Spin Physics Program in Jefferson Lab Hall C

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University of Virginia

Users Group Meeting
Jefferson Lab
June 20, 2007

Hall C Spin Structure Program

- Spin Structure Functions at 6 GeV:
  - Inclusive measurements
    - SSF's in the Nucleon Resonances Region - *RSS*
    - Proton SSF at high Bjorken x - SANE
    - Precision Deuteron spin structure - g_1^d/F_1^d
  - Semi-inclusive measurements
    - Flavor Decomposition of Nucleon Spin - SemiSANE
- Real Polarized Photons:
    - Polarized Compton Scattering
- Current four experiments rated A or A-
- Future: Spin Structure Functions with 12 GeV upgrade

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 $Q^2 \approx 1.3$ GeV² and $0.8 \leq W \leq 1.91$ GeV
- Study W dependence, onset of polarized local duality, twist-3 effects, using inclusive polarized scattering

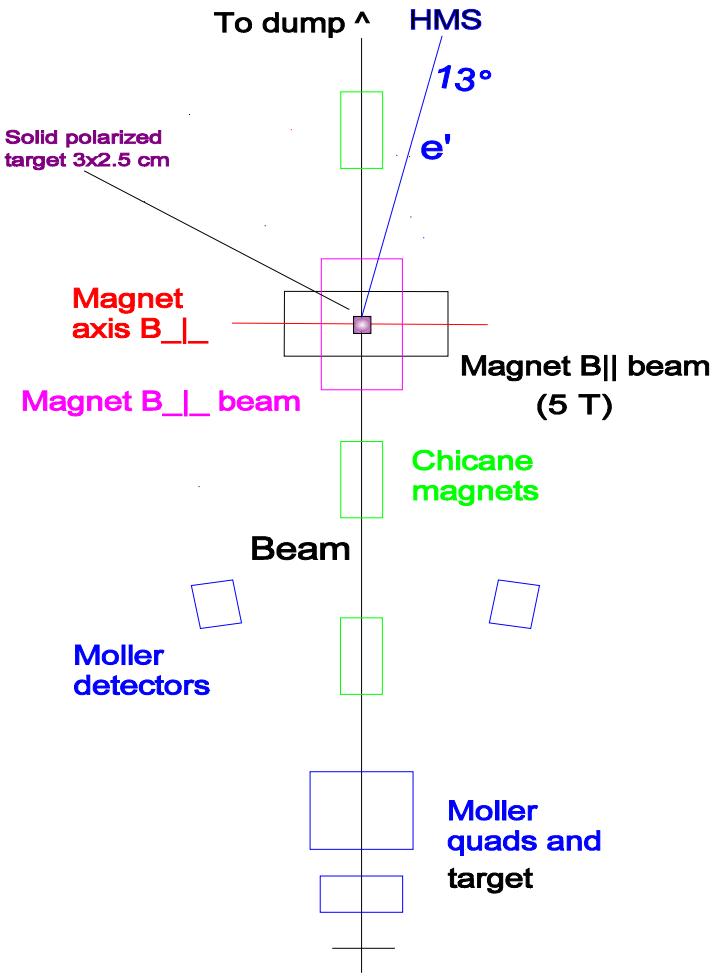
Resonances SSF Experiments

Lab	Experiment	Target	Q^2 [GeV/c]^2	Measured quantity
SLAC	E143 (E80)	NH_3 p(rotons) & d (euterons)	0.5 1.3	$A_{\|\|}$
JLab	Hall A 94-010	^3He	0.1 to 0.9 (6 values)	$A_{\|\|}$,$A_\perp$
	CLAS eg1a-b	NH_3 p & d	0.2 to 5 (over 12 values)	$A_{\|\|}$
	Hall C RSS	NH_3 p & d	1.3	$A_{\|\|}$,$A_\perp$
	Hall A 01-012	^3He	~1. to ~4.	$A_{\|\|}$,$A_\perp$

- *RSS* is only complete spin structure experiment in the resonances:
  - proton and neutron (from deuteron)
  - parallel and perpendicular asymmetries

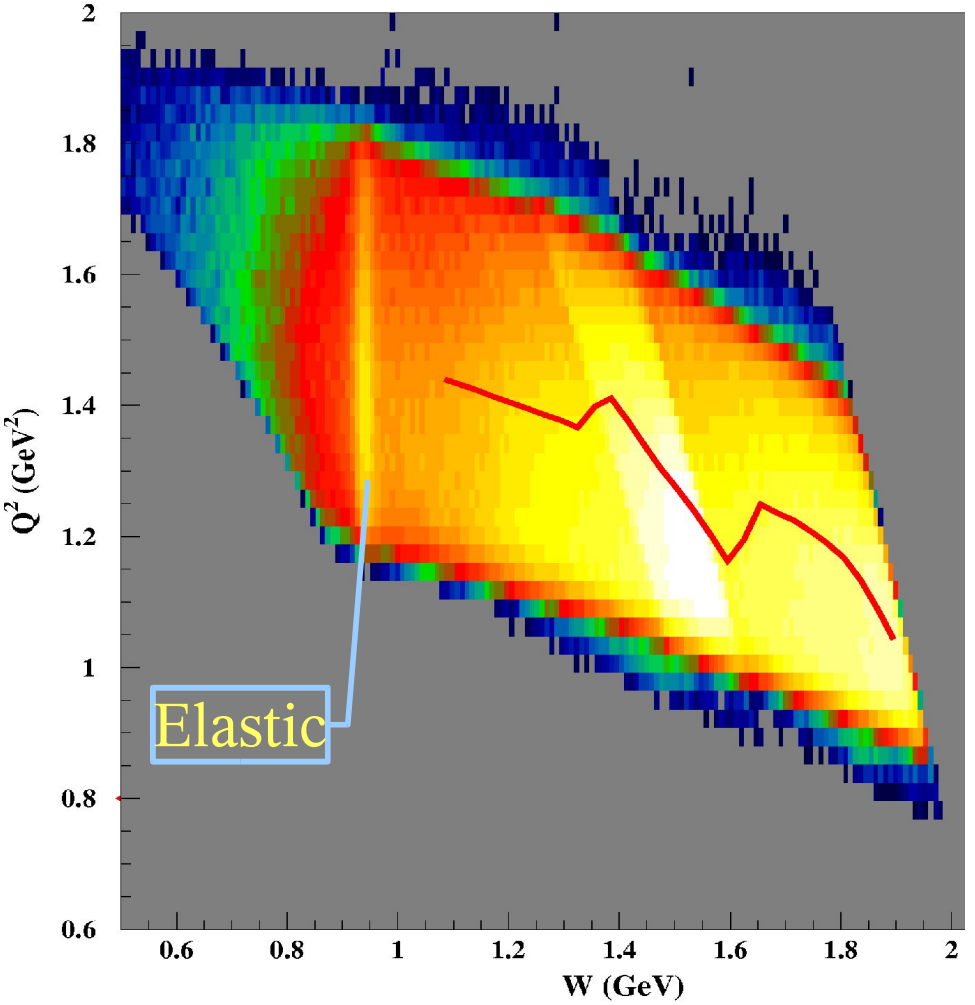
RSS Technique

- Equipment: TJNAF Hall C
  - CEBAF polarized electron beam
    - 2 cm diameter raster at target
    - I = 85-150 nA
  - Target: polarized ammonia NH_3, ND_3.
    - Luminosity ~10^{35} $s^{-1}cm^{-2}$
  - HMS electron detector
- Data run: Jan.-Feb. 2002
    - 160 M proton triggers
    - 350 M deuteron triggers



RSS Kinematics

- Beam energy 5.755 GeV
- HMS angle 13.15°
- HMS central momenta:
  - 4.71 GeV/c
  - 4.08 GeV/c
- Final state mass range:
  - 0.8 GeV $\leq W \leq$ 2.0 GeV
- $\langle Q^2 \rangle = 1.28$ [GeV/c]^2



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

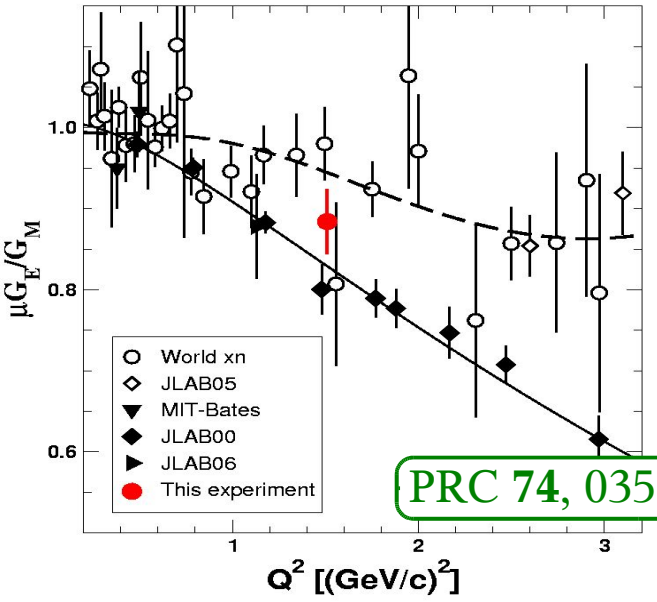
$$A_{\parallel,\perp} = \left(\frac{\epsilon}{f P_b P_t C_N} + C_D\right) + A_{rc}$$

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

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

	***Polarization* [%]**	
	$A_{\parallel}$	$A_{\perp}$
Moller - Beam	71	66
NMR - NH_3	70±1.7	
NMR - ND_3	20±1	

Proton Elastic	***G_E/G_M Sensitivity***	***Use***
$A_{\parallel}$	Low	P_b P_t
$A_{\perp}$	High	G_E/G_M



PRC **74**, 035201 (2006)

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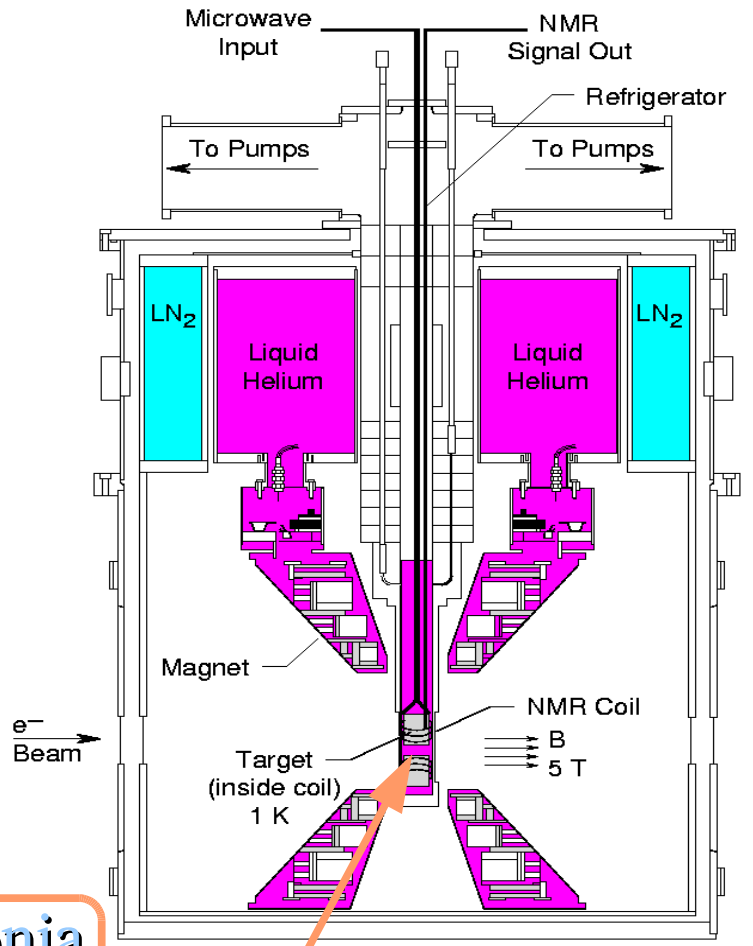

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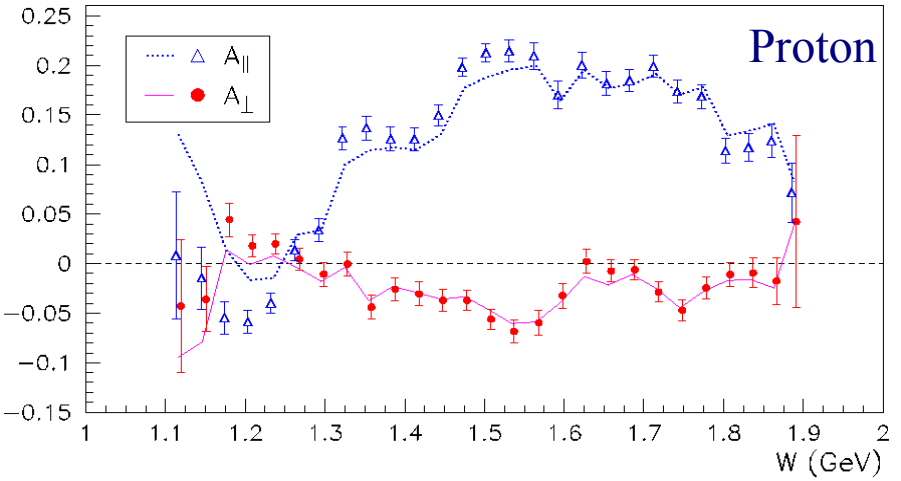
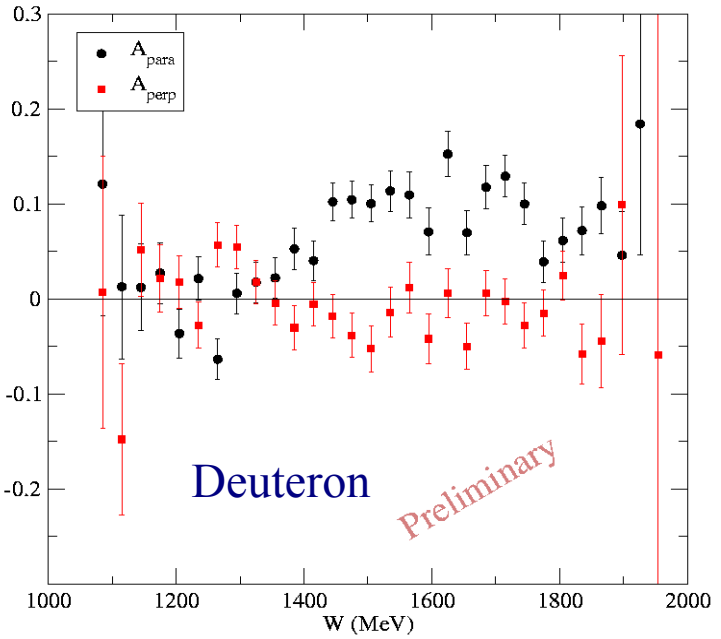




Spin Asymmetries A_1, A_2

- Combine $\mathbf{A_{\parallel}}$, $\mathbf{A_{\perp}}$ to get virtual Compton absorption asymmetries:

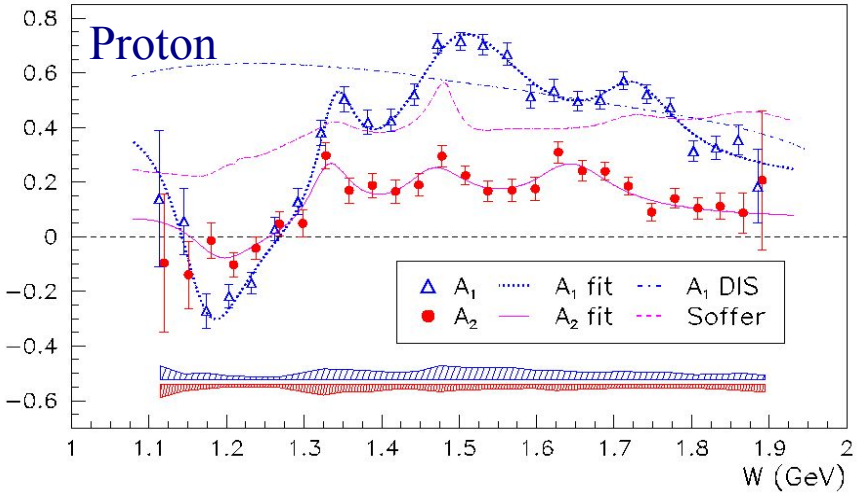
$$A_1 = \frac{1}{(E+E')D'}\left((E - E'\cos\theta)A_{\parallel} - \frac{E'\sin\theta}{\cos\phi}A_{\perp}\right)$$

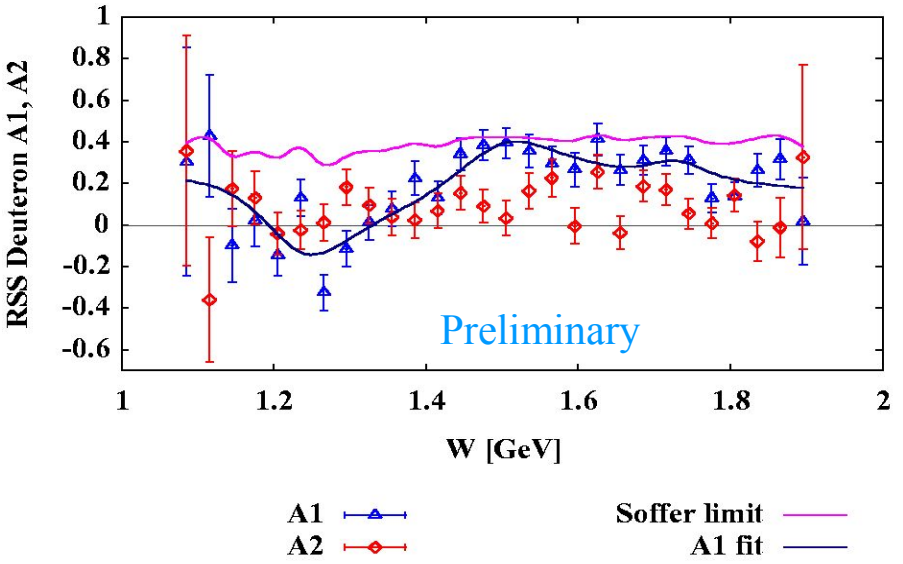
$$A_2 = \frac{\sqrt{Q^2}}{2ED'}\left(A_{\parallel} + \frac{E - E'\cos\theta}{E'\sin\theta\cos\phi}A_{\perp}\right)$$

- $\mathbf{A_1}$, $\mathbf{A_2}$ have minimal model dependence
  - $D'(E,E',\theta,R)$ is function only of kinematics and $\boldsymbol{R} = \sigma_L/\sigma_T$
    - Proton $\boldsymbol{R}$, $\boldsymbol{F_1}$ from E. Christy's fit to Hall C *e-p* data
    - Deuteron $\boldsymbol{R}$, $\boldsymbol{F_1}$ from P. Bosted's fit to world data

Spin Asymmetry results

- A_1, A_2 for proton, deuteron in resonances are unique:
  - *RSS* is only experiment that can separate A_1, A_2
- Proton final results
  - PRL **98**, 132003 (2007)
- Deuteron, neutron
  - in preparation





Proton Spin Structure Functions

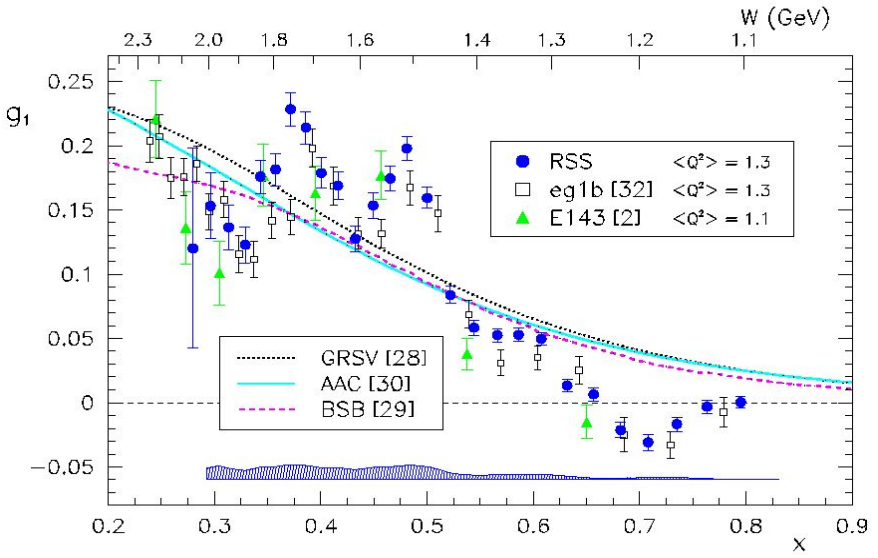
- Use unpolarized F_1

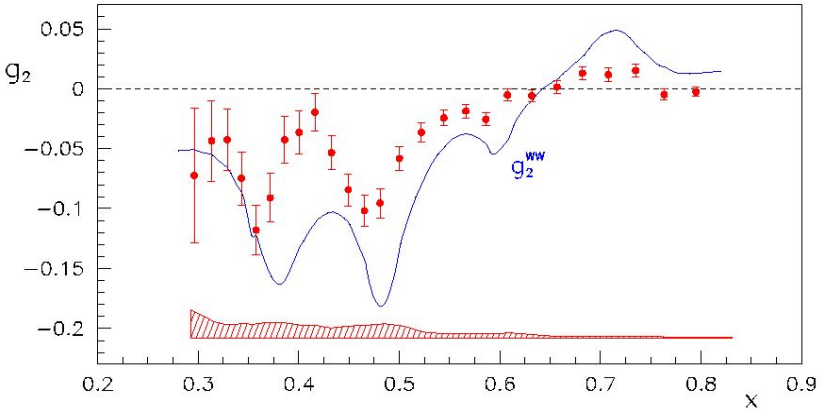
$$g_1 = \frac{F_1}{1+\gamma^2}(A_1 + \gamma A_2)$$

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

- High precision, high resolution measurement
  - First world data for g_2^p in the resonances
  - Clear higher-twist in g_2^p

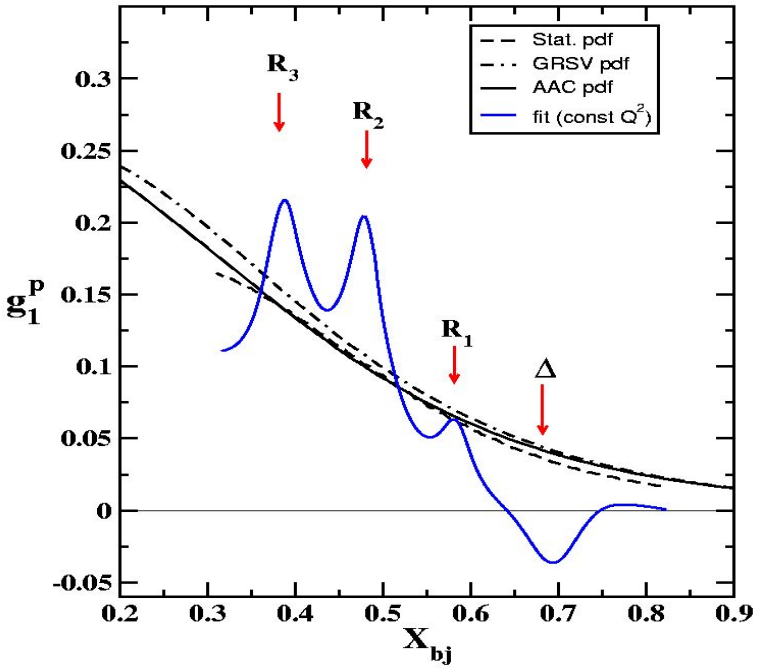
$$\bar{g}_2(x,Q^2) = g_2(x,Q^2) - g_2^{WW}(g_1(x,Q^2))$$





Bloom-Gilman Local Duality for g_1^p

- Integrate (at $\langle Q^2 \rangle = 1.28$ GeV^2)
  - g_1 fit over A_1 fit resonances
  - g_1 from PDF's evolved to same Q^2 with target mass corrections
- Polarized (B-G) Local Duality:
  - ratio of integrals = 1



Resonances	W low	W high	Integral ratios PDFs/Resonances Average	Error Data	Error PDFs
Delta	1.11	1.30	**3.93**	0.58	0.37
R1350	1.30	1.39	**1.36**	0.10	0.07
R2	1.39	1.68	**0.78**	0.05	0.04
R3	1.68	1.81	**0.79**	0.06	0.04
Global	1.08	1.91	**1.17**	0.08	0.06

- Only *approximate* Global Duality in *RSS*
  - Large x resummations increase discrepancy by 1.3 (S. Liuti *et al.*)

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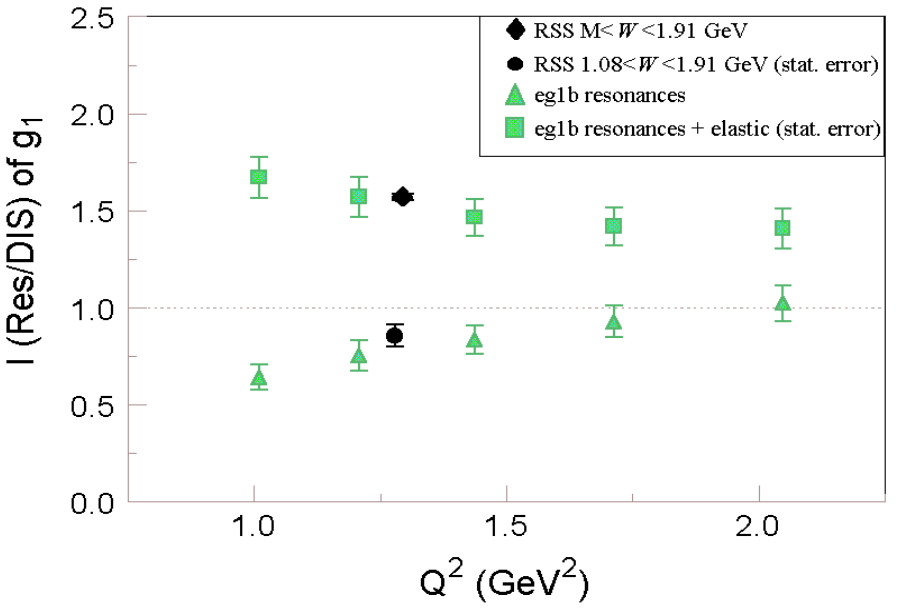

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- Polarized global duality seems to work above $Q^2 \approx 1.8$ GeV^2

Sum Rules (Proton)

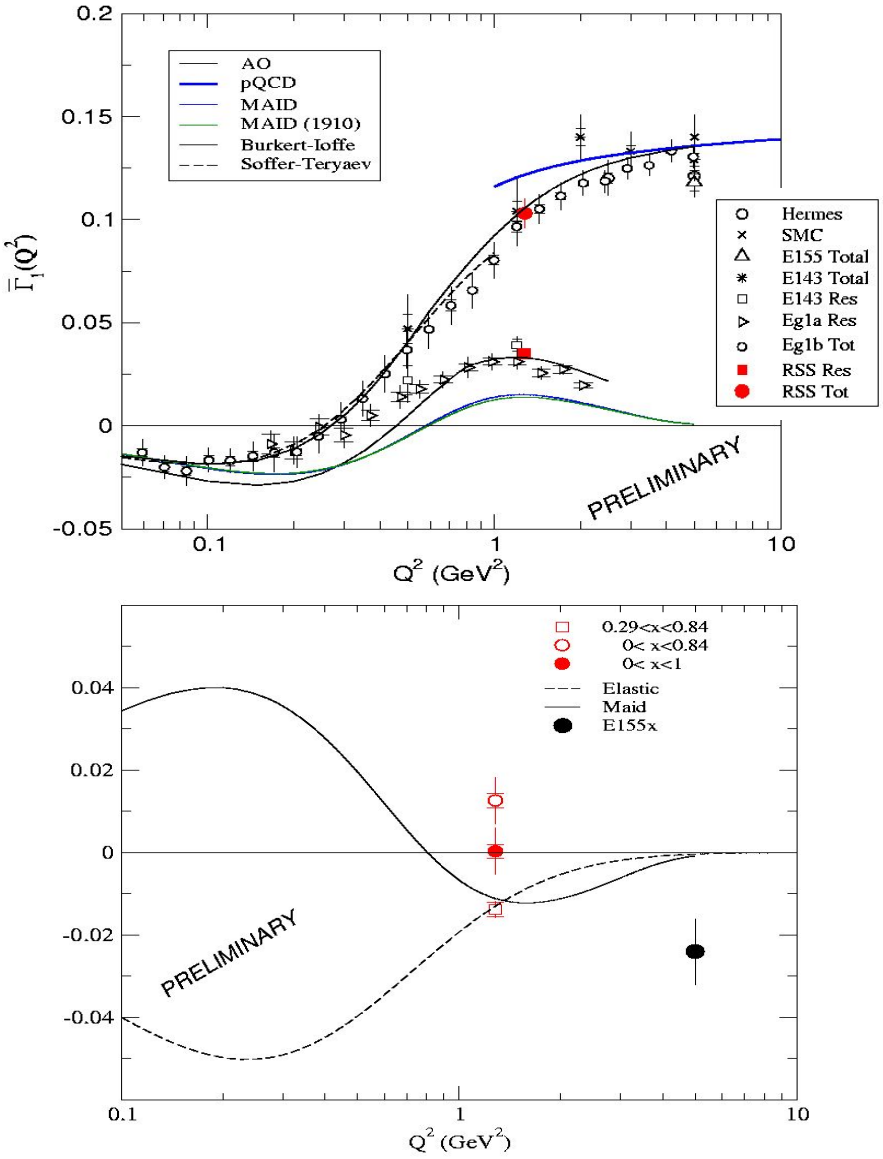
- First moment of g_1 (extended GDH or Ellis-Jaffe sum rule)

$$\overline{\Gamma}_1(Q^2) = \int_0^{1-el} g_1(x, Q^2)\,dx$$

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

- First moment of g_2 (Burkhardt-Cottingham)

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



Twist-3 in g_2^p

- Third moment of g_2 is related by the OPE to twist-3 matrix element d_2 representing q-g correlations

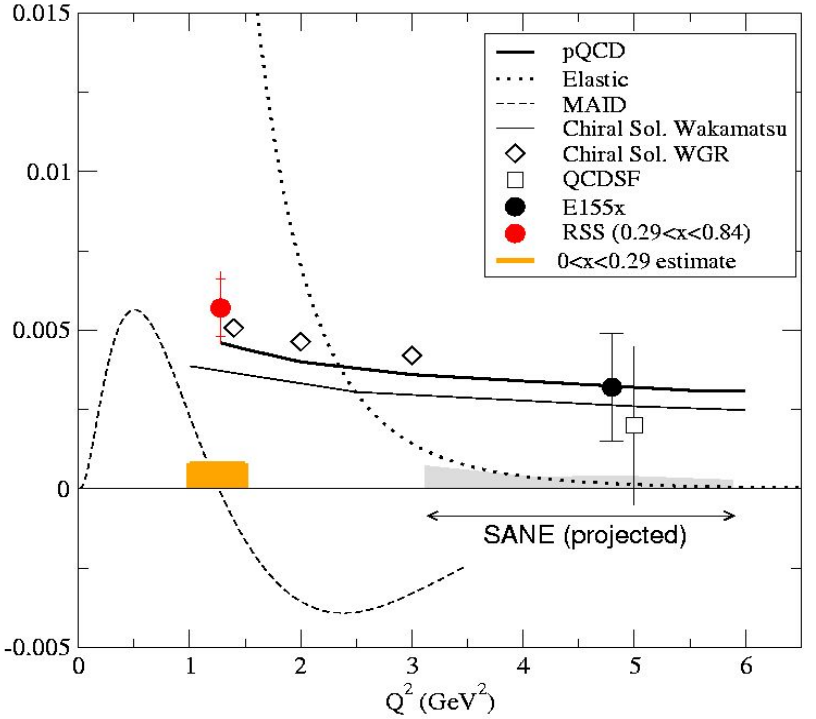
$$d_2^{Cornwall-Norton}(Q^2) = 3\int_0^1 x^2 \overline{g_2}(x,Q^2)\,dx$$

$$= \int_0^1 x^2 (2\,g_1(x,Q^2) + 3\,g_2(x,Q^2))\,dx$$

- At low Q^2 *Nachtmann* moments probe clean dynamic higher twists

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

S. Matsuda and T. Uematsu, NP B168 (1980) 181



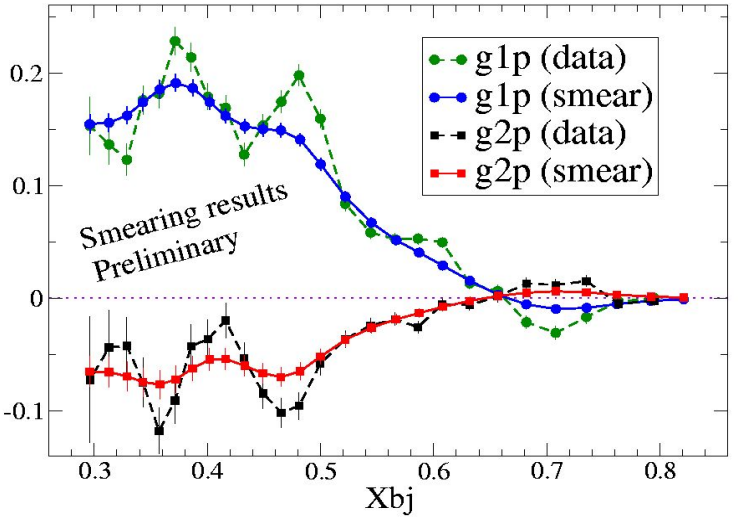
RSS measured ($0.29 < x < 0.84$)

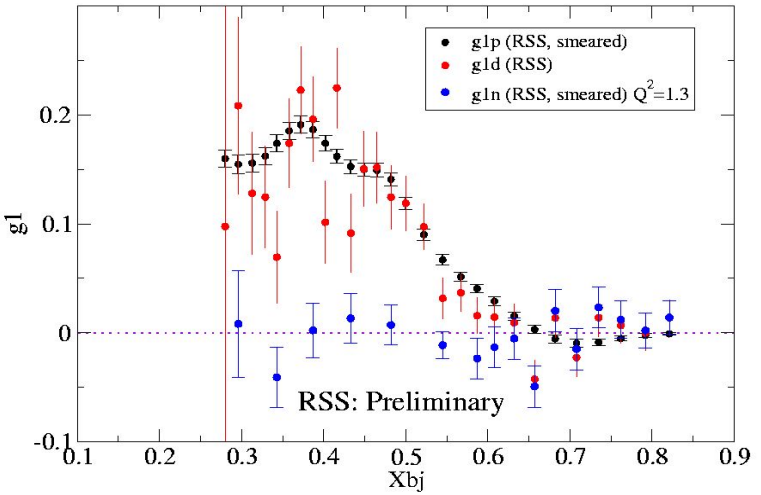
$d_2^{C\text{-}N}(1.3\ \text{GeV}^2) = 0.0057 \pm 0.0011$ (published)

$d_2^{Nachtmann} = 0.0036 \pm 0.0006$ (preliminary)

Neutron Spin Structure

- Extract neutron quantities from *p* and *d*
- Bodek-Ritchie version of Atwood-West smearing
  - generate smeared proton $\Delta\sigma^s_{\parallel}$, $\Delta\sigma^s_{\perp}$ by convolution of G_1, G_2 with nucleon momentum distribution to get g^s_1, g^s_2
  - subtract smeared proton from deuteron to get smeared neutron quantities
  - x-dependent D-state correction $w_d(x)$
    Melnitchouk, Piller, Thomas, PL B346, 165(1995)





$$g_{1,2}^{n(s)}(x,Q^2) = \frac{g_{1,2}^{d}(x,Q^2)}{w_d(x)} - g_{1,2}^{p(s)}(x,Q^2)$$

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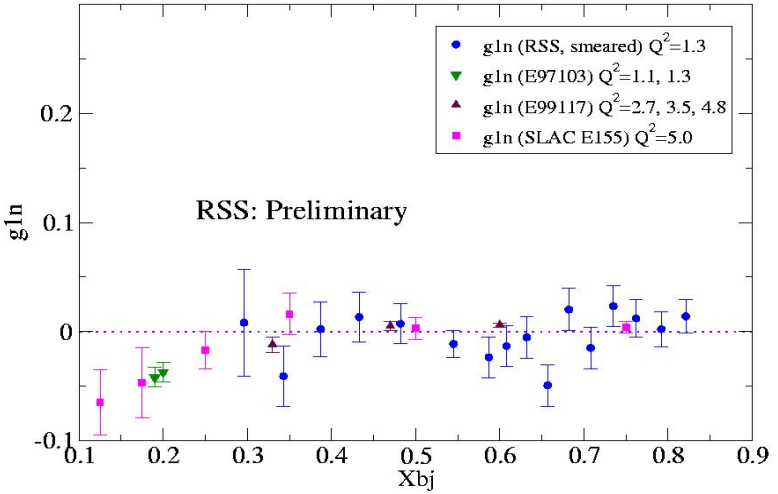
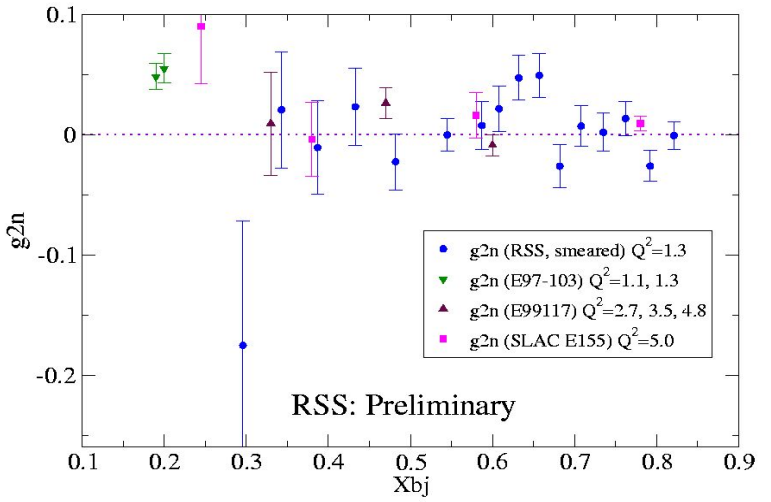




Outlook

- Two publications, two more in preparation:
  - Deuteron and neutron spin structure
  - Complete set of sum rules for both nucleons:
    - first moment of g_1: extended GDH and Ellis-Jaffe
    - first moment of g_2: Burkhardt-Cottingham
    - third moments of g_2: twist-3
    - combined *p* and *n* first moments
      - non-singlet: Bjorken
      - singlet: deuteron
    - combined *p* and *n* $g_{1,2}$ second moment:
      - Efremov-Leader-Teryaev (valence quarks)

Credits

Analysis Team

- Karl Slifer
- Shigeyuki Tajima
- Frank Wesselmann
- Peter Bosted
- Eric Christy
- Paul McKee
- Hongguo Zhu
- Mark Jones
- Oscar Rondon

Special Thanks

- Don Crabb
- Donal Day
- Mahbub Khandaker
- Hamlet Mkrtchyan
- JLab Hall C
- JLab Target group

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

SANE Collaboration
U. Basel, C. Newport U., Florida International U., Hampton U.,
Norfolk S. U., North Carolina A&T S. U., IHEP-Protvino, U. of Regina,
Rensselaer Polytechnic I., Rutgers U., Seoul National U., Temple U.,
TJNAF, U. of Virginia, College of William & Mary, Yerevan Physics I.

Spokespersons: S. Choi (Seoul), Z-E. Meziani (Temple), O. A. Rondon (U. of Virginia)

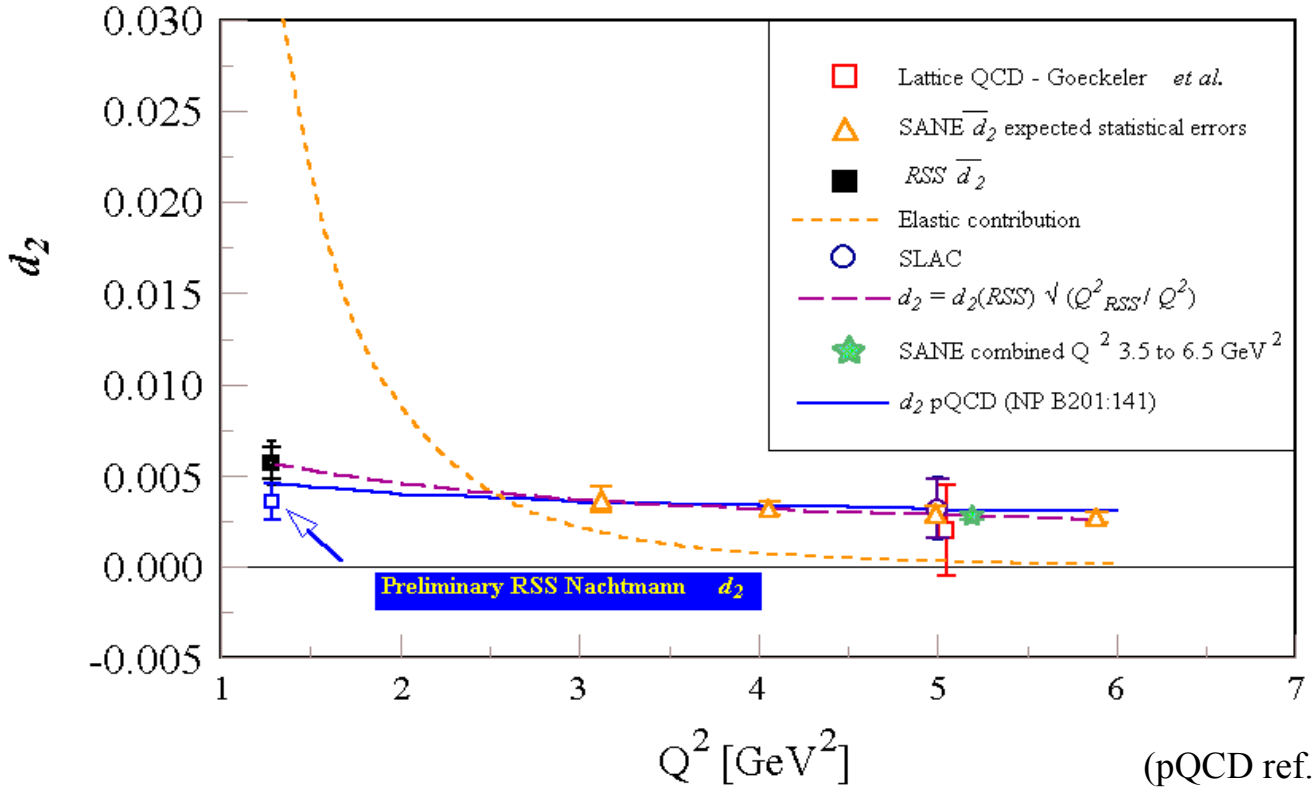
- Measure proton spin structure function $g_2(x, Q^2)$ and spin asymmetry $A_1(x, Q^2)$ for $2.5 \leq Q^2 \leq 6.5$ GeV^2 and $0.3 \leq x \leq 0.8$

- **SANE meets DOE 2011 Milestone for Proton Spin Structure**

SANE Physics

- Goal is to learn all we can about proton SSF's from an inclusive double polarization measurement:
  - twist-3 effects from moments of g_2 and g_1
  - comparisons with Lattice QCD, QCD sum rules, bag models, chiral quarks
  - Study x dependence (test nucleon models) and Q^2 dependence (evolution)
  - Exploration of "high" x region: A_1's approach to $x = 1$
  - Test polarized local duality for final state mass $W > 1.4$ GeV
- Method:
  - Measure inclusive spin asymmetries for two orientations of target spin relative to beam helicity (anti-parallel and near-perpendicular)
  - Detect electrons with novel large solid angle electron telescope **BETA**

SANE Expected Results



(pQCD ref. from A. Deur)

- SANE expected errors for $\overline{d}_2 = \int_{xmin}^{xmax} x^2 (2g_1 + 3g_2) dx$
  - $\delta\overline{d}_2(Q^2 = 3\ \text{GeV}^2) = 7\text{x}10^{-4}, \quad 0.29 < x < 0.85$
  - $\delta\overline{d}_2(3.5 \text{ to } 6.5\ \text{GeV}^2) = 2\text{x}10^{-4}, \quad 0.41 < x < 0.96$

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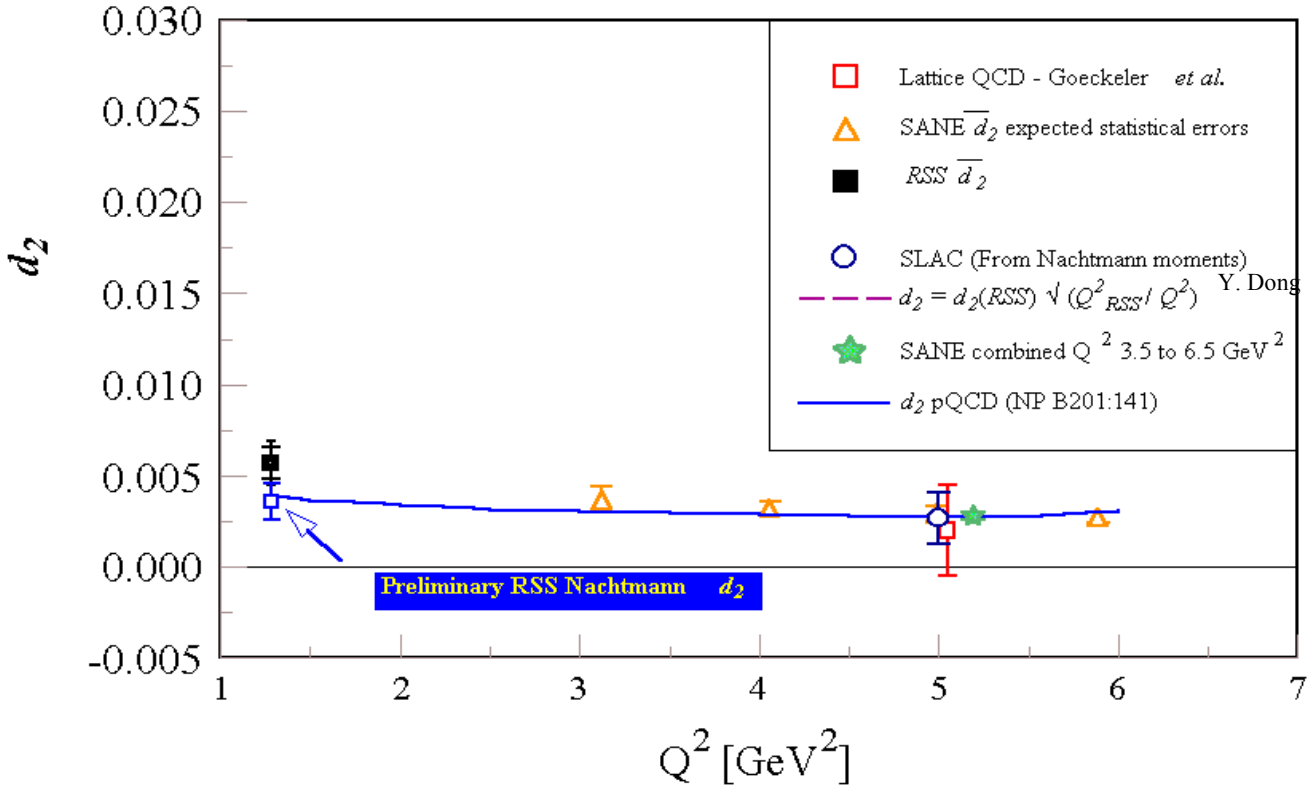

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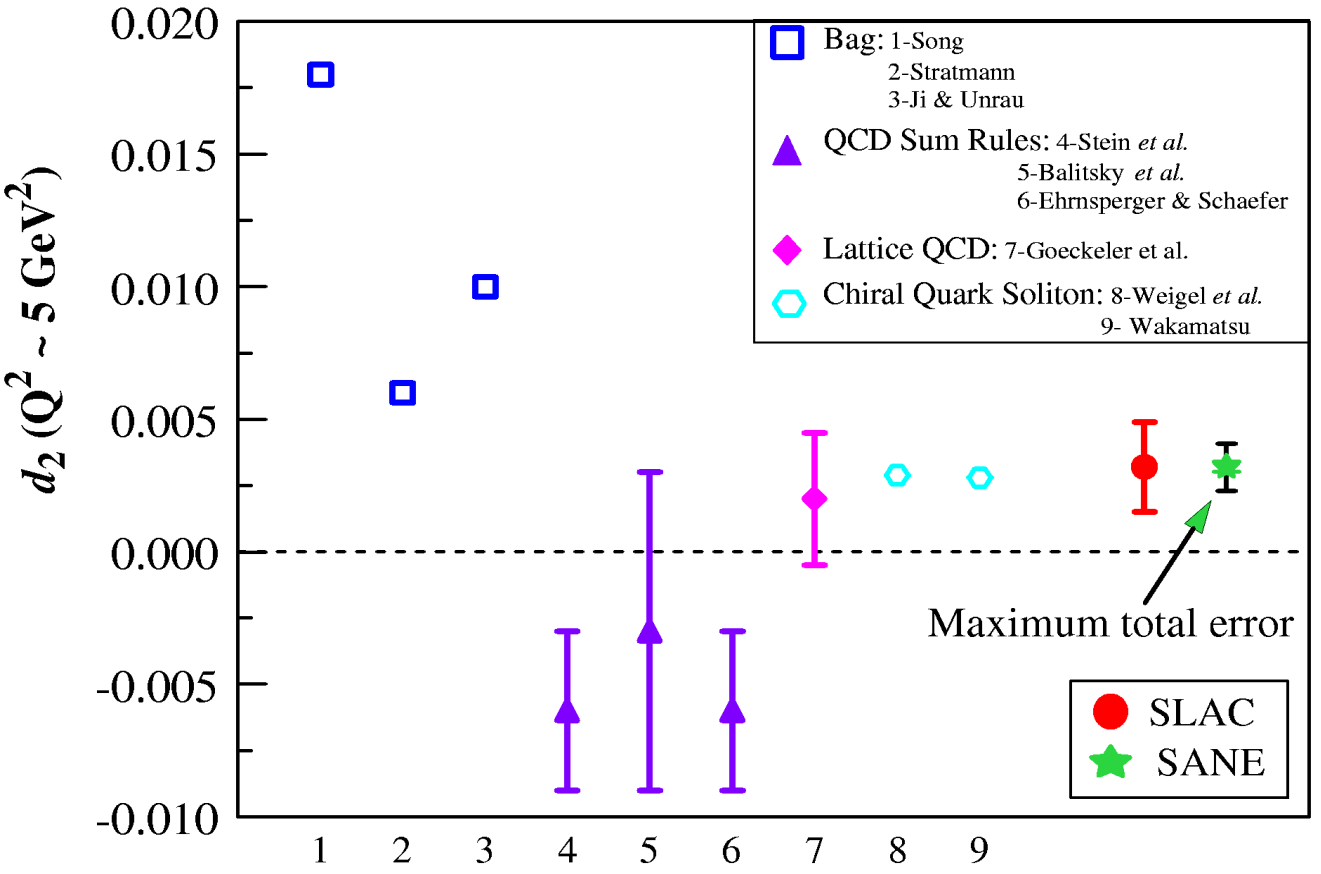
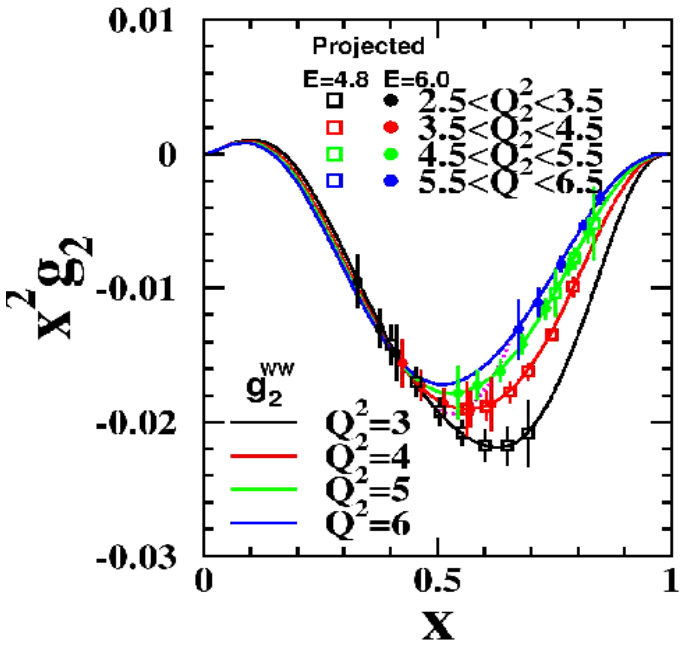
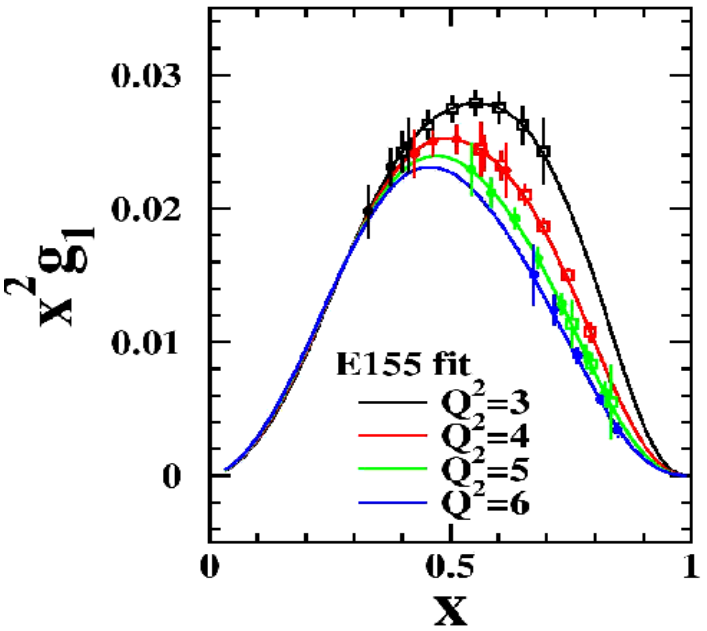
SANE Expected Results (Ia)



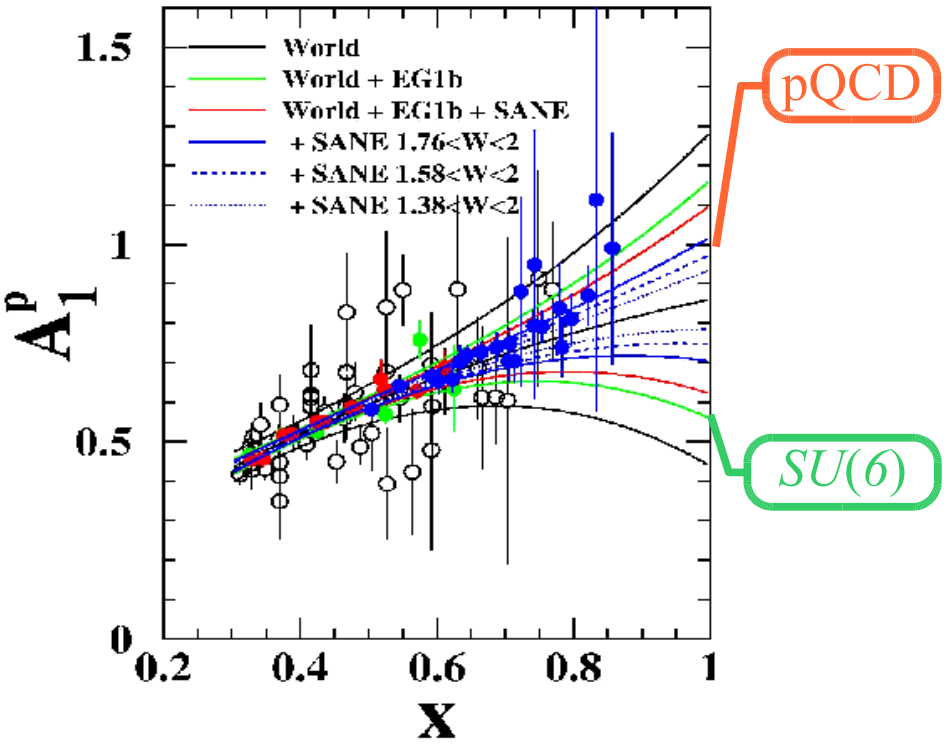
SANE Expected Results (II)

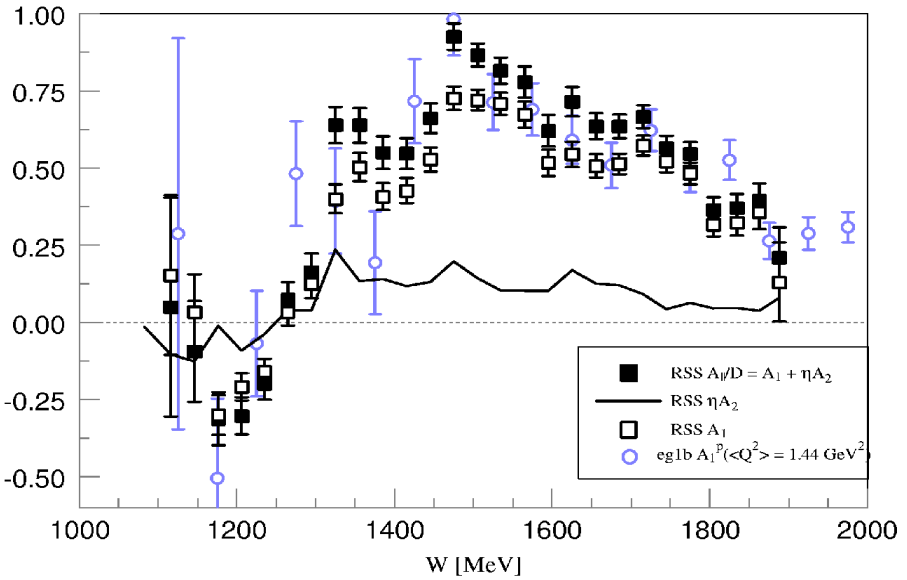




- x dependence at constant Q^2 and Q^2 dependence at fixed x (illustrative binning)
- data are concentrated in the region most sensitive to $x^2 g_{2,1}$
  - (estimates based on 75% beam and target polarization and 85 nA beam current)

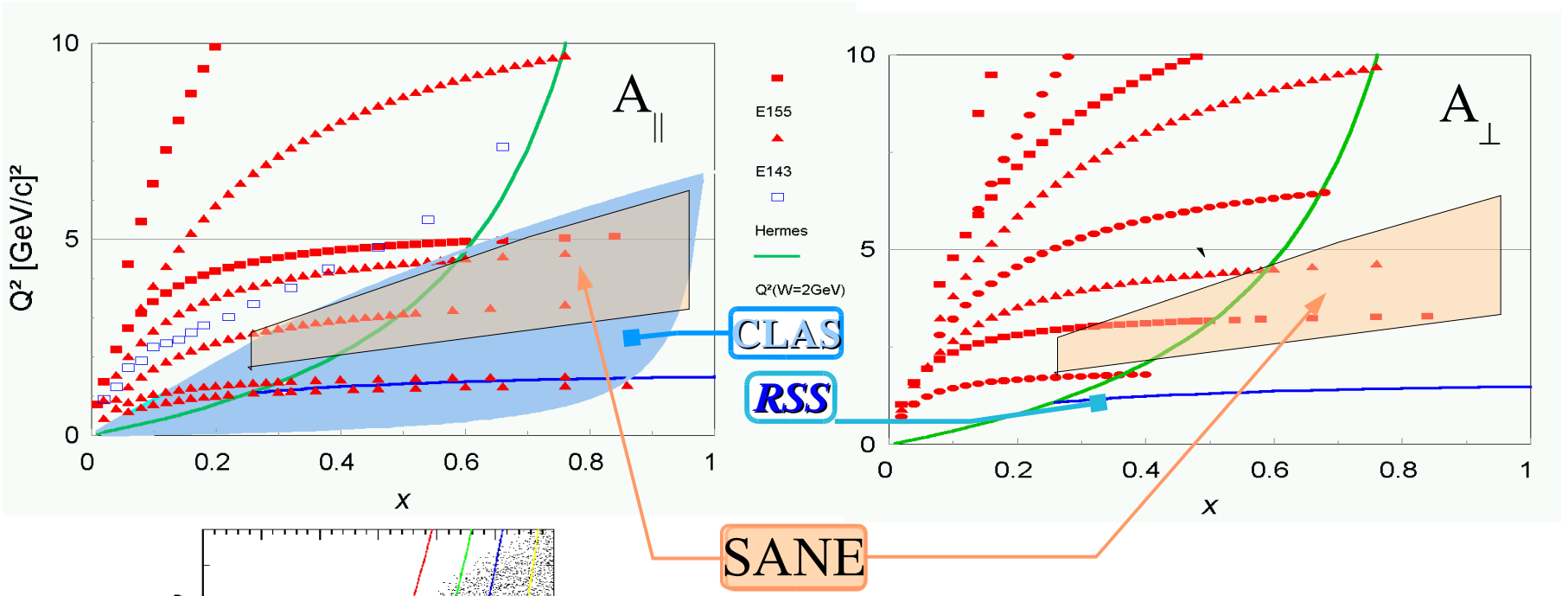
SANE Expected Results (III)

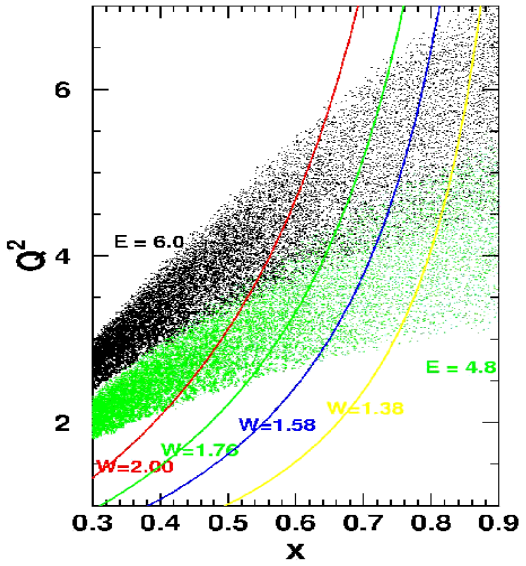




- Constrain extrapolations of A_1^p to $x = 1$ within +/- 0.1 (using duality)
- Both $A_{||}$ and $A_{\perp}$ are required to get accurate, model-free A_1: $A_2 > 0$
- SANE's measured A_2 will contribute to improve world's A_1 data set

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





- Two beam energies: **6 GeV**, **4.8 GeV**
- Very good high ***x*** coverage with detector at 40°

SANE Layout

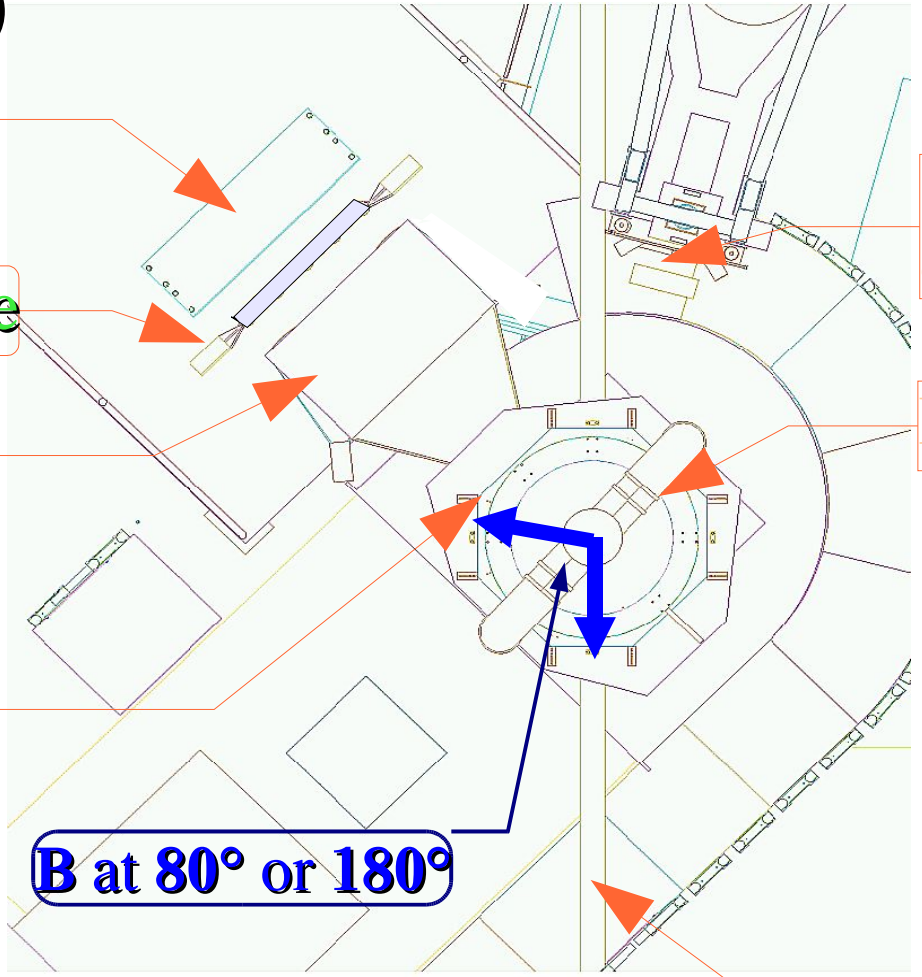
BETA (40°)

BigCal

Lucite Hodoscope

Gas Cherenkov

Forward Hodoscope



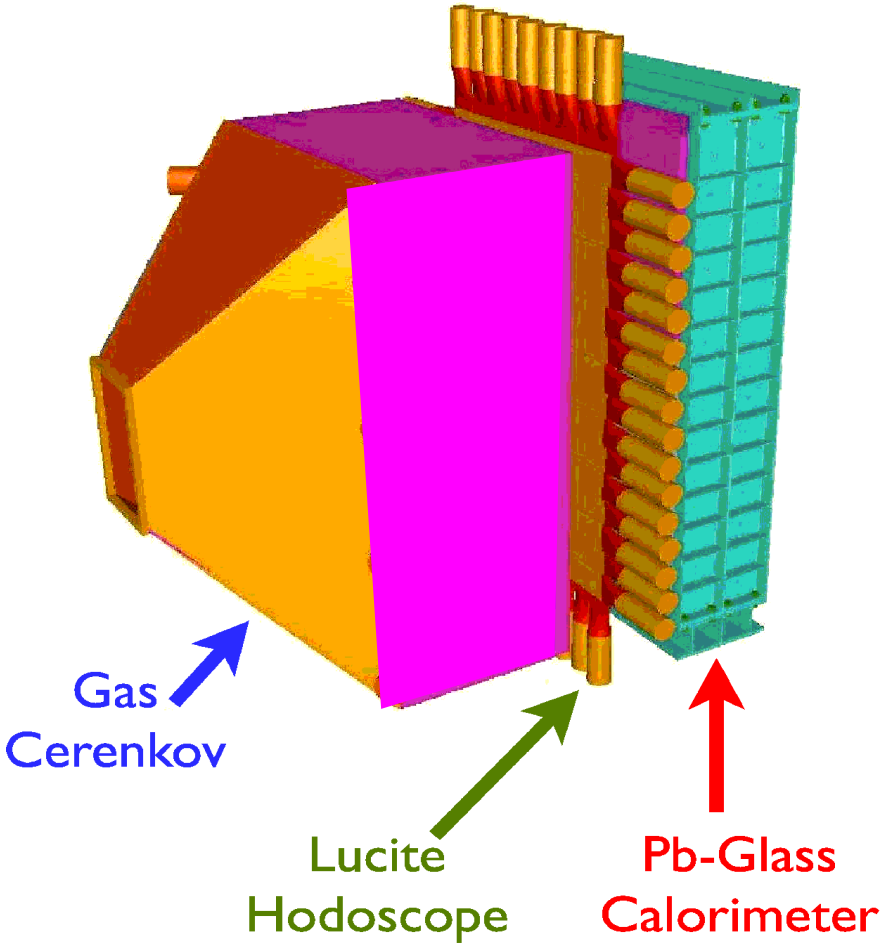
HMS (13°- 48°)
calibrations, backgd.

Polarized Target

Beam Line

Big Electron Telescope Array - BETA

- **BigCal** lead glass calorimeter:
  main detector, being built for *GEp-III*.
- **Gas Cherenkov**: additional pion rejection
- Tracking **Lucite hodoscope**
- Tracking fiber-on-scintillator **forward hodoscope**
- BETA's characteristics
  - Effective solid angle = 0.194 sr
  - Energy resolution 5%/√ *E*(GeV)
  - 1000:1 pion rejection
  - vertex resolution ~ 5 mm
  - angular resolution ~ 1 mr
- Target field sweeps low *E'* background



(Artist view of Reference design)

Beam Time

PAC31 "A" rating

	Energy	θ_N	Time (h)
Calibration	2.4	off, 0, 180	47
Production	4.8	180	70
	4.8	80	130
	6.0	80	200
	6.0	180	100
Systematics	Packing Fraction		20
	Mollers		21
	Total beam time		588
Overhead	Anneals		62
	Energy Change		48
	Target Rotation		48
	Stick Changes		48
	Total Overhead		206

Commissioning 14 calendar days

Total 70 calendar days

SANE Membership

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SANE Status

- Thirteen collaboration meetings since 11/2003, latest on 3/31/2006
- Submitted Beam Request on 9/14/06
- Hall C schedule: SANE tentatively to start in 7/2008
- Readiness review in July 2007

SUMMARY

Steady progress over 3+ years

SANE is pioneering spin physics with large non-magnetic detectors

A High Precision Measurement of the Deuteron Spin Structure Function g_1^d/F_1^d

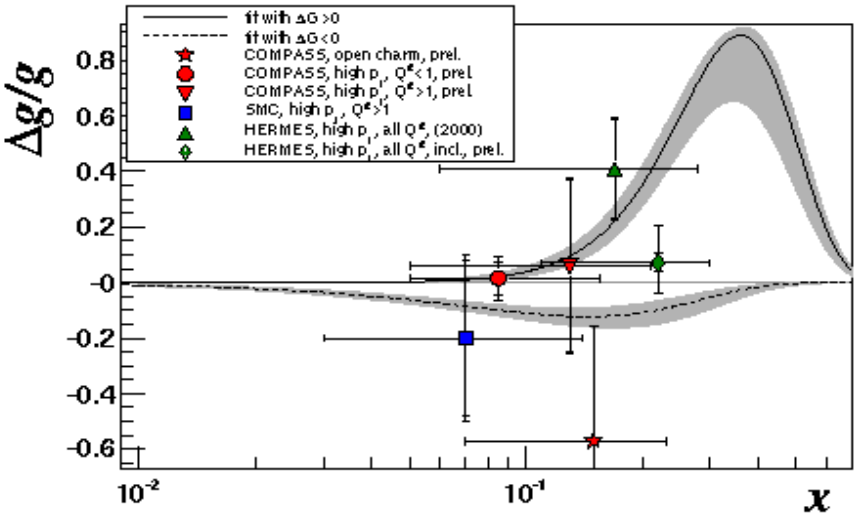
TJNAF E07-011
U. Basel, C. Newport U., Duke U., Florida International U., Hampton U., U. of Kentucky, U. of Maryland, St. Norbert C., Norfolk S. U., North Carolina A&T S. U., IHEP-Protvino, Ohio U., U. of Regina, Rensselaer Polytechnic I., Rutgers U., TJNAF, U. of Virginia, College of William & Mary, Yerevan Physics I.

Spokespersons: P. Bosted (JLab), F. Wesselmann (Norflok), X. Jiang (Rutgers)

- Make definitive measurement of deuteron spin structure function $\boldsymbol{g_1^d/F_1^d}(x,Q^2)$ in DIS kinematics with a 6 GeV beam
- Goal is to provide anchor points to NLO pQCD with higher twist corrections fit to extract the gluon polarization $\Delta \boldsymbol{g}(x)$
- Also, test nuclear effects on spin structure with ND_3 and ^{6}LiD targets

Method and Sample of Expected Results

- Fit pQCD evolution in Q^2 of $g_1^d(x, Q^2)$ data to extract polarized quark and gluon distributions
  - $1 < Q^2 < 5$ GeV^2 and $0.15 < x < 0.6$ with BETA at 30° and 6 GeV beam
  - low Q^2 medium x data with HMS, 4.8 GeV
  - $A_{||}$ data taken in part during SemiSANE
- Test nuclear effects on deuteron spin structure comparing ND_3 vs ^{6}LiD data (spin "EMC" effect)
- Approved for 8 days plus SemiSANE time on deuterium, with A rating



(From G. Mallot, COMPASS)

Method and Sample of Expected Results

- Fit pQCD evolution in Q^2 of $g_1^d(x, Q^2)$ data to extract polarized quark and gluon distributions
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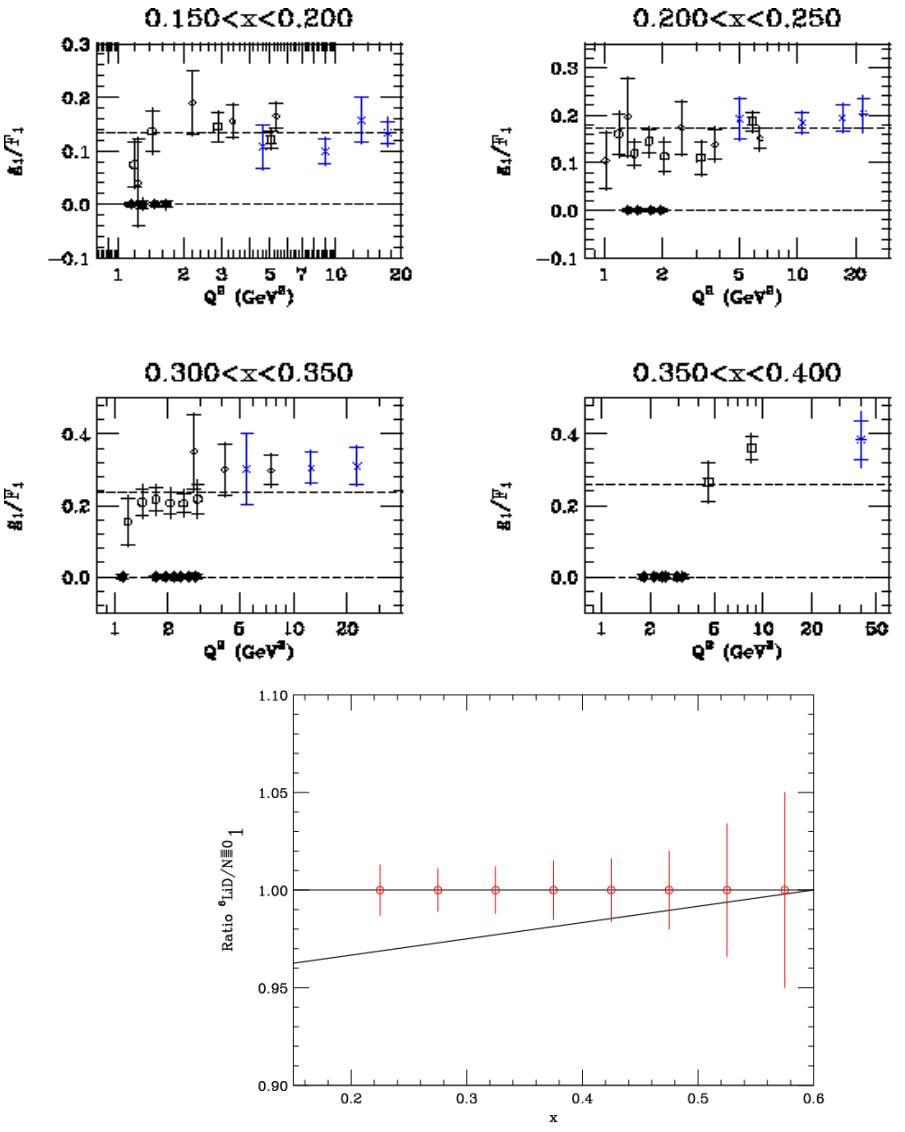


SemiSANE
Flavor Decomposition of Nucleon Spin

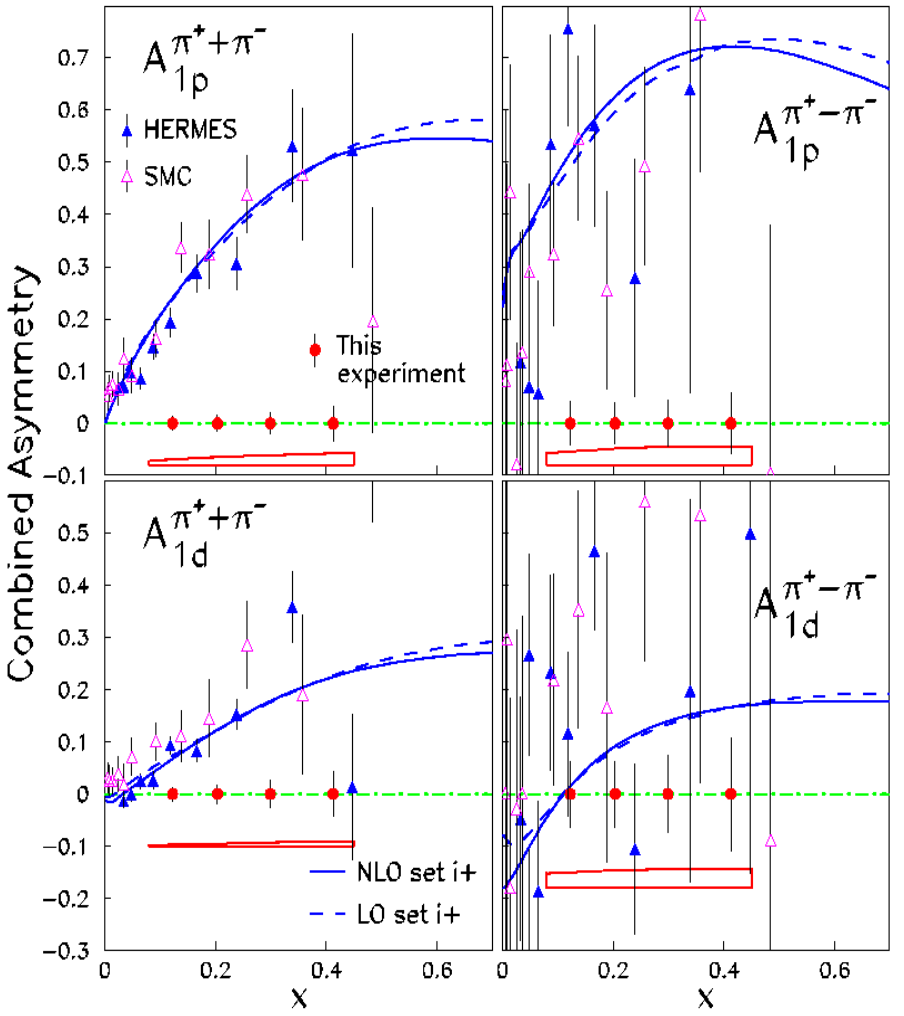
TJNAF E04-113
Argonne National Lab, Duke U., Florida International U., Hampton U., U. Kentucky, U. Maryland, U. Massachusetts, Rensselaer Polytechnic I., Norfolk S. U., Old Dominion U., U. Regina, Rutgers U., Temple U., TJNAF, U. of Virginia, C. of William & Mary, Yerevan Physics I.

Spokespersons: P. Bosted (JLab), D. Day (U. of Virginia), X. Jiang (Rutgers), M. Jones (JLab)

- Measure proton and deuteron semi-inclusive spin asymmetries in polarized DIS reactions $p(e,e'h)$ and $d(e,e'h)$: Semi-SANE
  - $h = \pi^{+,-}, K^{+,-}$, $1.2 \leq Q^2 \leq 3.2$ GeV^2, $0.12 \leq \boldsymbol{x} \leq 0.43$, for hadrons with $0.5 \leq z \leq 0.7$
  - Extract the Δu, Δd, Δs, and anti-quark spin components
- Detect electrons with BigCal at 30° and hadrons with HMS

Method and Sample of Expected Results

- Form $A_{1N}^{\pi+ - \pi-}$ to get valence quark helicities (Leader-Christova LO and NLO methods)
  - combine with inclusive data to probe polarized light sea flavor asymmetry
  - three other LO and one NLO methods
- Compare $A_{1N}^{\pi+ + \pi-}$ with inclusive result to test factorization
- Expected results for the *u* and *d* flavor asymmetries several times more precise than current world data
- Approved for 25 days with A- rating



Method and Sample of Expected Results

- Form $A_{1N}^{\pi^+ - \pi^-}$ to get valence quark helicities (Leader-Christova LO and NLO methods)
  - combine with inclusive data to probe polarized light sea flavor asymmetry
  - three other LO and one NLO methods
- Compare $A_{1N}^{\pi^+ + \pi^-}$ with inclusive result to test factorization
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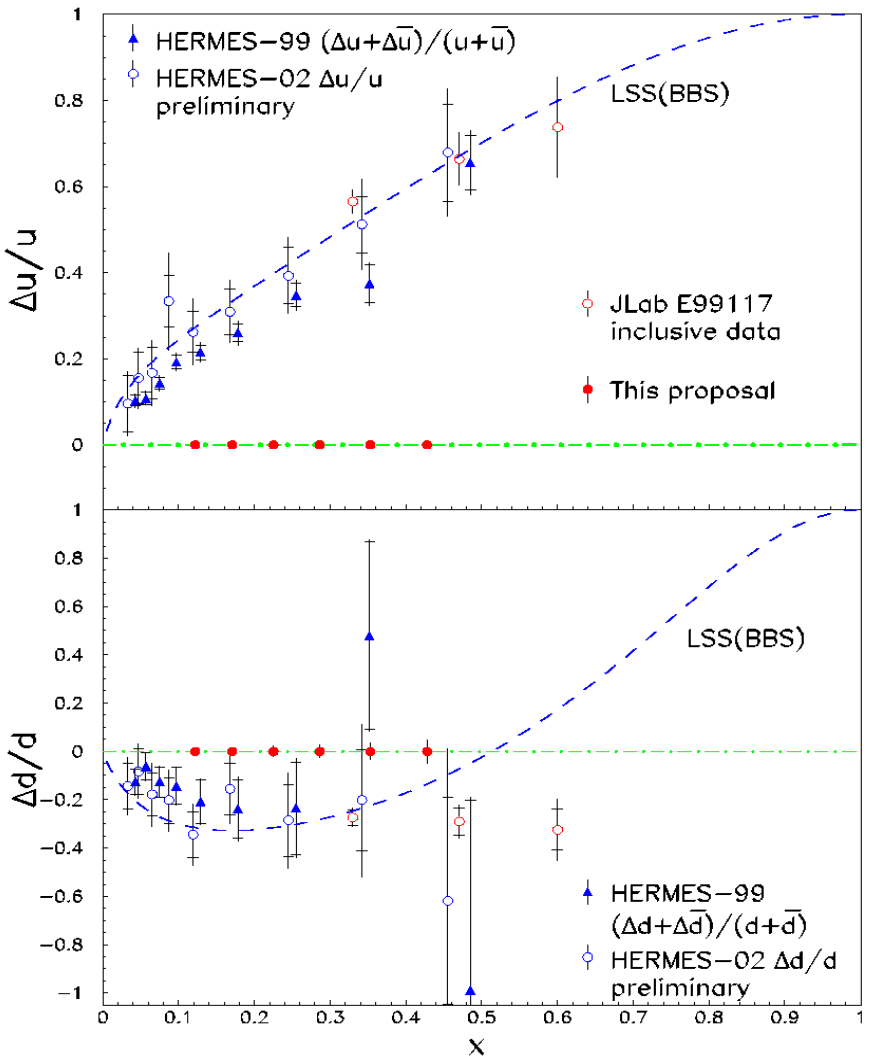
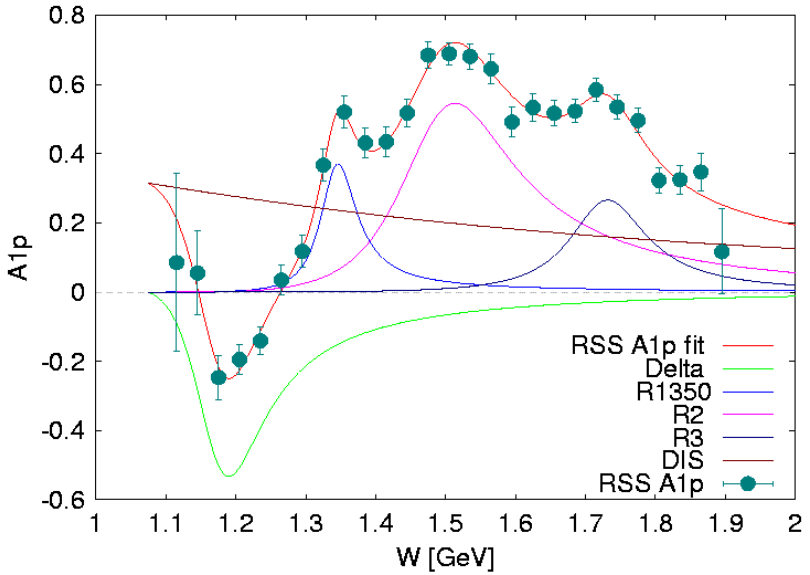
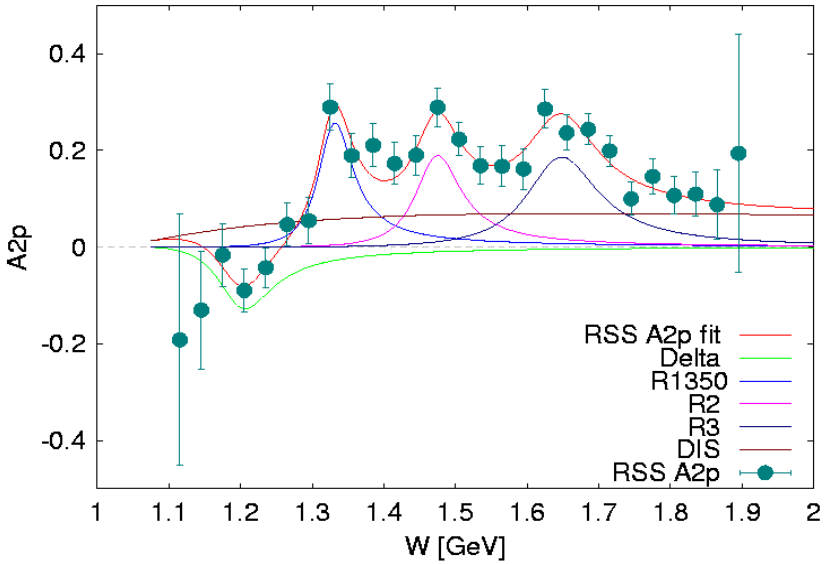


RSS Fit to the SA's





- Four Breit-Wigner resonance shapes plus DIS background
- Fit A_1 and A_2 independently
- Reduced χ^2 = 1.2 - 1.4 for 12 d.o.f.

Beyond Inclusive Scattering

- Eight quark distribution functions:
  - $\boldsymbol{k}_\perp$ independent (leading twist)
    - F_1, g_1: inclusive
    - δ : transversity (h_T)
  - $\boldsymbol{k}_\perp$ dependent
    - $g_T = g_1 + g_2$: inclusive, mixed twist
    - $h_{1L}^\perp$, $h_{1T}^\perp$: semi-inclusive, *T*-even
    - $f_{1T}^\perp$, $h_1^\perp$: semi-inclusive, *T*-odd

- Spin Dependent Fragmentation: Semi-Inclusive Leptoproduction
  - Detect hadron (π, K,..)-lepton in coincidence
  - Semi-inclusive Asymmetry

$$A_1^h(x,z,Q^2) = \frac{\sum e_f^2 \Delta q_f(x,Q^2) D_f^h(z,Q^2)}{\sum e_f^2 q_f(x,Q^2) D_f^h(z,Q^2)}$$
$$z = E_h/\nu$$

- Spin Dependent Exclusive Scattering: Generalized Parton Distributions