11 Electron-positron annihilation processes in MCSANCee

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

11.1 Introduction

Radiative corrections with effects due to polarization of the initial particles will play an important role in the high-precision program at the $\texttt{FCC}_{ee}$. `MCSANCee` is a Monte Carlo generator of unweighted events for polarized 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 to calculate cross-sections of general Standard Model (SM) processes with up to three final state particles [3, 4]. By using the SANC system, we calculated electroweak radiative corrections at the one-loop level to the polarized Bhabha scattering [5, 6] which is the basic normalization process at e^+e^- colliders. For processes

$$e^+e^- \to \mu^-\mu^+ \ (\tau^-\tau^+,\, ZH) \tag{11.149}$$

we made a few upgrades of the standard procedures in the SANC system. We investigated the effect of the polarization degrees of initial particles to the differential cross-sections. We found that the EW corrections to the total cross-section range from -18 percent to $+69$ percent. 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 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 due to soft photon emission, σ^{hard} is due to hard photon 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 (HA) approach:

$$\sigma^{\text{Part}}_{\chi_1\chi_2} = \frac{1}{2s}\sum_{\chi_i, i\geq 3}\Big|\mathcal{H}^{\text{Part}}_{\chi_1\chi_2\chi_3\ldots}|^2 d\text{LIPS}, \tag{11.150}$$

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

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

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

11.3 Numerical results and comparison

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

$$\begin{aligned}
&\alpha^{-1}(0) = 137.03599976,\\
&M_W = 80.4514958 \text{ GeV}, \quad M_Z = 91.1876 \text{ GeV}, \quad \Gamma_Z = 2.49977 \text{ GeV},\\
&m_e = 0.51099907 \text{ MeV}, \quad m_\mu = 0.105658389 \text{ GeV}, \quad m_\tau = 1.77705 \text{ GeV},\\
&m_d = 0.083 \text{ GeV}, \quad m_s = 0.215 \text{ GeV}, \quad m_b = 4.7 \text{ GeV},\\
&m_u = 0.062 \text{ GeV}, \quad m_c = 1.5 \text{ GeV}, \quad m_t = 173.8 \text{ GeV}.
\end{aligned}$$

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 polarized Born and hard Bremsstrahlung with the results `WHIZARD` [7], and `CalcHEP` [8] programs shows an agreement within statistical errors. Unpolarized *soft + virtual* contribution agree with the results of [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 the ones give in paper [11].

The integrated cross-sections of processes (11.149) and the relative corrections δ are given in the Tables C.9 [12], and C.10 [13] for various energies and beam polarization degrees.

In these Tables we summarize the estimation of the Born and one-loop cross-sections in pb and the relative corrections δ in percent 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 polarizations P_{e^+} and P_{e^-} of the positron and electron beams, respectively. The energy values 250, 500, and 1000 GeV were taken. The relative correction δ is defined as

$$\delta = \frac{\sigma^{\text{1-loop}} - \sigma^{\text{Born}}}{\sigma^{\text{Born}}} \cdot 100\%. \tag{11.151}$$

11.4 Conclusion

As can be seen from the Tables C.9 and C.10 the difference between values δ for polarization degrees of initial particles (0, 0) and (-0.8, 0; -0.8, -0.6; -0.8, +0.6) amounts a significant value: 6-20 %.

In assessing theoretical uncertainties for future e^+e^- colliders, it is necessary to achieve the accuracy of approximately 10^{-4} for many observables. Estimating the value δ at different

Table C.9: Processes $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$: Born vs 1-loop.

P_{e^-},	P_{e^+}	$\sigma^{\rm Born}_{\mu^+\mu^-}$, pb	$\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb	δ,%	$\sigma^{\rm Born}_{\tau^+\tau^-}$, pb	$\sigma^{\rm 1-loop}_{\tau^+\tau^-}$, 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	0.08535(1)	0.1163(1)	36.2(1)	0.08534(2)	0.1134(1)	33.6(1)
−0.8,	0	0.09213(1)	0.1212(1)	31.6(1)	0.09213(1)	0.11885(2)	29.0(1)
−0.8,	−0.6	0.04608(1)	0.06169(1)	33.9(1)	0.04608(1)	0.06067(1)	31.7(1)
−0.8,	+0.6	0.1382(1)	0.1807(1)	30.8(1)	0.1382(1)	0.1770(1)	28.1(1)

Table C.10: Process $e^+e^- \to ZH$: Born vs 1-loop.

P_{e^-},	P_{e^+}	$\sigma^{\rm Born}_{ZH}$, pb	$\sigma^{\rm 1-loop}_{ZH}$, 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)

degrees of polarization of the initial states, we see that taking into account beam polarization 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 the work on introduction of higher-order corrections, as well as on the implementation of multiphoton emission contributions.

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