

Search for $e \rightarrow \tau$ Charged Lepton Flavor Violation at the EIC with the ECCE Detector

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Abstract

The recently approved Electron-Ion Collider (EIC) will provide a unique new opportunity for searches of charged lepton flavor violation (CLFV) and other new physics scenarios. In contrast to the $e \leftrightarrow \mu$ CLFV transition for which very stringent limits exist, there is still a relatively large discovery space for the $e \rightarrow \tau$ CLFV transition, potentially to be explored by the EIC. With the latest detector design of ECCE (EIC Comprehensive Chromodynamics Experiment) and projected integral luminosity of the EIC, we find the τ -leptons created in the DIS process $ep \rightarrow \tau X$ are expected to be identified with high efficiency. A first ECCE simulation study, restricted to the 3-prong τ -decay mode and with limited statistics for the Standard Model backgrounds, estimates that the EIC will be able to improve the current exclusion limit on $e \rightarrow \tau$ CLFV by an order of magnitude.

1. Charged-Lepton Flavor Violation and Leptoquarks

The discovery of neutrino oscillations provided conclusive evidence of lepton flavor violation. Lepton flavor violation in the neutrino sector also results in charged lepton flavor violation (CLFV) through loop-suppressed processes such as $\mu \rightarrow e\gamma$. However, the resulting predicted CLFV rates are highly suppressed due to the small neutrino masses – $\text{Br}(\mu \rightarrow e\gamma) < 10^{-54}$ – and are far beyond the reach of any current or planned experiments. On the other hand, many Beyond Standard Models (BSM) scenarios predict CLFV rates that are both much larger and within reach of ongoing or near-future experiments. For example, supersymmetry-based models predict rates as high as $\text{Br}(\mu \rightarrow e\gamma) \sim 10^{-15}$ [1], while the current experimental limit on the $\mu \rightarrow e\gamma$ process already reached $\text{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [2]. On the other hand, while there have been extensive searches for CLFV processes between the first and second lepton generations, denoted as CLFV(1,2) for brevity, the constraints on CLFV(1,3) processes that involve $e \leftrightarrow \tau$ transitions are weaker by several orders of magnitude. These constraints on CLFV(1,3) [3, 4] were obtained through searches for $e + p \rightarrow \tau + X$, $\tau \rightarrow e\gamma$, and $p + p \rightarrow e + \tau + X$ at HERA [5, 6], BaBar [7], and the LHC [8] respectively. However, there are many BSM scenarios such as grand unified theories with leptoquarks and R-parity violating supersymmetry that predict CLFV(1,3) rates that are enhanced compared to CLFV(1,2) processes, motivating continued searches dedicated for $e \leftrightarrow \tau$ transitions.

We carry out the simulation analysis based on the design of the ECCE Detector (recommended as Detector 1 by the EIC Detector Proposal Advisory Panel [9]), for determining the sensitivity to the CLFV(1,3) process $e + p \rightarrow \tau + X$ in the leptoquark framework [3, 4], though such analysis could also be performed in the SMEFT framework [4]. Leptoquarks are color triplet bosons that carry both lepton (L) and baryon (B) numbers, coupling leptons to quarks and mediating the $e + p \rightarrow \tau + X$ CLFV(1,3) process at tree-level, as shown in Fig. 1. The leptoquarks are classified into 14 types [10] based on their fermion number

$F = 3B + L$ ($F = 0$ or $|F| = 2$), spin (scalar or vector), chiral couplings to leptons (left-handed or right-handed), $SU(2)_L$ representation (singlet, doublet, or triplet), and $U(1)_Y$ hypercharge.

In the region where the leptoquark mass M_{LQ} is much larger than the characteristic energy scale of the experiment, represented by the center-of-mass energy \sqrt{s} and the four-momentum transfer $\sqrt{Q^2}$, the CLFV(1,3) process $e + p \rightarrow \tau + X$ is mediated by a contact interaction and the tree-level cross section for $F = 0$ or $|F| = 2$ leptoquarks takes the form:

$$\begin{aligned} \sigma_{F=0} &= \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2} \right]^2 \times \\ &\int dx \int dy \{x\bar{q}_\alpha(x, xs)f(y) + xq_\beta(x, -u)g(y)\}, \\ \sigma_{|F|=2} &= \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2} \right]^2 \times \\ &\int dx \int dy \{xq_\alpha(x, xs)f(y) + \bar{q}_\beta(x, -u)g(y)\}, \end{aligned} \quad (1)$$

where $u = x(y-1)s$ with x the Bjorken scaling variable and y the fractional energy loss of the electron in the proton-rest frame. The kinematic y -dependent functions $f(y)$, $g(y)$ are $f(y) = 1/2$, $g(y) = (1-y)^2/2$ and $f(y) = 2(1-y)^2$, $g(y) = 2$ for scalar and vector leptoquarks, respectively. The quantity $\lambda_{1\alpha}\lambda_{3\beta}/(M_{LQ}^2)$ characterizes the strength of the contact interaction. The λ_{ij} parameters, assumed to be real numbers for this analysis, denote the leptoquark couplings between the i -th lepton generation and j -th quark generation.

The ZEUS and H1 experiments at HERA placed upper limits on $\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2$ [11, 5, 12, 6]. The HERA data set corresponded to $\sqrt{s} = 300$ and 318 GeV and a total integrated luminosity of up to 130 pb⁻¹. With several orders of magnitude increase in the luminosity, the EIC has the potential to improve upon the HERA limits for both diagonal ($\alpha = \beta$) and off-diagonal ($\alpha \neq \beta$) components, and provide complementary information [4] to the constraints

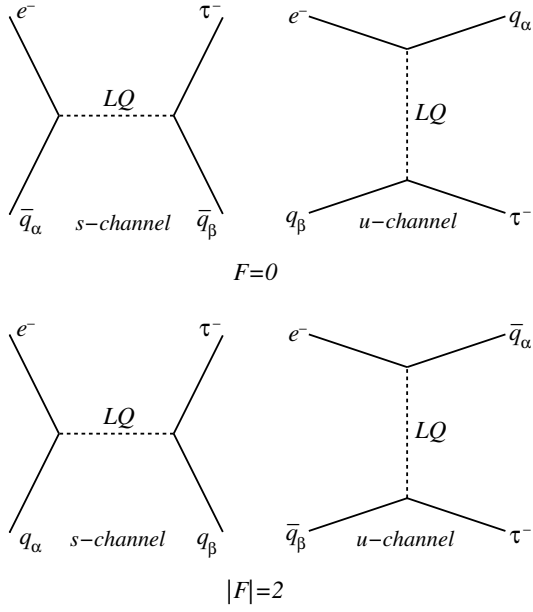


Figure 1: From [3]: Representative Feynman diagrams for $e \rightarrow \tau$ scattering processes via one-leptoquark mediator. The fermionic number F is assumed to be conserved, as in the BRW effective model [10]. The partonic cross section is convoluted with the PDF of the initial state (anti)quark of each diagram, and depends on the parameter $\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2$.

74 from BaBar and the LHC.

75 2. EIC/ECCE Simulation and Vertex Identification

76 The EIC Comprehensive Chromodynamics Experiment
 77 (ECCE) detector concept [13] addresses the full EIC sci-
 78 ence mission as described in the EIC community White
 79 Paper [14] and the 2018 National Academies of Science
 80 (NAS) Report [15]. It is simultaneously fully capable,
 81 low-risk, and cost-effective. ECCE strategically repur-
 82 poses select components of existing experimental equip-
 83 ment to maximize its overall capabilities within the enve-
 84 lope of planned resources. For example, the central barrel
 85 of the detector incorporates the storied 1.4 T BaBar super-
 86 conducting solenoid, and the sPHENIX barrel hadronic
 87 calorimeter currently under construction.

88 The goal of this work is to study the potential for
 89 discovering the $e^-p \rightarrow \tau^-X$ CLFV process at the EIC
 90 based on realistic detector simulations, and identification
 91 of such events over Standard Model (SM) backgrounds
 92 that include neutral-current (NC) deep inelastic scatter-
 93 ing (DIS), charged-current (CC) DIS, and photoproduc-
 94 tions. CLFV events leading to a final-state τ and are char-
 95 acterized by a high-momentum isolated τ which is bal-
 96 anced by a jet in the transverse plane. Since the τ will
 97 decay into stable particles after a short flying distance of
 98 $\sim \mu\text{m}$, only its decay products are visible in the detec-
 99 tor. A critical requirement of CLFV searches is thus the
 100 secondary vertex reconstruction performance which relies
 101 on the tracking and especially the vertex detectors. The

102 ECCE conceptual design uses state-of-the-art technolo-
 103 gies consisting Monolithic Active Pixel Sensor (MAPS)
 104 based silicon vertex/tracking subsystem to achieve high
 105 precision primary and decay vertex determination.

106 The three SM background processes affect the CLFV
 107 searches as follows: First, the SM NC DIS events are very
 108 similar to leptoquark events where the τ decays to only
 109 one charged particle plus neutrinos in the final state, mak-
 110 ing this channel very difficult to study. Secondly, due
 111 to the presence of at least one neutrino in all τ -decay
 112 channels, significant missing p_T is expected. This fea-
 113 ture is similar to the SM CC DIS events. The third main
 114 background of concern is from photoproduction events,
 115 mostly due to their very high yield. In this study, we fo-
 116 cus the identification of CLFV candidate events that con-
 117 tain a high- p_T quark-initiated jet along with an isolated
 118 and high- p_T τ which replaces the scattered electrons in the
 119 typical NC DIS events, and the rejection of events from all
 120 three SM background processes.

121 Based on the number of the charged particles in the final
 122 state, the dominant τ decay modes can be categorized into
 123 “1-prong” (one charged particle) and “3-prong” (three
 124 charged particles). The “3-prong” decay modes have
 125 a branching ratio of $\sim 15\%$ while the “1-prong” modes
 126 have a branching ratio of $\sim 85\%$. Although the “1-prong”
 127 modes have larger branching ratio, they are more de-
 128 manding to identify. For example, the “1-prong” mode
 129 could be one of the two leptonic decays, $\tau \rightarrow e\bar{\nu}_e\nu_\tau$ or
 130 $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$. If the charged particle is an electron, it is very
 131 similar to DIS NC events. If the charged particle is a muon,
 132 it will require good muon identification. Another possible
 133 “1-prong” mode is $\tau \rightarrow \nu_\tau\pi^-$, containing one charged pion,
 134 and can be studied in the near future. In this study, we fo-
 135 cus only on searching for the τ “3-prong” decay events.

136 The features of “3-prong” leptoquark events include:
 137 1) no scattered electron is detected; 2) a high transverse-
 138 momentum (P_T) τ -jet consists of three charged particles
 139 within a relatively small cone; 3) all three charged par-
 140 ticles originate from a common secondary vertex; 4) a
 141 high P_T hadronic jet is found back-to-back from the τ -jet;
 142 and 5) a P_T -imbalance caused by the escaped neutrinos
 143 which should be part of the candidate τ -jet. In order to
 144 simulate such candidate events and the capability to iden-
 145 tify them, the leptoquark quark generator LQGENEP [16]
 146 (version 1.0) is used to produce the signal Monte-Carlo
 147 (MC) events, while Djangoh and Pythia generators are
 148 used to produce the background DIS and photoproduc-
 149 tion MC events, respectively. Considering the large mass
 150 of leptoquarks, we focus on the highest energy, 18×275
 151 GeV ep collision. For the LQGENEP simulation, the Q^2
 152 range is set to $> 10 \text{ GeV}^2$ and a default value of leptoquark
 153 mass 1.9 TeV from the generator is used, see Appendix
 154 A.1 for input files. Scanning through a series of lepto-
 155 quark mass values, no visible difference in the characteris-
 156 tics of these signal events was observed at EIC kinematics.
 157 The input files for background event generation are given
 158 in Appendix A.2 for DIS NC and CC, and Appendix A.3

159 for photoproduction. After passing the generated events
 160 through the ECCE GEANT4 simulation, an analysis algo-
 161 rithm with preliminary selection requirements based on
 162 the features of the signal and background events are ap-
 163 plied on both leptoquark and SM MC event samples.

164 As mentioned earlier, a precise identification capability
 165 of the interaction vertex is essential for the secondary ver-
 166 tex reconstruction and τ identification. Figure 2 shows the
 167 vertex resolution for different track multiplicities, where
 168 we see that the ECCE configuration can provide a vertex
 169 resolution of 20 – 30 μm while the decay length of τ lepton
 170 is $\sim 87\mu\text{m}$. Therefore the ECCE vertex resolution is suffi-
 171 cient for identifying τ decays.

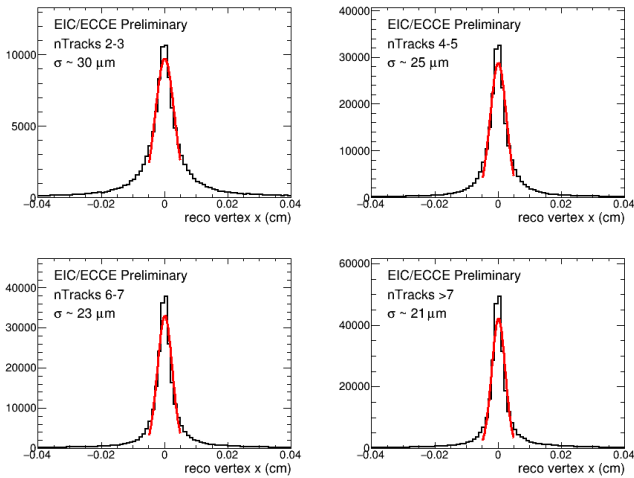


Figure 2: Primary vertex resolution: difference between truth and reconstructed information for different track multiplicity. Only the x -component is shown here, while y - and z -components show similar characteristics but are not shown.

171 To reconstruct the secondary vertex, we first look for 3-
 172 π candidate events. In the following, the charged pion's
 173 tracking information is from the simulated tracking and
 174 the vertex detector responses, though particle identifica-
 175 tion (PID) is based on generator information (namely,
 176 perfect PID is assumed). In our algorithm, one track is
 177 matched to a second track and the middle point at the closest
 178 approach is the candidate secondary vertex position
 179 which will be further justified based on the topological
 180 structure. For a given 3- π candidate event, there are three
 181 such pair-combinations and we can reconstruct three "inter-
 182 mediate" vertices and the candidate vertex will be the
 183 average of all three. Figure 3 shows the correlation of three
 184 intermediate vertices from the three pair combinations
 185 where the three decay lengths dl_{12} , dl_{13} , and dl_{23} , as ex-
 186 tracted by the distance from the primary to the secondary
 187 "intermediate" vertices, are shown as the x -axis, the posi-
 188 tive half of the y -axis, and the negative half of the y -axis,
 189 respectively. There are clearly two bands centralized at
 190 lines $y = \pm x$ and the 3- π vertex can be identified by requir-
 191 ing either or both correlations. In fact, when combined
 192 with vector alignment cuts, coincidence between two of
 193

194 the three "intermediate" vertices (either upper or lower
 195 half of Fig. 3) is usually enough to indicate a "3-prong"
 secondary vertex.

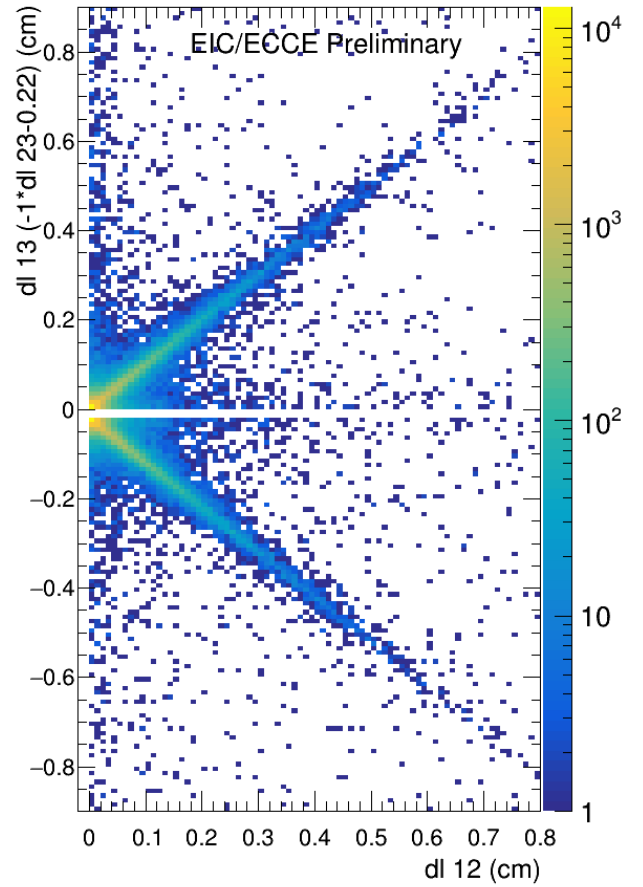


Figure 3: Coincidence among three "intermediate" vertices for 3- π event identification. The x -axis, the positive y and the negative y -axis (displaced and direction reversed for clarity), represent the "intermediate" vertices from the three pair-combinations 12, 13 and 23, respectively.

196

197 3. Event Selection

198 We used ten selection criteria to identify $e \rightarrow \tau$ events
 199 and to reject SM backgrounds. Their effects are shown in
 200 Fig. 4, where the vertical axis shows how many sample
 201 events pass each of the selection criteria, and the horizon-
 202 tal axis are the progressive selections defined as follows:

- 203 • input: initial input events. We used 10^6 (1M) MC
 204 events for each of leptoquark, DIS NC, DIS CC, and
 205 photoproduction processes;
- 206 • PrVtx: there must be a primary vertex reconstructed;
- 207 • Epzh: $\sum_h (E - p_z) > 18 \text{ GeV}$, where E and p_z are the en-
 208 ergy and the z -component (along the beams) of the
 209 3-momentum of the final state particles, respectively,
 210 and the summation is over all detected hadrons;
- 211 • misspt: $1 < \text{missing } p_T < 9 \text{ GeV}$, here the lower limit is
 212 to suppress events with small missing p_T , e.g. photo-
 213 production events, and the upper limit is to suppress

- 214 DIS events with large missing p_T caused by neutrinos
 215 (CC) or miss-detected electrons (NC);
- 216 • 3-pion: candidate 3 charged pions are found in a $\Delta R <$
 217 1.0 cone, where R is cone radius in the azimuth(ϕ)-
 218 pseudorapidity(η) space, $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$;
 - 219 • away1GeV: p_T sum of all tracks on the away-side of
 220 the candidate $3\text{-}\pi$, $\sum_{\Delta\phi(-\vec{p}_{3\pi}) < 1.0} p_T$, is > 1 GeV;
 - 221 • nearIso: p_T sum in a cone around the candidate $3\text{-}\pi$,
 222 $\sum_{\Delta R(\vec{p}_{3\pi}) < 1.0} p_T$, is < 3.0 GeV;
 - 223 • 3pi_pt: p_T sum of the 3 charged-pion candidate,
 224 $p_{T(3\pi)}$, is > 3.0 GeV;
 - 225 • 30 μm : candidate decay length reconstructed from
 226 any pair of the 3 charged pions is $> 30\mu\text{m}$;
 - 227 • dRsum: sum of the “distances” (in $\phi - \eta$ space) of
 228 the 3 charged pions decay vectors, $\Delta R_{1,2} + \Delta R_{1,3} +$
 229 $\Delta R_{2,3}$, is < 0.4 . Here the decay vector is defined as
 230 starting from the primary vertex and pointing to the
 231 secondary vertex;
 - 232 • decayL: average of the reconstructed decay lengths
 233 from three pair combinations of the $3\text{-}\pi$ candidate,
 234 $(dl_{12} + dl_{13} + dl_{23})/3$, is > 0.5 mm;
 - 235 • cMass: $\sqrt{M_{3\pi}^2 + p_{3\pi}^2 \sin^2\theta} + p_{3\pi} \sin^2\theta < 1.8$ GeV, where
 236 θ is the angle between the reconstructed decay direc-
 237 tion and the 3π momentum direction, and $M_{3\pi}$ is the
 238 mass reconstructed from the $3\text{-}\pi$ [17];
 - 239 • missing phi: missing p_T is azimuthally on the near
 240 side of the candidate $3\text{-}\pi$, that is, $\Delta\phi$ between $p_{3\pi}^{\rightarrow}$ and
 241 p_T^{miss} is < 1.0 .

242 From Fig. 4, it can be seen that the $e \rightarrow \tau$ events can be
 243 effectively selected with this set of preliminary cuts. In ad-
 244 dition, selections using the decay length are the most dis-
 245 criminating feature of the τ -jet. We illustrate this feature,
 246 characterized by the precision of ECCE’s vertex detector,
 247 in Fig. 5. The left panel shows a comparison between the
 248 true decay length from the generator and the decay length
 249 reconstructed from tracks at the detector level, while the
 250 right panel shows a 119 μm resolution of the decay length
 251 under ECCE configuration, capable for the τ vertex iden-
 252 tification.

253 4. Sensitivity to Leptoquarks

254 We can now deduce the sensitivity to the leptoquark
 255 signal cross section based on simulations of the 3-prong
 256 decay mode (15% branching ratio) of the τ lepton, dis-
 257 cussed in the last section, and considering different possi-
 258 ble values for the detection efficiency of the other τ de-
 259 cay modes. In Fig. 4, 1M MC event samples are gener-
 260 ated for each of the four processes: the leptoquark medi-
 261 ated signal process $e + p \rightarrow \tau + X$, and three back-
 262 ground processes, NC DIS, CC DIS, and photoproduc-
 263 tion. After all selection cuts are applied, including the re-
 264 quirement of detecting three pions corresponding to the
 265 3-prong tau decay mode, about 8K (7878) of the original

266 1M leptoquark signal events remain. For an integrated
 267 luminosity of 100 fb^{-1} , the 1M signal events generated
 268 corresponds to a signal cross section of 10^4 fb . Thus, if
 269 we assume that only the 3-prong mode has a non-zero
 270 detection efficiency, the minimum required cross section
 271 for detecting a single signal event in the 3-prong mode
 272 is $10^4 \text{ fb}/7878 = 1.3 \text{ fb}$. On the other hand, if we allow
 273 for the other tau decay modes and assume that they can
 274 be detected with the same efficiency as the 3-prong de-
 275 cay mode, then the number of candidate events that now
 276 survive selection cuts will be $7878/(15\%) = 52520$. Thus,
 277 in this case the minimum required cross section for de-
 278 tecting a single signal event will be $10^4 \text{ fb}/52520 = 0.19 \text{ fb}$.
 279 We also consider an intermediate scenario in which, in ad-
 280 dition to the 3-prong mode, we allow for the muon and
 281 single charge pion decay modes ($\sim 40\%$ branching ratio)
 282 and assume they can be detected at half the detection effi-
 283 ciency of the 3-prong decay. In this case the total number
 284 of candidate events that now survive all selection cuts will
 285 be $7878 + 7878/(15\%) \times (40\%) \times 1/2 = 18382$. In this case, the
 286 minimum required cross section to detect a single signal
 287 event is $10^4 \text{ fb}/18382 = 0.54 \text{ fb}$.

288 For searches of rare events like leptoquark mediated
 289 $e \rightarrow \tau$ transitions, the background simulation is more dif-
 290 ficult than the signal. Among the three types of back-
 291 ground events, the CC DIS background is easier to esti-
 292 mate because the total cross section is only $\approx 2.3 \times 10^4 \text{ fb}$,
 293 and the 1 M CC DIS MC events generated correspond to
 294 about 43% of the expected statistics for 100 fb^{-1} of inte-
 295 grated luminosity. There are 4 CC DIS events that pass
 296 the event selection, which can be scaled up to $4/43\% = 9$
 297 events for 100 fb^{-1} . With more careful optimization, this
 298 number can be suppressed even further. On the other
 299 hand, the NC DIS and photoproduction backgrounds are
 300 much harder to evaluate because their cross sections are
 301 much larger and of order 10^7 fb . Thus, the 1M generated
 302 MC events correspond to only $\sim 10^6/(10^7 \text{ fb} \times 100 \text{ fb}^{-1}) =$
 303 0.1% of the expected data sample for 100 fb^{-1} of integrated
 304 luminosity. With this limited MC event sample, zero NC
 305 and photoproduction event satisfies all selection criteria.
 306 Thus, at this stage, it is difficult to estimate how many
 307 background events will survive the selection if the MC
 308 sample is increased by factor 10^3 , which is needed to sim-
 309 ulate 100 fb^{-1} of NC DIS and photoproduction data.

310 At the moment, instead of providing a specific estimate
 311 of the background, we show in Fig. 6 the leptoquark cross-
 312 section ECCE could be sensitive to as a function of the
 313 number of background events that survive the event selec-
 314 tion for 100 fb^{-1} of integrated luminosity, based on a sim-
 315 ple calculation as follows: If the number of background
 316 events is B , the number of leptoquark signal events S
 317 should exceed the “ 3σ ” limit of the expected observed
 318 background events, $S + B > B + 3\sqrt{B}$, for the signal to
 319 be established. The corresponding cross section is scaled
 320 from the value where only one leptoquark signal event can
 321 be observed ($S = 1$).

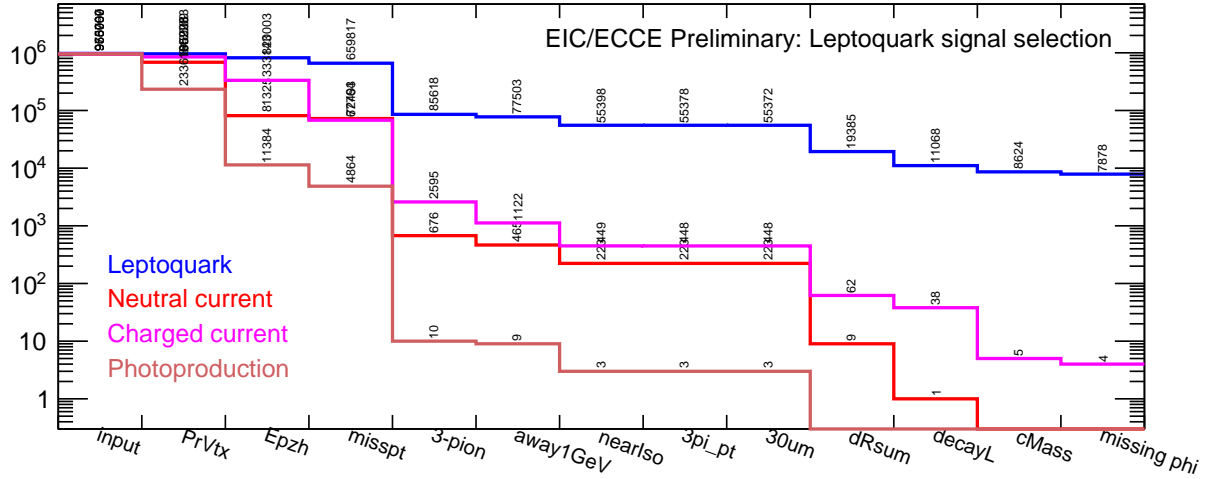


Figure 4: MC statistics of leptoquark (blue), DIS CC (red), DIS NC (magenta), and photoproduction (orange) events, as ten selection criteria are progressively applied on 1 M input events for each channel. Please see text for details.

322 As a best-case scenario estimate of the sensitivity to the
323 leptoquark signal cross section, we do not consider any
324 NC and photoproduction background event since none of
325 these events passed all the selection cuts on our limited
326 MC event sample. For a 5σ (99.99994% confidence level)
327 discovery criteria of $S/\sqrt{B} \geq 5$ (S being signal and B
328 being background) and use $B = 9$ events from CC back-
329 ground, we need $S = 15$ leptoquark events or a total of
330 $15 + 9 = 24$ events to claim $e \rightarrow \tau$ CLFV discovery. Al-
331 ternatively, detection of less than $9 + 9 = 18$ events will
332 provide a 3σ (99.7% C.L.) exclusion limit on the lepto-
333 quark cross section, which would be $1.3 \text{ fb} \times 3\sqrt{9} = 11.4 \text{ fb}$,
334 $0.54 \text{ fb} \times 3\sqrt{9} = 5.0 \text{ fb}$, and $0.19 \text{ fb} \times 3\sqrt{9} = 1.7 \text{ fb}$, for de-
335 tection possibility of “3-prong only”, “3-prong + 1-prong
336 with 50% efficiency”, and “all decay modes detected with
337 same efficiency as 3-prong”, respectively. The exclusion
338 potential, expressed in terms of $\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2$, are shown in
339 Figs. 7 and 8 for scalar and vector leptoquark states, re-
340 spectively. This is a preliminary estimate, and different
341 statistical methods and a larger MC event sample to bet-
342 ter estimate NC DIS and photoproduction backgrounds
343 could give rise to different estimates.

344 5. Summary

345 We carried out the first projection analysis for charged
346 lepton flavor violation in the $e \rightarrow \tau$ transition channel,
347 using EIC simulations with the ECCE detector configura-
348 tion. More work needs to be done in the future alongside
349 the development of ECCE into a project detector, such as
350 using detector-based particle identification, study more τ
351 decay modes, and carry out the background study with
352 higher statistics. Our current study, using the simulation
353 and detector resources at hand, shows that the EIC will
354 place a more stringent limit on $e \rightarrow \tau$ CLFV mediated by
355 leptoquarks than the previous HERA data. The very high

356 vertex resolution of the ECCE detector configuration plays
357 a critical role in our study.

358 6. Acknowledgements

359 We thank the EIC Silicon Consortium for cost esti-
360 mate methodologies concerning silicon tracking systems,
361 technical discussions, and comments. We acknowledge
362 the important prior work of projects eRD16, eRD18, and
363 eRD25 concerning research and development of MAPS
364 silicon tracking technologies.

365 We thank the EIC LGAD Consortium for technical
366 discussions and acknowledge the prior work of project
367 eRD112.

368 We thank Guillermo Gomez Ceballos Retuerto and Hu-
369 bert Spiesberger for their useful discussions and com-
370 ments.

371 We acknowledge support from the Office of Nuclear
372 Physics in the Office of Science in the Department of
373 Energy, the National Science Foundation, and the Los
374 Alamos National Laboratory Laboratory Directed Re-
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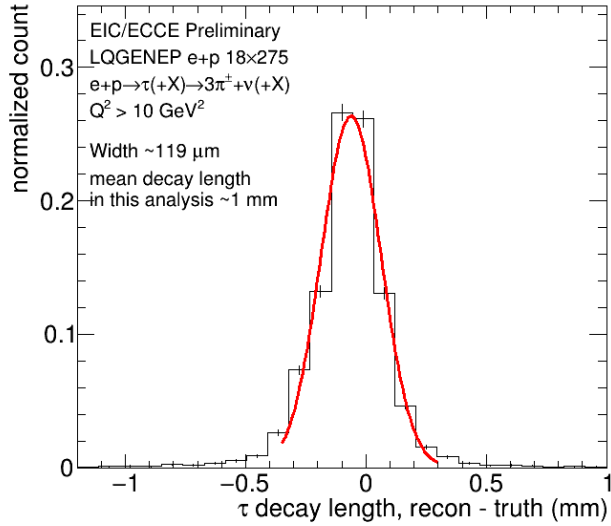
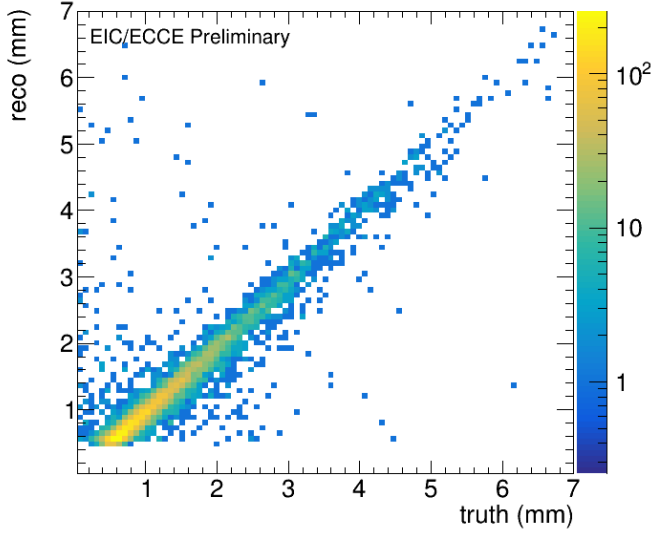


Figure 5: Top: Reconstructed decay length from Geant4 detector simulation vs. true decay length from generator level. Bottom: difference between reconstructed and true decay length with a Gaussian fit.

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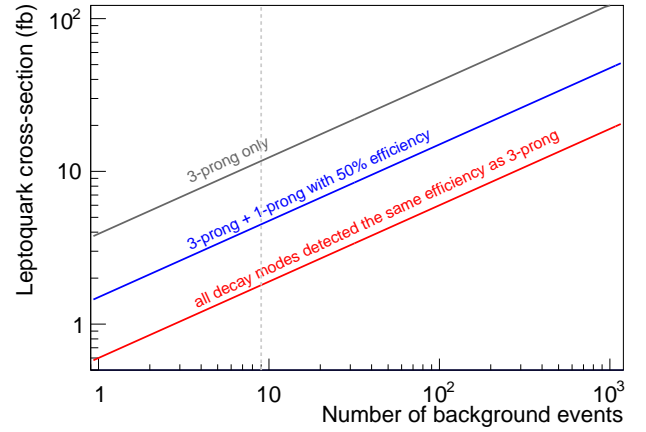


Figure 6: Cross section sensitivity for leptoquark search vs number of residual background events for 100 fb^{-1} integrated luminosity. The grey line corresponds to the scenario that only “3-prong” decay modes are detected. The blue line corresponds to the scenario where electron and pion “1-prong” decay modes could be detected with 50% efficiency of the “3-prong” case. And the red line shows the scenario if all decay modes were detected at the same efficiency as the “3-prong” case.

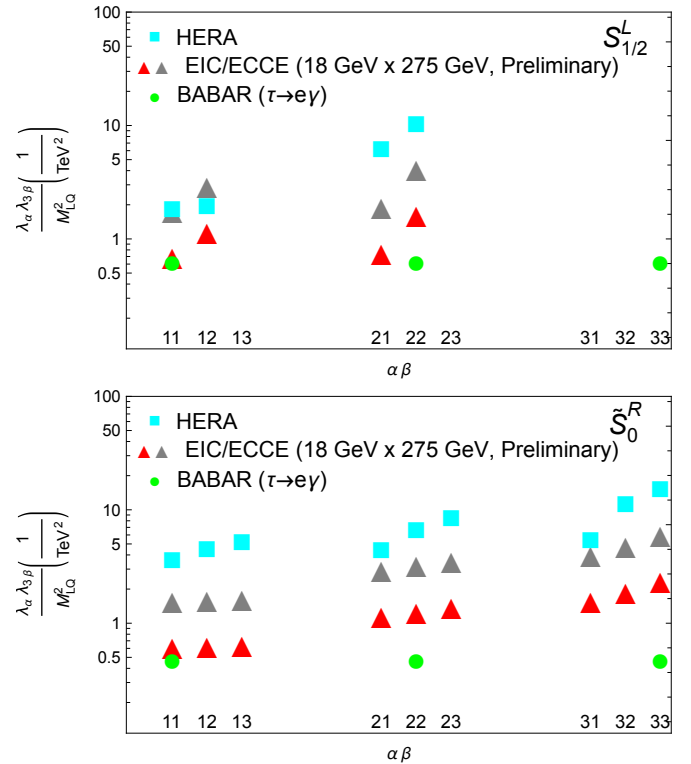


Figure 7: Limits on the scalar leptoquarks with $F = 0$ $S_{1/2}^L$ (top) and $|F| = 2$ S_0^R (bottom) from 100 fb^{-1} of ep 18×275 GeV data, based on a sensitivity to leptoquark-mediated $ep \rightarrow \tau X$ cross section of size 1.7 fb (red triangles) or 11.4 fb (grey triangles) with ECCE. Note that due to small value of \sqrt{s} , EIC cannot constrain the third generation couplings of $S_{1/2}^L$ to top quarks. Limits from HERA [11, 5, 12, 6] are shown as cyan solid squares, and limits from $\tau \rightarrow e\gamma$ decays [3] are shown as green solid circles.

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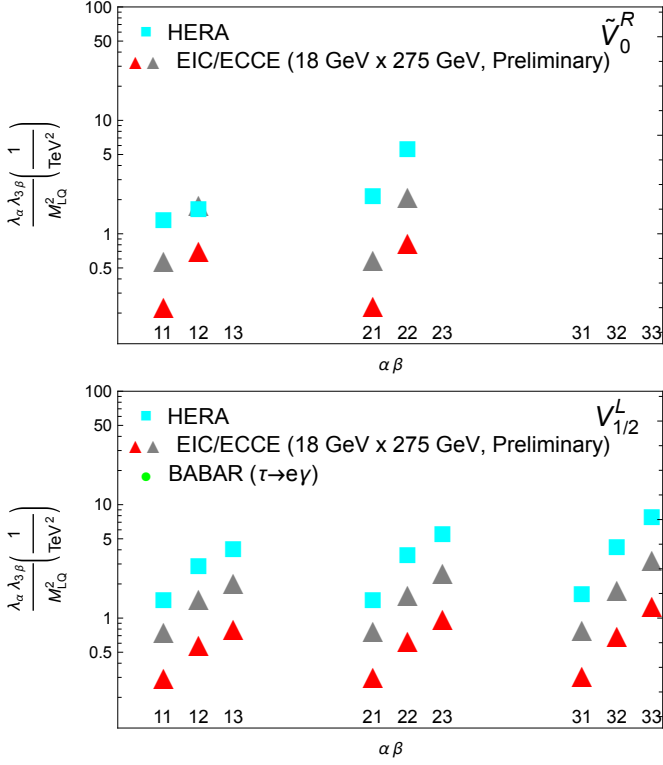


Figure 8: Limits on the vector leptoquarks with $F = 0 \tilde{V}_0^R$ (top) and $|F| = 2 V_{1/2}^L$ (bottom) from 100 fb^{-1} of ep $18 \times 275 \text{ GeV}$ data, based on a sensitivity to leptoquark-mediated $ep \rightarrow \tau X$ cross section of size 1.7 fb (red triangles) or 11.4 fb (grey triangles) from ECCE. Note that due to small value of \sqrt{s} , EIC cannot constraint the third generation couplings of \tilde{V}_0^R to top quarks. Limits from HERA [11, 5, 12, 6] are shown as cyan solid squares. Limits from $\tau \rightarrow e\gamma$ decays [3] exist but require some work to convert to the 4-fermion contact term. This will be done in the future.

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441 **Appendix A. Simulation Input Files and Other Details**

442 *Appendix A.1. LQGENEP Input Files for Leptoquark Signal Simulation*

The input file for Leptoquark event generation using LQGENEP 1.0, for $Q_{\min}^2 = 10 \text{ GeV}^2$, is shown in Fig. A.9.

```
N_evt, Mass, MinQ2, beampar(2), beampar(3), qi, qj, outfilename, seed
1000000, 1936.5, 10, 18, 275, 1, 1 LQGENEP_output_18x275_Qsq10_x0.001_1M_02.txt 3
```

Figure A.9: LQGENEP 1.0 input file for $ep 18 \times 275 \text{ GeV}$, $Q^2 > 10 \text{ GeV}^2$ setting.

443

444 *Appendix A.2. Djangoh Input Files for DIS NC and CC Background Event Simulation*

445 DIS background NC and CC events were generated with Djangoh.4.6.10, with the input files shown in Fig. A.10.

<pre>OUTFILENAM erhic-cc-yrad-floff_ep_18_275_q2_1 TITLE DJANGO 4.6.10 for eRHIC for proton, NLO at 18x275, Wmin=1.4 EL-BEAM 18.000 0.000 -1 IOUNITS 6 10 11 PR-BEAM 275.000 0.000 POLPDF 0 GSW-PARAM 2 1 3 1 1 1 2 1 1 1 1 KINEM-CUTS 3 0.000000100 1.0000 0.000000100 1.000 1.000 106 1.400 EGAM-MIN 000 INT-OPT-NC 0 0 0 0 0 0 0 0 0 INT-OPT-CC 1 20 0 20 INT-ONLY 0 INT-POINTS 30000 SAM-OPT-NC 0 0 0 0 0 0 0 0 0 SAM-OPT-CC 1 1 0 1 NUCLEUS 275.000 1 1 NUCL-MOD 1000 STRUCTFUNC 0 2 10150 LHAPATH /u/group/eic/users/yxzhao/EW/lhapdf5/install/share FLONG 0 0.01 0.03 ALFAS 1 1 0.20 0.235 NFLAVORS 0 5 RNDM-SEEDS -1 1 START 1000000 SOPHIA 0 OUT-LEP 1 FRAG 1 CASCADES 12 MAX-VIRT 5 CONTINUE</pre>	<pre>OUTFILENAM erhic-nc-yrad-floff_ep_18_275_q2_10 TITLE DJANGO 4.6.10 for eRHIC for proton, NLO at 18x275, Wmin=1.4 EL-BEAM 18.000 0.000 -1 IOUNITS 6 10 11 PR-BEAM 275.000 0.000 POLPDF 0 GSW-PARAM 2 1 3 1 1 1 2 1 1 1 1 KINEM-CUTS 3 0.000000100 1.0000 0.000000100 1.000 1.001 106 1.400 EGAM-MIN 000 INT-OPT-NC 1 18 18 18 18 0 0 0 0 INT-OPT-CC 0 0 0 0 INT-ONLY 0 INT-POINTS 30000 SAM-OPT-NC 1 1 1 1 1 0 0 0 0 SAM-OPT-CC 0 0 0 0 NUCLEUS 275.000 1 1 NUCL-MOD 1000 STRUCTFUNC 0 2 10150 LHAPATH /u/group/eic/users/yxzhao/EW/lhapdf5/install/share FLONG 0 0.01 0.03 ALFAS 1 1 0.20 0.235 NFLAVORS 0 5 RNDM-SEEDS -1 1 START 1000000 SOPHIA 3.4 OUT-LEP 1 FRAG 1 CASCADES 12 MAX-VIRT 5 CONTINUE</pre>
--	---

Figure A.10: Djangoh (4.6.10) input files for $ep 18 \times 275 \text{ GeV}$, DIS CC (left) and NC (right) background simulations for the leptoquark study. The Q_{\min}^2 is set at 1 GeV^2 and 10 GeV^2 for DIS CC and NC, respectively.

446 *Appendix A.3. Pythia Input File for Photoproduction Background Simulation*

447 The input file for photoproduction background generation using Pythia is shown in Fig. A.11.

```

pythia_ep_18x275_noradcor_Q2lt2.txt ! output file
name
11 ! lepton beam type
275, 18.0 ! proton and electron beam energy
2000000,100 ! Number of events
1e-09, 0.99 ! xmin and xmax
1e-09,1.00 ! ymin and ymax
1e-09,2 ! Q2min and Q2max
F2PY,1998 ! F2-Model, R-Parametrisation
0 ! switch for rad corrections; 0:no, 1:yes,
2:gen.lookup table
1 ! Pythia-Model = 0 standard GVM
generation in Pythia-x and Q2; = 1 GVM model with
generation in y and Q2 as for radgen
1,1 ! A-Tar and Z-Tar
1,1 ! nuclear pdf parameter1: nucleon mass number A,
charge number Z
201 ! nuclear pdf parameter2:
correction order x*100+y x= 1:L0, 2:NLO y:error set
! PMAS(4,1)=1.27 ! charm mass
MSEL=2
MSTP(14)=30
MSTP(15)=0
MSTP(16)=1
MSTP(17)=4 ! MSTP 17=6 is the R-rho measured as by
hermes, =4 Default
MSTP(18)=3
MSTP(19)=1 ! Hermes MSTP-19=1 different Q2
suppression, default = 4
MSTP(20)=0 ! Hermes MSTP(20)=0 , default MSTP(20)=3
MSTP(32)=8
MSTP(38)=4
MSTP(51)=7 ! if pdflib is linked than non pythia-
pdfs are available, like MSTP(51)=4046
MSTP(52)=1 ! ---> pdflib used MSTP 52=2
MSTP(53)=3
MSTP(54)=1
MSTP(55)=5
MSTP(56)=1
MSTP(57)=1
MSTP(58)=5
MSTP(59)=1
MSTP(60)=7
MSTP(61)=2
MSTP(71)=1
MSTP(81)=0
MSTP(82)=1
MSTP(91)=1
MSTP(92)=3 ! hermes MSTP(92)=4
MSTP(93)=1
MSTP(101)=3
MSTP(102)=1
MSTP(111)=1
MSTP(121)=0
! ----- Now all the PARPs -----
PARP(13)=1
PARP(18)=0.40 ! hermes PARP(18)=0.17
PARP(81)=1.9
PARP(89)=1800
PARP(90)=0.16
PARP(91)=0.40
PARP(93)=5.
PARP(99)=0.40
PARP(100)=5
PARP(102)=0.28
PARP(103)=1.0
PARP(104)=0.8
PARP(111)=2.
PARP(161)=3.00
PARP(162)=24.6
PARP(163)=18.8
PARP(164)=11.5
PARP(165)=0.47679
PARP(166)=0.67597 ! PARP165/166 are linked to MSTP17 as R_rho of
HERMES is used
! PARP(166)=0.5
! ----- Now come all the switches for Jetset -----
PARJ(1)=0.100
PARJ(2)=0.300
PARJ(11)=0.5
PARJ(12)=0.6
PARJ(21)= 0.40
PARJ(32)=1.0
PARJ(33)= 0.80
PARJ(41)= 0.30
PARJ(42)= 0.58
PARJ(45)= 0.5
! -----
MSTJ(1)=1
MSTJ(12)=1
MSTJ(45)=5
MSTU(16)=2
MSTU(112)=5
MSTU(113)=5
MSTU(114)=5
! ----- Now all the CKINs for pythia -----
CKIN(1)=1.
CKIN(2)=-1.
CKIN(3)=0.
CKIN(4)=-1.
CKIN(5)=1.00
CKIN(6)=1.00
CKIN(7)=-10.
CKIN(8)=10.
CKIN(9)=-40.
CKIN(10)=40.
CKIN(11)=-40.
CKIN(12)=40.
CKIN(13)=-40.
CKIN(14)=40.
CKIN(15)=-40.
CKIN(16)=40.
CKIN(17)=-1.
CKIN(18)=1.
CKIN(19)=-1.
CKIN(20)=1.
CKIN(21)=0.
CKIN(22)=1.
CKIN(23)=0.
CKIN(24)=1.
CKIN(25)=-1.
CKIN(26)=1.
CKIN(27)=-1.
CKIN(28)=1.
CKIN(31)=2.
CKIN(32)=-1.
CKIN(35)=0.
CKIN(36)=-1
CKIN(37)=0.
CKIN(38)=-1.
CKIN(39)=4.
CKIN(40)=-1.
CKIN(65)=1.e-09 ! Min for Q^2
CKIN(66)=-1. ! Max for Q^2
CKIN(67)=0.
CKIN(68)=-1.
CKIN(77)=2.0
CKIN(78)=-1.

```

Figure A.11: Pythia (6.428) input files for photoproduction for ep 18×275 GeV setting.