Perspectives for high-precision $\alpha_S(m_Z^2)$ determinations from future e^+e^- measurements at the FCC-ee

Letter of Interest submitted to Snowmass 2021

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Thematic Areas:

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
☐ (EF03) EW Physics: Heavy flavor and top quark physics
☐ (EF04) EW Physics: EW Precision Physics and constraining new physics
■ (EF05) QCD and strong interactions: Precision QCD
☐ (EF06) QCD and strong interactions:Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
☐ (EF08) BSM: Model specific explorations
☐ (EF09) BSM: More general explorations
☐ (EF10) BSM: Dark Matter at colliders

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The large amount of data expected to be recorded in e^+e^- collisions at the Future Circular Collider (FCC-ee) [1, 2] will offer multiple possibilities for unprecedented determinations of the strong coupling constant, $\alpha_S(m_Z^2)$, with per-mil uncertainties [3, 4, 5]. The experimental studies of hadronic observables, such as the R ratio [6, 7], tau decays [8, 9, 10]; Z and W decays [11, 12]; event shapes [13, 14, 15], and jet rates [16, 17]; hard [18, 19] and soft [20, 21] parton-to-hadron fragmentation functions; and the photon structure function $F_2^\gamma(x, Q^2)$ via photon-photon interactions [22], among others; combined with their careful analysis with the corresponding state-of-the-art perturbative QCD calculations, will provide accurate and precise $\alpha_S(m_Z^2)$ determinations.

The FCC-ee will deliver unparalleled samples of $5 \cdot 10^8$ W bosons and $3 \cdot 10^{12}$ Z bosons, decaying hadronically, in e^+e^- collisions at the Z pole ($\sqrt{s} \approx 91$ GeV) and WW threshold ($\sqrt{s} \approx 160$ GeV), respectively. The corresponding high-precision measurements of hadronic W and Z pseudo-observables (total widths, $\Gamma_{W,Z}$; ratio of hadronic-to-leptonic widths, R_ℓ; and peak hadronic cross section at the Z pole, σ_Z^{had}) will allow the extraction of the QCD coupling constant $\alpha_S(m_Z^2)$ with uncertainties below the 0.2% level [3, 12, 11] in a few different ways. With challengingly small statistical uncertainties, and accounting for the expected progress in the computation of theoretical higher-order N^{4}LO QCD $\mathcal{O}(\alpha_S^5)$, $\mathcal{O}(\alpha^2, \alpha^3)$ electroweak, and mixed QCD$\oplus$EW $\mathcal{O}(\alpha\alpha_S^2,\, \alpha\alpha_S^3,\, \alpha^2\alpha_S)$ corrections missing today, the leading propagated uncertainties on $\alpha_S(m_Z^2)$ will be of experimental systematic nature. The improvements on the detector design expected in order to match the systematic and statistical precision on Γ_Z, R_ℓ, and σ_Z^{had} [1] will be studied in order to determine the ultimate uncertainty eventually reachable in those $\alpha_S(m_Z^2)$ extractions at the FCC-ee.

For all extractions not depending on hadronic resonance (τ, Z, W) decays, measurements as a function of the invariant mass of the final hadronic system offer a self-normalized determination based on the QCD evolution equations. In this context, one can exploit the $3 \cdot 10^8$ e^+e^- hadronic events expected in the Higgs and top-quark operation runs at $\sqrt{s} \approx 240$ and 365 GeV, respectively. For analyses at lower energies than the Z pole, two specific possibilities have been considered in [23]. The first one is to organize data-taking from $\sqrt{s} \approx 30$ to 90 GeV center-of-mass energies, in such a way so as to record 10^9 $e^+e^- \to$ hadrons events at several intermediate energies. The second one consists in using the $e^+e^- \to \gamma +$ hadrons events with initial-state radiation (ISR) recorded from the foreseen data taking at and around the Z pole. The importance of detector design will be evaluated in particular regarding: i) the overall angular and momentum acceptance of the detector for hadrons, ISR, and (where relevant) scattered beam $e^\pm$; ii) the performance for flavoured (b/c/light-quark/gluon) jets reconstruction and corresponding mistagging probabilities; iii) the availability of light charged hadron ($\pi/K/p$) identification. The resulting detector requirements will be spelled out. The opportunities brought in by dedicated intermediate-energy runs for improving the detector calibration and checking the event simulations will be also investigated. This study might result in a more detailed FCC-ee running proposal.

For all methods above, theoretical developments are required in order to match the expected experimental precision, including computation of higher-order (both fixed-order and resummed log) QCD corrections, and non-perturbative QCD effects (hadronization, power-suppressed terms, hadron masses, etc.). The exploitation of modern jet substructure techniques to potentially improve the $\alpha_S(m_Z^2)$ determinations will be also considered and evaluated.

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