Large x Physics: Recent Results and Future Plans

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XLIII International Symposium on Multiparticle Dynamics

IIT, Chicago, IL

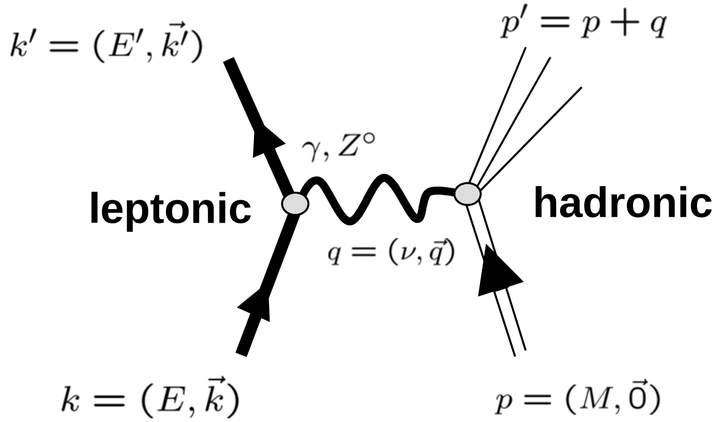
17 September 2013

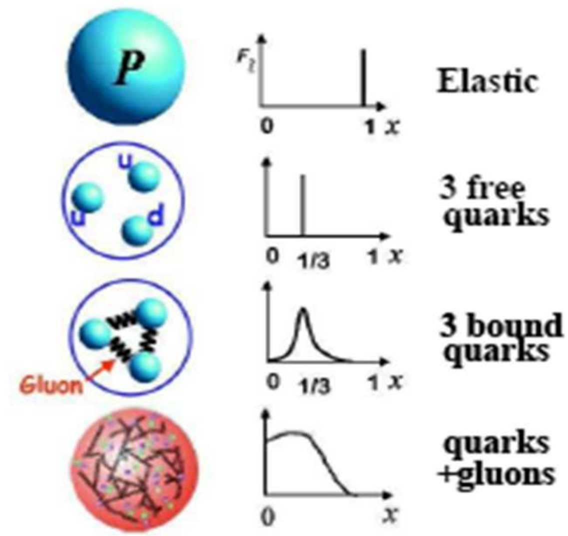
Why is high x interesting?

- Valence region defines a hadron –
  baryon number, charge, flavor content, total spin, …
- Keen discriminator of nucleon structure models
- High x, low Q^2 evolves to low x, high Q^2 -> impact on HEP
- New generation of experiments at JLab focused on high x
- New Drell-Yan experiment at FNAL focused on high x sea
- Proposed Electron Ion Collider can also explore high x

Some experiments in deep inelastic scattering

Partonic structure of the nucleon





Structure function

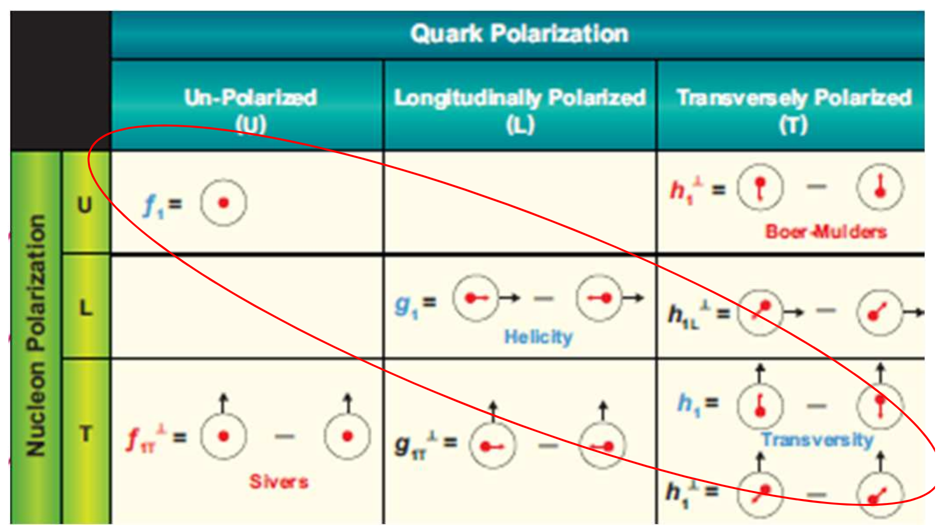
$$\sigma \propto F_2(x, Q^2)$$

Parton model

$$F_2(x) = x\Sigma e_i^2 (q_i(x) + \overline{q}_i(x))$$

Quark charge

Prob. of q in proton



Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 =$		$h_1^\perp =$ — Boer-Mulders
L		$g_1 =$ — Helicity	$h_{1L}^\perp =$ —
T	$f_{1T}^\perp =$ — Sivers	$g_{1T}^\perp =$ —	$h_1 =$ — Transversity $h_{1T}^\perp =$ —

EIC whitepaper

The Neutron Structure Function

Parton model ->

- Proton structure function:

$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

- Neutron structure function (isospin symmetry):

$$u_p(x) = d_n(x) \equiv u(x)$$

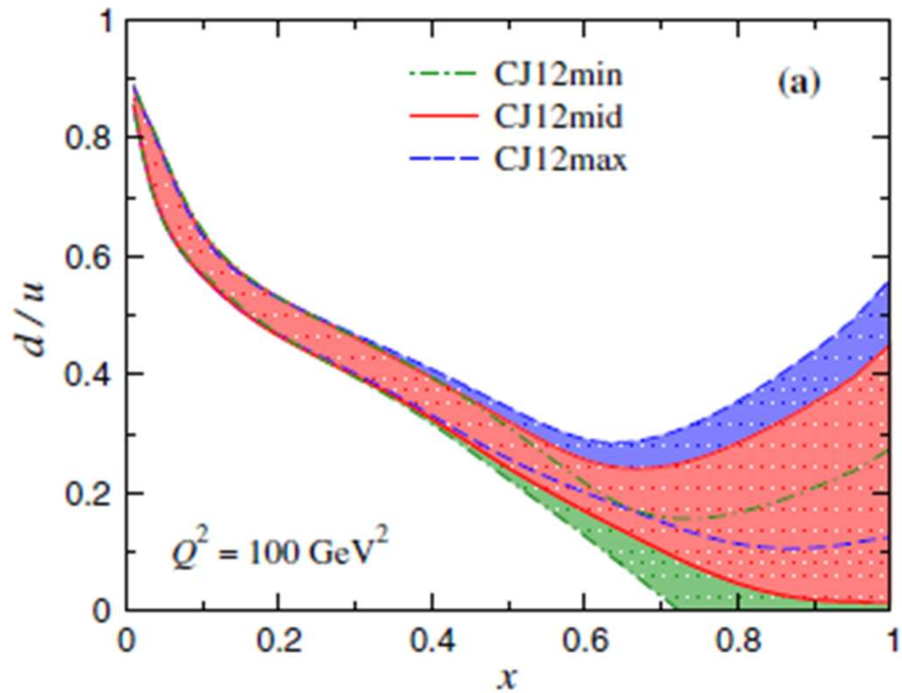
$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

- Ratio:

$$\frac{F_2^n}{F_2^p} = \frac{u+\bar{u}+4(d+\bar{d})+s+\bar{s}}{4(u+\bar{u})+d+\bar{d}+s+\bar{s}}$$

- Focus on high x:

$$\frac{F_2^n}{F_2^p} = \frac{[1+4(d/u)]}{[4+(d/u)]}$$

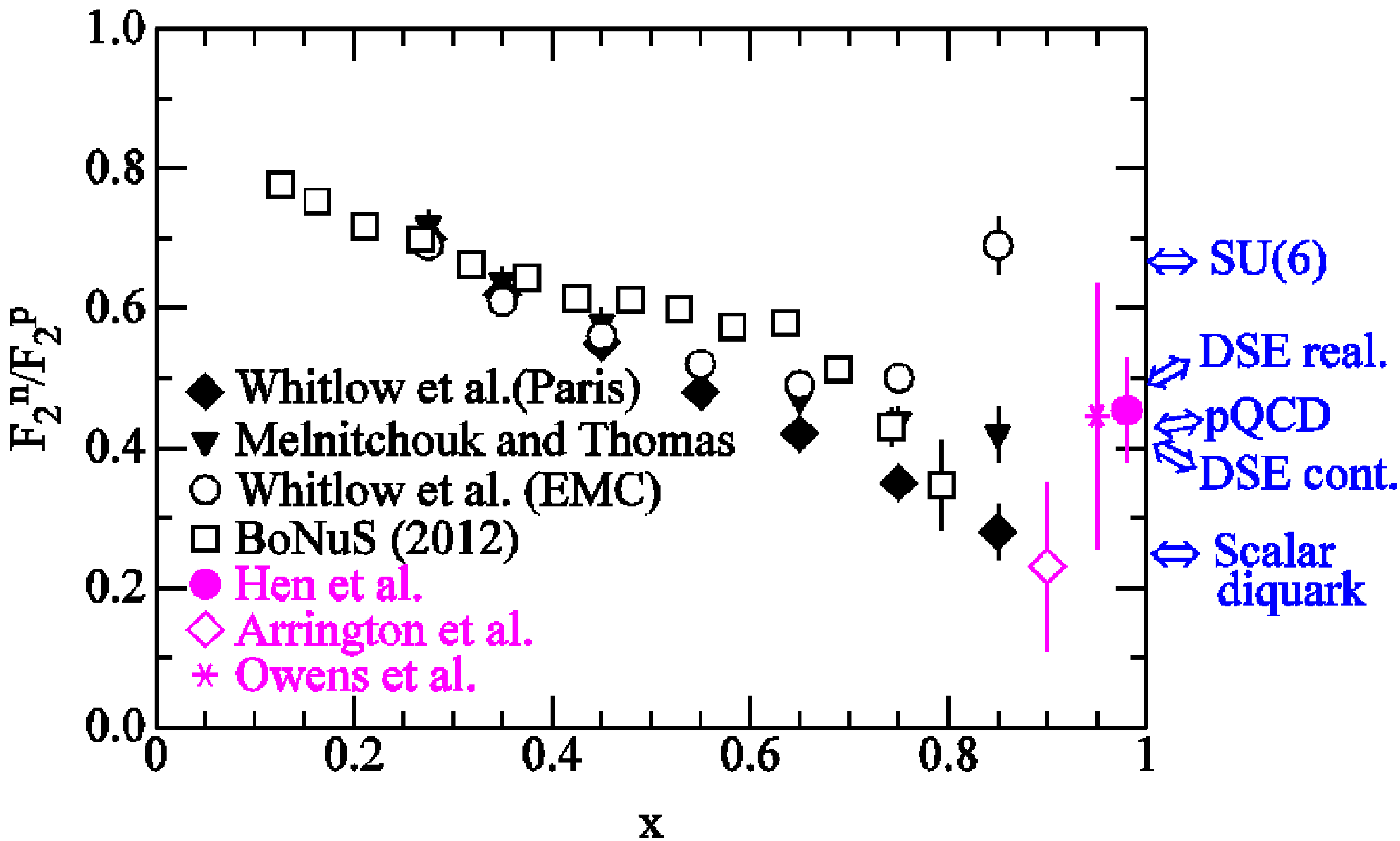


CJ12 J. Owens *et al*, PRD **87** (2013) 094012

- Three 12-GeV JLab experiments
  - Deuteron: radial TPC and CLAS12
  - ^{3}H/^{3}He: ^{3}H target and existing spectrometers
  - Proton : PVDIS and SoLID

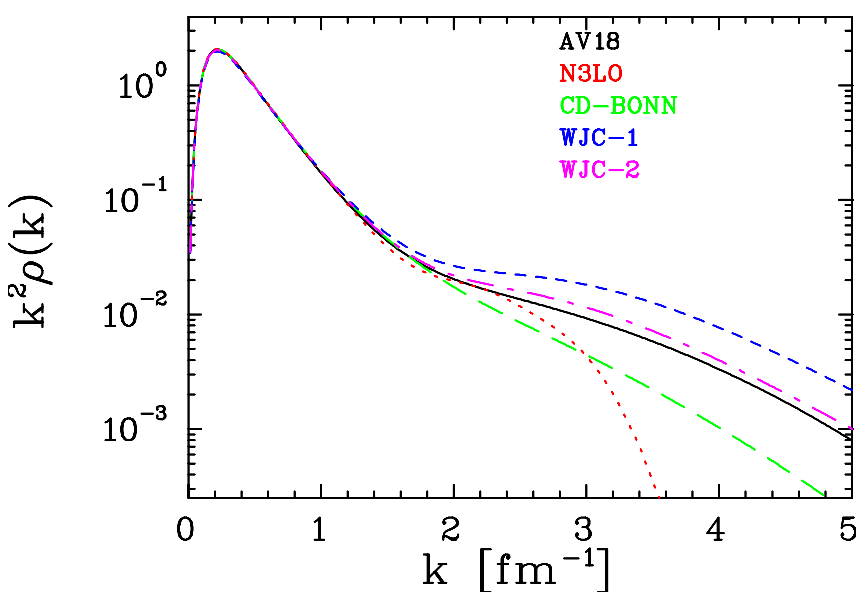
Upgraded JLab has unique capability to define the valence region

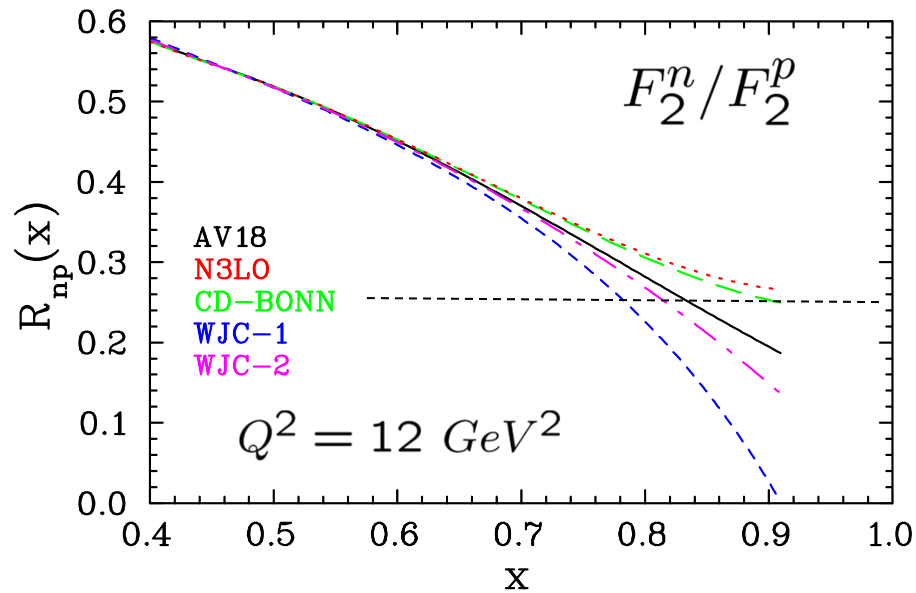
Present status: Neutron to proton structure function ratio



C. D. Roberts, RJH, S. Schmidt, arXiv: 1308.1236;
RJH, C. D. Roberts, RMP **82** (2010) 2991

Extractions with modern deuteron wave functions





The ratio at high *x* has a strong dependence on deuteron structure.

J. Arrington *et al*, J. Phys. G **36** (2009)

C. Accardi, *et al*., PRD81 (2010) CJ

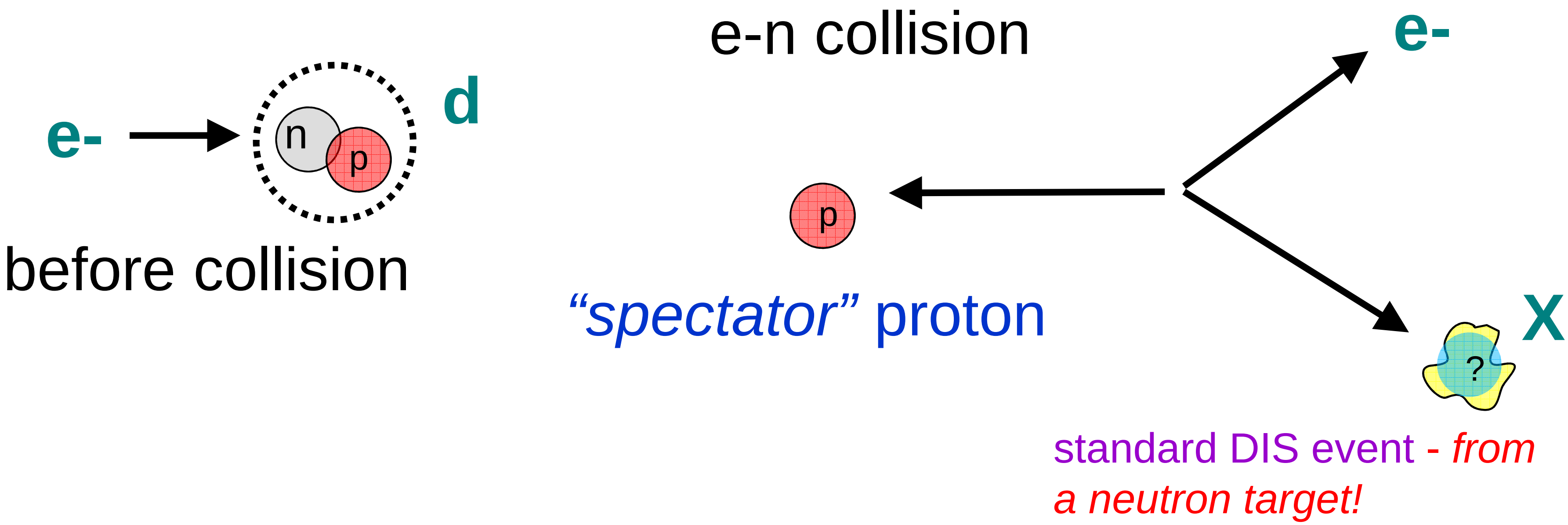
J. Arrington et al, PRL **108** (2012)

J. Owens et al, PRD **87** (2013) CJ12 PDF’s

More p/d data at JLab 12 GeV

E12-10-008 - J. Arrington, A. Daniel, D. Gaskell

The Spectator Tagging Approach: An Effective Free Neutron Target from Deuterium….



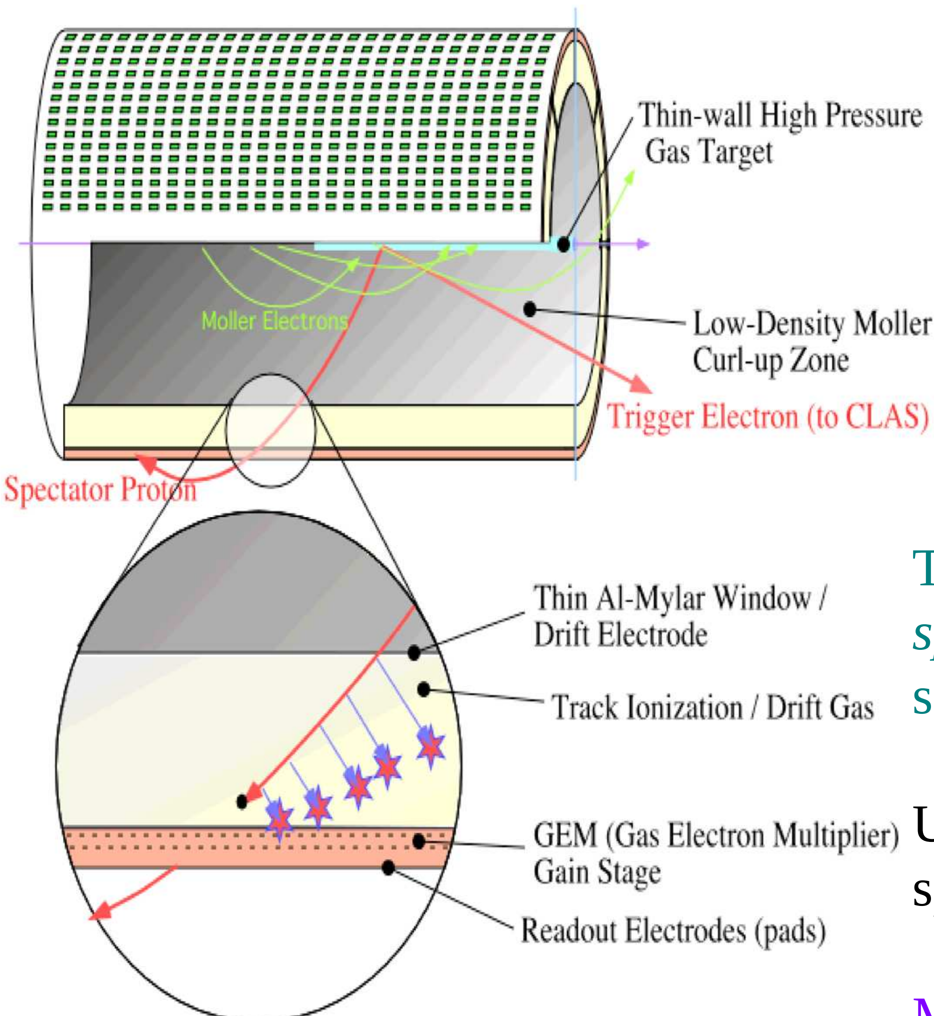
L.L. Frankfurt and M.I. Strikman, Phys. Rep. 76, 217 (1981)

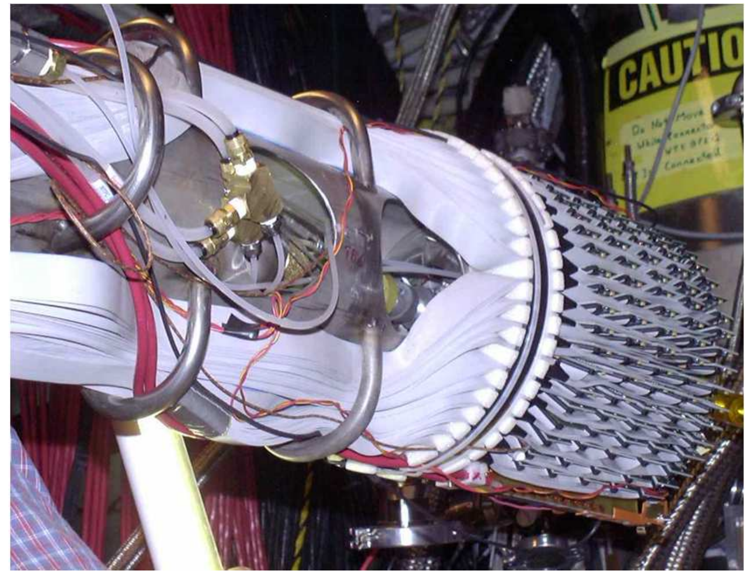
C. Ciofi degli Atti and S. Simula, Phys. Lett. B319, 23 (1993); Few-Body Systems 18, 55 (1995)

S. Simula, Phys. Lett. B387, 245 (1996); Few-Body Systems Suppl. 9, 466 (1995)

W. Melnitchouk, M. Sargsian and M.I. Strikman, Z. Phys. A359, 99 (1997)

BoNuS Experiment at JLab





Tag low momentum, backward angle *spectator* proton in deuterium = electron scattering from a free *Neutron* target

Use GEM-based radial TPC in JLab CLAS spectrometer

Measure neutron structure function F_2 to study quark structure of the nucleon at large x

Slide credit: C. Keppel

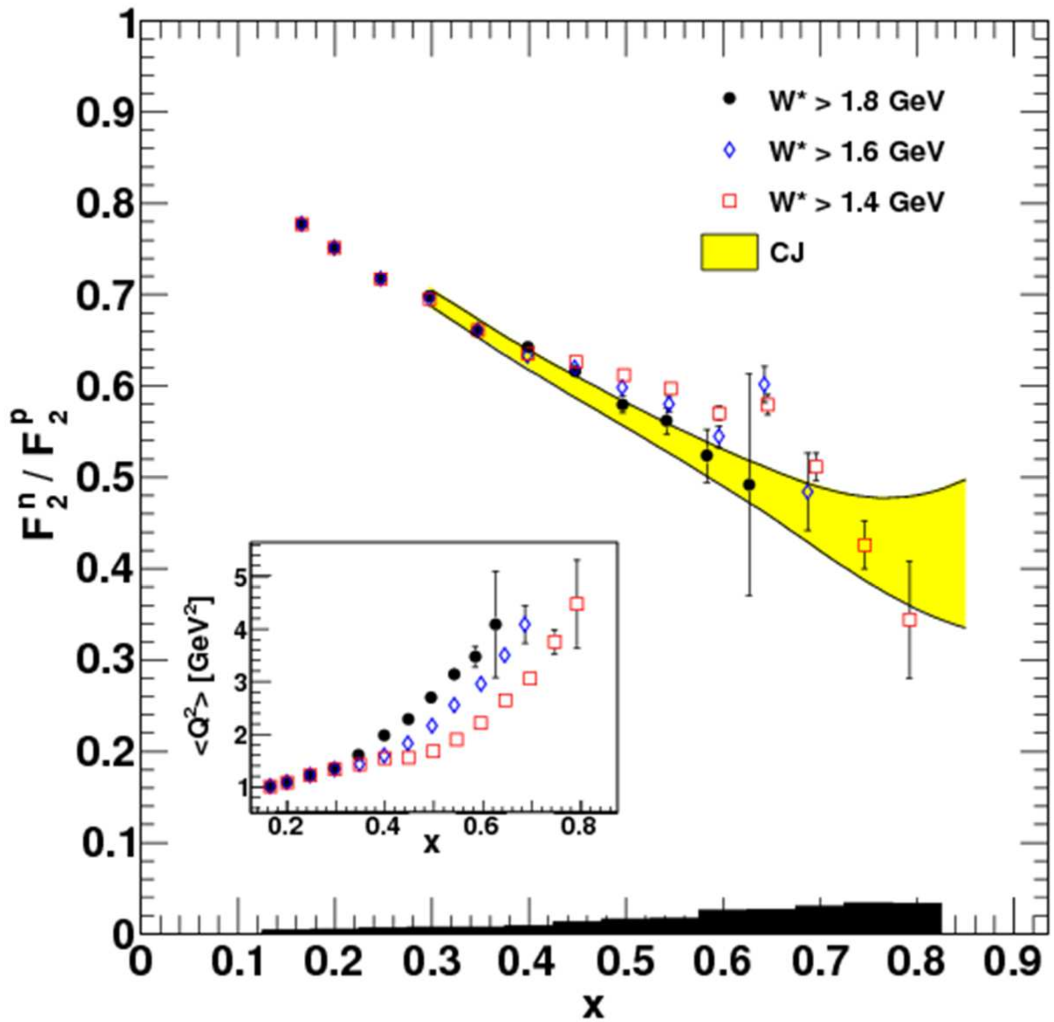
Results from BoNuS

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

$P_{spectator}$< 100 MeV/c,

$\theta_{spectator}$ < 90

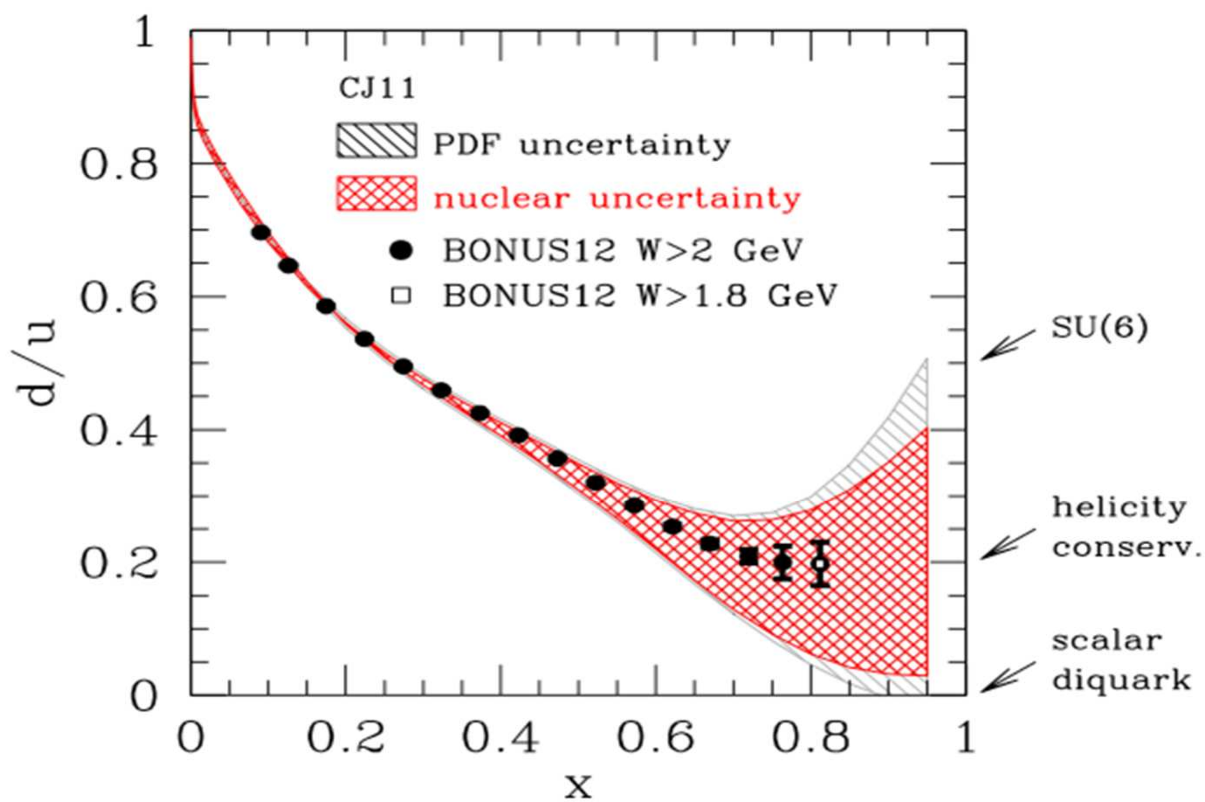
Textbook physics :) Plot is in the new edition of ***Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*** *(Chris Quigg)*

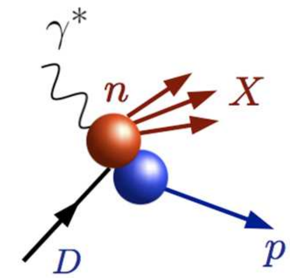


Still not quite large enough x……

Slide credit: C. Keppel

BoNuS: 12 GeV JLab experiment projections





Projected BoNuS12 uncertainties statistical + systematic

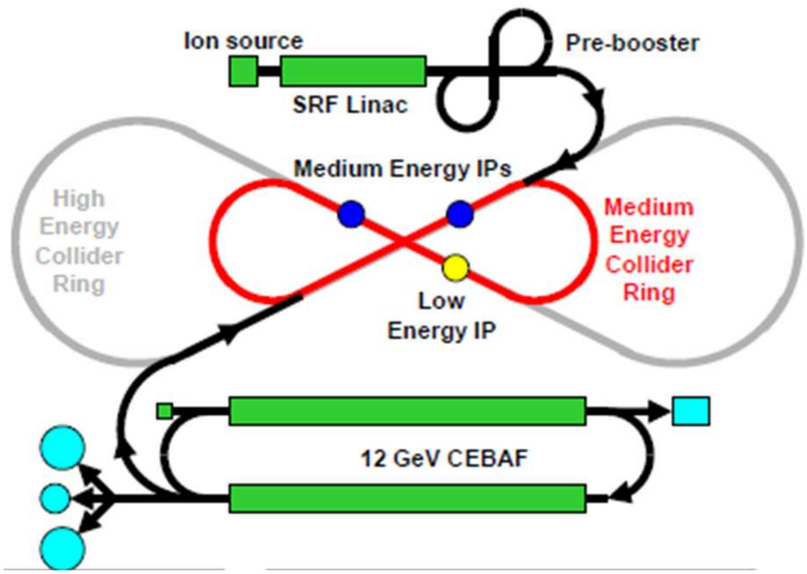
CJ 2011 pdfs - with nuclear uncertainty

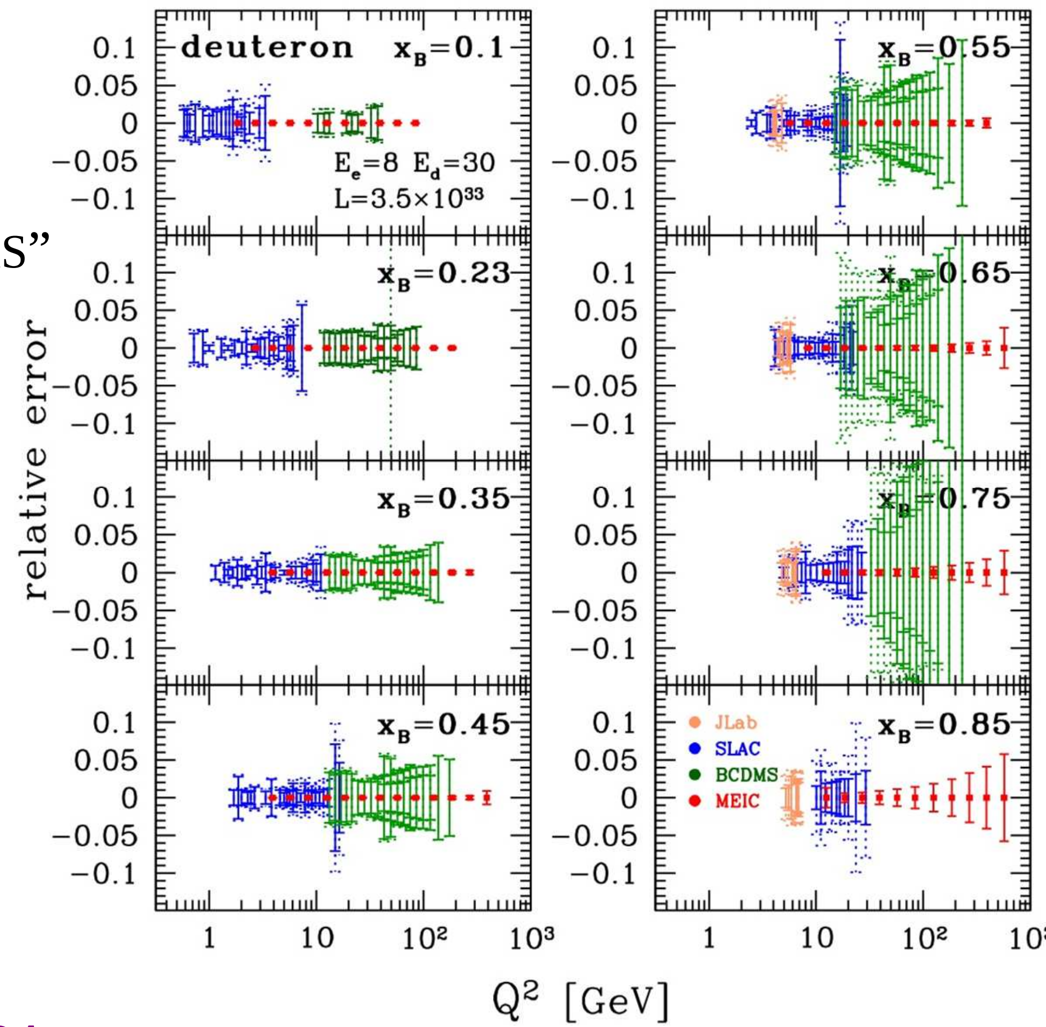
JLab E12-06-113, S. Bueltmann, M. Christy, C. Keppel, et al.

Adapted from C. Keppel

Spectator tagging at an EIC

- E_e=8 GeV, E_N=30 GeV
- Luminosity=3.5E33
- 26 weeks at 50% efficiency
- Detect ~30 GeV proton – "super BoNuS"
- EIC in China or USA or …





EIC has > 100 x luminosity of HERA,
polarized e and light ions, nuclear beams

Thanks to A. Accardi, R. Ent, C. Keppel

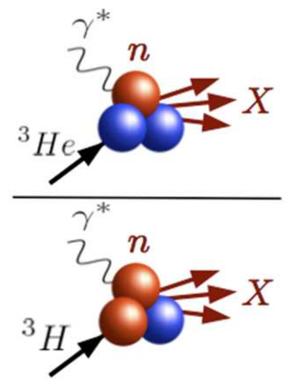
Nuclear Physicists' Approach to F_{2n}

- Problem:
  - The deuteron experiments present extraction complications.
- Nuclear physicists' solution: Add another nucleon.
- $^3H/^3He$ ratio: minimizes nuclear physics uncertainties

I. Afnan et al, PRC 68 (2003)

DIS from A=3 nuclei

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



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

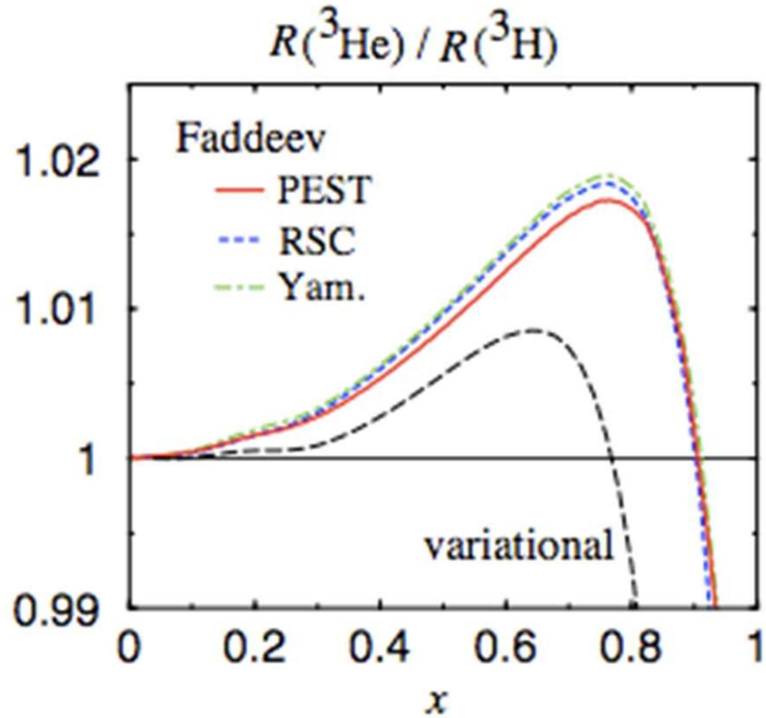
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

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

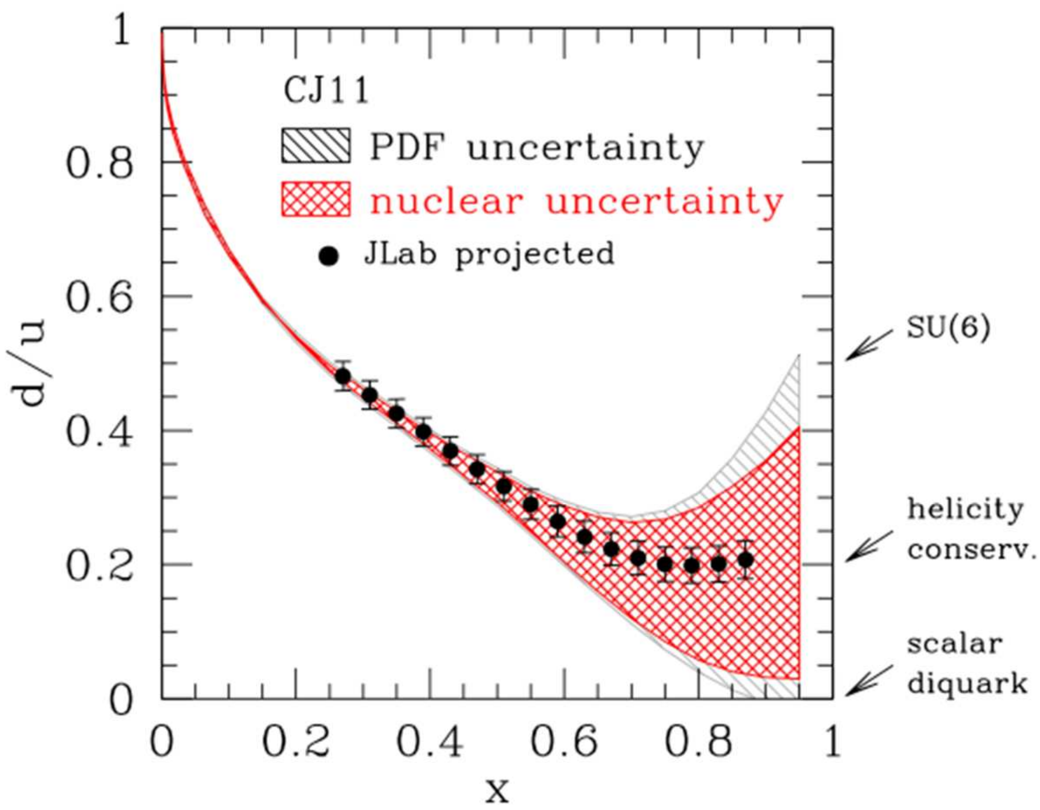
- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He

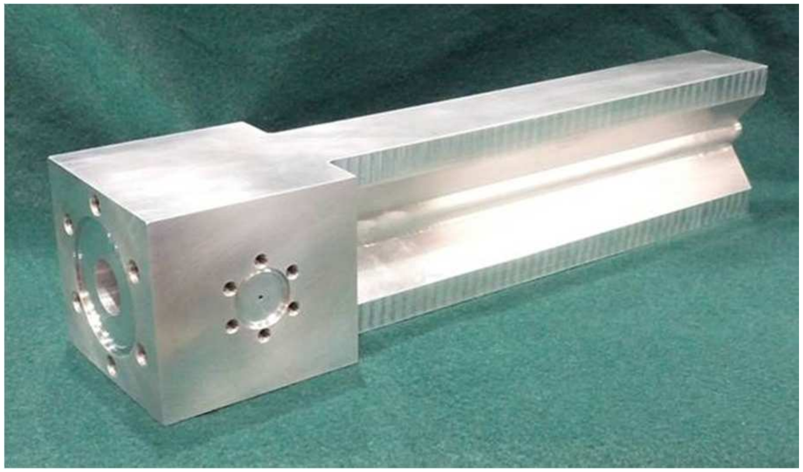
- Calculated to within 1%

- Most systematic and theoretical uncertainties cancel



DIS from A=3 nuclei - Projected Results





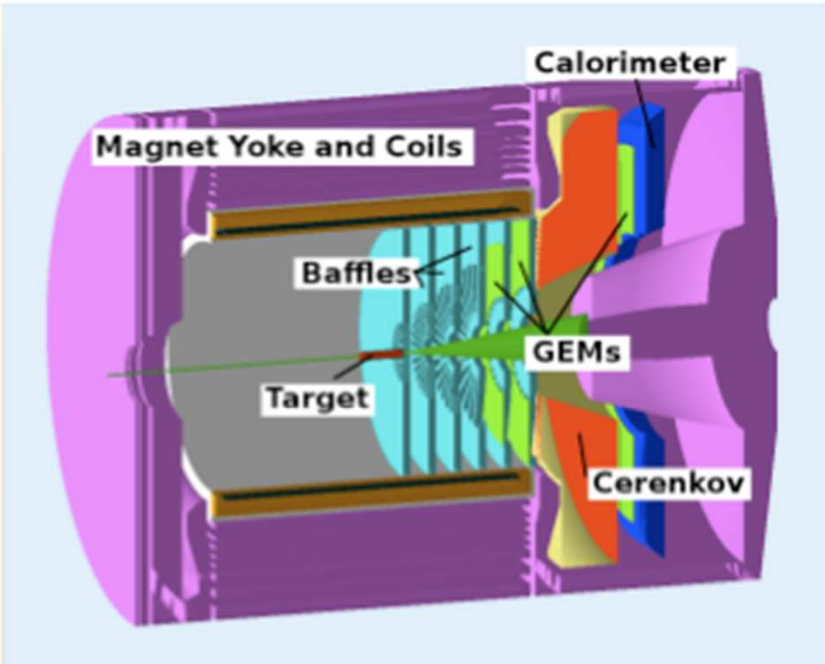
Thermo-mechanical design,
B. Brajuskovic *et al*, NIM A, arXiv: 1306.6000

E12-06-118 MARATHON: G. Petratos, J. Gomez, RJH, R. Ransome, *et al.*
Scheduled for 2015 at JLab

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

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

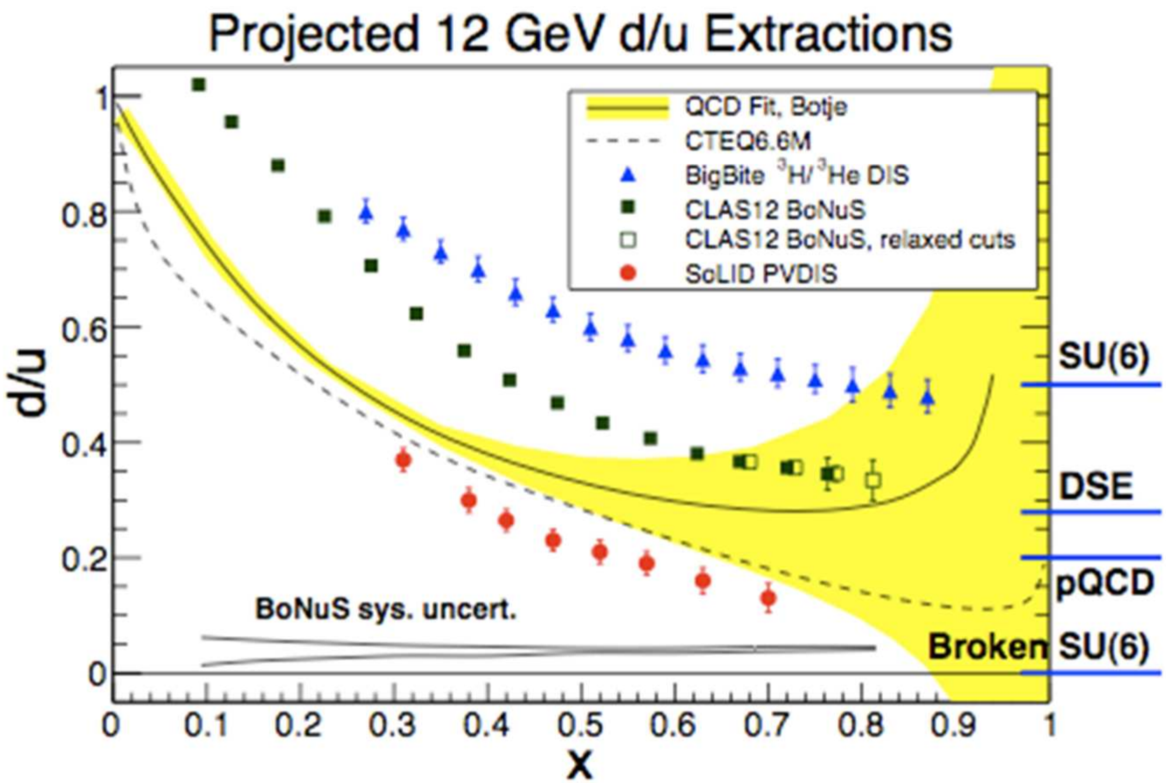
$$a_1(x) = 2\frac{\sum C_{1q} e_q (q+\bar{q})}{\sum e_q^2 (q+\bar{q})}, \quad a_3(x) = 2\frac{\sum C_{2q} e_q (q-\bar{q})}{\sum e_q^2 (q+\bar{q})}$$

Slide credit: S. Riordan

Clean Measurement of d/u with PVDIS

For high x on proton target:

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



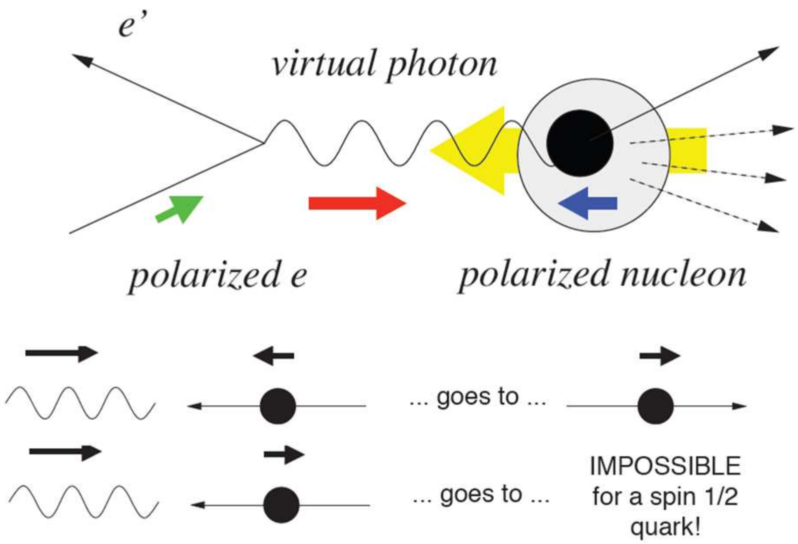
DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

- 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*

Slide credit: S. Riordan

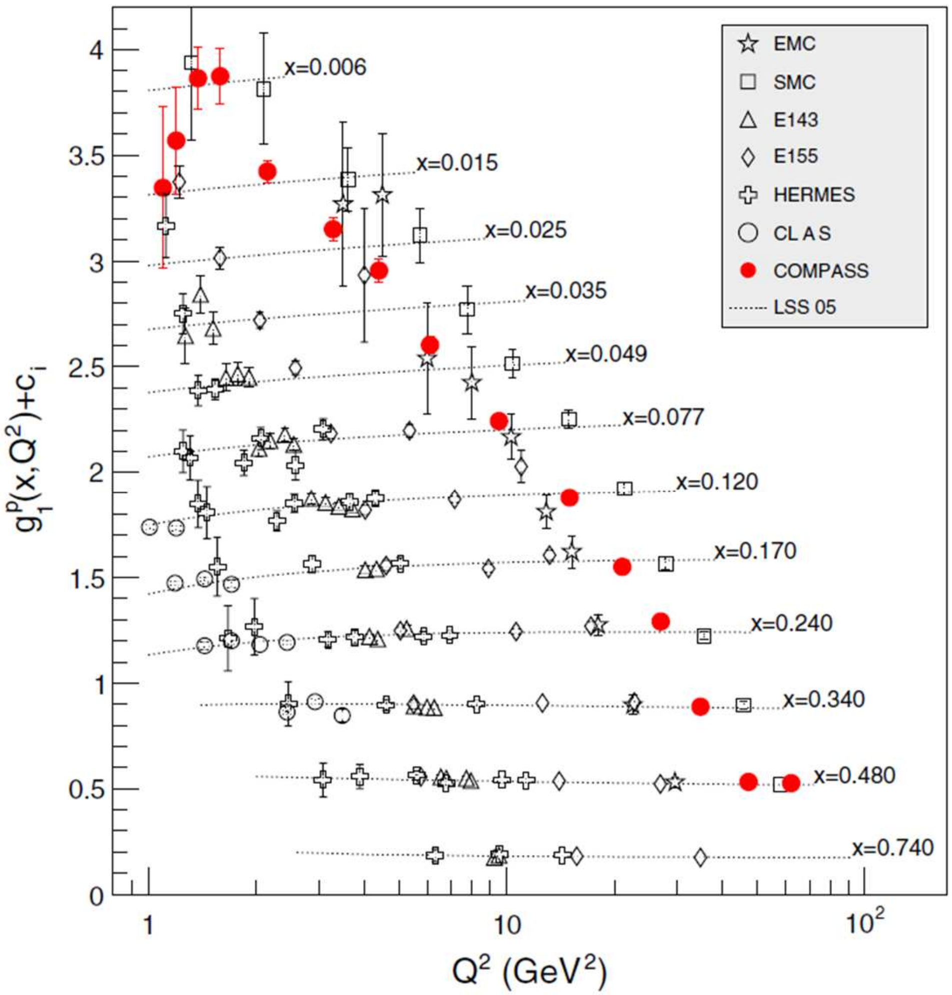
Spin Structure of the nucleon – valence region

Polarized electron scattering from a polarized nucleon



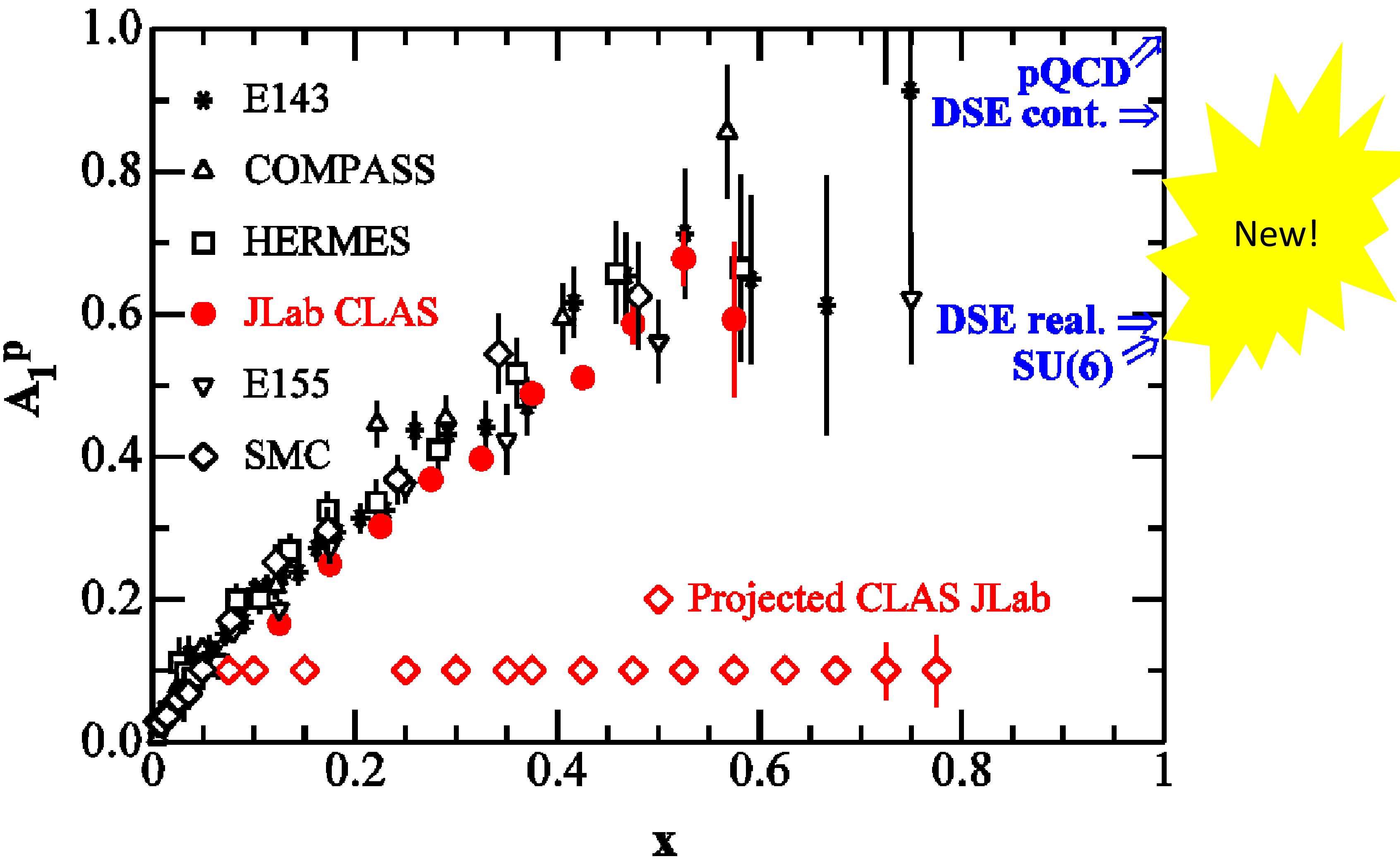
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1} = \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

NSAC **milestone HP14 (2018)**



C. Aidala et al, RMP (2013)

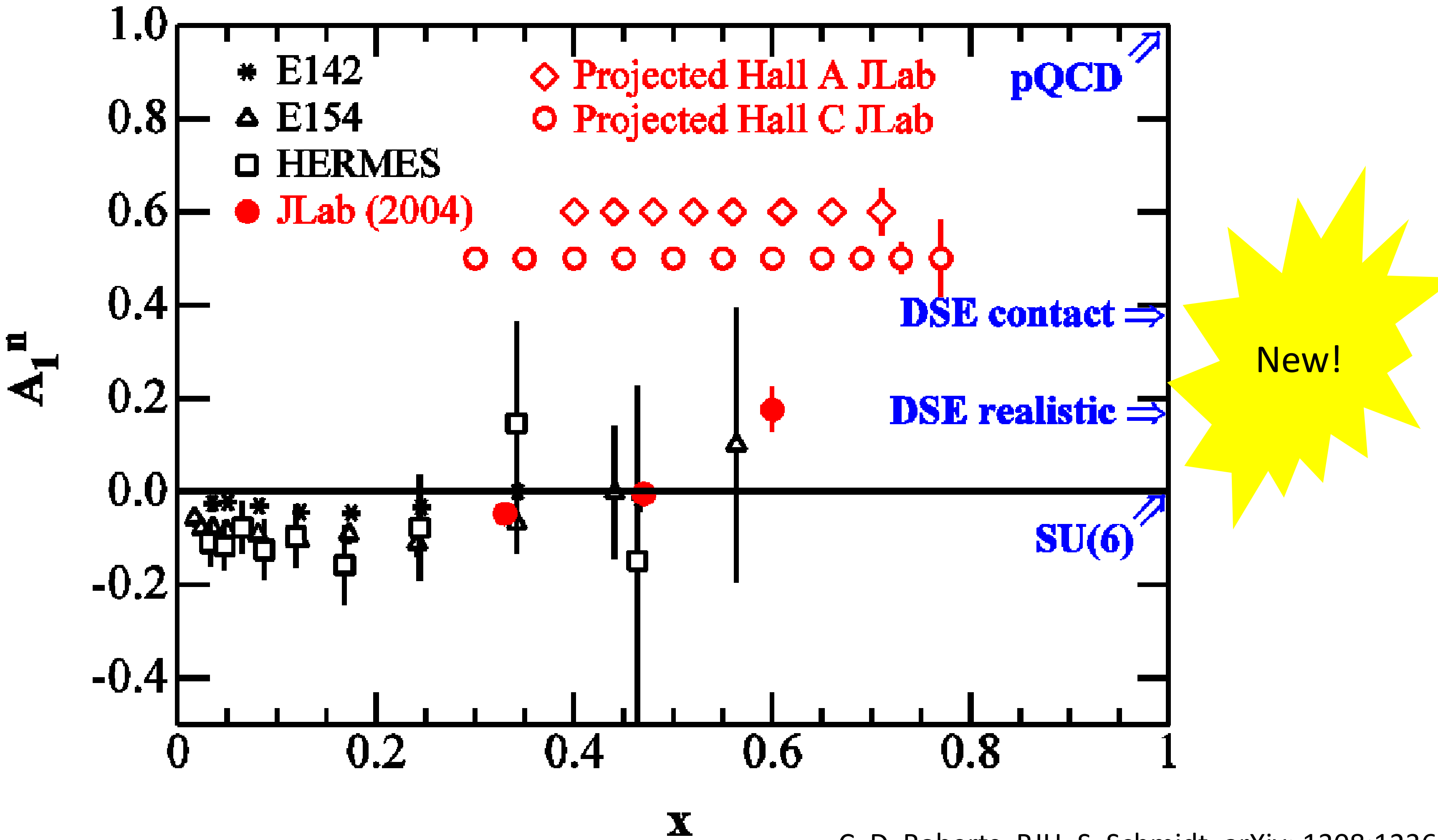
Measurements and Projections for A_1^p



JLab E12-06-109, S. Kuhn, D. Crabb, A. Deur, V. Dharmawardane, T. Forest, K. Griffioen, M. Holtrop, Y. Prok, et al.

C. D. Roberts, RJH, S. Schmidt, arXiv: 1308.1236

Measurements and Projections for A_1^n



C. D. Roberts, RJH, S. Schmidt, arXiv: 1308:1236

Scheduled for 2015 at JLab

JLab E12-06-110, X. Zheng, J.-P. Chen, Z.-E. Meziani, G. Cates et al.

JLab E12-06-122, B. Wojtsekhowski, G. Cates, N. Liyanage, Z.-E. Meziani, G. Rosner, X. Zheng, et al.

Transversity and tensor charge

- Quark transverse polarization in a transversely polarized nucleon:

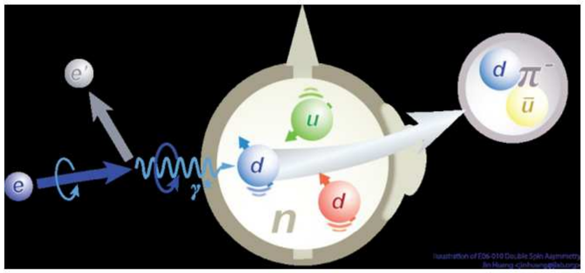
$h_{1T} =$

  - Can be probed in Semi-Inclusive DIS, Drell-Yan processes.
  - Quark-antiquark sea does not contribute.
  - Quark and gluon transversity distributions do not mix.
  - Nucleon tensor charge can be extracted from h_1.
  - Tensor charges are important for calculating nucleon EDMs.

Tensor Charge: Intrinsic property, like axial or vector charge

vector charge	axial charge	tensor charge
$\langle \; \| \gamma^\mu \| \; \rangle$	$\langle \; \| \gamma^\mu \gamma_5 \| \; \rangle$	$\langle \; \| \sigma^{\mu\nu} \gamma_5 \| \; \rangle$
$\int dx (q - \bar{q})$	$\int dx (\Delta q + \Delta \bar{q})$	$\int dx (\Delta_T q - \Delta_T \bar{q})$

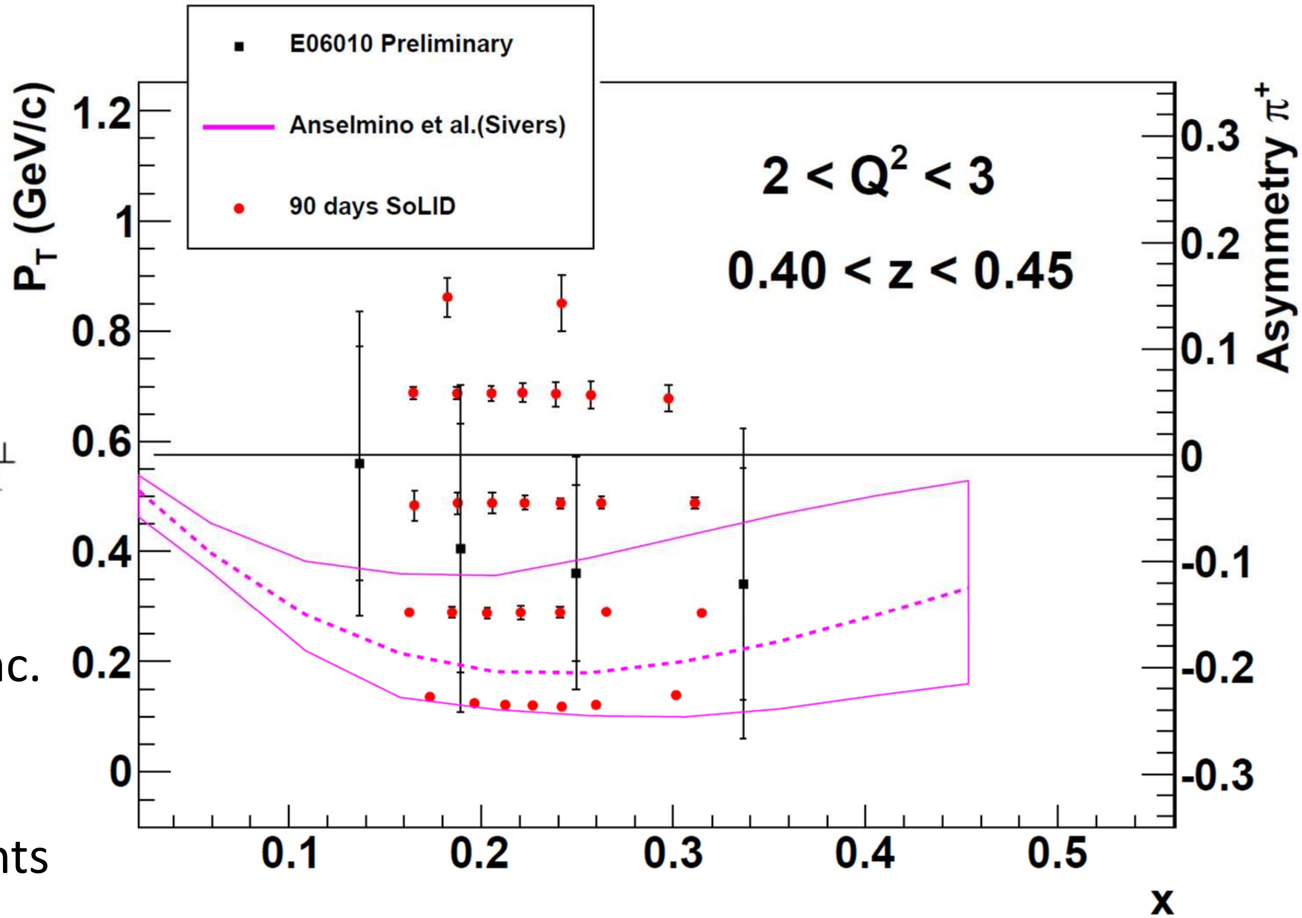
Transversity Projected Data -12 GeV JLab



$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^{\perp}$$

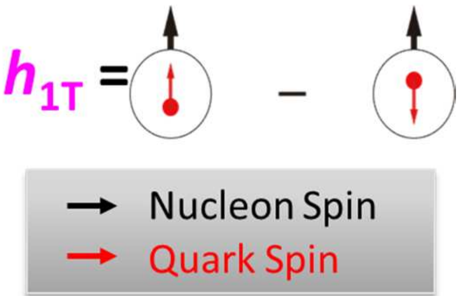
Collins frag. func.
KEK-B/Belle

Four 12-GeV JLab experiments



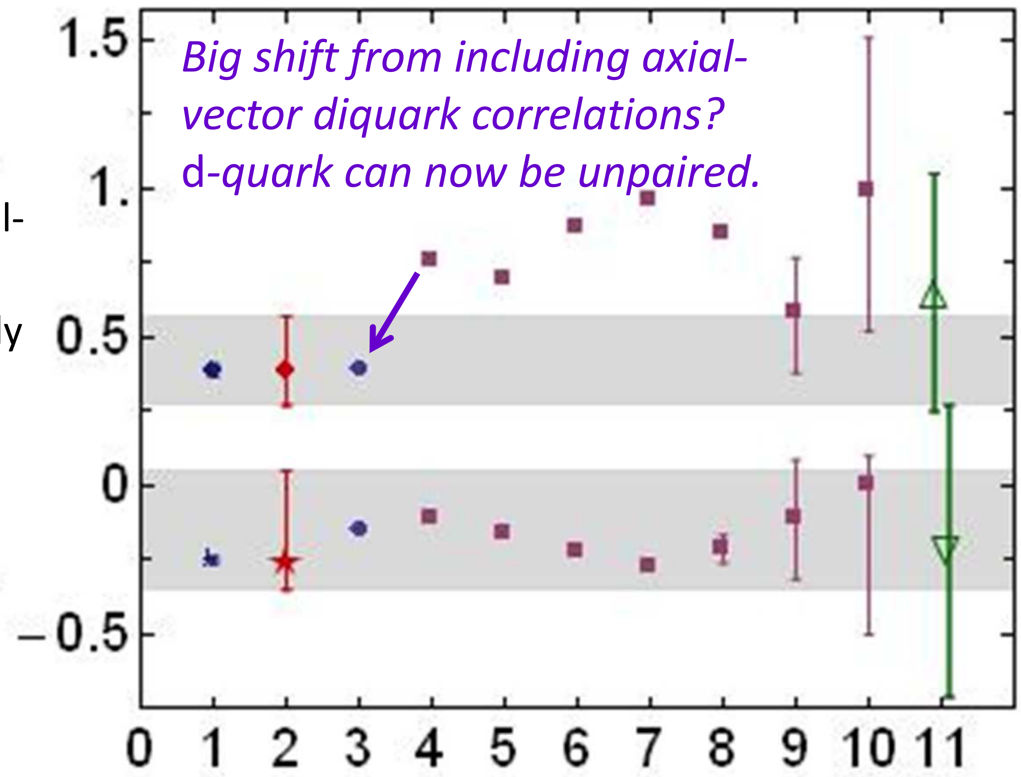
JLab E12-11-111: H. Avakian, F. Klein, M. Aghasyan, K. Joo, M. Contalbrigo, et al.
JLab E12-11-108: H. Gao, K. Allada, J.-P. Chen, X. Li, Z.-E Meziani, et al.
JLab E12-10-006: H. Gao, J.-P. Chen, X. Jiang, J.-C. Peng, X Qian et al.
JLab E12-09-018: G. Cates, E. Cisbani, G. Franklin, A. Puckett, B. Wojtsekhowski, et al.

Tensor Charge: $\sigma_{\mu\nu}$ current



$$\delta q = \int_0^1 dx\,\left(h_1^q(x) - h_1^{\bar{q}}(x)\right)$$

1. JLab 12 GeV Projection (Prokudin)
2. Anselmino *et al*., PRD87 (2013) 094019
3. Pitschmann *et al*. (DSE) (2013) [including axial-vector diquarks *but* contact interaction]
4. Hecht *et al*. (DSE), PRC64 (2001) 025204 [only scalar diquarks]
5. Cloët *et al*., PLB659 (2008) 214
6. Pasquini *et al*., PRD76 (2007) 034020
7. Wakamatsu, PLB653 (2007) 398
8. Gockeler *et al*., PLB627 (2005) 113
9. Gamberg *et al*., PRL 87 (2001) 242001
10. He *et al*., PRD52 (1995) 2960
11. Bacchetta *et al*., JHEP 1303 (2013) 119



Slide credit: C. D. Roberts

Concluding statement

- **Understanding hadrons will be one of science' greatest achievements**

- **Understanding the nucleon at high x is essential**
  - **Valence region defines the hadron**
  - **Test models of the nucleon**
  - **Descriptions of DIS in nuclei**
  - **QCD effects in high energy experiments**

- **New 21st century tools have positioned us well for the next decade**

- **We are camped on one of the most interesting frontiers in science**

Main injector at FNAL - 120 GeV protons

Fermilab Today — Thursday, Nov. 3, 2011

Feature

SeaQuest dives into a mysterious sea of particles

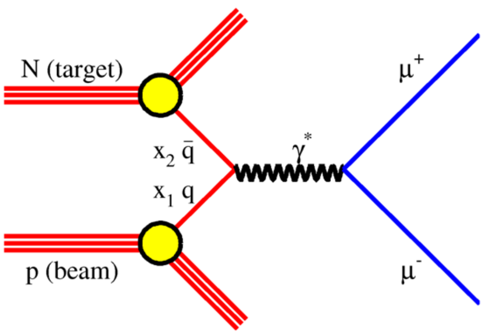
Scientists hope the SeaQuest detector will begin taking data in a couple of weeks. *Photo: Reidar Hahn*

D. Geesaman, P. Reimer, et al.

Longer term: Polarized FNAL, J-PARC at 50 GeV

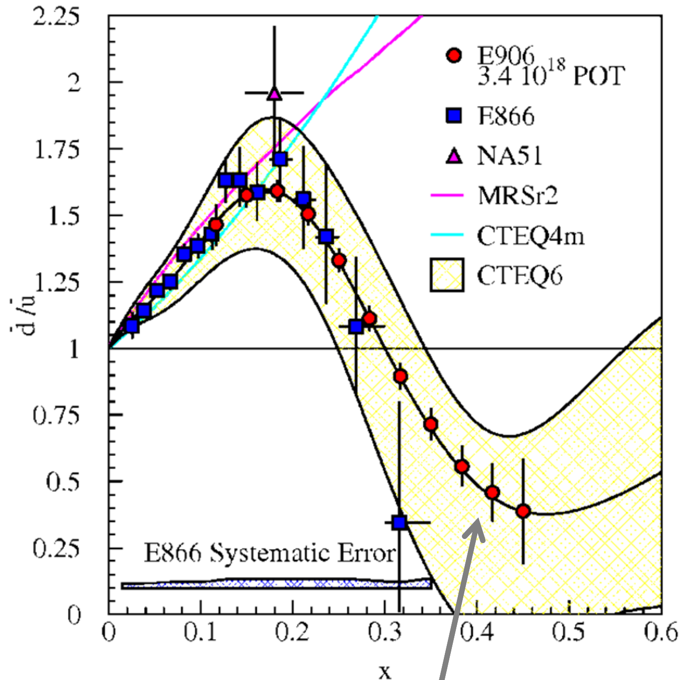
FNAL E906

Drell-Yan measurement of anti-quark distributions



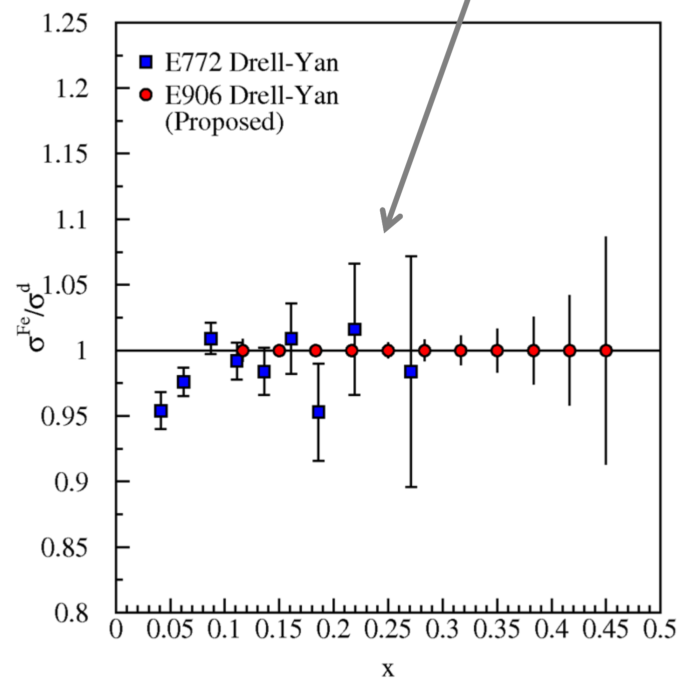
Experiment E906 FNAL
120 GeV, ideal energy

Beginning:
~ November 1, 2013

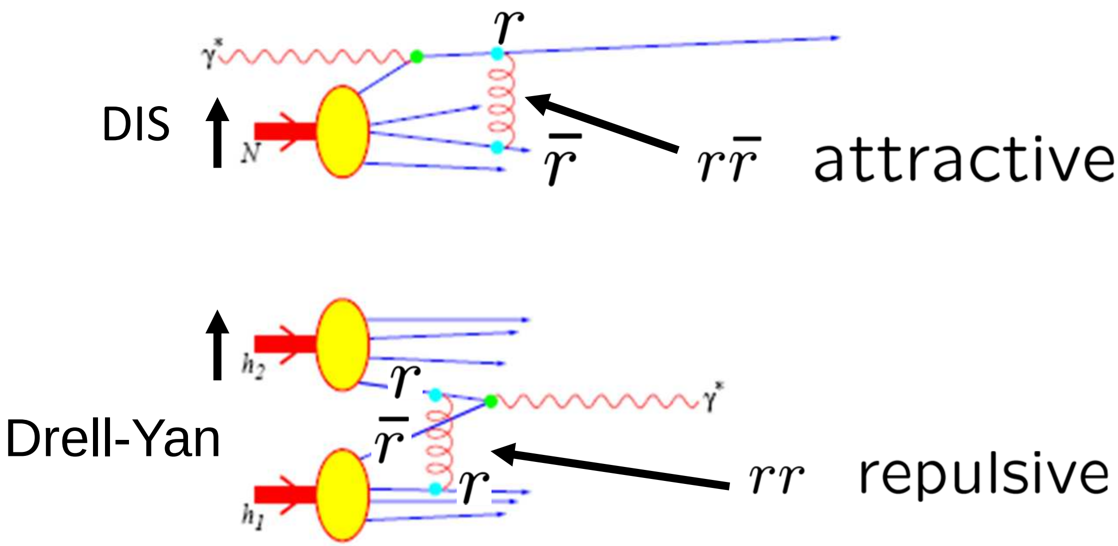


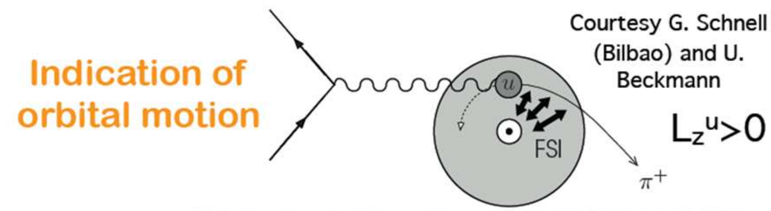
No model predicts dbar/ubar <1.

What is the A dependence of antiquarks?

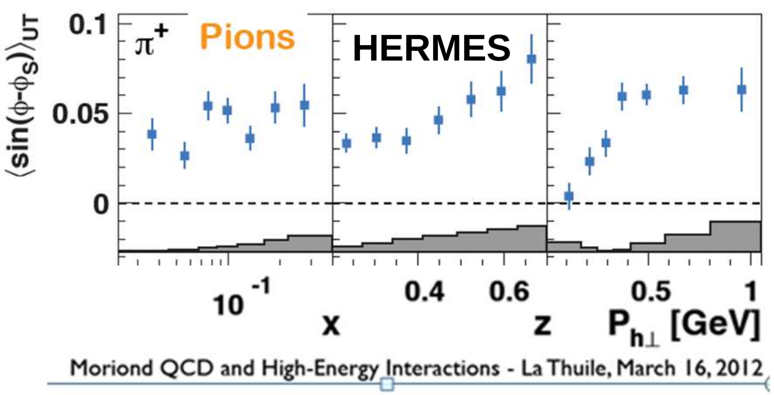


Transverse Momentum Distributions: The Sivers effect



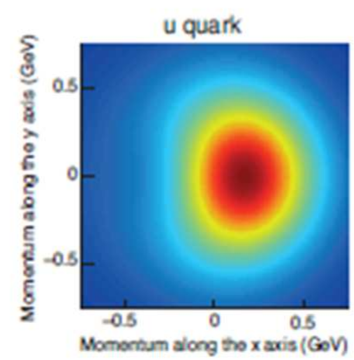


[M. Burkardt, Phys. Rev. D66 (2002) 114005]

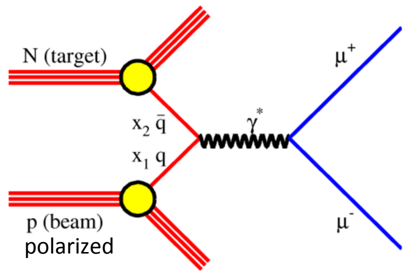


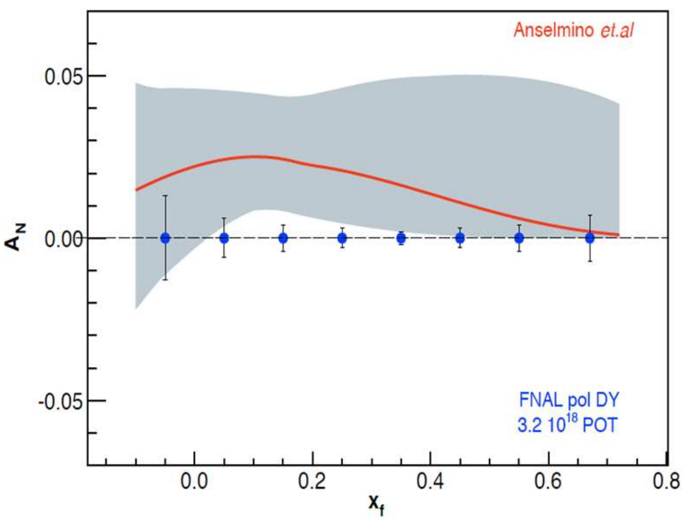
$$Sivers|_{DIS} = -Sivers|_{DY}$$

- ***NSAC*** Milestone HP13 (2015) "Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic scattering."
- COMPASS-II, RHIC-spin, polarized FNAL



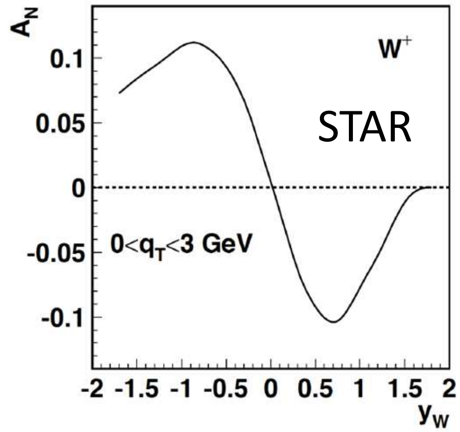
Polarized Drell-Yan and W production (2014+)

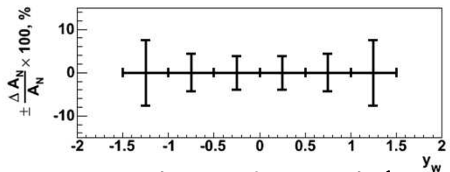




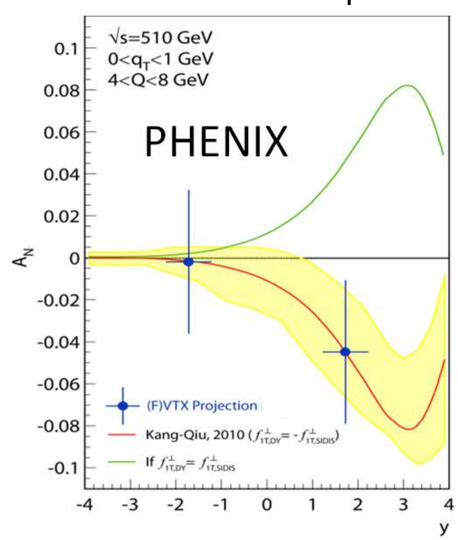
FNAL Polarized SeaQuest (>2017)

PAC: Stage I approval

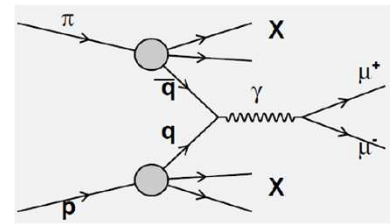


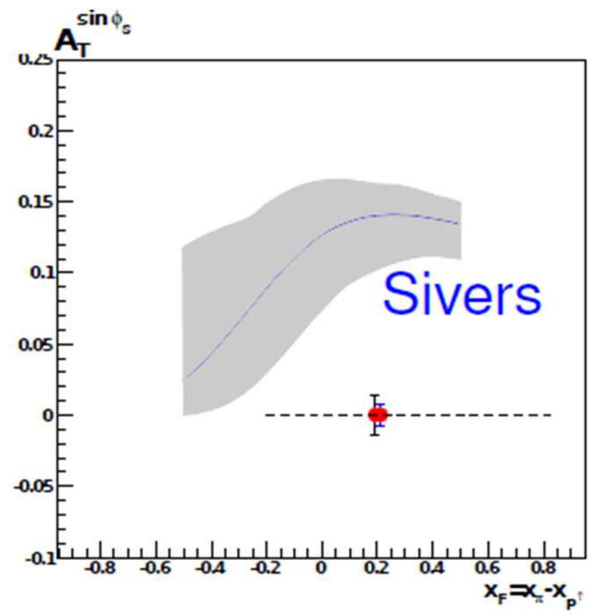


Delivered 500 pb^{-1}



Forward upgrades -> transverse spin asymmetries





COMPASS-II (2014, if upgraded)

Thanks to E. Aschenauer, W. Lorenzon, M. Liu, M. Grosse-Perdekamp

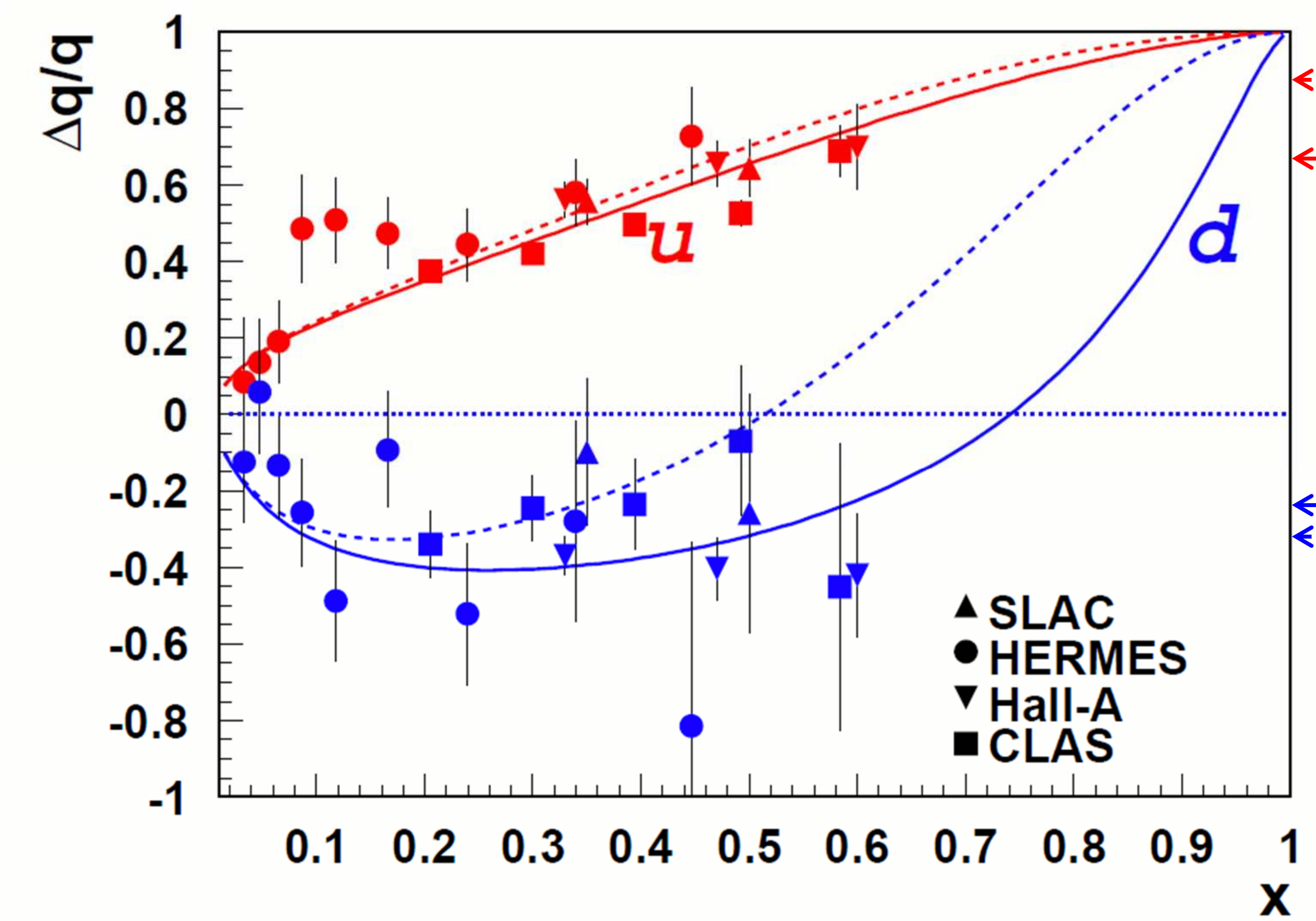
Spin dependent PDF predictions at large-x

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

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

Nucleon Model	F_2^n/F_2^p	d/u	Δu/u	Δd/d	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark	1/4	0	1	-1/3	1	1
DSE contact interaction	0.41	0.18	0.88	-1/3	0.38	0.83
DSE realistic interaction	0.49	0.28	0.65	-0.26	0.17	0.59
pQCD	3/7	1/5	1	1	1	1

Δd/d & Δu/u



DSE contact

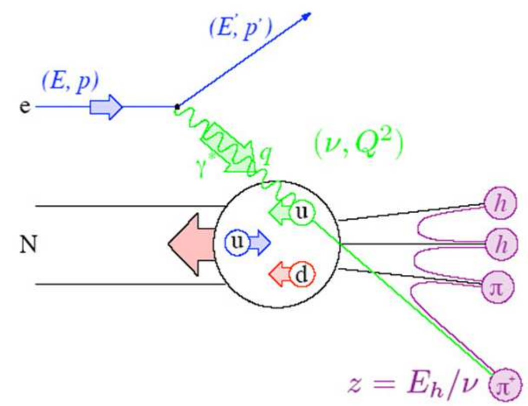
DSE realistic

DSE realistic

DSE contact

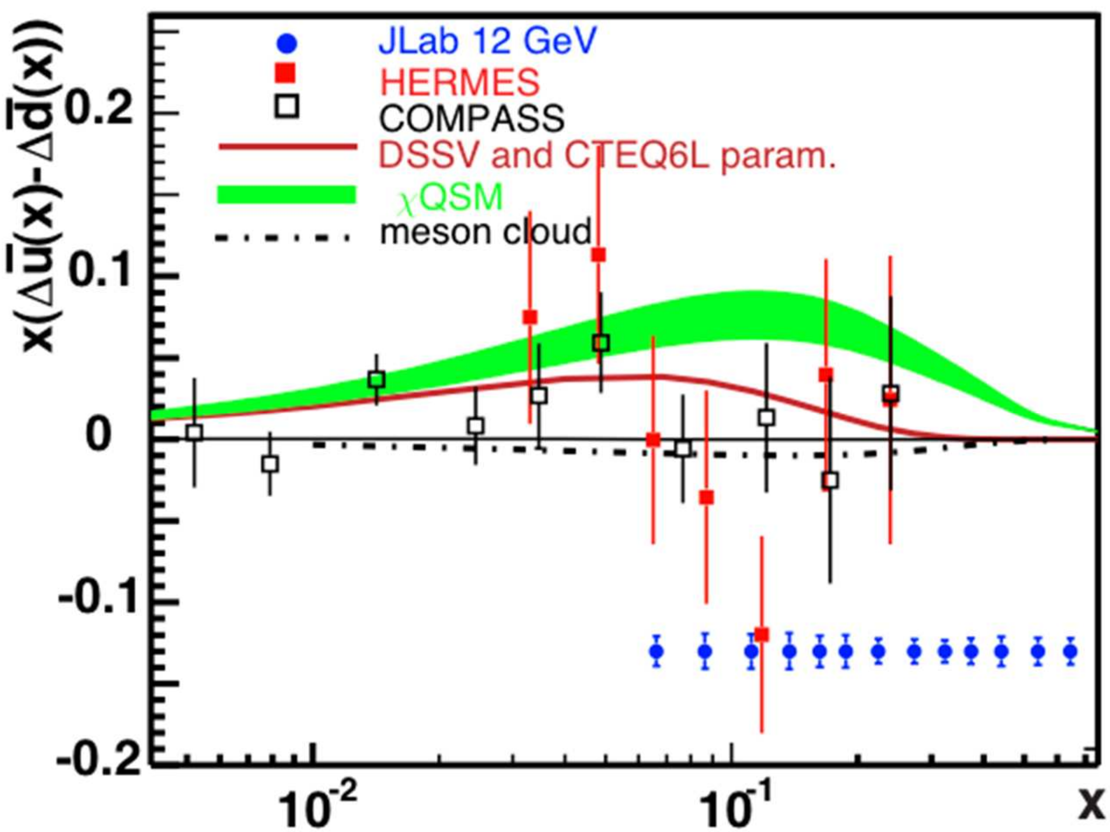
$$-\frac{1}{3} < \frac{\Delta d}{d} < -\frac{2}{9}$$

Is there a flavor asymmetry in the sea quark helicity distributions?



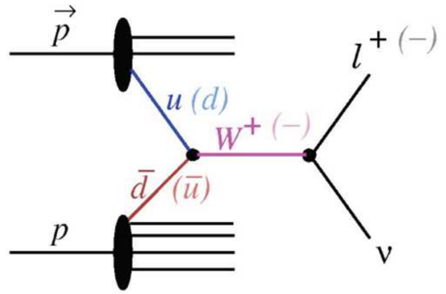
$$A_1^{h(p/d)}(x) = \frac{\sum_q e_q^2 D_q^h \Delta q(x)}{\sum_q e_q^2 D_q^h q(x)}$$

- Sea quark polarization at high x
- JLab 12 GeV (Hall B)
- Kaon detection - RICH



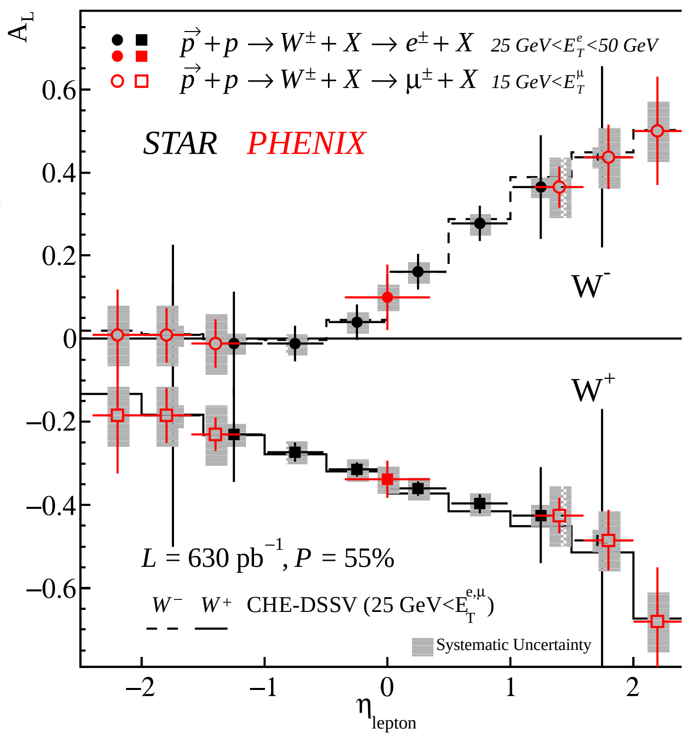
Plot credit: K. Hafidi

W production expected from RHIC runs 12+13



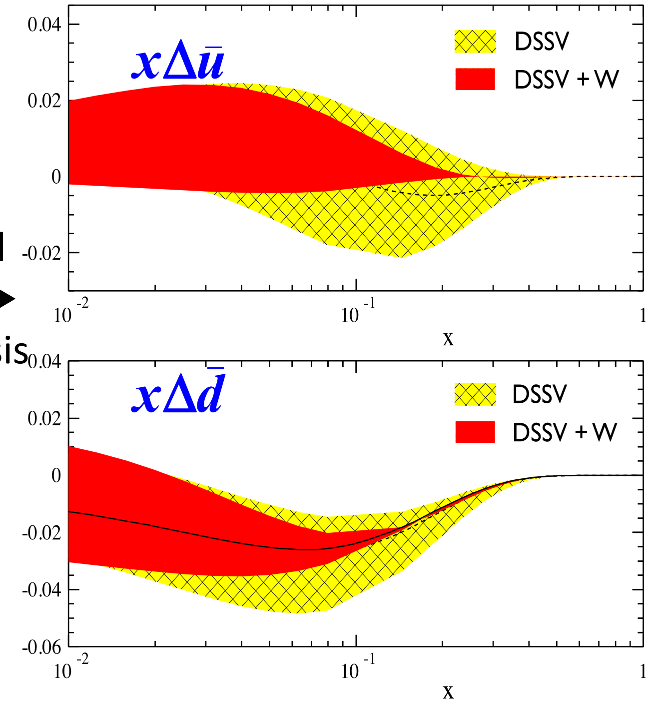
$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

- Provides an important check of SIDIS method
- No fragmentation function
- $Q^2 = M_W^2$ (no high twist effects)



Global analysis →

Statistical error only



NSAC milestone HP8 (2013)

B. Jacak, N. Xu, RHIC PAC 2012
http://www.bnl.gov/npp/pac0612.asp

Thanks to E. Aschenaur

BONUS in CLAS (Hall B at Jefferson Lab)

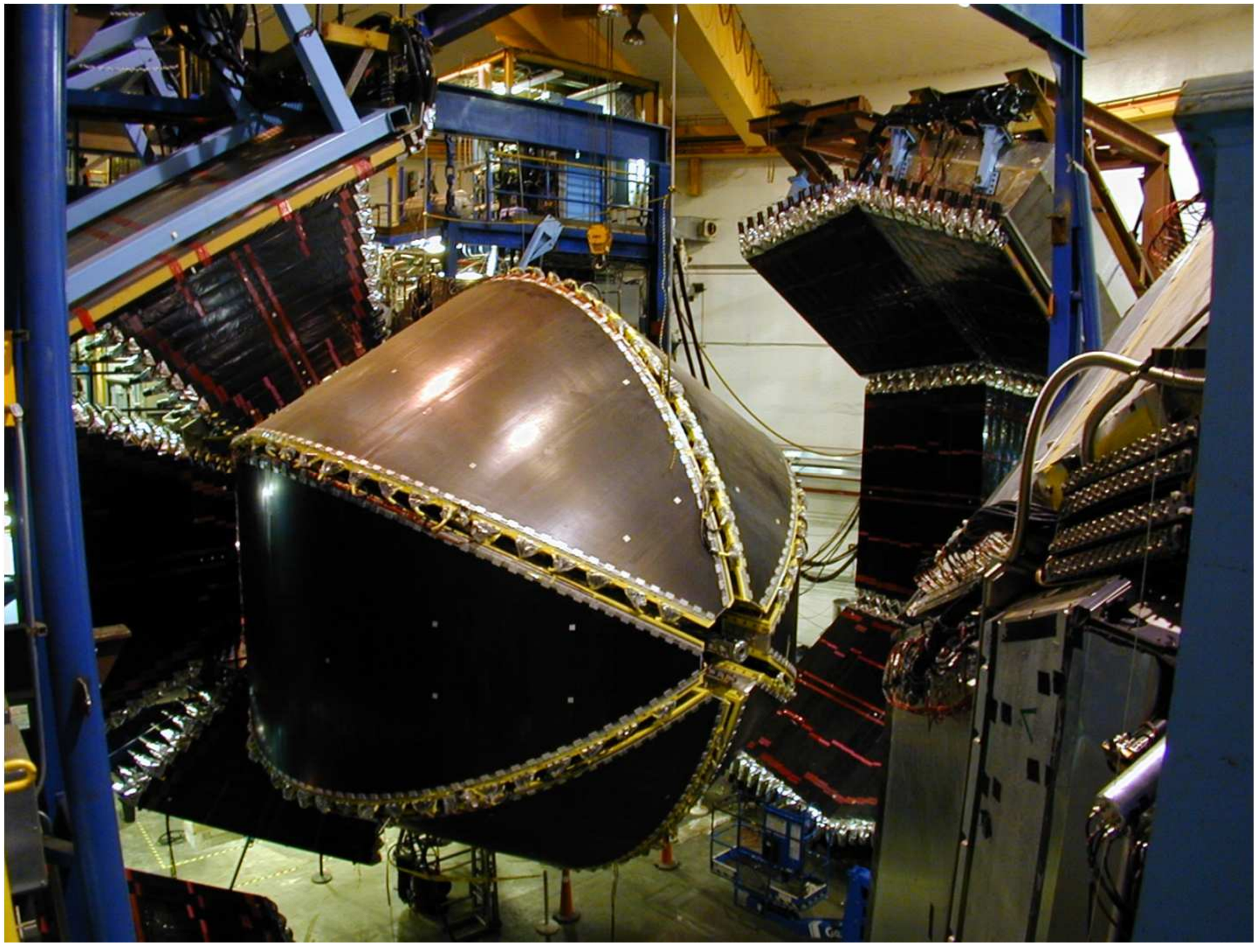
rTPC inside Solenoid inside CEBAF Large Acceptance Spectrometer (CLAS)

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