The Physics Behind the Bound Nucleon Structure Experiment's (BoNuS) PRL

Keith Griffioen
College of William & Mary
griff@physics.wm.edu

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Paper Submitted to PRL

Measurement of the neutron F_2 structure function via spectator tagging with CLAS

N. Baillie,[44,16] S. Tkachenko,[33,43] J. Zhang,[33,39] P. Bosted,[39,44] S. Bültmann,[33] M.E. Christy,[16] H. Fenker,[39] K.A. Griffioen,[44] C.E. Keppel,[16] S.E. Kuhn,[33] W. Melnitchouk,[39] V. Tvaskis,[39] K.P. Adhikari,[33] D. Adikaram,[33] M. Aghasyan,[21] M.J. Amaryan,[33] M. Anghinolfi,[22] J. Arrington,[1] H. Avakian,[39] H. Baghdasaryan,[43,33] M. Battaglieri,[22] A.S. Biselli,[11,5] D. Branford,[10] W.J. Briscoe,[15] W.K. Brooks,[41,39] V.D. Burkert,[39] D.S. Carman,[39] A. Celentano,[22] S. Chandavar,[32] G. Charles,[7] P.L. Cole,[18] M. Contalbrigo,[20] V. Crede,[13] A. D'Angelo,[23,36] A. Daniel,[32] N. Dashyan,[45] R. De Vita,[22] E. De Sanctis,[21] A. Deur,[39] B. Dey,[5] C. Djalali,[38] G. Dodge,[33] J. Domingo,[39] D. Doughty,[8,39] R. Dupre,[1] D. Dutta,[31] R. Ent,[39] H. Egiyan,[39,29] A. El Alaoui,[1] L. El Fassi,[1] L. Elouadrhiri,[39] P. Eugenio,[13] G. Fedotov,[38,37] S. Fegan,[42] A. Fradi,[24] M.Y. Gabrielyan,[12] N. Gevorgyan,[45] G.P. Gilfoyle,[35] K.L. Giovanetti,[26] F.X. Girod,[39] W. Gohn,[9] E. Golovatch,[37] R.W. Gothe,[38] L. Graham,[38] B. Guegan,[24] M. Guidal,[24] N. Guler,[33,*] L. Guo,[12,39] K. Hafidi,[1] D. Heddle,[8,39] K. Hicks,[32] M. Holtrop,[29] E. Hungerford,[17] C.E. Hyde,[33] Y. Ilieva,[38,15] D.G. Ireland,[42] M. Ispiryan,[17] E.L. Isupov,[37] S.S. Jawalkar,[44] H.S. Jo,[24] N. Kalantarians,[43] M. Khandaker,[30] P. Khetarpal,[12] A. Kim,[27] W. Kim,[27] P.M. King,[19,32] A. Klein,[33] F.J. Klein,[6] A. Klimenko,[33] V. Kubarovsky,[39,34] S.V. Kuleshov,[41,25] N.D. Kvaltine,[43] K. Livingston,[42] H.Y. Lu,[5,38] I .J .D. MacGregor,[42] Y. Mao,[38] N. Markov,[9] B. McKinnon,[42] T. Mineeva,[9] B. Morrison,[2] H. Moutarde,[7] E. Munevar,[15] P. Nadel-Turonski,[39,15] A. Ni,[27] S. Niccolai,[24] I. Niculescu,[26] G. Niculescu,[26] M. Osipenko,[22] A.I. Ostrovidov,[13] L. Pappalardo,[20] K. Park,[39,27] S. Park,[13] E. Pasyuk,[39,2] S. Anefalos Pereira,[21] S. Pisano,[21,24] S. Pozdniakov,[25] J.W. Price,[3] S. Procureur,[7] Y. Prok,[8,43] D. Protopopescu,[42] B.A. Raue,[12,39] G. Ricco,[22,14] D. Rimal,[12] M. Ripani,[22] G. Rosner,[10] P. Rossi,[21] F. Sabatié,[7] M.S. Saini,[13] C. Salgado,[30] D. Schott,[12] R.A. Schumacher,[5] E. Seder,[9] Y.G. Sharabian,[39] D.I. Sober,[6] D. Sokhan,[24] S. Stepanyan,[39] S.S. Stepanyan,[27] P. Stoler,[34] S. Strauch,[38] M. Taiuti,[14] W. Tang,[32] M. Ungaro,[9] M.F. Vineyard,[40] E. Voutier,[28] D.P. Watts,[10] L.B. Weinstein,[33] D.P. Weygand,[39] M.H. Wood,[4,38] L. Zana,[29] and B. Zhao[44,9]

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arxiv.org/abs/1110.2770

Measurement of the neutron F_2 structure function via spectator tagging with CLAS

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- ★ Two authors appeared in the electronic list after the opt-in deadline
- ★ The computer-generated author list has TeX bugs
- ★ The opt-in system does not include limited members
- ★ The opt-in system does not include term members who have moved on
- ★ A dozen authors were added after opting in via email after the deadline.

D. Schott,[12] R.A. Schumacher,[5] E. Seder,[9] Y.G. Sharabian,[39] D.I. Sober,[6] D. Sokhan,[24] S. Stepanyan,[39]
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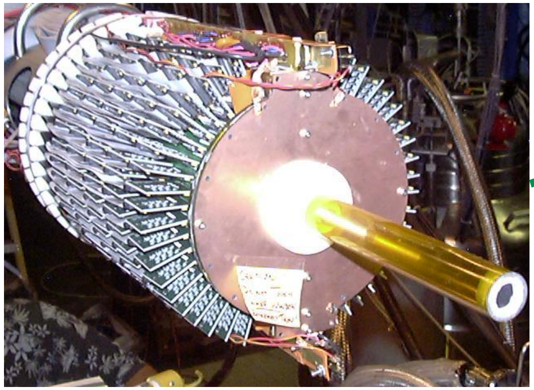
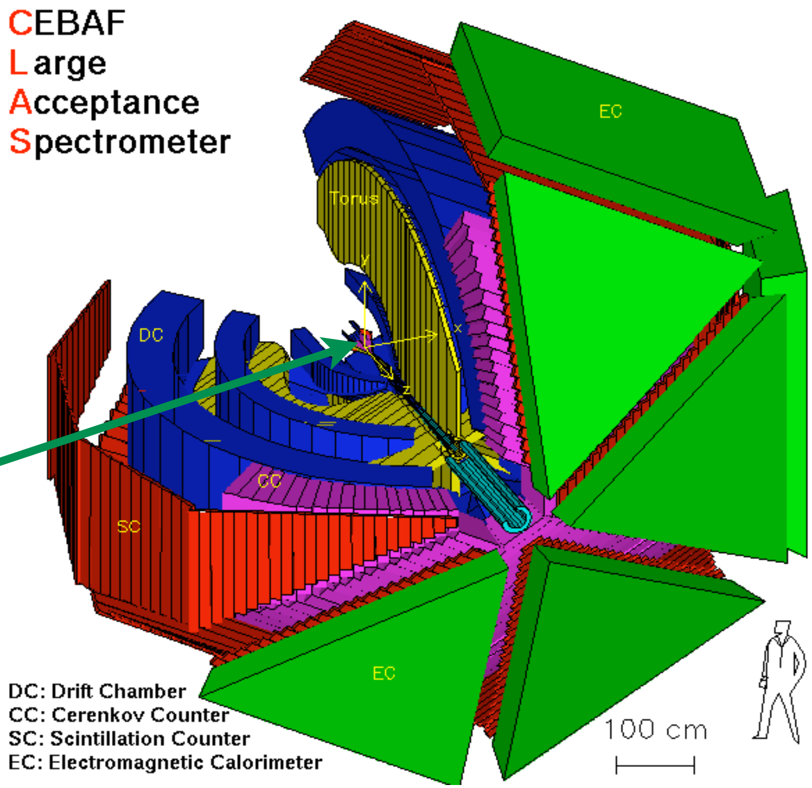
A CLAS Experiment with RTPC

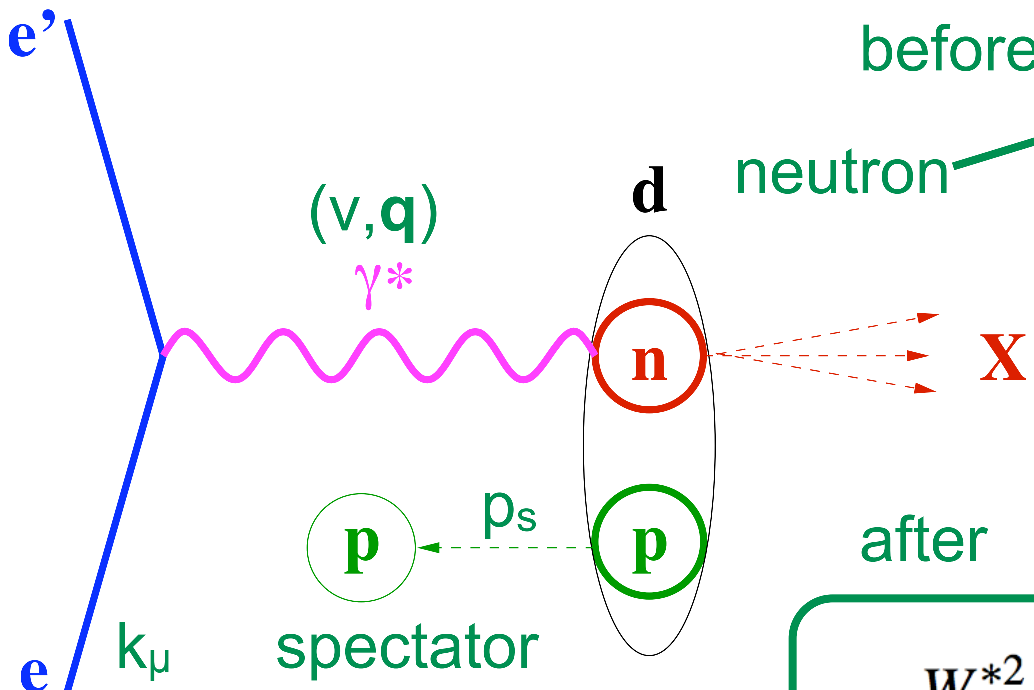
- Bound Nucleon Structure Experiment
- d(e,e'p_s)X [(deep) inelastic]
- deuterium target, spectator proton
- 70 < p_s < 180 MeV/c
- JLab Hall B CLAS with an RTPC
- measure F_2^n at high x

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

neutron

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

$$E_p + E_n = M_d$$

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

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

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

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

Off-Shell F_2

$R=\sigma_L/\sigma_T$

Light Cone

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

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

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

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

Spectral Function

Nonrelativistic w.f.

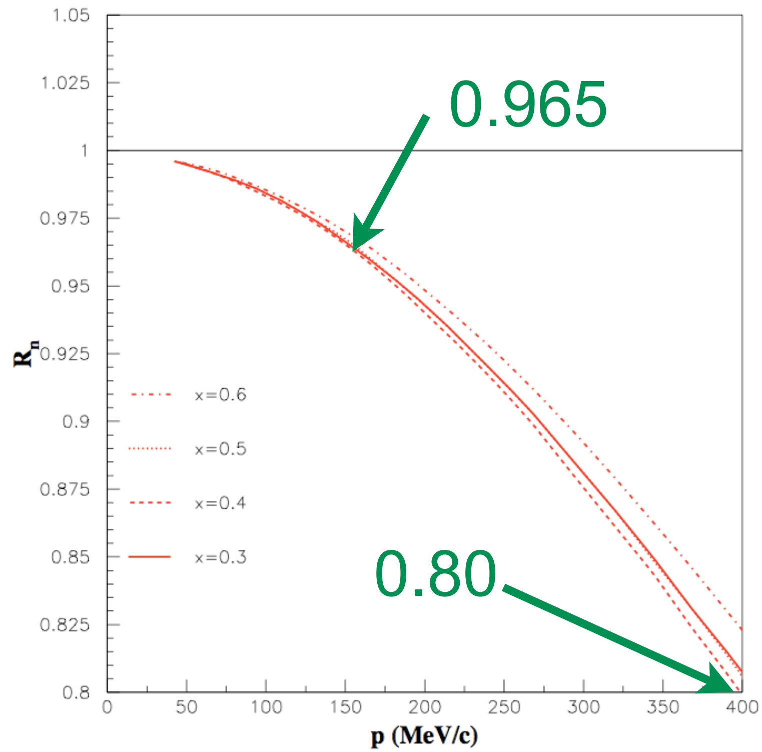
$$P(\vec{p}_s) = J|\psi_{\rm NR}(p_s)|^2$$

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

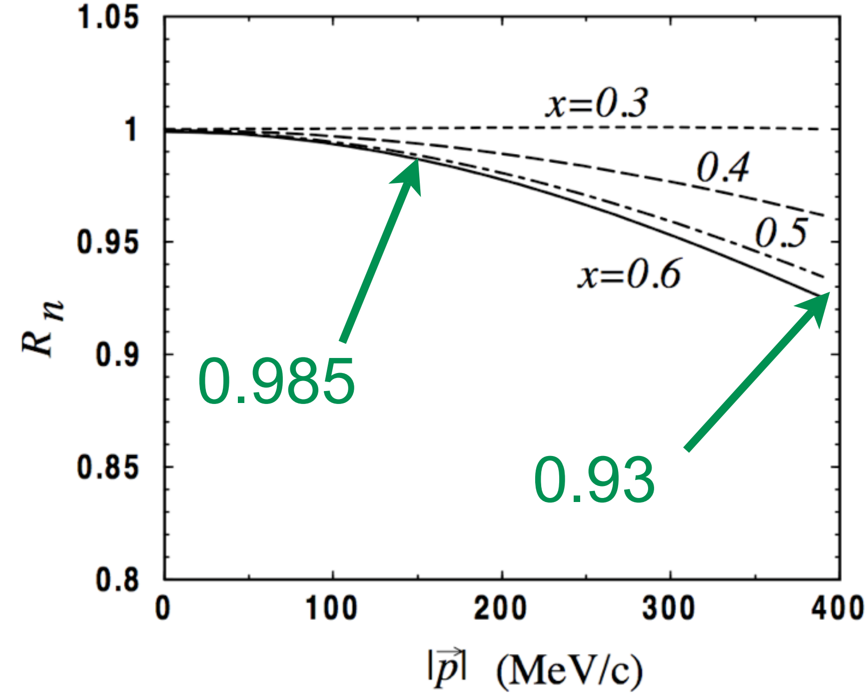
$$S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T = P(\vec{p}_s)d^3 p_s$$

Off-Shell Structure Functions

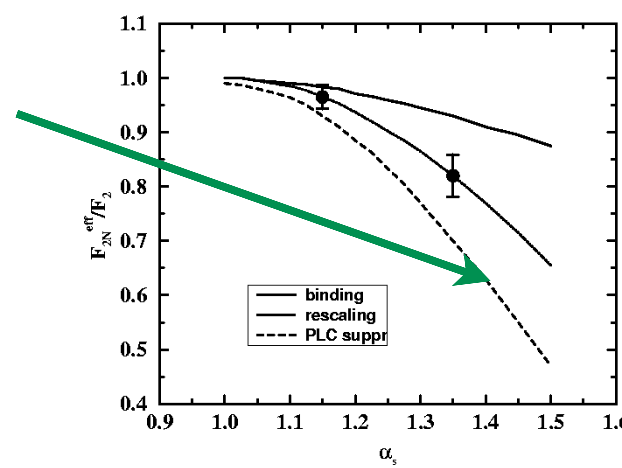
Liuti & Gross PLB356(95)157



Melnitchouk et al, PLB335(94)11

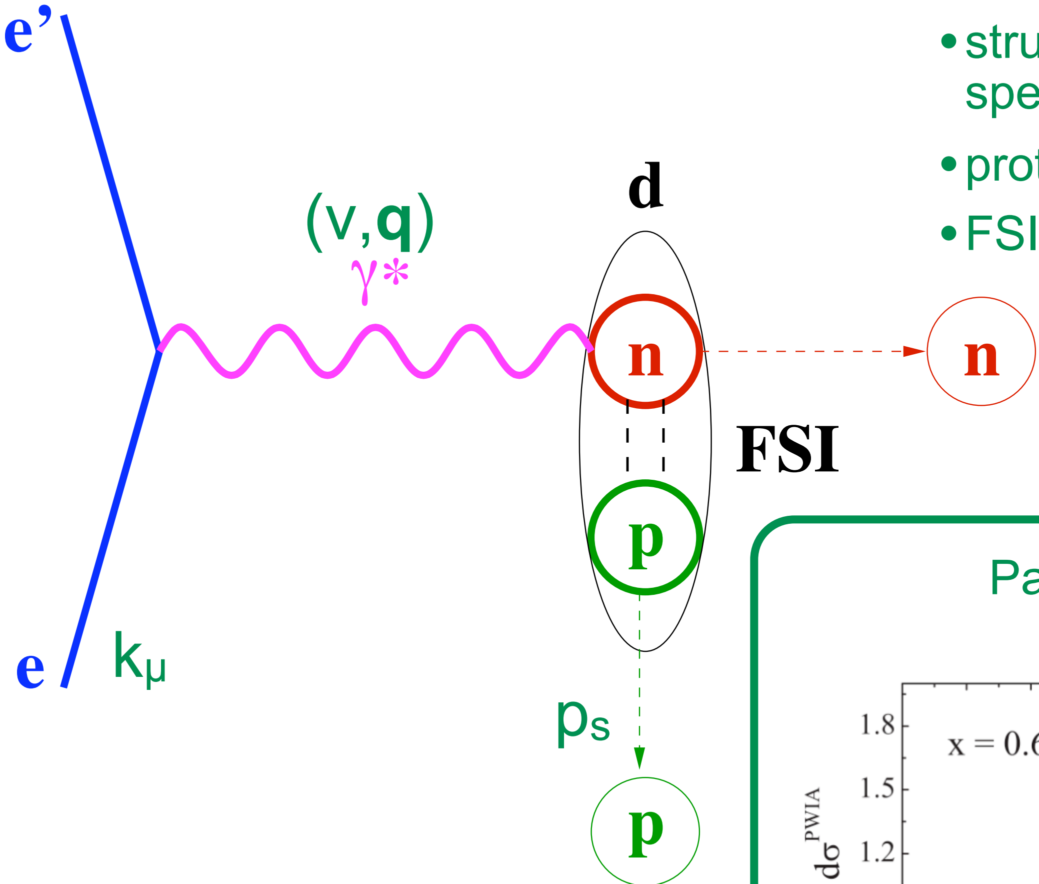


$$R_n \equiv (F_2^n)^{\rm eff}/(F_2^n)^{\rm free}$$



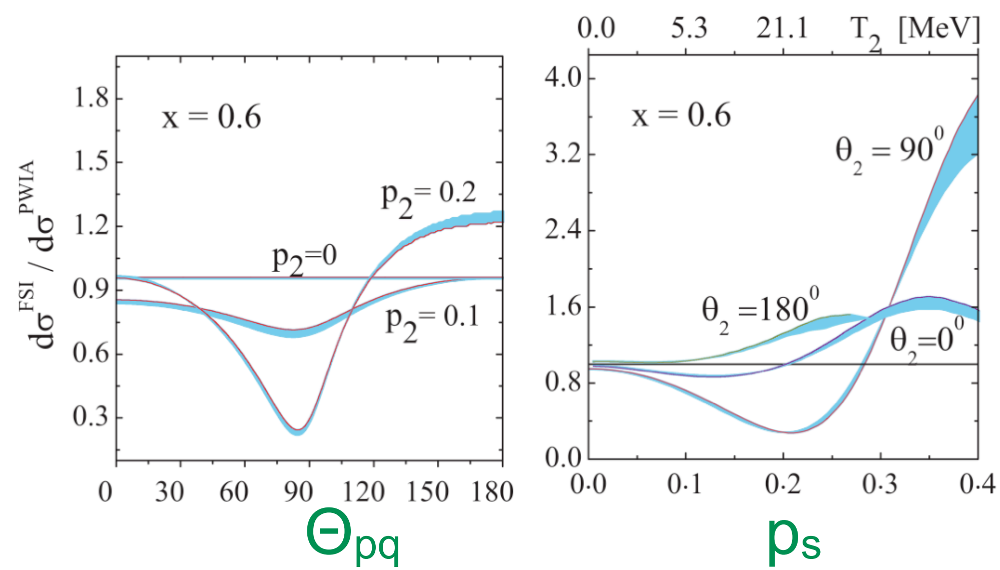
- R_n decreases with p_s or α
- at x*=0.5 and p_s=0.40 GeV/c, R_n deviates from 1 by 7-20% in these models
- at α=1.4 the deviation from unity could be 40%

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}

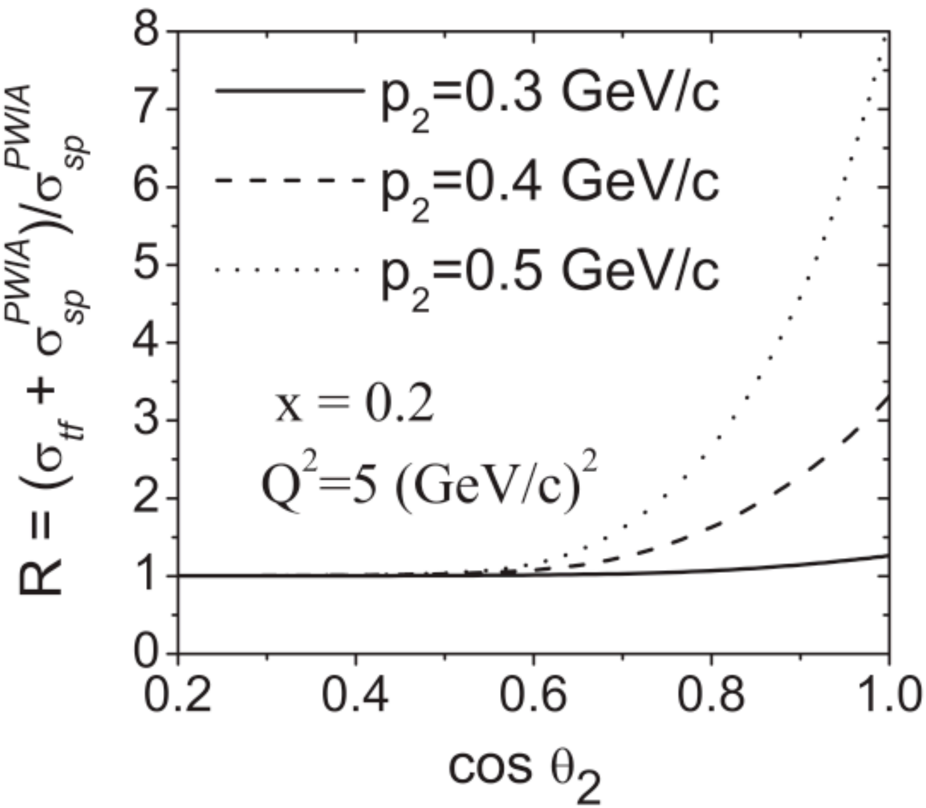
Palli et al, PRC80(09)054610



- several groups have calculated FSIs
- $\Theta_{pq} > 110^o$ minimizes FSIs

Target Fragmentation

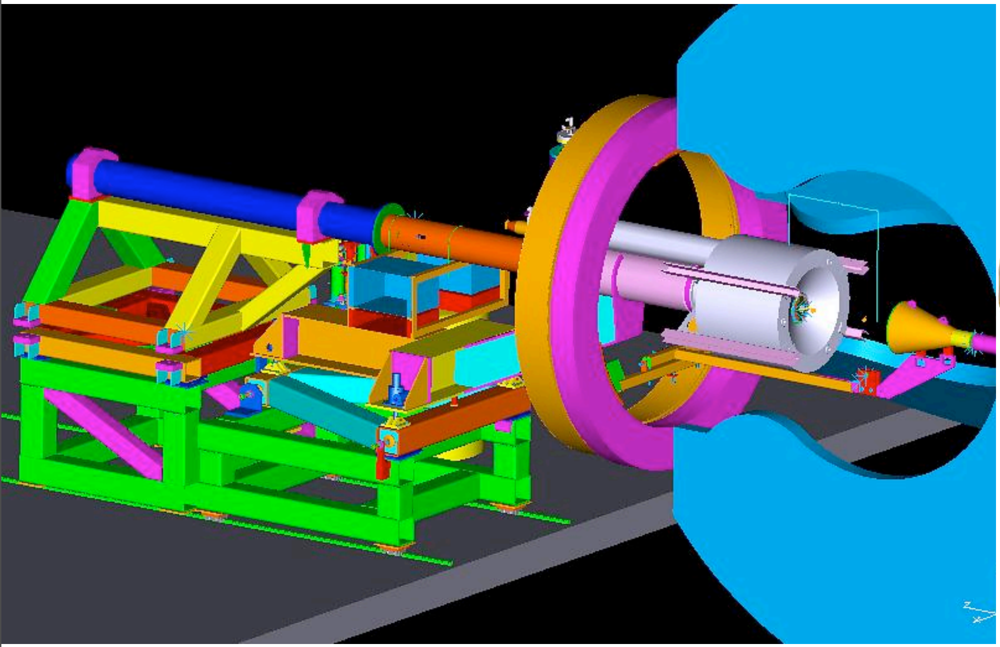
Palli et al, PRC80(09)054610

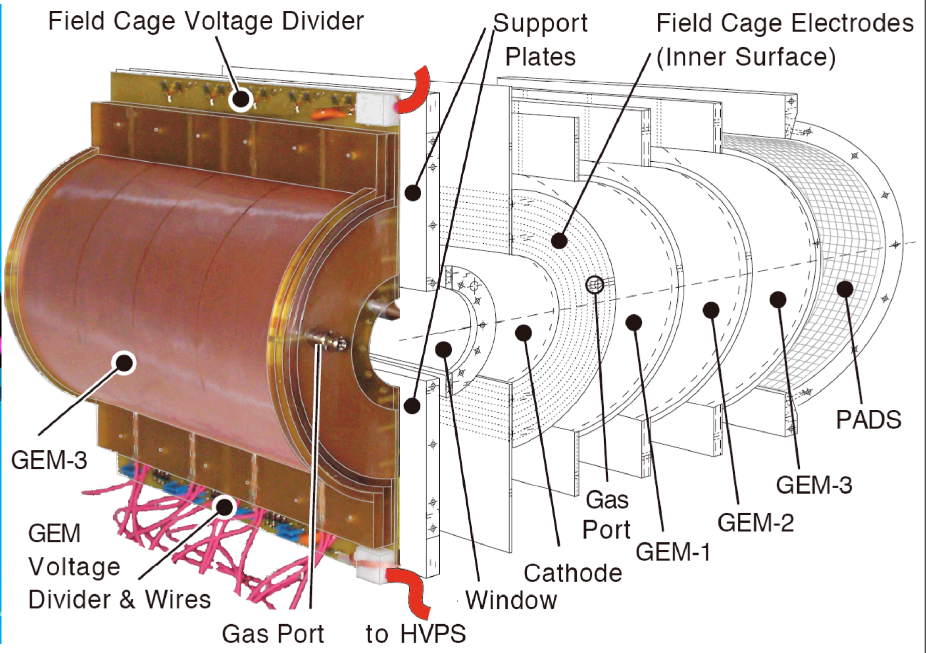


cos Θ_{pq}

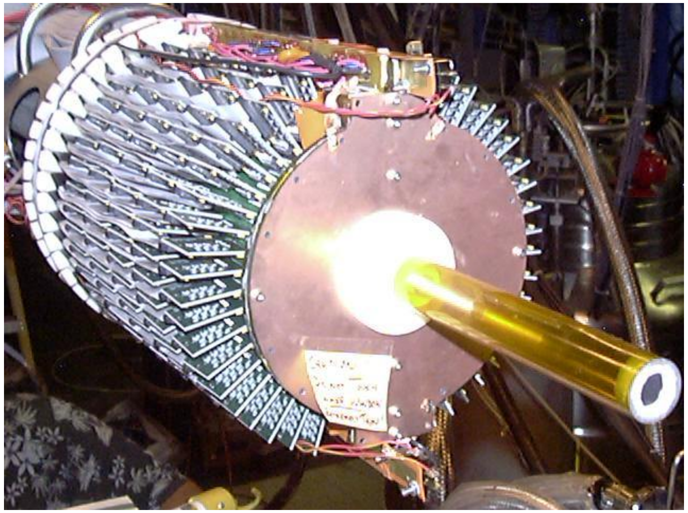
- target fragmentation enhances the proton yield only at forward angles (cos Θ_{pq} >0.6)
- this can be ignored

BoNuS Experiment

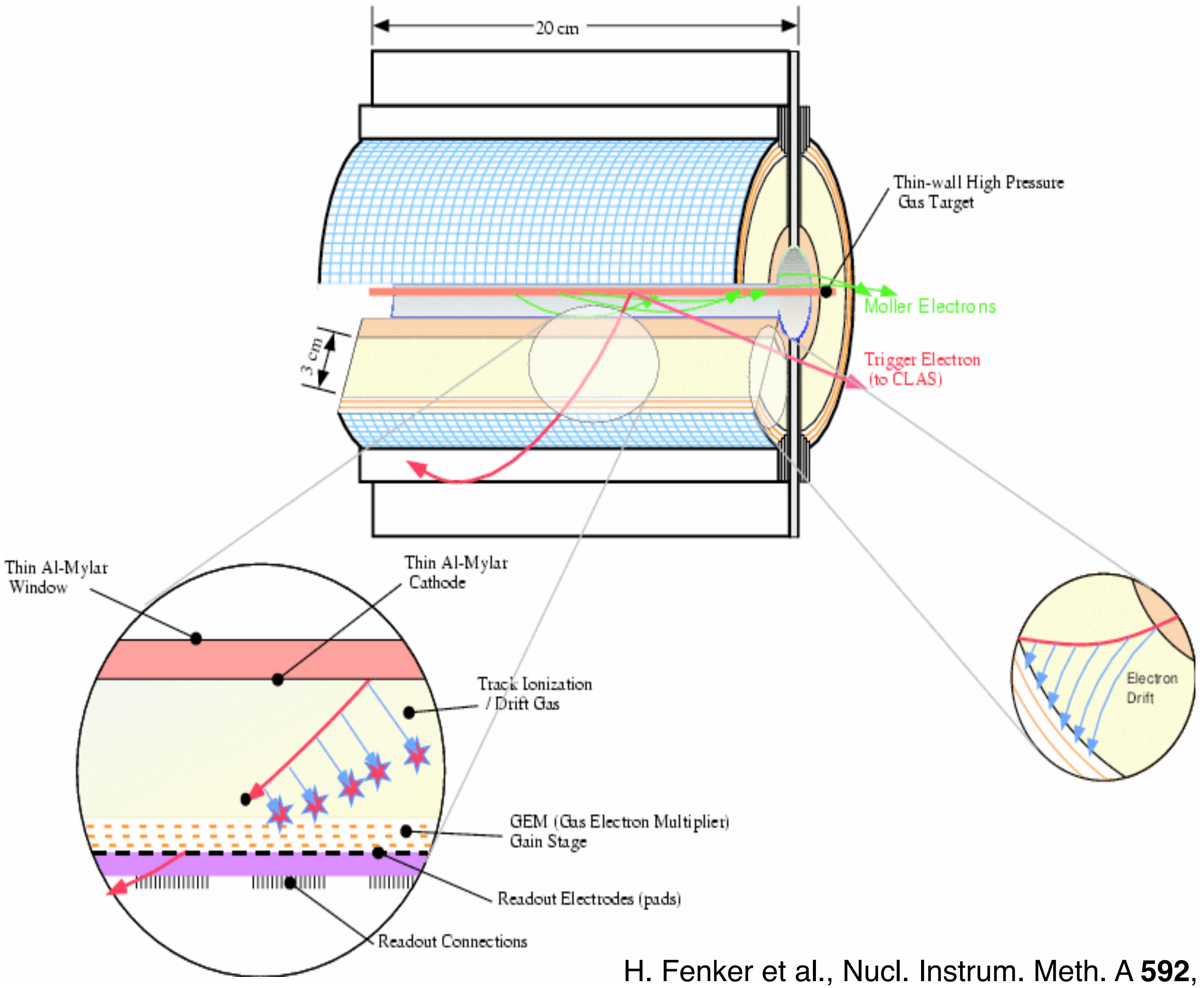




- Bound Nucleon Structure Experiment
- Hall B, JLab, CLAS
- $d(e,e'p_s)X$ with $0.07 < p_s < 0.15$ GeV/c
- E_{beam}=1.1, 2.1, 4.2, 5.3 GeV
- Radial time projection chamber for p_s
- Data taking in 2005



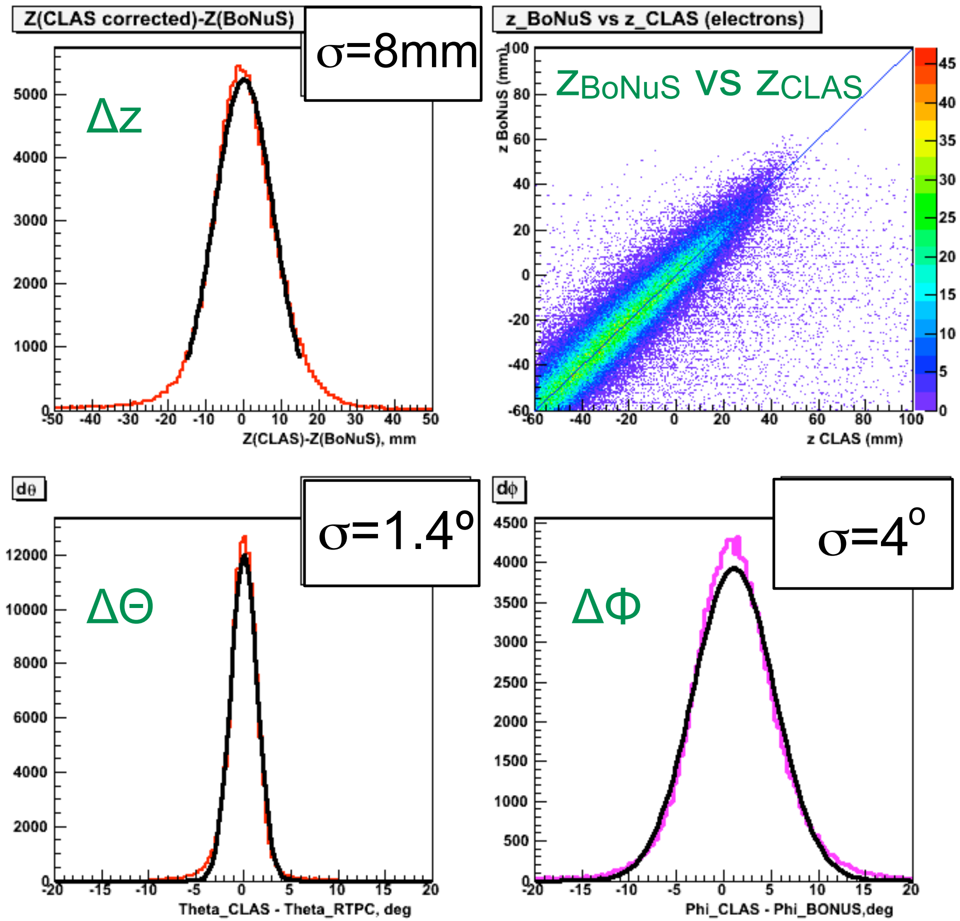
BoNuS Detector



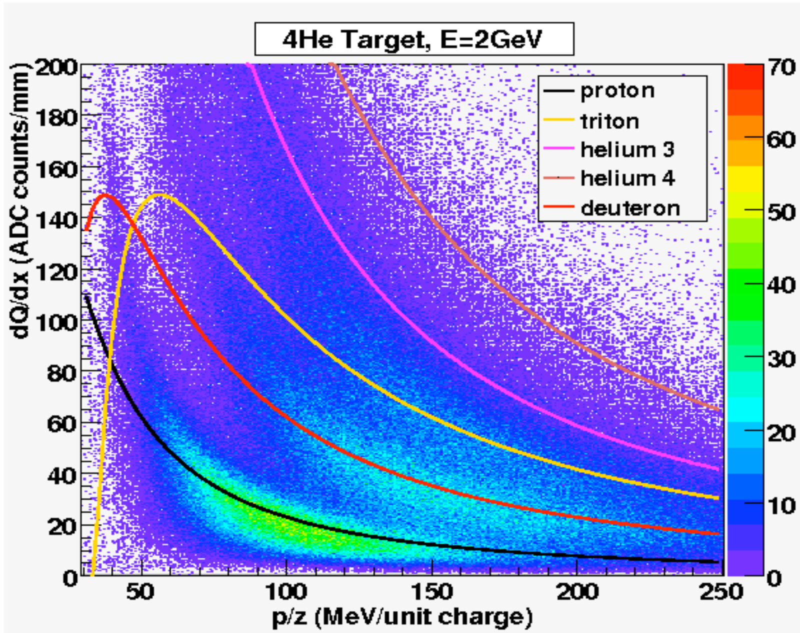
H. Fenker et al., Nucl. Instrum. Meth. A **592**, 273 (2008)

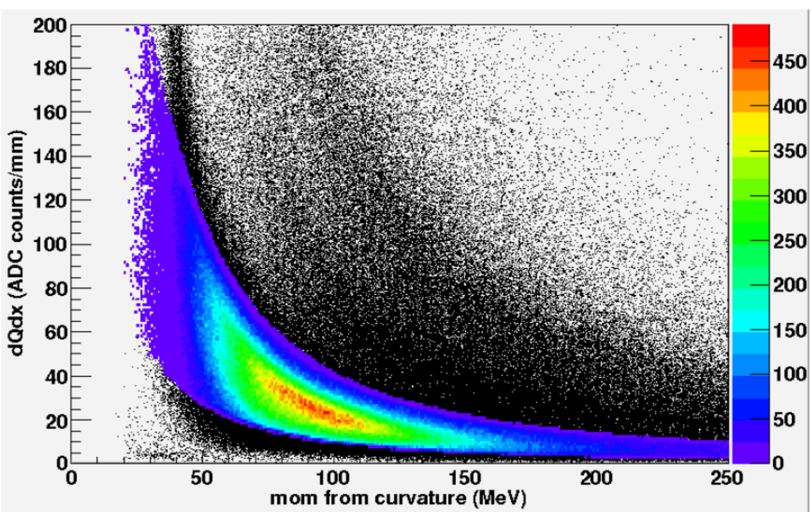
BoNuS RTPC Performance

- 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 RTPC Performance





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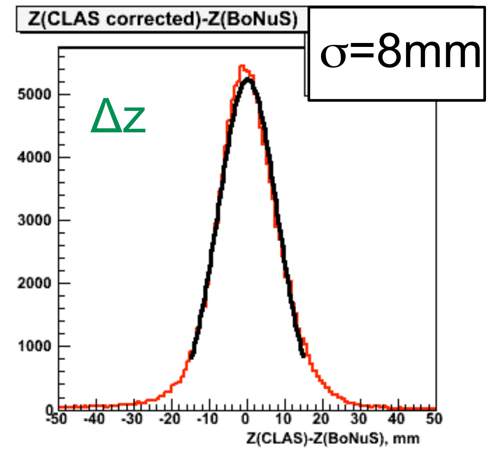
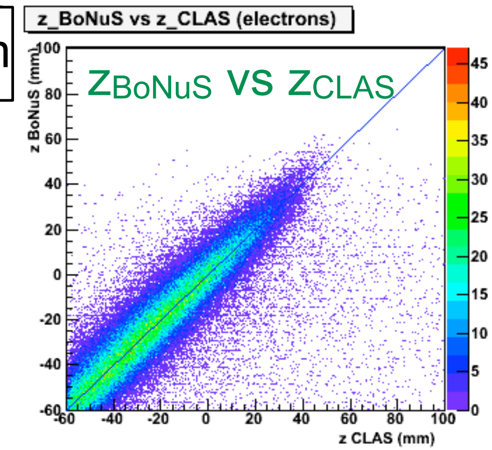
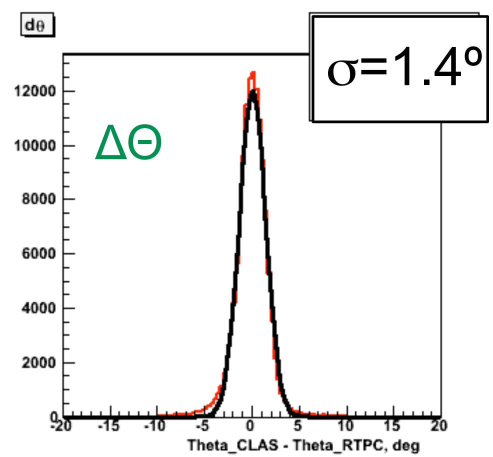
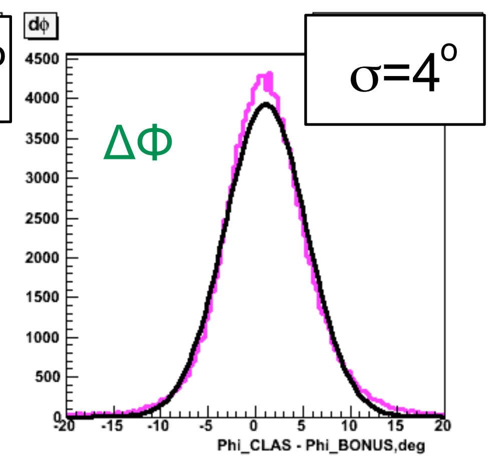


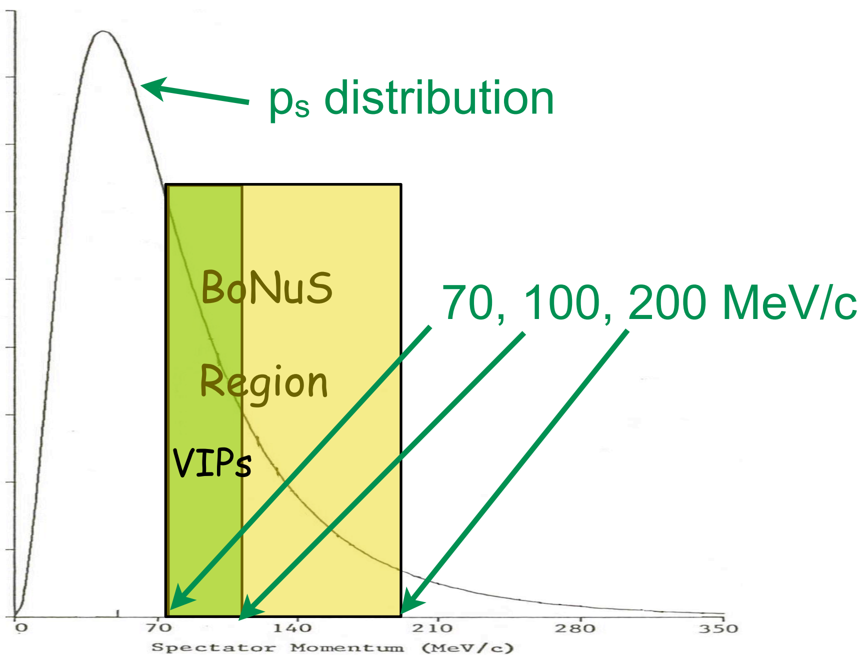


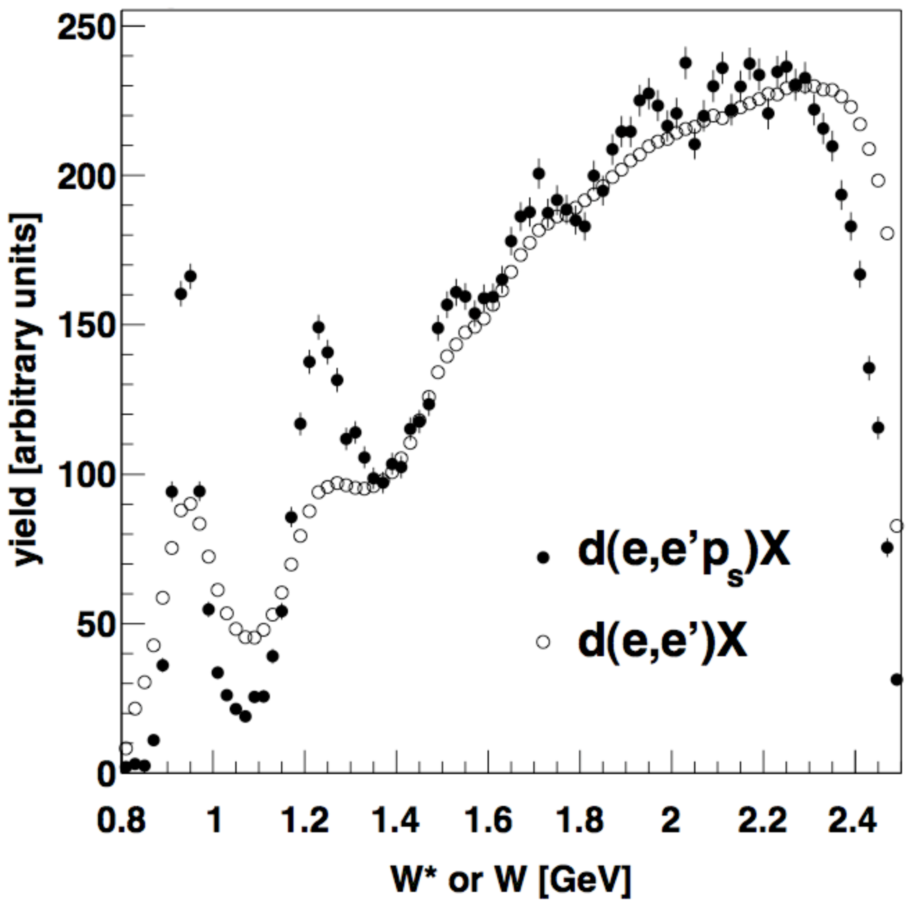




BoNuS Kinematic Correction

- 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*

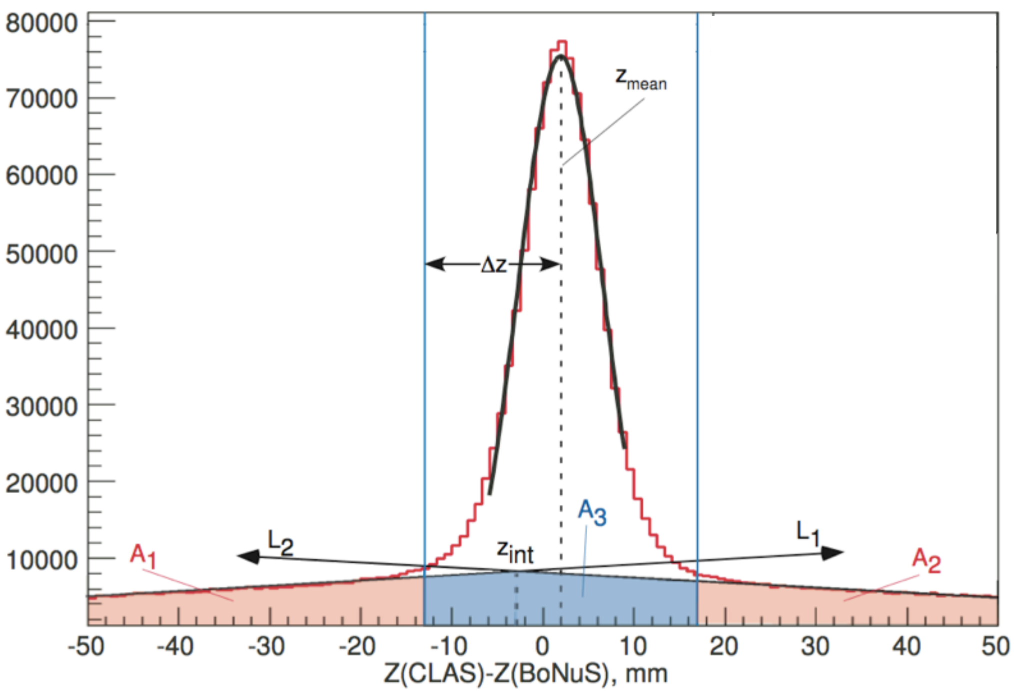




Two Analysis Methods

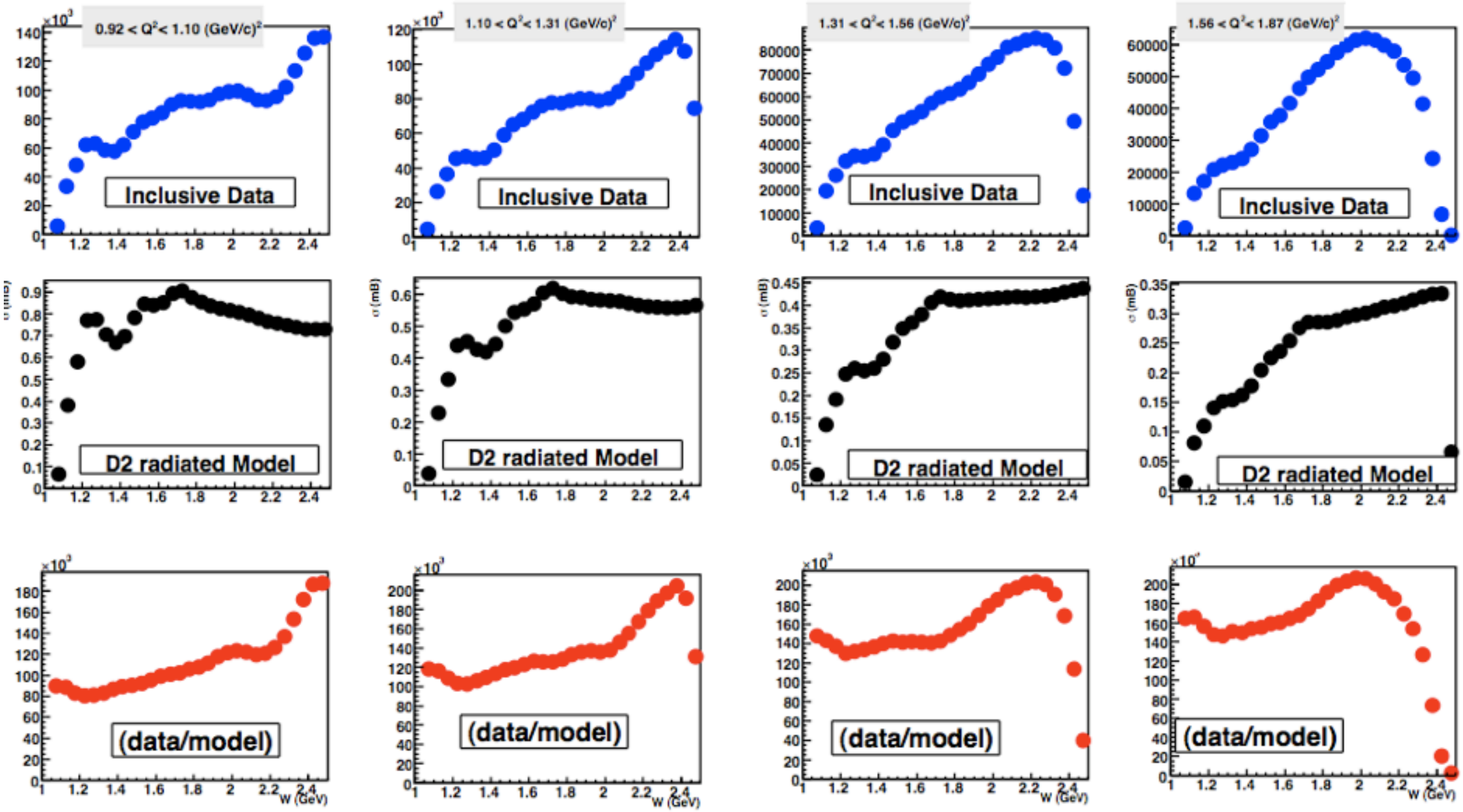
- The Ratio Method
  - ★ measure tagged counts divided by inclusive counts
  - ★ correct this ratio for backgrounds
  - ★ one scale factor gives F_2^n/F_2^d
- The Monte Carlo Method
  - ★ measure tagged counts
  - ★ divide by spectator model Monte Carlo results
  - ★ multiply by F_2^n used in the model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

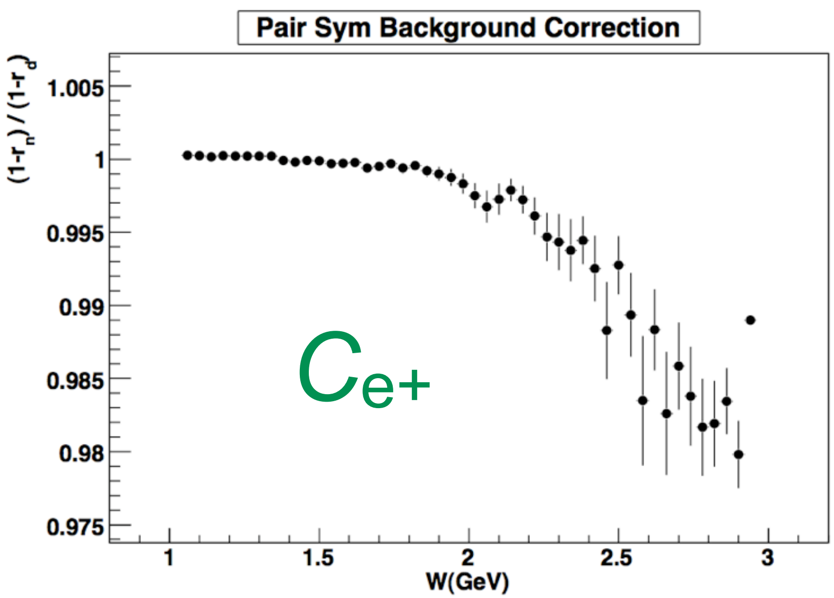
F_2^n/F_2^d from Tagged/Untagged Events

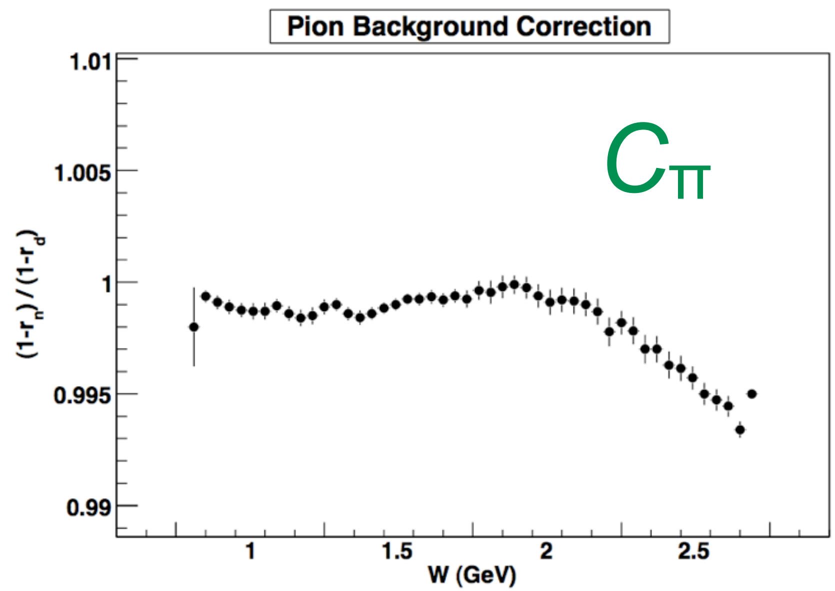
$$R_{corr} = \frac{\sum_{i=1}^{N_{tag}(W^*,Q^2)} \frac{1}{\epsilon_i(W,Q^2)} - R_{bg} \sum_{j=1}^{N_{bg}(W^*,Q^2)} \frac{1}{\epsilon_j(W,Q^2)}}{\sum_{k=1}^{N_{untag}(W,Q^2)} \frac{1}{\epsilon_k(W,Q^2)}}$$

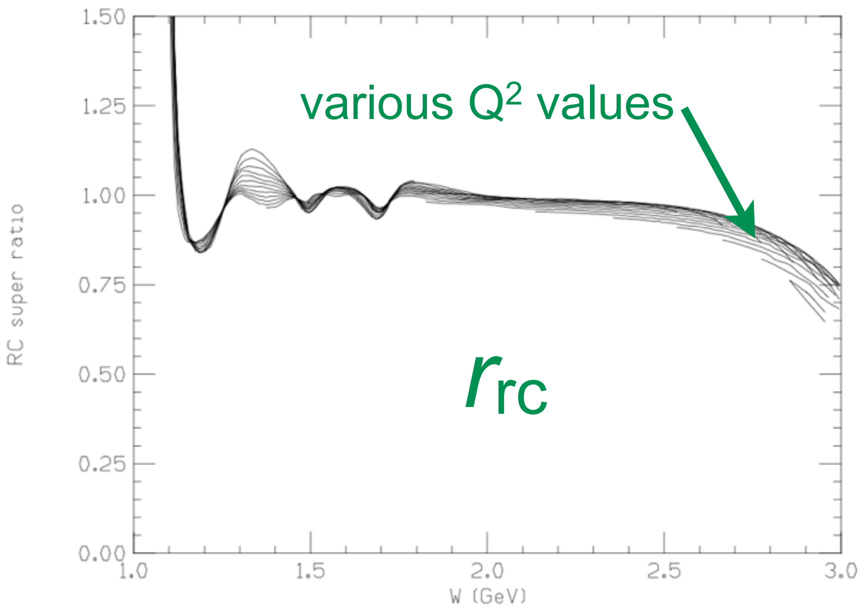
$$\frac{F_2^n}{F_2^d} = (R_{corr})(C_{e^+})(C_\pi)(r_{rc})(n)$$

- 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}

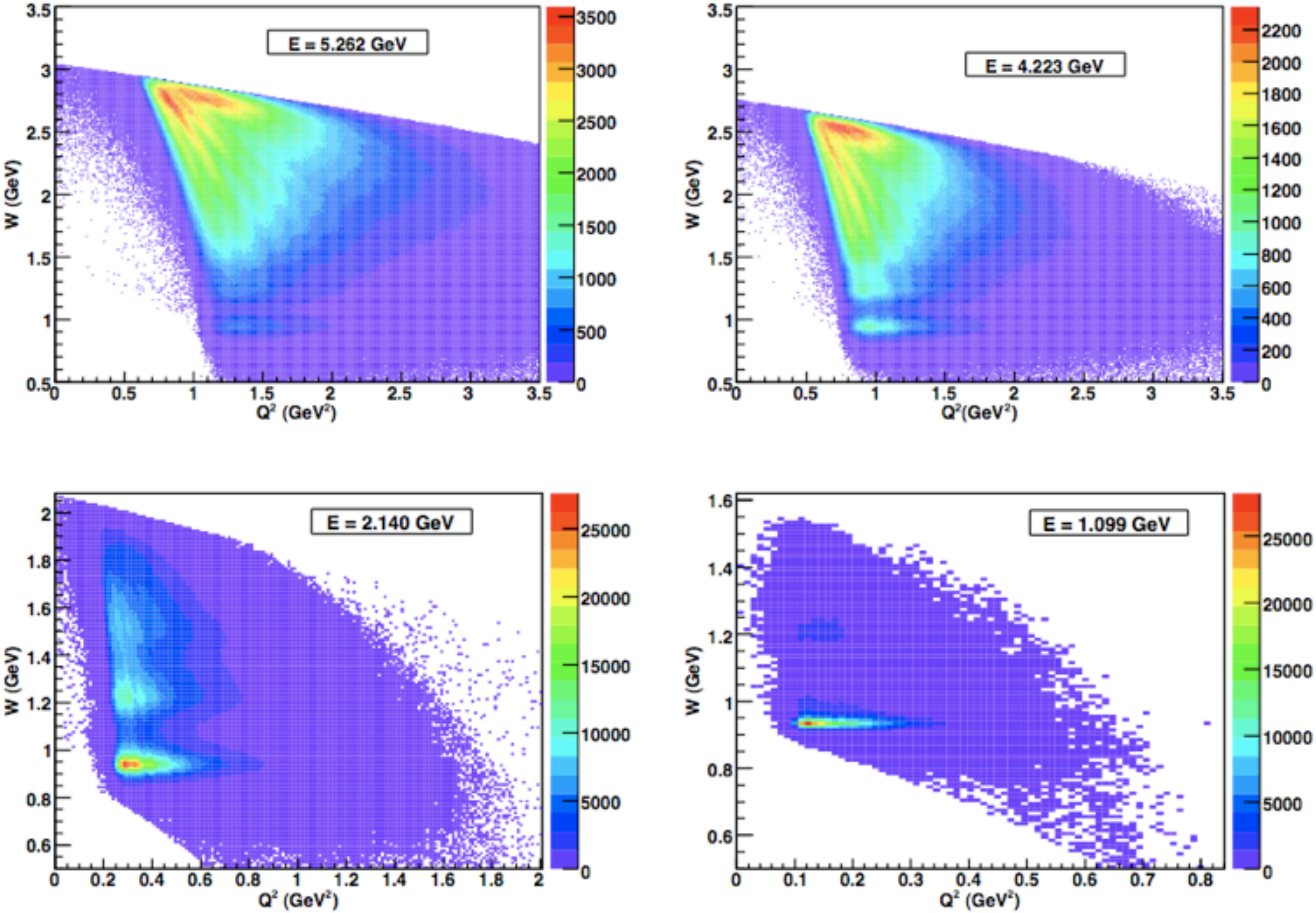




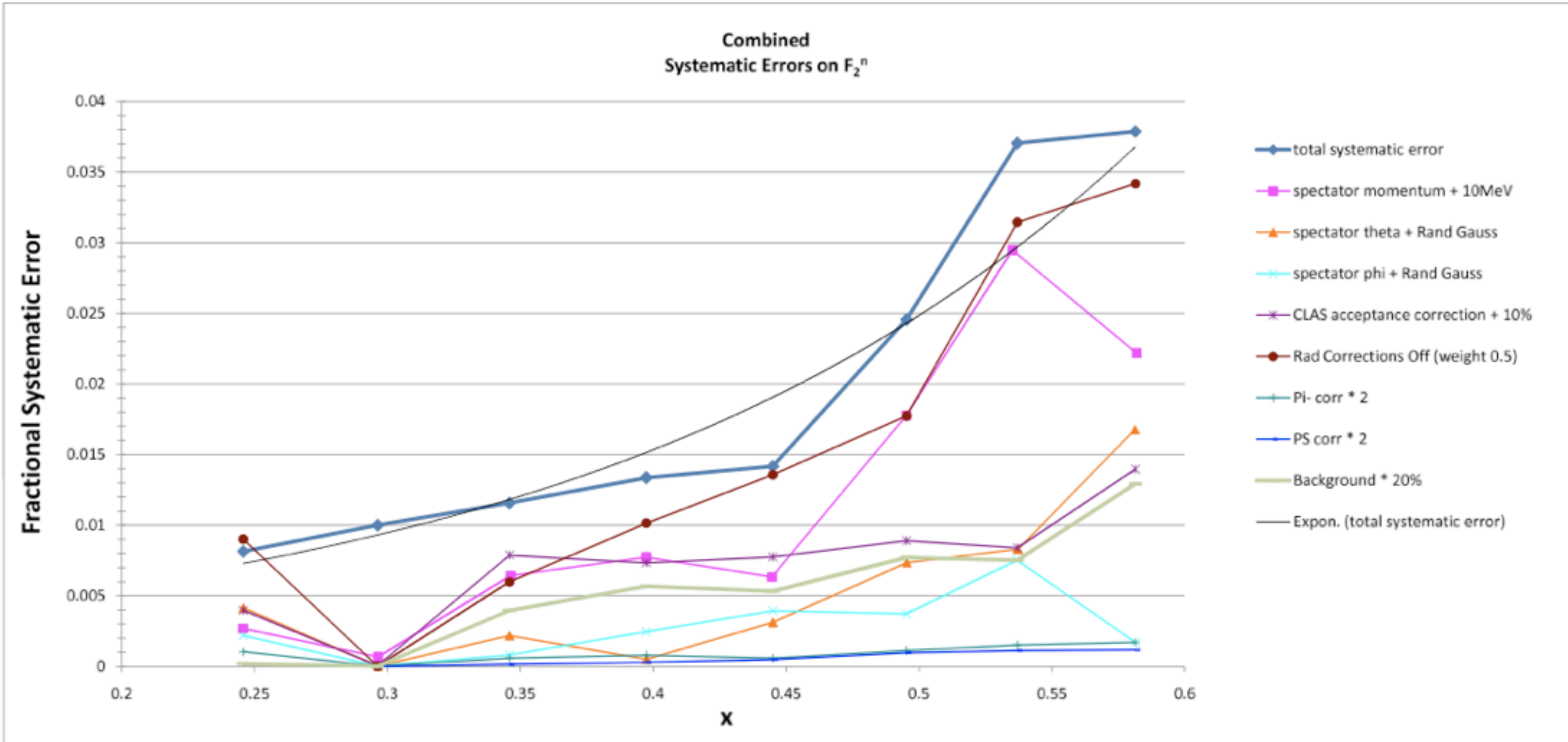


- C_{e+} correction < 2 %
- C_{π} correction < 1/2 %
- r_{rc} correction < 10% in the region 1.2<W<2.7 GeV
- $1/n = 0.02535 \pm 3.37\%$

Kinematic Coverage



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.

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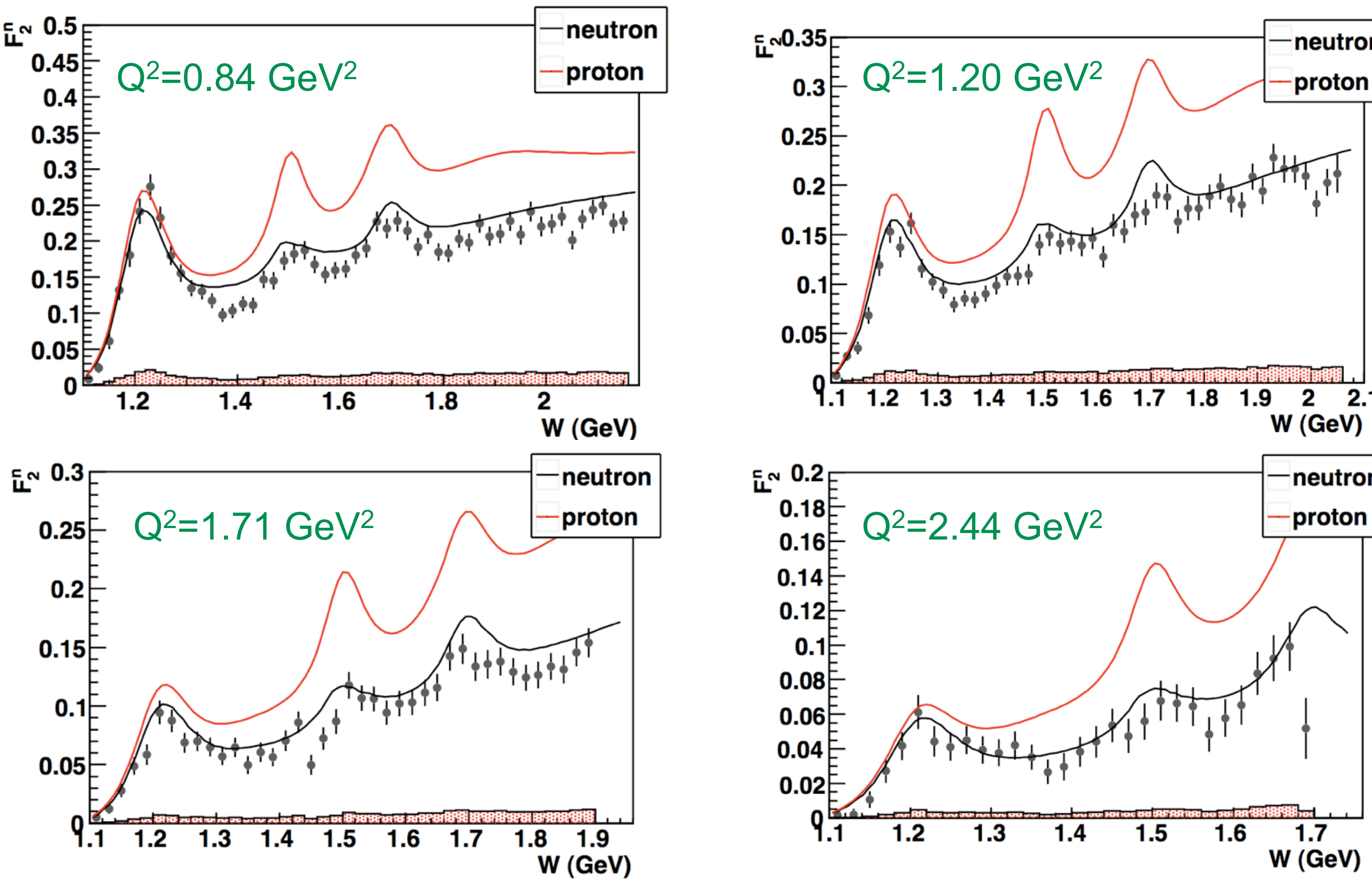
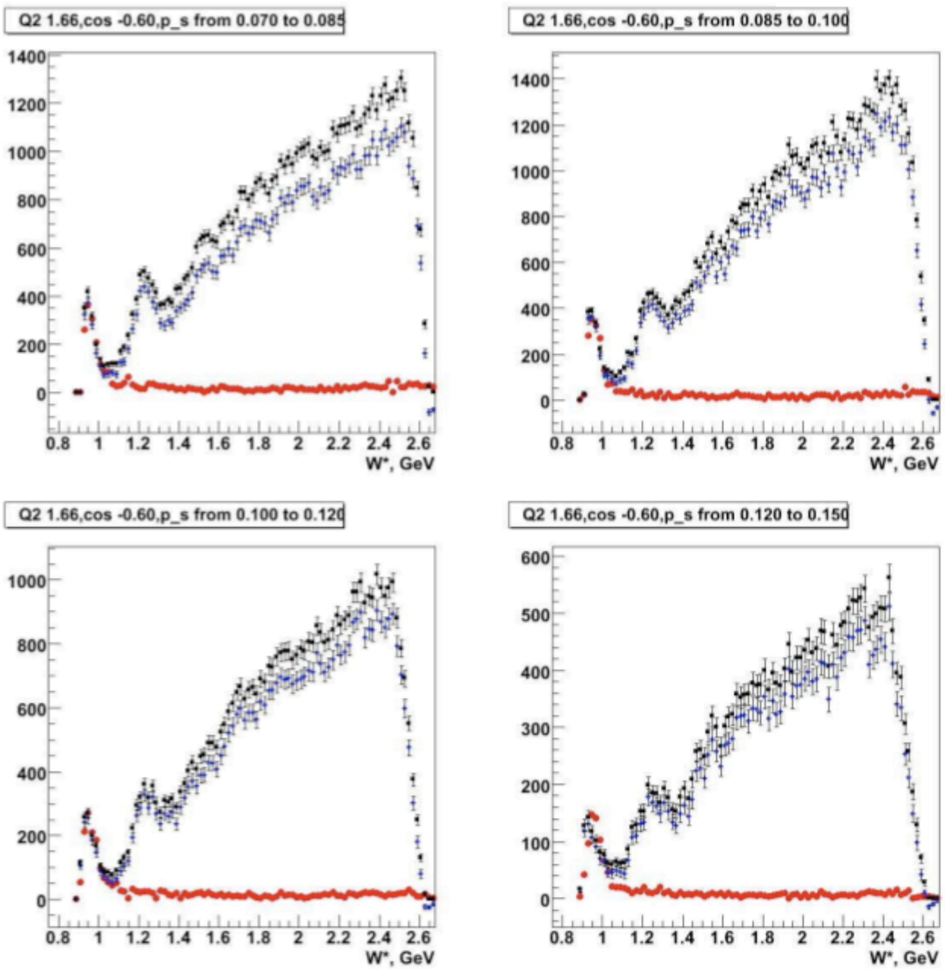
BoNuS F_2^n



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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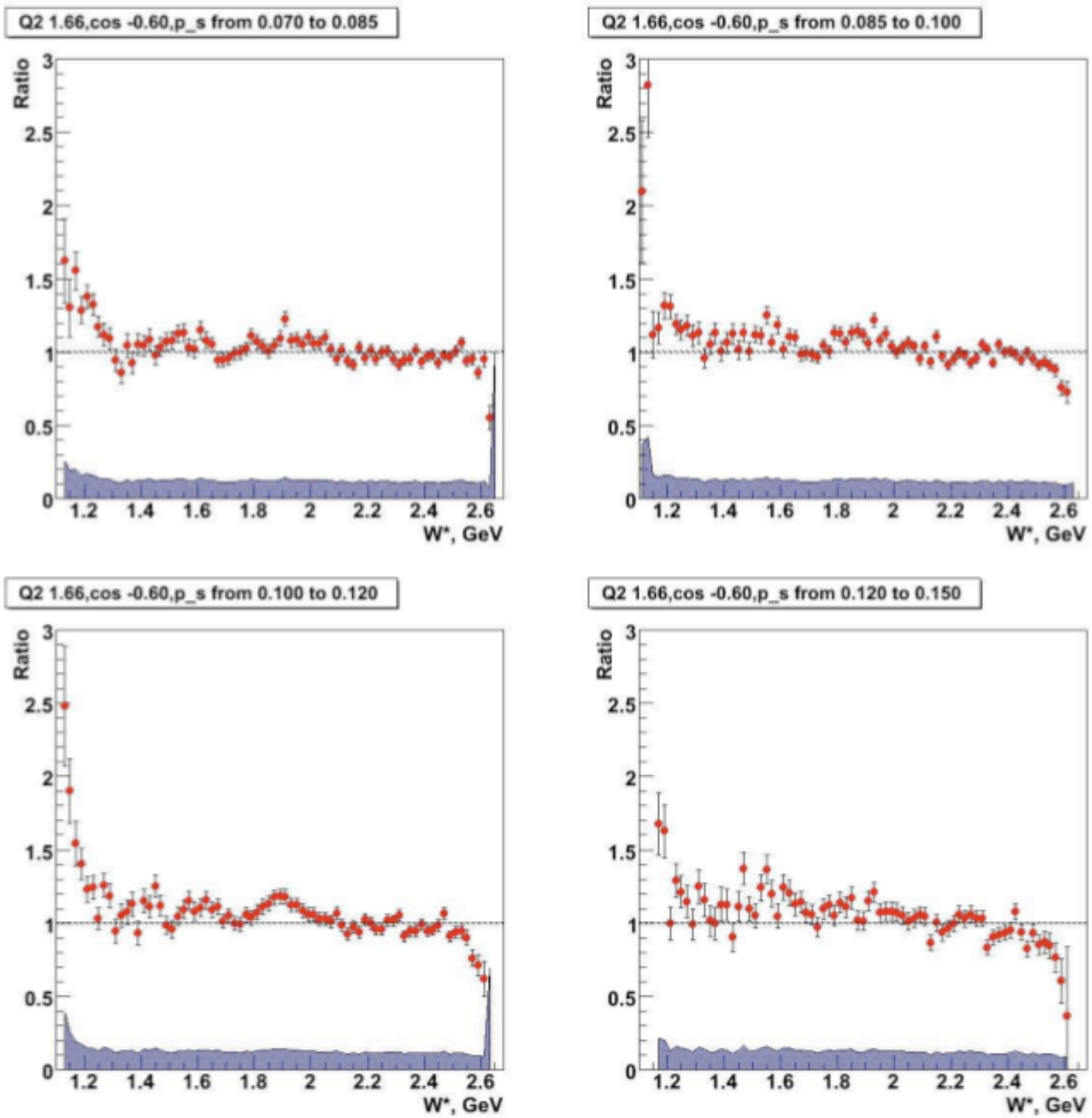
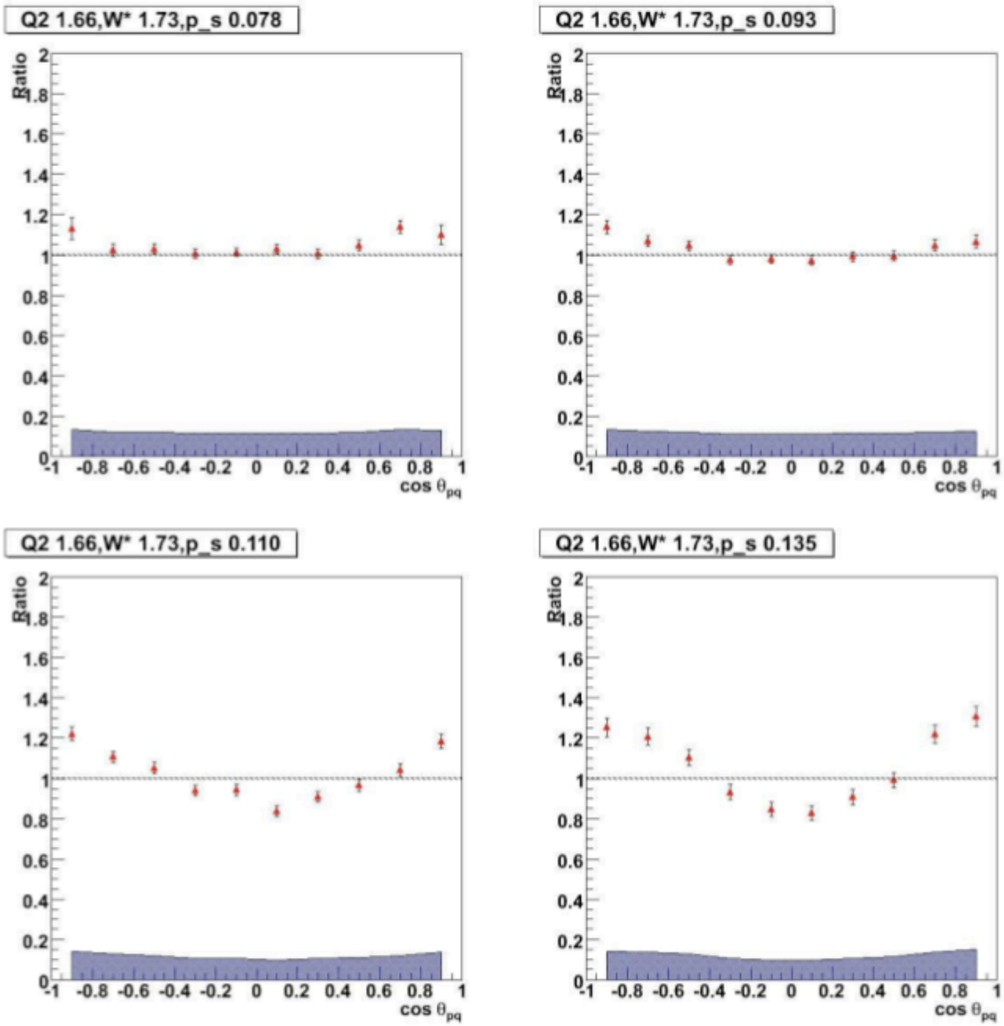
Data / MC vs W* for Different p_s



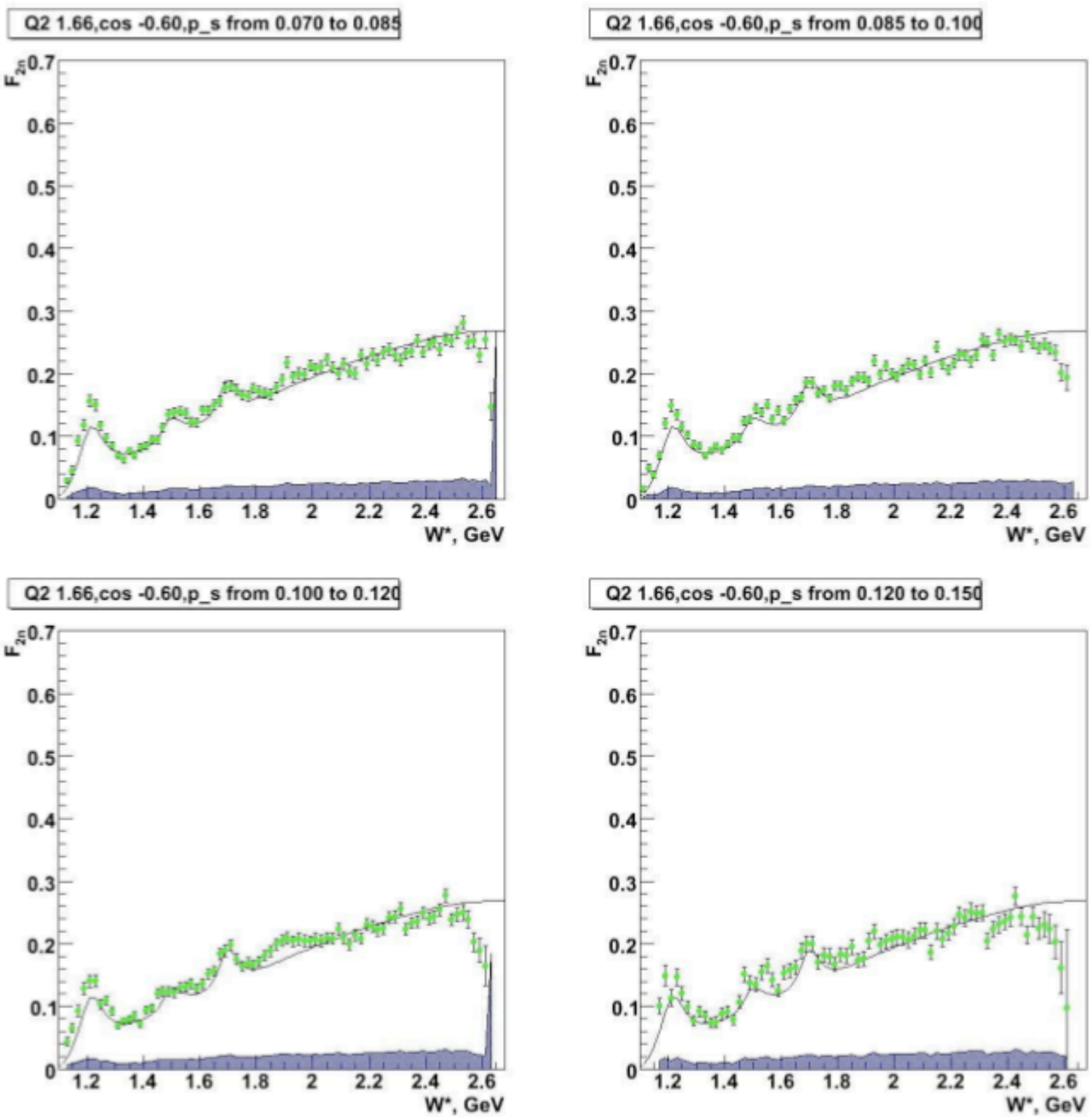
- Deviations from unity at low W* comes from difficulties of getting the model right for the resonances
- Generally the ratio is close to unity
- Perhaps some effects at high p_s

cosθ distributions / MC



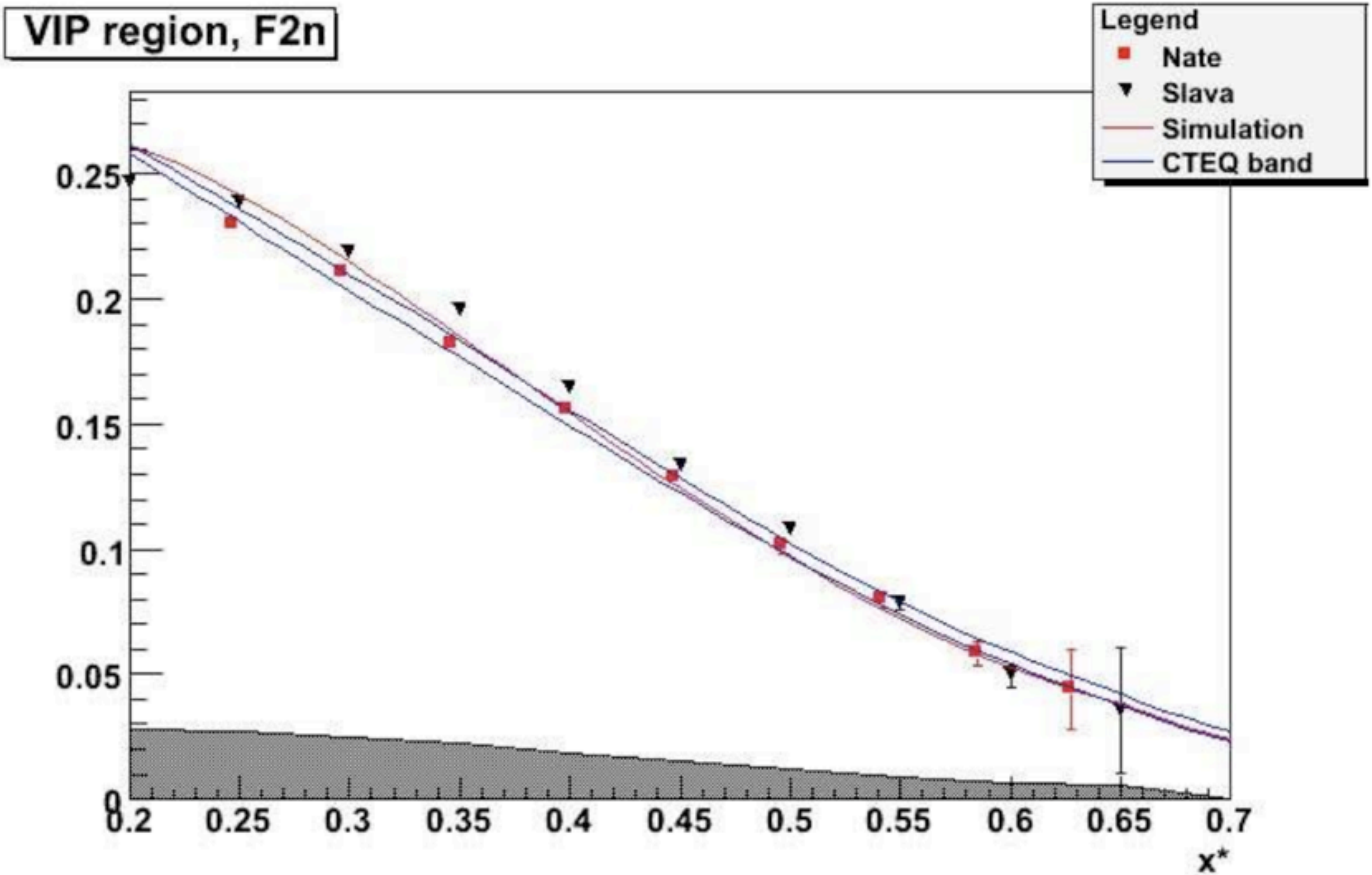
- At low p_s the data agree with the spectator model quite well
- At higher p_s the distributions deviate significantly from unity, indicating that VIP particles should have p_s<100 MeV/c

F_2^n for various p_s

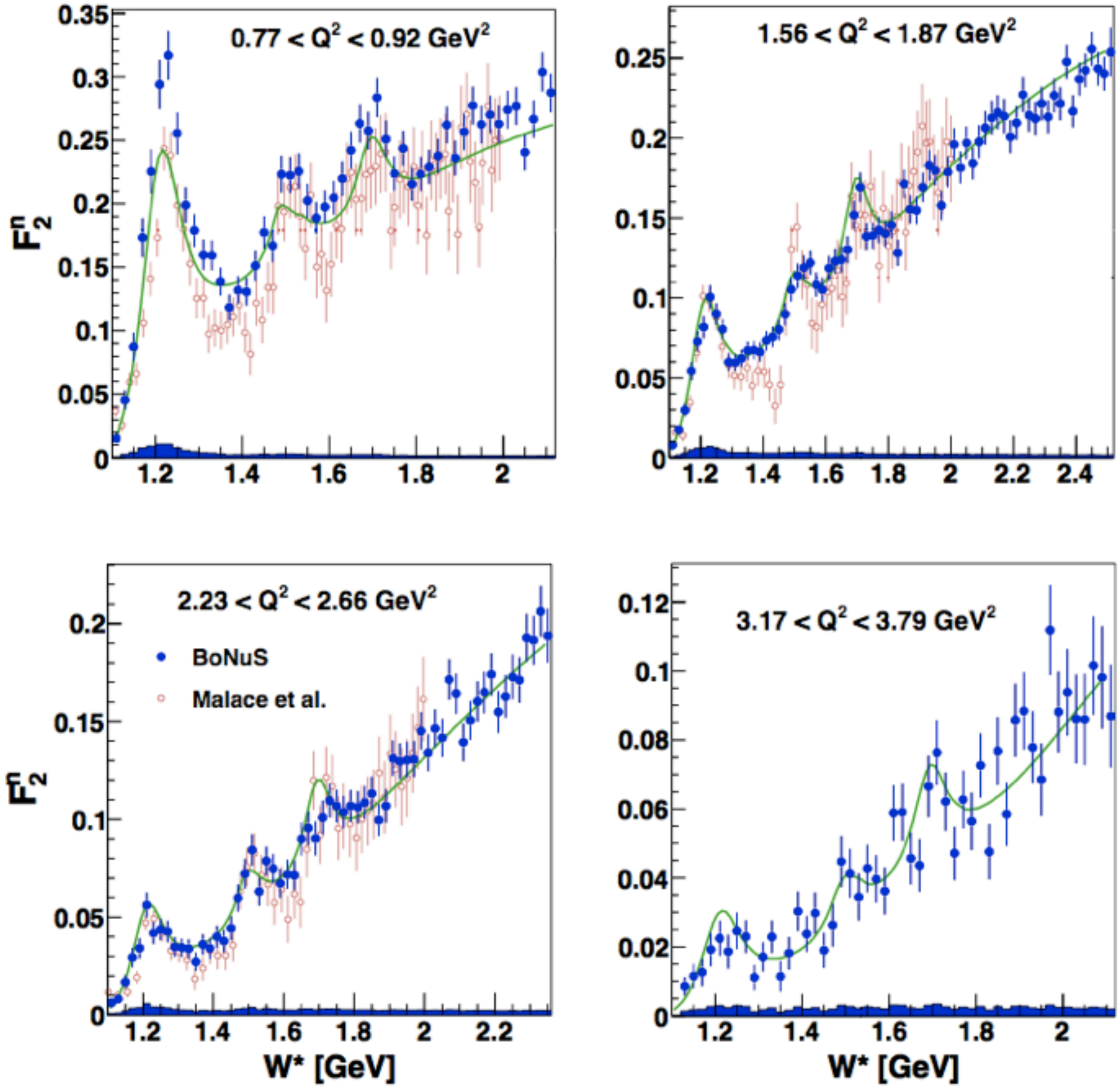


- Data show resonance peaks.
- Data agree quite well with resonance model of world data
- Dependence on spectator momentum is slight

Ratio and MC Method Comparison

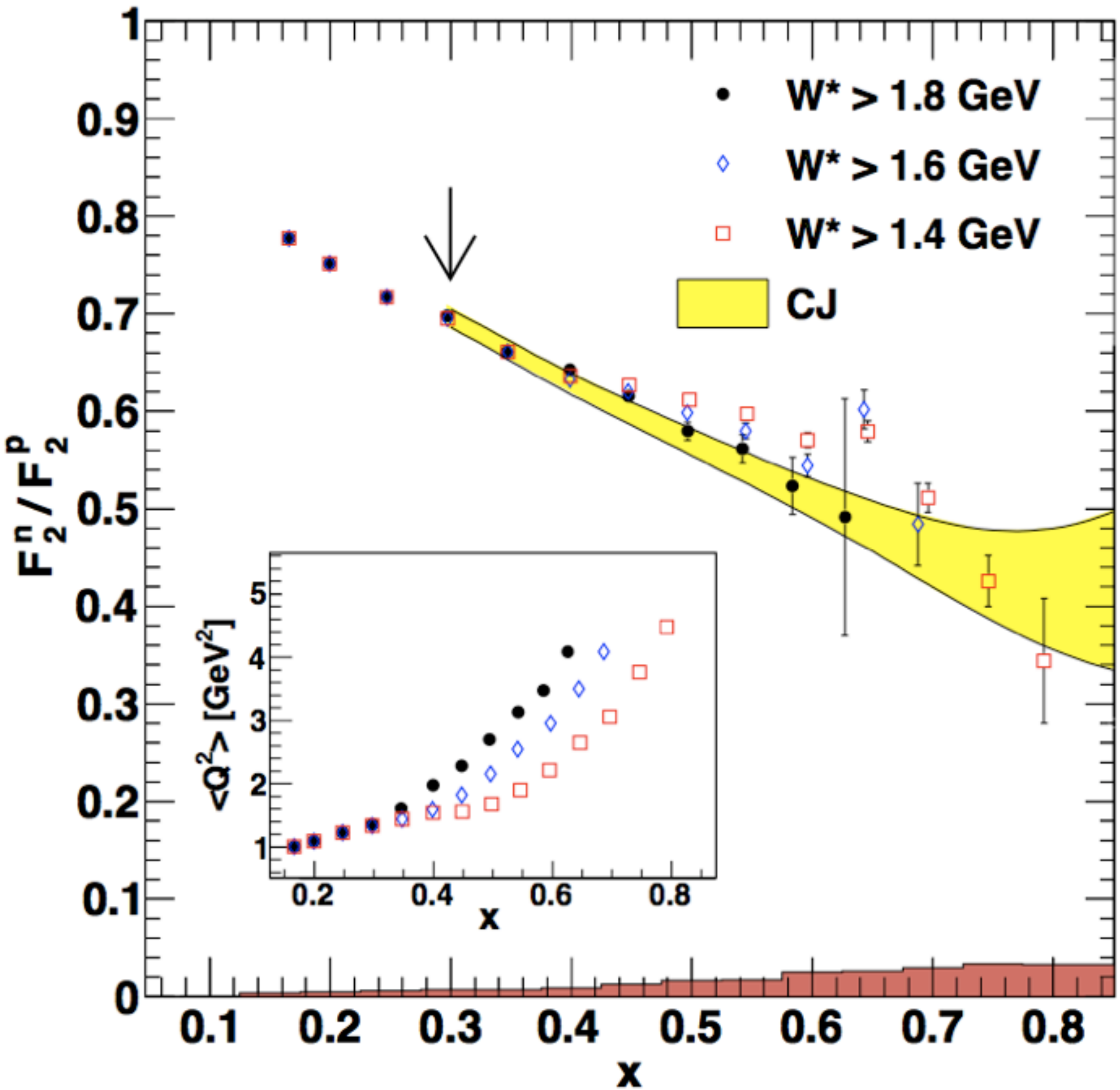


Final Data



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.

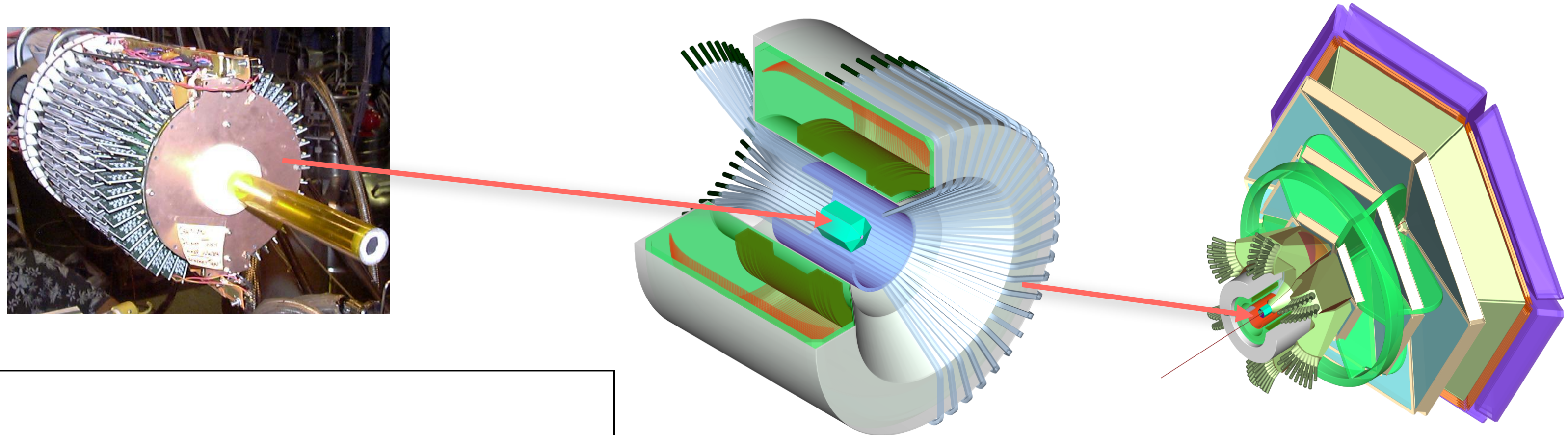
Conclusions

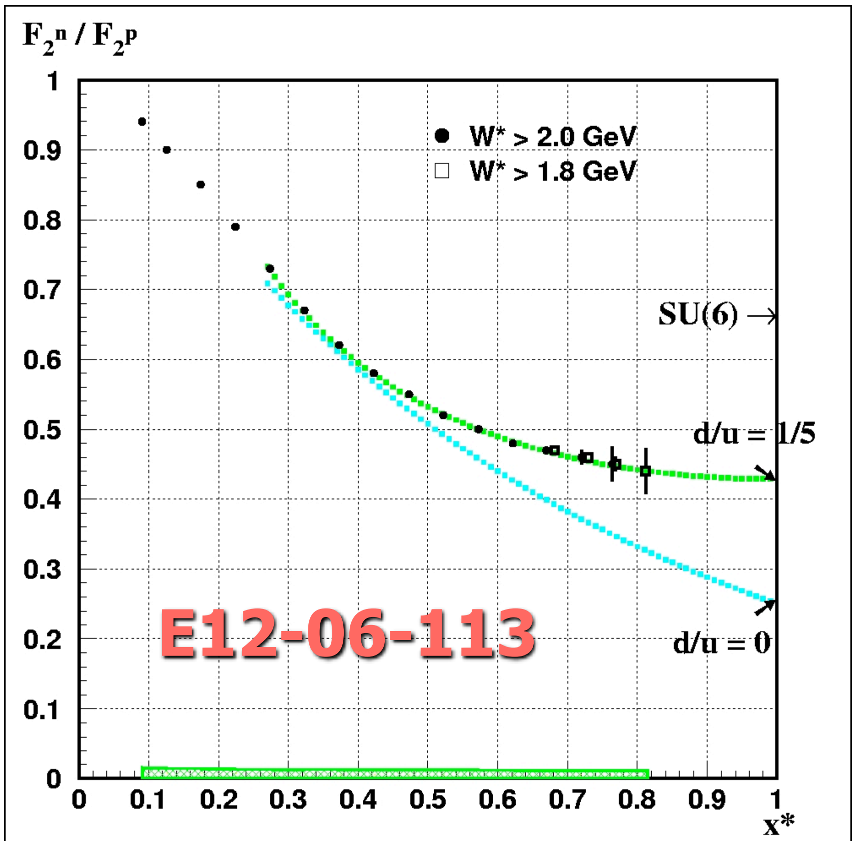
- BoNuS:
  - We have measured F_2^n on a “free” neutron target
  - No effects from Fermi motion and final-state interactions
  - No evidence for off-shell structure for p_s<100 MeV/c
  - F_2^n/F_2^p behaves at high x much like CETQ high-x fits
  - F_2^n resonance data will significantly improve the world data set, which up to now came from d with nuclear corrections
  - Long paper, with details of the off-shell study is in the works (S. Tkachenko), as is a paper on $D(e,e'\pi^- p_s p)$ (J. Zhang)

END OF TALK

END

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
- $\theta_{pq} > 110°$
- $x^*_{max} = 0.80$

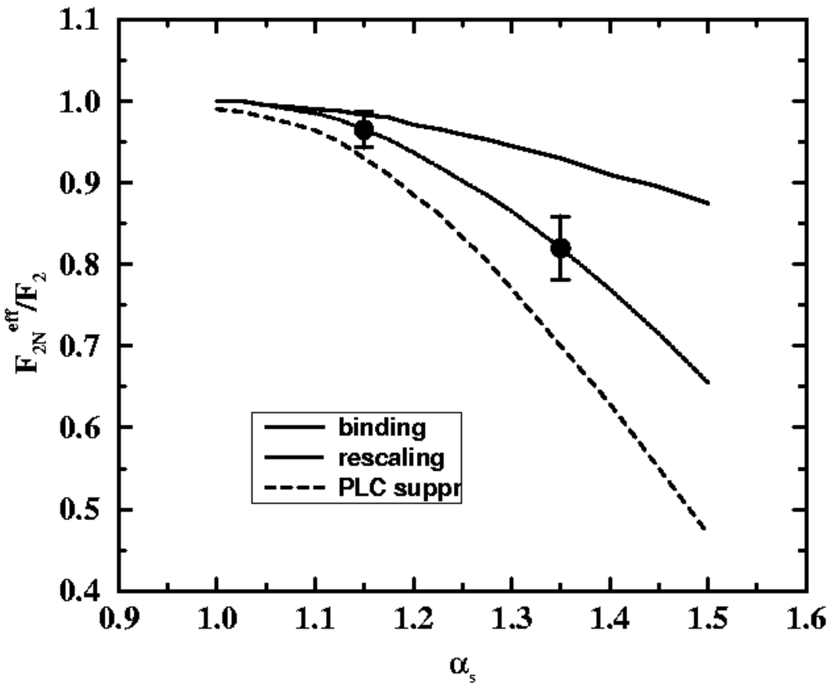
$W^* > 1.8$ GeV: $x^*_{max} = 0.83$

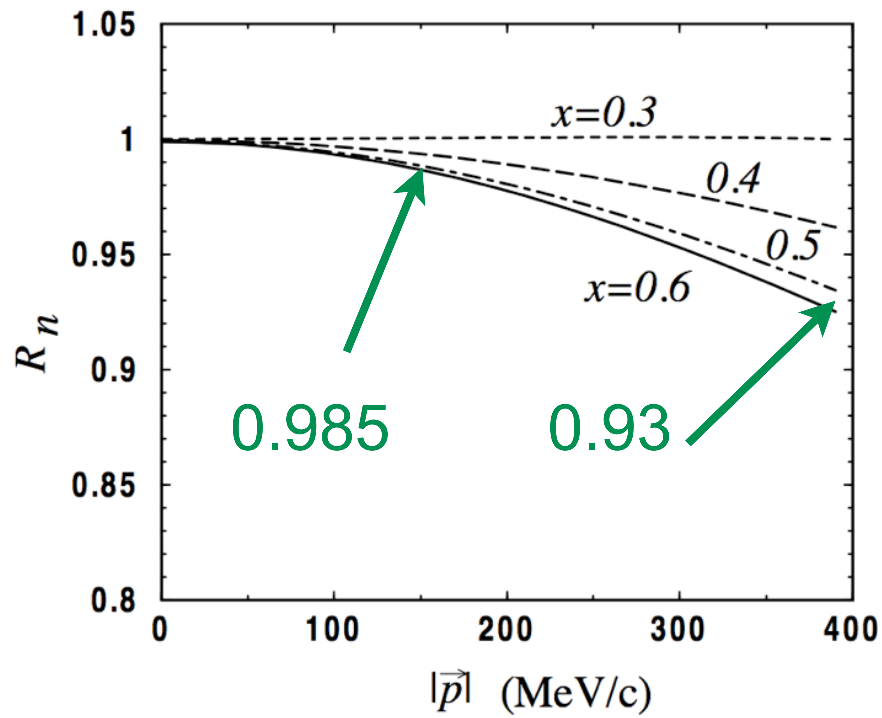
Off-Shell Structure Functions

Liuti & Gross PLB356(95)157

Melnitchouk et al, PLB335(94)11

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



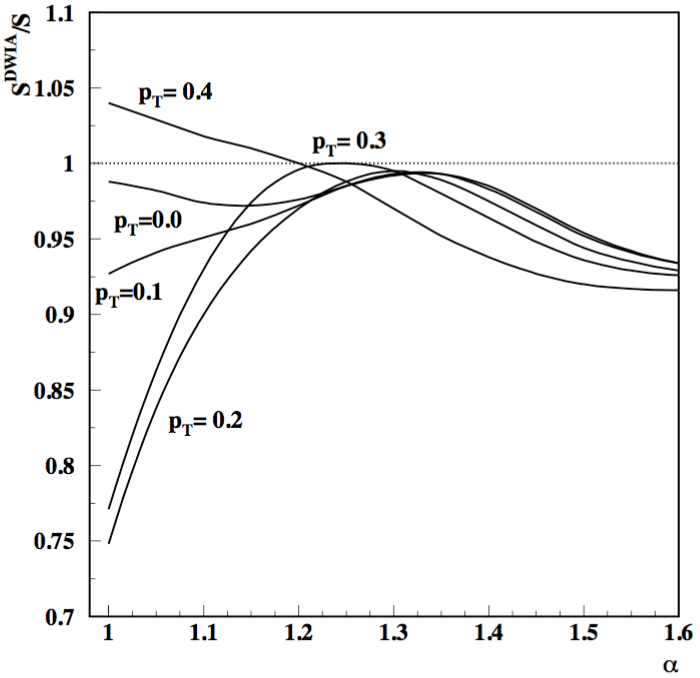


0.80

- Resonances induce huge variations in A_1 compared to the smooth deep-inelastic behavior (red)
- The world's collected wi

Spectral Functions

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



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