Theme 02-2-1123-2015/2022: Study of Fundamental Interactions in e^+e^- Collisions

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Report of ARIeL project, 2019-2021 ARIeL – Physics at Future e^+e^- colliders.

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Main goals of the project ARIeL are: theoretical support of experiments at future e^+e^- colliders and development of their experimental program.

- International cooperation: *DESY, Hamburg, Germany; DESY, Zeuthen, Germany*; *University of Silesia, Katovice, Poland*; *Baylor University, United States*; *INP, Krakow, Poland*; *INFN, Milan, Italy.*

Project participants became co-authors of the FCC-ee and CLICdp collaboration and were active participants in the FCC-ee, CLICdp and CEPC workshops (see Ref. [1-10]).

Main output is release of: integrator `MCSANCee`, integrator $\texttt{MCSANC}_{\gamma\gamma}$, generator `ReneSANCe`, project: `Zfitter 6.44`, `DIZET 6.45`, `XFitter`.
They are available at http://sanc.jinr.ru/download.php

0.1 Report: Publications, Workshops

All the stated objectives of the three years of the project are either completed or will be completed by the end of 2021. Total publications in peer-reviewed journals - 19, publications of the FCC collaboration - 6, presentations at international conferences and Workshops - 18.

0.2 Report: Theoretical support of experiments

1. Task: **The Monte Carlo event generator for simulation of processes at electron-positron colliders better than at one-loop level.**

   The Monte Carlo event generator `ReneSANCe` for simulation of processes at electron-positron colliders was created. Based on the `SANC` (Support for Analytic and Numeric Calculations for experiments at colliders) modules, the new generator takes into account complete one-loop and some higher-order electroweak radiative corrections with polarizations. The one-loop calculations were performed taking into account all masses in the full phase space.

Done

2. Task: **Interface NLO EW RC c PYTHIA.**

   The Monte Carlo generator `ReneSANCe` implements recording events to files in LHEF format. These files can be passed to the input of general purpose generators such as `PYTHIA` and `Herwig`, to simulate rigid sub-processes in these programs, taking into account complete one-loop electroweak corrections.

   Done

3. Task: **Development of a standard procedure for helicity approach.**

   A standard procedure has been developed for calculating the helicity amplitudes $2 \to 3$ and $2 \to 4$. The procedure has already been implemented in the calculations and is working successfully. Several seminars were held (DLNP, BLTP JINR; FCC-ee, CERN). Calculations of several processes have been carried out.

   Done

4. Task: **Support of `DIZET`, `Zfitter`.**

   a) Versions 6.45 and 7.0 of the `DIZET` (libraries for loop electroweak radiation corrections to the CM processes) package are finished. The `DIZET` release notes are sent to CERN Yellow Rep. Monogr.

   b) Version of `Zfitter` 7.00 is being prepared. For the first time, ISR corrections to the e^+e^- cross section and to the A_{FB} asymmetry will be available up to $\mathcal{O}(\alpha^6 L^6)$ order.

   Version 7.00 of the `Zfitter` project will be presented at the FCC-ee Workshop in June 2021.

   Done

5. Task: **Modules radiative corrections**

   - The calculations of electroweak radiation corrections at one loop level taking into account the polarization in the initial and final states, full phase space, massive case are done for: $e^+e^- \to e^+e^-$, $e^+e^- \to ZH$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \gamma Z$, $e^+e^- \to \gamma\gamma$, $e^+e^- \to \tau^+\tau^-$.
   - Building blocks for high order RC contributions Calculation of the next to leading logarithmic contributions of the order $\alpha^3 L^2$ for annihilation processes e^+e^- and Bhabha scattering ($L = \ln(s/m_e^2)$) are done. Calculation of $\alpha\alpha_s$ and α^2 radiative corrections introduced into four-fermionic processes.

   Done

6. Task: **Development of single-resonance approximation to complex processes**

   The work is finished for the process $e^+e^- \to Z\gamma, Z \to \mu^+\mu^-$, paper is under preparation.

   The work is in progress for the implementation of the processes $2 \to 4(5,6)$

7. Task: **Search for new physics in $e^+e^- \to \gamma\gamma$**

   CLIC collider sensitivity to $e^+e^- \to \gamma\gamma$ was evaluated using a full detector simulation. Expected limits on a finite electron size and some other parameters of BSM models were obtained. Results presented at LCWS2019 workshop, Sendai, Japan (October 2019).

   Done

8. Task: **Precision of the Higgs boson mass measurement**

   The main experimental factor limiting the Higgs mass measurement were studied. A preliminary evaluation of the Higgs mass precision was obtained based on the full simulation of the CLICdp detector. Results are presented at the AYSS-2020 conference.

   Mostly done, will be finalized by the end of 2021

9. Task: **Study of the anomalous quartic coupling in $e^+e^- \to W^+W^-$ at CLIC**

   SM background is evaluated and a preliminary set of selection cuts was developed. Further investigation is delayed since the signal MC generator is not ready yet.

   Task is postponed till 2022 and will be completed within the activity of Theme 1123

10. Task: **Measurement of the top quark polarization at CLIC**

    The expected experimental statistics is evaluated. Distributions of the sensitive variables are obtained. Statistical precision of the fit is estimated.

    The work is in progress, will be continued in 2022

11. Task: **Physics of two-photon collisions at CEPC**

    This item was added after the start of the Project. Our group has performed an extensive study of the two-photon physics at CEPC collider. The results are published as a chapter "Two-photon physics" in the "Whitebook of CEPC physics". We suggested studies of Higgs boson photoproduction, measurement of the tau lepton anomalous magnetic moment and many other studies.

    Done. We plan to extend our participation in the CEPC project

1 Publications

1.1 FCC Publications

- Standard Model Theory for the FCC-ee Tera-Z stage.
  CERN Yellow Reports: Monographs Vol 3 (2019).
- FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1. *Eur.Phys.J.**C**79,474(2019).*
- FCC-ee: The Lepton Collider : FCC CDR Volume 2. *Eur.Phys.J.Spec.Top.228,261-623(2019).*
- FCC-hh: The Hadron Collider : FCC CDR Volume 3. *Eur.Phys.J.Spec.Top.228,755-1107(2019).*
- HE-LHC: The High-Energy LHC. *Eur.Phys.J.Spec.Top.228,1109-1382(2019).*
- Theory report on the 11th FCC-ee workshop.
  CERN Yellow Reports: Monographs Vol 3 (2020).

1.2 Publications, peer-reviewed journals

- One-loop electroweak radiative corrections to polarized Bhabha scattering.
  Phys.Rev.D98,013001(2018).
- One-loop electroweak radiative corrections to polarized $e^+e^- \to ZH$.
  Phys.Rev.D100,073002(2019).
- Probing the strange content of the proton with charm production in charged current at LHeC. *Eur. Phys. J. C79, no. 10, 864 (2019).*
- Recent QCD results from the xFitter project - Probing the strange content of the proton with charmproduction in charged current at LHeC. *PoS DIS 2019, 025 (2019).*
- Calculating the five-loop QED contribution to the electron anomalous magnetic moment: Graphs without lepton loops. *Phys. Rev. D 100, no. 9, 096004 (2019).*
- Numerical calculation of 5-loop QED contributions to the electron anomalous magnetic moment. *J.Phys.Conf.Ser. 1525 (2020) 1, 012007.*
- Infrared and Ultraviolet Power Counting on the Mass Shell in Quantum Electrodynamics. *Nucl.Phys.B 961 (2020) 115232.*
- Polarized NLO EW e^+e^- cross section calculations with ReneSANCe-v1.0.0. *Comput. Phys. Commun., v.256, 2020.*
- QED and electroweak radiative corrections to polarized Bhabha scattering. *J. Phys. Conf. Ser., v.1525, n 1, 2020.*
- MCSANCee generator with one-loop electroweak corrections for processes with polarized e+e- beams. *J. Phys. Conf. Ser., v.1525 n 1, 2020.*
- Asymmetries in Processes of Electron-Positron Annihilation. *Symmetry, v.12, n 7, 2020.*
- One-loop electroweak radiative corrections to lepton pair production in polarized electron-positron collisions. *Phys. Rev. D, v.102, n 3, 2020.*
- Probing the strange content of the proton with charm production in charged current at LHeC. *Eur. Phys. J. C79, no. 10, 864 (2019).*
- Recent QCD results from the xFitter project - Probing the strange content of the proton with charmproduction in charged current at LHeC. *PoS DIS 2019, 025 (2019).*

- 2021: Process at the one loop level and taking into account polarization in the initial and final states: $e^+e^- \to \gamma Z$.
- 2021: Process at the one loop level and with polarization in the initial and final states: $e^+e^- \to \gamma\gamma$.
- 2021: Calculation of the next to leading logarithmic contributions of the order $\alpha^3 L^2$ for annihilation processes e^+e^- and Bhabha scattering, ($L = \ln(s/m_e^2)$).
- 2021: Process at the one loop level and taking into account polarization in the initial and final states: $e^+e^- \to \tau^+\tau^-$
- 2021: Update of Monte Carlo generator/integrator (`ReneSANCe` and `MCSANCee`): $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-, t\bar{t}, \gamma Z, \gamma\gamma, e^-\mu \to e^-\mu$

1.3 Workshops 2019-2022, 18 reports

1. DIZET Mini-Workshop, DESY, Zeuthen, 11-14 November 2019.
   https://indico.desy.de/indico/event/24616/

2. 19th International Workshop on Advanced Computing and Analysis Techniques in Physics Research, Saas Fee, Switzerland, 2019.
   https://indico.cern.ch/event/708041/

3. 13th APCTP - BLTP JINR Joint Workshop "Modern problems in nuclear and elementary particle physics", 14-20 July 2019,
   https://indico.jinr.ru/event/749

4. CEPC Topical Workshop: Theoretical Uncertainty Controls for the CEPC measurements Thursday, April 4, 2019, https://indico.ihep.ac.cn/event/9843/

5. 11th FCC-ee workshop: Theory and Experiments, CERN, 8-11 January 2019,
   https://indico.cern.ch/event/766859.

6. 3rd Fcc Physics and Experiments Workshop 13-17 January 2020.
   https://indico.cern.ch/event/838435/

7. 4rd Fcc Physics and Experiments Workshop 10-13 November 2020.
   https://indico.cern.ch/event/932973/

8. International workshop on the Circular Electron-Positron Collider, Oxford, 15-17 april 2019, https://indico.cern.ch/event/783429/

9. International workshop on the high energy Circular Electron-Positron Collider, Beijing, 18-20 November 2019, https://indico.ihep.ac.cn/event/9960/

10. XXIV International Scientific Conference of Young Scientists and Specialists (AYSS-2020) 9-13 November 2020, Dubna https://indico.jinr.ru/event/1119/

11. FCC week 2021, 28 June - 2 July, CERN - two Reports

12. ACAT 2021, 29 Nov - 3 Dec - two Reports
13. CEPC 2021, 14 - 17 April - one Report

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