Recent Spin structure results from inclusive electron scattering experiments at Jefferson Lab.

Nilanga Liyanage
University of Virginia

Spin physics at Jefferson Lab

Jefferson lab:

- high quality polarized beam
- high luminosity polarized targets
- large acceptance spectrometers

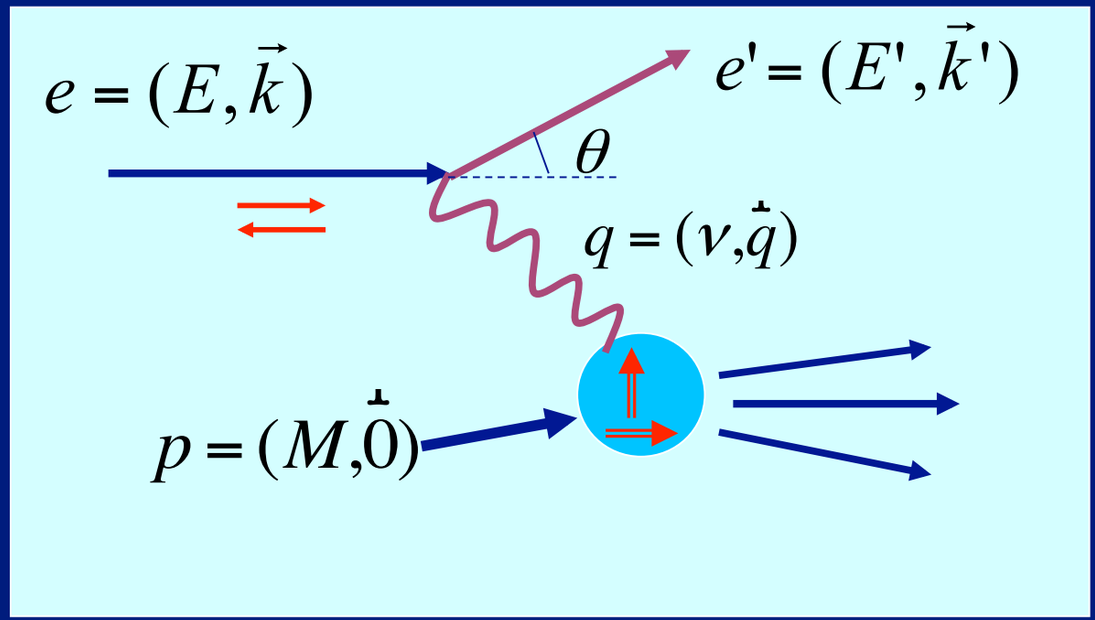
high precision spin structure data in the high x_{Bj} valence quark region.

What is special about the high-X_{Bj} region ?

Nucleon wave function dominated by valence quarks.

- A good place to test quark models; understand quark-gluon dynamics and SU6 symmetry breaking mechanisms.
- Firm pQCD predictions for x->1

Inclusive Electron Scattering



4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Invariant mass squared

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

Bjorken variable

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

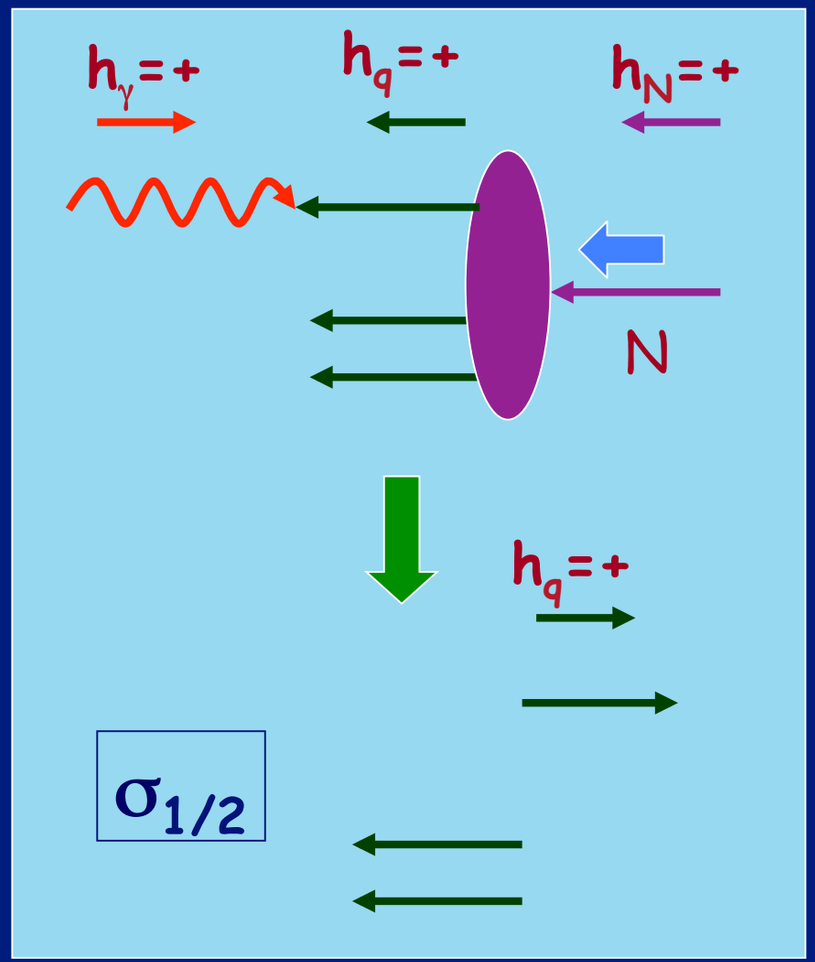
Unpolarized case

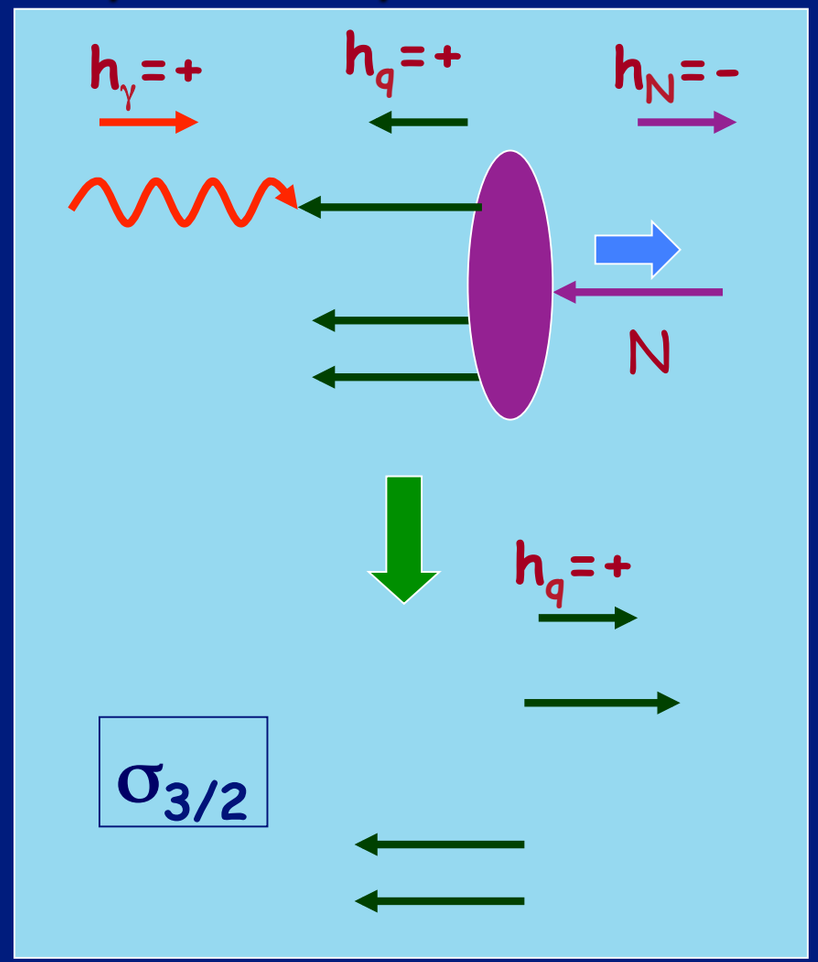
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

Polarized case

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

Virtual Photon Asymmetry





$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1}$$

Nucleon Structure at large x_{Bj}

Neutron Wavefunction (Spin and Flavor Symmetric)

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

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

Nucleon Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	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
pQCD	3/7	1/5	1	1	1	1

SU6 symmetry breaking terms in Valence quark models: higher energy for axial-vector spectator di-quark pair terms compared to scaler di-quark pair terms due to hyperfine interaction.

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

Nucleon Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	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
pQCD	3/7	1/5	1	1	1	1

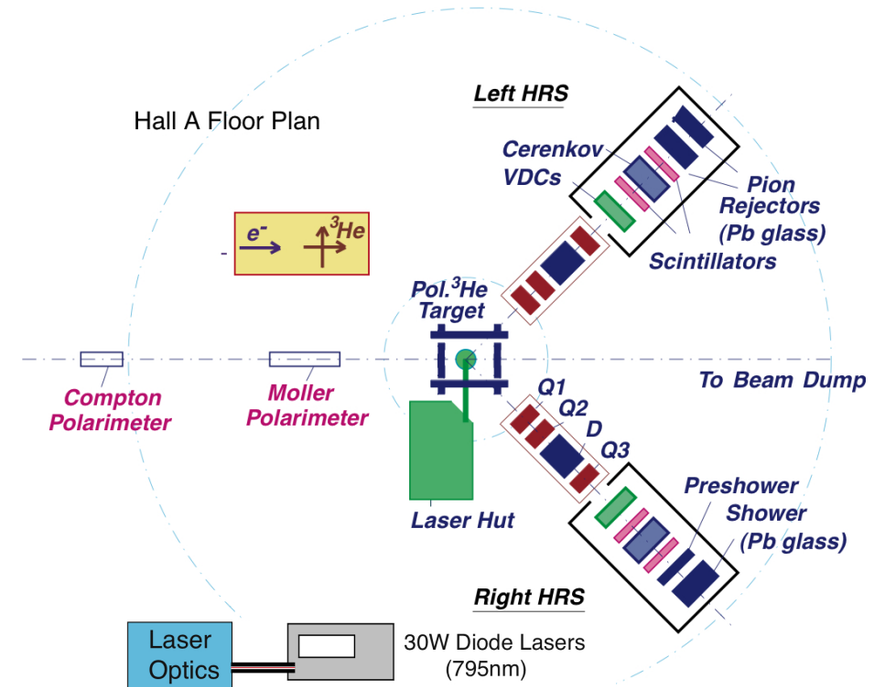
pQCD: as x->1, the struck quark has the same helicity as the parent nucleon.

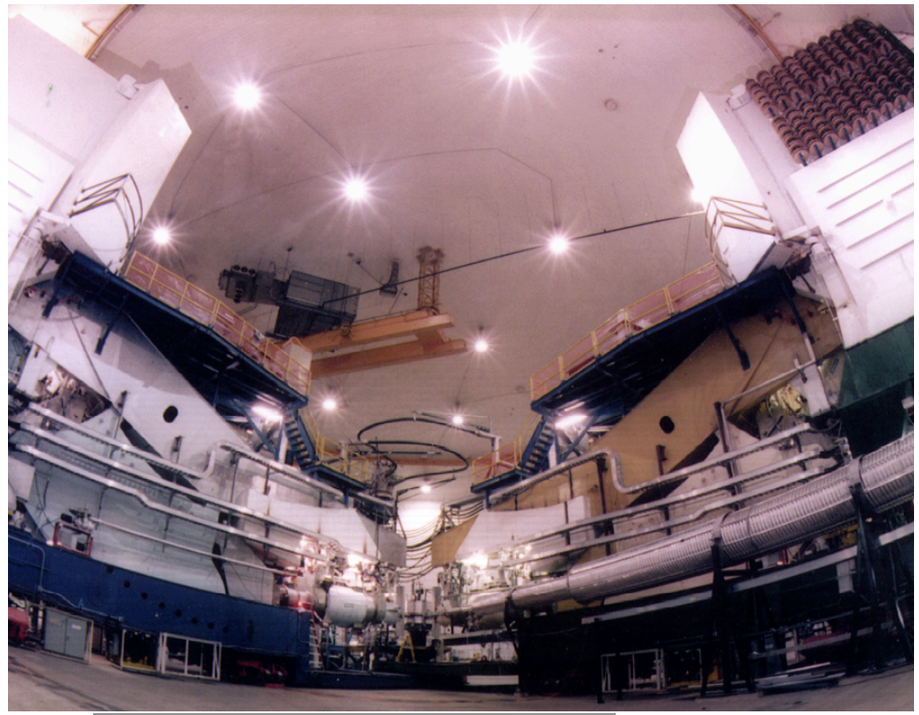
$$|n\uparrow\rangle = \frac{1}{\sqrt{2}}|d\uparrow (ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|d\uparrow (ud)_{S=1}\rangle - \frac{1}{3}|d\downarrow (ud)_{S=1}\rangle$$
$$- \frac{1}{3}|u\uparrow (dd)_{S=1}\rangle - \frac{\sqrt{2}}{3}|u\downarrow (dd)_{S=1}\rangle$$

Suppressed by an extra $(1-x)^2$

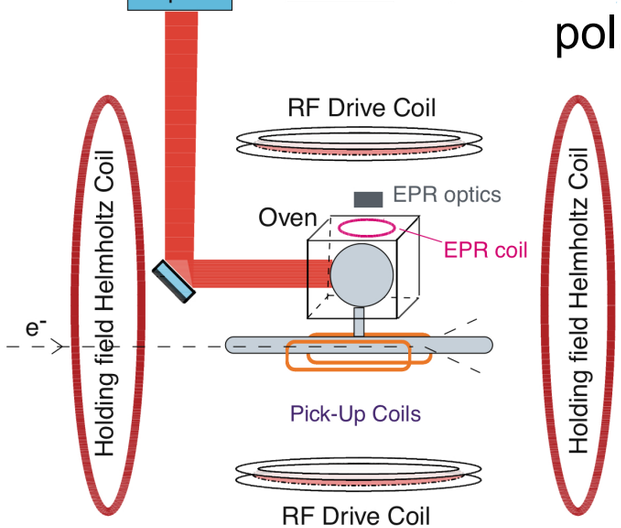
Nucleon Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

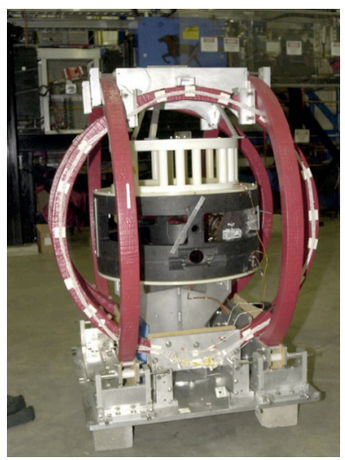
Experimental Hall A

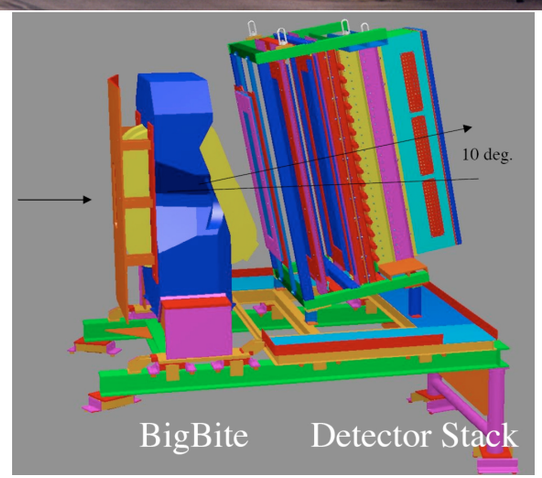




pol. ^{3}He target

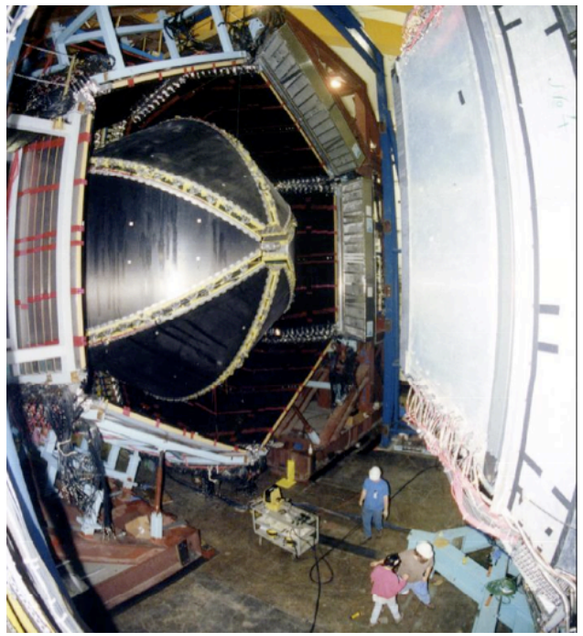


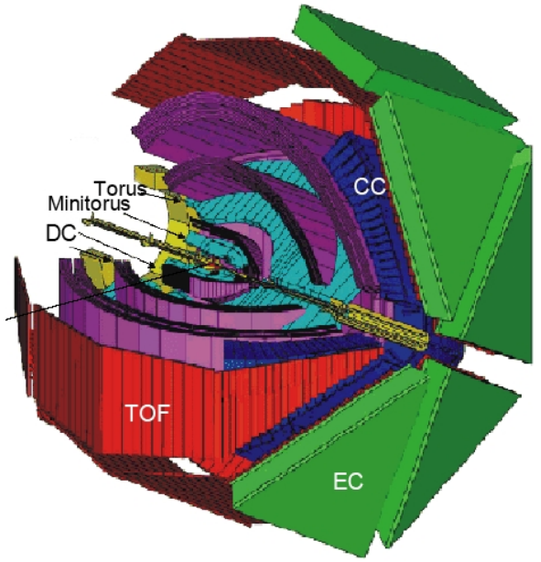


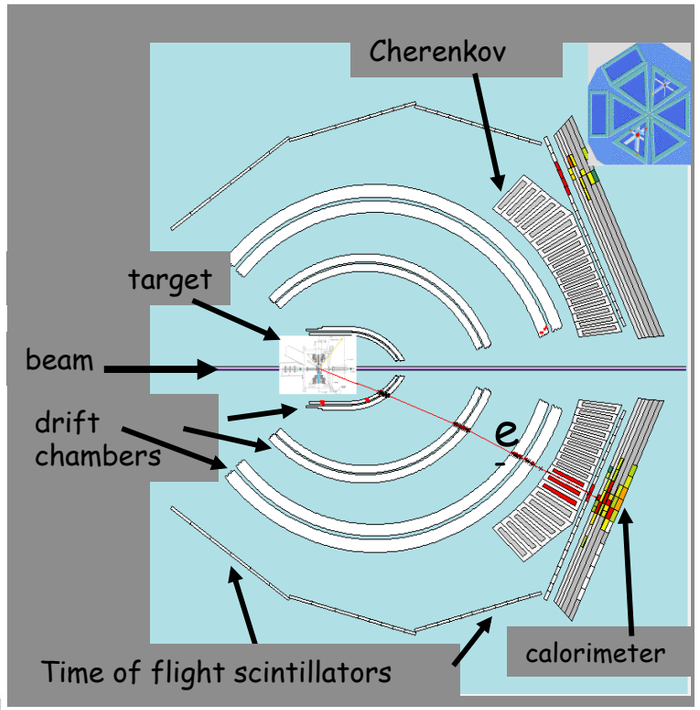


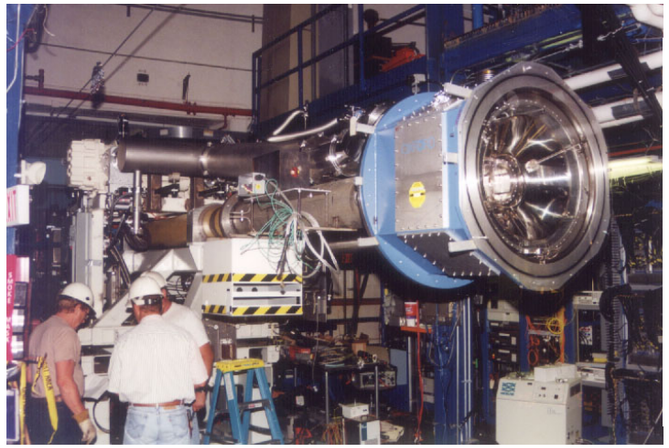
…plus transverse polarized proton target for g_{2p}

Experimental Hall B

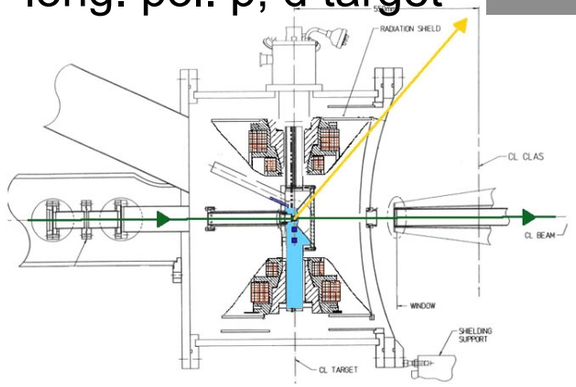








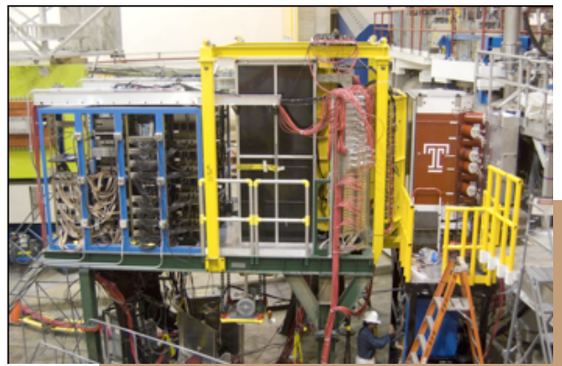
long. pol. p, d target



CLAS

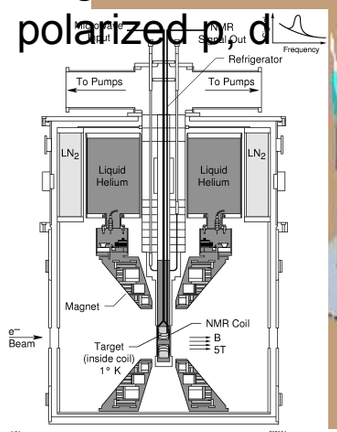
EG1, EG4, EG1-DVCS

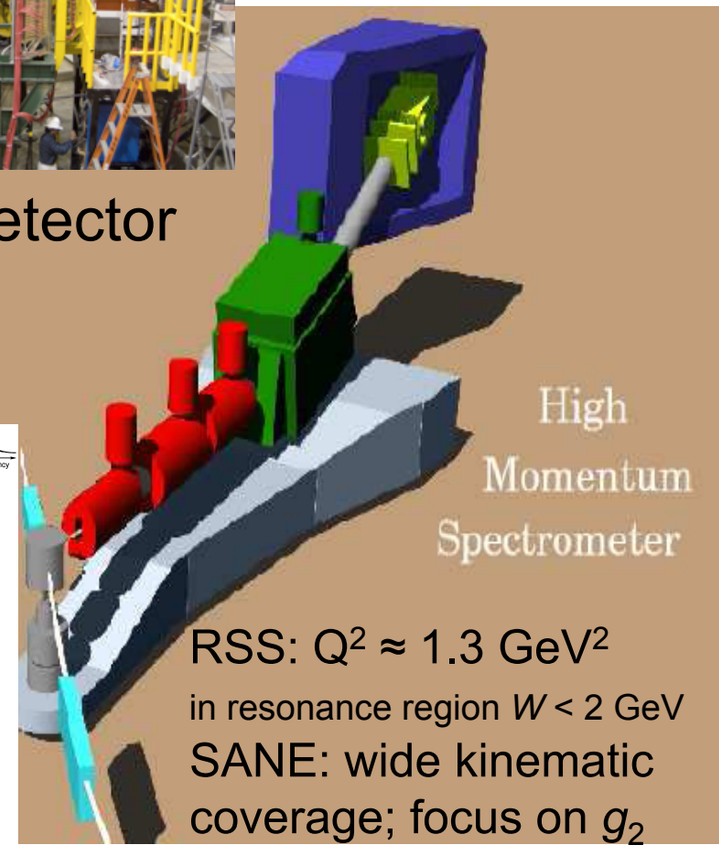
Experimental Hall C



BETA detector

Transverse and longi-tudinal polarized p, d

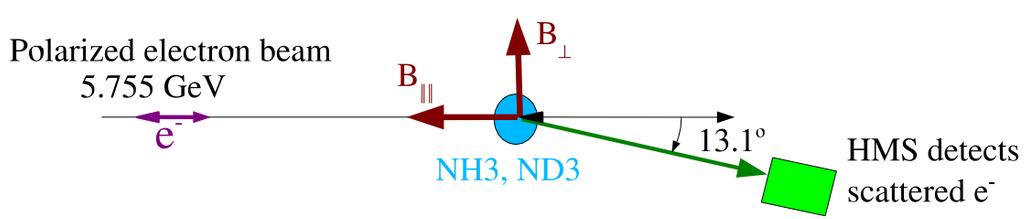


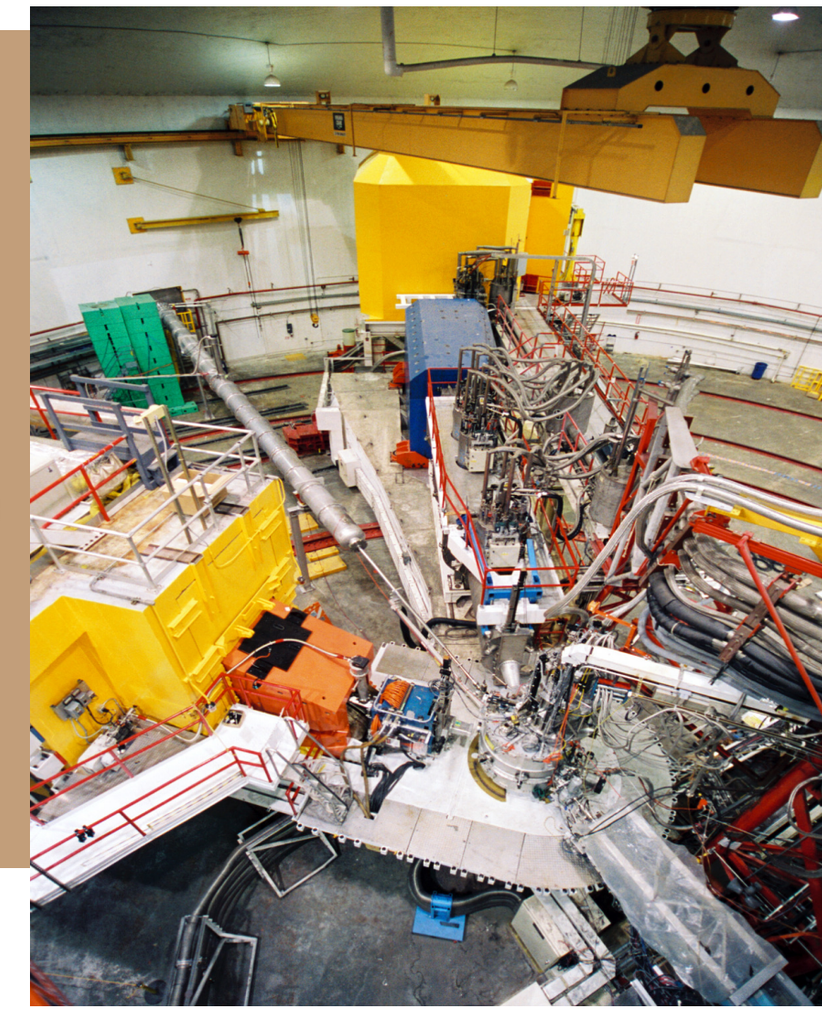


RSS: $Q^2 \approx 1.3$ GeV^2

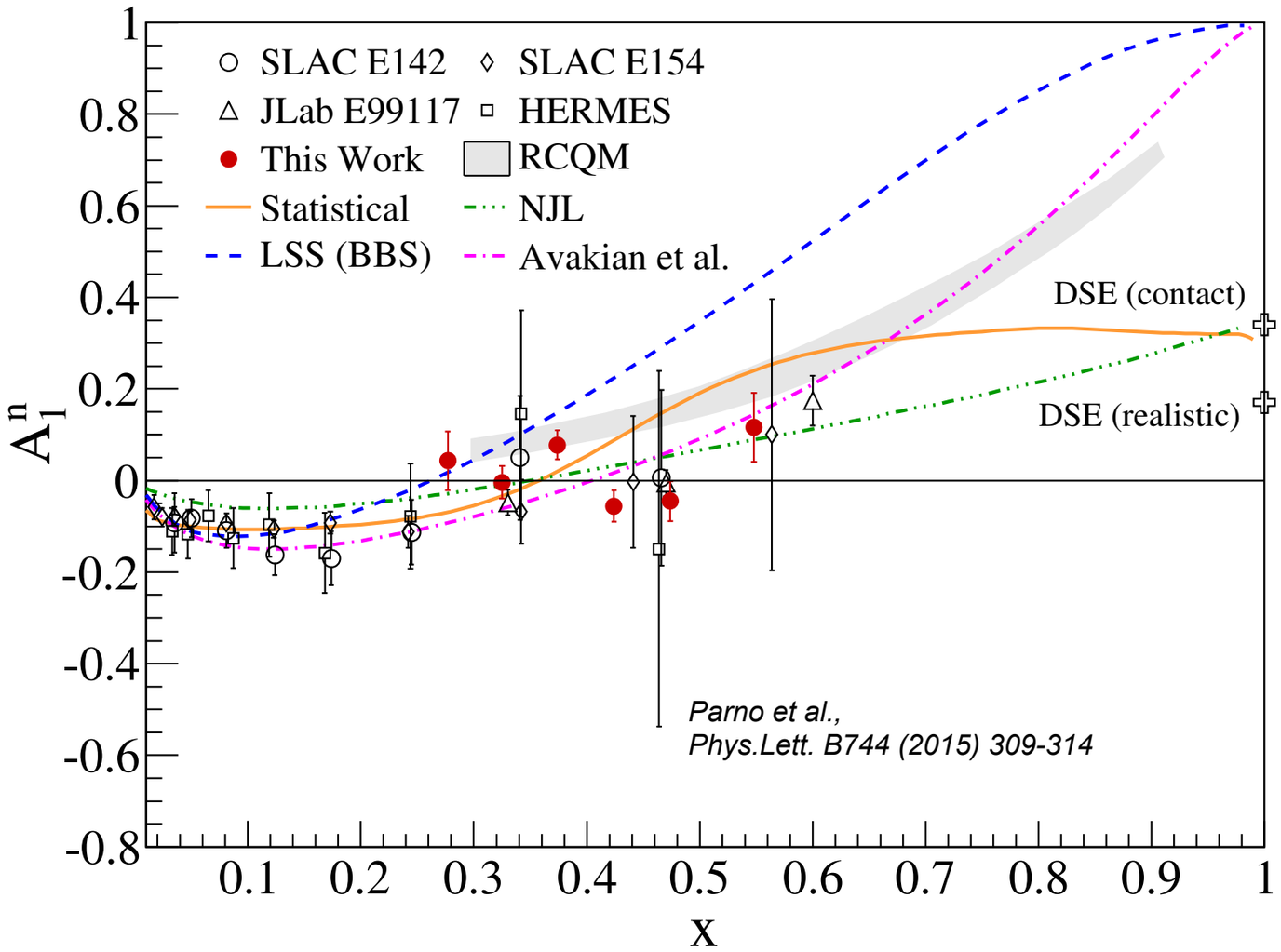
in resonance region $W < 2$ GeV

SANE: wide kinematic coverage; focus on g_2





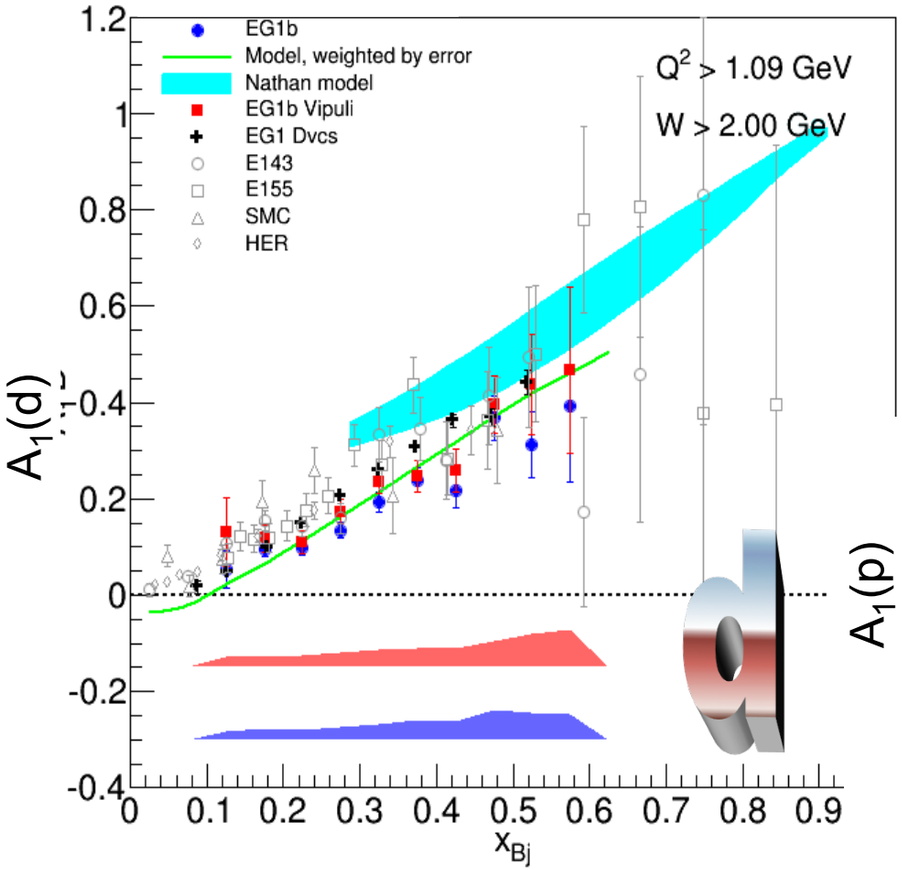
Spin structure functions at large *x*



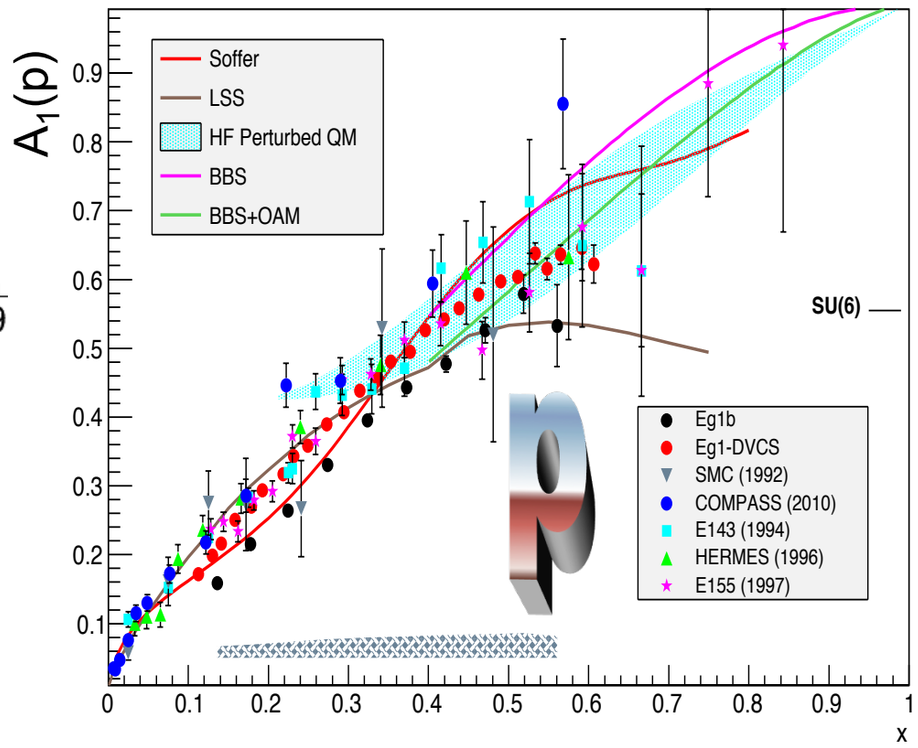
Hall A Experiment E06-014

Polarized 3He target, scattered electrons in Bigbite and HRS

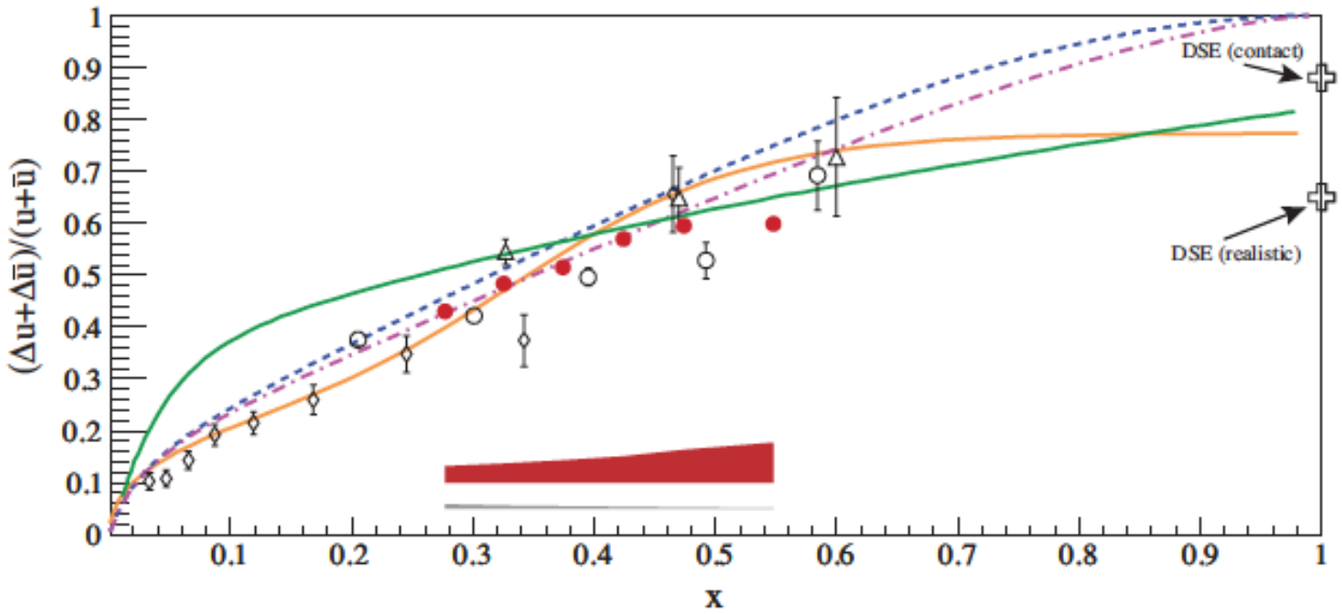
Spin structure functions at large *x*

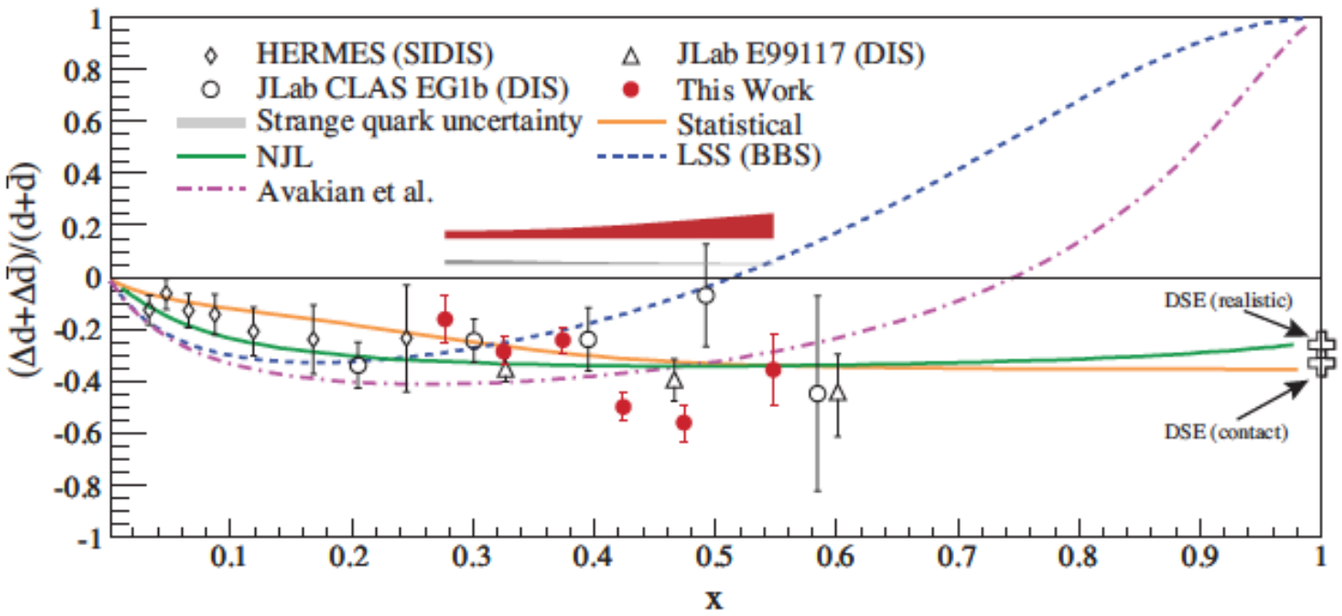


CLAS



Spin structure functions at large *x*





From Parno et al., Phys.Lett. B744 (2015) 309-314

Moments of spin structure functions

- Related to matrix elements of local operators - in principle accessible to lattice QCD calculations
- Sum rules relate moments to the total spin carried by quarks in the nucleon and to the axial vector coupling g_A of the nucleon
- At high Q^2, can be expanded in a power series (higher twist, OPE)
- At low Q^2, amenable to Chiral Perturbation Theory; constrained by GDH Sum Rule

Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6} + \text{QCD corr.}$

GDH Sum Rule: $\Gamma_1\left(Q^2 \to 0\right) \to -\frac{Q^2}{2M^2}\frac{\kappa^2}{4}$

$$\Gamma_1\left(Q^2\right) = \int_0^1 g_1\left(x,Q^2\right)dx$$

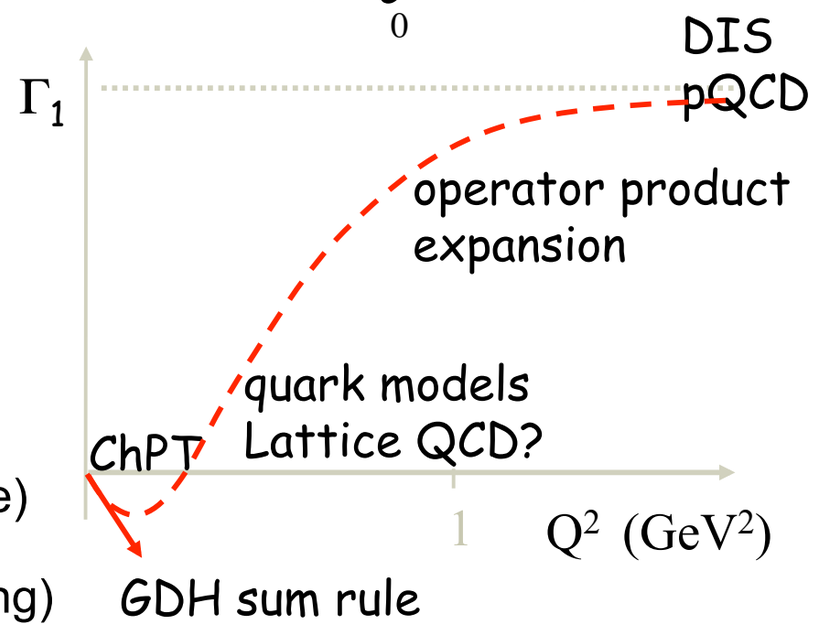
$$\Gamma_2(Q^2) = \int_0^1 g_2(x,Q^2)dx \quad (= 0)$$

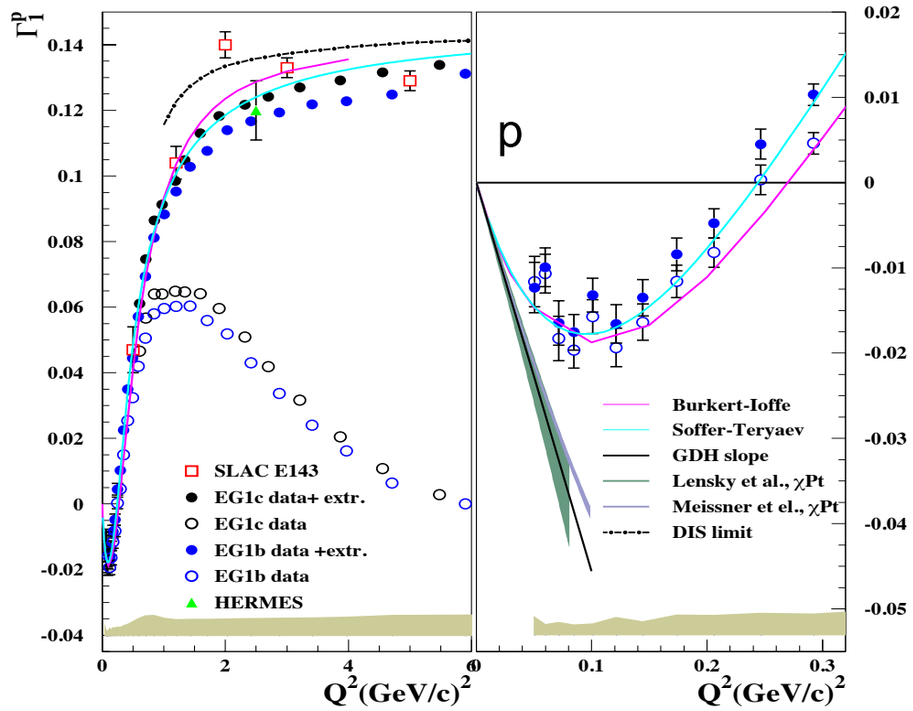
Burkhardt-Cottingham Sum Rule

$$d_2\left(Q^2\right) = 3\int_0^1 x^2 g_2^{HT}\left(x,Q^2\right)dx$$

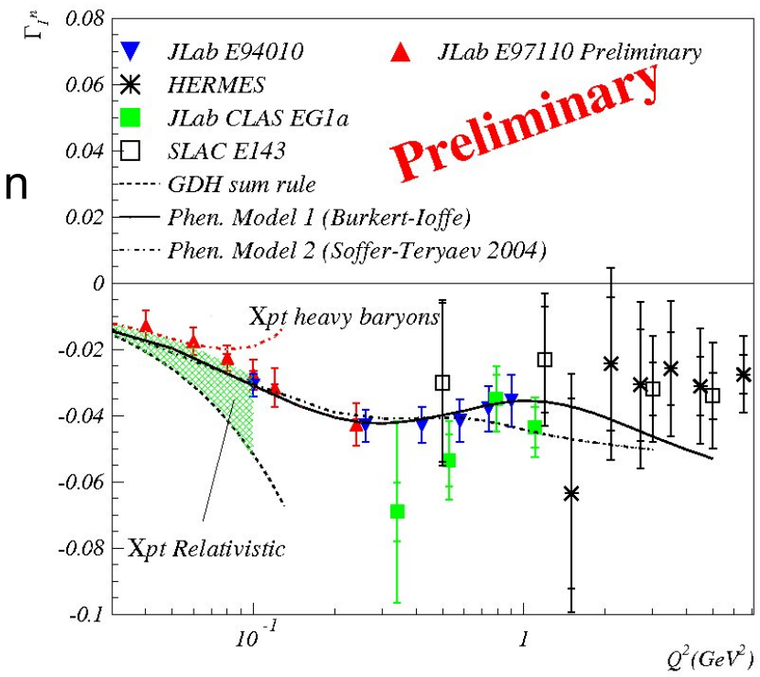
Twist 3 OPE matrix element (color force)

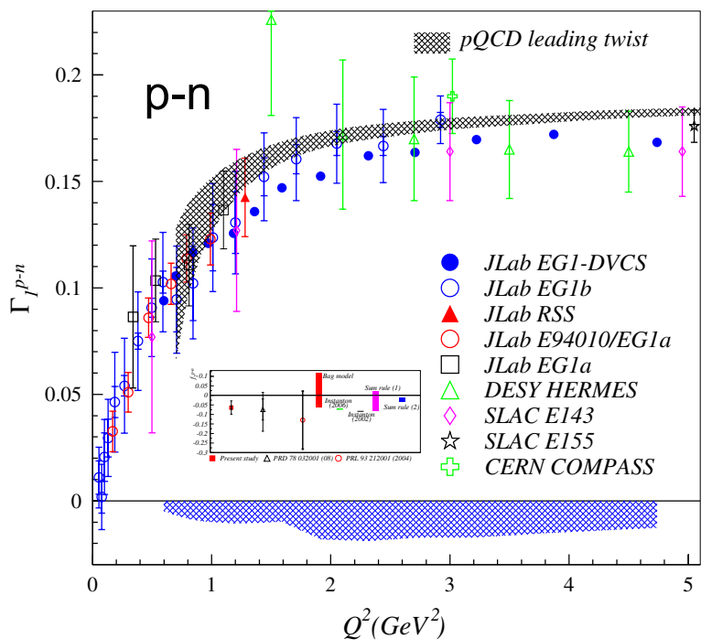
…and γ_0, δ_{LT} (connection to Compton scattering)

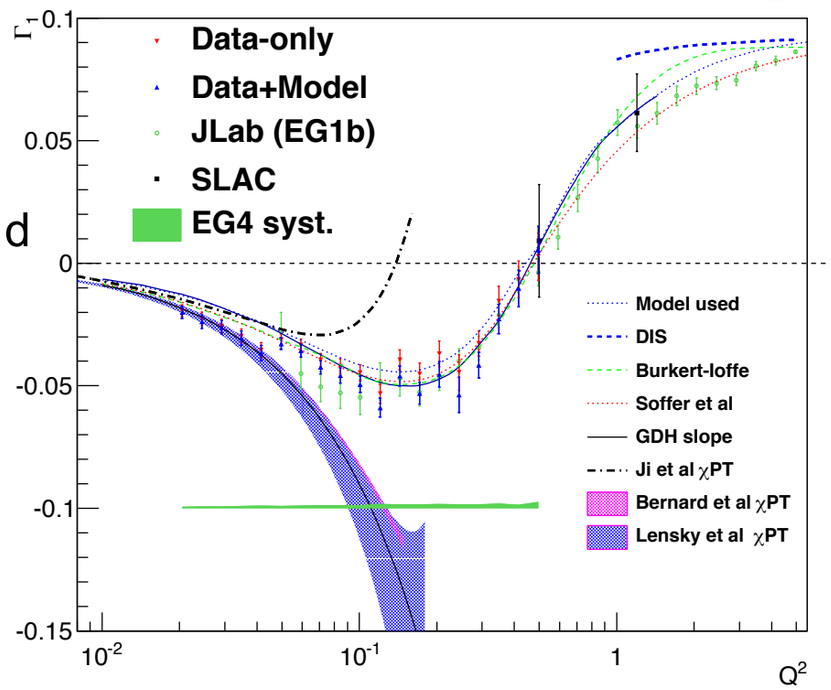



p
SLAC E143
EG1c data+ extr.
EG1c data
EG1b data +extr.
EG1b data
HERMES
Burkert-Ioffe
Soffer-Teryaev
GDH slope
Lensky et al., χPt
Meissner et el., χPt
DIS limit
Q²(GeV/c)²

Γ_1


n
JLab E94010
JLab E97110 Preliminary
HERMES
JLab CLAS EG1a
SLAC E143
GDH sum rule
Phen. Model 1 (Burkert-Ioffe)
Phen. Model 2 (Soffer-Teryaev 2004)
Preliminary
Xpt heavy baryons
Xpt Relativistic
Q²(GeV²)


p-n
pQCD leading twist
JLab EG1-DVCS
JLab EG1b
JLab RSS
JLab E94010/EG1a
JLab EG1a
DESY HERMES
SLAC E143
SLAC E155
CERN COMPASS
Q²(GeV²)


d
Data-only
Data+Model
JLab (EG1b)
SLAC
EG4 syst.
Model used
DIS
Burkert-Ioffe
Soffer et al
GDH slope
Ji et al χPT
Bernard et al χPT
Lensky et al χPT
Q²

Why is g_2 interesting ?

- tests twist-3 effects = quark-gluon correlations.
- d2 matrix element from the HT part of the g2.

$$d_2 = 3\int_0^1 dx x^2 \bar{g}_2(x) = \int_0^1 dx x^2 \left[3g_2(x) + 2g_1(x)\right]$$

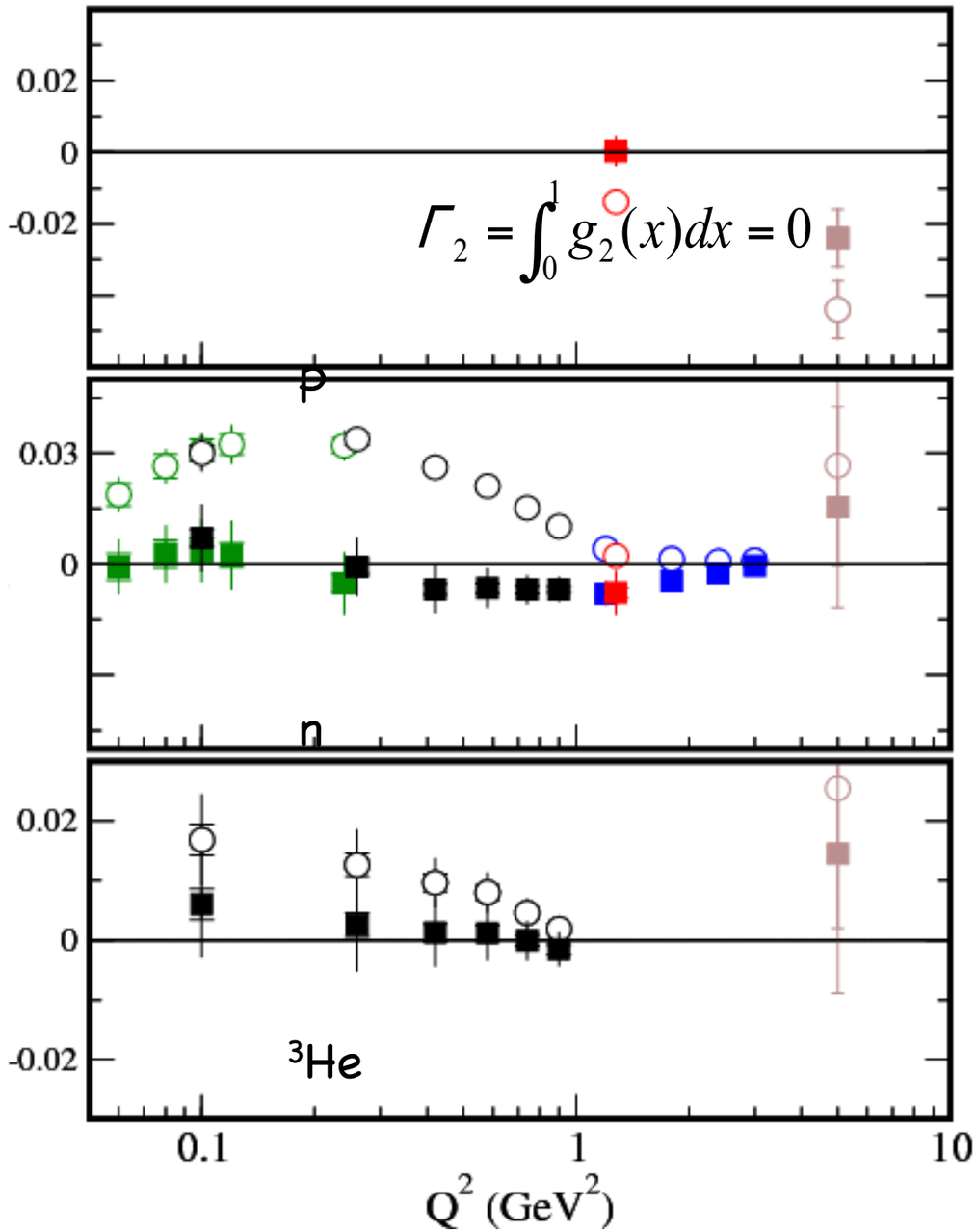
- Test predictions for d_2 from lattice QCD, QCD sum rules and quark models.
- d_2 related to transverse color Lorentz forces on the struck quark (Matthias Burkardt) – "chromodynamic lensing": Phys. Rev. D 88, 114502 (2013).
  - sign of d2 related to sign of transverse deformation (anomalous κ^q)
- polarizabilities of color fields (with twist-4 matrix element f2)

$$F_E = -\frac{M^2}{4}\chi_E = -\frac{M^2}{4}\left[\frac{2}{3}(2d_2 + f_2)\right]$$

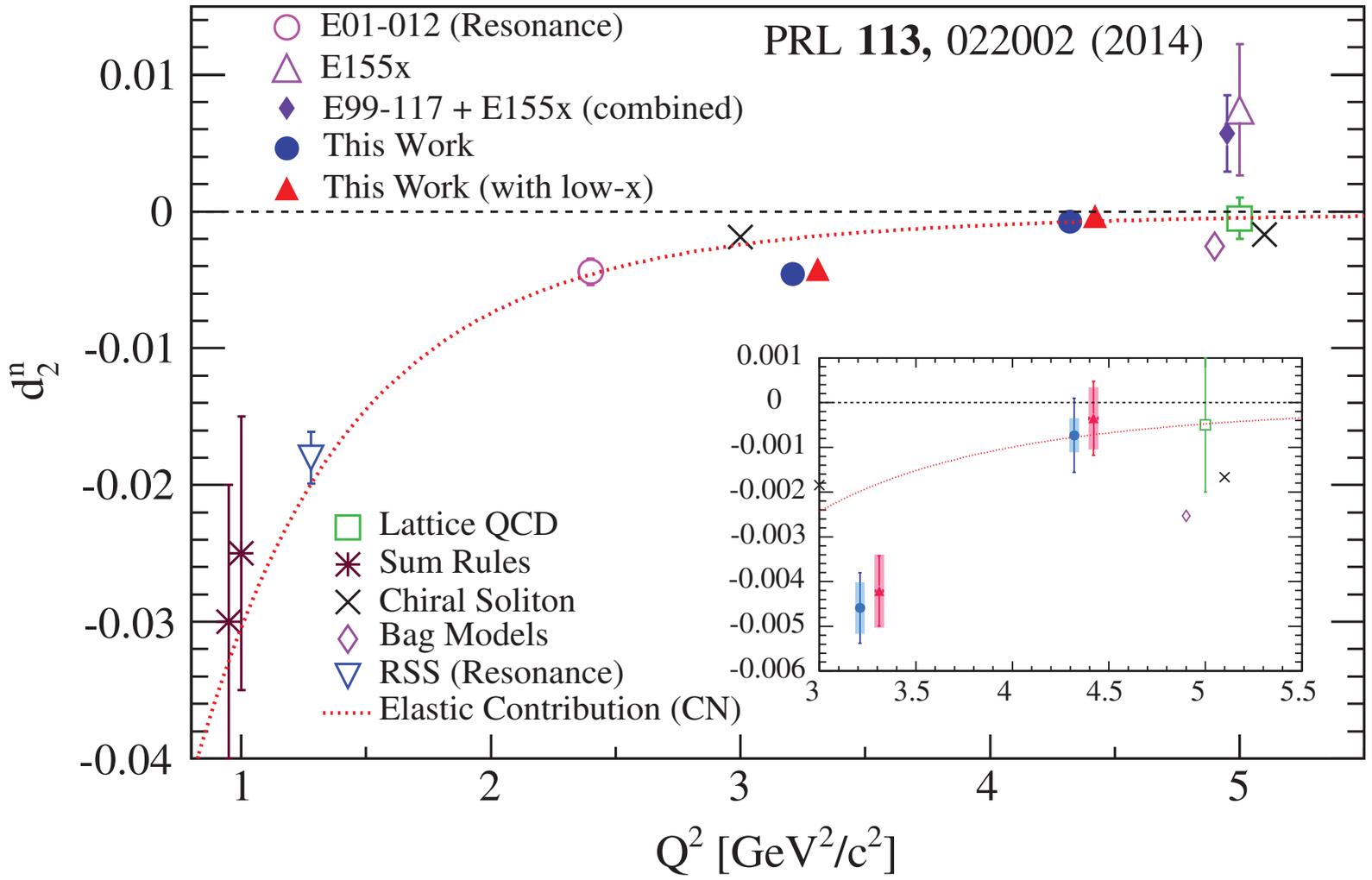
$$F_B = -\frac{M^2}{2}\chi_B = -\frac{M^2}{2}\left[\frac{1}{3}(4d_2 - f_2)\right]$$

Moments of g_2: BC sum rule

SLAC E155x
Hall C RSS
Hall A E94-010
Hall A E97-110 (preliminary)
Hall A E01-012 (preliminary)

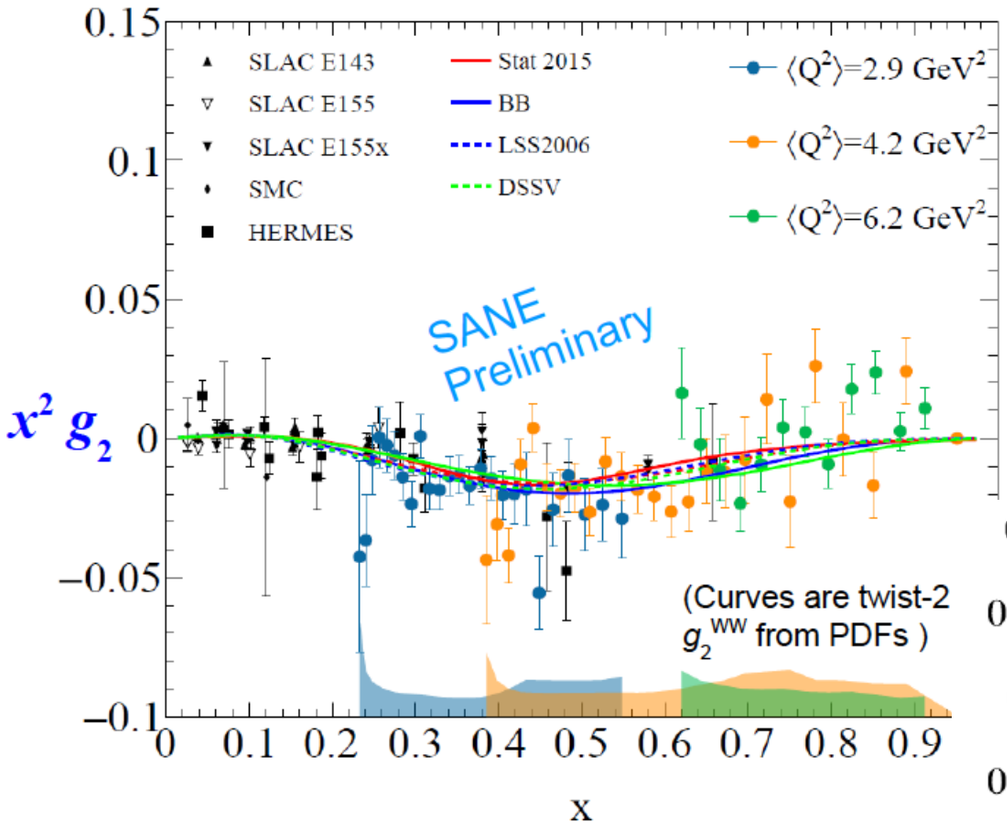


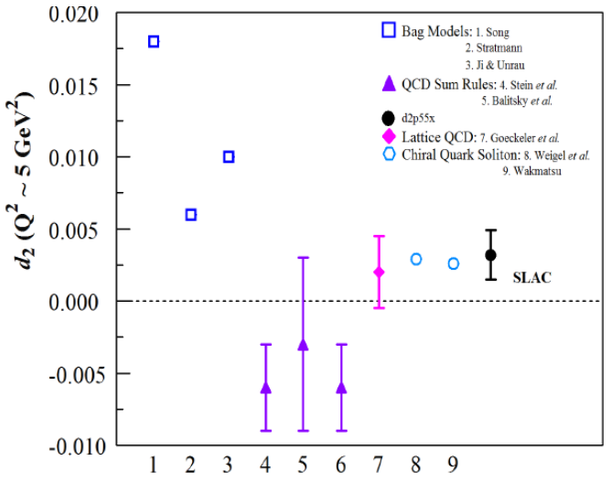
Moments of g_2:d_2^n

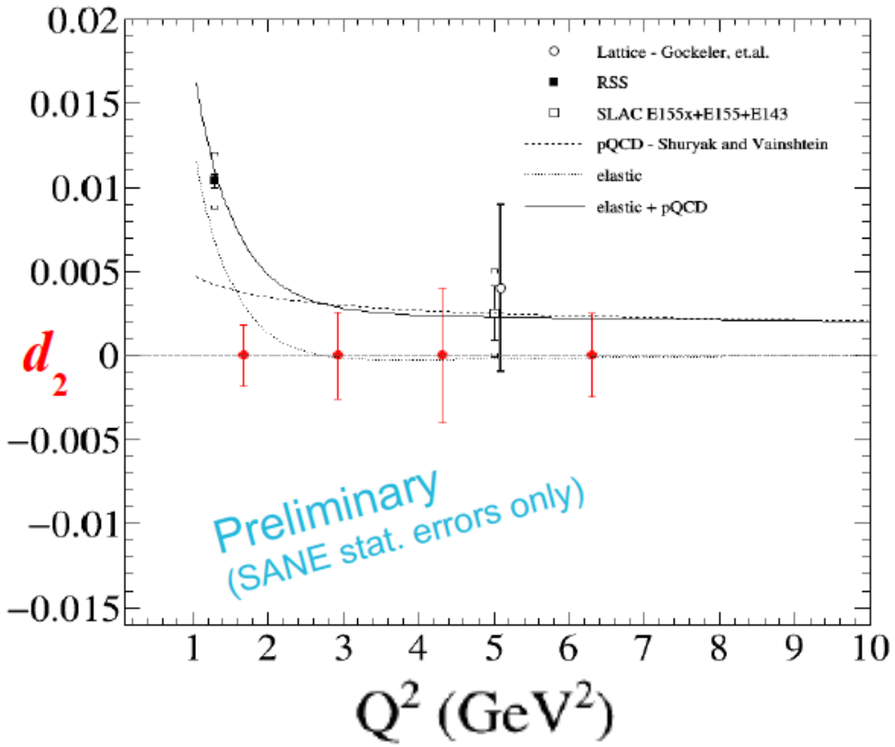


New results from Hall A
Experiment E06-014

Moments of g_2:d_2^p

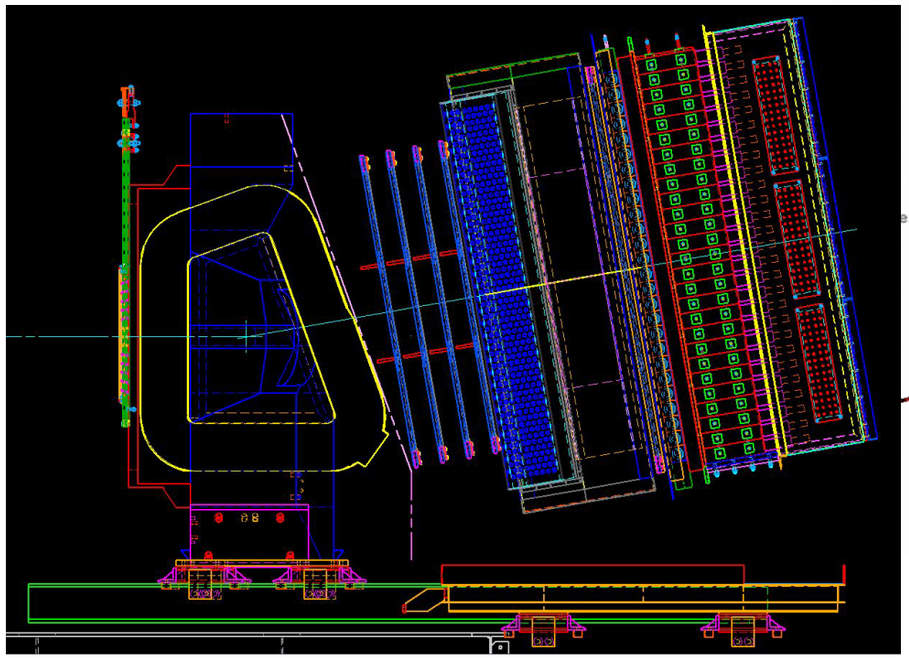




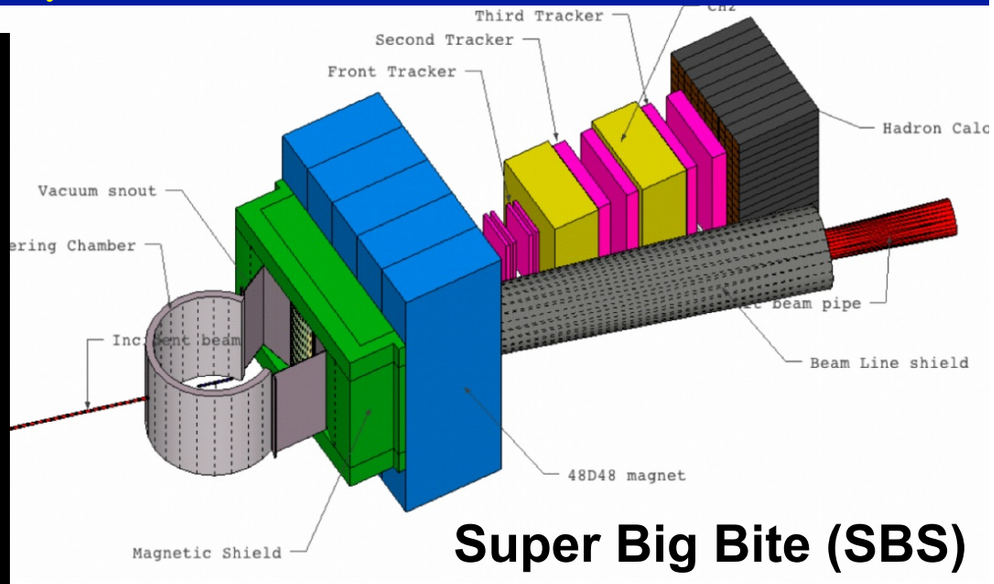


New results from Hall C SANE Experiment

12 GeV: NEW Capabilities - Hall A

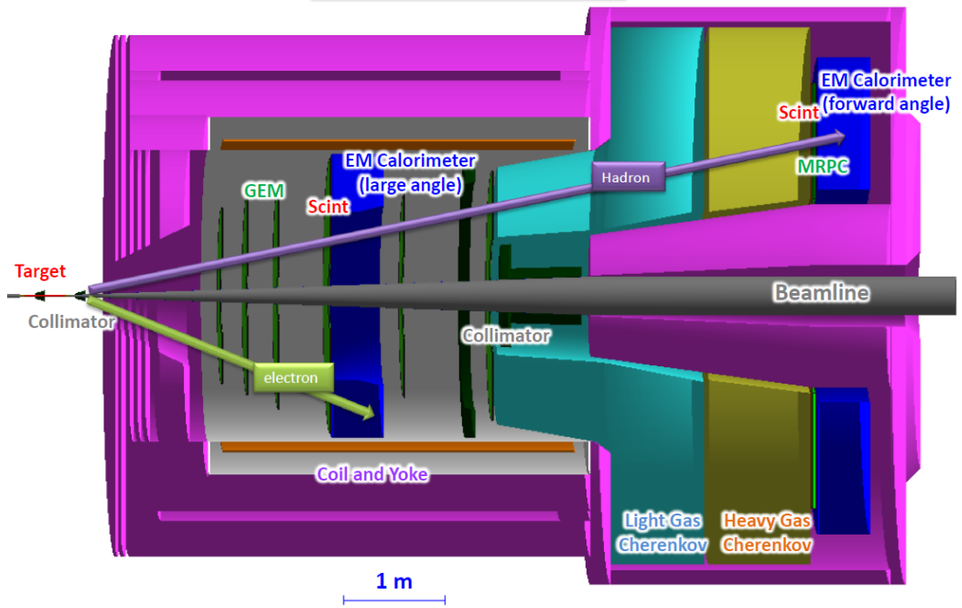


Bigbite with GEM tracker



Super Big Bite (SBS)

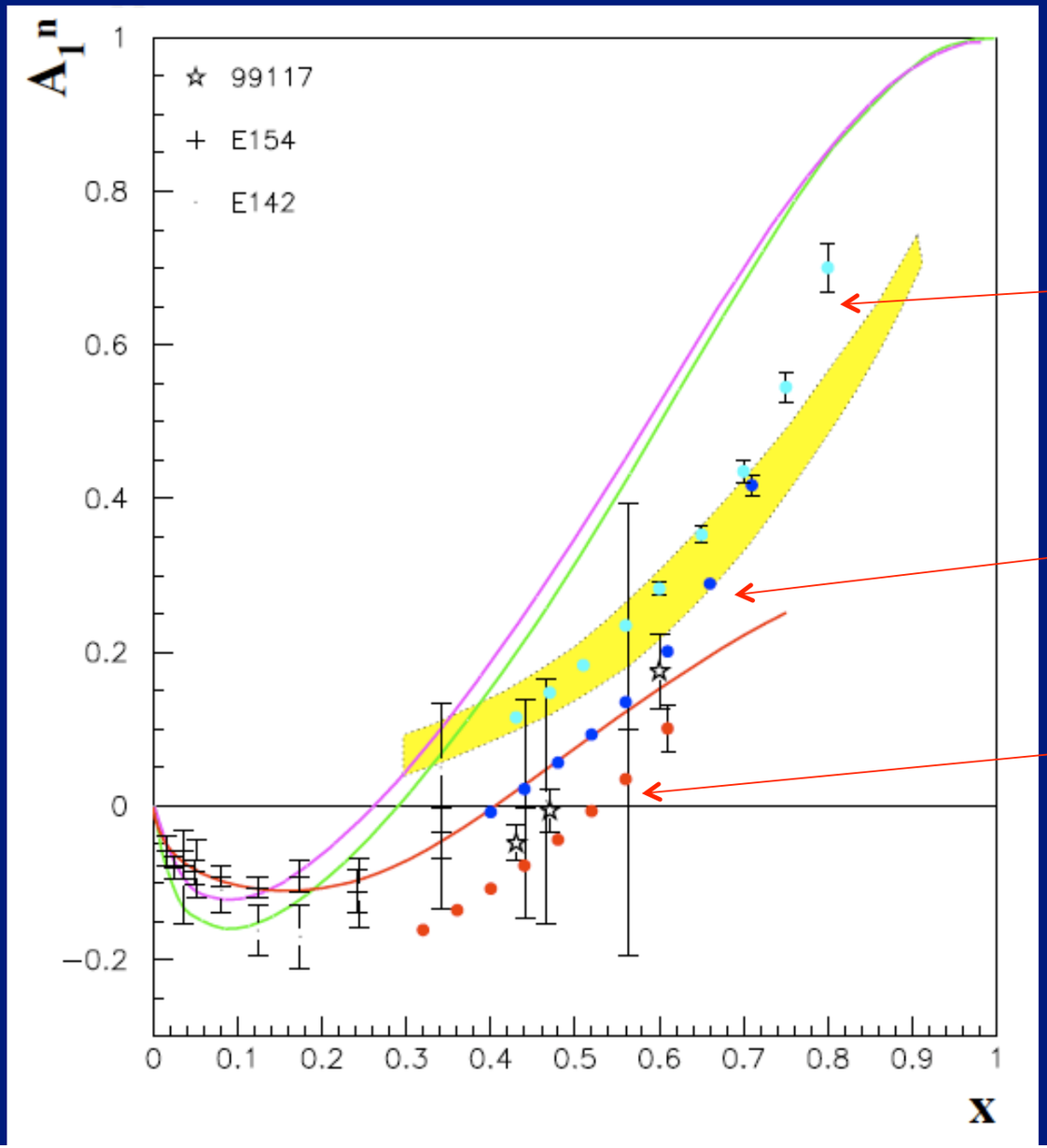
SoLID (SIDIS & J/ψ)



SoLID

- Large acceptance (2π)
- Kinematic coverage out to moderately large P_T
- Capable of quite high luminosity (10^{36} $cm^{-2}s^{-1}$)

Possibilities with Bigbite and Super-Bigbite

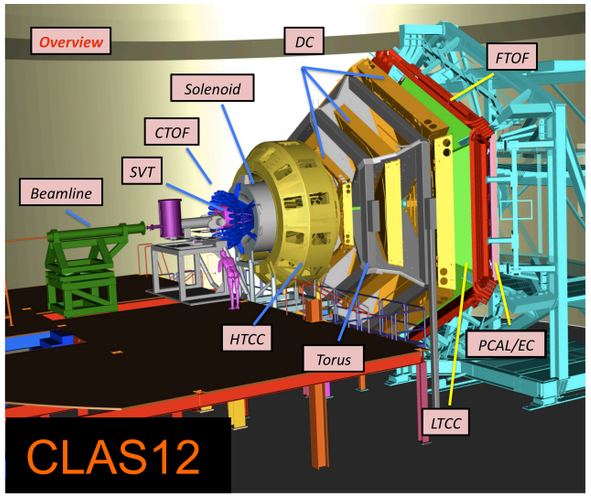


11 GeV, BB and SBS

8.8 GeV, BB only

6.6 GeV, BB only

12 GEV: NEW CAPABILITIES – HALL B



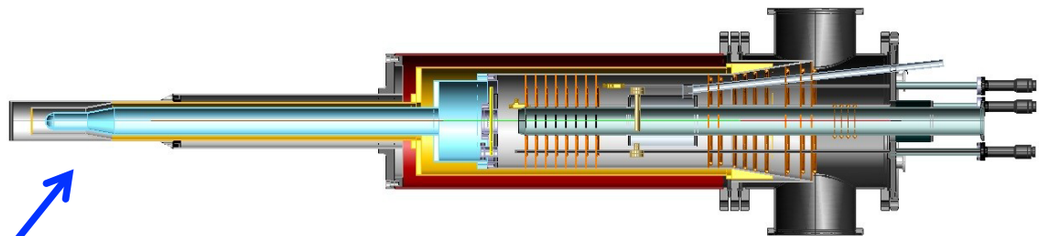
- VERY large acceptance
- Full PID (K and π)
  (K ID requires major new funds for RICH)
- Moderately high luminosity (10^{35} $cm^{-2}s^{-1}$)
  (matched to NH_3, ND_3)

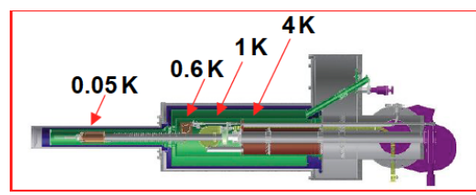
Polarized Targets

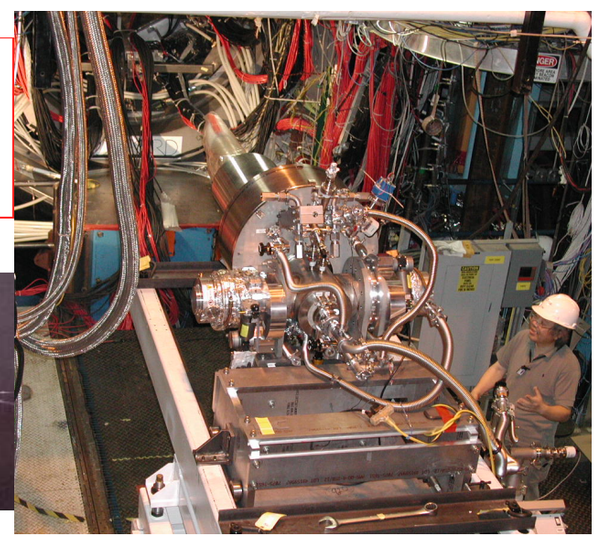
- Standard DNP longitudinal NH_3, ND_3 targets
  (funded by NSF MRI, under construction)
- HD-Ice target
  (suitability for e^- beam remains to be demonstrated)

Future longitudinally polarized target for CLAS12 (11 GeV program at Jefferson Lab)

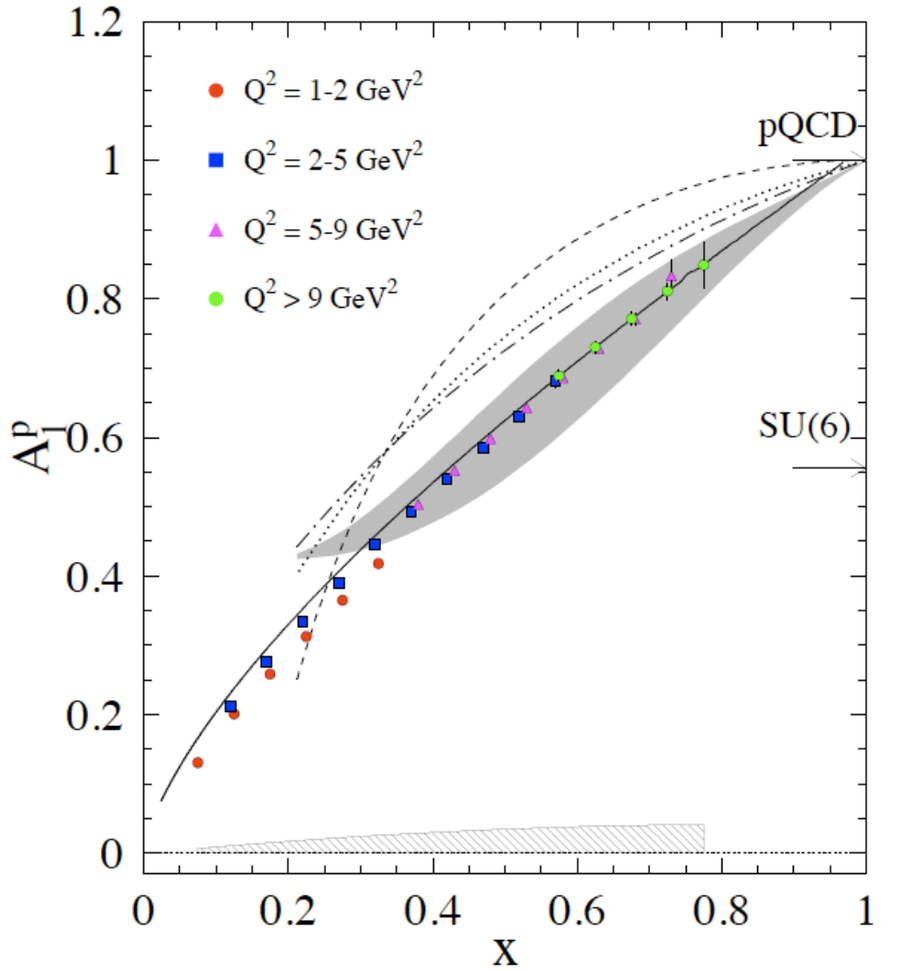
- Horizontal ^{4}He evaporation cryostat
- 5 T B-field provided by central detector

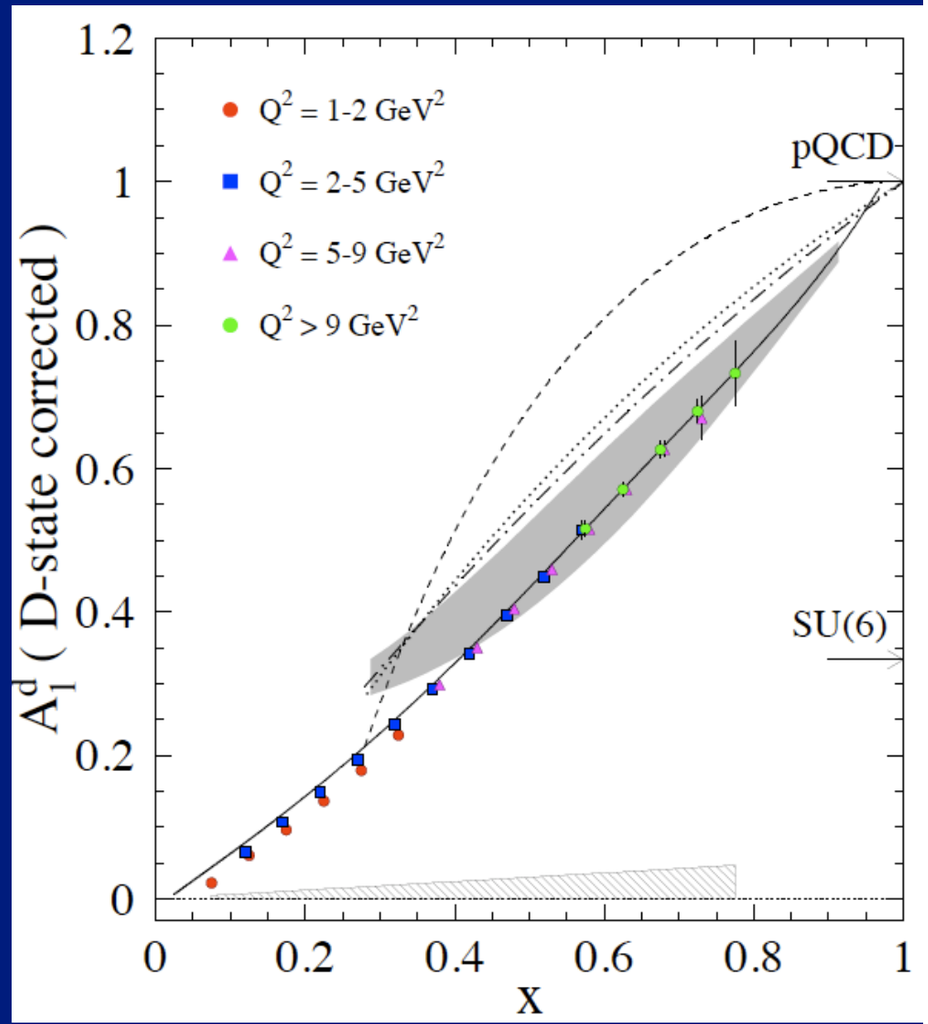




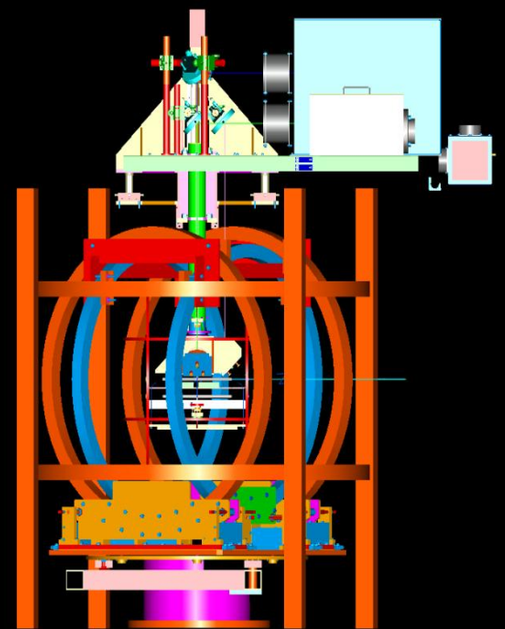


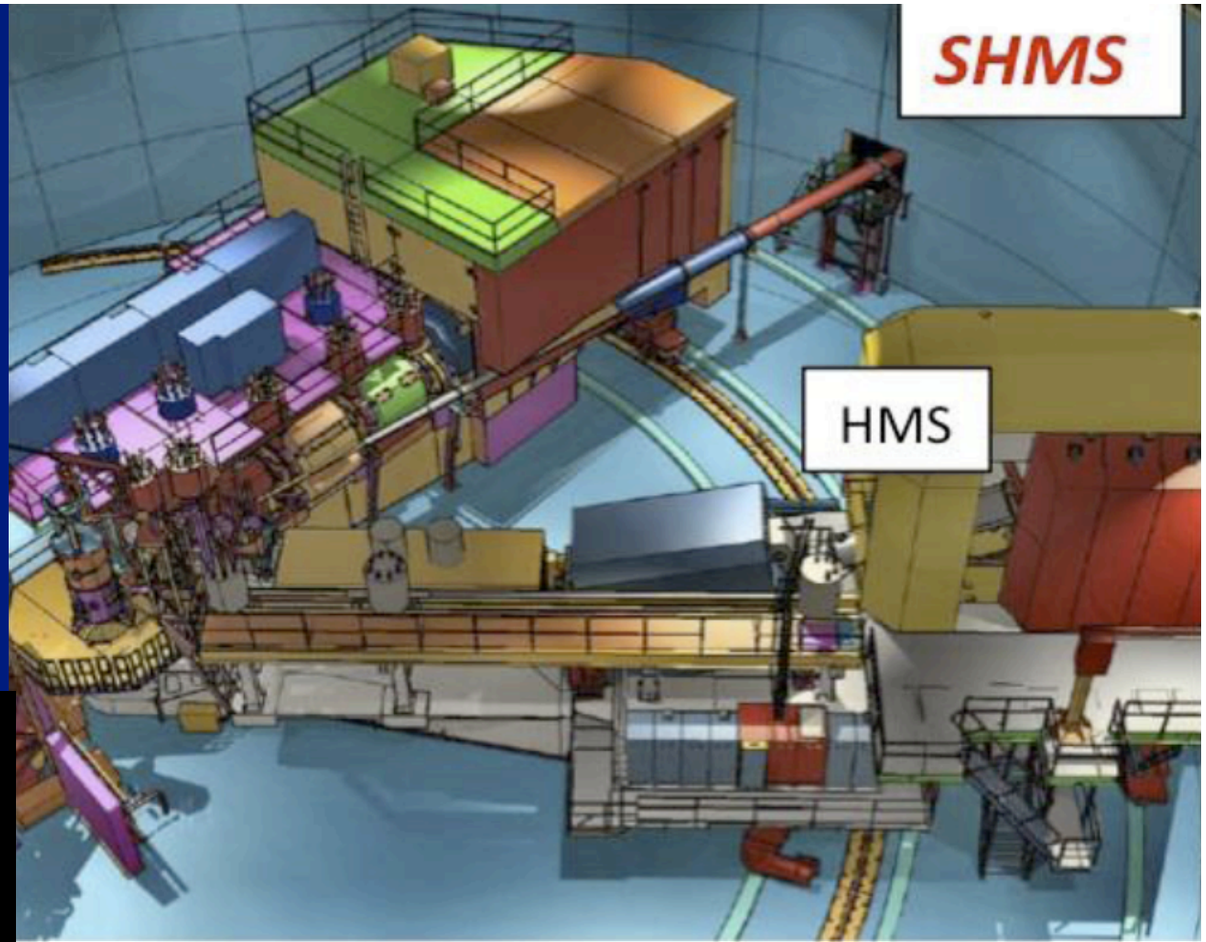
Hall B experiment E12-06-109: A_1^p and A_1^d





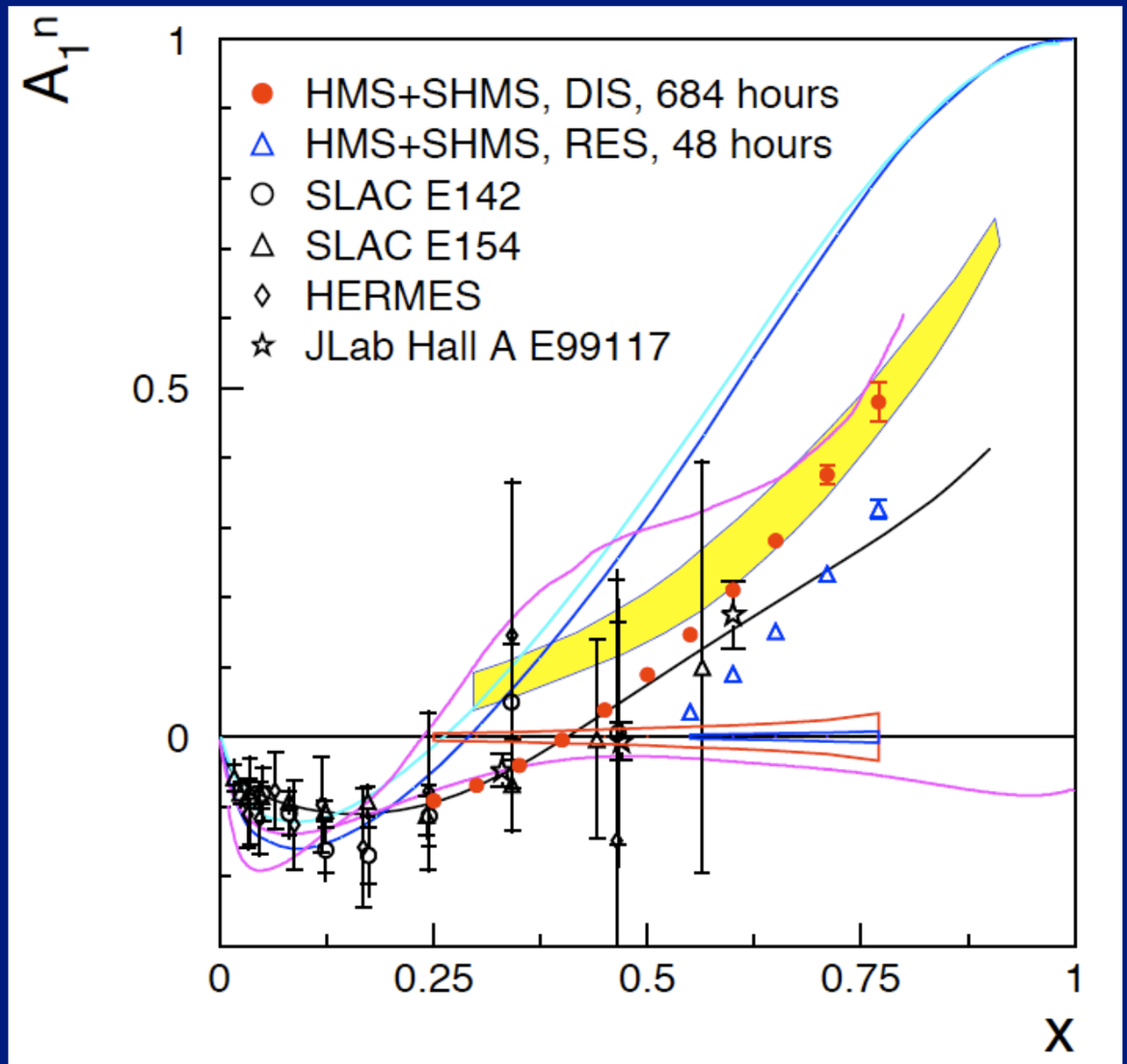
Hall C experiment E12-06-110: A_1^n

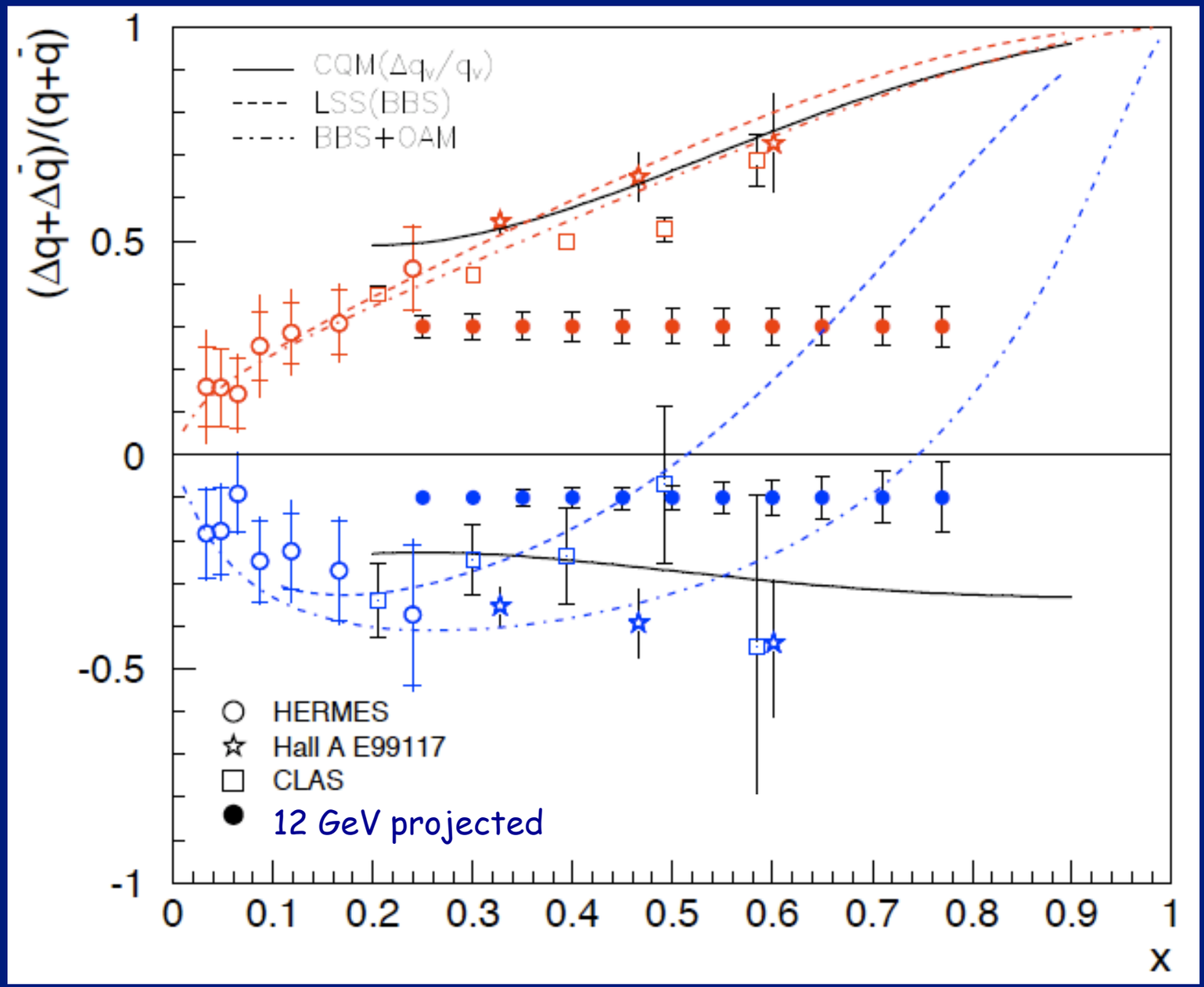




- SHMS + HMS pair
- 60 μA, ~ 90% polarized 11 GeV beam
- Polarized 3He target
  - 60% polarization
- 850 hours (35 days) of data

Hall C experiment E12-06-110: A_1^n




$(\Delta q+\Delta\bar{q})/(q+\bar{q})$
CQM($\Delta q_v/q_v$)
LSS(BBS)
BBS+OAM
HERMES
Hall A E99117
CLAS
12 GeV projected
1
0.5
0
-0.5
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x

Summary

- Jefferson lab polarized beam combined with high luminosity polarized targets and large acceptance spectrometers in halls A, B and C provides a unique opportunity to probe nucleon spin structure in the valence region with unprecedented precision.
  - recent results on A_1, A_2, g_1, g_2 for proton and neutron
  - $\Delta u/u$, $\Delta d/d$
  - crucial steps in understanding valence nucleon structure
  - New results on g2 and d2 for both neutron and proton
- Much more to expect with 12 GeV