Overview and Highlights of the JLab 6 GeV Program on Nucleon Structure Functions

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Users Group Workshop
JLab
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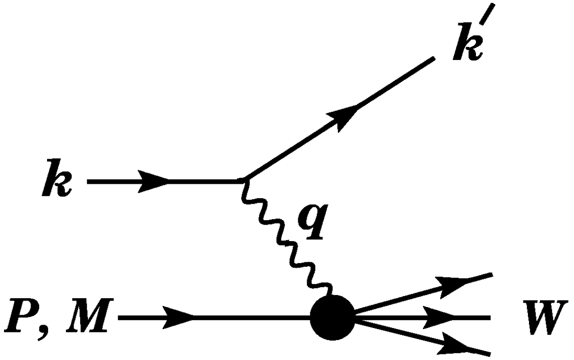
Inclusive Inelastic EM Scattering (Unpolarized and Spin Dependent): Structure Functions, Cross Sections, Asymmetries

Charged Inelastic *Lepton-Nucleon* Scattering

- Inelastic EM scattering: tool to explore structure of nuclei for over 50 years
- Use virtual photon γ^* as probe
- Best region for illuminating nucleon structure is Bjorken $x > 0.1$, where the γ^*'s hadronic structure does not contribute to the scattering
  - This region is JLab's domain
- Talk focus is on the proton and neutron, fundamental baryons:
  - Review of inclusive scattering results



(RPP Fig. 16.1)

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 these to 2 unpolarized and 2 polarized.
- Symmetric part of hadronic tensor: two SF's $\boldsymbol{W_1}$ and $\boldsymbol{W_2}$

$$W^S_{\mu\nu} = 2M\left[\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right]\boldsymbol{W_1}(\nu, Q^2) + \frac{2}{M}\left[\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2}q^\nu\right)\right]\boldsymbol{W_2}(\nu, Q^2)$$

  - lab frame nucleon's $p = (M, \mathbf{0})$, 4-momentum transfer $q = (E - E', \boldsymbol{k} - \boldsymbol{k}')$, $Q^2 = -q^2$, $\nu = E - E'$; all angles relative to beam

Inelastic *e* - *nucleon* Scattering

- For polarized electrons on polarized nucleons the anti-symmetric part of the hadronic tensor adds two polarized structure functions $\boldsymbol{G}_1$ and $\boldsymbol{G}_2$

$$W^{A}_{\mu\nu}=2\epsilon_{\mu\nu\lambda\sigma}q^{\lambda}\left\{M^2 S^{\sigma}\boldsymbol{G}_{\mathbf{1}}(\nu,Q^2)+\left[M\nu S^{\sigma}-p^{\sigma}S\cdot q\right]\boldsymbol{G}_{\mathbf{2}}(\nu,Q^2)\right\}$$

  - target spin S = (0, $\boldsymbol{S}$); $\boldsymbol{S}/|S|$ = $(\sin\theta_N \cos\phi_N, \sin\theta_N \sin\phi_N, \cos\theta_N)$

- The beam is represented by the symmetric, L^S and anti-symmetric L^A pieces of the leptonic tensor, for lepton mass *m* and spin *s*

$$L^{S}_{\mu\nu}=k^{\mu}k'^{nu}+k'^{\mu}k^{nu}-g^{\mu\nu}(k\cdot k'-m^2)$$
$$L^{A}_{\mu\nu}=m\epsilon_{\mu\nu\lambda\sigma}s^{\lambda}(k-k')^{\sigma}$$

Structure Functions in DIS

- The four SF's $\boldsymbol{G_1}$, $\boldsymbol{G_2}$, $\boldsymbol{W_1}$ and $\boldsymbol{W_2}$, contain all the information on nucleon structure that can be extracted from inclusive data
- In the high energy regime of DIS, $\boldsymbol{g_1}$ and $\boldsymbol{g_2}$ are expected to scale like $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ (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 $\boldsymbol{g_1}$ and $\boldsymbol{F_1}$ are also related to PDF's:

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

Structure Functions in Practice

- The hadronic tensor W is related to the forward Compton amplitude T : $W = 1/2\pi \,\mathrm{Im}\, T$
  - Inelastic EM scattering can be described in terms of photoabsorption cross sections of $J_z = \pm 1$ transverse (real or virtual) and $J_z = 0$ longitudinal (virtual only) photons

$$\frac{d^2\sigma}{d\,\Omega\, dE'} = \Gamma_T(\sigma_T + \epsilon\,\sigma_L) = \sigma_{Mott}\left(\frac{1}{\nu}\boldsymbol{F_2} + \frac{2}{M}\boldsymbol{F_1}\tan\left(\frac{\theta}{2}\right)\right)$$

  - The SF's and absorption cross sections are related

$$\boldsymbol{F_1} = \frac{K}{4\pi^2\alpha} M\,\sigma_T\,; \quad K = (1-x)\nu \qquad \frac{\boldsymbol{F_2}}{\boldsymbol{F_1}} = \frac{2x(1+\sigma_L/\sigma_T)}{1+(2xM)^2/Q^2} = \frac{2x(1+\boldsymbol{R})}{1+\gamma^2}$$

$$\boldsymbol{F_2} = \frac{K}{4\pi^2\alpha}\frac{\nu}{(\nu^2+Q^2)}\left[\sigma_T + \sigma_L\right] \qquad \boldsymbol{F_L} = \frac{K}{4\pi^2\alpha}\frac{Q^2}{\nu}\sigma_L = 2x\,\boldsymbol{F_1}\boldsymbol{R}$$

Structure Functions in Practice - II

- 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

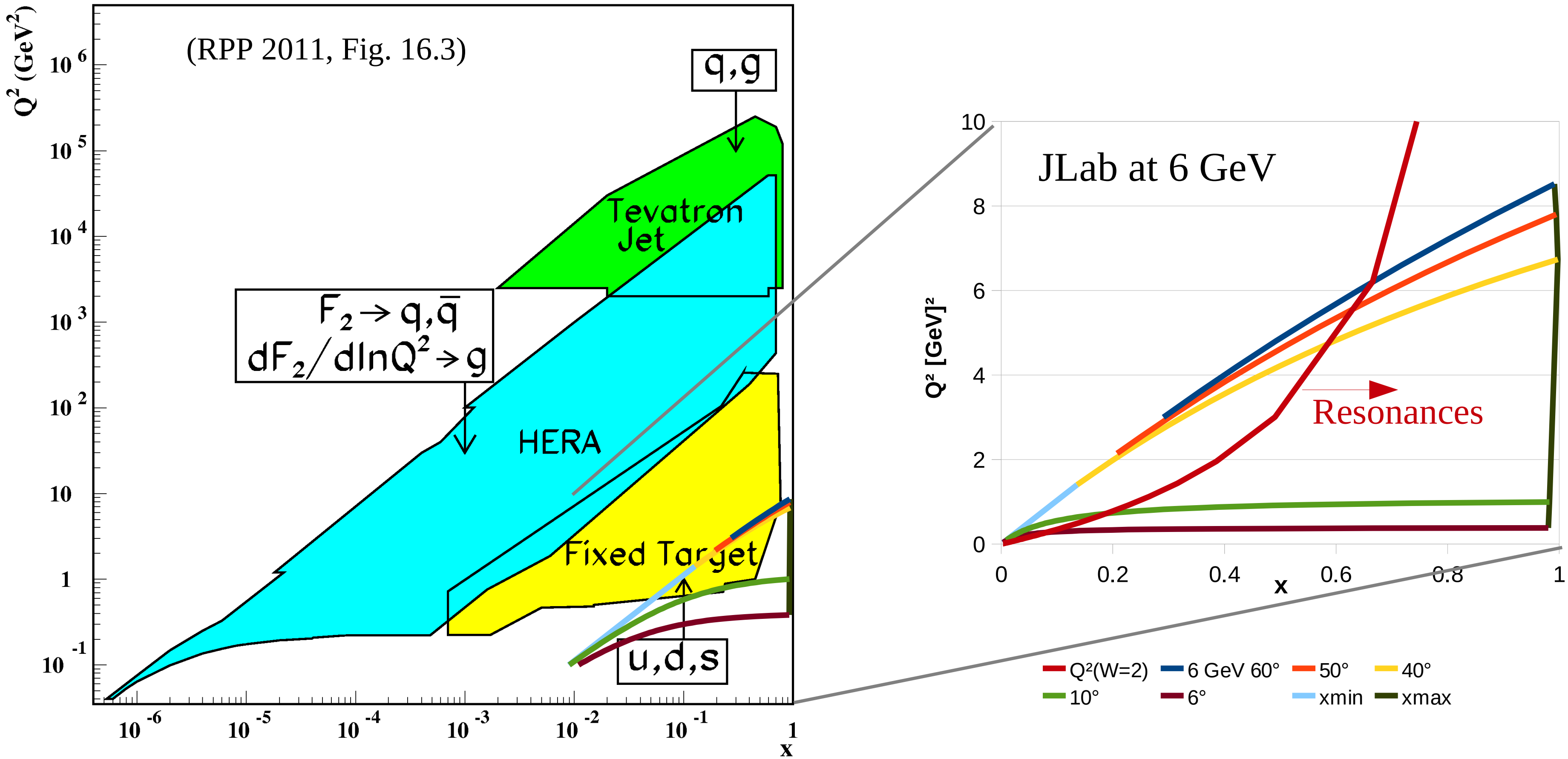
$$\boldsymbol{A_1} = \frac{\sigma_T^{(3/2)} - \sigma_T^{(1/2)}}{2\sigma_T}; \quad 2\sigma_T = \sigma_T^{(3/2)} + \sigma_T^{(1/2)}$$

$$\boldsymbol{A_2} = \frac{\sigma_{TL}^{(1/2)}}{2\sigma_T} \leq \sqrt{\frac{(1+A_1)}{2}R} \leq \boldsymbol{R}$$

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

$$\boldsymbol{A_2} = \frac{1}{F_1}\left(g_1 + \gamma\, g_2\right)$$

Kinematics Space



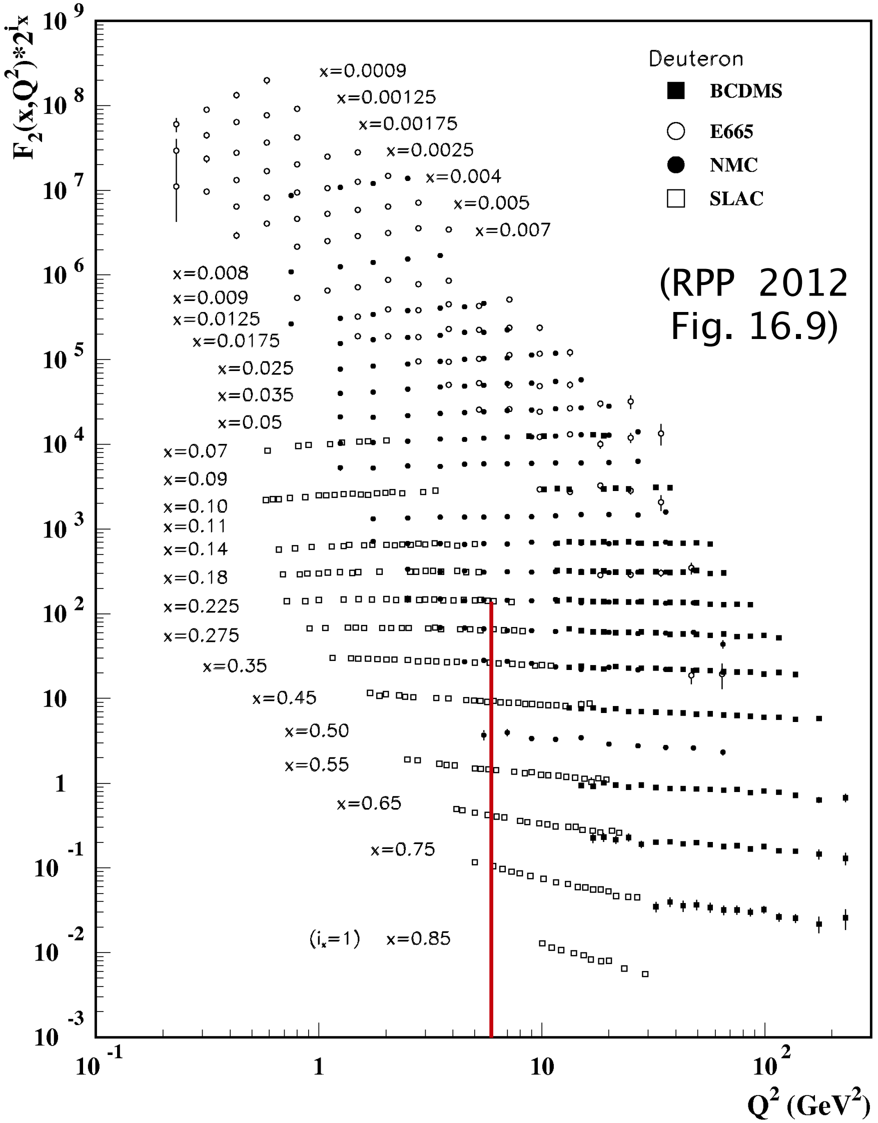
Structure Functions Program at 6 GeV
Unpolarized

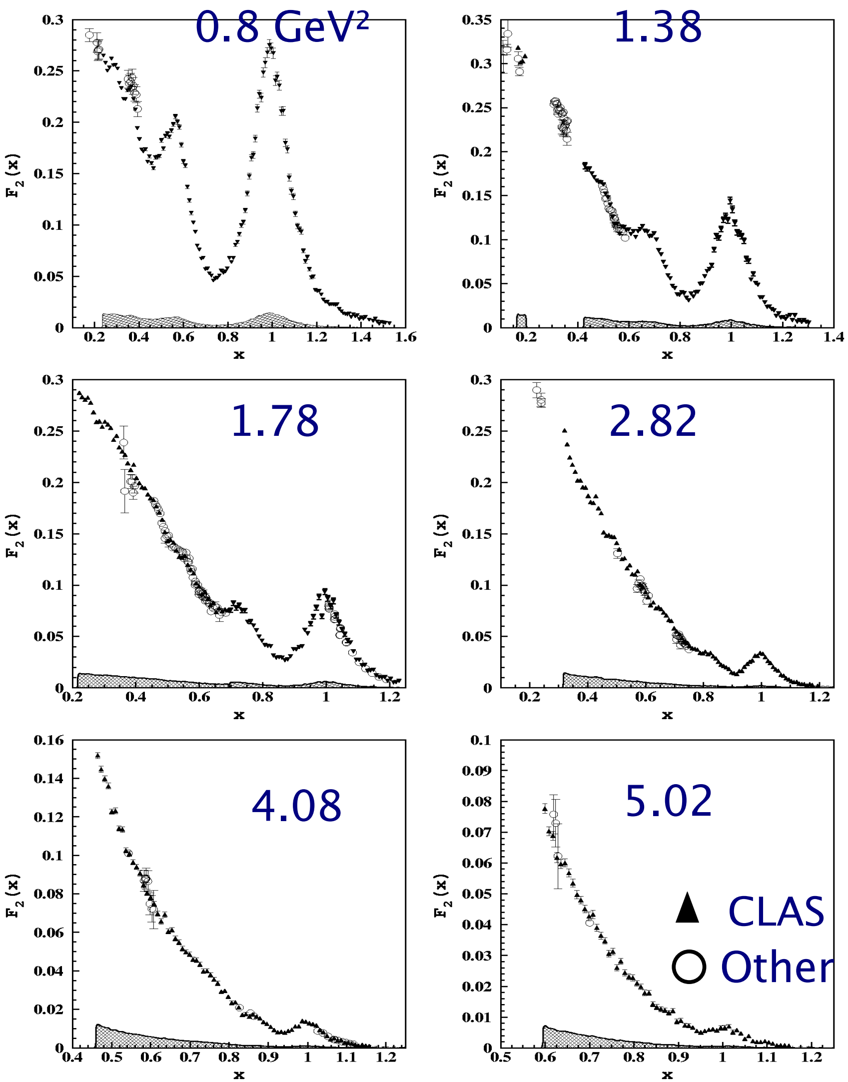
Spin Averaged Structure Functions

- World data and JLab contributions to spin averaged SF's
  - **Precision *p*, *d* data**
  - Duality in F_2
  - **LT separations to get F_L, *R***
  - **Duality in separated F_1, F_L**
  - **Moments, Higher Twists**
  - "free" neutron SF's, duality
  - **Nuclear SF's: *R***
  - Fits to F_1, F_2, R

Inclusive Program at 6 GeV				
Experiment	Hall	Target	Structure Function	Kinematics Q^2 [GeV]^2
E94-110	C	*p*	*R*	Resonances 3 - 4.5
E99-118	C	*p,d*	*R*	DIS, Resonances 0.1 - 1.7
CLAS e1/e2	B	*p, d*	F_2	Resonances < 4.5 GeV^2
E00-002	C	*p,d*	F_2	DIS, Resonances 0.1 - 1.5
E00-116	C	*p, d*	Cross sections	Resonances intermediate Q^2
E02-109	C	*d*	*R*	Resonances, Q. elastic 0.2 -2.5
E03-012	B	*n* in *d* (BoNuS)	F_2^n	Spectator tagging
E04-001 - I	C	C,Al,Fe	F_2, *R*	Resonances, Q.elastic 0.2 -2.5
E04-001 - II	C	C,Al,Fe	F_2, *R*	Resonances, Q. elastic 0.7 - 4
E06-009	C	*d*	*R*	Resonances, Q. elastic 0.7 - 4

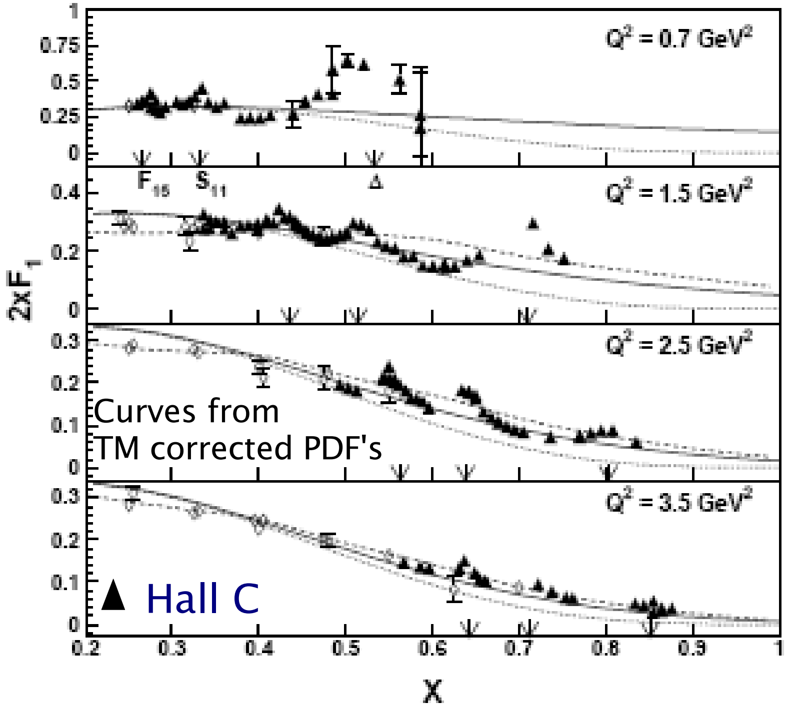
Precision: $F_2^{\,d}$ at high x, $Q^2 < 6$ GeV^2

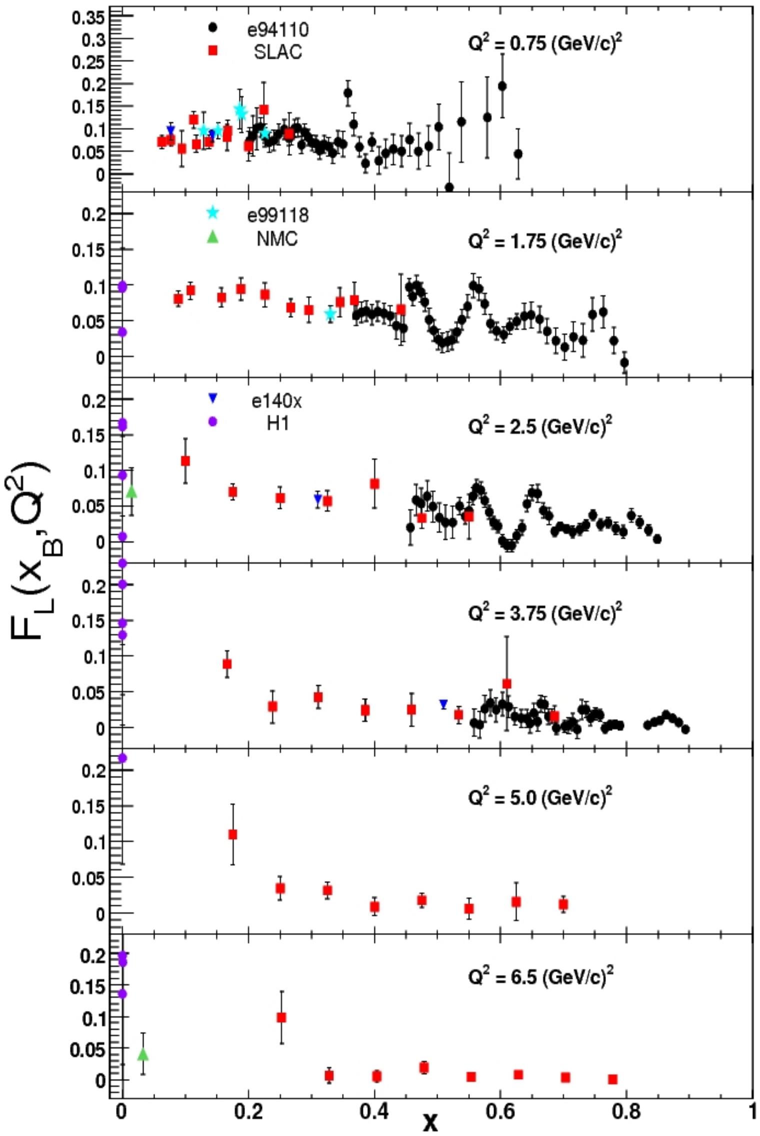




F_L, F_1 and R from L-T separations

- Measure *e-nucleon* cross section at different ε
  - Get σ_T , σ_L from linear fits





Moments and Higher Twists

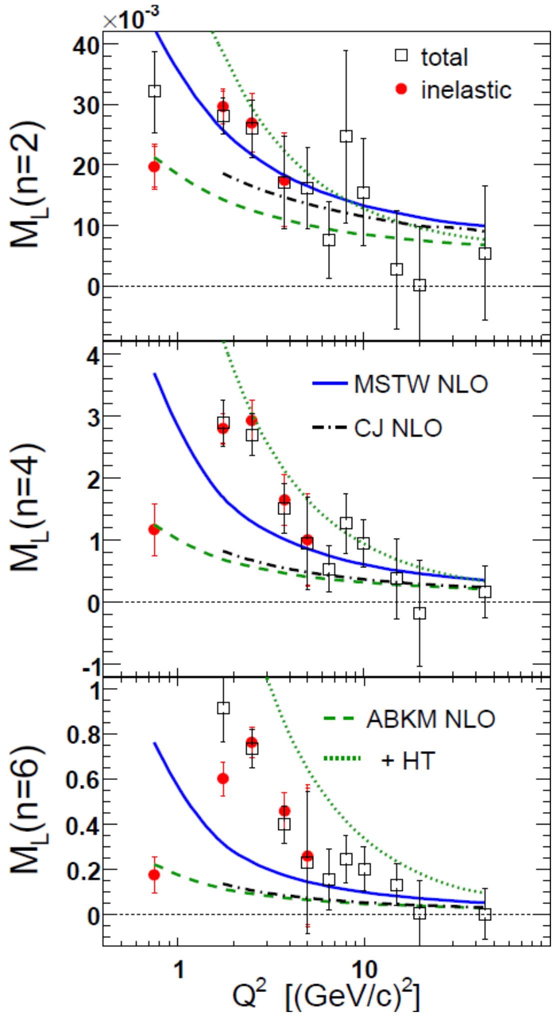
- Beyond log scaling violations:
  - **Higher Twists** (HT) or inverse Q^2 power corrections to SF's
- Moments of SF's are related to matrix elements of quark operators of given twist by the OPE
  - Moments expanded in power series of $(A(x)/\, Q^2)^{\mathbf{(twist\ -\ 2)}}$
  - Moments integrate over full x range: $M_{2,L}^{(n)}(Q^2) = \int_0^1 dx\, x^{n-2} F_{2,L}(x, Q^2)$
    - Contributions of resonances and elastic to moments at 6 GeV are substantial
  - Role of HT clouded by kinematic terms from operators of the same twist, but higher spin
    - "Target Mass" corrections required, or avoided with **Nachtmann** moments, instead of ordinary, Cornwall-Norton ones (above)

Moments of Spin Averaged SF's

- Nachtmann Moments
  - combination of separated SF's: $\boldsymbol{F}_L$ and $\boldsymbol{F}_2$, etc.
  - depend on Nachtmann scaling variable ξ
- Example: 2nd. moment $M_L^{n=2}$

$$M_L^{(2)}(Q^2)=\int_0^1 dx\frac{\xi^3}{x^3}\left[\boldsymbol{F}_L(x,Q^2)+\left(\frac{3}{5}\xi-8x\right)\frac{xM^2}{Q^2}\boldsymbol{F}_2(x,Q^2)\right]$$

$$\xi=2x/\left(1+\sqrt{1+\gamma^2}\right)$$



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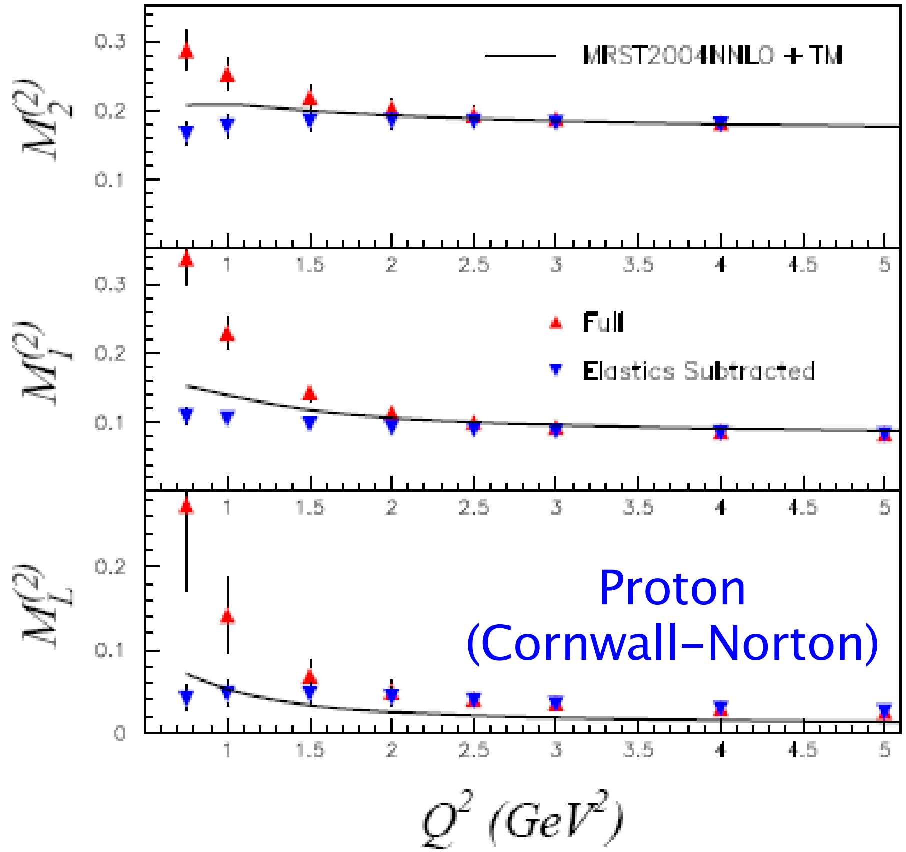
$$M_L^{(2)}(Q^2) = \int_0^1 dx \frac{\xi^3}{x^3}$$

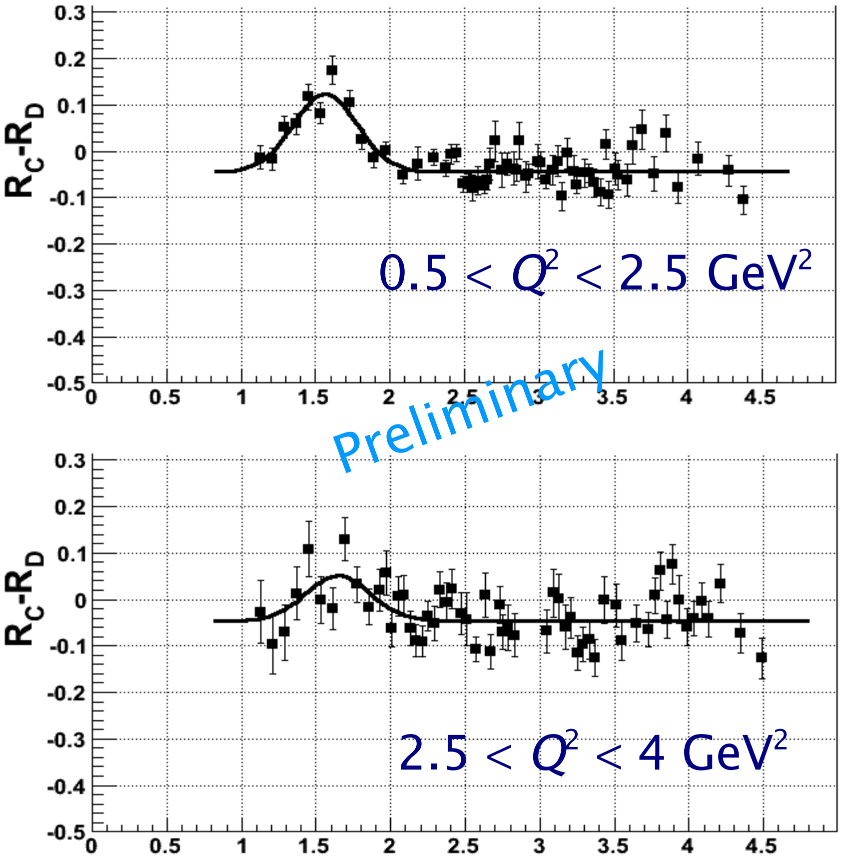
$$\left[\boldsymbol{F}_L(x,Q^2) + \left(\frac{3}{5}\xi - 8x\right) \frac{x M^2}{Q^2} \boldsymbol{F}_2(x,Q^2) \right]$$

$$\xi = 2x / \left(1 + \sqrt{1+\gamma^2} \right)$$



R in Nuclei

- Interesting because R_A looks to be smaller than R_d
  - SLAC results showed $R_A - R_d = 0$
  - New Hall C data show $R_d > R_A$
  - Analysis based on fits to F_1, F_2 and R in proton, deuteron and nuclei by P. Bosted, E.Christy and V. Mamyan



Structure Functions Program at 6 GeV
Spin Dependent

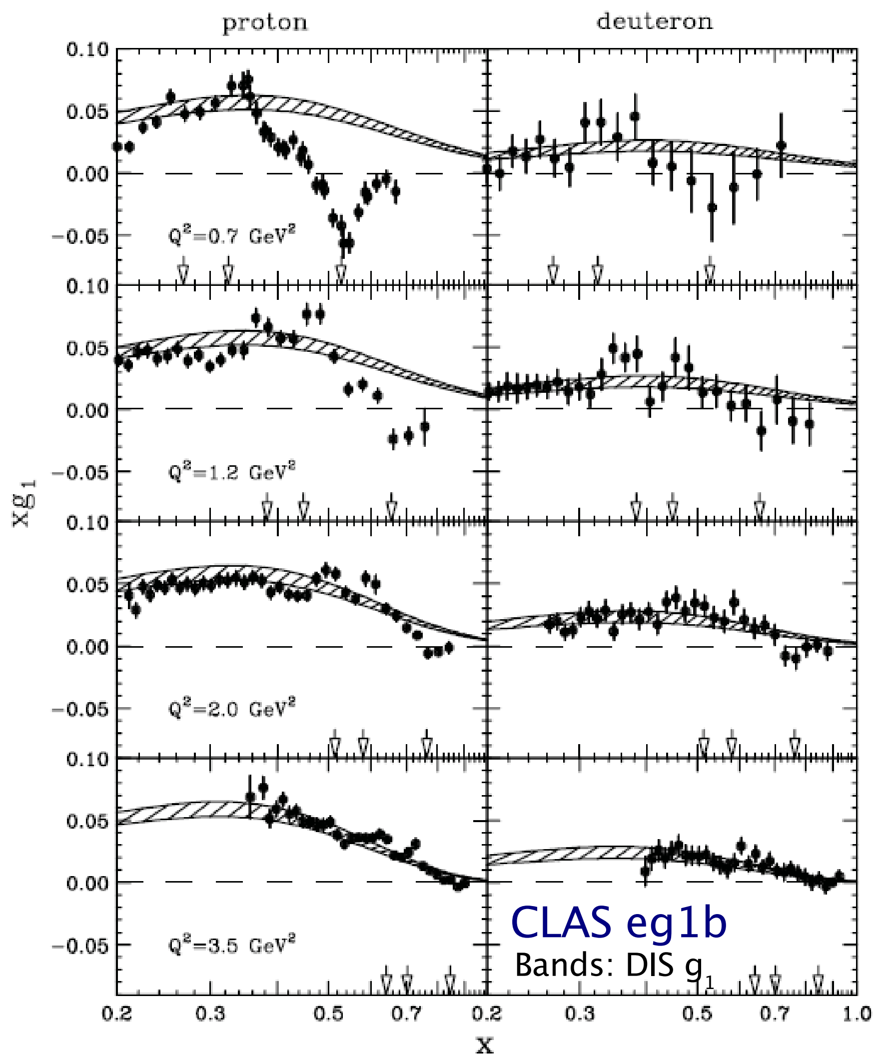
Spin Dependent Structure Functions

- g_1 measured in all halls
  - NH_3, ND_3 in all Halls
  - ^3He in Hall A
- g_2 in C and A
- **Duality in g_1**
- **Transverse structures A_2 and g_T**
- **Moments and twist-3**
- Sum Rules: GDH, B-C, Bjorken
- n SSF's from ^3He and from d - p

Inclusive Program at 6 GeV				
Experiment	**Hall**	**Target**	**Measured quantity**	**Kinematics Q^2 GeV^2**
94-010	A	^3He	$A_{\parallel}$, $A_{\perp}$	Resonances 0.1 – 0.9
CLAS eg1a-b	B	*p, d*	$A_{\parallel}$	DIS, Resonances 0.2 – 3.5
97-103	A	^3He	$A_{\perp}$	DIS 0.6 – 1.4
97-110	A	^3He	$A_{\parallel}$, $A_{\perp}$	Elastic, Resonances 0.02 – 0.5
99-117	A	^3He	$A_{\parallel}$, $A_{\perp}$	DIS 2.7, 3.5, 4.8
01-006 (RSS)	C	*p, d*	$A_{\parallel}$, $A_{\perp}$	Resonances 1.3
01-012	A	^3He	$A_{\parallel}$, $A_{\perp}$	Resonances 1 – 4
CLAS eg4	B	*p*	$A_{\parallel}$	Elastic, Resonances 0.01 – 0.5
07-003 (SANE)	C	*p*	$A_{\parallel}$, $A_{\perp}$	DIS, Resonances 1.6 – 6
06-014	A	^3He	$A_{\parallel}$, $A_{\perp}$	DIS <3>
08-027 (g2p)	A	*p*	$A_{\parallel}$, $A_{\perp}$	Resonances 0.03 – 0.3

Duality in $\boldsymbol{g_1}$

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



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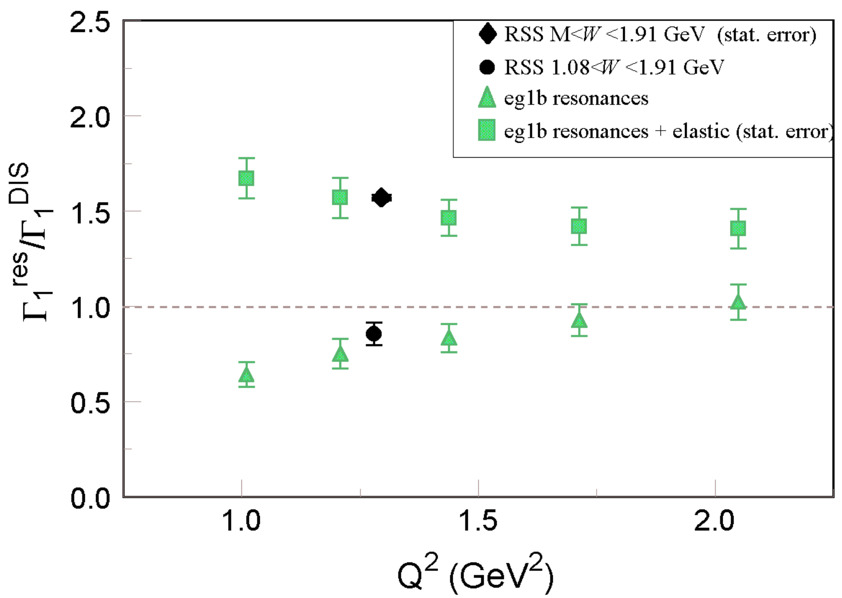
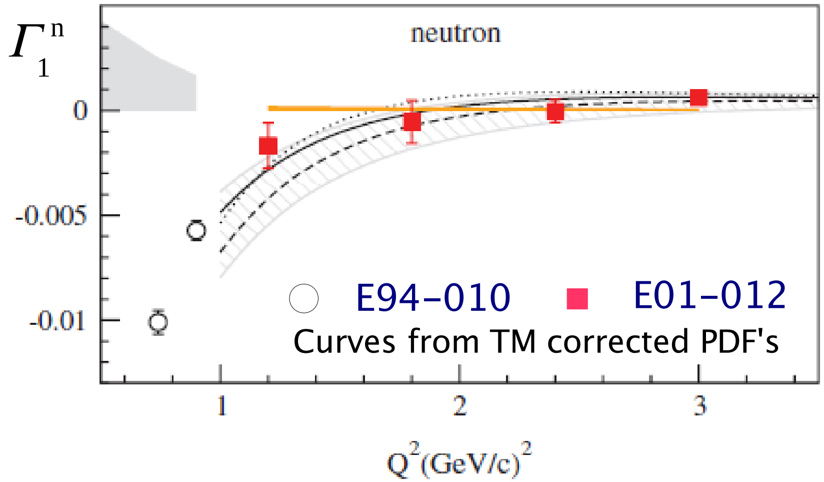




Tranverse Polarized Scattering: Unlocking Twist-3

- In tranverse polarized DIS two types of operators contribute at the same order to the Compton amplitude
  - twist-2 operators, i.e. the familiar handbag diagram
  - twist-3 operators, which correspond to *qgq* correlations

M. Anselmino et al. / Physics Reports 261 (1995) 1–124

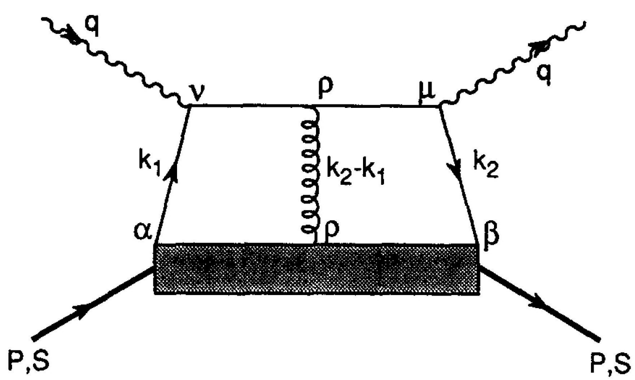


Fig. 10.3. DIS interaction involving quark-gluon correlation.

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

- direct access to twist-3 via $\boldsymbol{g_2}$:
  - "*Unique feature of spin-dependent scattering*" (R. Jaffe)

Transverse Spin Structure Function

- g_2 is combination of twist-2 and twist-3 components:

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$
$$= -g_1(x,Q^2) + \int_x^1 \frac{dx'}{x'} g_1(x',Q^2) - \int_x^1 \frac{dx'}{x'} \frac{\partial}{\partial x'} \left[\frac{m}{M} h_T(x',Q^2) + \xi(x',Q^2) \right]$$

  - Wandzura-Wilczek g_2^{WW} depends on g_1; chiral odd transversity h_T is twist-2; ξ represents quark-gluon correlations (twist-3)
  - ξ has two twist-3 contributions (JHEP 11 (2009) 093). For $m \ll M$

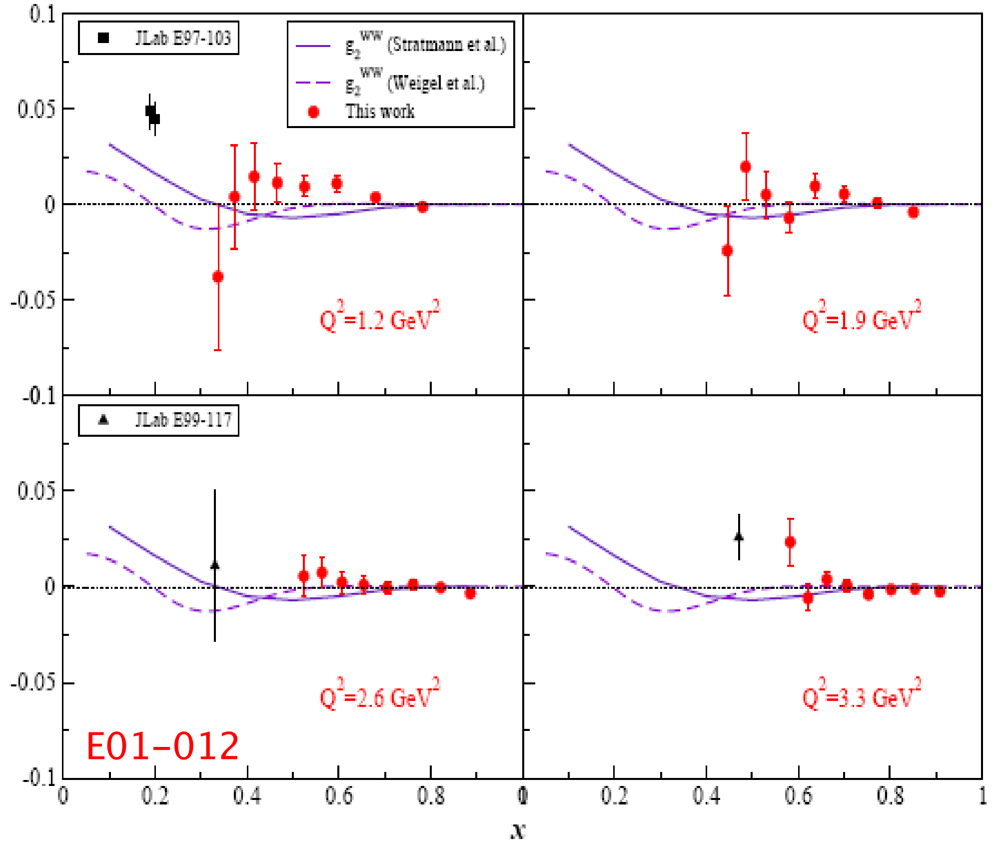
$$\bar{g}_2 = 1/2 \sum_i e_i^2 [\tilde{g}_T^i - \int_x^1 \frac{dx'}{x'} (\hat{g}_T^i - \tilde{g}_T^i)]; \quad \tilde{g}_T = q\,g\ term,\ \hat{g}_T = Lorentz\ invariance$$

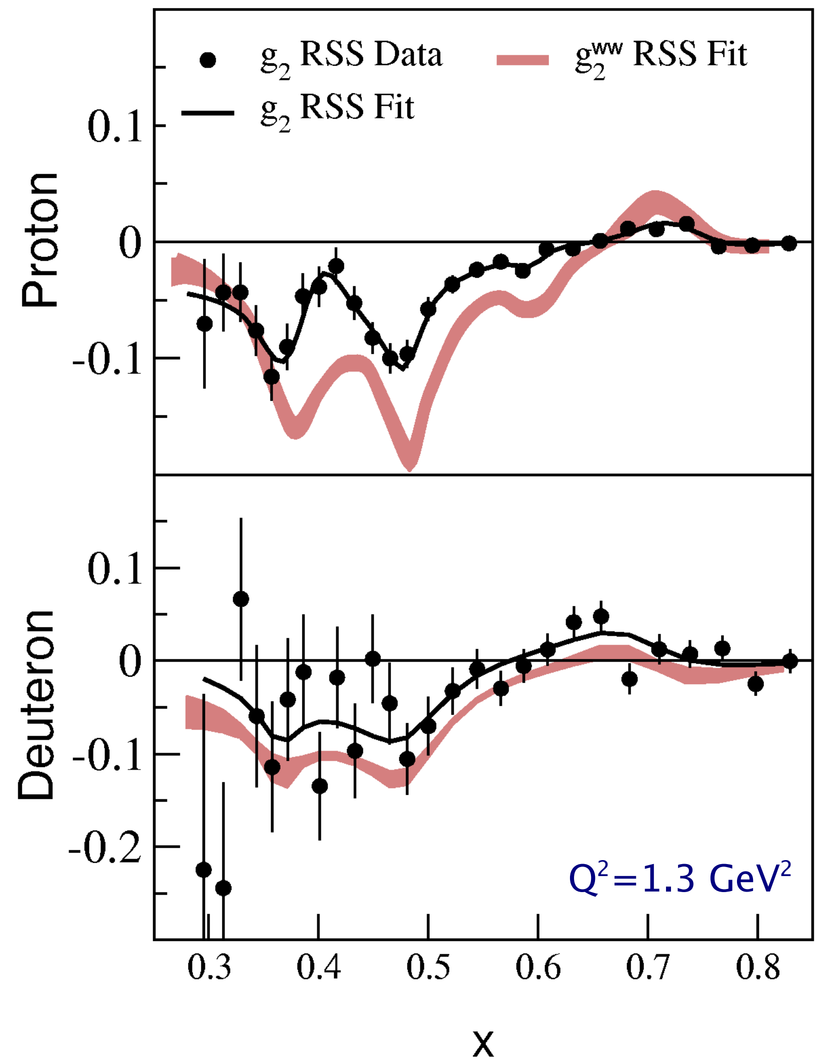
  - *Transverse spin* SF g_T measures spin distribution normal to γ^*

$$g_T = g_1 + g_2 = \int_x^1 \frac{dx'}{x'} [g_1 - \frac{\partial}{\partial x'} (\frac{m}{M} h_T + \xi)] = \frac{\nu}{\sqrt{Q^2}} F_1(x,Q^2) A_2(x,Q^2)$$

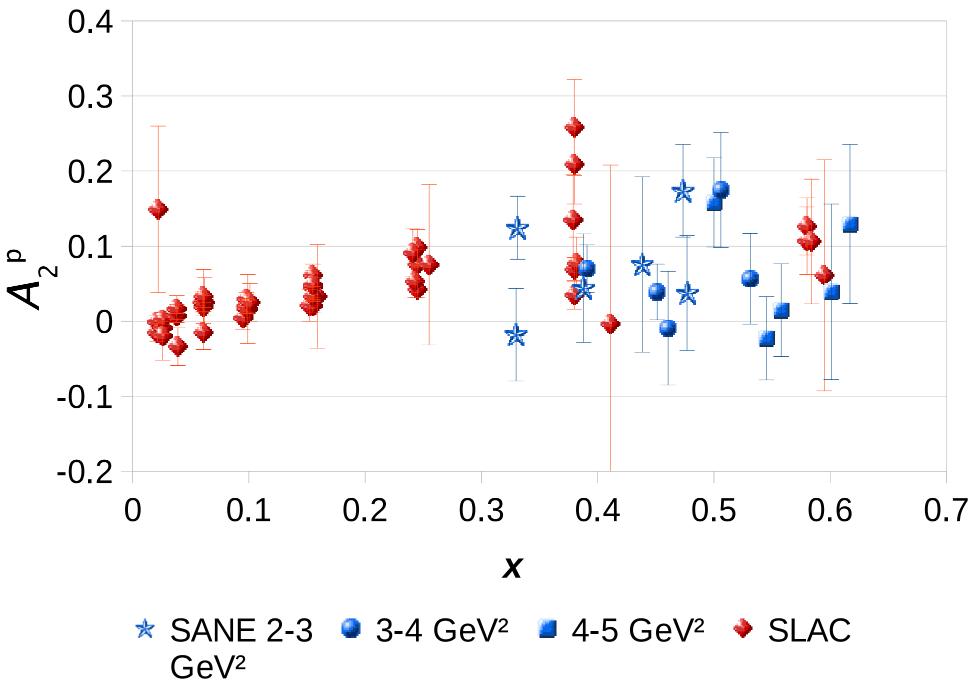
Polarized SF g_2

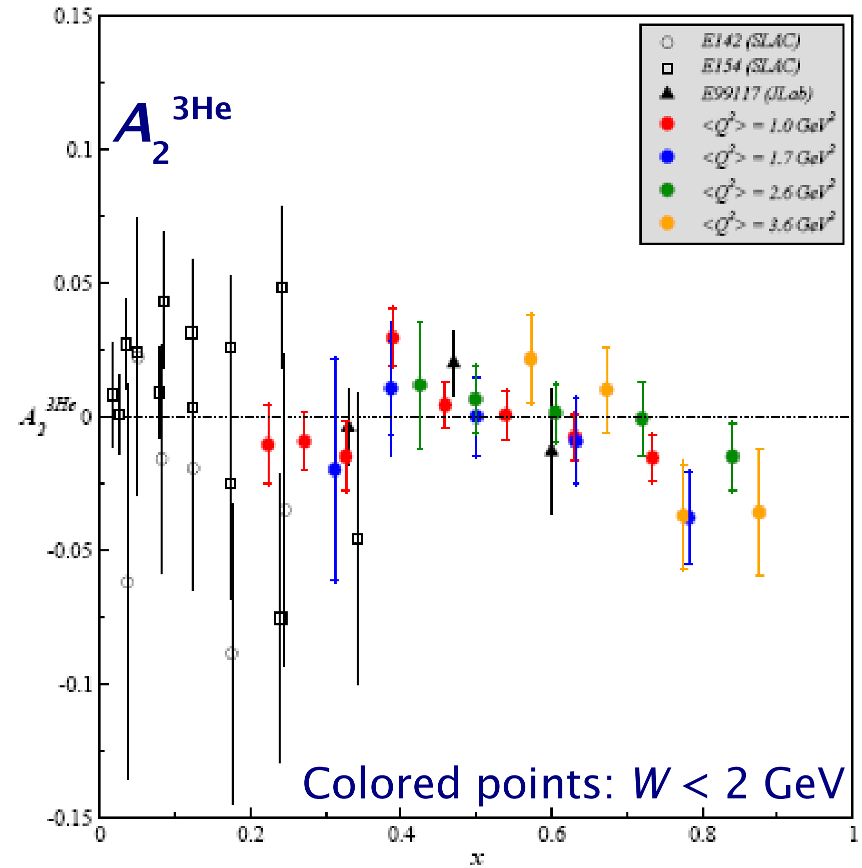
- g_2 in Hall A (below) and Hall C (right)





Spin Asymmetry A_2

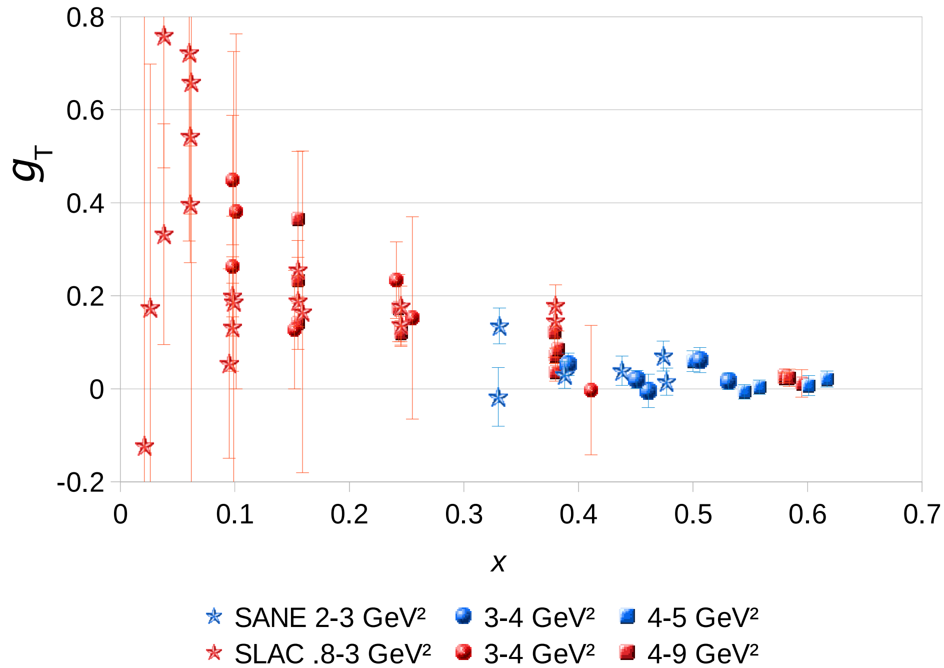


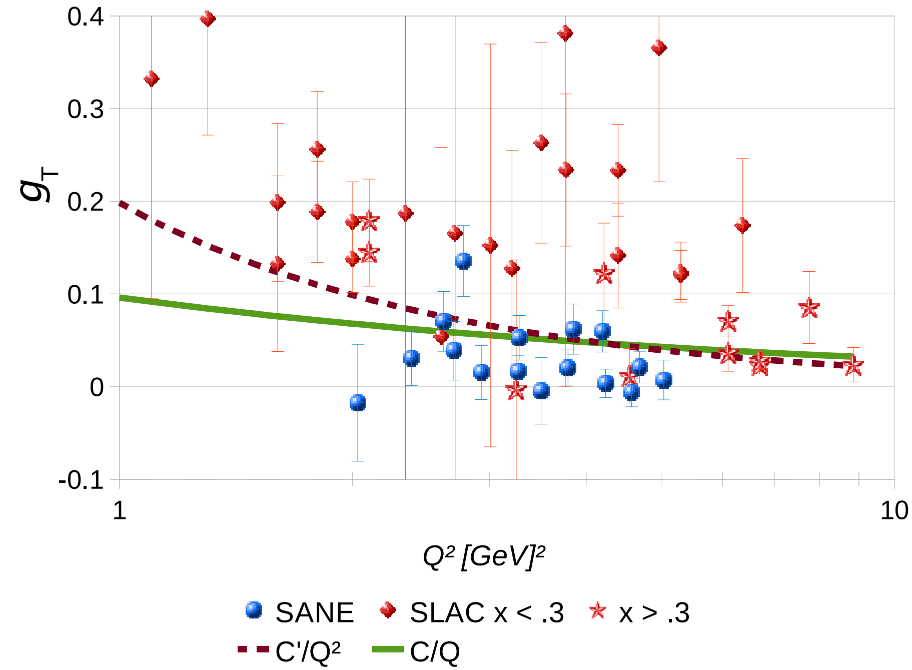


- DIS A_2^p not zero:
  - signal of transverse momentum

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

Transverse Spin SF g_T





- DIS $g_T^p = g_1 + g_2$ not zero
  - SANE data covers high *x*
- g_T, F_L evolutions similar but non-trivial
  - no simplifications possible at NLO (NPB 608 (2001) 235)

OPE for Polarized SF's

- C-N moments of $\boldsymbol{g_1}$ and $\boldsymbol{g_2}$ connected by OPE to twist-2 and twist-3 matrix elements $\boldsymbol{a_N}$ and $\boldsymbol{d_N}$

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

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

- twist-3 $\boldsymbol{d_2}$ – mean color-magnetic field along spin
  - $\boldsymbol{d_n}$ 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 $O(M^8/Q^8)$)

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

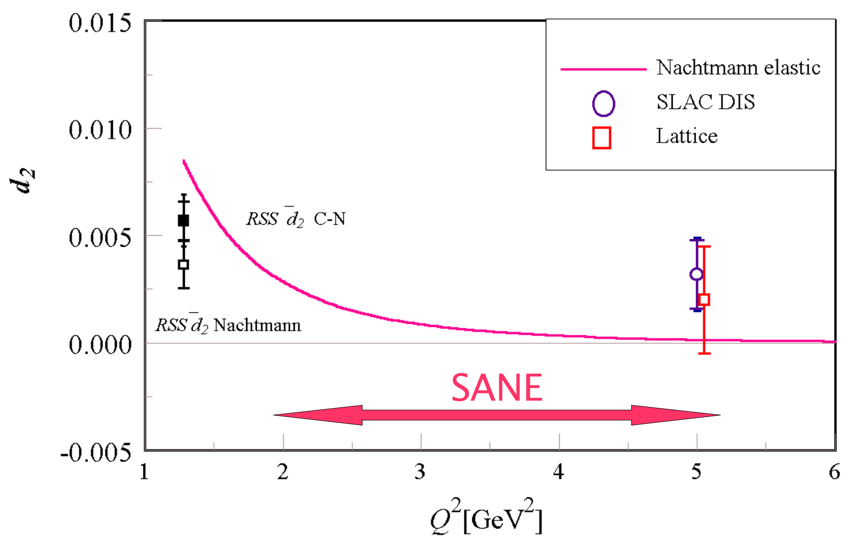
d_2 from *RSS* Third Moments

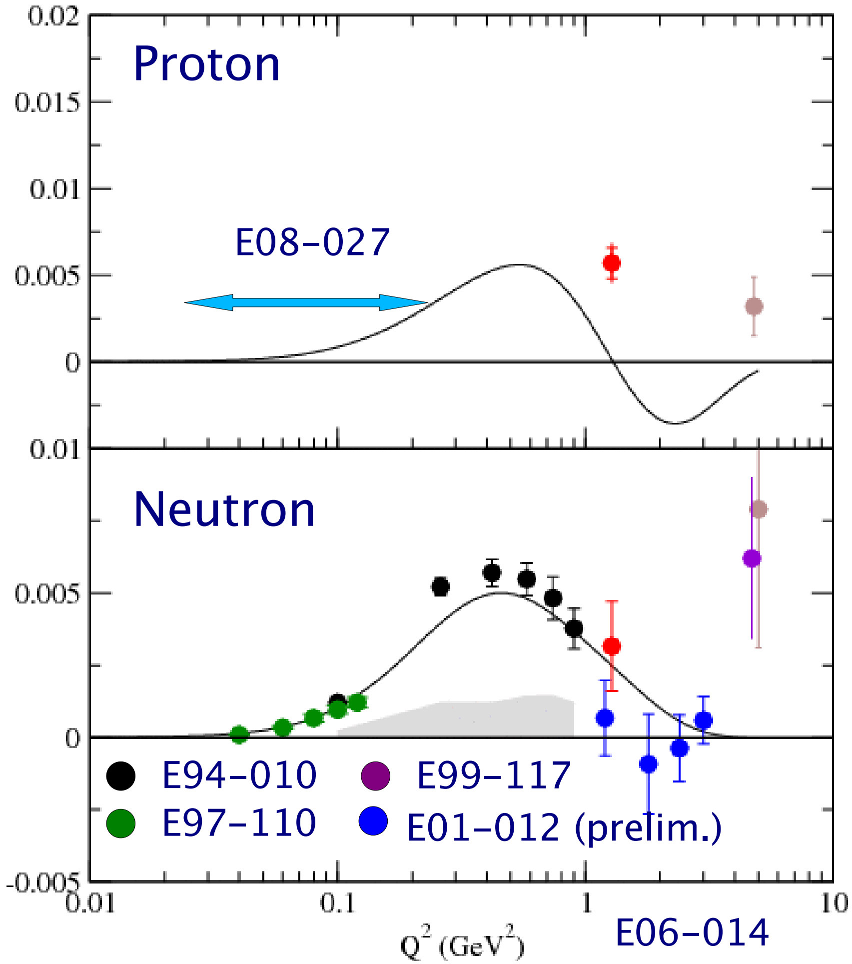
x ranges	Proton	Deuteron	Neutron
Measured			
CN	0.0057±0.0013	0.0082±0.0019	0.0031±0.0019
Nachtmann	0.0037±0.0010	0.0048±0.0015	0.0015±0.0012
$0 < x < 1$			
CN	0.0364±0.0028	0.0170±0.0035	−0.0180±0.0031
Nachtmann	**0.0104±0.0014**	**0.0027±0.0019**	**−0.0075±0.0021**

- Calculated moments at $<Q^2> = 1.3$ GeV^2, in three regions:
  - measured $0.32 < x < 0.82$; elastic (quasi-el. for deuteron);
  - unmeasured $x < 0.32$, suppressed by x^2.
- Non-zero d_2 for both nucleons (total errors shown)
  - Neutron approximated as D-state corrected d - p (good to $O(1\%)$)
- Ratios Nachtmann/CN < 1: large contribution of kinematic HT

Resonances d_2

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





The JLab SF Program goes on

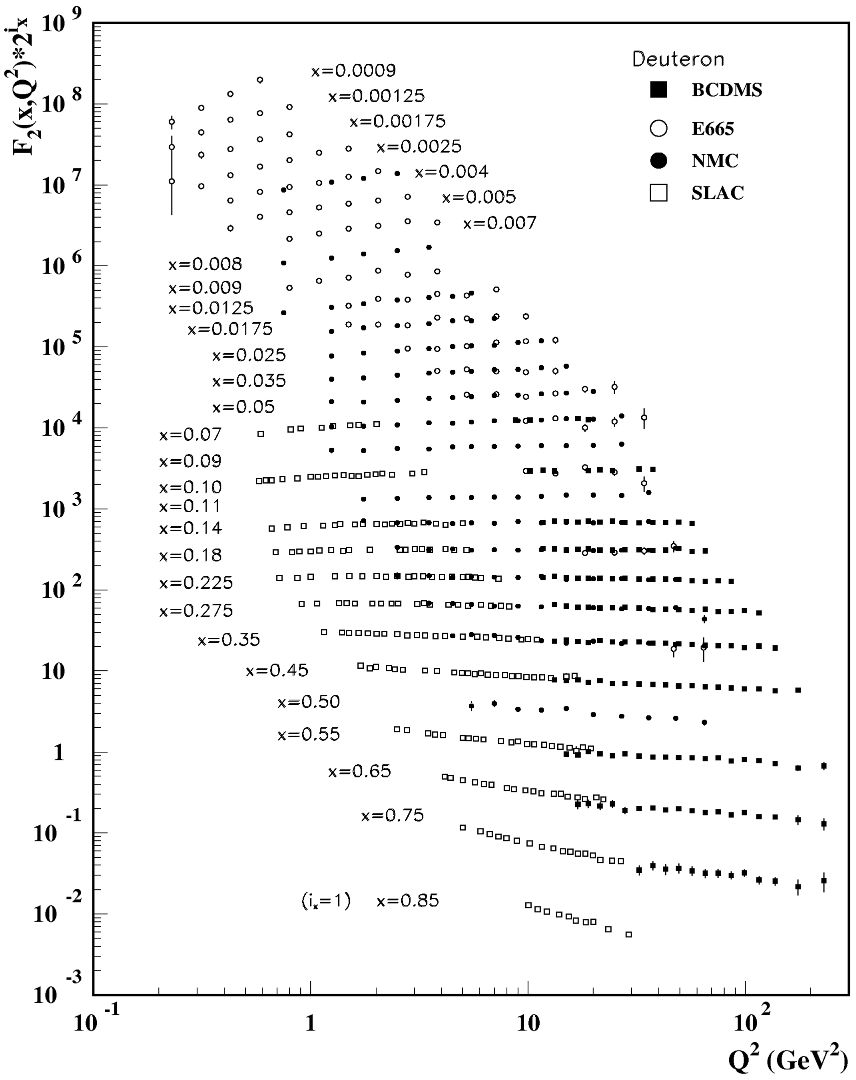
- New results from recent and older SF experiments still to come
- Experiments in all Halls at 11 GeV
- **J**efferson Lab **A**ngular **M**omentum Collaboration (JAM)
  - theorists and experimentalists effort to "*study the quark and gluon spin structure of the nucleon by performing global fits of PDFs*".
  - unique CEBAF capabilities in measuring small cross sections at extreme kinematics, the JAM spin PDFs are particularly tailored for studies at large Bjorken x , as well as the resonance-DIS transition region at low and intermediate $\boldsymbol{W}$ and $\boldsymbol{Q}^2$.
  - http://wwwold.jlab.org/theory/jam/

Credits

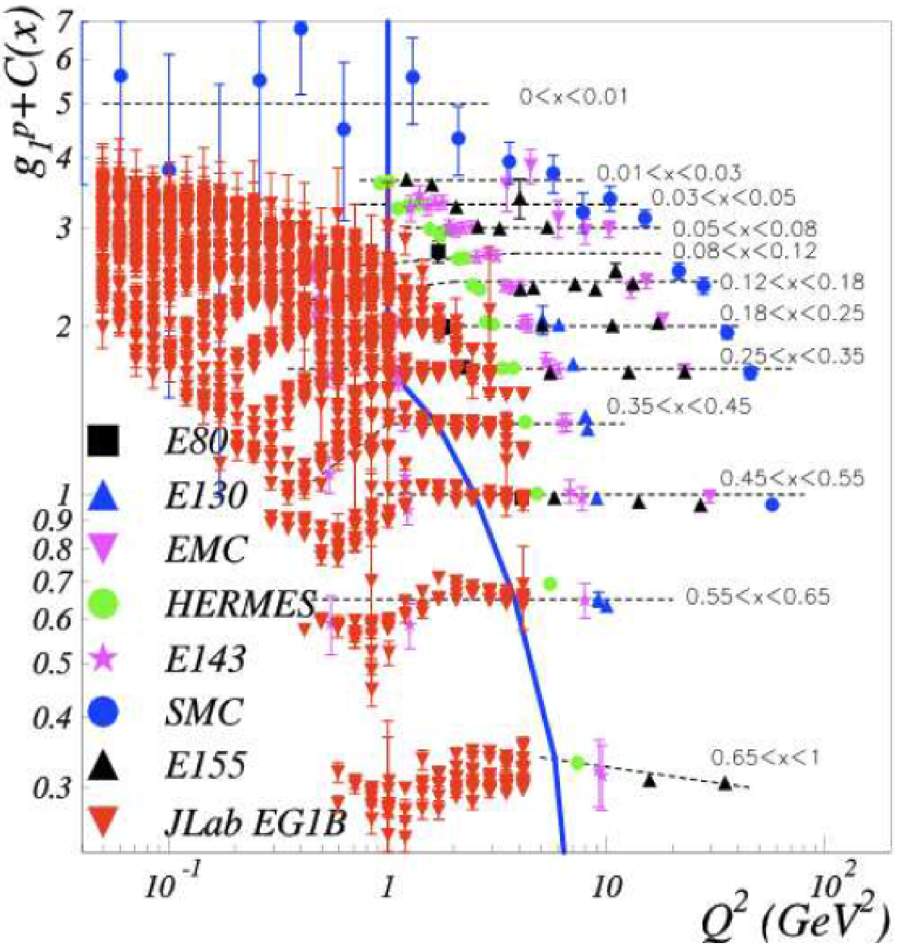
- F_2^d: PRC 73 045205 (2006)
- Separated F_1: E. Christy and W. Melnitchouk, arXiv:1104.0239v2
- F_L: AIP Conf.Proc. 1369 (2011) 137
- M_L: P. Monaghan, APS Spring 2012
- M_L, M_1, M_2: arXiv:1104.0239v2
- R_C - R_d: AIP Conf. Proc. 1369 (2011) 137
- eg1b duality: PRC 75 035203 (2007)
- g_1^n duality: PRL 101 182502 (2008)
- Hall A g_2^n: P. Solvignon, Ph.D. thesis
- Hall C g_2^p: P.RL 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 N. L., 2009

Extras

SF scaling



Deuteron
BCDMS
E665
NMC
SLAC
x=0.0009
x=0.00125
x=0.00175
x=0.0025
x=0.004
x=0.005
x=0.007
x=0.008
x=0.009
x=0.0125
x=0.0175
x=0.025
x=0.035
x=0.05
x=0.07
x=0.09
x=0.10
x=0.11
x=0.14
x=0.18
x=0.225
x=0.275
x=0.35
x=0.45
x=0.50
x=0.55
x=0.65
x=0.75
(i_x=1) x=0.85
Q^2 (GeV^2)



g_1^p+C(x)
0<x<0.01
0.01<x<0.03
0.03<x<0.05
0.05<x<0.08
0.08<x<0.12
0.12<x<0.18
0.18<x<0.25
0.25<x<0.35
0.35<x<0.45
0.45<x<0.55
0.55<x<0.65
0.65<x<1
E80
E130
EMC
HERMES
E143
SMC
E155
JLab EG1B
Q^2 (GeV^2)

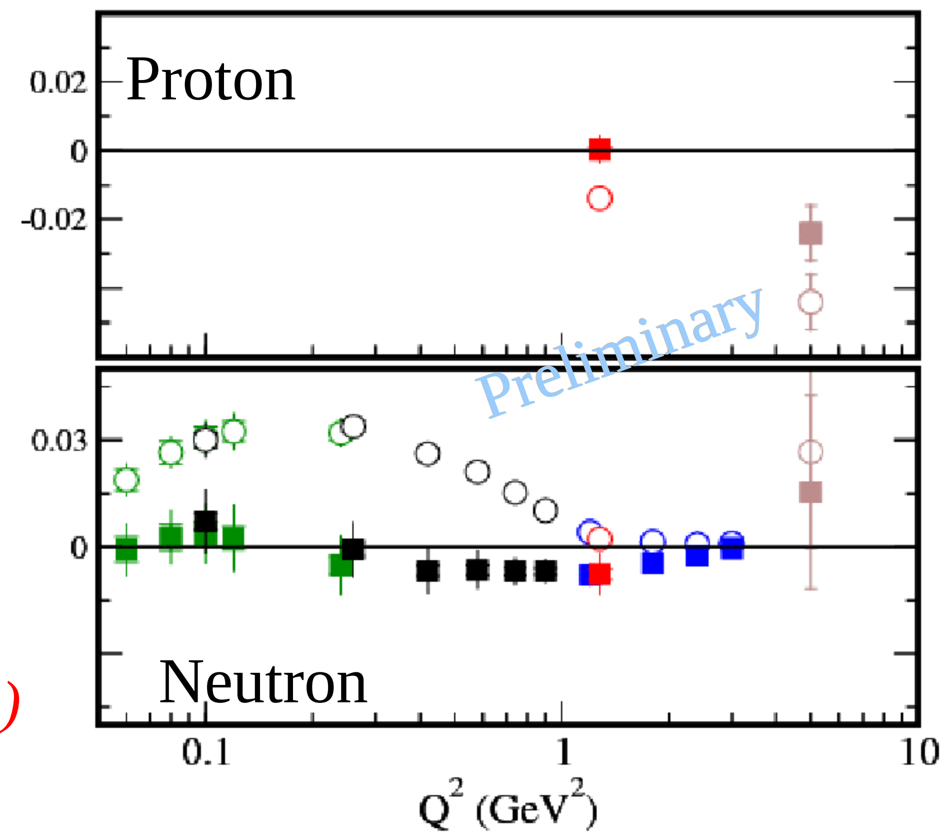
Sum Rules

- 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)

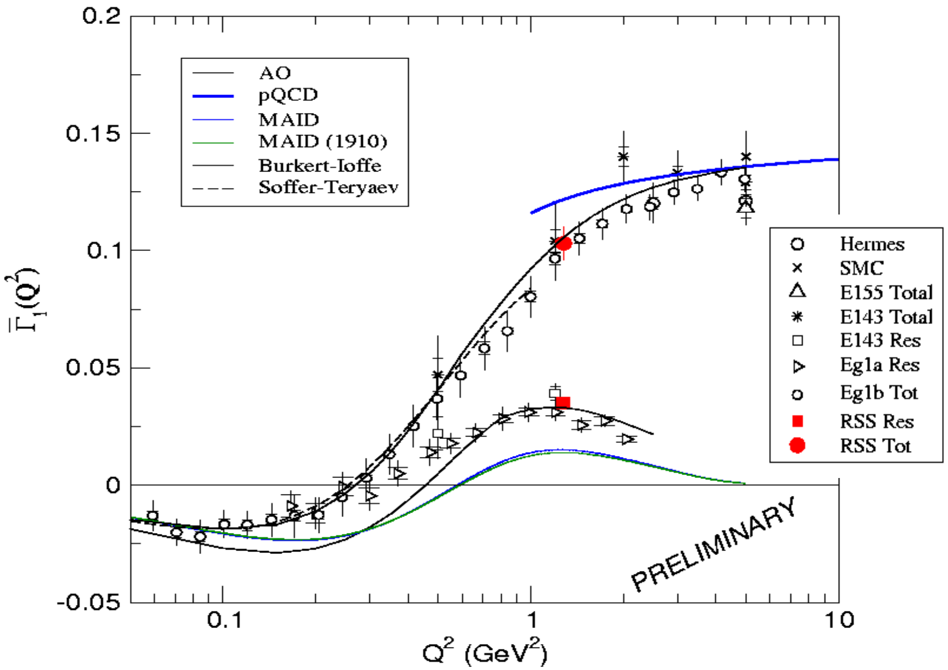


Sum Rules

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

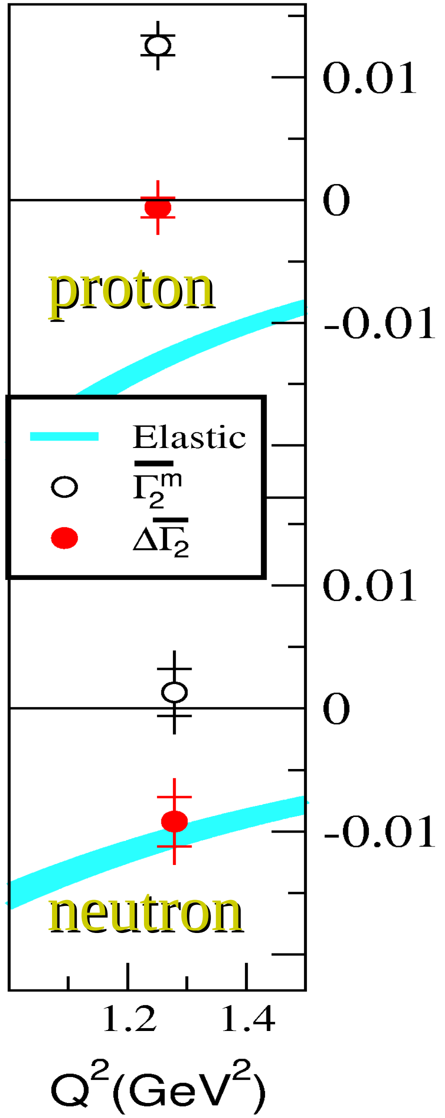
$$\overline{\Gamma_1}(Q^2) = \int_0^{1-el} g_1(x, Q^2)\,dx$$

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



Twist-3 and the Burkhardt-Cottingham Sum Rule

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



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 $2.5 \leq Q^2 \leq 6.5\,\mathrm{GeV}^2$, $0.3 \leq x_{Bj} \leq 0.8$

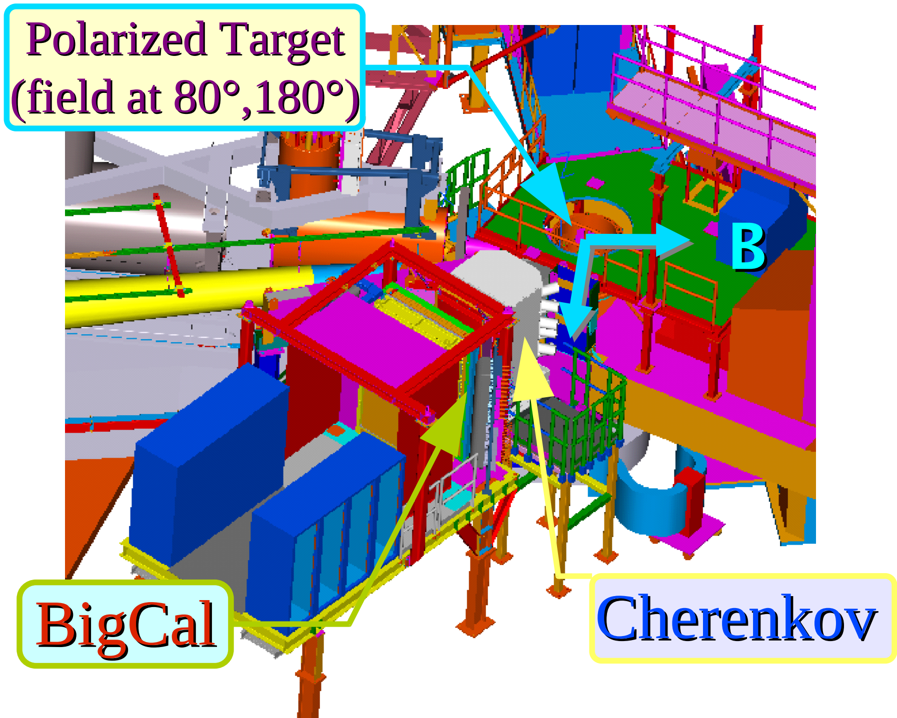
Measure inclusive double polarization near-orthogonal asymmetries to:

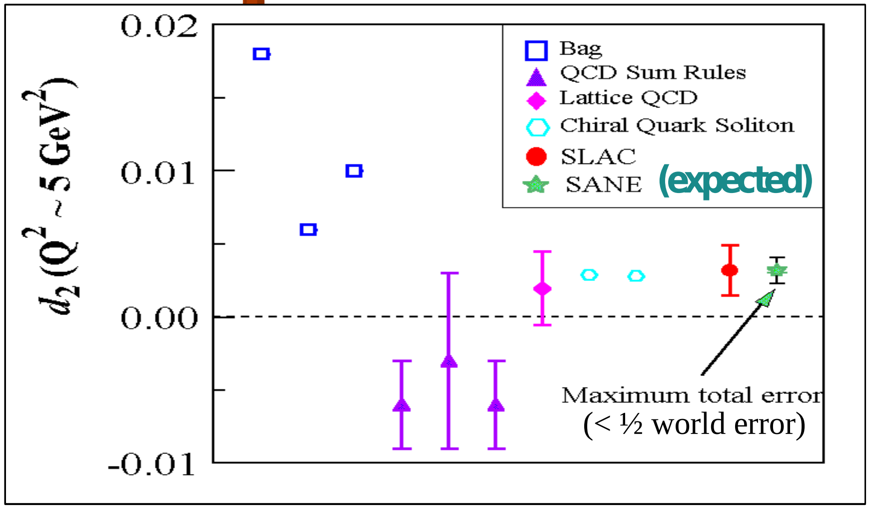
- access ***quark-gluon*** correlations using LO twist-3 effects (d_2 quark matrix element)
- compare with Lattice QCD, QCD sum rules, bag model, chiral quarks
- test nucleon models (x dependence) and Q^2 evolution
- explore $A_1(x \rightarrow 1)$; test polarized local duality

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

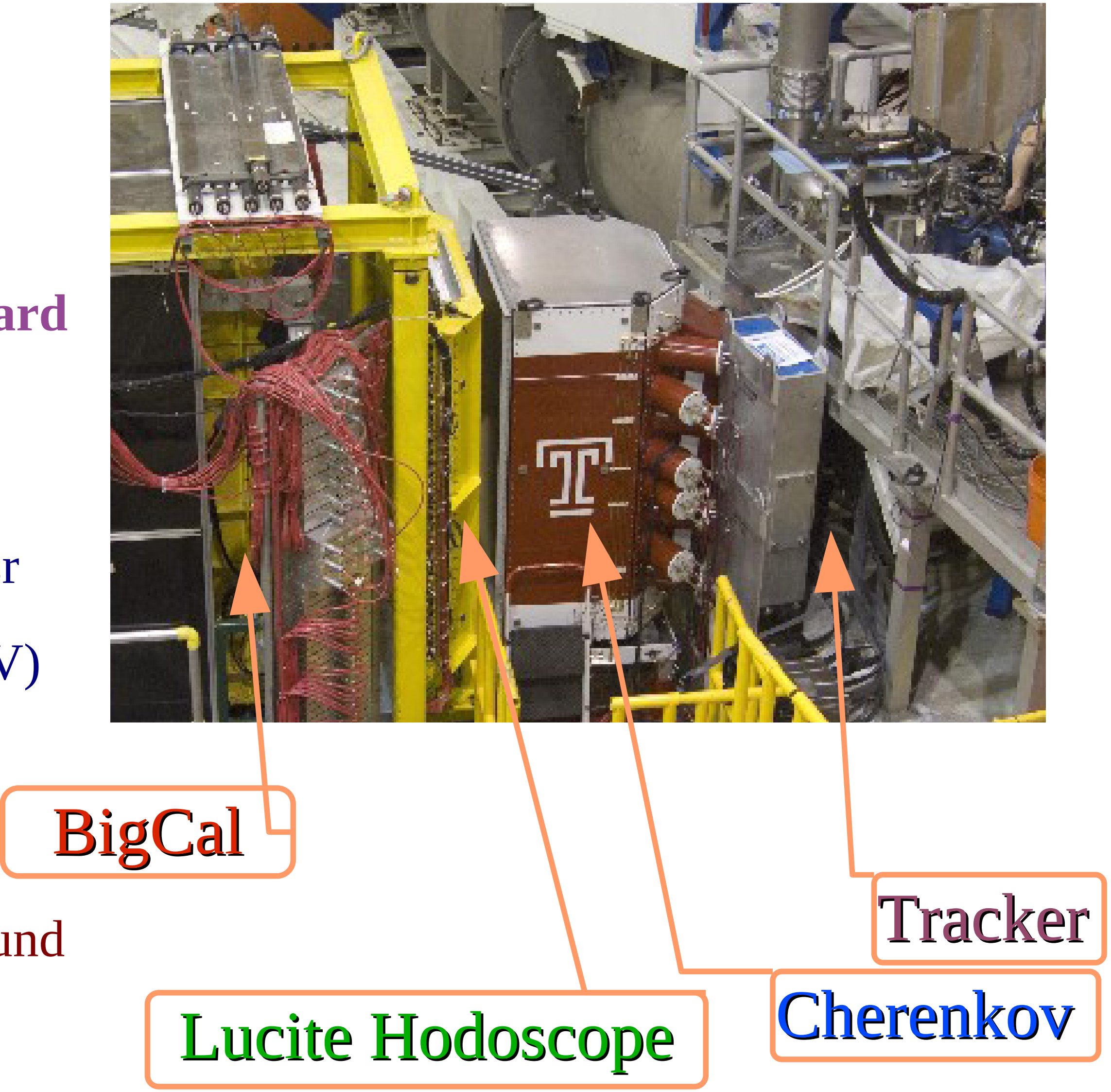
Took data in Hall C Jan-March 2009



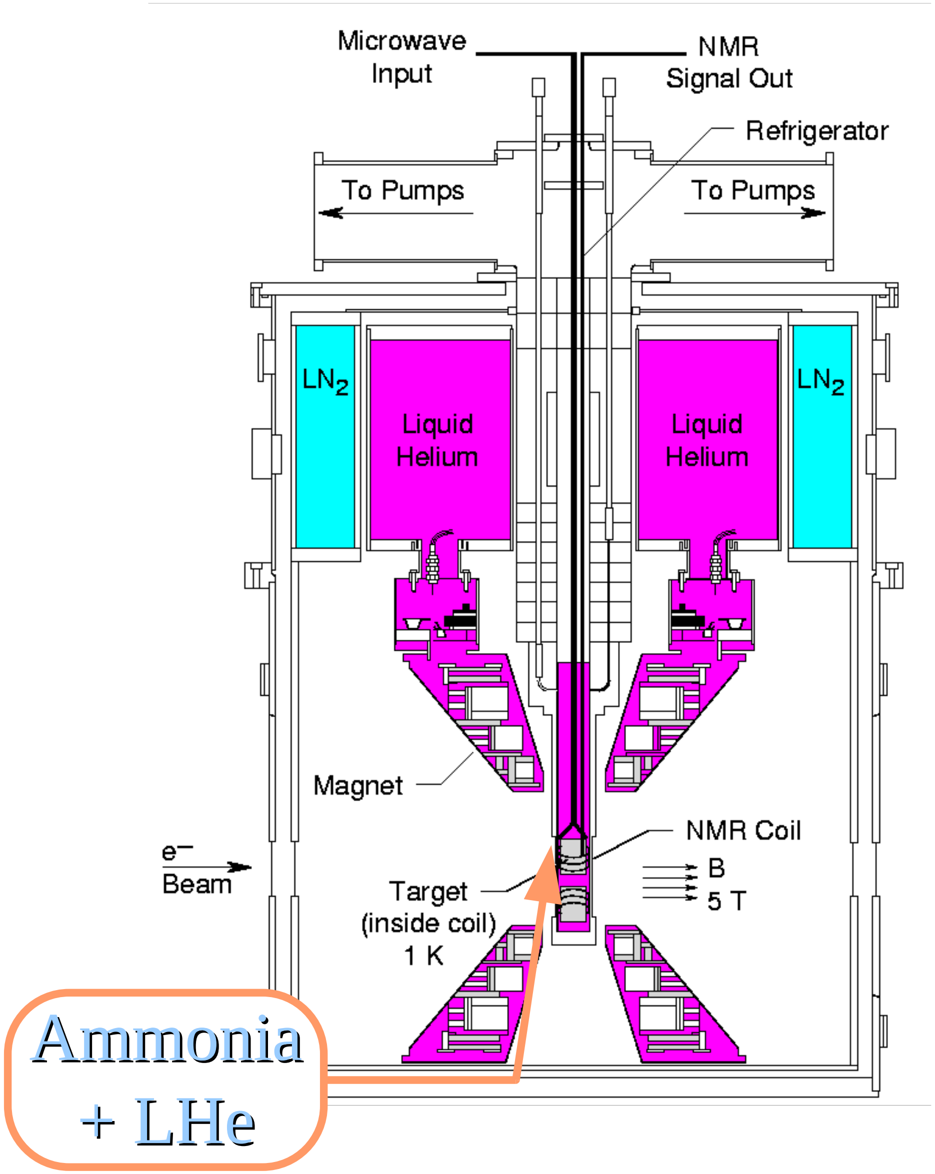


Big Electron Telescope Array – BETA

- **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*
- Damaged coils successfully repaired in Nov. '08 by JLab staff with Oxford Inst. help
- Down but not out.