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# Top and Electroweak Physics at the LHeC and the FCC-eh

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Highlights of the rich electroweak and top quark physics program at future LHeC and FCC-eh colliders are presented. The studies involve high precision analyses of the weak mixing angle, vector and axial-vector weak neutral couplings of light quarks, the polarization asymmetry in neutral current scattering, the CKM matrix element $|V_{tb}|$ and anomalous $Wtb$ couplings, flavor-changing neutral current $tu\gamma$ couplings, and flavor-changing neutral current $t \to uH$ branching ratios.

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## 1. Introduction

The ring linac colliders *LHeC* [1] and *FCC-eh* are future projects where an electron accelerated at an energy recovering linac is collided with a hadron from the LHC. They will be operated synchronously and simultaneously in parallel to the LHC operation. The scenarios studied here involve an electron beam energy of 60 GeV and an LHC proton beam of 7 TeV (LHeC) leading to a center-of-mass energy of 1.3 TeV, and an FCC-hh proton beam of 50 TeV (FCC-eh) leading to a center-of-mass energy of 3.5 TeV, respectively. An integrated luminosity of 1 ab$^{-1}$ is assumed. A detailed layout for the LHeC and FCC-eh detectors is available in the DELPHES simulation package. If realized, each project would allow to explore a new high energy frontier for eh physics. Precision electroweak (EW) measurements will be possible. Furthermore, such colliders would be top quark factories allowing to analyze the EW couplings of the top quark particularly well, and would allow to perform sensitive searches for new physics. A few highlights of such studies are presented in the following.

## 2. Electroweak Physics

Because of the very high luminosity, high measurement precision, and the extreme range of momentum transfer $Q^2$, the LHeC and FCC-eh are unique facilities to test the EW theory, if both neutral current (NC) and charged current (CC) deep inelastic scattering (DIS) is analyzed, ideally involving both electron and positron beams with different polarization states scattered on protons and isoscalar targets.

As an example, in NC scattering using the polarization asymmetry $A^-$ with

$$A^{\pm} = \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})} \tag{2.1}$$

the weak mixing angle can be measured dependent on $\mu = \sqrt{Q^2}$. This is shown in Fig. 1 (upper left), where the expected LHeC [1] and FCC-ep [2] measurements are compared to those from different collider and non-collider experiments. The LHeC and FCC-ep results can probe a large range of scale dependence between $\mu = [10, 1000]$ GeV extending current results.

Using NC and CC cross section data, simultaneously with the PDFs, the vector and axial-vector weak neutral couplings of light quarks can be extracted [2]. In Fig. 1 (upper right), for the case of up quarks (similar results are derived for down quarks, too) the LHeC and FCC-ep expected results are compared to LEP&SLD, Tevatron and HERA results. The very high precision of these measurements will not only represent a high precision test of the EW sector of the Standard Model (SM), but will also allow to find sources of possible new physics, such as from $Z'$ bosons, R-parity violating Supersymmetry (SUSY), or leptoquarks.

The polarization asymmetry $A'^{\pm} = 2/(P_L^{\pm} - P_R^{\pm}) \cdot A^{\pm}$ is used to study P-violation in NC-EW interactions [2]. The result for the FCC-ep is presented as a function of $Q^2$ in Fig. 1 (middle left). Due to an 11 times higher center-of-mass energy, around 100-1000 times higher luminosity, and 2-3 times higher expected polarization, previous HERA results [3] can be extended by 2-3 orders of magnitude in $Q^2$. From the figure can be gained that at $Q^2 \approx 10^5$ GeV$^2$ the pure Z exchange becomes important and can therefore be tested.



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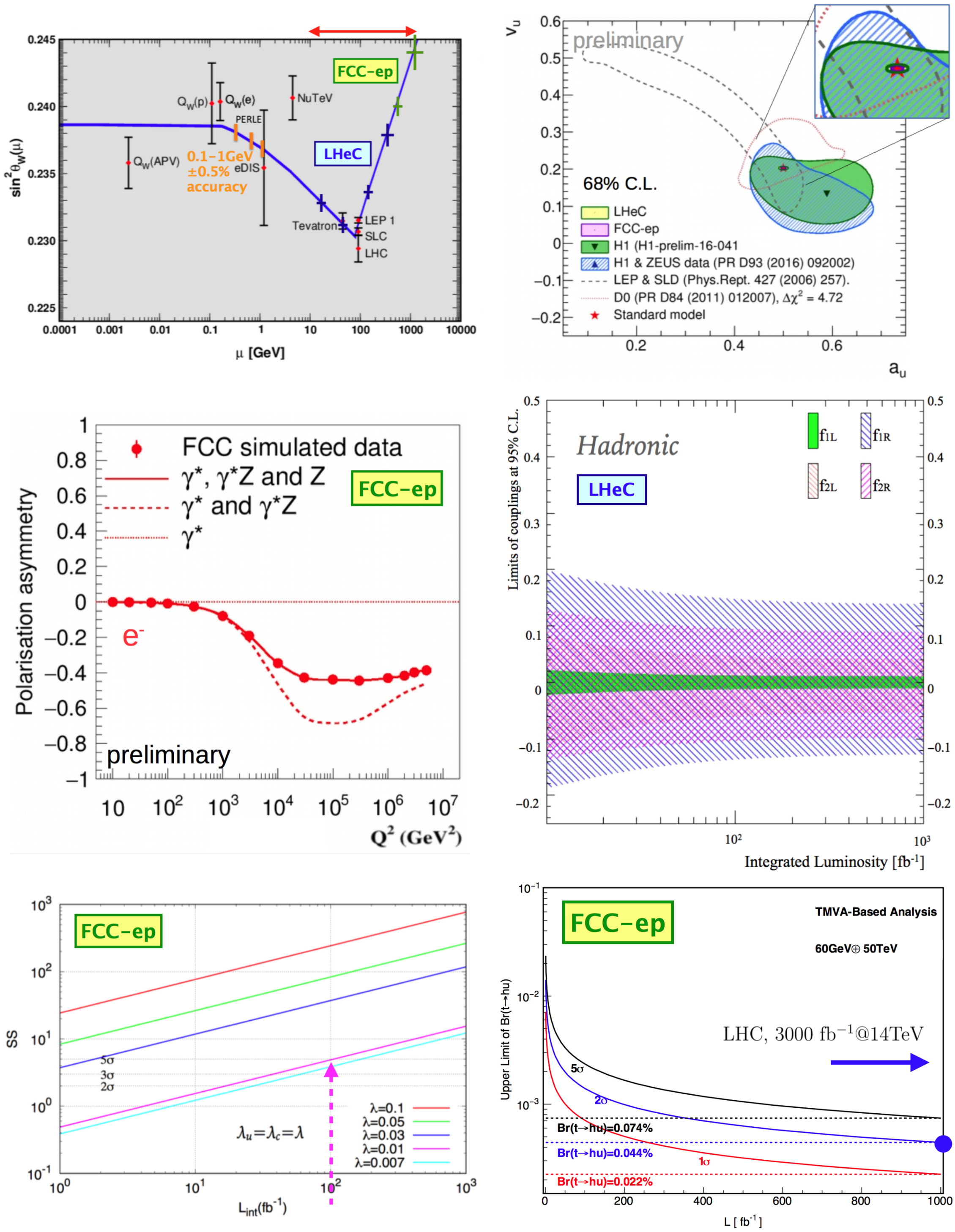


**Figure 1:** Dependence of the weak mixing angle in the MSbar definition on the energy scale $\mu$, taken from [4], compared to expectations from PERLE [5], LHeC [1], and FCC-ep [2] (upper left). Determination of the vector and axial-vector weak neutral couplings of up quarks at the LHeC and FCC-ep, simultaneously with the PDFs from a joint NLO QCD and electroweak $\chi^2$ analysis of simulated NC and CC cross section data [2] (upper right). The polarization asymmetry in NC-EW interactions as a function of $Q^2$ for the FCC-ep [2] (middle left). Expected sensitivities as a function of the integrated luminosity on the SM and anomalous $Wtb$ couplings [6] (middle right), on FCNC $tu\gamma$ couplings [7] (lower left), and on FCNC $t \to uH$ branching ratios [8] (lower right).

## 3. Top Quark Physics

SM top quark production at a future ep collider is dominated by single top quark production, mainly via CC DIS production. The total cross section is 1.73 pb at the LHeC [6] and 15.3 pb at the FCC-ep. The other important top quark production mode is $t\bar{t}$ photoproduction with a total cross section of 23 fb at the LHeC [9] and 663 fb at the FCC-ep. This makes a future ep collider an ideal tool to study in particular the EW interactions of the top quark.

One flagship measurement is the direct measurement of the CKM matrix element $|V_{tb}|$, i.e. without making any model assumptions such as on the unitarity of the CKM matrix or the number of quark generations. A realistic analysis of the single top quark CC DIS process at the LHeC including a detailed detector simulation using the DELPHES package [10] shows that already at 100 fb$^{-1}$ of integrated luminosity an uncertainty of 1% can be expected. This compares to a total uncertainty of 4.1% of the most accurate result at the LHC performed by the CMS experiment [11].

The same analysis can also be used to search for anomalous left- and right-handed $Wtb$ vector and tensor couplings analyzing the following effective Lagrangian:

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L - f_V^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(f_T^L P_L - f_T^R P_R)tW_{\mu}^{-} + h.c. \tag{3.1}$$

In the SM $f_V^L = 1$ and $f_V^R = f_T^L = f_T^R = 0$. Using hadronic top quark decays only, the expected accuracies in a measurement of these couplings as a function of the integrated luminosity at the LHeC are presented in Fig. 1 (middle right). The couplings can be measured with accuracies between 1-14% at 1 ab$^{-1}$.

Single top quark CC DIS production can also be used to search for Flavor Changing Neutral Current (FCNC) $tu\gamma$ couplings as given in

$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda}\bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c. \tag{3.2}$$

In a realistic analysis of final states including one electron and three jets (hadronic top quark decay), the distributions of the invariant mass of two jets (reconstructed $W$ boson mass) and an additional jet tagged as $b$-jet (reconstructed top quark mass) are used to further enhance signal over background events, mainly given by $W+$jets production. A detector simulation with DELPHES [10] is applied. The expected statistical significance as a function of the integrated luminosity is presented in Fig. 1 (lower left) for different values of the coupling strength $\lambda$ [7]. Assuming a coupling strength of $\lambda = 0.01$ an observation with $5\,\sigma$ standard deviations is expected already at an integrated luminosity of 100 fb$^{-1}$. For comparison, at the High Luminosity-LHC (HL-LHC) with 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV coupling strengths of $\lambda < 0.022$ can be excluded at the 95% C.L. [12]. At the International Linear Collider (ILC) with 500 fb$^{-1}$ at $\sqrt{s} = 250$ GeV coupling strengths of $\lambda < 0.02$ can be excluded at the 95% C.L. [13].

Another example for a sensitive search for anomalous top quark couplings is the one for FCNC $tHq$ couplings as defined in

$$L = \kappa_{tuH}\bar{t}uH + \kappa_{tcH}\bar{t}cH + h.c. \tag{3.3}$$

In CC DIS production, singly produced top anti-quarks could decay via such couplings into a Higgs boson and a light anti-quark. The analysis presented here studies $H \to b\bar{b}$ decays [8]. Largest backgrounds are given by $Z \to b\bar{b}$, SM $H \to b\bar{b}$ and single top quark production with hadronic top quark decays. The analysis assumes parameterized resolutions for electrons, photons, muons, jets and unclustered energy using typical parameters taken from the ATLAS experiment. Furthermore, a b-tag rate of 60%, a c-jet fake rate of 10%, and a light-jet fake rate of 1% is assumed. Then, the selection is optimized for LHeC and FCC-ep scenarios separately. Both cut-based and MVA-based analyses are explored. Figure 1 shows the expected upper limit on the branching ratio $\mathrm{Br}(t \to Hu)$ with $1\sigma$, $2\sigma$, and $5\sigma$, respectively, as a function of the integrated luminosity for the FCC-ep scenario. For a branching ratio of $\mathrm{Br}(t \to Hu) = 0.074\%$ an observation with a $5\sigma$ significance can be achieved with $1\,\mathrm{ab}^{-1}$ of integrated luminosity. These limits improve the sensitivity that can be achieved at the HL-LHC with $3000\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 14\,\mathrm{TeV}$, where in the absence of new physics $\mathrm{Br}(t \to Hu) < 0.23\%$ is expected at with a $3\sigma$ significance [14].

## 4. Summary

Future ep colliders such as the LHeC and the FCC-eh have a rich analysis program for EW and top quark physics. Many high precision EW measurements such as $\sin^2\theta_W$, light quark couplings to bosons, and polarization asymmetries, can be performed. The LHeC and FCC-eh colliders are also single top quark factories allowing, for example, high precision measurements of $|V_{tb}|$ at the 1% level and stringent searches for anomalous $Wtb$ couplings. Other top quark properties and couplings can also be studied with a high precision, such as FCNC $tu\gamma$ and $tuH$ couplings. Further exciting prospects for the LHeC and FCC-eh have been or are currently worked out.

## References


[1] J. L. Abelleira Fernandez *et al.* [LHeC Study Group], J. Phys. G **39**, 075001 (2012).

[2] D. Britzger and M. Klein, PoS DIS **2017**, 105 (2018).

[3] The H1 and ZEUS Collaborations, "Electroweak Neutral Currents at HERA", H1prelim-06-142, ZEUS-prel-06-022.

[4] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010) and 2011 partial update for the 2012 edition.

[5] D. Angal-Kalinin *et al.*, arXiv:1705.08783 [physics.acc-ph].

[6] S. Dutta, A. Goyal, M. Kumar and B. Mellado, Eur. Phys. J. C **75**, no. 12, 577 (2015).

[7] I. Turk Cakir, A. Yilmaz, H. Denizli, A. Senol, H. Karadeniz and O. Cakir, Adv. High Energy Phys. **2017**, 1572053 (2017).

[8] H. Sun and X. Wang, arXiv:1602.04670 [hep-ph].

[9] A. O. Bouzas and F. Larios, Phys. Rev. D **88**, no. 9, 094007 (2013).

[10] S. Ovyn, X. Rouby and V. Lemaitre, arXiv:0903.2225 [hep-ph].

[11] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1406**, 090 (2014).

[12] ATLAS Collaboration, arXiv:1307.7292 [hep-ex].

[13] J. A. Aguilar-Saavedra and T. Riemann, hep-ph/0102197; extrapolation to ILC: K. Agashe *et al.* [Top Quark Working Group], arXiv:1311.2028 [hep-ph].

[14] L. Wu, JHEP **1502**, 061 (2015).




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