



QCD at the FCC-ee

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Abstract In this note, we briefly review some theory aspects of Quantum Chromodynamics at the future circular lepton collider (FCC-ee).

1 Introduction

With its broad programme spanning energies that range from the Z pole to the top-pair threshold, the FCC-ee offers an ideal environment to study several aspects of particle phenomenology. The expected FCC-ee measurements will improve the knowledge of many Higgs and electroweak (EW) parameters with respect to previous colliders by up to one and two orders of magnitude, respectively. Moreover, it will offer great opportunities for the study of the properties of the top quark as well as to explore aspects of flavour physics. In order to use the above measurements to perform consistency tests of the Standard Model (SM) and to derive stringent indirect constraints on new-physics scenarios, it is crucial to reduce theory uncertainties to the level of the experimental ones. This demands unprecedented theoretical accuracy in the strong and the EW sectors of the SM for a variety of processes and observables (see e.g. ref. [1] and references therein), reaching the permille level in some cases. A complementary aspect will be the development of new observables to enhance the sensitivity of the analyses by improving the theoretical control and reducing undesired contamination from background effects. In this brief note, we will discuss some of the advances that will be instrumental in achieving this accuracy on the QCD front, and comment on open challenges towards the desired precision.

2 Event shapes, jets, and the strong coupling constant

A crucial theoretical ingredient needed to match the FCC-ee experimental accuracy is the knowledge of SM parameters that enter the calculations. A remarkable phenomenological application on the QCD side is the extraction of the strong coupling constant α_s , that constitutes the least well-known coupling in the gauge sector of the SM. Currently, the World Average quotes a $\sim 1\%$ uncertainty in its value ($\alpha_s(M_Z) = 0.1179 \pm 0.0010$) [2,3]. The most precise inputs arise from lattice calculations [3,4], whose uncertainties are expected to be reduced by a factor of two in the next decade (see e.g. [5,6] for a recent study).

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Conversely, precise determinations of α_s at FCC-ee will arguably come from electroweak pseudo observables (EWPO), such as the total cross section $\sigma(e^+e^- \rightarrow \text{hadrons})$ at the Z resonance peak or its ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ [7]. This quantity is particularly suitable to extract α_s due to the small non-perturbative hadronisation corrections that scale with the c.o.m. energy Q as $(\Lambda_{\text{QCD}}/Q)^6$ [8]. With the $\mathcal{O}(5 \times 10^{12})$ Z bosons produced at the FCC-ee, the experimental error on α_s extractions from fits of the above quantities will be of order $\mathcal{O}(0.00015)$ (see e.g. [7]), hence requiring a substantial reduction in the corresponding theoretical uncertainties. The status of theory computations for such inclusive observables is already very advanced, and QCD corrections are known up to N^4LO [9–11] (N^3LO corrections for massive bottom quarks are also known in a power series in m_b^2/Q^2 [12]). Similarly, EW and mixed QCD-EW corrections are available at least up to two loops (see e.g. [13–15] and references therein), and will be discussed elsewhere in this report. Other extractions of α_s at the FCC-ee can be derived from τ decays (see e.g. [3, 16, 17]) and even W [18] decays, using high-order perturbative QCD computations (see e.g. refs. [9–11, 19, 20]). However, some outstanding theoretical questions related to the treatment of non-perturbative contributions in fits from τ decays [21–23], as well as to the difference between extractions relying on contour-improved [24, 25] and fixed-order perturbative calculations adopted in the fits are still open. A deeper understanding of these aspects is necessary for robust measurements of α_s from FCC-ee data. Furthermore, the study of these decays at the FCC-ee will be instrumental to explore aspects of flavour physics and lepton flavour universality (see e.g. [26, 27] and references therein).

Finer details of strong dynamics can be explored through event shapes, designed to study the geometrical properties of hadronic events, or jet rates that, within a specific jet-clustering algorithm, allow one to classify the event in terms of its jet multiplicity. Owing to their sensitivity to QCD radiation, they are widely used to measure α_s , and to calibrate non-perturbative hadronisation models (see e.g. ref. [28] and references therein). Moreover, their relative simplicity allows for very accurate predictions. Fully differential calculations for the process $e^+e^- \rightarrow Z/\gamma^* \rightarrow q\bar{q} + X$ at N^3LO (α_s^3) in QCD for massless partons in the final state can be derived starting from the results of refs. [29–33] with the inclusive cross section at N^3LO [19]. Similarly, the production of heavy (notably bottom) quarks $e^+e^- \rightarrow Z/\gamma^* \rightarrow Q\bar{Q} + X$ can be described at NNLO in QCD using the predictions of refs. [34–36] and [12]. For higher jet-multiplicities, the computation of QCD radiative corrections with massless final-state partons has been pushed to NLO for $e^+e^- \rightarrow Z/\gamma^* \rightarrow n$ jets with $n = 5$ [37], and $n = 6, 7$ [38]. The perturbative description of kinematical regimes that require the all-order resummation of radiative corrections has also improved substantially in the past decade, and the state-of-the-art calculations for standard global event shapes and jet rates in $e^+e^- \rightarrow Z/\gamma^* \rightarrow q\bar{q} + X$ are either NNLL or N^3LL [39–55]. Accurate predictions can be also obtained for $e^+e^- \rightarrow Z/\gamma^* \rightarrow q\bar{q}g + X$ observables [56–59], particularly important for the study of gluon-initiated jets (and corresponding tuning of event generators). The computation of non-global observables [60], featuring angular cuts in the final state, poses a major theoretical challenge, and it is currently limited to lower logarithmic accuracy (see e.g. [61–68]). These observables are sensitive to the geometric pattern of soft QCD interference, and are therefore instrumental to our understanding of strong interactions at all orders.

The sensitivity of final-state observables on α_s makes them suitable for precise extractions of the strong coupling. Currently, different α_s determinations from these observables [39–41, 69–83] can differ from each other by a few standard deviations. Besides the high-precision perturbative ingredients described above, such fits require input on hadronisation effects. Non-perturbative radiation induces changes in the observable of $\mathcal{O}(\Lambda_{\text{QCD}}^P/Q^P)$ (typically

$p = 1$) that must be estimated to achieve the desired precision. Aside from the considered observable, the core difference between different α_s determinations lies in how one estimates hadronisation corrections. For instance, among the fits currently included in the World Average [3], these corrections are estimated either via Monte Carlo (MC) generators (e.g. in [71, 73, 75, 79, 82]) or with analytic models [40, 72, 76, 78] (based for instance on dispersive methods or shape functions [8, 84–95]).

In this context, the use of event generators is sometimes criticised on the ground that they are tuned on less accurate perturbative calculations, and therefore the separation between perturbative and non-perturbative components cannot easily be related to today's highest-accuracy predictions. Conversely, the analytic models fit simultaneously α_s and a non-perturbative model, though considering only the leading term in the expansion of the latter in powers of Λ_{QCD}/Q . The coefficient of this correction is extracted from data under the assumption that it does not vary across the spectrum of the event-shape observable used in the fit. Besides the natural question about the size of subleading power corrections, the approximation above leads to systematic uncertainties that affect the α_s fits at the few-percent level [96].

Thus, improving our understanding and control over hadronisation corrections is essential for precision at future colliders, and the FCC-ee might contribute in different ways. On the one hand, energies higher than those of previous lepton colliders would arguably justify further development of analytic models based on a power expansion in Λ_{QCD}/Q . On the other hand, the energy span and experimental accuracy of FCC-ee will be instrumental to gain better control of non-perturbative dynamics in MC generators, which will be beneficial in all measurements foreseen at FCC-ee, such as $e^+e^- \rightarrow t\bar{t}$, $e^+e^- \rightarrow W^+W^-$, and $e^+e^- \rightarrow ZH$. An endeavour of this type will crucially require the development of more accurate MC generators, both regarding the predictions for the hard scattering [97–105] and concerning the formulation of novel parton shower algorithms (both for QCD and QED radiation) that overcome the accuracy limitations of the current designs (see e.g. [106–118] for recent work). The resulting improved description of final-state radiation would be instrumental for the development of more accurate modelling of the fragmentation of jets initiated either by light or heavy partons. The understanding of the former is essential for the implementation of quark/gluon jet tagging [119–126] to the study of Higgs production at FCC-ee, while the latter is crucial, for instance, to investigate existing discrepancies in heavy-quark observables such as the forward-backward asymmetry [127–130]. Parallel important developments will concern the creation of improved models of colour reconnection, which could be precisely calibrated in reactions like $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q'\bar{q}'$ or $e^+e^- \rightarrow t\bar{t}$ [131]. In the context of jet observables discussed in this section, one can also envision using accurate α_s extractions either from EWPO or from future lattice calculations to model and tune non-perturbative aspects of event generators from differential distributions.

A complementary development would be to design observables with reduced sensitivity to hadronisation, for instance by exploiting the modern knowledge of jet dynamics and their substructure, also via machine learning technology (see e.g. [132] for a review). An example is to *groom* the final-state event so that non-perturbative corrections are reduced in well-identified regions of the observable spectrum (see e.g. [133–136]), hence opening promising avenues for complementary extractions of α_s [137]. An in-depth study of the effectiveness of these techniques at the energies of the FCC-ee, as well as the estimate of the remaining hadronisation corrections (see e.g. refs. [137, 138] for recent studies in specific observables), will be highly desirable in the coming years.

3 Top physics

An essential component of the FCC-ee programme is related to the study of top quarks. These are produced in colour-singlet pairs and are nearly free of background, which arises mainly from W^+W^- +jets production and is non-resonant at collision energies $Q \sim 2m_t$. Therefore, the foreseen threshold scan will lead to extremely precise measurements of top-quark properties such as its mass, width and $Z/\gamma t\bar{t}$ couplings, and will allow indirect constraints of the top Yukawa (y_t), which will be already known with $\sim 3\%$ accuracy after HL-LHC. These quantities are a central element of global fits, and the augmented precision will increase the sensitivity to indirect effects of new physics.

The most precise measurements of the top mass at hadron colliders rely on its direct reconstruction from kinematical distributions of the top decay in $t\bar{t}$ events. Today's state-of-the-art determination quotes a total error of about 500 MeV [3], and the experimental uncertainties will be reduced further after HL-LHC [139, 140]. These extractions, however, face significant theoretical limitations due to the complexity of the final state, and to the intrinsic ambiguities that affect the pole mass scheme used in these analyses, related to the presence of infrared renormalons in its definition (see e.g. [141, 142] for recent discussions). Conversely, at the FCC-ee, the top mass will be extracted through a precise threshold scan at c.o.m. energies close to $2m_t$, where the top-quark pair is non-relativistic and is subject to Coulomb-type interactions. This allows the definition of short-distance top-mass schemes that are not affected by ambiguities related to infrared physics and are particularly suitable to the production at threshold [143–147]. The clean measurements at the FCC-ee will also enable the comparison of the accurate experimental data to considerably more precise theory predictions than what is available for hadron colliders. The QCD calculations for the line-shape of the $t\bar{t}$ system at threshold ($\sigma_{t\bar{t}}$) reach a remarkable degree of precision. Although NNLO fixed-order QCD calculations are available (see e.g. [148]), in this kinematic regime, $\sigma_{t\bar{t}}$ receives a substantial contribution from Coulomb corrections due to the non-relativistic nature of the $t\bar{t}$ pair. The latter effects can be accurately described in the context of various effective field theories derived from non-relativistic QCD [149–151], which operate within the power counting $\alpha_s \sim v$ (with v being the small velocity of the top quarks). Predictions in this framework are already extremely accurate, and include QCD effects up to $N^3\text{LO}$ [152] (see also refs. [153, 154] and references therein for a more detailed discussion), approximate NNLL renormalisation-group improved corrections [155], and the inclusion of EW effects within an analogous EFT framework [156]. In general, only the physical final state $W^+W^-b\bar{b}+X$ is well-defined in perturbation theory, and therefore one must also include the contribution from (non-resonant) channels that do not involve the creation of a top-quark pair near their mass shell. These require embedding the non-relativistic EFT mentioned above into the unstable particle EFT [157, 158], where current predictions reach NNLO accuracy for the non-resonant part (see discussion in ref. [156]). Current projections quote an expected accuracy of about $\Delta m_t \sim \mathcal{O}(50)$ MeV [156] (see also refs. [159, 160]) for the top mass in the potential-subtracted scheme [146] from the FCC-ee.

These future measurements will exhibit a parametric sensitivity to both α_s and y_t . To maximize the sensitivity to the top mass and width, such parameters should be preferably obtained from other determinations. These are for instance measurements at the Z peak or lattice simulations of α_s (cf. Sect. 2), and direct measurements at HL-LHC of y_t . For the optimal exploitation of FCC-ee measurements, further theoretical developments are desirable, such as the $N^3\text{LO}$ corrections to the non-resonant channels (currently out of reach) as well as a next-to-leading logarithmic control over the initial state QED radiation, for which progress is currently ongoing (see e.g. [161, 162]).

The theoretical description of differential distributions is less accurate than that of the inclusive quantities just discussed, and reaches either NLO or NNLO only for specific observables [163, 164]. Thus, further progress is needed in these computations, which are central to control precisely the effect of experimental cuts. Some aspects of such calculations pose considerable theoretical challenges, for instance, concerning the differential calculations in the non-relativistic limit, or the assessment of non-factorisable radiative corrections to the decays of the two top quarks [165]. Another important aspect of differential predictions is that of MC event generators (see e.g. [166]), where theoretical improvement is needed in different directions. A first aspect involves the inclusion of higher-order QCD corrections to the hard scattering, for instance using matching technology along the lines of that developed in recent years at hadron colliders. A second development concerns the accurate description of $t\bar{t}$ production at threshold, for which significant challenges arise from the inclusion of Coulomb corrections discussed in this section within the framework of a fully exclusive event generator. Thirdly, another necessary improvement concerns the parton shower algorithms used to simulate QCD and QED radiation, both for what regards their logarithmic accuracy, as well as regarding the accurate description of radiation off the top-quark decays with a correct account of its finite width. Some aspects of this latter problem are addressed in refs. [167, 168] for top quarks produced in hadronic collisions; however, a full description of the hierarchy of scales involved in the process (i.e. v , m_t , the top width Γ_t) is not accounted for by existing algorithms. Finally, the study of non-perturbative power corrections to differential observables is also paramount to carry out a top-quark precision physics programme at the FCC-ee. Here, the accurate extraction of the top mass from the inclusive measurements discussed earlier can arguably be used as input to deepen the understanding of linear renormalon corrections to kinematic distributions (see e.g. ref. [169] for a recent study).

4 The Higgs sector

The FCC-ee will operate as a Higgs factory producing at least 10^6 Higgs bosons via the $e^+e^- \rightarrow ZH$ and W^+W^- fusion ($e^+e^- \rightarrow H\nu\bar{\nu}$) processes, allowing the precise determination of many Higgs couplings as well as of the Higgs boson width [7]. Besides considerable improvements compared to HL-LHC extractions, this data will be used to constrain some aspects of new physics beyond the SM. Conversely, some important couplings that are not directly accessible at FCC-ee will be only constrained indirectly, as it is the case for the top Yukawa or the trilinear coupling. The top Yukawa will be known at the 3 – 4% level after HL-LHC (the improvement on y_t foreseen at the FCC-ee is marginal [7]), providing key input to several measurements at the FCC-ee, such as the $t\bar{t}$ threshold scan discussed in Sect. 3. On the other hand, model-independent indirect constraints on the trilinear coupling (see e.g. [170–173]) are expected to reach $\mathcal{O}(40\%)$ precision, which in combination with HL-LHC will achieve a precision of about 30% [7]. This coupling will be then determined with an astonishing 5% precision at FCC-hh, also thanks to the precise knowledge of other Higgs branching ratios and EW couplings gained at FCC-ee. Reaching theoretical uncertainties aligned with the projections for these quantities requires dedicated developments in different areas of both QCD and EW calculations. An active programme focused on the computation of the EW and mixed QCD-EW corrections to the production and decay of a Higgs boson in the above processes is ongoing [174–185], and we refer to these references for a detailed discussion. In the following, we focus on the main pure QCD aspects.

The small background and low hadronic activity of the FCC-ee will allow a detailed study of the hadronic decays of the Higgs boson. Partial widths are currently known at the percent

level. Specifically, in the case of $H \rightarrow b\bar{b}$, N⁴LO QCD corrections are known in the limit of massless bottom quarks [11, 186, 187], and N⁴LO QCD corrections to $H \rightarrow gg$ have been computed in the heavy-top-mass limit [11]. Besides these partial decay widths, the simulation of Higgs decays at the differential level is paramount either to correct for experimental fiducial acceptances or for the study of differential distributions for angular observables and jet observables measured on the Higgs decays, which are sensitive to quark Yukawa couplings [188, 189] or new physics states (see e.g. [190–194]). The future development of heavy and light jet tagging and quark/gluon jet discrimination techniques can be exploited to gain sensitivity to Yukawa couplings to light quarks. This sensitivity can arise both via the decay of the Higgs boson to light, e.g. strange, quarks,¹ or indirectly via light-quark virtual corrections to the $H \rightarrow gg$ decay. The practical realisation of these ideas relies nevertheless on the assumption that sufficiently accurate theoretical predictions will be achieved to support the measurements. Considerable steps are being taken in this direction. The differential $H \rightarrow b\bar{b}$ decay is known up to N³LO [195–200] in the limit of massless b quarks and NNLO (and partially beyond) mass corrections are available [201–208]. Similarly, $H \rightarrow gg$ is known to NNLO in the heavy-top limit, though a N³LO calculation for this process is currently within reach. Finite quark mass corrections to $H \rightarrow gg$ are relevant at the level of precision foreseen at FCC-ee, and could be estimated at best at NNLO in QCD in the near future with state-of-the-art calculations (see e.g. [202, 209–212]). Calculations of hadronic event shapes and jet resolutions at NLO [213–215] and NNLO [216] in QCD have also been performed in recent years. As discussed in Sect. 2, the accurate description of these observables also requires the resummation of radiative corrections, which are obtained either by dedicated analytic calculations, largely obtained with the same techniques used in the context of $e^+e^- \rightarrow Z \rightarrow$ hadrons, or using exclusive event generators matched to parton showers [217–219]. Interesting theoretical challenges are posed by the consistent description of the radiation off massive quark loops at all perturbative orders (entering for instance $H \rightarrow gg$, as discussed, e.g. in refs. [220–226]) and whose understanding can play a crucial role in new physics scenarios that modify the quark Yukawa couplings (see e.g. refs. [227, 228] for a discussion at hadron colliders). Finally, a special role is again played by the modelling of non-perturbative corrections in hadronic final states that, due to the relatively low energy of the decay ($\sim m_H$), will have a sizeable impact on most differential measurements of the (hadronic) Higgs decay products. In this respect, the same considerations made in Sect. 2 apply, and the study of the Higgs boson at the FCC-ee will benefit enormously from future developments in the modelling of such effects evoked in Sect. 2.

The FCC-ee will also allow for the exploration of rare and exotic decays of the Higgs boson, such as $H \rightarrow Z\gamma, \mu\mu$ and $\mu\tau$ (the latter being forbidden in the SM). Experimental constraints on $H \rightarrow Z\gamma, \mu\mu$ will be already set at the 10% level at HL-LHC. While the improvement on these constraints reached at the sole FCC-ee will be marginal, the whole FCC programme will drastically reduce the uncertainty on the measurement of such couplings [229]. In addition, valuable information can be extracted from exclusive decays to mesons, which are sensitive to the Yukawa couplings to second- and first-generation quarks. Examples are the decays into $J/\psi, \phi, \rho$ and ω , in association with either a photon or a weak vector boson [230–234]. Accurate predictions for these decays in the framework of QCD factorisation are available (see e.g. [230, 235–237] and references therein). However, the tiny branching ratios will make the measurements very challenging due to the limited statistics at FCC-ee [7].

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¹ In optimistic scenarios constraints on first-generation Yukawa couplings can be obtained [188].

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