

Nucleon Resonance Spin Structure

K. Slifer

University of Virginia

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Deep-Inelastic Scattering and Related Subjects**

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Resonant Spin Structure (RSS)

of the Proton and Deuteron

Mark K. Jones
(JLab)

Oscar A. Rondon
(UVA)

Analysis

*Karl Slifer, Shige Tajima, Frank Wesselmann
Peter Bosted, Eric Christy*

JLab E01-006 Collaboration

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

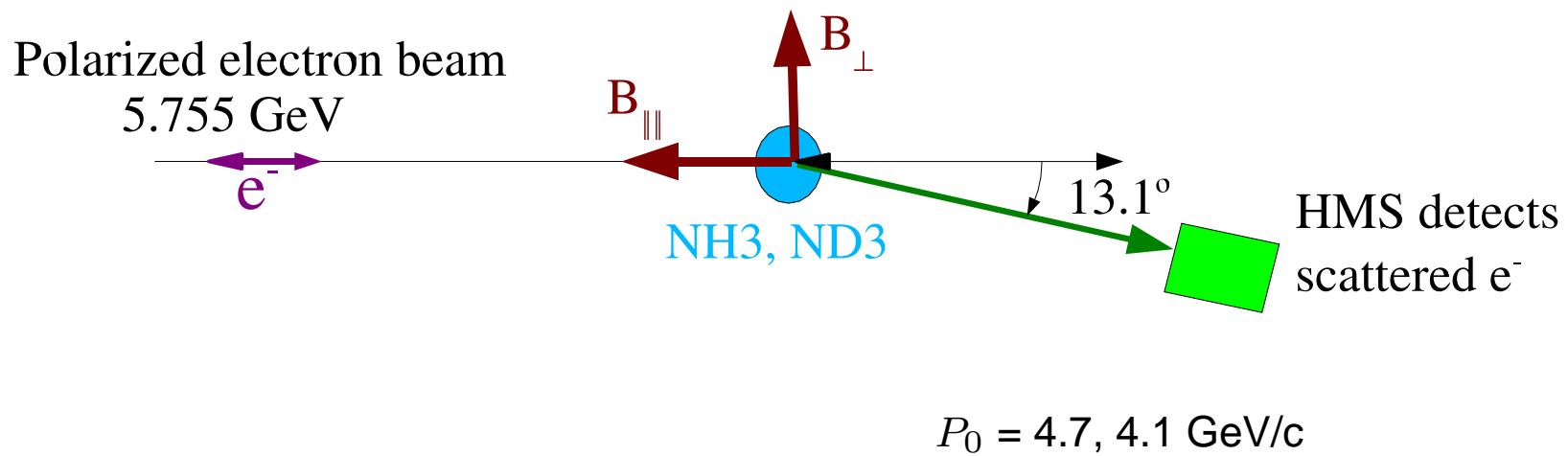
Resonant Spin Structure Experiment

Polarized electron scattering on polarized nuclei.

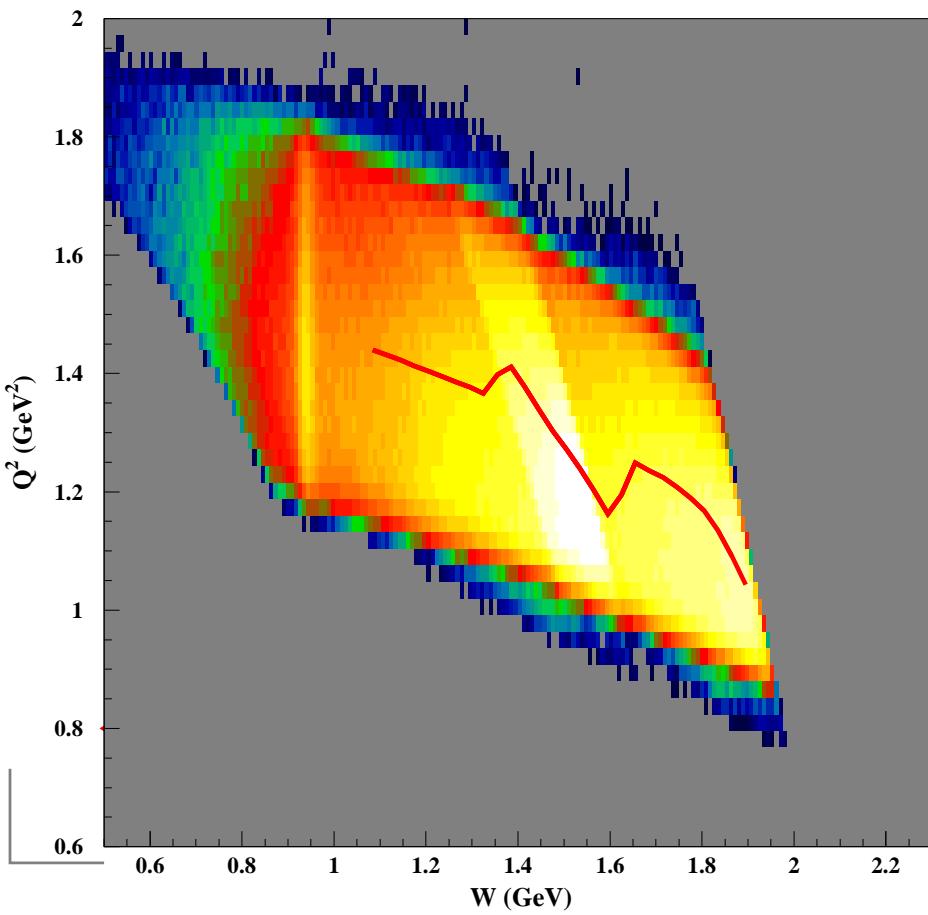
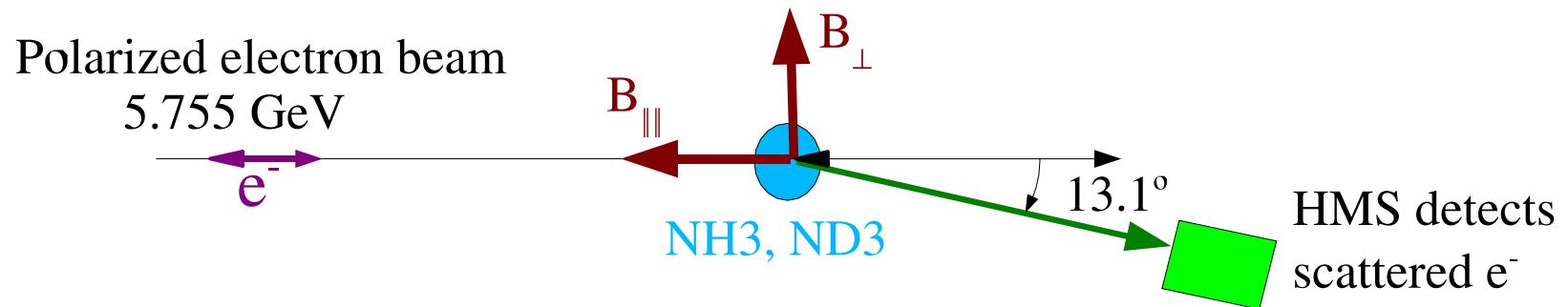
Proton and Deuteron in the resonance region.

- Measure $A_{||}$ and A_{\perp}
- Extract $A_1(W, Q^2)$ and $A_2(W, Q^2)$
- Extract $g_1(x, Q^2)$ and $g_2(x, Q^2)$
- Test for onset of polarized local duality
- Twist-3 effects in d_2 matrix element
- Extract Neutron Spin Structure Functions
- Evaluate Spin Sum Rules

Experimental set-up in Hall C



Experimental set-up in Hall C



$$P_0 = 4.7, 4.1 \text{ GeV}/c$$

$$Q^2 \approx 1.3 \text{ GeV}^2$$

$$W : 0.8 - 2.0 \text{ GeV}$$

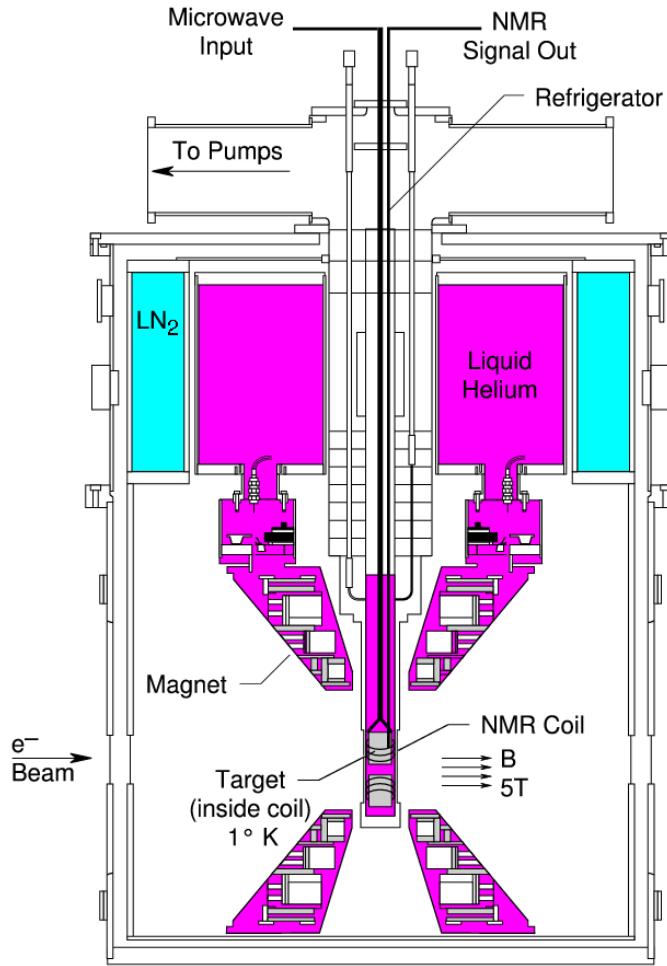
$$P_b = 65.6 \pm 2.6 \text{ for } B_{\parallel}$$

$$P_b = 70.9 \pm 1.7 \text{ for } B_{\perp}$$

$$I \approx 100 \text{nA}$$

Beam charge asym. < 0.1%

Polarized Target



Target Ladder

2 NH₃ cups

2 ND₃ cups

1 Carbon (7mm)

Target Field

5 Tesla

Para & perpendicular fields.

Polarization can be flipped by
180°. Ran \pm for equal times.

Target Polarization

NH₃ : $P_t \approx 0.68 \pm 0.017$

ND₃ : $P_t \approx 0.18 \pm 0.007$

Proton Elastic Asymmetry

$$A_{el} = \frac{K_1 \cos \theta^* + K_2 \left(\frac{G_E}{G_M} \right) \sin \theta^* \cos \phi^*}{\left(\frac{G_E}{G_M} \right)^2 + \tau/\epsilon}$$

Asymmetry in the \perp config 50 times more sensitive than in \parallel config for our kinematics.

	\parallel	\perp
$\frac{\Delta A_{el}/A_{el}}{\Delta \frac{G_E}{G_M}/\frac{G_E}{G_M}}$	0.02	1

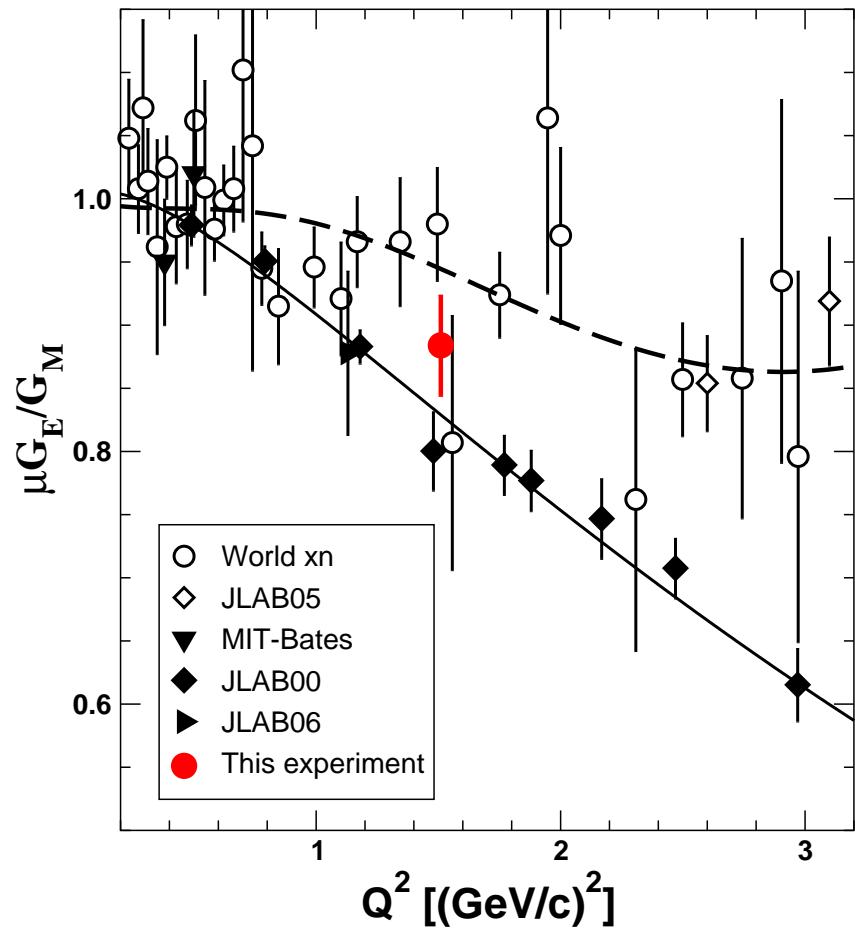
Proton Elastic Asymmetry

$$A_{el} = \frac{K_1 \cos \theta^* + K_2 \left(\frac{G_E}{G_M} \right) \sin \theta^* \cos \phi^*}{\left(\frac{G_E}{G_M} \right)^2 + \tau/\epsilon}$$

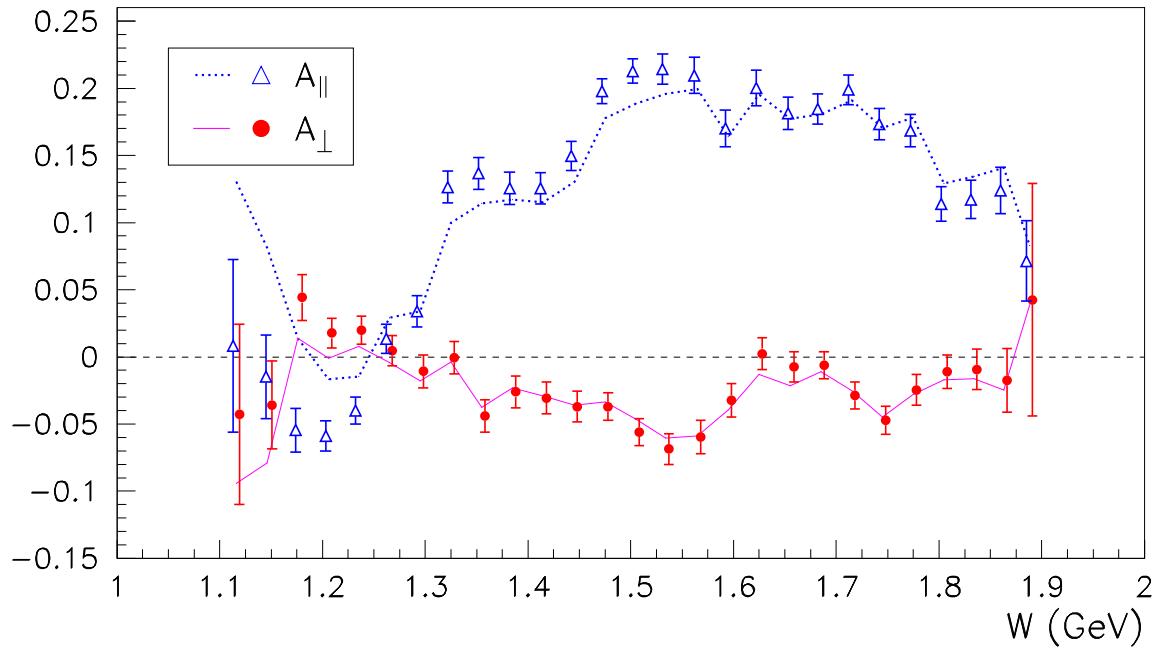
$$A_{\perp} \rightarrow \left(\frac{G_E}{G_M} \right)$$

Phys Rev C74 (2006) 035201

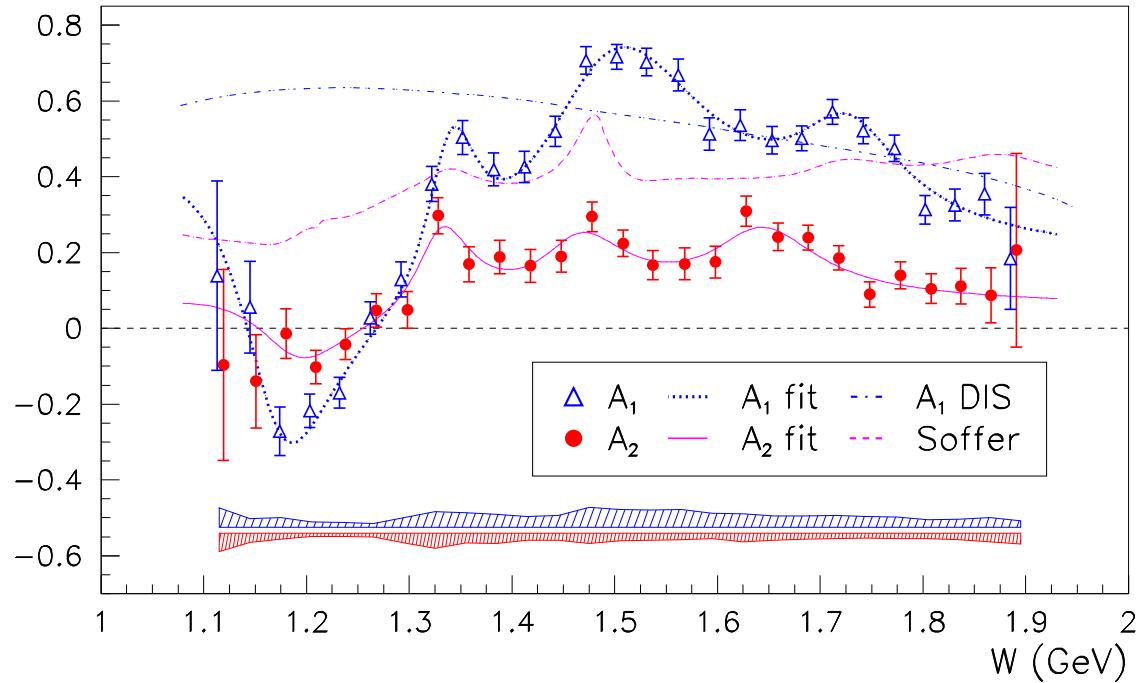
$$A_{\parallel} \rightarrow P_b P_t$$



Proton A_{\parallel} and A_{\perp}



Proton A_1 and A_2



$$A_1 = \frac{C}{D} \left(A_{||} - d A_{\perp} \right)$$

$$A_2 = \frac{C'}{D} \left(c' A_{||} + d' A_{\perp} \right)$$

D depends weakly on $R = \sigma_L / \sigma_T$

C, c', d, d' : kinematic factors

Spin Structure Functions

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

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

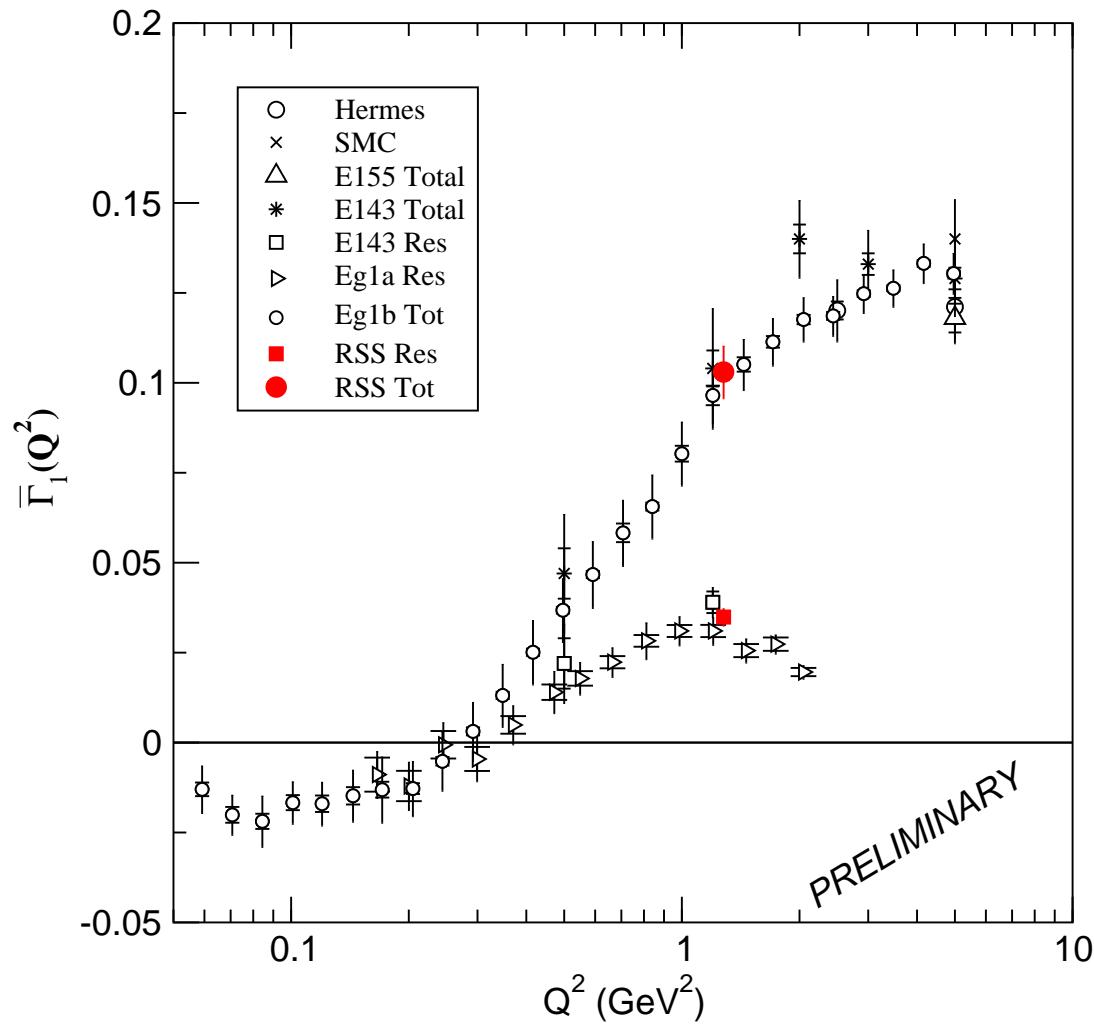
(F_1 , R from E. Christy fit to JLab unpolarized Hall C data.)

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

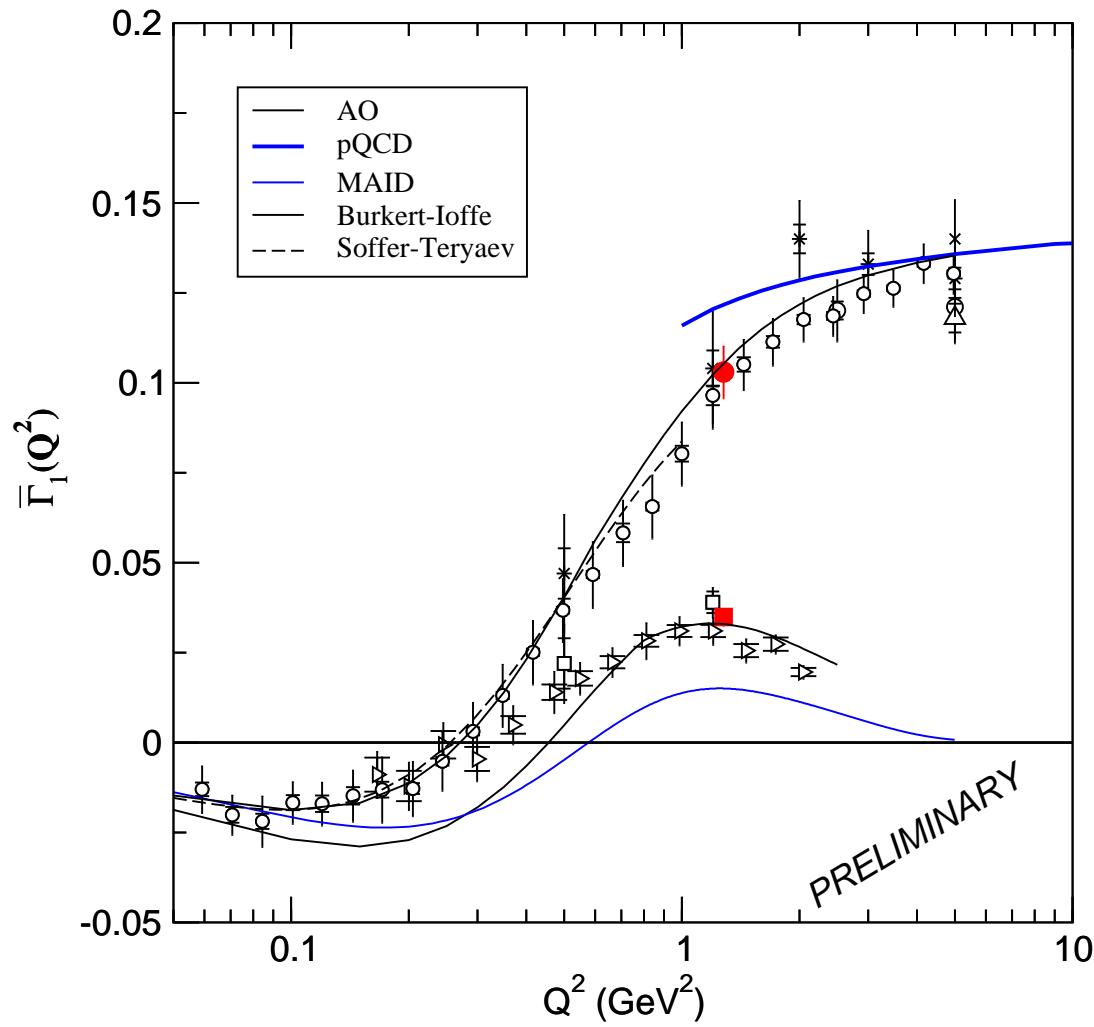
$$\Gamma_2(Q^2) = \int g_2(x, Q^2) dx$$

Evaluated with fits to our data, evolved to constant Q^2 .

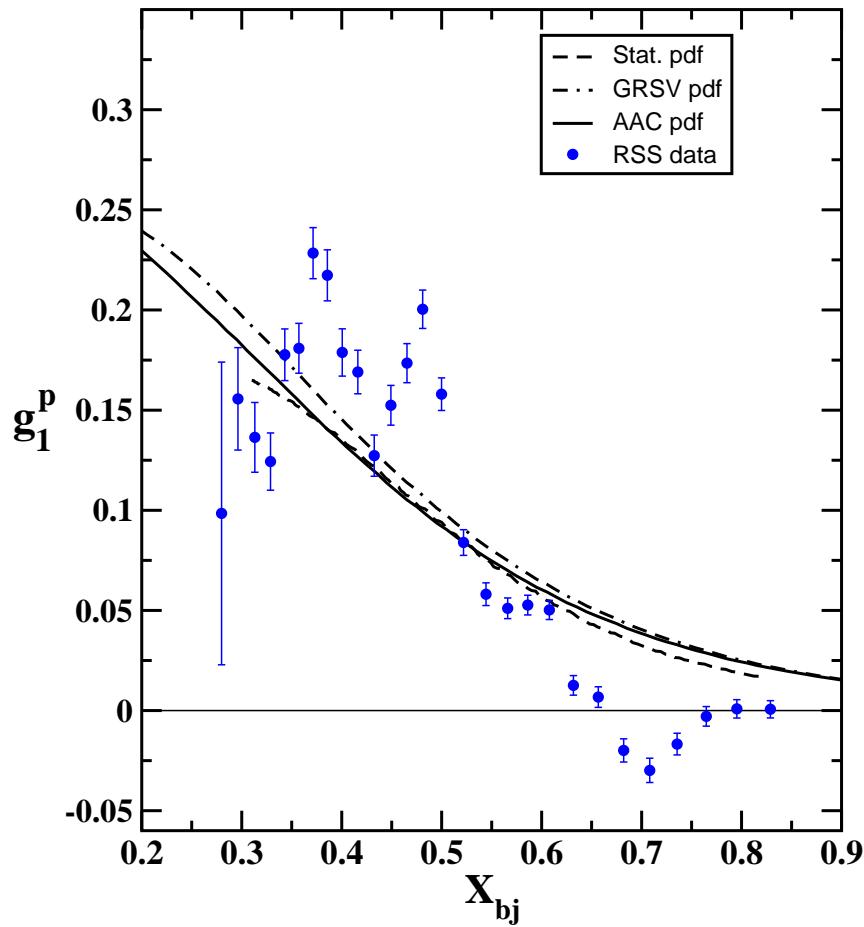
First Moment of g_1^p



First Moment of g_1^p



Proton g_1 : Duality



Data compared to PDFs

GRSV: Phys. Rev. D 53, (1996) 4775.

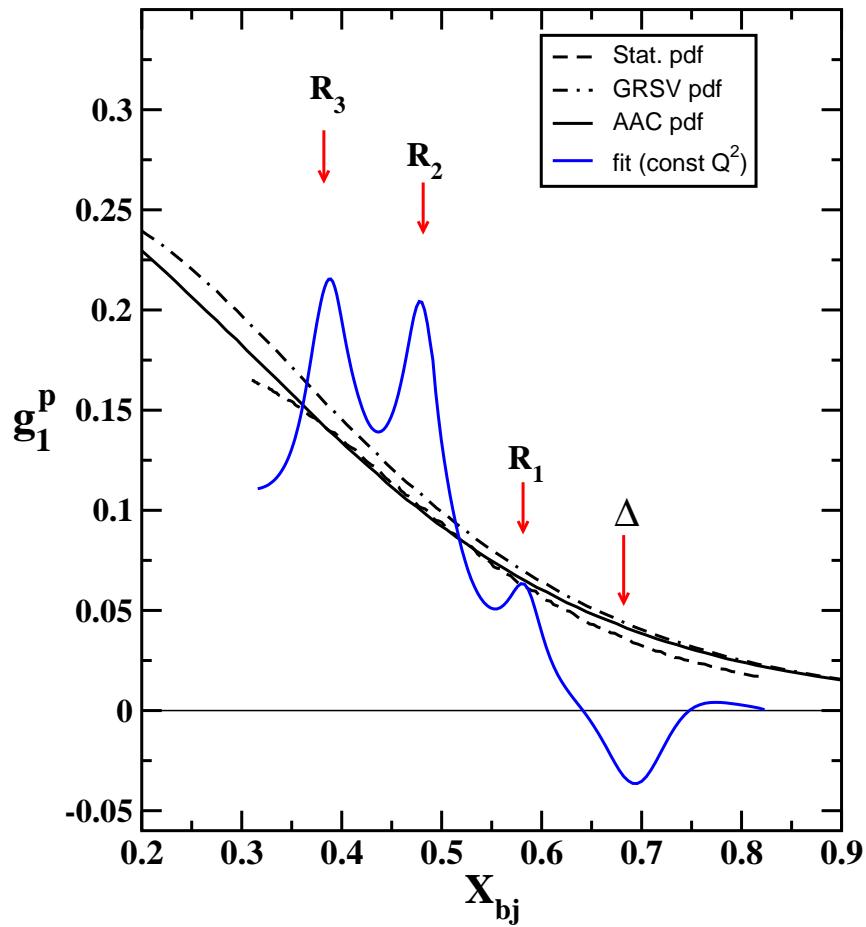
BSB: Eur. Phys. J. C 41, (2005) 327.

AAC: Phys. Rev. D 62, (2000) 034017.

All pdfs evolved to $Q^2 = 1.279$

target mass corrections applied.

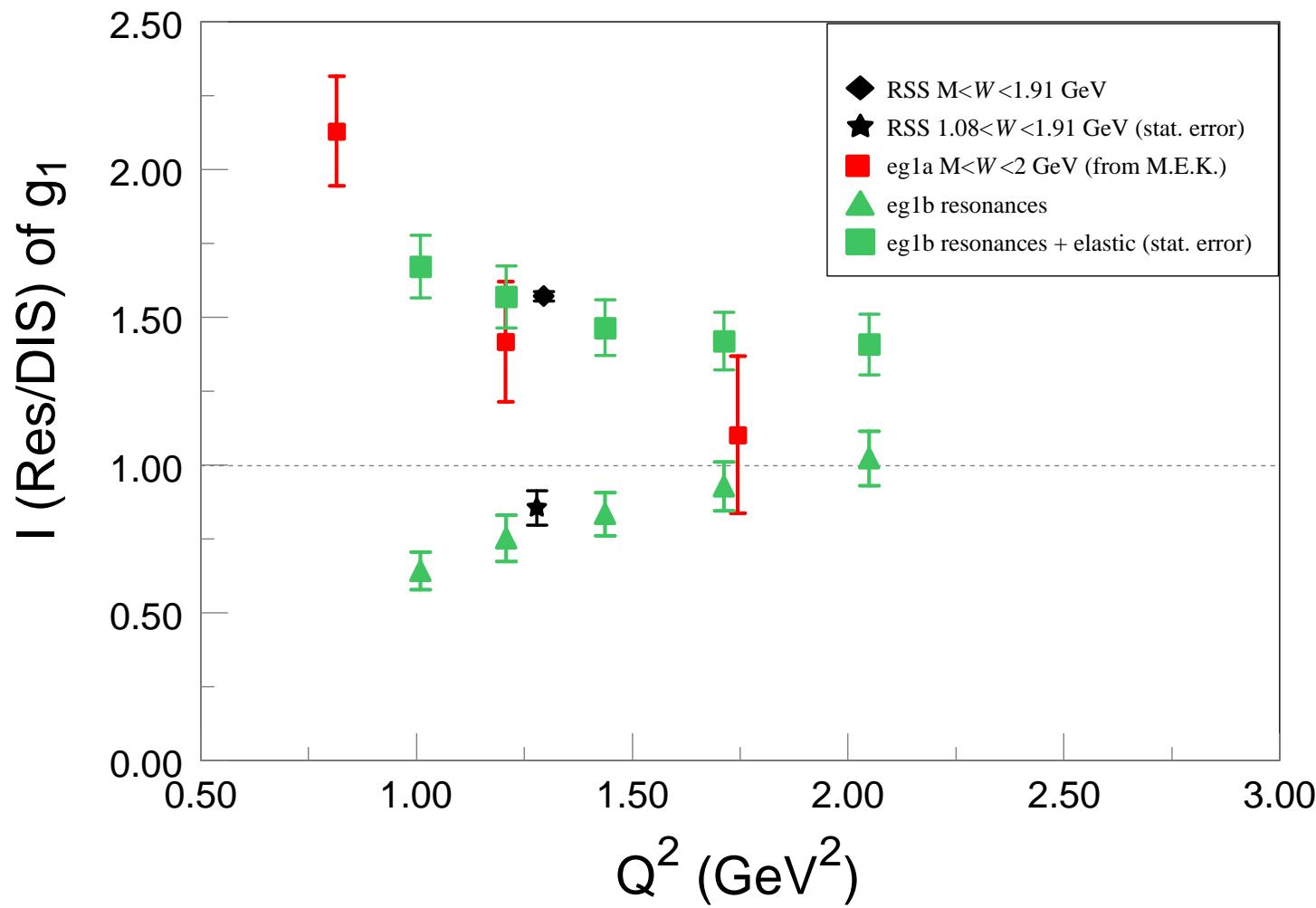
Proton g_1 : Duality



$$\text{Ratio} = \frac{\Gamma_1^{\text{PDF}}}{\Gamma_1^{\text{RSS}}}$$

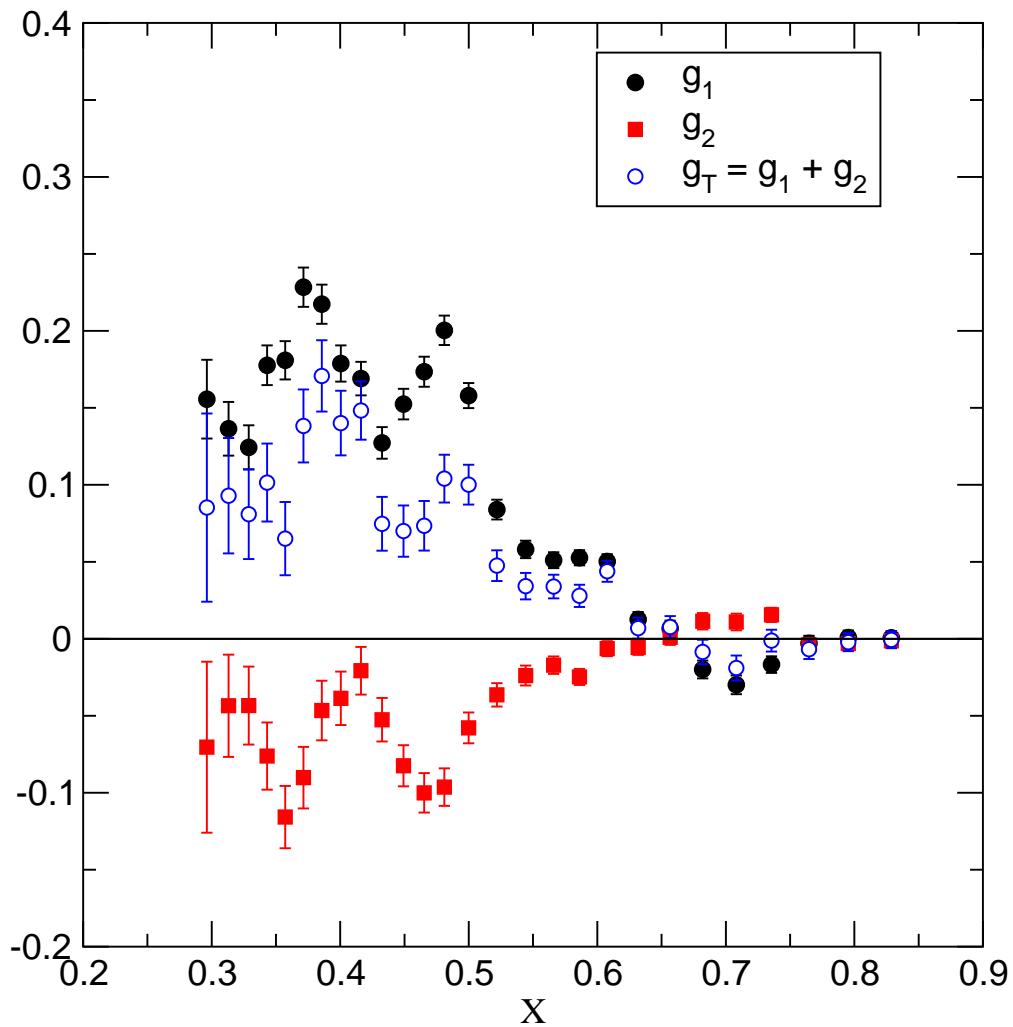
	BSB	GRSV	AAC	Ave
Global	1.11	1.23	1.14	1.17 ± 0.08
Δ	3.41	4.18	3.96	3.93 ± 0.58
R1	1.28	1.44	1.33	1.36 ± 0.10
R2	0.77	0.82	0.75	0.78 ± 0.05
R3	0.77	0.84	0.77	0.79 ± 0.06

Q^2 Dependence of Global Duality



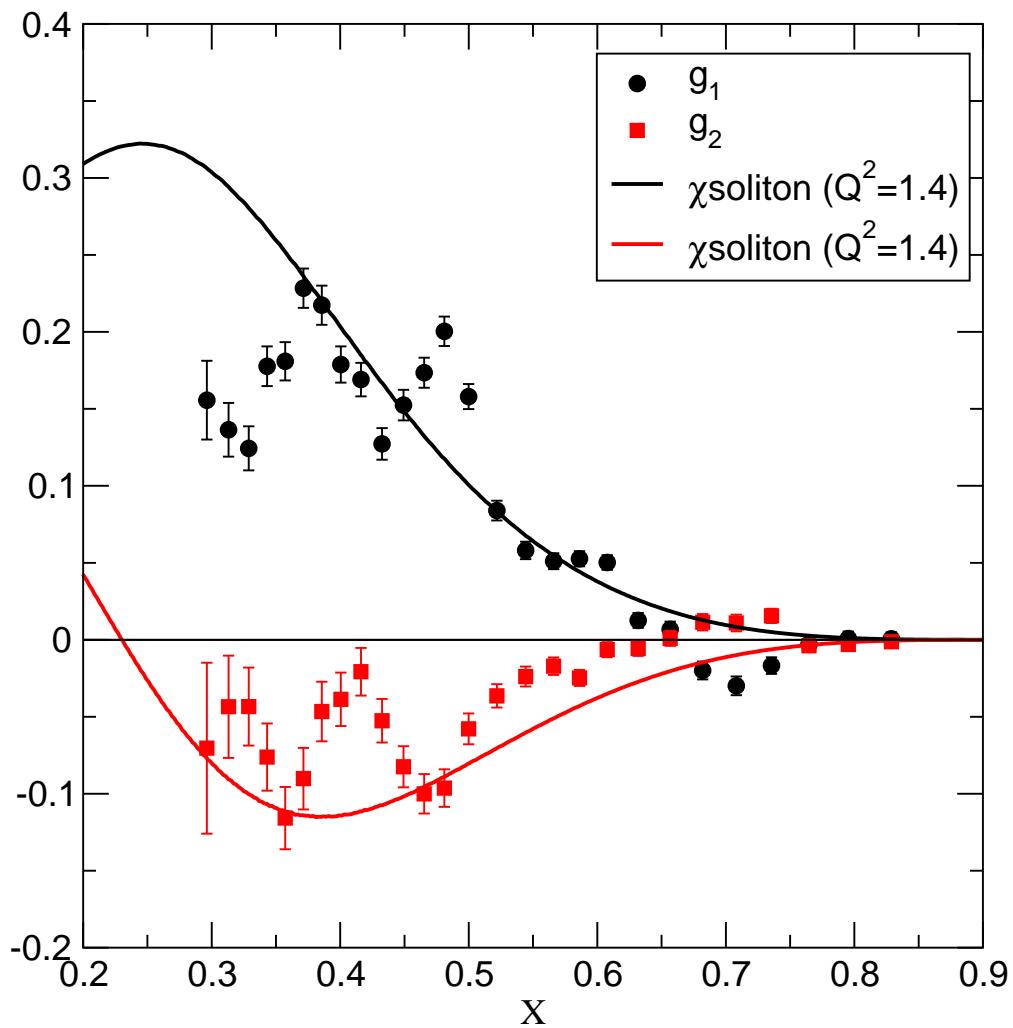
Melnitchouk, Ent & Keppel, Phys. Rep. 406, 127 (2005)

g_2 Structure Function



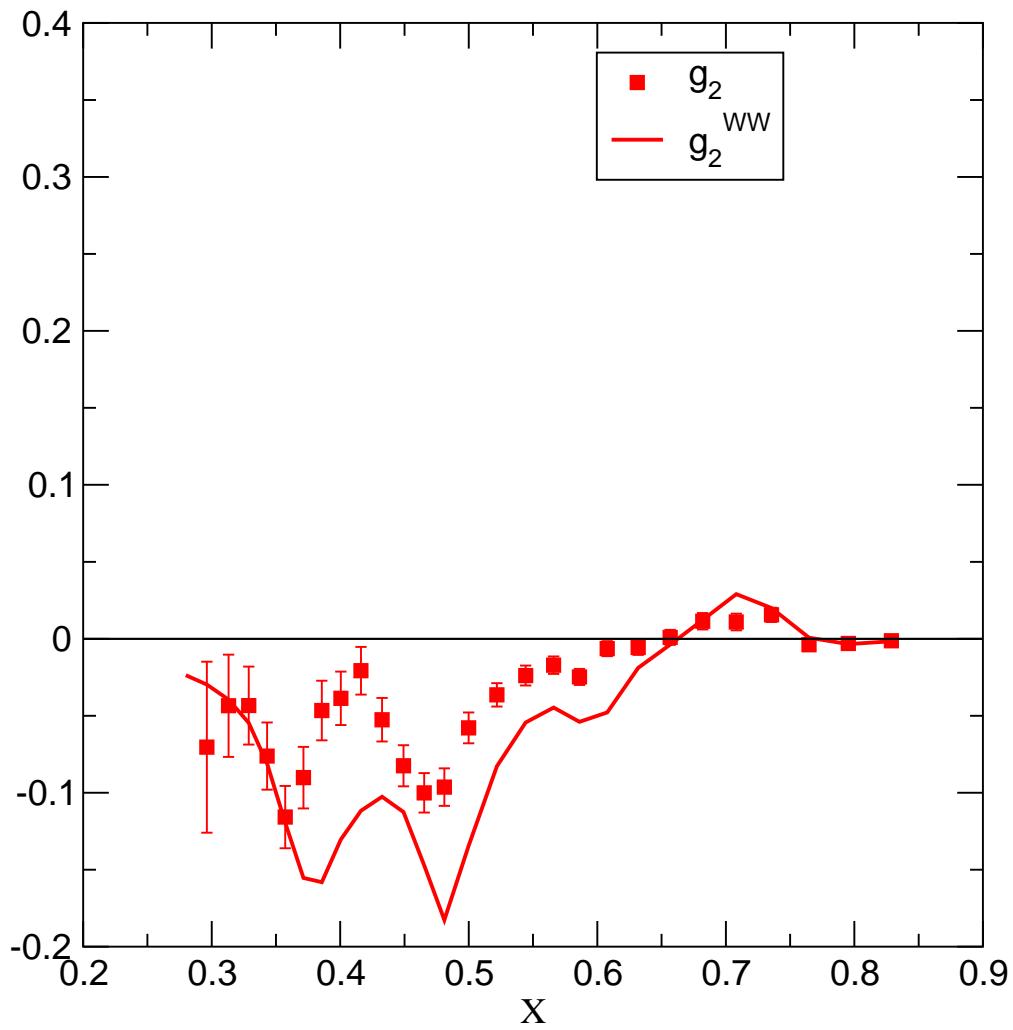
Transversely polarizable target
gives access to g_2

Chiral Soliton Model



Weigel, Gamberg and Reinhardt
Phys. Rev. D55 (1997) 6910.

Higher twist in g_2



$$g_2 = g_2^{\text{WW}} + \bar{g}_2$$
$$g_2^{\text{WW}} = -g_1 + \int_x^1 \frac{g_1}{y} dy$$

Twist-3 : d_2

$$d_2 = 3 \int_0^1 x^2 (g_2 - g_2^{\text{WW}}) dx$$

$$= 2 \int_0^1 x^2 \left(g_1 + \frac{3}{2} g_2 \right) dx$$

Twist-3 : d_2

$$d_2 = 3 \int_0^1 x^2 (g_2 - g_2^{\text{WW}}) dx$$

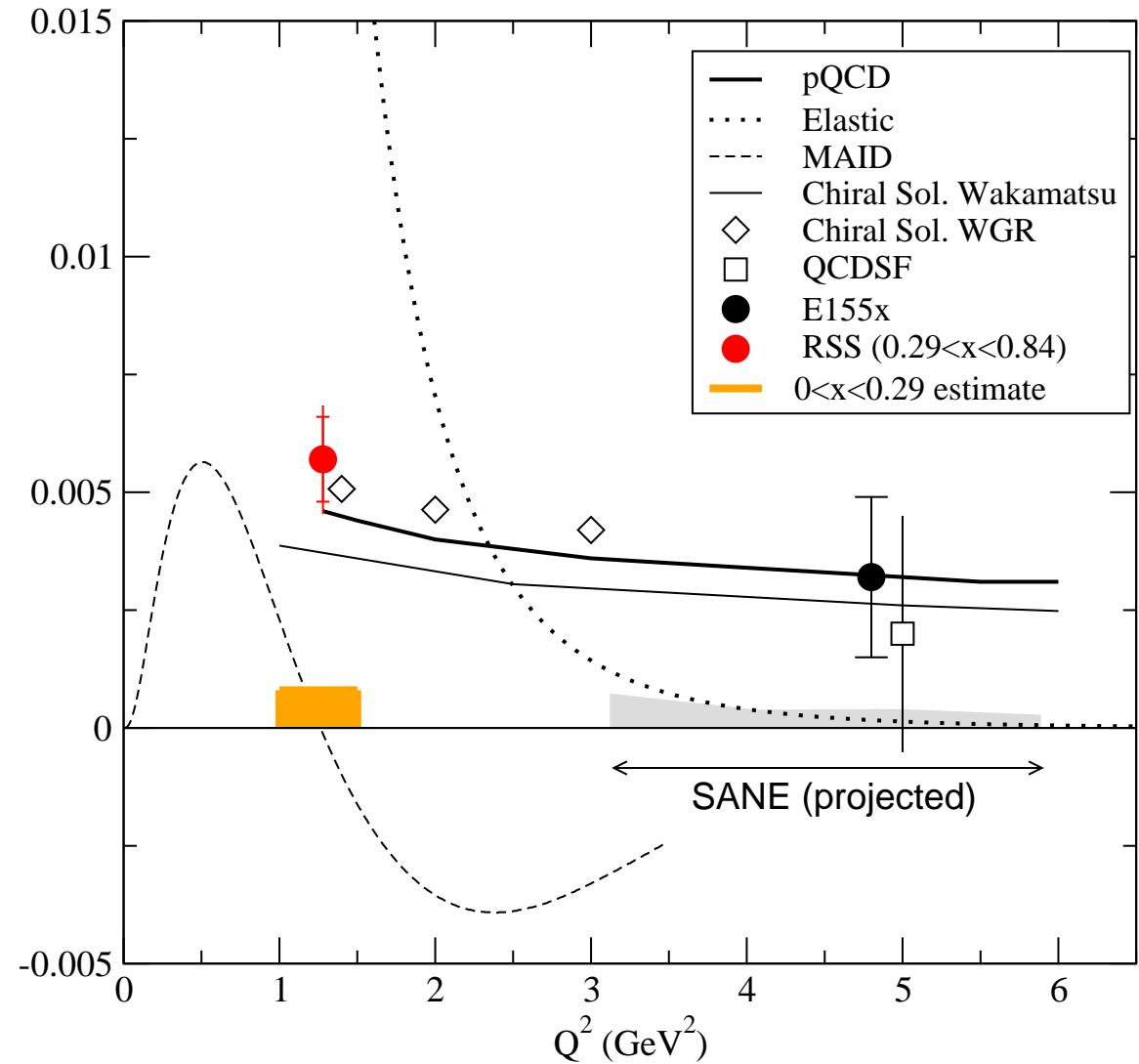
$$= 2 \int_0^1 x^2 (g_1 + \frac{3}{2}g_2) dx$$

Measured: $0.29 < x < 0.84$

$$\bar{d}_2 = 0.0057 \pm 0.0009 \pm 0.0007$$

Unmeasured estimate: $x < 0.29$

$$0.0008 \pm 0.0002$$

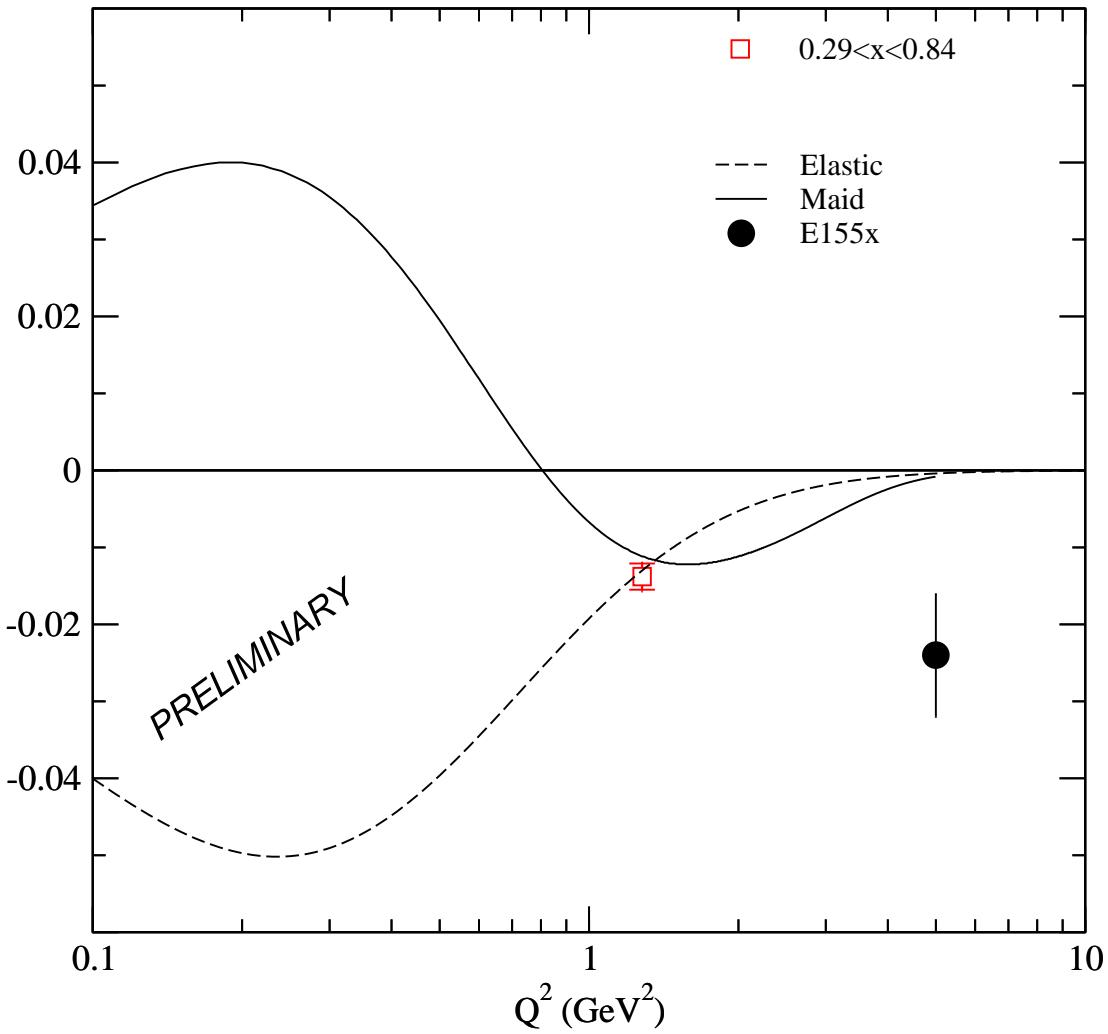


Burkhardt-Cottingham Sum Rule

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

H. Burkhardt, and W.N. Cottingham
Annals Phys. 56 (1970) 453.

Burkhardt-Cottingham Sum Rule

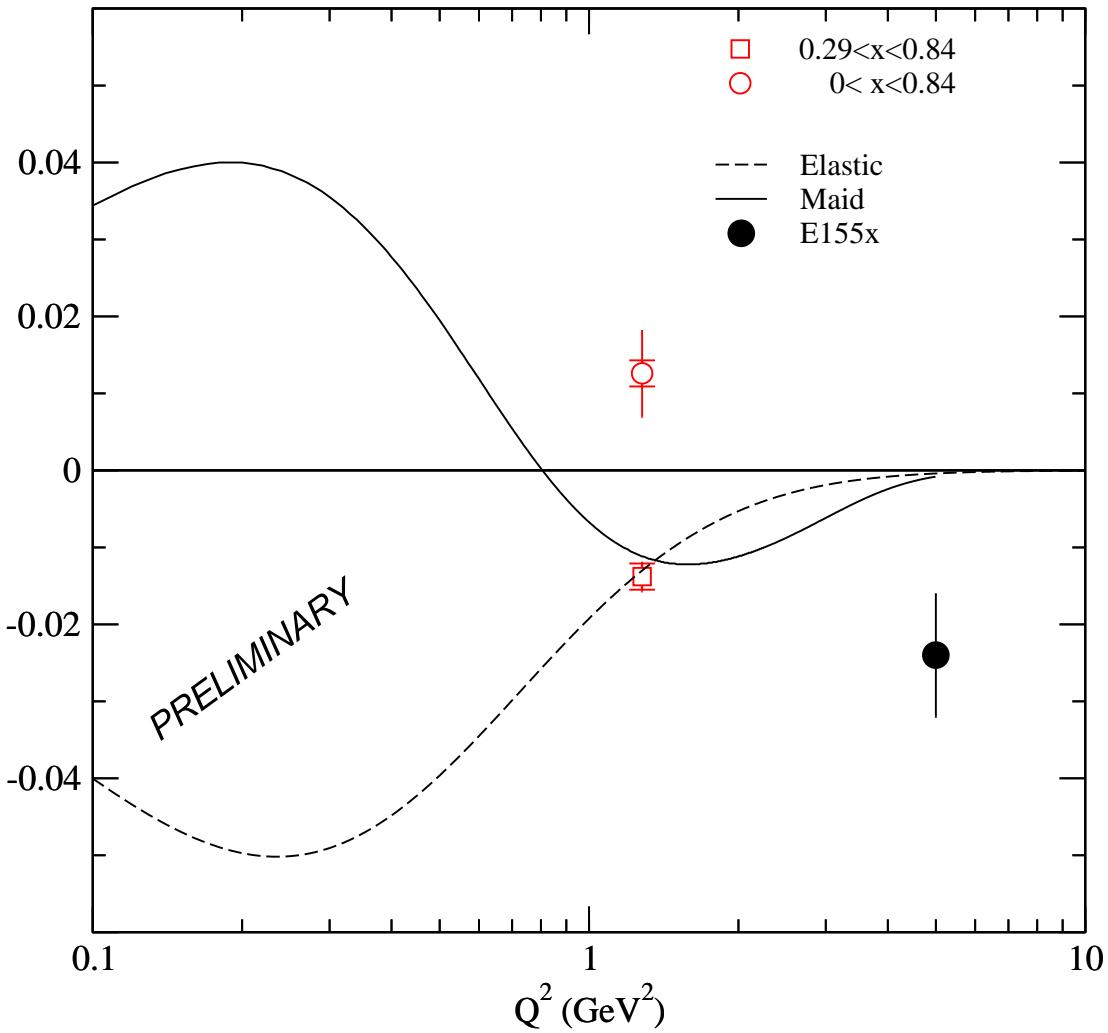


$$\int g_2(x, Q^2) dx$$

Resonance Region

$$0.29 < x < 0.84$$

Burkhardt-Cottingham Sum Rule

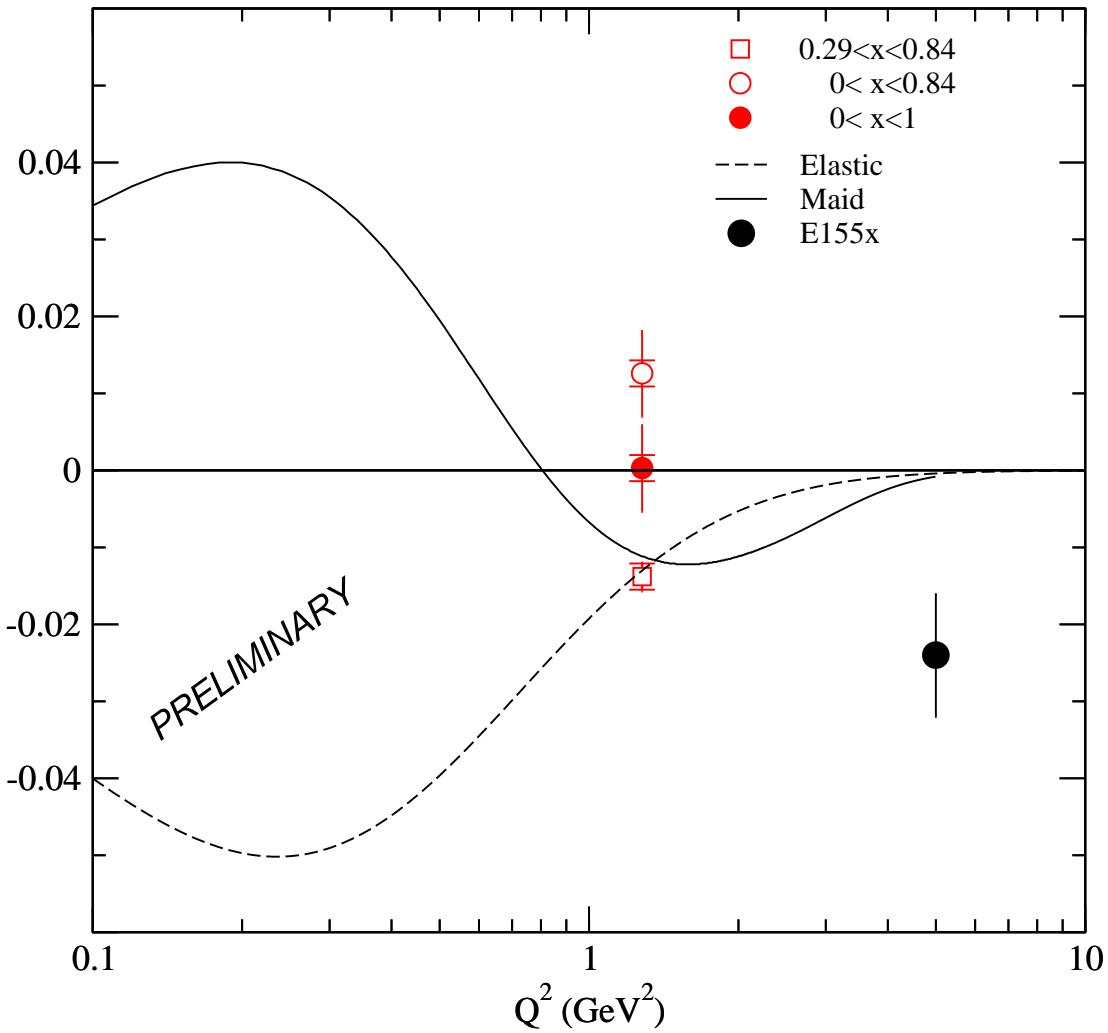


$$\int g_2(x, Q^2) dx$$

Inelastic

$$0 < x < 0.84$$

Burkhardt-Cottingham Sum Rule

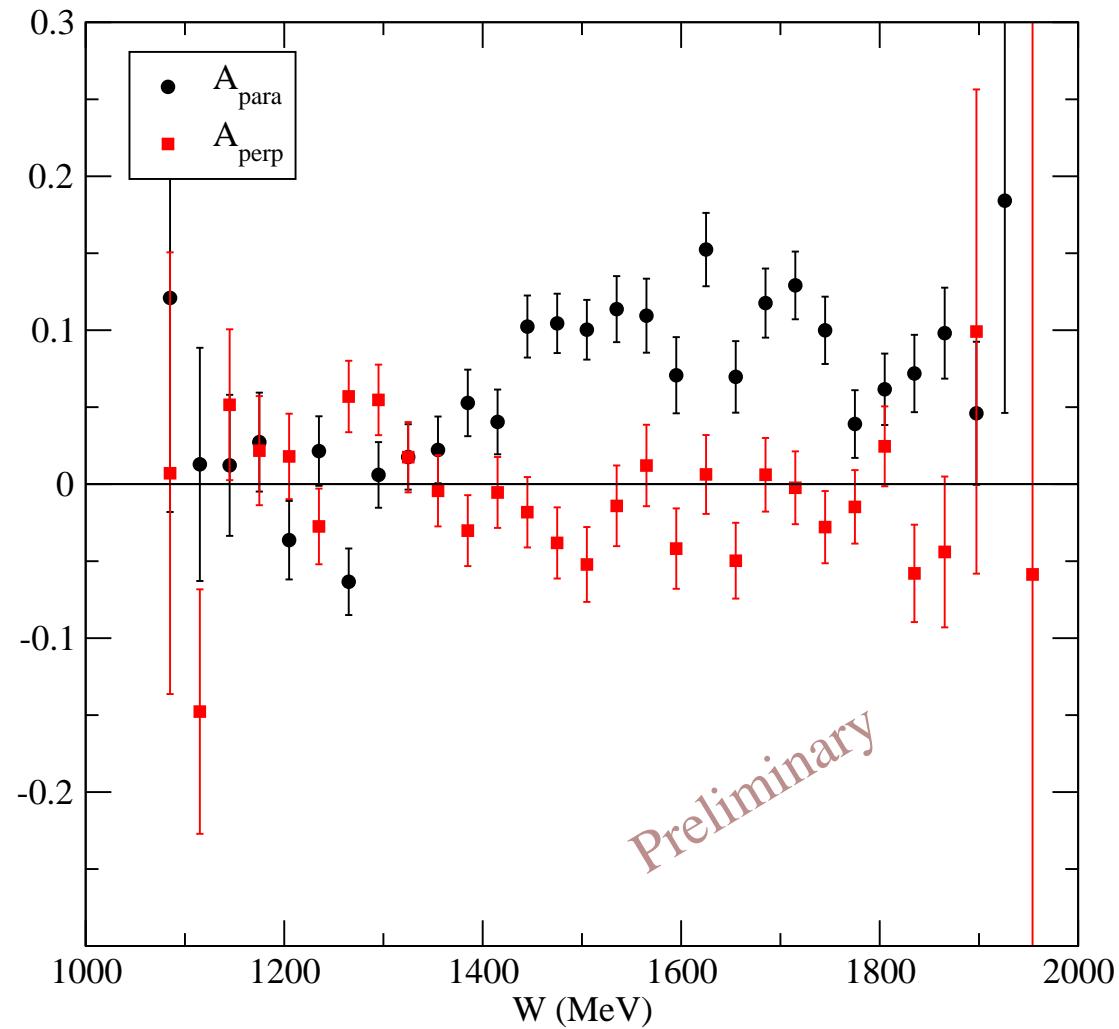


$$\int_0^1 g_2(x, Q^2) dx = 0$$

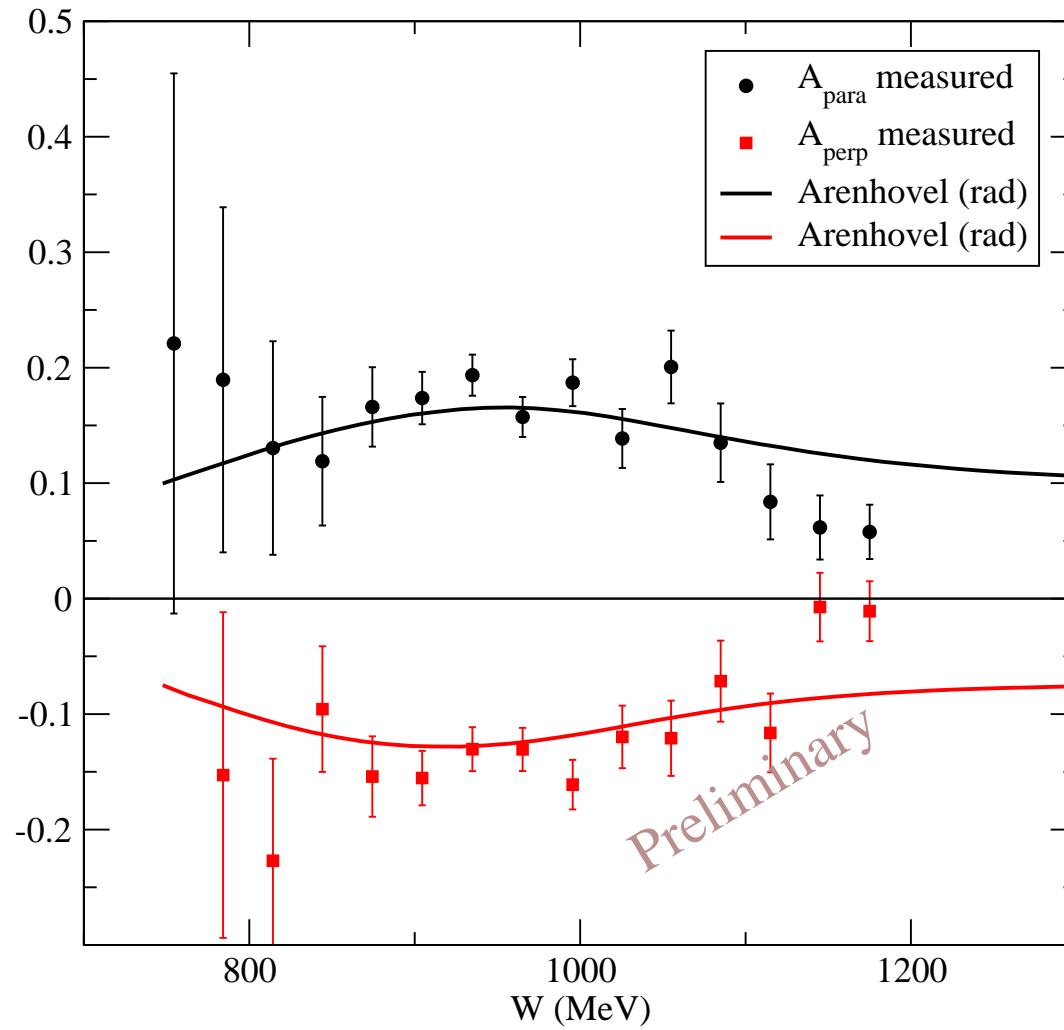
Total
0 < x < 1

Preliminary Deuteron and Neutron Results

Deuteron $A_{||}$ and A_{\perp}



Quasielastic Deuteron $A_{||}$ and A_{\perp}



Neutron Extraction

Subtract smeared proton SSFs from deuteron SSFs

$$\begin{aligned} g_1^{n,smr} &= g_1^d - g_1^{p,smr} \\ g_2^{n,smr} &= g_2^d - g_2^{p,smr} \end{aligned}$$

Smearing : Bodek-Ritchie version of Atwood-West technique.
convolution of the momentum distribution and on-shell SSF

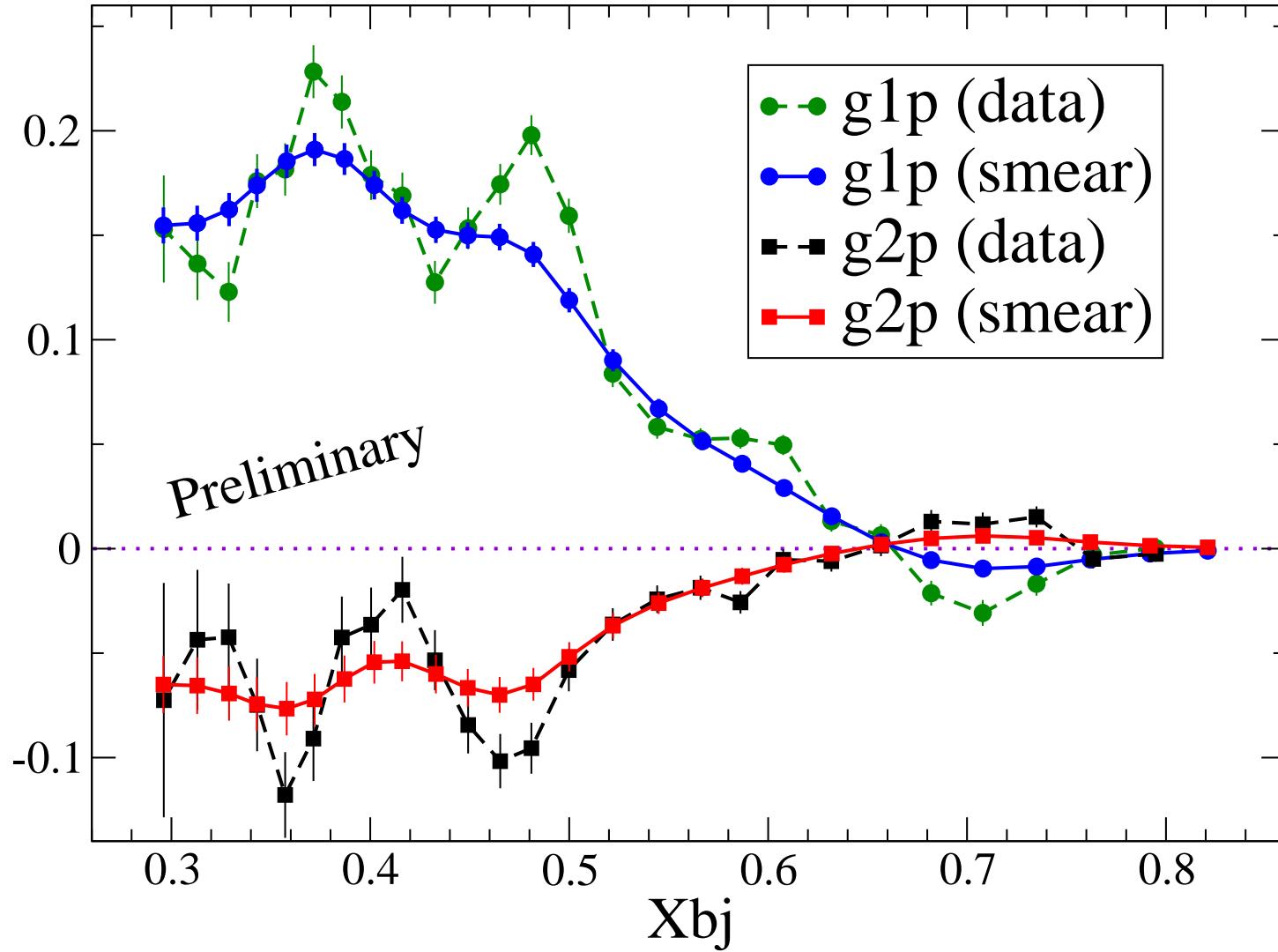
$$F(Q^2, \nu) = \int_0^\infty |f(\vec{p})|^2 g(Q^2, W', \nu') d\vec{p}$$

$f(\vec{p})$: momentum distribution

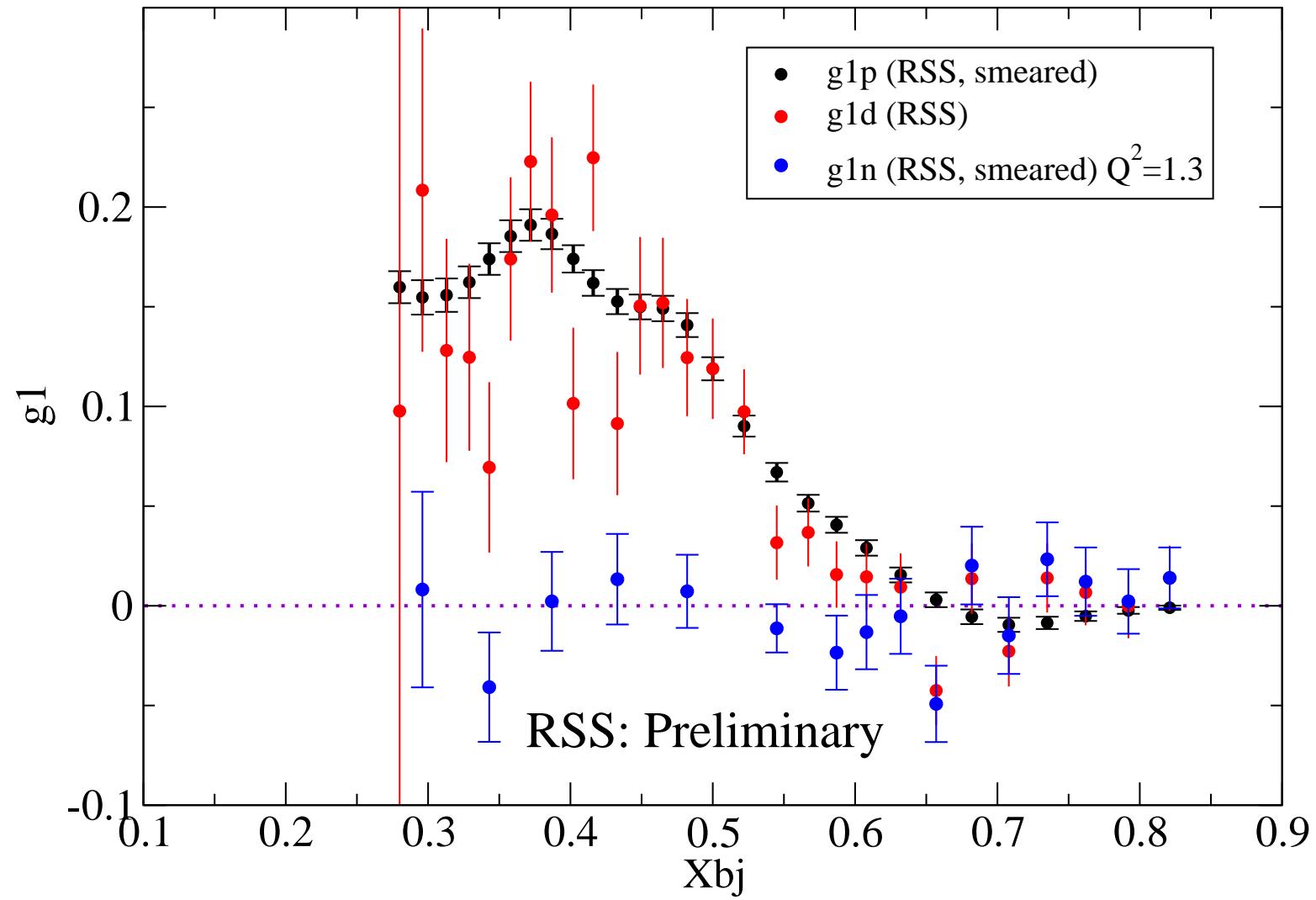
Phys. Rev. D 23 (1981) 1070

Phys. Rev. D 7 (1973) 773

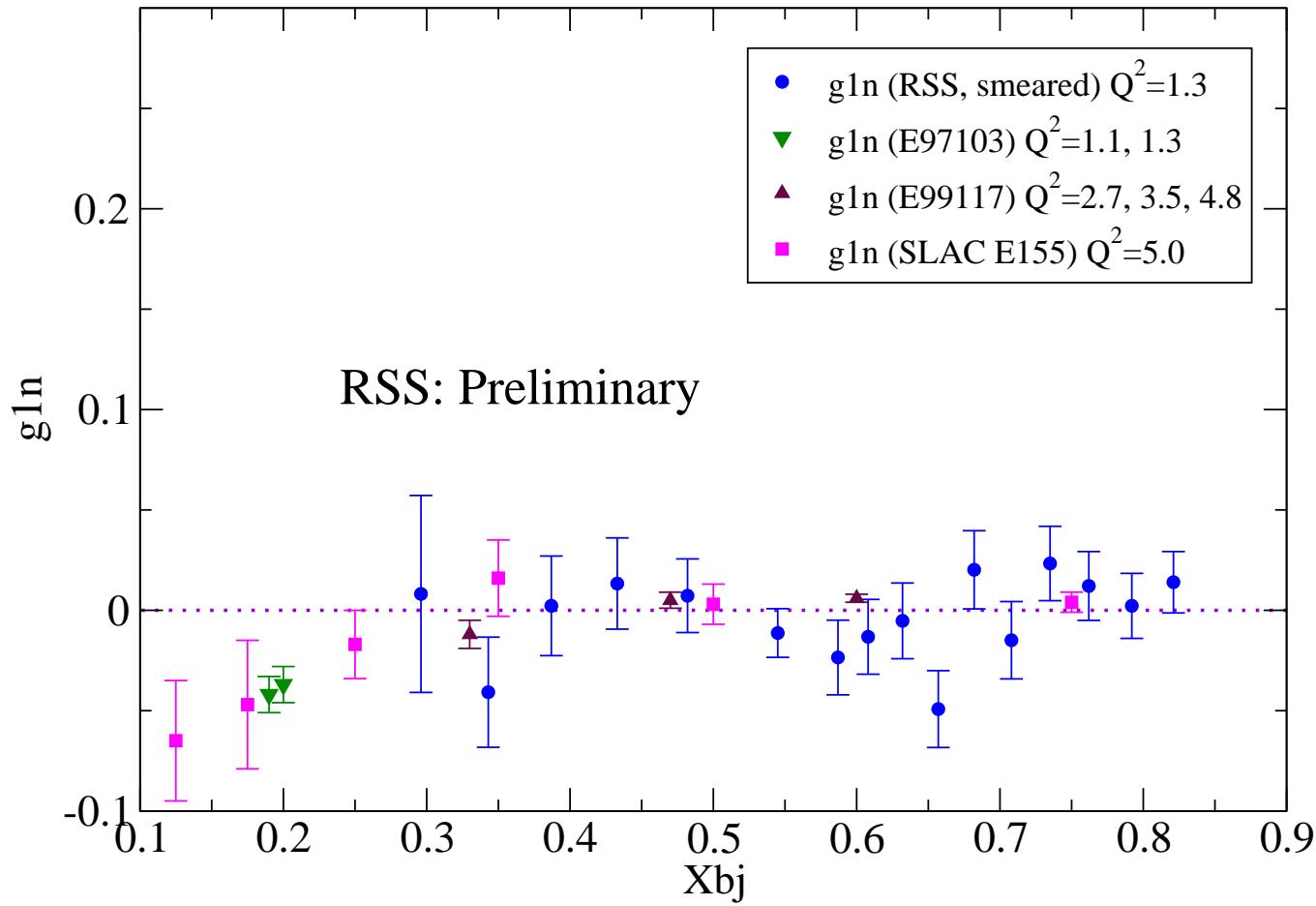
Proton Smearing



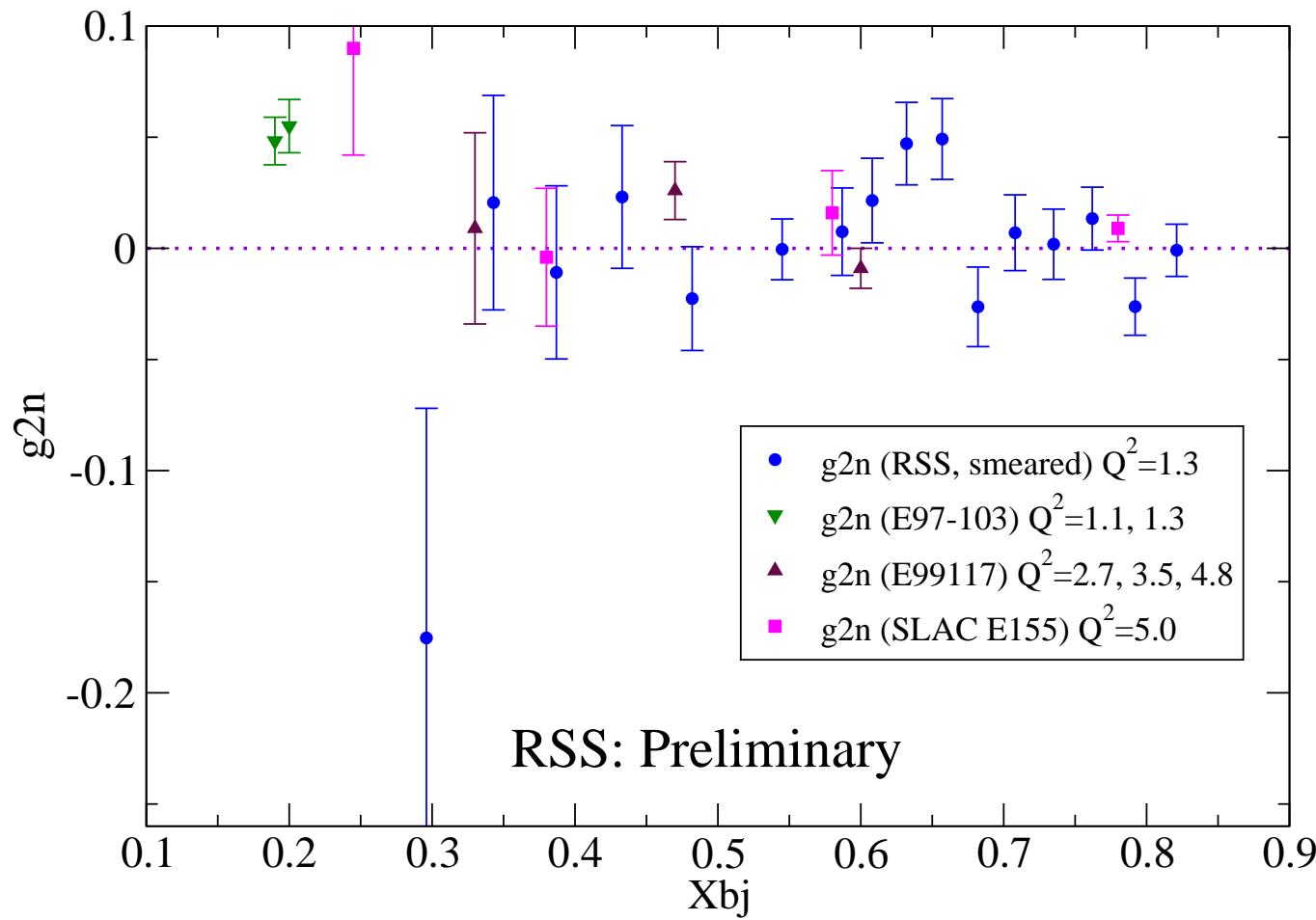
Neutron Extraction



Neutron $g_1(x, Q^2)$



Neutron $g_2(x, Q^2)$



RSS Summary

Proton Spin Structure

Elastic: [Phys Rev C74 \(2006\) 035201](#)

Inelastic: [Phys. Rev. Lett. 98, \(2007\) 132003](#)

Test of polarized duality at $Q^2 \approx 1.3 \text{ GeV}^2$

- Global Duality violated at 2σ level
- Local Duality violated strongly in the Delta
- and at 20%-30% level in the higher resonances

\bar{d}_2 : 5σ from zero.

BC sum rule satisfied by cancellation of elastic/inelastic.

Deuteron/Neutron Spin Structure

Preliminary Asymmetries

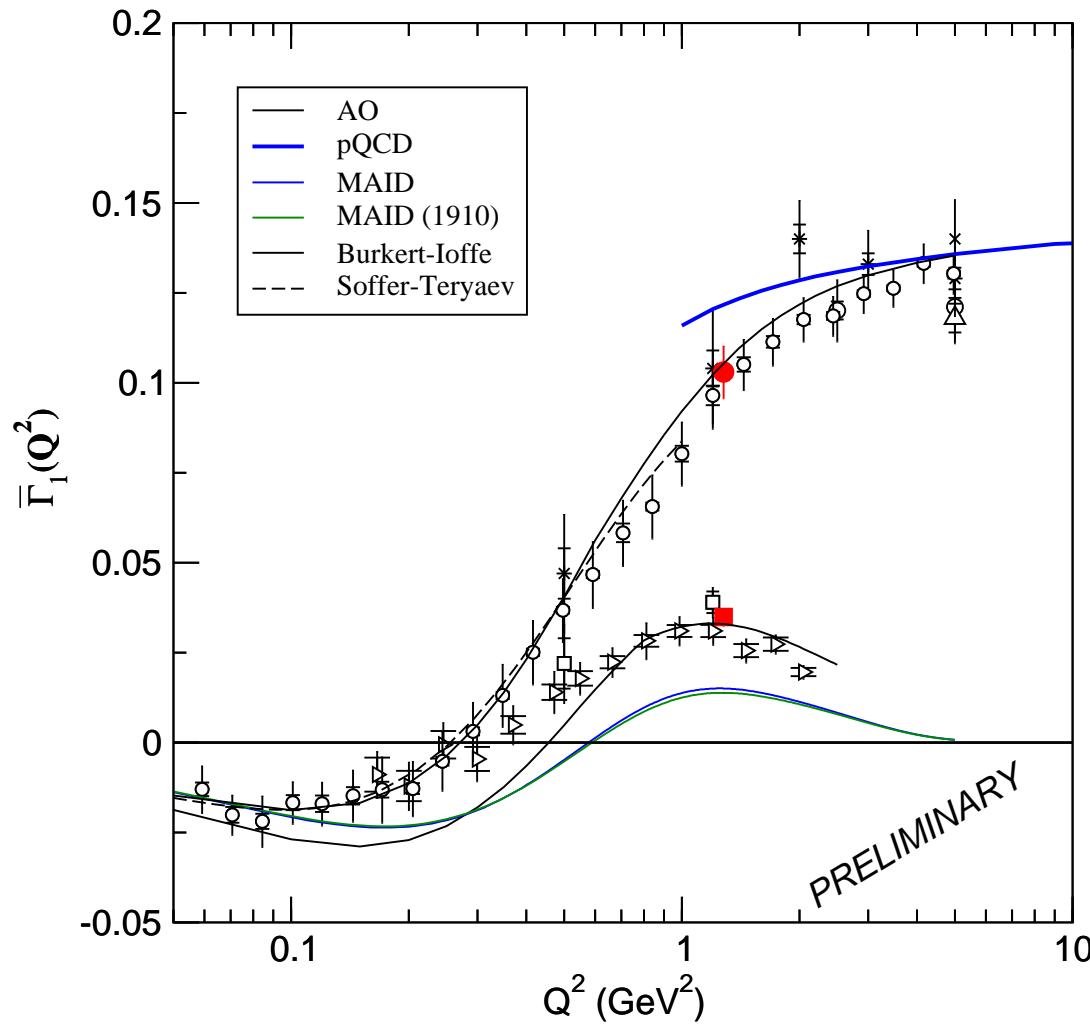
Extracted neutron, compared to world data

Backups

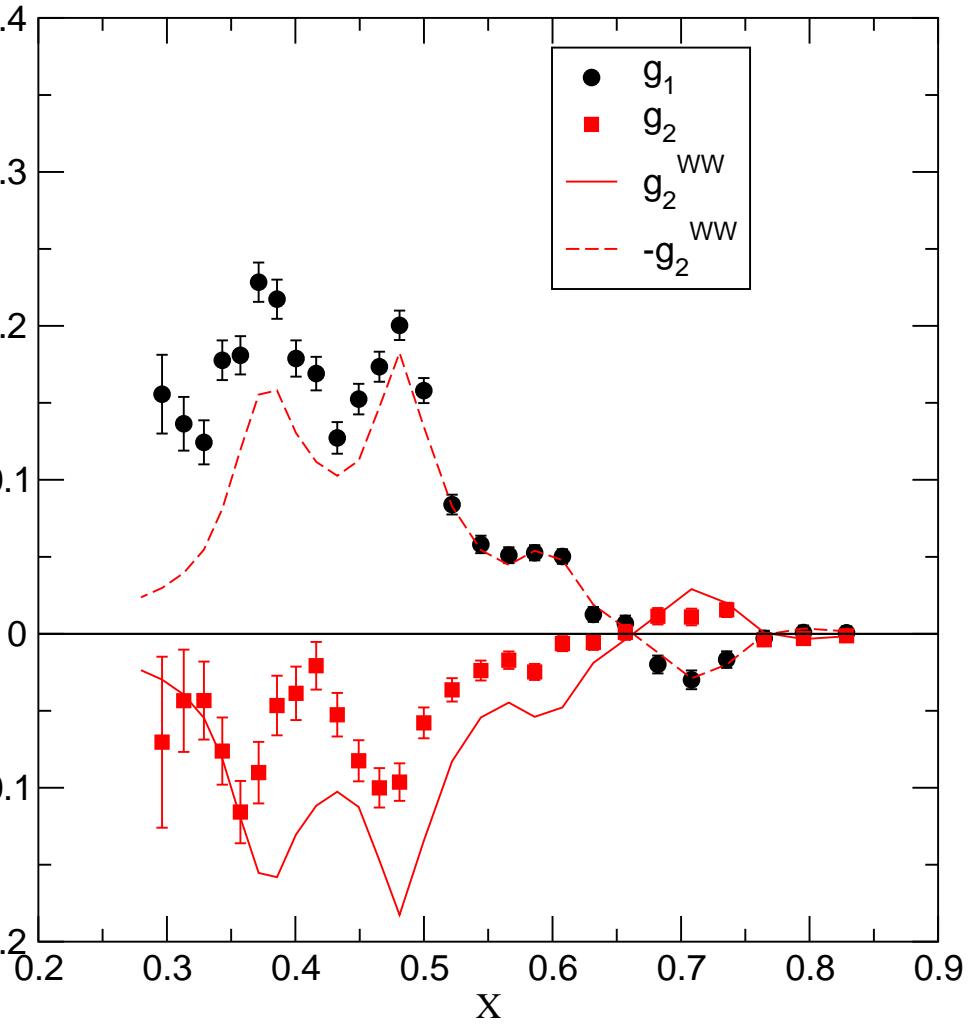
Sources of Systematic Error : Proton

Error source	$A_{ }$	A_{\perp}
Target polarization	1.1%	2.9%
Beam polarization	}	1.3%
Dilution Factor	4.9%	4.9%
Radiative corrections	2.7%	12.9%
Kinematic reconstruction	0.4%	0.4%

Upper limit of Resonance Integral

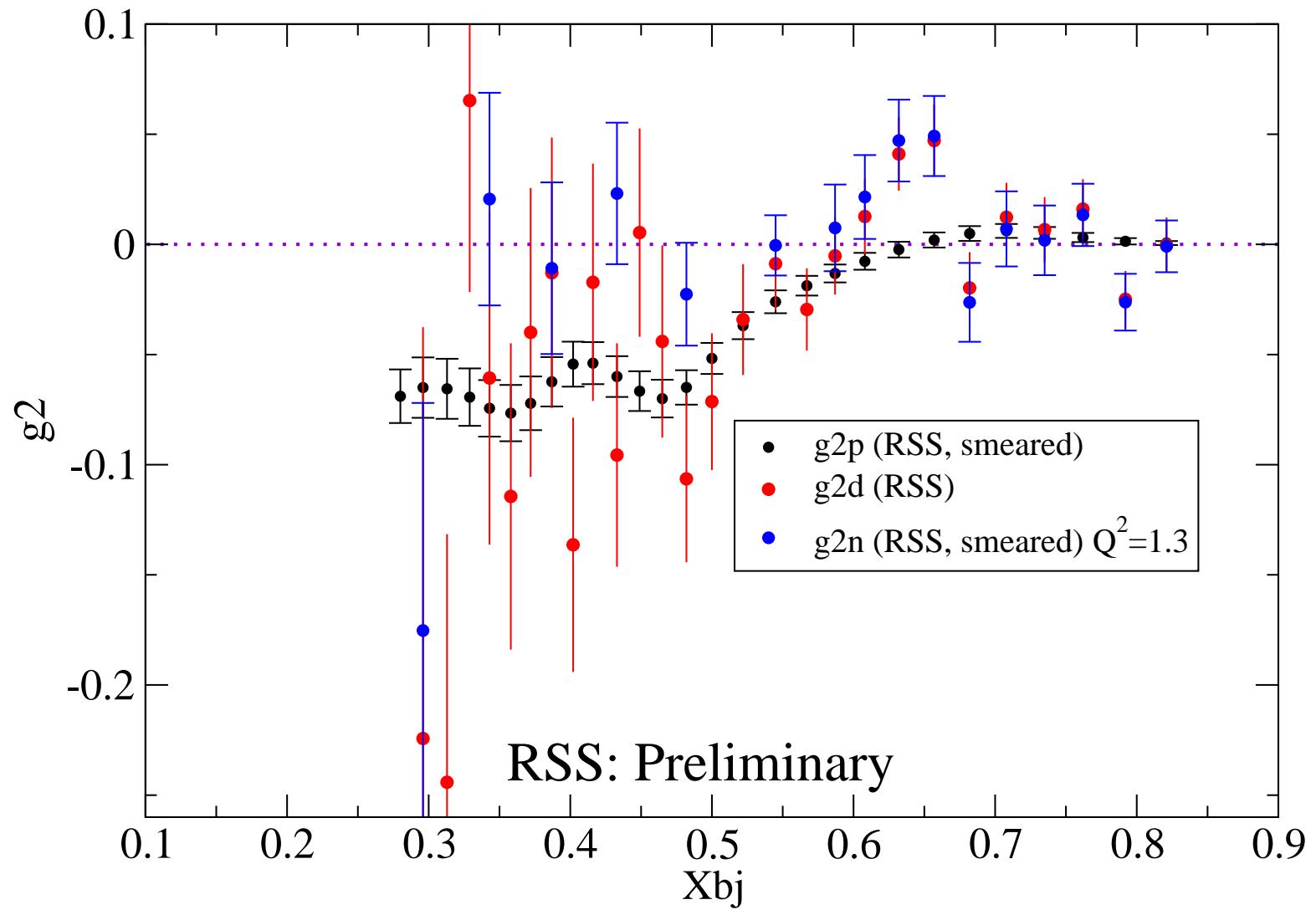


g_2 Structure Function



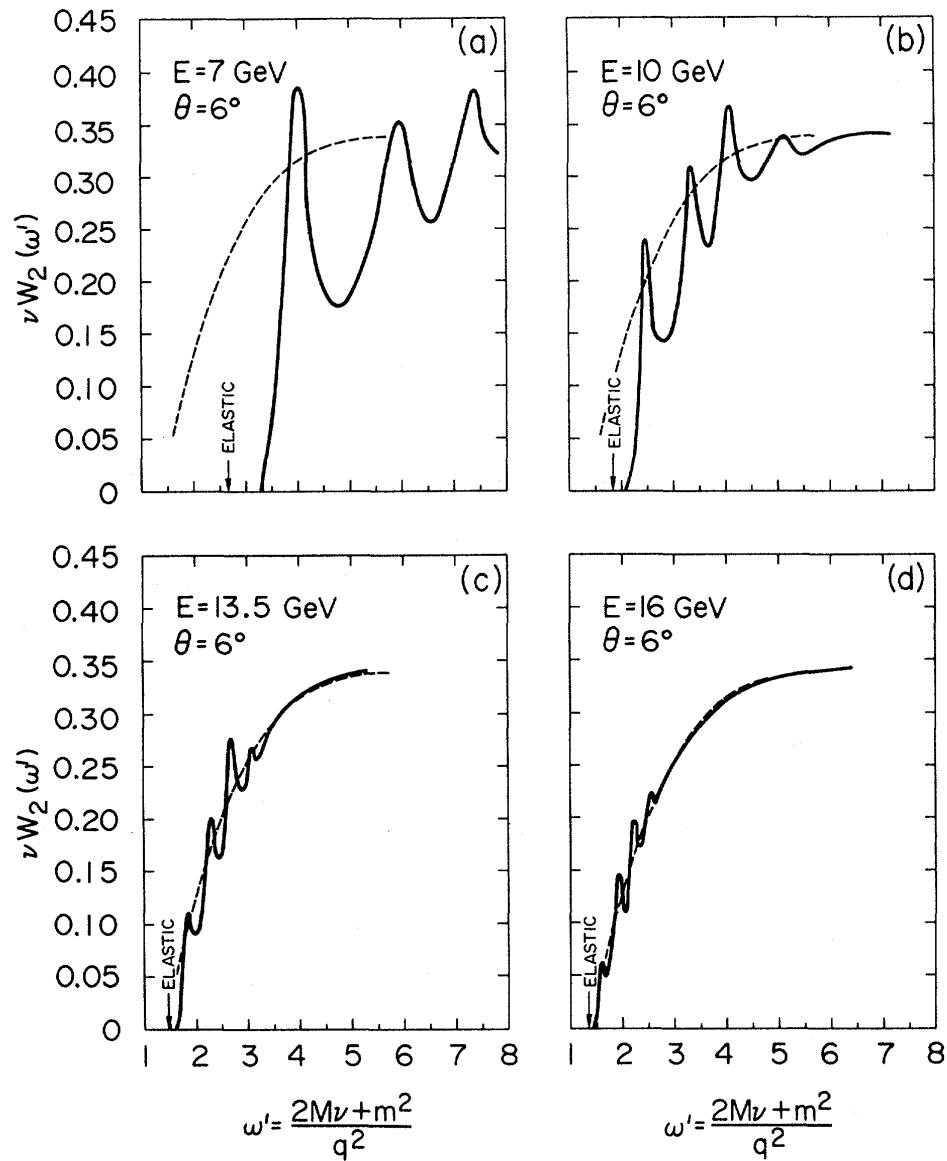
$$\begin{aligned} g_2 &= g_2^{WW} + \bar{g}_2 \\ g_2^{WW} &= -g_1 + \int_x^1 \frac{g_1}{y} dy \end{aligned}$$

Neutron Extraction



Duality Backgrounder

Quark-Hadron Duality



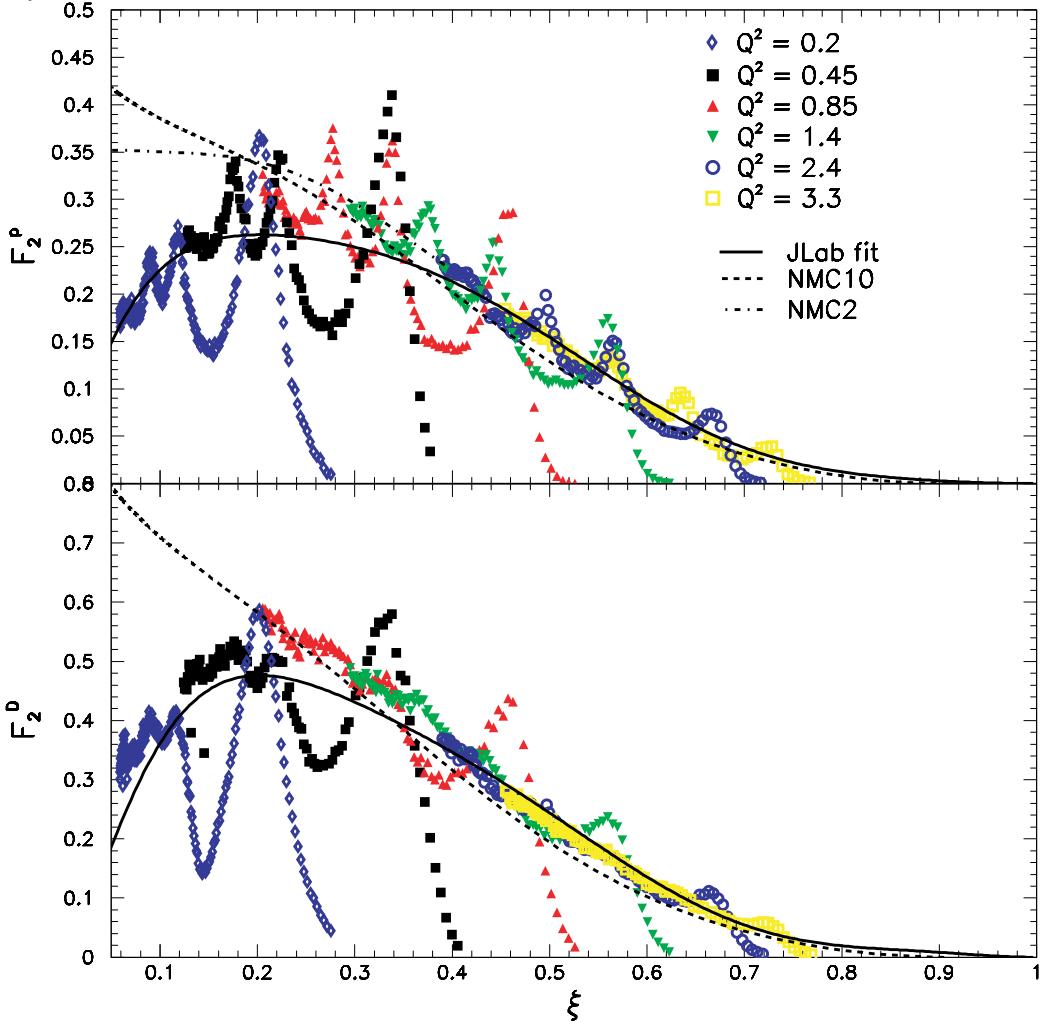
Bloom-Gilman (1970)

F_2 measured in the resonance region averages to the large Q^2 scaling curve

Phys. Rev. Lett. 25, 1140 (1970)

Phys. Rev. D4, 2901 (1971)

Quark-Hadron Duality



Recent Hall C data

Niculescu et. al PRL 85:1182(2000)

Proton and Deuteron F_2

Global duality within 10%

Local duality within 10%

● $W=1232$ MeV

● $W=1535$ MeV

● $W=1680$ MeV

$$\xi \equiv \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}}$$

Polarized Duality

- Testing for duality in the polarized structure functions.
- Expected to be violated in the $\Delta(1232)$ region.
 - $g_1^\Delta \leq 0$ in the resonance region, $g_1^\Delta \geq 0$ in DIS.
 - ⇒ Local Duality can not work in the Delta region.
 - ⇒ Global Duality can't work unless an equally large but opposite contribution is paired with the Δ .

Polarized Duality

Bianchi, Fantoni and Liuti, PRD 69:014505(2004)

1. Determine g_1^{res} at constant Q^2 .
2. Integrate over region of interest.
-> Local or Global
3. Compare to DIS result evolved to same Q^2 .

$$\Gamma_1^{\text{res}}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} g_1^{\text{res}} dx \quad \Gamma_1^{\text{dis}}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} g_1^{\text{dis}} dx$$

$$\Gamma_1^{\text{res}}(Q^2) = \Gamma_1^{\text{dis}}(Q^2) \Rightarrow \text{Duality}$$

Target Mass Corrections

Purely kinematic effects from finite value of $4M^2x^2/Q^2$.

$$\begin{aligned} g_1(x, Q^2) &= g_1(x, Q^2; M = 0) && \text{from PQCD} \\ &+ \frac{M}{Q^2} g_1^{(1)TMC}(x, Q^2) && \text{purely kinematical} \\ &+ \frac{h(x, Q^2)}{Q^2} + O(1/Q^4) && \text{higher twist} \end{aligned}$$

Global ratio : 1.42 ± 0.10 if large-x resummations for the PDFs (Bianchi et al, PRD 69, 014505 (2004)) are included.