

# RSS and SANE

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Spin Structure at Long Distance  
Jefferson Lab  
March 12, 2009

# Hall C 6 GeV Spin Structure Program

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

# *RSS* - Resonances Spin Structure

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

[TJNAF E01-006](#)

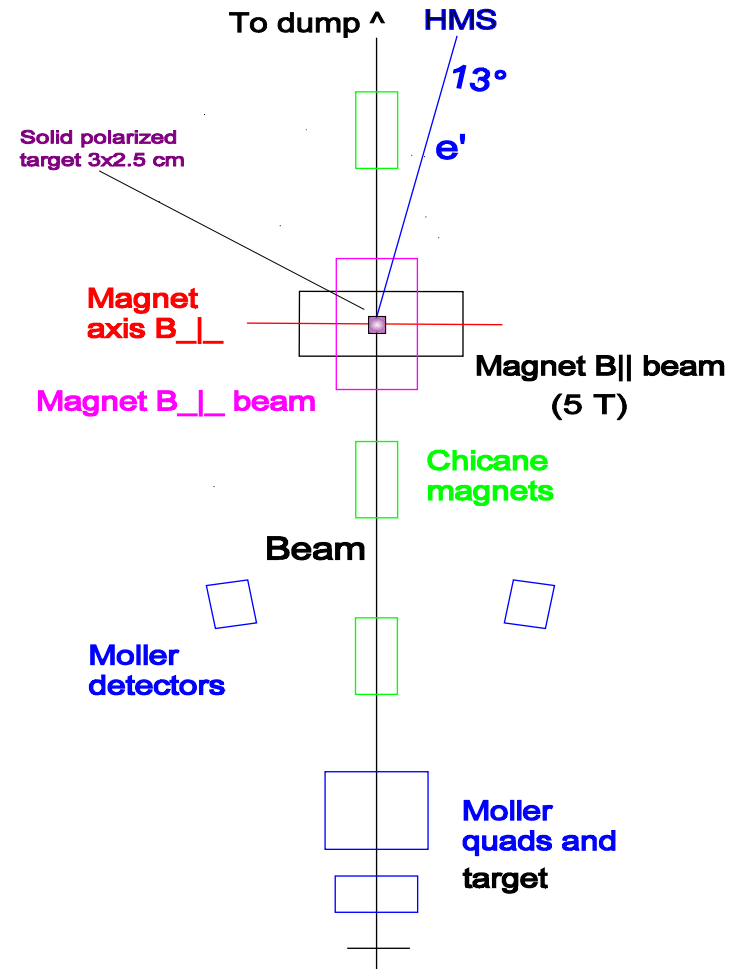
U. Basel, Florida International U., Hampton U., U. Massachusetts, U. Maryland,  
Mississippi S. U., North Carolina A&T U., U. of N. C. at Wilmington,  
Norfolk S. U., Old Dominion U., S.U. New Orleans, U. of Tel-Aviv,  
TJNAF, U. of Virginia, Virginia P. I. & S.U., Yerevan Physics I.

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

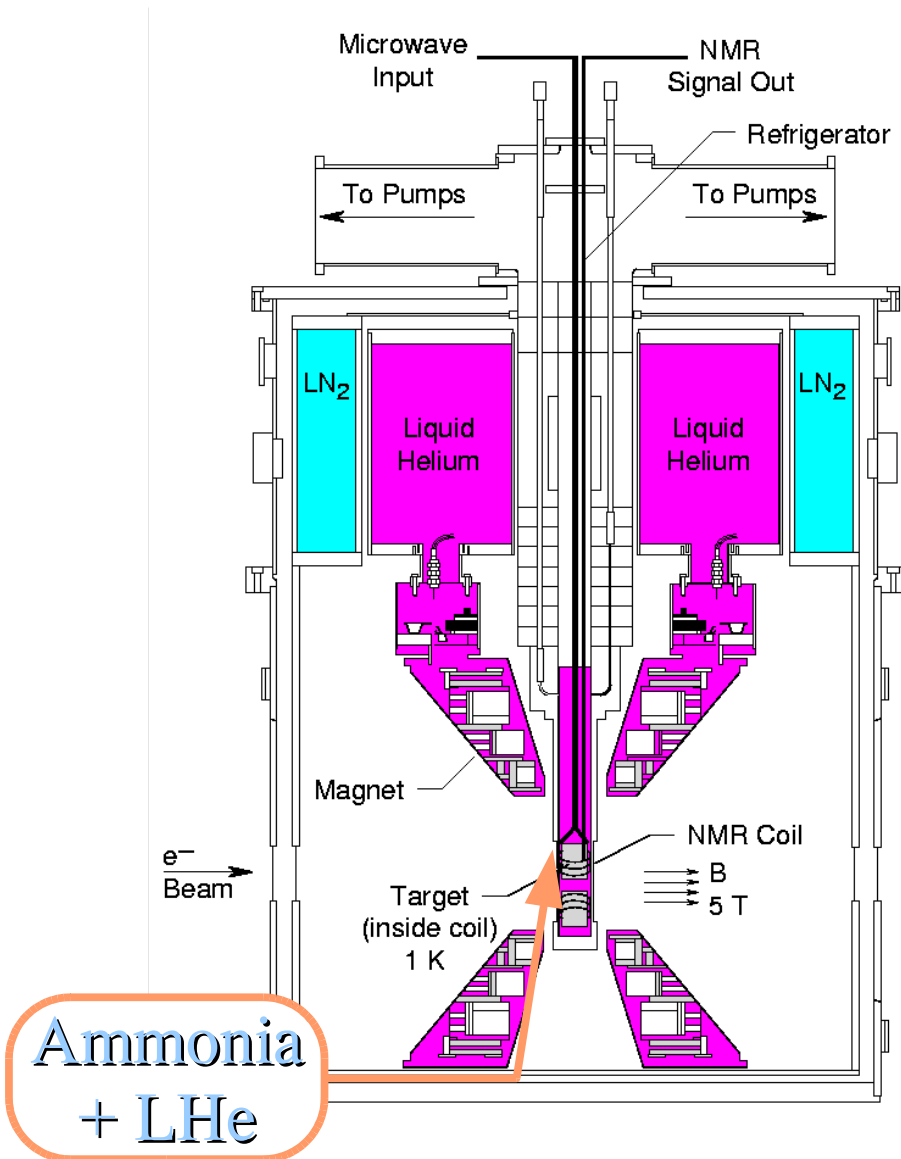
- Measure *proton* and *deuteron* spin asymmetries  $A_1(W, Q^2)$  and  $A_2(W, Q^2)$  at  $Q^2 \approx 1.3 \text{ GeV}^2$  and  $0.8 \leq W \leq 1.91 \text{ GeV}$
- Study  $W$  dependence of asymmetries, onset of polarized local duality, twist-3 effects, using inclusive polarized scattering

# RSS Technique

- Equipment: TJNAF Hall C
  - CEBAF polarized electron beam
    - 5.755 GeV- 66 to 71% polarization
    - 2 cm diameter raster at target
    - $I = 85\text{-}150$  nA
  - Target: polarized ammonia  $\text{NH}_3$ ,  $\text{ND}_3$ .
    - Luminosity  $\sim 10^{35} \text{ s}^{-1} \text{ cm}^{-2}$
  - HMS electron detector
- Kinematics
  - Final state mass range:
    - $0.8 \text{ GeV} \leq W \leq 1.91 \text{ GeV}$
  - $\langle Q^2 \rangle = 1.28 [\text{GeV}/c]^2$



# Polarized Target



- Dynamic Nuclear Polarized ammonia ( $\text{NH}_3$ ,  $\langle P \rangle \sim 70\%$  in beam) and deuterated ammonia ( $\text{ND}_3$ ,  $\langle P \rangle 20\text{-}30\%$ )
  - 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.

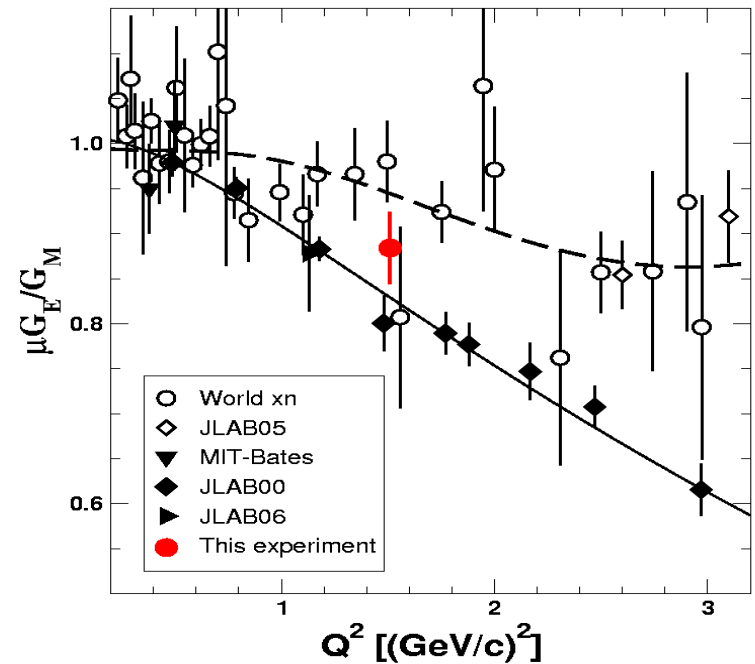
# Measured asymmetries $A_{\parallel}$ , $A_{\perp}$

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

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

- $N^-$ ,  $N^+$  = 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  $^{15,14}\text{N}$ 
  - proton  $C_D = 0$ , deuteron  $C_N \simeq 1$
- $A_{rc}$  = radiative correction

<i>Proton Elastic</i>	<i><math>G_E/G_M</math> Sensitivity</i>	<i>Use</i>
$A_{\parallel}$	Low	$P_b P_t$
$A_{\perp}$	High	$G_E/G_M$



PRC 74, 035201 (2006)

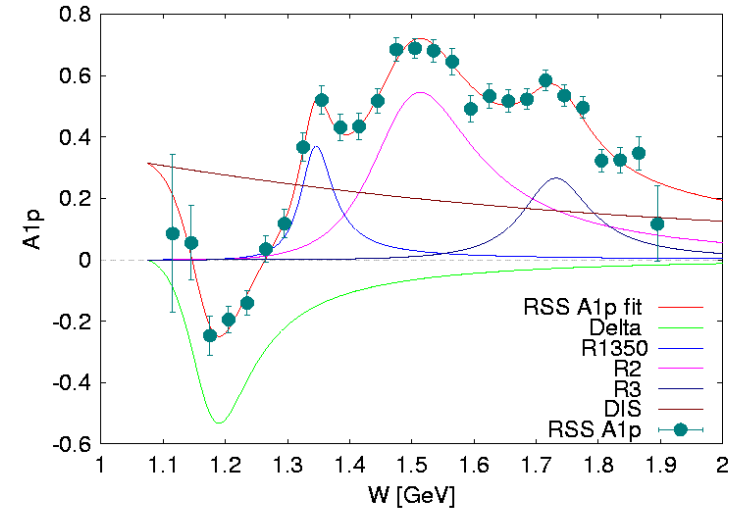
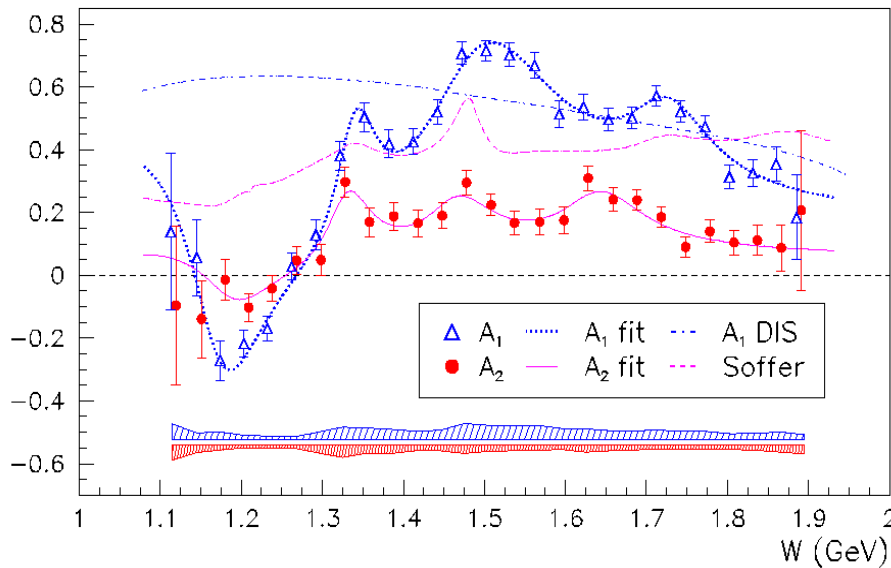
# RSS goal: Spin Asymmetries $A_1, A_2$

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

$$A_1 = \frac{1}{(E + E')D'} \left( (E - E' \cos \theta) A_{\parallel} - \frac{E' \sin \theta}{\cos \phi} A_{\perp} \right)$$
$$A_2 = \frac{\sqrt{Q^2}}{2ED'} \left( A_{\parallel} + \frac{E - E' \cos \theta}{E' \sin \theta \cos \phi} A_{\perp} \right)$$

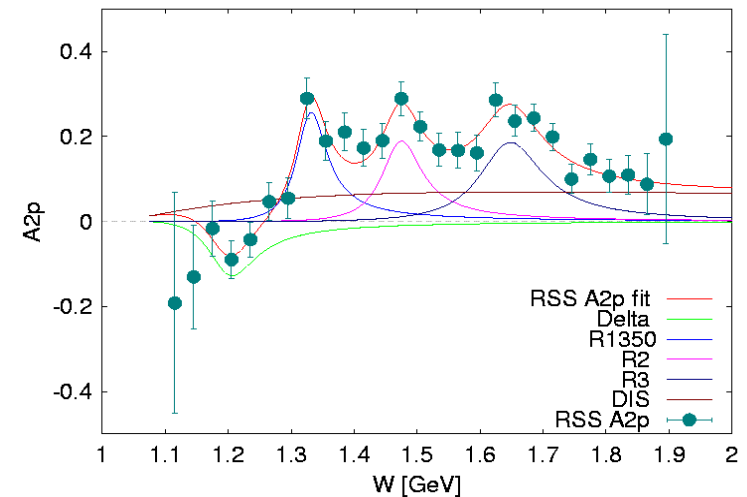
- $A_1, A_2$  have minimal model dependence
  - $D'(E, E', \theta, R)$  is function only of kinematics and  $R = \sigma_L / \sigma_T$ 
    - Proton  $R, F_1$  from fit to Hall C  $e-p$  data (E. Christy)
    - Deuteron  $R, F_1$  from fit to world data (P. Bosted)

# RSS Proton Spin Asymmetries



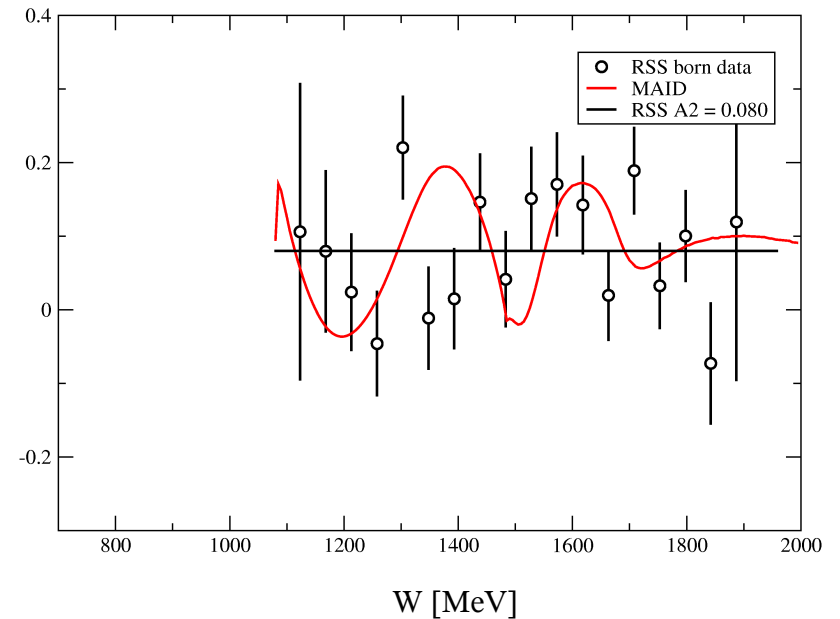
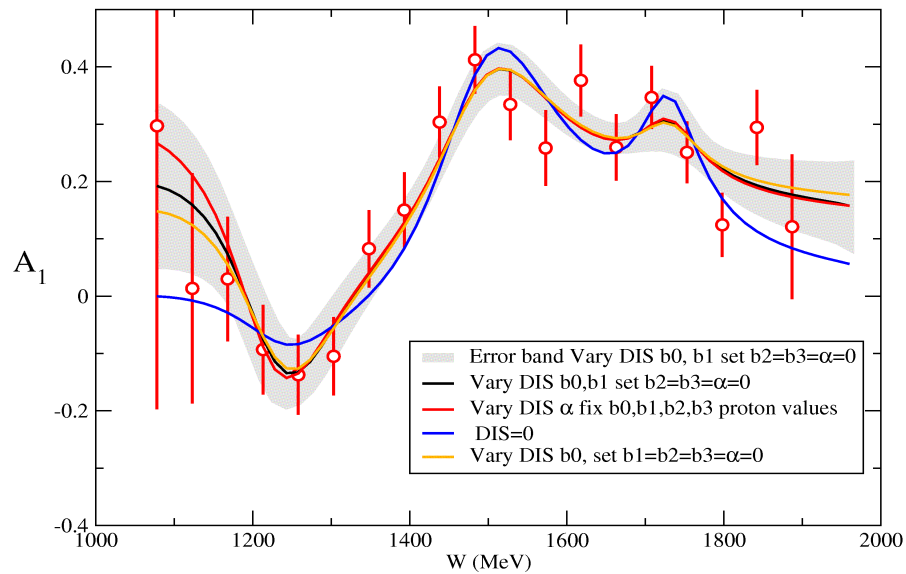
Fit  $A_1$  and  $A_2$  independently

- Four Breit-Wigner resonance shapes plus DIS background
- Reduced  $\chi^2 = 1.2 - 1.4$  for 12 d.o.f.
- PRL 98, 132003 (2007)



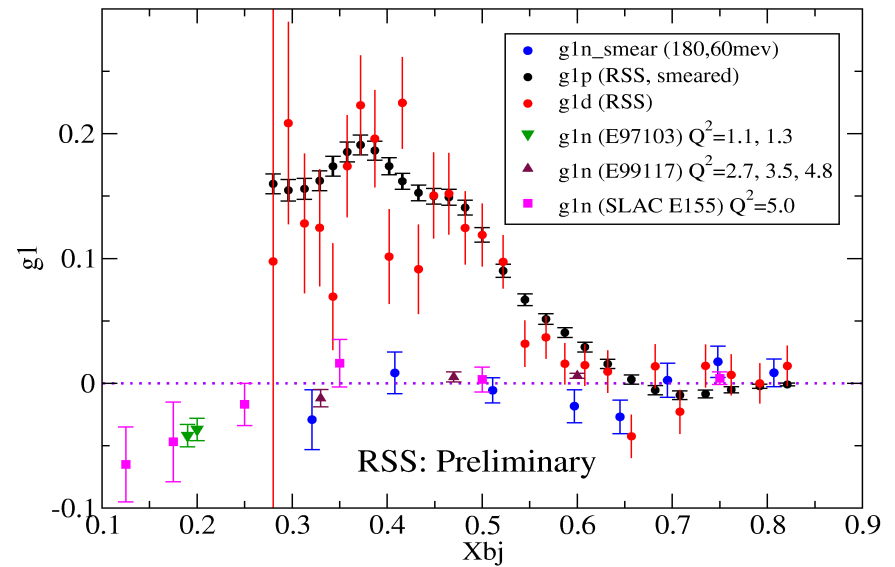
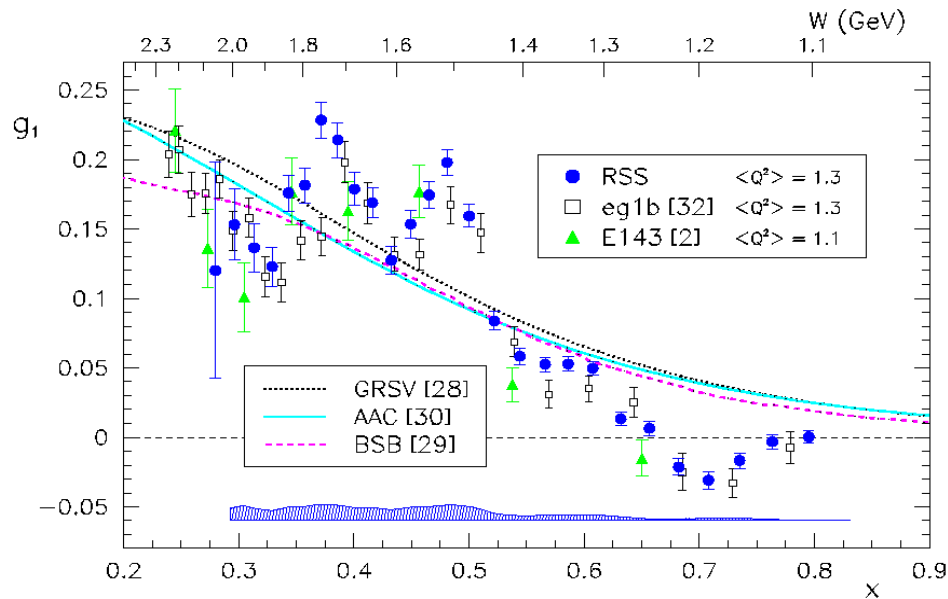


# RSS Deuteron Spin Asymmetries



- Fit deuteron  $A_1$  with three B-W resonances plus linear DIS
- Fit deuteron  $A_2$  with constant:  $A_2 = 0.083 \pm 0.017$

# RSS Spin Structure Functions



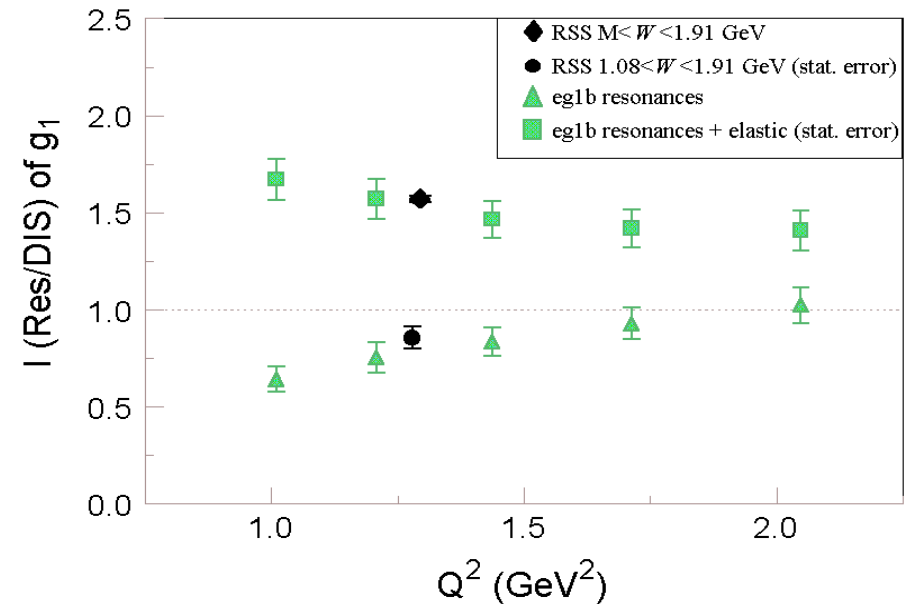
- Use measured unpolarized  $F_1$
- High precision, high resolution measurement
  - Extracting neutron SF's requires polarized proton smearing (Kulagin & Melnitchouk, PRC 77, 015210 (2008))

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

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

# RSS goal Bloom-Gilman Local Duality for $g_1^p$

- Polarized (B-G) Local Duality:  
Ratio of integrals (at constant  $Q^2$ ) = 1
  - $g_1$  fit over  $A_1$  fit resonances
  - $g_1$  from PDF's evolved to same  $\langle Q^2 \rangle = 1.28 \text{ GeV}^2$ , with target mass corrections
- Polarized global duality seems to work above  $Q^2 \approx 1.8 \text{ GeV}^2$



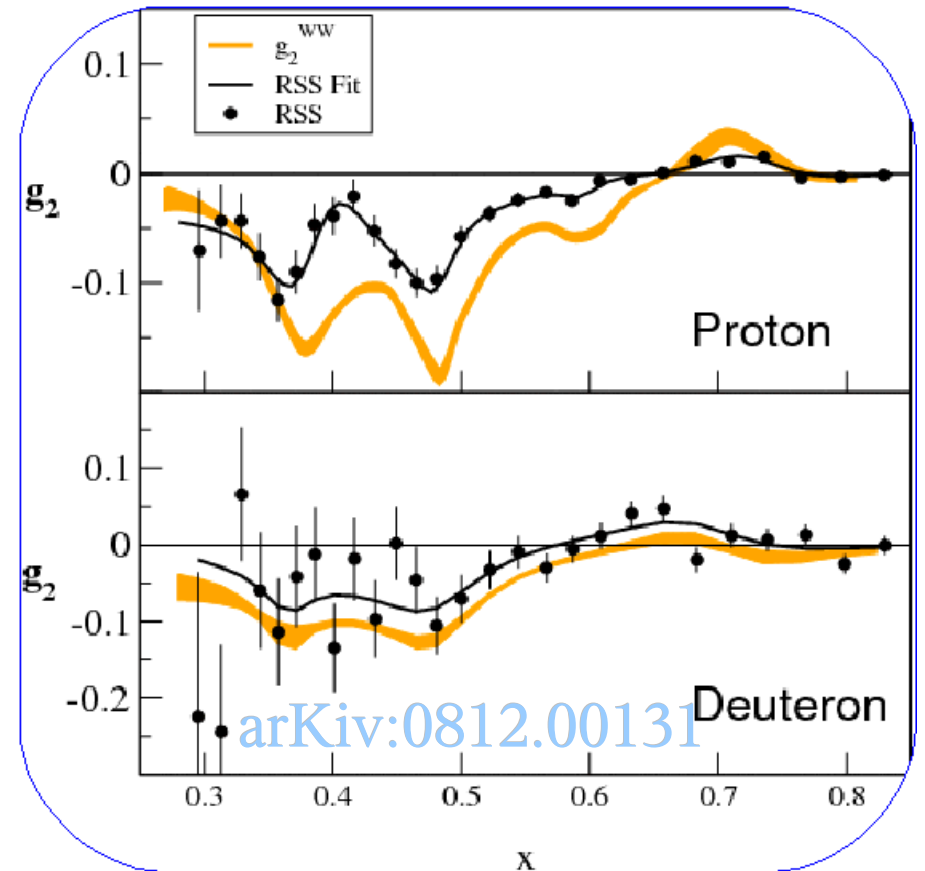
RESONANCES	W <sub>LOW</sub>	W <sub>HIGH</sub>	INTEGRAL RATIOS		
			PDFS/RESONANCES	ERROR	
			AVERAGE	DATA	PDFs
DELTA	1.11	1.30	3.93	0.58	0.37
R1350	1.30	1.39	1.36	0.10	0.07
R2	1.39	1.68	0.78	0.05	0.04
R3	1.68	1.81	0.79	0.06	0.04
GLOBAL	1.08	1.91	1.17	0.08	0.06

# $g_2$ Spin Structure Functions

- First world data for  $g_2^{p,d}$  in the resonances
- Clear higher-twist in  $g_2^p(x > 0.4)$
- $g_2^{ww}$  computed using *RSS* fit to  $g_1$  point by point

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

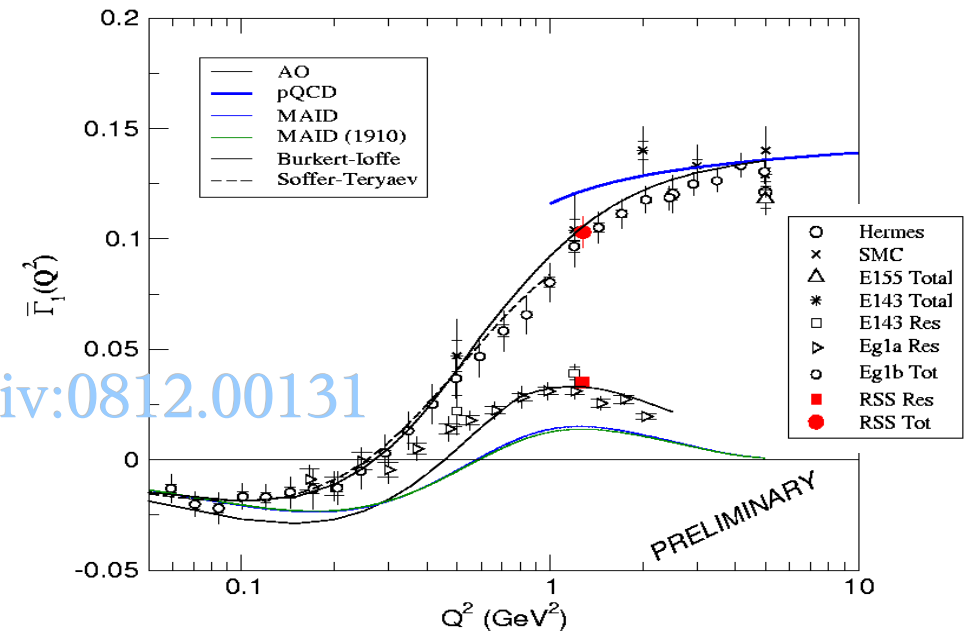
$$g_2^{ww}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 dy \frac{g_1(y, Q^2)}{y}$$



# Sum Rules

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

$$\begin{aligned}\overline{\Gamma}_1(Q^2) &= \int_0^{1-el} g_1(x, Q^2) dx \\ &= \frac{1}{36} ((a_8 + 3a_3) C_{NS} + 4a_0 C_S)\end{aligned}$$



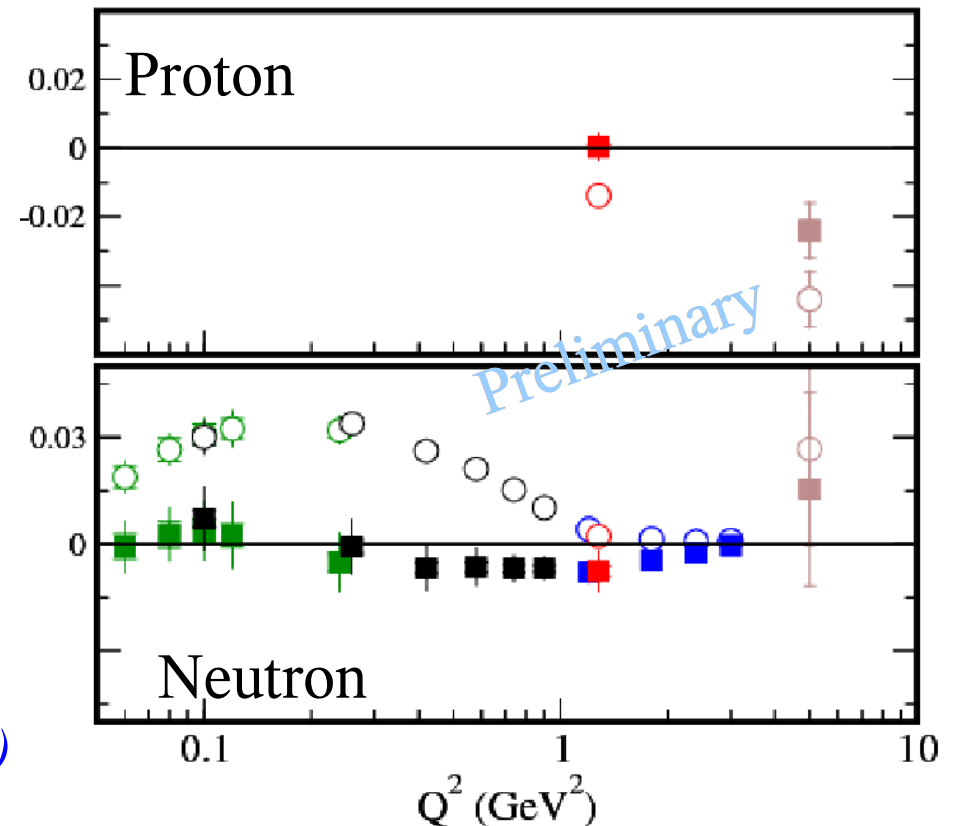
arKiv:0812.00131

# Sum Rules

- First moment of  $g_2$  (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 (very preliminary)*  
*E97-110, E94-010*
  - *SLAC E155x*
- (From K. Slifer)



# 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  $g_1$  and  $g_2$  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:  $Q^2 < \sim 5 \text{ GeV}^2$  and for the higher moments dominated by high  $x$  contributions:  $d_2$ (twist-3),  $a_2$ (twist-2)

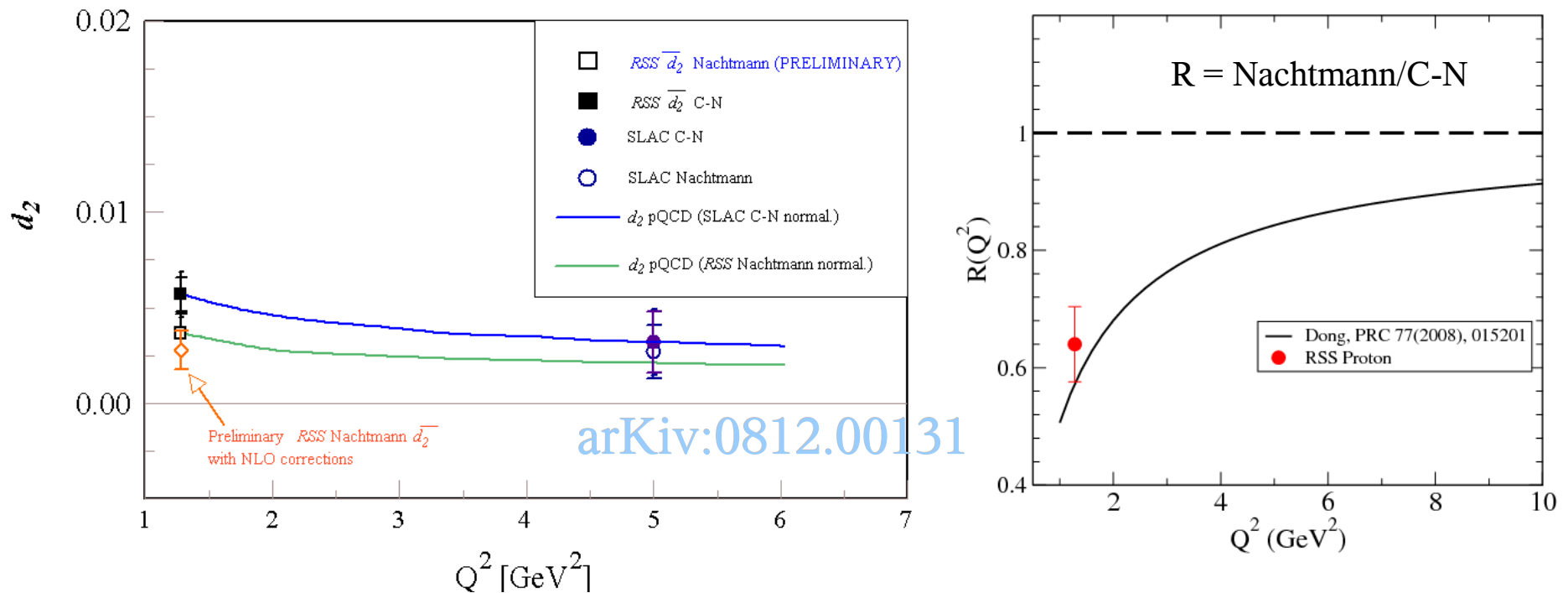
$$d_2^{\text{Nachtm.}}(Q^2) = \int_0^1 dx \xi^2 \left( 2 \frac{\xi}{x} g_1 + 3 \left( 1 - \frac{\xi^2 M^2}{2Q^2} \right) g_2 \right) \Rightarrow_{Q^2 \rightarrow \infty} \int_0^1 dx x^2 (2 g_1 + 3 g_2)$$

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

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

# Twist-3 (proton)

- The twist-3 matrix element  $d_2$  represents  $q-g$  correlations



**RSS** inelastic ( $0 < x < \text{inelastic threshold}$ );  $\overline{d_2}(x < 0.316) = 0$ , extrapolated from data

$$d_2^{\text{C-N}}(1.3 \text{ GeV}^2) = 0.0057 \pm 0.0013 \text{ (published)}$$

$$d_2^{\text{Nachtmann}} = 0.0037 \pm 0.0010 \text{ (total error): } \underline{\text{clean twist-3 to } > 3 \text{ sigmas}}$$



# Twist-3 (deuteron, etc.)

*RSS* inelastic ( $0 < x < \text{inelastic threshold}$ ),  $\overline{d}_2(x < 0.316) = 0$ , extrapolated from data

**Deuteron**  $d_2^{\text{C-N}} = 0.0082 \pm 0.0019$  (all total errors) [arKiv:0812.0031](https://arxiv.org/abs/0812.0031)

$d_2^{\text{Nachtmann}} = 0.0048 \pm 0.0015$ : clean twist-3 to 3 sigmas

**Neutron**  $d_2^{\text{Nachtmann}} = 0.0015 \pm 0.0019$  **Non-Singlet**  $d_2^{\text{Nachtmann}} = 0.0022 \pm 0.0026$

Y. B. DONG

PHYSICAL REVIEW C 77, 015201 (2008)

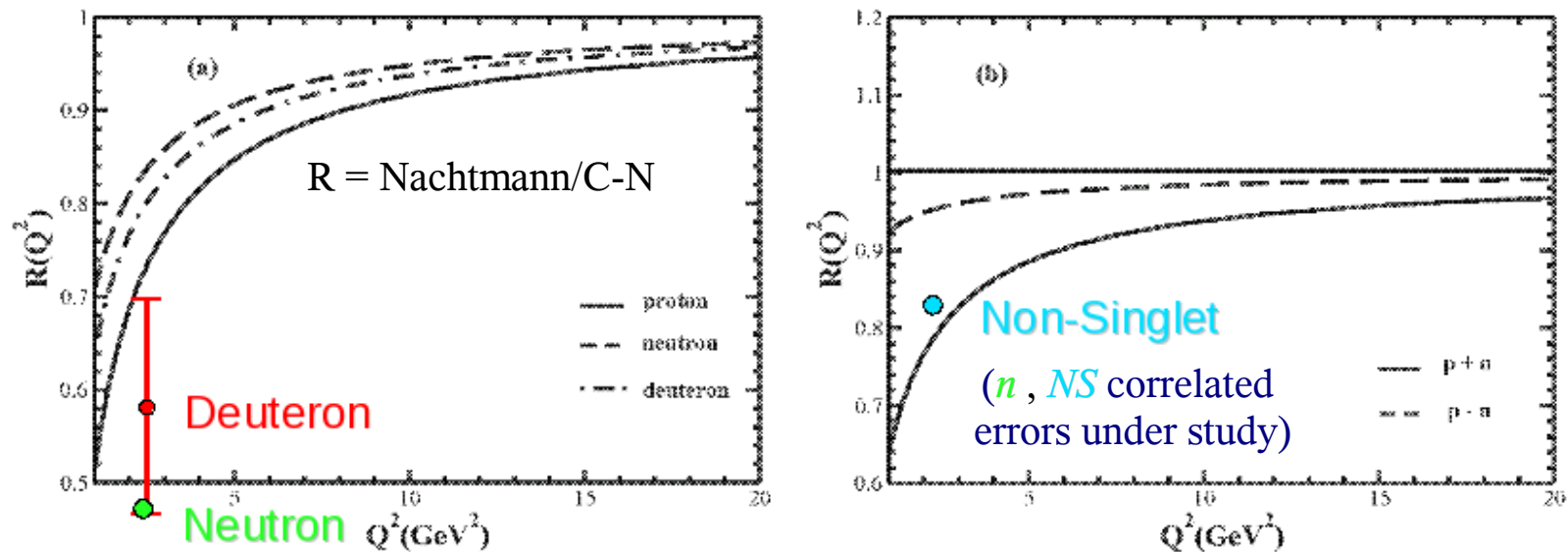


FIG. 1. Ratio  $R(Q^2)$ .

# 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

Argonne National Lab., Christopher Newport U., Florida International U.,  
Hampton U., Jefferson Lab., U. of New Hampshire, Norfolk S. U.,  
North Carolina A&T S. U., Mississippi S. U., Ohio U., IHEP - Protvino, U. of Regina,  
Rensselaer Polytechnic I., Rutgers U., Seoul National U., Southern U. New Orleans,  
Temple U., Tohoku U., U. of Virginia , Yerevan Physics I., Xavier U.

### Spokespersons:

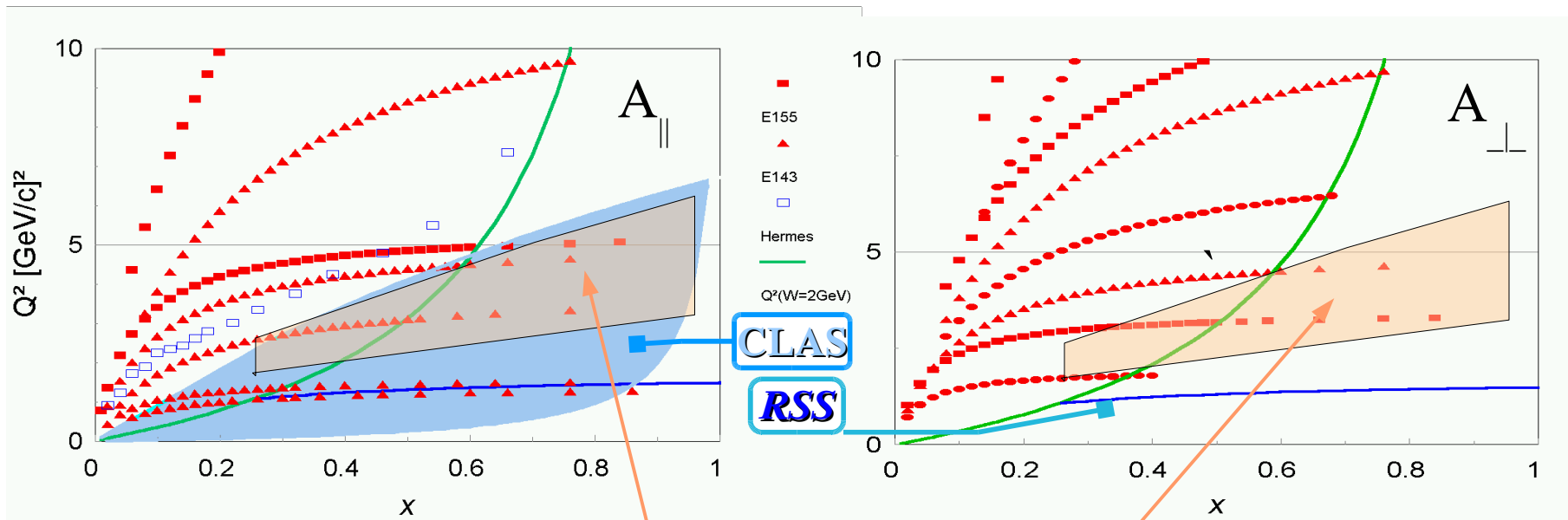
S. Choi (Seoul), M. Jones (JLab), Z-E. Meziani (Temple), O. A. Rondon (U. of Virginia)

- Measure **proton** spin structure function  $g_2(x, Q^2)$  and spin asymmetry  $A_1(x, Q^2)$  for  $2.5 \leq Q^2 \leq 6.5 \text{ GeV}^2$  and  $0.3 \leq x \leq 0.8$
- **SANE meets DOE 2011 Milestone for Proton Spin Structure**

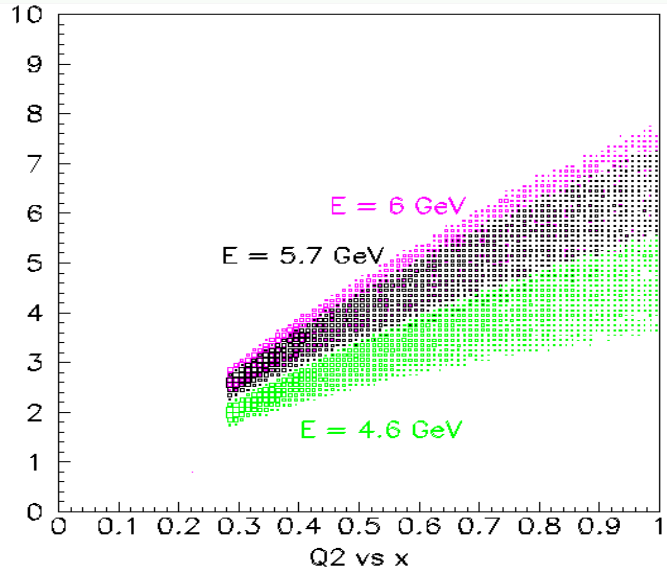
# SANE Physics

- 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  $g_1$ 
    - $d_2$  matrix element =  $\int_0^1 x^2 (3 g_2 + 2 g_1) dx$
  - 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**

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



SANE



- Two beam energies: **5.9 GeV**, **4.7 GeV**
- Very good high  $x$  coverage with detector at  $40^\circ$

# SANE Layout

BETA ( $40^\circ$ )

BigCal  
w. Gain Monitor

Lucite Hodoscope

Gas Cherenkov

Forward  
Hodoscope

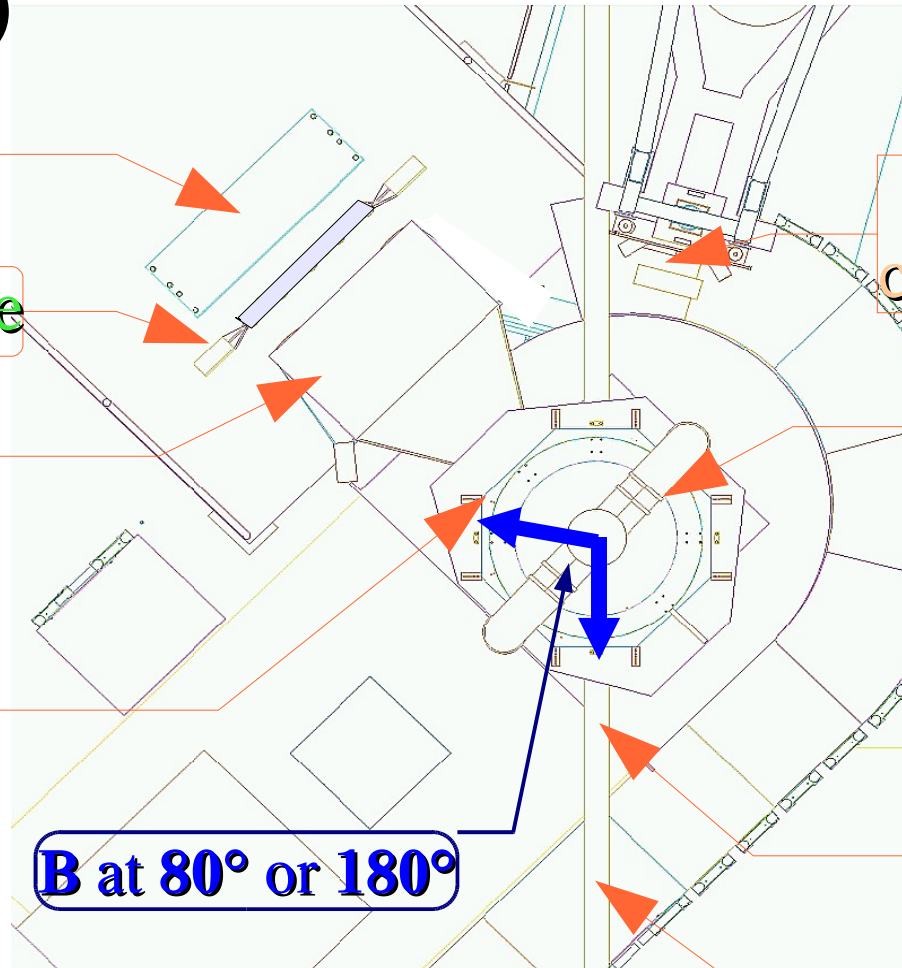
**B at  $80^\circ$  or  $180^\circ$**

HMS ( $15^\circ$ -  $42^\circ$ )  
calibrations, backgd.

Polarized Target

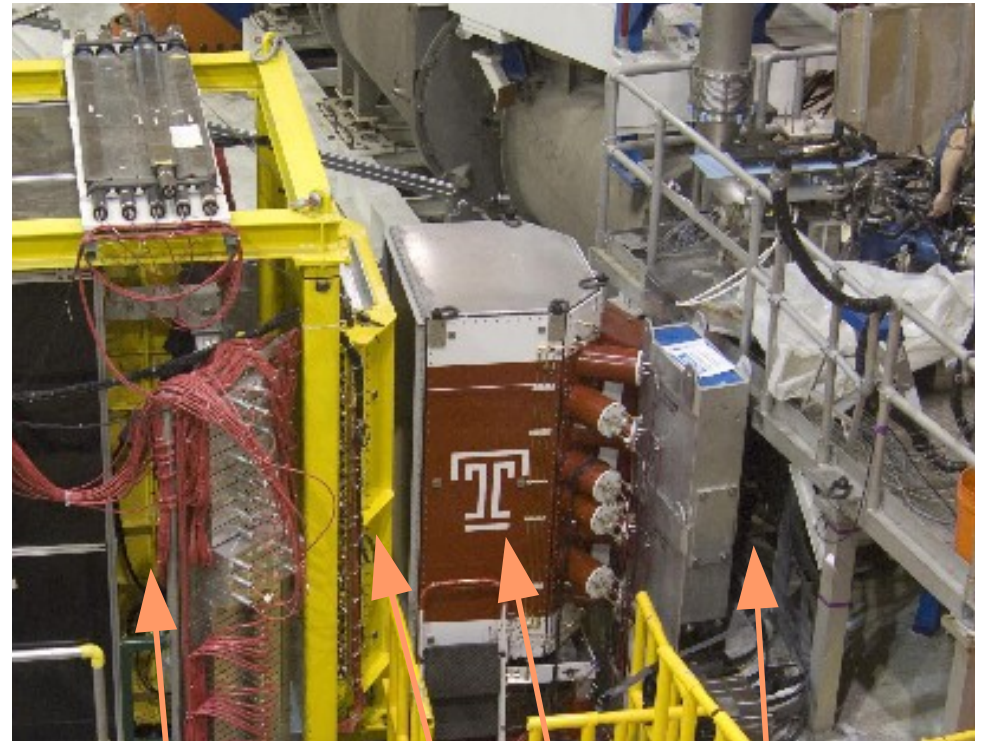
Target Beam  
position monitor

Beam Line



# 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  $8\%/\sqrt{E(\text{GeV})}$
  - 1000:1 pion rejection
  - vertex resolution  $\sim 5$  mm
  - angular resolution  $\sim 1$  mr
- Target field sweeps low  $E$  background
  - 180 MeV/c cutoff



BigCal

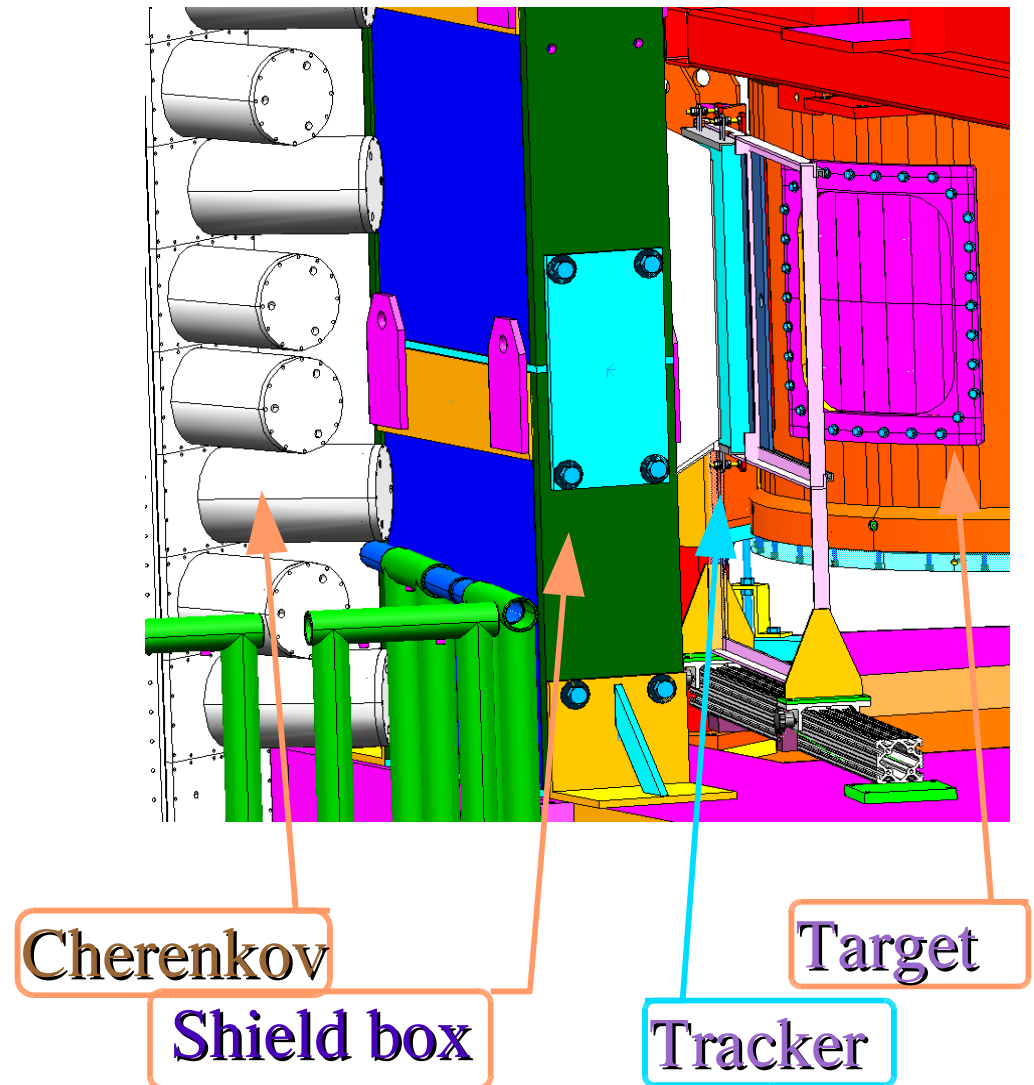
Lucite Hodoscope

Cherenkov

Tracker

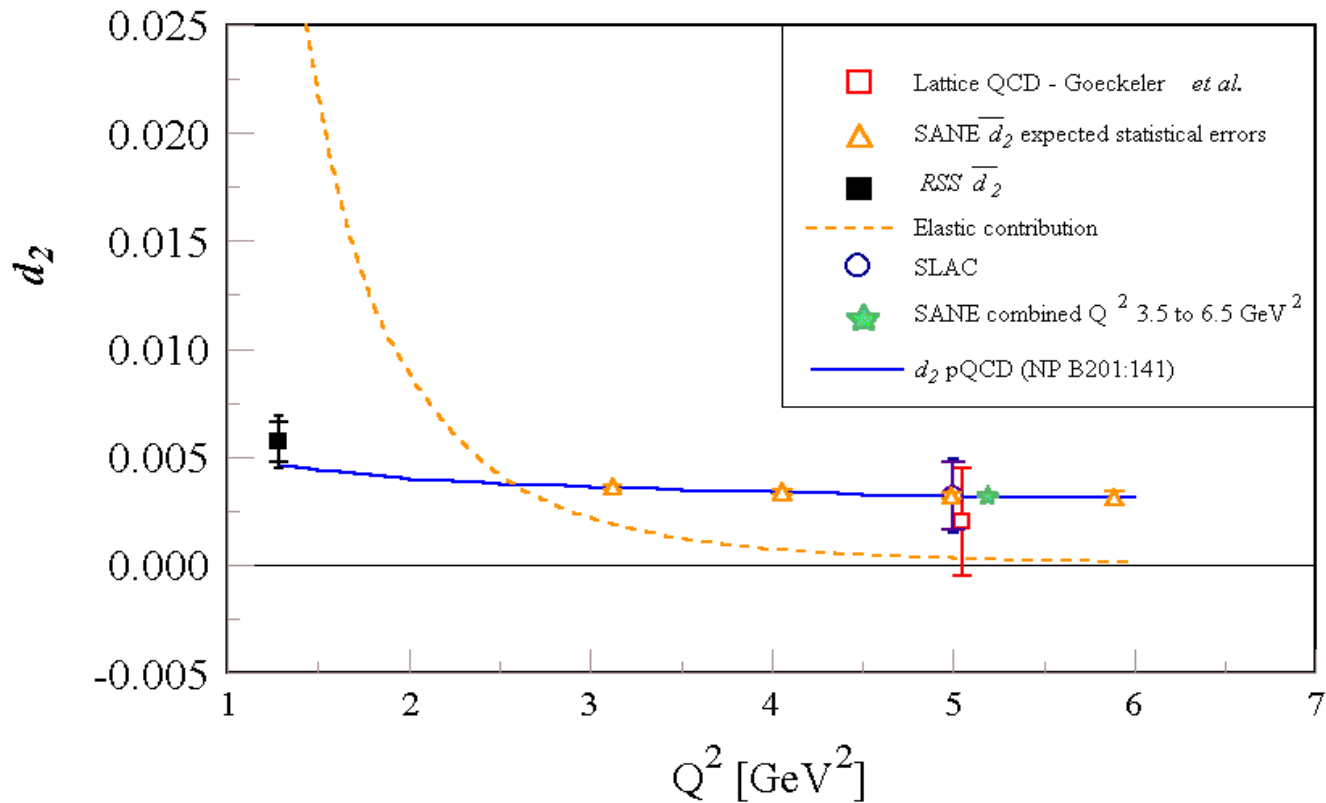
# Big Electron Telescope Array – BETA

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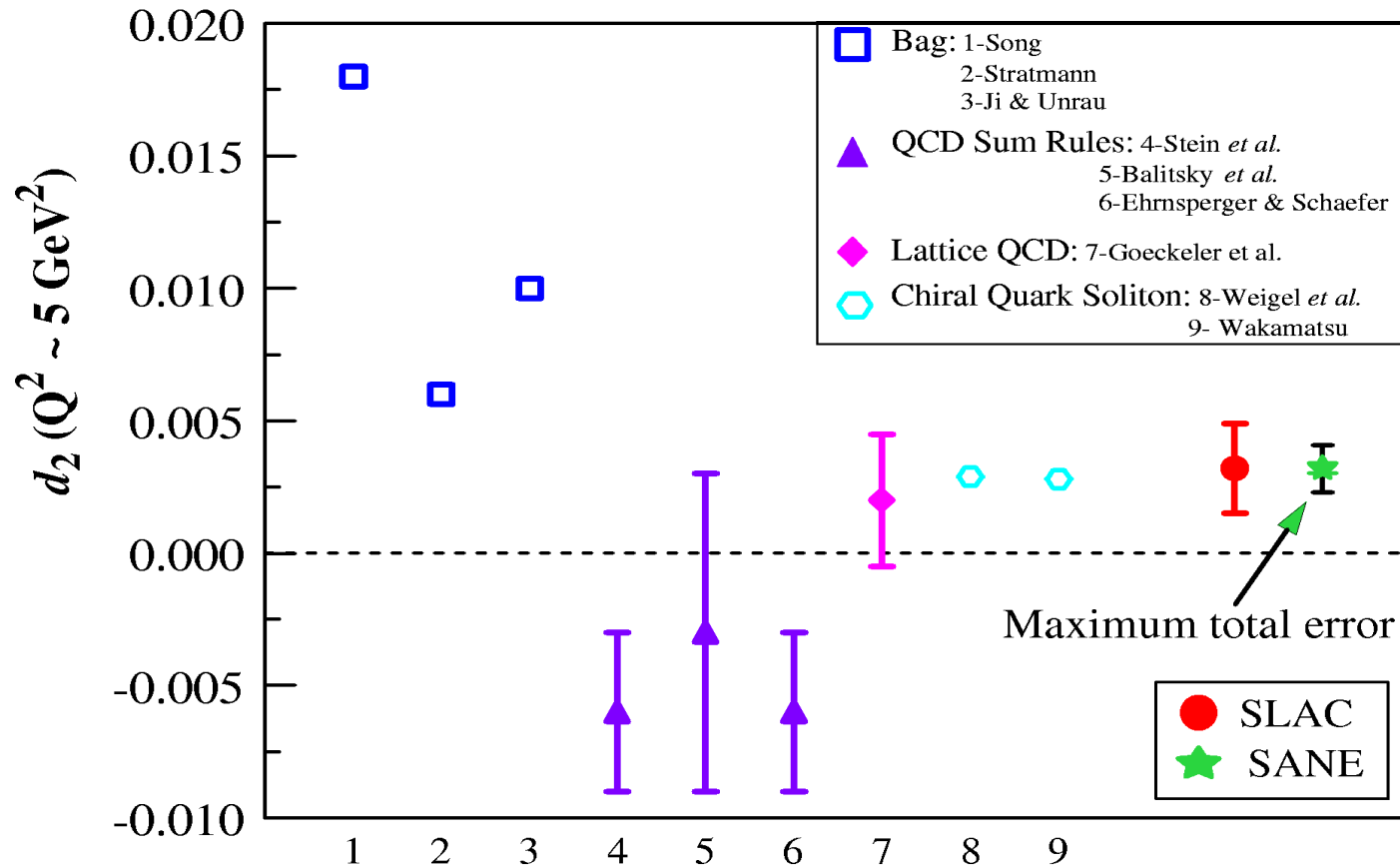
# SANE Expected Results (I)



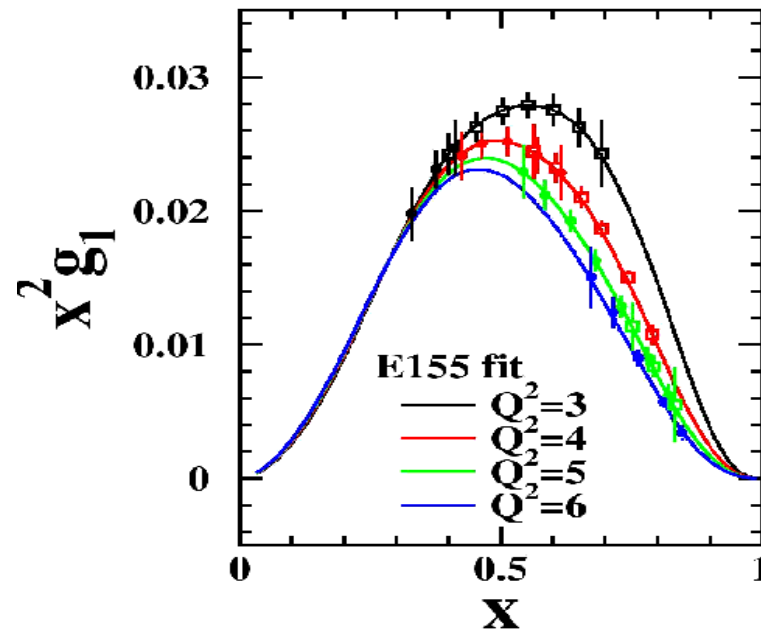
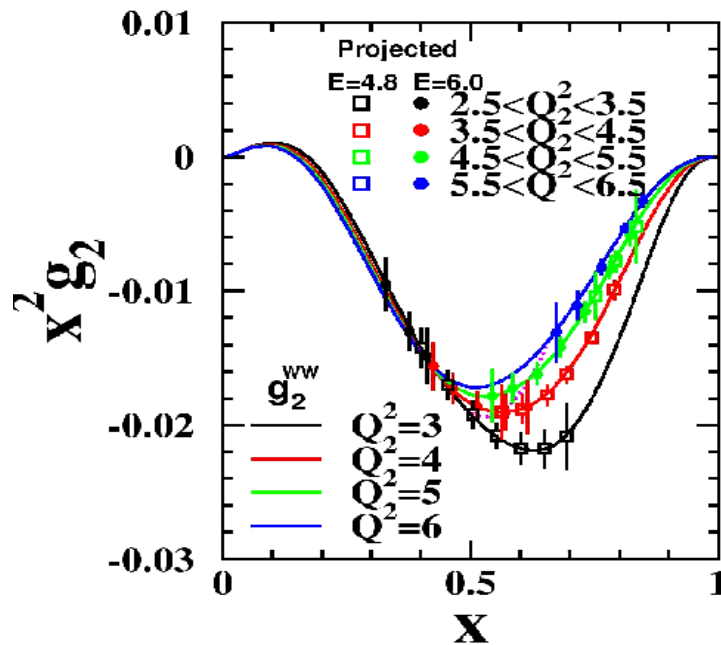
- SANE expected statistical errors for  $\overline{d}_2 = \int_{x_{\min}}^{x_{\max}} x^2 (2g_1 + 3g_2) dx$

$Q^2$ GeV <sup>2</sup>	$\Delta x$		$\delta d_2/d_2$	
	Proposal	Projected	Proposal	Projected
2.5 - 3.5	.29 - .85	.29 - .71	4.0%	4.6%
3.5 - 6.5	.41 - .96	.41 - .84	2.5%	3.2%

# SANE Expected Results (Ia)

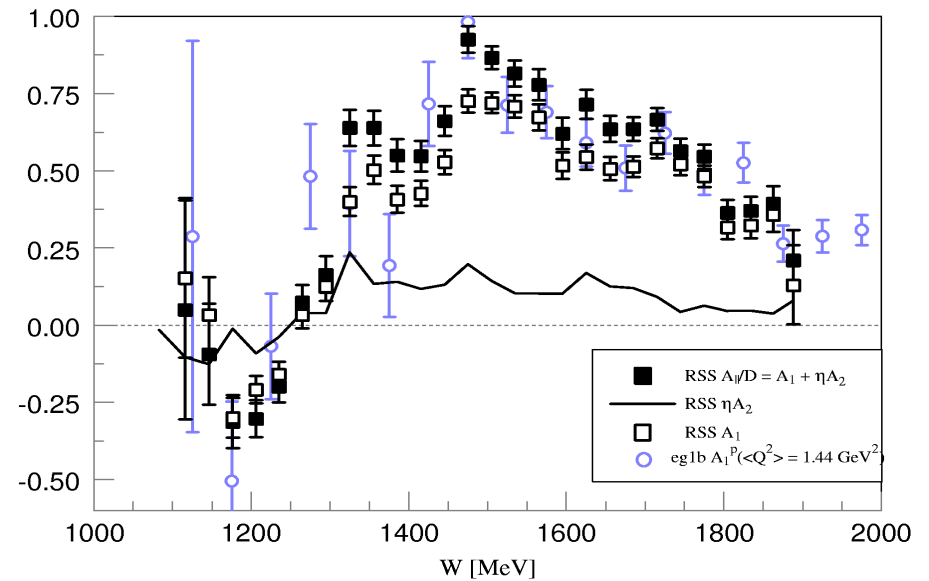
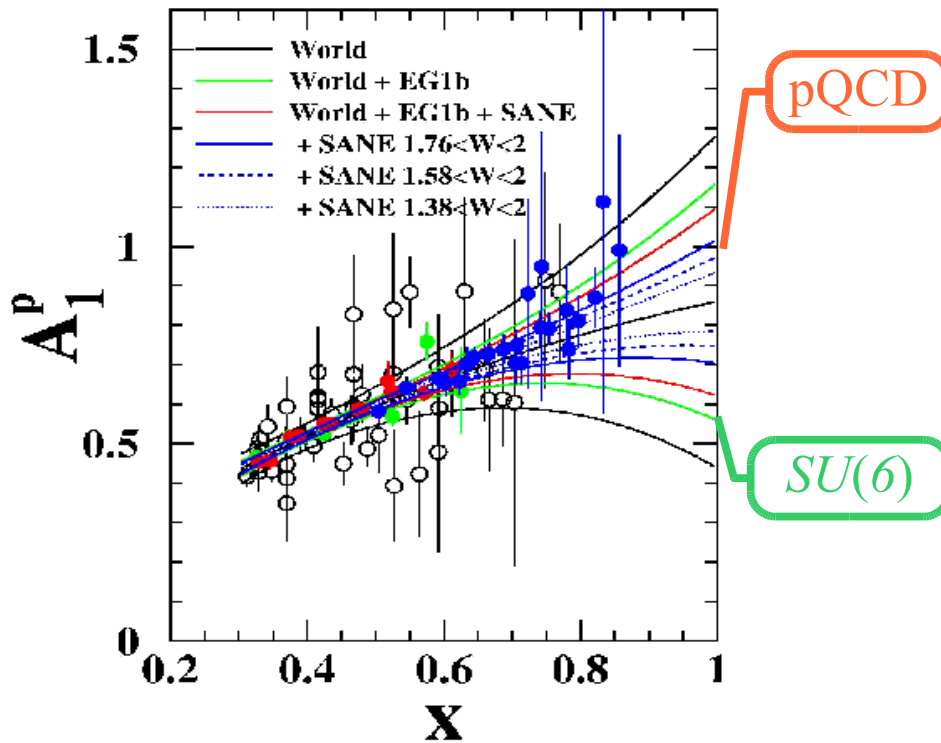


# SANE Expected Results (II)



- $x$  dependence at constant  $Q^2$  and  $Q^2$  dependence at fixed  $x$  (illustrative binning only)
- data are concentrated in the region most sensitive to  $x^2 g_{2,1}$ 
  - (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  $\pm 0.1$  (using duality)
- Both  $A_{\parallel}$  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

# Beam Time

	Energy GeV	$\theta_N$	Time (Proposal FOM h)		
			Proposal	Actual	fraction
<b>Calibration</b>	2.4	off, 0, 180	47	25	53%
<b>Production</b>	4.7	180	70	20*	29%
	4.7	80	130	98	75%
	5.9	80	200	143	72%
	5.9	180	100	$\geq 35$	$\geq 35\%$
<b>Commissioning</b> [ calendar days]			14.0	99	
<b>Total</b> [ calendar days]			70.0	141	

\* At 30% efficiency until 3/16/09

SANE Collaboration (E-07-003)

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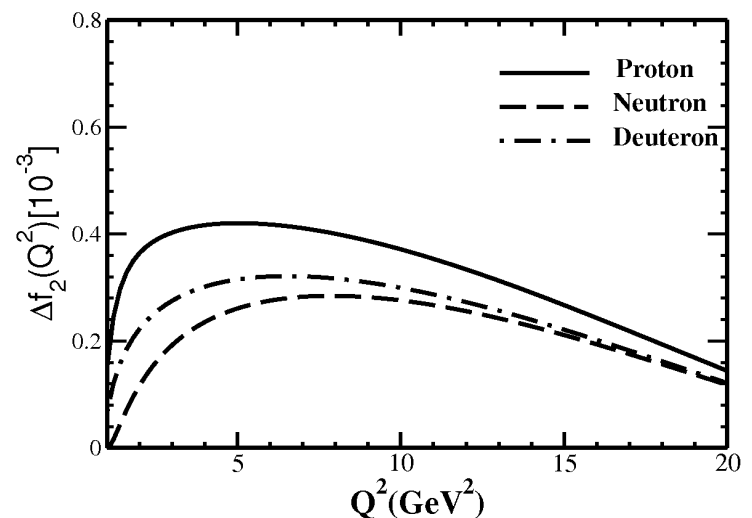
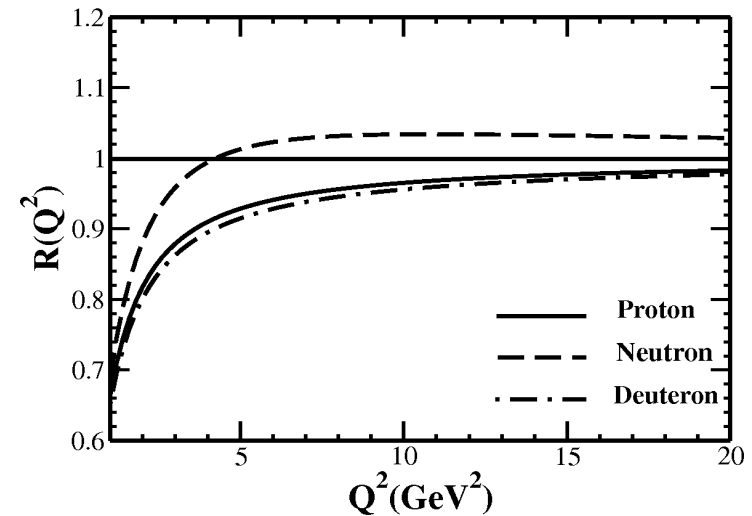
# Twist-3 operators

- The number of twist-3 operators increases with the order of the moment
- $d_n$  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  $d_2$
- There are three  $d_{i=1,2,3}^4$  operators associated with the fifth moment
  - with precise data 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

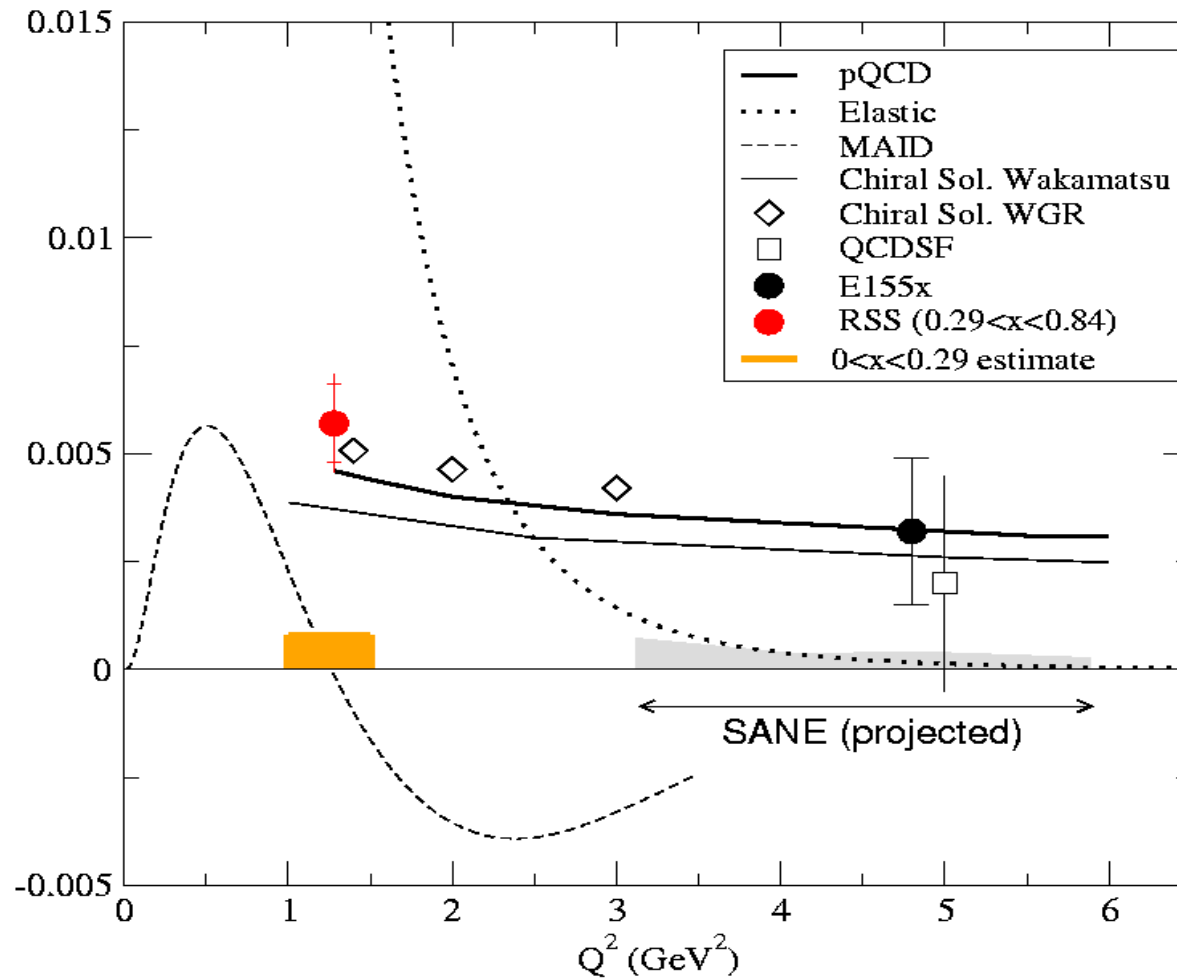


# Twist-2 and Twist-4

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

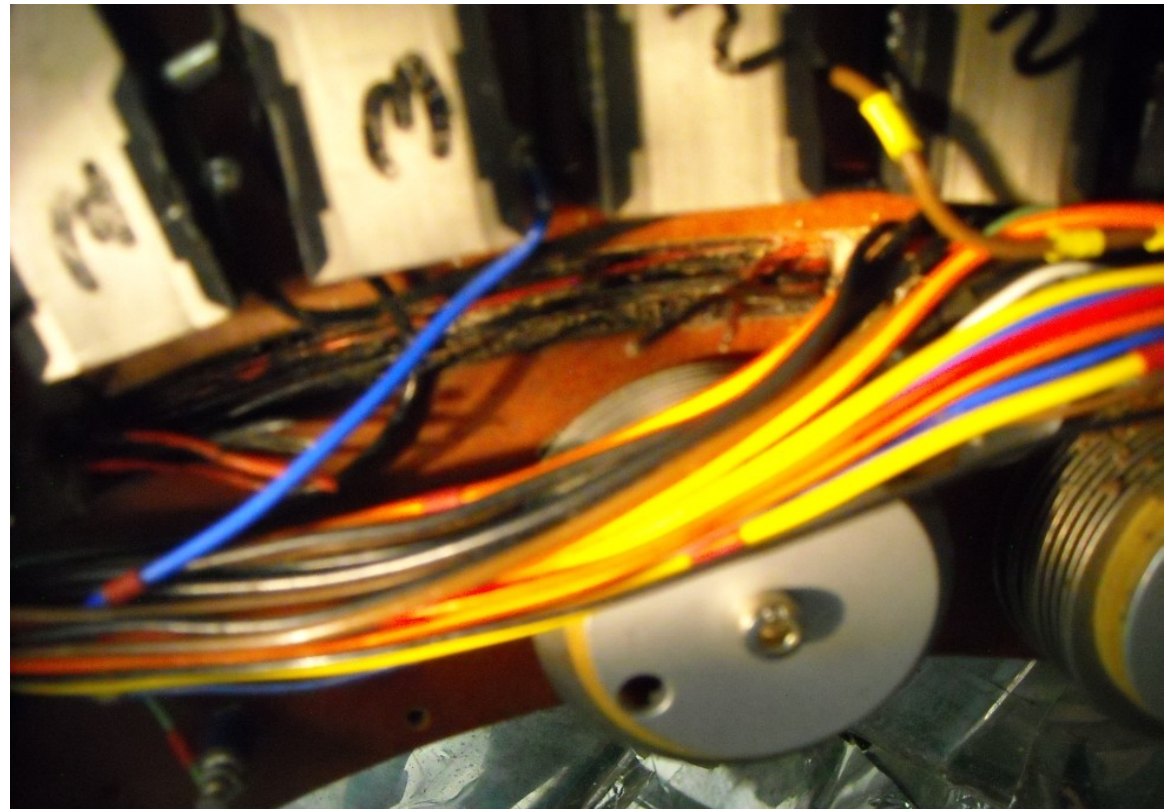


# Twist-3 in $g_2^p$



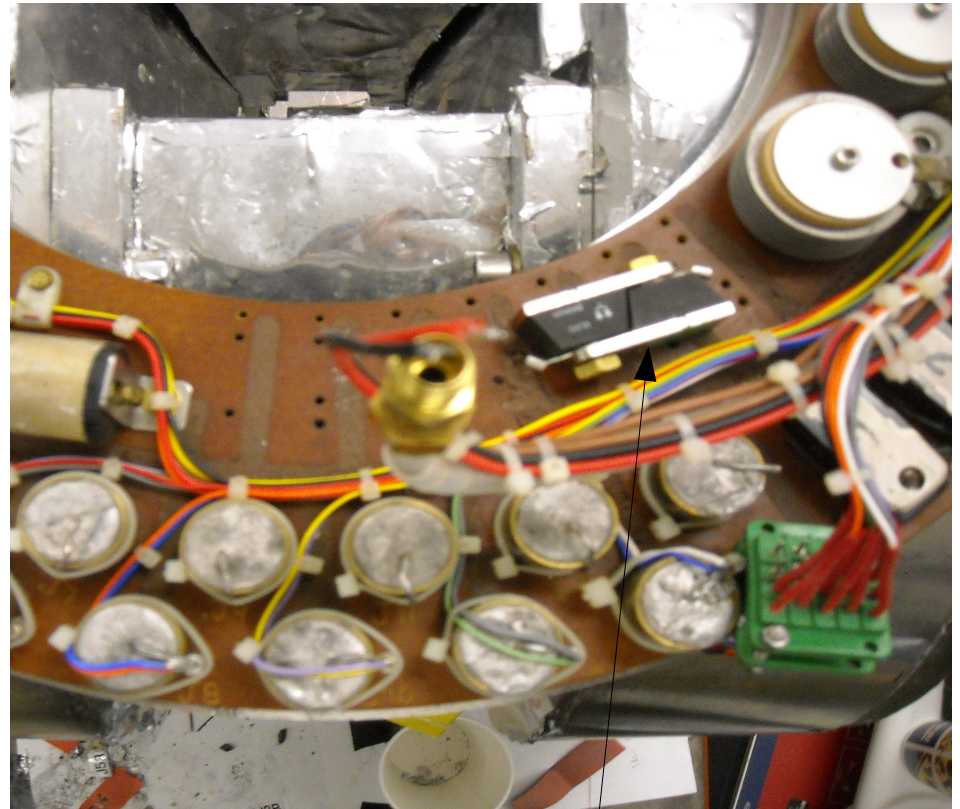
# Magnet Circuit Damage

- Diagnostics with the magnet cold indicated need to open it for repair
- Extensive testing (B. Vulcan, J. Beaufait and others) found multiple burned out wires connecting sections of one of the main coils
- A protection diode for one coil was also found to be broken.



# Magnet Repairs

- Oxford specialist Paul Brodie and J. Beaufait reconnected wires with ~1" superconducting joints and ~3" copper to copper contacts
- Replacement diodes were mounted on circuit board
- Magnet operation after repairs is delicate, prone to quench
- Protection circuits working



Replacement  
diodes