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

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We present the new Monte Carlo event generator `ReneSANCe` for simulation of processes at electron-positron colliders.
In the current release of the generator implemented:

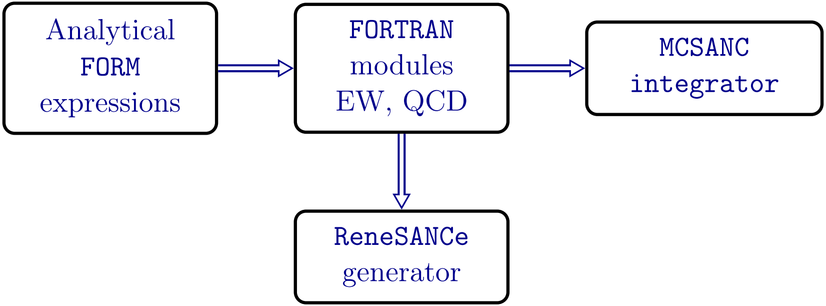
- Bhabha scattering ($e^+e^- \to e^-e^+$),
- Higgs-strahlung ($e^+e^- \to ZH$).

Based on the SANC (Support for Analytic and Numeric Calculations for experiments at colliders) modules the new generator takes into account complete one-loop and some higher-order electroweak radiative corrections, all the particle masses and polarizations. The new generator effectively operates in the collinear region and at the production threshold. It is constructed in such way that new processes can be easily added.

Motivation

It is very important to comprehensively take into account the effects of higher orders of perturbation theory due to strong, **electromagnetic** and **weak** interactions. An additional option of existing theoretical prediction tools should be the consideration of the beam **polarization** of future electron-positron accelerators. Provided that both beams are polarized, tests can be performed with unprecedented accuracy, either at the Z pole, or at the WW threshold, or at the peak of the ZH process, as well as at the tt threshold. Accounting for polarization will have far-reaching consequences for studies on the consistency of the electroweak theory, in particular in the Higgs sector.

The SANC/ARIeL framework and products family



Generator vs Integrator

Monte Carlo event generators are used to account for detector effects in experimental data and obtain predictions with which these experimental data will be compared. In addition, they can be used to obtain histograms of complex observables and pseudo-observables, without rerunning and rewriting the code. One can simply take the generated events and analyze them using `RIVET` or `ROOT`. In contrast to integrators where histograms are often hardcoded.

- main product – events
- any observables can be investigated
- any cuts can be applied
- need space for storing event files
- generally dispersion is higher

At the **tree level** the processes of e^+e^- collisions with polarization of initial particles are realized in the Monte Carlo (MC) programs `CalcHEP` and `WHIZARD` designed for efficient calculation of scattering cross sections and obtaining simulated events. Polarization is processed for both the initial and final states.

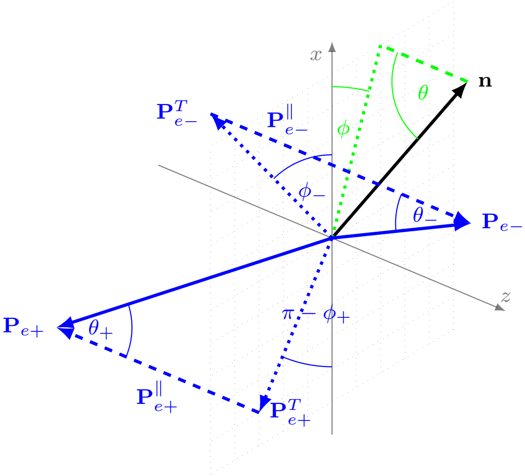
- WHIZARD
  W. Kilian, T. Ohl, J. Reuter, Eur.Phys.J.C71 (2011) 1742,
- CalcHEP
  A. Belyaev, N. Christensen, A. Pukhov,
  Comp. Phys. Comm. 184 (2013), pp. 1729-1769

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

- All calculations at the one-loop precision level are realized in the R_ξ gauge with three calibration parameters: ξ_A, ξ_Z and $\xi \equiv \xi_\mathsf{W}$.
- To parameterize 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 reducing the dependence on the gauge parameter, checking cancellation of ultraviolet poles, as well as checking various symmetry properties and the Ward identities.

Decomposition of the $e^{\pm}$ polarization vectors



Matrix element squared

Using helicity amplitudes, we can calculate a matrix element squared for an arbitrary polarization state of an electron and positron. In the first release only longitudinal polarization is implemented.

$$
\begin{aligned}
|\mathcal{M}|^2 = \; & L^{\shortparallel}_{e-} R^{\shortparallel}_{e+} |\mathcal{H}_{-+}|^2 + R^{\shortparallel}_{e-} L^{\shortparallel}_{e+} |\mathcal{H}_{+-}|^2 + L^{\shortparallel}_{e-} L^{\shortparallel}_{e+} |\mathcal{H}_{--}|^2 + R^{\shortparallel}_{e-} R^{\shortparallel}_{e+} |\mathcal{H}_{++}|^2 \\
& - \frac{1}{2} P^{\perp}_{e-} P^{\perp}_{e+} \,\mathrm{Re}\Big[e^{i(\Phi_+ - \Phi_-)} \mathcal{H}_{++} \mathcal{H}^*_{--} + e^{i(\Phi_+ + \Phi_-)} \mathcal{H}_{+-} \mathcal{H}^*_{-+} \Big] \\
& + P^{\perp}_{e-} \,\mathrm{Re}\Big[e^{i\Phi_-} \Big(L^{\shortparallel}_{e+} \mathcal{H}_{+-} \mathcal{H}^*_{--} + R^{\shortparallel}_{e+} \mathcal{H}_{++} \mathcal{H}^*_{-+} \Big) \Big] \\
& - P^{\perp}_{e+} \,\mathrm{Re}\Big[e^{i\Phi_+} \Big(L^{\shortparallel}_{e-} \mathcal{H}_{-+} \mathcal{H}^*_{--} + R^{\shortparallel}_{e-} \mathcal{H}_{++} \mathcal{H}^*_{+-} \Big) \Big],
\end{aligned}
$$

where

$$
L^{\shortparallel}_{e\pm} = \frac{1}{2}(1 - P^{\shortparallel}_{e\pm}), \quad R^{\shortparallel}_{e\pm} = \frac{1}{2}(1 + P^{\shortparallel}_{e\pm}), \quad \Phi_{\pm} = \phi_{\pm} - \phi,
$$

$\mathcal{H}_{--}$, $\mathcal{H}_{++}$,$\mathcal{H}_{-+}$,$\mathcal{H}_{+-}$ — helicity amplitudes.

Cross-section structure

The cross-section of processes at one-loop can be devided into four parts:

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

Contributions due to:
$\sigma^{\textbf{Born}}$ **— Born level cross-section,**
$\sigma^{\textbf{virt}}$ **— virtual(loop) corrections,**
$\sigma^{\textbf{soft}}$ **— soft photon Bremsstrahlung,**
$\sigma^{\textbf{hard}}$ **— hard photon Bremsstrahlung (with energy $\mathbf{E}_\gamma > \omega$).**
Auxiliary parameters λ ("photon mass") and ω cancel out after summation.

We decide to use the helicity approach for all contributions.
It provides us possibility to describe in the future:

- any initial (not only longitudinal) polarization
- polarization of final states
- spin correlations, polarization transfer from initial to final states

Calculations were carried out in the `SANC`-framework by `FORM`. For optimization we intensively used factorization introduced in `FORM` 4 and elimination of common subexpressions with temporary variables.

The result of calculation was automatically transformed into software modules in the Fortran language with the standard `SANC` interface. These modules incorporating physical calculations can be used in any code that understands the `SANC` interface.

$e^+e^- \to ZH$: HA for Born and Virtual parts

There are 6 non-zero HAs for virtual contribution:

$$\mathcal{H}_{+-+} = N(s)\sqrt{\frac{s}{2}}c_+\Big\{\sqrt{\lambda}c_-\left[\mathcal{F}_2^+(s,t)\ -\mathcal{F}_1^+(s,t)\right] - 4\sigma_e\mathcal{F}_0^+(s,t)\Big\},$$

$$\mathcal{H}_{+--} = N(s)\sqrt{\frac{s}{2}}c_-\Big\{\sqrt{\lambda}c_+\left[\mathcal{F}_2^+(s,t)\ -\mathcal{F}_1^+(s,t)\right] - 4\sigma_e\mathcal{F}_0^+(s,t)\Big\},$$

$$\mathcal{H}_{+-0} = N(s)\frac{\sin\vartheta_z}{2M_Z}\Big\{\sqrt{\lambda}\left[\beta_+\mathcal{F}_1^+(s,t)\ +\beta_-\mathcal{F}_2^+(s,t)\right] + 4\sigma_e L\mathcal{F}_0^+(s,t)\Big\},$$

where

$$L = s + M_Z^2 - M_H^2, \quad \lambda = \lambda(s, M_Z^2, M_H^2)\,,$$

$$\beta = \beta(s, M_Z^2, M_H^2) = \frac{\sqrt{\lambda}}{L}, \quad \beta_\pm = \beta \pm \cos\vartheta_Z,$$

$$c_\pm = 1 \pm \cos\vartheta_Z.$$

Expression for the amplitudes $\mathcal{H}_{-++}$ ($\mathcal{H}_{-+-}$) can be obtained from the expression $\mathcal{H}_{+-+}$ ($\mathcal{H}_{+--}$) by the replacement ($\sigma_e \to \delta_e, c_+ \to c_-, \mathcal{F}^+ \to \mathcal{F}^-$) and amplitude $\mathcal{H}_{-+0}$ – from $-\mathcal{H}_{+-0}$ by the replacement ($\sigma_e \to \delta_e$).

Form factors $\mathcal{F}_0^{\pm}(s,t) = 1$ and $\mathcal{F}_i^{\pm}(s,t) = 0$ should be set in order to get HAs for the Born.

Light-cone projection approach

We project all massive momenta with $p_i^2 = m_i^2$ to the light-cone of photon p_5 and introduce associated “momenta”:

$$k_i = p_i - \frac{m_i^2}{2p_i \cdot p_5} p_5, \quad k_i^2 = 0, \quad i = 1..4,$$

$$k_5 = -\sum_{i=1}^{4} k_i = K p_5, \qquad K = 1 + \sum_{i=1}^{4} \frac{m_i^2}{2p_i \cdot p_5} = 1 + \sum_{i=1}^{4} \frac{m_i^2}{2k_i \cdot p_5}$$

$$p_5 = -\sum_{i=1}^{4} p_i = K' k_5, \quad K' = 1 - \sum_{i=1}^{4} \frac{m_i^2}{2p_i \cdot k_5} = 1 - \sum_{i=1}^{4} \frac{m_i^2}{2k_i \cdot k_5}$$

Since vector k_5 appears to be light-like, we have the “momentum conservation” of the associated vectors.

$e^+e^- \to ZH$: HA for Hard Bremsstrahlung

There are 20 non-zero HAs for hard Bremsstrahlung:

$$\mathcal{M}_{--++} = 2em_1M_ZN(s')\left(\frac{\delta_e}{s_{15}} + \frac{\sigma_e}{s_{25}}\right)[1|2]\,\frac{\langle 3|5\rangle}{[3|5]},$$

$$\mathcal{M}_{++-+} = 2em_1M_ZN(s')\left(\frac{\sigma_e}{s_{15}} + \frac{\delta_e}{s_{25}}\right)[1|2]\,\frac{[3|5]\,\langle 1|5\rangle\,\langle 2|5\rangle}{\langle 3|5\rangle\,[1|5]\,[2|5]},$$

$$\mathcal{M}_{-+-+} = -2eM_ZN(s')\frac{\sigma_e}{s_{15}}\frac{[1|2]\,[1|3]\,\langle 1|5\rangle\,\langle 2|5\rangle}{\langle 3|5\rangle\,[2|5]},$$

$$\mathcal{M}_{+--+} = -2eM_ZN(s')\frac{\delta_e}{s_{25}}\frac{[1|2]\,[2|3]\,\langle 2|5\rangle\,\langle 1|5\rangle}{\langle 3|5\rangle\,[1|5]},$$

$$\mathcal{M}_{--0+} = \sqrt{2}em_1N(s')\left(\frac{\delta_e}{s_{15}}\frac{[2|3]}{[2|5]} + \frac{\sigma_e}{s_{25}}\frac{[1|3]}{[1|5]}\right)[1|2]\,\langle 3|5\rangle\,,$$

$$\mathcal{M}_{-+++} = -2eM_ZN(s')\sigma_e\left(\frac{[1|2]\,\langle 2|3\rangle\,\langle 2|5\rangle}{s_{25}\,[3|5]} + \frac{[1|5]\,\langle 3|5\rangle}{[2|5]\,[3|5]}\right),$$

$$\mathcal{M}_{+-++} = -2eM_ZN(s')\delta_e\left(\frac{[1|2]\,\langle 1|3\rangle\,\langle 1|5\rangle}{s_{15}\,[3|5]} - \frac{[2|5]\,\langle 3|5\rangle}{[1|5]\,[3|5]}\right),$$

$e^+e^- \to ZH$: HA for Hard Bremsstrahlung

$$\mathcal{M}_{++0+} = \sqrt{2}em_1 N(s')\Bigg([1|2]\left(\frac{\sigma_e}{s_{15}}\langle 1|5\rangle\langle 2|3\rangle + \frac{\delta_e}{s_{25}}\langle 2|5\rangle\langle 1|3\rangle\right) + \langle 3|5\rangle\left(\sigma_e - \delta_e\right)\Bigg)\frac{[3|5]}{[1|5]\,[2|5]},$$

$$\mathcal{M}_{-+0+} = -\sqrt{2}eN(s')\Bigg(\sigma_e\Big(\frac{[1|3]\langle 2|3\rangle\langle 1|5\rangle}{s_{15}} + \frac{[1|3]\langle 3|5\rangle}{[1|2]} + \frac{M_Z^2\langle 2|5\rangle}{s_{45}}\Big) + \delta_e\frac{m_1^2 s_{45}\langle 2|5\rangle}{s_{15}s_{25}}\Bigg)\frac{[1|2]}{[2|5]},$$

$$\mathcal{M}_{+-0+} = -\sqrt{2}eN(s')\Bigg(\delta_e\Big(\frac{[2|3]\langle 1|3\rangle\langle 2|5\rangle}{s_{25}} - \frac{[2|3]\langle 3|5\rangle}{[1|2]} + \frac{M_Z^2\langle 1|5\rangle}{s_{45}}\Big) + \sigma_e\frac{m_1^2 s_{45}\langle 1|5\rangle}{s_{15}s_{25}}\Bigg)\frac{[1|2]}{[1|5]},$$

where $s_{i5} = 2k_i\cdot p_5 = K'\langle i|5\rangle\,[5|i]$.

Other ones can be obtained using CP-symmetry.

Spin quantization axis

Freedom in the light-cone projection choice corresponds to arbitrariness of spin quantization direction. We use it to make expressions compact.

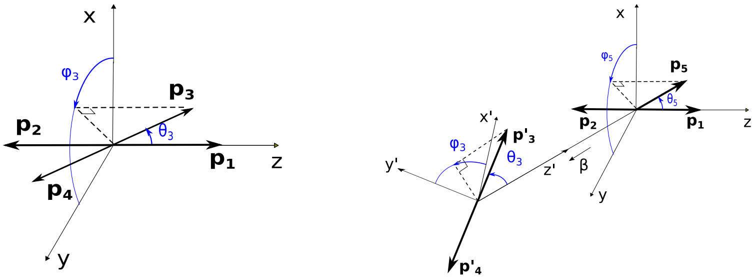
To obtain amplitudes $\mathcal{H}$ with definite helicity, spin-rotation matrices C should be applied for each index χ of incoming particles independently:

$$\mathcal{H}_{\dots\xi_i\dots} = eN(s')C_{\xi_i}^{\ \chi_i} A_{\dots\chi_i\dots}$$

$$C_{\xi_i}^{\ \chi_i} = \begin{bmatrix} \frac{\left[k_{i^\flat}\, p_5\right]}{[p_i\, p_5]} & \frac{m_i\langle k_{i^*}\, p_5\rangle}{\left\langle k_{i^*}\, k_{i^\flat}\right\rangle\langle p_i\, p_5\rangle} \\ \frac{m_i[k_{i^*}\, p_5]}{\left[k_{i^*}\, k_{i^\flat}\right][p_i\, p_5]} & \frac{\left\langle k_{i^\flat}\, p_5\right\rangle}{\langle p_i\, p_5\rangle} \end{bmatrix} = \begin{bmatrix} \frac{\langle k_{i^*}\, p_i\rangle}{\left\langle k_{i^*}\, k_{i^\flat}\right\rangle} & \frac{m_i\langle k_{i^*}\, p_5\rangle}{\left\langle k_{i^*}\, k_{i^\flat}\right\rangle\langle p_i\, p_5\rangle} \\ \frac{m_i[k_{i^*}\, p_5]}{\left[k_{i^*}\, k_{i^\flat}\right][p_i\, p_5]} & \frac{[k_{i^*}\, p_i]}{\left[k_{i^*}\, k_{i^\flat}\right]} \end{bmatrix}$$

$$\begin{aligned} p_i &= \{E_i, p_i^x, p_i^y, p_i^z\} & p_i^2 &= m_i^2 \\ k_{i^*} &= \{|\vec{p}_i|, -p_i^x, -p_i^y, -p_i^z\} & k_{i^*}^2 &= 0 \\ k_{i^\flat} &= p_i - \frac{m_i^2}{2p_i\cdot k_{i^*}} k_{i^*} & k_{i^\flat}^2 &= 0 \end{aligned}$$

$$e^+(p_1) + e^-(p_2) \to e^-(p_3) + e^+(p_4) + \gamma(p_5)$$
$$e^+(p_1) + e^-(p_2) \to Z(p_3) + H(p_4) + \gamma(p_5)$$



3-momenta $\vec{p}_1$, $\vec{p}_2$ and $\vec{p}_5$ lie in $y'z'$-plane, $\beta = \dfrac{|\vec{p}_3 + \vec{p}_4|}{E_3 + E_4} = \dfrac{s - s'}{s + s'}$.

Phase-space integrals

The cross sections are given by the following phase-space integrals:

$$\sigma(2\to 2) = \int\limits_{-1}^{1} d\cos\theta_3 \int\limits_{0}^{2\pi} d\phi_3 \, \frac{1}{64\pi^2 s} \, \frac{\sqrt{\lambda(s', m_3^2, m_4^2)}}{\sqrt{\lambda(s, m_1^2, m_2^2)}} \, |\mathcal{M}_2|^2 F_2,$$

$$\sigma(2\to 3) = \int\limits_{(m_3+m_4)^2}^{s(1-\omega)} ds' \int\limits_{-1}^{1} d\cos\theta_3 \int\limits_{0}^{2\pi} d\phi_3 \int\limits_{-1}^{1} d\cos\theta_5 \int\limits_{0}^{2\pi} d\phi_5 \, \frac{s-s'}{4096\pi^5 s s'} \, \frac{\sqrt{\lambda(s', m_3^2, m_4^2)}}{\sqrt{\lambda(s, m_1^2, m_2^2)}} \, |\mathcal{M}_3|^2 F_3.$$

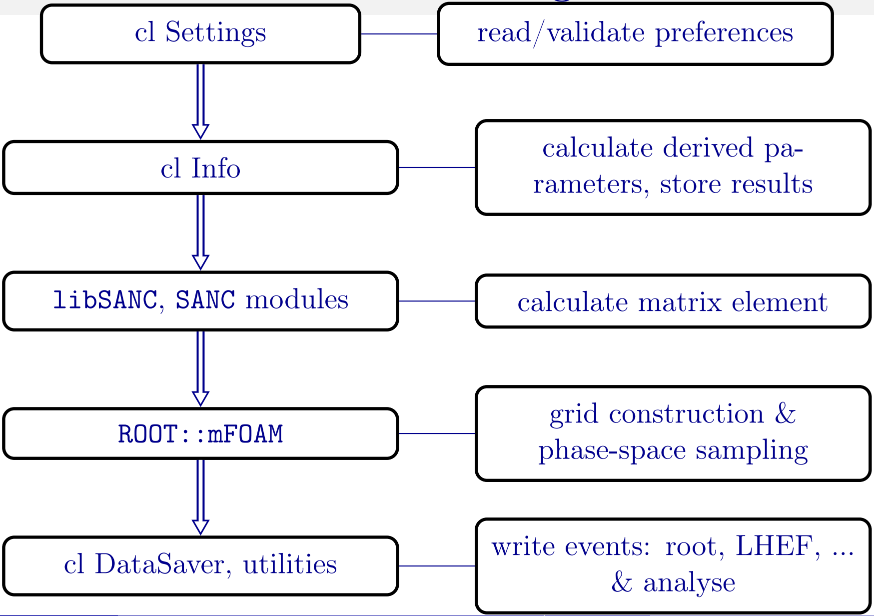
Here $F_2 = F_3 = 0$ for the region of phase-space excluded by kinematic cuts, and $F_2 = F_3 = 1$ otherwise.

ReneSANCe generator

- CMAKE build system
- Modular architecture
- c++ & FORTRAN
- For sampling we used adaptive algorithm mFOAM

Jadach, S. and Sawicki, P., Comp. Phys. Comm. 177 (2007), pp. 441–458

Scheme of ReneSANCe event generator structure



ReneSANCe settings

```
schema: {
properties: {
#!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# Process id:
pid : {type: integer, minimum: 101, maximum: 107}
    # 101 - e^+e^-  --> e^-e^+
    # 102 - e^+e^-  --> mu^-mu^+
    # 103 - e^+e^-  --> ZH
    # 104 - e^+e^-  --> gamma gamma
#!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# ALR:
alr  : {type: integer, minimum: 0, maximum: 2, default: 0}
# 0 - sigma, 1 - sigma RL-sigma LR, 2 - sigma RL+sigma LR
```

```
#!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# Process id:
pid : 103 # 101 - e^+e^-  --> e^-e^+
    # 102 - e^+e^-  --> mu^-mu^+
    # 103 - e^+e^-  --> ZH
    # 104 - e^+e^-  --> gamma gamma
#!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# ALR:
alr  : 0 # 0 - sigma, 1 - sigma_RL-sigma_LR, 2 - sigma_RL+si
#!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# Longitudinal polarization of initial particles:
lamep :    0 # e^+ polarization
lamem :    -0.8 # e^- polarization
```

```
Validation of 'pid'='108' failed:
'number is too big: 108.000, maximum is: 107.000'
Requirements:
type = "integer";
minimum = 101;
maximum = 107;
```

Sampling strategy

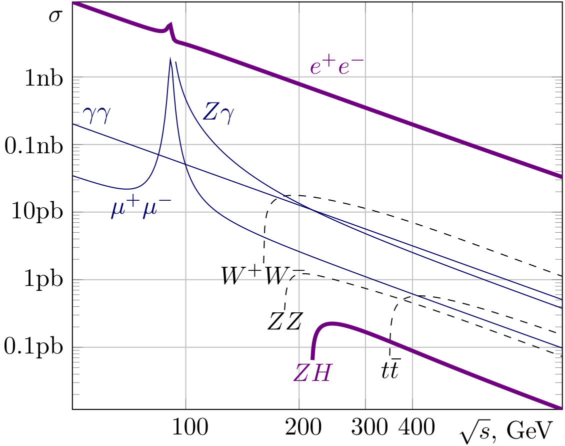
For sampling we used a multibranching strategy with variable transformation. We implemented two approaches.

- Manual sampling over branches. For each branch, we created a separate instance of the `FOAM` class. In this case, each branch can use both optimal variable transformation and the optimal `FOAM` setup. As a consequence, an additional stage is needed to calculate branching weights that slow down the initialization stage of the generator.
- Sampling is made using only one instance of the `FOAM`. Nevertheless, optimal variable transformation for each branch is also available. The `FOAM` is responsible for sampling over branching. It is performed by creating additional artificial dimension of integral with fixed division points.

ReneSANCe: NLO EW RC for polarized scattering

- NLO EW corrections for polarized e^+e^- scattering:
  - $e^+e^- \to e^+e^-$ (Bhabha) (Phys.Rev.D 98, 013001)
  - $e^+e^- \to ZH$ (Phys.Rev.D 100, 073002)
  - $e^+e^- \to \mu^+\mu^-$(or $\tau^+\tau^-$) (preliminary)
  - $e^+e^- \to Z\gamma$ (preliminary)
  - $e^+e^- \to \gamma\gamma$ (preliminary)
  - $e^+e^- \to t\bar{t}$ (in progress)
  - $e^+e^- \to \nu\bar{\nu}H$ (in progress)
  - $e^+e^- \to ZZ$ (in progress)
  - $e^+e^- \to f\bar{f}\gamma$ (future plans)
  - $e^+e^- \to f\bar{f}H$ (future plans)
- NLO EW corrections for polarized $\gamma\gamma$ scattering:
  - $\gamma\gamma \to e^+e^-$ (preliminary)
  - $\gamma\gamma \to \gamma\gamma$ (preliminary)
  - $\gamma\gamma \to Z\gamma$ (future plans)
  - $\gamma\gamma \to ZZ$ (future plans)

Basic processes of SM for e^+e^- annihilation



The cross sections are given for polar angles between $10^o < \theta < 170^o$ in the final state.

Numerical results: Setup for tuned comparison

We performed a tuned comparison of our results for polarized Born and hard Bremsstrahlung with the results WHIZARD and CalcHEP programs.

Initial parameters

$$\begin{array}{lll} \alpha^{-1}(0) = 137.03599976, & M_W = 80.451495 \text{ GeV}, & \Gamma_W = 2.0836 \text{ GeV}, \\ M_H = 125.0 \text{ GeV}, & M_Z = 91.1867 \text{ GeV}, & \Gamma_Z = 2.49977 \text{ GeV}, \\ m_e = 0.5109990 \text{ MeV}, & m_\mu = 0.105658 \text{ GeV}, & m_\tau = 1.77705 \text{ GeV}, \\ m_d = 0.083 \text{ GeV}, & m_s = 0.215 \text{ GeV}, & m_b = 4.7 \text{ GeV}, \\ m_u = 0.062 \text{ GeV}, & m_c = 1.5 \text{ GeV}, & m_t = 173.8 \text{ GeV}. \end{array}$$

$$\text{with cuts } |\cos\theta| < 0.9, \quad E_\gamma > 1 \text{ GeV}$$

`WHIZARD and CalcHEP`

- W. Kilian, T. Ohl, J. Reuter, Eur.Phys.J.C71 (2011) 1742,
- A.Belyaev, N.Christensen,A.Pukhov, Comp. Phys. Comm. 184 (2013), pp. 1729-1769

Comparison for $e^+e^- \to e^-e^+$, $\sqrt{s} = 250$ GeV

P_{e^+}	P_{e^-}	ω	code	σ^{Born}, fb	σ^{hard}, fb	$\sigma^{\text{B+v+s}}$, fb	$\sigma^{\text{1-loop}}$, fb	δ, %
-1	-1	10^{-5}	ReneSANCe	55.263(1)	127.55(1)	$-66.064(1)$	61.48(1)	11.26(1)
		10^{-4}			100.25(1)	$-38.731(1)$	61.52(1)	11.33(1)
			WHIZARD	55.264(1)	100.2(1)			
			CalcHEP	55.263(1)	100.2(1)			
-1	1	10^{-5}	ReneSANCe	55.346(1)	125.02(1)	$-65.409(2)$	59.61(1)	7.71(2)
		10^{-4}			97.90(1)	$-38.271(1)$	59.63(1)	7.74(1)
			WHIZARD	55.345(1)	97.8(1)			
			CalcHEP	55.346(1)	97.9(1)			
1	-1	10^{-5}	ReneSANCe	60.834(1)	137.61(1)	$-73.791(1)$	63.82(1)	4.91(2)
		10^{-4}			107.82(1)	$-43.948(1)$	63.88(1)	5.00(2)
			WHIZARD	60.833(1)	107.7(1)			
			CalcHEP	60.834(1)	107.8(1)			
1	1	10^{-5}	ReneSANCe	55.263(1)	127.55(1)	$-66.065(1)$	61.49(1)	11.27(1)
		10^{-4}			100.25(1)	$-38.731(1)$	61.52(1)	11.33(1)
			WHIZARD	55.263(1)	100.3(1)			
			CalcHEP	55.263(1)	100.2(1)			

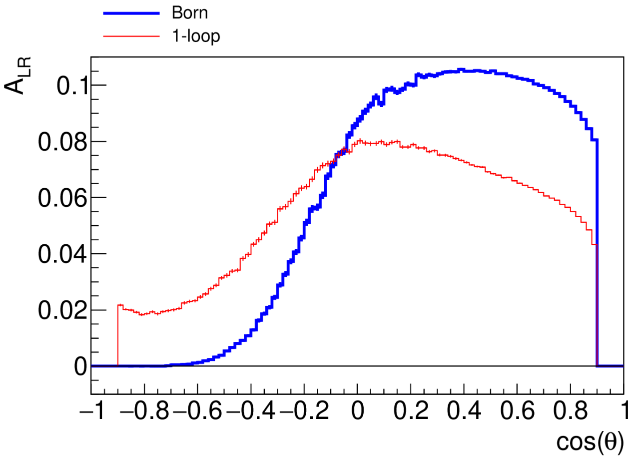
$|\cos\theta_{e^-}| < 0.9$, $|\cos\theta_{e^+}| < 0.9$

Results for $e^+e^- \to e^+e^-$ (Bhabha)

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
		$\sqrt{s} = 250$ GeV		
$\sigma^{\text{Born}}_{e^+e^-}$, pb	56.6763(1)	57.7738(1)	56.2725(4)	59.2753(5)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	61.731(6)	62.587(6)	61.878(6)	63.287(7)
δ, %	8.92(1)	8.33(1)	9.96(1)	6.77(1)
		$\sqrt{s} = 500$ GeV		
$\sigma^{\text{Born}}_{e^+e^-}$, pb	14.3789(1)	15.0305(1)	12.7061(1)	17.3550(2)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	15.465(2)	15.870(2)	13.861(1)	17.884(2)
δ, %	7.56(1)	5.59(1)	9.09(1)	3.05(1)
		$\sqrt{s} = 1000$ GeV		
$\sigma^{\text{Born}}_{e^+e^-}$, pb	3.67921(1)	3.90568(1)	3.03577(3)	4.77562(5)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	3.8637(4)	3.9445(4)	3.2332(3)	4.6542(7)
δ, %	5.02(1)	0.99(1)	6.50(1)	-2.54(1)

Born and 1-loop cross sections of Bhabha scattering and the corresponding relative corrections δ for $\sqrt{s} = 250$, 500 and 1000 GeV.

Distributions of the left-right asymmetry A_{LR} in $\cos\vartheta$, $\sqrt{s} = 500$ GeV



Comparison for $e^+e^- \to ZH$, $\sqrt{s} = 250$ GeV

P_{e^+}	P_{e^-}	ω	code	σ^{Born}, fb	σ^{hard}, fb	$\sigma^{\text{B+v+s}}$, fb	$\sigma^{\text{1-loop}}$, fb	δ, %
-1	-1	0	ReneSANCe	0	0.0260(1)	0	0.0260(1)	$+\infty$
			WHIZARD	0	0.0259(1)			
			CalcHEP	0	0.0260(1)			
-1	1	10^{-5}	ReneSANCe	350.00(1)	400.85(1)	$-28.82(1)$	372.03(1)	6.30(1)
		10^{-4}			306.51(1)	65.53(1)	372.04(1)	6.30(1)
			WHIZARD	349.99(1)	306.6(2)			
			CalcHEP	350.00(1)	306.5(1)			
1	-1	10^{-5}	ReneSANCe	552.45(1)	632.74(1)	$-177.74(1)$	455.00(1)	$-17.64(1)$
		10^{-4}			483.80(1)	$-28.81(1)$	454.99(1)	$-17.64(1)$
			WHIZARD	552.45(1)	483.7(3)			
			CalcHEP	552.46(1)	483.7(1)			
1	1	0	ReneSANCe	0	0.0260(1)	0	0.0260(1)	$+\infty$
			WHIZARD	0	0.0260(1)			
			CalcHEP	0	0.0261(1)			

Comparison for $e^+e^- \to ZH$, $\sqrt{s} = 500$ GeV

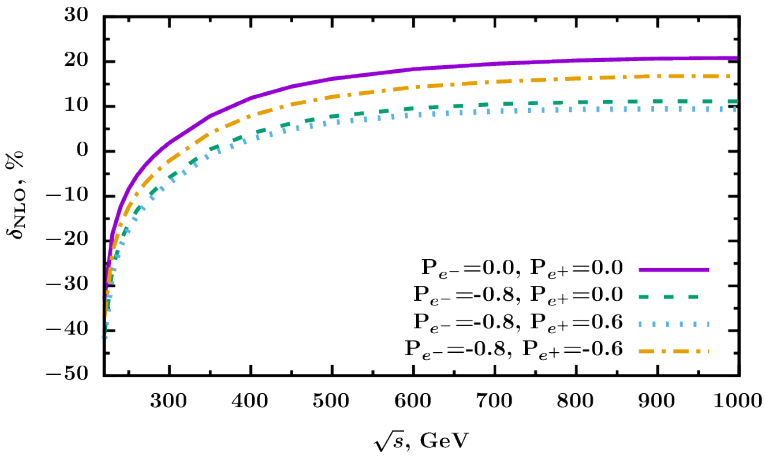
P_{e^+}	P_{e^-}	ω	code	σ^{Born}, fb	σ^{hard}, fb	$\sigma^{\text{B+v+s}}$, fb	$\sigma^{\text{1-loop}}$, fb	δ, %
-1	-1	0	ReneSANCe	0	0.2199(1)	0	0.2199(1)	$+\infty$
			WHIZARD	0	0.1341(1)			
			CalcHEP	0	0.2200(1)			
-1	1	10^{-5}	ReneSANCe	83.373(1)	121.97(1)	$-12.05(1)$	109.92(1)	31.84(1)
		10^{-4}			98.26(1)	11.66(1)	109.92(1)	31.84(1)
			WHIZARD	83.373(1)	98.34(1)			
			CalcHEP	83.373(1)	98.27(1)			
1	-1	10^{-5}	ReneSANCe	131.60(1)	192.53(1)	$-53.16(1)$	139.37(1)	5.91(1)
		10^{-4}			155.10(1)	$-15.73(1)$	139.37(1)	5.90(1)
			WHIZARD	131.60(1)	155.23(1)			
			CalcHEP	131.60(1)	155.08(1)			
1	1	0	ReneSANCe	0	0.2200(1)	0	0.2200(1)	$+\infty$
			WHIZARD	0	0.0854(1)			
			CalcHEP	0	0.2201(1)			

Results for $e^+e^- \to ZH$

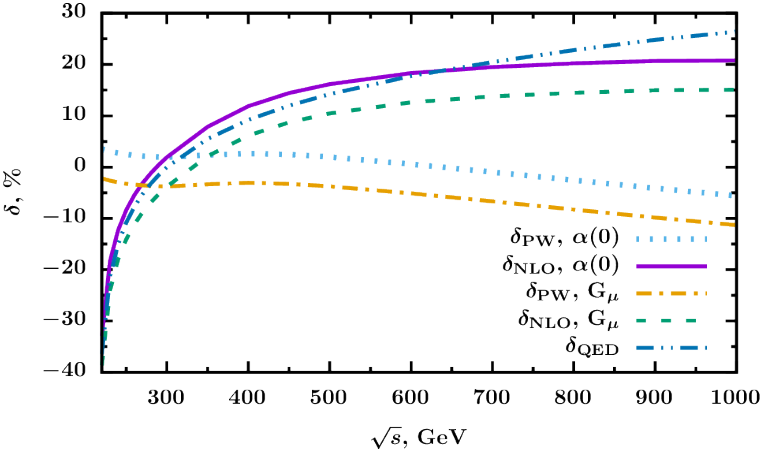
P_{e^-}	P_{e^+}	σ^{hard}, fb	σ^{Born}, fb	$\sigma^{\text{1-loop}}$, fb	δ, %
0	0	82.0(1)	225.59(1)	206.91(1)	-8.28(1)
-0.8	0	47.6(1)	266.05(1)	223.52(2)	-15.99(1)
-0.8	-0.6	46.3(1)	127.42(1)	111.76(2)	-12.29(1)
-0.8	0.6	147.1(1)	404.69(1)	335.28(1)	-17.15(1)

Hard, Born and 1-loop cross sections in fb of the process $e^+e^- \to ZH$ and relative correction δ in percents for energy 250 GeV and various polarizations of initial particles produced by `ReneSANCe`.

The complete one-loop relative corrections δ for various polarizations

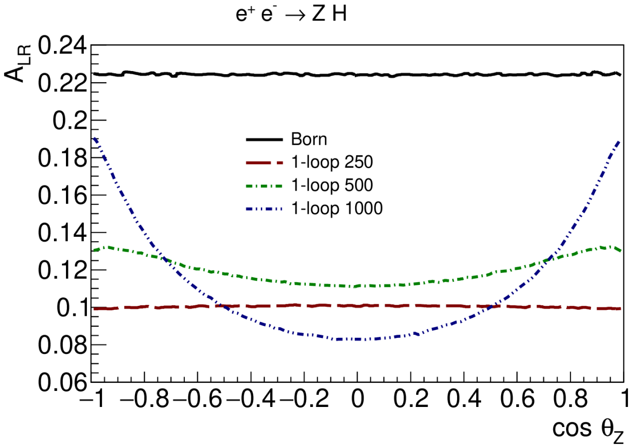


Relative corrections δ in percent of NLO



Pure weak (PW) and QED contributions in α_0 and G_μ EW-schemes

Distributions of the left-right asymmetry A_{LR} in $\cos\vartheta_Z$



Born and one-loop level for $\sqrt{s} = 250, 500, 1000$ GeV

RESUME: ReneSANCe

- Monte Carlo event generator ReneSANCe is under development
  - Events with unit weights
  - Polarized initial beams
  - Complete one-loop EW corrections
  - Possibility to produce events in Standard Les Houches Format
  - Simple installation & usage
  - Validation of input parameters

Release of ReneSANCe v1.0.0 is available at
http://sanc.jinr.ru/download.php.

Publication submitted in *CPC*.
arXiv:2001.10755

Current activities

- $e^+e^- \to \mu^+\mu^-$
  preparation for publication
- $e^+e^- \to \nu\bar{\nu}H$
  ~~tensor reduction~~
- $e^+e^- \to \tau^+\tau^-$
  integration with `Tauola`