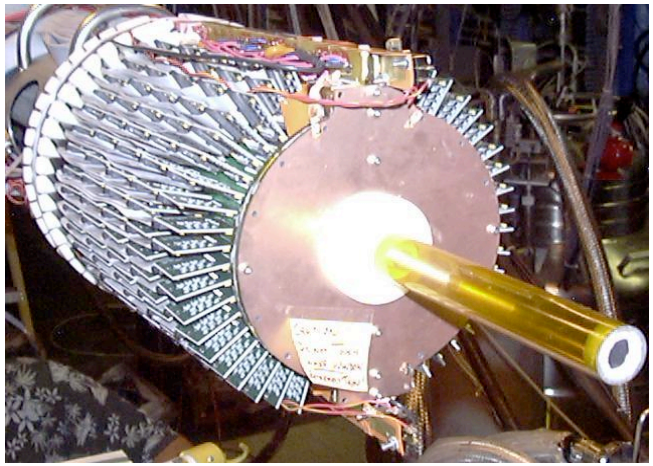
# Measurement of the Neutron Structure Function at Large x



PANIC 2011
MIT

Thia Keppel
Hampton University, Jefferson Lab

Jefferson Lab

HAMPTON UNIVERSITY

# $F_2^n/F_2^p$: Textbook Physics - d/u at large x

Quark-Parton Model

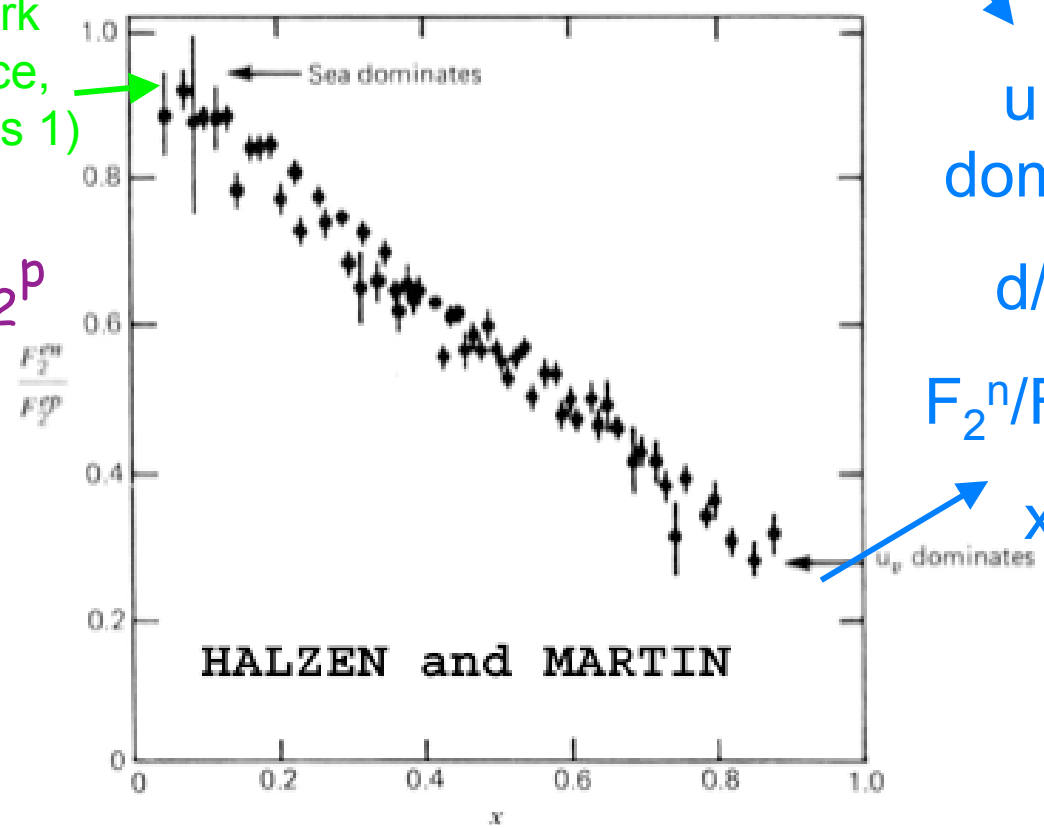
$$F_2^p(x) = x\sum_q e_q^2(q(x)+\bar{q}(x)) \underset{x\to 1}{\approx} x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

$$F_2^n(x) \underset{x\to 1}{\approx} x\left(\frac{4}{9}d(x)+\frac{1}{9}u(x)\right)$$

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

(sea quark dominance, approaches 1)

$F_2^n/F_2^p$




u quark dominance,

d/u –> 0

$F_2^n/F_2^p$ –> 1/4

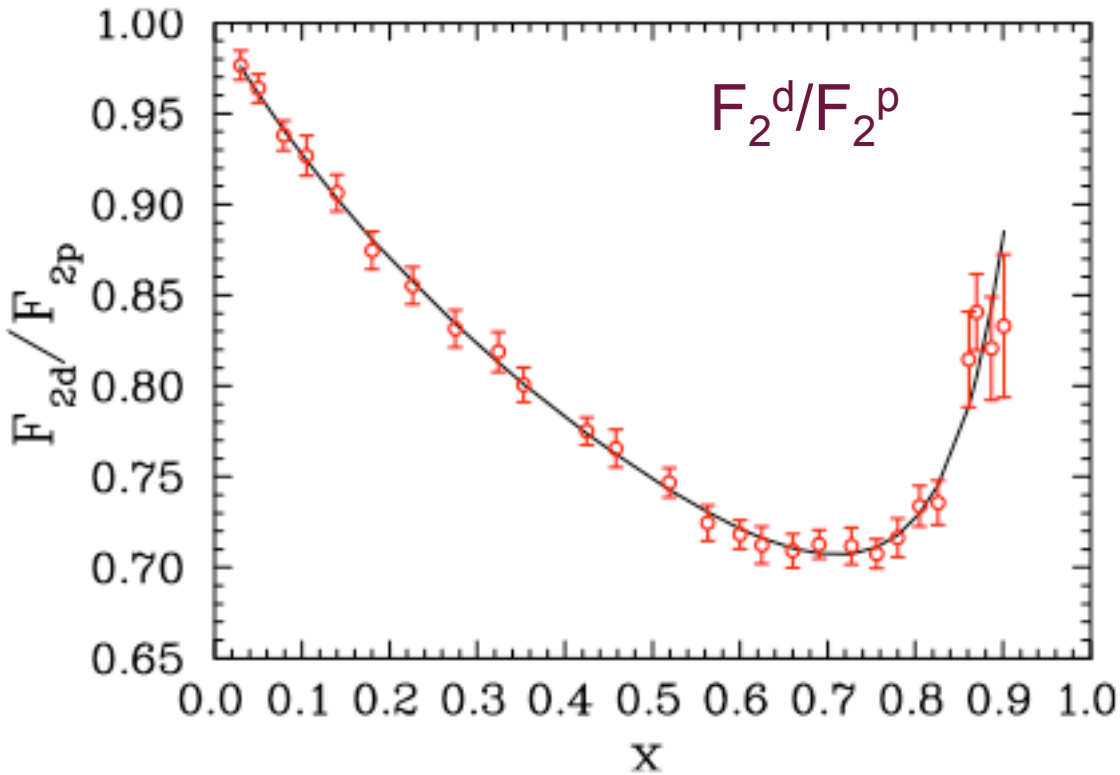
x –> 1

BUT.....

# The deuteron is a nucleus….

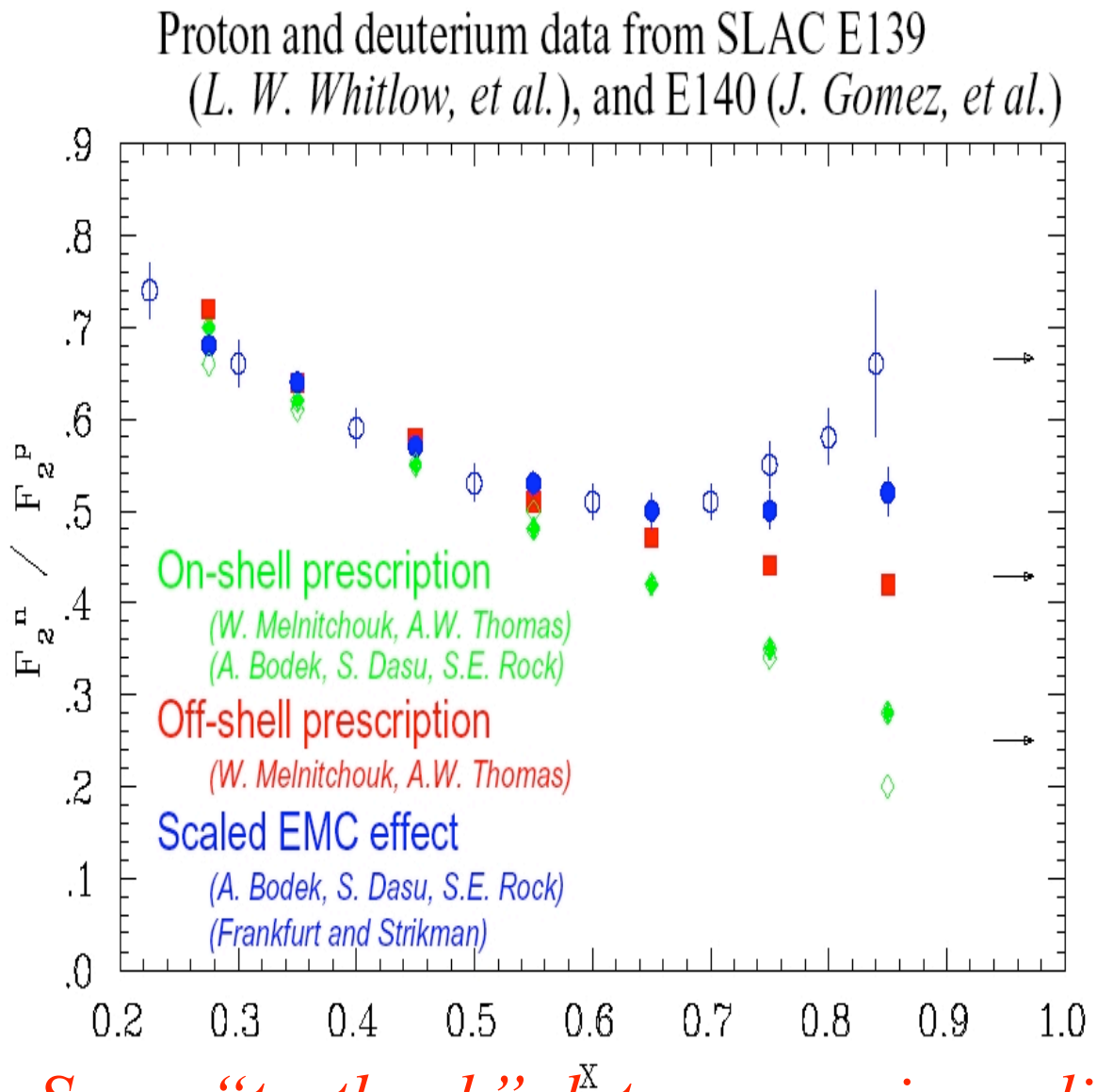
Neutron structure typically derived from deuterium target by subtracting proton

*Large* uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function,coherent scattering, final state interactions, nucleon structure modification ("EMC"-effect)……




SLAC data

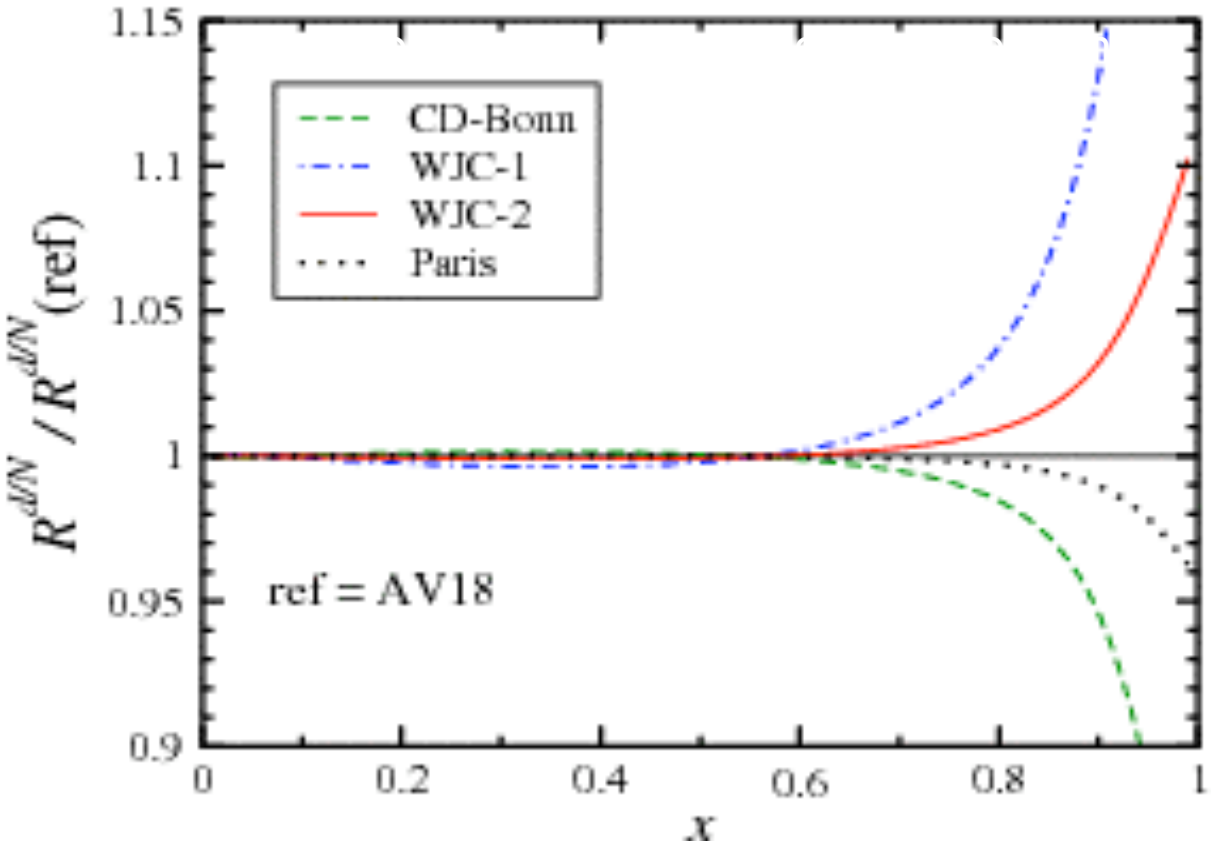
# This is a big problem….




*<u>Same</u> "textbook" data as previous slide!*

$0.2 < F_2^n/F_2^p < 0.8$ *?!?!*

# Large $x$ - Large Nuclear Effects




Accardi *et al*, Phys. Rev. D84:014008, 2011*Uncertainties in Determining Parton Distributions at Large x* *- talk this afternoon*

- 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, Δ(1232) and "exotic" degrees of freedom unknown
- FSI?

# $F_2^n/F_2^p$ is fundamental to understanding the proton structure

Proton Wavefunction (Spin and Flavor Symmetric)

$$\left| p \uparrow \right\rangle = \frac{1}{\sqrt{2}} \left| u \uparrow (ud)_{S=0} \right\rangle + \frac{1}{\sqrt{18}} \left| u \uparrow (ud)_{S=1} \right\rangle - \frac{1}{3} \left| u \downarrow (ud)_{S=1} \right\rangle$$

$$- \frac{1}{3} \left| d \uparrow (uu)_{S=1} \right\rangle - \frac{\sqrt{2}}{3} \left| d \downarrow (uu)_{S=1} \right\rangle$$

| Nucleon Model | $F_2^n/F_2^p$ | d/u |
|---|---|---|
| SU(6) | 2/3 | 1/2 |
| Valence Quark | 1/4 | 0 |
| pQCD | 3/7 | 1/5 |

# Predictions for d/u at large $x_{Bj}$

## Proton Wavefunction (Spin and Flavor Symmetric)

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u, d same shape u = 2d

SU(6) spin-flavor symmetry:

The mass difference between N and Δ implies symmetry breaking

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SU(6) symmetry broken - scalar valence diquark, u dominance

S=0 diquark dominance

- d/u=(0)/(1/2)=0
- Hyperfine-perturbed quark model (Isgur *at al.*) with one-gluon-exchange; MIT bag model with gluon exchange (Close & Thomas ); Phenomenological quark-diquark (Close) and Regge (Carlitz) arguments

# Predictions for d/u at large $x_{Bj}$

Proton Wavefunction (Spin and Flavor Symmetric)

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| Nucleon Model | $F_2^n/F_2^p$ | d/u |
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$S_z$ = 0, di-quark dominance, spin projection is zero

- d/u=(1/9)/(1/2+1/18)=1/5
- pQCD with helicity conservation (Farrar and Jackson); quark counting rules (Brodsky *et al.)*

[There are even more predictions…]

## $F_2^n/F_2^p$ (and, hence, d/u) is essentially unknown at large x:

- Conflicting fundamental theory pictures
- Data hindered by lack of free neutron target

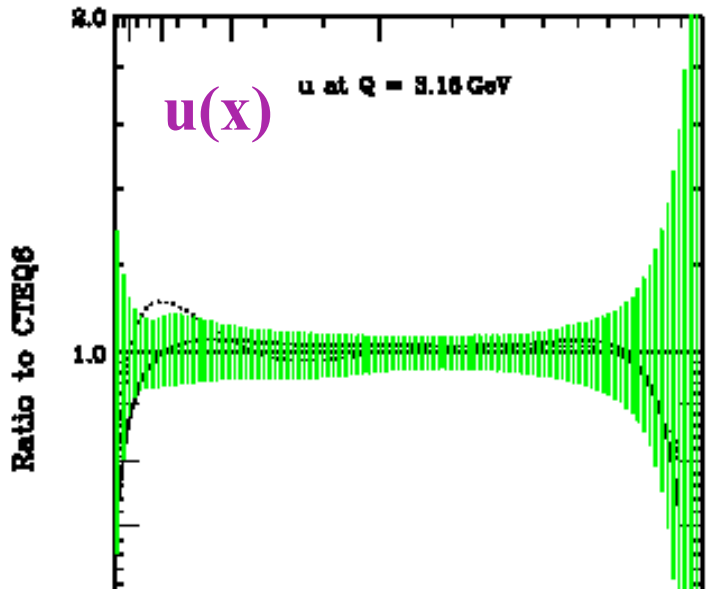
| | $F_2^n/F_2^p$ | d/u |
|---|---|---|
| SU(6) | 2/3 | 1/2 |
| Scalar Diquark | 1/4 | 0 |
| H-P Quark Model | 1/4 | 0 |
| pQCD | 3/7 | 1/5 |
| Counting Rules | 3/7 | 1/5 |

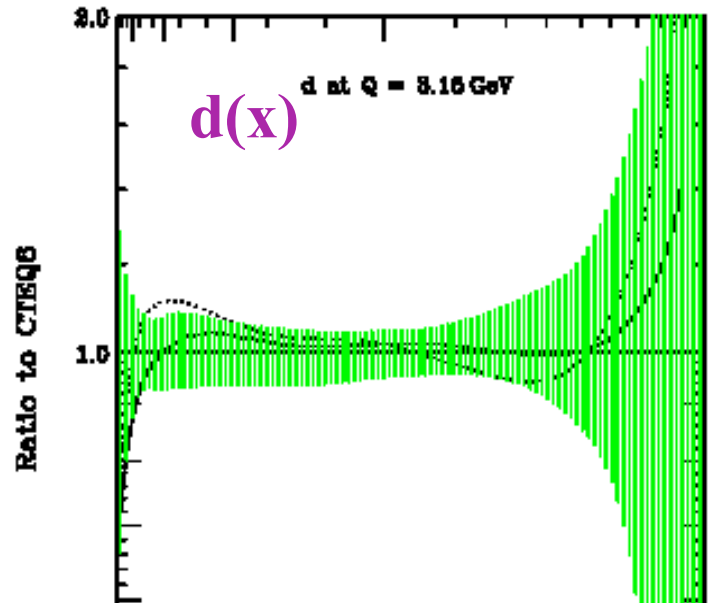
Review Articles :

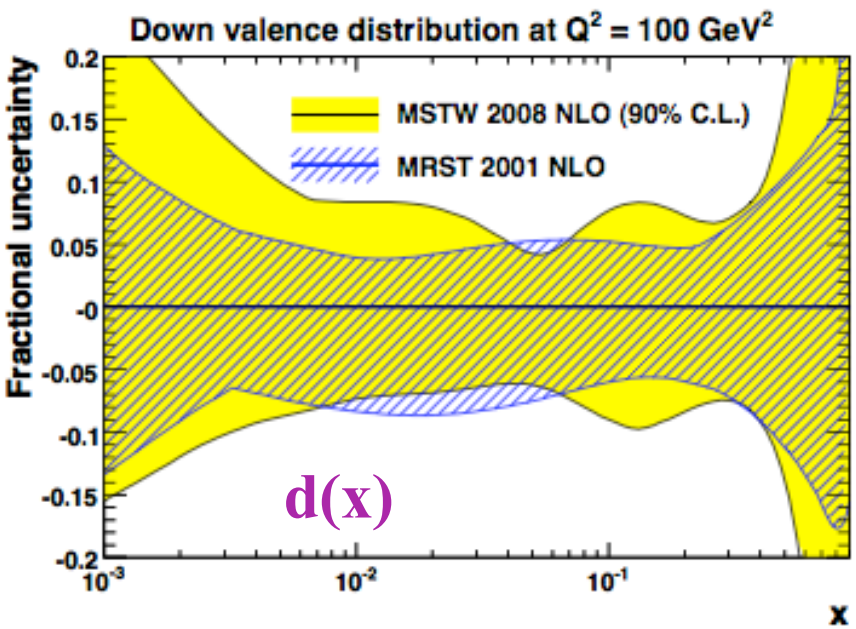
Isgur, Phys. Rev. D59, 34013 (1999)
Brodsky et al., Nucl. Phys. B441, 197 (1995)
Melnitchouk and Thomas, Phys. Lett. B377, 11 (1996)

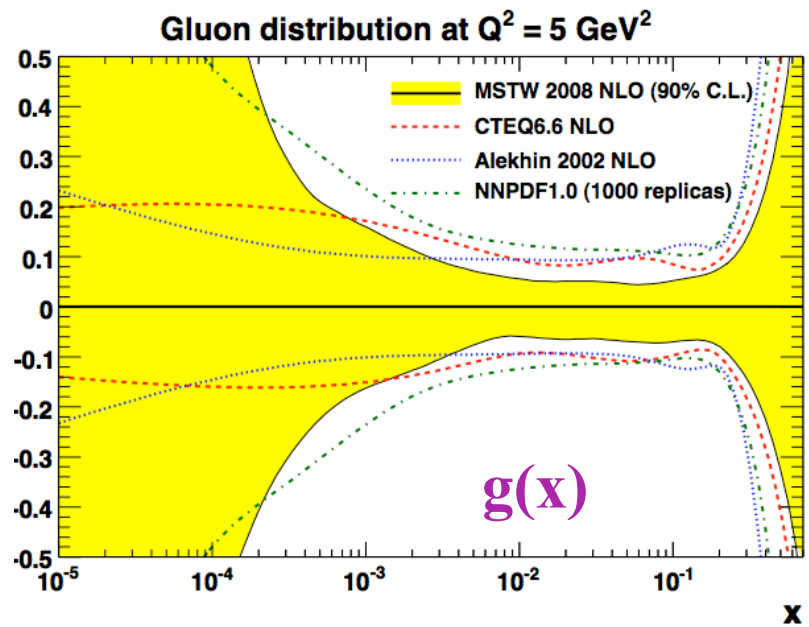
$F_2^n/F_2p$ (or d/u) can be almost anything!

# Translates Directly to Large x Valence pdf Uncertainties



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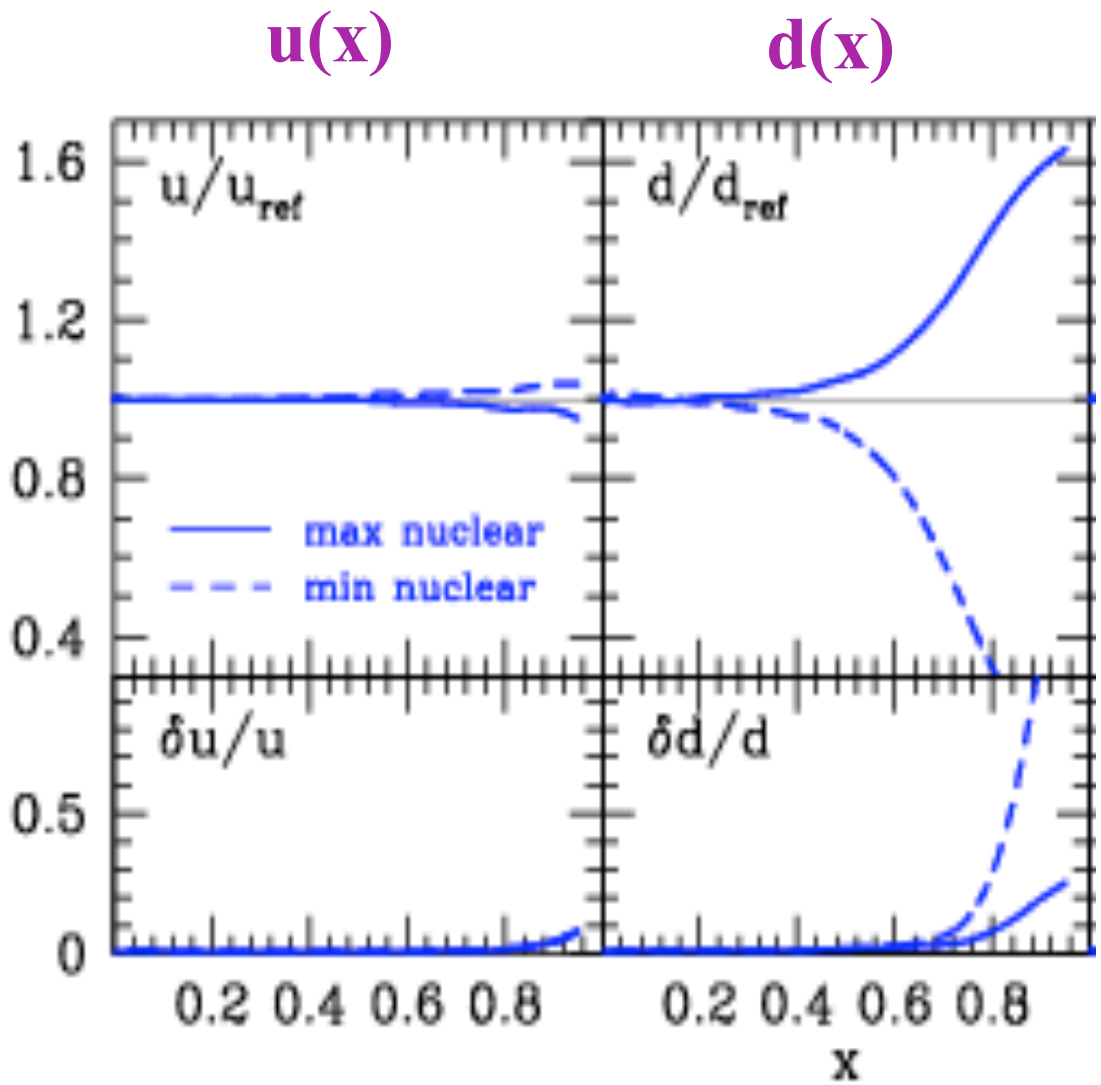
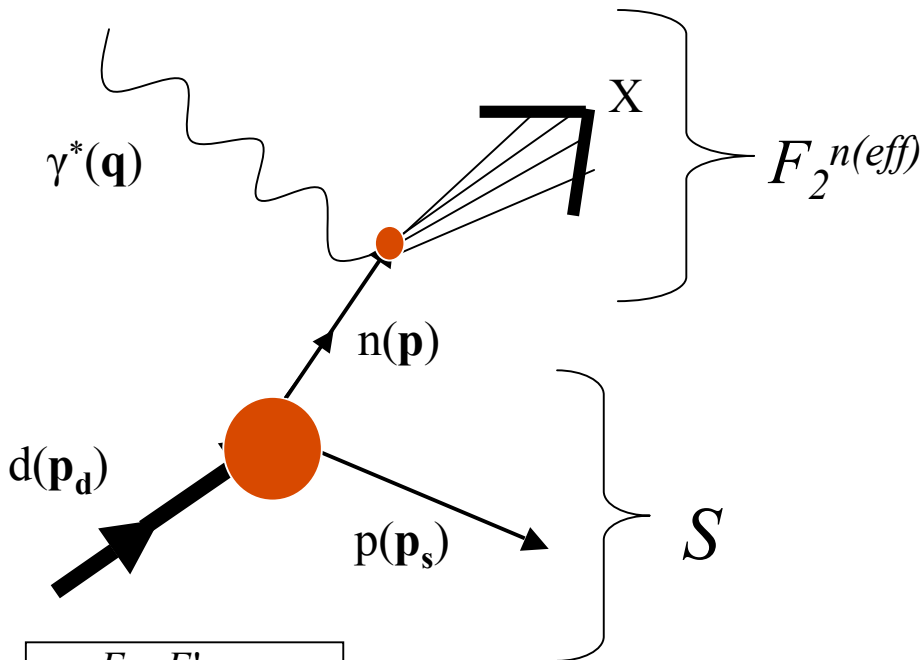



CJ2011 - see afternoon talk

# Can we reduce model dependence?

Yes! Within the nuclear impulse approximation. The virtual photon interacts with the neutron on a short enough time scale that the proton doesn't know what happened. The spectator continues on unperturbed w/ momentum $\mathbf{p_s} = -\mathbf{p}$

$$\frac{d\sigma}{dx dW^2 d\alpha d^2 p_T} \approx \frac{2\alpha_{em}^2(1-\nu/E)}{Q^4}\ \alpha\ \mathcal{S}(\alpha, p_T)\ F_2^{n(eff)}(W^2, p^2, Q^2)$$




$$\nu = E - E'$$
$$\alpha = (E_s - p_s^{\ z})/M$$
$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

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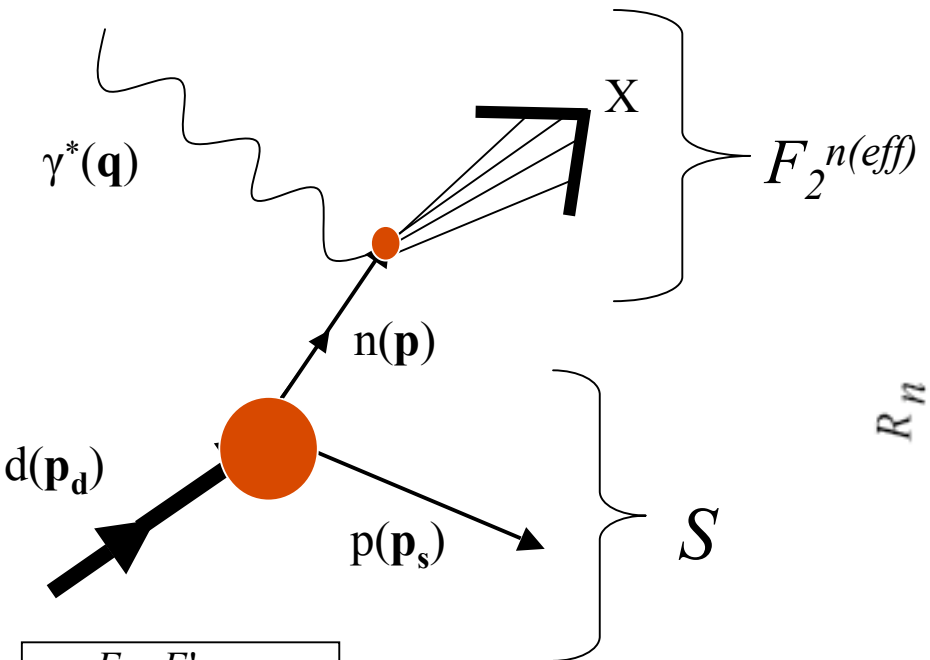
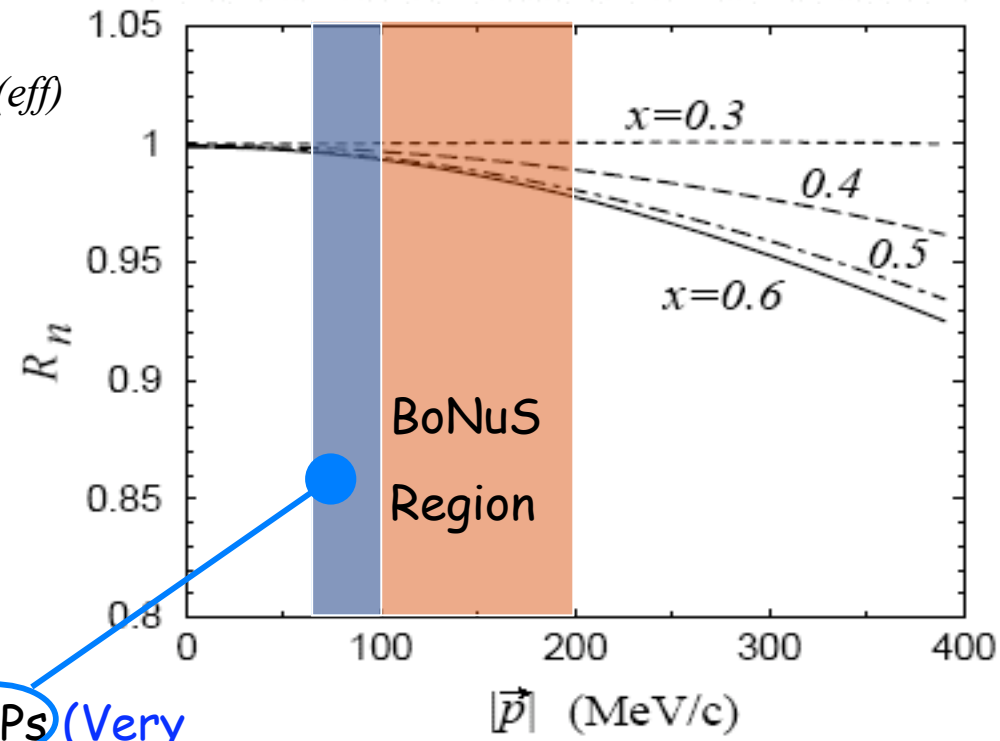


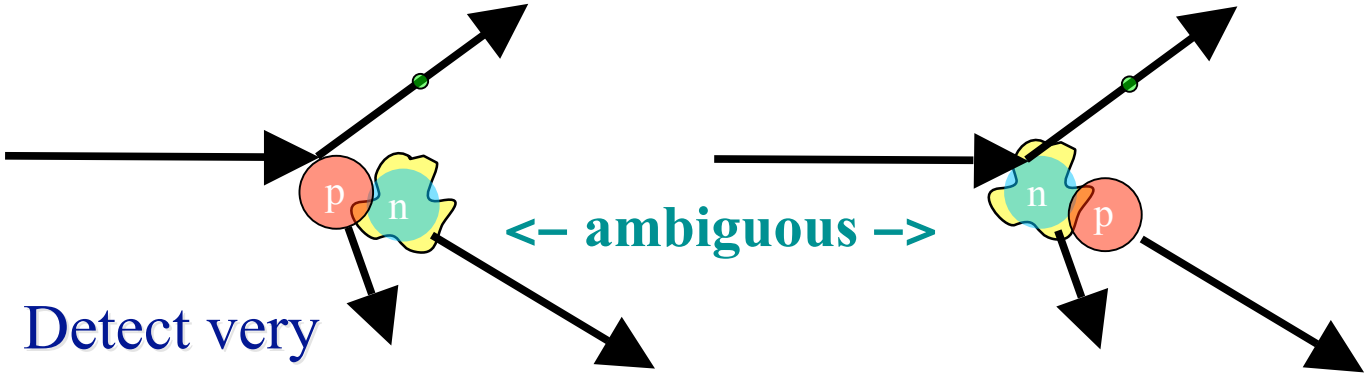

$$\nu = E - E'$$
$$\alpha = (E_s - p_s^{\,z})/M$$
$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

$$R_n \equiv F_2^{n(eff)}(W^2, Q^2, p^2)/F_2^n(W^2, Q^2)$$

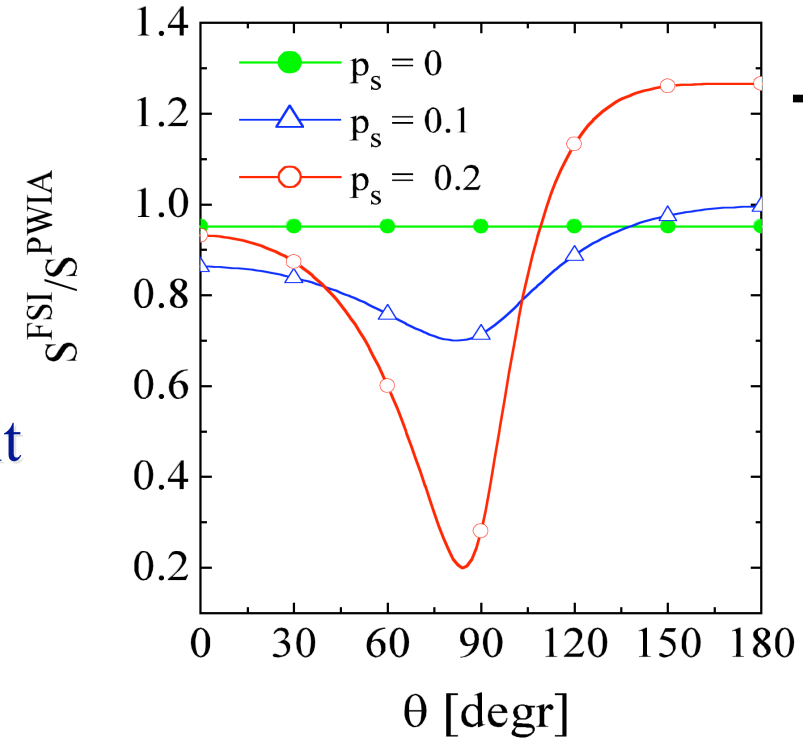


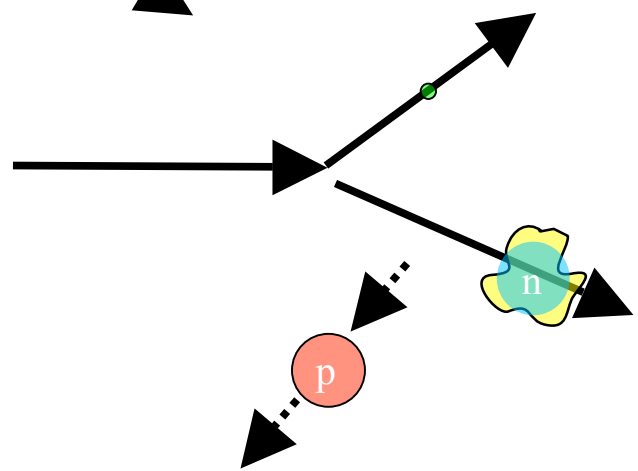

We focus on VIPs (Very Important Protons) where $R_n$ > 99%

# Need Low Momentum AND Large Angle



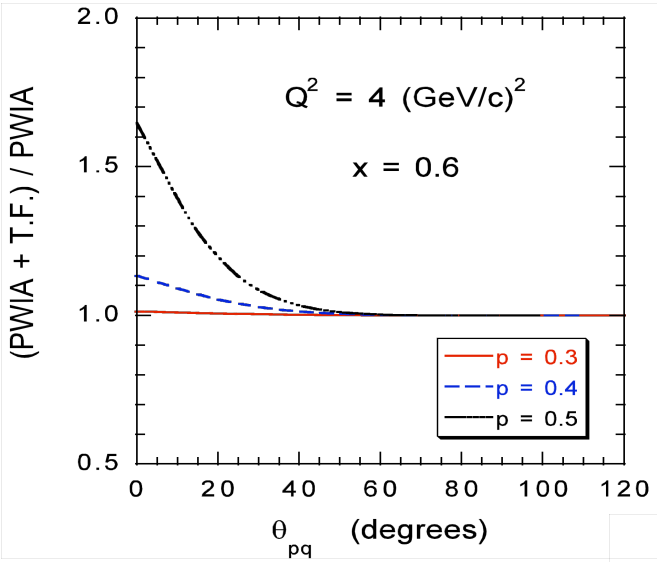

Detect very important low momentum protons. If the proton is also going *backwards* in the lab frame it is almost guaranteed to be only a spectator.




**Backward angle**
*Spectator* **proton =**
*Neutron* **target**

# Choice of Spectator Momentum and Angle

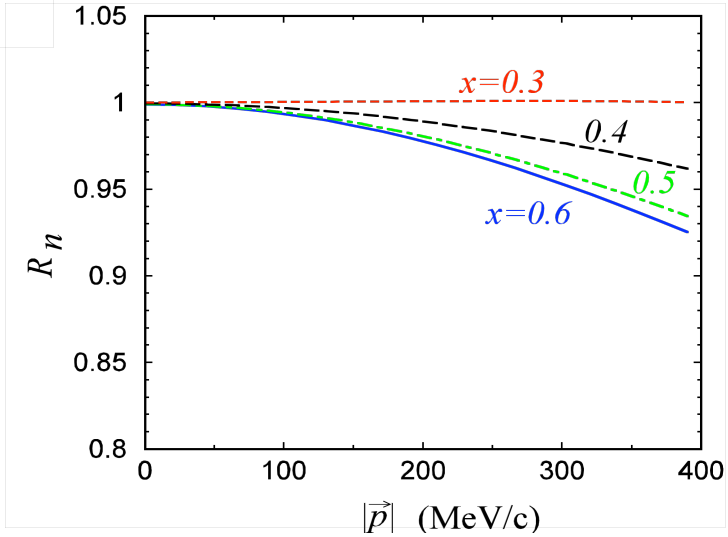


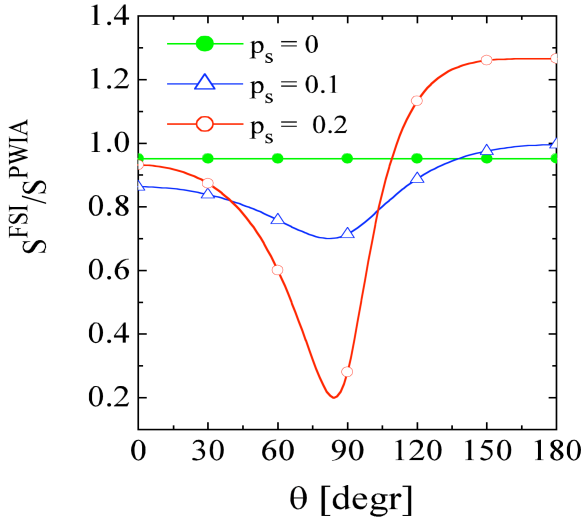

Target fragmentation

**negligible**

Bound / free neutron structure

***O* (1%)**




Final state interactions

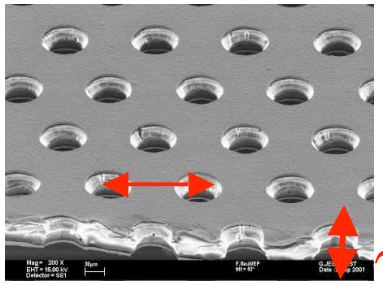
***O* (5%)**

BONUS is a Standard Inclusive Fixed Deuterium Target Electron Scattering Experiment, with a Tagged Spectator Proton to Ensure the Electron Scattered from the Neutron

## Spectator Proton Detector Features

- *Low momentum* spectator must escape target
  - Thin deuterium target
  - Low density detector media
  - Minimal insensitive material
- Large acceptance
  - Backward angles important
  - Symmetric about the target
- Detector sensitive to spectators, insensitive to background

# BONUS Radial TPC Design using Cylindrical Gas Electron Multipliers

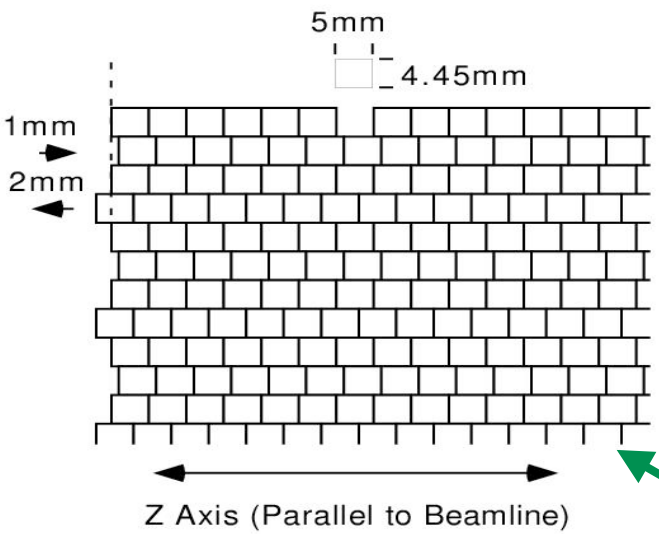


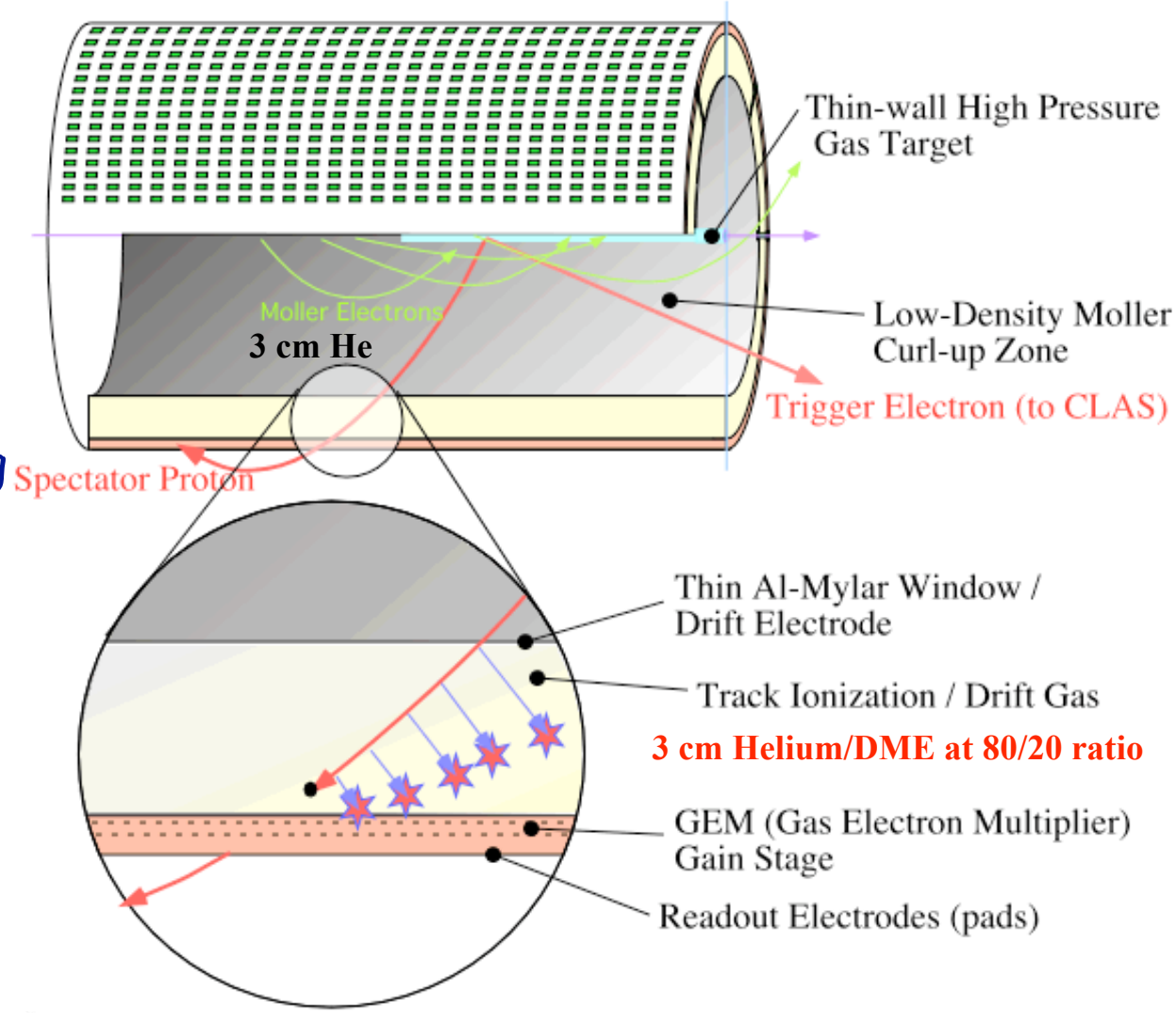
~50 $\mu$m

140 $\mu$m

φ, z from pads, r from time

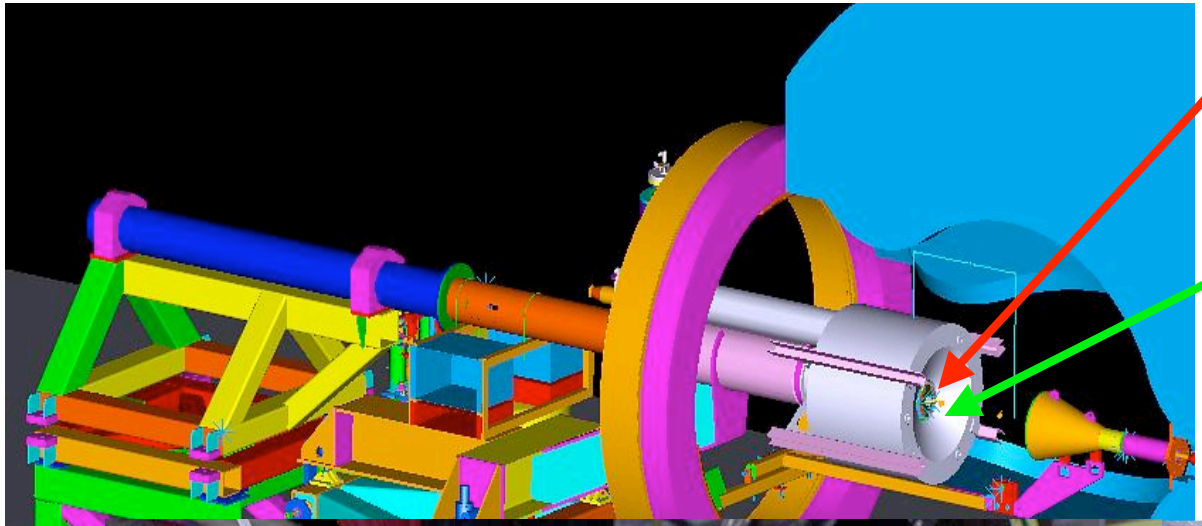
dE/dx from charge along track (particle ID)

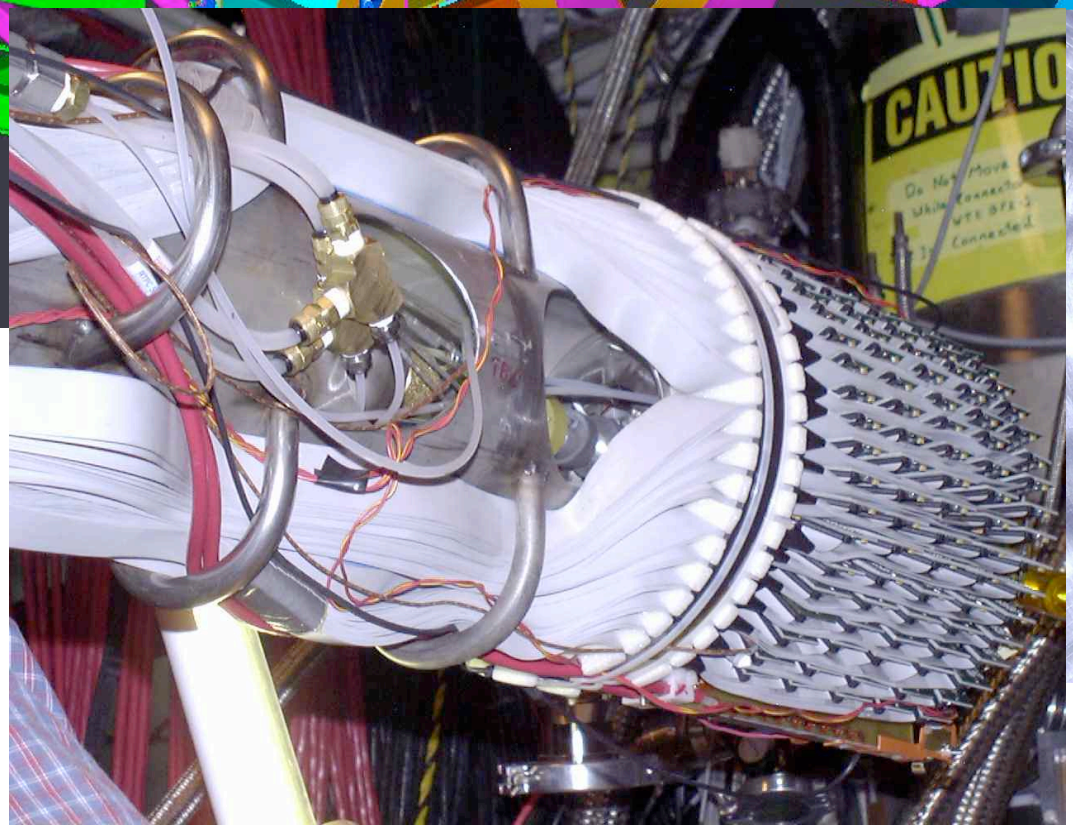


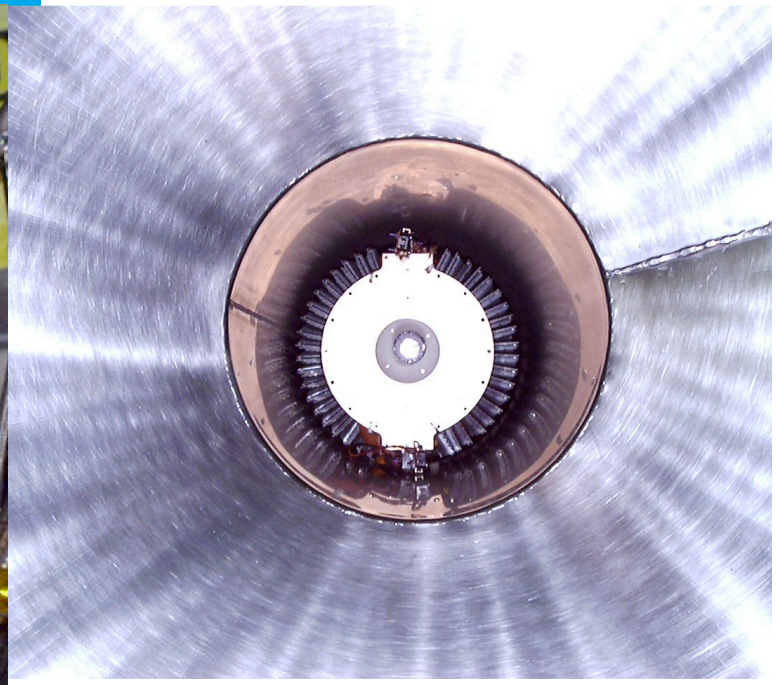




Stagger pads in z to improve theta angle reconstruction

# BONUS in CLAS



# BONUS in CLAS (Hall B at Jefferson Lab)

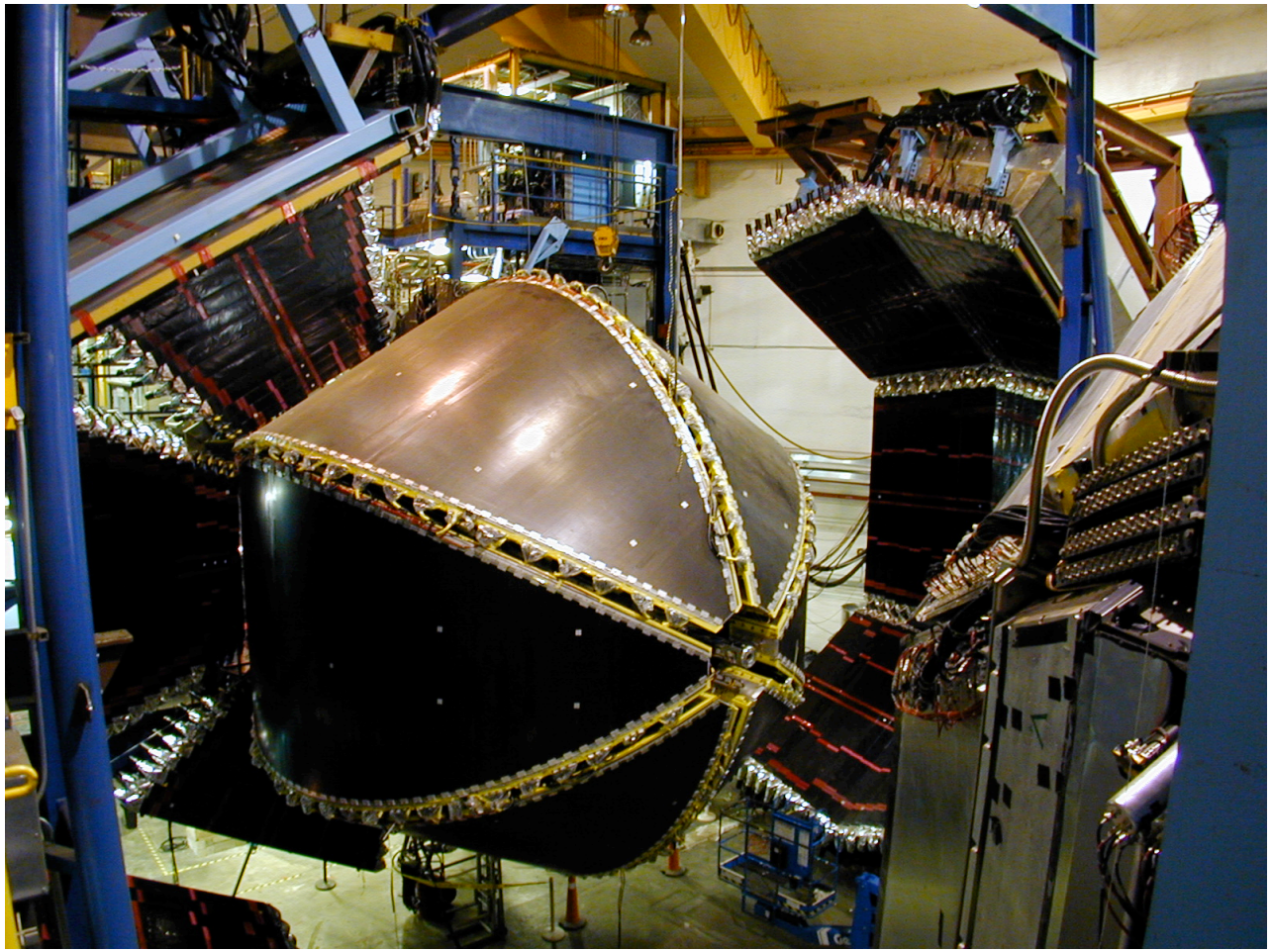
rTPC inside Solenoid inside CEBAF Large Acceptance Spectrometer (CLAS)

Track scattered $e^-$ in CLAS

Locate $e^-$ interaction point in target.

Electron tracked in CLAS provides trigger to BoNuS radial TPC

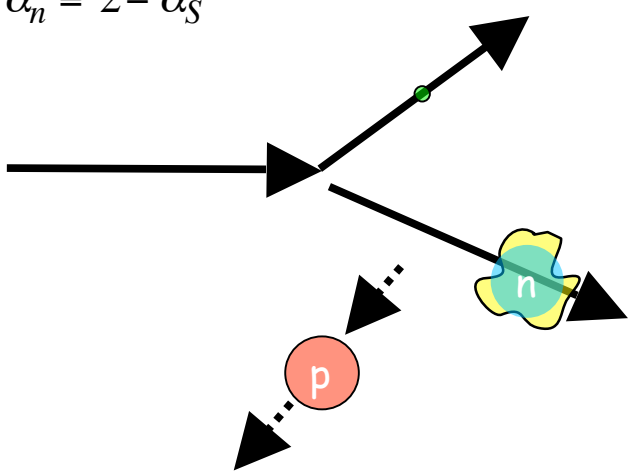
Link $p_{spectator}$ with electron vertex.



CLAS is made of Drift Chambers, Time of Flight Scintillators, Cerenkov counters and Electromagnetic Calorimeters for tracking, momentum determination, and Particle ID

# Spectator Tagging - results

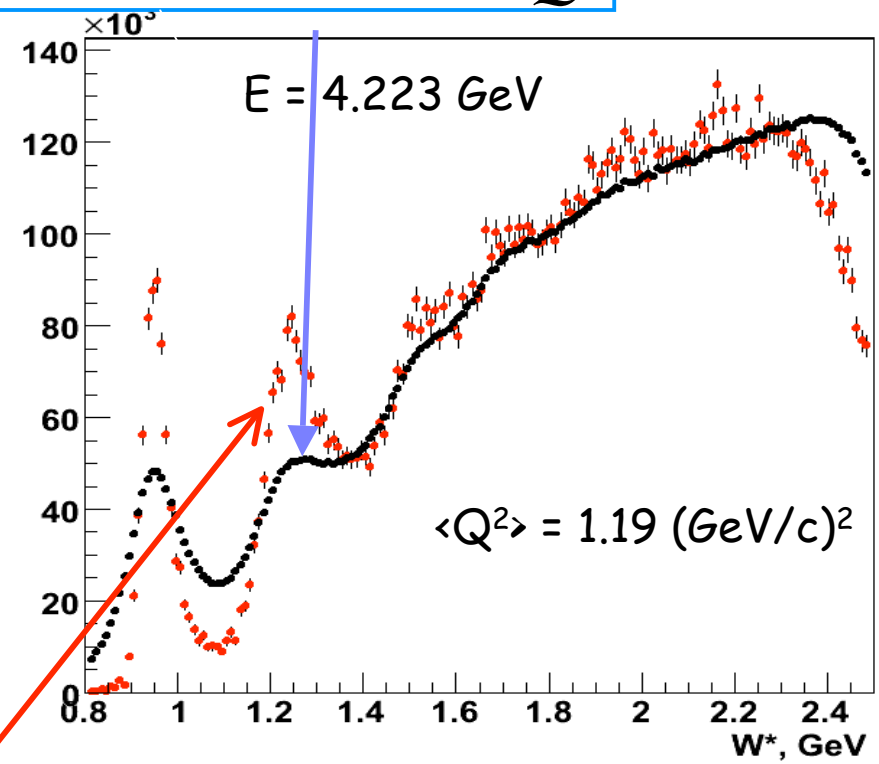
$$p_n = (M_D - E_S, -\vec{p}_S);$$
$$\alpha_n = 2 - \alpha_S$$



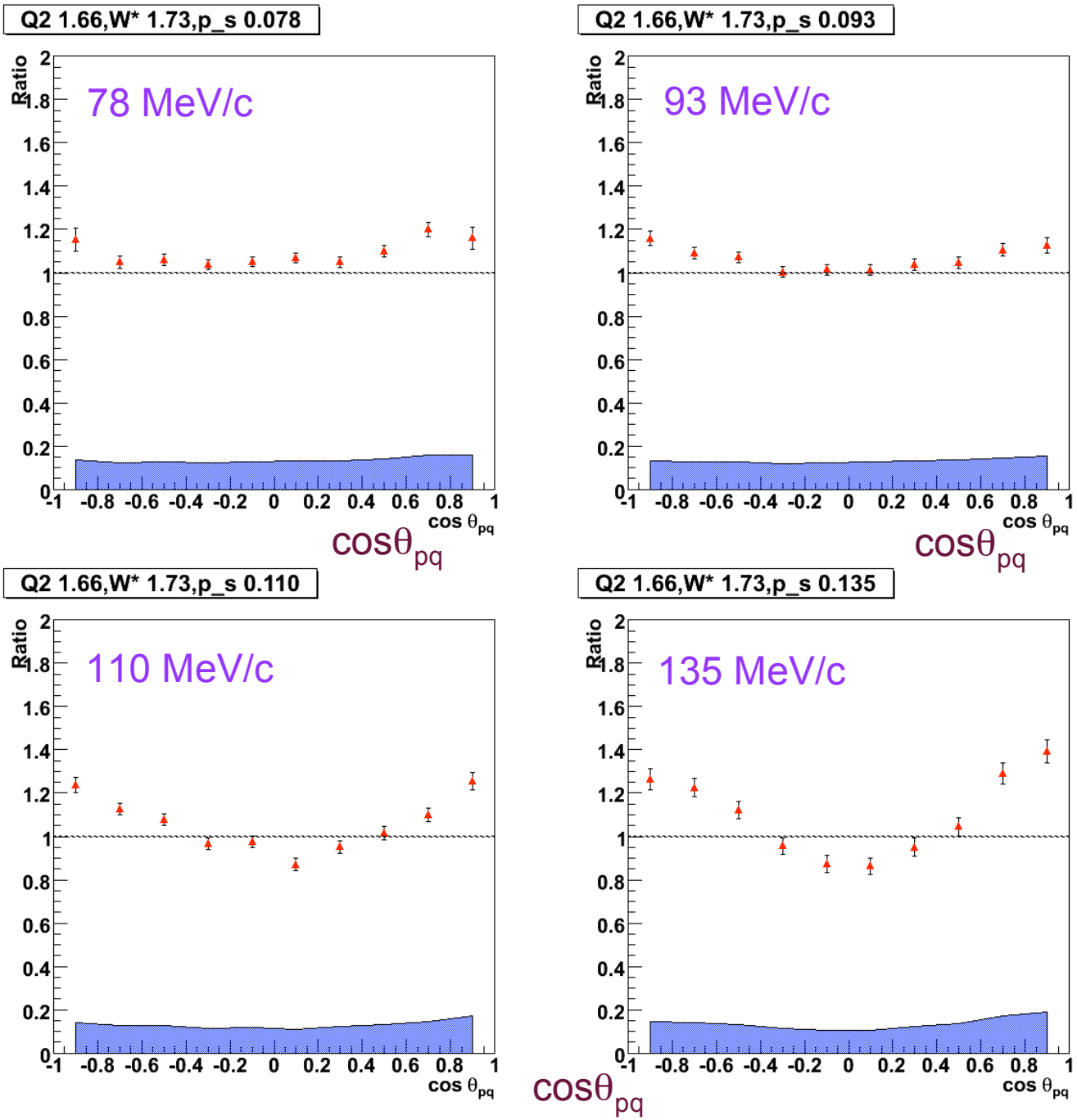

$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

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

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




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



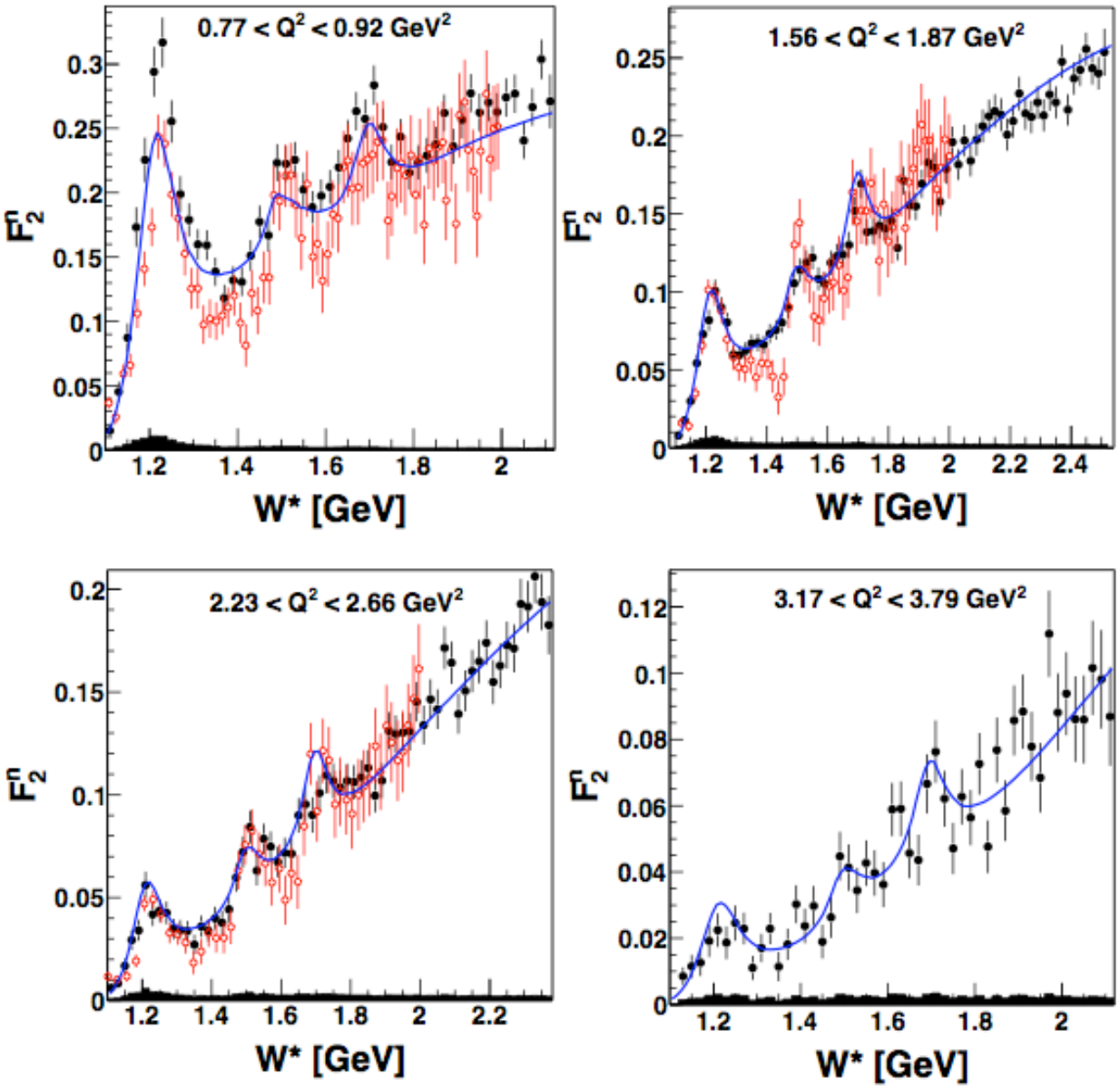

# Angular dependence

$Q^2$ = 1.66 $GeV^2$
W* = 1.73 GeV

- No significant deviations from PWIA ($p_s$< 100 MeV/c), first 2 panels

- Possible θ dependence at higher momenta

# Neutron Structure Function - results

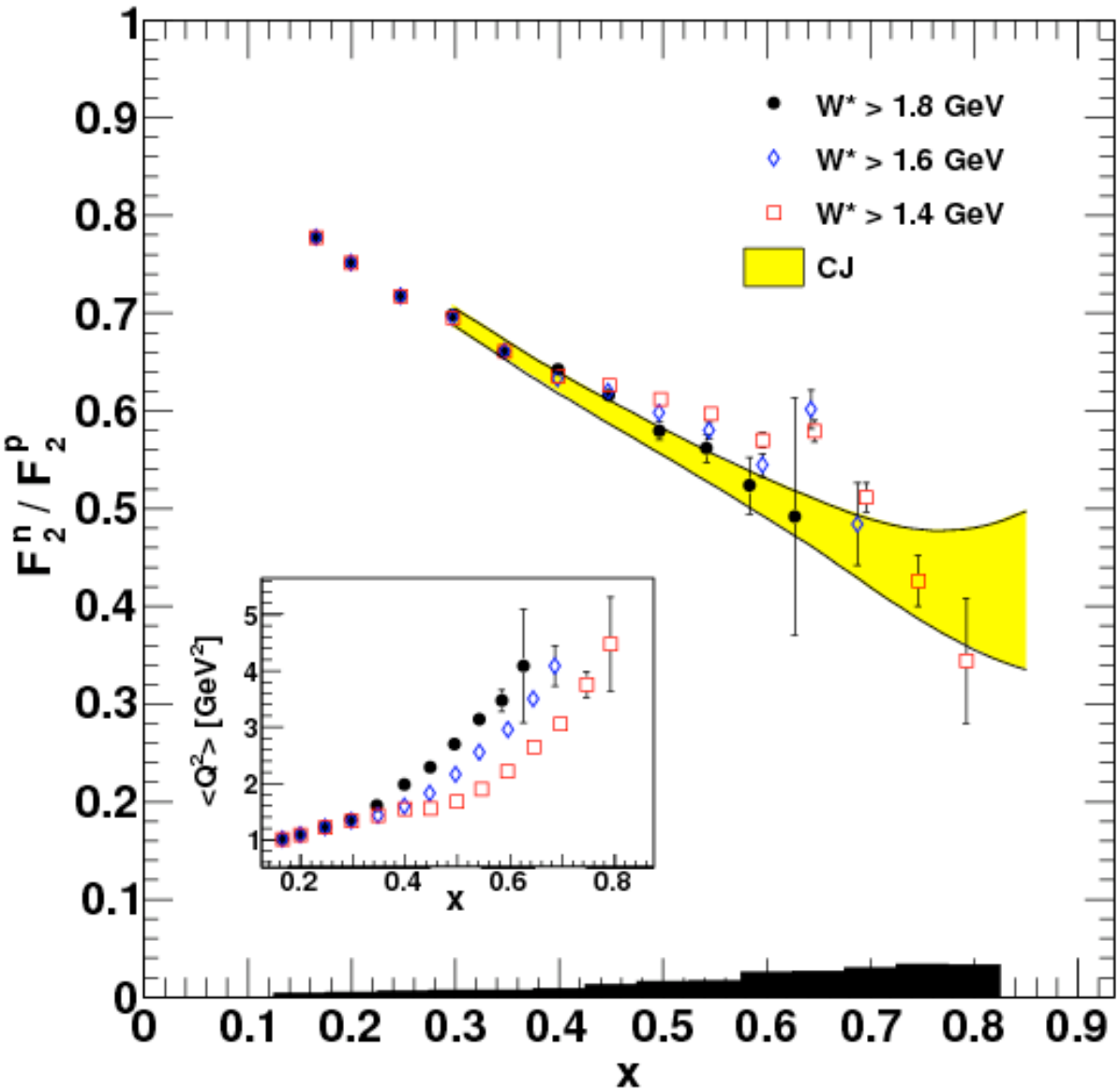



BONUS neutron data

Christy-Bosted fit

S.P. Malace *et al* analysis of deuterium data (Phys.Rev.Lett.104: 102001, 2010)

# Extracted $F_2^n/F_2^p$ (N. Baillie analysis)




- BONUS actually measures (n/d)*(d/p)

- RTPC tagged / untagged * precision d/p data on ratios at same kinematics (Hall C)

$P_{spectator} < 90$ MeV/c

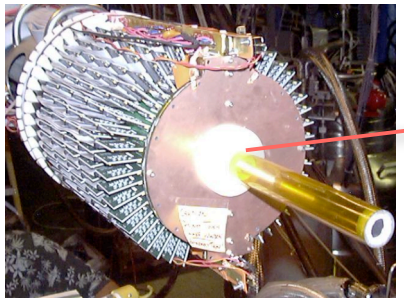
$\theta_{spectator} < 90$

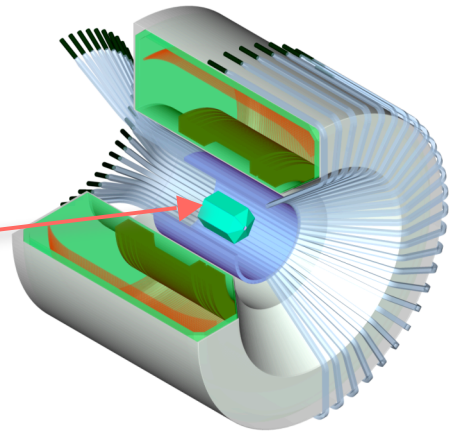
- Different $Q^2$ ranges for different x, W

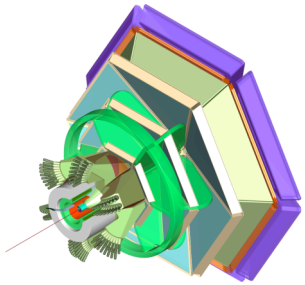
# Plans for 12 GeV

BONUS

E12-06-113

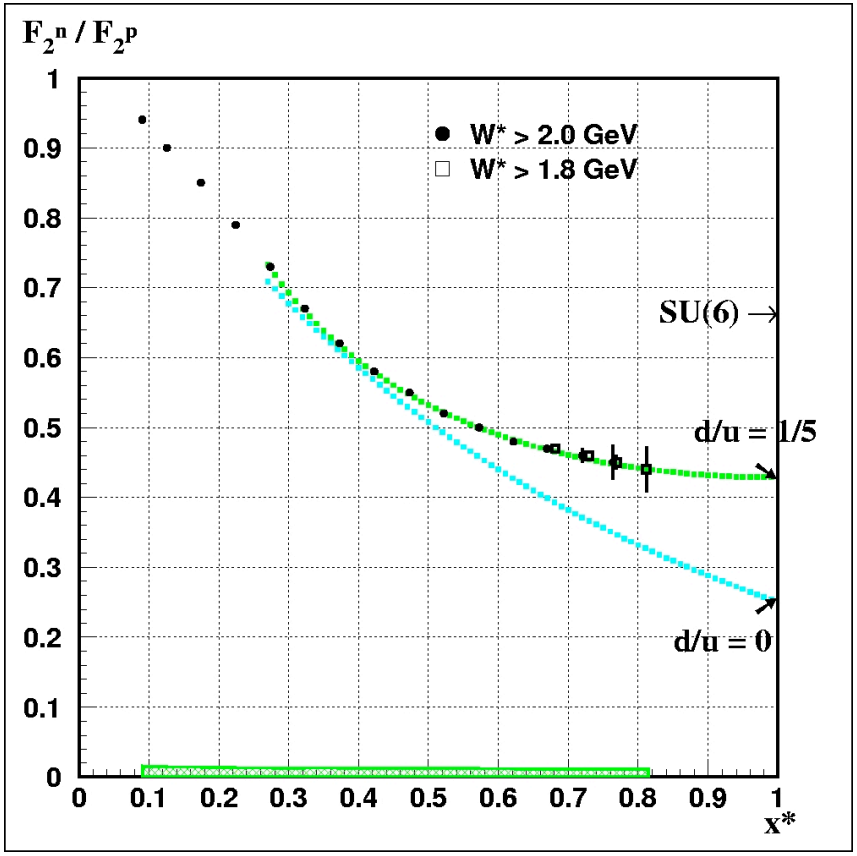






CLAS12 Central Detector

- Data taking of 35 days on $D_2$ and 5 days on $H_2$ with $L = 2 \cdot 10^{34}$ cm$^{-2}$ sec$^{-1}$
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- 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. $x^* = 0.83$



# Conclusions

- Effective free neutron target technique demonstrated (other experiments now utilizing / proposing)
- Large x n/p results consistent with CJ2011 pdf analysis
- Neutron resonance structure functions to be studied in detail, quark-hadron duality
- Detailed CLAS analysis note final
- Publication draft under review
- BONUS12 proposal approved