Project SANC, Abstract

Support of Analytic and Numeric Calculations for experiments at Colliders (project within JINR theme 02-0-1062-2002/2014 and after 2014 year within JINR theme 02-0-1081-2009/2019)

D.Yu. Bardin[1], P.Ch. Christova[2], L.V. Kalinovskaya, V.A. Kolesnikov, L.A. Rumyantsev, R.R. Sadykov, A.A. Sapronov, E.D. Uglov — NEOVP, DNLP, JINR, Dubna, Russia;
A.B. Arbuzov, S.G. Bondarenko — BLTP, JINR, Dubna, Russia;
W. von Schlippe — PNPI, RAN, Gatchina, 188300, Russia;
T. Riemann — DESY, Zeuthen, Germany;
G. Nanava — Scientific Computing Team Leader, Leibniz Universitat, Hannover, Germany;
Z. Was — IFJ, PAN, Krakow, Poland;
Lucia Di Ciaccio — ATLAS group of LAPP, Laboratoire d'Annecy-le-Vieux de physique des particules (LAPP), Annecy;
U. Klein, A. Glazov, J. Kretzschmar — CERN, DESY and University of Liverpool, England.

1 Introduction

This report summarises scientific activity performed within the SANC project (Support of Analytic and Numeric Calculations for experiments at Colliders) during 2001 and 2018 years.

The research area of this project spanned over LHC physics and hadron collision phenomenology, fixed order radiative corrections to the Drell–Yan processes, QCD-analysis of experimental data and DGLAP formalism.

Precision tests of the Standard Model (SM) at LHC nowadays become more and more important. The accuracy of the corresponding experimental studies grows up continuously with collected statistics, improved detector calibration, elaboration of analysis techniques etc. All that leads to new requirements on the accuracy of theoretical predictions challenged by the experimental data.

The SANC project roots back to early 2001. It was announced first in Ref. [1] and its first phase status report was widely presented at ACAT2002 in several talks [2]–[3].

The main prerequisites for the undertaken studies were the expertise of participants in the field of collider phenomenology and data analysis, long history of development of theoretical basis and instruments, access to the newest experimental results and active collaboration with the international scientific community.

The main aim of the project is creation of a computer system for semi-automatic calculations of realistic and pseudo-observables for various processes of elementary particle interactions "from the SM Lagrangian to event distributions" at the one-loop precision level for the present and future colliders – TEVATRON, LHC, electron Linear Colliders (ISCLC, CLIC), muon factories etc.

Computer-wise, SANC is an IDE (Integrated Development Environment) and is realized as

[1] deceased
[2] deceased

a server–client application. SANC client for version v.1.10 can be downloaded from servers at CERN *http://pcphsanc.cern.ch/* and Dubna *http://sanc.jinr.ru/*.

Physics-wise, all the calculations at the one-loop precision level are realized in the spirit of the book [4] in the R_ξ gauge and all the results are reduced up to the scalar Passarino–Veltman functions: A_0, B_0, C_0, D_0. This two distinctive features allow to perform several checks: e.g. to test gauge invariance by observation the cancellation of gauge parameters dependence, to test various symmetry properties and validity of various Ward Identities, all at the level of analytical expressions. The process of calculation is structured into several well-defined steps. With the help of SANC system it is easy to follow all steps of calculations for many SM decays and processes. This makes the SANC system particularly appealing for educational purposes.

The SANC system uses several computer languages, but only FORM — for analytic calculations [5]. All the codes are put into a special program environment, written in JAVA. At early phase it was used for a revision of Atomic Parity Violation [6], for a calculation of the one-loop electroweak radiative corrections for the process $e^+e^- \to f\bar{f}$ [7] and neutrino DIS [8]. Meantime, in Ref. [9] it was used for precision comparison of EW corrections for the SM boson decays into fermion-antifermion pair and in [10] for an improvements of PHOTOS Monte Carlo generator.

In the second phase of the project (2004–2010), the calculations were extended to a large number of HEP processes, with an emphasis on LHC physics. In Ref. [11] we have summarized the status of the SANC version 1.00, into which we implemented theoretical predictions for many high energy interactions of fundamental particles at the one-loop precision level for up to 4-particle processes. In this paper we placed an emphasis on an extensive discussion of the so-called “Precomputation procedure”, an important first step of calculations of the one-loop amplitudes for 3- and 4-particle processes in QED, QCD and EW theories. Finally, in Ref. [12] we described SANC version 1.10 upgraded both physics-wise and computer-wise compared to the version 1.00. As far as physics is concerned it contains an upgraded treatment of $u\bar{d} \to l^+\nu_l$ and $d\bar{u} \to l^-\bar{\nu}_l$ processes used for precision calculations of Drell–Yan processes (see Ref. [13]) and a complete implementation of $t \to b + l^+ + \nu_l$ CC decays up to numbers and MC generators [14, 15]. We also implemented several processes like $f_1\bar{f}_1ZZ \to 0$ and $f_1\bar{f}_1HZ \to 0$, and the process $H \to f_1\bar{f}_1A$ in three cross channels [16] in the EW branch, $\gamma\gamma \to \gamma\gamma$ scattering [17] and $l\,l \to \gamma\gamma^*$ in the QED branch, as well as a new QCD branch [18], [19]. Starting from Ref. [12] we use a generalized approach: we begin with a presentation of the covariant amplitudes for a process, say $f_1\bar{f}_1HZ \to 0$, where $\to 0$ means that all 4-momenta flow inwards. The derived scalar form factors can be used for any physically sensible cross channel (here two: annihilation $f_1\bar{f}_1 \to HZ$ and decay $H \to Zf_1\bar{f}_1$) after an appropriate permutation of their arguments (s,t,u). Then we compute helicity amplitudes for every cross channel separately. In the same spirit we considered the three channels of the process $f_1\bar{f}_1ZA \to 0$ [20].

The third phase (2010–2018) 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 SANC framework: top quark decays, QCD corrections to Drell–Yan [21],[22],[23], 4-boson processes ([24], [25] and [26]) and single top quark production. Drell-Yan-like processes [27], i.e. single Z and W boson production with consequent decay into a lepton pair [28],[29], 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 variation. DY analysis for LHC by the MCSANC integrator – [28] [30],[31] [32] and also ATLAS note ATL-PHYS-INT-2011-081 and [33], [34], [35], Tuned comparisons between independent results of several research ATLAS 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 accuracy level: [36], [37],[38], [39]. It has been extensively verified and cross checked against similar instruments and was proven to provide a reliable advanced cross section predictions at both parton and hadron levels.

2 Short description of the SANC system

The SANC system deals with the three models of elementary particle interactions QED, EW and QCD. Each tree consists of several levels of "folders" which end up with "files", normally three: FF (Form Factors), HA (Helicity Amplitudes) and BR (Bremsstrahlung). For labels of folders we use notations: b – for any boson; $f(f_1)$ – for any fermion (f_1 for massless fermions of the first generation whose mass is kept only in arguments of logarithmic functions); A, Z, W, H – for a photon, Z, W, H bosons; for files — the same but t, b, which mean here top and bottom quarks.

For many processes SANC calculations end up with MC integrators or event generators. But only few of them are embedded into the system itself, see Ref. [3]. The other codes are accessible as the stand alone ones. The latter widely use FORTRAN modules generated by the system (see below).

2.1 Basic notions: precomputation, amplitudes, form factors...

Precomputation is one of important concept of SANC ideology. Since many one-loop calculations are enormously time consuming, the idea is to precompute as many one-loop diagrams and derived quantities (renormalization constants, etc) as possible. The precomputation trees are presented and exhaustively discussed in the Ref. [11] and we refer the reader to this paper.

One has usually three files written in FORM, which compute:

- Covariant amplitude (CA) and scalar FF, cf. with the nucleon-nucleon-γ vertex parametrized by the two scalar FF $\mathcal{F}_{1,2}$: $\mathcal{A} \propto \gamma_\mu \mathcal{F}_1 + \sigma_{\mu\nu} q_\nu \mathcal{F}_2$;

- HA, which depend on FF, $\mathcal{H}_{\{\lambda_i\}}(\mathcal{F}_i)$, where $\{\lambda_i\}$ denotes a set of helicity quantum eigenvalues, typically spin projections onto a quantization axis. We remind that in the standard approach for an observable O one has: $O \propto |\mathcal{A}|^2$, while in terms of HA: $O \propto \sum_{\{\lambda_i\}} |\mathcal{H}_{\{\lambda_i\}}|^2$ and this drastically simplifies calculations since $\mathcal{H}_{\{\lambda_i\}}$ are scalar objects which are computed as complex numbers. Many other examples of CA and HA maybe found in Refs. [11], [12] and [16];

- Accompanying real BR. This module computes the contribution of the real bremsstrahlung to a relevant process. Typically we have both the calculations of inclusive quantities and fully differential ones for a use in the MC codes.

2.2 From analytic results to numbers

The chain of SANC calculations starts with on-line execution of module FF, followed by an s2n run (see short User Guide at our Project home pages, indicated in the Introduction), and subsequent execution of module HA with another s2n run. As the result, the system generates a FORTRAN code for the contribution of virtual corrections to a chosen process in the following schematic form: $d\Gamma(d\sigma) \sim \sum_{\lambda_i\lambda_j\lambda_k\lambda_l} \left|\mathcal{H}\left(\mathcal{F}^{\mathrm{Born+1loop+2loop}}\right)_{\lambda_i\lambda_j\lambda_k\lambda_l}\right|^2$.

Real corrections consists of Soft and Hard bremsstrahlung. They are computed by modules BR. The Soft has the Born-like kinematics, while Hard has + 1 particle's more phase space and typically the system creates a FORTRAN module which is used in subsequent MC calculations. For several processes, the system may compute complete one-loop corrections, including real bremsstrahlung for an inclusive observable.

For numerical computations we use the FORTRAN modules generated by the package s2n — a part of the system written in PERL. SANC includes its own FORTRAN library for numerical calculation of Passarino–Veltman functions and uses LoopTools as an alternative.

2.3 Types of SANC Outputs

Typical SANC outputs are:
• FORTRAN modules. These modules may be used in MC integrators and generators by ourselves or by the others;
• Contribution to tuned comparison. We participated in three workshops: Les Houches Workshop, see Proceedings 2006 [36], TEVATRON for LHC Report, 2007, [37], and Precision studies of observables in $pp \to W \to l\nu_l$ and $pp \to \gamma, Z \to l^+l^-$ processes at the LHC, see Report, 2017 [39].
• Standalone MC generators:
• generator for $t \to bl\nu$ decay;
• generator for $H \to 4\mu$ decay in the single Z pole approximation;
• MCSANC integrator.

2.3.1 Recent development of MCSANC integrator

The list of processes implemented in the MCSANC integrator [28], [30], [31], [32] includes Drell-Yan processes (inclusive), associated Higgs and gauge boson production and single-top quark production in s- and t-channel [30] The MCSANC-v1.20 version was used to calculate the following corrections to the Drell-Yan processes:

1. the missed - pure weak, initial and interference QED - one-loop contributions to the M_{inv} distribution;

2. the inverse photons contributions for fiducial cuts.

3. the photon-induced contributions. The implemented processes are: $q\gamma \to ql^{\pm}\nu_l$ (for CC DY), $q\gamma \to ql^+l^-$ (for NC DY) and $\gamma\gamma \to l^+l^-$ (for NC DY);

4. leading in $G_{m_t^2}$ two-loop EW and mixed EW⊗QCD radiative corrections;

5. forward-backward asymmetry A_{FB}^{ff}.

2.4 Electroweak corrections for ATLAS Drell-Yan analysis

Monte Carlo simulations in ATLAS analysis are typically based on the NLO QCD hard process event generators like `POWHEG++` or `MC@NLO` complemented with `PHOTOS` to generate QED FSR corrections. 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 under term "missed". 5note ATL-PHYS-INT-2011-081 and [38].

LHC data provide access to invariant mass regions where photon induced contribution to the Drell–Yan process becomes substantial relative to the quark-antiquark annihilation. More accurate estimation of this background for high mass resonance searches requires inclusion of $\gamma\gamma \to \ell^+\ell^-$ into the theory predictions. The predictions were obtained using implementation of this process in the `MCSANC` integrator with MRST2004QED PDF, which albeit deprecated, was the only set containing photon density at that time. The corrections were included as a systematic uncertainty in the ATLAS searches for high mass dilepton resonances [40]

Overall the calculations of HO EW except QED FSR corrections and their NNLO QCD combination methodology were 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 GeV and 66 GeV using an integrated luminosity of 1.6 fb^{-1} collected in 2011 [40].

- 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 4.9fb^{-1}. Invariant mass of the electrons pair, covered by the measurement is, $116 < M_{ee} < 1500$ GeV [35].

- Measurement of the inclusive $W^{\pm}$ and Z/γ cross sections in the electron and muon decay channels were performed in pp collisions at $\sqrt{s} = 7$ TeV [34].

- A QCD analysis is performed on the ATLAS data of inclusive W and Z boson production, jointly with ep deep inelastic scattering data from HERA. 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 $Q^2 = 1.9$ GeV^2 and x = 0.023 [41].

- Search for high-mass dilepton resonances in 20 fb^{-1} of pp collisions were performed at sqrt(s) = 8 TeV. A narrow resonance with Standard Model Z couplings to fermions is excluded at 95% confidence level for masses less than 2.79 TeV in the dielectron channel, 2.53 TeV in the dimuon channel, and 2.90 TeV in the two channels combined [7].

2.5 QCD analysis and HERAFitter developement

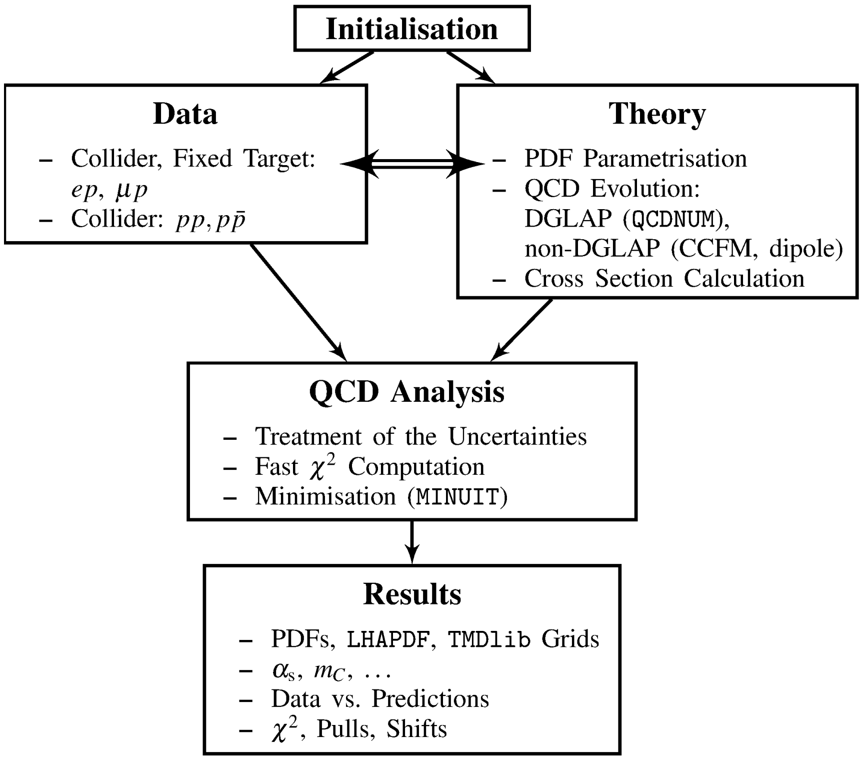

Figure 1: Schematic overview of the `HERAFitter` program.

The PDFs are determined from χ^2 fits of the theoretical predictions to the data. The `HERAFitter`, an open source project for QCD analysis of experimental data, was launched by colleagues from DESY and initially was meant for the analysis of DIS results obtained at HERA experiments. The diagram in Figure 1 gives a schematic overview of the HERAFitter structure and functionality, which can be divided into four main blocks.

With participation of the SANC group members it was subsequently extended to include proton-proton collisions measured at the LHC experiments.

The current version of the HERAFitter framework provides a set of tools for QCD analysis of pp, $p\bar{p}$ and ep scattering data, determination of PDFs and extraction of fundamental QCD parameters, such as heavy quark masses and strong coupling constant, and provides a common testing ground for theoretical models and consistency checks of the experimental results [49], [48], [42], [43], [44], [45], [46], [47].

3 Scientific activity in 2018 year.

- 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 of the analysis of experimental data.

- The research under development of the measurement of effective parameters 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 implementation in the `MCSANC` code, it is possible to set up an analysis chain to measure the mentioned variables. The sensitivity of effective Weinberg angle to the ATLAS data have been observed and possibility to extract it's value will be studied. Creation modern MC DYTURBO - standart ATLAS collaboration code for fitting $\sin_W^{eff}$. Our contribution is a complete EW library higher order correction to the parameter $\delta\rho$ (article in preparation). Participate in the meetings of LHC precision EW working group. [50]

- 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 into RUN-I data showed the additional information on the densities of the momentum distributions of s-quark at small values of x and gluons at large x. There is a need to continue these studies in RUN-II with high kinematic ranges and higher statistics.

- Now it was developed a technique and software for analysis of RUN-I data. It is necessary to adapt the program interface to the new RUN-II data format and expand its functionality.

4 Conclusion

As the result, the project solved most of the planned tasks. The results obtained by the participants have been presented more then 50 publications in peer-reviewed journals and reported on the international workshops and conferences. 10 diplomas thesis were defended for a bachelor's degree and 5 Master's thesis. 6 PhD thesis were defended and 2 doctoral thesis.

All tasks of the project has successfully evaluated in close co-operation with members of the ATLAS collaboration at CERN and DESY collaboration.

References

[1] D. Bardin, G. Passarino, L. Kalinovskaya, P. Christova, A. Andonov, S. Bondarenko, and G. Nanava, "Project 'CalcPHEP: Calculus for precision high-energy physics'", 2002, `hep-ph/0202004`.

[2] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and G. Passarino, *Nucl. Instrum. Meth.* **A502** (2003) 576–577.

[3] G. Nanava, *Nucl. Instrum. Meth.* **A502** (2003) 583–585.

[4] D. Yu. Bardin and G. Passarino, *The standard model in the making: Precision study of the electroweak interactions.* 1999.

[5] J. A. M. Vermaseren, `math-ph/0010025`.

[6] D. Yu. Bardin, P. Christova, L. Kalinovskaya, and G. Passarino, *Eur. Phys. J.* **C22** (2001) 99–104, `hep-ph/0102233`.

[7] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, and G. Nanava, *Phys. Part. Nucl.* **34** (2003) 577–618, [Fiz. Elem. Chast. Atom. Yadra34,1125(2003)], `hep-ph/0207156`.

[8] A. B. Arbuzov, D. Yu. Bardin, and L. V. Kalinovskaya, *JHEP* **06** (2005) 078, `hep-ph/0407203`.

[9] A. Andonov, S. Jadach, G. Nanava, and Z. Was, *Acta Phys. Polon.* **B34** (2003) 2665–2672, `hep-ph/0212209`.

[10] G. Nanava and Z. Was, *Acta Phys. Polon.* **B34** (2003) 4561–4570, `hep-ph/0303260`.

[11] A. Andonov, A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and W. von Schlippe, *Comput. Phys. Commun.* **174** (2006) 481–517, [Erratum: Comput. Phys. Commun.177,623(2007)], `hep-ph/0411186`.

[12] D. Bardin, S. Bondarenko, L. Kalinovskaya, G. Nanava, L. Rumyantsev, and W. von Schlippe, *Comput. Phys. Commun.* **177** (2007) 738–756, `hep-ph/0506120`.

[13] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and R. Sadykov, *Eur. Phys. J.* **C46** (2006) 407–412, [Erratum: Eur. Phys. J.C50,505(2007)], `hep-ph/0506110`.

[14] R. Sadykov, A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, and G. Nanava, *PoS* **TOP2006** (2006) 036.

[15] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, R. Sadykov, and W. von Schlippe, *Eur. Phys. J.* **C51** (2007) 585–591, `hep-ph/0703043`.

[16] D. Bardin, S. Bondarenko, L. Kalinovskaya, G. Nanava, and L. Rumyantsev, *Eur. Phys. J.* **C52** (2007) 83–92, `hep-ph/0702115`.

[17] D. Bardin, L. Kalinovskaya, V. Kolesnikov, and E. Uglov, "Light-by-light scattering in SANC", in *International School-Workshop on Calculations for Modern and Future Colliders (CALC 2006) Dubna, Russia, July 15-25, 2006*, 2006, `hep-ph/0611188`.

[18] A. Andonov, A. Arbuzov, S. Bondarenko, P. Christova, V. Kolesnikov, and R. Sadykov, hep-ph/0610268.

[19] A. Andonov, A. Arbuzov, S. Bondarenko, P. Christova, V. Kolesnikov, and R. Sadykov, *Phys. Part. Nucl. Lett.* **4** (2007) 451–460.

[20] D. Bardin, S. Bondarenko, L. Kalinovskaya, G. Nanava, L. Rumyantsev, and W. von Schlippe, *Eur. Phys. J.* **C54** (2008) 187–197, 0710.3083.

[21] A. Andonov, A. Arbuzov, S. Bondarenko, P. Christova, V. Kolesnikov, G. Nanava, and R. Sadykov, *Phys. Atom. Nucl.* **73** (2010) 1761–1769, 0901.2785.

[22] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and R. Sadykov, *Eur. Phys. J.* **C54** (2008) 451–460, 0711.0625.

[23] A. Arbuzov, A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, V. Kolesnikov, G. Nanava, and R. Sadykov, *PoS* **ACAT08** (2008) 109.

[24] D. Bardin, L. Kalinovskaya, and E. Uglov, *Phys. Atom. Nucl.* **73** (2010) 1878–1888, 0911.5634.

[25] D. Y. Bardin, L. Kalinovskaya, and E. Uglov, *Phys.Atom.Nucl.* **76** (2013) 1339–1344, 1212.3105.

[26] D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, W. von Schlippe, and E. Uglov, *Phys. Part. Nucl. Lett.* **14** (2017), no. 6 811–816, 1709.05978.

[27] A. B. Arbuzov and R. R. Sadykov, *J. Exp. Theor. Phys.* **106** (2008) 488–494, 0707.0423.

[28] A. Arbuzov, R. Sadykov, and Z. Was, *Eur.Phys.J.* **C73** (2013), no. 11 2625, 1212.6783.

[29] S. Antropov, A. Arbuzov, R. Sadykov, and Z. Was, *Acta Phys. Polon.* **B48** (2017) 1469, 1706.05571.

[30] S. G. Bondarenko and A. A. Sapronov, *Comput.Phys.Commun.* **184** (2013) 2343–2350, 1301.3687.

[31] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, U. Klein, V. Kolesnikov, L. Rumyantsev, R. Sadykov, and A. Sapronov, *JETP Lett.* **103** (2016), no. 2 131–136, 1509.03052.

[32] A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, R. Sadykov, A. Sapronov, and T. Riemann, *J. Phys. Conf. Ser.* **762** (2016), no. 1 012062.

[33] D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, L. Rumyantsev, A. Sapronov, and W. von Schlippe, *JETP Lett.* **96** (2012) 285–289, 1207.4400.

[34] ATLAS Collaboration, G. Aad *et al.*, *Phys.Lett.* **B725** (2013) 223–242, 1305.4192.

[35] ATLAS Collaboration, G. Aad *et al.*, *JHEP* **1406** (2014) 112, 1404.1212.

[36] C. Buttar *et al.*, "Les houches physics at TeV colliders 2005, standard model and Higgs working group: Summary report", in *Physics at TeV colliders. Proceedings, Workshop, Les Houches, France, May 2-20, 2005*, 2006, hep-ph/0604120.

[37] Electroweak Working Group, TeV4LHC-Top Collaboration, C. E. Gerber *et al.*, "Tevatron-for-LHC Report: Top and Electroweak Physics", 2007, 0705.3251.

[38] J. Butterworth, G. Dissertori, S. Dittmaier, D. de Florian, N. Glover, *et al.*, 1405.1067.

[39] S. Alioli *et al.*, *Eur. Phys. J.* **C77** (2017), no. 5 280, 1606.02330.

[40] ATLAS Collaboration, G. Aad *et al.*, *Phys.Rev.* **D90** (2014), no. 5 052005, 1405.4123.

[41] ATLAS Collaboration, G. Aad *et al.*, *Phys.Rev.Lett.* **109** (2012) 012001, 1203.4051.

[42] T. Carli, D. Clements, A. Cooper-Sarkar, C. Gwenlan, G. P. Salam, *et al.*, *Eur.Phys.J.* **C66** (2010) 503–524, 0911.2985.

[43] M. Botje, *Comput.Phys.Commun.* **182** (2011) 490–532, 1005.1481.

[44] S. Alekhin, O. Behnke, P. Belov, S. Borroni, M. Botje, *et al.*, 1410.4412.

[45] HERAFitter developers' team Collaboration, P. Belov *et al.*, *Eur.Phys.J.* **C74** (2014), no. 10 3039, 1404.4234.

[46] R. Sadykov, 1401.1133.

[47] HERAFitter developers' Team Collaboration, S. Camarda *et al.*, 1503.05221.

[48] xFitter Developers' Team Collaboration, F. Giuli *et al.*, *Eur. Phys. J.* **C77** (2017), no. 6 400, 1701.08553.

[49] analysis team Collaboration, F. Giuli, *PoS* **EPS-HEP2017** (2017) 375, 1708.03623.

[50] A. Sapronov, S. Bondarenko, and L. Kalinovskaya.