



NEW EXPERIMENTAL RESULTS ON ELECTROMAGNETIC FORM FACTORS, POLARIZABILITIES AND SPIN STRUCTURE FUNCTIONS

**Nucleon Spin Structure at Low Q: A Hyperfine View
ECT* July 2-6 2018**

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OLD DOMINION UNIVERSITY (NORFOLK, VA)

OVERVIEW

History and Introduction

Form factor experiments

Compton scattering and polarizabilities

Spin structure at low resolution scales

Outlook

Resonance
Structure

PDFs

Hyperfine
Structure

Duality
OPE, twist > 2

Δq ΔG
 $x \rightarrow 1$

Sum
Rules

Chiral Perturbation Theory

lattice

GDH
 $\alpha E^1, \beta M^1$
 $\gamma^0, \delta L^1$

R_p, R_z, \dots

$\Delta \Sigma$

(P)V)CS

LOW-Q NUCLEON SPIN STRUCTURE - A SHORT TRIP DOWN HISTORY LANE

Zeeman, P. Over den invloed eener magnetisatie op den aard van het door een stof uitgezonden licht. *Versl. Kon. Akad. Wetensch. Amsterdam* **5**, 181–184, 242–248 (1896)

- Late 1800's: First sightings of Spin
- 1922-1926: Spin established
- 1927-33: Proton spin and anomalous magnetic moment

Gerlach, W. & Stern, O.: Der experimentelle Nachweis der Richtungsquantelung im Magnetfeld. *Z. Phys.* **9**, 349–352 (1922)
 Pauli, W.: Über den Einfluß der Geschwindigkeitsabhängigkeit der Elektronenmasse auf den Zeemaneffekt. *Z. Phys.* **31**, 373–385 (1925)
 Uhlenbeck, G. E. & Goudsmit, S. A. Ersetzung der Hypothese vom unmechanischen Zwang durch eine Forderung bezüglich des inneren Verhaltens jedes einzelnen Elektrons. *Naturwiss.* **13**, 953–954 (1925)

Nuclear Spin and Hyperfine Structure

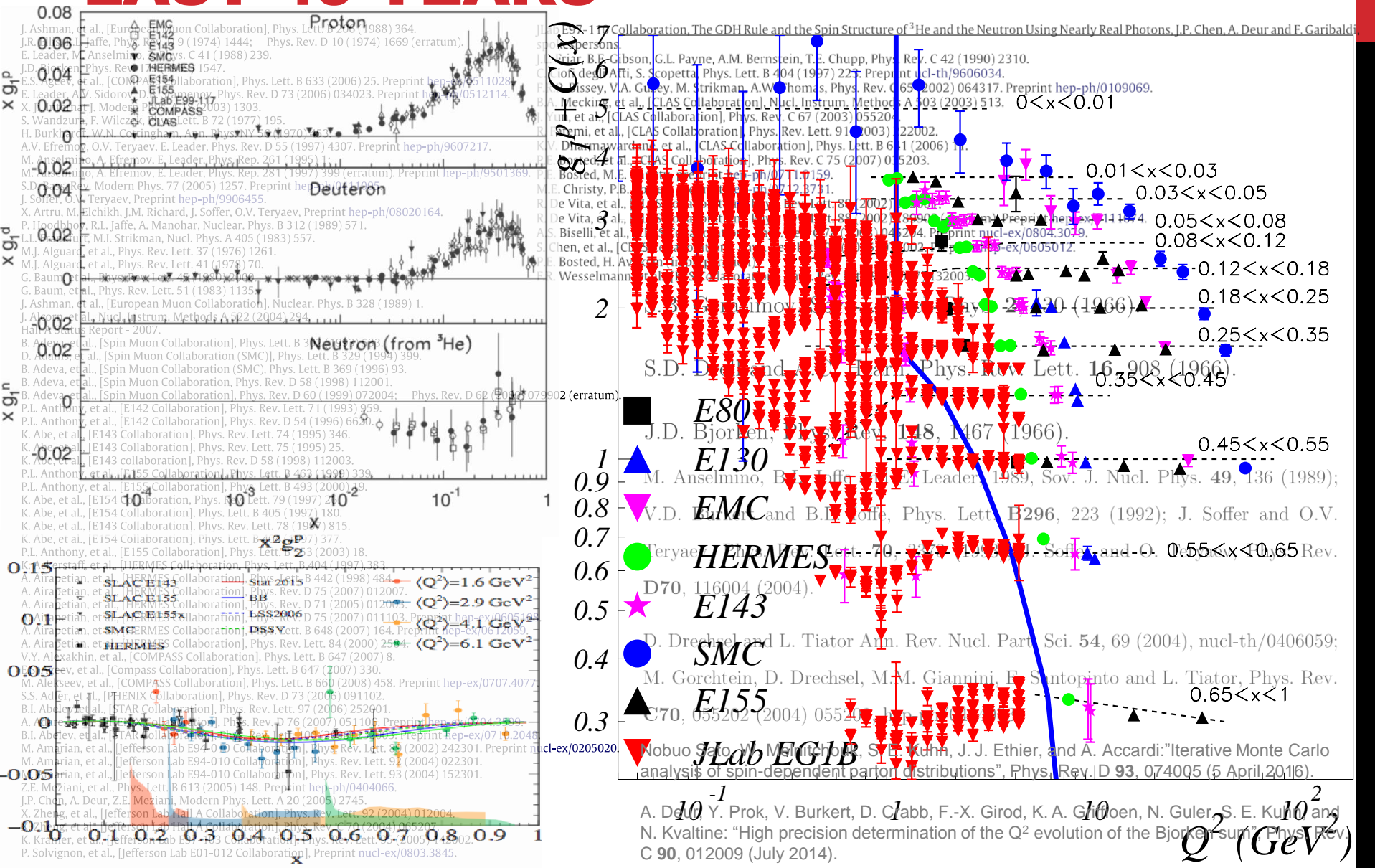
H. E. White
 Phys. Rev. **35**, 441 – Published 1 March 1930

History

The unusual heat capacity of hydrogen was discovered. Forms of molecular hydrogen were first proposed by Paul Harteck and Karl Friedrich Bonhoeffer in 1929. The Nobel prize in physics for the creation of quantum mechanics. The "ortho" and "para" forms of hydrogen" was singled out as its most noteworthy. Pure parahydrogen has since been achieved using rapid cooling. Solid parahydrogen ($p\text{-H}_2$) samples which are notable for



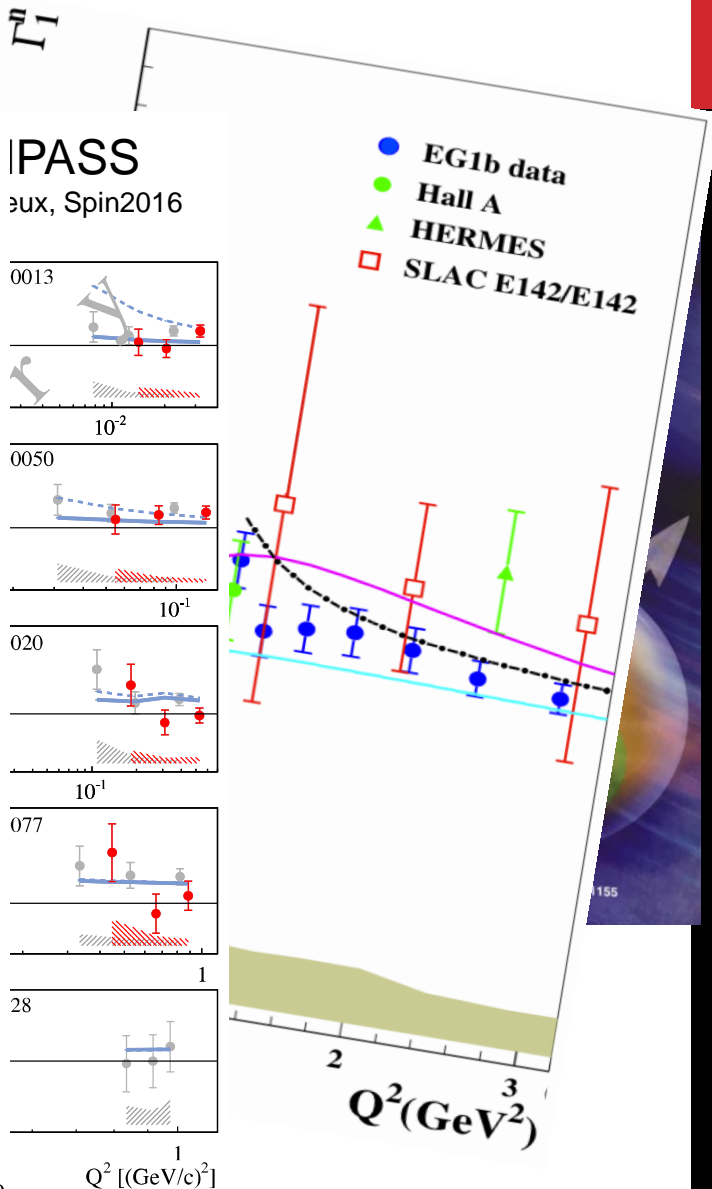
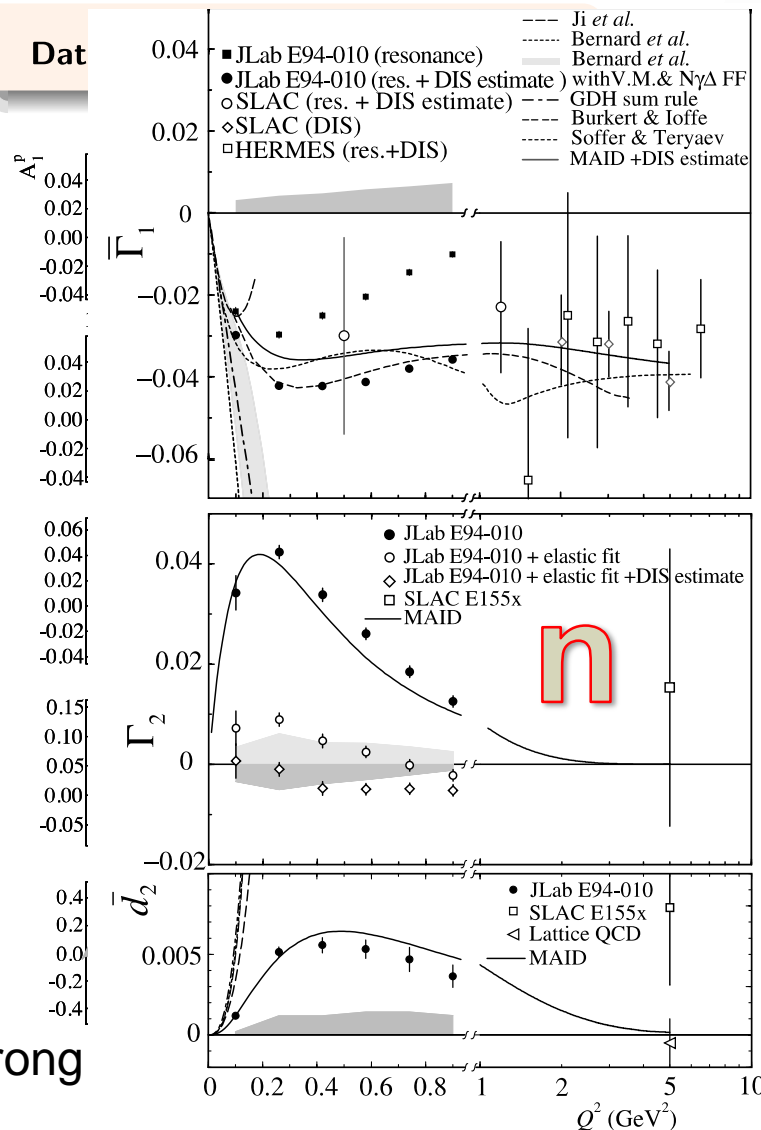
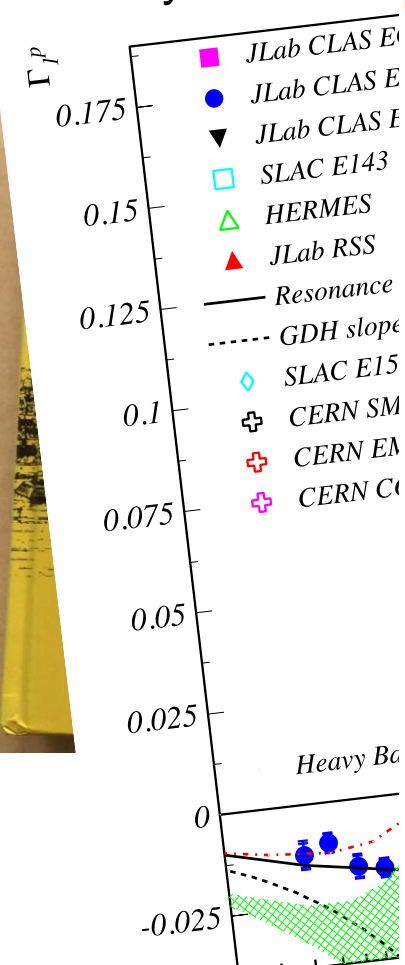
SPIN STRUCTURE IN THE LAST 40 YEARS



RECENT HISTORY ON LOW-Q SPIN STRUCTURE

Many dedicated

Date



... and still going strong

Nucleon Spin Structure at Low Q: **A Hyperfine View** ECT* July 2-6 2018

So we have a plethora of data about nucleon spin structure...

But what is the connection to atomic energy levels ?

ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

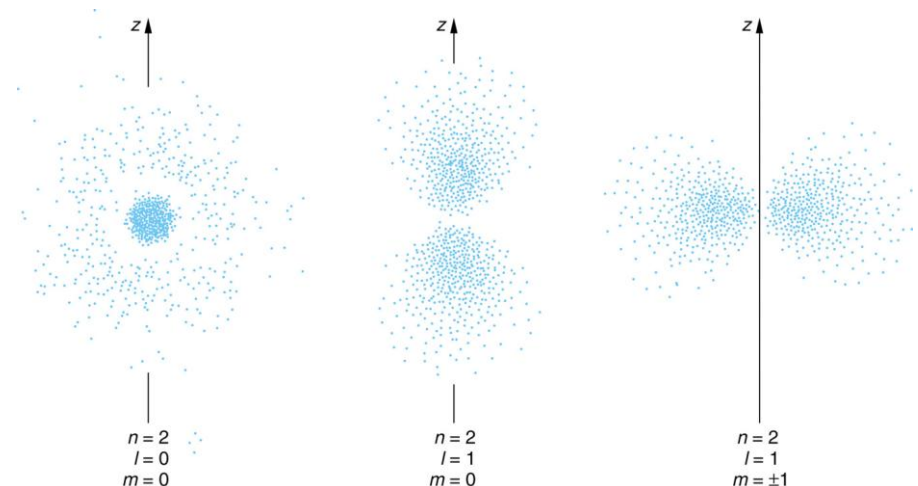
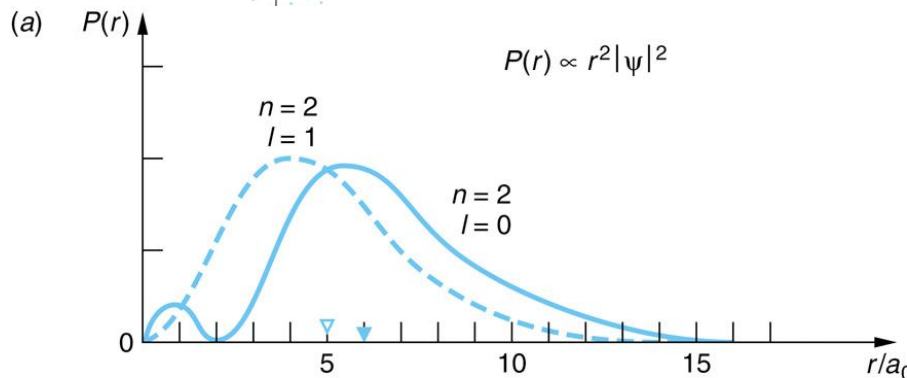
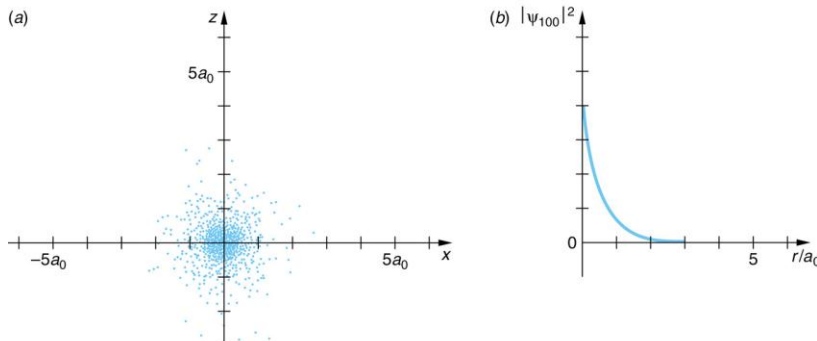
$$Ry = m_e c^2 \alpha^2 / 2 = 13.6 \text{ eV}$$

$$a_0 = \hbar c / (m_e c^2 \alpha) = 53 \text{ pm}$$

1.) Gross Structure: Nuclear Charge \rightarrow Energy levels $E_{nl} = -\frac{m_r}{m_e} \frac{Z^2}{n^2} Ry$

Wave functions: $R_{1,0}(r) = \frac{2}{a^{3/2}} e^{-r/a}$; $R_{2,0}(r) = \frac{2-r/a}{\sqrt{8}a^{3/2}} e^{-r/2a}$; $R_{2,1}(r) = \frac{r/a}{\sqrt{24}a^{3/2}} e^{-r/2a}$

Characteristic radius $a = \frac{m_e}{m_r Z} a_0$



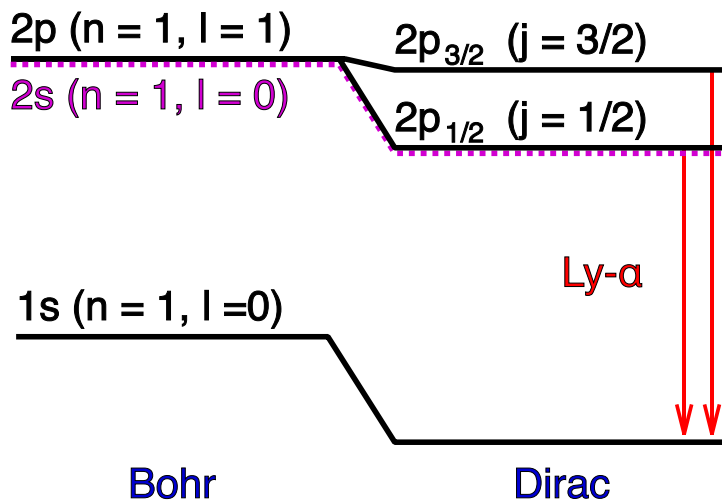
ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

1b.) “Fine Structure” = Relativistic (incl. spin-orbit) corrections

$$\Delta E_n = E_n \times \frac{\alpha^2}{n^2} \left(\frac{3}{4} - \frac{n}{j + \frac{1}{2}} \right)$$

1c.) QED corrections (Lamb shift)

$$\Delta E_{\text{Lamb}} = \alpha^5 m_e c^2 \frac{1}{4n^3} \left[k(n, \ell) \pm \frac{1}{\pi(j + \frac{1}{2})(\ell + \frac{1}{2})} \right] \text{ for } \ell \neq 0 \text{ and } j = \ell \pm \frac{1}{2}$$



ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

2.) “Hyperfine Structure”

Nuclear magnetic dipole moment

Dipole-Dipole interaction

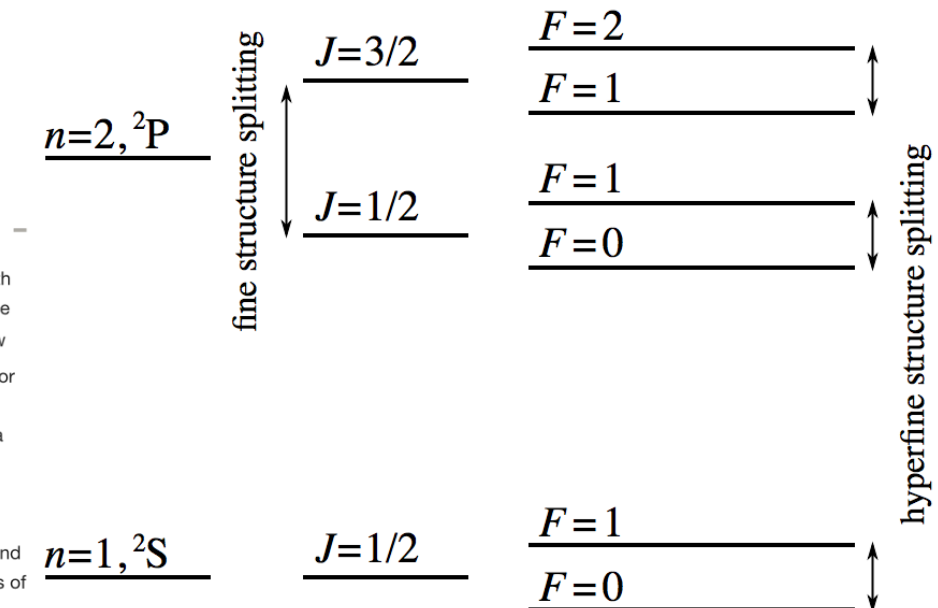
$$I=1/2$$

Nuclear Spin and Hyperfine Structure

H. E. White
Phys. Rev. **35**, 441 – Published 1 March 1930

ABSTRACT

Assuming that hyperfine structure in spectral lines has its origin in the coupling of a nuclear spin with electron resultant J , a comparison between gross structure and hyperfine structure is made from the following relation, $\frac{\Delta\nu_g}{\Delta\nu_f} = \frac{m_p}{4im_e}$. For those atomic systems for which the electron configurations show LS or jj coupling, the agreement with the above equation is quite as good as would be expected. For electronic configurations which do not show LS or jj coupling it is doubtful whether such a comparison of gross structure with hyperfine structure can be suitably made. From the meagre data as yet available, one is led to suspect that nuclear spin is due to the last electrons, protons, or both (most probably electrons) added to the nucleus in atomic construction. These electrons should, in accordance with the principles of the wave-mechanics, have a *probability density* spherically symmetrical about the nucleus. The difference between the electrons associated with the nucleus and the outer electrons is that the nuclear electrons carry with them in space quantization the total mass of the atom.



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DOI: <https://doi.org/10.1103/PhysRev.35.441>

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Fig. 1. The figure shows the experimental curve, the Mott curve, and the point-charge, point-magnetic-moment curve. The experimental curve passes through the points with the attached margins of error. The margins of error are not statistical; statistical errors would be much smaller than the errors shown. The limits of error are, rather, the largest deviations observed in the many measurements of the points and the limits of error in several months. Absolute cross sections given in the ordinate scale were not measured experimentally but were taken from theory. The radiative corrections of Schwinger have been ignored since they affect the angular distribution hardly at all. The radiative corrections do influence the absolute cross sections. Experimental points in the figure refer to areas under the elastic peaks taken over an energy interval of ± 1.5 Mev centering about the peak. Data at the various points are uncanceled in several months. Other than the energy interval is increased to ± 2.5 Mev about the peak; the latter widths include essentially all the area under the peak.

ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

4a.) (Quasi-) Static two-photon effects: RCS, POLARIZABILITIES, ...

Re-arrangement of charge and magnetization
distribution inside proton due to external field
Analog: Attraction between charge and dielectric

$$\alpha_{E1}, \beta_{M1} \longrightarrow E_n$$

$$\gamma_0 \longrightarrow \text{HFS}$$

4b.) (Deeply) virtual two-photon effects: VVCS, GENERALIZED POLARIZABILITIES, ...

Elastic and Inelastic contributions
(Intermediate excitations of the proton)

Related to moments of (spin) structure
functions through dispersion relations
(sum rules)

$$\alpha_{E1}, \beta_{M1} [Q^2]$$

$$\gamma_0$$

$$\delta_{LT}$$

$$\Delta q$$

PDFs

GDH

(P)VCS

Resonance Structure

ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

Putting it all together – example HFS (courtesy K. Griffioen, W&M):

$$E_{\text{HFS}}(e^- p) = 1.4204057517667(9) \text{ GHz} = (1 + \Delta_{QED} + \Delta_R^p + \Delta_S) E_F^p + \dots$$

(21 cm)

$\Delta_S = \Delta_Z + \Delta_{\text{pol}}$

Zemach: $\Delta_Z = -2\alpha m_e \langle r \rangle_Z (1 + \delta_Z^{\text{rad}})$

$$\langle r \rangle_Z = -\frac{4}{\pi} \int_0^\infty \left(\frac{dQ}{Q^2} \right) \left[G_E(Q^2) \frac{G_M(Q^2)}{1+\kappa} - 1 \right]$$

$$\delta_Z^{\text{rad}} = \frac{\alpha}{3\pi} \left[2 \ln \frac{\Lambda^2}{m^2} - \frac{4111}{420} \right]$$

$$\Delta_{\text{pol}} = \frac{\alpha m_e}{2\pi(1+\kappa)M} (\Delta_1 + \Delta_2)$$

$$\Delta_1 = \frac{9}{4} \int_0^\infty \left(\frac{dQ^2}{Q^2} \right) \left\{ F_2^2(Q^2) + \frac{8m_p^2}{Q^2} B_1(Q^2) \right\}$$

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

$$B_1 = \int_0^{x_{\text{th}}} dx \beta(\tau) g_1(x, Q^2)$$

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

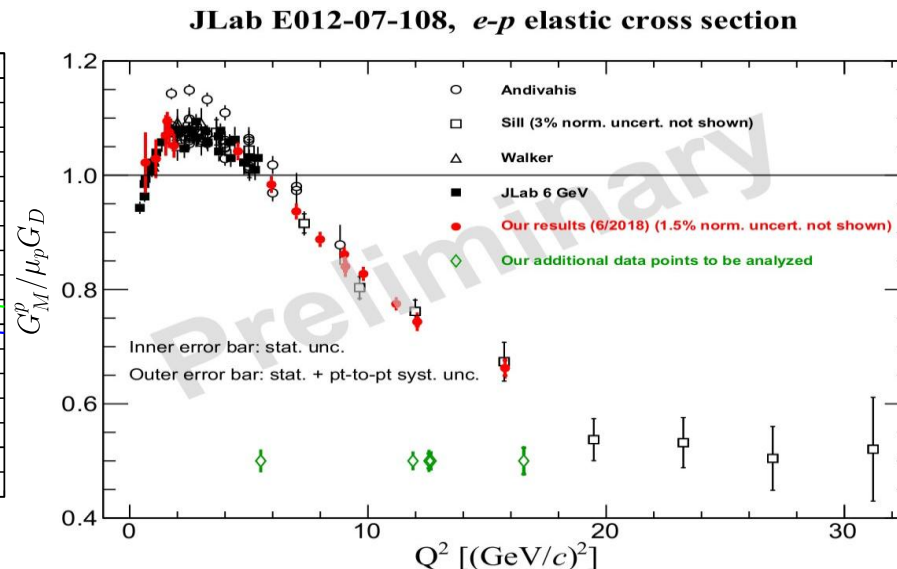
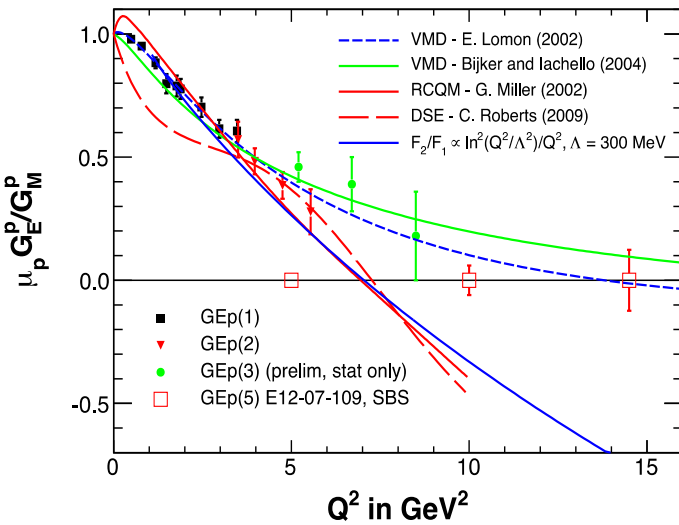
$$\beta(\tau) = \frac{4}{9} \left(-3\tau + 2\tau^2 + 2(2-\tau)\sqrt{\tau(\tau+1)} \right)$$

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

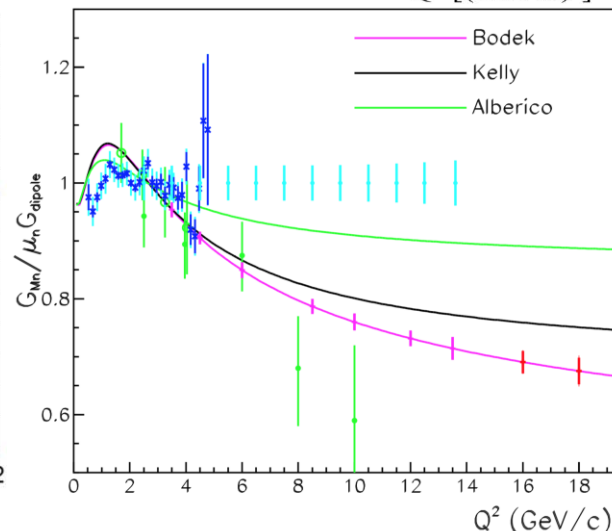
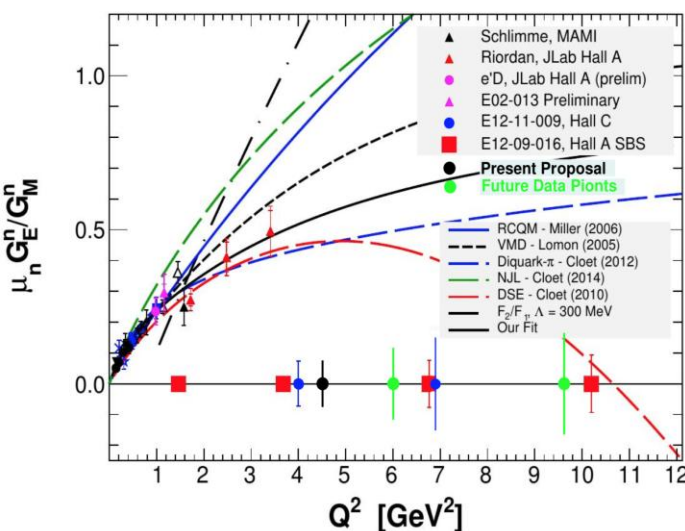
Measurements of form factors, (generalized) polarizabilities and (spin) structure functions at small Q^2 are crucial.

ELECTROMAGNETIC FORM FACTORS

See talks by
Jan C. Bernauer,
Ashot Gasparyan,
Aldo Antognini



$R_p,$
 R_z, \dots

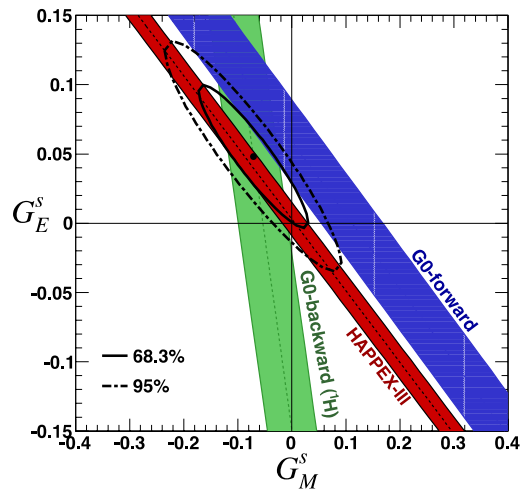


Z. Ye et al. / Physics Letters B 777 (2018) 8–15

$$\left(\frac{d\sigma}{d\Omega} \right)_0 = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \frac{\epsilon (G_E^N)^2 + \tau (G_M^N)^2}{\epsilon (1 + \tau)}$$

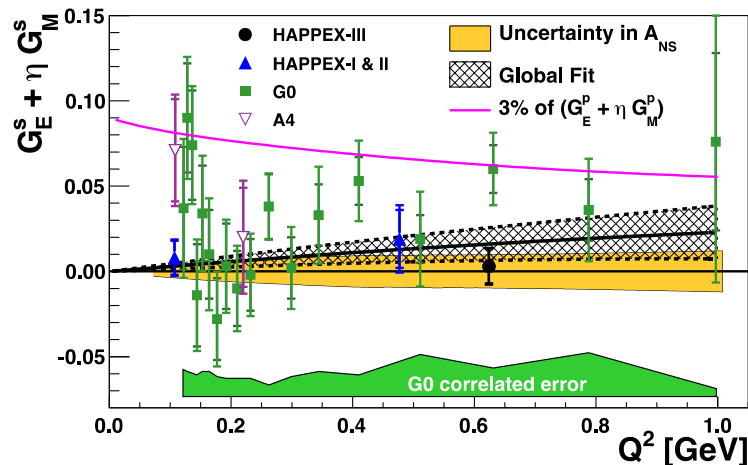
$$\tau = \frac{Q^2}{4m_N^2}, \quad \epsilon = \left[1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}$$

OTHER JLAB RESULTS

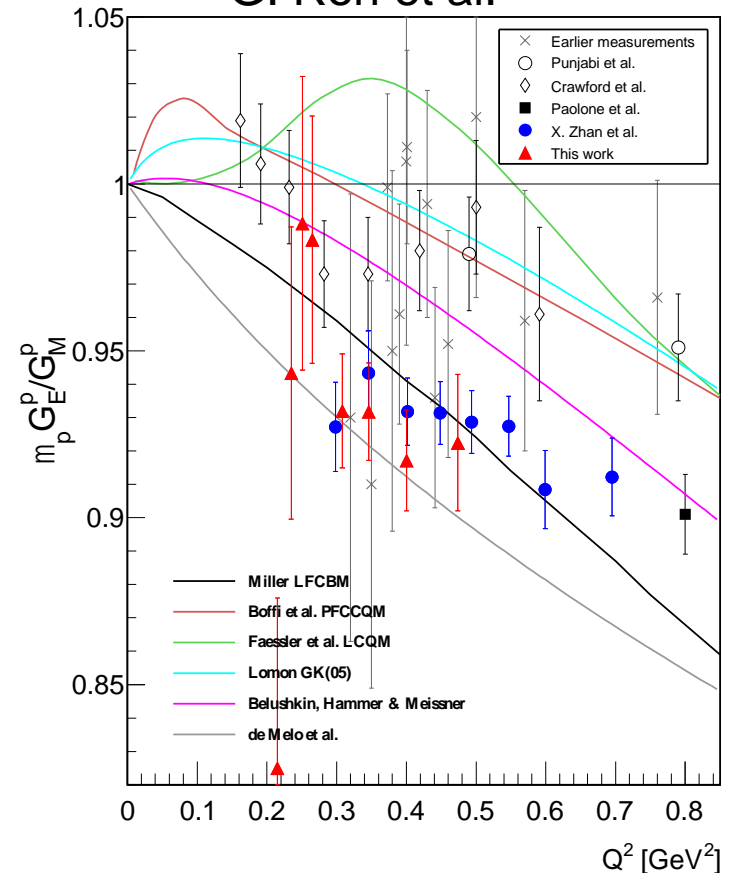


Strange FFs
HAPPEX III
JLab Hall A
Z. Ahmed et al.
+ G0 Hall C

FIG. 2: Constraints on G_E^s and G_M^s at $Q^2 \sim 0.62 \text{ GeV}^2$. The experimental bands are from the results presented in this letter (HAPPEX-III) and the G0 measurements [7, 17].

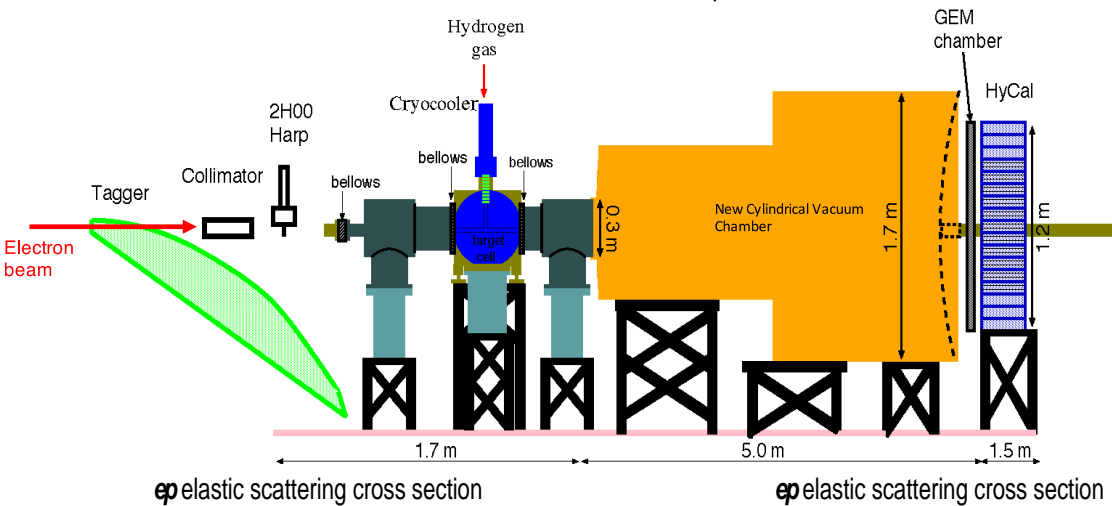


Low Q^2 G_E^p/G_M^p
E08-007
JLab Hall A
G. Ron et al.

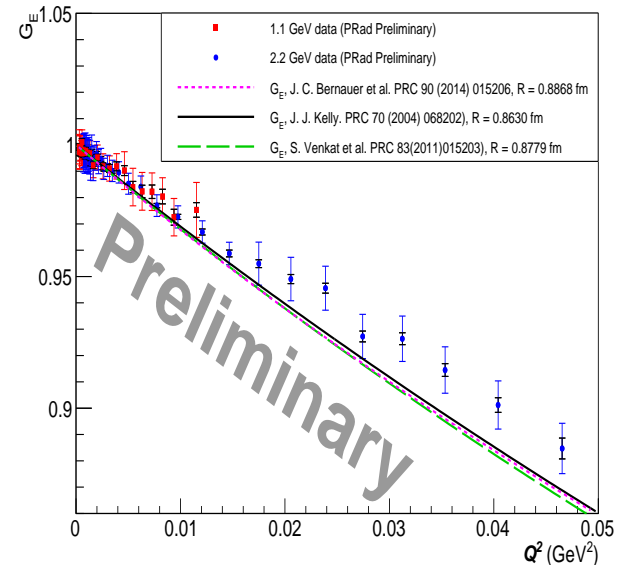
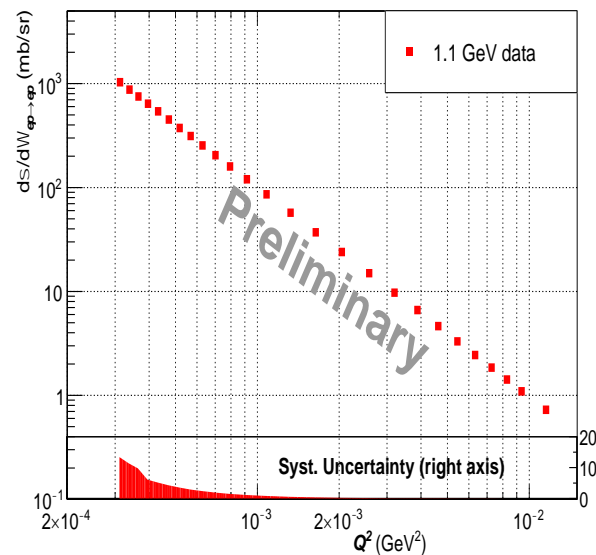
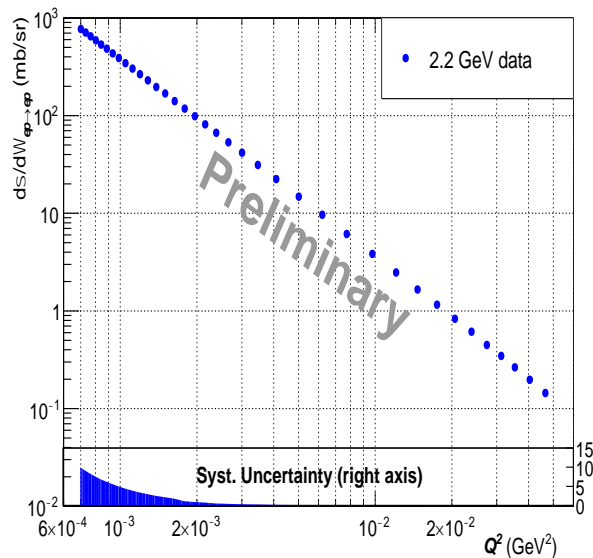
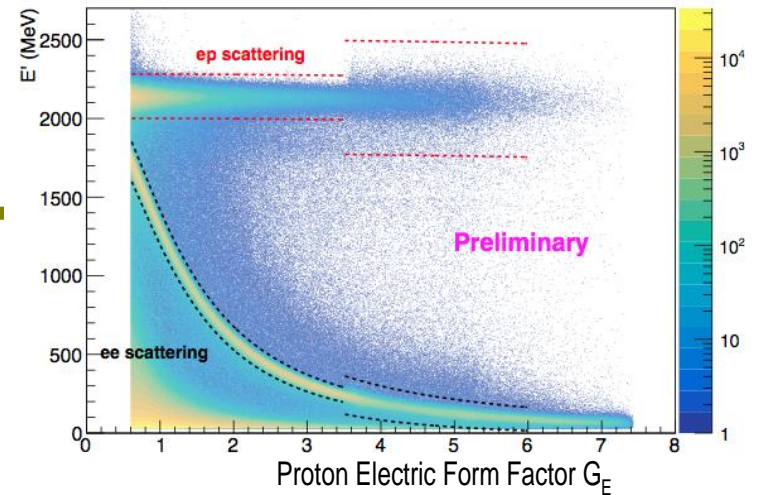


THE PRAD EXPERIMENT AT JLAB

PRad Setup (Side View)



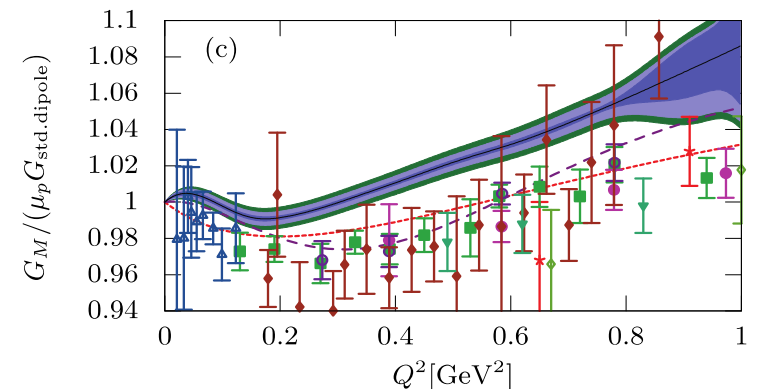
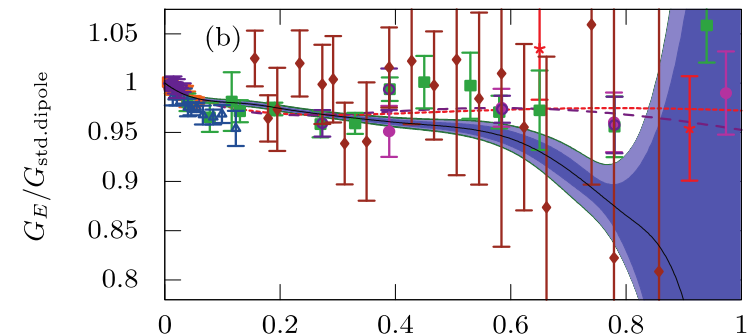
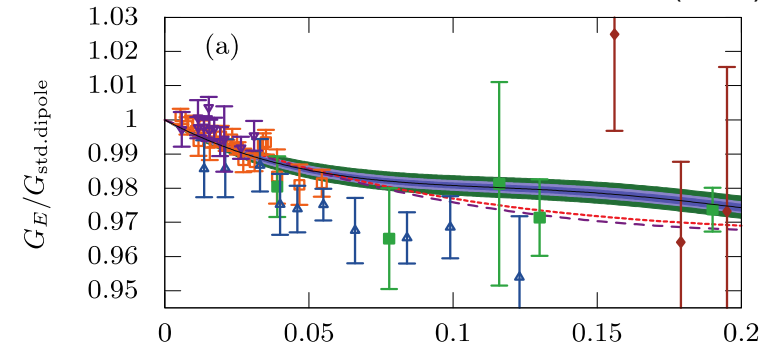
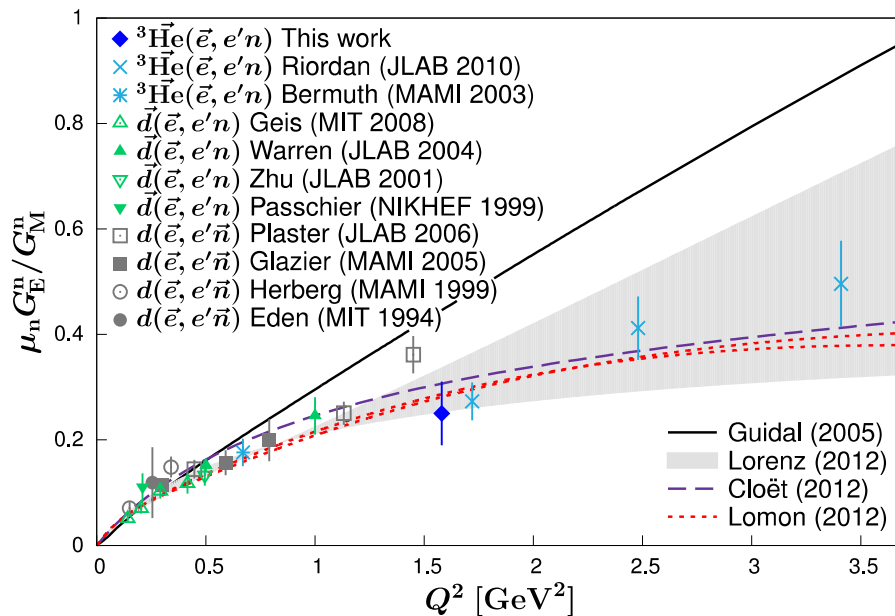
Cluster energy E' vs. scattering angle θ (2.2 GeV)



MAINZ FORM FACTOR EXPERIMENTS

J. C. Bernauer et al.,
PHYSICAL REVIEW C **90**, 015206 (2014)

B. S. Schlimme et al.



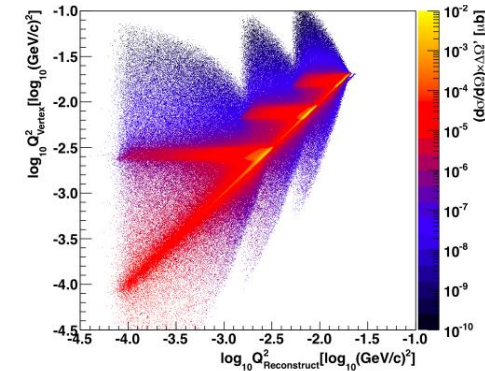
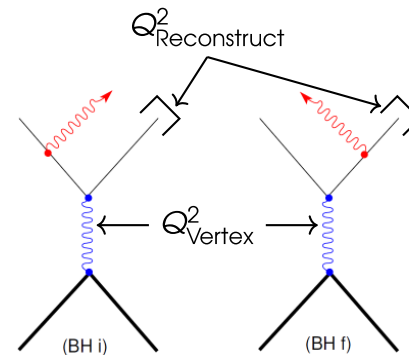
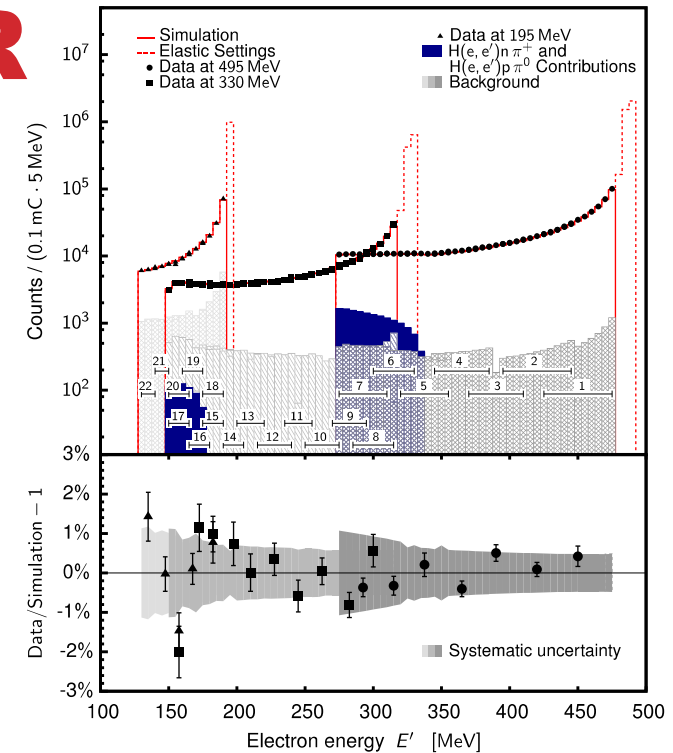
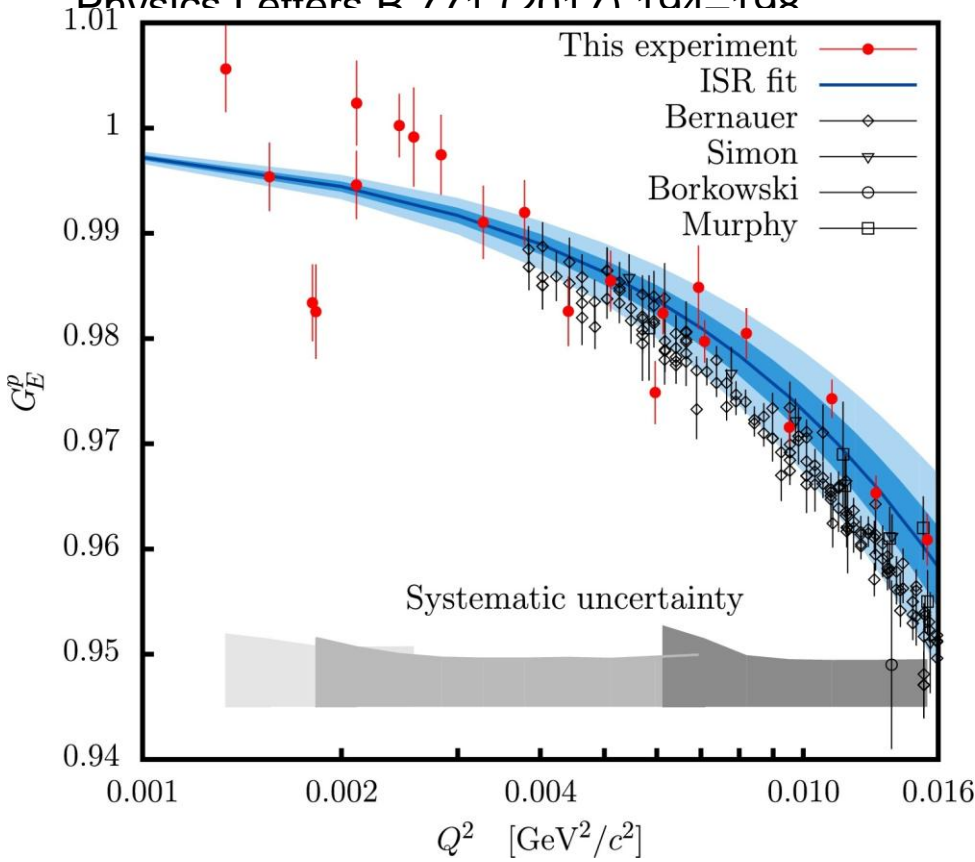
- | | | |
|------------------|-----------------|------------------|
| --- [4] no TPE | ■ Price [67] | ■ Borkowski [64] |
| - - [2] | ■ Berger [87] | ■ Bartel [89] |
| —+— Christy [56] | ■ Hanson [88] | ■ Murphy [92] |
| —+— Simon [60] | ■ Janssens [57] | ■ Bosted [68] |

MAINZ FORM FACTOR EXPERIMENTS II

Initial State Radiation method
(ISR)

M. Mihovilovic et al.,

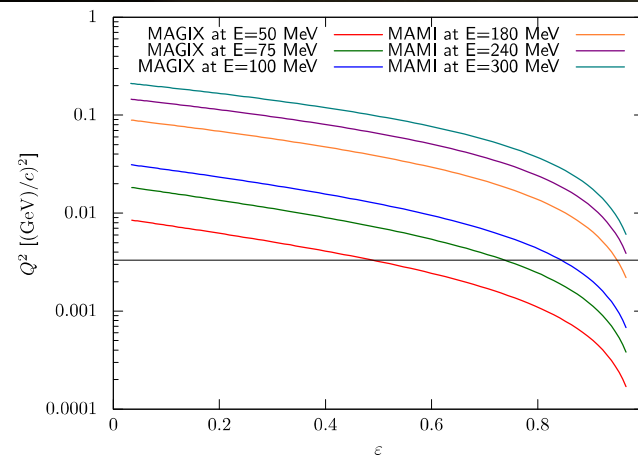
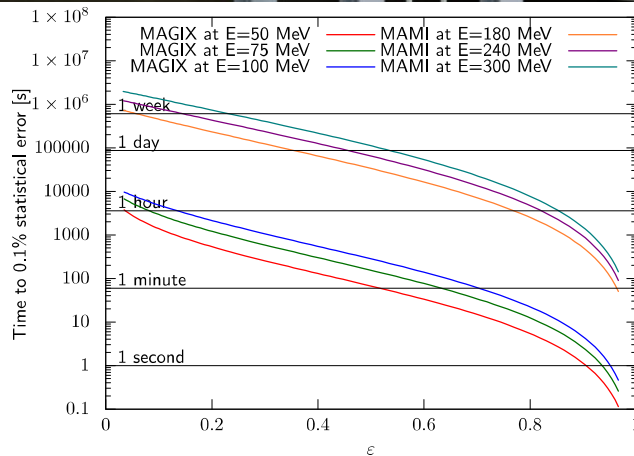
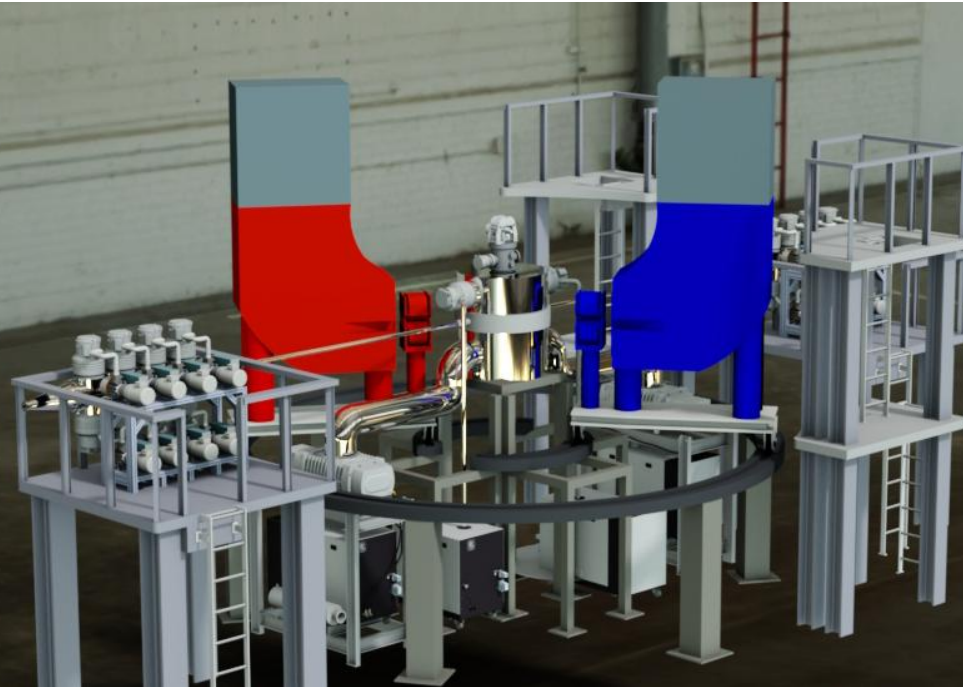
Physics Letters B 771 (2017) 104–108



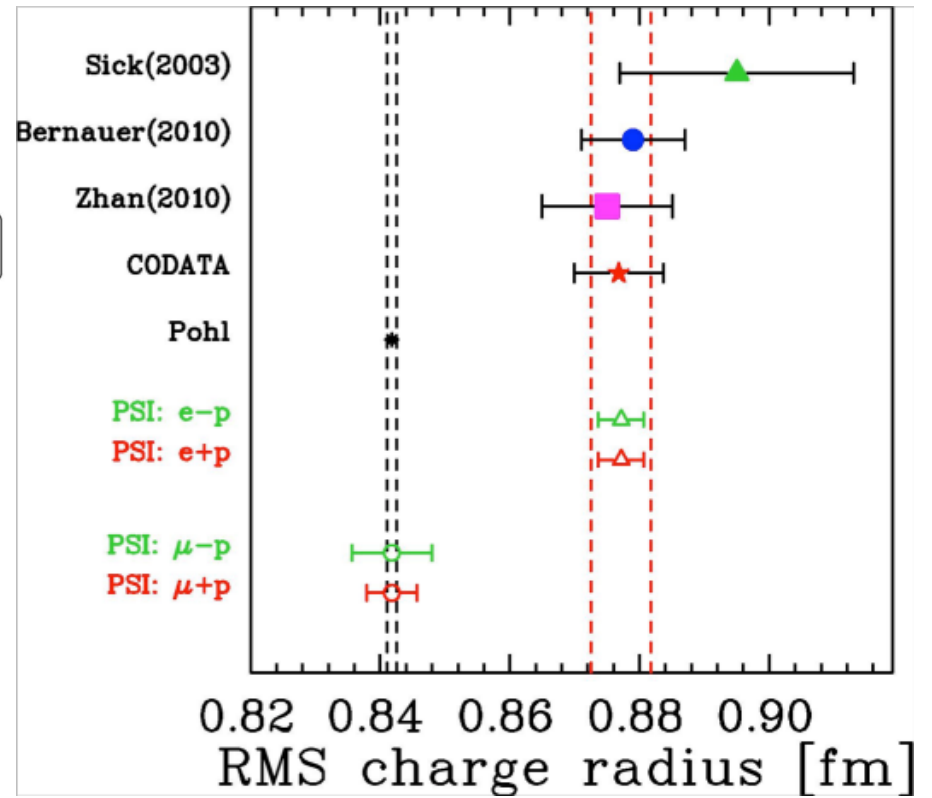
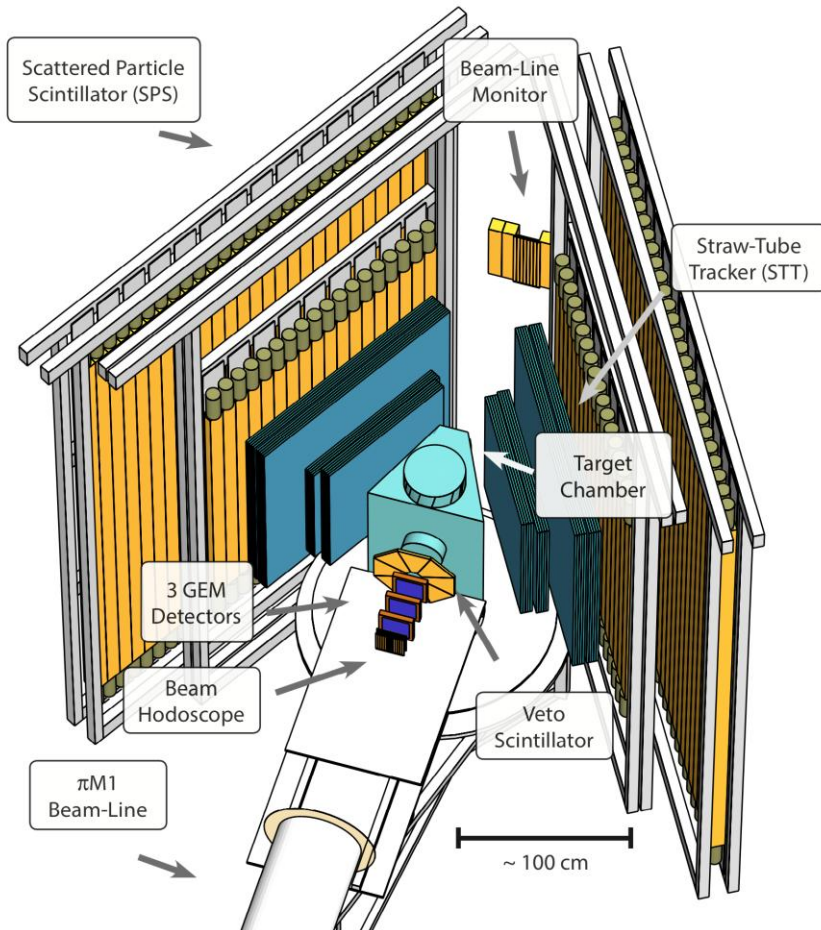
- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

MAINZ - FUTURE

MAGIX
with
MESA



MUSE



Anticipated results

See talks by
Nikos Sparveris,
Mohammed Ahmed,
Pilippe Martel

POLARIZABILITIES

Forward Compton Scattering amplitudes (real photons - RCS):

$$f(\nu) = -\alpha/M + [\alpha_{E1} + \beta_{M1}] \nu^2 + \dots \text{ (spin-independent)}$$

$$g(\nu) = -\alpha\kappa^2/2M^2 \nu + \gamma_0 \nu^3 + \dots \text{ (spin-dependent)}$$

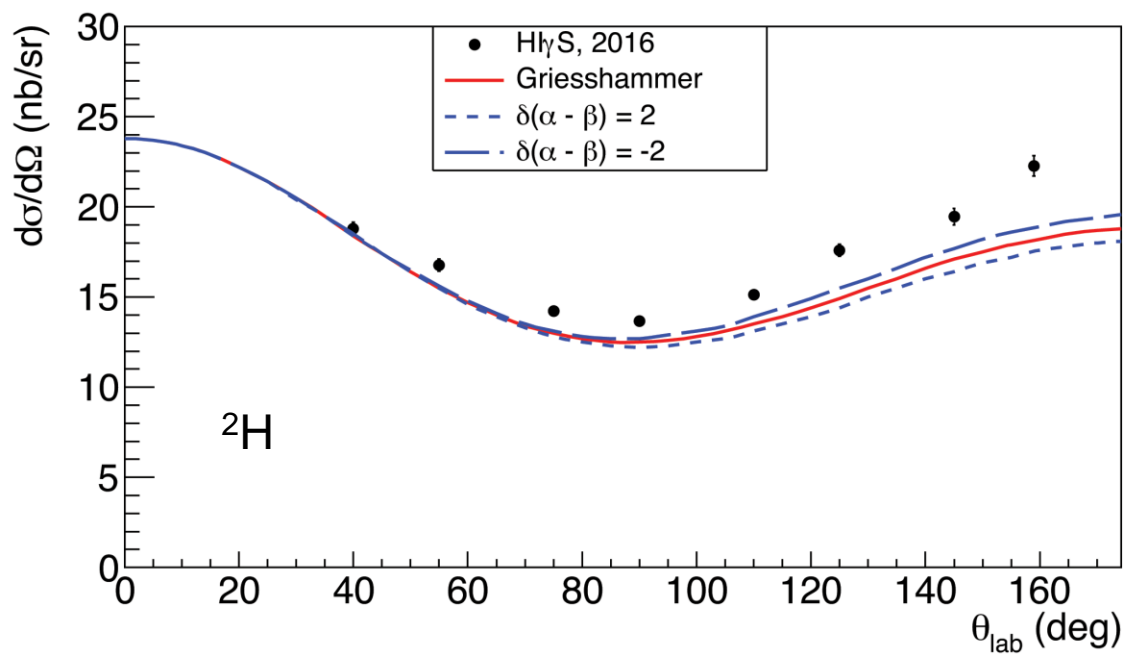
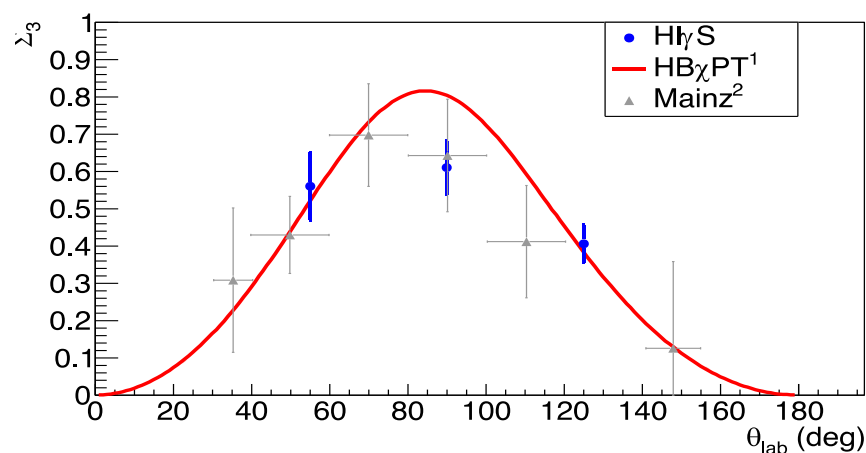
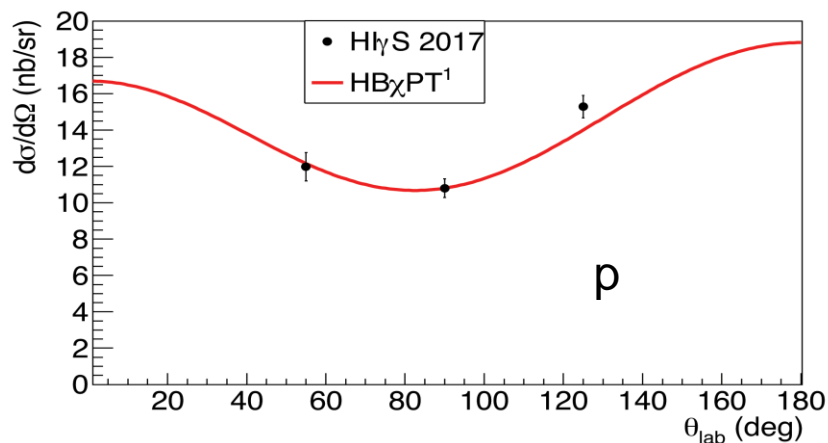
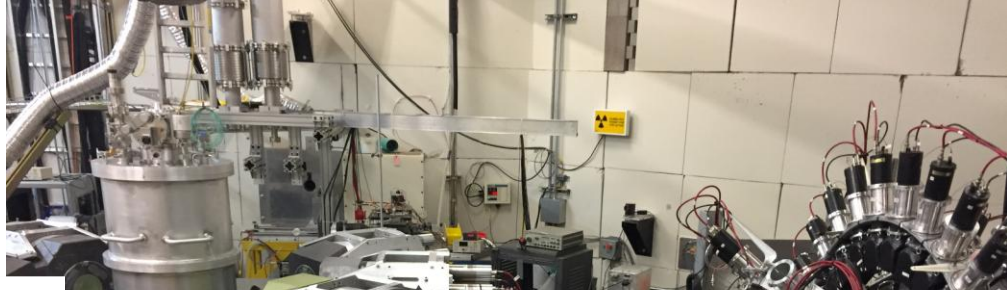
Virtual Compton Scattering amplitudes (VCS, VVCS...):

Generalized polarizabilities dependent on Q^2

Additional (longitudinal and transverse-longitudinal) polarizabilities

α_{E1}, β_{M1}
 γ_0, δ_{LT}

RCS: Hi γ s@TUNL



ng to-date – Theoretical calculations
(published)

with large angular coverage on total
cross sections, these data will
r the extraction of neutron

nmetry (Σ_3) at low energies.
larizabilities using Low-Energy
arizabilities

RCS AT MAMI

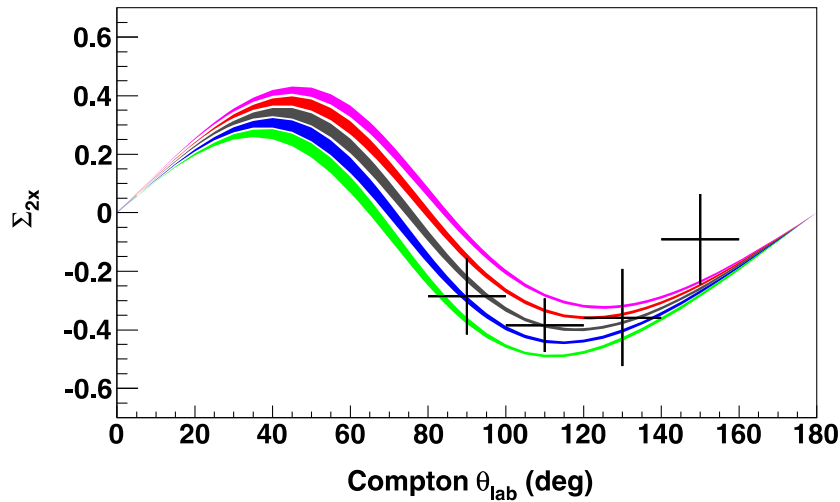


FIG. 3 (color online). Σ_{2x} for $E_\gamma = 273$ – 303 MeV. The curves are from a dispersion theory calculation [11] with α , β , γ_0 , and γ_π held fixed at their experimental values, and γ_{M1M1} fixed at 2.9.

PRL 114, 112501 (2015)

Measurements of Double-Polarized
Compton Scattering Asymmetries and
Extraction of the Proton Spin
Polarizabilities

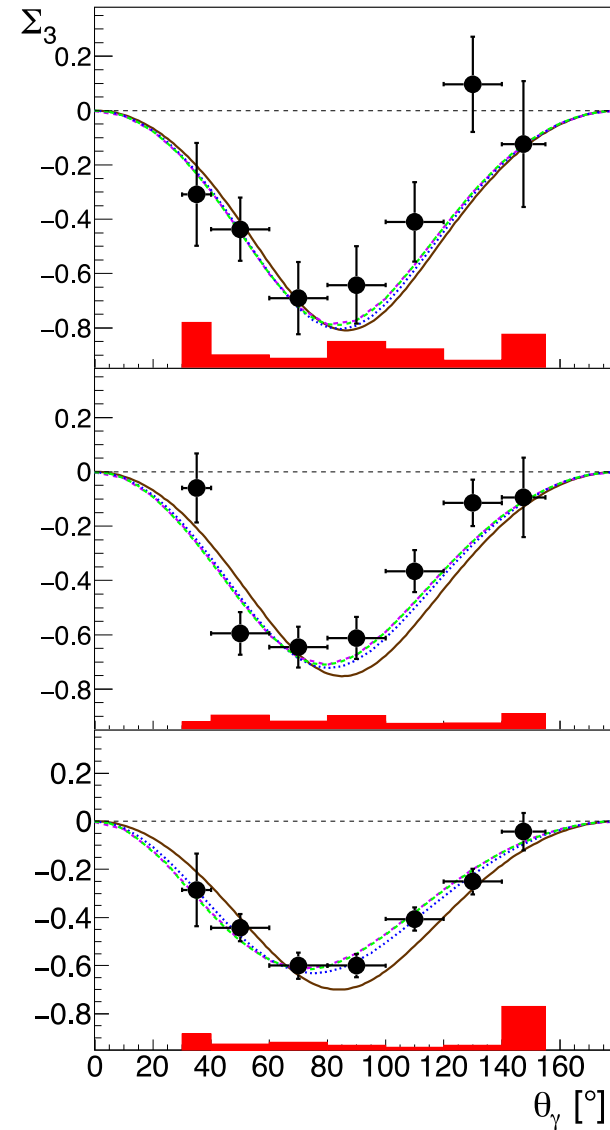
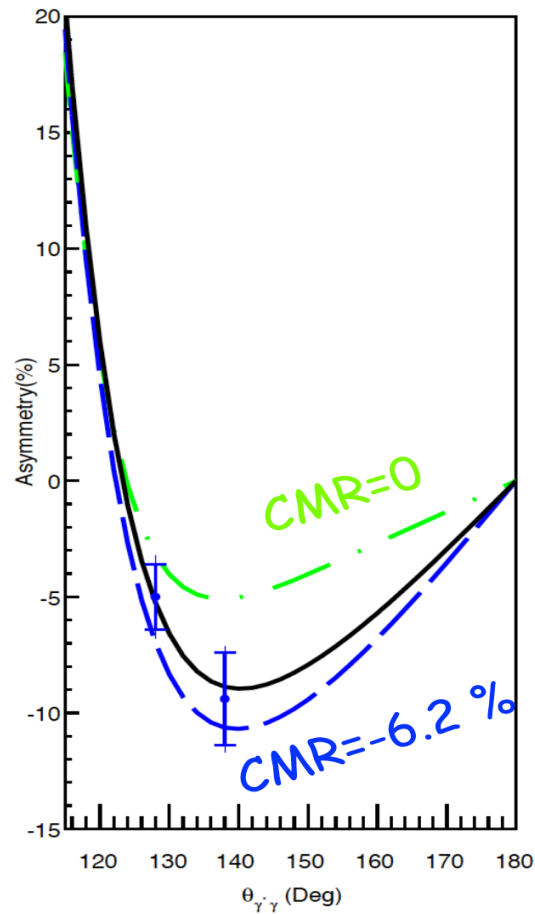


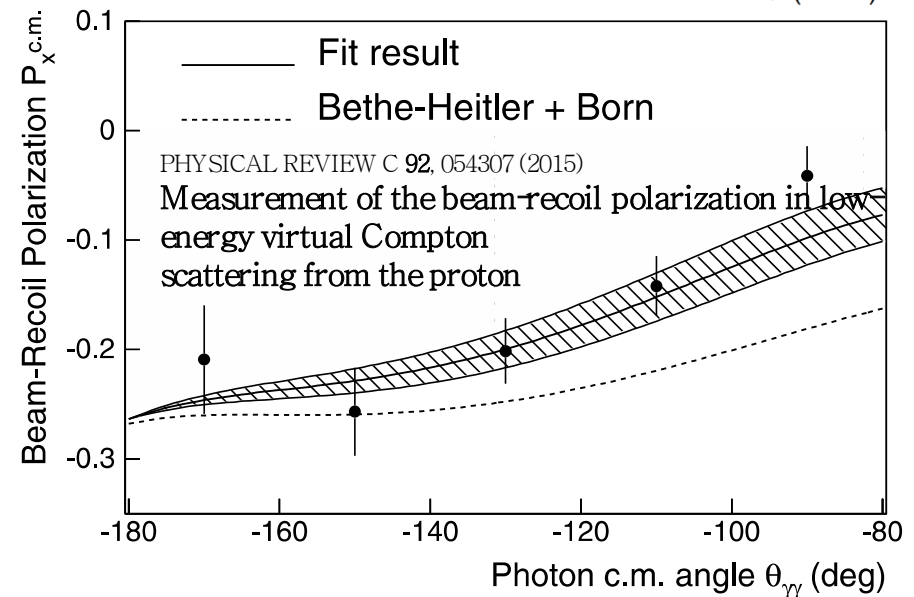
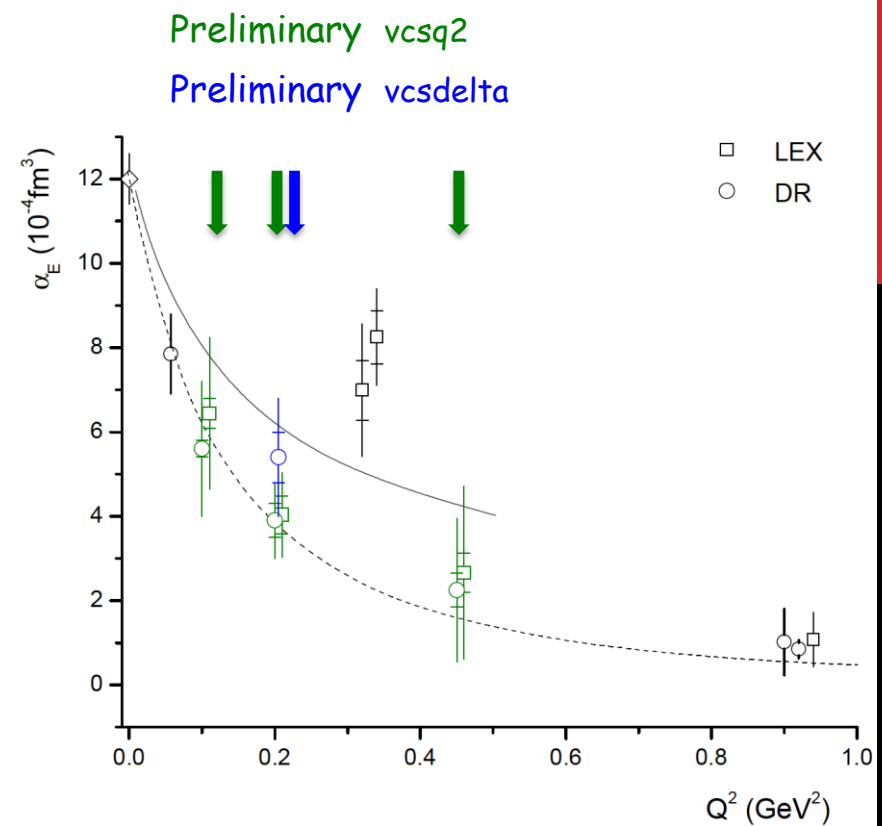
Fig. 4. Beam asymmetry Σ_3 for three energy ranges (uppermost: 79–98 MeV, middle: 98–119 MeV, lowermost: 119–139 MeV).

arXiv:1611.03769v2

VCS AT MAMI

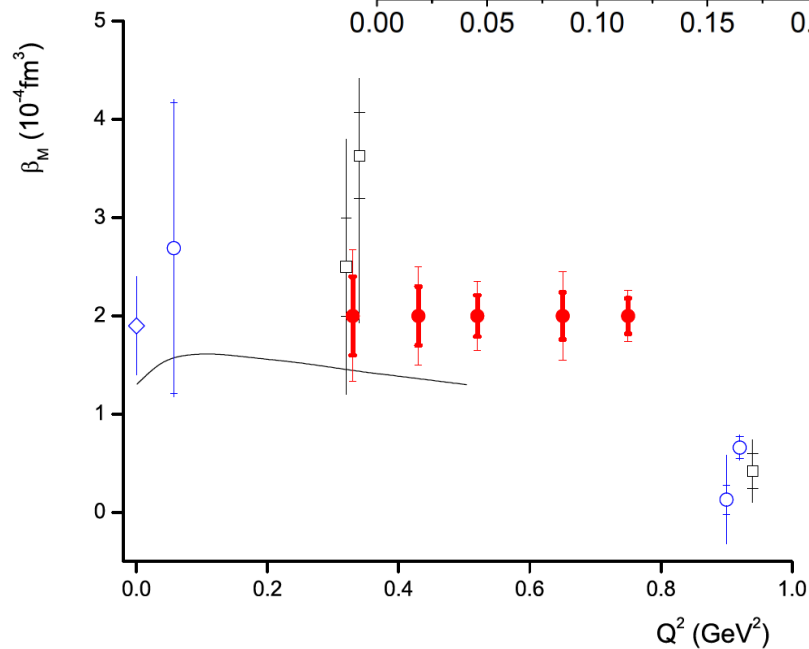
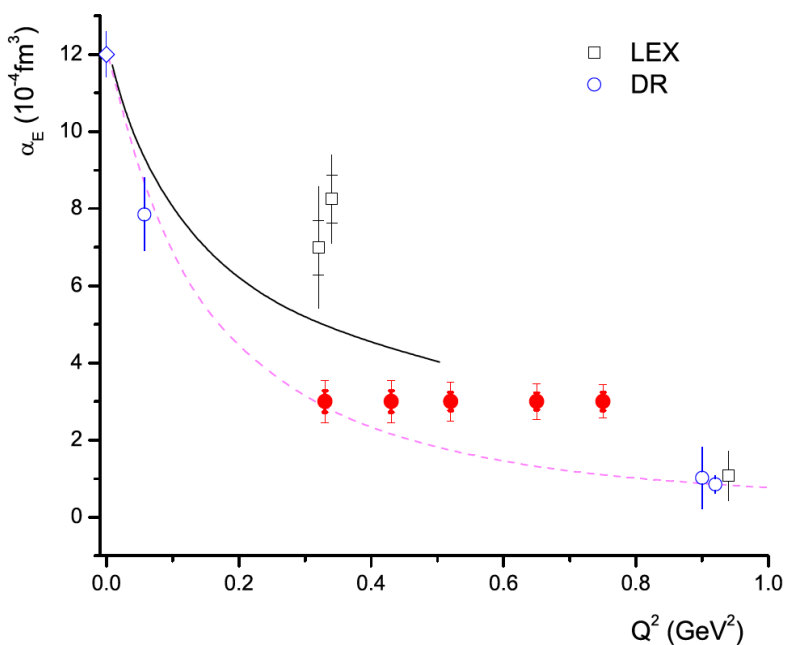


vcsdelta: first measurement of the $N \rightarrow \Delta$ C2 amplitude through the photon channel

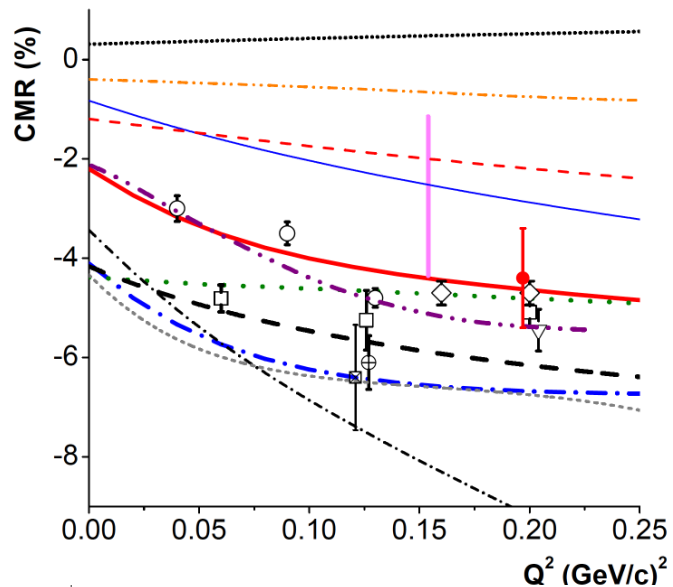


VCS AT JLAB AND ELSEWHERE

E12-15-001 @ Jlab Projected Measurements



- photon channel
- Hall A
- MAMI
- ◇ CLAS
- ⊕ Bates
- ▽ Elsner et al
- ⊗ Pospischil et al
- MAID
- · — DMT
- Sato Lee
- - - Sato Lee (bare)
- · · SAID
- · · Large-Nc
- DSEM
- · · PV
- · · GH
- · · HQM
- - - Capstick
- | Lattice QCD



SPIN STRUCTURE FUNCTIONS

See talks by
Karl Slifer, Emanuele
Pace, Jian-ping Chen,
Marco Ripani,
Mohammed Ahmed

Real and virtual photons

Sum rules

Resonance
Structure

Δq ΔG
 $x \rightarrow 1$

$\Delta\Sigma$

SUM
RULES

PDFs

Duality
OPE, twist > 2

GDH
 α_{E1} , β_{B1}
 γ_0 , δ_{LT}

$$\frac{4\pi^2\alpha}{K} \mathcal{M}(1, -\frac{1}{2} \rightarrow 1, -\frac{1}{2}) \sim \sigma_{1/2}^T = \frac{4\pi^2\alpha}{K} \frac{1}{M} (F_1 + g_1 - \gamma^2 g_2)$$

$$\frac{4\pi^2\alpha}{K} \mathcal{M}(1, \frac{1}{2} \rightarrow 1, \frac{1}{2}) \sim \sigma_{3/2}^T = \frac{4\pi^2\alpha}{K} \frac{1}{M} (F_1 - g_1 + \gamma^2 g_2)$$

$$\frac{4\pi^2\alpha}{K} \mathcal{M}(1, -\frac{1}{2} \rightarrow 0, \frac{1}{2}) \sim \sigma_{1/2}^{TL} = \sigma'_{LT} = \frac{4\pi^2\alpha}{K} \frac{\gamma}{M} (g_1 + g_2)$$

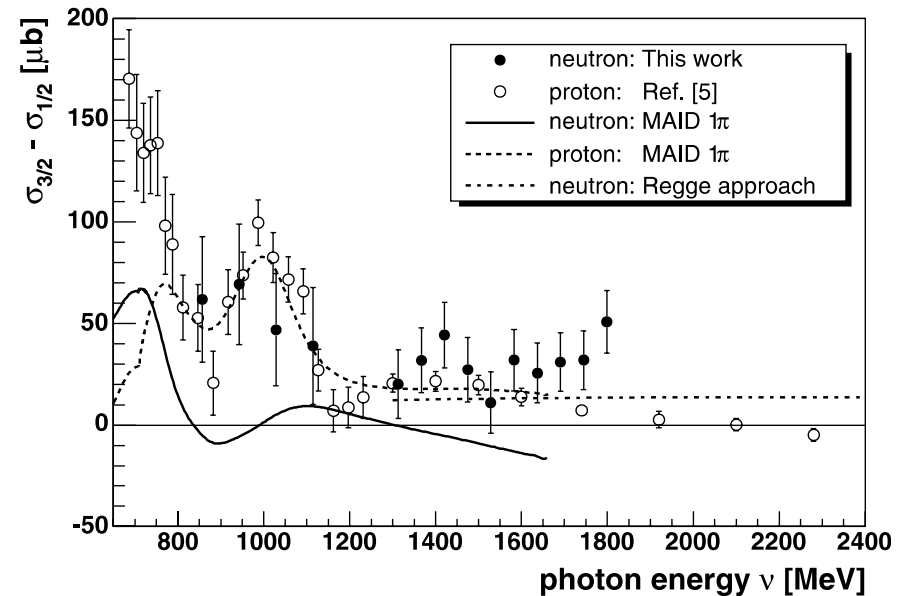
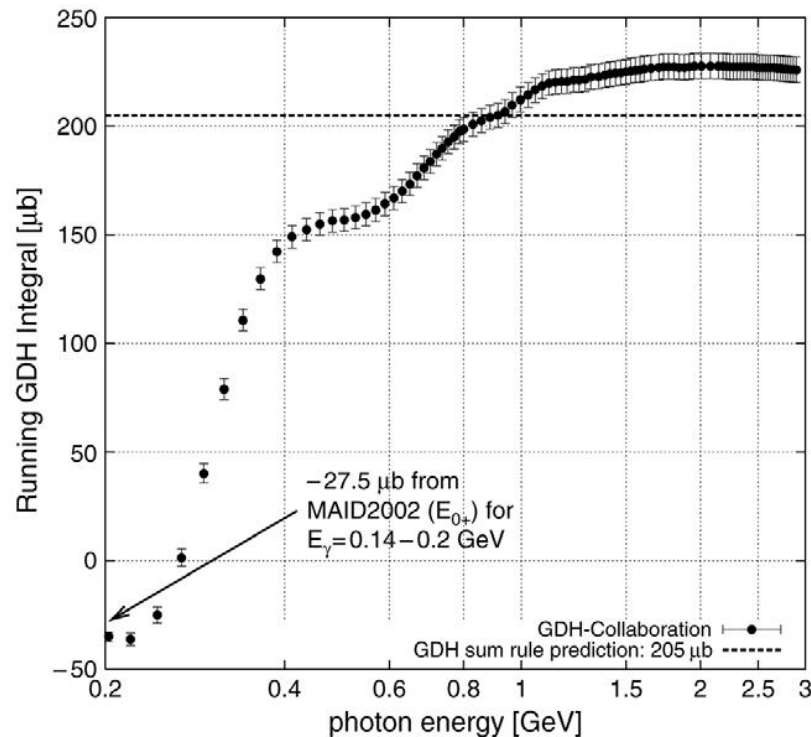
$$\frac{4\pi^2\alpha}{K} \mathcal{M}(0, \frac{1}{2} \rightarrow 0, \frac{1}{2}) \sim \sigma_{1/2}^L = \frac{4\pi^2\alpha}{K} \frac{1}{M\nu} \left(M \left(1 + \frac{1}{\gamma^2} \right) F_2 - \nu F_1 \right)$$

REAL PHOTONS: GDH

Mainz and Bonn

$$I(D)_{GDH} = \int_{\omega_{th}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega = \frac{2\pi^2\alpha}{m^2} \kappa^2$$

K. Helbing / Progress in Particle and Nuclear Physics 57 (2006) 405–469



PRL 94, 162001 (2005)

Measurement of Helicity-Dependent Photoabsorption Cross Sections on the Neutron from 815 to 1825 MeV

Measured “running” GDH integral up to 2.9 GeV including the threshold contribution.

...and a program to measure the GDH Sum Rule on ^2H between 3 and 20 MeV at TUNL

VIRTUAL PHOTONS: Inclusive lepton scattering

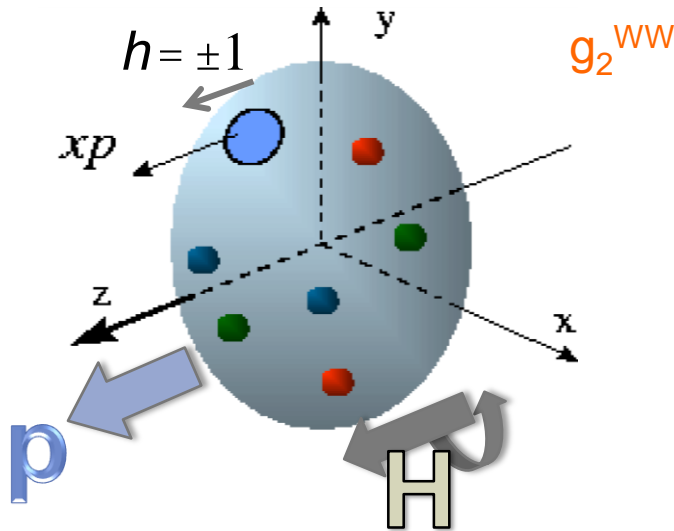
Parton model:

$$F_1(x) = \frac{1}{2} \sum_i e_q^2 q_i(x) \quad (\text{and } F_2(x) \gg 2x F_1(x))$$

$$g_1(x) = \frac{1}{2} \sum_i e_q^2 D q_i(x) \quad \left(\text{and } g_2(x) \approx -g_1(x) + \int_x^1 \frac{g_1(y)}{y} dy \right)$$

$$\frac{d^2\sigma}{dE' d\Omega} = \sigma_{\text{point}}$$

$$\left[\frac{2}{M} \overbrace{F_1(Q^2, \nu)}^{\text{Spin independent}} \tan^2 \frac{\theta}{2} + \frac{F_2(Q^2, \nu)}{\nu} \right] \left[\pm 2 \tan^2 \frac{\theta}{2} \left[(E + E' \cos \theta) \frac{M^2}{\nu} g_1(Q^2, \nu) - g^2 M^2 g_2(Q^2, \nu) \right] \right]$$



$$q(x, Q^2), \langle h \times H \rangle q(x, Q^2)$$

Traditional “1-D” Parton
Distributions (PDFs)
(integrated over many
variables)

At finite Q^2 : pQCD evolution ($q(x, Q^2)$, $\Delta q(x, Q^2)$)
⇒ DGLAP equations) and gluon radiation

$$g_1(x, Q^2)_{pQCD} = \frac{1}{2} \sum_q e_q^2 [(\Delta q + \Delta \bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi} \delta C_q) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \frac{\delta C_G}{N_f}]$$

⇒ access to gluons. $\delta C_q, \delta C_G$ – Wilson coefficient functions

SIDIS: Tag the flavor of the struck quark with the
leading FS hadron ⇒ separate $q_i(x, Q^2)$, $\Delta q_i(x, Q^2)$

Jefferson Lab kinematics: $Q^2 \gg M^2 \Rightarrow$ target mass effects,
higher twist contributions and resonance excitations

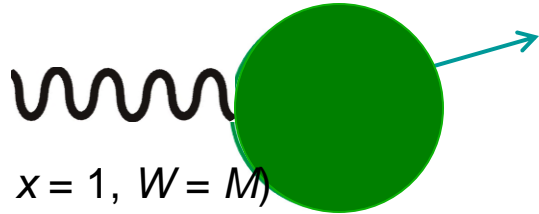
- Non-zero $R = \frac{F_2}{2xF_1} \frac{4M^2 x^2}{Q^2} + 1 - 1, g_2^{HT}(x) = g_2(x) - g_2^{WW}(x)$
- Further Q^2 -dependence (power series in $\frac{1}{Q^n}$)

⇒ Landscape of SFs

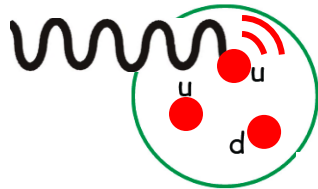
(depends on x and the resolution of the virtual photon $\sim 1/Q^2$)

$$W = \text{final state invariant mass} = \sqrt{M^2 + \left(\frac{1}{x} - 1\right) Q^2}$$

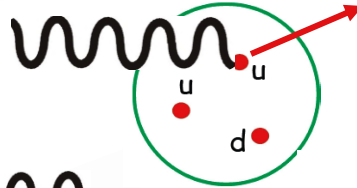
- Elastic scattering
(Whole system recoils, $x = 1$, $W = M$)



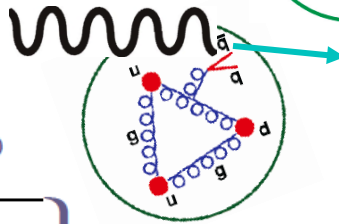
- Resonances
($x < 1$, $W < 2 \text{ GeV}$)



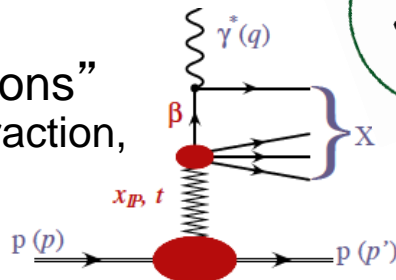
- Valence quarks
($x \geq 0.3$, $W > 2 \text{ GeV}$)



- Sea quarks, gluons
($x < 0.3$)



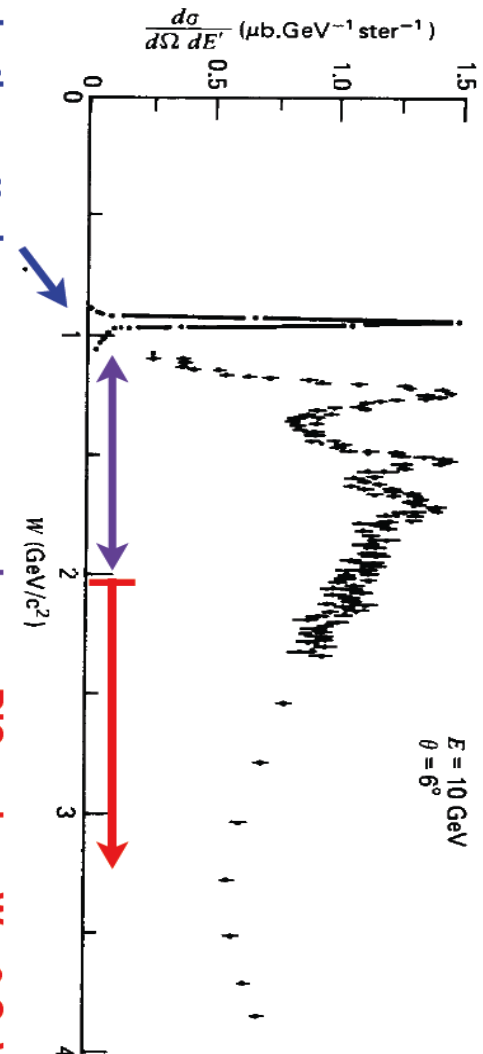
- “Wee Partons”
($x \rightarrow 0$, Diffraction, Pomerons)



elastic scattering

resonance region

DIS regime: $W > 2 \text{ GeV}$



Moments of spin structure functions

Related to matrix elements of local operators - in principle accessible to lattice QCD calculations

Sum rules relate moments to the total spin carried by quarks in the nucleon and to the axial vector coupling g_A of the nucleon

At high Q^2 , can be expanded in a power series (higher twist, OPE)

At low Q^2 , amenable to Chiral Perturbation Theory; constrained by GDH Sum Rule

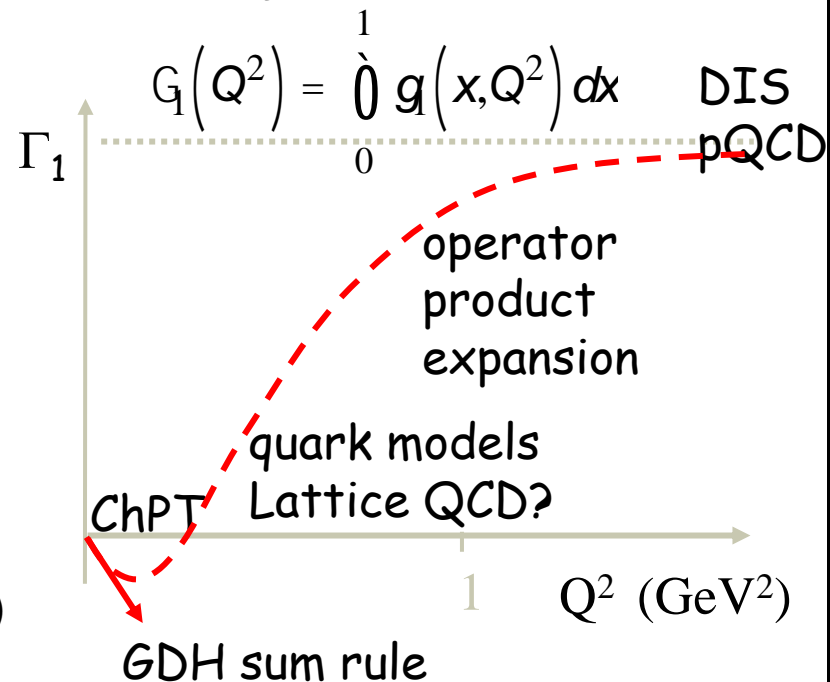
Bjorken Sum Rule: $G_1^p - G_1^n = \frac{g_A}{6} + \text{QCD corr.}$

GDH Sum Rule: $G_1(Q^2 \rightarrow 0) \rightarrow -\frac{Q^2}{2M^2} \frac{k^2}{4}$

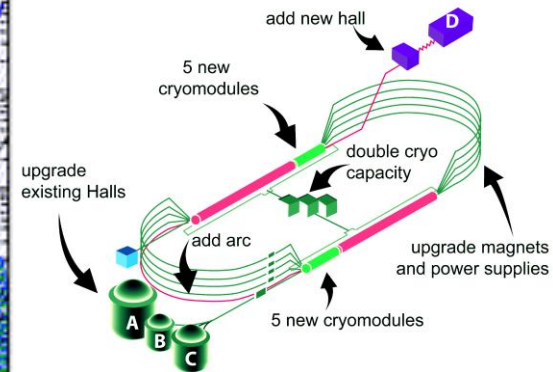
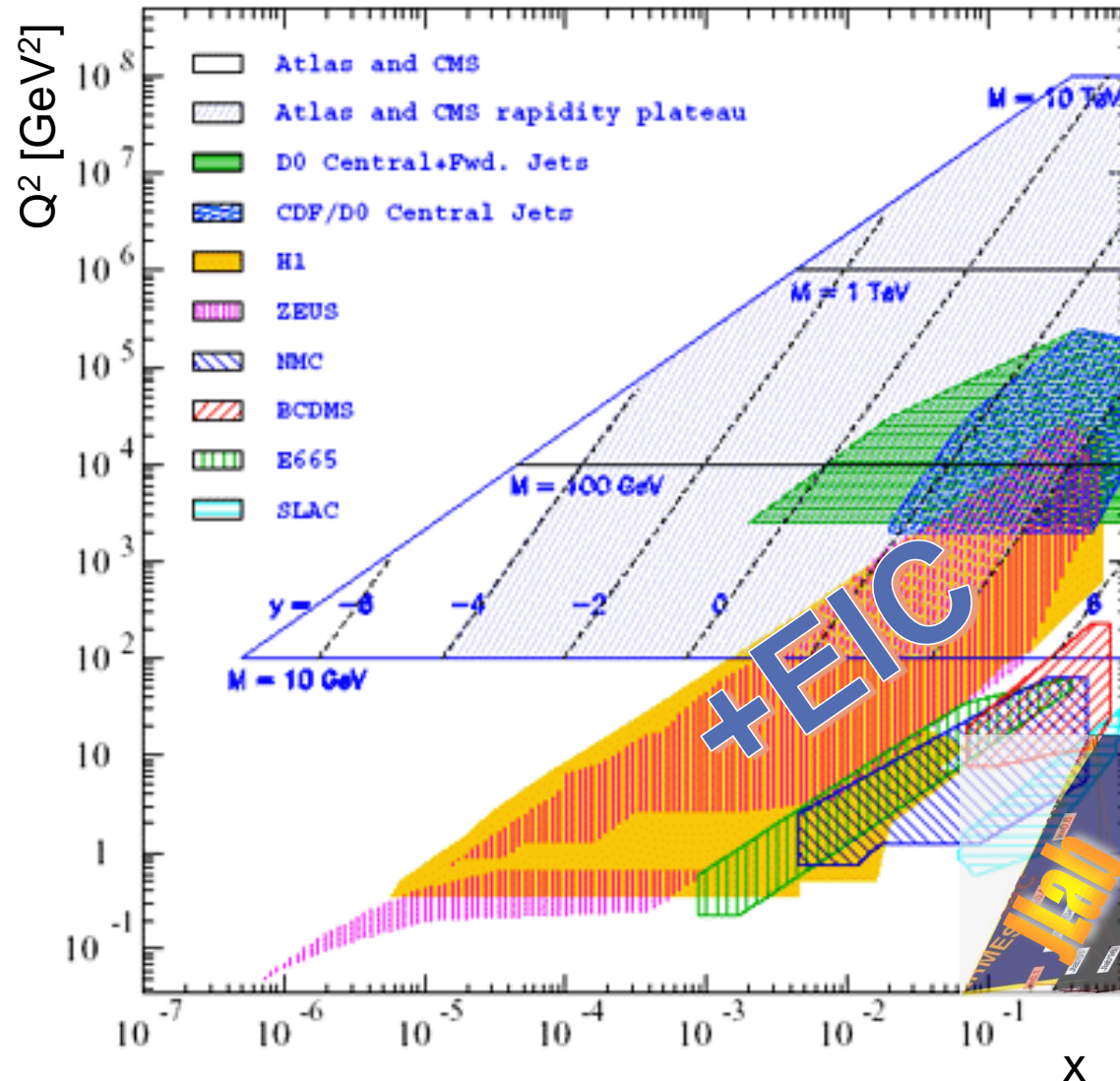
$G_2(Q^2) = \int_0^1 g_2(x, Q^2) dx$ ($= 0$) Burkhardt-Cottingham Sum Rule

$d_2(Q^2) = 3 \int_0^1 x^2 g_2^{HT}(x, Q^2) dx$ Twist 3 matrix element (color force)

...and γ_0, δ_{LT}



JEFFERSON LAB IN PERSPECTIVE



JLab DIS

Now: 12 GeV

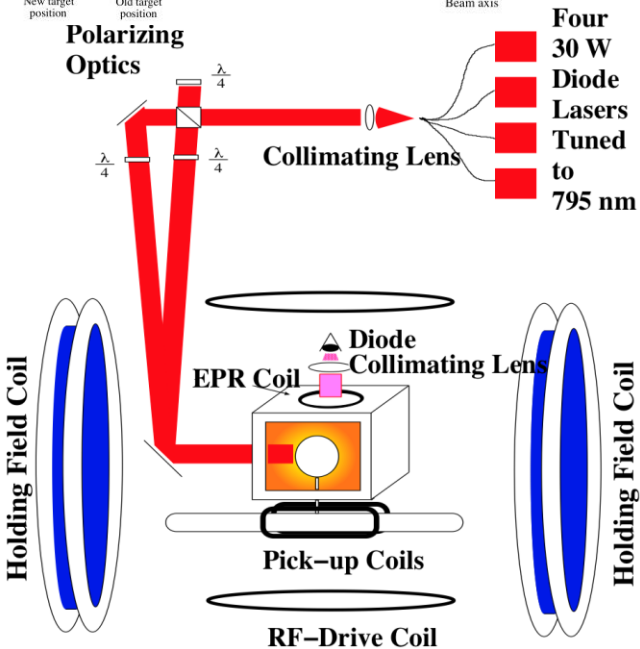
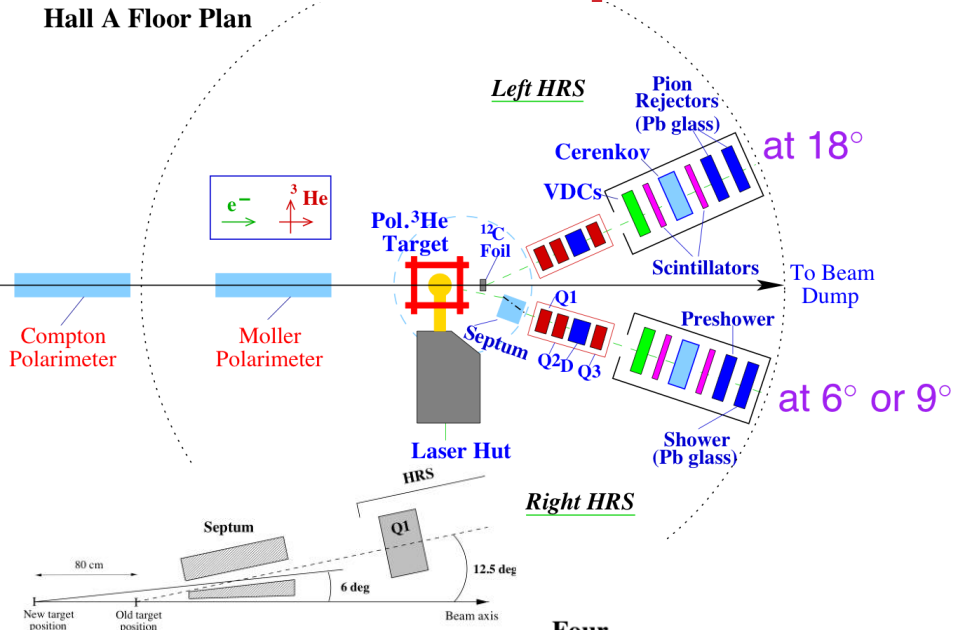
$Q^2 = 1 \dots 13 \text{ GeV}^2$

$x = 0.06 \dots 0.8$

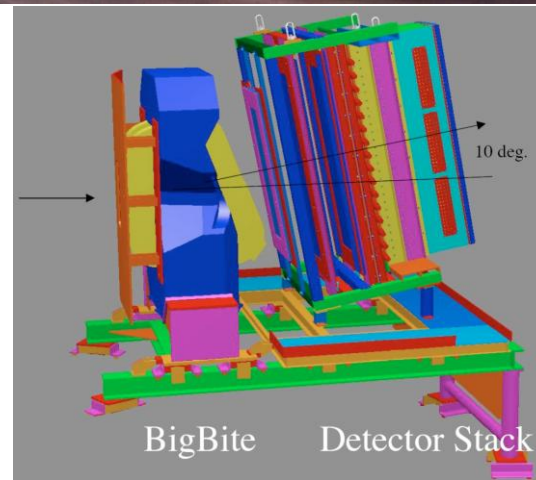
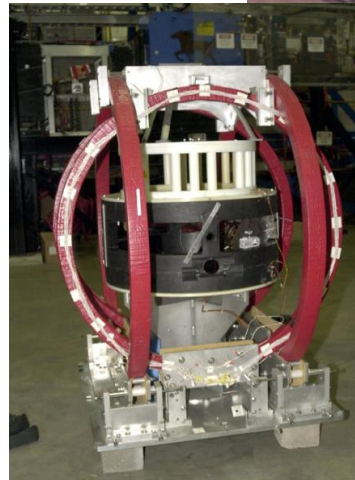
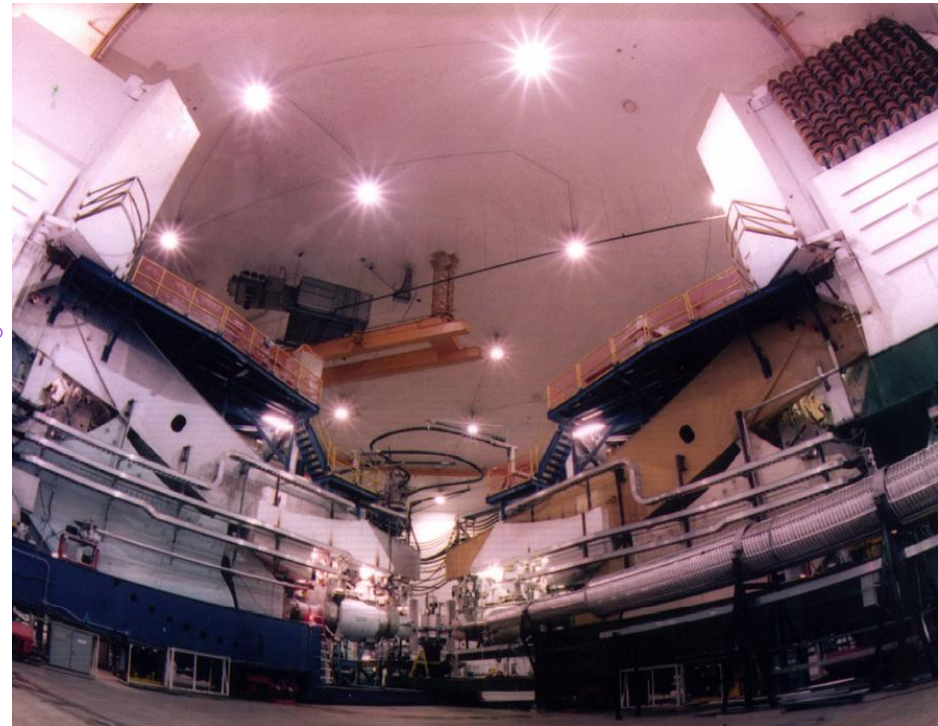
$W < 4 \text{ GeV}$

Experimental Hall A

Hall A Floor Plan



pol. ^3He target



...plus transverse polarized proton target for g_{2p}

Experimental Hall A

E08-027: Measurement of g_{2p} and the Longitudinal-Transverse Spin Polarizability

E-06-014: Precision Measurements of the Neutron d_2 : Towards the Electric χ_E and Magnetic χ_B Color Polarizabilities

E06-010: Measurement of Single Target-Spin Asymmetry in Semi-Inclusive Pion Electroproduction on a Transversely Polarized ^3He Target

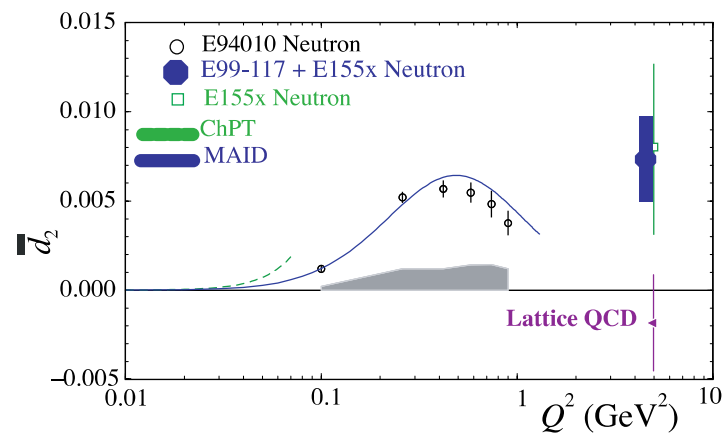
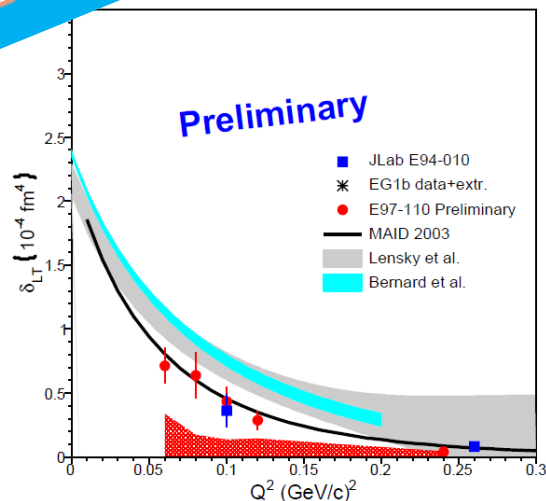
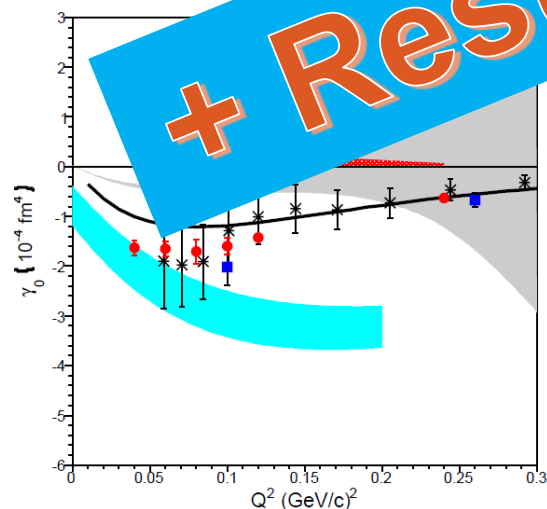
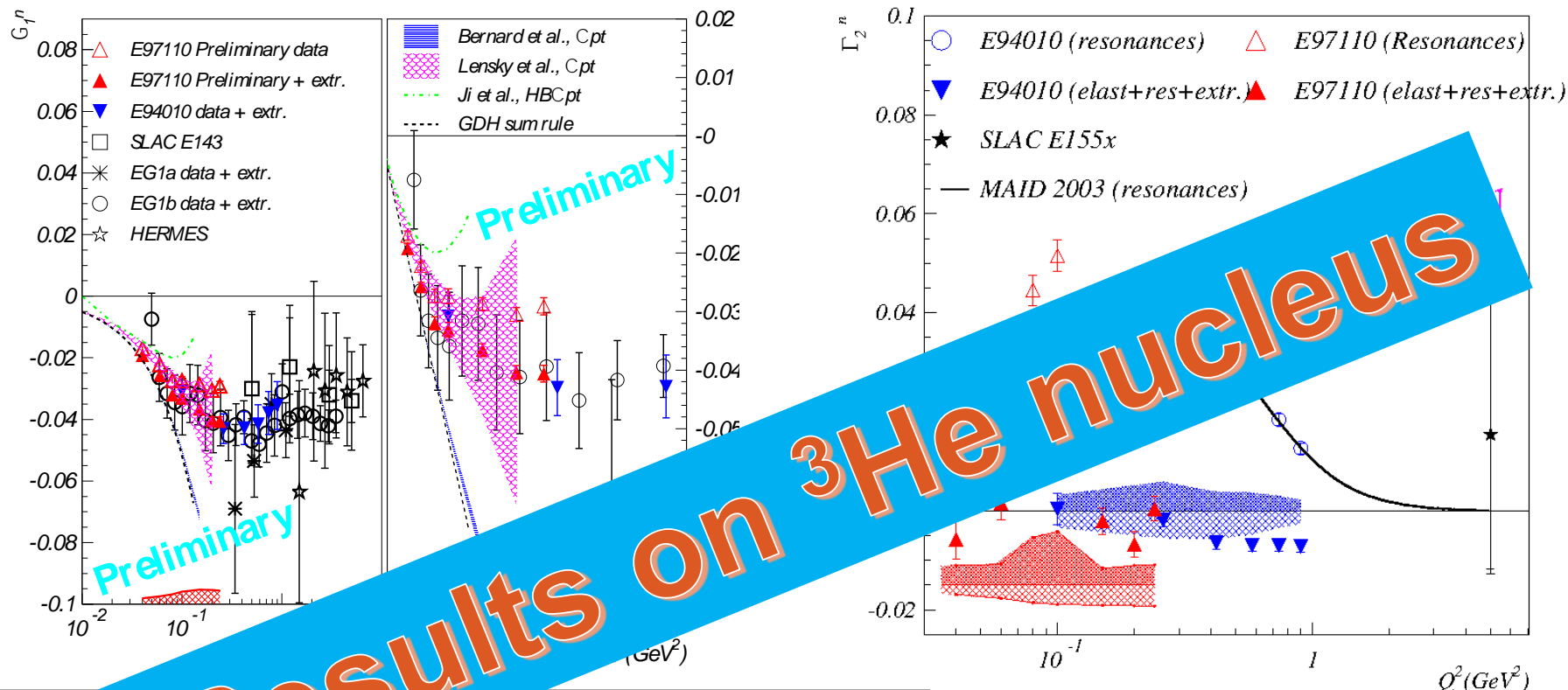
E01-012: Spin Duality

E99-117: Precision Measurement of the Neutron Asymmetry A_{1n} at Large x using CEBAF at 6 GeV

E97-110: The GDH Sum Rule, the Spin Structure of ^3He and the Neutron using Nearly Real Photons

E94-010: Neutron Extended Gerasimov Drell Hearn Sum Rule

NEUTRON EXP. – HALL A

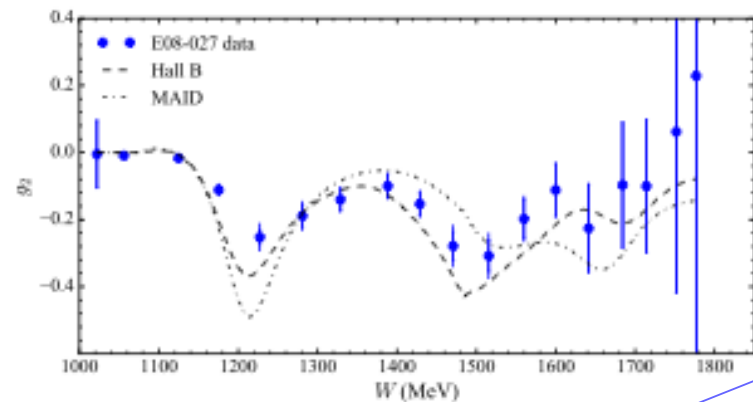


$$Q^2 = 0.08 \text{ GeV}^2$$

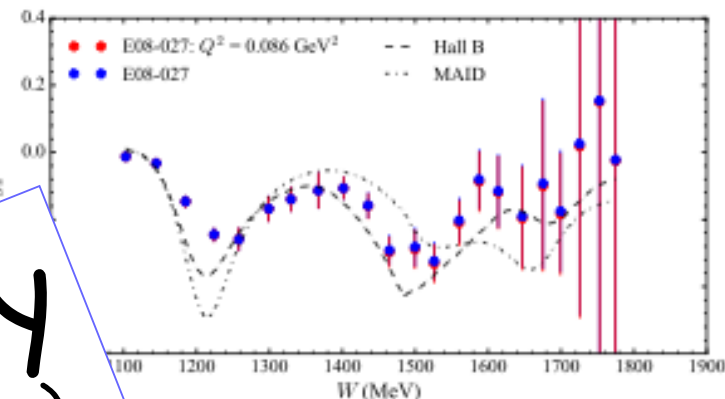
preliminary
(but analysis complete)

$$Q^2 = 0.13 \text{ GeV}^2$$

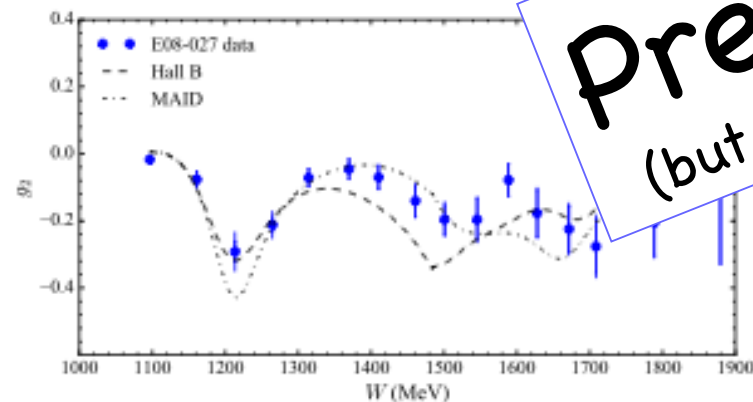
$$Q^2 = 0.04 \text{ GeV}^2$$



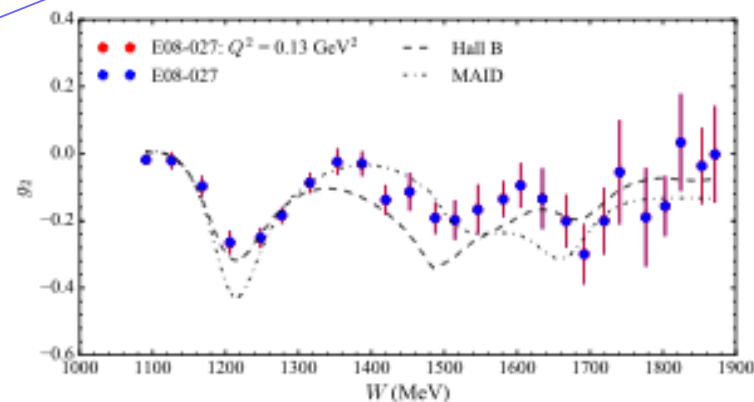
(a) $E_0 = 2254 \text{ MeV}$ 5T Transverse



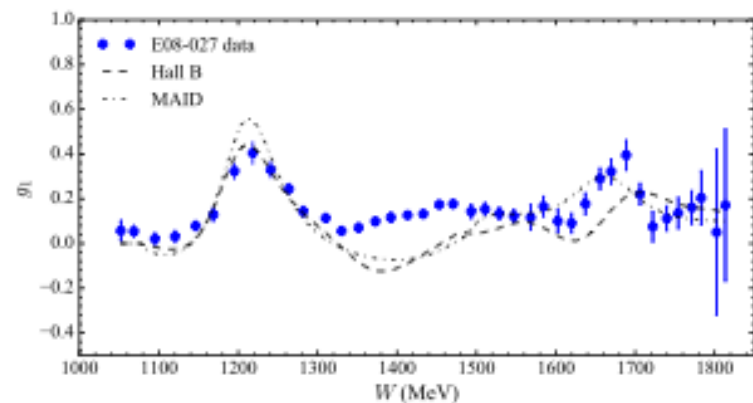
(a) $E_0 = 2254 \text{ MeV}$ 5T Transverse



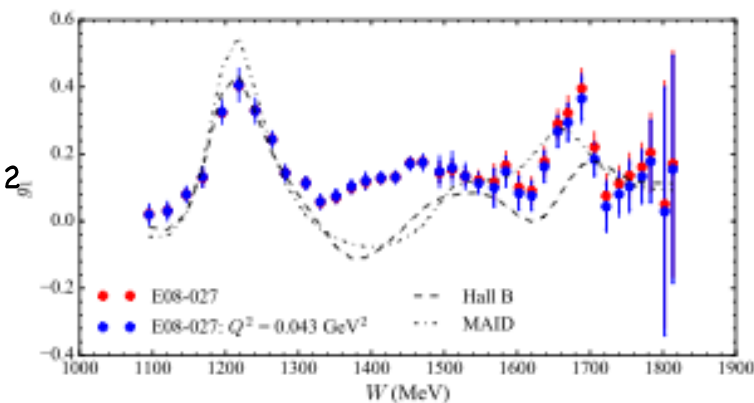
(b) $E_0 = 3350 \text{ MeV}$ 5T Transverse



(b) $E_0 = 3350 \text{ MeV}$ 5T Transverse

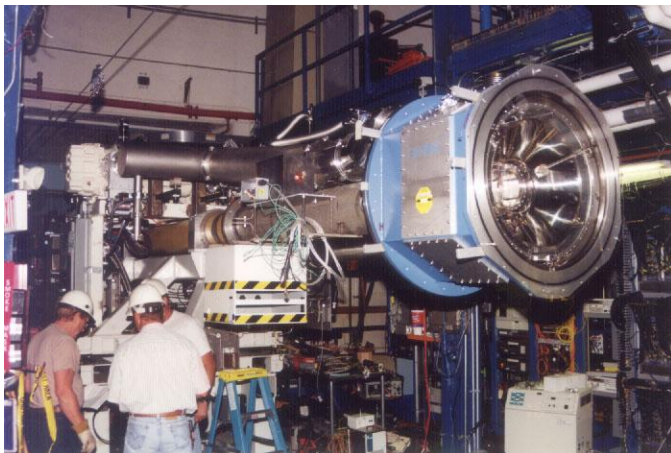
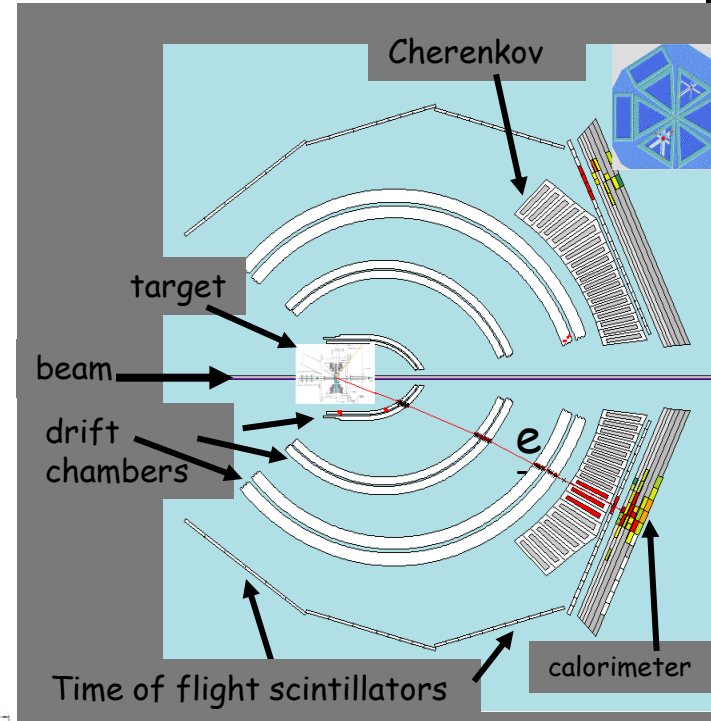
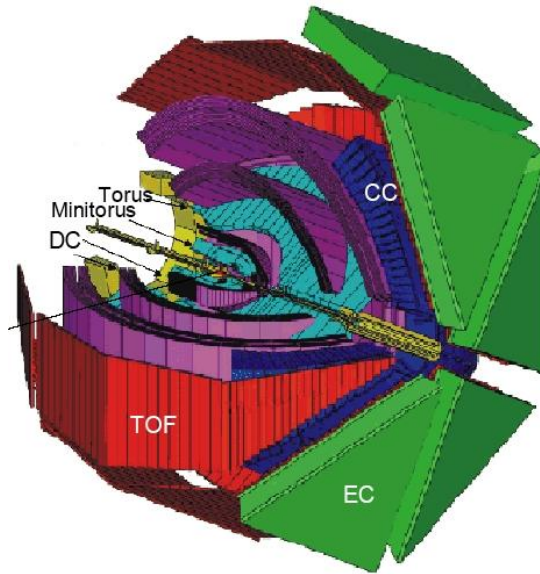
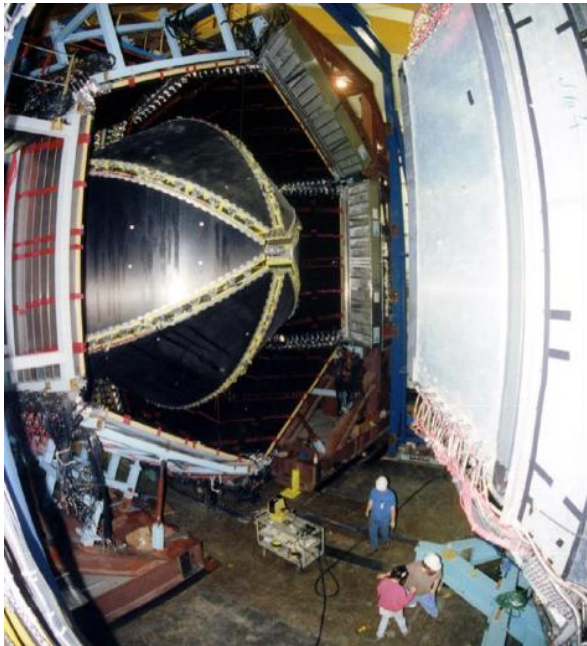


(c) $E_0 = 2254 \text{ MeV}$ 5T Longitudinal

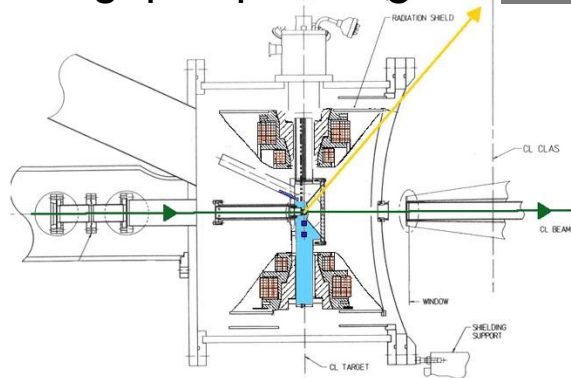


(c) $E_0 = 2254 \text{ MeV}$ 5T Longitudinal

Experimental Hall B



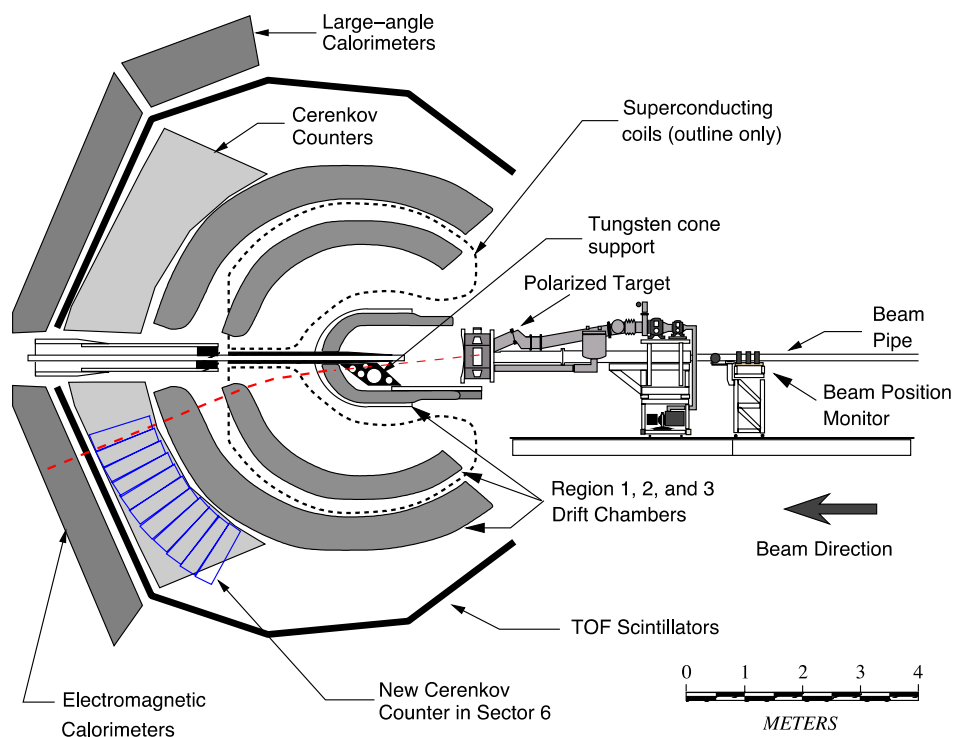
long. pol. p, d target



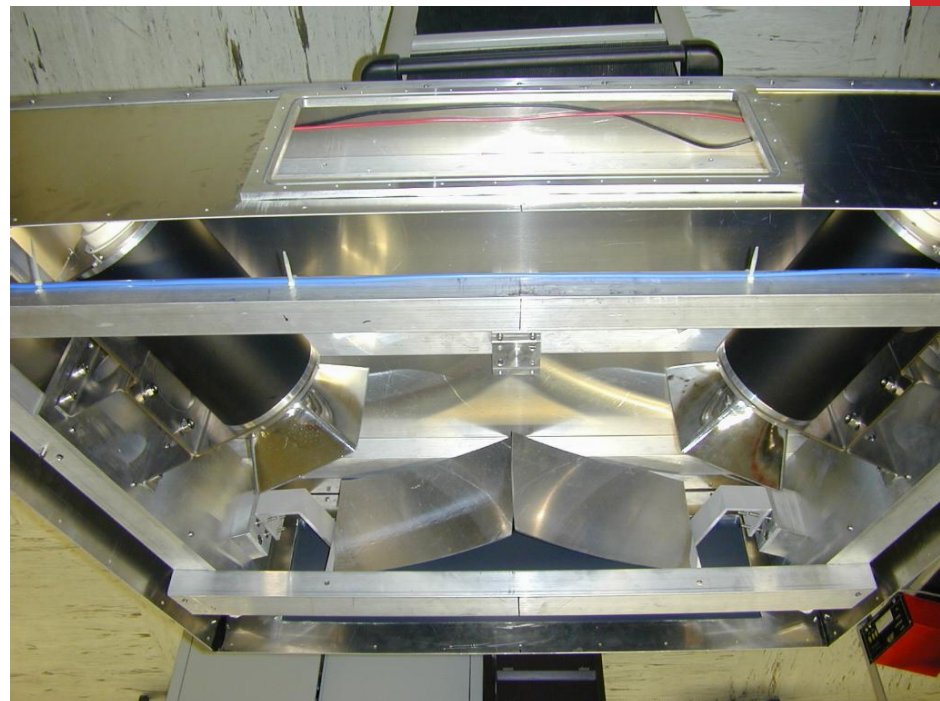
CLAS

EG1, EG4, EG1-DVCS

EG1: Largest possible kinematic coverage -> inbending and outbending configuration,
 $E = 1.6 \dots 5.8 \text{ GeV}$

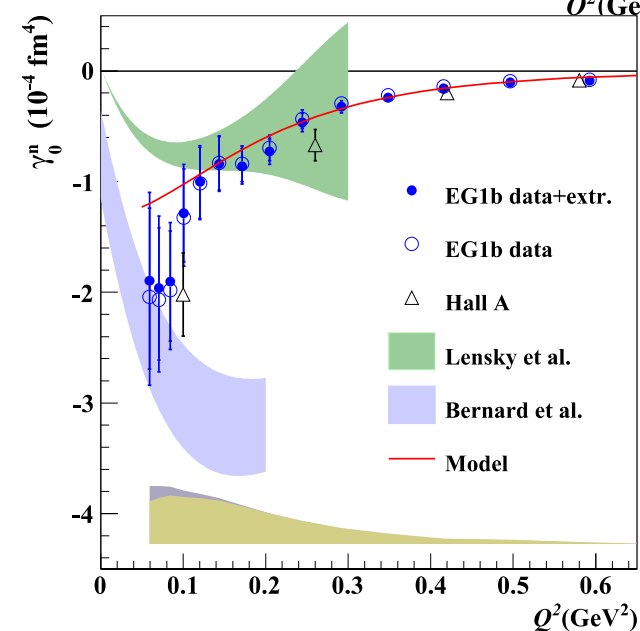
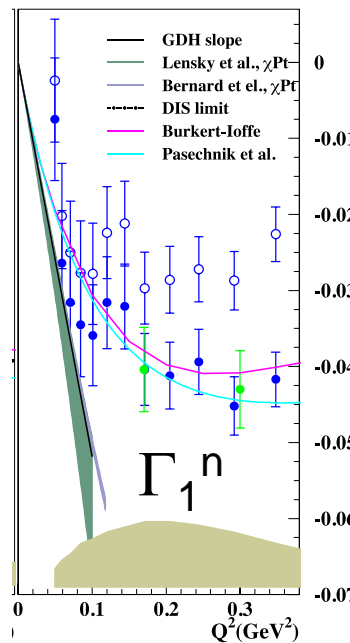
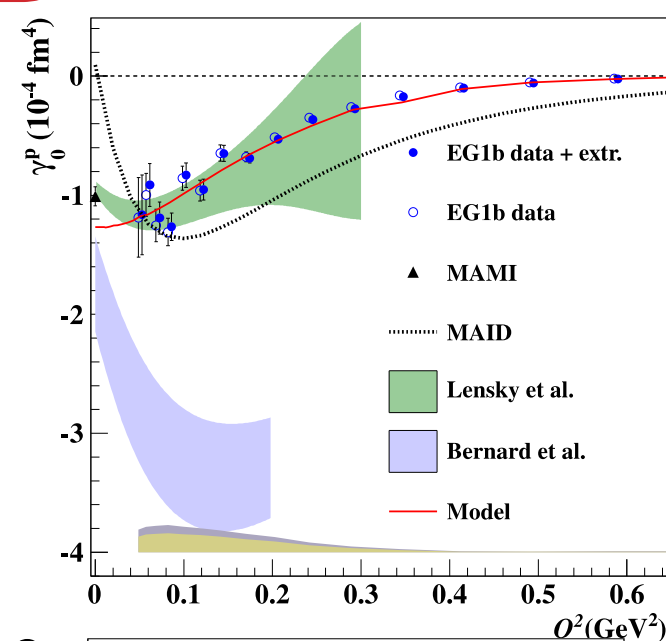
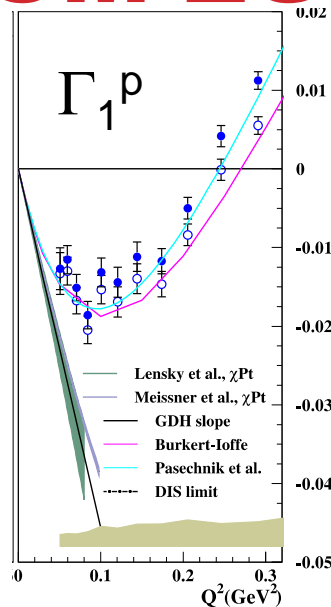
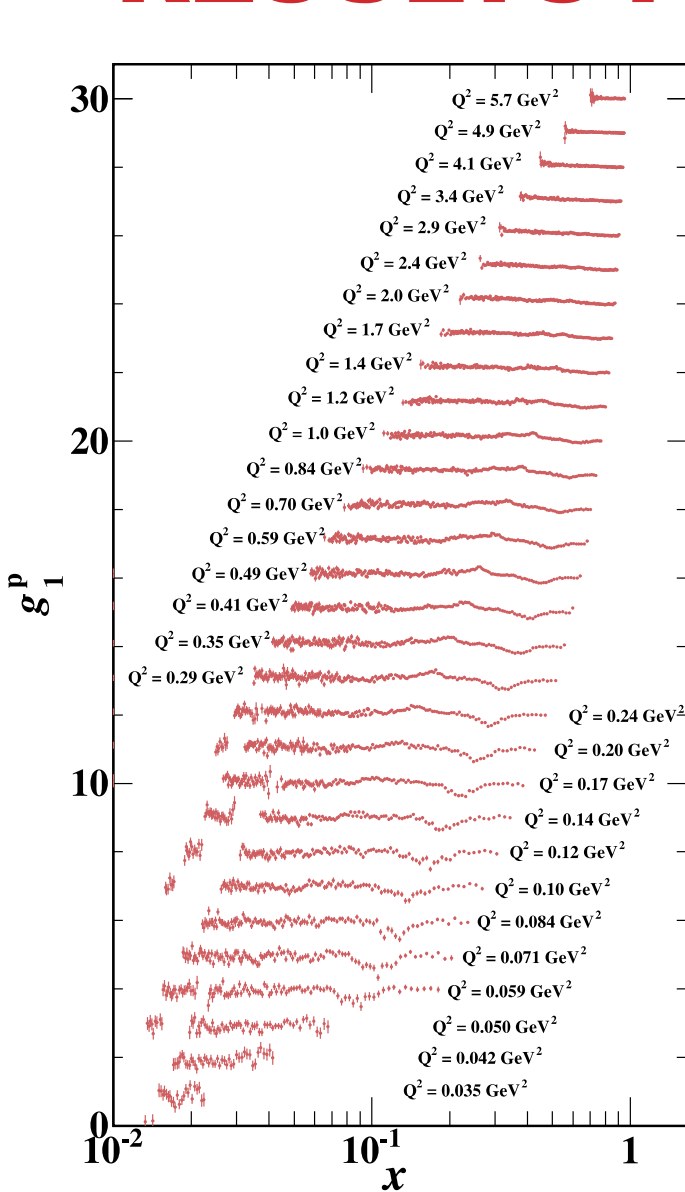


... and EG1-DVCS: Highest statistics at large x , Q^2

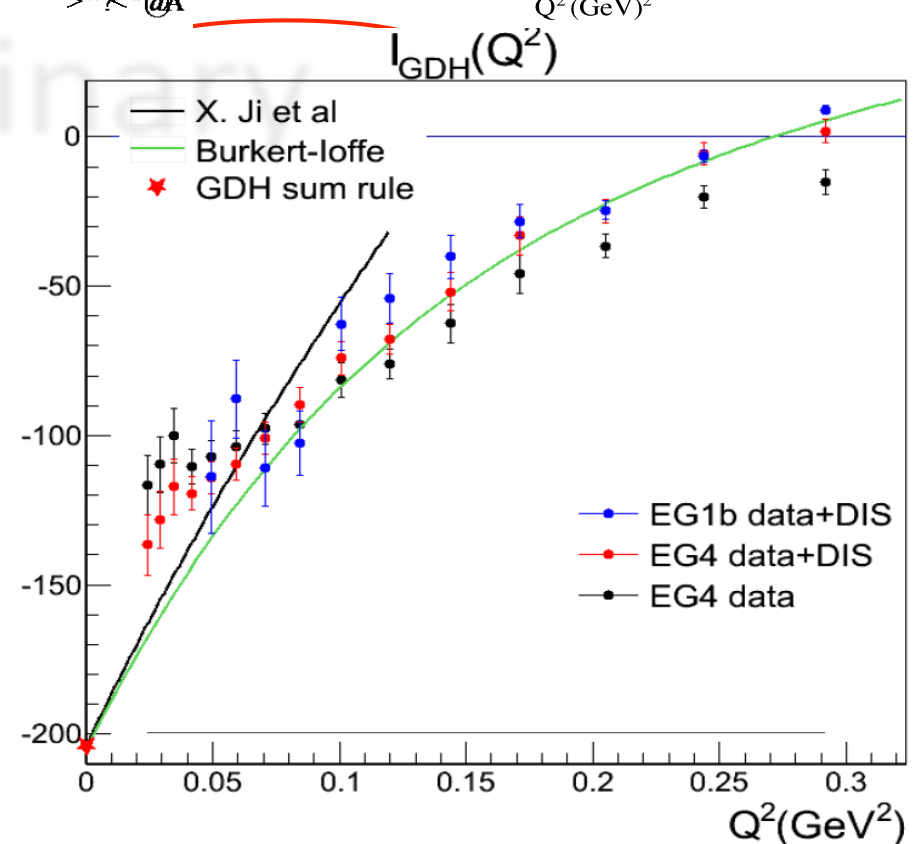
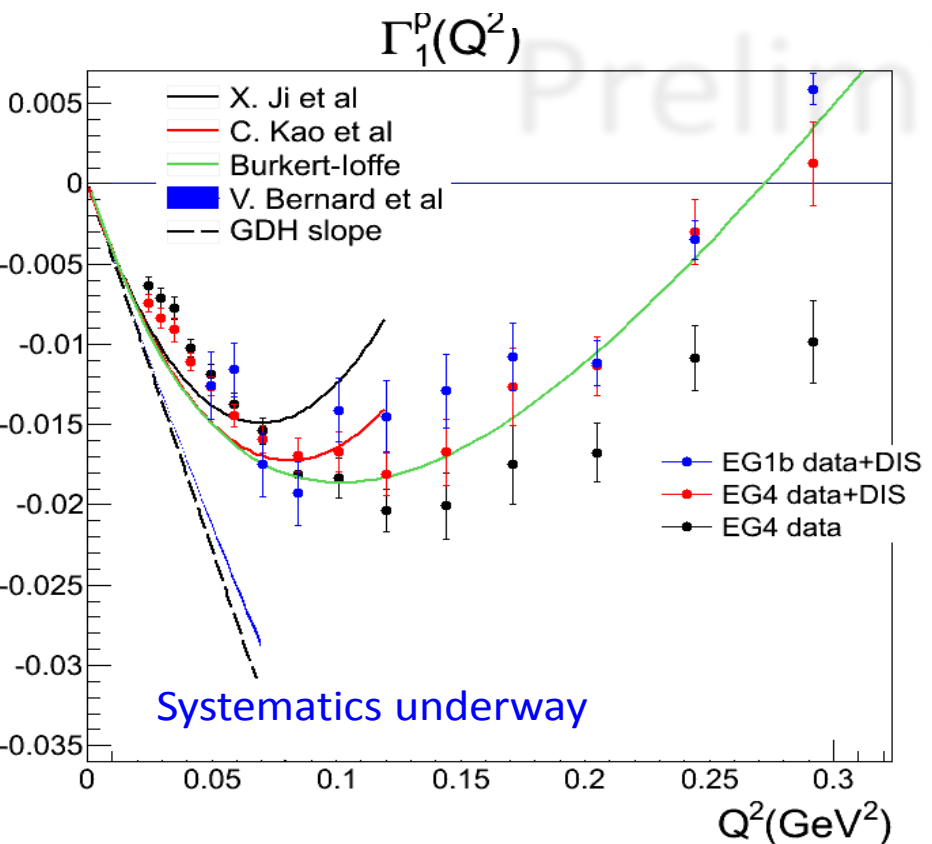
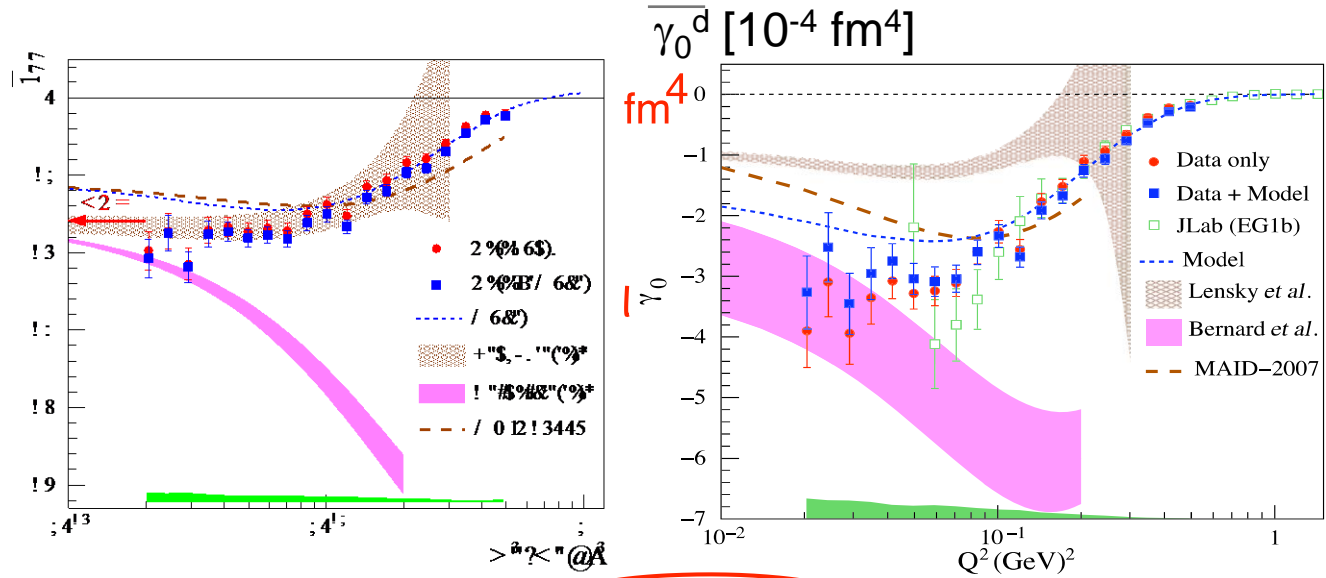


EG4: Focus on low $Q^2 \Rightarrow$ lower beam energies, new Cerenkov for optimal acceptance in outbending configuration, θ_e as small as 6 degrees

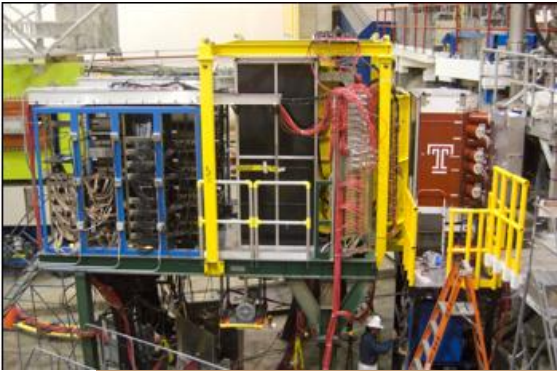
RESULTS FROM EG1B



RESULTS FROM EG4

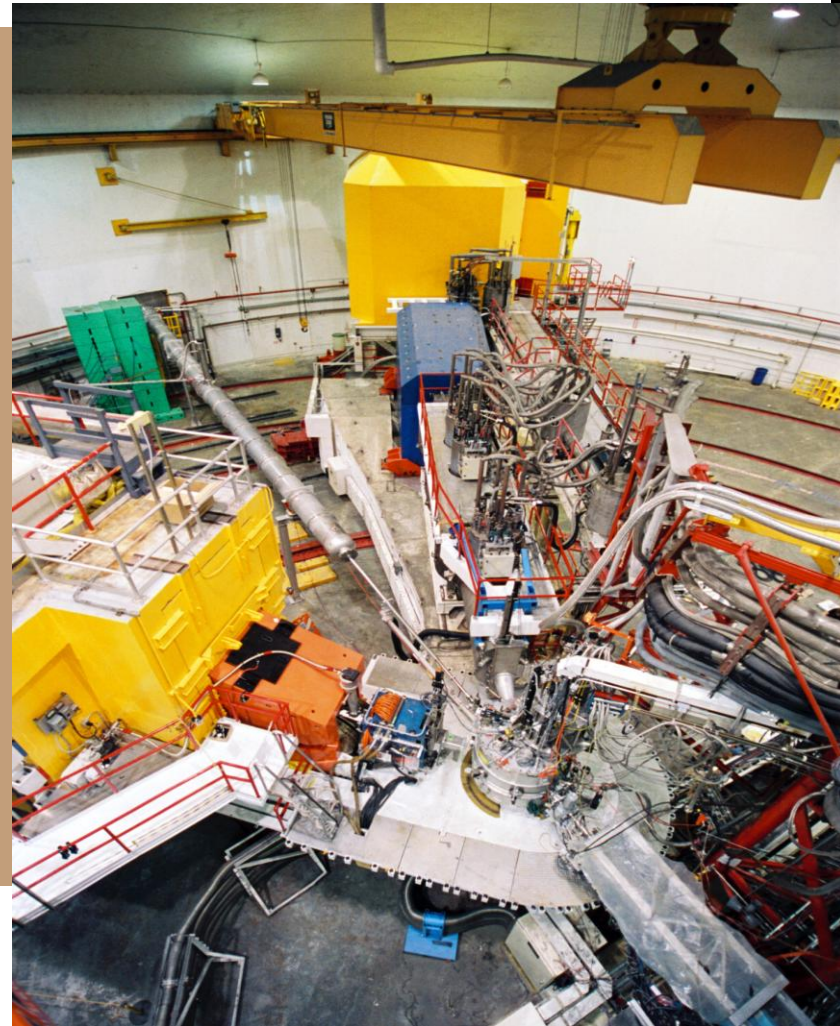
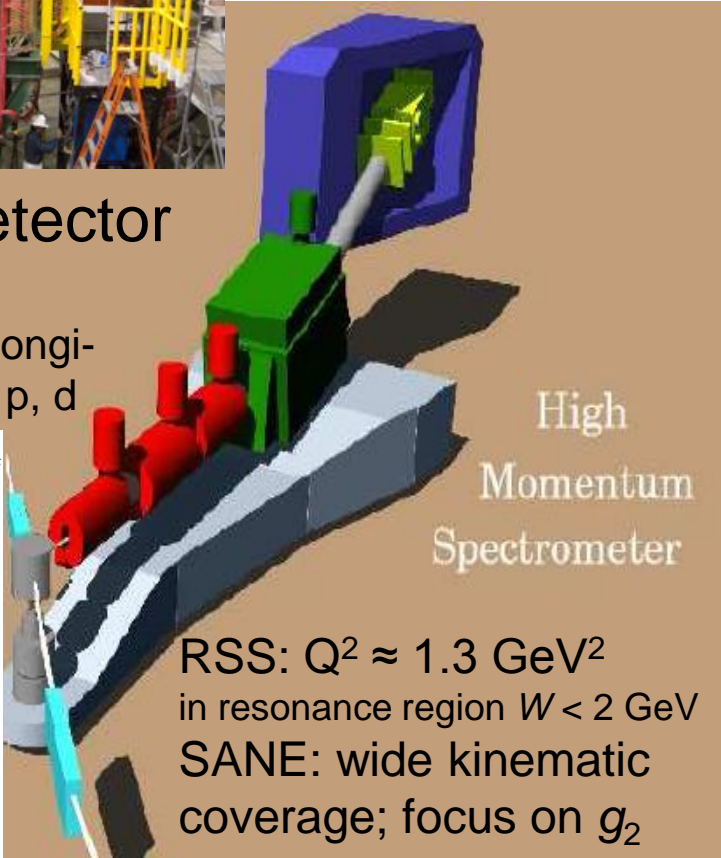
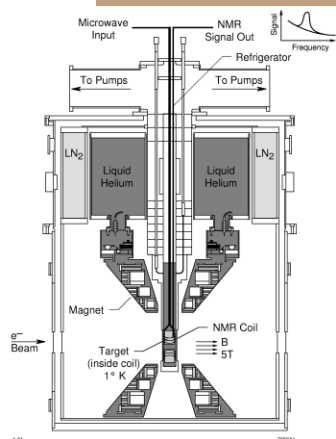


Experimental Hall C

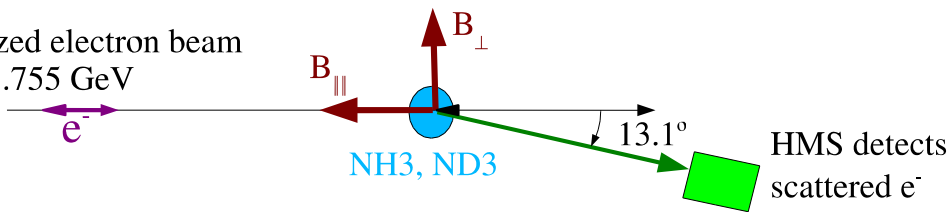


BETA detector

Transverse and longitudinal polarized p, d

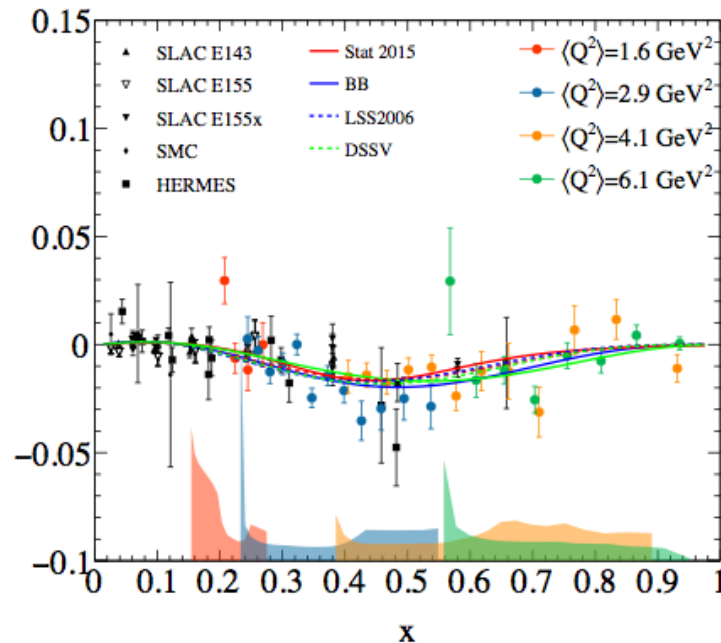
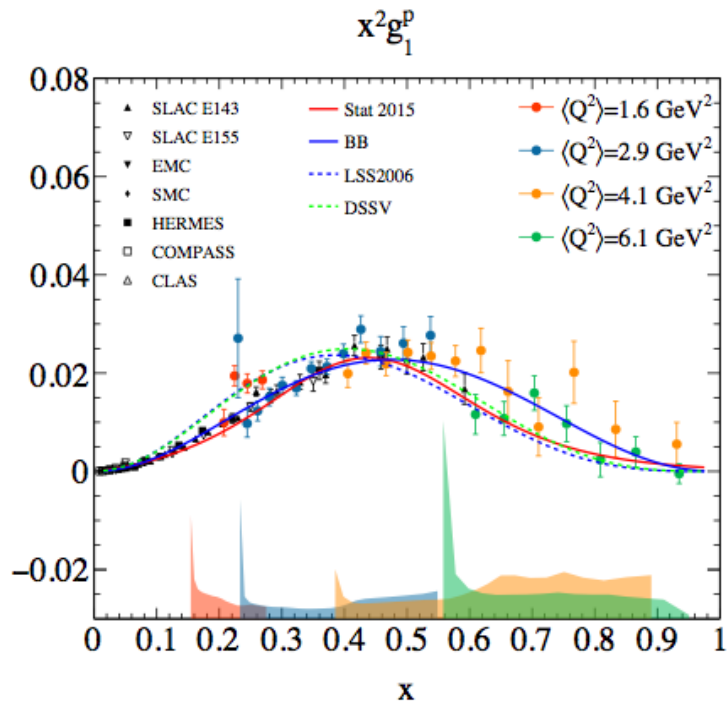
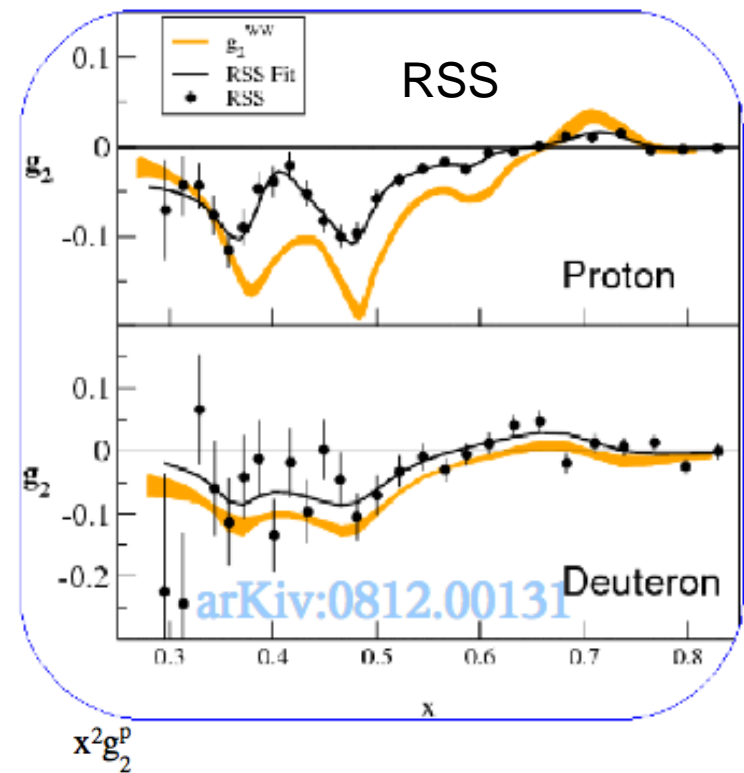


Polarized electron beam
5.755 GeV



The Spin Structure Function g_2 – Hall C

~~SLAC E143 and E155~~



SUMMARY

- ❖ **Low-Q Form Factors and Structure Functions: Long and distinguished program with many dedicated workshops in the past**
- ❖ **RCS, VCS, DVCS (and in the future even VVCS): similarly vibrant community**
- ❖ **Many new data coming out or to be taken soon**
- ❖ **⇒ Significant reduction of the uncertainties on HFS and charge radius extraction due to nucleon/nuclear structure**
- ❖ **Important need: Consistent and accurate models of FFs and SFs (including TPE) using all available data**
- ❖ **...to be matched by new theoretical developments in χ PT, effective theories, dispersion relation analysis and LQCD**