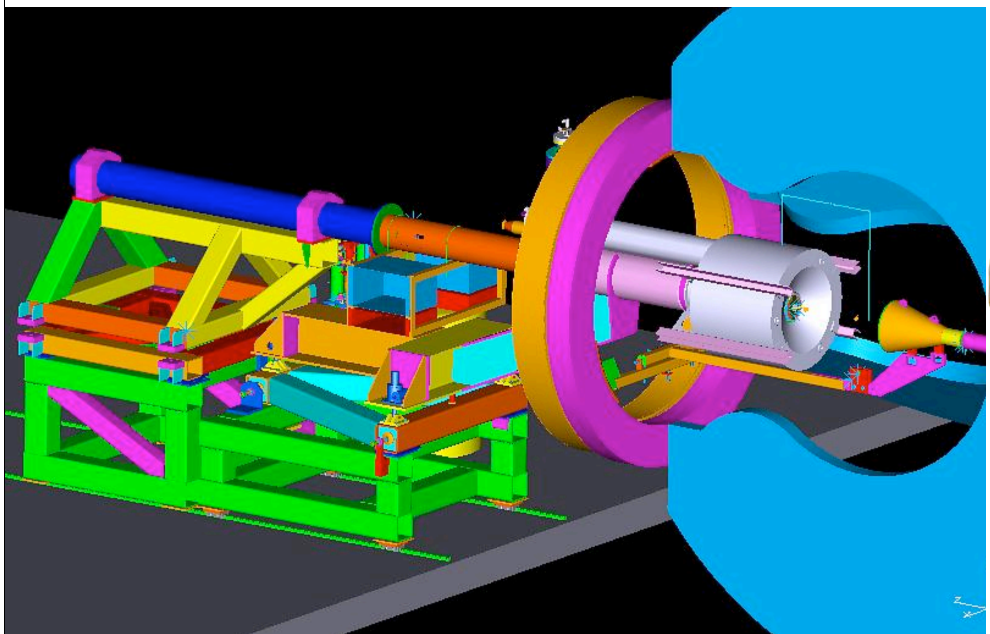
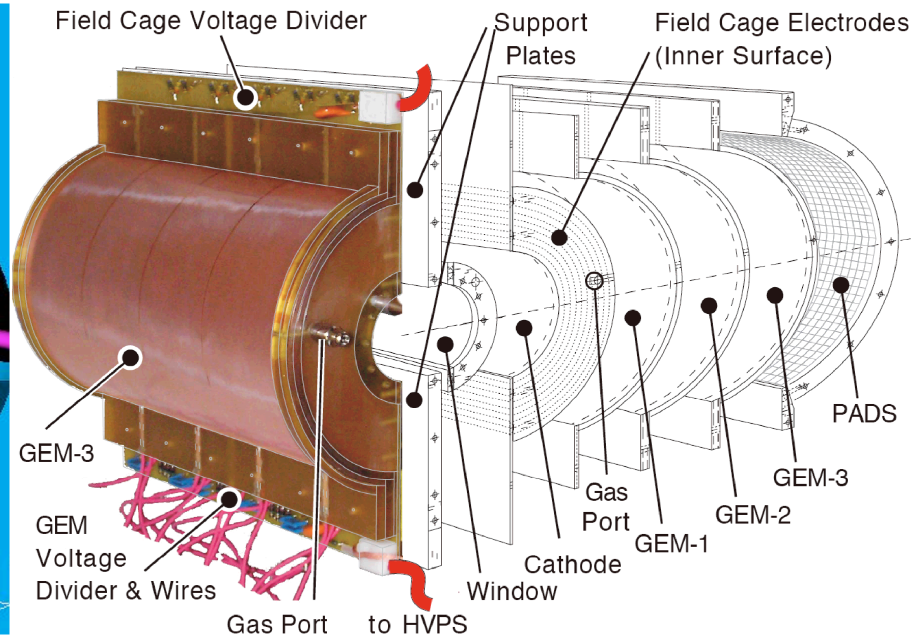
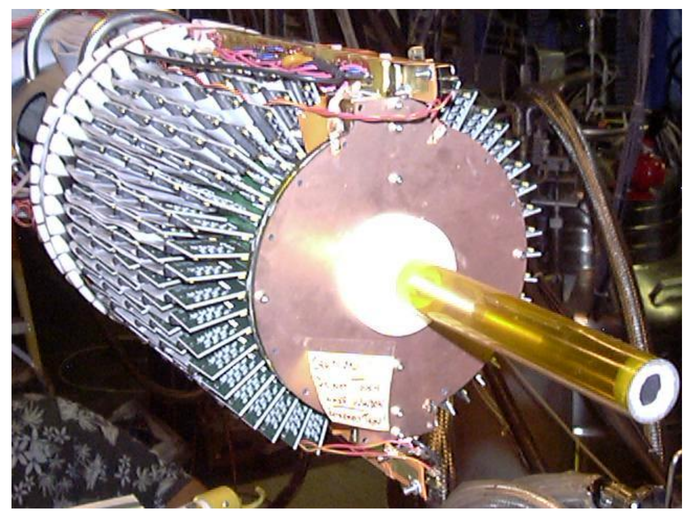
BoNuS Experiment

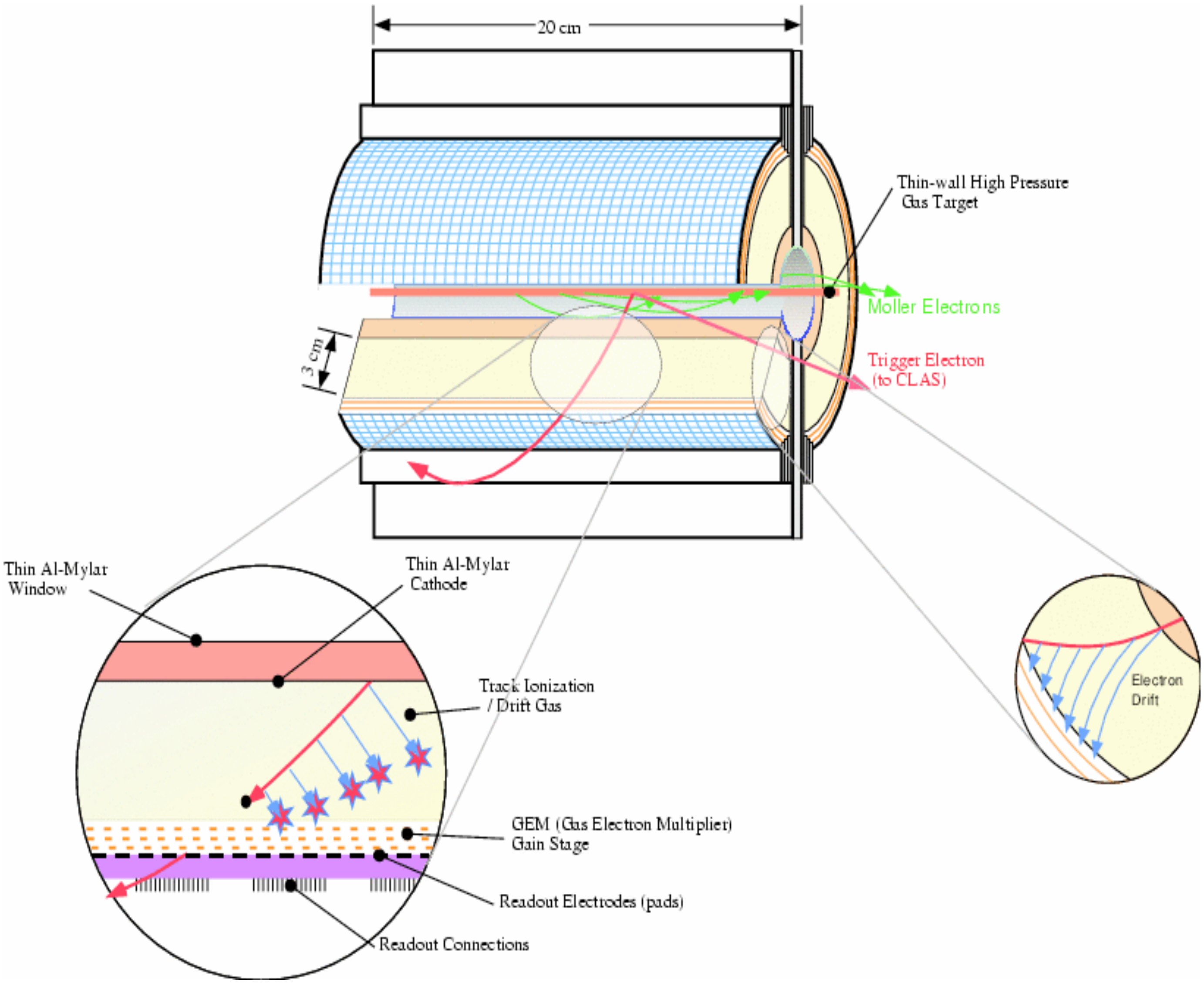




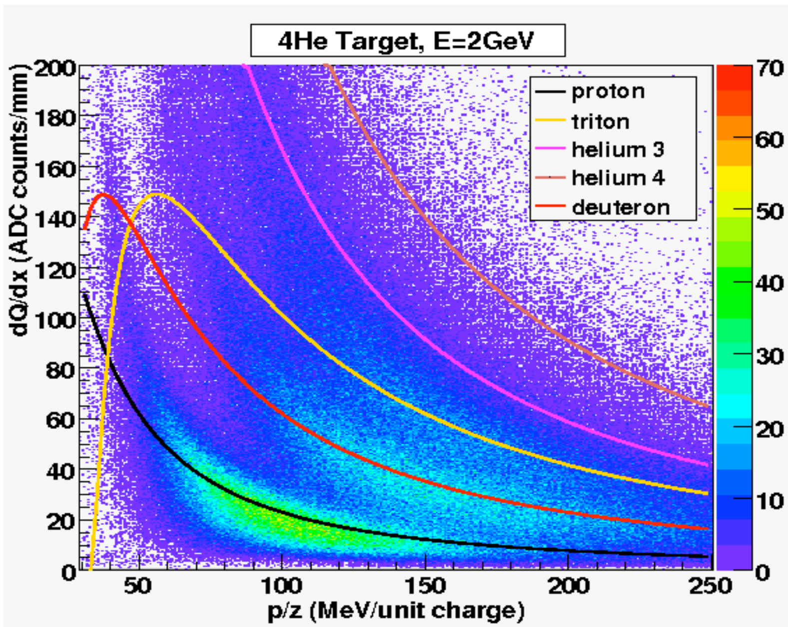
- Bound Nucleon Structure Experiment
- Hall B, JLab, CLAS
- $d(e,e'p_s)X$ with $0.07 < p_s < 0.15$ GeV/c
- E_{beam}=1.1, 2.1, 4.2, 5.3 GeV
- Radial time projection chamber for p_s
- Data taking in 2005

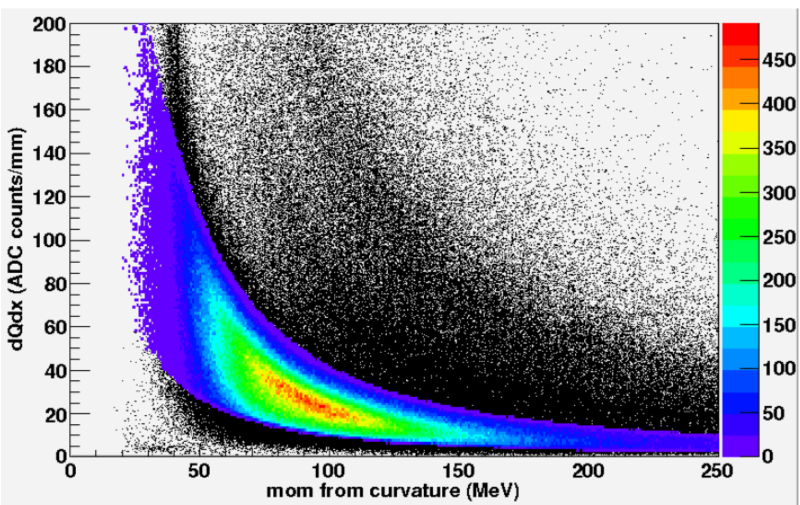


BoNuS Detector

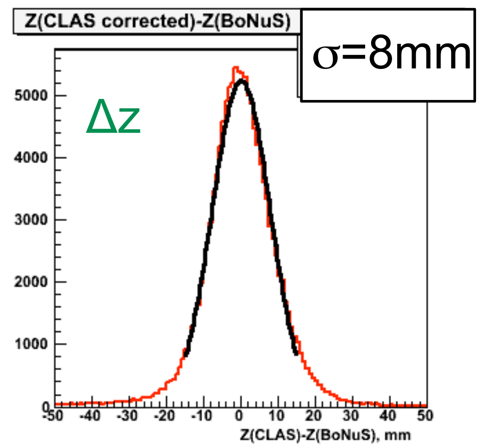


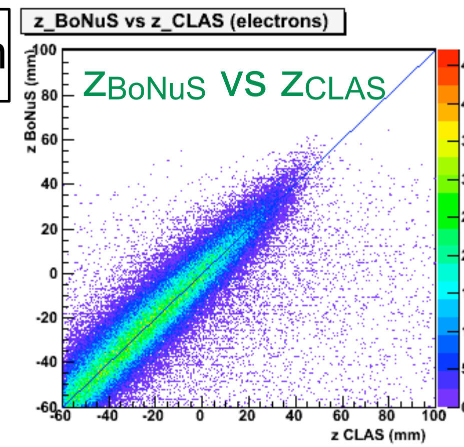
BoNuS RTPC Performance

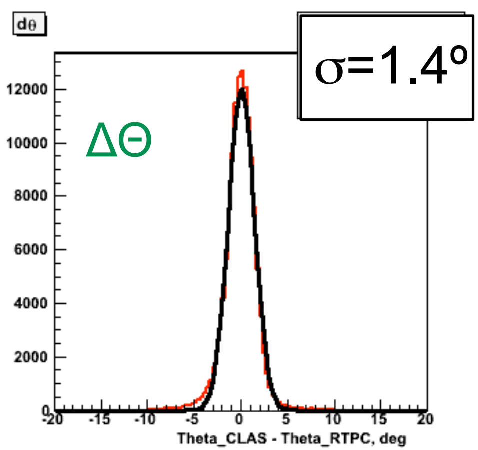


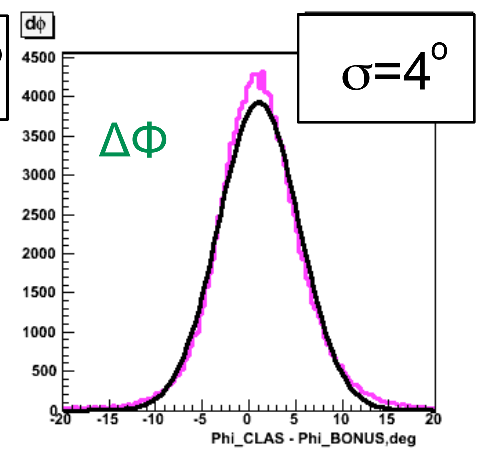


- upper left: dE/dx vs. p/Z for He target
- lower left: dE/dx vs. p for deuterium target
- below RTPC+CLAS resolution for common e^- events



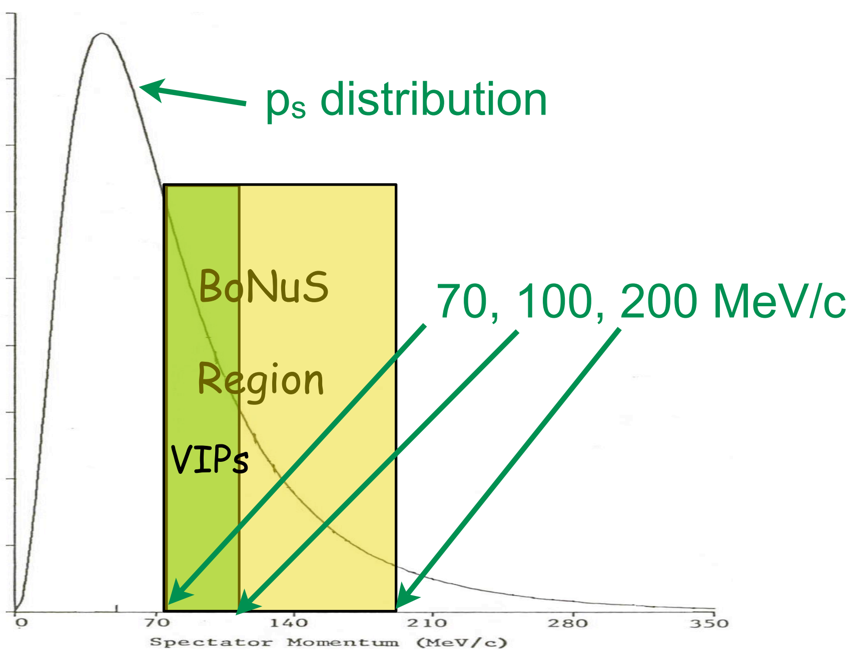


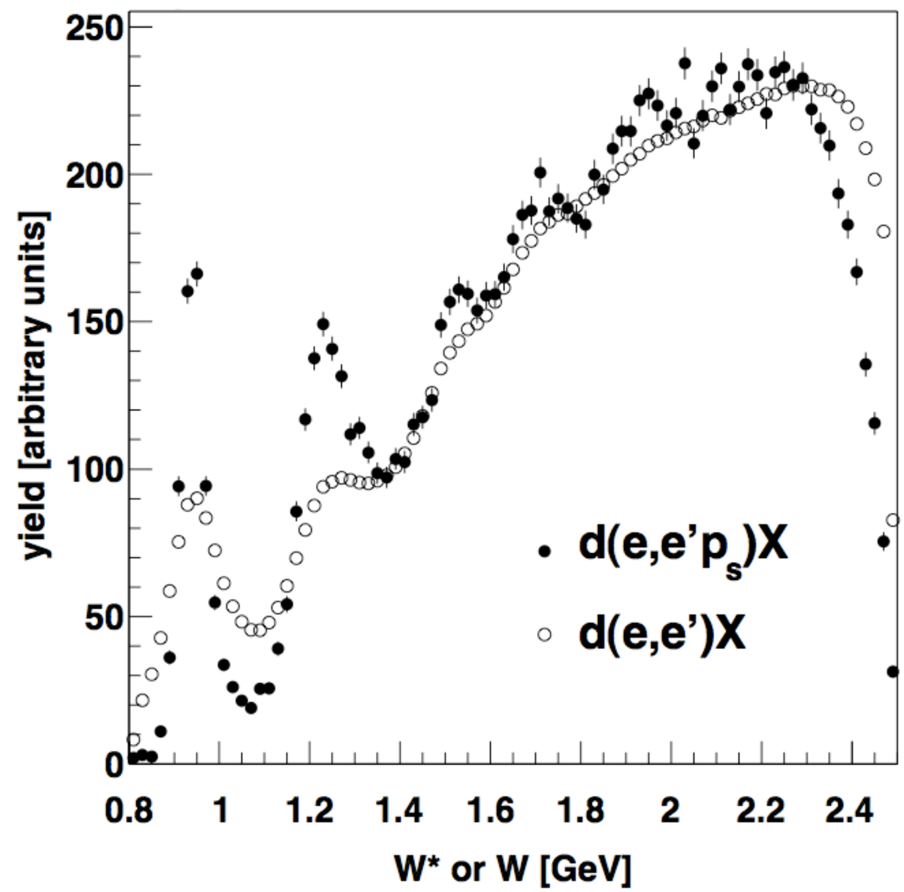




BoNuS Kinematic Correction

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

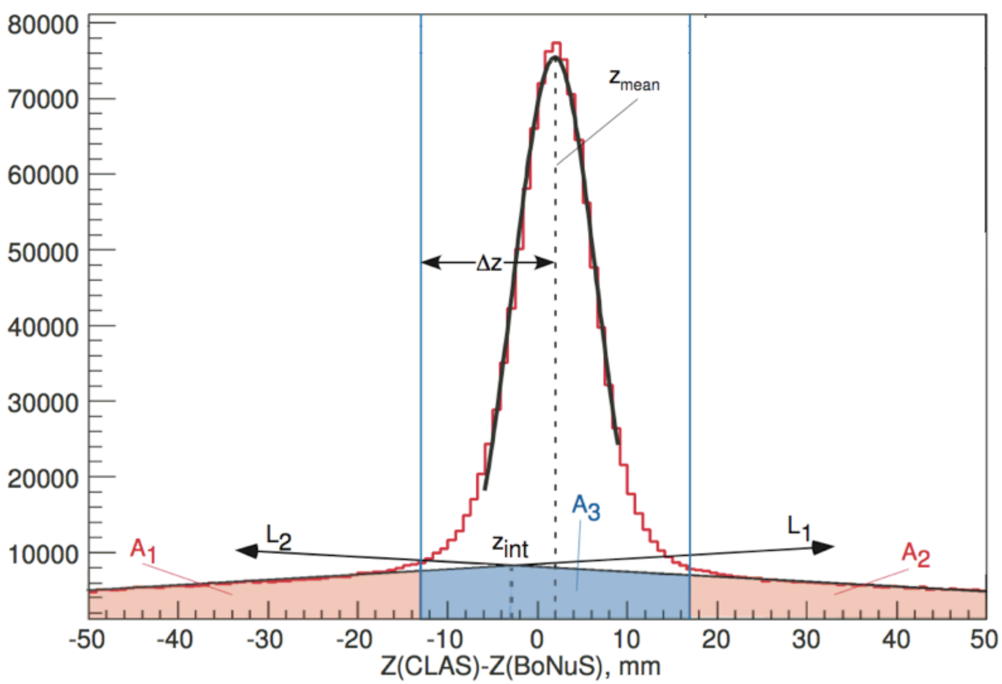




Two Analysis Methods

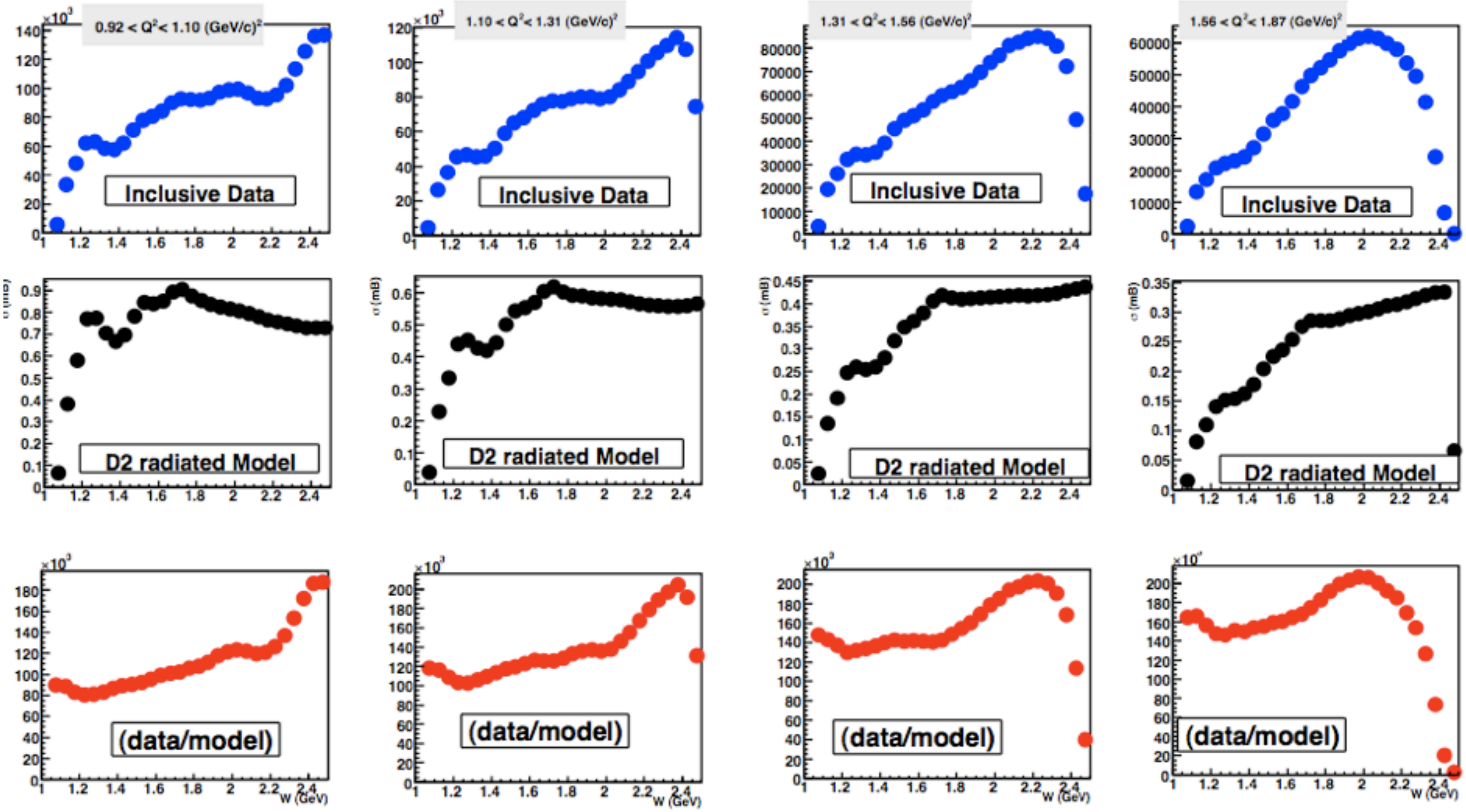
- The Ratio Method
  - ⋆ measure tagged counts divided by inclusive counts
  - ⋆ correct this ratio for backgrounds
  - ⋆ one scale factor gives F_2^n/F_2^d
- The Monte Carlo Method
  - ⋆ measure tagged counts
  - ⋆ divide by spectator model Monte Carlo results
  - ⋆ multiply by F_2^n used in the model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

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
- Bottom Row: Relative efficiency ε (*i.e.* Top Row / Middle Row)

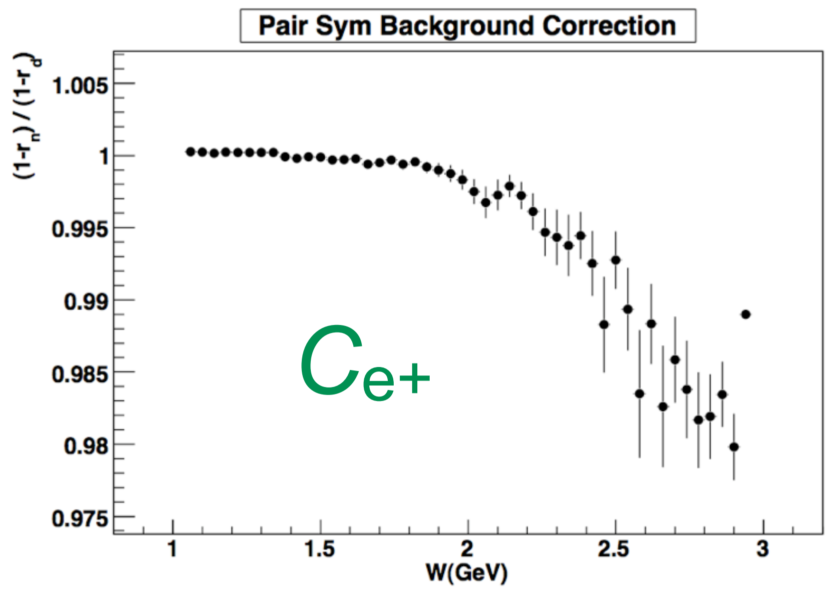
F_2^n/F_2^d from Tagged/Untagged Events

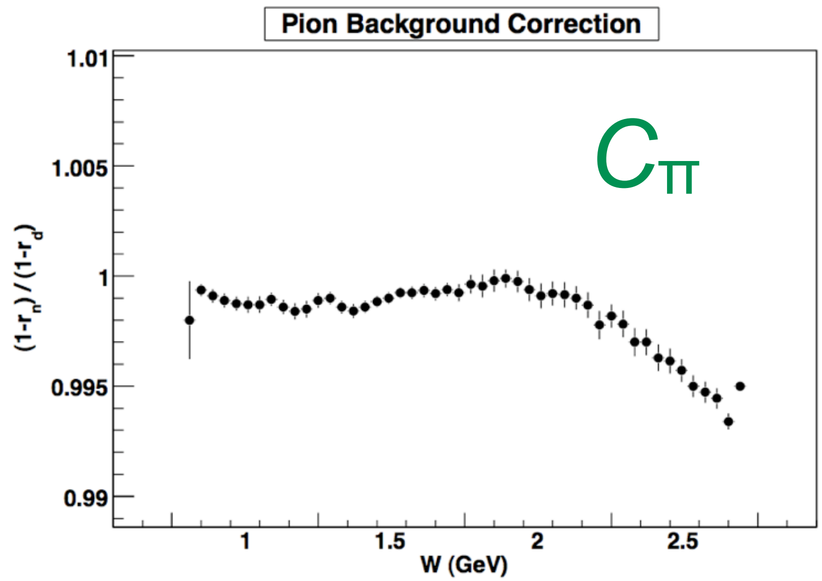
$$R_{corr} = \frac{\displaystyle\sum_{i=1}^{N_{tag}(W^*,Q^2)} \frac{1}{\epsilon_i(W,Q^2)} - R_{bg} \sum_{j=1}^{N_{bg}(W^*,Q^2)} \frac{1}{\epsilon_j(W,Q^2)}}{\displaystyle\sum_{k=1}^{N_{untag}(W,Q^2)} \frac{1}{\epsilon_k(W,Q^2)}}$$

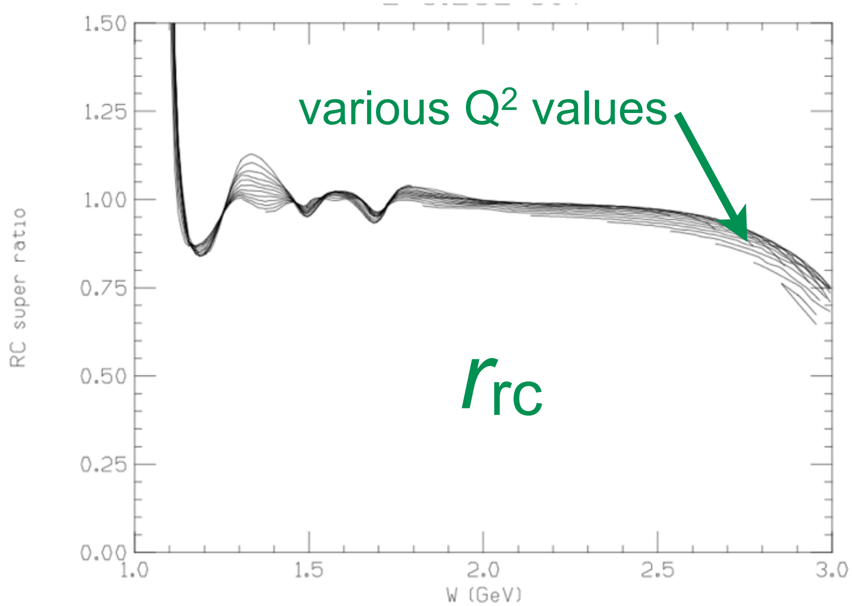
$$\frac{F_2^n}{F_2^d} = (R_{corr})(C_{e^+})(C_\pi)(r_{rc})(n)$$

- 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}

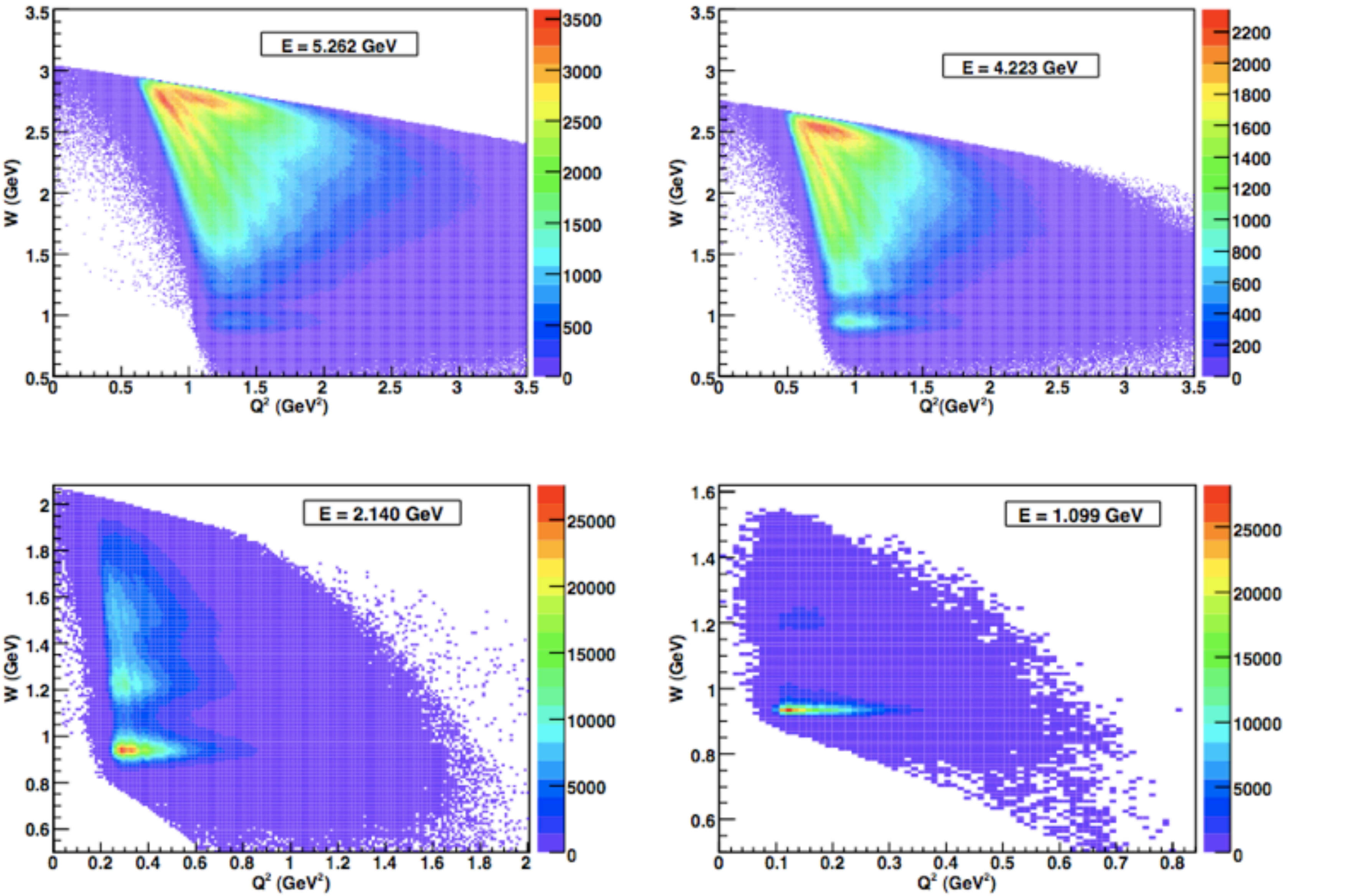






- C_{e+} correction < 2 %
- C_{π} correction < 1/2 %
- r_{rc} correction < 10% in the region 1.2<W<2.7 GeV
- $1/n$ = 0.02535 ± 3.37%

Kinematic Coverage



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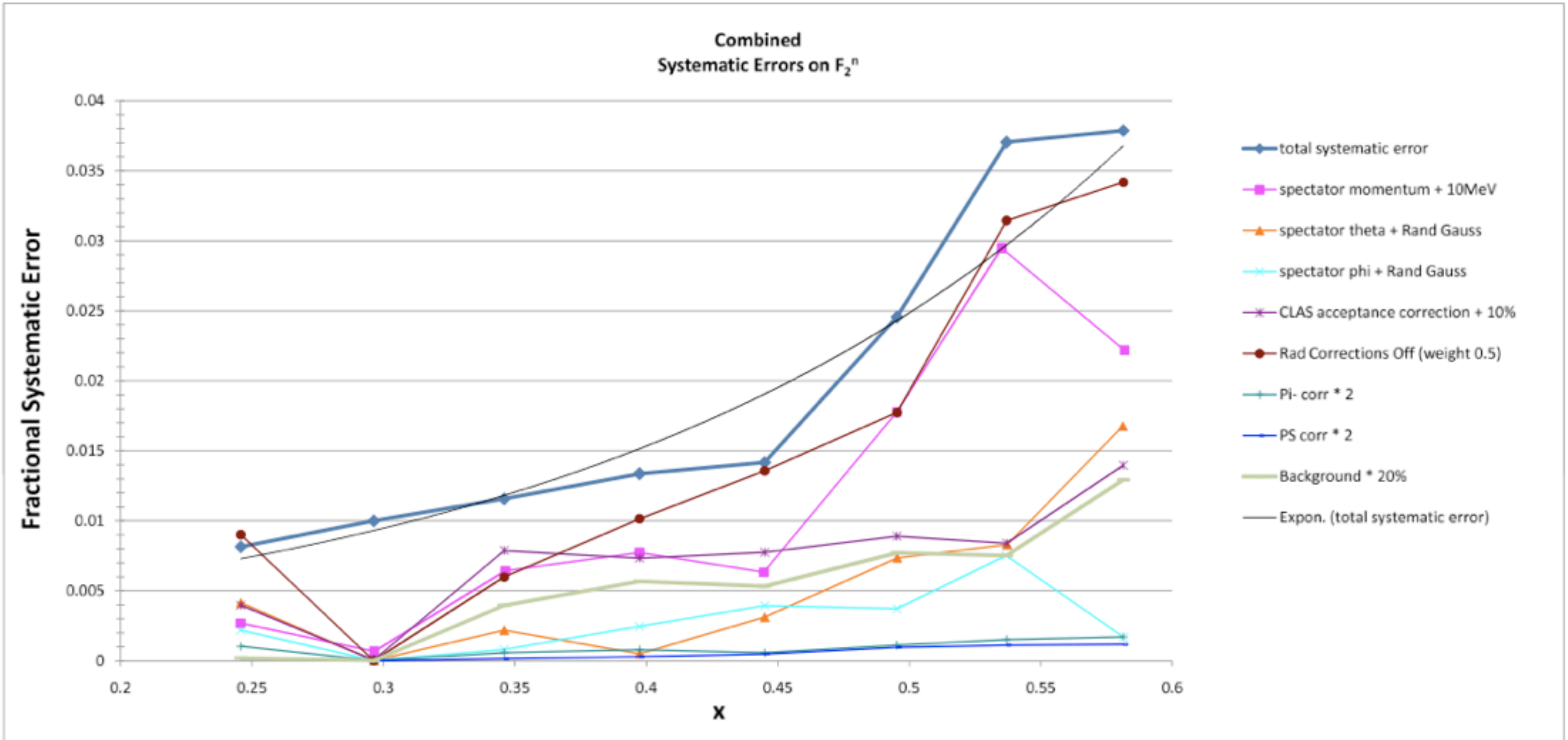
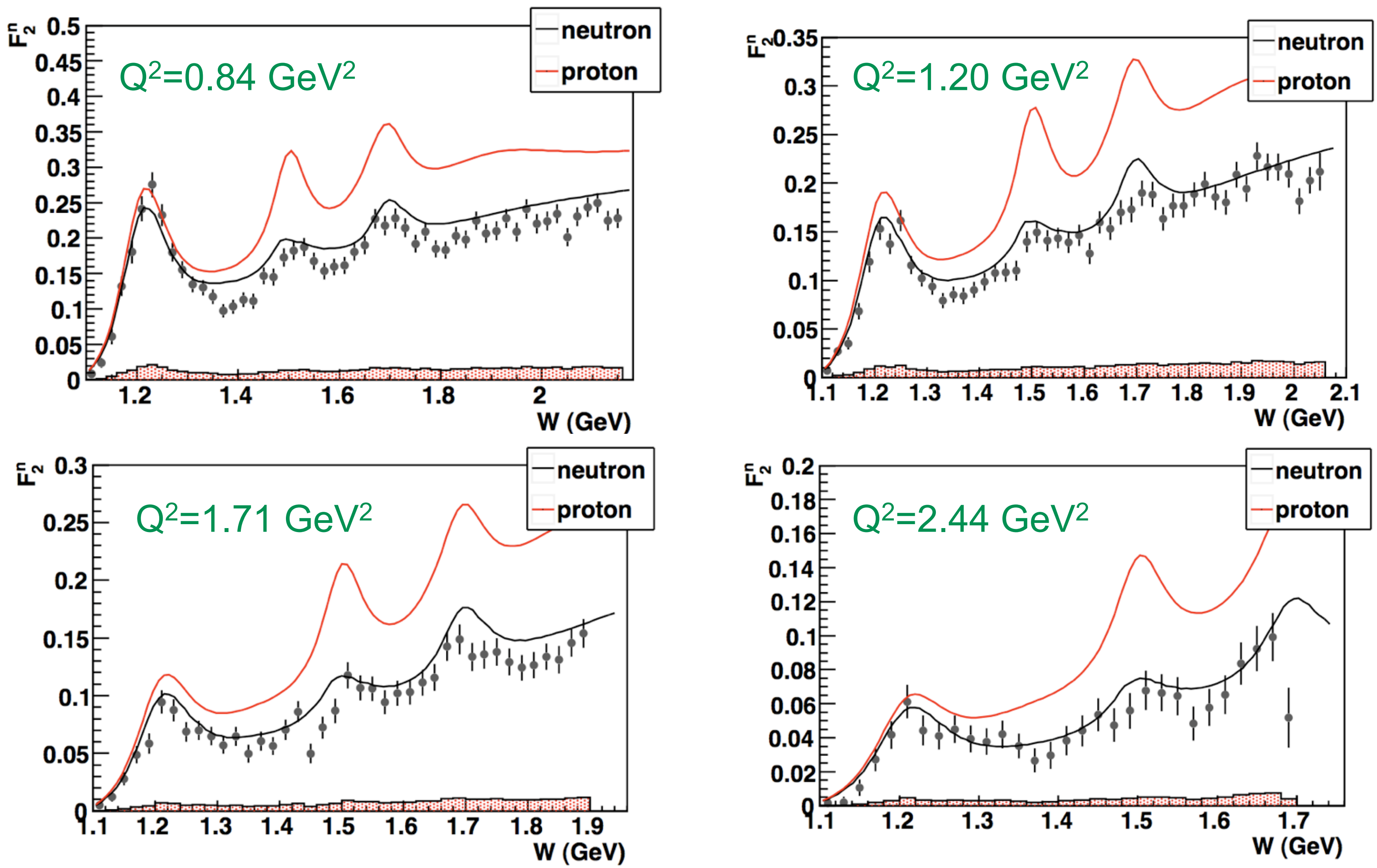
Systematic Errors



- 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.

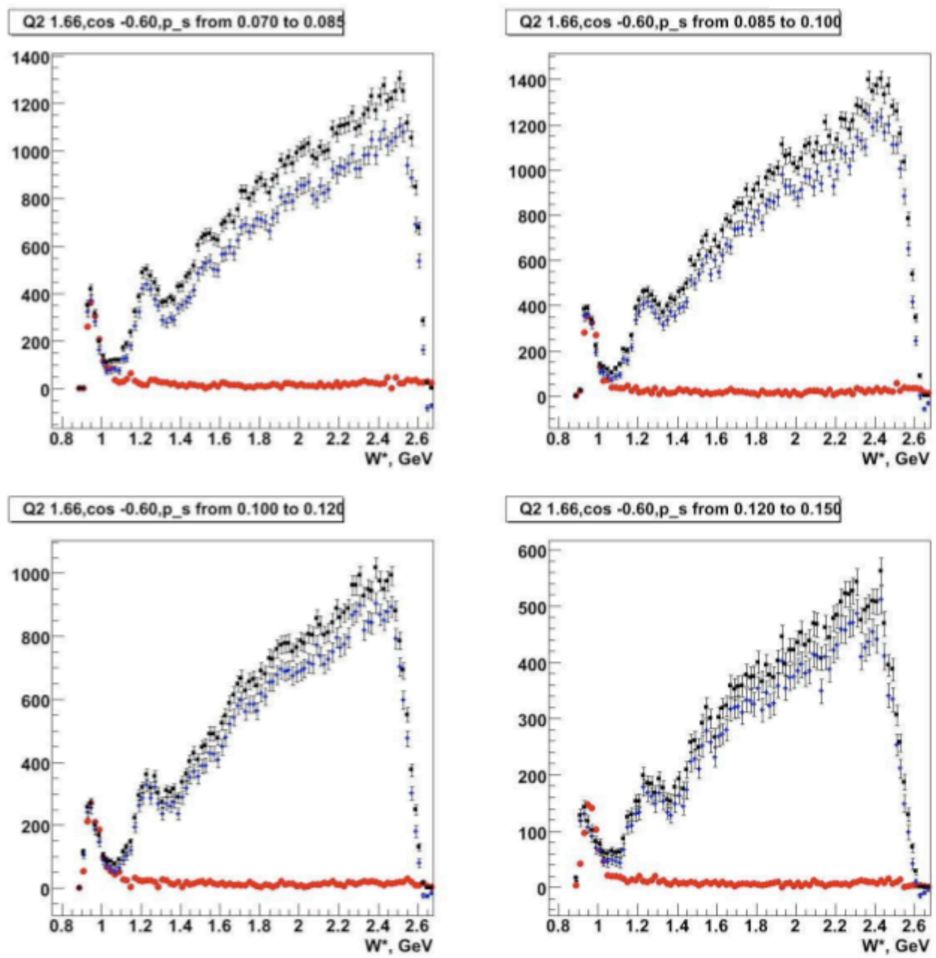
BoNuS F_2^n



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

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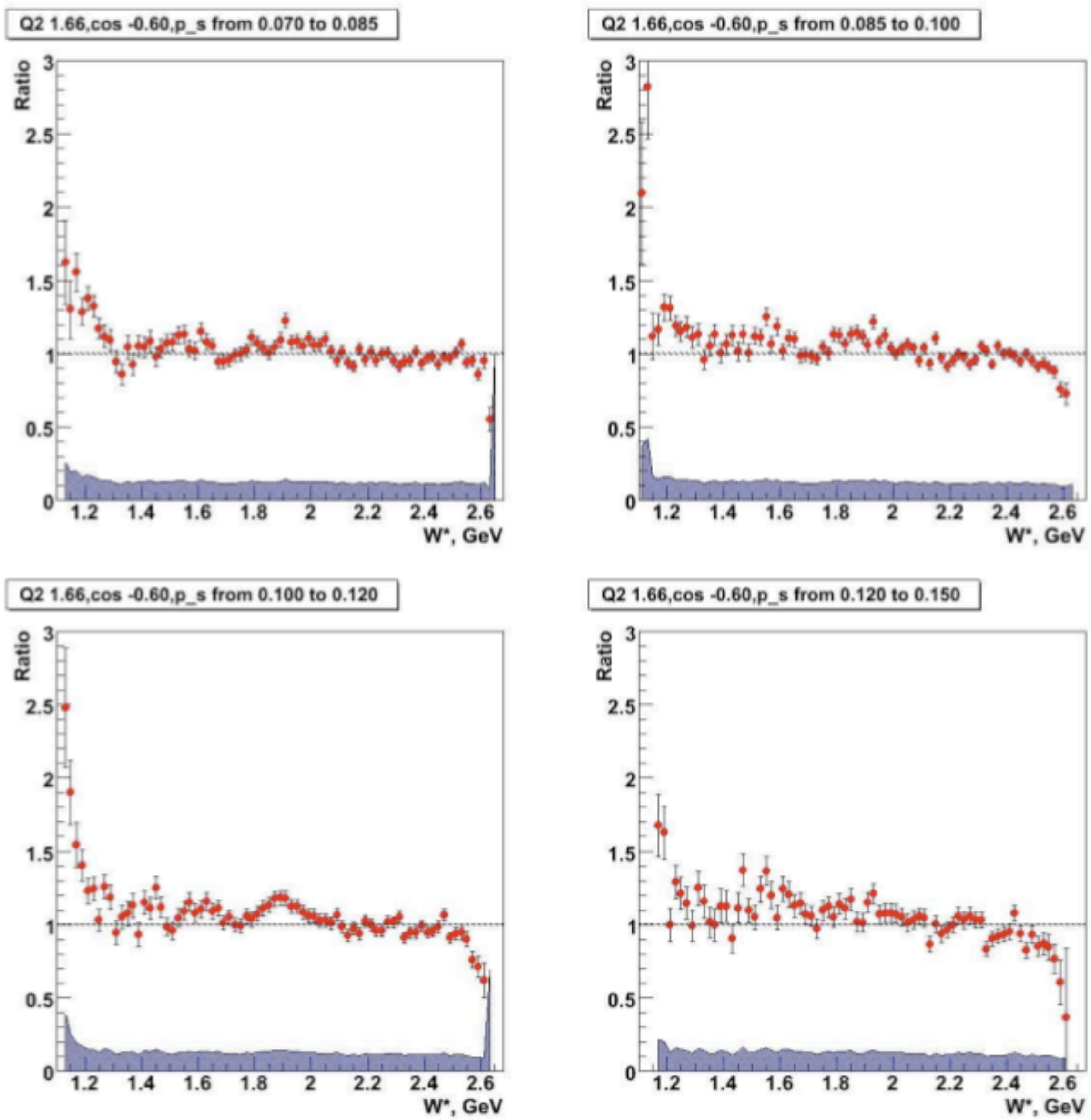
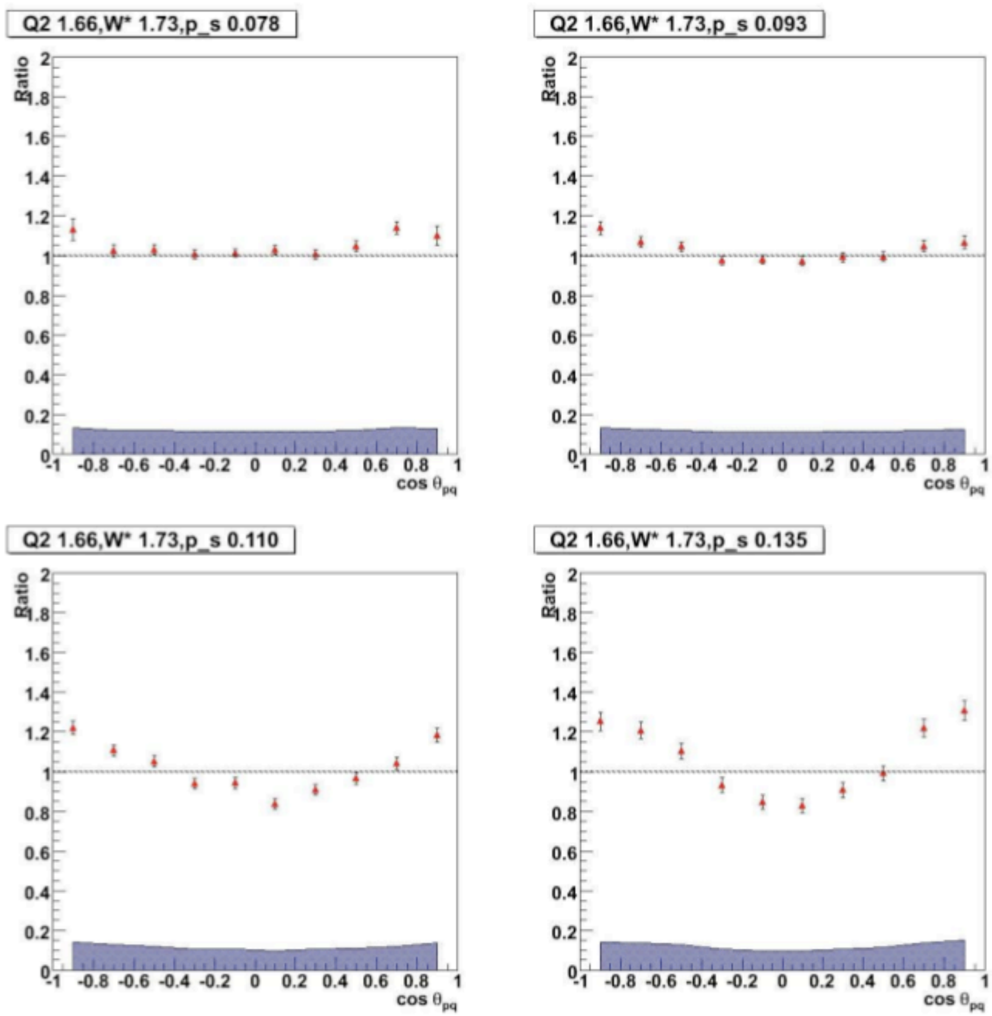
Data / MC vs W* for Different p_s



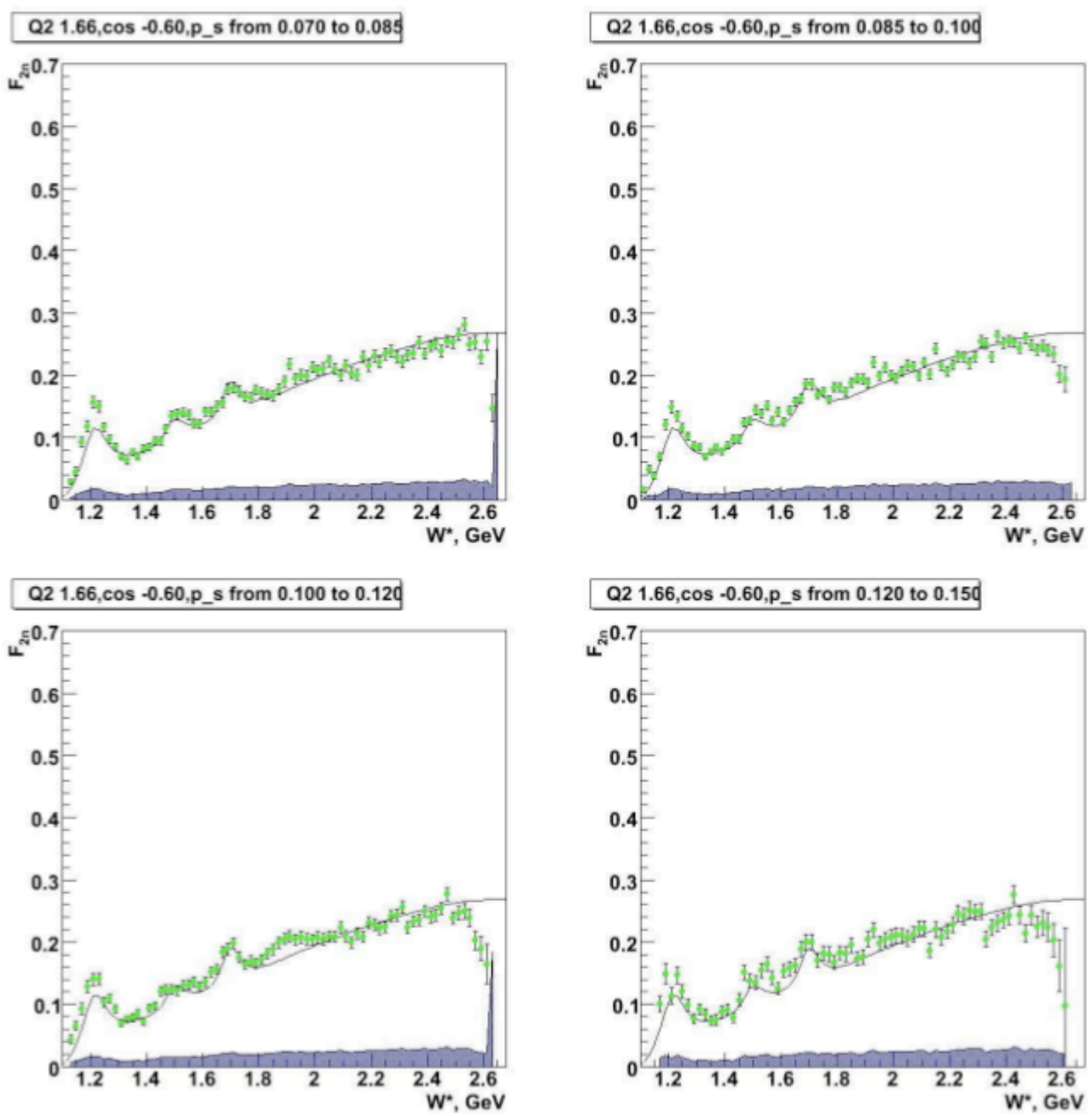
- Deviations from unity at low W* comes from difficulties of getting the model right for the resonances
- Generally the ratio is close to unity
- Perhaps some effects at high p_s

cosθ distributions / MC



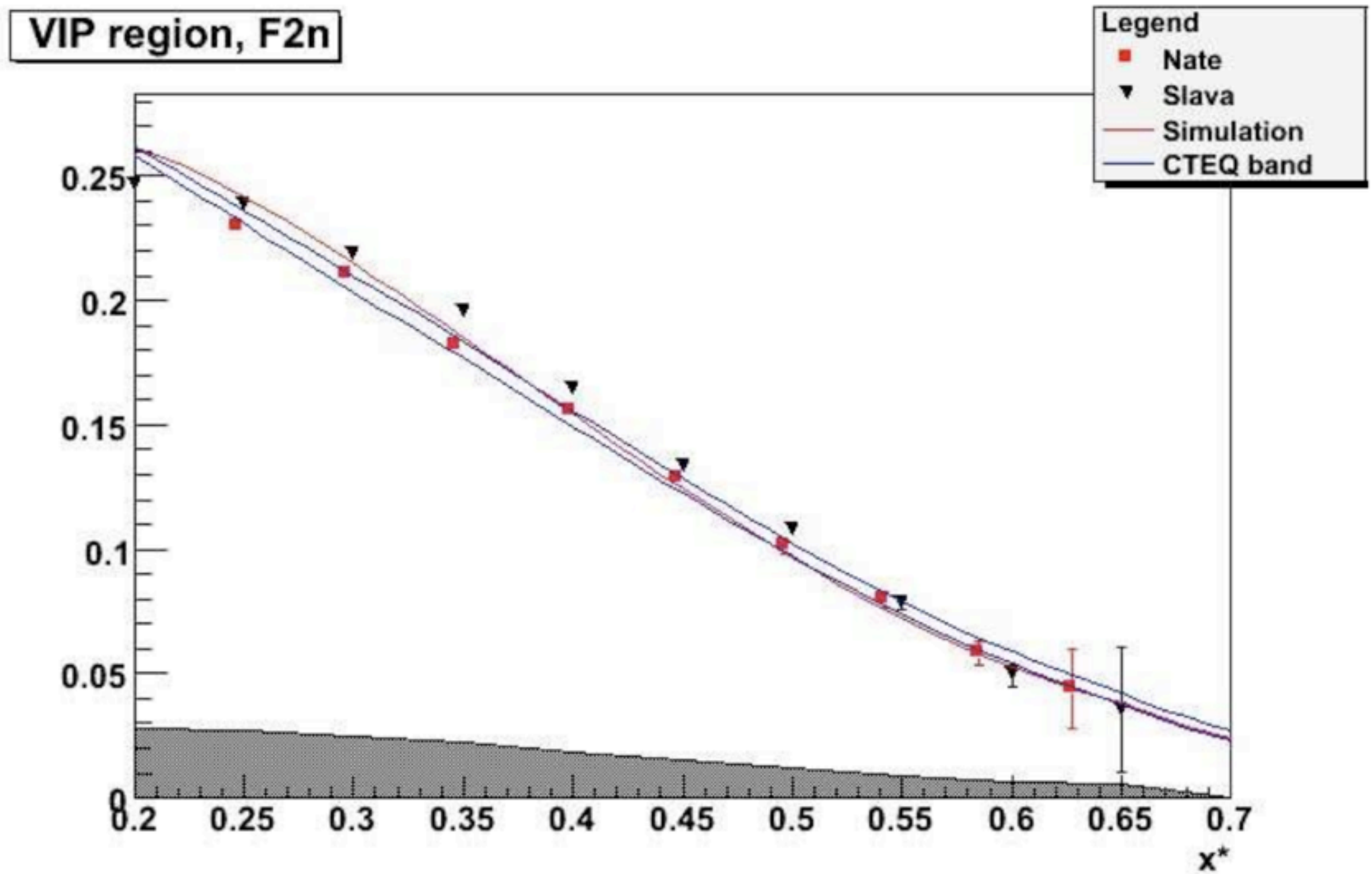
- At low p_s the data agree with the spectator model quite well
- At higher p_s the distributions deviate significantly from unity, indicating that VIP particles should have p_s<100 MeV/c

F_2^n for various p_s

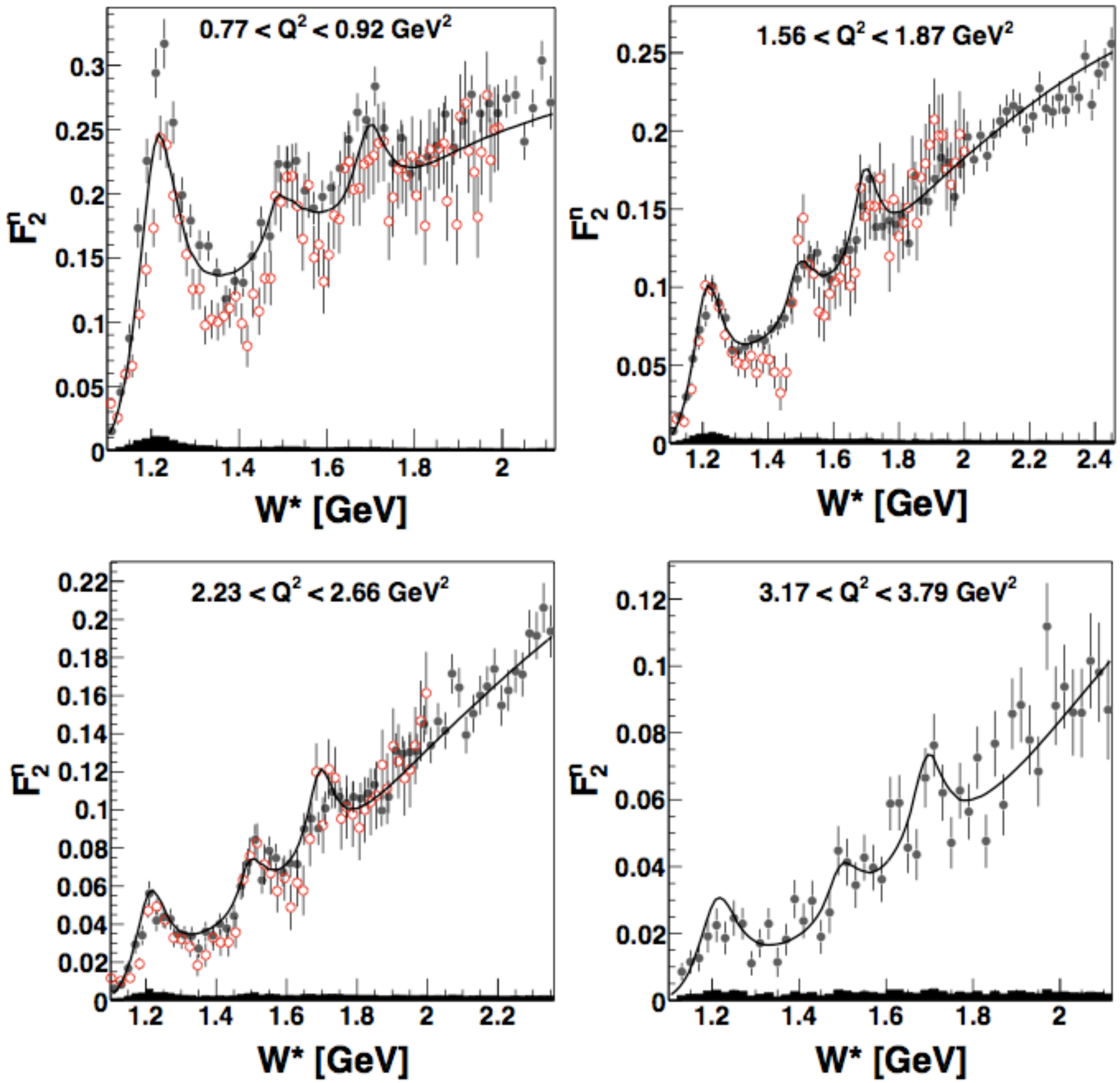


- Data show resonance peaks.
- Data agree quite well with resonance model of world data
- Dependence on spectator momentum is slight

Ratio and MC Method Comparison

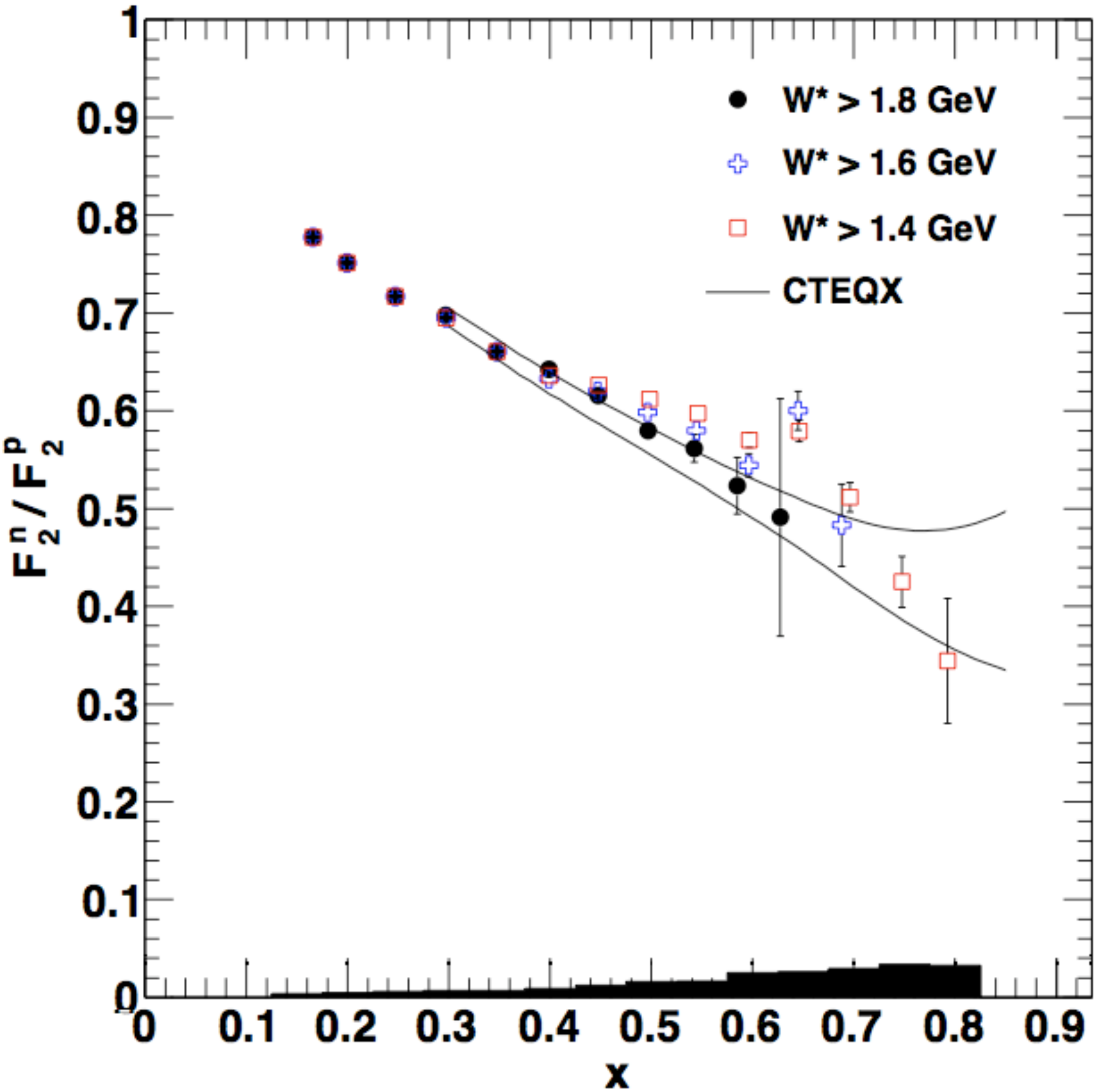


Final Data



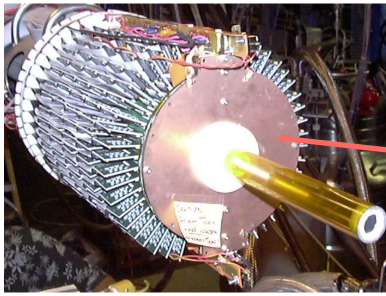
Various data compared to a state of the art nuclear physics extraction of neutron structure functions from deuterium (red points, Malace, et al.)

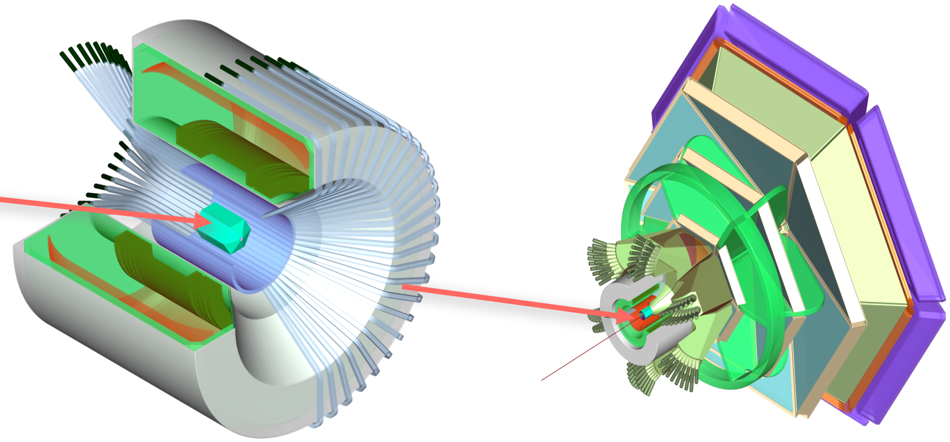
BoNuS F_2^n/F_2^p

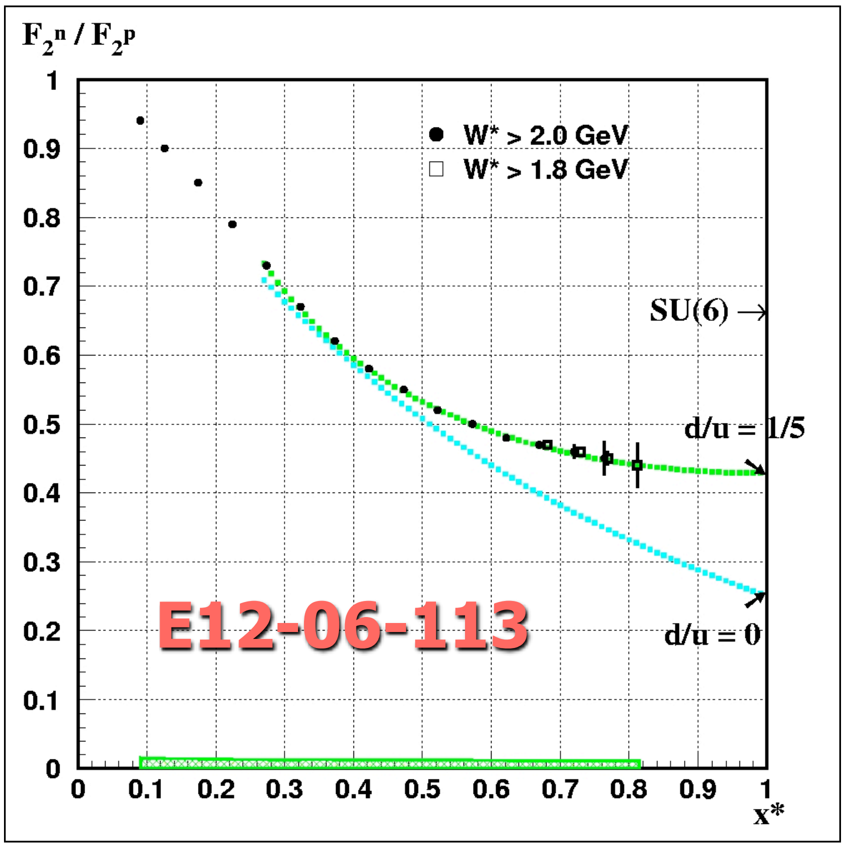


- F_2^n/F_2^n vs. x
- Curves are CETQ error bands
- CETQ cuts off at low x because Q^2 is too low
- Lower cuts in W* imply higher x but the inclusion of resonance contributions.
- Results are consistent with CETQ trends at high x.

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 Effect
  - no evidence for off-shell structure for p_s<140 MeV/c
  - F_2^n/F_2^p behaves at high x much like CETQ high-x fits
  - F_2^n resonance data will significantly improve the world data set, which up to now came from d with nuclear corrections
- CLAS12:
  - new BoNuS proposal is approved