PROCEEDINGS OF SCIENCE

Beyond the Standard Model physics at the LHeC and the FCC-he

Christian Schwanenberger*
DESY, NotkestraSSe 85, D-22607 Hamburg, Germany
E-mail: christian.schwanenberger@cern.ch

Oliver Fischer
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
E-mail: oliver.fischer@mpi-hd.mpg.de

Electron-proton colliders are a suitable laboratory to study certain classes of physics and are in general complementary to the proton-proton and electron-positron colliders. In this overview we present an updated summary of selected topics relating to searches for beyond the Standard Model physics in electron-proton collisions. We will focus in particular on the Large Hadron electron Collider, and the possible electron-hadron mode of the Future Circular Collider.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

*Speaker.

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(EPS-HEP2019)563

1. Introduction

One of the most important tasks of high-energy particle physics these days are precision measurements of the Higgs boson properties, which was discovered and is being scrutinized at the Large Hadron Collider (LHC) with presently $\sim 5\%$ precision. The latter will remain limited by systematic uncertainties, relating among others to the PDF measurements [1].

A new generation of machines colliding electrons and protons could help with both, Higgs precision measurements [2, 3, 4] and improving the PDF sets, thereby enhancing the LHC precision: the Large Hadron electron Collider (LHeC) [5] which can run concurrently to the LHC at ∼1.2 TeV centre-of-mass energy with a total integrated luminosity of 1 ab^{-1}, and the electron-proton mode of the Future Circular Collider (FCC-he), with a foreseen center-of-mass energy above 3 TeV and total luminosities of up to 3.5 ab^{-1} [6, 7].

Below, we will discuss a selection of opportunities that the LHeC and FCC-he will bring for searches for Beyond the SM (BSM) physics. Its most prominent aspects for BSM scenarios with low production rates, e.g. from vector boson fusion, are its clean and (almost) pile up free detector environment and the low SM background production rates.

2. Selected topics

An important number of phenomenological BSM studies at electron-proton colliders have been carried out, a recent and reasonable complete list of these studies can be found in ref. [8]. The BSM scenarios under consideration include leptoquarks, e-q compositeness, anomalous gauge bosons and top couplings. Many of these results have been produced in the last years, and the rate is increasing, demonstrating the BSM community craving for new input. We do not attempt to summarize all the existing results in a brief overview talk but rather focus on a few selected examples. These will show the complementarity and advantages between the proton-proton and electron-proton colliders.

2.1 Leptoquarks

The persisting anomalies in lepton flavor universality observables at LHCb motivate theory explanations with 3$^{\text{rd}}$ generation scalar or vector particles, the so-called leptoquarks. Their phenomenology is similar in many ways to R-parity violating SUSY scenarios. Recent limits from ATLAS require for the leptoquarks to be heavier than 1.5 TeV for 1,2 generations [9], with the comparable CMS limits being 1 TeV [10].

In the collision of electrons and protons a leptoquark that couples to the first generation of SM fermions can be singly produced as s channel resonance. With low amounts of background the characteristic kinematics of the final state can be well tested and also allow the measurements of spin, quantum numbers, and the flavor structure of its couplings. A recent article discussing this class of physics is ref. [11].

2.2 Light and almost mass-degenerate Higgsinos

The long-standing dark matter problem can be solved by weakly interacting massive particles (WIMPs), for which viable candidates are the neutral components of the super partners of the Higgs

PoS(EPS-HEP2019)563

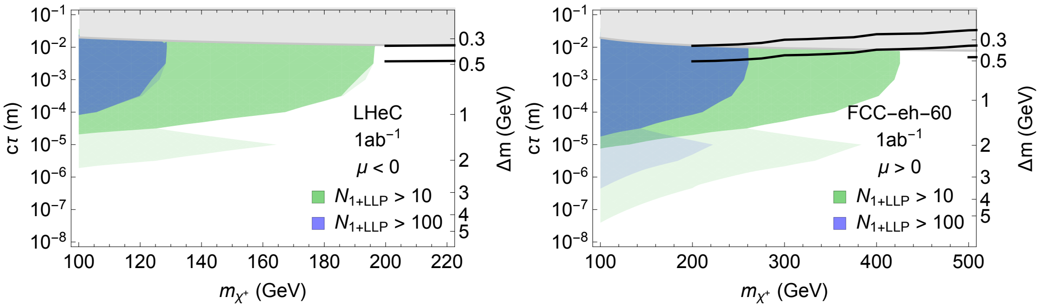

Figure 1: Regions in the mass-lifetime Higgsino parameter plane where more than 10 or 100 events with at least one displaced decay are observed at the LHeC (left) and FCC-he (right). Light shading indicates the uncertainty in the predicted number of events due to different modelling assumptions. The black curves are the optimistic and pessimistic projected bounds from HL-LHC disappearing track searches, see ref. [12] for details.

doublet, called Higgsinos. Among these supersymmetric particles, radiative corrections render the charged component heavier than the neutral one, which remains stable on cosmological time scales due to the absence of a decay channel as long as R parity is conserved.

At proton-proton colliders, the Higgsinos can be produced via vector boson fusion. The almost-prompt decays of the charged components can be measured in principle via a soft pion and lots of missing energy, however, in practice it is unfeasible to detect the pion in the QCD backgrounds. At an electron-proton collider the almost-prompt chargino decay can be searched for via disappearing track analyses. It is also possible to detect the soft pion in the final state, and with the clear background and excellent vertexing its displacement or impact parameter could be measurable for distances as small as $\sim 100\mu$m. Thus, what looks like hadronic noise at pp colliders is in principle detectable at ep colliders. The LHeC and the FCC-he can test these scenarios for Higgsino masses up to 180 GeV and 410 GeV, respectively.

2.3 The dark vector portal

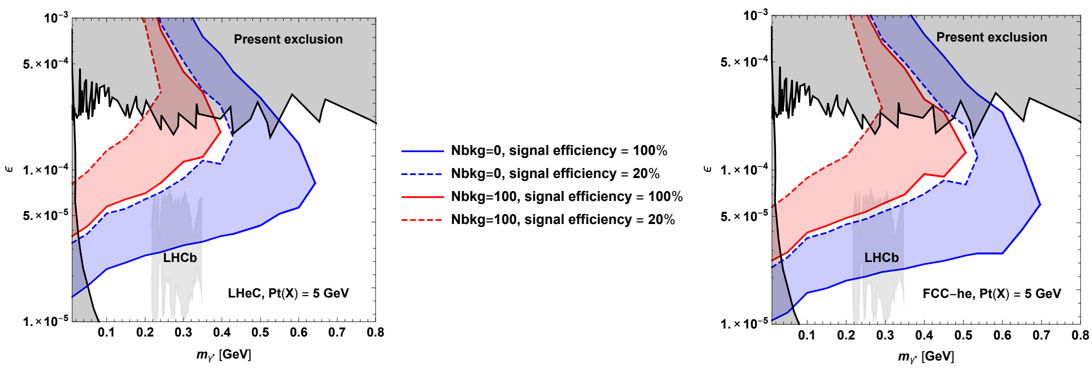

Figure 2: Sensitivity of dark photon searches in ep collisions via displaced dark photon decays. The contour lines (at the 90% confidence level) consider a p_t cut on the final state hadrons of 5 GeV. Different assumptions on efficiency (100% and 20% for the solid and dashed lines, respectively) and number of backgrounds (zero and 100 background events for the blue and red areas, respectively) shown. See ref. [13] for details.

PoS(EPS-HEP2019)563

Portal models to test generic dark sectors as benchmarks as discussed at the update of the European Strategy for Particle Physics. One benchmark model is the so-called vector portal, given by an additional $U(1)_X$ symmetry that mixes with the SM $U(1)$ gauge factor:

$$\mathscr{L}_{\text{vector}} = -\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} \tag{2.1}$$

This model contains a vector mediator also referred to as the dark photon, and arises naturally in models with light thermal Dark Matter. It brings a new mass scale in the MeV-GeV range and new physics which is feebly-coupled to SM.

Searches for displaced vertices of the long lived dark photon at the ep colliders were discussed in ref. [13]. It was found that for masses between ~ 10 MeV and below ~ 1 GeV the signature allows to test parts of the parameter space that are difficult to impossible to test in other experiments, like LHCb, beamdump, or low energy electron-positron colliders, cf. fig. 2.

2.4 The scalar portal

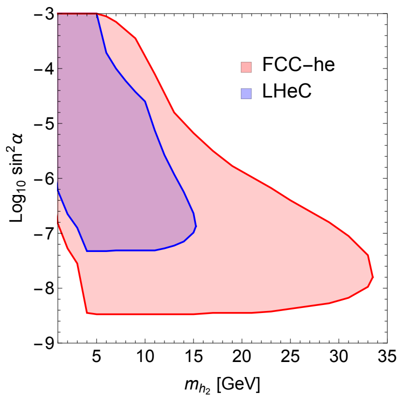

Figure 3: Sensitivity contour at the LHeC and FCC-he to the displaced decays of long-lived scalar particles h_2 that are pair produced from the decays of a SM-like Higgs boson h_1. The contours are for 3 events each, and consider displacements larger than 50μm to be free of background.

Another generic dark sector benchmark model is given by the so-called scalar portal. In this model class, an additional scalar particle S is postulated which can mix with the SM Higgs doublet and thus acquires suppressed interactions with the SM particles:

$$\mathscr{L}_{\text{scalar}} = (\mu S + \lambda S^2) H^\dagger H \tag{2.2}$$

In general, the mass eigenstate can have a range of masses and decay into pairs of SM particles that are kinematically available. If it is lighter than the Higgs boson, its suppressed decay rate gives rise to long life times of the scalar. The prospects of a Higgs boson decaying into two scalar particles which in turn decay promptly into 2 b-jets each was studied in [14]. It was found that the sensitivities at the LHeC are much better than the HL-LHC performance.

A recast[1] from exotic Higgs decays into long-lived light scalar particles was done, using ref. [12]. The analysis considers Higgs decays into a pair of long-lived scalar particles S with masses around 20 GeV. The scalars decay into the heaviest SM fermion: $S \to f\bar{f}$. Under the assumption that final state particles with transverse momenta above 400 MeV and a displacement $> 50\,\mu$m can be detected with 100% efficiency, it was shown that the LHeC and the FCC-he are sensitive

[1] O. Fischer, unpublished.

PoS(EPS-HEP2019)563

to this signature for masses up to 15 and 35 GeV, respectively, and mixings below 10^{-7} and 10^{-8}, respectively, cf. fig. 3.

The prospects to study heavy scalar particles that mix with the Higgs boson and decay into two vector bosons was studied in ref. [15]. Therein it was shown that for masses below about 500 GeV the sensitivity of the LHeC are better compared with the HL-LHC due to the smaller backgrounds, while for masses around and above one TeV the pp collider becomes more sensitive. This is particular interesting because of the "Madala hypothesis", which posits the existence of a heavy scalar with a mass around 300 GeV, cf. e.g. ref. [16].

2.5 The pseudo scalar portal

Pseudo-scalar portals feature pseudo scalars that have interactions with the field strength tensors of the SM gauge group:

$$\mathscr{L}_{\text{ps}} = \frac{a}{f_a} \tilde{F}_{\mu\nu} F^{\mu\nu} \tag{2.3}$$

A prominent example are axions, which couple to the gluon field strength and are a possible solution to the strong CP problem. Searches for axions and axion-like particles (ALPs) in the mass range from GeV to the TeV range are possible at colliders. Recently, the search for ALPs via the diphoton signature, which allows for the determination of the ALP mass, was discussed at the LHeC and FCC-he [17]. It was found that the ep colliders have some prospective advantages over the current LHC limits.

2.6 Sterile neutrinos

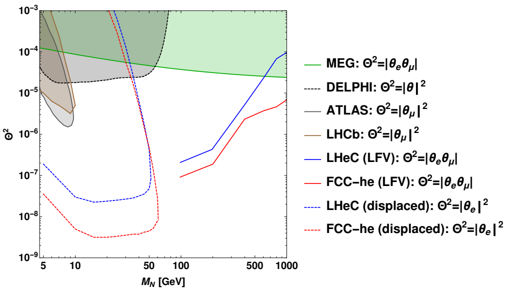

Figure 4: Sensitivity of the sterile neutrino searches (at 95% C.L.) and the displaced vertex searches (at 95% C.L.) compared to the current exclusion limits from ATLAS [18], LHCb [19], LEP [20], and MEG [21]. For details, see ref. [22].

Sterile neutrinos represent a well-motivated class of BSM physics, which aim at generating the light neutrino masses and can thus explain the observed neutrino oscillations. Recently, a comprehensive overview over the possible searches for sterile neutrinos at ee, ep, and pp colliders was given in ref. [23] and the complementarities were outlined.

For masses below m_W the heavy neutrino mass eigenstates are long lived and can be searched for via their displaced decays in the clean detector environment of the LHeC or the FCC-he. For masses at the weak scale up to $\sqrt{s}$ the prospects of discovering sterile neutrinos via lepton-flavor violating sigantures with jets are much better compared to the corresponding proton-proton collider, cf. 4. Another opportunity with ep colliders is the explicit reconstruction of sterile neutrino parameters by observing heavy neutrino-antineutrino observations [24].

PoS(EPS-HEP2019)563

2.7 Not discussed recent topics

Again, the above represents a small sample of the variety of studies on BSM at ep colliders. Further subjects that were recently studied entail, e.g.: Light Sleptons and EWkinos[2]; Lorentz invariance breaking [25]; Doubly-charged Higgs bosons [26]; The Light gluino gap [27]; Leptoquarks and heavy neutrinos [28]; Prompt EWkinos [29]; Effective Majorana Neutrinos [30]; Charged scalar bosons [31]; Georgi-Machacheck model [31]; Extended Higgs sectors [32]; Light charged Higgs bosons [33].

3. Conclusions

The above scenarios make it plain that electron proton colliders are essential to fully exploit the potential of proton-proton colliders, via improving PDF sets or via their complementarity. They offer a variety of opportunities for BSM searches, in particular for particles with long life times and for signals that are buried in hadronic backgrounds, and in general for new physics that resides on a mass scale around the ditop threshold.

The key features of the ep collider which bring about these advantages are the excellent tracking of the detectors, which is made possible by the clean environment and the negligibly small amount of pile up. Moreover, the luminosity is considerable and comparable to the HL-LHC, which enables to study all physics that can be produced via vector boson fusion, such as the Higgs.

To conclude: ep colliders are complementary to pp and bring many new opportunities.

References

[1] M. Klein, Annalen Phys. **528** (2016) 138.

[2] M. Kumar, X. Ruan, R. Islam, A. S. Cornell, M. Klein, U. Klein and B. Mellado, Phys. Lett. B **764** (2017) 247 [arXiv:1509.04016 [hep-ph]].

[3] Y. L. Tang, C. Zhang and S. h. Zhu, Phys. Rev. D **94** (2016) no.1, 011702 [arXiv:1508.01095 [hep-ph]].

[4] D. Angal-Kalinin *et al.*, J. Phys. G **45** (2018) no.6, 065003 [arXiv:1705.08783 [physics.acc-ph]].

[5] O. Bruening and M. Klein, Mod. Phys. Lett. A **28** (2013) no.16, 1330011 [arXiv:1305.2090 [physics.acc-ph]].

[6] A. Abada *et al.* [FCC Collaboration], Eur. Phys. J. C **79** (2019) no.6, 474.

[7] A. Abada *et al.* [FCC Collaboration], Eur. Phys. J. ST **228** (2019) no.4, 755.

[8] G. Azuelos, M. D'Onofrio, O. Fischer and J. Zurita, PoS DIS **2018** (2018) 190 [arXiv:1807.01618 [hep-ph]].

[9] M. Aaboud *et al.* [ATLAS Collaboration], Eur. Phys. J. C **79** (2019) no.9, 733 [arXiv:1902.00377 [hep-ex]].

[10] Y. Takahashi [CMS Collaboration], arXiv:1901.03570 [hep-ex].

[11] J. Zhang, C. X. Yue and Z. C. Liu, Mod. Phys. Lett. A **33** (2018) no.06, 1850039.

[2] Azuelos, to be published

PoS(EPS-HEP2019)563

[12] D. Curtin, K. Deshpande, O. Fischer and J. Zurita, JHEP **1807** (2018) 024 [arXiv:1712.07135 [hep-ph]].

[13] M. D'Onofrio, O. Fischer and Z. S. Wang, arXiv:1909.02312 [hep-ph].

[14] S. Liu, Y. L. Tang, C. Zhang and S. h. Zhu, Eur. Phys. J. C **77** (2017) no.7, 457 [arXiv:1608.08458 [hep-ph]].

[15] L. Delle Rose, O. Fischer and A. Hammad, Int. J. Mod. Phys. A **34** (2019) no.23, 1950127 [arXiv:1809.04321 [hep-ph]].

[16] C. Mosomane, M. Kumar, A. S. Cornell and B. Mellado, J. Phys. Conf. Ser. **889** (2017) no.1, 012004 [arXiv:1707.05997 [hep-ph]].

[17] C. X. Yue, M. Z. Liu and Y. C. Guo, Phys. Rev. D **100** (2019) no.1, 015020 [arXiv:1904.10657 [hep-ph]].

[18] G. Aad *et al.* [ATLAS Collaboration], arXiv:1905.09787 [hep-ex].

[19] S. Antusch, E. Cazzato and O. Fischer, Phys. Lett. B **774** (2017) 114 [arXiv:1706.05990 [hep-ph]].

[20] P. Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **74** (1997) 57 Erratum: [Z. Phys. C **75** (1997) 580].

[21] J. Adam *et al.* [MEG Collaboration], Phys. Rev. Lett. **110** (2013) 201801 [arXiv:1303.0754 [hep-ex]].

[22] S. Antusch, O. Fischer and A. Hammad, arXiv:1908.02852 [hep-ph].

[23] S. Antusch, E. Cazzato and O. Fischer, Int. J. Mod. Phys. A **32** (2017) no.14, 1750078 [arXiv:1612.02728 [hep-ph]].

[24] S. Antusch, E. Cazzato and O. Fischer, Mod. Phys. Lett. A **34** (2019) no.07n08, 1950061 [arXiv:1709.03797 [hep-ph]].

[25] A. Michel and M. Sher, arXiv:1909.10627 [hep-ph].

[26] P. S. B. Dev, S. Khan, M. Mitra and S. K. Rai, Phys. Rev. D **99** (2019) no.11, 115015 [arXiv:1903.01431 [hep-ph]].

[27] D. Curtin, K. Deshpande, O. Fischer and J. Zurita, Phys. Rev. D **99** (2019) no.5, 055011 [arXiv:1812.01568 [hep-ph]].

[28] S. Mandal, M. Mitra and N. Sinha, Phys. Rev. D **98** (2018) no.9, 095004 [arXiv:1807.06455 [hep-ph]].

[29] C. Han, R. Li, R. Q. Pan and K. Wang, Phys. Rev. D **98** (2018) no.11, 115003 [arXiv:1802.03679 [hep-ph]].

[30] L. Duarte, G. Zapata and O. A. Sampayo, Eur. Phys. J. C **79** (2019) no.3, 240 [arXiv:1812.01154 [hep-ph]].

[31] G. Azuelos, H. Sun and K. Wang, Phys. Rev. D **97** (2018) no.11, 116005 [arXiv:1712.07505 [hep-ph]].

[32] H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D **96** (2017) no.9, 095003 [arXiv:1710.06284 [hep-ph]].

[33] J. Hernández-Sánchez, O. Flores-Sánchez, C. G. Honorato, S. Moretti and S. Rosado, PoS CHARGED **2016** (2017) 032 [arXiv:1612.06316 [hep-ph]].

PoS(EPS-HEP2019)563