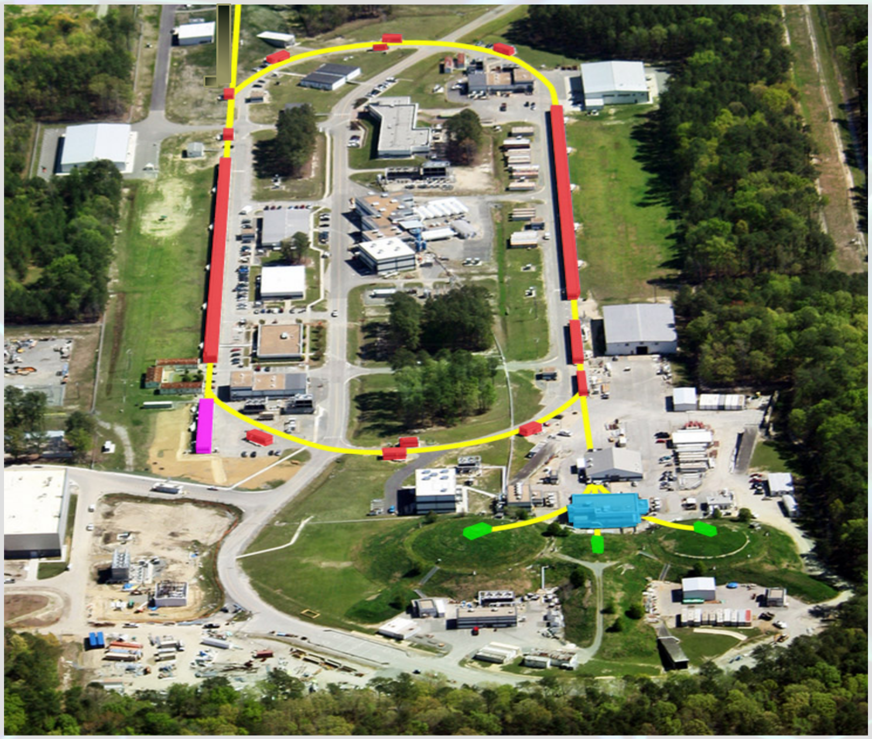
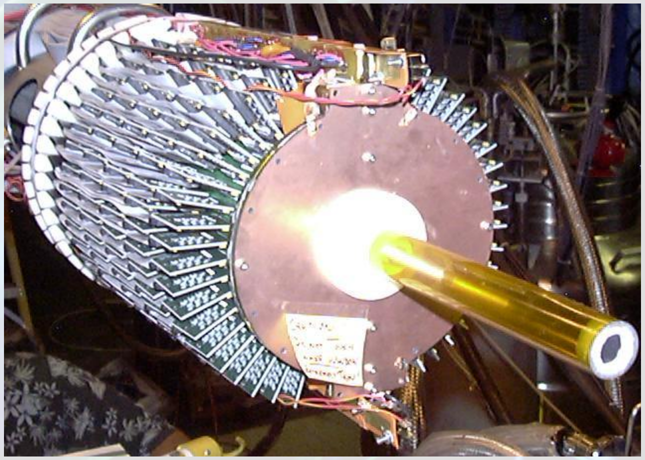
The Gottfried Sum Rule Revisited
(Using Precision Neutron Data)

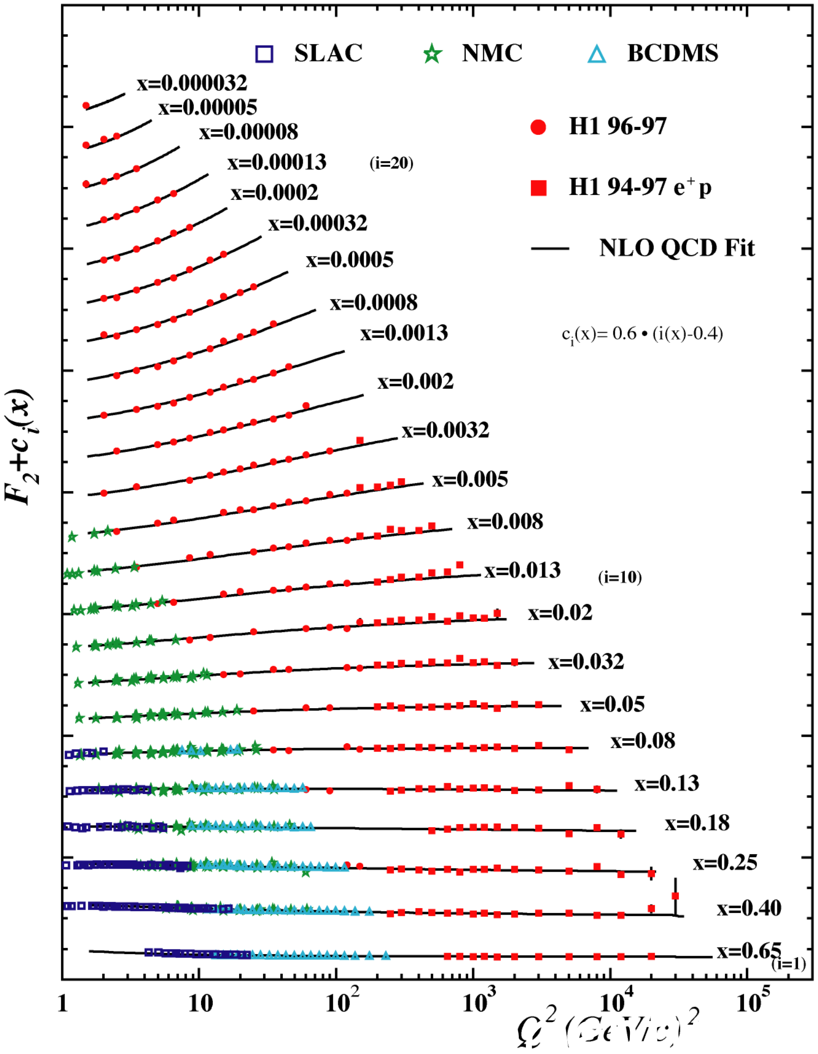


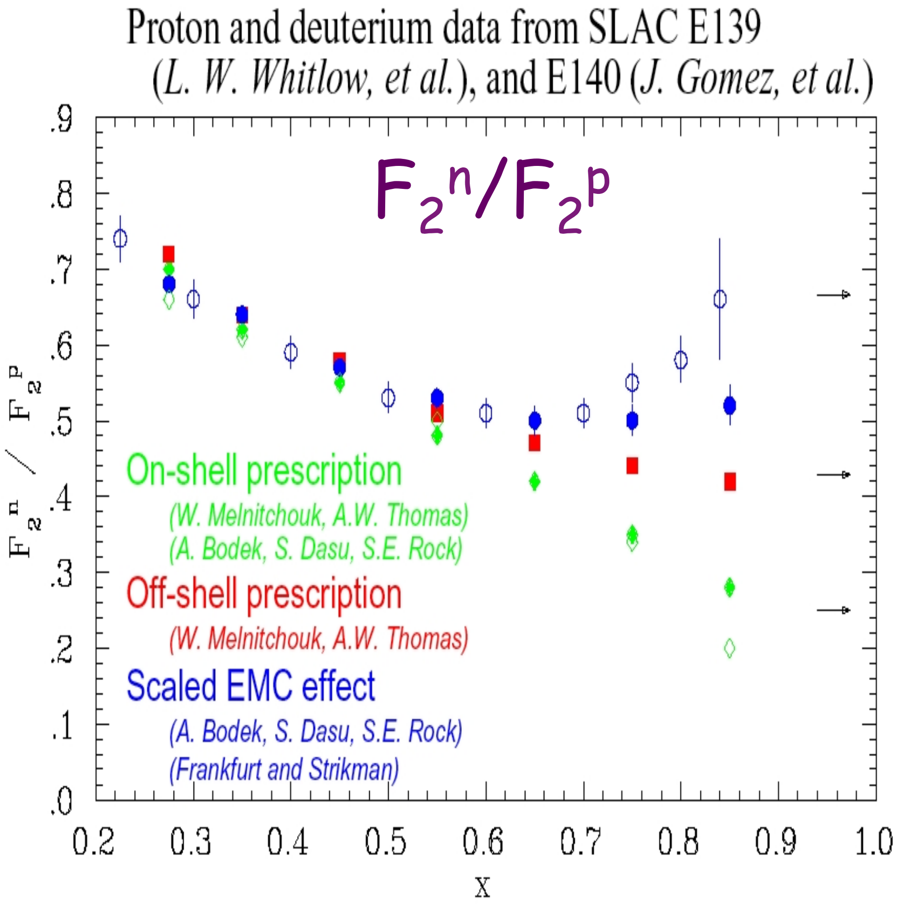


Thia Keppel
DIS 2015
Southern Methodist University

World data on F_2^p

But, no free neutrons in nature = no similar F_2^n plot




Proton and deuterium data from SLAC E139 (*L. W. Whitlow, et al.*), and E140 (*J. Gomez, et al.*)

- Deuterium target requires nuclear corrections

Outline

- A work in progress (*S. Malace,* E. Christy, A. Accardi, W. Melnitchouk, I. Niculescu, G. Niculescu)

- Precision *neutron* data is now possible
  - Theory progress in deuteron nuclear corrections
  - New precision data, effective neutron target data
  - Deuteron nuclear corrections in pdf fits, with complementary (d-sensitive) data

- Creating $F_2^{\mathbf{n}}(x,Q^2)$ data set applying state-of-the-art nuclear corrections to existing data
  - Broad kinematic range in available $F_2^{\mathbf{d}}(x,Q^2)$ data
  - Also use effective neutron target data (BONUS at JLab)

- Revisit Sum Rules that require $F_2^{\mathbf{n}}$
  - Gottfried
  - Momentum

Sum Rules I – Momentum Sum Rule

Sum rules involve differences of structure functions or cross-sections. The relative normalization between relevant cross-sections, therefore, must be accurately measured.
- CTEQ Handbook of Perturbative QCD

electron scattering

$$\frac{9(1+\delta)}{5+2\delta}\int_0^1 dx\,(F_2^{e^-p}+F_2^{e^-n}) = \int_0^1 dx\,x(u+\bar{u}+d+\bar{d}+s+\bar{s}) = 1-\varepsilon$$

$$\delta = \frac{\int_0^1 dx x(s+\bar{s})}{\int_0^1 dx x(u+\bar{u}+d+\bar{d})}$$

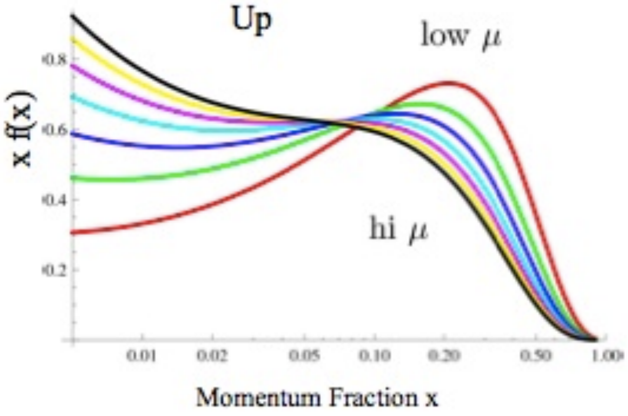
exp. data for $F_2^{p/n}$ +
$SU_f(3)$ symmetry for q^{sea} +
extraction $u(x)$, $d(x)$, $s(x)$

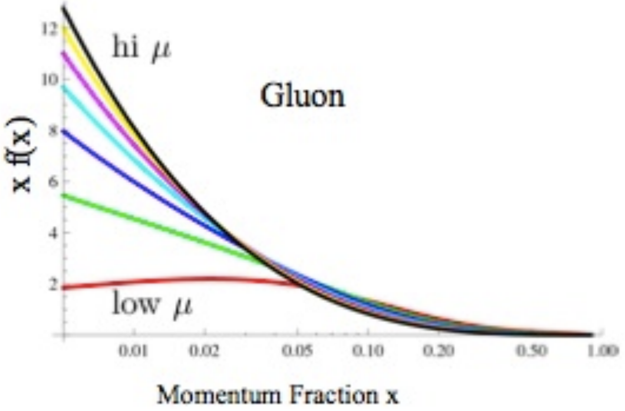
$0 \lesssim \delta \lesssim 0.06$
$\Rightarrow\ \varepsilon \approx (0.54 \div 0.56) \pm 0.04$

partons that don't couple to the photon (gluons) carry around half of N momentum

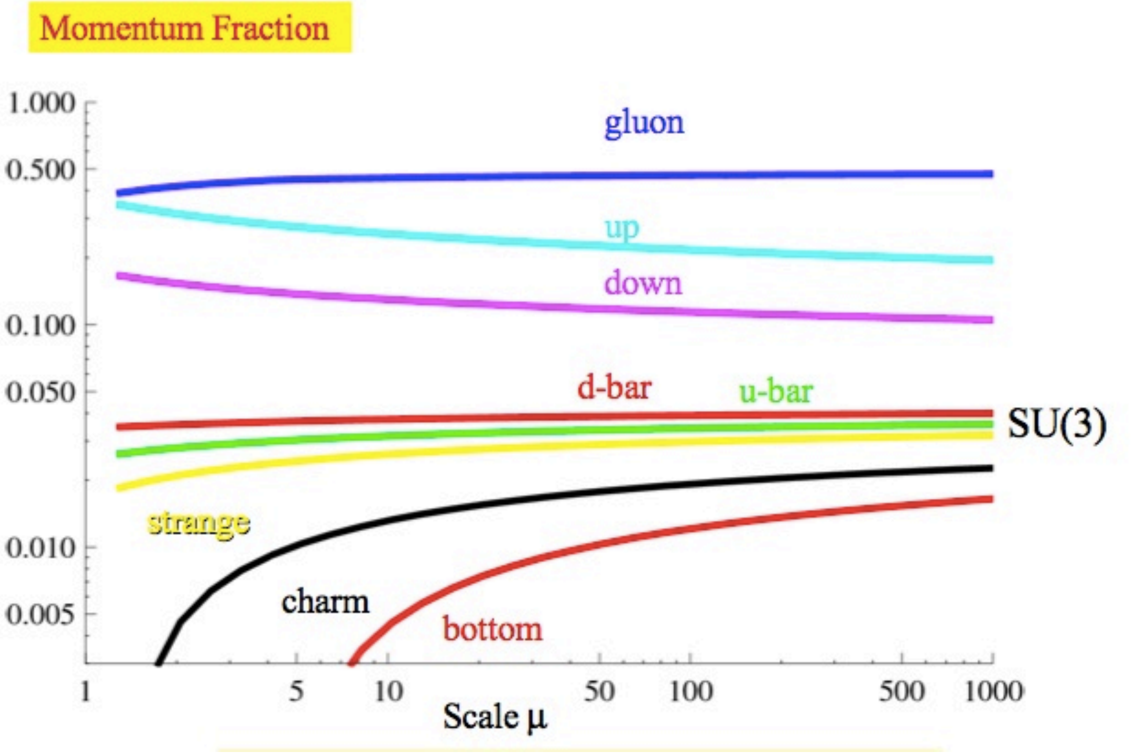
Knowledge of the gluon distribution comes indirectly from scaling violations generated according to the DGLAP evolution *and from the momentum sum rule which constrains the momentum fractions carried by all flavors of partons to add up to one.*

Sum Rules I – Momentum Sum Rule





Plots from F. Olness,
2010 CTEQ Summer School



- PDF fits use deuterium data
- Improved neutron leads to improved d(x, Q^2)…
- …leads in turn to improved g(x, Q^2)

Sum Rules II – Gottfried Sum Rule

$$S_G = \int_0^1 \frac{(F_2^{\mu p} - F_2^{\mu n})}{x} dx = \frac{1}{3} + \text{correction}$$

$\overline{\mathrm{U}} \neq \overline{\mathrm{D}}$ and
higher order perturbative corrections (small, Ross and Sachrajda, 1979)

$$S_G = \frac{1}{9}\left[4(U_p + \bar{U}_p) + (D_p + \bar{D}_p) - 4(U_n + \bar{U}_n) - (D_n + \bar{D}_n)\right]$$

$$= \frac{1}{3} + \frac{2}{3}\left[(\bar{U} - \bar{D})\right]$$

$$U_p = \int_0^1 u(x)dx,$$

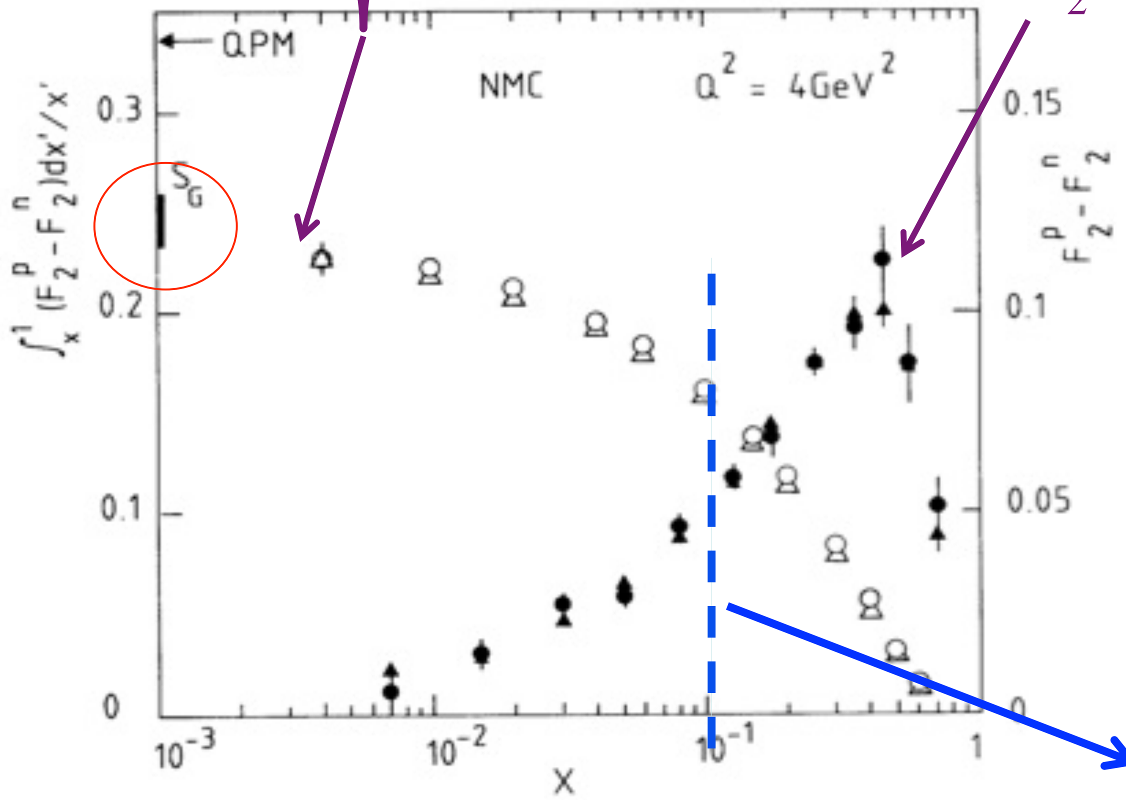
$$D_p = \int_0^1 d(x)dx,$$

The Gottfried Sum Rule provides information on the possible existence of a light antiquark flavor asymmetry in the nucleon sea.

Sum Rules II – Gottfried Sum Rule

$$S_G = \underbrace{\int_{x_{min}}^{1} \frac{(F_2^{\mu p} - F_2^{\mu n})}{x} dx}\, = \boxed{0.227} \pm 0.007 \pm 0.014 \text{ for } 0.004 \le x \le 0.8.$$

<< 1/3!



$F_2^p - F_2^n$

- Large asymmetry in the nucleon sea
- Pion cloud of the nucleon
- Extrapolation to the unmeasured region in *x*

– Abbate and Forte 2005 (NNPDF) 0.244 =/- 0.045

Assumes 2p – d = p – n

NMC Collaboration, Amaudruz, P., *et al.*, 1991, Phys. Rev. Lett. **66**, 2712

Deuteron nuclear corrections increasingly large

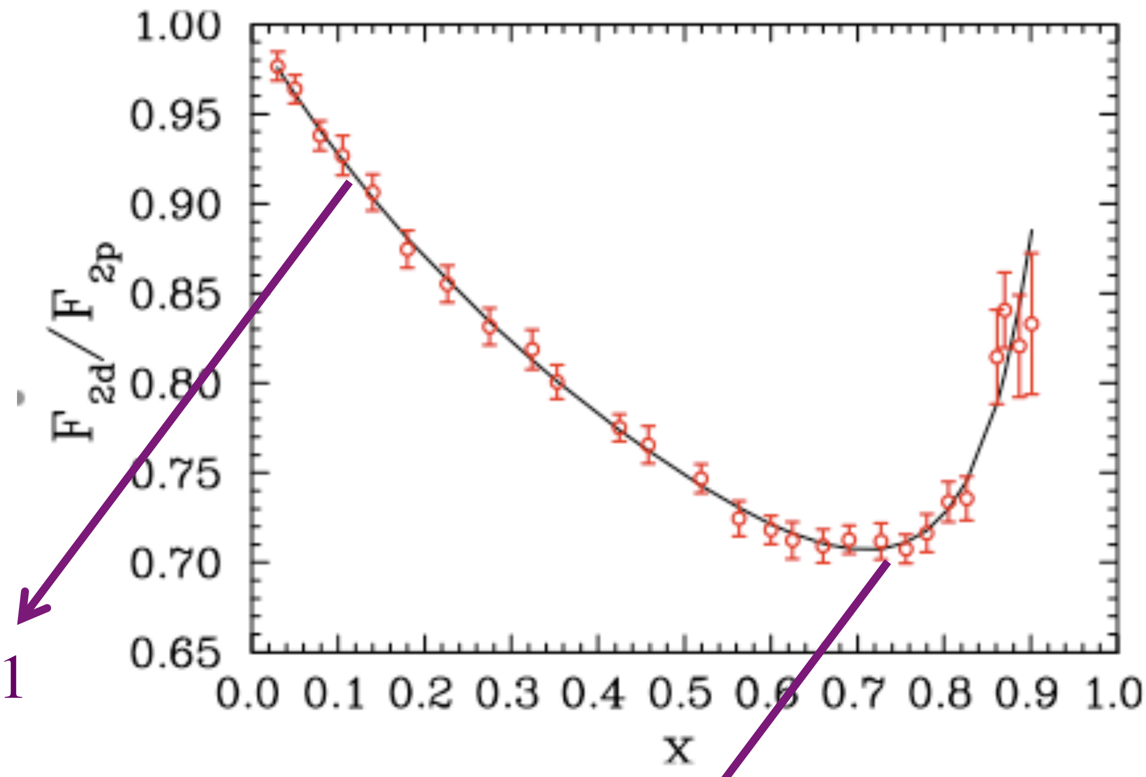
Deuteron Nuclear Effects

Challenging task

- Fermi motion
- Deuteron wave function
- Nucleon structure modification, EMC effect
- Off-shell effects
- ……..

F_2^d/F_2^p data from SLAC

$Q^2 = 12\ \mathrm{GeV}^2$

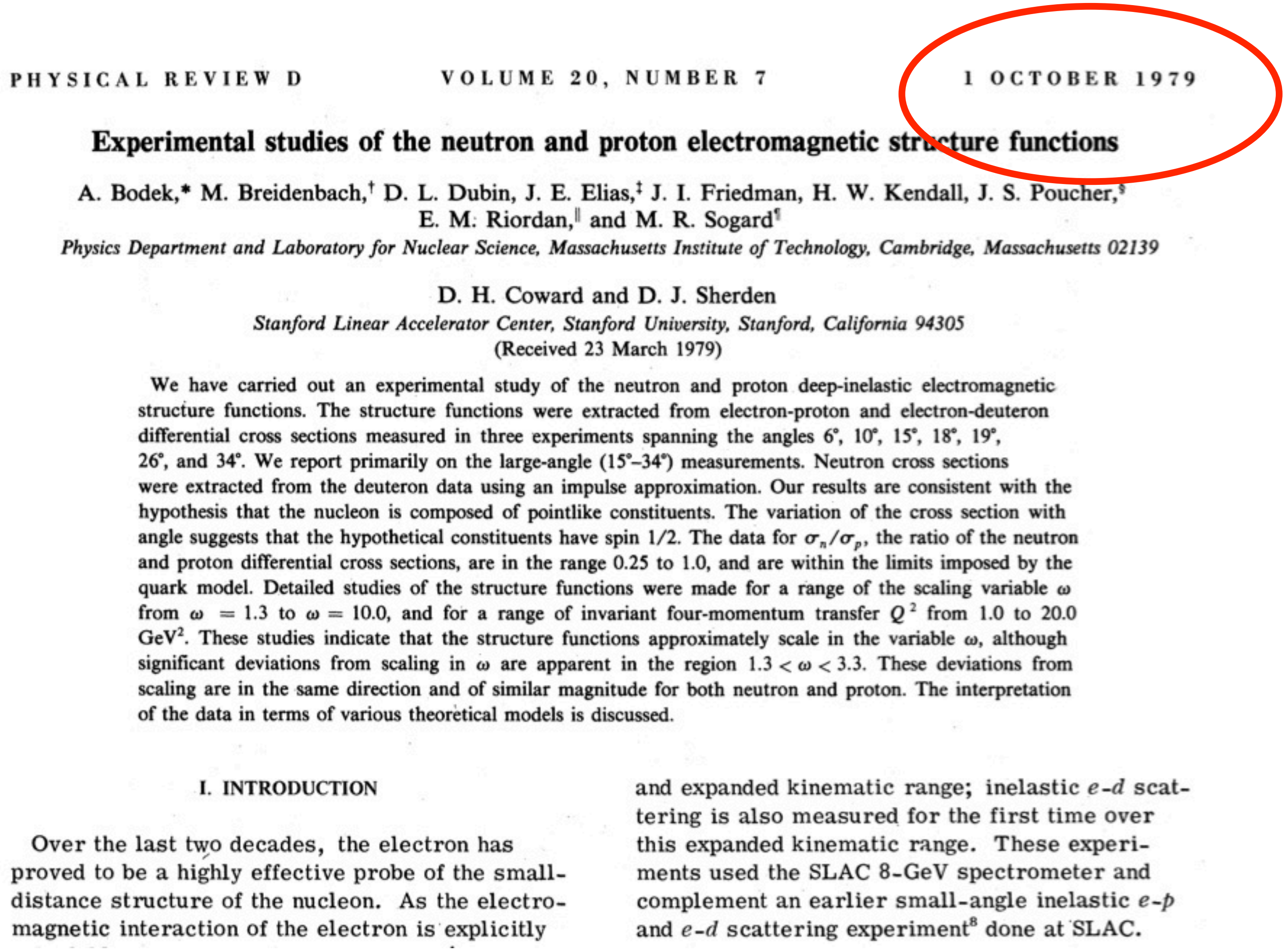


~10% at x~0.1

up to ~30% at larger x!

Plot in Arrington et al., ***J.Phys. G36 (2009) 025005***

An old problem – what's new?



PHYSICAL REVIEW D VOLUME 20, NUMBER 7 1 OCTOBER 1979

Experimental studies of the neutron and proton electromagnetic structure functions

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Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 23 March 1979)

We have carried out an experimental study of the neutron and proton deep-inelastic electromagnetic structure functions. The structure functions were extracted from electron-proton and electron-deuteron differential cross sections measured in three experiments spanning the angles 6°, 10°, 15°, 18°, 19°, 26°, and 34°. We report primarily on the large-angle (15°–34°) measurements. Neutron cross sections were extracted from the deuteron data using an impulse approximation. Our results are consistent with the hypothesis that the nucleon is composed of pointlike constituents. The variation of the cross section with angle suggests that the hypothetical constituents have spin 1/2. The data for σ_n/σ_p, the ratio of the neutron and proton differential cross sections, are in the range 0.25 to 1.0, and are within the limits imposed by the quark model. Detailed studies of the structure functions were made for a range of the scaling variable ω from $\omega = 1.3$ to $\omega = 10.0$, and for a range of invariant four-momentum transfer Q^2 from 1.0 to 20.0 GeV^2. These studies indicate that the structure functions approximately scale in the variable ω, although significant deviations from scaling in ω are apparent in the region $1.3 < \omega < 3.3$. These deviations from scaling are in the same direction and of similar magnitude for both neutron and proton. The interpretation of the data in terms of various theoretical models is discussed.

I. INTRODUCTION

Over the last two decades, the electron has proved to be a highly effective probe of the small-distance structure of the nucleon. As the electromagnetic interaction of the electron is explicitly

and expanded kinematic range; inelastic e-d scattering is also measured for the first time over this expanded kinematic range. These experiments used the SLAC 8-GeV spectrometer and complement an earlier small-angle inelastic e-p and e-d scattering experiment[8] done at SLAC.

CTEQ_Jefferson Lab PDF fits

A. Accardi, W. Melnitchouk (talks), J. Owens, N. Sato (theory)
E. Christy, C. Keppel, P. Monaghan (experiment)

New parton distributions from large-x and low-Q^2 data
Phys. Rev. D81:034016 (2010)

Uncertainties in determining parton distributions at large x
Phys. Rev. D84:014008 (2011)

Global parton distributions with nuclear and finite-Q^2 corrections
Phys. Rev. D87:094012 (2013)

PDFs at http://lhapdf.hepforge.org/lhapdf5/pdfsets
CJ collaboration: http://www.jlab.org/CJ

Goals:

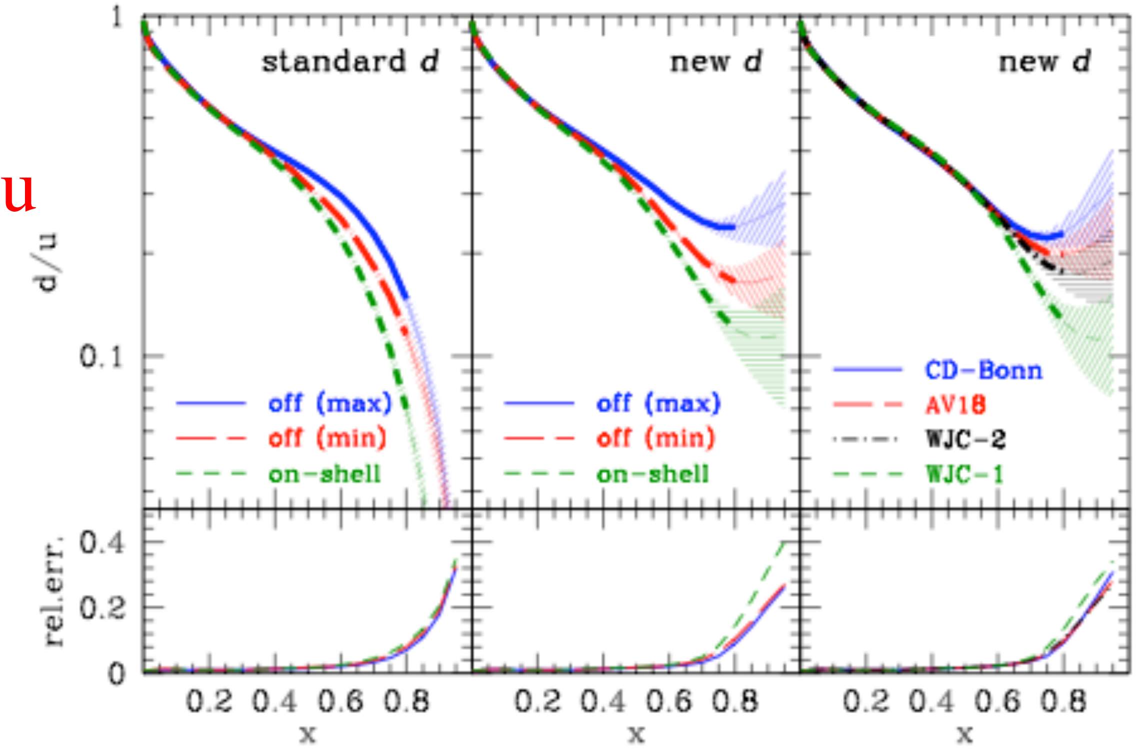
- Extend CTEQ fit to larger values of x and lower values of Q^2
- Incorporate data previously subject to kinematic cuts (SLAC and JLab largely)

To accomplish this:

- Need to relax conventional cuts defining "safe" region for issues such as higher twist, target mass - will now need to take these into account
- Allow d/u to go to a constant (not just $(1-x)^3$ type form)
- *Need accurate deuteron nuclear corrections*

Evaluate nuclear (deuterium) corrections by showing d/u ratios

The different nuclear corrections have the largest effect on the d PDF



d/u

- Standard d-quark parameterization

  (d -> 0 as x -> 1)
- AV18 wave function
- Range of off-shell models

- Modified d-quark parameterization

  (d/u -> c as x -> 1)
- AV18 wave function
- Range of off-shell models

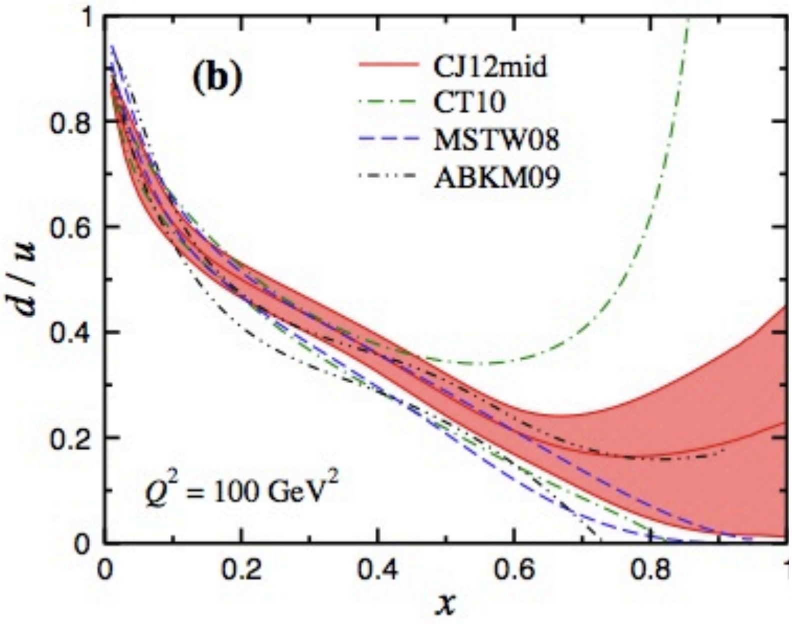
- Modified d-quark parameterization
- Fixed off-shell
- Range of deuteron wave functions

F_2^n better constrained

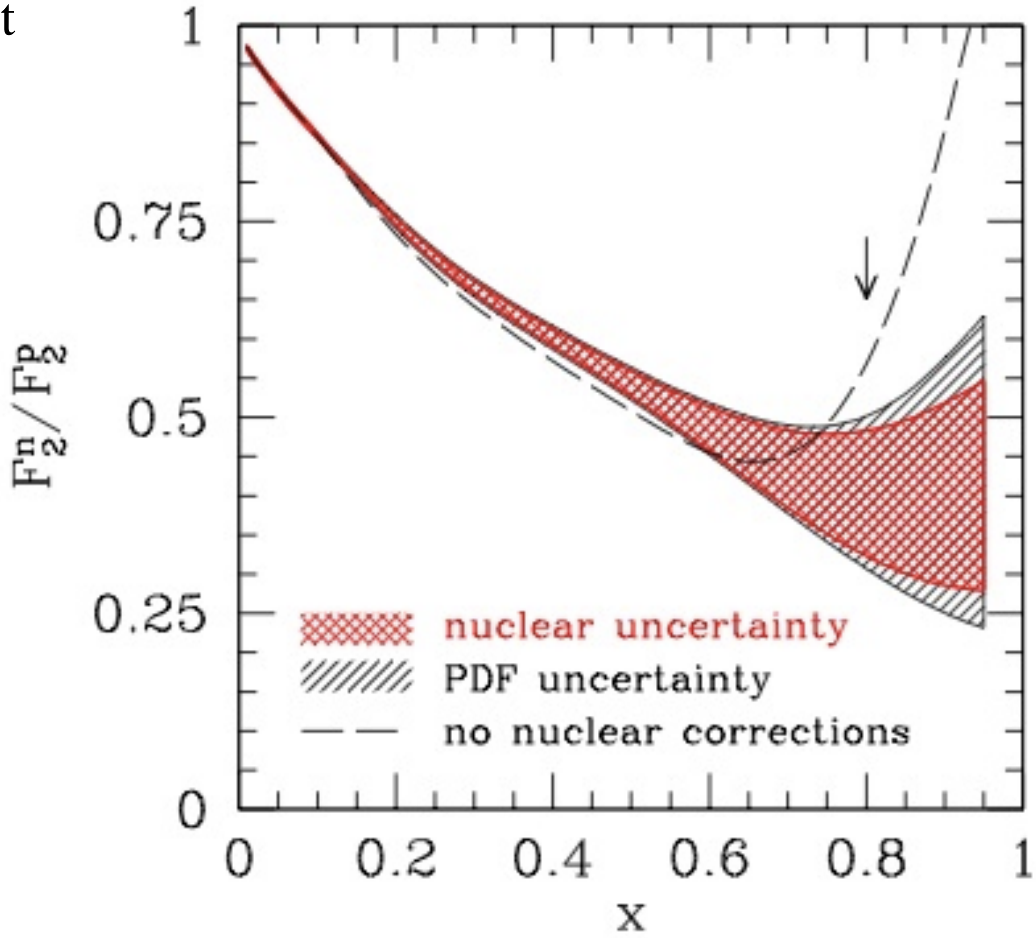
Resulting CJ uncertainty bands

- Nuclear corrections still dominant
- Significantly reduced

d/u



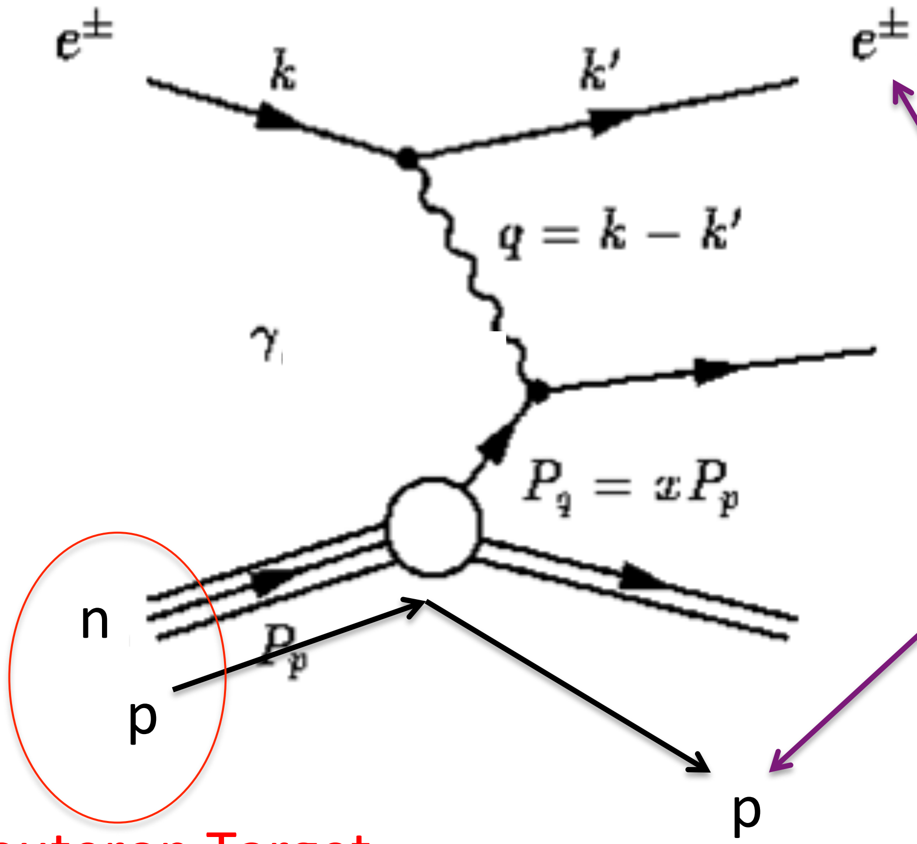
F_2^n/F_2^p



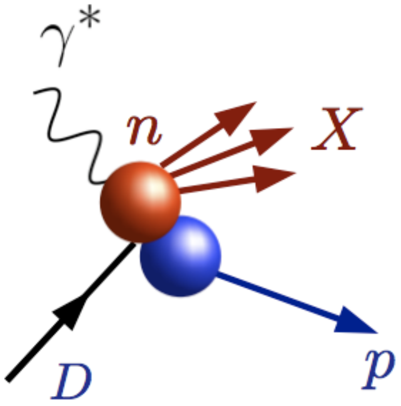
BONUS (Barely Off-Shell Neutron Structure) Experiment at JLab

See G. Niculescu talk

en scattering



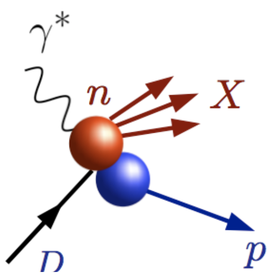
Deuteron Target



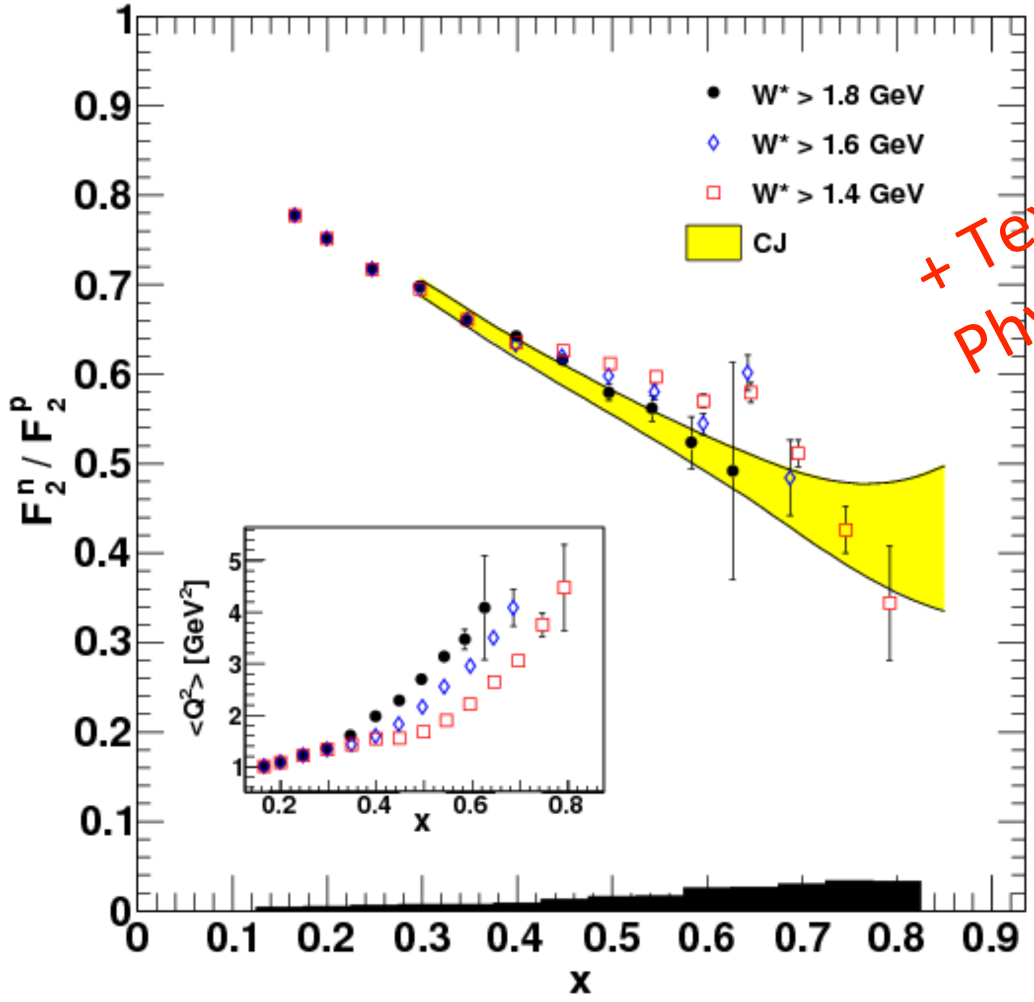
Measure DIS electron *in coincidence* with proton tag

- Protons at low momentum
  - Bound/free nucleon structure
  - *~70 MeV, challenging!*
- Protons at backward angle
  - Final state interactions

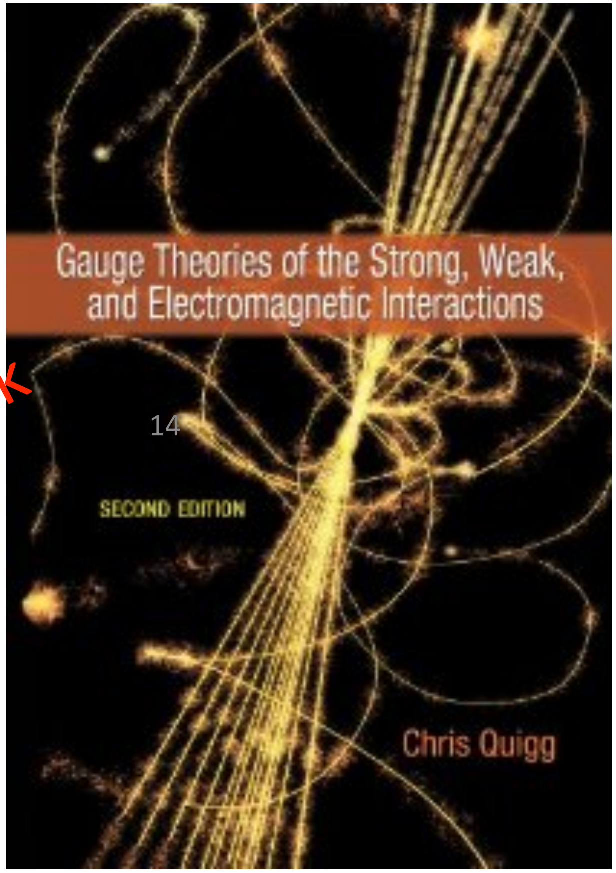
Low momentum proton tagging *achieved*



Phys. Rev. Lett. 108 (2012) 199902
Phys. Rev. C89 (2014) 045206 – editor's suggestion
Nucl. Instrum. Meth. A592 (2008) 273-286



+ Textbook Physics



Gauge Theories of the Strong, Weak, and Electromagnetic Interactions

SECOND EDITION

Chris Quigg

- > 200 *neutron* data points
- Input for (CJ) global PDF fits
- BUT – largely resonance region, not quite high enough x, Q^2

Improved Extraction of F_2^n from F_2^d and F_2^p

New method : employs iterative procedure of solving integral convolution equations

Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- Impulse Approximation – virtual photon scatters incoherently from individual nucleons

(Beyond IA: FSI not addressed in present analysis)

$$\underbrace{F_2^A(x,Q^2)}_{\text{nuclear } F_2} = \sum_{N=p,n} \int_x^{M_A/M} dy\, \underbrace{f_0^{N/A}(y,\gamma)}_{\substack{\text{light-cone momentum}\\ \text{distribution of}\\ \text{nucleons in nucleus}\\ \text{(smearing function)}}} \underbrace{F_2^N\left(\frac{x}{y},Q^2\right)}_{\text{nucleon } F_2} \qquad \gamma = \sqrt{1+\frac{4M^2x^2}{Q^2}}$$

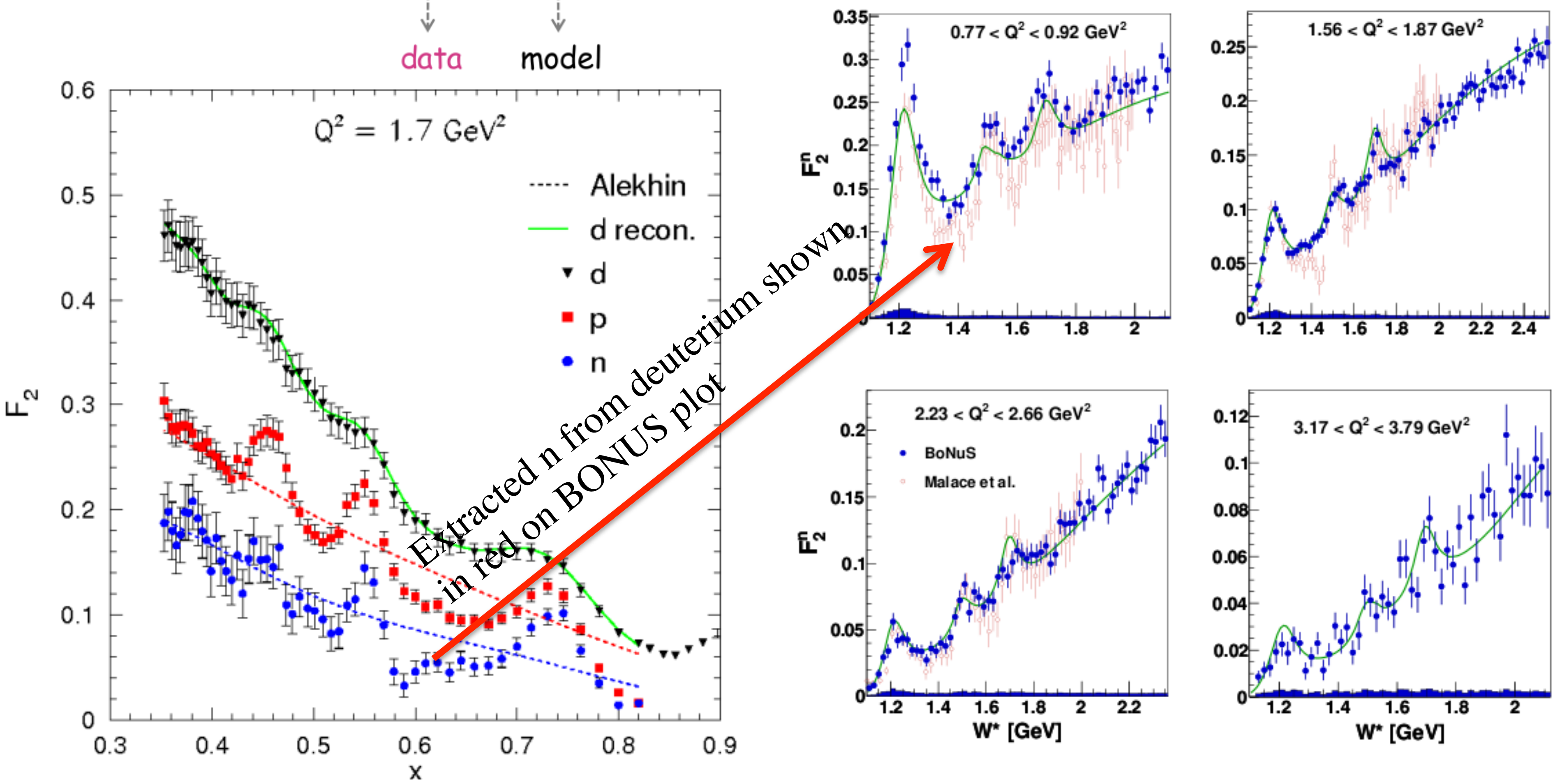
Application to Deuterium…

Extracted F_2^n from F_2^d and F_2^p: Resonance Region Data

(more challenging than DIS)

- Application of method to data:

$$\widetilde{F}_2^n(x) = \underset{\text{data}}{F_2^d(x)} - \underset{\text{model}}{F_2^{d(QE)}} - \overset{\text{model}}{\delta^{(off-shell)}} F_2^d(x) - \widetilde{F}_2^p(x) \dashrightarrow \text{data}$$

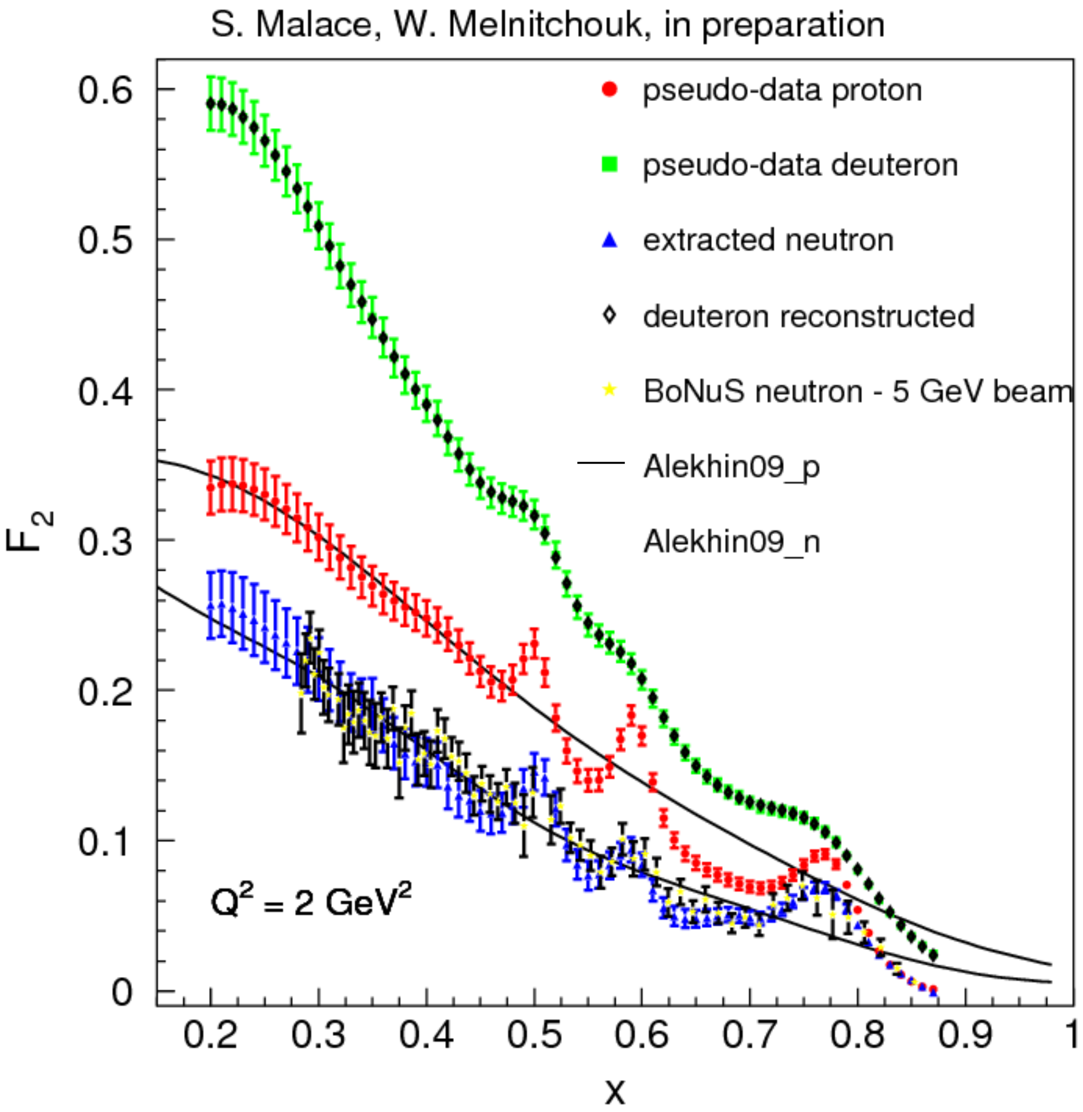


Extracted n from deuterium shown in red on BONUS plot

S.P. Malace, Y. Kahn, W. Melnitchouk, CK
PRL 104 102001 (2010)

Compares well to BoNuS data

Application of method to data: update in progress



- Updated nuclear corrections (off-shell and wave functions)

- Study systematics of extraction coming from:

→ Wave function employed

→ Limits to off-shell corrections

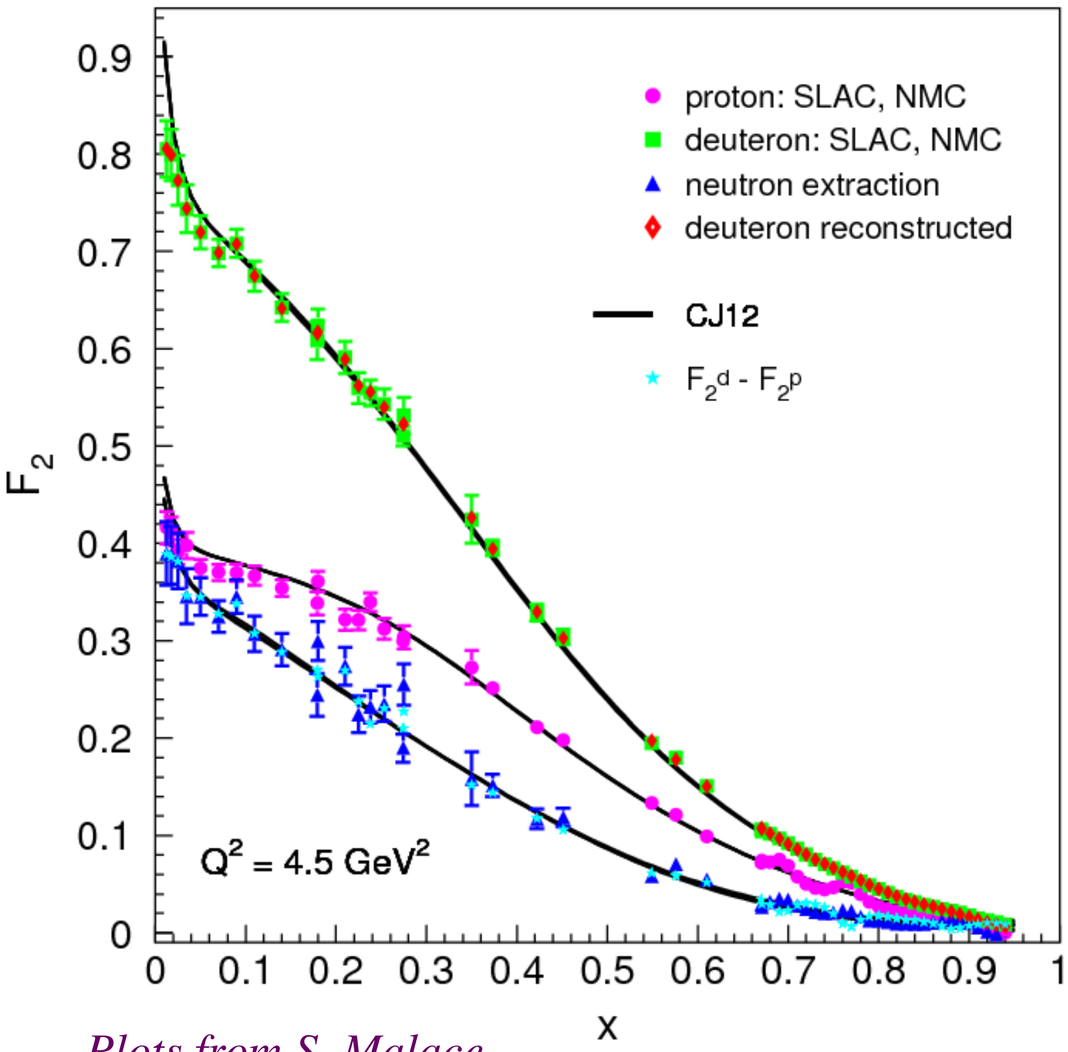
- Highlight advantages and limitations of method when applied to discrete points

S.P. Malace, W. Melnitchouk, in preparation

Extracting F_2^n from F_2^d and F_2^p for Sum Rules - I

Preliminary

F_2 at $Q^2 = 4.5$ GeV^2



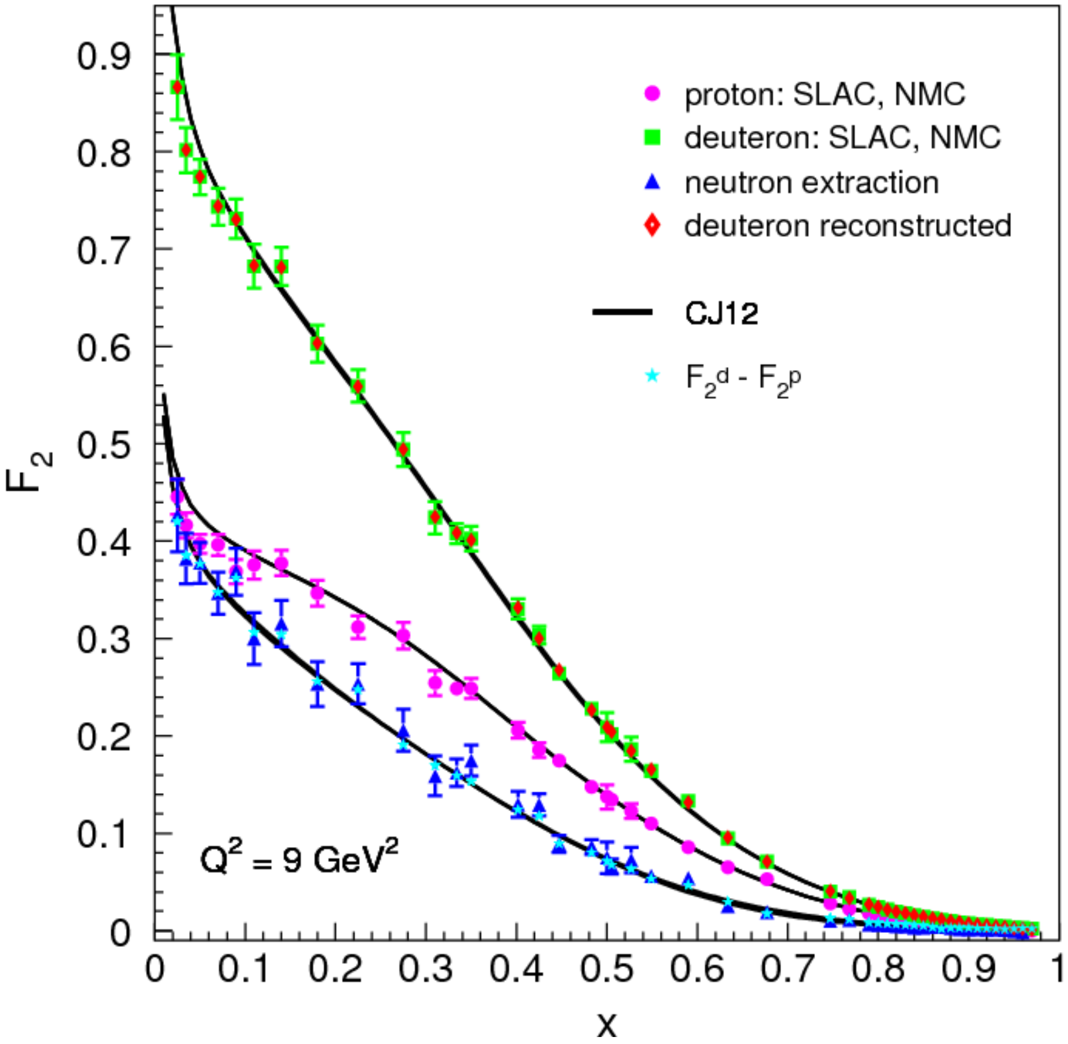
Plots from S. Malace

- Applying updated technique to extract F_2^n from data
  - AV18 and CJmin for off-shell
- *<u>Need to cover range in x for sum rule integrals</u>*
- Currently only using NMC and sub-set of SLAC
  - Will expand data set
  - Need <u>matched</u> p, d data
  - Will include BONUS
- Investigate CJ overshoot at x ~ 0.05
  - Important for GSR
  - C.-P. Yuan talk, “$\bar{d}/\bar{u}$ at x~0.01 mainly constrained by NMC F2d/ F2p data”

Extracting F_2^n from F_2^d and F_2^p for Sum Rules - II

Preliminary

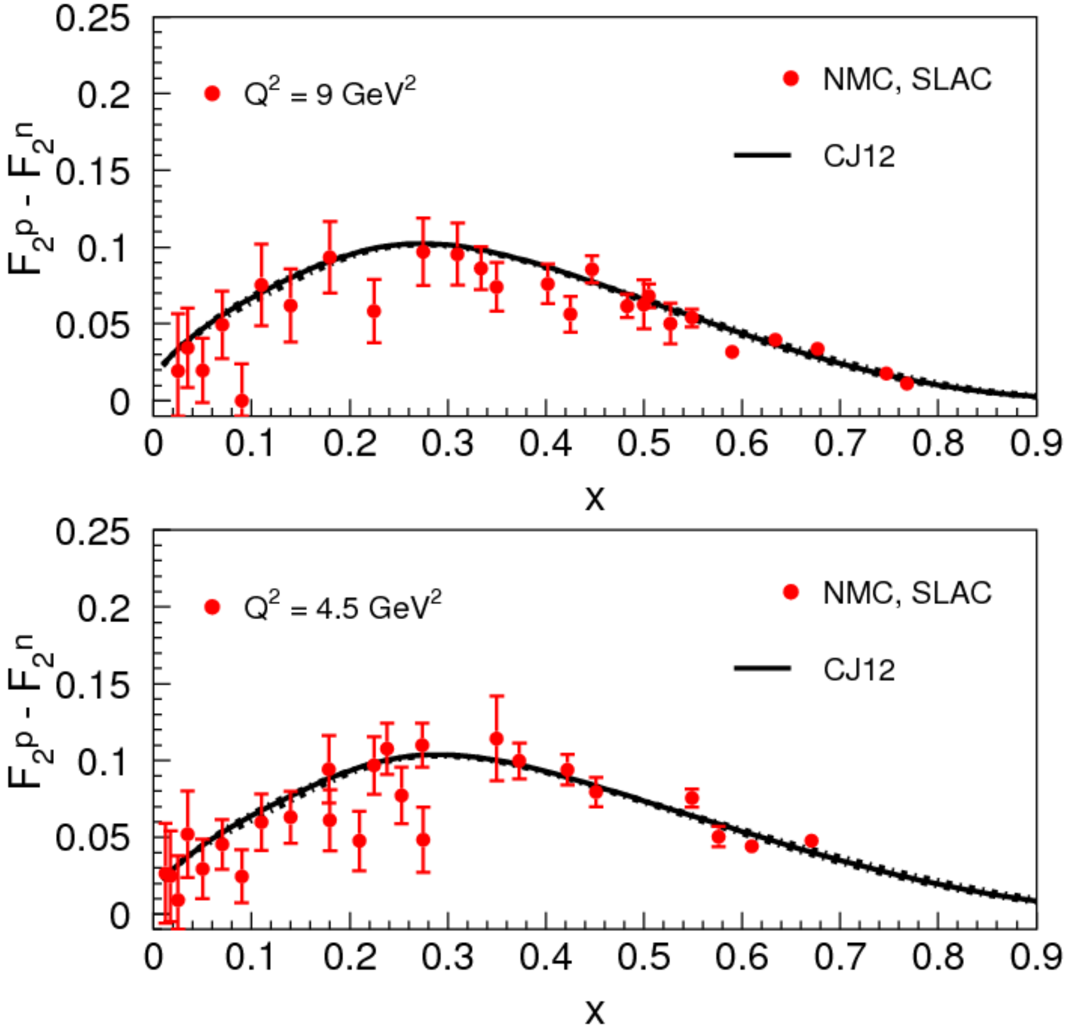
F_2 at $Q^2 = 9$ GeV^2



- Combined data set will have nice range in x for *various* Q^2 values
  - Can study Q^2 dependence of the sum rules from $\sim 2 < Q^2 < 9$ GeV^2
- Data technique agrees well with CJ
- Any GSR deviation should be mild, CJ predicts a ~5-10% difference between "correct" n and n from 2p-d at x ~ 0.2-0.3
  - region of largest nuclear correction to integral
  - reduction to GSR
- The data disagreement at x ~ 0.05 is a bit worse at the higher Q^2

Preliminary

Extracting F_2^n - F_2^p for GSR



Work in progress:

- Looks promising
- Add data
- Add additional Q^2 value(s)
- Perform integrations
- Uncertainty analysis of sum rules
- Investigate x~0.1 difference
- Momentum Sum Rule (likely more sensitive to nuclear corrections, not 1/x weighted)

Summary

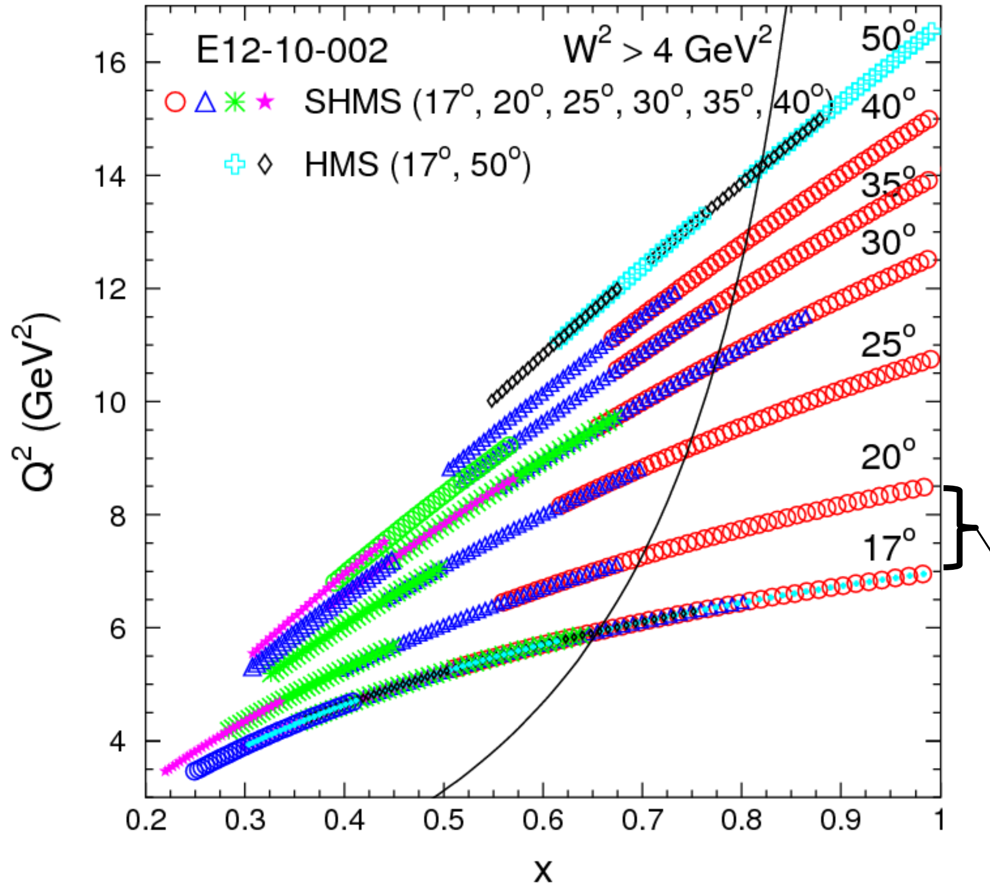
- Entering an era of precision *neutron* data
  - Driven by both theory and experiment
    - ✓ CJ nuclear corrections, BONUS
  - Reduce uncertainties on d(x), g(x) at large x
  - Determine d/u behavior
  - A wealth of precision deuterium data exists
    - ✓ Can use now for neutron extraction
    - ✓ Range in x and Q^2
  - *Revisit Sum Rules*

More data coming…. see backups!

Upcoming Data from JLab at 12 GeV

- E12-10-002: at Jefferson Lab in Hall C to measure precision cross sections and F_2 structure functions at large x and low to intermediate Q^2 on proton and deuteron

Kinematic coverage



S.P. Malace – contact and spokesperson
M.E. Christy, C. Keppel, I. Niculescu spokespeople

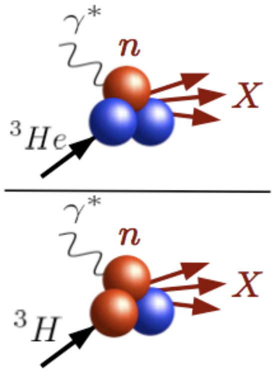
→ High precision cross sections on Hydrogen and Deuterium targets

→ Good coverage from one experiment in x, especially at intermediate Q^2: ideal for experimental re-evaluation of sum rules

We can extend the coverage to even lower x…

DIS from A=3 Nuclei (E12-10-103 Holt, Annand, Gomez, Petratos, Ransome)

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}\,, \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$



- Mirror symmetry of A=3 nuclei
  - Extract F_2^n/F_2^p from ratio of measured ^{3}He/^{3}H structure functions

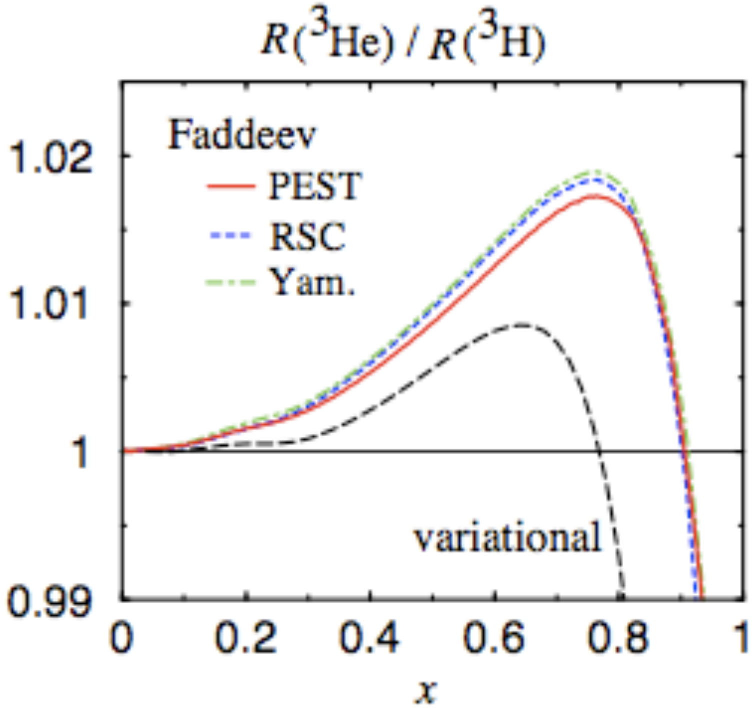
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{3He}/F_2^{3H}}{2F_2^{3He}/F_2^{3H} - \mathcal{R}}$$

$\mathcal{R}$ = SUPER ratio of "EMC ratios" for ^{3}He and ^{3}H

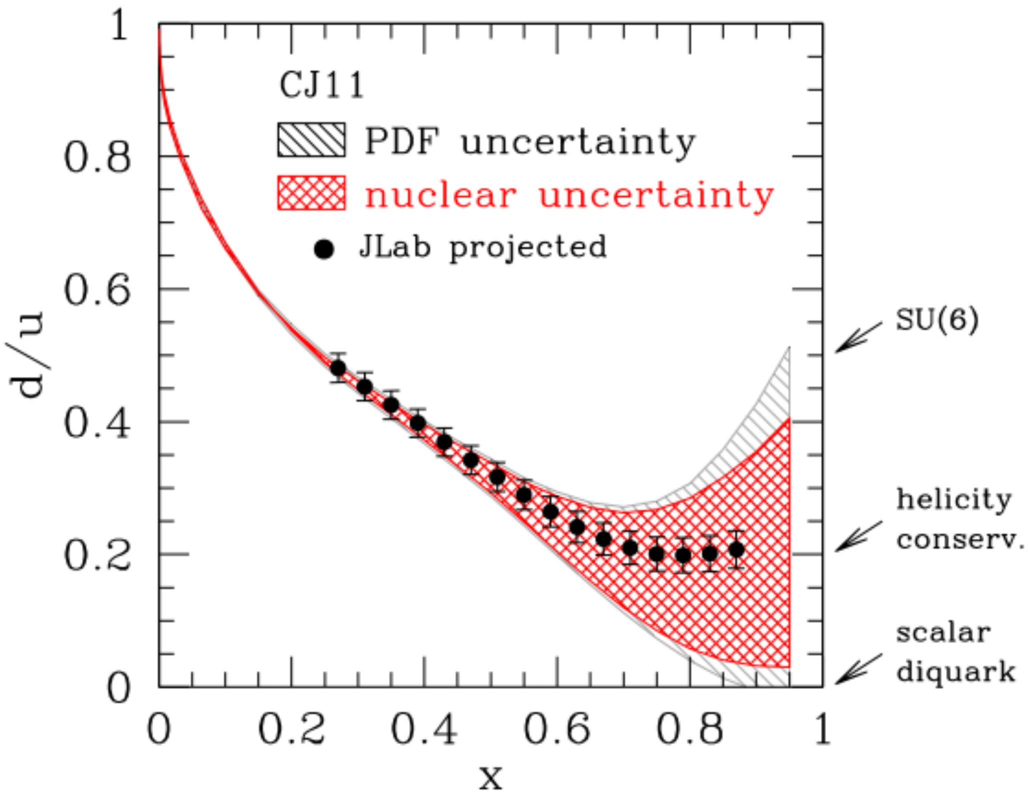
- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He

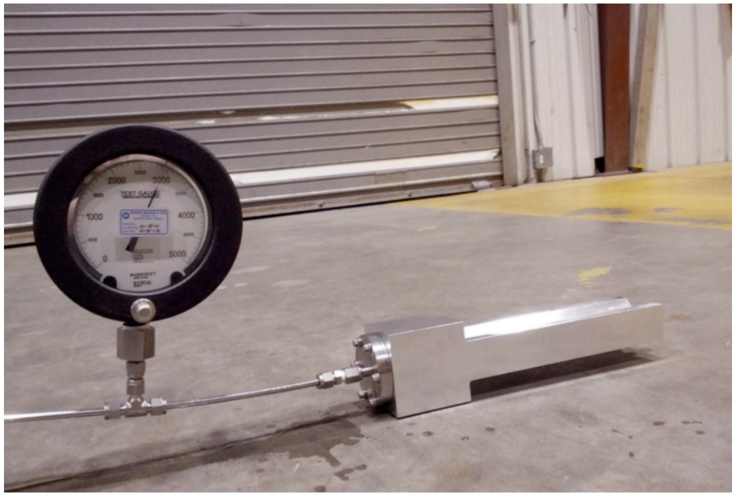
- Calculated to within 1%

- Most systematic and theoretical uncertainties cancel

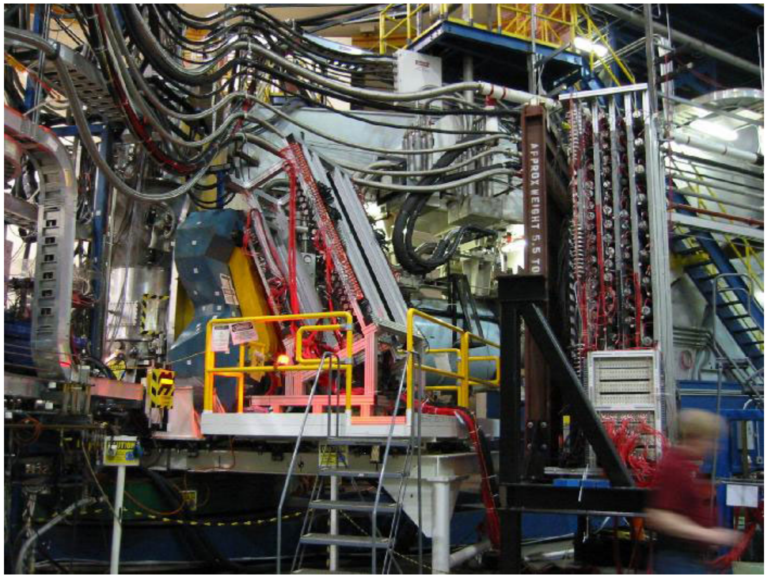


DIS from A=3 nuclei - Projected Results





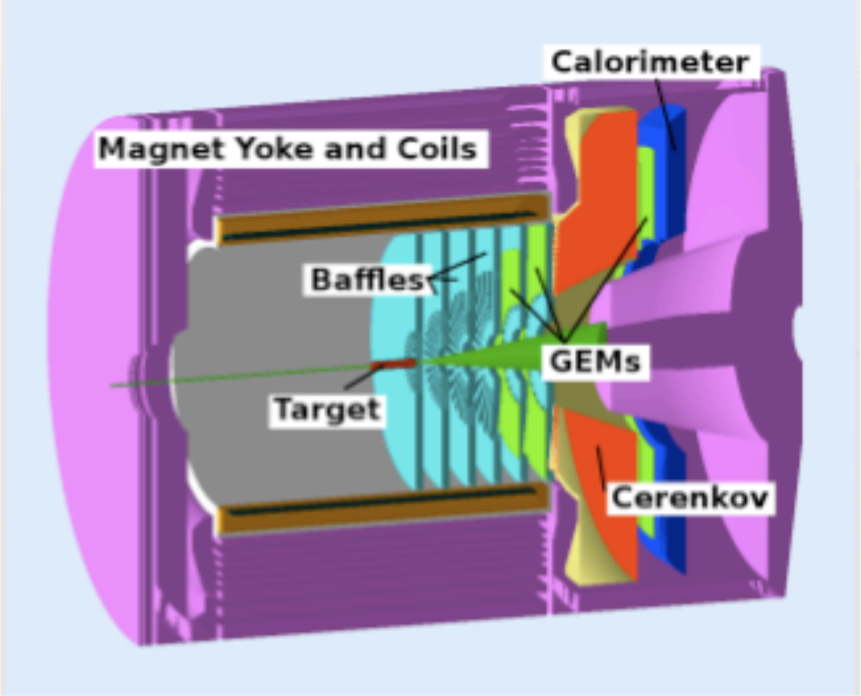
Test cell factor ~10 safety test, burst pressure above 3500 psi



Hall A BigBite Spectrometer

PVDIS Measurements - SoLID Proposed Setup

Solenoidal **L**arge **I**ntensity **D**evice - 12 GeV Hall A at JLab
Parity-violating DIS program on deuterium and hydrogen



SoLID provides large acceptance

- $2 < p < 8$ GeV
- $2 < Q^2 < 10\ \mathrm{GeV}^2$
- $0.2 < x_{\mathrm{bj}} < 1$
- Acceptance ~ 40%
- Lumin $\sim 5 \times 10^{38}\ \mathrm{Hz/cm^2}$

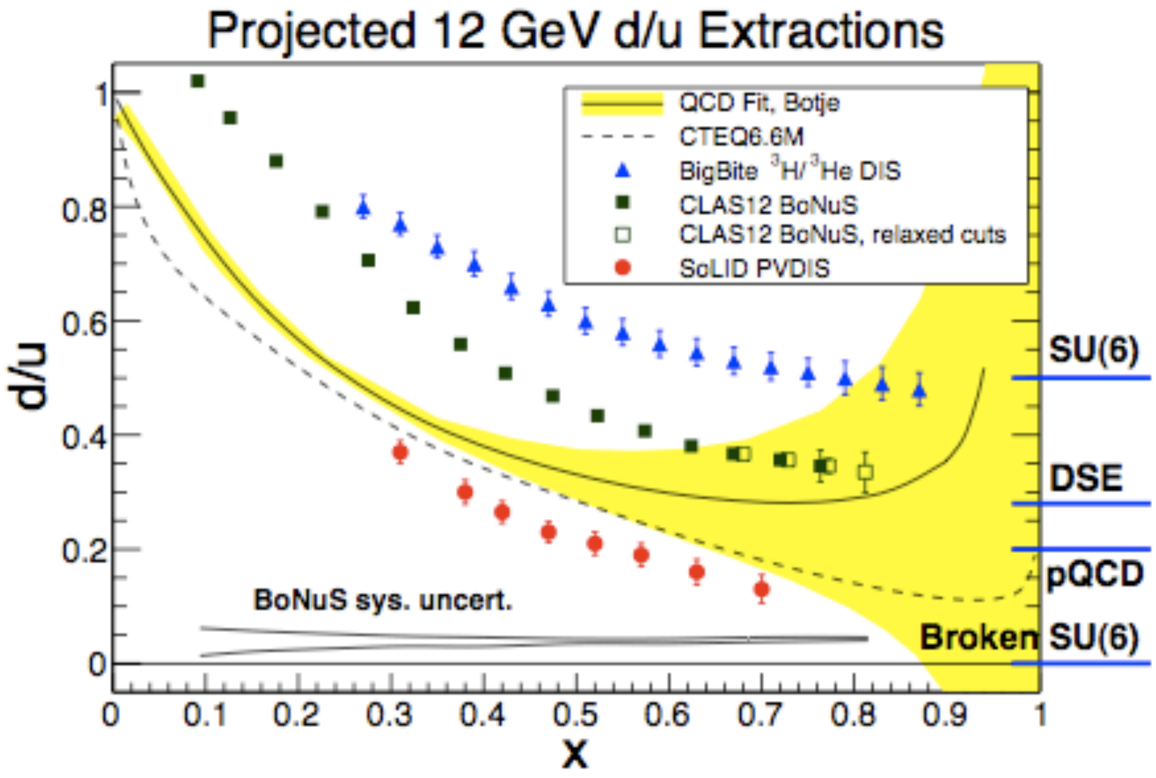
$$A_{\mathrm{PV}} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

$$a_1(x) = 2\frac{\sum C_{1q}e_q(q+\bar{q})}{\sum e_q^2(q+\bar{q})},\ a_3(x) = 2\frac{\sum C_{2q}e_q(q-\bar{q})}{\sum e_q^2(q+\bar{q})}$$

Clean Measurement of d/u with PVDIS

For high x on proton target:

$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$

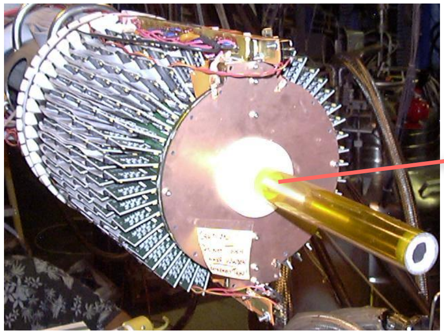


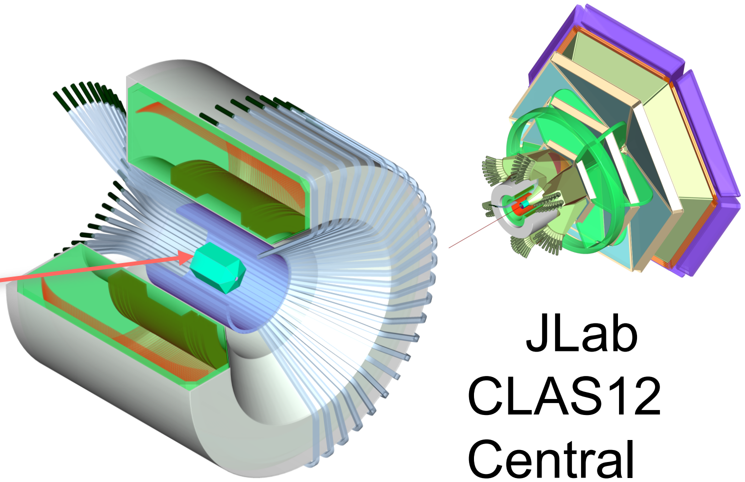
DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3\mathrm{H}/^3\mathrm{He}$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*

Plans for 12 GeV

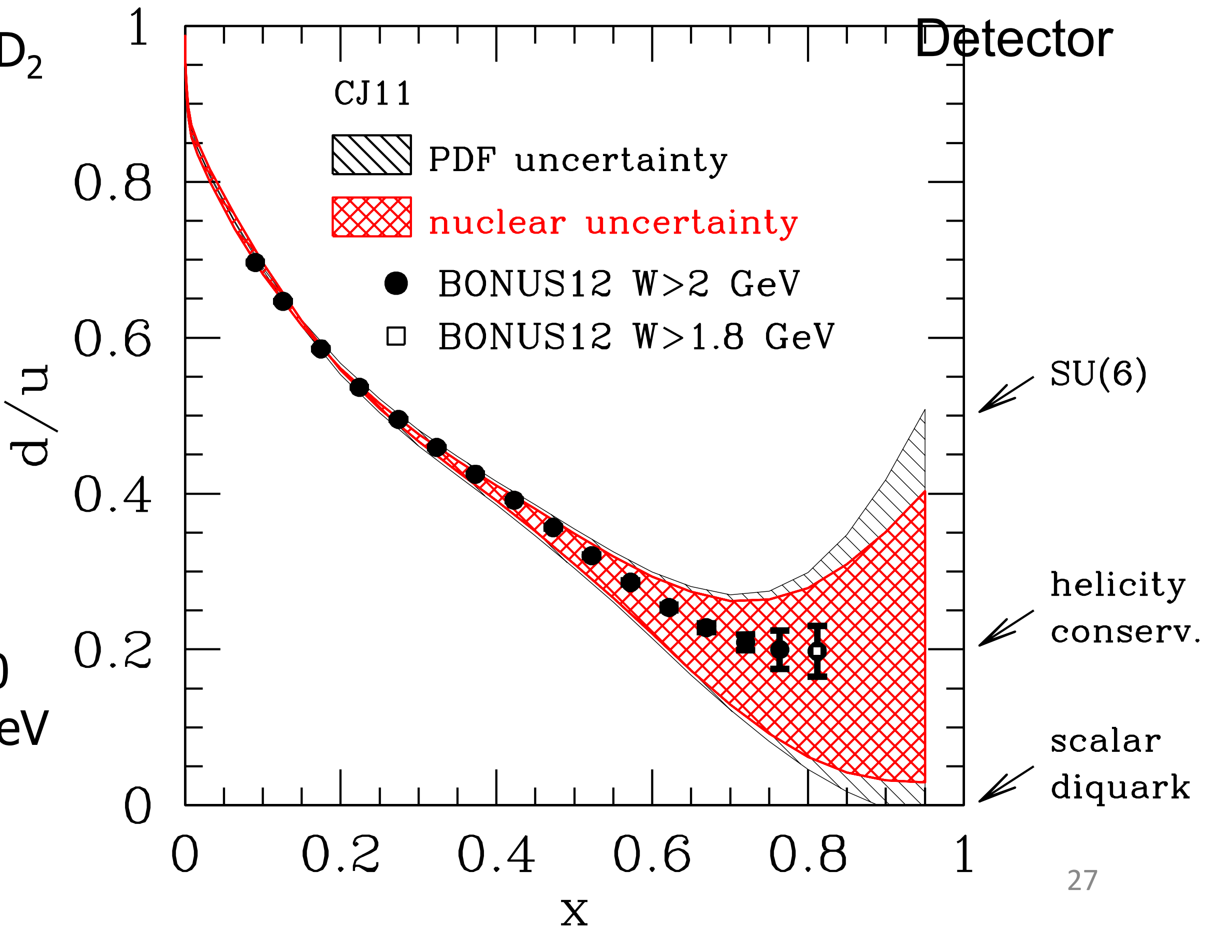
E12-06-113
“BONUS12”
approved





JLab
CLAS12
Central
Detector

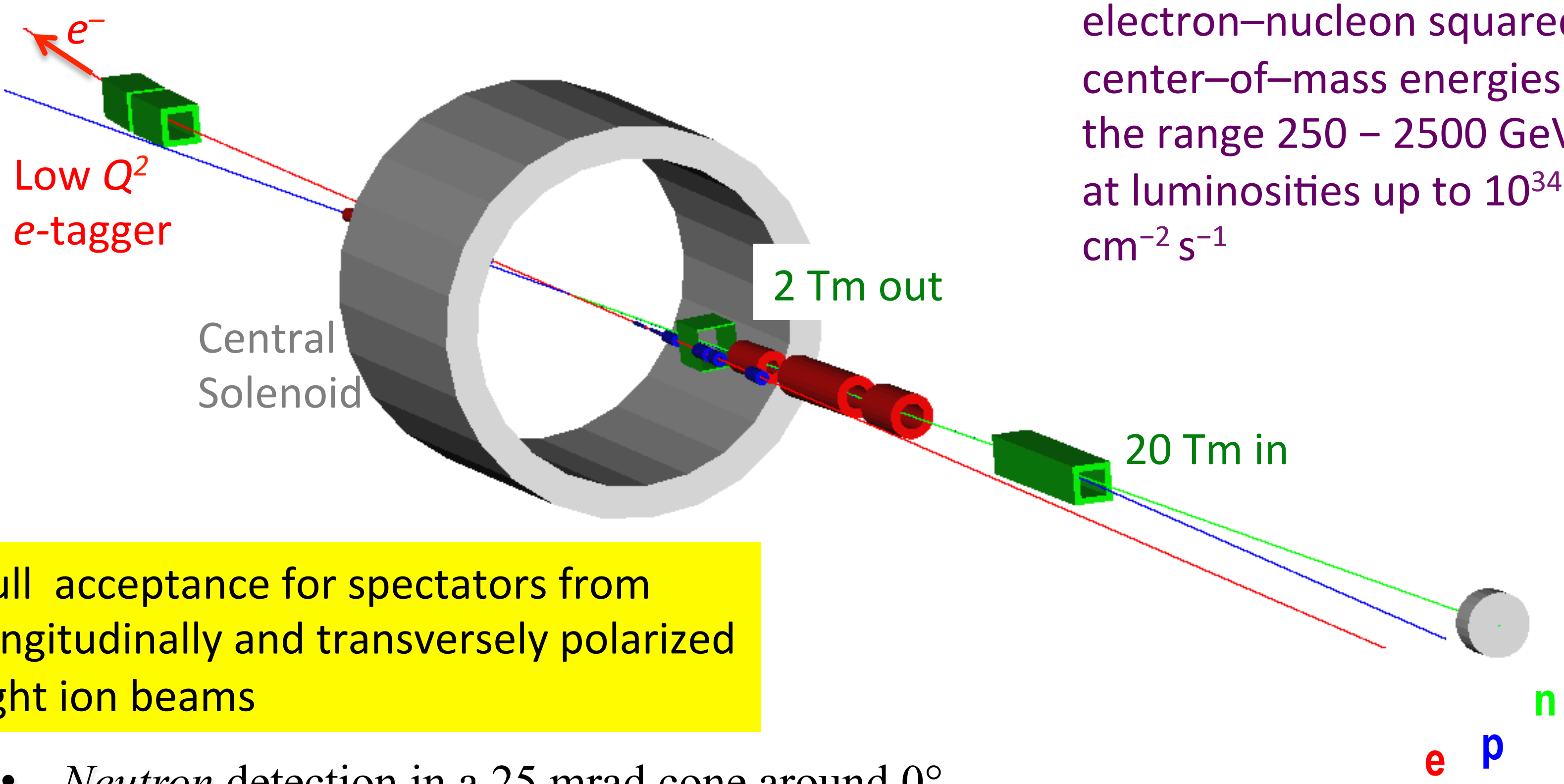
- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathrm{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $x^* = 0.80$
  Relaxed cut of $W^* > 1.8$ GeV
  gives max. $x^* = 0.83$



Tagged Structure Functions at the proposed Electron Ion Collider

The technique is uniquely suited to colliders: no target material absorbing low-momentum nucleons

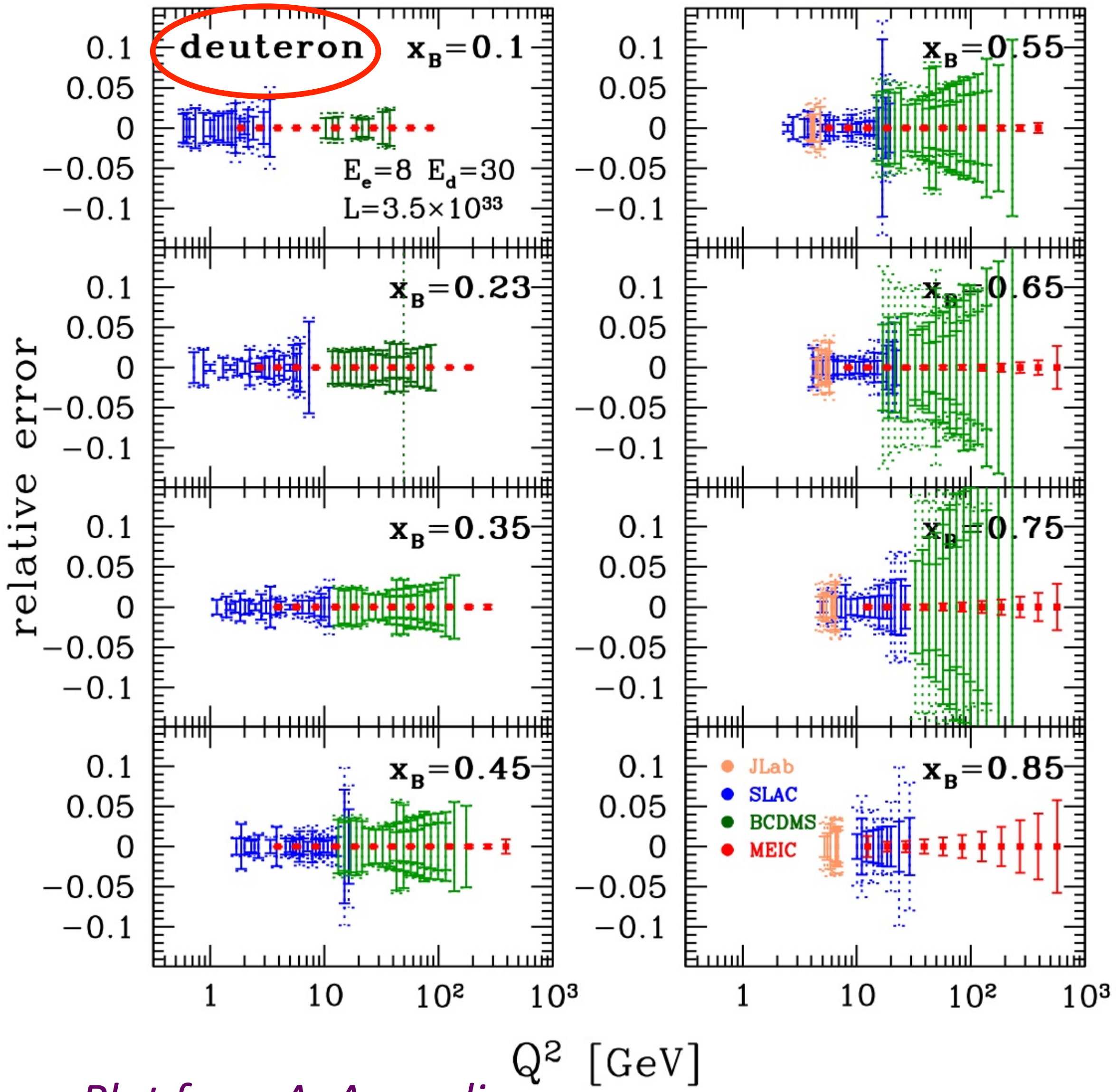
The mEIC designs provide electron–nucleon squared center–of–mass energies in the range 250 – 2500 GeV^2 at luminosities up to 10^{34} cm^{-2} s^{-1}



- Full acceptance for spectators from longitudinally and transversely polarized light ion beams

- *Neutron* detection in a 25 mrad cone around 0°
- Secondary high dispersive ion focus ~40 m downstream of IP

Projected mEIC Results - F_2^d Structure Function Relative Uncertainty



Plot from A. Accardi

Solid lines are statistical errors, dotted lines are stat+syst in quadrature

Huge improvement in Q^2 coverage and uncertainty

Could greatly aid pdf fitting efforts at large x

Will have tagged data at all kinematics, d *and n*

EIC will have excellent kinematics to measure neutron structure at large x!