# APPENDIX 3.5.C

## Theoretical support for $e^+e^-$ colliders with polarized beams

# 1 Introduction

As compared with the protons used at the LHC, the $e^+e^-$ collisions have much lower backgrounds, i.e. cleaner events and therefore provide a higher measurement precision. With respect to former $e^+e^-$ colliders (LEP, SLC, etc.) the re-estimation is also demanded of various effects from both experimental and theoretical sides. Precise measurements with polarized beams at the $e^+e^-$ colliders (EPC) like CLIC [1] require modern advanced theoretical support [2]-[4].

Physical programs of future $e^+e^-$ linear colliders [5]-[7] always demonstrated a great interest for the effects related to the presence of beam polarization.

Two mini-Workshops were held in January 2018 in CERN: a) *Precision EW and QCD calculations for the FCC studies: methods and techniques* [8] and *Multiloop/multiscale methods and techniques in the context of precise Z-boson studies* [9].

Having analyzed the status of EPC projects, a conclusion was made on the state of theoretical support - present theoretical accuracy is insufficient [10]-[11].

| | Measurement error | | | Intrinsic theory | |
|---|---|---|---|---|---|
| | ILC | CEPC | FCC-ee | Current | Future |
| $M_W$ [MeV] | 3-4 | 3 | 1 | 4 | 1 |
| $\Gamma_Z$ [MeV] | 0.8 | 0.5 | 0.1 | 0.5 | 0.2 |
| $\sin^2\vartheta_{eff}[10^-5]$ | 1 | 2.3 | 0.6 | 4.5 | 1.5 |

Table 1: Projected experimental and theoretical uncertainties for some electroweak precision pseudo-observables. Last column is based on estimations for: $\mathcal{O}(\alpha_{bos})$,$\mathcal{O}(\alpha,\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^3)$ and leading four-loop corrections entering through the $\rho$-parameter [10].

As can be seen from Table 1, a very significant progress in theory precision is required to be comparable with precision of the future experiments. Similar estimates apply for quite a lot of other electroweak pseudo-observables (EWPOs).

For the theoretical support of the interpretation of data the higher order corrections (more then 3-loops) must be calculated. Consideration of beam polarization is a novel requirement for theoretical predictions for $e^+e^-$ collisions at energies of the future EPC.

The uniqueness of the project consists in development of a Monte-Carlo event generator at a complete one-loop accuracy level (using the experience that we accumulated during the previous project SANC) with beam polarization taken into account and with the possibility to include higher-order corrections through the $\Delta\rho$ parameter (all calculations for the EW and QCD sectors that exist today in the world, see for example [12]).

[1] CLIC, CERN - *clic-study.web.cern.ch/*.

[2] P. H. Khiem *et al.*, "Full $\mathcal{O}(\alpha)$ electroweak radiative corrections to $t\bar{t}\gamma$ and $e^-e^+\gamma$ productions at ILC with GRACE-Loop", in *Proceedings, 9th Rencontres du Vietnam: Windows on the Universe: Quy Nhon, Vietnam, August 11-17, 2013*, pp. 261-264, 2013, http://www.arXiv.org/abs/1403.65561403.6556.

[3] T. Ohl, "WHiZard and O'Mega", in *Proceedings, LoopFest V: Radiative Corrections for the International Linear Collider: Multi-loops and Multi-legs: SLAC, Menlo Park, California, June 19-21, 2006*, 2006.

[4] C. M. Carloni Calame, G. Montagna, O. Nicrosini, and F. Piccinini, *Acta Phys. Polon.* **B46** (2015), no. 11 2227.

[5] ECFA/DESY LC Physics Working Group Collaboration, E. Accomando *et al.*, *Phys. Rept.* **299** (1998) 1-78, http://www.arXiv.org/abs/hep-ph/9705442hep-ph/9705442.

[6] CLIC Physics Working Group Collaboration, E. Accomando *et al.*, "Physics at the CLIC multi-TeV linear collider", in *Proceedings, 11th International Conference on Hadron spectroscopy (Hadron 2005): Rio de Janeiro, Brazil, August 21-26, 2005*, 2004, http://www.arXiv.org/abs/hep-ph/0412251hep-ph/0412251.

[7] A. Arbey *et al.*, *Eur. Phys. J.* **C75** (2015), no. 8 371, http://www.arXiv.org/abs/1504.017261504.01726.

[8] Report on Mini workshop: Precision EW and QCD calculations for the FCC studies: methods and tech- niques , https://indico.cern.ch/event/669224/, in preparation.

[9] A. Blondel, Motivation: experimental capabilities and requirements , talk at [9].

[10] A. Freitas, "Numerical multi-loop integrals and applications," Prog. Part. Nucl. Phys. **90**, 201 (2016) doi:10.1016/j.ppnp.2016.06.004 [arXiv:1604.00406 [hep-ph]].

[11] J. Gluza, Report from the EW precision calculations miniWorkshop , talk at 2nd FCC Physics Workshop , https://indico.cern.ch/event/618254/.

[12] I. Dubovyk, A. Freitas, J. Gluza, T. Riemann, J. Usovitsch, The two-loop electroweak bosonic corrections to $\sin^2\vartheta^b_{eff}$ , Phys. Lett. B762 (2016) 184 189. arXiv:1607.08375, doi:10.1016/j.physletb. 2016.09.012

# 2 Plans for scientific collaboration with other groups

1. Integrator and generator at the level of complete one-loop and leading multiloop radiative corrections − V.V. Makarenko, V.L. Yermolchyk, T. Riemann, J. Gluza.

2. Procedure for HA for Bremsstrahlung − G. Nanava.

3. Package for fit of $\sin^2\vartheta_W^{eff}$ EPC − S. Amoroso, A.A. Glazov.

4. MC for the Bhabha scattering – Z. Was, S. Jadach, S. Riemann, T. Riemann, J. Gluza, G.V. Fedotovich.
5. Complete two-loop RC order $\mathcal{O}(\alpha\alpha_s)$ – O.I. Veretin, B.A. Kniehl.
6. Modules for higher order RC – T. Riemann, J. Gluza.
7. Interface with PYTHIA – T. Sjostrandt.

# 3 Detailed basement of the Project

Experience of long-term cooperation of the main project executors will allow us to apply our traditional methods to the SM-based computer environment developed by us: the procedural approach, the method of analytical and FORTRAN building modules for RC, the helicity amplitude method. Therefore we have the basement for the implementation of both transverse and longitudinal beam polarizations into our calculations.

•• **Helicity amplitude approach and accounting for the polarization effects**

The active environment of our system allows to obtain an analytic result for the scalar form factors (FF), helicity amplitudes (HA) and Bremsstrahlung (BR) contributions. For calculating the HA's the Vega-Wudka [1], and Kleiss-Stirling [2] methods are used. Investigations of one-loop corrections for the method of helicity amplitudes comprise a well-developed and thoroughly tested basis of the Project [1]-[5]. Development of the procedure for obtaining helicity amplitudes for Bremsstrahlung naturally complements the procedure base.

The matrix element squared for a process at $e^+e^-$ collider with polarized beams can then be written as:

$$\begin{aligned}
&128\pi s\frac{d\sigma}{d\cos\theta} = (1+P^{||}_{e^-})(1-P^{||}_{e^+})|\mathcal{H}_{-+}|^2 \\
&+(1-P^{||}_{e^-})(1-P^{||}_{e^+})|\mathcal{H}_{--}|^2 + (1+P^{||}_{e^-})(1-P^{||}_{e^+})|\mathcal{H}_{++}|^2 \\
&-2P^T_{e^-}P^T_{e^+}\Big[\cos(\phi_- - \phi_+)\Re(\mathcal{H}_{++}\mathcal{H}^*_{--}) + \cos(\phi_- + \phi_+ - 2\phi)\Re(\mathcal{H}_{-+}\mathcal{H}^*_{+-}) \\
&+\sin(\phi_- + \phi_+ - 2\phi)\Im(\mathcal{H}_{-+}\mathcal{H}^*_{+-}) + \sin(\phi_- - \phi_+)\Im(\mathcal{H}_{++}\mathcal{H}^*_{--})\Big] \\
&+2P^T_{e^-}\Big[\cos(\phi_- - \phi)\Big((1-P_{e^+})\Re(\mathcal{H}_{+-}\mathcal{H}^*_{--}) + (1+P_{e^+})\Re(\mathcal{H}_{++}\mathcal{H}^*_{-+})\Big) \\
&-\sin(\phi_- - \phi)\Big((1-P_{e^+})\Im(\mathcal{H}_{+-}\mathcal{H}^*_{--}) + (1+P_{e^+})\Im(\mathcal{H}_{++}\mathcal{H}^*_{-+})\Big)\Big] \\
&-2P^T_{e^+}\Big[\cos(\phi_+ - \phi)\Big((1-P_{e^-})\Re(\mathcal{H}_{-+}\mathcal{H}^*_{--}) + (1+P_{e^-})\Re(\mathcal{H}_{++}\mathcal{H}^*_{+-})\Big) \\
&-\sin(\phi_+ - \phi)\Big((1-P_{e^-})\Im(\mathcal{H}_{-+}\mathcal{H}^*_{--}) + (1+P_{e^-})\Im(\mathcal{H}_{++}\mathcal{H}^*_{+-})\Big)\Big],
\end{aligned}$$

where $\mathcal{H}_{++}$, $\mathcal{H}_{--}$, $\mathcal{H}_{+-}$, $\mathcal{H}_{-+}$ denote the helicity amplitudes. Notations used in this equation are illustrated in Fig.1.

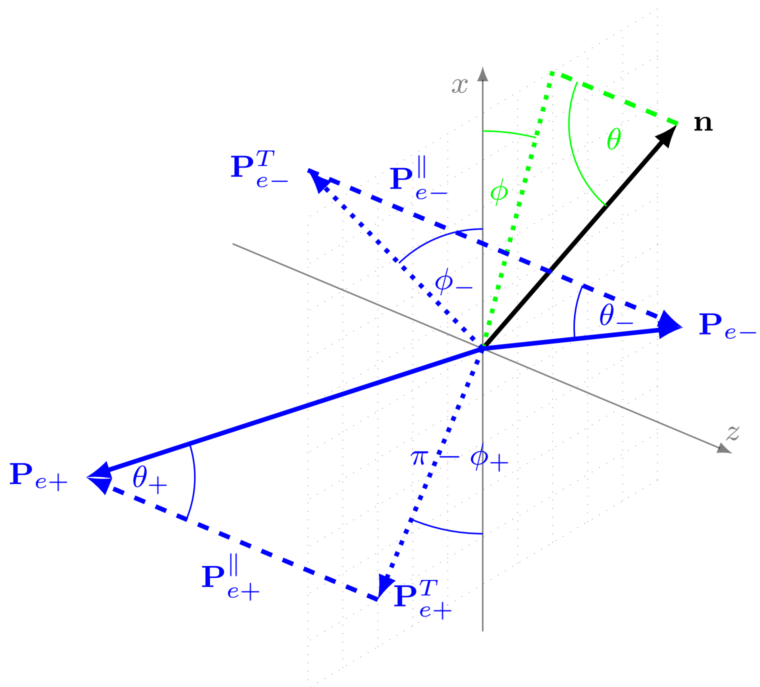


Figure 1: Decomposition of the $e^{\pm}$ polarization vectors into a longitudinal components $\mathbf{P}^{\parallel}_{e\mp} = \mathbf{P}_{e\mp}\hat{p}_{e\mp}$ in the direction of the electron/positron momentum and transverse components $\mathbf{P}^{T}_{e\mp}$ with respect to a fixed coordinate system $x, y, z$. The $z$-axis is in the direction of the electron momentum, and $\mathbf{n}$ is the reference direction.

[1] D. Bardin, et al., Electroweak radiative corrections to the three channels of the process f(1) anti-f(1) ZA $\to$ 0, Eur. Phys. J. C **54**, 187 (2008)

[2] A. Arbuzov, et al., Computer system SANC: its development and applications, J. Phys. Conf. Ser. **762**, no. 1, 012062 (2016).

[3] D. Bardin, et al., Electroweak radiative correction to the three channels of the process f(1) anti-f(1) H A $\to$ 0," Eur. Phys. J. C **52**, 83 (2007)

[4] D. Bardin, et al., SANCnews: Sector ffbb, Comput. Phys. Commun., 177, 2007, 738-756,

[5] A. Andonov, et al., SANCscope - v.1.00, Comput. Phys. Commun., 174, 2006, 481-517. [Erratum: Comput. Phys. Commun.177,623(2007)],

•• **Recent experience with Bhabha scattering at one-loop for polarized beams**

Theoretical description of Bhabha scattering with radiative corrections taken into account is crucial for high-precision measurement of this process and thus for luminosity monitoring at future $e^+e^-$ colliders. Our first attempt to estimate theoretical uncertainty for this process at one-loop level by MC was performed in [1].

We show that the full $\mathcal{O}(\alpha)$ electroweak radiative corrections provide a considerable impact on the differential cross section. Moreover, the corrections themselves are sensitive to polarization values of the initial beams.

[1] D. Bardin, A. Arbuzov, S. Bondarenko, Y. Dydyshka, L. Kalinovskaya, L. Rumyantsev and R. Sadykov, "One-loop electroweak radiative corrections to polarized Bhabha scattering," arXiv:1801.00125 [hep-ph].

•• **Higher-order radiative corrections for massless four-fermion processes**

The leading higher-order radiative corrections are accounted by using $\Delta\rho$ parameter at 2-, 3- and 4- loops level.

[1] S.G. Bondarenko, L.V. Kalinovskaya, A.A. Sapronov, Library for parameter $\Delta\rho$, (in preparation).

•• **Creation of the Interface PHYTIA/MCSANC**

The possible implementation of "all the best we have": the first stage (PHYTIA + PHOTOS) - to account the LO + PS + QED in the final state; second stage MCSANC - to account the NLO EW and higher order EW and QCD corrections via parameter $\Delta\rho$ with polarization effects taken into account.

In this way, the natural task is to reanalyze the generated events after the first stage of the analysis, PHYTIA + PHOTOS, with only one of MCSANC generator, i.e. the second, third and fourth stages are implemented as a single generator. For this analysis, the term of "reweighted events" is introduced.

The following preparatory stages of our work on reweighting of events were conducted:

1) The participation of our group in the work of international workshops on an tuned comparison of Drell-Yan processes in the channels of charged and neutral currents:

2) An interface MCSANC + (PHYTIA + PHOTOS) and MCSANC + (HERWIG + PHOTOS).

[1] P. Richardson, R. R. Sadykov, A. A. Sapronov, M. H. Seymour and P. Z. Skands, QCD parton showers and NLO EW corrections to Drell-Yan, JHEP **1206**, 090 (2012).

•• **Fits of the $\sin^2\vartheta_W^{eff}$**

Forward-backward asymmetry of the Drell-Yan process measured at the LHC can be used to determine effective weak mixing angle in a similar fashion as it was performed for LEP using the ZFITTER package. To perform this measurement the electroweak corrections from MCSANC can be included in the DYTURBO program [1] and used in the combined PDF and $\sin^2\vartheta_W^{eff}$ with the xFitter package [2]

[1] https://gitlab.cern.ch/DYdevel/DYTURBO

[2] S. Alekhin et al., HERAFitter, Eur. Phys. J. C75 (2015), no. 7 304, [arXiv:1410.4412]

•• **Creation of independent program modules for HO RC**

Modules contain complete one-loop calculations within the framework of the SM.

We use modules in our Monte Carlo integrator and generator, and also it is possible to introduce these modules into Monte Carlo generators of other groups, like this was done in [1].

[1] D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, W. Placzek, "Implementation of SANC EW corrections in WINHAC Monte Carlo generator". Acta. Phys.Polon. B40, 2009, 75, arXiv: 0806.3822 [hep-ph];

•• **Experience on the theoretical support HERA-LEP-LHC**

Our team worked successfully in this field for more than 30 years.

In particular we have a positive experience of calculating corrections for processes with polarization. The software products created by us (HECTOR, muela, ZFITTER, MCSANC and other codes) have been accepted by the teams HERA, LEP, LHC and other experiments.

- HERA

  HECTOR is the most successful project on the theoretical support of the polarization activity of the *ep*-accelerator HERA [1]-[2].

- LEP1, LEP2

  The success of a precise tests of the Standard Model on the quantum loop level conducted at LEP1 and LEP2 was substantially provided by ZFITTER [3]-[4], one of the most popular computer codes at LEP.

- LHC

  Preparation of a worthy theoretical support for the LHC at the level of promille is conducted quite actively by a number of strong groups. Precision comparisons of the theoretical predictions for these processes obtained by these groups within the framework of the Standard Model have been made, see, for example, the results of the "W-mass" working group: [5]-[7].

- Collaboration with other centers

  Within the Project we will also use the experience of our collaborators from other centers, in particular, from INP Krakow [8]-[9].

[1] A. Arbuzov, D.Y. Bardin, J. Blumlein, L. Kalinovskaya and T. Riemann, Hector 1.00: A Program for the calculation of QED, QCD and electroweak corrections to ep and lepton + - N deep inelastic neutral and charged current scattering, Comput. Phys. Commun. 94, 128 (1996), [hep-h / 9511434].

[2] D.Y. Bardin, J. Blumlein, P. Christova and L. Kalinovskaya, $\mathcal{O}(\alpha)$ QED corrections to neutral current polarized deep inelastic lepton-nucleon scattering, Nucl. Phys. B 506 (1997) 295, [hep-ph / 9612435].

[3] D.Y. Bardin at al., Comp. Phys. Comm. 133 (2001) 229; ibid. 174 (2006) 728, co-authored by some of the participants in this Project.

[4] A. B. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. W. Grunewald, K. Monig, S. Riemann and T. Riemann, Comput. Phys. Commun. **174**, 728 (2006), [hep-ph/0507146].

[5] Alioli S., Arbuzov A.B., Bondarenko S.G., ... Kalinovskaya .. et al., Precision studies of observables in $pp \to W \to l\nu_l$ and $pp \to \gamma, Z \to l^+l^-$ processes at the LHC, Eur.Phys.J. C 77 (2017) no.5, 280. doi:10.1140/epjc/s10052-017-4832-7 [arXiv: 1606.02330 [hep-ph]].

[6] Buttar C., Arbuzov A.B., Bondarenko S.G., ... Kalinovskaya .. et al., Standard Model Handles and Candles Working Group: Tools and Jets Summary Report, arXiv: 0803.0678 [hep-ph]

[7] Gerber C.E., ... Arbuzov A.B., Bondarenko S.G., Sadykov R.R...et al. Tevatron-for-LHC Report: Top and Electroweak Physics, arXiv: 0705.3251; FERMILAB-CONF-07-052.

[8] S. Jadach, W. Placzek, E. Richter-Was, B. F. L. Ward and Z. Was, Upgrade of the Monte Carlo program BHLUMI for Bhabha scattering at low angles to version 4.04, Comput. Phys. Commun. **102**, 229 (1997).

[9] S. Jadach, W. Placzek and B. F. L. Ward, BHWIDE 1.00: O(alpha) YFS exponentiated Monte Carlo for Bhabha scattering at wide angles for LEP-1 / SLC and LEP-2, Phys. Lett. B **390**, 298 (1997)