11 Electron–positron annihilation processes in MCSANCee

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The Monte Carlo event generator `MCSANCee` is used to estimate the significance of polarisation effects in one-loop electroweak radiative corrections. The electron–positron annihilation processes $e^+e^- \to \mu^-\mu^+$ ($\tau^-\tau^+$, ZH) are considered, taking into account conditions of future colliders.

11.1 Introduction

Radiative corrections with effects due to polarisation of the initial particles will play an important role in the high-precision programme at the FCC-ee. `MCSANCee` is a Monte Carlo generator of unweighted events for polarised e^+e^- scattering and annihilation processes with complete one-loop electroweak (EW) corrections. The generator uses the adaptive Monte Carlo algorithm `mFOAM` [1], which is a part of the `ROOT` [2] framework.

The SANC computer system is capable of calculating cross-sections of general Standard Model (SM) processes with up to three final-state particles [3, 4]. Using the SANC system, we calculated electroweak radiative corrections at the one-loop level to the polarised Bhabha scattering [5, 6], which is the basic normalization process at e^+e^- colliders. For processes

$$e^+e^- \to \mu^-\mu^+ \; (\tau^-\tau^+, \, ZH)\,, \tag{11.1}$$

we made a few upgrades of the standard procedures in the SANC system. We investigated the effect of the polarisation degrees of initial particles on the differential cross-sections. We found that the EW corrections to the total cross-section range from −18% to +69%, when the centre-of-mass energy $\sqrt{s}$ varies in the set 250 GeV, 500 GeV, and 1 TeV.

11.2 Cross-section structure

The cross-section of a generic $2 \to 2(\gamma)$ process $e^+e^- \to X_3X_4(\gamma)$ ($X_3X_4 = \mu^-\mu^+, \tau^-\tau^+, ZH$) reads

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\sum_{\chi_1,\chi_2}(1+\chi_1 P_{e^-})(1+\chi_2 P_{e^+})\sigma_{\chi_1\chi_2},$$

where $\chi_i = -1(+1)$ corresponds to a lepton with left (right) helicity state.

The cross-section at the one-loop level can be divided into four parts:

$$\sigma^{1-\text{loop}} = \sigma^{\text{Born}} + \sigma^{\text{virt}}(\lambda) + \sigma^{\text{soft}}(\lambda,\omega) + \sigma^{\text{hard}}(\omega),$$

where σ^{Born} is the Born level cross-section, σ^{virt} is the virtual (loop) contribution, σ^{soft} is the contribution due to soft-photon emission, and σ^{hard} is the contribution due to hard photon

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emission (with energy $E_\gamma > \omega$). Auxiliary parameters λ ('photon mass') and ω cancel out after summation.

We treat all contributions using the helicity amplitudes approach:

$$\sigma^{\text{Part}}_{\chi_1\chi_2} = \frac{1}{2s} \sum_{\chi_i, i\geq 3} \left|\mathcal{H}^{\text{Part}}_{\chi_1\chi_2\chi_3,\dots}\right|^2 \text{dLIPS}, \tag{11.2}$$

where Part ∈ {Born, virt, hard}, and dLIPS is a volume element of the Lorentz-invariant phase space.

The soft-photon contribution is factorised in front of the Born level cross-section:

$$\text{d}\sigma^{\text{soft}}_{\chi_1\chi_2} = \text{d}\sigma^{\text{Born}}_{\chi_1\chi_2} \cdot \frac{\alpha}{2\pi} K^{\text{soft}}(\omega, \lambda).$$

11.3 Numerical results and comparison

The following input parameters are used for numerical estimates and comparisons:

$$\begin{aligned}
&\alpha^{-1}(0) = 137.035\,999\,76, \\
&M_{\text{W}} = 80.451\,495\,8 \text{ GeV}, \quad M_{\text{Z}} = 91.1876 \text{ GeV}, \quad \Gamma_{\text{Z}} = 2.499\,77 \text{ GeV}, \\
&m_{\text{e}} = 0.510\,999\,07 \text{ MeV}, \quad m_\mu = 0.105\,658\,389 \text{ GeV}, \quad m_\tau = 1.777\,05 \text{ GeV}, \\
&m_{\text{d}} = 0.083 \text{ GeV}, \quad m_{\text{s}} = 0.215 \text{ GeV}, \quad m_{\text{b}} = 4.7 \text{ GeV}, \\
&m_{\text{u}} = 0.062 \text{ GeV}, \quad m_{\text{c}} = 1.5 \text{ GeV}, \quad m_{\text{t}} = 173.8 \text{ GeV}.
\end{aligned}$$

The following simple cuts are imposed:

$$\begin{aligned}
|\cos\theta| &< 0.9, \\
E_\gamma &> 1 \text{ GeV} \quad \text{(for comparison of hard bremsstrahlung).}
\end{aligned}$$

Tuned comparison of our results for polarised Born and hard bremsstrahlung with the results of the `WHIZARD` [7] and `CalcHEP` [8] programs shows an agreement within statistical errors. The unpolarised *soft + virtual* contribution agrees with the results of Ref. [9] for $e^+e^- \to \mu^+\mu^-(\tau^+\tau^-)$ and with the ones of the `GRACE` system [10]. For $e^+e^- \to ZH$, we found an agreement with the results of the `GRACE` system [10] and with those given in Ref. [11].

The integrated cross-sections of Eq. (11.1) and the relative corrections δ are given in Tables C.11.1 [12] and C.11.2 [13] for various energies and beam polarisation degrees.

In these tables, we summarise the estimates of the Born and one-loop cross-sections and the relative corrections δ of the processes $e^+e^- \to \mu^+\mu^-, (\tau^+\tau^-, ZH)$ for the set (0, 0; −0.8, 0; −0.8, −0.6; −0.8, +0.6) of longitudinal polarisations P_{e^+} and P_{e^-} of the positron and electron beams, respectively. Values of energy 250, 500, and 1000 GeV were taken. The relative correction δ is defined as

$$\delta = \frac{\sigma^{\text{1-loop}} - \sigma^{\text{Born}}}{\sigma^{\text{Born}}} \cdot 100\%. \tag{11.3}$$

11.4 Conclusion

As can be seen from Tables C.11.1 and C.11.2, the difference between values of δ for polarisation degrees of initial particles (0, 0) and (−0.8, 0; −0.8, −0.6; −0.8, +0.6) amounts to a significant value: 6–20%.

Table C.11.1: Processes $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$: Born vs one loop

P_{e^-}, P_{e^+}	$\sigma^{Born}_{\mu^+\mu^-}$ (pb)	$\sigma^{1-loop}_{\mu^+\mu^-}$ (pb)	δ (%)	$\sigma^{Born}_{\tau^+\tau^-}$ (pb)	$\sigma^{1-loop}_{\tau^+\tau^-}$ (pb)	δ (%)
$\sqrt{s} = 250$ GeV						
0, 0	1.417(1)	2.397(1)	69.1(1)	1.417(1)	2.360(1)	66.5(1)
−0.8, 0	1.546(1)	2.614(1)	69.1(1)	1.546(1)	2.575(1)	66.5(1)
−0.8, −0.6	0.7690(2)	1.301(1)	69.2(1)	0.7692(1)	1.298(1)	68.8(1)
−0.8, +0.6	2.323(1)	3.927(1)	69.1(1)	2.324(1)	3.850(1)	65.7(1)
$\sqrt{s} = 500$ GeV						
0, 0	0.3436(1)	0.4696(1)	36.7(1)	0.3436(1)	0.4606(1)	34.0(3)
−0.8, 0	0.3716(1)	0.4953(1)	33.3(1)	0.3715(1)	0.4861(1)	30.8(1)
−0.8, −0.6	0.1857(1)	0.2506(1)	35.0(1)	0.1857(1)	0.2466(1)	32.8(1)
−0.8, +0.6	0.5575(1)	0.7399(1)	32.7(1)	0.5575(1)	0.7257(1)	30.1(1)
$\sqrt{s} = 1000$ GeV						
0, 0	0.085 35(1)	0.116 3(1)	36.2(1)	0.085 34(2)	0.113 4(1)	33.6(1)
−0.8, 0	0.092 13(1)	0.121 2(1)	31.6(1)	0.092 13(1)	0.118 85(2)	29.0(1)
−0.8, −0.6	0.046 08(1)	0.061 69(1)	33.9(1)	0.046 08(1)	0.060 67(1)	31.7(1)
−0.8, +0.6	0.138 2(1)	0.180 7(1)	30.8(1)	0.138 2(1)	0.177 0(1)	28.1(1)

Table C.11.2: Process $e^+e^- \to ZH$: Born vs one loop

P_{e^-}, P_{e^+}	σ^{Born}_{ZH} (pb)	σ^{1-loop}_{ZH} (pb)	δ (%)
$\sqrt{s} = 250$ GeV			
0, 0	205.64(1)	186.6(1)	−9.24(1)
−0.8, 0	242.55(1)	201.5(1)	−16.94(1)
−0.8, −0.6	116.16(1)	100.8(1)	−13.25(1)
−0.8, +0.6	368.93(1)	302.2(1)	−18.10(1)
$\sqrt{s} = 500$ GeV			
0, 0	51.447(1)	57.44(1)	11.65(1)
−0.8, 0	60.680(1)	62.71(1)	3.35(2)
−0.8, −0.6	29.061(1)	31.25(1)	7.54(1)
−0.8, +0.6	92.299(1)	94.17(2)	2.03(2)
$\sqrt{s} = 1000$ GeV			
0, 0	11.783(1)	12.92(1)	9.68(1)
−0.8, 0	13.898(1)	13.91(1)	0.10(2)
−0.8, −0.6	6.6559(1)	6.995(1)	5.09(2)
−0.8, +0.6	21.140(1)	20.83(1)	−1.47(2)

In assessing theoretical uncertainties for future e^+e^- colliders, it is necessary to achieve an accuracy of approximately 10^{-4} for many observables. Estimating the value of δ at different degrees of polarisation of the initial states, we see that taking beam polarisation into account is crucial.

Further development of the process library of the Monte Carlo generator MCSANCee involves $e^+e^- \to \gamma\gamma$ (plus cross-symmetric processes) and ('W fusion') $e^+e^- \to \nu_e\nu_e H$. We have started work on the introduction of higher-order corrections, as well as on the implementation of multiphoton emission contributions.

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