Probing charged lepton flavor violation with a positron beam at CEBAF (JLAB)

Y. Furletova¹, S. Mantry²,a
¹ Thomas Jefferson National Accelerator Facility, Newport News, USA
² University of North Georgia, Dahlonega, Georgia

Received: 14 June 2021 / Accepted: 4 November 2021 / Published online: 22 November 2021
© The Author(s), under exclusive licence to Società Italiana di Fisica and Springer-Verlag GmbH Germany, part of Springer Nature 2021
Communicated by Nicolas Alamanos

Abstract The addition of a high intensity 11 GeV polarized positron beam at the Continuous Electron Beam Accelerator Facility (CEBAF) at JLAB would allow for a search of Charged Lepton Flavor Violation (CLFV) via the process $e^+N \to \mu^+X$. The proposed Solenoidal Large Intensity Detector (SoLID) spectrometer, in the configuration with muon chambers, would be ideal for such CLFV searches. Various new physics scenarios, including the phenomenologically convenient Leptoquark (LQ) framework, predict CLFV rates that are within reach of current or planned experiments. A positron beam with instantaneous luminosity, $\mathcal{L} \sim 10^{38}$ cm$^{-2}$ s$^{-1}$, could improve on existing HERA limits by two or three orders of magnitude. The availability of positron beam polarization would also allow for distentangling CLFV effects mediated by left-handed vs. right-handed LQs.

1 Introduction

The discovery of neutrino oscillations gave conclusive evidence that lepton flavor is not a conserved quantity. However, the observation of lepton flavor violation in the charged lepton sector has eluded all experimental searches to date. In fact, the non-zero mass of neutrinos predicts the existence of charged lepton flavor violating (CLFV) processes, such as $\mu \to e\gamma$, through loop induced mechanisms, as seen in Fig. 1.

However, the smallness of the neutrino masses makes this process highly suppressed with a branching fraction of $\text{Br}(\mu \to e\gamma) < 10^{-54}$ [20], far beyond the reach of any current or planned experiments.

However, many beyond the Standard Model (BSM) scenarios [30] predict significantly higher CLFV rates that are within reach of current or future planned experiments. A variety of experiments across the energy spectrum have searched for and set limits on CLFV processes that involve transitions between the electron and the muon. These include searches for muon decays $\mu^- \to e^-\gamma$ (MEG experiment [24]) and $\mu^- \to e^-e^-e^+$ (Mu3e experiment [25]), the $\mu \to e$ conversion process $\mu^- + A(Z, N) \to e^- + A(Z, N)$ (SINDRUM [28] and COMET [23] experiments), and the Deep Inelastic Scattering (DIS) process $e^\pm N \to \mu^\pm X$ [17]. The most stringent limits come from MEG [11], $\text{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$, and SINDRUM II [27], $\text{CR}(\mu-e, Au) < 7.0 \times 10^{-13}$. The H1 [6] and ZEUS [17] collaborations at HERA have also set limits through searches for the CLFV DIS process $e^\pm N \to \mu^\pm X$, seen in Fig. 2. While some of these CLFV limits are stronger than others, each can provide complementary information since they can probe different CLFV mechanisms in different types of processes. Furthermore, CLFV searches involving muons could have new significance in light of the recently observed muon anomalies such as the muon g-2 measurement [8,12] and the B-decay ratios $R_{K^{(*)}} = \text{Br}(B \to K^{(*)}\mu^+\mu^-)/\text{Br}(B \to K^{(*)}e^+e^-)$ [3,5] and $R_{D^{(*)}} = \text{Br}(B \to D^{(*)}\tau\bar{\nu}_\tau)/\text{Br}(B \to D^{(*)}e(\mu)\bar{\nu}_e(\mu))$ [4,7].

Here we explore the possibility of studying CLFV with a polarized positron beam at the Continuous Electron Beam Accelerator Facility (CEBAF) at JLAB in the DIS process:

$$e^+ + N \to \mu^+ + X.$$  

2 Charged lepton flavor violation at CEBAF

A high intensity positron beam at the CEBAF at JLAB can search for the CLFV process $e^+ N \to \mu^+ X$. The 11 GeV polarized positron beam will impinge on a proton target at rest, corresponding to a center of mass energy, $\sqrt{s} \sim 4.5$ GeV. In spite of the relatively small center of mass energy,
the high luminosity, \( L \sim 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \), will allow for significant improvement on existing limits from HERA [6, 17].

The experiment should be equipped with detectors, which could provide a trigger for muons (for example, muon chambers or a tagger after the hadron-absorber), as well as a good tracker and, if possible, a vertex detector, to minimize background from pion-decays. CLFV events have a similar topology to DIS events where the scattered electron is replaced by muon. The selection should be based on events which do not have electrons in the final state, but instead have a clear evidence of a muon track pointing to the vertex.

The proposed SoLID spectrometer (Solenoidal Large Intensity Detector) [18] will meet the above requirements. This high-luminosity and high-acceptance detector has been proposed for the JLAB 12 GeV program, and will be able to handle the expected high luminosity, \( L \sim 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \). In addition, SoLID can carry out measurements not only using high intensity unpolarized or polarized lepton beams, but also unpolarized or polarized nuclear targets, which will be important for distinguishing between different CLFV mechanisms [26].

The SoLID experiment will run in different detector configurations [18], such as the \( J/\psi \) production, Parity-Violating Deep Inelastic Scattering (PVDIS), or the dedicated Double Deeply Virtual Compton Scattering (DDVCS) configuration. For CLFV measurements \( J/\psi \) and DDVCS setups will be preferable, since both or them will be equipped with muon chambers. Figure 3 shows the \( J/\psi \) setup with muon chambers. The CLFV experimental program could run simultaneously with the other approved experiments, since it will not require any additional hardware equipment. In the \( J/\psi \) configuration, the SoLID spectrometer will be equipped with large-angle and a forward-angle muon detectors. In addition, high resolution Gas Electron Multiplier (GEM) chambers, Cherenkov detectors, and Calorimeters will help muon momentum reconstruction and identification. The expected muon detection efficiency in this setup is about 70% for a single muon [29].

The SoLID experiment will have an acceptance in the polar angle, \( \theta \), in the range of 8° to 24° and 22° to 35° for the SIDIS and PVDIS configurations, respectively, and full-2\( \pi \) acceptance in the azimuthal angle \( \phi \). This is typical for fixed target configurations where most of the cross section lies in the forward region due to the overall kinematic boost of the 11 GeV electron incident of the stationary proton.

Muon backgrounds must be suppressed or under control in order to extract bounds on the \( e^+ \rightarrow \mu^+ \) CLFV process. Due to the compact size of the detector, the typical decay length of pions is much bigger than the distance to the detector from their production vertex. The survival probability of a pion at a distance \( L \) away from its production vertex is given by [1]

\[
P(L) = e^{-L/\lambda_D}, \quad \lambda_D = \frac{p_\pi}{m_\pi c \tau},
\]

where \( \lambda_D \) is pion decay length and \( \tau = 26 \) ns is the mean-life of the pion in its rest frame. For example, at SoLID, the pions will be produced with typical momenta, \( p_\pi \), in the range of 1 to 7 GeV [2]. This corresponds to a range in the decay length of about 56 to 390 m. This range of decay lengths are to be compared with the distance of 5 m corresponding to the overall detector dimensions combined with its promiximity to the pion production vertex. This results in a pion survival probability range between 91% and 99% at a distance of 5 m from the pion production vertex. Thus, the muon background from pion decays is highly suppressed at SoLID compared to other fixed target experiments with large or non-compact detectors.
In order to further suppress the muon background from pion decays and or cosmic rays, it is important to have high precision charged particle tracking. Such tracking information will be used to reconstruct the charged particle trajectories and their production vertices. This allow for separating any signal muons produced at the CLFV vertex from the background muons coming from pion decays. In addition, the low center of mass energy $\sqrt{s} \sim 4.5$ GeV implies there will no muon backgrounds from the decays of open charm or bottom mesons. However, there can be muon backgrounds from the production of $J/\Psi$, via the strong interaction pair production of $c\bar{c}$, which can be easily rejected by tracking the resulting muon pair back to the $J/\Psi$ decay vertex. The SoLID experiment will have the capability for the needed charged particle tracking to reject muon backgrounds. In particular, it will have a tracking spatial resolution of 100 microns, allowing for a precise reconstruction of the muon decay vertices [2].

3 Leptoquark mediated CLFV

It becomes convenient to study CLFV in the Leptoquark (LQ) scenario in which the CLFV DIS processes $e^\pm \rightarrow \mu^\pm + X$ can be mediated at tree-level. LQs are color triplet bosons that mediate transitions between quarks and leptons and carry both baryon number and lepton number. As seen in Tables 1 and 2, according to the Buchmüller, Rückl and Wyler classification [16], there are 14 different types of LQs characterized by their spin (scalar or vector), fermion number $F = 3B+L$ (0 or $\pm 2$), chiral couplings to leptons (left-handed or right-handed), $SU(2)_L$ representation (singlet, doublet, triplet), and $U(1)_Y$ hypercharge.

The $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant and renormalizable interactions are given by the Lagrangian for $F = 0$ and $|F| = 2$ LQs as follows:

$$\mathcal{L}_{F=0} = h_{1/2}^{\tau R} \bar{q}_L \ell L \Sigma_{1/2} + h_{1/2}^{\tau L} \bar{q}_L \ell R \Sigma_{1/2} + h_{1/2}^{\tau L} \bar{q}_R \ell L \Sigma_{1/2} + h_{0}^{\tau L} \bar{q}_L \ell L V_{0}^{\mu} + h_{0}^{\tau R} \bar{q}_L \ell R V_{0}^{\mu}$$

$$+ h_{3/2}^{\tau L} \bar{q}_L \ell L \tilde{V}_{3/2}^{\mu} + h_{3/2}^{\tau R} \bar{q}_L \ell R \tilde{V}_{3/2}^{\mu} + h_{1/2}^{\tau L} \bar{q}_L \ell L \tilde{V}_{1/2}^{\mu} + h.c.,$$

$$\mathcal{L}_{|F|=2} = \tilde{g}_{0}^{\ell L} \bar{q}_L \ell L \Sigma_{0}^{L} + \tilde{g}_{0}^{\ell R} \bar{q}_L \ell R \Sigma_{0}^{R} + \tilde{g}_{0}^{\ell R} \bar{q}_R \ell L \Sigma_{0}^{L}$$

$$+ \tilde{g}_{1/2}^{\ell L} \bar{q}_L \ell L \tilde{V}_{1/2}^{L \mu} + \tilde{g}_{1/2}^{\ell R} \bar{q}_L \ell R \tilde{V}_{1/2}^{R \mu} + \tilde{g}_{1/2}^{\ell L} \bar{q}_L \ell L \tilde{V}_{1/2}^{L \mu} + h.c.$$  (3)

As shown schematically in Fig. 4, the LQs mediate CLFV transitions at tree-level, allowing for larger cross sections compared to other scenarios in which CLFV processes are typically loop suppressed. For LQ masses $M_{L,Q} \gg \sqrt{s}$, the tree-level processes in Fig. 4 are described by contact interactions. In this approximation, the cross-sections [22] for $e^-N \rightarrow \mu^-X$ via $F = 0$ and $|F| = 2$ LQs exchange take the form:

$$\sigma_{F=0} = \sum_{\alpha, \beta} \frac{s}{32\pi} \left[ \frac{\lambda_{1\alpha}\lambda_{2\beta}}{M_{L,Q}^2} \right]^2 \int dx \int dy \left\{ xq_{\alpha}(x,x)s(f(y) + xq_{\beta}(x,-u)g(y)) \right\}. \quad (5)$$
Similarly, for $e^+N \rightarrow \mu^+X$, the $F = 0$ and $|F| = 2$ LQ exchange cross section takes the form:

$$\sigma_{F=0}^{e^+p} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[ \frac{\lambda_{1\alpha} \lambda_{2\beta}}{M_{LQ}^2} \right]^2 \int dx \int dy \left\{ xq_{\alpha}(x, xs) f(y) + x\tilde{q}_{\beta}(x, -u)g(y) \right\},$$

respectively. Here the kinematic variables $u = x(y-1)s$ and $f(y) = 1/2$, $g(y) = (1-y)^2/2$ for a scalar LQ and $f(y) = 2(1-y)^2$, $g(y) = 2$ for a vector LQ. The $\lambda_{ij}$ couplings are the lepton-quark-LQ couplings where first and second indices denote the lepton and quark generations respectively, and can be related to the $h$ and $g$ couplings that appear at the Lagrangian level in Eqs. (3) and (4), up to overall signs and factors of $\sqrt{2}$ which can be shown in the last columns of Tables 1 and 2, and the subscripts $L$ or $R$ denote left-handed or right-handed coupling of the LQ to lepton. Note, that the first and second terms in the cross section formulae arise from an $s$-channel and $u$-channel LQ-exchange, respectively.

A global analysis using data obtained from the use of unpolarized and polarized electron and positron beams, as well as unpolarized and polarized nuclear targets, can allow for constraints on specific LQ states or combinations of states. Such an analysis can also be performed in the SMEFT framework [14, 15, 19]. In particular, the lepton beam polarization can be used to distinguish between contributions from left-handed and right-handed LQs. Comparing limits [21] obtained using a positron beam with those obtained from an electron beam can also help untangle contributions from $F = 0$ and $|F| = 2$ LQs due to the different combinations of quark and anti-quark parton distribution functions (PDFs) that appear in the $s$- and $u$-channels, as seen in Eqs. (5–8).

Finally, the use of proton vs deuteron nuclear targets can distinguish contributions of the different electric charge states of the LQs corresponding to coupling to up or down type quarks. Thus, the positron beam studies can be complementary to CLFV studies planned with an electron beam at the SOLID [18] experiment at JLAB and at the proposed Electron-Ion collider (EIC) [9, 22].

### 4 CLFV limits

The HERA [6, 17] collaborations quantified the results of the CLFV searches by setting limits on the coupling to mass ratios $\chi_{\alpha\beta} \equiv \frac{\lambda_{1\alpha} \lambda_{2\beta}}{M_{LQ}^2}$ that appear in the cross sections in Eqs. (5–8). For example, for the $F = 0$ LQ state $S_{1/2}^0$, limits of $\chi_{11} < 0.6 \text{ TeV}^{-2}$ and $\chi_{12} < 0.7 \text{ TeV}^{-2}$ were found [6]. A complete listing of HERA limits on various LQ states can be found in Refs. [6, 17]. For the purposes of comparing the reach at CEBAF to HERA limits, it becomes useful to define the quantity [22]

$$z \equiv \frac{\chi_{\alpha\beta}}{\chi^{\text{HERA}}_{\alpha\beta}},$$

which gives the ratio of $\chi_{\alpha\beta}$ to its upper limit, $\chi^{\text{HERA}}_{\alpha\beta}$, as set by HERA [6, 17]. Thus, the cross sections in Eqs. (5–8) can be written as a function of the variable $z$. The cross section at $z = 1$ corresponds to using evaluating it at the HERA limit $\chi_{\alpha\beta} = \chi^{\text{HERA}}_{\alpha\beta}$. Similarly, $z < 1$ corresponds to evaluating the cross section below the HERA limit $\chi_{\alpha\beta} < \chi^{\text{HERA}}_{\alpha\beta}$.

A positron beam at CEBAF can improve on the HERA limits. The HERA collider operated with a center of mass energy $\sqrt{s} = 300 \text{ GeV}$, much bigger than $\sqrt{s} \sim 4.5 \text{ GeV}$ for the CEBAF facility. Thus, for a fixed value of $\chi_{\alpha\beta}$, the LQ cross sections in Eqs. (5–8) at CEBAF are expected to be smaller by a factor of $(4.5/300)^2 \approx 2.25 \times 10^{-4}$ compared to HERA. However, compared to HERA, the CEBAF facility will have an instantaneous luminosity that will be larger by a factor of $\sim 10^6$ or $10^7$. Running the CEBAF experiment with instantaneous luminosity $\mathcal{L} \sim 10^{38} \text{ cm}^{-2} \text{ s}^{-1}$ for five years will yield the integrated luminosity $\mathcal{L}_{\text{int}} \sim 5 \times 10^6 \text{ fb}^{-1}$. Without taking efficiencies into account, this will allow for sensitivity to cross sections as small as $\sigma \sim 0.2 \times 10^{-6} \text{ fb}$ which will yield a number of events of order one.

In Fig. 5, we show the cross section at CEBAF for $e^+N \rightarrow \mu^+X$, via the exchange of the $F = 0$ left-handed scalar LQ, $S_{1/2}^0$, as a function of $z$. The various lines correspond to the cross section arising for a specific choice of $(\alpha, \beta)$ in Eq. (7), with all other terms set to zero. The set of four choices $(\alpha, \beta) = (11, 12, 21, 22)$ correspond to the red, black, magenta, and blue colors, respectively. We see that sensitivity to a cross section $\sigma \sim 0.2 \times 10^{-6} \text{ fb}$, will translate into a limit in the range $z \sim [0.005–0.05]$, depending on the specific choice of $(\alpha, \beta)$ corresponding to an improvement by two or orders of magnitude over the HERA limits, corresponding to $z = 1$.

The expected improvement on the HERA limits can also be complementary to the more stringent limits coming from other low energy experiments. For example, searches [27] of
The positron beam polarization dependence of cross section for $e^+N \rightarrow \mu^+X$ with center of mass energy $\sqrt{s} = 4.5$ GeV, via exchange of the F = 0 scalar LQ, $S_{1/2}^L$, as a function of the ratio $z$ defined in Eq. (11). The solid black line corresponds to the cross section for an unpolarized positron beam ($P_e = 0$). The gray band corresponds to the linear variation of the cross section with beam polarization, as shown in Eq. (12). The size of the band corresponds to a variation of the beam polarization between $[-80\%, 80\%]$

A lepton beam polarization can allow one to distinguish between left-handed and right-handed LQ effects. The lepton beam polarization is defined as:

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

(11)

where $N_R$ and $N_L$ denote the number of right-handed and left-handed leptons (electrons or positrons). Correspondingly, the chiral coupling of the LQ states to the lepton beam leads to cross section having a linear dependence on the beam polarization:

$$\sigma (P_e) = (1 \pm P_e) \sigma (P_e = 0).$$

(12)

Thus, by varying the degree of lepton beam polarization, one can better constrain left-handed and right-handed LQ states. In Fig. 6, we show the effect beam polarization when it is varied over the range $P_e = [-80\%, 80\%]$, according to Eq. (12). The solid black line denotes the unpolarized cross section ($P_e = 0$) for the $S_{1/2}^L$ LQ state with $\lambda_{11}\lambda_{22}$ non-zero and all other LQ couplings set to zero. In terms of $\chi_{12}$, the HERA limit is $\chi_{12}^{\text{HERA}} \sim 0.7$ TeV$^{-2}$. The gray band around the solid black line corresponds to the variation of the cross section with polarization.

The CLFV studies at CEBAF will also complement future studies at the Electron-Ion Collider (EIC) which will also search for $e \rightarrow \tau$ CLFV transitions [10,13,22]. In fact, due to its much larger luminosity, the CEBAF bounds on CLFV transitions between the first two lepton generations are still expected to be stronger than at the EIC. Thus, in general, the CEBAF positron program to explore CLFV processes can provide new insights and be complementary to other searches across a wide variety of experiments.
Conclusions

A polarized positron beam at CEBAF can play an important role in the search for charged lepton flavor violation, through a search for the process $e^+ N \rightarrow \mu^+ X$, at the intensity frontier. The polarization of the positron beam can distinguish between different CLFV mechanisms, such as left-handed vs. right-handed Leptoquarks. Its large luminosity allows for improving on HERA limits by two or three orders of magnitude and complementing CLFV searches in other experiments, including proposed CLFV studies at the Electron-Ion Collider (EIC) via searches for $eN \rightarrow \tau X$ [10,13,22].

Acknowledgements This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors’ comment: This article describes the potential for a future positron beam facility at JLAB for probing Charged Lepton Flavor Violation. As such, there is no data available.]

References

1. $\pi^+$ acceptance corrections for $\pi \rightarrow \mu$ decay, 2004
2. Solid (solenoidal large intensity device) updated preliminary conceptual design report, 2017
3. R. et al. Aaij, Test of lepton universality with $b\rightarrow k^+\mu^+\nu_{\mu}$ decays. Journal of High Energy Physics, 2017(8), 2017
4. R. et al. Aaij, Test of lepton flavor universality by the measurement of the $b\rightarrow d^{*+}$ branching fraction using three-prong decays. Phys. Rev. D, 97(7), 2018
5. Roel Aaij et al. Test of lepton universality in beauty-quark decays. 3 2021
6. F.D. Aaron et al., Search for Lepton Flavour Violation at HERA. Phys. Lett. B 701, 20–30 (2011)
7. A. Abdesselam et al., Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^\ast)$ with a semileptonic tagging method. 4 2019
8. B. et al. Abi. Measurement of the positive muon anomalous magnetic moment to 0.46 ppm. Physical Review Letters, 126(14), Apr 2021
9. A. Accardi et al., Electron ion collider: The next QCD frontier: Understanding the glue that binds us all. Eur. Phys. J. A 52(9), 268 (2016)
10. A. Accardi, V. Guzy, A. Prokudin, C. Weiss, Nuclear physics with a medium-energy electron-ion collider. Eur. Phys. J. A 48, 92 (2012)
11. A.M. Baldini et al., The design of the MEG II experiment. Eur. Phys. J. C 78(5), 380 (2018)
12. G. W. Bennett, B. Bousquet, H. N. Brown, G. Bunce, R. M. Carey, P. Cushman, G. T. Danby, P. T. Debevec, M. Deile, H. Deng, and et al. Final report of the e821 muon anomalous magnetic moment measurement at bnl. Phys. Rev. D, 73(7), 2006
13. ge D. Boer et al. Gluons and the quark sea at high energies: distributions, polarization, tomography, 2011
14. Radja Bougezel, Frank Petriello, Daniel Wiegand, Removing flat directions in standard model EFT fits: How polarized electron-ion collider data can complement the LHC. Phys. Rev. D 101(11), 116002 (2020)
15. Radja Bougezel, Frank Petriello, and Daniel Wiegand. Disentangling SMEFT operators with future low-energy PVES experiments. 4 2021
16. W. Buchmuller, R. Ruckl, and D. Wyler. Leptoquarks in Lepton - Quark Collisions. Phys. Lett. B, 191:442–448, 1987. [Erratum: Phys.Lett.B 448, 320–320 (1999)]
17. S. Chekanov et al., Search for lepton-flavor violation at HERA. Eur. Phys. J. C 44, 463–479 (2005)
18. J. P. Chen, H. Gao, T. K. Hemmick, Z. E. Meziani, P. A. Souder, and the SoLID Collaboration. A white paper on solid (solenoidal large intensity device), 2014
19. Vincenzo Cirigliano, Kaori Fuyuto, Christopher Lee, Emanuele Mereghetti, Bin Yan, Charged lepton flavor violation at the EIC. JHEP 03, 256 (2021)
20. A.M. Baldini et al., Eur. Phys. J. C 76, 434 (2016)
21. Yulia Furtletova, Sonny Mantry, Using polarized positrons to probe physics beyond the standard model. AIP Conf. Proc. 1970(1), 030005 (2018)
22. Matthew Gonderinger and Michael J. Ramsey-Musolf. Electron-to-tau lepton flavor violation at the electron-ion collider. J. High Energy Phys., 2010(11), 2010
23. M.J. Lee. COMET Muon Conversion Experiment in J-PARC. Front. Phys., 6, 2018
24. R.P. Litchfield. Muon to electron conversion: The COMET and Mu2e experiments. In Interplay between Particle and Astroparticle physics, 12 2014
25. A. Schönig, S. Bachmann, R. Narayan, A novel experiment to search for the decay $\mu \rightarrow eee$. Phys. Proc. 17, 181–190 (2011)
26. P. Taxil, E. Tugcu, J.-M. Virey, Search and identification of scalar and vector leptoquarks at hera with polarization. Eur. Phys. J. C 14(1), 165–178 (2000)
27. A. van der Schaar, SINDRUM II. J. Phys. G 29, 1503–1506 (2003)
28. P. Wintz, Results of the SINDRUM-II experiment. Conf. Proc. C 980420, 534–546 (1998)
29. S. Zhao, A. Camsonne, D. Marchand, M. Mazouz, N. Sparveris, S. Stepayan, E. Voutier, and Z. W. Zhao. Double deeply virtual compton scattering with positron beams at solid, 2021
30. P.A. Zyla et al., The review of particle physics. Prog. Theor. Exp. Phys. 2020, 083C01 (2020)