ReneSANCe event generator for high-precision e^+e^- physics

Renat Sadykov†, Andrej Arbuzov†, Serge Bondarenko†, Yahor Dydyshka†,‡, Lidia Kalinovskaya†, Leonid Rumyantsev†, Vitaly Yermolchyk†,‡

†Joint Institute for Nuclear Research ‡Institute for Nuclear Problems BSU

Abstract

We present a new version of Monte Carlo event generator ReneSANCe. The generator takes into account complete one-loop electroweak (EW) corrections, higher order QED corrections in leading logarithm (LL) approximation and some higher order EW corrections to processes at e^+e^- colliders with finite particle masses and arbitrary polarizations of initial and final particles. ReneSANCe effectively operates in the full phase space for a wide range of center-of-mass energies.

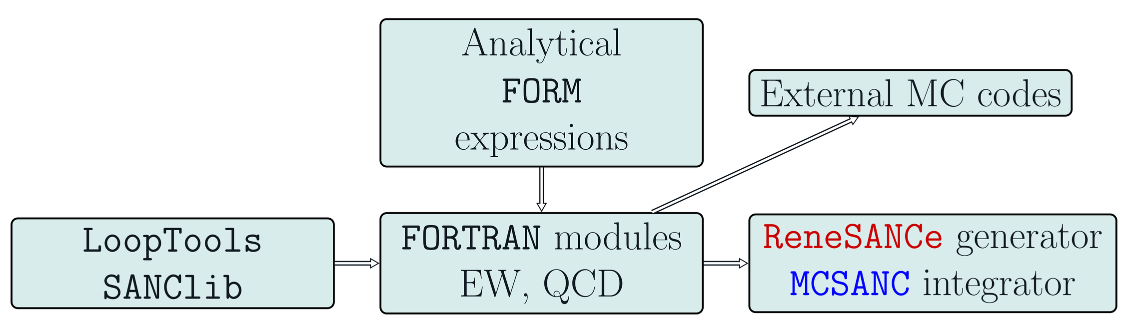
Introduction

Renewed SANC Monte Carlo event generator (ReneSANCe) [1] is a program for simulation of processes at e^+e^- colliders.

- The following processes are fully implemented:
  - Bhabha scattering ($e^+e^- \to e^-e^+$) [2]
  - Higgs-strahlung ($e^+e^- \to ZH$) [3, 4]
  - s-channel ($e^+e^- \to \mu^-\mu^+, \tau^-\tau^+$) [5]
- Based on the SANC modules [6]
- Complete one-loop and some higher-order electroweak radiative corrections
- All particle masses and polarizations
- Effectively operates in collinear regions and in wide range of center-of-mass energies
- New processes can be easily added

The SANC framework and products

The scheme of the SANC framework is shown in figure. Analytical expressions are obtained for the form factors and amplitudes of generalized processes $ffbb \to 0$, $4b \to 0$ and $4f \to 0$ and stored as FORM expressions. The latter are translated to FORTRAN modules for specific processes with NLO EW and QCD corrections. The modules are utilizing LoopTools and SANClib packages for loop integral evaluations.

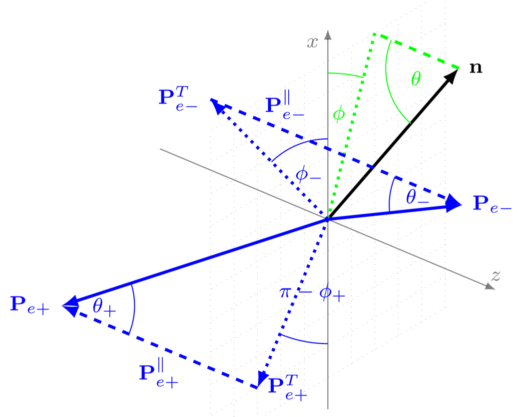


Polarization

The state of arbitrary polarization of initial e^+ and e^- can be described by polarization vectors

$$\vec{P}_{e^\pm} = (f_\pm \sin\theta_\pm \cos\phi_\pm, f_\pm \sin\theta_\pm \sin\phi_\pm, \pm f_\pm \cos\theta_\pm),$$

where $f_\pm \in [0;1]$ is the polarization degree, $\theta_\pm \in [0;\pi]$ is the polar angle, and $\phi_\pm \in [0;2\pi]$ is the azimuthal angle. The matrix element squared for a process with initial e^+ and e^- can be written as



$$|\mathcal{M}|^2 = \sum_{\lambda_{e^+}\lambda_{e^-}\lambda'_{e^+}\lambda'_{e^-}} \rho^{e^+}_{\lambda_{e^+}\lambda'_{e^+}} \rho^{e^-}_{\lambda_{e^-}\lambda'_{e^-}} \mathcal{H}_{\lambda_{e^+}\lambda_{e^-}} \mathcal{H}^*_{\lambda'_{e^+}\lambda'_{e^-}}$$

with helicity density matrices

$$\rho^{e^+} = 1/2 \begin{pmatrix} 1+P^{\parallel}_{e^+} & P^{\perp}_{e^+} e^{-i(\phi_+-\phi)} \\ P^{\perp}_{e^+} e^{i(\phi_+-\phi)} & 1+P^{\parallel}_{e^+} \end{pmatrix}, \quad \rho^{e^-} = 1/2 \begin{pmatrix} 1+P^{\parallel}_{e^-} & -P^{\perp}_{e^-} e^{i(\phi_--\phi)} \\ -P^{\perp}_{e^-} e^{-i(\phi_--\phi)} & 1+P^{\parallel}_{e^-} \end{pmatrix}.$$

Here $P^{\parallel}_{e^\pm} = \pm f_\pm \cos\theta_\pm$, $P^{\perp}_{e^\pm} = f_\pm \sin\theta_\pm$, and $\mathcal{H}_{\lambda_{e^+}\lambda_{e^-}}$ are helicity amplitudes (for details see the talk by Yahor Dydyshka) for a process with initial e^+ and e^-.

Cross section at one-loop level

The calculations are organized in a way to control consistency of result.

- Calculations at the one-loop precision level are realized in the unitary gauge and R_ξ gauge with three gauge parameters: ξ_A, ξ_Z and $\xi \equiv \xi_W$
- To parametrize ultraviolet divergences, dimensional regularization is used
- Loop integrals are expressed in terms of standard scalar Passarino-Veltman functions: A_0, B_0, C_0, D_0

These features make it possible to carry out several important checks at the level of analytical expressions, e.g., checking the gauge invariance by eliminating the dependence on the gauge parameter, checking cancellation of ultraviolet poles, as well as checking various symmetry properties and the Ward identities.
The cross section of processes at one-loop can be divided into four parts:

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

where σ^{Born} — Born level cross section, σ^{virt} — virtual (loop) corrections, σ^{soft} — soft photon bremsstrahlung, σ^{hard} — hard photon bremsstrahlung (with energy $E_\gamma > \omega$). Auxiliary parameters λ ("photon mass") and ω cancel out after summation.

Higher order improvements

- Higher order improvements added through $\Delta\rho$ parameter: $s_W^2 \to \bar{s}_W^2 \equiv s_W^2 + \Delta\rho\, c_W^2$.
  At the two-loop level, the quantity $\Delta\rho$ contains two contributions:

$$\Delta\rho = N_c X_t \left[1 + \rho^{(2)}\left(M_H^2/m_t^2\right) X_t\right] \left[1 - \frac{2\alpha_s(M_Z^2)}{9\pi}(\pi^2+3)\right],$$

  where $X_t = \sqrt{2} G_F m_t^2/(16\pi^2)$.
- The master formula for ISR corrections in the LL approximation:

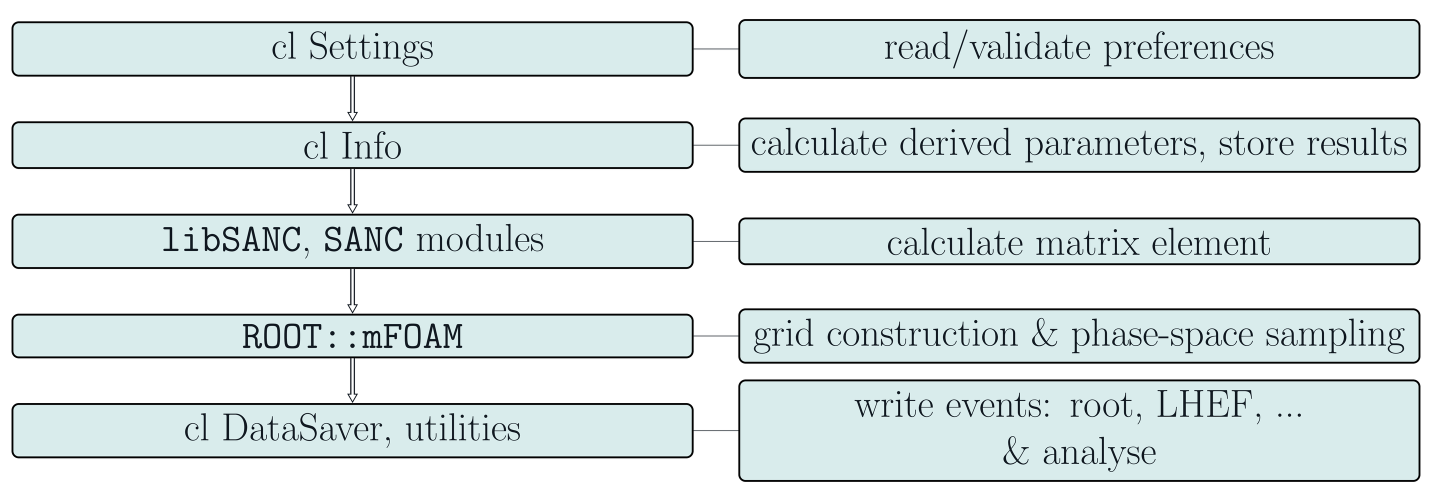
$$\sigma^{\text{LLA}} = \int_0^1 dx_1 \int_0^1 dx_2 \mathcal{D}_{ee}(x_1)\mathcal{D}_{ee}(x_2)\sigma_0(x_1,x_2,s)\Theta(\text{cuts}),$$

where $\sigma_0(x_1,x_2,s)$ is the Born level cross section of the annihilation process with reduced energies of the incoming particles. $\mathcal{D}_{ee}(x)$ describe the density of probability to find an electron with an energy fraction x in the initial electron.

$$\mathcal{D}_{ee}(x) = \mathcal{D}^{\gamma}_{ee}(x) + \mathcal{D}^{\text{pair}}_{ee}(x),$$
$$\mathcal{D}^{\gamma}_{ee}(x) = \delta(1-x) + \frac{\alpha}{2\pi}(L-1)P^{(1)}(x) + \left(\frac{\alpha}{2\pi}(L-1)\right)^2 \frac{1}{2!}P^{(2)}(x) + \left(\frac{\alpha}{2\pi}(L-1)\right)^3 \frac{1}{3!}P^{(3)}(x) + \left(\frac{\alpha}{2\pi}(L-1)\right)^4 \frac{1}{4!}P^{(4)}(x) + \mathcal{O}\left(\alpha^5 L^5\right),$$
$$\mathcal{D}^{\text{pair}}_{ee}(x) = \left(\frac{\alpha}{2\pi}L\right)^2 \left[\frac{1}{3}P^{(1)}(x) + \frac{1}{2}R_s(x)\right] + \left(\frac{\alpha}{2\pi}L\right)^3 \left[\frac{1}{3}P^{(2)}(x) + \frac{4}{27}P^{(1)}(x) + \frac{1}{3}R_p(x) - \frac{1}{9}R_s(x)\right] + \mathcal{O}\left(\alpha^4 L^4\right).$$

Pair corrections can be separated into singlet ($\sim R_{s,p}$) and non-singlet ones ($\sim P^{(n)}$). We take into account both by default. The large logarithm is $L = \ln(s/m_e^2)$, where $\sqrt{s}$ is chosen as factorization scale.

Code structure

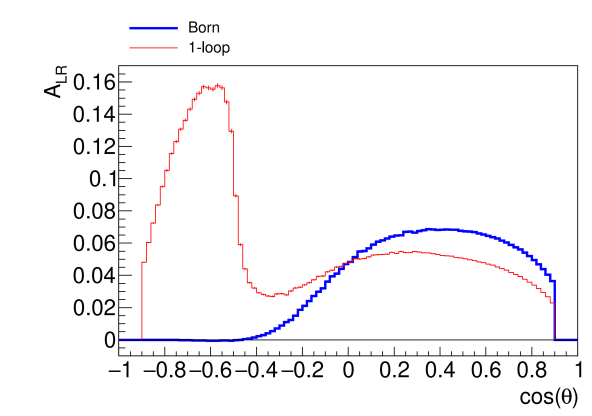


Some results

Tables: Born and one-loop cross sections and relative corrections $\delta = \sigma^{\text{1-loop}}/\sigma^{\text{Born}} - 1$.
Figures: distributions in $\cos\theta$ for left-right asymmetry $A_{\text{LR}} = (\sigma_{\text{RL}} - \sigma_{\text{LR}})/(\sigma_{\text{RL}} + \sigma_{\text{LR}})$

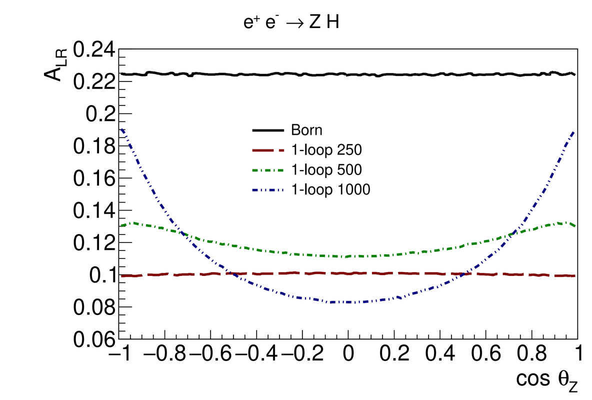
$e^+e^- \to e^-e^+$ at $\sqrt{s} = 250$ GeV, $|\cos\theta_{e^\pm}| < 0.9$

P_{e^+}, P_{e^-}	**0, 0**	0, −0.8	−0.6, −0.8	0.6, −0.8
σ^{Born}, pb	**56.676(1)**	57.774(1)	56.273(1)	59.275(1)
$\sigma^{\text{1-loop}}$, pb	**61.73(1)**	62.59(1)	61.88(1)	63.29(1)
δ,%	**8.9(1)**	8.3(1)	10.0(1)	6.8(1)



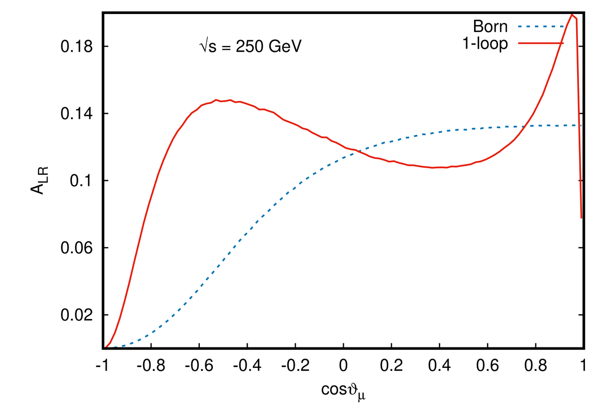
$e^+e^- \to ZH$ at $\sqrt{s} = 250$ GeV, no cuts

P_{e^+}, P_{e^-}	**0, 0**	0, −0.8	−0.6, −0.8	0.6, −0.8
σ^{Born}, fb	**225.59(1)**	266.05(1)	127.42(1)	404.69(1)
$\sigma^{\text{1-loop}}$, fb	**206.77(1)**	223.33(2)	111.67(2)	334.99(1)
δ,%	**−8.3(1)**	−16.1(1)	−12.4(1)	−17.2(1)



$e^+e^- \to \mu^-\mu^+$ at $\sqrt{s} = 250$ GeV, no cuts

P_{e^+}, P_{e^-}	**0, 0**	0, −0.8	0.3, −0.8	−0.3, 0.8
σ^{Born}, fb	**1653.7(1)**	1804.0(1)	2257.2(1)	1844.0(1)
$\sigma^{\text{1-loop}}$, fb	**4534(1)**	4923(1)	6115(1)	5047(1)
δ,%	**174.2(1)**	172.9(1)	170.9(1)	173.7(1)



Conclusions

- Monte Carlo event generator ReneSANCe is released
  - Events with unit weights
  - Initial and final state polarization
  - Complete one-loop EW corrections
  - LL QED and higher order weak corrections through $\Delta\rho$
  - Output in the Standard Les Houches Format
  - Simple installation & usage
  - Processes:
    - $e^+e^- \to e^-e^+, \mu^-\mu^+, \tau^-\tau^+, ZH$ — DONE
    - $e^+e^- \to \gamma\gamma, \gamma Z, t\bar{t}$ • $\mu^\pm e^- \to e^-\mu^\pm$, $e^-e^- \to e^-e^-$ — IN PROGRESS
  - Tuned comparison showed agreement with CalcHEP, WHIZARD, GraceLoop and aITALC
  - **PLANS**: new processes, resonance approx., QED showers, EW Sudakov logarithms

ReneSANCe v1.2.1 is available at
http://sanc.jinr.ru/download.php https://renesance.hepforge.org

References

[1] R. Sadykov and V. Yermolchyk, Comput. Phys. Commun. **256**, 107445 (2020).
[2] D. Bardin et al., Phys. Rev. D **98**, 013001 (2018).
[3] S. Bondarenko et al., Phys. Rev. D **100**, 073002 (2019).
[4] A. Arbuzov et al., Symmetry **13**, 1256 (2021).
[5] S. Bondarenko et al., Phys. Rev. D **102**, 033004 (2020).
[6] A. Andonov et al., Comput. Phys. Commun. **174**, [Erratum: Ibid. 177, 623–624 (2007)], 481 (2006).