The g_2 Structure Function

Recent results from the SANE experiment

8th Workshop of the
APS Topical Group on
Hadronic Physics

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Argonne National Laboratory

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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

$$\sigma_0 = \frac{4\alpha^2 E'^2}{q^4}\left[\frac{2}{M}F_1 \sin^2(\theta/2) + \frac{1}{\nu}F_2 \cos^2(\theta/2)\right]$$
$$2\sigma_0 A_\parallel = -\frac{4\alpha^2}{Q^2}\frac{E'}{E}\left[\frac{E+E'\cos\theta}{M\nu}g_1 - \frac{Q^2}{M\nu^2}g_2\right]$$
$$2\sigma_0 A_\perp = -\frac{4\alpha^2}{MQ^2}\frac{E'^2}{E}\sin\theta\cos\phi\left[\frac{1}{M\nu}g_1 + \frac{2E}{M\nu^2}g_2\right]$$

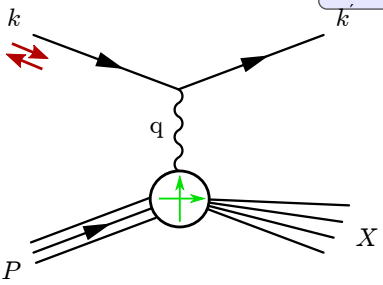
Structure Functions

$$F_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\ q_i(x,Q^2)$$
$$F_2(x,Q^2) = 2xF_1(x,Q^2)$$
$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\ \Delta q_i(x,Q^2)$$
$$g_2(x,Q^2) = ?$$

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?

$$A_\parallel \propto g_1 - \frac{2Mx}{\nu}g_2$$
$\rightarrow$ g_2 suppressed by $1/\nu$
$$A_\perp \propto g_1 + g_2$$
$\rightarrow$ In DIS region both contribute.

$\Rightarrow A_\perp$ **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

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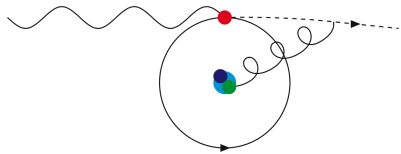
M. Burkardt Phys.Rev.D 88,114502 (2013) and Nucl.Phys.A 735,185 (2004).

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

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

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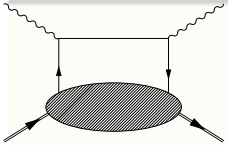
Twist-2 (Wandzura, Wilczek, 1977)



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

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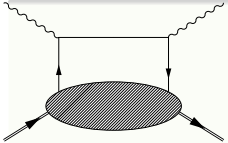

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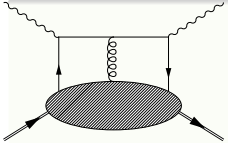

$$\begin{aligned} \bar{g}_2(x,Q^2) &= -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y} \\ &\equiv g_2^{tw3}(x,Q^2) \end{aligned}$$

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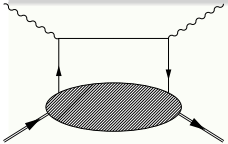

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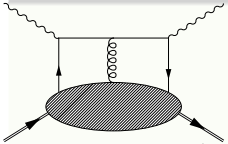

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$$d_2(Q^2) = 3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$
$$= \int_0^1 x^2(2g_1(x,Q^2) + 3g_2(x,Q^2))dx$$

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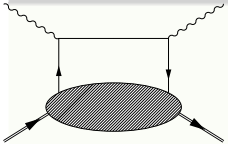

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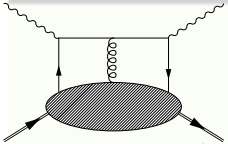

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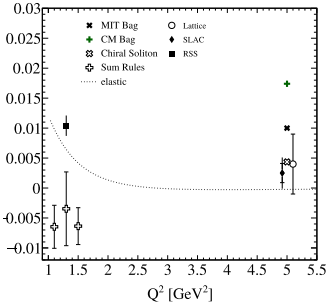
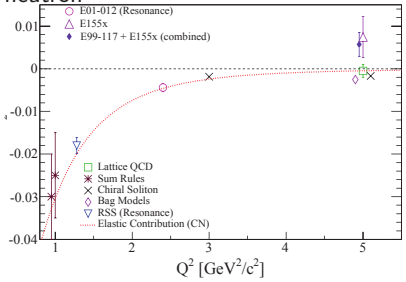
As Q^2 decreases,
when do higher twists begin to matter?
When is the color force non-zero?

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, A. Rajan)

Predictions and previous measurements of d_2

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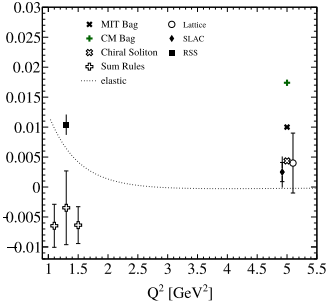

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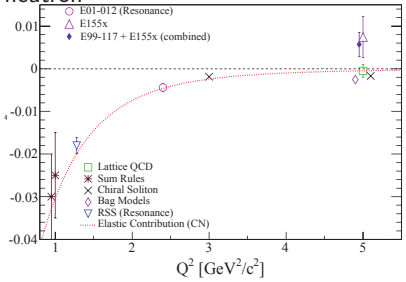

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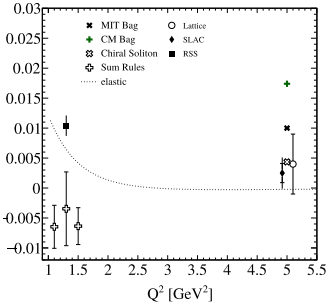

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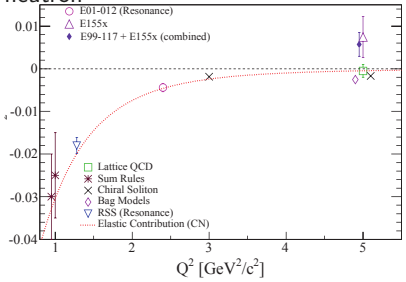

Lattice QCD

- 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.

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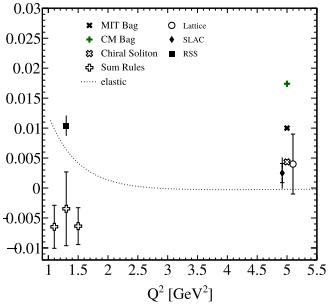

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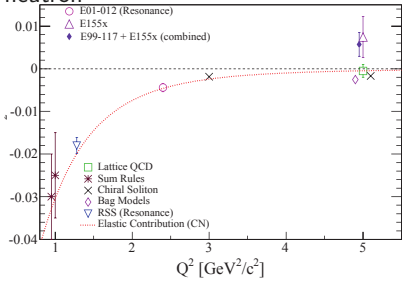

Lattice QCD

- 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, 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.
- 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

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Important starting point for Nucleon Tomography

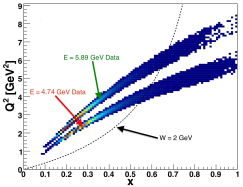
- Extraction of $\bar{g}_2$ is clean (free of non-local effects, fragmentation functions).
- Higher twist distribution $\bar{g}_2$ provides important boundary condition for HT GPDs
- Quark OAM calculated from Higher twist GPDs
- First point in Qui-Sterman M.E. found in SIDIS

Complementary Jlab Experiments

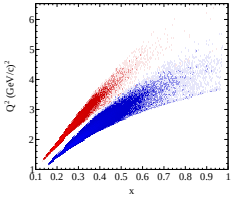
Similar kinematic coverage
Both used 4.7 GeV and 5.9 GeV beams
Both measured $A_{\parallel}$ and $A_{\perp}$

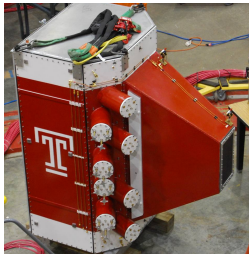
Both required new gas Cherenkov counters with existing detectors

Hall A → neutron
E06-014 : d_2^n



Hall C → proton
E07-003 : SANE

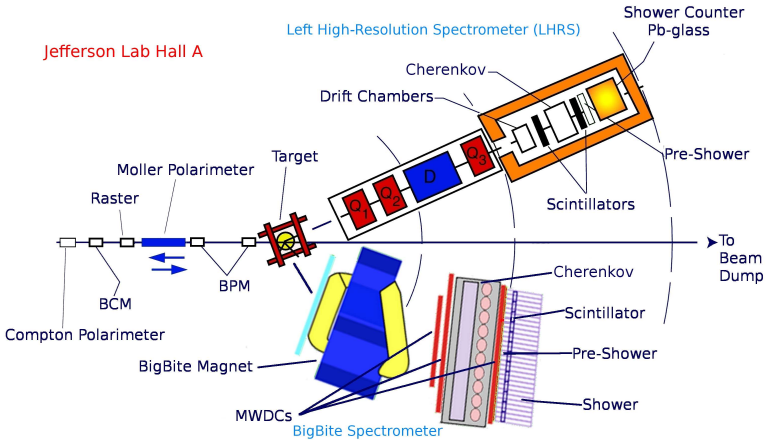




E06-014 : The d_2^n Experiment

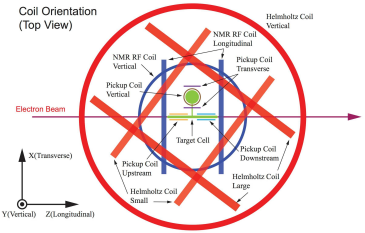
Spokespeople

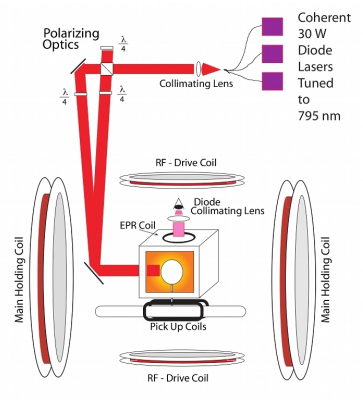
B. Sawatzky, S. Choi, X. Jiang, and Z.-E. Meziani



E06-014 : The d_2^n Experiment

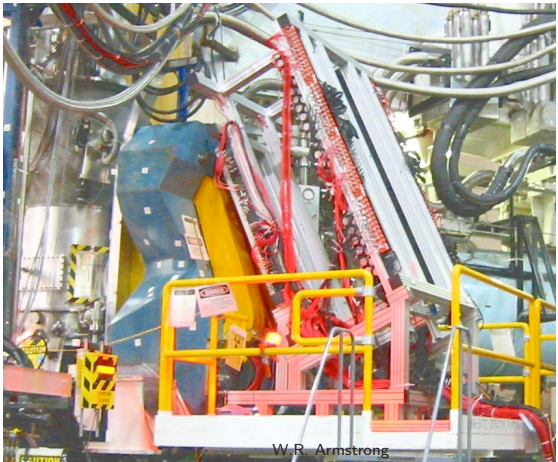
- Polarized ^{3}He target

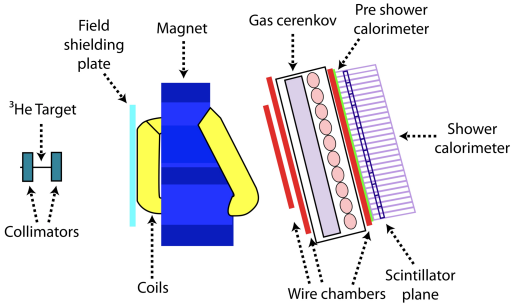




E06-014 : The d_2^n Experiment

- Polarized ^{3}He target
- BigBite spectrometer





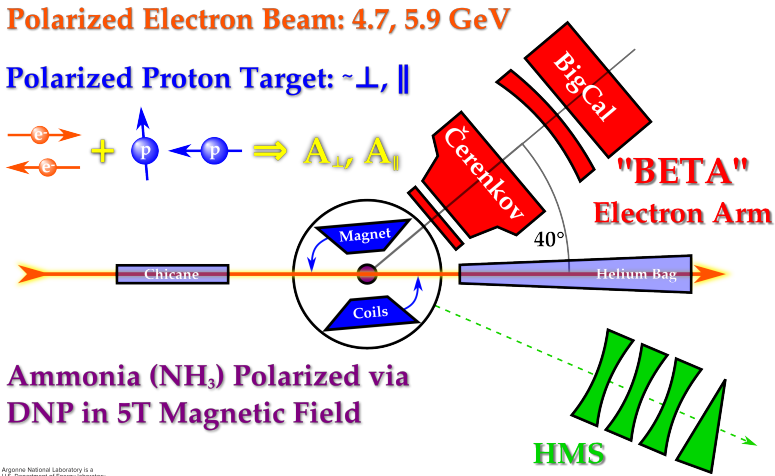
E06-014 : The d_2^n Experiment

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

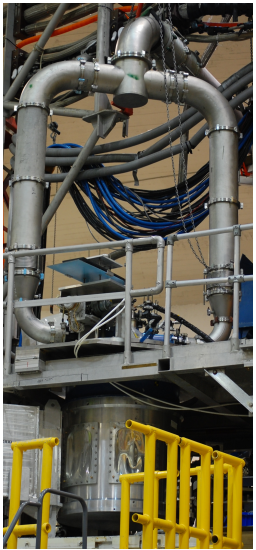
E07-003 : Spin Asymmetries of the Nucleon Experiment

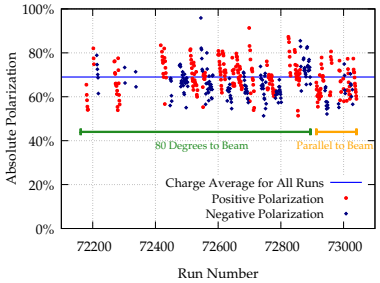
Spokespeople

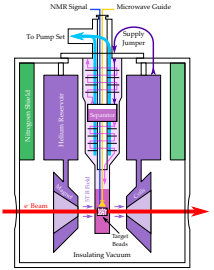
S. Choi, M. Jones, Z.-E. Meziani, O.A. Rondon



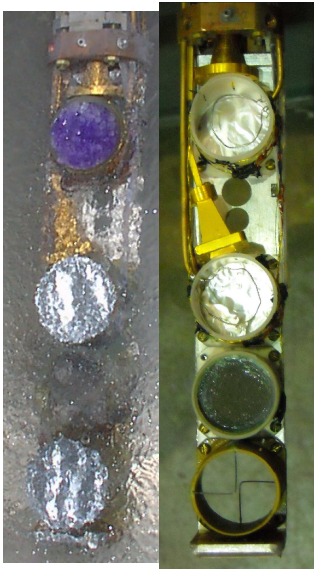
E07-003 : Polarized Ammonia Target



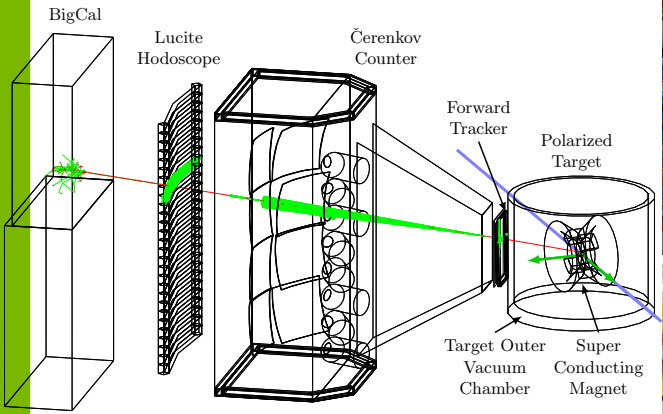


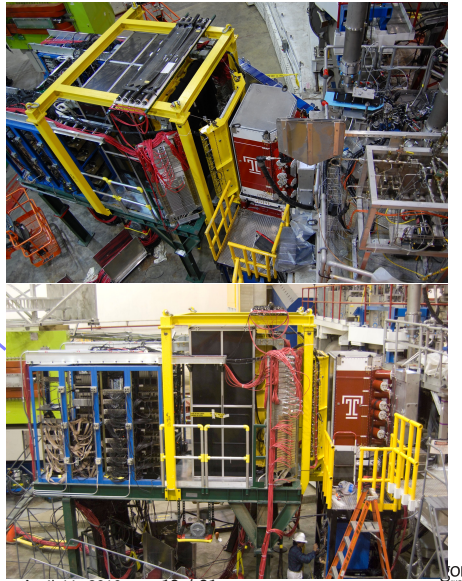


- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%



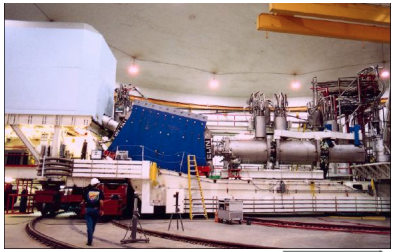
E07-003 : **B**ig **E**lectron **T**elescope **A**rray

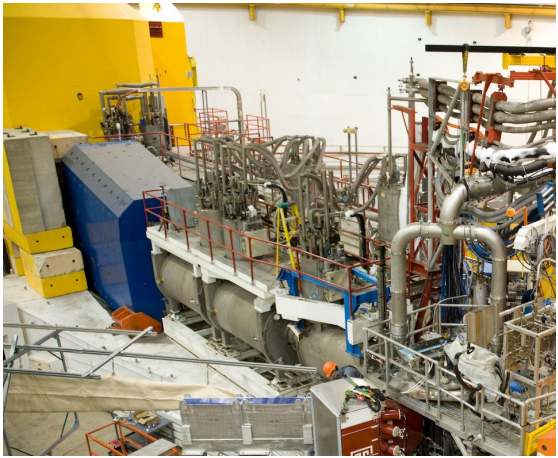




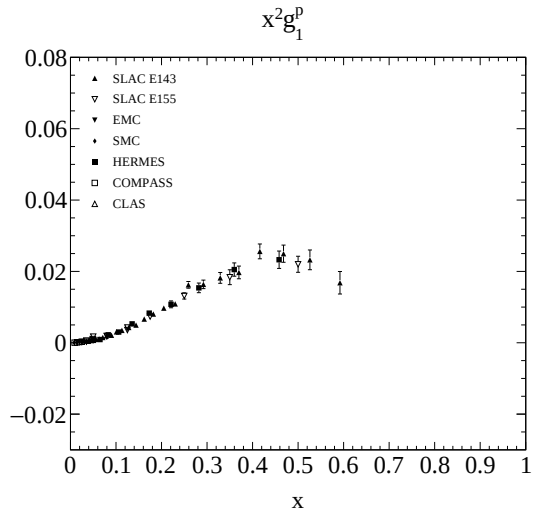
E07-003 : Spin Asymmetries of the Nucleon Experiment

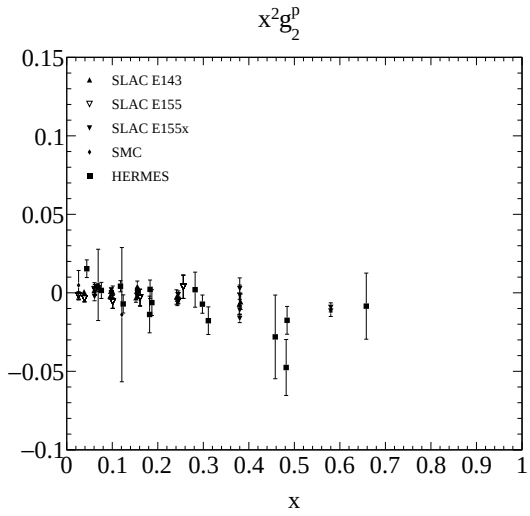
HMS data taken as well for resonance spin structure (Hoyoung Kang) and G_E/G_M (Anusha Liyanage)





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





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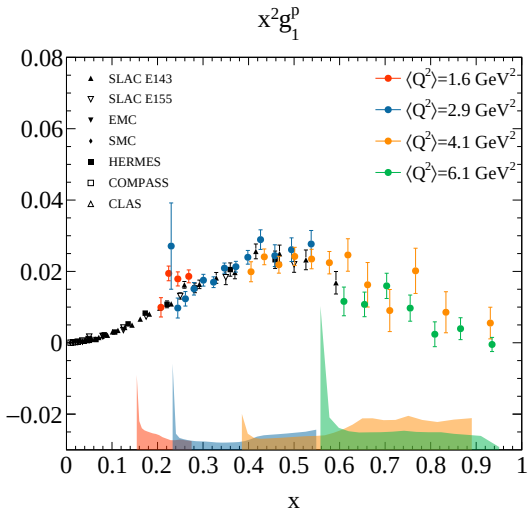

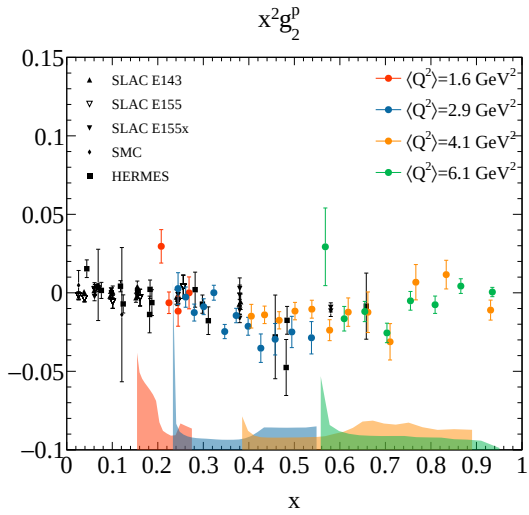

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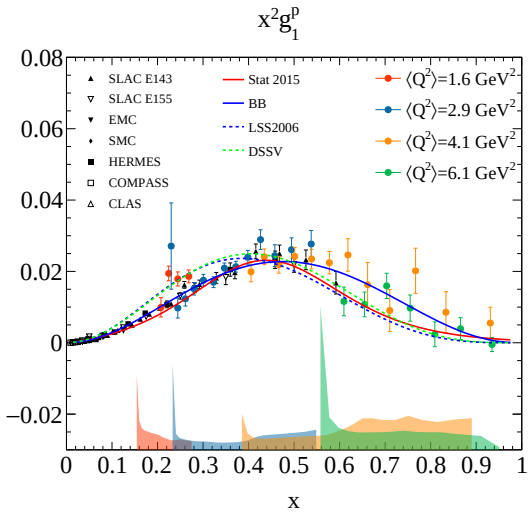
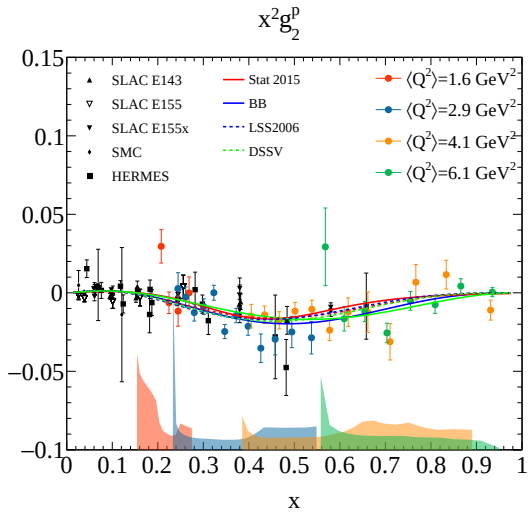
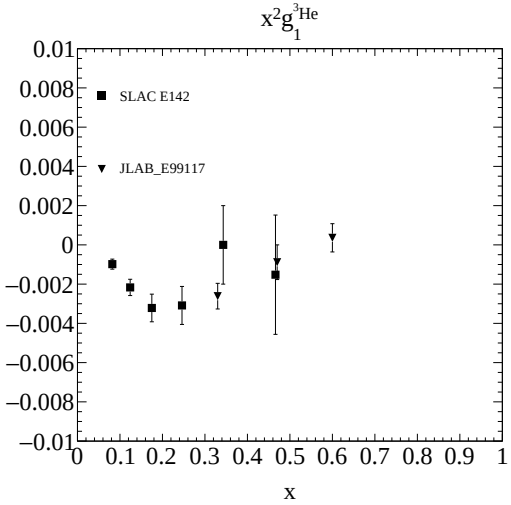
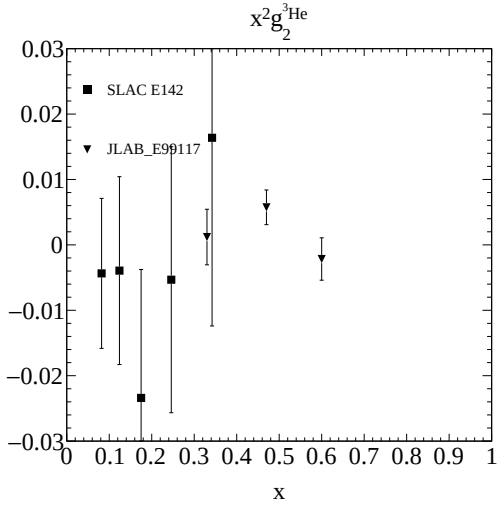




d_2^n results for $x^2 g_1^{^3He}$ and $x^2 g_2^{^3He}$





Models are showing g_2^{WW}

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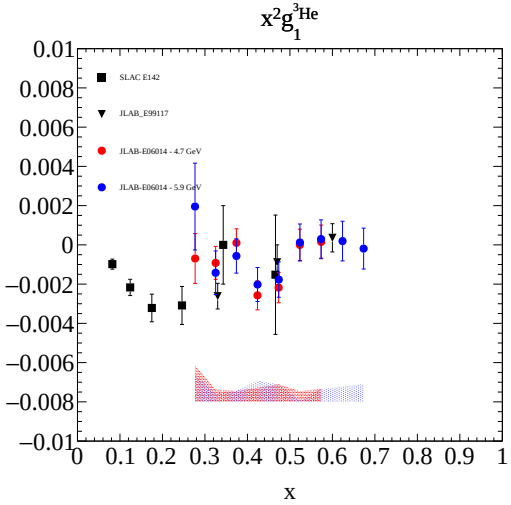

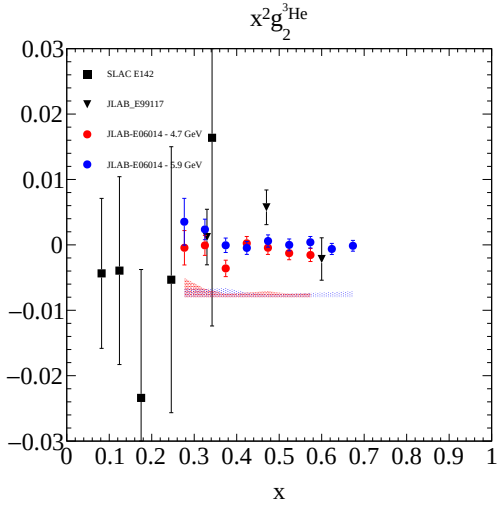

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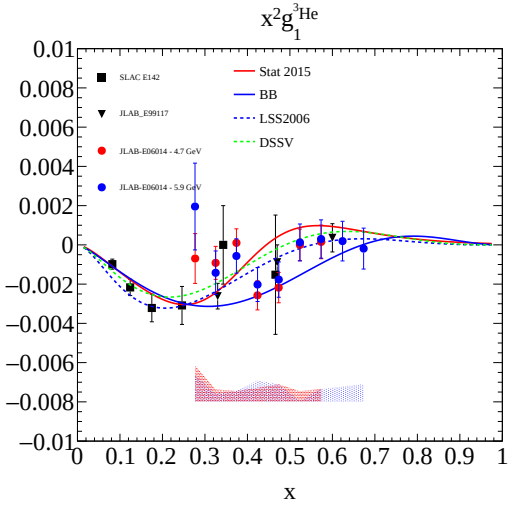
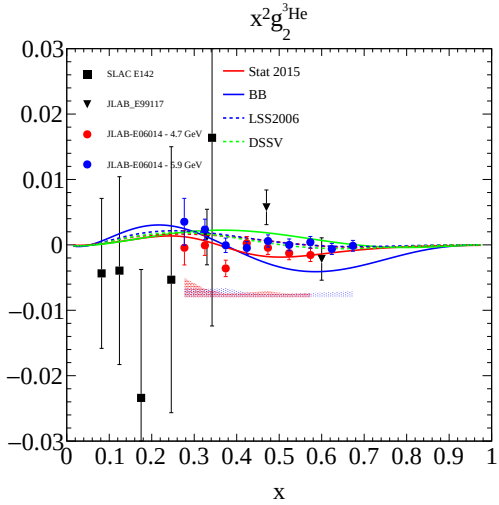
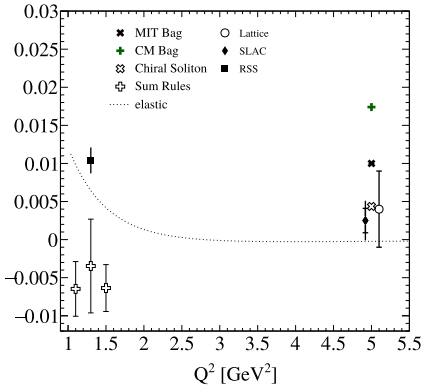


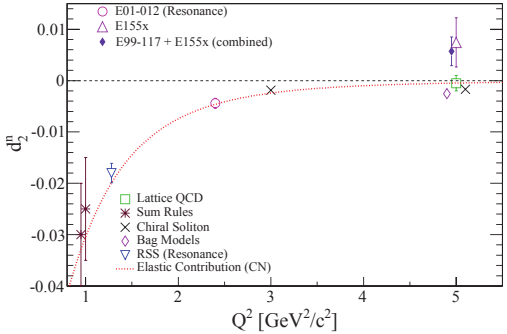


Models are showing g_2^{WW}

proton

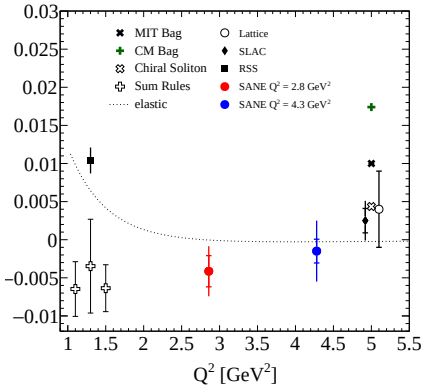


neutron

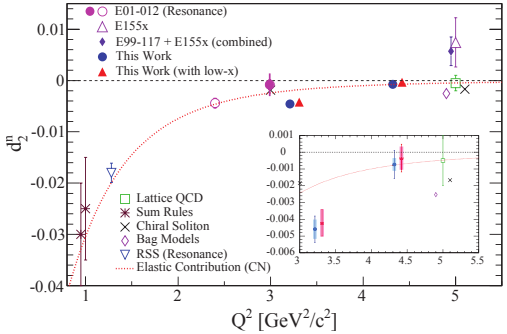


Existing data

proton



neutron

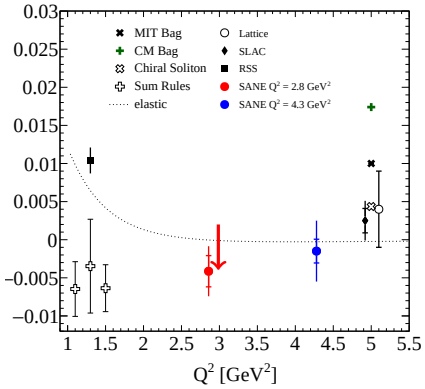


Neutron from d_2^n experiment: D.Flay, et.al. PRD.94(2016)no.5,052003

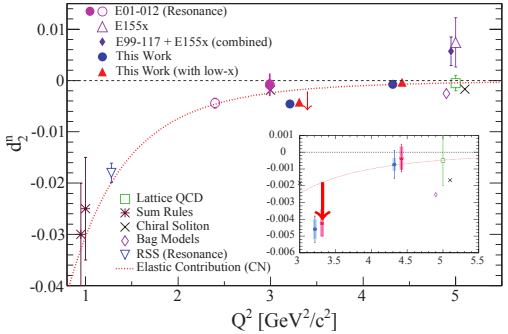
SANE and d_2^n Result

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

proton



neutron



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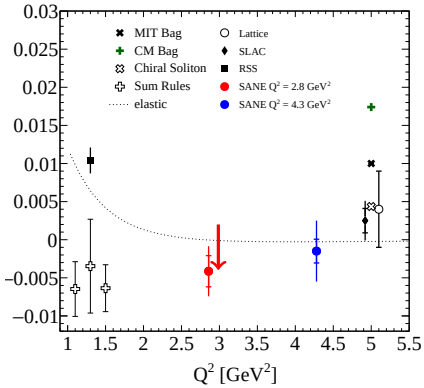
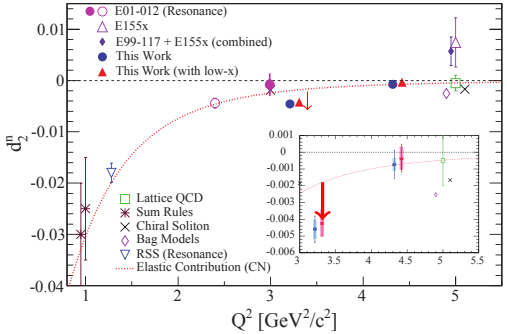
- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
- Is this an isospin independent average color force?

proton



neutron



Neutron from d_2^n experiment: 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^p Results

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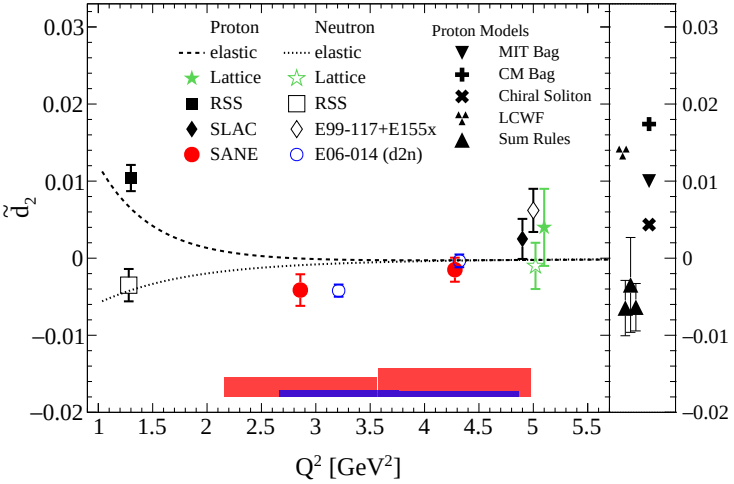
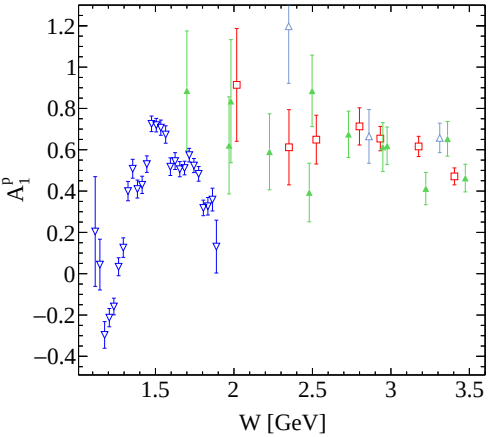
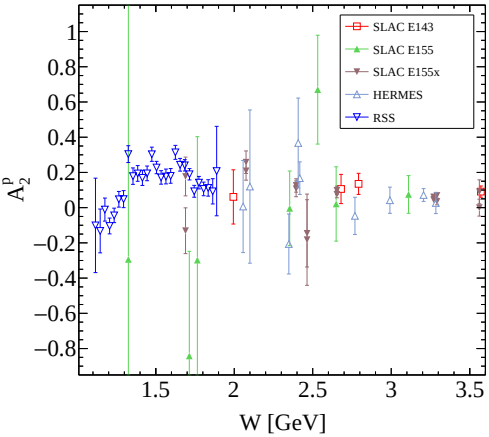


Virtual Compton Scattering Asymmetries





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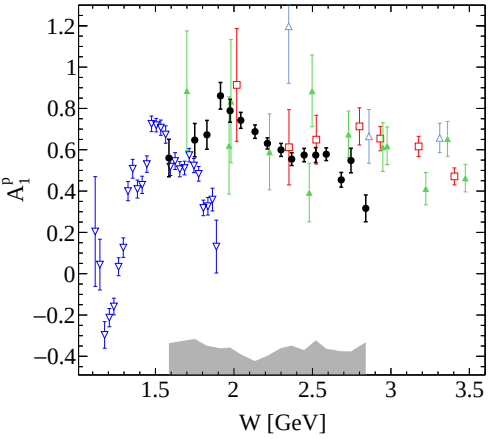

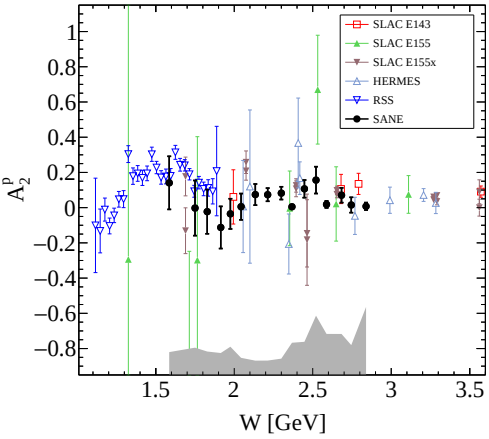

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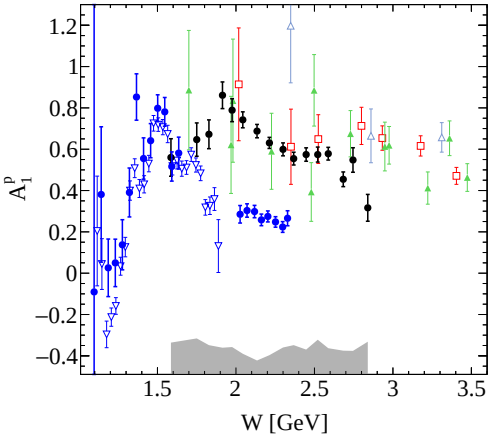
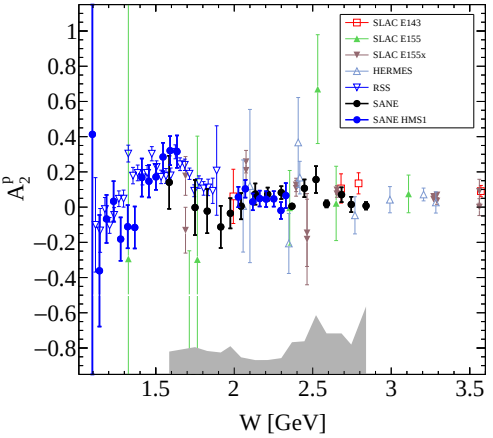
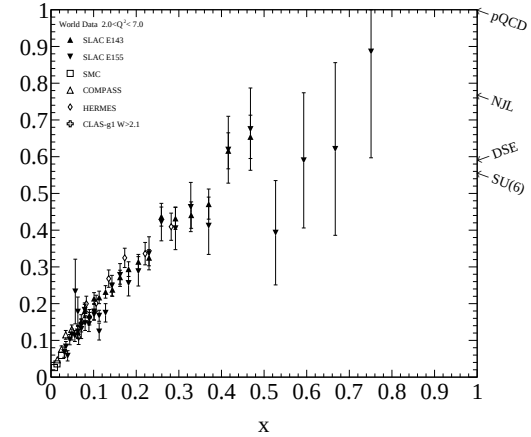
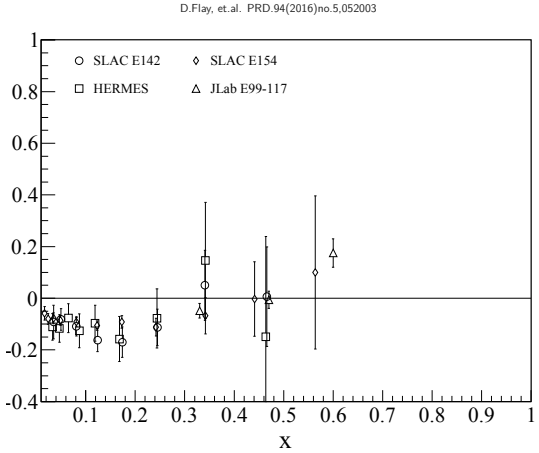




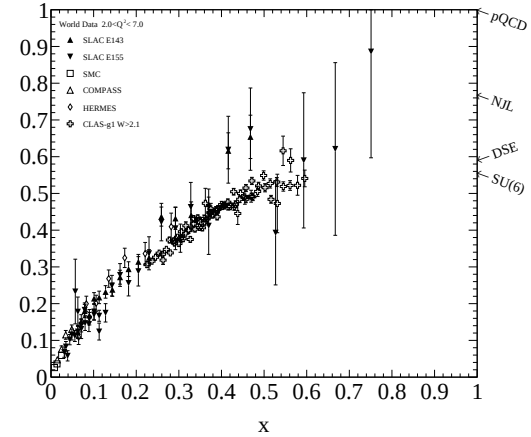
Valence domain: A_1 at high x

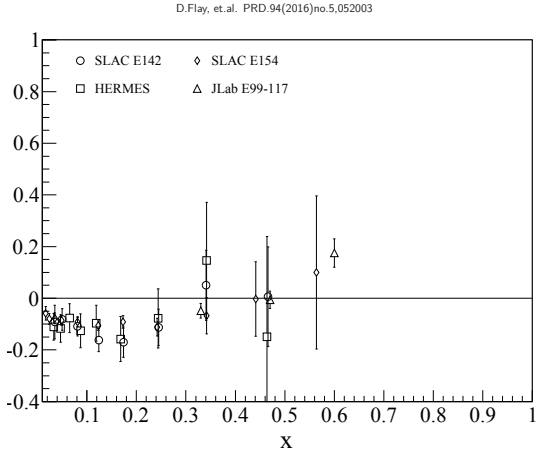




- A_1 as x$\rightarrow 1$

Valence domain: A_1 at high x





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

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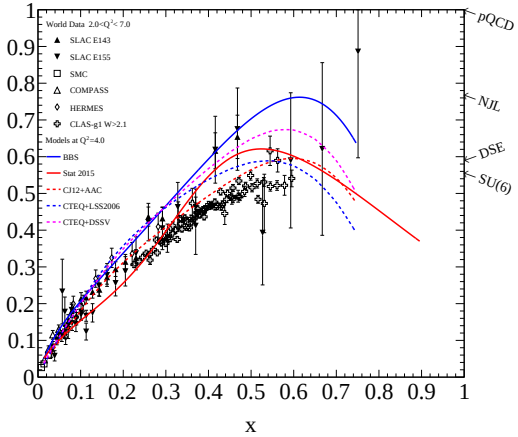

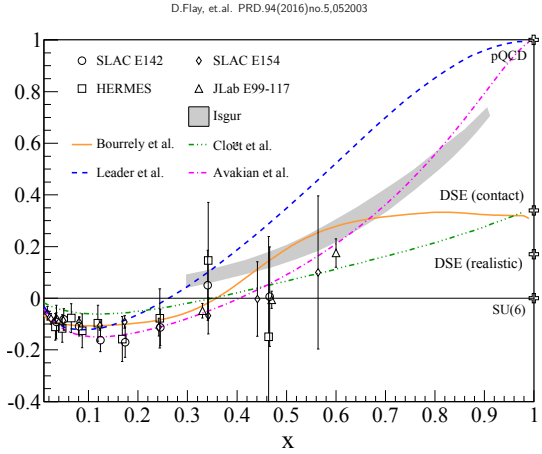

- A_1 as x$\to 1$
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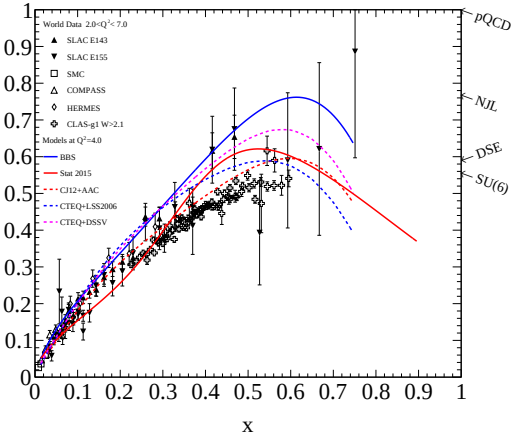
- Many predictions from models and fits

Valence domain: A_1 at high x



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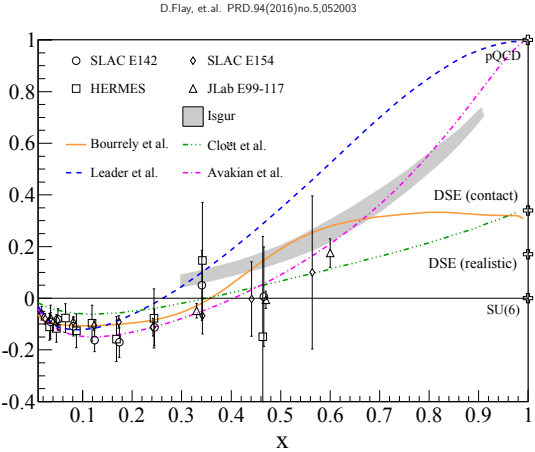
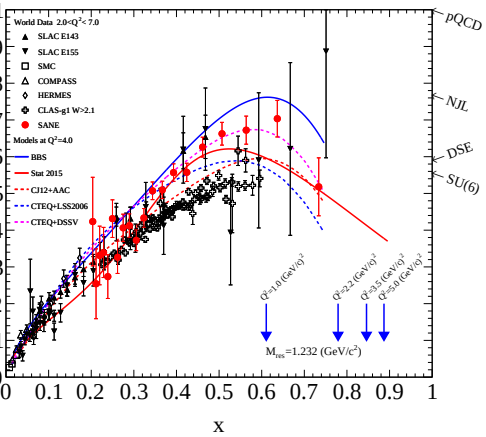


- Dyson-Schwinger Equations (DSE) $x = 1$ predictions (Roberts, Holt, Schmidt)

Valence domain: A_1 at high x



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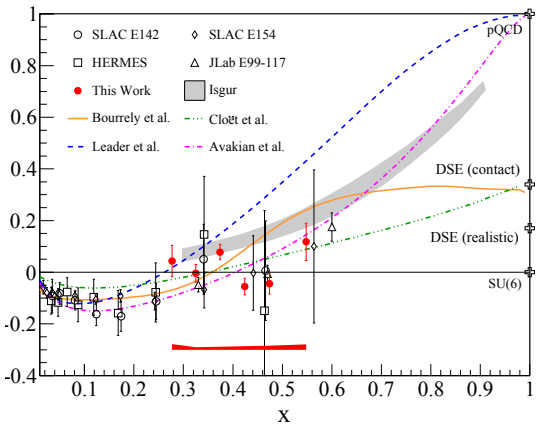
D.Flay, et.al. PRD.94(2016)no.5,052003



- 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

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

Thank You!