New Results on Nucleon Spin (Highlights from Jefferson Lab)

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INPP - U. of Virginia

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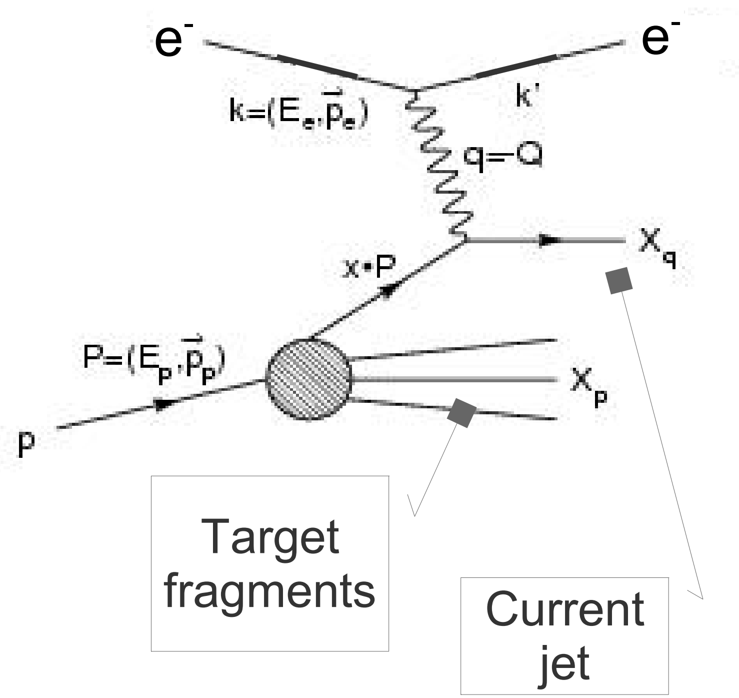
Probing the Nucleon Spin with Polarized Electromagnetic Scattering

Charged Inelastic *Lepton-Nucleon* Scattering

- Use virtual photon γ^* as probe
  - Best region for illuminating nucleon structure is Bjorken $x > 0.1$, where the γ^* hadronic structure does not contribute to the scattering
  - This region is JLab's domain
- Talk focus is on nucleon spin from double-polarization experiments
  - transverse target polarization
  - inclusive scattering results; connection to semi-inclusive studies
  - summary of program at 11 GeV

Inelastic EM Scattering



Inclusive Scattering: Undetected final state

(http://www.desy.de/~gbrandt/feyn/)

Inelastic *e* - *nucleon* Scattering

- Inclusive EM scattering is described in terms of the hadronic and leptonic tensors: nucleon structure and beam.
- General expression for hadronic tensor involves eleven terms:
  - six structure functions (SF's) for spin-averaged beam and target states and five for double-polarized scattering.
  - symmetries reduce SF's to unpolarized $\boldsymbol{W_1}$, $\boldsymbol{W_2}$, polarized $\boldsymbol{G_1}$, $\boldsymbol{G_2}$
- Anti-symmetric part of hadronic tensor depends on $\boldsymbol{G_1}$, $\boldsymbol{G_2}$:

$$W^{A}_{\mu\nu} = 2\epsilon_{\mu\nu\lambda\sigma} q^{\lambda} \left\{ M^2 S^{\sigma} \boldsymbol{G_1}(\nu, Q^2) + \left[M\nu S^{\sigma} - p^{\sigma} S\cdot q \right] \boldsymbol{G_2}(\nu, Q^2) \right\}$$

  - lab frame nucleon's $p = (M, \mathbf{0})$; four-momentum transfer $q = (E - E', \boldsymbol{k} - \boldsymbol{k}')$, $Q^2 = -q^2$; energy transfer $\nu = E - E'$; angles relative to beam.

Structure Functions in Inclusive DIS

- The four SF's G_1, G_2, W_1 and W_2, contain all the information on nucleon structure that can be extracted from inclusive data
- In the high energy regime of DIS, g_1 and g_2 are expected to scale like F_1 and F_2 (up to log violations)

$$\lim_{Q^2,\nu\to\infty} M^2\nu\, G_1(\nu,Q^2)=g_1(x)$$
$$\lim_{Q^2,\nu\to\infty} M\nu^2 G_2(\nu,Q^2)=g_2(x)$$
$$x=Q^2/(2M\nu)$$

$$\lim_{Q^2,\nu\to\infty} M\,W_1(\nu,Q^2)=F_1(x)$$
$$\lim_{Q^2,\nu\to\infty} \nu\,W_2(\nu,Q^2)=F_2(x)$$
$$\frac{F_2(x)}{F_1(x)}=2x \quad (Callan-Gross)$$

- In the quark parton model g_1 and F_1 are also related to PDF's:

$$F_1(x)=\frac{1}{2}\sum e_f^2(q_f^{\uparrow}(x)+q_f^{\downarrow}(x))$$
$$g_1(x)=\frac{1}{2}\sum e_f^2(q_f^{\uparrow}(x)-q_f^{\downarrow}(x))$$

Virtual Compton Asymmetries

- For polarized beam and target, the spin SF's are also related to photon cross-sections and asymmetries
  - Along the γ^* axis, the helicity of the photon-nucleon system is 3/2 or ½ for transverse photons, ½ for longitudinal ones
  - The spin asymmetry (SA) $\boldsymbol{A_1}$ is defined in terms of the difference for 3/2 and ½ helicity cross sections
  - The SA $\boldsymbol{A_2}$ is defined in terms of the interference between initial transverse and final longitudinal amplitudes

$$\boldsymbol{A_1} = \frac{\sigma_T^{(3/2)} - \sigma_T^{(1/2)}}{\sigma_T^{(3/2)} + \sigma_T^{(1/2)}}$$

$$\boldsymbol{A_2} = \frac{\sigma_{TL}^{(1/2)}}{\sigma_T^{(3/2)} + \sigma_T^{(1/2)}} \leq \boldsymbol{R} = \frac{\sigma_L}{\sigma_T}$$

$$\boldsymbol{A_1} = \frac{1}{F_1}\left(g_1 - \gamma^2 g_2\right); \quad \gamma = \frac{2xM}{\sqrt{Q^2}}$$

$$\boldsymbol{A_2} = \frac{\gamma}{F_1}\left(g_1 + g_2\right) = \frac{\gamma}{F_1}\boldsymbol{g_T}$$

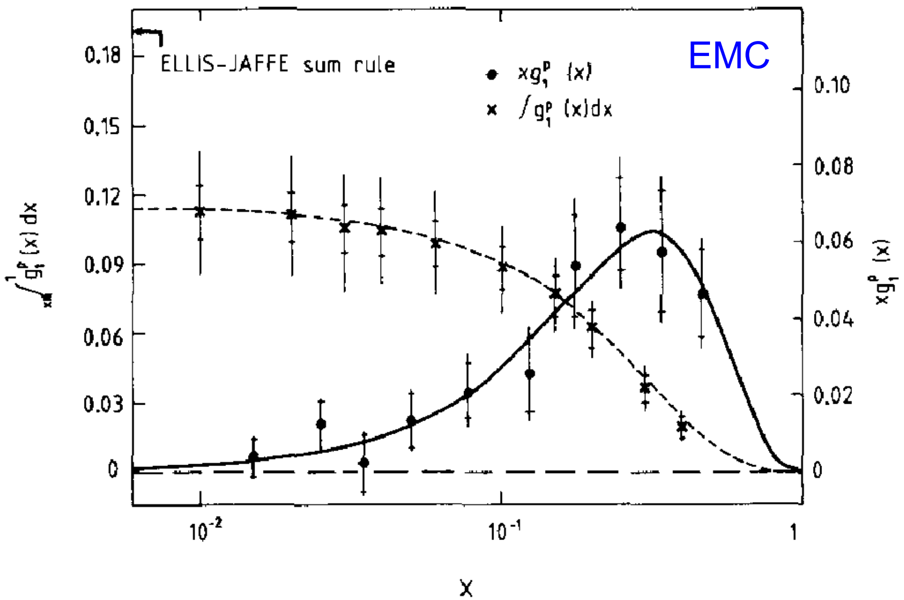
Nucleon Spin "Crisis"

- Nucleon spin is calculated from the first moment of $\boldsymbol{g_1}$

$$\int_0^1 dx\, g_1^p(x) = \frac{1}{36}[4E_0 \boldsymbol{a_0} + 3E_3 a_3 + E_8 a_8]$$

$$\boldsymbol{a_0} = \sum q = \Delta u + \Delta d + \Delta s$$

- Singlet axial-vector matrix element $\boldsymbol{a_0}$ is sum of quark spins: $\boldsymbol{a_0 = 0.33 \pm .03 \pm .05}$ (COMPASS 2007)



(PL B206, 364 (1988))

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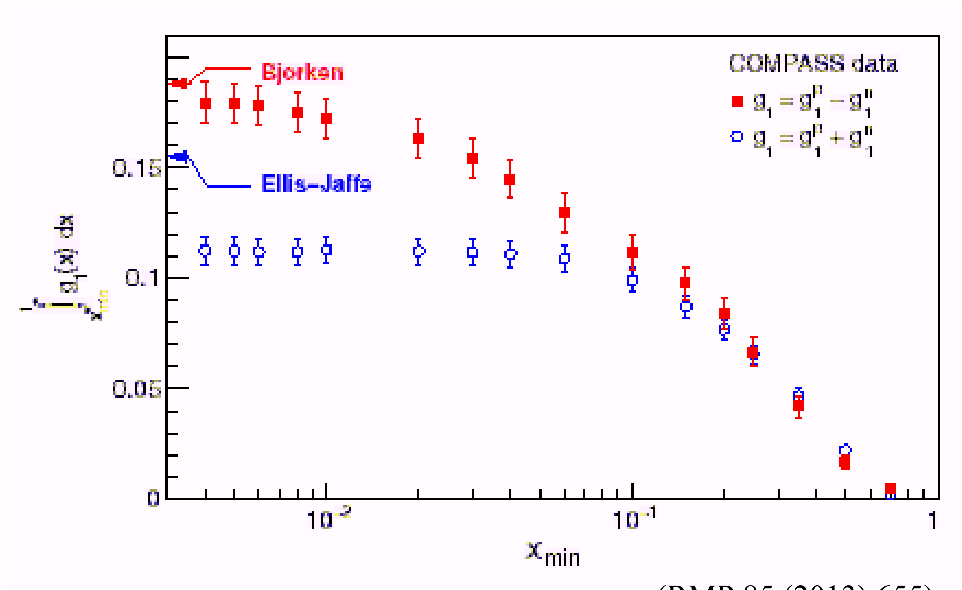
- Δg ~ 0: need *L* to get ½ h/2π



(RMP 85 (2013) 655)

$$\frac{1}{2} = \frac{1}{2}\sum \Delta q + \Delta g + L$$

$$= (.12 \pm .03) + (.11 \pm .12) + L$$

$\overline{MS}$ scheme at 4 GeV^2

(Nocera et al. (NFRR) arXiv:1206.0201)

Nucleon Spin beyond G_1 and G_2

- Need to go beyond a_0 to understand nucleon spin
  - Orbital angular momentum (OAM) ***L*** is needed.
- Partons have transverse momentum, implies OAM
  - Muller, Ji, Radyushkin, Generalized Parton Distributions – GPDs
  - functions of Mandelstam t, light cone momentum ξ
  - exclusive scattering, DV Compton, meson

$$H(x,\xi=t=0)=q(x)=f_1(x)$$
$$\tilde{H}(x,\xi=t=0)=\Delta q(x)=g_1(x)$$
$$E(x,\xi,t),\quad \tilde{E}(x,\xi,t)$$

(no partonic analogs)

$$J_q=\frac{1}{2}\int_{-1}^{1}dx\,x\left[H^q(x,\xi,t=0)+E^q(x,\xi,t=0)\right]$$

(Ji's sum rule)

$$\sum J_q=\sum\Delta q+L_q$$

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- Partons have transverse momentum, implies OAM
  - Mulders *et al.*, Transverse Momentum Distributions – TMDs
  - functions of x and k_t
  - Semi-inclusive scattering (detect final *e*, one hadron)

Transverse Momentum Distributions by Polarization			
***Target* ↓ \ *quark* →**	***U***	***L***	***T***
U	$f_1(x, k_t)$		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1 $h_{1T}^{\perp}$

Longitudinal SSF (leading twist)

$$g_1(x)=\sum g_1^q(x)=\sum\int d^2\vec{k}_t\, g_{1L}(x,\vec{k}_t^2)$$

Transverse SSF (twist-3)

$$g_{1T}^{(1)}(x)=\sum g_{1T}^{q(1)}(x)=\sum\int d^2\vec{k}_t\,\frac{\vec{k}_t^2}{2M^2}\, g_{1T}^q(x,\vec{k}_t^2)$$

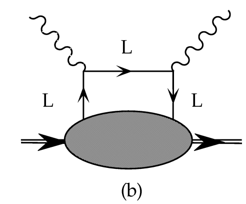
$$g_T(x)=g_1(x)+\frac{d}{dx}g_{1T}^{(1)}=g_1(x)+g_2(x)$$

PDF's: an Experimentalist's View

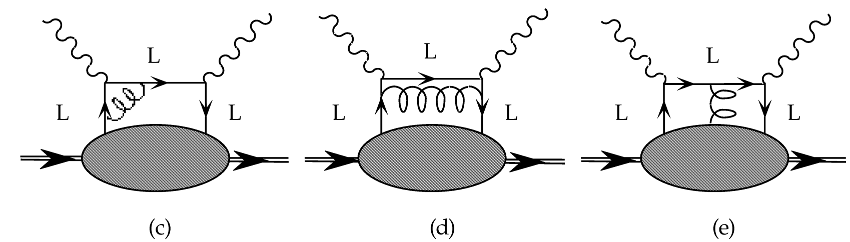
Type of scattering	Beam polarization	Target polarization	Probed properties	Observable
Inclusive	None	None	parton longitudinal momentum	W1, W2
	Yes	Longitudinal	parton helicity	G1
	Yes	Transverse	*qg* correlations (twist-3)	G2
	Yes	None	parity violation	Electroweak asymmetry
	None	Yes	longitudinal form factor	$A_V^d(F_{LT}^{1-1})$
Semi-inclusive	None	Yes	transverse momentum, spin	azimuthal asymmetries, h1, Sivers, h1T, h1L
	Yes	Longitudinal	quark flavor helicity	azimuthal asymmetries
	Yes	Transverse	partonic interactions	azimuthal asymmetries **$\cos(\varphi-\varphi_s)$**
Exclusive	None	Yes	generalized PD's	Bethe-Heitler interference DVCS A_{UL}
	Yes	None	GPD's	DVCS A_{LU}
	Yes	Yes	orbital angular momentum	azimuthal asymmetries

Transverse Polarized Scattering: Unlocking Twist-3

- Twist-2 and twist-3 operators contribute at same order in transverse polarized scattering
  - twist-2: handbag diagram
  - twist-3: *qgq* correlations
- direct access to twist-3 via g_2:
  - "*Unique feature of spin-dependent scattering*" (R. Jaffe)
- difference of transverse cross sections



twist-2



log Q^2 α_{QCD} twist-3

(Comments NPP, 19,239 (1990))

$$\frac{d^2\sigma^{(\uparrow\rightarrow)}}{d\Omega\, dE'} - \frac{d^2\sigma^{(\downarrow\rightarrow)}}{d\Omega\, dE'} = \frac{4\alpha^2 E'}{Q^2 E} E'\sin\theta\cos\phi\left[M\, G_1(\nu,Q^2)+2E\, G_2(\nu,Q^2)\right]$$

Why is g_2 interesting?

- test twist-3 effects = *quark-gluon* correlations
- higher twist corrections to g_1 with d_2 matrix element
- test of lattice QCD, QCD sum rules, quark models from moments
- polarizabilities of color fields (with twist-4 matrix element f_2)
    - magnetic $\chi_B = (4d_2 + f_2)/3$ and electric $\chi_E = (4d_2 - 2f_2)/3$.
- third moment related to color Lorentz force on transverse polarized quark (M. Burkardt, AIP Conf.Proc. 1155 (2009) 26)
    - sign of d_2 related to sign of transverse deformation (κ^q)
- contains chiral odd twist-2 = quark transverse spin (mass term)
    - test quark masses (covariant parton models)

g_2 and g_T Spin Structure Functions

Experimentally measured quantities

$$g_T(x) = g_1(x) + g_2(x) = F_1(x) A_2(x) / \gamma$$

Decomposition of g_T [1]

$$g_T(x) = \int d^2\vec{k}_t \frac{\vec{k}_t^2}{2M^2} \frac{g_{1T}^q(x, \vec{k}_t^2)}{x} \;+\; \frac{m}{M}\frac{h_1(x)}{x} \;+\; \tilde{g}_T(x)$$

TMD quark mass term qgq interaction

Applying twist-2 Wandzura-Wilczek approximation of g_2

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

$$g_T(x) = \int_x^1 dy \frac{g_1(y)}{y} + \frac{m}{M}\left[\frac{h_1(x)}{x} - \int_x^1 dy \frac{h_1(y)}{y}\right] + \tilde{g}_T(x) - \int_x^1 dy \frac{\tilde{g}_T(y) - \hat{g}_T(y)}{y}$$

Twist-3 for the nucleon (neglecting quark mass)

$$\bar{\boldsymbol{g}}_2 = \frac{1}{2}\sum e_q^2 \left[\tilde{g}_T^q - \int_x^1 \frac{dy}{y}\left(\hat{g}_T^q(y) - \tilde{g}_T^q(y)\right)\right];$$ $\tilde{g}_T = qg$ term, $\hat{g}_T$ = Lorentz invariance [2]

Extracting TMD $g_{1T}^{(1)}$ from measured inclusive g_2

$$g_2(x) = \frac{d}{dx} g_{1T}^{(1)}(x) + \hat{g}_T(x).$$

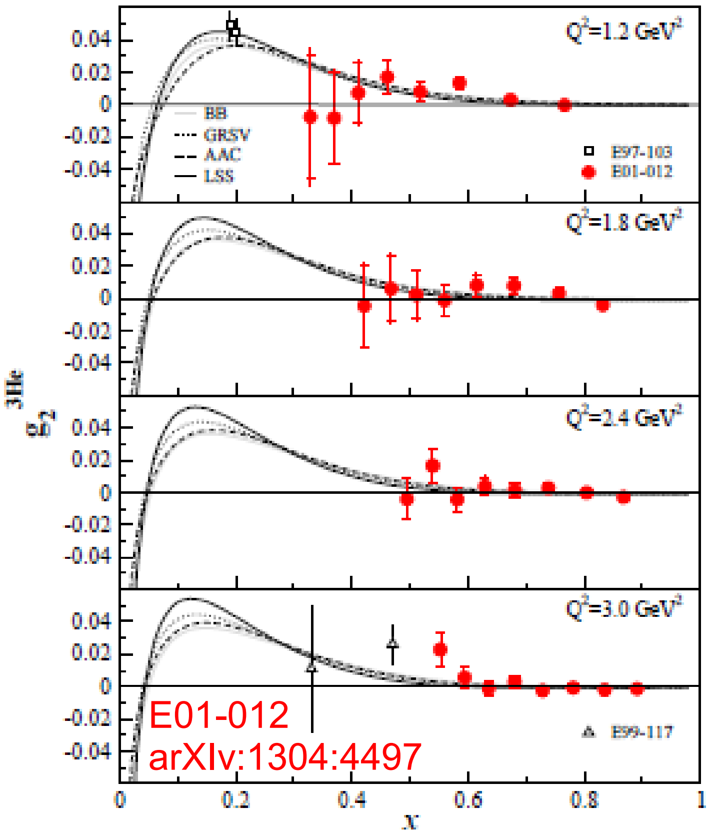
[1] hep-ph/9408305v1
[2] JHEP 0911 (2009) 093

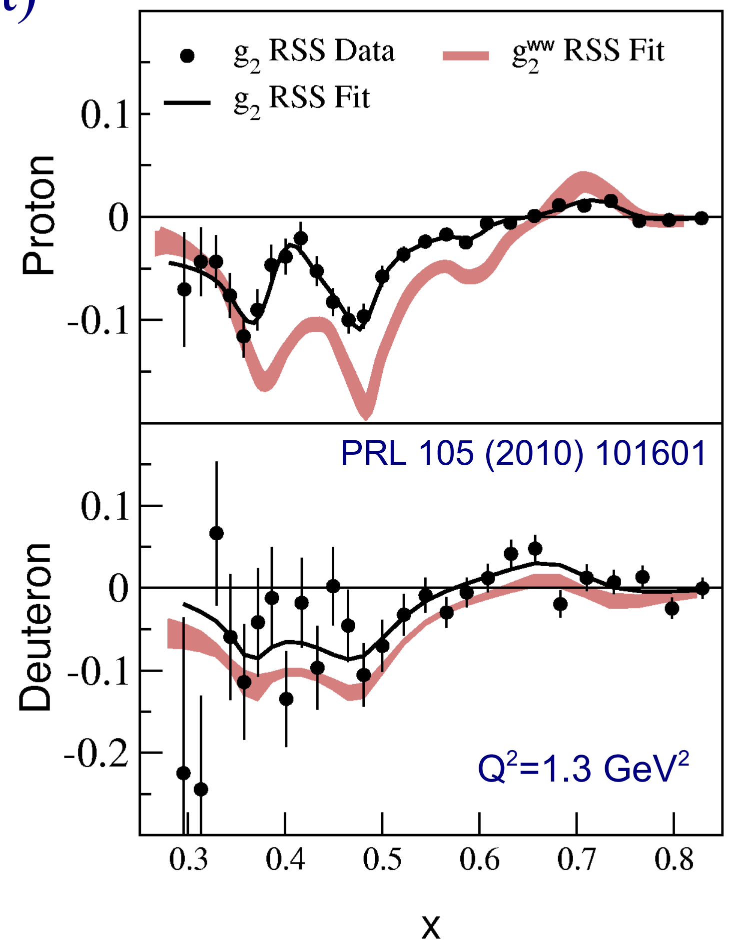
Recent SSF Studies at JLab

Hall	Publication	Measurement	Experiment
CLAS	PL B672 (2009) 12	Moments of g1p and g1d for 0.05 < Q**2 < 3.0-GeV**2	eg1b
CLAS	PL B704 (2011) 397	Beam Spin Asymmetries in Semi-Inclusive pi0 production	eg1b
CLAS	PR C80 (2009) 035206	Beam Spin Asymmetries in DVCS with CLAS at 4.8-GeV	eg1-dvcs
CLAS	PRL 105 (2010) 262002	Single and Double Spin Asymmetries in Deep Inelastic Pion Electroproduction with a Longitudinally Polarized Target	eg1b
Hall A	arXiv:1304.4497	Moments of Neutron g2 SF at Intermediate Q**2	01-012
Hall A	PRL 107 (2011) 072003	Single Spin Asymmetries in Charged Pion Production from SIDIS on a Transversely Polarized 3He Target	06-010
Hall A	PRL 108 (2012) 052001	Beam-Target Double Spin Asymmetry A_LT in Charged Pion Production from DIS on a Transversely Polarized He-3 Target	06-010
Hall C	PRL 105 (2010) 101601	Probing Quark-Gluon Interactions with Transverse Polarized Scattering	01-006
Hall A	Very preliminary	Precision d2n: Color Polarizabilities	06-014
Hall C	Very preliminary	Spin Asymmetries of the Nucleon – SANE	07-003
Hall A	Very very preliminary	g2p and the Longitudinal-Transverse Spin Polarizability	08-027
JAM JLab Angular Momentum	APS April 2013	Global PDF fits	Phenomenology

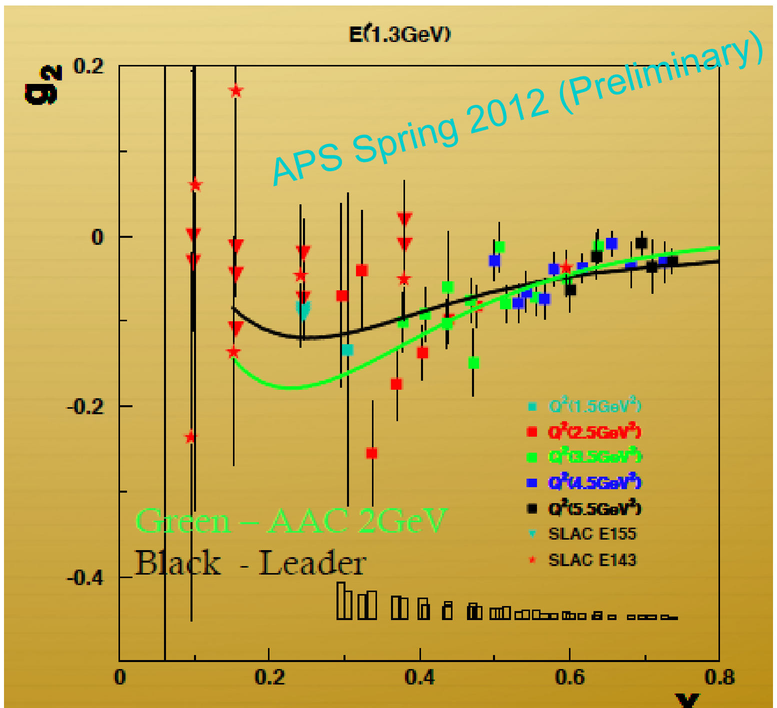
g_2 in the Resonances

- g_2 in Hall A (below) and Hall C (right)

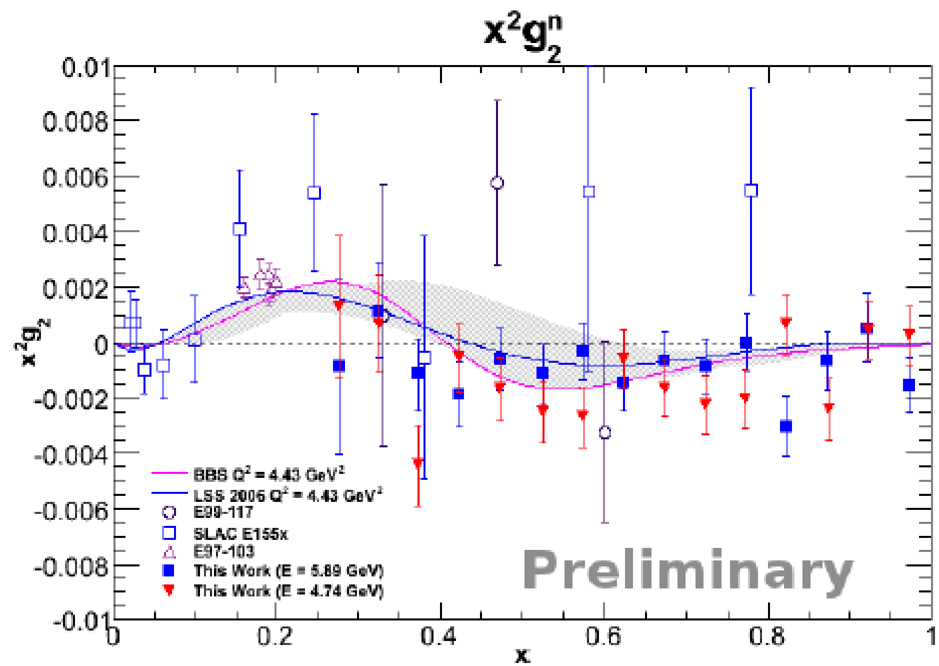




g_2 in DIS and Resonances



(H. Baghdasaryan)



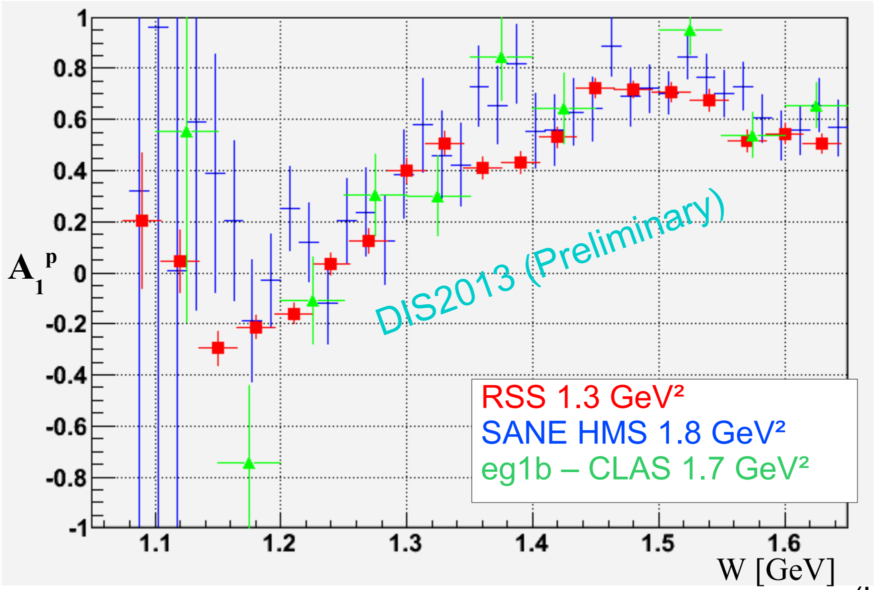
(M. Posik)

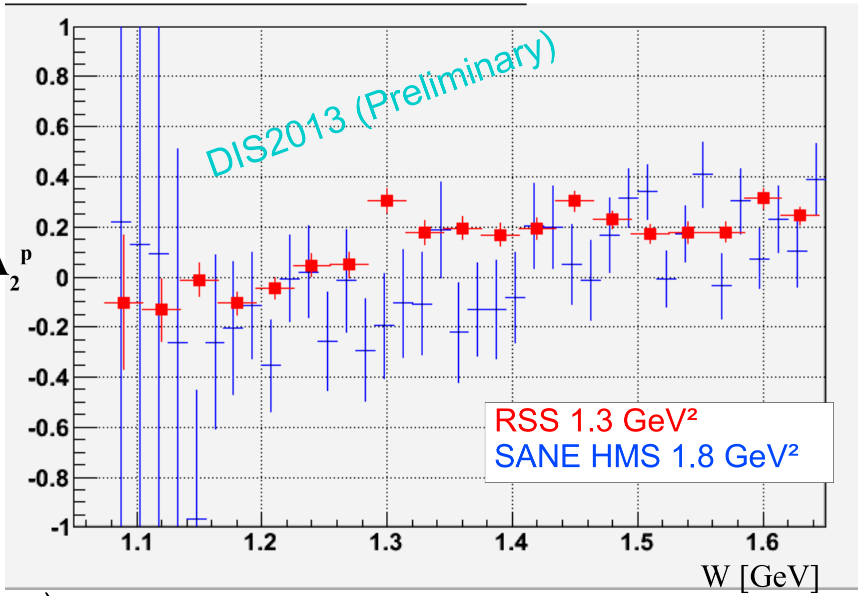
(No external radiative corrections)

- Proton (NH_3)
  - Hall C SANE (E07-003)
  - $0.3 < x < 0.8 \quad 2.5 < Q^2 < 6.5$
- Neutron (on ^3He)
  - Hall A d2n (E06-014)
  - 4.7 and 5.9 GeV beam

Spin Asymmetries A_1 and A_2

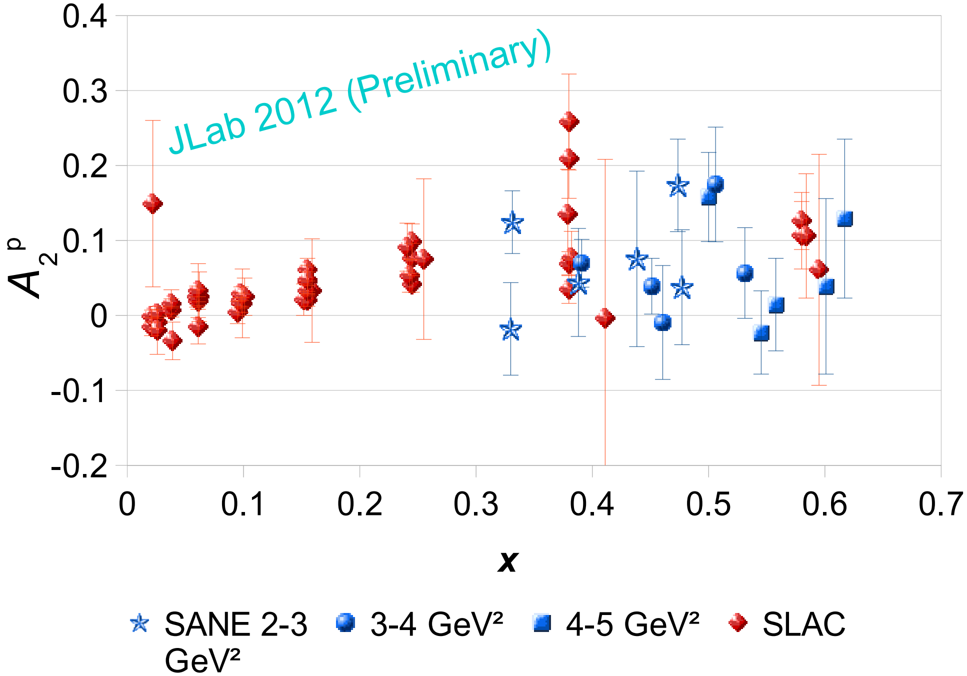
- Model independent separation of proton spin asymmetries in the resonances from longitudinal and transverse measured asymmetries

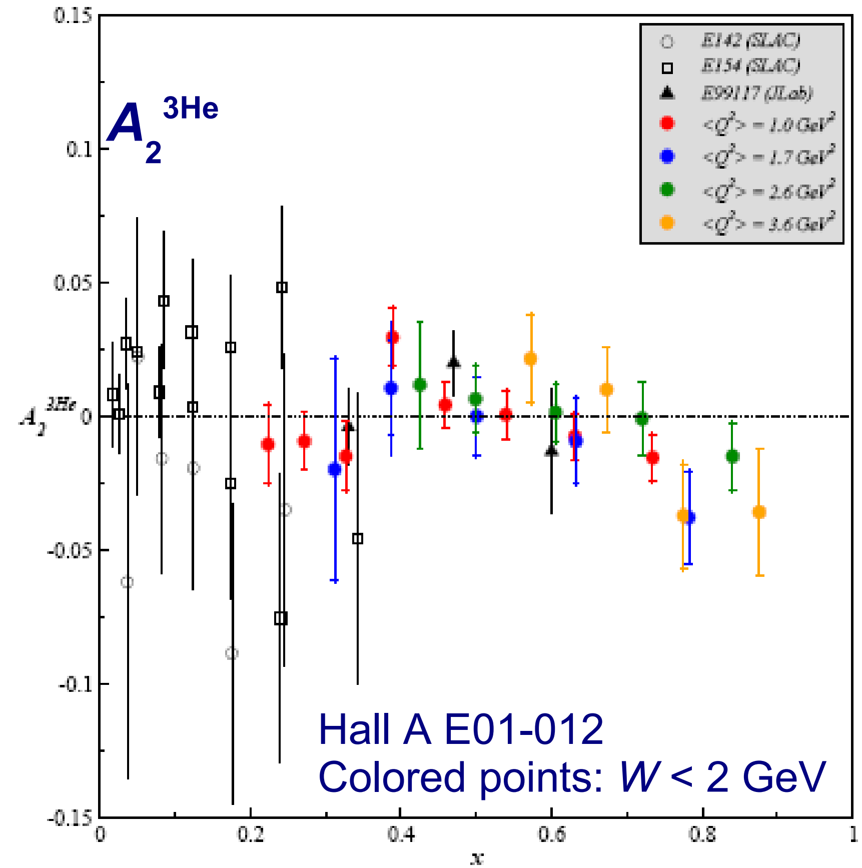




(H-y. Kang)

Spin Asymmetry A_2



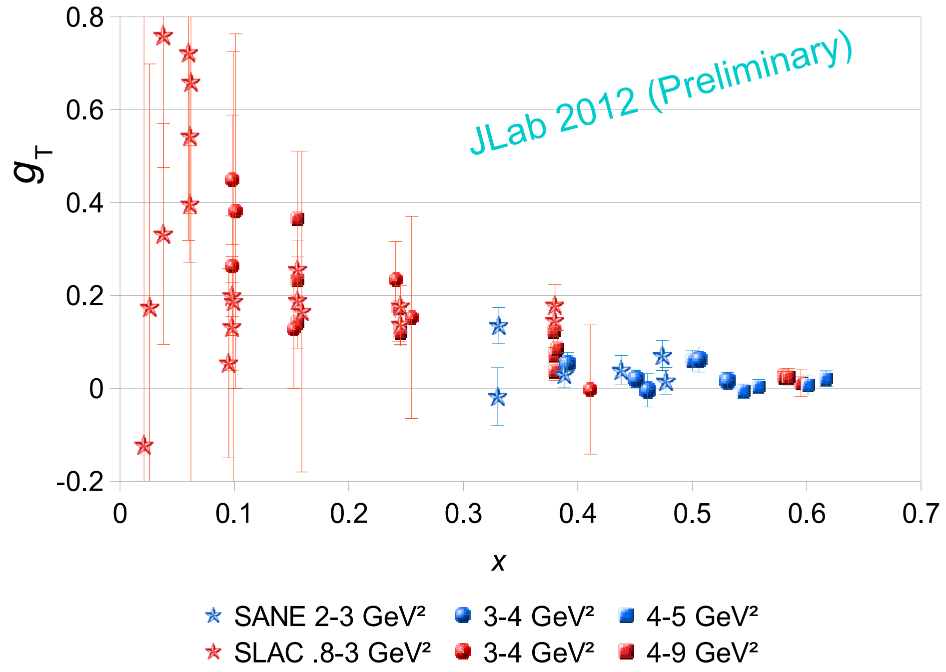


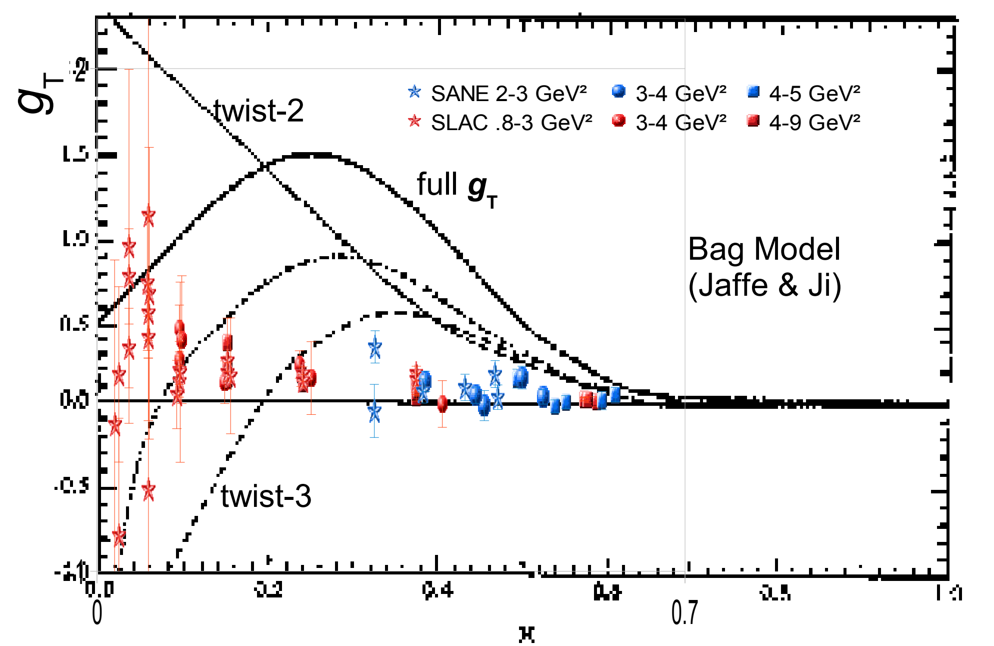
(P. Solvignon)

- DIS A_2^p not zero:
  - signal of transverse momentum

More DIS A_2^{3He} coming (E06-014)

SANE Goal: DIS Transverse Spin SF g_T^p



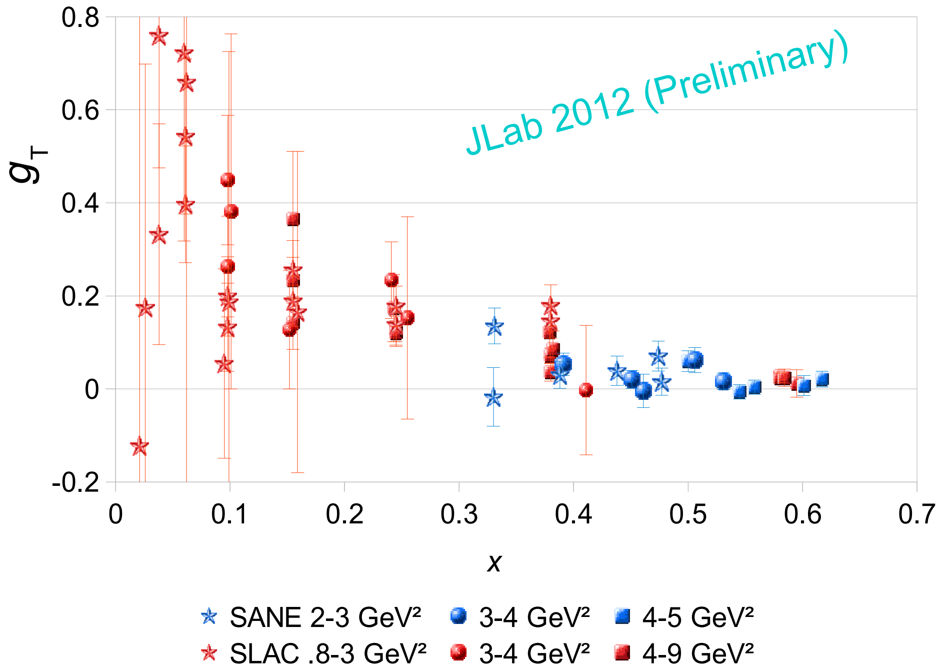


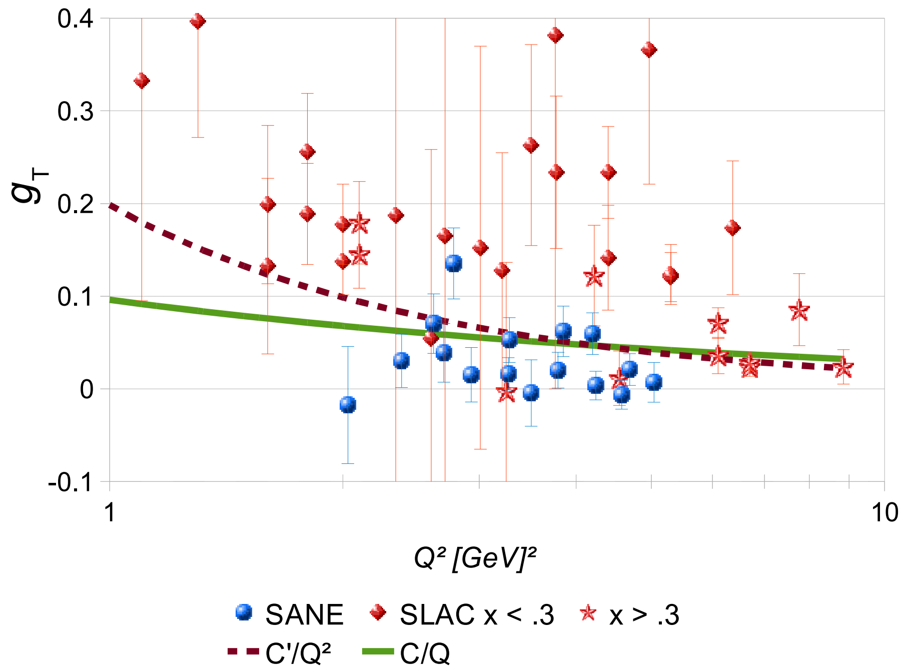
Tangerman & Mulders hep-ph/9408305v1

- $g_T^p = F_1\, A_2/\gamma$, measures spin distribution normal to γ^*
- SANE $\langle g_T^p(x>.3)\rangle = 0.023 \pm 0.006$

- Bag Model (1990's)
  - Data scaled by 2.5
  - Model updates needed

SANE Goal: DIS Transverse Spin SF g_T^p



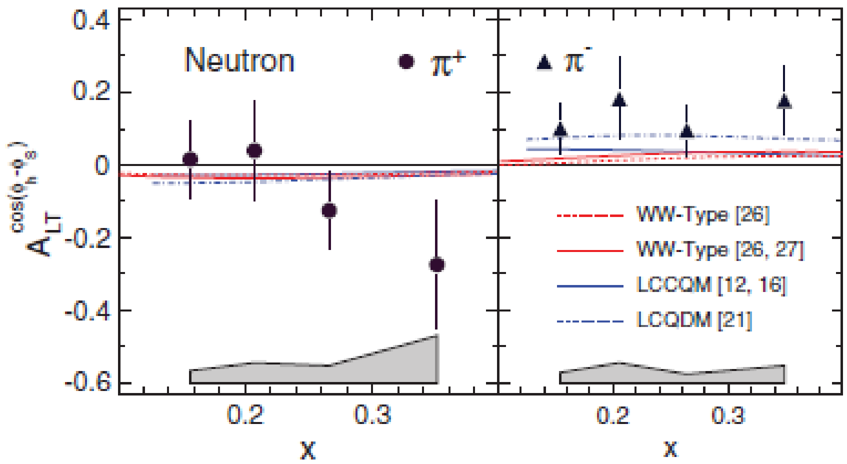


- $g_T^p = F_1\, A_2/\gamma$, measures spin distribution normal to γ^*
- SANE $\langle g_T^p(x>.3)\rangle = 0.023 \pm 0.006$

- g_T evolution non-trivial
  - no simplification possible at NLO (NPB 608 (2001) 235)

Double Spin SIDIS A_{LT}

- $g_{1T}^{\perp}(x, \boldsymbol{k}_t)$ is chiral-even TMD for quarks with longitudinal helicity in a transverse polarized target
- Weighted by $\boldsymbol{k}_t^2/2M^2$ and integrated over k_t, generates a $\cos(\phi\text{-}\phi_s)$ azimuthal A_{LT}, measurable in SIDIS



Hall A E06-010,
PRL 108 (2012) 05200

$$\frac{A_{LT}(x,y,z)}{(|\vec{P}_T|/M)\cos(\phi-\phi_s)} = \frac{C(x,y)\sum e^2 g_{1T}^{(1)(x)} D^h(z)}{C'(x,y)\sum e^2 f_1(x) D^h(z)}$$

OPE for Polarized SF's

- C-N moments of g_1 and g_2 connected by OPE to twist-2 and twist-3 matrix elements a_N and d_N

$$\Gamma_1^{(N)} = \int_0^1 x^N g_1(x, Q^2)\, dx = \frac{1}{2} a_N + O(M^2/Q^2), \qquad N = 0, 2, 4, \ldots$$

$$\Gamma_2^{(N)} = \int_0^1 x^N g_2(x, Q^2)\, dx = \frac{N}{2(N+1)} (d_N - a_N) + O(M^2/Q^2), \qquad N = 2, 4, \ldots$$

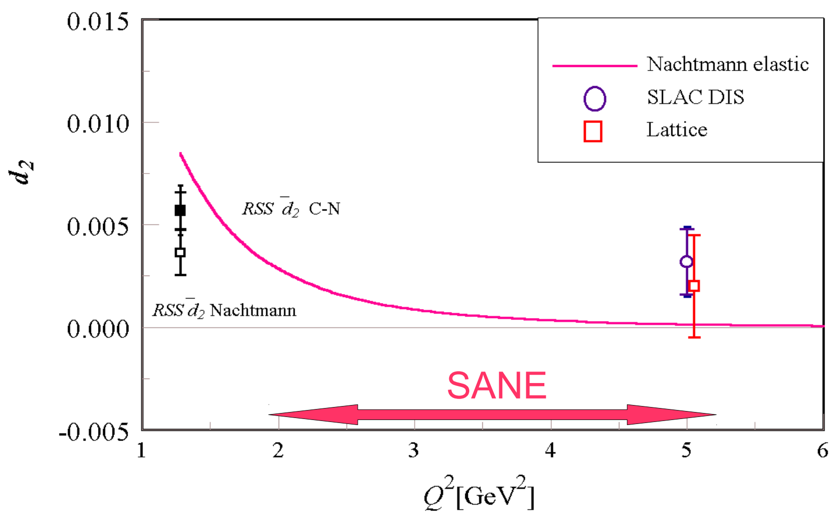
- twist-3 d_2 – mean color-magnetic field along spin
  - d_n is shorthand for $\tilde{d}_n = \sum_i d_i^n(\mu^2) E_{i,3}^n(Q^2/\mu^2, \alpha_s(\mu^2))$
  - At low-moderate Q^2 Nachtmann moments are needed to obtain dynamic twist-3 matrix elements (no target mass effects to $O(M^8/Q^8)$)

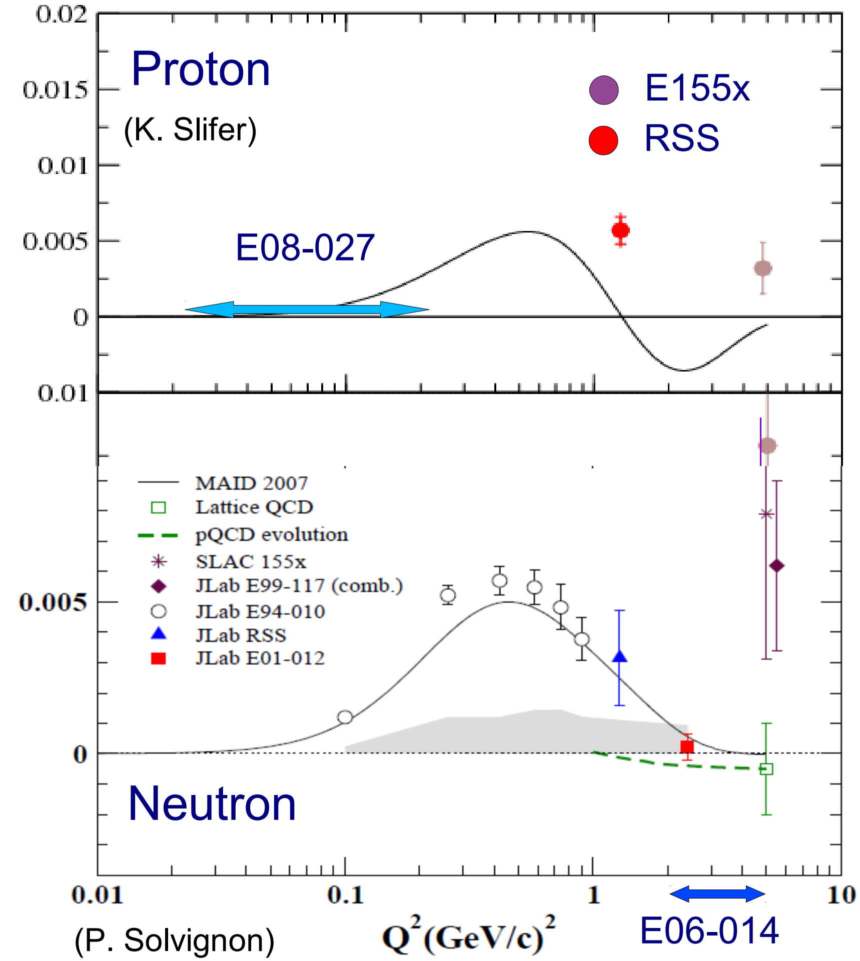
$$d_2(Q^2) = \int_0^1 dx\, \xi^2 \left(2 \frac{\xi}{x} g_1 + 3\left(1 - \frac{\xi^2 M^2}{2Q^2}\right) g_2 \right) \Rightarrow_{Q^2 \to \infty} \int_0^1 dx\, x^2 (2 g_1 + 3 g_2)$$

Resonances d_2

- Plots show contribution of resonances to d_2 CN integral
  - Data with $Q^2 < \sim 4$ GeV^2 need Nachtmann integrals
  - Add Nachtmann elastic: dominant at $Q^2 < 2$ GeV^2

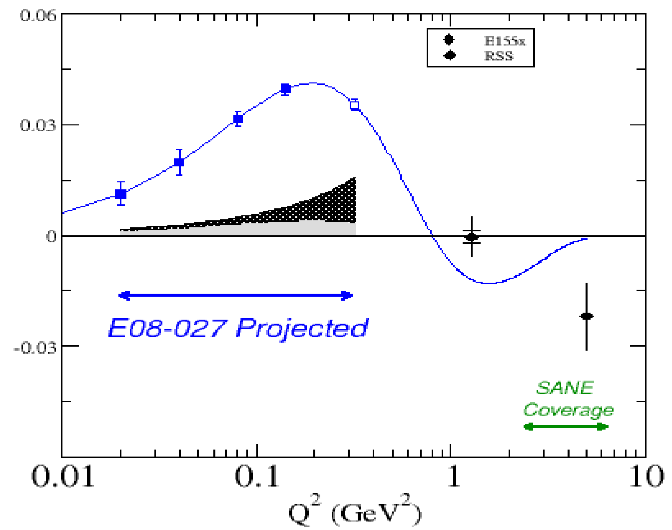
(E155x, E99-117 DIS too)

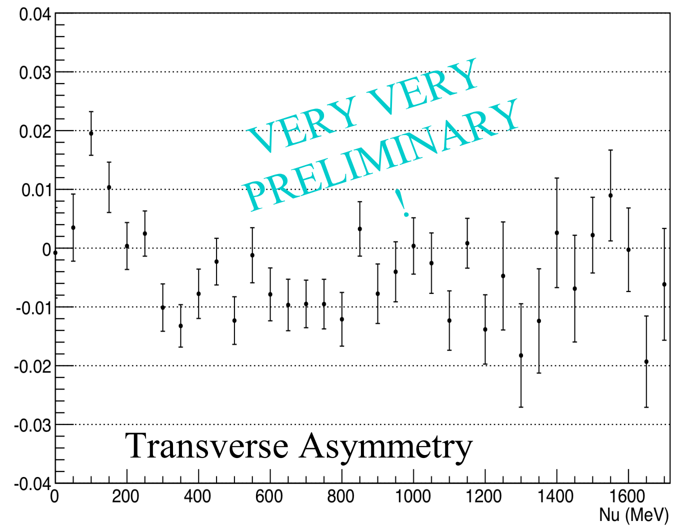




g_2^p at Low Q^2 – E08-027

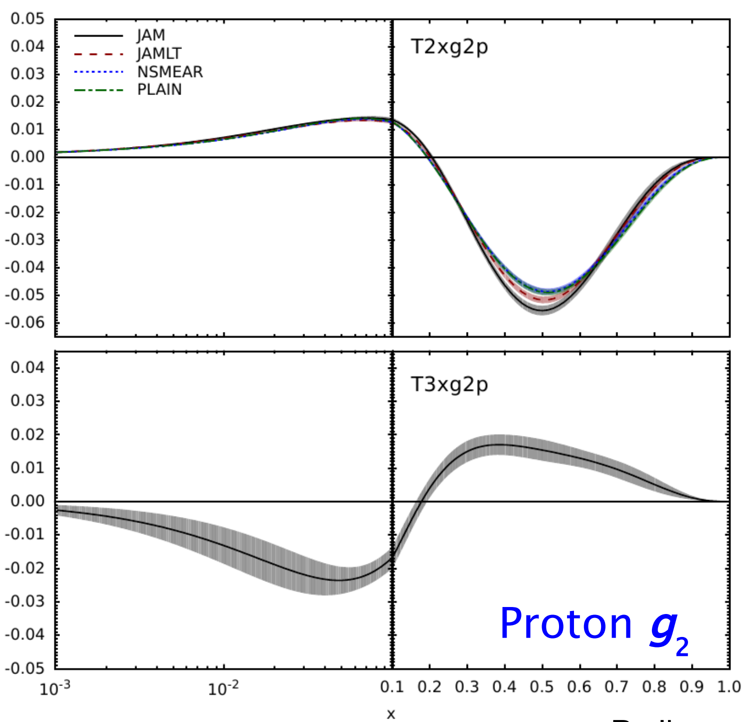
- Goals:
  - BC Sum Rule: violation suggested for proton at large Q^2, but found satisfied for the neutron and ^{3}He.
  - Spin Polarizability: Major failure (>8σ) of χPT for neutron δ_{LT}. Need g_2 isospin separation to solve.
  - Hydrogen Hyper Fine Splitting and Proton Charge Radius: Lack of knowledge of g_2 at low Q^2, is one of the leading uncertainties (E08-007)
- Took data in 2012. Analysis in progress

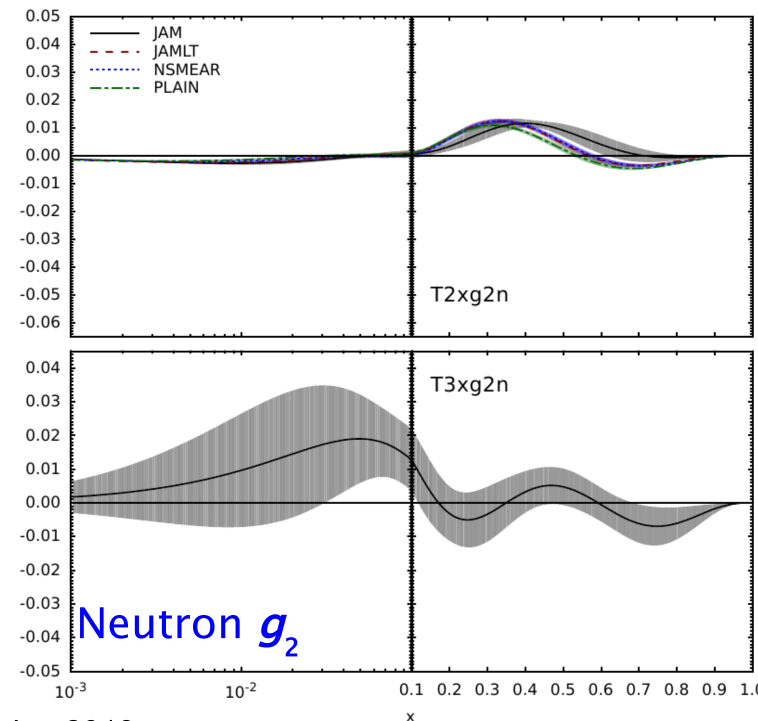




(K. Slifer)

Jefferson Angular Momentum – JAM Collaboration



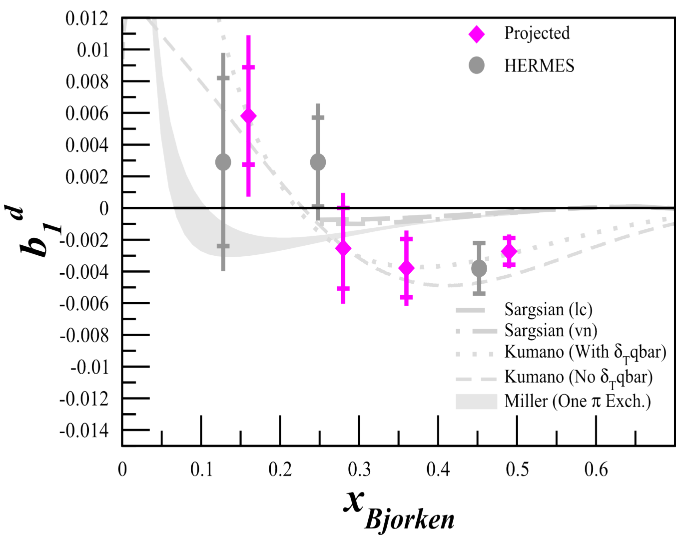


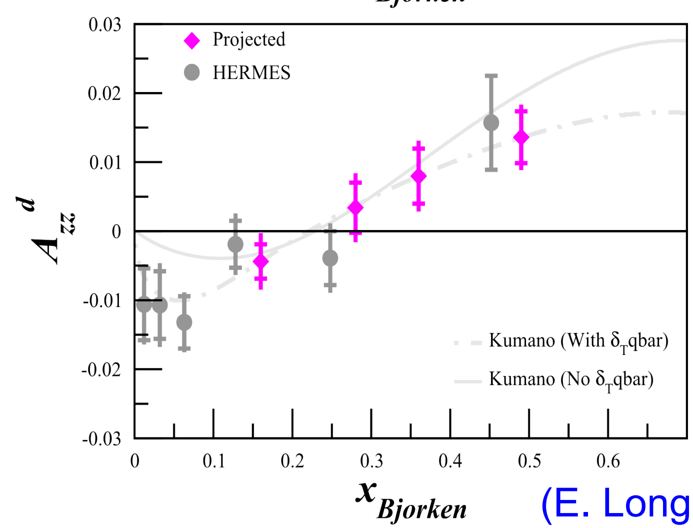
P. Jimenez- Delgado APS Spring 2013

- Joint theorists and experimentalists effort to "*study the quark and gluon spin structure of the nucleon by performing global fits of PDFs*".
- JAM's spin PDFs are tailored for studies at large Bjorken *x*, as well as the resonance-DIS transition region at low and intermediate ***W*** and ***Q*²**.
http://wwwold.jlab.org/theory/jam/

Deuteron Tensor S. F. b_1

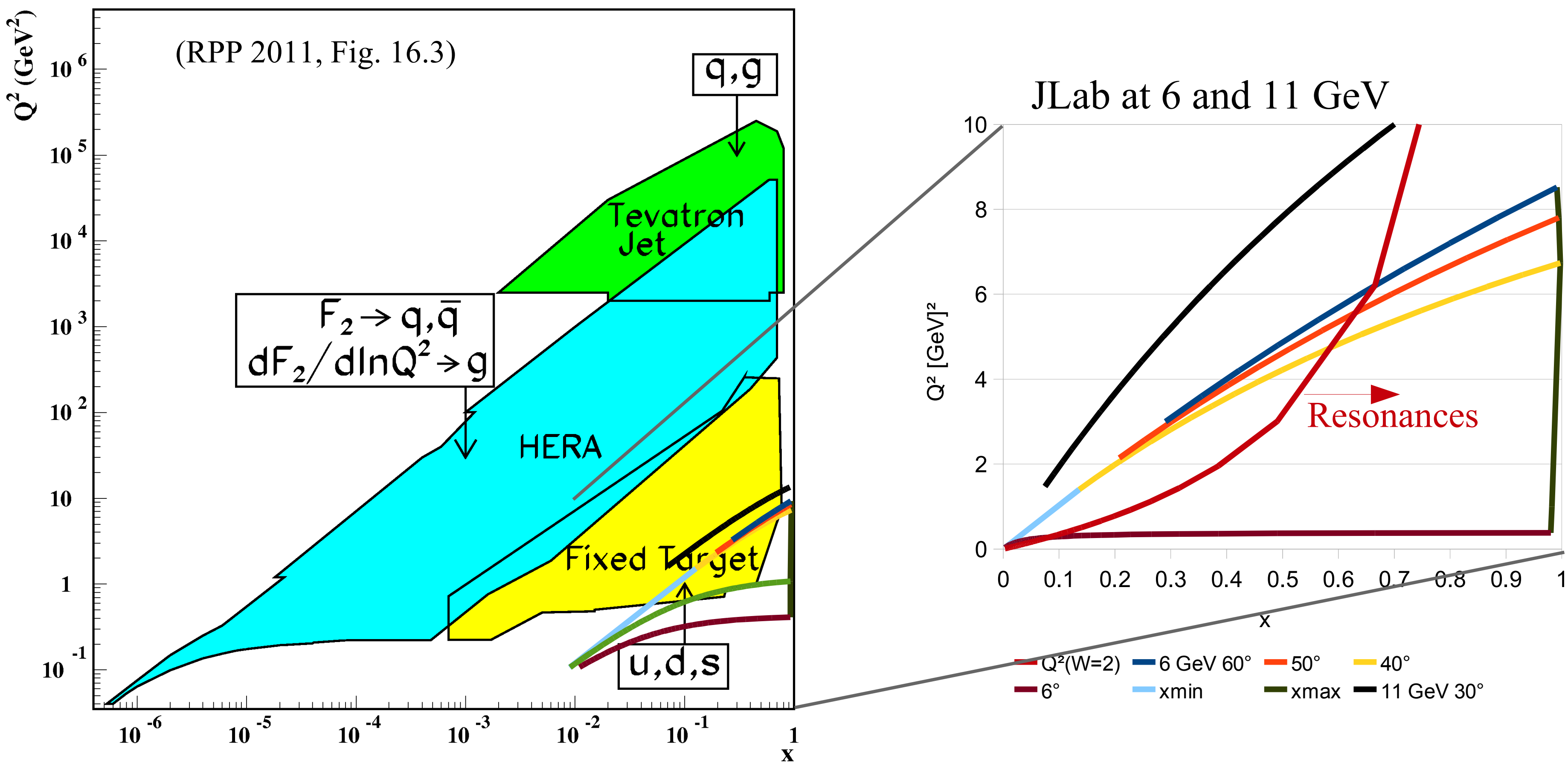
- Spin structure beyond ½ h/2π
  - Deuteron tensor b_1 due to nuclear spin 1 h/2π
  - could result from rescattering at small Bjorken x
  - reproducing HERMES $b_1(x\sim0.4) < 0$ important
- Measure tensor $A_{zz} = -(2/3)\, b_1/F_1$
  - use tensor polarized ND_3 target
  - PR12-13-010 C1 approved by JLab PAC40 with A- rating





(E. Long)

Kinematics Space at JLab



PAC Approved and Conditionally Approved (C1) Nucleon Spin Program at 12 GeV

Experiment	Hall	Title	Beam days	Rating
E12-06-114	A	Measurements of Electron-Helicity Dependent Cross Sections of Deeply Virtual Compton Scattering with CEBAF at 12 GeV	100	A
E12-06-122	A	Measurement of neutron asymmetry A1n in the valence quark region using 8.8 GeV and 6.6 GeV beam energies and Bigbite spectrometer in Hall A	23	A-
E12-09-018	A	Measurement of the Semi-Inclusive pi and kappa electro-production in DIS regime from transversely polarized 3He target with the SBS&BB spectrometers in Hall A	64	A-
E12-10-006	A	An update to PR12-09-014: Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic Electro Pion Production on a Trasversely Polarized 3He Target at 8.8 and 11 GeV	90	A
E12-11-007	A	Asymmetries in Semi-Inclusive Deep-Inelastic Electro-Production of Charged Pion on a Longitudinally Polarized He-3 Target at 8.8 and 11 GeV	35	A
E12-11-108	A	Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic (e,e'\pi^{\pm}) Reaction on a Transversely Polarized Proton Target	120	A
E12-06-109	B	The Longitudinal Spin Structure of the Nucleon	80	A
E12-06-119	B	Deeply Virtual Compton Scattering with CLAS at 11 GeV	200	A
E12-07-107	B	Studies of Spin-Orbit Correlations with Longitudinally Polarized Target	103	A-
E12-09-008	B	Studies of the Boer-MuldersAsymmetry in Kaon Electroproduction with Hydrogen and Deuterium Targets	56	A-
E12-09-009	B	Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with polarized hydrogen and deuterium targets	103	B+
E12-11-003	B	Deeply Virtual Compton Scattering on the Neutron with CLAS12 at 11 GeV	90	A
PR12-12-009	B	Measurement of transversity with dihadron production in SIDIS with transversely polarized target		A
PR12-12-010	B	Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector		A
E12-06-110	C	Measurement of Neutron Spin Asymmetry A1n in the Valence Quark Region Using an 11 GeV Beam and a Polarized 3He Target in Hall C	36	A
E12-06-121	C	A Path to 'Color Polarizabilities' in the Neutron:A Precision Measurement of the Neutron g_2 and d_2 at High Q^2 in Hall C	29	A-
E12-09-017	C	Transverse Momentum Dependence of Semi-Inclusive Pion Production	32	A-
PR12-12-005		The Longitudinal Photon, Transverse Nucleon, Single-Spin Asymmetry in Exclusive Pion Electroproduction		
PR12-11-111	B	Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using the CLAS12 Detector		A
PR12-12-009	B	Measurement of transversity with dihadron production in SIDIS with transversely polarized target		A
PR12-12-010	B	Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector		A
PR12-13-011	C	The Deuteron Tensor Structure Function b1		A-

The JLab Nucleon Spin Program goes on

- New results from recent and older SF experiments still to come
- Twenty one experiments on spin in all Halls at 11 GeV
  - over 1150 beam days
  - over half rated A
- Strong theory – experiment interaction
- Bright future for nucleon spin physics in the 12 GeV era

Extras

Moments and Higher Twists

- Beyond log scaling violations:
  - Higher Twists (HT): inverse Q^2 power corrections to SF's
  - HT represent parton correlations beyond free quark picture
  - Access to HT: Moments of SF's related by the OPE to matrix elements of quark operators of given twist
  - Moments expanded in power series of $(A(x)/\,Q^2)^{(\text{twist - 2})}$
  - Moments integrate over full x range: $M_{2,3}^{(n)}(Q^2)=\int_0^1 dx\, x^n\, g_{1,2}(x,Q^2)$
    - Resonances and elastic contribute at JLab's beam E
  - HT clouded by kinematic operators of same twist, but higher spin
    - "Target Mass" corrections required, or avoided using Nachtmann moments, instead of ordinary, Cornwall-Norton moments (above)

d_2 from *RSS* Third Moments

Moments at $\langle Q^2 \rangle = 1.3$ GeV^2, in three regions:

- measured $.32 < x < .8$; elastic (quasi-el. for deuteron);
- unmeasured $x < 0.32$, suppressed by x^2.

x ranges	Proton	Deuteron	Neutron
Measured			
CN	0.006± 0.001	0.008± 0.002	0.003± 0.002
Nachtmann	0.004± 0.001	0.005± 0.002	0.002± 0.001
$0 < x < 1$			
CN	0.036± 0.003	0.017± 0.004	-0.018± 0.003
Nachtmann	**0.010± 0.001**	**0.003± 0.002**	**-0.008± 0.002**

- Non-zero d_2 for both nucleons (total errors shown)
  - OPE valid to $N=2 < Q^2/M_0^2 \sim 1.3/0.5^2$ (DIS – resonances duality)

    (Ji & Unrau, PR D52 (1995) 72)
  - Neutron approximated as D-state corrected *d* - *p* (good to $O(1\%)$)
- Ratios Nachtmann/CN < 1: large contribution of kinematic HT

Spin Asymmetries of the Nucleon Experiment - SANE
(TJNAF E07-003)

PHYSICS: proton spin structures $g_2(x, Q^2)$ and $A_1(x, Q^2)$ for $2.5 \leq Q^2 \leq 6.5 GeV^2$, $0.3 \leq x_{Bj} \leq 0.8$

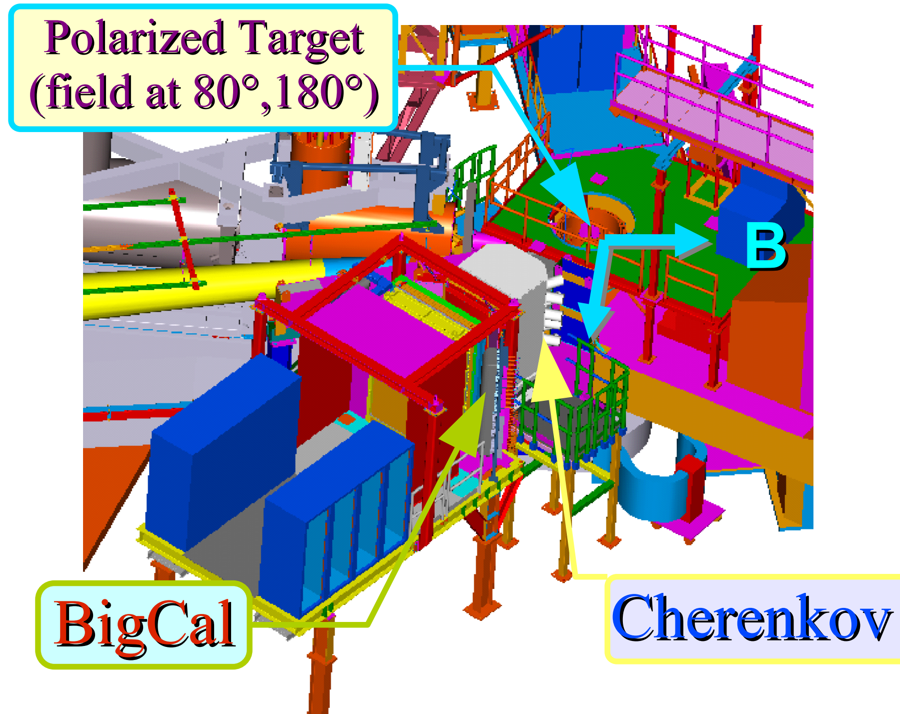
Measure inclusive double polarization near-orthogonal asymmetries to:

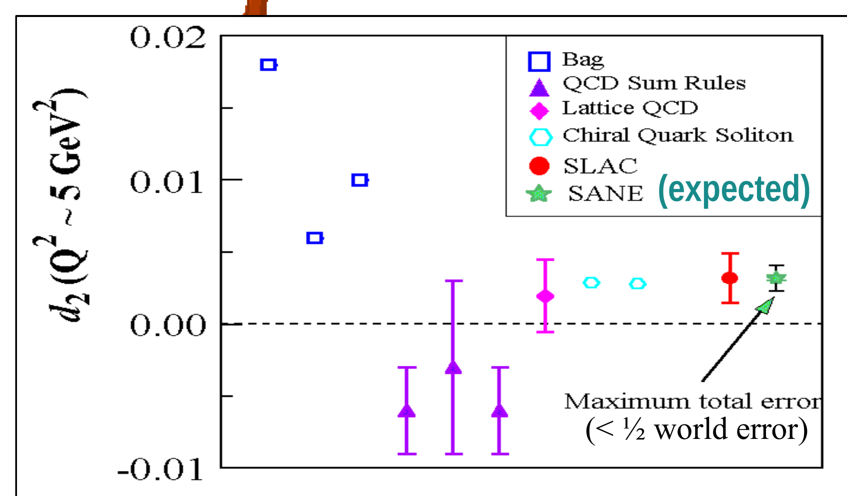
- access ***quark-gluon*** correlations using LO twist-3 effects (d_2 quark matrix element)
- compare with Lattice QCD, QCD sum rules, bag model, chiral quarks
- test nucleon models (x dependence) and Q^2 evolution
- explore $A_1(x \rightarrow 1)$; test polarized local duality

METHOD:

- **CEBAF 4.7 & 5.9 GeV polarized electrons**
- **Solid polarized ammonia target**
- **BETA,** novel large solid angle (.2 sr) electron telescope:
  - calorimeter + gas Cherenkov + tracking

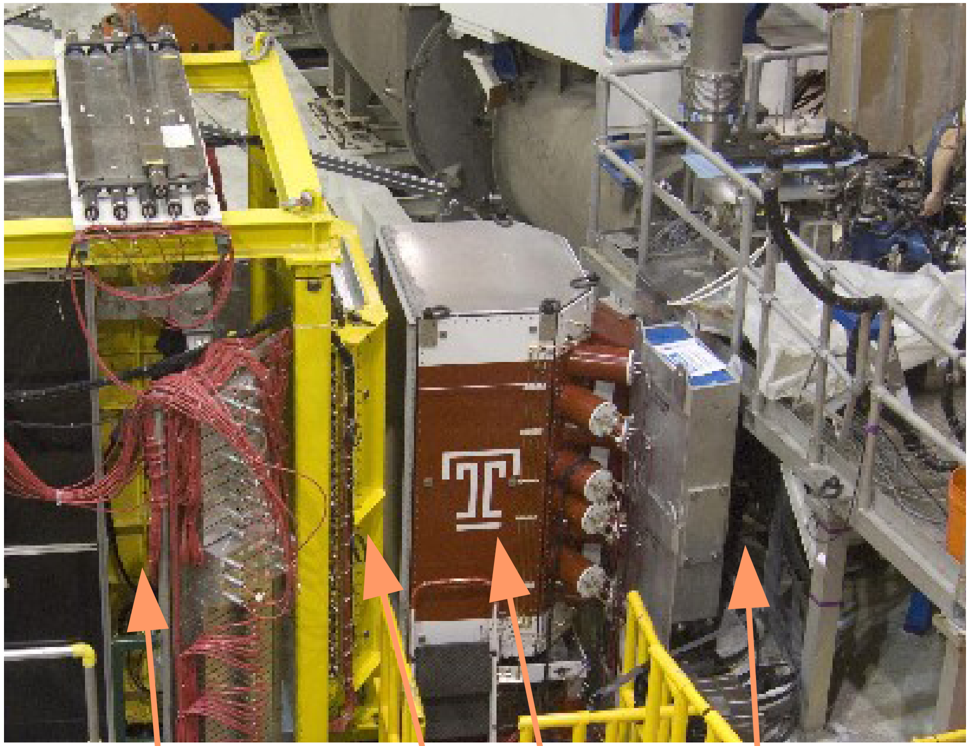
Took data in Hall C Jan-March 2009



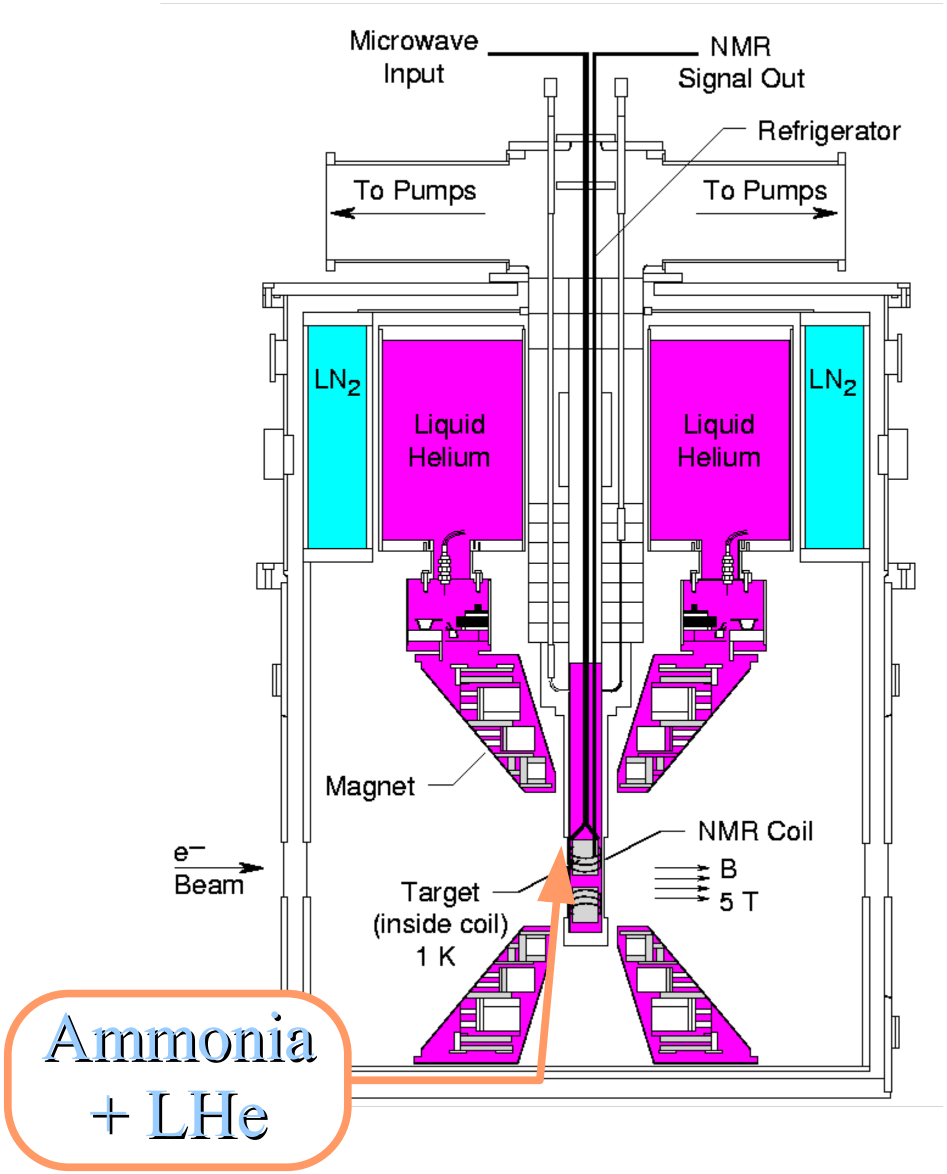


Big Electron Telescope Array – BETA

- BigCal lead glass calorimeter: main detector used in *GEp-III*.
- Tracking **Lucite hodoscope**
- **Gas Cherenkov:** pion rejection
- Tracking fiber-on-scintillator **forward hodoscope**
- BETA specs
  - Effective solid angle = 0.194 sr
  - Energy resolution $9\%/\sqrt{E(\text{GeV})}$
  - 1000:1 pion rejection
  - angular resolution ~ 1 mr
- Target field sweeps low *E* background
  - 180 MeV/c cutoff



Polarized Target



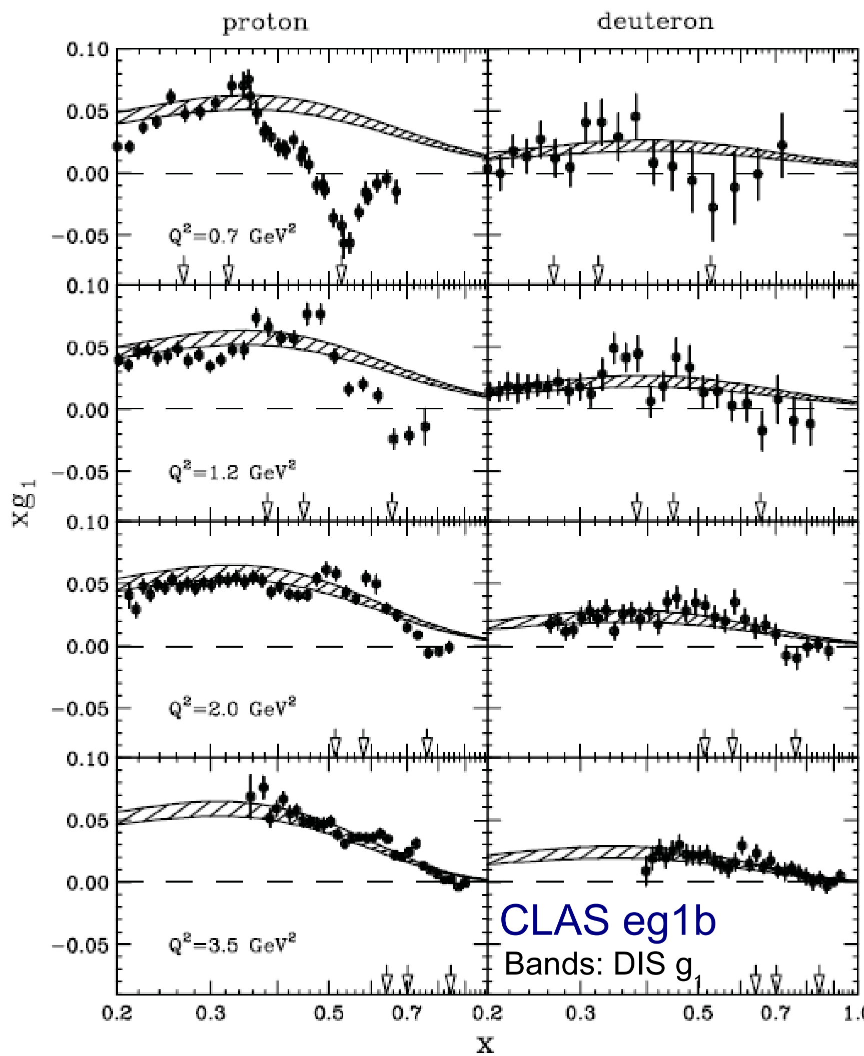
- Dynamic Nuclear Polarized ammonia (NH_3, <P> ~ 70% in beam) and deuterated ammonia (ND_3, <P> 20-30%)
  - Wide range of field orientations
- Target used in six experiments before SANE:
  - SLAC E143, E155, E155x (g_2)
  - JLab GEn98, GEn01, *RSS*

SANE Status and Plans

- SANE goals
  - DIS $g_T^p = g_1 + g_2$ – shown at conferences
  - Moments of g_1, g_2, twist-3 matrix element d_2
    - working on extending x range, low x systematics, optimized binning
  - Spin Asymmetries A_1, A_2 – shown at conferences,
    - parameterizing W and Q^2 dependence for world data fits
  - HMS inelastic asymmetries – preliminary results shown at DIS 2013
    - extend **RSS** PRL 105 (2010) 101601 low x range for B-C sum rule, d_2
  - elastic form factors – publication in preparation
- Long paper draft in progress

Duality in g_1

- Bloom – Gilman duality for spin SF's
  - Local Duality only above Δ(1232)
  - Global duality (for $W > \pi$ threshold, or from elastic) obtains above $Q^2 > 1.8$ GeV^2
  - seen in *p*, *d*, and ^{3}He
  - DIS SSF's from PDF's extrapolated with target mass corrections



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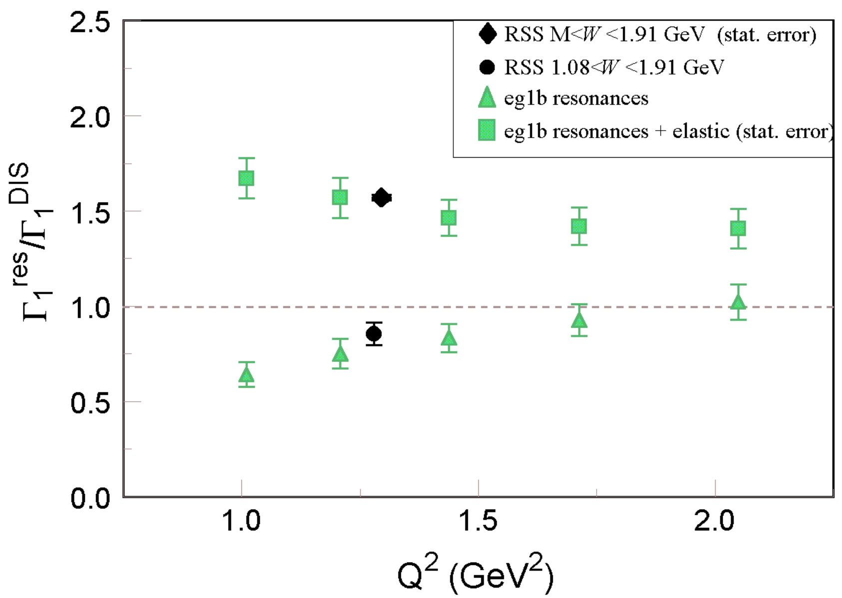
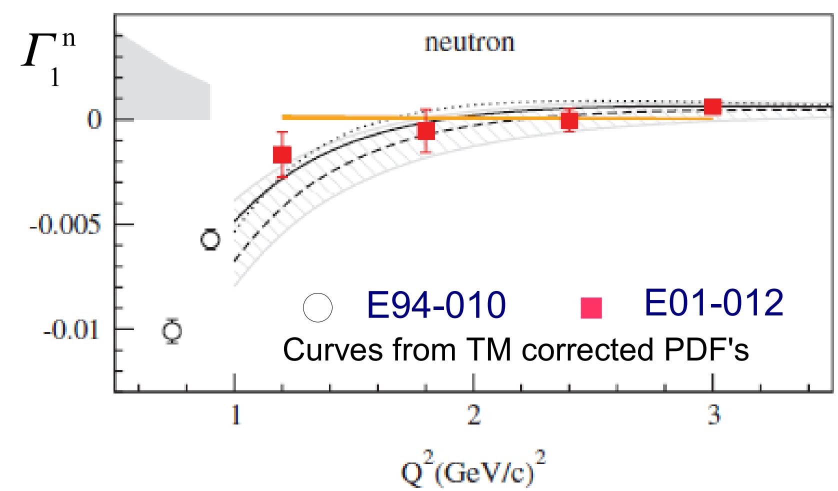


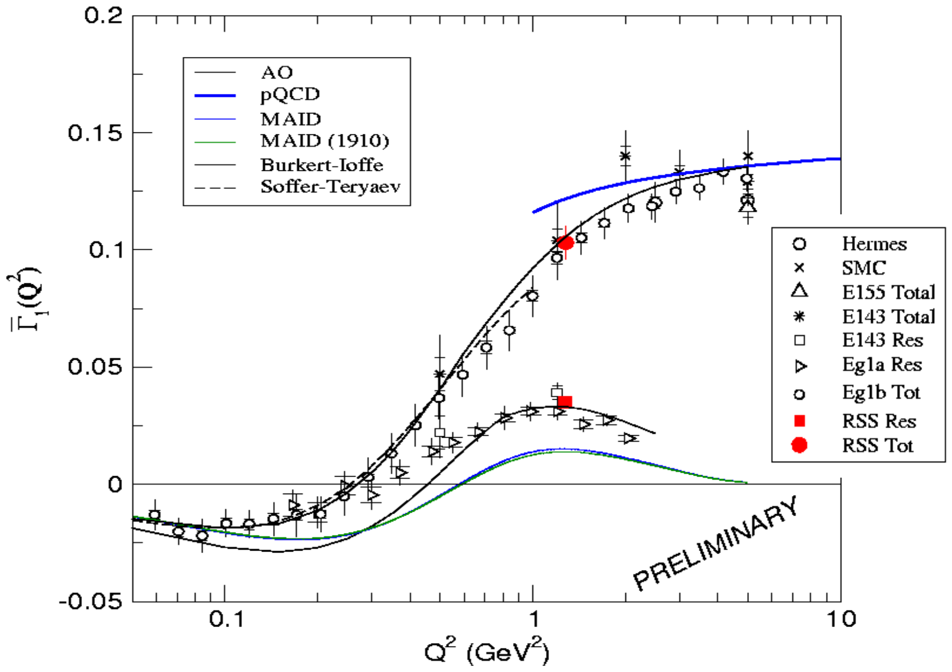


Sum Rules

- First moment of g_1 (extended GDH or Ellis-Jaffe sum rule)

$$\overline{\Gamma_1}(Q^2) = \int_0^{1-el} g_1(x, Q^2)\,dx$$

$$= \frac{1}{36}\left((a_8 + 3a_3)C_{NS} + 4a_0 C_S\right)$$

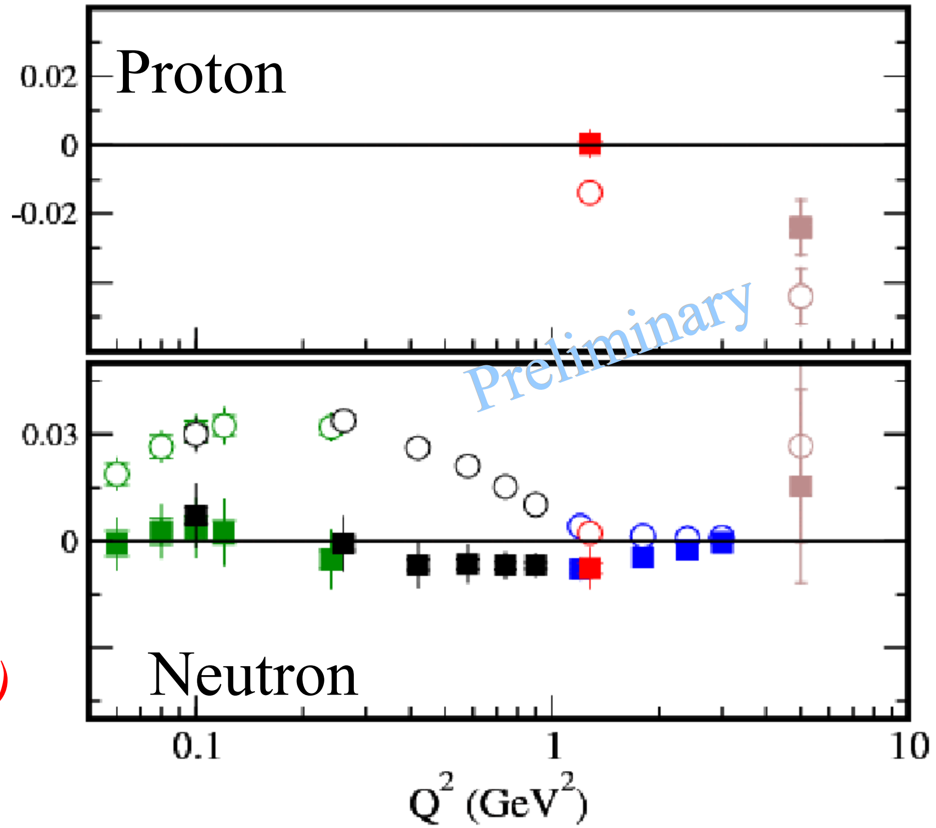


Sum Rules

- First moment of $\boldsymbol{g_2}$ (Burkhardt-Cottingham S. R.)

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

- Free of QDC radiative and target mass corrections (Kodaira et al. PLB345(1995) 527)
  - *RSS full (solid), measured (open)*
  - *Hall A E01—012 (preliminary)* *E97-110*, *E94-010*
  - *SLAC E155x*



(From K. Slifer)

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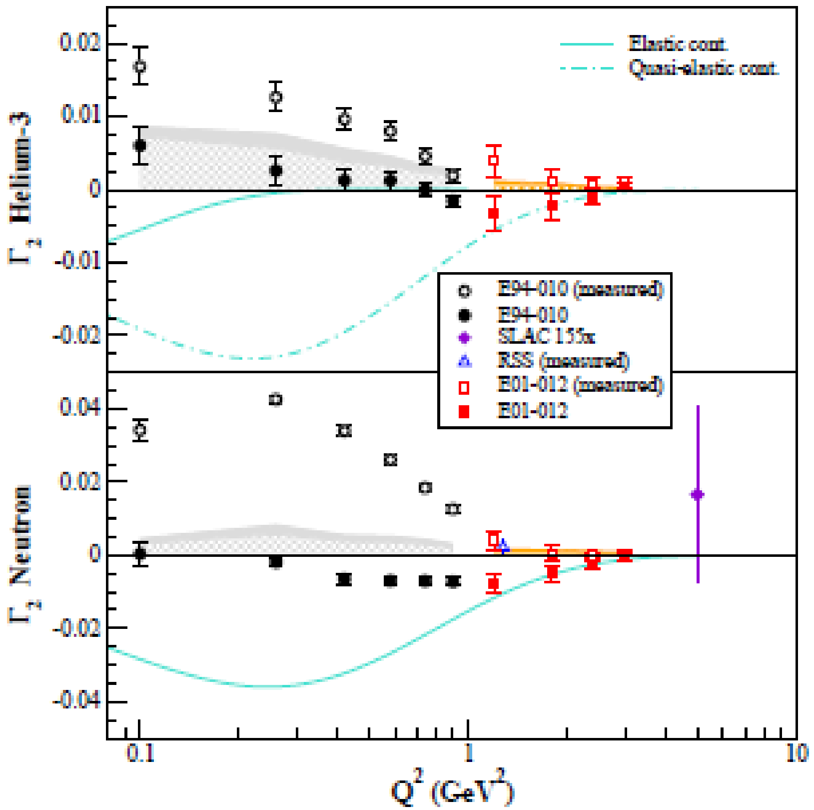
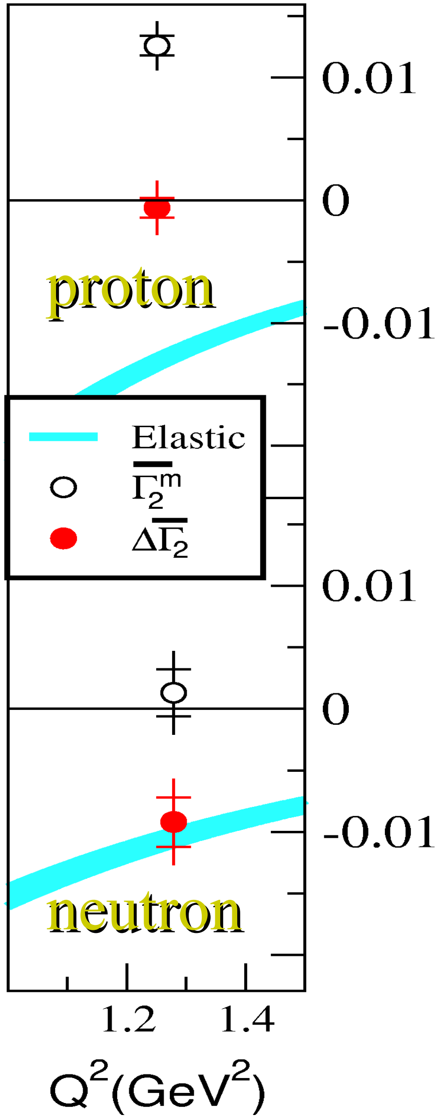


(From K. Slifer)

Twist-3 and the Burkhardt-Cottingham Sum Rule

- BC sum rule $\Gamma_2 = 0 = \Gamma_2^{ww} + \overline{\Gamma}_2 + \Gamma_2(\text{el})$
  - dispersion relation not from OPE, free from gluon radiation, TMC's
  - twist-2 part $\Gamma_2^{ww} \equiv 0$
- BC is higher-twist + elastic
  - $\Gamma_2 = \overline{\Gamma}_2(\text{unm.}) + \overline{\Gamma}_2(\text{measur.}) + \Gamma_2(\text{el})$
  - $\Delta\overline{\Gamma}_2 = \Gamma_2 - \overline{\Gamma}_2(\text{u}) = \overline{\Gamma}_2(\text{m}) + \Gamma_2(\text{el})$
- $\Delta\overline{\Gamma}_2 \neq 0$: assuming BC, implies significant HT at $x < x_{min}$, **or**, if twist-3 ~ 0 at low x,
  - BC fails: isospin dependence? nuclear effects?



Credits

- eg1b duality: PRC 75 035203 (2007)
- $g_1{}^n$ duality: PRL 101 182502 (2008)
- Hall A $g_2{}^n$: P. Solvignon, Ph.D. thesis
- Hall C $g_2{}^p$: PRL 105 (2010) 101601
- $A_2{}^{3He}$: P. Solvignon, Ph.D. thesis
- SANE $A_2{}^p$, g_T: H. Baghdasaryan and the Analysis team
- $d_2{}^{p,n}$: K. Slifer, Seminar, Argonne Nat. Lab., 2009