Probing *Quark-Gluon* Interactions with Transverse Polarized Scattering

Oscar A. Rondón
University of Virginia

Quark Confinement and Hadron Structure IX
UC Madrid
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Polarized Inclusive Scattering:
Structure Functions, Twists, Moments

Polarized Inelastic lepton-nucleon Scattering

- The nucleonic component of inclusive inelastic scattering of polarized charged leptonic beams on polarized nucleons is represented by the anti-symmetric (spin dependent) part of the hadronic tensor

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

  - 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
  - target spin $S = (0, \boldsymbol{S})$, $\boldsymbol{S}/|S| = (\sin\theta_N \cos\phi_N, \sin\theta_N \sin\phi_N, \cos\theta_N)$
  - Two polarized structure functions $\boldsymbol{G_1}(\nu, Q^2)$ and $\boldsymbol{G_2}(\nu, Q^2)$
- The beam polarization comes in through the anti-symmetric leptonic tensor, for lepton mass m and spin s

$$L^A_{\mu\nu} = m\epsilon_{\mu\nu\lambda\sigma} s^\lambda (k - k')^\sigma$$

G_1 and G_2 in DIS

- $\boldsymbol{G_1}$ and $\boldsymbol{G_2}$, along with the unpolarized $\boldsymbol{W_1}$ and $\boldsymbol{W_2}$, contain all the information on nucleon structure that can be extracted from inclusive inelastic electromagnetic scattering
- 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)

$$\lim_{Q^2,\nu\to\infty} M^2\nu\, G_1(\nu,Q^2)=g_1(x) \qquad \lim_{Q^2,\nu\to\infty} M\, W_1(\nu,Q^2)=F_1(x)$$

$$\lim_{Q^2,\nu\to\infty} M\,\nu^2 G_2(\nu,Q^2)=g_2(x) \qquad \lim_{Q^2,\nu\to\infty} \nu\, W_2(\nu,Q^2)=F_2(x)$$

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

- In the quark parton model $\boldsymbol{g_1}$ and $\boldsymbol{F_1}$ are also related to PDF's:

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

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

Operators and structure functions - I

- The hadronic tensor W is related to the forward Compton amplitude
  - $W = 1/2\pi \, \mathrm{Im} \, T$
- Two types of operators, corresponding to two Feynman diagrams, contribute to the Compton amplitude at the same order
  - twist-2 operators which correspond to the familiar handbag diagram
  - twist-3 operators which correspond to *qgq* correlations

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

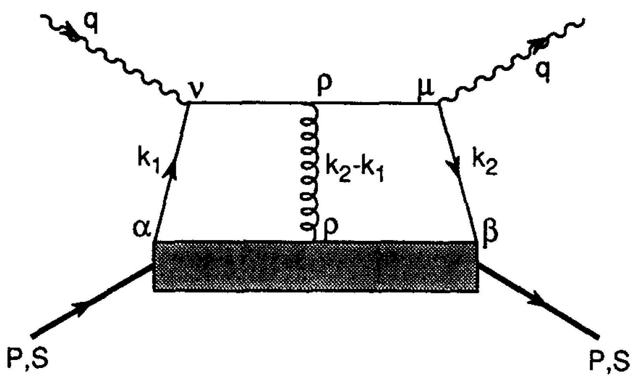

Fig. 10.3. DIS interaction involving quark-gluon correlation.

Operators and structure functions - II

- The Operator-Product Expansion (OPE) relates the Cornwall-Norton - CN moments of $\boldsymbol{g_1}$ and $\boldsymbol{g_2}$ to the twist-2 and twist-3 matrix elements $\boldsymbol{a}_{\mathrm{N}}$ and $\boldsymbol{d}_{\mathrm{N}}$

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

$$\Gamma_2^{(N)} = \int_0^1 x^N g_2(x, Q^2)\, dx = \frac{N}{2(N+1)} (\boldsymbol{d}_N - \boldsymbol{a}_N) + O(M^2/Q^2), \quad N = 2, 4, \ldots$$

- twist-3 $\boldsymbol{d}_2$ – mean color-magnetic field along spin – from second moments

- At low-moderate Q^2 Nachtmann, not CN, moments are needed to obtain dynamic twist-3 matrix elements free of target mass effects to $O(M^8/Q^8)$

$$\boldsymbol{d}_2^{Nacht.}(\boldsymbol{Q^2}) = \int_0^1 dx\, \xi^2 \left(2 \frac{\xi}{x} g_1 + 3 \left(1 - \frac{\xi^2 M^2}{2 Q^2}\right) g_2 \right) \Rightarrow_{Q^2 \to \infty} \int_0^1 dx\, x^2 (2 g_1 + 3 g_2)$$

$$\xi = 2x / \left(1 + \sqrt{[1 + (2xM)^2 / Q^2]}\right)$$

Spin Structure Function g_2

- No simple interpretation for g_2 in the parton model as for leading twist g_1
- Measured g_2 can be decomposed into g_1 dependent part (twist-2 Wandzura-Wilczek g_2^{WW}) and twist-3 pieces

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

- h_T is twist-2 chiral odd transversity; ξ represents q-g correlations (twist-3)
- There is no OPE rule for first moment $\Gamma_2^{(0)}$

Spin Dependent Scattering: a Window on twist-3 and *quark-gluon* Interactions

- To separate G_1 and G_2 measure cross section differences for opposite beam helicities with target spins parallel and transverse to the beam

$$\Delta\sigma(\theta,\theta_N,\phi)=\frac{4\alpha^2 E'}{Q^2 E}\left[(E\cos\theta_N+E'\cos\alpha)M\,G_1+2EE'(\cos\alpha-\cos\theta_N)G_2\right]$$

$\cos\alpha=\sin\theta_N\sin\theta\cos\phi+\cos\theta_N\cos\theta,\ \ (\theta,\phi: \textit{final lepton angles})$

- parallel spins: $\cos\alpha=\cos\theta\rightarrow G_1$ dominates

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

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$$\cos\alpha=\sin\theta_N\sin\theta\cos\phi+\cos\theta_N\cos\theta,\quad (\theta,\phi: \textit{final lepton angles})$$

- transverse spins: $\cos\alpha=\sin\theta\cos\phi\rightarrow$ G_1 and G_2 contribute

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

  - model independent separation of g_1 and g_2
  - direct access to twist-3 via g_2: <u>interacting *qg* is first step to confinement</u>
  - "*Unique feature of spin-dependent scattering*" (R. Jaffe)

Experiment

RSS - *R*esonances *S*pin *S*tructure

Precision Measurement of the Nucleon Spin Structure Functions in the Region of the Nucleon Resonances

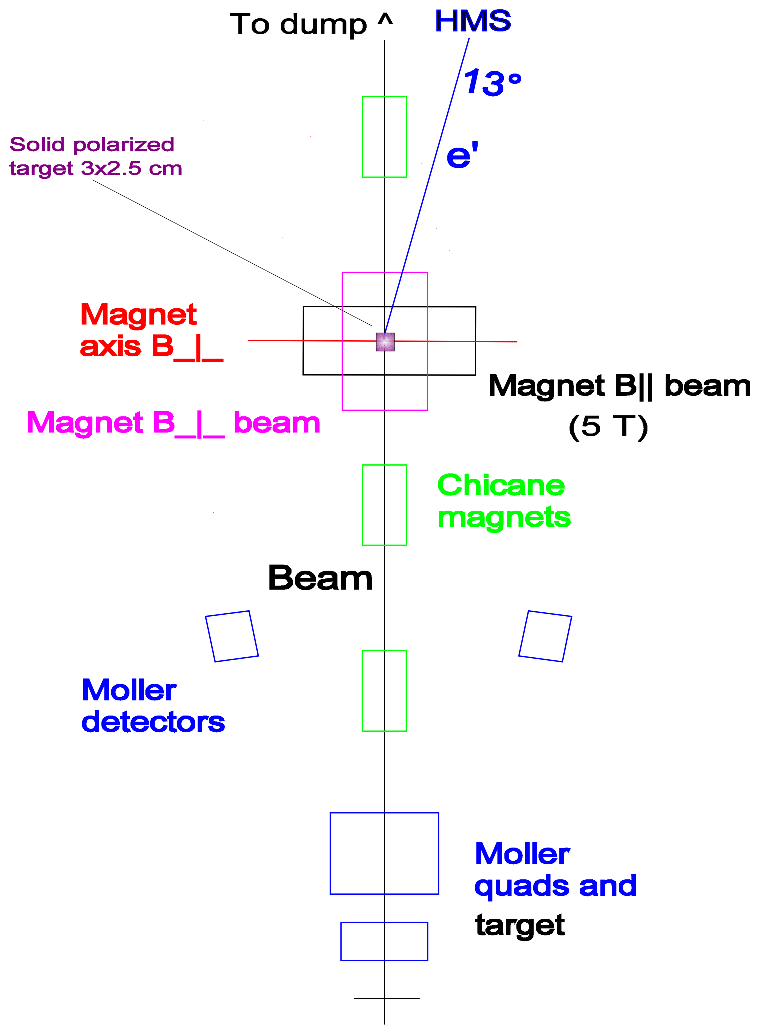
TJNAF E01-006
U. Basel, Florida International U., Hampton U., U. Massachusetts, U. Maryland, Mississippi S. U., North Carolina A&T U., U. of N. C. at Wilmington, Norfolk S. U., Old Dominion U., S.U. New Orleans, U. of Tel-Aviv, TJNAF, U. of Virginia, Virginia P. I. & S.U., Yerevan Physics I.

Spokesmen: Oscar A. Rondon (U. of Virginia) and Mark K. Jones (Jefferson Lab)

- Measure ***proton*** and ***deuteron*** spin asymmetries $\mathbf{A_1}(W, Q^2)$ and $\mathbf{A_2}(W, Q^2)$ at $Q^2 \approx 1.3$ GeV^2 and $0.8 \leq W \leq 1.91$ GeV
- Goals: study W dependence of asymmetries, onset of polarized local duality, and twist-3 effects, using inclusive polarized scattering

RSS Technique

- CEBAF polarized electron beam
  - 5.755 GeV- 66 to 71% polarization
  - 1 cm radius raster, I = 85-150 nA
- Target: polarized ammonia NH_3, ND_3.
  - Luminosity ~10^{35} $s^{-1}cm^{-2}$
  - In-beam polarization: 70% (*p*), 20% (*d*)
- Jefferson Lab Hall C High Momentum Spectrometer (HMS)
- Kinematics
  - Final state mass $0.8 \leq W \leq 1.91$ GeV
  - $\langle Q^2 \rangle = 1.28$ GeV^2; $\Delta Q^2 = \pm\, 0.21$ GeV^2



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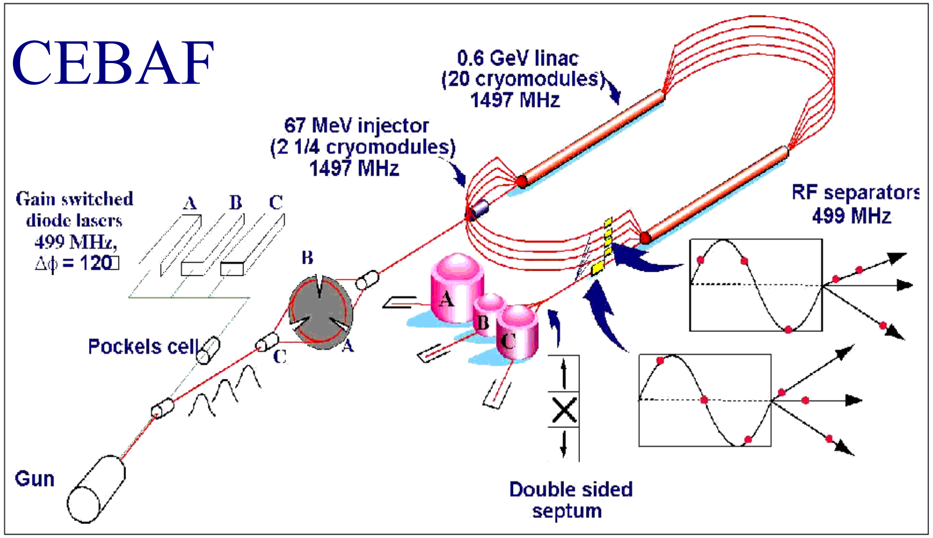


Measured asymmetries $A_{\parallel}$, $A_{\perp}$

$$A_{\parallel,\perp} = \left(\frac{\epsilon}{f P_b P_t C_N} + C_D\right) + A_{rc}$$

$$\epsilon = (N^- - N^+)/(N^- + N^+)$$

- N^-, N^+ = charge normalized, dead time and pion corrected yields for +/- beam helicities
- P_b, P_t = beam, target polarizations
- f = dilution factor
- C_N, C_D = polarized nucleons in $^{15,14}N$
  - proton $C_D = 0$, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction

Spin Asymmetries and Structure Functions

- Combine $\mathbf{A}_{\|}$, $\mathbf{A}_{\perp}$ to get virtual Compton absorption asymmetries

$$A_1 = \frac{1}{(E+E')D'}\left((E-E'\cos\theta)A_{\|} - \frac{E'\sin\theta}{\cos\phi}A_{\perp}\right)$$

$$A_2 = \frac{\sqrt{Q^2}}{2ED'}\left(A_{\|} + \frac{E-E'\cos\theta}{E'\sin\theta\cos\phi}A_{\perp}\right)$$

- Get g_1, g_2 from A_1, A_2 and F_1

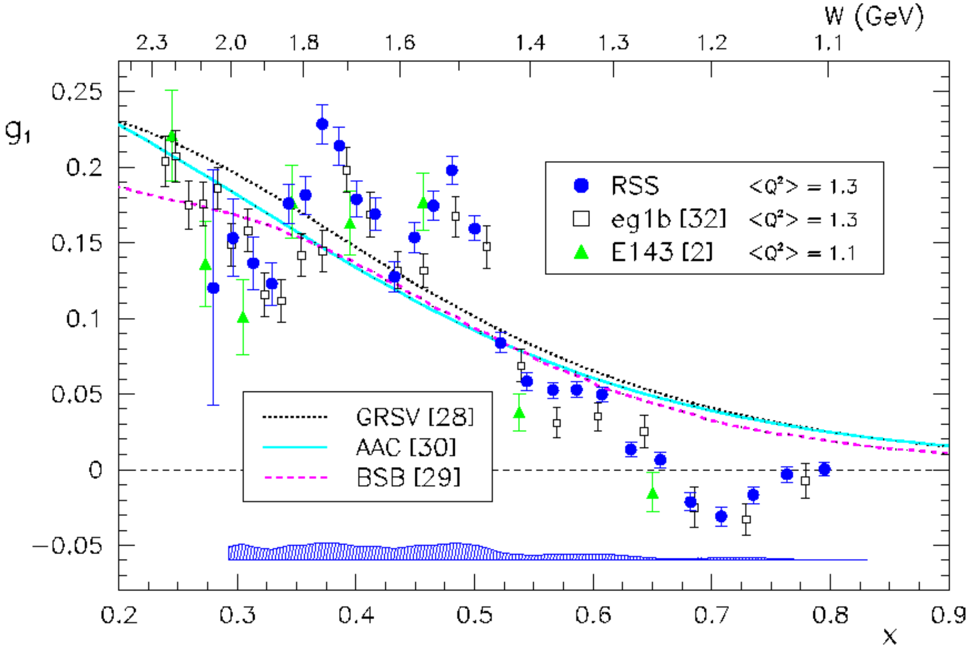
$$g_1 = \frac{F_1}{1+\gamma^2}(A_1 + \gamma A_2)$$

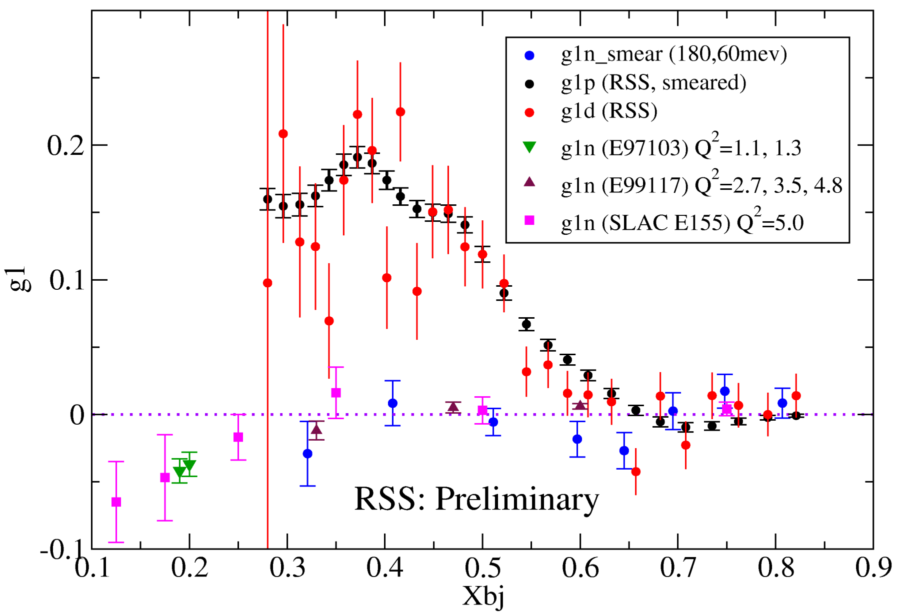
$$g_2 = \frac{F_1}{1+\gamma^2}\left(\frac{A_2}{\gamma} - A_1\right); \quad \gamma = \frac{2xM}{\sqrt{Q^2}}$$

- Minimal model dependence
  - $D'(E,E',\theta,R)$ is function only of kinematics and $R = \sigma_L/\sigma_T$
  - R, F_1: proton fit to Hall C *e-p* data (E. Christy); deuteron fit to world data (P. Bosted)

Results

RSS Spin Structure Functions $g_1^{p,d}$

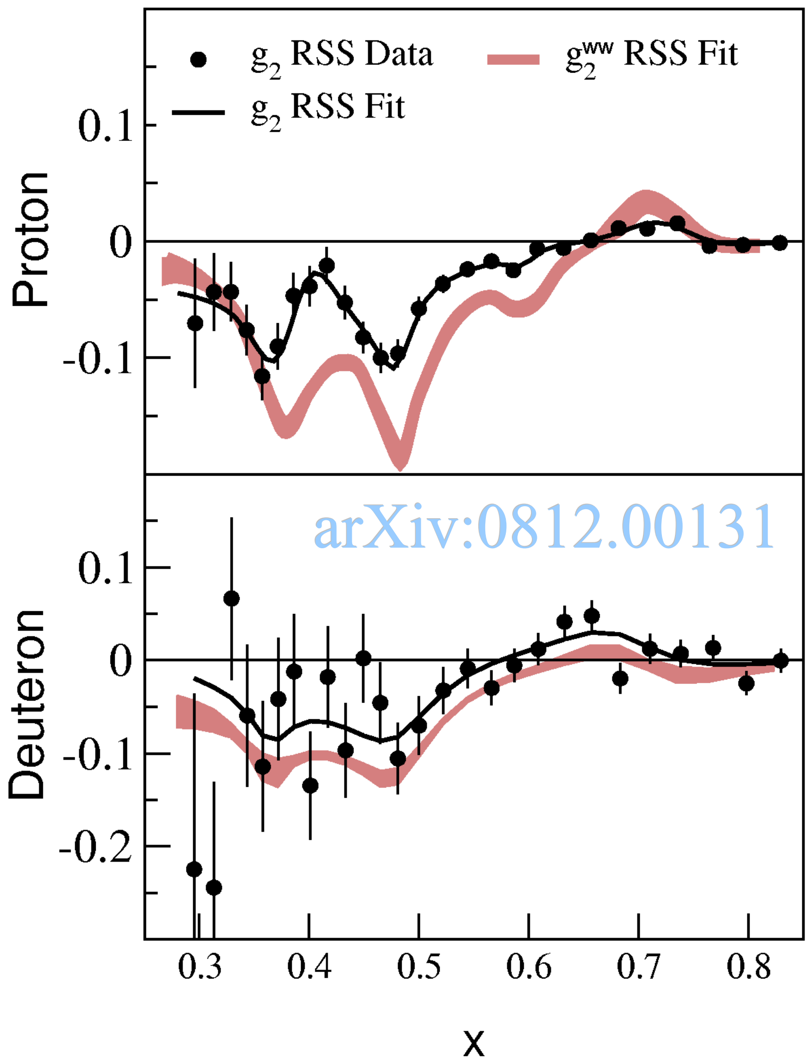




F. Wesselmann *et al*., Phys.Rev.Lett. **98**, 132003 (2007) (including spin asymmetries $\mathbf{A_1}$, $\mathbf{A_2}$)

In preparation

g_2 Spin Structure Functions



- First world data for $g_2^{p,d}$ in the resonances
- g_2^{WW} computed using *RSS* fit to g_1 point by point
- HT $\overline{g}_2$(low x) $\cong 0$ within errors
  - $\overline{g}_2(x < x_{min} = 0.317) = 0 \pm \delta\overline{g}_2$
  - systematic error $\delta\overline{g}_2$ estimated by extrapolating fit errors $\delta\overline{g}_2(x_{min})$ to $x = 0$

Moments of g_1 and g_2

- Split SSF's in three regions:
  - unmeasured $x < x_{min}$ (= 0.317); suppresed by x^2 weight (possible divergence $g_2(x \to 0)$ does not affect 3rd moment)
  - measured $x_{min} < x < x_{inel.threshold}$ (=0.82)
  - elastic (quasi-el. for deuteron)
- $<Q^2> = 1.28$ GeV^2
- Calculated CN and Nachtmann moments in each region
- Errors are total (quadratic sums)
- Neutron moments approximated as D-state corrected deuteron minus proton (good to $O(1\%)$)

$$\Gamma^n = \frac{1}{\gamma_D} \Gamma^d - \Gamma^p$$

$$\gamma_D = 0.926 \text{ (D-state)}$$

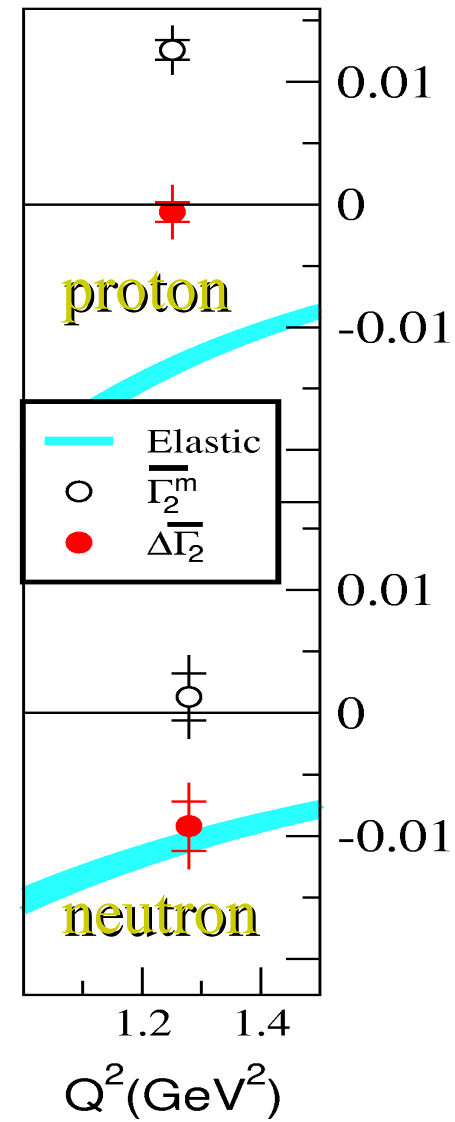
d_2: Third Moments

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

- Observe twist-3 to better than 6 sigmas for proton, 3 sigmas for neutron
- Large contribution of kinematic higher twists in CN (target mass effect):
  - ratios Nachtmann/CN < 1
- Detailed, extensive tables for Γ_1, $\Gamma_2^{(3)}$ for *p*, *d*, *n* and non-singlet (Bjorken S.R.) to appear in PRL Sep. 3 issue (arXiv:0812.00131, K. Slifer, O. R., *et al.*)

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?



Outlook for Transverse Polarized Scattering: Near Term

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

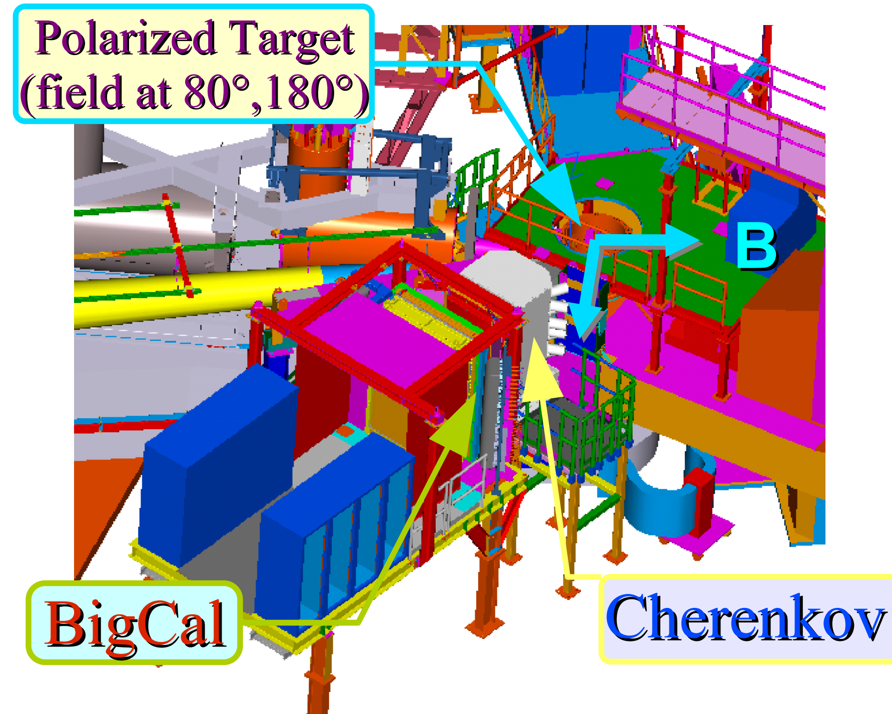
Measure inclusive double polarization near-orthogonal asymmetries to:

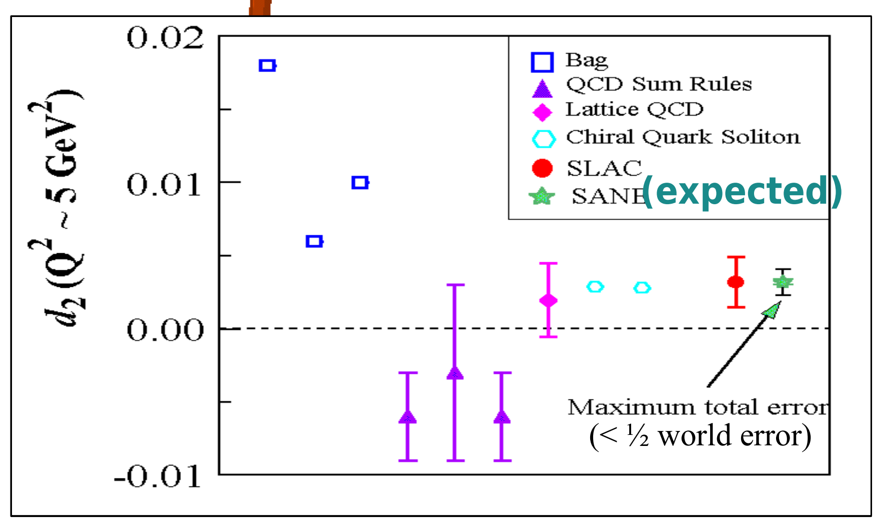
- access ***quark-gluon*** correlations using LO twist-3 effects (d_2 quark matrix element)
- compare with Lattice QCD, QCD sum rules, bag model, chiral quarks
- test nucleon models (x dependence) and Q^2 evolution
- explore $A_1(x \rightarrow 1)$; test polarized local duality

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





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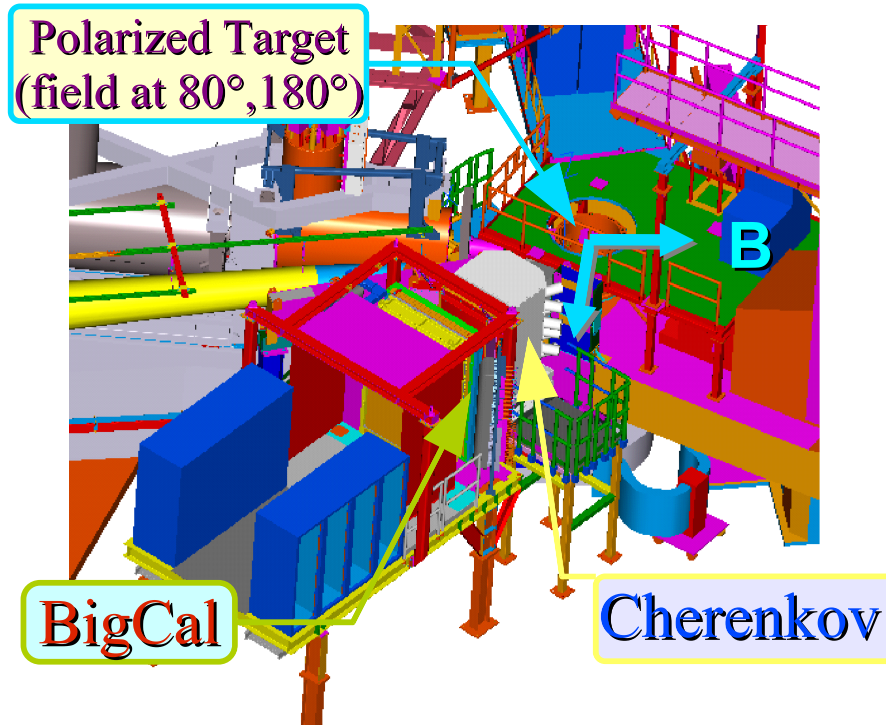
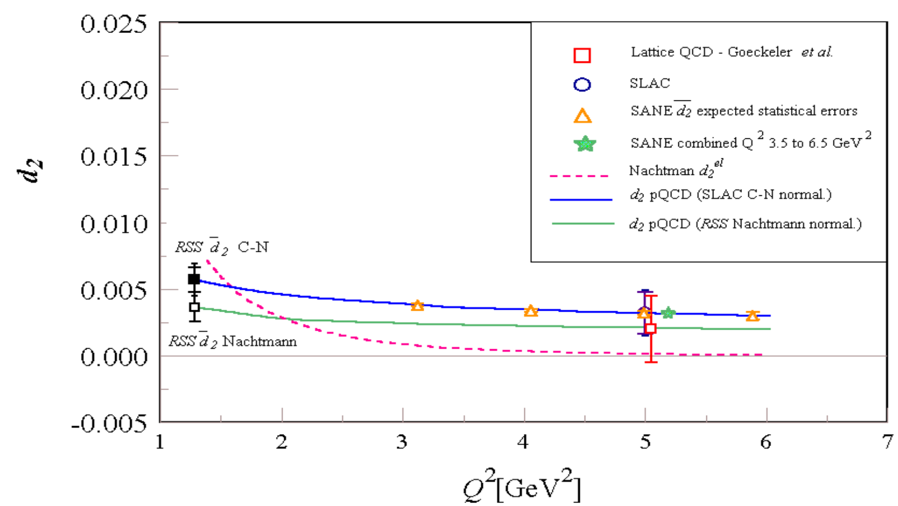
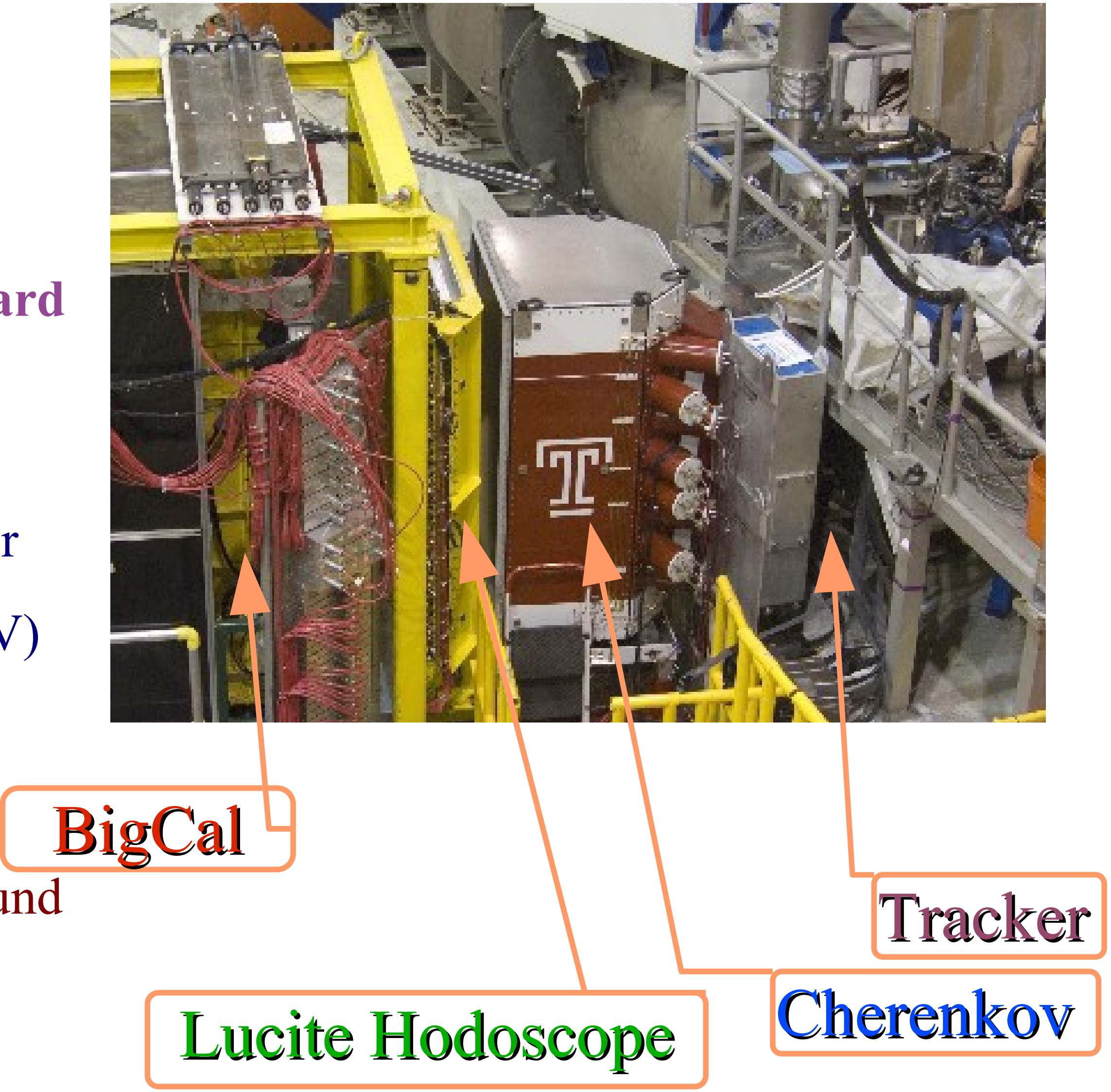


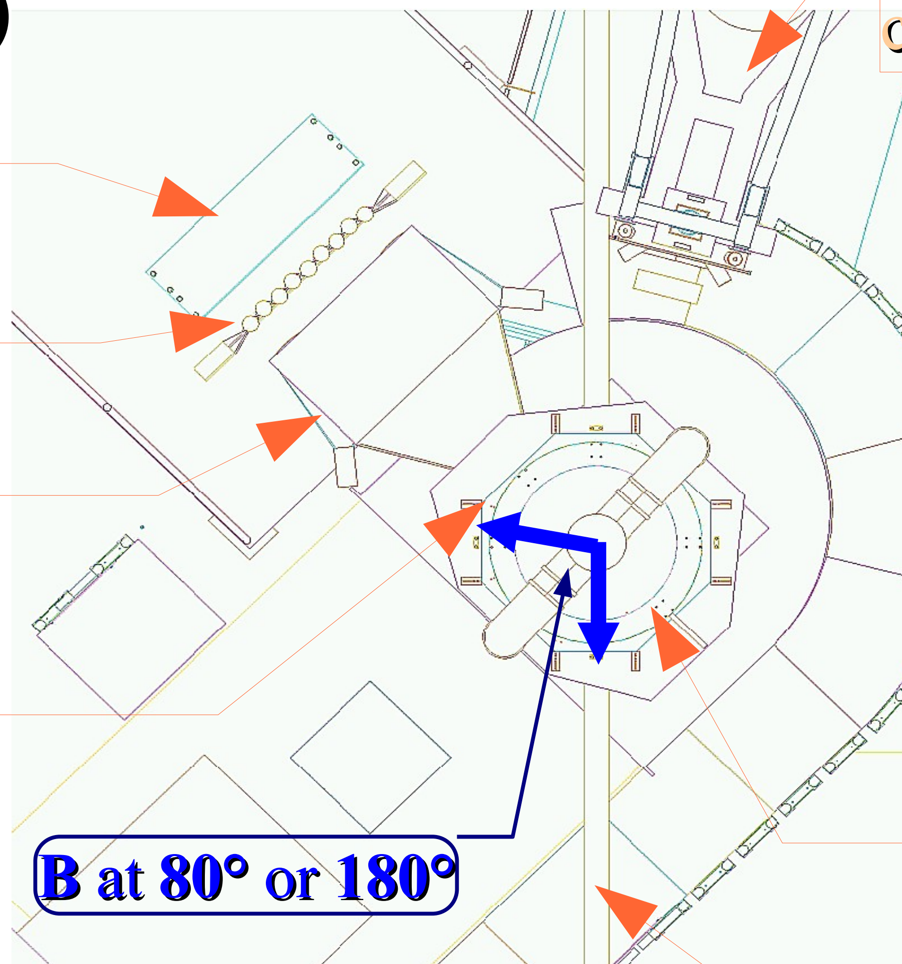


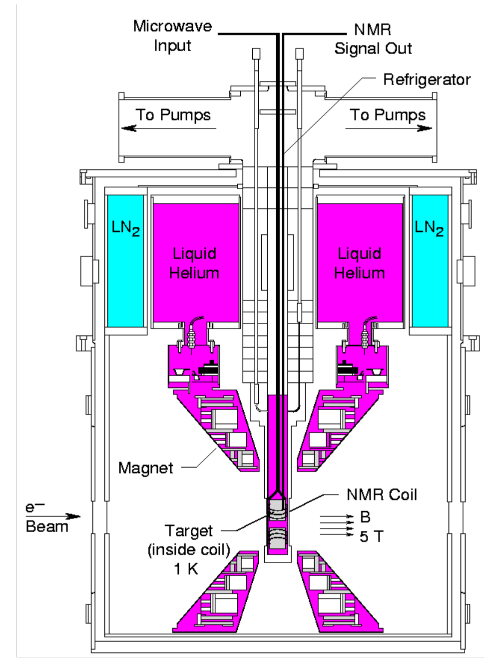
Big Electron Telescope Array – BETA

- **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 $9\%/\sqrt{E}$(GeV)
  - 1000:1 pion rejection
  - angular resolution ~ 1 mr
- Target field sweeps low *E* background
  - 180 MeV/c cutoff

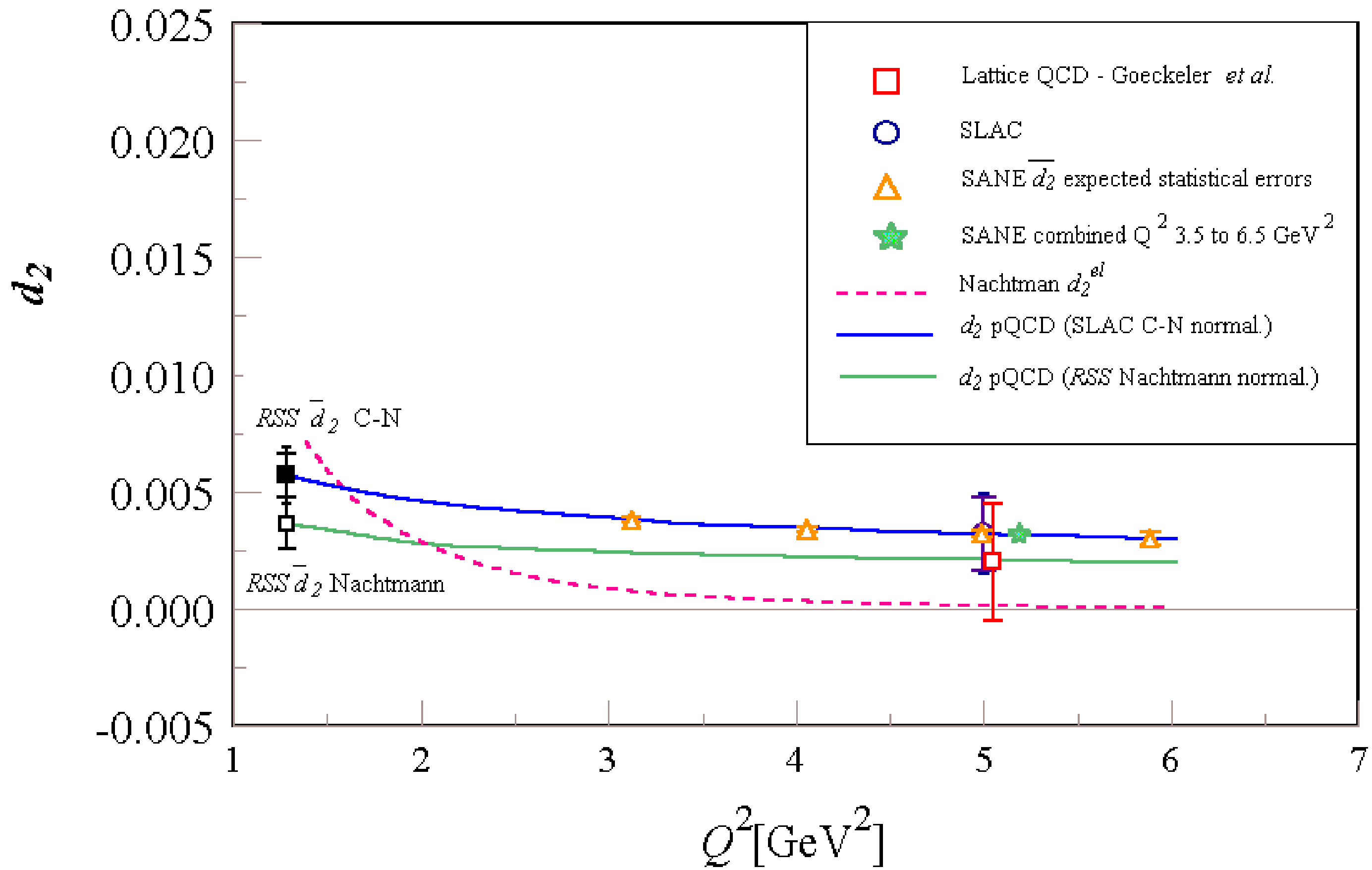


SANE Layout


BETA (40°)
BigCal
Lucite Hodoscope
Gas Cherenkov
Forward Hodoscope
B at 80° or 180°
HMS (15°- 42°) calibrations, backgd.
Polarized Target
Beam Line


Microwave Input
NMR Signal Out
Refrigerator
To Pumps
To Pumps
LN_2
LN_2
Liquid Helium
Liquid Helium
Magnet
NMR Coil
e⁻ Beam
Target (inside coil) 1 K
B 5 T

Sample of SANE Expected Results

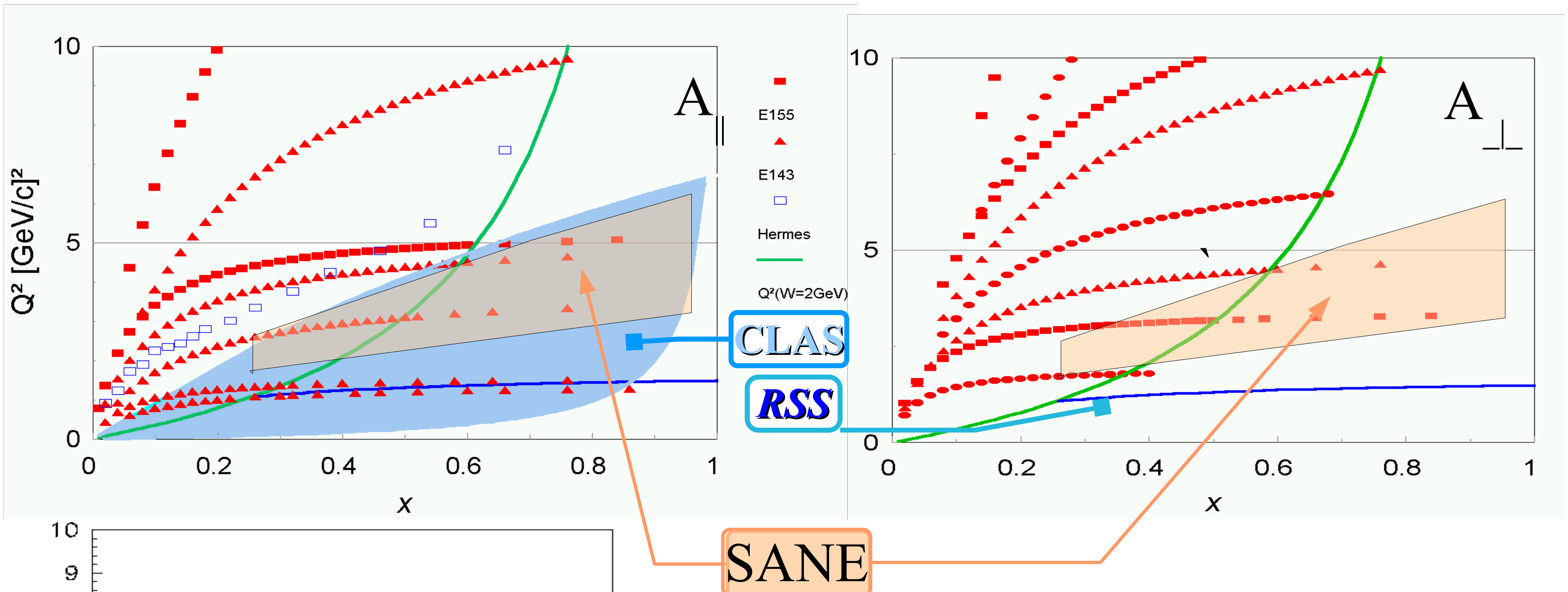


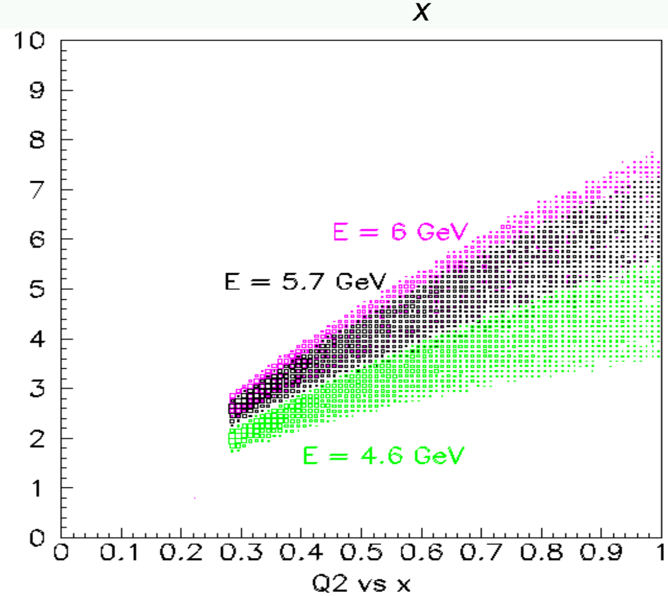
SANE expected statistical errors

for $\overline{d}_2 = \int_{xmin}^{xmax} x^2 (2g_1 + 3g_2)dx$

Q^2 GeV^2	x_{min} - x_{max} Projected	$\delta d_2/d_2$ Projected
2.5 - 3.5	.29 - .71	4.6%
3.5 - 6.5	.41 - .84	3.2%

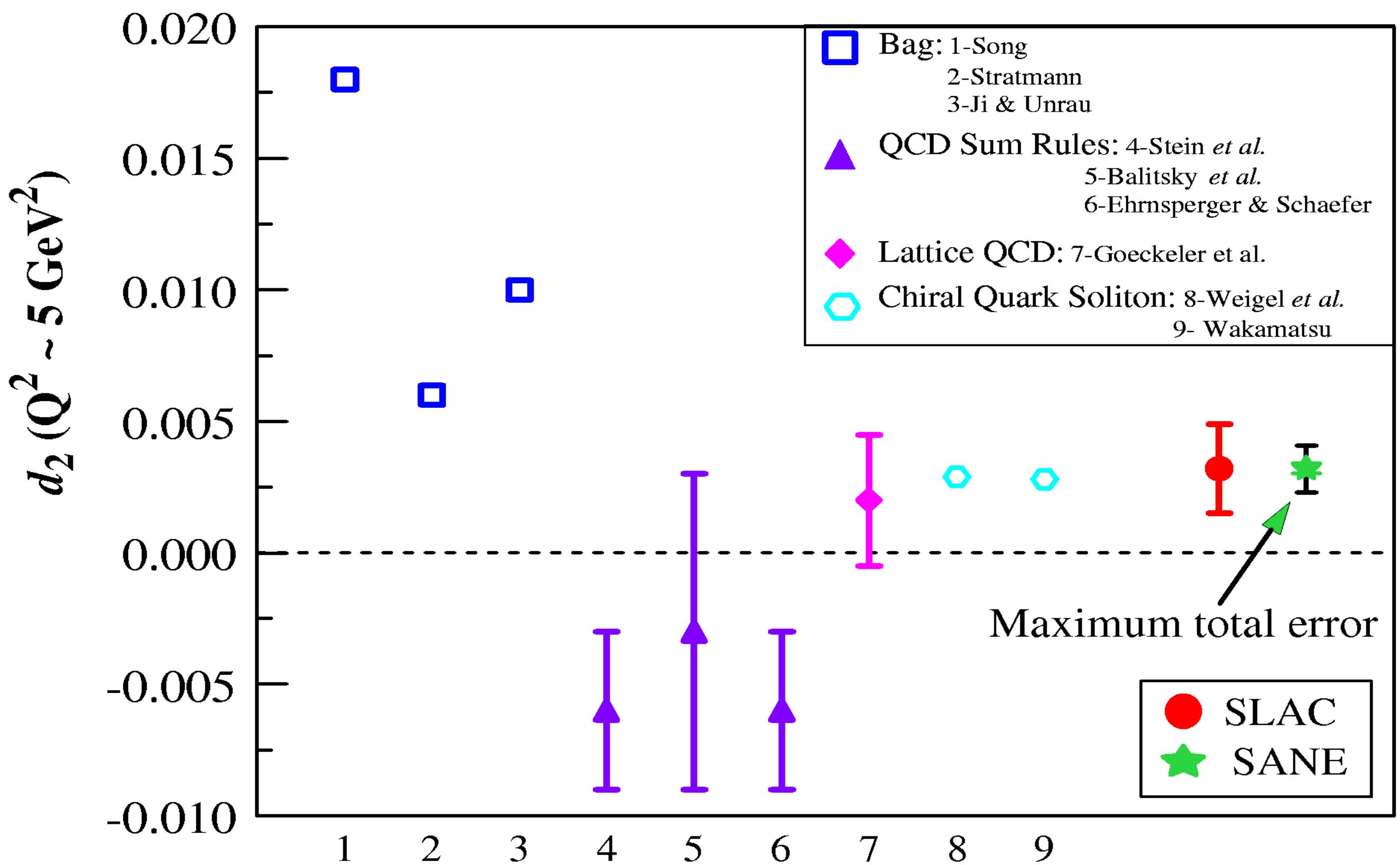
World data on $A_{\|}$, $A_{\perp}$ and SANE kinematics



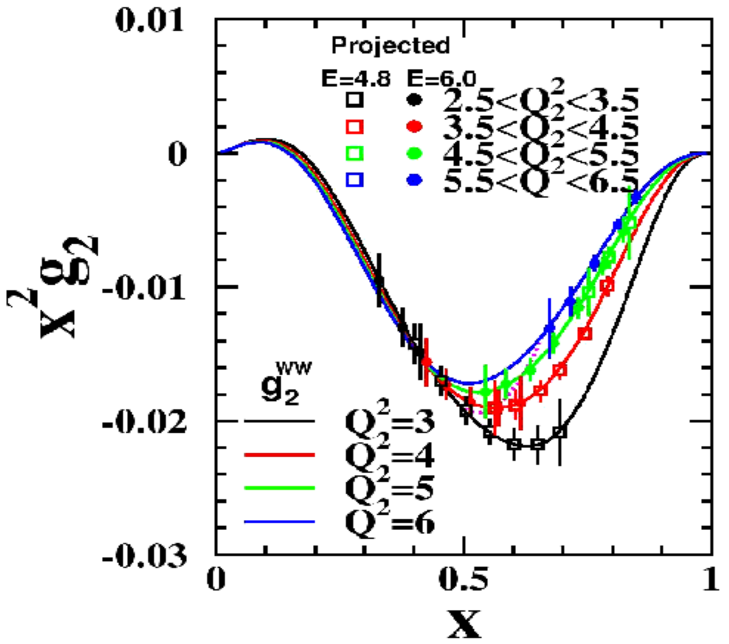


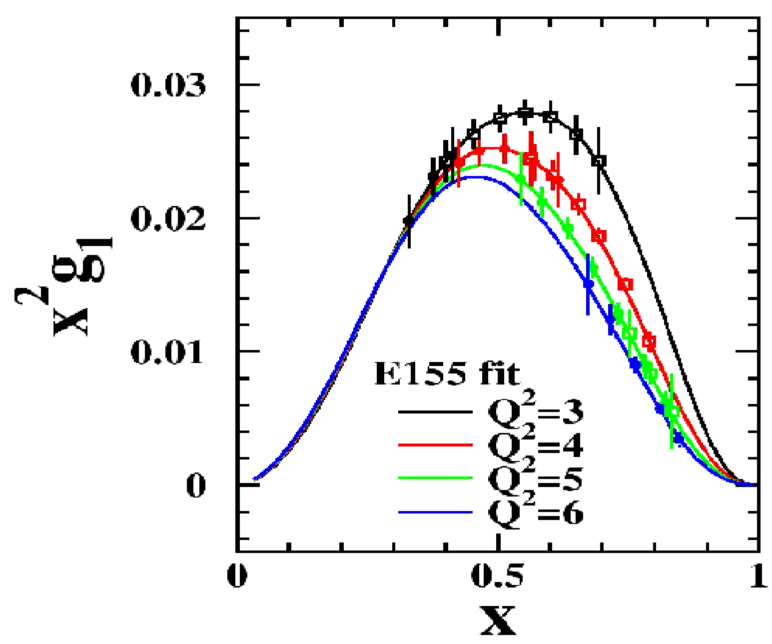
- Two beam energies: **5.9 GeV**, **4.7 GeV**
- Very good high ***x*** coverage with detector at 40°

SANE Expected Results (Ia)



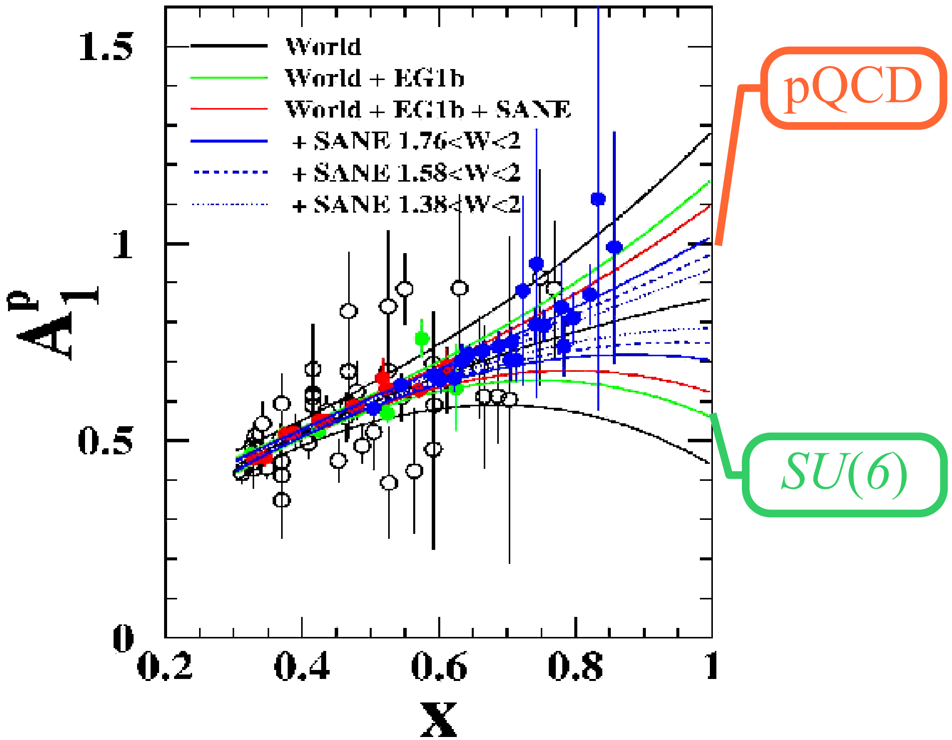
SANE Expected Results (II)

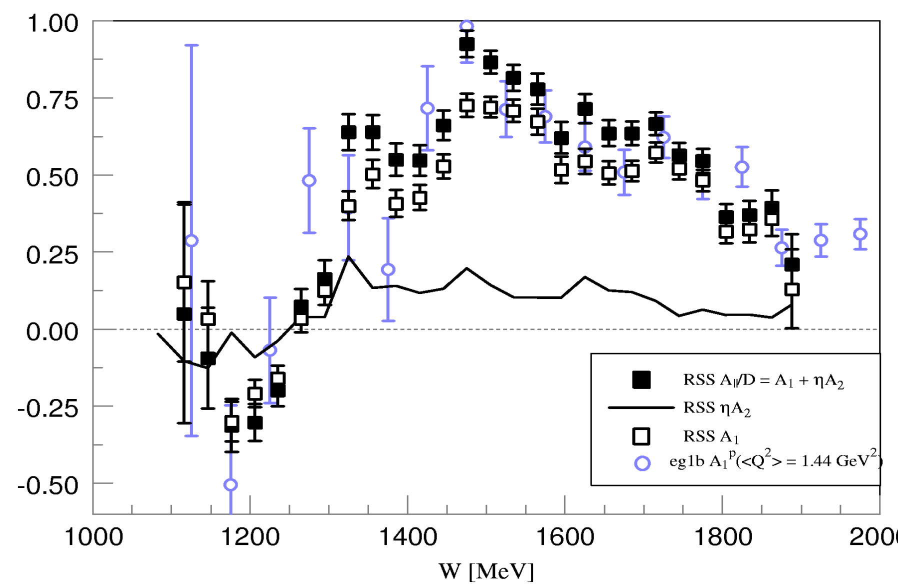




- ***x*** dependence at constant ***Q^2*** and ***Q^2*** dependence at fixed ***x*** (illustrative binning only)
- data are concentrated in the region most sensitive to ***$x^2g_{2,1}$***
  - (estimates based on 75% beam and target polarization, and 85 nA beam current)

SANE Expected Results (III)





- Constrain extrapolations of $\mathbf{A_1^p}$ to $x = 1$ within +/- 0.1 (using duality)
- Both $\mathbf{A_\parallel}$ and $\mathbf{A_\perp}$ are required to get accurate, model-free $\mathbf{A_1}$: $\mathbf{A_2} > 0$
- SANE's measured $\mathbf{A_2}$ will contribute to improve world's $\mathbf{A_1}$ data set

SANE Beam Time

	Energy	θ_N	Time (Proposal FOM h)		
	GeV		**Proposal**	**Actual**	**fraction**
Calibration	2.4	off, 0, 180	47	25	53%
Production	4.7	180	70	31	44%
	4.7	80	130	103	80%
	5.9	80	200	151	75%
	5.9	180	100	40	40%
Total production			500	325	65%

SANE Collaboration (E-07-003)

P. Solvignon
Argonne National Laboratory, Argonne, IL

E. Brash, **P. Carter, A. Puckett, M. Veilleux**
Christopher Newport University, Newport News, VA

W. Boeglin, P. Markowitz, J. Reinhold
Florida International University, Miami, FL

I. Albayrak, O. Ates, C. Chen, E. Christy, C. Keppel,
M. Kohl, **Y. Li**, **A. Liyanage**, P. Monaghan, **X. Qiu**,
L. Tang, **T. Walton**, **Z. Ye,** L. Zhu
Hampton University, Hampton, VA

P. Bosted, J.-P. Chen, S. Covrig, W. Deconink, A. Deur,
C. Ellis, R. Ent, D. Gaskell, J. Gomez, D. Higinbotham,
T. Horn, M. Jones, D. Mack, G. Smith, S. Wood
Thomas Jefferson National Accelerator Facility, Newport News, VA

J. Dunne, D. Dutta, **A. Narayan, L. Ndukum, Nuruzzaman**
Mississippi State University, Jackson. MI

A. Ahmidouch, S. Danagoulian, **B. Davis, Martin Jones**
North Carolina A&M State University, Greensboro, NC

M. Khandaker
Norfolk State University, Norfolk, VA

A. Daniel, P.M. King, J. Roche
Ohio University, Athens, OH

A.M. Davidenko, Y.M. Goncharenko, V.I. Kravtsov,
Y.M. Melnik, V.V. Mochalov, L. Soloviev, A. Vasiliev
Institute for High Energy Physics, Protvino, Moscow Region, Russia

C. Butuceanu, G. Huber
University of Regina, Regina, SK

V. Kubarovsky
Rensselaer Polytechnic Institute, Troy, NY

L. El Fassi, R. Gilman
Rutgers University, New Brunswick, NJ

S. Choi, **H-K. Kang**, **H. Kang**, **Y. Kim**
Seoul National University, Seoul, Korea

M. Elaasar
State University at New Orleans, LA

W. Armstrong, D. Flay, Z.-E. Meziani, **M. Posik,**
B. Sawatzky, **H. Yao**
Temple University, Philadelphia, PA

O. Hashimoto, D. Kawama, **T. Maruta,**
S. Nue Nakamura, **G. Toshiyuki**
Tohoku U., Tohoku, Japan

K. Slifer
University of New Hampshire

H. Baghdasaryan, M. Bychkov, D. Crabb, D. Day, E. Frlez,
O. Geagla, N. Kalantarians, **K. Kovacs,** N. Liyanage,
V. Mamyan, J. Maxwell, J. Mulholland, D. Pocanic,
S. Riordan, O. Rondon, M. Shabestari
University of Virginia, Charlottesville, VA

L. Pentchev
College of William and Mary, Williamsburg, VA

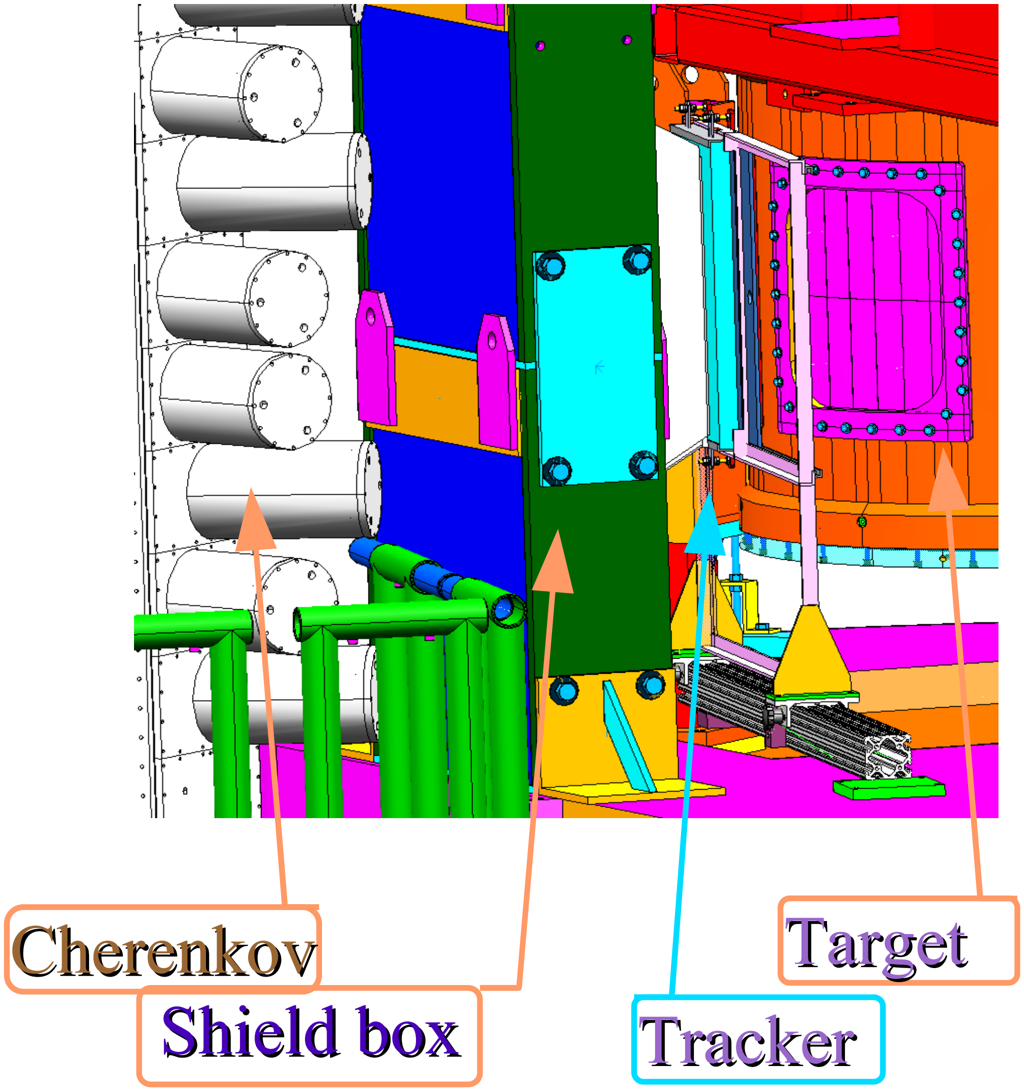
F. Wesselmann
Xavier Unniversity, New Orleans, LA

A. Asaturyan, H. Mkrtchyan, V. Tadevosyan
Yerevan Physics Institute, Yerevan, Armenia

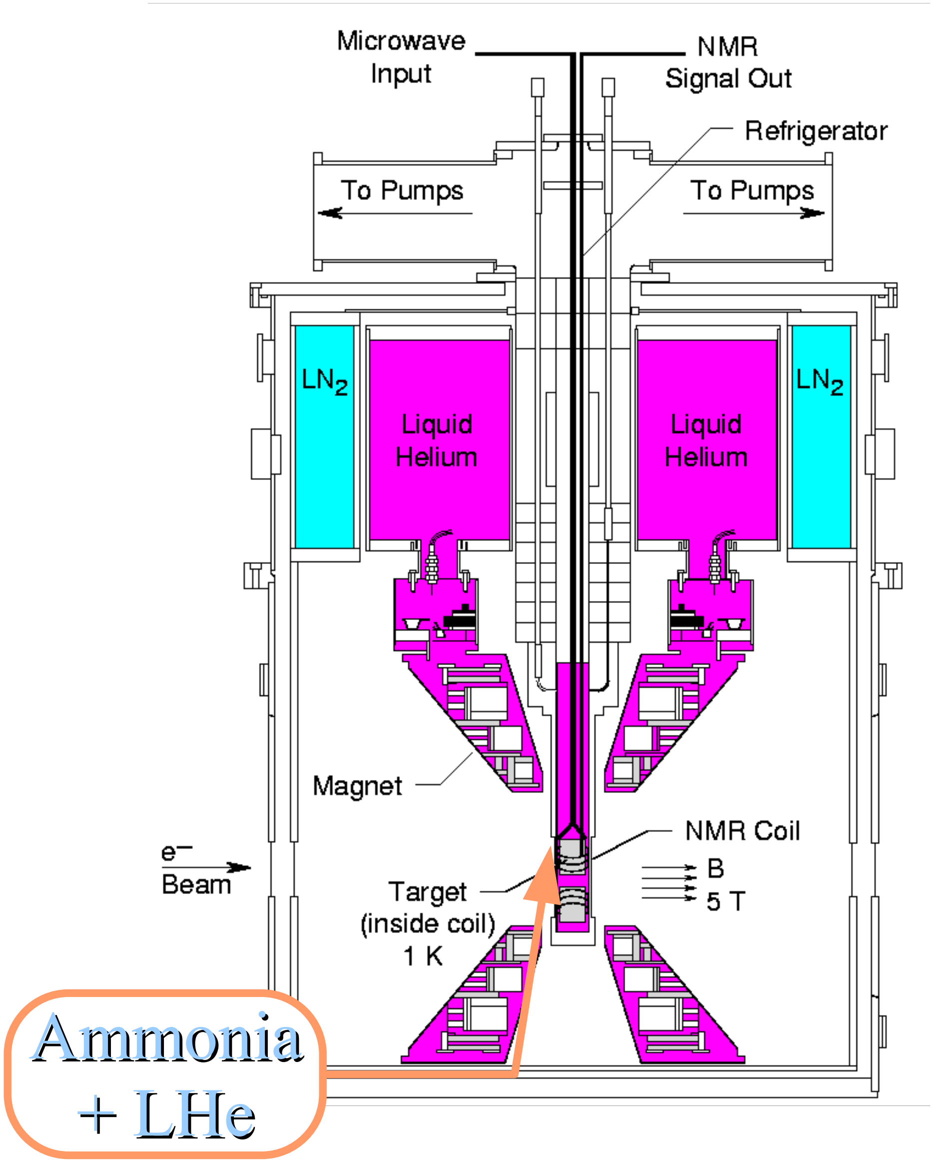
Ph.D. student, **M.S. Student**, **Student**

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's characteristics
  - Effective solid angle = 0.194 sr
  - Energy resolution $8\%/\sqrt{E}$(GeV)
  - 1000:1 pion rejection
  - vertex resolution ~ 5 mm
  - angular resolution ~ 1 mr
- Target field sweeps low E background
  - 180 MeV/c cutoff

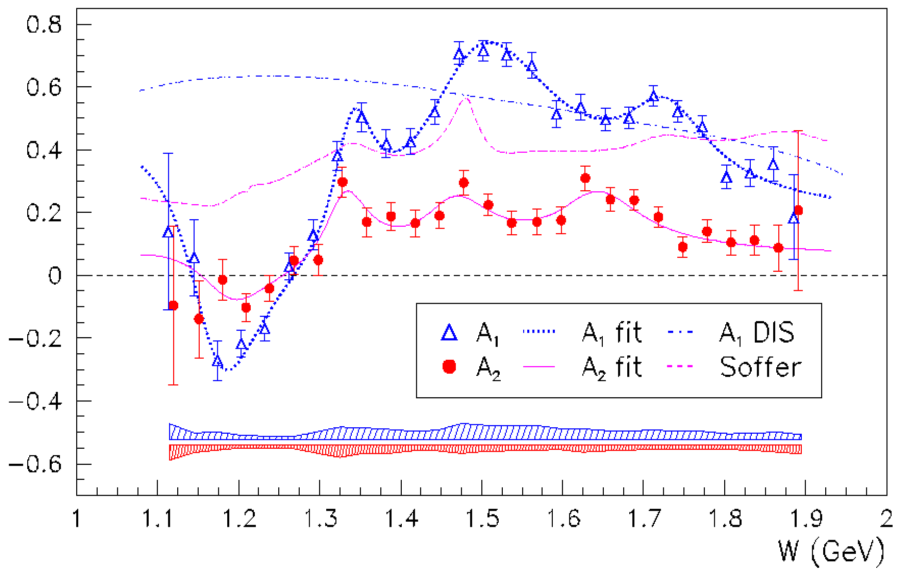


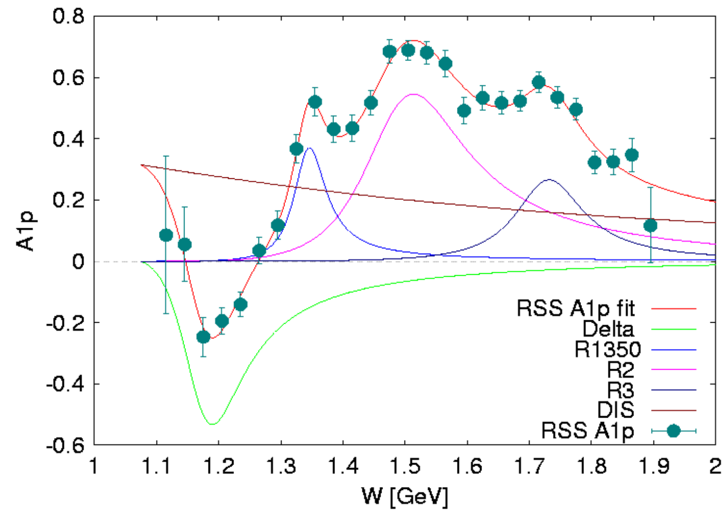
Polarized Target



- 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.

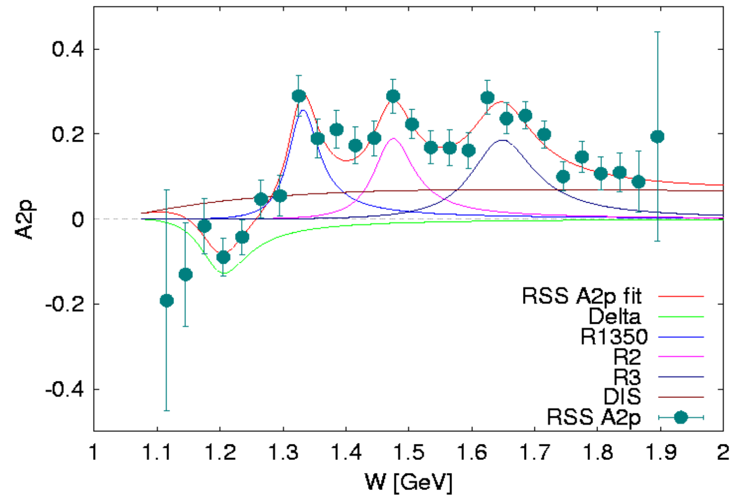
RSS Proton Spin Asymmetries



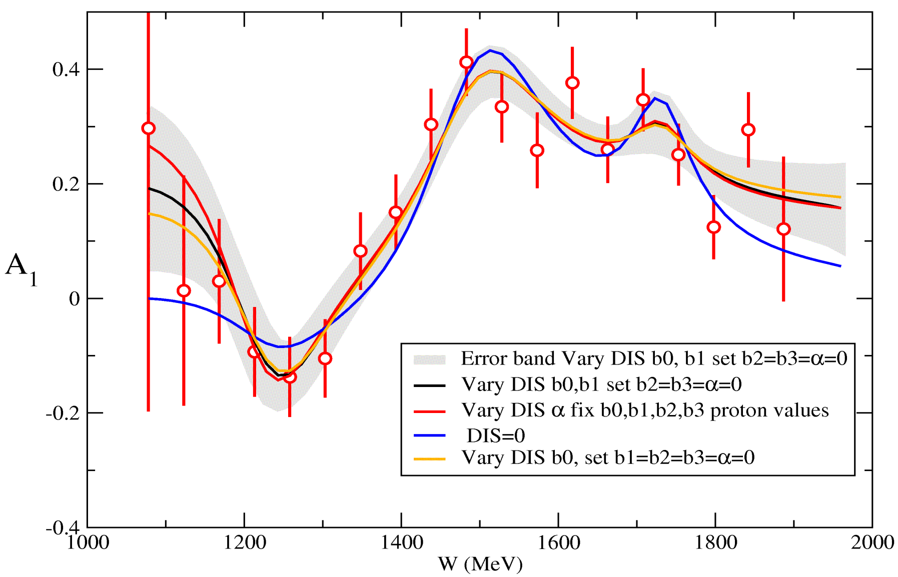


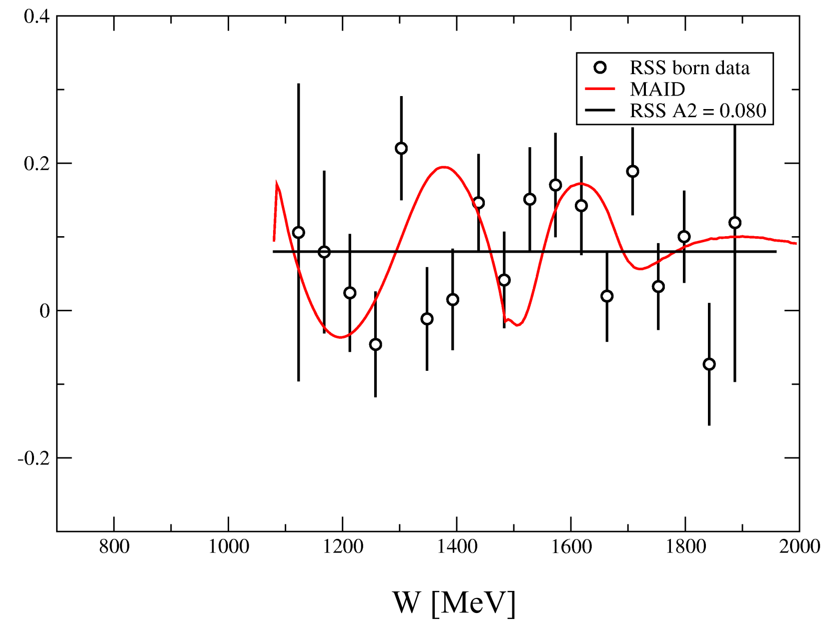
Fit $\mathbf{A}_1$ and $\mathbf{A}_2$ independently

- Four Breit-Wigner resonance shapes plus DIS background
- Reduced $\chi^2 = 1.2 - 1.4$ for 12 d.o.f.



RSS Deuteron Spin Asymmetries





- Fit deuteron $\mathbf{A_1}$ with three B-W resonances plus linear DIS
- Fit deuteron $\mathbf{A_2}$ with constant: $\mathbf{A_2} = 0.083$ +/- 0.017

Nachtmann moments and quark matrix elements

- Matrix elements representing interactions (higher twists) between quarks and gluons can be expanded in terms of Nachtmann moments
  - Free of target mass effects to $O(M^8/Q^8)$: **dynamic higher twists** can be extracted
  - Both $\boldsymbol{g_1}$ and $\boldsymbol{g_2}$ SSF's are needed: transverse asymmetry data (e.g. *RSS,* SANE)
  - Nachtmann moments reduce to conventional Cornwall-Norton (C-N) at high Q^2
  - Required at low momentum transfers: $Q^2 <\sim 5$ GeV² and for the higher moments dominated by high x contributions: $\boldsymbol{d_2}$(twist-3), $\boldsymbol{a_2}$(twist-2)

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

$$a_2^{Nacht.}(Q^2) = 2\int_0^1 dx\left(\frac{\xi^3}{x}\left[1-\frac{9}{25}\frac{\xi^2M^2}{Q^2}\right]g_1 - \frac{12}{5}\frac{x\xi M^2}{Q^2}g_2\right) \Rightarrow_{Q^2\to\infty} 2\int_0^1 dx\,x^2 g_1$$

$$\xi = 2x/\{1+\sqrt{[1+(2xM)^2/Q^2]}\}$$

S. Matsuda, T. Uematsu, NP B168 (1980) 181; A. Piccione, G. Ridolfi, NP B513 (1998) 301;
W.Melnitchouk, R. Ent, C, Keppel, Phys.Rept.406, 127, 2005. Y. B. Dong, PRC78:028201, 2008

Twist-3 operators

- The number of twist-3 operators increases with the order of the moment
- $\boldsymbol{d_n}$ notation is shorthand for $\tilde{d}_n = \sum_i d_i^n(\mu^2) E_{i,3}^n(Q^2/\mu^2, \alpha_s(\mu^2))$
  - d_i^n are the matrix elements, *i* is the spin index, *n* is the moment order
  - $E_{i,3}^n$ are twist-3 Wilson coefficients
- There is only one d_1^2, the one usually labeled $\boldsymbol{d_2}$
- There are three $d^4_{i=1,2,3}$ operators associated with the fifth moment
  - with precise data are available over a wide range of Q^2 the evolution equations for the 5th. moments could be solved to extract these higher spin twist-3 matrix elements (Ji and Chou, PRD 42, 3637 (1990))
  - 5th. moment dominated by high *x* data: Nachtmann moments required

Twist-2 and Twist-4

- TOP:
  - Ratio of Nachtmann to CN moments of twist-2 $\boldsymbol{a_2}$ matrix element: proton and deuteron sensitive to kinematic twists
- BOTTOM
  - Difference between the extracted values of the twist-4 $\boldsymbol{f_2}$ matrix element using Nachtmann vs CN moments: twist-4 is insensitive to target mass
  - (Y.B. Dong, Phys.Rev.C78:028201,2008)