Proton Electric + Magnetic Form Factors and the Proton Radius

Ethan Cline
ethan.cline@stonybrook.edu

Center for Frontiers in Nuclear Science
Stony Brook University
Stony Brook,NY

Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA

International School of Nuclear Physics
from quarks and gluons to hadrons and nuclei

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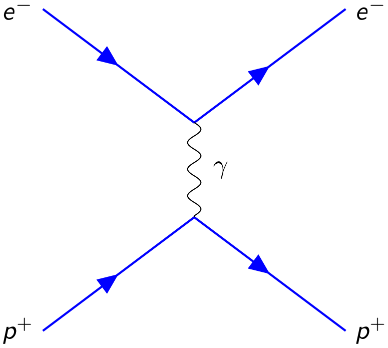
Electron-Proton Scattering

Elastic *ep* scattering probes proton form factors.

$$\left(\frac{d\sigma}{d\Omega}\right)_{red} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$

- G_E related to charge distribution, $G_E(0) = 1$
- G_M related to magnetic distribution, $G_M(0) = \mu_p$

$$\langle r_p^2 \rangle \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

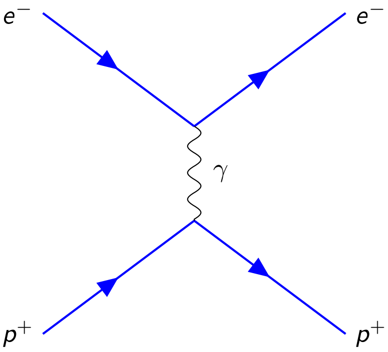


Elastic Scattering Kinematics

For elastic scattering, with a known beam energy, we only have one independent variable, Q^2

$$Q^2 = 4EE' \sin^2(\tfrac{\theta}{2})$$

- Q^2 totally determined by θ
- At low Q^2 measuring θ determines $G_E(Q^2)$
- $G_M(Q^2)$ enters into cross section $\propto Q^2$



Rosenbluth Separation

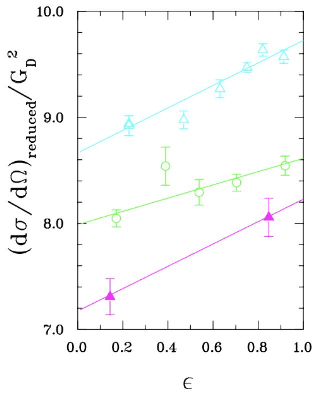
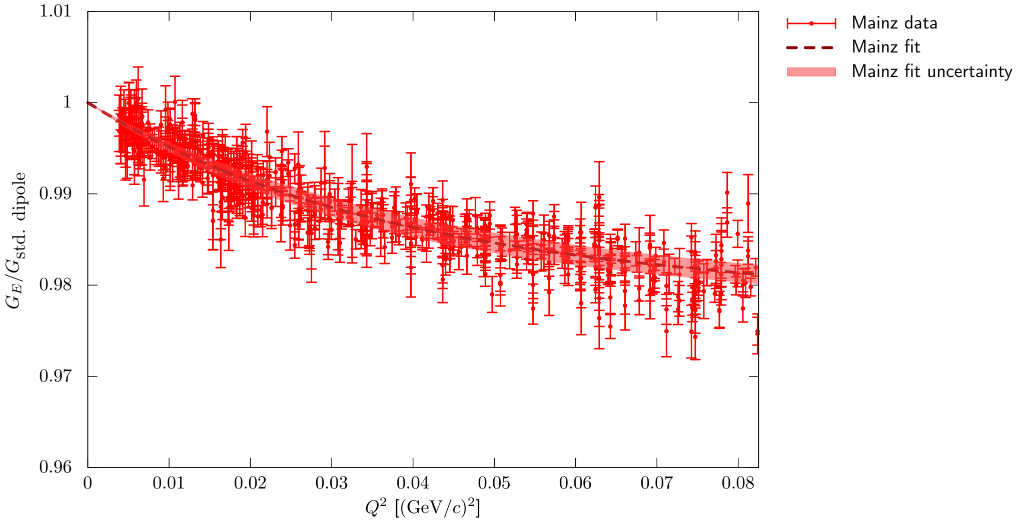


Figure 3: Demonstration of the Rosenbluth separation method based on the data from [And94]. The Q^2 values shown are 2.5 (open triangle), 5.0 (circle) and 7.0 (filled triangles) GeV^2.

- $d\sigma/d\Omega_{red} = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$
- Conveniently linear in ε
- Choose kinematics to be constant in Q^2 and at different ε
- Intercept gives G_M
- Slope gives G_E
- Figure from: https://arxiv.org/pdf/hep-ph/0612014.pdf

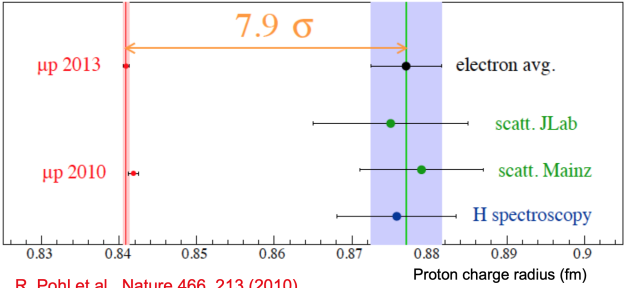
Extracting the Proton Radius



G_E from the Mainz proton radius measurement.

The Original Proton Radius Puzzle

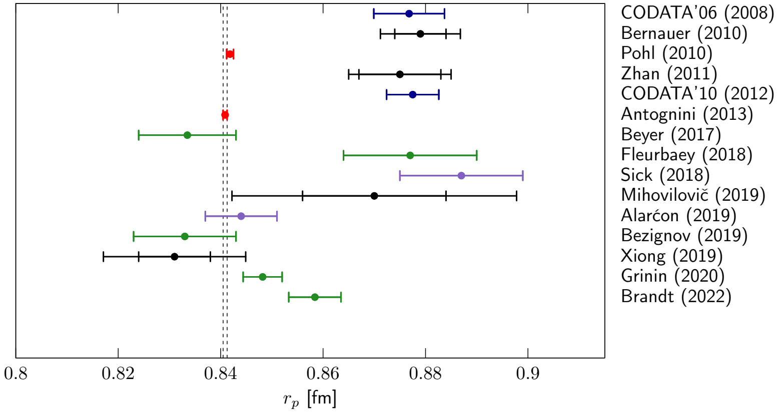
electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)
muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

"Although the uncertainty of the muonic hydrogen value is significantly smaller than the uncertainties of these other values, its negative impact on the internal consistency of the theoretically predicted and experimentally measured frequencies . . . was deemed so severe that the only recourse was to not include it in the final least-squares adjustment on which the 2010 recommended values are based." - https://physics.nist.gov/cuu/Constants/Preprints/lsa2010.pdf

The Puzzle Deepens



The Status in 2013: What's Next?

r_p (fm)	ep	μp
Spectroscopy	0.877 ± 0.007	0.841 ± 0.0004
Scattering	0.875 ± 0.006	**??**

- No high precision muon-proton scattering experiment to date
- Highly desirable to perform another electron-proton scattering experiment
- Measure two-photon exchange in muons and electrons
- MUSE!

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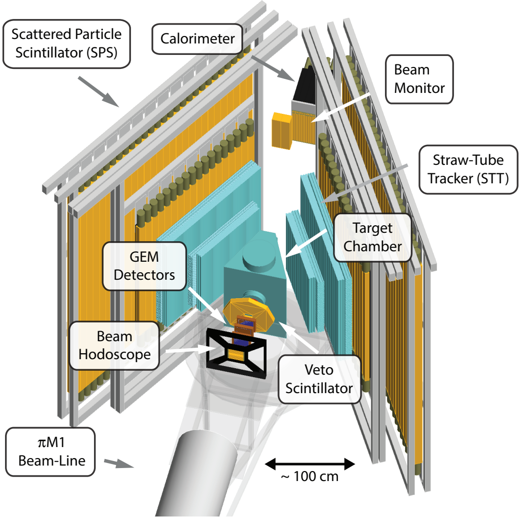
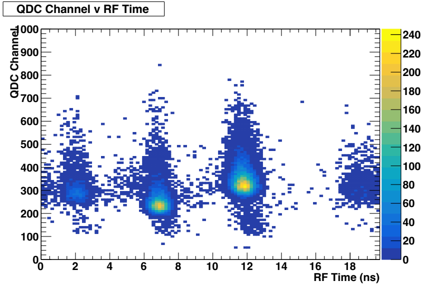
MUSE



- Secondary beam line
- Measure incoming beam event by event
- Beam contains e's, μ's, and π's
- Can select positive or negative charge polarities
- Veto to reject beam halo and decay events
- Use RF signal for PID via TOF
- Veto π's in the trigger



Kinematics of MUSE

Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle range	20° - 100°
Azimuthal coverage	30% of 2π typical
ε	$0.26 - 0.94$
Q^2 range for electrons	0.0016 GeV^2 - 0.0820 GeV^2
Q^2 range for muons	0.0016 GeV^2 - 0.0799 GeV^2

- Simultaneous elastic ep and μp scattering $\rightarrow$ can test lepton universality
- Can measure both lepton charge polarities $\rightarrow$ direct test of two photon exchange effect
- Some systematic uncertainties cancel in comparisons
- Precisely capture difference in cross sections and in radii

Physics Coverage of MUSE

- First high precision measurement of μp scattering for TPE and at precision necessary to inform PRP
- Direct comparison between ep and μp scattering at cross section level to test rad. corr. and lepton universality
- Low energy πp scattering important for χPT
- Search for $\sigma(\pi^+ p)/\sigma(\pi^- p)$ resonances
- Blinded analysis
- All low-Q^2 physics

High Q^2 Behavior

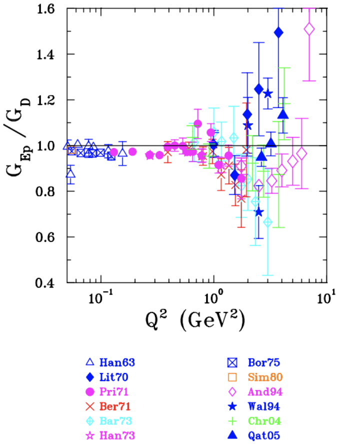


Figure 5: Data base for G_{Ep} obtained by the Rosenbluth method; the references are [Han63, Lit70, Pri71, Ber71, Bar73, Han73, Bor75, Sim80, And94, Wal94, Chr04, Qat05].

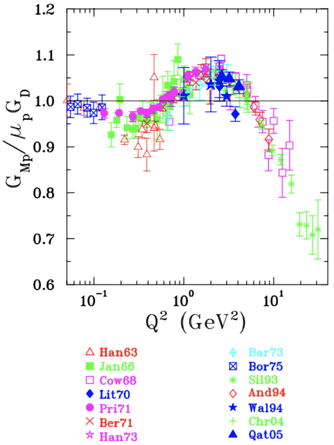
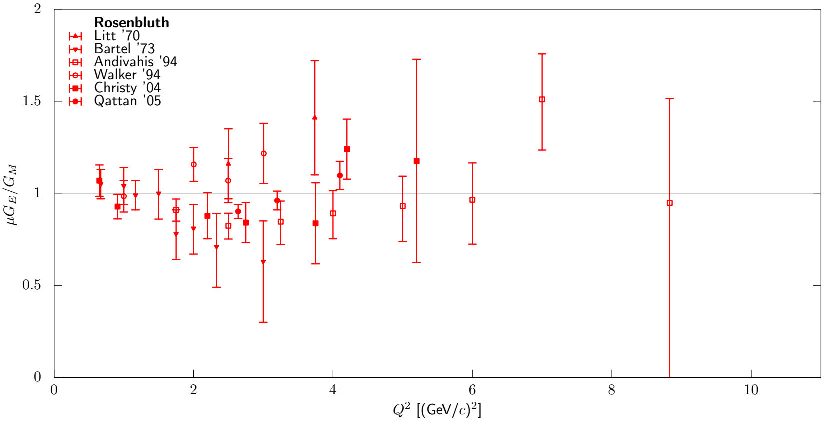


Figure 6: Data base for G_{Mp} obtained by the Rosenbluth method; the references are [Han63, Jan66, Cow68, Lit70, Pri71, Ber71, Han73, Bar73, Bor75, Sil93, And94, Wal94, Chr04, Qat05].

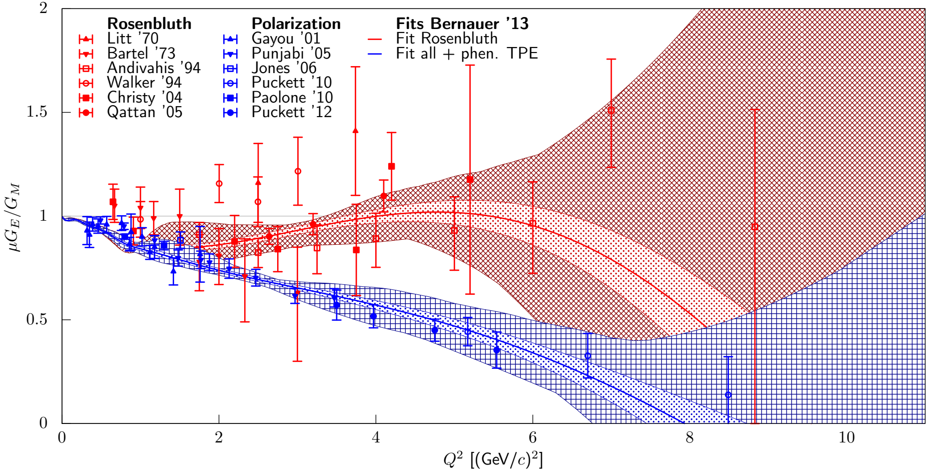
https://arxiv.org/pdf/hep-ph/0612014.pdf

Rosenbluth Ratio



In agreement with scaling!

Discrepancy in Ratios



What's Going On?

- Hard two-photon exchange
- Radiative correction with strong ε dependence, causes G_E to fall quickly
- Effect Rosenbluth more than polarization
- Soft TPE typically considered in existing analysis

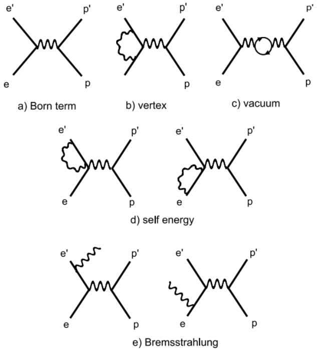


Figure 24: Born term and lowest order radiative correction graphs for the electron in elastic *ep*.

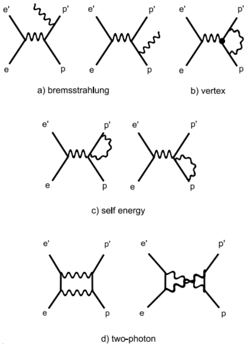
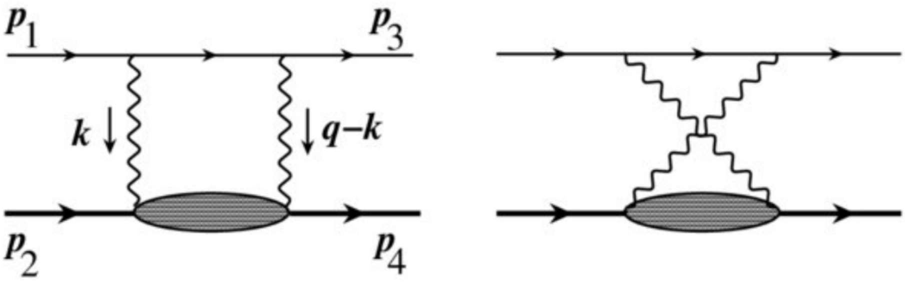


Figure 25: Lowest order radiative correction for the proton side in elastic *ep* scattering.

https://arxiv.org/pdf/hep-ph/0612014.pdf

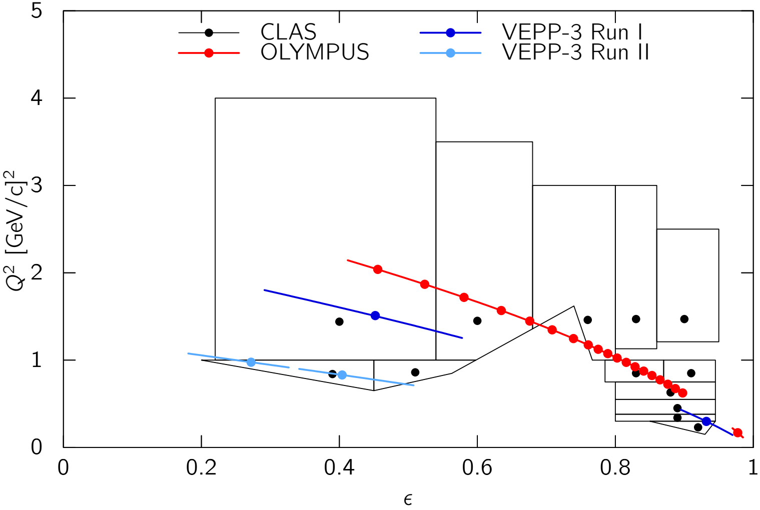
Hard Two-Photon Exchange



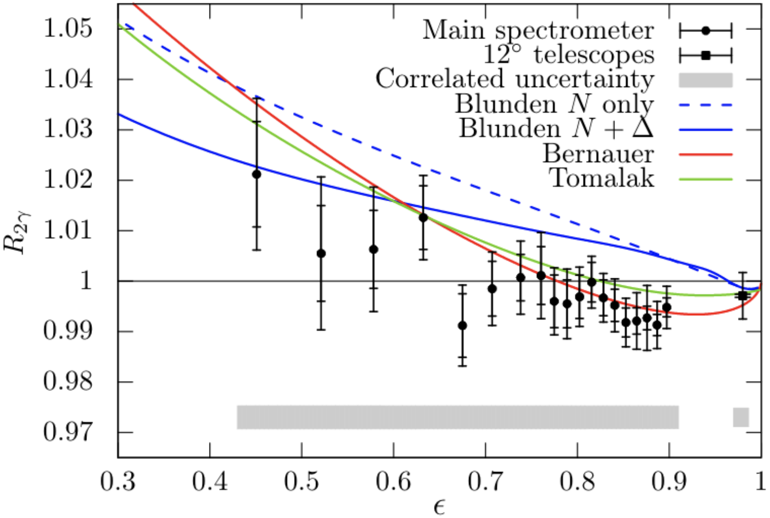
Model dependent calculation of the intermediate proton state!

Let's Measure TPE

$$R_{2\gamma} = \frac{\sigma_{e^+}}{\sigma_{e^-}} = 1 - 2\delta_{2\gamma}$$

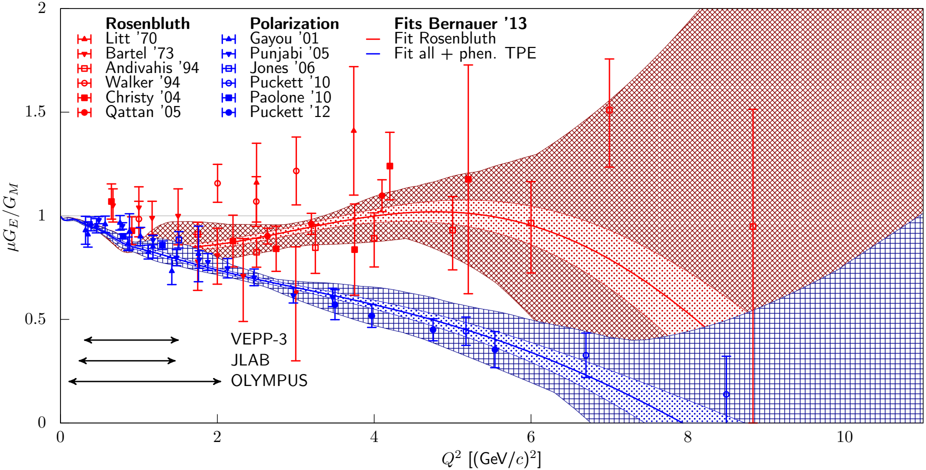


Let's Measure TPE



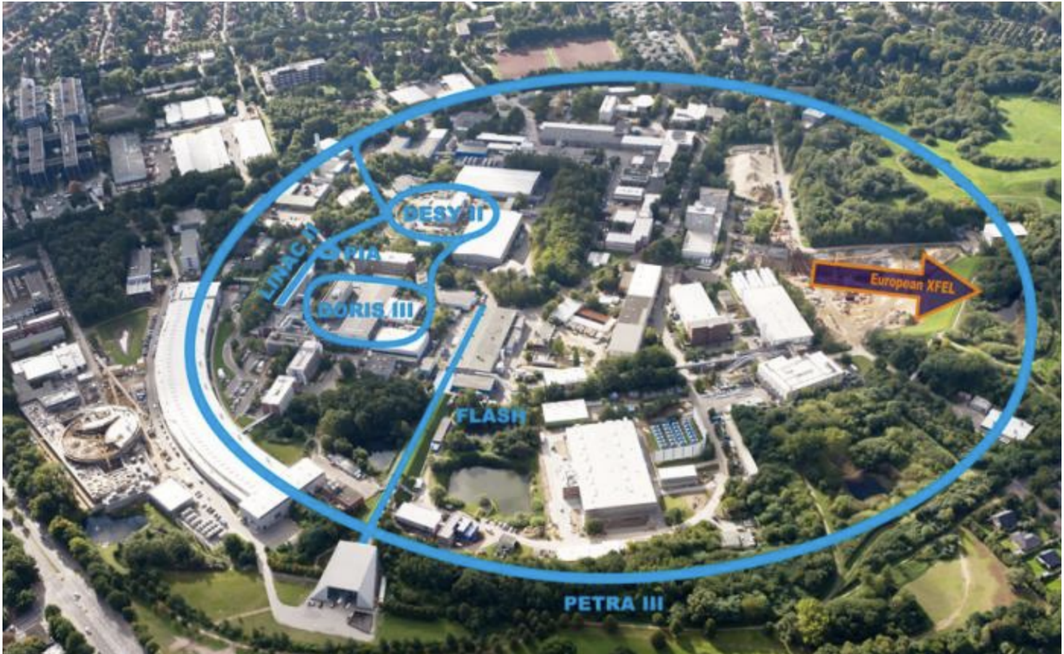
Disagreement with existing theory at larger ε, but small TPE in measured range.

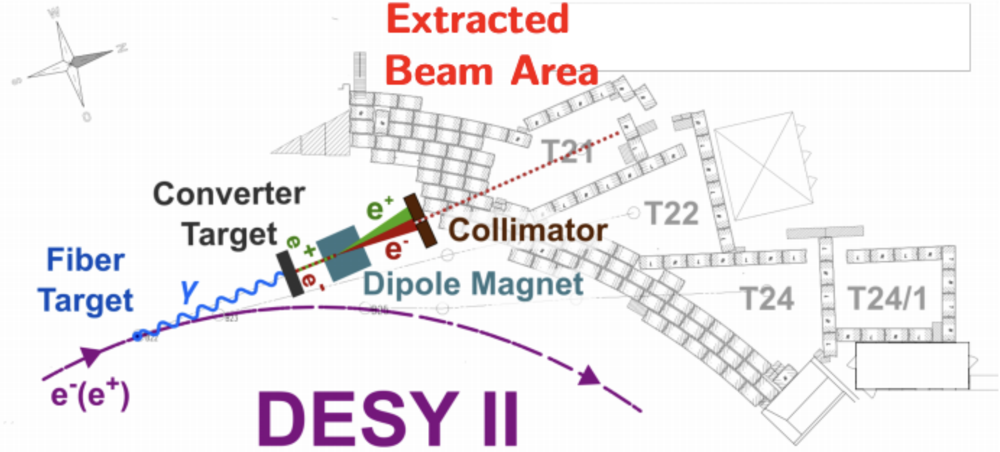
Existing Two-Photon Reach



Discrepancy enhanced at larger Q^2

TPEX @ DESY!

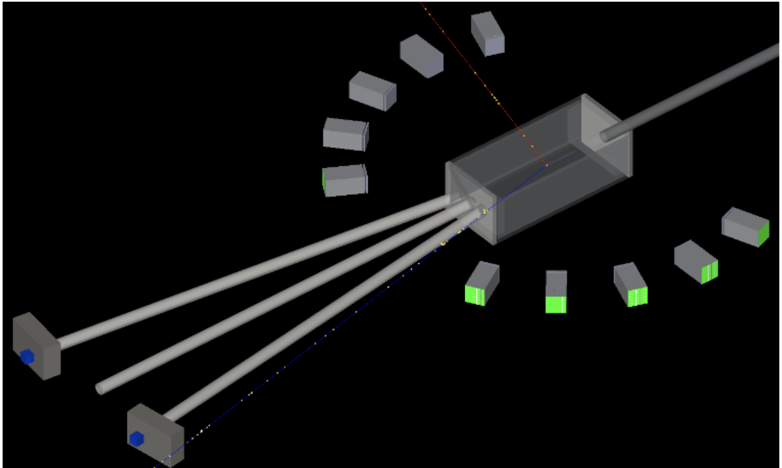



Extracted
Beam Area
T21
T22
T24
T24/1
Converter
Target
Collimator
Fiber
Target
γ
e+
e-
Dipole Magnet
e-(e+)
DESY II

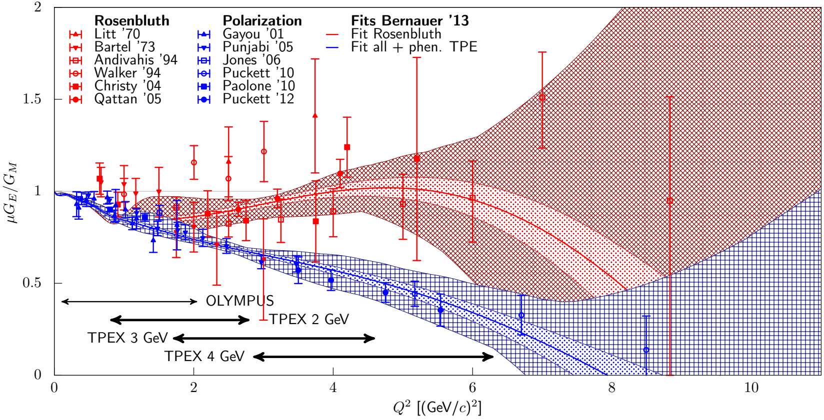
TPEX Sketch

- Conceptually simple
- Could run at DESY with e^+ and e^- beam
- Direct $R_{2\gamma}$ measurement

- LH_2 target
- 5 sets of 5×5 $PbWO_4$ crystals
- 2 luminosity monitors



TPEX Projected Reach



TPEX reach with positrons at DESY.

Positrons at JLab

- Could run TPEX in 2-3 years if new extracted beam line becomes available.
- Financial challenges make this difficult.
- Longer term - positrons at JLab!
- Estimated to begin roughly in parallel with EIC

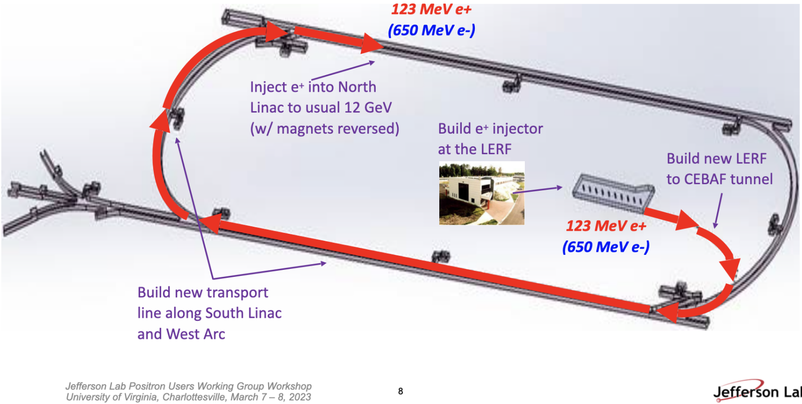
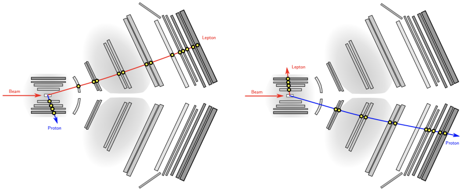
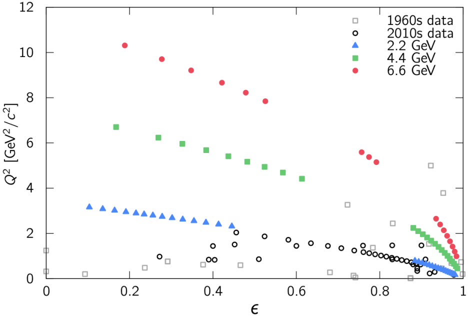


Figure from Joe Grames at Positron Working Group Workshop, March 7, 2023

Measuring TPE with CLAS12



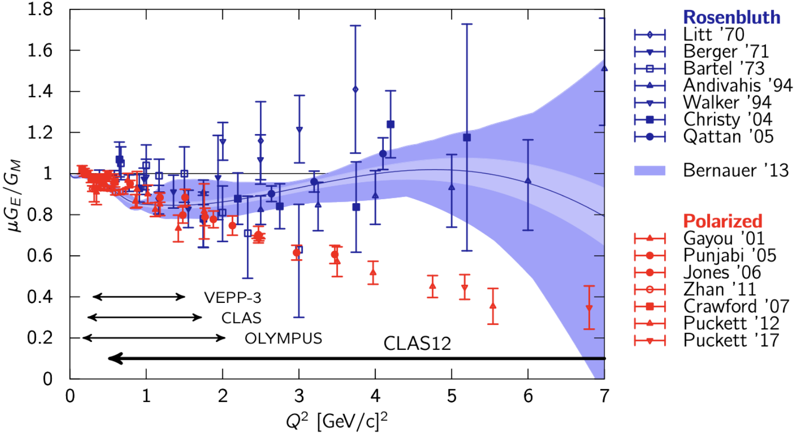


- Using a future positron beam at JLab
- Beam energy of 2.2, 4.4, and 6.6 GeV
- CLAS12 apparatus
- Extensive reach in Q^2 and ε

- Significant overlap with OLYMPUS and TPEX
- Approved with an "A" rating by PAC

Figure from: https://arxiv.org/pdf/2308.08777.pdf

Measuring TPE with CLAS12



Comprehensive coverage possible with future positron beam at JLab.

Summary

- Interesting physics accessible with $e^{\pm}p$ and $\mu^{\pm}p$ scattering
- From low to high Q^2
- Current and future experiments will probe wide kinematic range
- Stay tuned for future MUSE results and upcoming positron beams!