

SANC system and its applications for LHC

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Abstract. The SANC computer system is aimed at support of analytic and numeric calculations for experiments at colliders. The system is reviewed briefly. Recent results on high-precision description of the Drell-Yan processes at the LHC are presented. Special attention is paid to the evaluation of higher order final-state QED corrections to the single W and Z boson production processes. A new Monte Carlo integrator `mcsanc` suited for description of a series of high-energy physics processes at the one-loop precision level is presented.

1. Introduction

After the discovery at the LHC of a new particle which is very likely the long awaited Higgs boson, the precision tests of the Standard Model (SM) became of crucial importance. Moreover, the absence of clear signals of new physics at the LHC stimulates comparisons of high-precision predictions received within the SM with the experimental data. The rather accurate measurement of the Higgs boson mass performed at the LHC fixed the last free parameter of the SM. This potentially allows to compute theoretical predictions by means of perturbation theory to a very high precision level. The corresponding experimental accuracy is continuously growing up with accumulating of statistics and development of analysis techniques. To provide adequately accurate theoretical predictions, one has to take into account and combine different relevant effects.

2. SANC Project

SANC is a computer system for Support of Analytic and Numeric calculations for experiments at Colliders [1, 2]. It can be accessed through the Internet at <http://sanc.jinr.ru/>. The SANC system is suited for calculations of NLO QED, electroweak (EW), and QCD radiative corrections (RC) to various SM processes. Automatized analytic calculations in SANC provide FORM and FORTRAN modules [3]. Stand-alone FORTRAN modules for differential cross sections as well as Monte Carlo programs (integrators and generators) are available to download.

A schematic flowchart of the SANC system is presented in Fig. 1. In the core of the system, analytic calculations of amplitudes, cross sections, and other quantities for various processes are computed by means of the FORM language [4]. The results of analytic calculations are translated automatically into FORTRAN modules which can be used by external programs. The modules extensively use internal and external [5] FORTRAN libraries of Passarino-Veltman functions.

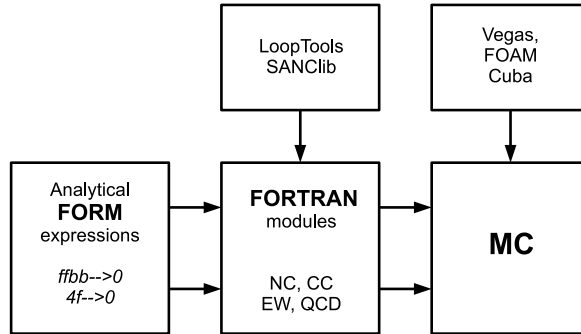


Figure 1. A schematic flowchart of the SANC system.

3. Description of Drell-Yan processes in SANC

High-precision theoretical description of Drell-Yan (DY) like processes (i.e. single Z and W boson production) at the LHC is of great importance. In fact, these processes have large cross sections, clear signatures in detectors, and they are rather well suited for tests of the SM and searches for new physics. So DY processes provide *standard candles* for detector calibration at the LHC and the Tevatron. Single Z and W boson production is also used at the LHC for extraction of parton distribution functions (PDF) in the kinematical region which has not been accessed by earlier experiments. It is planned to get the most precise experimental values for the mass and width of W boson using the future high statistics data on the charged current DY process. DY processes will also provide background to many other reactions being of interest at the LHC. Moreover, some new physics searches like the ones for contact four-fermion interactions will be performed in these channels. Therefore it is crucial to control the theoretical predictions for production cross sections and kinematic distributions of both the neutral current (NC) and charged current (CC) DY processes.

The experimental precision tag for inclusive observables in DY processes is about 1%. That means we need to provide the accuracy of theoretical predictions of about 0.3% in order not to spoil the results of the LHC data analysis. This is a challenge for the theory. Aiming at high precision of DY description we need to take into account the following effects:

- QCD contributions at LO, NLO and NNLO;
- parton showers and hadronization effects;
- EW RC at one-loop at least;
- most important higher order EW contributions (re-summed where possible);
- an interplay of QCD and EW corrections;
- a tuned input: coupling constants, the hadronic vacuum polarization, and PDF for the appropriate energy scales and x -values.

All relevant effects should be implemented in a Monte Carlo event generator which can be directly used in the experimental data analysis. Actually, treating all the listed effects in a single code is a very involved task. More realistic is the possibility to make a chain of event generators, which pass generated events one to another and *dress* them with additional effects.

With a tuned set-up we got an excellent agreement with several other groups in the values of EW RC to the CC [6] and NC [7] DY processes, see Table 1. Examples of differential distributions of the EW RC contributions are given in Fig. 2 and Fig. 3 for the CC channel and in Fig. 4 and

Table 1. Tuned comparisons between SANC and other codes in predictions on DY processes.

Processes	Codes	Ref.
CC DY (NLO EW)	SANC, HORACE, WGRAD2	[6]
NC DY (NLO EW)	SANC, HORACE, ZGRAD2	[7]
CC & NC DY (NLO QCD & EW)	SANC, HORACE, WZGRAD, RADY, FEWZ, DYNLO, POWHEG-w, POWHEG-z	[8]

Fig. 5 for the NC one. The relative effect of EW RC is defined as

$$\Delta = \frac{\sigma(\mathcal{O}(\alpha)) - \sigma(\text{Born})}{\sigma(\text{Born})} \cdot 100\%. \quad (1)$$

A new series of tuned comparisons is going on within the W -mass workshop [8]. QCD corrections are also taken into consideration, and the set-up is adjusted to simulate the experimental conditions.

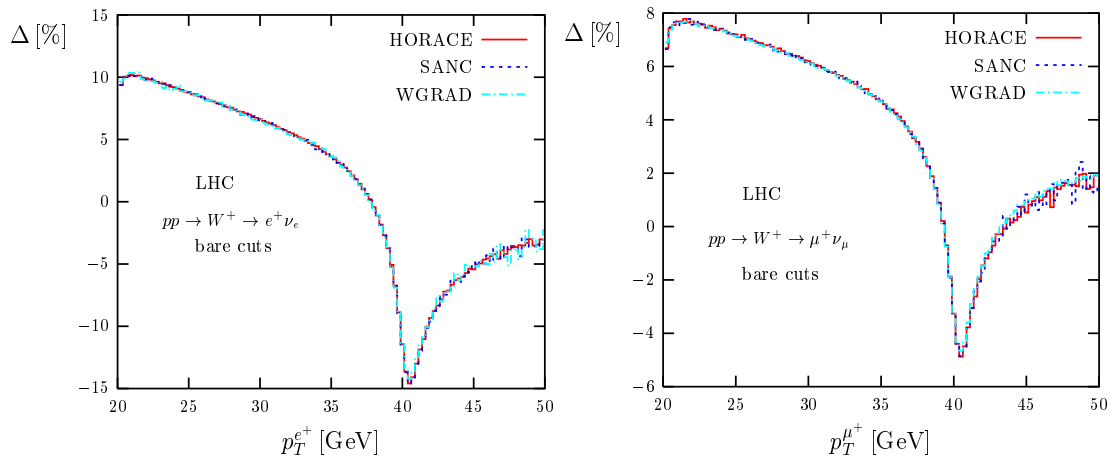


Figure 2. Tuned comparison of positron (left) and anti-muon (right) transverse momentum distribution in the CC DY process [6].

4. Final State Radiation in single W and Z production

Numerically, the effect of QED final-state radiation (FSR) off charged leptons at the LHC is very large. The corresponding correction can reach, *e.g.*, even about 200% in the distribution of e^+e^- invariant mass in NC DY. For this reason FSR deserves special attention. Recently a dedicated study [9] of the effect was performed by the joint effort of SANC and PHOTOS [10] groups.

Our goals were:

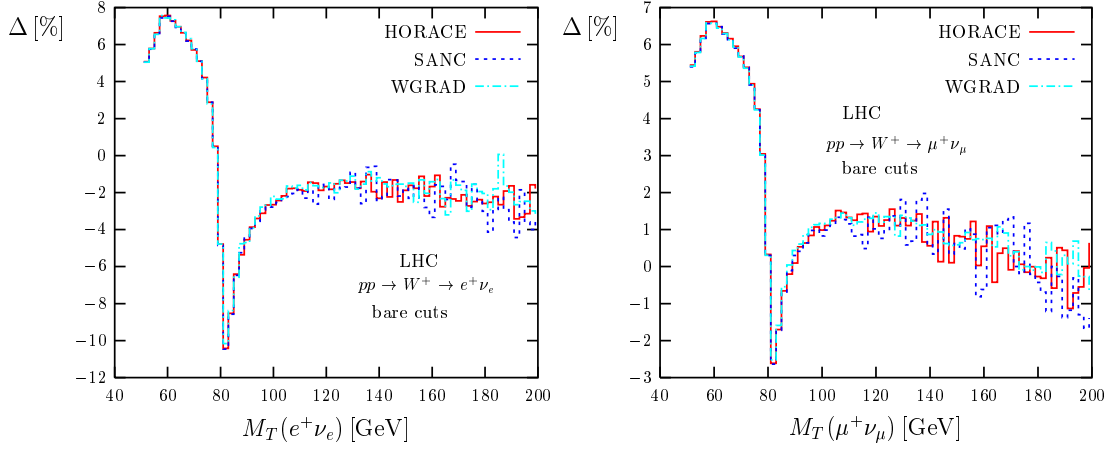


Figure 3. Tuned comparison of $e^+\nu_e$ (left) and $\mu^+\nu_\mu$ (right) transverse mass distribution in the CC DY process [6].

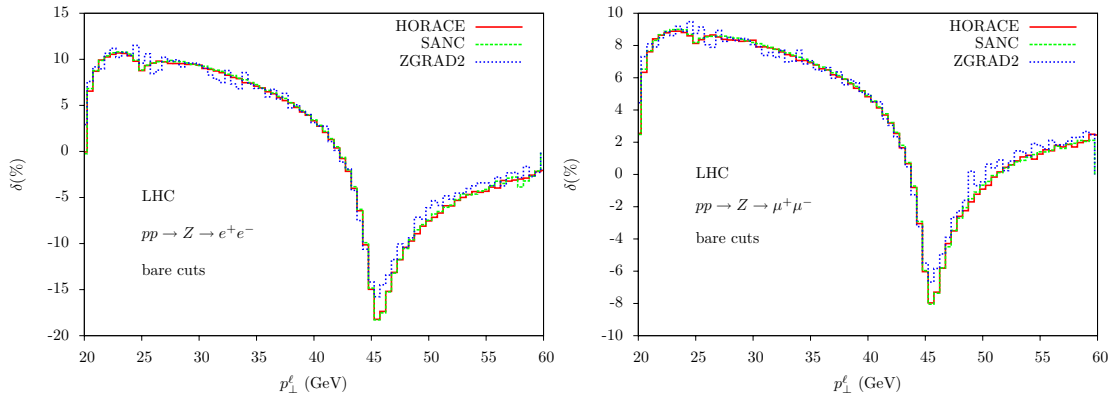


Figure 4. Tuned comparison of positron (left) and anti-muon (right) transverse momentum distribution in the NC DY process [7].

- to perform a comparison between **SANC** and **PHOTOS** in the *single* and *multiple* photon modes for FSR in DY processes both for neutral and charged currents;
- to check that QED FSR is properly installed in the programs;
- to tune separation of the FSR QED corrections from the complete EW NLO ones.

In **PHOTOS** the bremsstrahlung corrections to decays of W and Z bosons are treated in a special way in the next-to-leading approximation with exponentiation. **PHOTOS** is linked to the **PYTHIA** program in the standard Monte Carlo simulation through **HepMC** interface. In **SANC** the complete EW corrections at one-loop are calculated for single W and Z production. The FSR QED corrections can be separated from the rest of EW corrections by means of flags in **SANC** Monte Carlo event generators and integrators.

For a tuned comparison of FSR effects in **SANC** and **PHOTOS** we used the following set-up. Parton level cross-section was convoluted with **CTEQ6L1** PDF set with running scale $Q^2 = s$, where s is the total energy in the center-of-mass system of partons. The C++ version of **PHOTOS** program was used together with **Pythia8** which provided the Born-level events in **HEPevt** format that subsequently was passed to **PHOTOS** to simulate photon radiation off the final charged leptons.

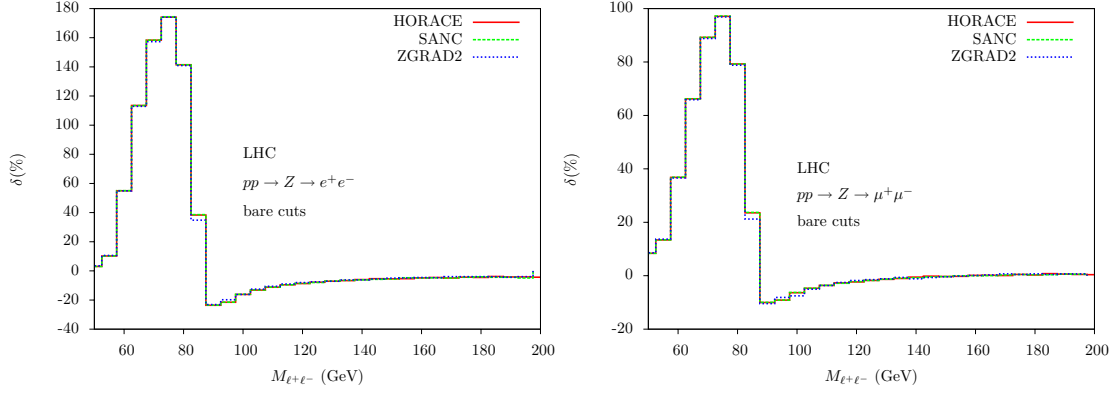


Figure 5. Tuned comparison of e^+e^- (left) and $\mu^+\mu^-$ (right) invariant mass distribution in the NC DY process [7].

PHOTOS was running in single and multiple photon modes with matrix-element corrections turned on. Here the relative corrections are defined as:

$$\delta = \frac{\sigma(\mathcal{O}(\alpha)FSR) - \sigma(\text{Born})}{\sigma(\text{Born})} \quad (2)$$

for single photon radiation, and

$$\delta_{h.o.} = \frac{\sigma(\text{h.o.FSR}) - \sigma(\mathcal{O}(\alpha)FSR)}{\sigma(\text{Born})} \quad (3)$$

for higher order FSR contributions.

Let us look at the comparison of a single photon, *i.e.* $\mathcal{O}(\alpha)$, FSR contribution to CC and NC DY processes presented in Fig. 6 and Fig. 7, respectively. The distributions in the lepton transverse momentum and transverse (invariant) mass agree pretty well. Nevertheless, the implementations of the FSR effect in SANC and PHOTOS are different: there is a small systematic shift, as can be seen from the corresponding distribution in the lepton pseudorapidity, see Fig. 8. This shift is due to the specific feature of the PHOTOS program: simulation of FSR by means of PHOTOS doesn't change the total cross section, while the true $\mathcal{O}(\alpha)$ FSR makes a small change.

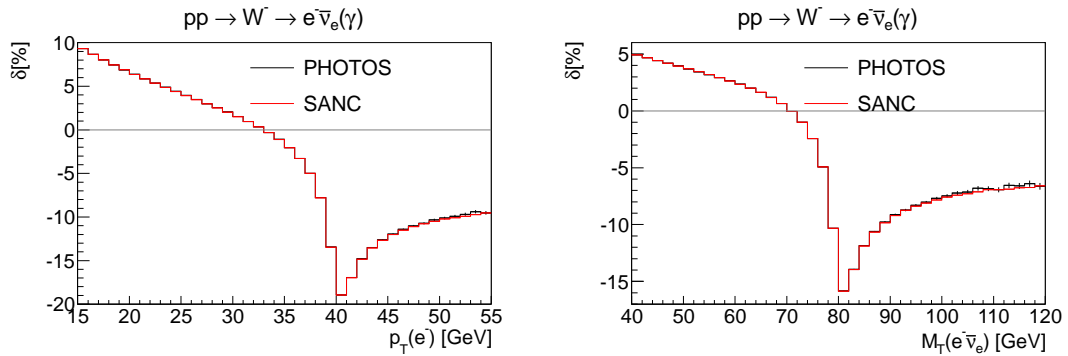


Figure 6. Tuned comparison of transverse momentum (left) and transverse mass (right) distributions in CC DY.

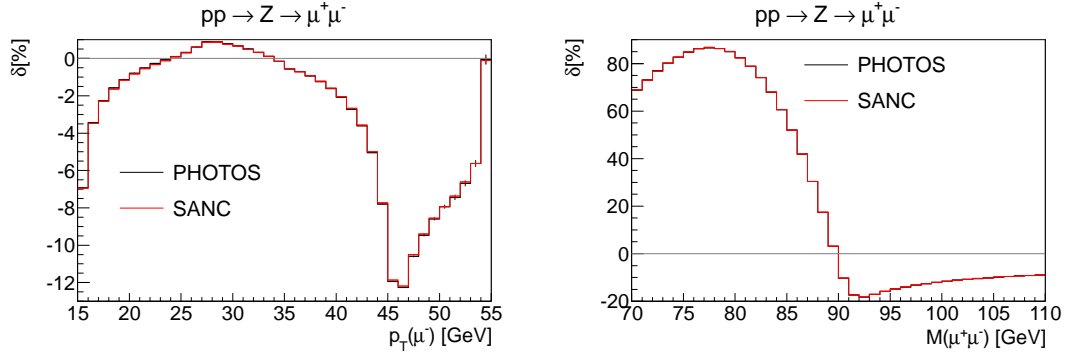


Figure 7. Tuned comparison of transverse momentum (left) and invariant mass (right) distributions in NC DY.

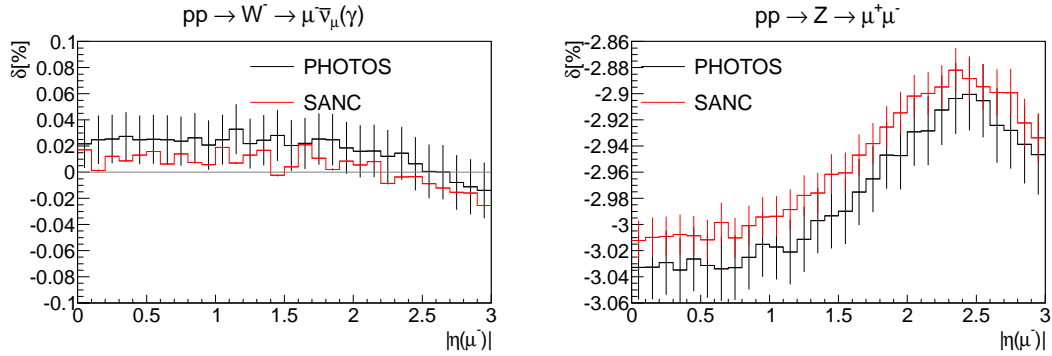


Figure 8. Tuned comparison of lepton pseudorapidity distribution in CC (left) and NC (right) DY processes.

Large corrections in the first order make it necessary to look at higher orders. Fig. 9 gives an example of comparison in higher orders. **SANC** computes the second and third order photonic FSR within the collinear leading logarithmic approximation, thus the results are sensitive to the choice of the QED factorization scale. **PHOTOS** performs exponentiation of the first order corrections. One should also keep in mind that in experimental analysis one typically applies the so-called calorimetric event selection (where charged leptons are re-combined with accompanying photons) which reduces the effect and uncertainties of the FSR considerably, as can be seen from Fig. 10 in comparison with Fig. 6.

5. Monte Carlo integrator `mcsanc`

Recently a Monte Carlo integrator (weighted events) based on **SANC** modules [3] was created [11, 12]. It features:

- calculations of fully differential cross sections for DY and inclusive cross sections of higgsstrahlung and single-top production;
- provides both NLO EW and QCD corrections;
- support of different EW schemes: $\alpha(0)$, $\alpha(M_Z)$, and G_μ ;
- fixed and running factorization and renormalization scale options;
- kinematic cuts, recombination are foreseen;

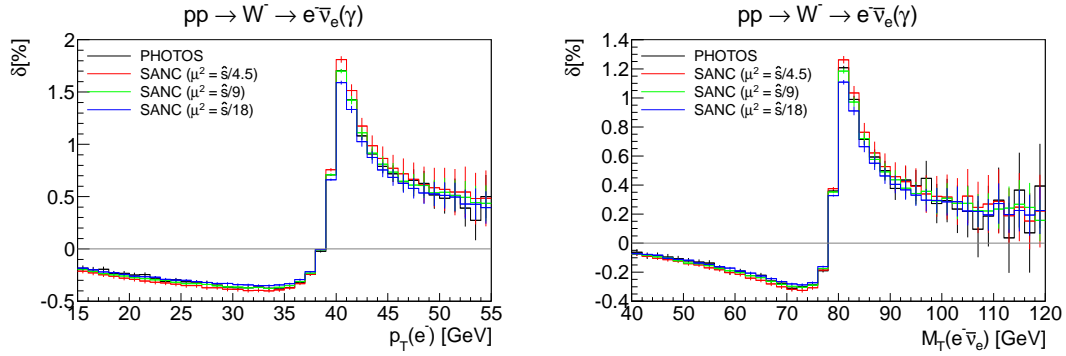


Figure 9. Comparison of higher order FSR contribution to transverse momentum (left) and transverse mass (right) distributions in CC DY.

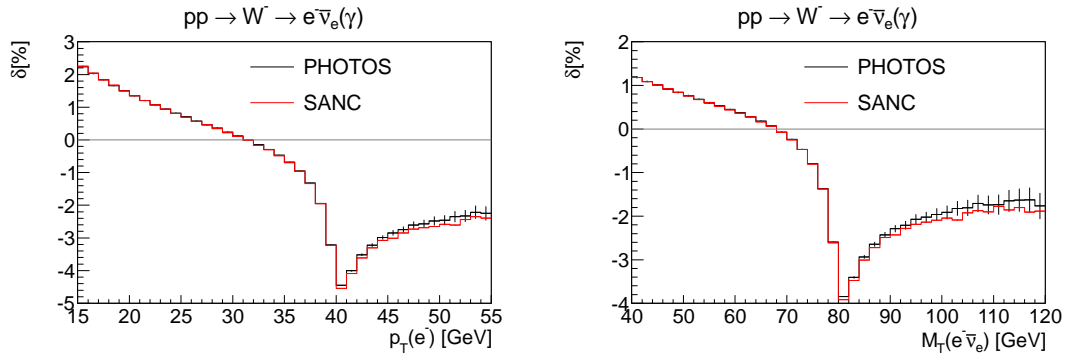


Figure 10. Tuned comparison of transverse momentum (left) and transverse mass (right) distributions in CC DY with calorimetric event selection.

- parallel calculation on multi-core machines thanks to Cuba library <http://www.feynarts.de/cuba/>;
- easy installation and configuration (GNU autotools, LHAPDF, input configurations for physics parameters, cuts, histogramming).

The code is suited to be run on multi-core computers. To get a high precision in differential distributions it takes many hours. That's why it is important to take care on stability and rescue. For this reason integration state files of the Vegas algorithm are saved while running Cuba after every iteration and upon run completion. The files can be used to increase statistics or restore from an interrupted run, *e.g.* when the batch time quota has been exceeded. When the code is run on a multi-core systems, the calculation is automatically split by the number of cores with an aid of `$CUBACORES` environment variable. The parallelization efficiency is limited due to inter-process communications: the optimal number of cores is 8, after which the run time doesn't reduce and efficiency (CPU load) remains below 50%.

The list of processes presently implemented in `mcsanc` is shown in Table 2. The process id notation is the following: first digit is the sign of EW current, and the last two digits specify the final particle choice:

`0xx` means neutral current, $xx = 01(e), 02(\mu), 03(\tau), 04(HZ)$;

$\pm 1xx$ means charged current, $xx = 01(e), 02(\mu), 03(\tau), 04(HW), 05, 06$ (top quark production in s and t channels).

Table 2. List of processes implemented in `mcsanc`

pid	$f + f \rightarrow$	SANC ref.
001:003	$\ell^+ + \ell^- (\ell = e, \mu, \tau)$	[13, 14]
004	$Z^0 + H$	[2, 3]
$\pm 101:103$	$\ell^\pm + \nu_\ell$	[15]
± 104	$W^\pm + H$	-
105	$t + b$ (s -channel)	[11, 16]
106	$t + q$ (t -channel)	-//-
-105	$\bar{t} + b$ (s -channel)	-//-
-106	$\bar{t} + q$ (t -channel)	-//-

6. Conclusions

A brief overview of the SANC project is presented. The status of tuned comparisons between the results of SANC and other codes for EW corrections to Drell-Yan production is discussed.

The comparison of SANC and PHOTOS for single and multiple photon emission was performed for the neutral and charged current DY processes. The results agree within 0.1%.

New Monte Carlo integrator `mcsanc-v1.01` is available to download on <http://sanc.jinr.ru>. The tool is aimed for calculation of NLO EW and QCD corrections to Drell-Yan, higgs-strahlung, and single top quark production processes in pp collisions.

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