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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.).

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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 α_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 constant is α_S, with an overall uncertainty at per-mille level, $\delta\alpha_S \sim 10^{-3}$. Currently, α_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 τ leptons and W/Z bosons decays.

2.1 α_S from e^+e^- event shapes and jet rates

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

$$\tau = 1 - T = 1 - \max_{\hat{n}} \frac{\Sigma|\vec{p}_i \cdot \hat{n}|}{\Sigma|\vec{p}_i|} \qquad C = \frac{3}{2}\frac{\Sigma_{i,j}|\vec{p}_i||\vec{p}_j|\sin^2\theta_{i,j}}{(\Sigma_i|\vec{p}_i|)^2}, \tag{1}$$

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 α_S are the n-jet rates, $R_n = \frac{\sigma_{n-\text{jet}}}{\sigma_{\text{tot}}}$, 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 α_S at $\delta\alpha_S/\alpha_S < 1\%$ at the FCC-ee.

2.2 α_S from hadronic τ decays

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

$$R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e} = S_{\text{EW}} N_{\text{C}} \left(1 + \Sigma_{n=1}^{4} c_n \left(\frac{\alpha_S}{\pi}\right)^n + O(\alpha_S^5) + \delta_{\text{np}}\right), \tag{2}$$

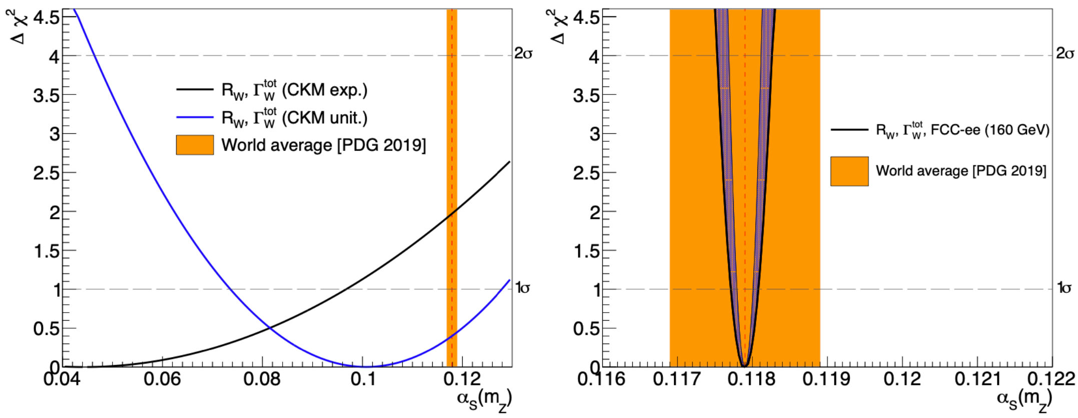

Figure 1: $\Delta\chi^2$ fit profiles of the $\alpha_S(m_Z)$ extracted from the combined N^{3}LO analysis of the total W width ($\Gamma_W^{\text{tot.}}$) and hadronic-to-leptonic W decay ratio (R_W), compared to the current $\alpha_S(m_Z)$ world average (vertical orange band). Left: Extraction with the 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 δ_{np} power-suppressed non-perturbative (NP) corrections. Experimentally, this ratio has determined with a ± 0.23% precision, and this leads to a determination of $\alpha_S(m_Z) = 0.1187 \pm 0.0018$ (± 1.5%).
The dominant source of theoretical uncertainty in the extraction of α_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 ± 1.5%. NP correction are also relevant in the determination of α_S from hadronic τ decays. These can be sizeable for $O(\Lambda^2_{\text{QCD}}/m^2_\tau)$ and they can be controlled by new high-precision measurements of the hadronic τ spectral function.
Statistical uncertainty will be negligible at the FCC-ee, considering the $\sim 10^{11}$ τ 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_τ 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_τ 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 α_S can be reduced well below the current $\delta\alpha_S/\alpha_S \sim 1\%$ level.

2.3 α_{S} from hadronic W boson decays

Analogously to the case of the hadronic τ decays, the extraction of α_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

$$R_W(Q) = \frac{\Gamma_W^{\text{had.}}(Q)}{\Gamma_W^{\text{lep.}}(Q)} = R_W^{\text{EW}}\left(1 + \Sigma_{i=1}^4 a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + O(\alpha_S^5) + \delta_{\text{mix}} + \delta_{\text{np}}\right) \tag{3}$$

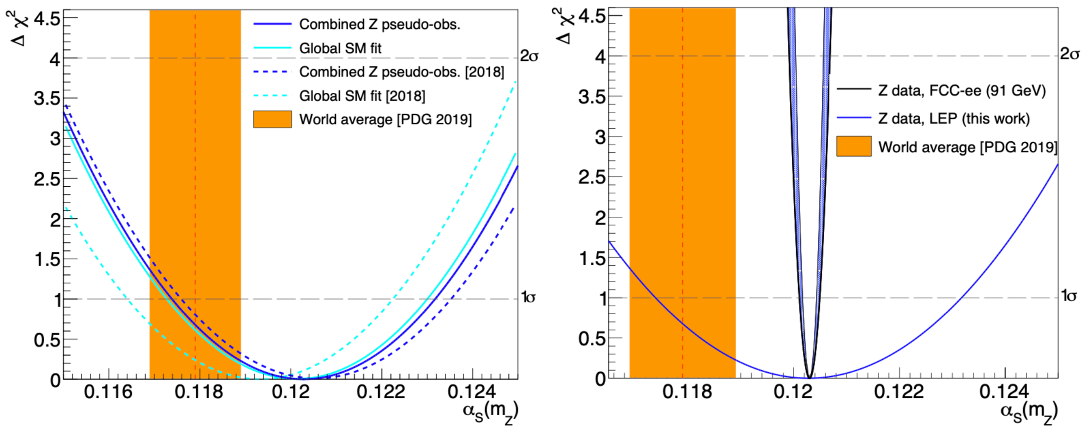

Figure 2: $\Delta\chi^2$ fit profiles of $\alpha_S(m_Z)$ extracted from the combined Z pseudo-observables analysis and/or the global SM fit compared to the current world average (orange band). Left: Current results (solid lines) compared to the previous 2018 fit (dashed lines). Right: Extraction expected 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 $R_W^{\rm EW}$ representing the pure EW contribution to the ratio, $a_i(Q)$ the coefficients of the perturbative expansion, $\delta_{\rm mix}$ the mixed QCD+EW corrections, and $\delta_{\rm np}$ the power-suppressed NP corrections. α_S is then extracted at N^{3}LO from a simultaneous fit of 2 W boson pseudo-observables [3]: R_W and $\Gamma_W^{\rm tot.}$. 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 $\Gamma_W^{\rm tot.}$, which have been measured in $e^+e^- \to W^+W^-$ 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 $\Gamma_W^{\rm tot.}$ 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 $\alpha_S^5, \alpha^3, \alpha\alpha_S^2$ and $\alpha^2\alpha_S$ 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 α_S from hadronic Z boson decays

Following the same procedure described in Sec. 2.3, α_S can be extracted at N^{3}LO from a simultaneous fit of 3 Z boson pseudo-observables [3]: R_Z, $\Gamma_Z^{\rm tot.}$ and $\sigma_Z^{\rm had.}$, yielding $\alpha_S = 0.1203 \pm 0.0029$ ($\pm$ 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 $\alpha_S^5, \alpha^3, \alpha\alpha_S^2$ and $\alpha^2\alpha_S$ corrections. In this way, α_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).

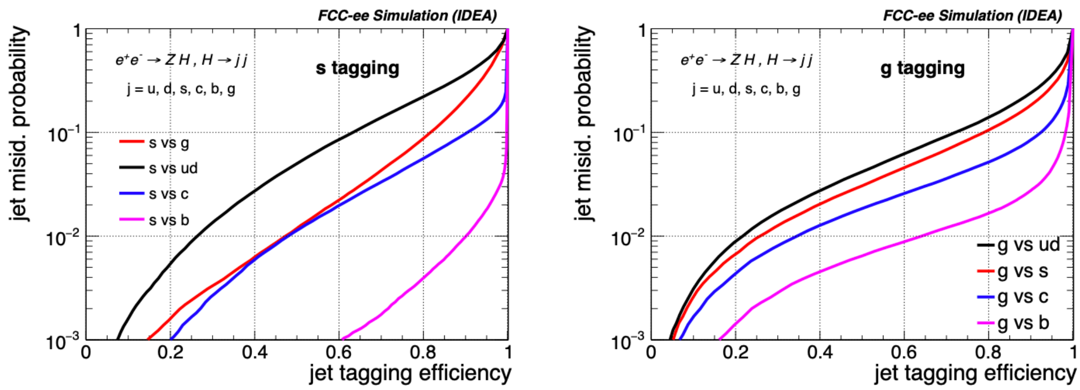

Figure 3: Evaluation of `ParticleNetIdea` performance in terms of a receiver operating characteristic (ROC) curve for the identification of different jet flavours i.e., s (left), and g (right). The different jet flavours considered background are indicated on the labels. The IDEA detector configuration is used. These plots are taken from Ref. [10].

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 $\lambda^{\kappa}_{\beta} = \Sigma_{i\in\mathrm{jet}} z_i^{\kappa}\theta_i^{\beta}$ (with z_i and θ_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 ($\kappa = 1, \beta = 2$), $p_{\mathrm{T}}^{\mathrm{D}}$ ($\kappa = 0, \beta = 2$) 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 patters could be studied exploiting the expected 10^6 $e^+e^- \to ZH(\to gg)$ events, together with the $e^+e^- \to Z \to b\bar{b}g$ 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

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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 α_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 $e^+e^- \rightarrow W^+W^-$, 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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