Latest Results From JLab Longitudinal Spin Experiments

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Outline

- QCD and spin physics
- Polarized DIS and spin structure functions
- Experiments at Jefferson Lab for g_1 and g_2
- SANE and EG4
- Other experiments for g_2 and at 12 GeV
- Summary

Nucleon Spin Structure

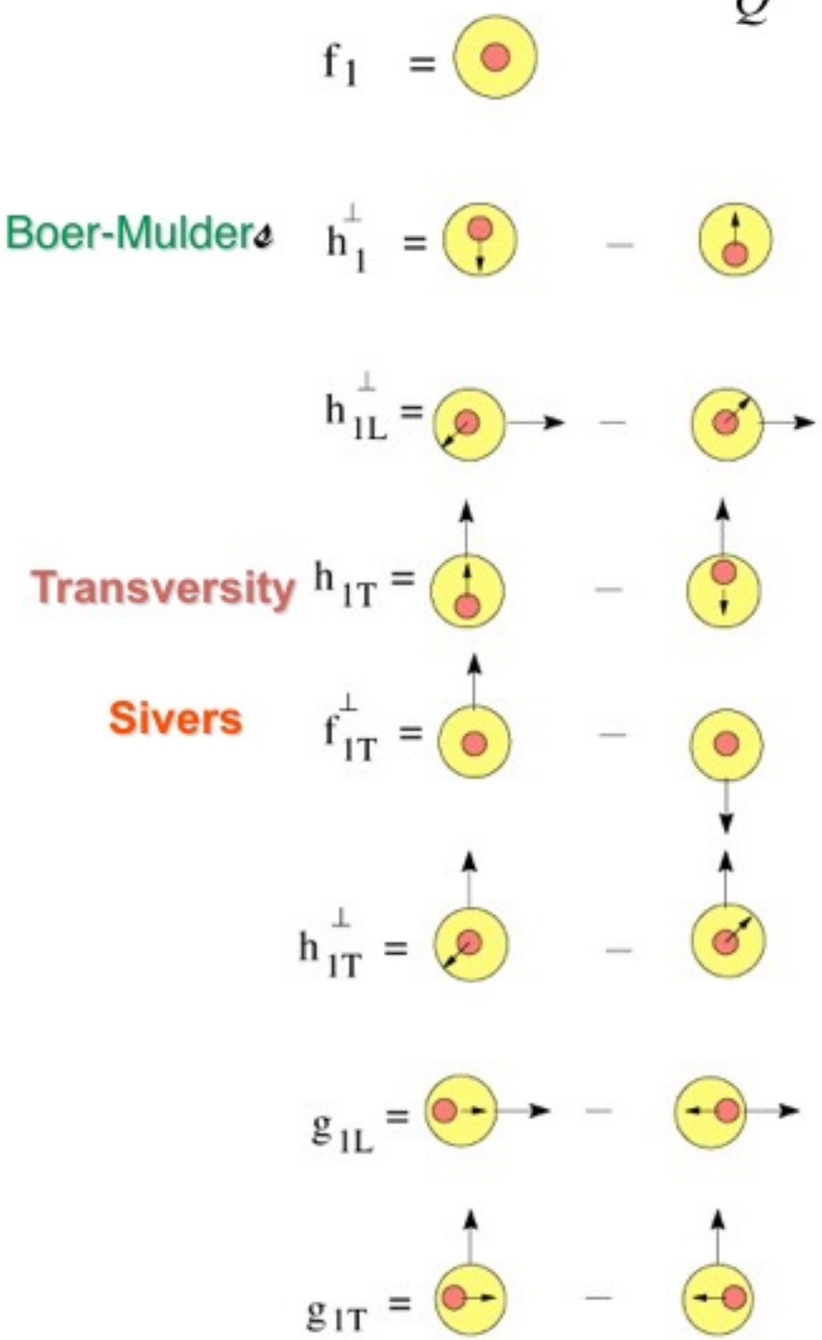
- Explaining nucleon spin in terms of quarks and gluons (QCD)
  - Nucleon spin is 1/2
    - De-composition is not trivial
    - ~30% from quark spins
    - Little or no polarized gluons

Solving the Puzzle

- Spin structure functions g_1 and g_2
  - Electron scattering on polarized targets (p, d, ^{3}He)
- Gluon polarization
  - Direct measurement from polarized pp scattering (PHENIX, STAR)
  - QCD evolution from spin structure functions
- Orbital Angular Momentum (OAM)
  - Generalized Parton Distributions

All Eight Quark Distributions Are Probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4} \times$$



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Polarized beam and target

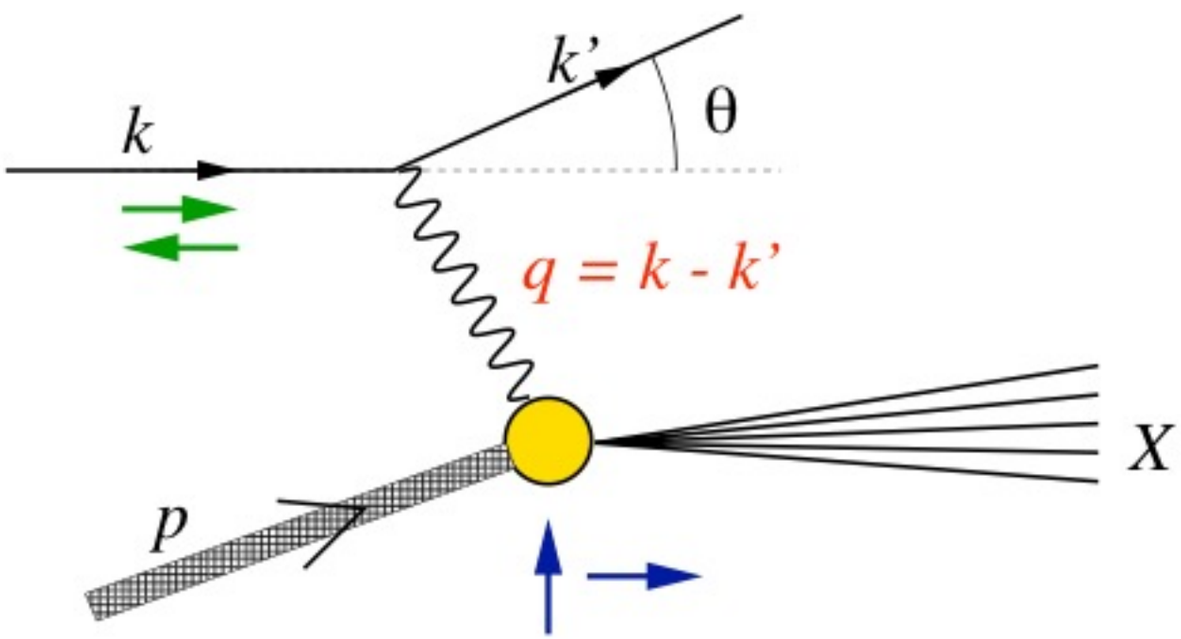
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z, P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λ_e: Beam Polarization

Inclusive e-N Scattering

Deep Inelastic Scattering



$$x_{\text{Bjorken}} = \frac{Q^2}{2M_N\nu}$$

- Four-momentum transfer

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

- Energy transfer to the hadron

$$\nu = E - E'$$

- Mass of the hadronic residual (or invariant mass)

$$W = \sqrt{(p+q)^2}$$
$$= \sqrt{M_N^2 + 2M_N\nu - Q^2}$$

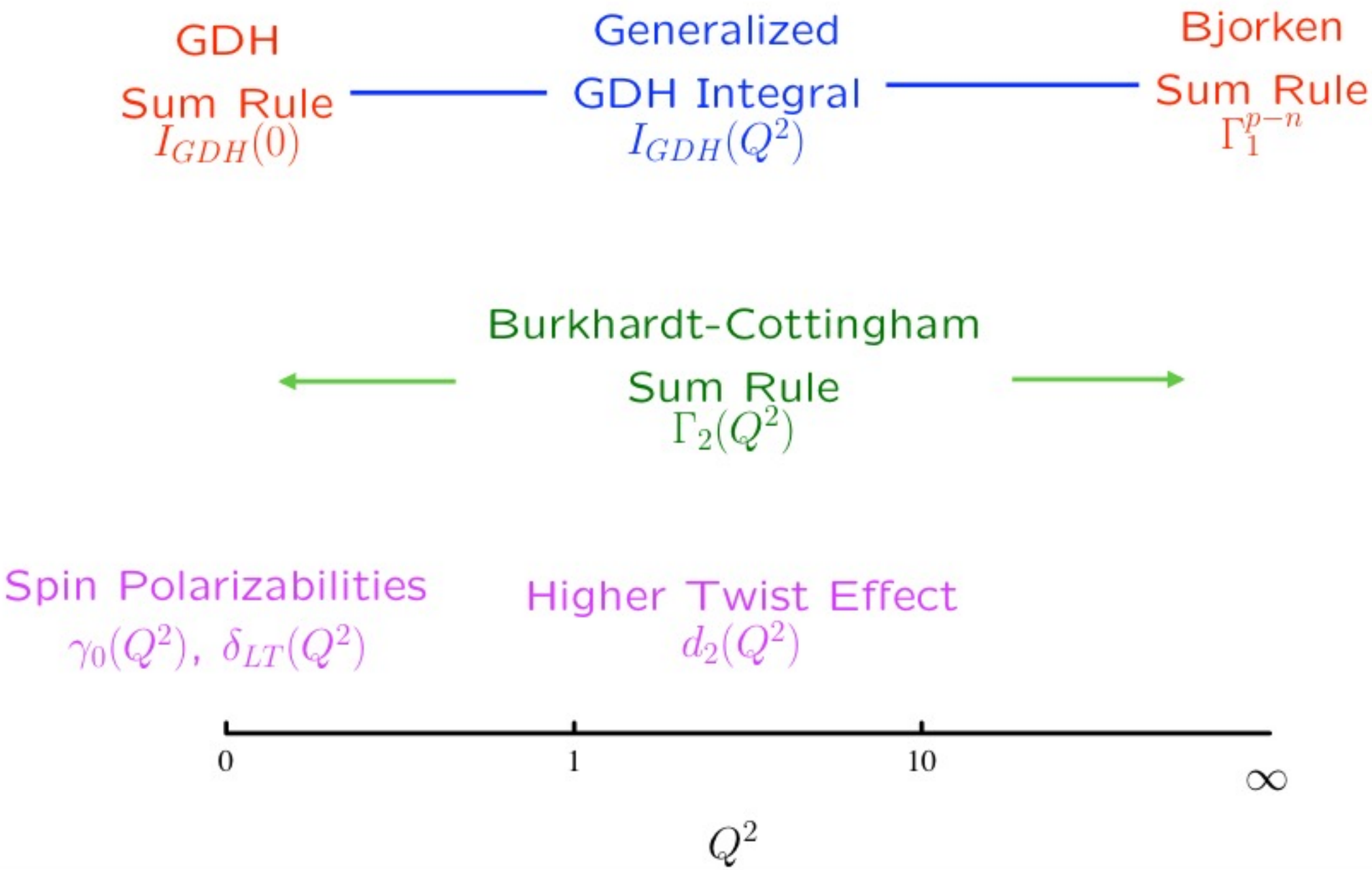
Cross Section & Spin Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left[\frac{F_2}{\nu} + 2\frac{F_1}{M}\tan^2\frac{\theta}{2}\right]$$

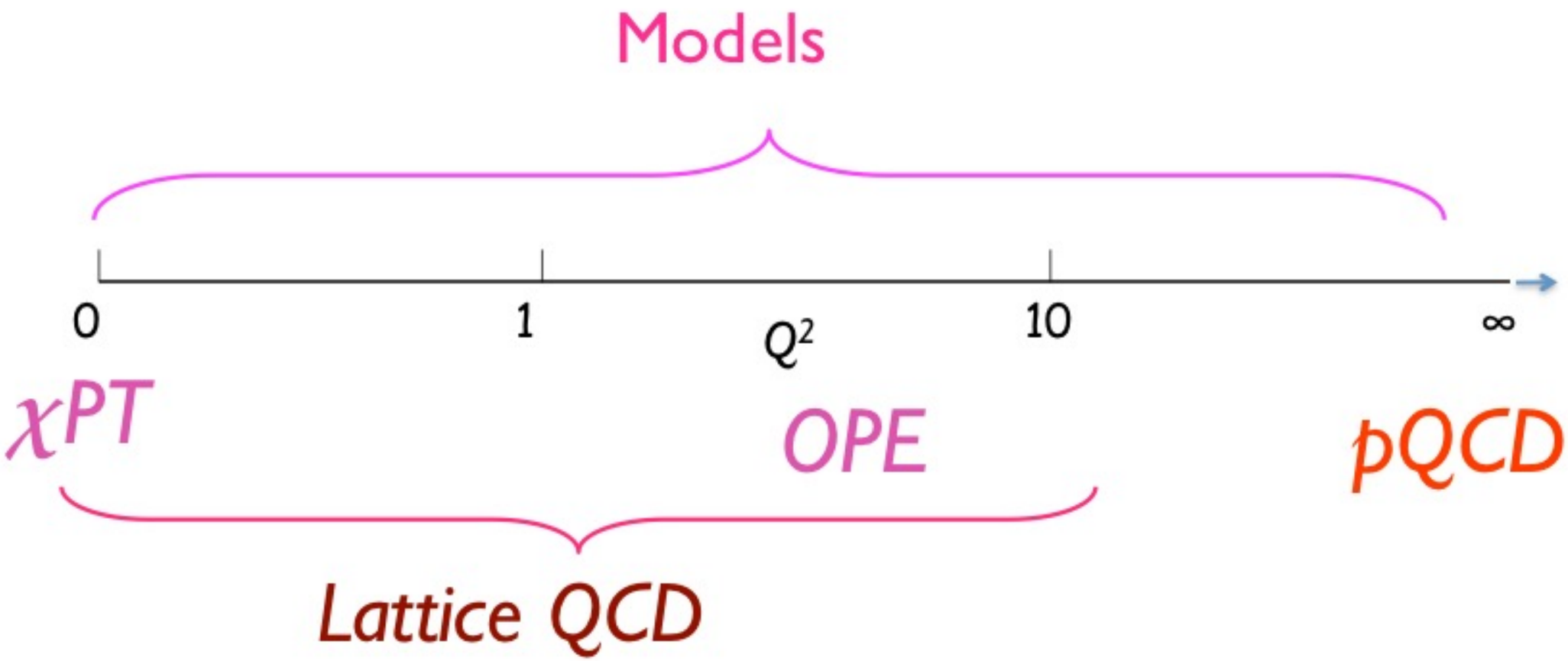
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1 - \frac{Q^2}{\nu}g_2\right]$$

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{E}\frac{1}{\nu^2}(\nu g_1 + 2Eg_2)$$

What to do with g_1 and g_2



Probe Resolution and Theory Tools



Moment of g_1

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

- $Q^2 \to 0$

$$\Gamma_1(Q^2) = -\frac{Q^2}{8M^2}\kappa^2 + O\left(\frac{Q^4}{M^4}\right) \quad \text{(GDH Sum Rule as } Q^2 \to 0,\text{)}$$

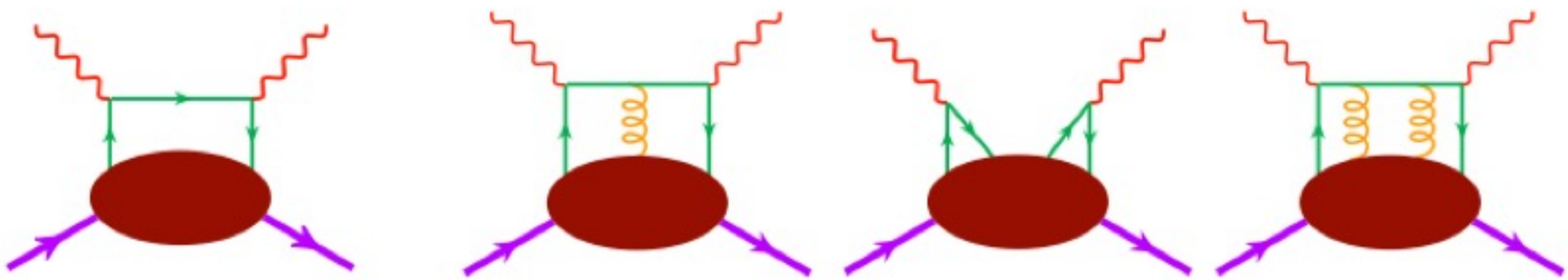
- $Q^2 \to \infty$

$$\begin{aligned} \Gamma_1(Q^2) &= \frac{1}{2}a^{(0)} + \frac{M^2}{9Q^2}(a^{(2)} + 4d^{(2)} + 4f^{(2)}) + O(\frac{M^4}{Q^4}) \\ \Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) &= \frac{1}{6}\left|\frac{g_A}{g_V}\right| \quad \text{as } Q^2 \to \infty \quad \text{(Bjorken Sum Rule)} \end{aligned}$$

g_2 and Higher Twists

- Decomposition of g_2

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



single quark scattering

$\tau = 2$

qq & qg correlations

$\tau > 2$

g_2 and quark-gluon correlations

- a twist-2 term (Wandzura-Wilcek)

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(x,Q^2)\,dx$$

- a twist-3 term with a suppressed twist-2 piece

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

Transversity

qg correlations

d_2 Matrix Element

- Dynamical twist-3 matrix element

$$d_2(Q^2) = 3\int_0^1 x^2 \overline{g}_2(x, Q^2)\, dx$$

$$d_2(Q^2) = \int_0^1 x^2 \left[3g_2(x, Q^2) + 2g_1(x, Q^2)\right]\, dx$$

World Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	SLAC COMPASS HERMES JLab SANE	SLAC COMPASS HERMES	SLAC JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	COMPASS HERMES JLab RSS	COMPASS HERMES JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	COMPASS JLab E08-027	COMPASS	JLab E97-110
g_1 at high Q^2	SMC, HERMES JLab EG1	SMC, HERMES JLab EG1	HERMES
g_1 at low Q^2	SLAC, HERMES JLab EG1	SLAC, HERMES JLab EG1	HERMES
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

JLab Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	JLab SANE		JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	JLab E08-027		-110
g_1 at high Q^2	JLab EG1		
g_1 at low Q^2	JLab EG1	JLab EG1	
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

Hall-C

Hall-A

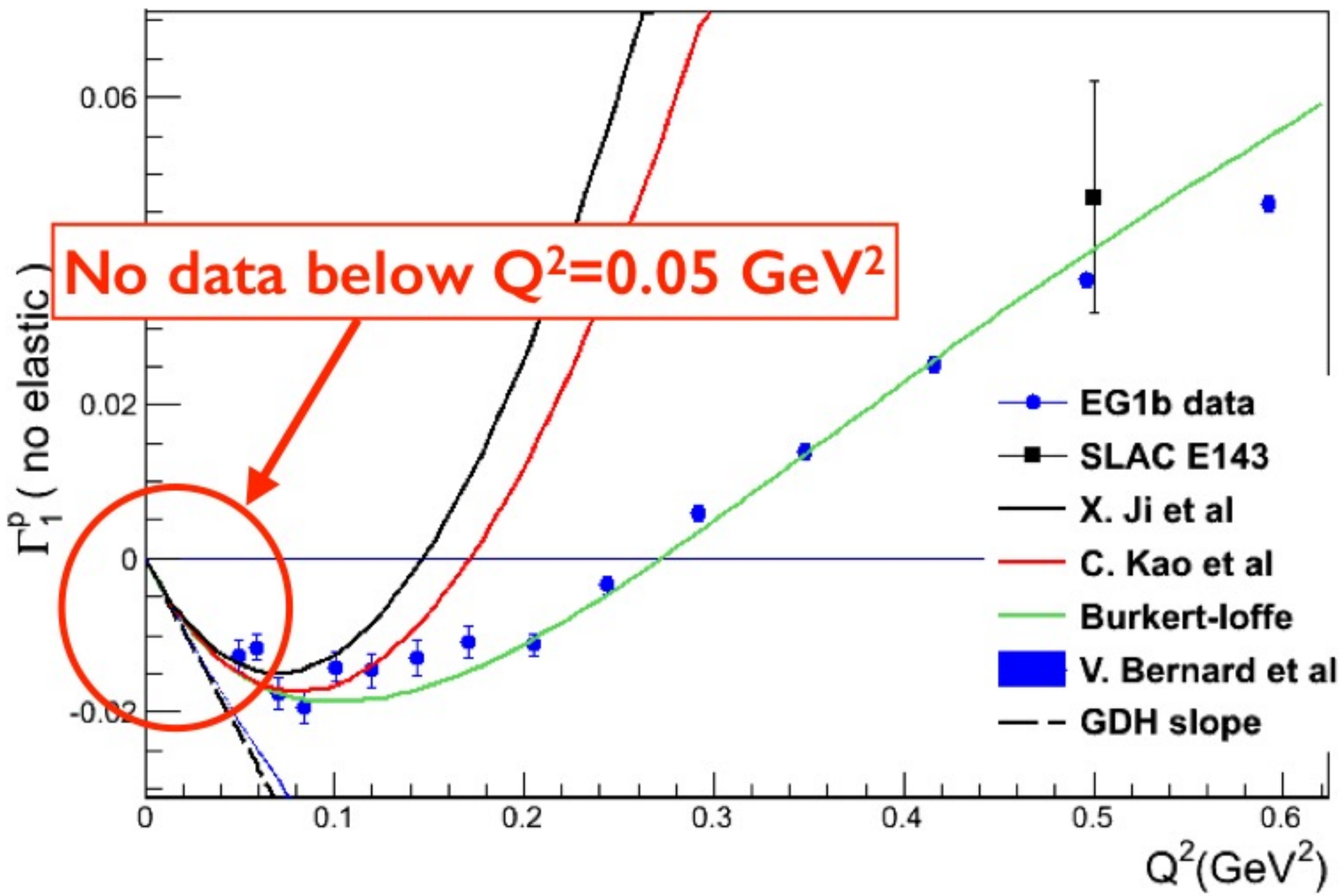
Focus of This Talk

Will be briefly mentioned

Hall-B

CLAS eg4
Proton Spin at Low Q^2

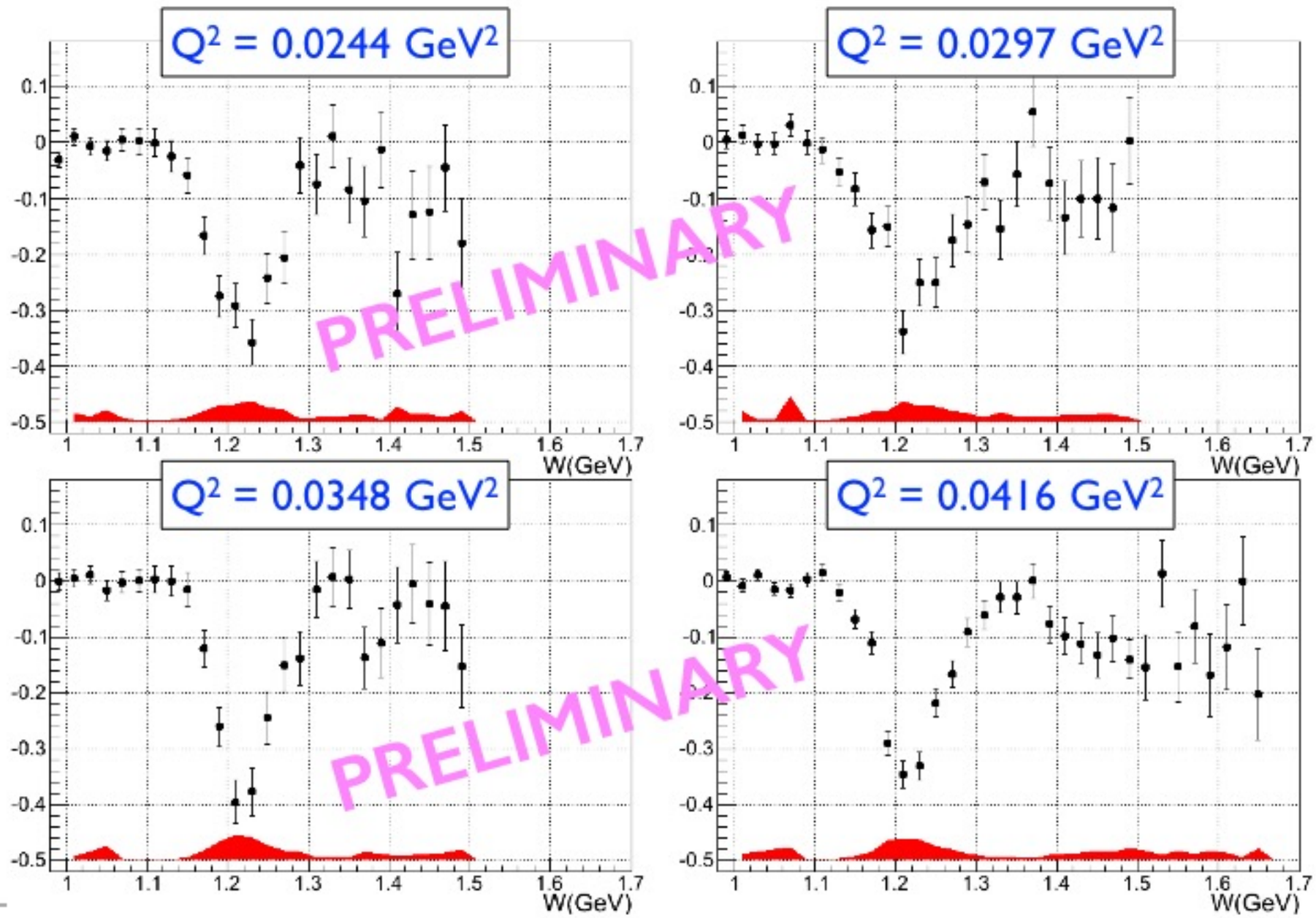
Previous Results



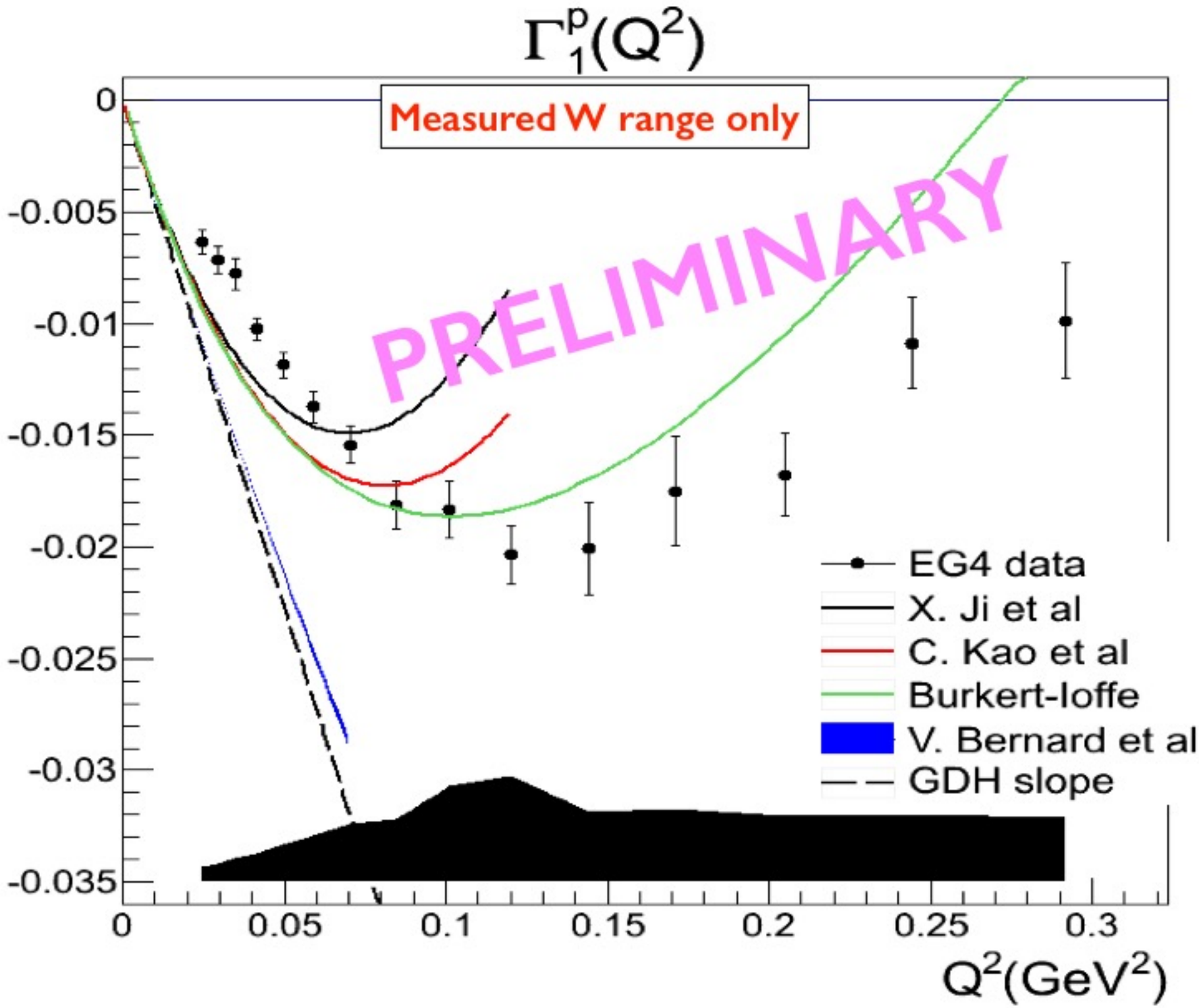
Experiment Summary

- **Beam**: polarized electron beam (Jefferson Lab) at **1.0, 1.3, 2.0, 2.3** and **3.0** GeV
- **Target**: Polarized **Proton** (NH_3) and **Deuteron** (ND_3) target
  - Orientation: parallel (180°)
- **Detectors**: **CLAS** of Hall-B
- Scattering angle: ~8° to ~30°

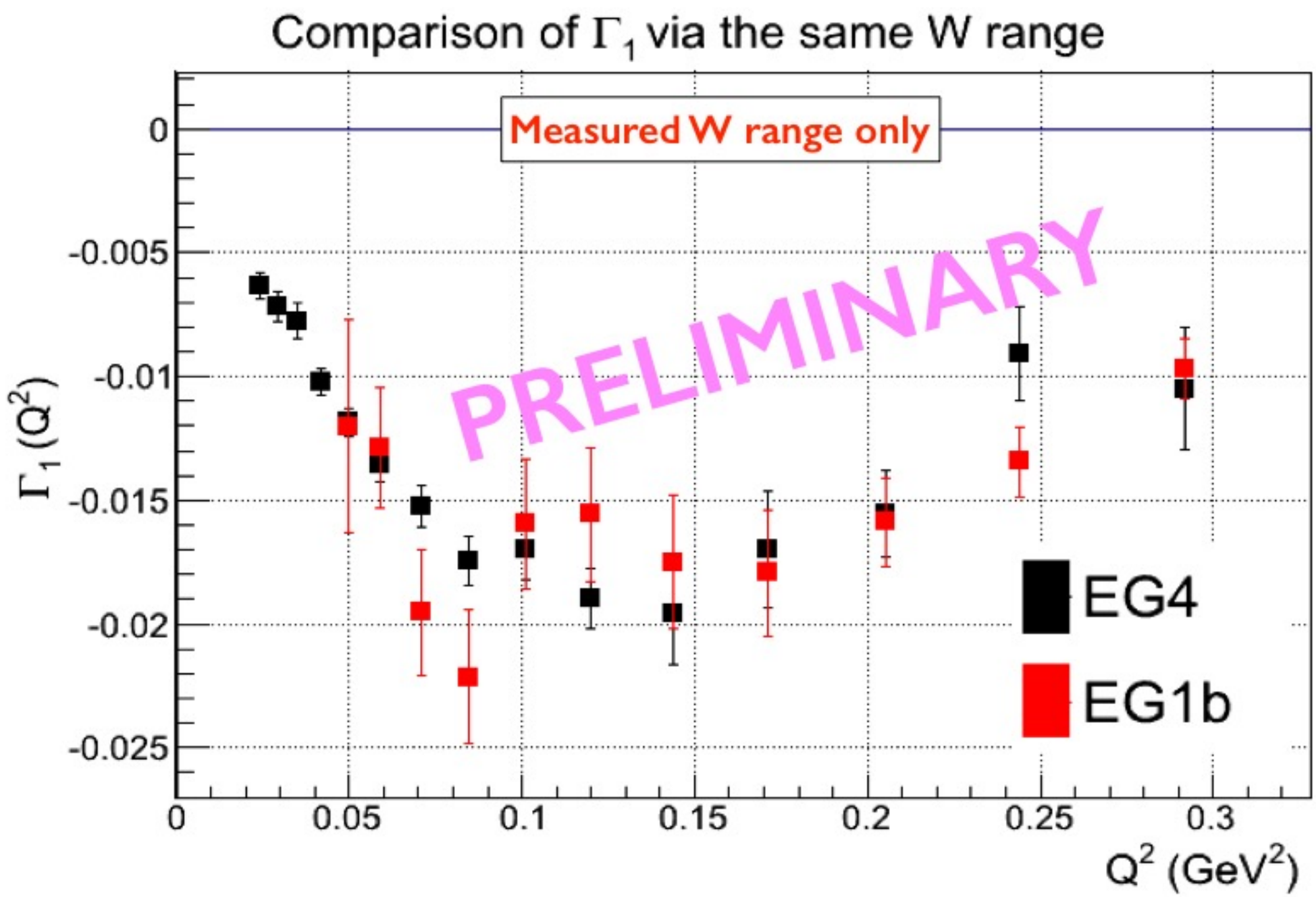
Spin Structure Function g_1



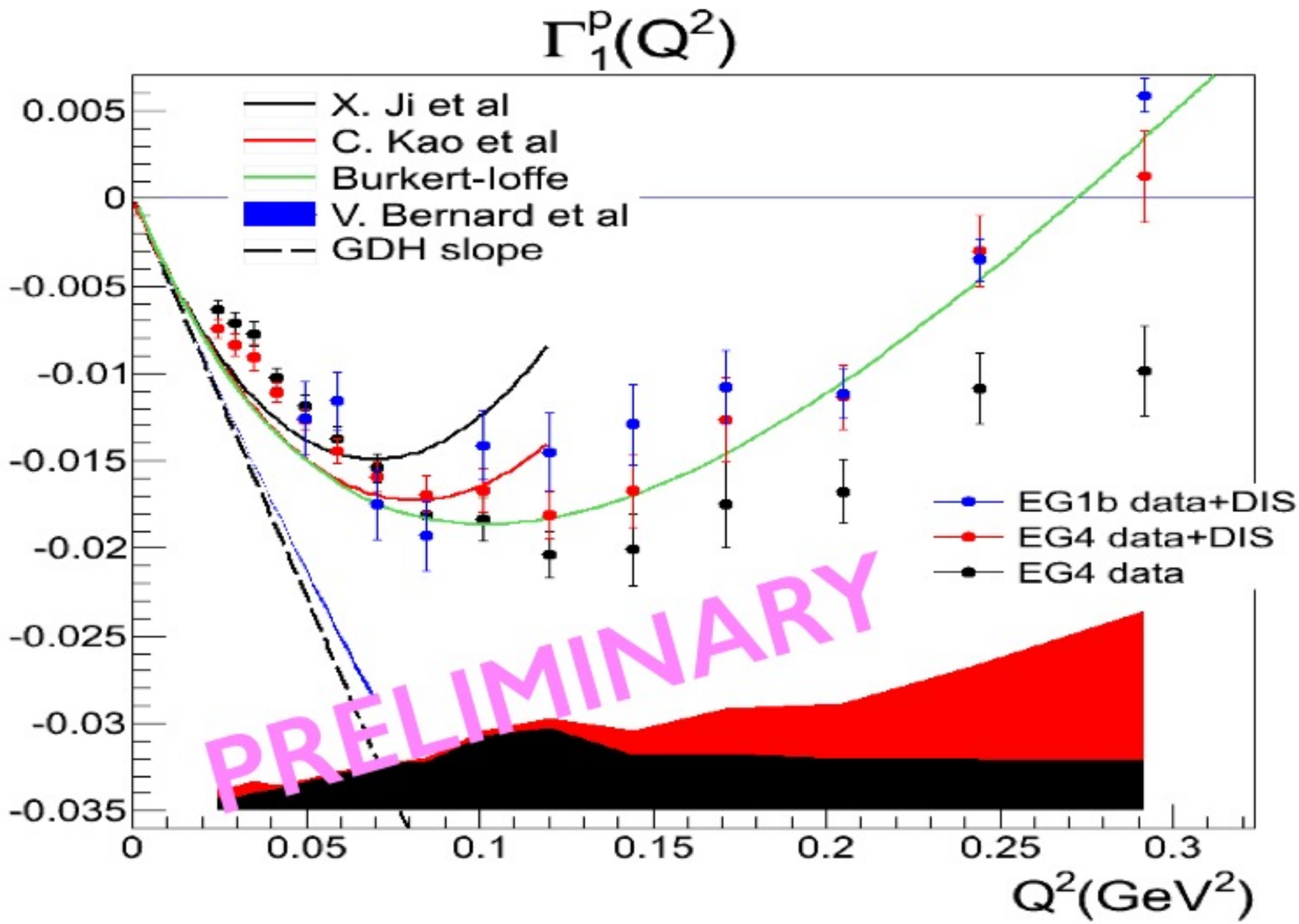
First Moment



Comparison with eg1b



First Moment with DIS



Spin Asymmetries of the Nucleon Experiment

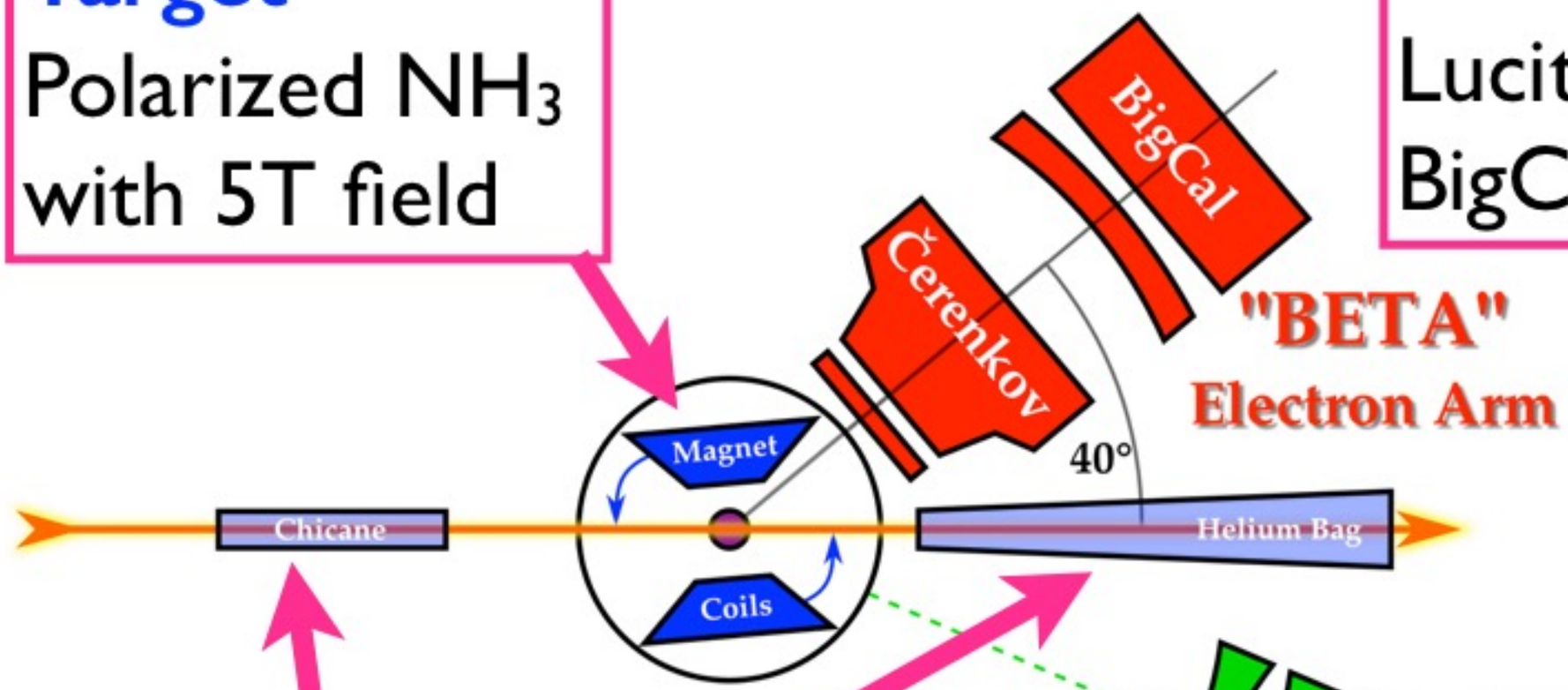
Experiment Summary

- **Beam**: polarized electron beam (Jefferson Lab) at **4.7** and **5.9** GeV
- **Target**: Polarized **Proton** (NH_3) target
  - Polarization: ~71%
  - Orientation: parallel (180°) or "**perpendicular**" (80°)
- **Detectors**: **BETA** and **HMS** of Hall-C
- Scattering angle: 40° for BETA, 15.5° or 20° for HMS

Setup

Electron Arm
Tracker
Cerenkov
Lucite
BigCal

Target
Polarized NH_3
with 5T field

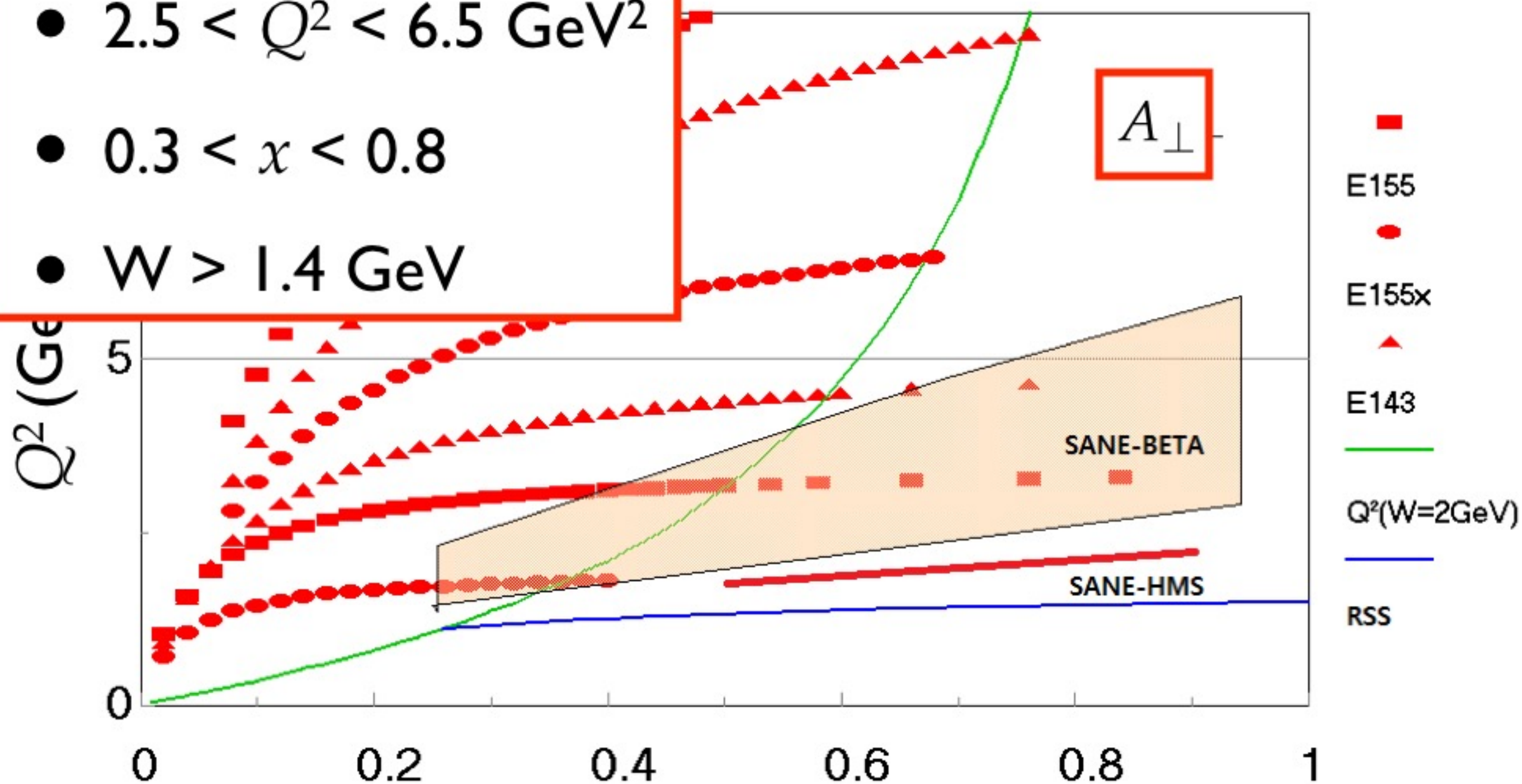


Beamline
Chicane
He bag

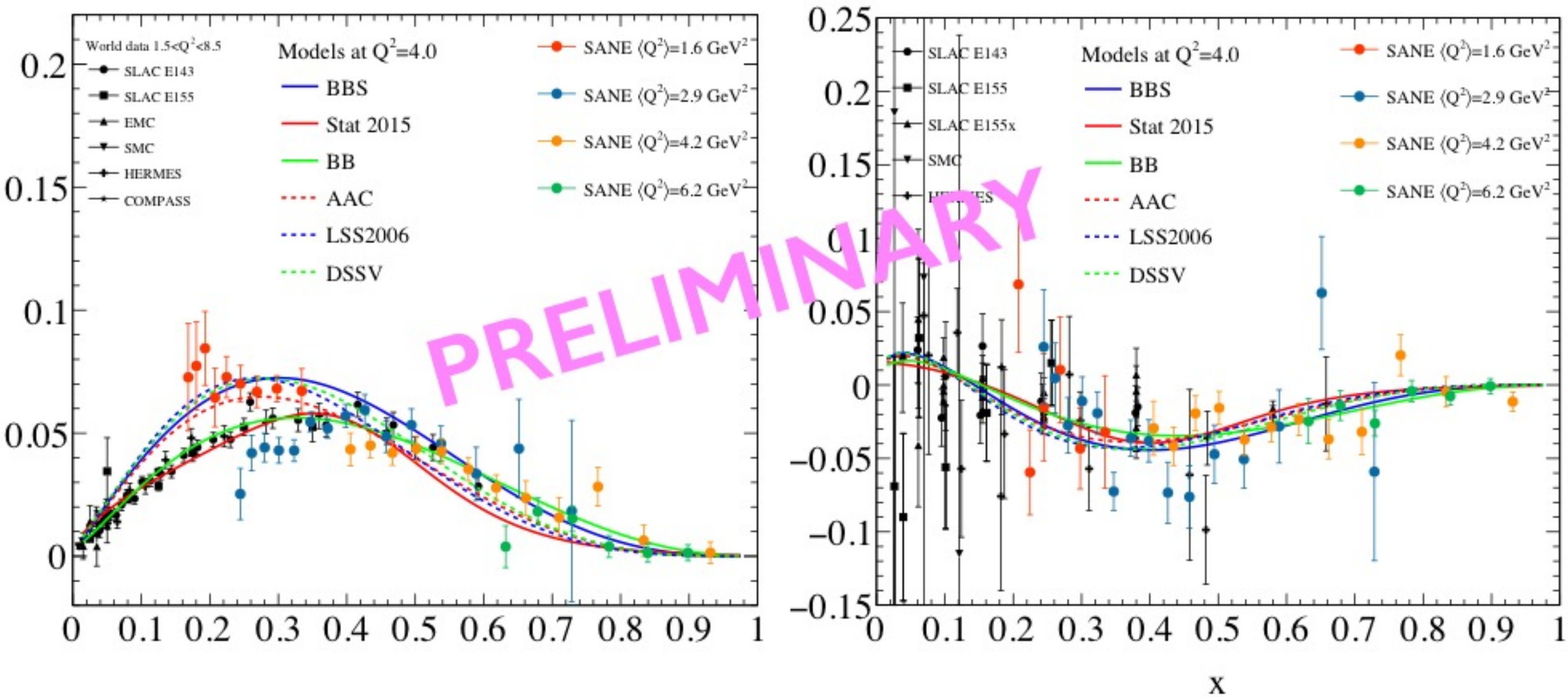
HMS
Packing fractions
Monitoring

Kinematic Coverage

- $2.5 < Q^2 < 6.5$ GeV^2
- $0.3 < x < 0.8$
- W > 1.4 GeV

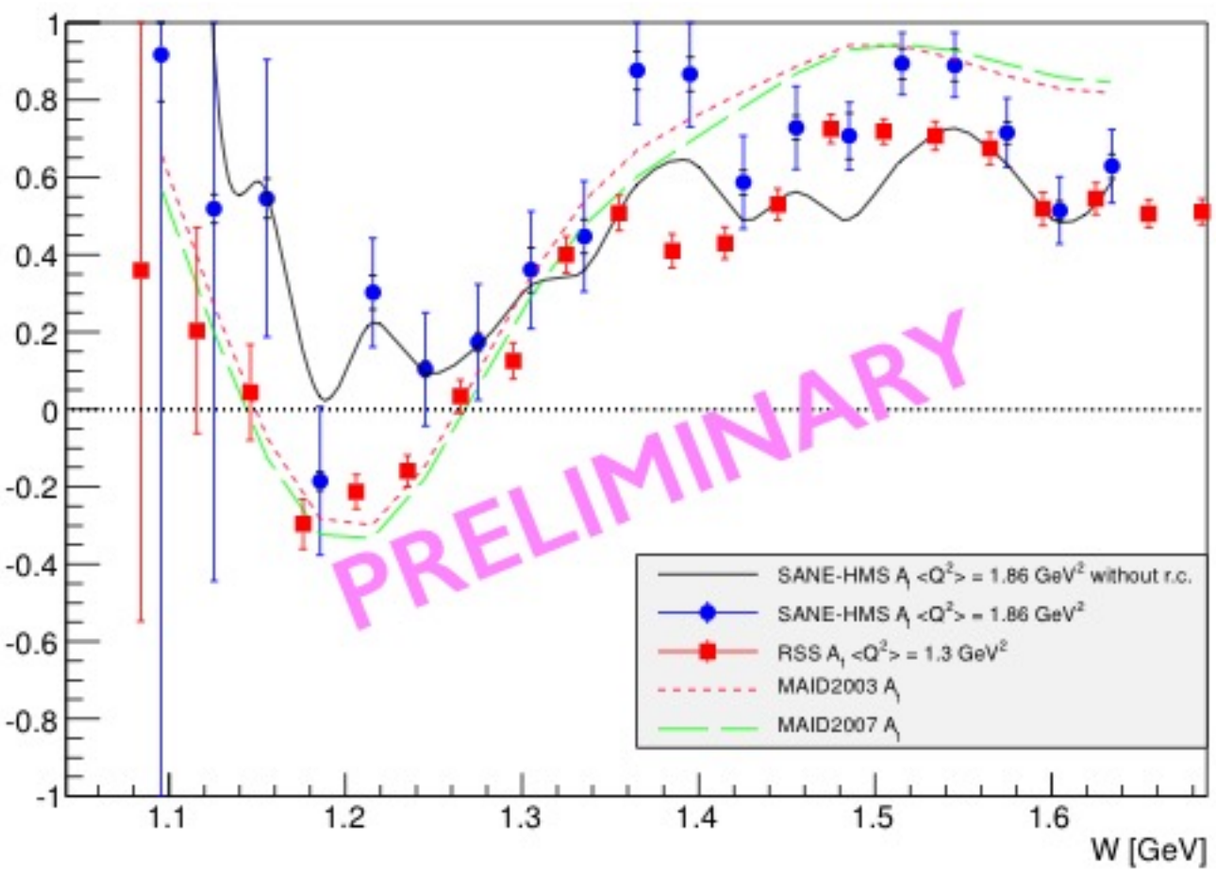


Proton g_1 and g_2

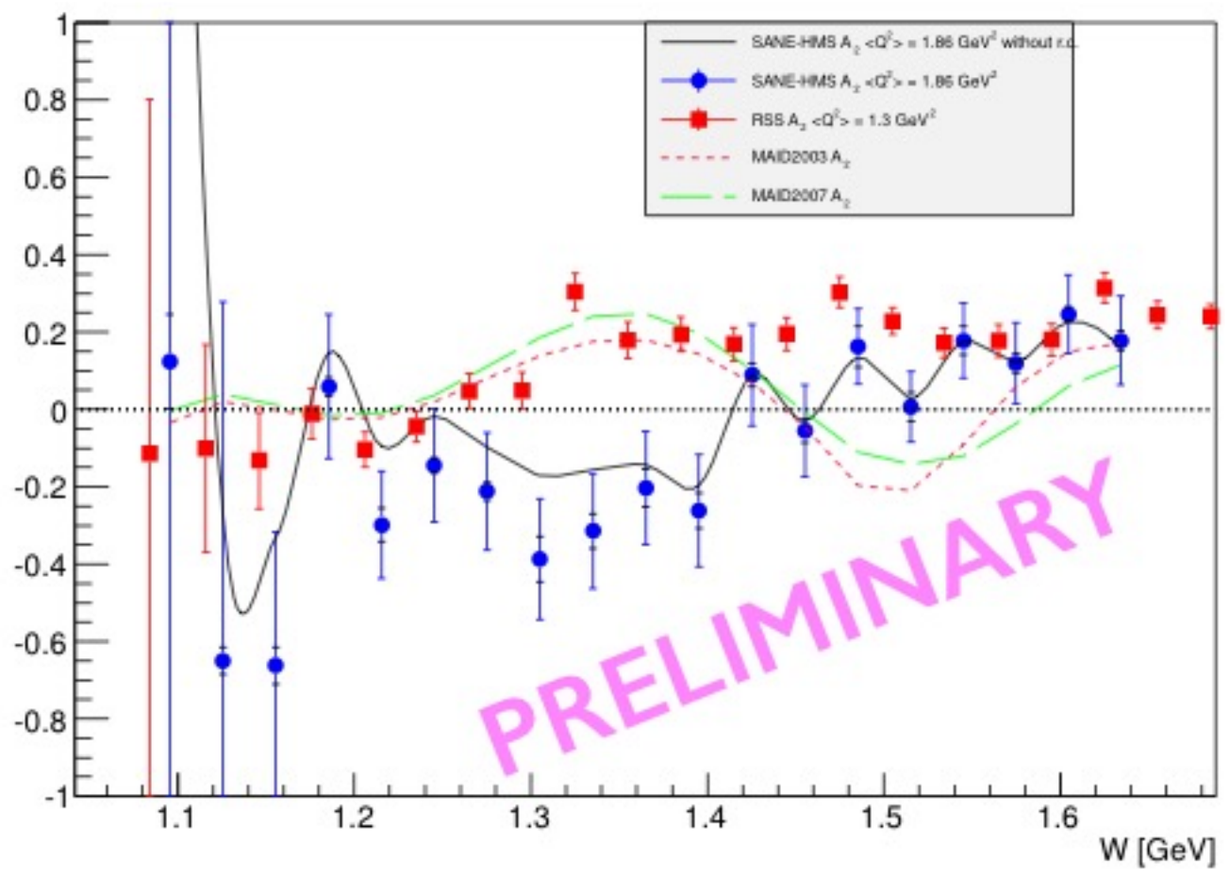


A_1 and A_2 with HMS

A_1

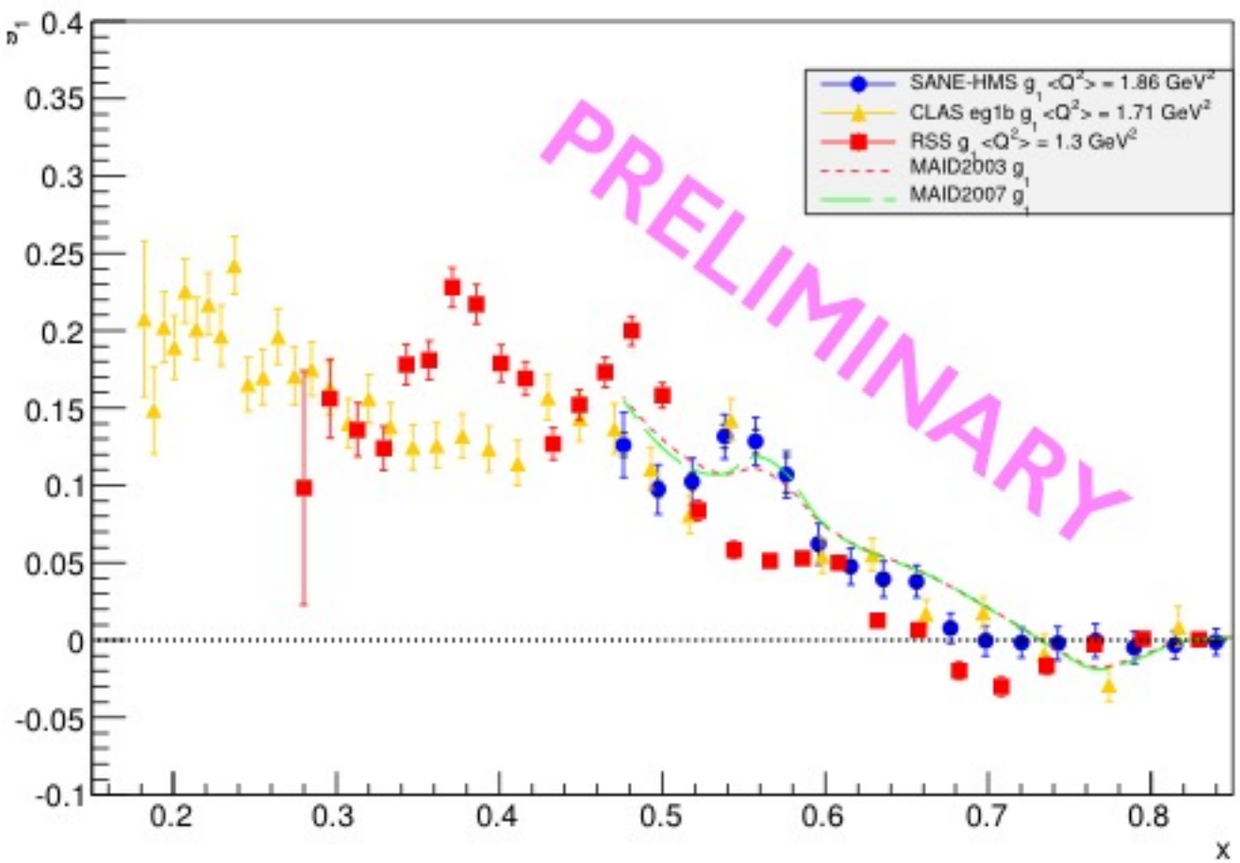


A_2

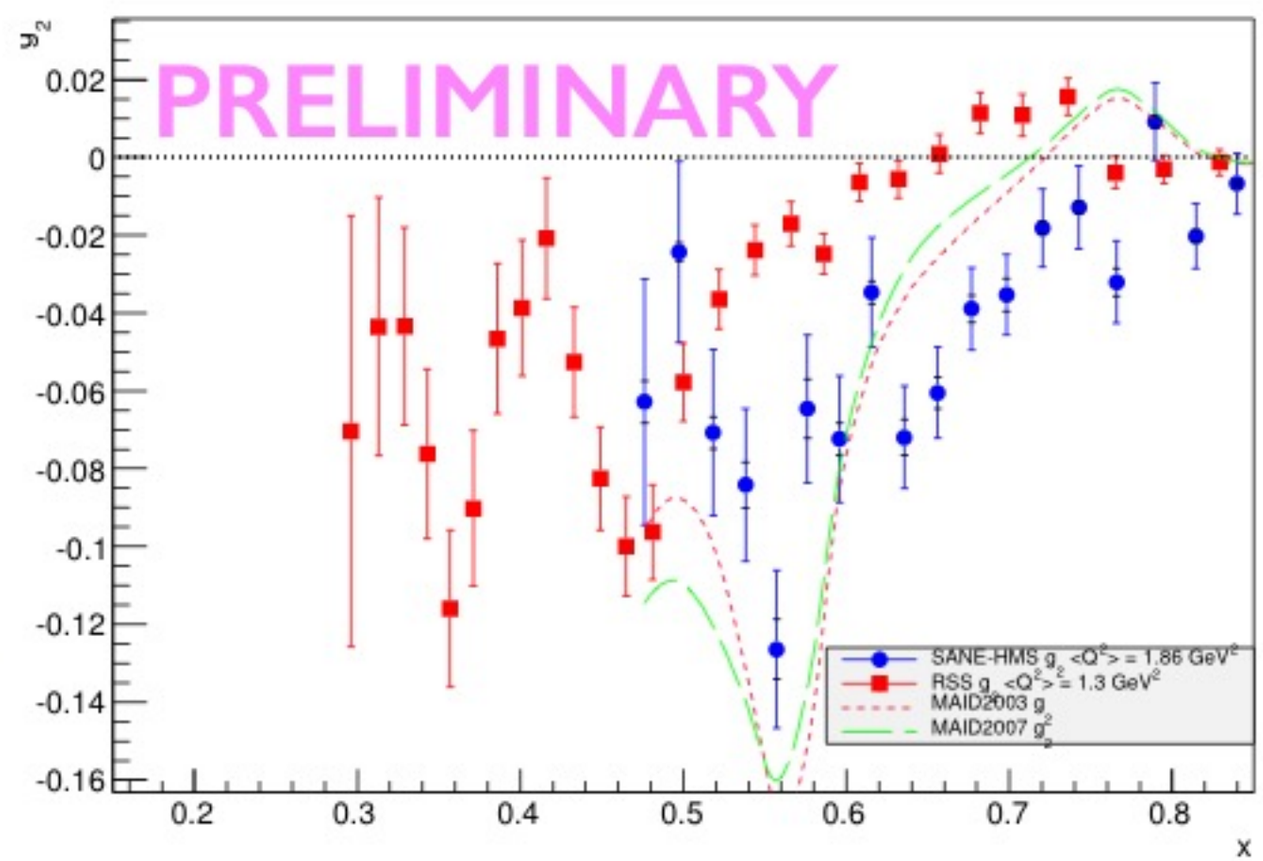


Proton g_1 and g_2 with HMS

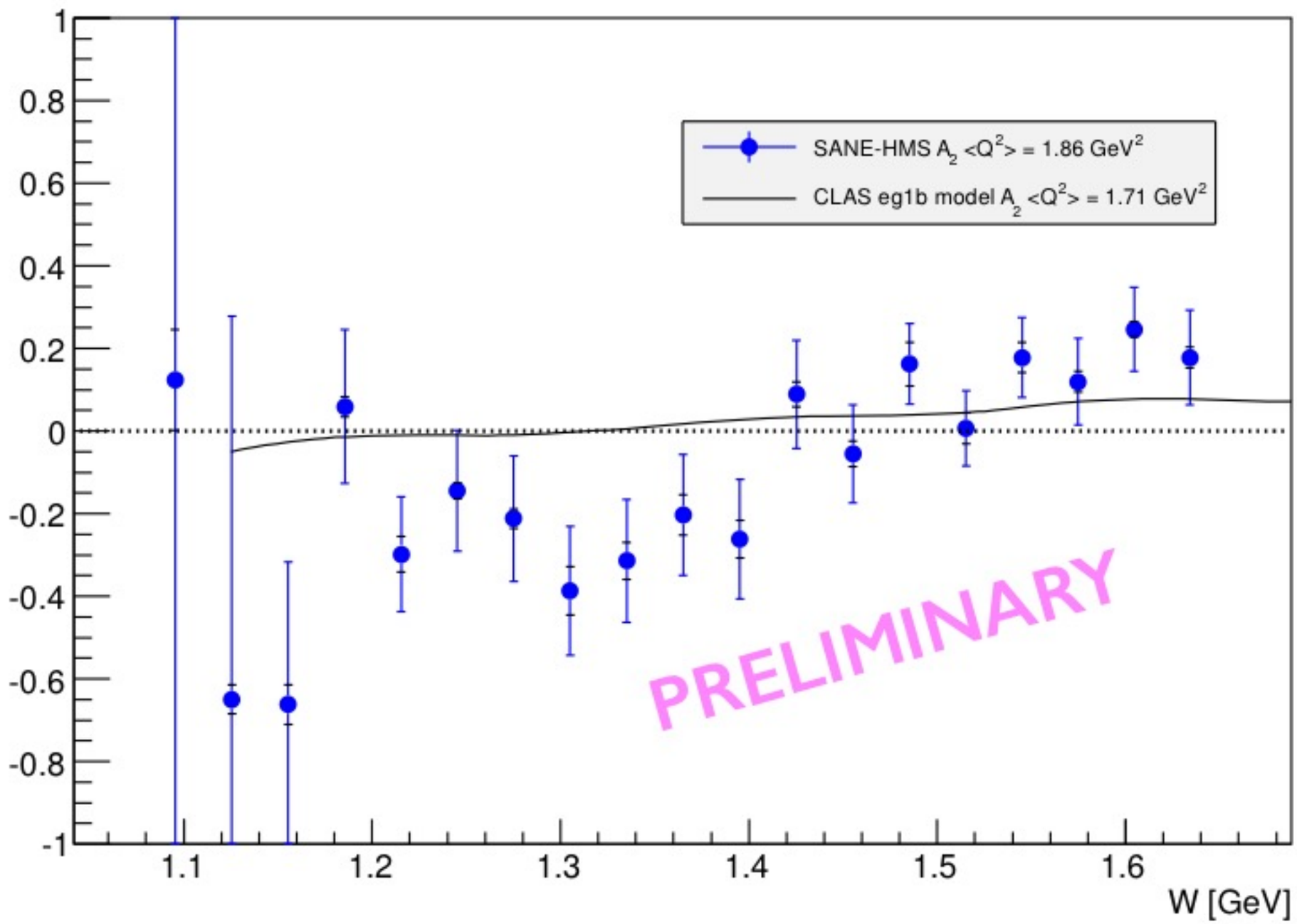
g_1



g_2



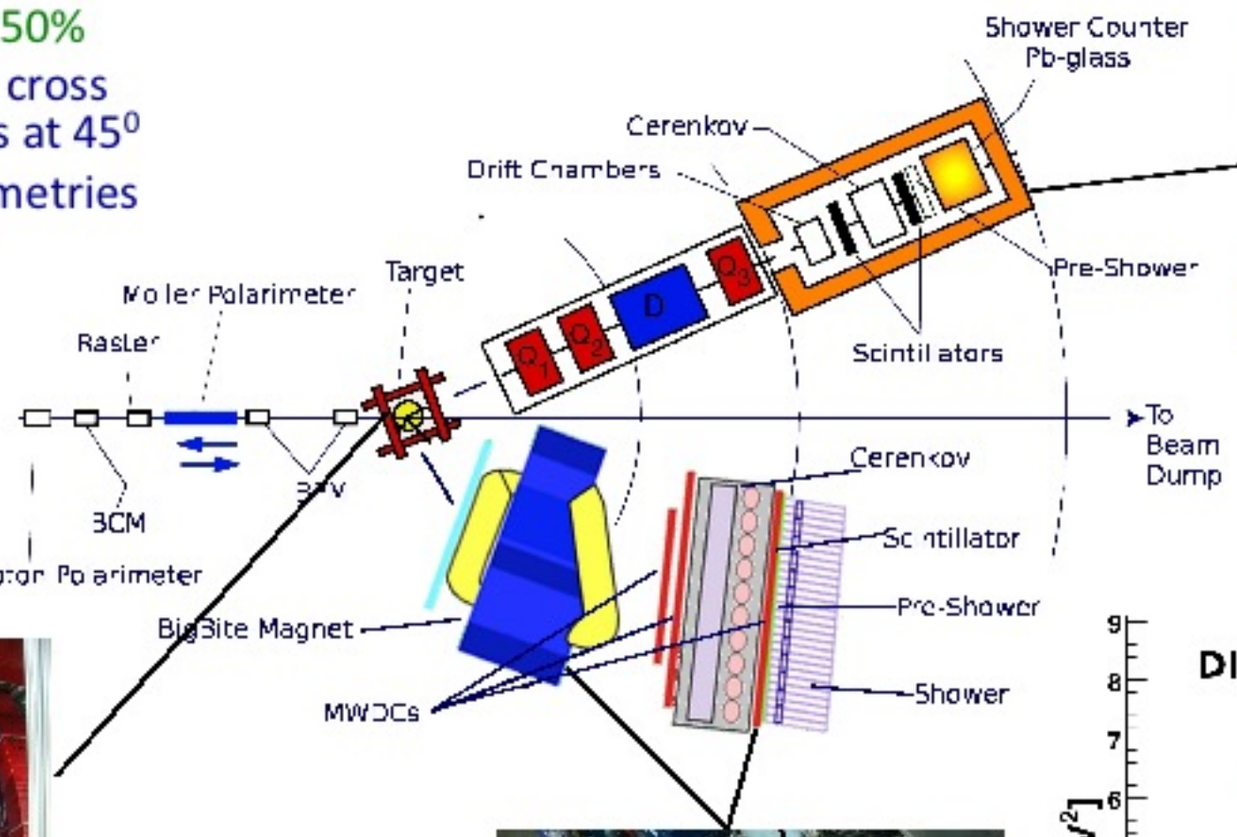
Proton A_2 and Model

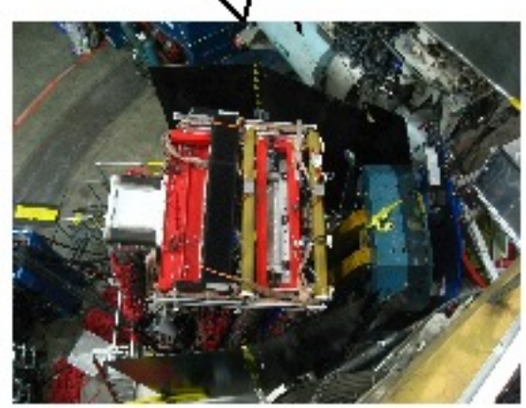


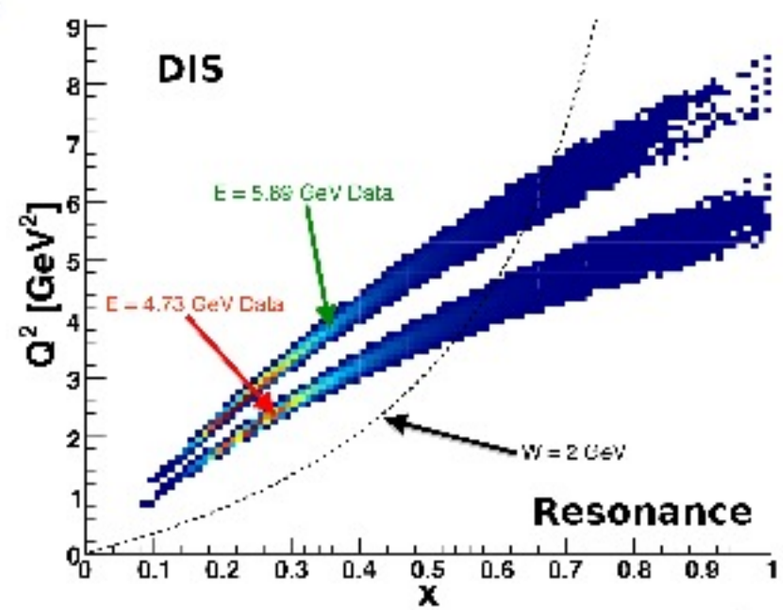
Precision Measurement of d_{2^n}

New Experiment at JLab

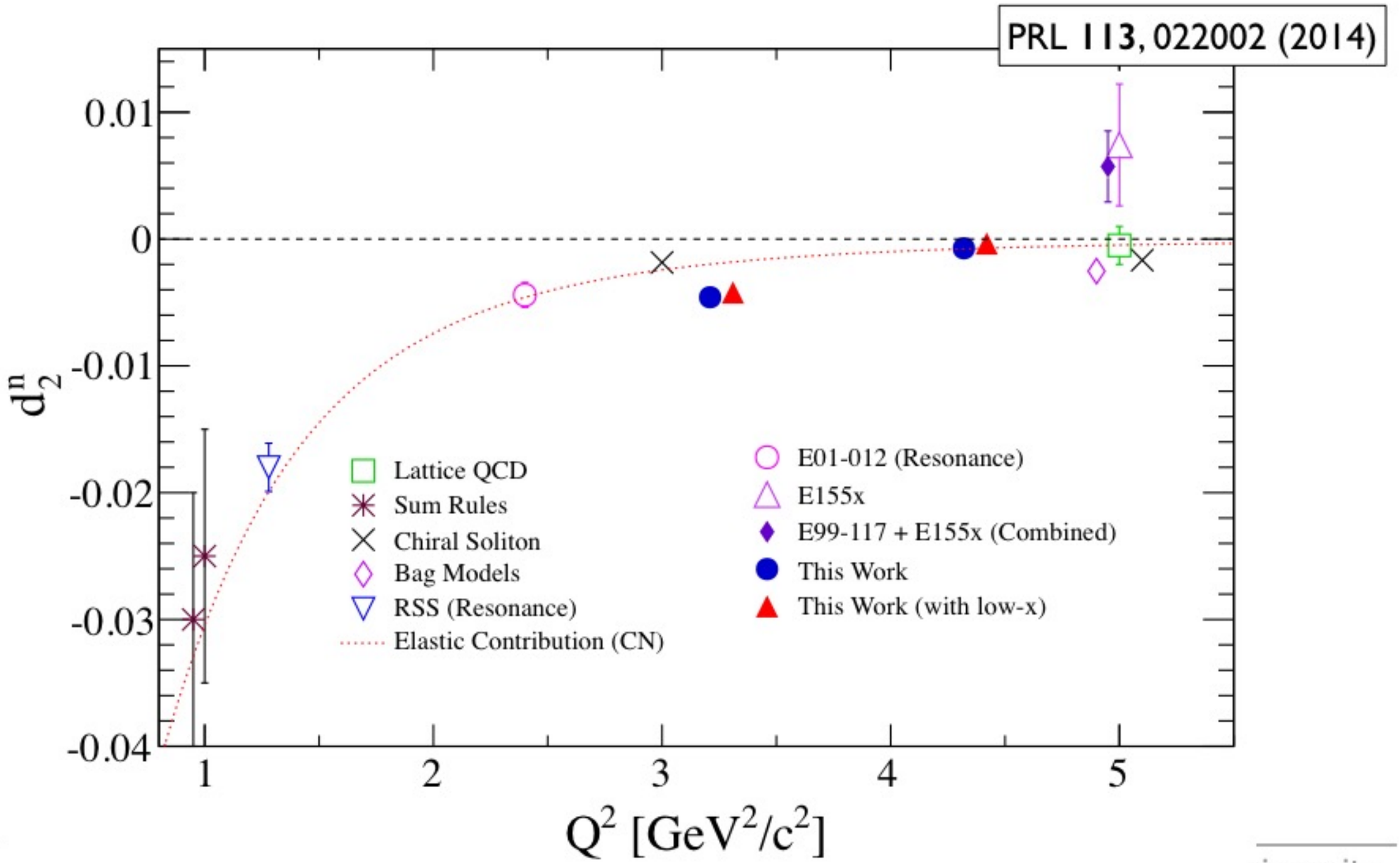
- Polarized electron beam: E=4.74, 5.89 GeV, polarization ~ 71%
- Polarized ^{3}He target ~ 50%
- HRS used for absolute cross section measurements at 45^0
- Bigbite used for asymmetries measurements at 45^0







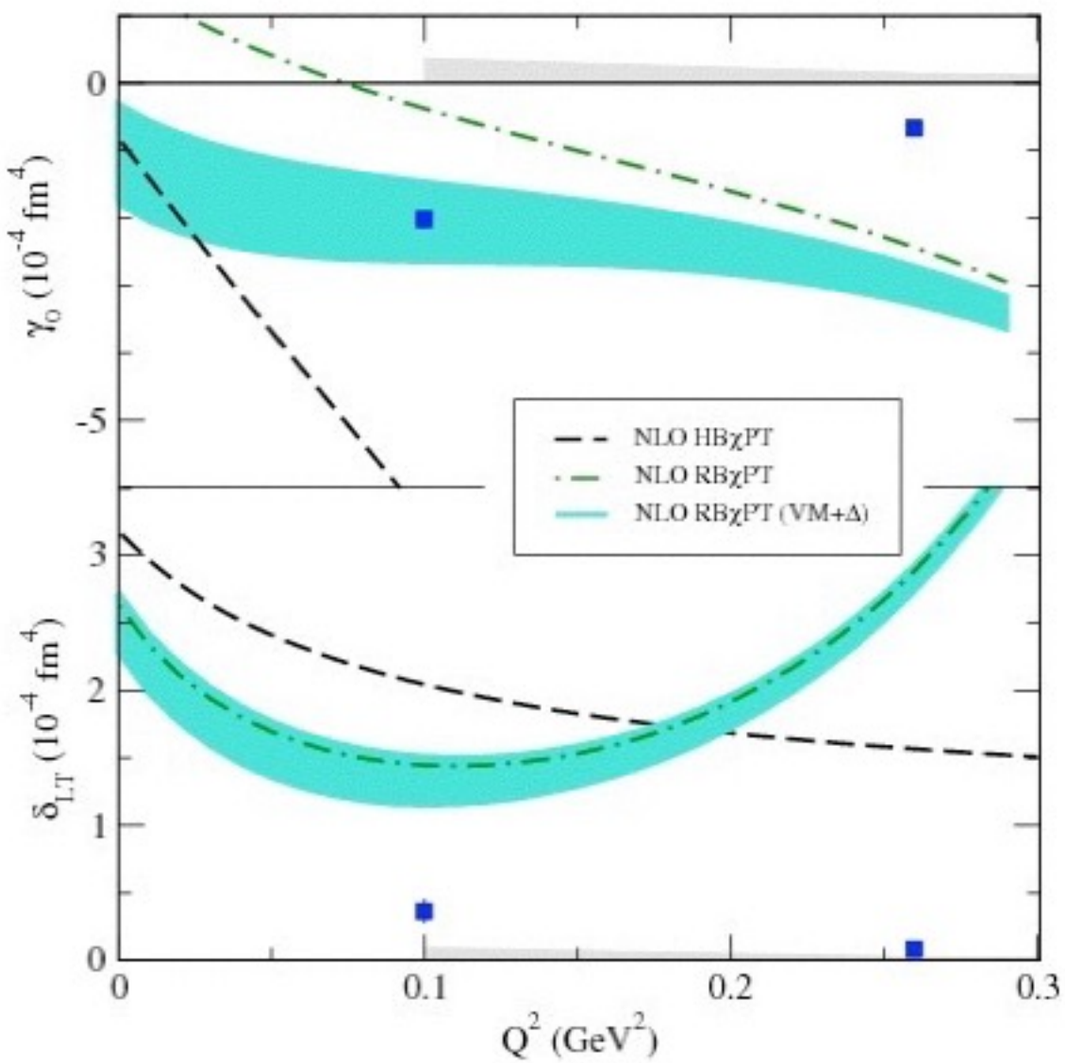
d_2^n Results


PRL 113, 022002 (2014)
0.01
0
-0.01
-0.02
-0.03
-0.04
d_2^n
1
2
3
4
5
Q^2 [GeV^2/c^2]
Lattice QCD
Sum Rules
Chiral Soliton
Bag Models
RSS (Resonance)
Elastic Contribution (CN)
E01-012 (Resonance)
E155x
E99-117 + E155x (Combined)
This Work
This Work (with low-x)

Spin Polarizabilities at Small Q^2

Neutron Spin Polarizabilities at Low Q^2

Neutron (E94010)



$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_x^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_x^{x_0} x^2\left[g_1 + g_2\right]$$

Possible clue from isospin combination with similar data on the proton

E08-027 : Proton g_2 Structure Function

Fundamental spin observable has never been measured at low or moderate Q^2

A- rating by PAC33

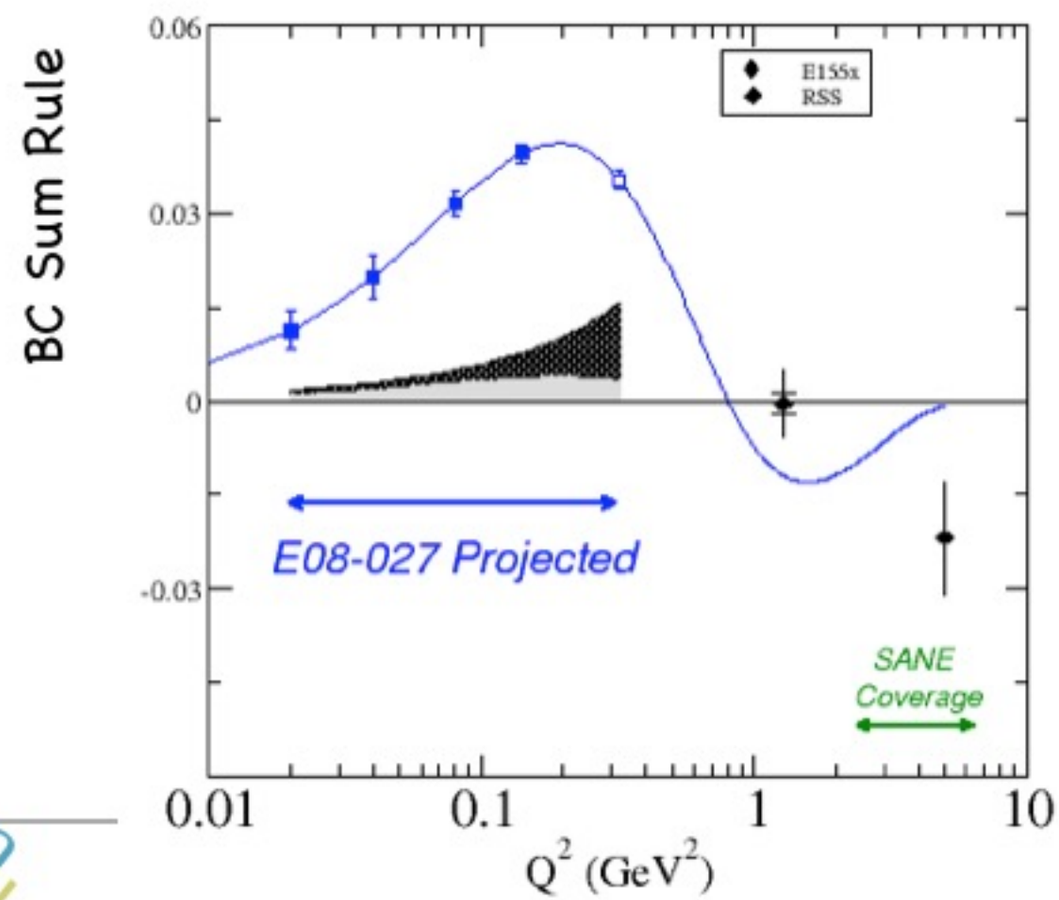
Spokesmen: Camsonne, Crabb, Chen, Slifer

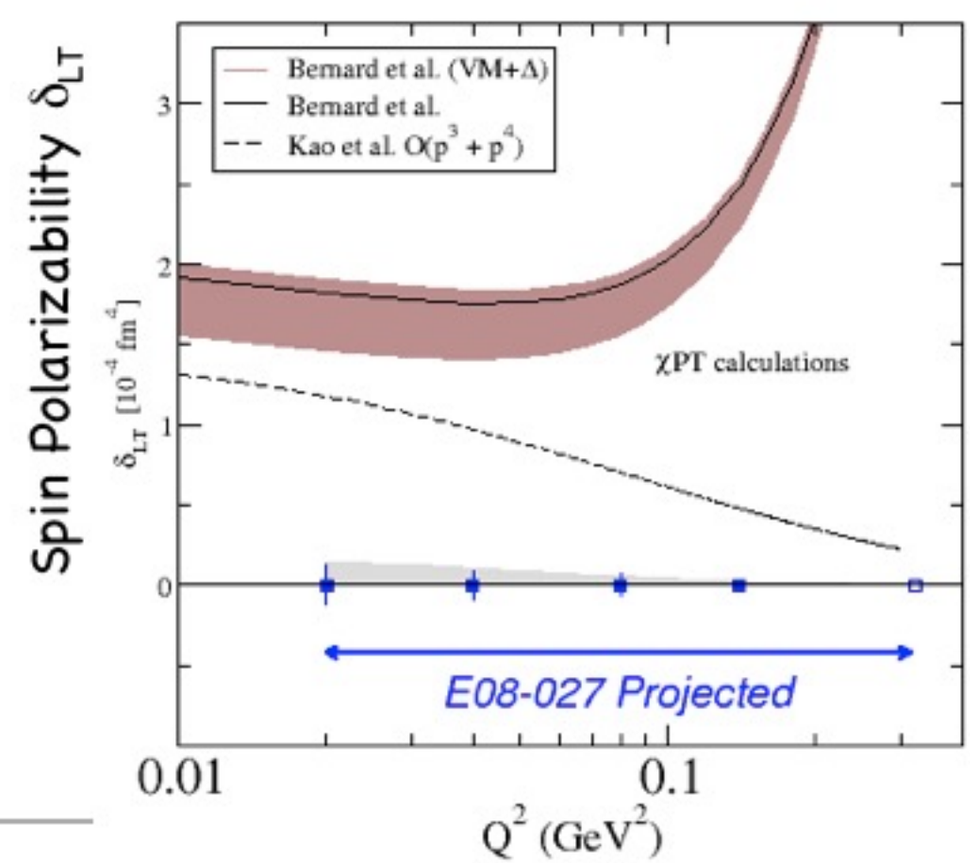
BC Sum Rule : violation suggested for proton at large Q^2, but found satisfied for the neutron & ^{3}He.

Spin Polarizability : Major failure (>8σ) of χPT for neutron δ_{LT}. Need g_2 isospin separation to solve.

Hydrogen HyperFine Splitting : Lack of knowledge of g_2 at low Q^2 is one of the leading uncertainties.

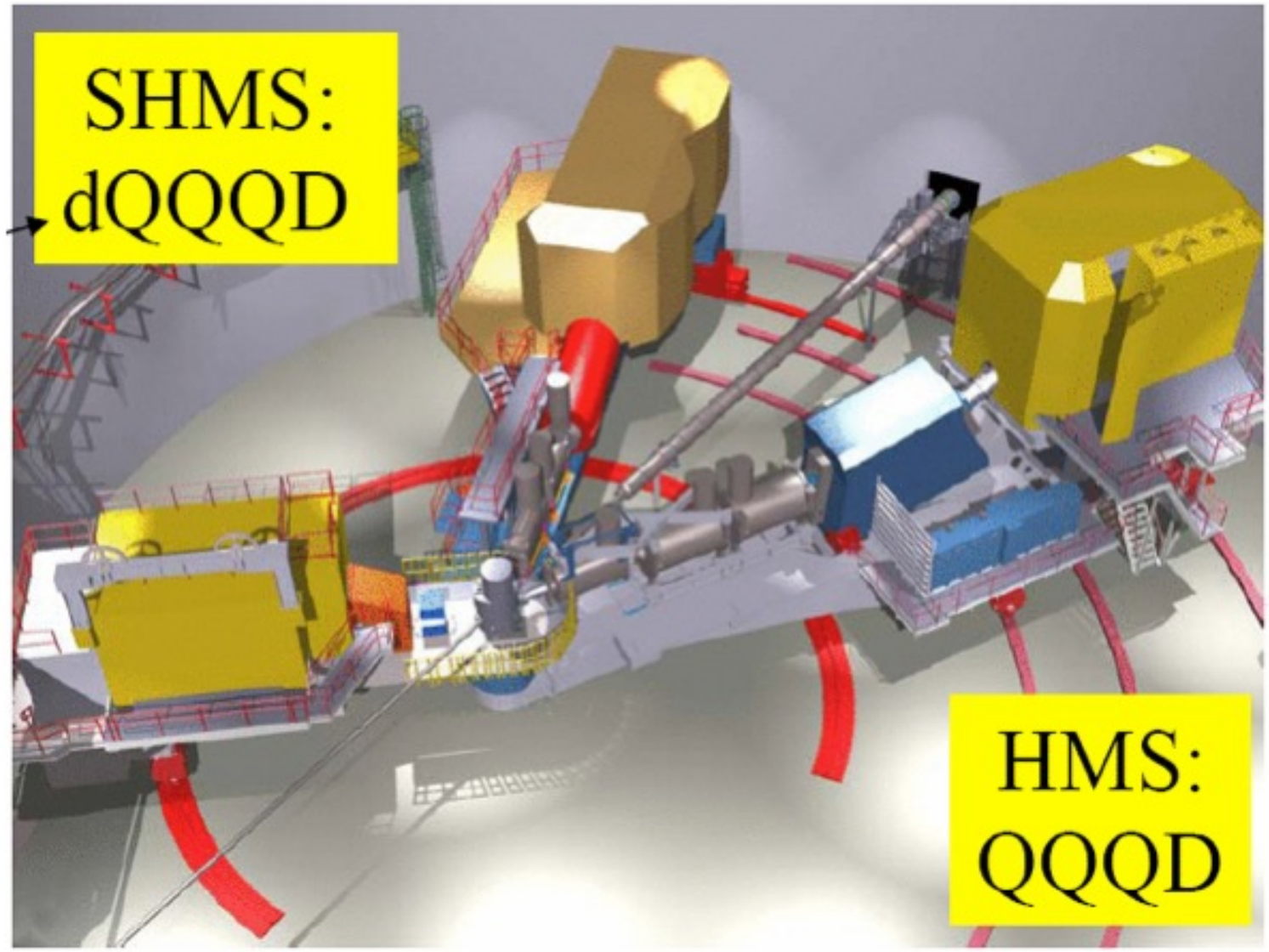
Proton Charge Radius : one of the leading uncertainties in extraction of $\langle R_p \rangle$ from μ–H Lamb shift.





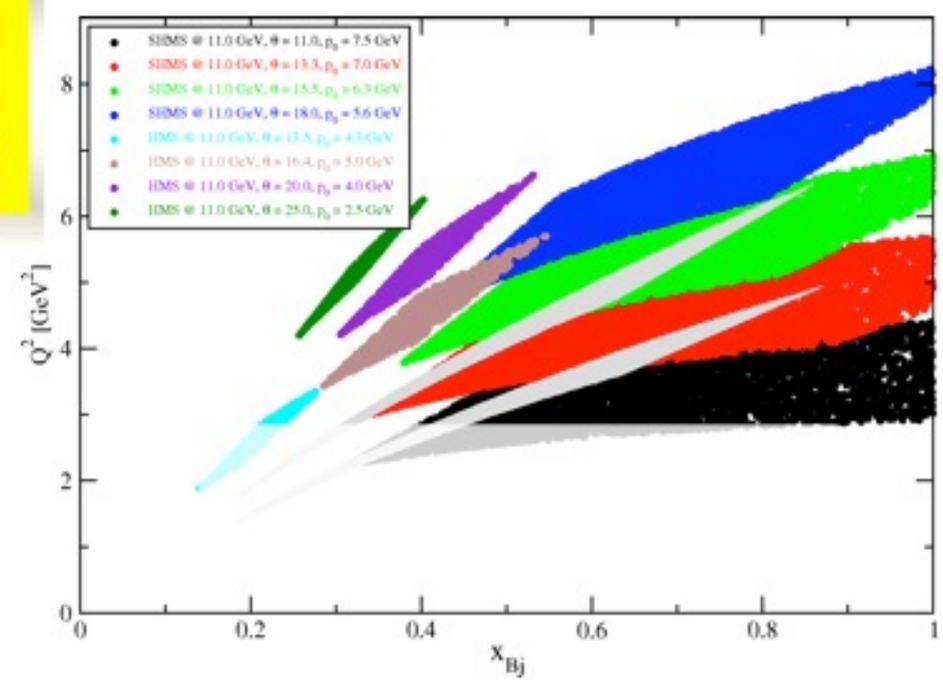
Spin Structure Functions at 12 GeV

E12-06-121: d_2^n, g_2^n

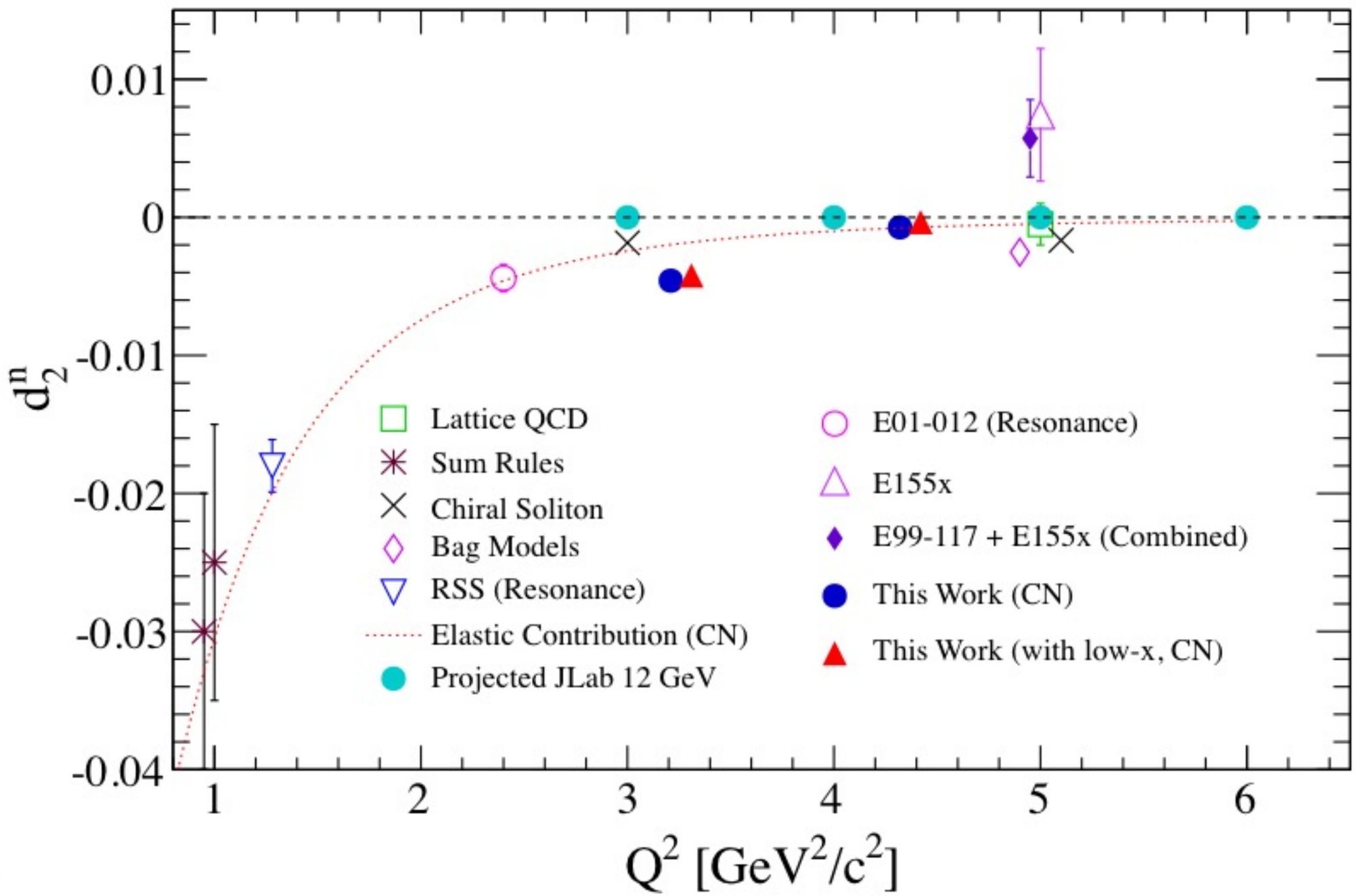


- Hall C: SHMS + HMS
- One beam energy
  - 11 GeV
- Each arm measures a total cross section independent of the other arm.
- Experiment split into four pairs of 125 hour runs with spectrometer motion in between.

- SHMS collects data at Θ = 11°, 13.3°, 15.5° and 18.0° for 125 hrs each
  - data from each setting divided into 4 bins
- HMS collects data at Θ = 13.5°, 16.4°, 20.0° and 25.0° for 125 hrs each



JLab 12 Projection of d_2^n



Summary

- Extensive measurements for g_1 over large Q2 region
  - Both for the proton and the neutron
  - New efforts to go down to very low Q2 (EG4)
- Limited data for g_2, especially for the proton
  - Precision measurements of g_2/d_2: higher twists
  - Puzzles in generalized spin polarizabilities at low Q2
    - Test of χPT calculations: δ_{LT} puzzle
  - New data will be available
    - for the proton (SANE, E08027)
    - for the neutron (E97110, E06014)
- Continues at 12 GeV