Neutron Structure Function from BoNuS

Stephen Bültmann

Old Dominion University

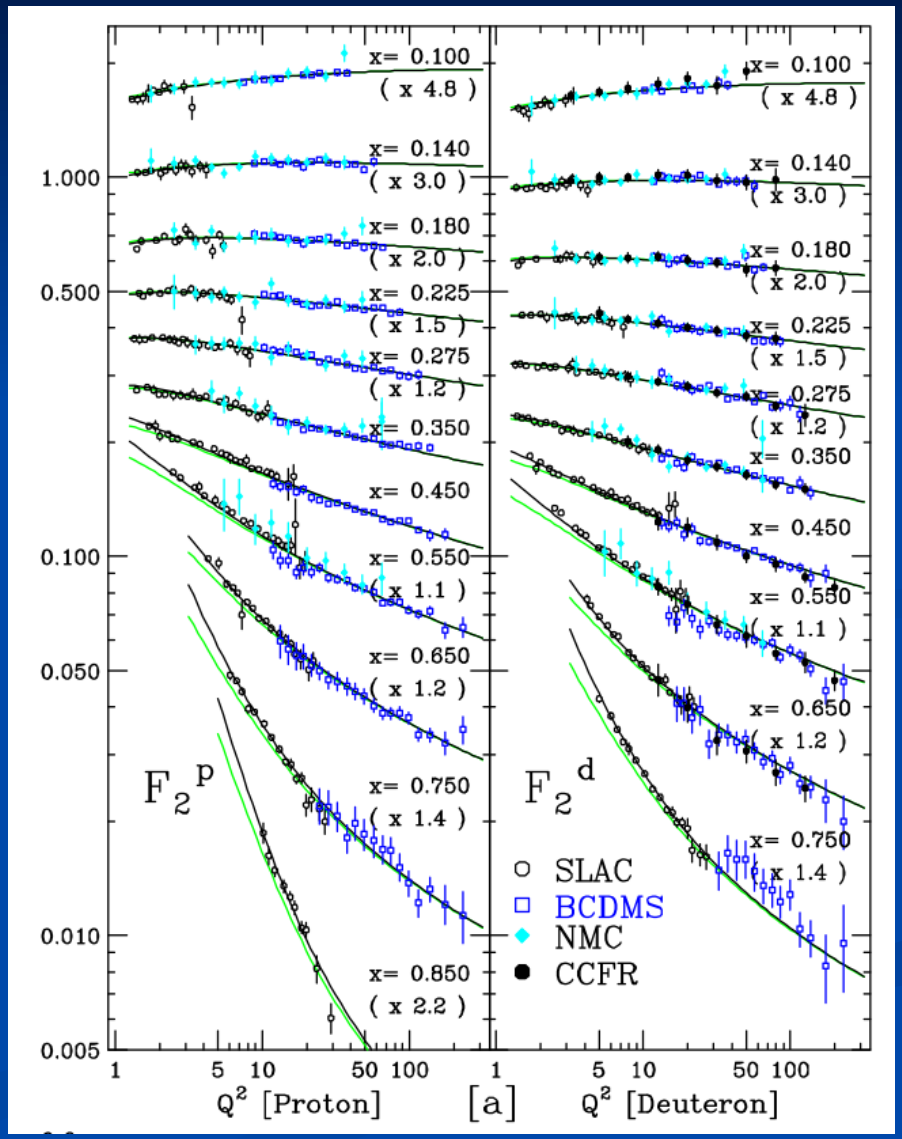
for the CLAS Collaboration

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

CIPANP 2012, St. Petersburg, May/June 2012

Structure of the Nucleon

- Deep inelastic electron-proton scattering revealed a substructure of the proton in the late 1960s
- The structure functions of protons, deuterons and nuclei were measured extensively with leptons
- Very high precision measurements for the proton and deuteron F_2 structure functions were obtained over a very large kinematic range
  - Q^2 = four-momentum transfer
  - x = Bjorken scaling variable
- Comparable data are still missing for the neutron structure

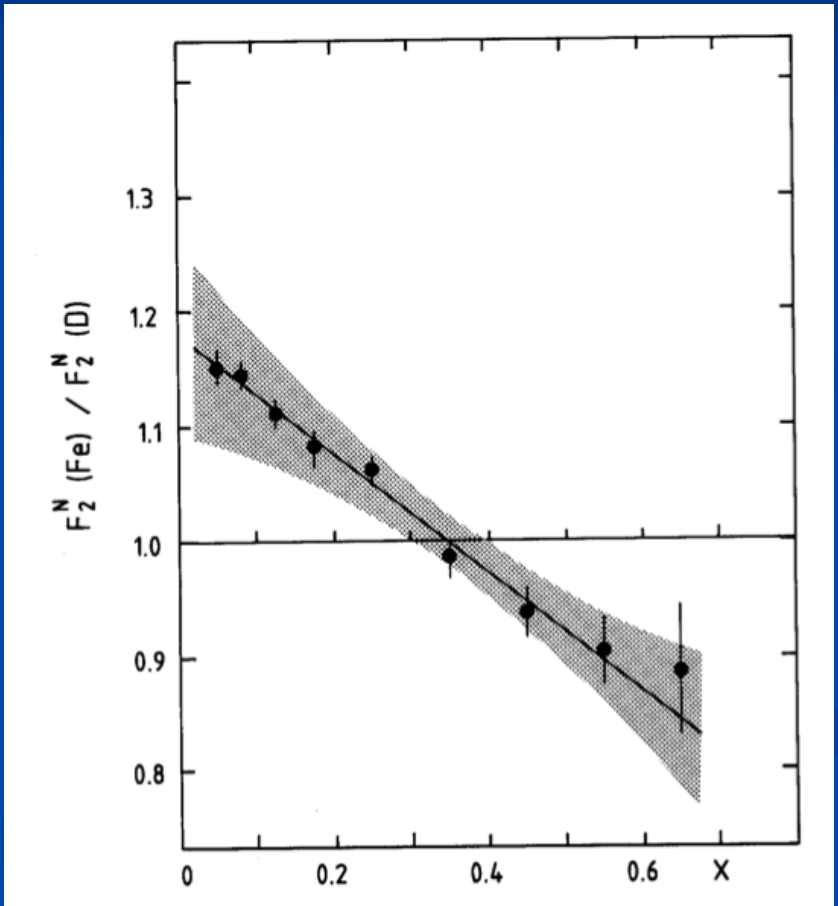


From U. K. Yang and A. Bodek, Eur. Phys. J. C13, 241 (2000)

EMC Effect

- The European Muon Collaboration made a comparison measurement of the nucleon structure function F_2 for heavy nuclei and deuterium
  - → Nucleons inside nuclei are not free
- Neutron structure function

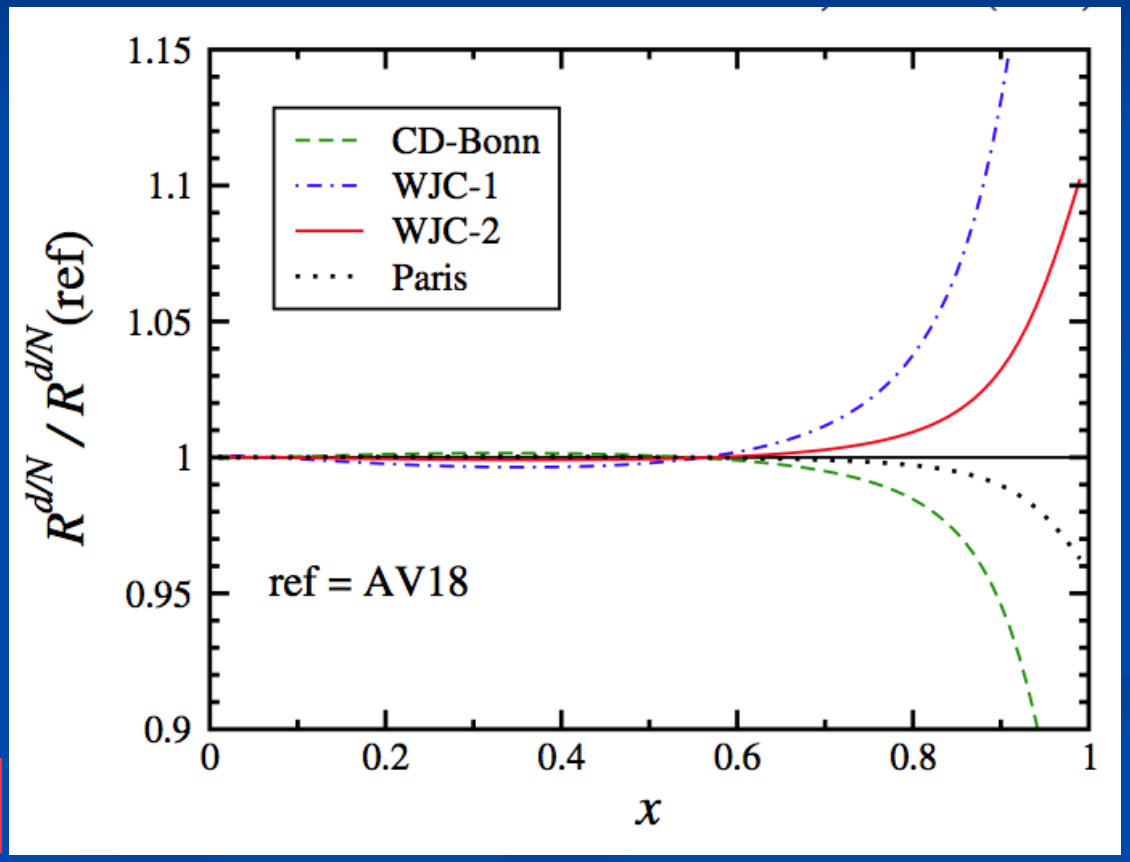
  $F_2^n \neq F_2^d - F_2^p$
- Neutron structure function F_2^n is commonly obtained from measurements on bound neutrons, e.g. using deuterium targets
- Extraction of F_2^n at large x introduces theoretical model dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, …)



From J.J. Aubert et al., Phys. Lett. B 123, 275 (1983)

Structure Function Ratio

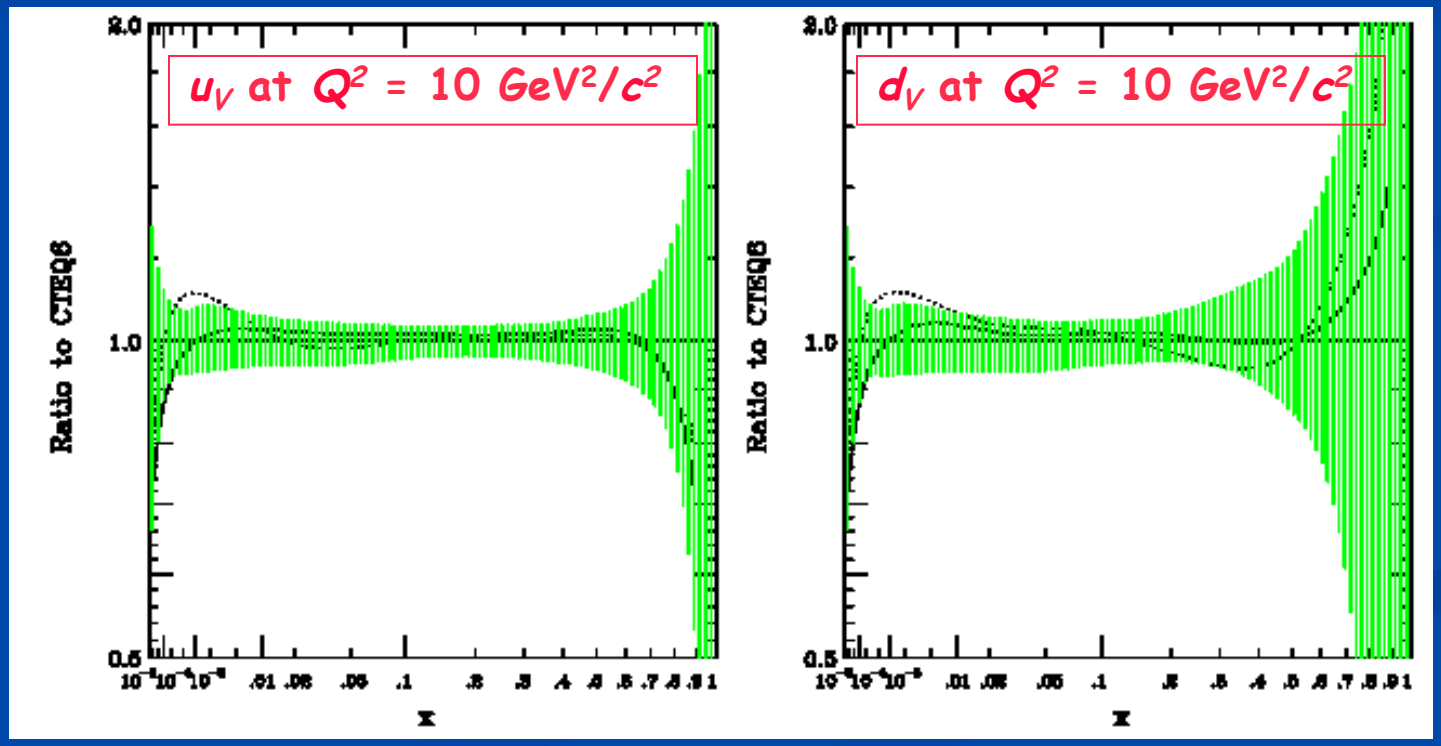
- The dependence of the structure function ratio $R^{d/N} = F_2^d / F_2^N$ on the deuteron wave function model
- Very large variations at high x between the different models



A. Accardi et al.,
Phys. Rev. D 84, 014008 (2011)

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 parametrizations

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

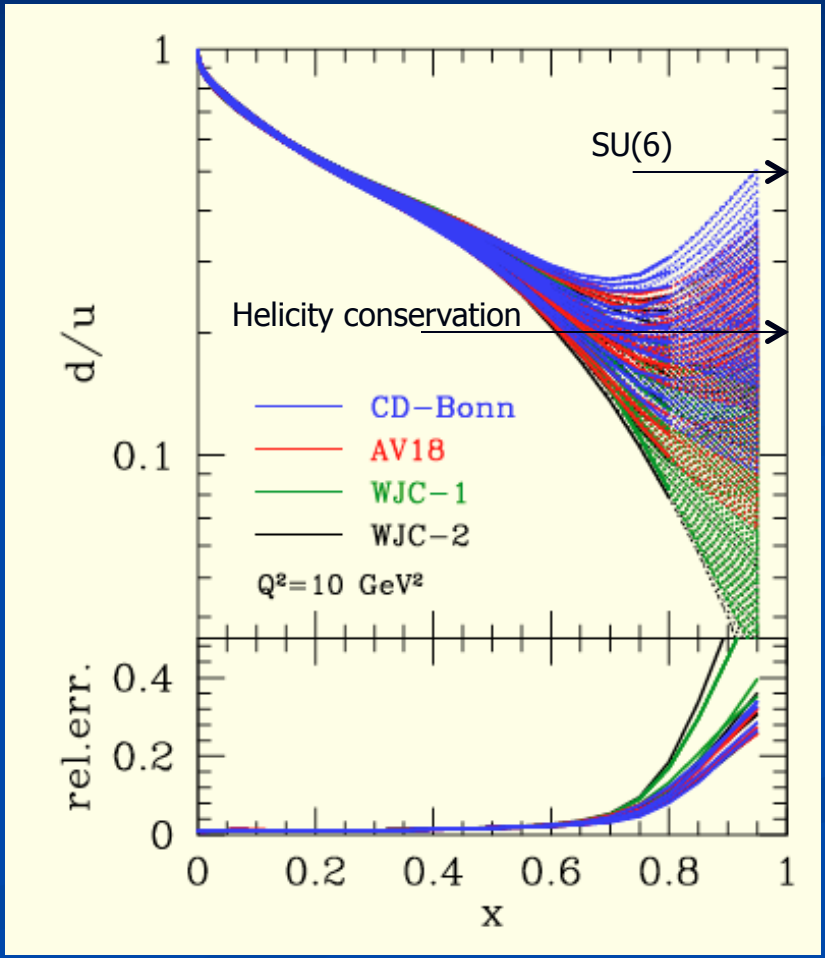
$$\frac{F_2^n}{F_2^p} \approx \frac{1 + 4\, d/u}{4 + d/u}$$

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

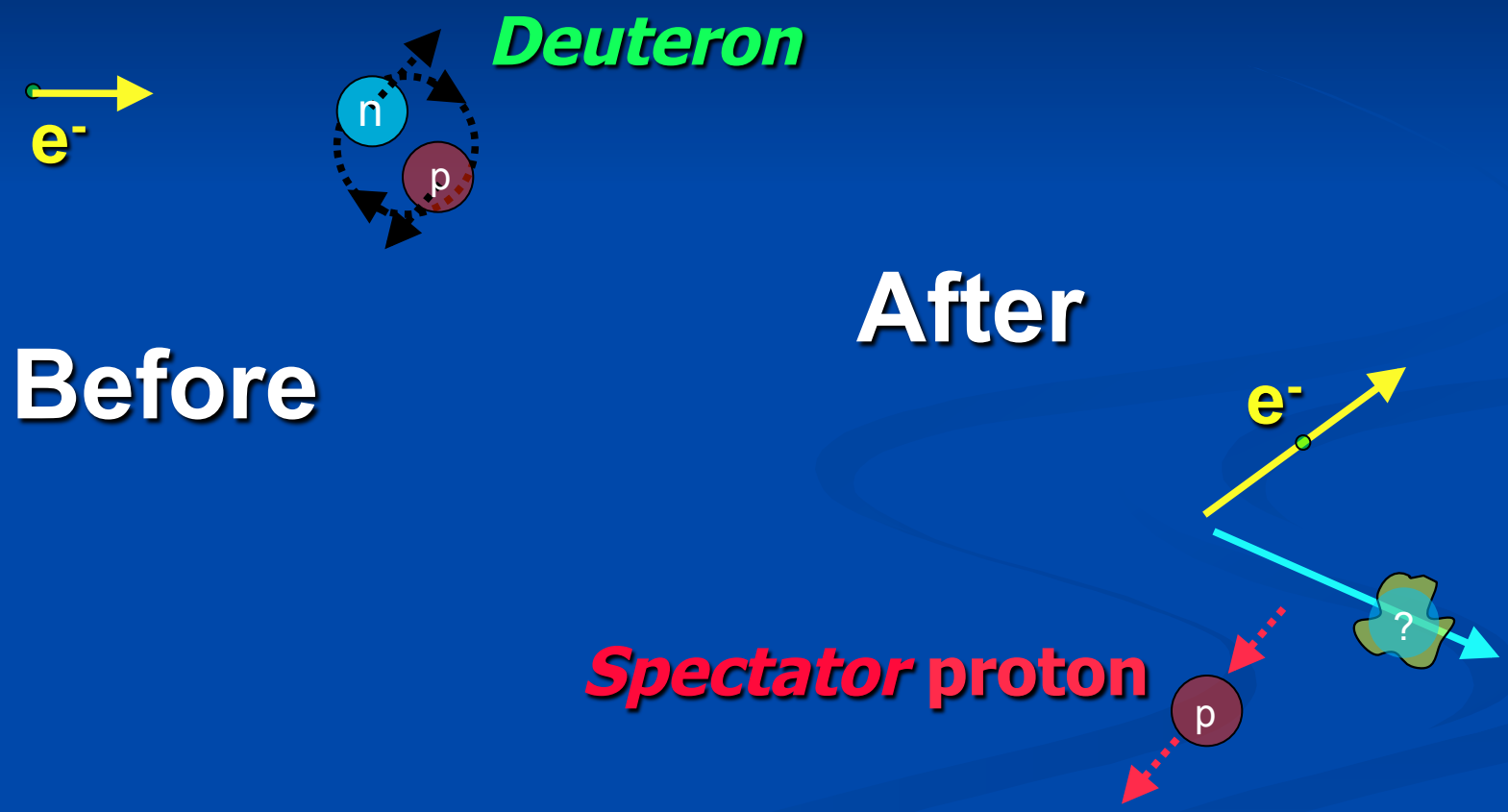
$$\Longrightarrow \quad \frac{d}{u} \approx \frac{4\, F_2^n / F_2^p - 1}{4 - F_2^n / F_2^p}$$

Extraction of F_2^n / F_2^p or d/u from measurements results at large x in strong dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, ...)

CTEQ6x / JLab Fits (CJ)
Accardi et al., Phys. Rev. D 81, 034016 (2010)



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 measuring the recoiling spectator proton results in improved resolution of invariant mass spectrum

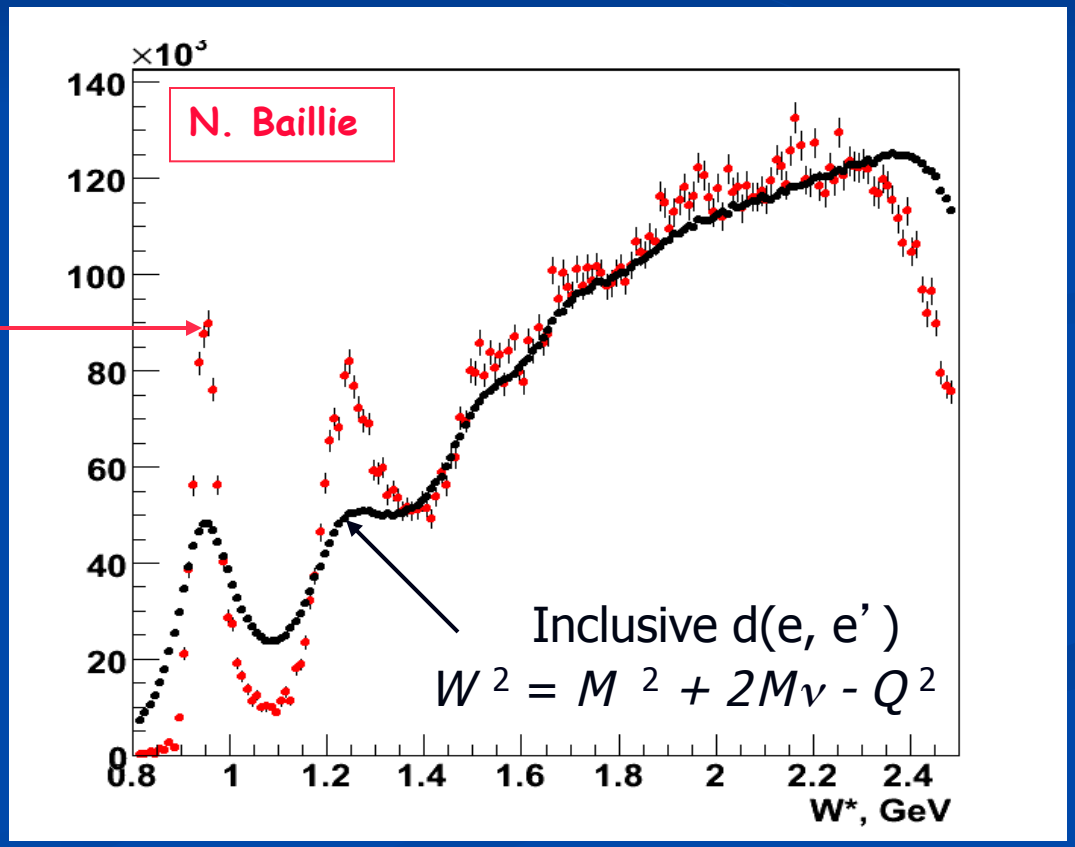
Measurement from BoNuS

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

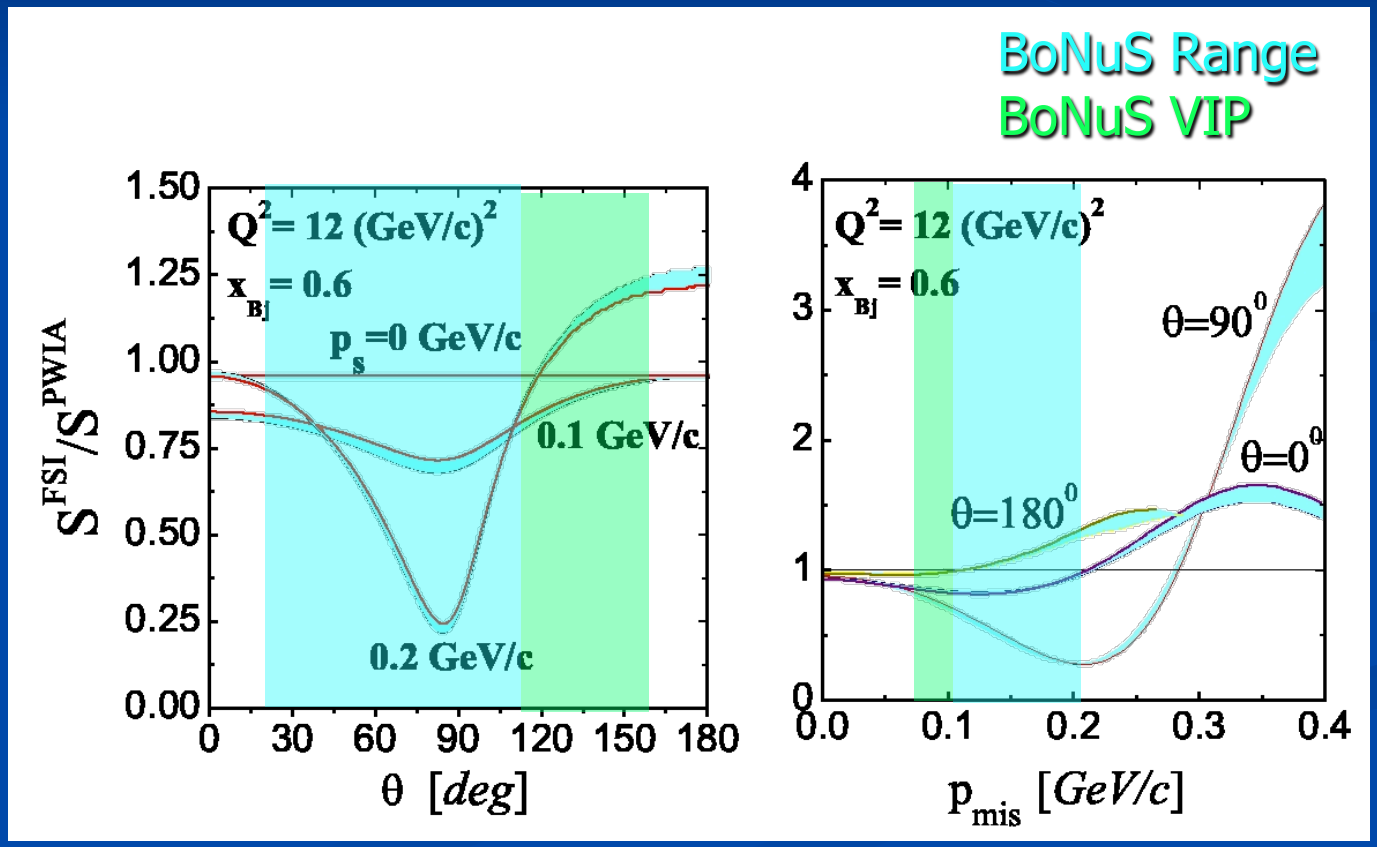


Final State Interactions

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

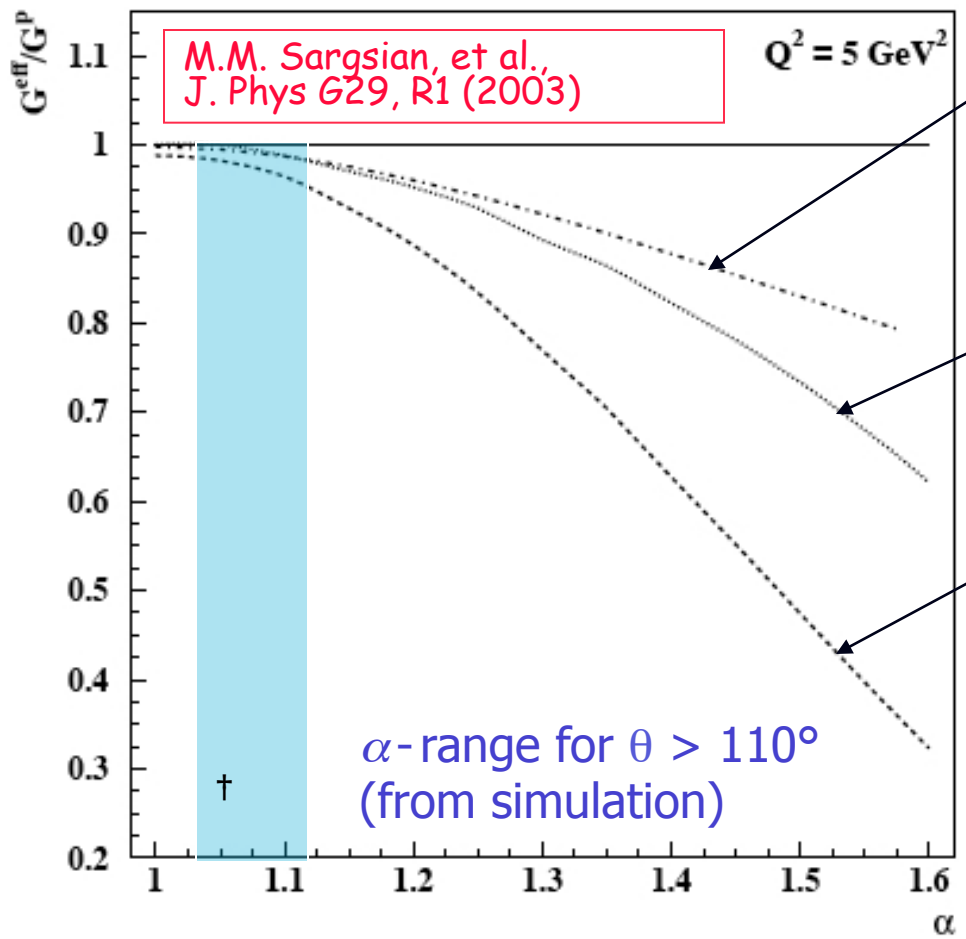


Update 2006 of C. Ciofi degli Atti and B.Z.Kopeliovich, Eur. Phys. J. A17, 133 (2003)

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)

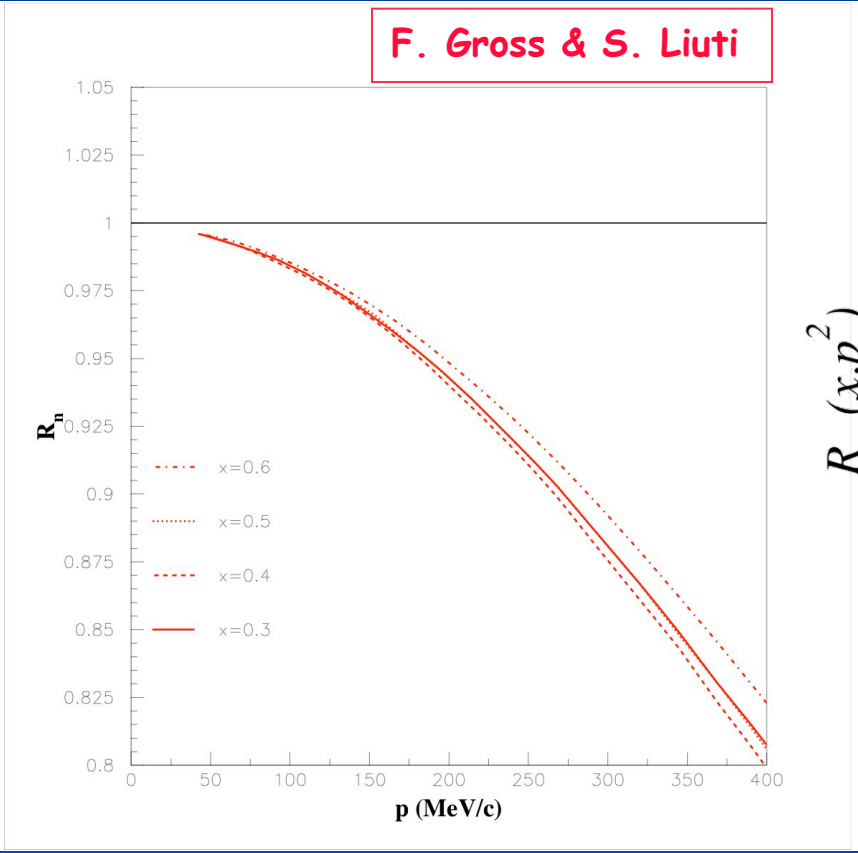
Measure α up to 1.6

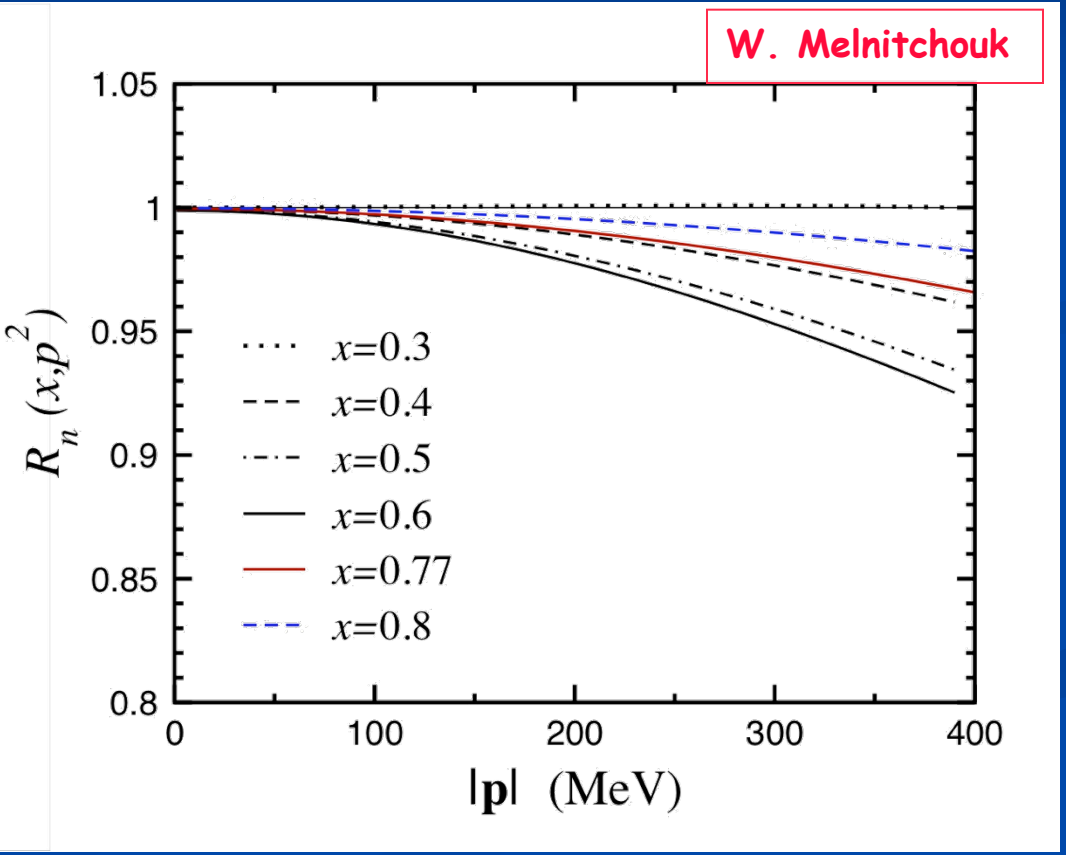
Most events have $\alpha < 1.1$

α = light cone momentum fraction of spectator nucleon

Nucleon Off-Shell Correction

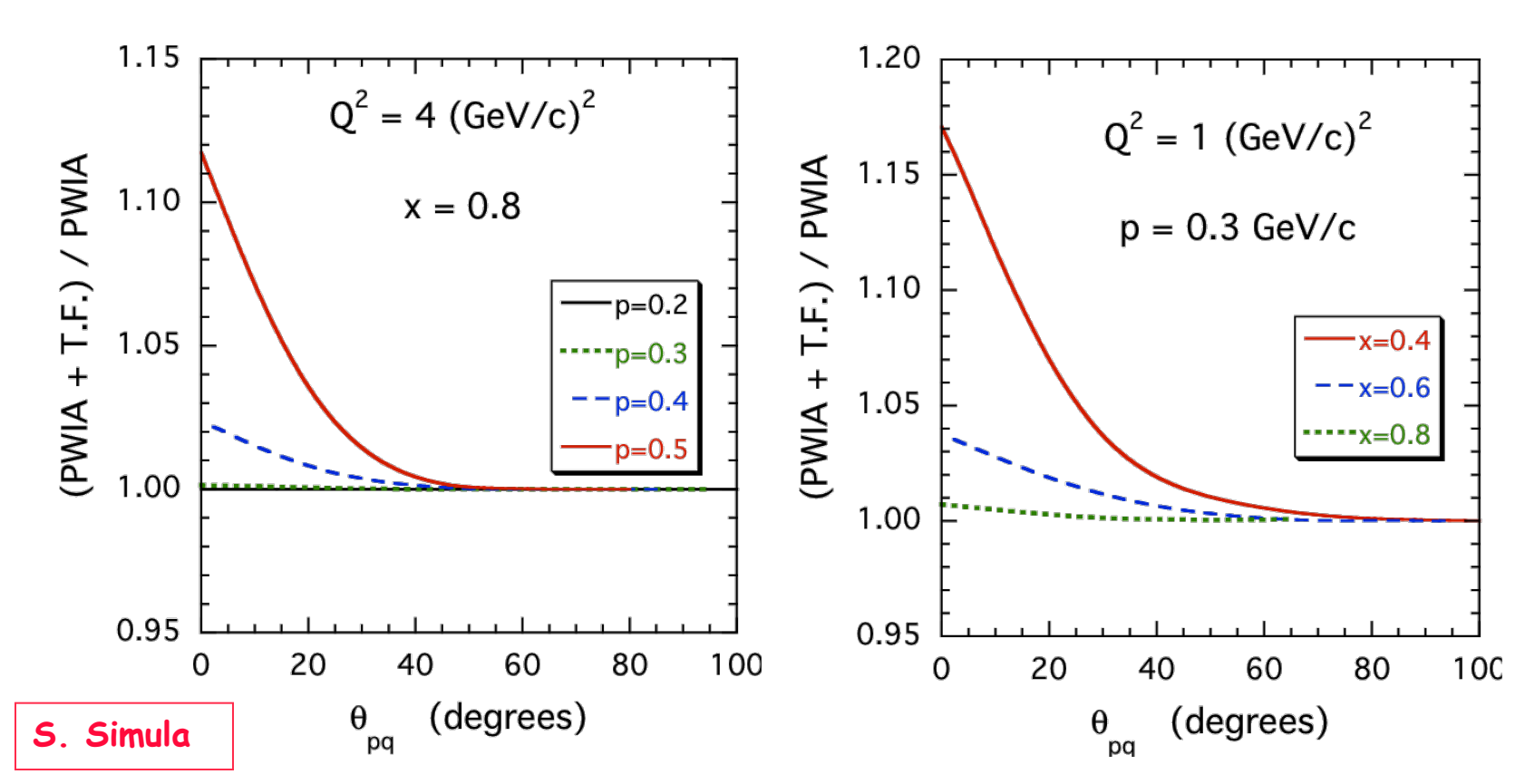
- Ratio of bound to free nucleon structure function
- Agreement between calculations for $x < 0.8$ and $p_s < 100$ MeV/c by W. Melnitchouk (updated 2010) and F. Gross and S. Liuti





Effect of Target Fragmentation

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

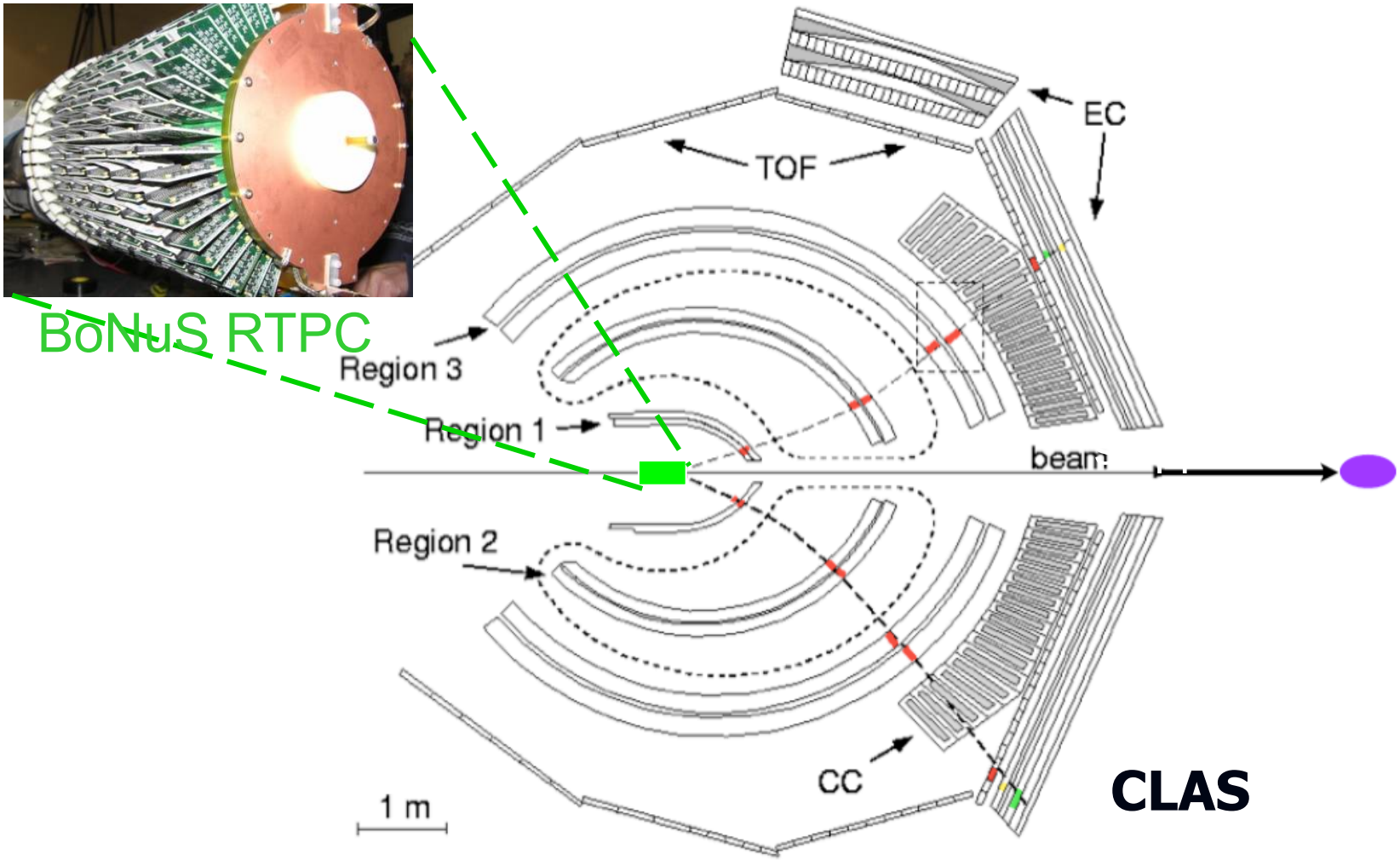


The BoNuS Experiment

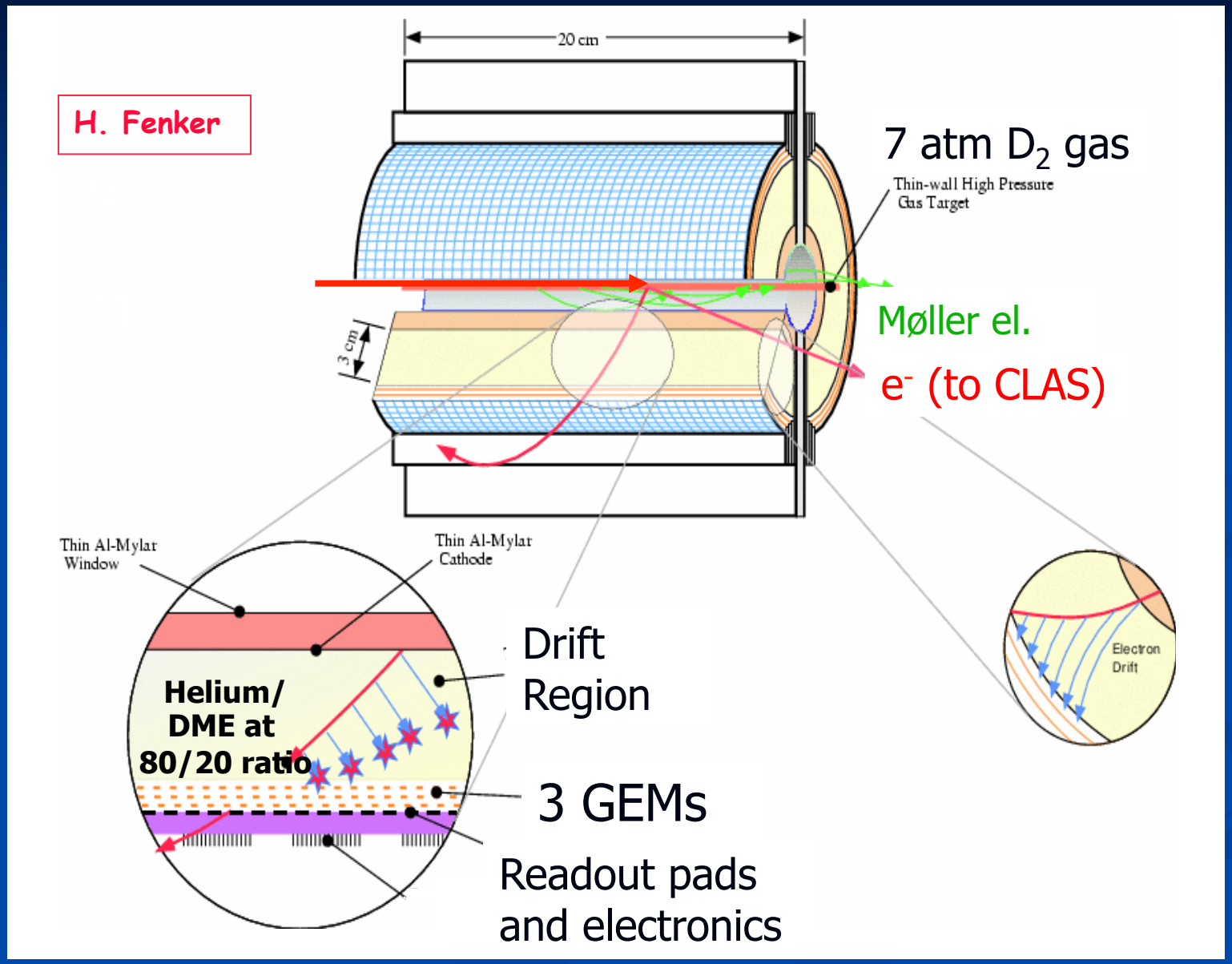
Inelastic scattering of electrons on a deuteron target **$d\,(e, e'\ p_s)\,X$**

- 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

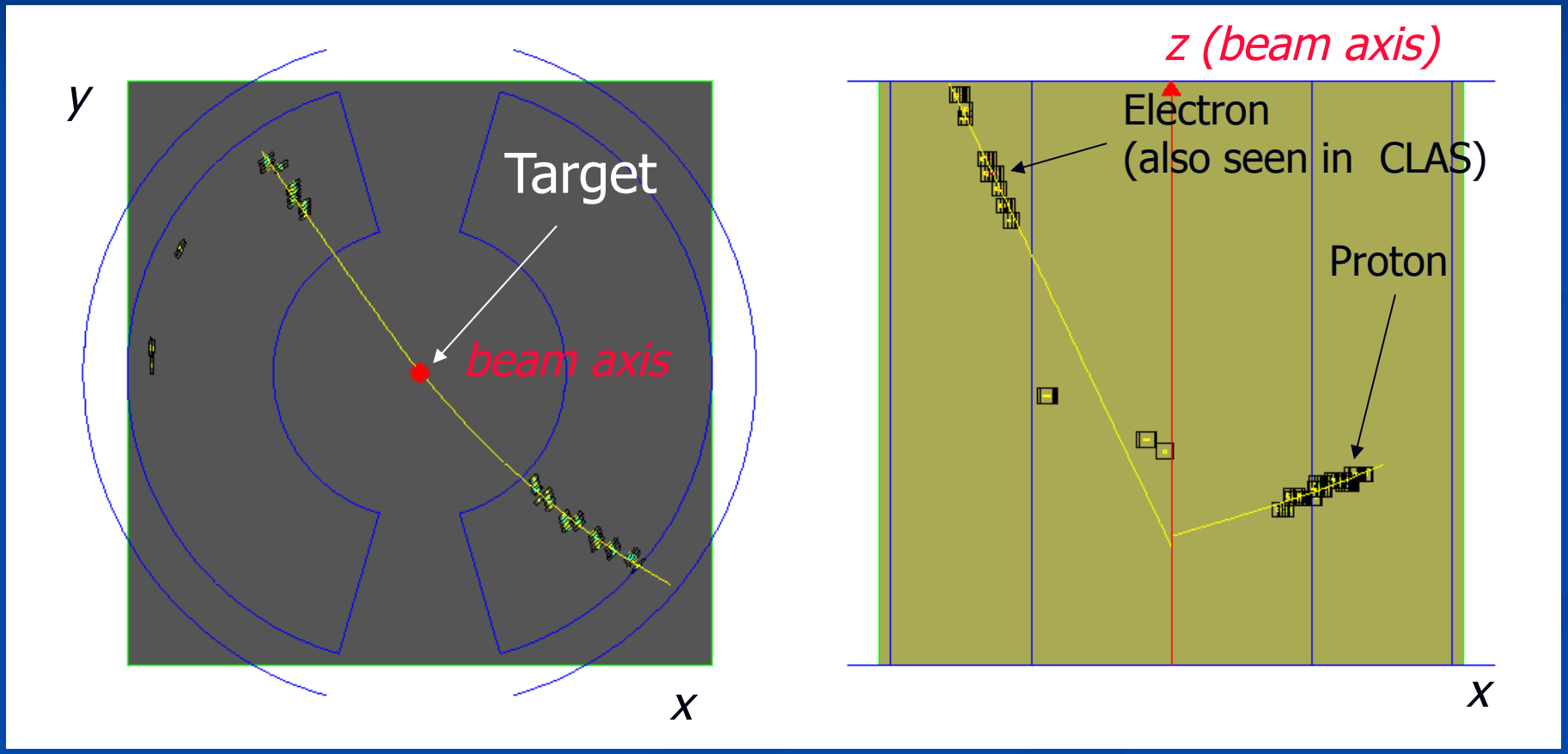


Conceptual Design of BoNuS RTPC



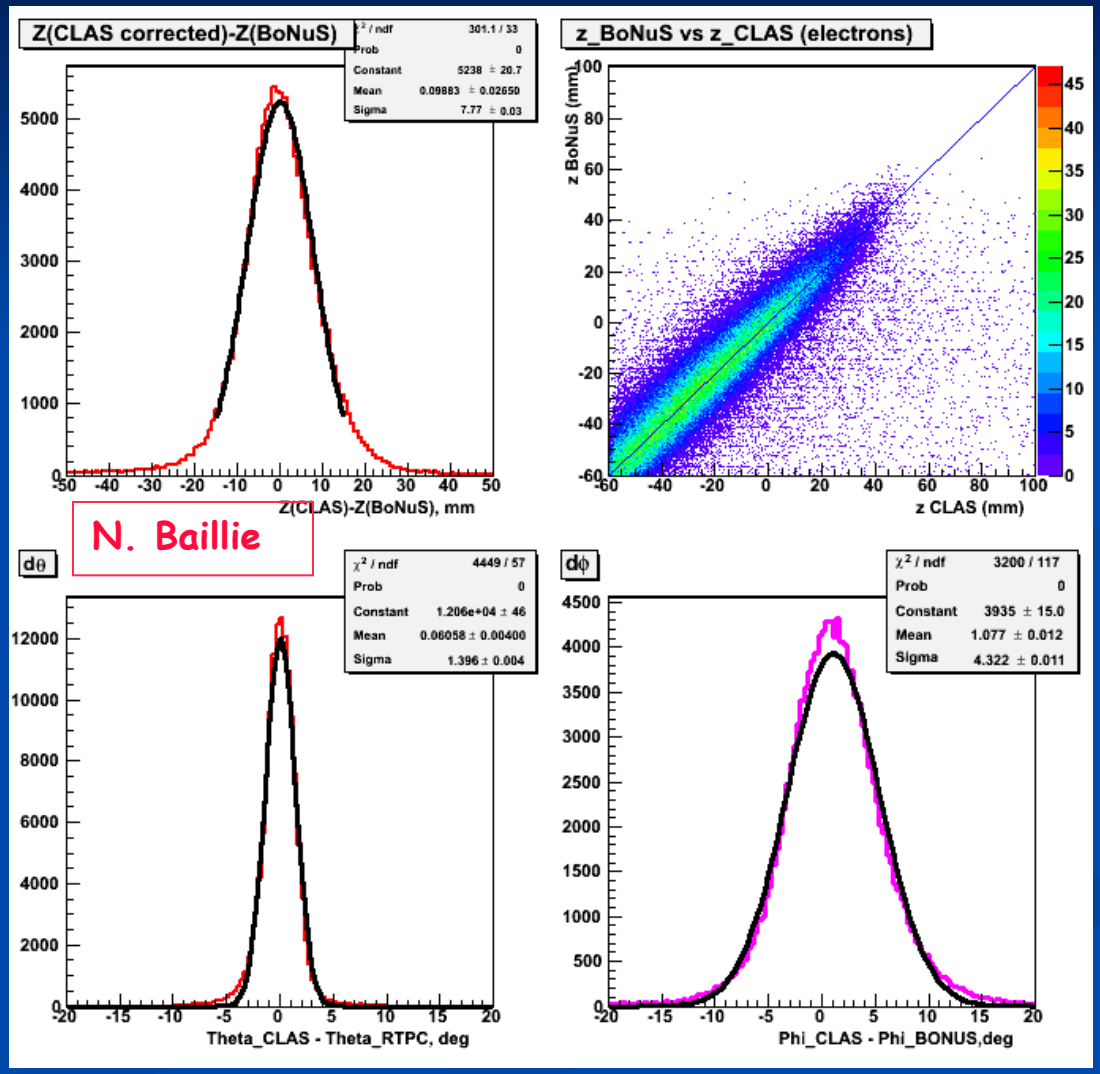
Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

Increase RTPC HV to sensitize detector to minimum ionizing electrons



Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

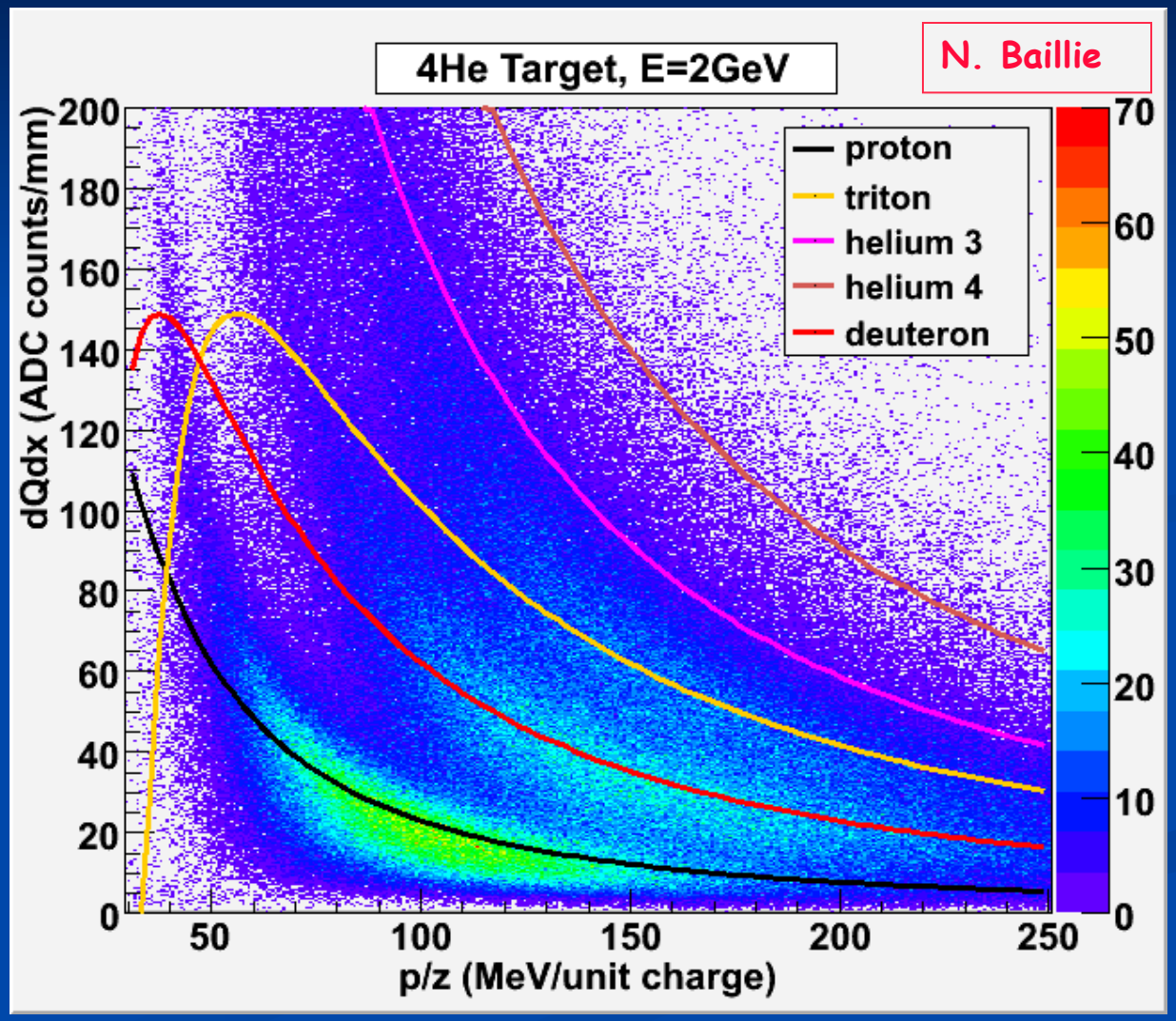
Data taken end of 2005 run with 1.1 GeV electrons



Scattered electron measured in CLAS and by the RTPC

Energy Loss in RTPC

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



BoNuS Analysis Methods

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
- Published results are based on the Ratio Method

Ratio Method

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

$$R_{\exp} = \frac{N_{tagged}(\Delta Q^2, \Delta W^*, \Delta p_s) / A_e(Q^2, W^*)}{N_{incl}(\Delta Q^2, \Delta W) / A_e(Q^2, W)}$$

$$R_{\exp} = \frac{F_2^{\,n}(Q^2, W^*)}{F_2^{\,d}(Q^2, W)} \; I_{\mathrm{VIP}}$$

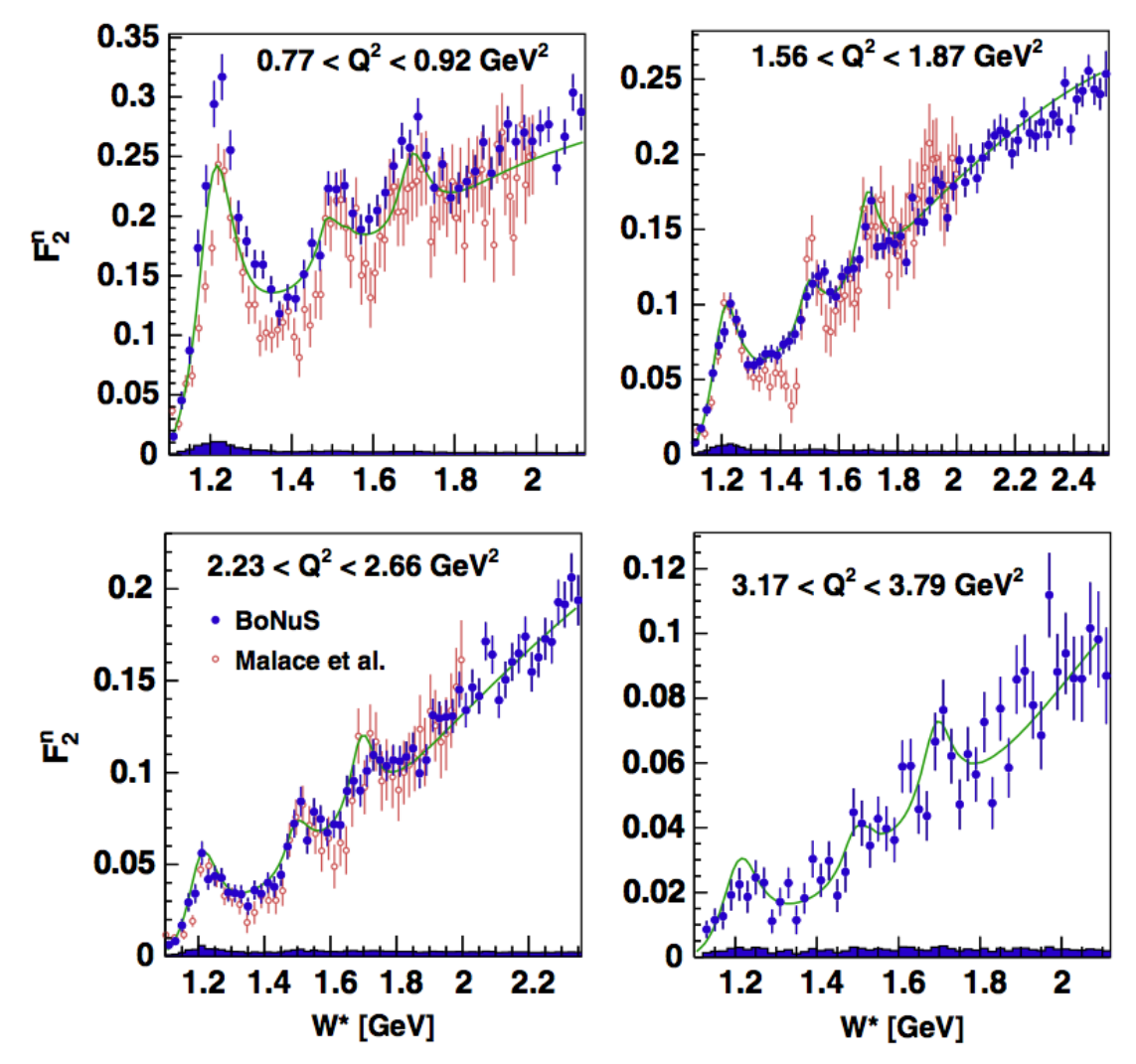
I_{VIP} = integrated spectral function over proton acceptance within RTPC VIP cuts

$$\frac{F_2^{\,n}}{F_2^{\,p}} = R_{\exp} \frac{F_2^{\,d}}{F_2^{\,p}} / I_{\mathrm{VIP}}$$

Ratio Method

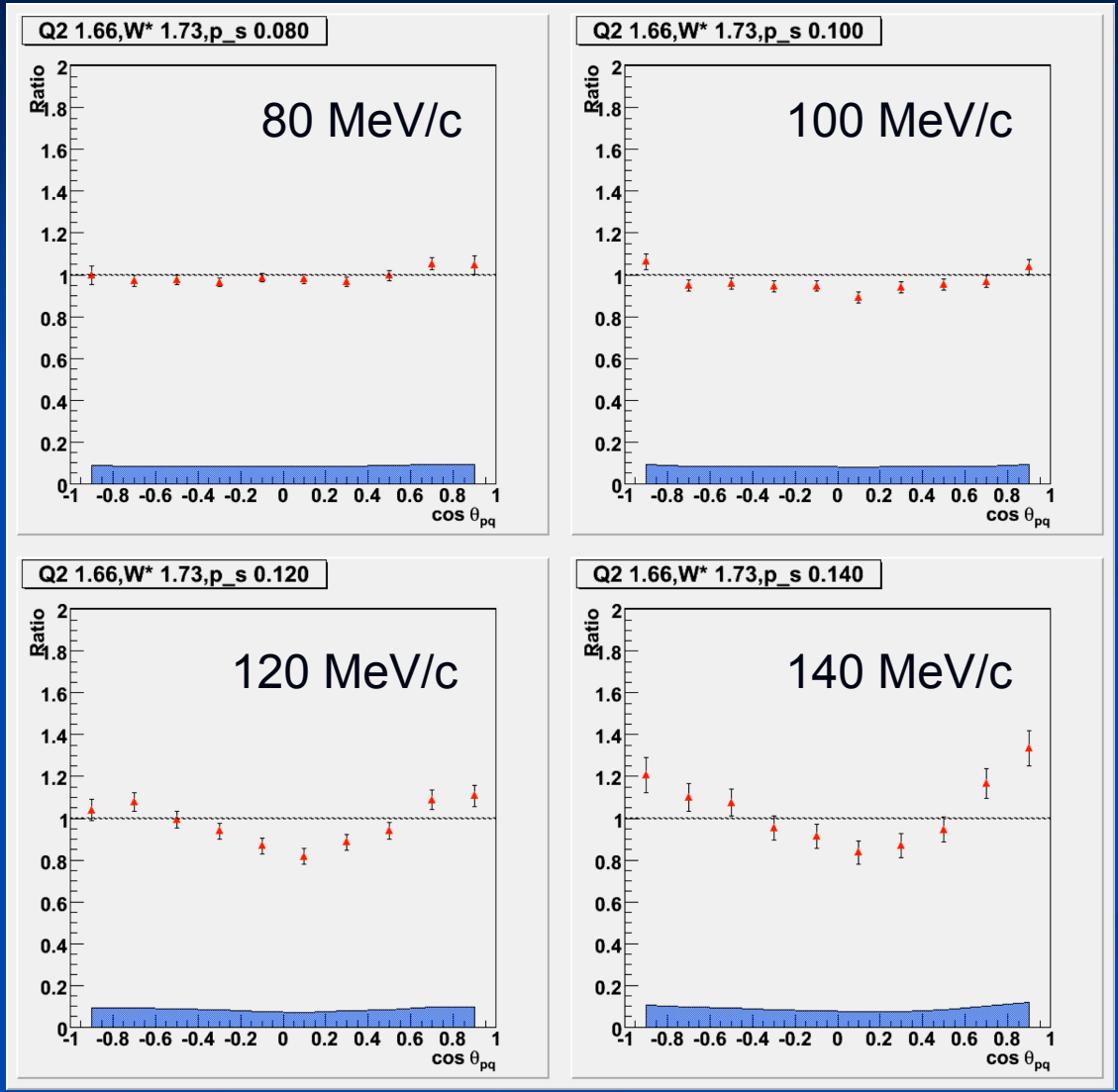
- Effective neutron structure function F_2^n
- Backward angles shown cos Θ_{pq} > -0.25
- F_2^n model of Bosted and Christy plotted for comparison
  M.E. Christy and P.E. Bosted, PR C77, 065206 (2008)
- Very good agreement between model and data
- Comparison with model dependent extraction from inclusive F_2^d data
  S.P. Malace et al., PRL 104, 102001 (2010)

N. Baillie, et al., PRL 108, 142001 (2012)



Monte Carlo Method

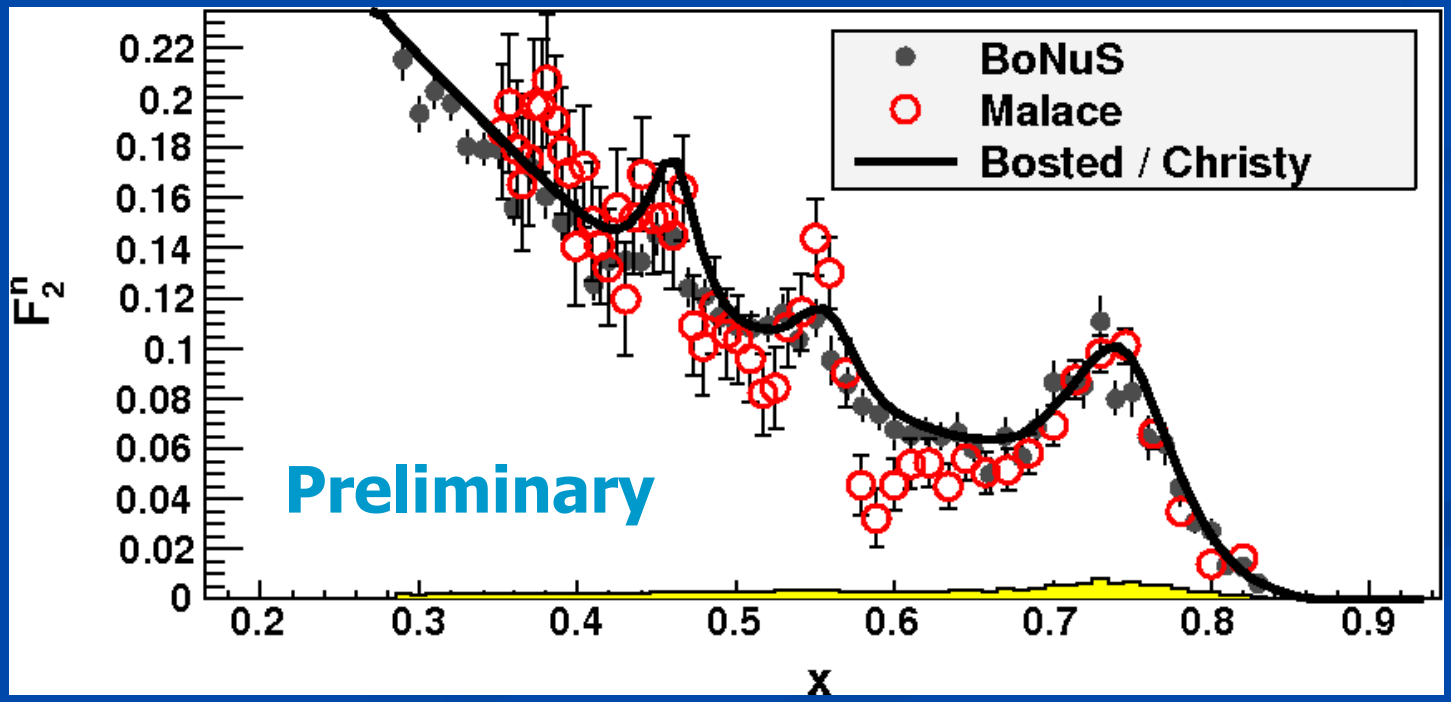
- Angular dependence for Q^2 = 1.66 (GeV/c)^2 and W^* = 1.73 GeV
- At small spectator momentum, basically no deviations from unity
- At larger spectator momentum, deviation from unity in agreement with model by C. degli Atti, indicating FSI and off-shell effects



S. Tkachenko

Ratio Method

- Extracted neutron structure function F_2^n in resonance region
  - 5.3 GeV beam energy
  - $Q^2 = 1.7\ \mathrm{GeV}^2/c^2$
  - $-0.75 < \cos\Theta_{pq} < -0.25$ (backward angles 105° - 140°)
  - $70\ \mathrm{MeV}/c < p_s < 90\ \mathrm{MeV}/c$
- 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.



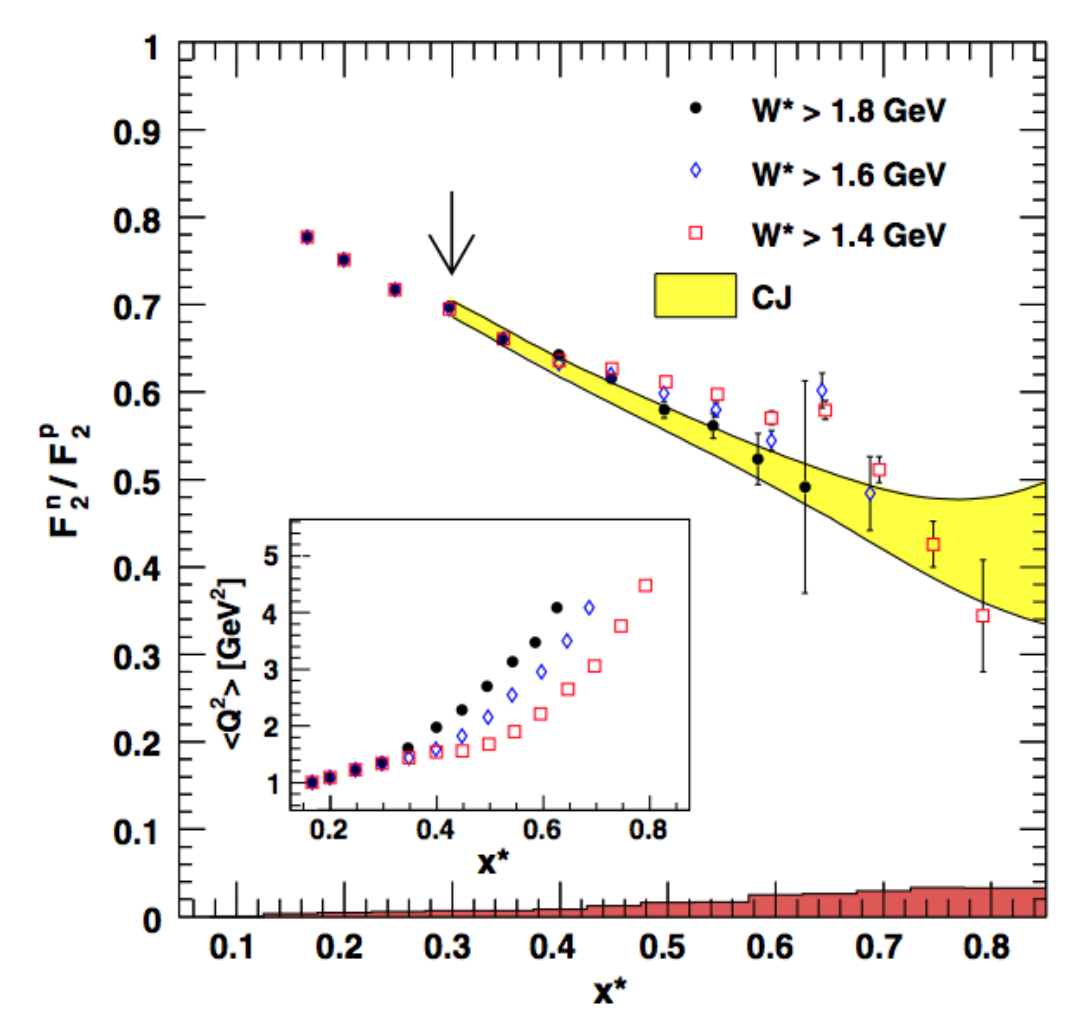
N. Baillie

Structure Function Ratio

- Ratio of neutron to proton F_2 structure functions
- Precise measurement on quasi-free neutron up to $x^* \approx 0.6$
- Exploratory analysis up to $x^* \approx 0.8$ with inclusion of the resonance region
- Normalization of the ratio to 0.695 at $x^* = 0.3$

CJ: A. Accardi et al., PRD 84, 014008 (2011)

N. Baillie, et al., PRL 108, 142001 (2012)

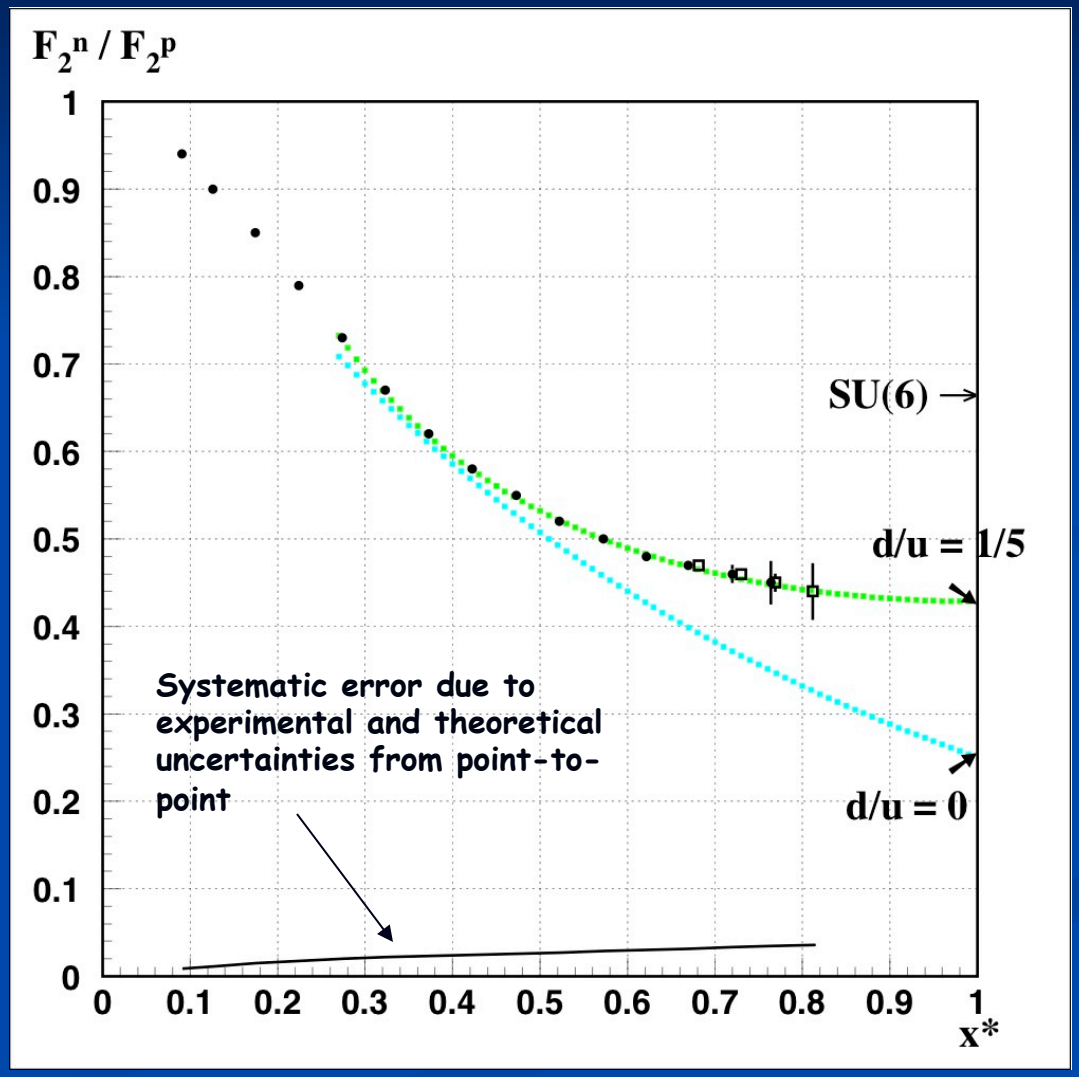


New RTPC for BoNuS12

- 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° 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

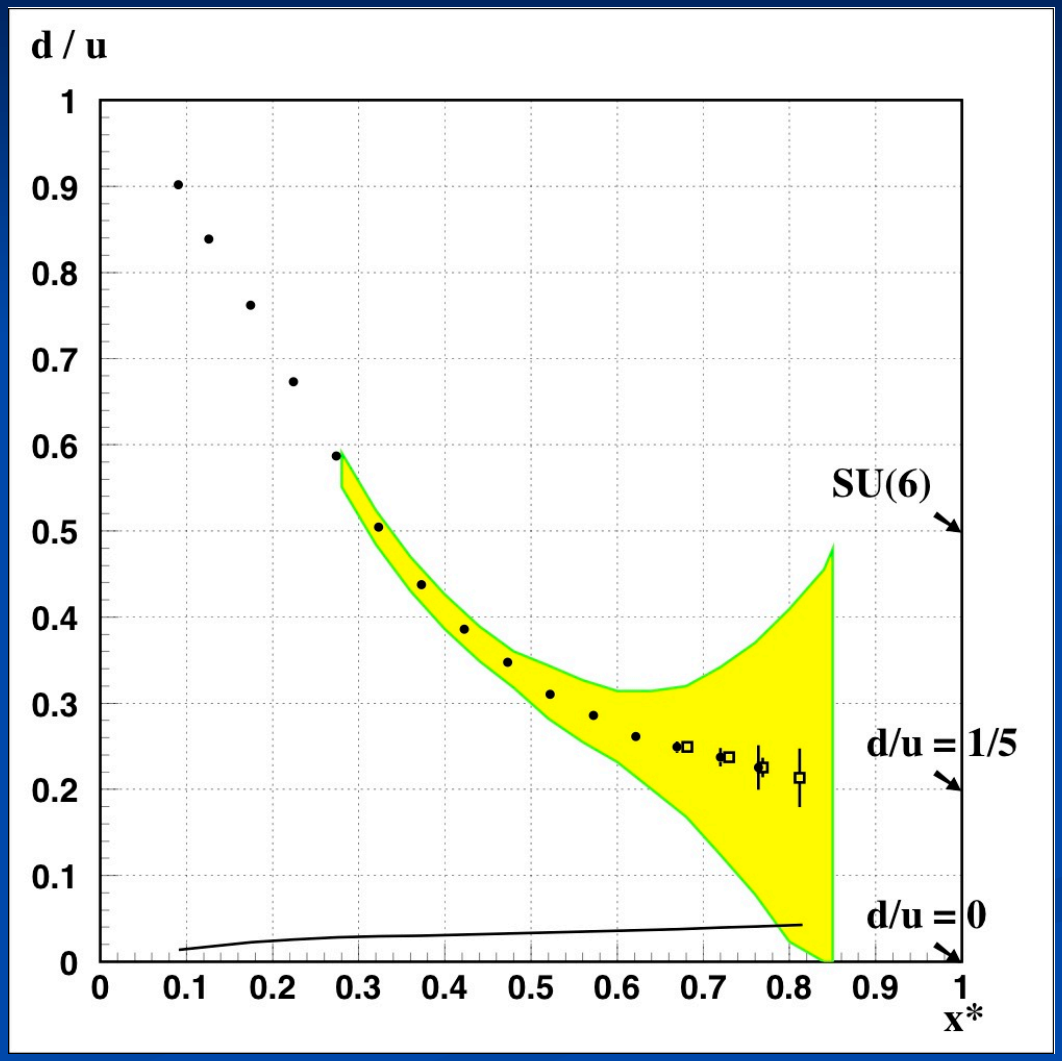
- 35 days of data taking on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$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



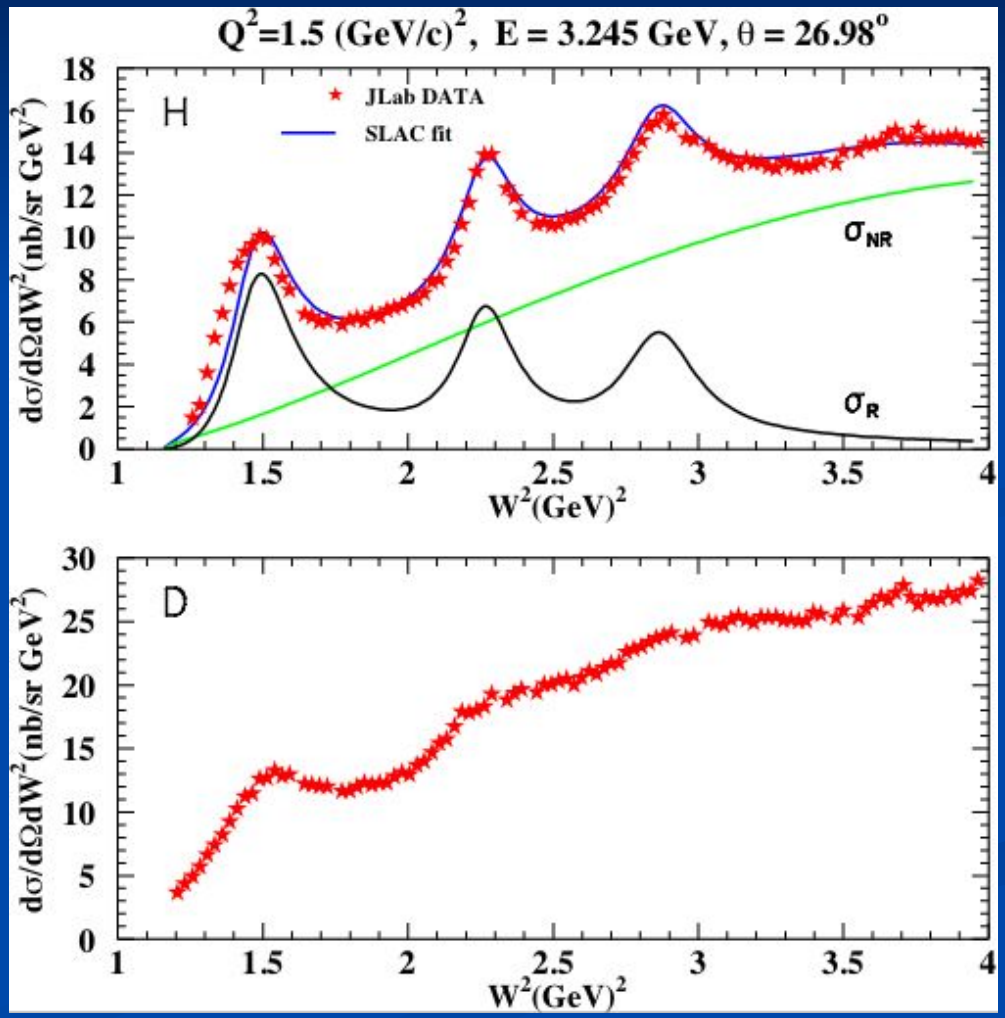
Conclusions

- Successfully used spectator tagging with BoNuS experiment in 2005
- First measurement of *free* neutron resonance structure
- Two analysis approaches give comparable results
- 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)
- 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

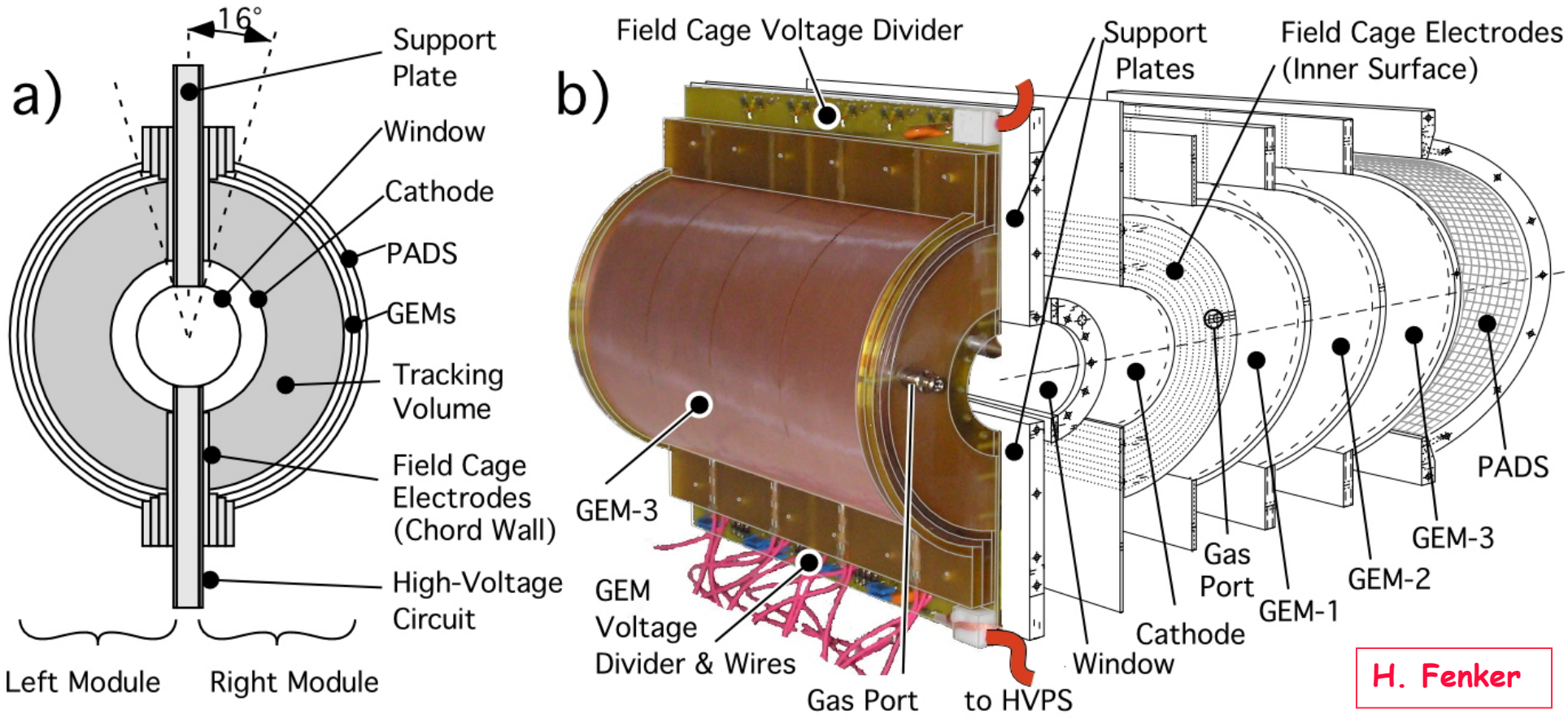
Additional Slides

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.

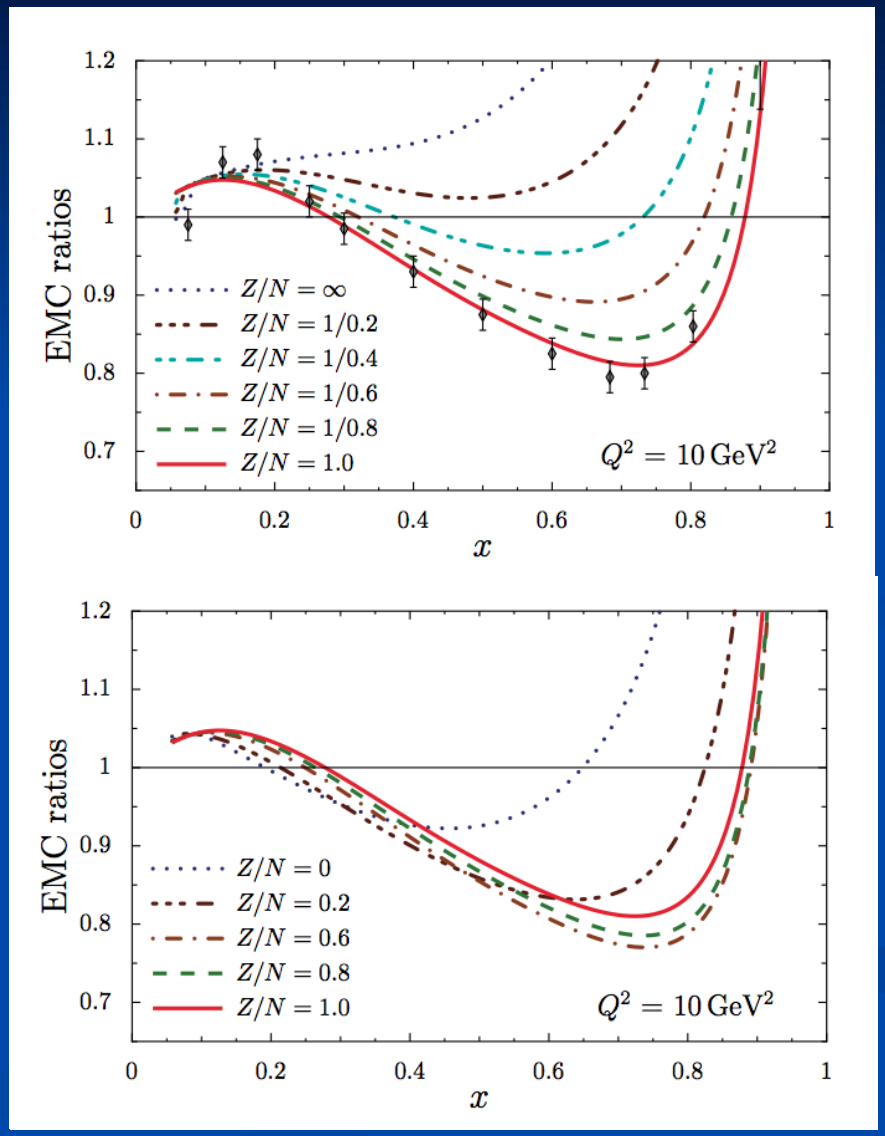


The BoNuS Recoil Detector



EMC Effect

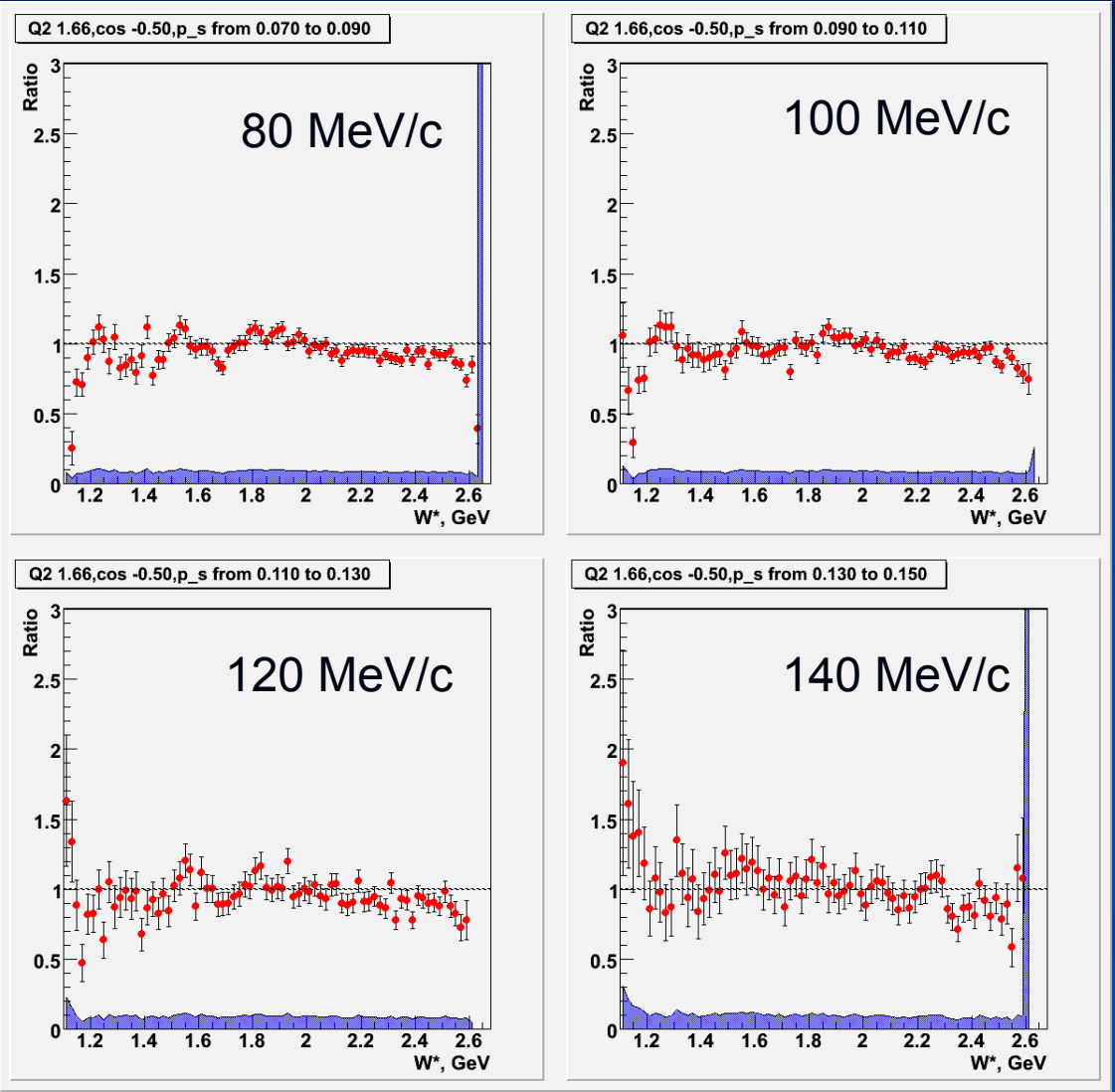
- Neutron or proton excess in nuclei leads to an isovector-vector mean field
- ⇨ Possible isospin dependent EMC Effect
- Calculations can likely be extended to lighter nuclei
- Combination of BoNuS12 and measurement on mirror nuclei could potentially be sensitive to measure this effect



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

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