Experimental Nuclear and Particle Physics at ODU

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Students:

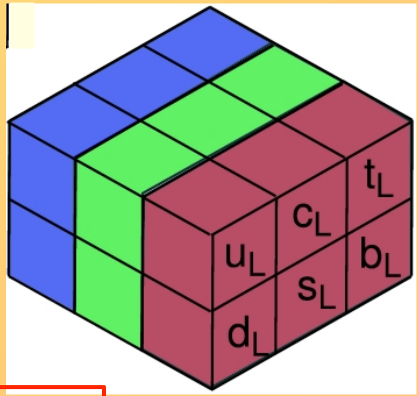
Lee Allison, Mohamed Hashir Rashad, Mariana Khatchatryan, Michael Kunkel, Georgie Mbianda Njencheu, Holly Szumila-Vance, Bayram Torayev…, YOU? ?????

http://www.physics.odu.edu/nucexpt/index.html

Seminars: Most Thursdays at 4:00 p.m. (PSB2 Seminar Room 2108)

Fundamental Problem of Nuclear and Hadronic Physics

- Nearly all well-known ("visible") mass in the universe is due to hadronic matter (protons, neutrons, Deltas, pions, hyperons,…)
- Fundamental theory of hadronic matter exists since the 1960's:
  Quantum Chromo Dynamics
  - "Colored" quarks (u,d,c,s,t,b) and gluons; Lagrangian
- BUT: knowing the ingredients doesn't mean we know how to build hadrons and nuclei from them!
  - akin to the question:
    "Given bricks and mortar, how do you build a house?"



- Four related puzzles:
  - What is the "quark-gluon wave function" of known hadrons?
  - What are their excited states, and can we understand their structure?
  - How are hadrons (nucleons) bound into nuclei?
    Does their quark-gluon wave function change inside a nucleus?
  - How do fast quarks and gluons propagate inside hadronic matter?
    How do fast quarks and gluons turn back into observable hadrons?

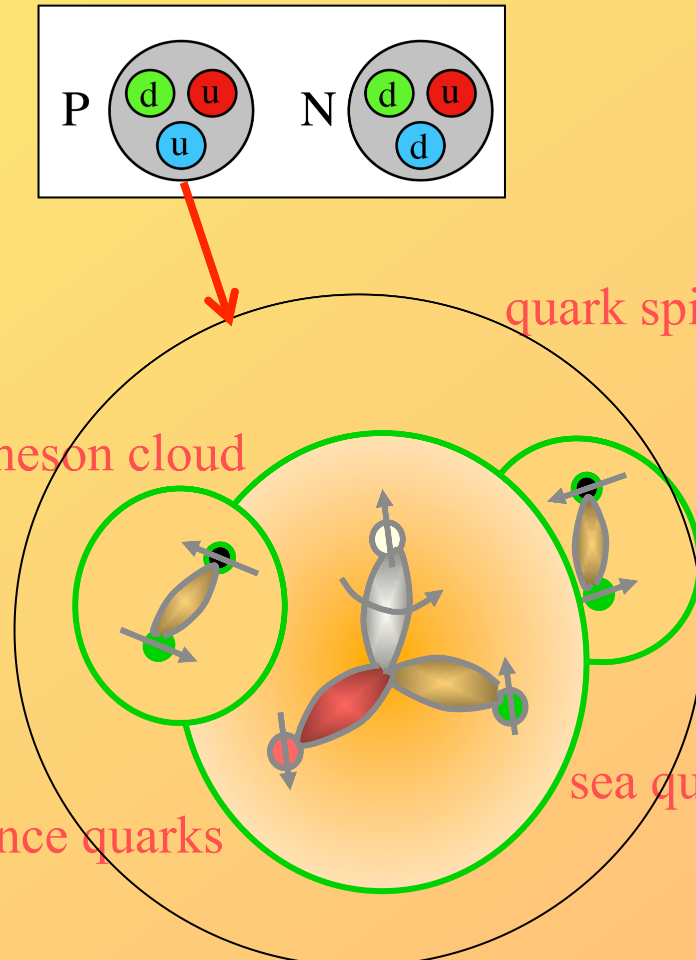
Hadron Structure

- Simple-most (constituent quark) model of nucleons (protons and neutrons)

- … becomes much more complicated once we consider the full relativistic quantum field theory called QCD

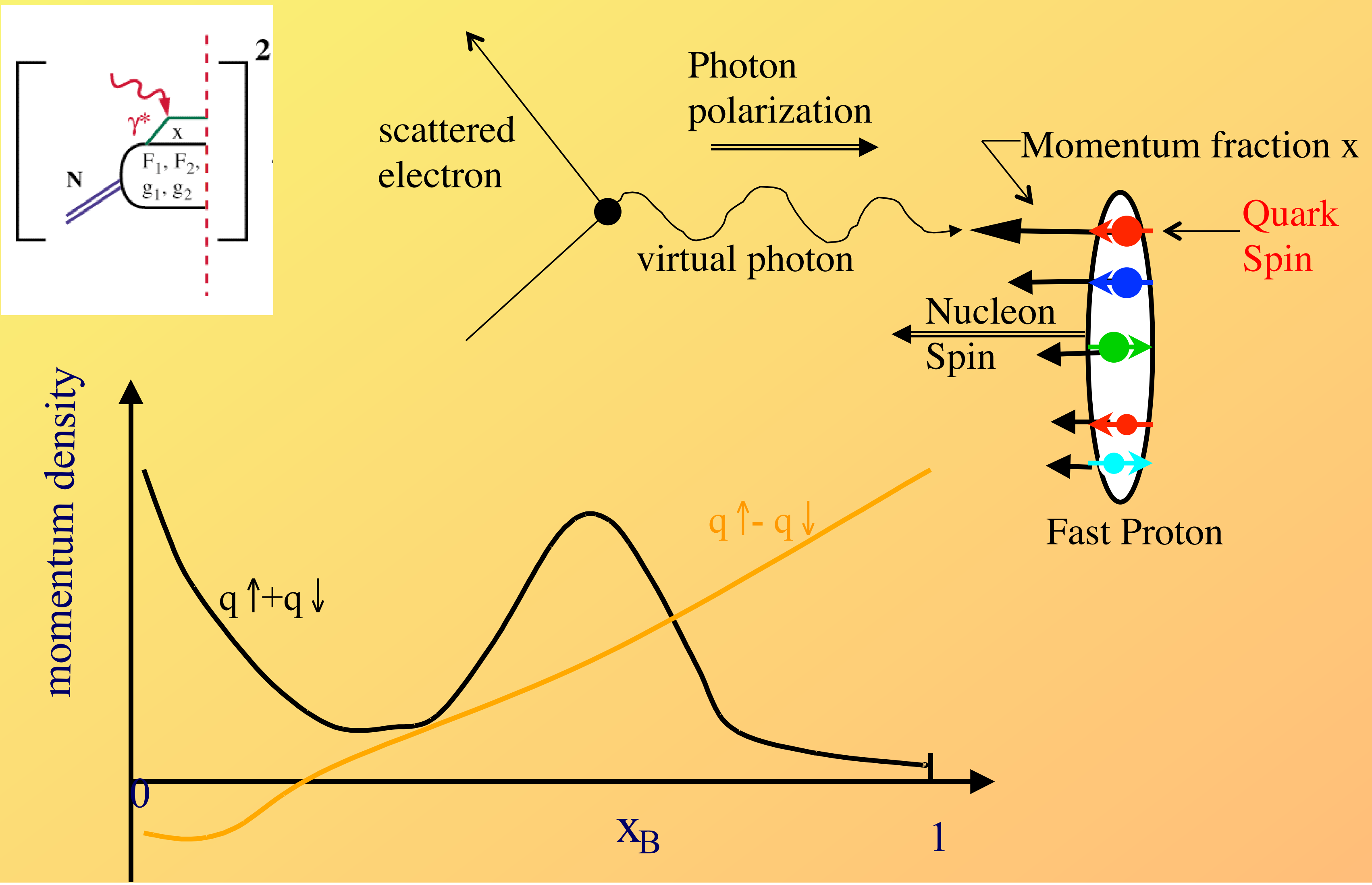
- Effective theories: Quark model, χPT, sum rules, …

- and Lattice QCD!

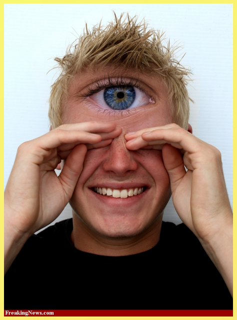


Nucleon Structure Functions -

momentum and spin distribution of quarks



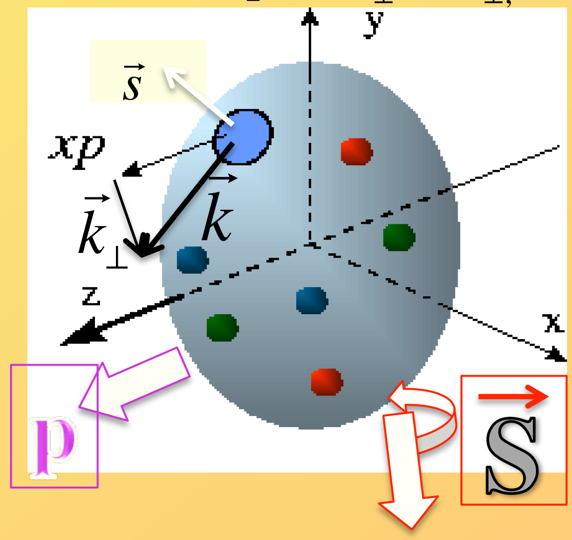
3D Partonic Structure

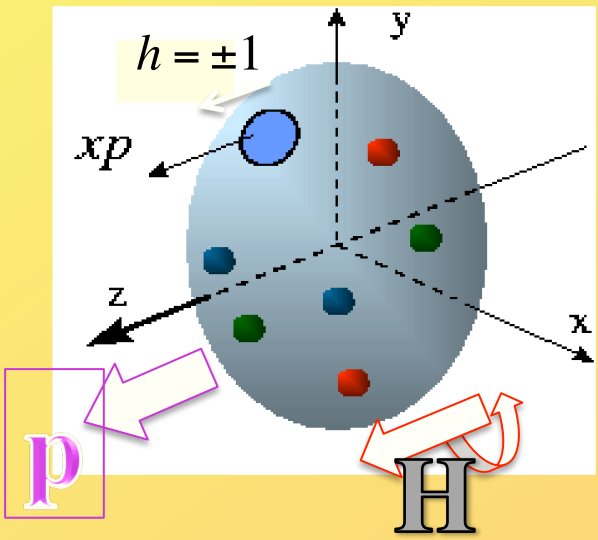


- From 1-D to 3-D:

3-D Picture of parton flavor, spin and momentum (TMDs)

$$q(H,\vec{S}_\perp,x,\vec{k}_{\perp,},h,\vec{s}_\perp;Q^2)$$

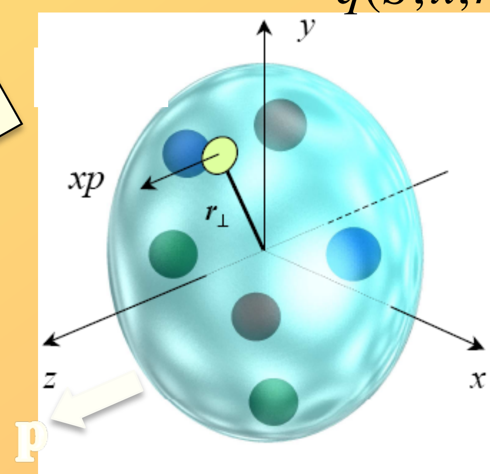


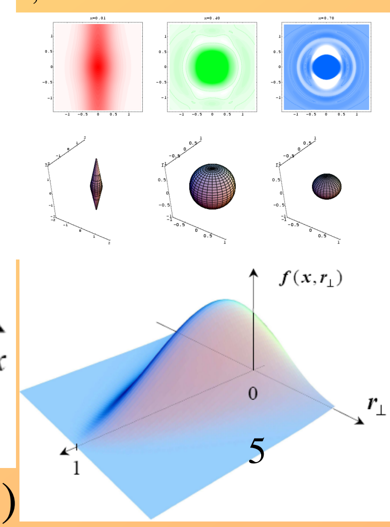


$$q(x;Q^2),\langle h\cdot H\rangle q(x;Q^2)$$

Traditional "1-D" Parton Distributions (PDFs)
(inclusive, integrated over many variables)

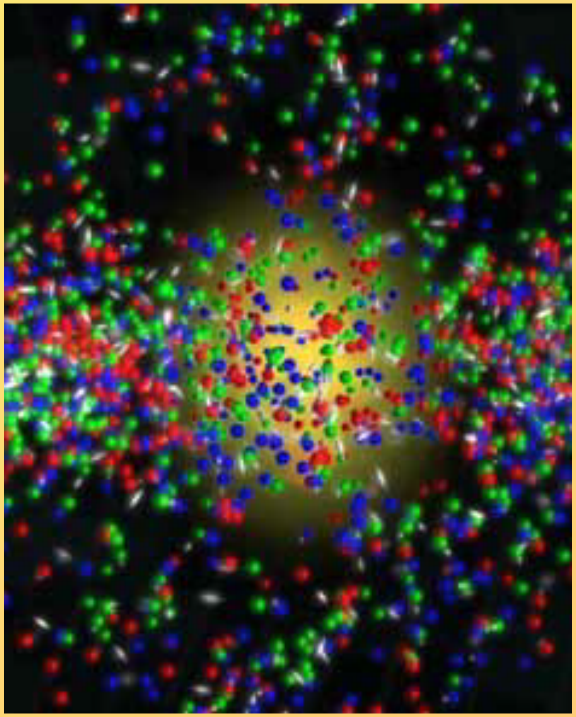
$$q(\vec{S},x,\vec{r}_{\perp,},\vec{s};Q^2)$$





3-D parton orbits (GPDs)

Nuclear Structure

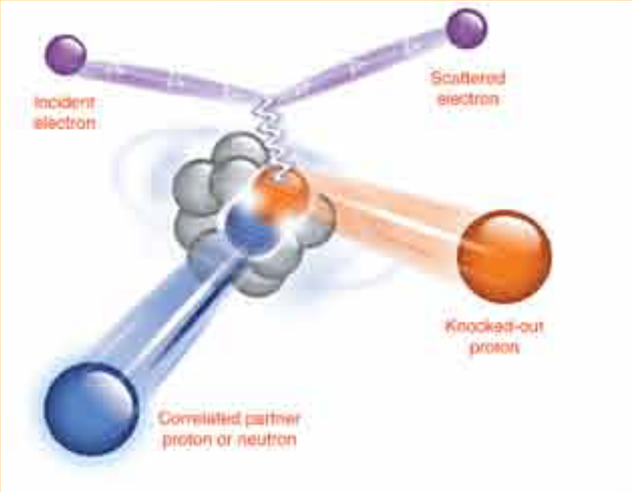


- Even more complicated!
(**not** simply a bag of nucleons)

- Effective degrees of freedom: nucleons, mesons, nucleon resonances… augmented by phenomenological NN potentials

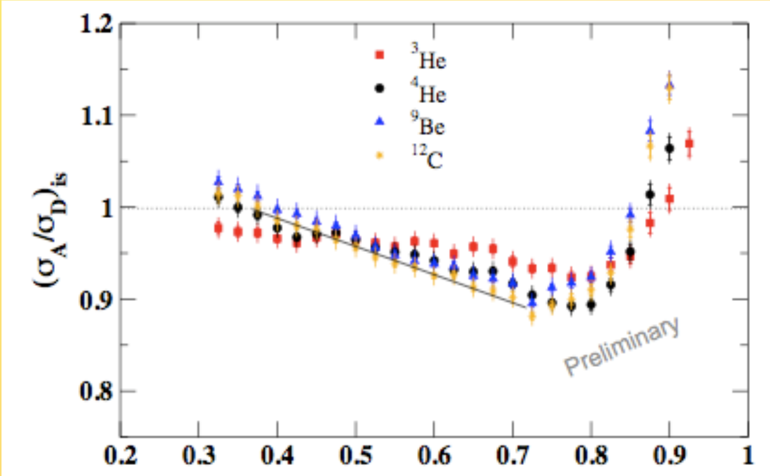
- Effective theories: low-energy EFT, χPT, relativistic and non-relativistic potential models, shell model,…

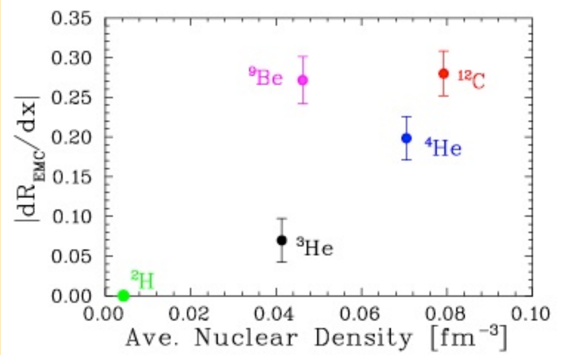
- and Lattice QCD???

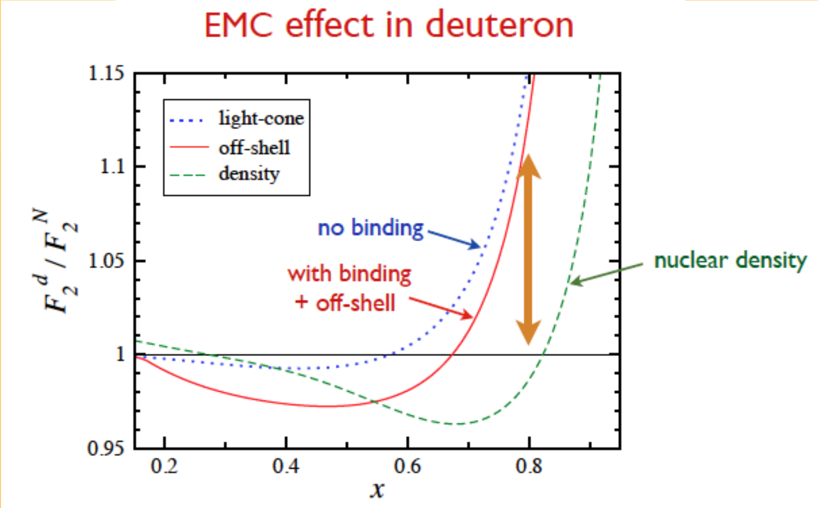


EMC Effect

- Universal shape for all nuclei
- Depth of depletion increases with A
- 1000’s of models since 1986
  - EMC = “Every Model is Cool”
- Clear connection to local nuclear density / SRC (co-discovered at ODU)
- Mean field effect?
- …or concentrated in SRC / high momentum / “off shell” nucleons?
- Still an unsolved problem
- Should exist even in the deuteron







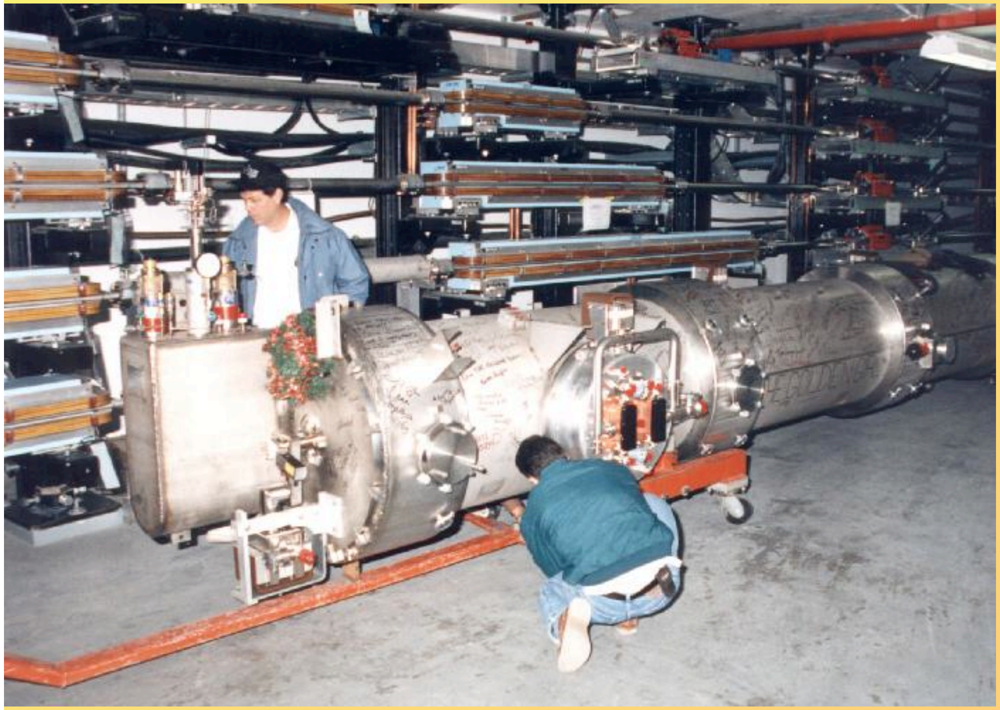
Where do we do our experiments?

Our group is one of the biggest contributors to the Jefferson Lab program

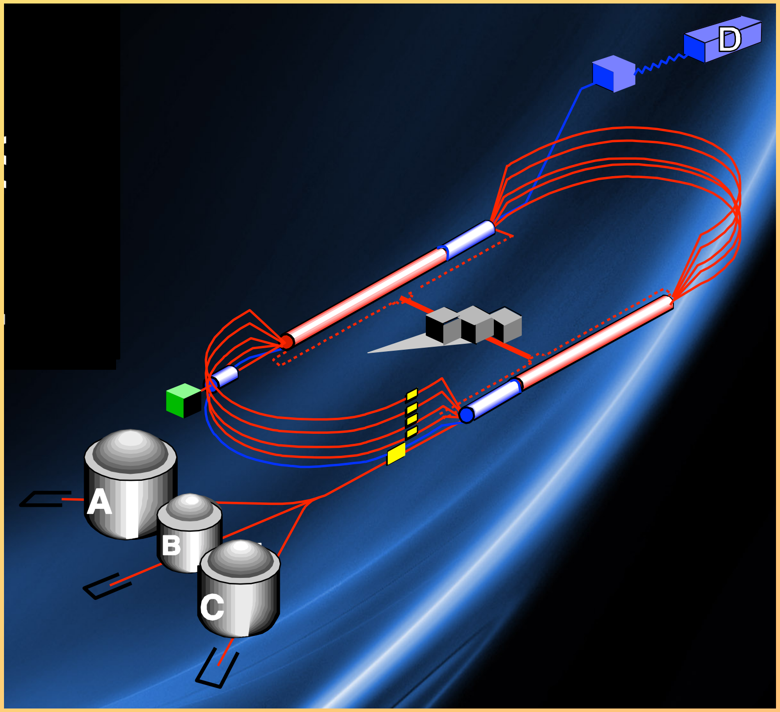
And all of it close to home!

How do we do our experiments?

Electrons are accelerated by CEBAF up to 12 GeV…



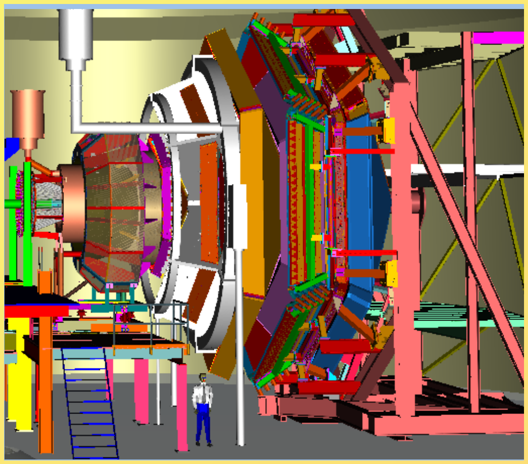
…and directed into one of the 4 Experimental Halls

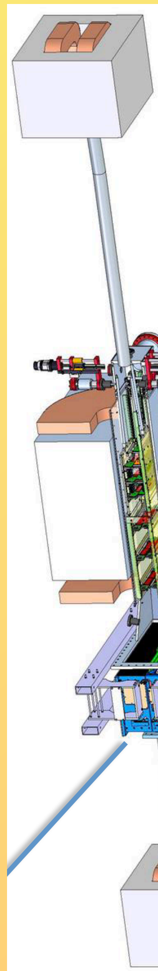


Note: Synergy with CAS at ODU

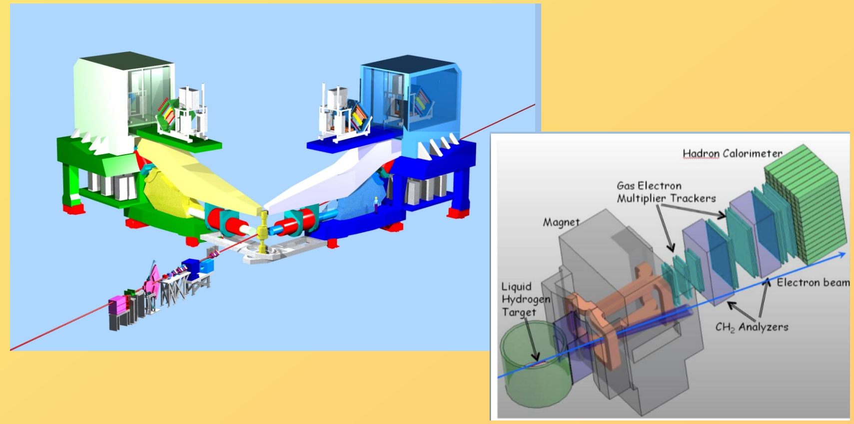
Scattered electrons and debris are **detected**…

CLAS12 in Hall B (**C**EBAF **L**arge **A**cceptance **S**pectrometer)



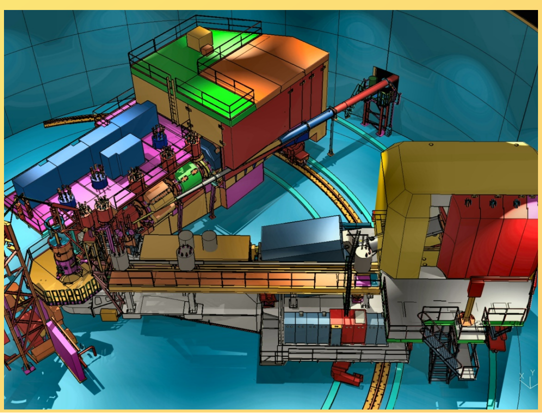


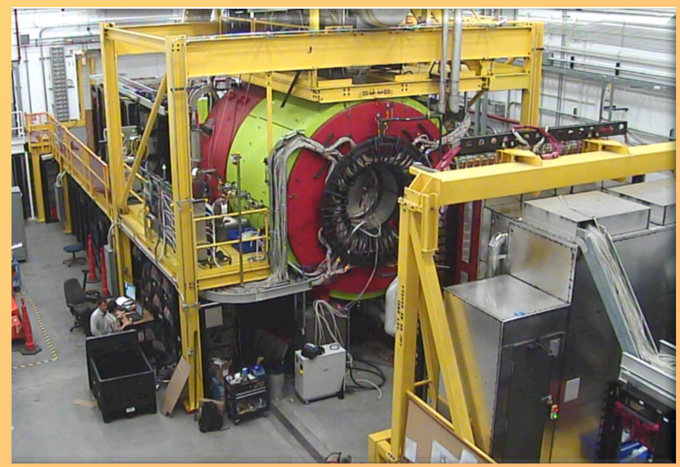
HPS Exp. Hall B



HRS and SuperBigbite in Hall A

HMS and SHMS in Hall C





GLUEX in Hall D

… and the data analyzed.

(Presently, we analyze the abundant wealth of existing data from CLAS)

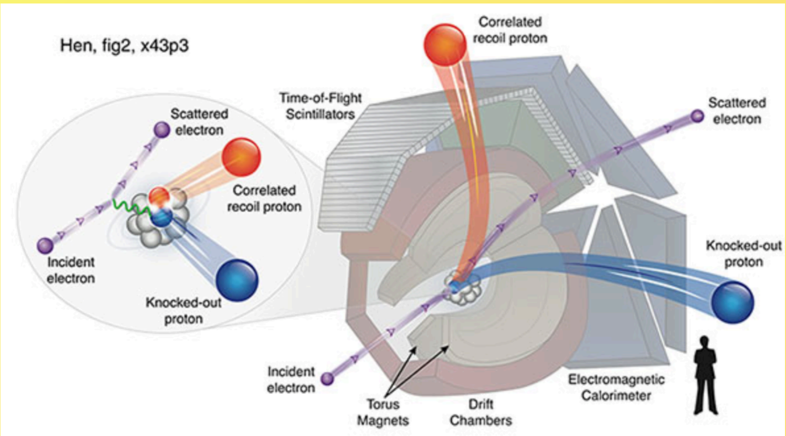
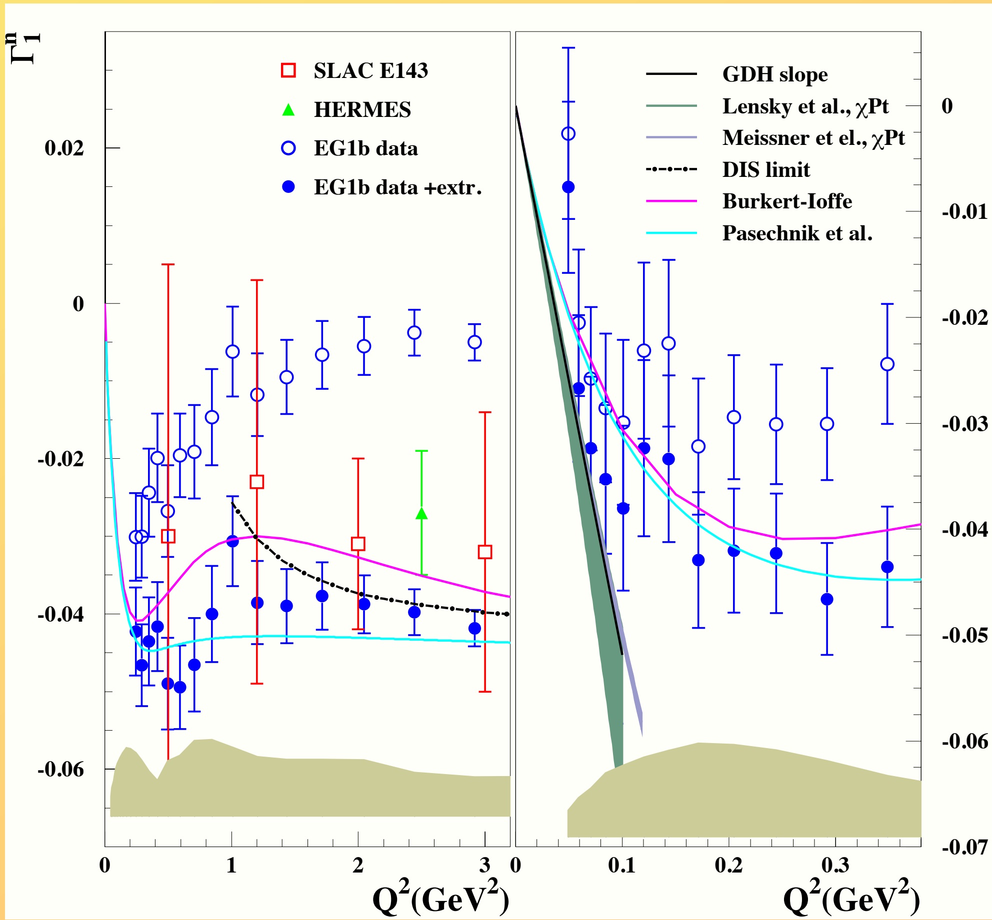


Illustration of Jefferson Lab's CEBAF Large Acceptance Spectrometer, along with an event reconstructed from the data. In this experiment, an incident 5 GeV electron scatters from a nucleon that has briefly paired up with another in a short-range correlation. Jefferson Lab's CEBAF Large Acceptance Spectrometer completely surrounds an experimental target and is roughly spherical, measuring 30 feet across. As particles flying out of the target enter the detector, their paths are bent by a magnet and are measured by successive layers of different types of particle detectors.

Average momentum of correlated protons and neutrons in nuclei – a Science publication

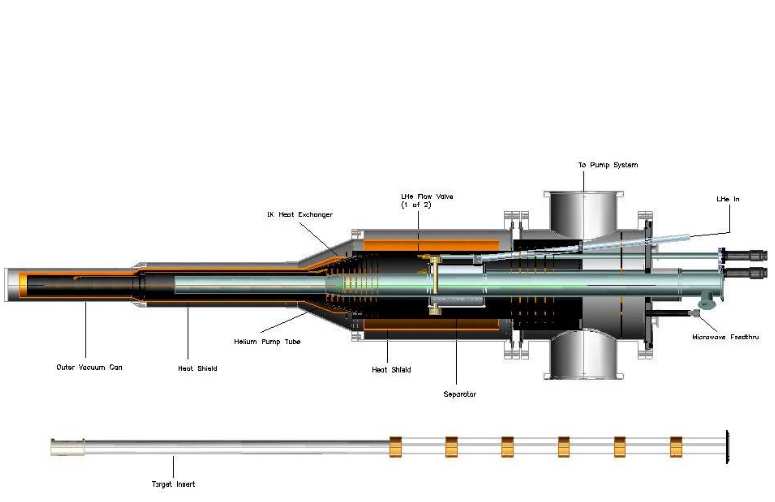
…as well as meson decays, exotic hadrons, medium modification of nucleons, …

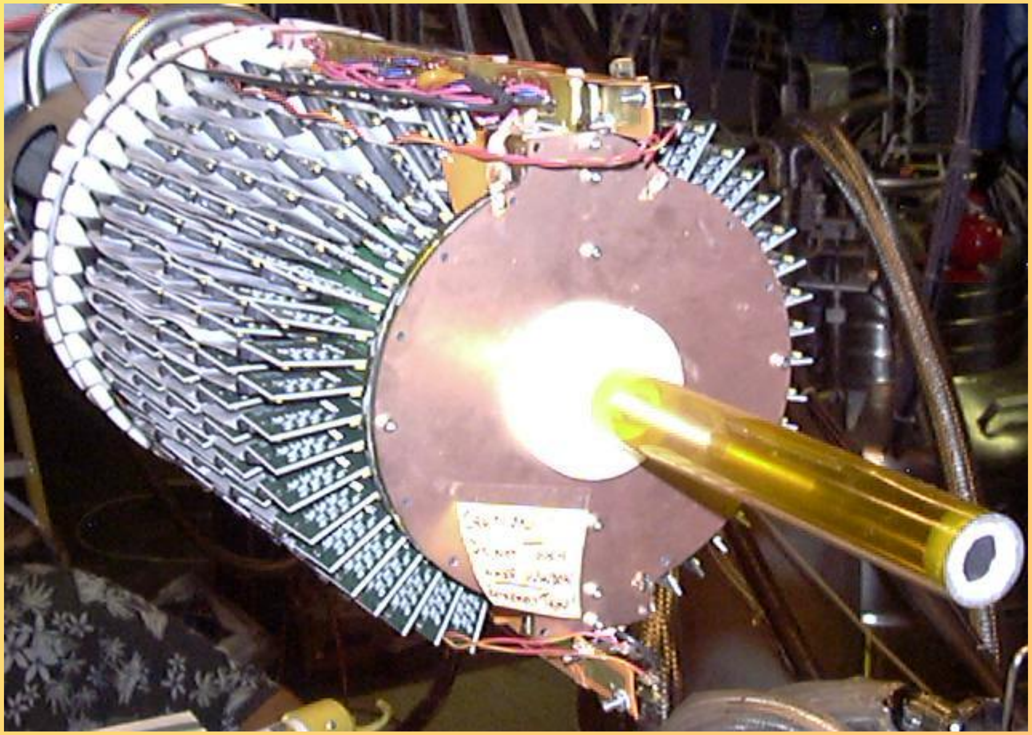


Spin Structure of the Nucleon

Building detectors for Jefferson Lab

CLAS Region 2 DCs ^ and pol. target ↓

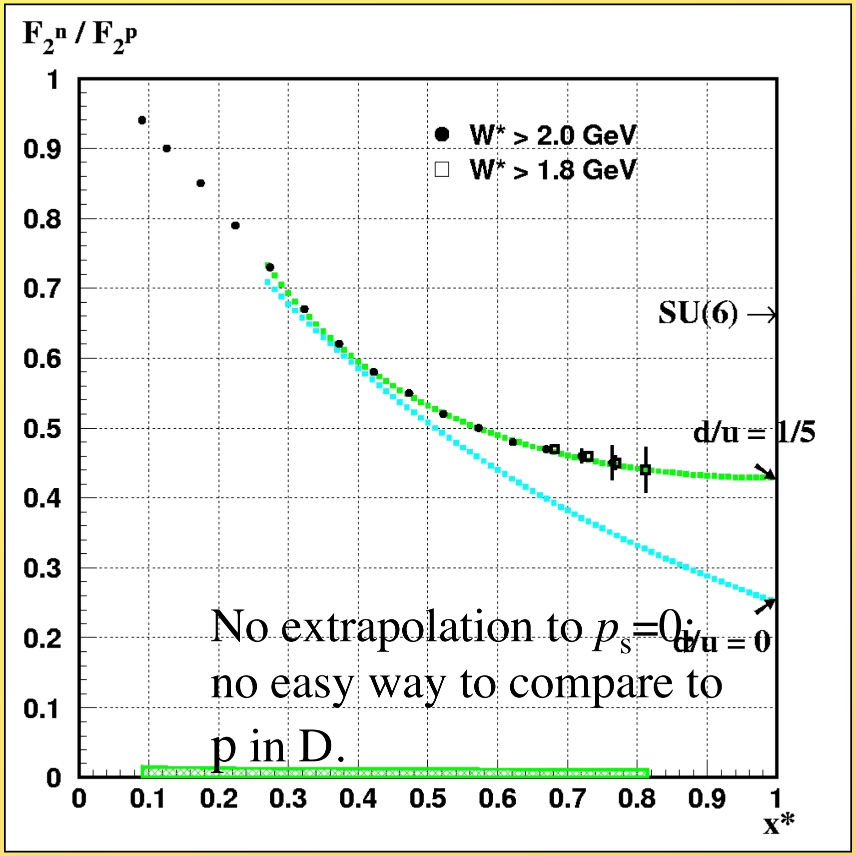




RTPC for BONuS

Plus scintillators for Hall A (and cosmic ray telescope), refurbished scintillators for Hall C, drift chambers for COMPASS experiment, etc…

The future: JLab at 11 GeV



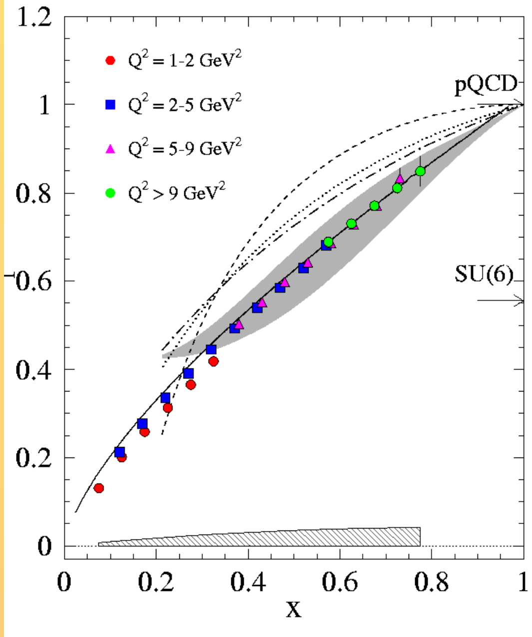
No extrapolation to p_s=0;
no easy way to compare to
p in D.

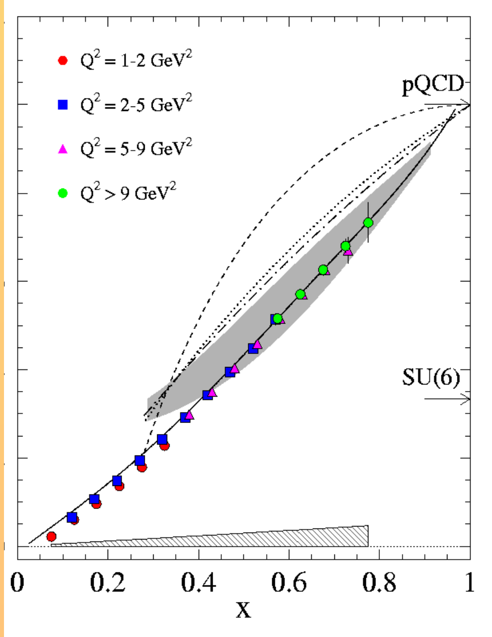
BoNuS 12

EG12

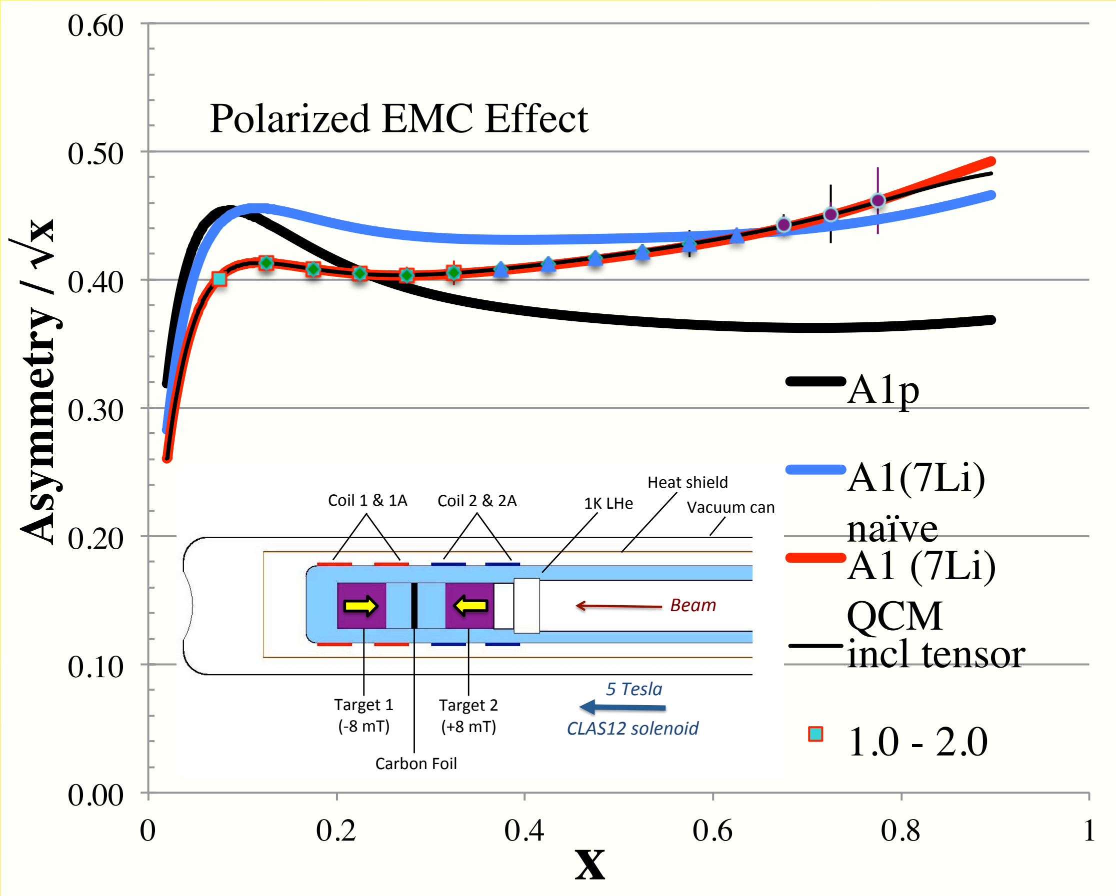
Proton

Deuteron

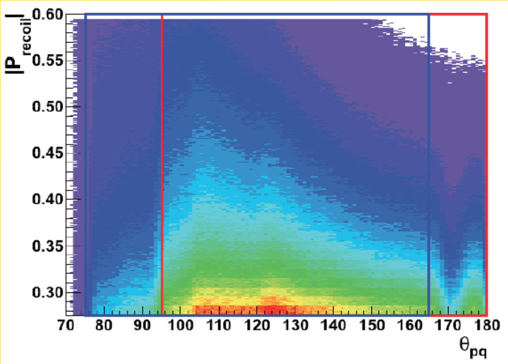


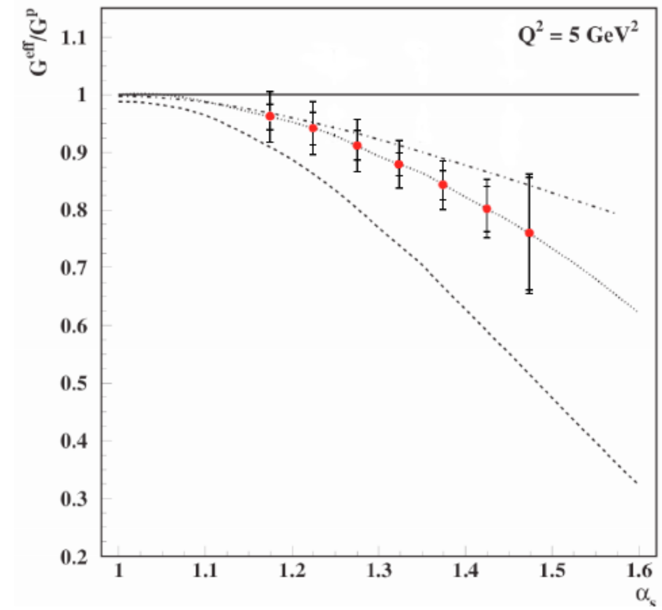


The future: JLab at 11 GeV



"Tagged EMC Effect"





The future landscape of Nuclear Physics

1. Study how nucleons are made up from quarks (“flavor”, **p**, **L**, **S** -> 3D tomography)
2. Study how hadronic quark structure is influenced by the nuclear environment
3. Understand nuclear structure and dynamics in terms of quark degrees of freedom
4. Study extreme forms of nuclear matter: high energy (Quark-Gluon plasma, “color glass condensates”), high density (short range correlations, n stars,…), non-zero strangeness (hypernuclei, strangelets, …), limits of stability (radioactive beams)…
5. Study fundamental symmetries and Physics beyond the standard model
6. Develop new applications in medicine, energy, materials, se

Electron machines

Hadron Machines

FermiLab

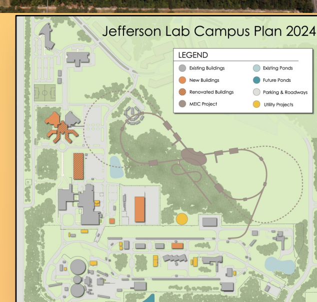
J-PARC

LHC

FAIR

Jlab at 12 GeV

Electron-Ion-Collider (2020s?)



…
+ Belle (Japan),
…

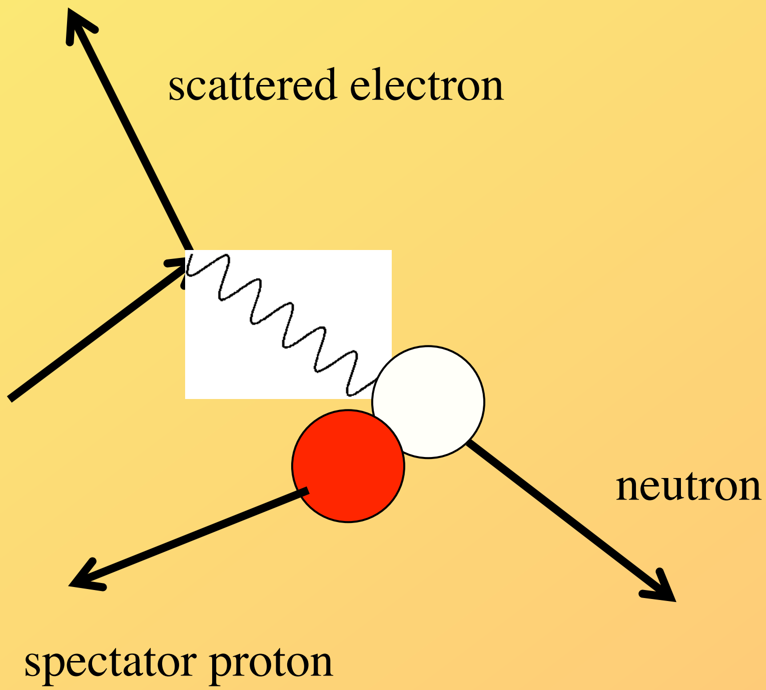
Project for New Students

If we want to know what *all* the quarks inside the nucleon are doing, we must compare protons to neutrons

- The neutron is not exactly the same as the proton.
- We have lots of data on the proton, but very little on the neutron
- Why? Because there is no free neutron target.
- To study the neutron we have to use deuterium or sometimes ^3He
- BUT – deuterium gives a smeared picture of the neutron because the neutron is not at rest in the deuteron

One Solution…

Detect the spectator proton so that you know how fast the neutron was moving before it interacted with the electron



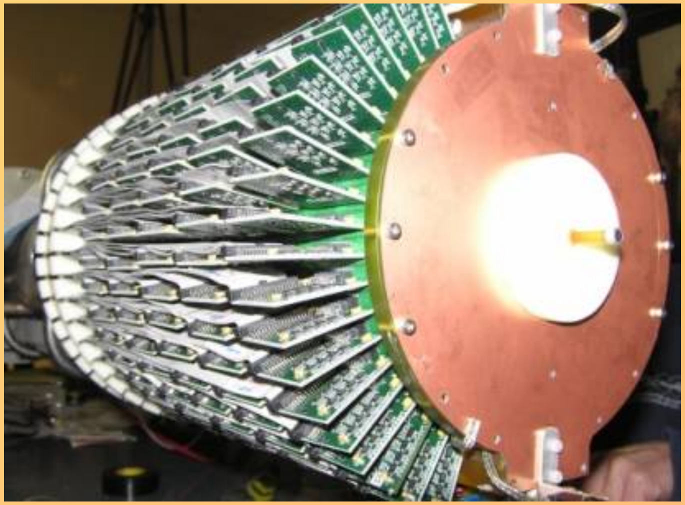
You need to detect low energy protons, especially at backward angles compared to the momentum transfer.

Barely off-shell Nucleon Structure (BoNuS)

- Electron beam energies: 2.1, 4.2, 5.3 GeV
- Spectator protons were detected by the newly built Radial Time Projection Chamber (RTPC)
- Scattered electrons and other final state particles were detected by CEBAF Large Acceptance Spectrometer (CLAS)
- Target: 7 atm D_2 gas, 20 cm long
- Data were taken from Sep. to Dec. in 2005

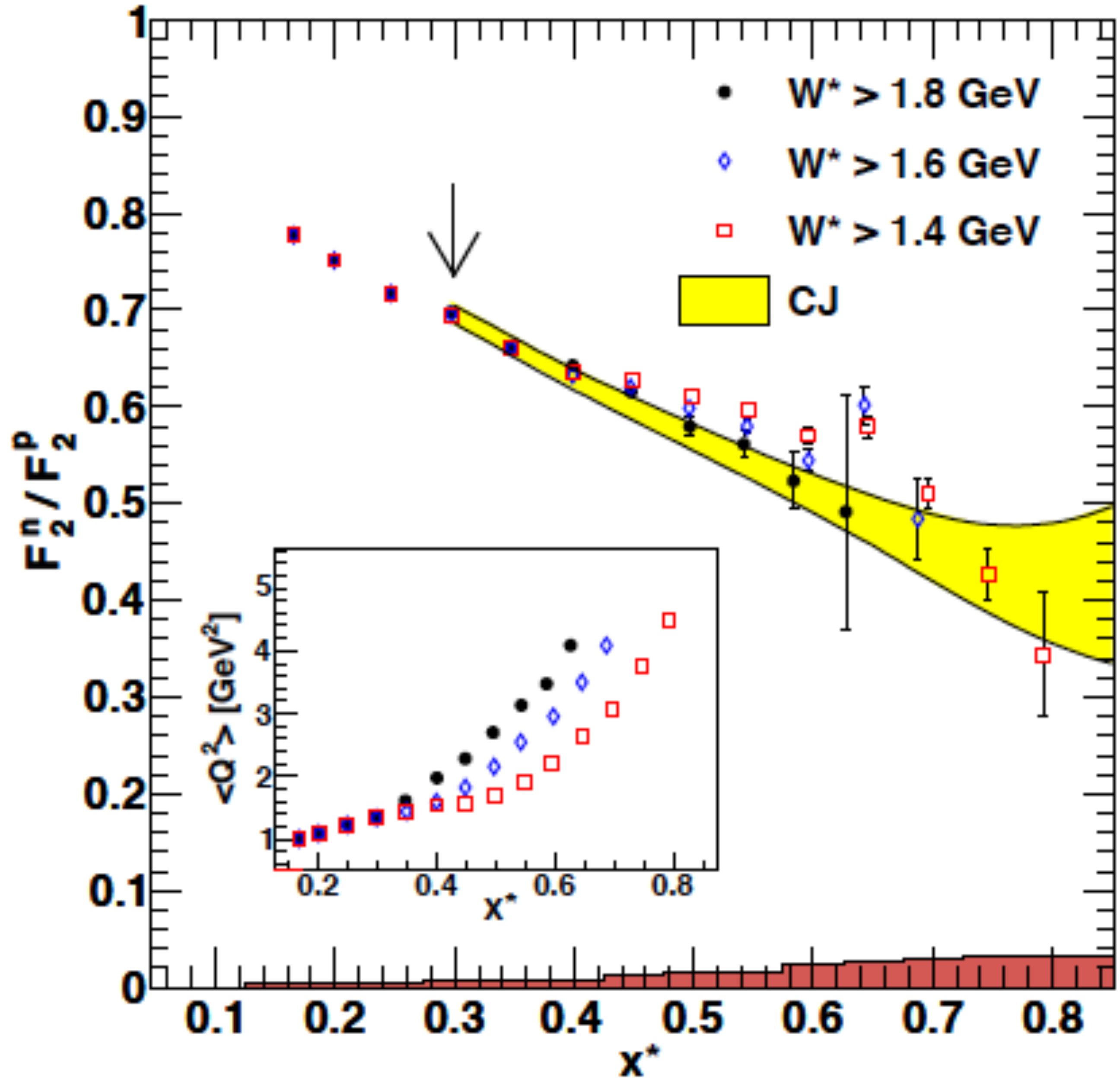
Primary Goal: to understand the momentum distribution of u and d quarks in the neutron

Secondary Goal: to use as a neutron target for studying neutron resonances



Project for New Students

6 GeV BoNuS Result



We need 12 GeV data to extend these measurements to higher x.

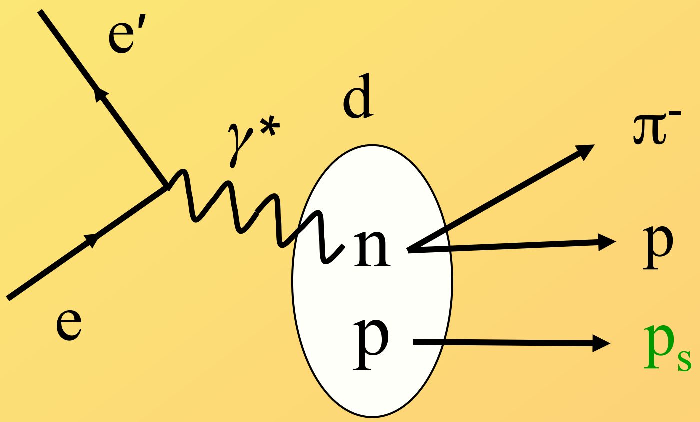
Beam time approved!

N. Baillie *et al*., PRL **108** 199902 (2012)

Another Topic: Semi-inclusive π or K electro-production

$$D(e,e'\pi p_s)X \quad \text{or } D(e,e'K p_s)X$$

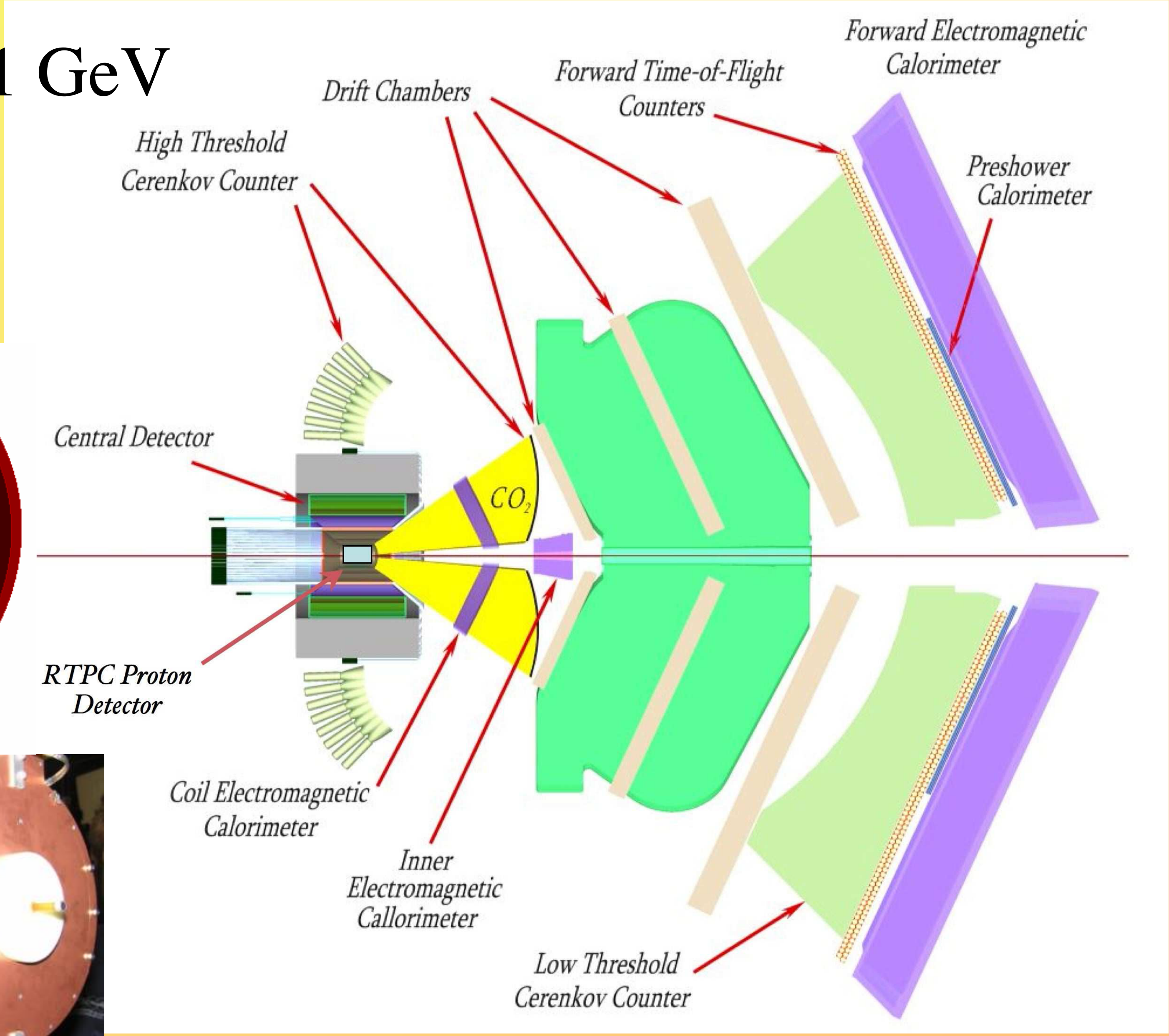
Detecting the scattered electron, the recoil proton, and an energetic meson will enable us to isolate contributions from the u and d quarks in the neutron.

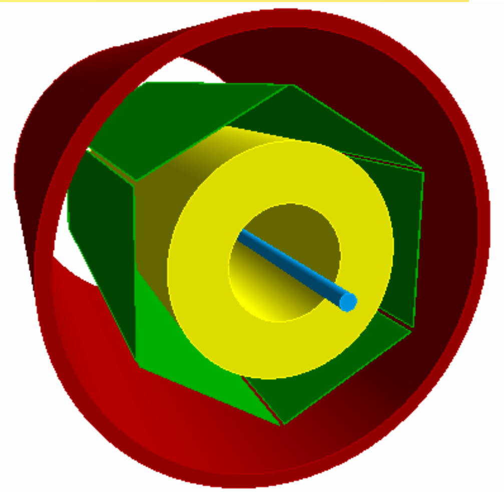


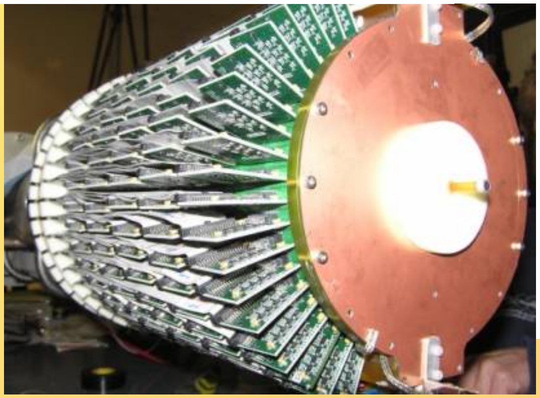
Low momentum "spectator" proton

Project for New Students

BoNuS @11 GeV







Project for New Students

Research Project – we have funding for 1 or 2 students, depending on the result of a pending proposal.

- Starting in Summer 2015, work on R&D for the new BoNuS recoil detector
  - Construct prototype low pressure wire chamber
  - Might make some tests related to the RTPC
- Do simulations to help design BoNuS @11 GeV and become familiar with how to analyze data
- Fall 2015 or Spring 2016: start analyzing existing deuteron data to look at pion production, etc. Prepare for BoNuS experiment.
- Help ODU team to test and install drift chambers in Hall B
- Take shifts in CLAS12; become an expert on one subsystem (probably drift chambers)
- Thesis: BoNuS @ 11 GeV or existing data, depending on the timing of the BoNuS run.

Contact Sebastian and/or Gail for more Information

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- Gail Dodge

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And where do you go from here?

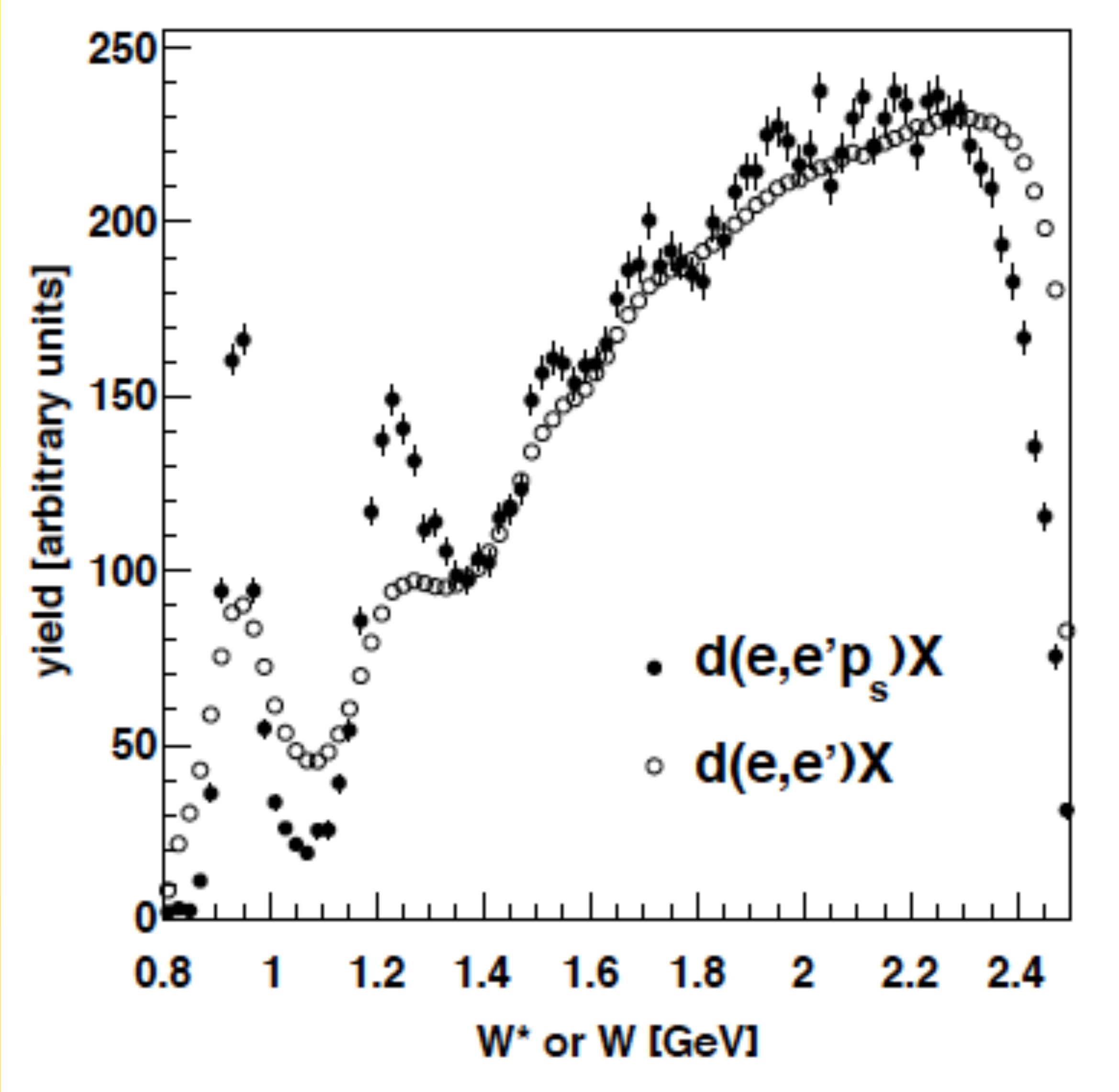
- Former Ph.D. Students in our group have attained permanent positions as faculty, at National Labs and in Industry
- Recent graduates have jobs in Medical Physics, at INTEL, and as postdocs at national labs and prestigious Universities world-wide (Jefferson Lab, UVa, PSU, University of Taiwan, Jülich,…)

Project for New Students

BoNuS Data

Detecting the spectator proton allows us to correct for the initial momentum of the neutron in the deuteron. The resonances are much clearer.

N. Baillie *et al*., PRL **108** 199902 (2012)



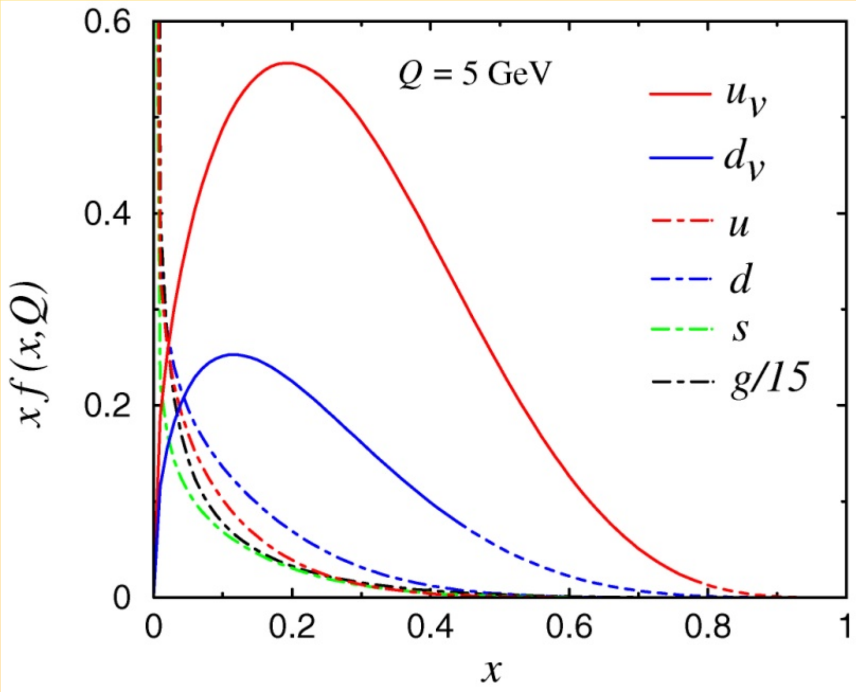
Project for New Students

Nucleon Structure Functions

(in the quark-parton model)

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

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



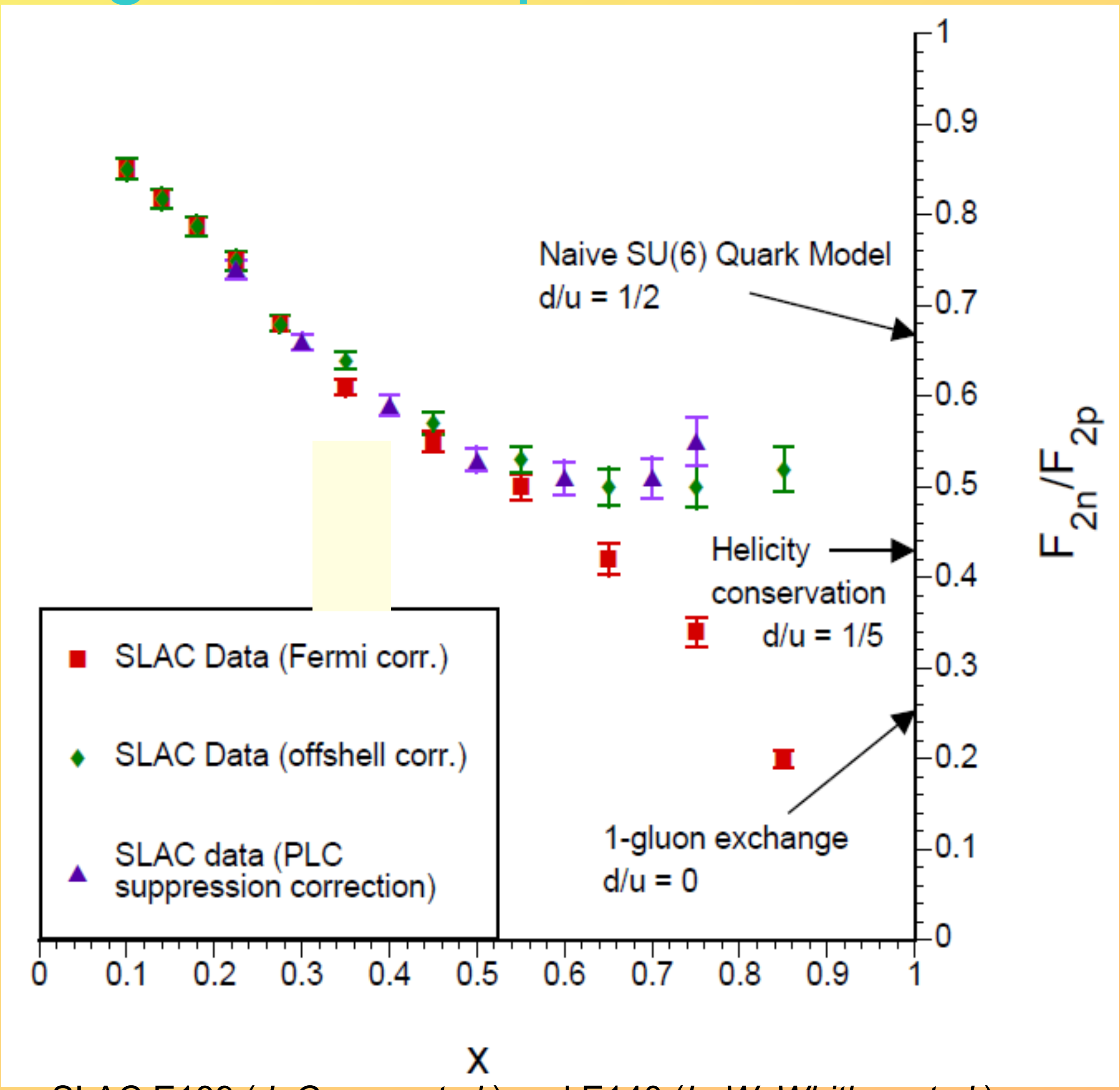
Dominated by the valence quarks' contribution at large x

Project for New Students

Very Strong Model Dependence

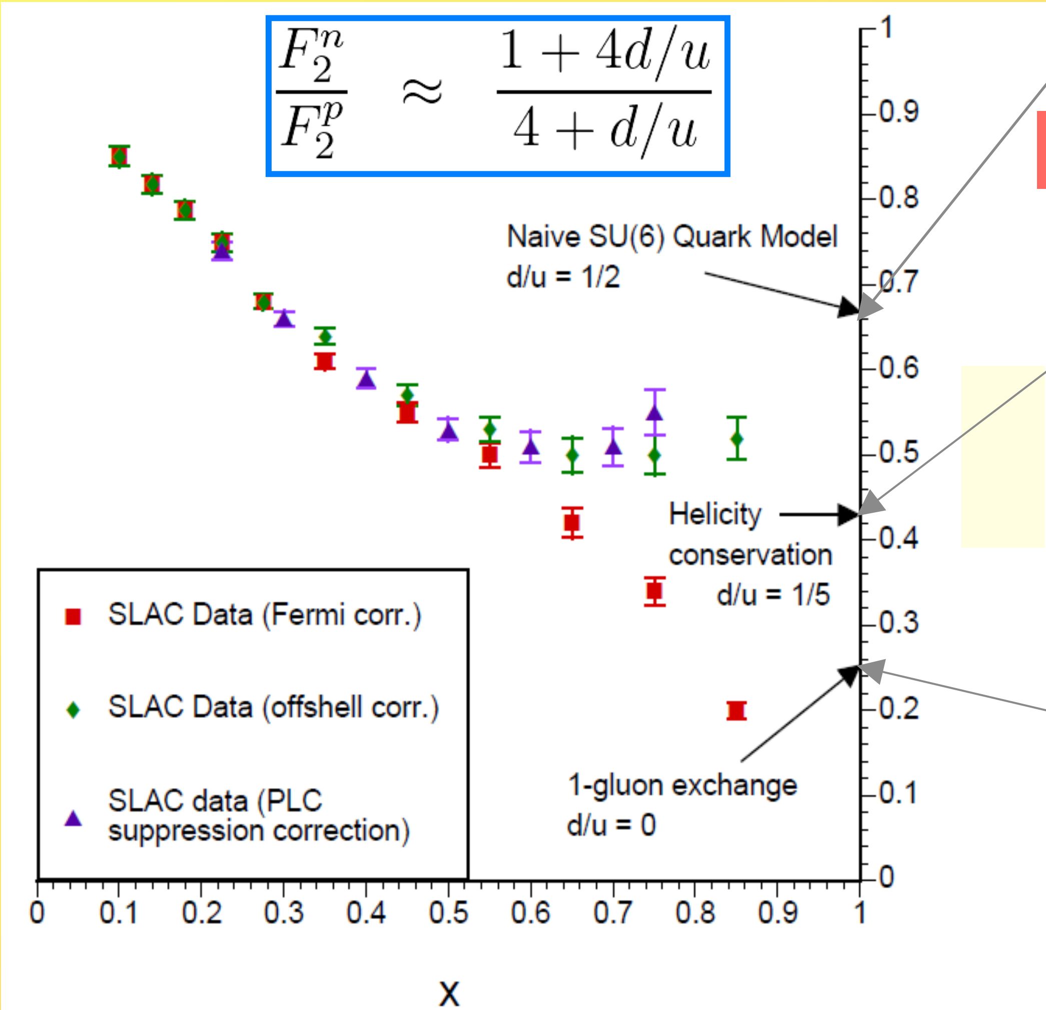
$$\boxed{\frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+d/u}}$$

Extracting the neutron from data on deuterium has a strong model dependence.



SLAC E139 (*J. Gomez et al.*) and E140 (*L. W. Whitlow et al.*)

Project for New Students



$$\frac{F_2^n}{F_2^p} = \frac{2}{3}, \qquad \frac{d}{u} = \frac{1}{2}$$

SU(6) symmetry $\mathbf{u_v(x) = 2d_v(x)}$

$$\frac{F_2^n}{F_2^p} \to \frac{3}{7}, \qquad \frac{d}{u} \to \frac{1}{5}$$

$$\frac{F_2^n}{F_2^p} \to \frac{1}{4}, \qquad \frac{d}{u} \to 0$$

SLAC E139 (*J. Gomez et al.*) and E140 (*L. W. Whitlow et al.*)