Recent results for the d_2 matrix element from JLab

QCD Evolution 2019

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Argonne NATIONAL LABORATORY

Outline

- Physics motivation for measuring the g_2 spin structure function
- The twist-3 matrix element d_2
- Recent JLab experimental results

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

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

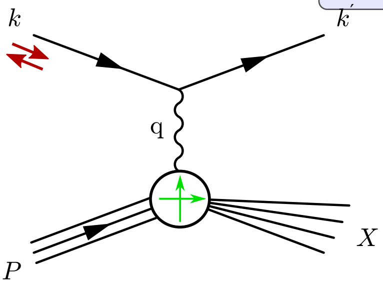
$$A_{\perp} = \frac{\sigma^{\Leftarrow\downarrow} - \sigma^{\Leftarrow\uparrow}}{\sigma^{\Leftarrow\downarrow} + \sigma^{\Leftarrow\uparrow}}$$

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

$$\nu = E - E'$$

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

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



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** g_2

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

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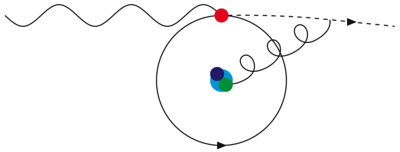
M. Burkardt Phys.Rev.D 88,114502 (2013) and Nucl.Phys.A 735,185 (2004).

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

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

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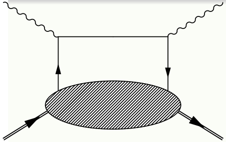
Twist-2 (Wandzura, Wilczek, 1977)



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

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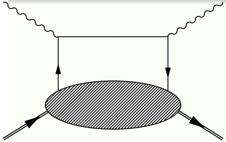

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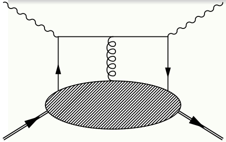

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M} h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y} \equiv g_2^{tw3}(x,Q^2)$$

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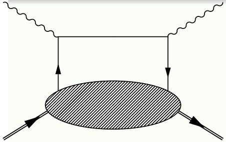

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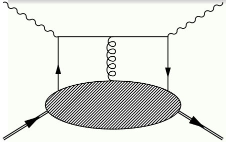

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$$d_2(Q^2) = 3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$
$$= \int_0^1 x^2(2g_1(x,Q^2) + 3g_2(x,Q^2))dx$$

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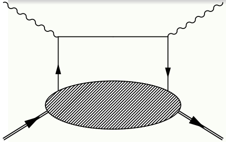

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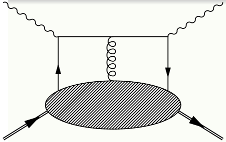

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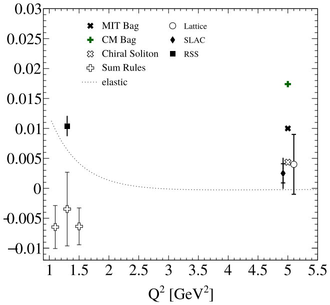
As Q^2 decreases,

when do higher twists begin to matter?

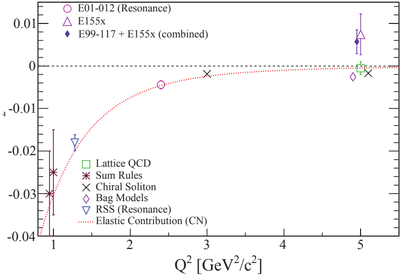
When is the color force non-zero?

Predictions and previous measurements of d_2

proton



neutron



Lattice QCD

- Ab initio calculations can be done on the lattice

Work in progress: method to extract d2 from lattice Sivers shift (WA, F.Aslan, M.Engelhardt, S.Liuti, M.Burkardt, A.Rajan)

Predictions and previous measurements of d_2

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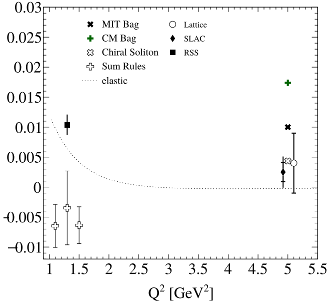

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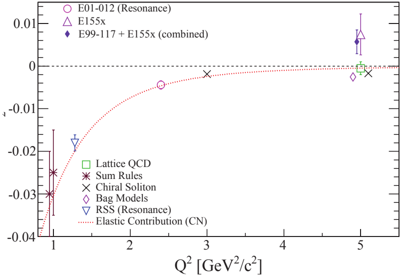

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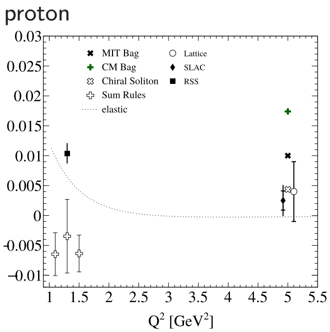

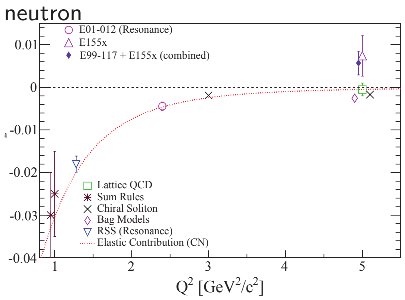

Lattice QCD

- Ab initio calculations can be done on the lattice
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- Proton results agree with SLAC but neutron results do not.

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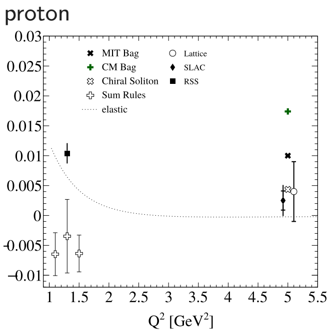

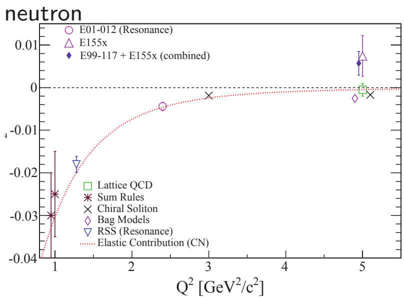

Lattice QCD

- 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

Work in progress: method to extract d2 from lattice Sivers shift (WA, F.Aslan, M.Engelhardt, S.Liuti, M.Burkardt, A.Rajan)

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 (M.Burkardt).
- Test lattice QCD calculations (note: **modern calculations needed!**)
- $\bar{g}_2$ and d_2 relations to quark OAM (A.Rajan, A.Courtoy, M.Engelhardt, S.Liuti)
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g_2 is important for QCD

- Extraction of $\bar{g}_2$ is clean (free of non-local effects, fragmentation functions).
- Related to Color forces (see M.Burkardt's talk)
- Higher twist distribution $\bar{g}_2$ provides limit for HT GPDs (see F.Aslan's talk)
- Quark OAM calculated from Higher twist GPDs (see B.Kriesten's talk)
- First integration point for Qui-Sterman M.E. found in SIDIS Sivers effect (see M.Schlegel's talk)

Complementary Jlab Experiments

Hall A

Hall C

Similar kinematic coverage

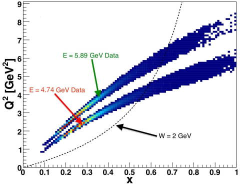
Both used 4.7 GeV and 5.9 GeV beams

Both measured $A_{||}$ and $A_{\perp}$

Both required new gas Cherenkov counters with existing detectors

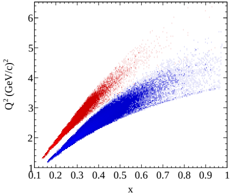
Hall A $\rightarrow$ neutron

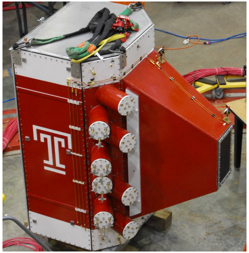
E06-014 : d_2^n



Hall C $\rightarrow$ proton

E07-003 : SANE

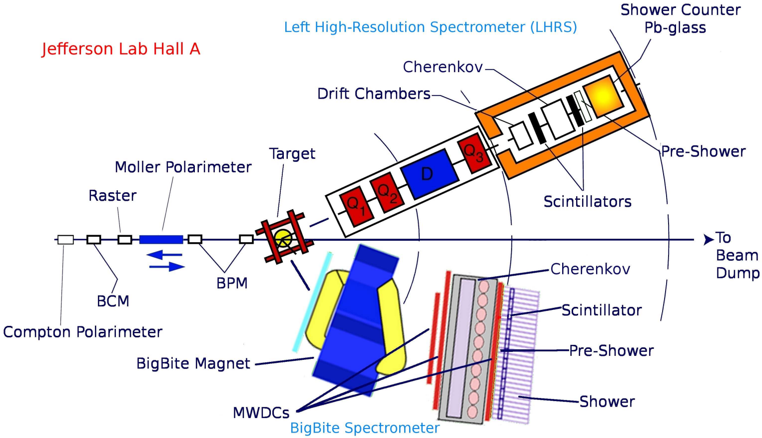




E06-014 : The d_2^n Experiment

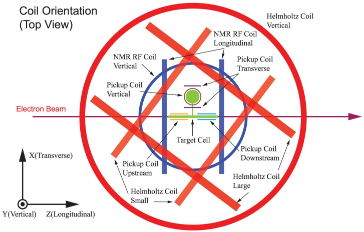
Spokespeople

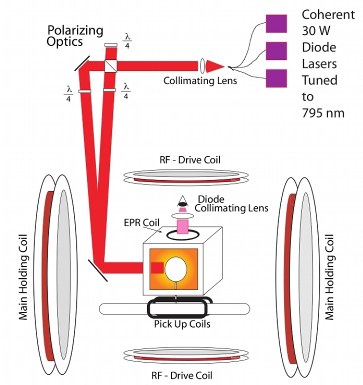
B. Sawatzky, S. Choi, X. Jiang, and Z.-E. Meziani



E06-014 : The d_2^n Experiment

- Polarized ^{3}He target





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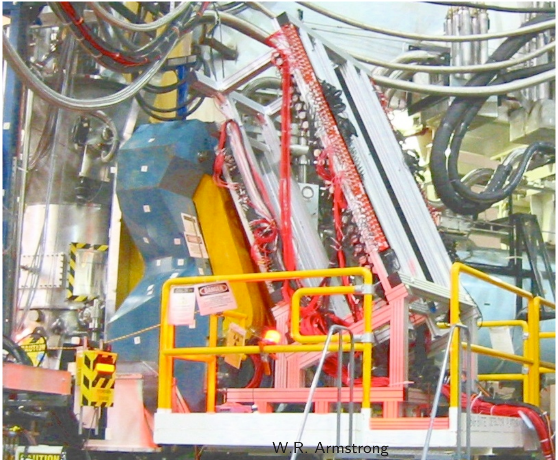
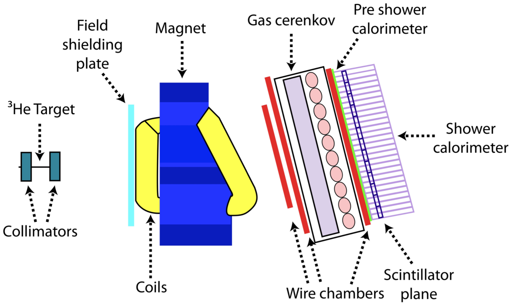
- Polarized ^{3}He target
- BigBite spectrometer





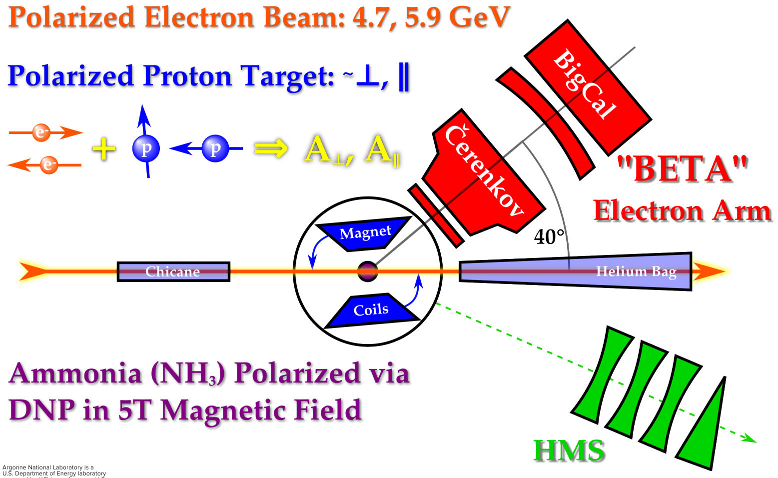
E06-014 : The d_2^n Experiment

- Polarized ^{3}He target
- BigBite spectrometer
- HRS data taken as well.

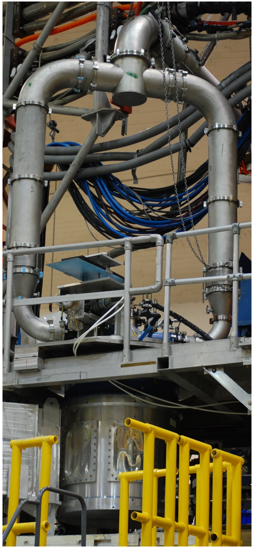
E07-003 : Spin Asymmetries of the Nucleon Experiment

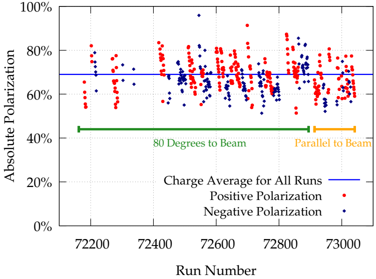
Spokespeople

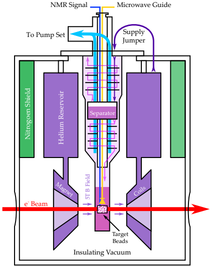
S. Choi, M. Jones, Z.-E. Meziani, O.A. Rondon



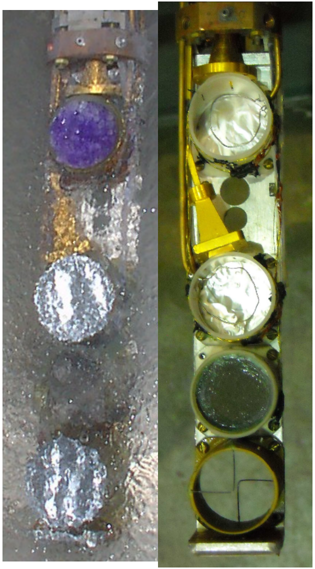
E07-003 : Polarized Ammonia Target



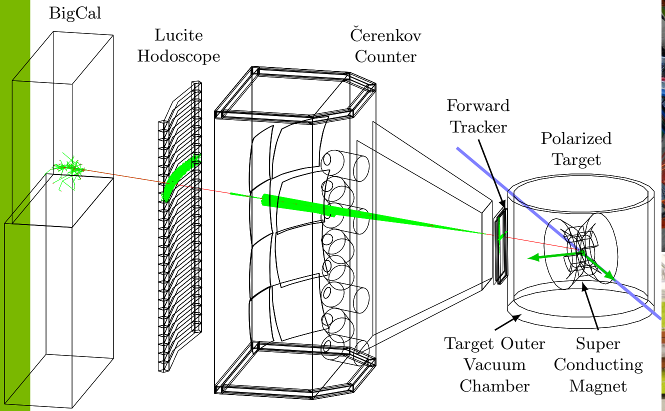


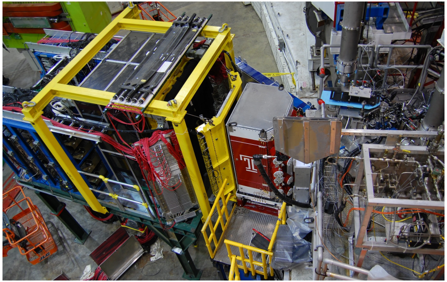


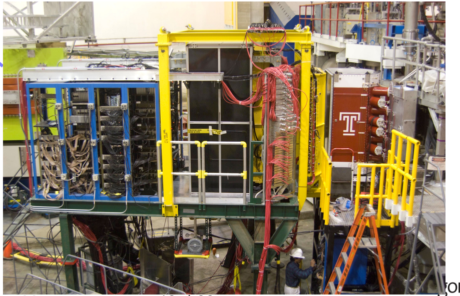
- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%



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

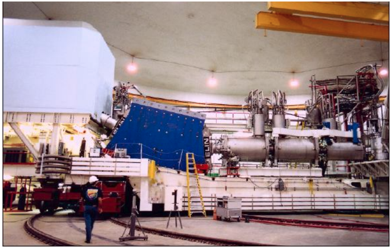


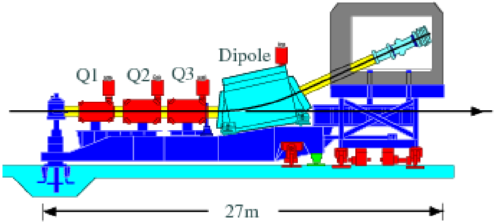


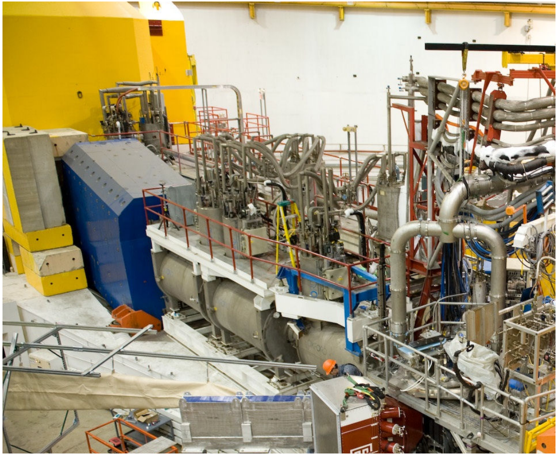


E07-003 : Spin Asymmetries of the Nucleon Experiment

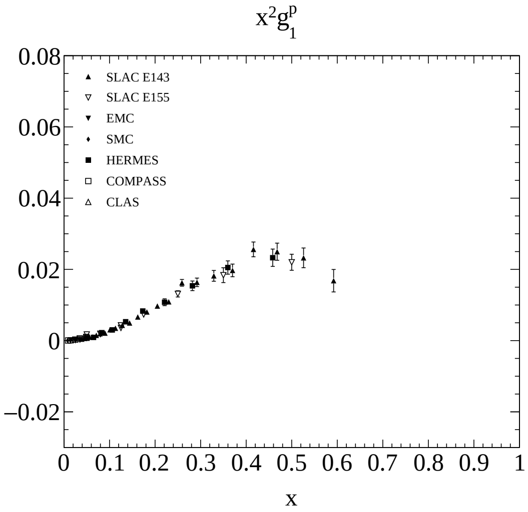
HMS data taken as well for resonance spin structure (Hoyoung Kang) and G_E/G_M (Anusha Liyanage)

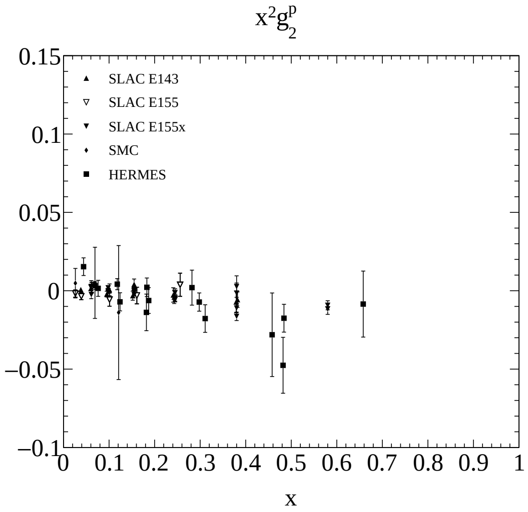






SANE results for $x^2 g_1^p$ and $x^2 g_2^p$





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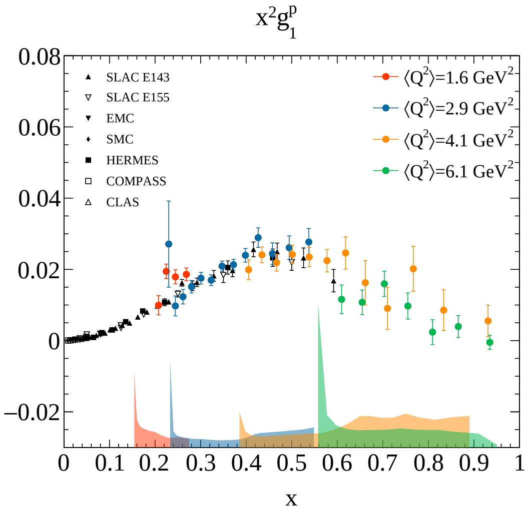

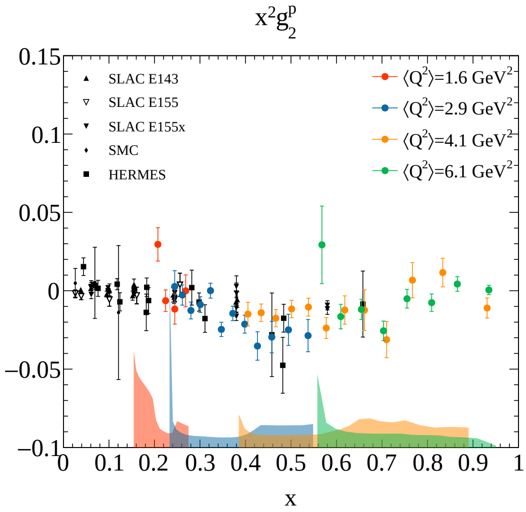

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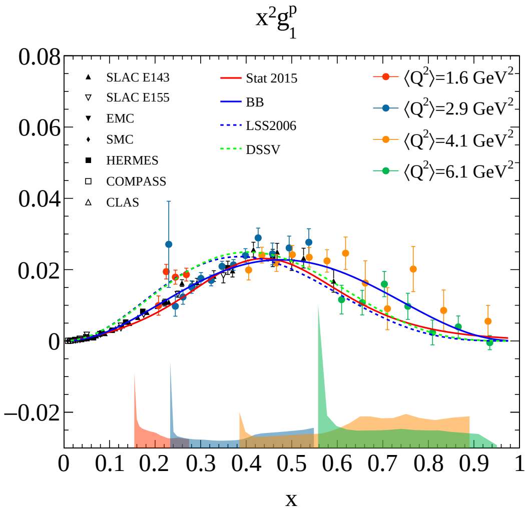
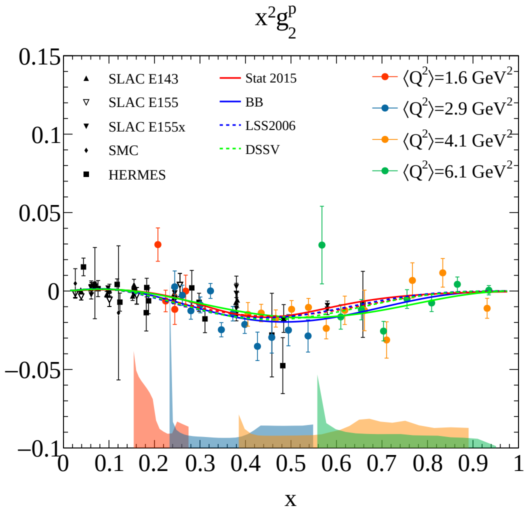
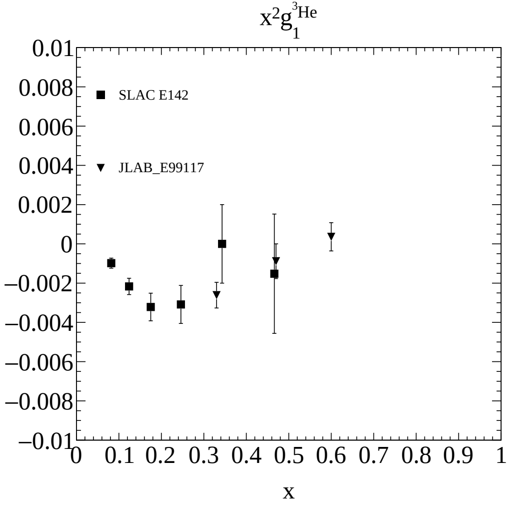
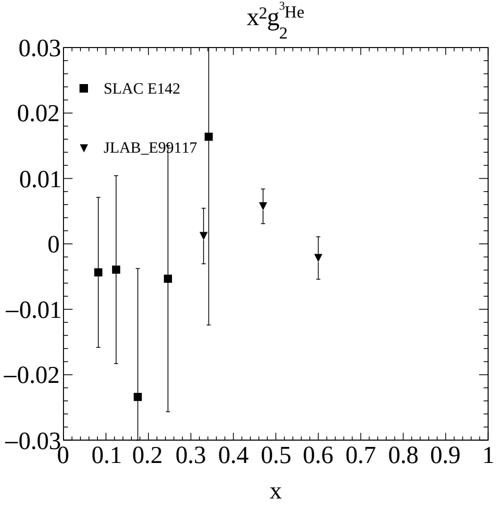




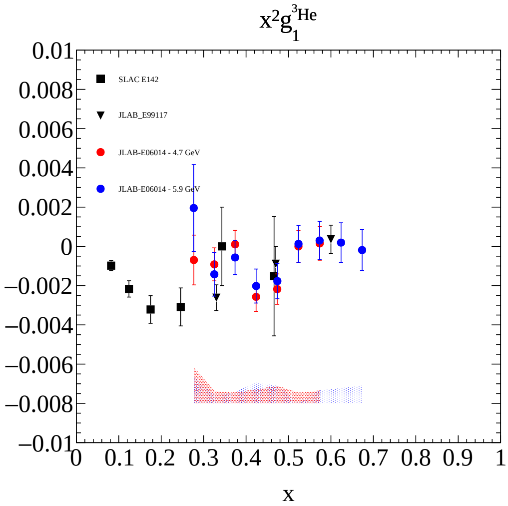
d_2^n results for $x^2 g_1^{^3He}$ and $x^2 g_2^{^3He}$

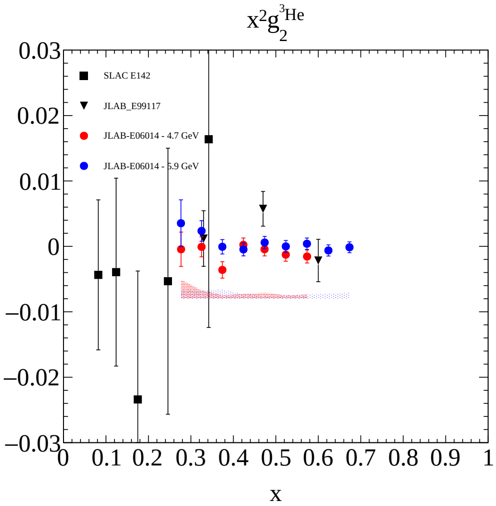




Models are showing g_2^{WW}.

d_2^n results for $x^2 g_1^{^3He}$ and $x^2 g_2^{^3He}$





Models are showing g_2^{WW}

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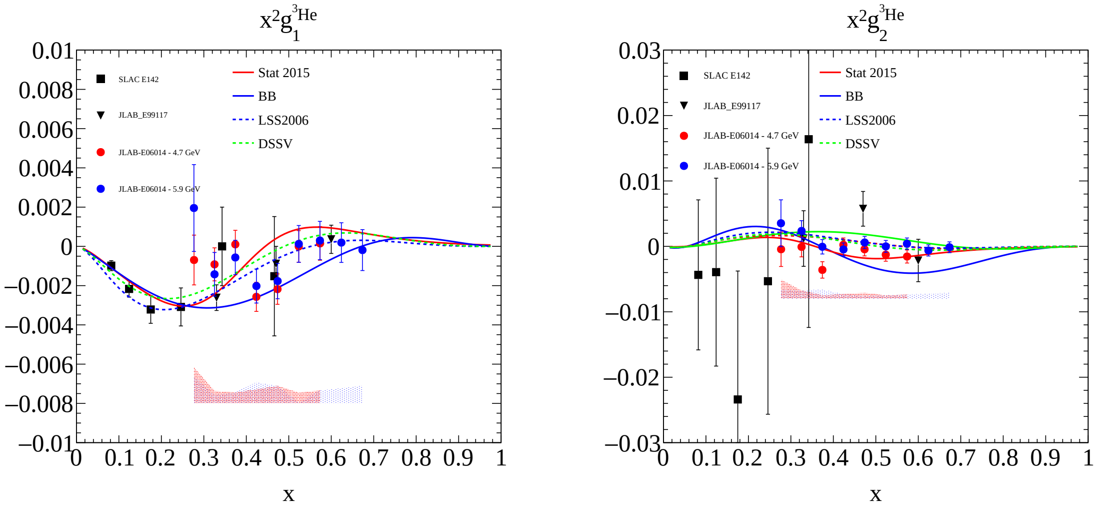
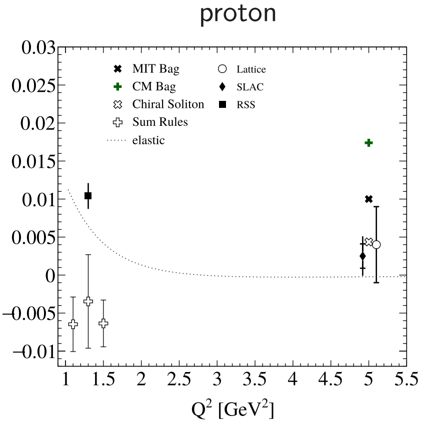
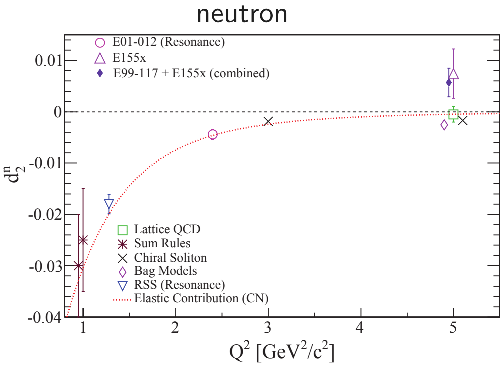


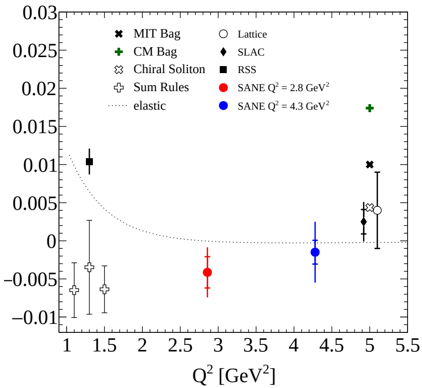
Models are showing g_2^{WW}



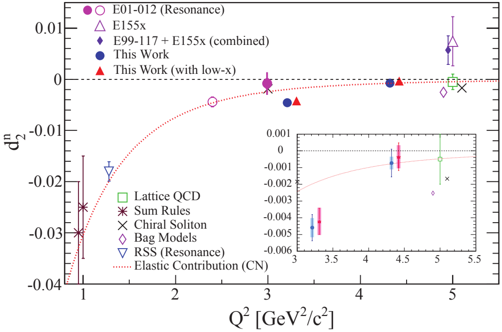


Existing data

proton



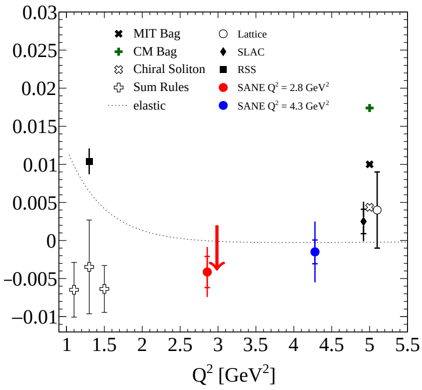
neutron



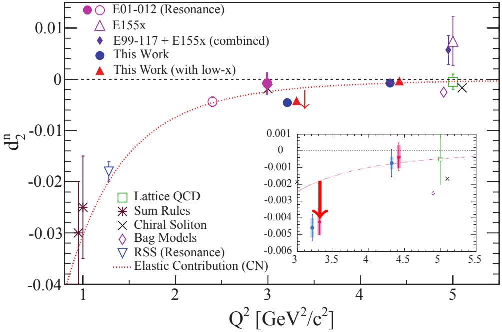
Neutron from d_2^n experiment: D.Flay, et.al. PRD.94(2016)no.5,052003

SANE and d_2^n Result

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



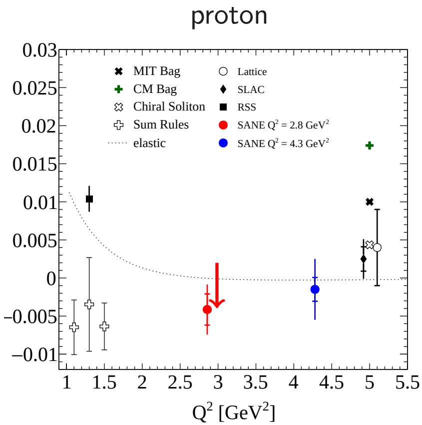
neutron

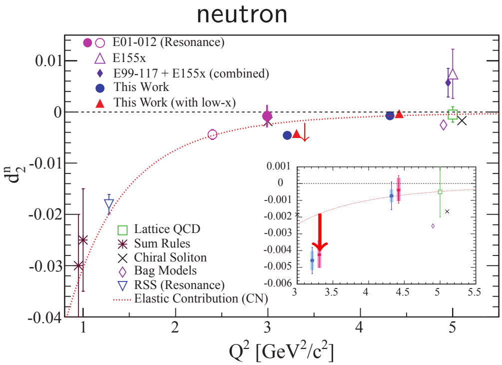


Neutron from d_2^n experiment: D.Flay, et.al. PRD.94(2016)no.5,052003

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?





Neutron from d_2^n experiment: 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?
- Updated Lattice calculations are long over due!

d_2 Results

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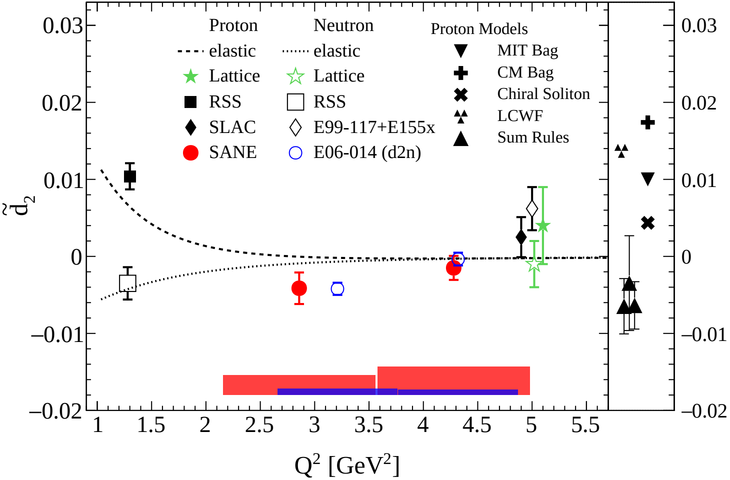
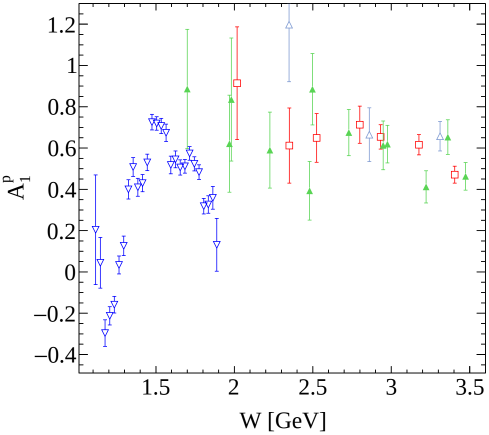
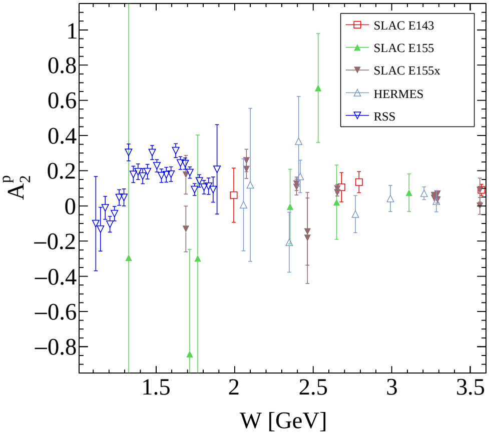


Virtual Compton Scattering Asymmetries





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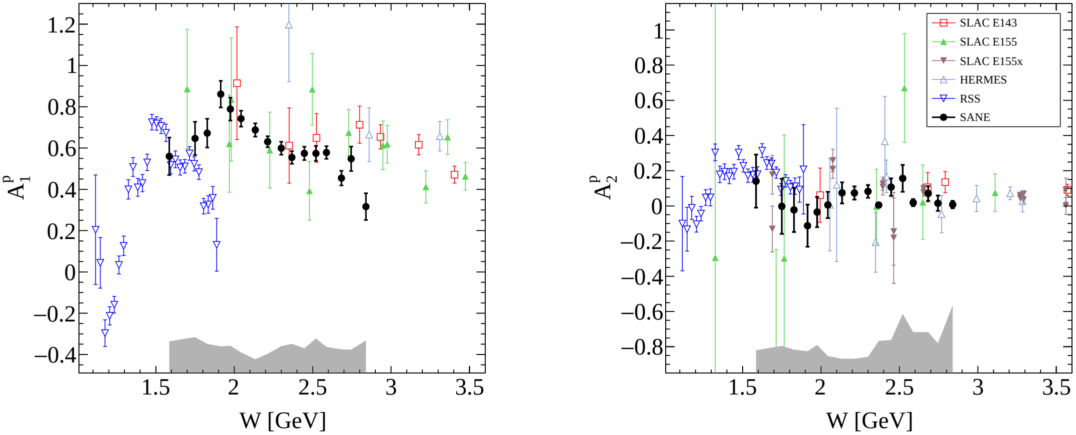
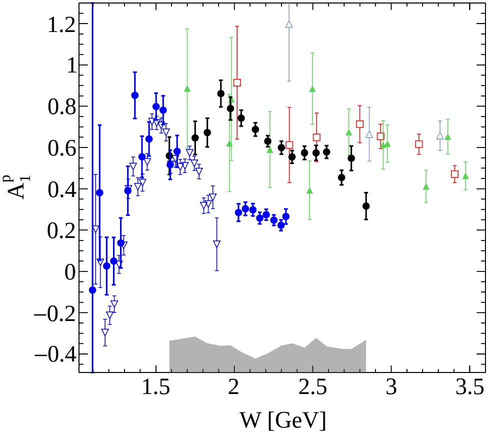
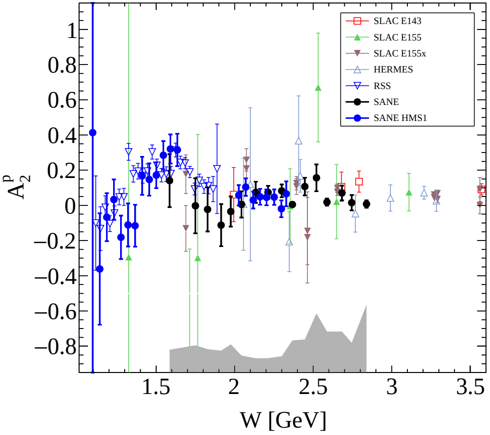
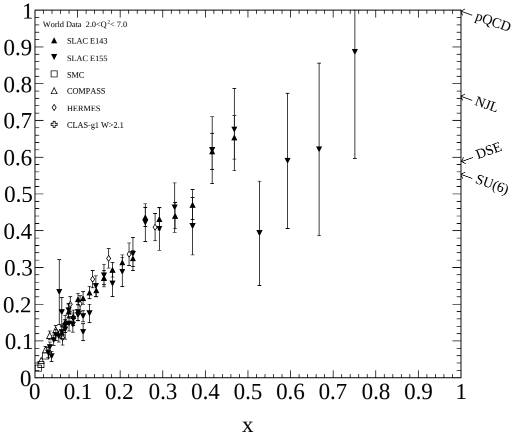


Virtual Compton Scattering Asymmetries

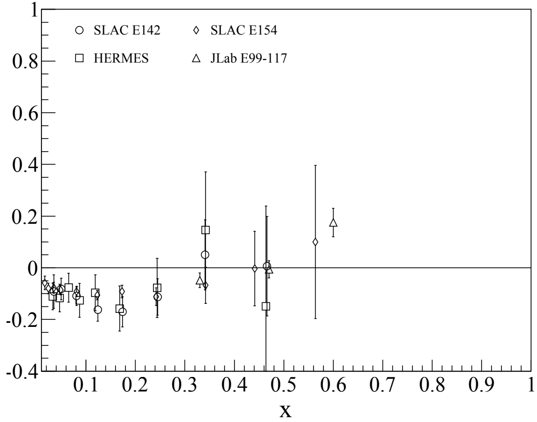




Valence domain: A_1 at high x

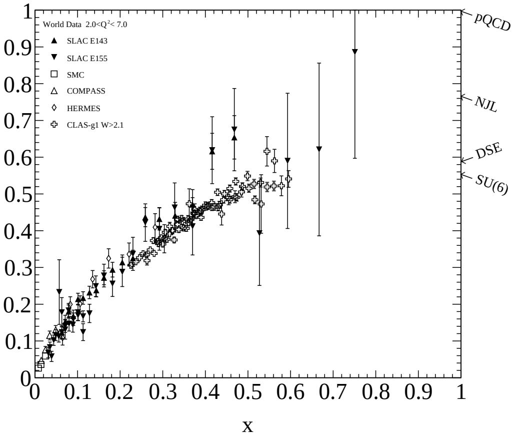


D.Flay, et.al. PRD.94(2016)no.5,052003

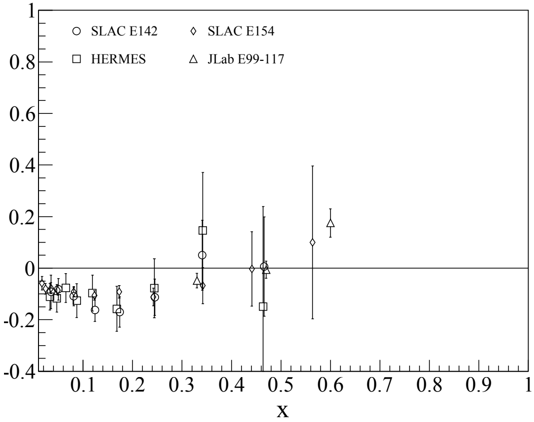


- A_1 as x$\rightarrow$ 1

Valence domain: A_1 at high x

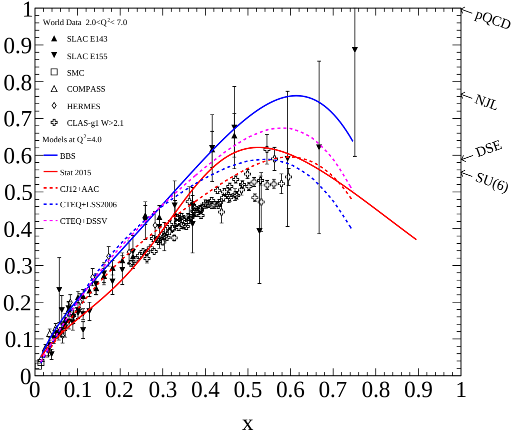


D.Flay, et.al. PRD.94(2016)no.5,052003



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

Valence domain: A_1 at high x



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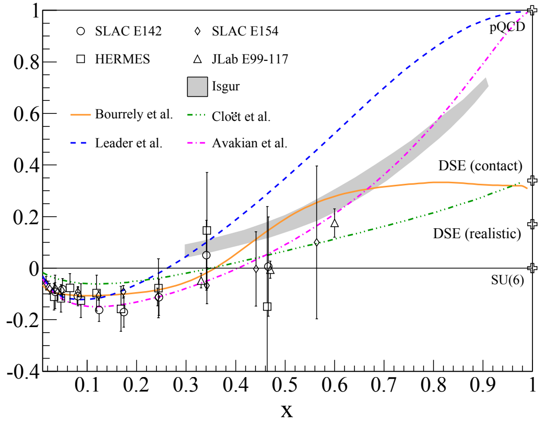
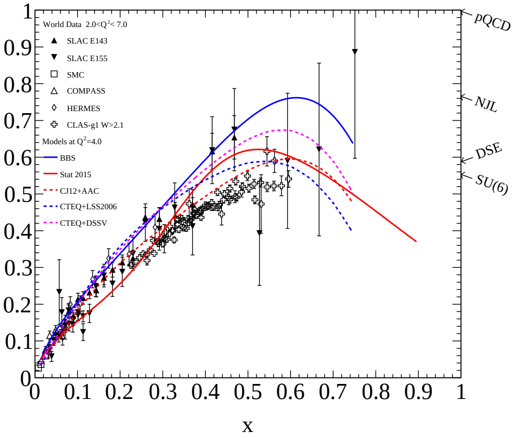


- A_1 as $x \to 1$
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.
- Many predictions from models and fits

Valence domain: A_1 at high x



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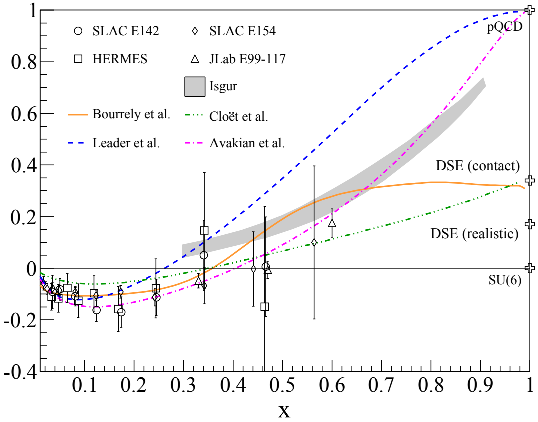

- A_1 as x$\rightarrow$ 1
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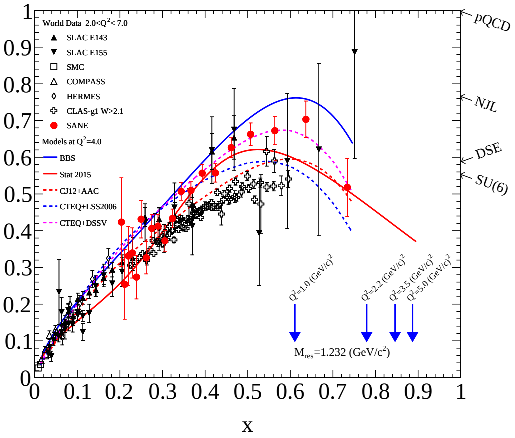
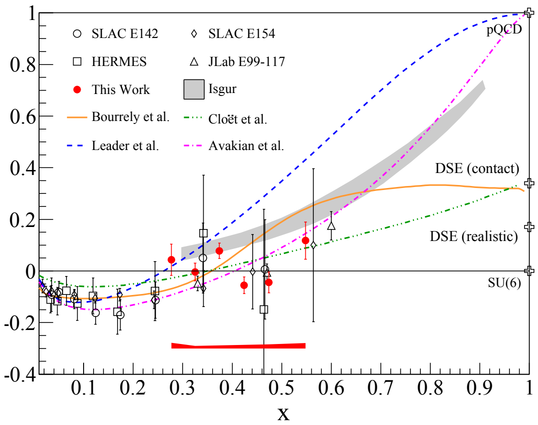
- Dyson-Schwinger Equations (DSE) $x = 1$ predictions (Roberts, Holt, Schmidt)

Valence domain: A_1 at high x



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



- A_1 as x$\to$ 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 $\to$ use duality to check limit

Summary

- SANE results *significantly* improve world data on g_2^p and g_1^p (archival paper in the works)
- d_2^p and d_2^n **scale dependence is puzzling** and should be compared with modern Lattice calculations
- d_2^p and d_2^n results suggest some interesting QCD physics
- **Precision** g_2 measurements at varying Q^2 are needed to verify apparent scale dependence
- JLab at 12 GeV provides an excellent opportunity to study g_2

Thank You!

Backup

d_2 Extraction

$$d_2 = 3 \int x^2 \bar{g}_2(x) dx$$
$$\bar{g}_2(x) = g_2^{exp} - g_2^{WW}$$

$$g_1^{exp}(x,Q^2) = g_1^{\tau=2}(x,Q^2) + g_1^{\tau=3}(x,Q^2) + g_1^{\tau=4}(x,Q^2) + \ldots$$
$$g_2^{exp}(x,Q^2) = g_2^{\tau=2}(x,Q^2) + g_2^{\tau=3}(x,Q^2) + g_2^{\tau=4}(x,Q^2) + \ldots$$

The Wandzura-Wilczek relation gives the twist-2 contribution to g_2

$$g_2^{WW}(x) = g_2^{\tau=2}(x) = -g_1^{\tau=2}(x) + \int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_1^{\tau=2}(y)$$

but we need only the leading twist $g_1^{\tau=2}$, not g_1^{exp}.

However, target mass and finite Q^2 corrections need to be made. The important twist-3 contribution to g_1 shows up as a target mass correction in the Blumlein-Tkabladze relation

$$g_1^{\tau=3}(x) = \frac{4M^2x^2}{Q^2}\left[g_2^{\tau=3}(x) - 2\int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_2^{\tau=3}(y)\right] \quad (1)$$

Need to disentangle different twist contributions

Twist-2 TMCs

Twist-2 TMC corrections to g_2 : WW Relation

$$g_2^{(\tau 2+TMC)}(x,Q^2) = -\frac{x}{\xi\rho^3} g_1^{(\tau 2)}(\xi,Q^2) + \frac{1}{\rho^4}\int_\xi^1 \frac{dz}{z}\Big[\frac{x}{\xi} - (\rho^2-1) + \frac{3(\rho^2-1)}{2\rho}\ln\frac{z}{\xi}\Big] g_1^{(\tau 2)}(z,Q^2)$$
$$= g_2^{WW}(x,Q^2; M\to 0)$$

where $\rho^2 = (1+\frac{4M^2x^2}{Q^2})$

$$g_2^{WW}\left[g_1^{(\tau 2)}\right] = -g_1^{\tau 2}(x) + \int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_1^{\tau 2}(y)$$
$$g_2^{WW}\left[g_1^{(\tau 2+\textbf{TMC})}\right] = -g_1^{\tau 2+\textbf{TMC}}(x) + \int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_1^{\tau 2+\textbf{TMC}}(y)$$
$$g_2^{WW}\left[g_1^{\tau 2+\tau 3}\right] \neq -g_1^{\tau 2+\tau\mathbf{3}}(x) + \int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_1^{\tau 2+\tau\mathbf{3}}(y)$$

WW relation holds in presence of target mass effects.

Twist-3 TMCs

Twist-3 TMC corrections to g_1: BT Relation

$$g_1^{\tau 3}(x) = \frac{4M^2x^2}{Q^2}\left[g_2^{\tau 3}(x) - 2\int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_2^{\tau 3}(y)\right] \tag{2}$$

$$= g_1^{BT}(x) \tag{3}$$

B & T emphasized the need to take full account of this type of term if twist-3 terms are kept in the cross sections.

$$g_1^{BT}\left[g_2^{\tau 3}\right] = \frac{4M^2x^2}{Q^2}\left[g_2^{\tau 3}(x) - 2\int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_2^{\tau 3}(y)\right]$$

$$g_1^{BT}\left[g_2^{(\tau 3+\textbf{TMC})}\right] = \frac{4M^2x^2}{Q^2}\left[g_1^{\tau 3+\textbf{TMC}}(x) - 2\int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_1^{\tau 3+\textbf{TMC}}(y)\right]$$

$$g_1^{BT}\left[g_2^{\boldsymbol{\tau 2+\tau 3}}\right] \neq \frac{4M^2x^2}{Q^2}\left[g_1^{\boldsymbol{\tau 2+\tau 3}}(x) - 2\int_x^1 \frac{\mathrm{dy}}{\mathrm{y}} g_1^{\boldsymbol{\tau 2+\tau 3}}(y)\right]$$

BT relation holds in presence of target mass effects.