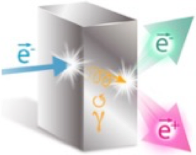
Two-Photon Exchange Measurements with Positron Beams

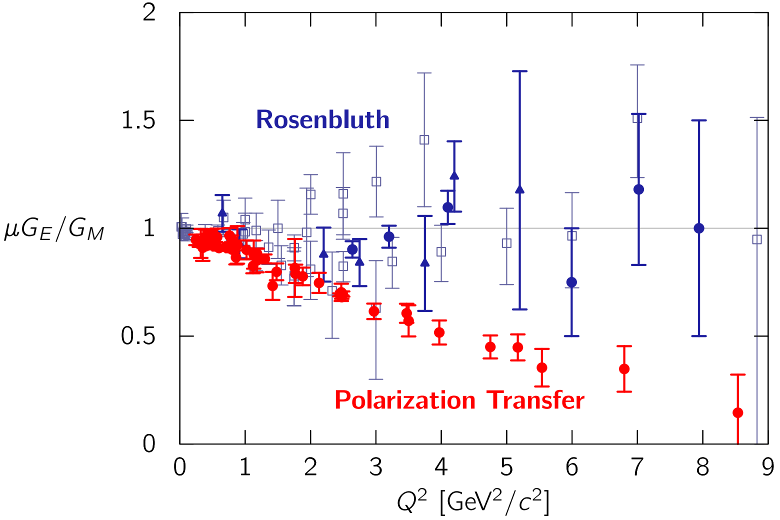
Axel Schmidt

Town Hall Meeting on Hot and Cold QCD

September 24, 2022



Measurements of the proton's form factors are discrepant.



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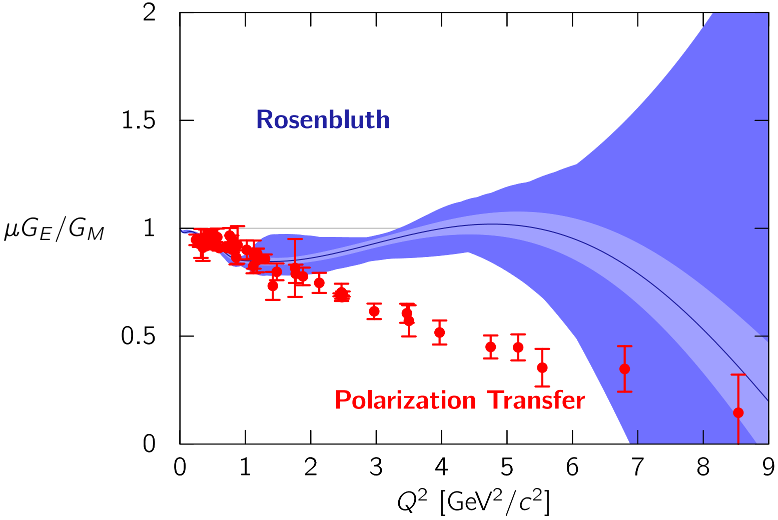
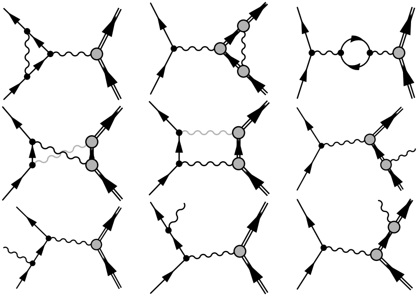
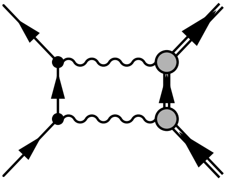


The one "missing" radiative correction is hard two-photon exchange.

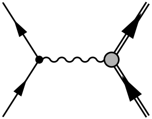
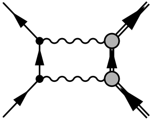
The standard set

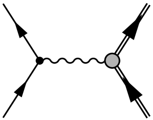
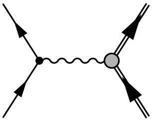
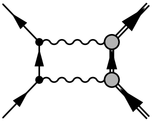


Hard two-photon exchange



TPE produces an asymmetry between electron and positron scattering.

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

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

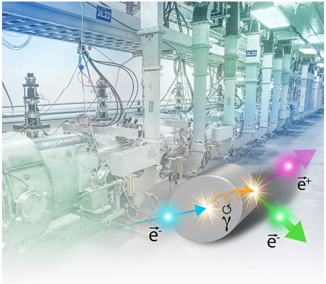
The current status:

- Hard TPE is difficult to calculate.
- Recent experiments did not settle the issue.
- No current facility has GeV-scale positrons.
- Form Factor discrepancy is uncomfortable as we embark on 3D tomography.

A new positron facility will settle TPE and do so much more.

Jefferson Lab Positron Working Group

- Web: `https://wiki.jlab.org/pwgwiki/index.php/Main_Page`
- Join the mailing list: `mailto:pwg-request@jlab.org`



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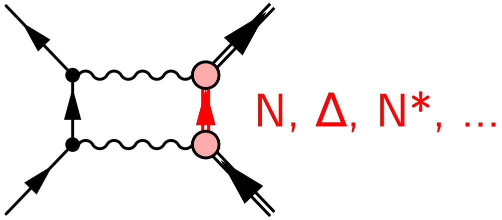
TPEX: Two-Photon Exchange eXperiment

Calculations of two-photon exchange come with model dependency.

Hadronic Approaches

- Treat off-shell propagator as collection of hadronic states.
- e.g. Ahmed, Blunden, Melnitchouk, PRC 102, 045205 (2020)



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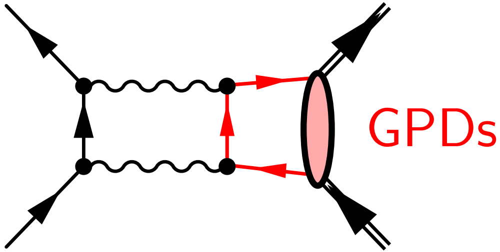
- e.g. A. Afanasev et al., PRD 72, 013008 (2005)



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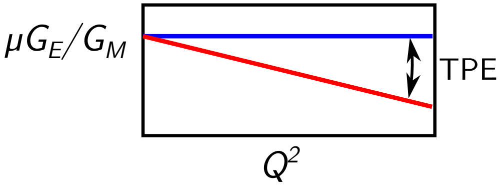
- Assume the discrepancy is caused by TPE, estimate the effect.
- e.g. A. Schmidt, JPG 47, 055109 (2020)



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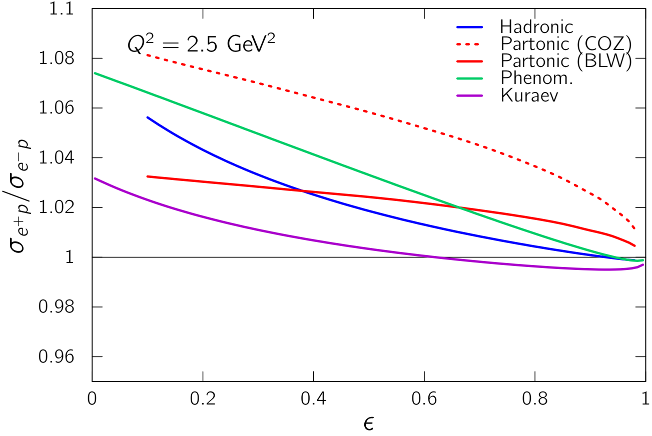
Alternate Approaches

- e.g., E. A. Kuraev et al., Phys. Rev. C 78, 015205 (2008)

Theory predictions for $\sigma_{e^+p}/\sigma_{e^-p}$ are not in agreement.



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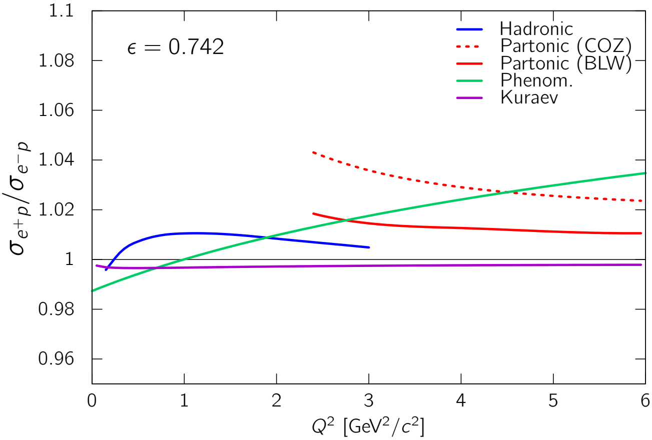
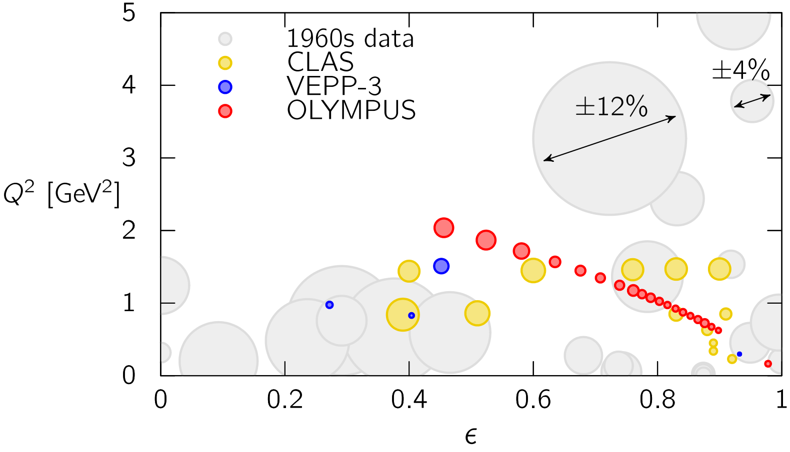
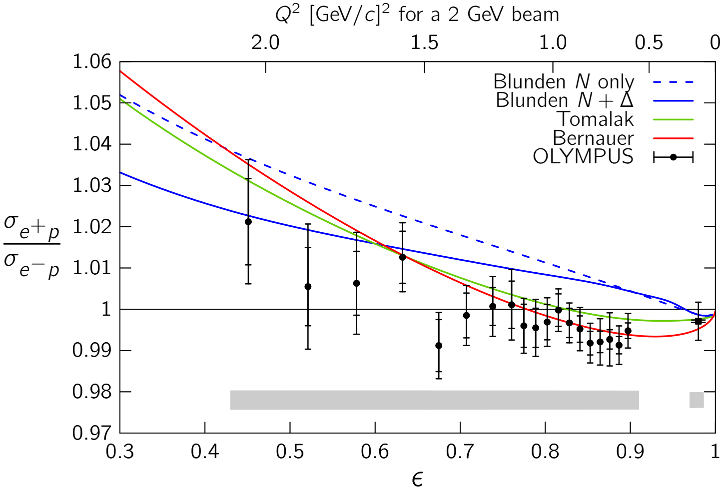


Three recent experiments measured hard TPE.



OLYMPUS observed a small TPE effect.



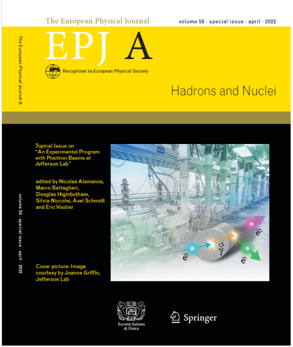
Henderson et al., PRL 118, 092501 (2017)

Positron Program at JLab

- 19 contributions for experimental concepts
- $>$ 1000 PAC days

Positron Partial Program Summary

Experiment Label (EPJ A)	Experiment Short Name	Hall	Detector	Target	Polarity	p (GeV/c)	P (%)	I (μA)	Time (d)	PAC Grade
Two Photon Exchange Physics										
57:144	$H(e,e'p)$	B	CLAS12$^+$	H_2	$+/-_s$	2.2/3.3/4.4/6.6	0	0.060	53	
57:188	$H(\vec{e},e'\vec{p})$	A	ECAL/SBS	H_2	$+/-_p$	2.2/4.4	60	0.200	121	
57:199	r_p r_d	B	PRad-II	H_2 D_2	+	0.7/1.4/2.1 1.1/2.2	0	0.070 0.010	40 39	
57:213	$\vec{H}(e,e'p)$	A	BB/SBS	$N\vec{H}_3$	$+/-_s$	2.2/4.4/6.6	0	0.100	20	
57:290	$H(e,e'p)$	A	HRS/BB/SBS	H_2	$+/-_s$	2.2/4.4	0	1.000	14	
57:319	SupRos	A	HRS	H_2	$+/-_p$	0.6–11.0	0	2.000	35	
58:36	$A(e,e')A$	A	HRS	He	$+/-_p$	2.2	0	1.000	38	
Nuclear Structure Physics										
57:186	p-DVCS	B	CLAS12	H_2	$+/-_s$	2.2/10.6	60	0.045	100	C2
57:226	n-DVCS	B	CLAS12	D_2	$+/-_s$	11.0	60	0.060	80	
57:240	p-DDVCS	A	SoLID$^\mu$	H_2	$+/-_s$	11.0	(30)	3.000	100	
57:273	He-DVCS	B	CLAS12/ALERT	^4He	$+/-_s$	11.0	60			
57:300	p-DVCS	C	SHMS/NPS	H_2	+	6.6/8.8/11.0	0	5.000	77	C2
57:311	DIS	A/C	HRS/HMS/SHMS		$+/-_s$	11.0				
57:316	VCS	C	HMS/SHMS	H_2	$+/-_s$		60			
Beyond the Standard Model Physics										
57:173	C_{3q}	A	SoLID	D_2	$+/-_s$	6.6/11.0	(30)	3.000	104	D
57:253	LDM	B	PADME ECAL/HCAL	C $PbW0_4$	+	11.0	0	0.100	180 120	
57:315	CLFV	A	SoLID$^\mu$	H_2	+	11.0				
								Total (d)	**1121**	



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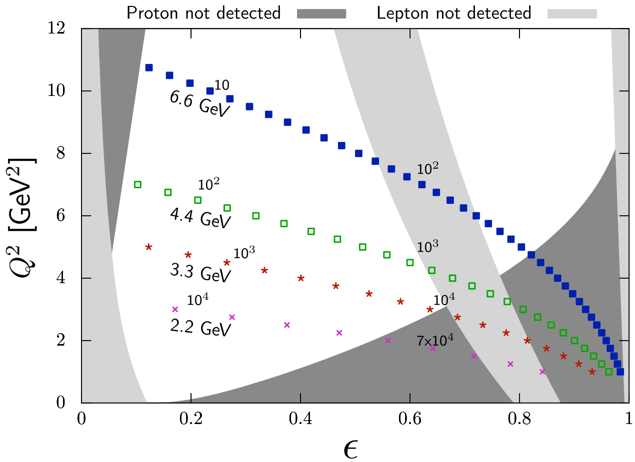
Two-photon exchange

See C. Munoz Camacho's talk from Friday

Beyond Standard Model

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



J. C. Bernauer et al., Eur.Phys.J.A 57, p. 144 (2021)

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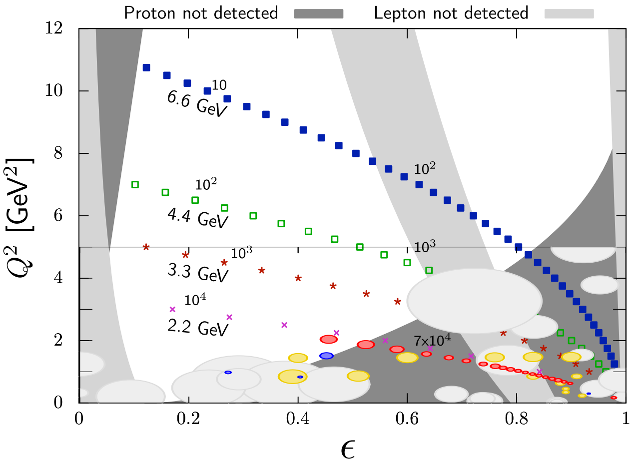

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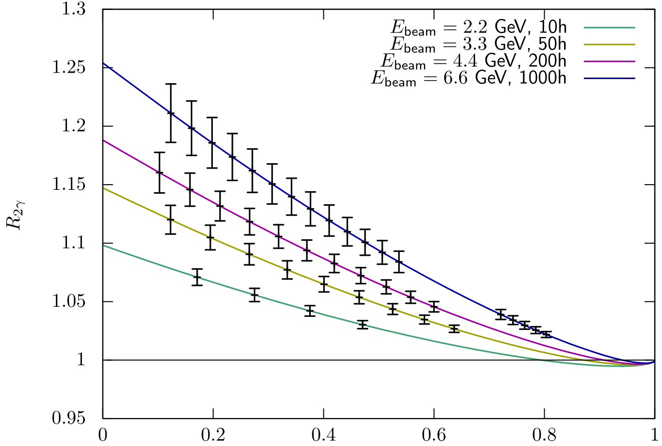


J. C. Bernauer et al., Eur.Phys.J.A 57, p. 144 (2021)

New observables provide independent constraints.

Additional TPE Form Factors: $\delta\tilde{G}_E$, $\delta\tilde{G}_M$, $\delta\tilde{F}_3$

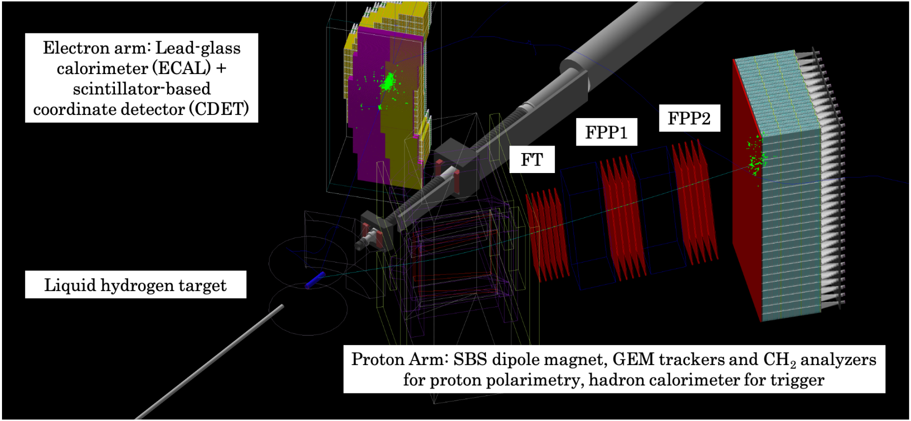
- Cross section:
  $\sigma_R = G_M^2 + \frac{\epsilon}{\tau}G_E^2 + 2G_M \mathrm{Re}\left(\delta\tilde{G}_M + \frac{\epsilon\nu}{M^2}\tilde{F}_3\right) + 2\frac{\epsilon}{\tau}G_E \mathrm{Re}\left(\delta\tilde{G}_E + \frac{\epsilon\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(\alpha^4)$
- Polarization Transfer: $\frac{P_t}{P_l} =$
  $\sqrt{\frac{2\epsilon}{\tau(1+\epsilon)}}\frac{G_E}{G_M}\cdot[1+\mathrm{Re}\left(\frac{\delta\tilde{G_M}}{G_M}\right)+\frac{1}{G_E}\mathrm{Re}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right)-\frac{2}{G_M}\mathrm{Re}\left(\delta\tilde{G_M} + \frac{\epsilon\nu}{(1+\epsilon)M^2}\tilde{F}_3\right)]+\mathcal{O}(\alpha^4)$
- Beam-normal SSA:

$$B_n = \frac{4mM\sqrt{2\epsilon(1-\epsilon)(1+\tau)}}{Q^2\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)}\times \left[-\tau G_M \mathrm{Im}\left(\tilde{F}_3 + \frac{\nu}{M^2(1+\tau)}\tilde{F}_5\right) - G_E \mathrm{Im}\left(\tilde{F}_4 + \frac{\nu}{M^2(1+\tau)}\tilde{F}_5\right)\right] + \mathcal{O}(\alpha^4)$$

- Target-normal SSA:

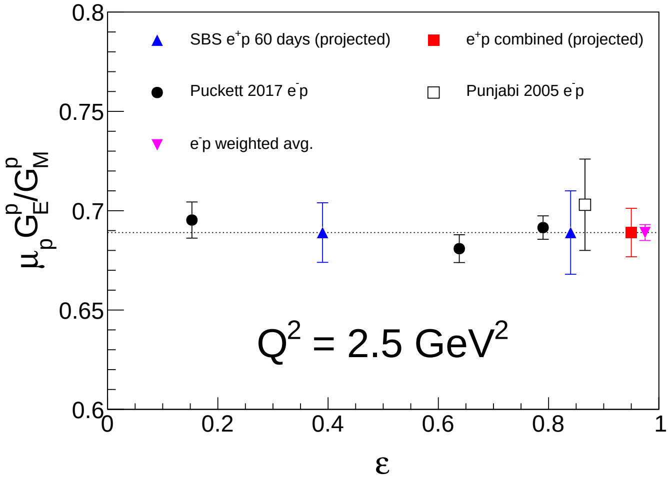
$$A_n = \frac{\sqrt{2\epsilon(1+\epsilon)}}{\sqrt{\tau}\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)}\times \left[-G_M \mathrm{Im}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E \mathrm{Im}\left(\delta\tilde{G}_M + \frac{2\epsilon\nu}{M^2(1+\epsilon)}\tilde{F}_3\right)\right] + \mathcal{O}(\alpha^4)$$

With Super BigBite, even e^+ polarization transfer would be feasible.

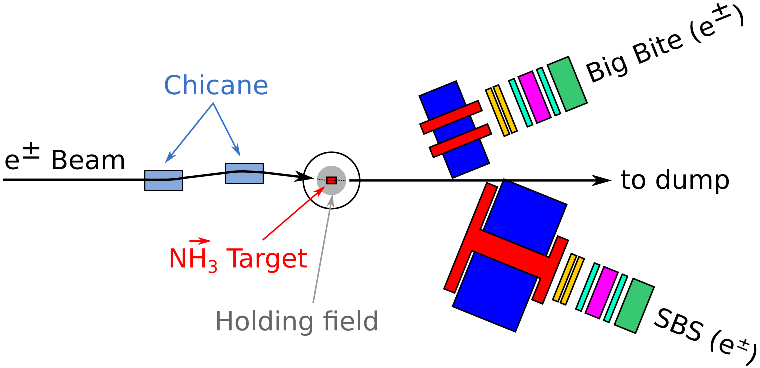


A. J. R. Puckett et al., Eur.Phys.J.A 57, p. 188 (2021)

e^+ and e^- measurements can prove if ϵ-dependence comes from TPE.

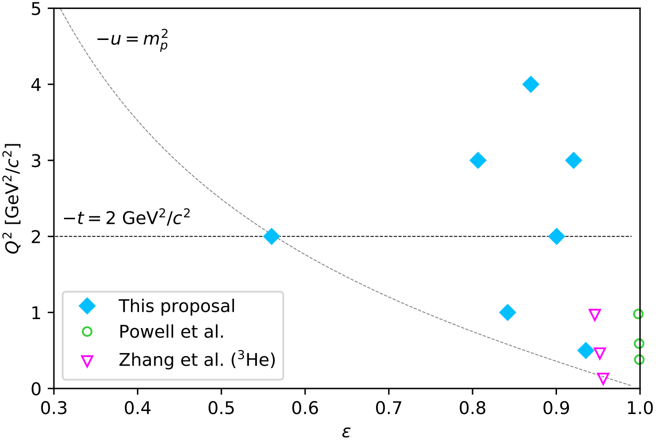


A transversely polarized proton target would reveal the imaginary part of the TPE amplitude.



Grauvogel, Kutz, Schmidt, Eur.Phys.J.A 57, p. 213 (2021)

A measurement at JLab would cover new ground.



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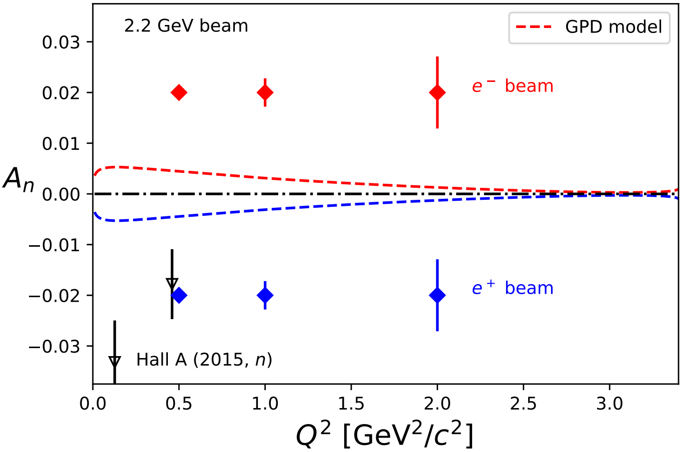
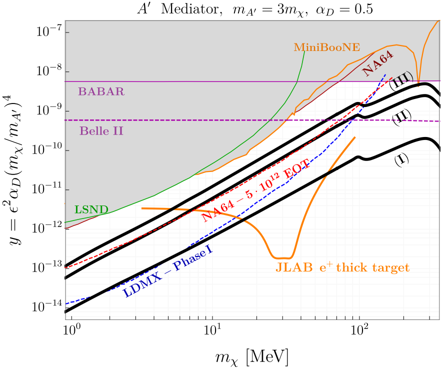


Uses for positrons beyond TPE, DVCS:

- Searches for light dark matter



Uses for positrons beyond TPE, DVCS:

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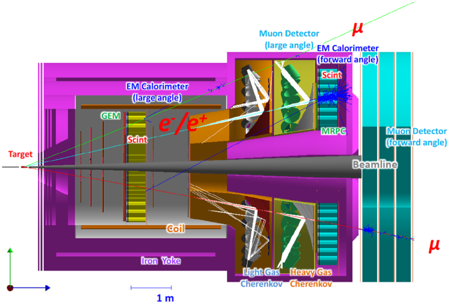
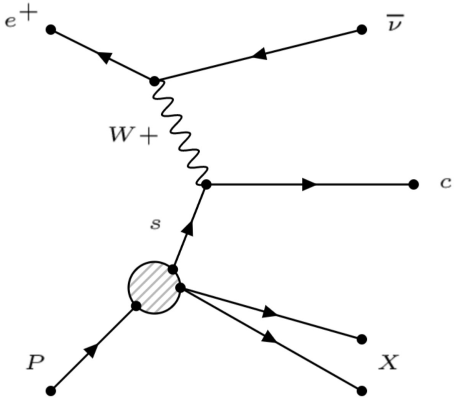
- Charged lepton flavor violation



Uses for positrons beyond TPE, DVCS:

- Searches for light dark matter
- Charged lepton flavor violation
- Measuring strangeness through charm-tagging in charge-current DIS



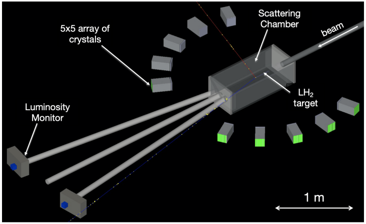
TPEX proposal aims to use existing positron infrastructure at DESY.

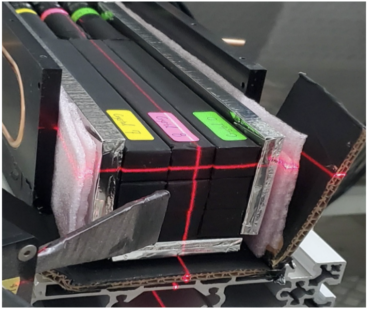
DESY

- 30 nA e^+ up to 6.3 GeV
- TPEX would require a new e^+ extracted beam line
- Proposal submitted to DESY, but additional projects, needed to justify costs

TPEX

- 20 cm lH_2 target
  - 200× OLYMPUS lumi.
- 10 calorimeter arrays
  - No magnet





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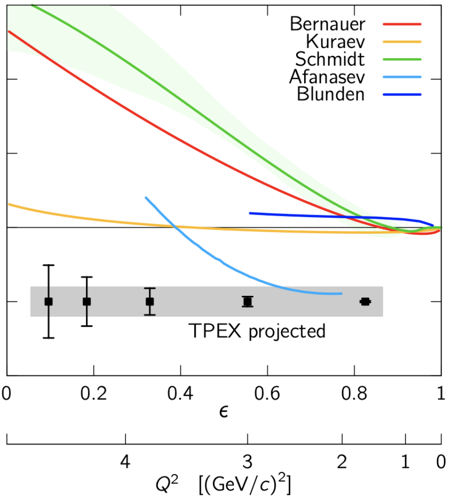
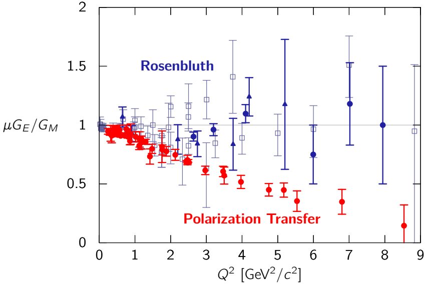


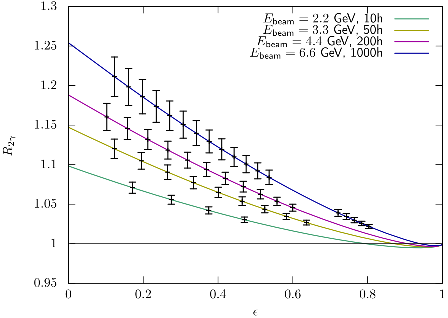
To recap:

- Discrepancy in proton FFs is uncomfortable.



To recap:

- Discrepancy in proton FFs is uncomfortable.
- Positron beam at JLab would allow:
  - Thorough mapping of TPE



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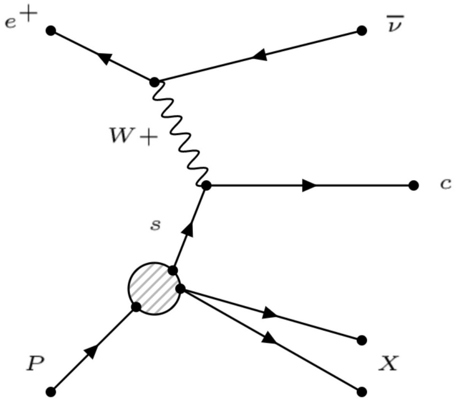
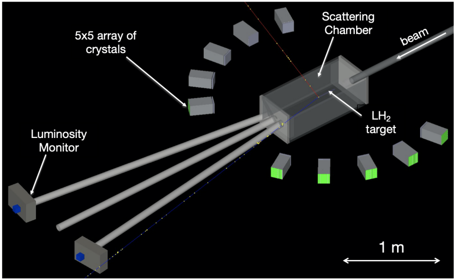
  - Lots of other physics too



To recap:

- Discrepancy in proton FFs is uncomfortable.
- Positron beam at JLab would allow:
  - Thorough mapping of TPE
  - Lots of other physics too
- TPEX at DESY makes use of existing infrastructure.



Conclusions:

- The proton form factor discrepancy is uncomfortable, both for high-Q^2 form factors and for the upcoming campaign to map 3D nucleon structure.

- The most interesting and useful TPE measurements are $3 \leq Q^2 \leq 5$ GeV^2, to build a bridge between hadronic and partonic theory models.

- Positrons are becoming an important part of the JLab 12 GeV physics program, for TPE, nucleon structure, and a rich medley of other questions.

Check out the Positron Working Group's white paper:
`https://epja.epj.org/component/toc/?task=topic&id=1430`

Initiative:

We recommend the allocation of necessary resources to implement high duty-cycle polarized positron beams at CEBAF.

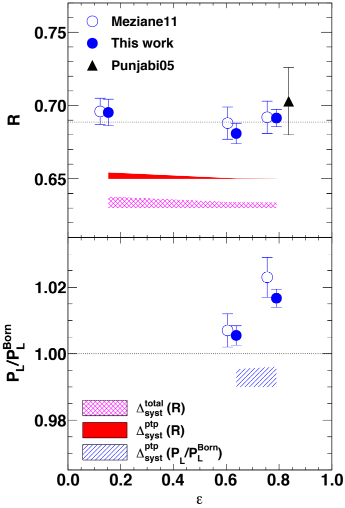
Using the 12 GeV CEBAF and capitalizing on positron source innovations at Jefferson Lab, high duty cycle polarized electron and positron beams, together with the outstanding capabilities of Jefferson Lab detectors, will enable a unique science program at the luminosity and precision frontier. It will comprise the mapping of two-photon exchange effects as well as essential measurements of the 3D structure of hadrons. It will also offer new opportunities to investigate electroweak physics and physics beyond the standard model.

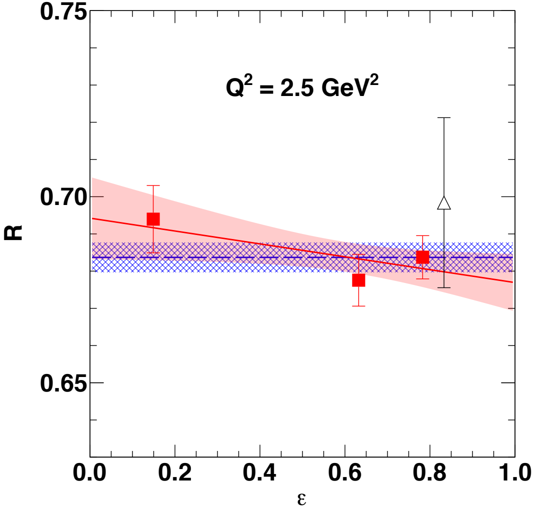
Back Up

Two-photon exchange concepts at Jefferson Lab

- e^+p/e^-p at CLAS12
  - J. C. Bernauer et al.
  - Campaign to map out TPE once and for all
- e^+p/e^-p at SBS
  - E. Cline et al.
  - Quick, targeted measurement at low-ϵ
- e^+p super-Rosenbluth, Hall C
  - J. Arrington, M. Yurov
  - Demonstrate opposite bias in G_E/G_M
- e^+A/e^-A in Hall C
  - T. Kutz et al.
  - First measurement of TPE on nuclei
- e^+ polarization transfer at SBS
  - A. J. R. Puckett et al.
  - Show ϵ-dependence comes from TPE
- Target-normal single spin asymmetry at SBS
  - G. N. Grauvogel et al.
  - Imaginary part of TPE amplitude

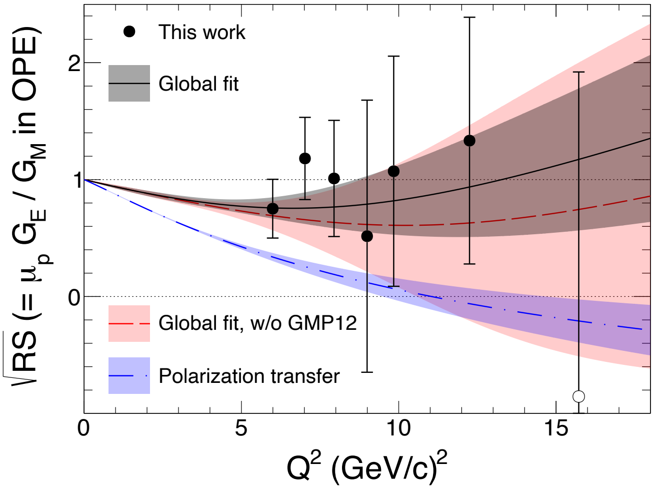
GEp-2γ showed surprising ϵ-dependence of P_l.





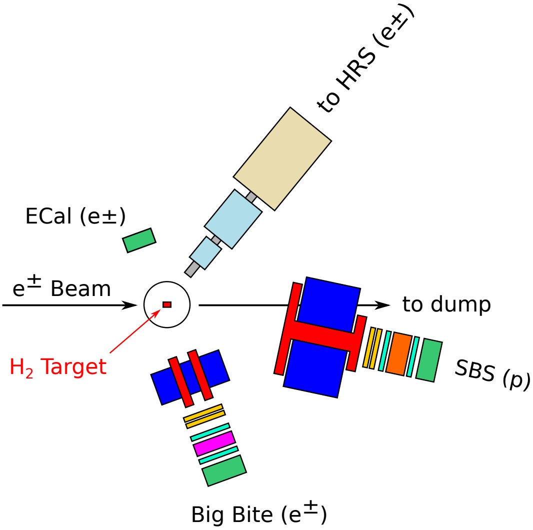
A. J. R. Puckett et al., Phys. Rev. C 96, 055203 (2017)

GMp results show that the FF discrepancy persists at high Q^2.



M. E. Christy et al., Phys. Rev. Lett. 128, 102002 (2021)

Super BigBite would allow quicker measurement at the expense of coverage.



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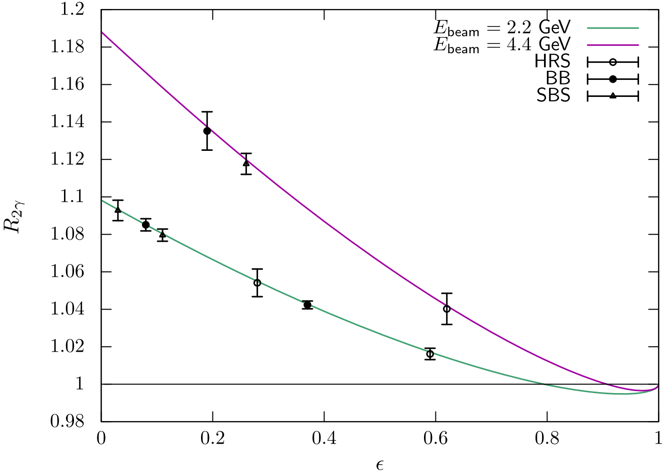
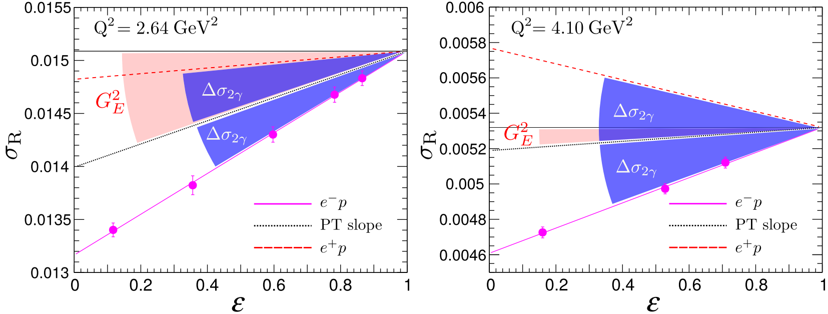


E. Cline et al., Eur.Phys.J.A 57, p. 290 (2021)

A super-Rosenbluth measurement with e^+ would clearly show the bias caused by TPE.



J. R. Arrington, M. Yurov, Eur.Phys.J.A 57, p. 290 (2021)

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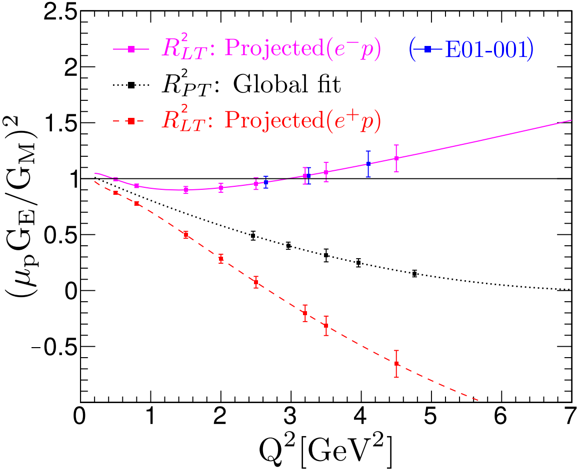

J. R. Arrington, M. Yurov, Eur.Phys.J.A 57, p. 290 (2021)