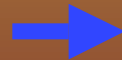


# Spectator Tagging - Quo Vadis?

Sebastian Kuhn  
*Old Dominion University*

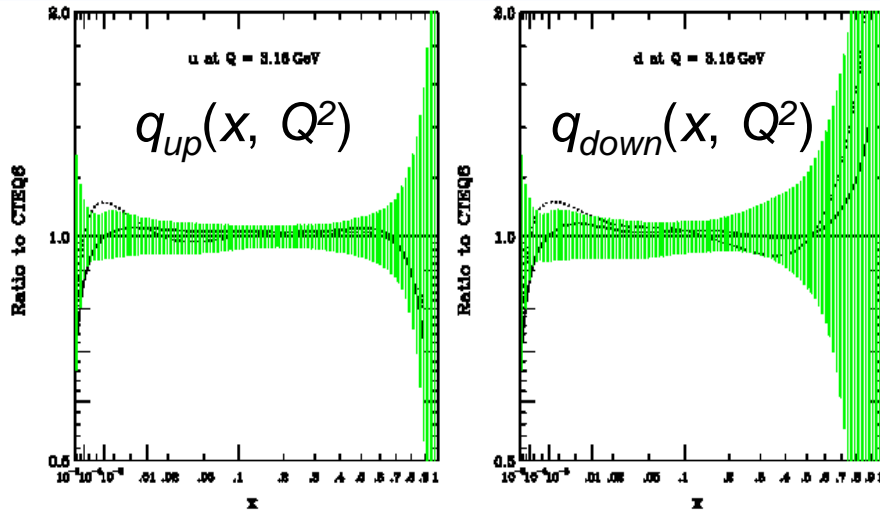


# Overview

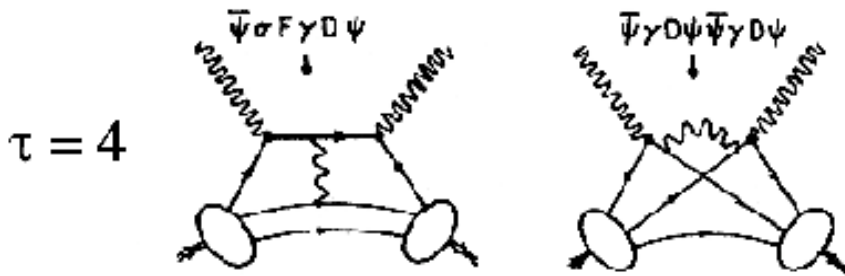
- Neutron Structure and Binding Effects (C.K.)
- Spectator Tagging as a Tool
- The “Deeps” Experiment with CLAS
- The “BoNuS” Experiment with CLAS (C.K.)
- New Experiments with the “BoNuS” RTPC (EG6 with a  $^4\text{He}$  target)
- The Data Mining Initiative
- The 11 GeV Future of Spectator Tagging

# Structure Functions and Moments

$$\frac{d\sigma}{d\Omega dE'} = \sigma_{Mott} \left( \frac{F_2(x)}{\nu} + 2 \tan^2 \frac{\theta_e}{2} \frac{F_1(x)}{M} \right); \quad F_2(x, Q^2) = x \sum_{f=up,down,\dots} z_f^2 (q_f(x, Q^2) + \bar{q}_f(x, Q^2))$$

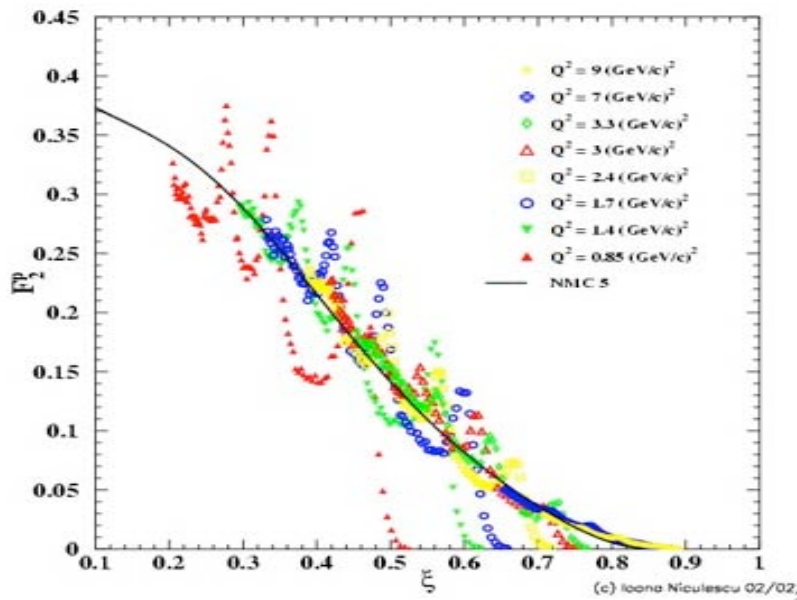
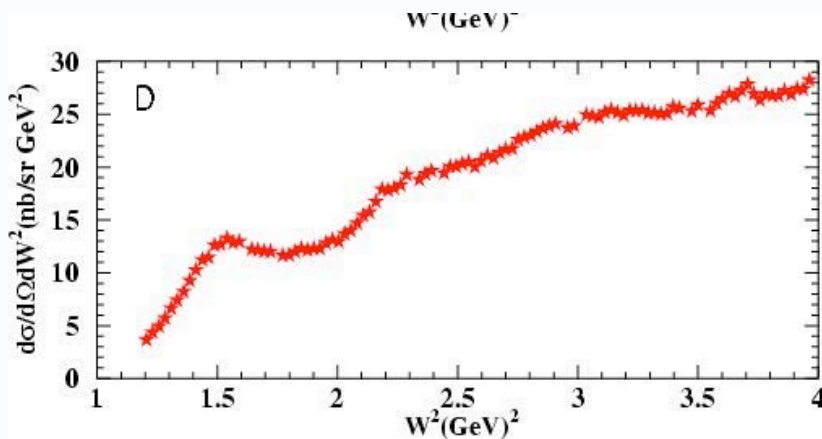


- $q_{down}/q_{up}(x \rightarrow 1)$  is a crucial test of valence quark models
  - SU(6) breaking, pQCD,...
- Precise PDFs at large  $x$  needed as input for LHC, neutrino experiments...
  - Large  $x$ , medium  $Q^2$  evolves to medium  $x$ , large  $Q^2$
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large  $x$



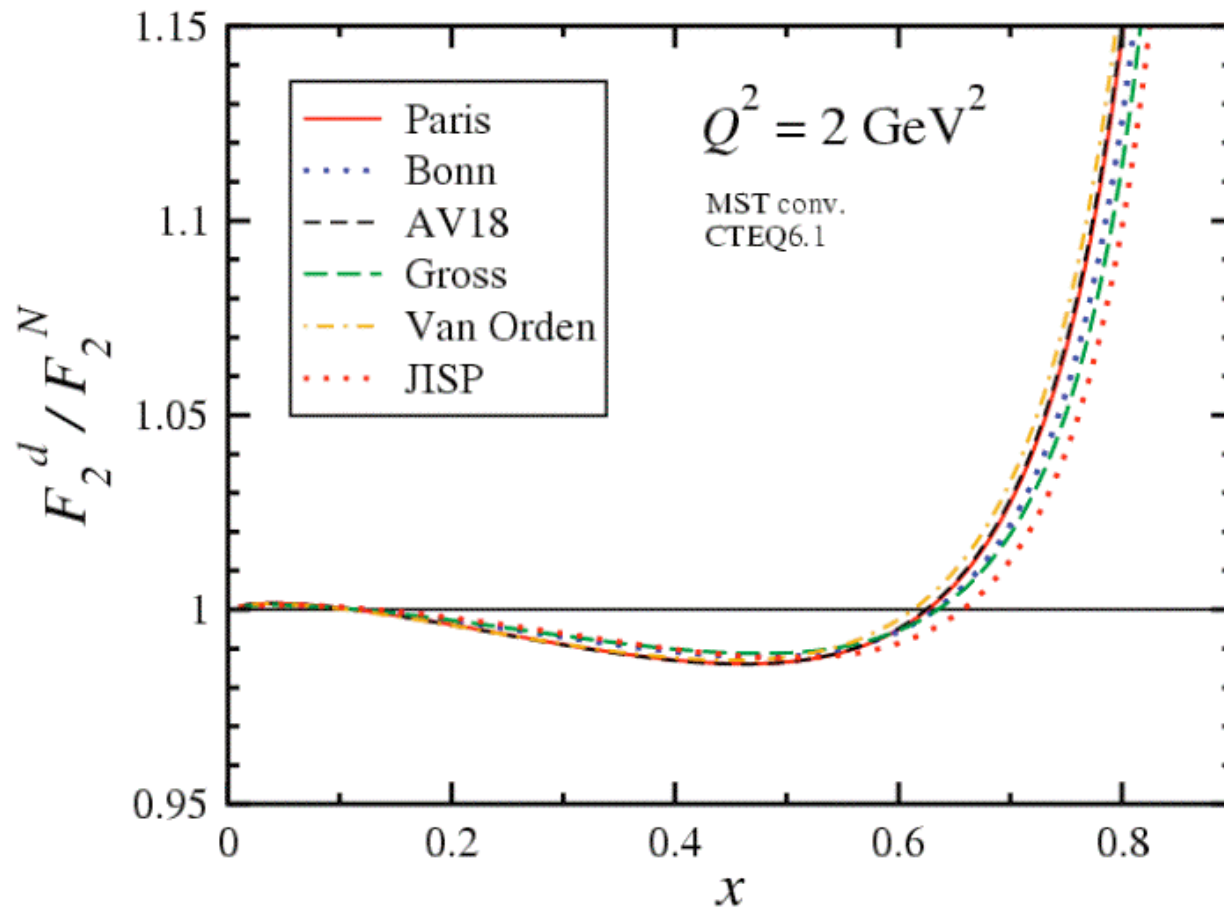
$$M_n^{CN}(Q^2) = \int_0^1 dx x^{(n-2)} F_2(x, Q^2) = \sum_{\tau=2k}^{\infty} E_{n\tau}(\mu, Q^2) O_{n\tau}(\mu) \left( \frac{\mu^2}{Q^2} \right)^{\frac{1}{2}(\tau-2)} + \text{TM corr.}$$

# Structure Functions and Resonances



- Precise structure functions in Resonance Region constrain nucleon models  
[Separate resonant from non-resonant background; isospin decomposition]
- Needed as input for spin structure function data, radiative corrections, ...
- Compare with DIS structure functions to test duality

# Large $x$ - Large Nuclear Effects



- Even simple “Fermi Smearing” leads to significant dependence on D wave function
- Different models for off-shell and “EMC” effects lead to large additional variations
- Contributions from MEC,  $\Delta(1232)$  and “exotic” degrees of freedom unknown
- FSI?

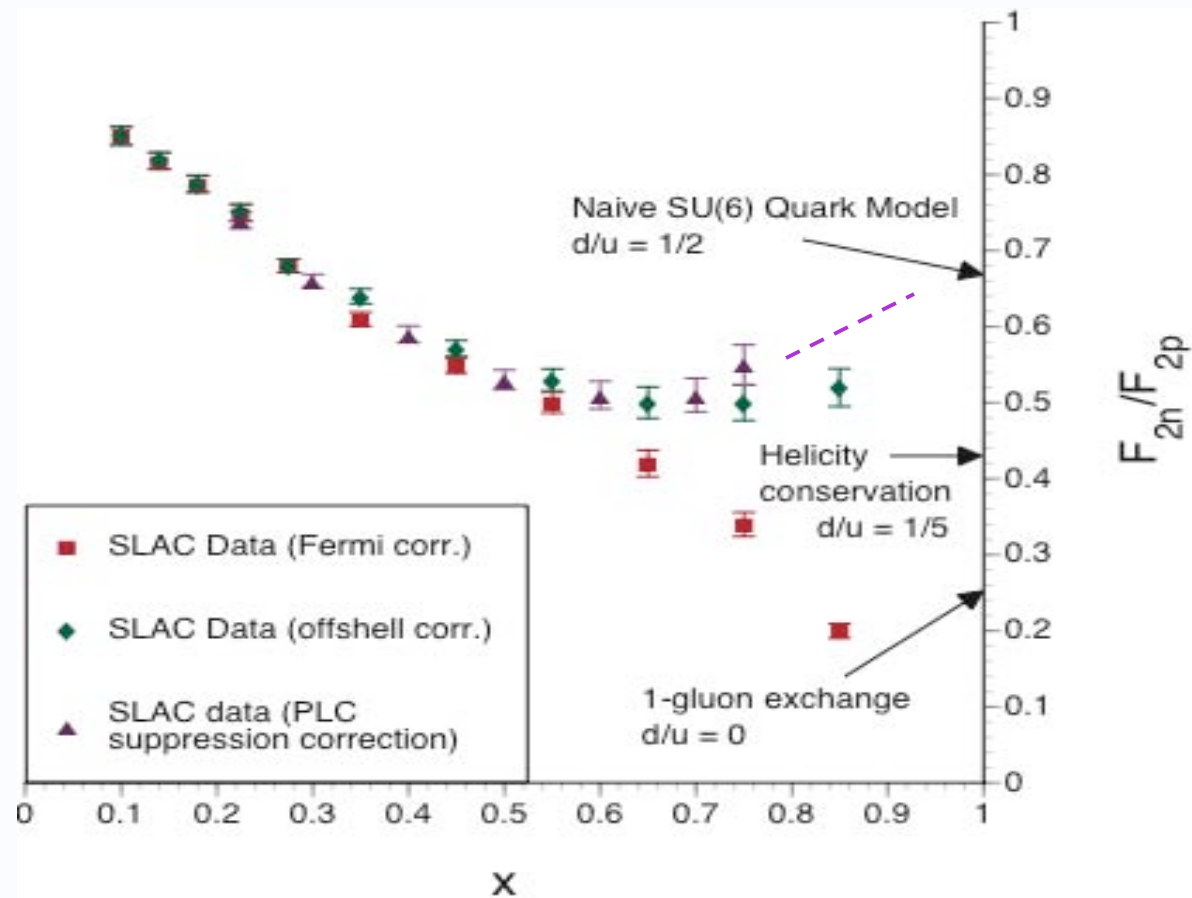
# Present Knowledge of d/u (x → 1)

$$\frac{F_{2n}}{F_{2p}} \approx \frac{1 + 4d/u}{4 + d/u} \Rightarrow$$

$$\frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}$$


$$F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1$$

???

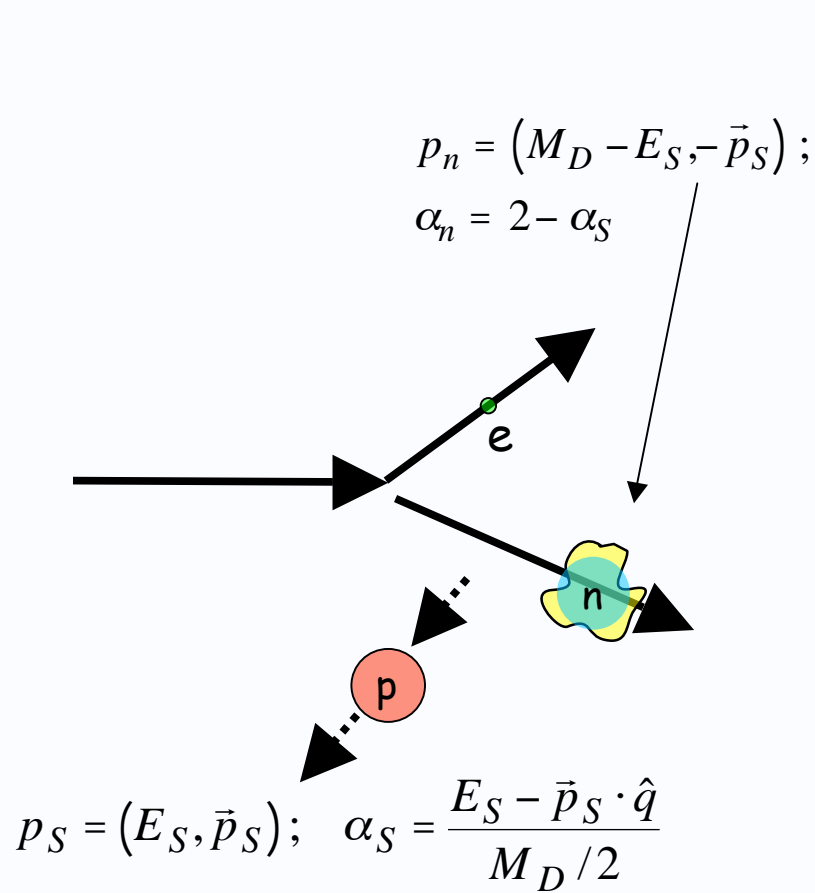


- Limited by “Nuclear Binding Uncertainties”

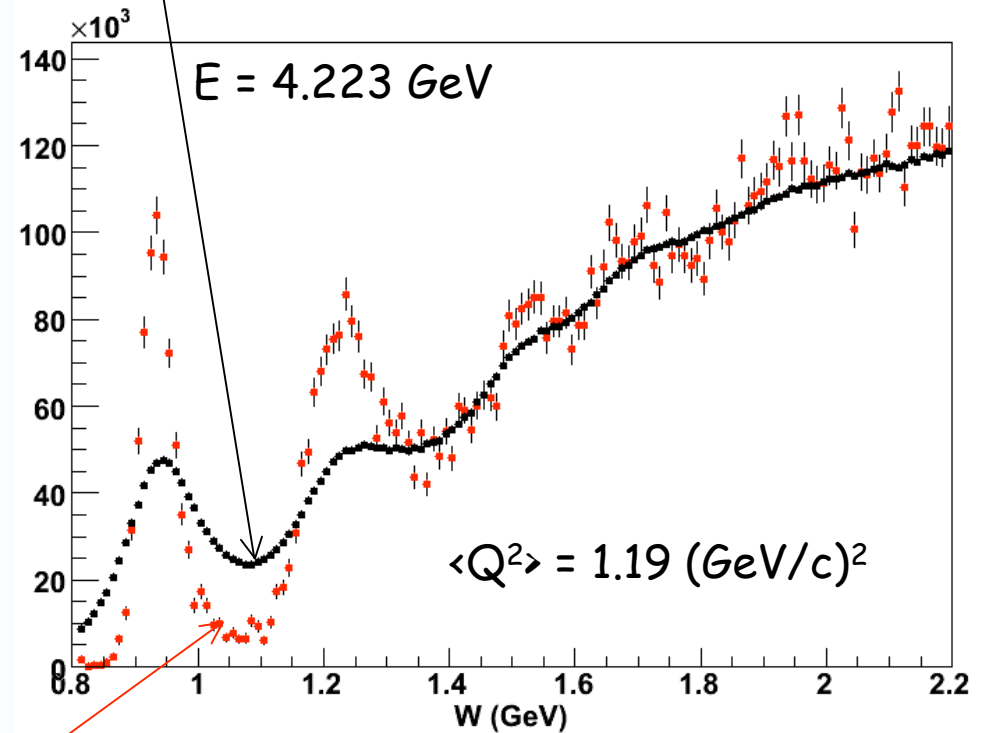
# Bound Neutron Structure Functions - 2 Questions:

- 1) How can we explore the structure of the neutron if all we have are neutrons bound in nuclei?
    - In many cases, a neutron bound in deuterium can be considered “nearly free”.
    - BUT: For certain kinematics (large  $x > 0.5$ , resonance region  $W < 2$ ) the high-momentum (short-distance tail) of the deuteron wave function plays a large role and might distort the result.
  - 2) Can we learn something about what happens to a nucleon if it is part of a short-distance pair?
    - Many ideas: Off-shell modifications of on-shell structure functions, color delocalization, suppression of point-like components,  $\Delta\Delta$  components, extra mesons or 6-quark bags
    - Fundamental question about QCD in bound hadron systems that we haven't understood yet. Relevant for QCD phase diagram (high baryon density, neutron stars, color superconductivity?)
- 

# Our Tool: "Spectator Tagging"



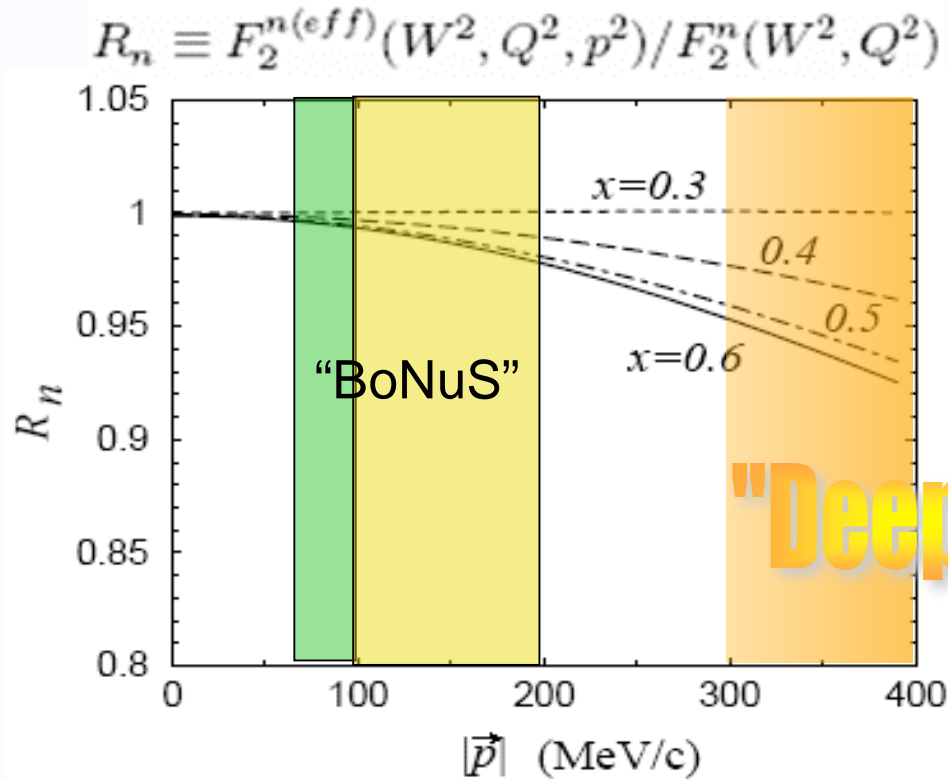
$$W^2 = M^2 + 2M\nu - Q^2$$



$$\begin{aligned}
 W^{*2} &= (p_n + q)^2 = p_n^\mu p_{n\mu} + 2((M_D - E_S)\nu - \vec{p}_n \cdot \vec{q}) - Q^2 \\
 &\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2
 \end{aligned}$$

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



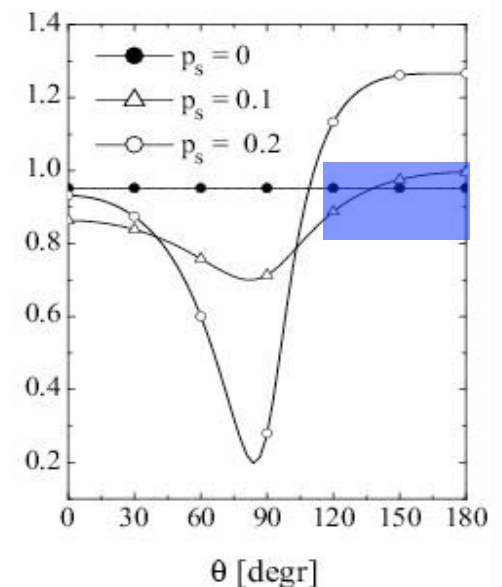
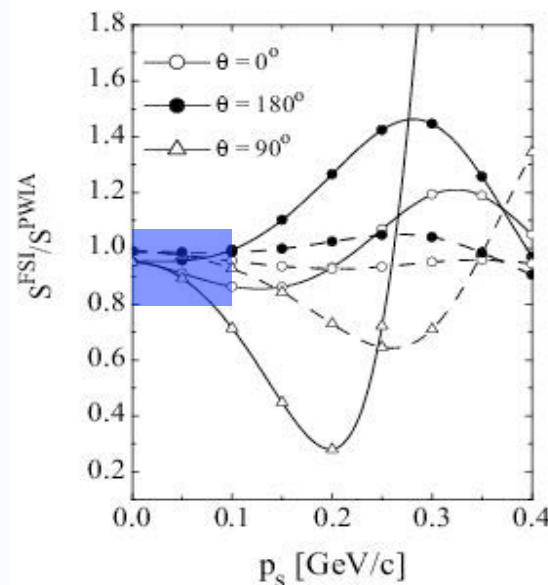


# Modifications to Simple Spectator Picture

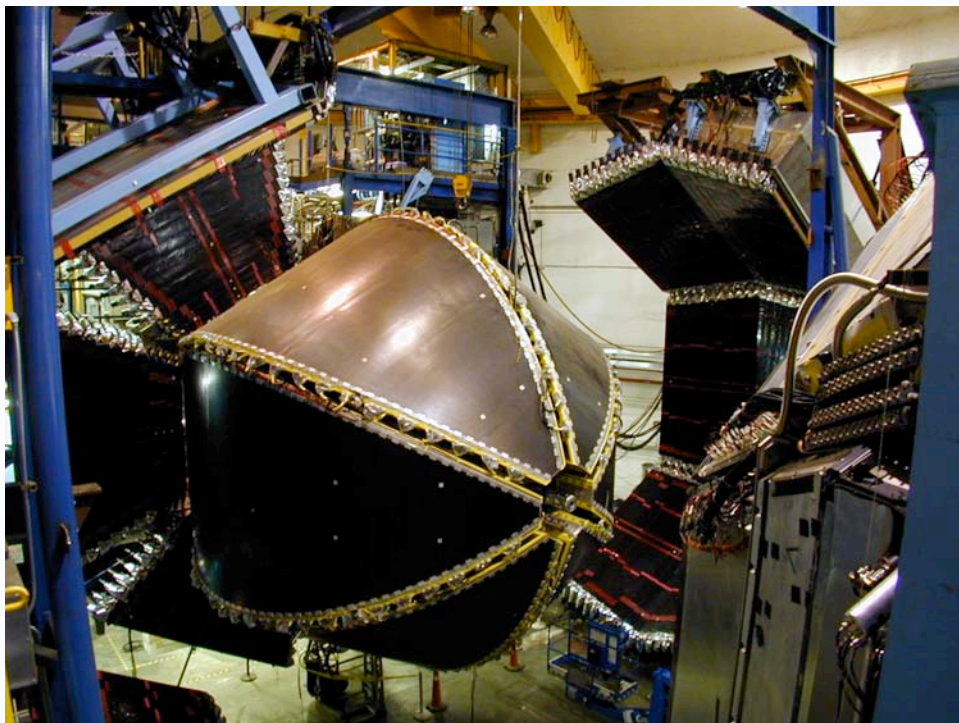
Final State Interactions ↓

Binding Effects ↑

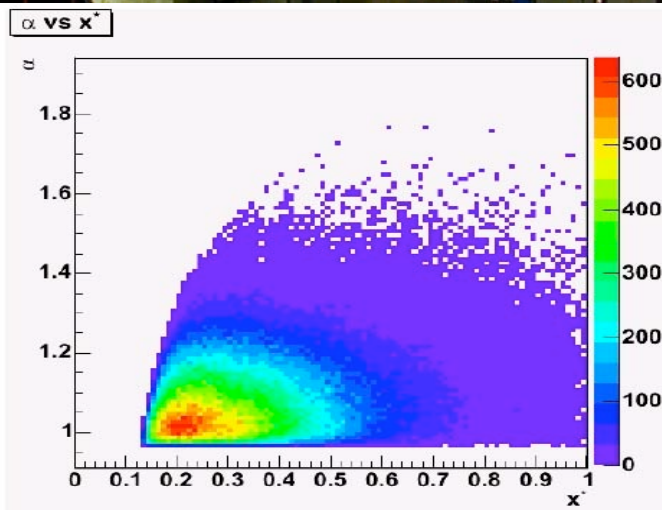
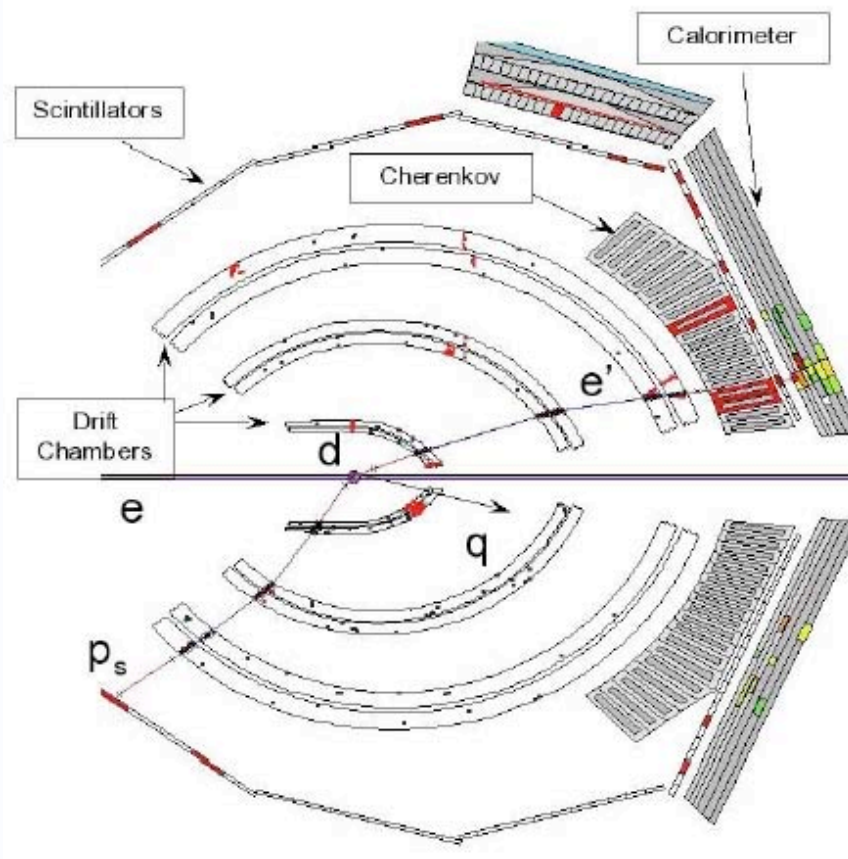
Ciofi degli Atti and  
Kopeliovich, Eur. Phys.  
J. A17(2003)133



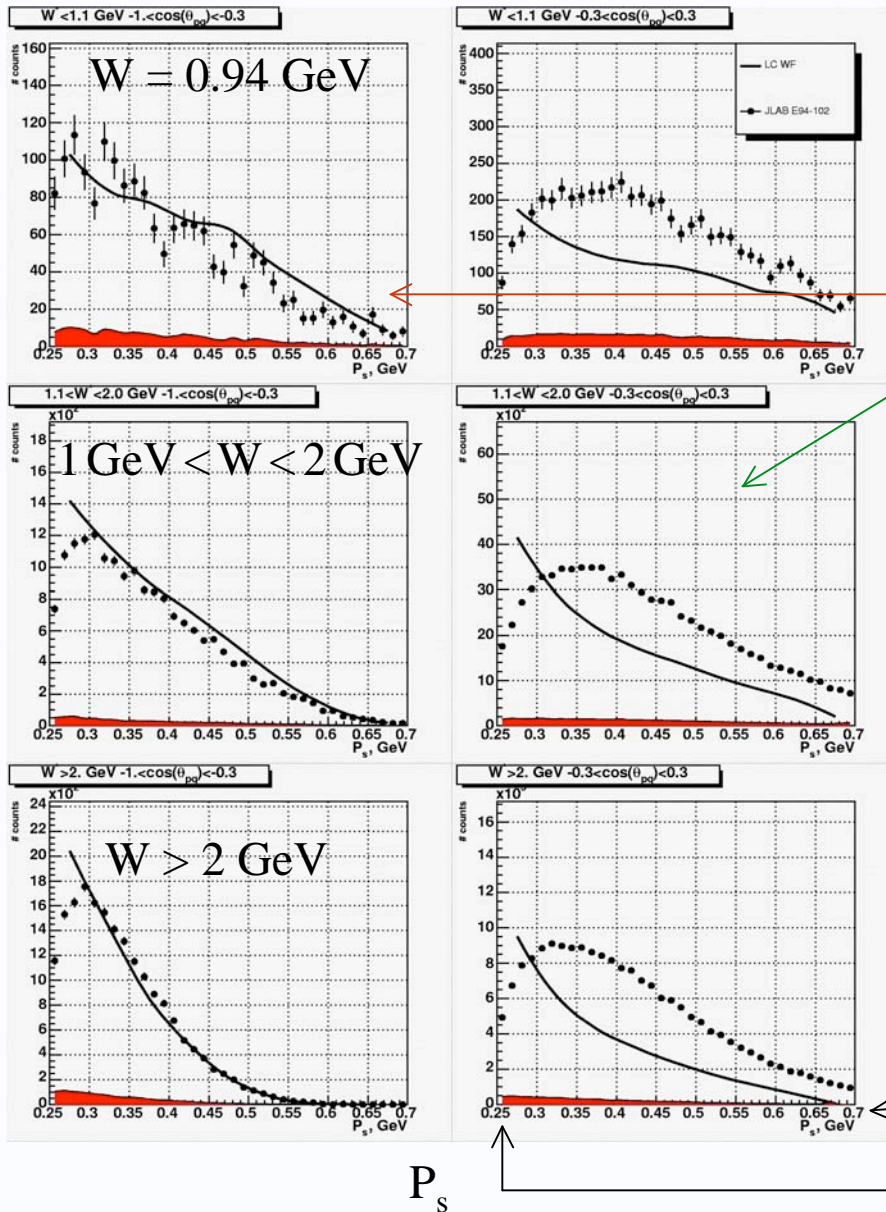
# High spectator momenta (0.25 - 0.7 GeV/c): “Deeps”



CLAS



# Results from “Deep’s”: Momentum Distribution



Vertical axis: Number of events

Horizontal axis: Proton momenta from 250 to 700 MeV/c

Left: Angular range  $> 107.5^\circ$

Right: Angular range  $72.5^\circ - 107.5^\circ$

3 different ranges in the final state mass  $W$  of the unobserved struck neutrons

PWIA model with “light cone”-wave function for deuterium

# Deviations from free structure function: Off-shell Effects [should depend on $\alpha$ ( $p_s$ ), $x$ , $Q^2$ ]

$$\frac{F_{2N}^{eff}(x = 0.6, Q^2, \alpha)}{F_{2N}^{eff}(x = 0.2, Q^2, \alpha)}$$

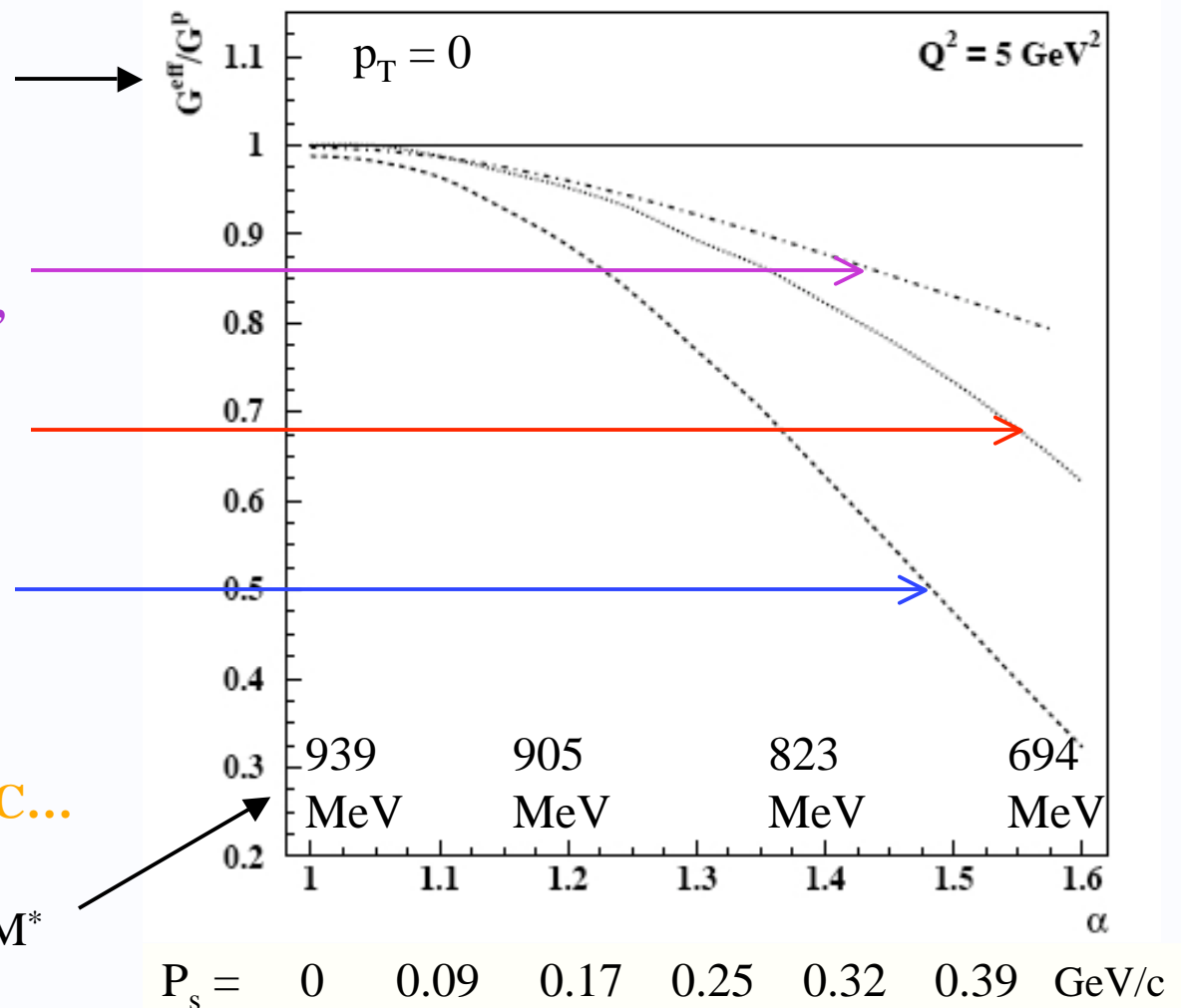
Modification of the off-shell scattering amplitude (Thomas, Melnitchouk et al.)

Color delocalization  
Close et al.

Suppression of “point-like configurations”  
Frankfurt, Strikman et al.

... plus 6-quark bags,  $\Delta\Delta$ , MEC...

“Off-shell” mass of the nucleon  $M^*$

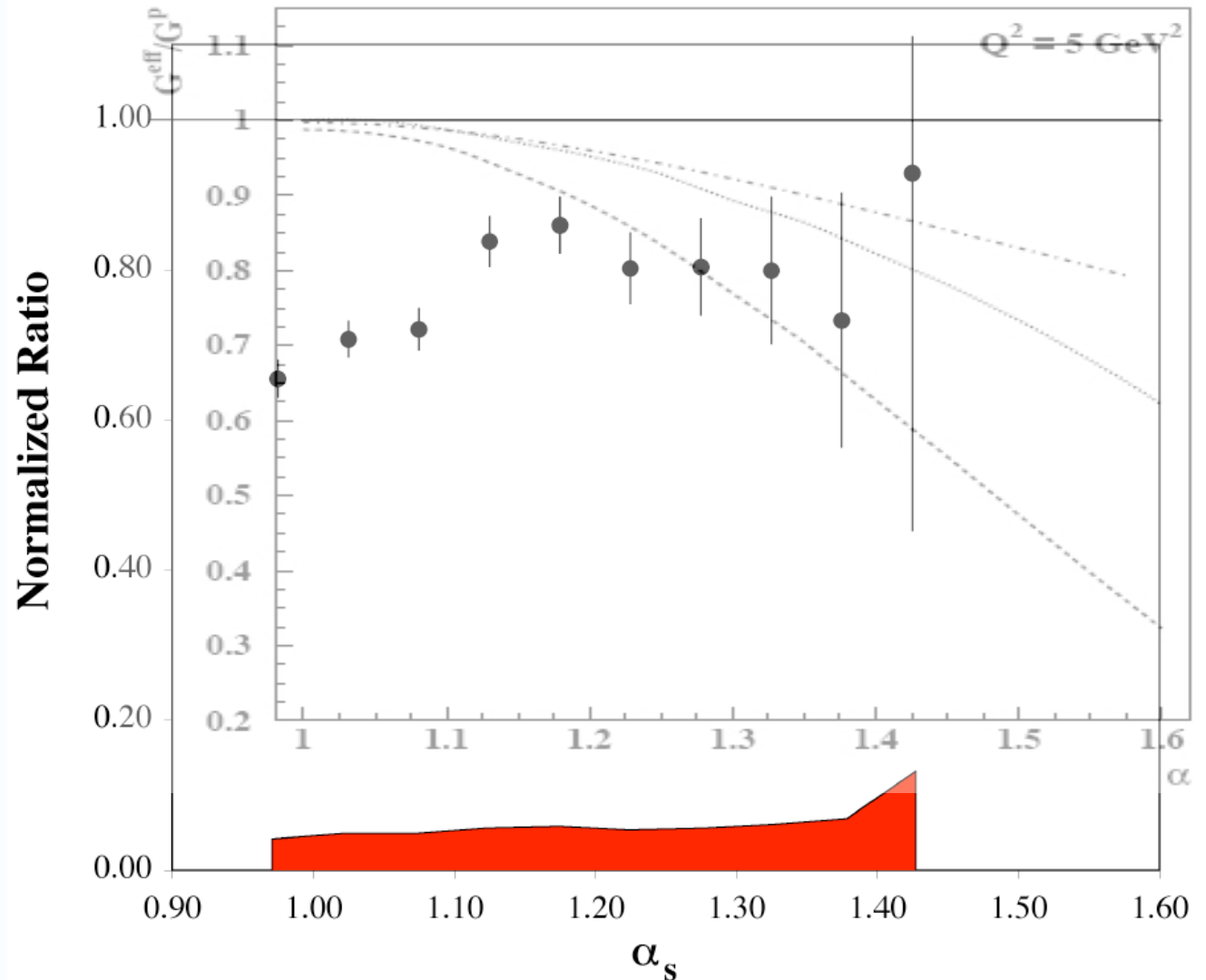


# Results from “Deeps”: Ratio Method

Ratio =

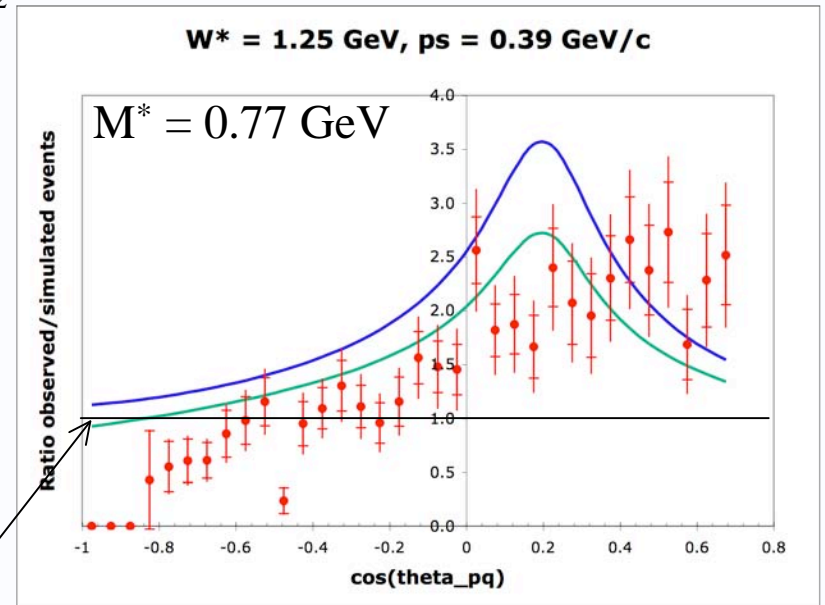
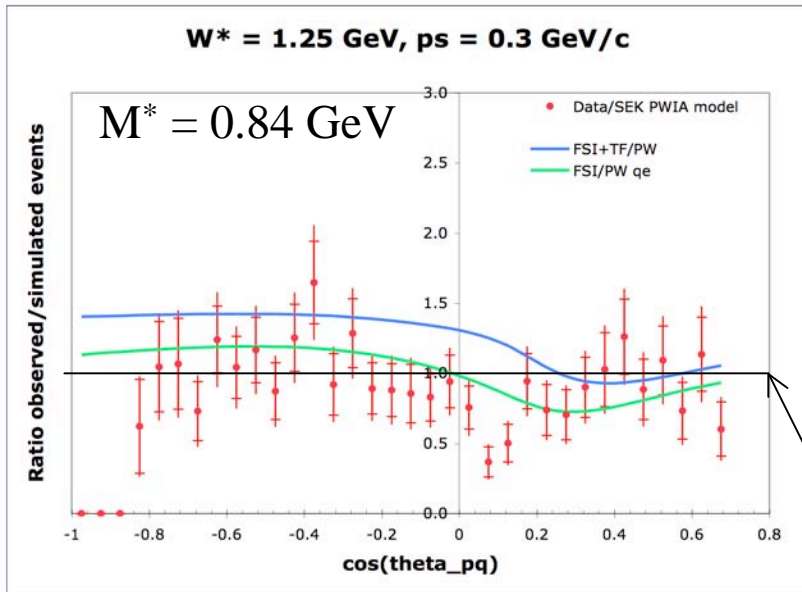
$$\frac{\sigma(x^* = 0.55, \alpha_s) \text{ (bound n)}}{\sigma(x^* = 0.25, \alpha_s) \text{ (bound n)}} \bigg/ \frac{\sigma(x = 0.55) \text{ (free n)}}{\sigma(x = 0.25) \text{ (free n)}}$$

- Independent of deuteron WF, acceptance, kinematic factors
- Should be sensitive to off-shell effects at large x, but also influenced by FSI and target fragmentation
- Fixed  $p_T = 0.3 \text{ GeV}/c$  - TOO LARGE!

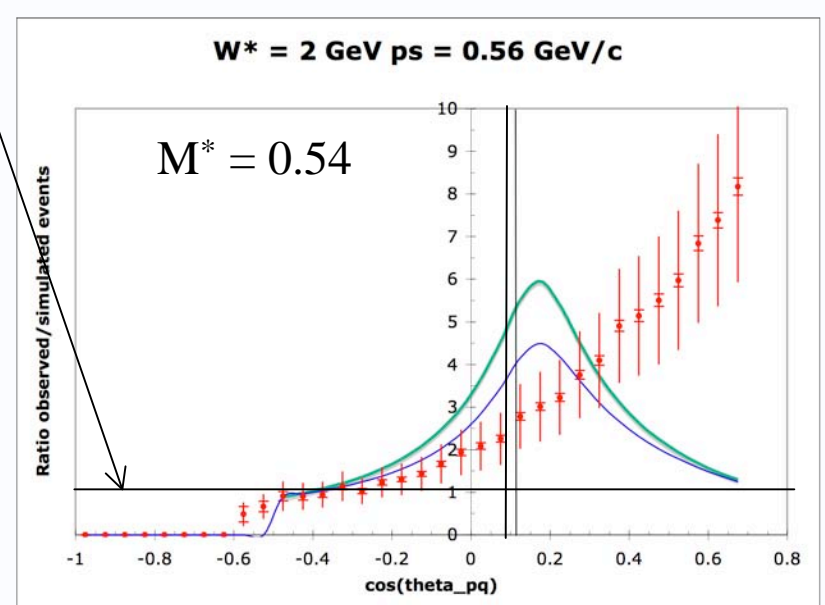
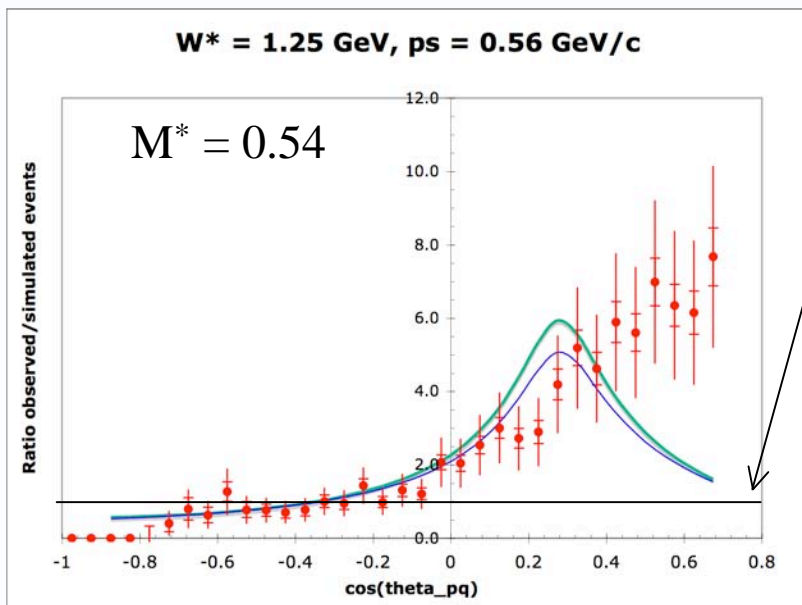


# Results from “Deeps”: Comparison w/ FSI model (CdA et al.)

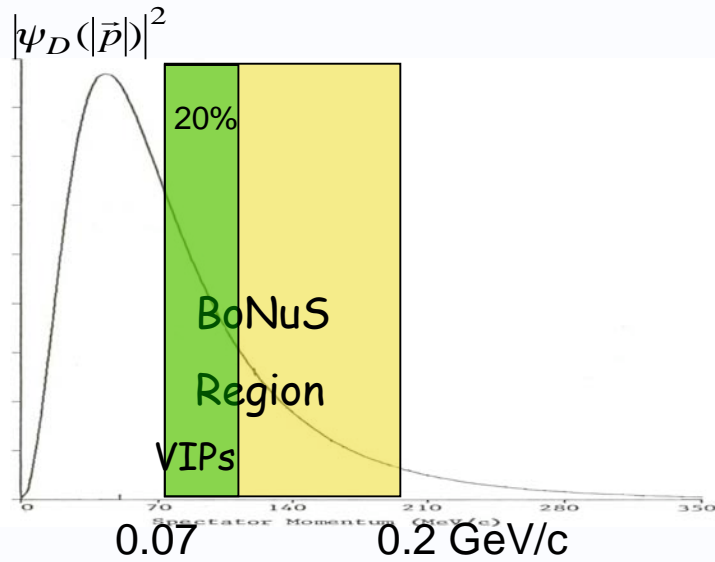
$Q^2 = 1.8 \text{ GeV}^2$



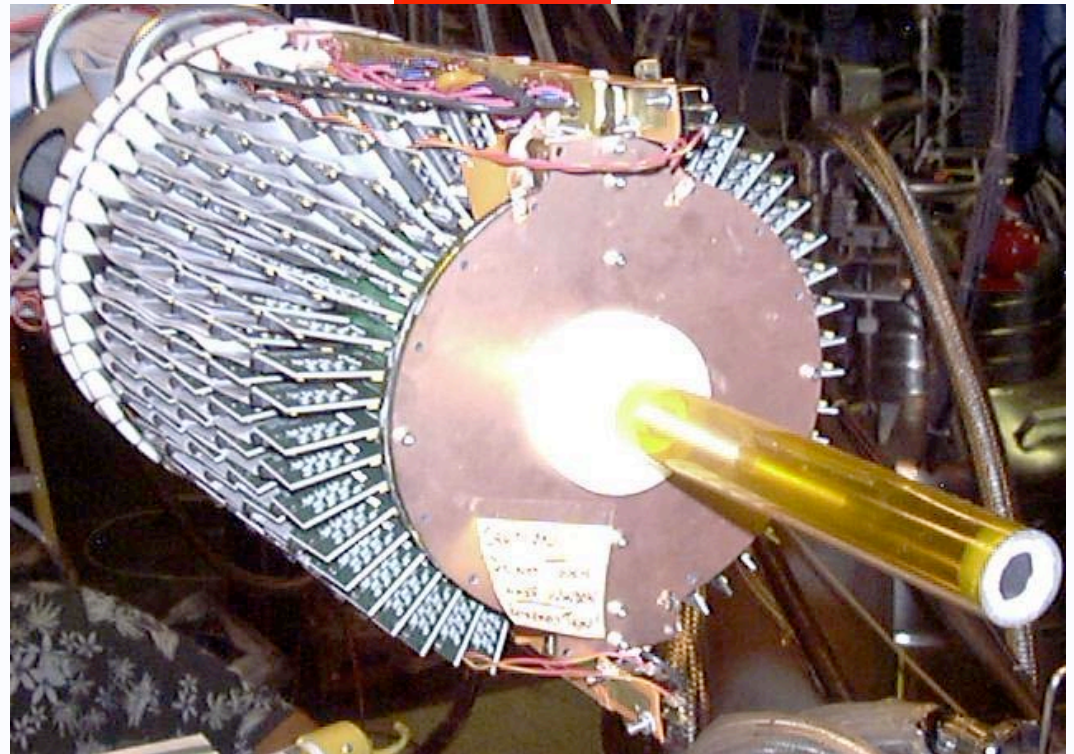
PWIA



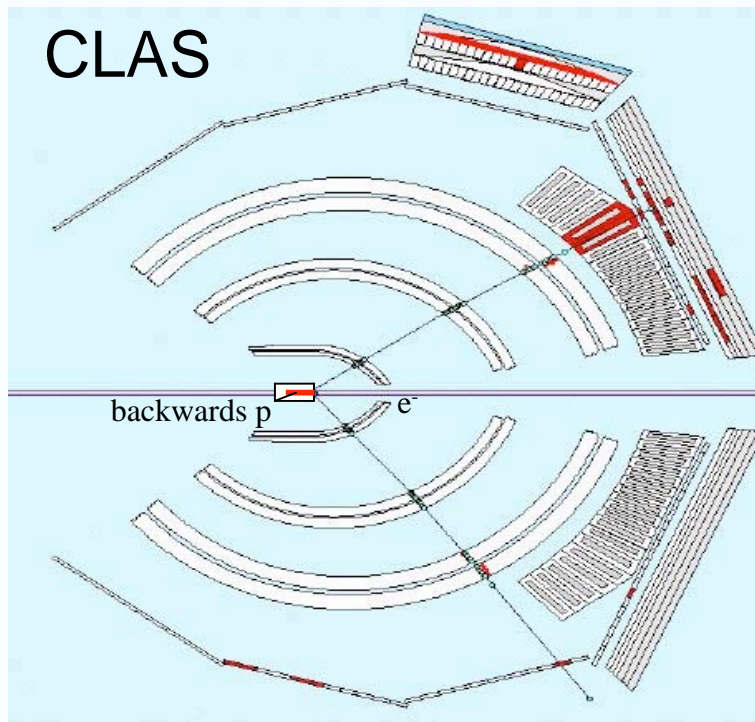
# Low Spectator Momenta - Nearly Free Neutrons ?



The **bonus** Experiment



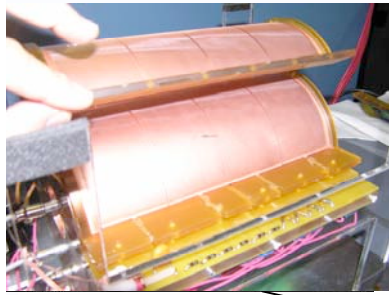
Radial TPC (view from downstream)



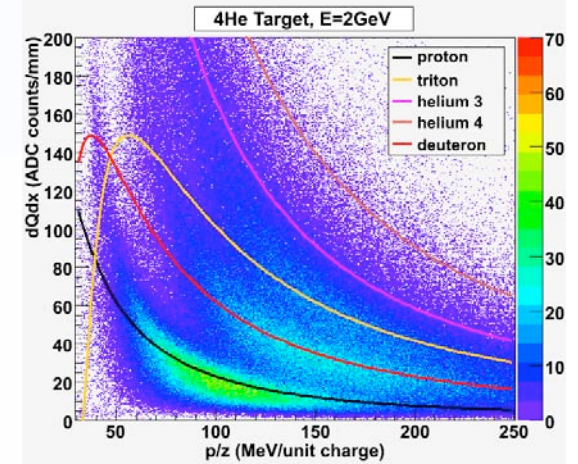
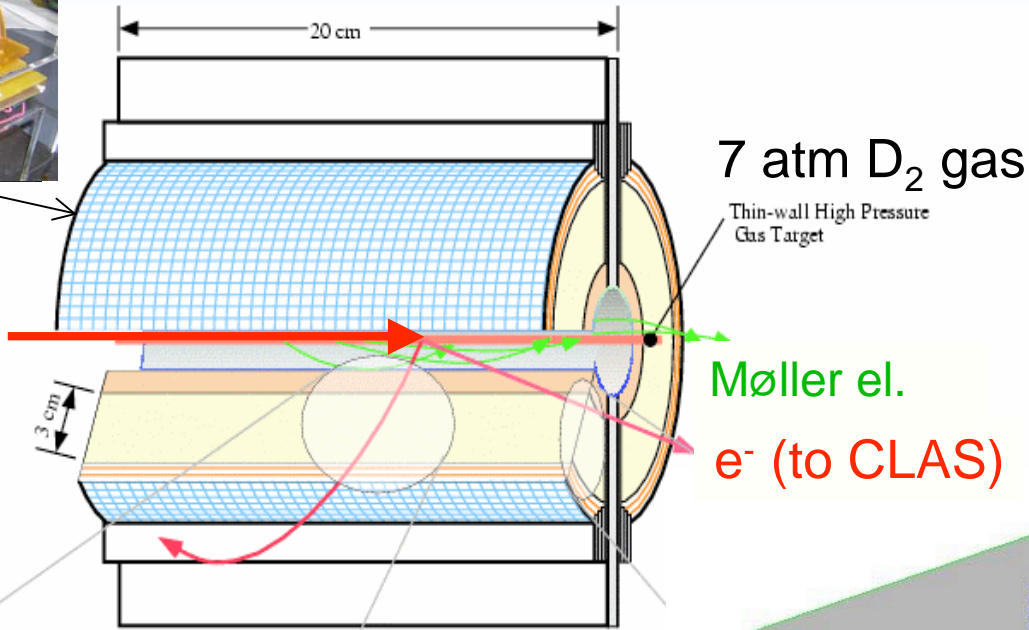
\*BoNuS = **B**arely off-shell **N**ucleon **S**cattering

\*\*RTPC = Radial Time Projection Chamber

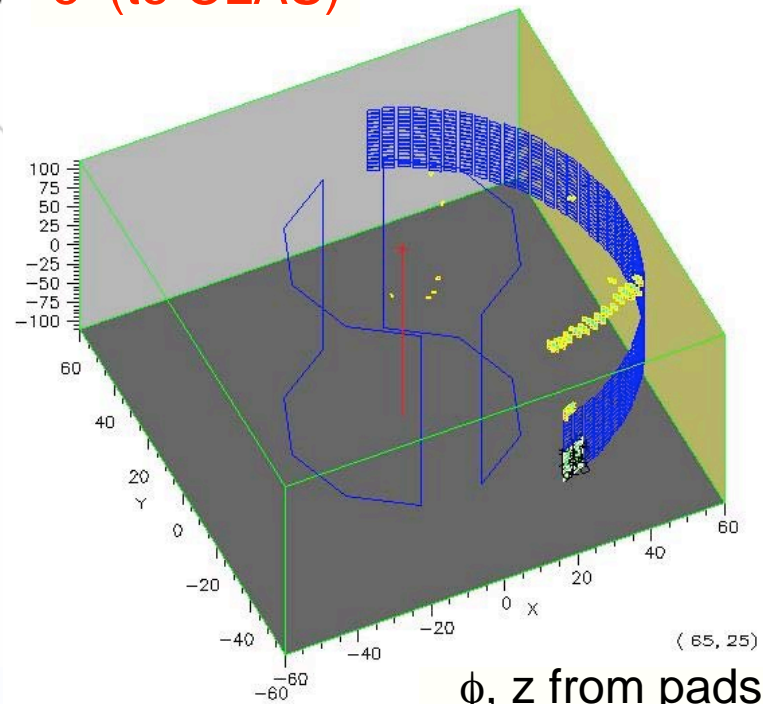
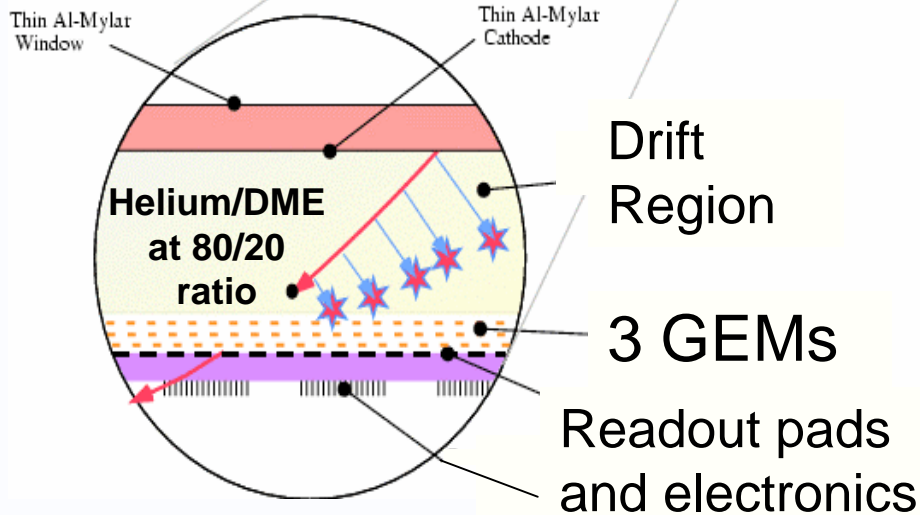
# BoNuS RTPC



Gas  
Electron  
Multiplier

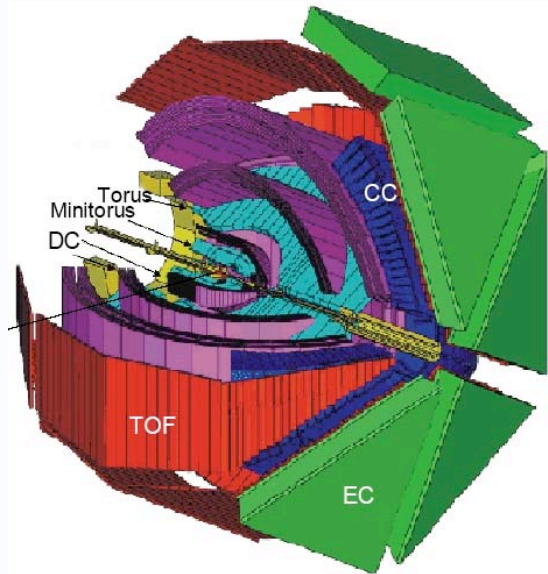


dE/dx from charge  
along track (particle ID)

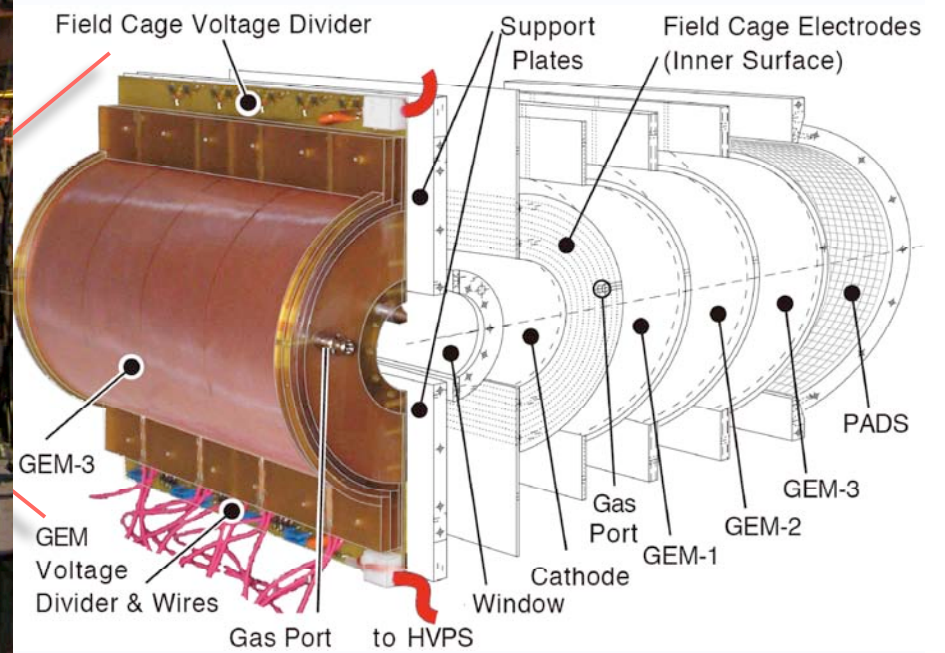
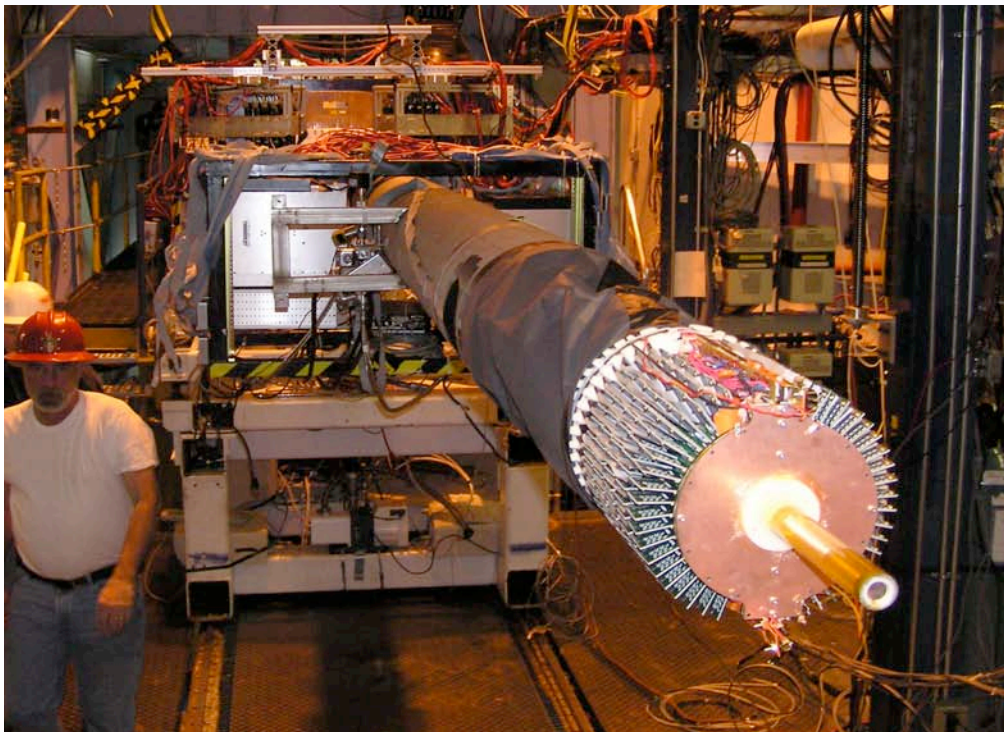
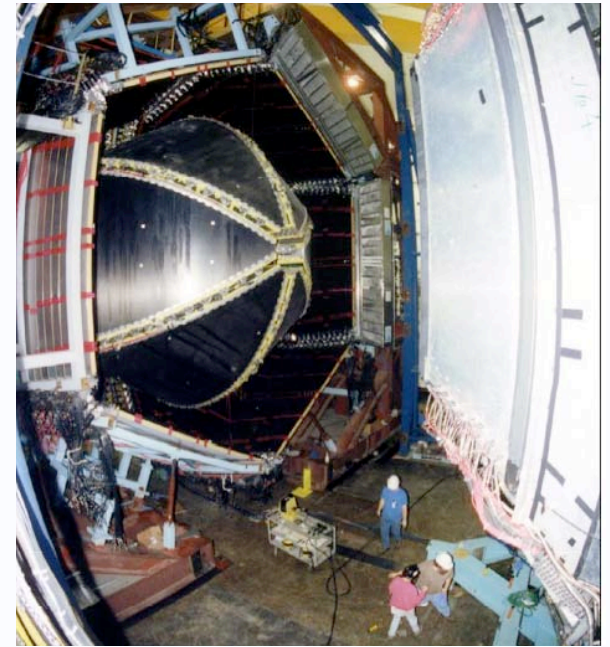


$\phi, z$  from pads  
 $r$  from time



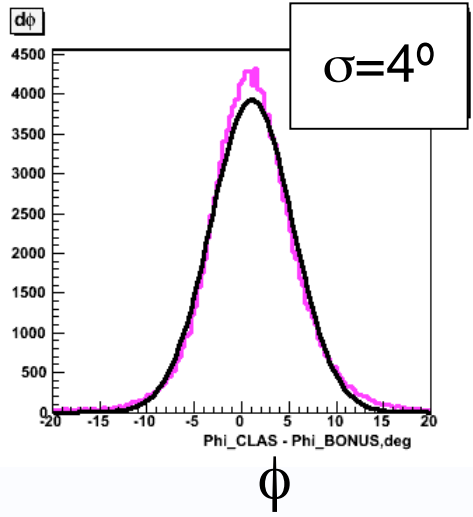
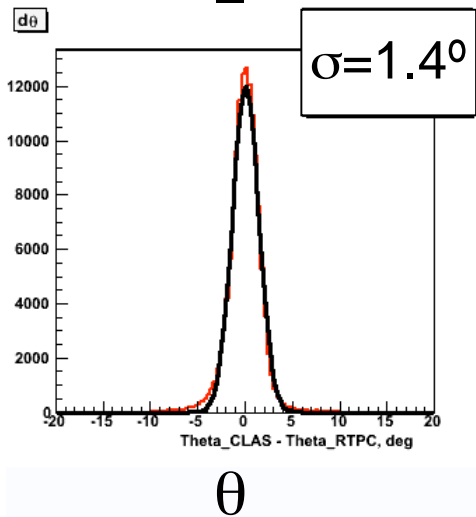
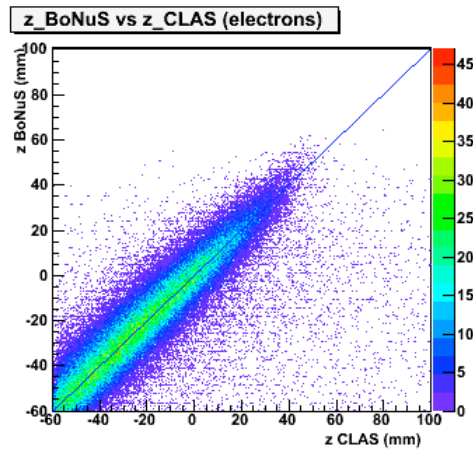
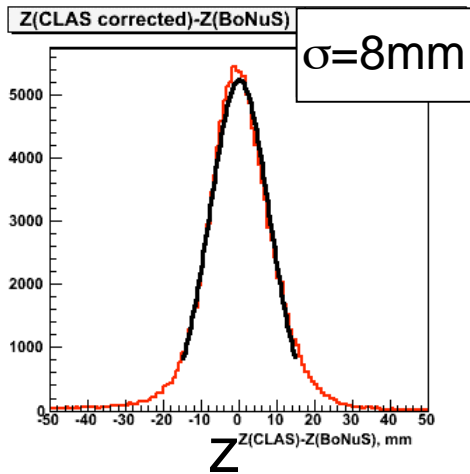


# BoNuS in CLAS

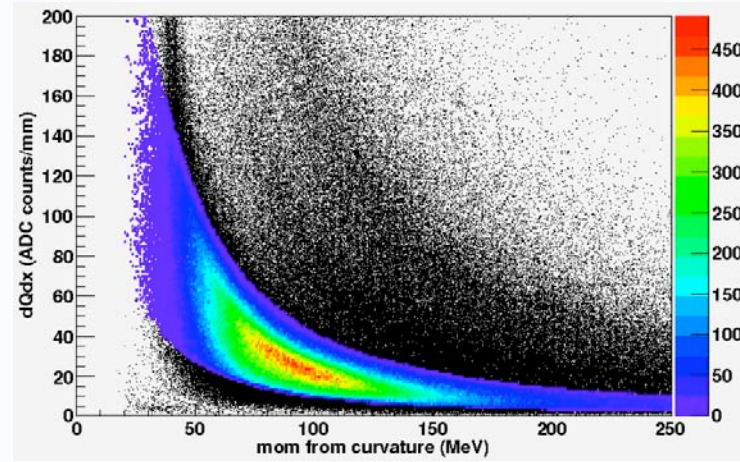


# RTPC Performance

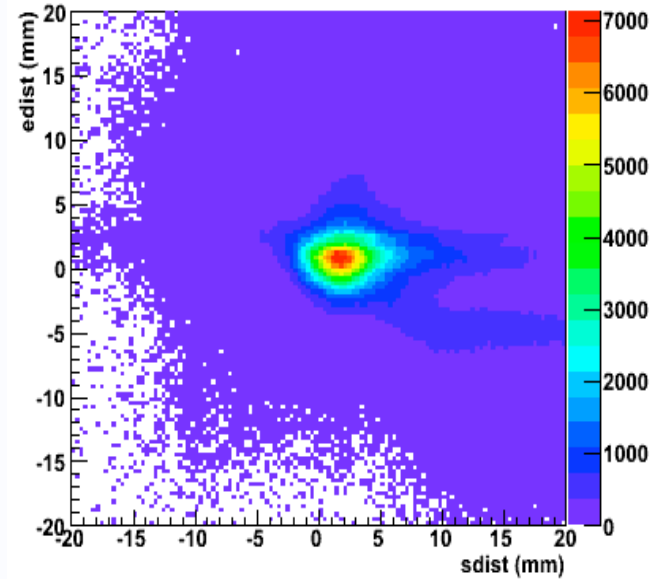
$e^-$  reconstructed in CLAS & RTPC



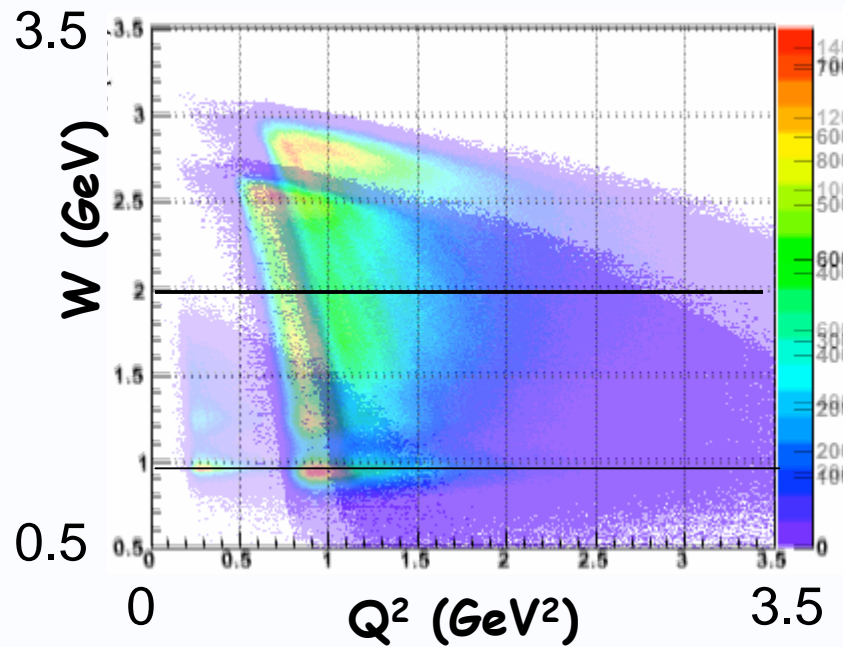
Particle ID (after gain calibration of each channel)



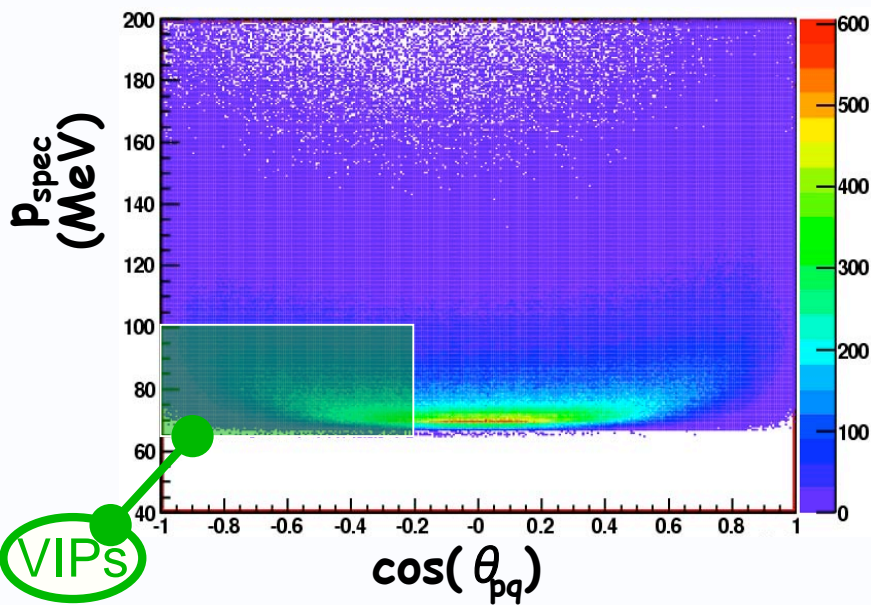
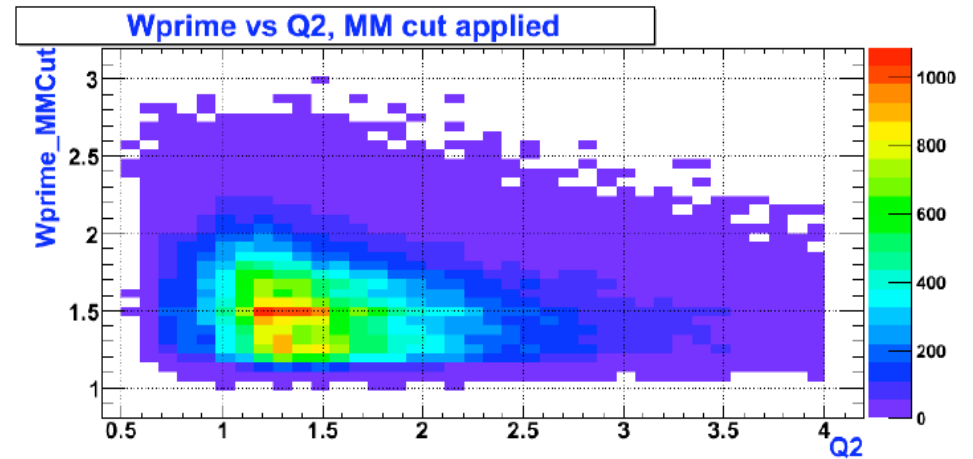
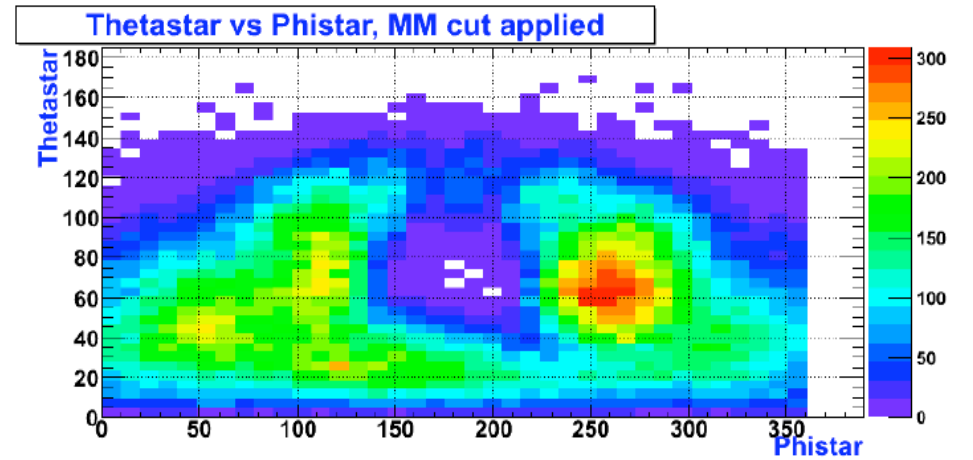
Out-of-time track suppression



# Kinematic Coverage - 2.1, 4.2 & 5.3 GeV

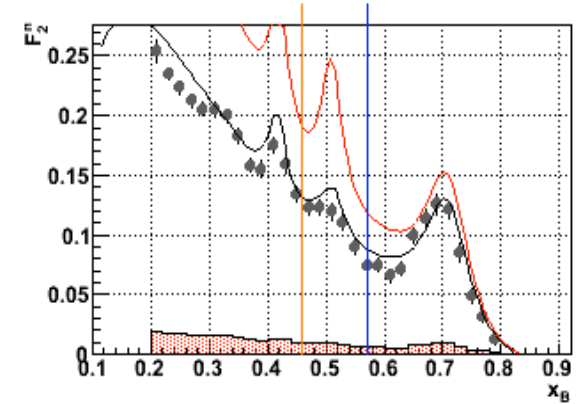
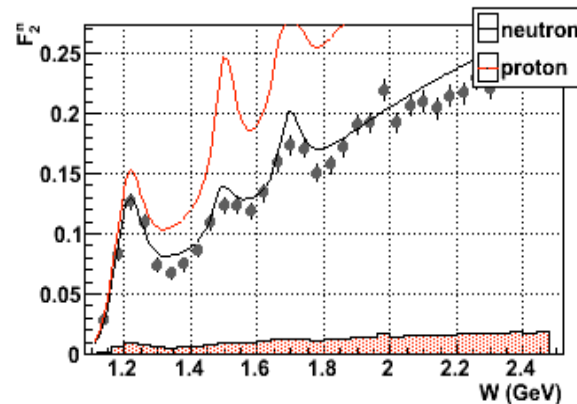
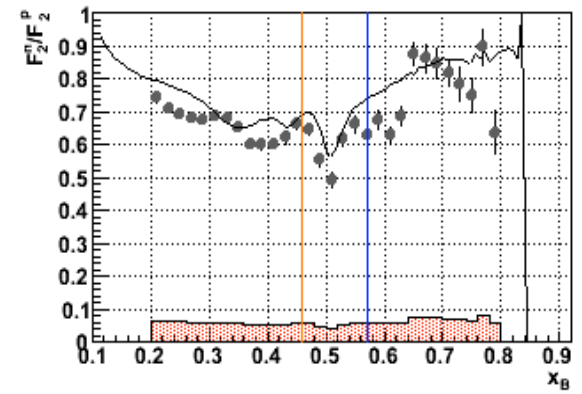
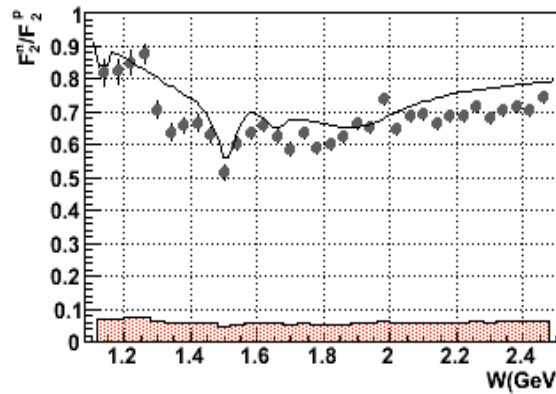
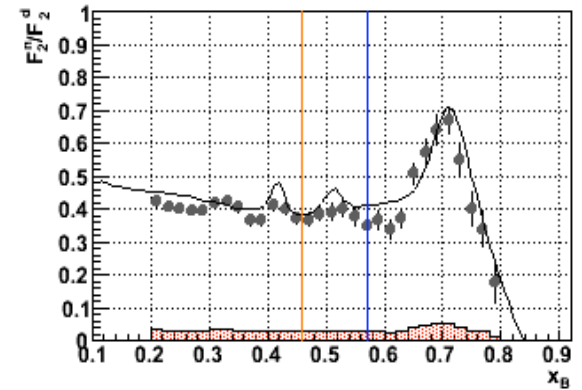
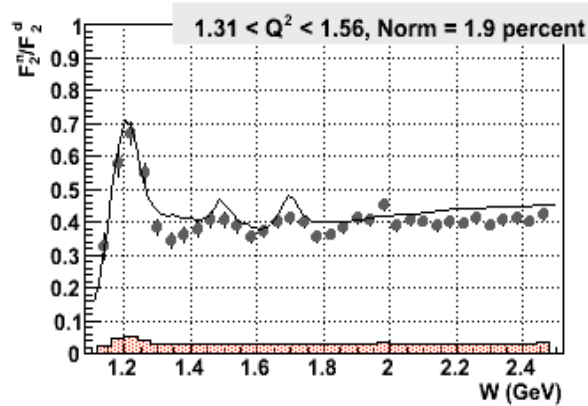


Kinematics coverage,  $D(e, e' \pi^- p)_p$ ,  $E = 5.3$  GeV

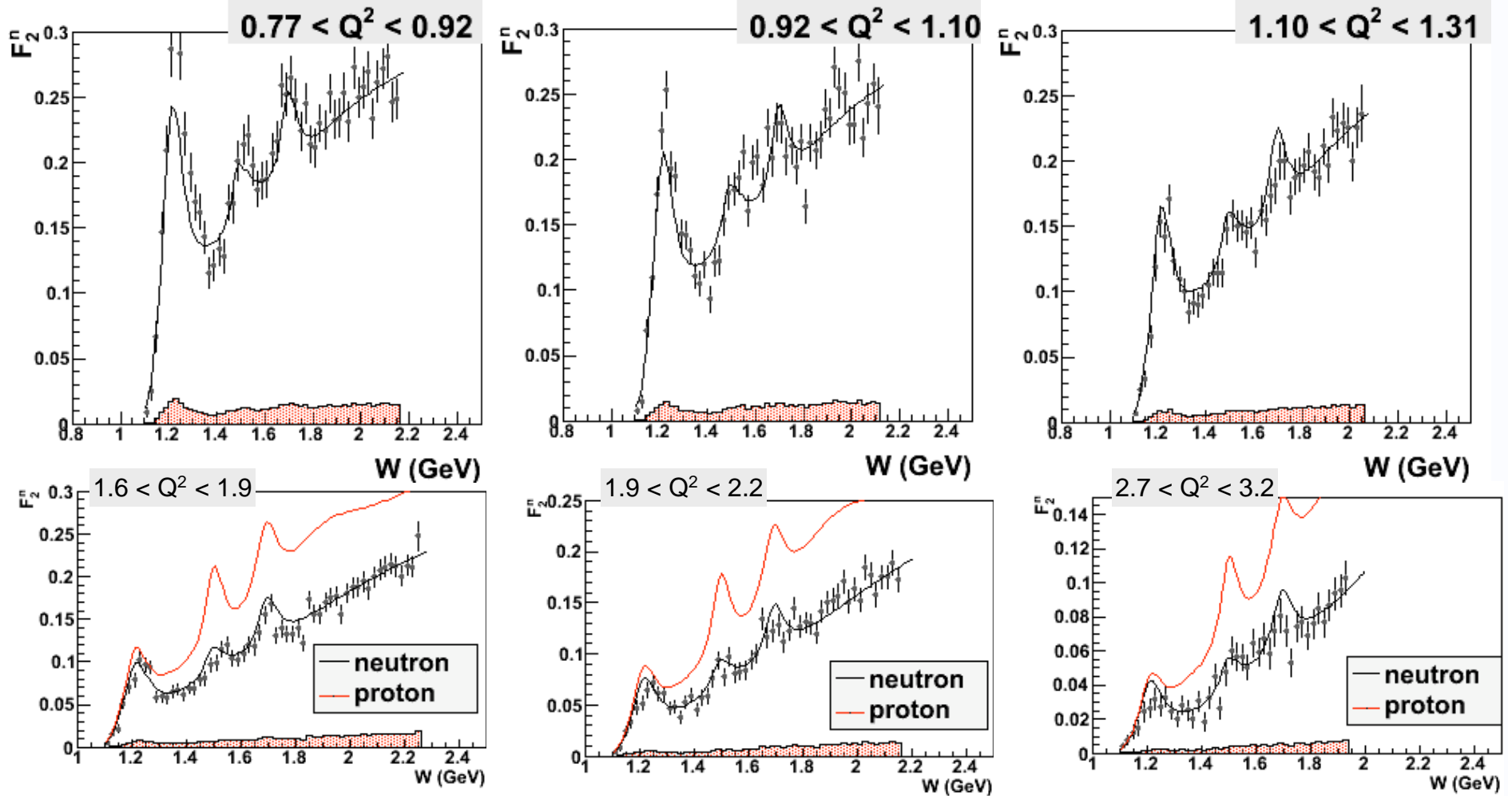


# Preliminary Results from BoNuS

- Measured tagged n / inclusive d
- Corrected for  $e^-$  acceptance and normalized to “known” ratio at high  $W$
- Multiplied with known  $F_{2d}$  to get bottom row.

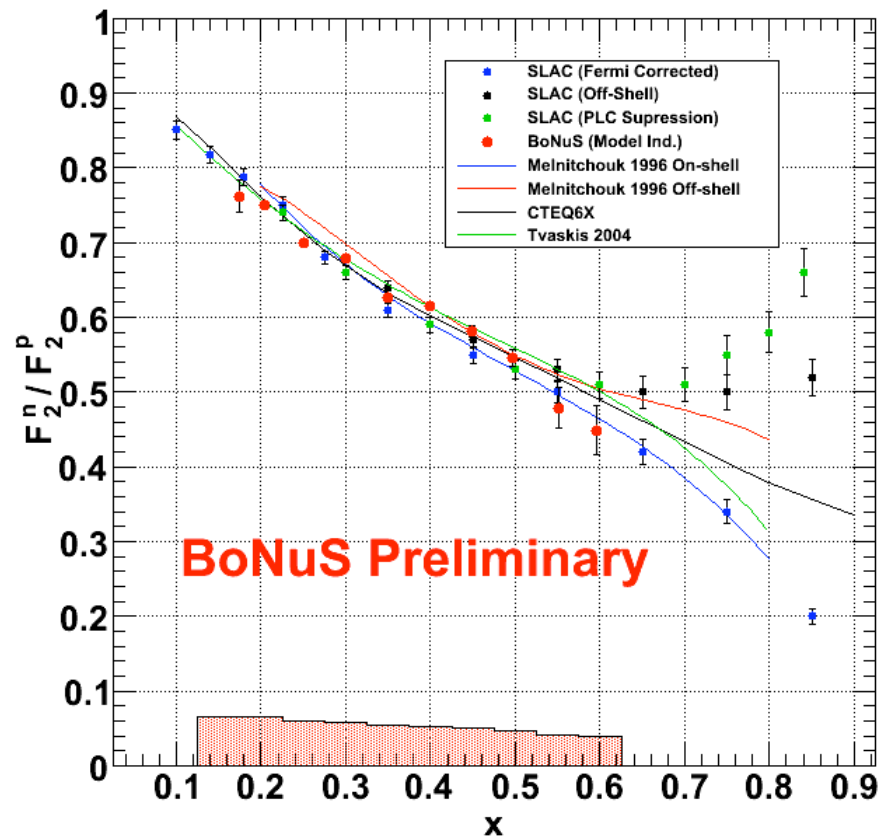


# Preliminary Results from BoNuS (ii)



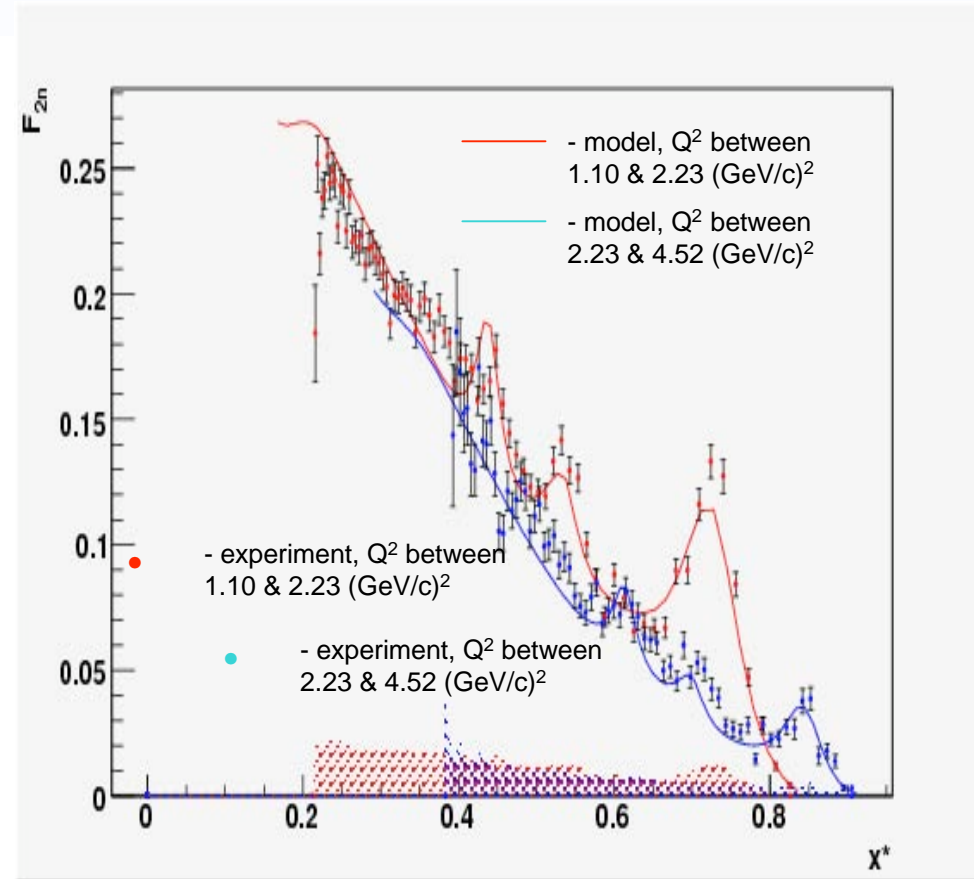
“Free” neutron structure function compared with a model by P. Bosted

# Preliminary Results from BoNuS (iii)



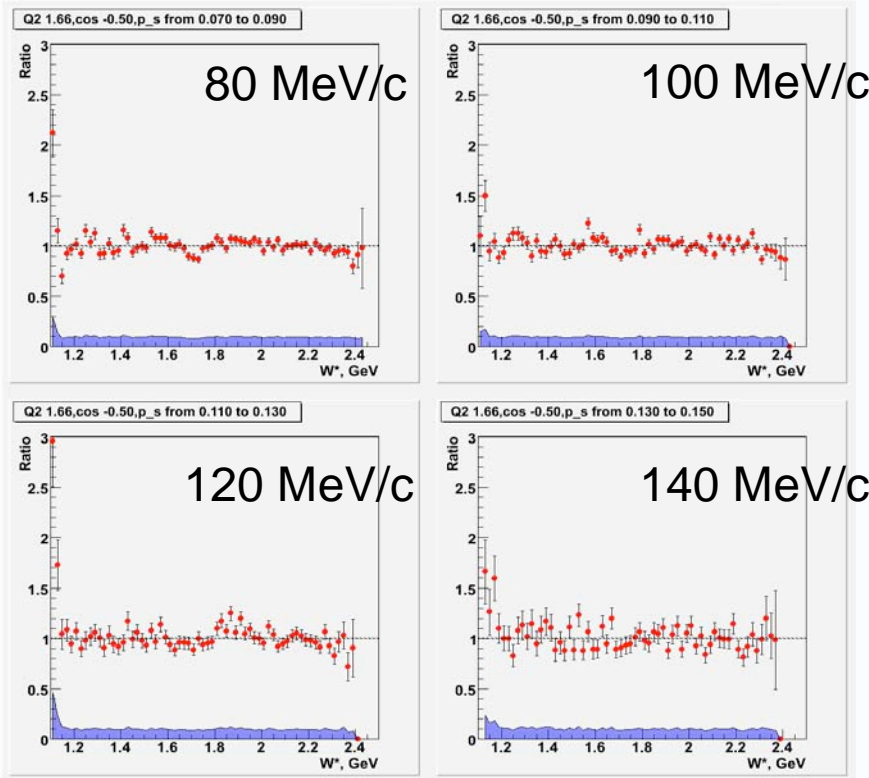
Cut on  $W > 1.8$

5 GeV Data



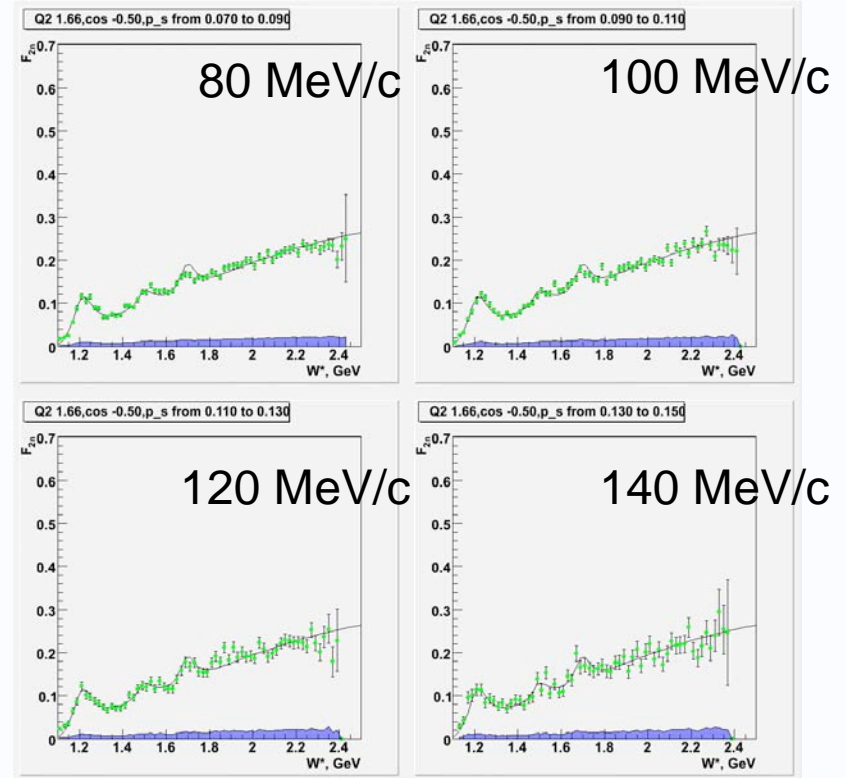
# Preliminary Results from BoNuS (iv)

Testing the Spectator Assumption - dependence on  $p_s$



$W^*$  [GeV]

Ratio Data/Model

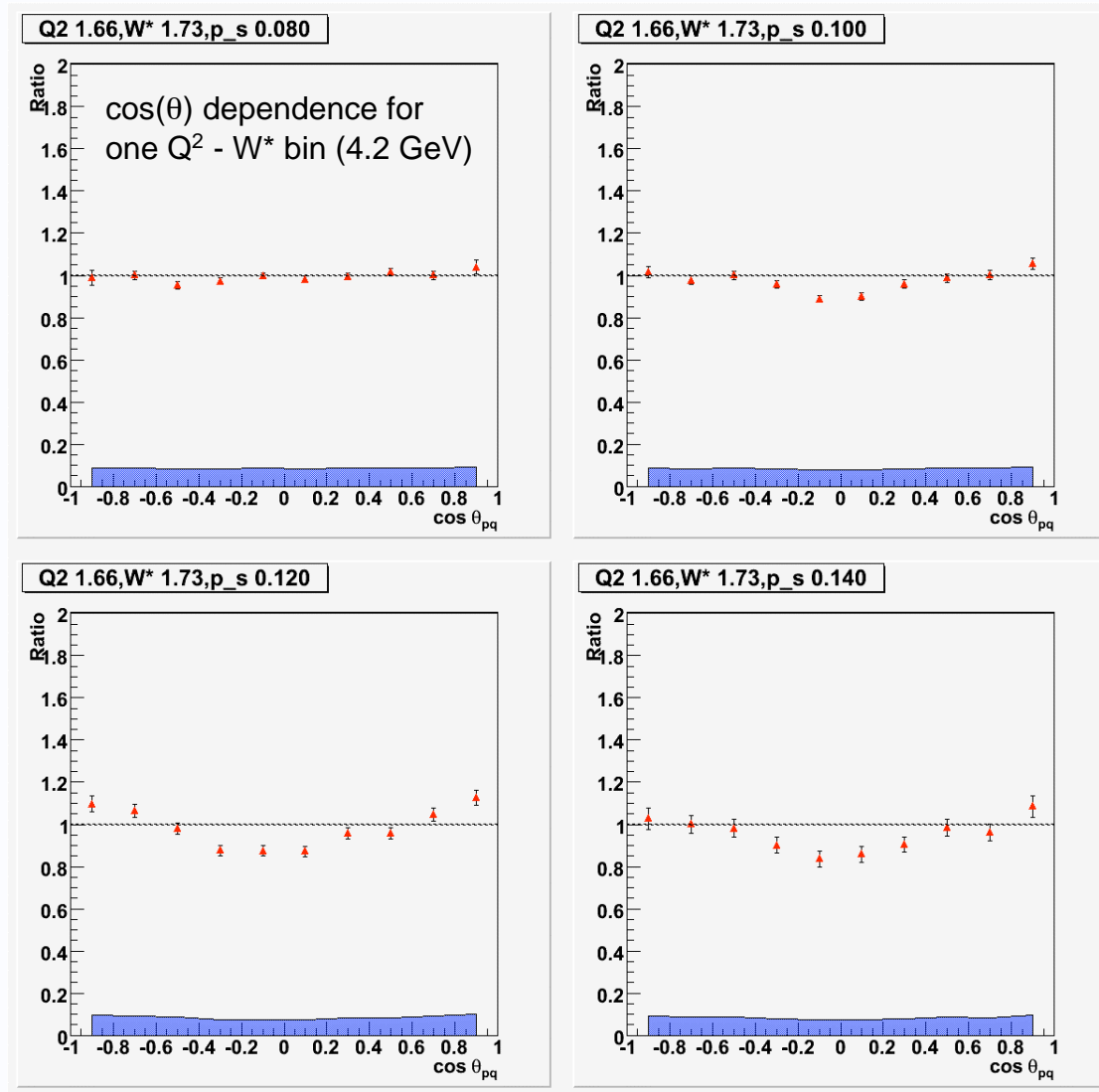


$W^*$  [GeV]

Extracted "effective structure function"  $F_{2n}$

- Data have radiative elastic tail subtracted
- Simulation uses simple spectator model, radiative effects, full model of RTPC and CLAS

# Preliminary Results from BoNuS ( $\nu$ )



Testing the Spectator Assumption - dependence on  $\theta_{pq}$

- So far, no strong deviations from naïve PWIA spectator picture at lower spectator momenta
- Possible indication of  $\theta$ -dependence at higher  $p_s$
- Have systematics for a wide range in  $Q^2$ ,  $W^*$  and beam energies

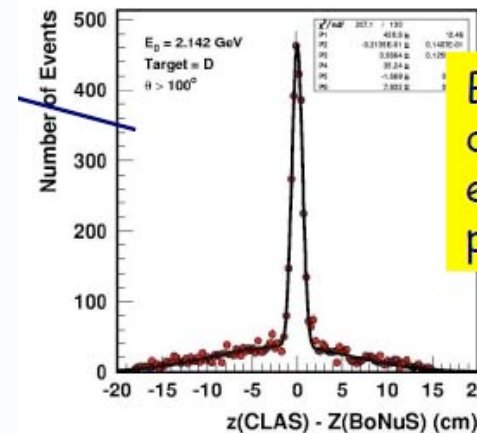
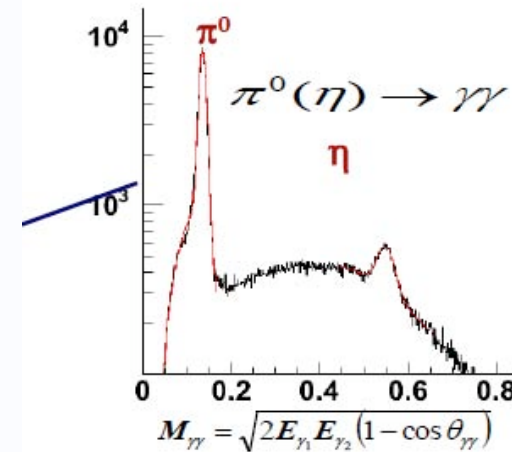
$$W^* = 1.73 \text{ GeV}$$
$$Q^2 = 1.66 \text{ (GeV/c)}^2$$



# 2<sup>nd</sup> RTPC Experiment - EG6

- Deeply Virtual Compton Scattering from Helium:  ${}^4\text{He}(e, e'\gamma {}^4\text{He})$
- Search for exotic mesons in  $\gamma^* + {}^4\text{He} \rightarrow M + {}^4\text{He} \rightarrow 4 \gamma\text{'s} + {}^4\text{He}$
- Slightly modified (improved!) RTPC
- Significantly increased data rate
- Ran in Fall 2009
- Can be used to extract data on spectator  ${}^3\text{He}$  and compare to spectator  ${}^3\text{H}$  (struck proton with known structure function!)

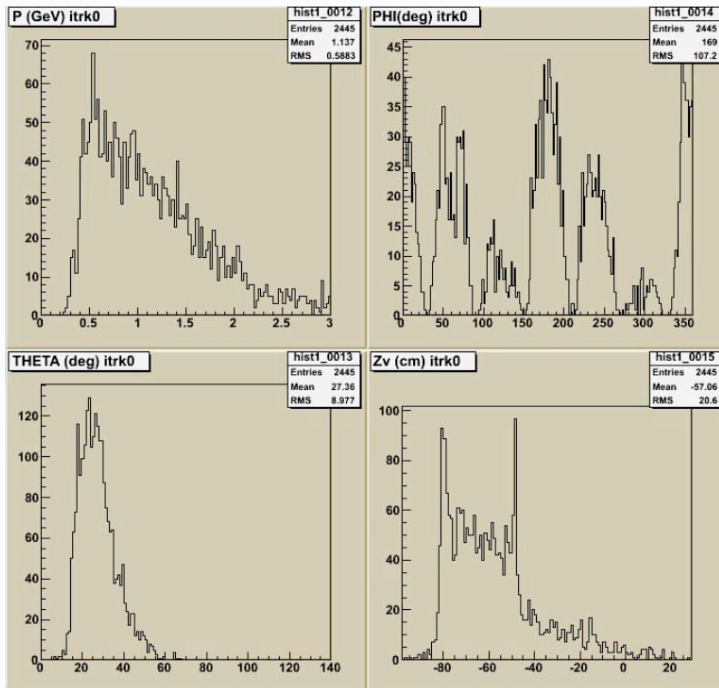
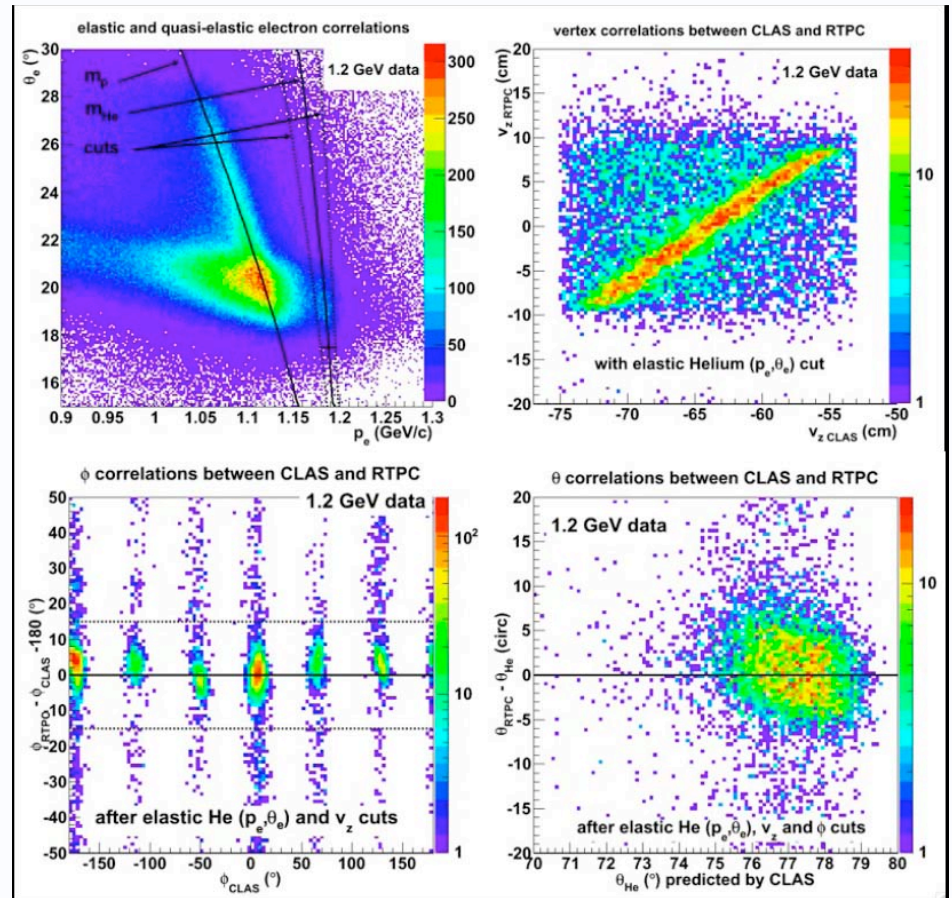
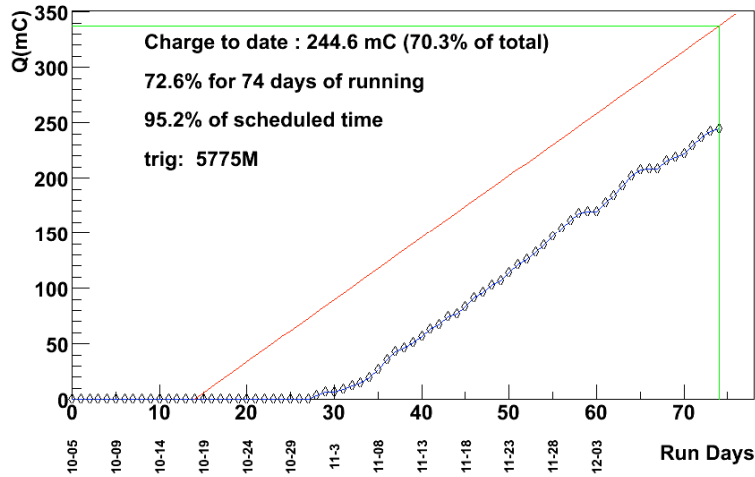
DVCS IC for detection of photons at small angles



BoNuS RTPC for detection of low energy recoiling  $\alpha$ -particles ( ${}^4\text{He}$ )

# 2<sup>nd</sup> RTPC Experiment - EG6

Accumulated Charge 2009-12-17

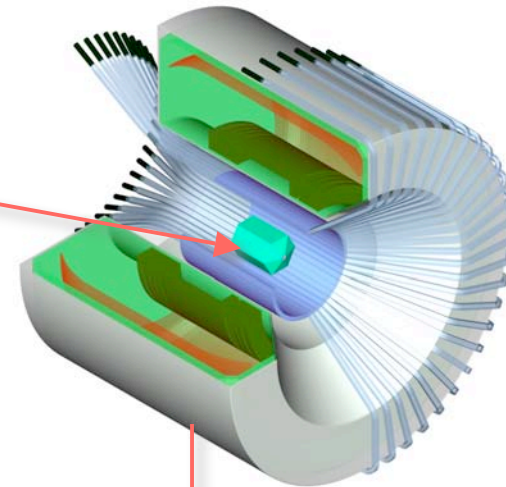
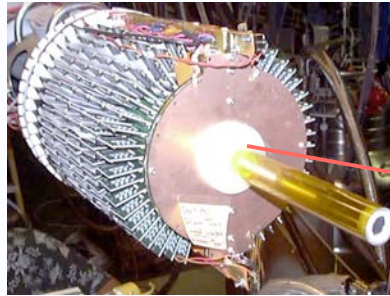


Detector calibration, 1<sup>st</sup> step analysis under way  
 1<sup>st</sup> results maybe in 1 year

# CLAS data mining

- Joint effort of a large group of people (many of them here) to re-analyze existing nuclear target data from CLAS
- Proposal to DOE for funding (mostly for a dedicated postdoc) - presently “in limbo”
- Relevant for spectator physics:
  - E6 data,  $d(e, e' p_s) X$  : extend  $Q^2$  range, lower p momentum threshold
  - E6 data: Look for  $d(e, e' \Delta_s) \Delta$  and other “exotic” final states
  - EG1/EG4/EG1-DVCS: study  $\vec{d}(\vec{e}, e' p) n$  vs. missing momentum to learn more about spin effects and FSI
- Discussion Friday afternoon

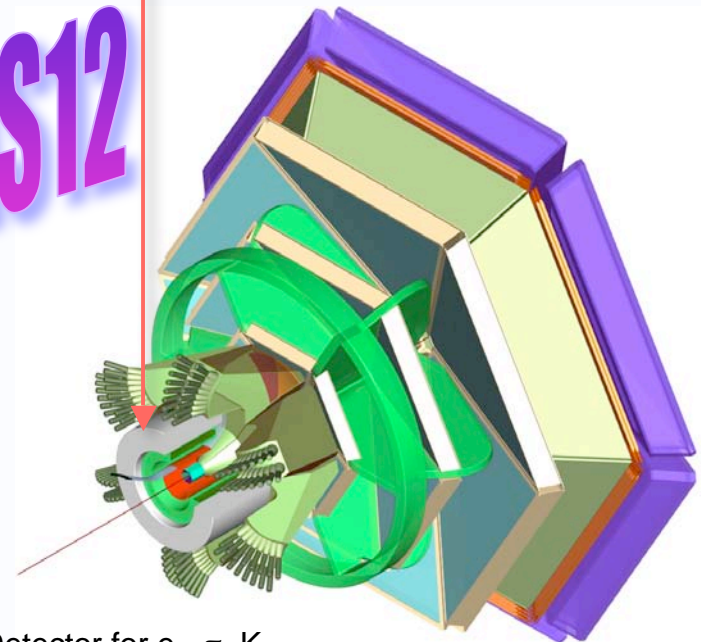
# Plans for Jefferson Lab at 11-12 GeV



Central  
Detector

- CLAS12 will have central detector for medium-low momentum large angle particles
- Can be replaced by “BoNuS” type RTPC for much lower spectator momenta
- Can insert polarized target inside Central Detector - study tagged pol. SFs? (Polarized EMC effect LOI [Brooks] approved by PAC35)

CLAS12

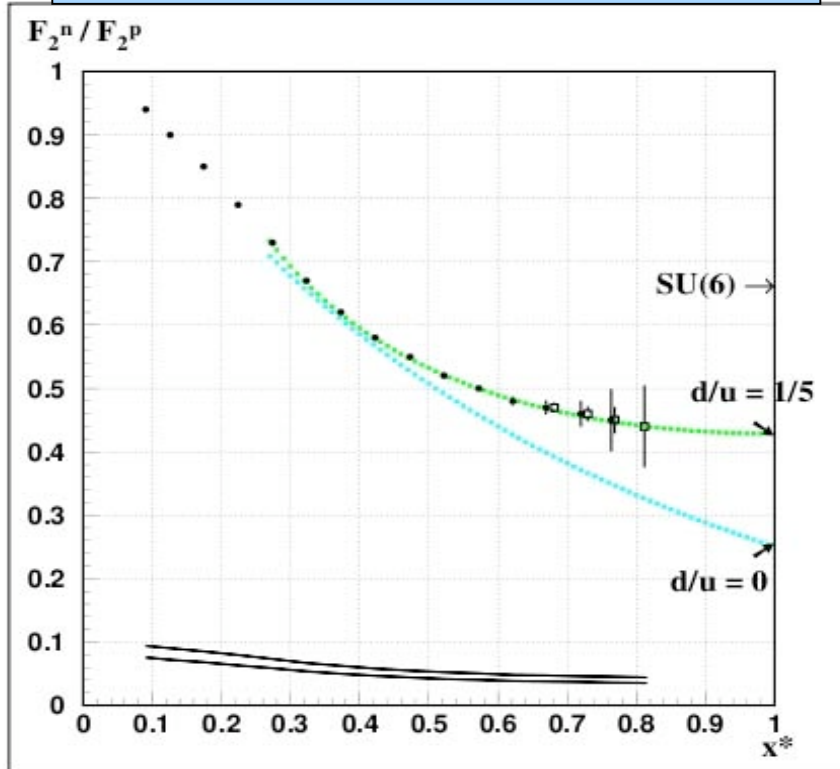


Forward Detector for  $e^-$ ,  $\pi$ ,  $K$ ,...

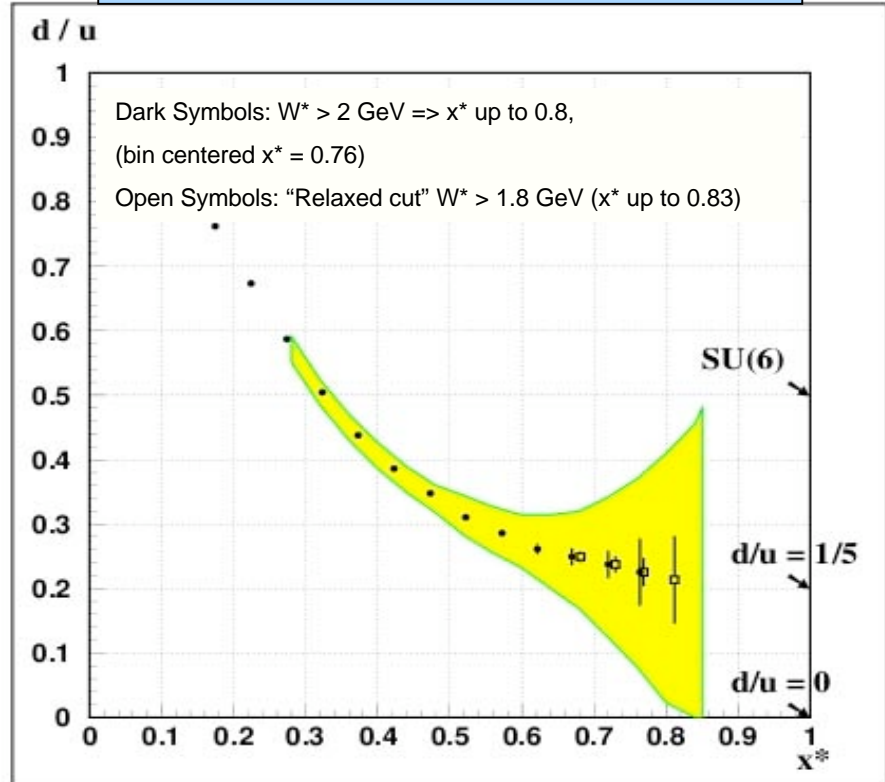
# Expected Results -

BoNuS12  
E12-06-113

Neutron/Proton structure function



d/u



Data taking of 35 days on  $D_2$  and 5 days on  $H_2$   
with  $\mathcal{L} = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$

•DIS region with

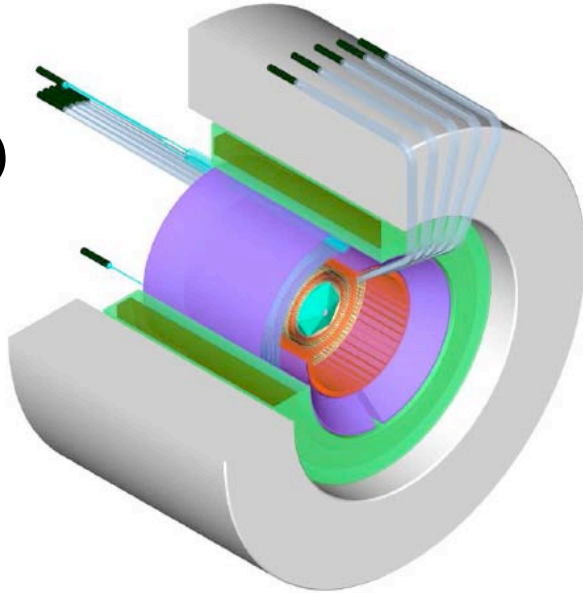
- $Q^2 > 1 \text{ GeV}^2/c^2$
- $W^* > 2 \text{ GeV}$
- $p_s > 70 \text{ MeV}/c$
- $-10^\circ < \theta_{pq} < 170^\circ$

# Expected Results - Deeps12

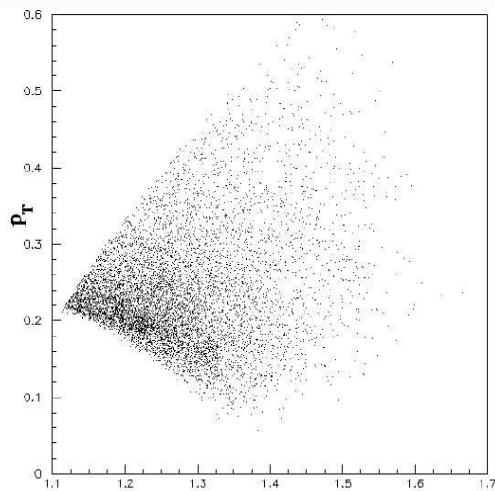
$D(e, e' p_s)$

LOI

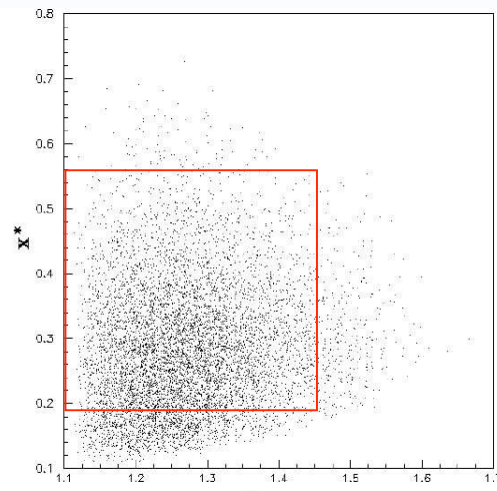
12-07-102



- Significantly increase kinematic coverage in  $x$ ,  $Q^2$  while remaining in DIS and “backward spectator” kinematics
- Can augment  $\alpha_s = 1$ , small  $p_T$  region with data from BoNuS12 - can get closer to “ideal” kinematics
- Possibly combination with n detector for a comparison of  $d(e, e' p_s)X$  with  $d(e, e' n_s)X$
- Requires a new, full proposal and significant simulation work
- EG6 will also be continued at higher energy - two LOIs (Milner, Hafidi) approved by most recent PAC35



$\theta_{pq} > 110^\circ$



$Q^2 > 1.5, W > 2$

# Conclusion - Status of Spectator Experiments

- Lots of data with coincident spectator detection already exist, many have been (partially) analyzed
  - FSI seems very important in perpendicular and forward kinematics
  - simple spectator picture with LC wave functions seems to work reasonably in some kinematic regions
  - Possible modifications of internal nucleon structure (dependent on spectator momentum) still an open question
- New data from EG6 will extend this study to  $^4\text{He}$  target
- Data mining initiative will unlock much more information from all nuclear data taken with CLAS
- Lots more exciting experiments after JLab energy upgrade!
- Requires theory-experiment interaction: Agree on definition of “reduced cross section”; need predictions of this cross section including FSI over large kinematic range (not only for  $p_T = 0$  ;-)
- ULTIMATE GOAL: EIC - can smoothly map out  $p_{\text{spect.}}$  from 0 to 1 GeV/c

Happy Birthday (belated), Mark

