An Overview of Recent Nucleon Spin Structure Measurements at Jefferson Lab

Kalyan Allada
Massachusetts Institute of Technology

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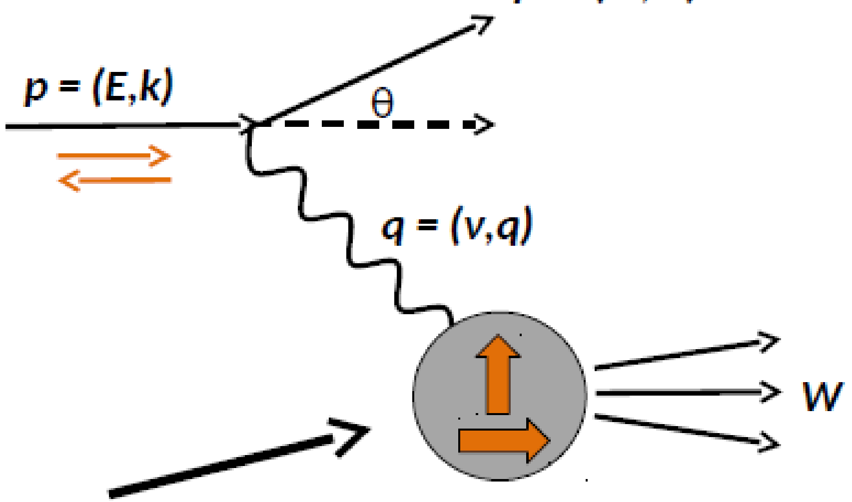
Outline

- A brief review of polarized inclusive electron scattering
  - structure functions, spin polarizabilities and sum rules
- Comparison of data with χPT calculations at low Q^2
  - Spin polarizabilities on ^{3}He at low Q^2
  - g_1 moment on proton at low Q^2
  - Ongoing analysis of g_2 on proton at low Q^2
- Results of g_2 and d_2 measurements at large Q^2 on proton and neutron targets
- Semi-inclusive DIS: Transversity related measurements at JLab

Inclusive Electron Scattering

kinematics

$$\vec{q} = \vec{k} - \vec{k}\,'$$
$$Q^2 = -q^2 = 4EE'\sin^2\frac{\theta}{2}$$
$$x = \frac{Q^2}{2M\nu}$$



Inclusive inelastic cross section:

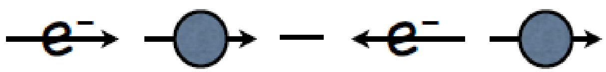
$$\sigma_0 = \sigma_{\mathrm{Mott}}\left[\alpha F_1(x,Q^2) + \beta F_2(x,Q^2) + \gamma g_1(x,Q^2) + \delta g_2(x,Q^2)\right]$$

Structure functions:

- spin-averaged (unpolarized): F_1 and F_2
- spin-dependent (polarized): g_1 and g_2
- electron and target spins are parallel (anti-parallel) or their spins are perpendicular

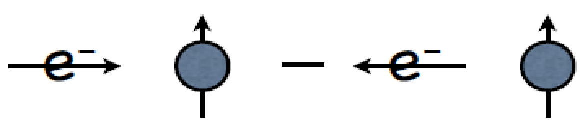
Experimental Technique

Cross-section differences:

$\Delta\sigma_{\|} =$ 

Longitudinally polarized nucleon

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

$\Delta\sigma_{\perp} =$ 

Transversely polarized nucleon

$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\sin\theta\left[g_1 + \frac{2ME}{\nu} g_2\right]$$

$\Delta\sigma_{\perp}$ is relatively difficult to measure experimentally – requires transversely polarized target

Structure Functions

- At Bjorken limit, g_1 related to polarized parton distribution functions

$$g_1 = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x) \qquad \Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$$

- No simple relation between g_2 and PDFs at Bjorken limit

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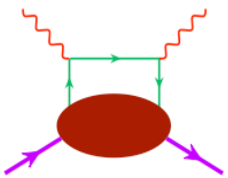
- g_2 contain leading twist (g_2^{WW}) + twist-3 part ($\bar{g}_2$)

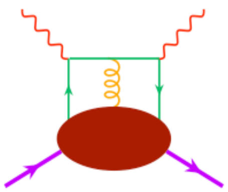
$$g_2(x, Q^2) = g_2^{\mathrm{WW}}(x, Q^2) + \bar{g}_2(x, Q^2)$$

where

Twist-2



Twist-3



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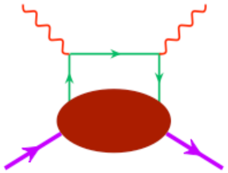
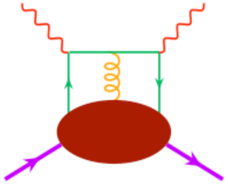


Twist-3



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

where

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

(Wandzura & Wilczek, 1977)

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

(Cortes, Pire & Ralston, 1992)

quark transverse momentum contribution

(Transversity)

twist-3 part which arises from quark-gluon interactions

Spin Structure Moments

- First moment of g_1: $$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\,dx$$

related total spin carried by the quarks

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6}$$

g_A: nucleon axial charge

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- First moment of g_2 : $$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2)\,dx = 0$$ Burkhardt-Cottingham (BC) Sum Rule

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- 2[nd] moment of g_2 (x^2 weighting) :
  - At low Q^2 – spin polarizabilities, test of Chiral Perturbation (χPT) theory

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\,\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]\,dx$$

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\,[g_1 + g_2]\,dx$$

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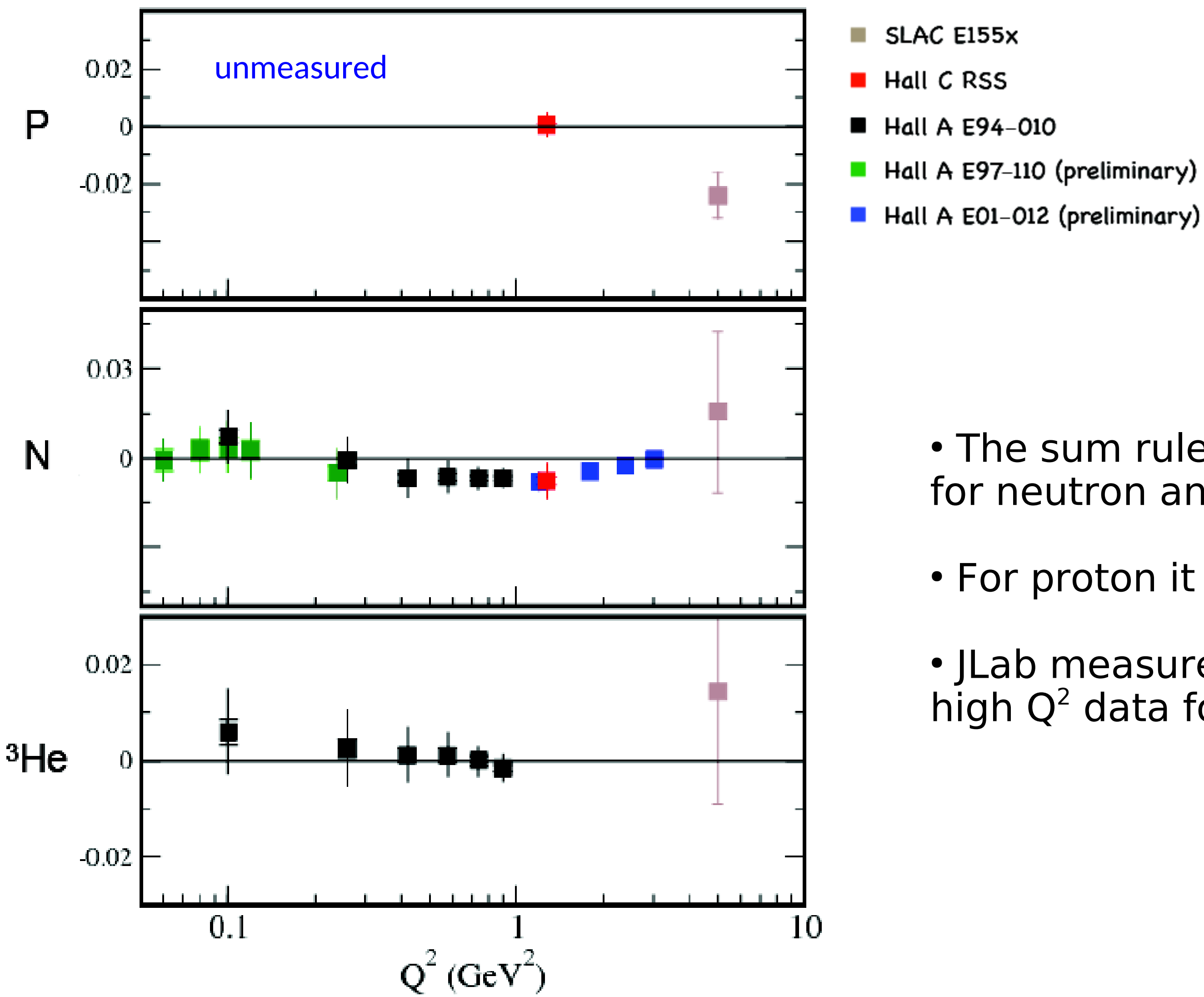
$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\ [g_1 + g_2]\,dx$$

- At High Q^2 – color polarizability or color Lorentz force, test of lattice QCD

$$\bar{d}_2(Q^2) = \int_0^{x_0} dx\ \ x^2[2\mathrm{g}_1(x,Q^2) + 3\mathrm{g}_2(x,Q^2)]$$

d_2 is a measure of color Lorentz force acting on the stuck quark in the instance after being hit by a virtual photon (M. Burkardt, PRD 88, 114502 (2013))

BC Sum Rule



$$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2)\, dx = 0$$

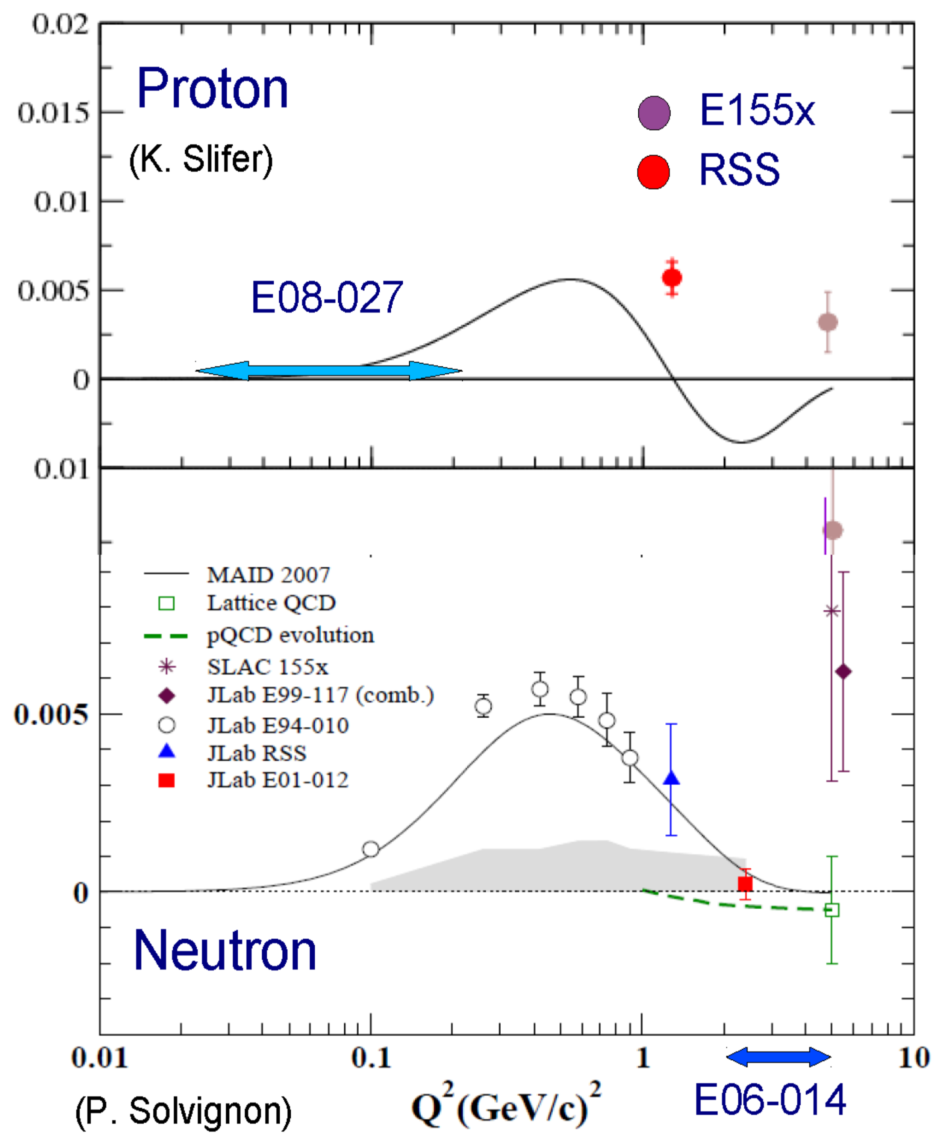
H. Burkhardt and W. N. Cottingham, Annals. Phys., 56(1970)453

- The sum rule satisfied within the errors for neutron and ^{3}He
- For proton it is almost unmeasured
- JLab measurement will provide low and high Q^2 data for proton

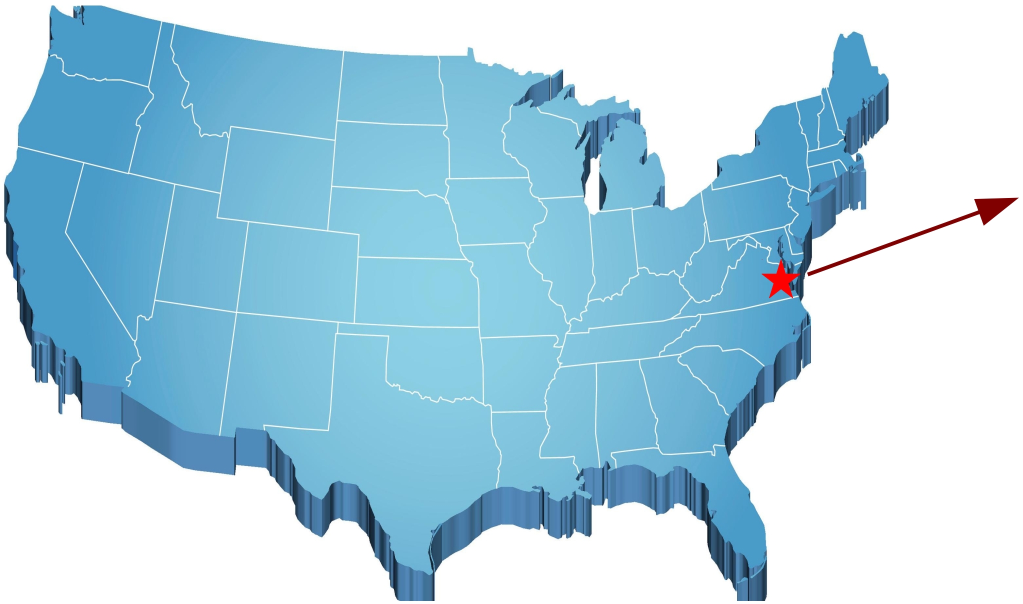
Existing d_2 Measurements

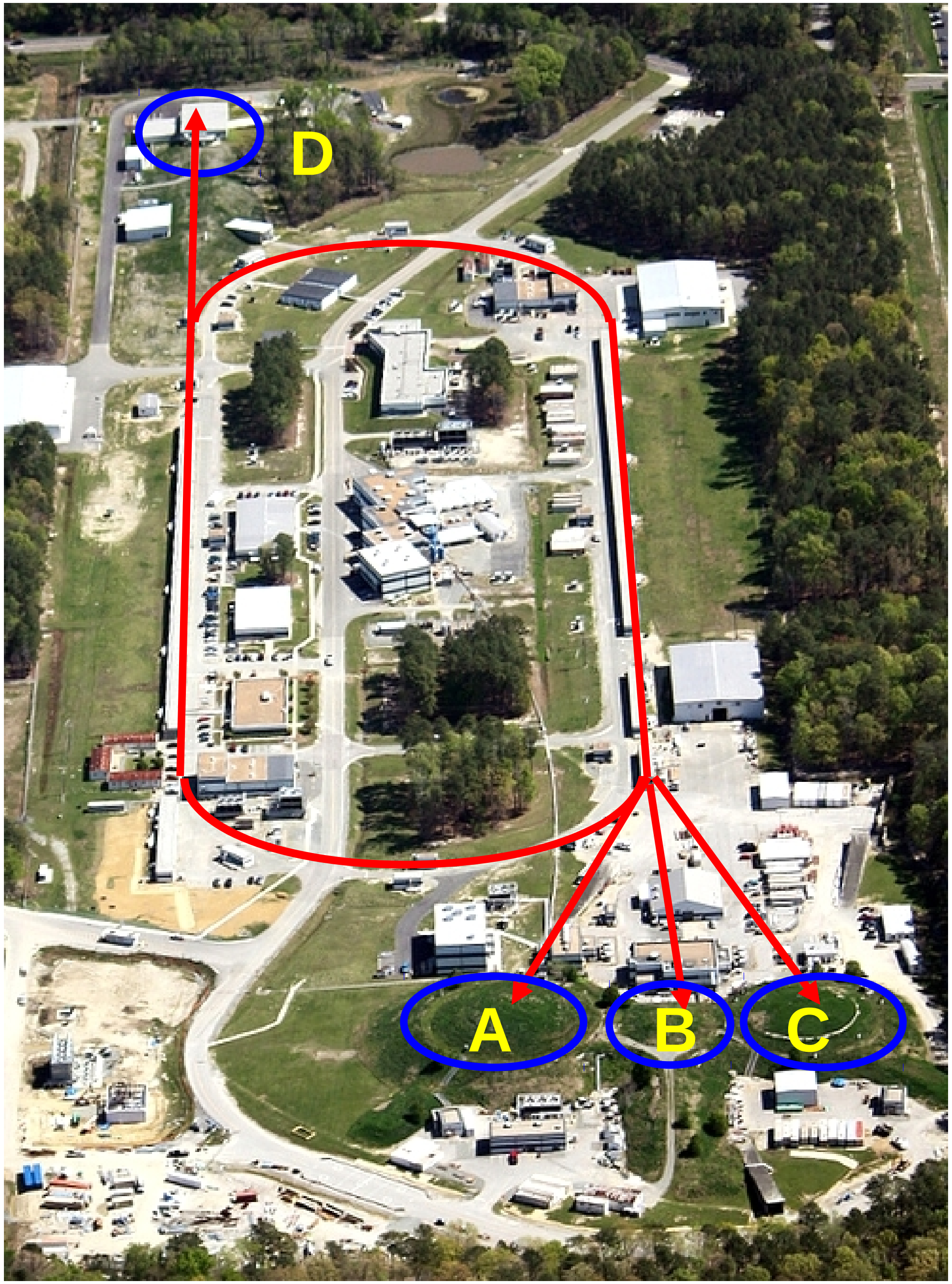
$$\bar{d}_2(Q^2)=\int_0^{x_0} x^2[2g_1(x,Q^2)+3g_2(x,Q^2)]\,dx$$

- d_2 moments for proton and neutron
- Only contributions from the measured region
- Contributions from unmeasured low-x region usually not significant due to x^2 weighting
- Recent JLab measurements will provide low Q proton and high Q^2 neutron data



Jefferson Lab

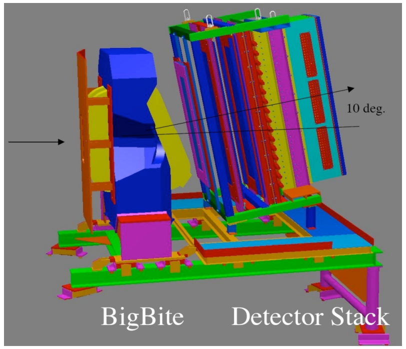


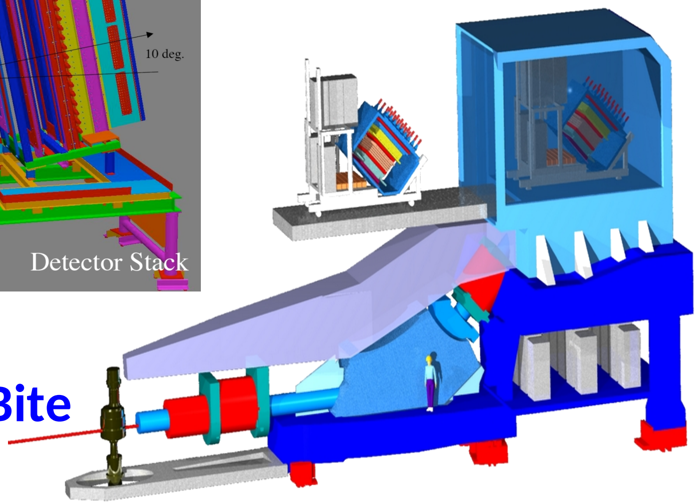


- Continuous electron beam
- Energy 0.4 GeV to 6 GeV (until 2012)
- Avg. Polarization: ~ 85%
- Beam Current: up to 200 uA

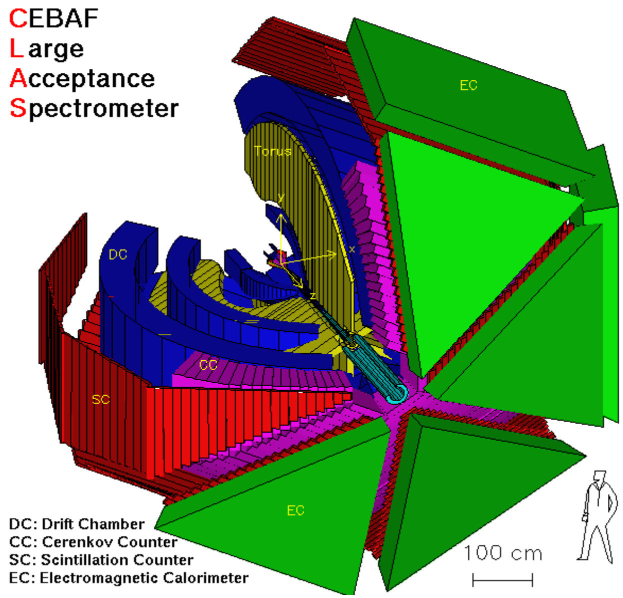
- Energy upgrade: up to 12 GeV (in-progress)
- Four Halls: A, B, C and D (new)
- High energy run expected in Fall 2015

Jefferson Lab at 6 GeV

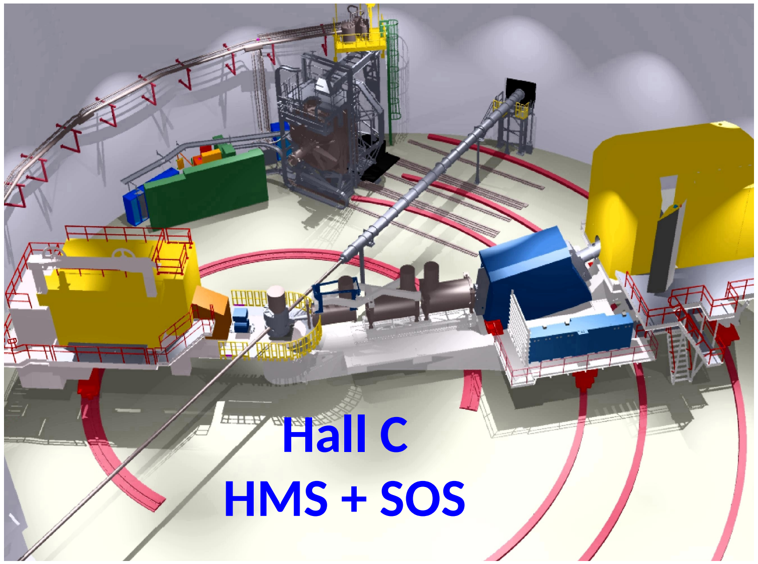




Hall A
HRS + BigBite



Hall B CLAS



Hall C
HMS + SOS

- Hall A : Polarized ^3He, NH_3
- Hall B : Polarized NH_3, ND_3
- Hall C : polarized NH_3, ND_3

Recent Measurements at JLab

- **E97-110 (saGDH, Hall A):**
  ^{3}He(n) to measure g_1 and g_2 at very low Q^2 (0.02-0.3 GeV^2) (preliminary results)
- **EG4 (CLAS, Hall B):**
  NH_3(p) and ND_3(d) to measure g_1 at very low Q^2(0.02 - 0.5 GeV^2) (preliminary results)
- **E08-027 (g2p, Hall A):**
  NH_3(p) to measure g_2 moments at very low Q^2 (0.02-0.2 GeV^2) (analysis)
- **E06-014 (d2n, Hall A):**
  ^{3}He(n) to measure g_1 and g_2 at high Q^2 (2-6 GeV^2) (published)
- **E07-003 (SANE, Hall C):**
  NH_3(p) to measure g_2 at high Q^2 (2-6 GeV^2) (preliminary results)

High Q^2

E97-110: Small Angle GDH Experiment

<u>Spokespersons:</u> J.-P. Chen, A. Deur, F. Garibaldi

- Precision measurement of the moments of spin structure functions at low Q^2 (0.02-0.24) GeV^2 for the neutron (^{3}He)

- Covered an unmeasured region of kinematics to test theoretical calculations (Chiral Perturbation theory)

- Inclusive experiment: $^3\vec{\text{He}}(\vec{e}, e')X$

- Polarized electron beam
  - Avg. P_{beam} = 75 %

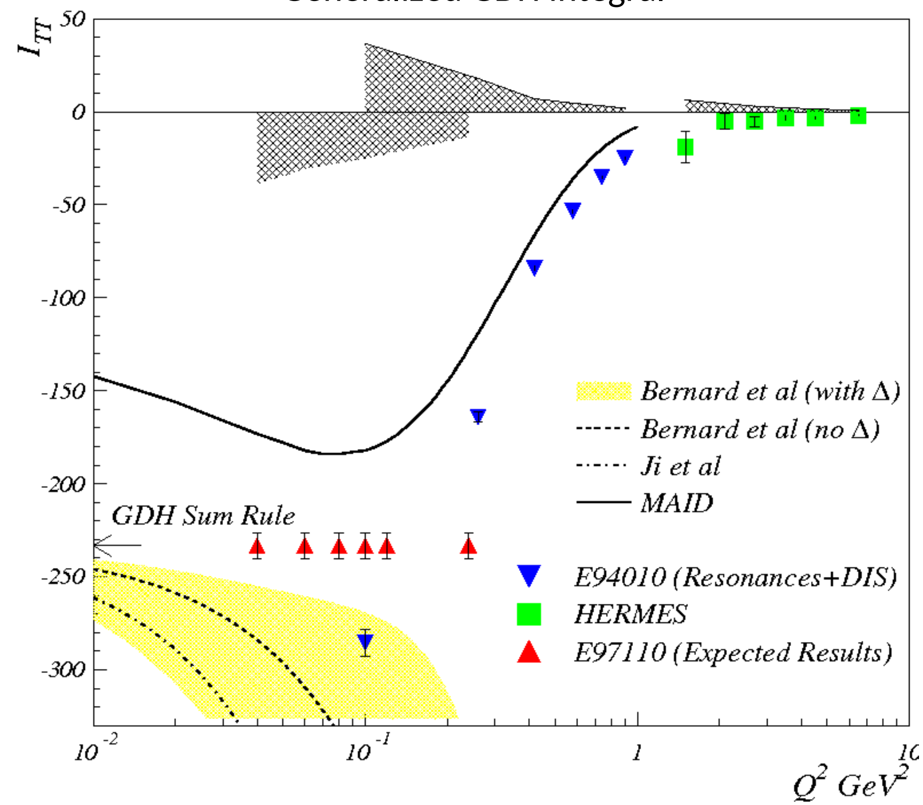
- Polarized ^{3}He target (para & perp):
  - Avg. P_{target} = 40 %

- Measured cross-section differences

$$I_{\text{GDH}} = \int_{\nu_{\text{th}}}^{\infty} \frac{\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)}{\nu} d\nu = -2\pi^2 \alpha \left(\frac{\kappa}{M}\right)^2$$

κ: anomalous magnetic moment

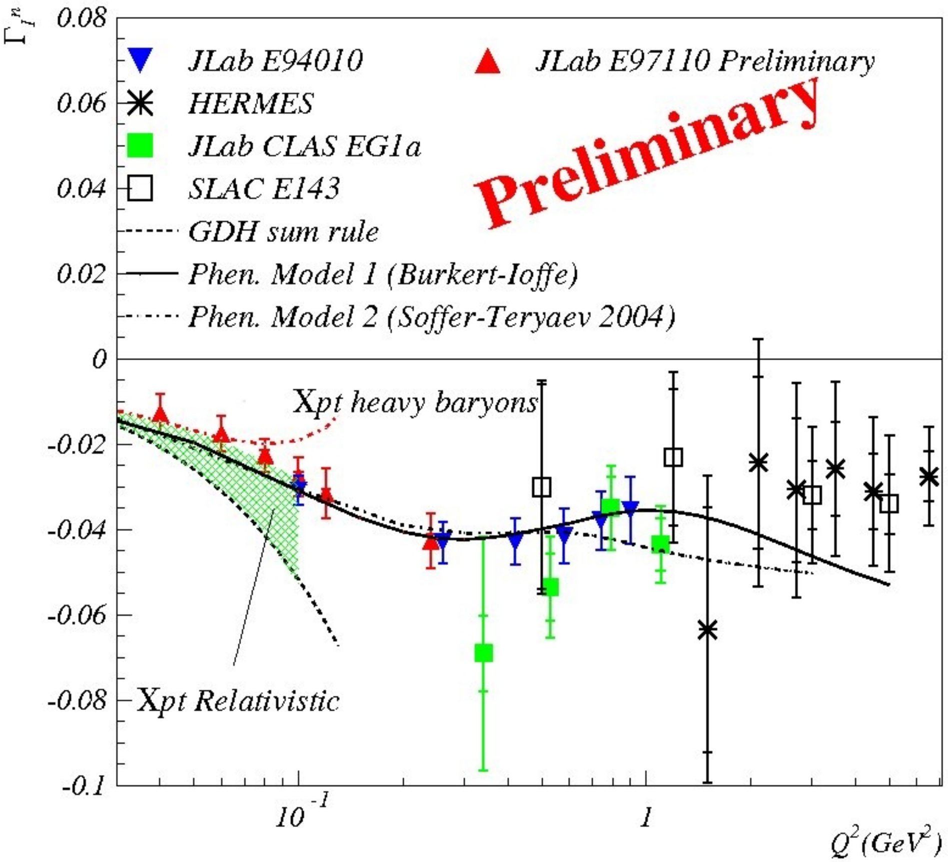
Generalized GDH integral



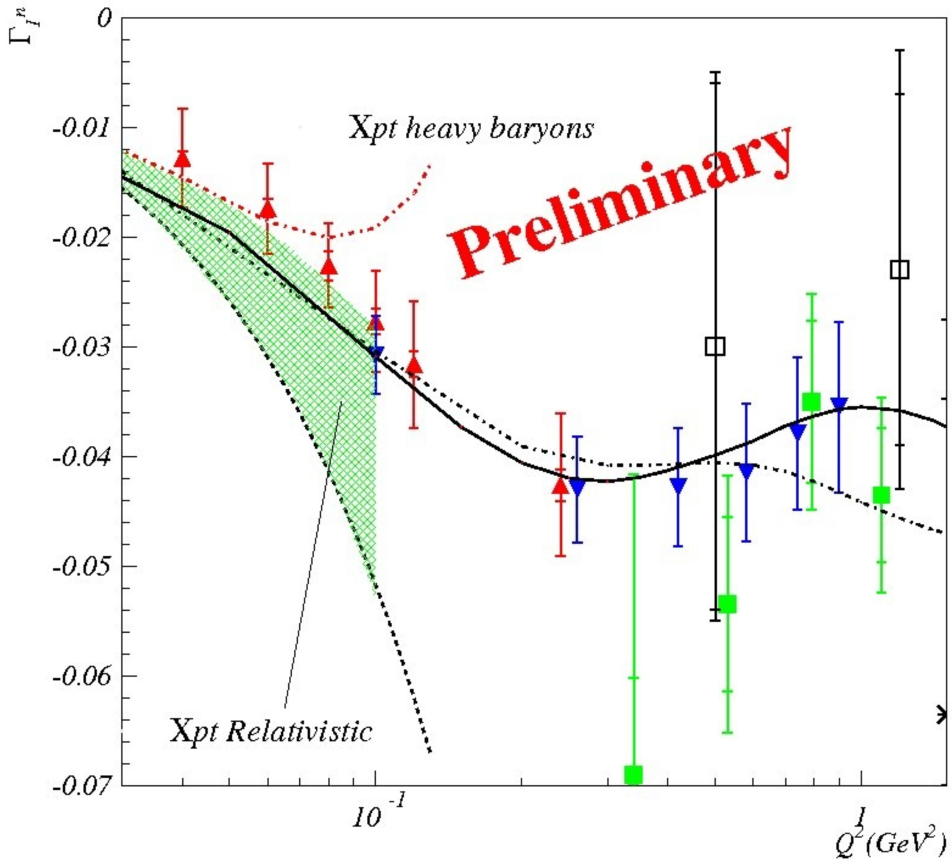
E97-110: First Moment of g_1

$$\Gamma_1 = \int_0^{x_0} g_1(x, Q^2)\, dx$$

Neutron



Neutron (zoomed)



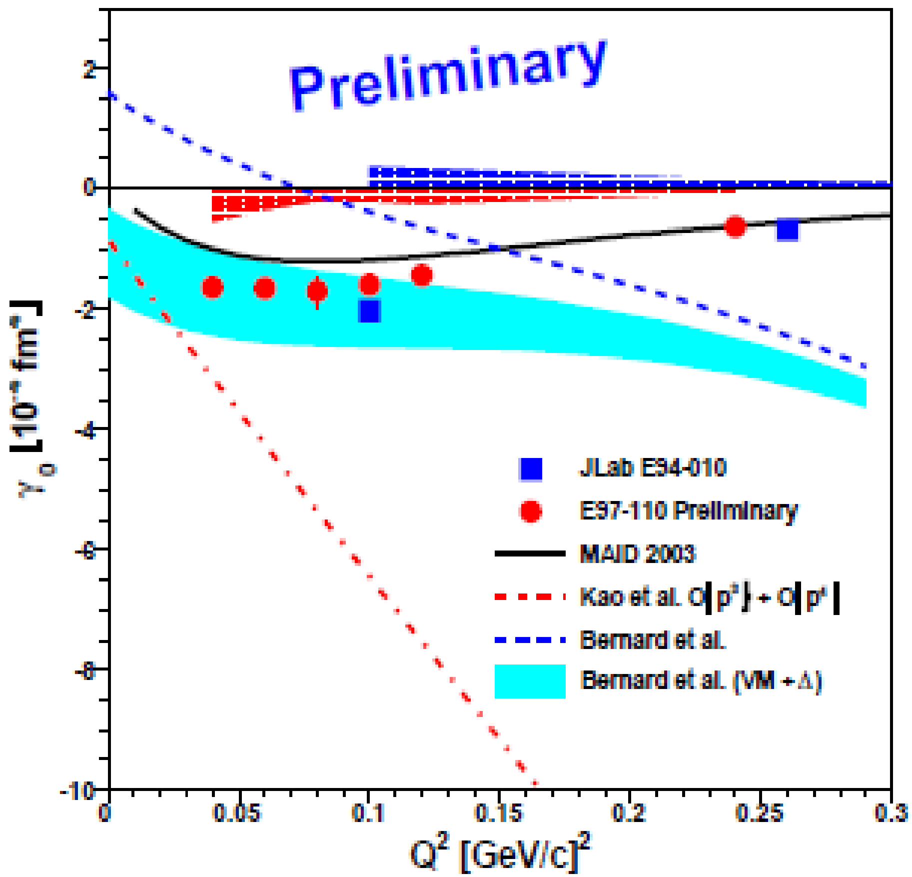
V. Sulkosky (UVa)

E97-110: Spin Polarizability

(V. Sulkosky)

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

Neutron



- Generalized spin polarizabilities γ_0 and δ_{LT} are a benchmark test of χPT

- Difficulty in including the nucleon resonance contributions

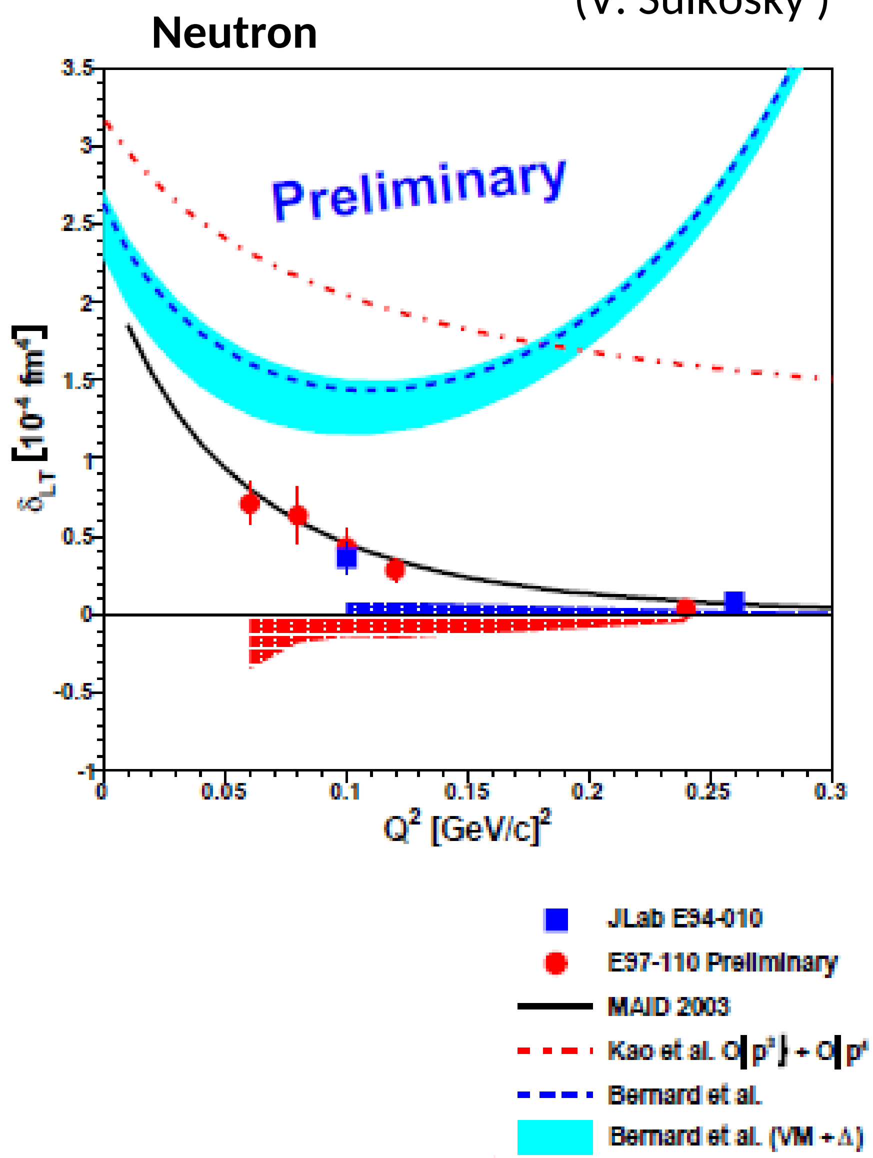
- γ_0 is sensitive to resonances, δ_{LT} is not

- Neutron results for γ_0

E97-110: Spin Polarizability

(V. Sulkosky)

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \, [g_1 + g_2]$$



- Neutron results for δ_{LT}

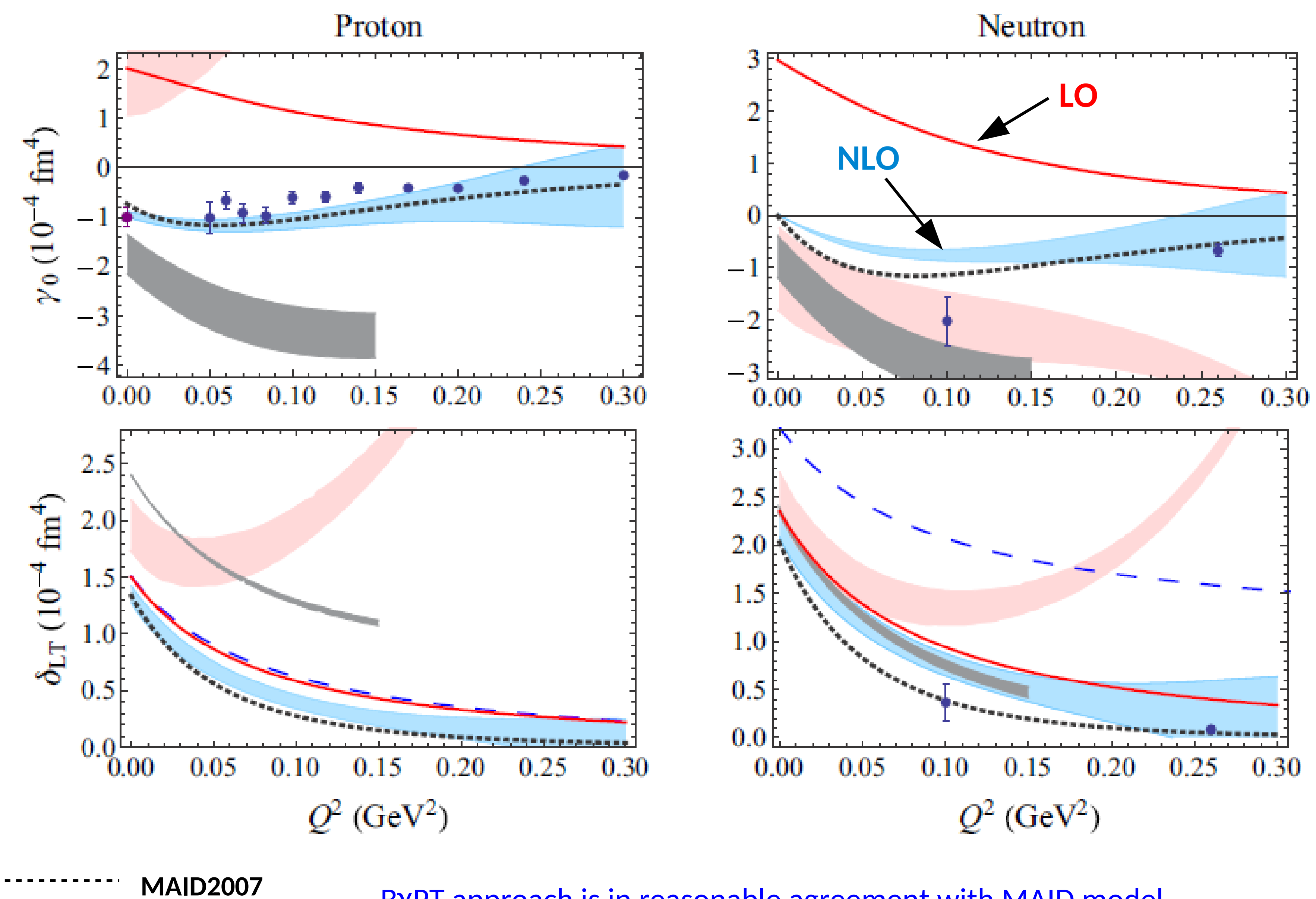
- δ_{LT} is seen as a more suitable testing ground – insensitive to Δ-resonance

- Data is in significant disagreement with χPT calculations (old)

- New calculations available from:
  - Bernard et al., PRD 87, 054032 (2013) – covariant BχPT
  - Kochelev & Oh, PRD85 (2012) 016012 – axial anomaly
  - Lensky et al., PRC 90, 055202 (2014) – BχPT approach

BχPT approach by Lensky et al., seems to agree with MAID model

V. Lensky , J. M. Alarcon, V. Pascalutsa , PRC 90, 055202 (2014)



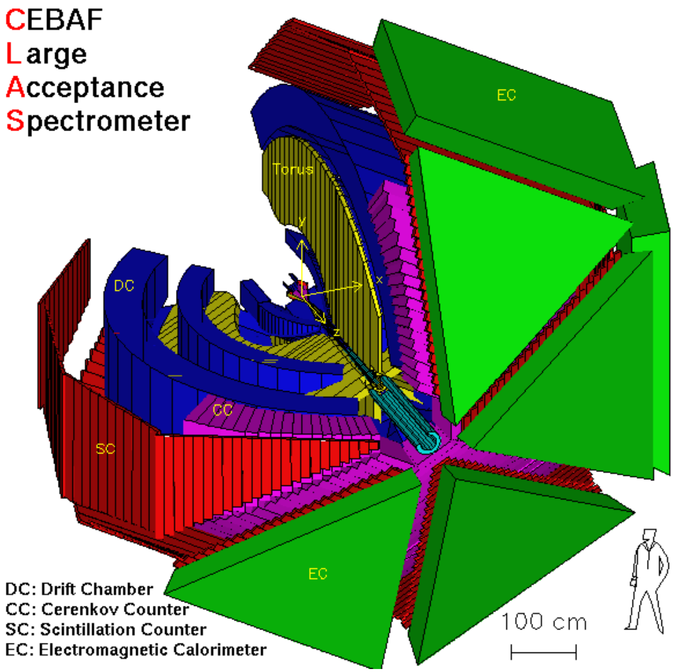
BχPT approach is in reasonable agreement with MAID model

The EG4 Experiment

Spokespersons

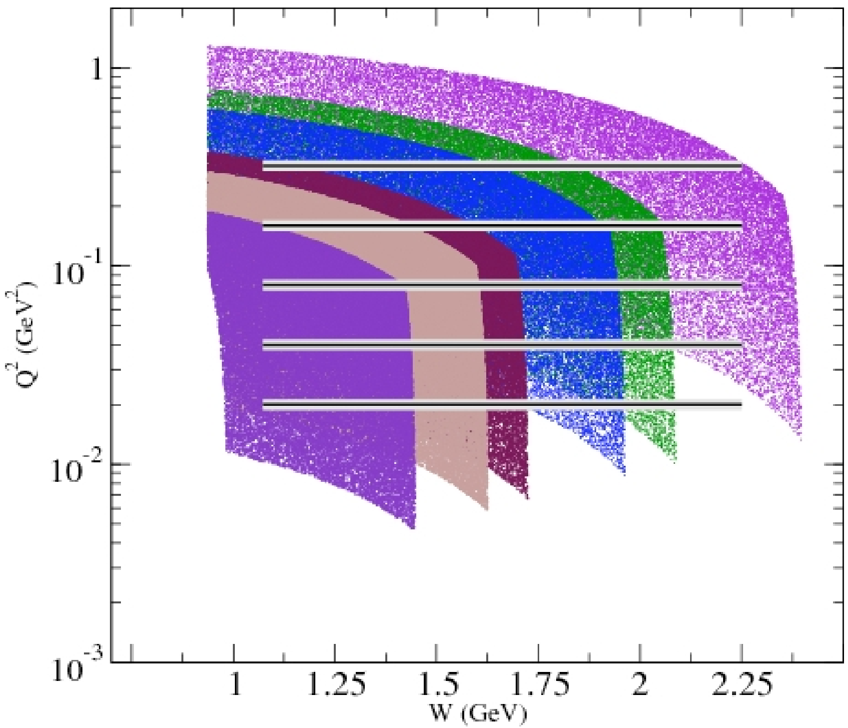
NH_3 (p): M. Battaglieri, A. Deur, R. De Vita, M. Ripani (Contact)

ND_3 (d): A. Deur(Contact), G. Dodge, K. Slifer



- Low Q^2 measurement of g_1 from NH_3(p) and ND_3(d)
- Goal : test of χPT as Q^2 -> 0

Kinematic coverage



E = 1.0, 1.3, 2.0, 2.5, 3.0 GeV

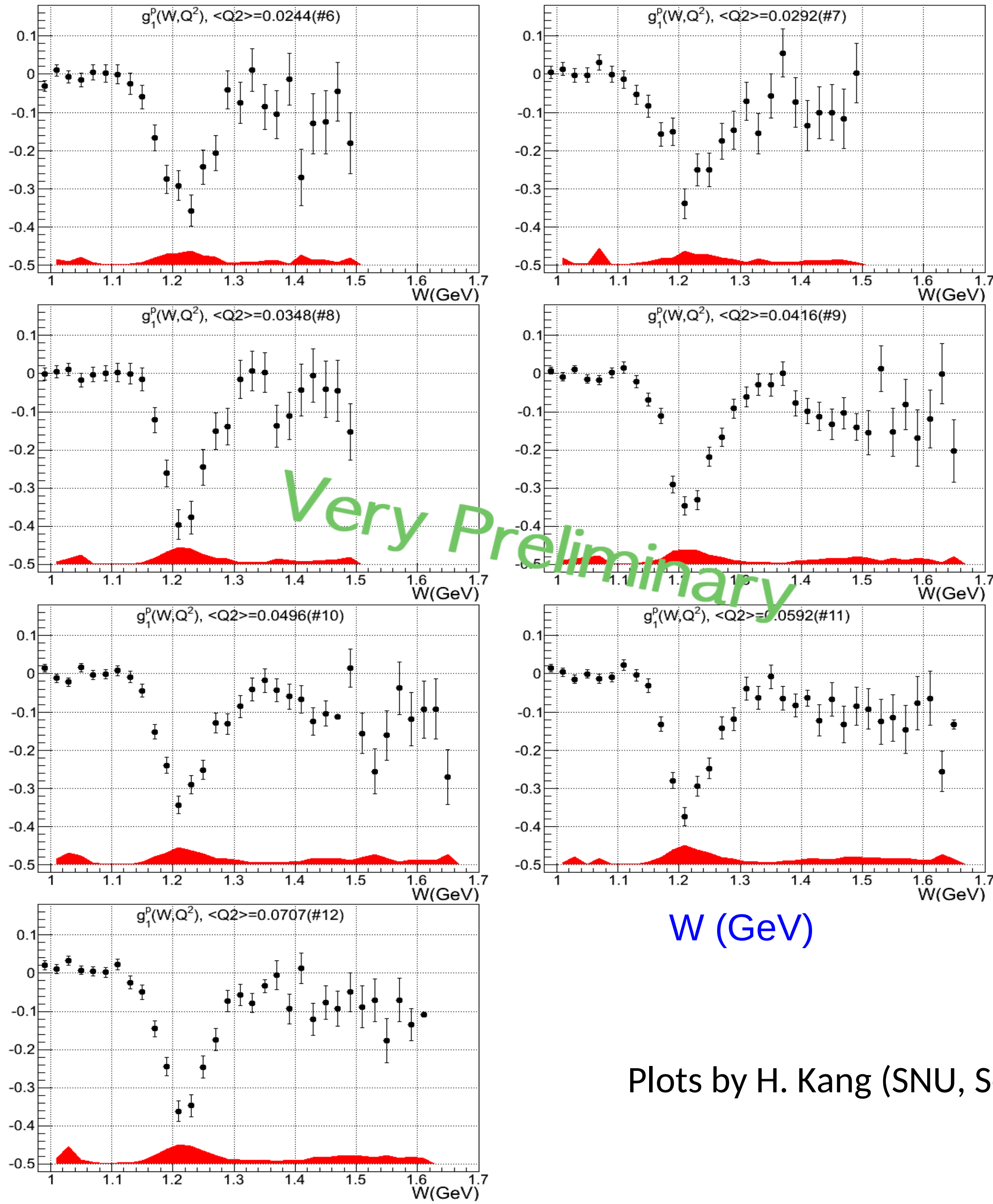
$0.02 < Q^2 < 0.7$ GeV^2

Resonance Region

Courtesy K. Slifer (UNH)

The EG4 Experiment: Proton g_1

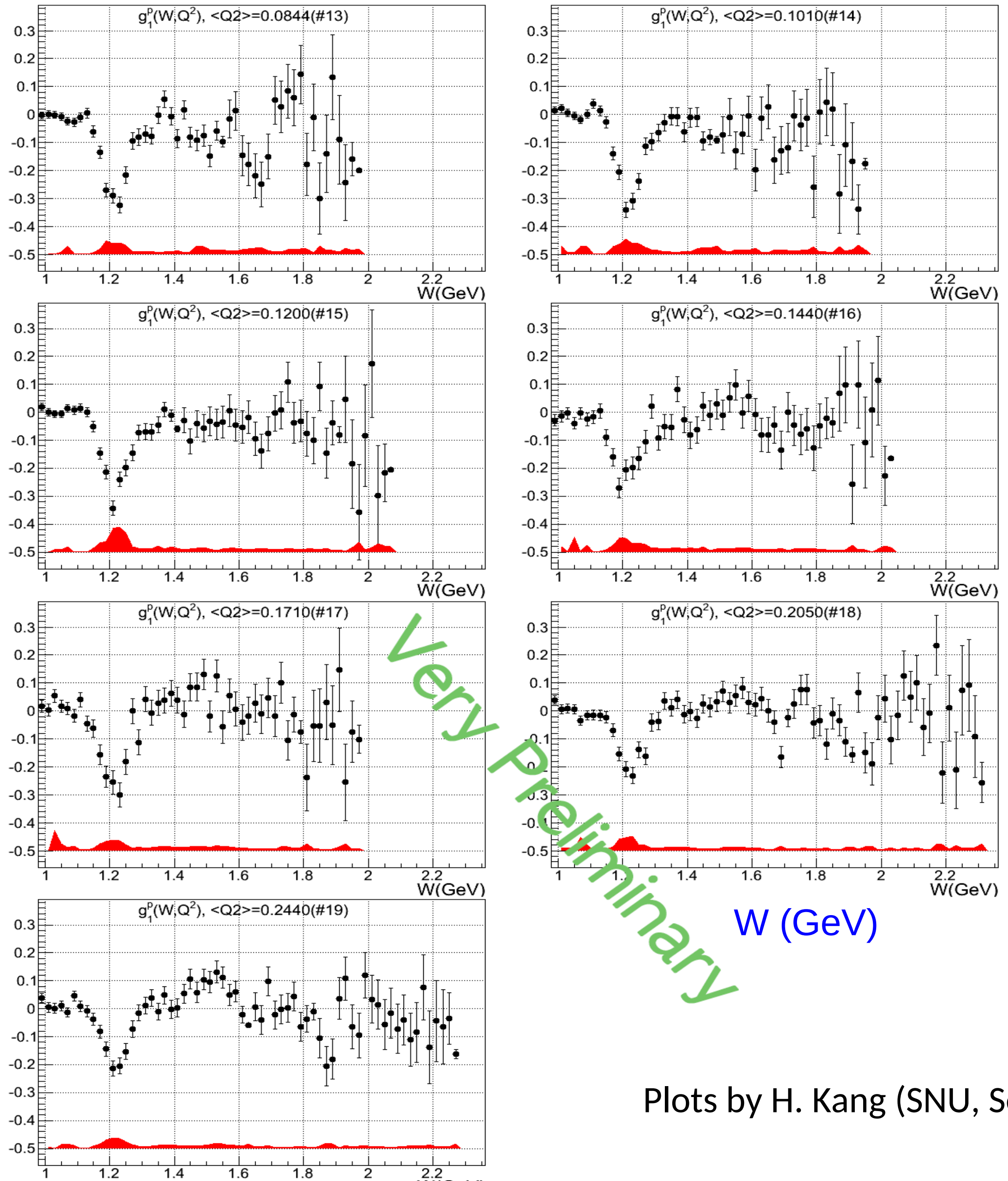
Q^2 = 0.024 - 0.071 GeV^2



Plots by H. Kang (SNU, Seoul)

The EG4 Experiment: Proton g_1

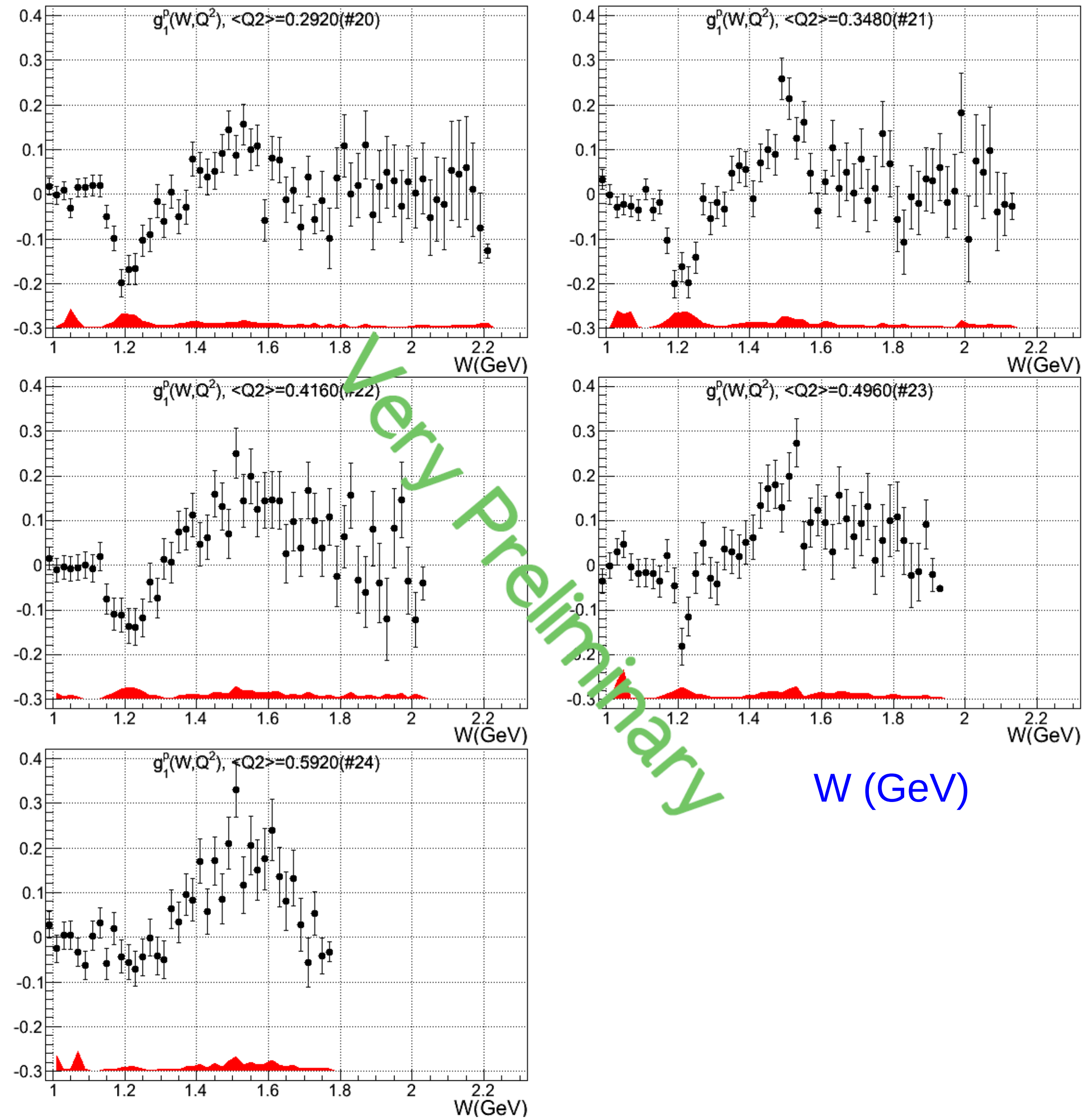
Q^2 = 0.084 - 0.244 GeV^2



Plots by H. Kang (SNU, Seoul)

The EG4 Experiment: Proton g_1

Q^2 = 0.292 - 0.592 GeV^2



W (GeV)

Plots by H. Kang (SNU, Seoul)

The EG4 Experiment: Proton Γ_1

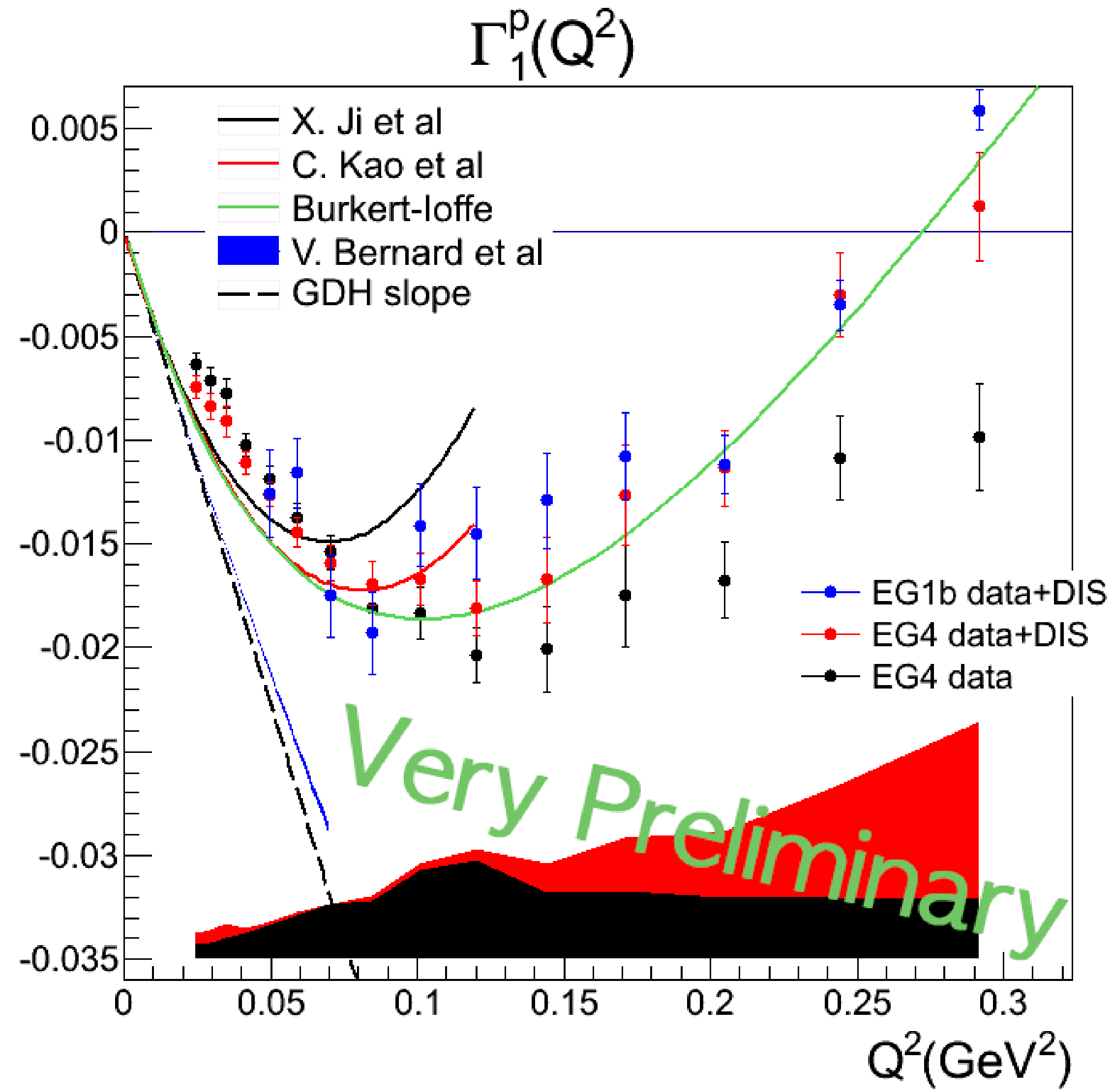
$$\Gamma_1^p = \int_0^{x_0} g_1(x, Q^2)\, dx$$

Heavy baryon ChPT:
- X. Ji et al., PLB v 472, 1-4
- C. Kao et al., PRD v69 056004

Phenomenological model:
- Burkert-Ioffe, PLB v296 223

Relativistic Baryon ChPT:
- V. Bernard et al., PRD v87 054032

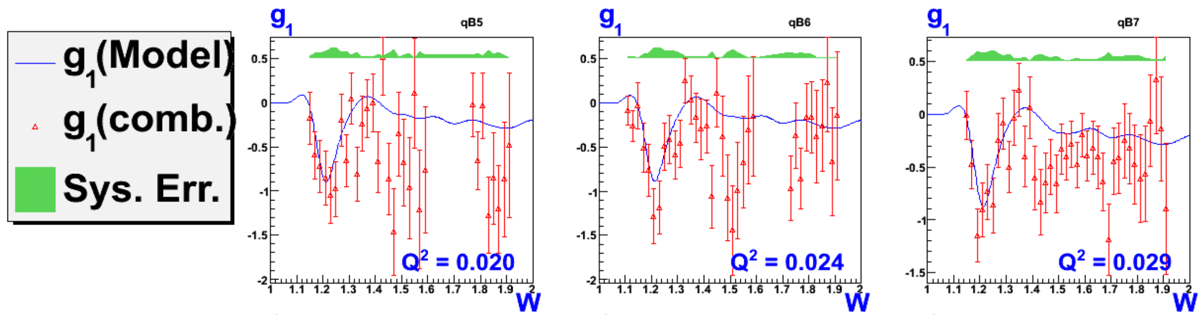
Data+DIS : includes low-x contribution (model)

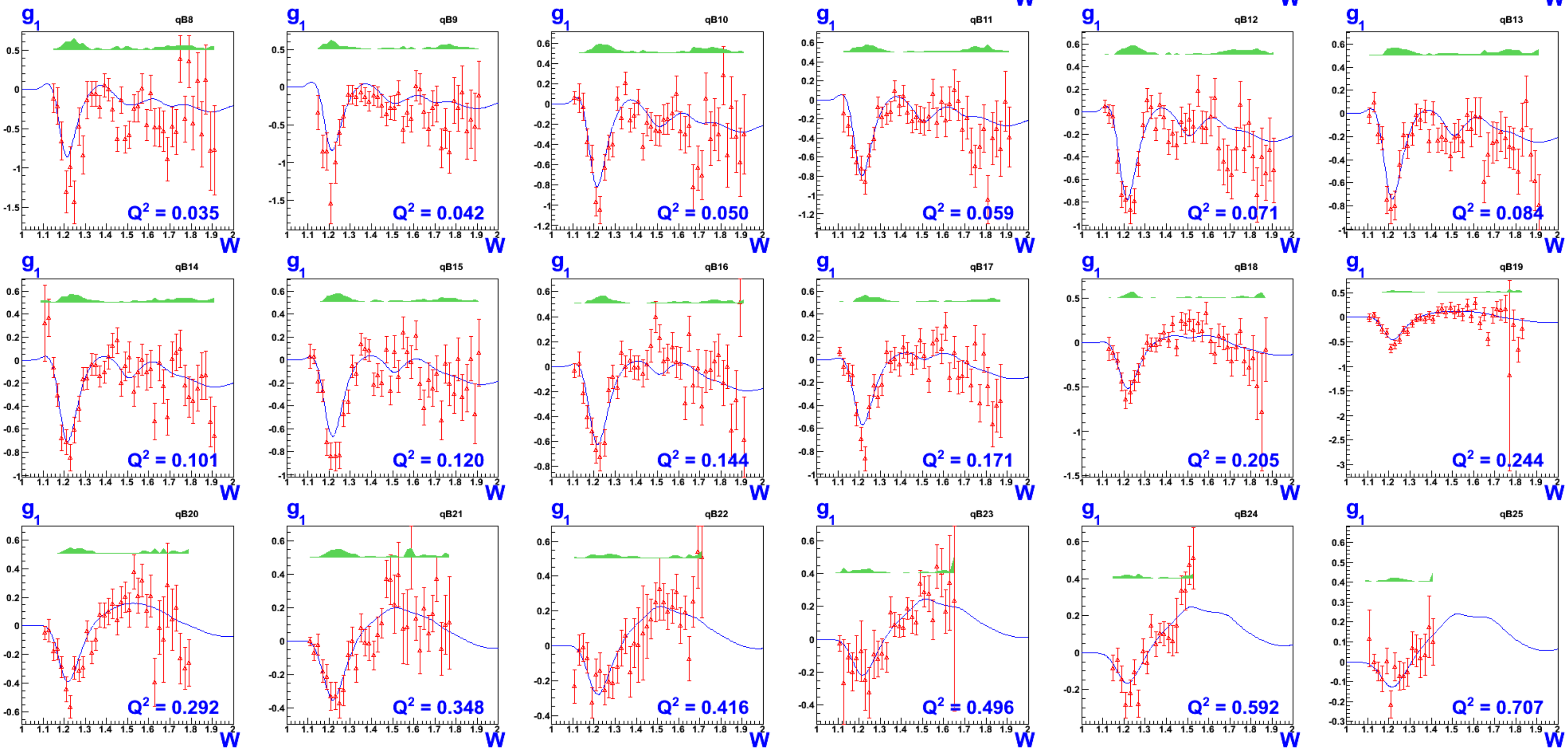


Plot by H. Kang (SNU, Seoul)

The EG4 Experiment: Deuteron g_1

Q^2 = 0.02 - 0.71 GeV^2

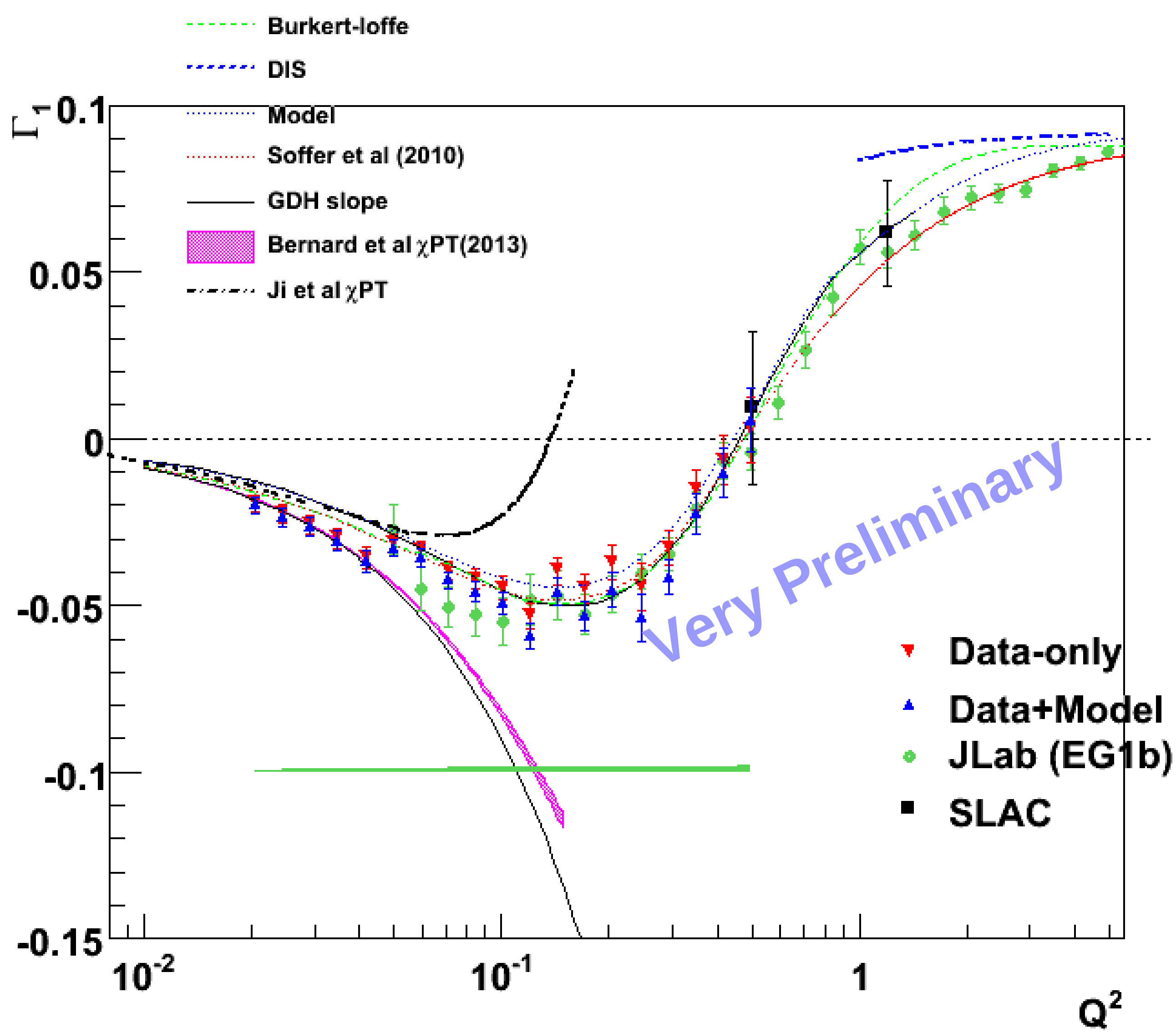




Plots by K. Adhikari (MSState)

The EG4 Experiment: Deuteron Γ_1

$$\Gamma_1^d = \int_0^{x_0} g_1(x, Q^2)\, dx$$



Data+Model :
includes low-x contribution (model)

Plots by K. Adhikari (MSState)

Hall A g2p Experiment

Spokespersons: A. Camsonne, J.-P. Chen, D. Crabb, K. Slifer

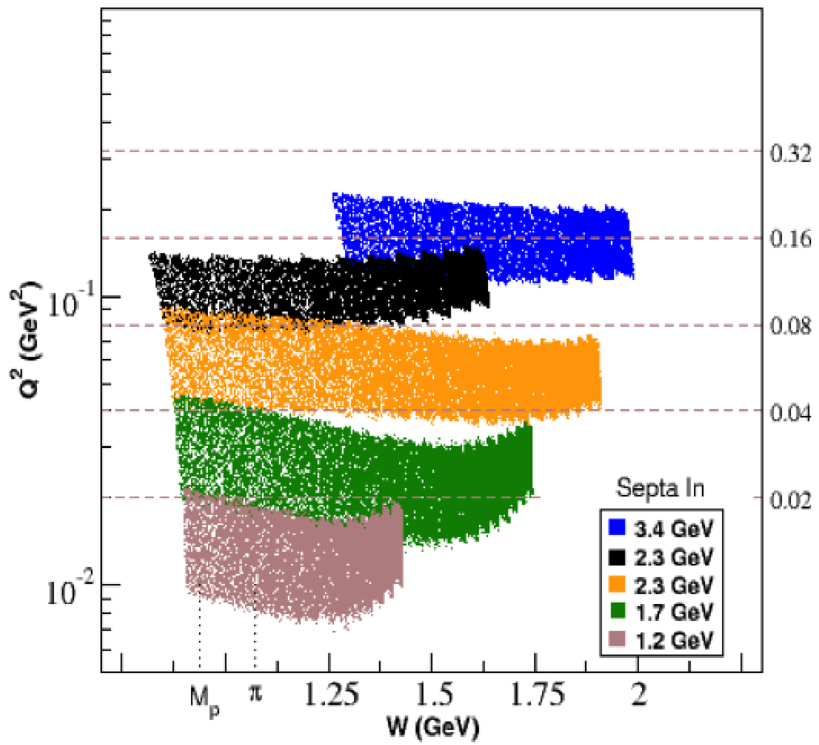
- First measurement of g_2 for the proton at low to moderate Q^2
  - BC sum rule, δ_{LT} polarizability, check χPT calculations

- Polarized electron beam

- Transversely polarized NH_3(p) target
  - Two different magnet settings (5 T, 2.5 T)
  - Ave. pol. for 5T: ~70%
  - Avg pol. for 2.5T: ~15%

- Will measure cross-section differences to extract g_2(p)
  - $\Delta\sigma_{||}$ from EG4 expt.
  - $\Delta\sigma_{\perp}$ from this expt.

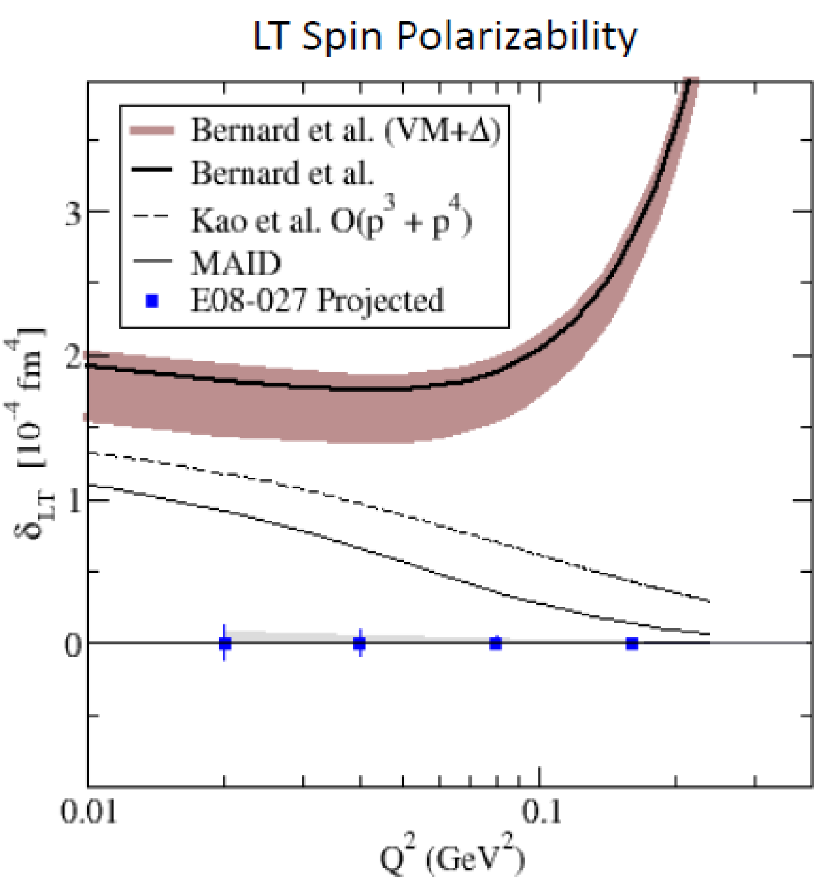
Kinematic coverage

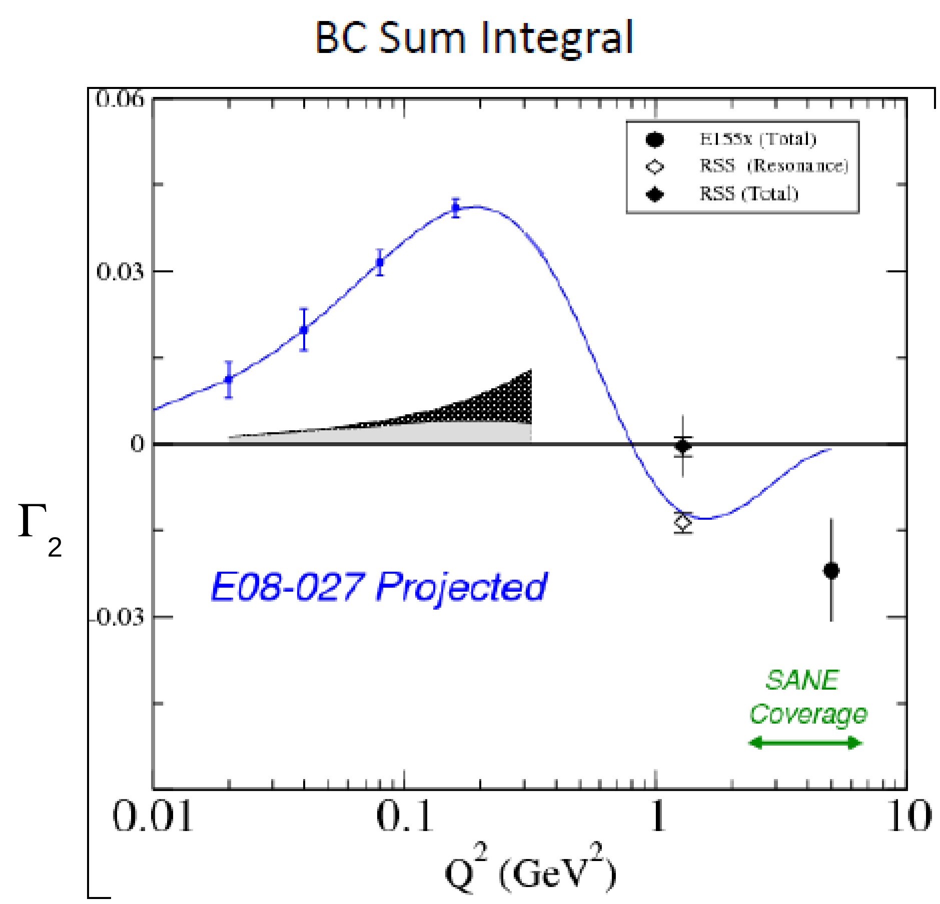


W < 2 GeV

0.02 < Q^2 < 0.2 GeV^2

g2p Experiment: Projections for Proton





See Ryan Zielinski's talk on Thursday afternoon for details:
Parallel Session 5: Hadron Structure & Meson Baryon Interaction WG

E07-003 (SANE) Experiment in Hall C

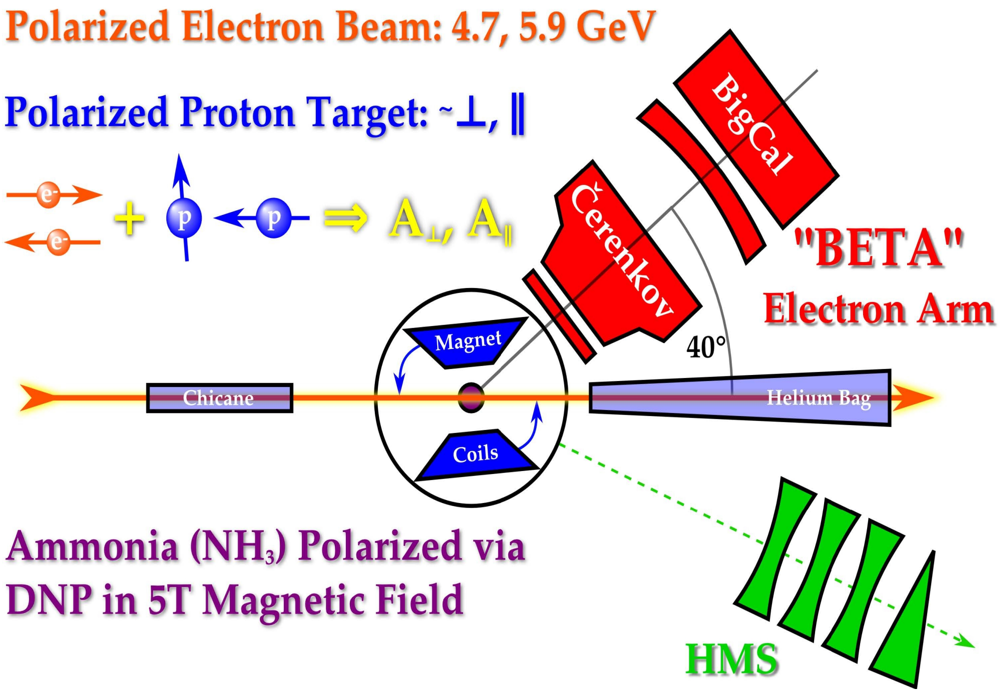
Spokespersons: S. Choi, M. Jones , Z-E. Meziani, O. A. Rondon (Contact)

- Goal: Measure the proton spin structure function g_2 (x, Q^2) and spin asymmetry $A_1(x,Q^2)$

- Q^2 = 2.5 - 6.5 GeV^2
- x = 0.3 – 0.8

- Method: Measure parallel and near-transverse inclusive double spin asymmetries

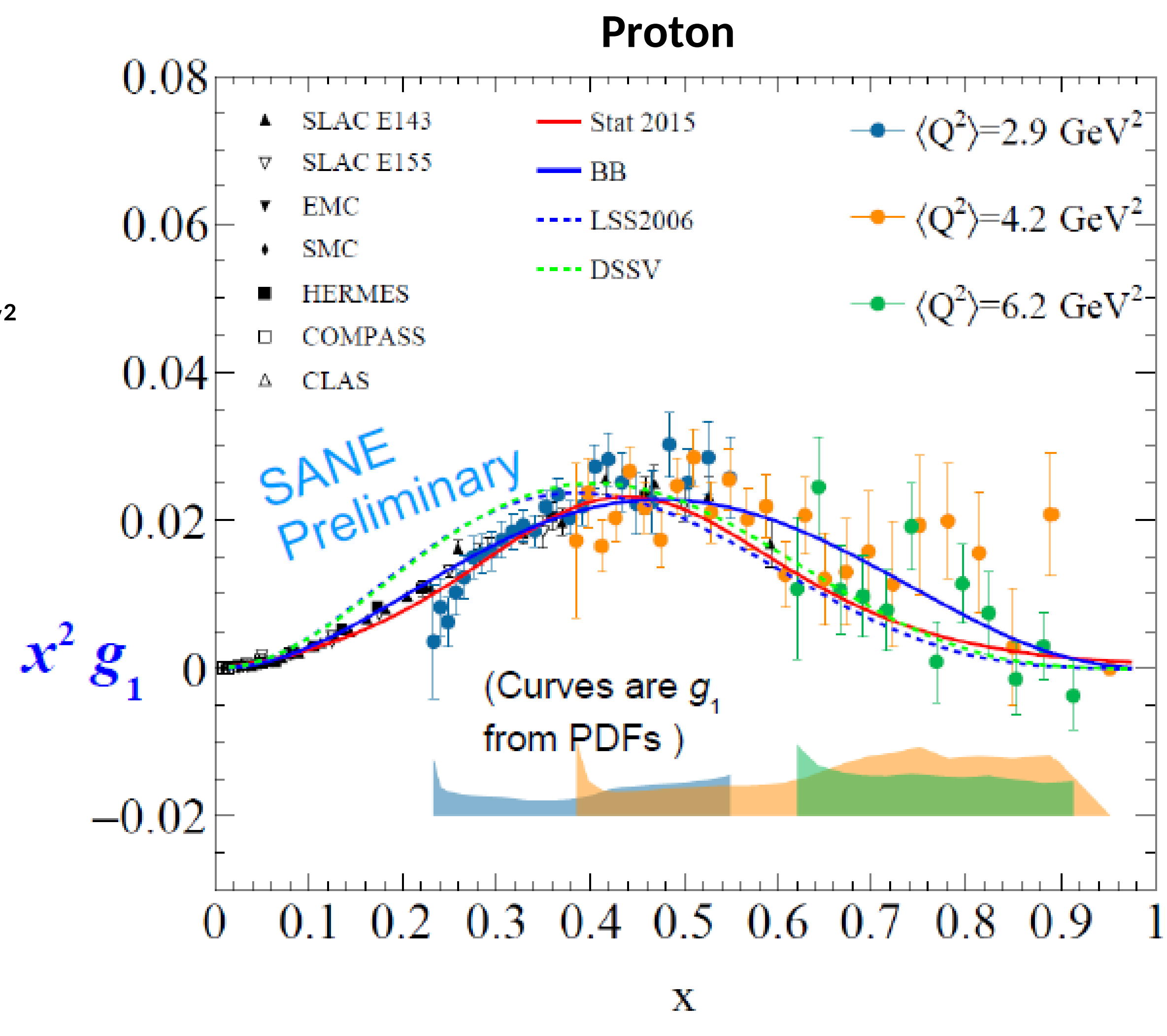
- Polarized NH_3(p) target



Courtesy O. Rondon (UVA)

Proton g_1 (SANE)

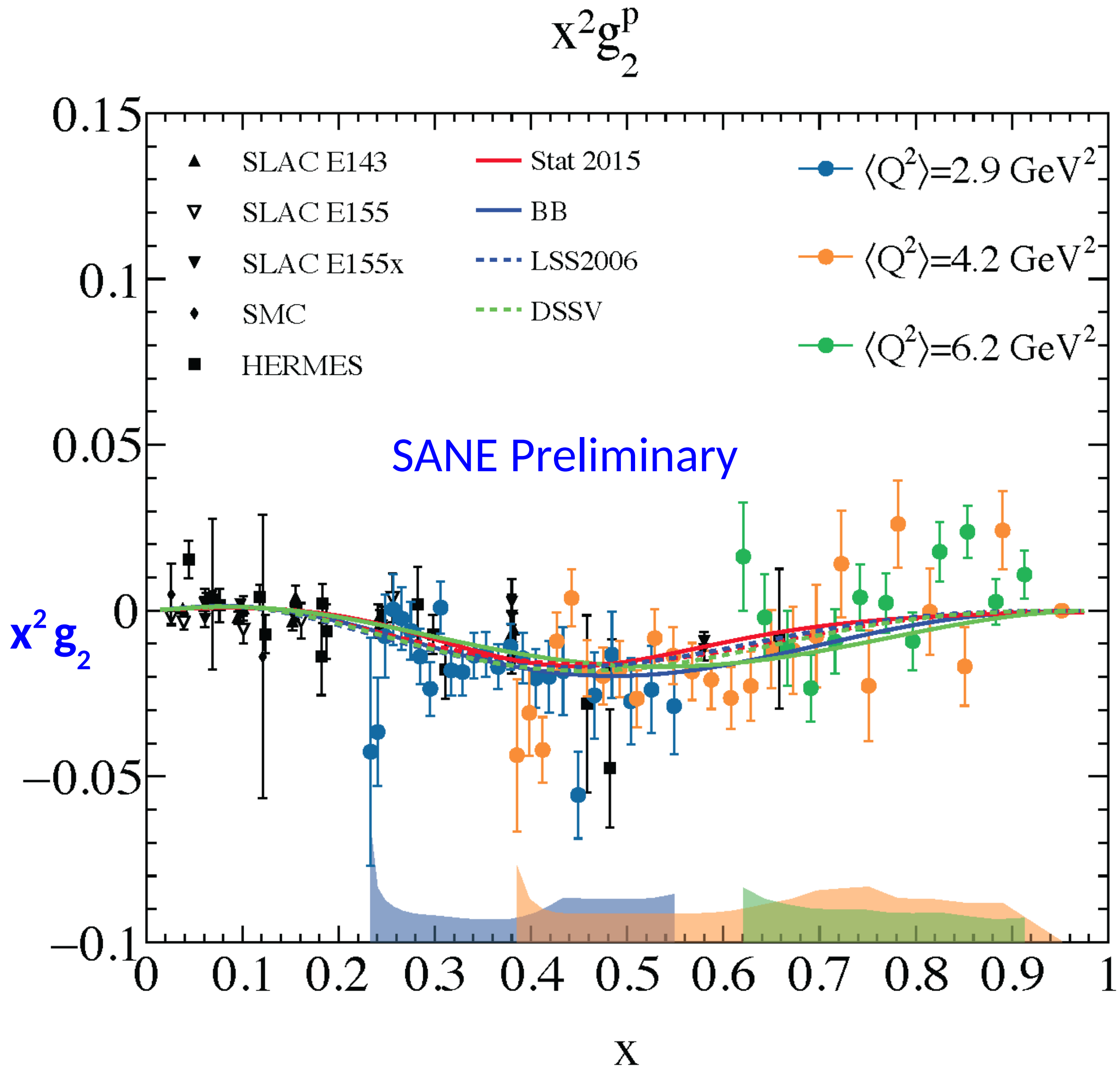
- BETA proton data
  - DIS and Resonances
  - g_1, g_2^{WW} curves from PDFs at Q^2 = 4 GeV²
  - E' >= 0.6 GeV
  - more data at Q^2 = 1.6 GeV² coming
  - SLAC E143, E155, E155x,SMC and HERMES DIS data



(W. Armstrong)

SANE Experiment: Proton g_2

- BETA proton data
- DIS and Resonance data
- g_2^{WW} curves using g_1 at $Q^2 = 4$ GeV^2
- E'> 0.6 GeV
- More data at $Q^2 = 1.6$ GeV^2



(W. Armstrong, ANL)

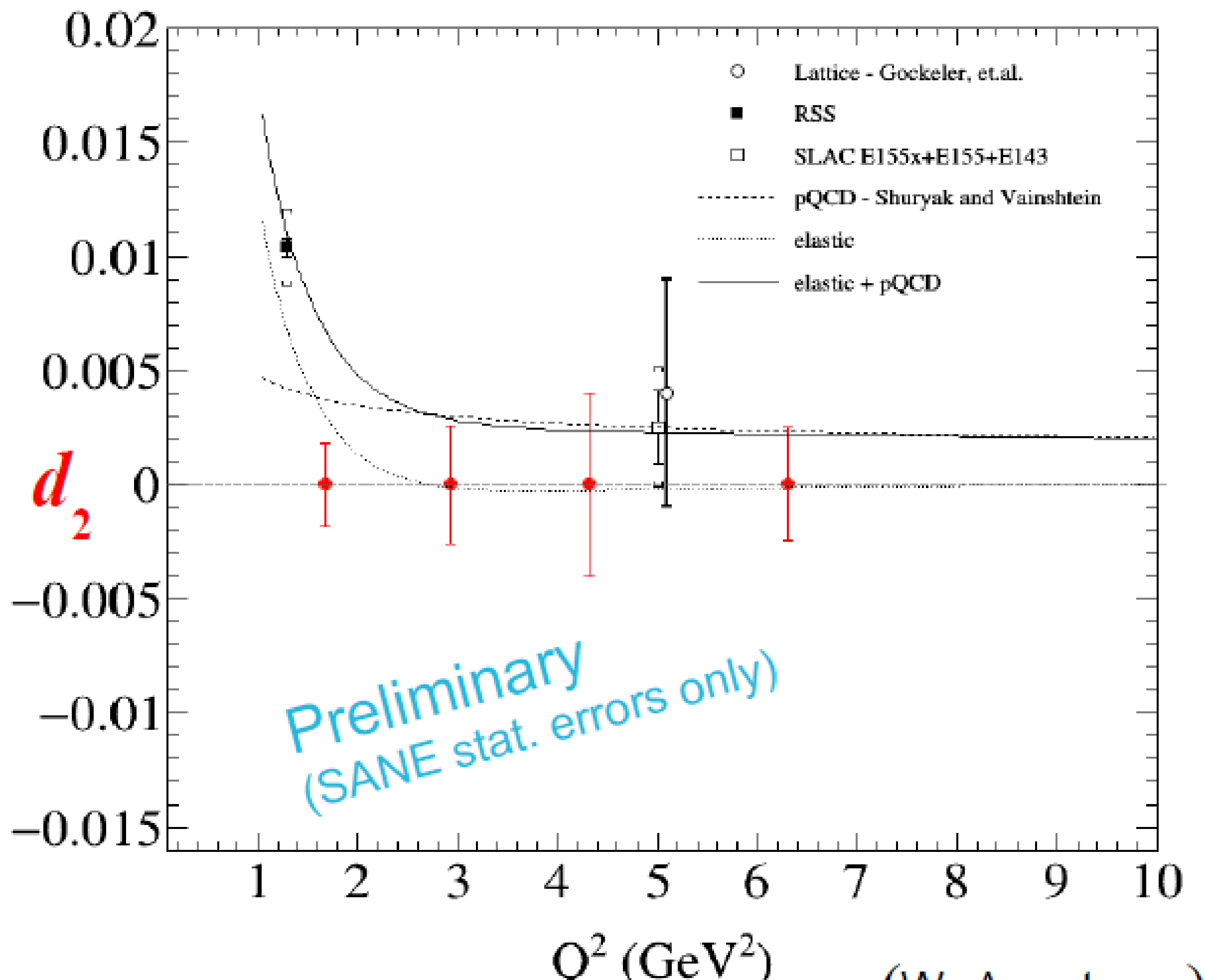
Proton d_2 Projections

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

Nachtmann moments are needed to get twist-3 free of target mass corrections

Expected statistical errors for d_2

Proton



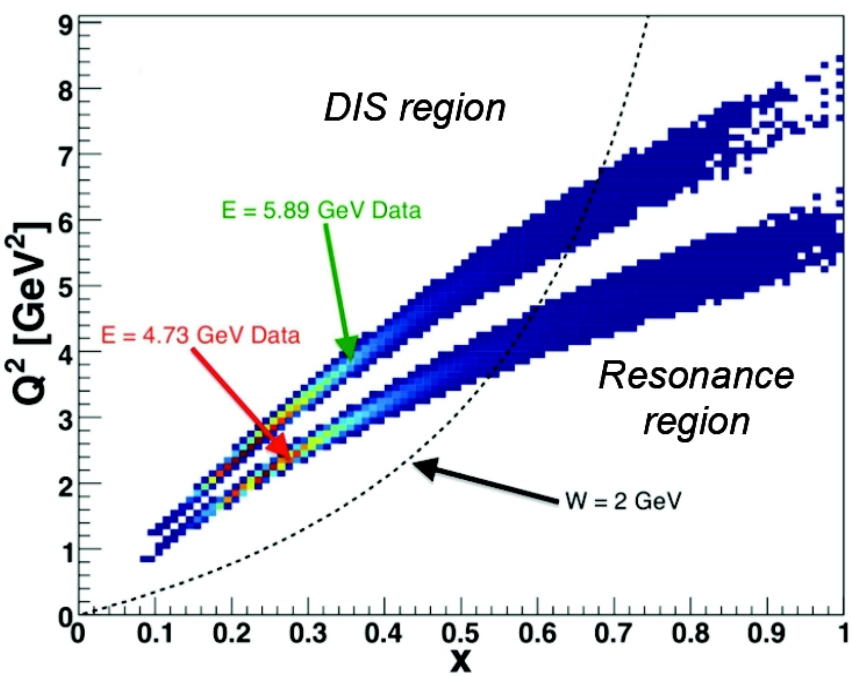
(W. Armstrong)

E06-014 (d2n) Experiment

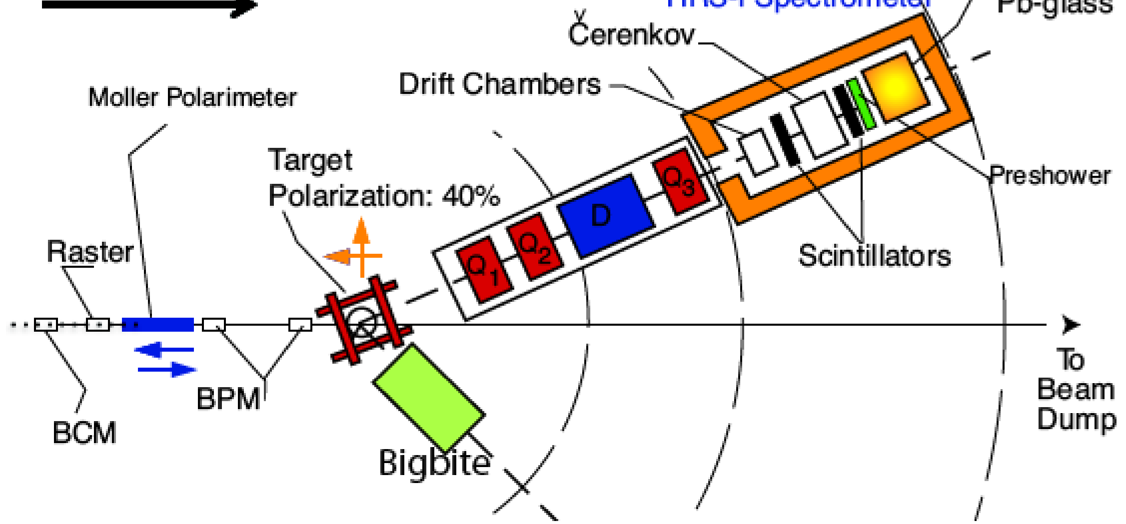
Spokespeople: B. Sawatzky, S. Choi, X. Jiang and Z.-E.Meziani

- Goal : Measure d_2 and A_1 spin asymmetry for neutron
- 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

Kinematic coverage

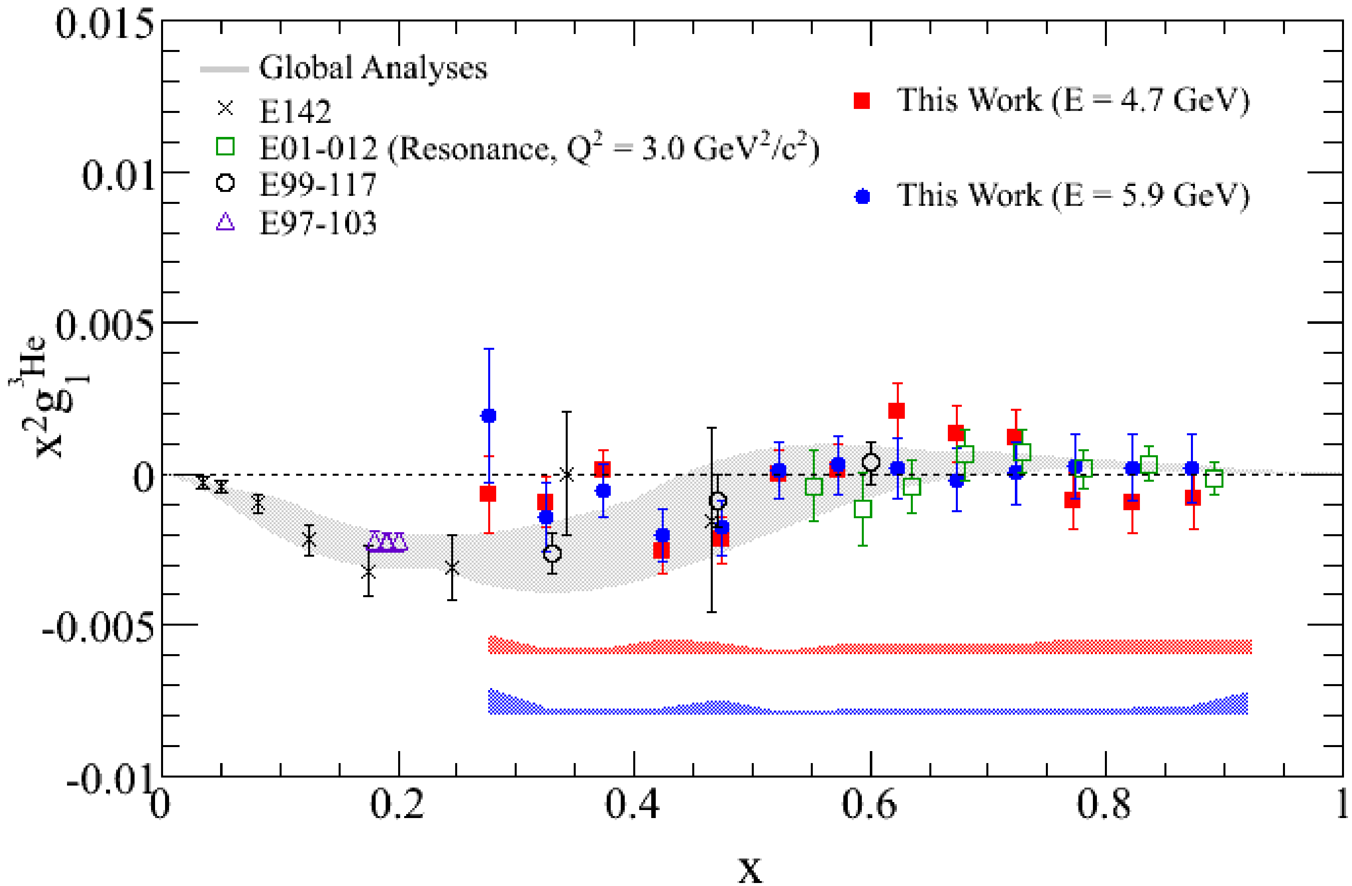


Beam direction



E06-014 Experiment: $x^2 g_1$ for ^3He

$\langle Q^2 \rangle = 3.2\ (GeV/c)^2$
$\langle Q^2 \rangle = 4.3\ (GeV/c)^2$

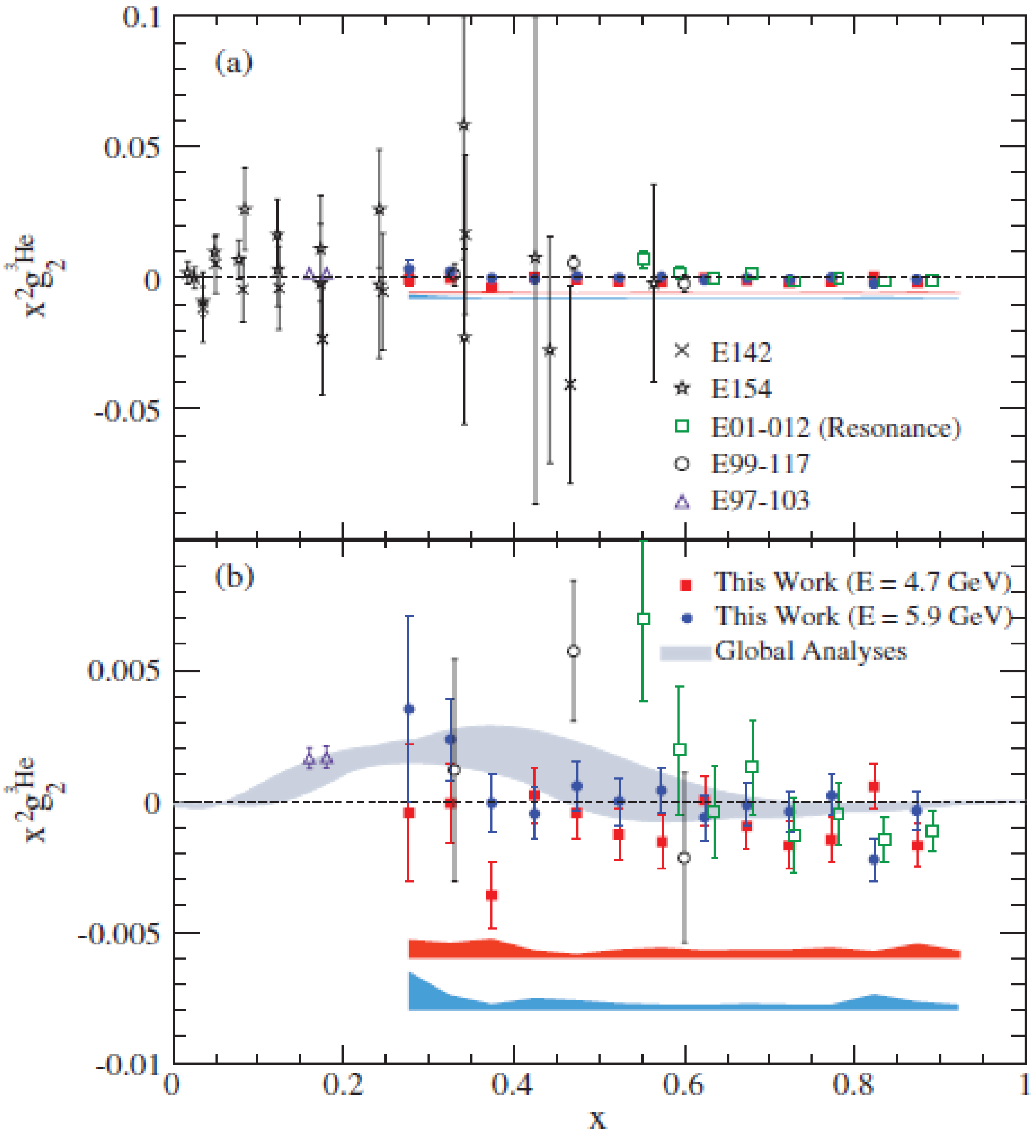


E06-014 Experiment: x^2g_2 for ^{3}He

$\langle Q^2 \rangle = 3.2\ (\mathrm{GeV}/c)^2$
$\langle Q^2 \rangle = 4.3\ (\mathrm{GeV}/c)^2$

- Panel (a) shows comparison to world data

- Panel (b) is zoomed on y-axis to show error bars



*Posik et al., PRL **113** 022002 (2014)*

E06-014 Experiment: d_2 for the Neutron

- Results are consistent with Lattice QCD prediction

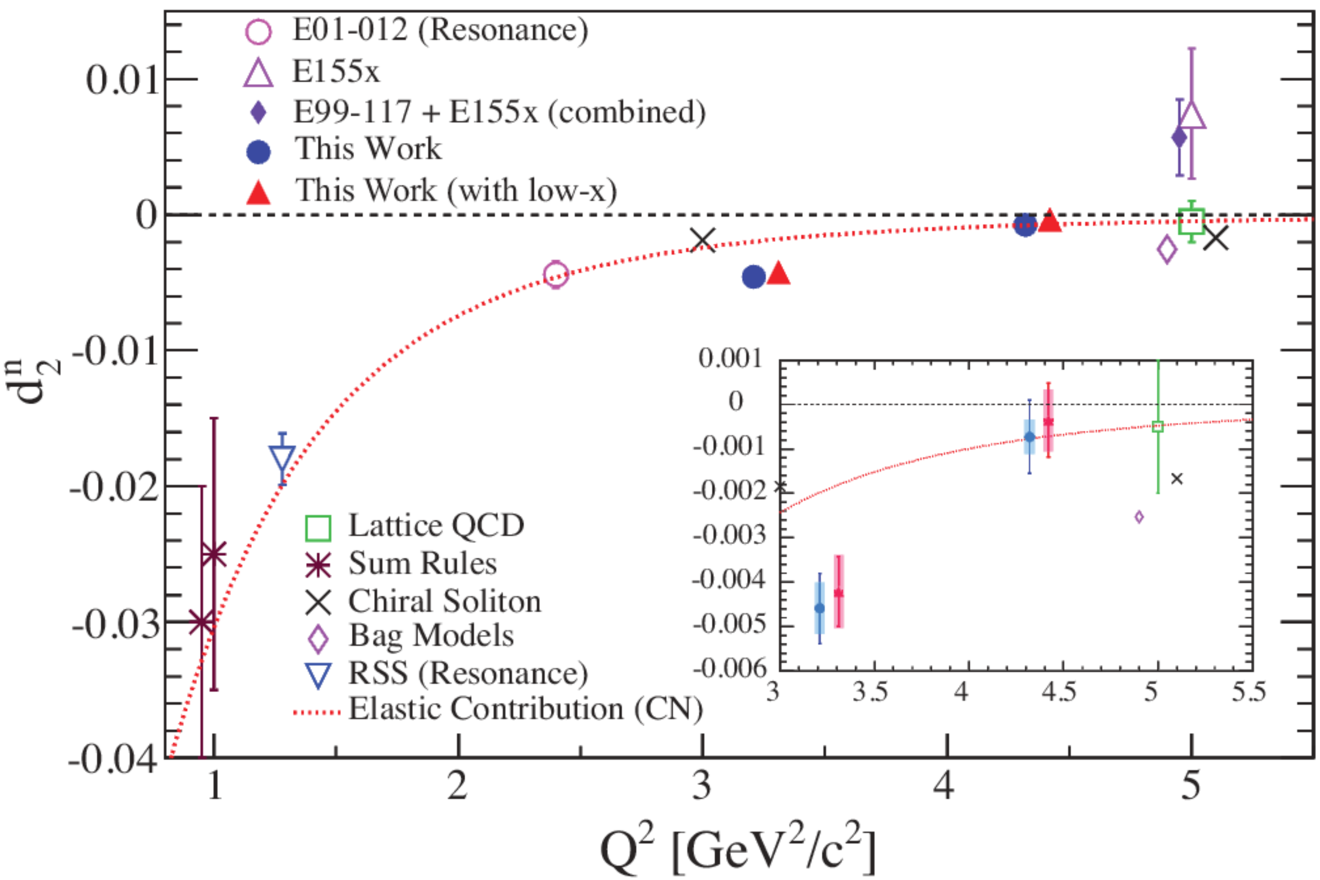
- d_2^n extracted at
  - $\langle Q^2\rangle \sim 3.3$ GeV^2 (E=4.7 GeV data)
  - $\langle Q^2\rangle \sim 4.3$ GeV^2 (E=5.9 GeV data)

- Shaded boxes in inset are systematic uncertainties

- Low-x contribution (0.02 < x < 0.25) is provided by fits to world data (small impact)

- ^{3}He → neutron correction using eff. polarization method applied to d_2 (Bissey et al. Phys Rev C, 65:064137, 2002)

Posik et al., PRL ***113*** *022002 (2014)*

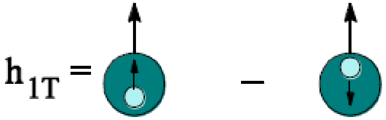


Courtesy B. Sawatzky (JLab)

What about quark transverse spin distribution ?

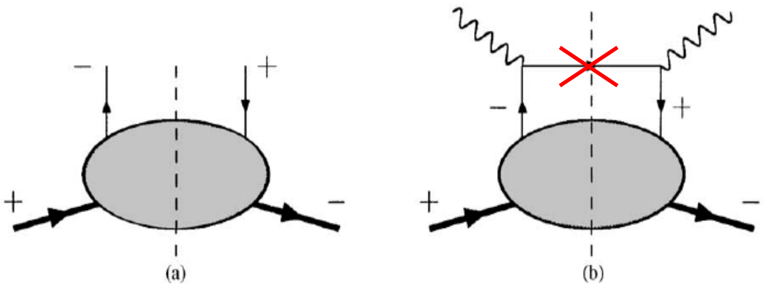
Transversity Distribution (h_1)

- Transversity : distribution of transversely polarized quarks in transversely polarized nucleon



- Related to nucleon tensor charge: $\delta q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x) \right] dx$

- Helicity flip amplitude -



- Suppressed in the DIS process – need another chiral odd function
- Can be accessed through Semi-inclusive DIS via chiral-odd Collins fragmentation function

$$\sigma^{ep^{\uparrow} \rightarrow ehX} \propto \sum_q h_1^q \otimes \sigma^{eq \rightarrow eq} \otimes FF^{q \rightarrow h}$$

- Measure transverse target single spin asymmetry: $A_{UT} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = A_{UT}^{Collins} + A_{UT}^{Sivers} + A_{UT}^{Pretz}$

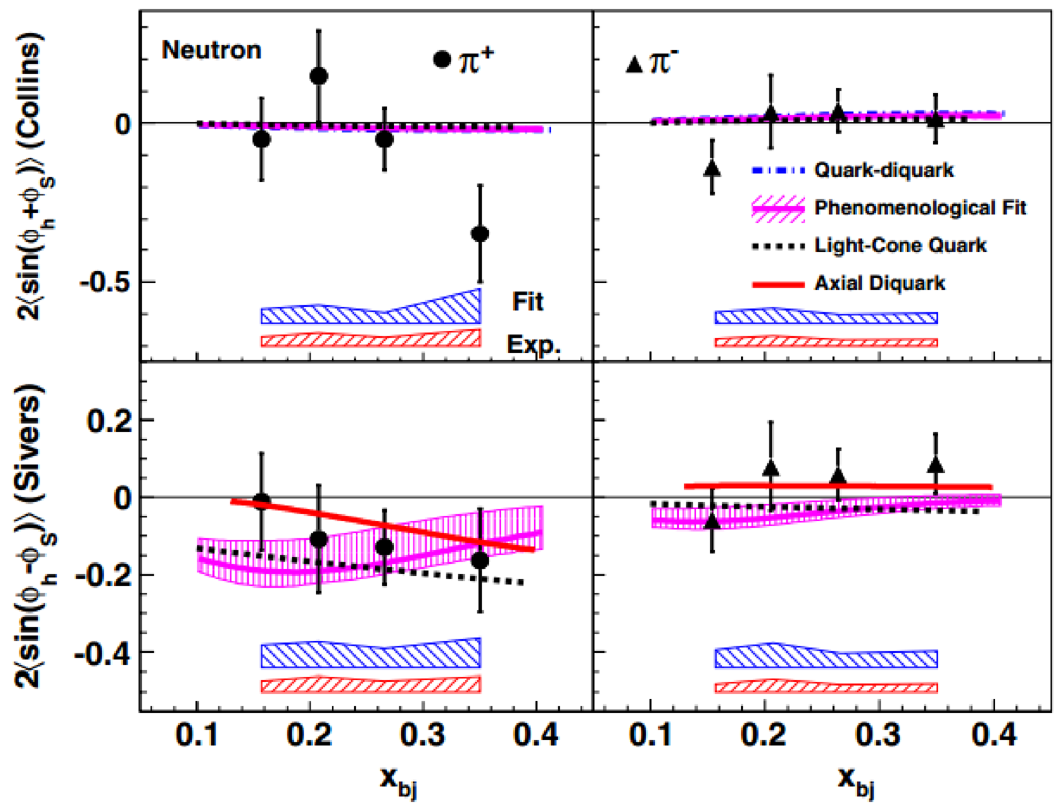
Hall A Transversity Experiment: Collins and Sivers Moments

$$e + n^{\uparrow}_{eff} \rightarrow e' + \pi^{\pm} + X$$

$$A_{UT}^{Collins} \propto \frac{\sum e_q^2 h_1^q \otimes H_1^{\perp q}}{\sum e_q^2 f_1^q \otimes D_1^q}$$

$$A_{UT}^{Sivers} \propto \frac{\sum e_q^2 f_1^{\perp q} \otimes D_1^q}{\sum e_q^2 f_1^q \otimes D_1^q}$$

Collins and Sivers Moments



- Neutron SSA extracted from measured ^{3}He asymmetry in SIDIS
- Covers valence region
- Favors negative values for π^+ Sivers
- Neutron Collins and Sivers moments consistent with models predictions (2011)

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

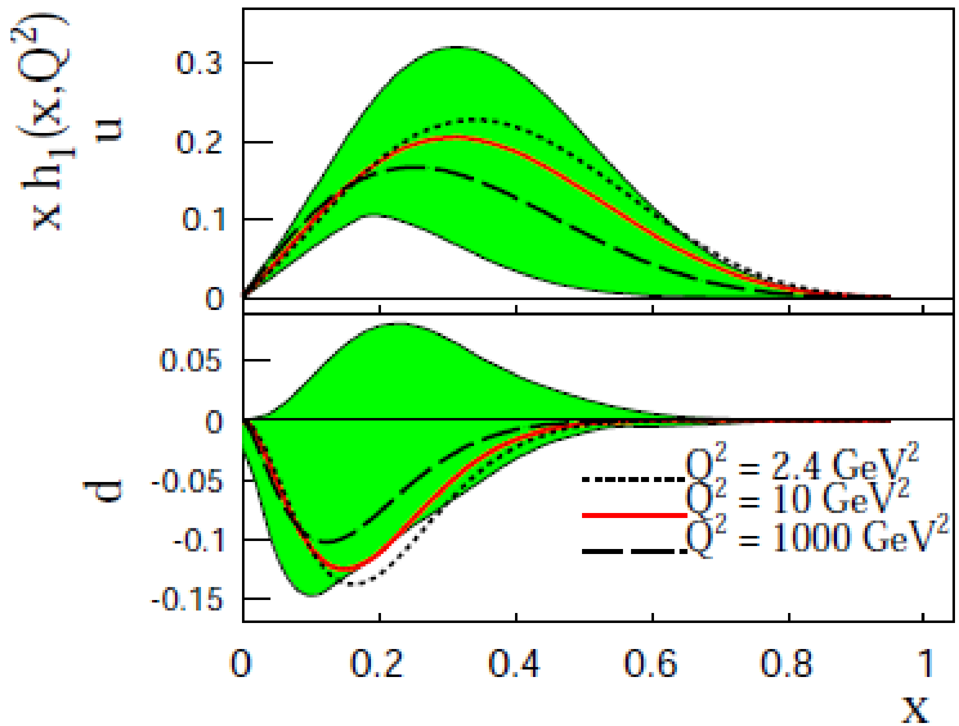
X. Qian et al., PRL 107 (2011) 072003

Global Extraction of Transversity

- Global analysis of transversity:
  includes HERMES (p), COMPASS (p/d) and JLab (^{3}He) data

- Still large uncertainties – need more precise data
  - A comphrensive SIDIS program at JLab 12 GeV

Transversity distribution



Z-B. Kang et al., arXiv:1505.05589

Summary

- Data on nucleon spin structure from several recent measurements at JLab are now available:
  - preliminary data for proton g_1 at low Q^2
  - preliminary data on Γ_1 and δ_{LT} on neutron at low Q^2
  - preliminary data on g_1 and g_2 for proton at high Q^2 (DIS, Resonances)
  - published data on g_1 and g_2 for neutron at high Q^2 (DIS)

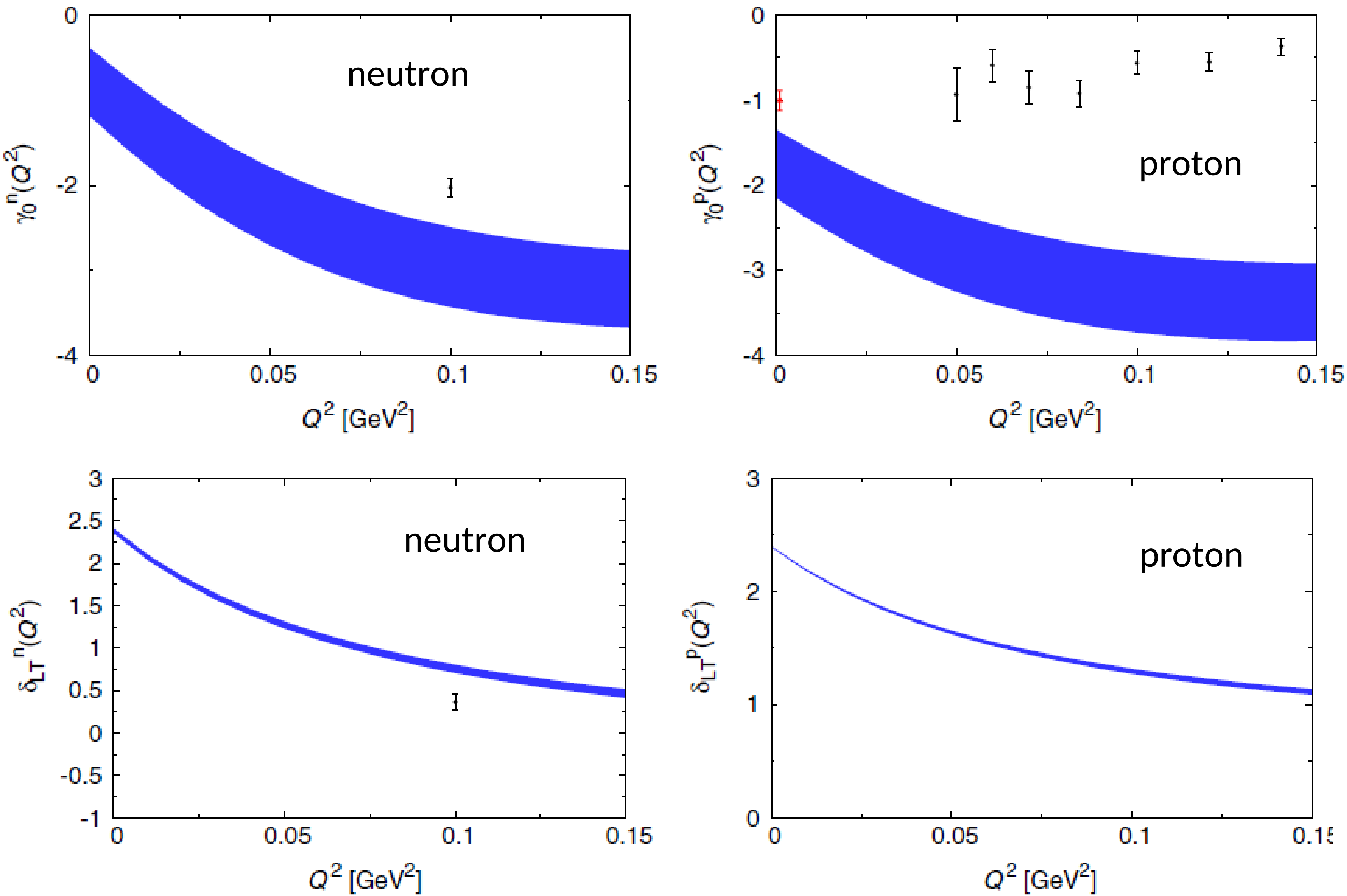
- Low Q^2 proton g_2 data is still being analyzed

- Many recent advances on the χPT theory front to explain the δ_{LT} puzzle
  - Much needed low Q^2 data on proton will be available soon

- Data from first generation of experiments led to the extraction of transversity distribution
  - Very precise SIDIS data to follow in the 12 GeV era at JLab

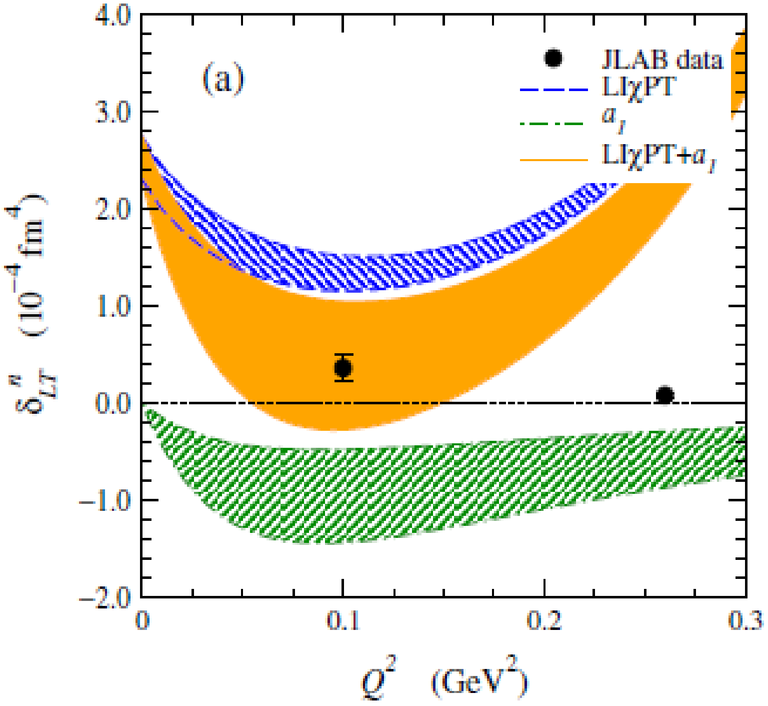
Spare Slides

V. Bernard, E. Epelbaum, H. Krebs and Ulf-G. Meißner , PRD 87, 054032 (2013)

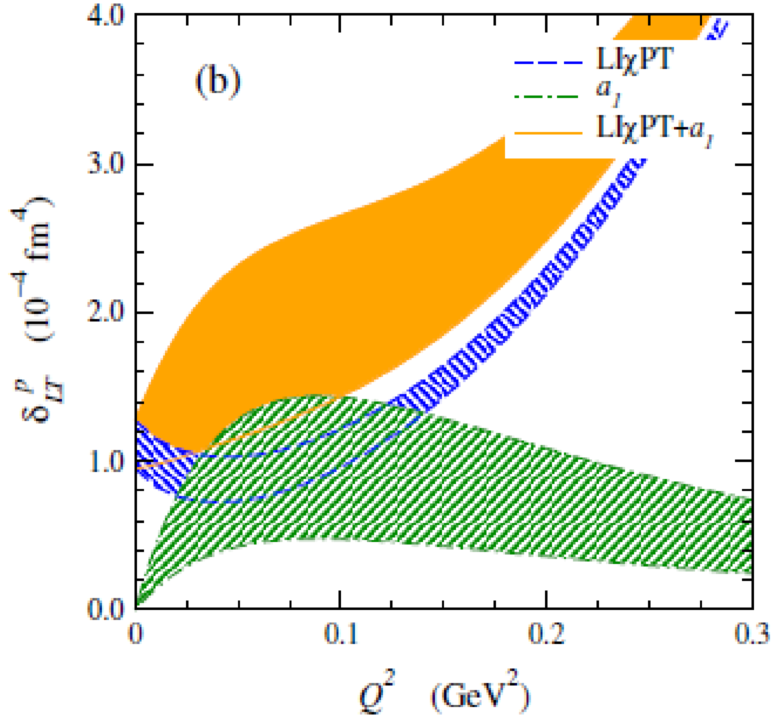


N. Kochelev and Y. Oh, PRD 85, 016012 (2012)

neutron



proton



Improved agreement with neutron