High-precision QCD physics at FCC-ee

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The Future Circular Collider (FCC) is a post-LHC project aiming at direct and indirect searches for physics beyond the SM in a new 100 km tunnel at CERN. In addition, the FCC-ee offers unique possibilities for high-precision studies of the strong interaction in the clean environment provided by $e^+e^-$ collisions, thanks to its broad span of center-of-mass energies ranging from the Z pole to the top-pair threshold, and its huge integrated luminosities yielding $10^{12}$ and $10^8$ jets from Z and W bosons decays, respectively, as well as $10^5$ pure gluon jets from Higgs boson decays. In this contribution, we will summarize studies on the impact the FCC-ee will have on our knowledge of the strong force including: (i) QCD coupling extractions with per-mille uncertainties, (ii) parton radiation and parton-to-hadron fragmentation functions, (iii) jet properties (light-quark-gluon discrimination, $e^+e^-$ event shapes and multijet rates, jet substructure, etc.), (iv) heavy-quark jets (dead cone effect, charm-bottom separation, gluon $\rightarrow c\bar{c}, b\bar{b}$ splitting, etc.); and (v) non-perturbative QCD phenomena (color reconnection, baryon and strangeness production, Bose-Einstein and Fermi-Dirac final-state correlations, etc.).
1. Introduction

A crucial aspect for many physics measurements is a precise understanding of Quantum Chromodynamics (QCD). An accurate determination of the strong coupling constant $\alpha_S$ is mandatory to improve the precision of the production cross sections and decays calculation. The computation of higher-order $N^n$LO and $N^n$LL resummation corrections is also central because it can increase the precision in observables predictivity. Another pivotal ingredient is a precise picture of jet substructure, parton showering, hadronization and colour reconnection, whose understanding benefits any hadronic final state.

The FCC-ee program [1], with its large integrated luminosities and clean environment, offers a rich QCD program. QCD studies with an unprecedented precision can be performed due to the large expected number of events at the FCC-ee of roughly $\sim 10^{11}$ $Z$ at $\sqrt{s} = 91$ GeV, $\sim 10^7$ $W^+W^-$ at $\sqrt{s} = 160$ GeV and $\sim 10^6$ $ZH$ at $\sqrt{s} = 240$ GeV.

2. The strong coupling constant

The least precisely known of all interaction coupling constants is $\alpha_S$, with an overall uncertainty at per-mille level, $\delta\alpha_S \sim 10^{-3}$. Currently, $\alpha_S$ is determined by comparing 7 experimental observables to perturbative QCD (pQCD) predictions, plus a global average at the $Z$ pole scale. The relevant observable for $e^+e^-$ collisions are $e^+e^-$ jet shapes and hadronic $\tau$ leptons and $W/Z$ bosons decays.

2.1 $\alpha_S$ from $e^+e^-$ event shapes and jet rates

As already done at LEP [2], the thrust ($\tau$) and the $C$-parameter defined in Eq. 1 can be used to extract $\alpha_S$:

$$\tau = 1 - T = 1 - \max \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

$$C = \frac{3}{2} \frac{\Sigma_{i,j} |\vec{p}_{i,j}| \sin^2 \theta_{i,j}}{(\Sigma |\vec{p}_i|)^2},$$

with $\theta_{i,j}$ the angle between particle $i$ and $j$ and $\vec{p}_{i,j}$ the momentum respectively. Other quantities which are sensitive to $\alpha_S$ are the $n$-jet rates, $R_n = \frac{\sigma_{n-jet}}{\sigma_{tot}}$, and therefore were used to extract the strong coupling constant. The comparison between the experimental measurements and $N^3$LO+$N^2$LL predictions yields $\alpha_S(m_Z) = 0.1171 \pm 0.0027$ ($\pm 2.6\%$).

At lower $\sqrt{s}$, the $n$-jet rates up to 7 jets could be studied, while runs at higher $\sqrt{s}$ could be used to study jet rates in regimes where the probability of hard gluon emission increases. Moreover, a better understanding of hadronization mechanism and improvements in logarithmic resummation to $N^3$LL for jet rates would allow the extraction of $\alpha_S$ at $\delta\alpha_S/\alpha_S < 1\%$ at the FCC-ee.

2.2 $\alpha_S$ from hadronic $\tau$ decays

The very precise LEP and B-factories $e^+e^- \rightarrow \tau^+\tau^-$ data, together with higher-order pQCD corrections to the hadronic $\tau$ width, allow a remarkably accurate $\alpha_S$ extraction from hadronic $\tau$ decays. The quantity of interest is the ratio of the hadronic $\tau$ width and the electron $\tau$ width, defined as follows:

$$R_\tau = \frac{\Gamma(\tau^- \rightarrow \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e)} = S_{EW} N C \left(1 + \Sigma_{n=1}^4 c_n \left(\frac{\alpha_S}{\pi}\right)^n + O(\alpha_S^5) + \delta_{np}\right),$$

where $S_{EW}$ is the electroweak factor, $N$ is the number of quark flavors, and $C$ is the Cabibbo-Kobayashi-Maskawa matrix element. The hadronic contribution is approximated by a power series in $\alpha_S$, and the leading term is $\propto \alpha_S^3$. The remaining terms are resummation effects, which are treated up to order $\alpha_S^5$.
High-precision QCD physics at FCC-ee
Francesco Giuli

Figure 1: $\Delta \chi^2$ fit profiles of the $\alpha_S(m_Z)$ extracted from the combined N$^3$LO analysis of the total $W$ width ($\Gamma_{\text{tot.}}$) and hadronic-to-leptonic $W$ decay ratio ($R_W$), compared to the current $\alpha_S(m_Z)$ world average (vertical orange band). Left: Extraction with the present $W$ data assuming (blue curve) or not (black curve) CKM unitarity. Right: Extraction expected at the FCC-ee, with the total (experimental, parametric, and theoretical in quadrature) uncertainties (outer parabola) and with the experimental uncertainties alone (inner parabola). These plots are taken from Ref. [3].

where $S_{EW}$ represents the pure electroweak (EW) contribution to the ratio, $N_C$ the number of colours, $c_n$ the coefficients of the perturbative expansion, and $\delta_{np}$ power-suppressed non-perturbative (NP) corrections. Experimentally, this ratio has determined with a $\pm 0.23\%$ precision, and this leads to a determination of $\alpha_S(m_Z) = 0.1187 \pm 0.0018$ ($\pm 1.5\%$).

The dominant source of theoretical uncertainty in the extraction of $\alpha_S$ comes from the discrepancy between the Fixed Order Perturbation Theory (FOPT) and the Contour-Improved Perturbation Theory (CIPT), two different approaches for evaluating the perturbative expansion. Currently, this uncertainty is at the level of $\pm 1.5\%$. NP correction are also relevant in the determination of $\alpha_S$ from hadronic $\tau$ decays. These can be sizeable for $O(\Lambda_{QCD}^2/m^2_\tau)$ and they can be controlled by new high-precision measurements of the hadronic $\tau$ spectral function. Statistical uncertainty will be negligible at the FCC-ee, considering the $\sim 10^{11}$ $\tau$ produced at the $Z$-pole, and parametric and systematic uncertainties will dominate. To fully exploit this huge statistics, a reduction in the spread of theoretical determinations of $R_\tau$ is mandatory. This necessarily implies a better understanding of the discrepancies arising from the CIPT and FOPT comparison. Furthermore, a better determination of the spectral functions entering the $R_\tau$ calculation is compulsory, and this can be achieved exploiting new data coming from Belle II or the FCC-ee itself. In this way, the uncertainty on $\alpha_S$ can be reduced well below the current $\delta\alpha_S/\alpha_S \sim 1\%$ level.

2.3 $\alpha_S$ from hadronic $W$ boson decays

Analogously to the case of the hadronic $\tau$ decays, the extraction of $\alpha_S$ from hadronic $W$ boson decays can be performed considering the ratio of the hadronic width to the lepton with, as described in Eq. 3

$$R_W(Q) = \frac{\Gamma_{\text{had}}^W(Q)}{\Gamma_{\text{lep}}^W(Q)} = R_{W}^{\text{EW}} \left( 1 + \sum_{i=1}^{4} a_i(Q) \left( \frac{\alpha_S(Q)}{\pi} \right)^i + O(\alpha_S^5) + \delta_{\text{mix}} + \delta_{np} \right)$$

(3)
High-precision QCD physics at FCC-ee

Francesco Giuli

Figure 2: $\Delta \chi^2$ fit profiles of $\alpha_S(m_Z)$ extracted from the combined $Z$ pseudo-observables analysis and/or the global SM fit compared to the current world average (orange band). Left: Current results (solid lines) compared to the previous 2018 fit (dashed lines). Right: Extraction expected at the FCC-ee - with central value (arbitrarily) set to $\alpha_S(m_Z) = 0.12030$ and total (experimental, parametric, and theoretical in quadrature) uncertainties (outer parabola) and experimental uncertainties alone (inner parabola) – compared to the present one from the combined $Z$ data (blue line). These plots are taken from Ref. [3].

with $R_{EW}^W$ representing the pure EW contribution to the ratio, $a_i(Q)$ the coefficients of the perturbative expansion, $\delta_{\text{mix}}$ the mixed QCD+EW corrections, and $\delta_{\text{np}}$ the power-suppressed NP corrections. $\alpha_S$ is then extracted at N$^3$LO from a simultaneous fit of 2 $W$ boson pseudo-observables [3]: $R_W$ and $\Gamma_W^{\text{tot}}$. With the assumption of CKM unitarity, a value of $\alpha_S(m_Z) = 0.101 \pm 0.027$ is obtained (with negligible theoretical and parametric uncertainties), as depicted in Fig. 1 (left). The large uncertainty is mostly due to the poor experimental knowledge of $R_W$ and $\Gamma_W^{\text{tot}}$, which have been measured in $e^+e^- \rightarrow W^+W^-$ LEP events. If CKM unitarity is not assumed, the resulting value of the strong coupling constant is basically unconstrained, as shown in Fig. 1 (left).

At the FCC-ee, the uncertainties on $R_W$ and $\Gamma_W^{\text{tot}}$ will be largely reduced, thanks to the high statistics at the $WW$ threshold. With a factor of 10 reduction of the theoretical uncertainties due to missing $a_5^2, a_3^3, a a_3^2$ and $a^2 a_5$ corrections, a final QCD coupling extraction of $\alpha_S(m_Z) = 0.11790 \pm 0.00023$ with 2 per-mille total error is possible, as illustrated in Fig. 1 (right).

2.4 $\alpha_S$ from hadronic $Z$ boson decays

Following the same procedure described in Sec. 2.3, $\alpha_S$ can be extracted at N$^3$LO from a simultaneous fit of 3 $Z$ boson pseudo-observables [3]: $R_Z$, $\Gamma_Z^{\text{tot}}$, and $\sigma_Z^{\text{had}}$, yielding $\alpha_S = 0.1203 \pm 0.0029$ (2.3%), as depicted in Fig. 2 (left).

Having $10^5$ times more $Z$ bosons than at LEP, together with an exquisite systematic and parametric precision would allow a remarkable improvement in the theoretical predictions of the $Z$ boson pseudo observables, and therefore a reduction in the strong coupling uncertainty by almost 2 orders of magnitude. This experimental precision has to be matched by a reduction in the theoretical uncertainties by almost a factor of 5 by computing missing $a_5^5, a^3, a a_5^2$ and $a^2 a_S$ corrections. In this way, $\alpha_S$ can be extracted with a 2 per-mille accuracy, namely $\alpha_S(m_Z) = 0.11790 \pm 0.00023$, as reported in Fig. 2 (right).
3. Jet substructure

Jet substructure studies play a crucial role in improving our knowledge of parton shower (PS) and hadronization mechanism. In particular, jet angularities [4], defined as $A_{\kappa}^{\beta} = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$ (with $z_i$ and $\theta_i$ representing the energy fraction and angular distance to jet axis of constituent $i$), constitute an intriguing starting point. The parameters $\kappa \geq 0$ and $\beta \geq 0$ regulate the energy and angular weighting respectively. Multiplicity ($\kappa = 0$, $\beta = 0$), width ($\kappa = 1$, $\beta = 1$), mass ($\kappa = 1$, $\beta = 2$), $p_T$ ($\kappa = 0$, $\beta = 2$) and Les Houches Angularity ($\kappa = 1$, $\beta = 0.5$) are the most common examples. Specifically, this last quantity offers an incredible opportunity to study different PS algorithms between generators. The FCC-ee would be crucial in addressing such differences in PS and hadronization modelling. For example, the gluon radiation patterns could be studied exploiting the expected $10^6 e^+e^- \rightarrow ZH (\rightarrow gg)$ events, together with the $e^+e^- \rightarrow Z \rightarrow b\bar{b}g$ events (assuming that $b$-jets are tagged with high efficiency. Therefore, these studies conducted at the FCC-ee would lead directly to improved MC tuning, together with a better understanding of NP QCD.

4. Quark-gluon tagging

One of the most exciting (but challenging) prospects in $pp$ collisions is light-quark gluon discrimination. Being able to efficiently identify the flavour of the parton which initiates the jet is critical for the success of the physics program of future EW factories [5]. An accurate light quark-gluon discrimination would allow precise Beyond the Standard Model (BSM) searches for signals without leptons, $b$- or top-quarks, as well as would produce an enhancement of light quark-rich signals i.e. $t\bar{t}H$ or pure EW $W/Z + jets$.

Recently, a new generation of advanced machine learning based jet tagging algorithms has been developed [6–9], bringing almost 2 orders of magnitude improvement in background rejection when comparing to the traditional approaches in Heavy Flavour and gluon tagging. In particular, within
the context of the FCC-ee, the ParticleNetIdea [10] has been developed, and Figure 3 shows its high performances in discriminating light quark jets from s-quark (left) and gluons (right).

5. Conclusion

To fully exploit present and future collider programs, a precise understanding of both perturbative and NP QCD is highly needed. At the FCC-ee, a plethora of unique QCD studies would be possible. Among them, the most relevant are the extraction of the strong coupling constant $\alpha_S$ from jet event shapes and hadronic $\tau/W/Z$ decays with a per mille level accuracy and jet substructure studies, which could greatly improve our current knowledge of parton shower and hadronization. Thanks to the large pure quark/gluon samples in the extremely clean environment of a lepton collider, precise quark-gluon discrimination studies would be carried out with a much better discriminating power than the one in $p\bar{p}/pp$ collisions. Finally, due to the large number of expected $e^+e^- \to W^+W^-$, the huge statistics ($\times 10^4$ LEP) could be exploited to measure the $W$ boson mass, $m_W$, both (semi-)leptonically and hadronically to constrain colour reconnection at the 1% level or below.

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