Low Q^2 Measurement of g_2^p and the δ_{LT} Spin Polarizability

A. Camsonne J. P. Chen

Thomas Jefferson National Accelerator Facility

Karl J. Slifer

University of New Hampshire

Spin Structure at Long Distance Workshop
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Overview

The inclusive nucleon SSF g_1 and g_2 are measured over wide range,

but

g_2^p remains unmeasured below Q^2=1.3 GeV^2

This Experiment

Measure g_2^p in the resonance region for $0.02 < Q^2 < 0.4$ using the Hall A septa and the polarized ammonia target.

Motivations

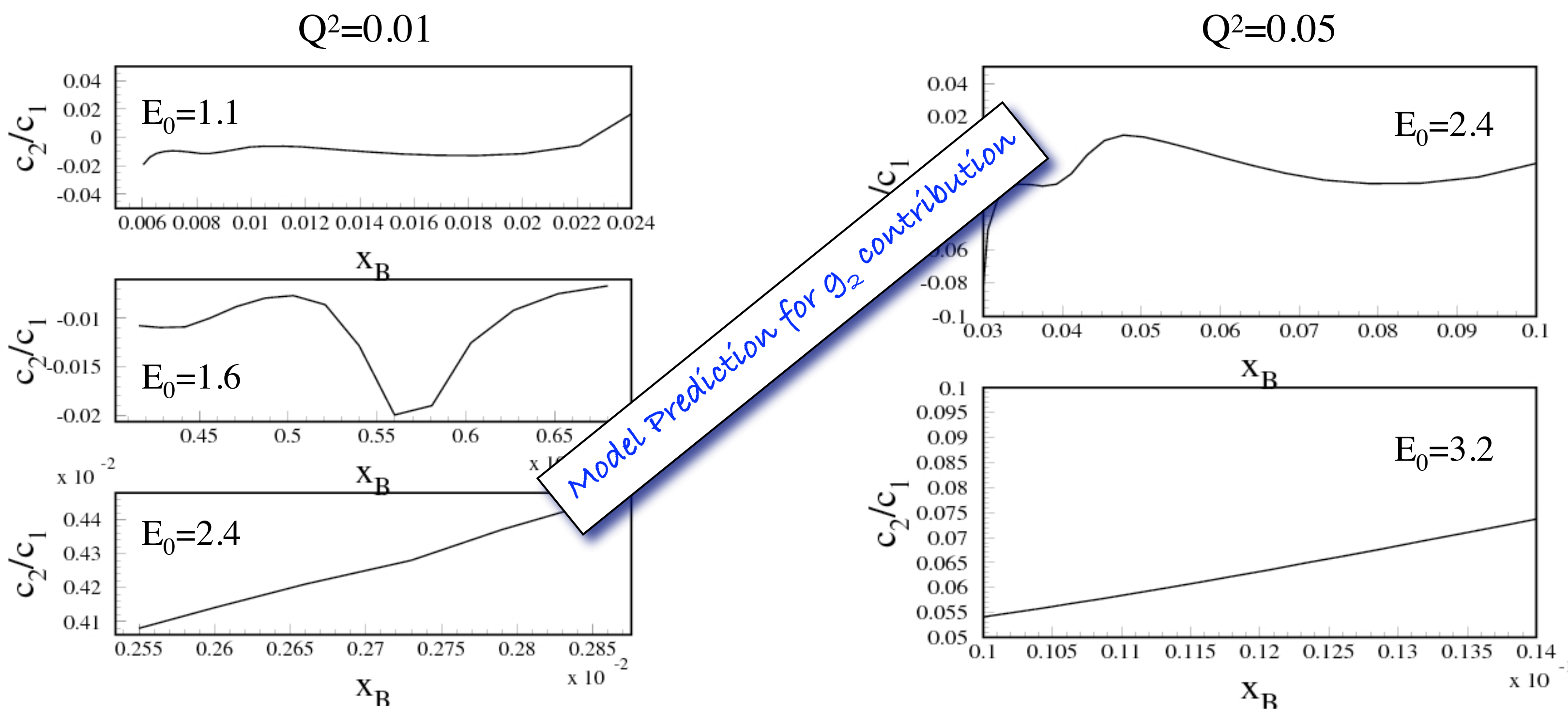
- g_2^p is a fundamental spin observable.
- BC Sum Rule violation suggested at large Q^2.
- State of the Art χPT calculations fail for neutron spin polarizability δ_{LT}.
- Knowledge of g_2^p is a leading uncertainty in Hydrogen Hyperfine calculations.
- Resonance Structure, in particular the $\Delta(1232)$.
- Also a leading uncertainty in longitudinal measurements of g_1^p (Hall B EG1, EG4).

Impact on Longitudinal Measurements of g_1

Longitudinal cross section difference

$$\Delta\sigma_{\|} \propto (E + E'\cos\theta)\, g_1 - 2Mx\, g_2$$

$$\frac{c_1}{c_2} = \frac{2Mxg_2}{(E+E'\cos\theta)g_1}$$



reproduced from EG4 proposal

EG4 Systematic

$P_B P_T$	1-2%
^{15}N Background	1-2%
$\mathcal{L}$ and Filling Factor	3.0%
Electron Efficiency	<5%
Radiative Corrections	5.0%
Modeling of g_2	1-10%

(Q^2 Dependent)

Our measurement of g_2^p will reduce this error to less than 1% for all Q^2

Hydrogen Hyperfine Structure

NCG PRL **96** 163001 (2006)

$$\Delta E = 1420.405\,751\,766\,7(9) \;\; \text{MHz}$$
$$= (1+\delta)E_F$$

$$\delta = (\delta_{QED} + \delta_R + \delta_{small}) + \Delta_S$$

Structure Dependent

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

Inelastic

Elastic Scattering

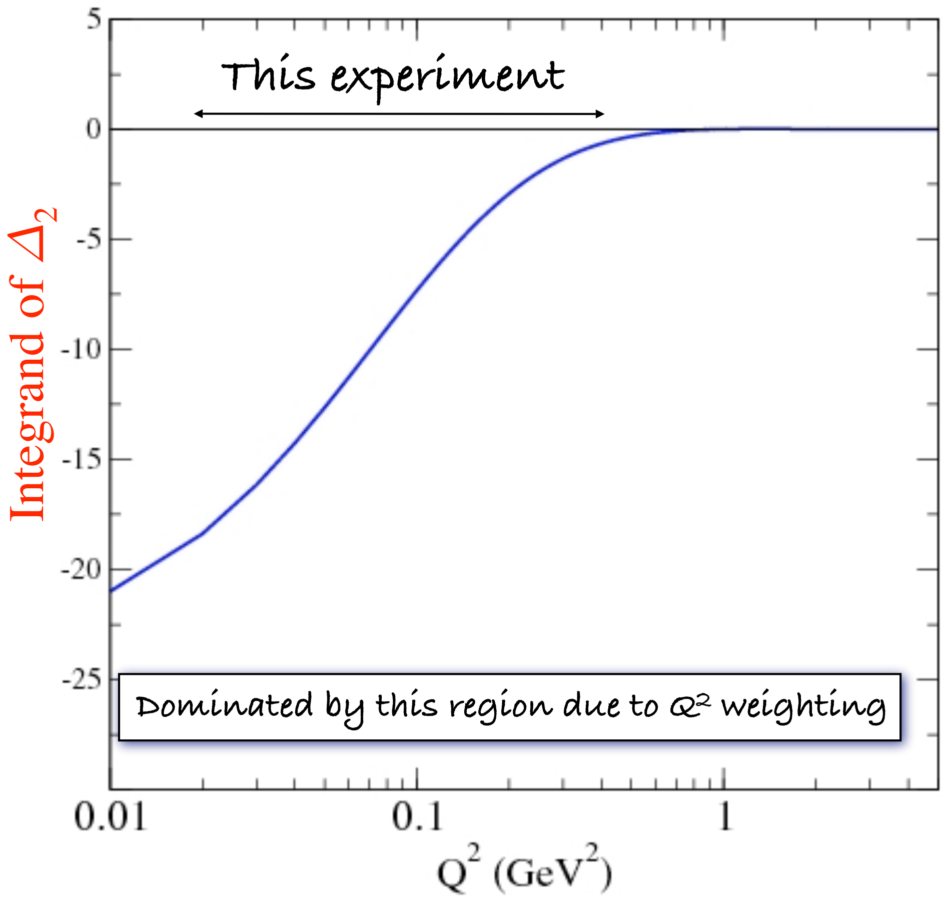
$$\Delta_{POL} = \frac{\alpha m_e}{\pi g_p m_p}(\Delta_1 + \Delta_2)$$

$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$B_2(Q^2) = \int_0^{x_{th}} dx \beta_2(\tau) g_2(x, Q^2)$$

$$\beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)}$$

Hydrogen Hyperfine Structure



$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

g_2^p unknown in this region:

Δ_2	$=$	-0.57	Hall B Model
Δ_2	$=$	-1.98	MAID Model
Δ_2	$=$	-1.86	Simula Model

We will provide first real constraint on Δ_2

Generalized Sum Rules

Ji and Osborne, J. Phys. **G27**, 127 (2001)

Unsubtracted Dispersion Relation + Optical Theorem:

$$S_1(\nu, Q^2) = 4\int_0^\infty \frac{d\nu'\nu'}{\nu'^2 - \nu^2} G_1(\nu', Q^2)$$

$$S_2(\nu, Q^2) = 4\int_0^\infty \frac{d\nu'\nu}{\nu'^2 - \nu^2} G_2(\nu', Q^2)$$

Extended GDH Sum

$$\Gamma_1 = \int g_1 dx = \frac{Q^2}{8} S_1(0, Q^2)$$

GDH Sum Rule at $Q^2=0$

Bjorken Sum Rule at $Q^2=\infty$

BC Sum Rule

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

Superconvergence relation valid at any Q^2

B&C, Annals Phys. **56**, 453 (1970).

Generalized Forward Spin Polarizabilities

Drechsel, Pasquini and Vanderhaehen, Phys. Rep. **378**, 99 (2003).

$$g_{TT}(\nu, Q^2) = \frac{\nu}{2\pi^2}\mathcal{P}\int_{\nu_0}^{\infty}\frac{d\nu' K}{\nu'^2 - \nu^2}\sigma_{TT}(\nu', Q^2) \qquad g_{LT}(\nu, Q^2) = \frac{1}{2\pi^2}\mathcal{P}\int_{\nu_0}^{\infty}\frac{d\nu'\nu' K}{\nu'^2 - \nu^2}\sigma_{LT}(\nu', Q^2)$$

LEX of g_{TT} and g_{LT} lead to the Generalized Forward Spin Polarizabilities

$$\gamma_0(Q^2) = \left(\frac{1}{2\pi^2}\right)\int_{\nu_0}^{\infty}\frac{K(\nu, Q^2)}{\nu}\frac{\sigma_{TT}(\nu, Q^2)}{\nu^3}d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1(x, Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x, Q^2)\right]$$

$$\delta_{LT}(Q^2) = \left(\frac{1}{2\pi^2}\right)\int_{\nu_0}^{\infty}\frac{K(\nu, Q^2)}{\nu}\frac{\sigma_{LT}(\nu, Q^2)}{Q\nu^2}d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1(x, Q^2) + g_2(x, Q^2)\right]$$

Existing Data

These integral relations allow us to test the underlying theory over a wide kinematic range

Existing Data

$g^n_{1,2}$ and g^p_1 : Precision data exists even at very low Q^2

Ongoing/Future Analyses

Hall A SAGDH : $g^n_{1,2}$

Hall B EG1 & EG4 : g^p_1

Hall B transverse : large Q^2 semi-inclusive

Hall C SANE : large Q^2

Hall A d2n : $g^n_{1,2}$

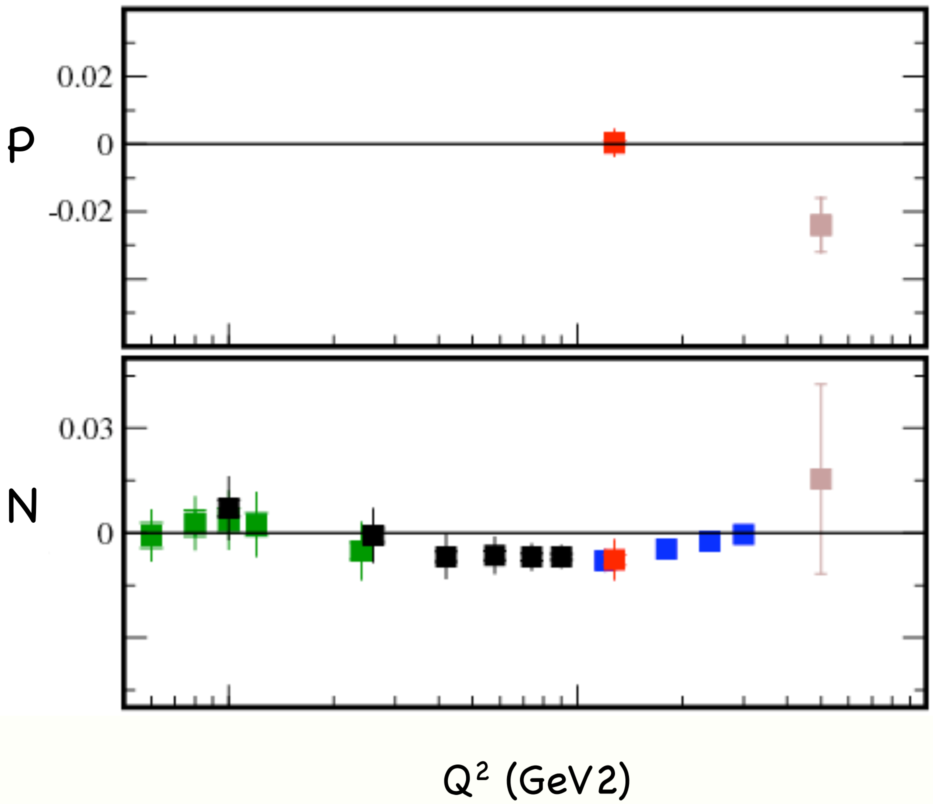
No g^p_2 data below Q^2=1.3 GeV^2

PAC33 Theory Comments

PR-08-027: *A Measurement of g_2^p and the Longitudinal-Transverse Spin Polarizability*

The physics case for measuring g_2^p and its moments has not diminished since PAC31, when this proposal was last submitted (and conditionally approved). There is a clear need to fill in the gaps in the data set on the g_2 structure functions of the nucleon, and this experiment aims to do just that. In strengthening the case for collecting the high-Q^2 data, the authors have made clear connections to the BC sum rule, which is an important test of our understanding of QCD, as well as the impact of their data on other analyses (e.g. from CLAS), which have previously had to make assumptions about g_2^p when extracting g_1^p data.

BC Sum Rule Existing Data



Proton g2p still relatively unknown for such a fundamental quantity.

Need more high quality data like RSS

Sane: running now

$2.3 < Q^2 < 6$ GeV2

E08-027, 2011

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

χPT Calculations

The implementation of χPT utilizes approximations which must be tested

For example:
- The order to which expansion is performed.
- Heavy Baryon approximation.
- How to address short distance effects.

χPT now being used to extrapolate Lattice QCD to the physical region.

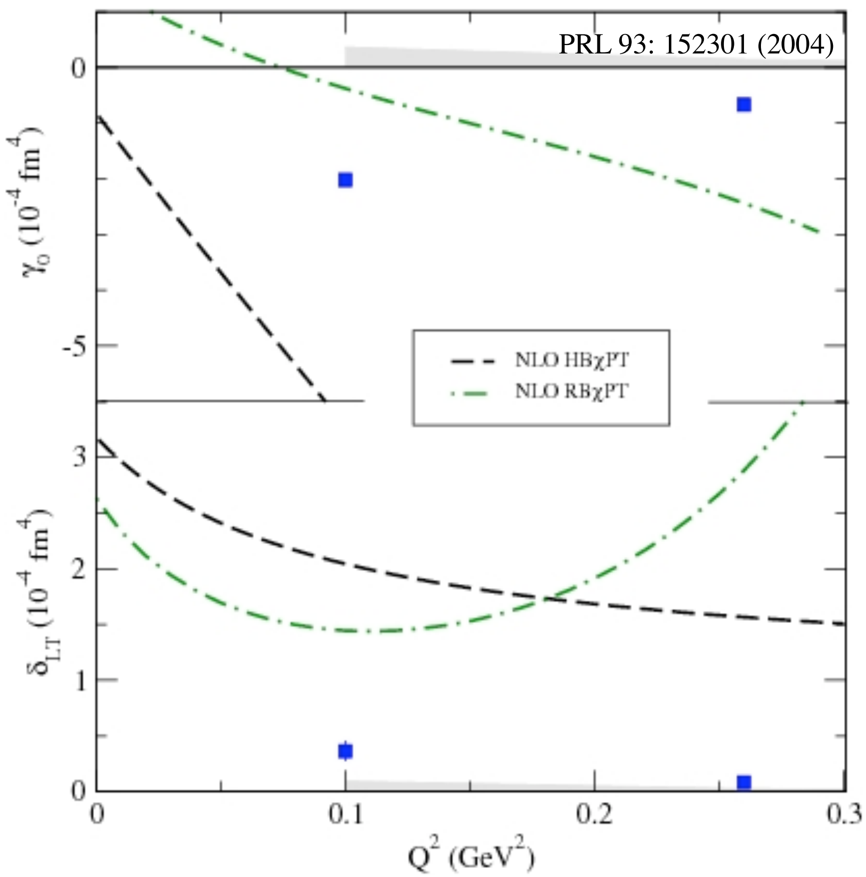
Quark mass: From few hundred MeV to physical quark mass.
Volume: From finite to infinite
Lattice spacing: From discrete to continuous.

Example: QCDSF Lattice group utilizes Meissner et al. χPT calc

Crucial to establish the reliability of calculations and to determine how high in Q^2 (energy) we can go

Forward Spin Polarizabilities

Neutron



$$\gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2} x^2 \right]$$

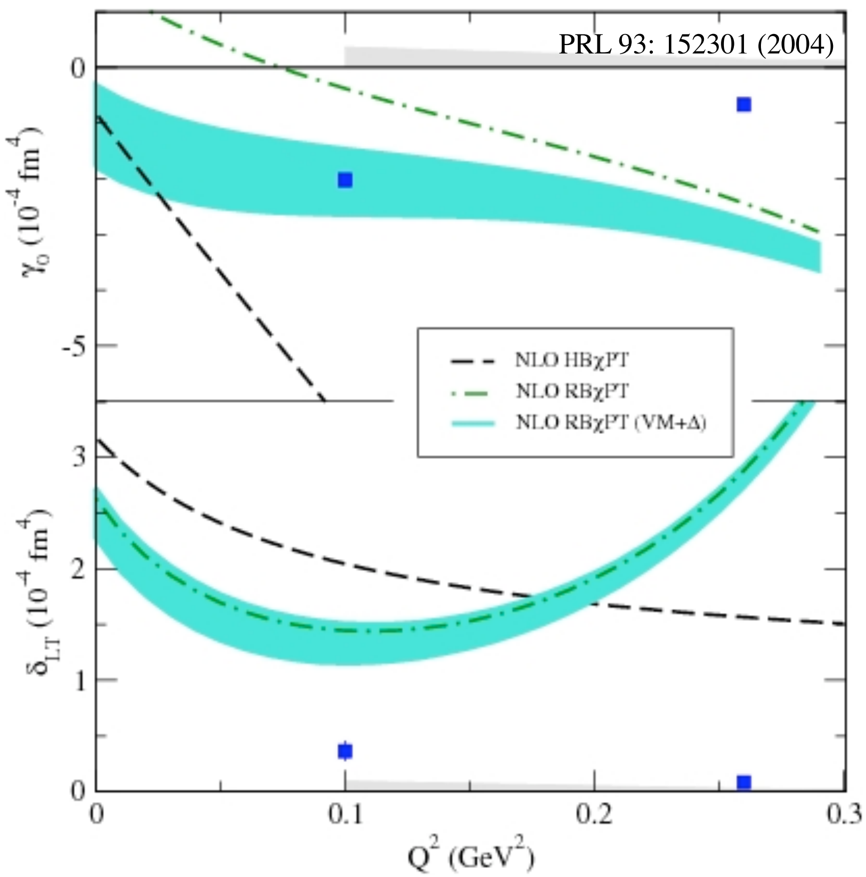
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1 + g_2 \right]$$

Heavy Baryon χPT Calculation
Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

Relativistic Baryon χPT
Bernard, Hemmert, Meissner
PRD 67:076008(2003)

Forward Spin Polarizabilities

Neutron



$$\gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2} x^2 \right]$$

Add Δ by hand:
major effect for γ_0 but not for δ_{LT}

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1 + g_2 \right]$$

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Status of χPT calculations

$\pi+\Delta$ term not under control in χPT calcs. δ_{LT} much less sensitive to this term

δ_{LT} : was expected to be easiest quantity for χPT calcs

$Q^2=0.1$

χPT calc	$GDH(Q^2)$	Γ_1^P	Γ_1^N	Γ_1^{P-N}	γ_0^n	δ_{LT}^n	γ_0^p
HB	poor	poor	poor	good	poor	bad	bad
RB(Δ +VM)	good	fair	good	fair	good	bad	bad

$Q^2=0.05$

HB		good	good			
RB(Δ +VM)		good	good			

Interest from Theorists

State of the Art χPT calculations fail to reproduce δ_{LT}. WHY?

B. Holstein, T. Hemmert, C.W. Kao, N. Kochelev, U. Meissner, M. Vanderhaeghen, C. Weiss

Convergence? Working on NNLO.
$\pi\Delta$ term included properly?
Short range effects beyond π N?
Isoscalar in nature? t-channel axial vector meson exchange?
An effect of the QCD vacuum structure?

Isospin separation is critical to understand the nature of the problem

See Talk by A. Deur

$$\delta_{LT}^{P} - \delta_{LT}^{N} \qquad \delta_{LT}^{P} + \delta_{LT}^{N}$$

Contains a "Bjorken-like" part due to g_1 and an unknown part due to g_2

From theoretical point of view, usually easier to deal with isospin separated quantity

Experimental Setup

Major Installation

UVA/Jlab 5 T Polarized Target

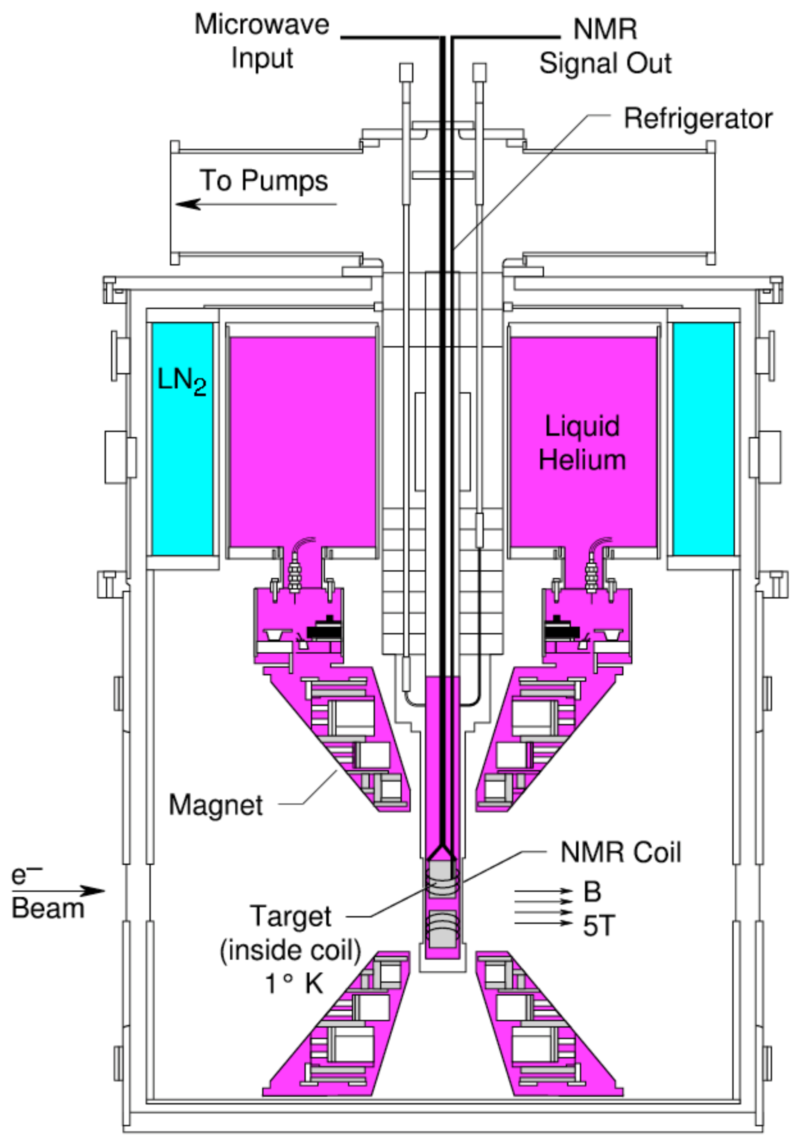
Upstream Chicane and supports

Slow raster and Basel SEM.

Instrumentation for 50-100 nA beam.

Local beam dump.

Hall A Septa.



Significant problems seen with existing Polarized Target Magnet during SANE.

Will have to be addressed for g2p to run

Septa: 3 Options

Two Cryogenic Septa

Advantages: Scenario assumed in proposal. Ideal for physics.

Drawbacks: Requires Septa repair, cryo during QWEAK

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Single Cryogenic Septa

Advantages: Still cover Q^2 range of proposal

Drawbacks: Lose systematic cross-check.
Need additional beamtime.
No good for low Q^2 proton FF experiment

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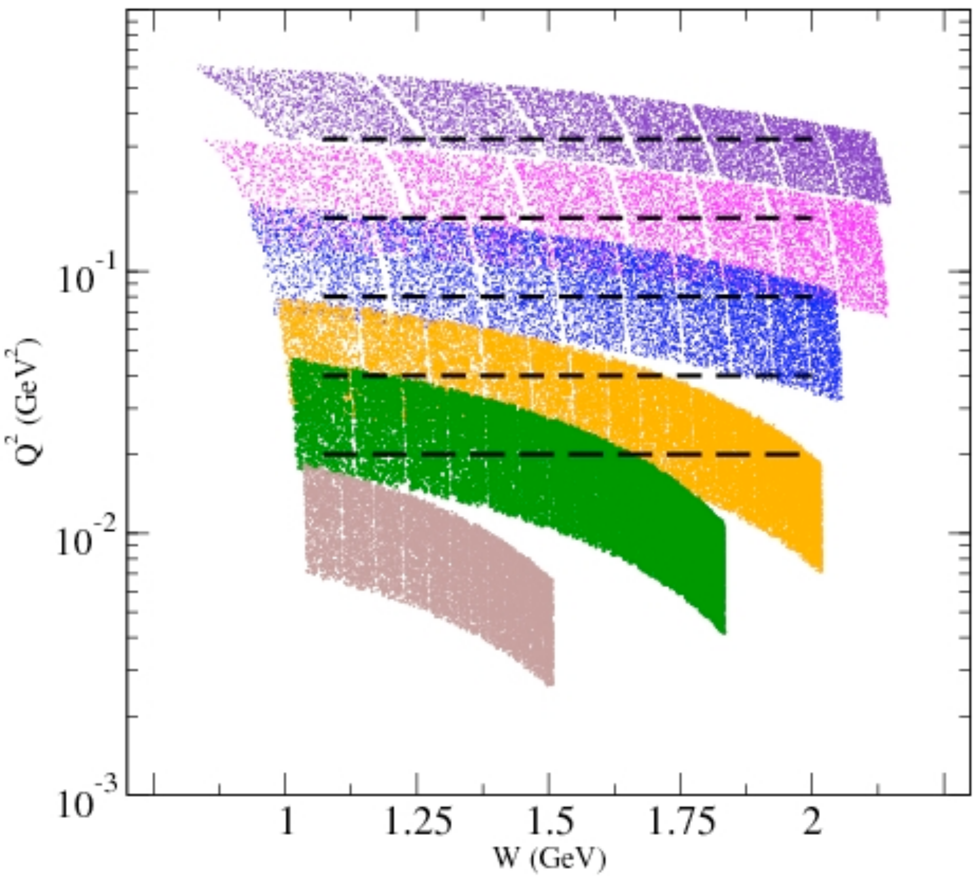
Warm Septa run + a Separate "HRS only" run

Advantages: Avoid repairing the cold septa. Reduce our total cryo-load.
Achieves Q^2 coverage of proposal (and a bit more).

Drawbacks: Need design that works with polarized target "Sheet of Flame"
Significant amount of time to deinstall warm septa
and move the target back from its retracted position.

Original PAC Kinematics



$$\vec{e} + \vec{P} \rightarrow e' + X$$

$$0.02 < Q^2 < 0.4$$

$$W_\pi < W < 2\text{GeV}$$

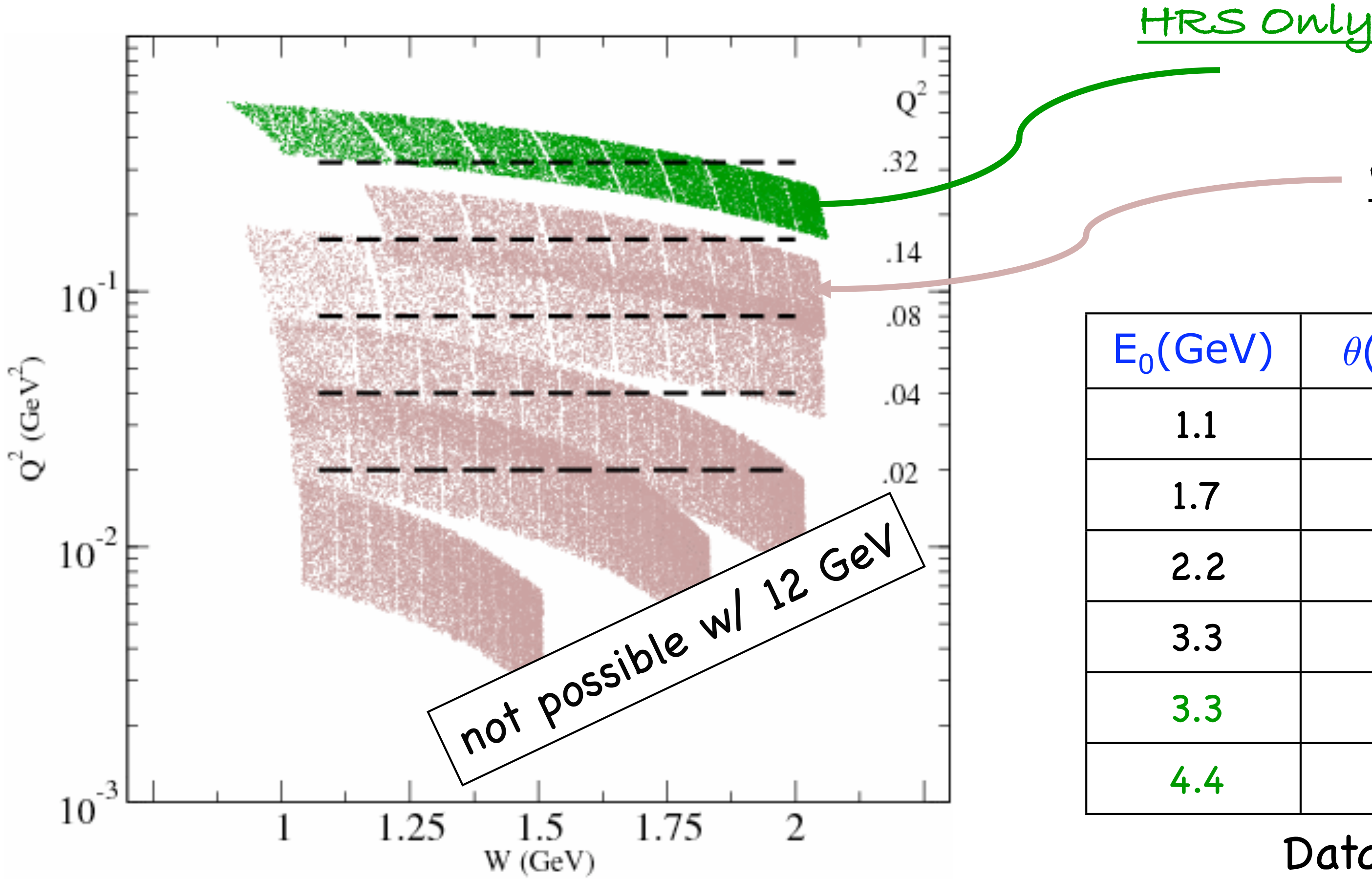
E_0(GeV)	θ(deg)	Days
1.1	6	1.0
1.7	6	1.5
2.2	6	1.6
3.3	6	2.9
4.4	6	2.7
4.4	9	6.0

Data Taking 15.7

Overhead 8.4

Total Days 24.1

Warm Septa+HRS only



E_0(GeV)	θ(deg)	Days
1.1	6	1.0
1.7	6	1.5
2.2	6	1.6
3.3	6	2.9
3.3	8	1.7
4.4	12.5	7.6

Data Taking 16.3

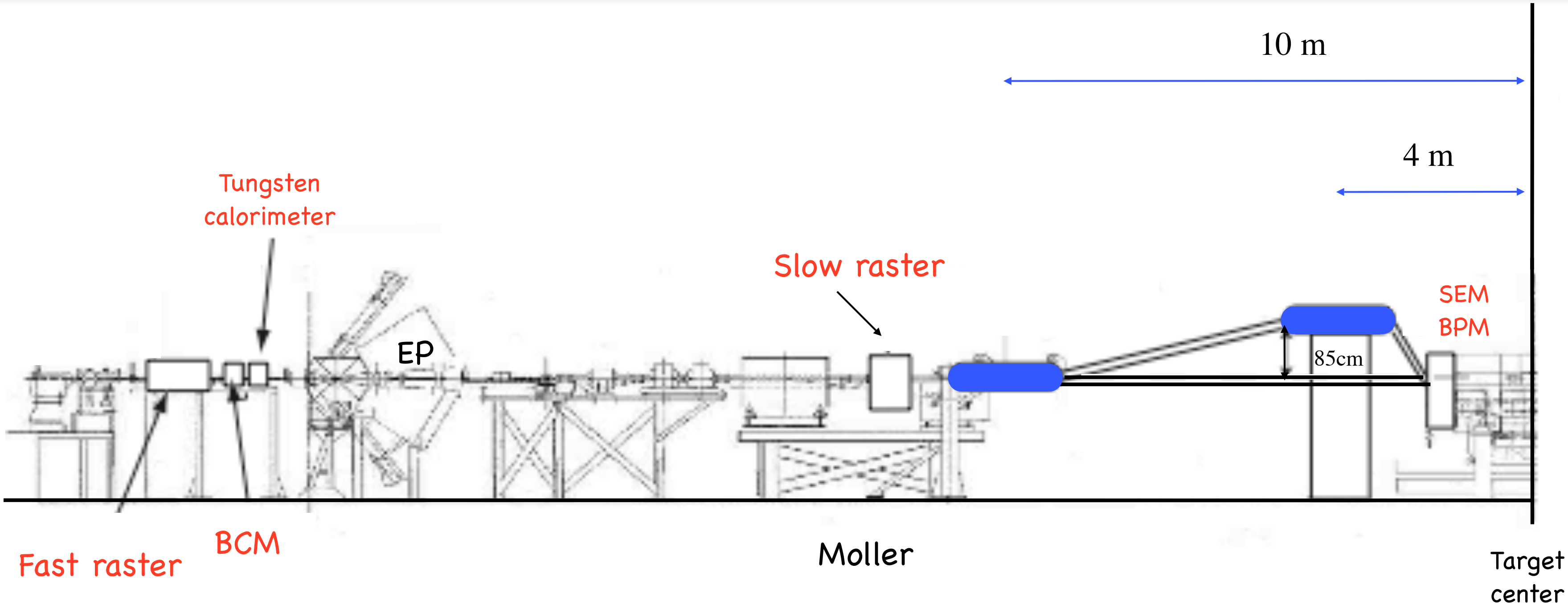
Overhead 8.9

Total Days 25.2

Achieves all physics goals of proposal

But requires additional month (?) of configuration change

Beamline Chicane



Chicane Design : Jay Benesh (JLab CASA)

Utilize open space upstream of target.

Two upstream Dipoles, one with vertical D.O.F.
Reuse the dipoles from the HKS experiment.

Beam dump is above beamline.
Below may be possible (being investigated)

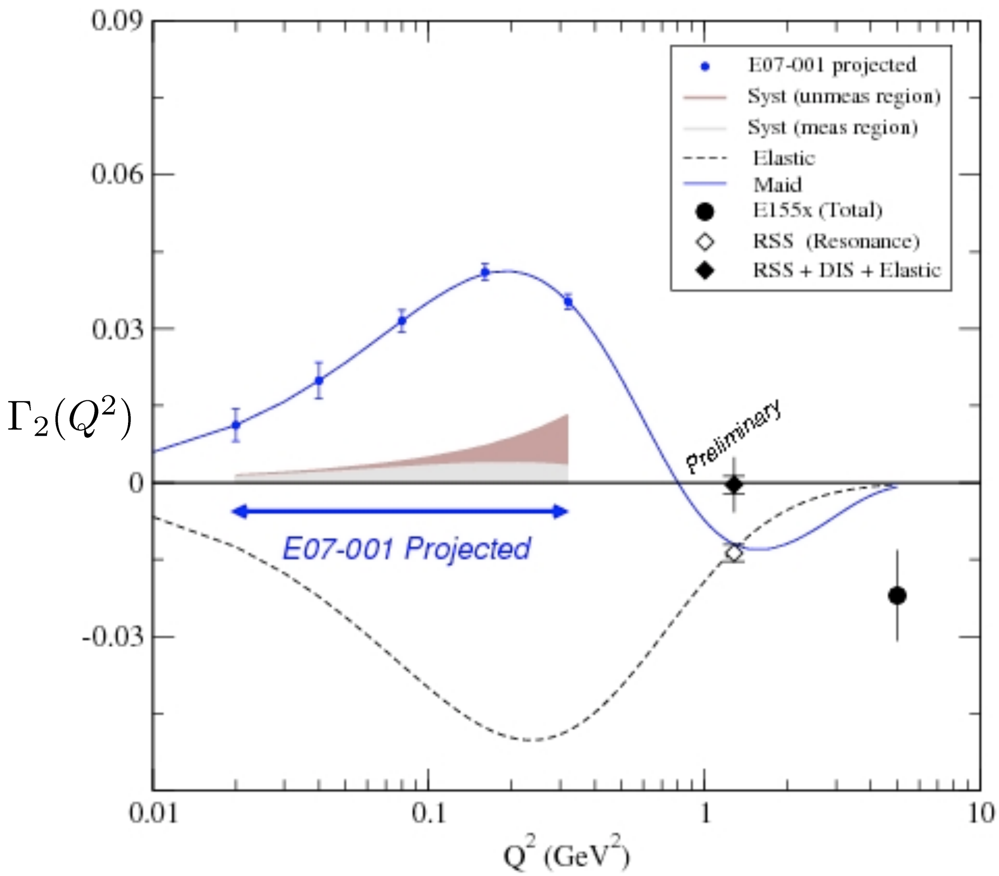
One of the HKS Magnets used for Hall C "minibend".

Need to locate replacement.

No design time w/out budget

Projected Results

BC Sum Rule



Burkhardt-Cottingham Sum Rule

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

SLAC proton data inconsistent with B.C.

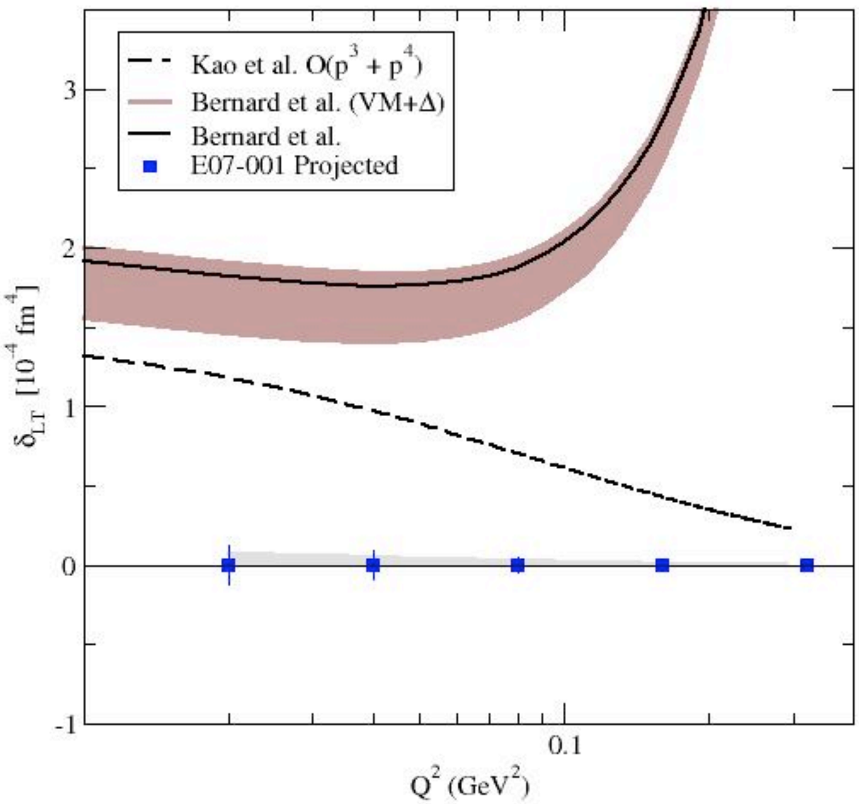
P. L. Anthony *et al.* , Phys. Lett. **B553**, 18 (2003).

But, appears to hold for neutron

P. L. Anthony *et al.* , Phys. Lett. **B553**, 18 (2003).

M. Amarian *et al.* Phys. Rev. Lett. 92 (2004) 022301.

LT Spin Polarizability



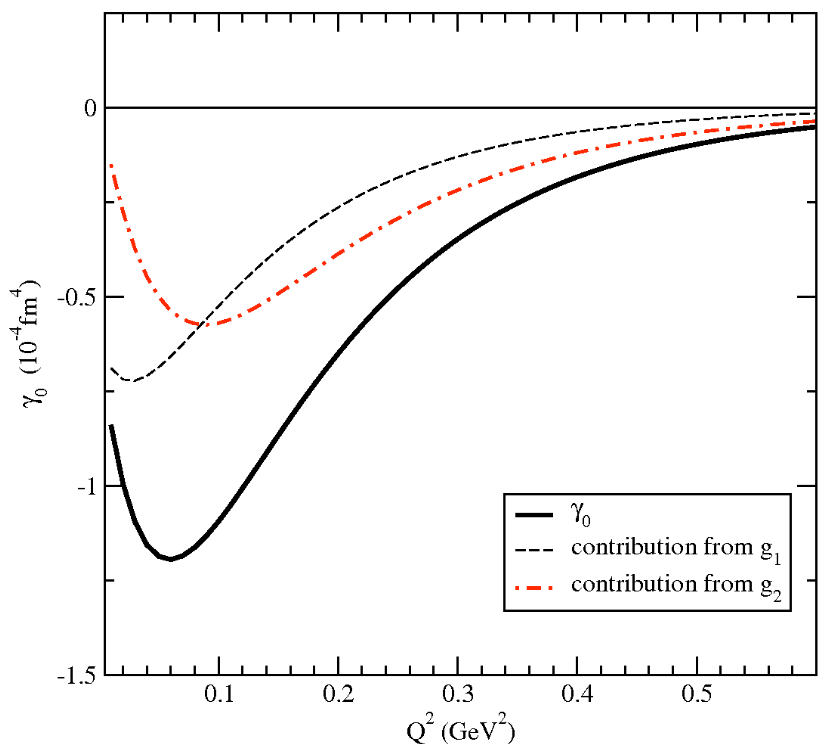
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1(x,Q^2) + g_2(x,Q^2)\right]$$

Able to unambiguously test available calcs.

Provide benchmark for <u>any</u> future calc.

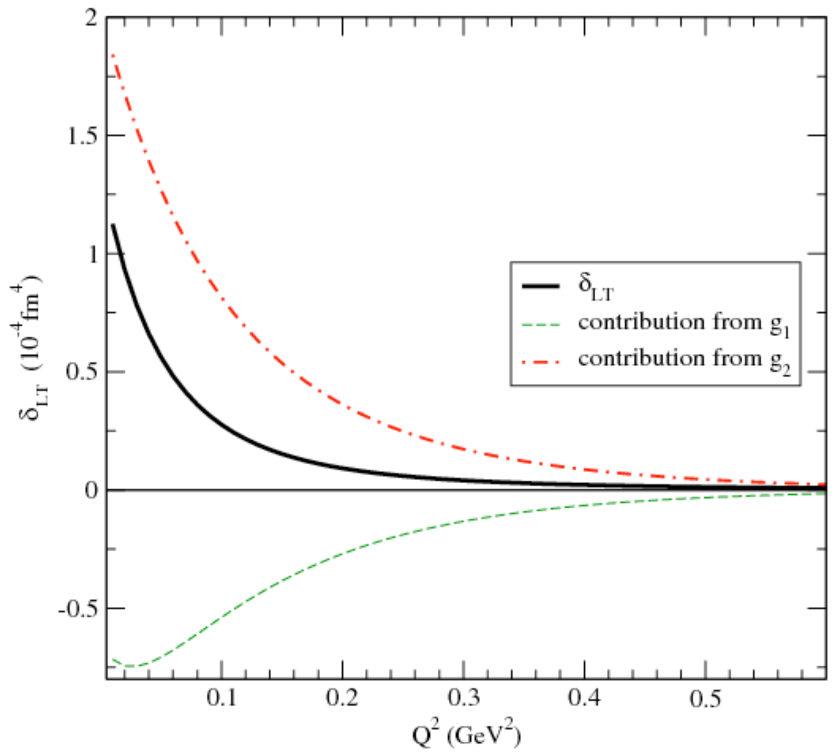
MAID Model Prediction for g2 contribution to polarizabilities

Spin Polarizability $\gamma_0^p(Q^2)$



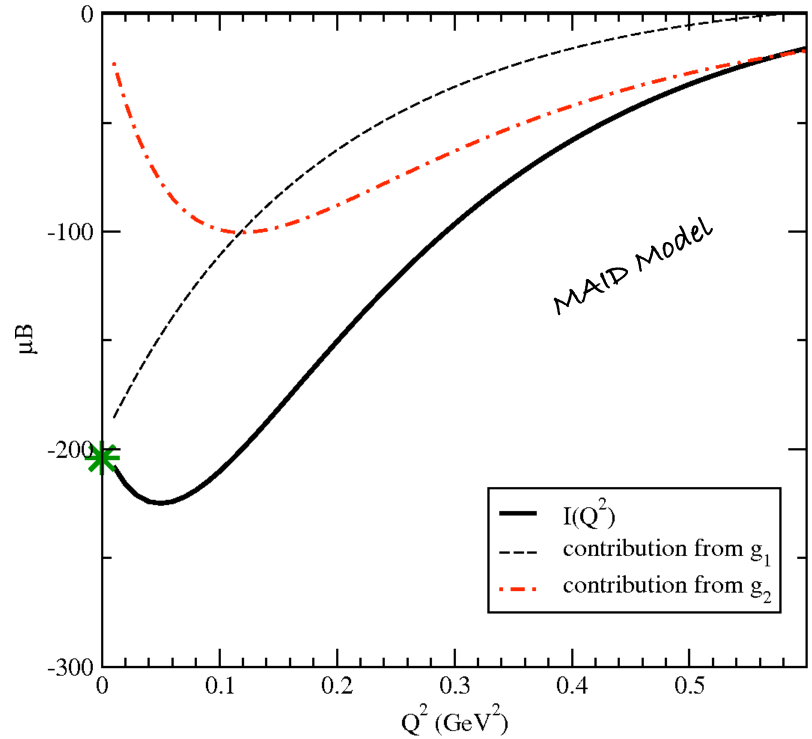
$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2x^2}{Q^2}g_2\right]dx$$

Spin Polarizability $\delta_{LT}^p(Q^2)$



$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\,[g_1 + g_2]dx$$

Extended GDH Integral



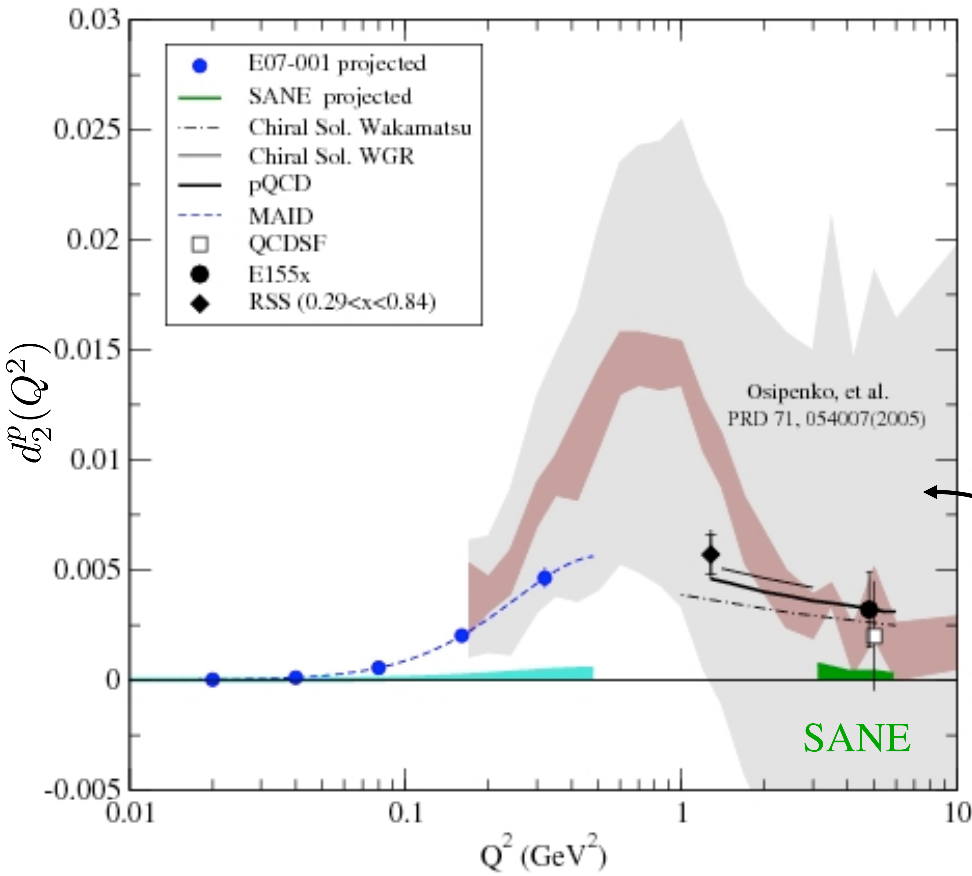
$$I(Q^2) = \frac{16\pi^2\alpha}{Q^2} \int_0^{x_0} \left[g_1 - \frac{4M^2x^2}{Q^2} g_2 \right] dx$$

Examples of publications which use this formalism

1. [Hall A E94010] *Phys. Rev. Lett.* **93** (2004) 152301
2. Y.Prok *et al.* [EG1B collab] In preparation.

1. [Hall A E94010] *Phys. Rev. Lett.* **89** (2002) 242301
2. [HERMES collab] *Eur. Phys. J.* **C 26**, (2003) 527

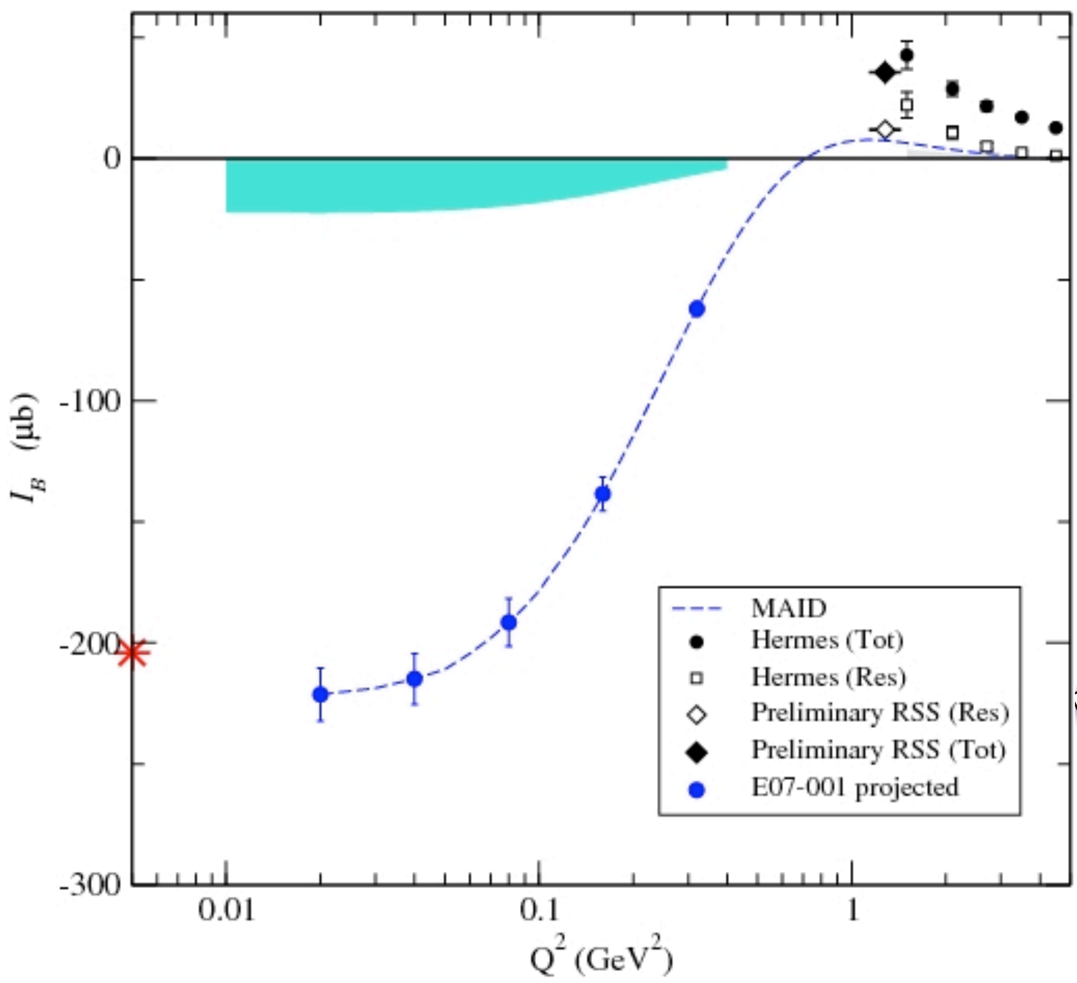
Proton $d_2(Q^2)$



$$d_2(Q^2) = 3\int x^2 \left[g_2(x,Q^2) - g_2^{WW}(x,Q^2)\right] dx$$
$$= \int x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right] dx$$

Huge systematic from lack of $g_2{}^p$ data

Extended GDH Sum



$$I_B = \frac{8\pi^2\alpha}{M}\int_{\nu_0}^{\infty}\left[g_1 - \frac{4M^2x^2}{Q^2}g_2\right]dx$$

Sensitive to behavior which is normally masked in Γ_1 as $Q^2 \rightarrow 0$

Summary

g_2^p

Hydrogen Hyperfine Structure

Extended GDH Sum

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

Summary

g_2^p unmeasured below Q^2=1.3 GeV^2.

24 days to measure g_2^p at low Q^2

This experiment is not possible with 12 GeV.

Test Integral relations and Sum Rules

BC Sum Rule

$d_2^p(Q^2)$

Extended GDH Sum

Eliminate leading systematic of EG4 measurement of Hall B.

Hydrogen Hyperfine Splitting

g_2 is large contribution to systematic uncertainty

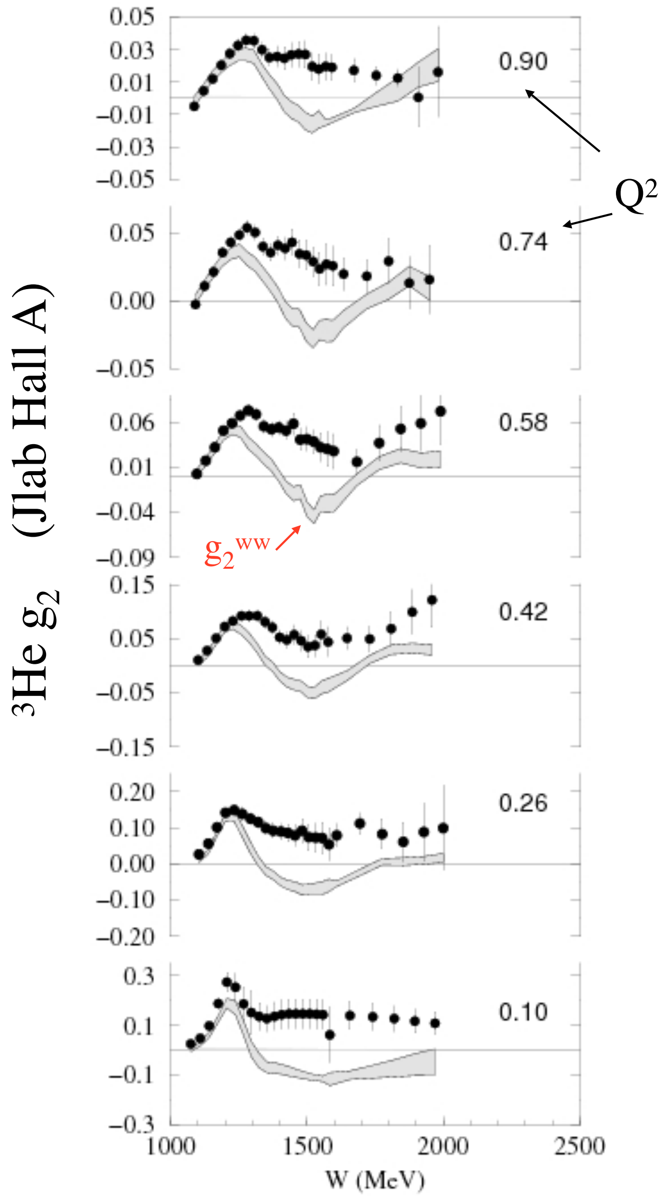
Contribution dominated by $Q^2<0.4$

State of the art χPT calcs work well for many spin-dependent quantities up to 0.1 GeV^2

But fail for δ_{LT}. WHY? Need isospin separation to resolve.

Backups

Existing Resonance g_2 Data



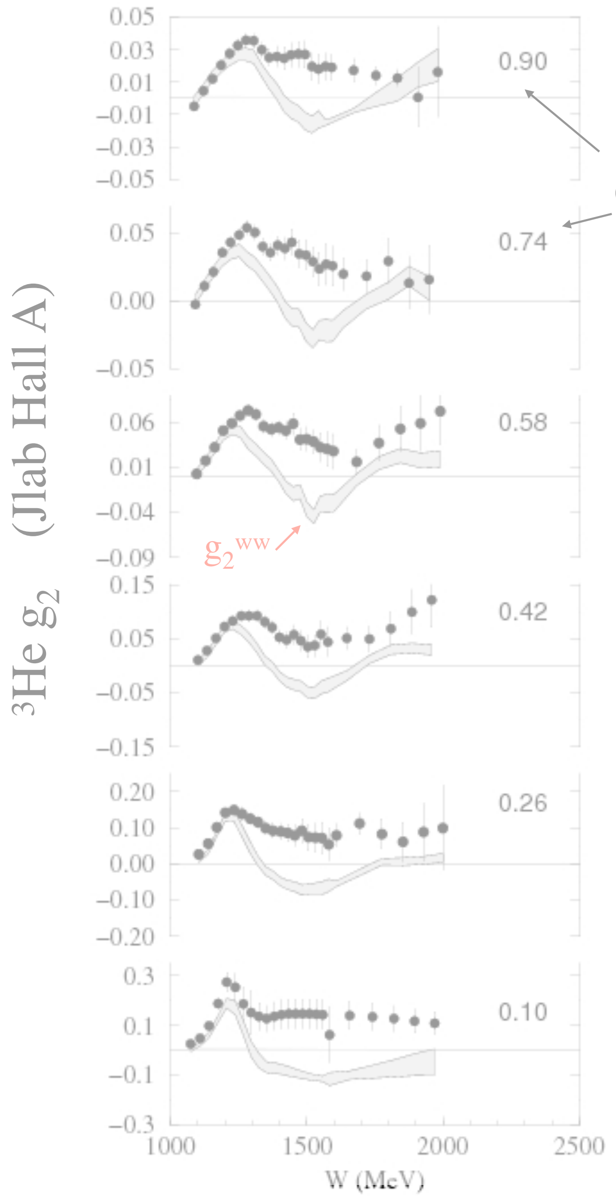
^3He g_2

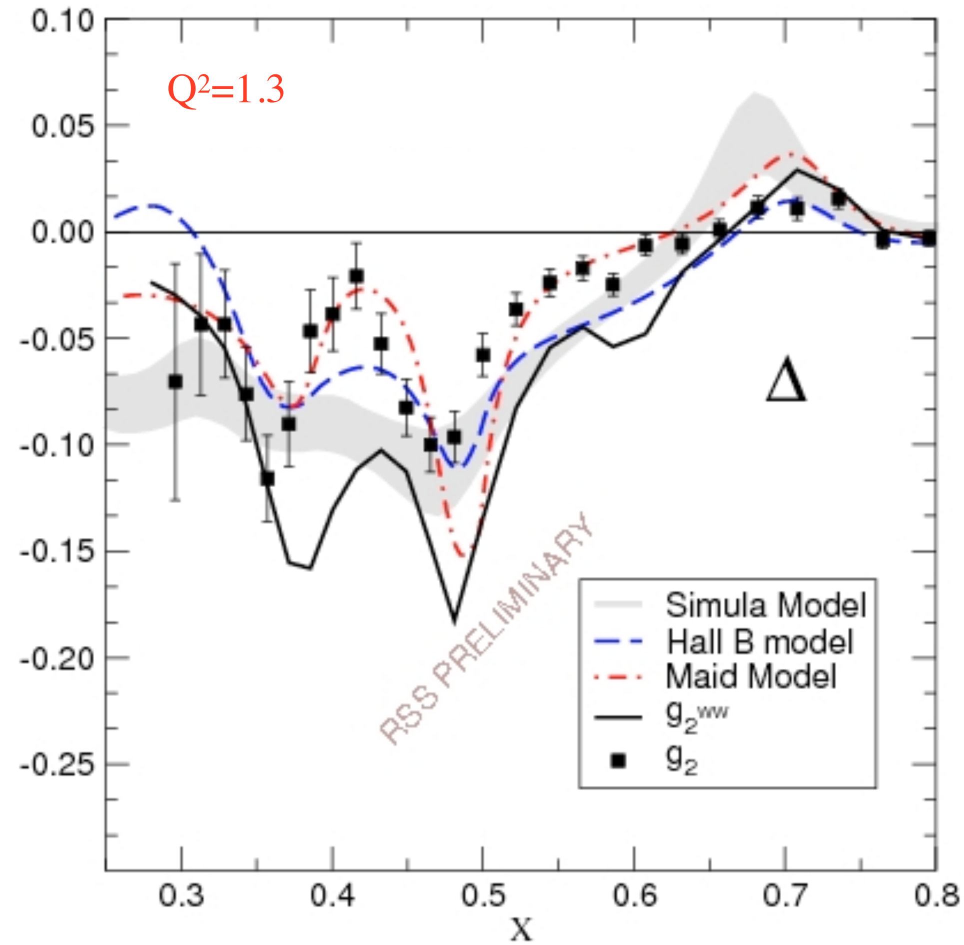
$0.10 < Q^2 < 0.9$ GeV^2

Large deviation from leading twist behaviour

g_2^{WW} not good description of data

Existing Resonance g_2 Data



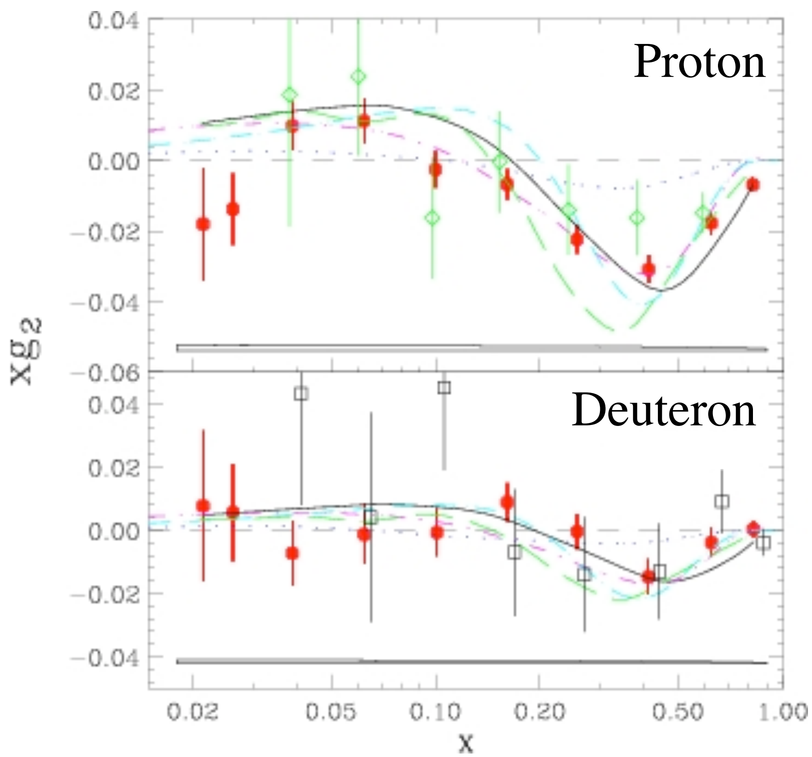


Lowest Q^2 Existing Proton Data

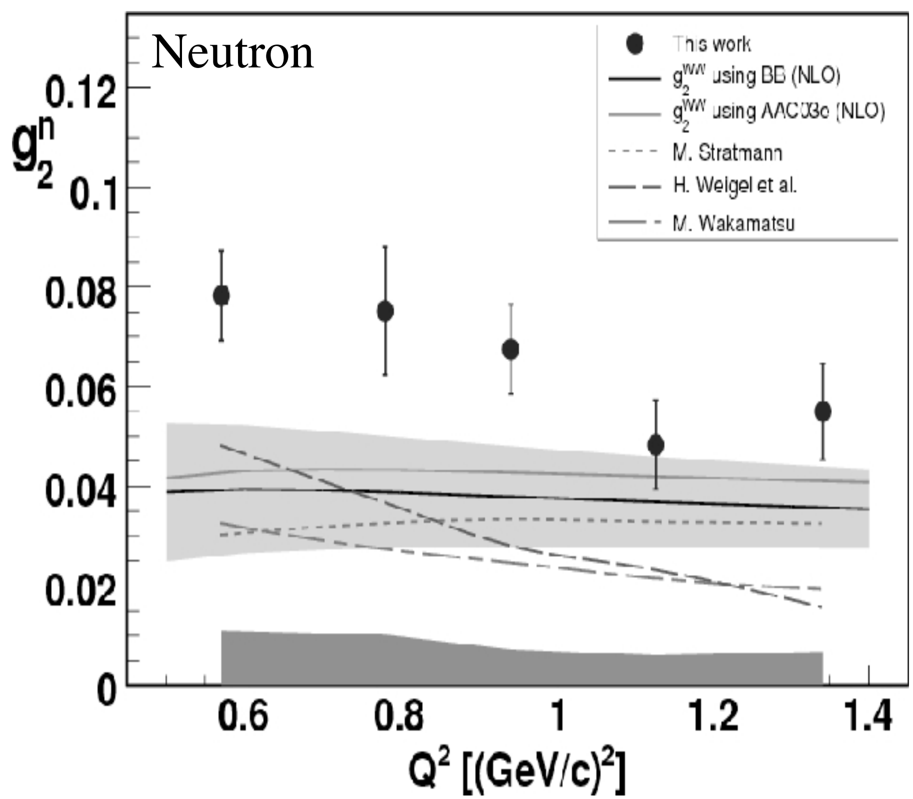
(Jlab Hall C : RSS)

Existing DIS g_2 Data

SLAC: $\langle Q^2 \rangle = 5$ GeV^2



Jlab Hall A: x≈0.2



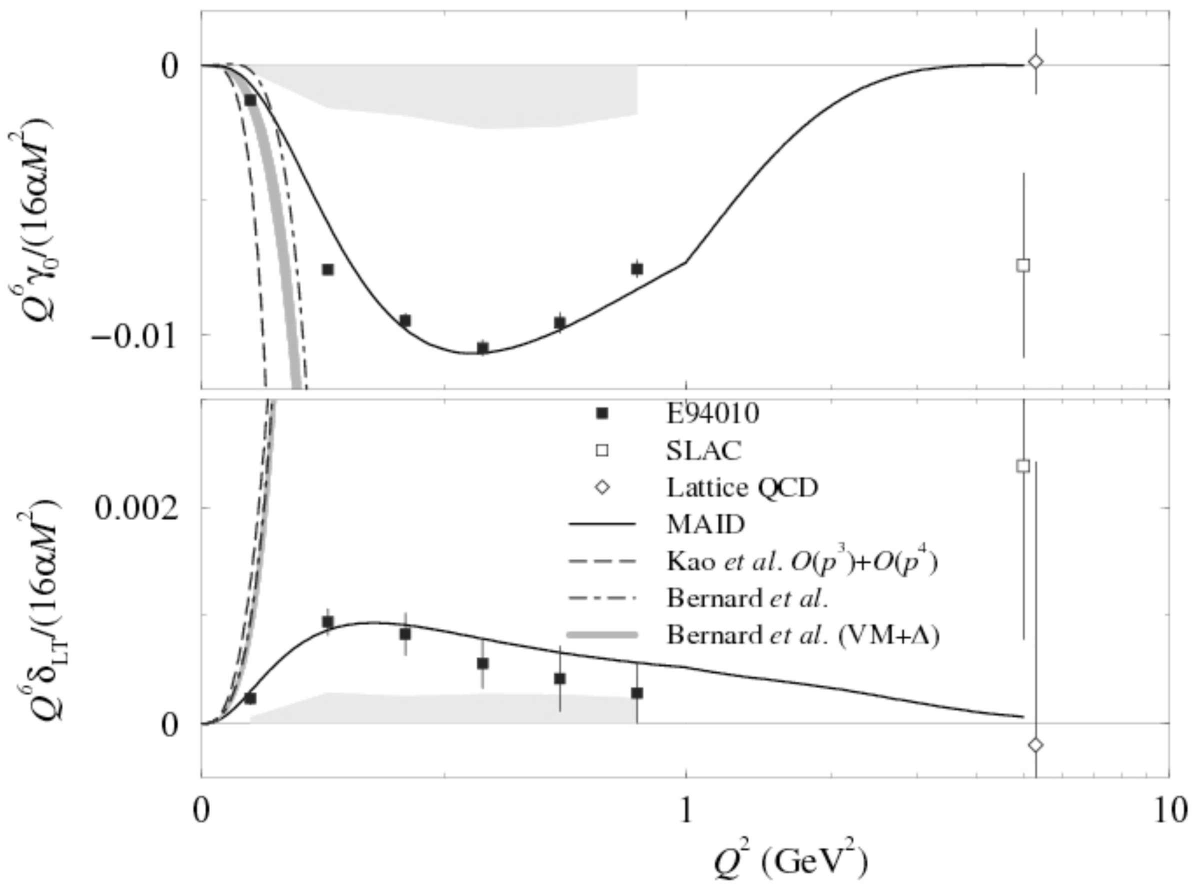
Total Systematic

Source	(%)
Cross Section	5-7
Target Polarization	3
Beam Polarization	3
Radiative Corrections	3
Parallel Contribution	<1
Total	7-9

Forward Spin Polarizabilities

Scaling of polarizabilities expected at large Q²

$$\delta_{LT}(Q^2) \rightarrow \frac{1}{3}\gamma_0(Q^2)$$



Not observed yet for Neutron

PRL 93: 152301 (2004)

Hydrogen Hyperfine Structure

NCG 2006: Utilized CLAS model assuming 100% error

$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$
$$= -0.57 \pm 0.57$$

If we assumed this uncertainty is realistic
we will improve this by order of magnitude

$$\begin{aligned} \Delta_1 &= 6.38 \pm 0.92\text{ppm} && \text{CLAS model} \\ &= 3.55 \pm 2.48\text{ppm} && \text{Simula model} \end{aligned}$$

Elastic piece larger but with similar uncertainty

$$\Delta_Z = -41.01 \pm 0.49\text{ppm}$$

$$\begin{aligned} \Delta_{POL} &= 0.2265(\Delta_1 + \Delta_2)\text{ppm} \\ &= 1.3 \pm 0.3\text{ppm} \end{aligned}$$

0.13 ppm of this error comes from Δ_2

So if the 100% error is realistic, we would cut error on Δ_{POL} in half

In fact, g_2^p unknown in this region:

$$\Delta_2 = -1.98 \quad \text{MAID Model}$$
$$\Delta_2 = -1.86 \quad \text{Simula Model}$$

So 100% error is probably too optimistic

We will provide first real constraint on Δ_2

d2->0

$$g_2^{WW} = -g_1 + \int_{x_0}^{x} \frac{g_1}{y} dy \qquad (1)$$

where

$$x_0 = \frac{Q^2}{Q^2 + 2Mm_\pi + m_\pi^2}$$

In the limit $Q^2 \to 0$, $x_0 = 0$ so the integral in Eq. 1 vanishes and $g_2^{WW} = -g_1$. At the same time, $A_2 = \frac{\sigma_{LT}}{\sigma_T}$ vanishes as $Q^2 \to 0$ because real photons have no longitudinal component. Therefore,

$$A_2 \propto (g_1 + g_2) = 0$$

or

$$g_2 = -g_1$$

so $g_2 = g_2^{ww}$ as $Q^2 \to 0$

Chiral Perturbation Theory

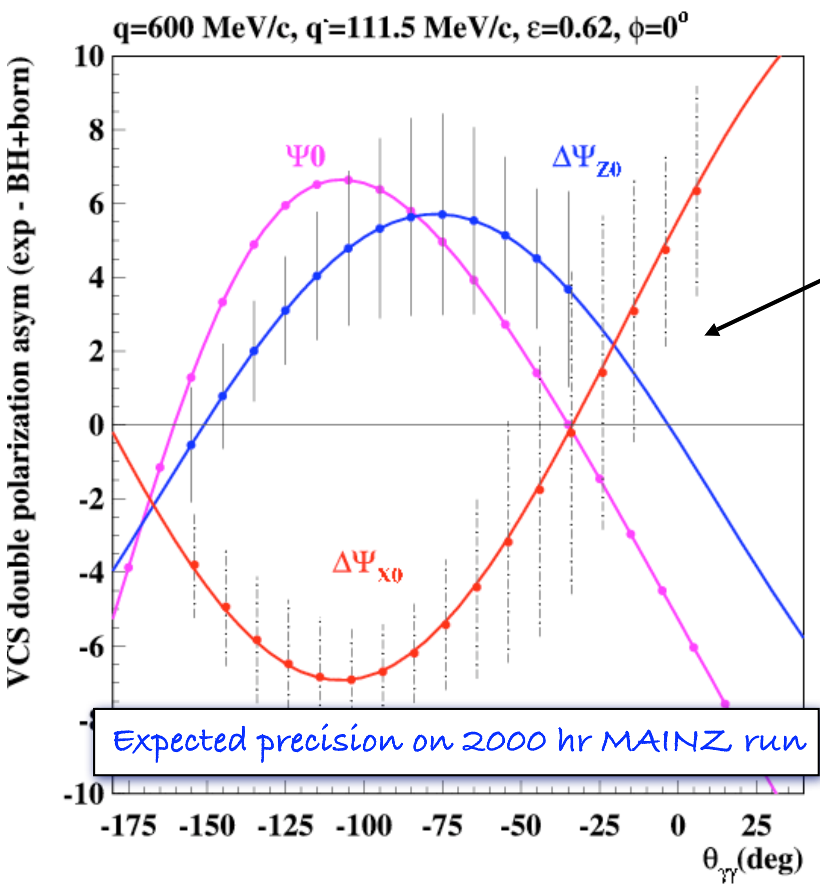
Though quantum chromodynamics (QCD) is generally accepted as the underlying theory of the strong interactions, a numerical check of the theory in the confinement region is difficult due to the strong coupling constant. A plethora of models have been inspired by QCD, but none of these models can be quantitatively derived from QCD. Only two descriptions are, in principle, exact realizations of QCD, namely chiral perturbation theory and lattice gauge theory.

D. Drechsel (GDH 2000), Mainz Germany, June 2000

Generalized Polarizabilities

Fundamental observables that characterize nucleon structure.

Guichon *et al*. Nucl. Phys. A 591, 606 (1995).



VCS observables are sensitive to the GPs

Need additional out of plane measurements to get γ_0 which is related to the VCS GPs at Q^2=0.

$$\gamma_0 = \gamma_1 - \gamma_3 - 2\gamma_4 \quad \text{at } Q^2=0$$

No simple relation between δ_{LT} and the VCS GPS

Measurement of δ_{LT} complementary to the VCS GP measurements