Spin Content of the Nucleon

or

What We've Learned from Polarized Electron Scattering

Karl J. Slifer
University of New Hampshire

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or

What We've Learned from Polarized Electron Scattering,

I've

(in the last few months)

Karl J. Slifer
University of New Hampshire

This Talk

Burkhardt—Cottingham Sum Rule

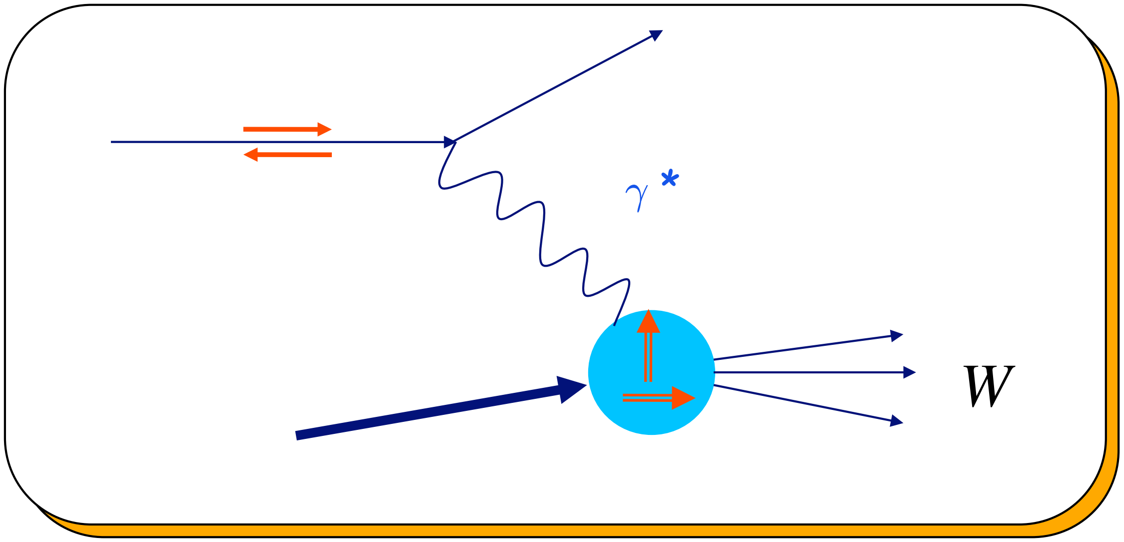
What does the JLab data tell us?
Is it enough to make a definitive statement?

Higher Twist Measurements at Jlab

Target Mass Corrections

impact on the clean extraction of Higher Twist

Inclusive Electron Scattering



When we add spin degrees of freedom to the target and beam, 2 Addiitonal SF needed.

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

$$+\gamma\, g_1(x,Q^2) + \delta\, g_2(x,Q^2)$$

Inclusive **Polarized** Cross Section

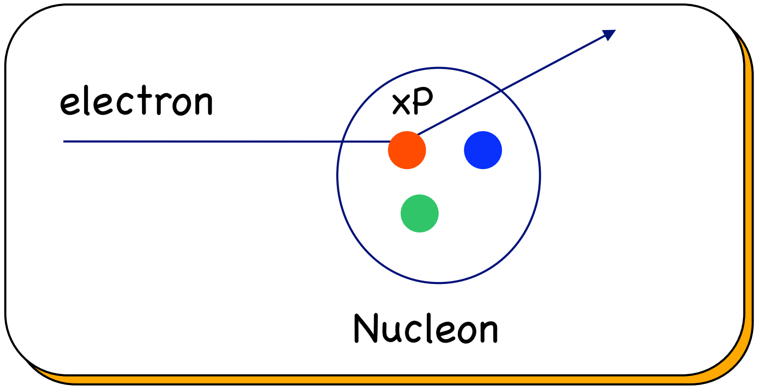
all four SF needed for a complete description of nucleon structure

Parton Model

Interpretation of the Structure Functions

Impulse Approximation in DIS

no time for interaction between partons



distributions of quark momentum and spin in the nucleon.

$$F_1(x) = \frac{1}{2}\Sigma e_i^2 \left[q_i(x) + \overline{q}_i(x)\right]$$

runs over all quark flavors

$$F_2(x) = 2xF_1(x)$$

$$g_1(x) = \frac{1}{2}\Sigma e_i^2 \Delta q_i(x)$$

$$g_2(x) = ???$$

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.

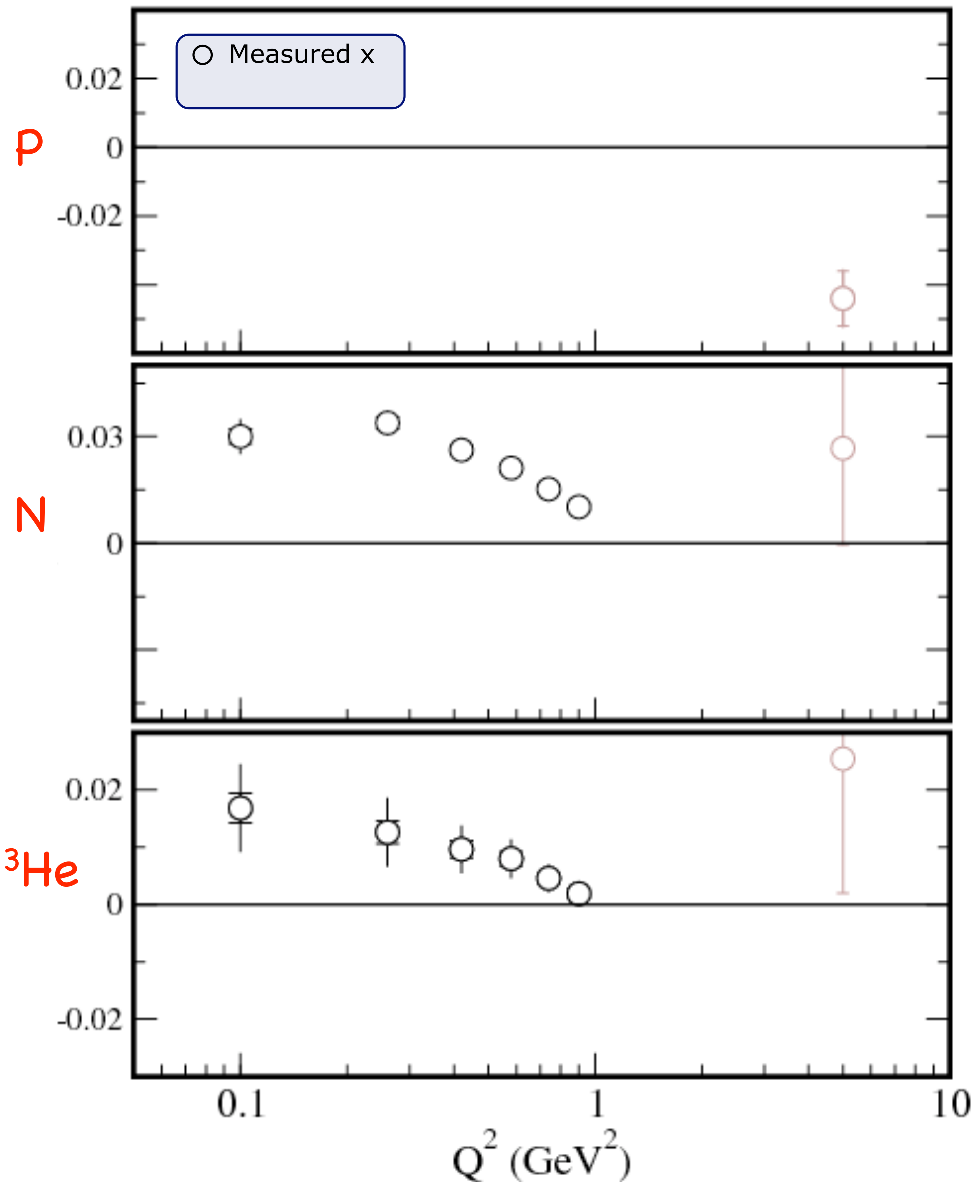
Relies on the virtual Compton scattering amplitude S_2 falling to zero faster than $1/\nu$ as $\nu \to \infty$

Discussion of possible causes of violations

R.L. Jaffe Comm. Nucl. Part. Phys. 19, 239 (1990)

"If it holds for one Q^2 it holds for all"

BC Sum Rule



Existing World Data on Γ_2

for Proton Neutron and ^3He

BLACK : E94010. (Hall A, ^3He)

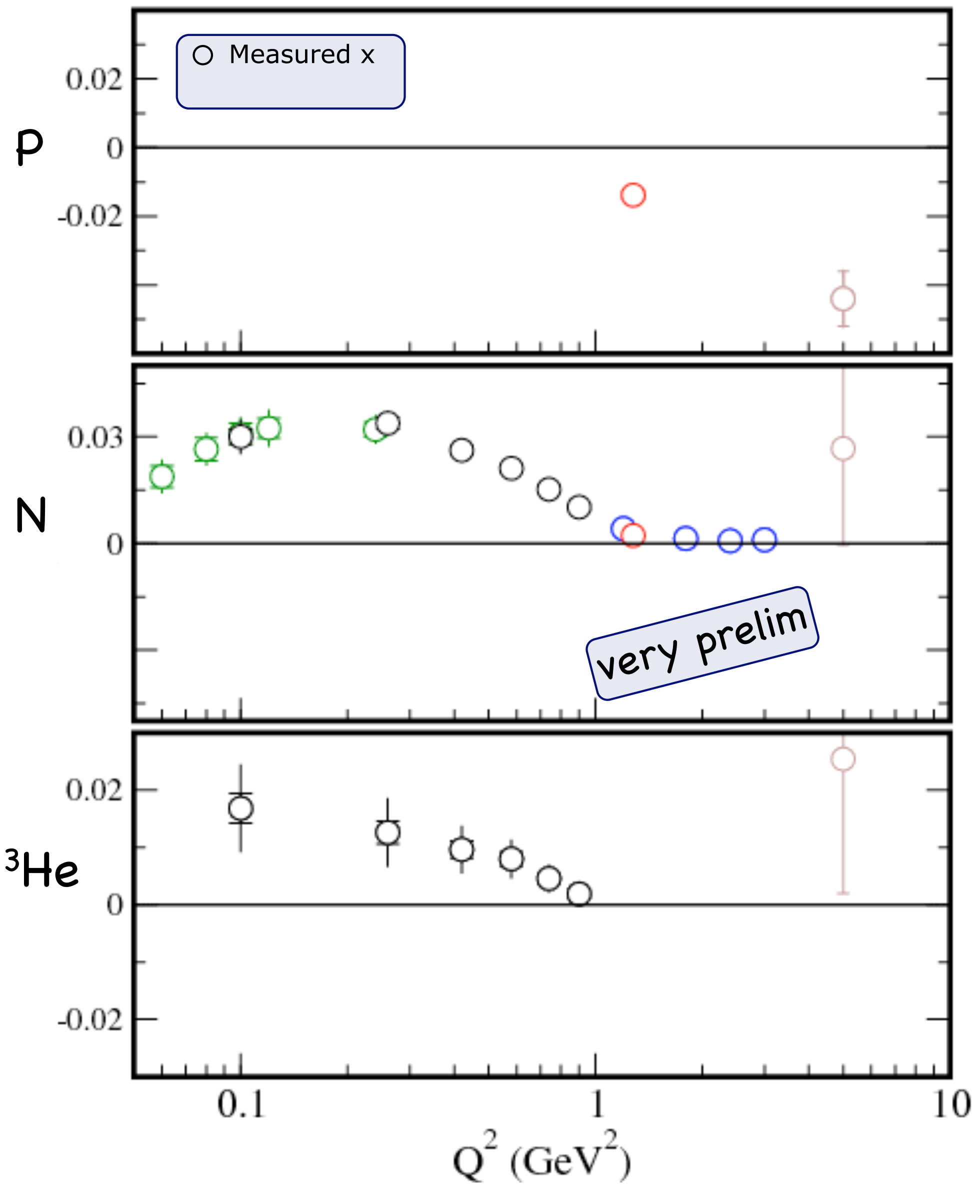
BROWN : E155. (SLAC NH3,^{6}LiD)

Note:

SLAC "Measured" = 0.02 < x < 0.8

JLAB "Measured" ≈ Resonance Region

BC Sum Rule



BRAND NEW DATA!

Very Preliminary

RED : RSS. (Hall C, NH_3,ND_3)

K. Slifer, O. Rondon *et al.* in preparation

BLUE: E01-012. (Hall A, ^3He)

courtesy of P. Solvignon

GREEN: E97-110. (Hall A, ^3He)

courtesy of V. Sulkosky

Thanks also to the spokesmen of these experiments!

RSS: Mark Jones, Oscar Rondon

E01-012: N. Liyanage, J.P.Chen, Seonho Choi

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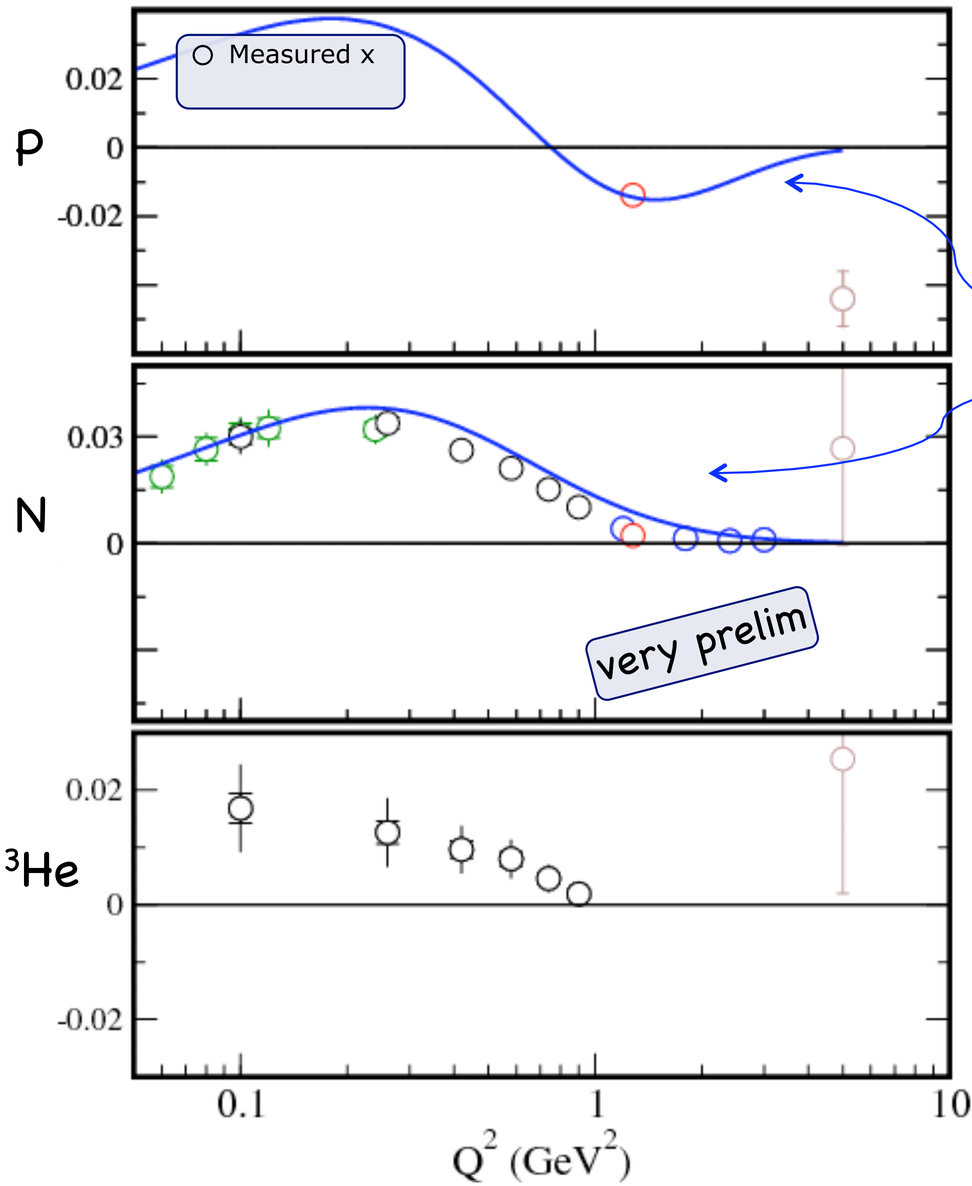
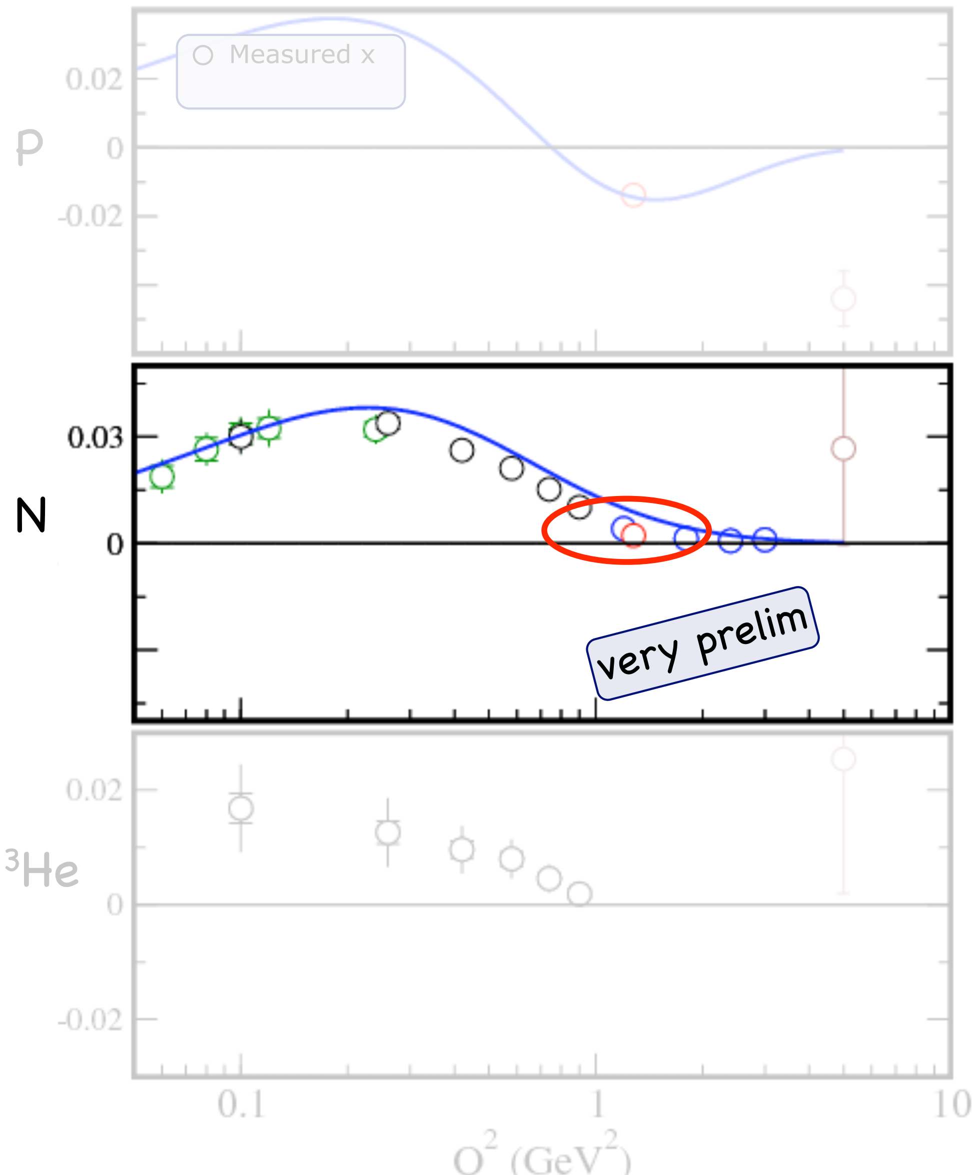
BC Sum Rule



Good agreement with MAID model of resonance region for JLab data

BC Sum Rule



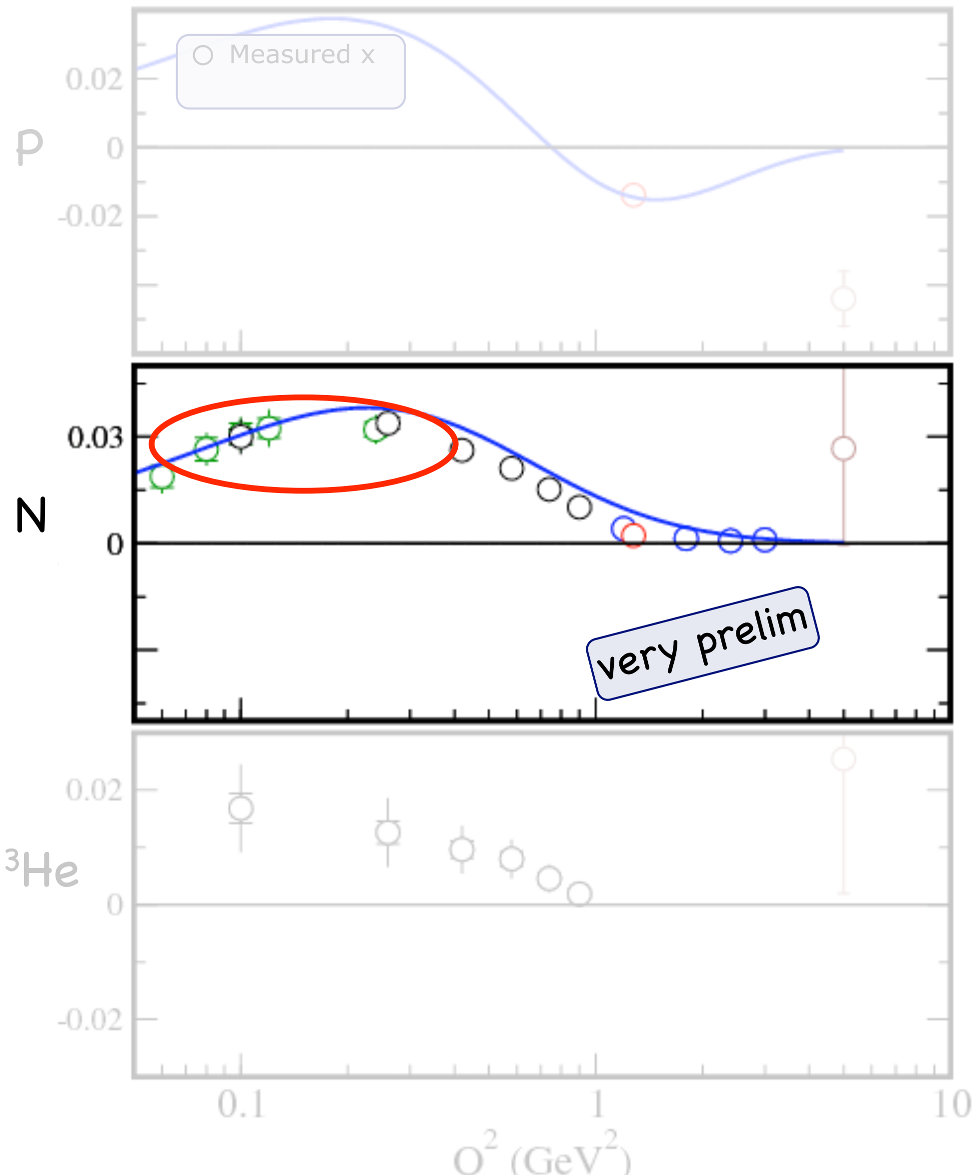
Neutron results around Q^2=1.3 GeV^2 from 2 very different experiments:

RSS in Hall C: Neutron from ND_3 & NH_3

E01-012 in Hall A : Neutron from ^{3}He

Excellent agreement!

BC Sum Rule

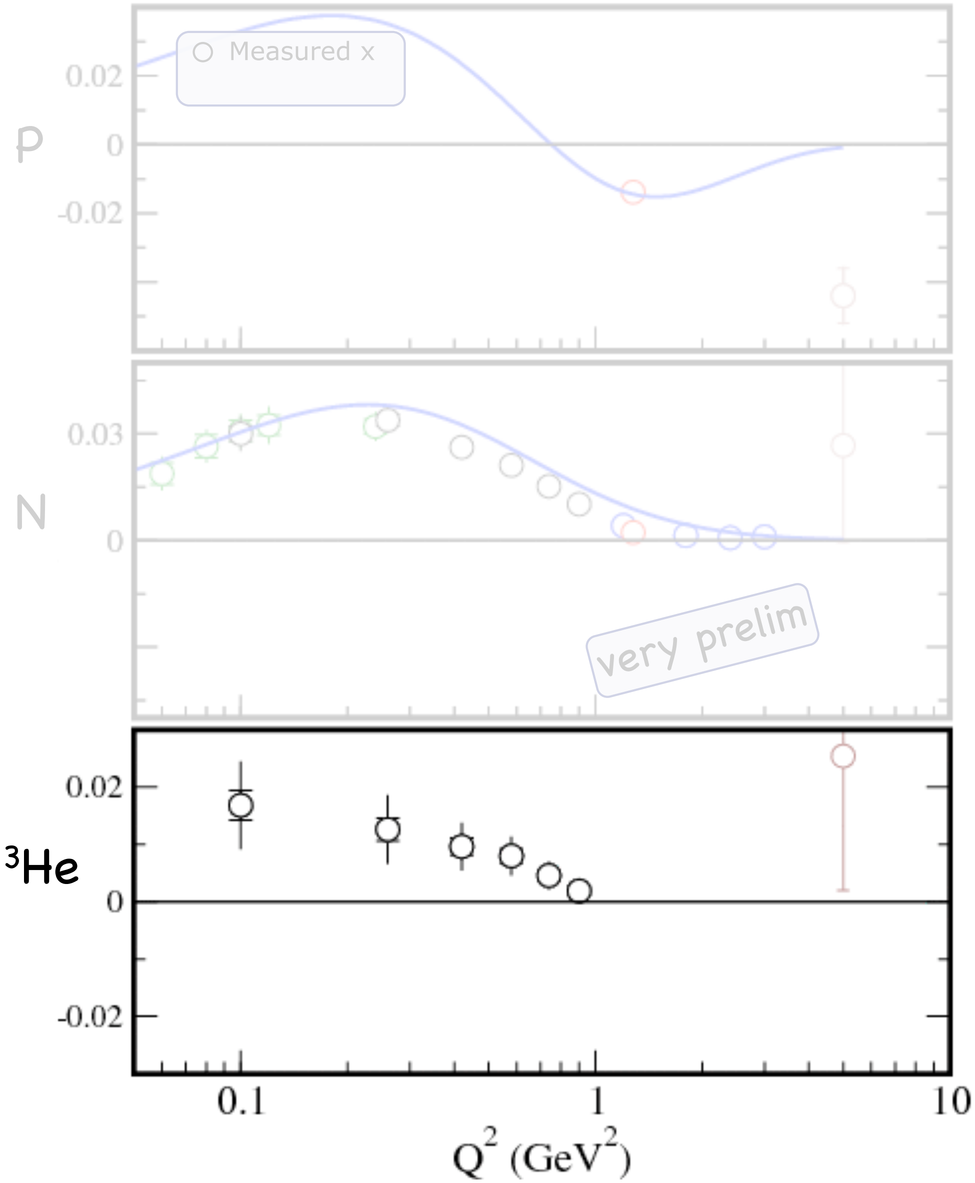


Good overlap at low Q^2 of the old and new neutron data

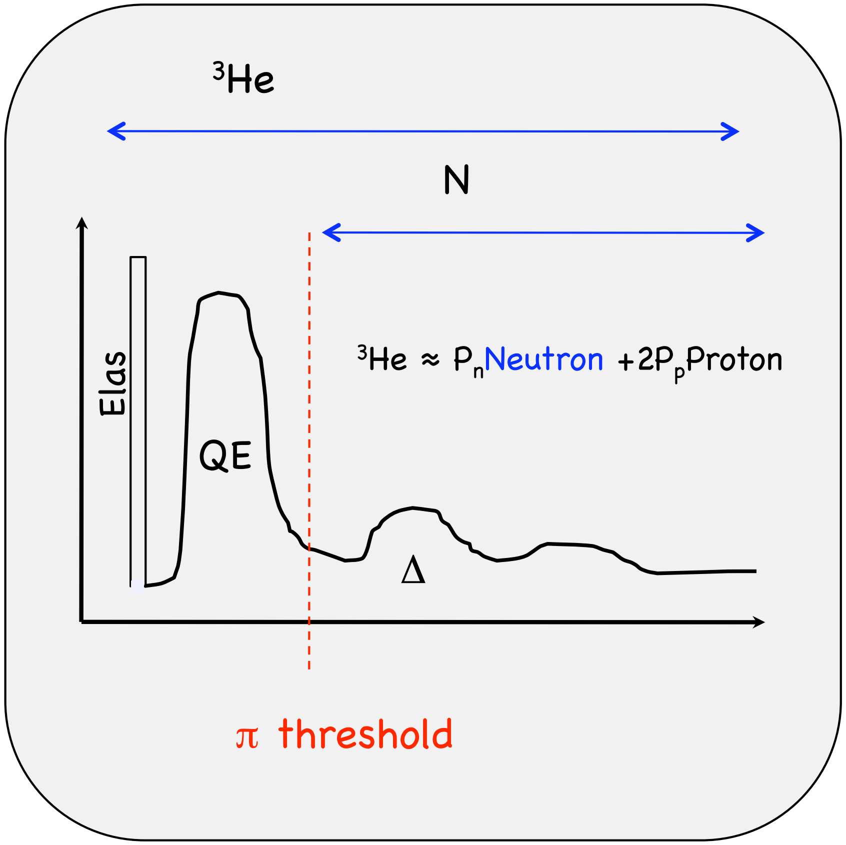
E94010 : Hall A ^{3}He old

E97-110 Hall A ^{3}He new

BC Sum Rule



Difference between N and ^{3}He Sum rules



Note: ^{3}He requires use of nuclear elastic

BC Sum Rule

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

BC = RES+DIS+ELASTIC

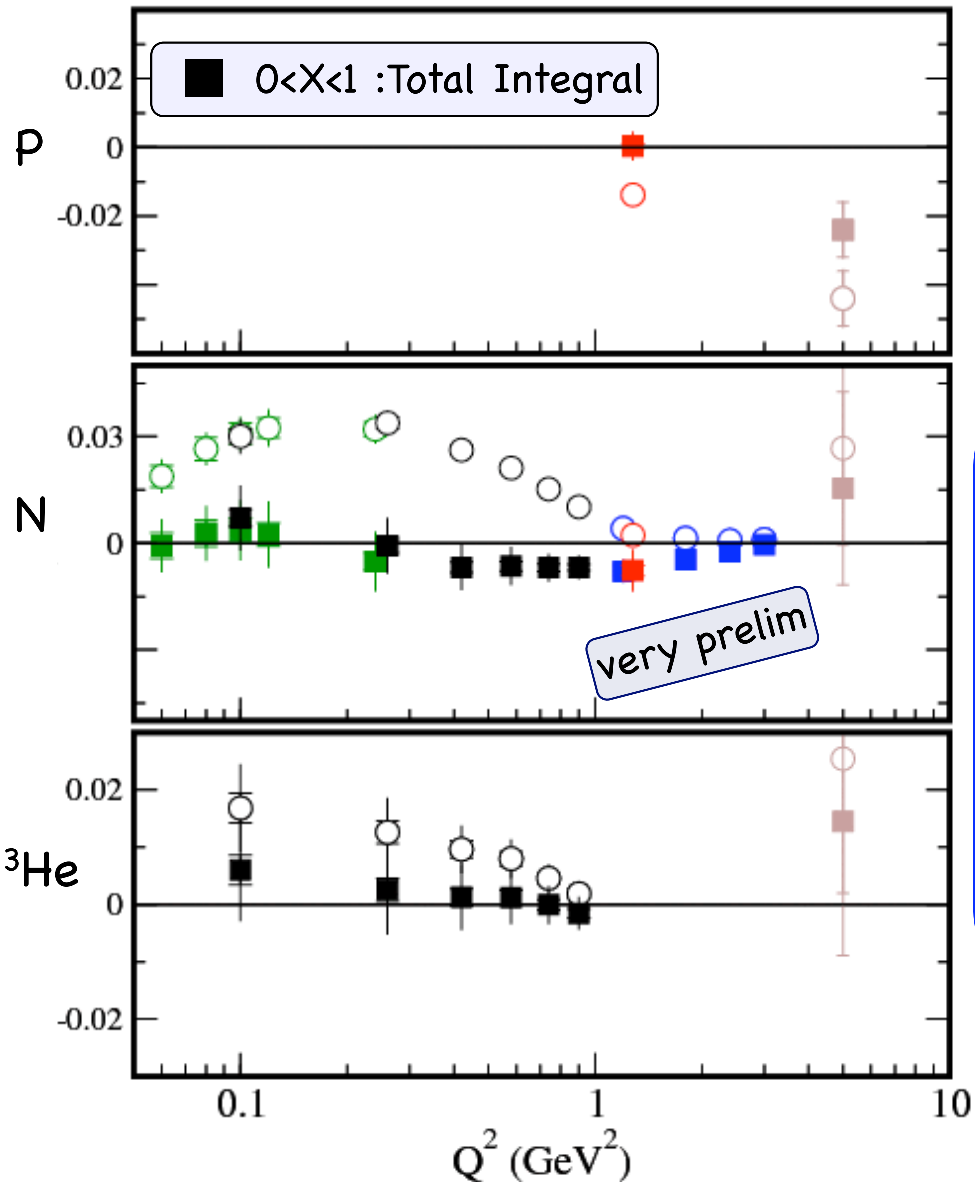
"RES": Here refers to measured x-range

"DIS": refers to unmeasured low x part of the integral. Not strictly Deep Inelastic Scattering due to low Q^2

Assume Leading Twist Behaviour

Elastic: From well know FFs (<5%)

BC Sum Rule



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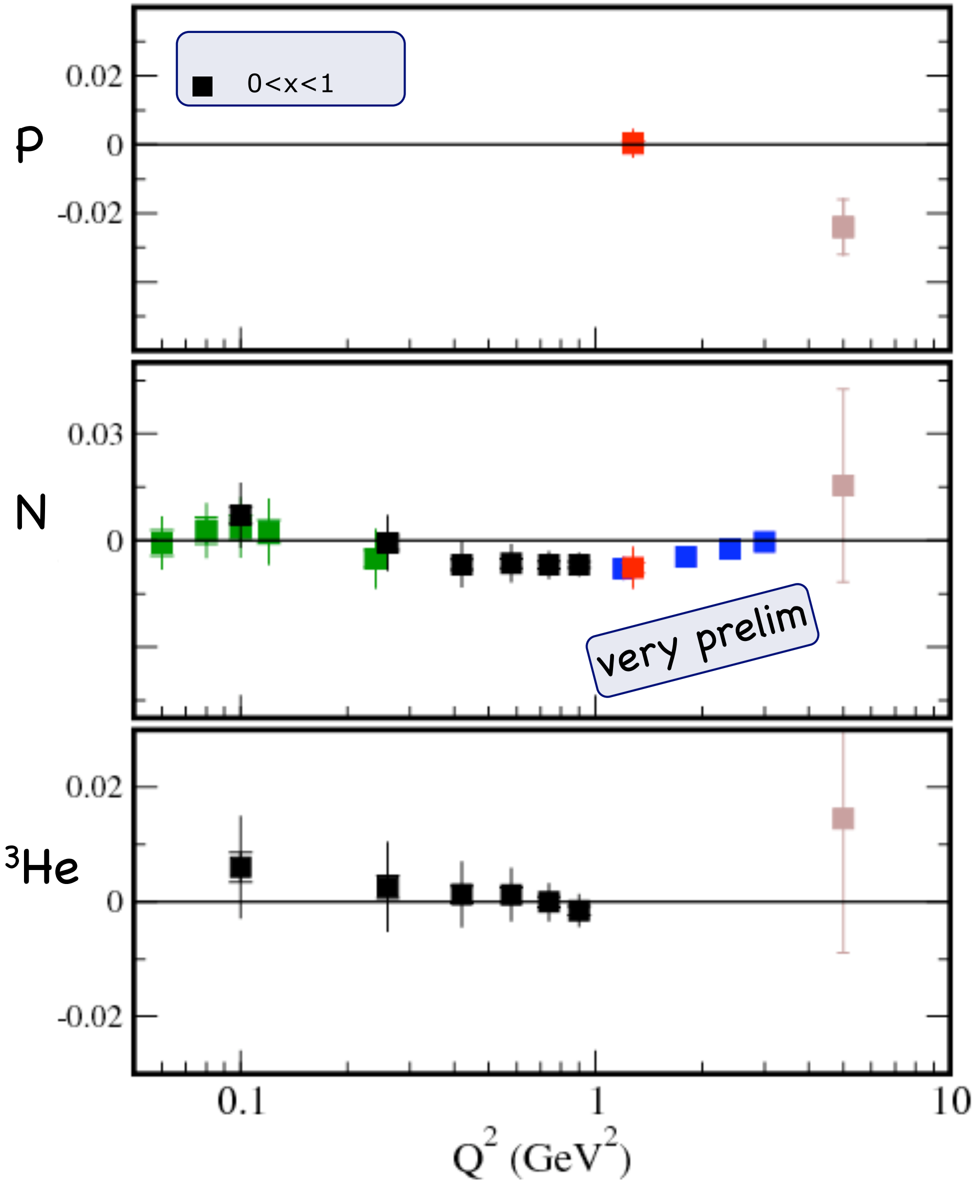
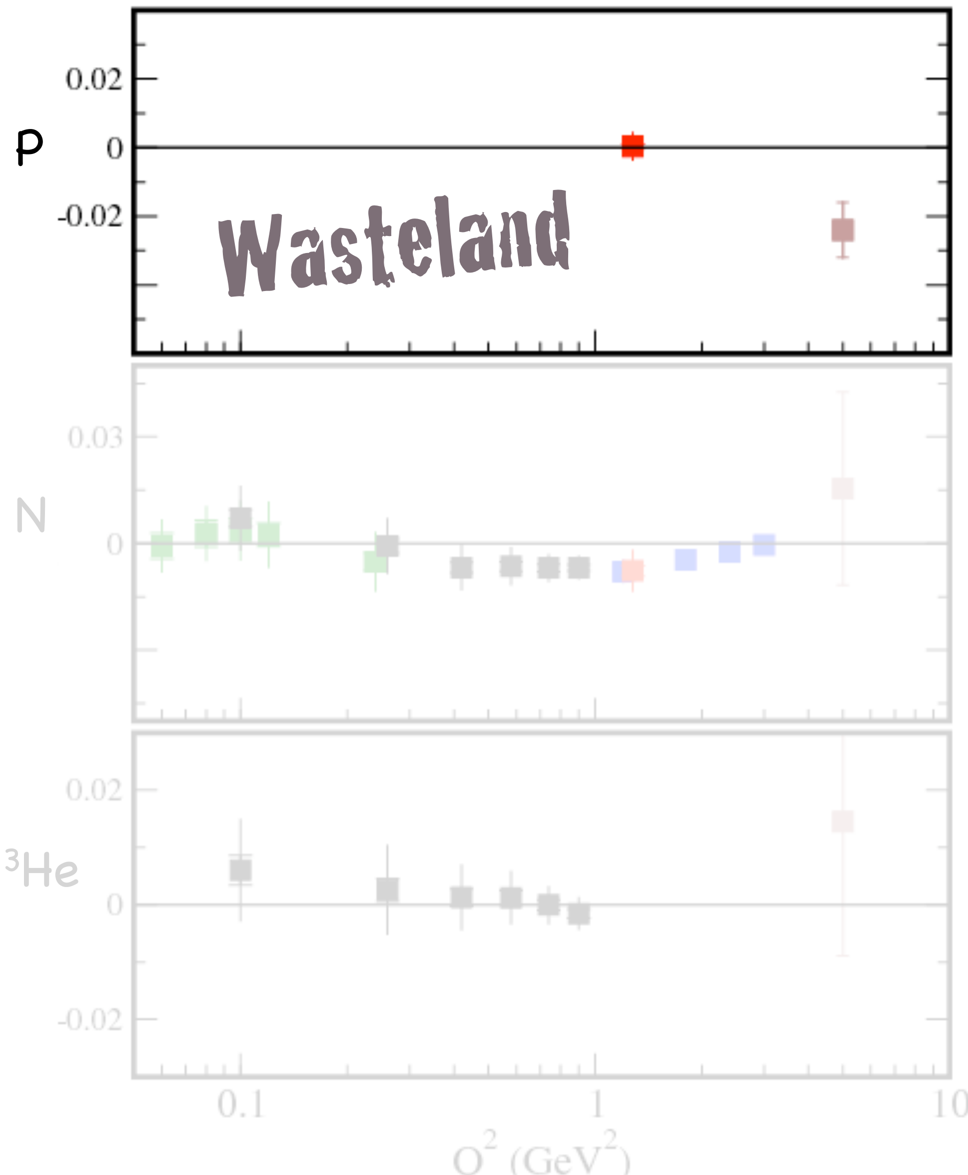


BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

BC satisfied w/in errors for Neutron
(But just barely in vicinity of Q^2=1!)

BC satisfied w/in errors for ^{3}He

BC Sum Rule



Proton g2p still relatively unknown for such a fundamental quantity.

Need more high quality data like RSS

<u>Upcoming Experiments</u>

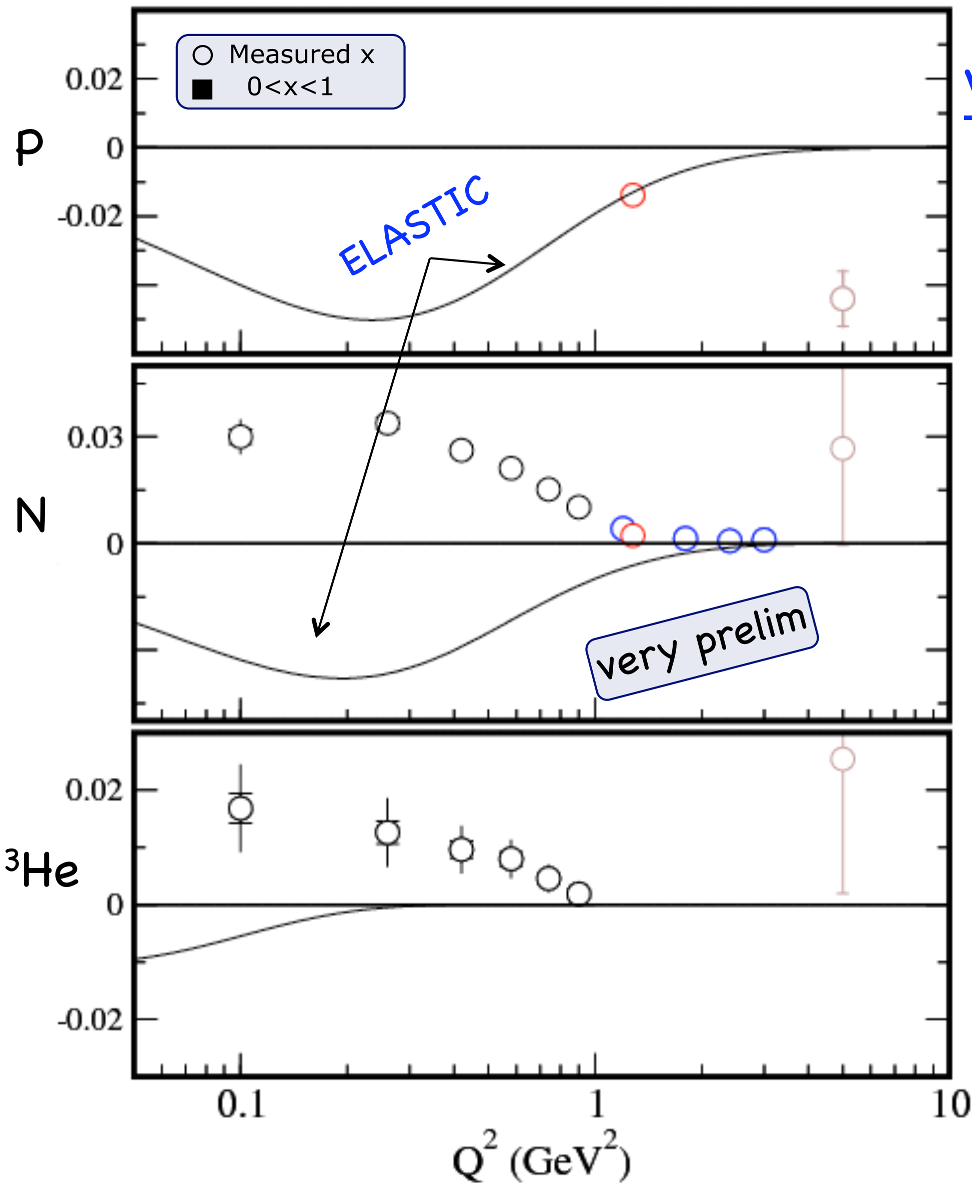
Sane: setting up now!

$2.3 < Q^2 < 6$ GeV2

"g2p" in Hall A, 2011

$0.015 < Q^2 < 0.4$ GeV^2

BC Sum Rule



What can BC tell us about Low-X?

Alternatively, if we assume BC holds we can learn something about the unmeasured part of Integral

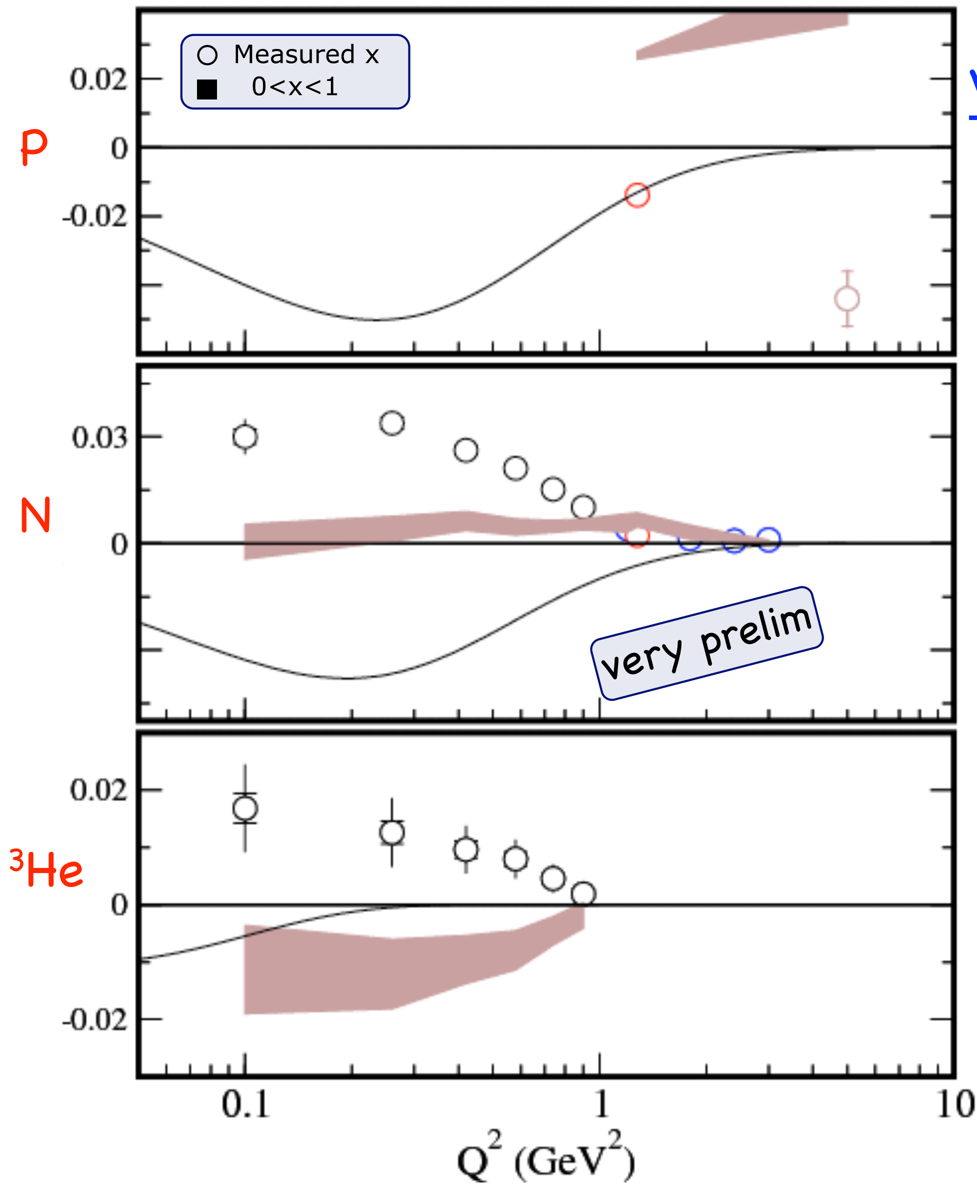
$$\int_0^1 g_2(x, Q^2)dx = 0$$

BC = 0 => Res + Elas + "DIS"

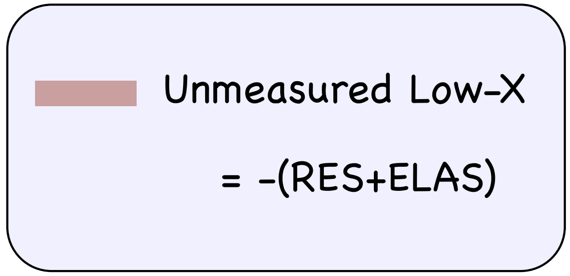
Unmeasured Low-x part

"DIS" = -(RES+ELAS)

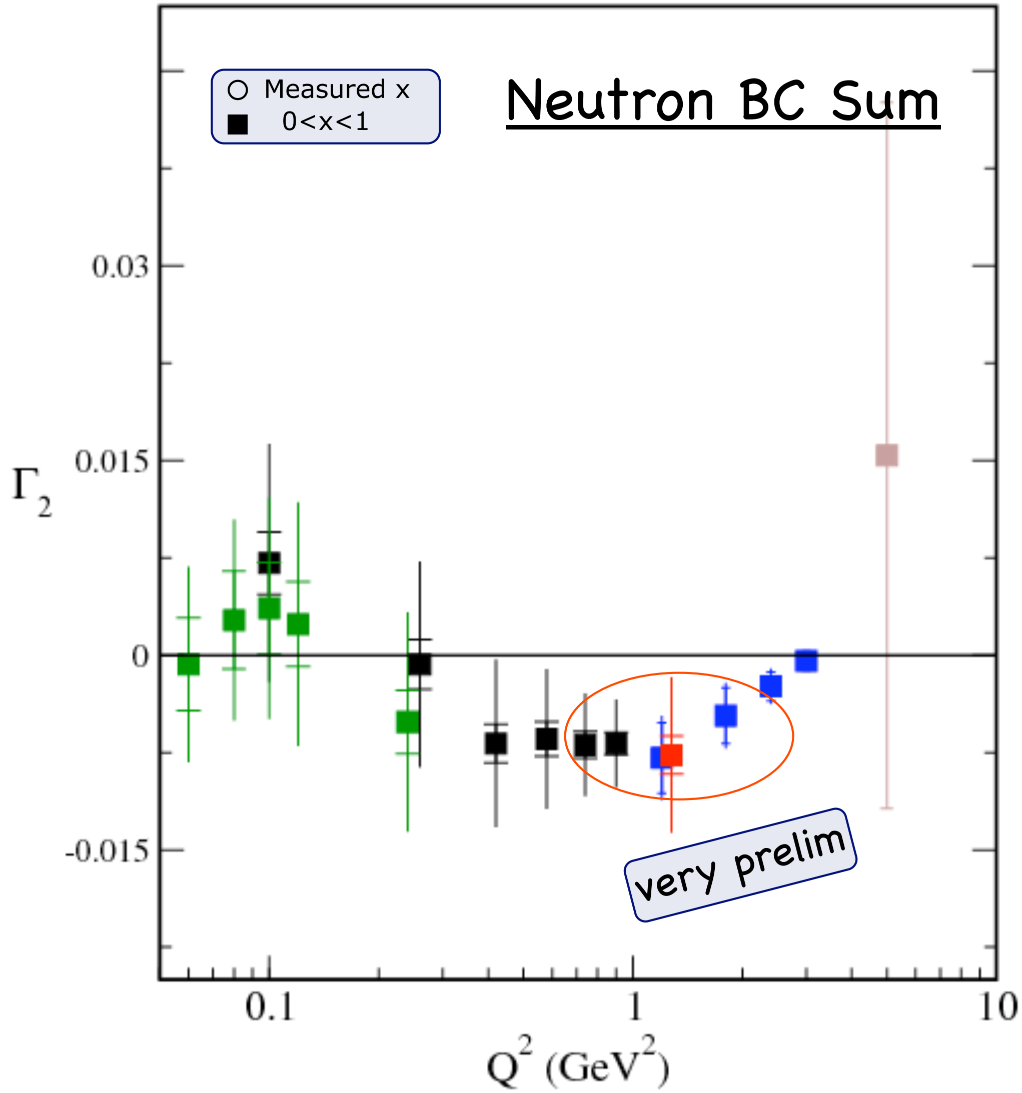
BC Sum Rule



What can BC tell us about Low-X?



BC Sum Rule



Standard Deviations from Zero

Q^2	Tot σ	Stat σ
0.74	1.7	6.6
0.9	2.0	7.9
1.2	2.4	2.9
1.8	1.9	2.2
2.4	1.8	2.2

Just on the edge of being interesting

Statistical precision allows unambiguous test, but limited by large systematics.

Highly desirable to revisit E94010 systematics. RC and DIS could perhaps be improved with newer data.

Higher Moment

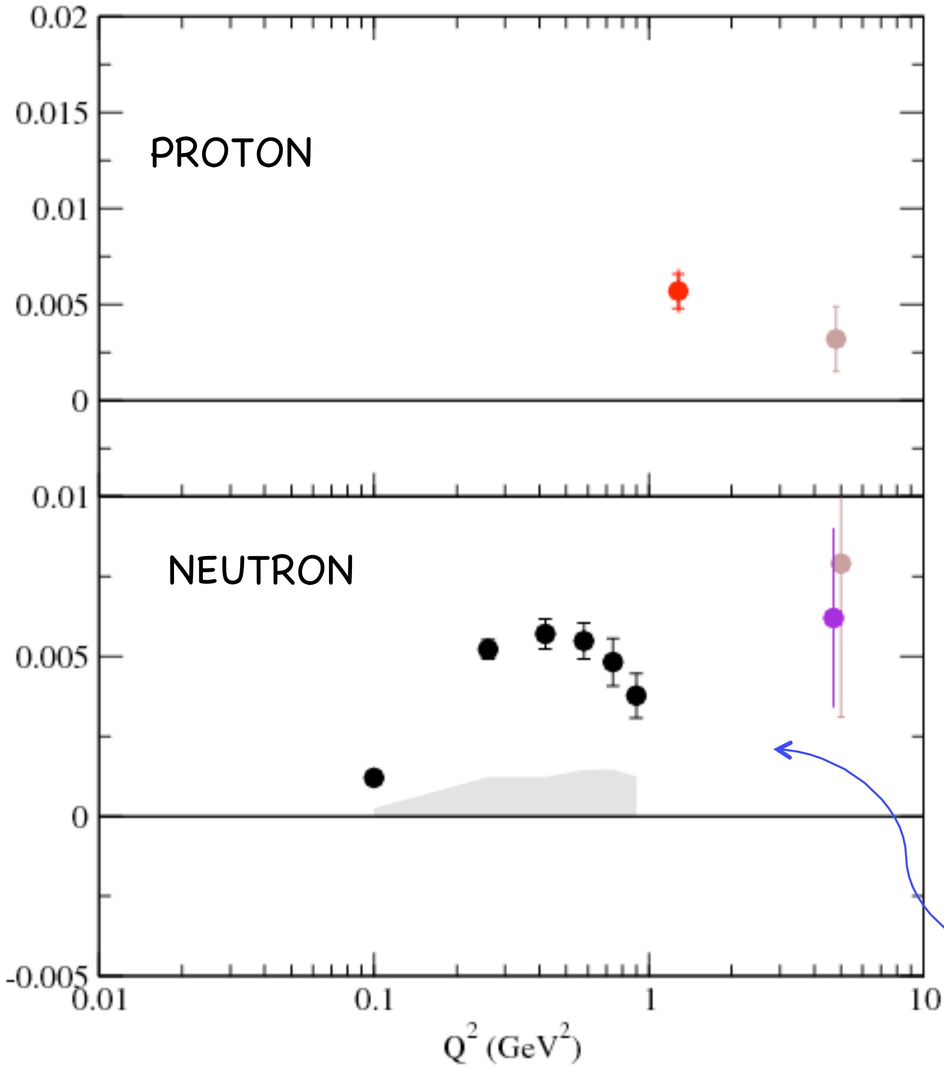
Cornwall Norton Moment

$$I(Q^2) = 2\int_0^{1-\varepsilon} x^2 (2g_1 + 3g_2)\,dx$$

$I(Q^2) \neq$ the twist-3 matrix element but very interesting all the same.

More on this later…

I(Q^2)



Existing World Data on I(Q^2)

BLACK : E94010

M. Amarian, *et al*. PRL. 92 (2004) 022301

BROWN : E155

P.Anthony, *et al*. PLB. 553 (2003) 18

RED : RSS.

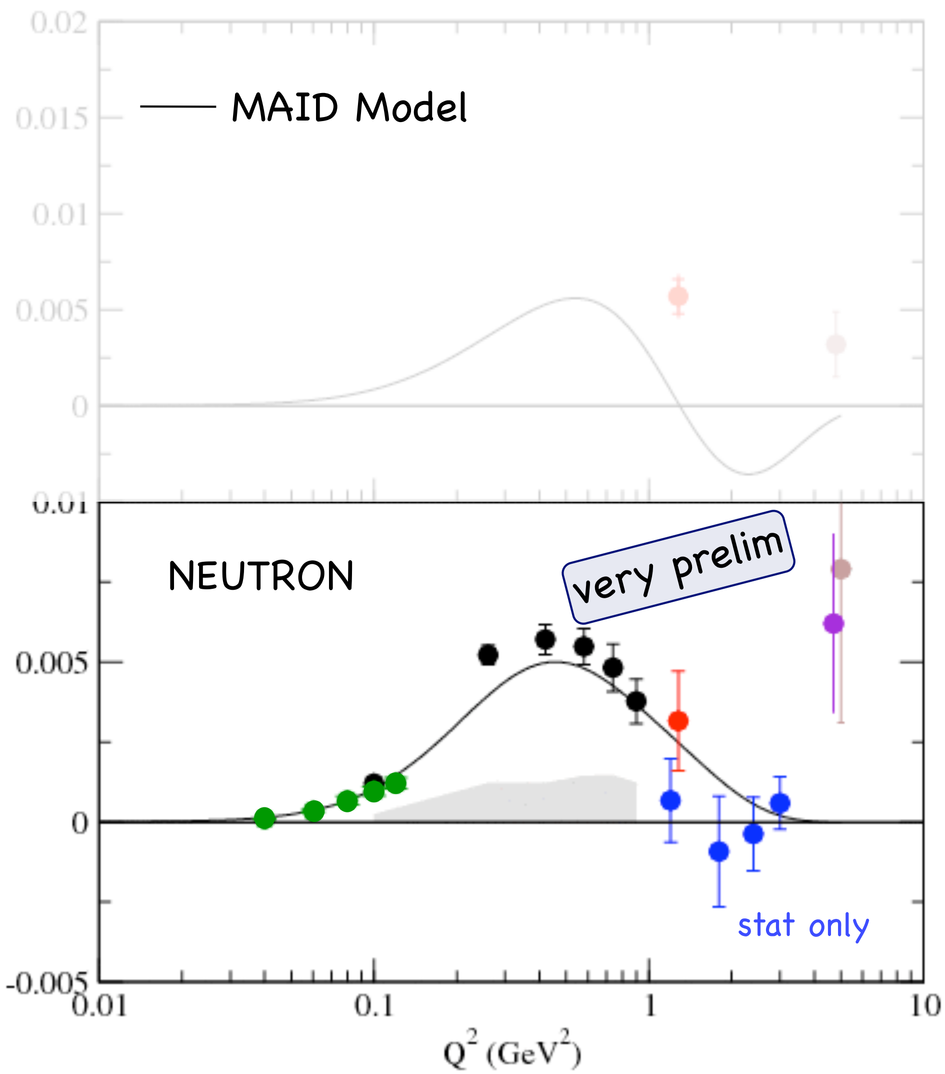
Wesselman, Slifer, Tajima *et al*. PRL 98(2007)132003.

Magenta: E99-117

X. Zheng *et al*. PRC 70(2004)065207

What's happening at large Q^2?

I(Q^2)



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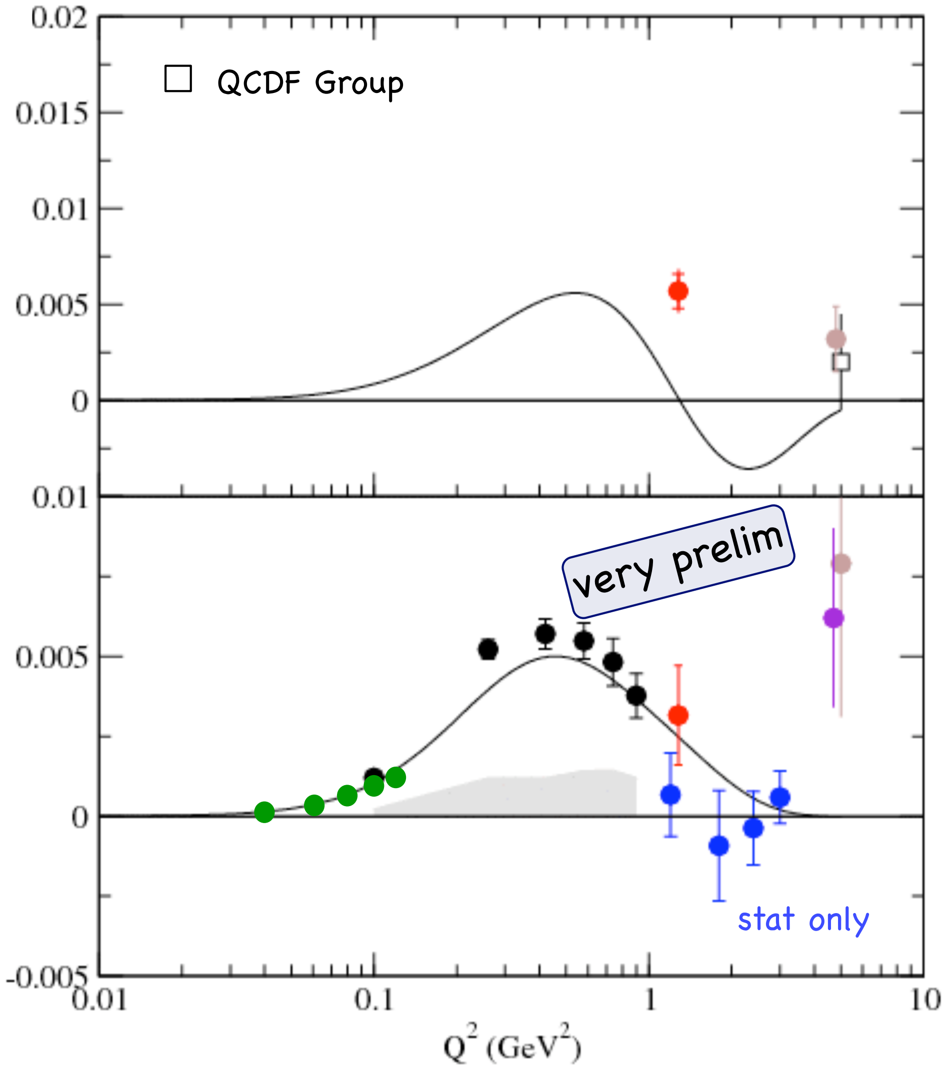
$I(Q^2)$



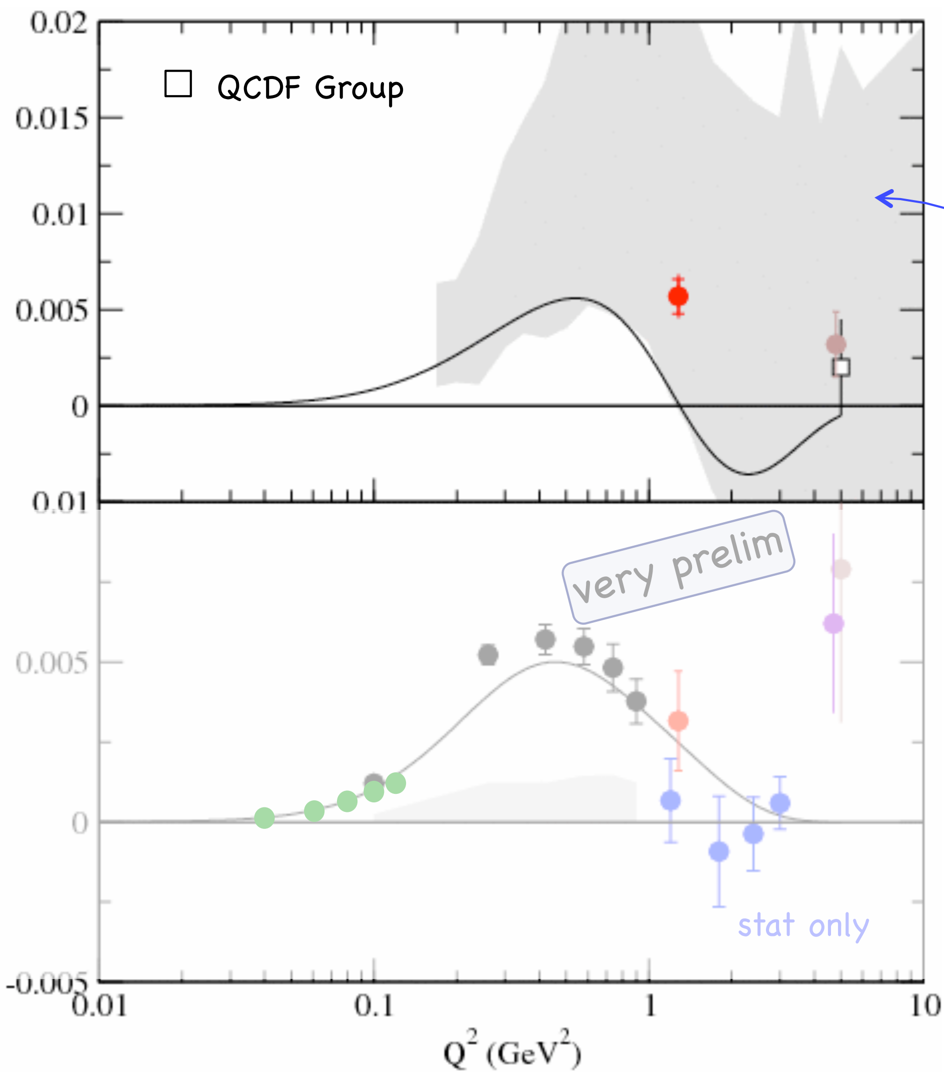
$I(Q^2)$->0 for Q^2=0 and Q^2=infinity

largest around Q^2=1

Not too useful to the OPE in this region, but excellent gauge of "QCD complexity"

(i.e. where's the most difficult place to make any meaningful QCD calculation?)

I(Q²)

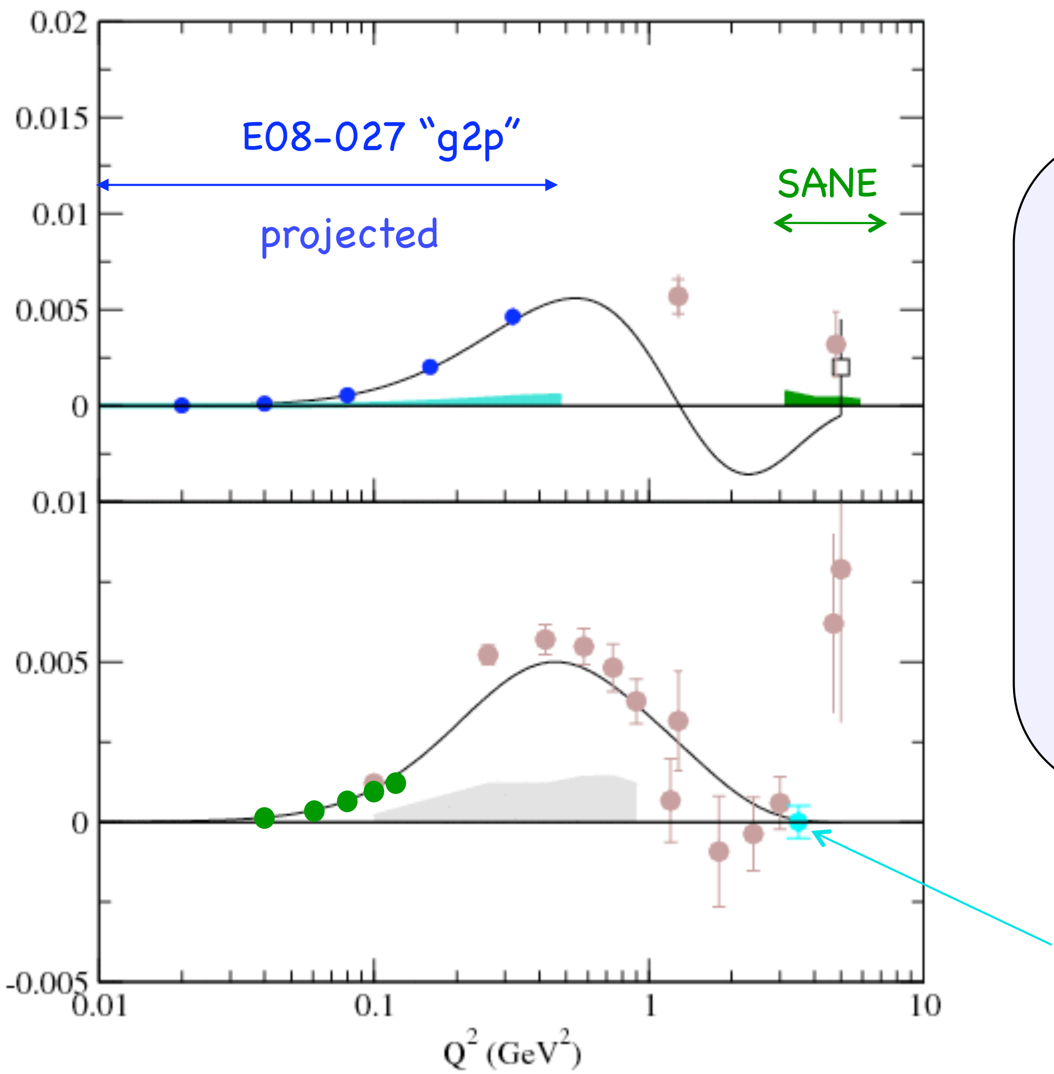


Osipenko *et al*. PRD. 71 (2005) 054007

Shaded Region: Estimate of I(Q²)

Large uncertainty due to lack of knowledge of g2p

I(Q²)



<u>Upcoming 6 GeV Experiments</u>

Sane: Fall 2008

$2.3 < Q^2 < 6$ GeV2

“g2p” in Hall A, 2011

$0.015 < Q^2 < 0.4$ GeV²

“d2n” in Hall A, 2009

$Q^2 = 3$ GeV²

Operator Product Expansion

Expansion of SF moments in powers of $1/Q^2$ ("twist")

example:

$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)dx = \sum_{\tau=2,4,\dots} \frac{\mu_2(Q^2)}{Q^{\tau-2}}$$

$$\mu_4 = \frac{1}{9}M^2\left(\tilde{a}_2 + 4\tilde{d}_2 + 4\tilde{f}_2\right)$$

leading twist ($\tilde{a}_2$)

twist-3 ($\tilde{d}_2$)

twist-4 ($\tilde{f}_2$)

Lowest order (twist-2) maps to the succesful parts of the parton model.

Higher twists arise from non-perturbative multiparton interactions

Cornwall-Norton Moments

$$I(Q^2) = 2\int_0^{1-\varepsilon} x^2(2g_1 + 3g_2)dx$$

$$= \tilde{d}_2(Q^2) + \vartheta\left(\frac{M^2}{Q^2}\right)$$

Typical method of extracting twist-3 matrix element

But completely ignores TMC!

Very significant below $Q^2 \approx 5$

Y.B. Dong PRC 77(2008) 015201

Y.B.Dong PLB 653,(2007)18

Nachtmann Moments

Nachtmann Moments:

$$M_2^3(Q^2) = \int_0^1 dx\left(\frac{\xi^4}{x^2}\right)\left\{\frac{x}{\xi}g_1 + \left[\frac{3}{2}\left(\frac{x}{\xi}\right)^2 - \frac{3}{4}\frac{M^2}{Q^2}x^2\right]g_2\right\}$$

$$= \frac{\tilde{d}_2}{2}$$

Matsuda & Uematsu, N.Phys. B53(1998)301

Piccione & Ridolfi N. Phys. B513(1998)301

Generalization of CN moments to protect from the TMC

$$\frac{M^2}{Q^2} \rightarrow 0 \quad M_2^3 \rightarrow \int x^2(2g_1 + 3g_2)dx$$

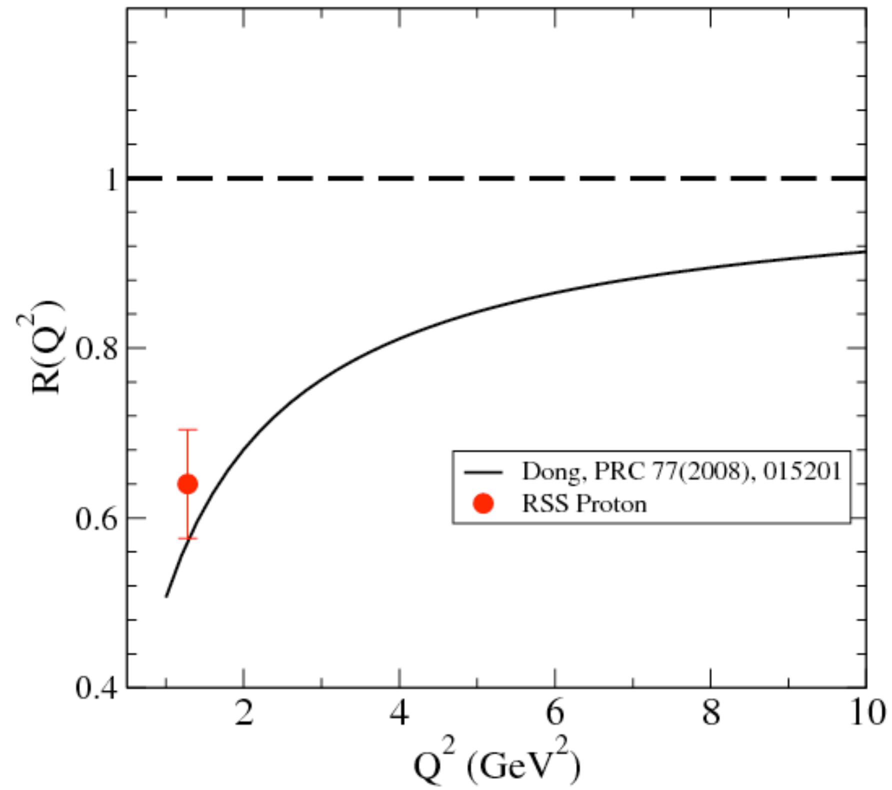
Reduces to familiar form

Not a new idea, but difficult to implement unless g_2 measured simultaneously with g_1

Quantifying Size of TMC

$$R(Q^2) = \frac{2M_2^3(Q^2)}{I(Q^2)}$$

R->1 in case of vanishing nucleon mass



R always less than 1 => $I(Q^2)$ overestimates twist-3

Target Mass Corrections must be applied in order to obtain clean dynamical Twist-3

Generalization of Γ_1

$$M_1^1(Q^2) = \int_0^1 dx \left(\frac{x}{\xi}\right)^2 \left\{ \left[\frac{x}{\xi} - \frac{1}{9}\left(\frac{M}{Q}\right)^2 x\xi \right] g_1 - \left(\frac{M}{Q}\right)^2 x^2 \frac{4}{3} g_2 \right\}$$

$$\frac{M^2}{Q^2} \to 0 \quad M_1^1 \to \Gamma_1$$

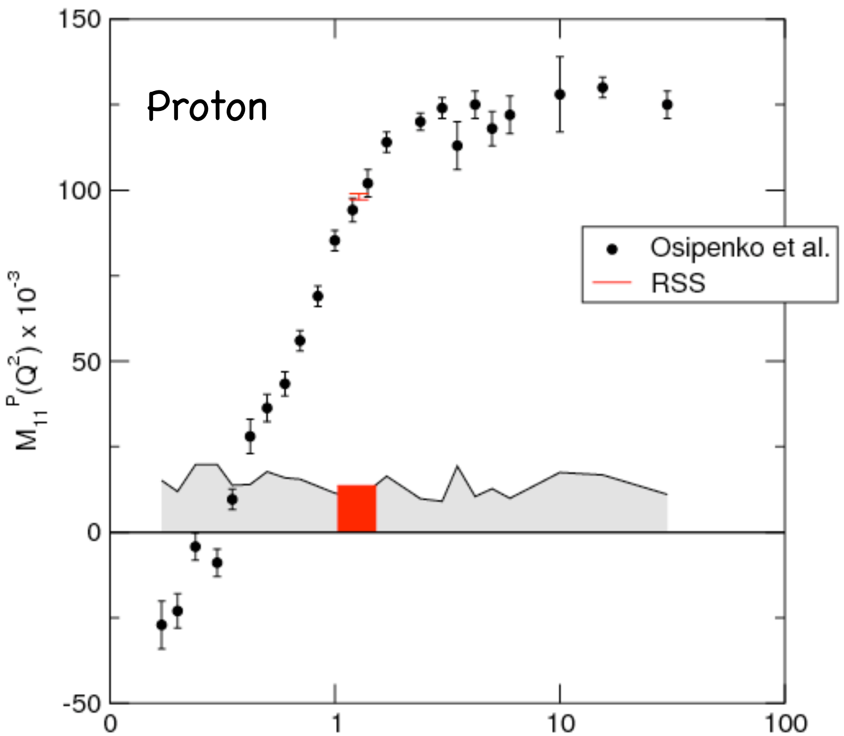
Matsuda & Uematsu, N.Phys. B53(1998)301

Piccione & Ridolfi N. Phys. B513(1998)301

<u>Osipenko *et al.* PRD 71, 054007 (2005)</u>

Global analysis of g1p data. Allows to cleanly extract leading twist term.

TMC not as large as for $I(Q^2)$



Summary

Burkhardt—Cottingham Sum Rule

Good coverage for Neutron. Proton g2p is still relatively unknown.

Data seems to validate BC, but at the 2.5σ level around Q^2=1

Important to update the systematics of the old experiments

Assuming BC holds, we can use JLab data to say something about low-x.

Target Mass Effects

TMC are significant at JLab kinematics

Nachtmann moments protect the SSF from TMC

Must use Nachtmann Moments in order to cleanly extract Higher twists

JLab 6 GeV Program

Still lots of Good Physics to be completed before the upgrade.

Backups

References

BLACK : E94010. (Hall A, ^3He)

M. Amarian, *et al*. PRL. 92 (2004) 022301
K. Slifer, et al. PRL. 101:022303,2008

RED : RSS. (Hall C, NH_3,ND_3)

Wesselman, Slifer, Tajima et al.
PRL 98(2007)132003.
Slifer, Rondon *et al*. in preparation

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P.Anthony, *et al*. PLB. 553 (2003) 18

Magenta E99-117(Hall A, ^3He)

X. Zheng et al. PRC 70(2004)065207

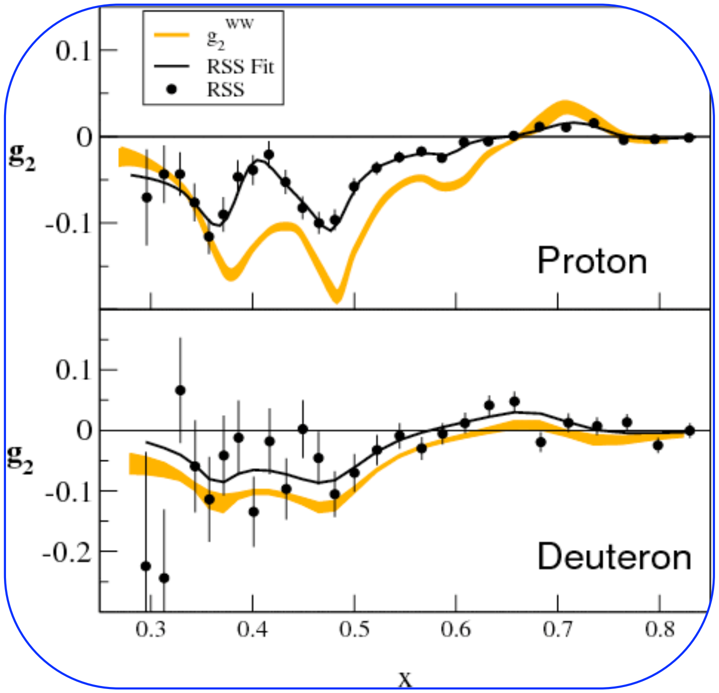
BLUE: E01-012. (Hall A, ^3He)

P. Solvignon et al. arXiv:0803.3845 (PRL accepted)
P. Solvignon *et al.* in preparation

SHADED : Theory

Osipenko *et al*. PRD. 71 (2005) 054007

BC Sum Rule



Unmeasured Contributions

Low-X Estimate

Assume $g_2 = g_2^{WW}$ at low x.

Supported by RSS data

15% variation seen depending on choice of g_1 used.

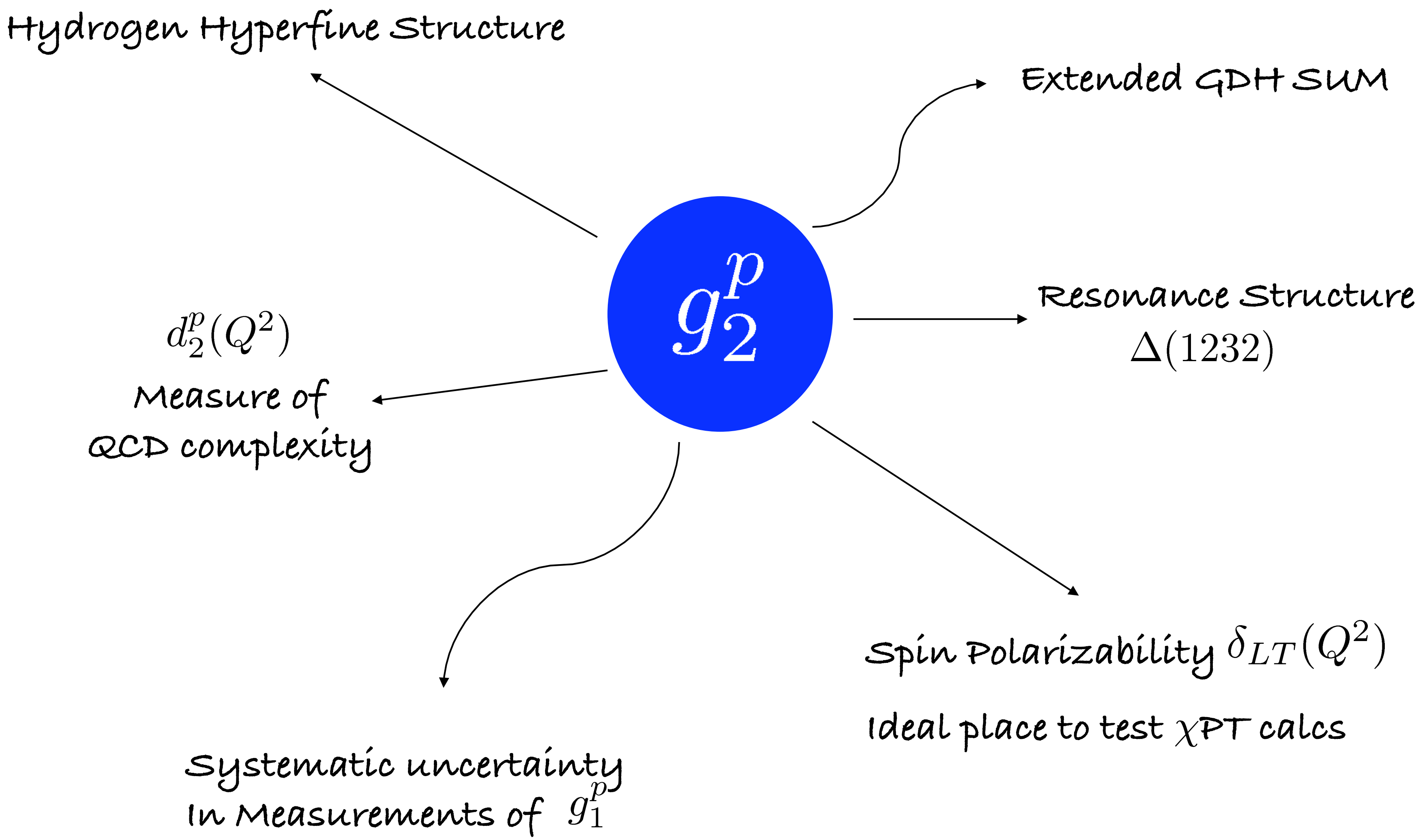
ELASTIC: X=1

$$g_1^{el}(x,Q^2) = \delta(x-1)G_M(Q^2)\frac{G_E(Q^2)+\tau G_M(Q^2)}{2(1+\tau)}$$

$$g_2^{el}(x,Q^2) = \delta(x-1)\tau G_M(Q^2)\frac{G_E(Q^2)-G_M(Q^2)}{2(1+\tau)}$$

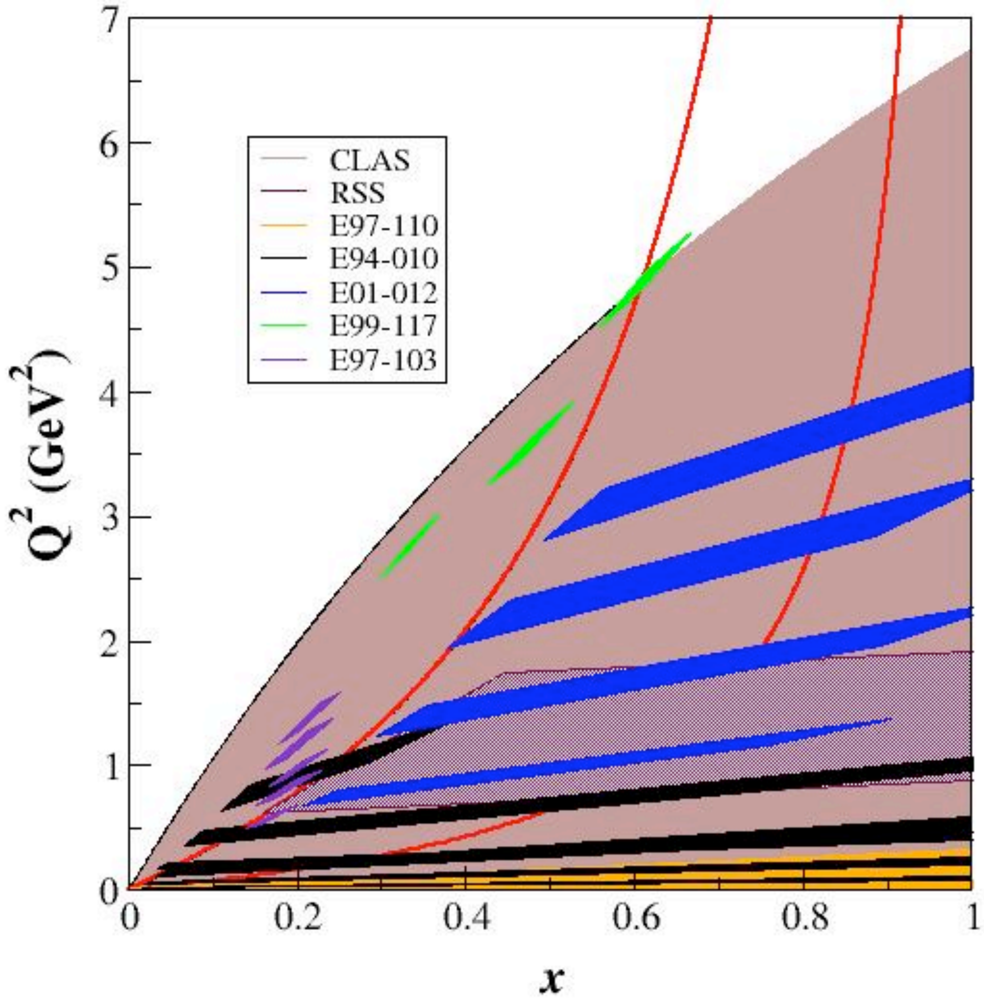
(Form Factor uncertainties less than 5%)

Summary



Hydrogen Hyperfine Structure
Extended GDH SUM
g_2^p
Resonance Structure
$\Delta(1232)$
$d_2^p(Q^2)$
Measure of
QCD complexity
Spin Polarizability $\delta_{LT}(Q^2)$
Ideal place to test χPT calcs
Systematic uncertainty
In Measurements of g_1^p

JLab Kinematic Coverage



Overview of available kinematic range at JLab

Uniquely positioned to provide data in transition region of QCD

Target Mass Corrections

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

$$g_1(x,Q^2) = g_1(x,Q^2,M=0)$$

From PQCD

$$+\frac{M}{Q^2} g_1^{(1)TMC}(x,Q^2)$$

Purely kinematical

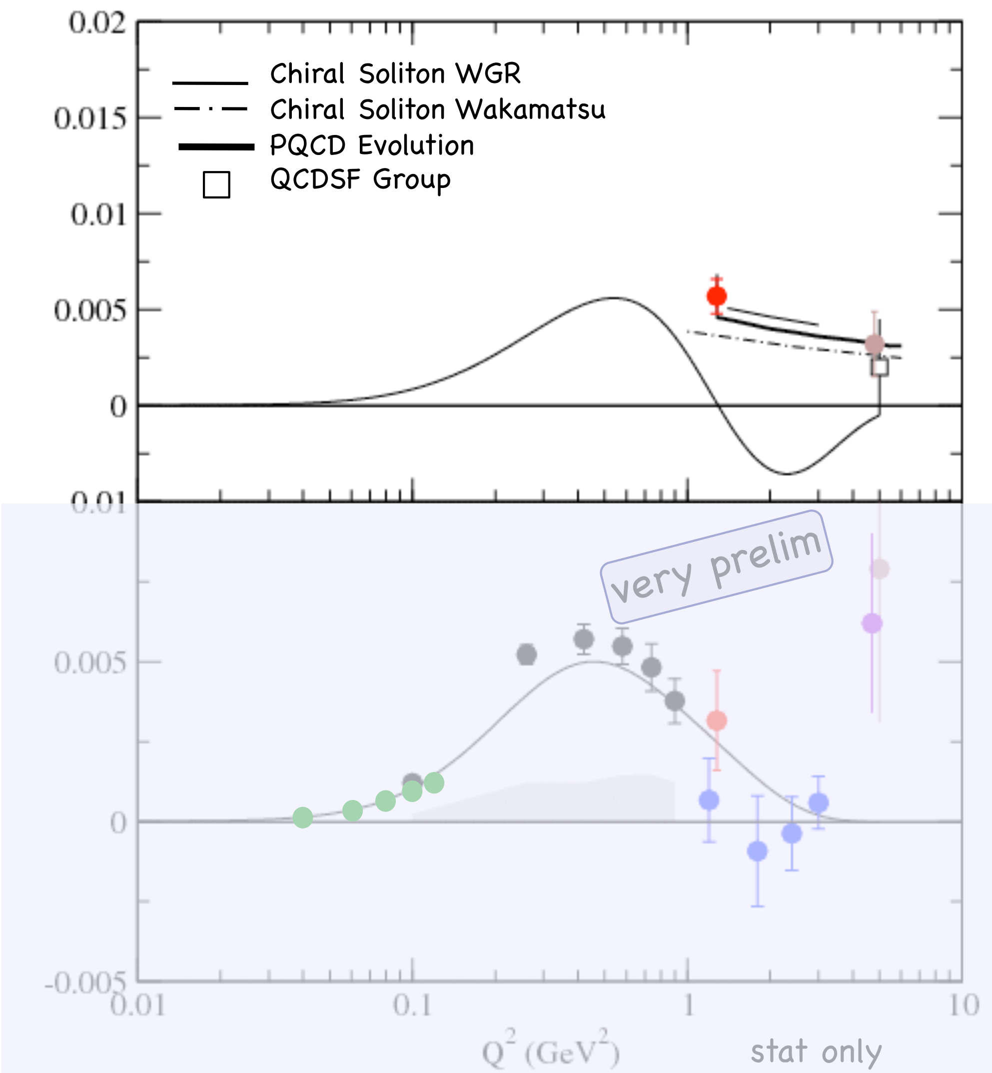
$$+\frac{h(x,Q^2)}{Q^2} + \vartheta(1/Q^4)$$

Higher twist

$$\int_0^1 x^2 g_1(x,Q^2)dx = \frac{1}{2}\tilde{a}_2 + \vartheta\left(\frac{M^2}{Q^2}\right)$$

$$\int_0^1 x^2 g_2(x,Q^2)dx = \frac{1}{3}\left(\tilde{d}_2 - \tilde{a}_2\right) + \vartheta\left(\frac{M^2}{Q^2}\right)$$

$I(Q^2)$



Q^2 evolution predicted well by PQCD and Chiral Soliton models.

WGR: PRD55 (1997) 6910
Wakamatsu: PLB 487(2000)118
PQCD: Nucl. Phys. B201 (1982) 141
QCDSF: PRD63, 074506(2001)

g_2 Structure Function

<u>Wandzura-Wilczek relation</u> PLB **72** (1977) 195

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

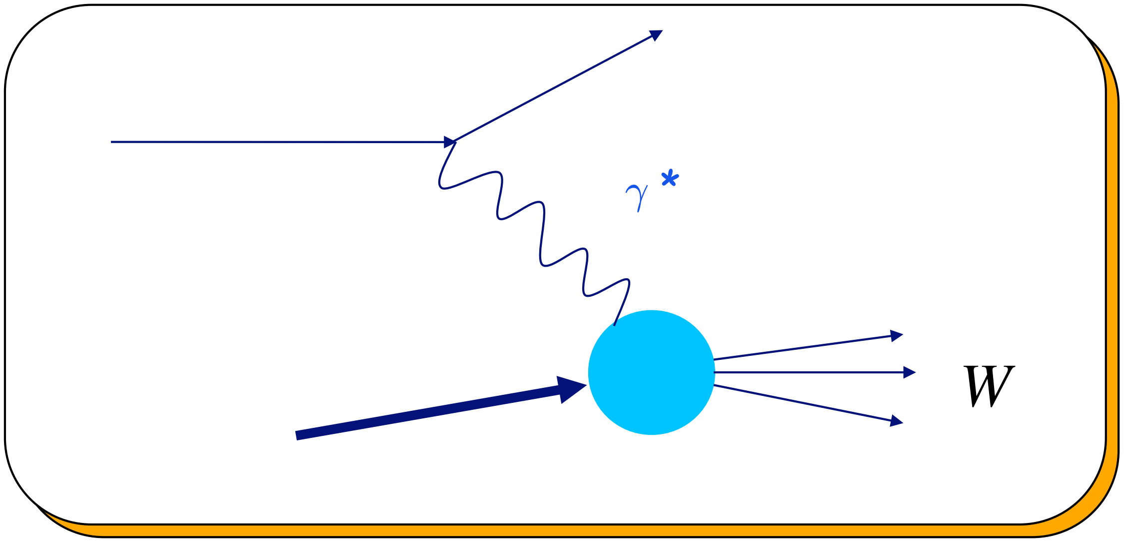
Leading twist determined entirely by g_1

$$g_2 = g_2^{WW} + \overline{g}_2$$

Higher twist

g_2 doesn't exist in Parton Model.
Good quantity to study higher twist

Inclusive Electron Scattering



$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

Inclusive Cross Section

deviation from point-like behavior
characterized by the Structure Functions