Proc. Natl. Conf. Theor. Phys. **36** (2011), pp. 6-13

HIGH PRECISION ELECTROWEAK PHYSICS AT LHC: DRELL-YAN PROCESSES

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Abstract. *Cross sections of single Z and W boson production processes at LHC will be measured with high precision. These processes are used for luminosity monitoring, extraction of parton density functions, calibration of detectors, and for the most precise definition of the W boson mass. Construction of an adequately accurate theoretical description of these processes is under development. QCD and electroweak radiative corrections and the present theoretical uncertainty are discussed. Recent results of the SANC project are presented.*

I. MOTIVATION

Charged and neutral current Drell–Yan (DY) [1, 2] processes[1] are very important at the modern hadron-hadron colliders as for precision tests of the Standard Model (SM) as well as for various *new physics* searches. These processes have large cross sections, clear signatures in detectors and a rather accurate theoretical description. Remind that the detection of high-energy muons by the modern general-purpose detectors at LHC and Tevatron can be performed with the best accuracy in comparison to the one of any other outgoing particle. Detection of electrons and tau-leptons is not as efficient as the one of muons, but still it is better than the one of the pure hadronic final states. On the other hand the theoretical predictions for these processes obtained within the Standard Model are rather solid and precise. For these reasons the DY processes provide so called *standard candles* for detector calibration at LHC and Tevatron. The Neutral Current (NC) and the Charged Current (CC) DY processes will be also used at LHC for extraction of partonic density functions (PDF) in the kinematical region which has not been accessed by earlier experiments. It is planned at LHC to obtain 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. Recently, Tevatron published a new combined CDF and D0 results [3, 4] on the W mass and width measurements

$$M_W[\text{Tevatron}] = 80.420 \pm 0.031 \text{ GeV}, \quad (1)$$

$$\Gamma_W[\text{Tevatron}] = 2.046 \pm 0.049 \text{ GeV}, \quad (2)$$

which appeared to be more precise than the corresponding numbers obtained at LEP [5]

$$M_W[\text{LEP}] = 80.376 \pm 0.033 \text{ GeV}, \quad (3)$$

$$\Gamma_W[\text{LEP}] = 2.196 \pm 0.083 \text{ GeV}. \quad (4)$$

[1]These processes at high energy colliders such as Tevatron and LHC are called also as the processes of single W and Z boson production.

These achievements show that hadron-hadron colliders can be really used for high-precision tests of the Standard Model.

DY processes will provide also background to many other reactions being of interest at LHC. Moreover, some searches for *new physics* like the ones for contact four-fermion interactions, unparticles [6], or Z' and W' bosons will be performed in these channels. Therefore it is crucial to control the accuracy of the theoretical predictions for the standard DY processes. In this context the question arises: "Are we ready to provide an adequately accurate theoretical description of Drell-Yan processes at LHC?"

The experimental precision tag for inclusive observables in Drell-Yan 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 forthcoming 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 in LO, NLO and NNLO;
- parton shower and hadronisation effects;
- EW radiative corrections in one-loop at least;
- most important higher order contributions (resummed where possible);
- an interplay of QCD and EW corrections;
- a tuned input: coupling constants, the hadronic vacuum polarization, and PDFs for the appropriate energy scales and x-values.

And all relevant effects should be implemented in a Monte Carlo event generator to be directly used in experimental data analysis. Actually, treating all the listed effects in a single code is a very difficult task. A more realistic choice is to make a chain of computer codes, which pass generated events from one to another and "dress" them with additional effects. For example, parton showers in Drell-Yan processes can be applied with the help of the PYTHIA [7] or HERWIG [8] codes for events generated by another program.

Our group (led by D.Yu. Bardin and L.V. Kalinovskaya) actively participates in international efforts aimed at the increasing of precision in the theoretical description of the DY processes. Our studies are performed with help of the SANC computer system. The latter is developed for Support of Analytic and Numeric calculations for experiments at Colliders [9, 10]. It is accessible at `http://sanc.jinr.ru/` and `http://pcphsanc.cern.ch/`. The SANC system is suited for calculations of one-loop QED, EW, and QCD RC to various SM processes. Automatized analytic calculations in SANC provide `FORM` [11] and `FORTRAN` modules [12].

For Drell-Yan-like processes within the SANC project we have:

— complete one-loop EW RC in CC [13] and NC [14] cases,

— photon induced DY processes [15],

— higher order photonic FSR in the leading logarithm approximation,

— NLO QCD corrections [16, 17],

— interface to parton showers [18] in PYTHIA and HERWIG based on the standard Les Houches Accord format,

— higher order photonic and pair FSR in the leading logarithmic approximation,

— Monte Carlo integrators and event generators.

Tuned comparisons with results of HORACE and Z(W)GRADE for EW RC to CC and NC DY were performed within *Les Houches* '05, '07 and *TEV4LHC* '06 workshops. A very good agreement was found, see *e.g.* Fig. 1. But this perfect agreement doesn't mean that the problem is solved. In fact there is quite a few effects which go beyond the given comparison in which only electroweak one-loop corrections were taken into account.

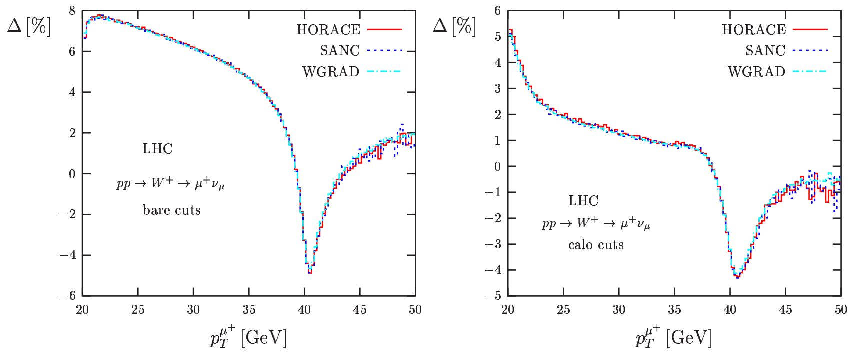

Fig. 1. Set-up: $P_T(l,\nu) > 20$ GeV, $|\eta(l)| < 2.5$; $\alpha(0)$ EW scheme; MRST2004QED PDF set; NLO QED DIS subtraction scheme.

II. QCD CORRECTIONS

QCD radiative corrections to DY processes have been extensively studied in the literature [19, 20, 21]. But only recently the relevant NNLO corrections for differential distributions have been derived [22, 23, 24]. There are several MC generators taking into account QCD NLO corrections and some higher order effects, *e.g.* MC@NLO [25], POWHEG [26, 27], MCFM [28], and ResBos [29]. With the help of the SANC system we also evaluated NLO QCD corrections [16]. Our results are in a good agreement with the ones of MCFM for both CC and NC channels, see Fig. 2. The ACOT factorization scheme [30] with massive quarks was applied in SANC to treat the heavy quark contributions.

For a realistic application, one has to take into account also QCD parton showers, see e.g. Fig. 3 where their effect is shown for the μ^+ transverse distribution. It can be done with help of the standard packages like PYTHIA [7] and HERWIG [8]. Note that the showers will wash out the negatively weighted events, which can be seen in the resonance region in Fig. 2 (left).

Fig. 4 shows that the parton shower effects in the two codes which are used for data simulation at LHC differ from each other quite a lot. The present deviation gives a considerable source of uncertainty in the DY processes description at large transverse momenta of leptons. Of course, it is planned to adjust the parton shower simulation in both codes to the forthcoming LHC data.

To have a realistic accurate theoretical prediction it is required also to use the proper set of parton density functions (PDF). The problem is that PDFs were extracted

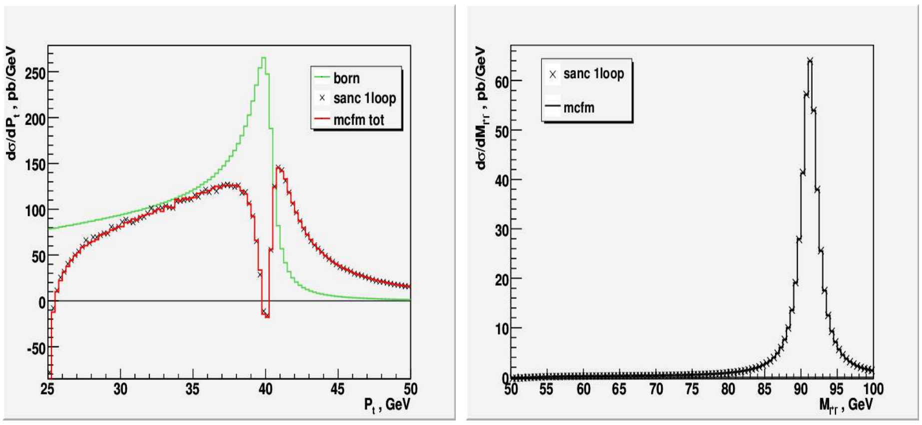

Fig. 2. Lepton transverse momentum in CC DY with and w/o parton shower effects(left) and Z-boson transverse momentum distribution in NC DY.

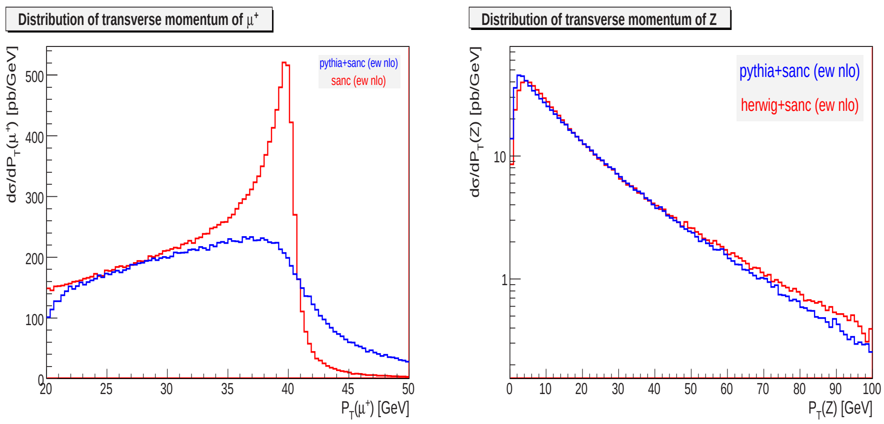

Fig. 3. Lepton transverse momentum in CC DY with and w/o parton shower effects(left) and Z-boson transverse momentum distribution in NC DY with different parton shower models.

from experimental data being obtained in kinematical domains which are different from the ones accessed at LHC. It is verified that the difference between predictions obtained when using alternative modern NLO and NNLO PDF sets is of the order of 2 percent. Nevertheless, the standard Monte Carlo event generators PYTHIA and HERWIG have only the leading order partonic cross sections. According to the general prescriptions of the QCD factorization theorems those should be converted with the Leading Order (LO) PDF. To take into account QCD NLO (NNLO) effects one can construct a re-weighting procedure, which involves the factor of NLO/LO (NNLO/LO) ratio. Such a re-weighting correction in percent is shown in Fig. 5 To our mind the difference is too large to be explained just by the step from LO to NLO. That was realized aslo by the MRST group [31] who issued a modified version of the LO PDF.

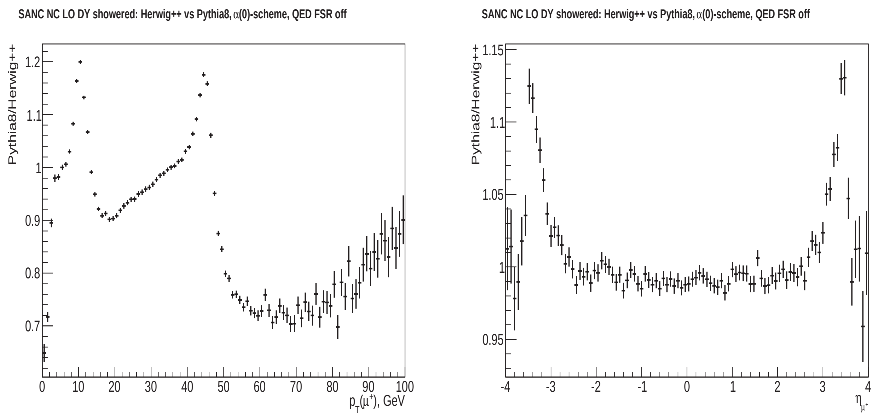

Fig. 4. The ratio of the differential distributions in lepton transverse momentum (left) and rapidity (right) obtained using PYTHIA and HERWIG parton shower routines.

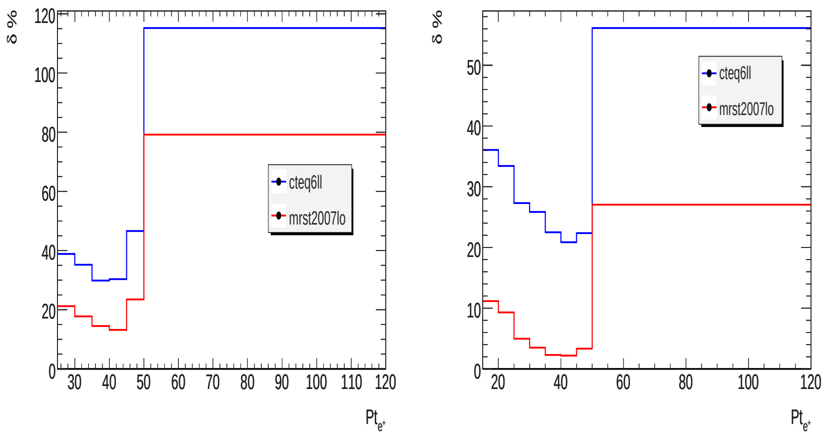

Fig. 5. Difference between LO and NLO QCD predictions for e^+ transverse momentum distributions in CC (left) and NC (right) DY at LHC with $E_{CM} =$ 10 GeV.

III. EW CORRECTIONS

It has been shown (see Sect. 3 of Ref. [32]) that EW corrections to inclusive DY cross sections and to their differential distributions in the $Z(W)$-resonance region are comparable in size with the QCD ones. Roughly, the EW RC are only about two or three times less than the QCD ones. Naively one would expect the ratio to be of the order of $\alpha_{QED}(M_Z)/\alpha_{QCD}(M_Z) \sim 0.1$. But EW corrections have an enhancement due to the EW Sudakov logarithms and due to large collinear logarithms from the final state radiation off charged leptons. That makes EW corrections being numerically important.

The one-loop EW RC were computed for the DY processes by SANC in Refs. [13, 14, 15] and extensively compared with results of other groups, see *e.g.* Refs. [32, 33, 34]. An excellent agreement was established for tuned comparisons both in CC and NC currents, see *e.g.* Fig. 1 taken from Ref. [33].

Recently, the standard SANC modules for parton-level DY cross sections with one-loop EW RC have been implemented into the MC event generator WINHAC [34]. Preliminary results of comparisons performed between SANC and WINHAC for higher order contributions due to multiple final state radiation in CC DY show a good agreement, in spite of different methods used for description of the effect, see Fig. 6.

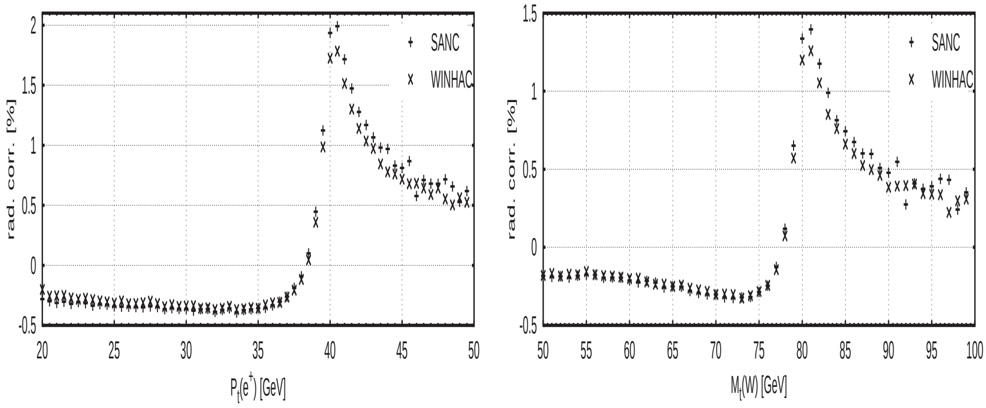

Fig. 6. Higher order FSR corrections in percent for BARE positron transverse momentum (left) and W transverse mass (right) distributions in CC DY.

Recently some partial results on the genuine interplay of QCD and QED effects in two-loop virtual corrections were published [35]. But still those effects should be extended for the case of real radiation and quantified numerically for realistic conditions of LHC.

IV. OUTLOOK

The resulting theoretical uncertainty in description of DY processes at LHC should combine errors coming from several sources: 1) PDF parametrization; 2) QCD (and QED) factorization scheme and scale dependence; 3) pure QCD higher order terms; 4) pure EW higher order terms; 5) interplay between EW and QCD effects; 6) ambiguities in evaluation of heavy quark contributions; 7) hadronic vacuum polarization uncertainty. Technical errors coming from the limited numerical precision and dependence on auxiliary internal parameters of computer codes should be also taken into account. The present accuracy of PDF in the kinematical region relevant for LHC lead to a huge uncertainty in DY cross section of the order of 5% or even more. This value is two times larger than the difference between the predictions received just by variation of the existing PDF parametrization. But as discussed above the situation will be improved only after new fits of PDF based on the LHC data (on DY!). QCD and QED evolution in PDF should be taken into account simultaneously. Factorization scheme and scale dependence in the present calculation and computer codes are considerable. They should be reduced by adjustment of the scheme and scale choices and by including relevant higher order effects. To get the requested precision we need an advanced implementation in Monte Carlo codes of NNLO QCD corrections and soft gluon re-summation. Complete two-loop EW corrections to Drell-Yan hardly can be calculated in the nearest future, but some numerically important contributions like the EW Sudakov logs or two-loop vacuum polarization and multiple final state radiation, are to be taken into account. In the ideal case all the relevant effects should be combined in a single Monte Carlo event generator or at least in a system (or chain) of generators, which can sum up different effects. A lot of work in this direction has been already done. Several groups are participating in workshops and tuned comparison programs. The SANC group continues development of its own codes for DY description as well as participation in knowledge exchange with other groups.

ACKNOWLEDGMENTS

This work was supported by the RFBR grant 10-02-01030.

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Received 30-09-2011.