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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 CKM matrix elements $|V_{td}|$, $|V_{ts}|$, $|V_{tb}|$, and anomalous Wtb couplings, flavor-changing neutral current $tu\gamma/Z$ 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* [2] 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. Such colliders would give the possibility to achieve high precision electroweak (EW) measurements, 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 this report.

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.

2.1 The effective weak mixing angle $\sin^2\theta_{\mathrm{W}}$

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 $\sin^2\theta_{\mathrm{W}}$ can be measured dependent on $\mu = \sqrt{Q^2}$. This is shown in Fig. 1 (left), where the expected LHeC [1] and FCC-eh [3] measurements are compared to those from different collider and non-collider experiments. The LHeC and FCC-eh results can probe a large range of scale dependence between $\mu = [10, 1000]$ GeV extending current results.

2.2 Electroweak effects in inclusive NC and CC DIS cross sections

Using NC and CC cross section data, simultaneously with the PDFs, the vector g_V^f and axial-vector g_A^f weak neutral couplings of a fermion and a Z boson ($f = e$ or $f = q$ for electron or quark) can be extracted [3]. The (effective) coupling parameters depend on the electric charge, Q_f, and the third component of the weak-isospin, $I^3_{\mathrm{L},f}$. Using $\sin^2\theta_{\mathrm{W}} = 1 - \frac{M_W^2}{M_Z^2}$, one can write

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\,\rho'_{\mathrm{NC,CC}}\left(I^3_{\mathrm{L},f} - 2Q_f\,\kappa_{\mathrm{NC},f}\,\kappa'_{\mathrm{NC}}\,\sin^2\theta_{\mathrm{W}}\right), \text{ and} \tag{2.2}$$

$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\,\rho'_{\mathrm{NC,CC}}\,I^3_{\mathrm{L},f} \,\text{with}\, f = (e,u,d)\,. \tag{2.3}$$

The parameters $\rho_{\mathrm{NC},f}$ and $\kappa_{\mathrm{NC},f}$ are real parts of complex form factors which include higher-order loop corrections [4, 5, 6], and contain non-leading flavour-specific components. They are sensitive to contributions beyond the SM and the structure of the Higgs sector. Multiplicative anomalous contributions to these factors, denoted as $\rho'_{\mathrm{NC,CC}}$ and κ'_{NC}, are introduced, and it is tested if they agree with unity (for more detail see Ref. [7]). Uncertainties of these parameters are obtained in a fit together with the PDFs.

Figure 1 (middle) shows the two-dimensional uncertainty contours of these anomalous form factors for the LHeC and FCC-eh scenarios, compared to uncertainties from the LEP+SLD combination. While LEP is mainly sensitive to the parameters of leptons or heavy quarks, ep scattering is more sensitive to light quarks (u,d,s), and thus the LHeC/FCC-eh measurements are highly complementary [8]. It is found that these parameters can be determined with very high experimental precision, better than 1%.

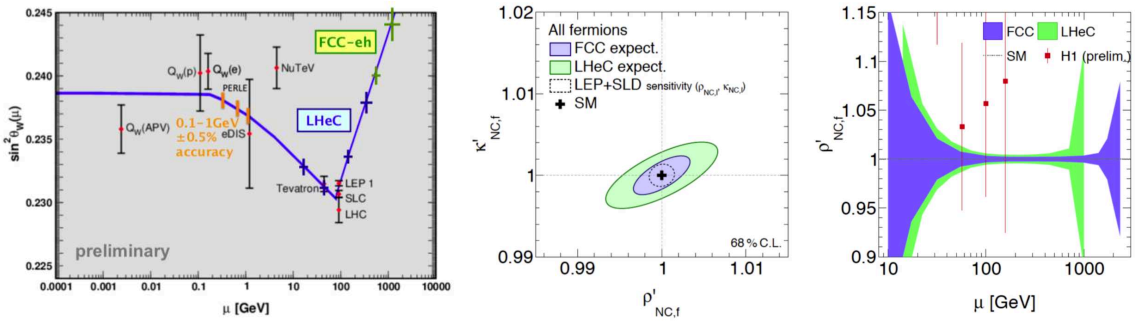

Figure 1: Left: Dependence of the weak mixing angle in the MSbar definition on the energy scale μ, taken from [9], compared to expectations from PERLE [10], LHeC [1], and FCC-eh [3] (upper left). Middle: Expected uncertainties at 68 % C. L. for the determination of the ρ'_{NC} and κ'_{NC} parameters assuming a single anomalous factor equal for all fermions. The LHeC and FCC-eh results are compared with the achieved uncertainties from the LEP+SLD combination [8] for the determination the respective leptonic quantities. Right: Test of the scale dependence of the anomalous ρ and κ parameters for two different LHeC scenarios.

An important test of the SM can be performed by determining the effective coupling parameters as a function of the momentum transfer μ. In case of κ'_{NC}, this is equivalent to measuring the running of the effective weak mixing angle, $\sin\theta_{\mathrm{W}}^{\mathrm{eff}}(\mu)$, as in Fig. 1 (left). One can see that in case of ρ'_{NC} this quantity can be determine with a precision of up to 0.1 % and better than 1 % over a wide kinematic range of almost two orders of magnitude in μ. This allows for high sensitivity to new physics beyond the SM in the EW sector.

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 [11] and 15.3 pb at the FCC-eh. The other important top quark production mode is $t\bar{t}$ photoproduction with a total cross section of 0.05 pb at the LHeC [12], and 1.14 pb [13] at the FCC-eh. This makes a future ep collider a top quark factory, ideal to study top quarks with a high precision, and in particular to analyze their electroweak interaction.

3.1 Wtq Couplings

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. An elaborate analysis [11] of the single top quark CC DIS process at the LHeC including a detailed detector simulation using the DELPHES package [14] 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 currently most accurate result at the LHC Run-I performed by the CMS experiment [15].

The same analysis [11] can also be used to search for anomalous left- and right-handed Wtb vector (f_1^L, f_1^R) and tensor (f_2^L, f_2^R) couplings analyzing the following effective Lagrangian:

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L - f_1^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(f_2^L P_L - f_2^R P_R)tW_{\mu}^{-} + h.c. \ , \qquad (3.1)$$

where $g = e/\sin\theta_{\mathrm{W}}$, and P_L (P_R) denotes the left (right) handed projection operator. In the SM $f_1^L = 1$ and $f_1^R = f_2^L = f_2^R = 0$. The effect of anomalous Wtb couplings is consistently evaluated in the production and the decay of the antitop quark. Using hadronic top quark decays only, the expected accuracies in a measurement of these couplings as a function of the integrated luminosity are presented in Fig. 2 (upper left), derived from expected 95% C.L. limits on the cross section yields. The couplings can be measured with accuracies between 1-14% at 1 ab^{-1}.

Similarly, the CKM matrix elements $|V_{tx}|$ ($x = d, s$) can be extracted using a parameterization of deviations from their SM values with very high precision through W boson and bottom (light) quark associated production channels, where the W boson and b-jet (light jet) final states can be produced via s-channel single top quark decay or t-channel top quark exchange [16]. As an example, analyzing the processes

Signal 1: $pe^- \rightarrow \nu_e \bar{t} \rightarrow \nu_e W^- \bar{b} \rightarrow \nu_e \ell^- \nu_\ell \bar{b}$

Signal 2: $pe^- \rightarrow \nu_e W^- b \rightarrow \nu_e \ell^- \nu_\ell b$

Signal 3: $pe^- \rightarrow \nu_e \bar{t} \rightarrow \nu_e W^- j \rightarrow \nu_e \ell^- \nu_\ell j$

in an elaborate analysis including a detailed detector simulation using the DELPHES package [14], the expected accuracies on $|V_{ts}|$ at the 2σ confidence level (C.L.) are shown as a function of the integrated luminosity in Fig. 2 (upper right) for the FCC-eh. At 2 ab^{-1} of integrated luminosity and an electron polarization of 80%, the 2σ limits improve on existing limits from the LHC [17] (interpreted by [18]) by almost an order of magnitude. Analyzing Signal 3 alone will allow for the first time to achieve an accuracy of the order of the actual SM value of $|V_{ts}^{\mathrm{SM}}| = 0.04108^{+0.0030}_{-0.0057}$ as derived from an indirect global CKM matrix fit [19], and will therefore represent a direct high precision measurement of this important top quark property. In these studies, upper limits at the 2σ level down to $|V_{ts}| < 0.037$, and $|V_{td}| < 0.037$ can be achieved.

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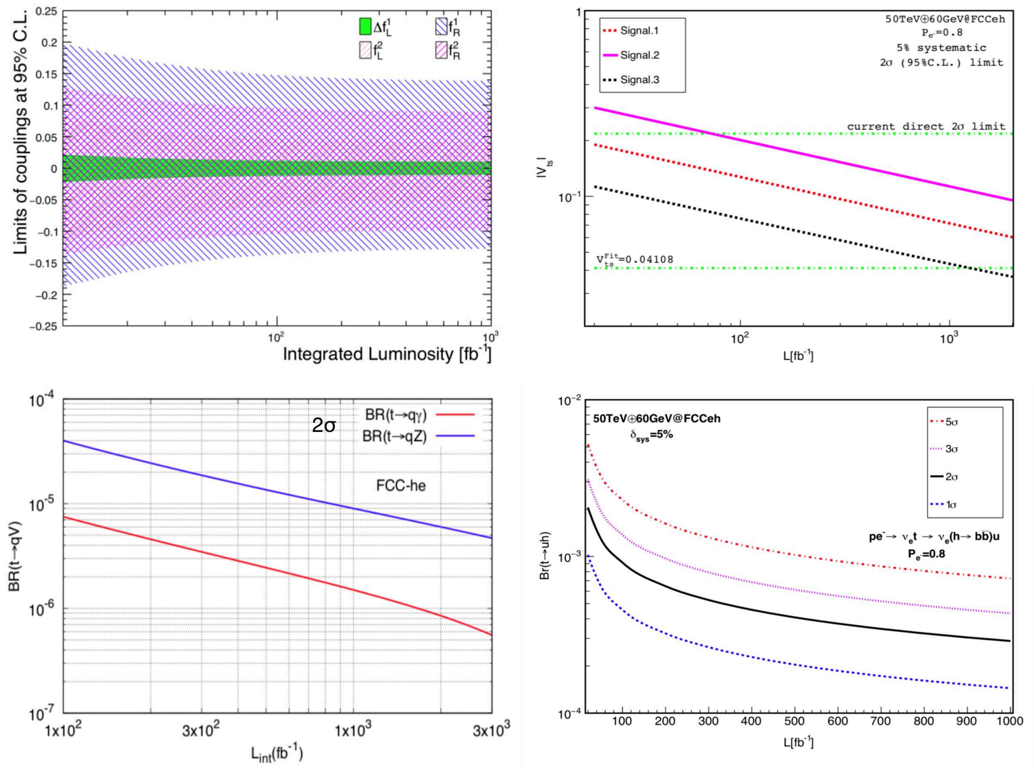

Figure 2: Expected sensitivities as a function of the integrated luminosity on the SM and anomalous Wtb couplings [11] (upper left), on $|V_{ts}|$ (upper right) [16], on FCNC $t \to qV$ branching ratios (lower left) [20], and on FCNC $t \to uH$ branching ratios [22] (lower right).

3.2 FCNC Top Quark Couplings

Single top quark NC DIS production can be used to search for Flavor Changing Neutral Current (FCNC) $tu\gamma$, $tc\gamma$, tuZ, and tcZ couplings [20] as given in

$$L = \sum_{q=u,c} \left(\frac{g_e}{2m_t} \bar{t}\sigma^{\mu\nu}(\lambda_q^L P_L + \lambda_q^R P_R) q A_{\mu\nu} + \frac{g_W}{4c_W m_Z} \bar{t}\sigma^{\mu\nu}(\kappa_q^L P_L + \kappa_q^R P_R) q Z_{\mu\nu} \right) + h.c. \,, \tag{3.2}$$

where g_e (g_W) is the electromagnetic (weak) coupling constant, c_W is the cosine of the weak mixing angle, $\lambda_q^{L,R}$ and $\kappa_q^{L,R}$ are the strengths of the anomalous top FCNC couplings (the values of these couplings vanish at the lowest order in the SM). In an elaborate analysis events including at least one electron and three jets (hadronic top quark decay) with high transverse momentum and within the pseudorapidity acceptance range of the detector are selected. 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. Signal and background interference effects are included. A detector simulation with DELPHES [14] is applied.

The expected limits on the branching ratios BR($t \to q\gamma$) and BR($t \to qZ$) as a function of the integrated luminosity at the 2σ, 3σ, and 5σ C.L. are presented in Fig. 2 (lower left). Assuming an integrated luminosity of $2\,\text{ab}^{-1}$, with a significance of 2σ C.L., limits of BR($t \to q\gamma$) $< 8 \cdot$

10^{-7} and $\mathrm{BR}(t \to qZ) < 4 \cdot 10^{-6}$ are expected at the FCC-eh. This is precise enough to actually study concrete new phenomena models, such as SUSY, little Higgs, and technicolor, that have the potential to produce FCNC top quark couplings. The sensitivity on FCNC $tq\gamma$ couplings even exceeds expected sensitivities from the High Luminosity-LHC (HL-LHC) with $300\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 14\,\mathrm{TeV}$, and from the International Linear Collider (ILC) with $500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 250\,\mathrm{GeV}$ [21].

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

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

This can be studied in CC DIS production, where singly produced top anti-quarks could decay via such couplings into a light anti-quark and a Higgs boson decaying into a bottom quark-antiquark pair, $e^- p \to \nu_e \bar{t} \to \nu_e H\bar{q} \to \nu_e b\bar{b}\bar{q}$ [22]. Another signal involves the FCNC tHq coupling in the production vertex, i.e. a light quark from the proton interacts via t-channel top quark exchange with a W boson radiated from the initial electron producing a b quark and a Higgs boson decaying into a bottom quark-antiquark pair, $e^- p \to \nu_e Hb \to \nu_e b\bar{b}b$ [22]. This channel is superior in sensitivity to the previous one due to the clean experimental environment when requiring three identified b-jets. 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. A 5% systematic uncertainty for the background yields is added. Furthermore, 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. The selection is optimized for the different signal contributions separately. Figure 2 (lower right), shows the expected FCC-eh upper limit on the branching ratio $\mathrm{Br}(t \to Hu)$ with 1σ, 2σ, 3σ, and 5σ C.L. as a function of the integrated luminosity for the $e^- p \to \nu_e Hb \to \nu_e b\bar{b}b$ signal process. For an integrated luminosity of $1\,\mathrm{ab}^{-1}$, upper limits of $\mathrm{Br}(t \to Hu) < 0.22 \cdot 10^{-3}$ are expected. These limits improve the sensitivity by almost one order of magnitude compared to what can be achieved at the HL-LHC with $3000\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 14\,\mathrm{TeV}$, where $\mathrm{Br}(t \to Hu) < 0.23 \cdot 10^{-2}$ is expected at a 3σ significance [23], to be compared to $\mathrm{Br}(t \to Hu) < 0.35 \cdot 10^{-3}$ achieved at the FCC-eh.

3.3 Other Top Quark Property Measurements and Searches for New Physics

Other exciting results not presented here involve, for example, the study of the CP-nature in $t\bar{t}H$ production [24], searches for anomalous $t\bar{t}\gamma$ and $t\bar{t}Z$ chromoelectric and chromomagnetic dipole moments in $t\bar{t}$ production [12], the study of top quark spin and polarization [25], and the investigation of the top quark structure function inside the proton [26, 1].

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 $\sin^2\theta_{\mathrm{W}}$, 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.

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