Top-Quark and Electroweak Physics at LHeC and FCC-eh

Future energy frontier electron-proton colliders

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ABSTRACT

The proposed high-luminosity TeV-scale electron-proton colliders LHeC and FCC-eh at CERN provide unique opportunities for precision Standard Model measurements. In this letter the prospects for precision measurements of the properties of the top-quark and its impact for searches, of parameters of electroweak theory, as well as the direct production of weak bosons in electron-proton collisions are discussed. A much more complete discussion is found in the recent conceptual design reports of the LHeC [1, 2] and the FCC-eh [3].

I. TOP QUARK PHYSICS

SM top quark production at a future ep collider is dominated by single top quark production, mainly via CC DIS production with $\sigma_{\rm tot} = 1.89\,{\rm pb}$ (15.3 pb) at the LHeC [2] (FCC-eh) [3]), and by $t\bar{t}$ photoproduction with $\sigma_{\rm tot} = 0.05\,{\rm pb}$ (1.14 pb) at the LHeC [2] (FCC-eh [3]). This makes a future LHeC or FCC-eh a top quark factory and an ideal tool to study top quarks with high precision.

Wtq Couplings and Top Quark Polarisation. The top quark couplings with gauge bosons can be modified significantly in models with new top (or third generation) partners, such as in some extensions of the minimal supersymmetric standard model, in little Higgs models, top-color models, top seesaw, top compositeness, and others. Testing them is therefore of utmost importance to find out whether there are other sources of electroweak symmetry breaking that are different from the standard Higgs mechanism. One flagship measurement is the direct measurement of the CKM matrix element $|V_{tb}|$, without making any model assumptions such as unitarity of the CKM matrix or the number of quark generations. At the LHeC already at $100\,{\rm fb}^{-1}$ of integrated luminosity an uncertainty of 1% can be expected. This compares to a total uncertainty of 4.1 % at the LHC Run-I [4]. Anomalous left- and right-handed Wtb vector and tensor couplings [2, 3] can be measured with 1–14 % accuracies. Similarly, the CKM matrix elements $|V_{tx}|$ $(x = d, s)$ can be extracted at 6 % (LHeC) to 3.7,% (FCC-eh) 2σ levels [2, 3]. Single top quarks produced in $e^+p \to t\bar{\nu}$ also possess a high degree of spin polarisation allowing a detailed percent level study of top quark spin and polarisation [2].

Top-γ and Top-Higgs Couplings. The LHeC is particularly well suited to directly measure the $t\bar{t}\gamma$ vertex, since in $t\bar{t}$ photoproducton the highly energetic incoming photon only couples to the top quark. This provides a direct measurement of the $t\bar{t}\gamma$ coupling, and therefore of another important top quark property, the top quark charge. In contrast, at the LHC the $t\bar{t}\gamma$ vertex is probed in $t\bar{t}\gamma$ production, where the final state photon can also be produced from other vertices. Measuring the $t\bar{t}\gamma$ magnetic and electric dipole moments will greatly improve indirect constraints from $b \to s\gamma$, and even from the future LHC at $\sqrt{s} = 14\,{\rm TeV}$ [2]. The CP-nature of the top-Higgs coupling can be analysed at the LHeC in $ep \to \bar{t}H$ production. Measuring just the fiducial inclusive production cross section gives a powerful probe of the CP properties of the $t\bar{t}H$ coupling [2].

FCNC Top Quark Couplings. Single top quark NC DIS production can be used to search for Flavour Changing Neutral Current (FCNC) $tu\gamma$, $tc\gamma$, tuZ, tcZ, and couplings [2, 3] Already at the LHeC the level of precision is close to actual predictions of concrete new physics models, such as SUSY, little Higgs, and technicolour, that have the potential to produce FCNC top quark couplings. The expected limits will improve on existing limits from the LHC by one order of magnitude [2], will be similar to limits expected from the High Luminosity-LHC (HL-LHC) with $3000\,{\rm fb}^{-1}$ at $\sqrt{s} = 14\,{\rm TeV}$, and will improve limits from the International Linear Collider (ILC) with $500\,{\rm fb}^{-1}$ at $\sqrt{s} = 250\,{\rm GeV}$ by an order of magnitude [2]. At the FCC-ep, the sensitivity to FCNC $tq\gamma$ couplings even exceed expected sensitivities from the HL-LHC [3]. FCNC tqH couplings [2, 3] can be studied in CC DIS production. At the FCC-eh, expected limits improve on what can be achieved at the HL-LHC [5] by almost one order of magnitude. The expected measurements of FCNC couplings show the competitiveness of the LHeC and FCC-eh results, and document the complementarity of the results gained at different colliders [2, 3].

II. ELECTROWEAK PHYSICS AT THE LHEC

The LHeC is a unique facility where electroweak interactions can be studied with a very high precision in a largely unexplored kinematic regime of spacelike momentum transfer Q^2 which exceeds the weak scale $M^2_{W,Z}$ by two orders of magnitude leading to very large weak effects and cross-section asymmetries. This can be exploited for ultra-precise electroweak measurements. A first thorough study has been made of inclusive neutral- and charged-current deep-inelastic lepton proton scattering cross section data including their systematic uncertainties [6] basics of which have been presented in the updated LHeC CDR [2] Based on simultaneous fits of electroweak physics parameters and parton distribution functions, the uncertainties of Standard Model parameters as well as a number of parameters describing physics beyond the Standard Model were estimated, such as the oblique parameters S, T, and U. An unprecedented precision at the sub-percent level is expected for the measurement of the weak neutral-current couplings of the light-quarks to the Z boson, improving their present precision by more than an order of magnitude. The weak mixing angle can be determined with a precision of about ± 0.00015, and its scale dependence can be studied in the range between about 25 and 700 GeV. An indirect determination of the W-boson mass in the on-shell scheme is possible with an experimental uncertainty down to 6 MeV. Comparable studies of electroweak physics at the FCC-eh have not been pursued yet. Interesting comparisons may be made with lower energy measuremenst at the EIC.

III. CONCLUSION

The proposed high-luminosity TeV-scale electron-proton colliders LHeC and FCC-eh at CERN provide unique opportunities for precision measurements of the properties of the top-quark and of effects of electroweak interactions. As the processes of NC and CC DIS are mediated through spacelike momentum transfer the measurements in DIS are often complementary to measurements in the timelike domain in e^+e^- or pp collisions and represent a unique area of particle physics.

REFERENCES

Additional details and a complete set of references can be found in the LHeC Conceptual Design Reports (CDR):

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