Precision of Drell-Yan processes description at LHC

A. B. Arbuzov*
Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, 141980 Russia

Abstract

The present precision of the theoretical description of single Z and W bosons production at LHC is discussed. To reach the 1 percent experimental precision tag one has to take into account interplay of different effects like perturbative electroweak and QCD radiative corrections and parton shower effects. Contributions to the resulting theoretical uncertainty are discussed Numerical results for typical LHC conditions are presented.

This seminar is devoted to the memory of Albert Nikiforovich Tavkhelidze. The subject of my talk is directly related to his name, since at first the process of lepton pair production in hadronic collisions was considered in 1969 in paper [1] by Matveev, Muradian and Tavkhelidze. Independently this processes was studied in Ref. [2] by Drell and Yan.

1 Motivation

Charged and neutral current Drell–Yan (DY) processes are very important for precision tests of the Standard Model (SM) at hadron colliders. They have large cross sections, clear signatures in detectors and a rather accurate theoretical description. So these processes provide the standard candles for detector calibration at LHC and Tevatron. Single Z and W boson production 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 to get the most precise experimental values for the mass and width of W boson using the future high statistics data on the CC DY process. Just recently we got news from Tevatron [3] about the fact that the precision of W mass measurement at the hadron collider exceeded the one achieved at LEP.

DY processes will also provide background to many other reactions being of interest at LHC. Moreover, even 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 NC and CC 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 showers and hadronization;
- electroweak (EW) radiative corrections in one-loop at least;
- most important higher order EW contributions (re-summed where possible);

* **e-mail**: arbuzov@theor.jinr.ru

- 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.

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. For example, multiple photon final state radiation in Drell-Yan processes can be supplied for events generated by a some general purpose code like HERWIG [4], PYTHIA [5] or Sherpa [6] by means of the standing alone code PHOTOS [7].

SANC is a computer system for Support of Analytic and Numeric calculations for experiments at Colliders [8, 9]. It can be accessed through the Internet at `http://sanc.jinr.ru/` and at `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` and `FORTRAN` modules [10] .

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

— complete one-loop EW RC in CC [11] and NC [12] cases,

— photon induced DY processes [13],

— higher order photonic FSR in the leading logarithm approximation,

— NLO QCD corrections [14, 15],

— interface to parton showers 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.

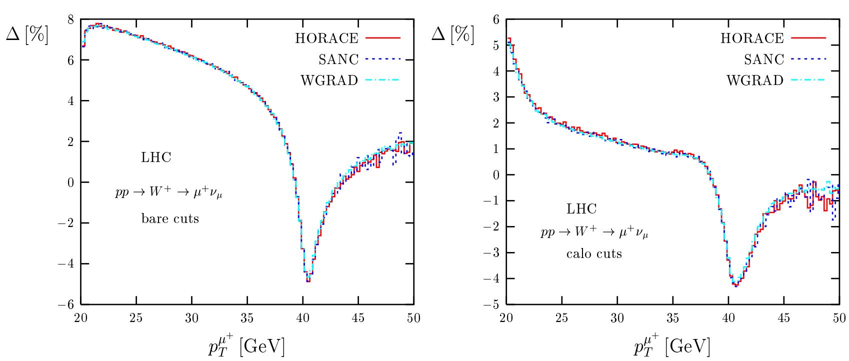

Figure 1: Set-up: $P_T(l,\nu) > 20$ GeV, $|\eta(l)| < 2.5$; $\alpha(0)$ EW scheme; MRST2004QED PDF set; NLO QED DIS subtraction scheme.

2 QCD corrections

QCD radiative corrections to DY have been extensively studied in the literature [16, 17, 18]. Recently the corresponding NNLO corrections for differential distributions have been derived [19, 20, 21]. There are several MC generators taking into account QCD NLO corrections and some higher order effects *e.g.* MC@NLO [22], POWHEG [23], MCFM [24], and ResBos [25]. With help of SANC we also evaluated the NLO QCD corrections [14] using the factorization scheme with massive quarks. Our results are in a good agreement with the ones of MCFM for both CC and NC channels, Fig. 2. The ACOT factorization scheme [26] with massive quarks was applied in SANC to treat the heavy quark contributions to DY.

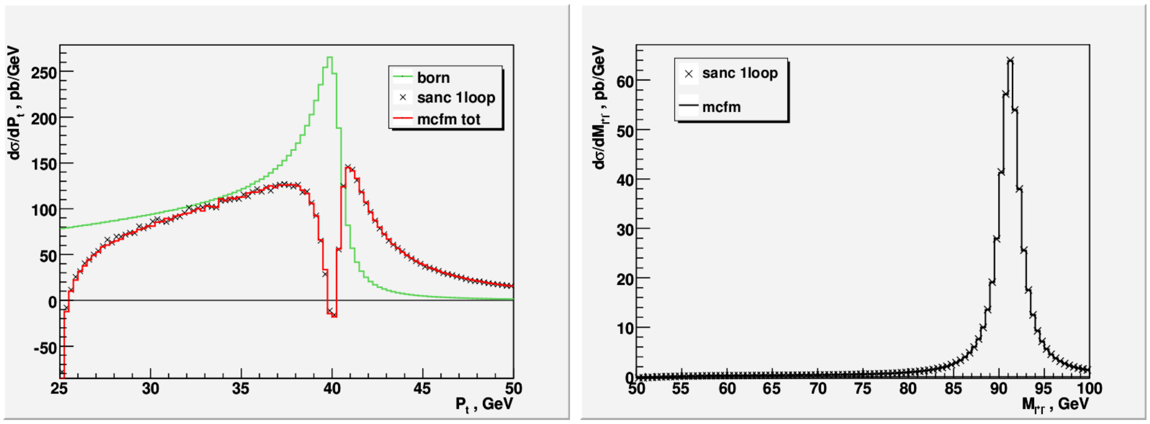

Figure 2: Lepton transverse momentum in CC DY with and w/o parton shower effects(left) and Z-boson transverse momentum distribution in NC DY.

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 [5] and HERWIG [4]. Note that the showers will wash out the negatively weighted events, which can be seen in the resonance region in Fig. 2.

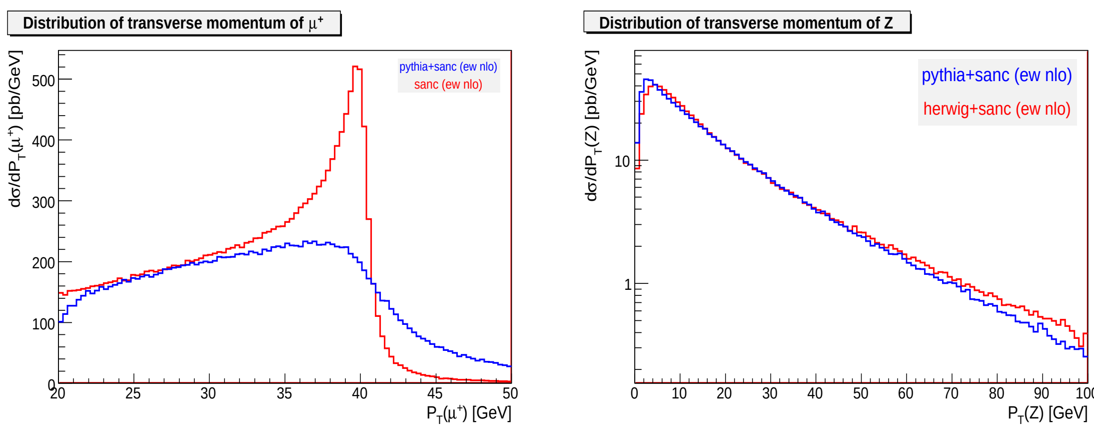

Figure 3: Lepton transverse momentum in CC DY with and w/o parton shower effects(left) and Z-boson transverse momentum distribution in NC DY with different parton shower models.

Fig. 4 show that parton shower effects in the codes that are most used for data simulation at LHC differ from each other considerably. It is assumed that PYTHIA is more tuned for the Tevatron data than HERWIG, but the present deviation still points out to a considerable source of uncertainty in the DY processes description. Of course it is planned to adjust the parton shower simulation in both codes to the forthcoming LHC data.

In spite of the fact that QCD NNLO radiative corrections to inclusive DY cross sections are known in the literature for about 30 years, only recently the corresponding corrections to differential distributions were obtained. Computer codes FEWZ [20] and DYNNLO [21] allow now to look at the difference between the NLO and NNLO predictions. This effect is of the level of 2-3% for typical conditions [27]. It is important that at the NNLO level the dependence of the result on the QCD factorization and renormalization scales is found to be below 1% for most cases.

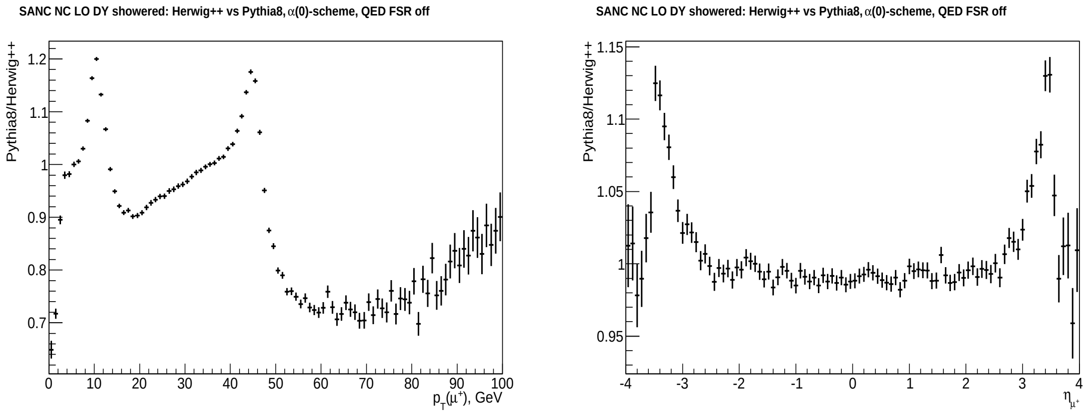

Figure 4: The ratio of the differential distributions in lepton transverse momentum (left) and rapidity (right) obtained using PYTHIA and HERWIG parton shower routines.

3 Electroweak corrections

It has been shown in Sect. 3 [U. Baur *et al.*] of Ref. [28] 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 relation to be of the order of $\alpha_{QED}(M_Z)/\alpha_{QCD}(MZ) \sim 0.1$. EW corrections have an enhancement due to the EW Sudakov logarithms and the final state radiation off charged leptons.

The one-loop EW RC were computed for the DY processes by SANC in Refs. [11, 12, 13] and extensively compared with results of other groups, see *e.g.* Refs. [28, 29, 30]. An excellent agreement was established for tuned comparisons both in CC and NC currents, see *e.g.* Fig. 5 taken from Ref. [29].

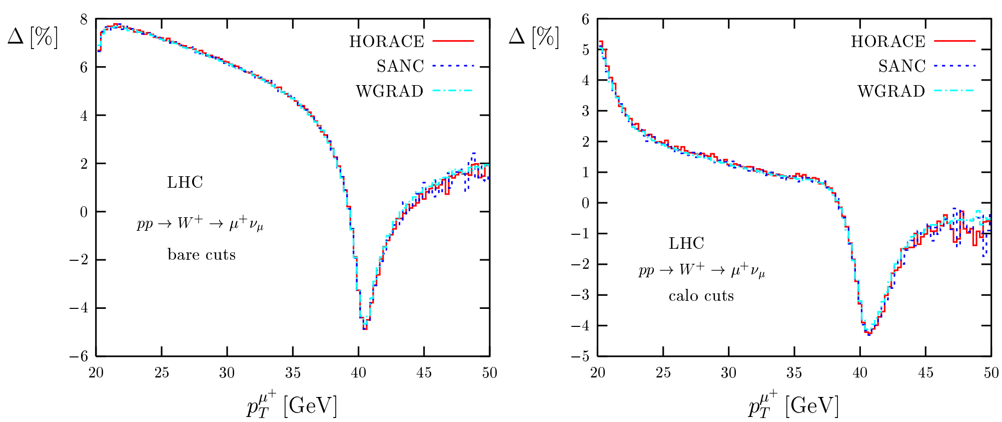

Figure 5: RC to μ^+ transverse momentum in CC DY for BARE (left) and CALO (right) set-ups.

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 [30]. 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. We are working now on implementation of the EW corrections to the ZINHAC code [31], which deals with the neutral current Drell-Yan processes.

Unknown higher order EW corrections give a contribution to the resulting uncertainty. It can be estimated by looking at the result of EW scheme variation. For example passing from the $\alpha(0)$ scheme to G_μ one leads to the change in the DY cross section of the order of 2 percent.

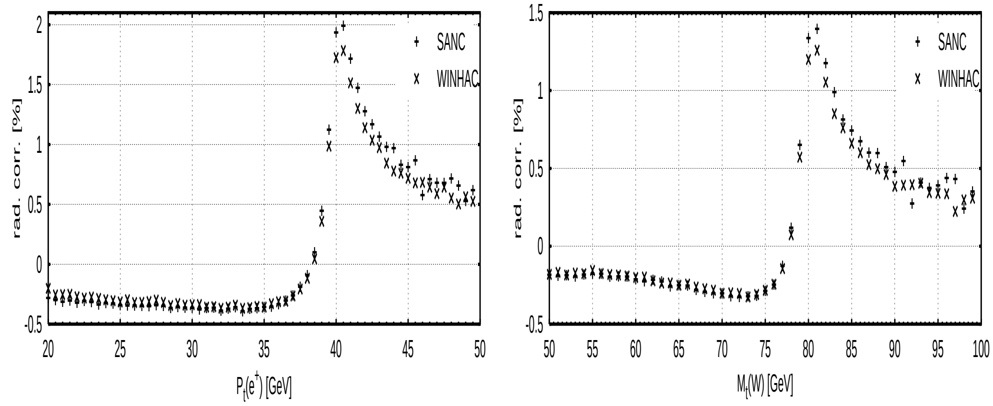

Figure 6: Higher order FSR corrections in percent for BARE positron transverse momentum (left) and W transverse mass (right) distributions in CC DY.

Certainly, $\alpha(0)$ is not an optimal scheme for high energy processes, so that the difference is a very crude upper estimate of the corresponding uncertainty.

4 Parton density function uncertainty

One of the key input for accurate theoretical description of the Drell-Yan processes are parton density functions. Remind that they are extracted from various experimental data, mainly on deep inelastic scattering. Nowadays we have several independent fits of PDF at the LO, NLO and NNLO levels of QCD analysis. It is worth to note that recently an important step in construction of PDFs was done when an advanced treatment of heavy quark masses m_c and m_b was implemented. This fact is important for Drell-Yan description, since the c and b quarks give contributions especially to the neutral current case. As the result the modern PDF sets pretend to provide a rather high precision, which can be estimated from two sides. First, one can look at the nominal precision of the fits which is provided together with the sets. And second, one can compare the theoretical DY cross sections received when using different independent PDFs. In Ref. [27] it is shown that various modern NLO sets give results which agree at the level of about 2-3% and the internal uncertainties estimates of the codes themselves are even below this range. Remind that a couple of years before we quoted 5% uncertainty in DY coming from PDFs.

Nevertheless, one should keep in mind that PDFs were extracted from experimental data lying mainly in the kinematical region being far from the one relevant for DY at LHC both in x and Q^2 values. So one has to relay on evolution and interpolation. Moreover the quark content contributing to nucleon structure functions in DIS is not the same as the one in DY. In this case additional uncertainties can come from assumptions about see and heavy quarks and made during PDF fitting. In particular, the condition of equality between up and down see quarks contributions at small x values can be not true and therefore lead to an additional error in the predictions.

On the other hand, there is one more way to verify the robustness of the PDF fits. Namely, one can compare the results obtained in two cases:

1) LO set of PDF convoluted with the LO parton cross section;

2) NLO set of PDF (from the same fit) convoluted with NLO parton cross section(s).

Remind that this procedure gives almost the same for the case in deep inelastic scattering observables (reproducing the data used in the fit), only the χ^2 value in the LO fit is higher. But for the DY the difference is large ($> 20\%$) in the resonance region, see Fig. 7. To my mind, such a big difference is a clear indication for a hidden uncertainty in PDFs.

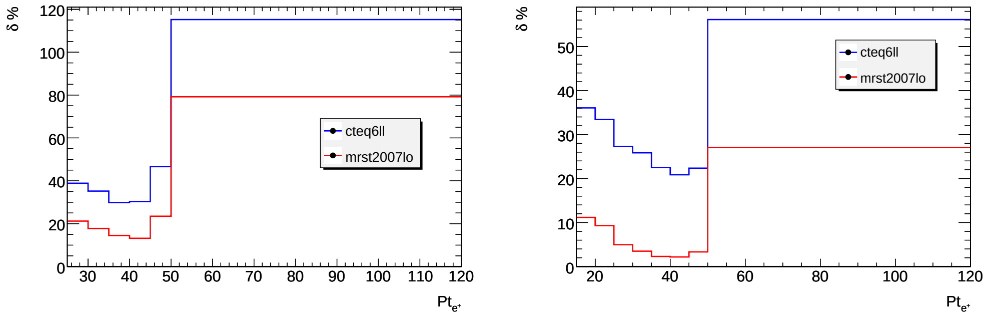

Figure 7: Difference between CC (left) and NC (right) electron transverse momentum distributions received with LO (CTEQ6LL in red and MRST2007LO* in blue) and NLO (CTEQ6M) PDFs.

The unpleasant large difference is known to the community. In Ref. [32] it was claimed that both LO and NLO parton distributions have faults. So the authors proposed a modified optimal LO set (MRST2007LO*). As can be seen from Fig. 7, that using the "optimal" LO PDF set really shifts the predictions towards the NLO case. But the question remains, why only the LO set is modified, while the NLO (and NNLO) PDFs can suffer from the same ambiguities.

5 Outlook

The resulting theoretical uncertainty in description of DY processes at LHC should combine errors coming from several sources: 1) PDF parameterization; 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. 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 parameterizations. 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 add up different effects. Interplay of these effects like additive or multiplicative treatment of EW and QCD corrections has to be studied. 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.

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References

[1] V.A. Matveev, R.M. Muradian, A.N. Tavkhelidze, JINR preprint P2-4543, Dubna, 1969.

[2] S.D. Drell and T.M. Yan, Phys. Rev. Lett. **25** (1970) 316 [Erratum-ibid. **25** (1970) 902].

[3] M. P. Sanders [CDF and D0 Collaborations], arXiv:1009.2903 [hep-ex].

[4] G. Corcella *et al.*, JHEP **0101**, 010 (2001).

[5] T. Sjostrand, S. Mrenna, and P. Skands, JHEP **0605**, 026 (2006).

[6] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, JHEP **0902** (2009) 007 [arXiv:0811.4622 [hep-ph]].

[7] P. Golonka and Z. Was, Eur. Phys. J. C **45** (2006) 97 [arXiv:hep-ph/0506026].

[8] A. Andonov *et al.*, Comput. Phys. Commun. **174**, 481 (2006); **177**, 623 (*Erratum*) (2007).

[9] D. Bardin, *et al.*, Comput. Phys. Commun. **177** (2007) 738.

[10] A. Andonov *et al.*, Comput. Phys. Commun. **181** (2010) 305.

[11] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava and R. Sadykov, Eur. Phys. J. C **46**, 407 (2006), **50**, 505 (*Erratum*) (2007).

[12] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and R. Sadykov, Eur. Phys. J. C **54**, 451 (2008).

[13] A. B. Arbuzov and R. R. Sadykov, J. Exp. Theor. Phys. **106**, 488 (2008).

[14] A. Andonov, A. Arbuzov, S. Bondarenko, P. Christova, V. Kolesnikov and R. Sadykov, Phys. Part. Nucl. Lett. **4**, 451 (2007).

[15] A. Andonov *et al.*, Phys. Atom. Nucl. **73** (2010) 1810.

[16] G. Altarelli, R. K. Ellis, and G. Martinelli, Nucl. Phys. B **157**, 461 (1979).

[17] J. Kubar-Andre and F. E. Paige, Phys. Rev. D **19**, 221 (1979).

[18] R. Hamberg, W.L. van Neerven, and T. Matsuura, Nucl. Phys. B **359**, 343 (1991), **644**, 403 (*Erratum*) (2002).

[19] C. Anastasiou *et al.*, Phys. Rev. D **69**, 094008 (2004).

[20] K. Melnikov and F. Petriello, Phys. Rev. D **74**, 114017 (2006).

[21] S. Catani, L. Cieri, G. Ferrera, D. de Florian and M. Grazzini, Phys. Rev. Lett. **103**, 082001 (2009) [arXiv:0903.2120 [hep-ph]].

[22] S. Frixione and B. R. Webber, arXiv:0812.0770 [hep-ph].

[23] P. Nason, JHEP **0411** (2004) 040; S. Frixione, P. Nason and C. Oleari, JHEP **0711** (2007) 070.

[24] R. K. Ellis *et al.* [QCD Tools Working Group], arXiv:hep-ph/0011122.

[25] C. Balazs and C. P. Yuan, Phys. Rev. D **56** (1997) 5558.

[26] M. A. G. Aivazis, J. C. Collins, F. I. Olness, and W. K. Tung, Phys. Rev. D **50**, 3102 (1994).

[27] N. Adam, V. Halyo and S. A. Yost, arXiv:1006.3766 [hep-ph].

[28] C. Buttar *et al.*, arXiv:0803.0678 [hep-ph].

[29] C.E. Gerber *et al.* [TeV4LHC-Top and Electroweak Working Group], arXiv:0705.3251 [hep-ph].

[30] D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, and W. Placzek, Acta Phys. Pol. B **40**, 75 (2009).

[31] http://th-www.if.uj.edu.pl/ZINHAC

[32] A. Sherstnev and R. S. Thorne, Eur. Phys. J. C **55** (2008) 553 [arXiv:0711.2473 [hep-ph]].