

Computer system SANC: its development and applications

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Abstract. The SANC system is used for systematic calculations of various processes within the Standard Model in the one-loop approximation. QED, electroweak, and QCD corrections are computed to a number of processes being of interest for modern and future high-energy experiments. Several applications for the LHC physics program are presented. Development of the system and the general problems and perspectives for future improvement of the theoretical precision are discussed.

1. Introduction

The main problem of particle physics today is to define the energy domain of the Standard Model (SM) applicability. Precision tests of the Standard Model (SM) at LHC nowadays become more and more important. The accuracy of the corresponding experimental studies grows continuously with collected statistics, improved detector calibration, elaboration of analysis techniques *etc.* The experimental data should be confronted to high-precision theoretical predictions obtained within the SM. Searches for new physical phenomena require accurate SM theoretical predictions as well. The absence of clear signals of SUSY and other new physics scenarios at LHC makes SM studies more and more actual. On the other hand, Tevatron has proved that a hadron collider can make precision measurements of electroweak (EW) processes and verify the SM predictions. Remind that Tevatron reached the precision of the w boson mass measurement better than LEP. For high-precision theoretical predictions we need to take into account several effects of different kind. The predictions should be presented in a form suitable to be used in the data analysis. All that leads to new requirements on the accuracy of theoretical predictions challenged by the experimental data.

The subject of the present report is the description of the SANC computer system which is a tool for systematic derivation of high-precision theoretical predictions within the Standard Model for various processes studied at modern high-energy colliders. Several examples of SANC applications will be given.

2. The SANC Project

SANC is a project to Support Analytic and Numeric calculations for experiments at Colliders. The development of the SANC project started at JINR in 2001. The roots of the project are the computer programs ZFITTER [1] and HECTOR [2] which were developed earlier with



participation of the SANC team members. These programs were extensively used in the analysis of LEP and HERA experimental data.

The SANC system implements calculations of complete (real and virtual) NLO QCD and EW corrections for the Drell–Yan process, associative Higgs and gauge boson production, single top production and many other SM processes. All calculations are performed within the on-mass-shell renormalization scheme in the R_ξ gauge which allows an explicit control of the gauge invariance by examining cancellation of the gauge parameters in the analytical expression for the matrix element. The theoretical basis of the system is provided by the book [3].

During the first phase (2001–2005), the computer system SANC–v1.10 for semi-automatic calculations at the one-loop precision level (EW and QCD) of realistic and pseudo-observables (event distributions and decay rates) has been created [4, 5]. The SANC system was made publicly available for external users at <http://sanc.jinr.ru>. During its second phase (2006–2009) the work on the SANC integrated development environment was suspended, and instead the concept of SSFM (Standard SANC FORM/FORTRAN Modules), aimed for usage in physical applications, was realized [6]. The third phase (2010–present time) was mostly devoted to physical applications of SANC Monte Carlo Integrators and Generators based on the above mentioned modules. Meantime, modules for several more processes were implemented into the SANC framework: top quark decays, QCD corrections to Drell–Yan processes, 4-boson processes, and single top quark production.

The SANC framework features advanced computing methods for the calculation of a number of processes in the next-to-leading order approximation in QCD and EW theory. It has been extensively verified and cross checked against similar instruments and was proven to provide reliable advanced predictions at both parton and hadron levels.

The scheme of the SANC framework is shown in figure 1. Analytical expressions are obtained for the form factors and amplitudes of generalized processes $f\bar{f}b\bar{b} \rightarrow 0$ and $4f \rightarrow 0$ and stored as FORM expressions. The latter are translated to Fortran modules for specific parton level processes with NLO QCD and EW corrections. The modules are utilizing LoopTools and SANClib packages for loop integral evaluations. To build a Monte Carlo code one convolutes the partonic cross sections from the modules with the parton density functions and feeds the result as an integrand to any Monte Carlo algorithm implementation, e.g. FOAM or Cuba. The module’s procedures for partonic cross sections are significantly unified and allow to calculate fully differential hadronic cross sections.

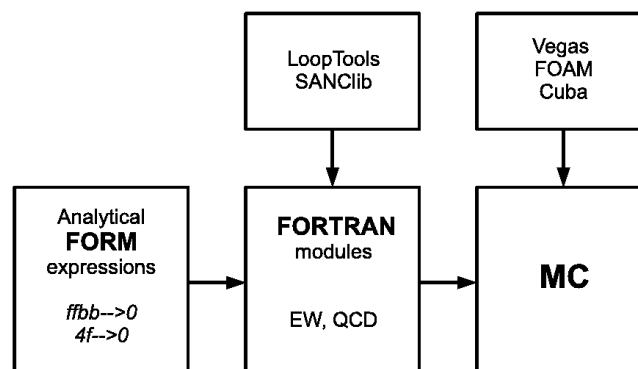


Figure 1. The SANC framework scheme.

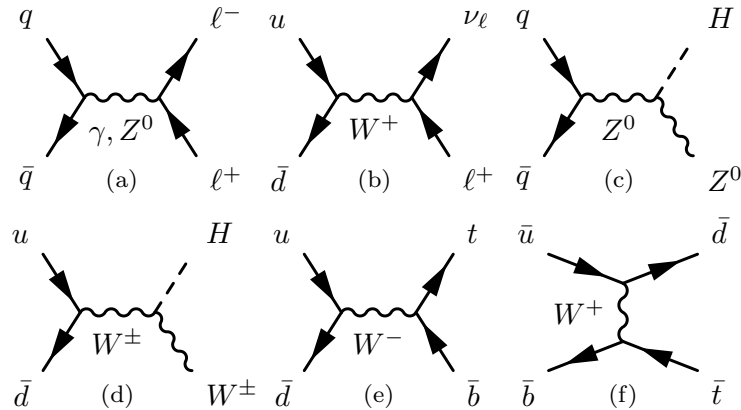


Figure 2. Feynman graphs for tree level Drell–Yan processes (neutral (a) and charged (b) currents), Higgs and gauge boson production (neutral (c) and charged (d) currents), and single top-quark production (s -channel (e) and t -channel (f)), implemented in the **MCSANC** integrator.

Table 1. NC and CC DY processes. LO, NLO EW, NLO QCD cross sections are given in picobarns and compared with corresponding values obtained with the program MCFM. The correction factors δ are shown in %.

$pp \rightarrow$	$Z^0(\mu^+\mu^-)$	$W^+(\mu^+\nu_\mu)$	$W^-(\mu^-\bar{\nu}_\mu)$
LO	3338(1)	10696(1)	7981(1)
LO MCFM	3338(1)	10696(1)	7981(1)
NLO QCD	3388(2)	12263(4)	9045(4)
NLO MCFM	3382(1)	12260(1)	9041(5)
NLO EW	3345(1)	10564(1)	7861(1)
$\delta_{QCD}, \%$	1.49(3)	14.66(1)	13.35(3)
$\delta_{EW}, \%$	0.22(1)	-1.23(1)	-1.49(1)

2.1. MCSANC integrator

The list of processes implemented in the recently updated version of the **MCSANC** integrator [7, 8] includes Drell–Yan processes (inclusive), associated Higgs and gauge boson production and single-top quark production in s and t channels, see figure 2. The **MCSANC** integrator is suited for simulation of realistic distributions taking into account LHC experimental conditions. The code allows to study how various radiative corrections affect observable distributions.

Below we provide numerical cross checks for the **MCSANC** integrator. The **SANC** DY NLO electroweak corrections were thoroughly verified with other calculations earlier during theoretical workshops on the subject and tête-à-tête comparisons, see e.g. Refs. [9, 10, 11]. The newer QCD results are validated using the MCFM [12] program. table 1 contains results for integrated LO and NLO EW and QCD cross sections obtained with the **MCSANC** integrator. The LO and NLO QCD values are in agreement with the MCFM program within statistical errors.

In the **MCSANC-v1.20** version of the Monte-Carlo tool based on the **SANC** modules, the inverse photon ($q\gamma$) and ($\gamma\gamma$) configurations in the initial pp state of beam, which contribute to Drell–Yan processes, are added. The **MCSANC-v1.20** version was used recently to calculate the

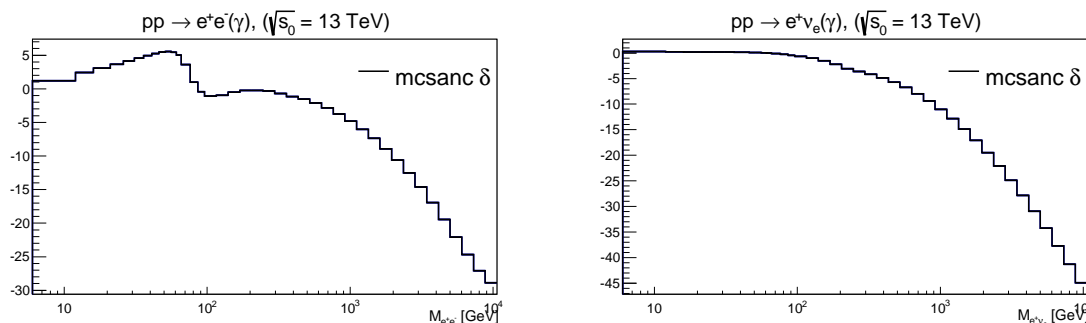


Figure 3. δ_{missed} contributions $pp \rightarrow e^+e^-(\gamma)$ (left) and $pp \rightarrow e^+\nu_e(\gamma)$ right at $\sqrt{s} = 13$ TeV.

Process	LO, pb	NLO($q\gamma$), pb	δ , %
$pp \rightarrow e^+e^-$	606.63(1)	606.20(1)	-0.071(1)
$pp \rightarrow \mu^+\mu^-$	586.49(1)	586.07(1)	-0.073(1)
$pp \rightarrow e^+\nu_e$	8.291(1)	8.378(1)	1.06(1)
$pp \rightarrow \mu^+\nu_\mu$	5.476(1)	5.540(1)	1.17(1)
$pp \rightarrow e^-\nu_e$	3298.46(3)	3299.51(3)	0.032(1)
$pp \rightarrow \mu^-\nu_\mu$	2610.50(2)	2611.25(2)	0.029(1)
Process	LO, pb	NLO($\gamma\gamma$), pb	δ , %
$pp \rightarrow e^+e^-$	606.63(1)	607.38(1)	0.124(1)
$pp \rightarrow \mu^+\mu^-$	586.49(1)	587.22(1)	0.124(1)

Table 2. Contributions of the ($q\gamma$) and ($\gamma\gamma$) configuration in the initial pp state

following corrections to the Drell–Yan processes at $\sqrt{s} = 13$ TeV: 1) the so-called missed, *i.e.* pure weak, initial and interference QED one-loop contributions to the M_{inv} distribution; 2) the inverse photon contributions for typical ATLAS fiducial cuts. The obtained results were used by the ATLAS Standard Model group for the Drell–Yan data analysis.

The estimation of four-boson background processes is very important for new physics searches. For example, according to the SM calculations of $\gamma\gamma \rightarrow \gamma Z$ the number of background events is about 5×10^3 to 3×10^4 corresponding to clear $\gamma\gamma \rightarrow H \rightarrow \gamma\gamma$ signal of about 45 to 70 events per 500 fb^{-1} for the 160 to 320 GeV energy range of a $\gamma\gamma$ mode of a linear e^+e^- machine. To study the Higgs boson properties one needs to have angular distributions for each helicity amplitude of these processes. We implemented into the four-boson sector of the SANC system processes like: $\gamma\gamma \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow \gamma Z$, $Z \rightarrow \gamma\gamma\gamma$, $\gamma\gamma \rightarrow ZZ$ in the SM at the one-loop level in the R_ξ gauge with taking into account of all masses (Z boson and internal ones) [13]. The corresponding package for numeric calculations is presented on the project web-site. In order to cross-check the results we made a comparison with other calculations.

3. SANC Applications

3.1. Electroweak corrections for Drell–Yan analysis

The Drell–Yan-like processes, *i.e.* single Z and W boson production with consequent decay into a lepton pair, provide at LHC the ultimate benchmark in the experimental precision. The theoretical description of these processes within the SM is constructed taking into account various possible effects including radiative corrections, PDF uncertainties and scale variations. Tuned comparisons between independent results of several research groups show a perfect agreement in description of QCD and electroweak radiative corrections in the one-loop (NLO) approximation. Higher order effects are also shown to be important to provide the required

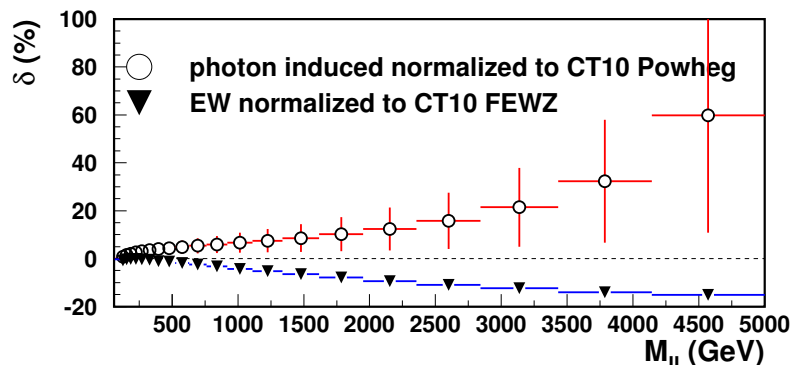


Figure 4. Photon induced background contributions calculated with $p_{T,\ell} > 25$ GeV and $\eta_\ell < 2.5$, MRST2004QED photon PDF and $\sqrt{s} = 8$ TeV over a wide invariant mass range. Calculations are performed with MCSANC [7].

accuracy level.

Monte Carlo simulations in an ATLAS analysis are typically based on the NLO QCD hard process event generators like POWHEG++ or MC@NLO complemented with PHOTOS to generate final state electromagnetic radiation. This approach does not take into account a set of higher order electroweak corrections (HO EW) when considering Drell–Yan processes: pure weak (PW) contributions, initial–final QED interference (IFI) and what remains from initial state radiation (ISR) after subtraction of collinear divergences. These corrections are sometimes referred in this text under the term “missed”.

At present the best fixed order approximation of the Drell–Yan cross section is NNLO QCD and NLO EW. However, their proper combination requires also the calculation of $\mathcal{O}(\alpha\alpha_S)$ contributions, which is currently not available in complete form. In view of it’s importance for the data analysis, two methods of combination of HO EW and QCD corrections in the theoretical predictions were compared in [14].

LHC data provide access to invariant mass regions where the photon induced contribution to the Drell–Yan process becomes substantial relative to quark-antiquark annihilation. A more accurate estimation of this background for high mass resonance searches requires the inclusion of $\gamma\gamma \rightarrow \ell^+\ell^-$ into the theory predictions. The predictions were obtained using an implementation of this process in the MCSANC integrator with MRST2004QED PDF, which albeit deprecated, was the only set containing a photon density at that time. The results of this estimation are presented in figure 4 together with HO EW (except QED FSR) corrections, which appear to have opposite sign. The corrections were included as a systematic uncertainty in the ATLAS searches for high mass dilepton resonances [15].

Calculation of HO EW (except QED FSR) corrections and their NNLO QCD combination methodology was routinely used in the ATLAS Standard Model and BSM analysis:

- Measurements of the Drell–Yan differential cross sections at $\sqrt{s} = 7$ TeV in the e and μ channels for invariant masses between 26 and 66 GeV using an integrated luminosity of 1.6 fb^{-1} collected in 2011 [16]. Theory comparisons show that fixed order next-to-next-to-leading-order QCD predictions provide a significantly better description of the results than next-to-leading-order QCD calculations, see figure 5.

- Measurements of the high-mass Drell–Yan differential cross sections at $\sqrt{s} = 7$ TeV in the e^+e^- channel based on integrated luminosity of 4.9 fb^{-1} . Invariant mass of the electron pair, covered by the measurement, is $116 < M_{ee} < 1500 \text{ GeV}$ [17].
- Measurement of the inclusive W^\pm and Z/γ cross sections in the electron and muon decay channels in pp collisions at $\sqrt{s} = 7\text{TeV}$ [18].
- A QCD analysis performed with the ATLAS data of inclusive W and Z boson production, jointly with ep deep inelastic scattering data from HERA. The ATLAS data exhibited sensitivity to the light quark sea composition and magnitude at Bjorken $x \sim 0.01$. Specifically, the data supported the hypothesis of a symmetric composition of the light quark sea at low x . The ratio of the strange-to-down sea quark distributions is determined to be $1.00(+0.25-0.28)$ at absolute four-momentum transfer squared $Q^2 = 1.9 \text{ GeV}^2$ and $x = 0.023$ [19].
- Search for high-mass dilepton resonances in 20 fb^{-1} of pp collisions at $\sqrt{s} = 8 \text{ TeV}$. Results are presented from an analysis of proton-proton collisions at a center-of-mass energy of 8 TeV corresponding to an integrated luminosity of 20.3 fb^{-1} in the e^+e^- channel and 20.5 fb^{-1} in the $\mu^+\mu^-$ channel. A narrow resonance with Standard Model Z couplings to fermions is excluded at the 95% confidence level for masses less than 2.79 TeV in the e^+e^- channel, 2.53 TeV in the $\mu^+\mu^-$ channel, and 2.90 TeV in the two channels combined [15].

3.2. QCD analysis and HERAFitter development

A precise determination of PDFs as a function of x and Q^2 requires large amounts of experimental data that cover a wide kinematic region and that are sensitive to partonic densities of different kinds. Measurements of inclusive Neutral Current (NC) and Charge Current (CC) Deep Inelastic Scattering (DIS) at the lepton-proton (ep) collider HERA provided crucial information for determining the PDFs. Different processes in proton-proton (pp) and proton-antiproton ($p\bar{p}$) collisions at the LHC and the Tevatron, respectively, provide complementary information on the DIS measurements.

The PDFs are determined from χ^2 fits of the theoretical predictions to the data. The xFitter (formerly HERAFitter) [20] project is developed for the QCD analysis of experimental data, was launched by our colleagues from DESY and initially was meant for the analysis of DIS results obtained at HERA experiments. With participation of SANC group members it was subsequently extended to include proton-(anti)proton collisions measured at the LHC experiments [20, 21, 22].

There are also examples of SANC system applications to calculations of radiative corrections to neutrino deep inelastic scattering [23] and to the process of high-energy lepton bremsstrahlung on heavy nuclei [24].

4. Outlook

The plans of the SANC project for the nearest future are listed below.

- The implementation of new processes into the SANC Monte Carlo generators and integrators at the hadron level. To obtain relevant theoretical predictions for the cross sections at the NLO level of the processes with LHC conditions and other experiments at accelerators: $ud \rightarrow W\gamma$ (EW&QCD); $ff \rightarrow W^+W^-$ (QCD); $b\gamma \rightarrow tW$ (QCD), $bg \rightarrow tW$ (QCD).

- Study of QED radiative correction contributions in the initial and final states of Drell–Yan type processes in order to coordinate them with standard programs for the analysis of experimental data.

- Research under development of the measurement of effective parameters of the Standard Model such as weak mixing angle, gauge couplings, and rho-parameter using recent LHC data. Having access to and knowledge of the specifics in the higher order electroweak corrections

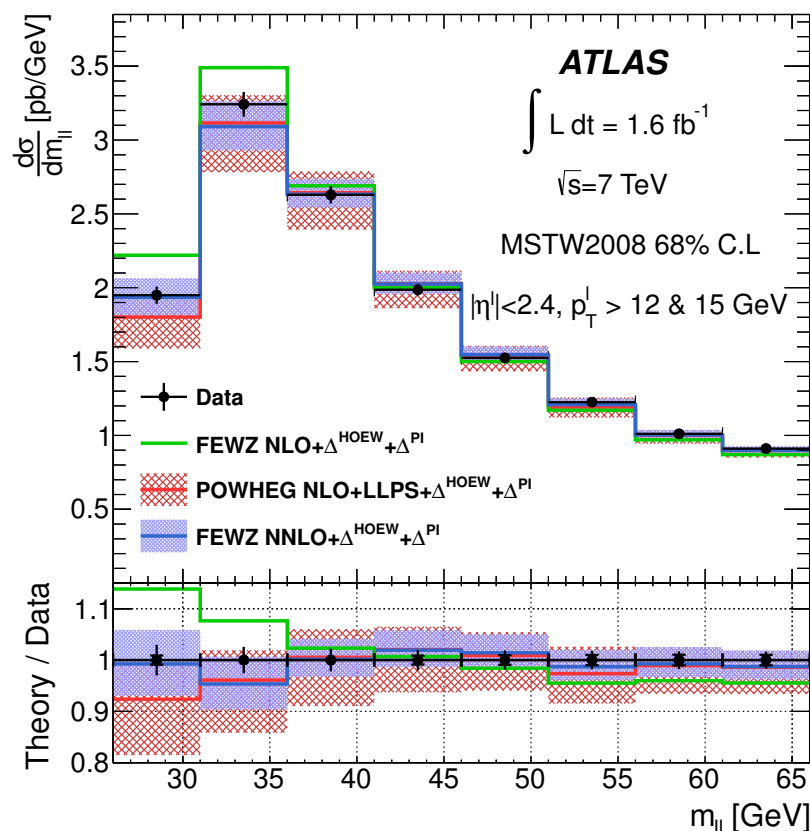


Figure 5. The measured fiducial differential cross section, $d\sigma/dm_{\ell\ell}$ for the nominal analysis as a function of the invariant mass $m_{\ell\ell}$ (solid points) compared to NLO predictions from FEWZ, NLO+LLPS predictions from POWHEG and NNLO predictions from FEWZ (all including higher-order electroweak and photon induced corrections). The predictions are calculated using MSTW2008 PDF sets with the appropriate order of perturbative QCD. The uncertainty bands include the PDF and α_s variations at 68% CL, scale variations between 0.5 and 2 times the nominal scales, and the uncertainty in the PI correction. The ratios of all three theoretical predictions (solid lines) to the data are shown in the lower panels. The data (solid points) are displayed at unity with statistical (inner) and total (outer) measurement uncertainties.

implementation in the MCSANC code, it is possible to set up an analysis chain to measure the mentioned variables. A sensitivity of the effective Weinberg angle to ATLAS data has been observed and the possibility to extract its value will be studied.

- Analysis of Drell–Yan type processes in the context of QCD. The purpose of this research is to tune the functions of parton distributions based on experimental data of proton-proton collisions. Application of HERAFitter to RUN-I data showed additional information on the densities of the momentum distributions of s -quark at small values of x and of gluons at large x . There is a need to continue these studies in RUN-II with high kinematic ranges and higher statistics.

- Collaboration with DESY (Hamburg) on the project ZeeD. The project ZeeD (analysis of $Z \rightarrow ee$ events at DESY) is aimed to study Drell–Yan processes. Now it was developed a technique and software for the analysis of RUN-I data. It's necessary to adapt the program

interface to the new RUN-II data format and expand its functionality.

Working in this direction we try to approach several general problems which are relevant for increasing the precision of theoretical predictions. The key problems are:

- Matching specific higher order corrections with general tools like PYTHIA or HERWIG without double counting of effects
- Estimation of the theoretical uncertainty. We have a considerable scheme and scale dependence for EW corrections and make the optimal choice.
- Interplay of EW and QCD RC to DY: implementation of $\mathcal{O}(\alpha\alpha_s)$ RC with matching to existing results.
- NLO treatment of QED evolution in PDFs should be done for a consistent treatment of QED initial state radiation (ISR).

In conclusion, we would like to underline that precision tests of the SM at LHC are of ultimate importance. Many effects of different nature should be taken into account for these tests. The SANC project contributes to studies of EW observables. But only common efforts of different groups guarantee the construction of reliable theoretical predictions. The forthcoming analysis of the LHC Run2 data provide new challenges for theoreticians.

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