6 $e^+e^- \to \gamma\gamma$ at large angles for FCC-ee luminometry

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Abstract

We examine large-angle two-photon production in e^+e^- annihilation as a possible process to monitor the luminosity of the FCC-ee. We review the current status of the theoretical predictions and perform an exploratory phenomenological study of the next-to-leading and higher-order QED corrections using the Monte Carlo event generator BabaYaga@NLO. We also consider the one-loop weak corrections, which are necessary to meet the high-precision requirements of the FCC-ee. Possible ways to approach the target theoretical accuracy are sketched.

6.1 Introduction

The successful accomplishment of the FCC-ee physics goals requires a detailed knowledge of the collider luminosity. The ambitious FCC-ee target is a luminosity measurement with a total error of the order of 10^{-4} (or even better) and calls for a major effort by both the experimental and theoretical community.

At the FCC-ee, the standard luminosity process is expected to be small-angle Bhabha scattering, likewise at the LEP. However, the process of large-angle two-photon production, i.e., $e^+e^- \to \gamma\gamma$, has also been recently proposed as a possible alternative normalization process for FCC-ee operation [1–3]. Actually, this is a purely QED process at leading order at any energy; it receives QED corrections from the initial state only and does not contain at order α the contribution due to the vacuum polarisation (in particular, hadronic loops), which enters at next-to-next-to-leading-order (NNLO) only. Conversely, the cross-section of $e^+e^- \to \gamma\gamma$ is significantly smaller than that of small-angle Bhabha scattering but adequate everywhere at the FCC-ee, with the exception of the running at the Z resonance. Moreover, the process is affected by a large background, owing to large-angle Bhabha scattering.

In spite of these limitations, the possibility of using photon-pair production as a luminosity process at the FCC-ee is an interesting option to be pursued. Contrarily to Bhabha scattering, which received a lot of attention over the past decades, there is rather scant theoretical literature about $e^+e^- \to \gamma\gamma$ annihilation and the most recent phenomenological results refer to e^+e^- colliders of moderate energies [4–7]. Moreover, the few available Monte Carlo (MC) generators [5, 7] are tailored for low-energy accelerators and need to be improved for the high-energy, high-precision requirements of the FCC-ee.

In this contribution, we provide a first assessment of the current status of the theoretical accuracy for large-angle two-photon production at FCC-ee energies. For this purpose, we use the MC program BabaYaga@nlo [5, 8–11], which includes next-to-leading-order (NLO) QED corrections matched to a QED parton shower, and compute the one-loop weak corrections

*This contribution should be cited as:
C.M. Carloni, M. Chiesa, G. Montagna, O. Nicrosini, F. Piccinini, $e^+e^- \to \gamma\gamma$ at large angles for FCC-ee luminometry, DOI: 10.23731/CYRM-2020-003.71, in: Theory for the FCC-ee, Eds. A. Blondel, J. Gluza, S. Jadach, P. Janot and T. Riemann,
CERN Yellow Reports: Monographs, CERN-2020-003, DOI: 10.23731/CYRM-2020-003, p. 71.

Table B.6.1: Two-photon production cross-section at LO, NLO, and higher-order QED corrections for four FCC-ee c.m. energies. Numbers in parentheses are the relative contributions of NLO and higher-order QED corrections.

$\sqrt{s}$ (GeV)	LO (pb)	NLO (pb)	Higher-order (pb)
91	39.821	41.043 [+3.07%]	40.868(3) [−0.44%]
160	12.881	13.291 [+3.18%]	13.228(1) [−0.49%]
240	5.7250	5.9120 [+3.26%]	5.884(2) [−0.49%]
365	2.4752	2.5582 [+3.35%]	2.5436(2) [−0.59%]

from heavy boson exchange. The QED corrections to $e^+e^- \to \gamma\gamma$ at order α were previously calculated some time ago [12–14] and NLO electroweak corrections are reported in Refs. [15–17]. A generator based on Ref. [14] was used at LEP for the analysis of photon-pair production at energies above the Z [18]. Here, we perform an exploratory phenomenological study of the QED corrections at NLO and evaluate the impact of higher-order contributions due to multiple photon emission, by considering typical values for the c.m. energies of the FCC-ee. Possible perspectives to achieve the target theoretical accuracy are briefly outlined.

6.2 Theoretical approach and numerical results

According to the theoretical formulation implemented in BabaYaga@nlo, the photonic corrections are computed using a fully exclusive QED parton shower matched to QED contributions at NLO. The matching of the parton shower ingredients with the NLO QED corrections is realised in such a way that its $O(\alpha)$ expansion reproduces the NLO cross-section, and exponentiation of the leading contributions owing to soft and collinear radiation is preserved, as in a pure parton shower algorithm. Various studies and comparisons with independent calculations [6, 11, 19] showed that this formulation enables a theoretical accuracy at a level of 0.1% (or slightly better) for the calculation of integrated cross-sections.

To meet the high-precision requirements of FCC-ee, we also computed the one-loop weak corrections due to heavy boson exchange. The calculation was performed by treating the ultraviolet divergencies in dimensional regularisation and using the computer program Recola [20], which internally adopts the Collier [21] library for the evaluation of one-loop scalar and tensor integrals. In our calculation, we used the on-shell renormalization scheme, with complex mass values for the heavy boson masses [22].

In the following, we show a sample of numerical results obtained using the code BabaYaga@nlo. They refer to four canonical c.m. energy values, which are representative of the expected FCC-ee operation programme (Z pole, WW, ZH, and $t\bar{t}$ thresholds)

$$\sqrt{s} = 91,\ 160,\ 240,\ 365\ \text{GeV} \tag{6.1}$$

To study the effects due to the QED corrections, we consider a simulation set-up, in which we require at least two photons within the angular acceptance $20^\circ \leq \theta_\gamma \leq 160^\circ$ with energy $E_\gamma \geq 0.25 \times \sqrt{s}$. In Table B.6.1, we examine the impact of the QED radiative corrections on the integrated cross-sections, when considering these kinematic cuts.

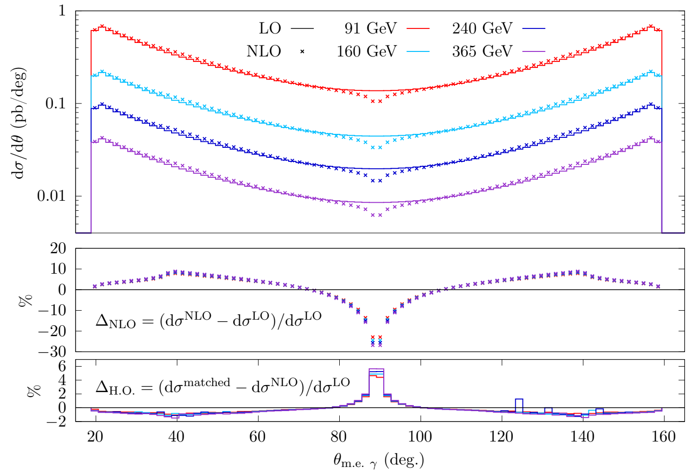

Fig. B.6.1: Top: Angular distribution of the most energetic photon, for four FCC-ee c.m. energies. Bottom: Relative contributions of NLO and higher-order QED corrections.

The photon-pair production cross-section is shown for different accuracy levels, i.e., at LO, NLO QED, and including higher-order contributions due to multiphoton radiation. The numbers in parentheses are the relative contributions due to NLO and higher-order QED corrections, respectively. It can be observed that the NLO corrections are at the level of a few percent, while the higher-order contributions amount to about 5‰ and reduce the effect due to $O(\alpha)$ corrections.

A representative example of the effects due to QED corrections on the differential cross-sections is given in Fig. B.6.1, which shows the angular distribution of the most energetic photon for the four energy points. One can see that the NLO corrections are particularly important in the central region, where they reach the 20–30% level, being mainly due to soft-photon radiation. This effect is partially compensated for by the higher-order corrections, which amount to some percent in the same region.

We also preliminarily explored the contribution of one-loop weak corrections, to conclude that their size is at the percentage level, i.e., roughly as large as QED contributions beyond NLO. A more detailed investigation of their effects is being made.

6.3 Summary and outlook

We have examined large-angle two-photon production in e^+e^- annihilation as a possible process to monitor the luminosity at the FCC-ee. We have assessed the present status of the theoretical accuracy through an exploratory phenomenological study of the radiative corrections to $e^+e^- \to \gamma\gamma$ annihilation at the c.m. energies of main interest. To this end, we have improved the theoretical content of the code BabaYaga@nlo, which includes exact NLO QED corrections matched to parton shower, by computing the weak corrections due to the presence of heavy bosons in the internal loops.

The accuracy of the present calculation can be estimated to be at the 0.1% level or slightly better. A first way to improve it is given by the calculation of NNLO fermion loop contributions, accompanied by the computation of the same-order real pair corrections, along the lines described in Refs. [19, 23]. This should be sufficient to get close to an accuracy at the 10^{-4} level. Beyond that, a full calculation of NNLO QED corrections and, eventually, of two-loop weak contributions will ultimately be needed to reach the challenging frontier of the 10 ppm theoretical accuracy. These developments are now under consideration.

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