Spin Asymmetries of the Nucleon Experiment

SANE Results

Virtual Hall C Collaboration Meeting

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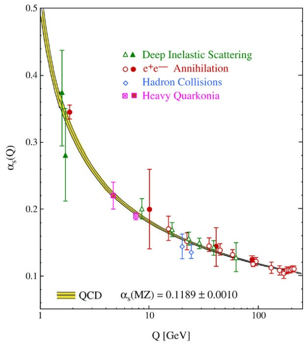
Argonne NATIONAL LABORATORY

The Strong Force

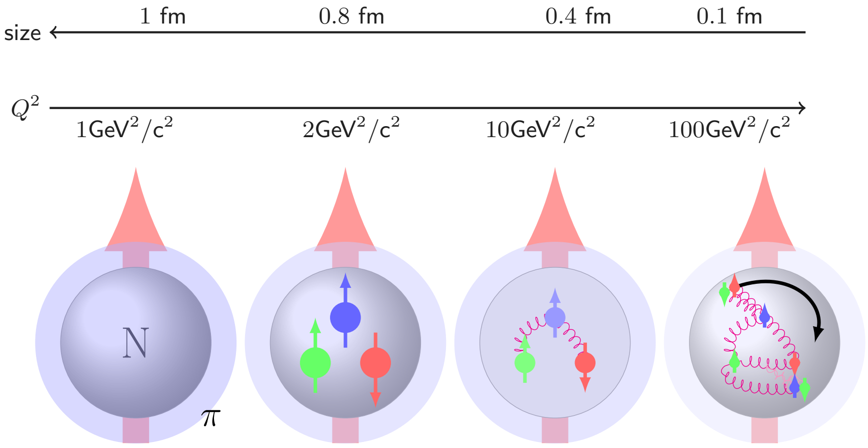
Quantum Chromodynamics

- $L_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$
- The degrees of freedom are the QCD quark and gluon fields, **not the constituent quarks!**
- The QCD coupling constant α_s is a function of Q^2.
- Asymptotic freedom $\rightarrow$ 2004 Nobel prize (Gross,Wilczek,Politzer)
- Many successful predictions from pQCD at high energies.



QCD is believed to be the correct theory of the strong force.
QCD should be able to describe the structure of the proton and neutron.
However, perturbative techniques cannot describe the complex bound state of quark and gluon fields composing the proton.

What does the nucleon look like?



Use our understanding of pQCD at high Q^2 to begin to test our understanding at lower Q^2 $\rightarrow$ Operator Product Expansion

Deep Inelastic Scattering

$$\sigma_0 = \frac{4\alpha^2 E'^2}{q^4}\left[\frac{2}{M}F_1 \sin^2(\theta/2) + \frac{1}{\nu}F_2 \cos^2(\theta/2)\right]$$

$$2\sigma_0 A_{\parallel} = -\frac{4\alpha^2}{Q^2}\frac{E'}{E}\left[\frac{E+E'\cos\theta}{M\nu}g_1 - \frac{Q^2}{M\nu^2}g_2\right]$$

$$2\sigma_0 A_{\perp} = -\frac{4\alpha^2}{MQ^2}\frac{E'^2}{E}\sin\theta\cos\phi\left[\frac{1}{M\nu}g_1 + \frac{2E}{M\nu^2}g_2\right]$$

Structure Functions

$$F_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\; q_i(x,Q^2)$$

$$F_2(x,Q^2) = 2xF_1(x,Q^2)$$

$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\; \Delta q_i(x,Q^2)$$

$$g_2(x,Q^2) = ?$$

Asymmetries

$$A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$

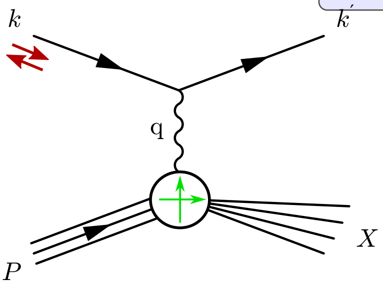
$$A_{\perp} = \frac{\sigma^{\Leftarrow\downarrow} - \sigma^{\Leftarrow\uparrow}}{\sigma^{\Leftarrow\downarrow} + \sigma^{\Leftarrow\uparrow}}$$

$$x = Q^2/(2M\nu)$$

$$\nu = E - E'$$

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

$$Q^2 = -q^2 = 4EE'\sin^2(\theta/2)$$



Why is a transversely polarized target needed?

$$A_{\parallel} \propto g_1 - \frac{2Mx}{\nu}g_2$$

→ g_2 suppressed by $1/\nu$

$$A_{\perp} \propto g_1 + g_2$$

→ In DIS region both contribute.

⇒ $A_{\perp}$ directly sensitive to non-perturbative effects!

The dynamical twist-3 matrix element: d_2

$$\int_0^1 dx x^{n-1}\{g_1 + \frac{n}{n-1} g_2\} = \frac{1}{2} d_{n-1} E_2^n(Q^2, g)$$

For $n = 3$

$$\int_0^1 x^2\{2g_1 + 3g_2\}dx = d_2$$

Interpretations of d_2

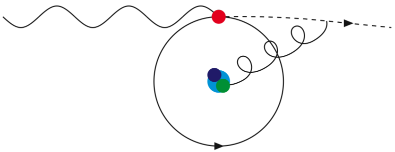
- Color Polarizabilities (X.Ji 95, E. Stein et al. 95)
- **Average Color Lorentz force** (M.Burkardt)

M. Burkardt Phys.Rev.D 88,114502 (2013) and Nucl.Phys.A 735,185 (2004).

$$d_2 = \frac{1}{2MP^{+^2}S^x}\langle P, S \mid \bar{q}(0)gG^{+y}(0)\gamma^+ q(0) \mid P, S\rangle$$

but with $\vec{v} = -c\hat{z}$

$$\sqrt{2}G^{+y} = -E^y + B^x = -(\vec{E} + \vec{v} \times \vec{B})^y$$

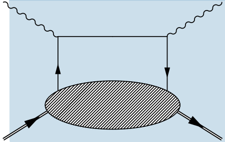


$d_2 \Rightarrow$ average color Lorentz force acting on quark moving backwards (since we are in inf. mom. frame) the instant after being struck by the virtual photon.

$\langle F^y \rangle = -2M^2 d_2$

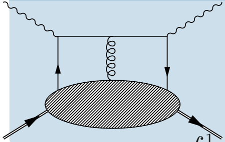
Quark-gluon Correlations : $g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$

Twist-2 (Wandzura, Wilczek, 1977)



$$g_2^{WW}(x,Q^2) = -g_1^{LT}(x,Q^2) + \int_x^1 g_1^{LT}(y,Q^2)\mathrm{d}y/y$$
$$\equiv g_2^{tw2}(x,Q^2)$$

Twist-3 (Cortes, Pire, Ralston, 1992)

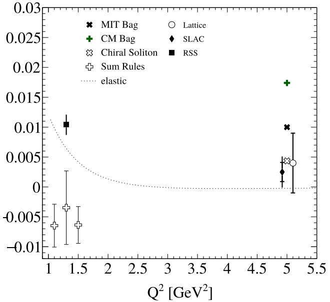


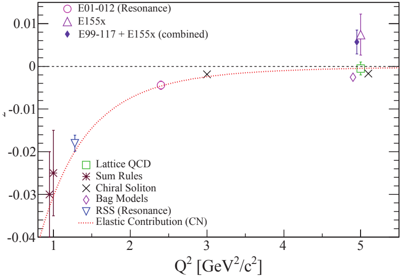
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$
$$\equiv g_2^{tw3}(x,Q^2)$$

$$d_2(Q^2) = 3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$
$$= \int_0^1 x^2(2g_1(x,Q^2) + 3g_2(x,Q^2))dx$$

As Q^2 decreases,
when do higher twists begin to matter?
When is the color force non-zero?

Predictions and previous measurements of d_2





Lattice QCD

- Ab initio calculations can be done on the lattice
- Existing d_2 lattice results in the quenched approximation (PRD.63.074506)
- Proton results agree with SLAC but neutron results do not.
- Updated and improved lattice results long overdue

Physics with g_2

- Polarized DIS is uniquely poised to provide insight into quark-gluon correlations.
- Direct access to higher twist using transversely polarized target.
- Twist-3 matrix element d_2^p proprotional to an average Lorentz color force.
- Ab initio QCD calculations from the lattice are tested (and modern calculations needed!)
- $\bar{g}_2$ and d_2 connected to quark OAM (PRD 98 (2018) no.7, 074022)
- JLab provides best opportunity to explore valence region

Precision measurments of g_1 and g_2 at JLab provide great insight into the non-perturbative structure of the nucleon and test our understanding of QCD

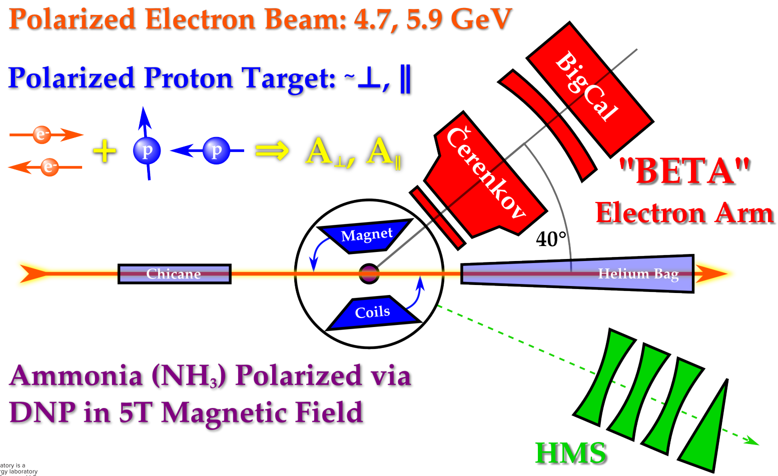
Important starting point for Nucleon Tomography

- Extraction of $\bar{g}_2$ is clean (free of non-local effects, fragmentation functions).
- Higher twist distribution $\bar{g}_2$ provides important boundary condition for HT GPDs
- Quark OAM calculated from Higher twist GPDs
- First point in Qui-Sterman M.E. found in SIDIS

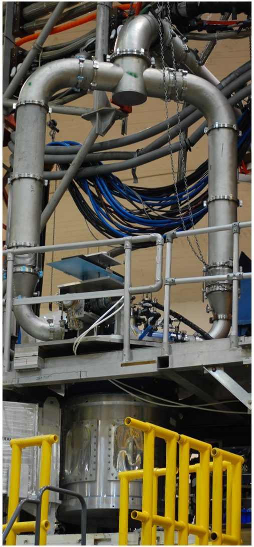
E07-003 : Spin Asymmetries of the Nucleon Experiment

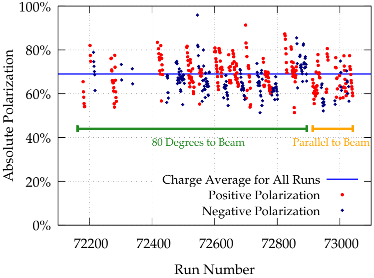
Spokespeople

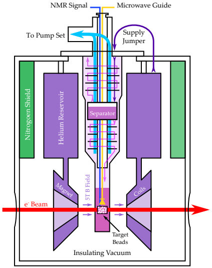
S. Choi, M. Jones, Z.-E. Meziani, O.A. Rondon



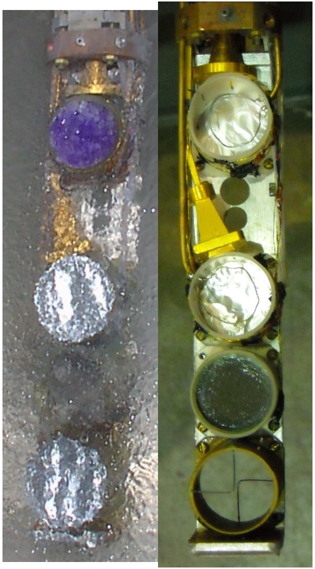
E07-003 : Polarized Ammonia Target



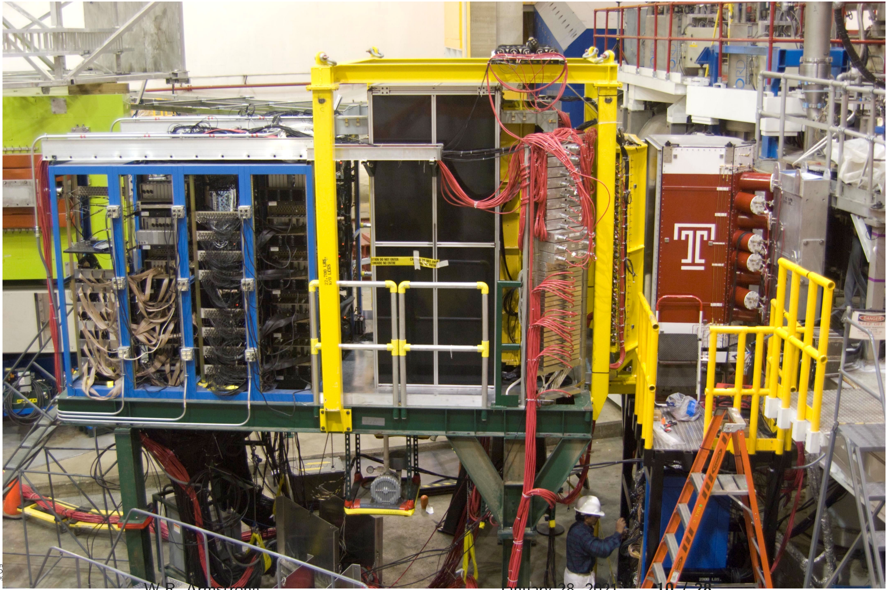




- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%



Big Electron Telescope Array



BigCal

Two Sections

The upper section from Yerevan Physics Institute used during RCS experiment.

- It consists of $4 \times 4 \times 40cm^3$ lead-glass blocks
- They are arranged in a 30×24 array

Lower section from IHEP in Protvino, Russia.

- It consists of $3.8 \times 3.8 \times 45cm^3$ lead-glass blocks
- They are arranged in 32×32 array

1,744 lead glass blocks total.

Figure : Bigcal lead-glass blocks

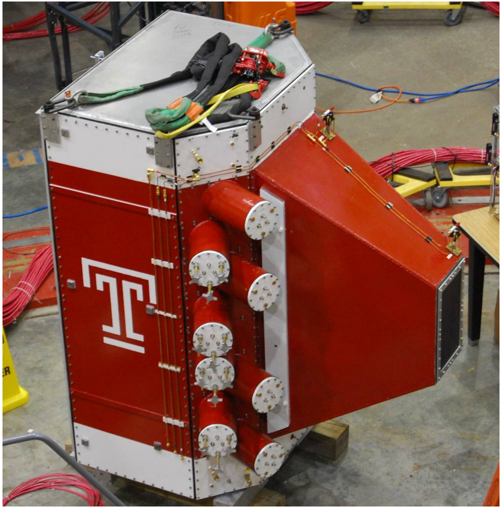
Bigcal was previously used in the GEp series of experiments

SANE Gas Cherenkov

Gas Cherenkov from Temple University.

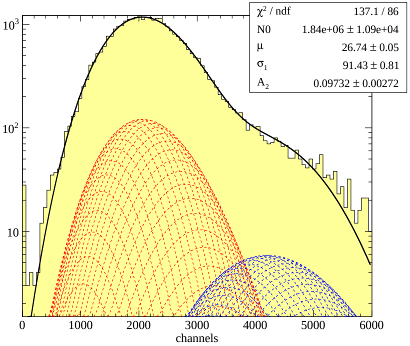
Design

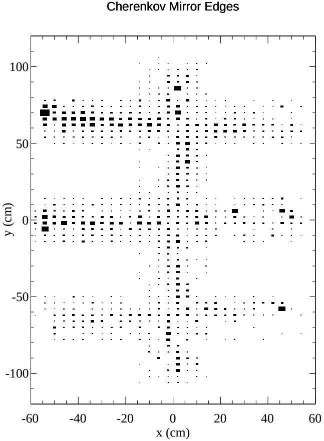
- Filled with nitrogen gas at atmosphere.
- Uses 4 spherical and 4 toroidal mirrors to focus light to photomultiplier tubes.
- Used 3 inch quartz window Photonis PMTs for UV transparency
- Mirror blanks were sent to CERN for special coating for high reflectivity far into the UV.

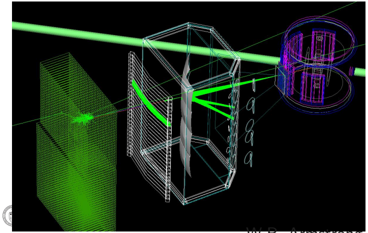


Gas Cherenkov on Hall C floor

Cherenkov ADCs





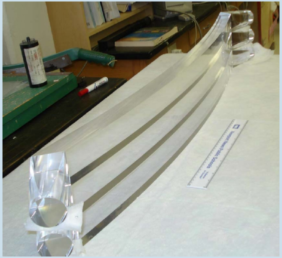


Lucite Hodoscope

Lucite Hodoscope is from North Carolina A&T State University.

Design

- 28 curved Lucite bars with light guides mounted to edges cut at 45°
- PMT with light guide mounted at both ends of each bar.



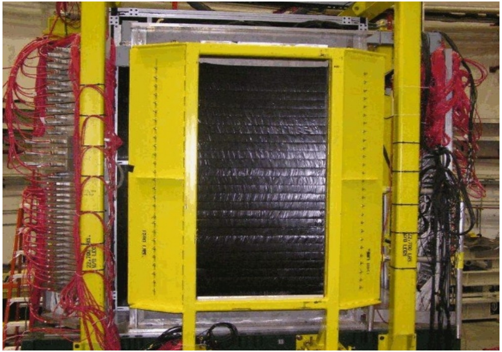


Figure : Lucite Hodoscope in Hall C

Forward Tracker

Forward tracker is from Norfolk State University and University of Regina

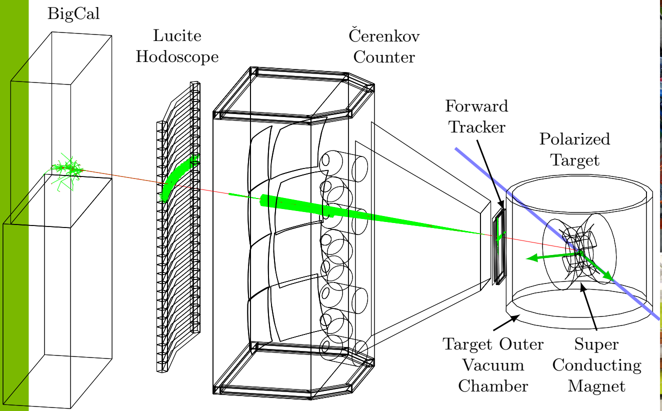
Design

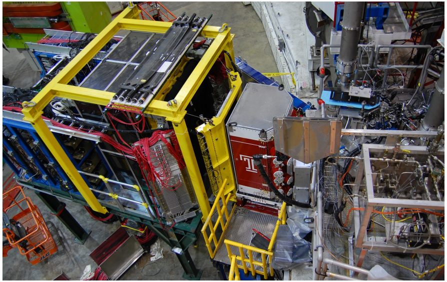
- 3 layers of 3×3 mm^2 scintillators.
- 1 horizontally segmented layer closest to the target consisting of 72 segments
- 2 vertically segmented layers consisting of 128 segments each
- WLS fibers glued to each bar with fibers connected to Hamamatsu 64-Channel PMTs

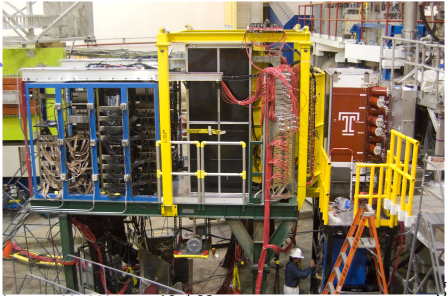
Forward tracker was not used in any analysis.

Forward tracker in position between Cherenkov snout and target OVC

E07-003 : **B**ig **E**lectron **T**elescope **A**rray

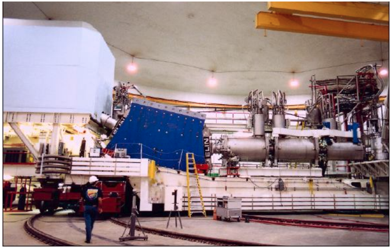


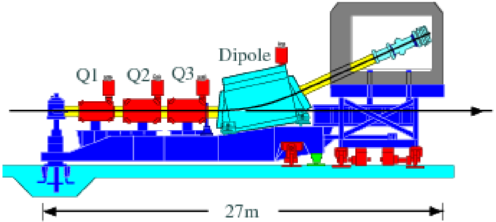


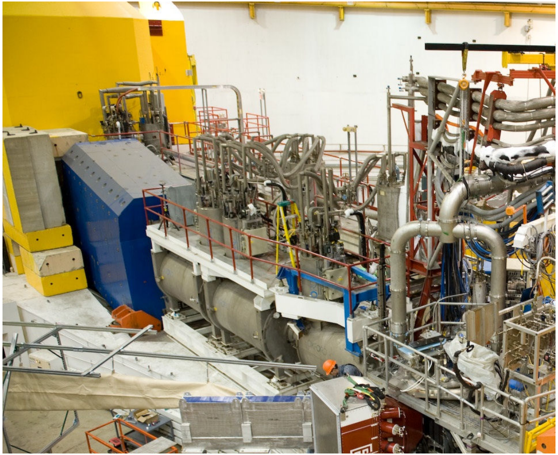


E07-003 : Spin Asymmetries of the Nucleon Experiment

HMS data taken as well for resonance spin structure (Hoyoung Kang) and G_E/G_M (Anusha Liyanage)

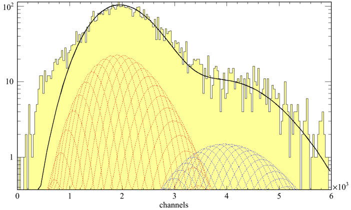


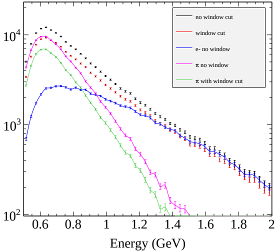


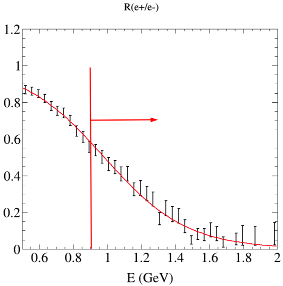


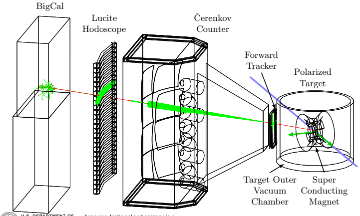
Pair Symmetric Background

- End-to-end full simulation of BETA spectrometer developed
- Pairs produced at target look like DIS events (one charged particle in BETA)
- Pairs produced outside the target travel in a straight line → **doubles Cherenkov signal**



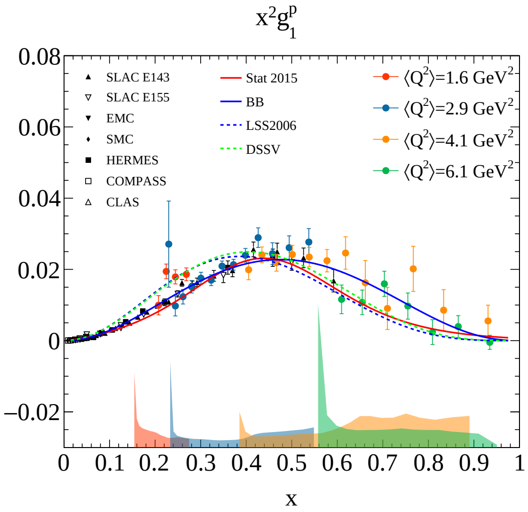


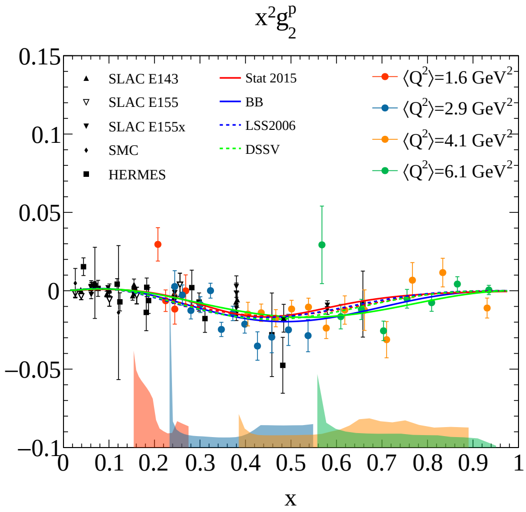




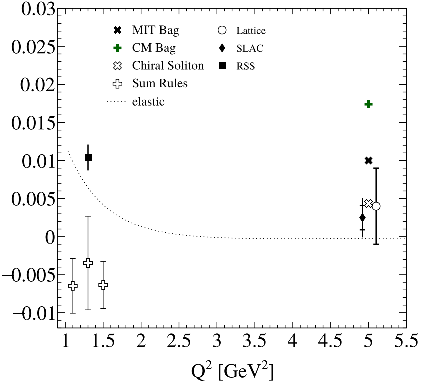
Cherenkov ADC window cut allows for a lower minimum energy cut → **larger x coverage**

SANE results for $x^2 g_1^p$ and $x^2 g_2^p$

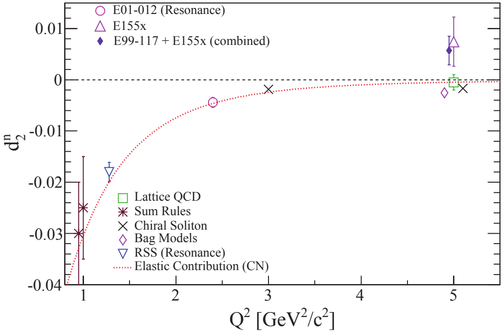




proton



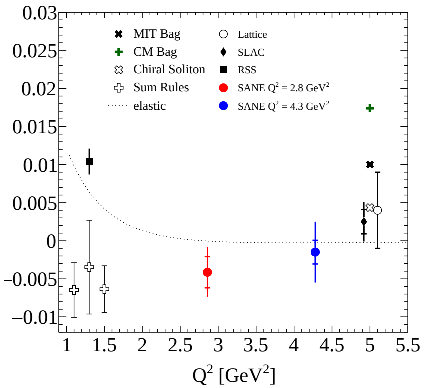
neutron



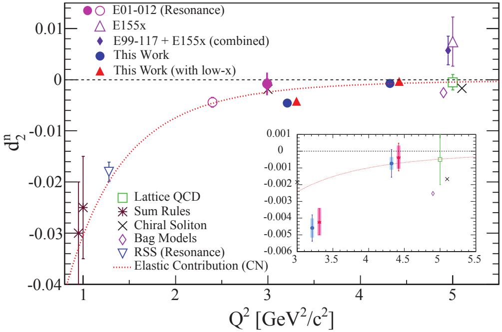
Existing data

- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
- Is this an isospin independent average color force?

proton



neutron



Neutron from d_2^n experiment: M.Posik, et.al. PRL.113(2014) and D.Flay, et.al. PRD.94(2016)no.5,052003

SANE and d_2^n Result

- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
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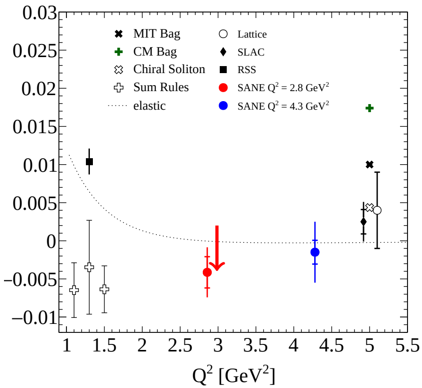
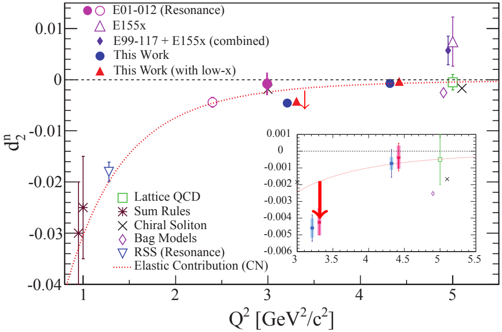
proton



neutron



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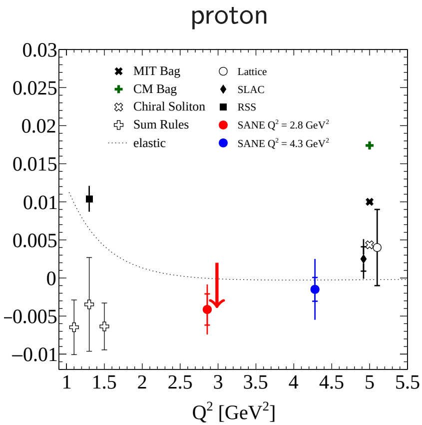
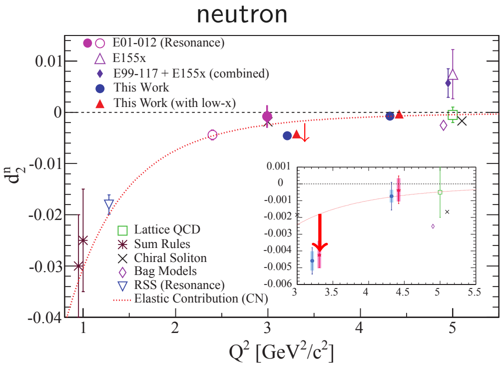




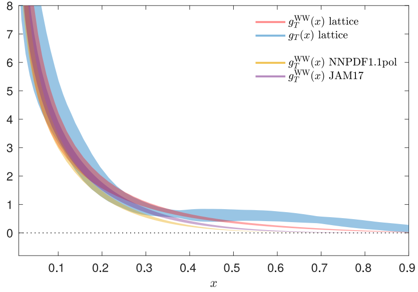
Neutron from d_2^n experiment: M.Posik, et.al. PRL.113(2014) and D.Flay, et.al. PRD.94(2016)no.5,052003

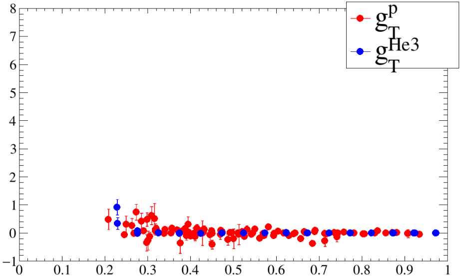
SANE and d_2^n Result

- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
- Is this an isospin independent average color force?
- Lattice calculations are making progress!

Recent Lattice Calculations

First calculation of twist-3 distribution from lattice.



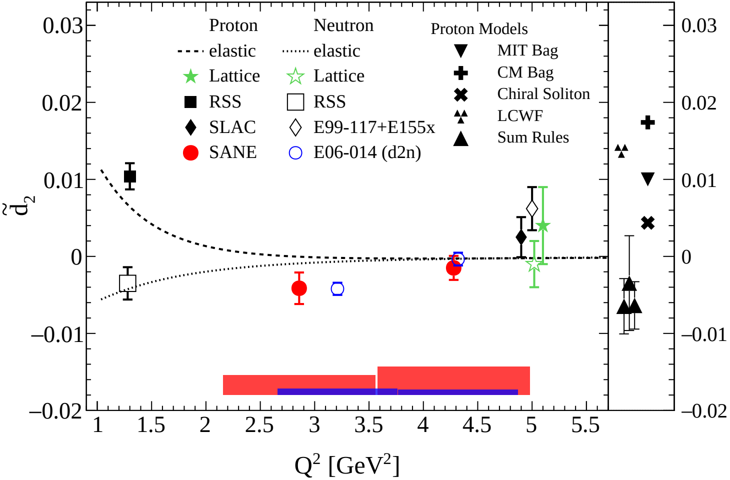


Constantinou, et.al., Phys.Rev.D 102 (2020)

- Results for g_T SANE and d2n.
- Lattice results compute g_T^{p-n}
- Lattice uncertainties are rather large compared to experimental errors at high-x

d_2^p Results

PRL 122, 022002 (2019)



SANE Publications and Manuscripts

- A. Liyanage, et.al., *Proton form factor ratio $\mu G_E^p / G_M^p$ from double spin asymmetry* Phys.Rev.C 101 (2020) 3, 035206
- W.R. Armstrong, et.al., *Revealing Color Forces with Transverse Polarized Electron Scattering*, PRL 122, 022002 (2019)

Instrumentation Papers:

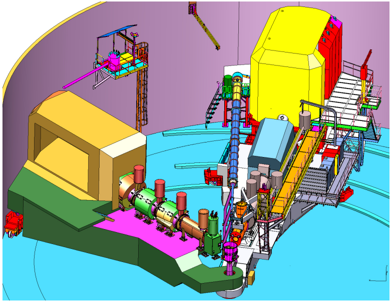
- J.D. Maxwell, et.al., *Design and Performance of the Spin Asymmetries of the Nucleon Experiment* Nucl.Instrum.Meth. A885 (2018) 145-159
- W.R. Armstrong, et.al., *A threshold gas Cherenkov detector for the Spin Asymmetries of the Nucleon Experiment* Nucl.Instrum.Meth. A804 (2015) 118-126

In preparation

- Resonance spin structure functions
- A_1 at large x

JLab at 12 GeV

- JLab 12GeV neutron experiments (Hall C and Hall A) will extend to higher Q^2 with more uniform coverage.
- A dedicated experiment with transversely polarized proton target is worthwhile effort at 12 GeV.
- Proposal to match the expected neutron precision, possible options: Hall C, SOLID, CLAS12
- High x and high Q^2 data on g_1 **and** g_2 is needed to **cleanly** extract the leading twist PDFs $\rightarrow$ At present many fits use data down to $Q^2 = 1\text{GeV}^2$!



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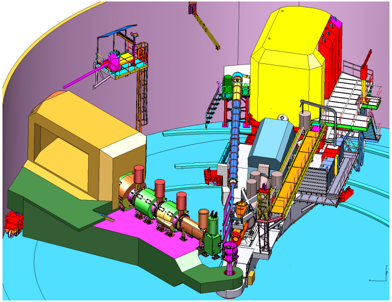
- A dedicated experiment with transversely polarized proton target is worthwhile effort at 12 GeV.
- Proposal to match the expected neutron precision, possible options: Hall C, SOLID, CLAS12
- High x and high Q^2 data on g_1 **and** g_2 is needed to **cleanly** extract the leading twist PDFs $\rightarrow$ At present many fits use data down to $Q^2 = 1\text{GeV}^2$!



SANE 2 $\rightarrow$ insane

A new proposal in Hall C for PAC.

- Need to confirm puzzling scale dependence of $\tilde{d}_2^p$
- Better kinematic coverage at 12 GeV with SHMS (and HMS, BETA?)
- Precision measurements will compliment SoLID program
- NH3 target technology has limitations (large dilution) and has magnet configuration challenges

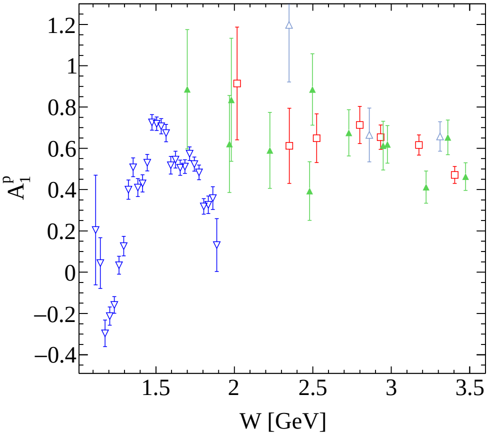
Summary

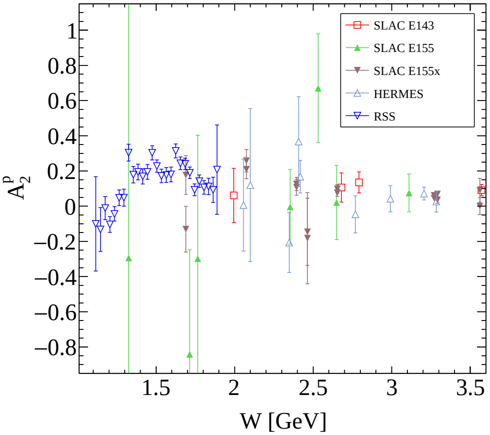
- SANE results *significantly* improve world data on g_2^p and g_1^p (archival paper in the works)
- d_2^p scale dependence is puzzling and should be compared with modern Lattice calculations
- d_2^p and d_2^n results together seem to indicated some interesting QCD physics
- **Precision** g_2 measurements are needed to better understand the scale dependence
- Working on archiving and preserving data for the future use.

Data tables found at `https://userweb.jlab.org/~whit/SANE/results/tables`.
Note: these tables are subject to change.

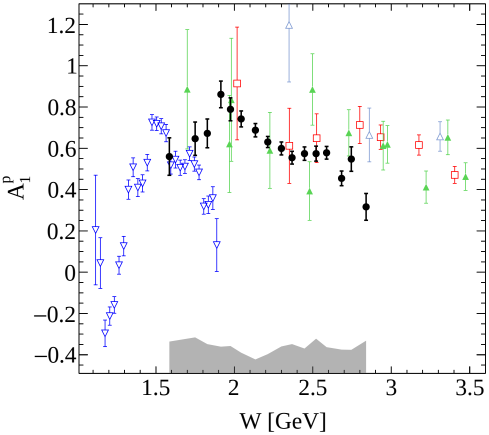
Thank You!

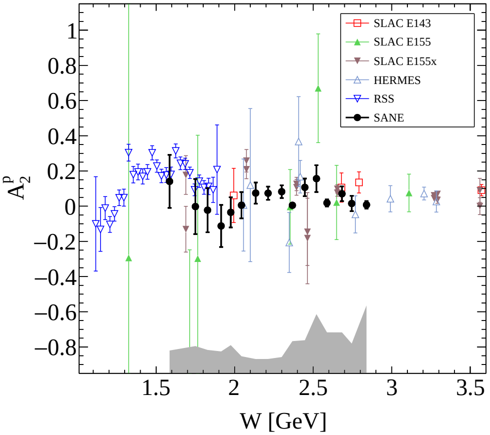
Virtual Compton Scattering Asymmetries



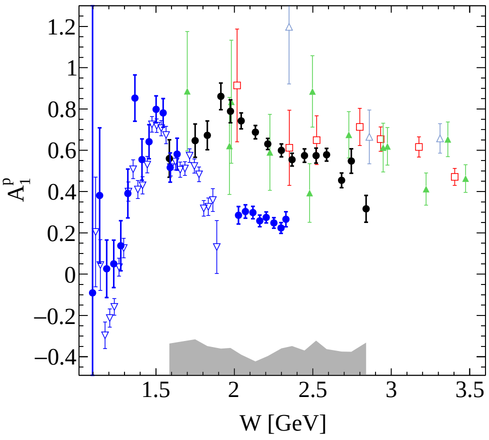


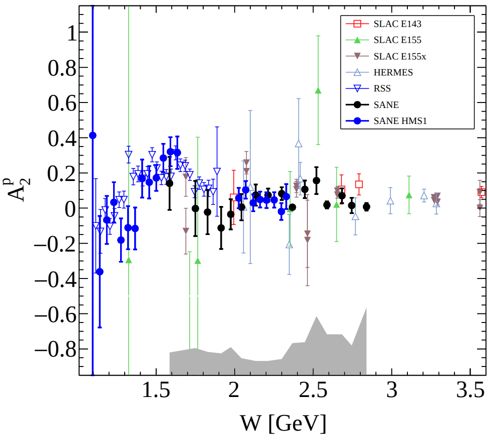
Virtual Compton Scattering Asymmetries



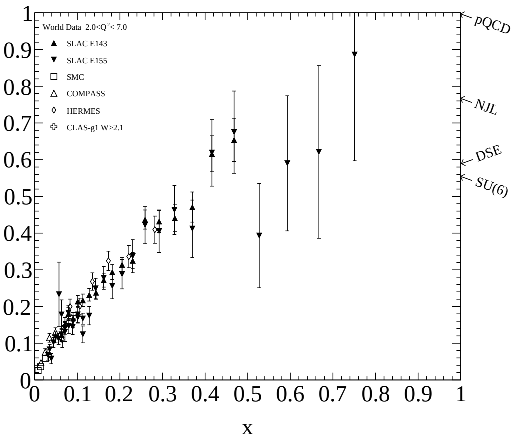


Virtual Compton Scattering Asymmetries

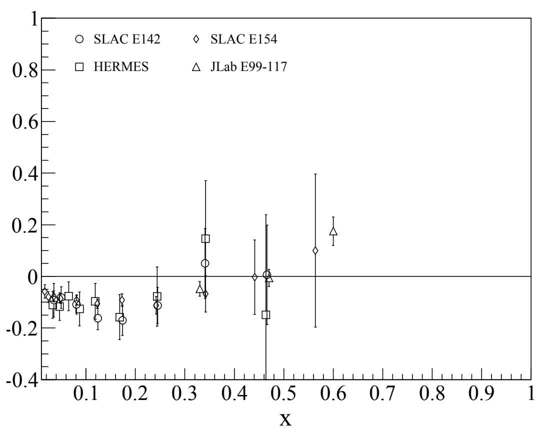




Valence domain: A_1 at high x

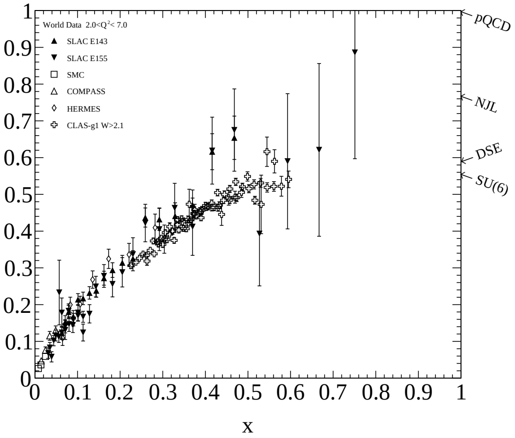


D.Flay, et.al. PRD.94(2016)no.5,052003



- A_1 as x→ 1

Valence domain: A_1 at high x



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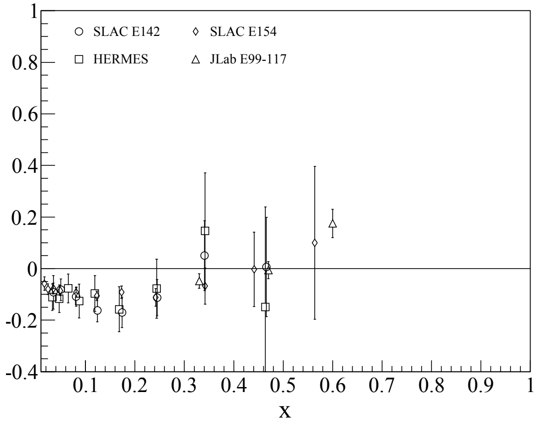
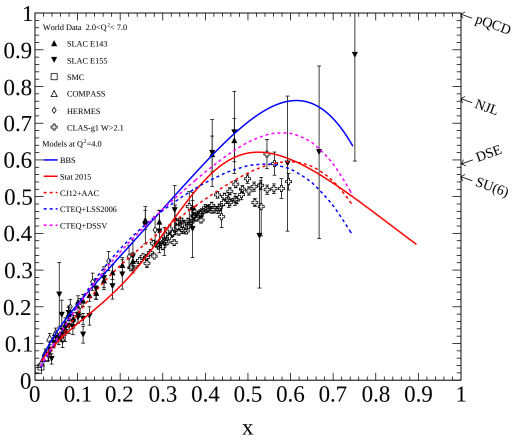
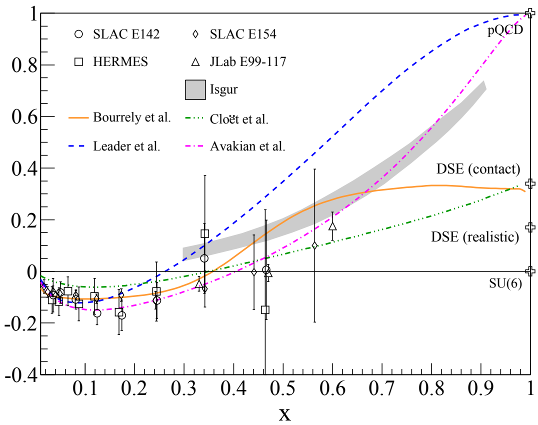


- A_1 as x$\rightarrow 1$
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.

Valence domain: A_1 at high x

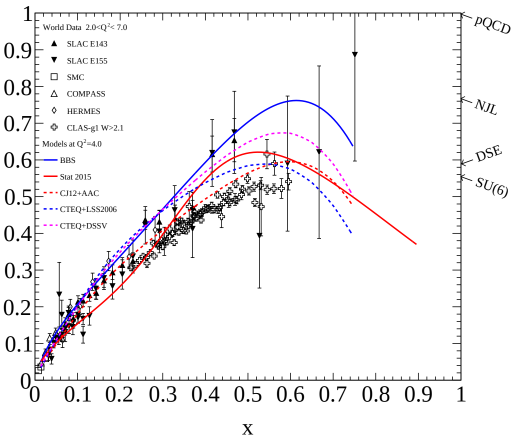


D.Flay, et.al. PRD.94(2016)no.5,052003



- A_1 as x$\rightarrow$ 1
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.
- Many predictions from models and fits

Valence domain: A_1 at high x



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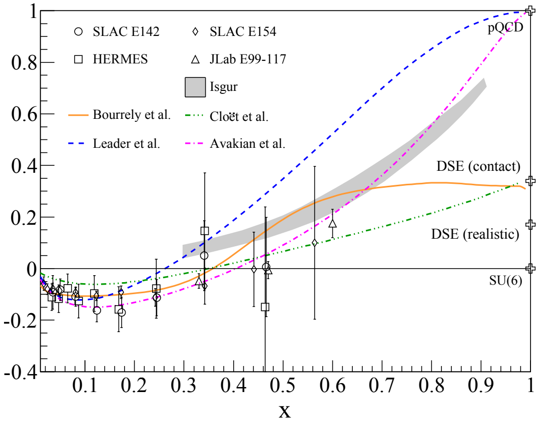

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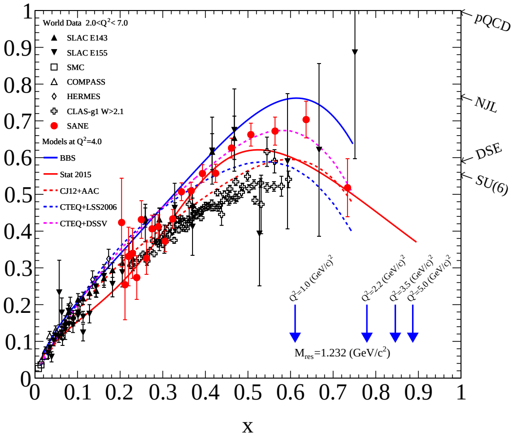
Valence domain: A_1 at high x



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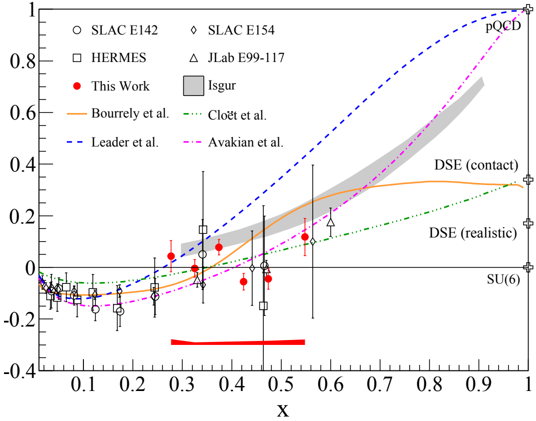

- A_1 as x$\rightarrow 1$
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.
- Many predictions from models and fits

- Dyson-Schwinger Equations (DSE) $x = 1$ predictions (Roberts, Holt, Schmidt)
- SANE data goes out to x$\simeq$0.8 $\rightarrow$ use duality to check limit