The SANE and d_2^n Experiments and QCD Color Forces

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The Strong Force

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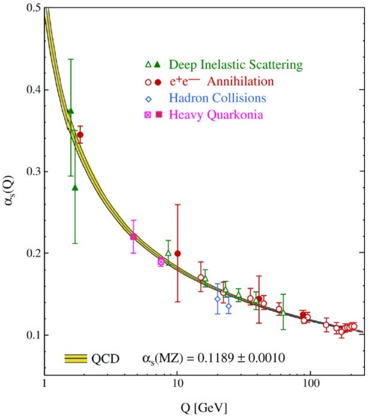
Quantum Chromodynamics

- $L_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$
- 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 → 2004 Nobel prize (Gross,Wilczek,Politzer)
- Many successful predictions from pQCD at high energies.



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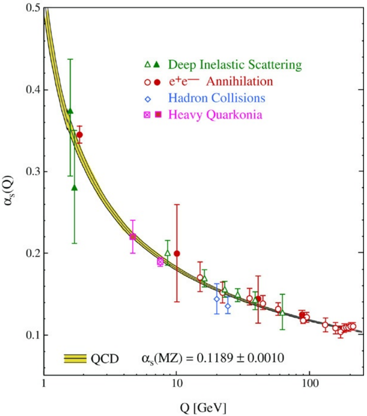

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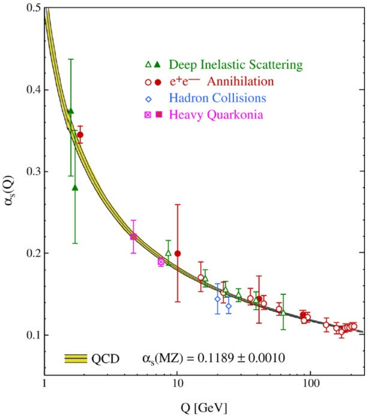

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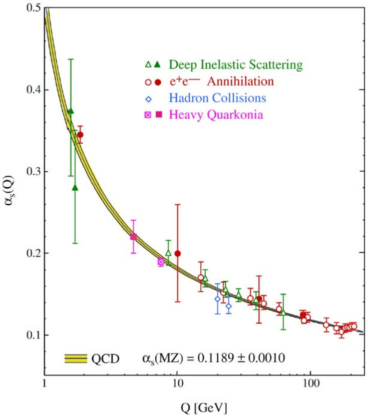

QCD is believed to be the correct theory of the strong force.
QCD should be able to describe the structure of the proton and neutron.
However, perturbative techniques cannot describe the complex bound state of quark and gluon fields composing the proton.

What does the nucleon look like?

size ←

Q^2 →

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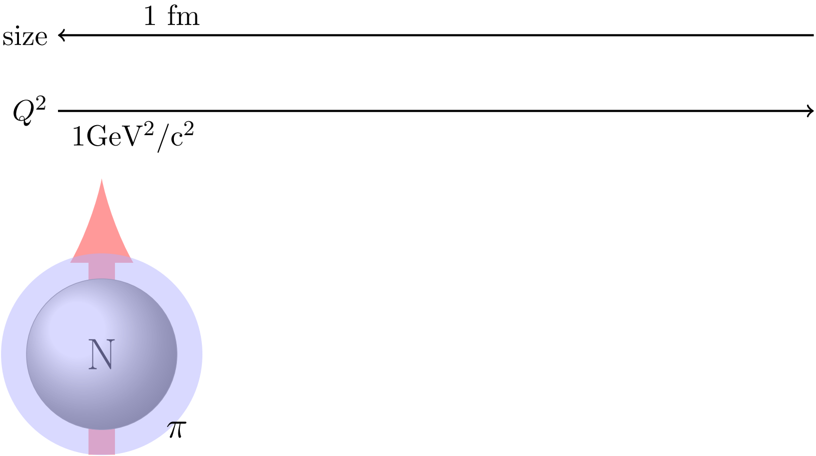

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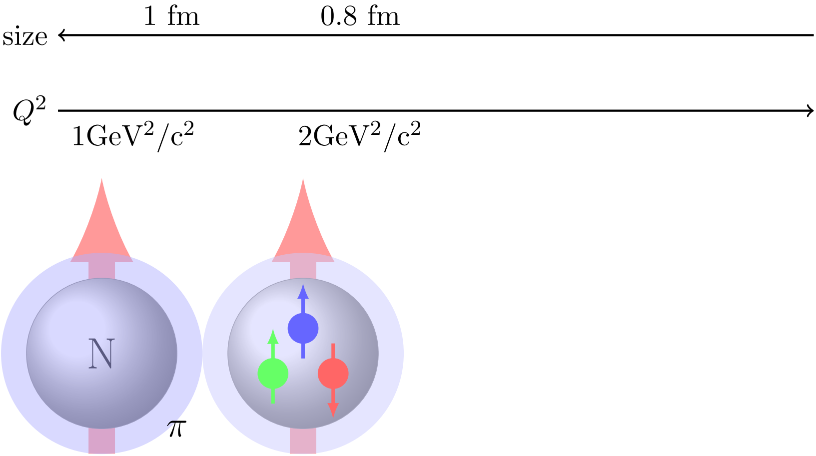

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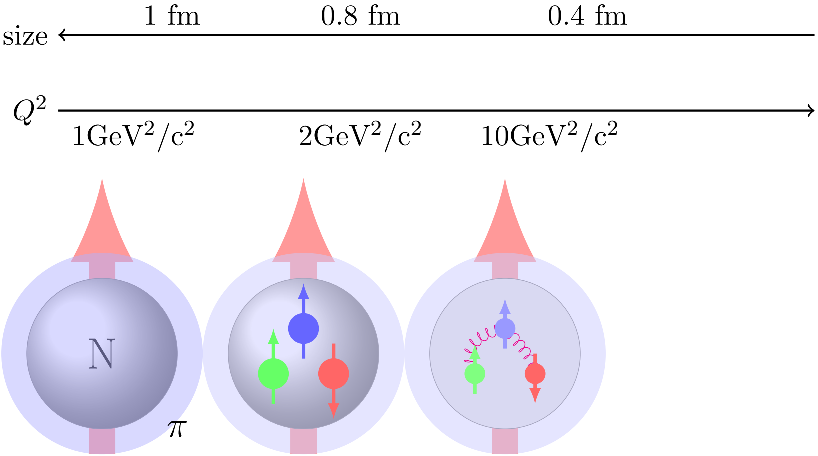

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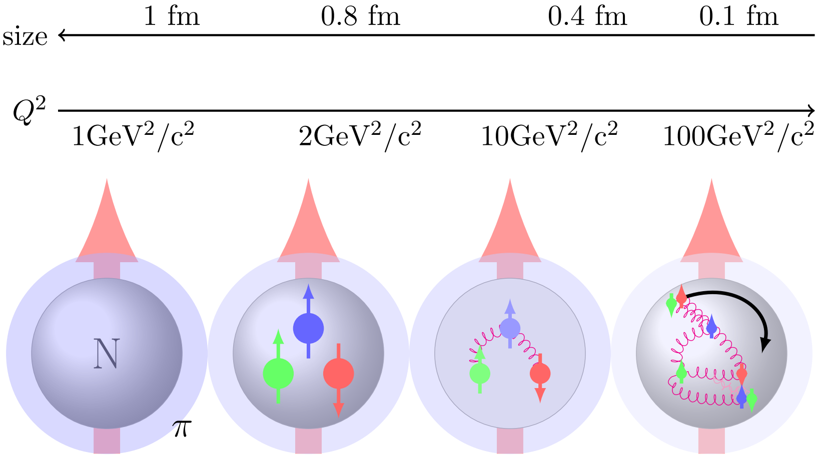

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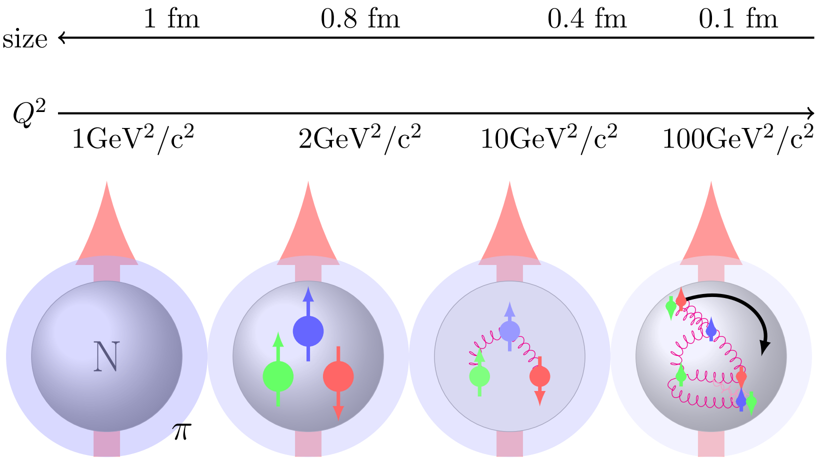


Use our understanding of pQCD at high Q^2 to begin to test our understanding at lower Q^2 $\rightarrow$ Operator Product Expansion

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

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

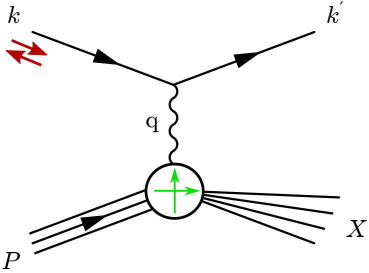
$$A_\perp = \frac{\sigma^{\Leftarrow\downarrow} - \sigma^{\Leftarrow\uparrow}}{\sigma^{\Leftarrow\downarrow} + \sigma^{\Leftarrow\uparrow}}$$

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

$$\nu = E - E'$$

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

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



Why is a transversely polarized target needed?

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

$\rightarrow$ 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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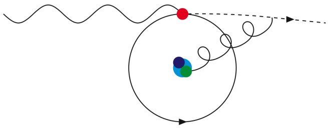
M. Burkardt Phys.Rev.D 88,114502 (2013)and Nucl.Phys.A735,185(2004).

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

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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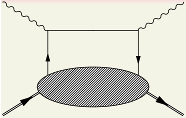

$$g_2^{WW}(x,Q^2) = -g_1^{LT}(x,Q^2) + \int_x^1 g_1^{LT}(y,Q^2)\mathrm{d}y/y$$
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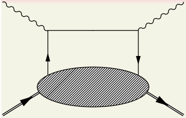

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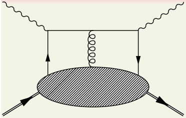

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$
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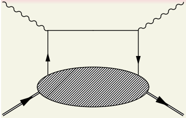

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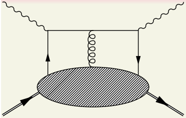

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$$= \int_0^1 x^2(2g_1(x,Q^2) + 3g_2(x,Q^2))dx$$

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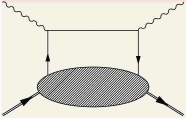

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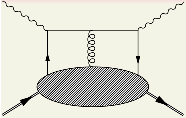

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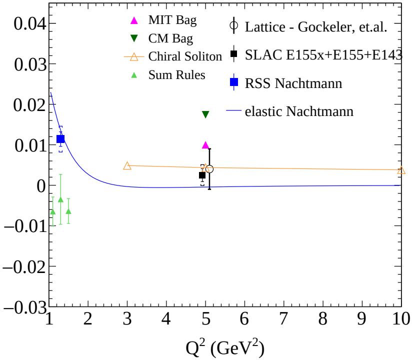
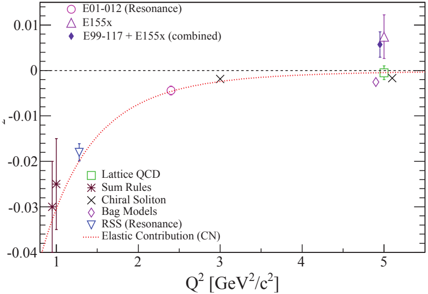
As Q^2 decreases,
when do higher twists begin to matter?
When is the color force non-zero?

Predictions and previous measurements of d_2

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

$$d_2^{Nacht} = \int_0^1 \xi^2 \left[2\frac{\xi}{x}g_1 + 3\left(1 - \frac{\xi^2 M^2}{2Q^2}\right) g_2\right]dx$$





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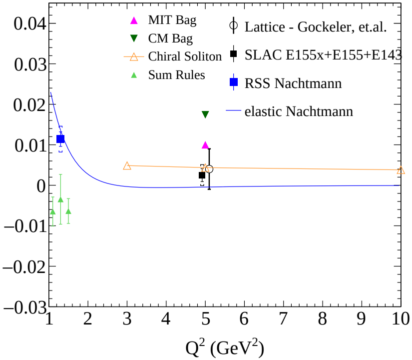

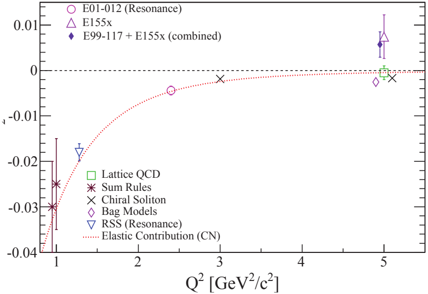

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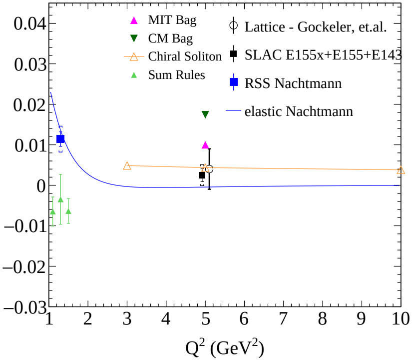

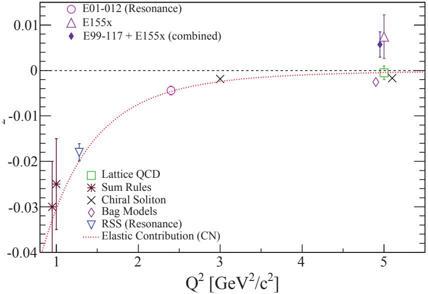

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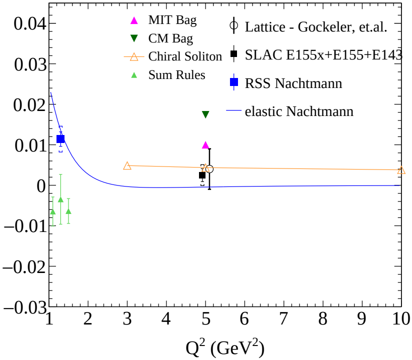

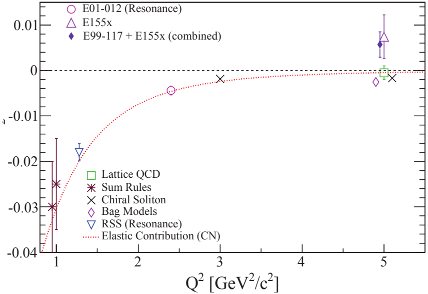

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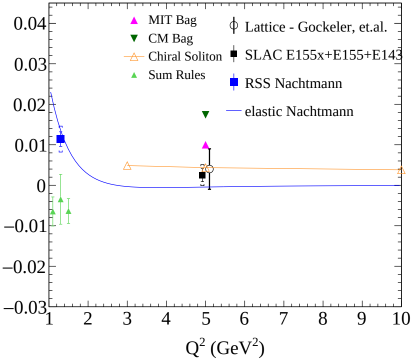

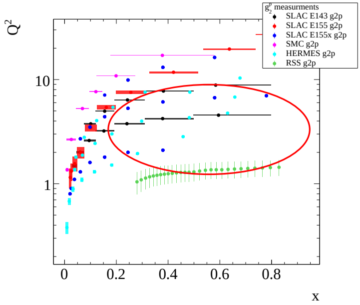

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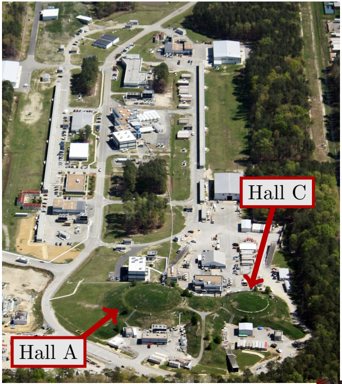
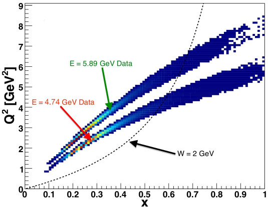
- First point in Qui-Sterman M.E. found in SIDIS

Complementary Jlab Experiments



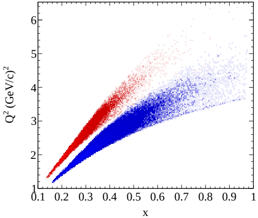
Hall A → neutron

E06-014 : d_2^n



Hall C → proton

E07-003 : SANE

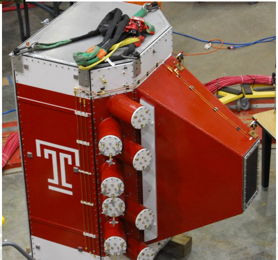


Similar kinematic coverage

Both used 4.7 GeV and 5.9 GeV beams

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

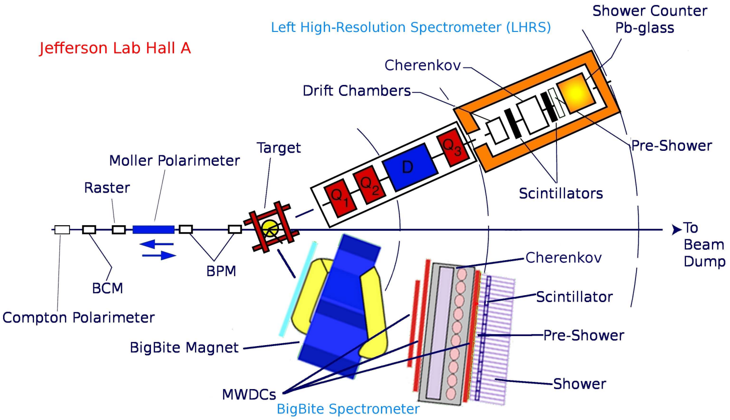
Both required new gas Cherenkov counters with existing detectors



E06-014 : The d_2^n Experiment

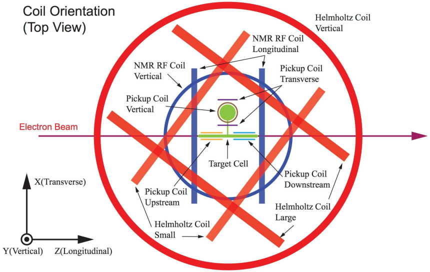
Spokespeople

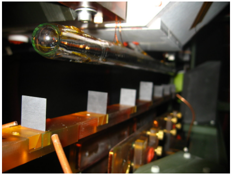
B. Sawatzky, S. Choi, X. Jiang, and Z.-E. Meziani

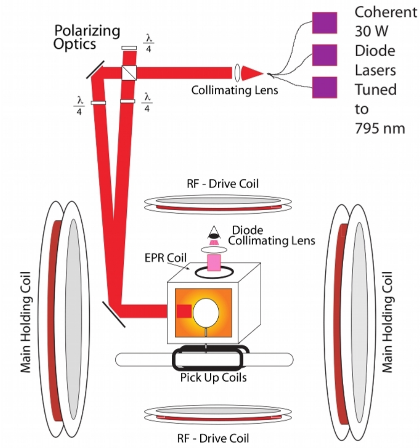


E06-014 : The d_2^n Experiment

- Polarized ^{3}He target

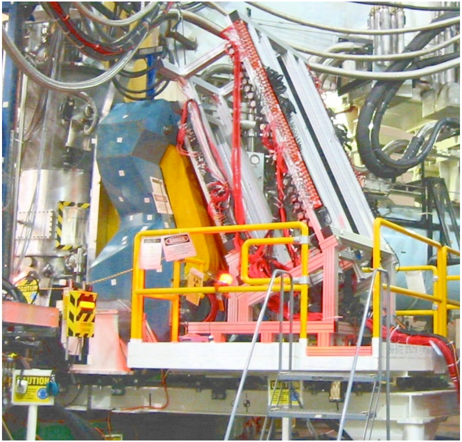


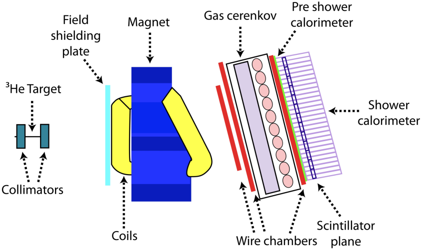




E06-014 : The d_2^n Experiment

- Polarized ^{3}He target
- BigBite spectrometer





E06-014 : The d_2^n Experiment

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

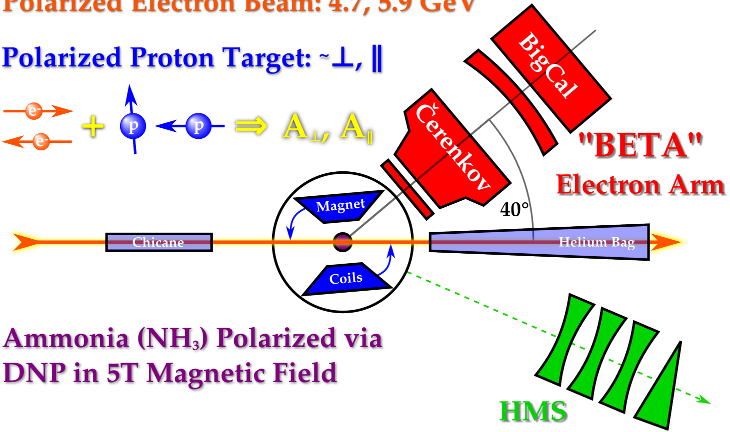
E07-003 : Spin Asymmetries of the Nucleon Experiment

Spokespeople

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

Polarized Electron Beam: 4.7, 5.9 GeV

Polarized Proton Target: ~⊥, ∥

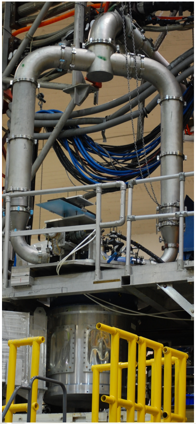


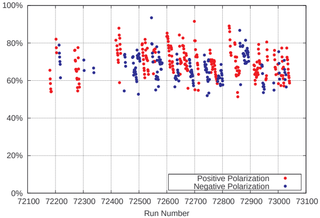
Ammonia (NH_3) Polarized via DNP in 5T Magnetic Field

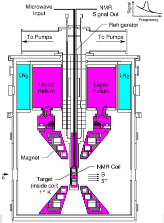
E07-003 : Spin Asymmetries of the Nucleon Experiment

SANE

- Polarized Ammonia Target





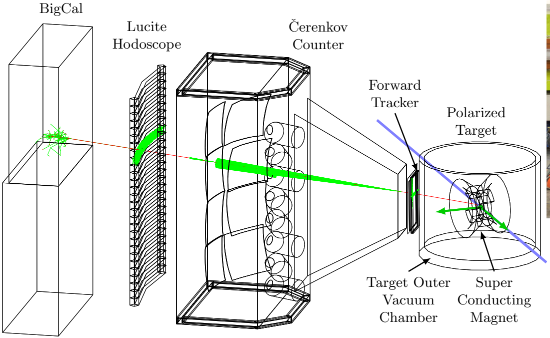


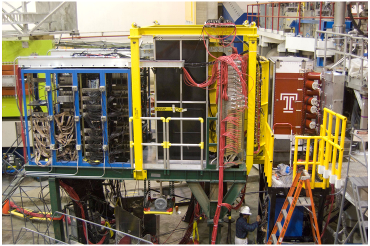
- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%

E07-003 : Spin Asymmetries of the Nucleon Experiment

SANE

- Polarized Ammonia Target
- **B**ig **E**lectron **T**elescope **A**rray

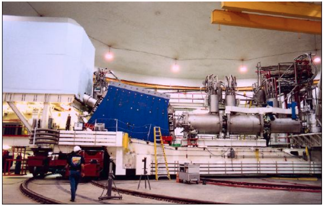


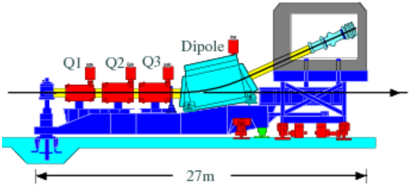


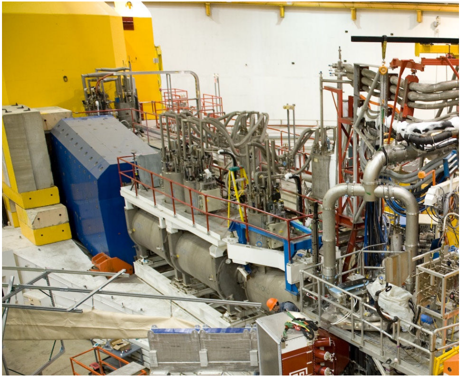
E07-003 : Spin Asymmetries of the Nucleon Experiment

SANE

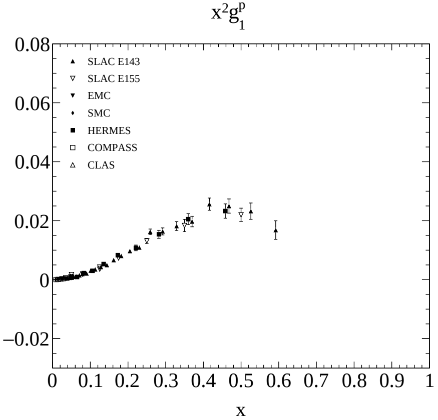
- Polarized Ammonia Target
- **B**ig **E**lectron **T**elescope **A**rray
- HMS data taken as well for resonance spin structure (Hoyoung Kang) and G_E/G_M (Anusha Liyanage)

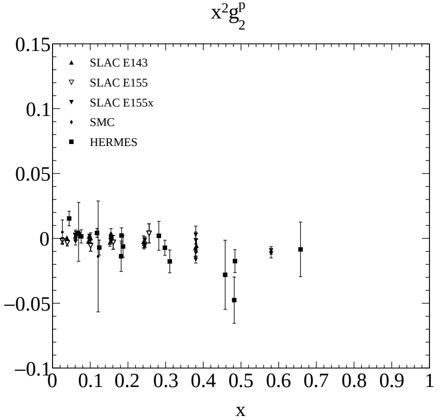






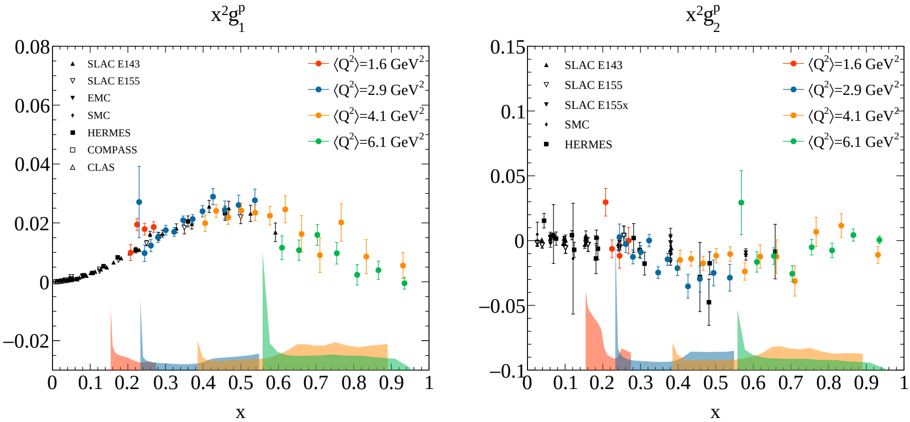
SANE results for $x^2 g_1^p$ and $x^2 g_2^p$





Models are showing g_2^{WW}.

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



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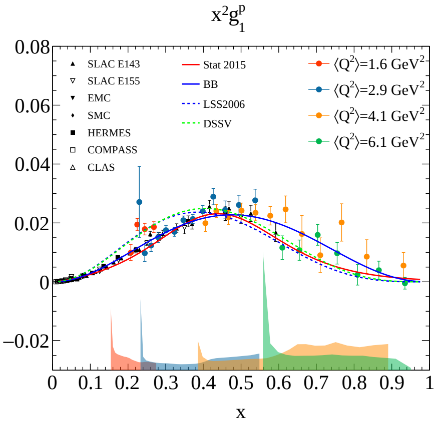
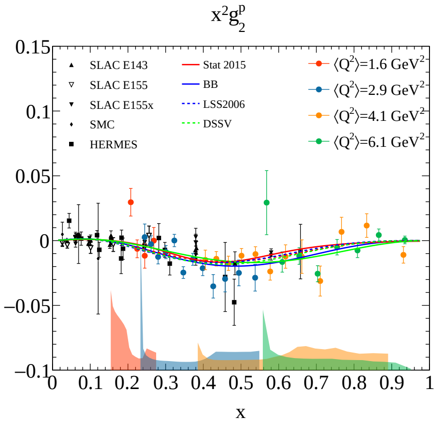
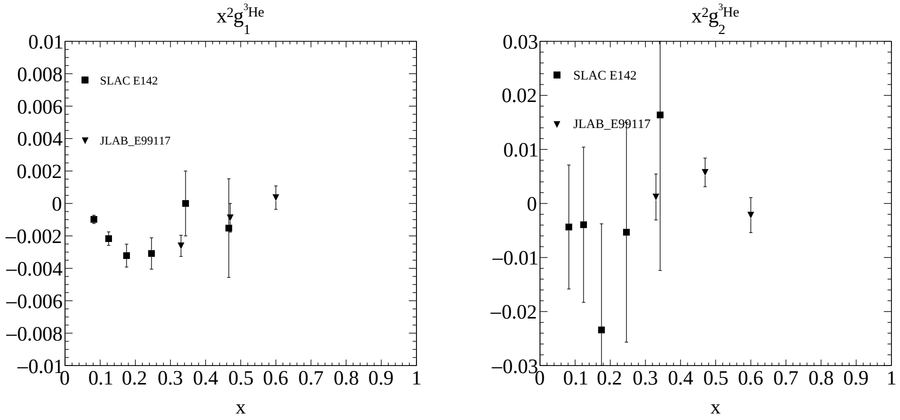




Models are showing g_2^{WW}.

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



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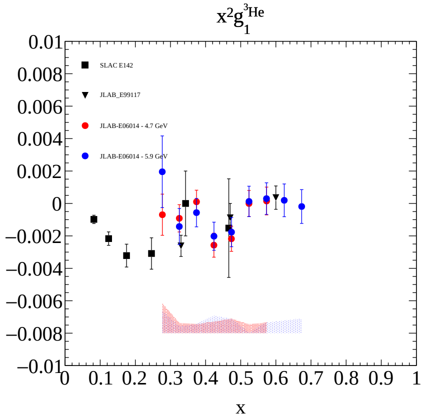

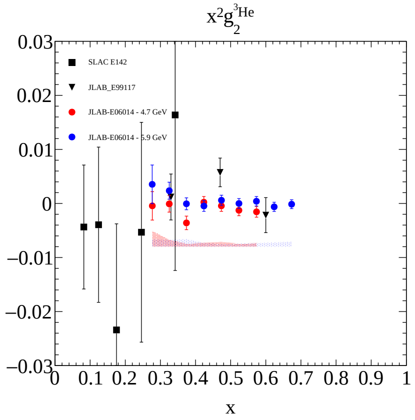

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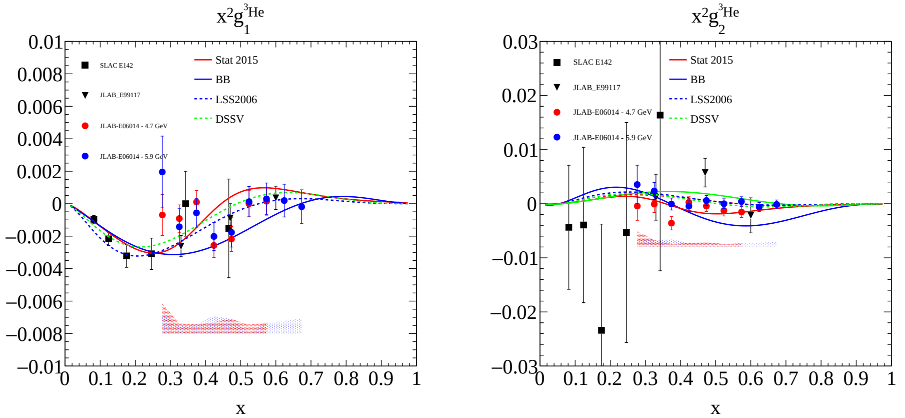
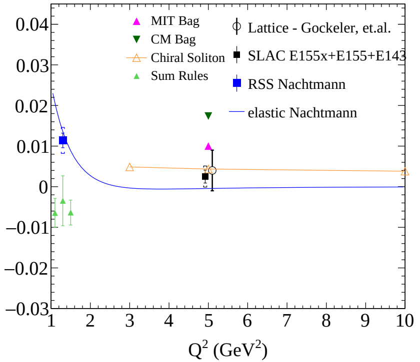


Models are showing g_2^{WW}.

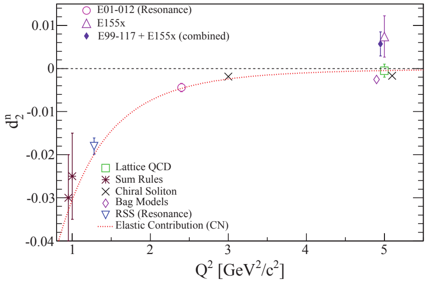
$$d_2^{CN} = \int_0^1 x^2(2g_1+3g_2)dx$$

$$d_2^{Nacht} = \int_0^1 \xi^2\left[2\frac{\xi}{x}g_1+3\left(1-\frac{\xi^2M^2}{2Q^2}\right)g_2\right]dx$$

proton



neutron



Existing data

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

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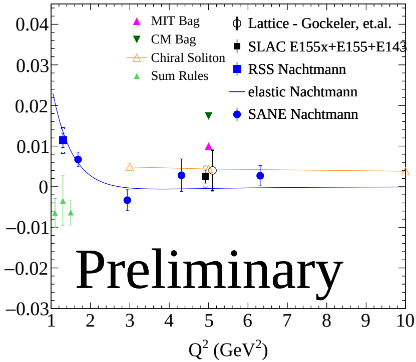
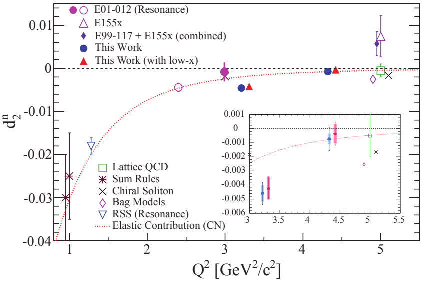


neutron



Recent results from d_2^n experiment
M.Posik, et.al. PRL.113(2014)

SANE and d_2^n Result

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

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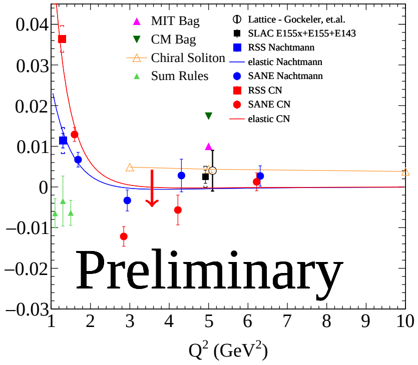
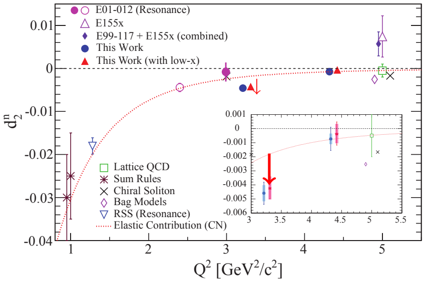


neutron



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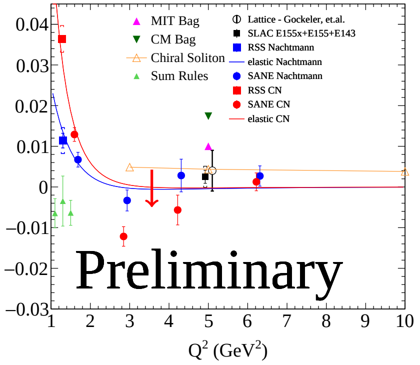
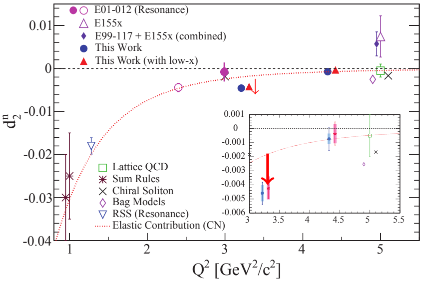
proton



neutron



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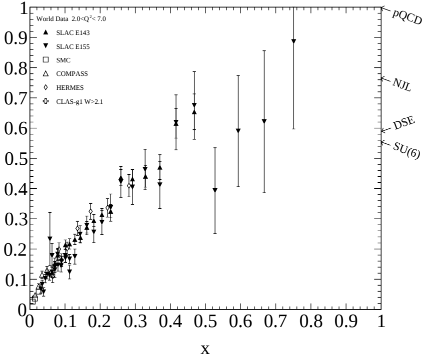
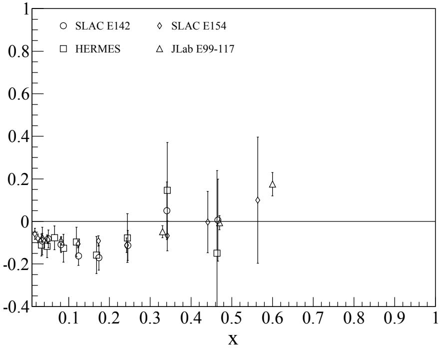
SANE and d_2^n Result

- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
- Is this a isospin independent average color force?
- Updated Lattice calculations are long over due!

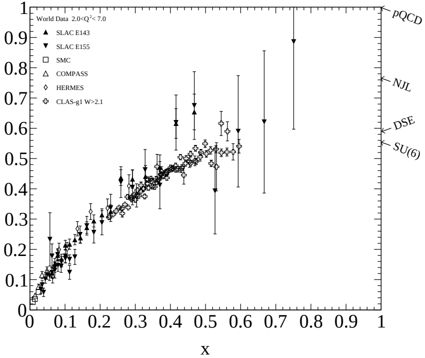
Valence domain: high x

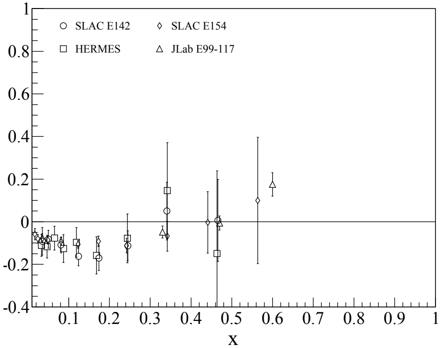




- A_1 as x$\rightarrow$ 1

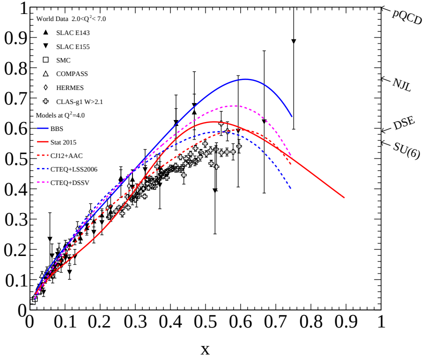
Valence domain: high x

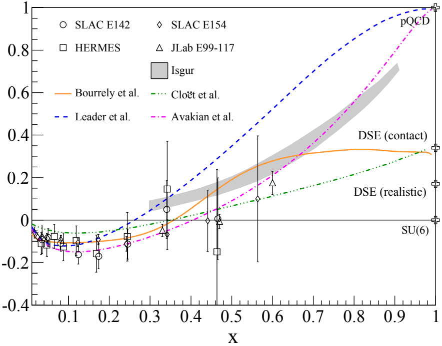




- A_1 as x→ 1
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.

Valence domain: high x





- A_1 as x→ 1
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- Many predictions from models and fits

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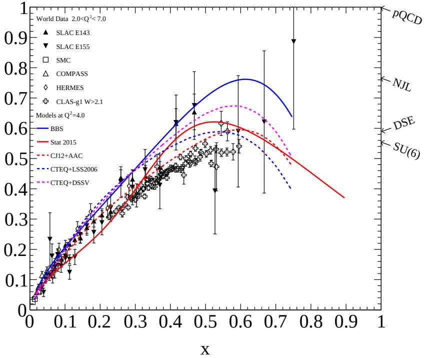

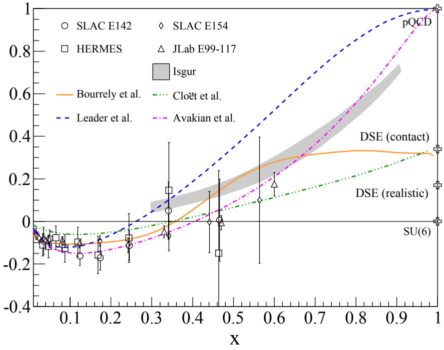

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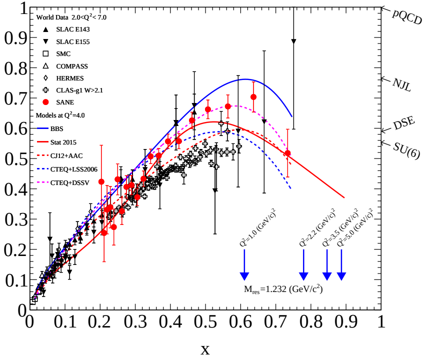

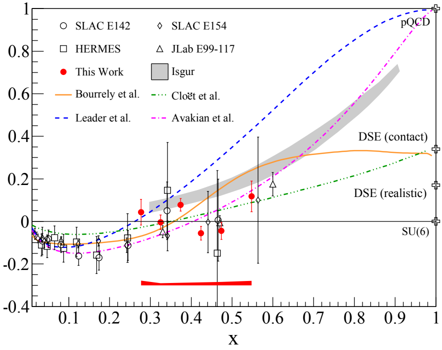

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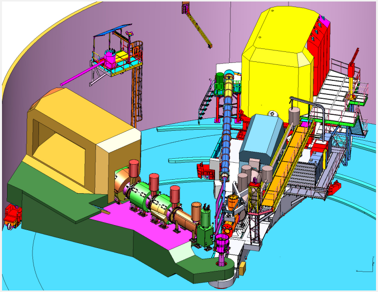
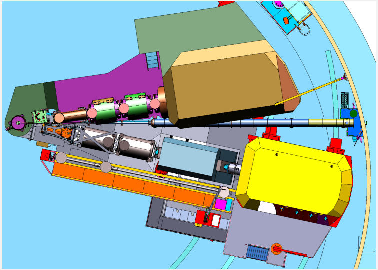
- Many predictions from models and fits
- Dyson-Schwinger Equations (DSE) $x = 1$ predictions (Roberts, Holt, Schmidt)

- SANE data goes out to x≃0.8 → use duality to check limit

Jlab at 12 GeV

SHMS in Hall C

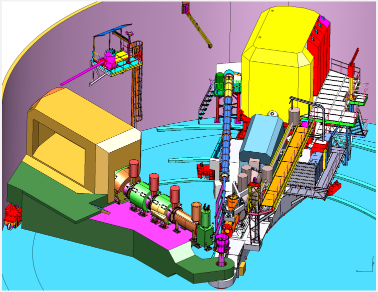


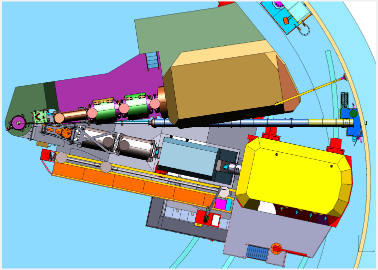


SHMS will be able to go to small angles (5.5°)

Jlab at 12 GeV

SHMS in Hall C





SHMS will be able to go to small angles (5.5°)

- JLab 12GeV neutron experiments (Hall C and Hall A) will extend to higher Q^2 with more uniform coverage.

Jlab at 12 GeV

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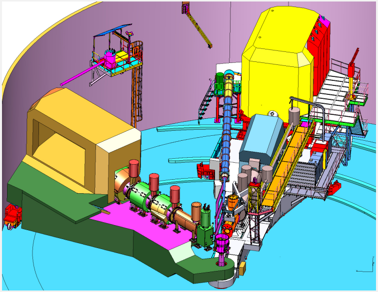

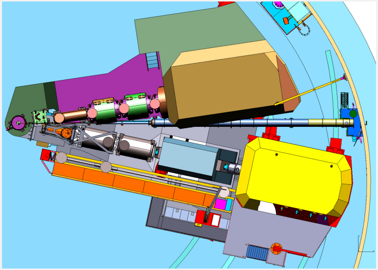

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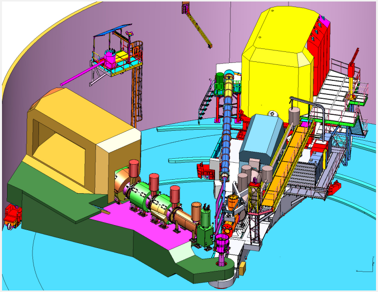
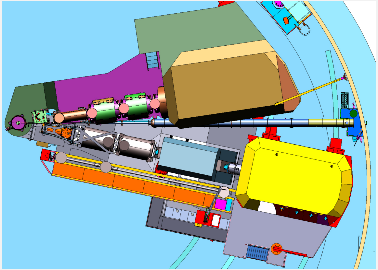
Jlab at 12 GeV

SHMS in Hall C





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- JLab 12GeV neutron experiments (Hall C and Hall A) will extend to higher Q^2 with more uniform coverage.
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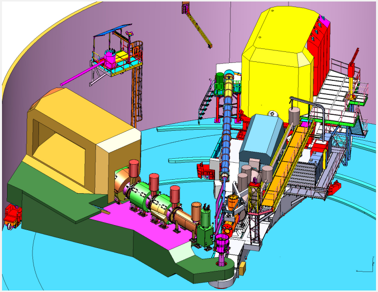
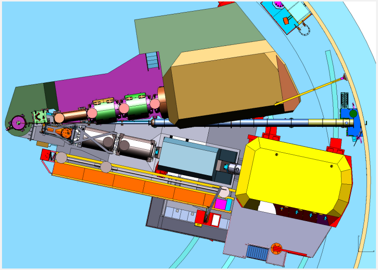
Jlab at 12 GeV

SHMS in Hall C





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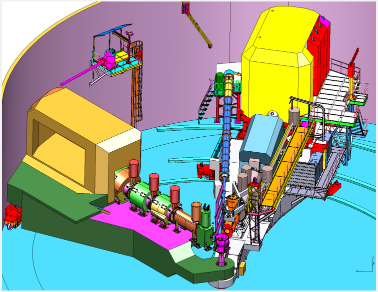
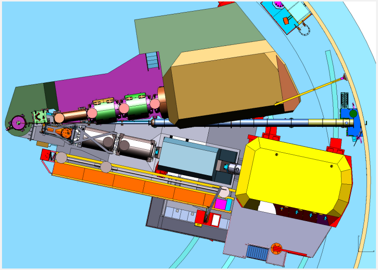
- A dedicated experiment with transversely polarized proton target is worthwhile effort at 12 GeV.
- Proposal to match the expected neutron precision, possible options: Hall C, SOLID, CLAS12
- High x and high Q^2 data on g_1 **and** g_2 is needed to **cleanly** extract the leading twist PDFs → At present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

Jlab at 12 GeV

SHMS in Hall C





SHMS will be able to go to small angles (5.5°)

- 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 $Q^2 = 1\text{GeV}^2$!
- While a future EIC will mainly focus on the **sea** quarks and gluons, JLab will continue to present a unique opportunity for studying QCD and the structure of the nucleon to high precision in the **valence region**.

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Thank You!

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