Low Energy Electron Positron Physics at Jefferson Lab
May 23, 2026

Positron physics program at Jefferson Lab

Wally Melnitchouk

Jefferson Lab

Overview

- Availability of positron beams (unpolarized & polarized) would open up an entire new frontier for hadron/nuclear structure & BSM studies at Jefferson Lab

- 3 main opportunities identified
  - → parton structure of nucleons and nuclei (GPDs/GFFs, PDF flavor asymmetries, …)
  - → multi-photon exchange phenomena (form factors, dispersive effects, …)
  - → tests of the Standard Model (dark photon searches, BSM physics, …)

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"low energy" — focus of this workshop

see talks by:

Piekarewicz, Sfienti, Guèye, Wojtsekhowski, Jakubaßa-Amundsen, Weiss, Scholberg, Ronchi ("multi-photon")

Battaglieri, Xiong, Mack, Pustyntsev, Mommers, Lin, Suleiman, Khachatryan ("BSM")

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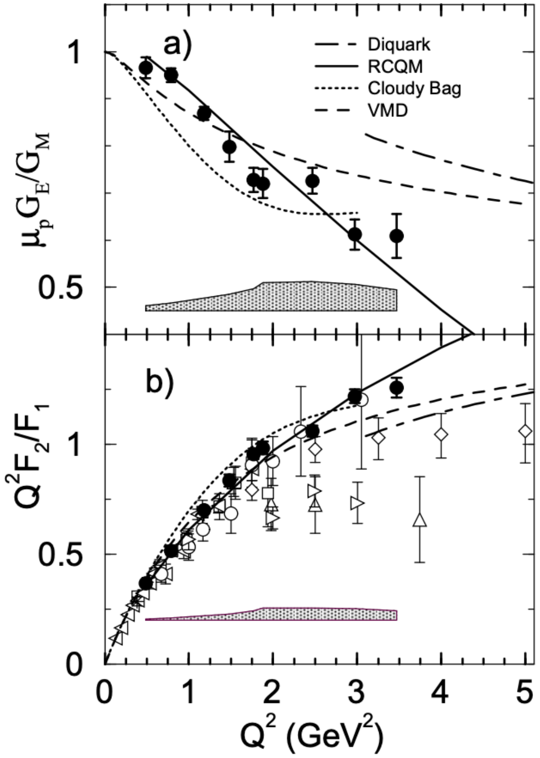
"high energy" — <u>not</u> focus of this workshop

… will partly cover in <u>this</u> talk

Some history

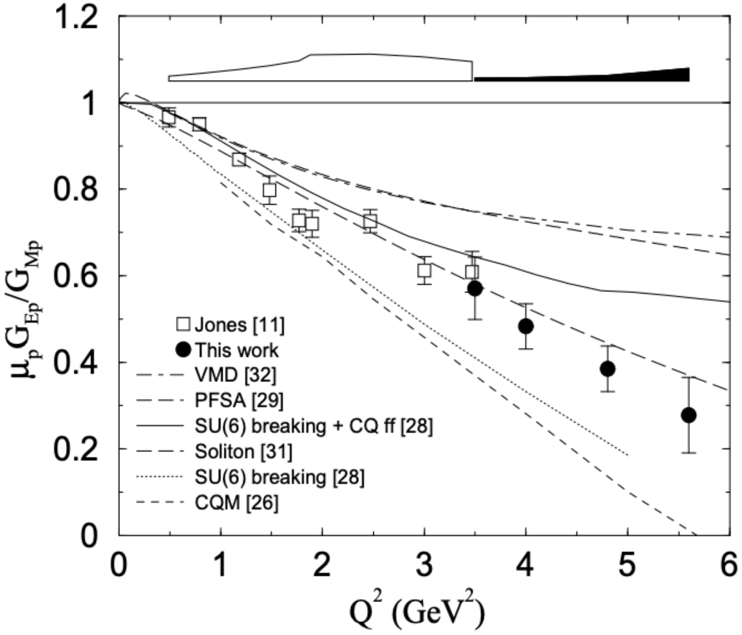
- Interest in two-photon physics in the 21st century came unexpectedly, with polarized *ep* scattering experiments in Jefferson Lab Hall A

G_{Ep}/G_{Mp} **ratio by polarization transfer in** $\vec{e}p \rightarrow e\vec{p}$



M. Jones et al., PRL ***84****, 1398 (2000)*

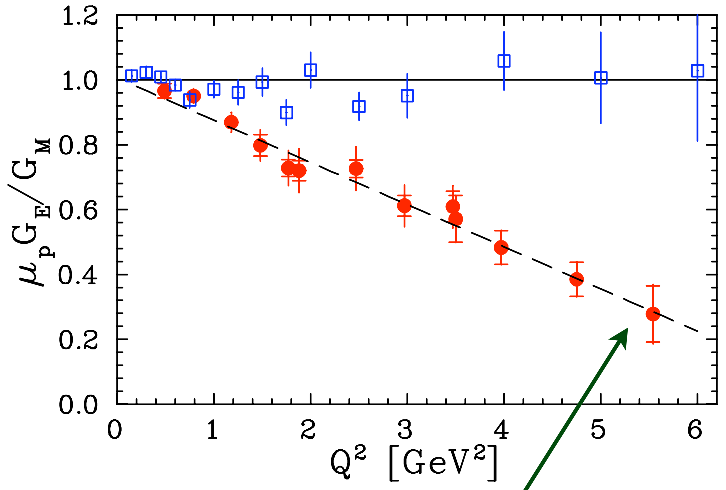
Measurement of G_{Ep}/G_{Mp} **in** $\vec{e}p \rightarrow e\vec{p}$ **to** $Q^2 = 5.6$ **GeV**^{2}



O. Gayou et al., PRL ***88****, 092301 (2002)*

Some history

- Dramatically different behavior of electron/magnetic proton form factor ratio for different extraction methods (should be equivalent in Born approximation)



Rosenbluth separation method — reduced cross section

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

$$\tau = Q^2/4M^2$$

$$\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$$

⟶ G_E from slope in ε dependence

⟶ suppressed at large Q^2

⟶ sizeable radiative corrections

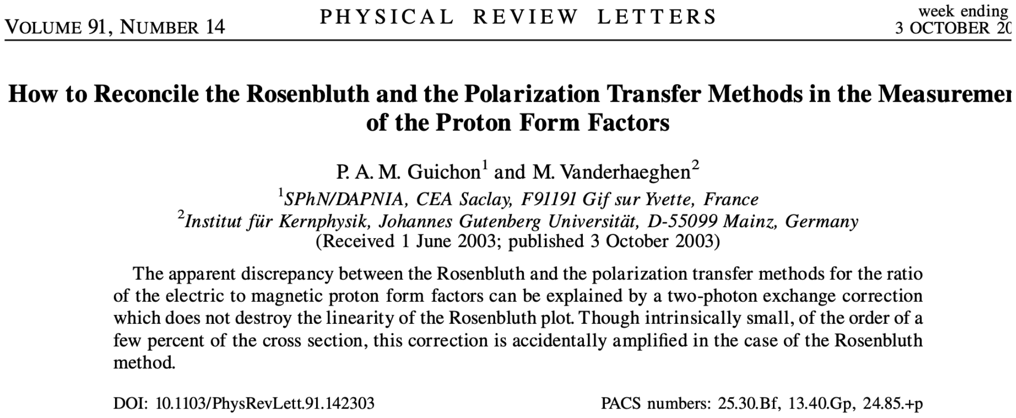
polarization transfer method

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\frac{P_T}{P_L}$$

⟶ $P_{T,L}$ recoil proton polarization in $\vec{e}\,p \to e\,\vec{p}$

⟶ many uncertainties cancel in ratio

Some history



VOLUME 91, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 20

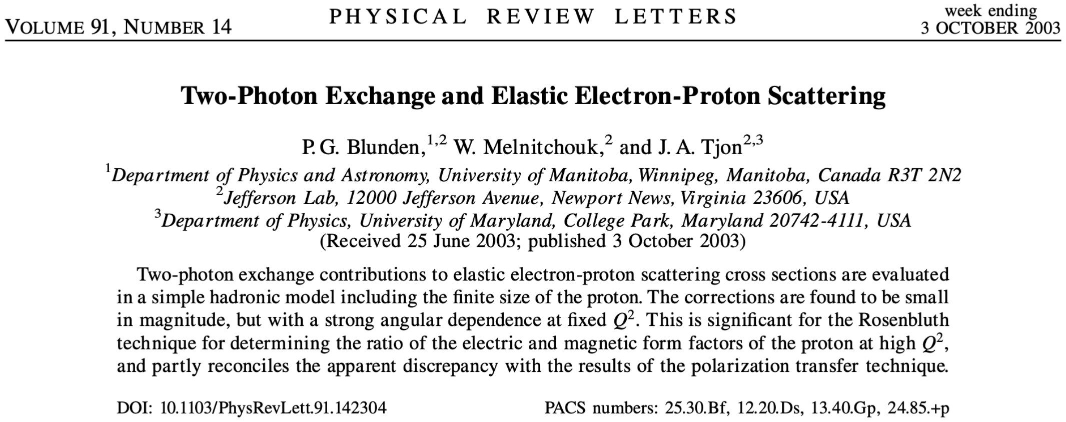
How to Reconcile the Rosenbluth and the Polarization Transfer Methods in the Measureme of the Proton Form Factors

P. A. M. Guichon[1] and M. Vanderhaeghen[2]
[1]*SPhN/DAPNIA, CEA Saclay, F91191 Gif sur Yvette, France*
[2]*Institut für Kernphysik, Johannes Gutenberg Universität, D-55099 Mainz, Germany*

(Received 1 June 2003; published 3 October 2003)

The apparent discrepancy between the Rosenbluth and the polarization transfer methods for the ratio of the electric to magnetic proton form factors can be explained by a two-photon exchange correction which does not destroy the linearity of the Rosenbluth plot. Though intrinsically small, of the order of a few percent of the cross section, this correction is accidentally amplified in the case of the Rosenbluth method.

DOI: 10.1103/PhysRevLett.91.142303 PACS numbers: 25.30.Bf, 13.40.Gp, 24.85.+p



VOLUME 91, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2003

Two-Photon Exchange and Elastic Electron-Proton Scattering

P. G. Blunden,[1,2] W. Melnitchouk,[2] and J. A. Tjon[2,3]
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[2]*Jefferson Lab, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*
[3]*Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA*

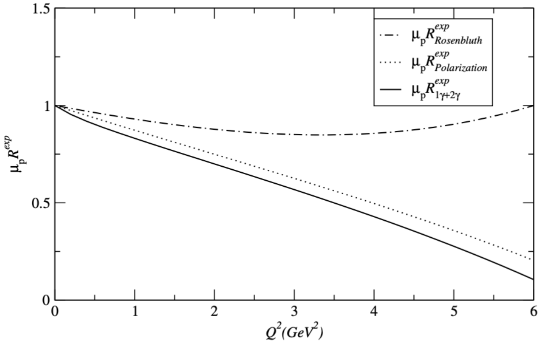
(Received 25 June 2003; published 3 October 2003)

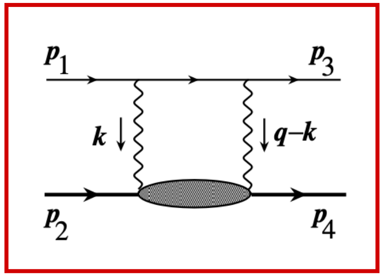
Two-photon exchange contributions to elastic electron-proton scattering cross sections are evaluated in a simple hadronic model including the finite size of the proton. The corrections are found to be small in magnitude, but with a strong angular dependence at fixed Q^2. This is significant for the Rosenbluth technique for determining the ratio of the electric and magnetic form factors of the proton at high Q^2, and partly reconciles the apparent discrepancy with the results of the polarization transfer technique.

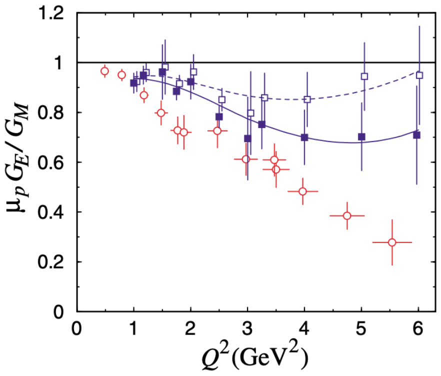
DOI: 10.1103/PhysRevLett.91.142304 PACS numbers: 25.30.Bf, 12.20.Ds, 13.40.Gp, 24.85.+p

→ extract two-photon exchange contribution needed to explain form factor discrepancy

→ first calculation of hadron-structure dependent part of two-photon exchange contribution

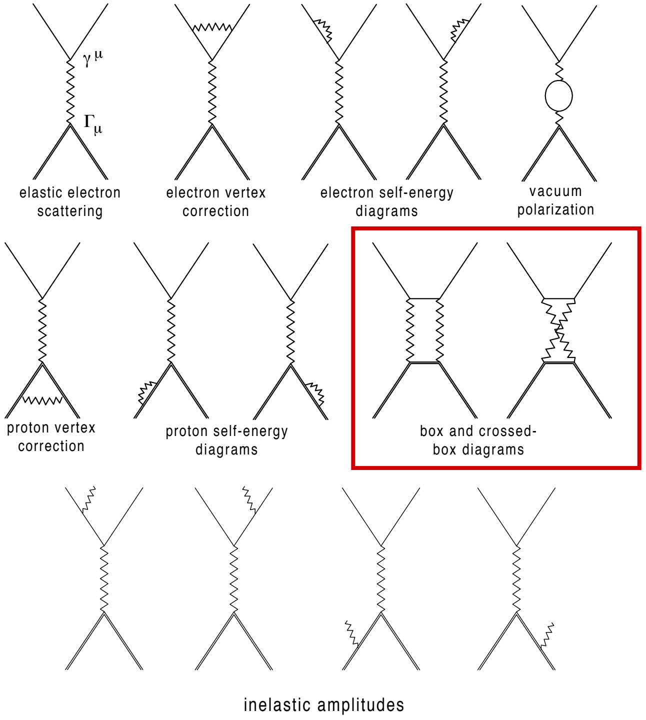






Two-photon exchange

- Born cross section modified by photon loop effects

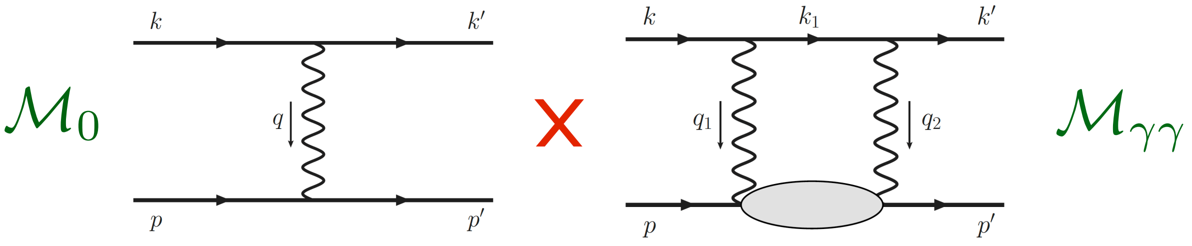


Born TPE

$$d\sigma = d\sigma_0\,(1+\delta)$$

δ contains additional ε dependence, mostly from box diagrams

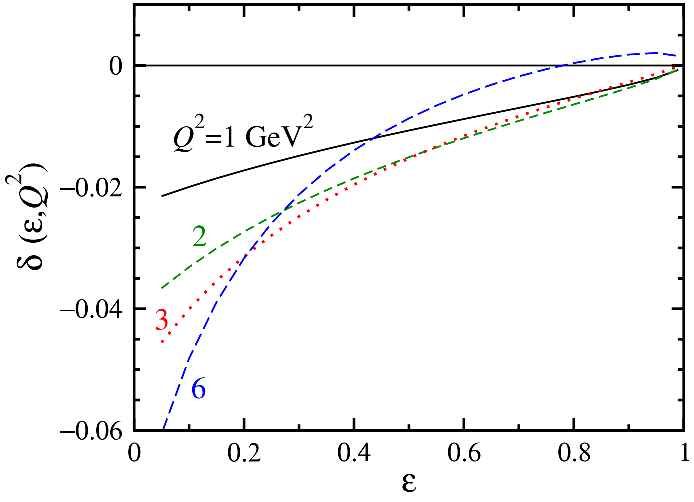
- Interference between Born and TPE amplitudes



Two-photon exchange

- Correction to cross section

$$\delta^{(2\gamma)} = \frac{2\mathcal{R}e\left\{\mathcal{M}_0^{\dagger}\ \mathcal{M}_{\gamma\gamma}\right\}}{|\mathcal{M}_0|^2}$$

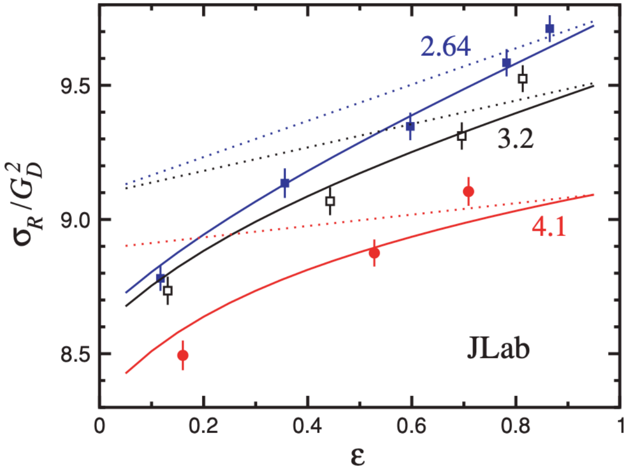


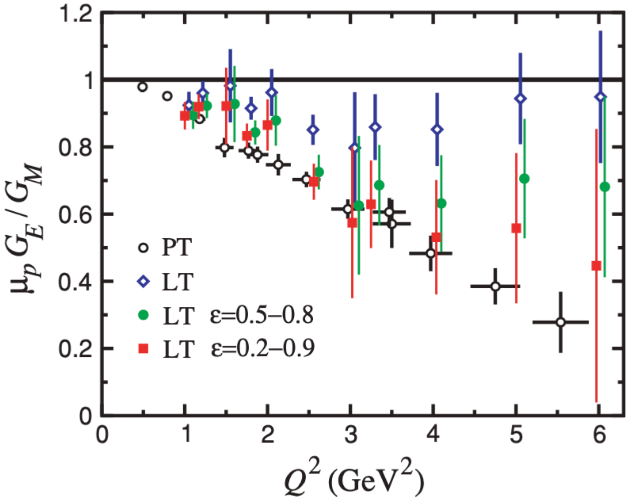
⟶ nonlinearity grows with Q^2

⟶ positive slope will *reduce* Rosenbluth ratio

Blunden, WM, Tjon, PRC ***72****, 034612 (2005)*

- TPE can resolve much of the discrepancy between Rosenbluth and polarization transfer data





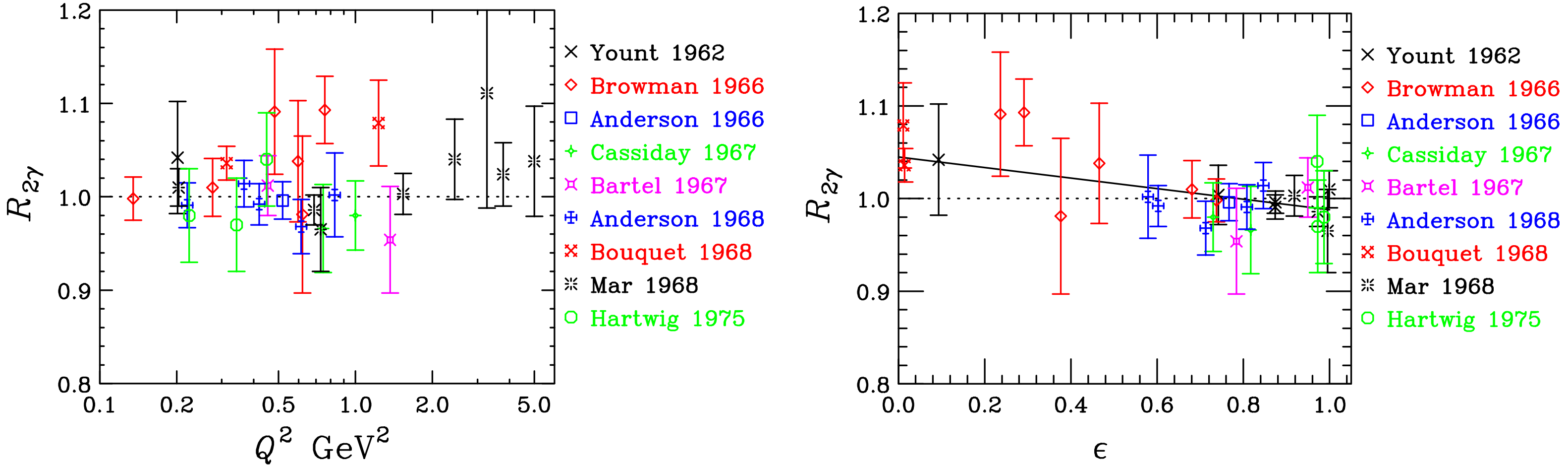
⟶ but is there any *direct* evidence?

TPE in e^+p to e^-p ratio

- TPE interference changes sign for positrons vs. elections

$$R_{2\gamma} = \frac{d\sigma^{e^+}}{d\sigma^{e^-}} \approx 1 - 2\,\delta_{2\gamma}$$

- Old data from $1960\text{s} - 1970\text{s}$



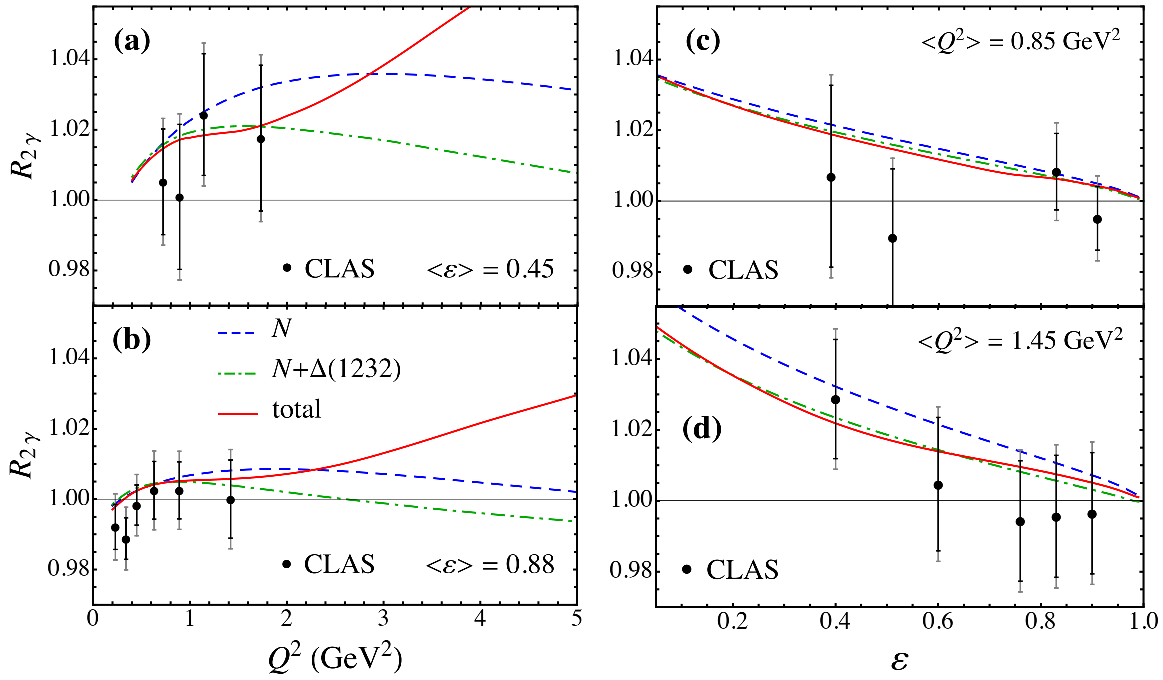
→ uncertainties too large for definitive conclusions…

TPE in e^+p to e^-p ratio

- More recent measurements from CLAS at JLab, using tertiary e^+e^- beam

(produced by passing primary electron beam through radiator ⟶ bremsstrahlung photon beam ⟶ pass through a convertor ⟶ electron/positron pairs)

B. Mecking



- CLAS, *Rimal et al., PRC **95**, 065201 (2017)*

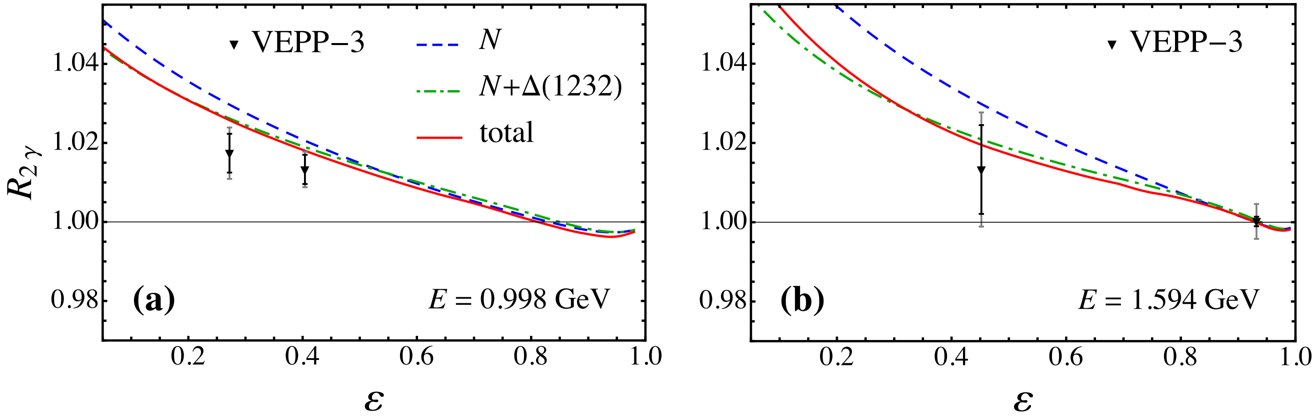
*Ahmed, Blunden, WM, PRC **102**, 045205 (2020)*

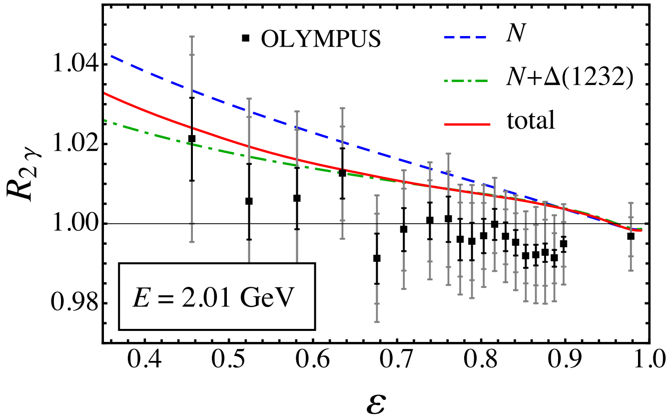
— dispersive calculation with all major N^* resonances in intermediate state

⟶ consistent with TPE calculations

TPE in e^+p to e^-p ratio

- Other measurements from VEPP-3 (Novosibirsk) and OLYMPUS (DESY)



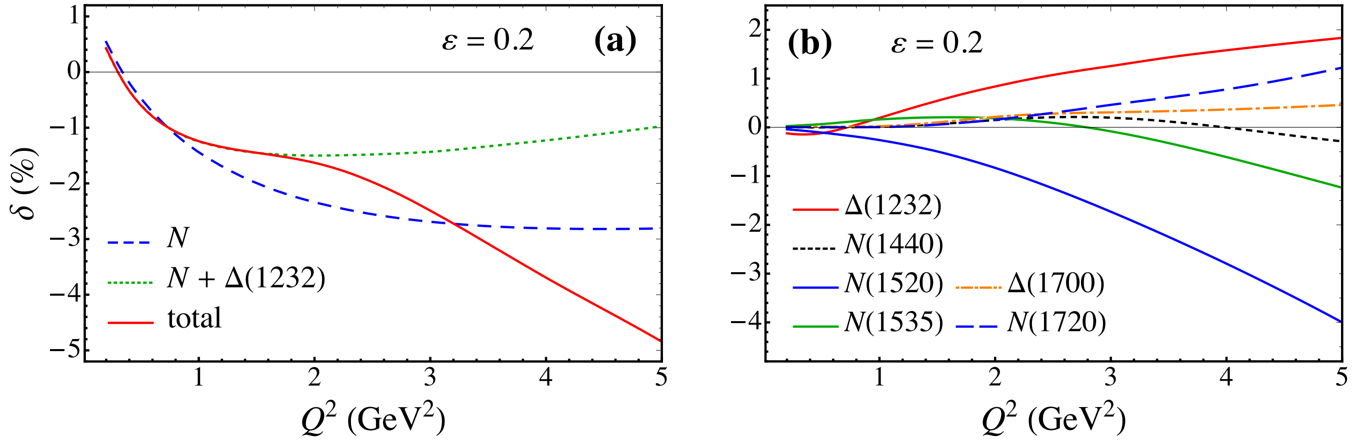


→ indication from data of $1\% - 2\%$ TPE effect at backward angles

TPE in e^+p to e^-p ratio

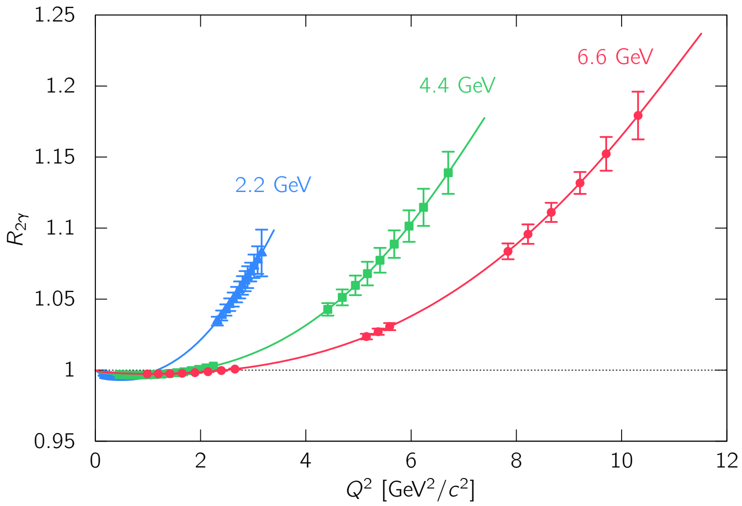
- Most measurements have been at large ε (forward angles) and low Q^2 where TPE are somewhat suppressed

- Optimal sensitivity at small ε (backward angles) and $Q^2 \gtrsim (3-4)\,\mathrm{GeV}^2$



Ahmed, Blunden, WM
*PRC **102**, 045205 (2020)*

→ positron beam at JLab could settle decades old question



PR12+23-008
Schmidt et al.

Parton structure of the nucleon

— generalized parton distributions —

Energy-momentum tensor

- Matrix elements of energy-momentum tensor give *gravitational form factors* (GFFs) of proton, which parametrize fundamental information about proton structure and dynamics (mass, spin, mechanical properties)

$$\langle p', \vec{s}\,' | T_q^{\mu\nu} | p, \vec{s}\,\rangle = \bar{u}(p', \vec{s}\,') \left[\underset{\substack{\uparrow \\ \text{mass/energy}}}{A_q(t)} \frac{P^\mu P'^\nu}{M} + \underset{\substack{\uparrow \\ \text{total angular} \\ \text{momentum}}}{J_q(t)} \frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_\alpha}{M} + \underset{\substack{\nwarrow \\ \text{pressure, force}}}{D_q(t)} \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \cdots \right] u(p, \vec{s}\,)$$

Burkert, Elouadrhiri, Girod, Lorcé, Shanahan
*RMP **95**, 041002 (2023)*

- GFFs related to moments of GPDs, $e.g.$

$$\int_{-1}^{1} dx\, x H_q(x, \xi, t) = A_q(t) + \xi^2 D_q(t)$$

- GPDs not measured directly, but enter high energy scattering observables such as deeply-virtual Compton scattering (DVCS), hard exclusive meson production, time-like Compton scattering, single diffractive hard exclusive processes (SDHEPs)

→ inferred from global QCD analysis of experimental data (+ lattice?)

$e.g.$, QGT Topical Collaboration, JAM Collaboration, …

Deeply-virtual Compton scattering

- GPDs enter DVCS cross section as complex integrals over parton momentum fraction x

$$\frac{d^5\sigma}{dQ^2\,dx_B\,dt\,d\phi\,d\phi_e} \sim \sum_q e_q^2 \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon}\right] H_q(x,\xi,t) + \cdots$$

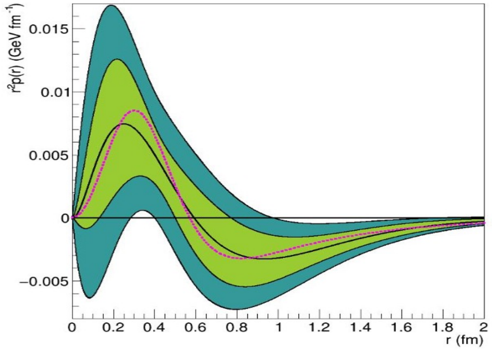
→ represented in the form Compton form factors (CFFs)

$$\mathcal{H}_q(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left[\frac{1}{x-\xi} \pm \frac{1}{x+\xi}\right] H_q(x,\xi,t) - i\pi H_q(\xi,\xi,t) = \mathcal{R}e\,\mathcal{H}_q(\xi,t) + i\,\mathcal{I}m\,\mathcal{H}_q(\xi,t)$$

- Real and imaginary parts of CFFs related by fixed-t dispersion relation

$$\mathcal{R}e\,\mathcal{H}_q(\xi,t) = \underset{\substack{\Big\uparrow \\ \text{directly related to } D\text{-term}}}{\mathcal{C}_{\mathcal{H}}(t)} + \frac{1}{\pi}\mathcal{P}\int_{0}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathcal{I}m\,\mathcal{H}_q(\xi,t)$$

→ information on real & imaginary parts of CFFs gives access to GFFs, and mechanical properties of proton

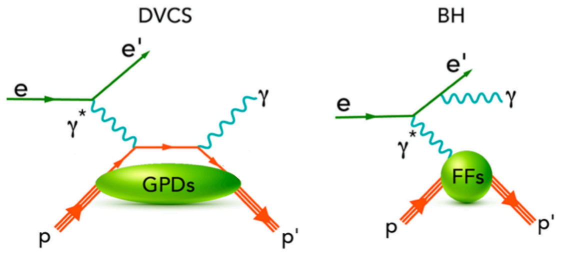


Burkert et al.
Nature ***557****, 396 (2018)*

Deeply-virtual Compton scattering

- Physical cross section has contributions from DVCS and competing Bethe-Heitler process

$$d^5\sigma^e_\lambda = d^5\sigma_{\mathrm{BH}} + d^5\sigma_{\mathrm{DVCS}} + \underset{\substack{\nwarrow \\ \text{lepton polarization}}}{\lambda}\, d^5\widetilde{\sigma}_{\mathrm{DVCS}} + \underset{\substack{\nwarrow \\ \text{lepton charge}}}{e}\,(d^5\sigma_{\mathrm{INT}} + \lambda\,\widetilde{\sigma}_{\mathrm{INT}})$$

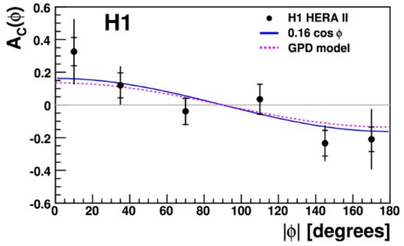


Burkert et al., RMP ***95****, 041002 (2023)*

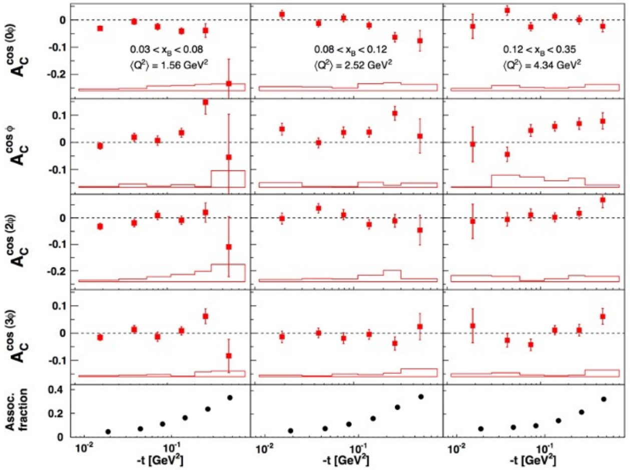
$\longrightarrow$ $d^5\sigma_{\mathrm{DVCS}} \sim \mathcal{H}\cdot\mathcal{H}^* + \cdots$ DVCS bilinear in CFFs

$\longrightarrow$ $d^5\sigma_{\mathrm{INT}} \sim F_1\cdot\mathcal{H} + \cdots$ interference term linear in CFFs

- Beam charge asymmetry allows separation of interference term from DVCS, and clean extraction of CFFs



H1 (2009)



HERMES (2008)

- Observables with polarized beam and/or target allow access to additional combinations of CFFs

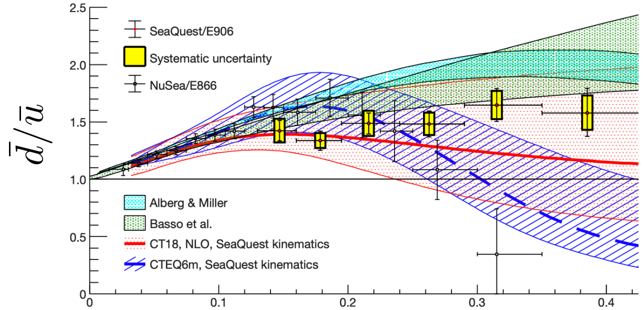
Parton structure of the nucleon

— strange-antistrange asymmetry —

Lepton charge asymmetry in DIS

- Unique opportunity to explore matter – antimatter asymmetry

⟶ antiquark asymmetry between $\bar{u}$ and $\bar{d}$ established



Dove et al.
Nature ***590****, 561 (2021)*

⟶ strange-antistrange asymmetry predicted
from χSB but has never been observed

(important elsewhere, *e.g.* W mass determinations, supernova explosions, …)

⟶ most direct way to access asymmetry is via γZ interference

$$\frac{d^2\sigma^i}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\,\eta^i\left\{\left(1 - y - \frac{x^2y^2M^2}{Q^2}\right)F_2^i + y^2xF_1^i \mp \left(y - \frac{y^2}{2}\right)xF_3^i\right\}$$

dominated
by γ exchange

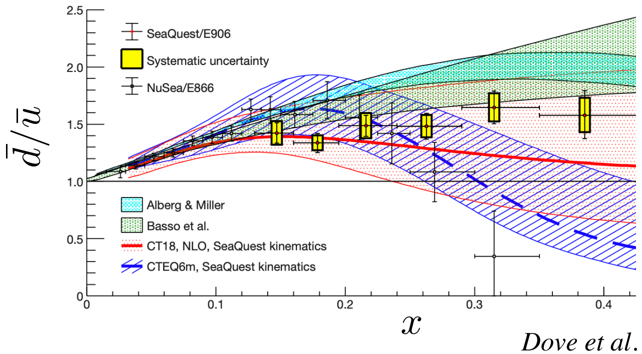
$$\sim (g_A^e \pm \lambda_e g_V^e)\, xF_3^{\gamma Z}$$

accessed
via BCA

accessed through PVDIS
but suppressed by
$g_V^e \sim 1 - 4\sin^2\theta_W$

Lepton charge asymmetry in DIS

Unique opportunity to explore matter – antimatter asymmetry



Dove et al. *Nature* ***590***, *561 (2021)*

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At quark level, $F_3^{\gamma Z}$ depends on C-odd combinations of PDFs

$$F_3^{\gamma Z} = \tfrac{4}{3}\left(\tfrac{1}{2} - \tfrac{4}{3}\sin^2\theta_W\right)(u - \bar{u}) + \tfrac{2}{3}\left(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right)(d - \bar{d}) + \boxed{\tfrac{2}{3}\left(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right)(s - \bar{s})}$$

- ⟶ valence u and d PDFs well known from global QCD analyses
- ⟶ signal is small and challenging to isolate from inclusive DIS alone
- ⟶ additional information $e.g.$ from semi-inclusive DIS with e^+ & e^- … but requires modeling of hadronization effects

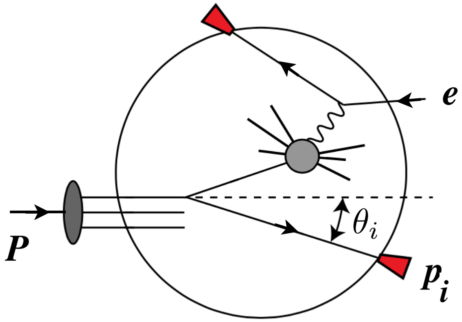
Nucleon energy-energy correlators

- Proposed new observables based on recent developments in pQCD: "energy-energy correlators" (EECs)

⟶ measure scattered lepton, and energy of produced hadrons in final state

$$\Sigma_N(Q^2,\theta) \; = \; \sum_i \int d\sigma(x_B, Q^2, p_i)\, x_B^{N-1} \, \frac{\bar{n}\cdot p_i}{P} \, \delta(\theta^2 - \theta_i^2)$$

weighted cross section related to "moments"
of PDFs & TMDs (integrals over x at fixed angles)



Liu, Zhu, PRL ***130****, 091901 (2023)*

⟶ for small θ_i cross section factorizes into nucleon EEC and partonic cross section

$$\Sigma_N(Q^2,\theta) \; = \; \sum_i f^i_{\rm EEC}(N,\theta^2,\mu) \int d\zeta\, \zeta^{N-1} \frac{d^2\hat{\sigma}_i(\mu)}{d\zeta dQ^2}$$

where nucleon EEC is related to moment of PDF

$$f^i_{\rm EEC}(N,\theta^2,\mu) = I_{ij}(N,\theta^2,\mu) \int_0^1 dx\, x^{N-1} f_j(x,\mu)$$

perturbatively calculable

⟶ "hybrid" between DIS and SIDIS, gives complementary information

Outlook

I’ve given 3 good reasons for positrons at JLab…

… and look forward to hearing many more during the rest of the workshop.