The experiment that motivated two-photon effect studies

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for the SBS Collaboration

Positron Working Group Workshop Meeting

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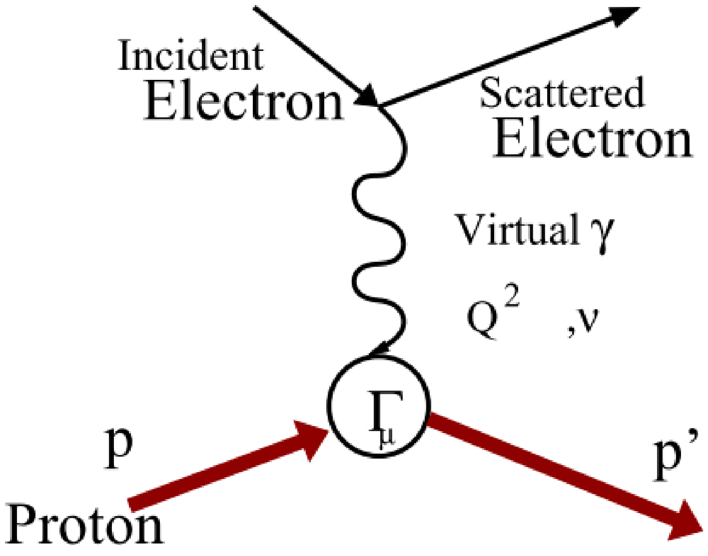
Electron scattering to determine nucleon form factors

One-photon exchange (OPE)



Nucleon vertex:

$$\Gamma_\mu(p',p) = \underbrace{F_1(Q^2)}_{Dirac}\gamma_\mu + \frac{i\kappa_p}{2M_p}\underbrace{F_2(Q^2)}_{Pauli}\sigma_{\mu\nu}q^\nu$$

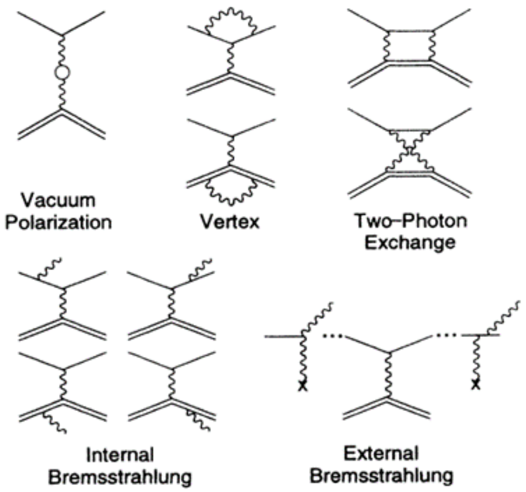
$$G_E(Q^2) = F_1(Q^2) - \kappa_N \tau F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_N F_2(Q^2), \tau = \frac{Q^2}{4M_N}$$

At $Q^2 = 0$ $\quad G_{Mp} = 2.79 \; G_{Mn} = -1.91$

$$G_{Ep} = 1 \; G_{En} = 0$$

- Need to calculate the radiative corrections to get to the OPE



Cross-section measurements $N(e,e')$ ⟶ $$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\frac{E_e}{E_{beam}}\frac{1}{1+\tau}\left(G_E^2 + \frac{\tau}{\epsilon}G_M^2\right)$$

Beam-target Asymmetries $\vec{N}(\vec{e},e')N$ ⟶ $$A_{perp} = \frac{-2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}\frac{G_E}{G_M}}{(\frac{G_E}{G_M})^2 + \frac{\tau}{\epsilon}}$$

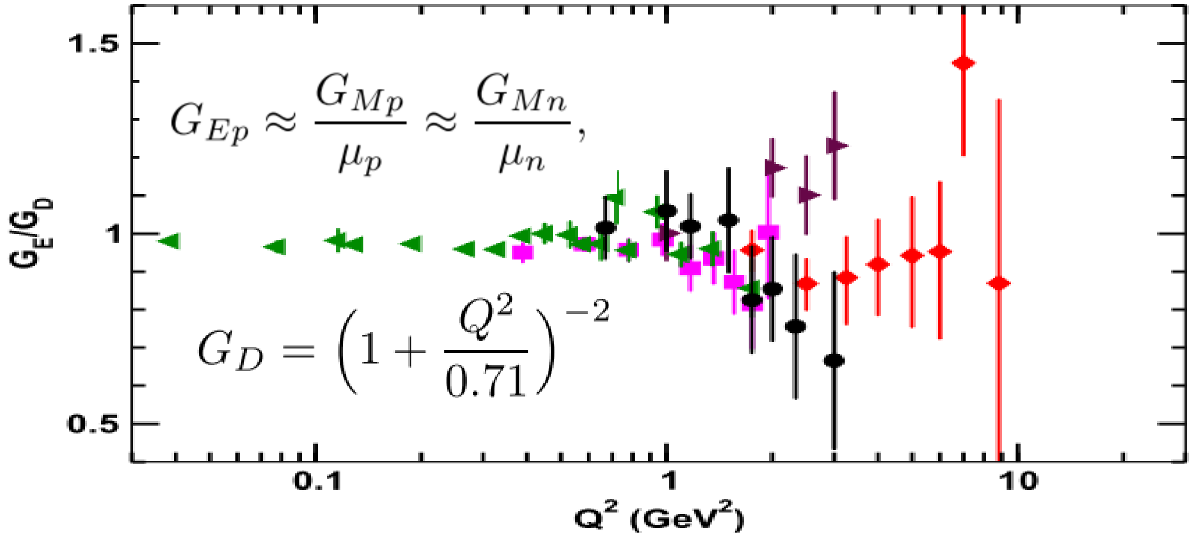
Recoil polarization $N(\vec{e},e')\vec{N}$ ⟶ $$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_{beam}+E_e)}{2M}\tan\frac{\theta_e}{2}$$

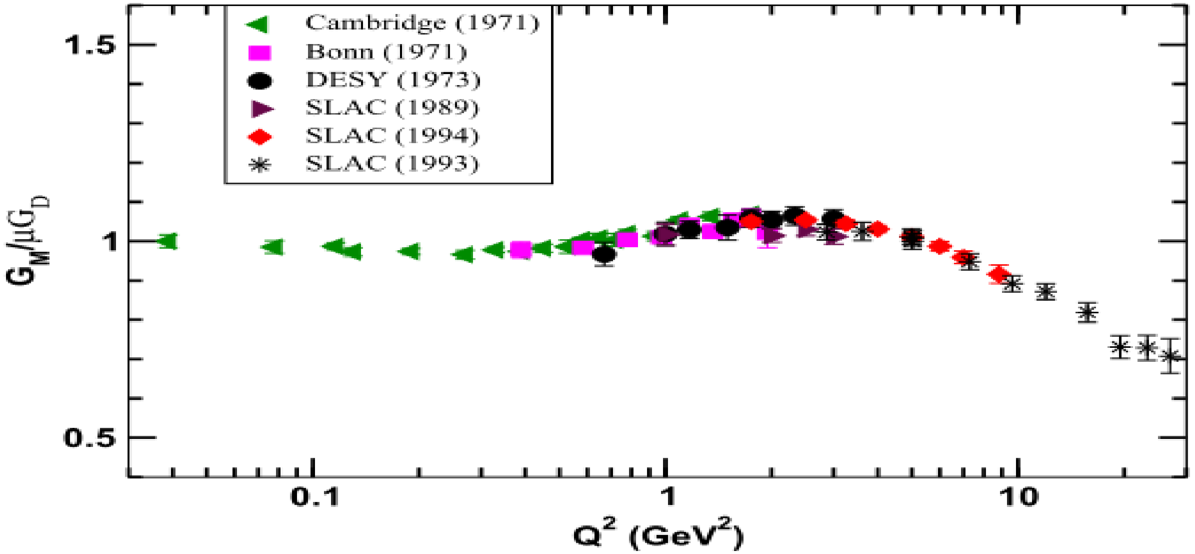
Status of proton form factor in early 1990's

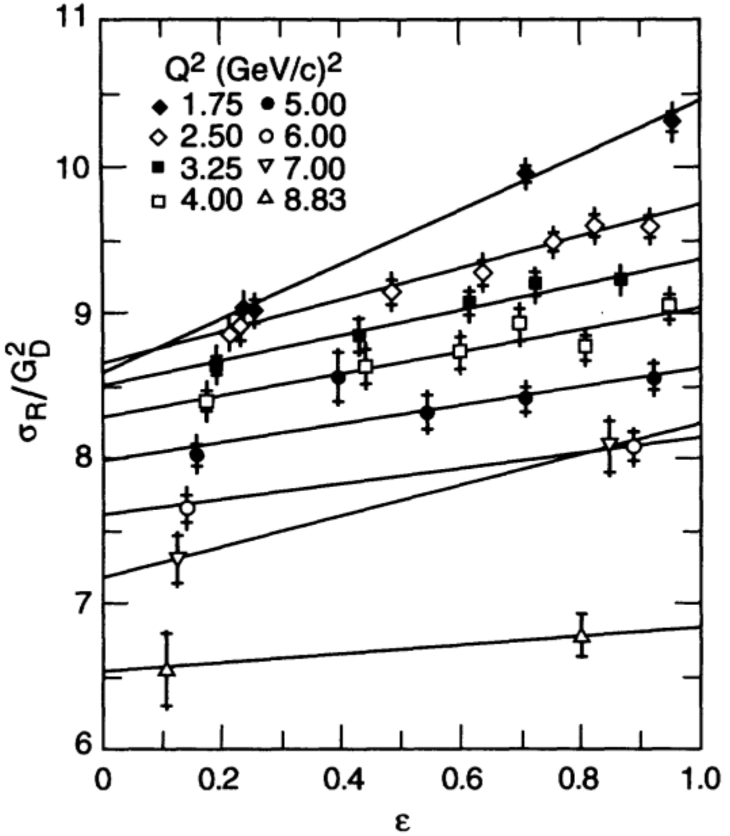
- Since 1950's there is a large body of data using cross sections
- Contribution of G_E to total cross section drops as Q^2 increases.

$$\sigma_R \equiv \frac{d\sigma}{d\Omega}\frac{(1+\tau)\epsilon}{\sigma_{ns}\tau} = \frac{\epsilon}{\tau}G^2_{E_p}(Q^2) + G^2_{M_p}(Q^2)$$

$$\frac{d\sigma}{d\Omega}_{raw} = R_{corr}\left(\frac{d\sigma}{d\Omega}\right)$$







L. Andivahis et al., Phys. Rev. D **50**, 5491 (1994)

$Q^2 = 7$

ε	R_{corr}
0.143	0.85
0.857	0.71

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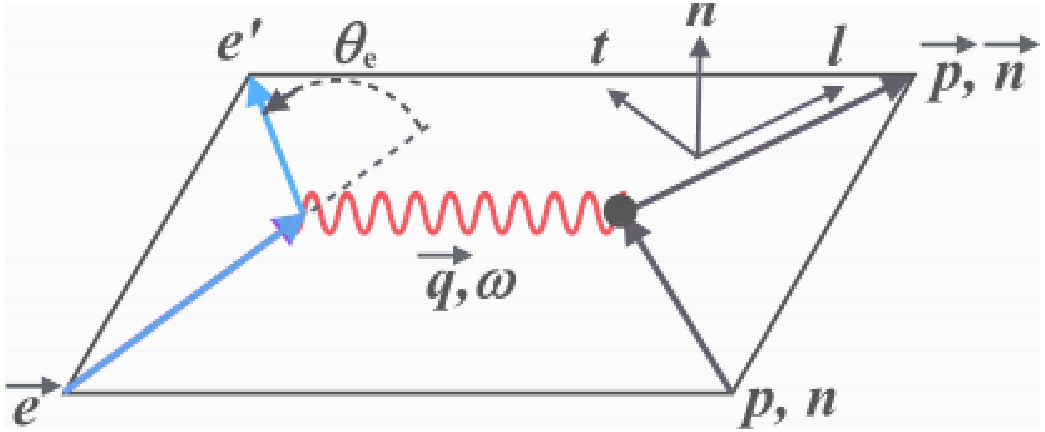
Recoil polarization to measure proton electric form factor

Theorists proposed using polarization observables

A.I. Akhiezer, M.P. Rekalo, Dokl. Akad. Nauk Ser. Fiz. 180, 1081 (1968), Sov. Phys. Dokl. 13, 572 (1968); N. Dombey, Rev. Mod. Phys. 41, 236 (1969); R. G. Arnold, C. E. Carlson, and F. Gross, Phys. Rev. C 23, 363 (1981).

Elastic scattering of polarized electron on an unpolarized nucleon

Proposal in 1989, Charles Perdrisat and Vina Punjabi to extract proton G_E/G_M by recoil polarization using the Hall A HRS spectrometers with a polarimeter in the focal plane of the HRS.



$$I_o P_n = 0$$

$$I_o P_\ell = h P_e \frac{(E_{beam} + E_e)}{M} \sqrt{\tau(1+\tau)} \tan^2 \frac{\theta_e}{2} G_M^2$$

$$I_o P_t = -h P_e 2\sqrt{\tau(1+\tau)} \tan \frac{\theta_e}{2} G_E G_M$$

$$I_o = G_E^2 + \frac{\tau}{\epsilon} G_M^2$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell} \frac{(E_{beam} + E_e)}{2M} \tan \frac{\theta_e}{2}$$

P_n P_t and P_l are normal, transverse and longitudinal components of the recoil polarization

Determine the polarization components with a focal plane polarimeter

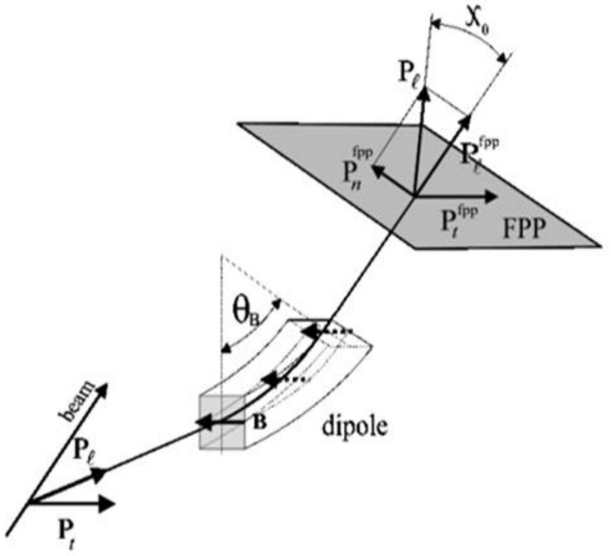


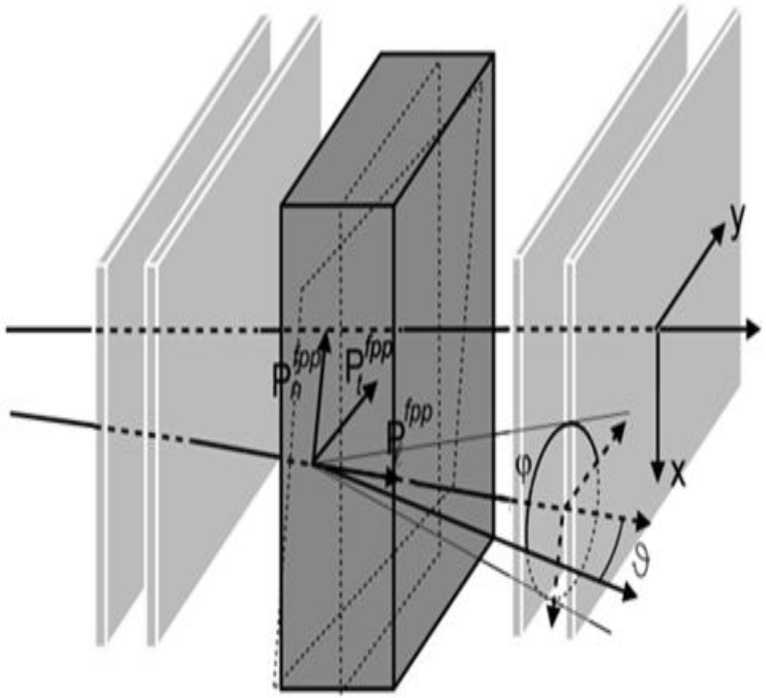
FIG. 15. Precession of the polarization component P_ℓ in the dipole of the HRS by an angle χ_θ.

$$P_t^{\text{fpp}} = h P_t$$

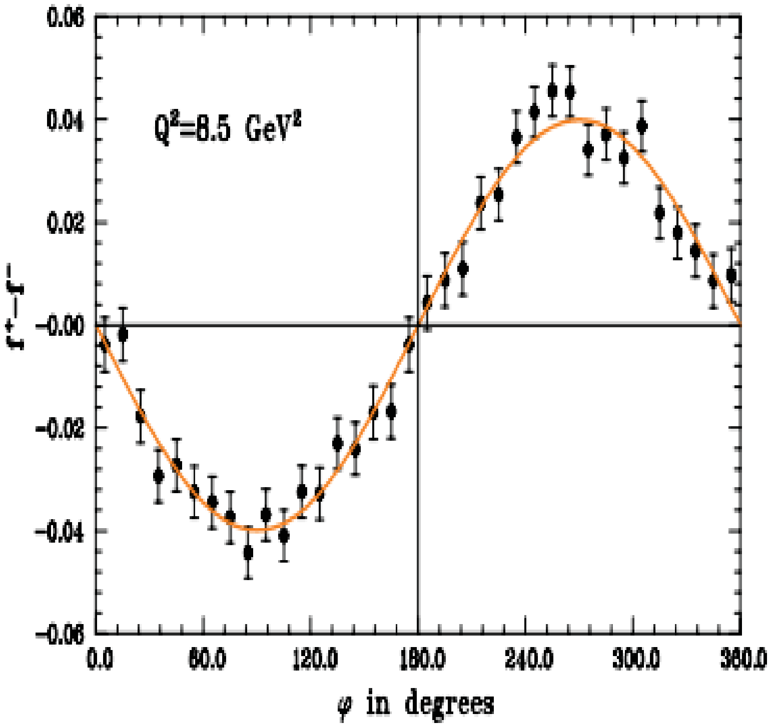
$$P_n^{\text{fpp}} = h P_\ell \sin \chi_\theta$$

$$\chi = \gamma(\mu_p - 1)\Theta_{bend}$$

Scatter the protons in carbon analyzer and measure the azimuthal distributions for each beam helicity

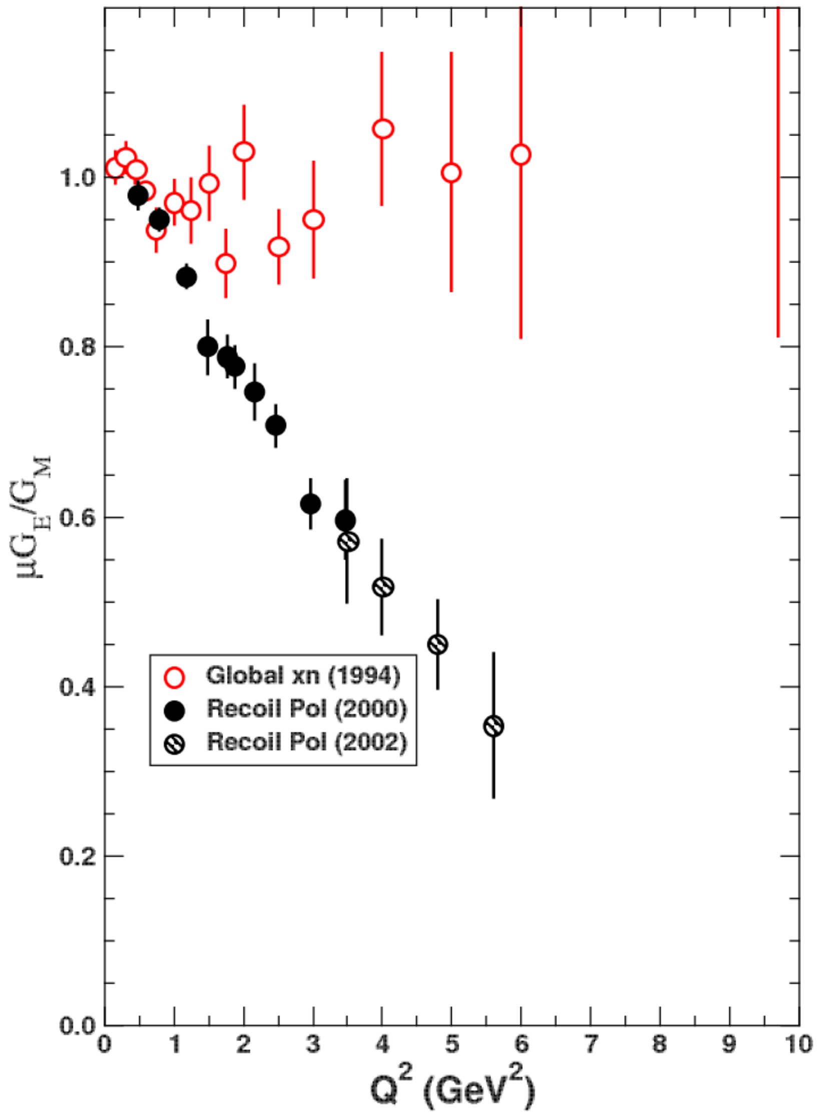


Difference of beam helicity states



$$f_+ - f_- = A_y[P_t^{fpp}\cos\phi - P_n^{fpp}\sin\phi]$$

Recoil polarization measurements at JLab

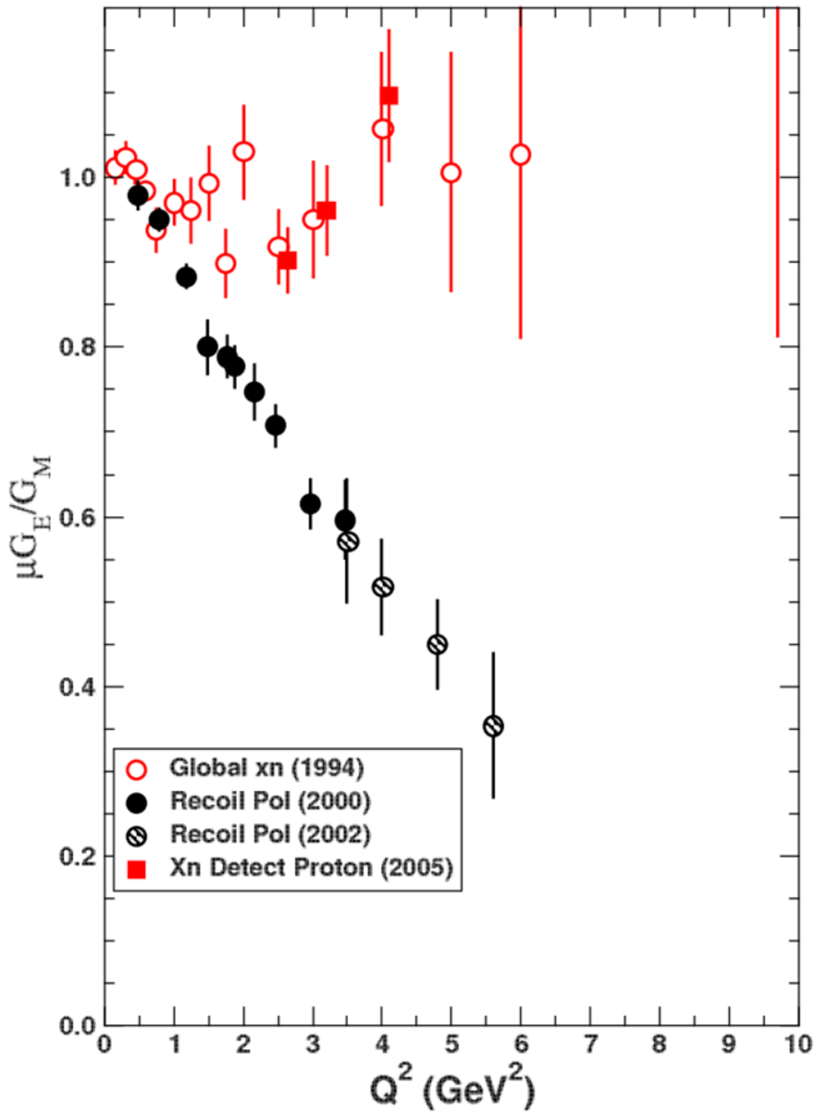


- Global cross section data analysis R.C. Walker et al., Phys. Rev. D 49, 5671 (1994)
- Recoil polarization measurements
  - Measured to Q^2 = 3.5 GeV^2 in Hall A using two HRS with FPP in RHRS *M.K. Jones et al. Phys. Rev. Lett. 84, 1398 (2000). Long paper in V. Punjabi et al., Phys. Rev. C 71, 055202 (2005)*
  - Measured to Q^2 = 5.6 GeV^2 with FPP moved to LHRS and Calorimeter. *O. Gayou et al., Phys. Rev. Lett. 88, 092301 (2002) and A. J. R. Puckett et al., Phys. Rev. C 85:045203 (2012)*

<u>Why the difference between the two methods?</u>

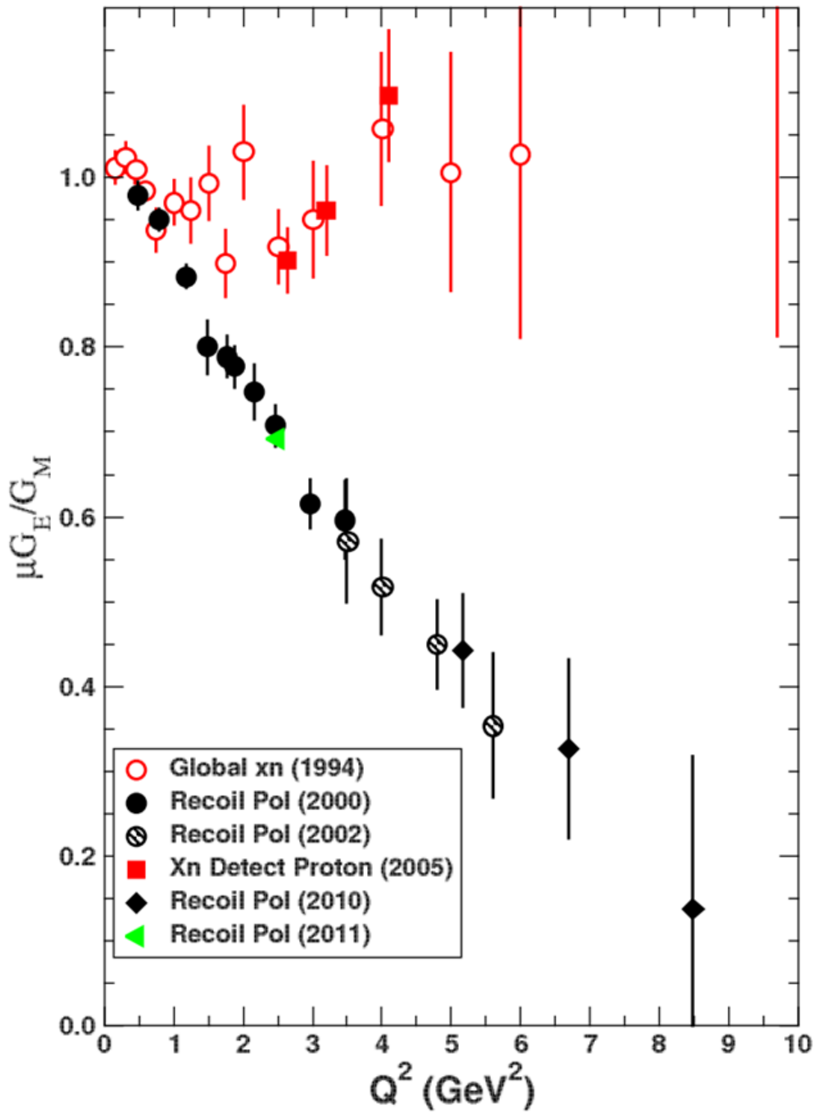
- Systematic problem with recoil polarization
  - Used different HRS. Develop “geometric” model to evaluate the error on the spin matrix through the HRS
- Cross section measurements
  - Re-evaluate the standard radiative correction.
  - Redo global analysis. New Hall C elastic data.
  - New measurement elastic p(e,p). Detecting the elastic proton.
  - Calculate hard two photon exchange contribution

Recoil polarization measurements at JLab

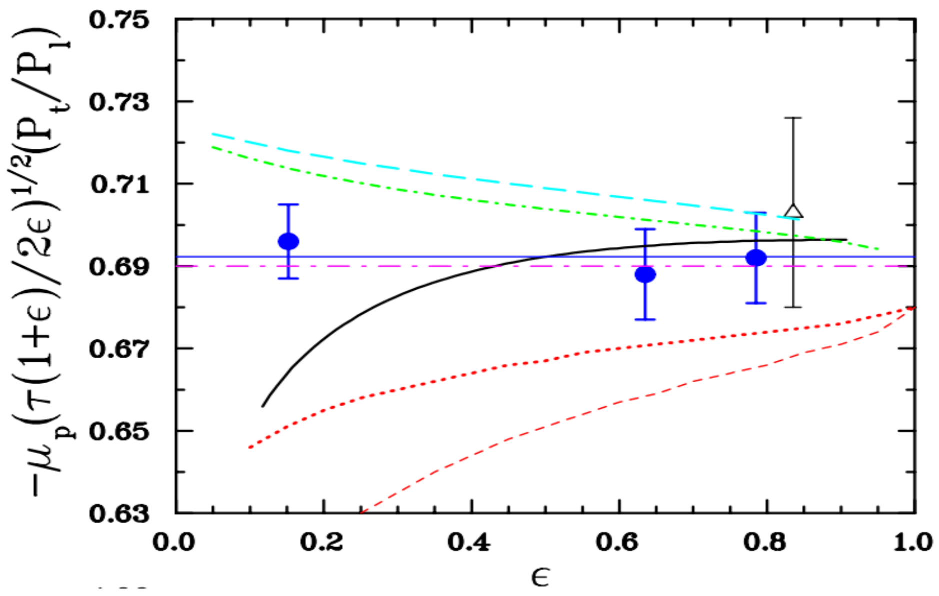


- Detect elastic proton and do Rosenbluth separation
  - Proton momentum fixed at each ε
  - Cross section is nearly constant with e
  - Reduces size of ε-dependent radiative corrections
  - Reduces systematic error from beam energy and scattering angle
  - I. Qattan et al. PRL 94, 142301 (2005),Recent long paper

Recoil polarization measurements at JLab

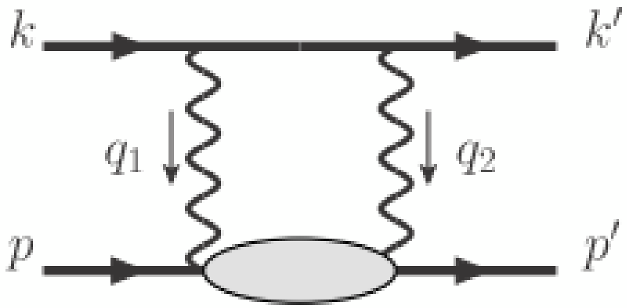


- Move to Hall C to do recoil polarization
- New FPP in HMS and larger Calorimeter
  - Measure to $Q^2 = 8.5$ GeV^2
    - *A. Puckett et al., Phys. Rev. Lett. 104, 242301 (2010)*
  - Measure to $Q^2 = 2.5$ GeV^2. Measure ε dependence
    - *M. Meziane et al. , Phys. Rev. Lett. 106, 132501 (2011)*

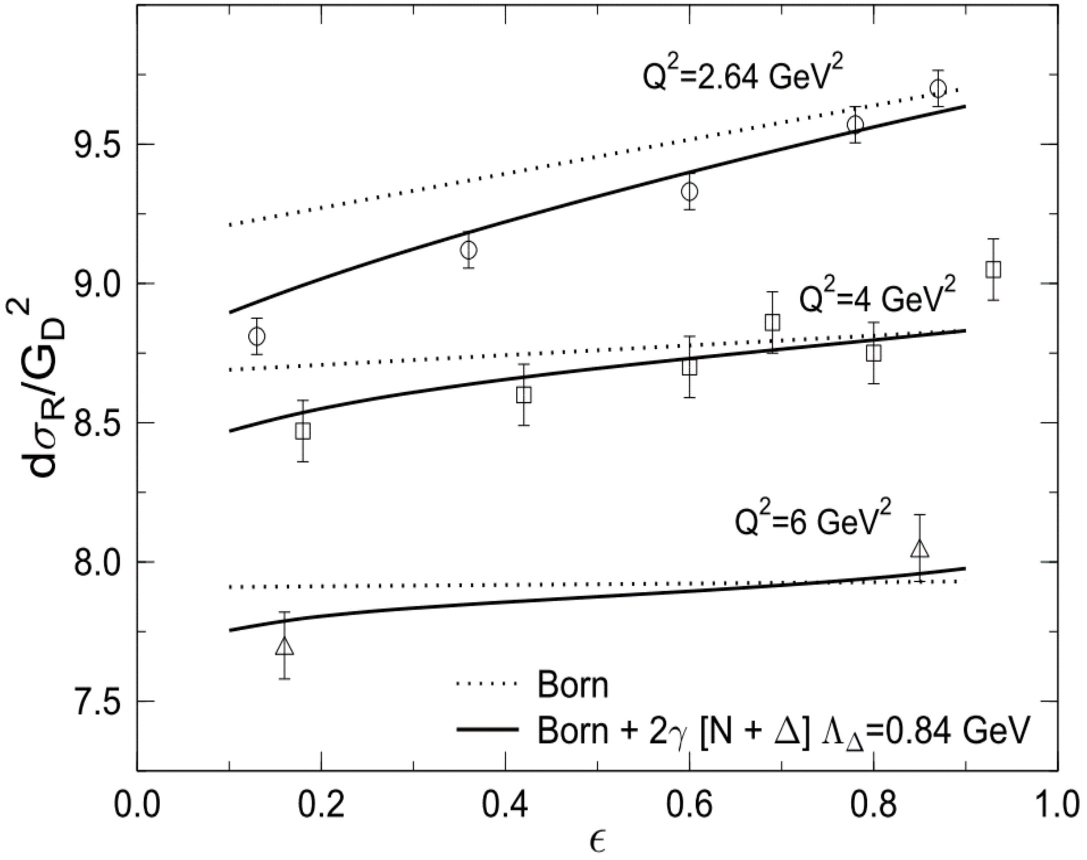


Two-photon exchange (TPE) contribution to elastic ep scattering

Two photon exchange box diagram



- Calculation of TPE box diagram with N and Δ by S. Kondratyuk, P. G. Blunden, W. Melnitchouk, and J. A. Tjon, Phys. Rev. Lett. 95 , 172503 (2005)
- Born calculation uses G_E/G_M from recoil polarization experiment



- Guichon and Vanderhaeghen Phys. Rev. Lett. 91, 142303 (2003) provided a generalized formalism for elastic scattering.
- Calculation of the two hard photon box diagram exchange (TPE) contribution involves knowledge of the hadronic structure
- At large Q^2 , TPE contribution of a few percent of the cross section could explain the difference and is the same order as the contribution of G_E to the cross section.

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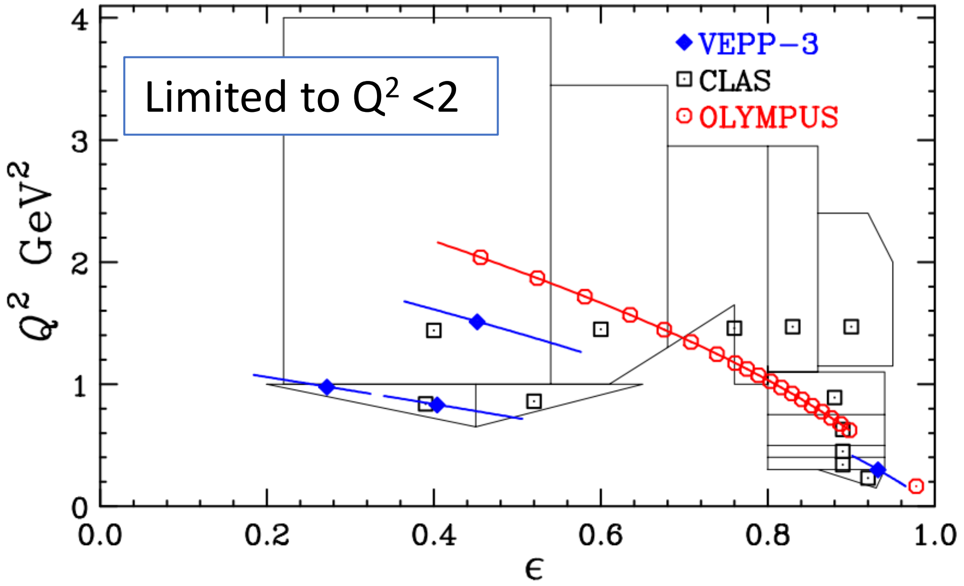
Direct measure of Two-photon exchange contribution

<u>Measure ratio of positron+proton to electron+proton elastic cross sections</u>

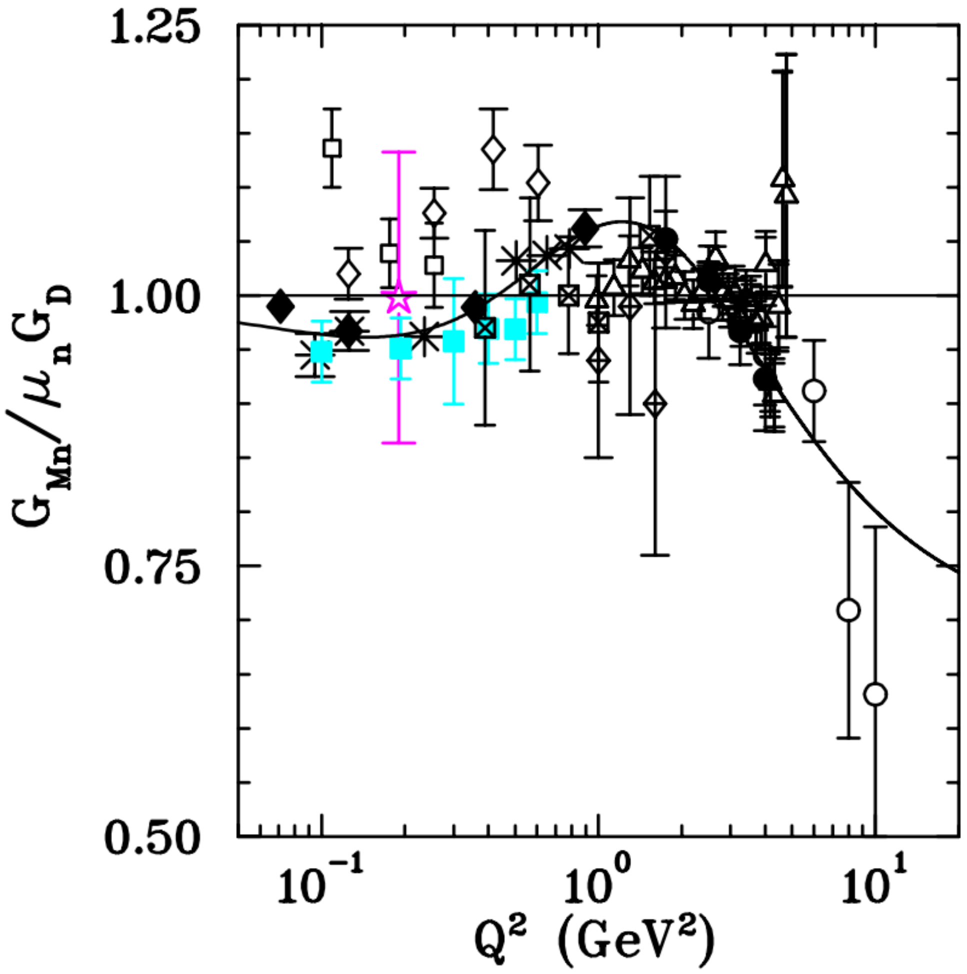
<u>Experiments</u>

- Using monoenergetic beams from a storage ring incident on an internal gas target.
  - The VEPP-3 experiment at Novosibirisk at 1.0 and 1.6 GeV I. A. Rachek et al. , Phys. Rev. Lett. 114 , 062005 (2015), arXiv:1411.7372.
  - The OLYMPUS experiment at DESY at 2.01 GeV B. S. Henderson et al. , Phys. Rev. Lett. 118 , 092501 (2016)
- The CLAS experiment used a mixed beam of positrons and electrons with beam energies from 0.8 to 3.3 GeV allowing for simultaneous detection of electron and positron scattering events in the CLAS D. Adikaram et al. , Phys. Rev. Lett. 114 , 062003 (2015),
- Review article: A. Afanasev, P.G. Blunden, D. Hasell, B.A. Raue, Progress in Particle and Nuclear Physics, v95, 2017

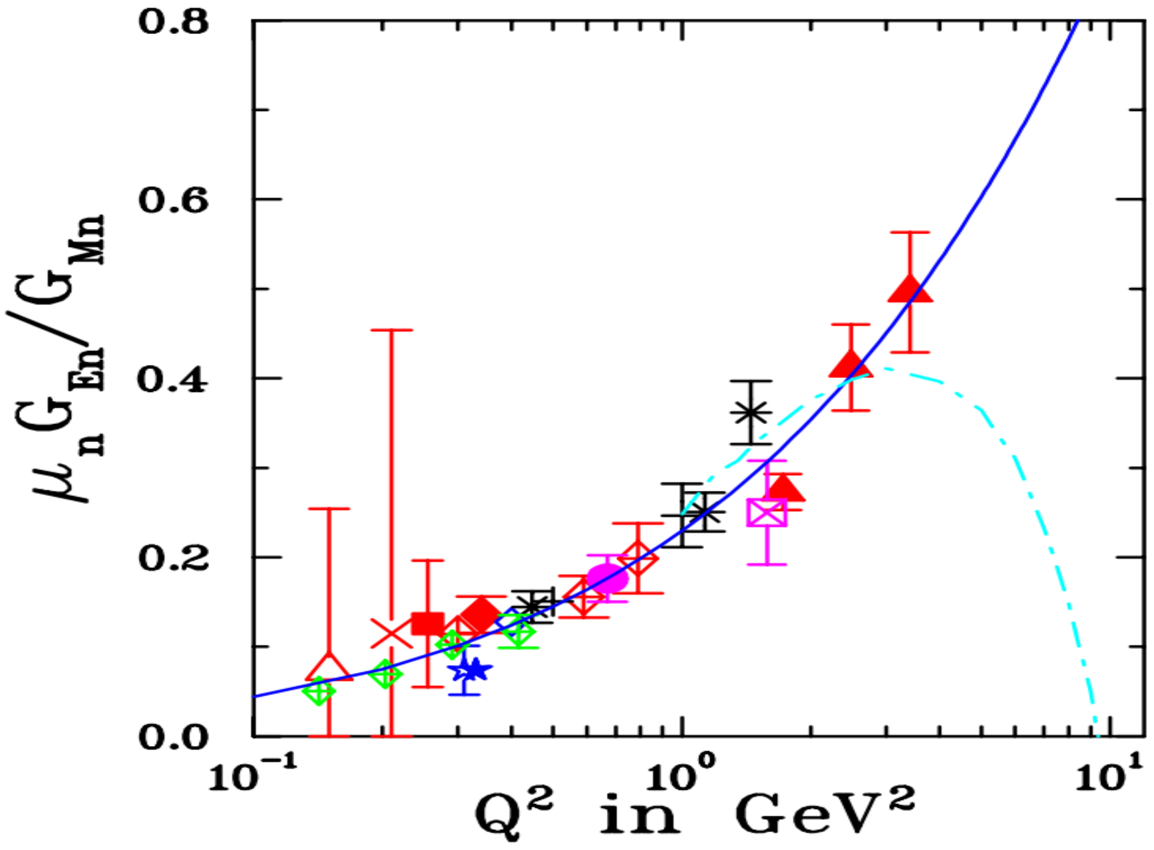


Status of Neutron Magnetic and Electric form factors around 2010

- Hall B measured neutron G_M with CLAS for Q^2 = 1 to 4.8 GeV^2
- Early SLAC measurements to Q^2 = 10 GeV^2
- Experiments at Mainz and JLab for Q^2 < 1 GeV^2



- Hall A measured neutron G_E/G_M to Q^2 = 3.4 GeV^2 with beam-target asymmetries
- JLab and Mainz various experiments use quasi-free scattering on deuteron in recoil polarization and beam-target asymmetry to G_E/G_M to Q^2 < 2 GeV^2

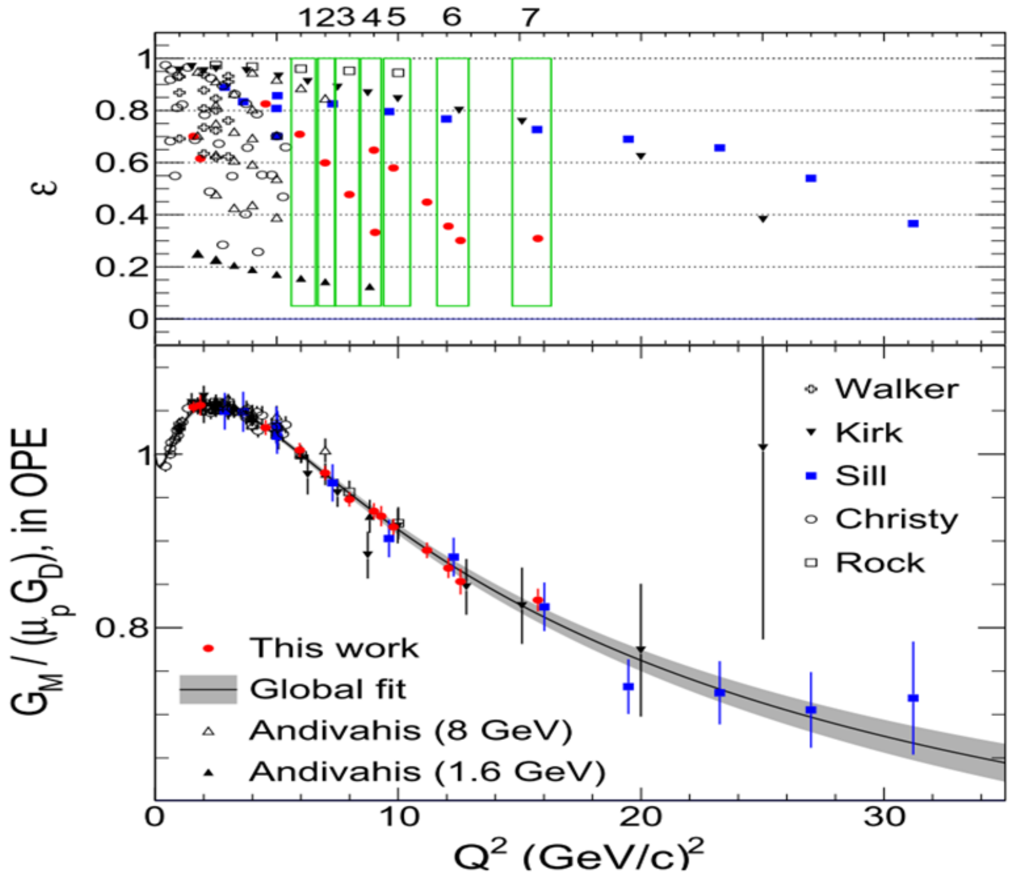


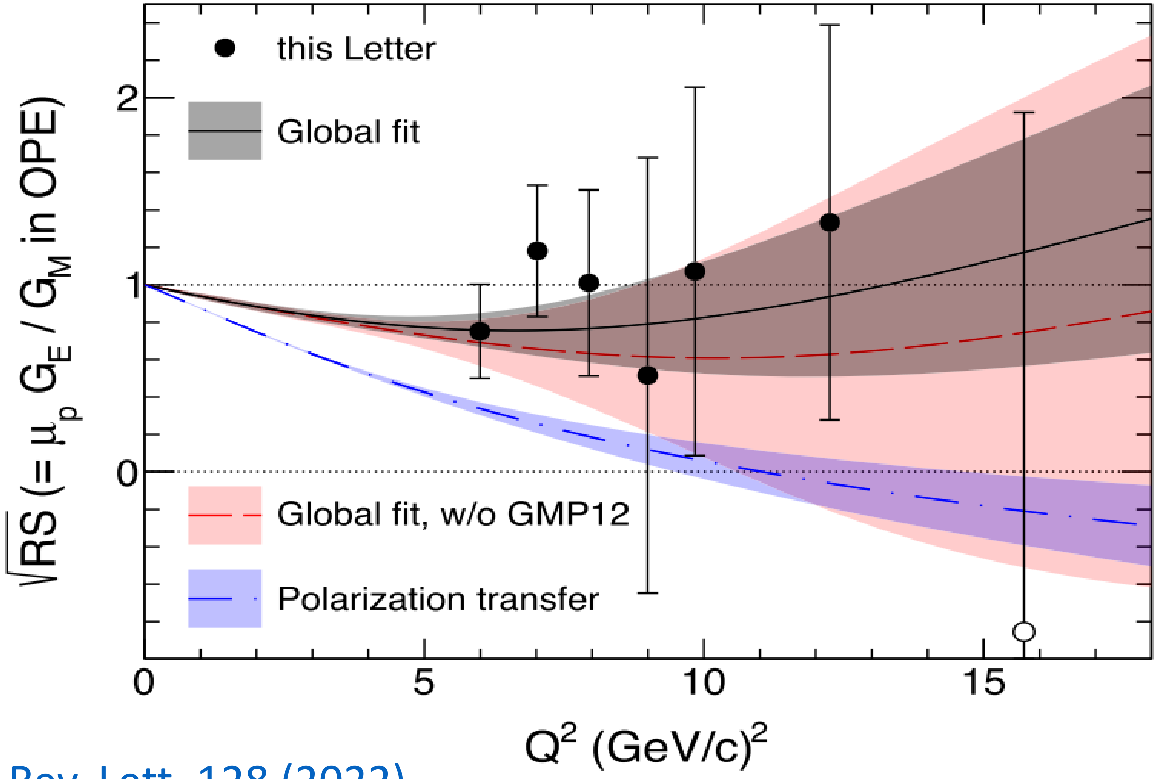
Hall A: Proton magnetic form factor, G_M, at Q^2 = 15.75

- High luminosity needed to do longitudinal-transverse separation.
- Use the Left and Right HRS in Hall A to measure cross sections at different epsilon to extract G_M and G_E/G_M.
- Hard two-photon exchange contributions at 4% level to explain difference

$$\sigma_R = \tau\, G_M^2(Q^2) + \varepsilon\, G_E^2(Q^2) = \sigma_T + \varepsilon\, \sigma_L$$
$$= G_M^2(Q^2)(\tau + \varepsilon\, \mathrm{RS}(Q^2)/\mu_p^2),$$

$$G_M = \mu_p(1 + a_1\tau)/(1 + b_1\tau + b_2\tau^2 + b_3\tau^3),$$
$$\mathrm{RS} = 1 + c_1\tau + c_2\tau^2.$$

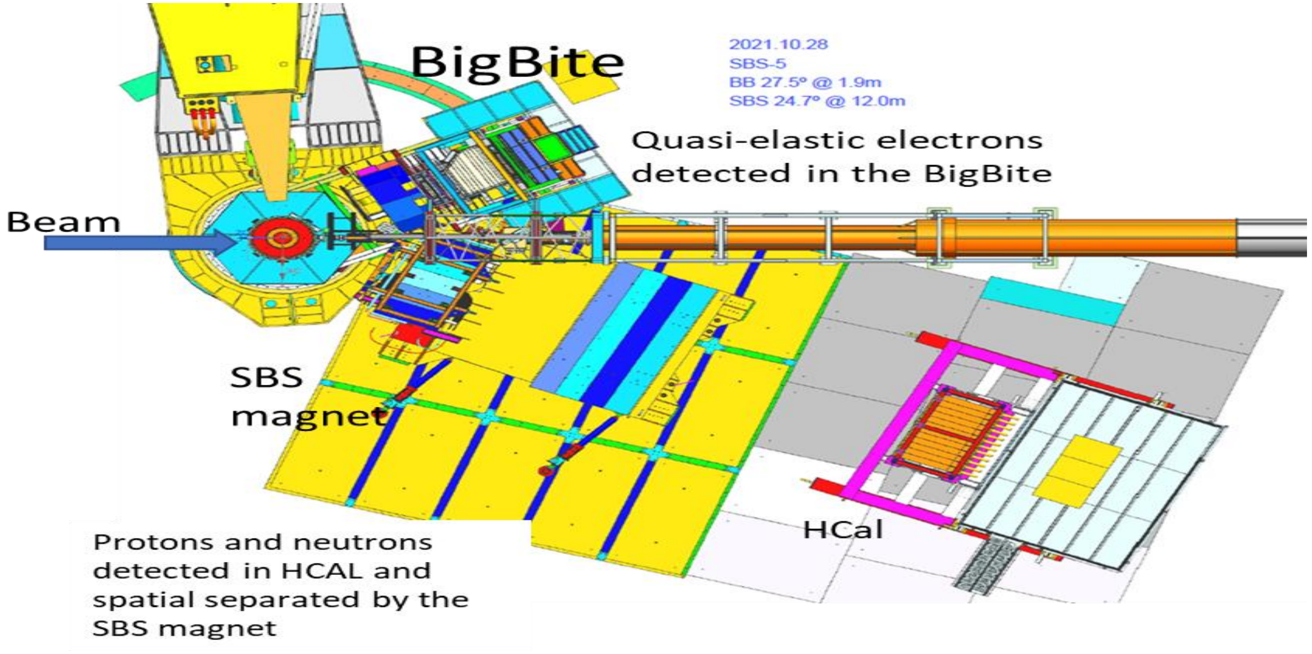


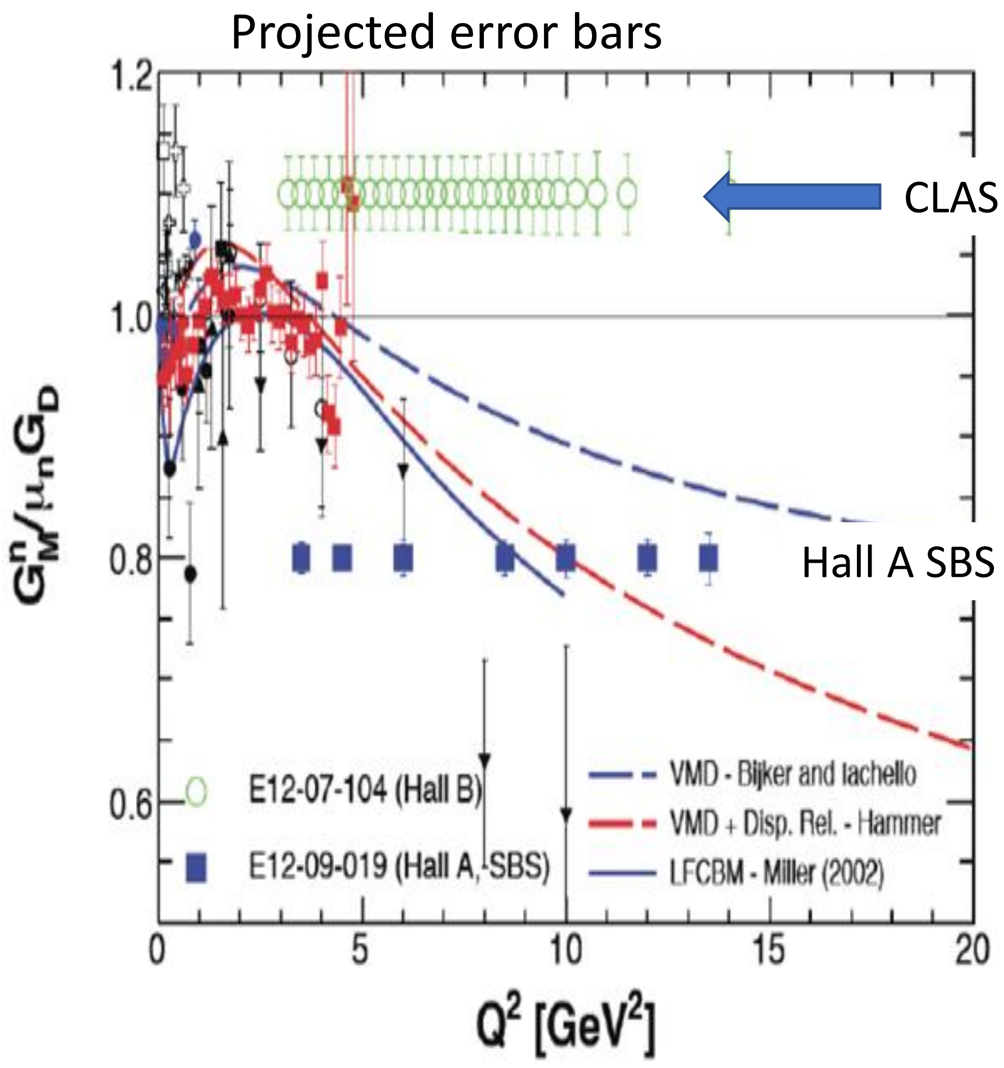


Plots from [Phys. Rev. Lett. 128 (2022)]

Measurement of neutron magnetic form factor

- Measured GMn from the ratio of cross section in quasi-elastic D(e,e'n) to D(e,e'p)
- Measured at Q^2 = 3, 4.5, 7.4 , 9.9 and 13.5 GeV^2
- Ran from Sept 2021 to March 2022
- Experiment E12-20-010 (nTPE)
  - At Q^2 = 4.5 GeV^2 measured an additional point at ε= 0.80
  - Rosenbluth separation to determine neutron TPE.
- Hall B has completed the same type of measurement using CLAS





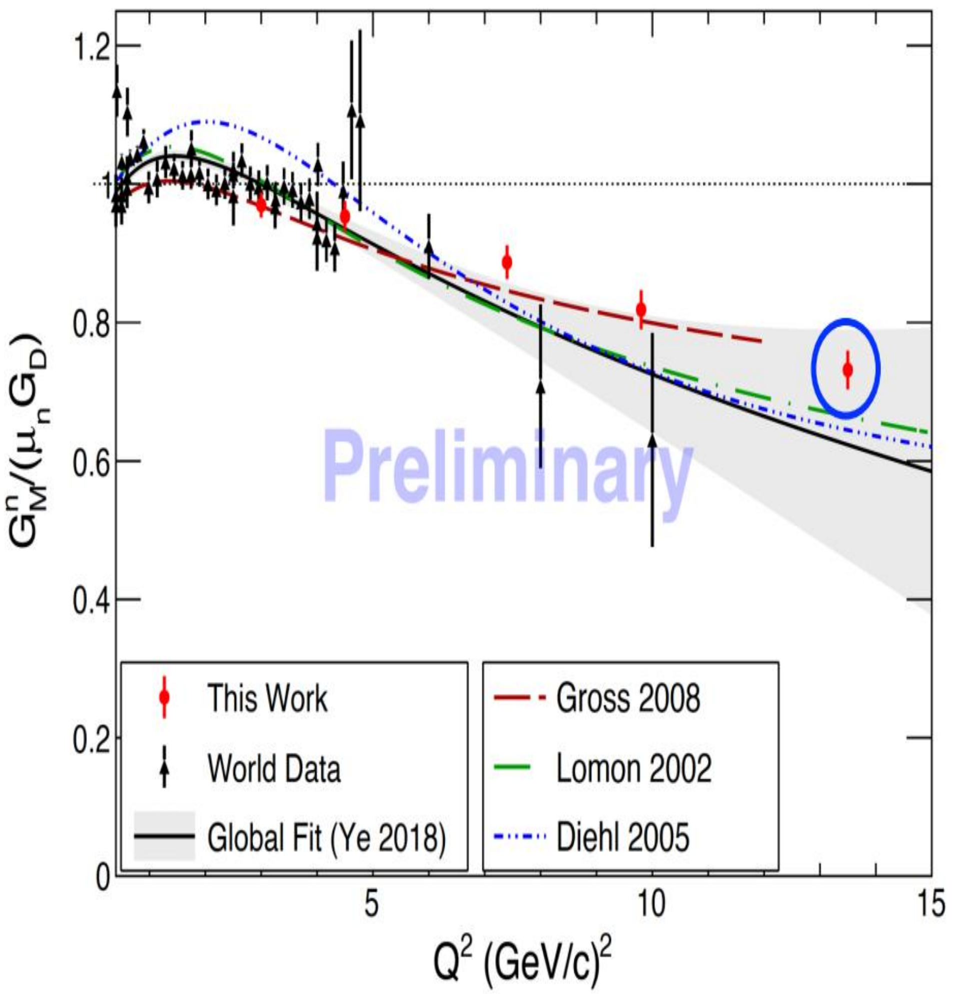
Measurement of neutron magnetic form factor

$$R_{np} \equiv \frac{\sigma_{d(e,e'n)p}}{\sigma_{d(e,e'p)n}} \approx \frac{\sigma_{en\to en}}{\sigma_{ep\to ep}}$$

$$\approx \frac{\epsilon {G_E^n}^2 + \tau {G_M^n}^2}{\epsilon {G_E^p}^2 + \tau {G_M^p}^2}$$

$$\implies G_M^n \approx \sqrt{\frac{R_{np}\sigma_R^p - \epsilon {G_E^n}^2}{\tau}}$$

- Plot from Provakar Datta's talk at GHP2025 and APS April 2025.
- Thanks to hard work of the graduate students involved in the SBS GMn experiment: Vanessa Brio (Catania University), John Boyd (University of Virginia), Provakar Datta (University of Connecticut), Nathaniel Lashley-Colthirst (Hampton University), Ralph Marinaro (University of Glasgow), Anuruddha Rathnayake (University of Virginia) , Maria Satnik (William & Mary), Sebastian Seeds (University of Connecticut), Ezekiel Wertz (College of William and Mary)

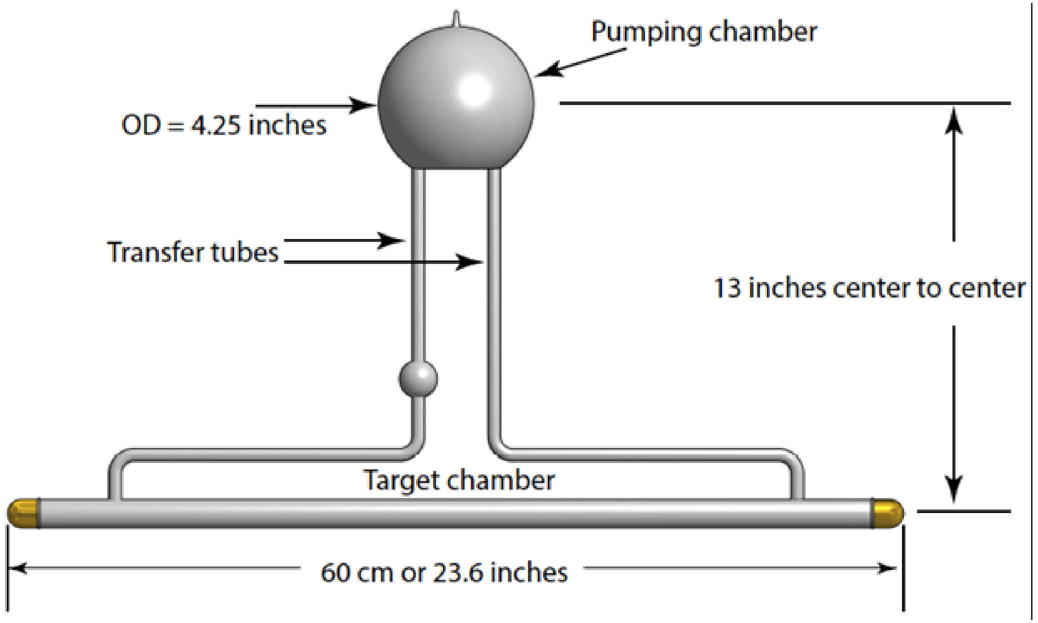


Neutron electric form factor by beam-target asymmetry

- Used polarized 3He target as an effective polarized neutron target. U of Virginia led effort with College of W&M and JLab support.
- Measured asymmetry in scattering of polarized electron beam on polarized neutron
- Achieved peak performance of 55% neutron polarization at 50uA beam current with 60cm long cell

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$A = -\frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}}{G_E^2 + \frac{\tau}{\epsilon}G_M^2}\Big[\sin\theta^*\cos\phi^* G_E G_M + \sqrt{\tau\left[1+(1+\tau)\tan^2\frac{\theta_e}{2}\right]}\cos\theta^* G_M^2\Big].$$



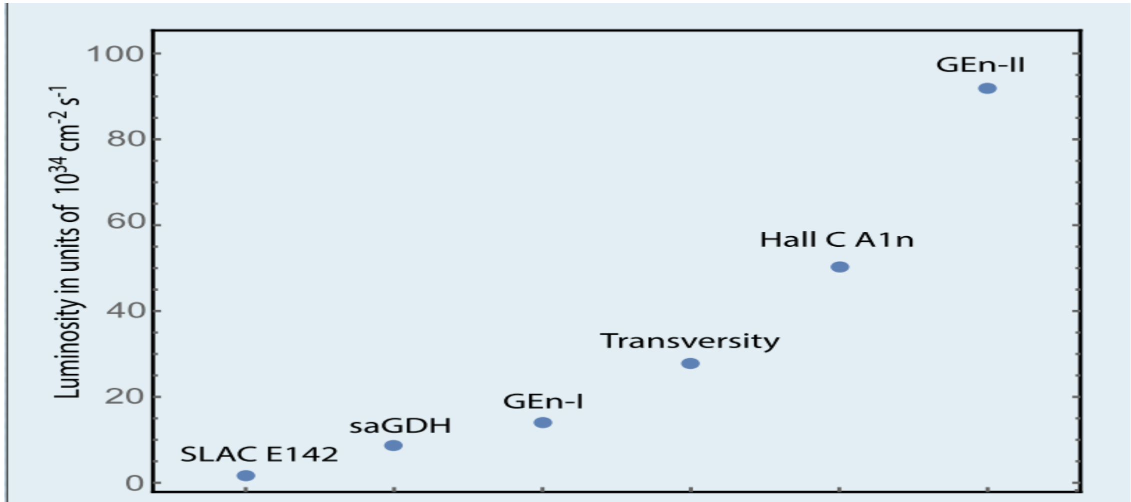
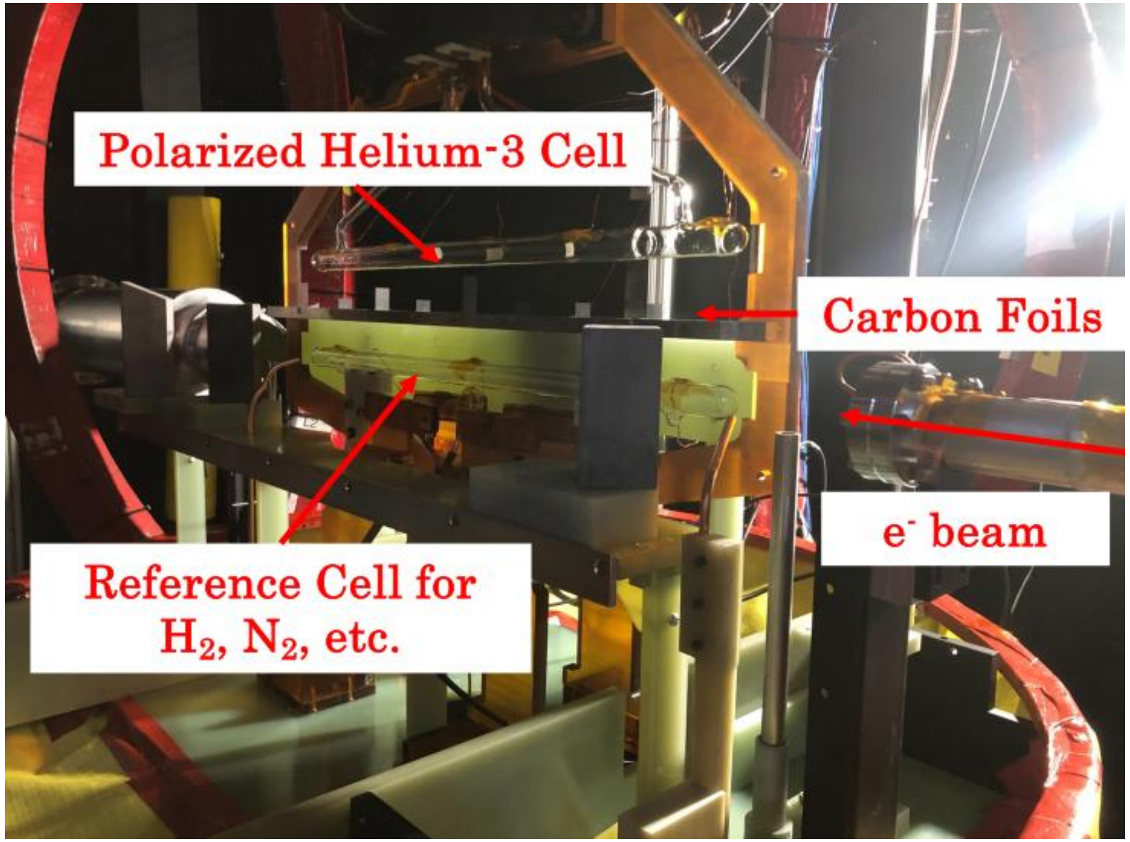


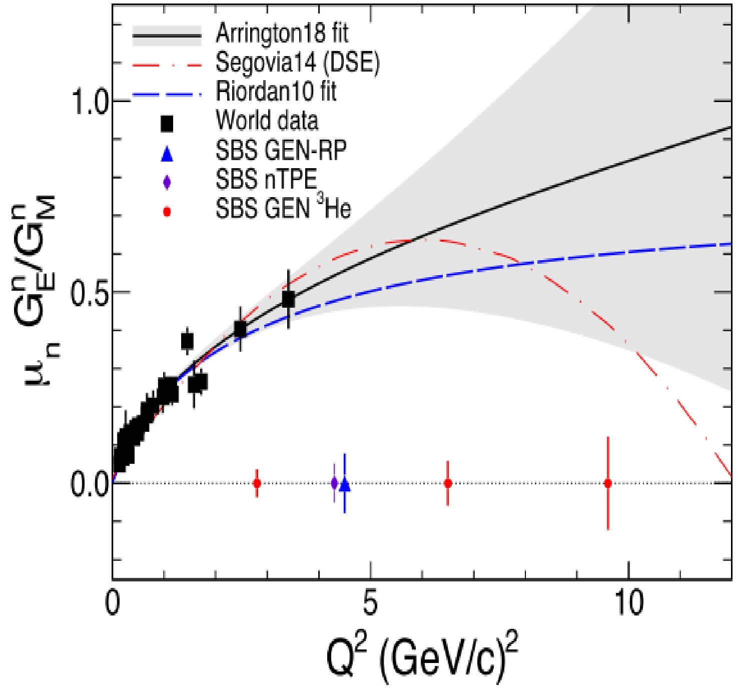
Figure 3. Luminosity, weighted by the square of polarization, is shown for the polarized ^{3}He targets used in various experiments dating back to SLAC E142 (published in 1991).

GEN2: Neutron electric form factor by beam-target asymmetry

- Use same BigBite and Super BigBite Spectrometer as GMN
- Measured at Q^2 = 3, 6.8 and 9.9 GeV^2
  - Increased Q^2 range by approximately 3x
- Experiment ran from Oct 2022 to Oct 2023.



Projected error bars

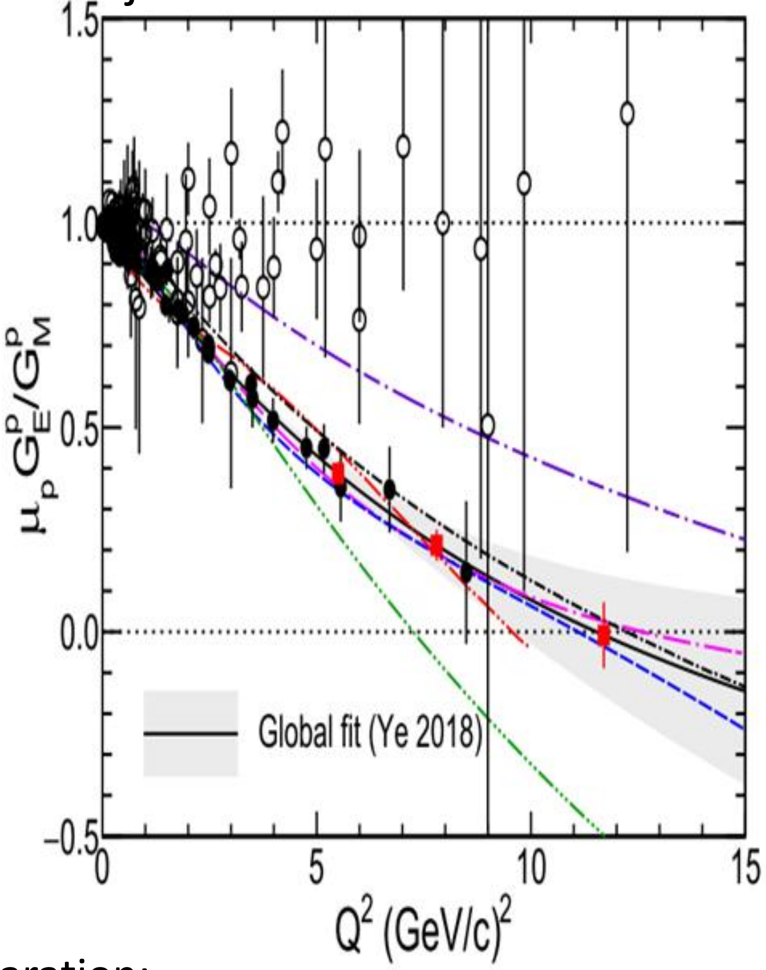


Thanks to hard work of the graduate students on GEN2: Faraz Chahili (Syracuse University), Kate Evans (William & Mary), Vimukthi Gamage (University of Virginia), Jack Jackson (William & Mary), Sean Jeffas (University of Virginia), Jacob Koenemann (University of Virginia), Gary Penman (University of Glasgow), Braian Mederos (University of Virginia), Hunter Presley (University of Virginia)

GEP Experiment measure proton G_E/G_M to Q^2 = 12 GeV^2

- New detectors for electron detection
  - Large 1656 lead glass blocks in Electron Calorimeter (ECAL)
    - Enclosure by Yerevan AANL and NCCU.
    - New PMT base design and testing over 2000 PMTs by JMU.
    - Installation done and overseen by Jlab staff with support from Virginia Tech, UTK, MSU, AANL and other universities.
  - Coordinate Detector
    - Two planes, each with 1176 scintillator bars.
    - Covers active area of 104 x 294 cm2
    - U. of Idaho and CNU led effort.
- SBS spectrometer for proton detection
  - Magnet used to precess spin.
    - Insert pole shims to increase integral Bdl to 2.4 Tm
  - Focal plane polarimeter: front tracker with 8 GEM planes, 50cm thick plastic analyzer followed by rear tracker with 8 GEM planes
  - GEM chambers constructed by U. of Virginia.
  - Hadron Calorimeter

Projected error bars



Thanks to hard work of graduate students on GEP working on the installation and preparation: Mahmoud Gomina (Virginia Tech), Nikolas Hunt (U of Connecticut), Jacob McMurtry (U of Virginia), Leonard Giuseppe Re (Catania University), Ben Spaude (William & Mary), Jhih-Ying Su (U of Massachusetts Amherst), Vidura Vishvanath (U of Virginia)

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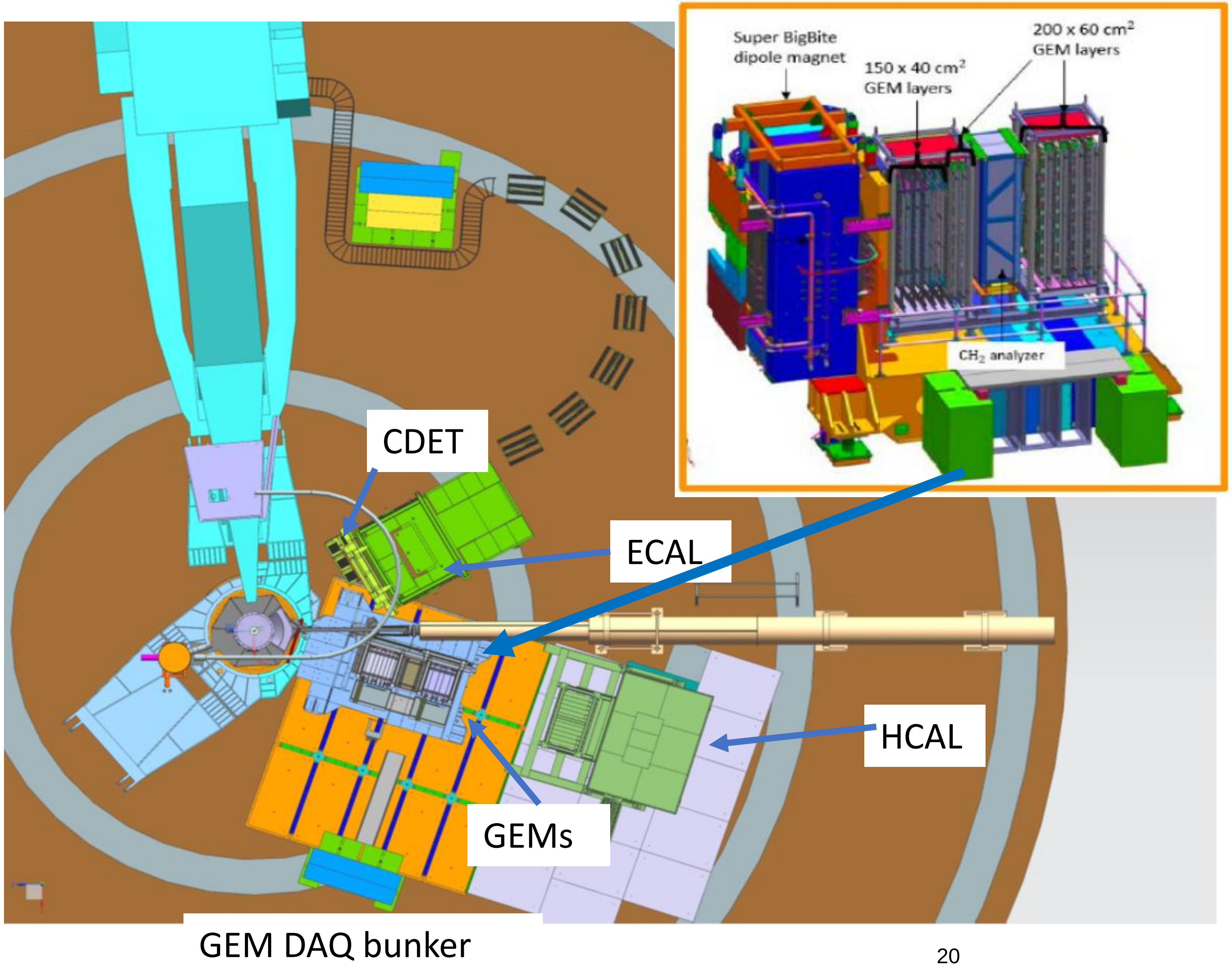
GEP : Proton GE/GM by recoil polarization



Electron Detection

- Electron Calorimeter (ECAL)
  - 1656 Lead glass blocks
  - Trigger formed in FADC from clusters
  - Need good energy calibration at FADC
  - Tight cut on elastic to reduce accidentals
  - Measure angle and energy
- Coordinate Detector (CDET)
  - 2352 scintillator bars
  - Measures vertical angle
  - Aids track finding in front GEMs
  - Reduce the photon background

Proton Detection

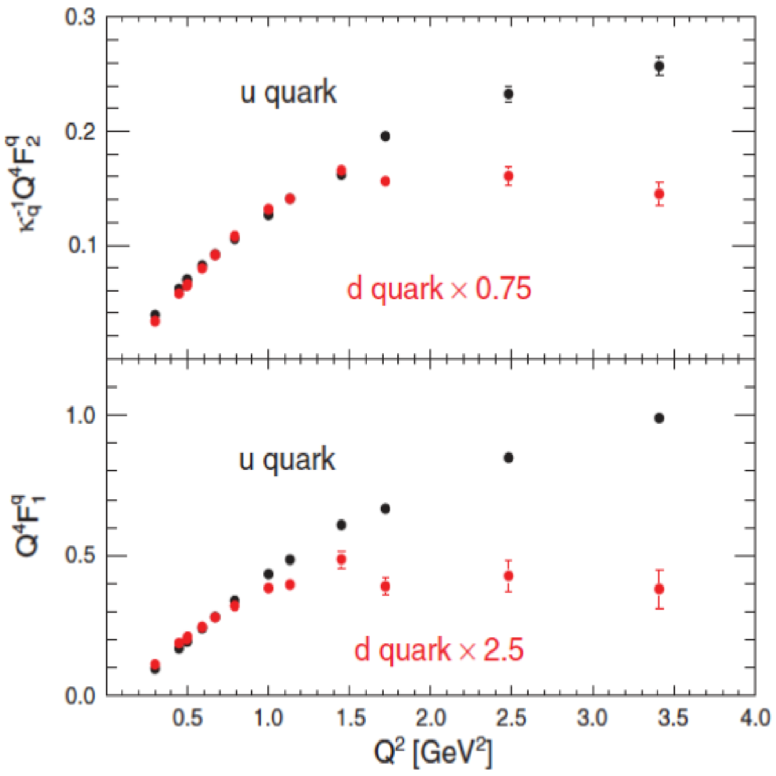
- FPP is GEMS Front and rear tracker
  - Each 8 layers of GEMs
  - Measure momentum, z-target, angles
  - Plastic analyzer for rescattering protons
  - Measure the recoil polarization of protons
- Hadron Calorimeter (HCAL)
  - 288 iron/scintillator blocks
  - Trigger formed in FADC from clusters
  - Aids track finding in rear trackers

Flavor decomposition of the form factors

Charge symmetry and assume contribution to nucleon is only from the up and down quarks

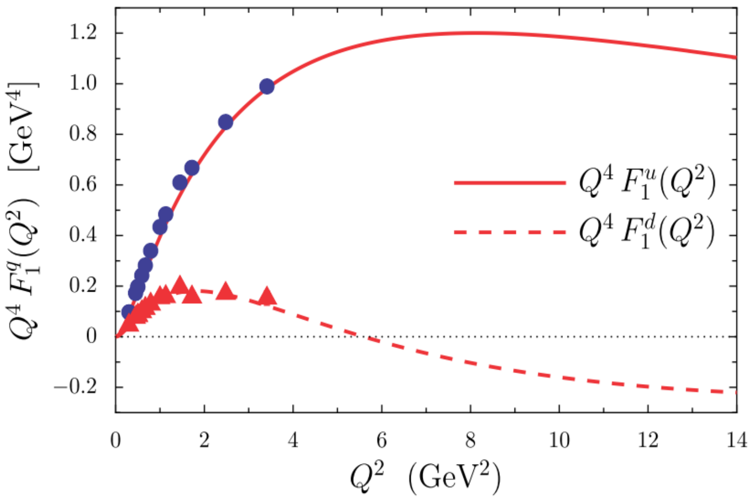
$$G_{(E,M)p} = \frac{2}{3}G_{(E,M)u} - \frac{1}{3}G_{(E,M)d}$$
$$G_{(E,M)n} = \frac{2}{3}G_{(E,M)d} - \frac{1}{3}G_{(E,M)u}$$

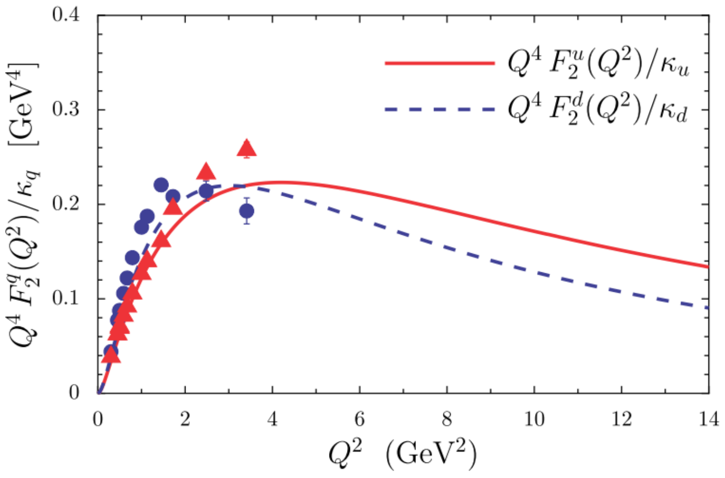
$$F_{(1,2)u} = 2F_{(1,2)p} + F_{(1,2)n}$$
$$F_{(1,2)d} = F_{(1,2)p} + 2F_{(1,2)n}$$



G. Cates, C. de Jager, S. Riordan, B. Wojtsekhowski
Phys. Rev. Lett. 106 (2011) 252003

I. Cloët and G. A. Miller Phys. Rev. C **86**, 015208 demonstrated that in a constituent quark model with the valence quarks, represented by quark-diquark combinations and immersed in a cloud of pions can reproduce the data.





Form factors and Generalize Parton Distributions

M. Diehl and P. Kroll Eur.Phys.J. C73 (2013) 4, 2397
Fitted form factor data by assuming a form for the valence GPD

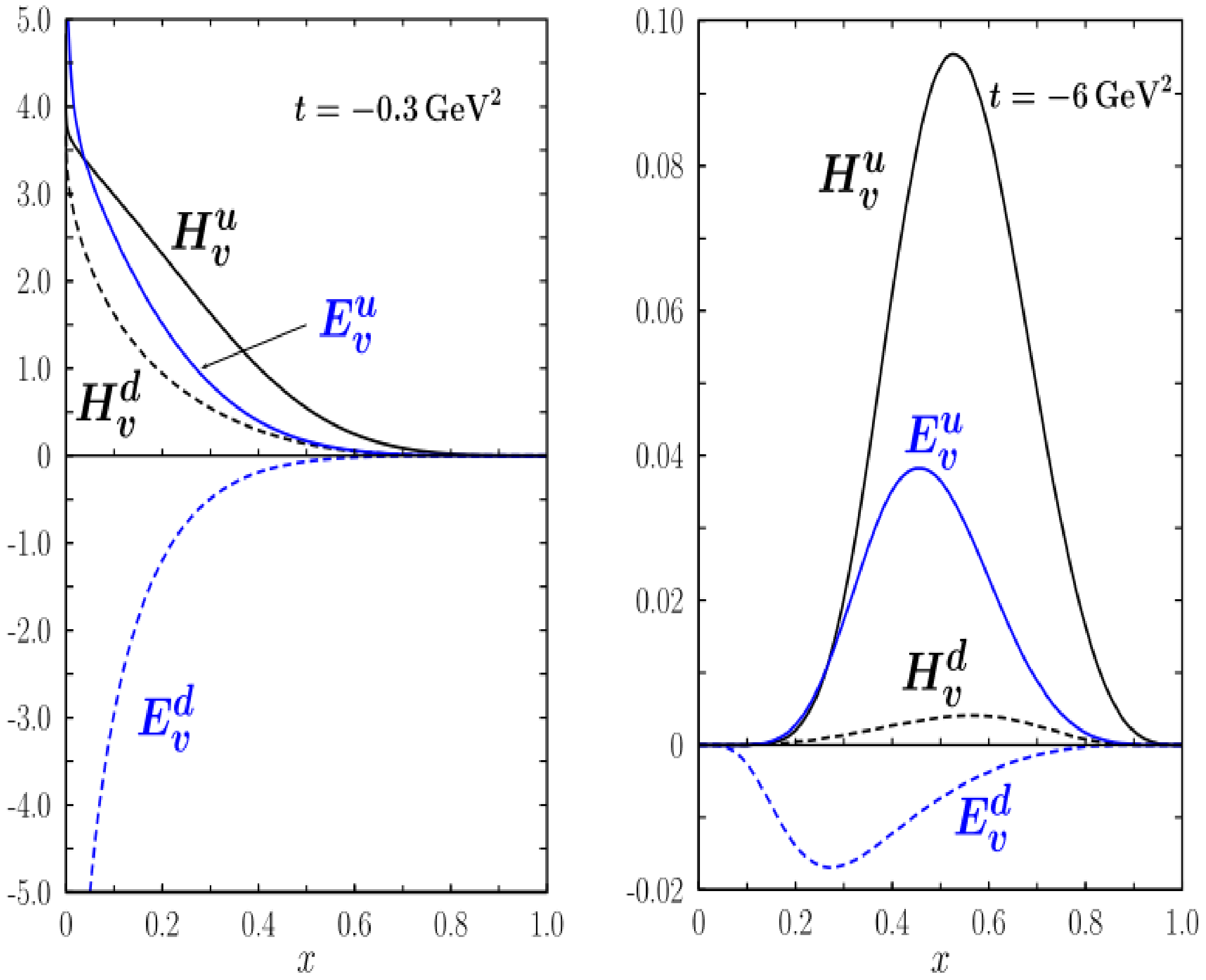
$$F_1^q(t) = \int_0^1 dx\, H_v^q(x,t)$$

$$F_2^q(t) = \int_0^1 dx\, E_v^q(x,t)$$

Large Q^2 form factor data determines the large x behavior of the valence GPD

Use Ji's sum rule to determine total angular momentum of up and down quarks

$$J_v^u = 0.230^{+0.009}_{-0.024}\,, \qquad J_v^d = -0.004^{+0.010}_{-0.016}$$



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Calculation using continuum Schwinger function methods

Plot from talk by Craig Roberts at the QCHSC24 (arXiv:2503.05984)
Summarizes recent papers by his group.

Parameter free Faddeev equation predictions by Z.-Q. Yao, D. Binosi, Z.-F. Cui, C. D. Roberts, arXiv:2403.08088.

The Schlessinger point method (SPM) to objectively assess the likelihood that the data support the existence of a zero in G_E/G_M by P. Cheng, Z.-Q. Yao, D. Binosi, C. D. Roberts, Phys. Lett. B 862 (2025) 139323.

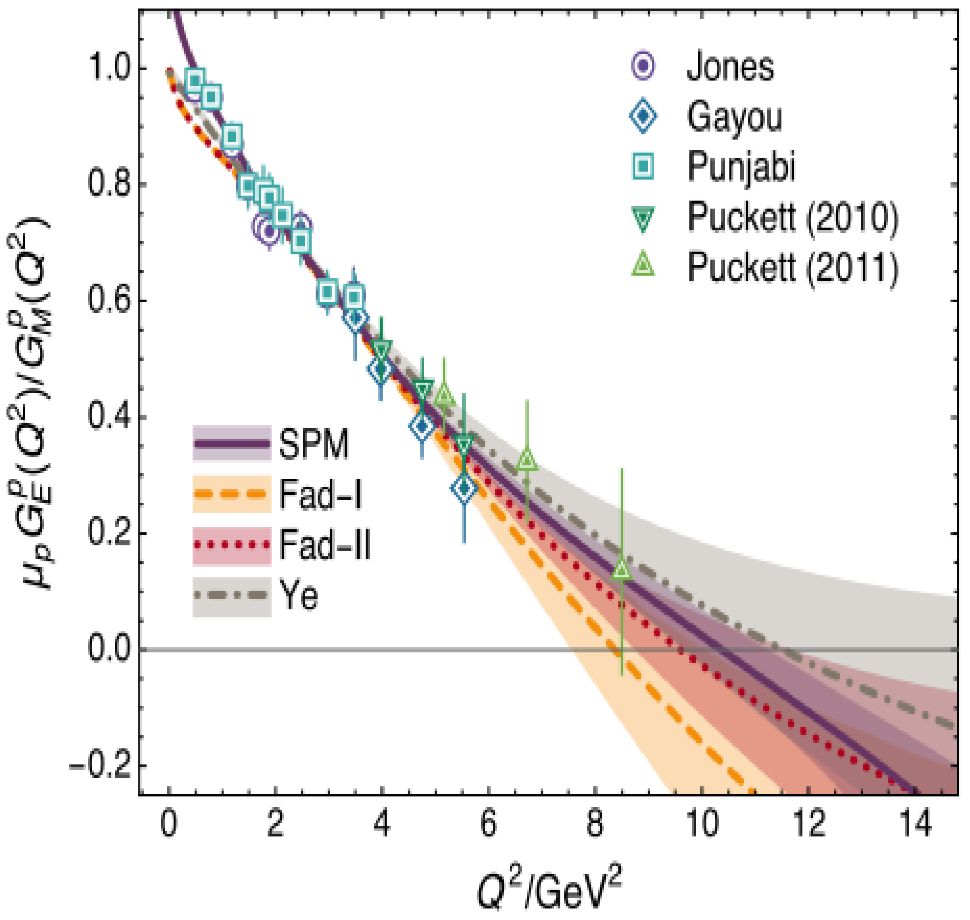

Figure 3: Prediction for the ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$ obtained in the objective SPM analysis of available data [60–64] that is described in Ref. [65]. For comparison, the figure also depicts the parameter-free Faddeev equation predictions [57, Fad-I, Fad-II] and the curve obtained via a subjective phenomenological fit to the world's electron + nucleon scattering data [66, Ye]. Both theory and phenomenology deliver a zero crossing at a location that is compatible with the SPM prediction.

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Lattice QCD calculations of proton and neutron form factor

In proceedings of LATTICE2024 by S. Syritsyn, M. Engelhardt, S. Krieg, J. Negele and A. Pochinsky
arXiv:2502.17283

Calculate connected and disconnected diagrams

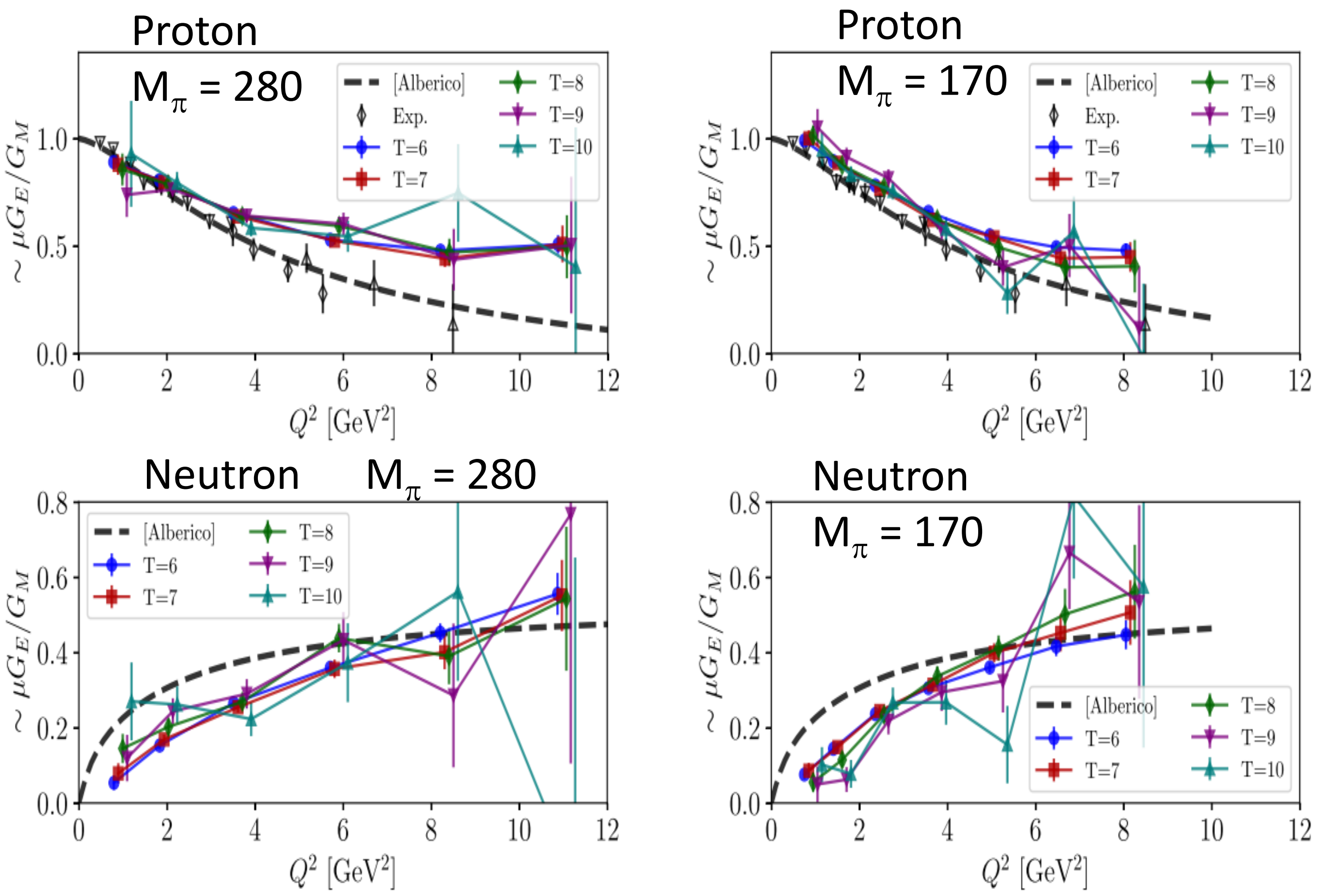

Figure 5: Ratio of the form factors G_E/G_M of the proton (top) and neutron (bottom) on the D5 ($m_\pi \approx$ 280 MeV, left) and D6 ($m_\pi \approx$ 170 MeV, right) ensembles. Both connected and disconnected contributions are included. The black data points are experimental values and the dashed lines are phenomenological fits [17]

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Conclusion

- Precision determination of elastic form factors need theoretical and experimental understanding of the TPE contributions.
  - Need dedicated positron accelerator with high luminosity needed to make measurements in the ε and Q^2 region where TPE contribution are expected to be the largest.

- The JLab Hall A SBS form factor program is nearing completion
  - At GHP2025, Provakar Datta presented preliminary results for the neutron G_M to Q^2 = 13.5 GeV^2
  - Completed measurements of the neutron G_E/G_M to Q^2 = 10 GeV^2 using beam-target asymmetries
    - 60cm long polarized 3He cell. Factor of two larger FOM than previous targets.
  - Completed measurements of the neutron G_E/G_M at Q^2 = 4.5 GeV^2 using recoil polarization
    - Measure recoil polarization using charge exchange.
  - Completed installation of equipment for measurement of proton G_E/G_M to Q^2 = 12 GeV^2
    - Experiment is scheduled to start at the end of March.

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