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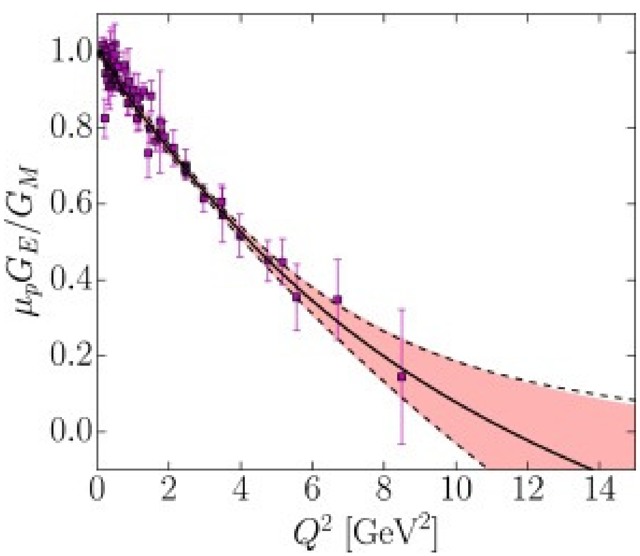
E12-07-108: GMp-12 (and TPE at high Q^2)

John Arrington

Hall A Collaboration Meeting, February 2022



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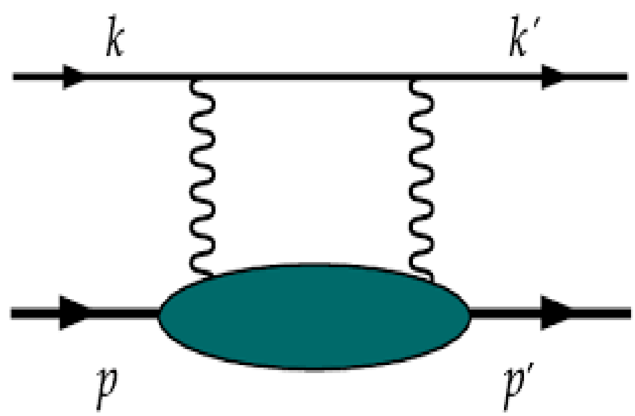

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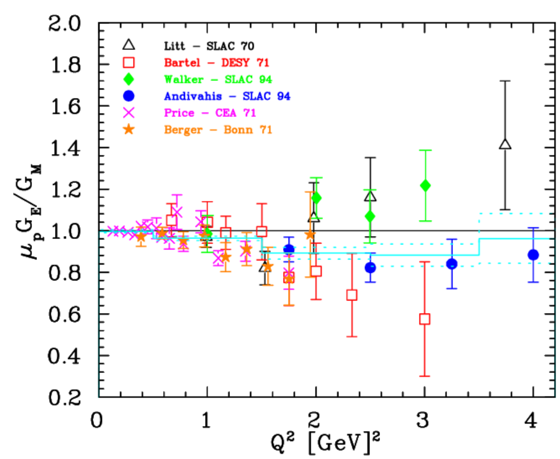

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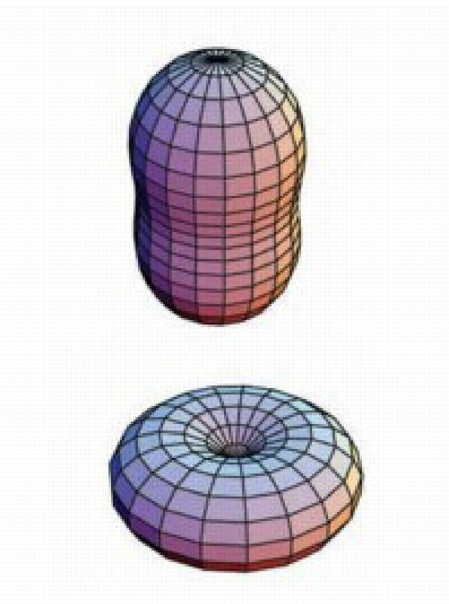

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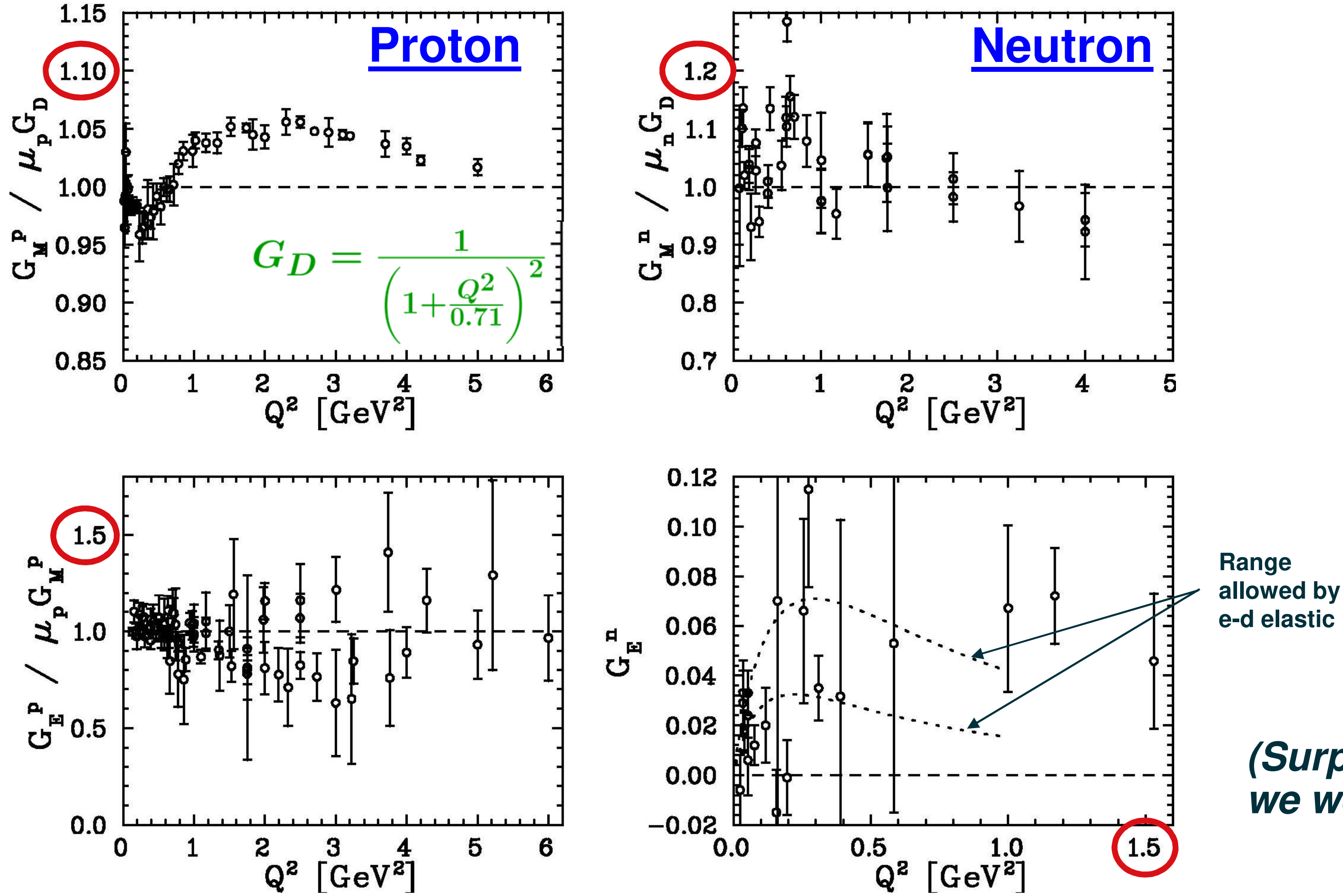
Nucleon Electromagnetic Form Factors

- **Fundamental properties of the proton and neutron**
  - Provide deviation of cross section from point-particle scattering
  - Contain information on charge, magnetization distributions
  - Connect to distribution, dynamics of quarks in hadrons
- **Experimental program reinvented at JLab**
  - Considered by many to be well understood by mid/late 80s
  - Polarization techniques → dramatic advances in Q^2 range, precision
- **Many applications of these new data/techniques**
  - Precise knowledge of FFs needed by other experiments
  - Advances in other programs, relying on same techniques

Where Were We ~20 Years Ago?



(Surprisingly close to where we were 30 years ago)

Unpolarized Elastic e-N Scattering

Nearly all of the measurements used Rosenbluth separation

$\sigma_R = d\sigma/d\Omega\ [\varepsilon(1+\tau)/\sigma_{Mott}] = \tau G_M^2 + \varepsilon G_E^2$

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

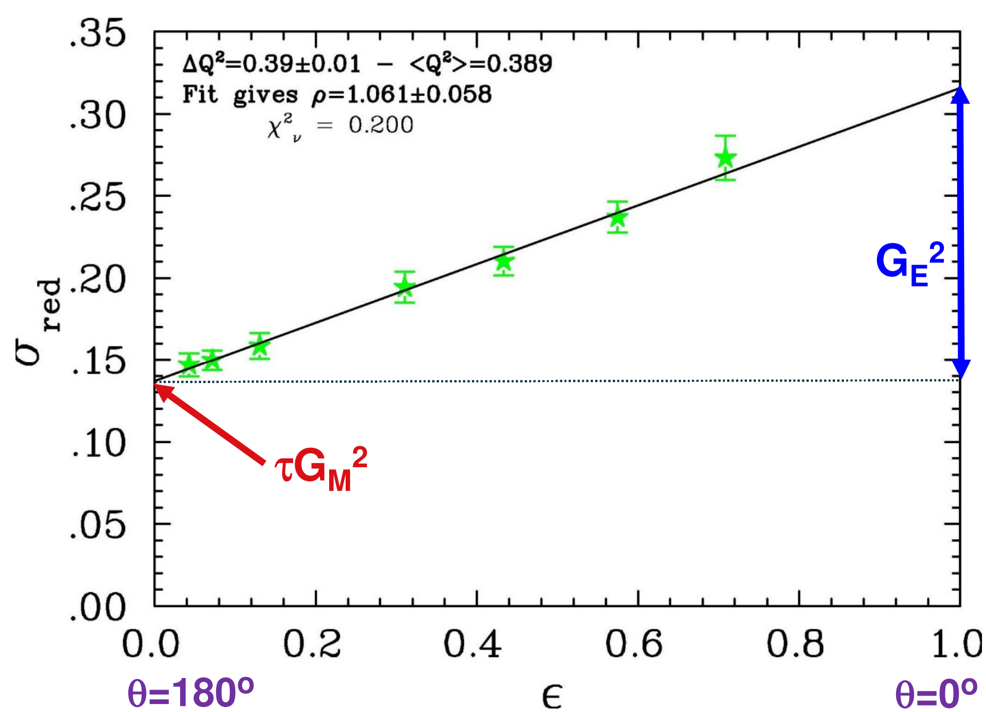
$\varepsilon = [\ 1 + 2(1+\tau)\tan^2(\theta/2)\ ]^{-1}$

Reduced sensitivity when one term dominates:

- **G_M if $\tau << 1$**
- **G_E if $\tau >> 1$**
- **G_E if $G_E^2 << G_M^2$** (neutron)

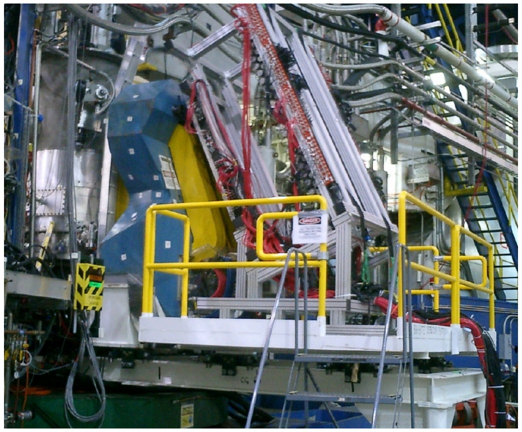
Lack of free neutron target:

Corrections for nuclear effects and proton contributions



New techniques: Polarization and A(e,e'N)

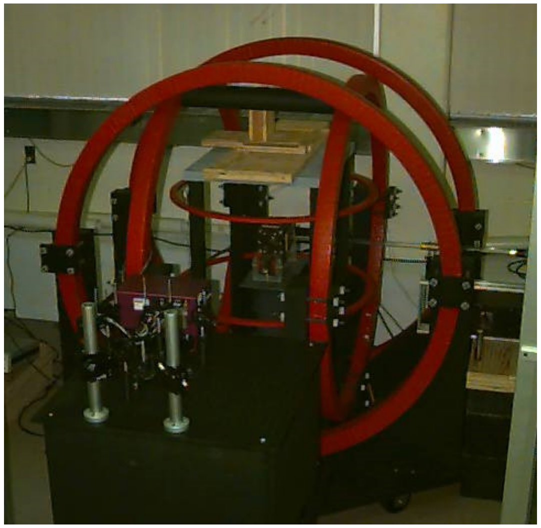
- **Mid '90s brought measurements using improved techniques**
  - Polarized beams with polarized target or recoil polarimeter
  - Large, efficient neutron detectors for ^{2}H(e,e'n)
  - Improved models for nuclear corrections



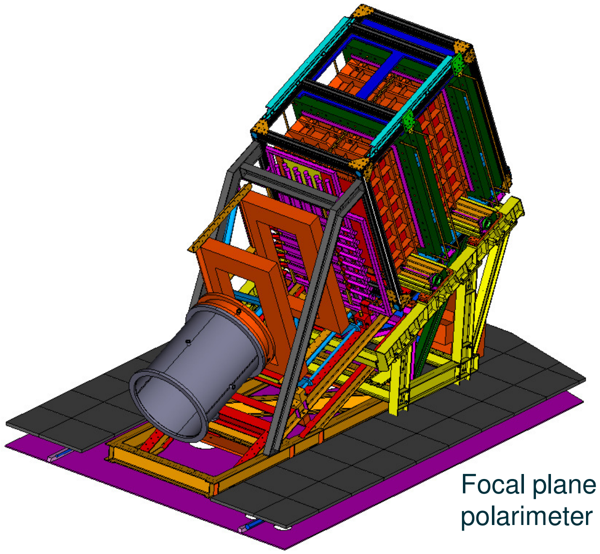
Bigbite in Hall A at JLab

L/T: $\tau G_M^2 + \varepsilon G_E^2$

Pol: G_E/G_M

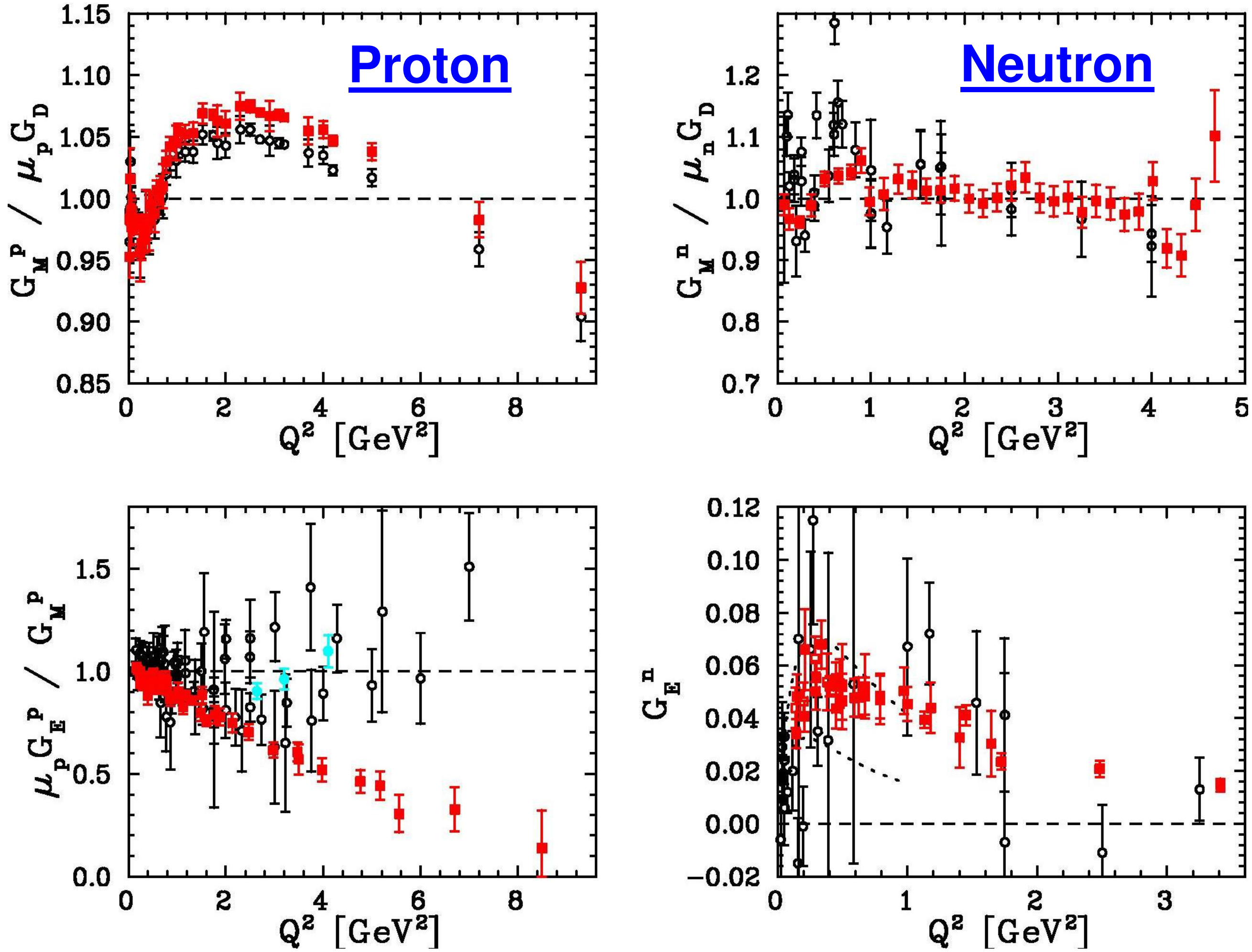


Polarized 3He target



Focal plane polarimeter

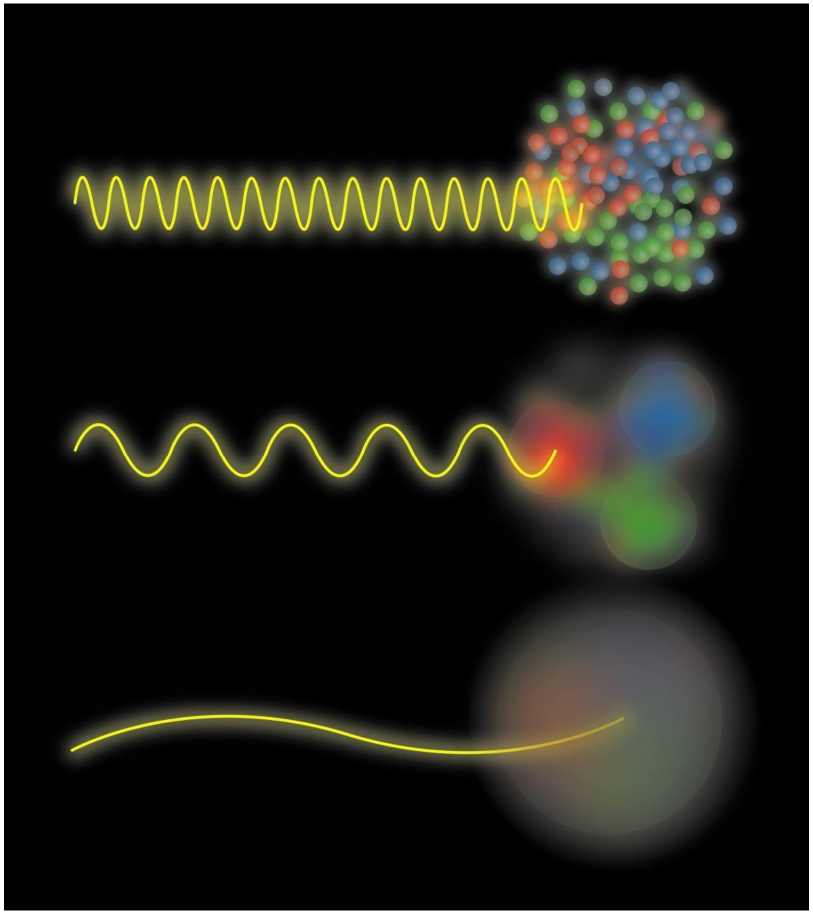
Nucleon Form Factors: 5 years ago



Impact of Recent Form Factor Measurements

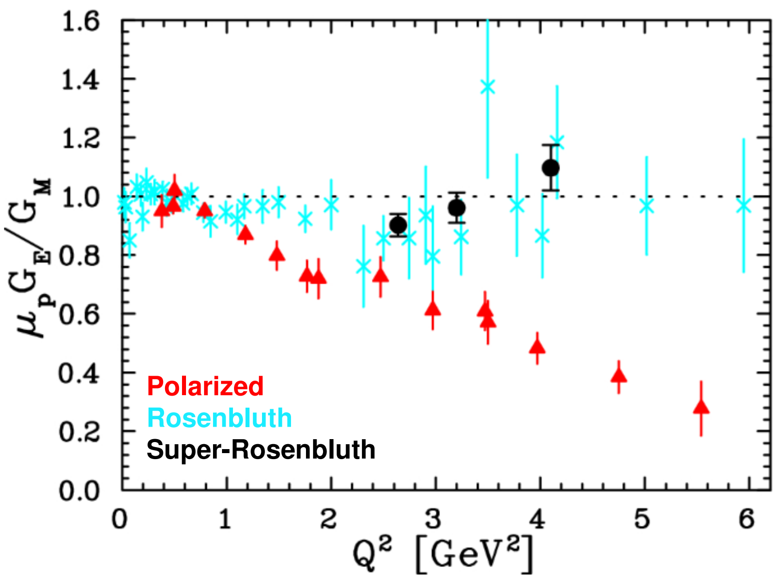
- **High-Q^2 Measurements** (2000+)
  - Quark structure, orbital angular momentum
  - Charge/magnetization densities in Infinite-Momentum Frame
- **Low/Modest-Q^2 Measurements** (2003+)
  - Comparison of charge, magnetic form factors
  - Flavor dependence up to 3.4 GeV^2
- **Proton charge, magnetization radii** (2010+)

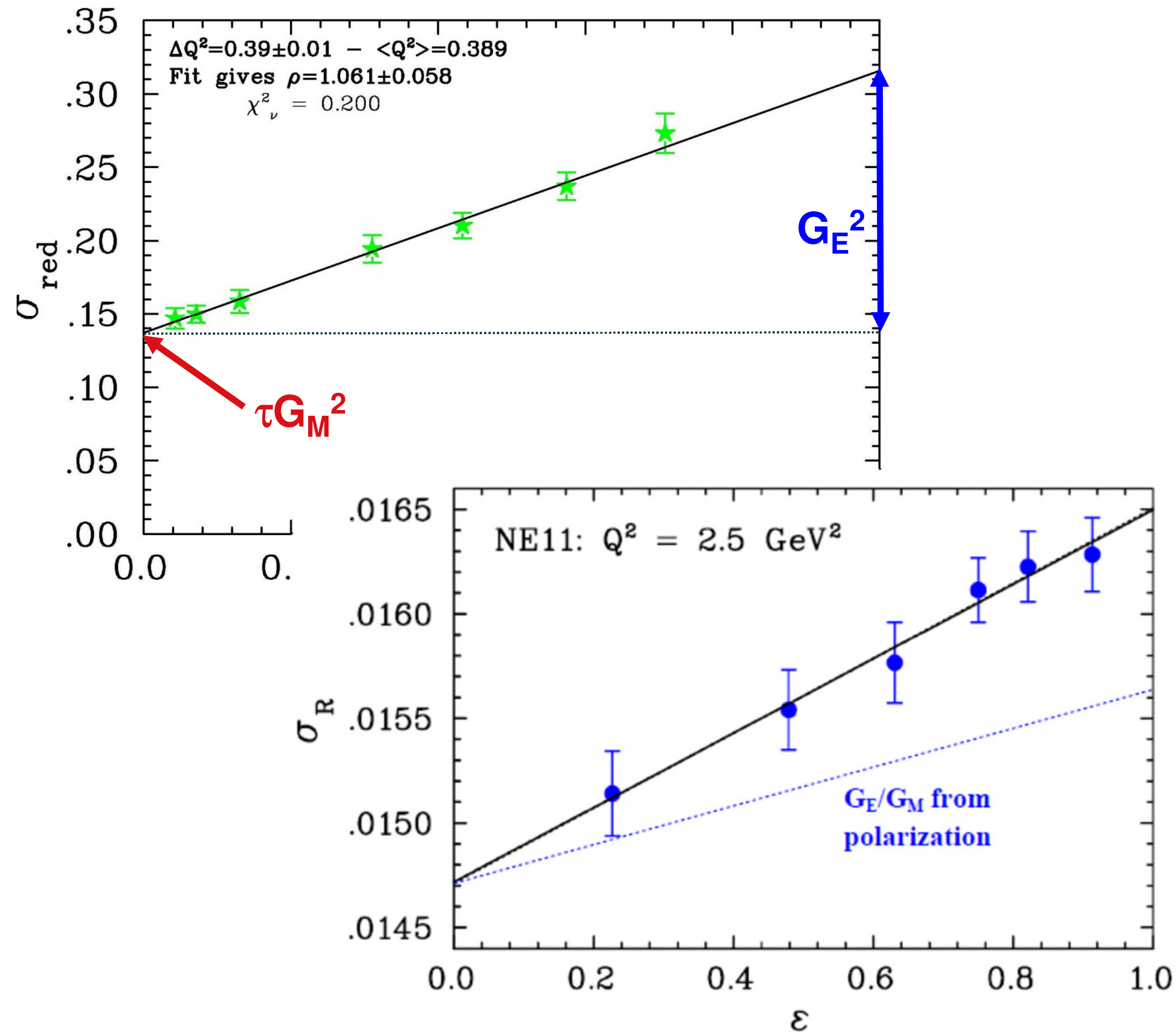
TWO-PHOTON EXCHANGE



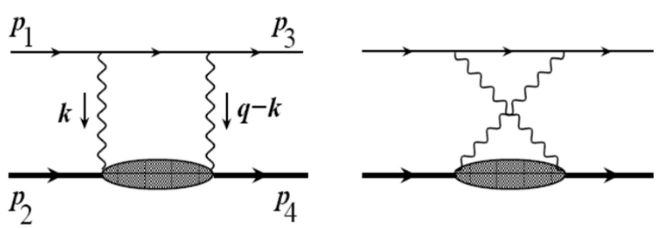
Graphic by Josh Rubin

Rosenbluth - Polarization discrepancy



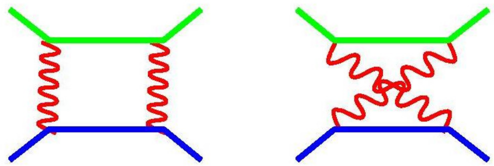


Leading explanation is hard 2-γ exchange, *not* included in standard radiative corrections of Mo-Tsai, etc.



Expected to be relatively small effect: few % or less
Can still change Rosenbluth significantly

Two-photon exchange corrections (early days)



Two-photon exchange effects can explain discrepancy in G_E

Guichon and Vanderhaeghen, PRL 91, 142303 (2003)

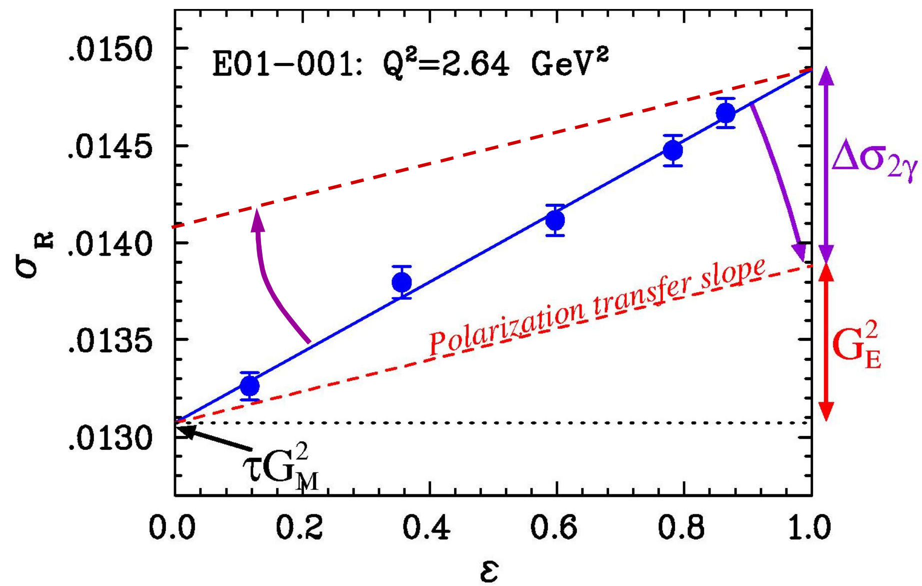
Requires ~6% ε-dependence, weakly dependent on Q^2, roughly linear in ε

JA, PRC 69, 022201 (2004)

If this were the complete story, LT would give G_M, Polarization gives G_E/G_M

- This is wrong and introduces large errors - sometimes larger than the real TPE corrections!

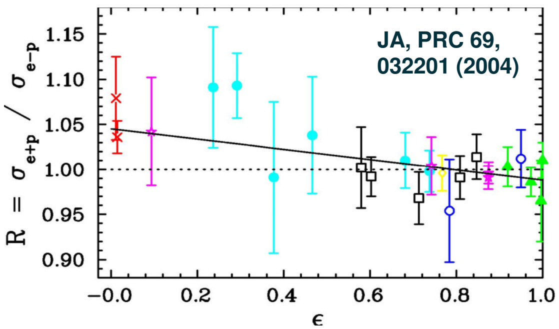
Important to quantify TPE and to constrain calculations to estimate TPE on other reactions



2γ contributions from e+p / e-p ratios

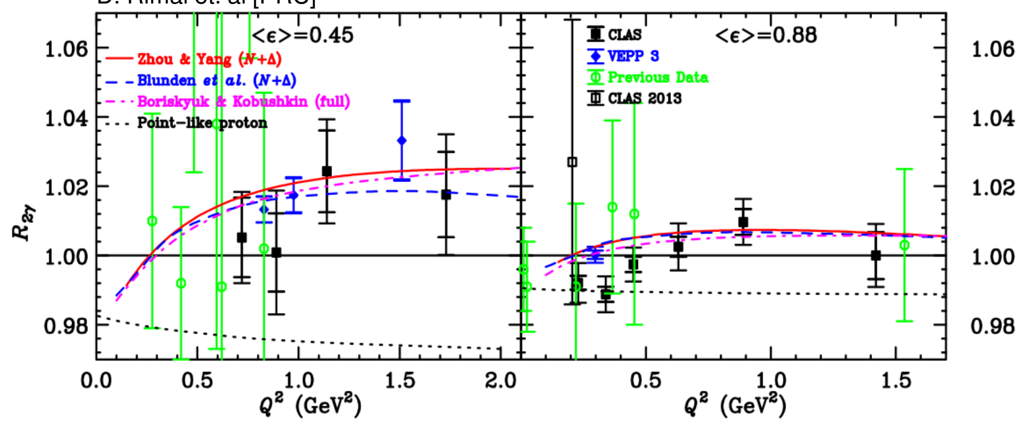
Hard 2γ contribution comes in with different signs for e+p and e-p => $\sigma+/\sigma- = R_{2\gamma} \sim 1-2\delta_{2\gamma}$

Evidence for TPE (only low Q^2 data) from earlier measurements

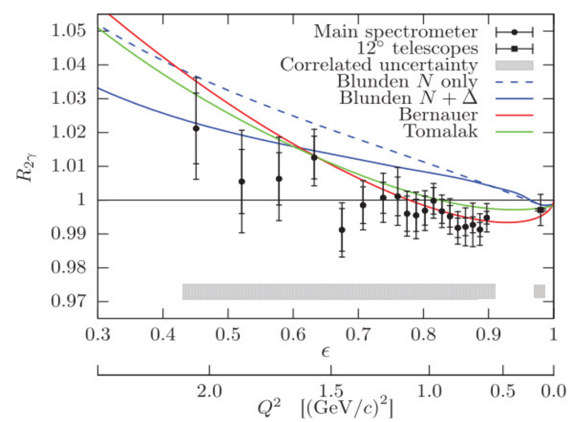


New data from
- VEPP-3
- CLAS
- OLYMPUS

D. Rimal et. al [PRC]



OLYMPUS PRL 118, 092501 (2017)



Conclusions from combined analysis of
A. Afanasev, P. G. Blunden, D. Hasell, and B. A. Raue:

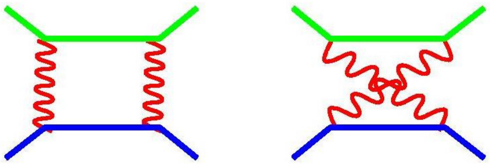
→ CLAS and VEPP-3 and OLYMPUS data exclude no TPE hypothesis at >95% confidence level

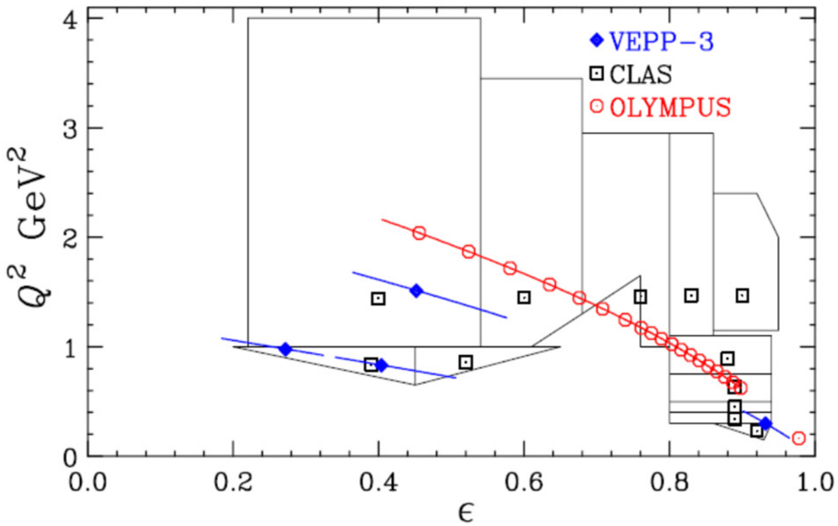
→ Data of insufficient precision to distinguish calculations of 2-γ contributions

→ Renormalization of OLYMPUS results required at twice the estimated uncertainty

Two-Photon Exchange – where we are today

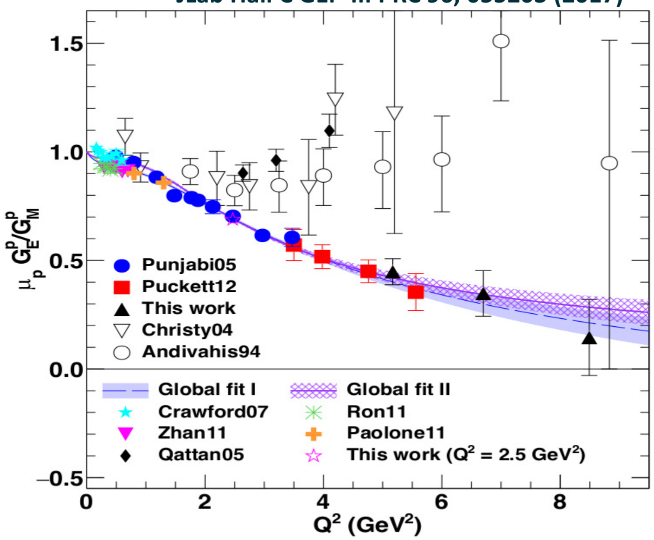
$$R \equiv \frac{\sigma_{e+}}{\sigma_{e-}} = \frac{(A_{1\gamma}+A_{2\gamma})^2}{(A_{1\gamma}-A_{2\gamma})^2} \approx 1 + 4\,\mathrm{Re}(A_{2\gamma}/A_{1\gamma})$$





Direct measurements (e$^+$-e$^-$ comparisons) of TPE up to 0.5 GeV^2 (old data), up to 2 GeV^2 (new generation)

JLab Hall C GEP-III PRC 96, 055203 (2017)



Indirect indications of TPE (via discrepancy) for ~2-7 GeV^2 – limited high Q^2 precision

Multiple calculations give qualitative or semi-quantitative description of discrepancy and direct positron measurements

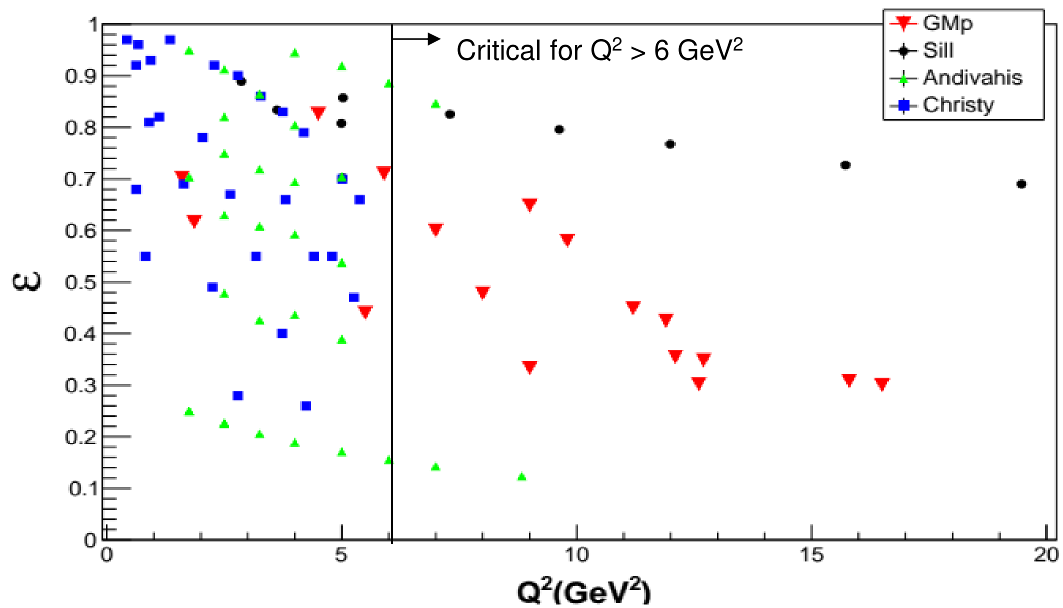
Goals of GMp-12

- Precise e-p elastic cross section over wide range of JLab-12 kinematics
  - Input to a wide range of analyses: QE scattering, GEp/GEn/GMn form factors
- Expand measurements of TPE to higher Q^2 values
- Improved extraction of GMp at high Q^2 (TPE constraints; lower ε for smaller extrapolation)

High precision, wide kinematic range:

- Checks of tracking, optics,…
- Updated radiative corrections

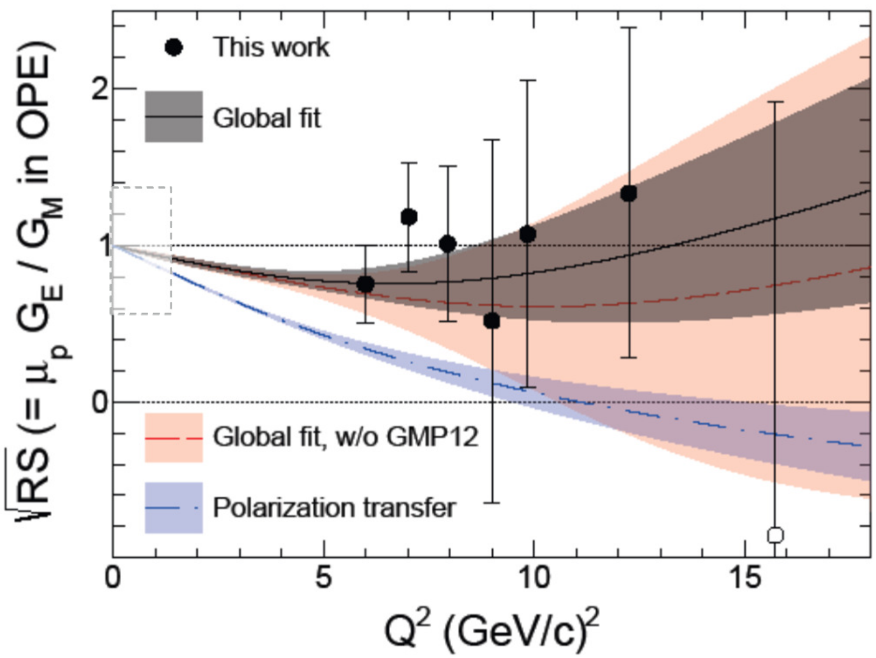
  A.V.Gramolin and D.M.Nikolenko, PRC 93 (2016) 055201
- Excellent systematic uncertainties
  - 1.2-1.3% point-to-point
  - 1.6% (2% RHRS) normalization

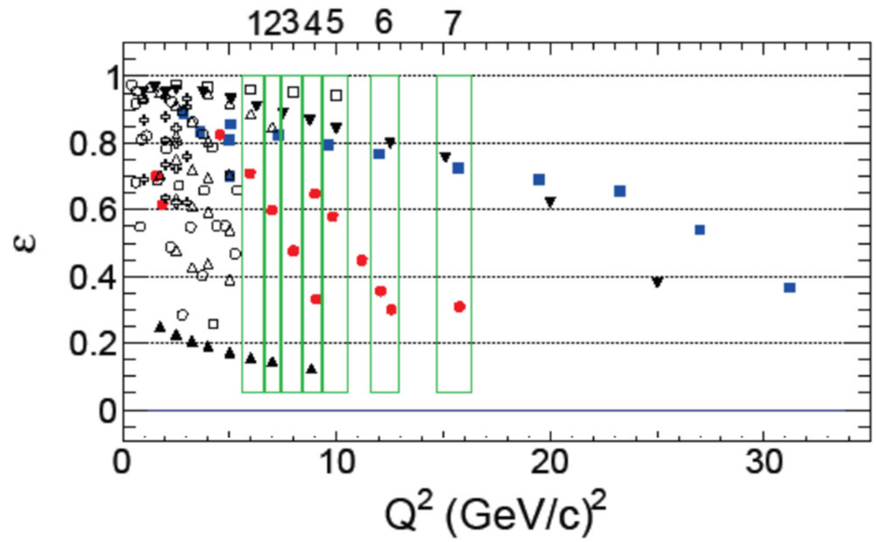


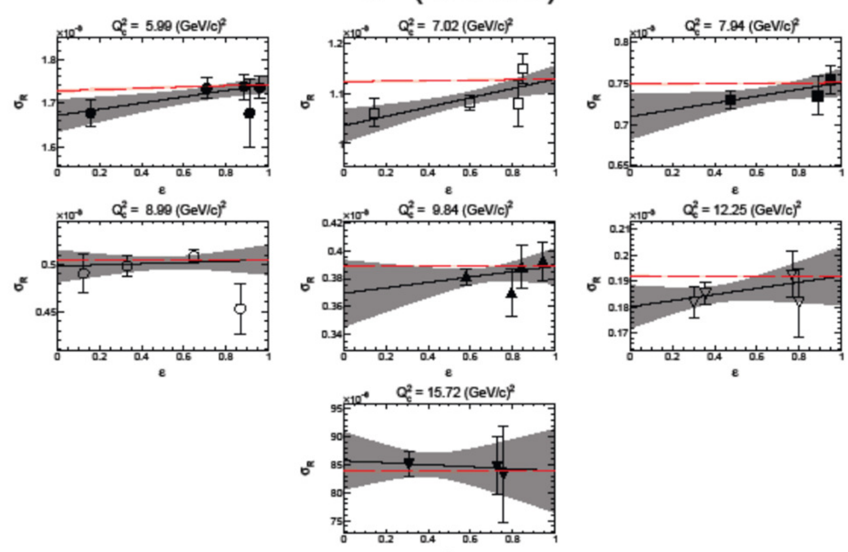
Rosenbluth separations

Global fit to Sill, Andivahis, Christy, and GMp12, all with updated RC, plus direct LT separation points (do not reflect the full high Q^2 data set)

Minimal low-Q^2 data included: fit focused on high-Q^2 behavior



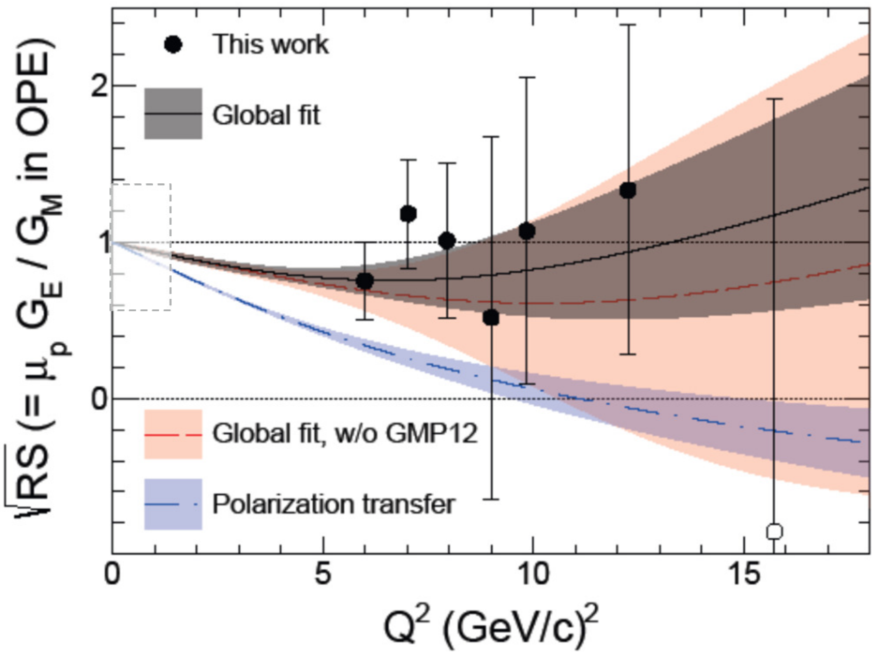


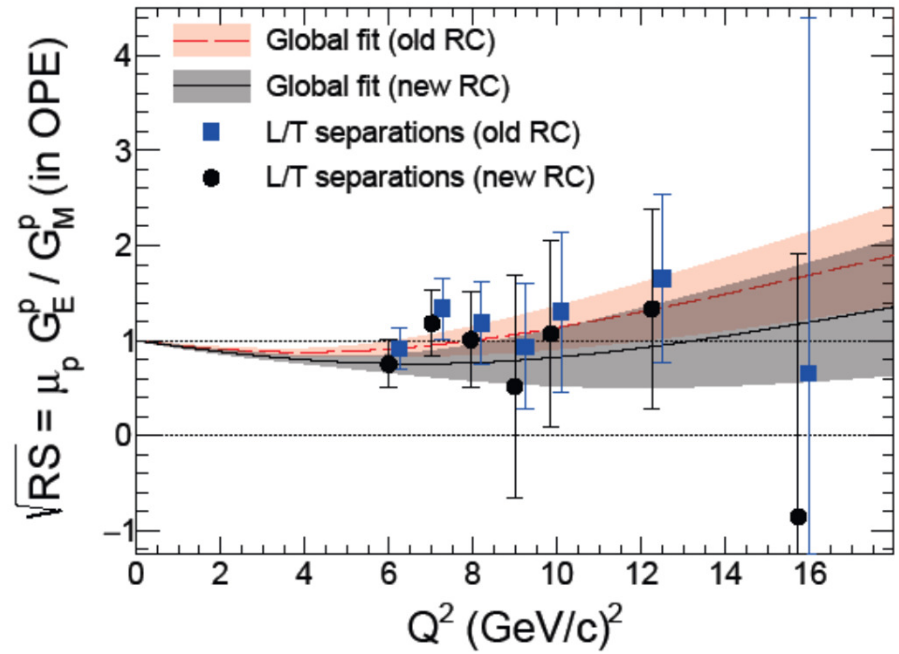


New data, updated RC: $\langle\Delta_{2\gamma}\rangle$ = 4.2 ± 2.0% (for Q^2>6 GeV^2)

Indications of TPE over full Q^2 range

Radiative corrections and TPE



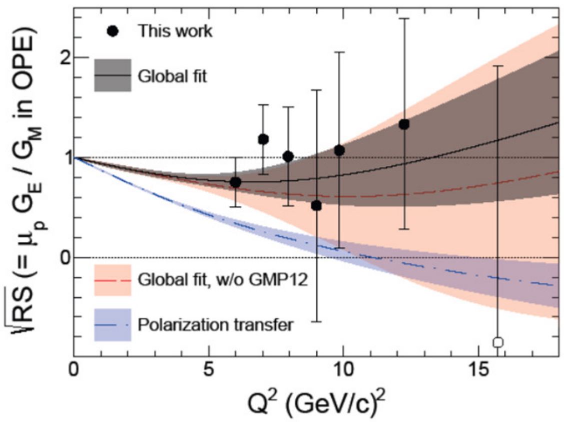


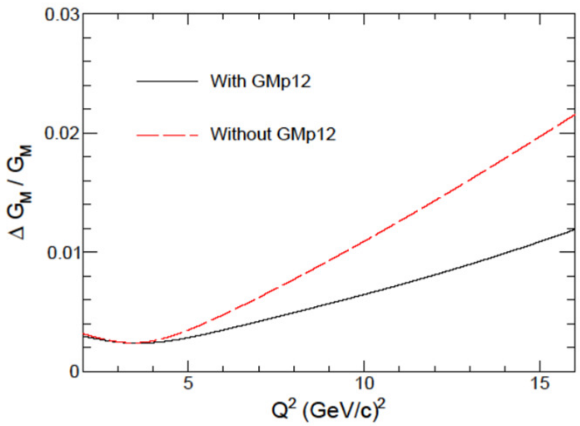
New data, updated RC: $\langle\Delta_{2\gamma}\rangle$ = 4.2 ± 2.0% (Q^2>6 GeV^2)
Using conventional RC: $\langle\Delta_{2\gamma}\rangle$ = 6.6 ± 2.1% (Q^2>6 GeV^2)

New RC resolves roughtly one-third of the discrepancy

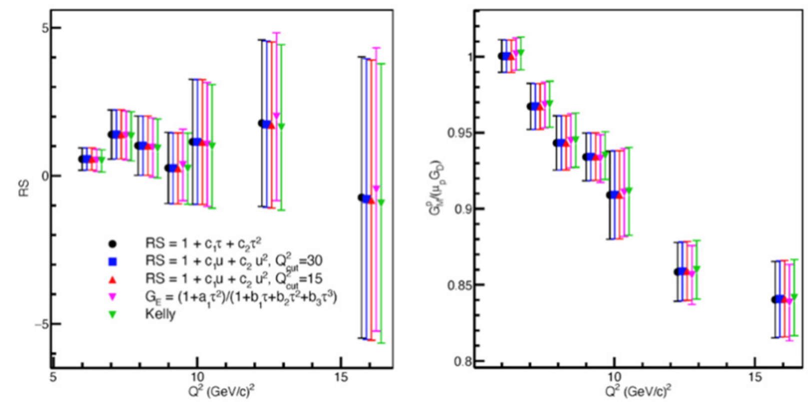
Even after this, discrepancy between continues to Q^2 > 15 GeV^2

Impact on Rosenbluth uncertainties

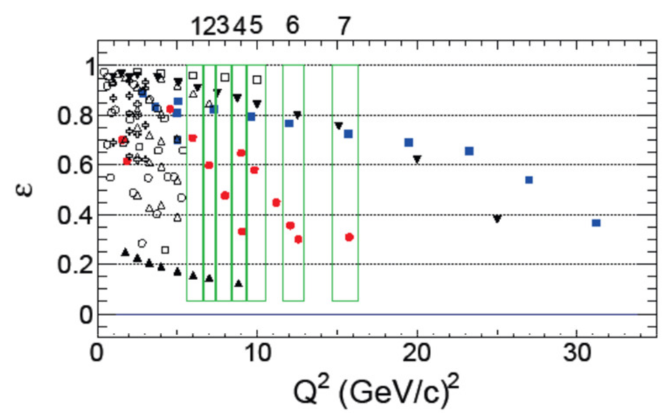




Rosenbluth extractions insensitive to global fit



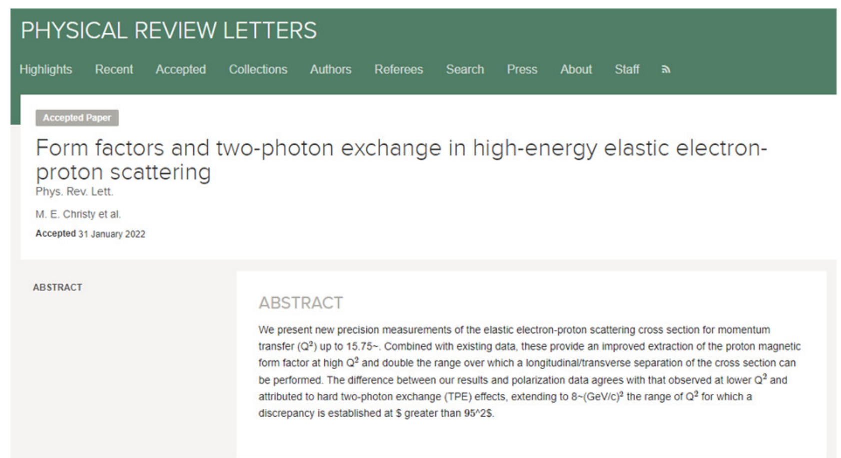
- Reduced Rosenbluth form factor uncertainties
- Better constraints on TPE (limited by Rosenbluth Uncertainties)
- Precise cross sections across JLab12 kinematics
    - Reduced extrapolation, TPE uncertainty
    - Direct input for several analyses



Goals of GMp-12

- Precise e-p elastic cross section over wide range of JLab-12 kinematics
- Expand measurements of TPE to higher Q^2 values
- Improved extraction of GMp at high Q^2

Accepted by PRL (last week), with 16 page supplement on experiment, analysis, RC, fits, TPE



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Accepted Paper

Form factors and two-photon exchange in high-energy elastic electron-proton scattering

Phys. Rev. Lett.

M. E. Christy et al.

Accepted 31 January 2022

ABSTRACT

ABSTRACT

We present new precision measurements of the elastic electron-proton scattering cross section for momentum transfer (Q^2) up to 15.75~. Combined with existing data, these provide an improved extraction of the proton magnetic form factor at high Q^2 and double the range over which a longitudinal/transverse separation of the cross section can be performed. The difference between our results and polarization data agrees with that observed at lower Q^2 and attributed to hard two-photon exchange (TPE) effects, extending to 8~(GeV/c)^2 the range of Q^2 for which a discrepancy is established at $ greater than 95^2$.

Sincere thanks to the many people who contributed

Spokespersons:

- John Arrington
- Eric Christy
- Shalev Gilad
- Vincent Sulkosky
- Bogdan Wojtsekhowski

Postdoc:

- Kalyan Allada

Ph.D students (all have defended):

- Thir Gautam (Hampton U.)
- Longwu Ou (MIT)
- Barak Schmookler (MIT)
- Yang Wang (W&M)
- Bashar Aljawrneh (NCA&T)

Analysis support:

- Andrew Puckett
- Alexander Gramolin

Early 12 GeV running over multiple run periods: Couldn’t have happened without strong collaboration and excellent lab support

Thanks to JLab accelerator team, Hall A target group, and all shift takers for their tremendous effort to make the GMp run successful

Form factors and two-photon exchange in high-energy elastic electron-proton scattering

M. E. Christy,[1] T. Gautam,[1] L. Ou,[2] B. Schmookler,[2] Y. Wang,[3] D. Adikaram,[4] Z. Ahmed,[5] H. Albataineh,[6] S. F. Ali,[7] B. Aljawrneh,[8,9] K. Allada,[2] S.L. Allison,[10] S. Alsalmi,[11] D. Androic,[12] K. Aniol,[13] J. Annand,[14] J. Arrington,[15,16] H. Atac,[17] T. Averett,[3] C. Ayerbe Gayoso,[3] X. Bai,[18] J. Bane,[19] S. Barcus,[3] K. Bartlett,[3] V. Bellini,[20] R. Beminiwattha,[21] J. Bericic,[4] H. Bhatt,[22] D. Bhetuwal,[22] D. Biswas,[1] E. Brash,[23] D. Bulumulla,[10] C. M. Camacho,[24] J. Campbell,[25] A. Camsonne,[4] M. Carmignotto,[7] J. Castellanos,[26] C. Chen,[1] J-P. Chen,[4] T. Chetry,[27] E. Cisbani,[28] B. Clary,[29] E. Cohen,[30] N. Compton,[27] J. C. Cornejo,[3,31] S. Covrig Dusa,[4] B. Crowe,[32] S. Danagoulian,[8] T. Danley,[27] W. Deconinck,[3] M. Defurne,[33] C. Desnault,[24] D. Di,[18] M. Dlamini,[27] M. Duer,[30] B. Duran,[17] R. Ent,[4] C. Fanelli,[2] E. Fuchey,[29] C. Gal,[18] D. Gaskell,[4] F. Georges,[34] S. Gilad,[2] O. Glamazdin,[35] K. Gnanvo,[18] A. V. Gramolin,[36] V. M. Gray,[3] C. Gu,[18] A. Habarakada,[1] T. Hague,[11] G. Hamad,[27] D. Hamilton,[14] K. Hamilton,[14] O. Hansen,[4] F. Hauenstein,[10] A. V. Hernandez,[7] W. Henry,[17] D. W. Higinbotham,[4] T. Holmstrom,[37] T. Horn,[7] Y. Huang,[18] G.M. Huber,[5] C. Hyde,[10] H. Ibrahim,[38] N. Israel,[27] C-M. Jen,[39] K. Jin,[18] M. Jones,[4] A. Kabir,[11] B. Karki,[27] C. Keppel,[4] V. Khachatryan,[40,41] P.M. King,[27] S. Li,[42] W. Li,[5] H. Liu,[43] J. Liu,[18] A. H. Liyanage,[1] D. Mack,[4] J. Magee,[3] S. Malace,[4] J. Mammei,[44] P. Markowitz,[26] S. Mayilyan,[45] E. McClellan,[4] F. Meddi,[28] D. Meekins,[4] K. Mesick,[46] R. Michaels,[4] A. Mkrtchyan,[7] B. Moffit,[4] R. Montgomery,[14] L.S. Myers,[4] P. Nadel-Turonski,[4] S. J. Nazeer,[1] V. Nelyubin,[18] D. Nguyen,[18] N. Nuruzzaman,[1] M. Nycz,[11] R.F. Obrecht,[29] K. Ohanyan,[45] C. Palatchi,[18] B. Pandey,[1] K. Park,[10] S. Park,[40] C. Peng,[47] F. D. Persio,[28] R. Pomatsalyuk,[35] E. Pooser,[4] A.J.R. Puckett,[29] V. Punjabi,[48] B. Quinn,[31] S. Rahman,[44] M.N.H. Rashad,[10] P.E. Reimer,[16] S. Riordan,[40] J. Roche,[27] I. Sapkota,[7] A. Sarty,[49] B. Sawatzky,[4] N. H. Saylor,[50] M. H. Shabestari,[22] A. Shahinyan,[45] S. Širca,[51] G.R. Smith,[4] S. Sooriyaarachchilage,[1] N. Sparveris,[17] R. Spies,[44] A. Stefanko,[31] T. Su,[11] A. Subedi,[22] V. Sulkosky,[2] A. Sun,[31] Y. Tan,[52] L. Thorne,[31] N. Ton,[18] F. Tortorici,[20] R. Trotta,[53] R. Uniyal,[7] G.M. Urciuoli,[28] E. Voutier,[24] B. Waidyawansa,[4] B. Wojtsekhowski,[4,*] S. Wood,[4] X. Yan,[54] L. Ye,[22] Z. H. Ye,[18,55] C. Yero,[26] J. Zhang,[18] Y. X. Zhao,[40] and P. Zhu[56]