Nucleon Form Factors with SBS Program in Hall A

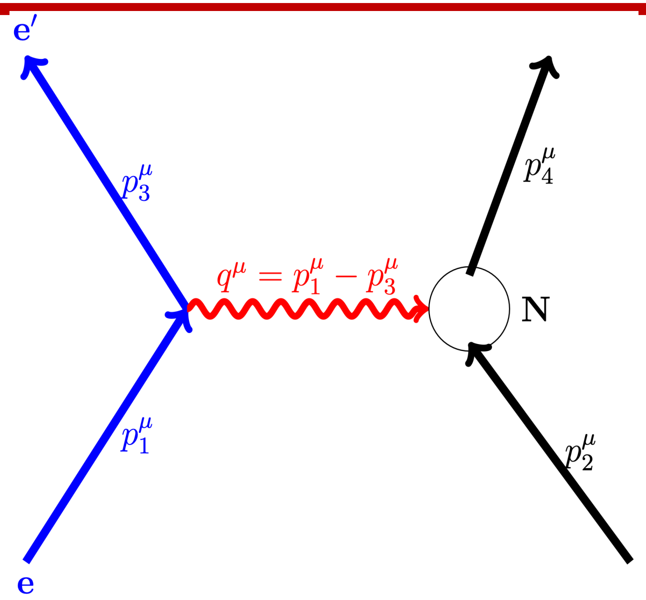
Jiwan Poudel
Jefferson Lab

Hall A/C Summer Meeting
June 2023

Outline

- Background and Motivation on Nucleon Form Factors (FF)
- Formalism of accessing Form Factors
- Global data sets on nucleon FF
- Form Factors with SBS Program in Hall A
- Summary

Background: Electron-Nucleon Scattering



- Scattering cross section (early version of one photon exchange): considering finite charge distribution

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left| \int \rho(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d^3\mathbf{r} \right|^2$$

Form Factor(FF)-> $|F(q)|^2$

- Nucleon Vertex: $$\Gamma^\mu = \left[\gamma^\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}q_\nu}{2M} F_2(Q^2)\right]$$

- F_1 -> Dirac FF (helicity conserving) and F_2 -> Pauli FF (helicity non-conserving)
- Rosenbluth Formula

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\left(F_1^2 + \frac{q^2}{4M^2} F_2^2\right) - \frac{Q^2}{2M^2} \left(F_1 + F_2\right)^2 \tan^2 \frac{\theta}{2} \right]$$

In the static limit (Q^2=0):

$F_{1p} = 1$, $F_{2p} = \kappa_p$

$F_{1n} = 0$, $F_{2n} = \kappa_n$

Background: Electron-Nucleon Scattering

- Sachs Form factors (FF): $G_E(Q^2) = F_1 - \frac{Q^2}{4M^2}F_2$ and $G_M(Q^2) = F_1 + F_2$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{G_E^2 + (\frac{Q^2}{4M^2})G_M^2}{1+(Q^2/4M^2)}\cos^2\frac{\theta}{2} + \frac{Q^2}{2M^2}G_M^2\sin^2\frac{\theta}{2}\right]$$

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

In the limit (Q^2=0):

$G_{Ep} = 1$, $G_{Mp} = \mu_p$

$G_{En} = 0$, $G_{Mn} = \mu_n$

- Virtual photon polarization: $\epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$

$$\tau = \frac{Q^2}{4M^2}$$

- Form Factors describes the internal structure of nucleon in terms of charge and magnetization distribution, and study on form factors started from 1950's.

Motivation

- Understanding the internal structure of nucleons precisely (for both proton and neutron)
- Test of nuclear models (VMD, pQCD, DSE…)
- Powerful tool to understand non-perturbative QCD
- Information of hadron structure as first moment of GPD

Reduction formulas at $\xi = t = 0$
for DIS and $\xi = 0$ for FFs

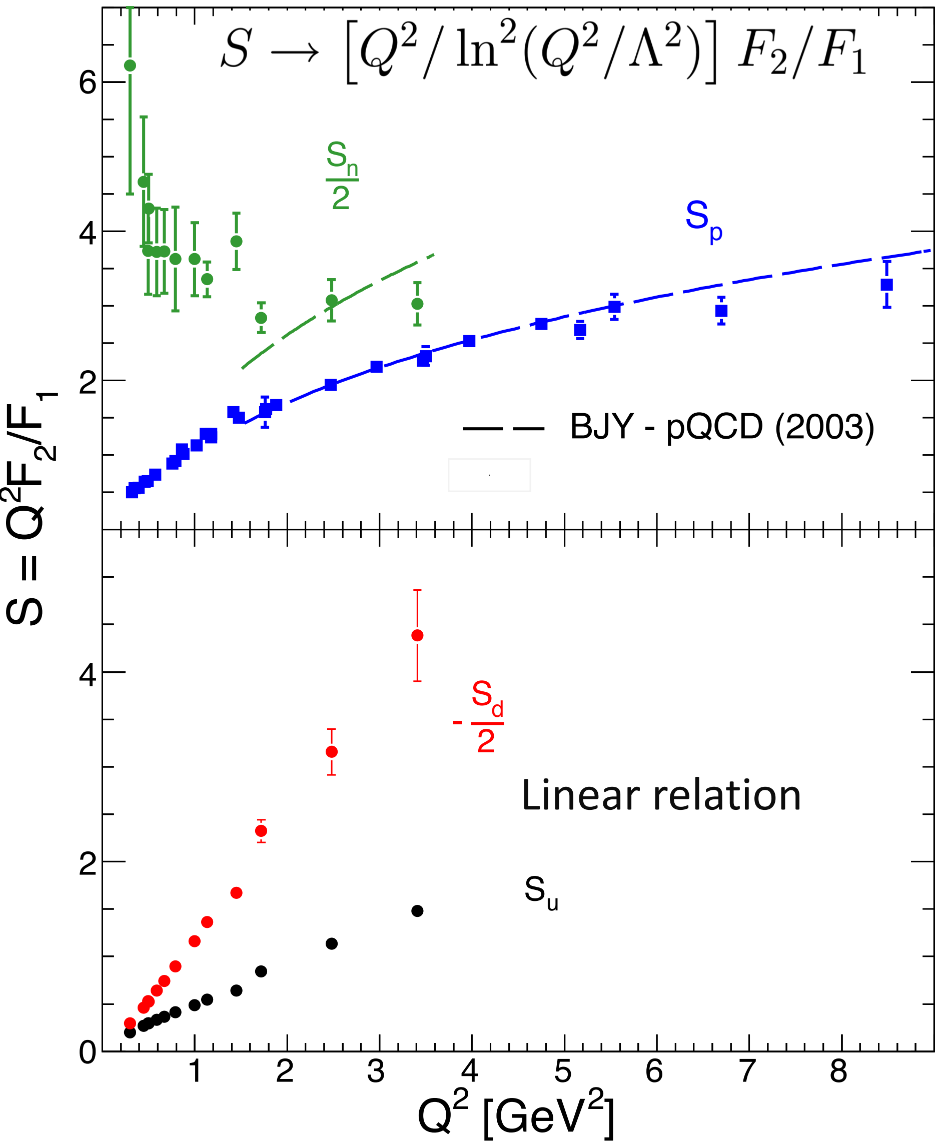
$$H^q(x, \xi = 0, t = 0) = q(x)$$

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

$$\int_{-1}^{+1} dx\, H^q(x, 0, Q^2) = F_1^q(Q^2)$$

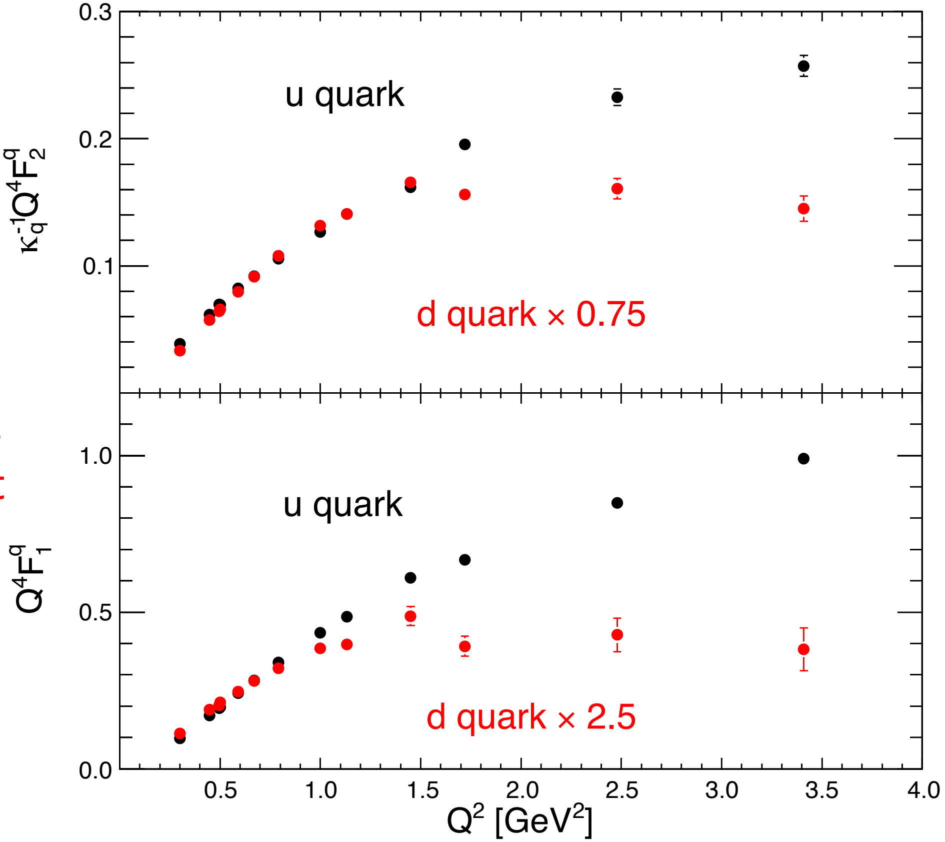
$$\int_{-1}^{+1} dx\, E^q(x, 0, Q^2) = F_2^q(Q^2)$$

Motivation: Flavor Decomposition



$$F^u_{1(2)} = 2\,F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2\,F^n_{1(2)} + F^p_{1(2)}$$

Down quark contribution is strongly suppressed in F_1 at high Q^2



G. Cates et al. Phys. Rev Lett. 106 (2011)

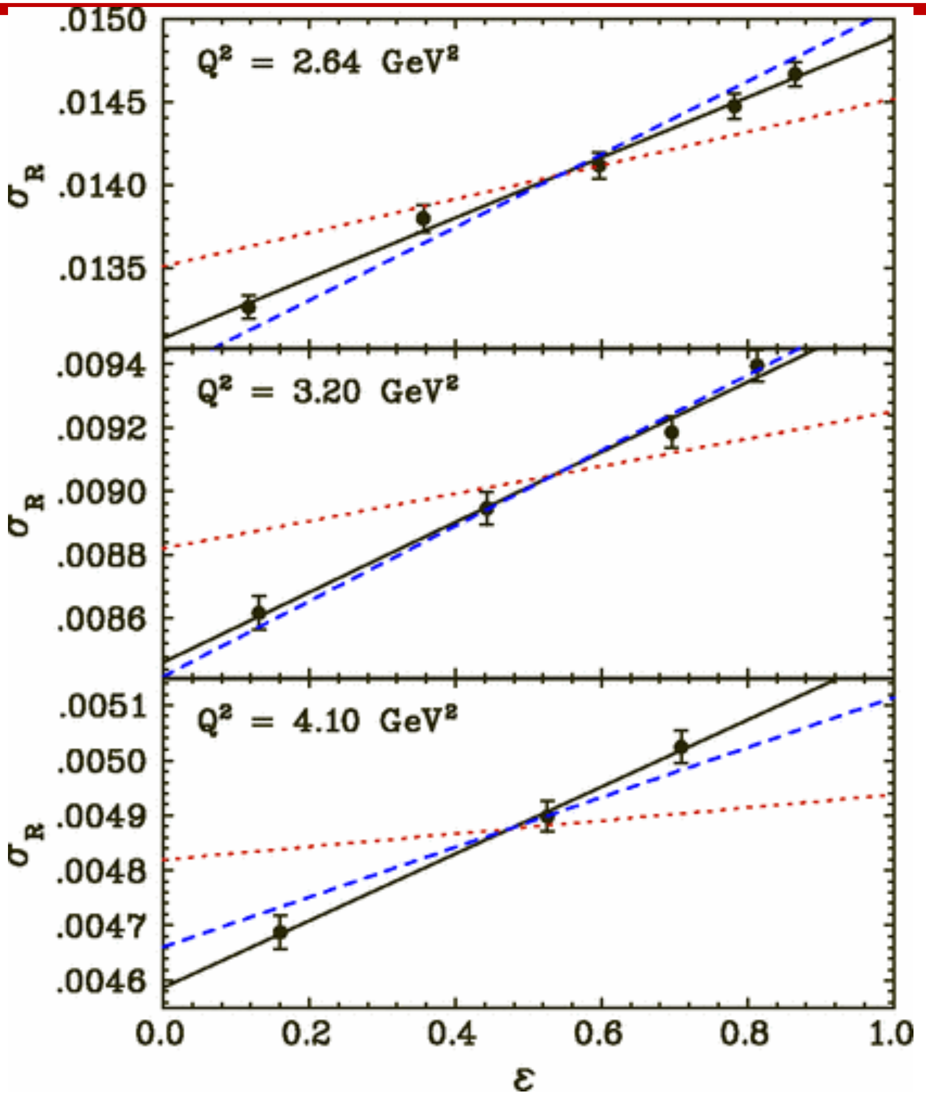
Formalism of Accessing FF

- Accessing form factors:
  - Rosenbluth separation method

$$\sigma_R = \epsilon(1+\tau)\frac{d\sigma}{d\Omega}\Big/\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left[\epsilon G_E^2 + \tau G_M^2\right]$$

- Slope of fit -> G_E^2 and intercept -> τG_M^2

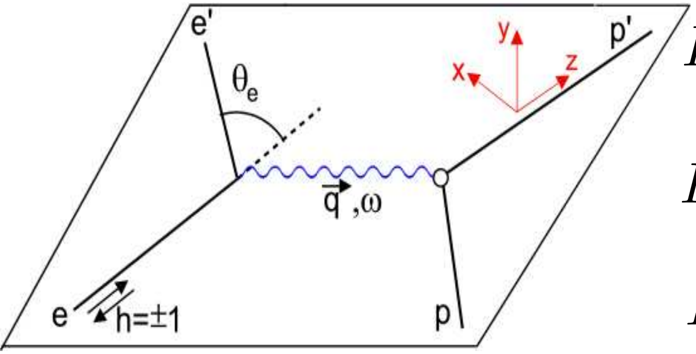
- Not suitable at high Q^2 as cross section is dominated by G_M^2 (G_E^2 is suppressed by factor τ)
- Should incorporate radiative corrections



Quattan et al. Phys. Rev. Lett. **94**, 142301 (2005)

Formalism

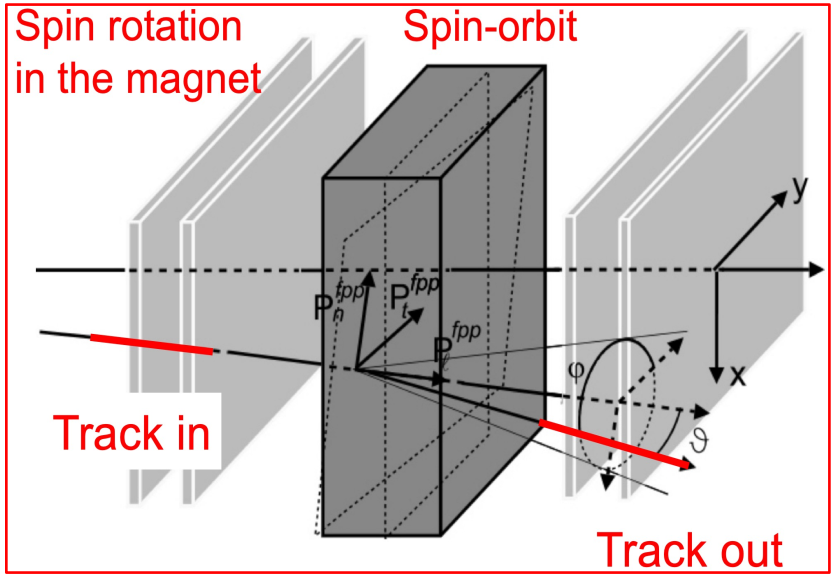
- Accessing form factors:
  - Polarization transfer (Recoil polarization) method: $\vec{e}N \rightarrow e\vec{N}$
  - Only Longitudinal and transverse component (no normal component on reaction plane)



$$P_l = \sqrt{\tau(1+\tau)}\frac{E_e + E_{e'}}{M} G_M^2 \tan^2\frac{\theta_e}{2} / I_0$$

$$P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2} / I_0$$

$$I_0 = G_E^2 + \frac{\tau}{\epsilon} G_M^2$$



$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}$$

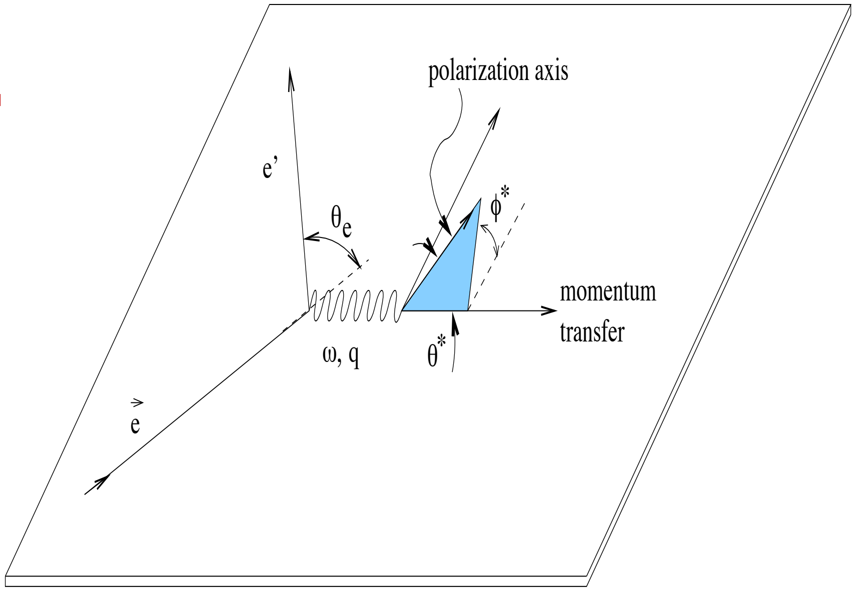
$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}(1 \pm A_y(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi))$$

$$A = \frac{f^+ - f^-}{f^+ + f^-} = (A_y P_x^{fpp}\sin\varphi - A_y P_y^{fpp}\cos\varphi)$$

$$\frac{P_t}{P_l} = \frac{P_x^{fpp}}{P_y^{fpp}}\sin\chi_\theta + \gamma_p(\mu_p - 1)\Delta\phi$$

- FF ratio is independent of beam polarization
- FF ratio is independent of analyzing power (A_y)

Formalism



- Accessing form factors:
  - Double polarization asymmetry method

$$\vec{e}\vec{N} \to eN$$

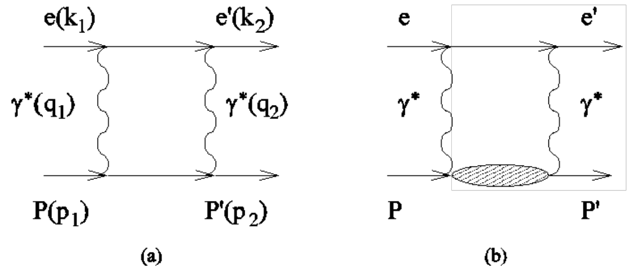
$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)}{G_E^2 + \frac{\tau}{\epsilon}G_M^2}\left[\sqrt{\tau(1+(1+\tau)\tan^2\frac{\theta}{2})}\cos\theta^* G_M^2 + \sin\theta^*\cos\phi^* G_M G_E\right]$$

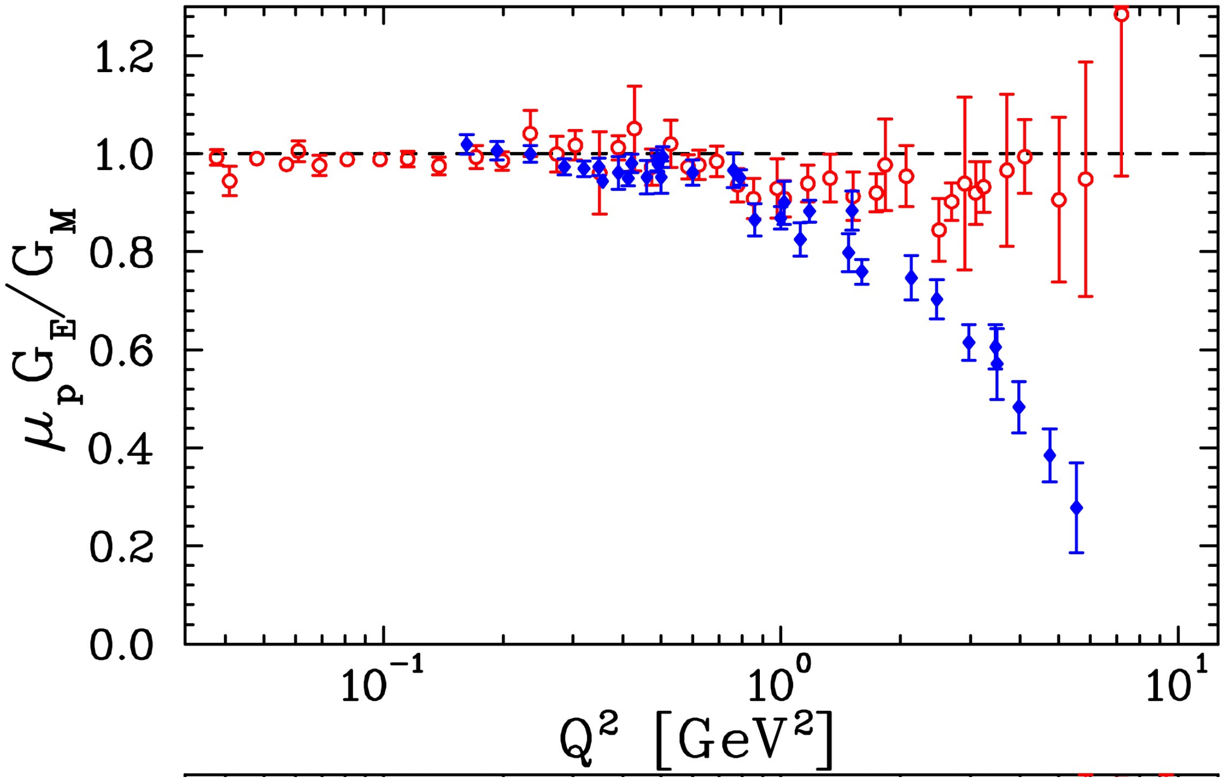
  - Target polarization perpendicular to momentum transfer in reaction plane (θ*=π/2, ϕ*=0 or 180)

$$\boxed{A = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2))\frac{G_E}{G_M}}{(\frac{G_E}{G_M})^2 + \frac{\tau}{\epsilon}}}$$

Global FF data: Experimental result

- Proton form factors with different methods: global fit



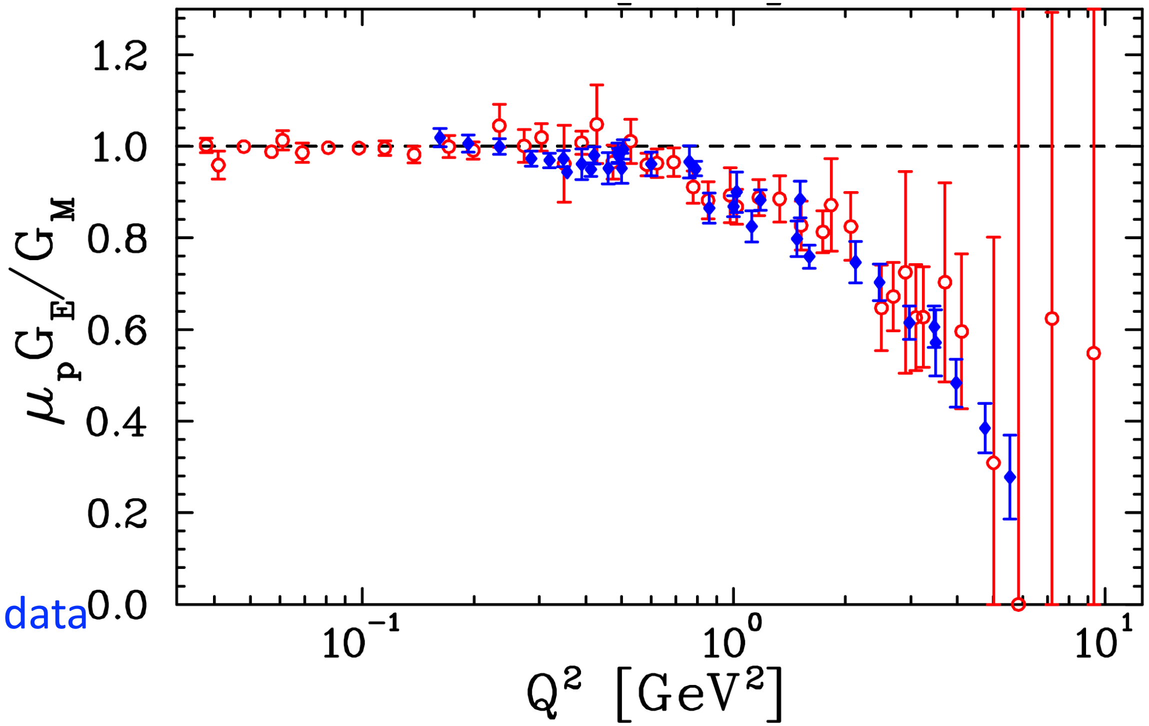


Arrington J. et al. Phys. Rev C 76 (2007)

Red: Cross-section data

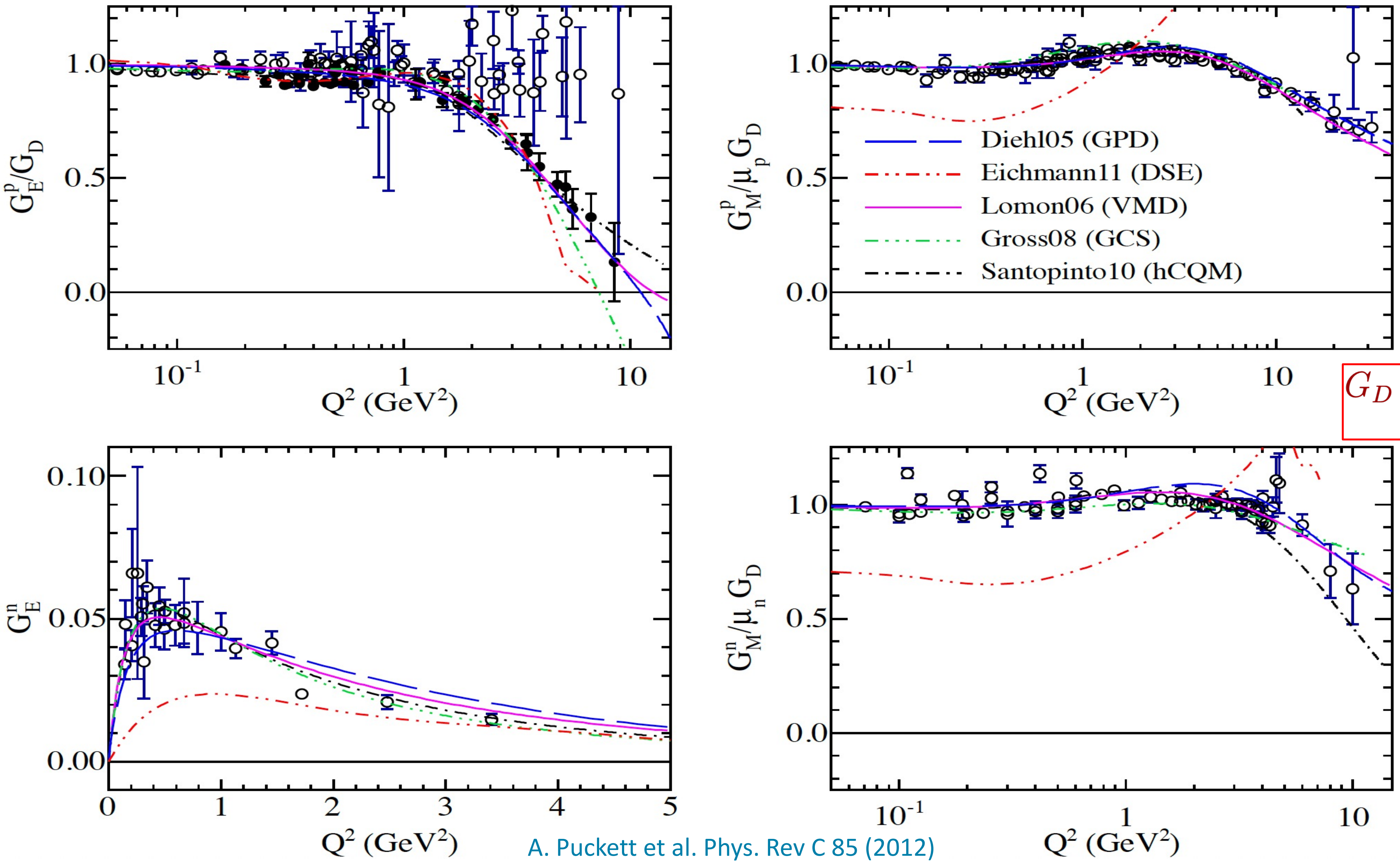
Blue: Polarization transfer data

After Two Photon exchange (TPE) correction



Jefferson Lab

Global FF data: Experimental result

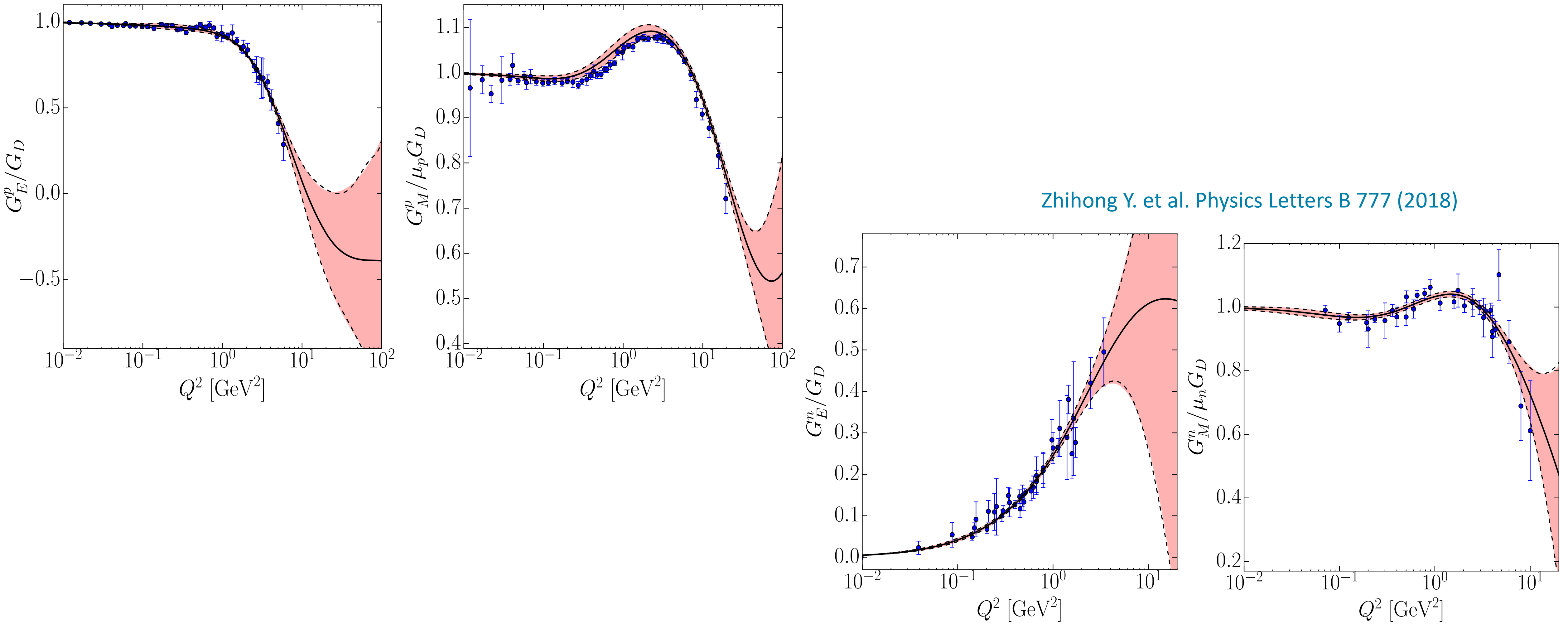


$$G_D = \frac{1}{\left(1+\frac{Q^2}{0.71\ GeV^2}\right)^2}$$

A. Puckett et al. Phys. Rev C 85 (2012)

Global FF data: global fit

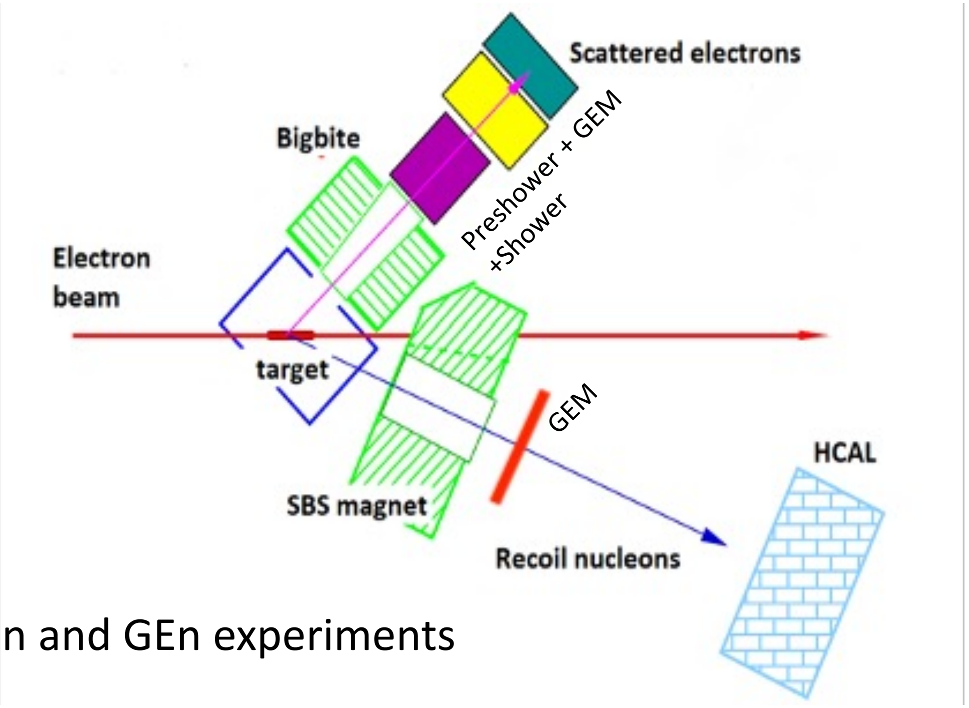
- Parameterization of global fit of proton and neutron data:



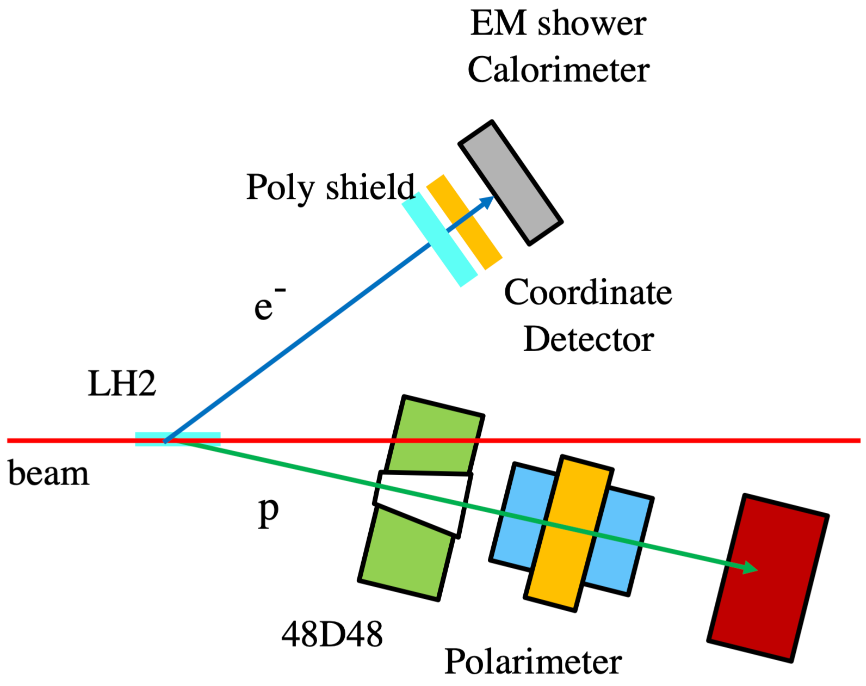
Zhihong Y. et al. Physics Letters B 777 (2018)

Form Factors with SBS @Hall A

- SBS -> Super Big-Bite Programs
  - E12-09-019 -> GMn (data collection completed in 2020)
  - E12-09-016 -> GEn/GMn (data collection 75% completed during 2023)
  - E12-17-004 -> GEn-RP (2024)
  - E12-07-109 -> GEp/GMp (2024)



GMn and GEn experiments



GEp experiment

SBS Program: E12-09-019 (GMn)

- Quasi-elastic electron scattering on deuterium target
- Ratio method to extract from nuclear target

$$R'' = \frac{\frac{d\sigma}{d\Omega}\big|_{\mathrm{d(e,e'n)}}}{\frac{d\sigma}{d\Omega}\big|_{\mathrm{d(e,e'p)}}}$$

- Correction due to nuclear target

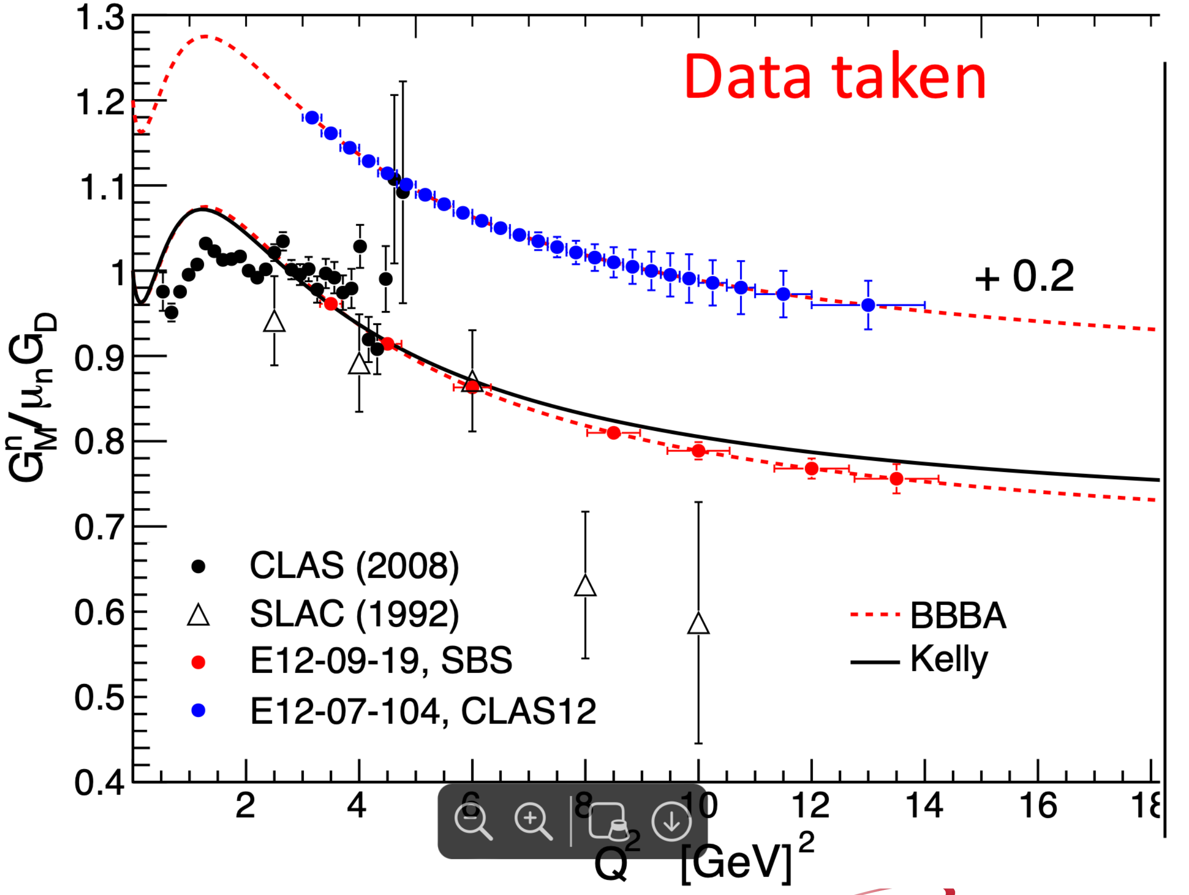
$$R' = \frac{\frac{d\sigma}{d\Omega}\big|_{\mathrm{n(e,e')}}}{\frac{d\sigma}{d\Omega}\big|_{\mathrm{p(e,e')}}} = \frac{R''}{1+\epsilon_{\mathrm{nuc}}}$$

- At Large Q2

$$R = R' - \frac{\eta\frac{\sigma_{\mathrm{Mott}}}{1+\tau}(G_E^n)^2}{\frac{d\sigma}{d\Omega}\big|_{\mathrm{p(e,e')}}} = \frac{\eta\sigma_{\mathrm{Mott}}\frac{\tau/\epsilon}{1+\tau}(G_M^n)^2}{\frac{d\sigma}{d\Omega}\big|_{\mathrm{p(e,e')}}}$$

Q^2 up to 13.5 $(\mathrm{GeV/c})^2$

Beam time -> 25 days



Jefferson Lab

SBS Program: E12-09-016 (GEn)

- Polarized electron scattered from Polarized Helium-3 target
- Double polarization asymmetry (A)

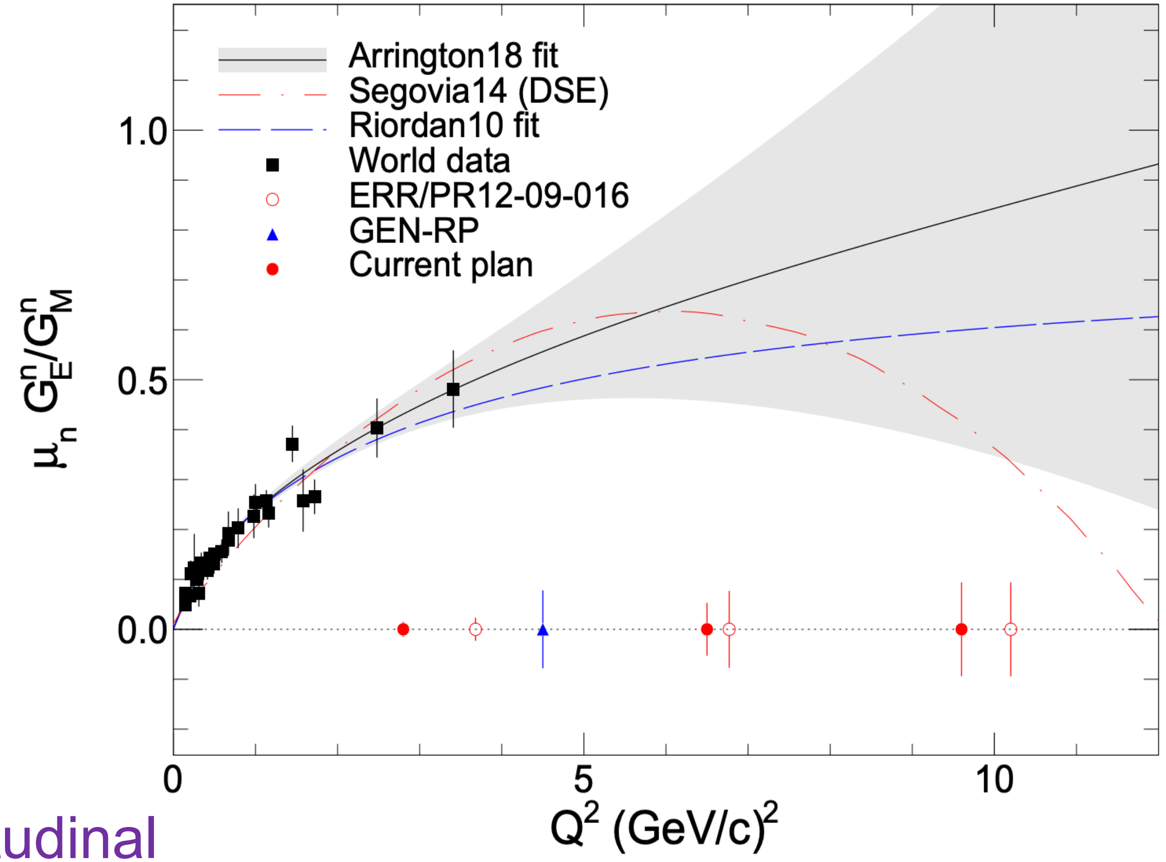
Q^2 up to 10 (GeV/c)^2

Beam time -> 50 days

$$A_{exp} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{\mathrm{phys}} = \frac{A_{exp}}{P_{\mathrm{beam}} P_{^3\mathrm{He}} P_n D_{\mathrm{N}_2} D_{\mathrm{FSI}} D_{\pi} D_{\mathrm{back}}}$$

$$A = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2))\frac{G_E}{G_M}}{(\frac{G_E}{G_M})^2 + \frac{\tau}{\epsilon}}$$



- Large angular acceptance of big-bite => Longitudinal contribution

SBS Program: E12-17-004 (GEn-RP)

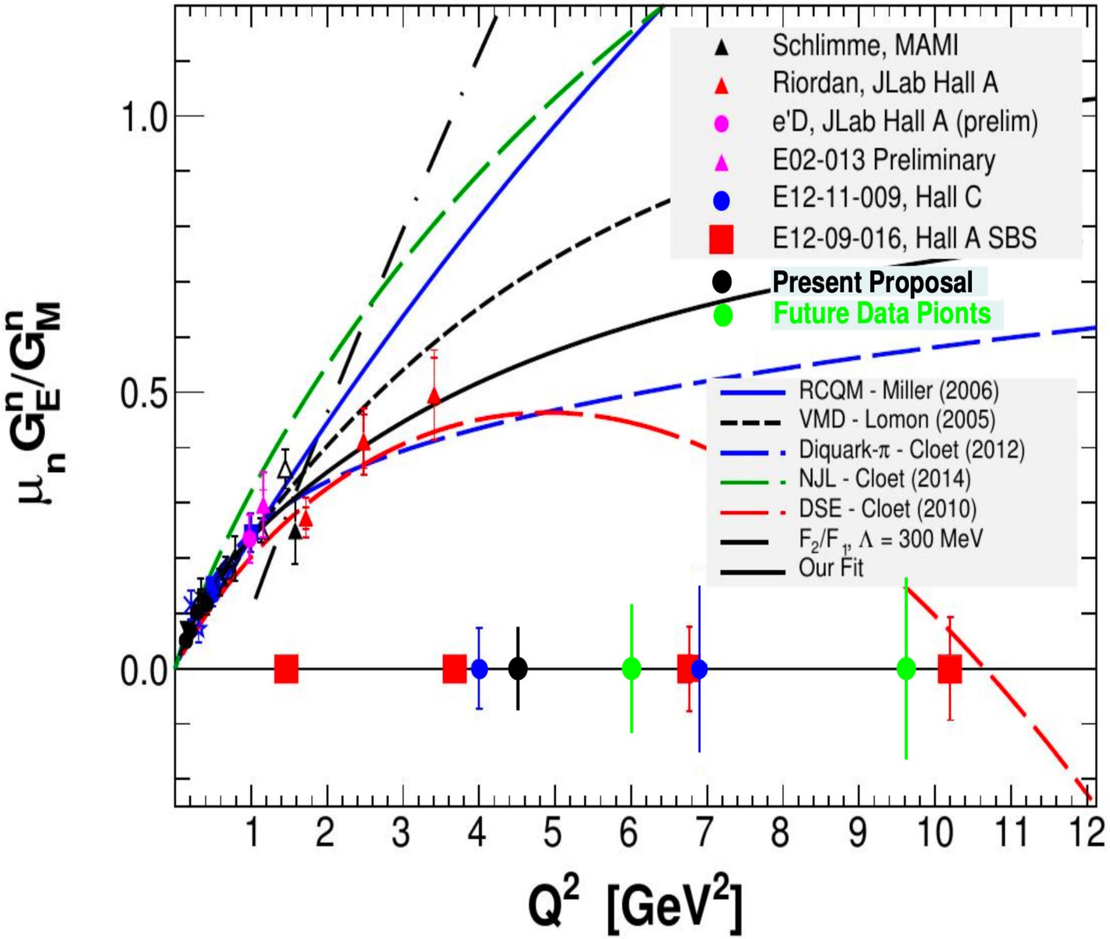
- Polarized electron scattered on deuterium target
- Polarization transfer method with recoil polarimetry
- Neutron polarimeter added to SBS-arm

$$\frac{G_E}{G_M} = -\frac{E_e + E_{e'}}{2M} \tan\frac{\theta_e}{2}\left(\frac{P_x^{fpp}}{P_y^{fpp}}\sin\chi_\theta + \gamma_p(\mu_p - 1)\Delta\phi\right)$$

- Independent of beam polarization and analyzing power of polarimetry, but need to maximize for higher efficiency (and higher statistics)
- Possible to access without changing beam energy and detector

- Scheduled for 2024

Q^2 at 4.5 $(GeV/c)^2$
Beam time -> 5 days



Jefferson Lab

SBS Program: E12-07-109 (GEp)

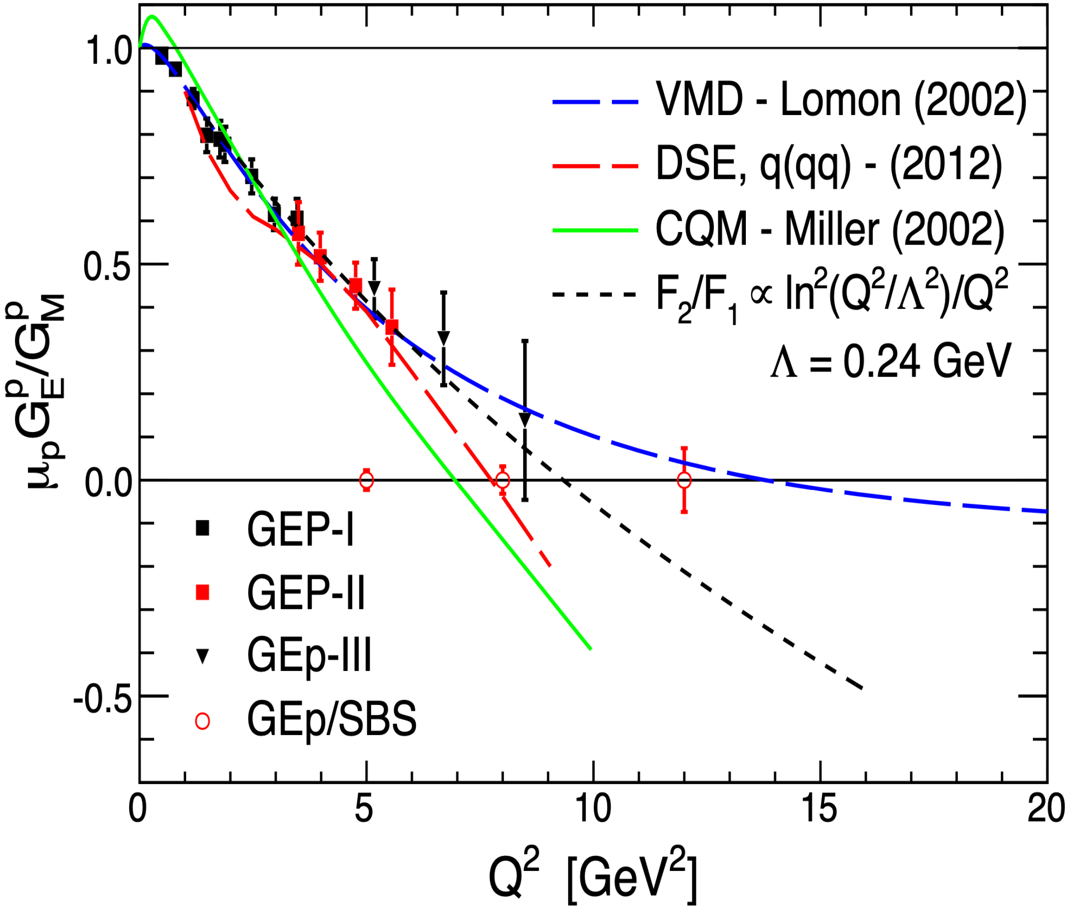
- Polarized electron scattering on liquid Hydrogen
- Polarization transfer method with recoil polarimetry
- Proton polarimeter in the SBS-arm

$$\frac{G_E}{G_M} = -\frac{E_e + E_{e'}}{2M} \tan\frac{\theta_e}{2} \left(\frac{P_x^{fpp}}{P_y^{fpp}} \sin\chi_\theta + \gamma_p(\mu_p - 1)\Delta\phi \right)$$

- Independent of beam polarization and analyzing power of polarimetry, but need to maximize for higher efficiency (and higher statistics)
- Gamma factor $\gamma_p \sim Q^2$
  - $\Rightarrow$ On large Q^2, mixing of transverse and longitudinal components

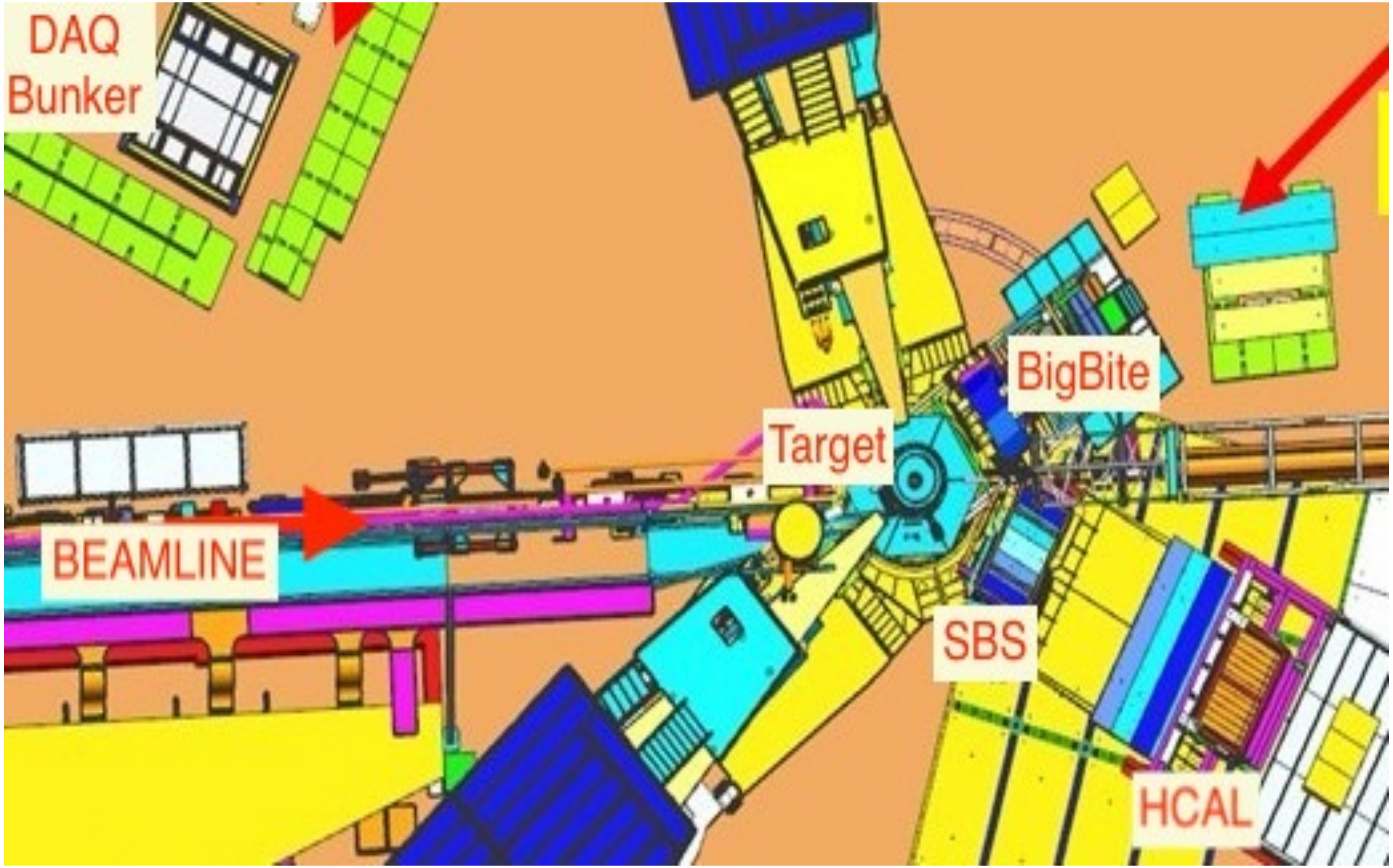
- Scheduled for 2024

Q^2 up to 12 $(GeV/c)^2$
Beam time -> 45 days



Jefferson Lab

SBS @Hall A



Summary

- Higher uncertainty of Nucleon FF at higher Q^2
- Measurement of FF is crucial to better understand the nucleons
- Ongoing effort to measure FF with SBS program in Hall-A
- One experiment has completed data taking in 2022, and analysis in progress
- Another experiment took 75% data during 2023, and analysis in parallel
- Two more experiments scheduled for 2024

Backup