Neutron Structure Function from BoNuS

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for the CLAS Collaboration

- The Structure of the Neutron at Large *x*
- The BoNuS Experiment in 2005
- First Results from the BoNuS Experiment
- BoNuS at 12 GeV
- Conclusions

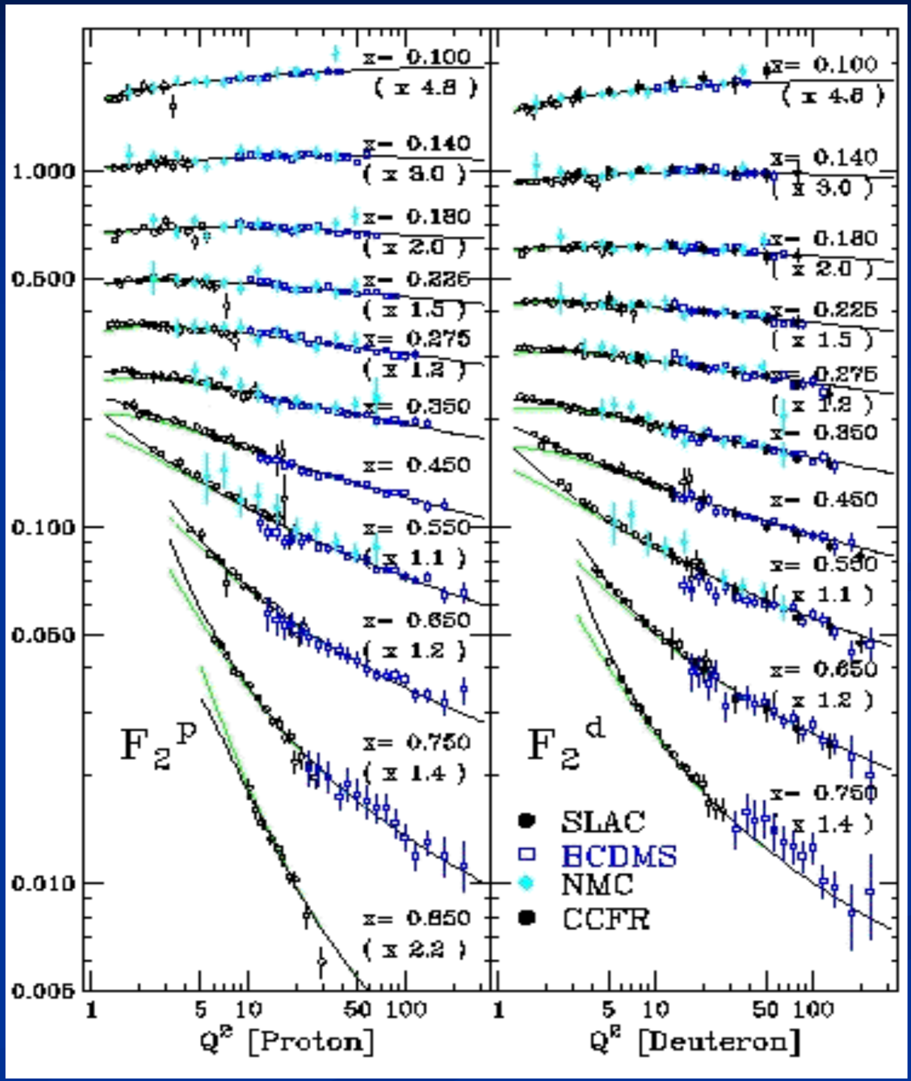
HiX2010, Jefferson Lab, October 2010

F_2 Structure Functions

- Comparable precision for proton and deuteron F_2 structure function measurements up to fairly large x
- Neutron structure function

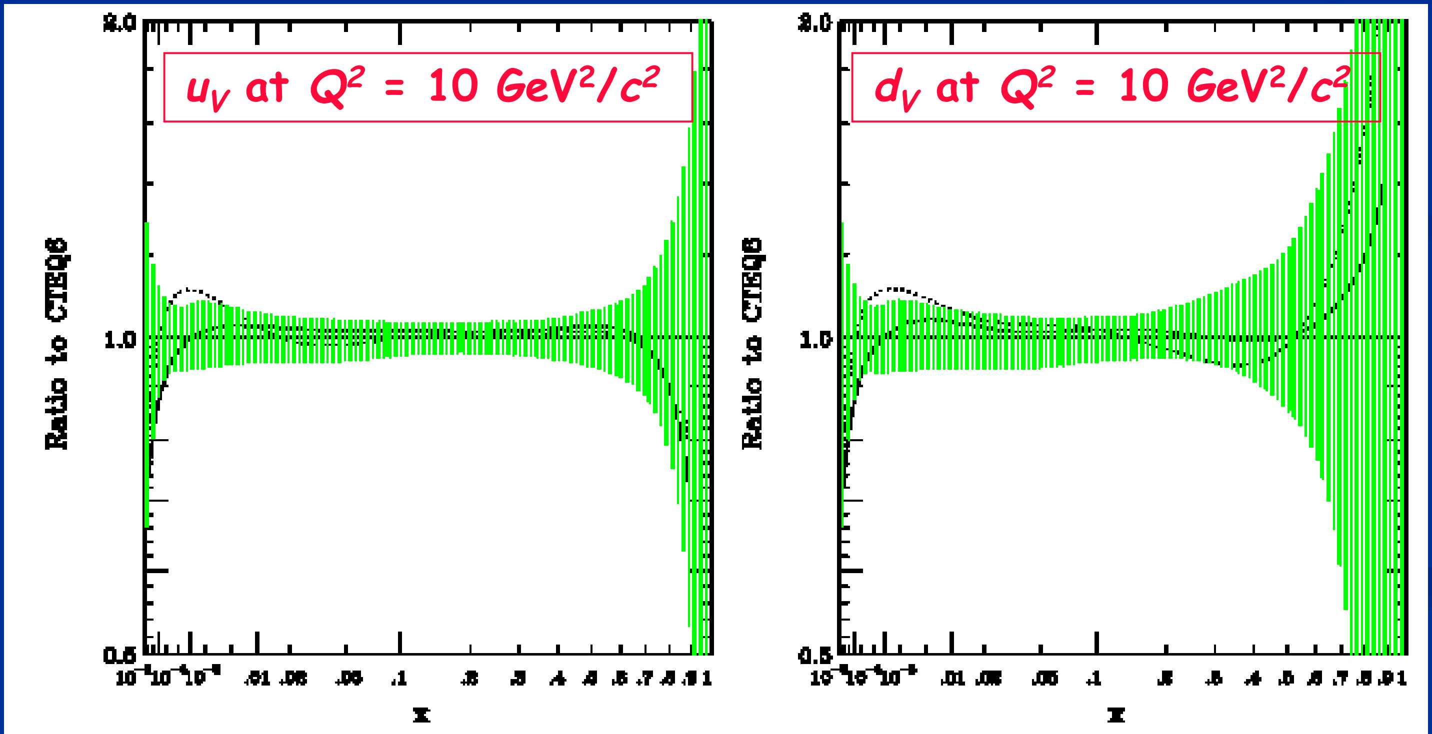
  $F_2^n \neq F_2^d - F_2^p$
- Neutron structure function F_2^n is obtained from measurements on bound neutrons, e.g. using deuterium targets
- Extraction of F_2^n at large x introduces theoretical model dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, …)

From U. K. Yang and A. Bodek, Eur. Phys. J. C13, 241 (2000)



u and *d* Quark Distribution Functions

Parton Distribution Functions (PDFs) for the u_V and d_V have increasing uncertainty at large x, in particular the d_V distribution being dependent on precise neutron measurements



Ratio of CTEQ5M1 to CTEQ6 parametrization

Structure Function Ratio F_2^n / F_2^p

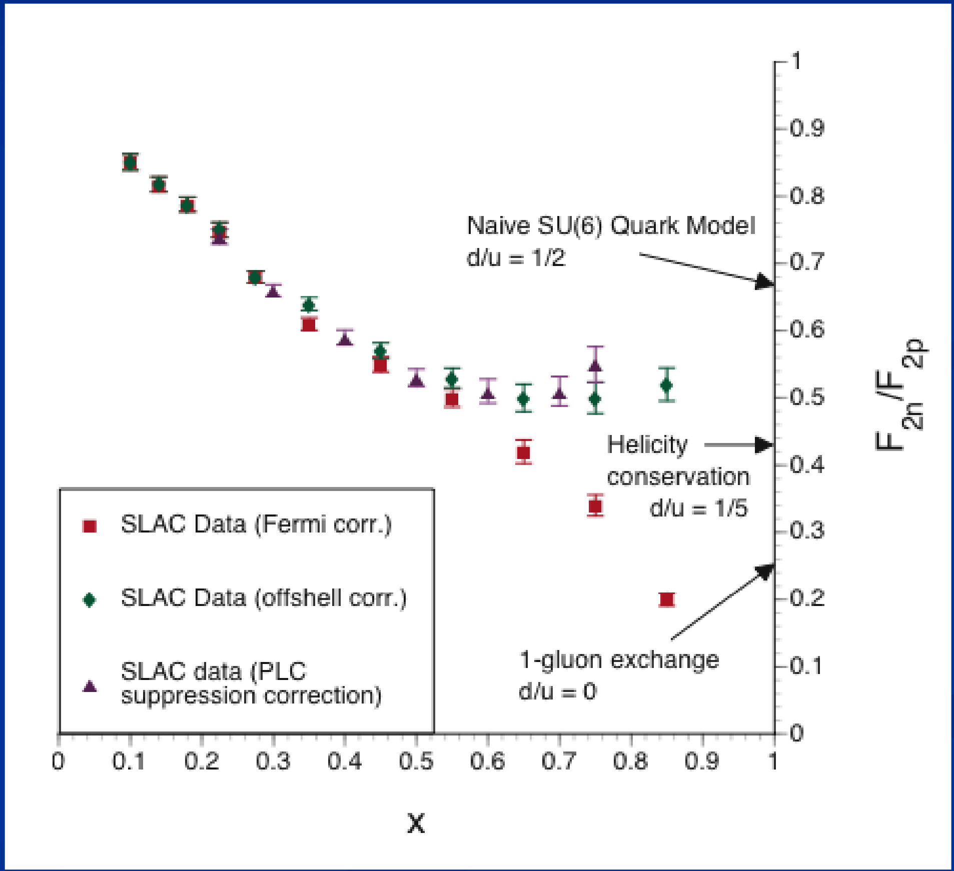
Structure function ratio F_2^n / F_2^p is related to valence quark ratio d/u

$$\frac{F_2^n}{F_2^p} \approx \frac{1 + 4\, d/u}{4 + \, d/u}$$

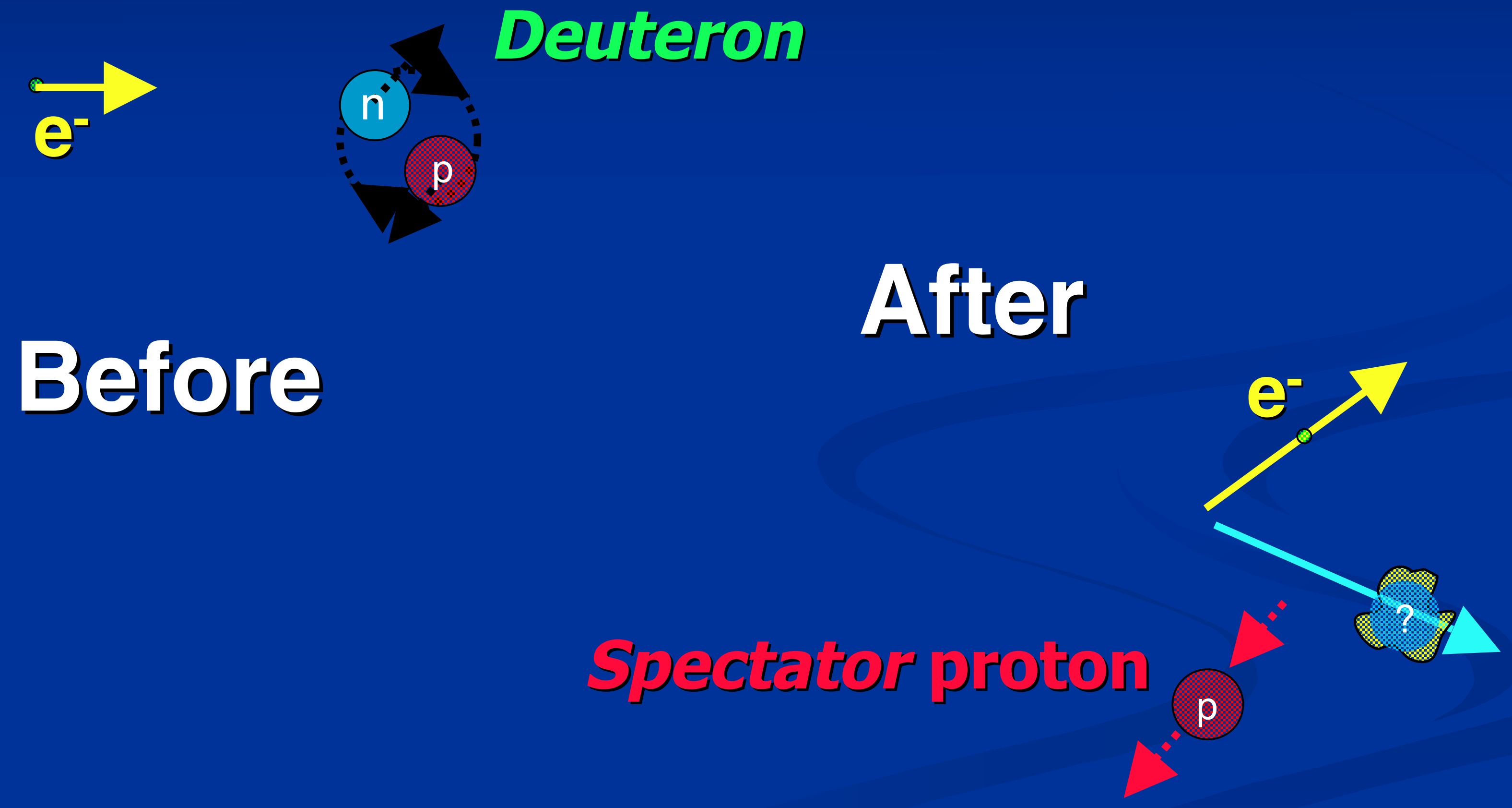
at leading order (and higher orders in DIS scheme) and for $x > 0.4$

$$\Rightarrow \quad \frac{d}{u} \approx \frac{4\, F_2^n / F_2^p - 1}{4 - F_2^n / F_2^p}$$

Extraction of F_2^n / F_2^p from the same data set results at large x in strong dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, …)



Spectator Tagging of Barely Off-Shell Neutrons in d (e, e′ p_s) X



Spectator Tagging of Barely Off-Shell Neutrons in d (e, e′ p_s) X

Correction of neutron kinematics by measured recoiling spectator proton results in improved resolution of invariant mass spectrum

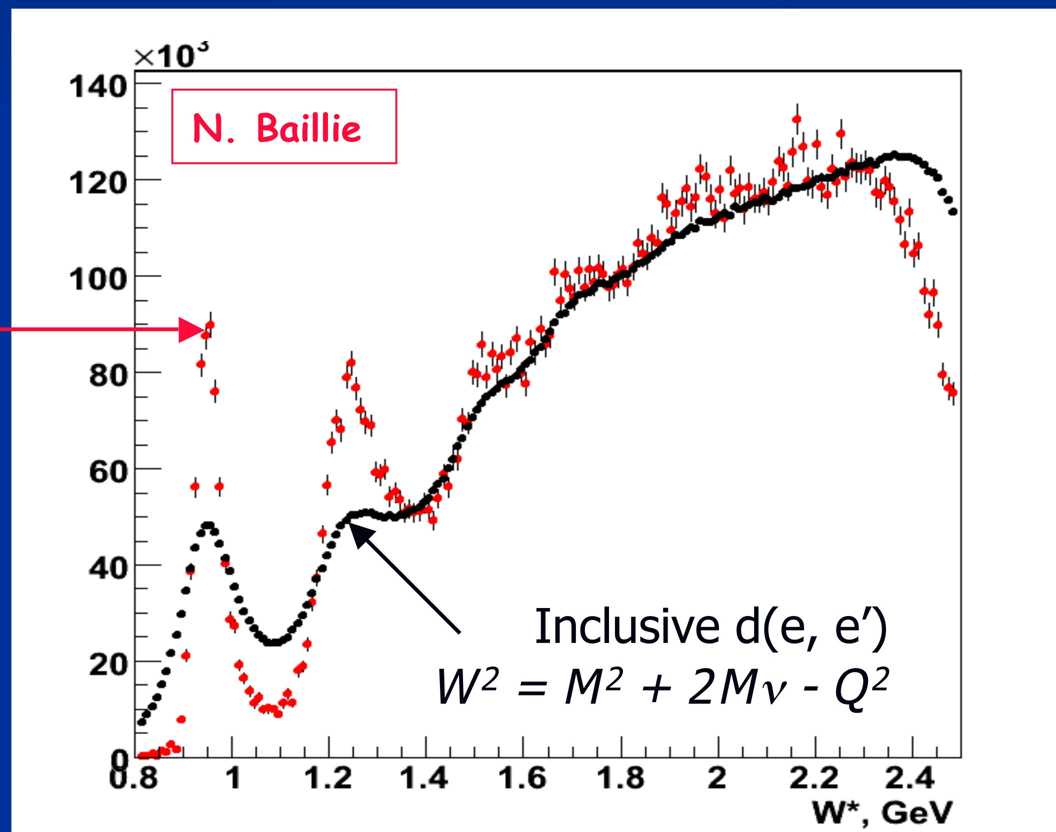
Measurement from BoNuS

Tagged d(e,e′ p_s)X

$$W^{*2} = (p_n + q)^2$$
$$\approx M^{*2} + 2M\nu(2 - \alpha) - Q^2$$

$$x^* = \frac{Q^2}{2\, p_n^{\mu}\, q_{\mu}} \approx \frac{Q^2}{2M\nu(2-\alpha)}$$

α = light cone momentum fraction of spectator nucleon

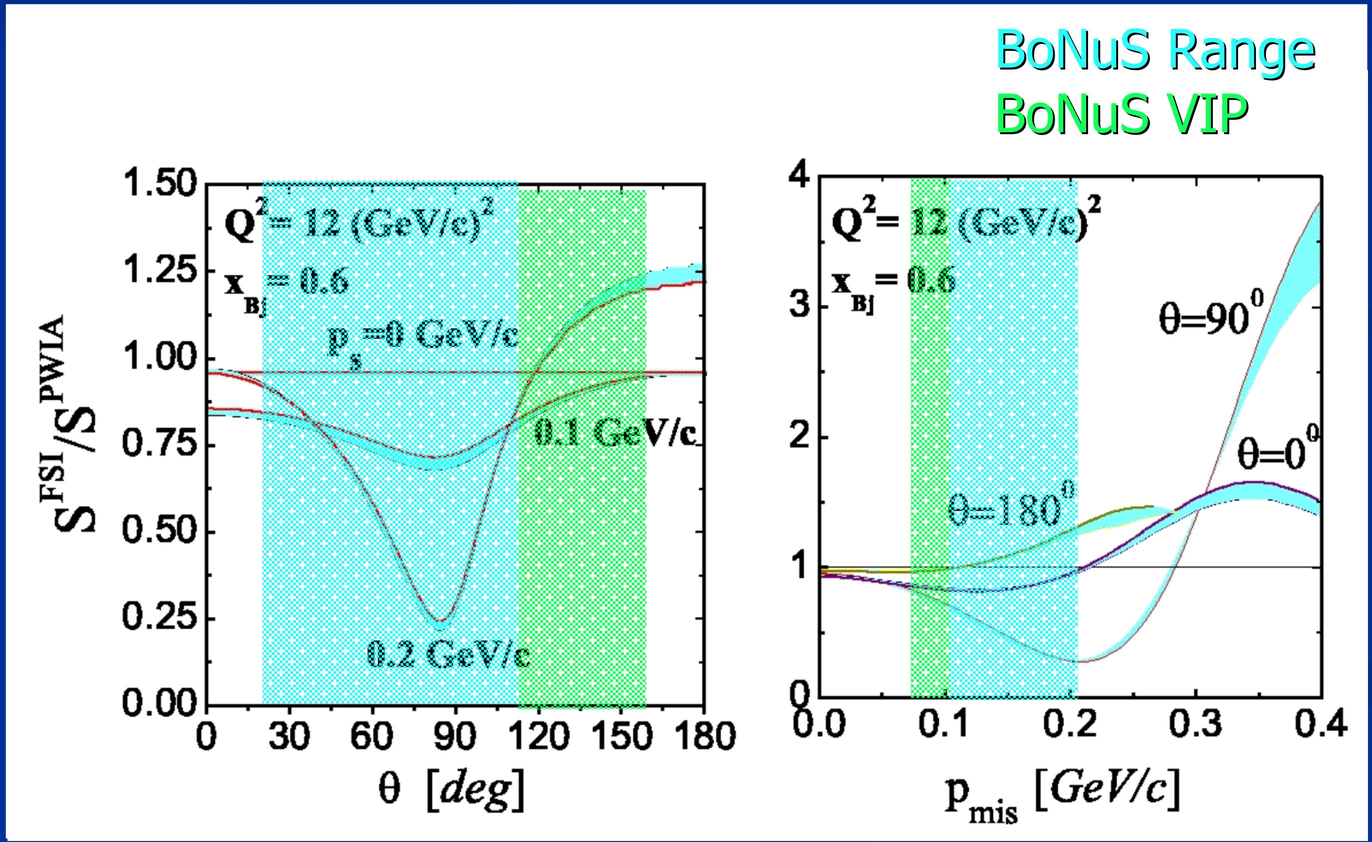


Final State Interactions

DIS ratio of neutron momentum distributions including FSI to PWIA

Small effect for spectator momenta < 100 MeV/*c* and backward scattering angles

Measure (map out) FSI over large range in θ and 70 MeV/*c* < p_s < 200 MeV/*c*

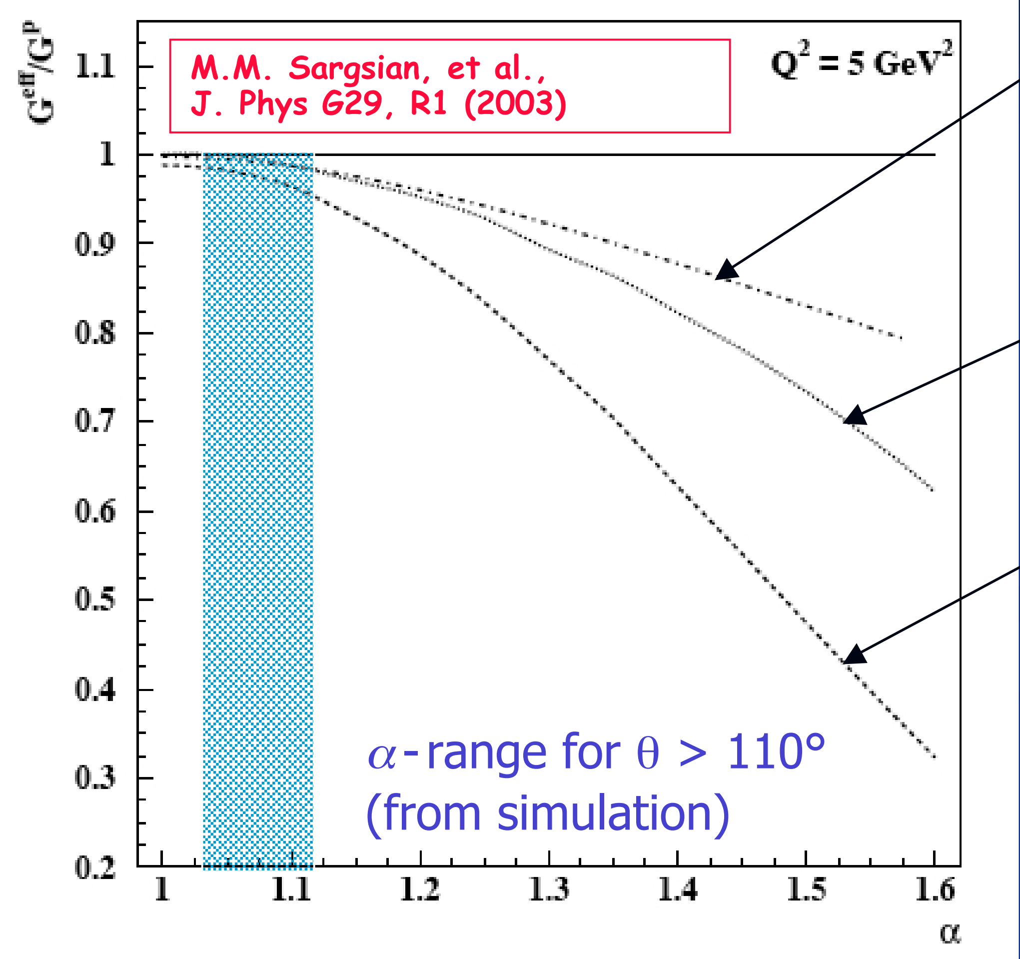


Update 2006 of C. Ciofi degli Atti and B.Z.Kopeliovich, Eur. Phys. J. A17, 133 (2003)

by C. Ciofi degli Atti and L.P. Kaptari

Off-Shell Effects

$$\frac{\dfrac{\sigma(x^* = 0.6\ ,\alpha)}{\sigma(x^* = 0.2\ ,\alpha)}(\text{bound p})}{\dfrac{\sigma(x = 0.6\ )}{\sigma(x = 0.2\ )}(\text{free p})}$$



Modification of the off-shell scattering amplitude

W. Melnitchouk, A. Schreiber, W. Thomas, Phys. Rev. D 49, 1183 (1994)

Colour delocalization

F. Close, R. Roberts, G. Ross, Phys. Lett. B 129, 346 (1983)

PLC suppression

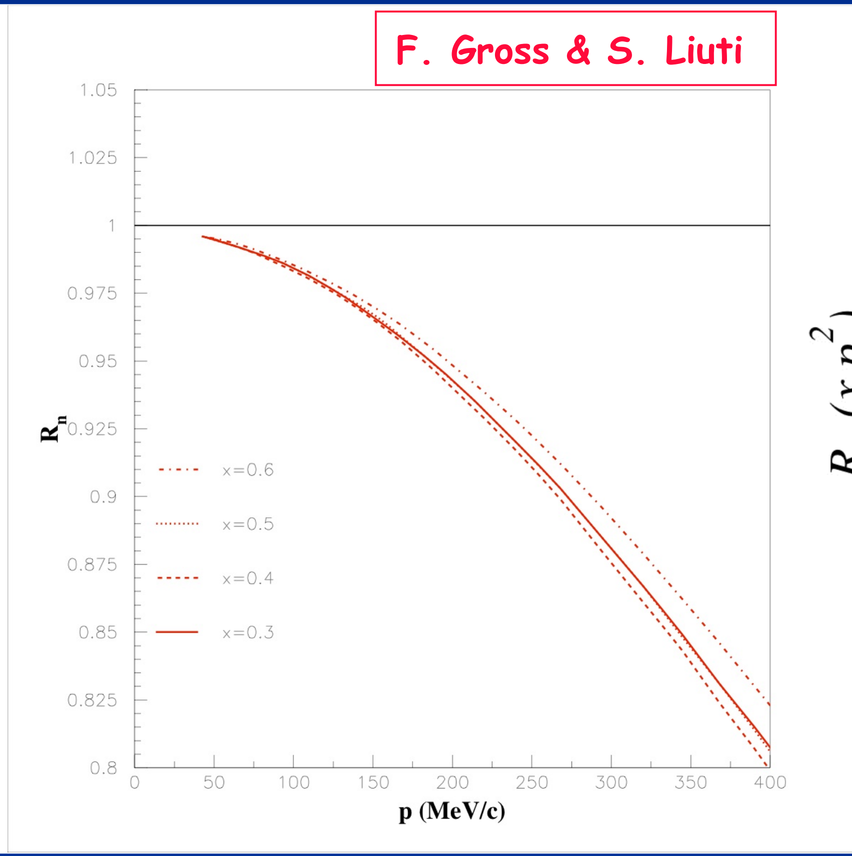
L. Frankfurt and M. Strikman, Nucl. Phys. B 250, 143 (1985)

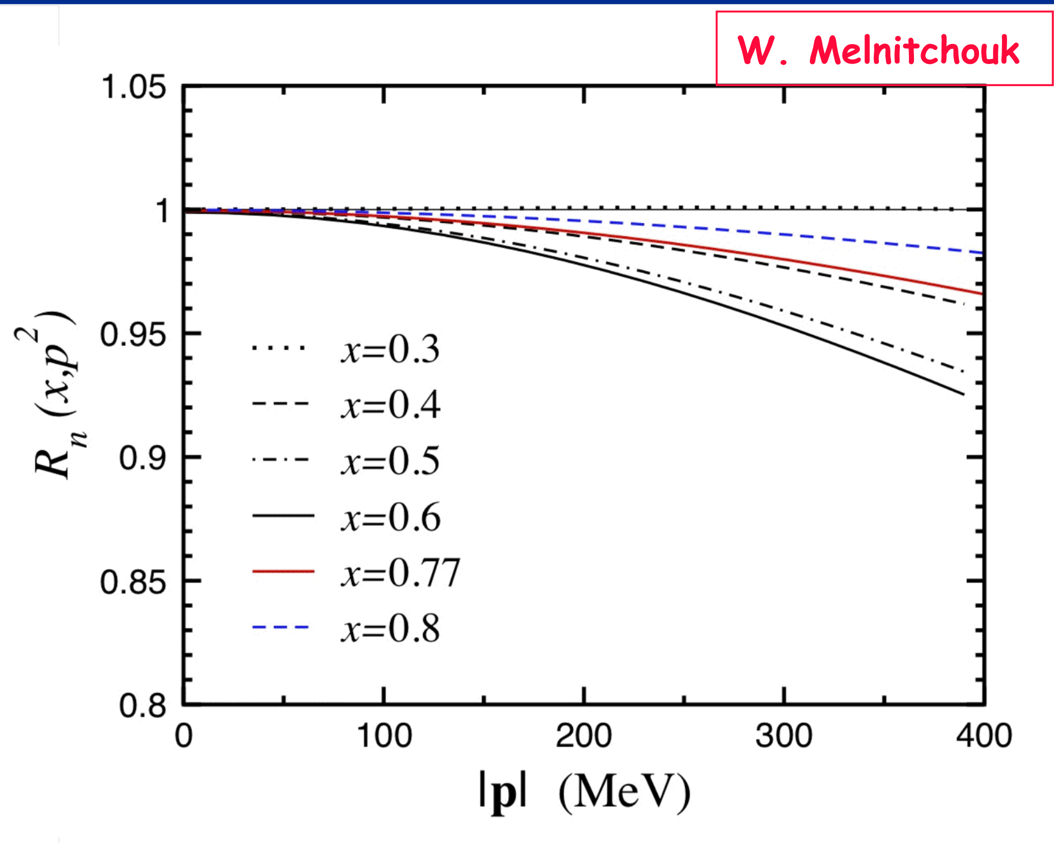
Measure α up to 1.6
Most events have α < 1.1

α = light cone momentum fraction of spectator nucleon

Nucleon Off-Shell Correction

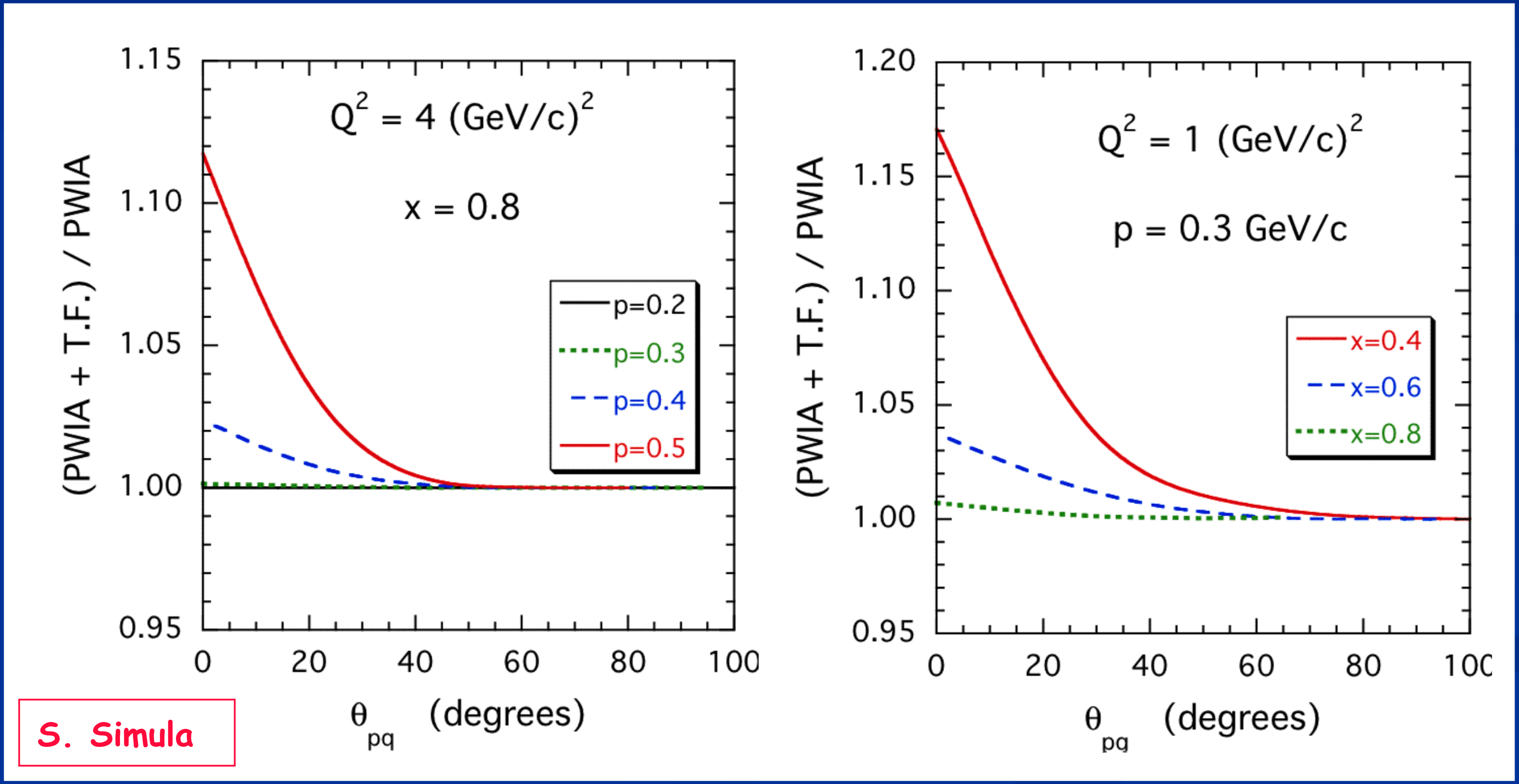
- Ratio of bound to free nucleon structure function
- Agreement between calculations for $x < 0.8$ and $p_s < 100$ MeV/c by W. Melnitchouk (updated 2010) and F. Gross and S. Liuti





Effect of Target Fragmentation

Effect of target fragmentation on PWIA calculations of semi-inclusive DIS from the deuteron (updated 2010 by S. Simula)



The BoNuS Experiment

Inelastic scattering of electrons on a deuteron target $d\,(e, e'\,p_s)\,X$

- 23 cm long deuterium gas target straw (∅ 6 mm and 7.5 atm pressure)

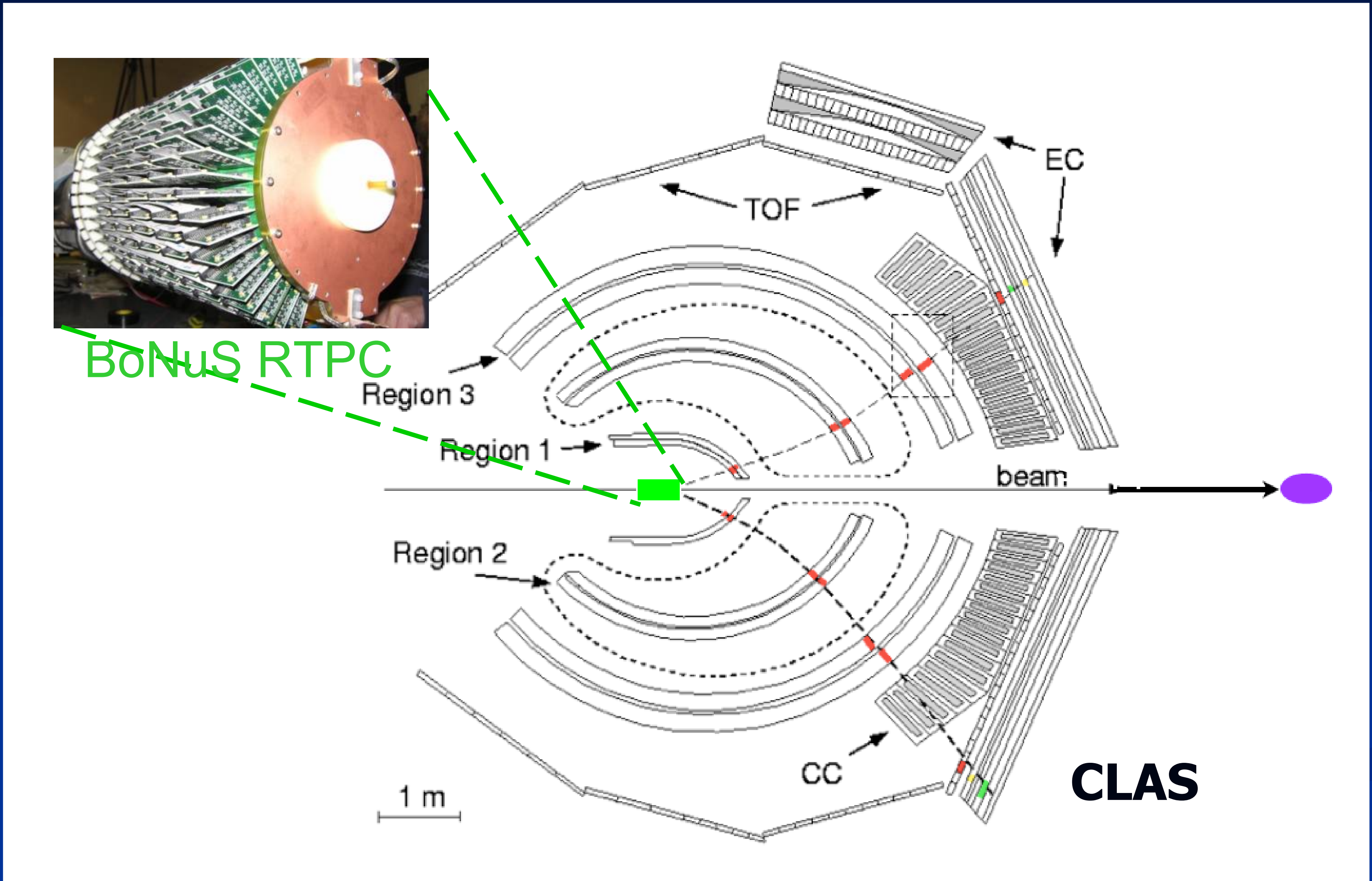
  Spectator protons have to leave target
- Large acceptance coverage including backward angles

  Backward angles: Target fragmentation region and reduced FSI
- Measure momentum by tracking in solenoidal magnetic field of 4 Tesla around target region (spectator momenta > 70 MeV/*c* (E_{kin} = 2.6 MeV))

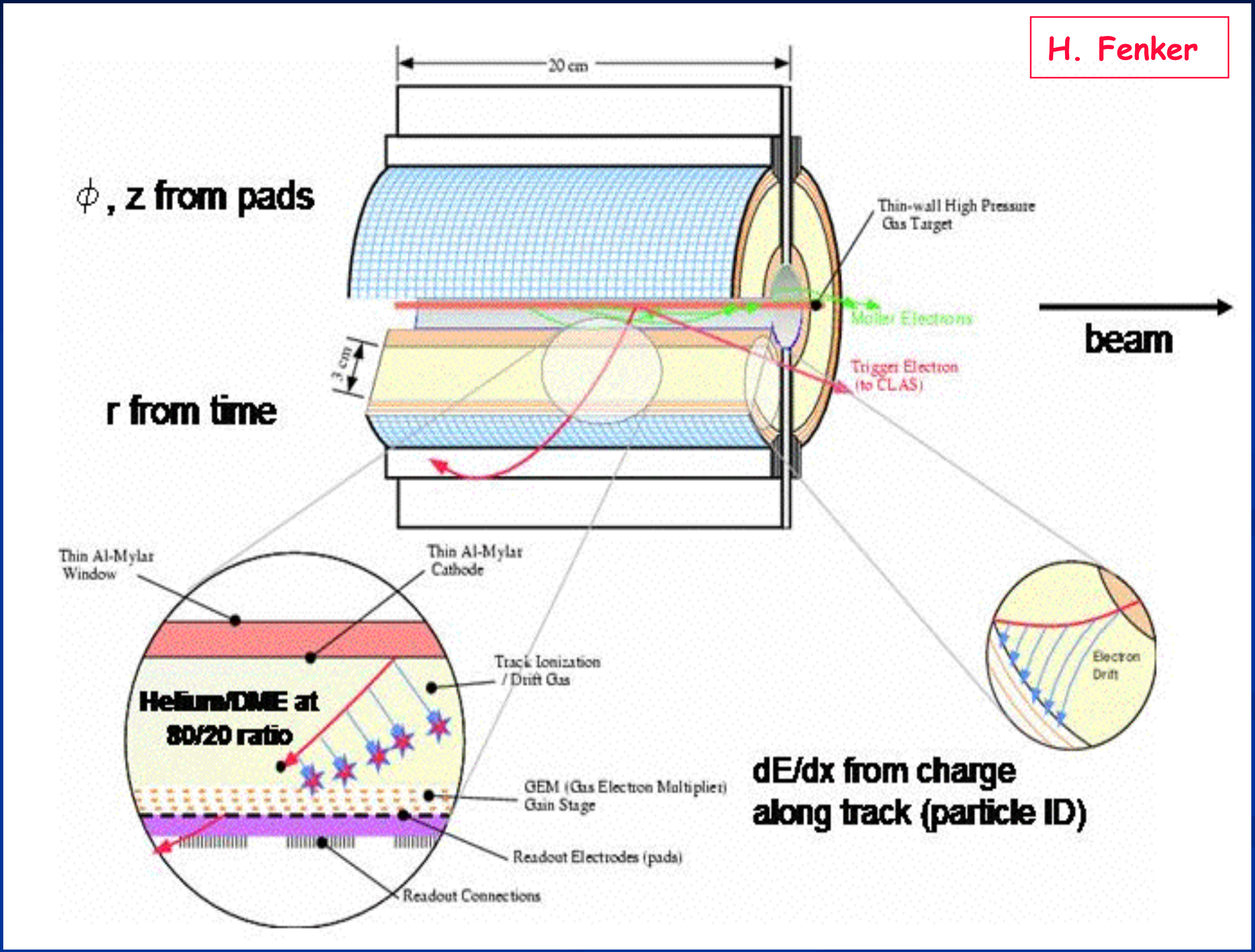
  Small spectator momenta: Reduced on-shell approximation (and fragmentation in conjunction with backward scattering angles)
- Measure energy deposit for particle identification

  Spectator protons are 20 to 50 times minimum ionizing
- Measurement done at 2.1, 4.2, and 5.3 GeV electron beam energy
- Typical luminosity $5 \cdot 10^{32}$ cm^{-2} sec^{-1} (DAQ limitation)

The BoNuS Experiment

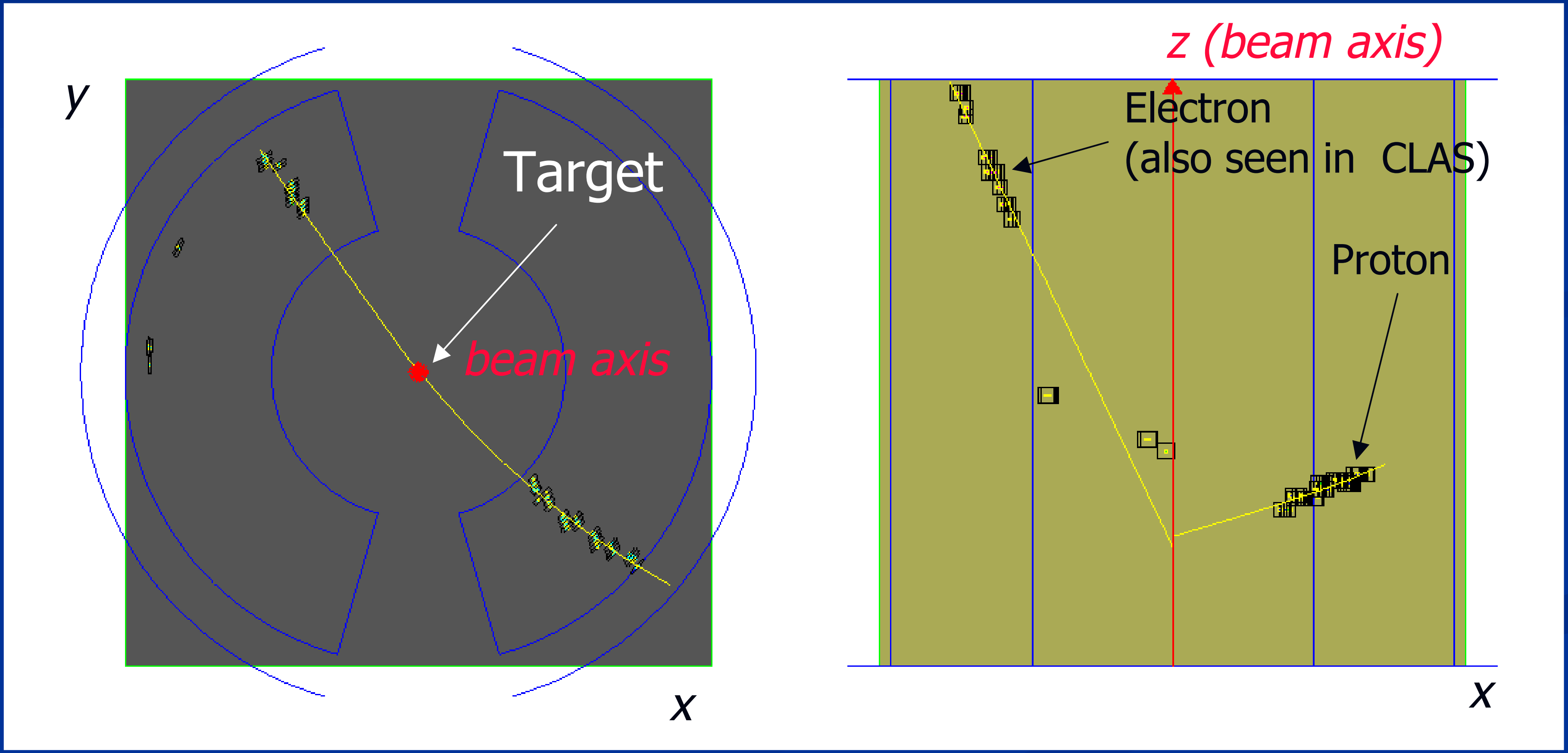


Conceptual Design of BoNuS RTPC



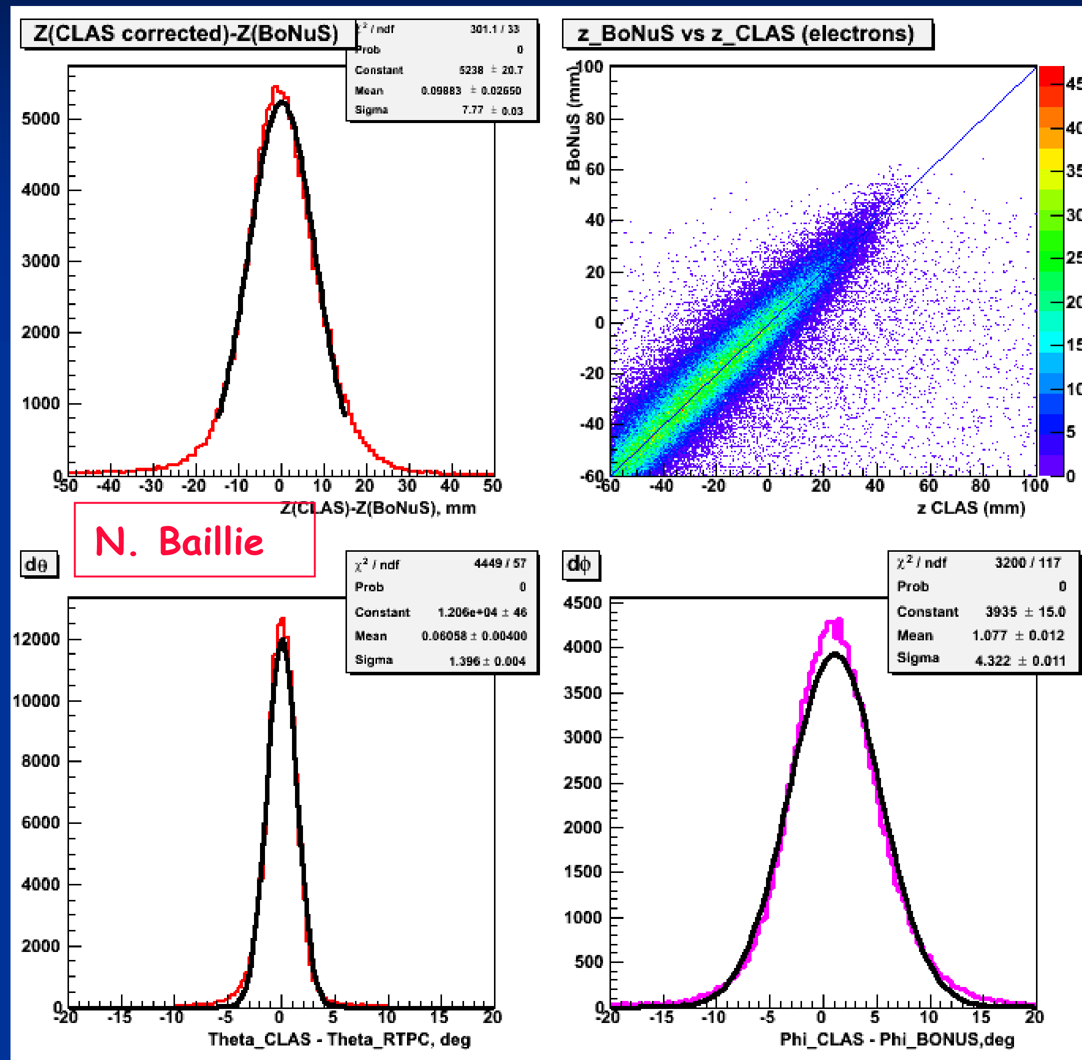
Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

Increase RTPC HV to sensitize detector to minimum ionizing electrons



Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

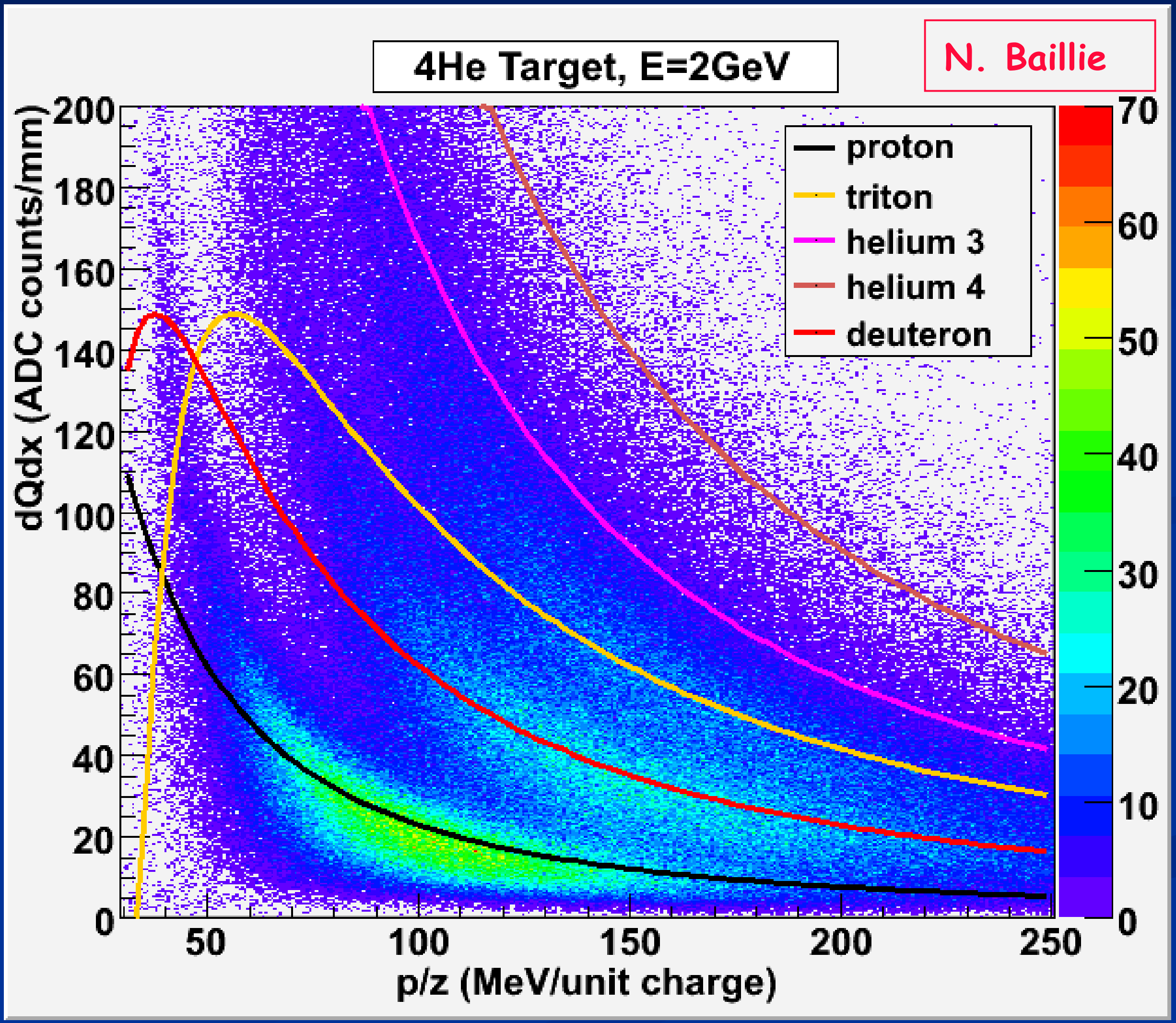
Data taken end of 2005 run with 1.1 GeV electrons



Scattered electron measured in CLAS and by the RTPC

Status of BoNuS Analysis

- Energy loss as a function of measured momentum after calibration of RTPC
- Particle identification in RTPC using ^{4}He gas target



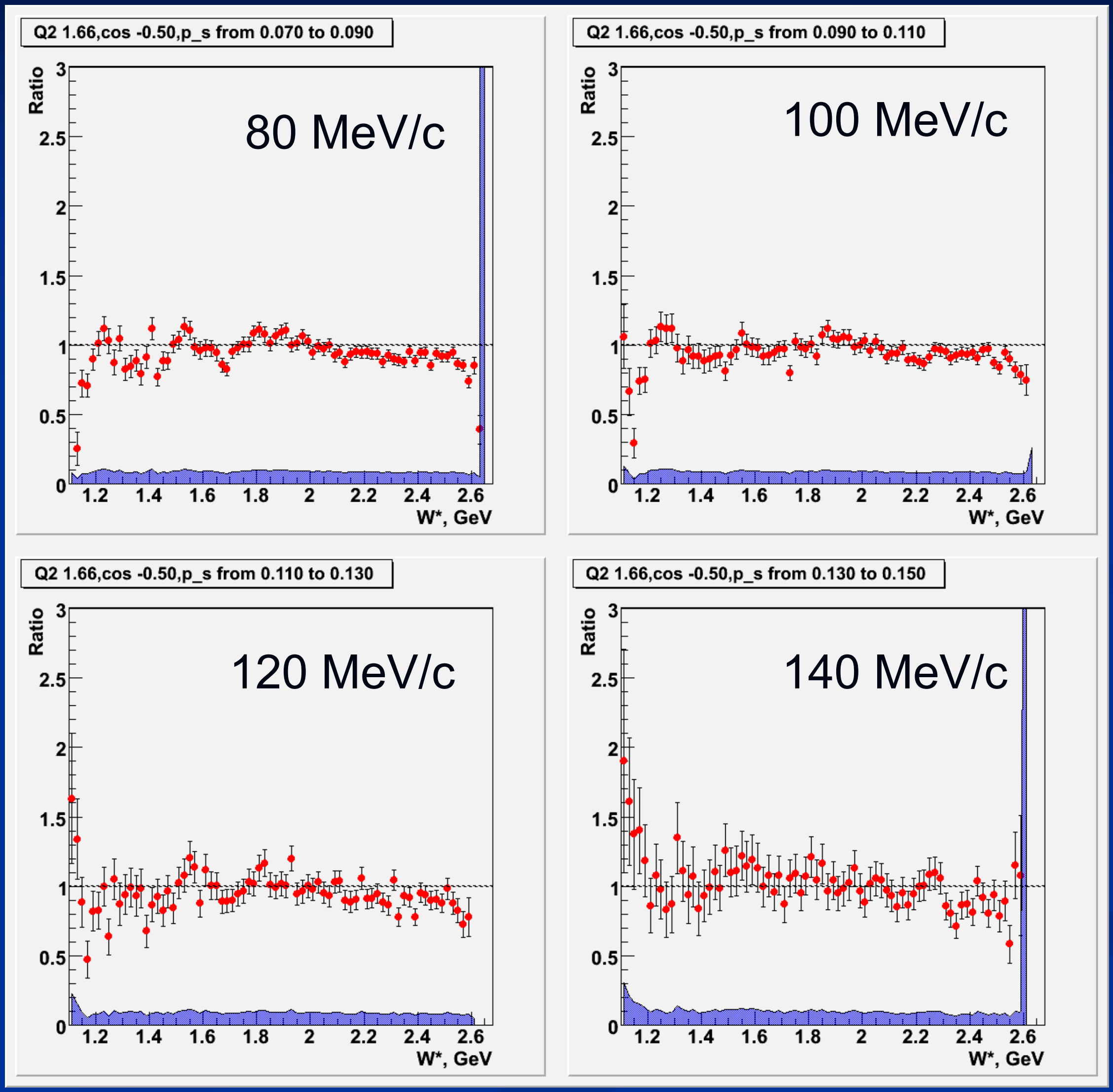
Status of BoNuS Analysis

Two analysis methods employed

- Ratio method
  - Forming ratio between spectator tagged events to inclusive deuteron scattering events for a given kinematic bin
  - Normalization and CLAS acceptance controlled by ratios
- Monte Carlo method
  - Forming ratio between spectator tagged events to MC simulation of CLAS with events generated according to PWIA spectator model
- Both methods are in very good agreement

Monte Carlo Method

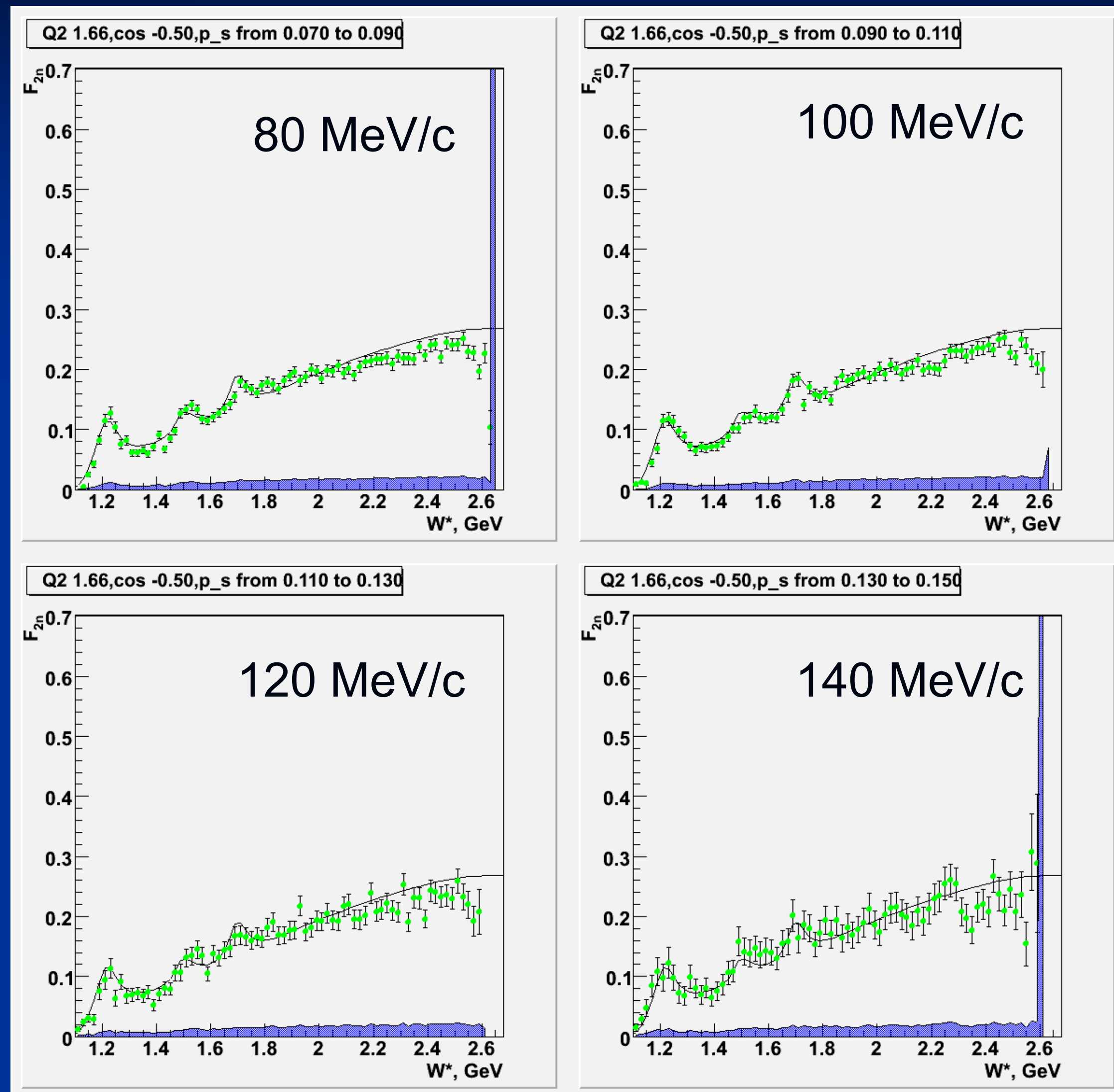
- Ratio of tagged event rate and MC simulation from PWIA spectator model
- Backward angles shown $\cos\Theta_{pq} < -0.25$



S. Tkachenko

Monte Carlo Method

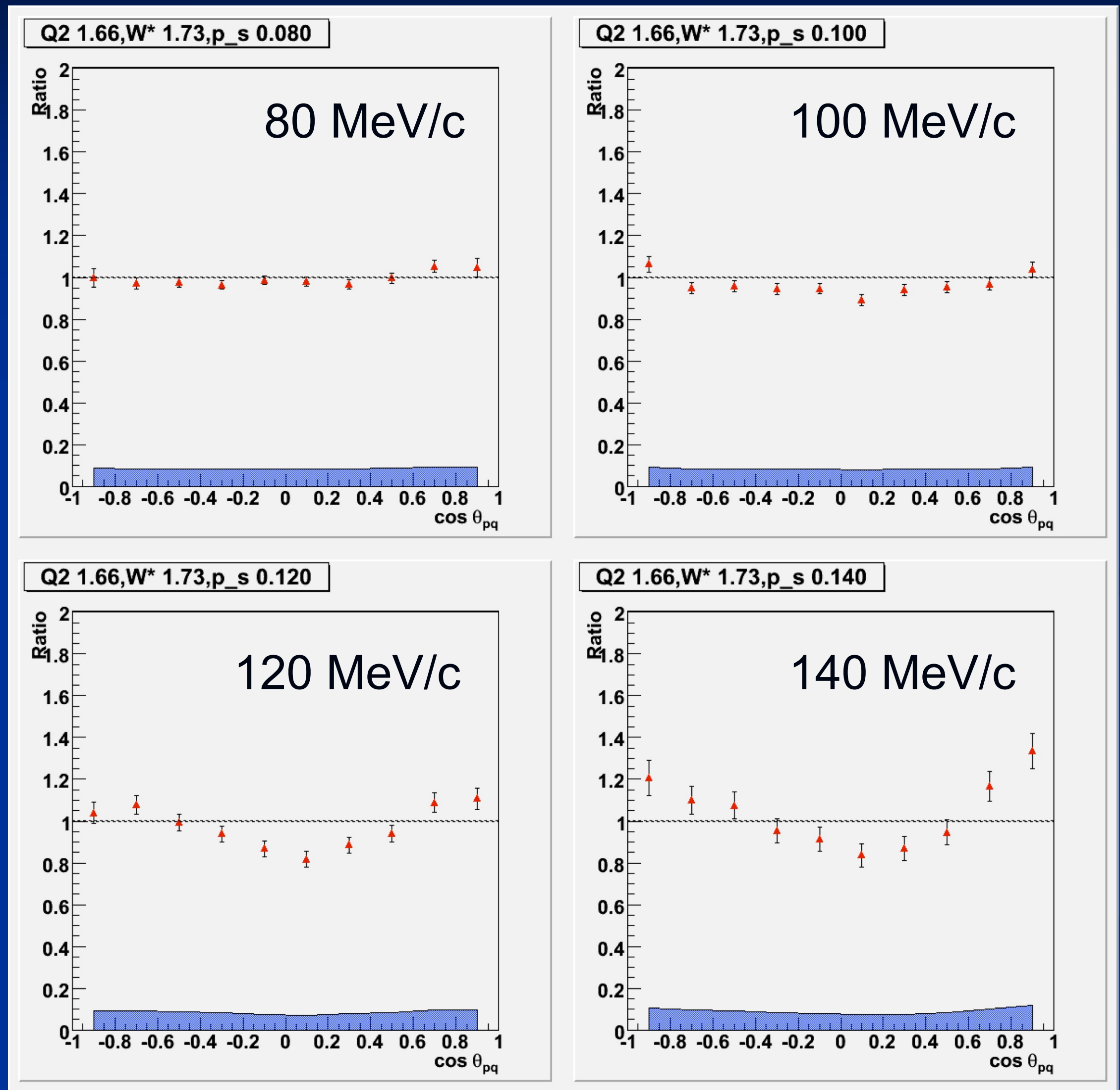
- Effective neutron structure function F_2^n
- Backward angles shown $\cos\,\Theta_{pq} > -0.25$
- F_2^n model of Bosted and Christy plotted for comparison
- Very good agreement between model and data



S. Tkachenko

Monte Carlo Method

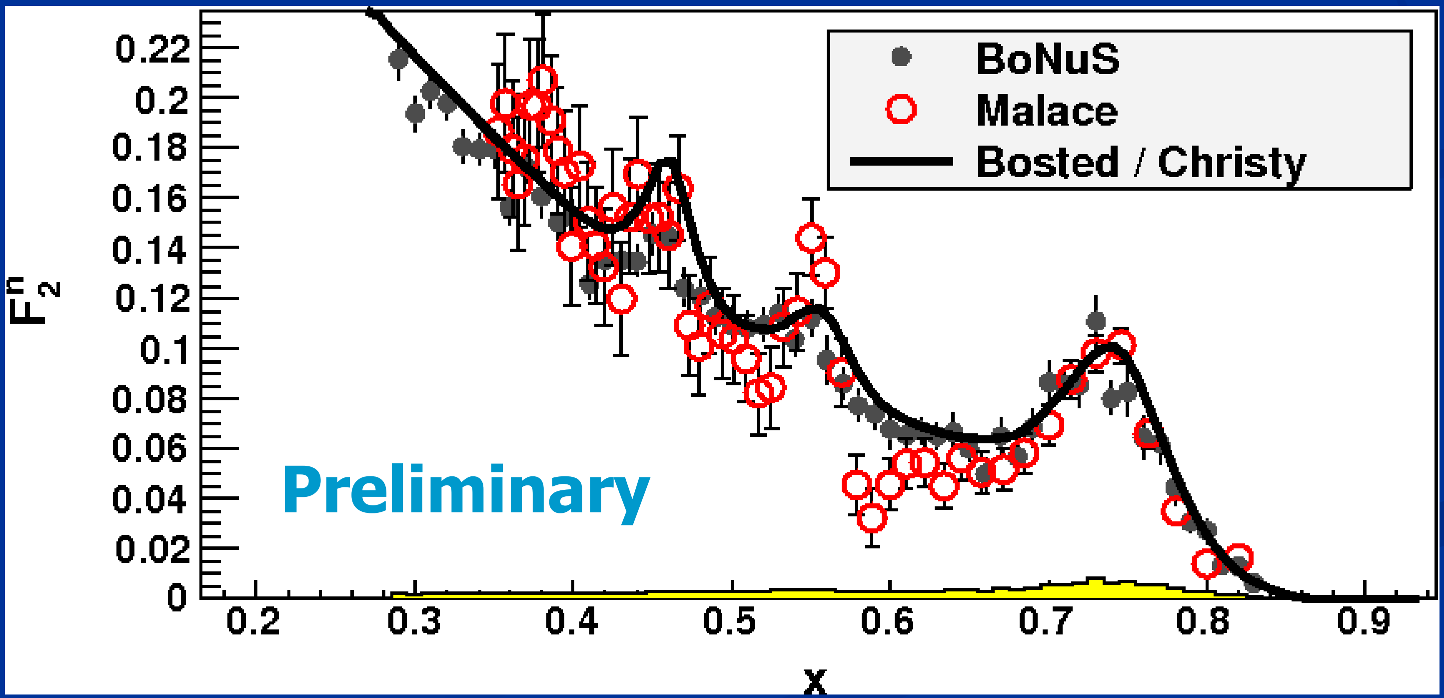
- Angular dependence for Q^2 = 1.66 (GeV/c)^2 and W^* = 1.73 GeV
- At small spectator momentum, basically no deviations from unity
- At larger spectator momentum, deviation from unity in agreement with model by C. degli Atti, indicating FSI and off-shell effects



S. Tkachenko

Ratio Method

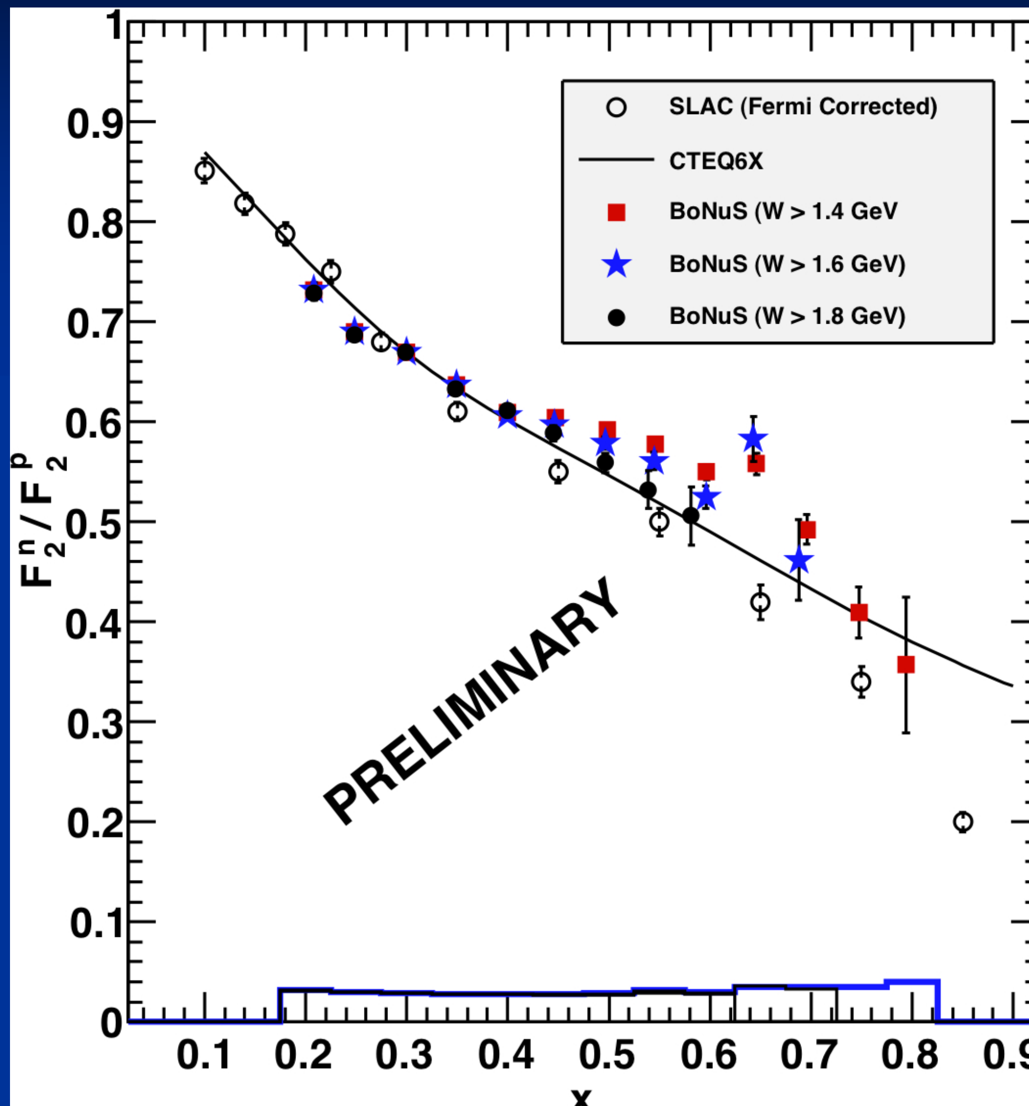
- Extracted neutron structure function F_2^n in resonance region
  - 5.3 GeV beam energy
  - $Q^2 = 1.7\ GeV^2/c^2$
  - $-0.75 < \cos\Theta_{pq} < -0.25$ (backward angles 105º - 140º)
  - $70\ MeV/c < p_s < 90\ MeV/c$
- F_2^n model of Bosted and Christy plotted for comparison
- Open data points are from analysis of inclusive data by S. Malace et al.



N. Baillie

Status of BoNuS Analysis

- Analysis and analysis note finished
- CLAS review under way
- Publications in preparation



N. Baillie

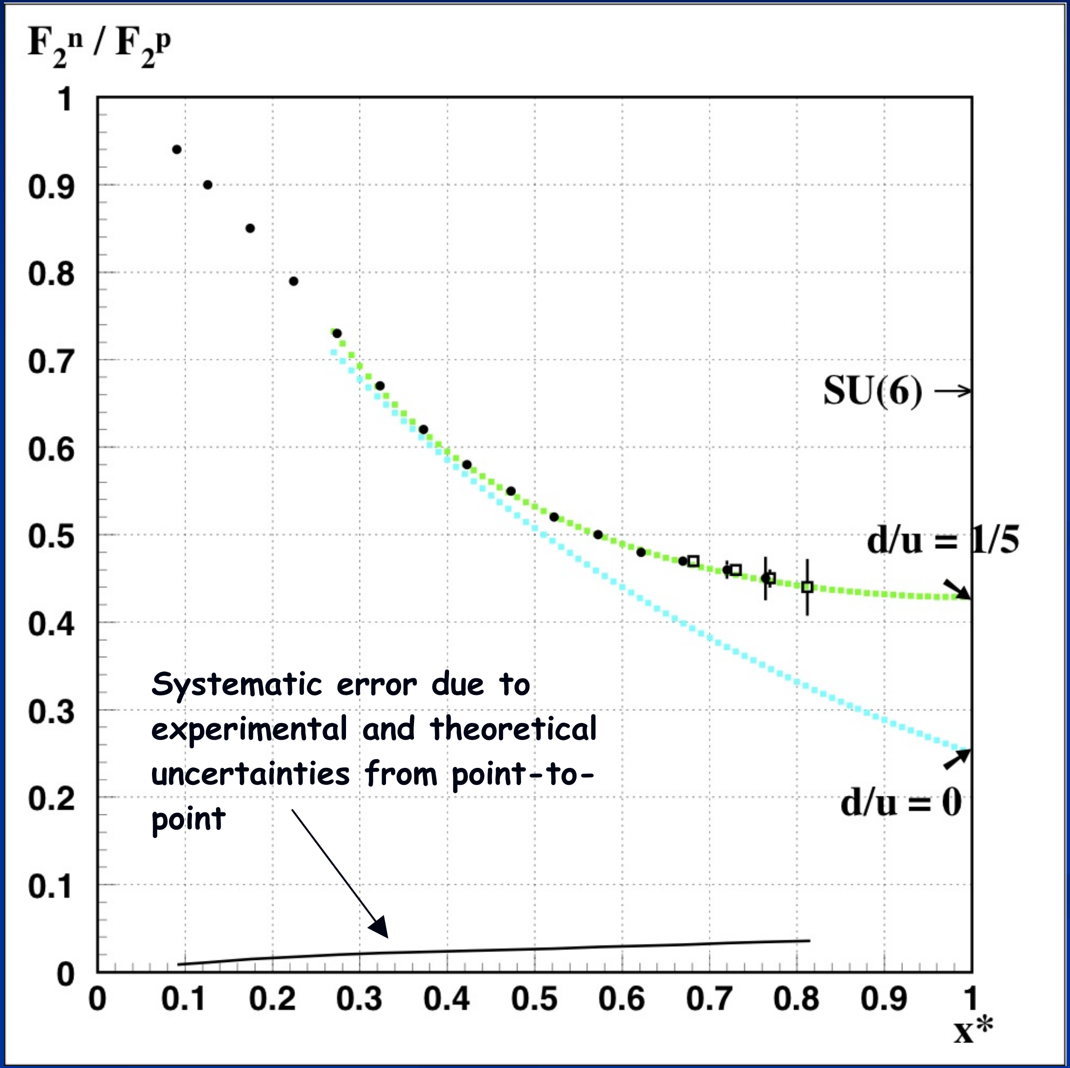
New RTPC for BoNuS12

- Basically same design and construction as BoNuS
- Double RTPC and target length to increase luminosity to $2 \cdot 10^{34}\ cm^{-2}\ s^{-1}$ and backward scattering angle acceptance
- Increase active detector region radially from 3 cm to 4 cm to improve momentum resolution, especially for higher momentum protons
- Use Ne/DME drift gas for increased *dE/dx* and better PID
- Increase phi coverage by removing central spine (as in EG6)
- Use new GEM foil design for continuous 360^{o} azimuthal coverage
- 6 mm diameter gas cell with 30 µm thin walls
- Potentially change to new readout chip
- Use forward vertex tracker (micromegas) for improved vertex reconstruction

BoNuS12 Expected F_2^n/F_2^p Accuracy

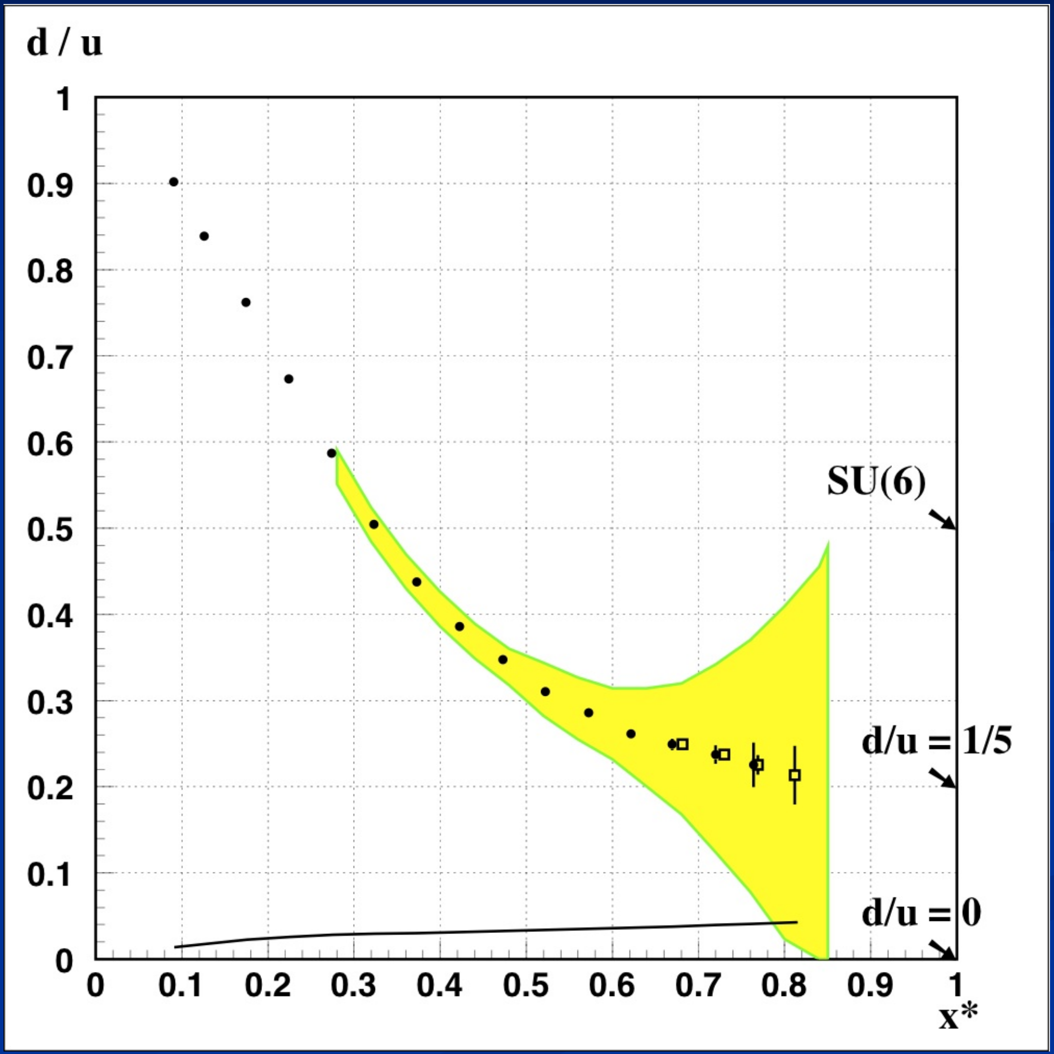
- 35 days of data taking on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$
- Overall scale error 5%

Updated duality-based models by F.E. Close and W. Melnitchouk, PRC 68, 035210 (2003)



BoNuS12 Projected *d / u* Accuracy

- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- Open squares represent data points for *W* *> 1.8 GeV



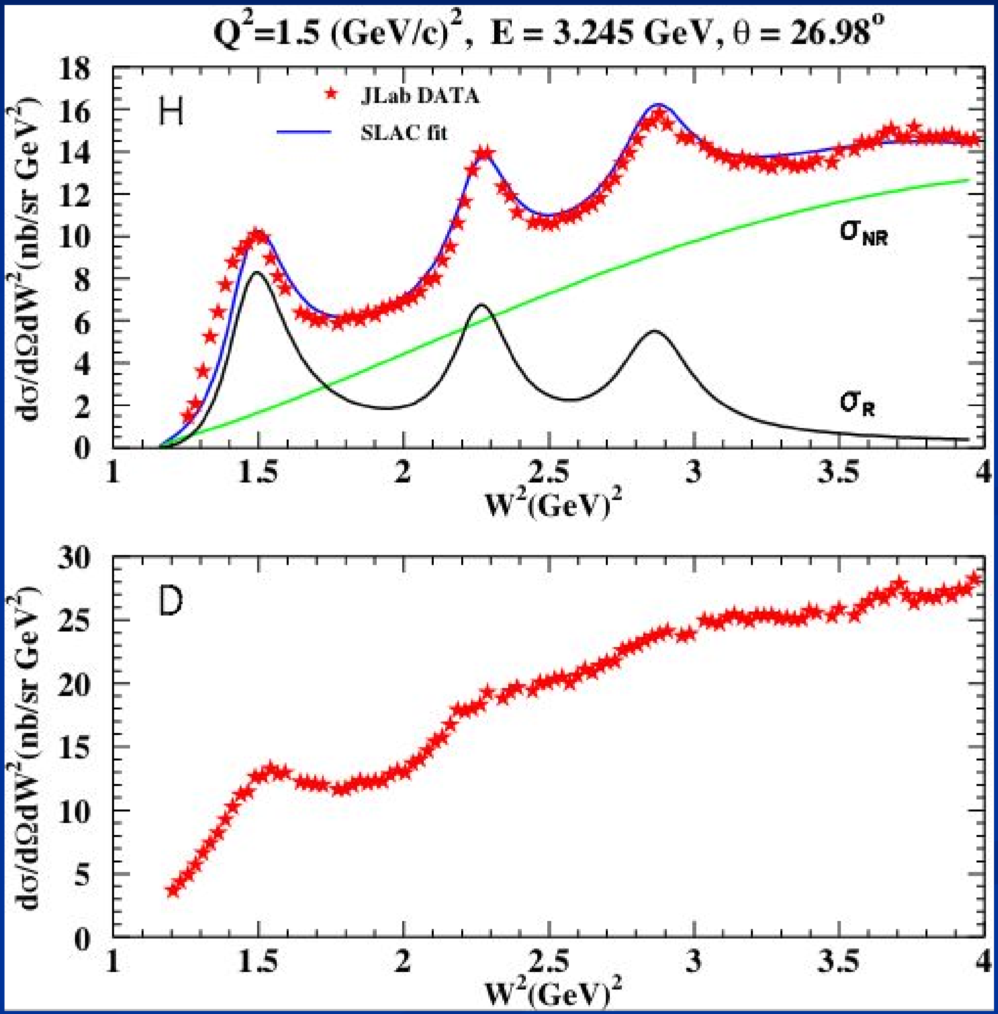
Conclusions

- Successfully used spectator tagging with BoNuS experiment in 2005
- First measurement of *free* neutron resonance structure
- Two analysis approaches give comparable results
- Analysis notes under review and publications being prepared
- Extend measurement with 11 GeV electron beam energy to reach higher x to be able to distinguish between different models for d/u
- Use upgraded CLAS12 spectrometer together with new RTPC recoil detector replacing vertex tracker in new central detector
- Plan to increase luminosity by at least a factor of 40 as compared to the BoNuS experiment of 2005 (factor of 4 compared to EG6) by increasing
- BoNuS creates an effective free neutron target
- BoNuS facilitates a broad program of physics, including F_2^n and F_2^n/F_2^p measurements at large x

Additional Slides

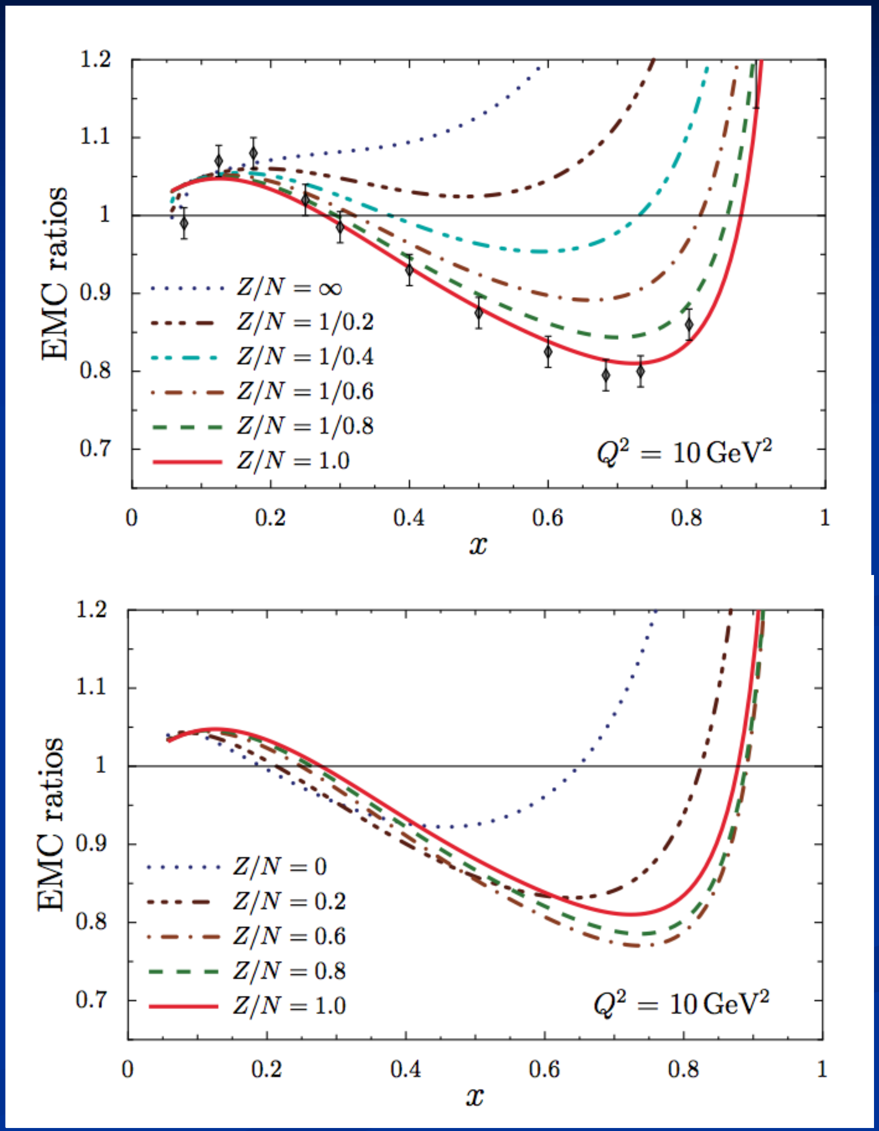
Inclusive Neutron Resonance Electroproduction

- Cross sections measured at Jefferson Lab Hall C
- Resonance structure well resolved for proton data
- Deuteron data show only Δ(1232) resonance clearly (not resolved anymore at Q^2 = 2 GeV^2)
- Extraction of neutron requires modeling of (non-)resonant components, including Fermi motion, nuclear binding effects, etc.



EMC Effect

- Neutron or proton excess in nuclei leads to an isovector-vector mean field
- ⇨ Possible isospin dependent EMC Effect
- Calculations can likely be extended to lighter nuclei
- Combination of BoNuS12 and measurement on mirror nuclei could potentially be sensitive to measure this effect



I.C. Cloët, W. Bentz and A.W. Thomas, PRL 102, 252301 (2009)

The BoNuS Recoil Detector