New Results on Spin Structure Functions at Very Low Momentum Transfers (Q^2) from Jefferson Lab

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Mississippi State University

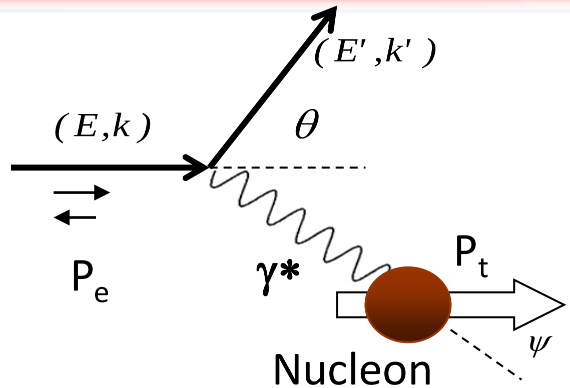
For the CLAS collaboration

- Spin structure at Low Q^2 - Formalism and Motivation
- Recent Data
- Summary and Outlook

Jefferson Lab
Thomas Jefferson National Accelerator Facility

MISSISSIPPI STATE UNIVERSITY

Inclusive Lepton Scattering & Structure Functions



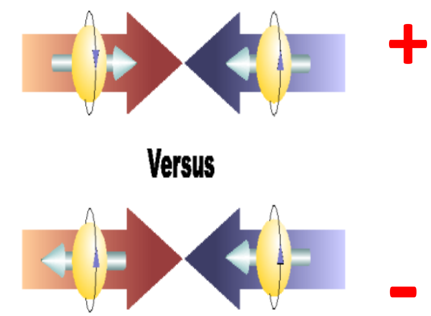
Kinematics

$\nu = \mathrm{E} - \mathrm{E'}$

$\mathrm{Q}^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$

$W^2 = M^2 + 2M\nu - Q^2$

$x = \frac{Q^2}{2M\nu}$



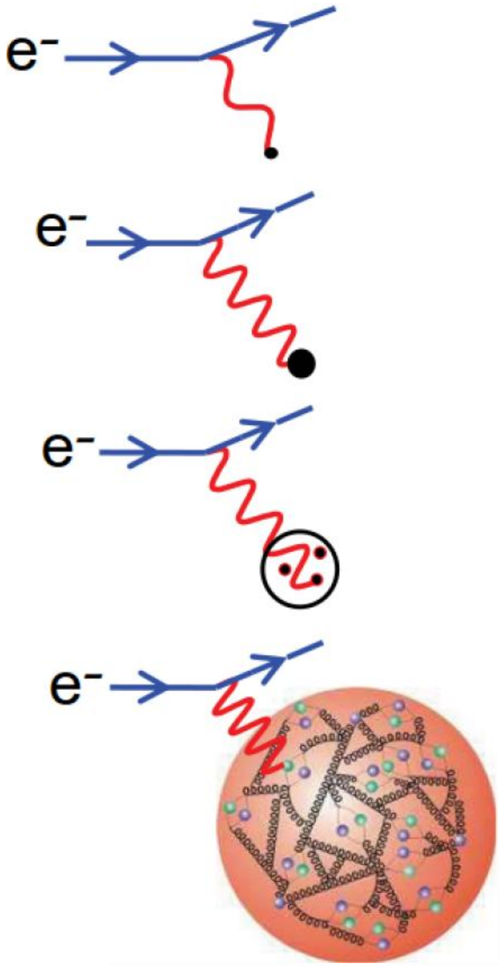
Cross-section: In the case of a target polarization along the beam:

$$\frac{d^2\sigma}{dE'd\Omega} = \sigma_{\text{point}}\left[\overbrace{\frac{2}{M}F_1(Q^2,\nu)\tan^2\frac{\theta}{2} + \frac{F_2(Q^2,\nu)}{\nu}}^{\text{Spin independent}} \pm 2\tan^2\frac{\theta}{2}\left[(E+E'\cos\theta)\frac{M^2}{\nu}g_1(Q^2,\nu) - \gamma^2 M^2 g_2(Q^2,\nu)\right]\right]$$

With $\gamma^2 = \frac{Q^2}{\nu^2}$ and, **+/- for antiparallel/parallel** beam-target polarizations

In the DIS limit, structure functions are directly related to polarized and unpolarized quark distribution functions

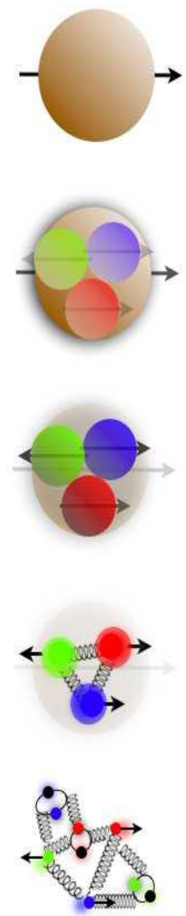
Nucleon Structure vs Distance Scale



(virtual) photon interacts with

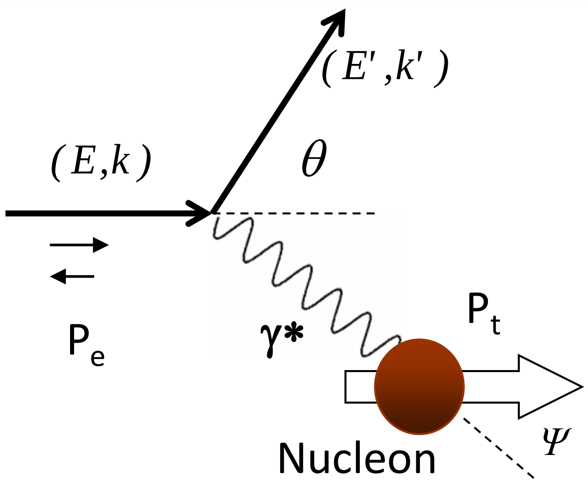
magnetic moment			GDH Sum Rule
pions, nucleon			Chiral Perturbation Theory
constituent quarks, N*			Lattice QCD (?)
multiple partons			Perturbative QCD
single partons			Bjorken Sum Rule Asymptotic freedom

Q^2 increases



Detect and analyze the kinematical distribution of the scattered electrons (cross-sections) for target information at various levels of detail.

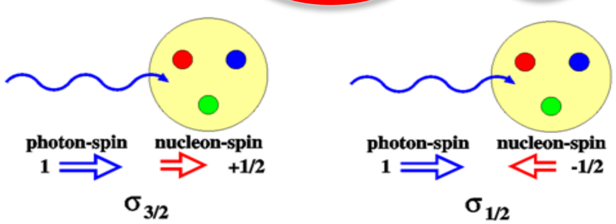
View in Terms of the Photo-absorption Cross Sections and Asymmetries



- Lepton scattering can be viewed as **the two step interaction** - emission of a virtual photon and then the absorption of the photon by the target.
- Therefore, the **spin structure functions are related with four independent virtual photo-absorption cross sections and their asymmetries**:

Certain combinations of the virtual photo-absorption cross sections provide us with certain structure functions, such as:

$$g_1 = \frac{MK}{8\pi^2\alpha(1+\gamma^2)}\left(\sigma^T_{1/2} - \sigma^T_{3/2} + 2\gamma\sigma^{TL}_{1/2}\right) \rightarrow$$



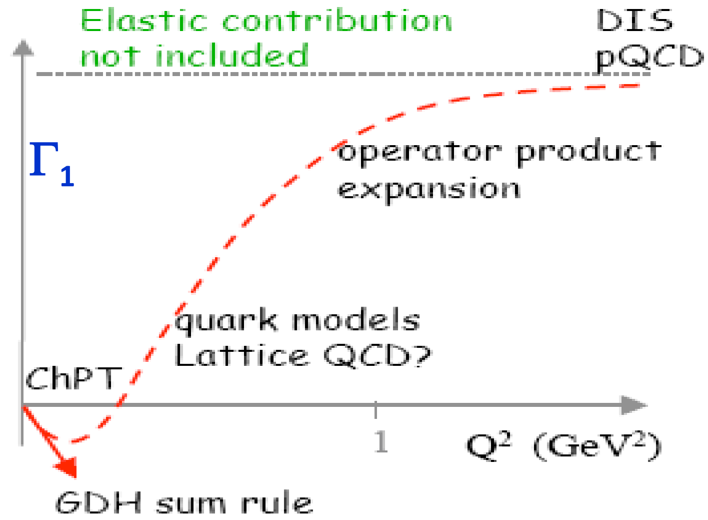
$$A_1(x,Q^2) = \frac{\sigma^T_{\frac{1}{2}} - \sigma^T_{\frac{3}{2}}}{\sigma^T_{\frac{1}{2}} + \sigma^T_{\frac{3}{2}}} = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

$$A_2(x,Q^2) = \frac{2\sigma^{TL}_{\frac{1}{2}}}{\sigma^T_{\frac{1}{2}} + \sigma^T_{\frac{3}{2}}} = \frac{\gamma[g_1(x,Q^2) + g_2(x,Q^2)]}{F_1(x,Q^2)}$$

Virtual photon asymmetries

with $\gamma^2 = \frac{4M^2x^2}{Q^2} = \frac{Q^2}{\nu^2}$

Low Q^2 Motivation - Integrals



- At low momentum transfers (Q^2), one can study the **transition from partonic (quark-gluon) to hadronic (nucleonic) descriptions of Strong interaction by testing & constraining effective theories** based on QCD such as **Chiral Perturbation Theory (χPT).**
- Low Q^2 region (<~0.1 GeV^2): χ**PT** Calculations:
  - **Relativistic Baryon χPT with Δ,** Bernard, Hemmert, Meissner;
  - **Heavy Baryon χPT,** Ji, Kao, Osborne; Kao, Spitzenberg, Vanderhaeghen
  - Lensky, Alarcón, Pascalutsa, PRC**90**, 055202 (2014).
  - Bernard, Epelbaum, Krebs, Ulf-G. Meißner, Phys. Rev. D **87**, 054032 (2013)

Interesting variation with Q^2

Hadron ⟶ Parton

$$\overline{\Gamma}_1 = \int_0^{x_{th}} g_1\left(x, Q^2\right) dx$$

$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_{th}} (g_1 - \frac{2M^2x^2}{Q^2} g_2) dx \xrightarrow{(Q^2 \to 0)} -\frac{\kappa^2}{4}$$

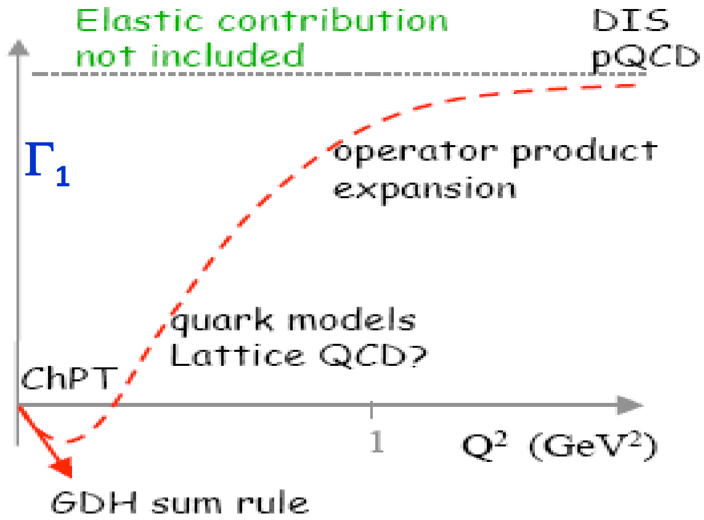
GDH

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_{th}} (g_1 - \frac{2M^2x^2}{Q^2} g_2) x^2 dx$$

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

Low Q^2 Motivation - First Moment of g_1

- At low momentum transfers (Q^2), one can study the **transition from partonic (quark-gluon) to hadronic (nucleonic) descriptions of Strong interaction by testing & constraining effective theories** based on QCD such as **Chiral Perturbation** Theory (χPT).



- In the **parton model, it is the fraction of the nucleon spin** contributed by the quark helicities
  - Enters directly into two historically important sum rules - **Ellis-Jaffe sum rule (Spin Crisis) and Bjorken sum rule (QCD validation).**
  - Some low Q^2 predictions from **χPT** and phenomenological models

Interesting variation with Q^2

Hadron ⟶ Parton

$$\overline{\Gamma}_1 = \int_0^{x_{th}} g_1\left(x, Q^2\right) dx$$

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GDH

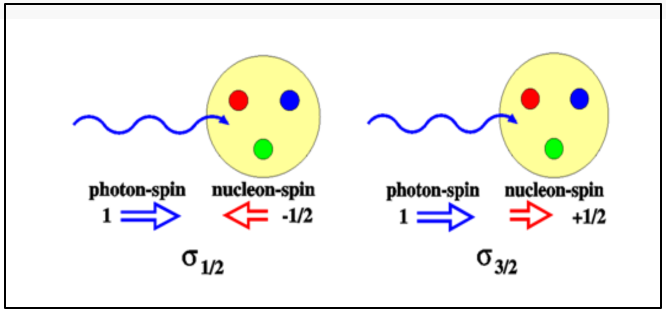
$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_{th}} \left(g_1 - \frac{2M^2x^2}{Q^2} g_2\right) x^2 dx$$

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

Low Q^2 Motivation - Generalized GDH Integral

Gerasimov, Drell and Hearn (GDH) Sum Rule (PRL 16(1966) 908; Sov.J.Nucl Phys.2 (1966) 430)

$$\int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu}\left(\sigma^{3/2}(\nu) - \sigma^{1/2}(\nu)\right) = \frac{2\pi^2 \alpha \kappa^2}{M^2}$$



ν_{th} is pion production threshold, κ = anomalous magnetic moment

First measurements at Mainz (up to 800 MeV), Bonn (up to 3 GeV) & LEGS (up to 421 MeV) agree with the predictions.

Extension of GDH Sum Rule to $Q^2 > 0$ (virtual photons) using the dispersion relation for the **forward virtual photon Compton scattering amplitude** $S_1(\nu=0, Q^2>0)$, just as the real photon GDH sum rule derived from the **dispersion relation for the invariant Compton amplitude** $S_1(\nu, Q^2 = 0)$.

$$\bar{I}_{TT}(Q^2) = \frac{2M^2}{Q^2}\int_0^{x_{th}} \left(g_1 - \frac{2M^2 x^2}{Q^2} g_2\right) dx \xrightarrow{(Q^2 \to 0)} -\frac{\kappa^2}{4}$$

GDH

The new sum rule **yields the GDH sum rule at $Q^2 = 0$, and the Bjorken sum rule in the DIS regime**, thus establishing a smooth connection between the hadronic worlds of quark-confinement & partonic world of asymptotic freedom.

Low Q^2 Motivation - Generalized Nucleon Spin Polarizabilities

Forward spin polarizability

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

Sensitive to resonances

Longitudinal transverse spin polarizability

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

Insensitive to the Δ resonance

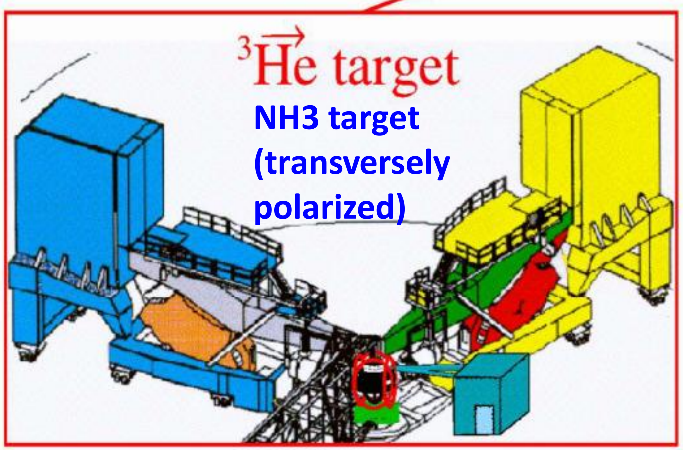
- **Generalized polarizabilities: extensions polarizabilities to the case of virtual photon Compton scattering.**
  - can be calculated in χPT at low Q^2.
  - **converge faster** than the first moments due to power weighting by 1/ν or x and **thus easier to determine from the low energy measurements.**
  - Thus, **reduced dependence on the extrapolations to the unmeasured regions at large ν or small x**, and **higher sensitivity to the low energy behavior** of the cross sections (particularly the threshold behaviour), **hence better tools to test χPT and phenomenological model predictions**

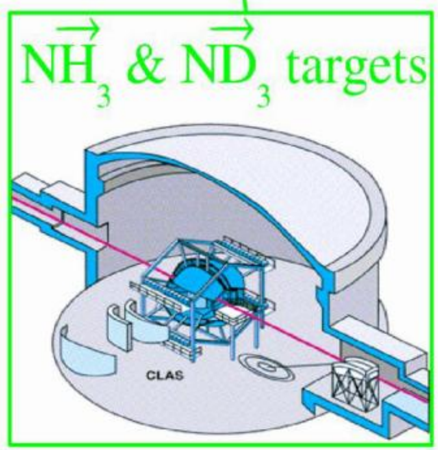
Jefferson Lab Experimental Halls

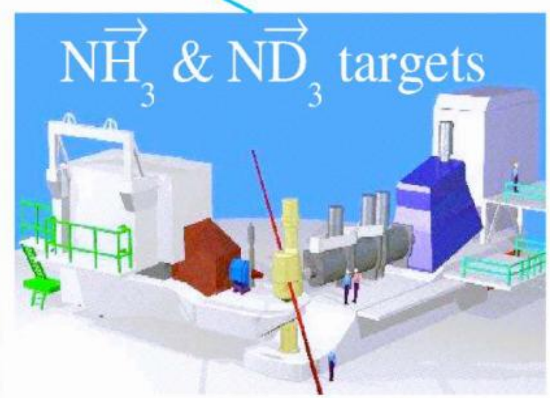
6 GeV polarized
CW electron beam
Pol=85%, 200μA

Now upgraded
to 12 GeV

The electron beam can be delivered simultaneously to the three halls with high polarization





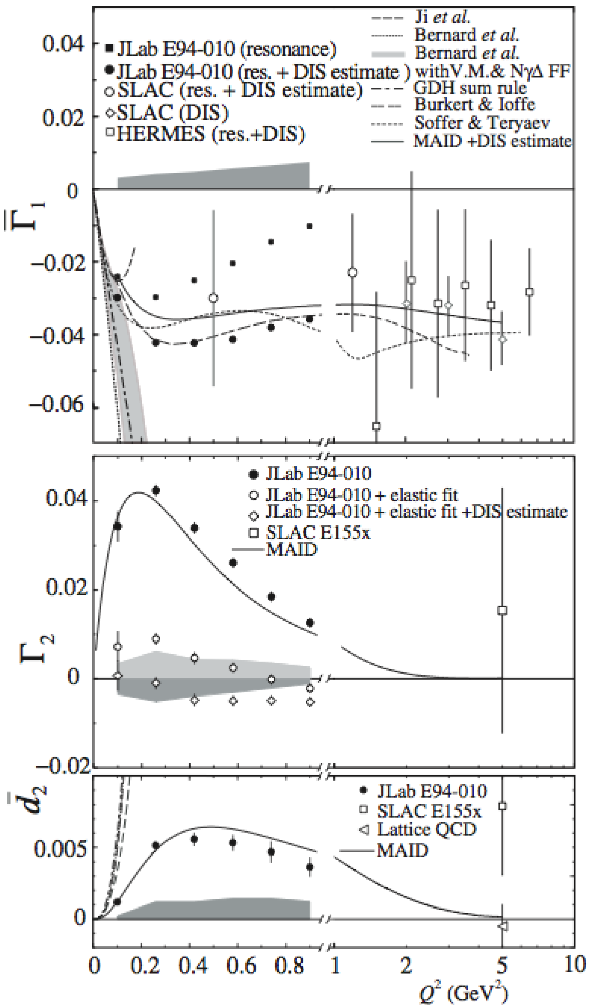


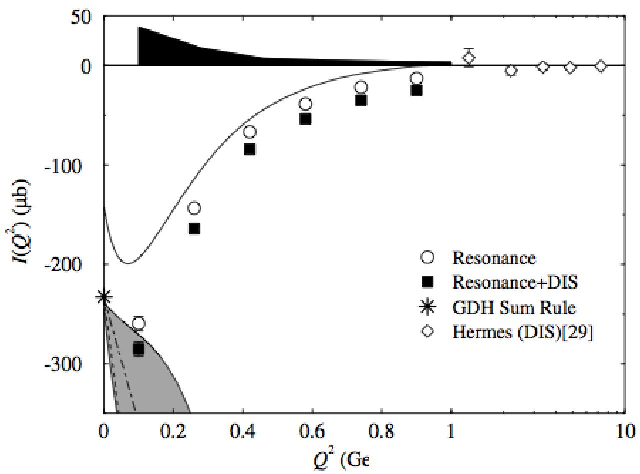
HallA: two HRS'

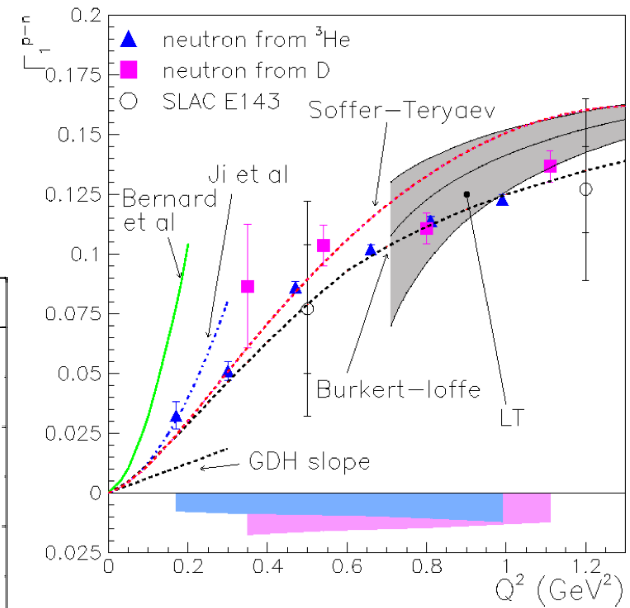
Hall B:CLAS

Hall C: HMS+SOS

Hall A E94-010 Experiment







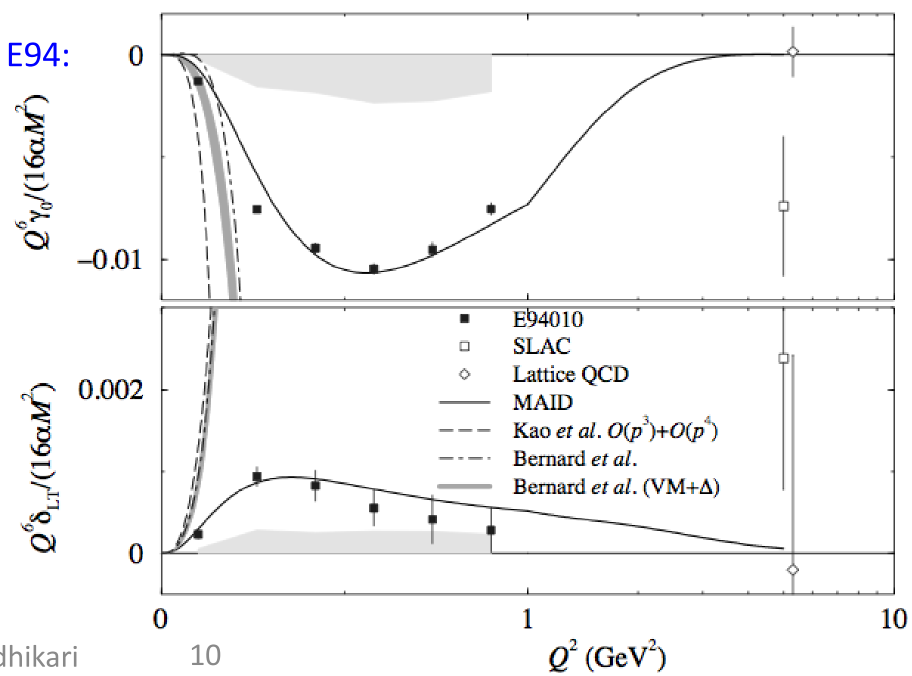
Hall A publications from E94:

PRL 101, 022303 (2008)

PRL 93, 152301 (2004)

PRL 92, 022301 (2004)

PRC 70, 065207 (2004)



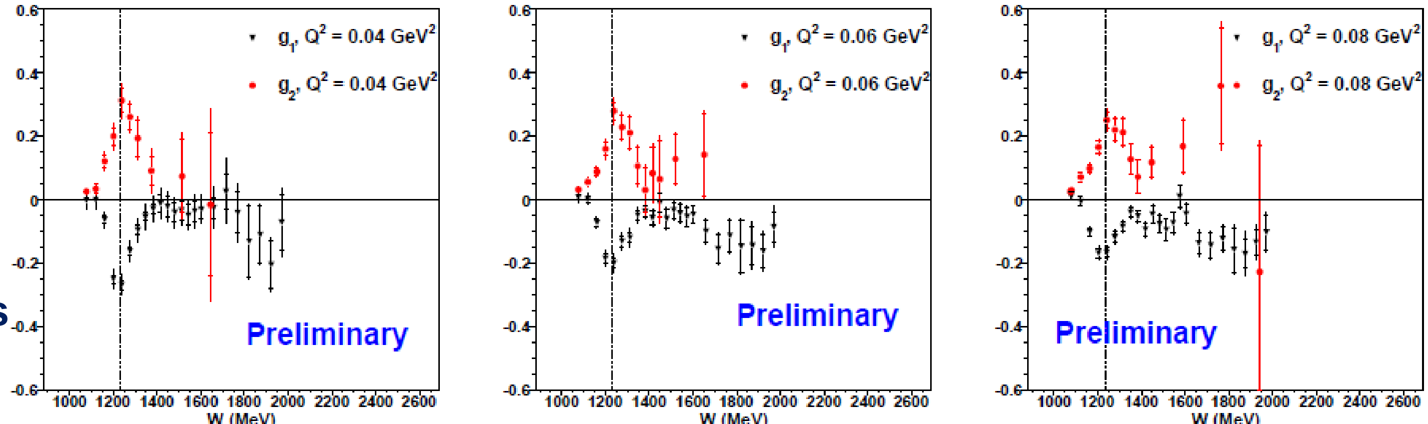
$$^3\vec{\mathrm{He}}(\vec{e},e')X$$

Hall-A E97-110: Low Q2 Spin Structure

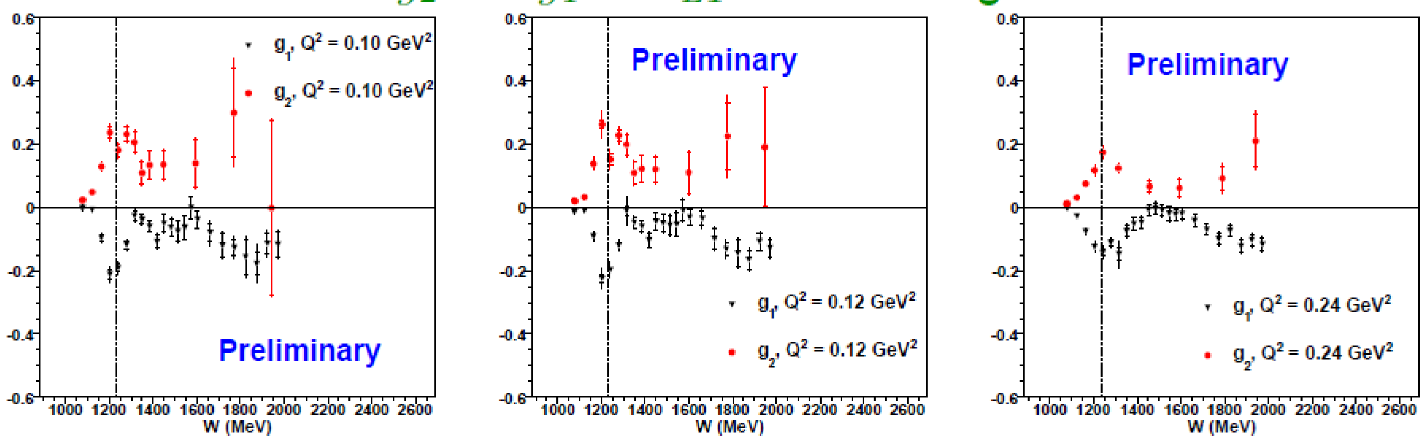
- **Inclusive measurement**: $^{3}\vec{\mathrm{He}}(\vec{e},e')X$
  - Scattering angles of 6° and 9°
  - Polarized (~ 75%) electron beam
  - Pol. (~ 40%) **^{3}He target** (para & perp)
- **Measured polarized cross-section differences**

Spokesmen: J.-P. Chen, A. Deur, F. Garibaldi

g_1, g_2 results



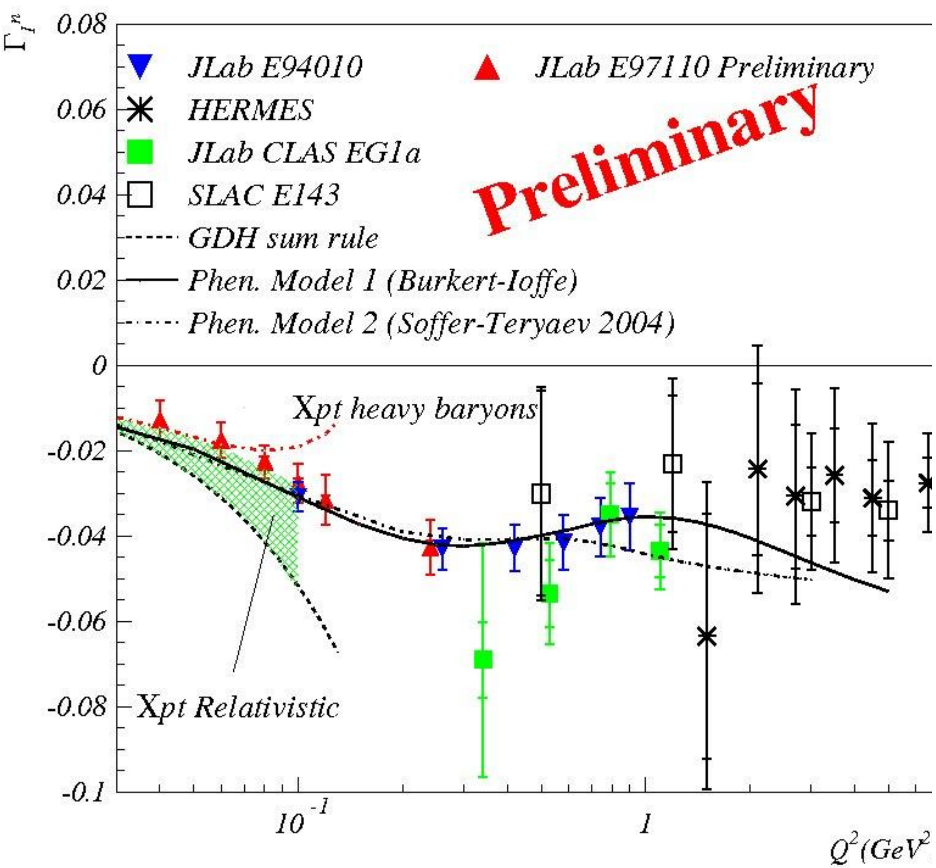
$g_2 \approx -g_1 \Rightarrow \sigma_{LT} \approx 0$ in Δ region

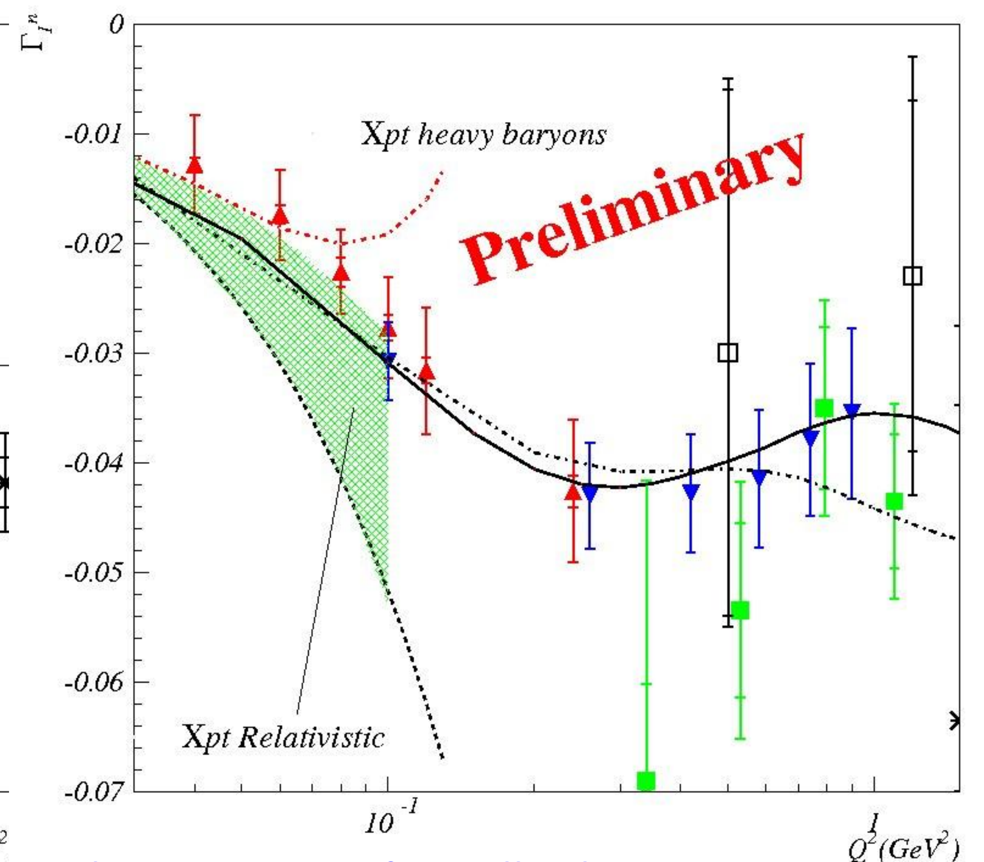


Plots courtesy of V. Sulkosky

E97-110: First Moment of g^n_1

$$\Gamma_1 = \int_0^{x_0} g_1(x, Q^2)dx$$

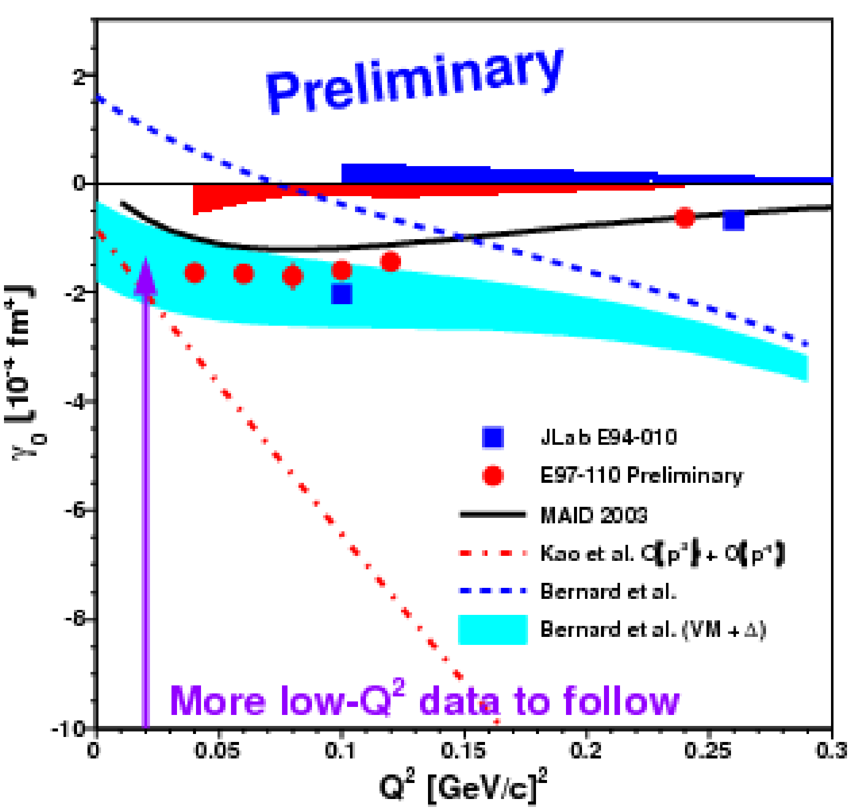


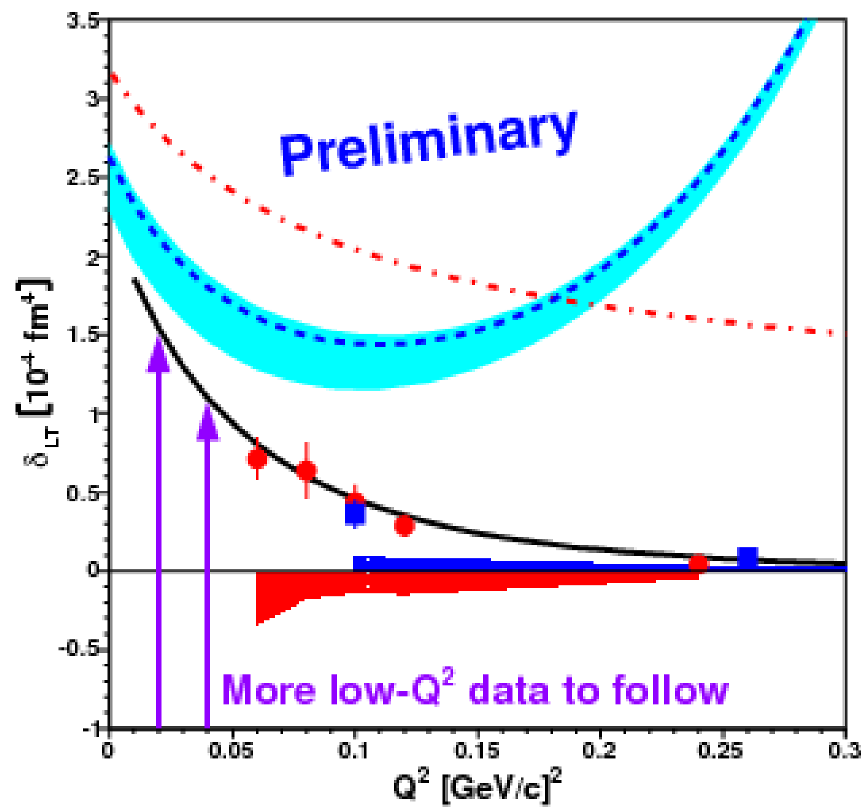


Plots courtesy of V. Sulkosky

E97-110: New Results for Neutron Spin Polarizabilities

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right] \qquad \delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

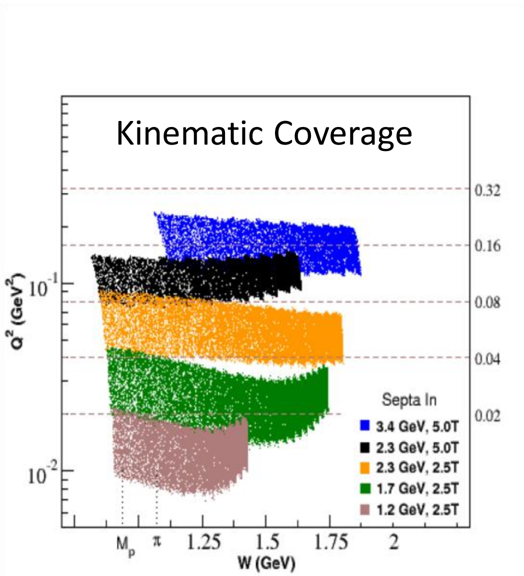


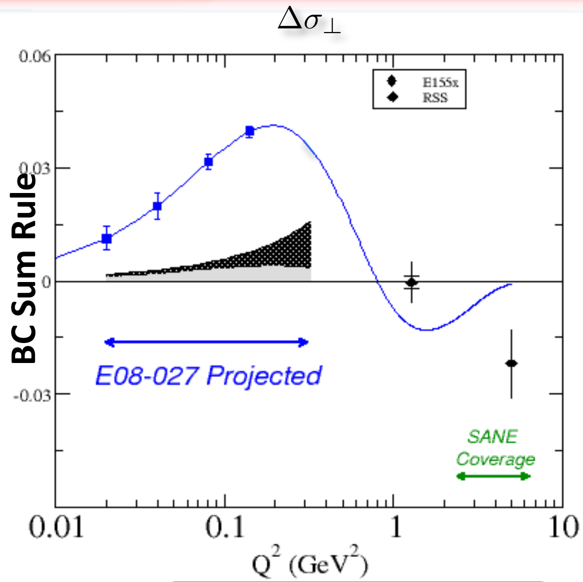


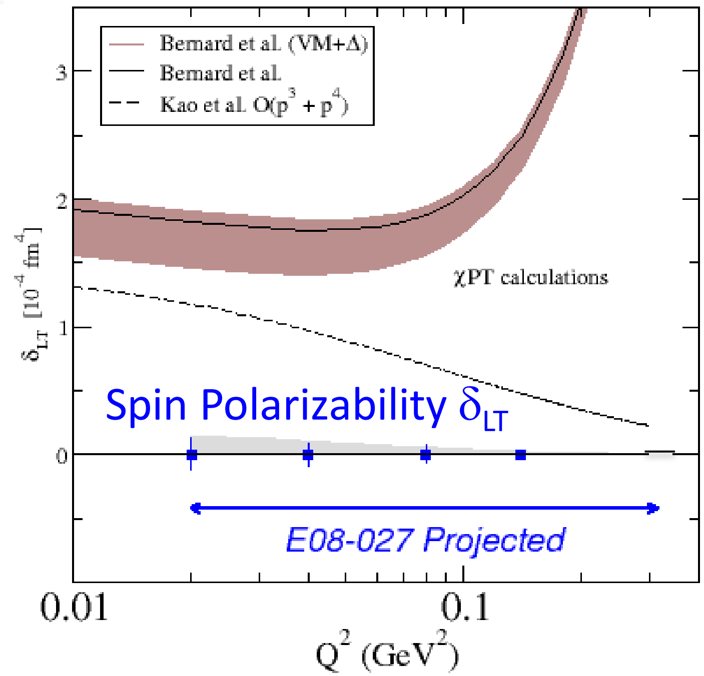
Surprising failure of χPT: no Δ resonance contribution expected for δ_{LT}

Hall A g2p: Proton Spin Structure Functions

Plots courtesy of
R. Zielinski & T. Badman



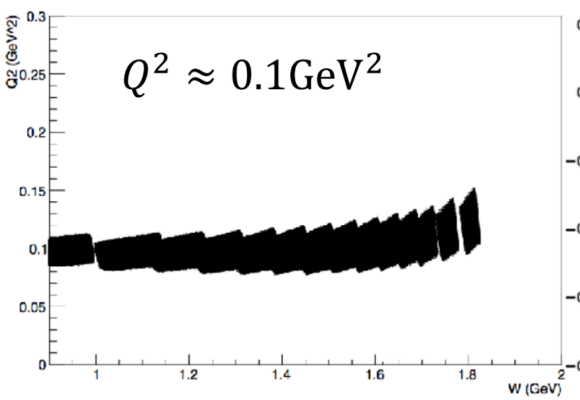


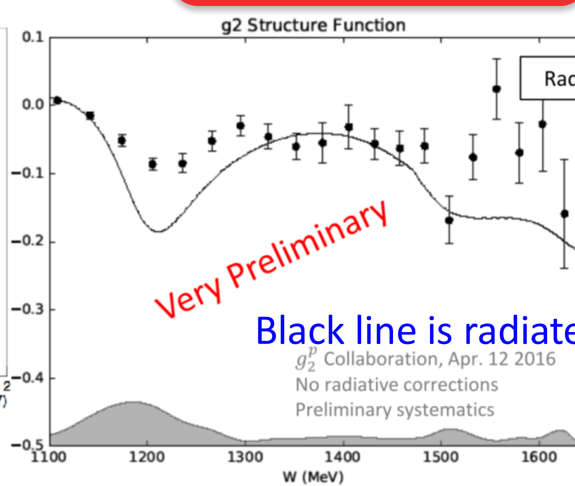


$M_p < W < 2$ GeV

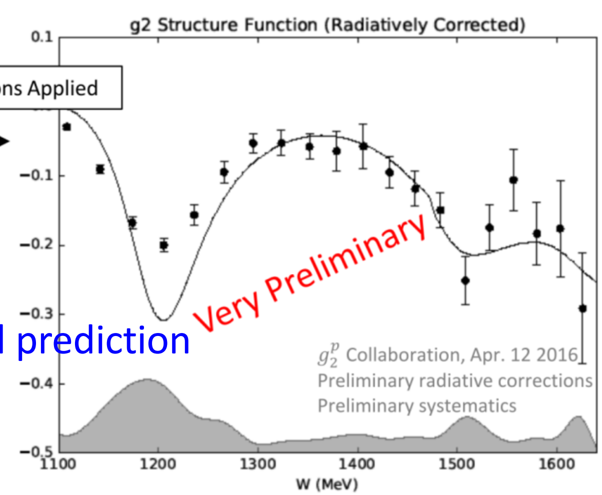
$0.02 < Q^2 < 0.2$ GeV^2

2.254GeV 5T Transverse Kinematic Coverage





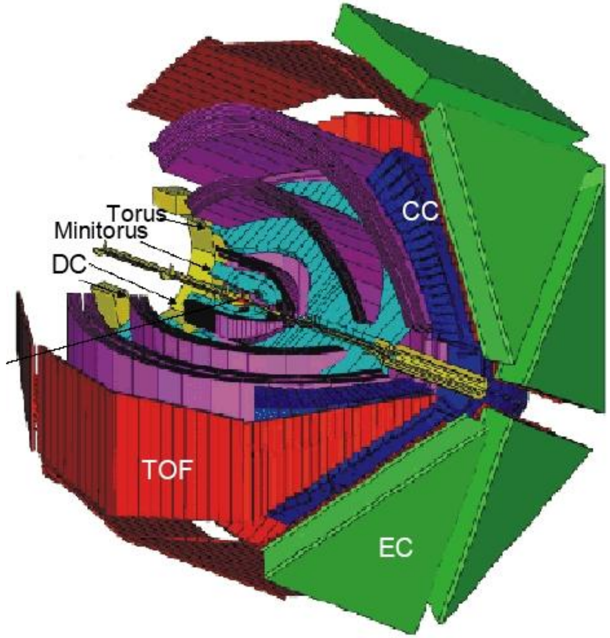
Radiative Corrections Applied



Black line is radiated model prediction

Jefferson Lab

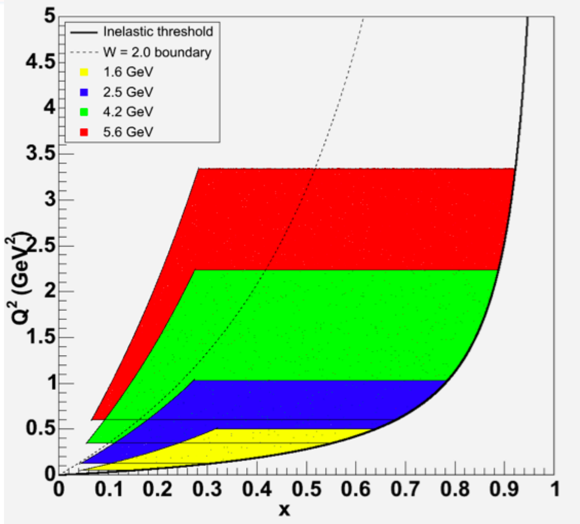
Hall B CLAS Experiment EG1



Measured large range in Q^2 and W

0.05 < Q^2 < 5.0 GeV^2 in 39 bins

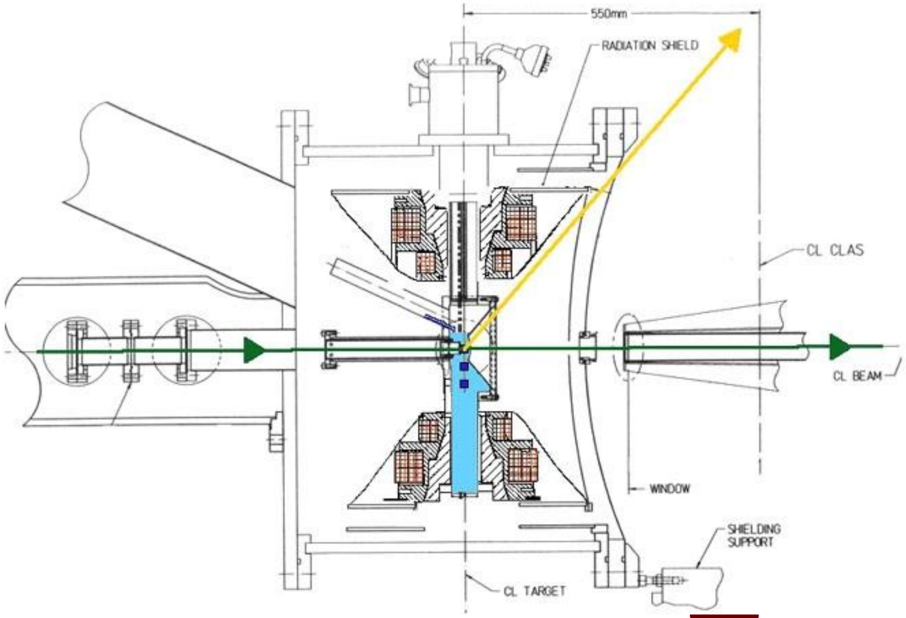
W < 3.0 GeV in 10 MeV 300 bins



Longitudinally polarized (~ 70%) electrons

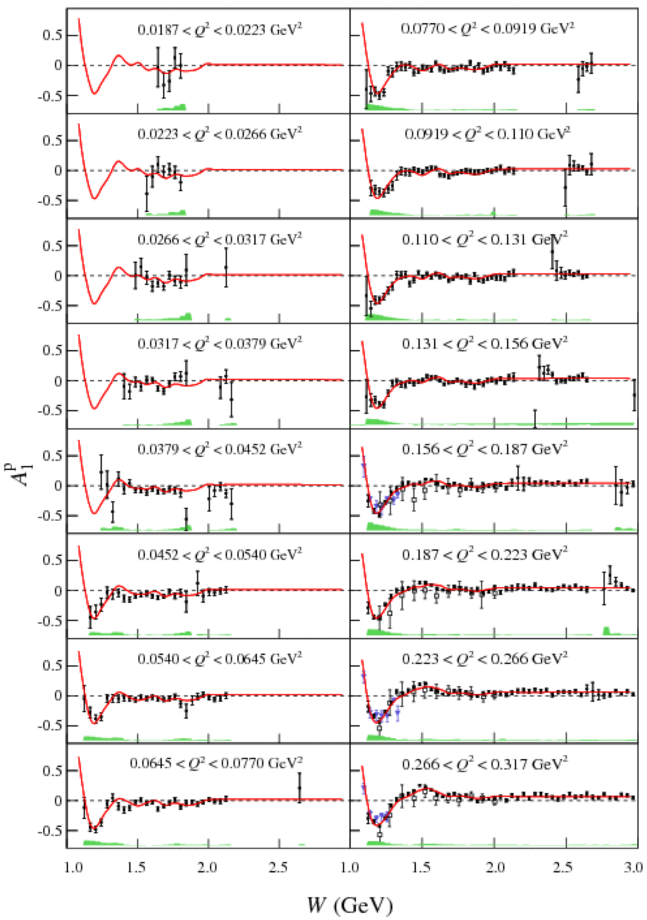
Beam energies: 1.6, 2.5, 4.2, 5.7 GeV

Polarized solid ammonia targets NH_3 , ND_3

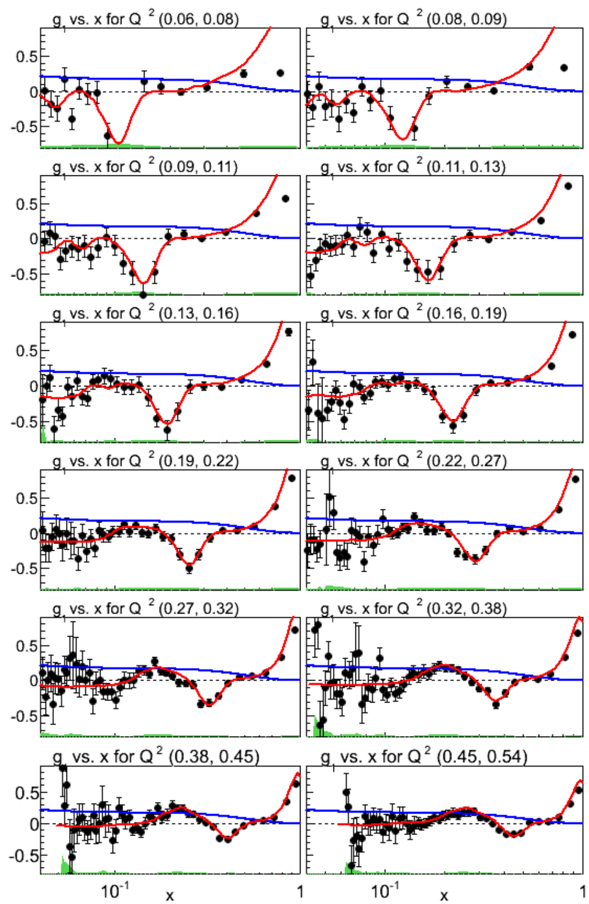


EG1b: g_1 at Low Q^2

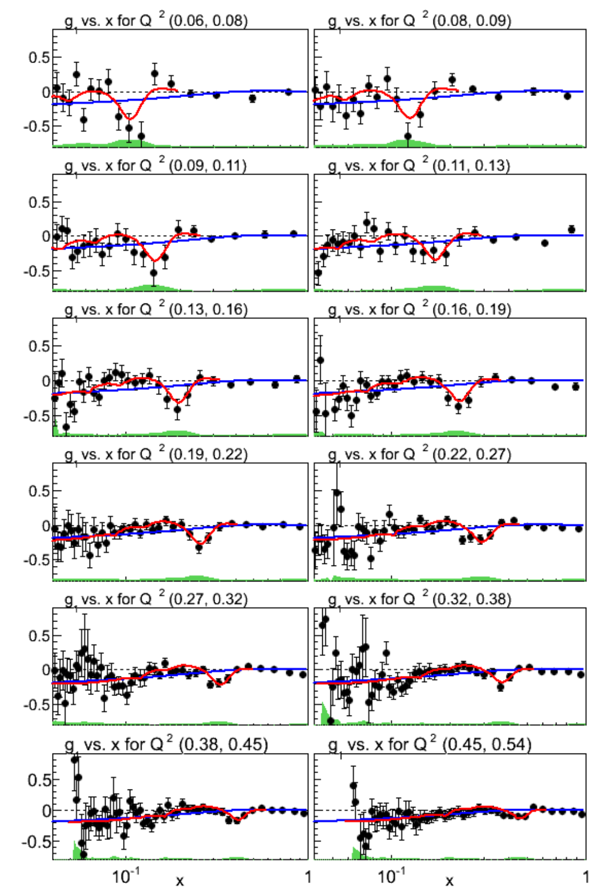
Proton



Deuteron



Neutron



N. Guler et al – PhysRevC.92.055201

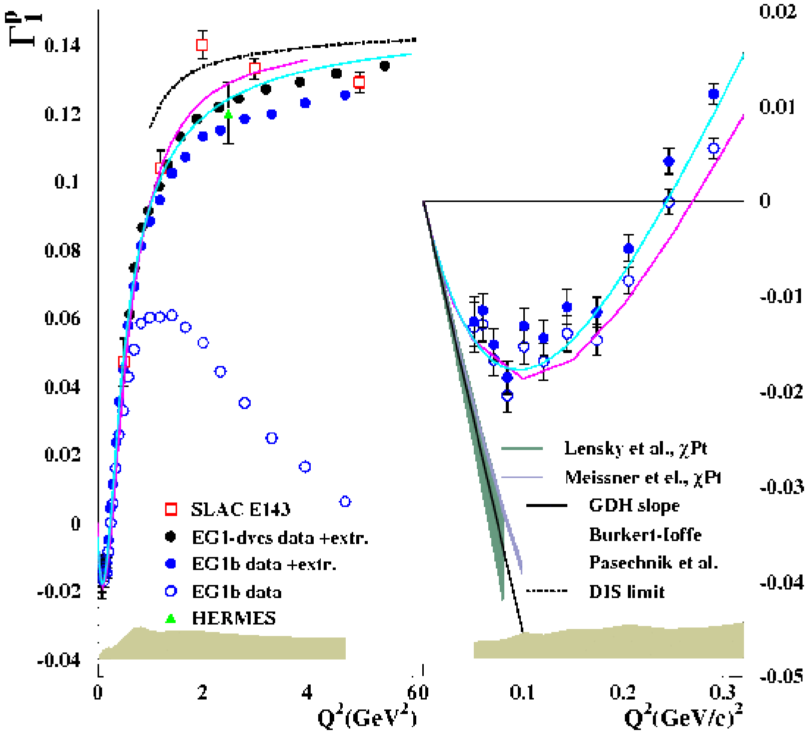
Plots courtesy of R. Fersch

EG1 results: $\Gamma_1 = \int g_1(x,Q^2)dx$

Shows expected trend toward DIS result at high Q^2

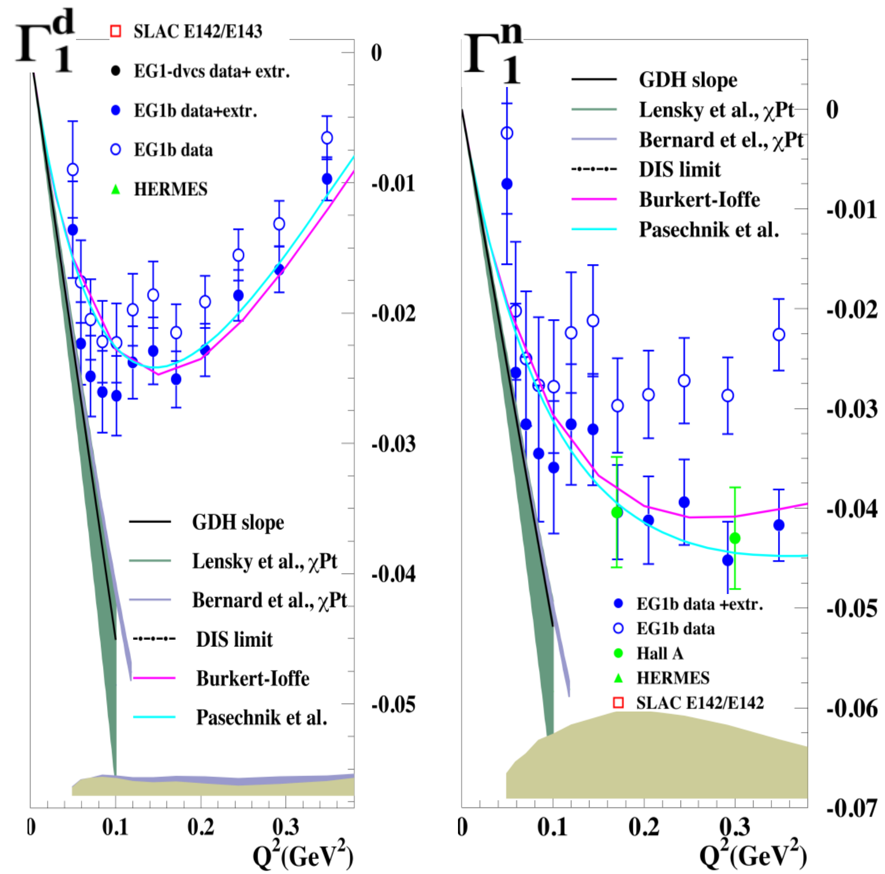
At low Q^2 observed a negative slope as expected from GDH Sum Rule.

Agreement with χPT at the lowest points.



Proton results from R. Fersch

Deuteron & neutron results from N. Guler



Deuteron analysis was repeated with full data set and more extended results were obtained for the Γ_1 at low to moderate Q2 region.

EG1: γ_0 from p,d, & n

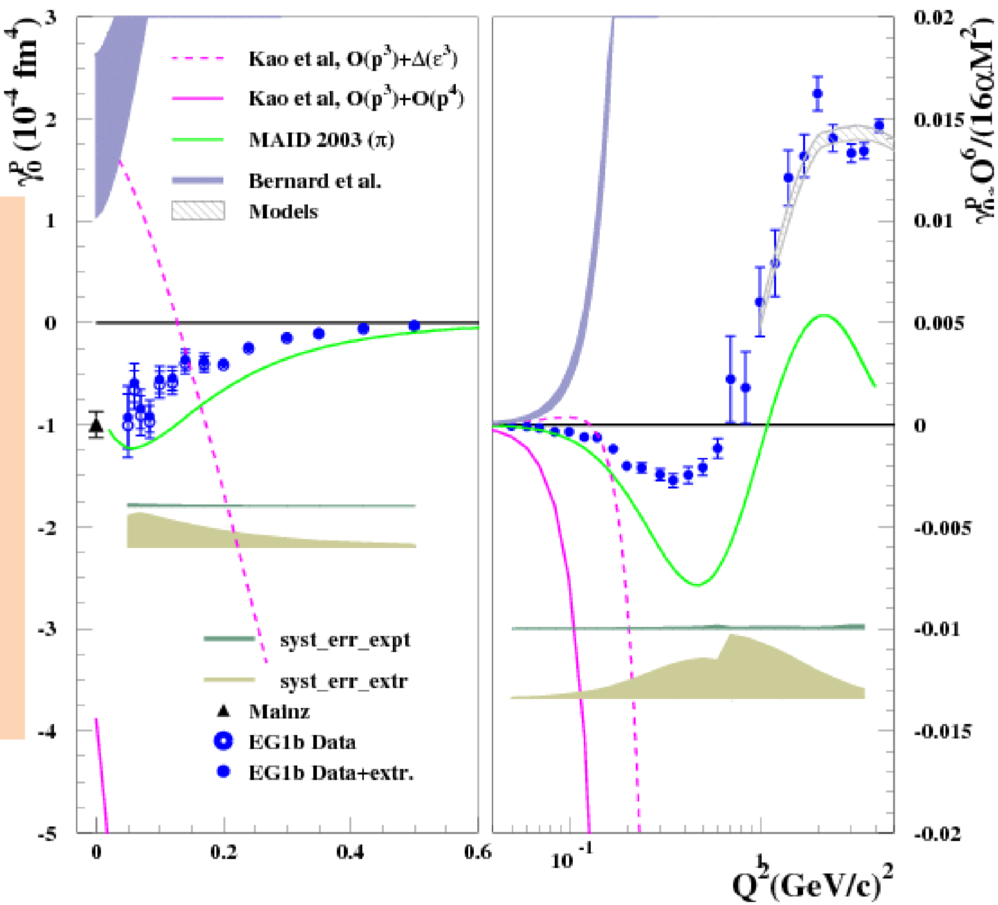
$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} A_1 F_1 x^2 dx$$

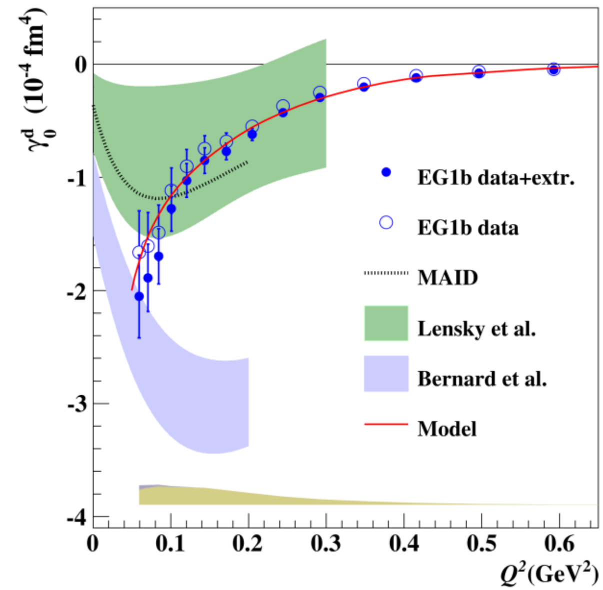
F_1 obtained from from fit to world data

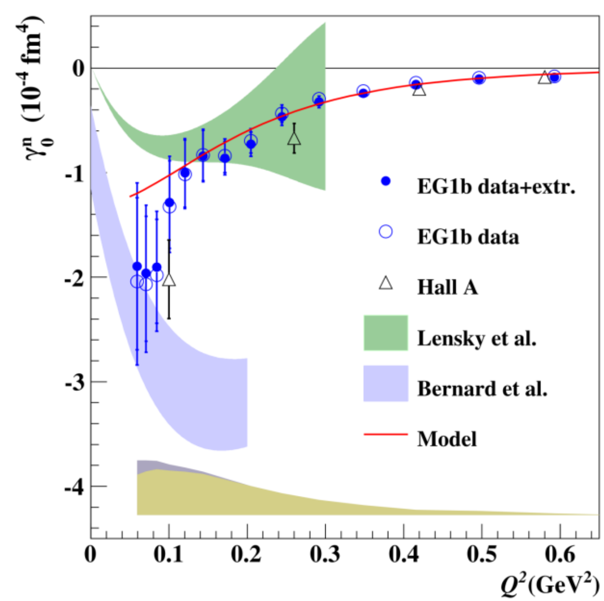
Discrepancy with MAID - mainly due to parametrizations of F_1.

No agreement with χPT, even at Q^2 = 0.05 GeV^2

Observed some evidence of expected Q^6 scaling at $Q^2 \approx 1.5$ GeV^2







Hall B CLAS Experiment: EG4

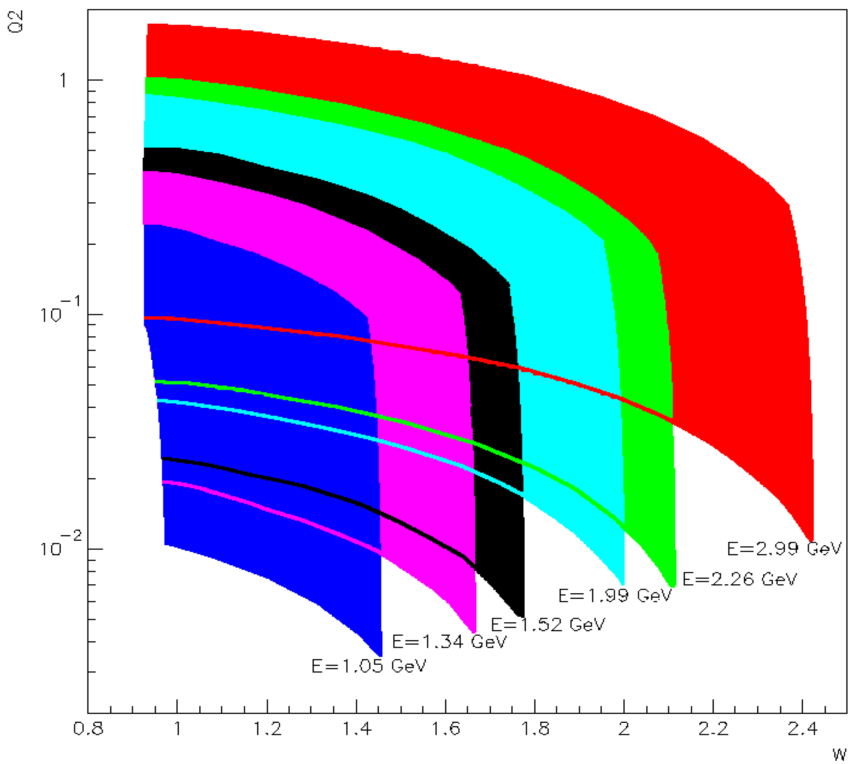
"EG4":

- Similar conditions to **EG1**
- Kinematical coverage extended down to $Q^2 = 0.015$ GeV^2 using
  - lower beam energies -1.0, 1.3, 2.0, 2.3, 3.0 GeVs
  - electron outbending CLAS configuration
  - a new Cerenkov detector.
- Measurement of g_1 at low Q^2
- Test of χPT as Q^2 0
- Measured Absolute XS differences
- Goal : **Extended GDH Sum Rule**
  Proton
  Deuteron
- Ran in 2006

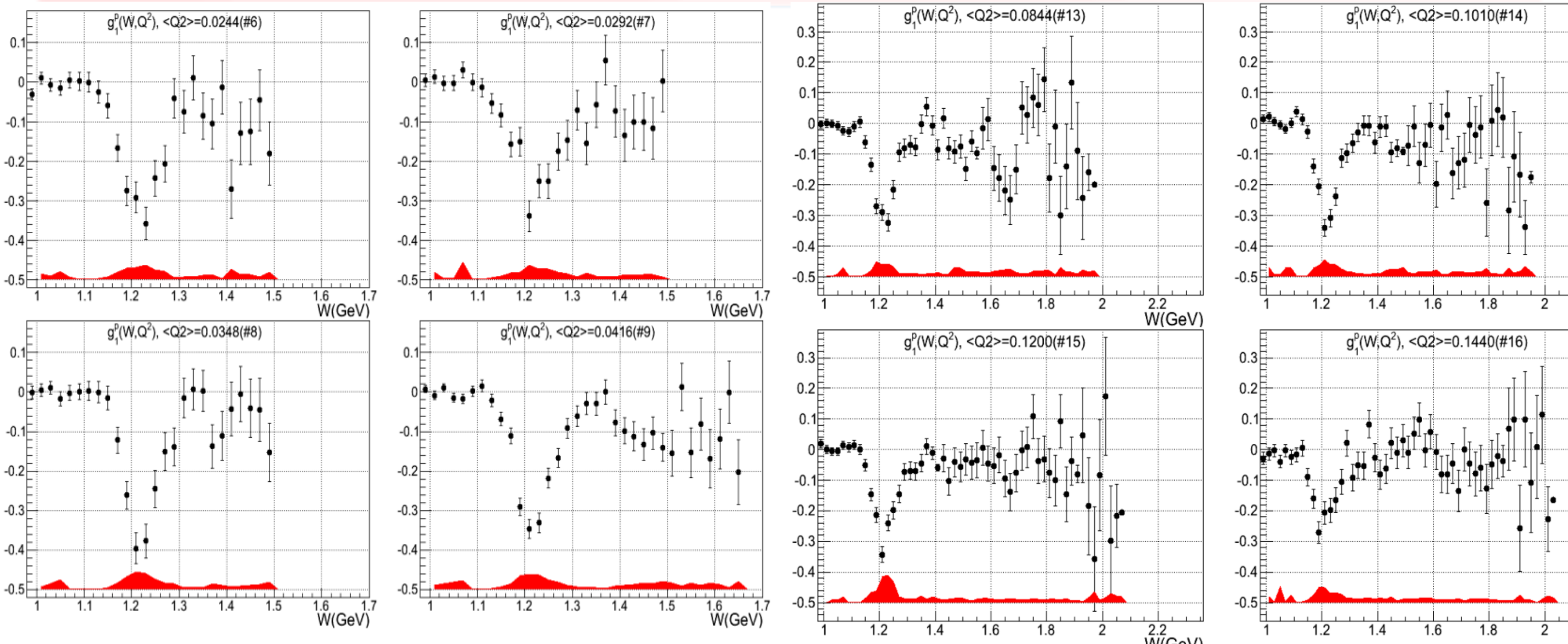
Spokespersons:

NH_3: M. Battaglieri, A. Deur, R. De Vita, M. Ripani

ND_3: A. Deur, G. Dodge, K. Slifer



EG4 – Proton g_1 Results



Red bands are total systematic uncertainties.

Preliminary

Plots courtesy of
H. Kang

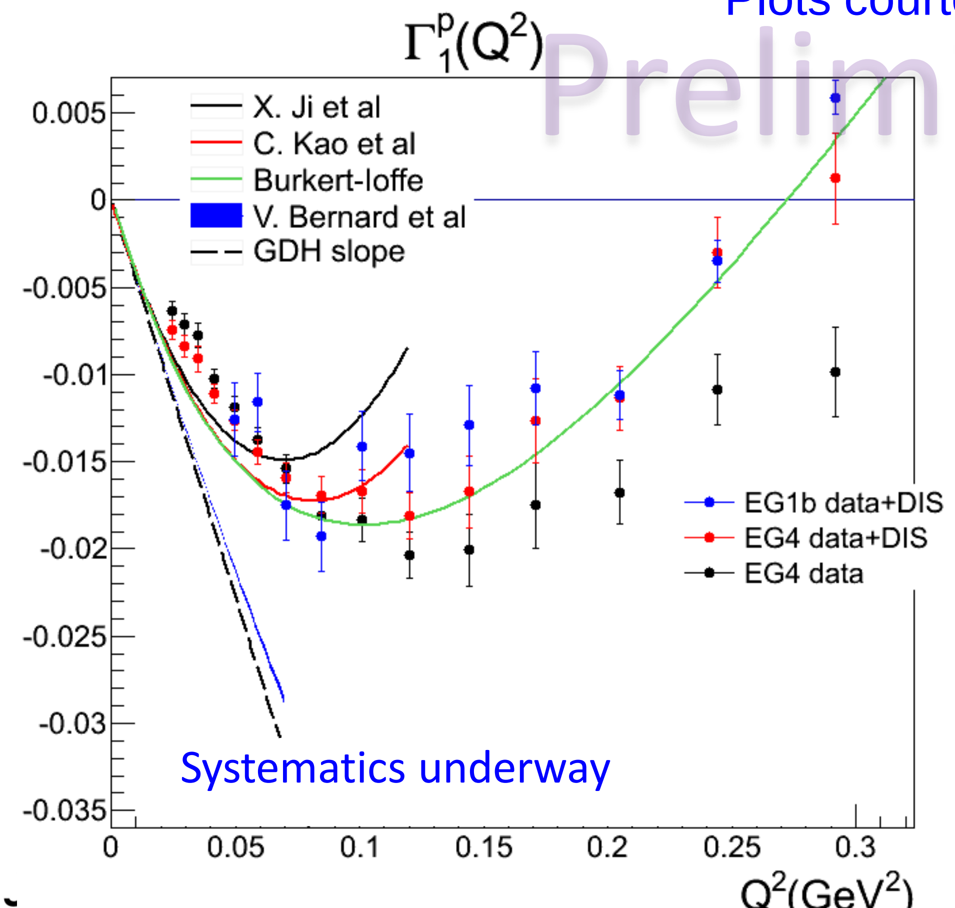
EG4 Proton Results: **First moment**

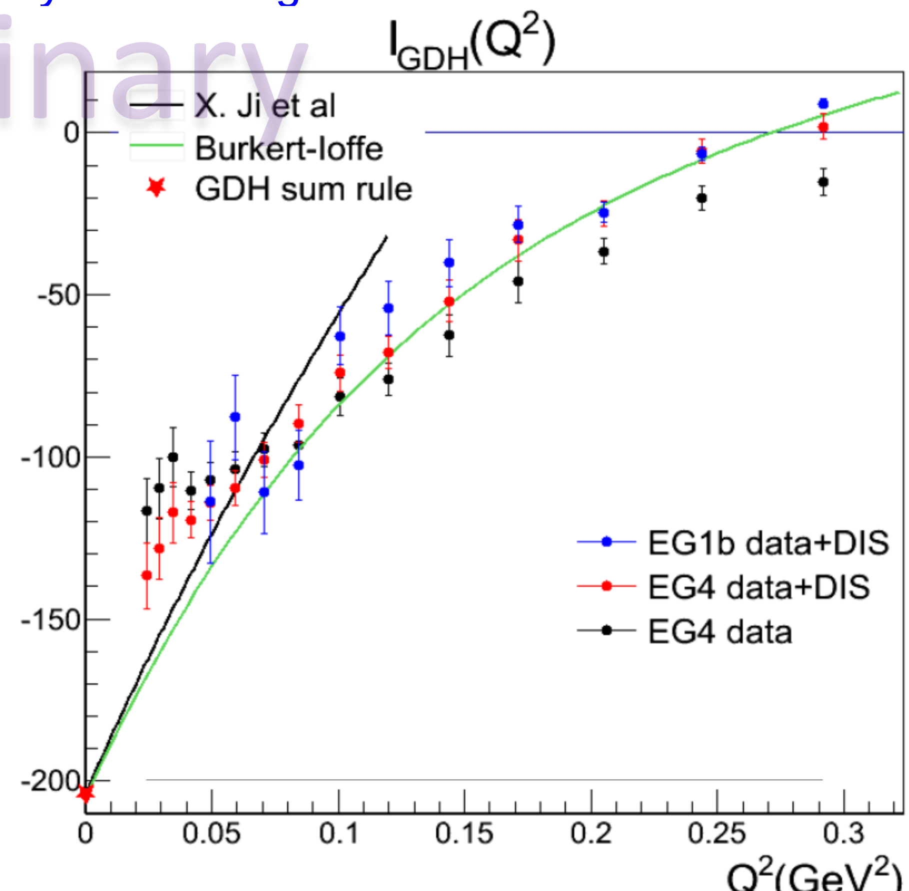
$$\bar{\Gamma}_1 = \int_0^{x_{th}} g_1\left(x, Q^2\right) dx$$

$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_{th}}\left(g_1 - \frac{2M^2x^2}{Q^2}g_2\right)dx \underset{(Q^2 \to 0)}{\Longrightarrow} -\frac{\kappa^2}{4}$$

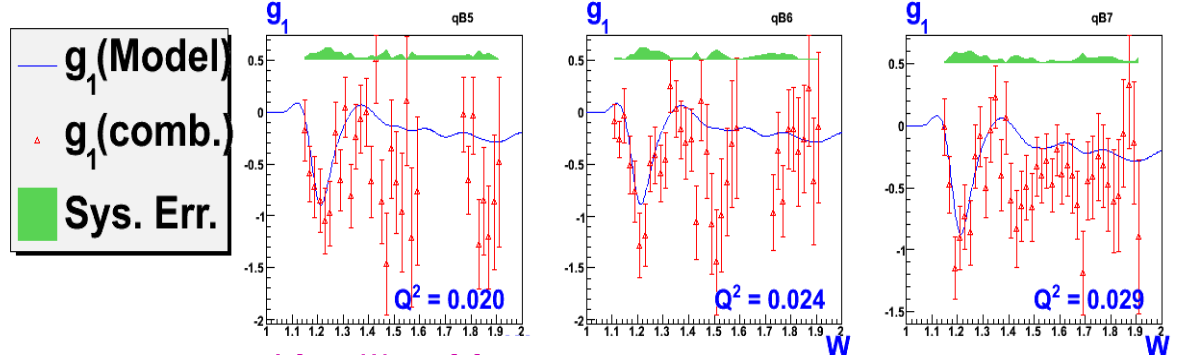
GDH

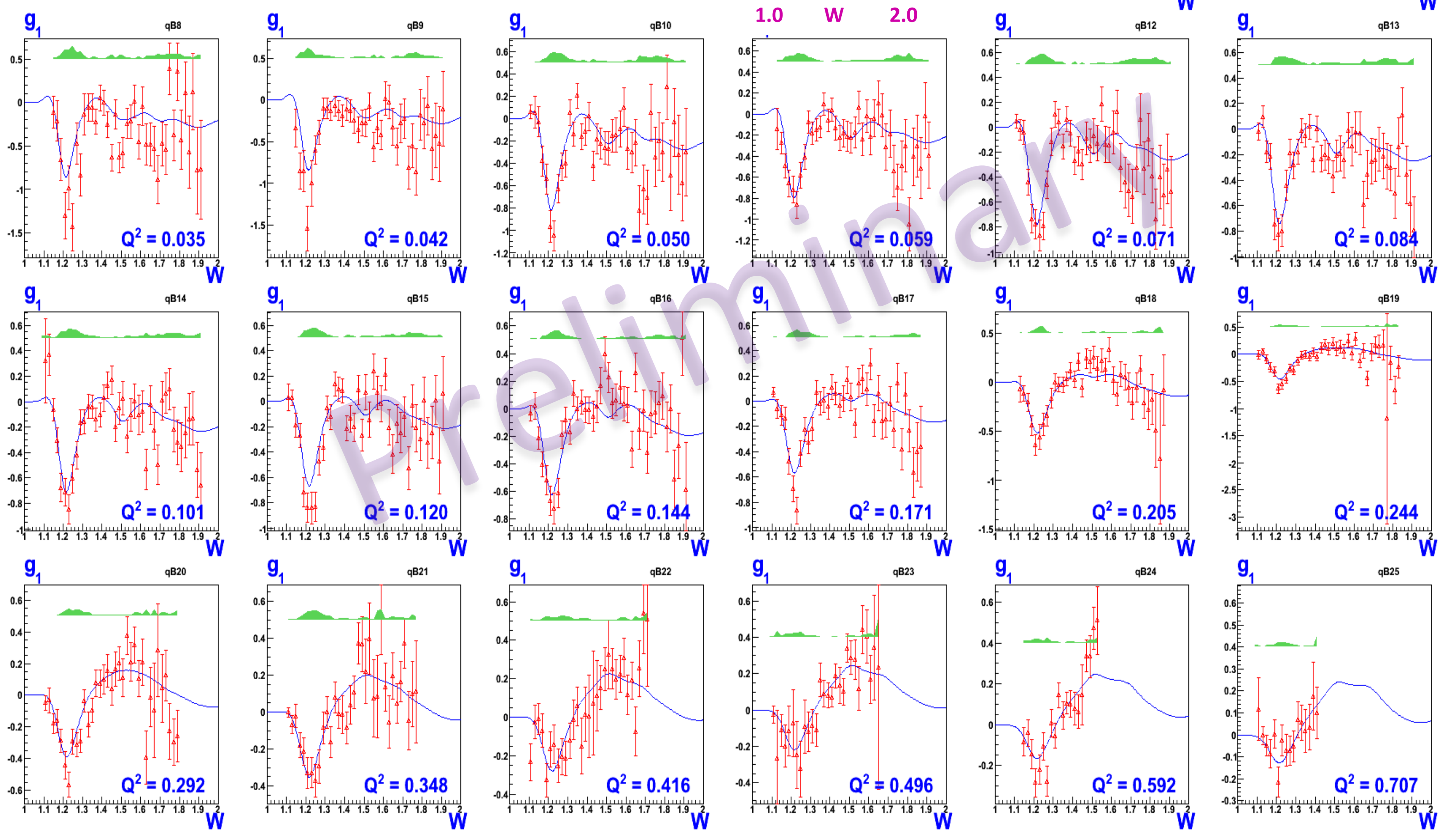
Plots courtesy of H. Kang





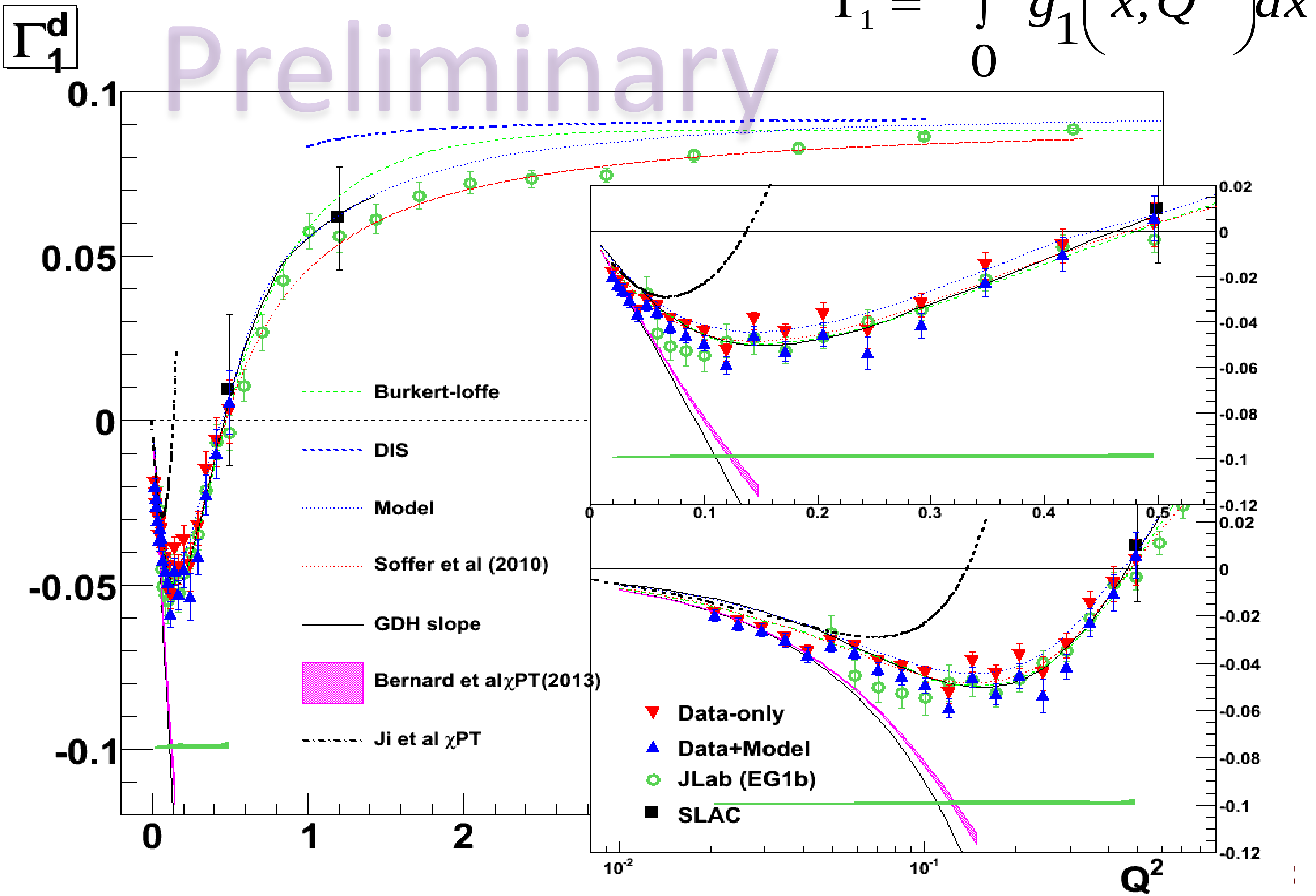
EG4 Results: Extracted g_1 (Deuteron)





Results: First Moment

$$\overline{\Gamma}_1 = \int_0^{x_{th}} g_1\left(x, Q^2\right) dx$$



Results: Generalized GDH integral (I_{TT}) & Generalized Forward Spin polarizability (γ_0)

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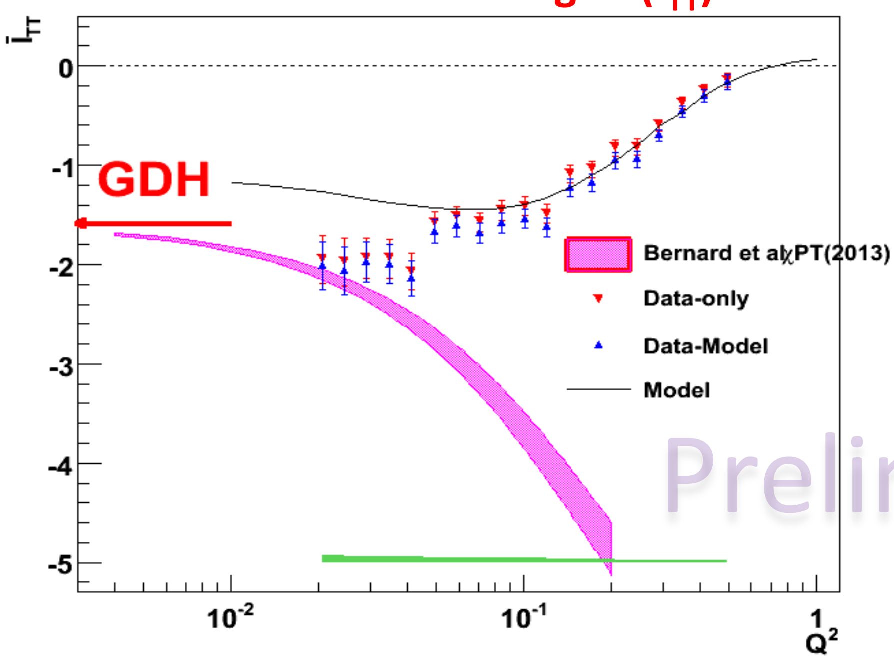
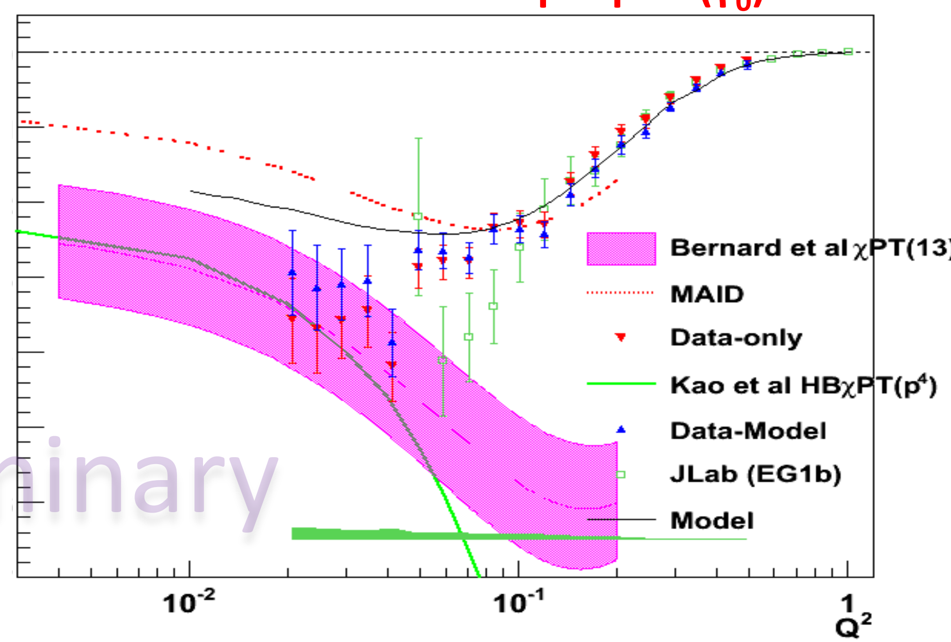
$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_{th}}\left(g_1 - \frac{2M^2x^2}{Q^2}g_2\right)dx \xrightarrow{(Q^2 \to 0)} \underbrace{-\frac{\kappa^2}{4}}_{\text{GDH}}$$

$$\gamma_0 = (16\alpha M^2/Q^6)\int_0^{x_{th}}\left(g_1 - \frac{2M^2x^2}{Q^2}g_2\right)x^2dx$$

Generalized GDH integral (I_{TT})

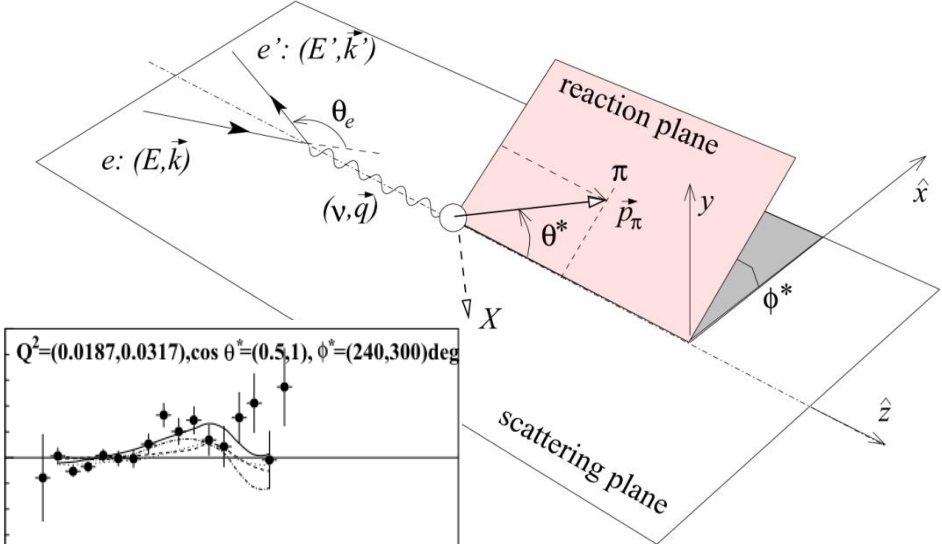


Generalized forward spin pol. (γ_0)

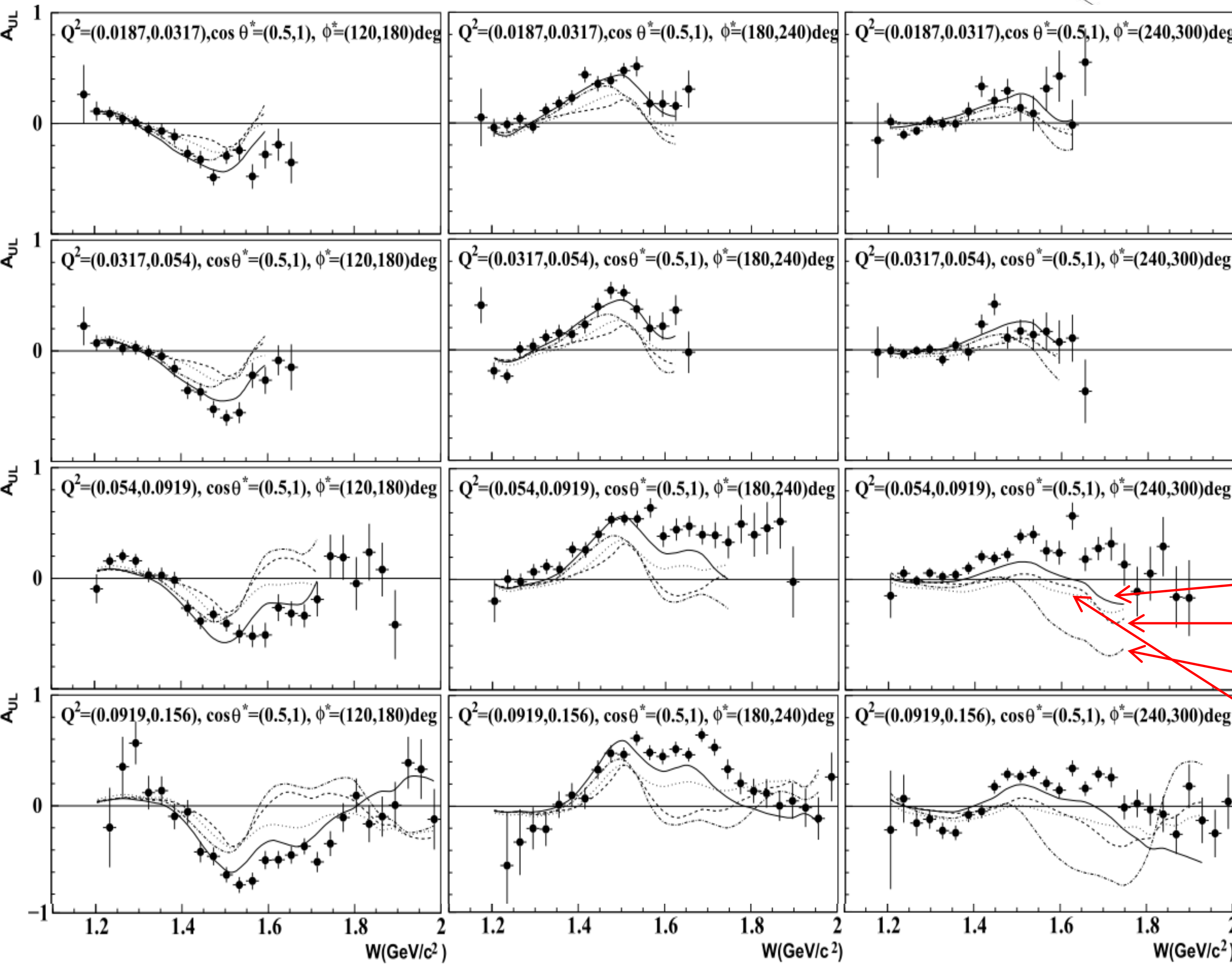


Preliminary

EG4: Spin Asymmetry A_{UL} Results on $p(e,e'\pi^+)n$



Plots courtesy of Xiaochao Zheng



The target spin asymmetries A_{UL} for the π^+n channel

Models:
JANR (solid),
MAID2007 (dashed),
SAID (dash-dotted),
DMT2001 (dotted)

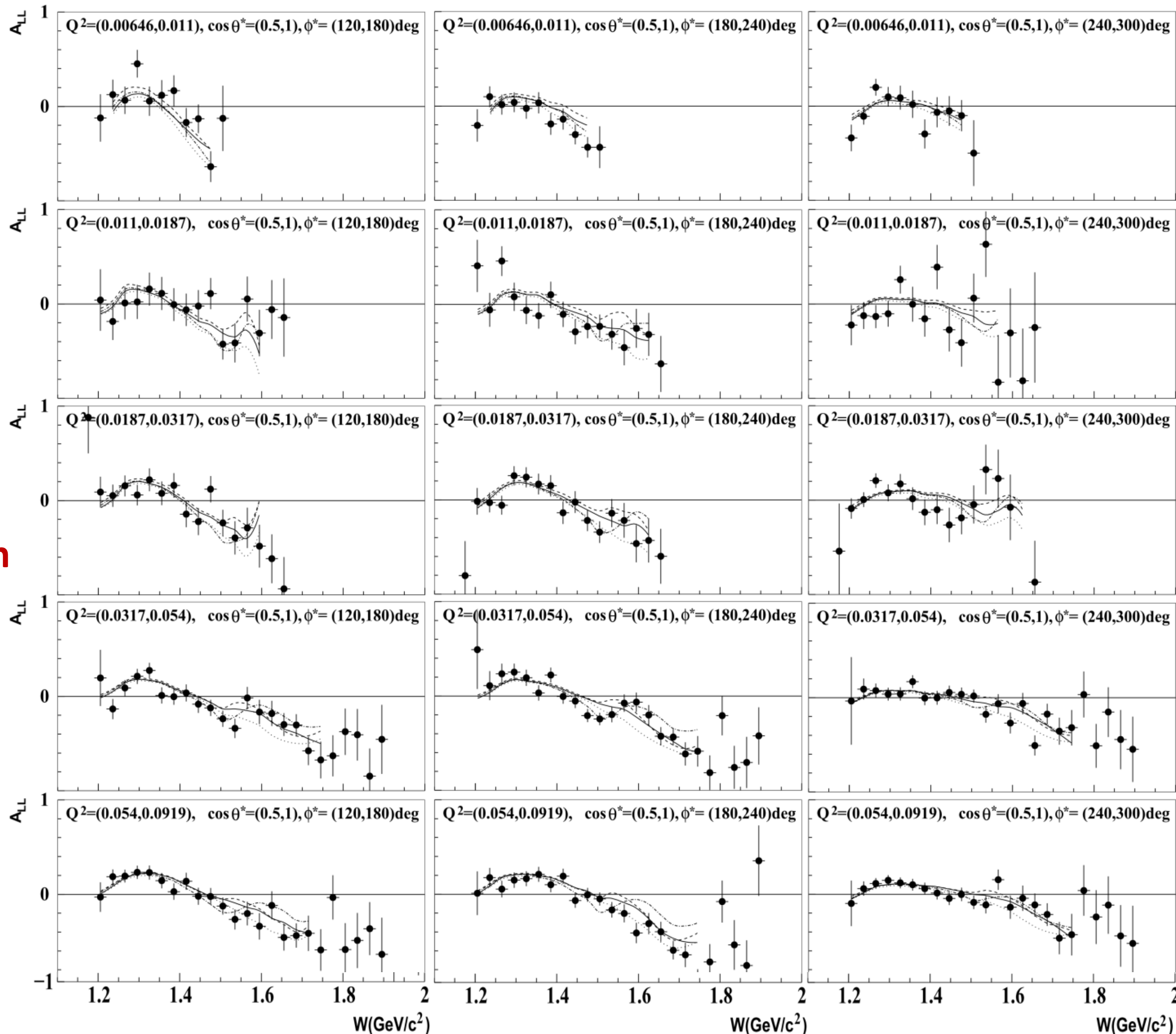
MISSISSIPPI STATE UNIVERSITY

EG4: Spin Asymmetry A_{LL} Results on $p(e,e'\pi^+)n$

Plots courtesy of Xiaochao Zheng

Results on the double-spin symmetries A_{LL} for π^+n channel in different Q^2 bins

The paper **Measurement of Target and Double-spin Asymmetries for ep-> $e\pi^+(n)$ Reaction in the Nucleon Resonance Region at Low Q^2** nearly ready for publication.



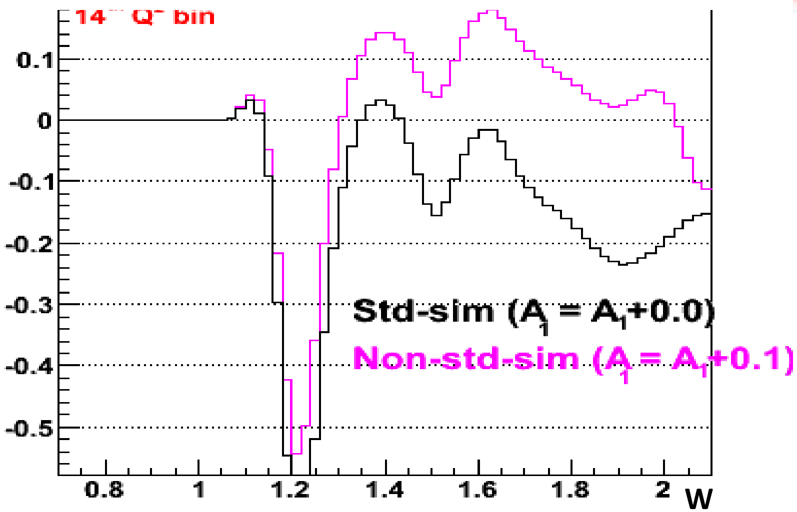
Summary

- A wealth of new low Q^2 data on the nucleon spin structure in the non-perturbative regime has been produced in Hall A, and B at Jefferson Lab as part of a broad spin physics program
- Nucleon polarizability γ_0 is a more stringent test of χPT than Γ_1. χPT converge very slowly for the spin polarizabilites.
- Low Q^2 analysis of EG4 data from Hall B and g2p data from Hall A are in the final stages.
- At very low Q^2 the EG4 results show good agreement with other Jlab results and with available χPT predictions.
- Neutron data extraction from EG4's deuteron and proton data is expected in near future.
- Ongoing 6 GeV data analyses and the future 12 GeV JLab measurements at low Q^2 are expected to shed more light on the nucleon spin structure in the non-perturbative region.

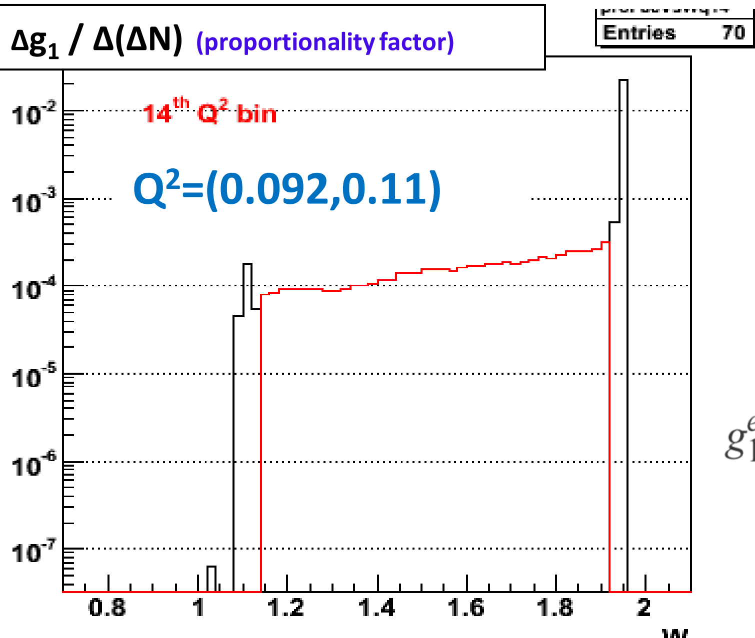
Thank you!

Method for g_1 calculation

Model g_1 in Q^2=(0.092,0.11)

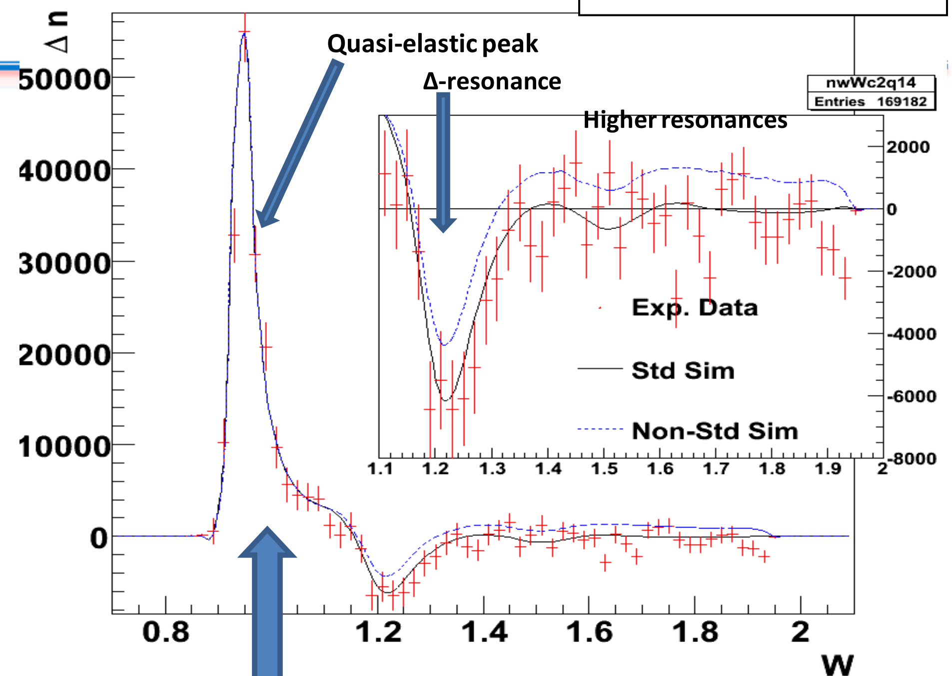


$\Delta g_1 / \Delta(\Delta N)$ (proportionality factor)



$\Delta N = (N^+ - N^-)$

Q^2=(0.092,0.11)

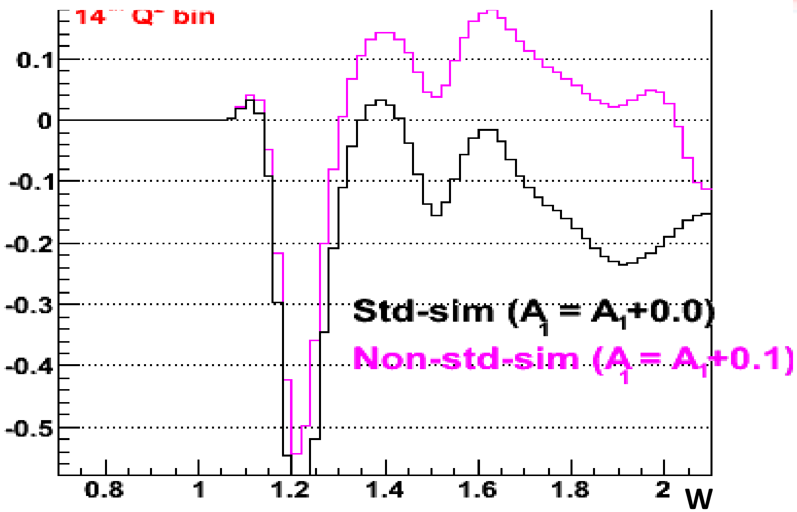


First, simulated data was normalized w.r.t data by comparing in q.e. region.

$$g_1^{extr}(W,Q^2) = g_1^{Standard} + \frac{\Delta n^{data}(W,Q^2) - \Delta n^{standard}(W,Q^2)}{B(W,Q^2)}$$

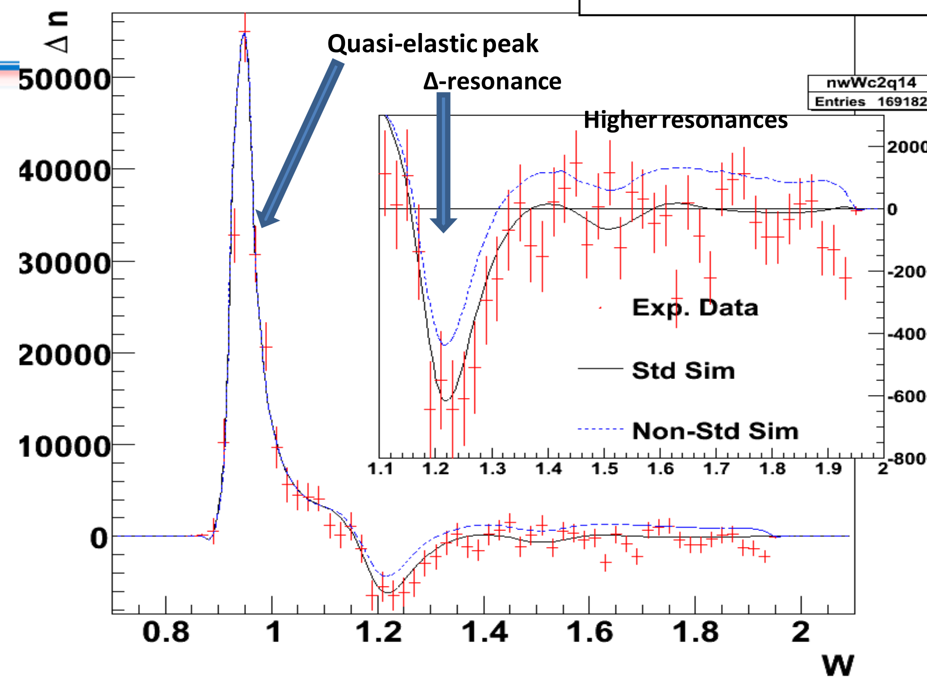
Method for g_1 calculation

Model g_1 in Q^2=(0.092,0.11)

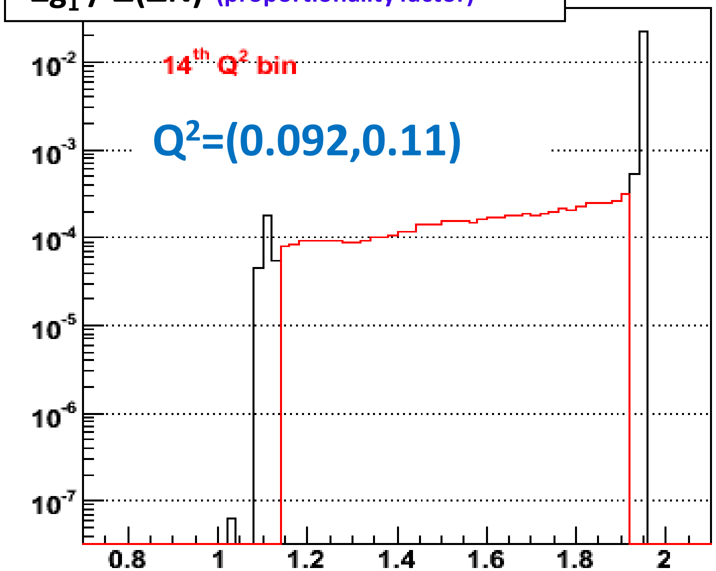


$\Delta N = (N^+ - N^-)$

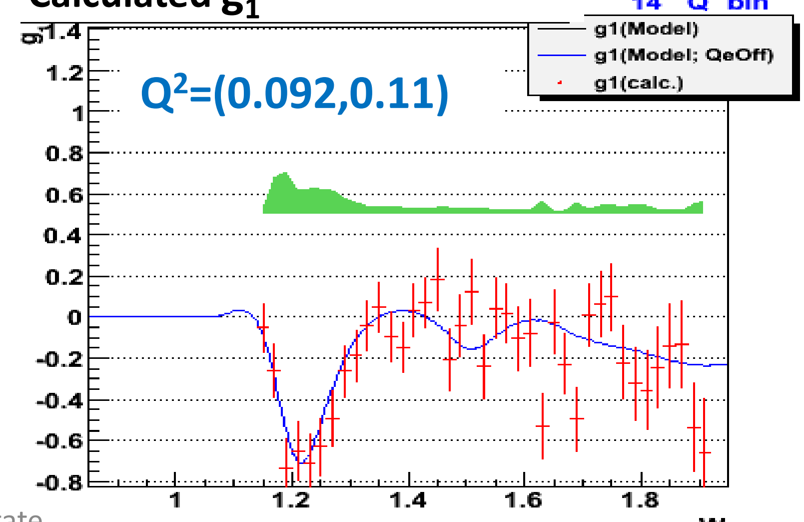
Q^2=(0.092,0.11)



$\Delta g_1 / \Delta(\Delta N)$ (proportionality factor)



Calculated g_1



Sources of Systematic errors

1) **Overall scaling factor** (Mostly due to PbPt, Target length)
2) **Radiative corrections**
3) **Model Uncertainties**
4) Contaminations of polarized H in the target and π^- in the scattered electrons.
5) Beam energy measurement
6) CC-efficiency estimation
7) e^+e^- pair symmetric contamination

Estimation of Systematic errors

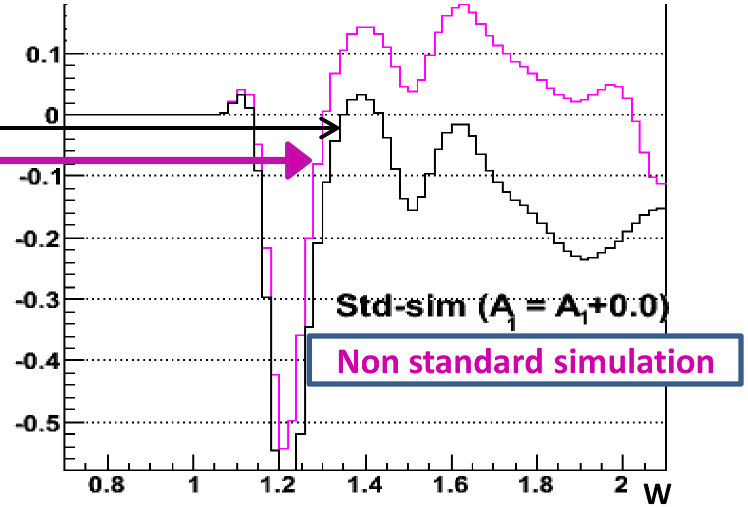
One Example:

Model Uncertainty Contribution

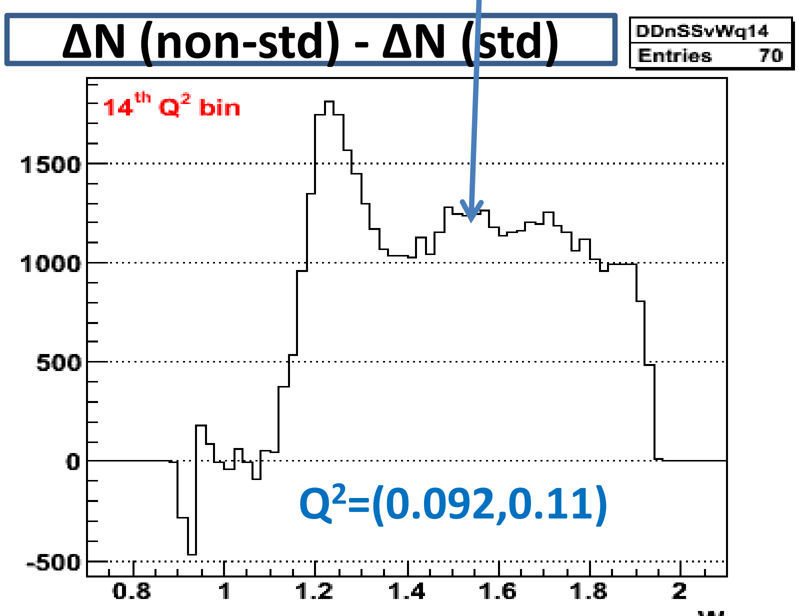
e.g., change $A_1/A_2/F_1/R$ within fit errors

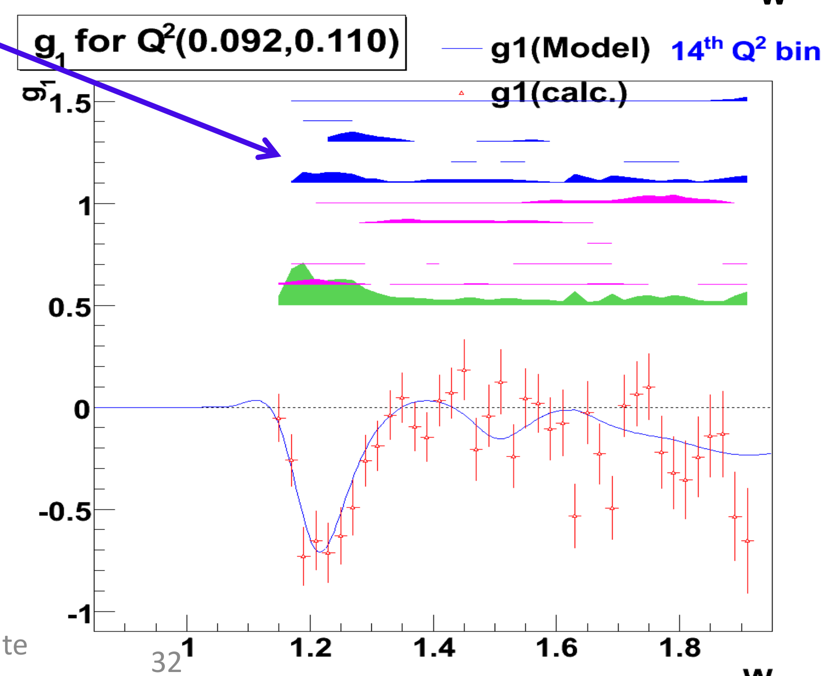
$$\Delta g_1^i(W,Q^2) = g_1^{standard} + \frac{\Delta n^i - \Delta n^{standard}}{B(W,Q^2)} - g_1^i$$

Model g_1 in Q^2=(0.092,0.11)

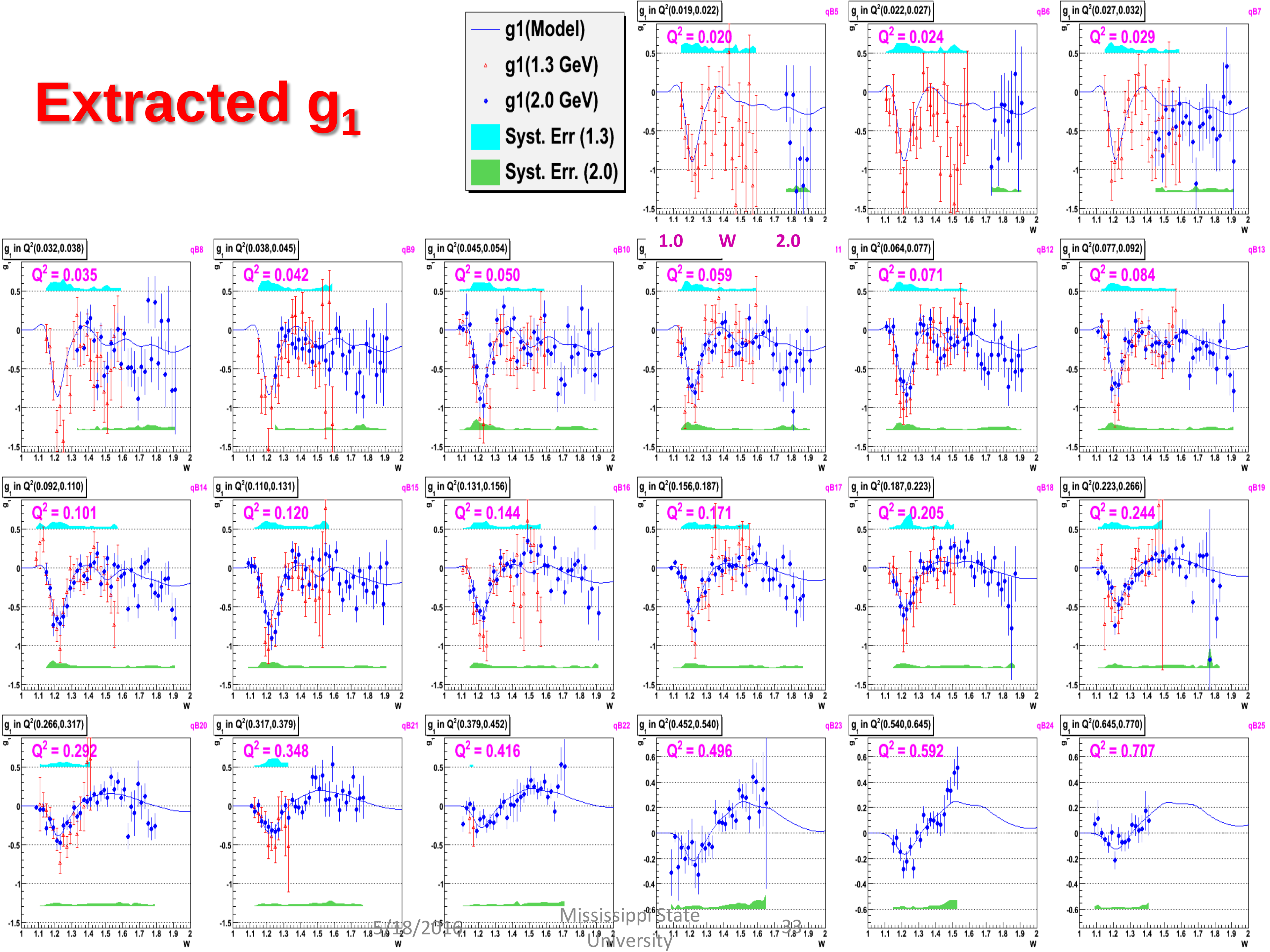


ΔN (non-std) - ΔN (std)





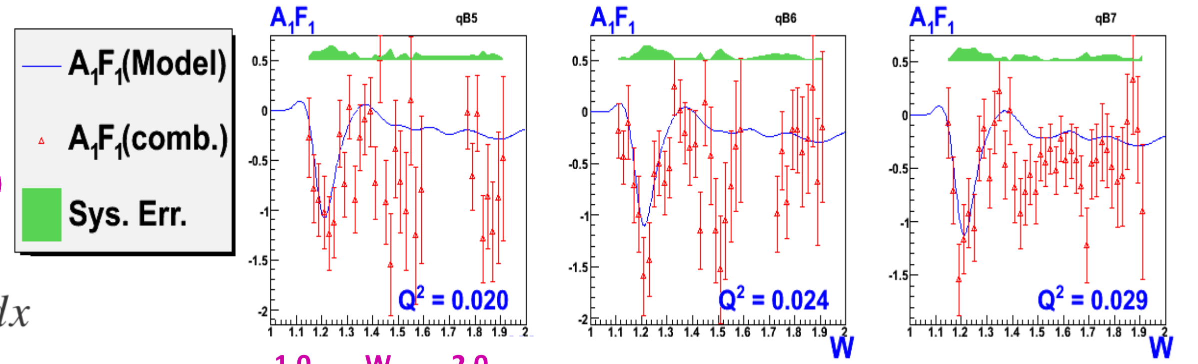
Extracted g_1

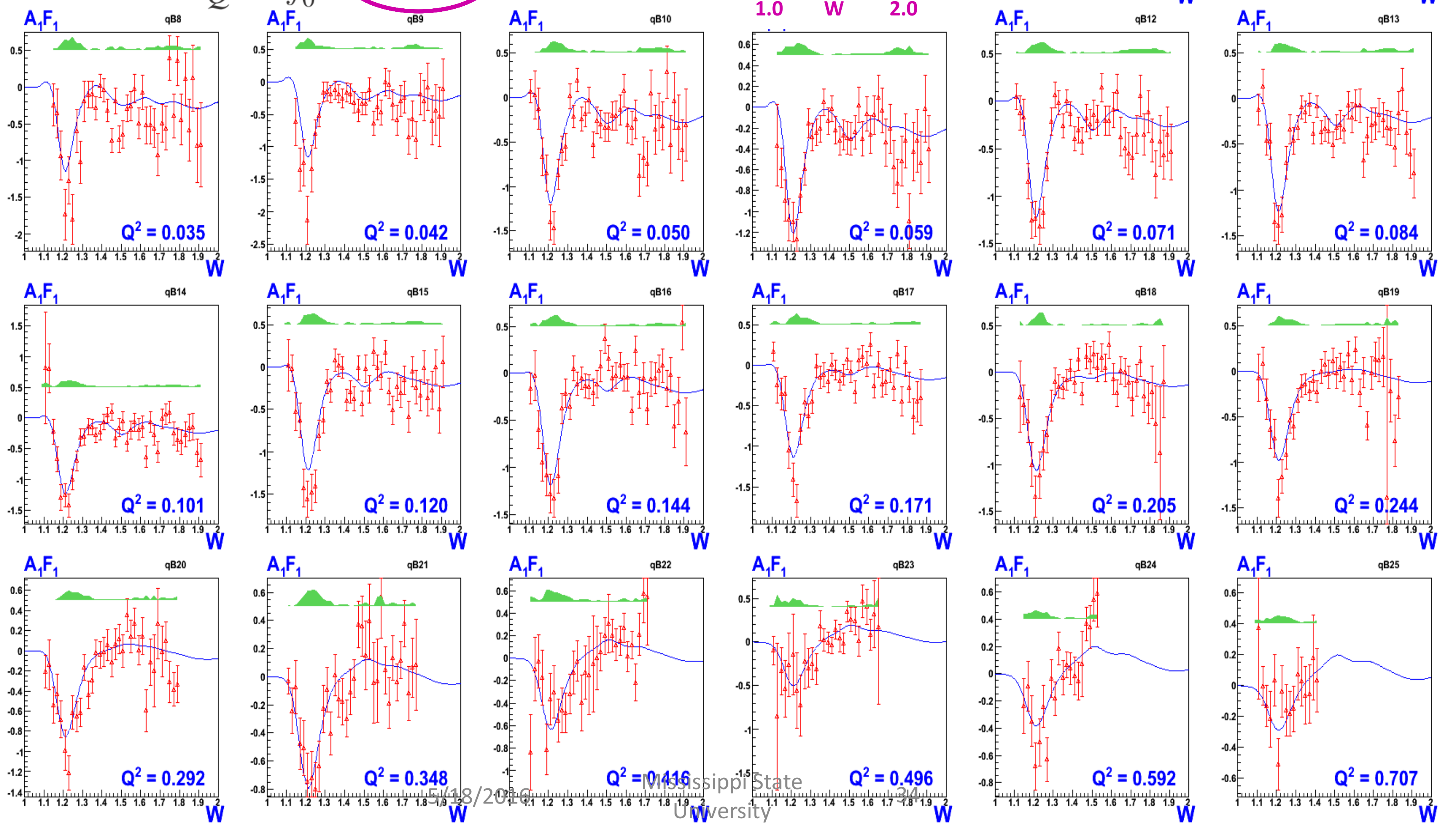


$A_1F_1 = g_1 - (4M^2x^2/Q^2)g_2$

$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_0(Q^2)} dx\, A_1F_1(x,Q^2)$$

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} A_1F_1(x,Q^2)\,x^2\,dx$$

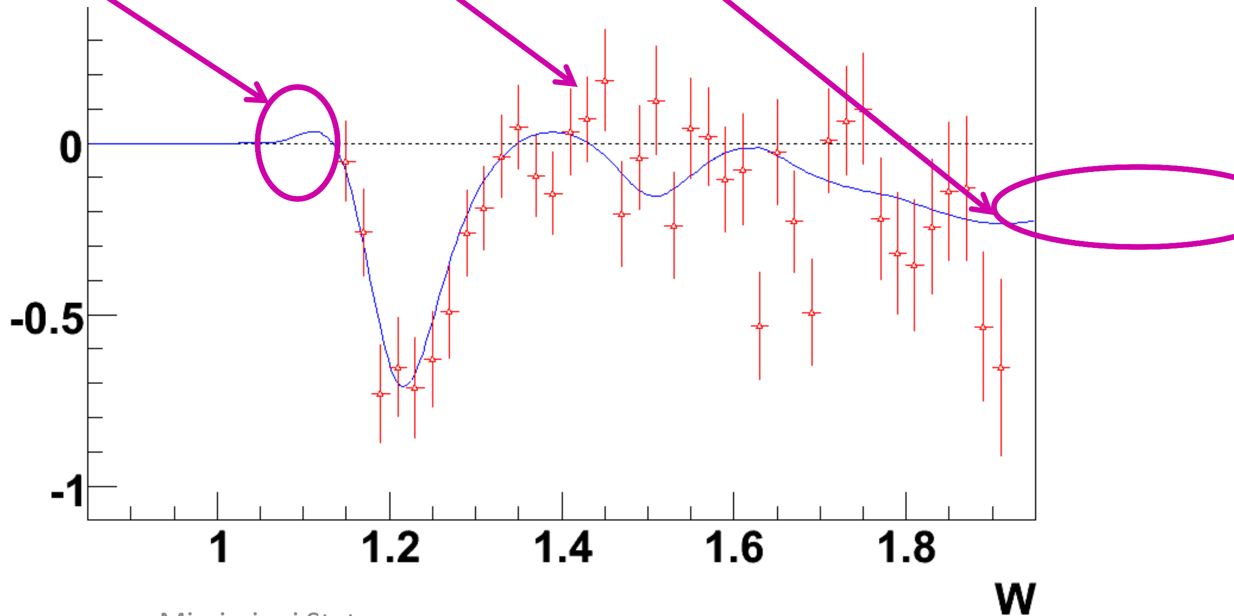




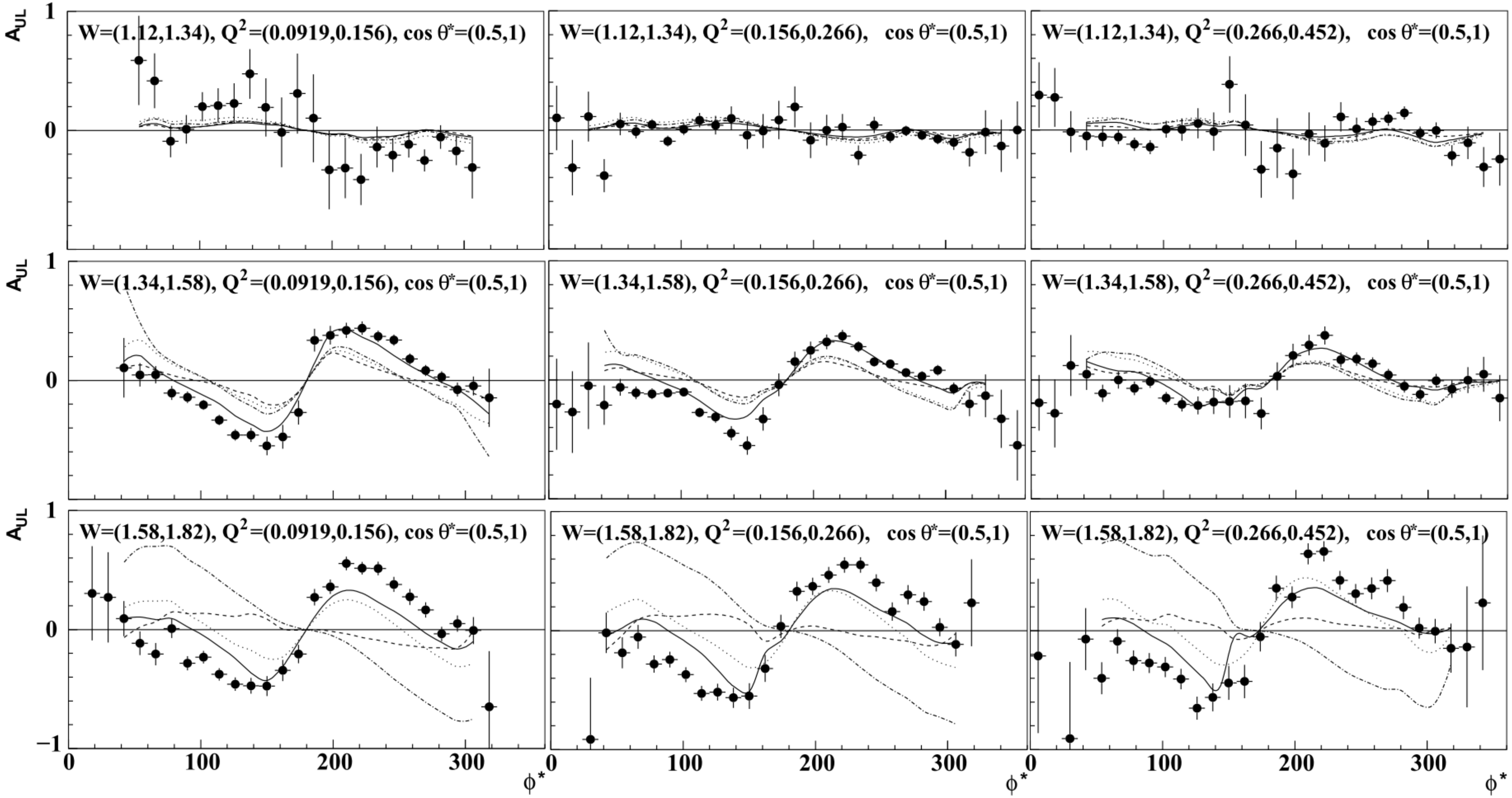
Calculation of Integrals

$$\begin{aligned}
\Gamma_1(Q^2) &= \int_{x=0.001}^{x(W_{data})} g_1(x,Q^2)dx && \text{model} \\
&+ \int_{x(W_{data})}^{W=1.15} g_1(x,Q^2)dx && \text{data (or model for gaps)} \\
&+ \int_{W=1.15}^{W=1.08} g_1(x,Q^2)dx && \text{model}
\end{aligned}$$

$$x = \frac{Q^2}{Q^2 + W^2 - M^2}$$



EG4: Spin Asymmetry A_{UL} Results on $p(e,e'\pi^+)n$

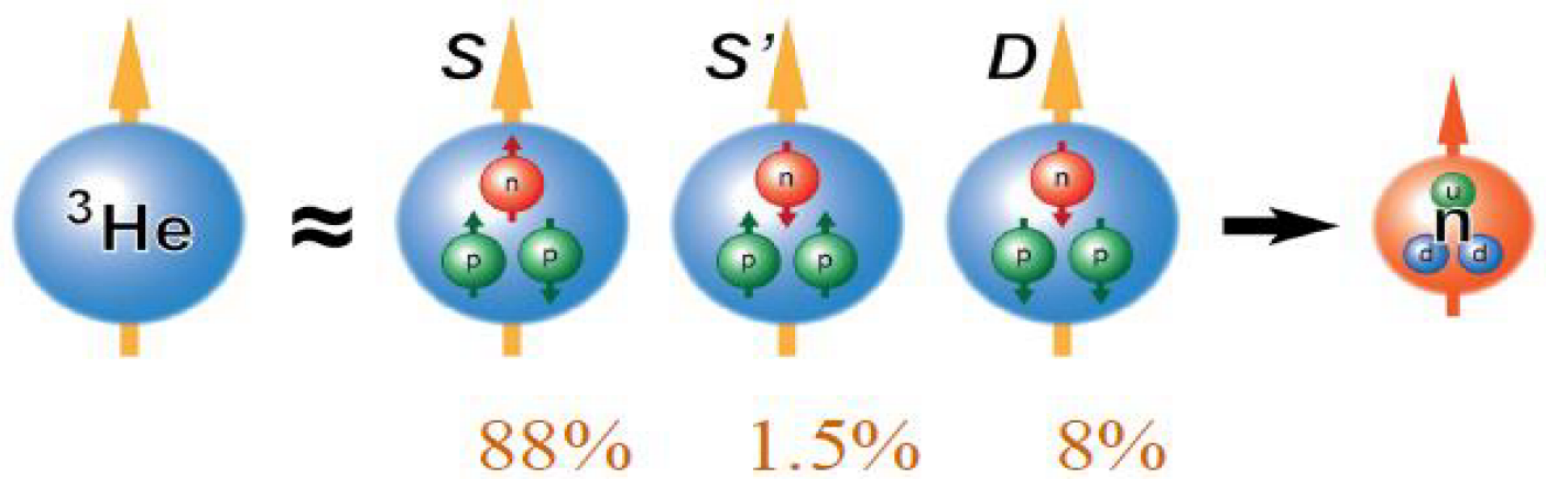


Target spin asymmetries A_{UL} for the π^+n channel as a function of the invariant mass φ^*

Plots courtesy of Xiaochao Zheng

Neutron Target

- Neutron mean lifetime is just under 15 mins.
- ^{3}He nucleus has two protons whose spins are paired, and a single neutron that accounts for most of the nuclear spin.
- So, ^{3}He is an effective polarized neutron target.



F. R. P. Bissey, A. W. Thomas, and I. R. Afnan, Phys. Rev. C64, 024004 (2001)