Measuring Hard Two-Photon Exchange at Jefferson Lab

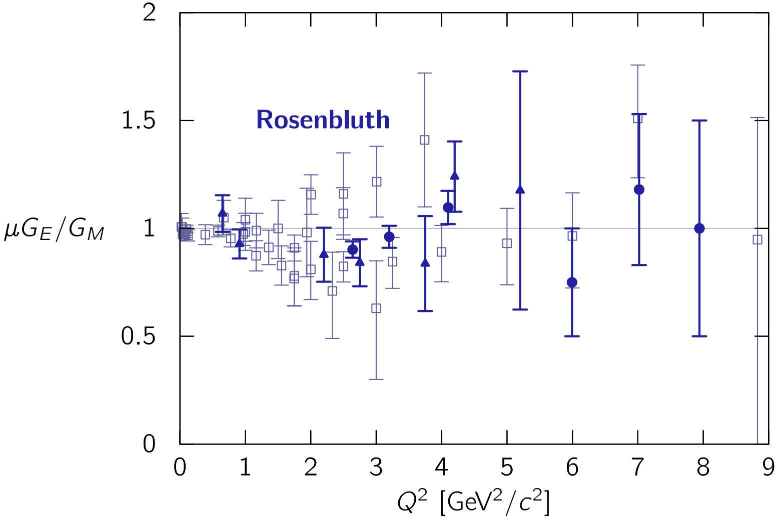
Axel Schmidt

2024 JLUO Annual Meeting

June 11, 2024

This work is supported by the US DOE Office of Science, Office of Nuclear Physics, under contract no. DE-SC0016583.

Measurements of the proton's form factors are discrepant.



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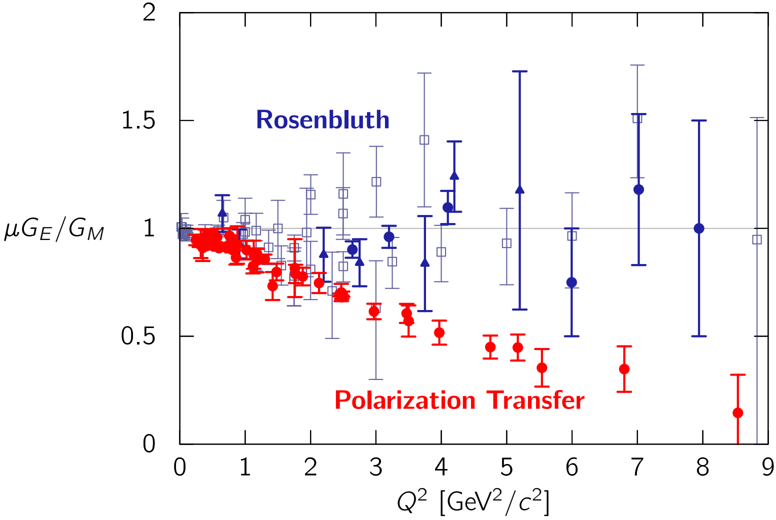

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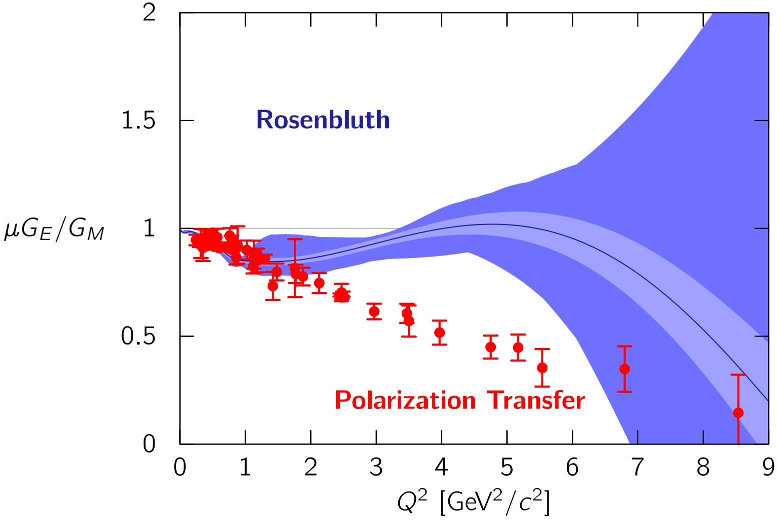
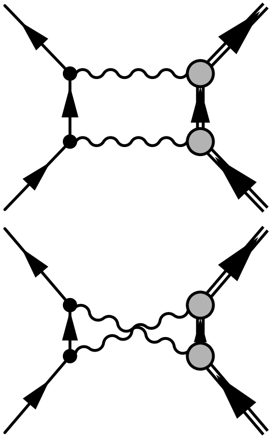


The current status is uncomfortable.

Two-photon exchange



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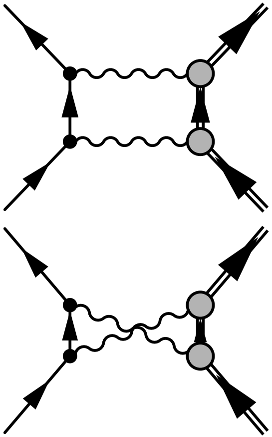


- Proton FFs are ambiguous.
- TPE is hard to calculate.
- Recent experiments inconclusive

- *Field is embarking on 3d imaging campaign of the nucleon.*

E12+23-08: Measuring two-photon exchange at CLAS12 with positrons.

- Spokespeople: J. C. Bernauer, V. D. Burkert, E. Cline, I. Korover, **A. Schmidt**, N. Santiesteban, T. Kutz

- Experimental details:
  - 55 days in Hall B with CLAS12
  - e^+, e^- beams at 2.2., 4.4, 6.6 GeV, unpolarized, ≈ 75 nA
  - Unpolarized H_2 target
  - Measure e^+p/e^-p elastic cross section ratio: $R_{2\gamma}$

- Developed from LOI12-18-004
  "Determination of two-photon exchange via e^+p/e^-p scattering with CLAS12"
  J. C. Bernauer et al., EPJA 57:144 (2021)

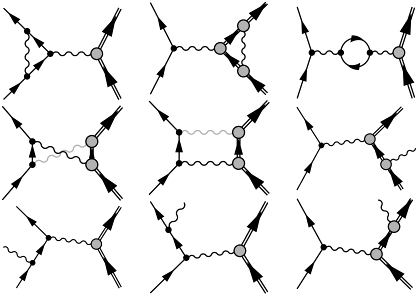
- Conditionally approved by PAC51 (2023) with an 'A' rating.

In my talk today:

- **Recent History**
  - Theoretical and experimental efforts on two-photon exchange
- **Our Proposed Experiment**
  - Our plan for using positrons at CLAS12
- **Alternate Approaches**
  - Work by others to nail down two-photon exchange

The one "missing" radiative correction is hard two-photon exchange (TPE).

The standard set



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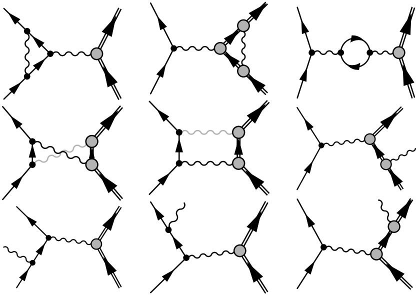

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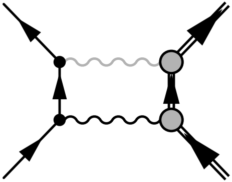

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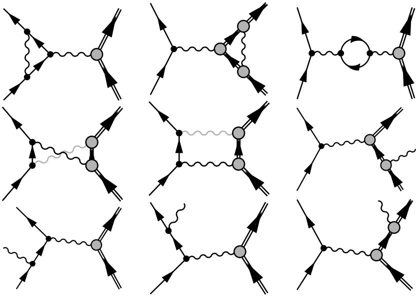

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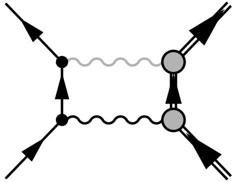

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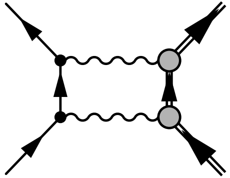
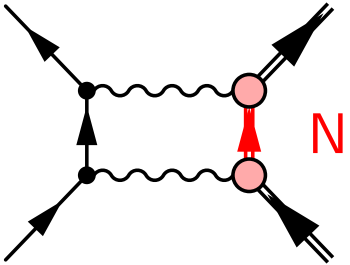


Calculations of two-photon exchange come with model dependency.



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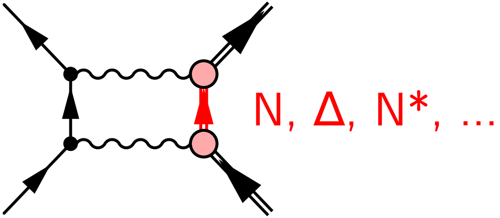
- Treat off-shell propagator as collection of hadronic states.
- e.g. Blunden, Melnitchouk, PRC '17, Ahmed et al., PRC '20, '23



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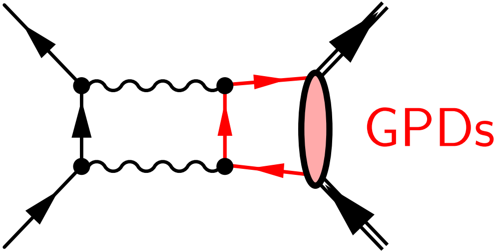

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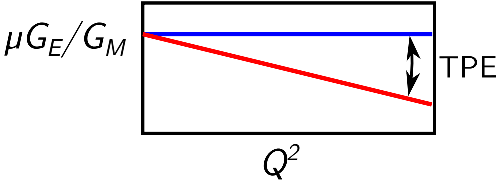
- e.g. Bernauer et al., PRC '14 A. Schmidt, JPG '20



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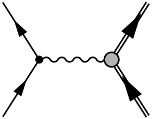
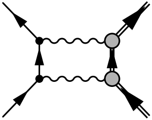
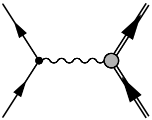
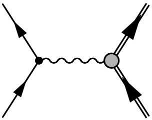
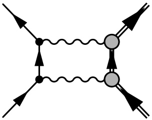
Alternate Approaches

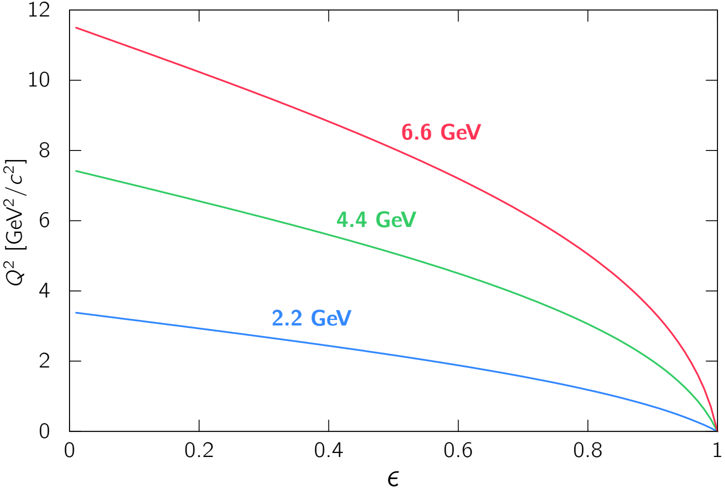
- e.g., Kuraev et al., PRC '08

TPE produces an asymmetry between electron and positron scattering.

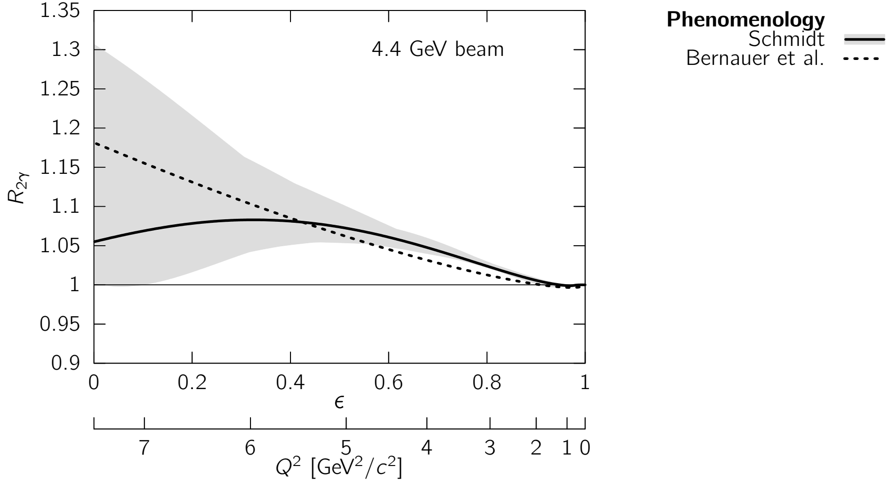
$\mathcal{M} =$  $+$  $+\, \mathcal{O}(\alpha^3)$

$\sigma \approx |\mathcal{M}|^2 = \Big|$  $\Big|^2 \pm 2\mathrm{Re}\Big[$   $\Big] + \mathcal{O}(\alpha^4)$

Elastic scattering is a 2D space



Predictions for $R_{2\gamma} = \sigma_{e^+p}/\sigma_{e^-p}$



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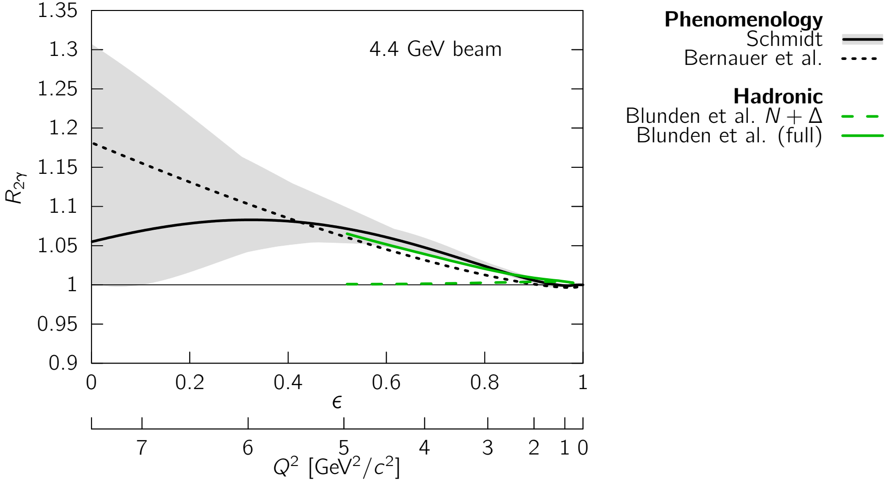

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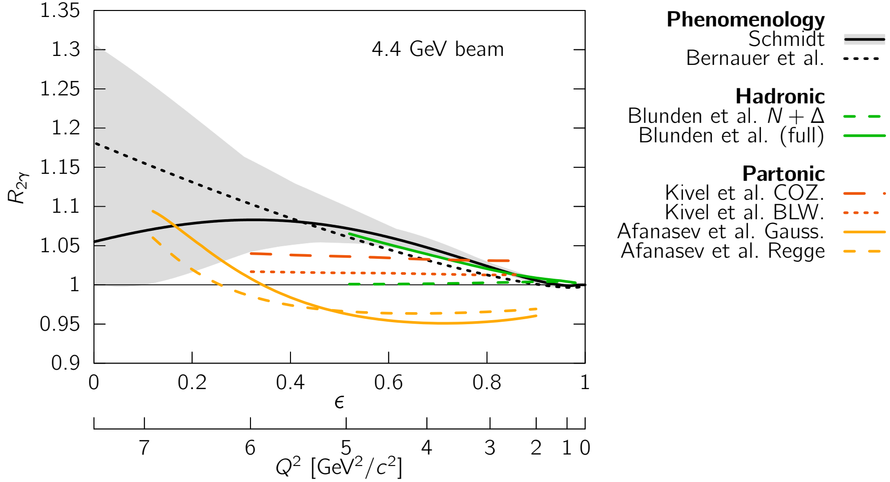

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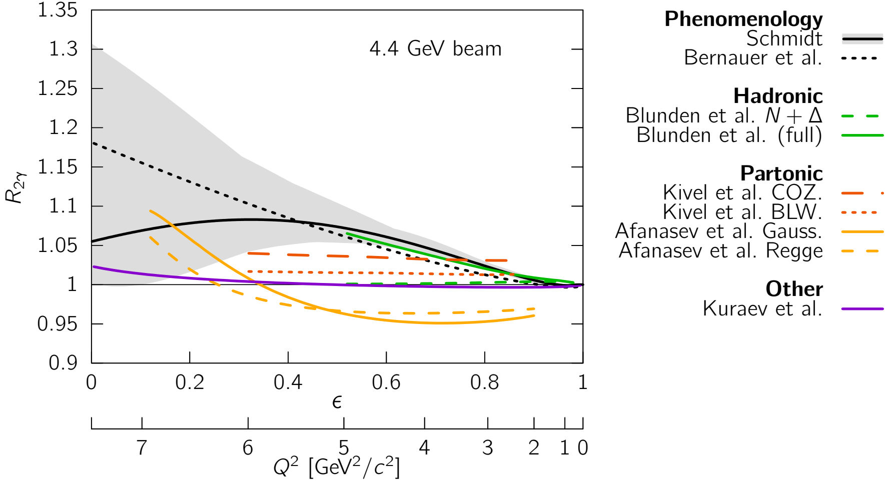
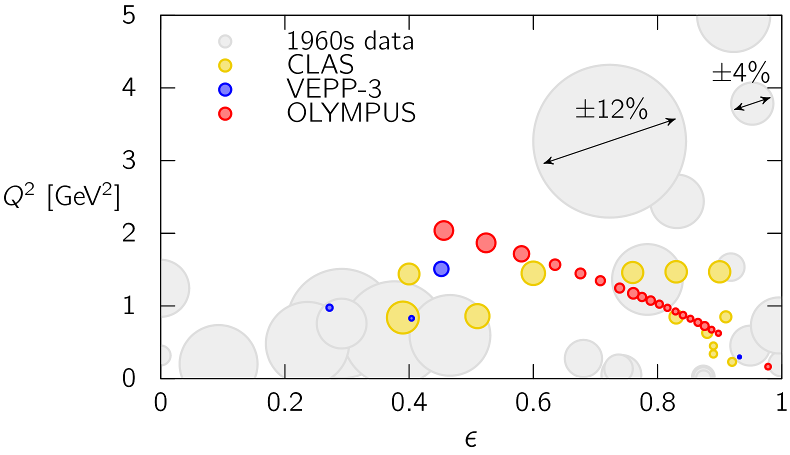
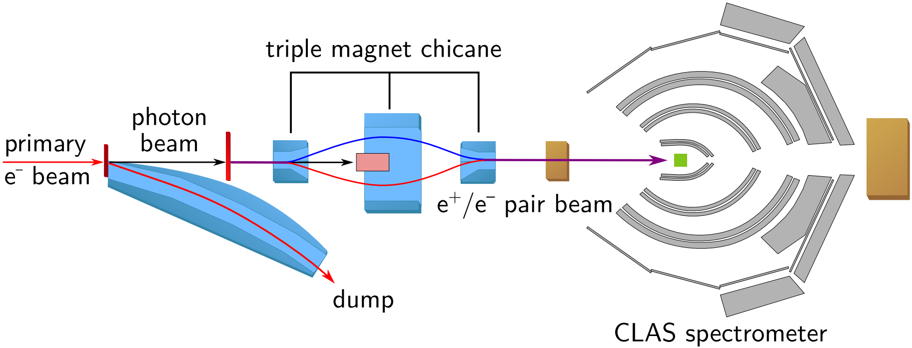


Three recent experiments measured hard TPE.



CLAS Two-Photon Exchange Experiment

TPE/eg5 run period (2010–11)



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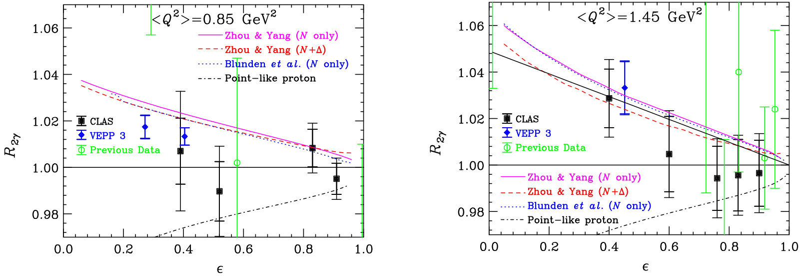
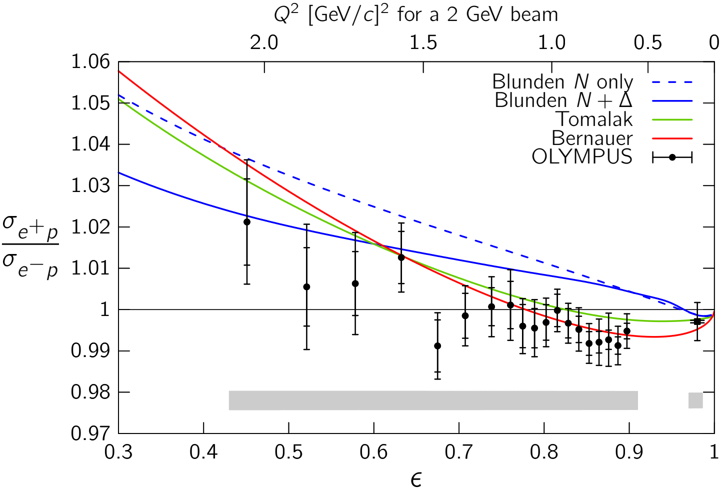


D. Adikaram et al., PRL 114, 062003 (2015)

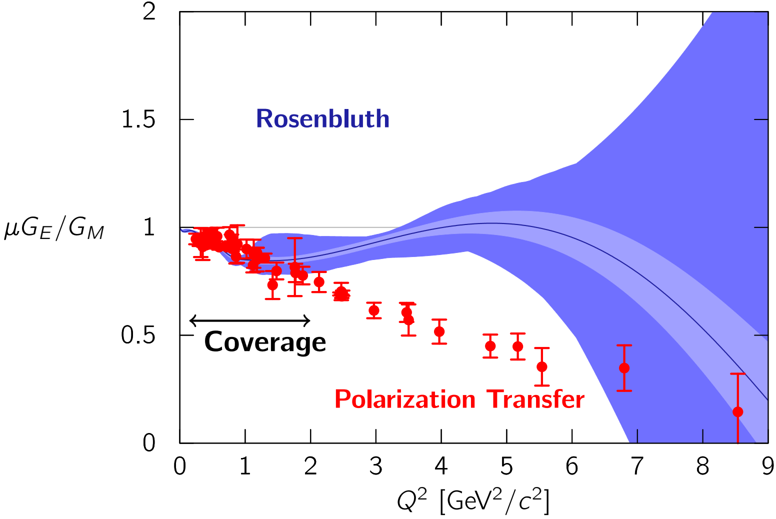
D. Rimal et al., PRC 95, 065201 (2017)

OLYMPUS observed a small TPE effect.



Henderson et al., PRL 118, 092501 (2017)

Recent measurements lacked the kinematic reach to be decisive.



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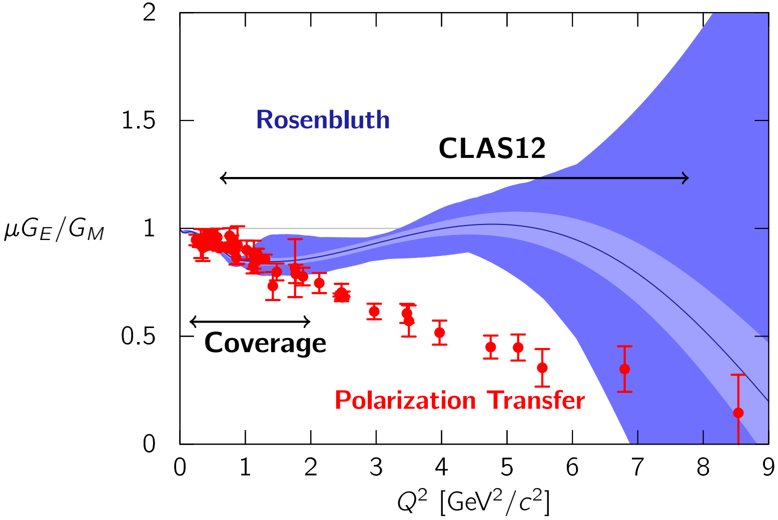
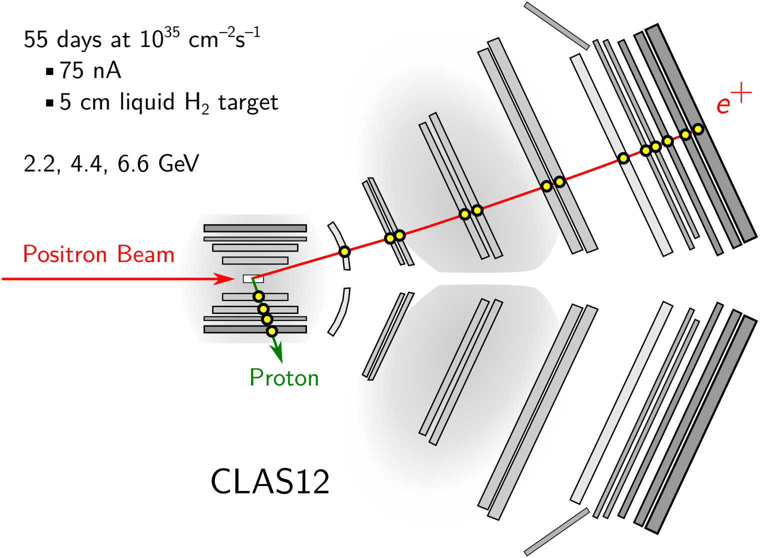


Our proposed experiment

55 days at 10^{35} cm^{-2}s^{-1}

- 75 nA
- 5 cm liquid H_2 target

2.2, 4.4, 6.6 GeV



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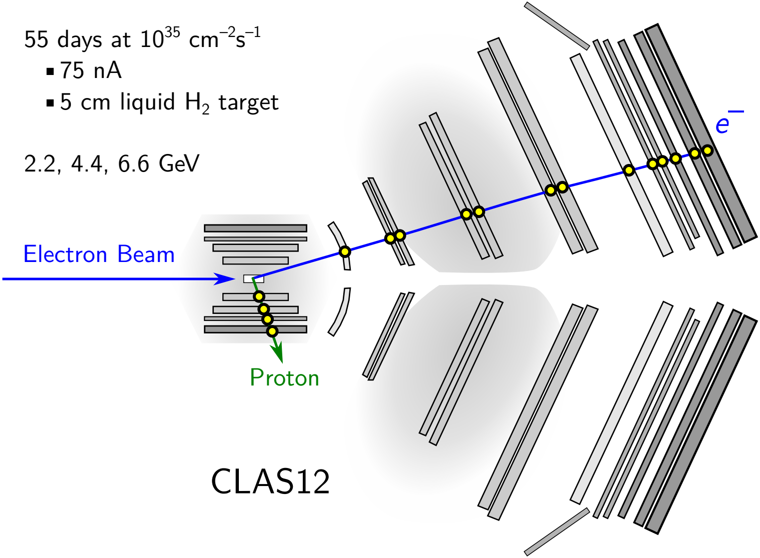
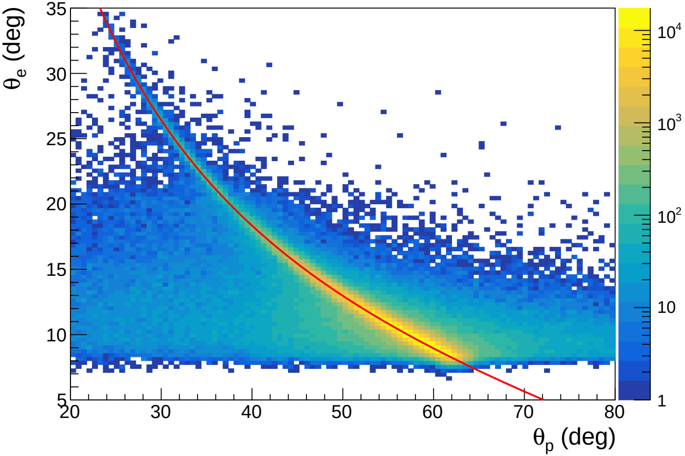


CLAS12 holds several key advantages over OLYMPUS

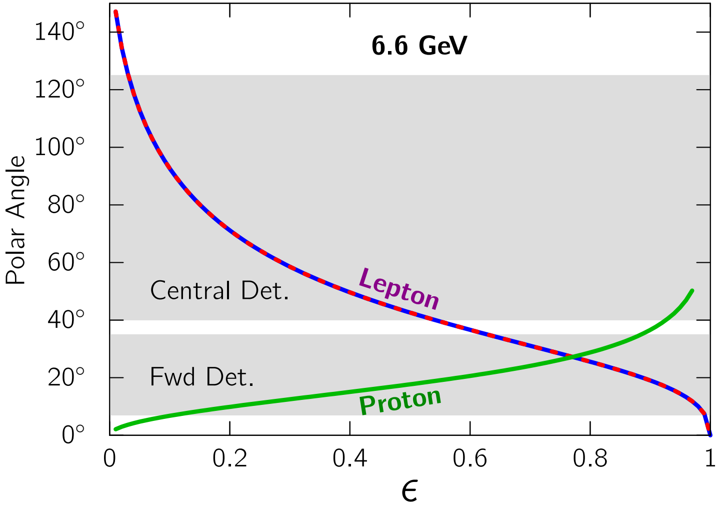
	OLYMPUS	**CLAS12**
Azimuthal acceptance	$\pi/4$	2π
Luminosity	$2 \cdot 10^{33}$	10^{35}
Beam energy	2 GeV	6.6 GeV

Elastic scattering is easy to identify in CLAS12.

2021 Run Group M data (6 GeV e^- on hydrogen)



We want to trigger on events with a lepton in the CLAS12 central detector.



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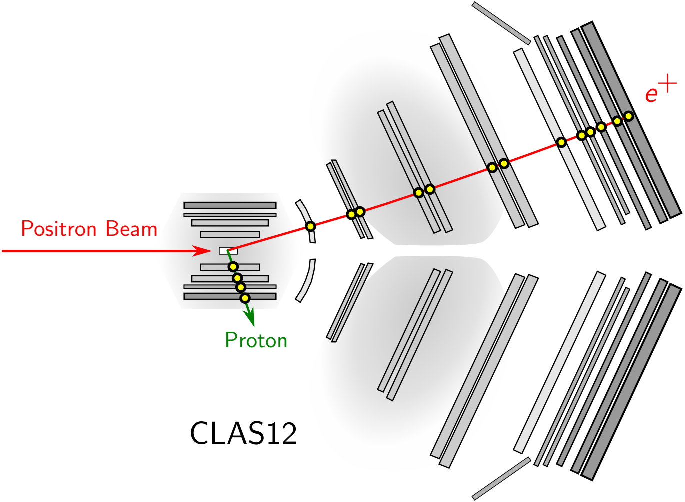

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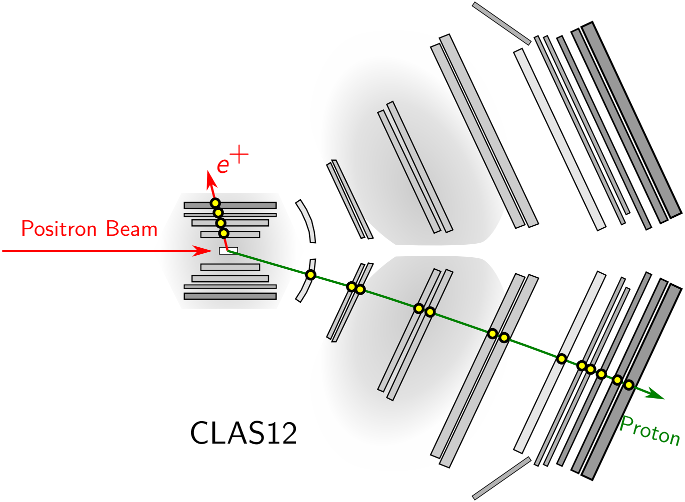
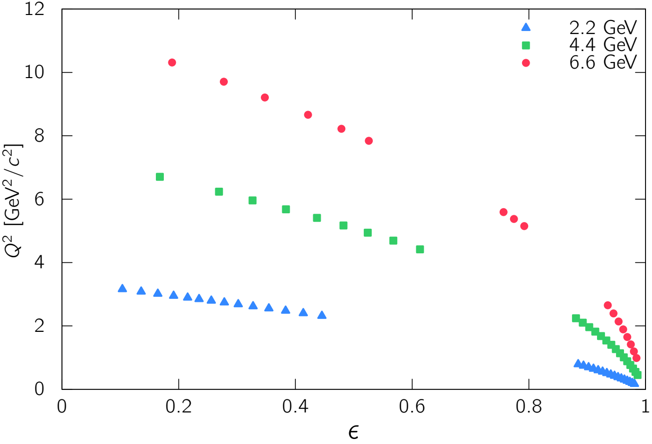


Triggering our experiment

- Recent data with similar conditions
  - Forward hadron trigger rate of **420 kHz**
  - Planned rate after high luminosity upgrade: **100 kHz**
  - Need a 5× reduction

- Possible trigger additions
  - CTOF/CND Coincidence
  - CVT Coincidence, including "roads"
    - ≈ 5× reduction
  - Kinematic Correlations between forward and central hits
    - further ≈ 10× reduction
  - Cherenkov veto

CLAS12 is ideal for mapping TPE over a wide phase space.



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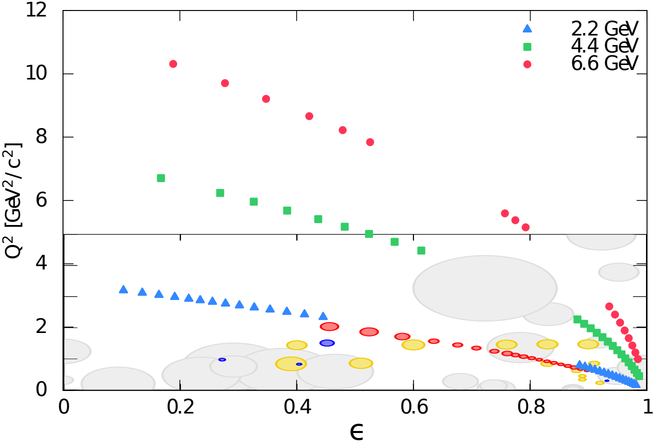

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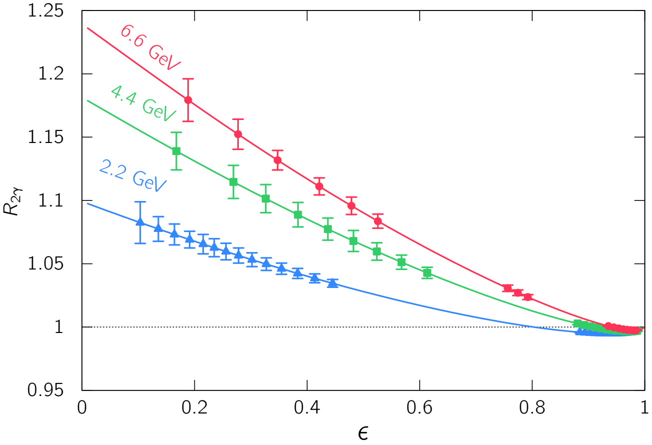

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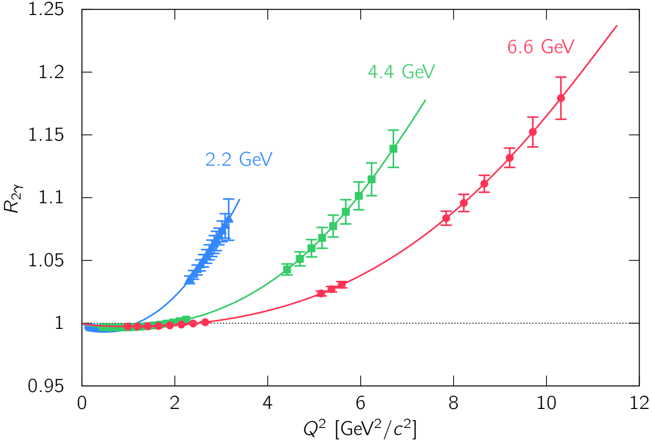

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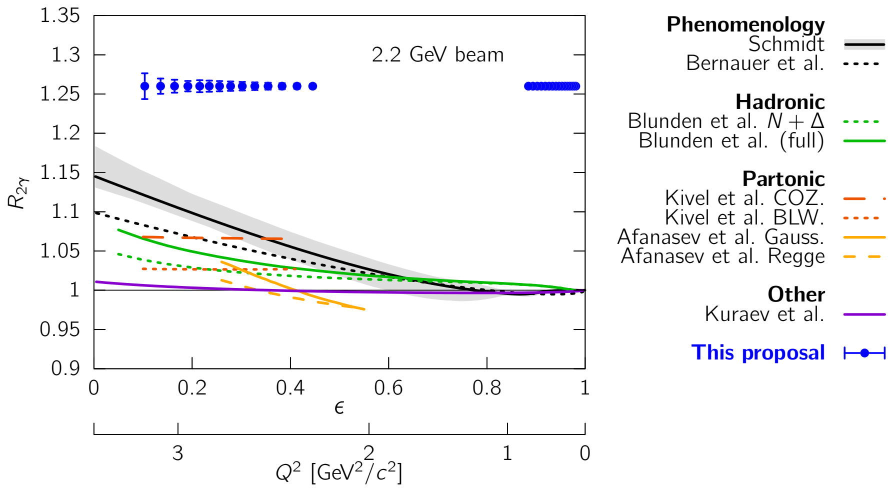

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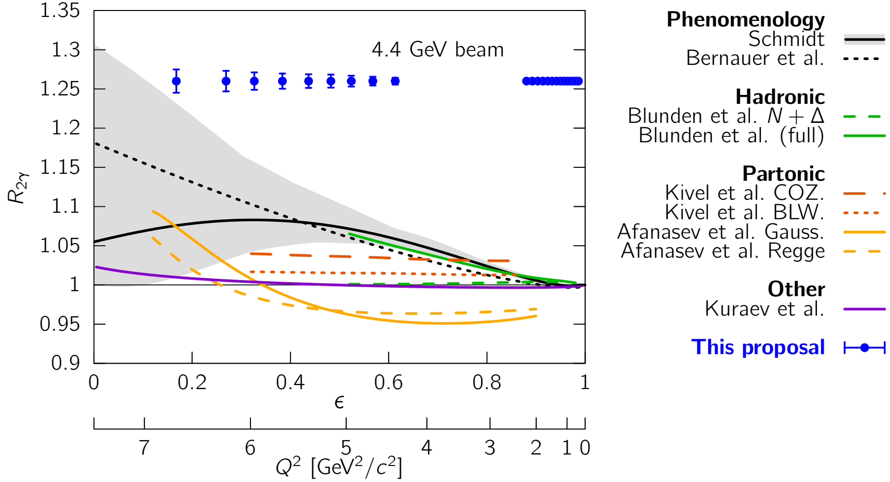

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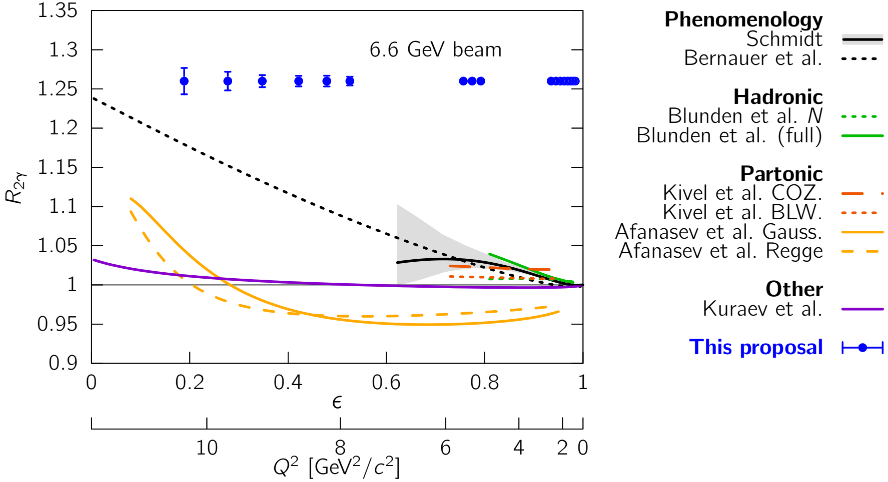


Jefferson Lab Positron Working Group

Read our white paper: EPJA 2022

Join our mailing list:
pwg-request@jlab.org

See talks tomorrow:

- Thia Keppel
- Yves Roblin

Theoretical work on other reactions

Stinson Lee

Atharva Naik

(adv. Andrei Afanasev)

Some recent theory results

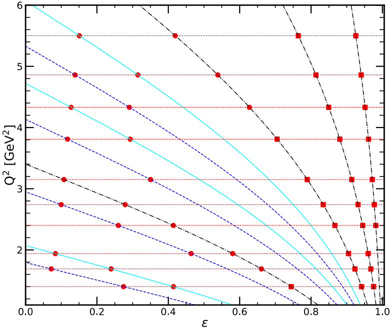
- Transverse Single Spin Asymmetries
  - Ahmed, Blunden, Melnitchouk, PRC 108, 055202 (2023)
  - Goity, Weiss, Willemyns, PLB 835, 137580 (2022)
  - Goity, Weiss, Willemyns, PRD 107, 094026 (2023)
- TPE and the Proton Radius
  - Naik, Afanasev, arXiv:2401.13892 (2024)
  - Lensky, Hagelstein, Pascalutsa, EPJA 58, 224 (2022)
- Effective Field Theory
  - P. Choudhary et al., EPJA 60, 3 (2024)

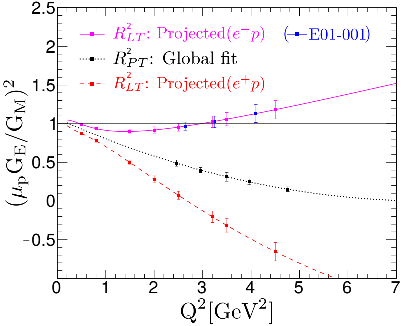
Positron Super-Rosenbluth Experiment (Hall C) E12+23-012

Spokespeople: M. Nycz, J. Arrington, N. Santiesteban, M. Yurov

Only detect recoiling proton

- Fixed $Q^2 \longrightarrow$ fixed spectrometer setting

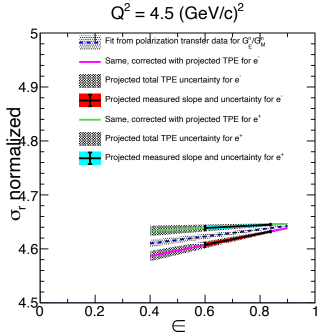


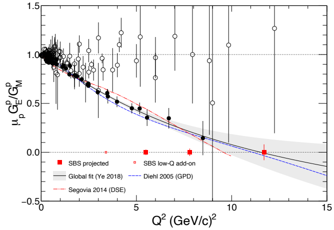


Super Big Bite nucleon form factor program

- Rosenbluth separation of G_E^n, G_M^n
  - E12-20-010 (E. Fuchey et al.)
  - 2024 Positron LOI

- Polarization transfer
  - LOI12+23-008, Puckett, Bernauer, Schmidt
  - 2024 Proposal: 2 days (e^-) at $Q^2 = 3.7$





Recap:

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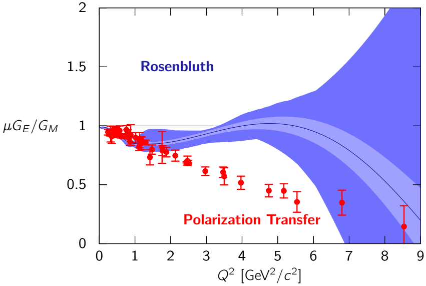

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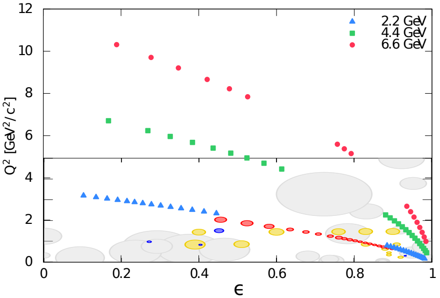
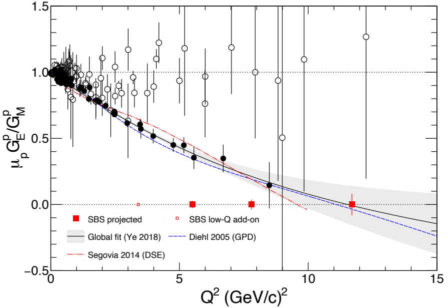


Recap:

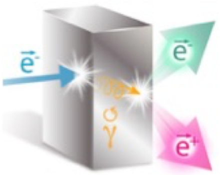
- TPE is still a problem.
- CLAS12 can make a definitive measurement
- Lots of other exciting developments!

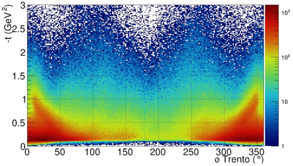


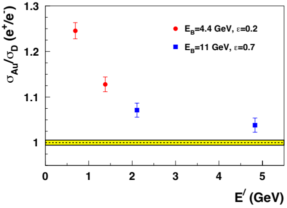
Let’s make positrons happen!

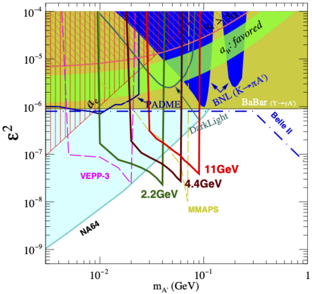
In addition to TPE:

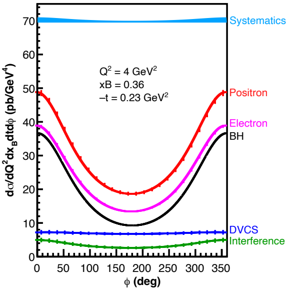
- DVCS and GPDs
- Coulomb corrections
- Dark photon searches
- Axial form factors
- ...

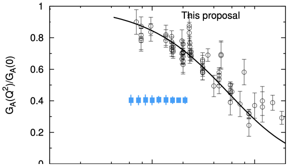






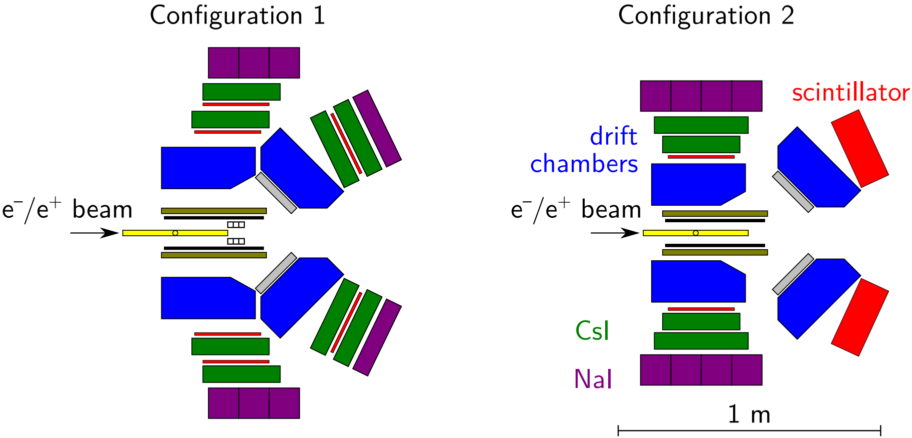




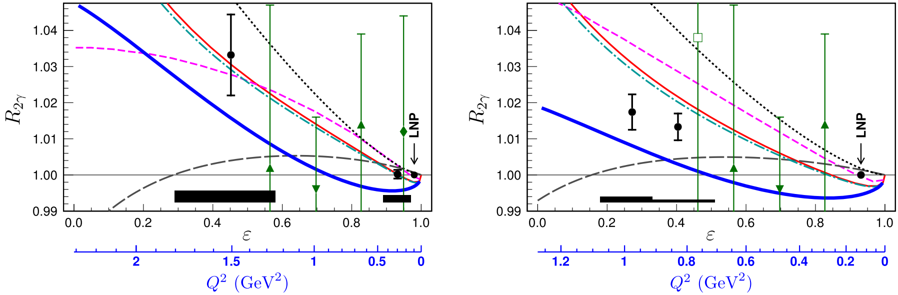


Back Up

VEPP-3, Novosibirsk, Russia

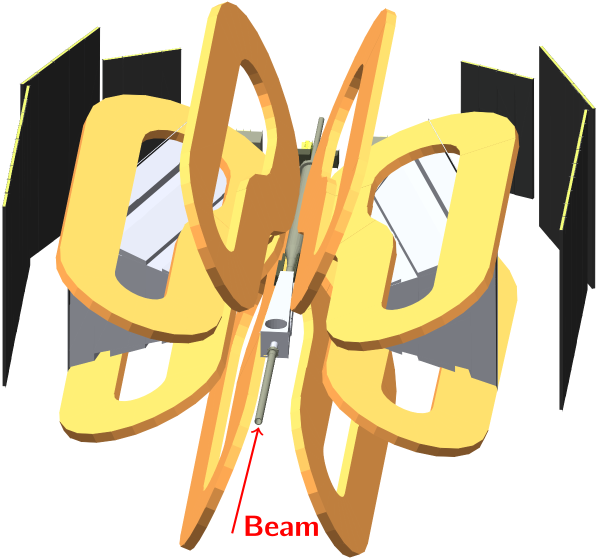


VEPP-3, Novosibirsk, Russia

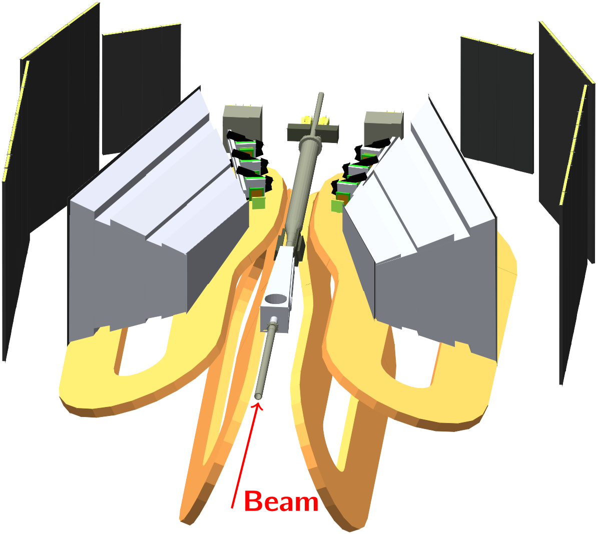


I. A. Rachek et al., PRL 114, 062005 (2015)

OLYMPUS, DESY, Germany



OLYMPUS, DESY, Germany



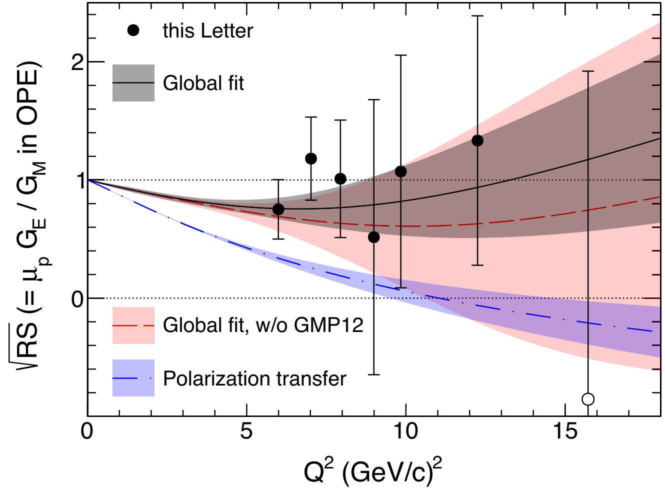
The polarization transfer results are not necessarily correct.

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 - 4\,G_M \mathrm{Re}\left(\delta\tilde{G}_M + \frac{\epsilon\nu}{M^2}\tilde{F}_3\right) - \frac{4\epsilon}{\tau}G_E \mathrm{Re}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(\alpha^4)$$

$$\frac{P_t}{P_l} = \sqrt{\frac{2\epsilon}{\tau(1+\epsilon)}}\frac{G_E}{G_M} \times [1 + \ldots$$
$$+ \mathrm{Re}\left(\frac{\delta\tilde{G_M}}{G_M}\right) + \frac{1}{G_E}\mathrm{Re}\left(\delta\tilde{G_E} + \frac{\nu}{m^2}\tilde{F}_3\right) - \frac{2}{G_M}\mathrm{Re}\left(\delta\tilde{G_M} + \frac{\epsilon\nu}{(1+\epsilon)m^2}\tilde{F}_3\right)$$
$$+ \mathcal{O}(\alpha^4) + \ldots]$$

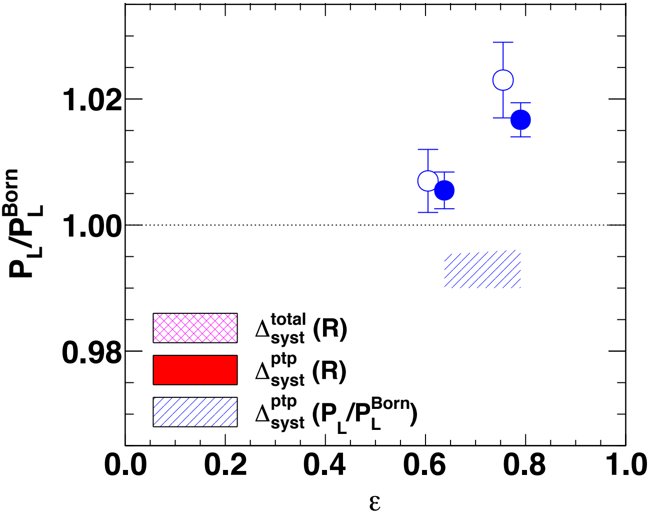
Formalism of Carlson, Vanderhaeghen, Annu. Rev. Nucl. Part. Sci., 2007

Hall A G_M^p Experiment confirms FF discrepancy to $Q^2 = 10$.



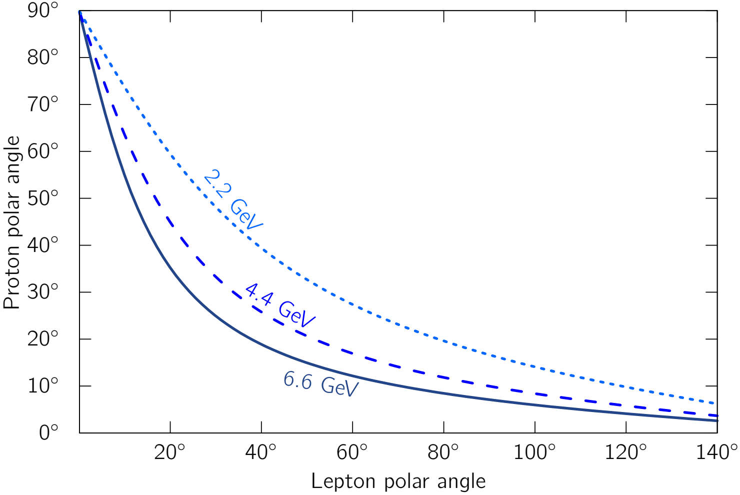
M. E. Christy et al., PRL 128, 102002 (2022)

GEP-2γ finds ϵ-dependence in P_l.

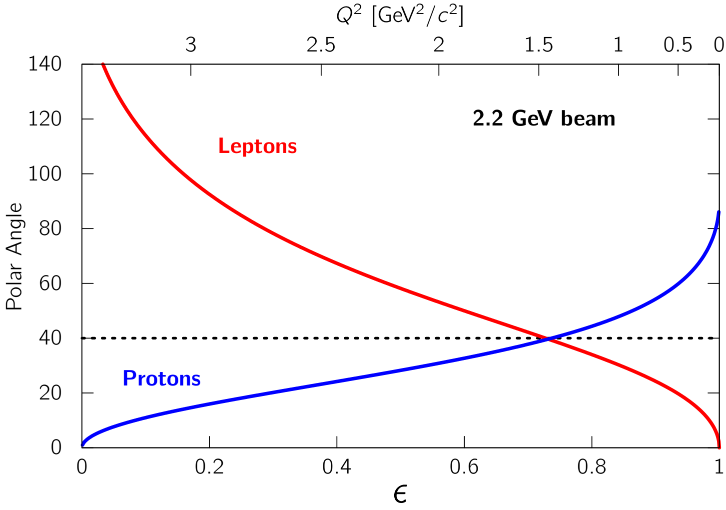


A. J. R. Puckett et al., PRC 98 019907 (2018)

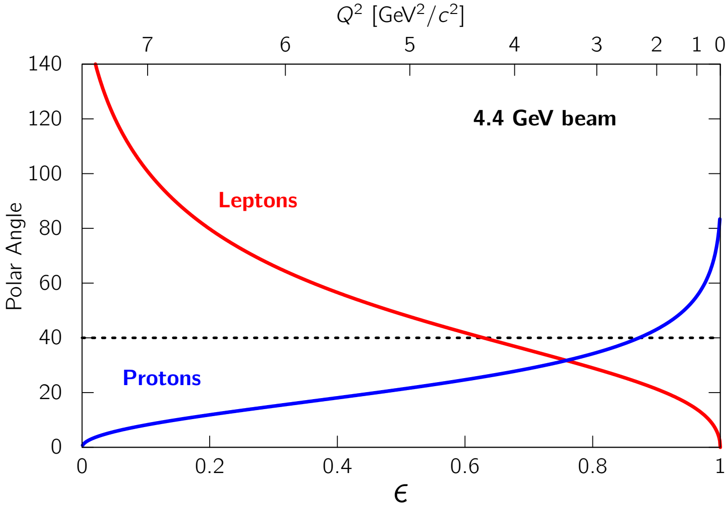
Kinematics: Lepton Angle vs. Proton Angle



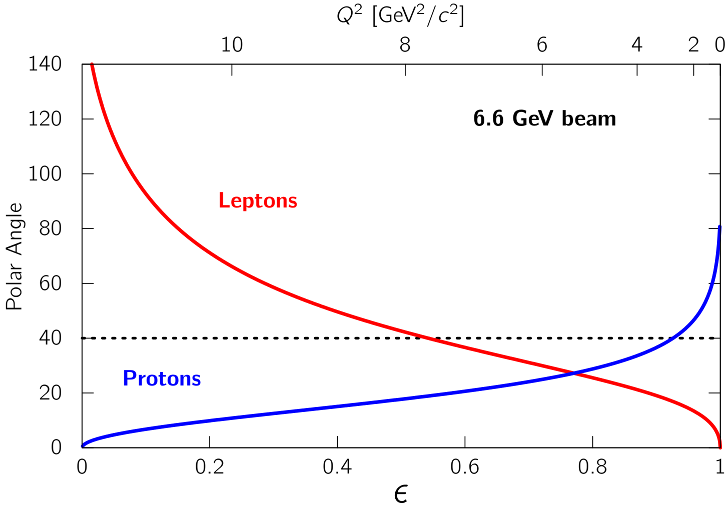
Kinematics: Angles at 2.2 GeV



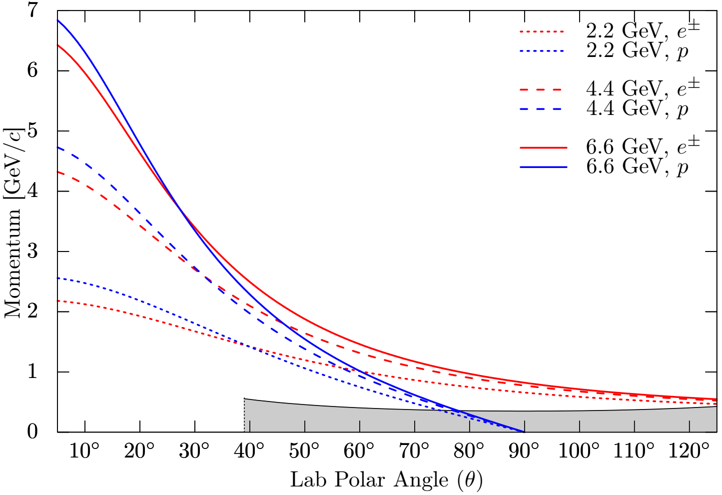
Kinematics: Angles at 4.4 GeV



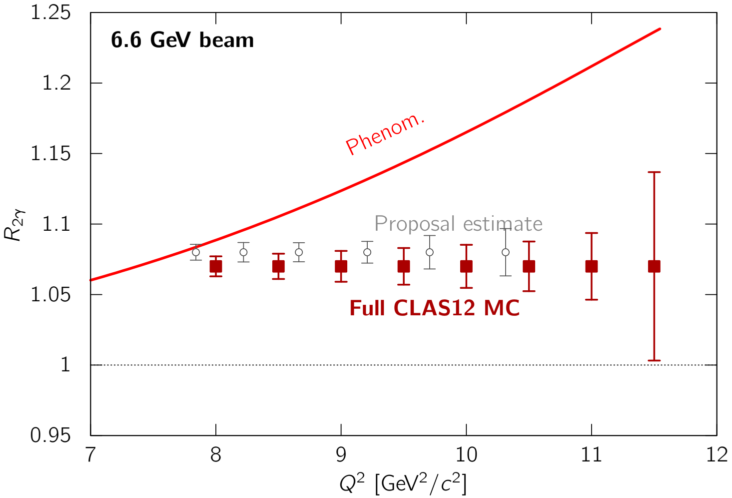
Kinematics: Angles at 6.6 GeV



Kinematics: Momenta vs. Angles



Impact of full CLAS12 MC



Our team

CLAS


Jan Bernauer


Axel Schmidt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OLYMPUS


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Nathaly Santiesteban


Tyler Kutz

Precision Form Factors

Limiting Systematics

- Over-all Scale: Relative e^+/e^- luminosity
  - Typical Hall B abs. accuracy: 2–5%
  - Relative should be much better: $< 1\%$
  - High-ϵ data is a cross check

Limiting Systematics

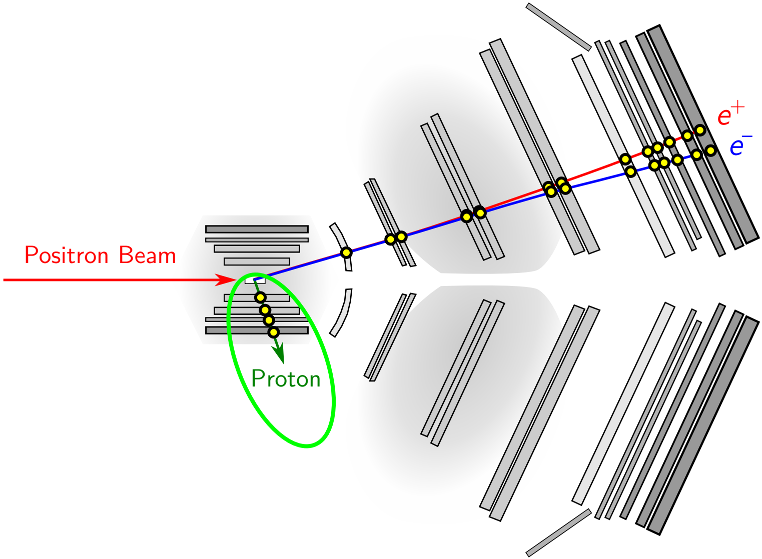
- Over-all Scale: Relative e^+/e^- luminosity
  - Typical Hall B abs. accuracy: 2–5%
  - Relative should be much better: $< 1\%$
  - High-ϵ data is a cross check

- Point-to-Point: Local efficiency
  - Magnetic fields bend e^+, e^- to different parts of the detector.
    - Polarity switching of solenoid and torus

$$R_{2\gamma} = \left[\left(\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \right)_{\uparrow\uparrow} \cdot \left(\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \right)_{\uparrow\downarrow} \cdot \left(\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \right)_{\downarrow\uparrow} \cdot \left(\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \right)_{\downarrow\downarrow} \right]^{1/4}$$

  - Need heavy-duty Monte Carlo
  - Fast-switching $e^+ \leftrightarrow e^-$ helps

Lesson 1: Define kinematics based on the proton



Lesson 2: Compare CLAS12 sectors to make unbiased checks.

$$r_{i,j} = \{N_{\text{exp}}/N_{\text{MC}}\}_i / \{N_{\text{exp}}/N_{\text{MC}}\}_j$$

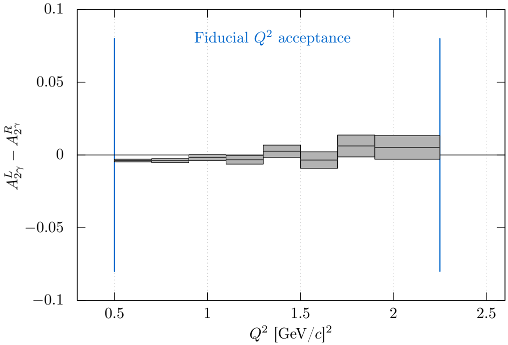
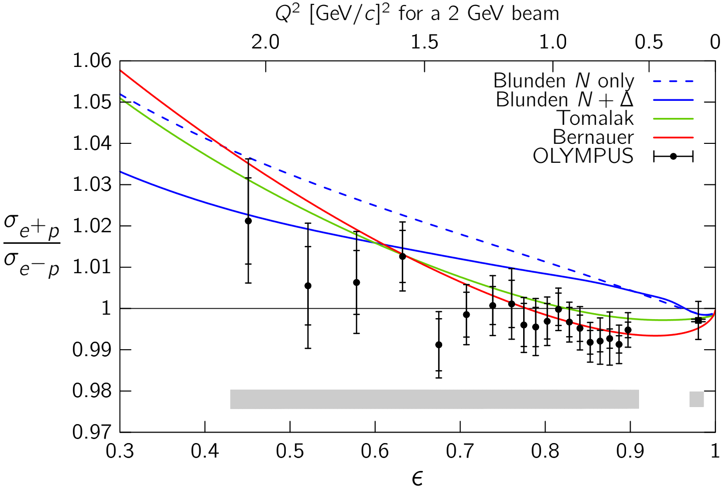
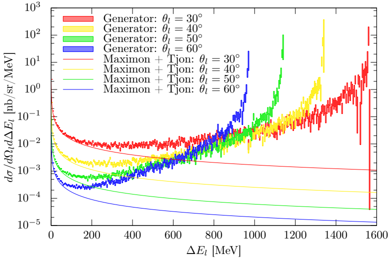


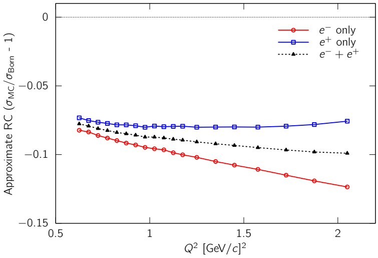
Fig. 9-2 from my thesis

Lesson 3: Independent normalization is valuable.



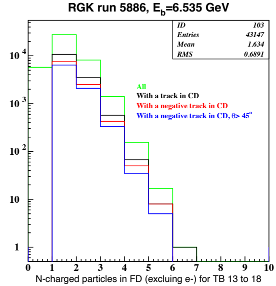
Lesson 4: Radiative corrections will be critical.

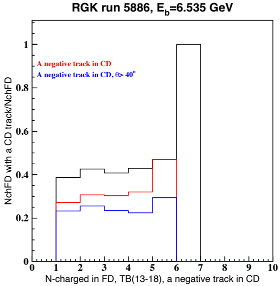




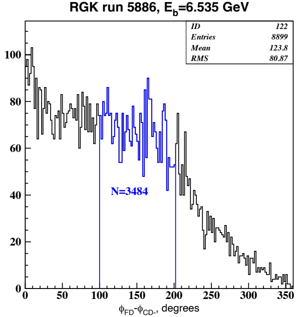
- Significant charge-odd corrections that are not hard TPE
- OLYMPUS tested several RC prescriptions, built custom radiative event generator.
- See white paper (`https://arxiv.org/abs/2306.14578`) from the recent ECT Workshop, as well as 2020 CFNS Workshop.

Run Group K data shows that we can get to a manageable trigger rate.





Coincident neg. central track
5x reduction



Loose coplanarity requirement
10x reduction

Study by S. Stepanyan