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Physics with a Positron Beam at Jefferson Lab

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Positron scattering from hadronic targets can provide new information that cannot be accessed with electron scattering alone. The asymmetry in deeply virtual Compton scattering cross sections between positrons and electrons can provide a critical handle on the Bethe-Heitler background process. A similar asymmetry in elastic scattering can reveal the contribution from two-photon exchange, which has been suggested as a possible explanation for the puzzling discrepancy in measurements of the proton's form factors at high momentum transfer. Positron capture and annihilation offer new ways to measure axial form factors, search for light dark matter, and probe fundamental symmetries. For these reasons, the Jefferson Lab Positron Working Group is working to bring positron capabilities to Jefferson Lab. Here, I present the design concept for producing and injecting polarized positrons into CEBAF, and review the range of experiments that would be made possible with positrons at Jefferson Lab.

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1. Introduction

Electron scattering is a favored tool for probing the structure of hadrons because the electron is point-like and interacts (primarily) through electromagnetism. In the first Born approximation, an electron is assumed to interact with the target hadron through the exchange of a single virtual photon. In this limit, there is no difference between electron scattering and positron scattering, and therefore nothing to be gained from the technical challenges of producing and accelerating positrons. Peering beyond this limit, higher-order contributions to the scattering process are slightly different for positrons, and the measurement of these differences can provide additional insight into hadron structure that electrons cannot access alone. Furthermore, the material from which we build targets is made out of matter———electrons, along with up and down valence quarks—rather than anti-matter. Positrons can participate in reactions, e.g., annihilation and various weak charged-current processes, which electrons cannot. Despite these benefits, laboratories around the world that formerly had positron acceleration capabilities (e.g., SLAC, DESY, Cornell, etc.) have moved away from fundamental nuclear physics.

The Jefferson Lab Positron Working Group (PWG) is a collaboration of accelerator and nuclear physicists who are excited by the possibilities that positrons offer and are advocating for the development of positron capabilities at Jefferson Lab. Recently the PWG published white paper as special topical issue of the European Physical Journal outlining the physics case and presenting experimental concepts [1]. In 2023, Jefferson Lab called for submissions to the Program Advisor Committee (PAC) for experimental proposals using a positron beam, and six proposals [2–7] and numerous letters of intent were received. Five of these proposals were conditionally approved (pending the realizating of the positron beam) forming the nucleus of a positron physics program at Jefferson Lab. While more detailed information can be found in the white paper and in the experimental proposals, in this contribution, I give an overview of physics case and give the status of the various efforts from the results of the 2023 PAC.

2. Deeply Virtual Compton Scattering

The Deeply Virtual Compton Scattering (DVCS) reaction, $ep \to ep\gamma$, is one of the cleanest ways to learn about the proton's Generalized Parton Distributions (GPDs). The reaction shares the same final state, however, as the Bethe-Heitler (BH) process, a QED process in which the out-going photon is radiated from either the incoming or outgoing electron. DVCS and BH interfere with each other, and so any measured cross section ($d\sigma$) will be an inevitable mixture of the two:

$$d\sigma \sim |\mathcal{M}_{ep\to ep\gamma}|^2 = |\mathcal{M}_{\mathrm{BH}}|^2 + |\mathcal{M}_{\mathrm{DVCS}}|^2 + 2\mathrm{Re}\left\{\mathcal{M}_{\mathrm{BH}}\mathcal{M}_{\mathrm{DVCS}}\right\}, \tag{1}$$

where $\mathcal{M}_{ep\to ep\gamma}$ is the total amplitude, $\mathcal{M}_{\mathrm{BH}}$ is the Bethe-Heitler amplitude and $\mathcal{M}_{\mathrm{DVCS}}$ is the DVCS amplitude. The interference term changes sign between an electron beam and a positron beam, and so measurements of a beam charge asymmetry can be used to determine $\mathcal{M}_{\mathrm{DVCS}}$, since $\mathcal{M}_{\mathrm{BH}}$ is well known from QED. Measuring such a charge asymmetry in DVCS is the motivation of two positron proposals, one in Hall C [2], and the other in Hall B [3].

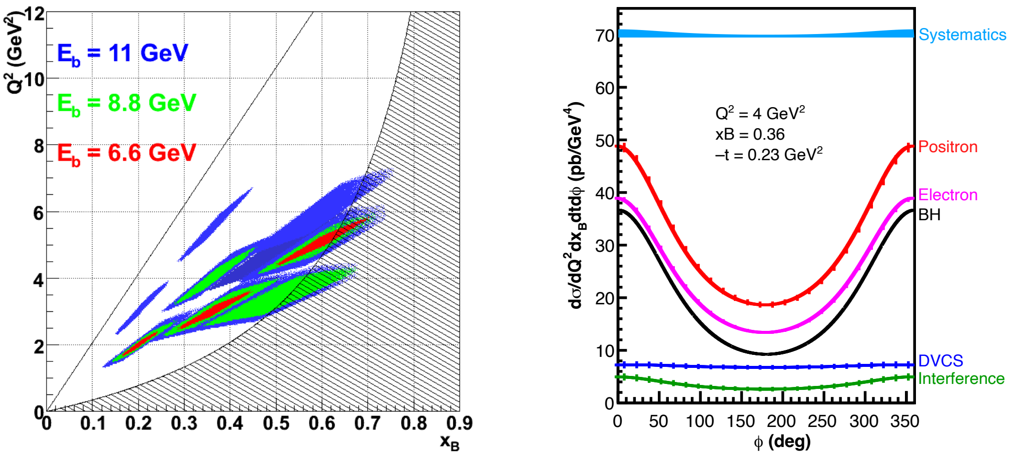


Figure 1: Left: kinematic coverage of E12-13-010 (electrons) in x_B, Q^2 space for all kinematic settings and beam energies (from [8]). The positron experiment, E12+23-006, will scan in Q^2 for the $x_B = 0.36$ settings. Right: projected uncertainties for an example bin for both the e^- (magenta) and e^+ (red) experiments and the breakdown between the pure BH (black) pure DVCS (blue) and interference (green) terms coming from Ref. [9]. Figure adapted from Ref. [2].

2.1 Hall C Proposal

E12+23-006 [2] proposes a 137-day measurement of DVCS cross sections with positrons in kinematics matching the $x_B = 0.36$ settings of the approved electron experiment E12-13-010 [8] (whose kinematics are shown in Fig. 1 left). The combined data can be used to form beam charge asymmetries to separate the BH and DVCS contributions. The experiments plan to measure both helicity-dependent and helicity-averaged cross sections. Both detect the scattered electron in the Hall C High Momentum Spectrometer (HMS), and the out-going photon in the Neutral Particle Spectrometer (NPS), an array of 1080 $PbWO_4$ crystals covering 25 msr. The is NPS installed on and makes use of the Super High Momentum Spectrometer (SHMS) carriage. Exclusive DVCS events are selected via the missing mass of the undetected proton. Fig. 1 right shows the projected uncertainties as a function of ϕ, the angle between the scattering and reaction planes, for one x_B, Q^2, t bin.

E12+23-006 developed from a white paper in the positron topical issue [10], and was proposed to the Jefferson Lab PAC in 2020 (as PR12-20-012) before finally receiving C1 conditional approval in 2023. One concern raised the PAC in 2020 was the degree to which positron data improved constraints of the proton's GPDs. A recent global re-analyis of DVCS data showed that the addition of positron data from the Hall C experiment strengthened constraints on the real part of the Compton Form Factor $\mathcal{H}$ by a factor of 3 [11].

2.2 Hall B Proposal

E12+23-002 [3] proposes a 100-day measurement of DVCS with both positrons and electrons using the CLAS12 Spectrometer [14] in Hall B with the goal of measuring beam charge asymmetries directly in the same experiment. The proposal developed from a white paper in the positron topical issue [15], was proposed to the Jefferson Lab PAC in 2020 (as PR2-20-009), before receiving C1

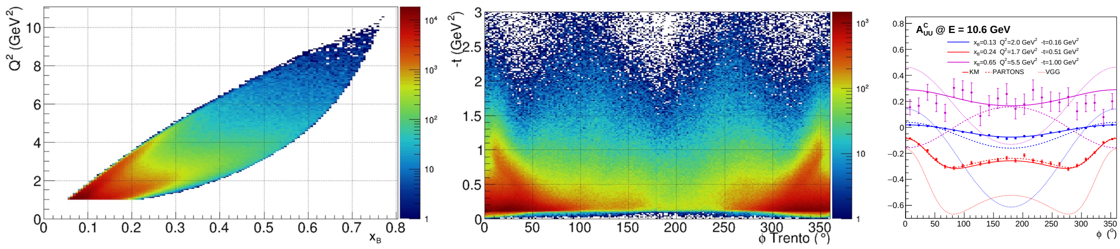


Figure 2: Left: projected kinmeatic coverage of E12+23-002 in x_B and Q^2. Middle: projected kinmeatic coverage in t and ϕ. Right: projected uncertainties for A^C_{UU} for three different kinematic bins along with theoretical predictions from Refs. [9, 12, 13]. Figures taken from [3].

conditional approval in 2023. In contrast to the Hall C measurement, all three final state particles can be detected to ensure exclusivity, with the lepton and photon detected in the CLAS12 forward detector, and the proton detected in the central detector. The large acceptance of CLAS12 for DVCS can be see in Fig. 2, left and middle. The experiment plans to run with the torus magnet in lepton-outbending polarity. The CLAS12 solenoid polarity will be periodically reversed in order to control systematic effects associated with the proton acceptance. Three different asymmetries can be determined from the experiment: the unpolarized charge asymmetry A^C_{UU}, the beam helicity-dependent charge asymmetry, A^C_{LU}, and the charge-averaged beam helicity asymmetry, A^0_{LU}, defined by:

$$A^C_{UU} \equiv \frac{(\sigma_{e^+\uparrow} + \sigma_{e^+\downarrow}) - (\sigma_{e^-\uparrow} + \sigma_{e^-\downarrow})}{\sigma_{e^+\uparrow} + \sigma_{e^+\downarrow} + \sigma_{e^-\uparrow} + \sigma_{e^-\downarrow}} \tag{2}$$

$$A^C_{LU} \equiv \frac{(\sigma_{e^+\uparrow} - \sigma_{e^+\downarrow}) - (\sigma_{e^-\uparrow} - \sigma_{e^-\downarrow})}{\sigma_{e^+\uparrow} + \sigma_{e^+\downarrow} + \sigma_{e^-\uparrow} + \sigma_{e^-\downarrow}} \tag{3}$$

$$A^0_{LU} \equiv \frac{(\sigma_{e^+\uparrow} - \sigma_{e^+\downarrow}) + (\sigma_{e^-\uparrow} - \sigma_{e^-\downarrow})}{\sigma_{e^+\uparrow} + \sigma_{e^+\downarrow} + \sigma_{e^-\uparrow} + \sigma_{e^-\downarrow}}, \tag{4}$$

where $\uparrow$ and $\downarrow$ refer to the beam helicity and e^+ and e^- refer to the beam charge. Fig. 2 right shows the projected uncertainties on A^C_{UU} for three different kinematic bins.

3. Multi-Photon Exchange

Positrons are valuable for understanding multi-photon exchange contributions because the interference term between one- and two-photon exchange, also changes sign with the change in beam charge. Two-photon exchange (TPE) in elastic scattering has attracted significant attention due to the discrepancy between measurements of the proton's form factor ratio $\mu_p G_E/G_M$, shown in Fig. 3. Whereas Rosenbluth separations of unpolarized cross section measurements indicate a roughly constant ratio, polarization transfer measurements show a clearly decreasing ratio as a function of Q^2. A non-negligible contribution from hard two-photon exchange, i.e., beyond the soft two-photon exchange correction of standard radiative corrections procedures, could bias the two techniques differently. Three experiments were conducted to measure the positron-proton elastic cross section ratio, $\sigma_{e^+p}/\sigma_{e^-p}$, but the results were inconclusive [22–24], largely because they lacked the reach to probe the Q^2 region where the form factor discrepancy is large. For this

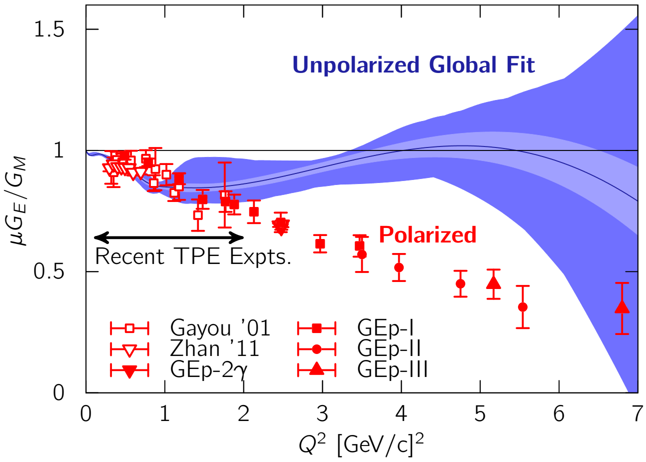


Figure 3: Polarization transfer measurements of the proton form factor ratio $\mu_p G_E/G_M$ as a function of Q^2 [16–20], compared with a global fit to unpolarized cross section data [21]. Recent experiments [22–24] lacked the reach to probe where the discrepancy is large.

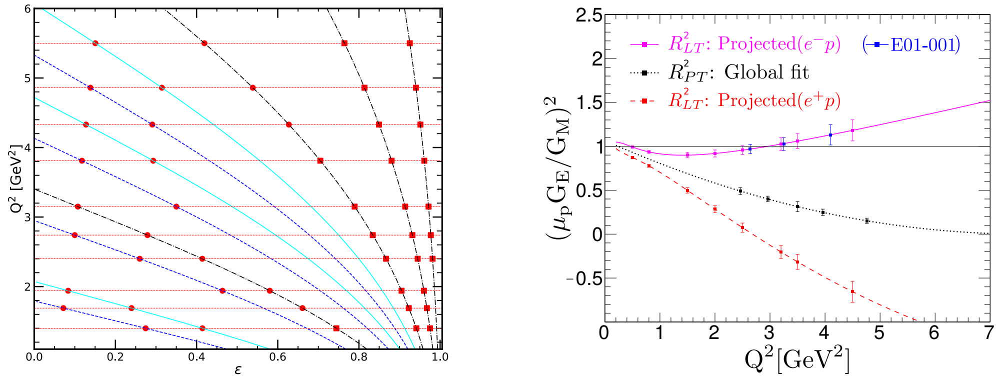


Figure 4: Left: kinematics proposed in E12-23-012. Right: projected results and uncertainties compared to an electron global fit [25], a polarization transfer fit [26], and the prediction for positions assuming TPE explains the full discrepancy between the two. Also shown are data from E01-001 [27]. Figures taken from [4].

reason, two new experiments were proposed to measure $\sigma_{e^+p}/\sigma_{e^-p}$ with the positron beam at Jefferson Lab [4, 5]. In addition, a third proposal was approved to measure deep inelastic scattering with positrons on nuclei to better constrain Coulomb corrections, another form of multi-photon exchange [6].

3.1 Positron Super-Rosenbluth

E12-23-012 [4] proposes a 56-day measurement of the elastic cross section with both electrons and positrons, at kinematics (see Fig. 4 left) allowing Rosenbluth separations to independently determine G_E^2 and G_M^2 at 10 values of Q^2. If there is a large contribution from hard TPE, the experiment will see a discrepancy between the electron and positron measurements. Projections are shown in Fig. 4 right. The proposal was developed from an earlier white paper [28], and received

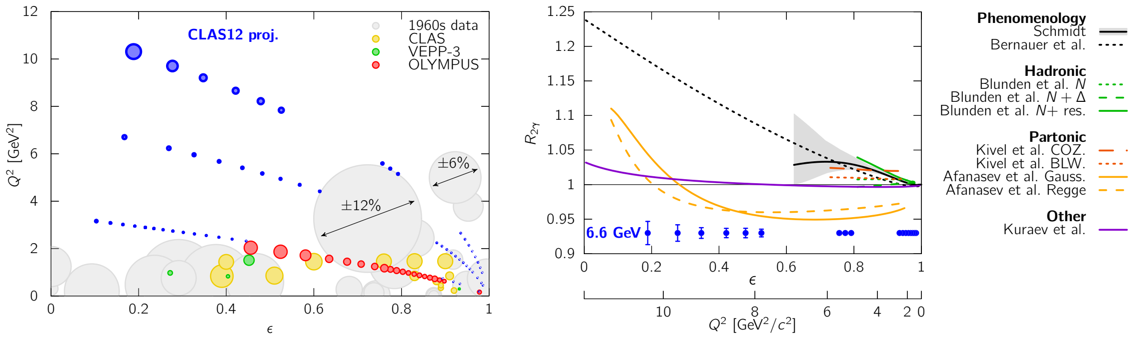


Figure 5: Left: the kinematics of $\sigma_{e^+p}/\sigma_{e^-p}$ measurements, including data from the 1960s [29–33], VEPP-3 [22], CLAS [34], and OLYMPUS [24], as well as the projected kinematics of E12-23-008 [5]. The size of the circles denotes the size of the uncertainties. Right: projected uncertainties for E12-23-008 in relation to theoretical predictions [21, 35–39].

C1 conditional approval in 2023.

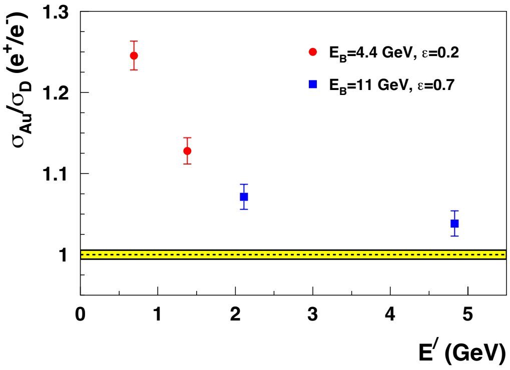
The experiment plans to use the Super-Rosenbluth technique, by which the recoiling proton will be detected (in the Hall C HMS) rather than the scattered lepton. This technique has several advantages, chiefly that the momentum of the proton is constant in Q^2. For every point with the same Q^2 setting, the magnetic field setting of the spectrometer can be left unchanged, reducing systematic sensitivities.

3.2 Two-Photon Exchange with CLAS12

E12-23-008 [5] proposes a 55-day measurement the ratio $\sigma_{e^+p}/\sigma_{e^-p}$ with CLAS12. The proposal was developed from an earlier white paper [40] and received conditional C1 approval in 2023. The combination of large acceptance, high luminosity, and high available beam energy allow the experiment to probe untouched regions of kinematic space where the form factor discrepancy is large (see Fig. 5). The lepton and proton will be detected in coincidence. For backward angles (high-Q^2, low-ϵ), the lepton will pass through the CLAS12 central detector, while the proton will pass through the forward detector. A new trigger scheme will need to be developed to record these events. Projected uncertainties for the 6.6 GeV setting, in relation to theoretical predictions [21, 35–39] are shown in Fig. 5 right.

3.3 Coulomb Corrections

E12+23-003 [6] was conditionally approved (C1) for a 9.3-day measurement of inclusive deep inelastic positron scattering on Au and d targets to study the impact of Coulomb corrections. Four kinematic points were chosen to compare with an appoved electron scattering experiment E12-14-002 [41]. The primary observable is to compare $\sigma_{\mathrm{Au}}/\sigma_d$ accross identical kinematics. Coulomb corrections would cause the change in this ratio, as a function of outgoing lepton energy, to be opposite for positrons and electrons. If the data with the two beam chrages are collected in the same run period with the same target, it would allow a degree of cancellation of normalization systematics. Projections for this scenario are shown in Fig. 6 left.



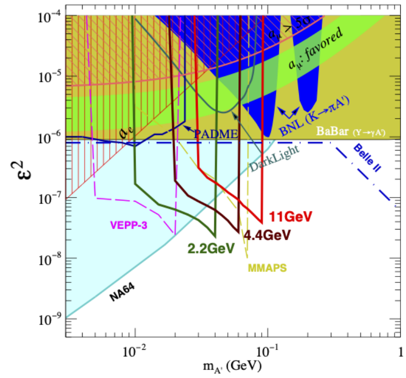


Figure 6: Left: projections for the double ratio $(\sigma_A^{e^+}/\sigma_d^{e^+})/(\sigma_A^{e^-}/\sigma_d^{e^-})$ and statistical uncertainty for E12+23-003, under the improved Effective Momentum Approximation. The normalization uncertainty in yellow assumes the optimistic scenario that electron data (E12-14-002) can be collected with the same target as part of the same run period. Figure taken from Ref. [6]. Right: The projected exclusion limits for the dark photon search proposed in PR12+23-005 (taken from [7]).

4. Searches for Dark Matter and Rare Phenomena

Due to the world around us being made of matter rather than anti-matter, positrons offer the possibility of doing physics through annihilation, or charged-current reactions that are not available to electrons. One possible clue in the origin of dark matter would be the presence of a so-called dark photon, or A', which may couple weakly to e^+e^-. This has received attention recently due to the observations of the ATOMKI Collaboration of an excess in the e^+e^- distribution produced from the decay of excited states of ^{8}Be that is consistent with a 17 MeV particle [42].

PR12+23-005 [7] proposed a 60-day search for an A' in the 15–90 MeV mass range through the reaction $e^+e^- \to \gamma(A')$. The final state would have a single photon, which would be detected in the PRad calorimter [43], from which the angles and energy could be used to calculate the missing mass of any undetected particle(s). The signature of an A' would be a bump in the missing mass spectrum. Two multi-wire proportional counters could be used to veto charged particle backgrounds. The proposal was deferred in 2023, but is being considered for resubmission. The projected exclusion limits are shown in Fig. 6 right.

5. Conclusion

The five approved positron experiments are now the nucleus of the Jefferson Lab positron program. The positron beam is envisioned as part of a long-term upgrade scenario for Jefferson Lab that lead to an increase in the terminal energy of CEBAF to 22 GeV, an upgrade which wide support from the community [44]. The PWG is working to develop new experimental concepts using positrons, and to find solutions to the technical challenges that must be overcome to bring the positron beam to fruition.

Acknowledgements

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