SANC integrator in the progress: QCD and EW contributions

D. Bardin\textsuperscript{a1), S. Bondarenko\textsuperscript{b), P. Christova\textsuperscript{a), L. Kalinovskaya\textsuperscript{a), L. Rumyantsev\textsuperscript{a,c), A. Sapronov\textsuperscript{a), W. von Schlippe\textsuperscript{d).}

\textsuperscript{a) Dahelepow Laboratory for Nuclear Problems, JINR, ul. Joliot-Curie 6, RU-141980 Dubna, Russia;}
\textsuperscript{b) Bogoliubov Laboratory of Theoretical Physics, JINR, ul. Joliot-Curie 6, RU-141980 Dubna, Russia;}
\textsuperscript{c) Rostov University, Russia;}
\textsuperscript{d) Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia.}

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Modules and packages for the one-loop calculations at partonic level represent the first level of SANC output computer product. The next level represents Monte Carlo integrator mcsanc\textsuperscript{*}, realizing fully differential hadron level calculations (convolution with PDF) for the HEP processes at LHC. In this paper we describe the implementation into the framework mcsanc first set of processes: DY NC, DY CC, $f_1f_1 \rightarrow HW^\pm(Z)$ and single top production. Both EW and QCD NLO corrections are taken into account. A comparison of SANC results with those existing in the world literature is given.

1. INTRODUCTION

Recent reviews of theoretical predictions and their uncertainties for basic LHC processes in the Standard Model (SM) can be found in Reports [1] and [2].

The interpretation of high-quality data of the LHC demands an equally high precision in the theoretical predictions at the level of quantum corrections. Apart from a detailed knowledge of higher-order EW and QCD corrections, the combination of their effects must be investigated. Advanced computational tools were developed to control the interplay of EW and QCD corrections: [3, 4, 5, 6] and [7].

In this paper new results of the computer system SANC (Support of Analytic and Numerical Calculations for experiments at Colliders) [8] are presented. In this system it is possible to achieve the one loop level predictions in the EW and QCD sectors on the same platform of the analytic procedures.

The first level of the computer products SANC are: analytical modules for scalar Form Factors (FF) and Helicity Amplitudes (HA) and accompanying bremsstrahlung contributions (BR or MC) and the s2n.f package producing the FORTRAN codes [9].

In this paper we discuss in some detail the results of the implementation at hadronic level in the newly developed mcsanc-1.0 integrator, based on the above mentioned modules. The processes are marked by process identifiers: pid=cnn, c=charge: 0-NC, ±-CC, and: nn=01(e), 02(μ), 03(τ) etc, see below.

- Drell–Yan-like single $W$ production: pid = ±102.
  \[ \bar{d} + u \rightarrow t^+ + l^- \]  \hspace{1cm} (1)
- Drell–Yan-like single $Z$ production: pid = 002.
  \[ q + \bar{q} \rightarrow l^+ + l^- \]  \hspace{1cm} (2)
- $HW^\pm(Z)$ production: pid = ±104 (004).
  At the parton level we consider
  \[ f_1f_1 \rightarrow HW^\pm(Z) \rightarrow 0 \]  \hspace{1cm} (3)
  (where $f_1$ stands for a massless fermion of the SM, while specifically for bosons we use $Z$, $W^\pm$, $H$). It should be emphasized also that the notation $f f$ limit to means that all external 4-momenta flow inwards; this is the standard SANC convention which allows to compute one-loop covariant amplitude (CA) and form factors (FF) only once and obtain CA for a specific channel by means of a crossing transformation.

- the $s$ and $t$ channels of single top quark production: pid = ±105(s), ±106(t).
  \[ \bar{b}u \rightarrow 0 \quad \text{and} \quad b\overline{u}d \rightarrow 0. \]  \hspace{1cm} (4)

Previous studies of these processes by SANC system, i.e. creation of the analytic platform and modules at the parton level were presented in [8] [10] [11] [12] [13] [14].

The paper is organized as follows. First, an overview of the mcsanc-1.0 integrator is given in section 2. In subsection 2.1 we describe a list of contributions to hard sub-processes and introduce their enumeration. Then we describe the parallel calculations issue. Section 3 contains numerical results for the processes in QCD and EW sectors. Input parameters, kinematical cuts, and the used PDFs can be found in subsection 3.1. Further, we present the complete predictions for inclusive cross sections at LO and NLO levels in the EW and QCD sectors for processes [11–13]. We systematically
compare our results for NLO QCD corrections with the program MCFM [16, 17] and, whenever possible, with other codes existing in the literature: [18], [19] (EW) and [20] (QCD).

In section 4 we summarize our results.

2. SANC INTEGRATOR

2.1 Description of id’s for hard sub-processes

At NLO level several hard sub-processes contribute to a given process. In general, it consists of several parts: LO–lowest order, Virt–virtual, Real–real brems(glue)strahlung and Subt–subtraction; Real, in turn, is subdivided into Soft and Hard contributions. We enumerate them through id=0–6:

- id0: LO, 2 → 2, tree-level, q ¯q′ NC or CC sub-processes.
- id1: Subt term, responsible for the subtraction of the initial quark mass (mq) singularities for q ¯q′ subprocesses, computed in a given subtraction scheme (MS or DIS). It depends on ln(mq).
- id2: Virt represents only the NLO EW parts, stands for pure EW one-loop virtual contributions. It depends on mq and may depend on an infrared regulator (e.g. on an infinitesimal photon mass). It is not present for QCD NLO contributions, where it is added to the soft contribution (see next item). For DY NC NLO EW process it contains all virtual contributions, both EW and QED.
- id3: For all processes, except DY NC, this stands for the sum of Virt and Real Soft (QED/QCD) contributions, therefore it does not depend on the infrared regulator but depends on mq and on the soft-hard separator ¯ω. For DY NC NLO EW processes it is just the Real Soft QED contribution that depends on the infrared regulator, on mq and on the soft-hard separator ¯ω.
- id4: For all processes this is just the Real Hard (QED/QCD) contribution that depends on mq and on ¯ω.
- id5: Subt term is responsible for the subtraction of the initial quark mass (mq) singularities for qg( ¯qg′) subprocesses (also computed in MS or DIS schemes). It contains a logarithmic mass singularities in mq.
- id6: The gluon-induced sub-process—an analog of id4 for qg( ¯qg′) sub-processes. They also contain logarithmic mass singularities which cancel those from id5.

The quark mass is used to regularize the collinear divergences, the soft-hard separator is a remainder of infrared divergences. The sum of contributions with id3 and id4 is independent of ¯ω. The sums id1+id2+id3+id4 and id5+id6 are separately independent of mq. Therefore, the entire NLO sub-process is independent of both unphysical parameters ¯ω and mq.

2.2 Parallel calculations

The mcsanc program takes advantage of parallelization in the Cuba library [21], [22], used as a Monte Carlo integrating tool. However, the parallelization efficiency is reduced by the overhead of inter-process communications.

Figure 1 shows time required to complete the NLO EW cross section calculation depending on the number of active CPU cores. The test was run on a dual-processor Intel Xeon machine with 12 real (24 virtual) cores with Linux operating system. The upper plot summarizes multicore CPU productivity: “total” is the wall clock time passed during the run; “user” is the CPU time consumed by the program (roughly equals to wall clock time multiplied by the number of cores in case of 100% efficiency); “system” is the time spent by the operating system on multiprocessing service.

One can see that the parallelization is efficient with number of cores up to 8, after which the total run time does not significantly decrease and the overhead CPU time (“user”) grows. It is also apparent from the lower...
plot that the average CPU load efficiency drops below 50% with more than 8 cores active.

3. NUMERICAL RESULTS

In this section the results, obtained by the mcsanc integrator, realizing fully differential hadron level calculations for the processes [1]–[4] are presented.

We produce comparison with numerical results for the NLO QCD corrections for all our processes between SANC and [16]. For the NLO electroweak corrections for Drell–Yan NC and CC processes (pid = 002, ±102) this was done early within the workshop [23]. For WH production, i.e. pid = ±104, in EW sector between SANC and [13] and in QCD sector between SANC and [20] for pid = ±105, ±106.

31 Setup: PDF, cuts, input parameters

For the numerical results in this section we have used the following setup.

• PDF set, scales, α_s. We use CT10(f[scale]) PDF from the LHAPDF library and compute α_s via a call to alphasPDF(r[scale]). Usually we set factorization scale (f[ scale]) equal to renormalization scale (r[scale]) and different for the processes under consideration: M_V for DY-like single V production; M_V+H for the processes Eq.(3); m_t for the processes Eq.(1).

• Phase-space cuts. We use loose cuts: for the final state particle transverse momenta p_T ≥ 0.1 GeV, no cuts for their rapidities and for the neutral current DY, in addition, M_V H ≥ 20 GeV. We demonstrate numerical results for Drell–Yan only for muon case and we are not dealing with effects of recombination. We choose ω = 10^{-4} and the cms energy √s = 14 TeV if not stated otherwise.

• Set of EW scheme and input parameters. We choose the G_F EW scheme, and input parameters are taken from PDG-2011 (on 16/05/2012):
  
  Coupling constants: α = 1/137.035999679, G_F = 1.16637 × 10^{-5}. Boson masses: M_W = 80.399 GeV, M_Z = 91.1876 GeV, M_H = 120 GeV. Boson widths: Γ_Z = 2.4952 GeV, Γ_W = 2.085 GeV. CKM matrix: V_{ud} = 0.9738, V_{us} = 0.2272, V_{cd} = 0.2271, V_{cs} = 0.9730. Lepton masses: m_e = 0.510998910 MeV, m_μ = 0.105658367 GeV, m_τ = 1.77682 GeV. Heavy quark masses: m_b = 4.67 GeV, m_c = 1.729 GeV. Masses of the four light quarks are taken from [24]: m_d = 0.066 GeV, m_u = 0.066 GeV, m_s = 0.150 GeV, m_c = 1.2 GeV.

32 Example of $M_{\mu^+\mu^-}$ distributions, DY NC

The standard ATLAS Monte Carlo (MC) generation uses the PYTHIA–PHOTOS chain of programs. PYTHIA [25],[26] has the leading order (LO) matrix element for a given process and takes into account Parton Showers (PS); PHOTOS [27], [28] and [29] describes multiphoton emission from the Final State (FSR) dilepton system. This procedure does not include certain next-to-leading order (NLO) EW corrections, like Pure Weak (PW) contributions, Initial–Final QED interference (IFI) and what remains from Initial State Radiation (ISR) after subtraction of collinear divergences.

In SANC one can evaluate the entire effect of these corrections as a difference of complete NLO EW corrections and the QED FSR corrections. See, for example, the distribution of the complete NLO EW corrections over Z boson invariant mass, δ(M_{\mu^+\mu^-}), for Drell–Yan-like single Z production around Z resonance, (δ = (dσ_{NLO}/dM_{\mu^+\mu^-})/(dσ_{LO}/dM_{\mu^+\mu^-}) − 1) and with taking into account only QED FSR corrections, Figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{δ in % with complete NLO EW (solid histogram) and FSR (dashed histogram) corrections}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Difference correction δ_{Diff} in % for the distribution over $M_{\mu^+\mu^-}$}
\end{figure}
NLO and FSR distributions in Figure 2 are barely distinguishable. The difference \( \delta_{\text{Diff}} = \delta_{\text{NLO}} - \delta_{\text{FSR}}(M_{\mu^+ \mu^-}) \) is shown in Figure 3.

As is seen, for the \( M_{\mu^+ \mu^-} \) interval around the \( Z \) resonance, \( \delta_{\text{Diff}} \) varies from +5% at the lower edge to −1% at the upper edge and therefore cannot be neglected, if the precision tag is equal to 1%, say.

### 33 Numerical results and comparison for LO, NLO EW, NLO QCD RC

- In Tables 1–3 we present LO and NLO inclusive cross sections for processes (1–2), (3) and (4), respectively.

| pid  | 002  | 102  | -102 |
|------|------|------|------|
| 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) |
| \( \delta_{\text{QCD}} \) | 1.49(3) | 14.66(1) | 13.35(3) |
| NLO EW | 3345(1) | 10564(1) | 7861(1) |
| \( \delta_{\text{EW}} \) | 0.22(1) | -1.23(1) | -1.49(1) |

Table 1: NC and CC DY processes, i.e. for pid = 002, ±102. LO, NLO EW, NLO QCD cross sections are given in picobarns and compared with corresponding values obtained with the aid of the program MCFM. Also correction factors are shown in %. The numbers illustrate good agreement within statistical errors of MC integration.

| pid  | 004  | 104  | -104 |
|------|------|------|------|
| LO   | 0.8291(1) | 0.9277(1) | 0.5883(1) |
| LO MCFM | 0.8292(1) | 0.9280(2) | 0.5885(1) |
| NLO QCD | 0.9716(3) | 1.0897(3) | 0.6866(3) |
| NLO MCFM | 0.9686(1) | 1.0901(2) | 0.6870(1) |
| \( \delta_{\text{QCD}} \) | 16.18(3) | 17.47(3) | 16.72(5) |
| NLO EW | 0.7877(1) | 0.8672(2) | 0.5508(1) |
| \( \delta_{\text{EW}} \) | -5.00(2) | -6.52(2) | -6.38(3) |

Table 2: The same is in Table 1 but for processes of \( HZ(W^\pm) \) production, i.e. pid = 004, ±104.

- In Table 4 we show QCD and EW cross section contributions to the processes of \( HW^\pm \) production, pid= ±104, detailed over id’s of the \texttt{mcsanc} integrator. As is seen for the chosen setup (Subsection 3.1) there is strong cancellation of the Soft and Hard contributions id’s=3,4 and gluon induced contributions id’s=5,6, the sum of contributions id’s=5+6 being negative. We remind that the sum of all contributions is independent of the unphysical parameters \( \bar{\omega} \) and \( m_q \).

| QCD  | pid  | 104  | -104 |
|------|------|------|------|
| id0  | 0.9277(1) | 0.5883(1) |
| id1  | 0.6916(1) | 0.4860(1) |
| id3  | -10.9233(1) | -6.9139(1) |
| id4  | 10.4547(1) | 6.5737(1) |
| id5  | -0.9717(1) | -0.6733(1) |
| id6  | 0.9107(1) | 0.6258(1) |
| NLO QCD | 1.0897(3) | 0.6866(3) |

Table 4: EW and QCD radiative corrections in picobarns detailed over id’s for pid= ±104, parameter \( \bar{\omega} = 10^{-4} \).
• The other comparisons.

1) EW corrections: a comparison of EW and QCD NLO corrections between mcsanc and papers [18] and [19] was done using corresponding setup. We received good agreement within statistical errors with the results presented in the references.

2) QCD corrections: a comparison between inclusive LO and NLO cross sections from mcsanc and Table 1 of paper [20] was carried out using tuned setup. Agreement within MC errors was found for LO, while for NLO only a qualitative agreement was reached, since we did not manage to reproduce the corresponding value for $\alpha_s(r)$.

More comparisons, including differential distributions (as in papers [3, 30]) will be presented elsewhere.

4. CONCLUSIONS

To match the experimental accuracy at the LHC, we direct our effort to developing a programming environment for the calculation of processes at one loop level and to creating the mcsanc integrator with EW and QCD branches at hadron level.

In this paper we have presented results for EW and QCD corrections to the following processes: $Z$ and $W$ production, $HZ$ and $HW^\pm$ production, and single top production, and Table 1 of paper [20] was carried out using tuned setup. Agreement within MC errors was found for LO, while for NLO only a qualitative agreement was reached, since we did not manage to reproduce the corresponding value for $\alpha_s(r)$.

More comparisons, including differential distributions (as in papers [3, 30]) will be presented elsewhere.

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