# Structure Functions of Bound Neutrons

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# Overview

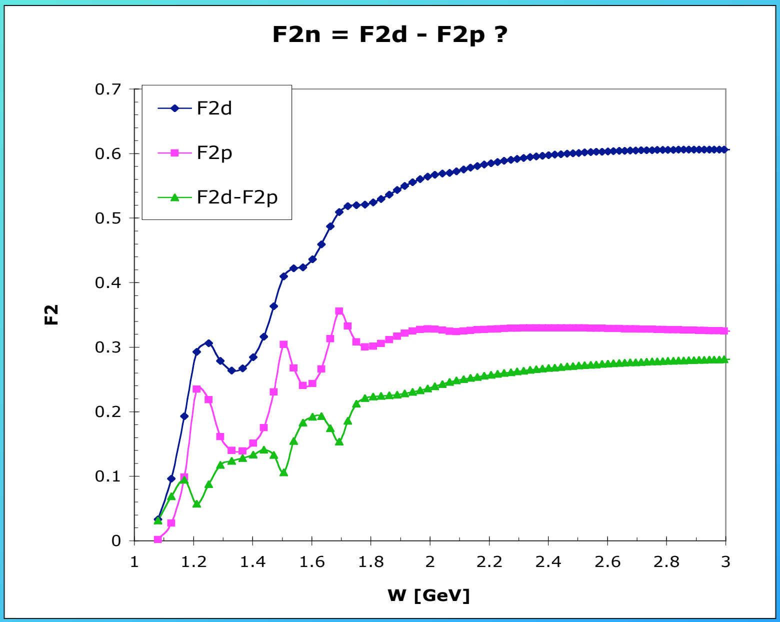
- Extracting neutron information from deuterium targets: Problems and challenges
- “Spectator Tagging”
- The “Deeps” experiment
- Results
  - Momentum distributions
  - Final state interactions
  - Structure Functions
- Future Plans and Summary

# Structure Functions of the Neutron

- Simple subtraction (deuteron-proton) yields nonsense
- Kinematic shift of the effective Bjorken variable x

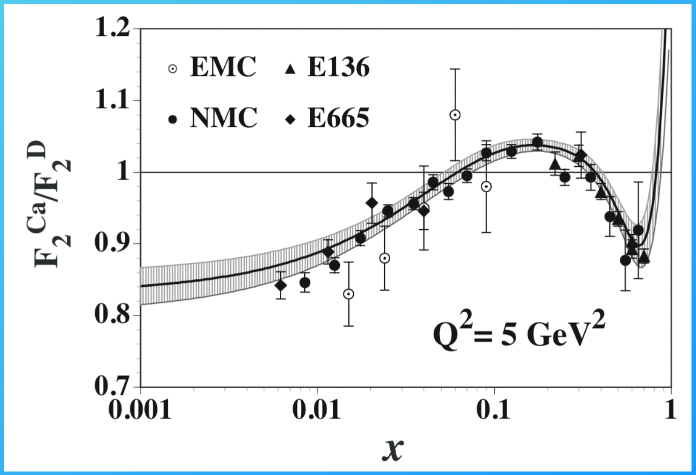
$$x_{\text{measured}} = \frac{Q^2}{2M\nu} \qquad x_{\text{relevant}} = \frac{Q^2}{2\left(E_n\nu - \vec{p}_n\cdot\vec{q}\right)}$$

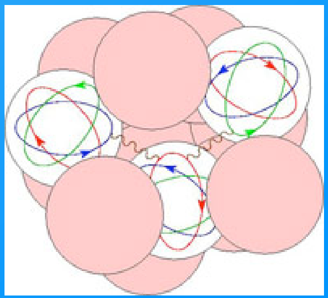
| | |
|---|---|
| 0.70 | 0.69 |
| 0.80 | 0.78 |
| 0.90 | 0.85 |
| 1.00 | 0.90 |




+ Binding effects, coherent scattering, final state interactions, non-nucleonic degrees of freedom in the ground state

("EMC"-effect)



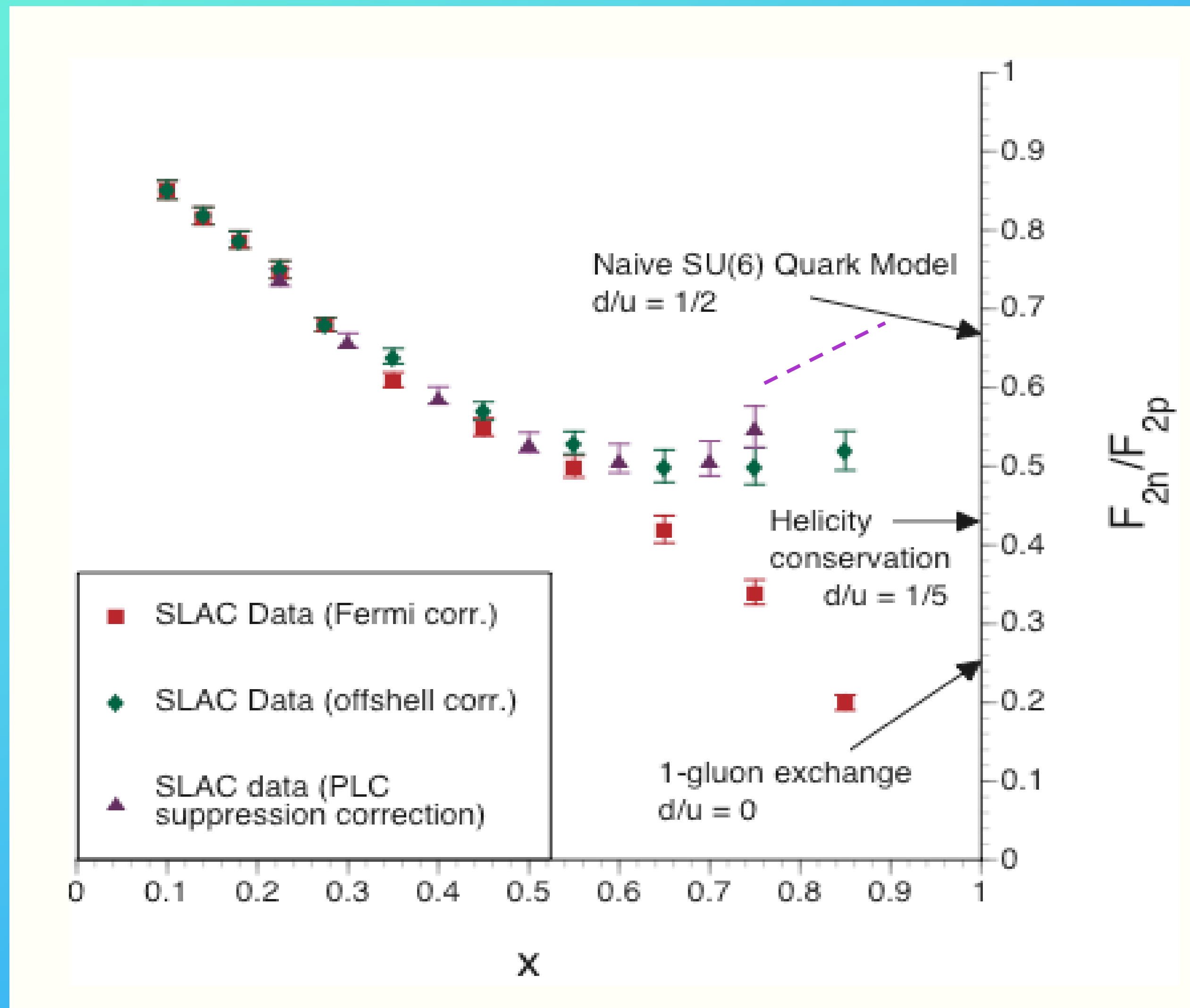
# Problem: d/u (x → 1)

Quark momentum / Nucleon momentum

(Momentum transfer)$^2$

$$x = \frac{Q^2}{2m\nu}$$

Nucleon mass   Energy transfer




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

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

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

???

# What can we do?

To learn more about the structure of the neutron and avoid these difficulties, we can study modifications of the neutron structure for bound neutrons in detail, to single out the best theoretical description of binding effects…

OR

…we can select the part of the "deuteron wave function" where binding and off-shell effects are minimized.

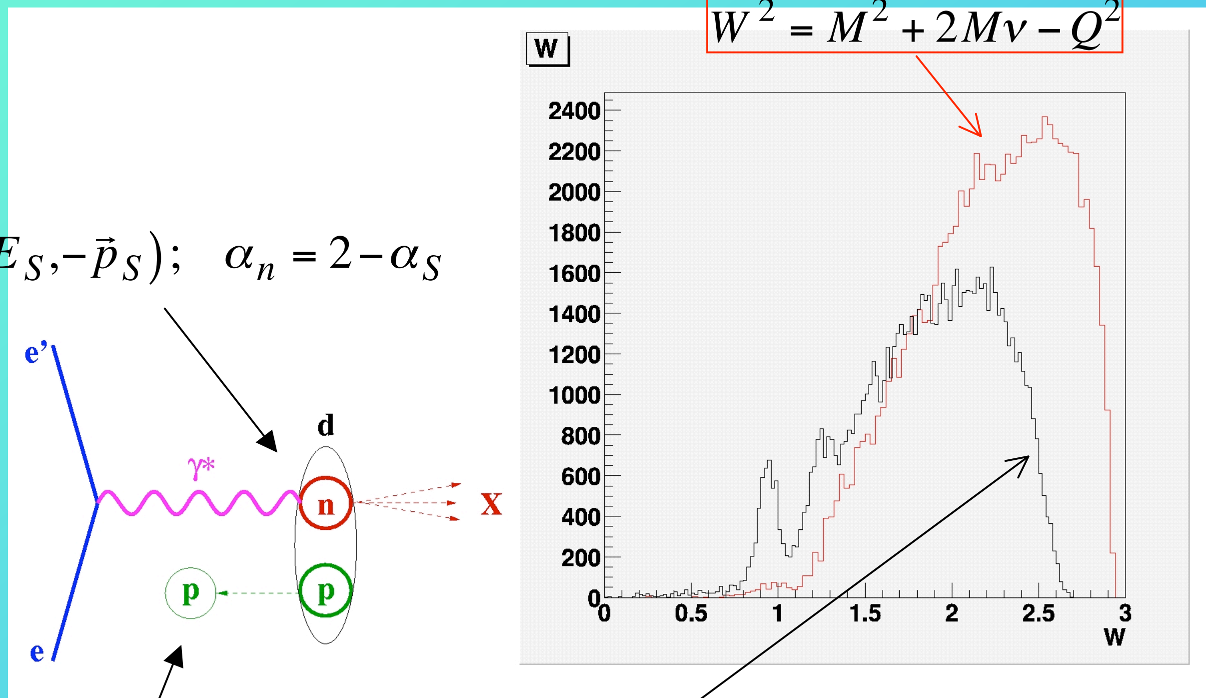
Method (in both cases): Lepton scattering off the deuteron with simultaneous detection of a "backwards going" proton:

$$D(e,e'p_s)X$$

# "Spectator Tagging"

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

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




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

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

$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

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

# Deviations from free structure function:
# *Off-shell Effects*

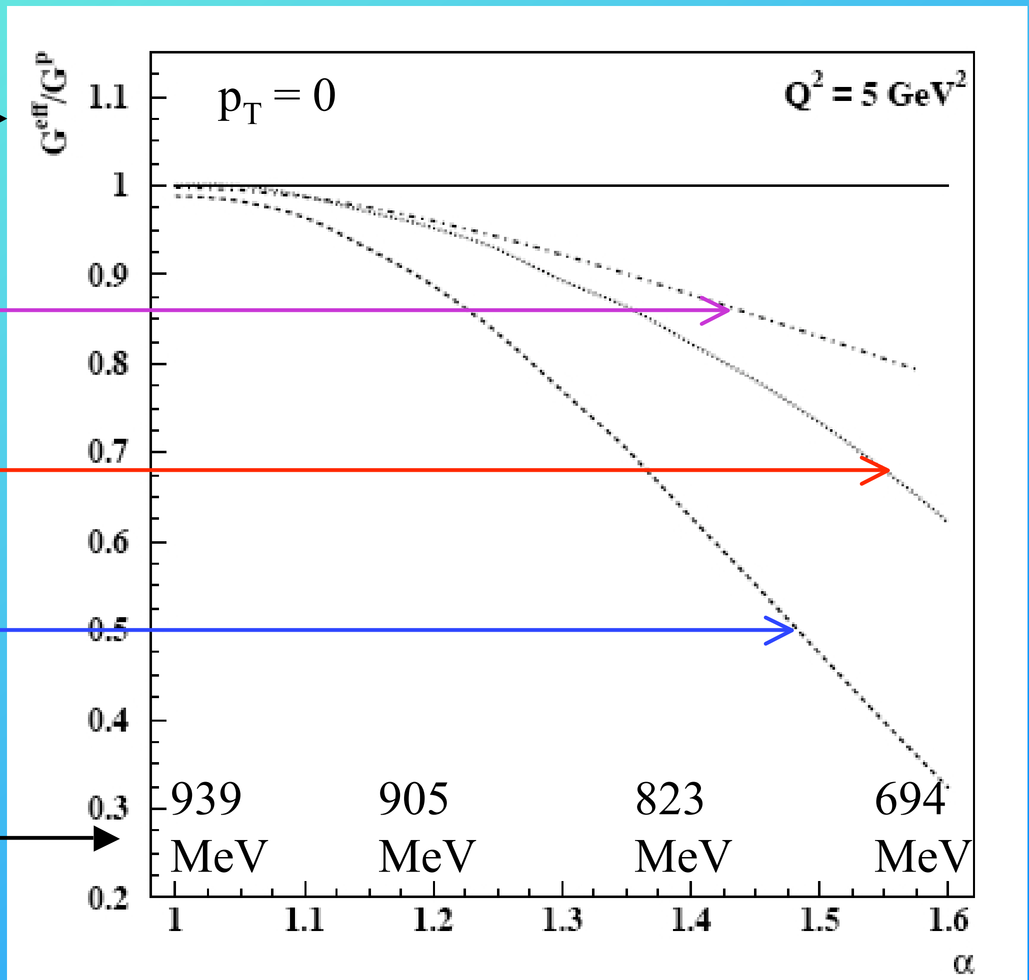
$$\frac{F_{2N}^{eff}(x=0.6,Q^2,\alpha)}{F_{2N}^{eff}(x=0.2,Q^2,\alpha)}$$

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

**Color delocalization Close et al.**

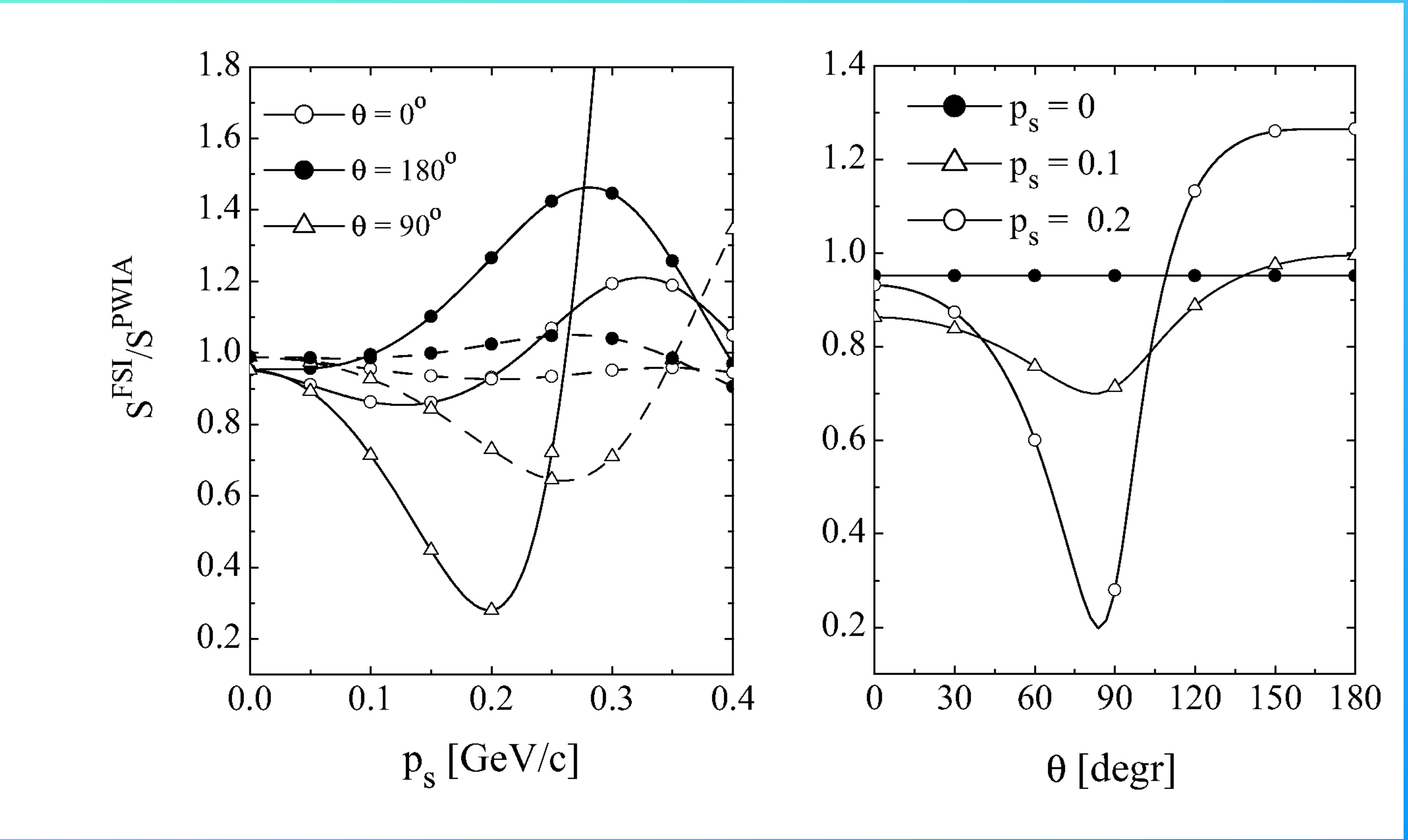
**Suppression of "point-like configurations" Frankfurt, Strikman et al.**

"Off-shell" mass of the nucleon M*




$P_s$ = 0 0.09 0.17 0.25 0.32 0.39 GeV/c

# Deviations from the simple "spectator"picture:
# *Final State Interaction*

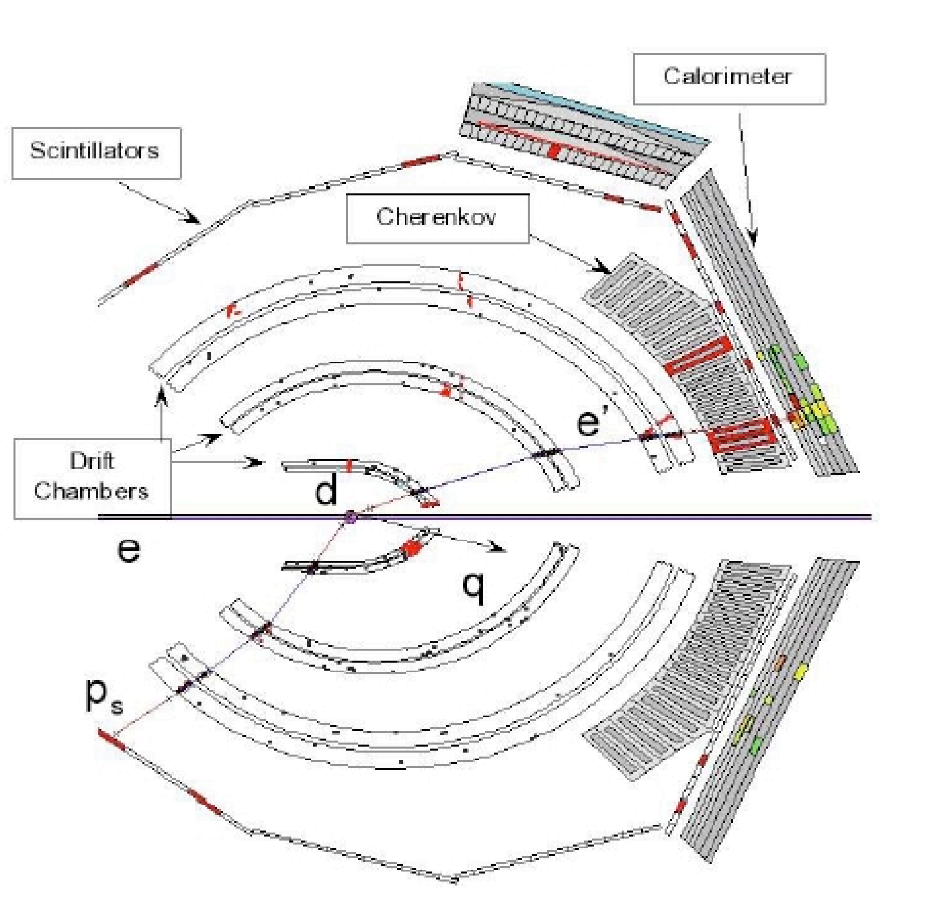



Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

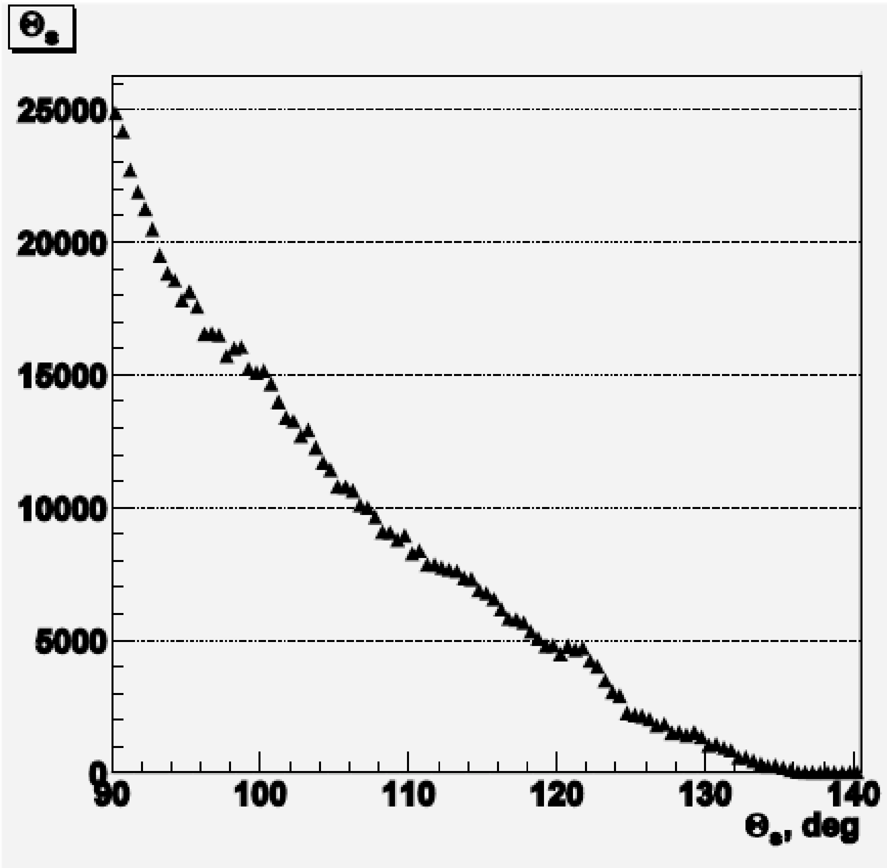
# Modification of Bound Neutrons - the $D(e,e'p_s)$ Experiment

- Experiment 94-102 at Jefferson Lab
- Run period "E6" in Hall B (CLAS)
- 5.75 GeV / 7 nA Electrons on a 5 cm long $LD_2$ target => $L=10^{34}/cm^2s$
- 8 calendar weeks in spring of 2002; 4.5 billion triggers
- CLAS-Collaboration and 2 Ph.D. students:
  Dr. Alexei Klimenko (ODU)
  and Cornel Butuceanu (W&M)

# Experimental Details



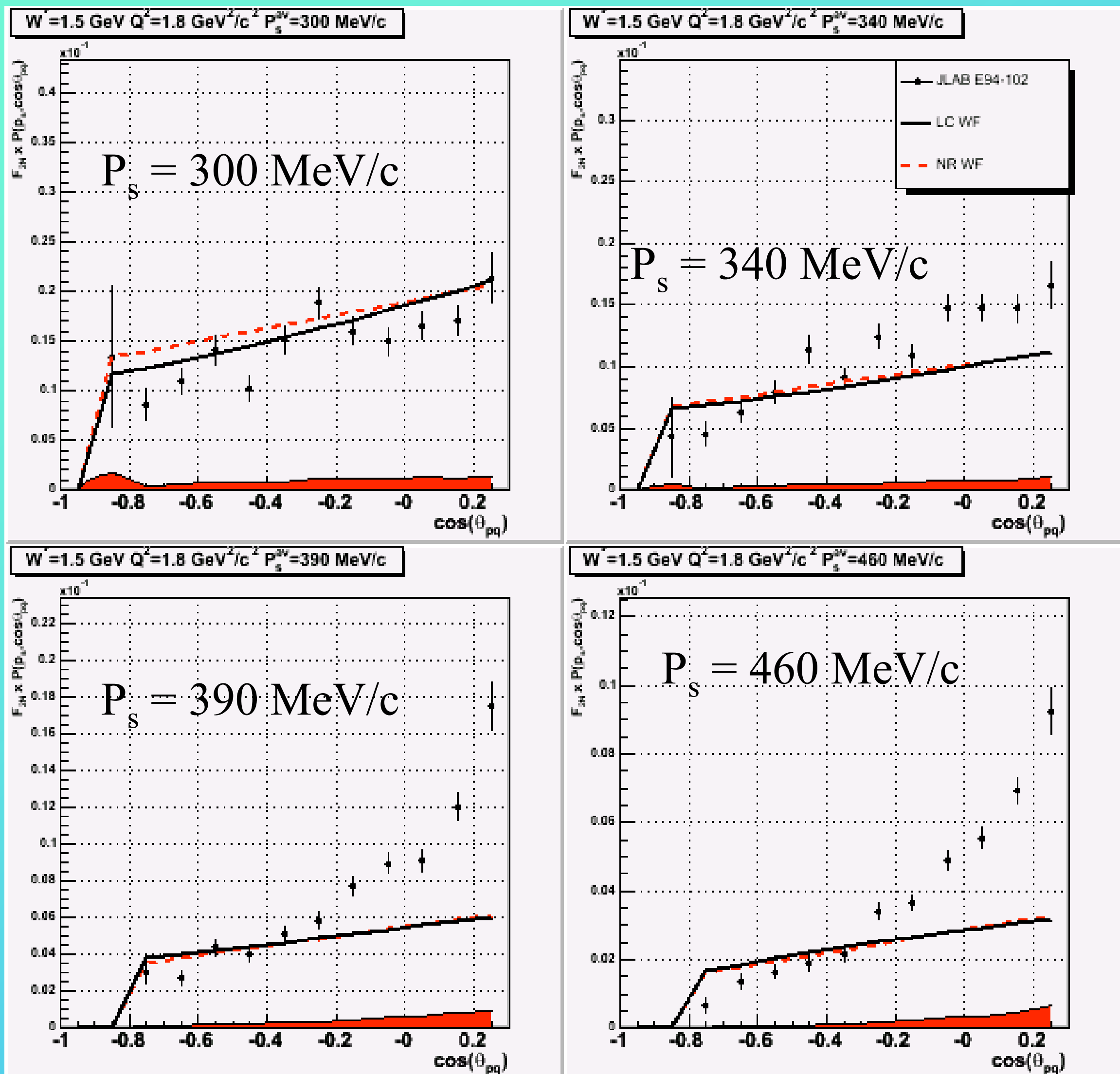

A typical event




Acceptance for protons in the backward hemisphere

# Results: Angular Distribution (W = 1.5 GeV)

$P(p,\theta_{pq})*F_{2n}(x^*,Q^2)$




Cosine of the angle between proton and momentum transfer

Vertical Axis: cross section divided by kinematic factors => $P(p,\theta_{pq})*F_{2n}(x^*,Q^2)$

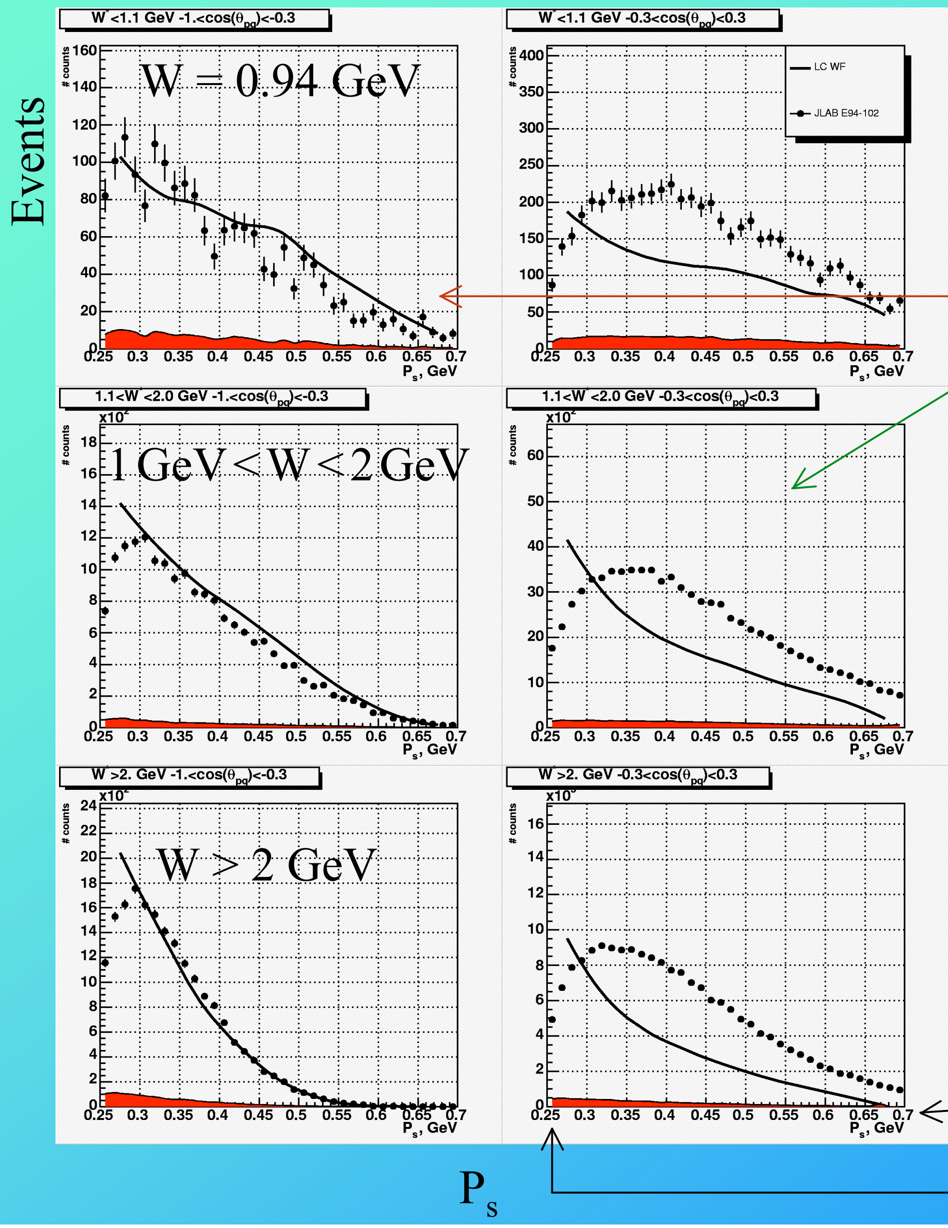
Unobserved final state in the mass range of the $S_{11}/D_{13}$ - resonances (1.5 GeV ± 0.125 GeV)

$Q^2 = 1.8\ GeV^2$

Different momenta of the detected protons

Lines: PWIA model with “light cone” or non-relativistic wave function for deuterium

# Results: Momentum Distribution




Vertical axis: Number of events

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

**Left: Angular range > 107.5$^{O}$**

**Right: Angular range 72.5$^{O}$ - 107.5$^{O}$**

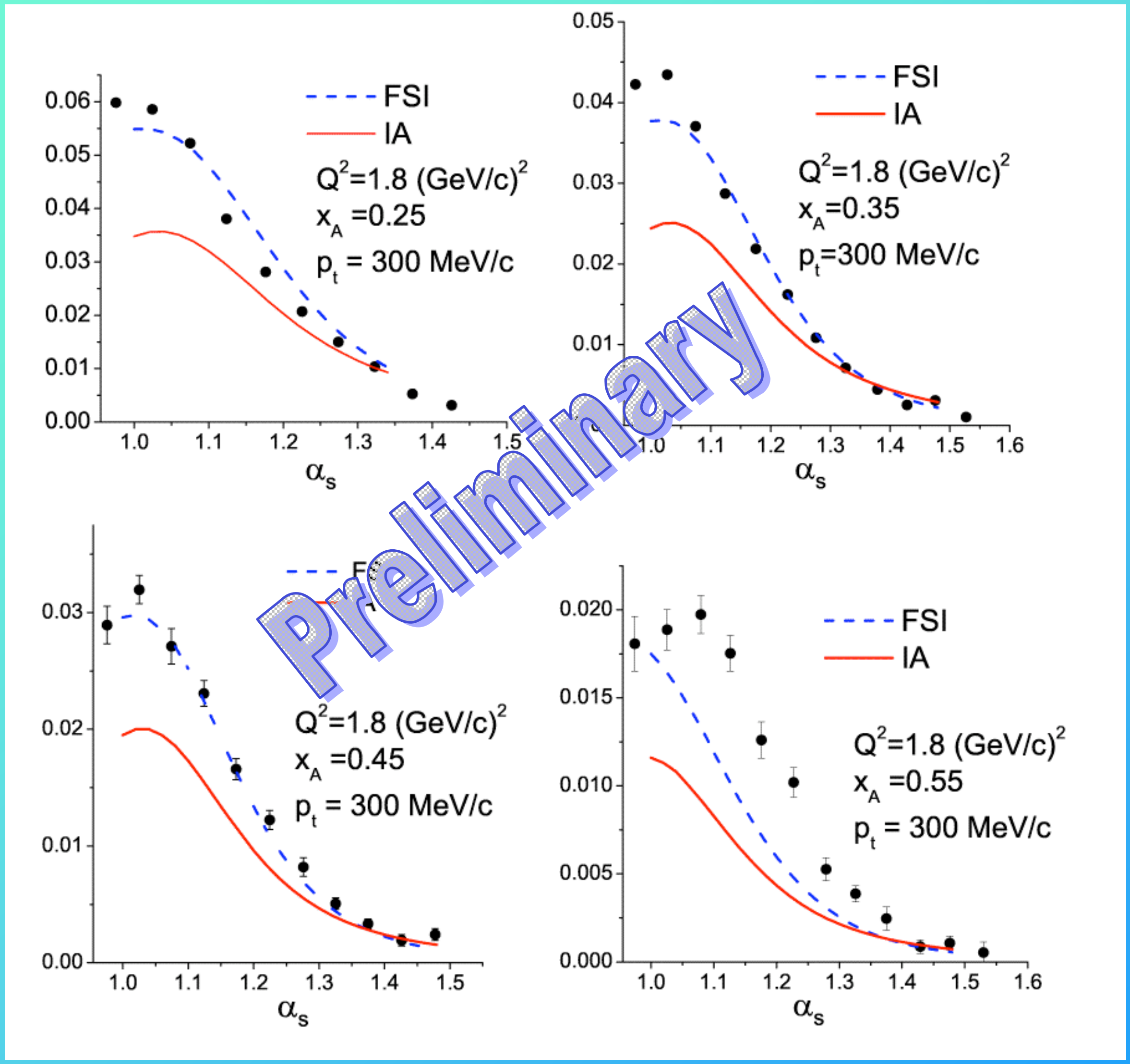
3 different ranges in the final state mass W of the unobserved struck neutrons

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

700 MeV/c

250 MeV/c

# Results: Dependence on $\alpha_s$ and $x^*$




Vertical axis: cross section divided by kinematic factors
$= S^{DWIA}(\alpha,p_T)*F_{2n}(x^*,Q^2)$

4 different values for $x^*$

Calculation by C. Ciofi degli Atti et al.

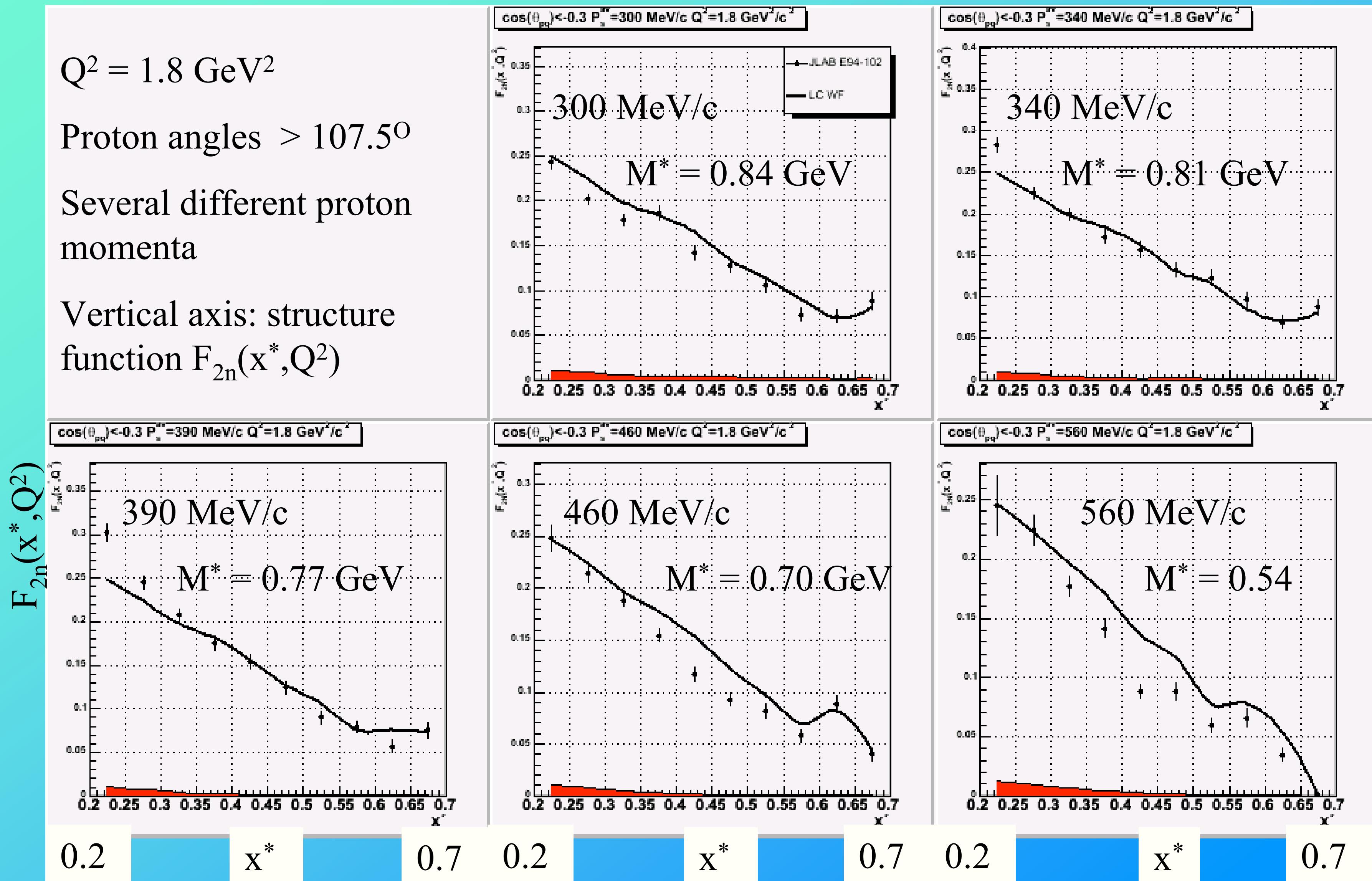
# Results: $x^*$ dependence

$Q^2 = 1.8\ GeV^2$

Proton angles $> 107.5^O$

Several different proton momenta

Vertical axis: structure function $F_{2n}(x^*,Q^2)$

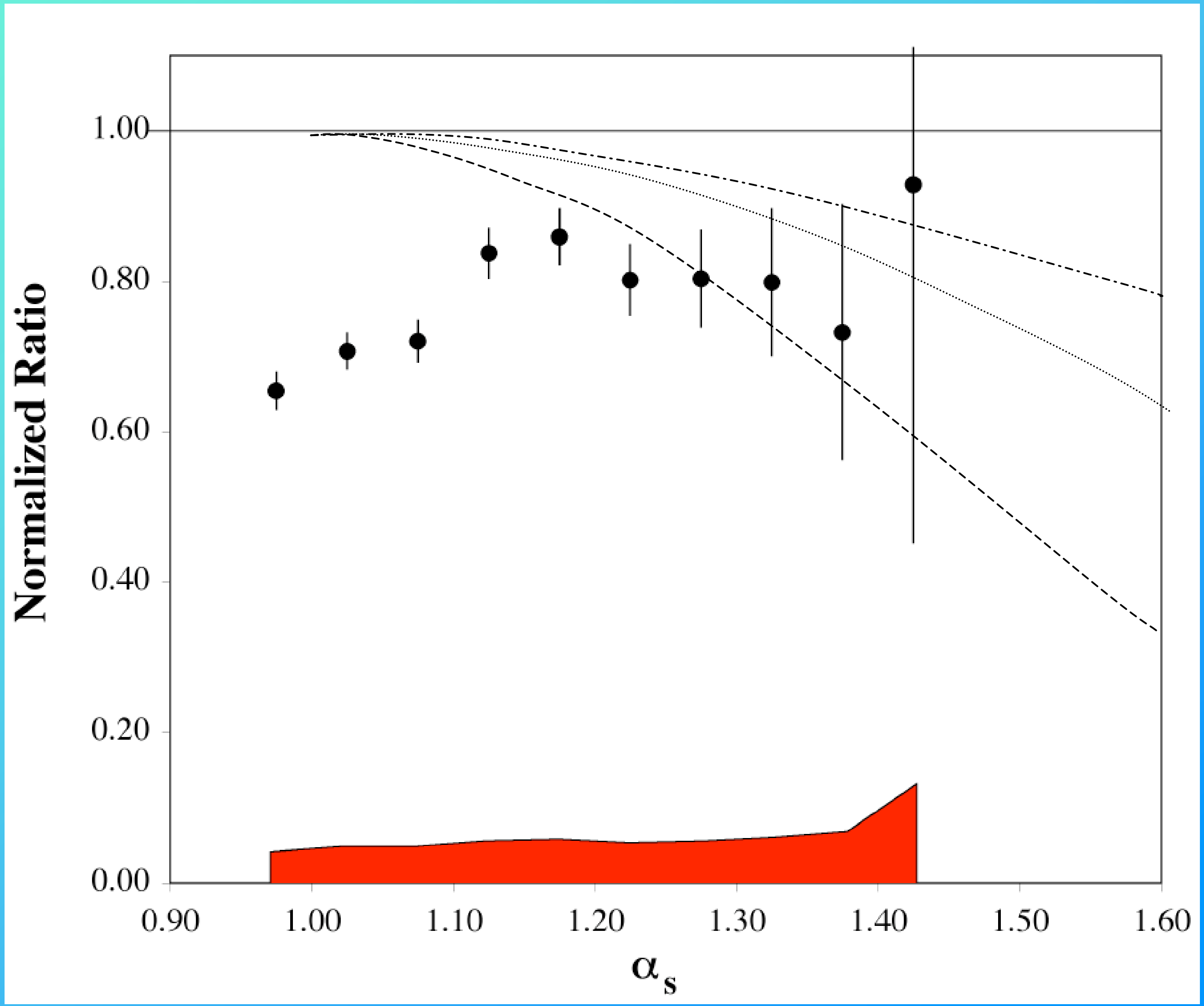


# Results: Ratio test

Ratio =

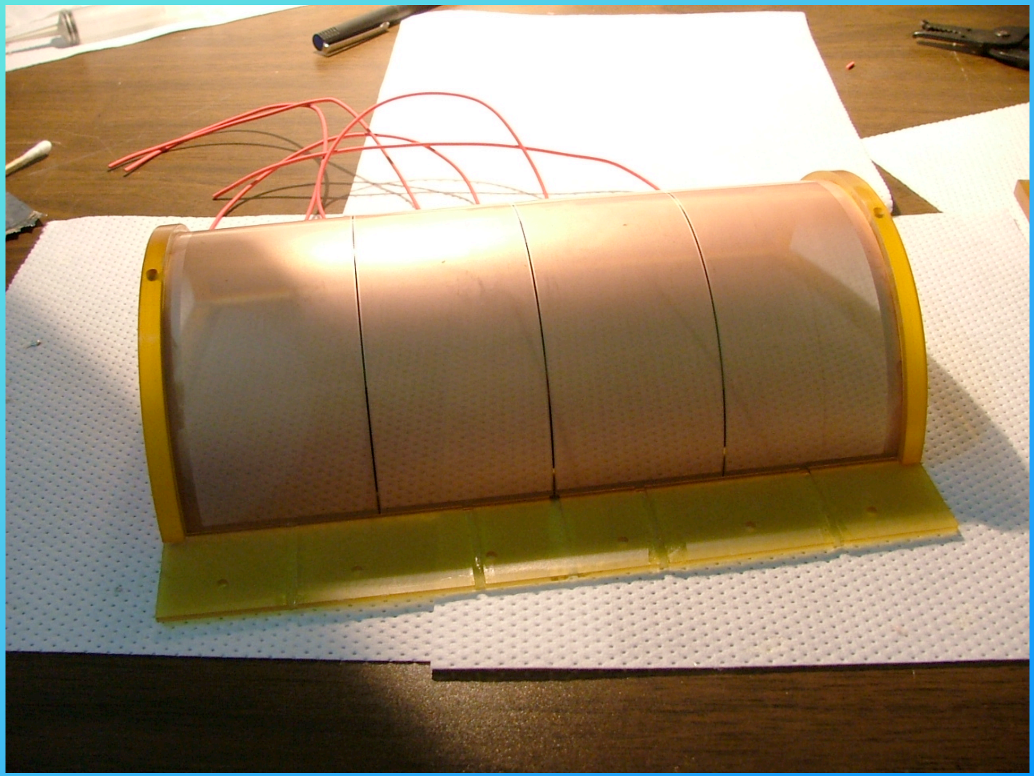
$$\frac{\dfrac{\sigma(x^*=0.55,\alpha_s)}{\sigma(x^*=0.25,\alpha_s)}(\text{bound n})}{\dfrac{\sigma(x=0.55)}{\sigma(x=0.25)}(\text{free n})}$$

- Independent of deuteron WF
- Mostly sensitive to off-shell effects at large x
- Fixed $p_T = 0.3$ GeV/c



# Inclusive Scattering off a "free" Neutron - the BoNuS* Experiment

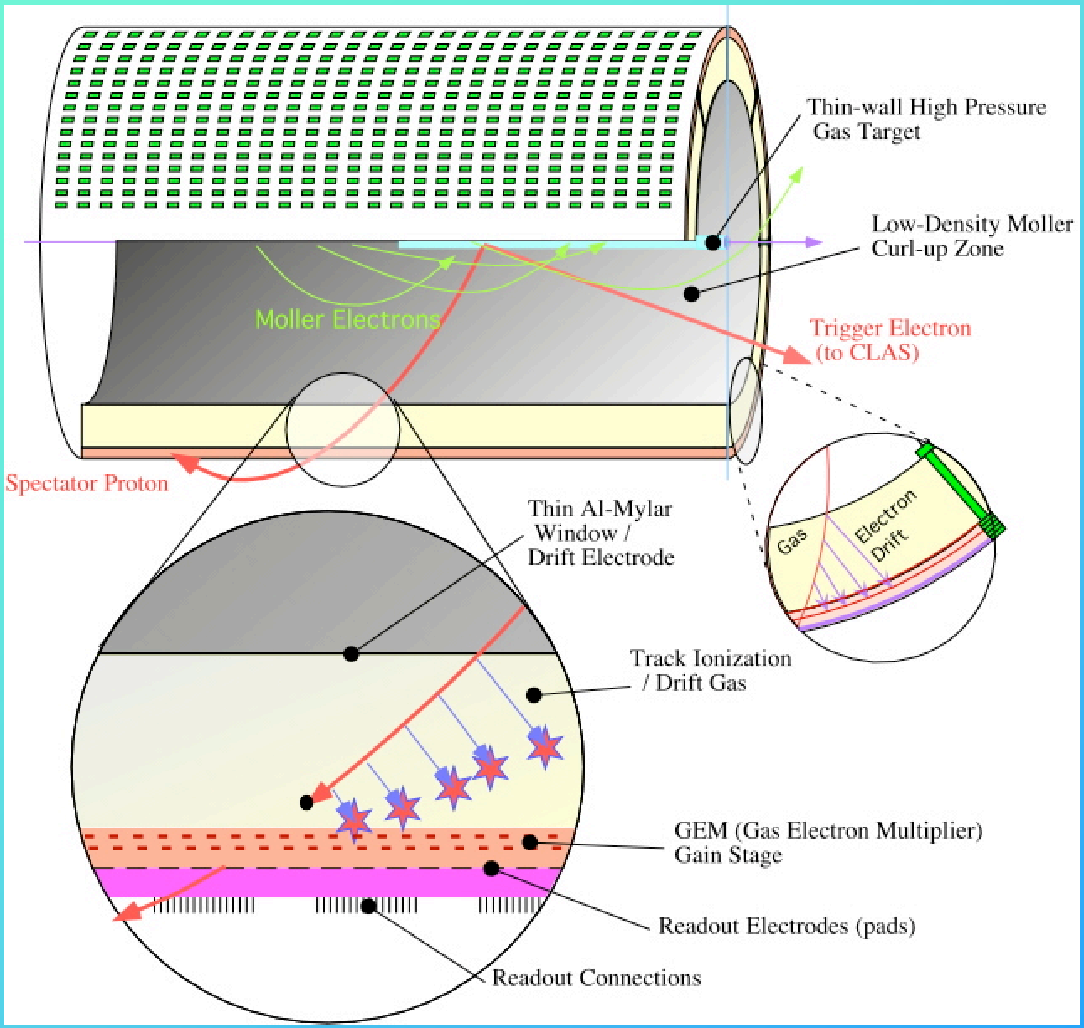
- Experiment 03-012 at Jefferson Lab in Hall B (CLAS)
- 4 and 6 GeV / 200 nA electrons impinging on a 4 mm Ø, 20 cm long $D_2$ gas target (7 atm) => $L = 0.4 \cdot 10^{34}/\text{cm}^2\text{s}$
- PAC-approved for 2 calendar months of running (Fall 2005)
- Old Domininon Univ., Jefferson Lab, Hampton Univ., William & Mary, James Madison Univ., and the CLAS collaboration



Radial TPC GEM foil plane

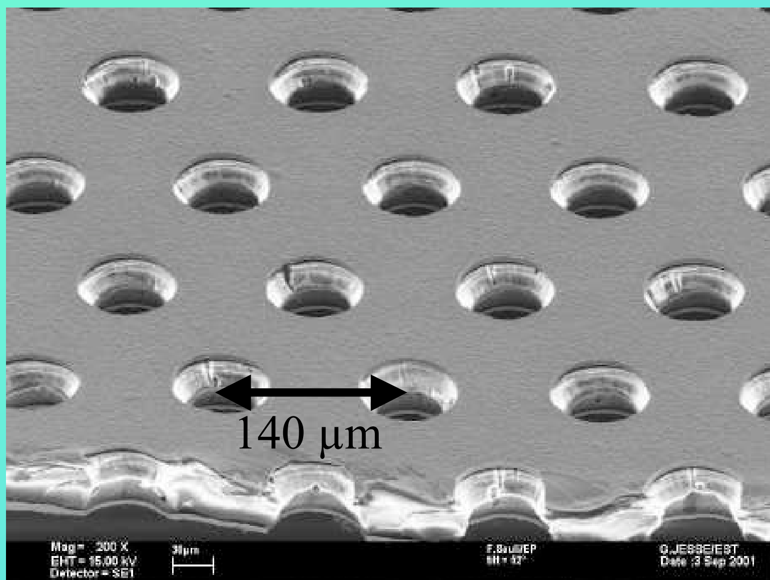
* BoNuS = **B**arely **o**ff-shell **Nu**cleon **S**cattering

# Target-detector system for slow protons

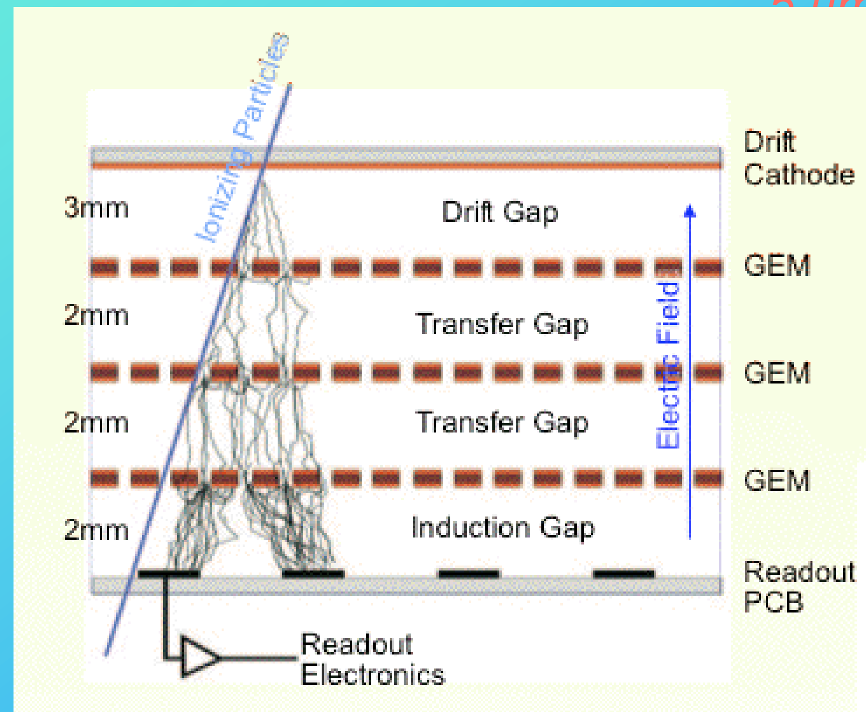


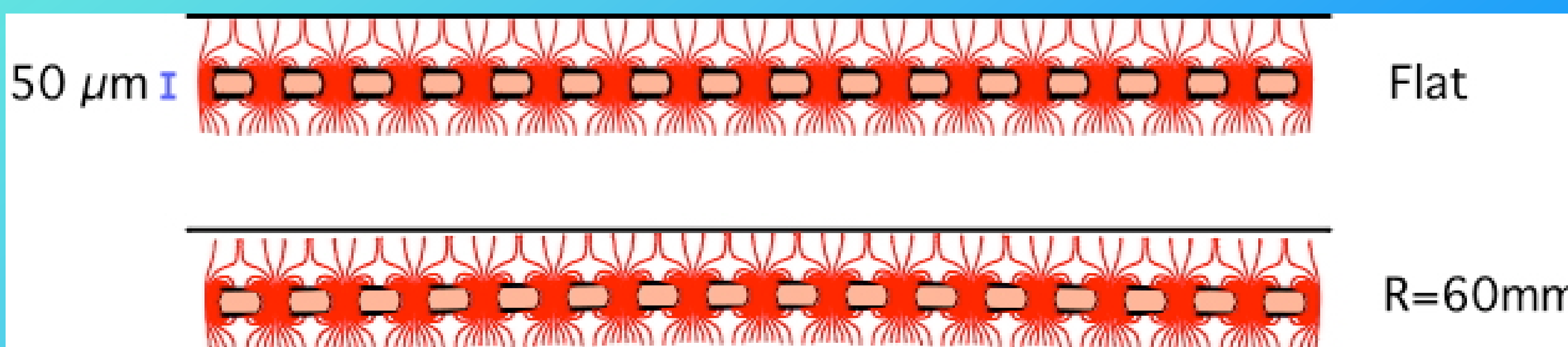

- Thin-walled gas target (7 atm., room temperature)
- **R**adial **T**ime **P**rojection **C**hamber (RTPC) with **G**aseous **E**lectron **M**ultipliers (GEMs)
- 2 Tesla longitudinal magnetic field (to suppress Möller electrons and to measure momentum)
- 3-dimensional readout of position and energy loss (“pads”)

# RTPC - GEMs

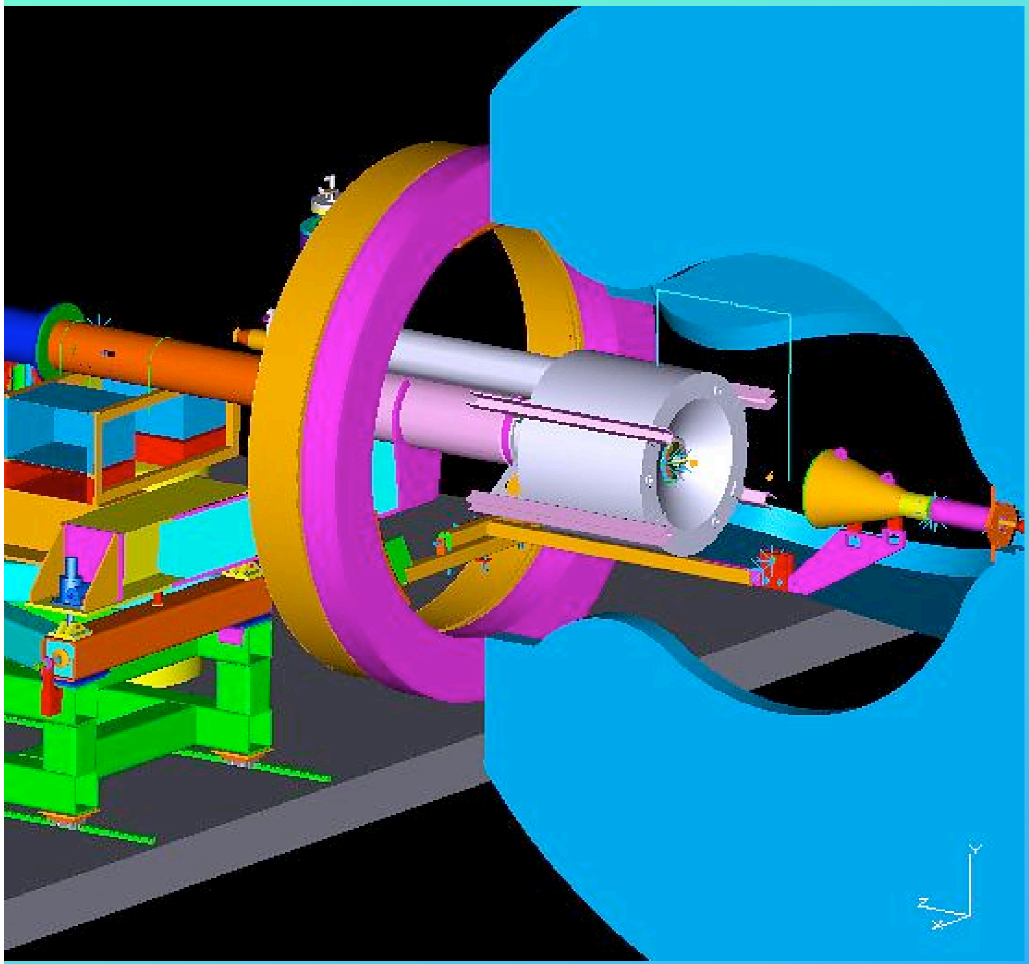


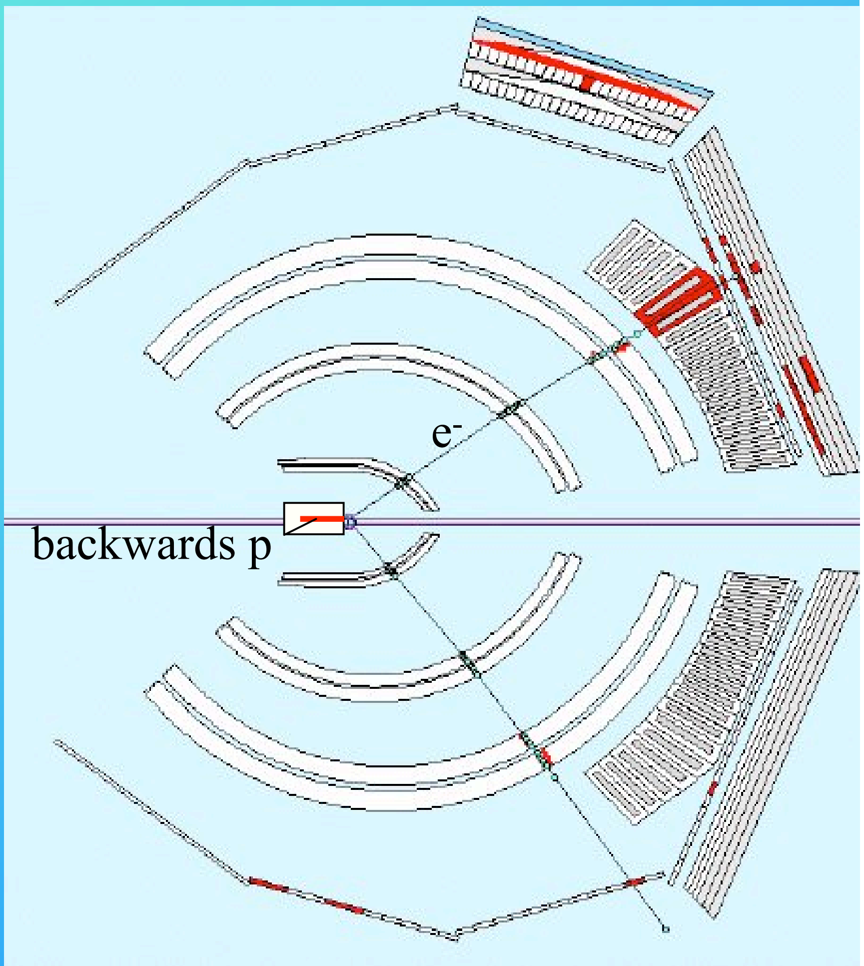

300-500 V, Gain 100-200



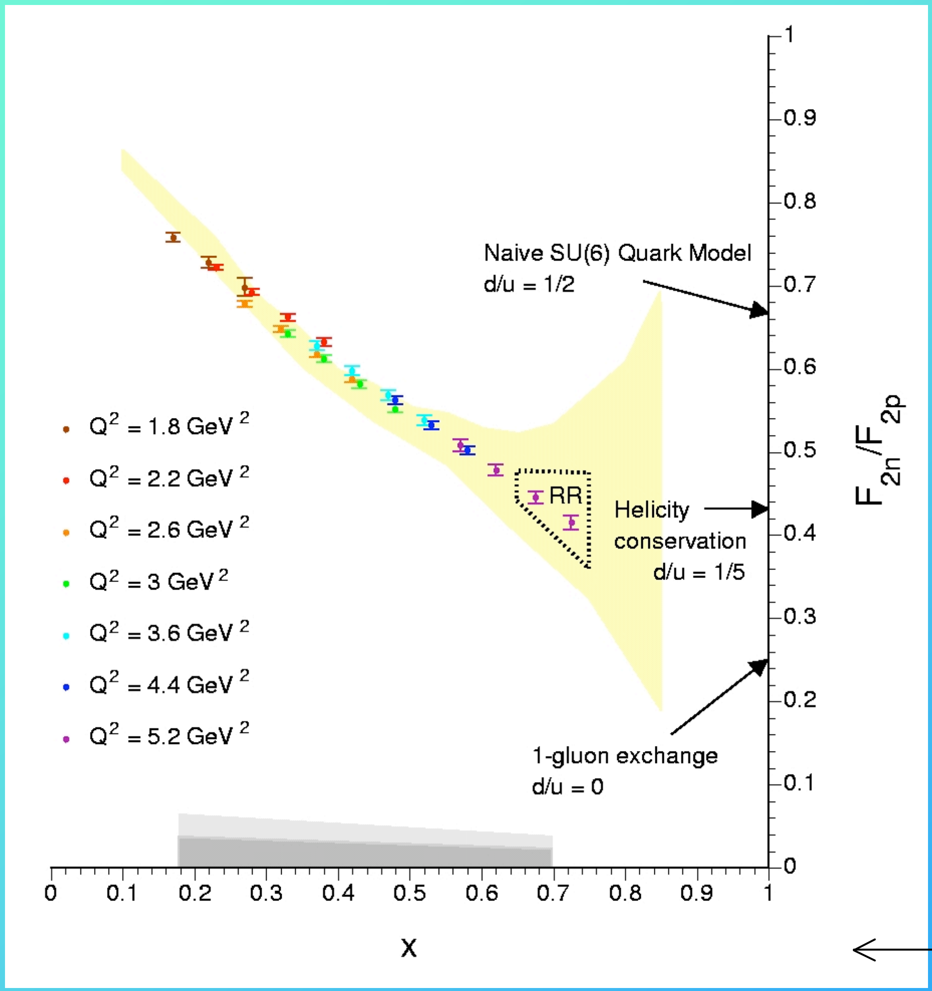



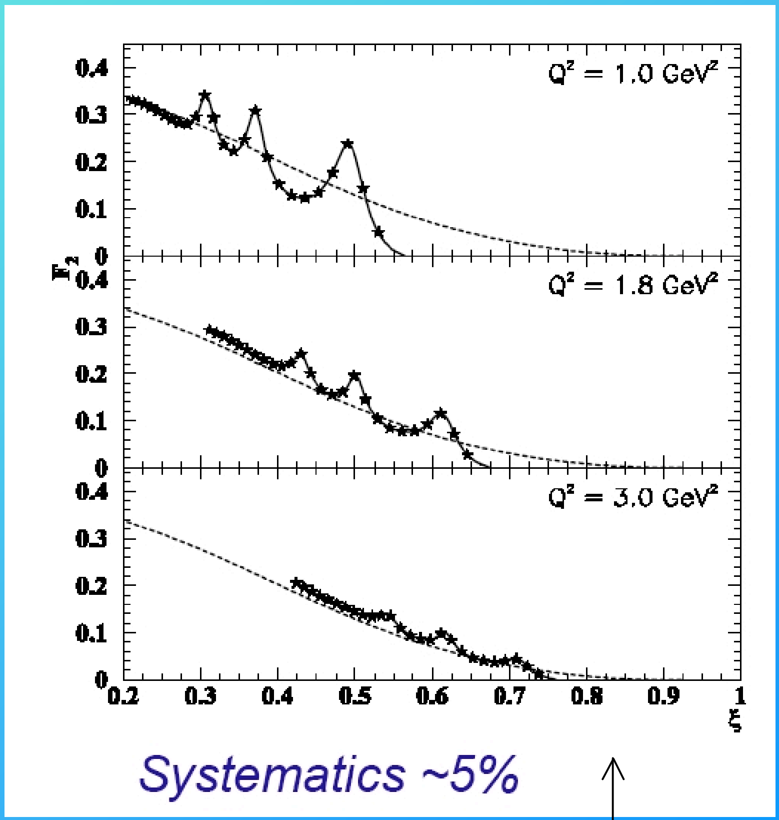
# BoNuS - Experimental Setup





# Expected Data



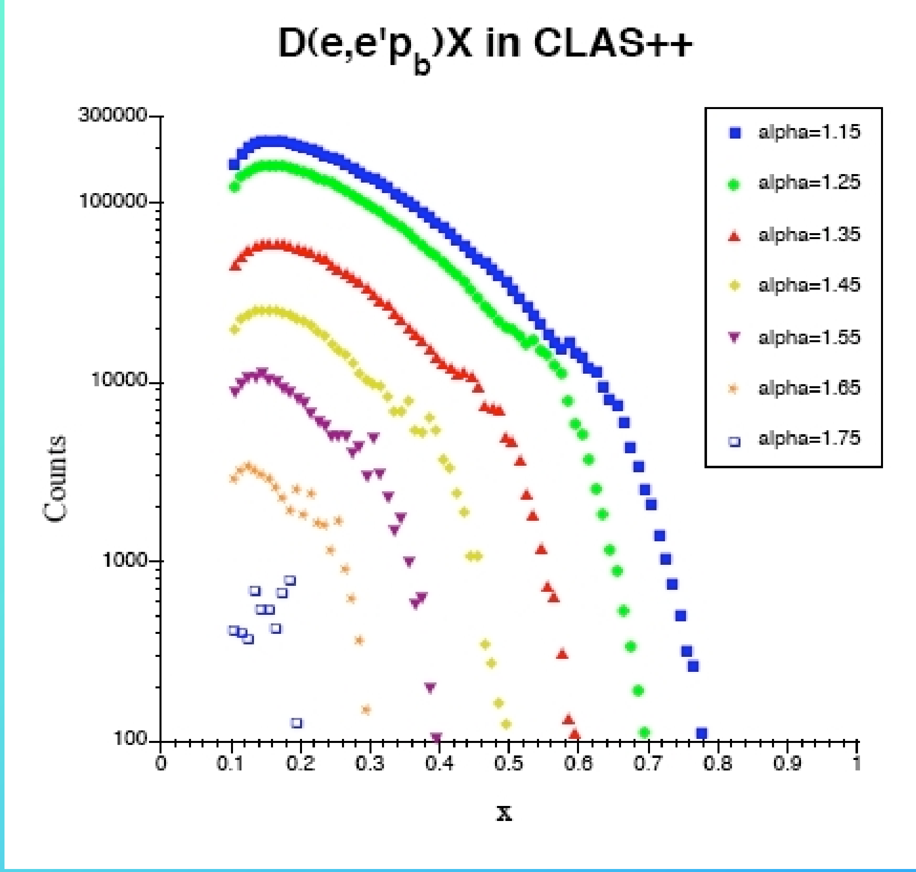




d/u

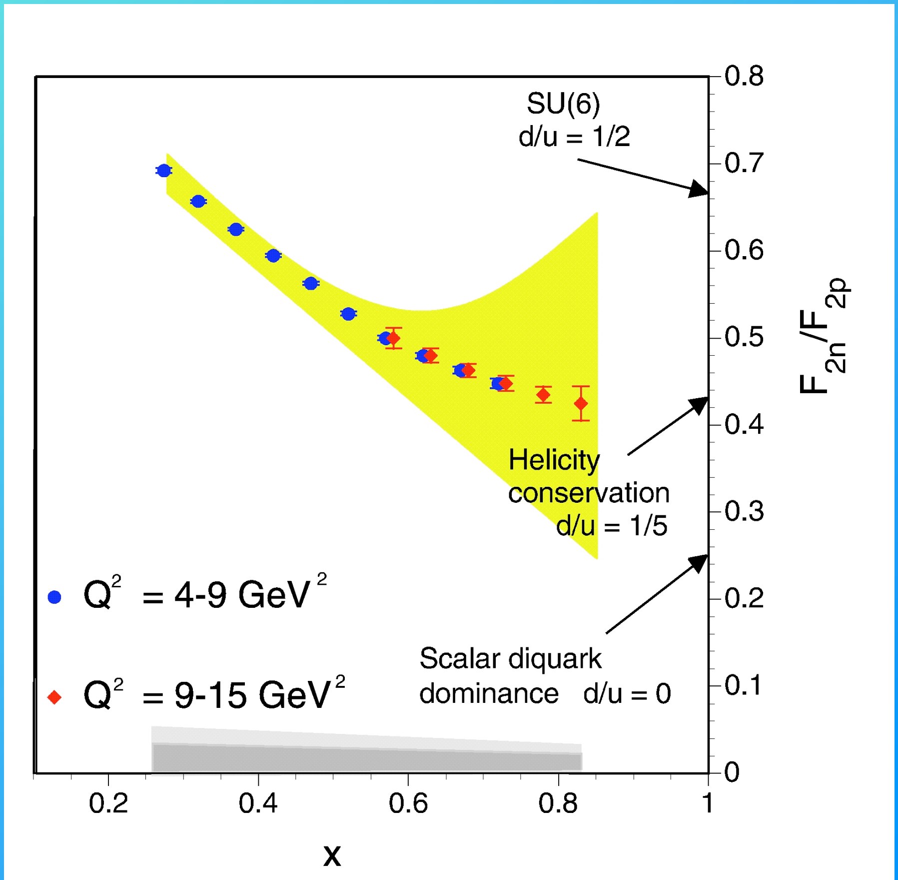
Resonance Structure

# The Future - Jlab at 12 GeV

## D(e,e'$p_s$)




## BoNuS



# Summary

- Light cone (as well as "non-relativistic") wave functions describe the momentum distribution of nucleons in deuterium rather well.
- Final state interactions play an important role, especially for sideways angles (relative to **q**) and large proton momenta. They are more pronounced for large final state mass W or small Bjorken x.
- For large "spectator" momenta (neutron is far "off-shell") we see a reduction of the structure function $F_{2n}$ compared to that for a free neutron.
- New measurements with small spectator momenta will allow us, for the first time, to extract $F_{2n}$ at large x without large nuclear uncertainties.
- A rich program awaits us with Jefferson Lab at 12 GeV.