FCC: QCD physics

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Abstract

The Future Circular Collider (FCC) will deliver unprecedented precision in the measurement of the properties and parameters of the Standard Model (SM), directly and indirectly probing new physics up to the 100-TeV scale. Its broad and diverse programme, including very high-luminosity e^+e^- collisions (FCC-ee) and hadronic collisions at the energy frontier (FCC-hh), will offer exceptional opportunities to advance knowledge of the strong interaction through high-precision measurements across a wide range of energy scales and scattering processes. Key measurements at the FCC-ee and FCC-hh are reviewed that will provide a deeper understanding of quantum chromodynamics (QCD) in the perturbative, non-perturbative and high-density regimes, and advance its theoretical description to a level of precision far beyond that of current collider experiments. The critical role played by QCD in determining key Standard Model quantities at FCC-ee is also discussed, highlighting how improved theoretical calculations and simulations are needed to match the foreseen FCC-ee experimental uncertainties.

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1 QCD physics at FCC-ee

Electron-positron collisions at the Future Circular Collider (FCC-ee) provide unparalleled opportunities for Higgs, electroweak (EW), top, flavour, and beyond standard model (BSM) physics [1], and also offer a unique environment to perform the most precise studies of the strong interaction, theoretically described by Quantum Chromodynamics (QCD). High-energy $\mathrm{e^+e^-}$ collisions provide a clean, controlled, and well-defined setup for QCD studies, avoiding the complications from the coloured initial states present in proton-proton and heavy-ion collisions. Unlike hadron colliders, where parton distribution functions (PDFs), multiparton interactions, and "beam remnants" complicate the understanding of colour dynamics, $\mathrm{e^+e^-}$ annihilation occurs at a fixed centre-of-mass (CM) energy with precisely known elementary kinematics and with a colourless initial state. In addition, events typically produce final states with well-separated jets and a well-defined parton flavour, enabling detailed studies of light-quark, heavy-quark, and gluon showering and hadronisation in a controlled setting. All such aspects allow precise experimental measurements, accurate theoretical predictions, and direct tests of perturbative (pQCD) and nonperturbative (NP) QCD, of impact for the full FCC-ee physics programme, whose indirect BSM physics reach, up to a 100-TeV energy scale for some operators, relies on searches for tiny deviations in the data from the SM predictions. Although QCD physics per se is not the primary driving force for future $\mathrm{e^+e^-}$ colliders, a precise understanding of the strong interaction is crucial to fully exploit the broad range of SM measurements and BSM searches to be performed:

- A precise determination of the QCD coupling $\alpha_S(m_Z^2)$ is needed to accurately and precisely predict all $\mathrm{e^+e^-}$ cross sections and decay rates which parametrically depend on it.
- Accurate pQCD calculations (both at fixed N^{n}LO and resummed N^{n}LL orders) are fundamental to describe hadronic final states and jet dynamics, and precisely extract multiple SM quantities from the data.
- Heavy-, light-quark, and gluon separation (through jet-flavour tagging techniques) is key for multiple SM measurements, such as measuring Higgs Yukawa couplings to quarks and gluons.
- Nonperturbative dynamics, such as hadronisation and colour reconnection, impacts all hadronic final states, playing a role, e.g., in studies of $\mathrm{e^+e^-} \to \mathrm{W^+W^-}, \mathrm{t\bar{t}} \to$jets processes.

The actual fulfilment of the unique Higgs, EW, top, flavour, and BSM programme accessible at FCC-ee, therefore requires parallel efforts in experimental and theoretical QCD studies. The detectors being planned for FCC-ee have the specifications (large acceptance, fine granularity, particle identification) needed to achieve the required experimental precision for EW, QCD, and flavour measurements. The main theoretical challenges for QCD calculations [2], in order to match the foreseen FCC-ee experimental precision summarised below, have been the subject of discussions at topical CERN workshops [3, 4].

The baseline FCC-ee programme [5, 6] considers $\mathrm{e^+e^-}$ collisions at four nominal CM energies: $\sqrt{s} \approx 91, 160, 240, 360\,\mathrm{GeV}$ with total integrated luminosities covering $\mathcal{L}_{\text{int}} \approx$ 200–3 ab^{-1} (four interaction points combined, and assuming 1.2×10^7 s/year). The characteristics of these four physics runs, aiming at probing the properties of the Z, W, H, and top quark with unprecedented precision, are listed in Table 1. To highlight the impact of QCD aspects, Table 1 also indicates the number of hadronic final-state (HFS) events expected in the "signal" $\mathrm{e^+e^-} \to \mathrm{Z, WW, ZH, t\bar{t}}$ and "background" $\mathrm{e^+e^-} \to \mathrm{Z^*} \to \mathrm{q\bar{q}}$ processes. The first observation is that the fully hadronic decays of the produced top, W, Z, and H bosons represent 67–80% of their inclusive final states, thereby highlighting the importance of precise and accurate QCD predictions for probing their properties (e.g., couplings). The HFS of these "signal" events will be characterised by the production of 2–6 partons with maximum jet energies $E_\mathrm{j} \approx$ 60–125 GeV. The bottom rows of Table 1 list the $\mathrm{e^+e^-} \to \mathrm{Z^*} \to \mathrm{q\bar{q}}$ cross sections and associated number of events expected for each of the four runs. The FCC-ee will produce about 5×10^{12}, 8×10^8, 1.5×10^8, 2×10^8 events, with typically two jets produced with maximum energies $E_\mathrm{j} \approx$ 45–180 GeV, in the Z, WW, ZH, and $\mathrm{t\bar{t}}$ runs, respectively. Such enormous HFS datasets will allow dedicated multidifferential studies of many QCD observables with negligible statistical uncertainties, in an extremely clean environment.

Beyond the baseline programme summarised in Table 1, QCD studies at other hadronic invariant masses $\sqrt{s_{\text{had}}}$ have been considered. First, it has been suggested to study HFS over the $\sqrt{s_{\text{had}}} \approx$ 20–80 GeV range by exploiting initial–state radiation (ISR) events during the high-luminosity Z-pole

Table 1: Characteristics of the physics runs in the baseline FCC-ee programme: CM energy, running time, integrated luminosity $\mathcal{L}_{\rm int}$, total number of Z, WW (including all $\sqrt{s}$ values from 157.5 GeV up), ZH, and $\rm t\bar{t}$ events expected (as well as in hadronic decay modes, indicating the number of partons produced and their maximum jet energies). The lower rows list the corresponding $\rm e^+e^- \to q\bar{q}$ cross section (with ISR) and expected number of HFS events, and the maximum jet energies, for each $\sqrt{s}$.

Run	Z	WW	ZH	$\rm t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
time (years)	4	2	3	1	4
$\mathcal{L}_{\rm int}$ (ab^{-1})	205	19.2	10.8	0.42	2.70
$\rm e^+e^- \to Z,\ WW,\ ZH,\ t\bar{t}$					
$N_{\rm evts}$ (Z, W, H, top)	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH	2×10^{6} $\rm t\bar{t}$	
$N_{\rm evts}$ (HFS decays)	4.2×10^{12}	1.1×10^{8}	1.2×10^{6}	0.9×10^{6}	
$N_{\rm partons}$ (HFS decays)	≥ 2	≥ 4	≥ 4	≥ 6	
$E_{\rm j}$ (max. jet scale probed)	45 GeV	40 GeV	45, 65 GeV	125 GeV	
$\rm e^+e^- \to Z^{(*)} \to q\bar{q}$					
σ	32.5 nb	40 pb	13.5 pb	5.3 pb	
$N_{\rm evts}$ (HFS)	4.2×10^{12}	7.7×10^{8}	1.5×10^{8}	1.7×10^{7}	
$E_{\rm j}$ (max. jet scale probed)	45 GeV	80 GeV	120 GeV	180 GeV	

run, and/or in dedicated short (about 1-month-long) $\rm e^+e^-$ runs at CM energies $\sqrt{s} \approx 40$ GeV and 60 GeV [7]. Data samples with $\mathcal{O}(10^9)$ hadronic events can be collected at those low $\sqrt{s_{\rm had}}$ points (Table 2, middle columns) that will provide valuable information, in particular, on NP and heavy-quark mass effects. In addition, a potential run at the Higgs mass pole, $\sqrt{s} = 125$ GeV, has been proposed as a means to measure the electron Yukawa coupling [8]. This latter run, if ever realised, would also provide an additional $\mathcal{O}(10^{10})$ hadronic events for QCD studies (Table 2, rightmost column).

Table 2: Characteristics of the HFS samples to be collected in ISR events at the Z pole, in two potential (1 month long) low-energy runs at $\sqrt{s} = 40,\ 60$ GeV [7], and in a proposed Higgs-mass run at $\sqrt{s} = 125$ GeV [8]. For each run, the $\sqrt{s_{\rm had}}$ probed, the $\rm e^+e^- \to q\bar{q}$ cross section, the expected number of events, and the maximum jet energies reached are listed.

Run	Z pole (ISR events)	40-GeV	60-GeV	$\rm e^+e^- \to H$
$\sqrt{s}$	88, 91, 94 GeV	40 GeV	60 GeV	125 GeV
time	4 years	1 month	1 month	3 years
$\mathcal{L}_{\rm int}$ (ab^{-1})	205	3.5	6.2	≈100
$\sigma(\rm e^+e^- \to q\bar{q})$	Depending on ISR selection criteria [7]	289 pb	162 pb	104 pb
$\sqrt{s_{\rm had}}$	20–80 GeV	40 GeV	60 GeV	125 GeV
$N_{\rm evts}$ (HFS)	$\mathcal{O}(10^9)$	$\mathcal{O}(10^9)$	$\mathcal{O}(10^9)$	$\mathcal{O}(10^{10})$
$E_{\rm j}$ (max. jet scale probed)	10–40 GeV	20 GeV	30 GeV	62 GeV

The exceptional number of EW bosons to be collected, as well as the exquisite control of the beam energy, and the possibility to run at the $\rm t\bar{t}$ threshold, allow carrying out measurements of fundamental SM quantities with statistical uncertainties improved by factors of 50–1000 compared to their current world averages. Table 3 lists the present precision and expected FCC-ee statistical and systematic uncertainties for key Z, W, top, and tau observables that can be used to extract fundamental QCD parameters, such as $\alpha_{\rm S}(m_{\rm Z}^2)$, and/or that are affected by QCD effects that need to be much better understood theoretically.

The detectors specifications needed to achieve experimental systematic uncertainties approaching the statistical precision will translate into unprecedented performance for jet flavour identification and energy resolution, aiming at precisely measuring the Z, W, H and top quark hadronic decays. Jets are

Table 3: Key experimental SM measurements with Z, W, top, and tau particles at FCC-ee, where QCD effects have an impact and/or from which precision QCD observables/quantities can be measured/extracted. For each observable, their present world-average precision, the foreseen FCC-ee statistical and systematic uncertainties, the method used in the measurement and leading uncertainty are listed.

Observable	present value	±	uncert.	FCC-ee **Stat.**	FCC-ee Syst.	Measurement method(s) leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	Z lineshape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	Z lineshape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadronic to leptonic decays Acceptance for leptons
σ^0_{had} ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.30	Ratio of $b\bar{b}$ to all-hadronic decays Stat. extrapol. from SLD
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole Jet charge determination
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	WW threshold scan and m_{inv} in W decays EW theory uncertainties dominate
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	WW threshold scan and m_{inv} in W decays EW theory uncertainties dominate
$\mathcal{B}(W \to \ell\nu_\ell)$ (%)	10.86	±	0.09	**0.001**	0.001	W decays EW theory uncertainties dominate
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	$t\bar{t}$ threshold scan pQCD scale uncertainties dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	pQCD scale uncertainties dominate
m_τ (MeV)	1 776.93	±	0.09	**0.002**	0.02	$Z \to \tau^+\tau^-$ decays estimator bias, ISR, FSR
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
$\mathcal{B}(\tau \to \mu\nu_\mu\nu_\tau)$ (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency

reconstructed, in this case, using the Durham algorithm [9] in the exclusive mode, i.e., clustering all particles in the event in a predefined number of (decay) jets. Advanced jet flavour taggers have been developed, such as ParticleNet (based on a graph neural network) [10, 11], and DeepJetTransformer [12] and ParticleTransformer [13] (based on transformer neural networks), that assign each jet a probability of originating from one of seven particle types: gluon (g), up (u), down (d), strange (s), charm (c), bottom (b), or hadronic tau (τ_h). The taggers use the information of all particle-flow candidates within a jet, including kinematics, track impact parameter, and particle identification (cluster-counting and time-of-flight) information. Table 4 shows typical working points in the efficiency-mistagging matrix for a ParticleTransformer q-tagger, trained on $e^+e^- \to Z(\nu\nu)H$ with $H \to jj$ events, where ϵ_j^q denotes the binary probability to tag a given jet of type $j = \{b, s, c, u, d, g\}$ as a jet of type q. The tagging efficiency is here indicatively fixed to $\epsilon_q^q = 80\%$, and the corresponding mistagging probabilities ϵ_j^q for $j \neq q$, are listed. Realistic jet-flavour analyses will exploit the full ROC tagging information [14]. The achieved jet-flavour (mis)tagging efficiencies for heavy quarks are more than ten times better than the current state-of-the-art at the LHC. The jet-flavour algorithms will be trained directly on data by exploiting the vast $Z \to q\bar{q}$ samples, $\mathcal{O}(10^{11})$ per diquark decay, in events where one jet flavour is tagged with ultrahigh purity (but, potentially, very low efficiency) thereby fixing the flavour of the "probe" jet on the away-side.

In this note, a few key examples that showcase the QCD programme at FCC-ee are discussed including $\alpha_S(m_Z^2)$ extractions, QCD effects on the m_W and m_{top} measurements, QCD in Higgs hadronic decays, and developments needed in the modelling of Monte Carlo (MC) parton showers. Many other important QCD studies, such as $Z \to q\bar{q}$ asymmetries [15–17]; production of quarkonia, heavy baryons,

Table 4: Representative jet-flavour tagging working points, obtained with ParticleTransformer [13] and realistic FCC-ee detector simulations [14], for a fixed 80% efficiency for any given parton flavour. The $\epsilon_{\mathrm{j}}^{\mathrm{q}}$ symbol indicates the probability to tag a jet of flavour j as a jet of flavour q, with $\mathrm{j}, \mathrm{q} = \mathrm{b}, \mathrm{c}, \mathrm{s}, \mathrm{u}, \mathrm{d}, \mathrm{g}$.

Jet flavour tagg. probab.	b quark	c quark	s quark	u quark	d quark	gluon
$\epsilon_{\mathrm{j}}^{\mathrm{b}}$	0.8	1.2×10^{-3}	1.0×10^{-4}	1.6×10^{-4}	1.8×10^{-4}	5.5×10^{-3}
$\epsilon_{\mathrm{j}}^{\mathrm{c}}$	0.014	0.8	1.6×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	0.015
$\epsilon_{\mathrm{j}}^{\mathrm{s}}$	2.4×10^{-3}	4.5×10^{-3}	0.8	0.21	0.24	0.12
$\epsilon_{\mathrm{j}}^{\mathrm{u}}$	3.0×10^{-3}	0.029	0.21	0.8	0.67	0.18
$\epsilon_{\mathrm{j}}^{\mathrm{d}}$	3.1×10^{-3}	0.030	0.24	0.67	0.8	0.18
$\epsilon_{\mathrm{j}}^{\mathrm{g}}$	0.012	0.041	0.12	0.18	0.18	0.8

and multiquark or other rare/exotic states [18–21]; exclusive hadronic decays of the H, Z, W bosons, and top quark [22]; running of quark masses [23]; among others, are not covered for lack of space. The document ends with a summary of QCD physics opportunities at FCC-hh [24], in particular with heavy-ions and far-forward detectors.

2 Determinations of the strong coupling constant

The very large FCC-ee integrated luminosities at the Z pole and WW thresholds provide multiple observables for precise determinations of the strong coupling constant $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}^2)$ [25,26]. An obvious motivation for higher precision in $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}^2)$ is the associated reduction in parametric uncertainties that it brings in theoretical calculations for FCC-ee, of which the error in the QCD coupling often constitutes a source of uncertainty (e.g. the $\mathrm{e^+e^-} \to \mathrm{t\bar{t}}$ cross section at threshold, or the $\mathrm{H} \to \mathrm{gg}$ partial width). The current world average [27] reaches a 0.8% uncertainty, $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}^2) = 0.1180 \pm 0.0009$, through a combination of several determinations from a range of datasets and observables. Its value and uncertainty are largely driven by highly precise extractions from lattice calculations [28], expected to be further improved by a factor of two in the next decade [29,30]. At FCC-ee, many observables can be used for precise extractions of α_{S}, among which the four highlighted in Table 5 are discussed next.

Table 5: Foreseen α_{S} extractions from $\mathrm{e^+e^-}$ data at FCC-ee: Present world-average and extraction method [27], expected FCC-ee statistical and systematic uncertainties (the two bottom categories need dedicated studies), and theory developments required to match the experimental precision.

Category	present $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}^2)$ $(\times 10^4)$ value ± uncertainty	FCC-ee Stat.	FCC-ee Syst.	Extraction method Theory developments needed
Z hadronic decays	1 208 ± 28	0.1	1	Combined R_ℓ^{Z}, Γ_{Z}, σ_{had}^0 fit $\mathcal{O}(\alpha_{\mathrm{S}}^5)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_{\mathrm{S}},\alpha^3)$, $\mathcal{O}(\alpha_{\mathrm{S}}^2,\alpha^2)$ corrs.
W hadronic decays	1 070 ± 350	2	2	Combined R_ℓ^{W}, Γ_{W} fit $\mathcal{O}(\alpha_{\mathrm{S}}^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_{\mathrm{S}},\alpha^3)$, $\mathcal{O}(\alpha_{\mathrm{S}}^2,\alpha^2)$ corrs.
τ hadronic decays	1 178 ± 19	$\ll$1	<10	Combined $\Gamma^{\tau,\mathrm{had}}$ and τ lifetime fit $\mathcal{O}(\alpha_{\mathrm{S}}^5)$, hadronisation corrections
Event shapes & jet rates	1 171 ± 31	$\ll$1	<10	Combination of event shapes and jet rates $\mathcal{O}(\alpha_{\mathrm{S}}^4)$, hadronisation corrections

Inclusive hadronic Z and W decays

The most precise determination at FCC-ee can be achieved from a combined fit of three inclusive pseudo-observables at the Z pole: the Z boson total width (Γ_{Z}, dominated by $\Gamma_{\mathrm{Z,had}}$), the total hadronic cross section at the resonance peak (σ_{had}^0), and the ratio of hadronic-to-leptonic branching fractions (R_ℓ^{Z}). These three pseudo-observables will be measured with 10^{-6}–10^{-5} experimental precision (Table 3), and are very suitable to extract α_{S} given their small sensitivity to hadronisation corrections, which scale with energy scale $\sqrt{s_{\rm had}}$ as $(\Lambda_{\rm QCD}/\sqrt{s_{\rm had}})^6$ [31]. With the 6×10^{12} Z bosons produced at FCC-ee, the total experimental uncertainty in $\alpha_{\rm S}$ extractions from fits of the above quantities is of the order of 0.1% [32]. Similar alternative extractions of $\alpha_{\rm S}$ at FCC-ee can be derived from W hadronic decays quantities ($\Gamma_{\rm W,had}$ and $R_\ell^{\rm W}$) [32, 33], whose experimental precision will be also improved by a factor of 100 compared to their current world averages (Table 3). The status of theory computations for these observables includes QCD corrections up to N^{4}LO [34–36], and N^{3}LO for massive bottom quarks in a power series in $m_{\rm b}^2/s_{\rm had}$ [37]. The knowledge of EW and mixed QCD-EW corrections is currently available at least up to two loops [38–44]. Existing studies on the $\alpha_{\rm S}$ extraction from the decay of EW bosons indicate that the calculation of higher-order corrections $\mathcal{O}(\alpha_{\rm S}^5)$, $\mathcal{O}(\alpha^3)$, and $\mathcal{O}(\alpha_{\rm S}, \alpha^3)$ or $\mathcal{O}(\alpha_{\rm S}^2, \alpha^2)$ for QCD, EW, and QCD $\oplus$ EW, respectively, will be critical to match the expected experimental precision [32].

Hadronic τ decays

The Z-pole run at FCC-ee will provide a data sample of $\mathcal{O}(4 \times 10^{11})$ tau leptons from $\rm Z \to \tau^+\tau^-$ decays (Table 1), whose properties (mass, lifetime, branching fractions, hadronic spectral functions) will be extracted with factors 50–500 improved statistical uncertainty compared to present world averages (Table 3). The determination of $\alpha_{\rm S}$ from the tau lepton data relies on measuring the ratio of hadronic to leptonic branching fractions, R_τ, and the tau lifetime, and fitting them to theoretical predictions that reach today a N^{4}LO perturbative accuracy [34, 36]. In both cases, the theory expressions depend on the value of m_τ, which introduces a parametric uncertainty that will be also negligible at FCC-ee. The R_τ fit procedure involves integrating spectral functions extracted from the tau hadronic decay invariant mass distributions and comparing them with theoretical predictions based on Finite Energy Sum Rules, which relate moments of the spectral function to the QCD parameters. By fitting the theoretical expressions to the experimental data, $\alpha_{\rm S}(m_\tau^2)$ is extracted, which can then be evolved to $\alpha_{\rm S}(m_{\rm Z}^2)$ using the Renormalisation Group Equations. The current experimental precision on $\alpha_{\rm S}(m_\tau^2)$ is about 1% [26], whose statistical uncertainty will be negligible at FCC-ee. Theoretically [45, 46], open questions remain concerning the treatment of NP effects [47–49], as well as the difference between extractions relying on contour-improved (CIPT) [50, 51] and fixed-order (FOPT) perturbation theory adopted in the fits [52, 53]. Recent investigations indicate that CIPT calculations might require a more robust estimate of NP corrections [52, 54, 55], with potential ways forward discussed in Refs. [56, 57]. A deeper understanding of these aspects, plus computing the next order in the perturbative expansion, $\mathcal{O}(\alpha_{\rm S}^5)$, is necessary for robust determinations of $\alpha_{\rm S}(m_{\rm Z}^2)$ from τ decays at FCC-ee, and must be pursued in the coming years.

Jet rates and event shape observables

The sensitivity to $\alpha_{\rm S}$ of differential observables measured in HFS, such as event shapes or jet rates, makes them suitable for precise extractions of the strong coupling [58–80]. These extractions rely on fitting accurate theoretical calculations [37, 61, 65, 66, 81–105] to experimental data [26]. The values of $\alpha_{\rm S}(m_{\rm Z}^2)$ obtained in such fits differ among each other by up to a few standard deviations (SDs). Different determinations rely on different observables, datasets, perturbative calculations, and modelling of hadronisation corrections. The latter typically induce $\mathcal{O}(\Lambda_{\rm QCD}/\sqrt{s_{\rm had}})$ effects on the observables used in the fit. These cannot be calculated from first principles, and are estimated with either MC models or analytic techniques [31, 106–117], with the latter providing a value of $\alpha_{\rm S}(m_{\rm Z}^2)$ that is up to 4% lower than the world average, with a tension that reaches the several-SDs level. This discrepancy is presently the subject of active discussions among experts [76, 77, 79, 80], where the main open points concern the precise assessment of hadronisation corrections in the theoretical predictions as well as the consistency of experimental data entering the fit. Future accurate measurements at FCC-ee will be crucial to shed light on this tension. New data collected at different CM energies and analysed with state-of-the-art methodologies (Table 2) will be instrumental to scrutinise existing extraction methodologies with full control over systematic uncertainties and correlations. Moreover, using the high-precision determination of $\alpha_{\rm S}(m_{\rm Z}^2)$ expected from inclusive Z decays as input parameter, event-shapes data can provide new insight into the accurate modelling of parton showers and hadronisation (both through analytic techniques and via MC generators), which is essential to the whole QCD programme at FCC-ee, such as in measurements of hadronic observables in $e^+e^- \to t\bar{t}$, $e^+e^- \to W^+W^-$, and $e^+e^- \to ZH$. In parallel with the modelling of hadronisation corrections, substantial advancements in high-order perturbative calculations for multijet cross sections are required for an optimal exploitation of the FCC-ee experimental programme.

Alternative approaches to the extraction of α_S at lepton colliders contemplate the design of observables with reduced sensitivity to hadronisation, e.g. via jet-substructure techniques [118, 119] that mitigate the impact of the obstacles discussed above. A detailed study of the effectiveness of these techniques at FCC-ee energies, as well as the precise estimate of the residual hadronisation corrections are highly desirable in the coming years to assess their potential [119, 120].

3 QCD effects on the measurement of the W-boson mass

The W boson mass (m_W) will be measured at FCC-ee through a threshold scan with dedicated runs at $\sqrt{s} = 157$ and $163\,\mathrm{GeV}$, in which the WW pair is produced (nearly) at rest. The W mass and width can be extracted with two methods. The first one uses a fit of the measured σ_{WW} vs. $\sqrt{s}$ lineshape to state-of-the-art theoretical predictions, treating m_W and Γ_W as free parameters [121]. In this case, the fully leptonic final state, $e^+e^- \to W^+W^- \to \ell\nu\,\ell\nu$, is experimentally preferred as it is subject to less backgrounds, and free from hadronic uncertainties. The second method is based on fits to the W-decay invariant mass distributions in different exclusive final states, with kinematic constraints [122]. Combining both methods, and taking into account the currently foreseen integrated luminosity (a factor of two larger than that used in Refs. [121, 122]), the final projected experimental precision on m_W will reach 0.24 MeV, roughly shared between statistical and systematic[3] uncertainties (Table 3).

Reaching the expected experimental precision on m_W, as extracted from the σ_{WW} vs. $\sqrt{s}$ lineshape, represents a formidable challenge for the field of precision calculations. Existing estimates [123] indicate that a theoretical uncertainty of 0.1% in the total cross section for $e^+e^- \to W^+W^-$ translates into a $\delta m_W \simeq 1.5$ MeV uncertainty in the W mass. Current state-of-the-art predictions [124, 125] reach a $\delta m_W \simeq 3$–5 MeV precision, whereas achieving an uncertainty $\delta m_W < 0.5$ MeV will require the calculation of the NNLO EW corrections (currently out of reach), as well as the inclusion of mixed EW-QCD [126] effects and a refined treatment of QED initial-state radiation [127]. Conversely, the impact of theoretical uncertainties in the direct m_W extraction via the reconstructed invariant mass of W boson decay products needs dedicated studies for a precise assessment. Among the leading theoretical systematics, NP effects in the hadronic decays of both W bosons are expected to play a role.

The WW-threshold run can be also exploited to improve the understanding of NP aspects of QCD, such as colour reconnection (CR), which accounts for final-state colour flow effects between the two hadronic decays of the two W bosons. In the absence of CR, the two $W \to q\bar{q}'$ systems should hadronise independently whereas, if CR occurs, the interaction between partons from different W bosons can modify the properties of their HFS distributions. The theoretical description of this phenomenon is done via phenomenological models [128, 129] implemented in MC generators. The measurement of key observables (where the precise m_W extracted from leptonic decays can be used as an input) in lepton + jets and fully hadronic WW decays at FCC-ee will benefit the development and tuning of such CR models.

4 QCD effects on the measurement of the top-quark mass

The properties of the top quark, in particular its mass (m_{top}) and width (Γ_{top}), will be studied at FCC-ee in a threshold scan with dedicated runs at $\sqrt{s} = 340, 345$ and $365\,\mathrm{GeV}$, in which the $t\bar{t}$ pair is produced (nearly) at rest. The top mass and width are extracted through a fit of the measured $\sigma_{t\bar{t}}$ vs. $\sqrt{s}$ lineshape to state-of-the-art theoretical predictions, leaving m_{top} and Γ_{top} as free-floating parameters. Suitable definitions of short-distance top-mass schemes, unaffected by infrared ambiguities [130–134], must be used for the $\sigma_{t\bar{t}}$ vs. $\sqrt{s}$ theoretical prediction. The potential-subtracted (PS) m_{top} scheme [133] is commonly used [135, 136]. Although NNLO and N^{3}LO fixed-order QCD calculations are available [137, 138],

[3]The systematic uncertainty is dominated by the centre-of-mass energy determination with resonant depolarisation.

the $\sigma_{t\bar{t}}$ threshold cross section is dominated by Coulomb interactions between the two quarks described within nonrelativistic QCD [139–141], valid in the regime in which the top quark velocity is of order α_S. Predictions in this framework include QCD effects up to N^{3}LO [142–144] approximate NNLL renormalisation-group improved corrections [145], and the inclusion of EW effects within an analogous EFT framework [146]. The description of the $W^+W^-b\bar{b}+X$ final state also requires including nonresonant channels without onshell top quarks. These nonresonant channels critically require embedding the aforementioned nonrelativistic EFT into the unstable particle EFT [147, 148], where current predictions reach NNLO accuracy [146]. The above state-of-the-art calculations, incorporated in the QQBAR_THRESHOLD code [142], have theoretical uncertainties from missing higher-order corrections, which propagate into $\mathcal{O}(35)$ MeV uncertainties on the extracted $m_{\text{top}}^{\text{PS}}$ value [149, 150].

Simulation studies analyse $t\bar{t}$ threshold data samples (including the expected FCC-ee beam energy spread (BES) with a standard deviation of 0.23% per beam) fitted to the QQBAR_THRESHOLD predictions with m_{top} and Γ_{top} left free, and with other parameters entering in the calculations constrained using Gaussian priors representing external constraints [150]. The value of $\alpha_S(m_Z^2)$ will be known within 10^{-4} from the Z pole run (Table 5) [32], while the value of top Yukawa coupling (y_t) is constrained within 3% according the expected HL-LHC precision [151]. The final foreseen experimental precision on m_{top} and Γ_{top} will be of about 7 and 13 MeV, respectively, dominated by statistical uncertainties (Table 3), whereas missing higher orders in the theoretical predictions amount to 35 (25) MeV on m_{top} (Γ_{top}) [150]. Achieving the theoretical precision to match the experimental uncertainties represents a formidable challenge for the field of precision QCD calculations, that goes far beyond the current state of the art. The next obstacles to be tackled in the coming years involve the computation of N^{4}LO corrections in the nonrelativistic EFT framework, as well as the description of QED effects at NNLL both in the collinear limit (e.g., ISR [152,153]) and in the soft limit (as discussed in Ref. [154]). Moreover, the optimal exploitation of the FCC-ee measurements might also require the N^{3}LO calculation for the nonresonant channels. The theoretical description of differential distributions is less accurate than that of the inclusive quantities just discussed, and reaches either NLO or NNLO accuracy only for specific observables [155, 156]. Further progress is needed in these computations, which are central to controlling precisely the effect of experimental cuts. Some aspects of these calculations pose considerable theoretical challenges, for instance regarding the differential calculations in the nonrelativistic limit, or the assessment of nonfactorisable radiative corrections to the decays of the two top quarks [157].

5 QCD in Higgs boson hadronic decays

Hadronic final states represent more than 80% of the total Higgs decays (including intermediate $H \to WW^*$, ZZ^* decays), but only the $H \to b\bar{b}$ channel will be probed at the HL-LHC. The clean experimental conditions at FCC-ee allow the study of hadronic decays of the Higgs boson, hence opening the possibility to constrain and measure its couplings to QCD partons. Differential observables measured in hadronic Higgs decays, such as event shapes and jet rates, are sensitive to new physics [158–162] and to gluon- and quark-Yukawa couplings, whose strength can be constrained both via indirect methods [163–165], or direct measurements by means of modern flavour-tagging techniques [11, 12]. A key example are recent studies of the extraction of the strange-quark Yukawa coupling by means of machine-learning techniques [166, 167], exploiting the significantly improved strange-jet tagging performance at FCC-ee (Table 4). Among the foreseen challenges in this measurement, a relevant theory bottleneck is the separation of the $H \to s\bar{s}$ decay from the Higgs (QCD- and EW-mediated) Dalitz decays characterised by gluon/photon splitting into a pair strange quarks, $H \to gg \to s\bar{s}g$ and $H \to \gamma\gamma \to s\bar{s}\gamma$. Initial investigations [168] indicate that this background can be drastically suppressed by a cut in the invariant mass of the pair of jets originating from the fragmentation of the two strange quarks, $m_{j_1j_2} \gtrsim 100$ GeV [169]. A robust theoretical control of the $H \to s\bar{s}$ signal in this region requires accurate perturbative calculations, as well as the resummation of logarithmic corrections stemming from soft-gluon radiation off the final-state strange quarks near the Higgs mass threshold, $m_{j_1j_2} \approx m_H$. Together with advancements in perturbative calculations, a second essential element is the development of improved hadronisation models to distinguish the fragmentation of (strange) quarks from that of gluons. Such models are instrumental for a reliable training of jet taggers (Table 4), and their calibration within future MC generators will highly benefit from the vast precise QCD datasets to be collected (Table 1).

The theoretical precision for the hadronic partial widths currently reach the per-cent level, with a parametric uncertainty in $\alpha_\mathrm{S}(m_\mathrm{Z}^2)$ that will be significantly reduced at FCC-ee with the expected 0.1% precision achieved from runs at the Z pole. In the case of $\mathrm{H} \to \mathrm{b\bar{b}}$, N^{4}LO QCD corrections are known in the limit of massless bottom quarks [36, 170, 171], and N^{4}LO QCD corrections to $\mathrm{H} \to \mathrm{gg}$ have been computed in the heavy-top limit [36]. Predictions for the differential $\mathrm{H} \to \mathrm{b\bar{b}}$ decay rate are known up to N^{3}LO in the limit of massless b quarks [172] and NNLO (and partially beyond) mass corrections are available [173–180]. Similarly, differential QCD predictions for $\mathrm{H} \to \mathrm{gg}$ are now available up to N^{3}LO in the large-top-mass limit [181, 182]. Finite quark mass corrections to $\mathrm{H} \to \mathrm{gg}$ are relevant at the level of precision foreseen at FCC-ee and could be included up to NNLO in QCD in the near future thanks to state-of-the-art calculations [174, 183–189]. Precision calculations of hadronic event shapes and jet rates in Higgs decays have been recently developed [182, 190–196], together with techniques for the treatment of quark-mass logarithms in gluonic decays [197–204]. Similarly to the Z boson case, hadronisation effects have a sizeable impact on event shapes and jet rates measured in HFS Higgs decays, confirming that improved modelling of hadronisation will be very beneficial for the FCC-ee Higgs programme.

6 QCD Parton Showers

Parton shower event generators [205] are crucial for the FCC-ee physics programme, enabling precise QCD and QED simulations for measurements, detector calibration, and training of analysis tools. Achieving the FCC-ee experimental precision requires next-generation MC tools with significantly improved theoretical accuracy. Simulating HFS events in MC generators involves three main stages: the hard scattering characterised by a large momentum transfer; the parton shower stage, in which the system evolves by radiating QCD partons towards lower momentum scales; and the NP stage, for the final transition of partons into hadrons.

A first area where substantial improvement is necessary concerns the formulation of parton shower algorithms, as current public tools are generally limited to leading logarithmic (LL) accuracy. The precision goals of FCC-ee requires at least NNLL accuracy. Recent advances, driven by linking parton showers with the field of QCD resummations, have achieved NLL accuracy for key observables [206–220], including an improved description of quark-mass effects [219]. Beyond NLL, key challenges include incorporating higher-order matrix elements [221–226], handling virtual corrections in soft and collinear limits [98, 226–230], and developing matching schemes that preserve the shower accuracy [231]. Recent progress has led to the first NNLL parton-shower algorithms for lepton colliders [232], suggesting fully general NNLL showers for FCC-ee applications within reach in the next decade. Standard parton-shower algorithms primarily rely on a semiclassical approach to the description of colour flow in the showering process, approximating soft quantum interference in parton fragmentation. To overcome this, ongoing research focuses on alternative algorithms that evolve the colour flow at the amplitude level [233, 234].

A second key area for improvement in MC generators is the simulation of hard scattering processes, entailing advanced QCD and EW perturbative calculations, and their integration with parton showers via matching techniques. Current matching methods, interface NLO [235–240] or NNLO [241–246] QCD calculations with LL showers, but recent progress in shower accuracy necessitates revisiting these techniques to preserve the accuracy beyond LL [231]. Additional challenges arise in matching schemes for unstable particle production near threshold (e.g., $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$, $\mathrm{e^+e^-} \to \mathrm{t\bar{t}}$), crucial for FCC-ee. While resonance-aware matching methods exist [156, 247, 248], incorporating a consistent description of the scale hierarchies in nonrelativistic decays remains an open problem.

A third area requiring advancement in MC generators for FCC-ee is the modelling of NP corrections, essential for describing light parton and heavy quark fragmentation which, in turn, is instrumental in the calibration of flavour-tagging algorithms. Improvements may come from refining existing models [249, 250] with higher-order parton showers or developing improved models based on, e.g., amplitude-evolution showers [251] and machine learning methods [252–254]. Tuning these models will benefit greatly from high-purity FCC-ee data samples enriched with specific parton flavours and hadronic measurements across various energy scales. Feasibility studies consider the possibility of collecting $\mathcal{O}(10^9)$ events across the $\sqrt{s_{\text{had}}} = 20$–$80\,\text{GeV}$ mass range via dedicated runs or ISR events off the Z-pole (Table 2). In addition, improved models of colour reconnection [128, 129], calibrated with FCC-ee data, are necessary to further improve the theoretical description of heavy resonance decays.

7 QCD physics opportunities at FCC-hh

The FCC-hh will offer unparalleled opportunities for QCD studies at partonic CM energies about ten times larger than those probed at the LHC, with vast datasets resulting from a tenfold increase in integrated luminosity. This will extend the pQCD kinematic reach significantly. Key highlights [5, 255, 256] include probing parton distribution functions (PDFs) at extremely small Bjorken-x, investigating beyond-DGLAP dynamics and parton saturation. Additionally, multi-TeV jets will test asymptotic freedom up to scales of $Q \approx 30$ TeV, and events with large jet multiplicities and vector boson + multijet processes will probe hard parton radiation and multiparton scatterings. Finally, large samples of boosted top-quarks, W, Z, and H bosons will enable studies of hadronic decays using jet substructure techniques.

Theoretical efforts will entail the combination of multi-loop QCD and electroweak calculations with high-precision PDFs at multi-TeV scales. Advancements in the description of the high-energy limit of QCD (e.g. the BFKL regime) will be required for predicting partonic scatterings at $x = 10^{-7}$. In the same regime, electroweak gauge bosons, leptons, and top quarks will be produced abundantly and incorporated into the PDFs alongside quarks and gluons providing a rich landscape for phenomenology.

7.1 Heavy-ion physics at FCC-hh

If suitable technological choices are made in the design of the FCC and its injectors, the collider will allow the study of nucleus-nucleus (AA) and proton-nucleus collisions up to nucleon-nucleon CM energies $\sqrt{s_{\text{NN}}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}\sqrt{s_{\text{pp}}}$. For a 100-TeV pp collider, this corresponds to $\sqrt{s_{\text{NN}}} = 39\,\text{TeV}$ for Pb-Pb and $64\,\text{TeV}$ for p-Pb collisions. Projected monthly integrated luminosity reach $100\,\text{nb}^{-1}$ for Pb-Pb [5] (Table 6). The FCC-hh extends the physics reach of HL-LHC by about one order in magnitude in both CM energy and luminosity. Exploratory studies [257, 258] have demonstrated that these conditions open up quantitatively novel opportunities for the study of the QCD high-temperature phase, the Quark Gluon Plasma (QGP). The increase in $\sqrt{s_{\text{NN}}}$ leads to a QGP phase that starts at significantly higher initial temperatures, lives significantly longer, and extends over a wider spatial region — with all three parameters being central for a detailed characterisation of essentially all partonic collective phenomena.

In AA collisions at FCC, the charm-quark will have thermal production rates and thus behave as an active degree of freedom of the plasma, thus changing bulk properties of the QGP. Thermally produced $\mathrm{c\bar{c}}$ pairs are expected to lead to an enhancement of the total charm hadron yield by up to 50%, compared to scaling from pp collisions: the measurement of this enhancement can provide a unique new sensitivity to the initial temperature of the QGP, which may reach $1\,\text{GeV}$ [257]. Abundantly produced electroweak gauge bosons and top quarks can be used to dope the QGP in novel, experimentally controlled ways, and numerous other opportunities for the study of hard probes have been identified. The reconstruction of the full decay topologies of high-momentum top-antitop events can provide, for the first time, a way to study the time-dependence of the QGP opacity to hard partons. Indeed, in the boosted decay chain $\mathrm{t} \to \mathrm{bW}$ and $\mathrm{W} \to \mathrm{q\bar{q}}$, the latter decay quarks interact with the QGP with a time delay of up to a few fm/c, increasing with the momentum of the top quark [259]. The heavy-ion programme at the FCC-hh also offers synergies with a wide range of other neighbouring physics fields, including unique opportunities for hadron spectroscopy, ultraperipheral collisions, and proton-nucleus collisions. For example, the measurement of top-antitop production in p-Pb collisions is expected to provide strong constraints on the gluon PDF in nuclei for $Q = m_{\text{top}}$ in a wide x range, up to $x = 0.7$ [260].

In the history of collider experiments with nuclear beams, all significant increases in CM energy have led to discoveries not anticipated before. Examples include the discovery of perfect fluidity at RHIC,

Table 6: Beam and machine parameters for heavy-ion operation in the *baseline* and *ultimate* scenarios, differing in the optical function β^* at the interaction point and bunch spacing [5].

	Unit	Baseline		Ultimate	
Collision mode	–	Pb-Pb	p-Pb	Pb-Pb	p-Pb
Number of Pb bunches	–	2760		5400	
Bunch spacing	[ns]	100		50	
Peak luminosity (1 experiment)	$[10^{27}\text{cm}^{-2}\text{s}^{-1}]$	80	13300	320	55500
Integrated luminosity (1 experiment, 1 month)	$[\text{nb}^{-1}]$	35	8000	110	29000

and of small-system parton collectivity at the LHC. For instance, the larger magnetic fields present in AA collisions at FCC will enable searches for manifestations of anomalous QCD hydrodynamics, such as manifestations of the chiral magnetic effect, with much higher sensitivity. Finally, the LHC discovery of small-system collectivity stresses the fundamental physics interest in extending the programme to cover p-A collisions. Beyond these scientific opportunities, the LHC provides an example of how the addition of a nuclear-beams programme to a hadron collider project can significantly increase the user base of the latter, and how it leads to R&D synergies in detectors and data analysis. The reasons above highlight the importance of designing FCC-hh and its injector chain such that it can serve the widemost scientific user community. Experiments at FCC should be in a position to address the broadest range of scientific questions that may come into experimental reach in the second part of the 21st century.

7.2 A forward-physics facility (FPF) at FCC-hh

The FCC-hh offers additional unique opportunities in QCD physics studies through the exploitation of the high-intensity beams of energetic particles, including neutrinos, produced in the forward region by pp collisions. A forward-physics facility (FPF) has been proposed at FCC-hh [261] following the LHC experience with the far-forward experiments FASER(ν) [262–265], SND@LHC [266, 267], and the proposed FPF [268, 269]. The enormous samples of multi-TeV neutrinos available at FPF@FCC will provide high-resolution deep-inelastic (DIS) probes of the unpolarised and polarised structure of protons and nuclei. First, high-energy neutrino DIS structure functions [270, 271] provide a precise quark/antiquark flavour separation at large x, which in turn reduces the theoretical uncertainties entering high-mass searches at FCC-hh. Second, neutrino DIS on a polarised target [272, 273] resolves the spin structure of the proton [274,275] providing complementary information to measurements at the Electron-Ion Collider [276]. Third, detecting neutrinos originating from p-Pb collisions provides information on nuclear structure [277–279] down to $x \approx 10^{-9}$, where nuclear PDFs are unconstrained and novel QCD regimes, such as gluon saturation, are expected to dominate. This kinematic region is also of prime importance for astroparticle physics experiments.

8 Conclusions

The exceptional capabilities of FCC will provide unique opportunities to probe the fine structure of the strong interaction and refine its theoretical description. Through its multifaceted physics programme, the FCC will shed new light on the behaviour of QCD in kinematic regimes that remain poorly understood, and significantly enhance the precision of theoretical predictions beyond the current state of the art. Such an unprecedented theoretical control will be pivotal for fully leveraging the vast amounts of data collected at FCC and achieving the anticipated precision in most critical measurements. While it will be years before the necessary QCD accuracy and precision goals are attained, the efforts initiated during the FCC feasibility study have begun defining a clear roadmap. The approval of the FCC project will catalyse the engagement of the strong-interaction theory community, fostering collaborative and synergistic efforts to achieve these objectives. The ongoing success in enhancing the precision of LHC predictions, beyond any previous expectation, gives confidence in the feasibility of these ambitious goals.

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