Form N 24

ARIeL: Physics at Future e^+e^- colliders

Project leader — L.V. Kalinovskaya

Deputy project leader — I.R. Boyko

I.R. Boyko, Ya.V. Dydyshka, A.S. Zhemchugov, L.V. Kalinovskaya, E.O. Lutsenko, Y.A. Nefedov, I.I. Novikov, N.E. Pukhaeva, S.S. Rzaeva, L.A. Rumyantsev, A. Rymbekova, R.R. Sadykov, A.A. Sapronov, P.V. Shvydkin, *NEOVP, DLNP, JINR, Dubna, Russia*,
A.B. Arbuzov, S.G. Bondarenko, *BLTP, JINR, Dubna, Russia*,
I.S. Pelevanyuk, *LIT, JINR, Dubna, Russia*,
I.K. Sklyarov, *"Dubna" University, JINR, Dubna, Russia*,
G.V. Fedotovich, *INP SB RAN, Novosibirsk, Russia*,
V.V. Makarenko, V.L. Yermolchyk, *INP BSU, Minsk, Belarus*,
G. Nanava, *University of Hanover, Germany*,
O.I. Veretin, B.A. Kniehl, *University of Hamburg, Germany*,
S. Amoroso, A.A. Glazov, *DESY, Hamburg, Germany*,
S. Riemann, T. Riemann, *DESY, Zeuthen, Germany*,
T. Sjostrandt, *Lund University, Sweden*,
J. Gluza, *University of Silesia, Katovice, Poland*,
Z. Was, S. Jadach, *Institute of Nuclear Physics, Krakow, Poland*

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3.2 Abstract

The main goal of this Project is the preparation of the physics research program for the next-generation high-energy electron-positron collider (EPC). It is widely believed that EPC will be the next major international collider which will dramatically improve our understanding of the fundamental structure of Nature.

Our team includes both experimentalists and theoreticians working in the field. Our experimentalists participate in the CLICdp collaboration ("Detector and Physics at CLIC collider"), with possible extension to the CEPC collider. The theory part of our team is involved in the development of modern tools for precision calculations of physics processes which can be investigated at future electron-positron collider.

In this Project we present a plan of studies that we will perform in the framework of the preparation of the EPC research program. To fully exploit the EPC physics potential one has to improve both the experimental technique and the precision of theoretical calculations. From the experimental side, we will evaluate the EPC sensitivity to different physics observables and new physics phenomena, using the CLICdp detector model as a benchmark scenario. The full simulation and reconstruction of signal and background events will be used in this study. From the theoretical side, we will develop software tools for the precise theoretical support of the experiments at EPC taken into account complete one-loop and leading radiative corrections (RC) at 2-loop, 3-loop and 4-loop level. In particular, we will develop a Monte-Carlo generator for various processes in collisions of polarized electron-positron beams.

Our team has more than 20 years expertise in the field. We have participated in experiments DELPHI (LEP-1 and LEP-2), ATLAS (LHC), CMS (LHC), BESIII (BEPCII). We have also participated in the following projects for theoretical support of experiments: ZFITTER (LEP-1 and LEP-2), HECTOR (HERA), MCSANC (LHC). Based on our previous researches, 2 doctoral and 9 candidate dissertations have been defended. More than 50 papers have been published by our group alone (and more than 1000 papers in the framework of different collaborations).

This Project is proposed for the period of 3 year. The total number of participants is 32 and the requested financial support is 114000 US dollars for the full period of the Project.

3.3. Introduction

The most urgent task of high-energy physics today is to find the limits of the Standard Model (SM) applicability. High-precision tests of the model are performed using all possible means including studies of rare decays, astrophysical observations etc., but the main tools here are high-energy colliders, in particular, the LHC. It is widely accepted that the next major machine should be an e^+e^- collider. EPC are best suited for the precision studies of elementary particles, with obvious advantages from well defined kinematics of the initial state and the absence of the large QCD background typical for hadronic colliders.

Currently there are 4 mature EPC projects under consideration: FCC (circular), CEPC (circular), ILC (linear), CLIC (linear). Among them, CLIC offer the widest spectrum of physics research. At the first CLIC energy stage (350-380 GeV) model-independent measurements of Higgs boson properties will be performed. Top quark mass will be measured by the threshold scan at 350 GeV. Other top quark properties will be precisely determined using the high statistics to be collected at 380 GeV. At the higher energy stages, 1.5 and 3 TeV, Higgs boson properties will be measured with an improved precision, thanks to the high luminosity and the large cross-section of the process $e^+e^- \to H\nu\nu$. In addition, a variety of searches for effects beyond the Standard Model will be performed at high energy stages.

To perform the tasks mentioned above one needs high-precision theoretical predictions for all SM processes which will be studied at the future colliders. Within this project we plan to construct modern theoretical predictions for most important observables. The required precision will be achieved by taking into account high order RC and polarization effects.

Within this Project we plan to perform the studies that are listed below.

Experimental side (evaluation of the CLIC physics potential):

Study of the annihilation process $e^+e^- \to \gamma\gamma$; Measurement of the Higgs boson mass; Measurement of the top quark polarization; Study of the quartic couplings $WW\gamma\gamma$ and $ZZ\gamma\gamma$.

Theoretical side:

Development of the Monte Carlo (MC) generator at the level of complete one-loop and leading multiloop radiative corrections and taking into account both longitudinal and transverse polarization for processes $e^+e^- \to e^+e^-$ ($\mu\mu, \tau\tau, tt, HZ, H\gamma, Z\gamma, ZZ, H\nu\nu, H\mu\mu, ff\gamma, \gamma\gamma$); Interfacing of NLO EW corrections with PYTHIA; Development of single-resonance approach to complex processes; Elaboration of the standard procedure for calculating the helicity amplitudes for the processes $2 \to 3, 4$; Creating and implementation the additional building blocks for the RC for the complete weak 2-loops and QCD 3-loops calculation, plus leading weak 3-loops and leading QCD 4-loops.

3.4 State of the research on the claimed scientific problem

Development of experimental program for e^+e^- colliders

Currently there are 4 advanced projects for the next-generation e^+e^- collider. CLIC (CERN) and ILC (Japan) are linear colliders projects, FCC (CERN) and CEPC (China) are circular ones. A unique feature of the CLIC project is its ultra-high annihilation energy (up to 3 TeV). A big advantage of FCC is the enormous statistics that can be collected at Z^0 resonance and at 250 GeV (at the maximum of $ee \to ZH$ cross-section). Advantages of ILC and CEPC are their relative affordability and reliance on well-established technologies. For the circular colliders (FCC and CEPC) there is an important advantage of re-using the tunnel for a next-to-next-generation hadron collider of ultra-high energy. More details on e^+e^- collider projects can be found in Appendix.

Each of the 4 projects has an advanced physics research program. The richest physics menu is offered by the CLIC project, which is currently the only one planning to collect a large sample of top quark pairs and to search for new physics at the energies well above the top pair threshold. Our group plans to participate in the further development of the CLIC research program.

In this Project we propose to carry out 4 different studies. Two of them ($ee \to \gamma\gamma$ and $\gamma\gamma \to WW$) are not planned by any other experiment, since they rely on the CLIC ultra-high collision energy. The measurement of top quark polarization was already studied within ILC project. We plan to complete a similar study for CLIC and we expect to demonstrate that CLIC sensitivity is similar to ILC. The measurement of Higgs boson mass is currently a weak side of the CLIC research program. The expected precision is 5 times worse than in other projects. We propose to apply a new analysis method which is especially suitable for the CLIC experimental environment, and we expect a very significant improvement in precision.

Development of software tools for precision calculations

At present there is no MC generator at more than tree level for polarized beams.

Theoretical support of high-precision experimental verification of the Standard Model in the experiments is carried out according to the following scheme: the results of theoretical calculations are introduced into the event generators using the Monte Carlo method.

The result of this Project will be a Monte-Carlo event generator with a complex account of the effects of higher order perturbation theory due to strong, electromagnetic and weak interactions, as well as with the option *to take into account the effects of polarization.*

i) The following Monte Carlo generators currently exist with the polarization taken into account, but without calculations of loop corrections. AMEGIC++ [3.4-1], makes use of helicity amplitudes and is a part of SHERPA; COMPHEP [3.4-2] uses the traditional trace techniques to evaluate the matrix elements; GRACE [3.4-3] (with the packages BASES and SPRING) uses the calculation of matrix elements via helicity amplitude techniques; WHIZARD [3.4-4] is a software system, intended for the effective calculation of scattering cross-sections of many-particles and simulated events, polarization is processed for both the initial and final states.

ii) There is series of papers [3.4-5] in which a calculation is given at a one-loop level of accuracy taking into account the polarization in the SM and in MSSM processes. Works are not accompanied by the development of the Monte Carlo event generator.

List of the references, can be found in Appendix 3.5.D

3.5. Description of the proposal:

The physics program of future high-energy e^+e^- colliders includes precision measurements of a vast amount of Standard Model (SM) processes as well as searches for phenomena beyond Standard Model (BSM). In the Project we will concentrate on the processes which are most relevant for the verification of the electroweak (EW) sector of the SM including EW gauge bosons, the Higgs boson, and the top quark. Our studies will include the theoretical support of experiments at the future e^+e^- colliders (taking into account the polarization effects) and the development of the experimental program of the CLIC collider, in particular the evaluation of CLIC sensitivity to various SM and BSM phenomena.

Part I: Theoretical support for future e^+e^- colliders

The plan for theoretical support is:

- Development of the Monte Carlo (MC) generator at the level of complete one-loop and leading multiloop radiative corrections and taking into account both longitudinal and transverse polarization for processes $e^+e^- \to e^+e^-$ ($\mu\mu, \tau\tau, tt, HZ, H\gamma, Z\gamma$, $ZZ, H\nu\nu, H\mu\mu, ff\gamma, \gamma\gamma$).

- Creating an interface to implement electroweak RC to PYTHIA.

- Implementation a single-resonance approach to describe complex processes.

- Elaboration of the standard procedure for calculating helicity amplitudes for processes $2 \to 3, 4$.

- Creating additional building blocks for the RC for the complete weak 2-loops and QCD 3-loops calculation and leading weak 3-loops and leading QCD 4-loops.

Precision tests of the Standard Model at colliders are one of the most important tasks of modern high-energy experiments. The accuracy of the corresponding experimental studies improves continuously with increased luminosity, novel detector technologies, elaboration of new analysis techniques, etc. All that leads to new requirements on the accuracy of theoretical predictions challenged by the experimental data.

High-energy e^+e^- colliders provide an experimental environment that allows studying with high precision very important ingredients of the SM, (see section 1 in Appendix 3.5.C):

• the Higgs boson properties via the Higgsstrahlung process $e^+e^- \to ZH$,
• the WW-fusion process $e^+e^- \to H\nu_e\bar{\nu}_e$, etc., see Appendix 3.5.C,
• the sine of effective weak mixing angle $\sin\vartheta_W^{eff}$,
• the top quark mass, width, and coupling constants in $e^+e^- \to t\bar{t}$,
• Bhabha scattering process $e^+e^- \to e^+e^-$, since it will be used for luminosity measurements, etc.

We are going to describe those processes by means of a Monte Carlo generator which will include the complete set of one-loop corrections supplemented with the most relevant higher-order contributions. A new feature of our results will be inclusion of the effects due to beam polarization.

The helicity amplitude (HA) formalism will be applied. It allows getting the cross-section by summing up the squares of helicity amplitudes (instead of squaring the sum of amplitudes in the conventional approach), see Eq.(1.15) in [3.5-7], or Fig. 1 in the Appendix 3.5.C. Therefore we have the basement for the implementation of both transverse and longitudinal beam polarizations.

The active environment of our system allows obtaining an analytical result for scalar form factors (FF), helicity amplitudes (HA), and Bremsstrahlung (BR) contributions. For the calculation of the HA's the Vega-Wudka [3.5-1], and Kleiss-Stirling [3.5-2] methods are used. All calculations in the HA to FF to BR are implemented in a single thread computing. The advantage of the calculation of the one-loop corrections using the helicity amplitudes (HA) method is the possibility to take into account the polarization effects [see Appendix 3.5.C].

Now the programs in the language of symbolic computation FORM [3.5-3] are created to calculate the processes of the following types: $4f \to 0$, $4b \to 0$ and $2f2b \to 0$. These programs compute one-loop ultraviolet-finite scalar form factors and amplitudes.

Analytical results are transferred to the numerical level using the software written in PERL. This package semi-automatically generates FORTRAN programs for subsequent numerical calculations of the decay probabilities and process cross-sections. To verify the correctness of the results, first of all we observe independence scalar form factors of the calibration parameters and Ward identities, and, secondly, we perform the extensive numerical comparison of our results with independent calculations known in the world: with FeynArts [3.5-4] and GRACE [3.5-5] systems, topfit program [3.5-6], etc.

Part II: CLIC experimental program

Recently JINR has joined the CLICdp (CLIC Physics and Detector) collaboration. The main activity of the JINR group in CLICdp will be the preparation of the program of physics research at the CLIC collider. In addition to this, JINR group will be involved in service work usual for any collaboration: validation of physics software, participation in publication and speaker's Committees, preparation of common papers, representation of the Collaboration at conferences and workshops.

For the preparation of the CLIC research program, JINR group plans to carry out the following studies:

1. Precision measurement of the QED process $e^+e^- \to \gamma\gamma$ and setting limits on the new physics models
2. Precision measurement of the Higgs boson mass
3. Measurement of the top quark polarization and determination of the anomalous top form-factors
4. Measurement of $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to ZZ$ scattering and search for anomalous quartic coupling

The above studies will be based on the full CLICdp detector simulation and reconstruction software. Both signal and background Monte-Carlo simulation will be used. The goal of the study is to demonstrate the possibility of the given measurement and to estimate the experimental precision that can be achieved with the full CLIC data sample. The details of the proposed studies are given below.

Precision measurement of $e^+e^- \to \gamma\gamma$ annihilation

The reaction $e^+e^- \to \gamma\gamma$ is the simplest QED process which can be predicted theoretically with very high precision. Experimentally it can be measured with very high precision as well, because the final state is extremely simple and unambiguous: two very energetic showers in the electromagnetic calorimeter and no tracks of energetic charged particles in the whole detector.

The $e^+e^- \to \gamma\gamma$ process is sensitive to various BSM models. By comparing the measured cross-sections with the Standard Model predictions we plan to set limits on the following BSM models: The QED cut-off (finite size of electron); A contact interaction within the framework of an effective Lagrangian theory; Compactified extra dimensions; The t-channel excited electron exchange.

A quick generator-level analysis shows that the LEP limits on the new physics scale can be improved by more than an order of magnitude. A typical energy scale that can be probed by CLIC is 5-20 TeV. This estimate has to be confirmed by a more detailed study. The JINR group will analyze the $e^+e^- \to \gamma\gamma$ process using the full detector simulation and reconstruction for signal and background events.

Precision measurement of the Higgs boson mass

Currently the Higgs boson mass (M_H) is known with a relatively low precision of about 240 MeV (combined LHC Run-1 result). Further improvement is necessary because theoretical predictions of exclusive Higgs decay modes are very sensitive to the Higgs mass used in calculations. A 15 MeV uncertainty on M_H is required to reach a permille-level precision on partial decay width calculations.

At e^+e^- colliders the Higgs boson mass can be determined using the process $e^+e^- \to ZH \to \mu\mu H$. M_H is reconstructed as the mass recoiling against the precisely measured $\mu\mu$ system. At circular colliders and at ILC the experimental conditions allow measuring M_H with 15-20 MeV precision. For CLIC the expected precision is much worse, about 110 MeV, mainly because of the large beam energy spread at CLIC.

JINR group proposes to measure the Higgs boson mass using a method which was recently proposed for ILC. In this method the kinematics of the initial collision is not used for the M_H reconstruction. The analyzed process is $e^+e^- \to ZH$ with subsequent decays $Z \to \mu\mu$ and $H \to bb$. The muon track measurement provides the precise determination of the Z boson 4-momentum, while only **directions** (but not energies) are measured for the b-jets.

The study performed for ILC has demonstrated a significant improvement in comparison to the recoil mass method. Even larger improvement is expected for the CLIC experimental environment.

The JINR group will perform a detailed study of performance of the new method in CLIC conditions. The analysis relies on the precise reconstruction of hadronic jets, b-jet identification (b-tagging), and knowledge of the transverse momentum spectra of incoming beams. Therefore, our study will be based on the full simulation of the beam delivery system and of the detector response, as well as on advanced algorithms of the event reconstruction.

Determination of the top quark polarization

The production of fermion-antifermion pairs $e^+e^- \to f\overline{f}$ is characterized by three observables: total production cross-section, forward-backward charge asymmetry and the average fermion polarization. Among these observables, the measurement of the fermion polarization is more complicated since usually it is only accessible via the kinematical correlations of the fermion decay products.

The polarization measurement in e^+e^- annihilation is only possible for tau leptons and top quarks. The tau polarization was extensively measured at LEP. It provided a vital input to the global electroweak fit, which finally resulted in the prediction of the Higgs boson mass, $114 < M_H < 161$ GeV. In particular, one of authors of this Project has participated in the tau polarization measurement at LEP-1 and performed the world only measurement at LEP-2 energies. In this Project the JINR group proposes a measurement of the top quark polarization at multi-TeV energies. The polarization can be measured from the distribution of the helicity angle θ_{hel} defined in the top rest frame as the angle between the top boost and the direction of a lepton from semileptonic top quark decay.

The sensitivity study for the ILC project has estimated the expected uncertainty on top polarization of the order of 0.01. The combination of the charge asymmetry and the polarization measurements can improve the expected LHC limits on anomalous top formfactors by 1-2 orders of magnitude. For CLIC, we expect even better precision since the integrated luminosity will be larger by at least a factor of 5 and the boosted kinematics at high energies makes the top pair reconstruction easier.

Study of vector boson pair production in $\gamma\gamma$ collisions

Within the Standard Model the gauge boson self-interaction not only includes the trilinear $WW\gamma$ and WWZ vertices but also quartic couplings $WWWW$, $WWZZ$, $WW\gamma\gamma$ and $WWZ\gamma$. In particular, pairs of W bosons can be produced in photon collisions $\gamma\gamma \to W^+W^-$.

At the same time, the process $\gamma\gamma \to ZZ$ is forbidden in SM at tree level. The loop-level contribution to $\gamma\gamma \to ZZ$ will be estimated within the theoretical part of this Project, however, it is expected to be very small. Hence, an observation of this process with a significant cross-section would be a clear sign of BSM effects. Another way to search for new physics is to study the allowed process $\gamma\gamma \to W^+W^-$, looking for small deviations from the SM predictions.

At CLIC, due to its very strong accelerating field, a significant fraction of the beam particles will radiate a hard photon before reaching the collision point. The collisions of radiated photons can be used to study a variety of processes that occur in $\gamma\gamma$ collisions.

A generator-level study shows that for high-energy CLIC running the majority of W pairs will be produced in $\gamma\gamma$ rather than in e^+e^- collisions. The background level can be kept at the level of about 10% by selecting the fully leptonic decays in $e\mu$ final state. The present LHC limits on anomalous quartic couplings can be improved by about one order of magnitude. Note that this result is based on a generator-level study and represent only a very rough estimate. A detailed full-simulation analysis will be performed in the framework of this Project for the $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to ZZ$ processes.

Summary on participation in the CLIC experimental program

In this project we propose to complete a detailed study of the CLIC physics potential in four different fields. For two of them, $e^+e^- \to \gamma\gamma$ and $\gamma\gamma \to W^+W^-$ processes, CLIC is expected to perform much better than any other proposed e^+e^- collider. For the measurement of top quark polarization CLIC sensitivity is expected to be similar or slightly better than at ILC. As for the measurement of the Higgs boson mass, the CLIC precision is currently estimated to be at least 5 times worse than for other e^+e^- collider projects. We propose to investigate a new method of M_H measurement which is expected to improve the precision very significantly. Even if the expected precision can not reach the level of CLIC competitors, still the new result would be an important input for the choice between different projects.

Past contributions of the project team

Our team is working in the field for many years. The list of our main publications and conference reports can be found in Section "The main activity of the JINR group" of the Appendix 3.5.D. In total, 11 authors of the Project are Doctors or Candidates of Science. Of them, 9 authors defended their theses in the field of this Project.

3.6 Assessment of human resources

<u>Leader:</u>
L.V. Kalinovskaya
<u>Deputy Leader:</u>
I.R. Boyko,
<u>Project Referees:</u>
1) V. Savrin, professor SINP MSU; 2) E. Khramov, JINR, DLNP

NN.	full name	status	FTE(%)	place of work
1.	Boyko Igor Romanovich	cs	50	NEOVP, DLNP, JINR
2.	Dydyshka Yahor Vyacheslavovich	r	100	NEOVP, DLNP, JINR
3.	Zhemchugov Alexei Sergeevich	cs	25	NEOVP, DLNP, JINR
4.	Kalinovskaya Lydia Vladimirovna	d	100	NEOVP, DLNP, JINR
5.	Lutsenko Evgenii Olegovich	s	100	NEOVP, DLNP, JINR
6.	Nefedov Yuri Anatolievich	cs	50	NEOVP, DLNP, JINR
7.	Novikov Ivan Igorevich	s	50	NEOVP, DLNP, JINR
8.	Pukhaeva Nelly Efimovna	cs	30	NEOVP, DLNP, JINR
9.	Rzaeva Sevda Sabir Qizi	cs	100	NEOVP, DLNP, JINR
10.	Rumyantsev Leonid Alexandrovich	cs	100	NEOVP, DLNP, JINR
11.	Rymbekova Ayerke	r	50	NEOVP, DLNP, JINR
12.	Sadykov Renat Rafailovich	cs	50	NEOVP, DLNP, JINR
13.	Sapronov Andrey Alexandrovich	cs	50	NEOVP, DLNP, JINR
14.	Shvydkin Pavel Valerievich	ps	50	NEOVP, DLNP, JINR
15.	Arbuzov Andrey Borisovich	d	50	BLTP, JINR
16.	Bondarenko Sergey Grigorievich	cs	50	BLTP, JINR
17.	Pelevanyuk Igor Stanislavovich	ps	30	LIT, JINR
18.	Sklyarov Igor Konstantinovich	s	30	Uni. "DUBNA"
19.	Fedotovich Gennadii Vasilievich	d		RAN, Novosibirsk
20.	Makarenko Vladimir Vladimirovich	cs		INP BSU, Minsk, Belarus
21.	Yermolchyk Vitalii Leonidovich	r		INP BSU, Minsk, Belarus
22.	Nanava Gizo	cs		Uni. Hannover, Germany
23.	Veretin Oleg	cs		Uni. Hamburg, Germany
24.	Kniehl A. Bernd	d		Uni. Hamburg, Germany
25.	Amoroso Simone	r		DESY, Hamburg, Germany
26.	Glazov Aleksandr Alimovich	d		DESY, Hamburg, Germany
27.	Riemann Sabina	cs		DESY, Zeuthen, Germany
28.	Riemann Tord	cs		DESY, Zeuthen, Germany
29.	Torbjorn Sjostrand	d		Lund University, Sweden
30.	Gluza Janusz	cs		INP, Katovice, Poland
31.	Was Zbignev	d		INP, Krakow, Poland
32.	Jadach Stanislav	d		INP, Krakow, Poland

Including:
students (s) — 3, postgraduate students (ps) — 2, researchers (r) — 4,
candidates of sciences (cs) ans Ph.D.— 15 , doctors and professors (d) — 8.

3.7 Justification of the expenditures

Hardware. At current stage, our main hardware tool is a computer. We plan to buy 1/2 PC per 3 years per 1 FTE (Dubna participants only). This is equivalent to 6 years lifetime of a computer.

Travels. At current stage, our main activity is computation and data analysis, that must be widely presented and discussed. So, our main spendings are:

- Travels to collaboration meetings
- Visiting our colleagues and co-authors in Hamburg, Cracow, Minsk, Novosibirsk, Rostov, etc
- Participations in international conferences
- Hosting our colleagues in Dubna

We expect approximately 10 2-week visits to CERN and European countries per year (about 0.9 travel per FTE, Dubna participants only), plus participating in 3-4 international conferences per year.

Form N26

Proposed time-table and necessary resources for completion
of the project **ARIeL: Physics at Future e^+e^- Colliders**

Names of the parts and systems of the setup, resources, and sources of financing			Cost of parts (thousand $) of the setup. Required resources	Proposals for distribution of financing and resources		
				1st year 2019	2nd year 2020	3rd year 2021
source of financing	budet	Expenditures from the budget including valuta means:				
		International collaboration	93000$	31000$	31000$	31000$
		Collaboration in Russia	12000$	4000$	4000$	4000$
		Computer equipment	9000$	3000$	3000$	3000$
	off budget	Means from grants:				

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Form N29

Estimated expenditures for the Project

ARIeL: Physics at Future e^+e^- Colliders

NN	Names of items of expenditures in $	Total cost	1 year 2019	2 year 2020	3 year 2021
	Direct expenditures for the Project:				
2.	Computer equipment	9000	3000	3000	3000
3.	Scientific trips, including:				
	a) foreign countries	93000	31000	31000	31000
	б) inside Russia	12000	4000	4000	4000
	в) 'protocol' works		-	-	-
	Total direct expenses	114000	38000	38000	38000

Project leader L.V. Kalinovskaya ”____”__________

Laboratory Director V.A. Bednyakov ”____”__________

Leading engineer-economist
of the Laboratory G.A. Usova ”____”__________

3.8 SWOT analysis

Strengths of the project

- The project team has a broad experience of experimental and theoretical studies at high energy colliders, based on the participation in the DELPHI, ATLAS and BES-III experiments.
- The theoretical part of the project will be based on a solid background, using the tools and methods developed during the ZFITTER (LEP-1, LEP-2), Hector (HERA), SANC (LHC) project.
- JINR is already a member of the CLICdp collaboration.

Weakness

The project team needs more young scientists involved into the experimental studies.

Opportunities

The results of the project may allow JINR to join any collaboration at any future high energy e^+e^- collider to be built, including ILC, CLIC, CEPC, FCC etc.

Threats

If no new big machine will be constructed in the world, the project prospects will be limited by feasibility studies and physics program preparation, with no implementation in real experiments.