PROCEEDINGS OF SCIENCE

QCD and $\gamma\gamma$ studies at the FCC-ee

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The Future Circular Collider (FCC) is a post-LHC project aiming at searches for physics beyond the SM in a new 80–100 km tunnel at CERN. Running in its first phase as a very-high-luminosity electron-positron collider (FCC-ee), it will provide unique possibilities for indirect searches of new phenomena through high-precision tests of the SM. In addition, by collecting tens of ab^{-1} integrated luminosity in the range of cente-of-mass energies $\sqrt{s}$ =90–350 GeV, the FCC-ee also offers unique physics opportunities for precise measurements of QCD phenomena and of photon-photon collisions through, literally, billions of hadronic final states as well as unprecedented large fluxes of quasireal γ's radiated from the e^+e^- beams. We succinctly summarize the FCC-ee perspectives for high-precision extractions of the QCD coupling, for studies targeting QCD dynamics, and for SM and BSM studies through $\gamma\gamma$ collisions.

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1. Introduction

Electron-positron collisions at the FCC-ee not only provide unparalleled opportunities for electroweak and beyond standard model (BSM) physics [1], but also offer a vast landscape of possibilities for precise measurements of QCD phenomena and of photon-initiated processes. Beyond their intrinsic value, such measurements will also leave an important legacy for any subsequent hadron collider, much as that from LEP and other e^+e^- colliders provided crucial benchmark constraints e.g. on the Monte Carlo parton radiation/fragmentation models used at the LHC. The FCC-ee working group WG5[1] aims at quantitatively exploring all such potentialities, with a view to informing a CERN Yellow Report on FCC-ee physics in 2017. Briefly summarized, these are the WG5 physics goals:

1. Determine the best achievable experimental and theoretical precision on the extraction of the QCD coupling α_s [2,3].

2. Exploit the unique high-precision QCD physics opportunities in the clean e^+e^- environment, with a view to improving future studies at pp colliders, including studies of QCD multijets, jet substructure, quark-gluon discrimination, q,g,c,b,(t) parton-to-hadron fragmentations, colour reconnections, multiparticle correlations, and rare hadron production and decays.

3. Assess photon-photon ($\gamma\gamma$) physics possibilities for SM and BSM studies.

4. Set goals for subdetector performance (including forward $e^\pm$ taggers for $\gamma\gamma$ physics, particle identification for hadronization studies, jet resolution requirements for precision QCD, etc.) and experimental conditions so that systematic uncertainties are of similar magnitude as statistical uncertainties.

5. Define experimental/phenomenological software needs to enable the measurements and precision interpretations.

6. Help evaluating the QCD impact on the rest of the FCC-ee physics program. In particular, establish background event generators for QCD and $\gamma\gamma$ processes.

With the exception of α_s determinations, the target studies are only just beginning, hence the points below are intended mainly as exhortations, highlighting some of the exciting possibilities. To set the stage, Table 1 lists the expected event numbers per year and interaction point (IP), for Z, W W, Z H, and $t\bar{t}$ at the FCC-ee (compared with ILC [4] and LEP in the bottom panel). In addition to accessing the previously unreachable Z H and $t\bar{t}$ thresholds, both ILC and FCC-ee clearly offer vastly increased statistics with respect to LEP, not only for Z but, in particular, the available samples of W W events will increase from about 11 000 (per IP) integrated over the full LEP2 running period to tens of millions, enabling truly high-statistics $e^+e^- \to W^+W^-$ measurements for the first time. This will be a highly fruitful testing ground, e.g. for colour reconnection studies (likewise for $t\bar{t}$ events), see e.g. [5], and for precision W-based extractions of α_s, competitive with the determinations at the Z pole.

[1] Participation in FCC-ee WG5 is open to anyone interested in studies of QCD and/or $\gamma\gamma$ physics via the main FCC-ee site: `http://CERN.ch/FCC-ee` (join us, subscribe).

$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
σ	43 nb	290 ab	4 pb	200 fb	0.5 pb	25 fb
$\mathcal{L}$/IP (cm^{-2} s^{-1})	4.3·10^{36}	2.2·10^{36}	7.6·10^{35}	1.8·10^{35}	5·10^{34}	5·10^{34}
$\mathcal{L}_{\rm int}$ (ab^{-1}/yr, 2 IPs)	86	45	15	3.5	1.0	1.0
Events/year (2 IPs)	3.7·10^{12}	1.3·10^{4}	6.1·10^{7}	7.0·10^{5}	5·10^{5}	2.5·10^{4}
Years needed (2 IPs)	2.5	1.5	1	3	0.5	3

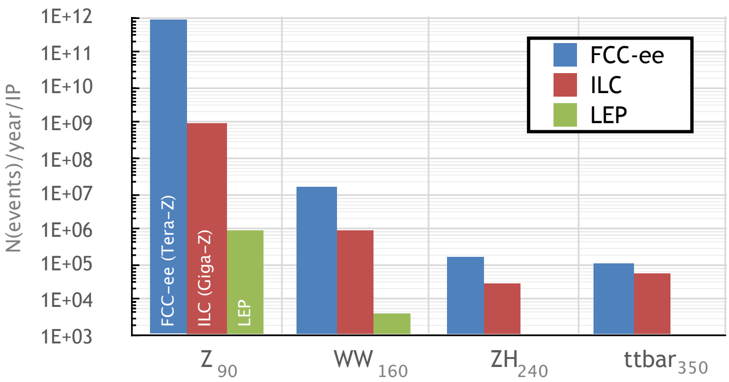

Figure 1: Top: Target luminosities, events/year, and years needed to complete the W, Z, H and top programs at FCC-ee. [$\mathscr{L}$ = 10^{35} cm^{-2} s^{-1} corresponds to $\mathscr{L}_{\rm int}$ = 1 ab^{-1}/yr for 1 yr = 10^{7} s] [6]. Bottom: Expected number of events/year, per interaction point, at the FCC-ee compared with ILC(Giga-Z) and LEP.

2. High-precision α_s determination

The combination of numerous high-precision hadronic observables will lead to an α_s determination with permille uncertainty at the FCC-ee as discussed in [2, 3]. First, the huge statistics of hadronic τ, W, and Z decays, studied with state-of-the-art perturbative calculations, will provide α_s extractions with very small uncertainties: $< 1\%$ from τ, and $<0.2\%$ from W and Z bosons. Fig. 2 left shows the expected result from the ratio of W hadronic/leptonic decays (R_W) alone [7]. In addition, the availability of millions of jets (billions at the Z pole) measured over a wide $\sqrt{s} \approx$ 90–350 GeV range, with light-quark/gluon/heavy-quark discrimination and reduced hadronization uncertainties (whose impact decreases roughly as $1/\sqrt{s}$), will provide α_s extractions with $<1\%$ precision from various independent observables: hard and soft fragmentation functions, jet rates, and event shapes. Last but not least, $\gamma\gamma \to$ hadrons collisions will allow for an accurate extraction of the QCD photon structure function (F_2^γ) and thereby of α_s.

3. High-Precision QCD studies

The extremely large event numbers for hadronic Z decays also make it possible to conceive very precise measurements of multijets (potentially applying aggressive cuts to probe topologies of specific interest, such as "hedgehogs" sensitive to multi-partonic coherence effects [9]), gluon- and b-jet fragmentation (including $g \to b\bar{b}$ splittings), and colour-reconnection effects inside Z decays. Importantly, good particle-identification capabilities would open up a whole world of detailed measurements to constrain the nature of hadronization, shining light on the confinement mechanism in QCD, and its dependence on quark and hadron masses and quantum numbers, with better statistics and reduced systematics compared with equivalent measurements from earlier e^+e^- colliders.

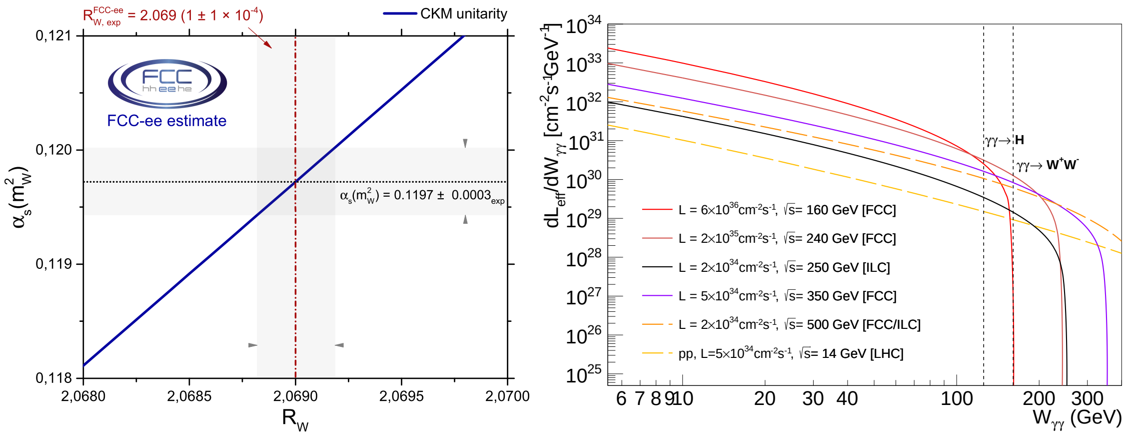

Figure 2: Left: Extraction of α_s from the hadronic/leptonic W decay ratio (R_W) expected at the FCC-ee [7]. Right: Effective two-photon luminosities as a function of $\gamma\gamma$ CM energy at FCC-ee, ILC, and pp at the LHC, for their nominal beam luminosities (vertical lines show $\gamma\gamma \to H, W^+W^-$ production thresholds) [8].

This includes not only single-particle spectra and multiplicities, but also measurements of Bose-Einstein, Fermi-Dirac, rapidity, spin, and flavour correlations. Proof-of-concept phenomenology studies are needed in all these areas. Searches can also be undertaken for the production of very rare hadrons which require the "coalescence" of multiple perturbatively created quarks, such as double- or triple-(c,b) baryons, in addition to the more traditionally studied onia states, the latter of which can be created from a single $g \to Q\bar{Q}$ splitting followed by colour reconnection.

Especially for jet rates and jet substructure measurements, it will be crucial to establish how the improvements in detector resolution, in conjunction with modern analysis techniques, will impact the achievable systematic uncertainties. For a representative value of Durham $k_T \sim 4.8$ GeV (large enough to effectively suppress hadronization corrections but small enough to allow significant event numbers), already the LEP statistics of order 1M hadronic Z decay events yield a statistical precision on the total jet rates below the 1% level for up to 6 jets, see Table 1.

N_J	3	4	5	6
$\geq N_J$ (incl)	640k	240k	60k	10k
N_J (excl)	400k	180k	50k	

Table 1: Number of N_J-jet events per 1M hadronic Z decays, for $\ln(y_{\rm cut}) = \ln(k_T^2/E_{\rm CM}^2) = -5.9$.

However, the systematic uncertainties at LEP were roughly an order of magnitude larger, with the existing measurements typically exhibiting a 10% or larger total uncertainty [10]. This is already now becoming insufficient to discriminate between the current state-of-the-art calculations and MC models [11], let alone those that will be around a few decades from now. Better calorimetric resolutions and use of more advanced analysis techniques, such as particle flow, are expected to make it possible to reduce these errors substantially. The larger statistics will allow probing higher k_T values as well as placing cuts to focus on specific topologies within these samples, and measure e.g. substructure- or coherence-sensitive observables with high precision, revealing details of quark & gluon jet (sub)structure beyond the (N)LL level and the patterns in which multiple soft (but perturbative) gluons are emitted from a system of N hard partons.

4. Photon-photon physics

Photon-fusion processes can also be studied exploiting the large flux of quasireal photons radiated from the e^+e^- beams, theoretically described using the effective photon approximation. The $\gamma\gamma$ kinematics can be constrained measuring the scattered $e^\pm$ with near-beam detectors, while the produced system is reconstructed from its decay products in the central detector. For $\gamma\gamma$ collisions, the available $e^\pm$ beam luminosity is reduced but nonetheless still substantial (Fig. 2, right). The $\gamma\gamma$ luminosity with more than 10% (50%) of the full CM energy is estimated to be about 1% (0.04%) of the e^+e^- one, allowing for precise studies of hadronic, W W, $\gamma\gamma$, and $\tau\tau$ final states, as well as about 100 $\gamma\gamma \to$ H events per ab^{-1} [8]. In the QCD sector, since $\sigma(\gamma\gamma \to \text{hadrons}) \propto 1/s$, at high $\sqrt{s}$ the rate of $\gamma\gamma$-induced hadronic events can actually be higher than the latter despite the factor 10^2–10^3 luminosity penalty, and the t-channel nature of the process may open an interesting window on BFKL-type ladders. In the electroweak sector, the measurement of $\gamma\gamma \to$ W W $\to$ 4 jets will yield more than 600 final counts which will allow for detailed studies of the trilinear W Wγ and quartic W W $\gamma\gamma$ couplings, either in the SM or assuming new physics scenarios in terms of dimension-6 and 8 effective operators [8].

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