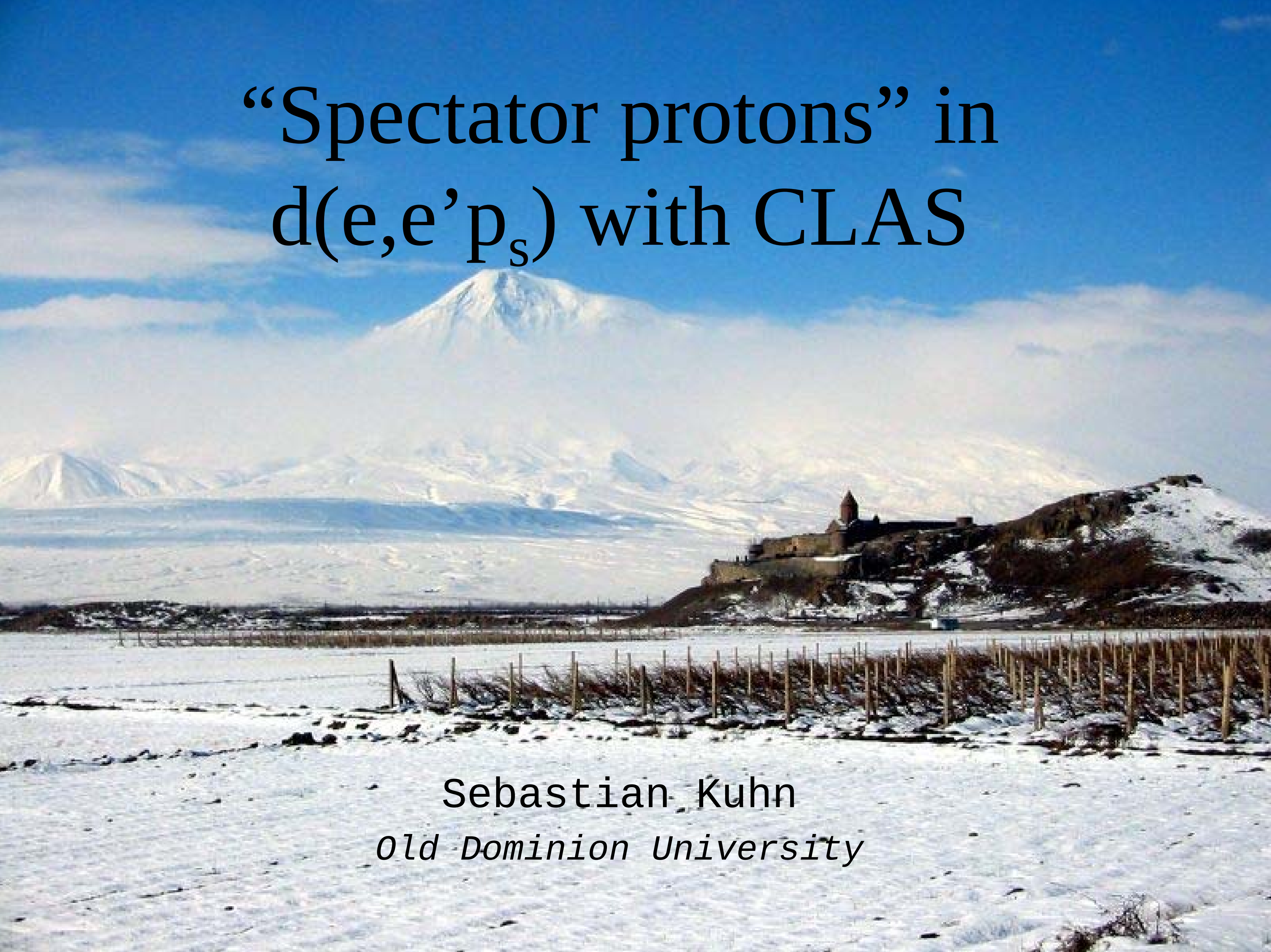


“Spectator protons” in $d(e,e'p_s)$ with CLAS

Sebastian Kuhn

Old Dominion University

In memoriam of Kim Egiyan

who was already thinking about all of this Physics when I still went to high school…

…and has been a invaluable supporter and friend on the "Deeps" experiment.

Overview

- Structure of a bound neutron
- “Spectator Tagging”
- The “Deeps” experiment
- Results
  - Momentum distributions
  - Final state interactions
  - Structure Functions
- The BoNuS experiment
- Future Plans and Summary

GOAL: Answer 2 related questions

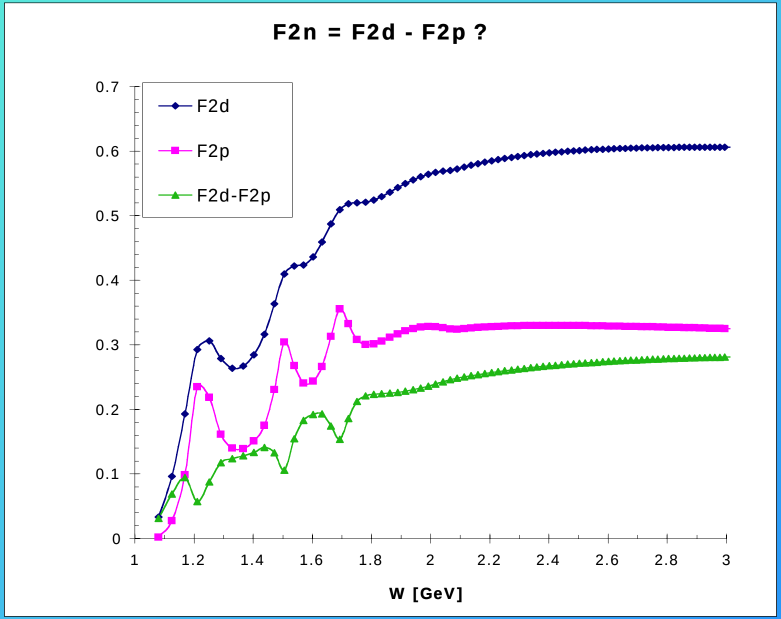
1) How can we explore the structure of the neutron if all we have are neutrons bound in nuclei?
   - In many cases, a neutron bound in deuterium can be considered “nearly free”.
   - BUT: For certain kinematics (large $x > 0.5$, resonance region $W < 2$) the high-momentum (short-distance tail) of the 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, “fusion” into hidden-color objects or even 6-quark bags

Structure Functions of the Neutron

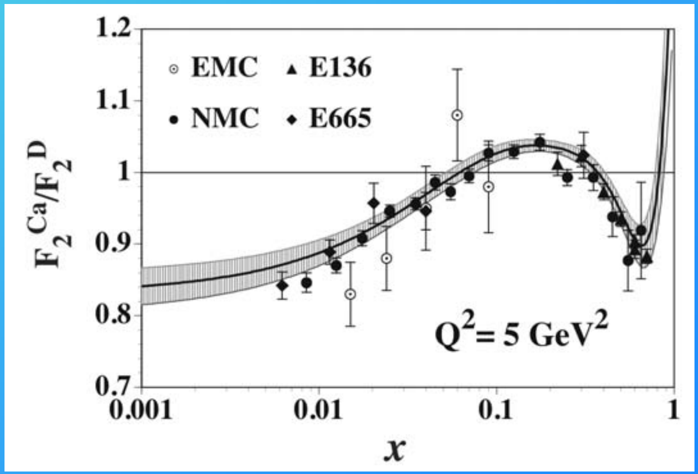
- Simple subtraction (deuteron-proton) yields nonsense
- Kinematic shift of the effective Bjorken variable x

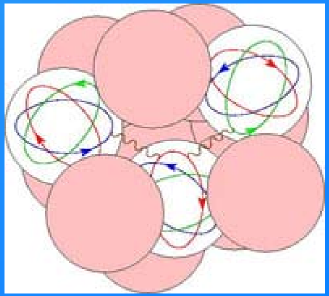
$x_{\text{measured}} = \dfrac{Q^2}{2M\nu}$	$x_{\text{relevant}} = \dfrac{Q^2}{2(E_n\nu - \vec{p}_n \cdot \vec{q})}$
0.70	0.69
0.80	0.78
0.90	0.85
1.00	0.90



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

("EMC"-effect)





Problem: d/u (x → 1)

$$\frac{\text{Quark momentum}}{\text{Nucleon momentum}}$$

(Momentum transfer)^2

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

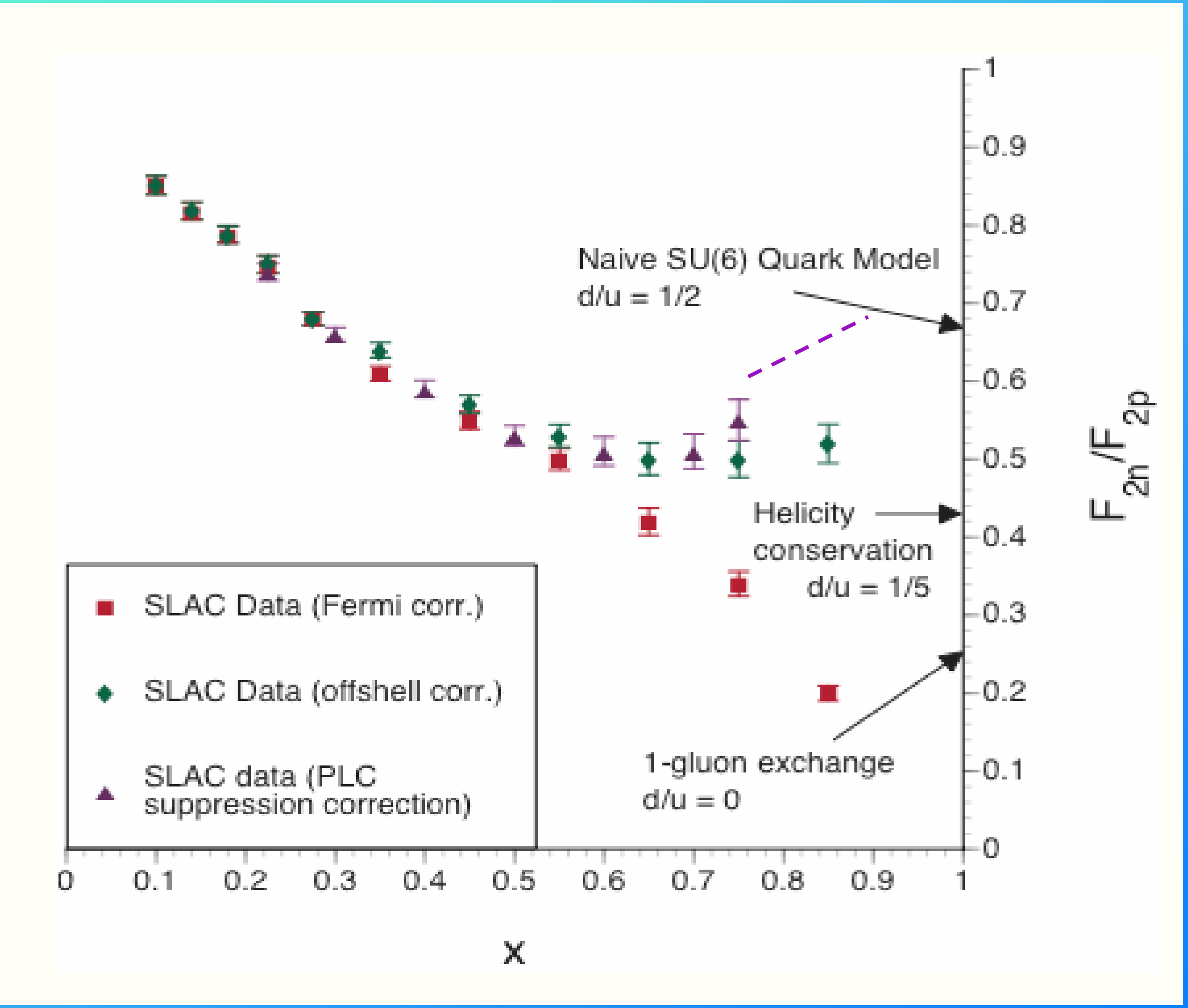
Nucleon mass Energy transfer

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

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

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

???



What can we do?

1) To learn more about the structure of the neutron we can "select the part of the deuteron wave function" where binding and off-shell effects are minimized, and we can kinematically correct for Fermi motion.

2) To learn more about structure modifications of a deeply bound nucleon, we can emphasize the high-momentum part of the deuteron wave function (corresponding to short distances).

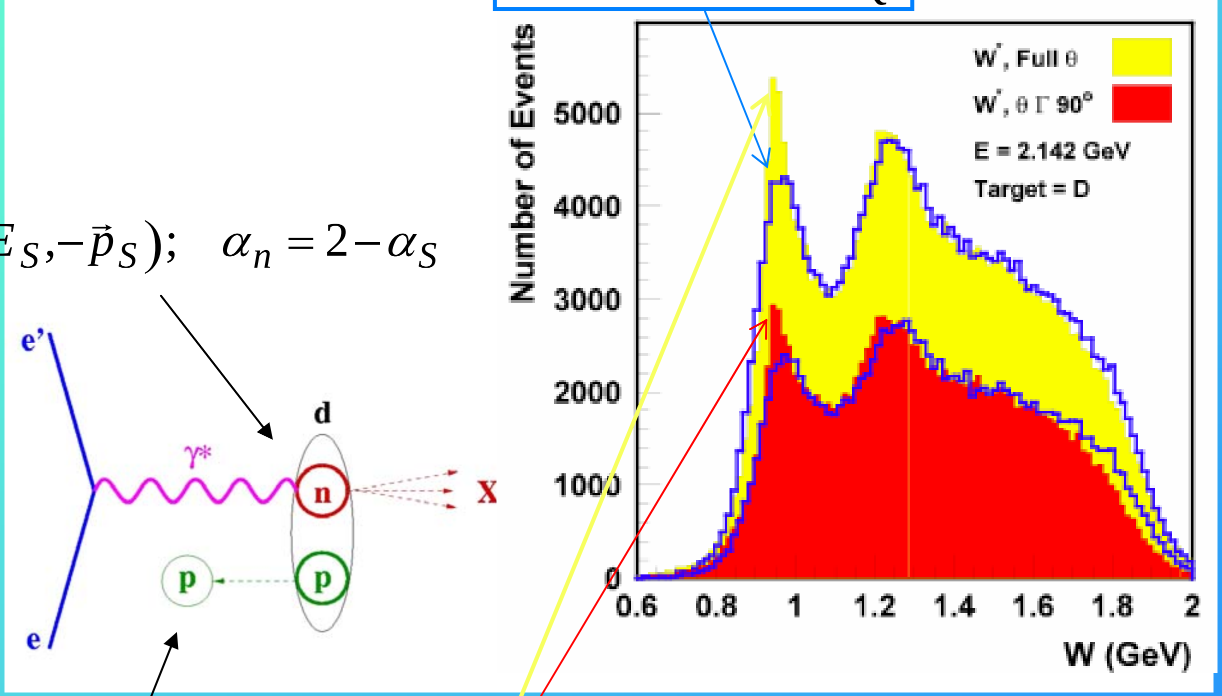
Method (in both cases): Lepton scattering off the deuteron with simultaneous detection of a backwards-going "spectator" proton:

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

“Spectator Tagging”

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

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



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

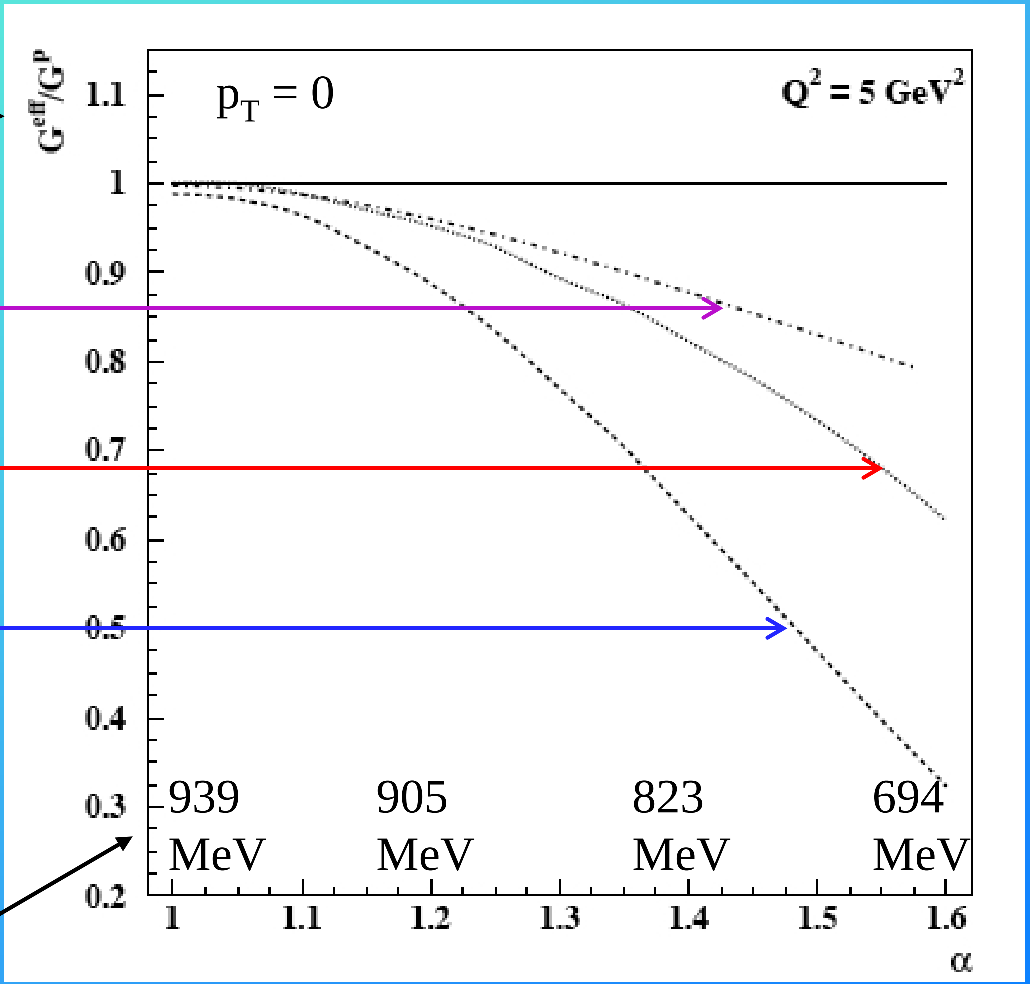
$$W^2 = (p_n + q)^2 = p_n{}^{\mu} p_{n\mu} + 2((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}) - Q^2$$

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

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

Deviations from free structure function:
Off-shell Effects (should depend on 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.

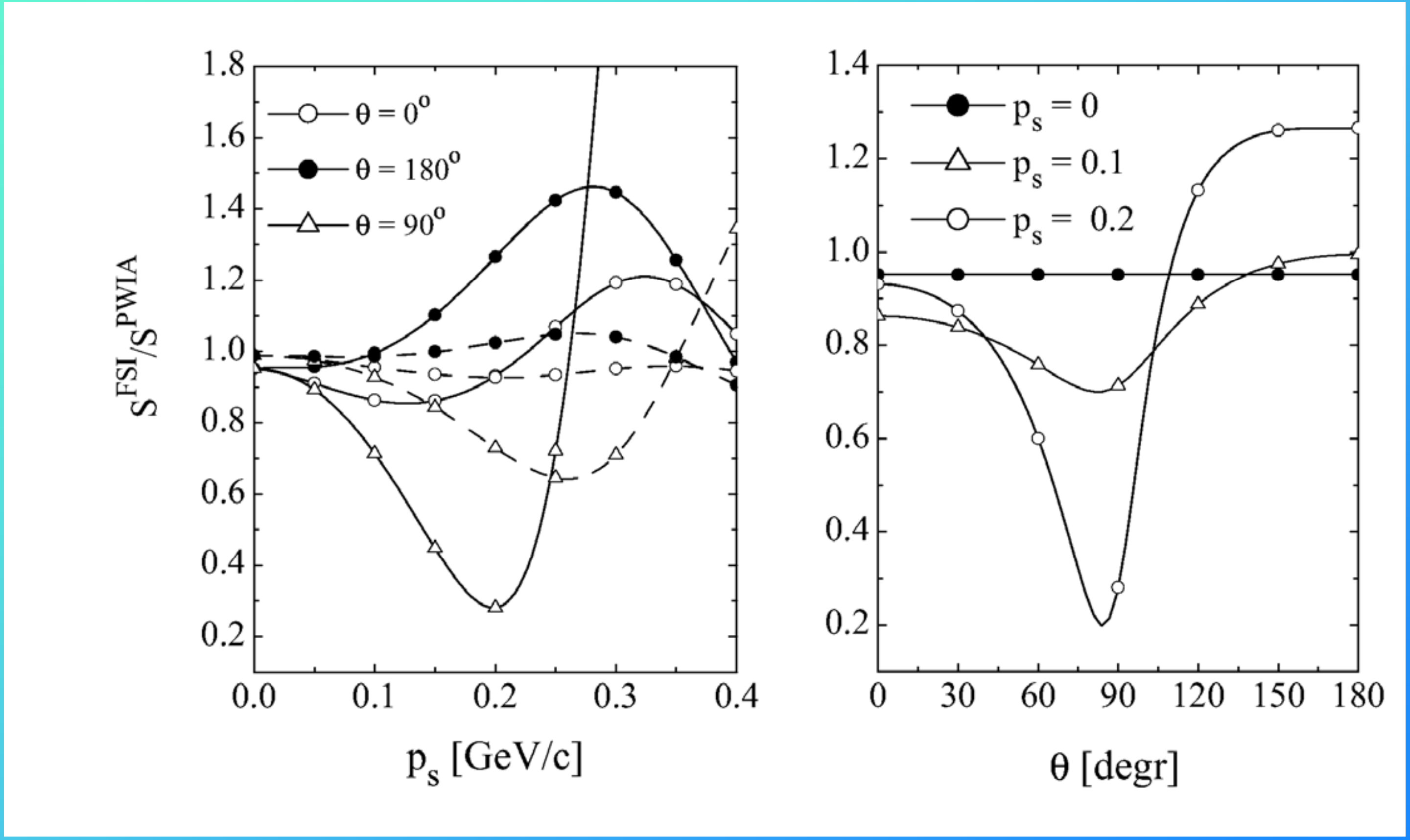
Suppression of "point-like configurations"
Frankfurt, Strikman et al.

… plus 6-quark bags

"Off-shell" mass of the nucleon M^*

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

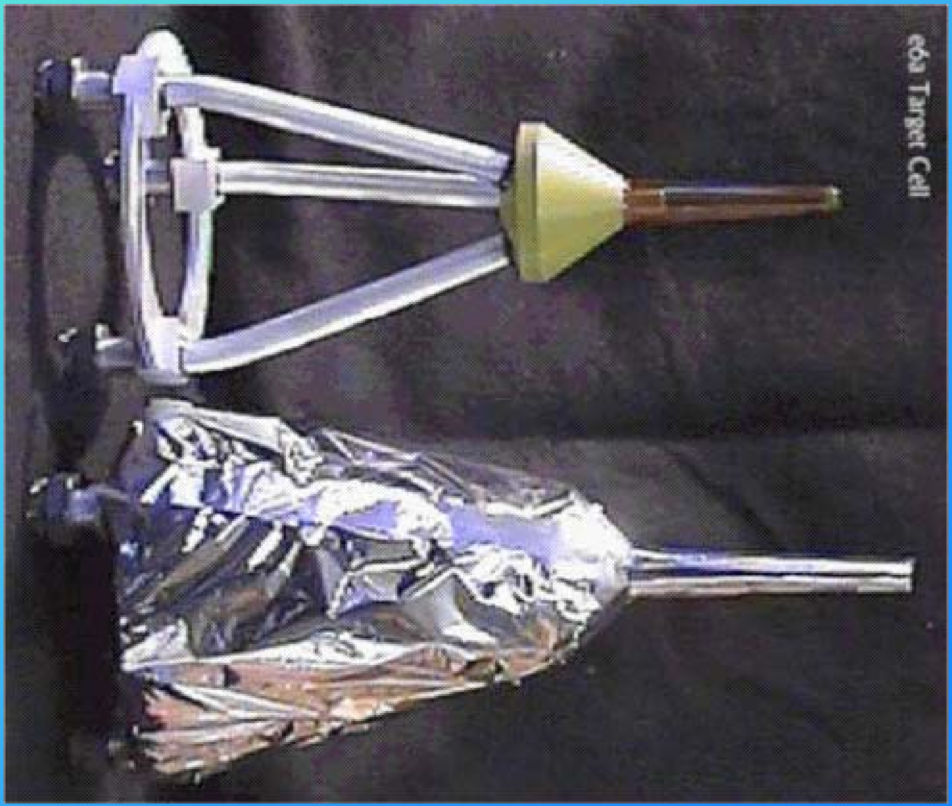
Deviations from the simple "spectator" picture:
Final State Interaction (should depend on θ_{qp_s})



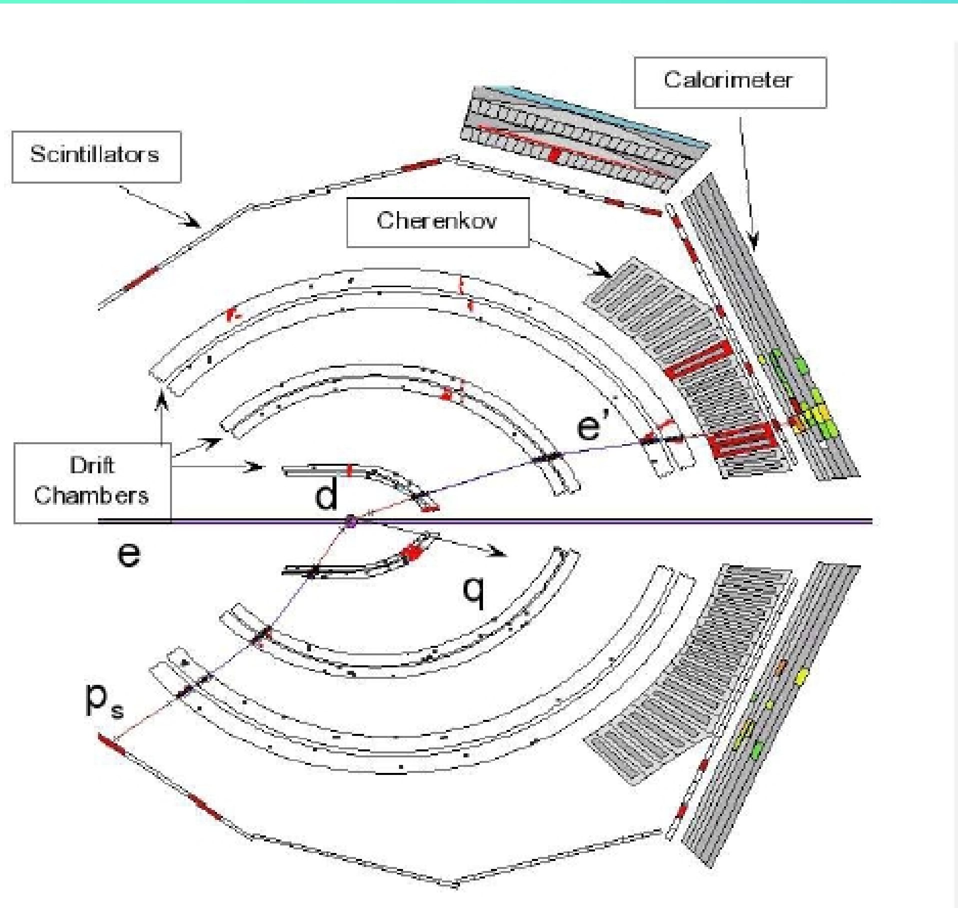
Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

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

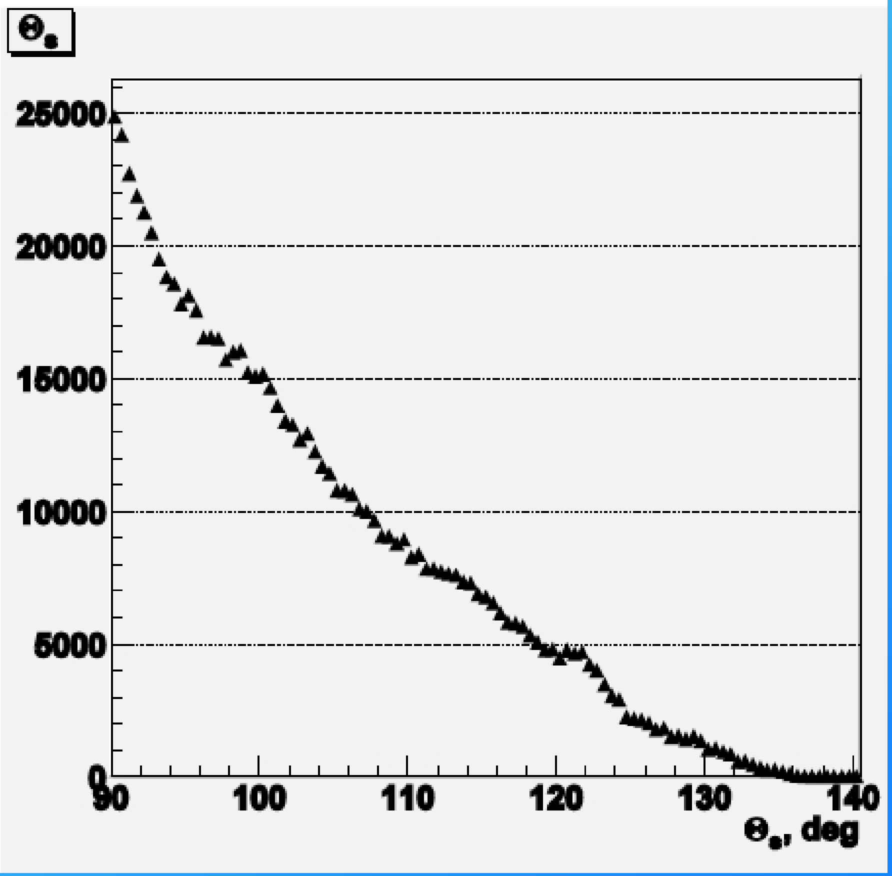
- CLAS Experiment 94-102 at Jefferson Lab led by **Kim**, K. Griffioen and SEK
- Run period "E6" in Hall B
- 5.75 GeV / 7 nA Electrons on a 5 cm long LD_2 target => $L=10^{34}/cm^2s$
- 8 calendar weeks in spring of 2002; 4.5 billion triggers
- 2 Ph.D. students:
  Dr. Alexei Klimenko (ODU) and Cornel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



Experimental Details

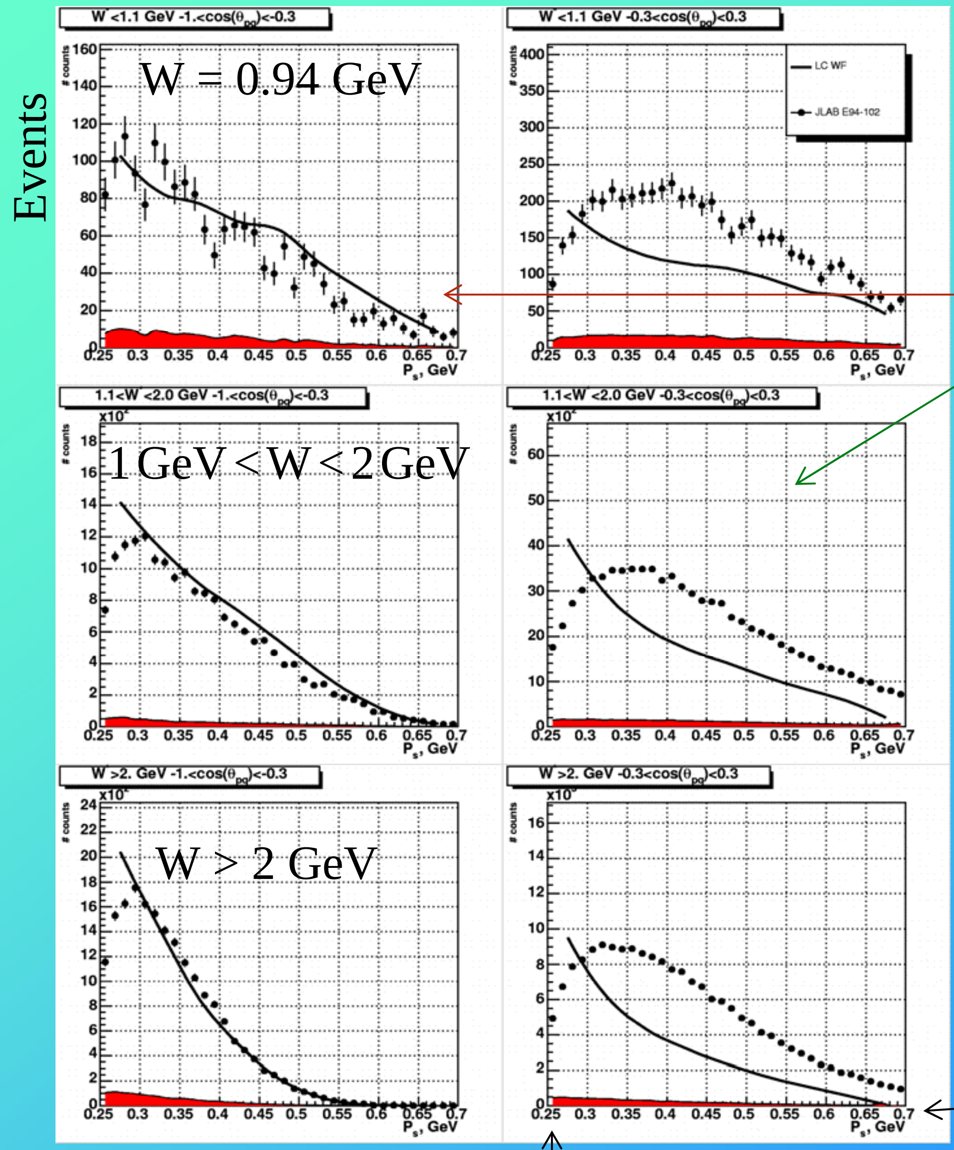


A typical event



Acceptance for protons in the backward hemisphere

Results: Momentum Distribution



P_s

Vertical axis: Number of events

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

Left: Angular range > 107.5°
Right: Angular range 72.5° - 107.5°

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

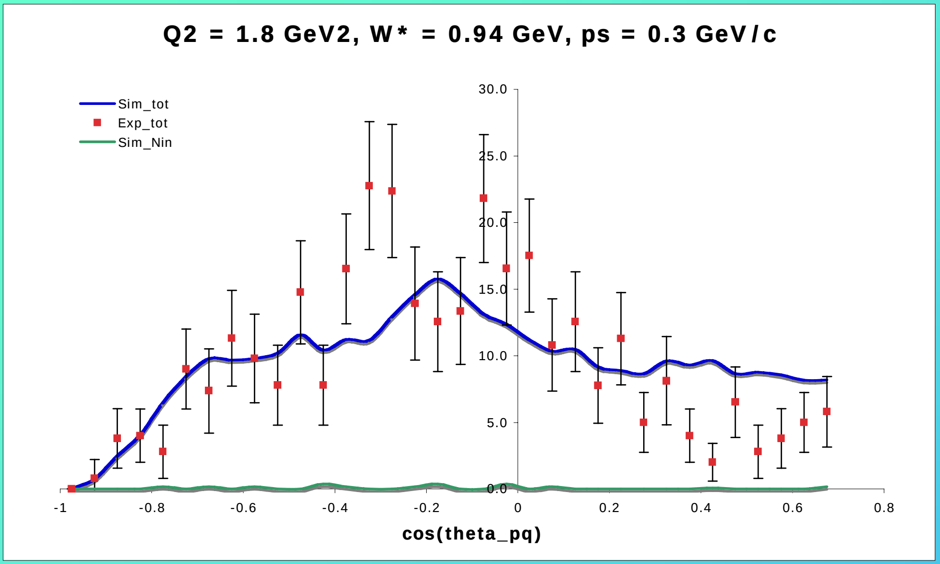
PWIA model with “light cone”-wave function for deuterium

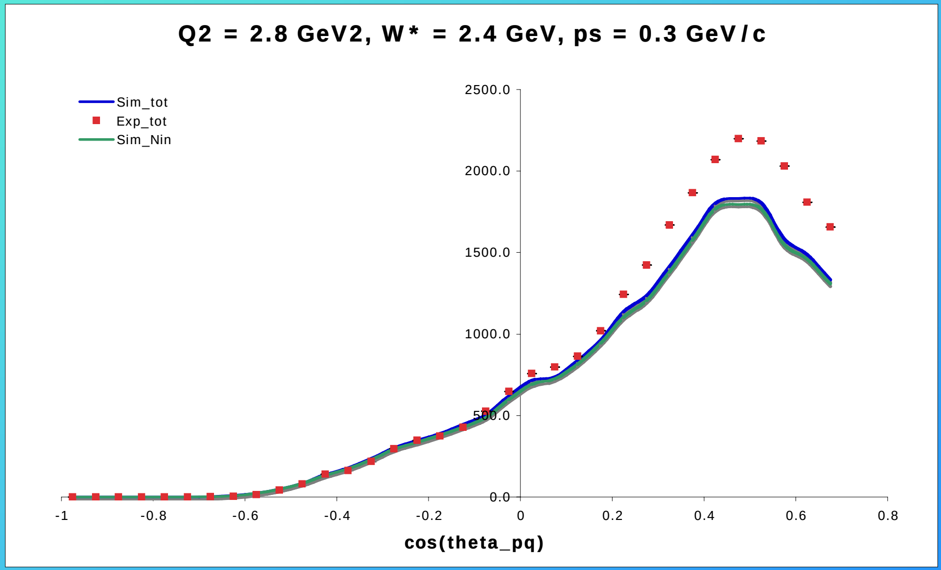
700 MeV/c

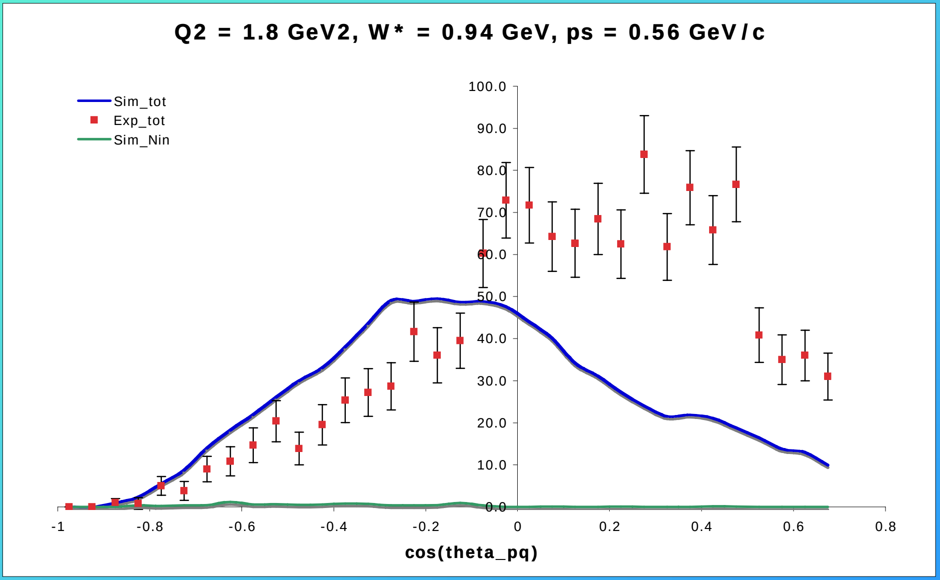
250 MeV/c

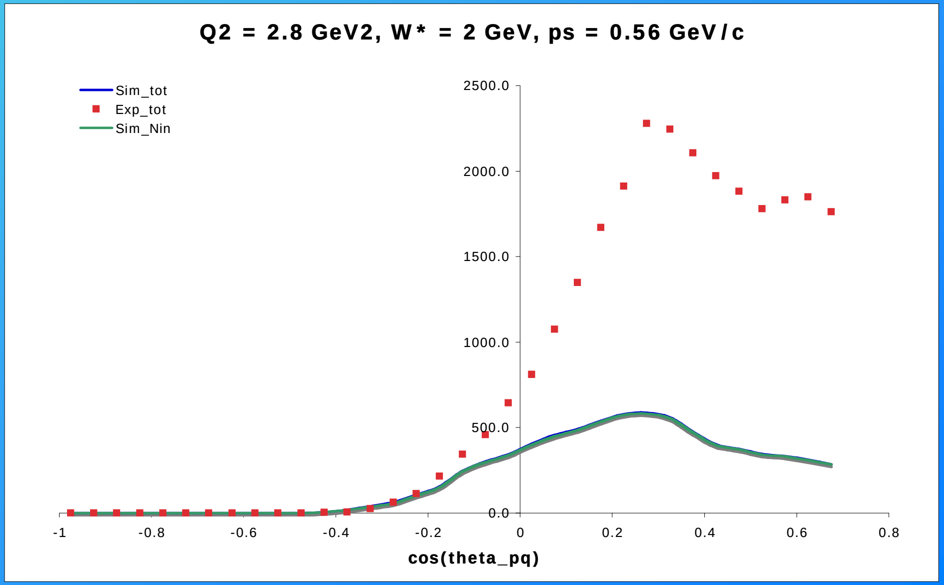
Results: Angular Distributions -

measured vs. simulated event rates

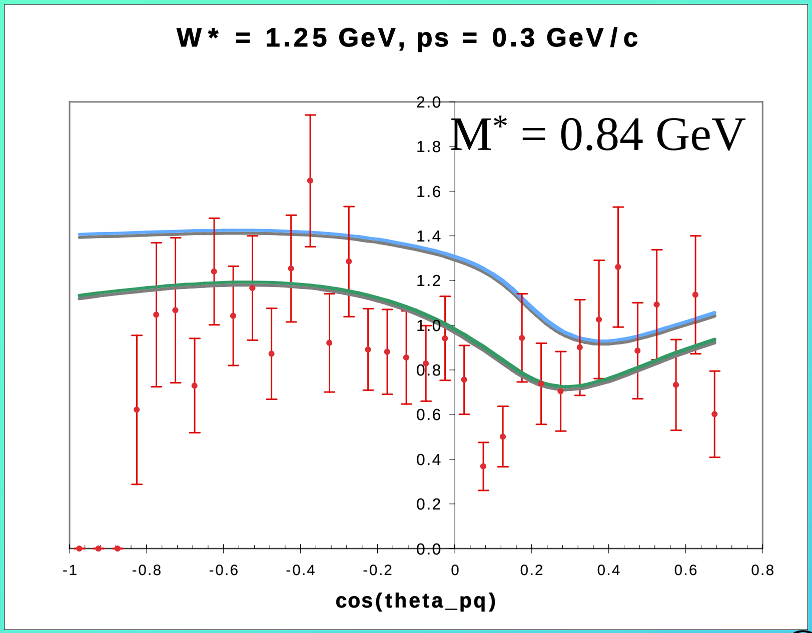


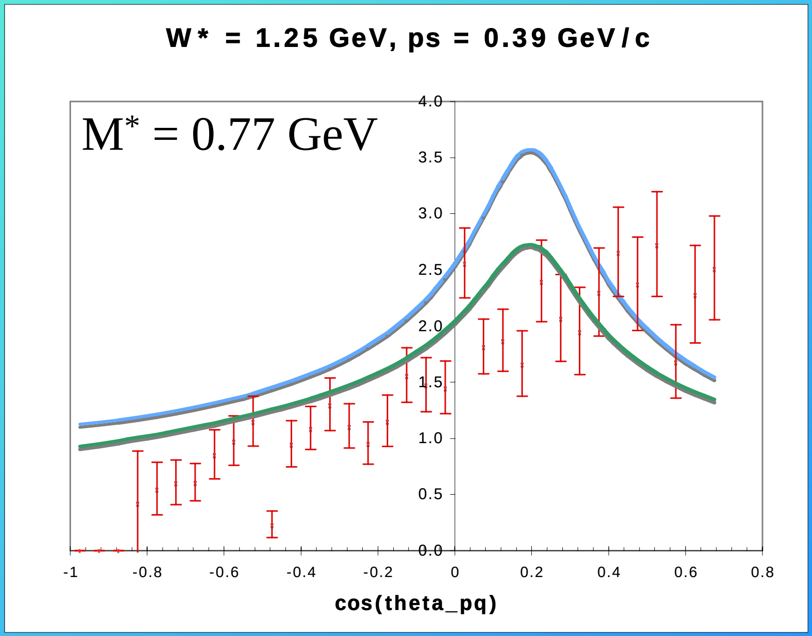




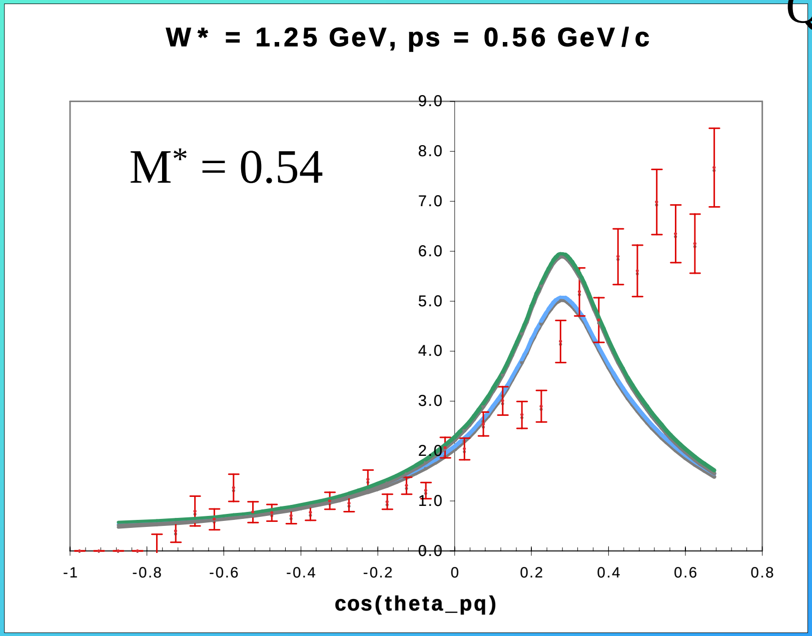


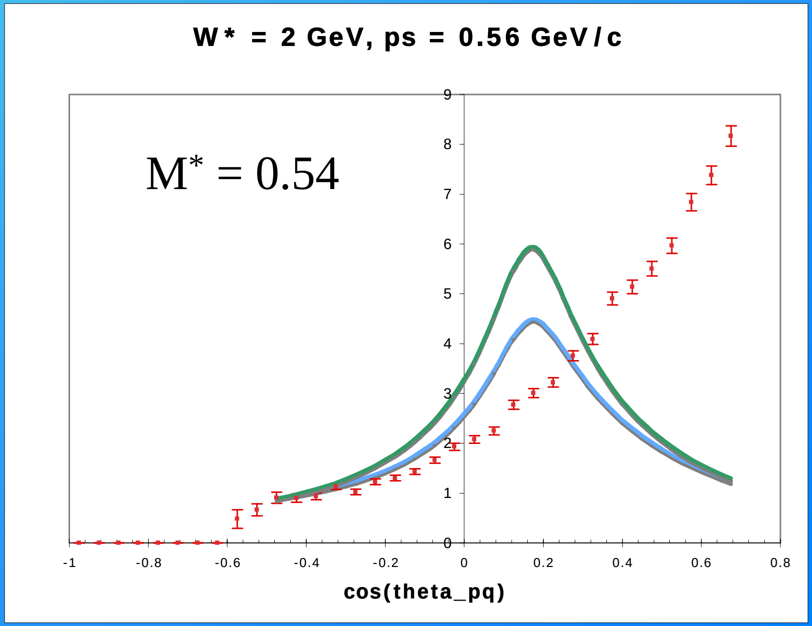
Results: comparison with FSI model by Ciofi degli Atti et al.



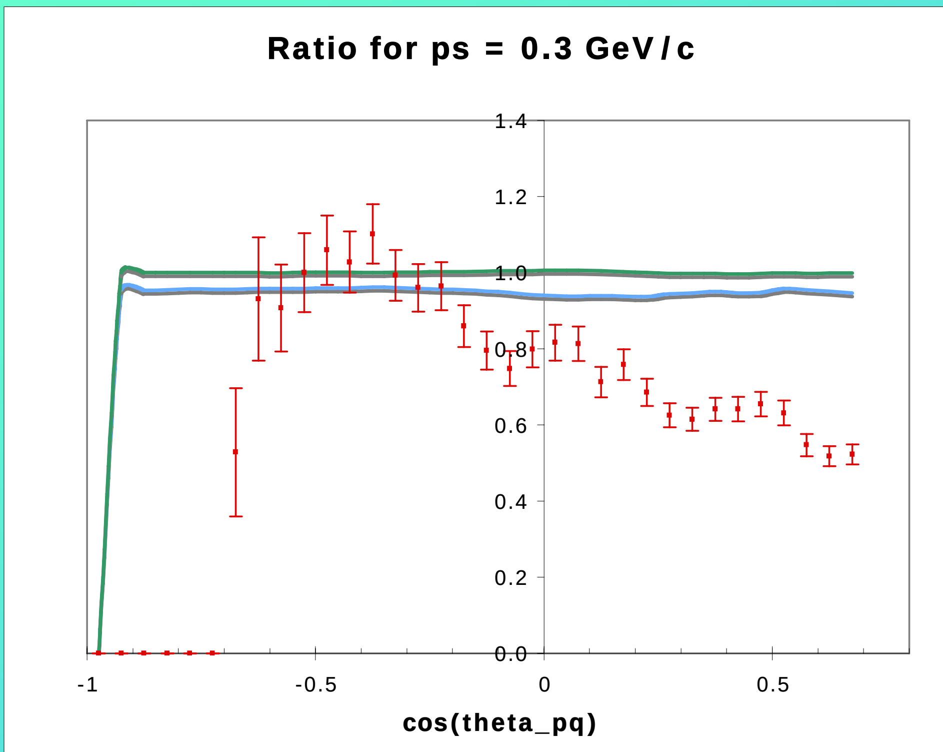


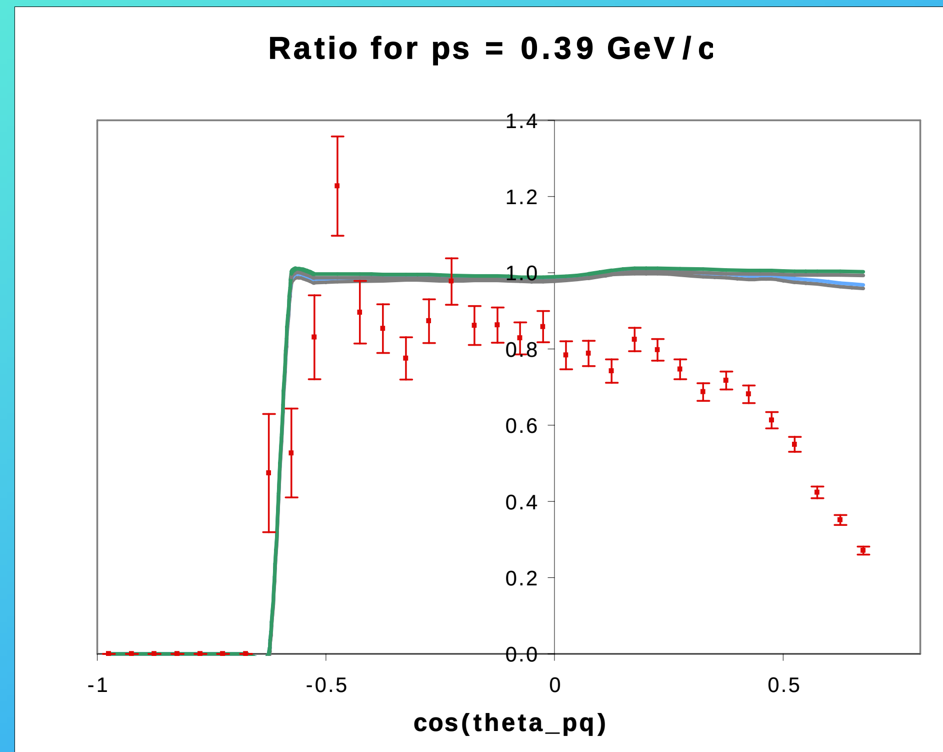
$Q^2 = 1.8\ \mathrm{GeV}^2$





Results: Ratio test



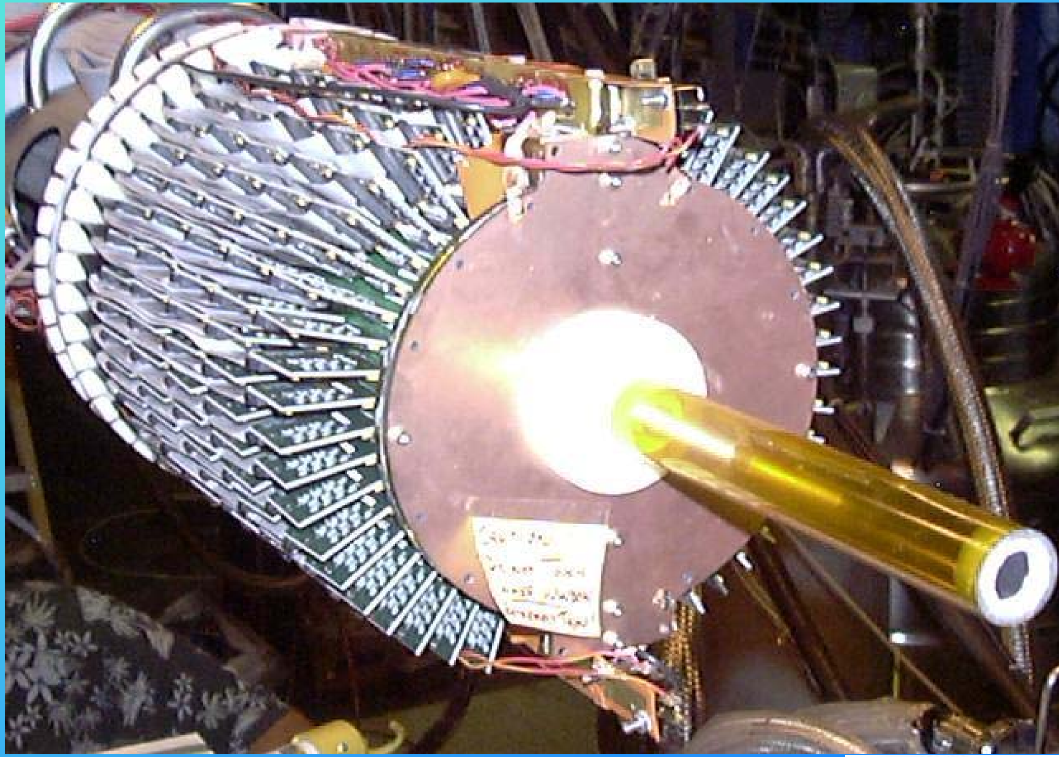


$$\text{Ratio} = \frac{\dfrac{\sigma(x^* = 0.45)}{\sigma(x^* = 0.25)}(\text{bound n})}{\dfrac{\sigma(x = 0.45)}{\sigma(x = 0.25)}(\text{free n})}$$

- 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

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

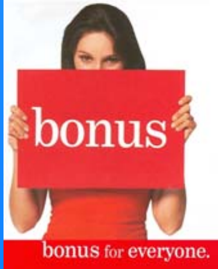
- D(e,e'p_{back}) at Jefferson Lab with CLAS and RTPC**
- 1, 2, 4 and 5 GeV electrons impinging on a 6 mm Ø, 20 cm long D_2 gas target (7.5 atm) => $L = 0.2 \cdot 10^{34}/\mathrm{cm}^2\mathrm{s}$
- Ran 3 months (October - December 2005)
- Jefferson Lab, Old Dominion Univ., Hampton Univ., William & Mary, James Madison Univ., Univ. of Houston and the CLAS collaboration



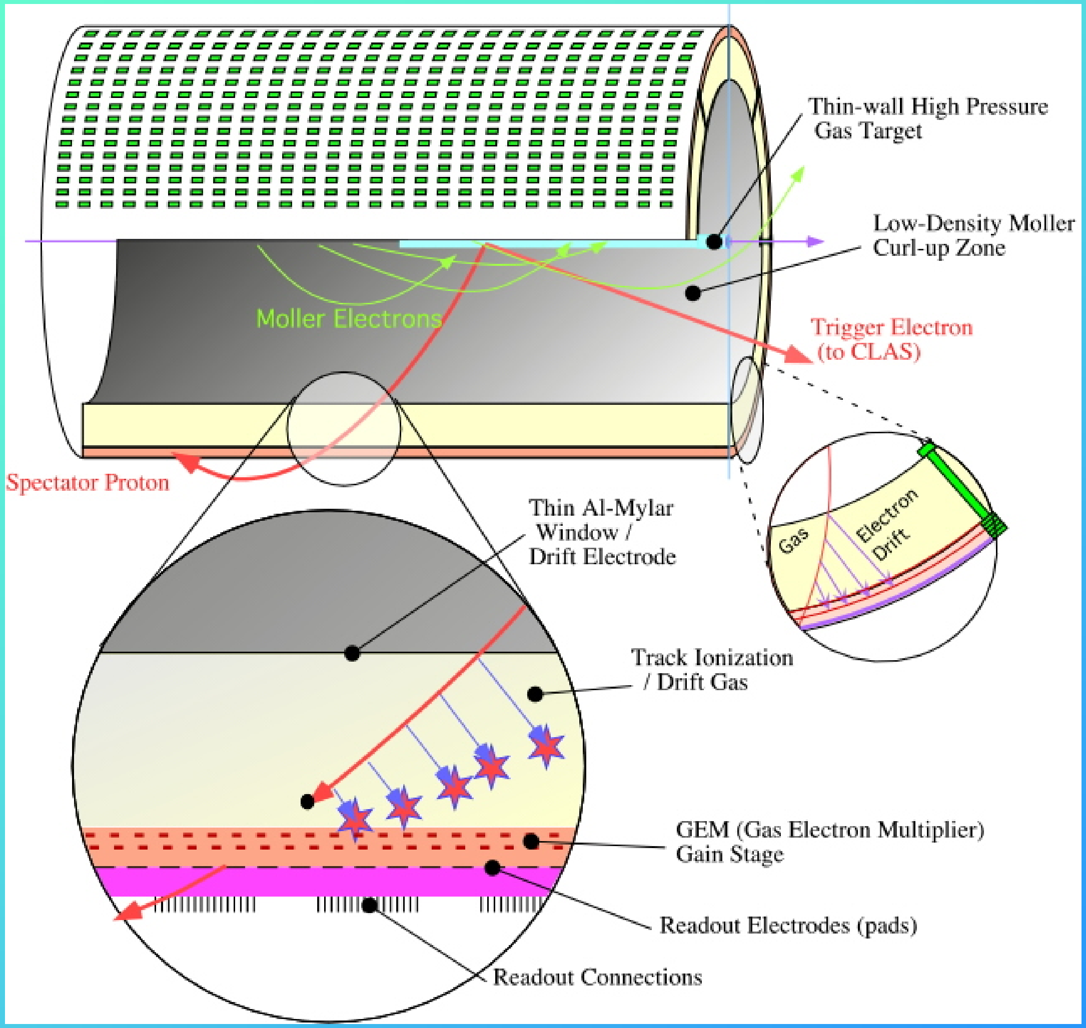
Radial TPC (view from downstream)

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

**RTPC = Radial Time Projection Chamber

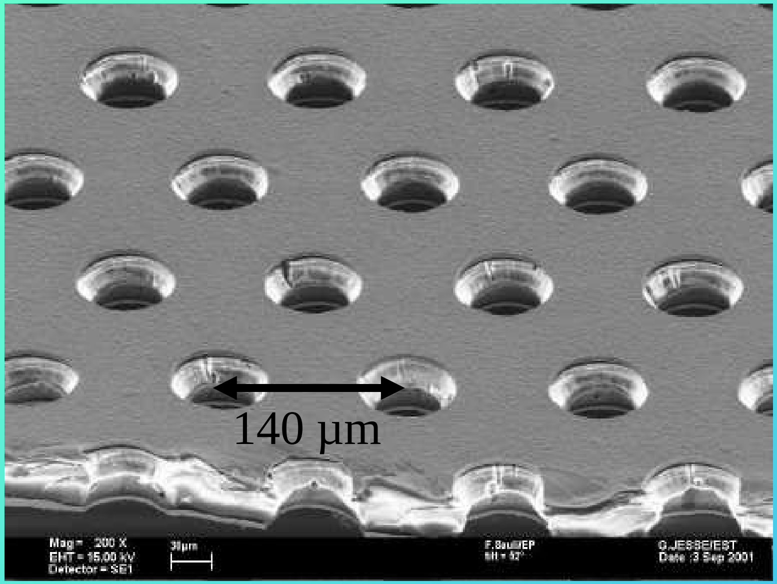


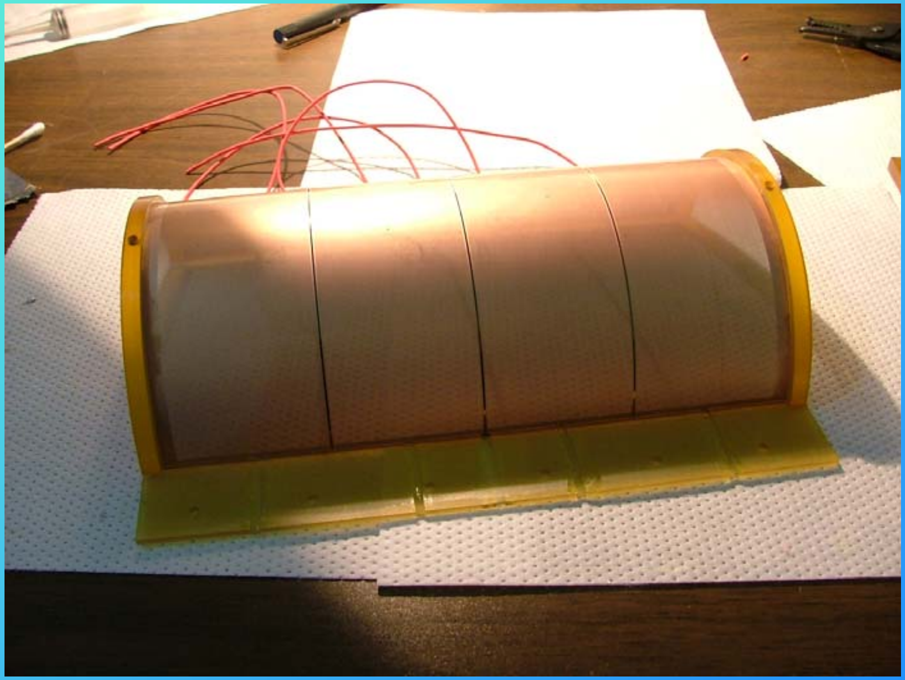
Target-detector system for slow protons



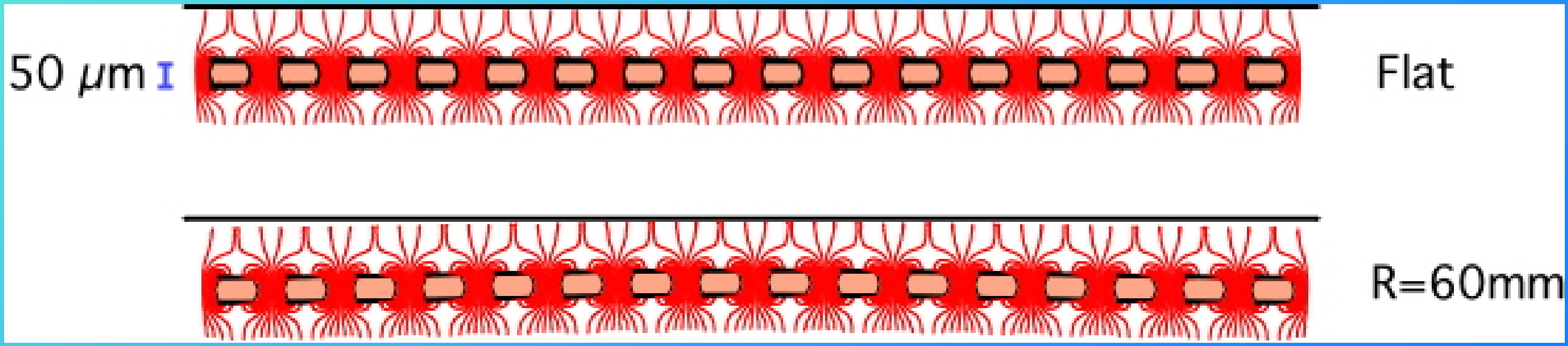
- Thin-walled gas target (7 atm., room temperature)
- **R**adial **T**ime **P**rojection **C**hamber (RTPC) with **G**aseous **E**lectron **M**ultipliers (GEMs)
- 4 Tesla longitudinal magnetic field (to suppress Möller electrons and to measure momentum)
- 3-dimensional readout of position and energy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

RTPC - GEMs

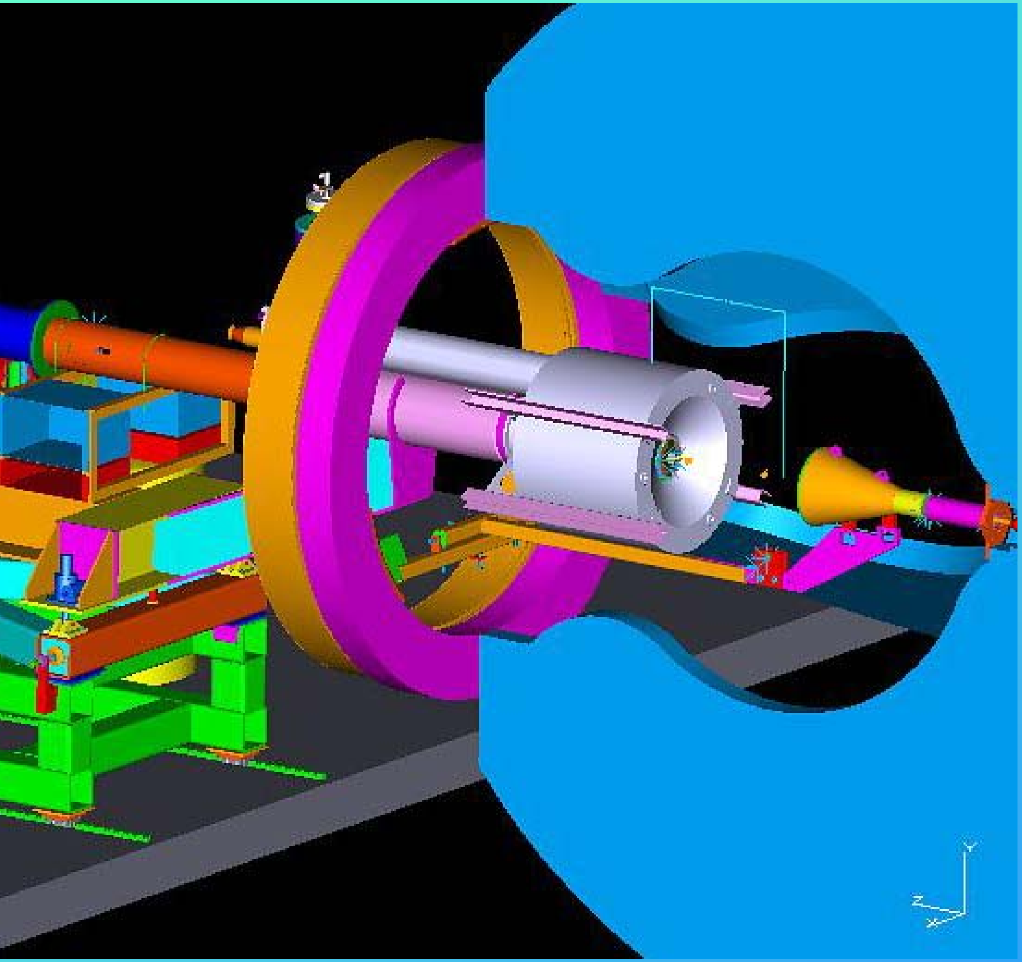


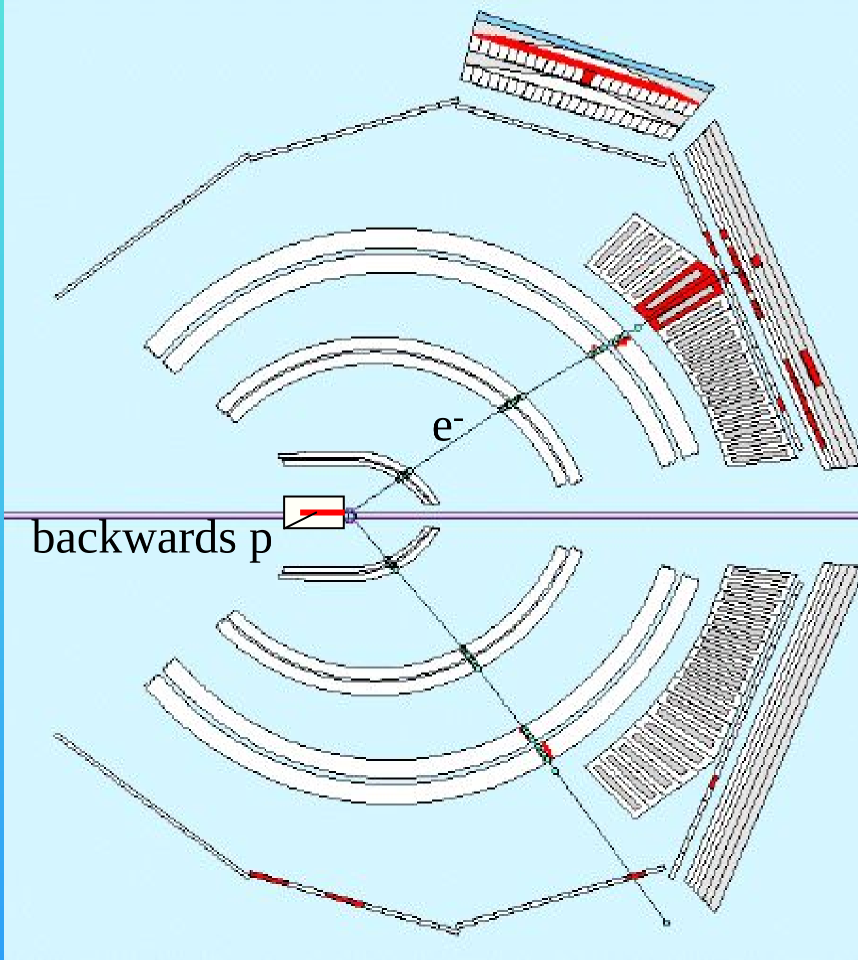


300-500 V, Gain 100-200, 3 layers

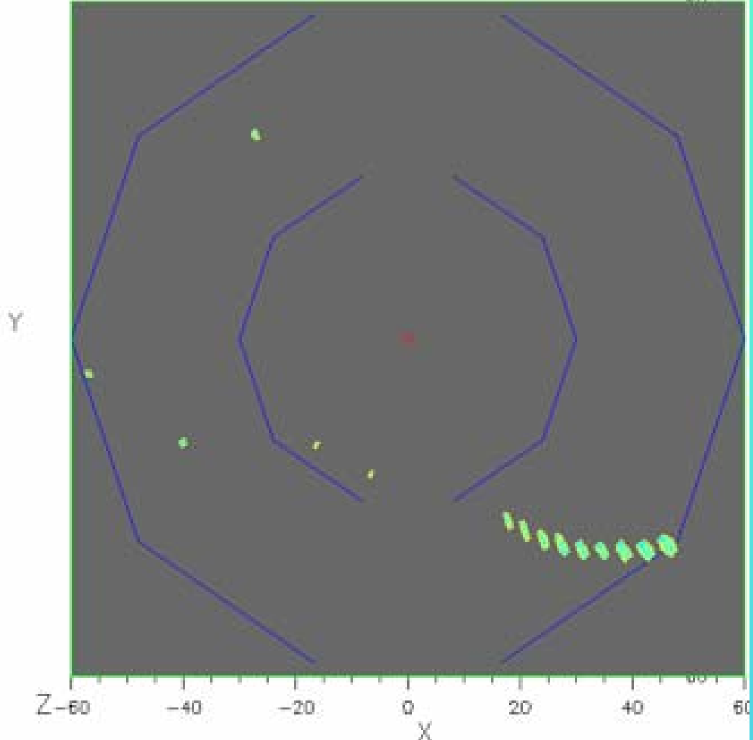


BoNuS - Experimental Setup

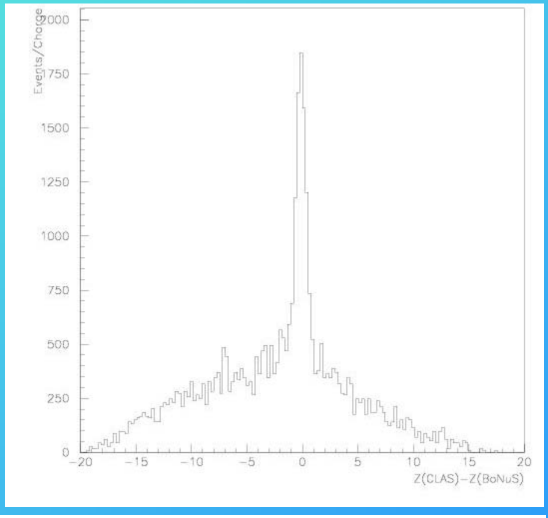




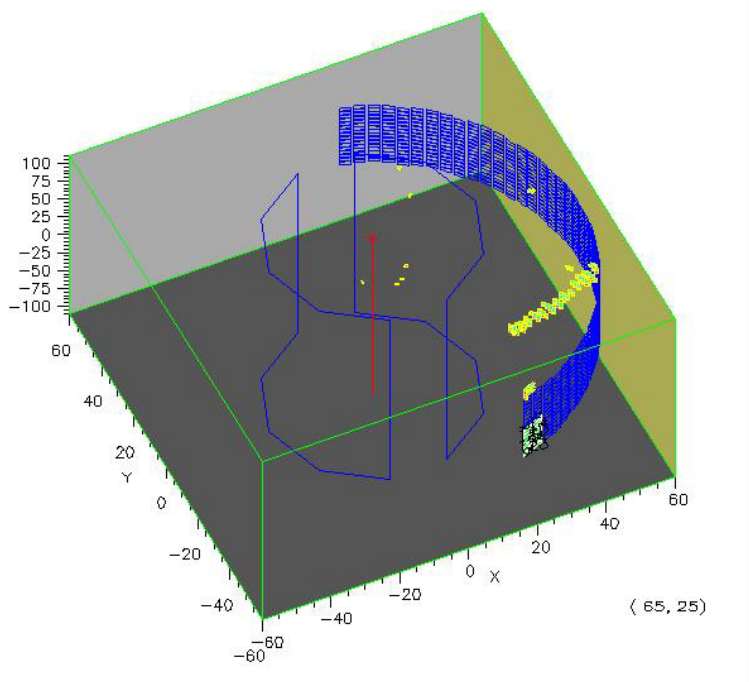
First results



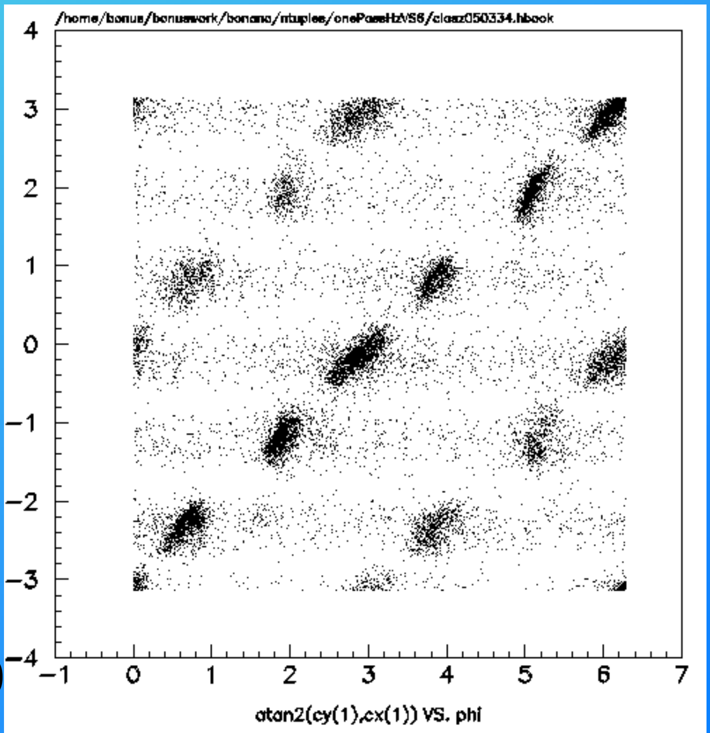
Electron-Proton
vertex difference



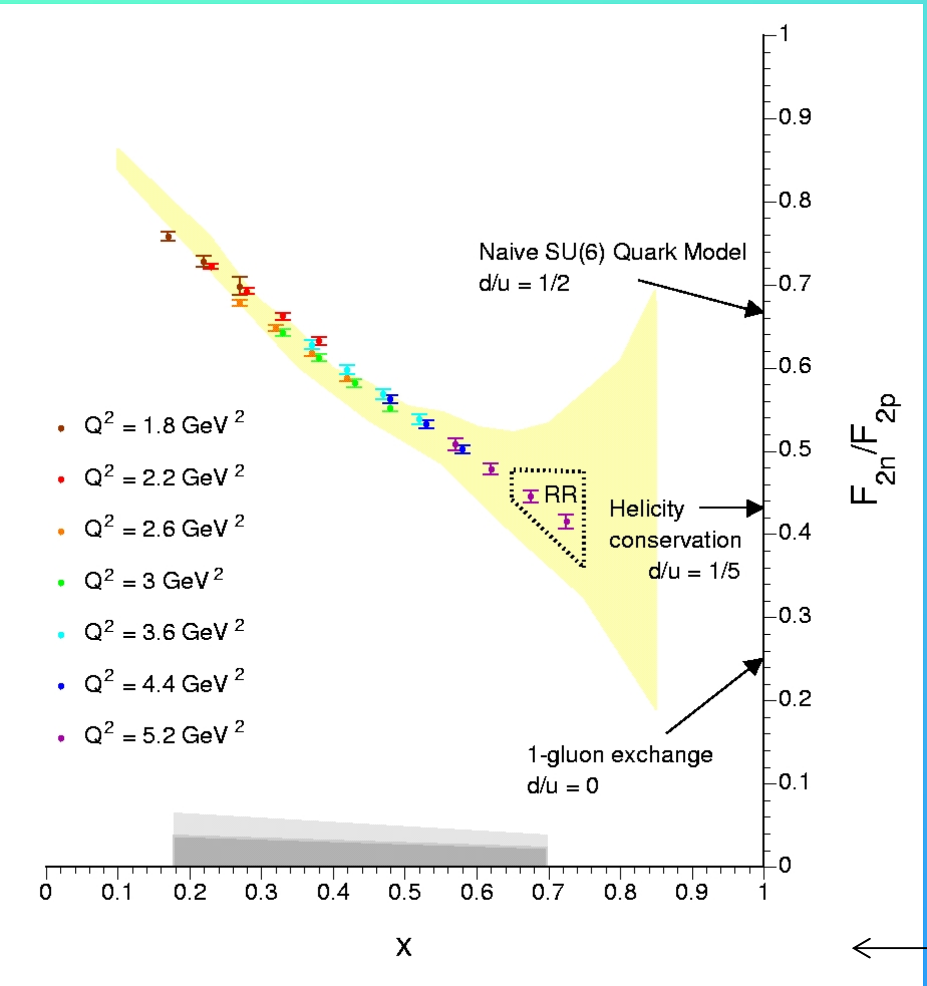
Proton
track
in
RTPC

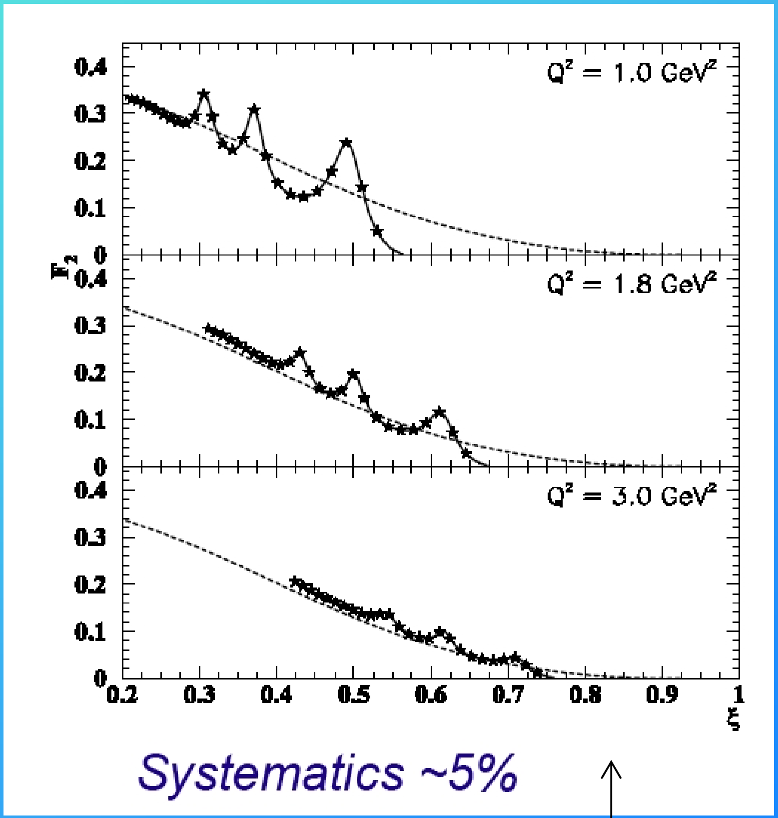


Phi-correlation
CLAS vs. RTPC
for elastic p(e,e'p)



Expected Data



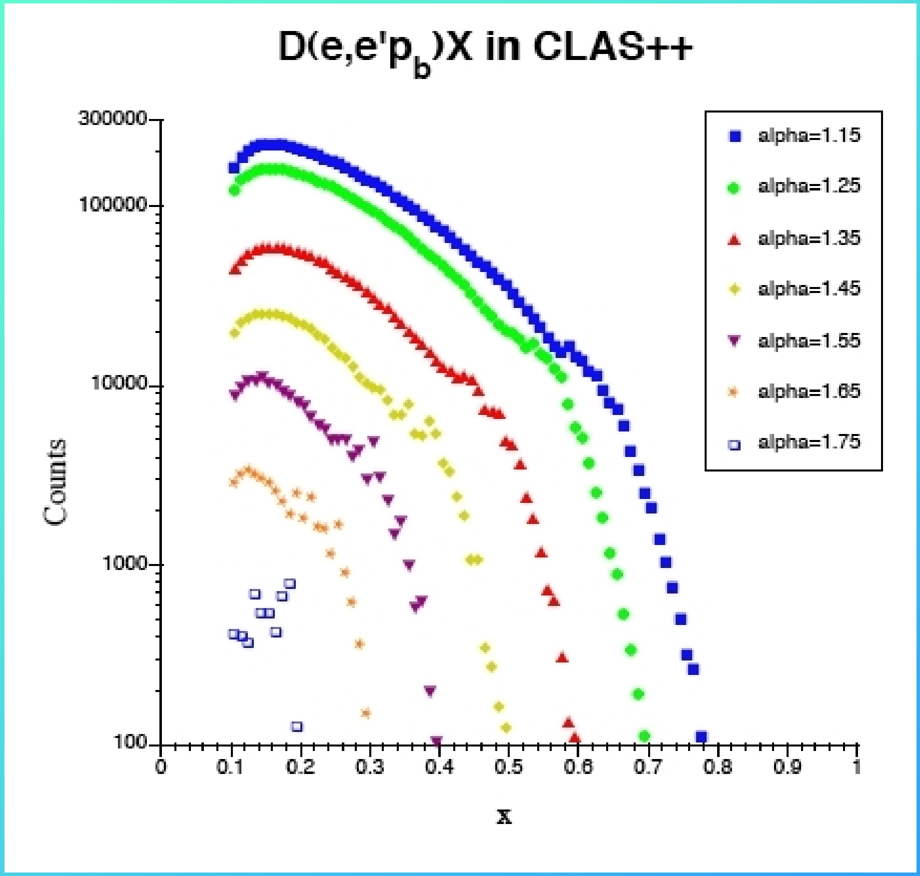


d/u

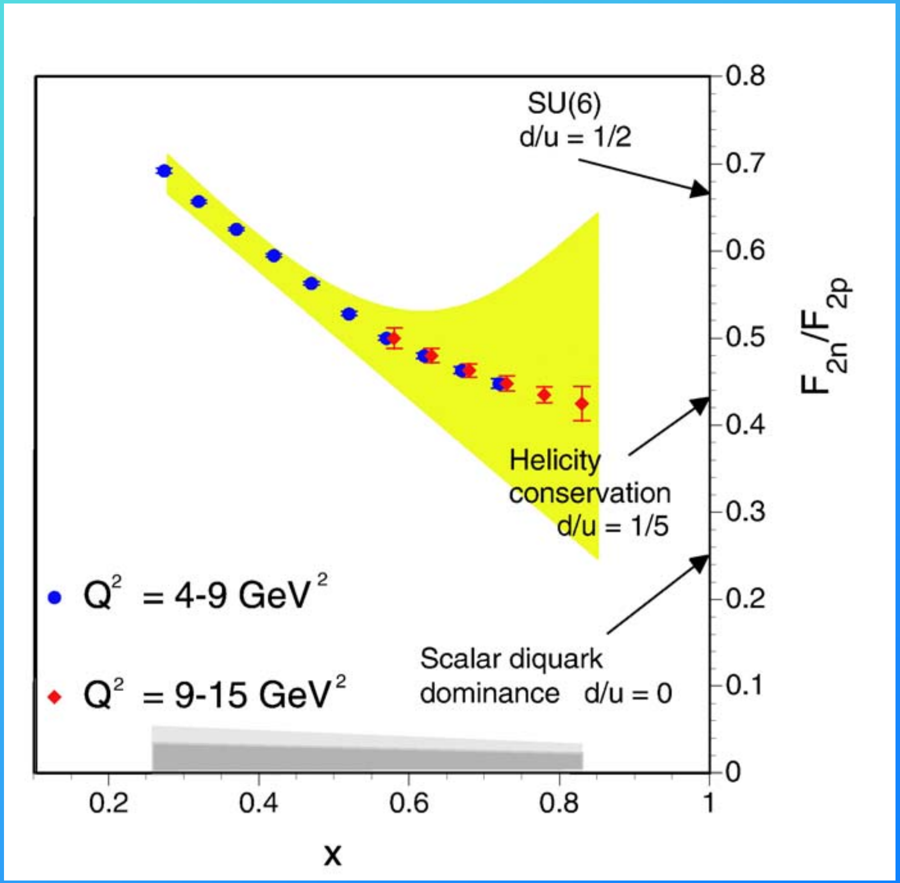
Resonance Structure

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 protons emitted “backwards” from deuterium rather well.
- Final state interactions play an important role, especially for more forward 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”) there may be 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.