Low Q^2 Measurement of g_2^p

and the

δ_{LT} Spin Polarizability

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Dec. 13, 2007

E07-001 Collaboration

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and The Hall A Collaboration

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Overview

Inclusive SSFs $g_{1,2}^{n}$ and g_1^p measured over wide range, but g_2^p unmeasured below $Q^2 = 1.3$ GeV^2

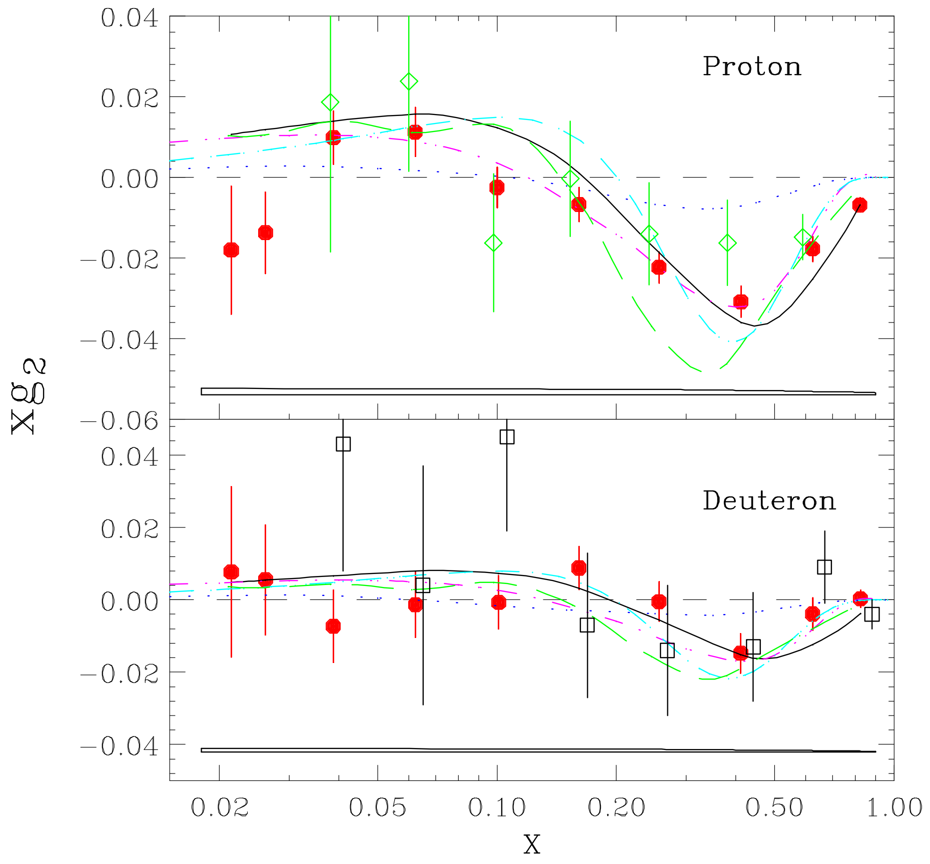
Motivations to measure g_2^p at low Q^2

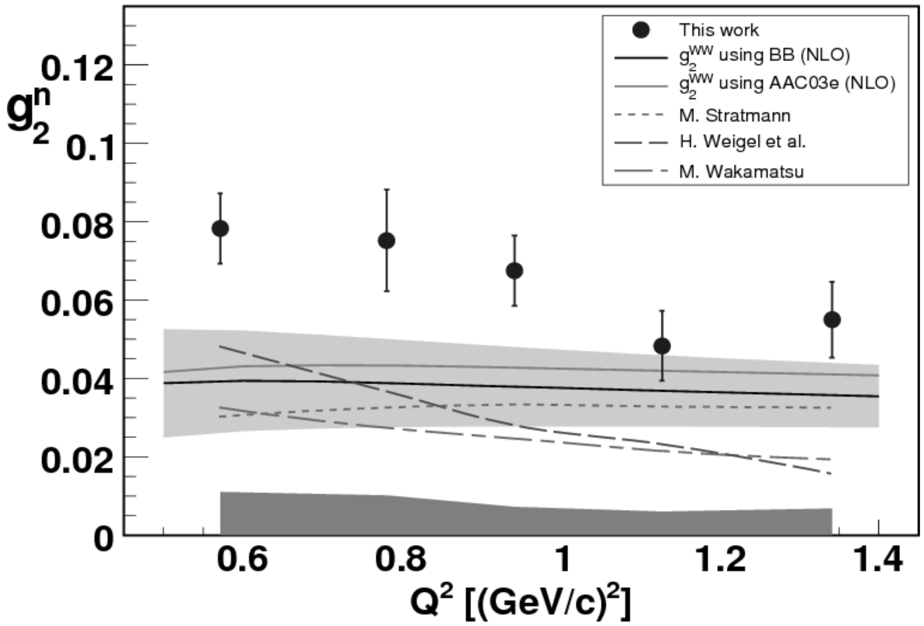
1. g_2^p central to our understanding of nucleon structure
2. χPT calculations fail for δ_{LT}^{n}
3. BC Sum Rule violation suggested at large Q^2
4. Leading uncertainty in Hyperfine Structure calcs
5. Leading uncertainty for EG4 experiment

E07-001

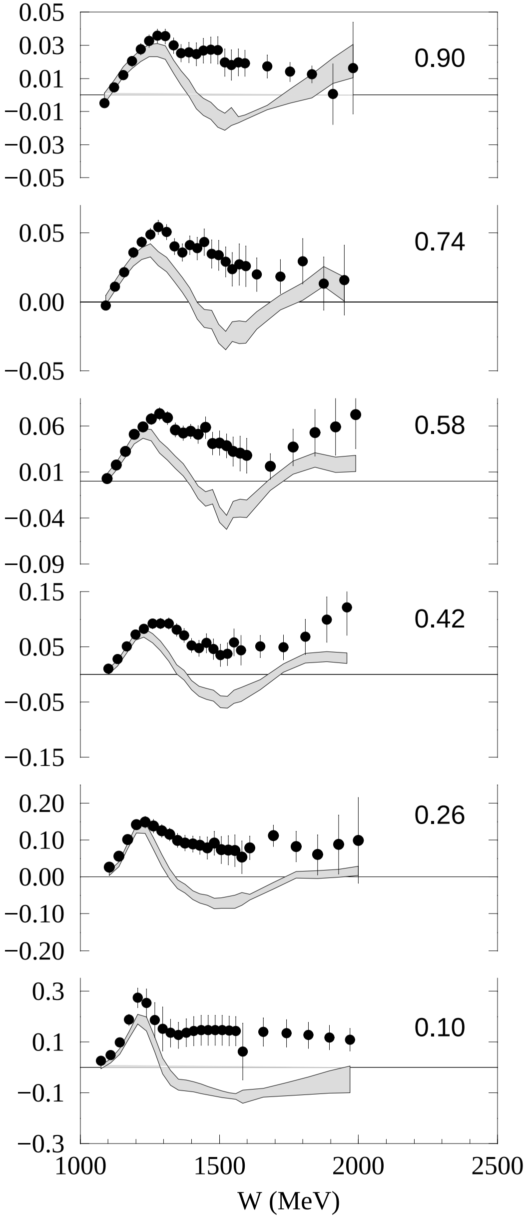
1. g_2^p in resonance region for $0.02 < Q^2 < 0.4$
2. Hall A septa with polarized ammonia target.

Existing DIS Data

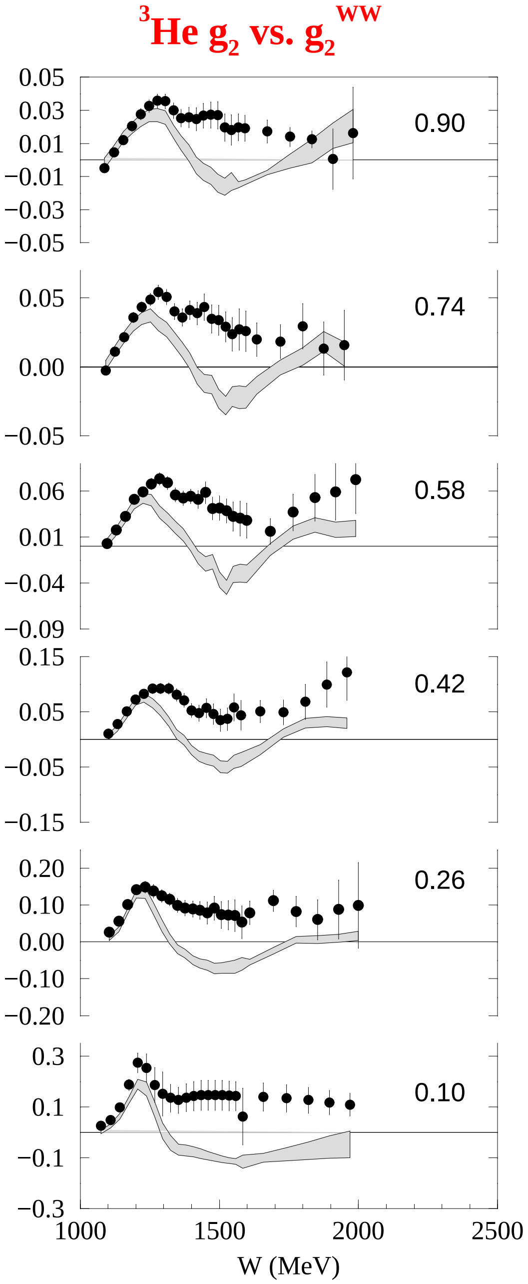


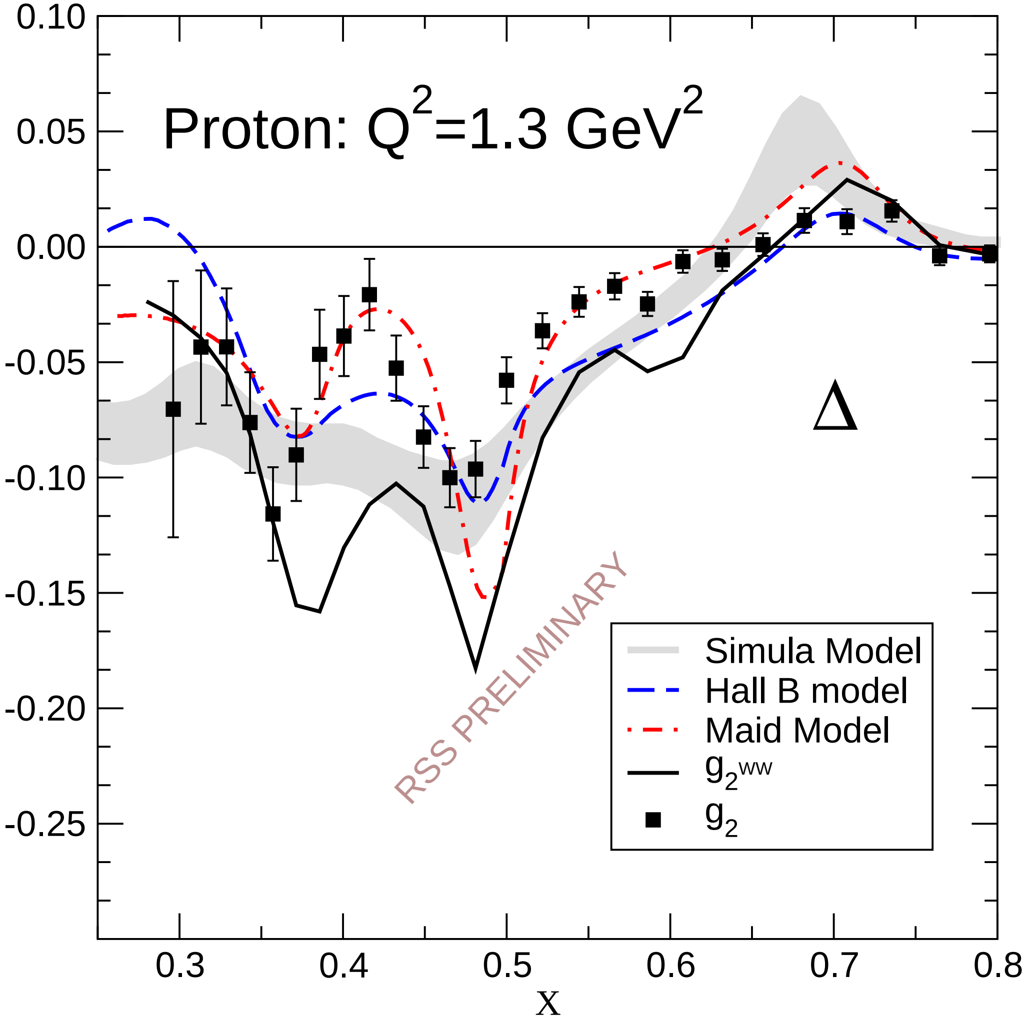


Existing Resonance Data


^{3}He g_2 vs. g_2^{WW}

Existing Resonance Data





Generalized Sum Rules

Unsubtracted Dispersion Relation + Optical Theorem leads to:

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

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

(and similar relation for g_2, S_2)

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

$$\mathrm{Re}[\tilde{g}_{\mathrm{TT}}(\nu, Q^2)] = (\frac{\nu}{2\pi^2})\mathcal{P}\int_{\nu_0}^\infty \frac{K(\nu', Q^2)\sigma_{TT}(\nu', Q^2)}{\nu'^2 - \nu^2} d\nu',$$

(and similar relation for σ_{LT}, g_{LT})

$S_1, S_2 \rightarrow$ set of Q^2-dependent sum rules.

Extended GDH Sum	$\int g_1 \, dx = \frac{Q^2}{8} S_1(0, Q^2)$
GDH Sum Rule at low Q^2	
Bjorken Sum Rule at large Q^2	
BC Sum Rule	$\int g_2 \, dx = 0$

LEX of $g_{TT}, g_{LT} \rightarrow$ The Generalized Spin Polarizabilities

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

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

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

Large Q^2	PQCD	Bjorken, BC
Intermediate Q^2	Lattice QCD	Extended GDH, BC
Low Q^2	χPT	GDH, Polarizabilities, BC

$g^n_{1,2}$ and g^p_1 : Precision data exists over wide kin range.

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

Chiral Perturbation Theory

Though quantum chromodynamics (QCD) is generally accepted as 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 has 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 (ChPT) and lattice gauge theory (LGT).

D. Drechsel (GDH 2000), Mainz, Germany, 14-17 Jun 2000.

χPT Calculations

Implementation of χPT utilizes approximations which must be tested

For example:

Order to which expansion is carried.

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.

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

Generalized Spin Polarizabilities

Fundamental observables that characterize nucleon structure.

Polarizabilities are a natural testing ground for χPT.

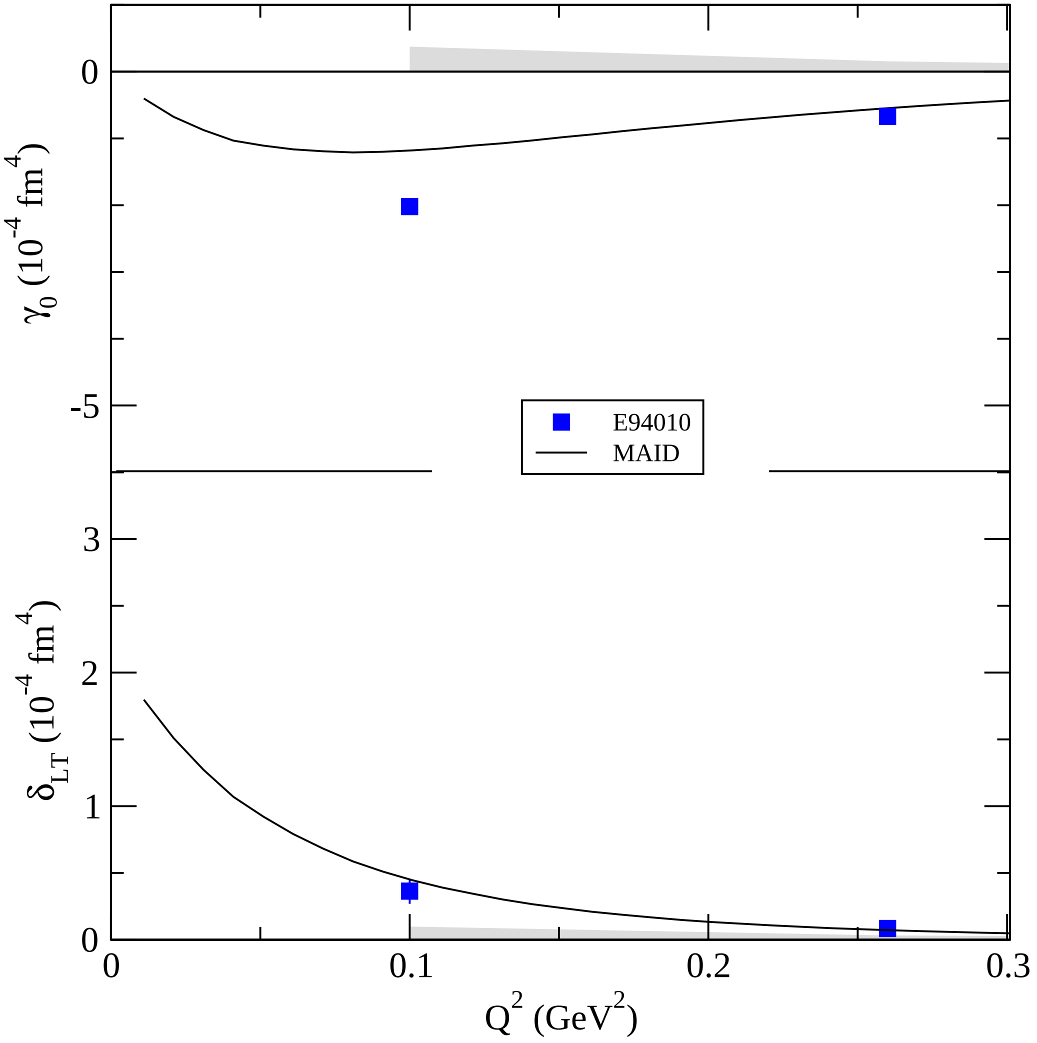
$1/\nu^2$-weighting leads to a fast convergence.

$\pi + \Delta$ term not well under control in χPT calculations:

δ_{LT} much less sensitive to Δ than γ_0

Expected that δ_{LT} would be good place to test χPT...

Neutron Polarizabilities

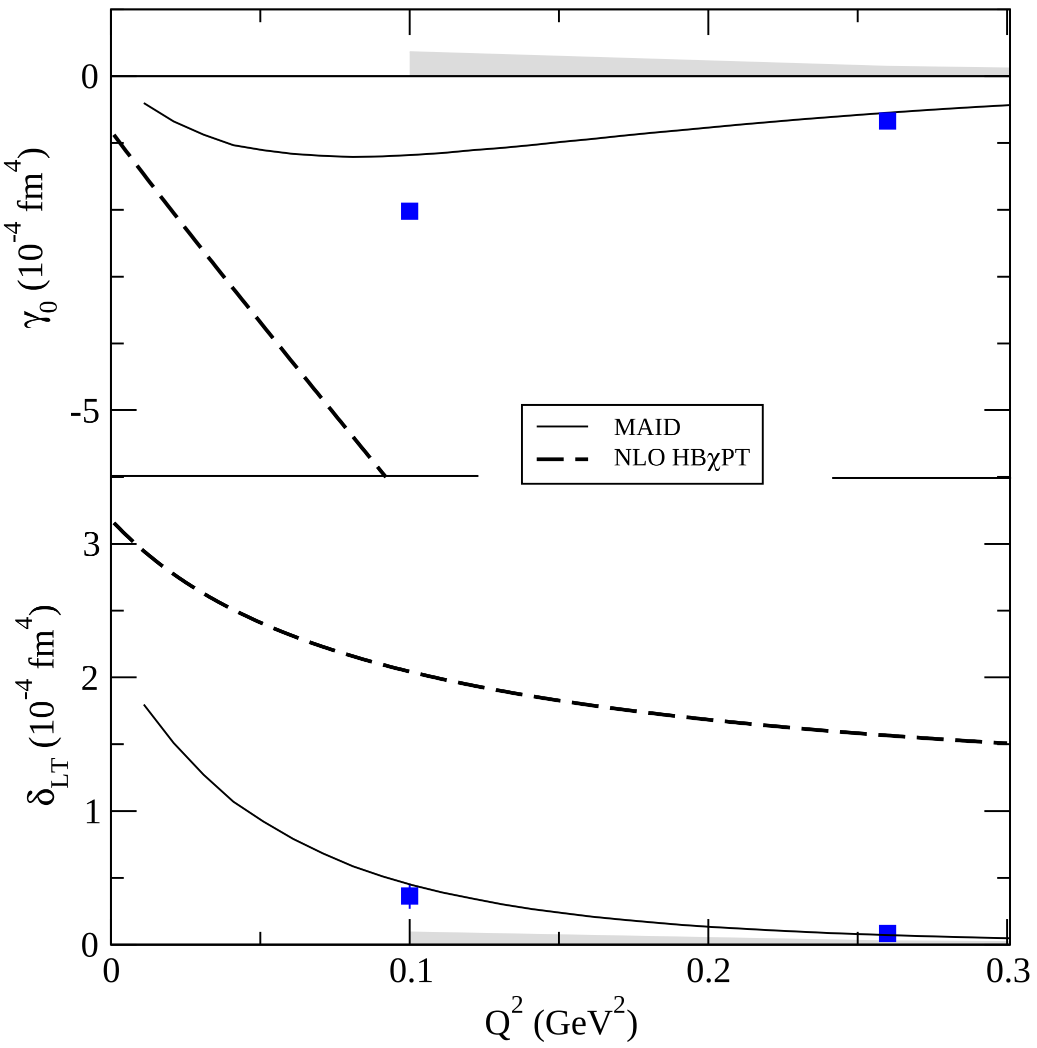


Neutron Data

PRL 93:152301 (2004)

MAID model : good agreement

Neutron Polarizabilities



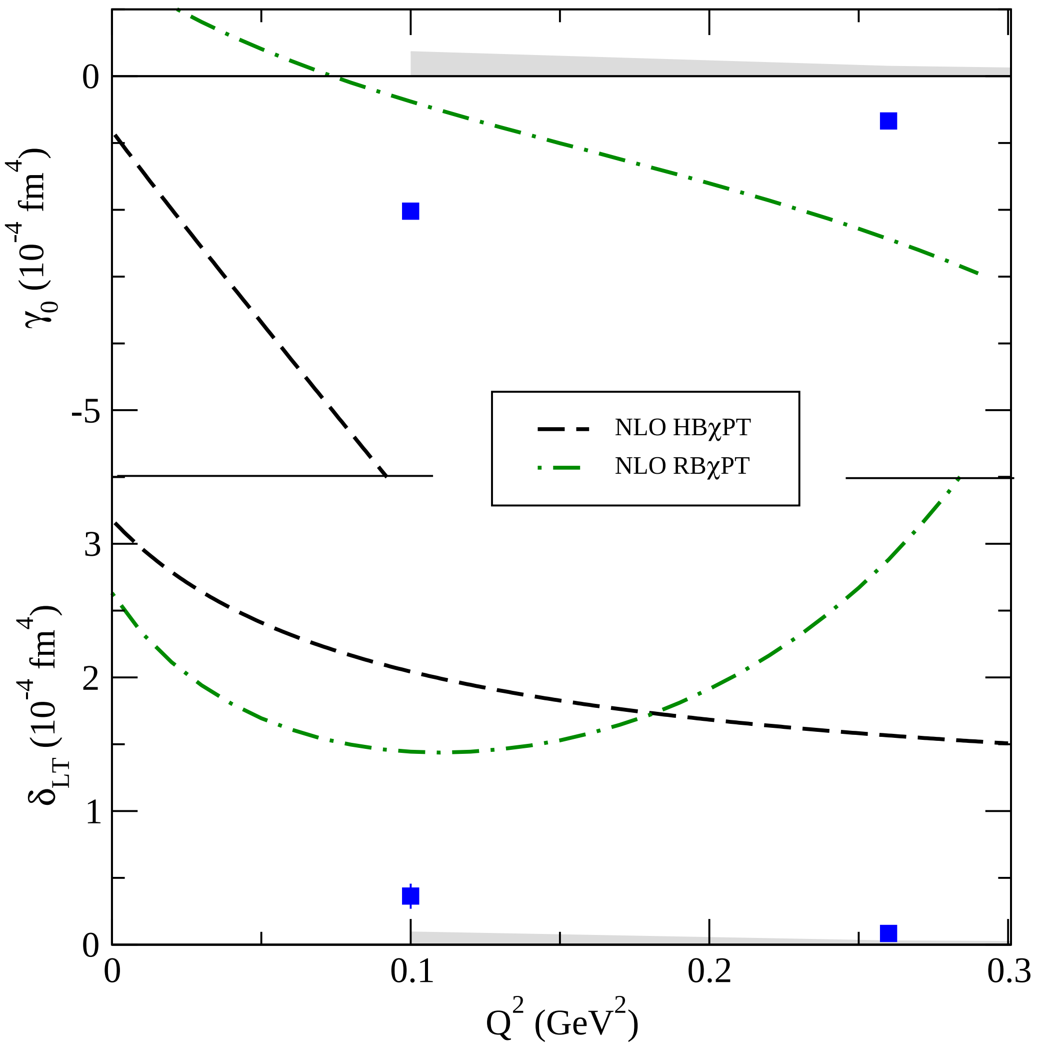
NLO χPT calculations

Heavy Baryon χPT

Kao, Spitzenberg, Vanderhaeghen

PRD 67:016001(2003)

Neutron Polarizabilities



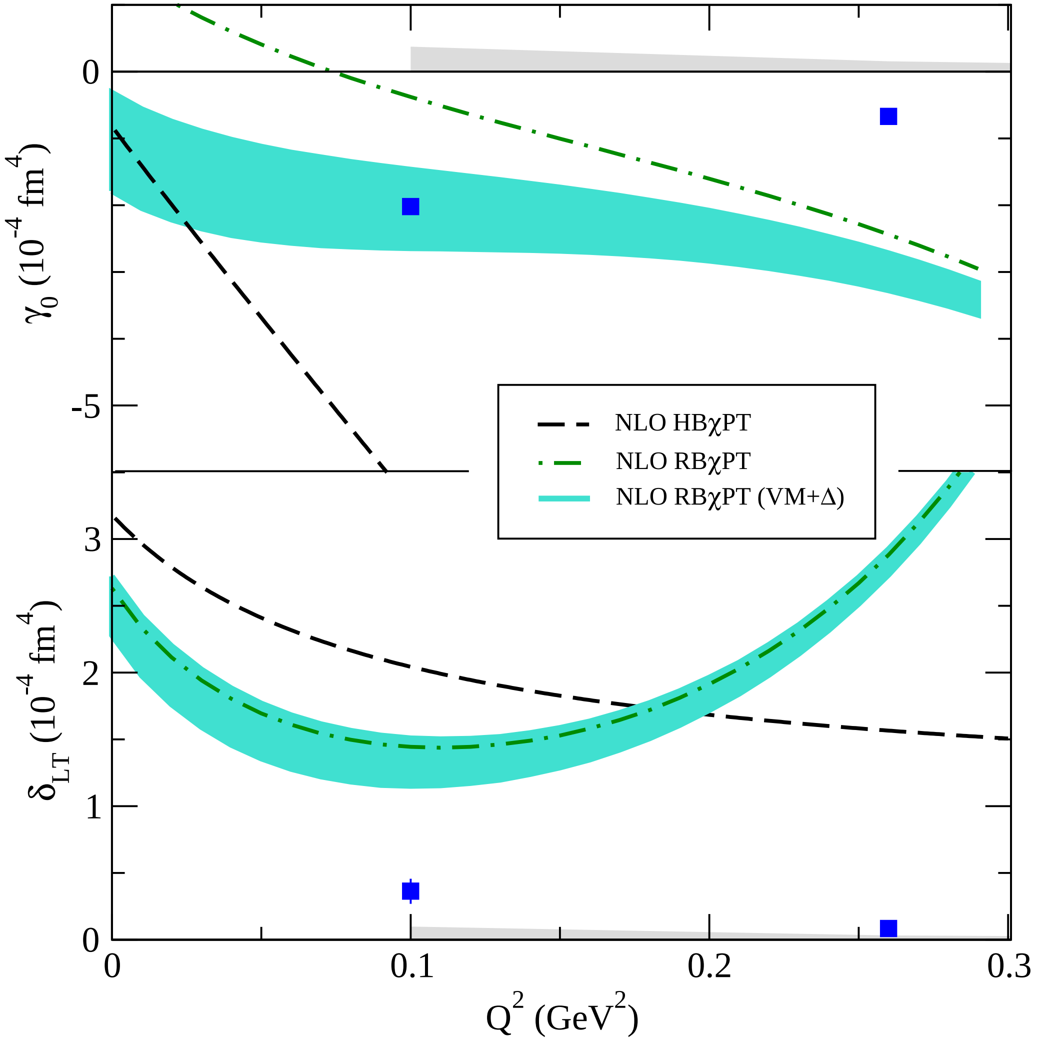
NLO χPT calculations

Relativistic Baryon χPT

Bernard, Hemmert, Meissner

PRD 67:076008(2003)

Neutron Polarizabilities



NLO χPT calculations

Relativistic Baryon χPT

Bernard, Hemmert, Meissner

PRD 67:076008(2003)

Including Δ + VM

Status of χPT calculations

$Q^2 = 0.1$

	I_A	Γ_1^p	Γ_1^n	Γ_1^{p-n}	γ_0^n	δ_{LT}^n
HB	poor	poor	poor	good	poor	bad
RB(Δ+VM)	good	fair	good	fair	good	bad

$Q^2 = 0.05$

	I_A	Γ_1^p	Γ_1^n	Γ_1^{p-n}	γ_0^n	δ_{LT}^n
HB		good	good			
RB(Δ+VM)		good	good			

SaGDH, EG4 : results down to 0.02 GeV^2 for g_1^p, g_1^n, g_2^n.

No g_2^p data below $Q^2 = 1.3$.

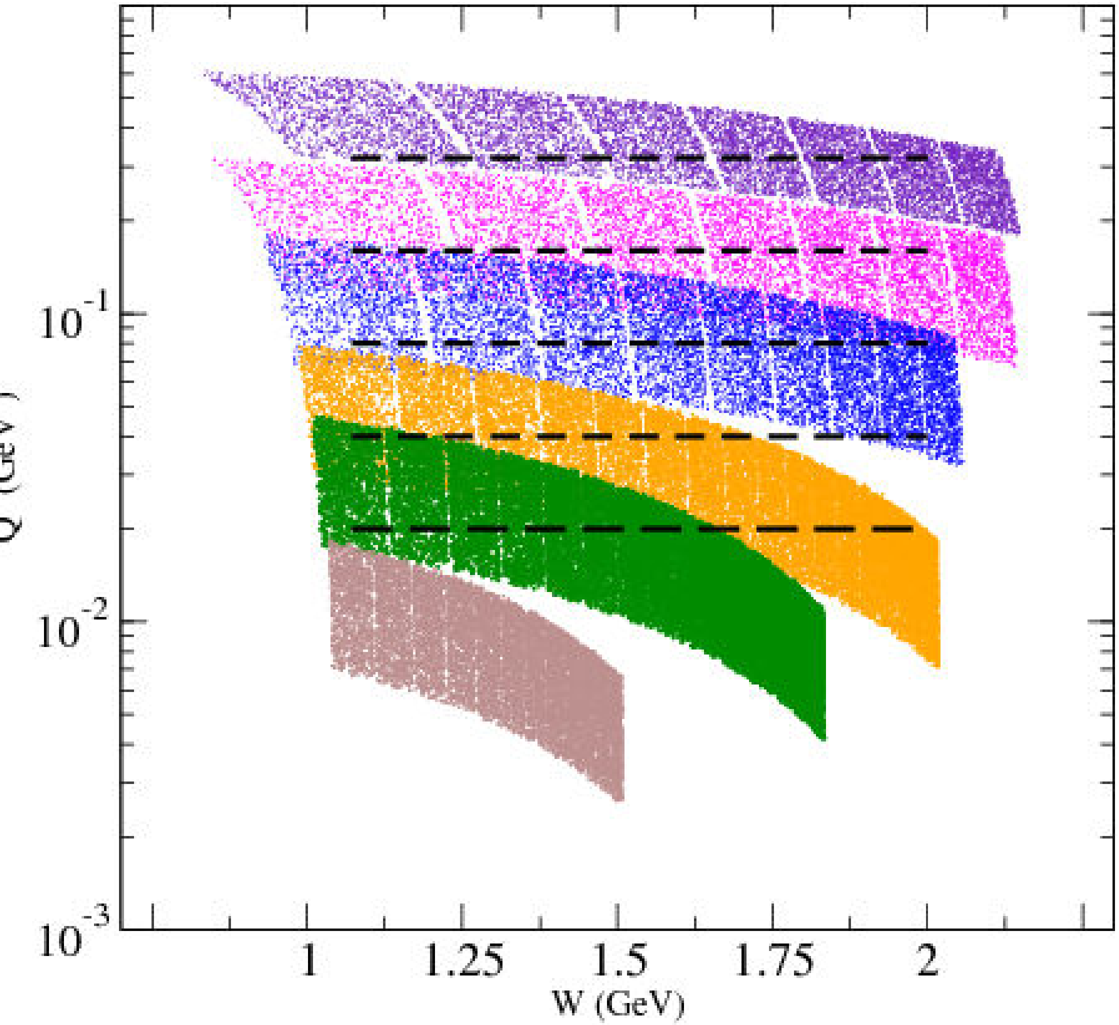
Discussion with Theorists

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

1. B. Holstein: *A real challenge to (χPT) theorists!*
2. Ulf-G. Meissner: *Working to properly include $\pi\Delta$. Reduce error.*
3. C. W. Kao:*Working on NNLO.*
4. T. Hemmert: *Short range effects beyond πN?*
5. Kochelev/Vanderhaghen: *t-channel axial vector meson exchange? Isoscalar in nature?*
6. C. Weiss: *An effect of QCD vacuum structure?*

To solve the puzzle and to understand the nature of the problem, need isospin separation.

The Experiment



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

$0.02 < Q^2 < 0.32$

$W_\pi < W < 2$ GeV

1. Polarized UVA/JLab target.
2. Septa Magnets.

Major Installation

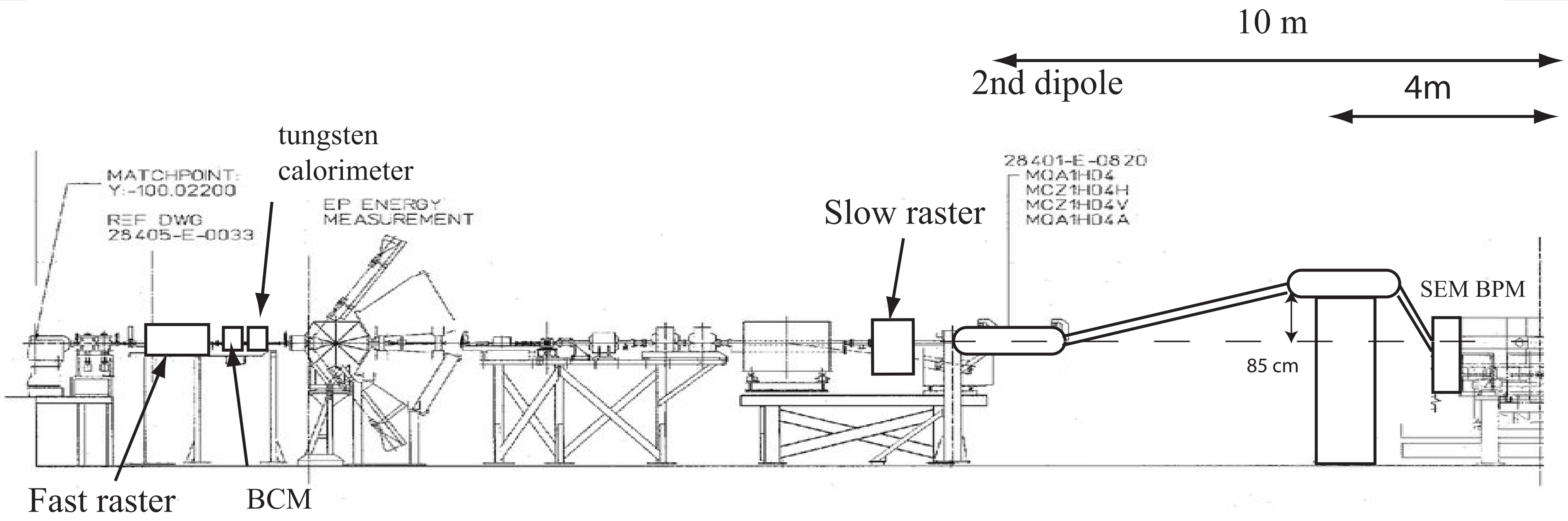
1. Similar to Hall C setup adapted to Hall A

   A. Installation of the UVA/JLab 5 T Polarized Target.
   B. Installation of an upstream Chicane and supports.
   C. Installation of the slow raster, and Basel SEM.
   D. Beamline instrumentation for 50-100 nA beam.
   E. Installation of a local beam dump.

+

2. Installation of the Hall A septa.

Chicane



Design : Jay Benesch (JLab CASA).

Reuse the dipoles for the HKS experiment.

Satisfies space constraints and provides sufficient bending power.

1^{st} dipole kicks the beam vertically.

2^{nd} dipole provides needed angle to compensate for the target field.

Total Systematic

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

Beam Time Request

E_0 (GeV)	θ	Time(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

Physics	15.7
Overhead	8.4

E07-001 Conditional Status

PAC31 Report

‘No particular technical obstacles were identified’.

Called for further justification of $Q^2 > 0.1$ points.

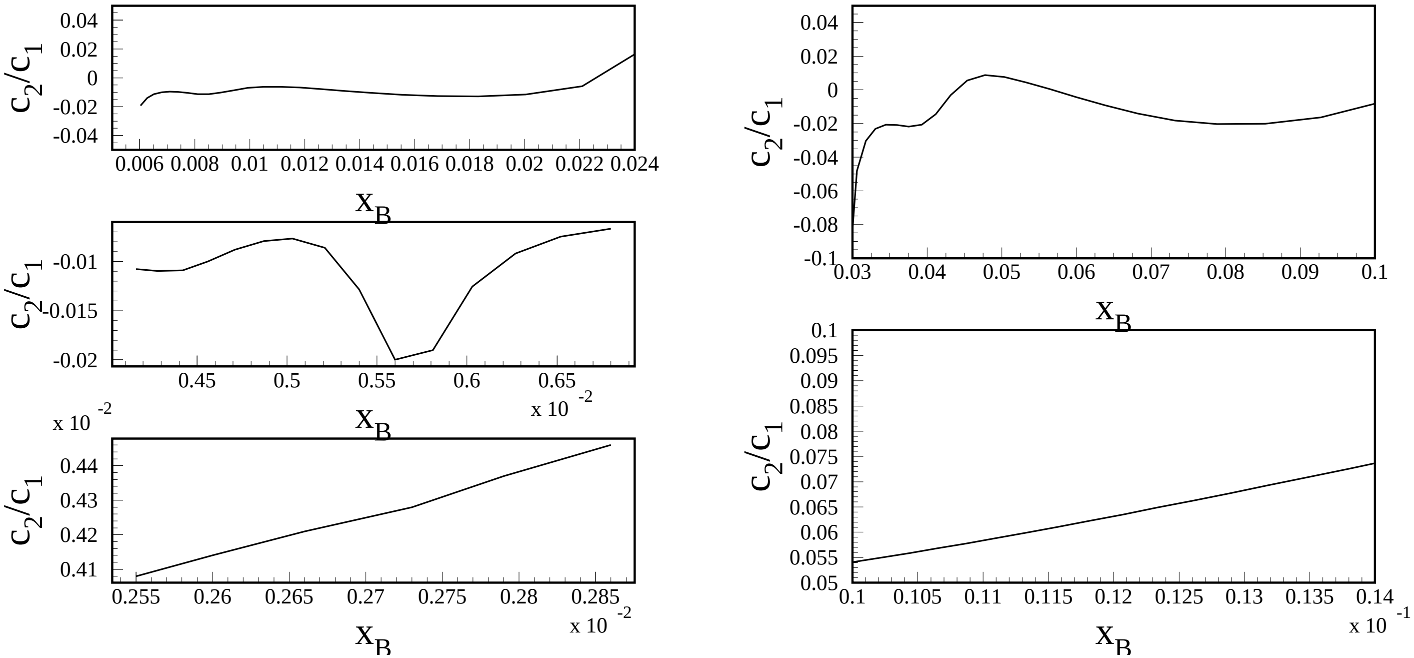
Specific PAC31 Issues

1. Impact on purely longitudinal measurements of g_1^p
2. Impact on calculations of Hyperfine Structure
3. Projected Results for BC Sum Rule, $d_2(Q^2)$

Impact on longitudinal g_1^p Measurements

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

$$\frac{c_2}{c_1} = \frac{2Mx g_2}{(E+E'\cos\theta) g_1}$$



EG4 Systematic

Beam and target polarization	1-2%	
^{15}N background	1-2%	
Luminosity and filling factor	3.0%	
Electron efficiency	$\leq$ 5%	
Radiative Corrections	5.0%	
Modeling of g_2	1-10%	Q^2 dependent
Extrapolation ($x \rightarrow 0$)	1-10%	Q^2 dependent

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

Hyperfine Structure

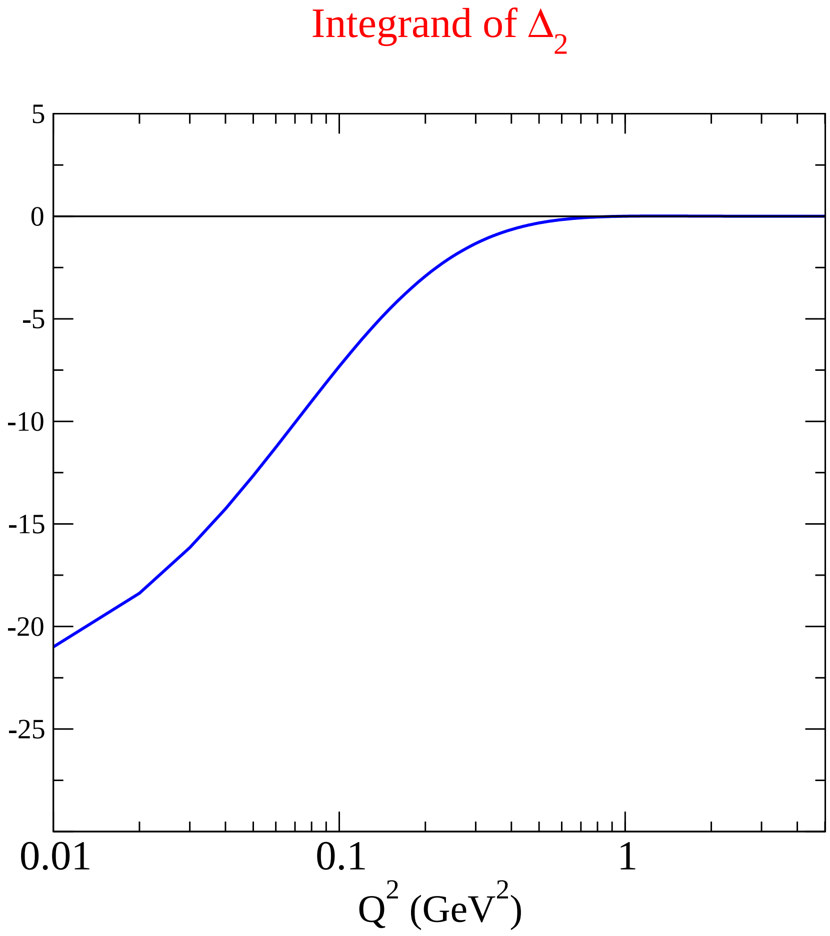
NCG PRL 96 163001 (2006)

$$\begin{aligned}\Delta E &= 1420.405\,751\,766\,7(9)\ \text{MHz} \\ &= (1+\delta)E_f \\ \delta &= 1 + \left(\delta_{\text{QED}} + \delta_R + \ \delta_{small}\right) + \Delta_S\end{aligned}$$

$$\begin{aligned}\Delta_S &= \Delta_Z + \Delta_{\text{pol}} \\ \Delta_{\text{pol}} &= \frac{\alpha m_e}{\pi g_p m_p}(\Delta_1 + \Delta_2) \\ \Delta_2 &= -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2) \\ B_2(Q^2) &= \int_0^{x_{\text{th}}} dx \beta_2(\tau) g_2(x, Q^2)\end{aligned}$$

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

Hyperfine Structure



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

$$= -0.57 \pm 0.57$$

(CLAS Model : 100% error)

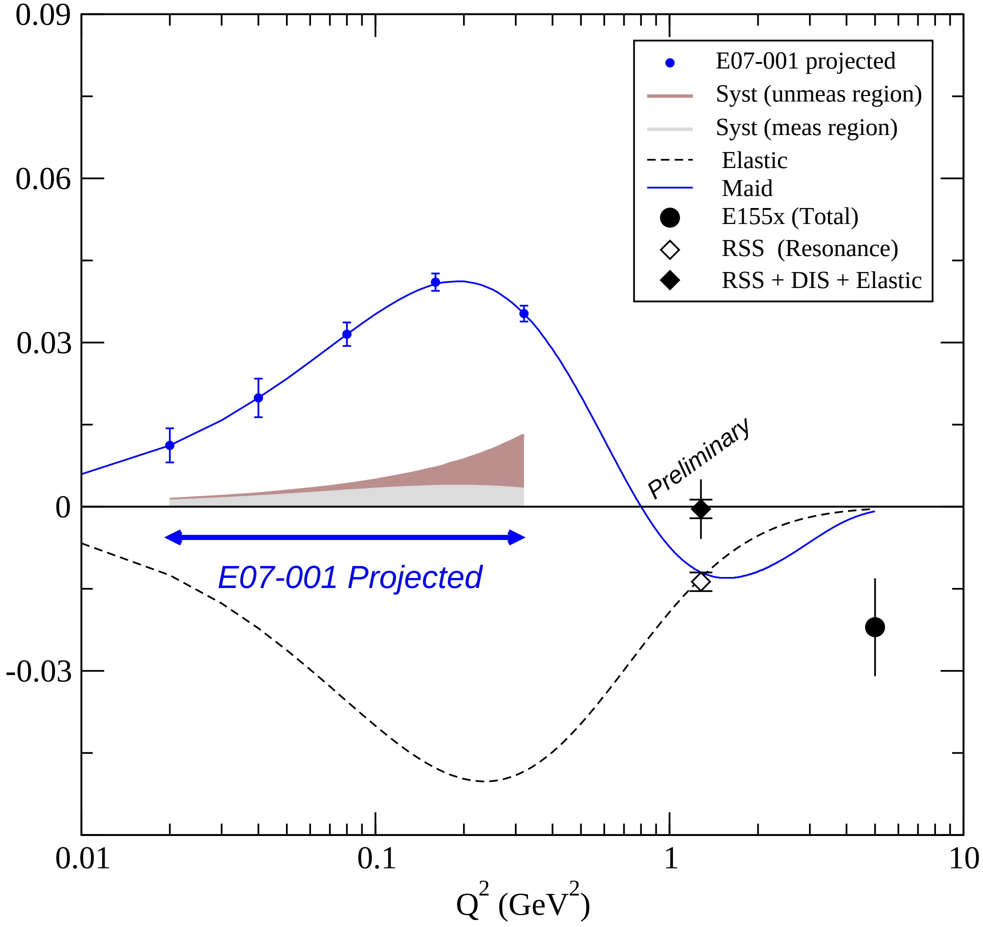
But, g_2^p unknown in this region:

Δ_2 dominated by $Q^2 < 0.4$

$\Delta_2 = -1.98$ MAID Model

$\Delta_2 = -1.86$ Simula Model

Projected Results



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

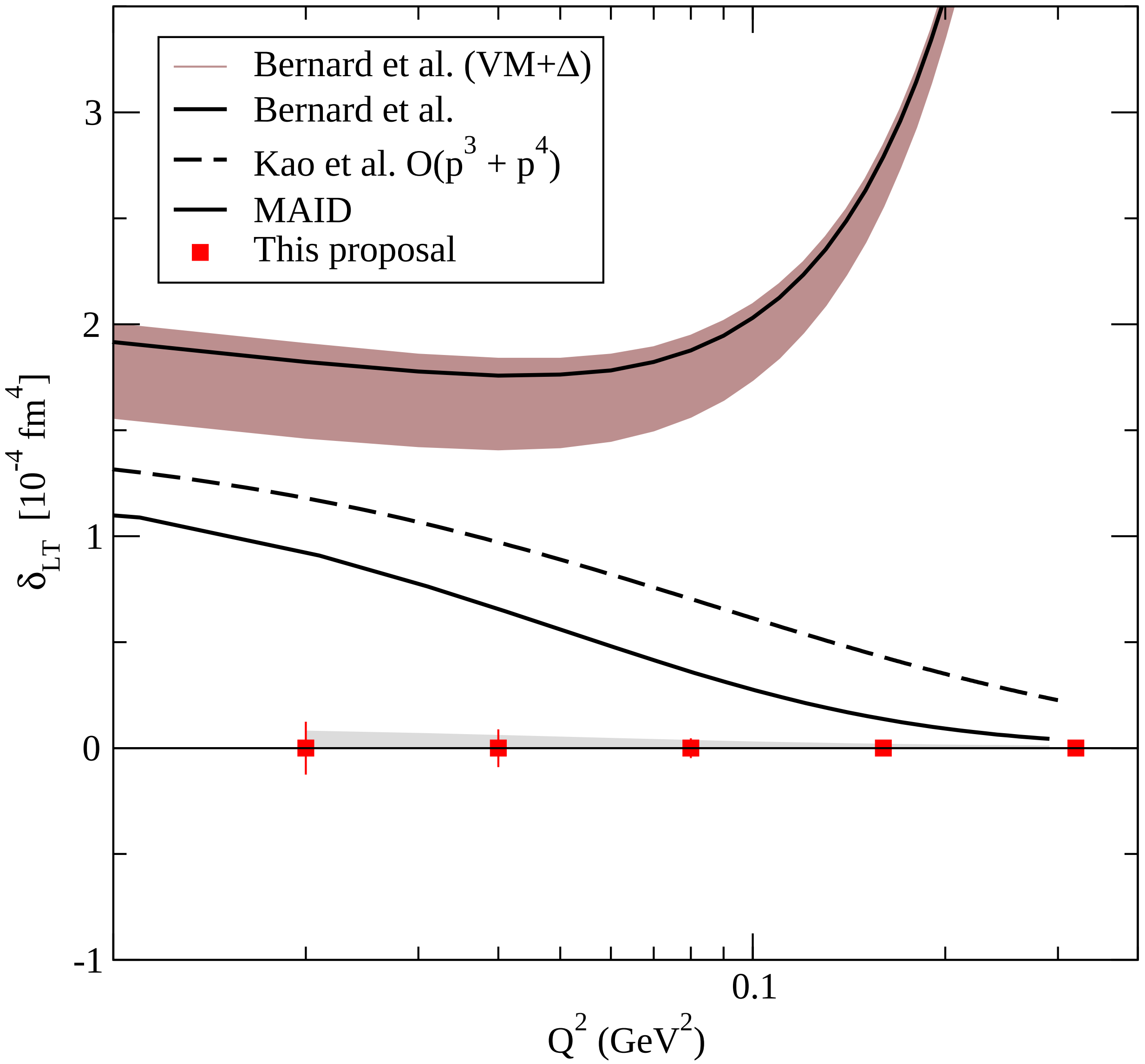
Holds for all Q^2

3 σ violation at $Q^2 = 5$.

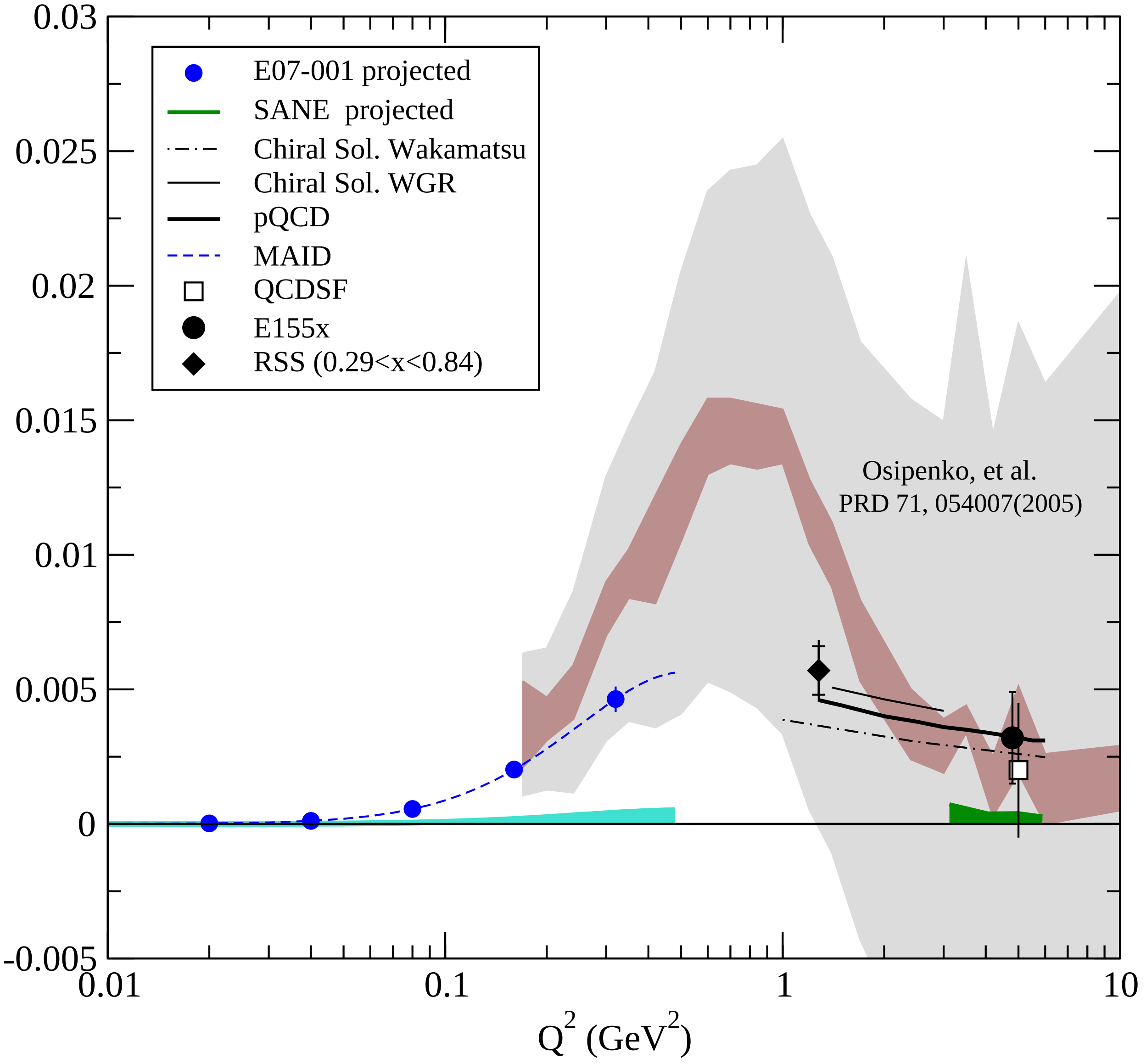
Appears to hold at $Q^2 = 1.3$

Appears satisfied for Neutron also

Projected Results

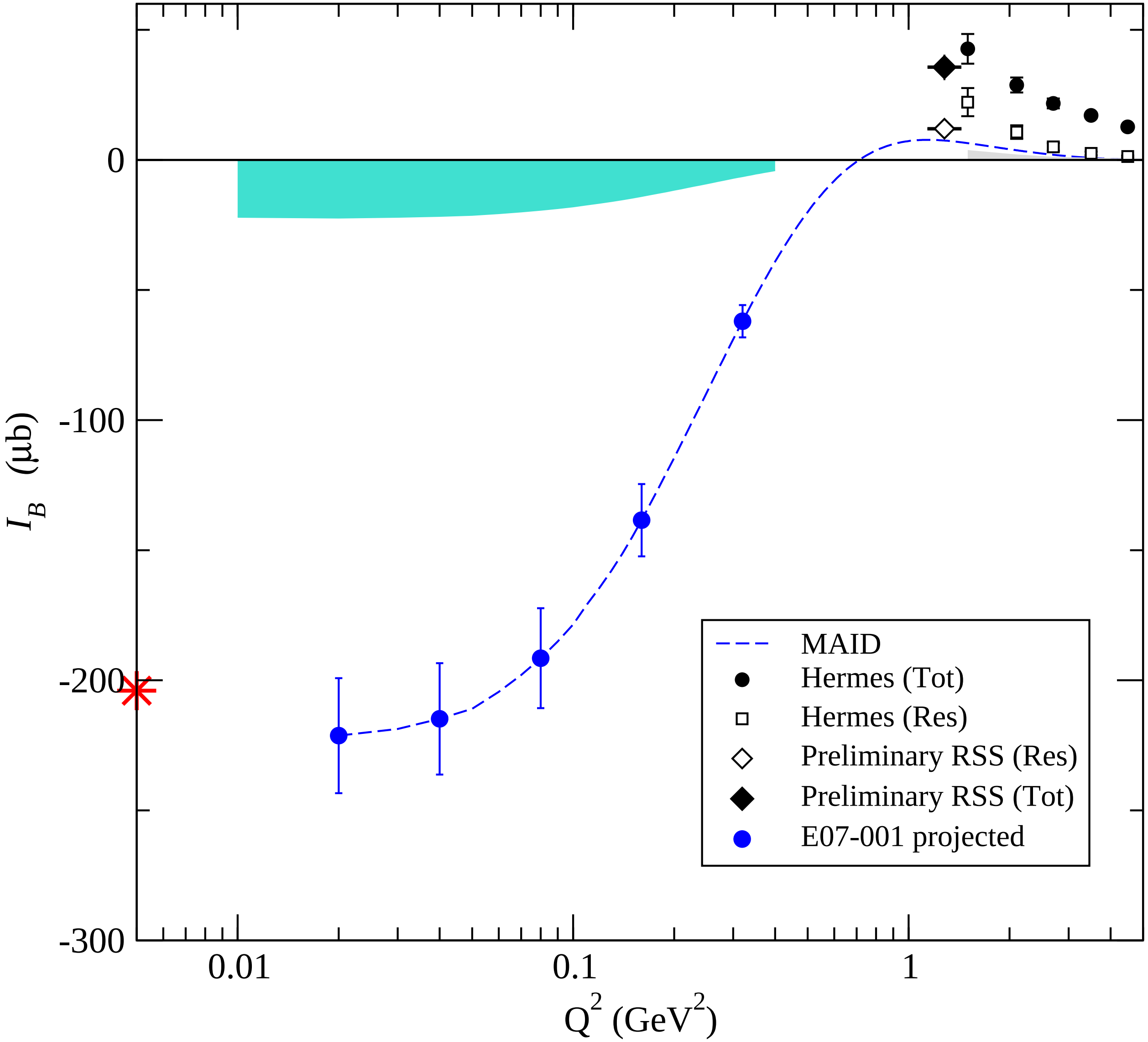


Projected Results

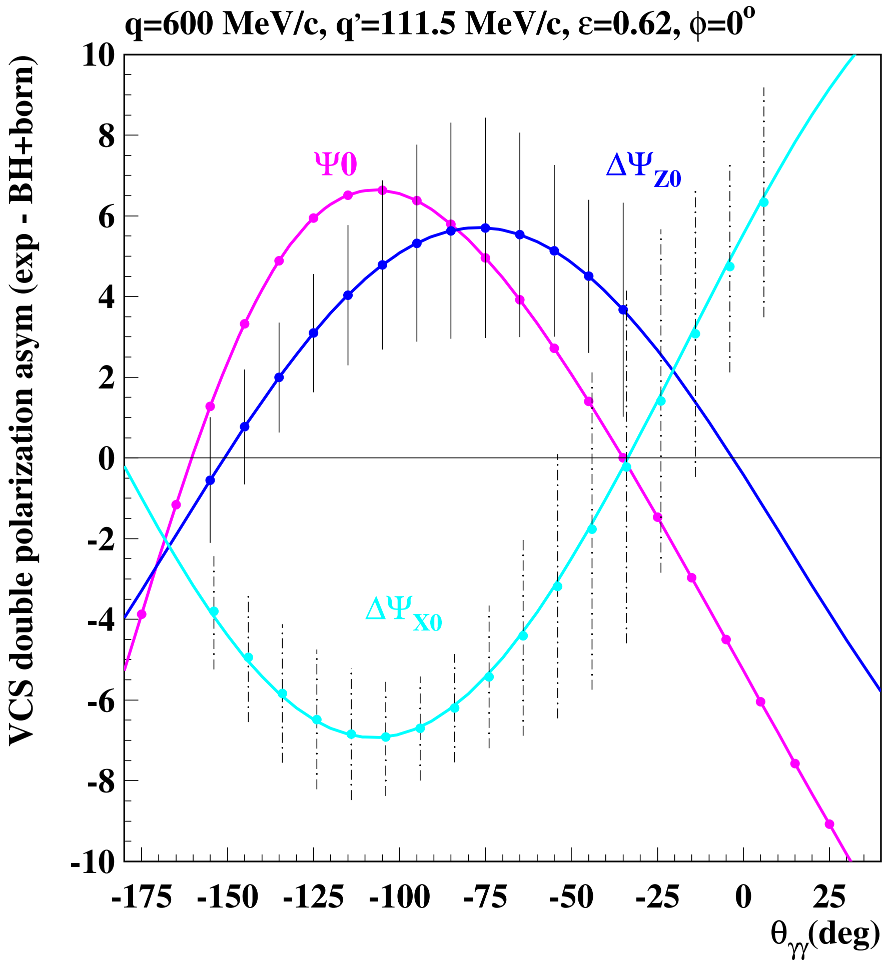


Osipenko, et al.
PRD 71, 054007(2005)

Projected Results



Relation to VCS Polarizabilities



VCS observables are some combination of GP.

$<--$ Expected precision on 2000 hr at MAINZ

Need additional out of plane measurements

to get γ_0 which is related to VCS GPs

at $Q^2 = 0$

δ_{LT} : No simple relation to VCS GPs.

Summary

- g_2^p unmeasured below $Q^2 = 1.3$ GeV^2. Not possible with 12 GeV.
- State-of-the-art χPT calcs work well for many spin-dependent quantities up to 0.1 GeV^2.

  δ_{LT} Puzzle: δ_{LT} was expected to be one of the best quantities to test χPT. Instead find disagreement with data by several hundred %.

  Theorists :*'Need isospin dependence in order to solve puzzle'*

  Establish reliability of χPT calculations

  Very important for LQCD chiral extrapolation.

- With 24 days, we can measure g_2^p with high precision.

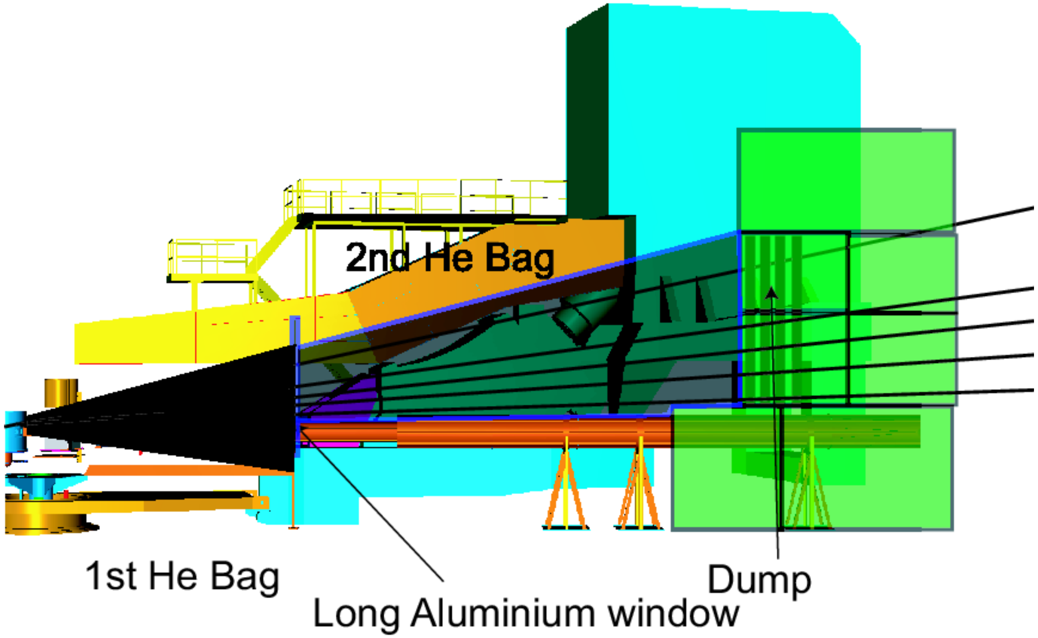
  BC Sum rule , d_2 integral, and extended GDH Sum.

  This kin region dominates contribution to Hyperfine Structure

  Reduce leading systematic of EG4 to $< 1\%$

Backup Slides

Local beam dump



Similar to Hall C GEN,RSS, SANE.

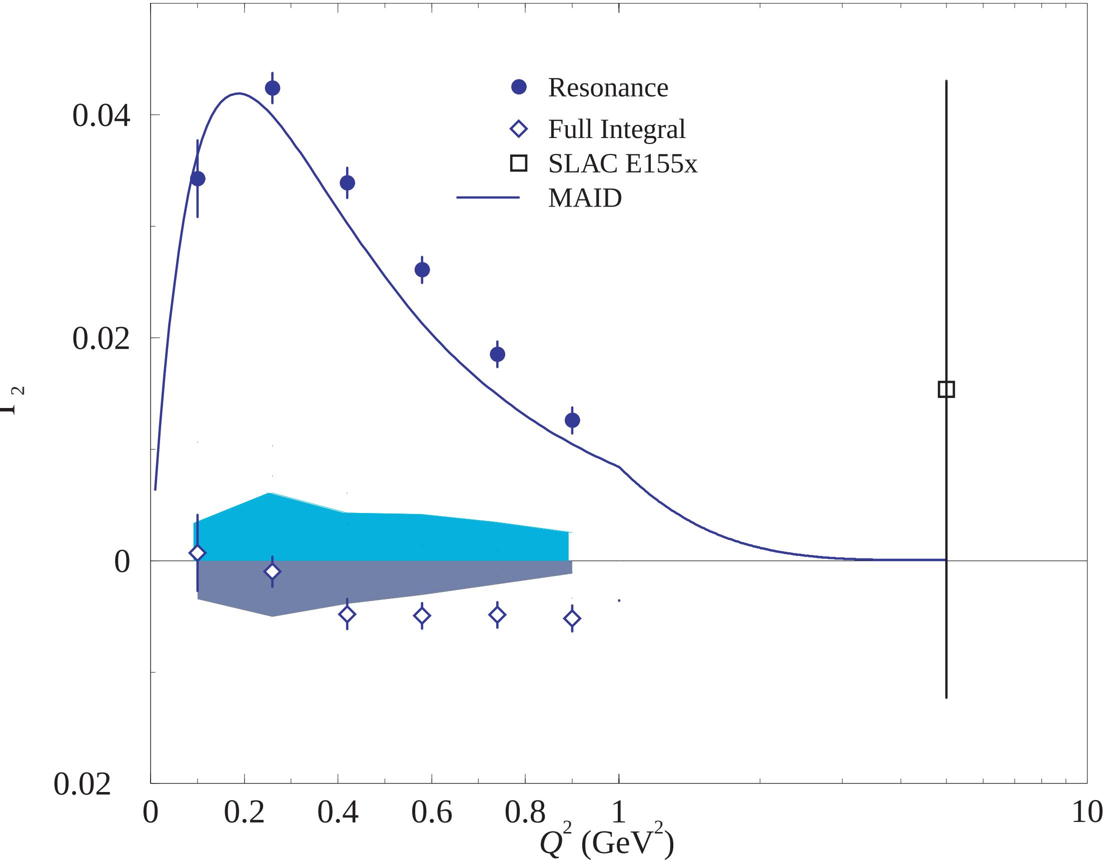
2 Helium Bags : retain use of standard dump

Dump : 35 cm iron, with concrete shielding.

70 nA of 4.4 GeV/c → 300 W energy deposit

No cooling needed.

B.C. Sum Rule (Neutron)



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

Also from dispersion relation

Appears to hold for neutron.

Beamline Instrumentation

Beam Current Monitor

1. Low current BCM will be commissioned for Parity exp. in 2009 (50-100 nA)
2. A. Freyberger: Those BCM will be able to be well calibrated using the Beam calorimeter designed for LEDEX which would allow 1% of BCM at low current.

Beam Position Monitor

1. BPM cavities from Happex.
2. Basel SEM : used in Hall C to determine beam position after rastering.

Slow raster : needed to spread heat load on target.

Overhead

Overhead	Number	Time Per (hr)	(hr)
Target anneal	27	2.5	67.5
Target rotation	2	16.0	32.0
Pass change	6	4.0	24.0
Packing Fraction	34	0.50	17.0
Momentum change	69	0.25	17.2
Target swap	2	8.0	16.0
Optics Calibration	2-3	8.0	16-24
Moller measurement	6	2.0	12.0
Septum angle change	1	8.0	8.0
Elastic calibration	2	4.0	8.0
			225.8

Cross Section Systematic

Source	(%)
Acceptance	4-6
Packing fraction	3.0
Charge determination	1.0
VDC efficiency	1.0
PID detector efficiencies	$\leq$1.0
Software cut efficiency	$\leq$1.0
Energy	0.5
Total	5-7

Hall A vs. Hall C

Installation in Hall C :

- Loss of approximately one half of the counting rate.
- The upstream beamline (including chicane) would need to be modified as in Hall A in order to properly transport the beam and to accommodate the displaced target.
- Moving the target upstream requires major modification of the pivot support, which is actually part of the SOS. Since space is much more limited in Hall C, it is not a simple task to place and support the Septum.
- We lose the valuable systematic check of having two independent cross section measurements.
- The Septa are designed to match the Hall A spectrometers and are not well suited to pair with the HMS. Lose years of analysis that have gone into understanding the optics of the HRS/septum pair.

Generalized Spin Polarizabilities

Low Energy Expansion of $\tilde{g}_{\rm TT}$:

$$\mathrm{Re}[\tilde{g}_{\rm TT}(\nu, Q^2)] = \left(\frac{2\alpha}{M^2}\right) I_A \nu + \gamma_0 \nu^3 + \mathcal{O}(\nu^5)$$

Taylor Expansion of the integral:

$$\frac{1}{2\pi^2} \int_{\nu_0}^{\infty} d\nu' \frac{K \sigma_{TT}}{\nu'^2} \left[\nu + (\nu^3/\nu'^2) + (\nu^5/\nu'^4) + \ldots\right]$$

Generalized Spin Polarizabilities

$\mathcal{O}(\nu^3)$ term: Spin Flip Polarizability

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

$\mathcal{O}(\nu^2)$ term of the g_{LT} expansion

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