ARIeL:
Physics at future e^+e^- colliders
Физика на будущих e^+e^- коллайдерах

Project leader: L.V. Kalinovskaya

Deputy: I.R. Boyko

Organizational matters

Theme: ATLAS

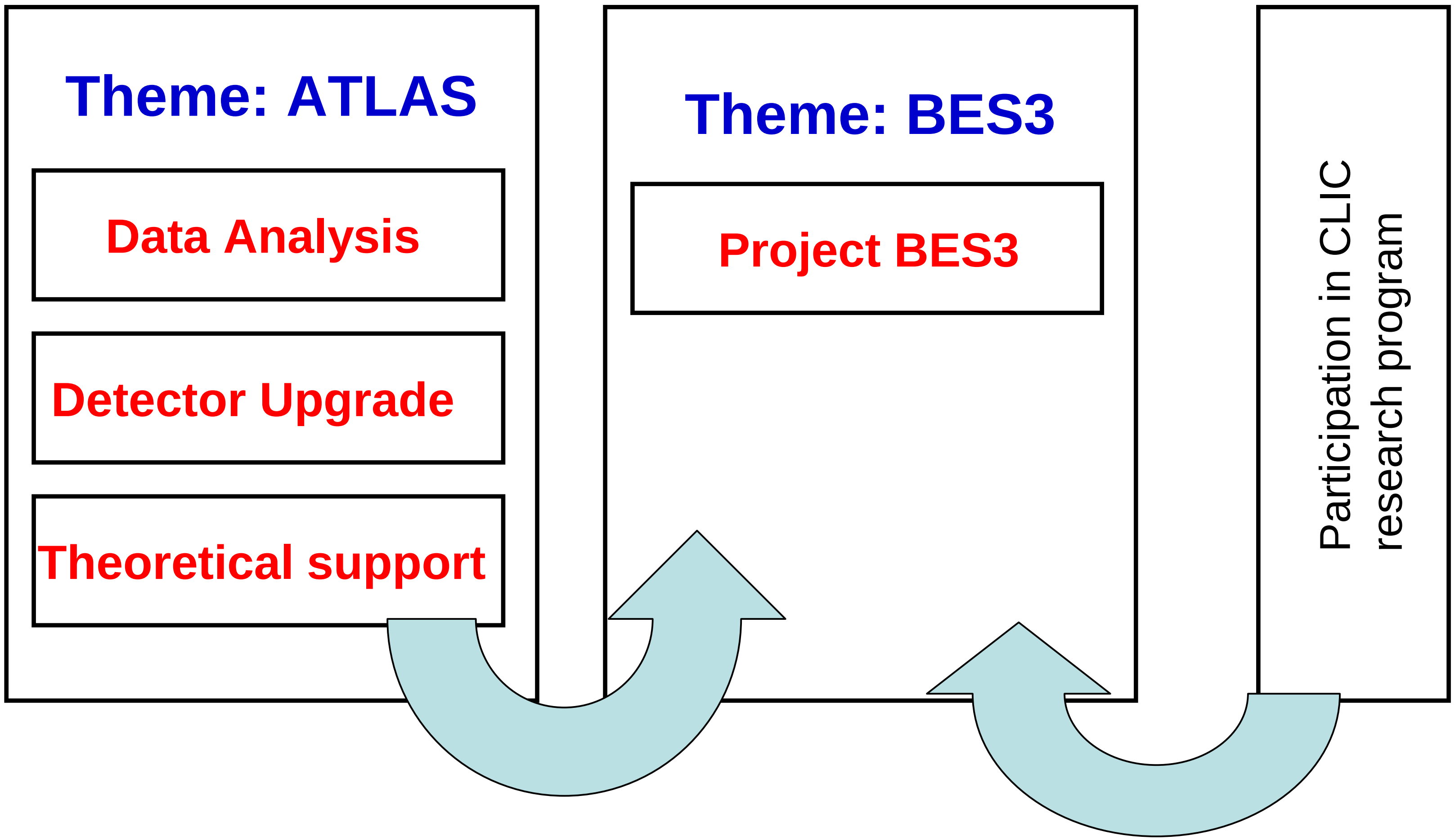
- **Data Analysis**
- **Detector Upgrade**
- **Theoretical support**

Theme: BES3

- **Project BES3**

Participation in CLIC research program

Organizational matters



Organizational matters

Theme: ATLAS

- **Data Analysis**
- **Detector Upgrade**

Theme: Study of funda-mental interactions in e^+e^- collisions

- **Project BES3**
- **Project ARIeL**

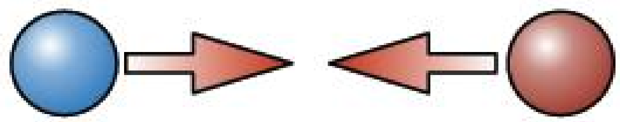
Why ARIeL?

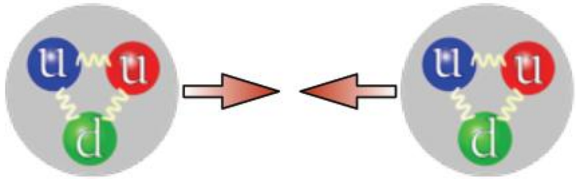
- **Advanced**
- **Research of**
- **Interactions in**
- **e^+e^-**
- **coLlisions**

What we will do

- Preparation of CLIC research program
  - ee→γγ
  - Higgs mass
  - γγ → WW and quartic coupling
  - Top quark polarization
- Theoretical support of experiments at e^+e^- colliders
  - Create e^+e^- generator at more than 1 loop with polarization
  - Interfacing NLO EW RC to PYTHIA
  - Develop single-resonance approach to complex processes
  - Elaborate a standard procedure for 2→4 helicity amplitudes
  - Create building blocks for complete weak 2-loops and QCD 3-loops, plus leading weak 3-loops and QCD 4-loops

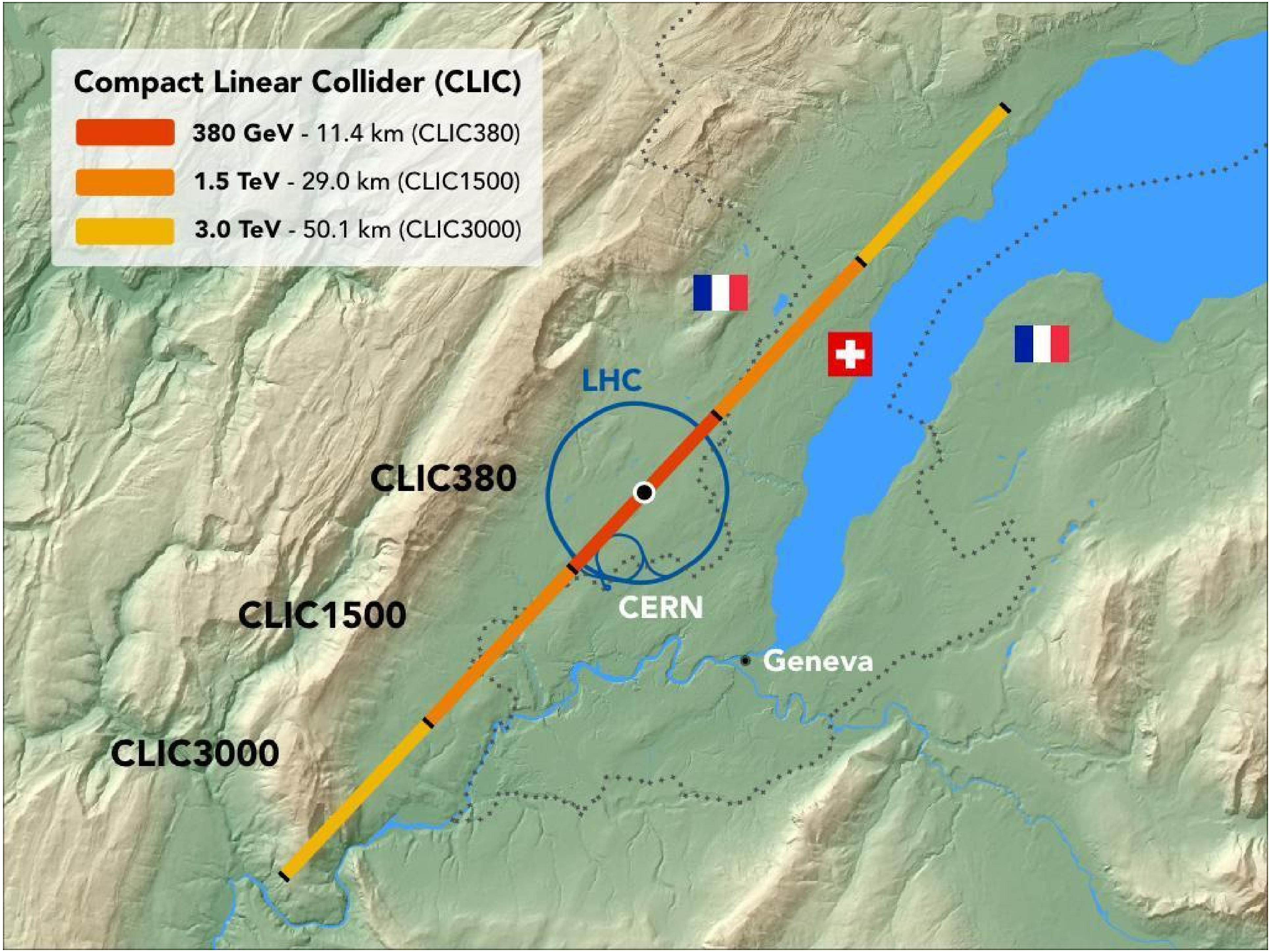
Future collider candidates



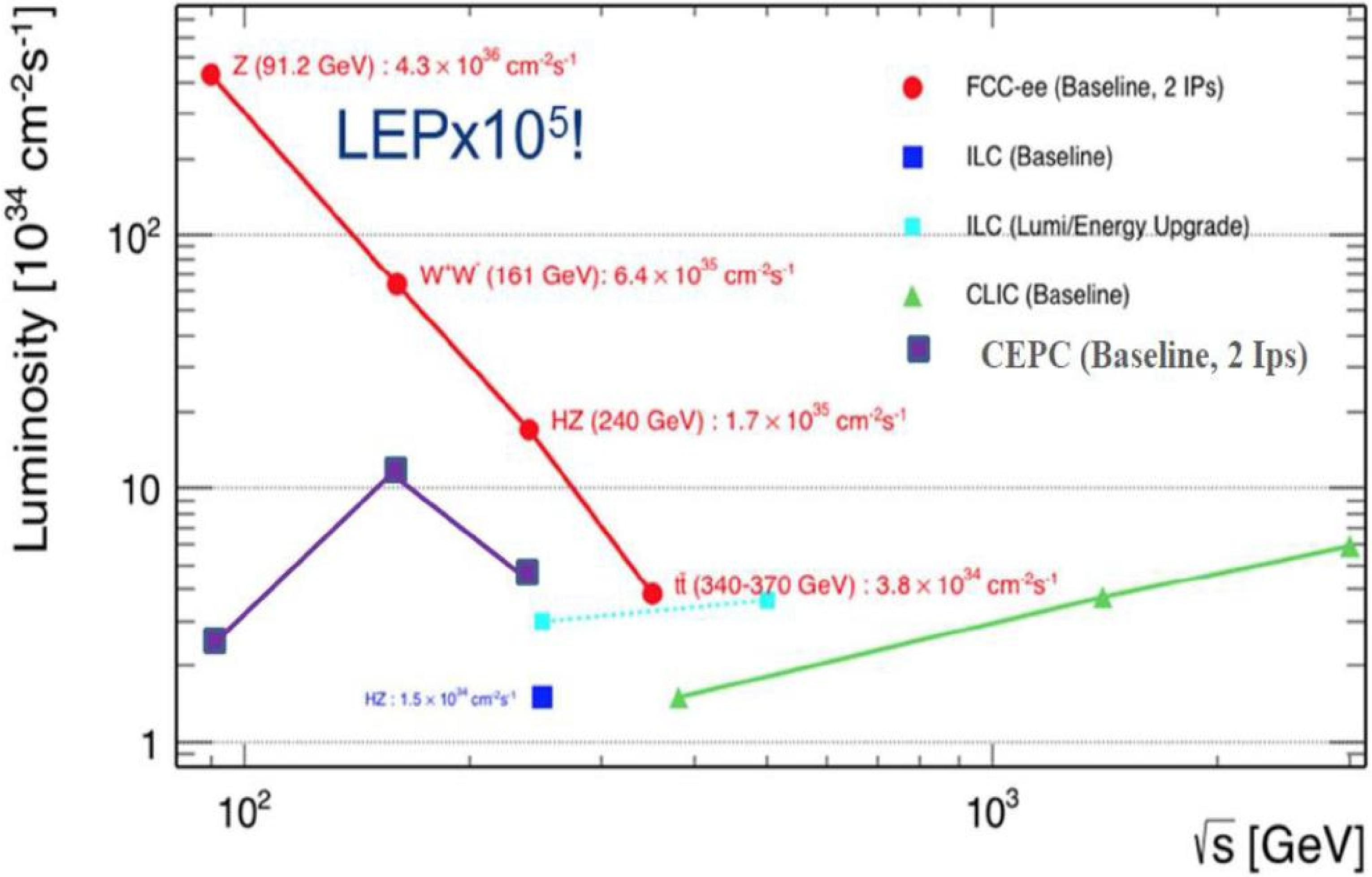


- ILC: 20 (30?) km, 250 (500?) GeV, Higgs factory
- CLIC: 50 km, 3000 GeV, Higgs, Top, discoveries
- CEPC: 100 km, 250 GeV, Higgs physics
- FCC: 100 km, 350 GeV, Higgs + Top

- HL LHC:
  14 TeV, 3 ab^{-1}
- HE-LHC:
  33 TeV, 2 ab^{-1}
- CEPC-pp:
  70 TeV, 10 ab^{-1}
- FCC-pp:
  100 TeV, 5 ab^{-1}


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

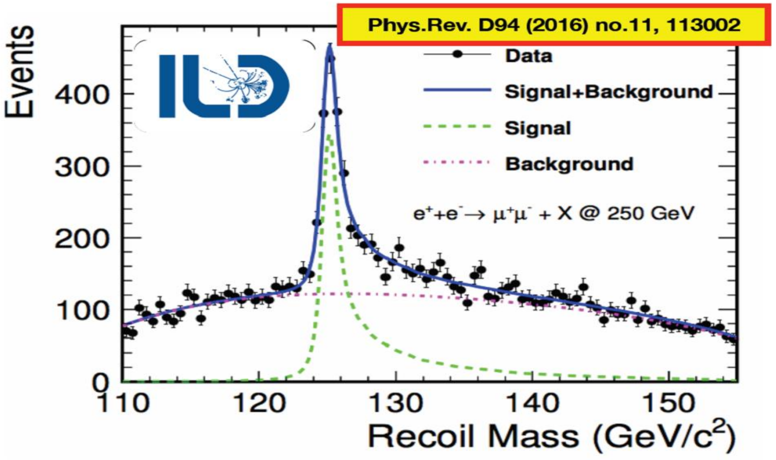
Comparison of e^+e^- projects

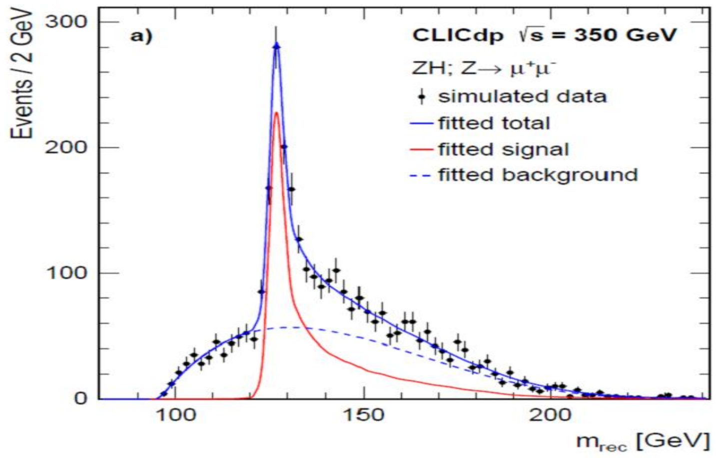


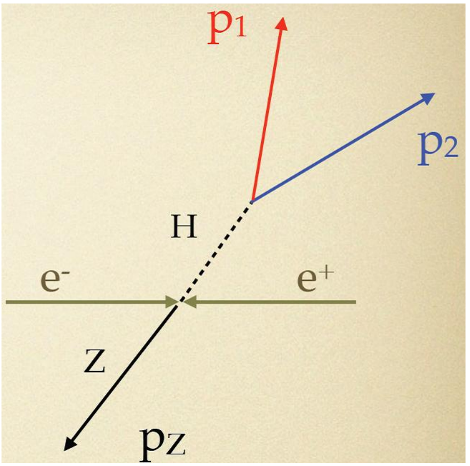
Preparation of CLIC research program

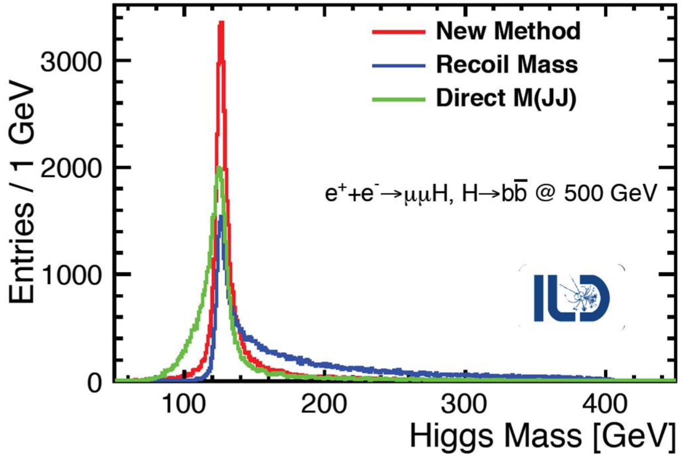
- Obviously, only 1 (may be 2) e^+e^- collider(s) will be built
- At some stage one will have to choose and decide
- We will provide input on CLIC physics potential
  - With $ee \to \gamma\gamma$ (electron radius) and $\gamma\gamma \to WW$ (quartic coupling) CLIC is unique and unbeatable, thanks to ultra-high energy
  - With top physics CLIC is similar to ILC and FCC, **if** they reach data taking at the top pair domain (unlikely!)
  - Higgs mass measurement is currently a weak side of CLIC (ILC/FCC/CEPC are 5 times better). We will try a new method which promises to improve CLIC precision a lot

Higgs mass measurement



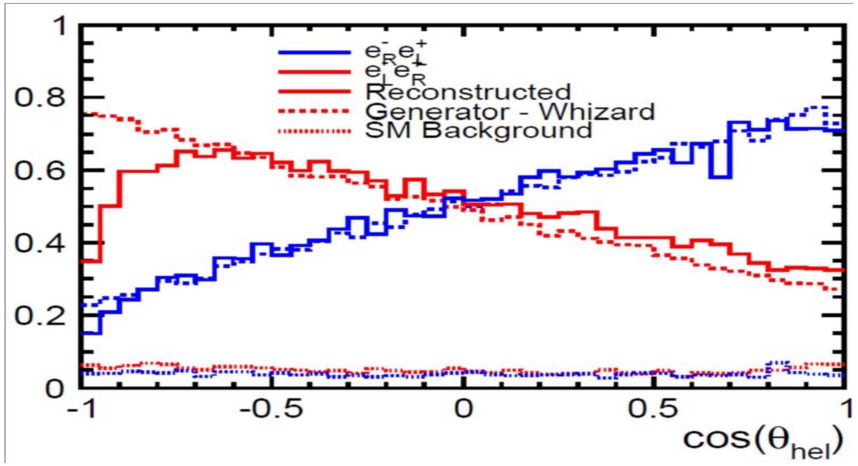


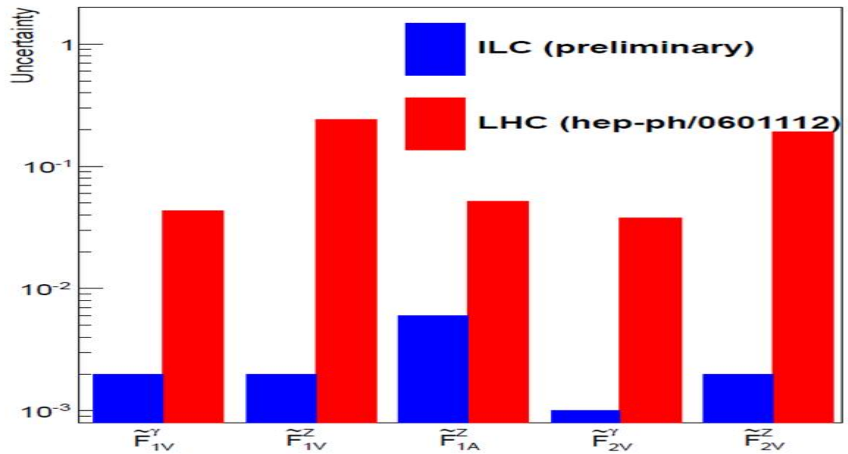




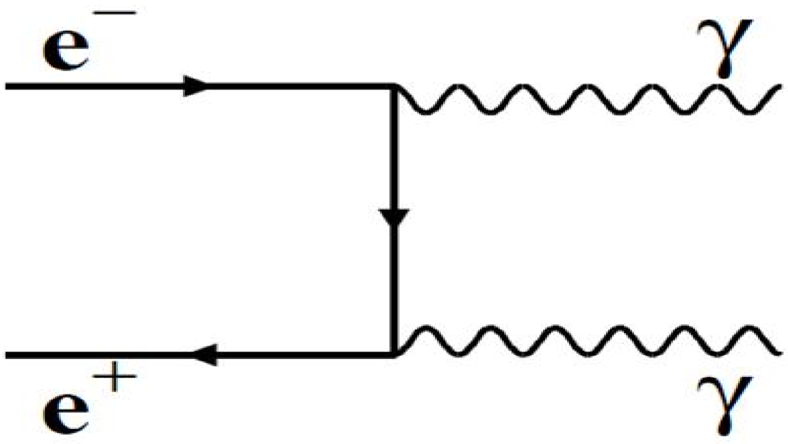
Top polarization at E≥380 GeV

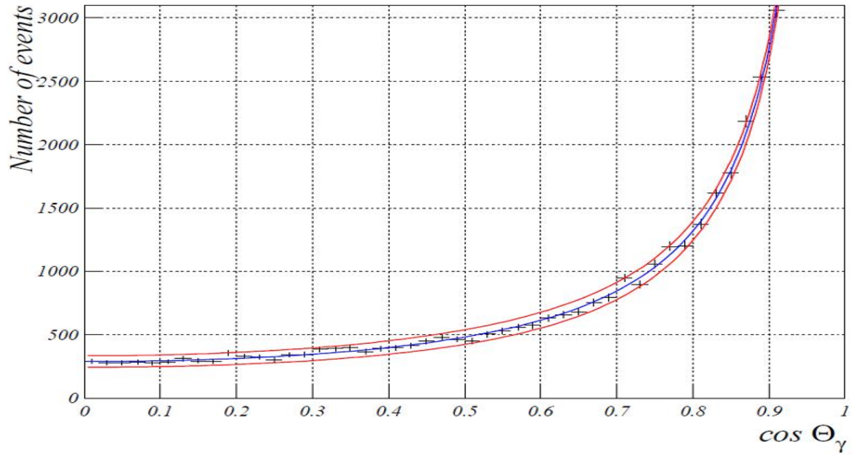
- Fermion pair production described by 3 observables: cross-section σ, asymmetry A_{FB}, polarization P
- $P=(N_R-N_L)/(N_R+N_L)$
- Only accessible via distribution of decay products
- Only available for τ and t





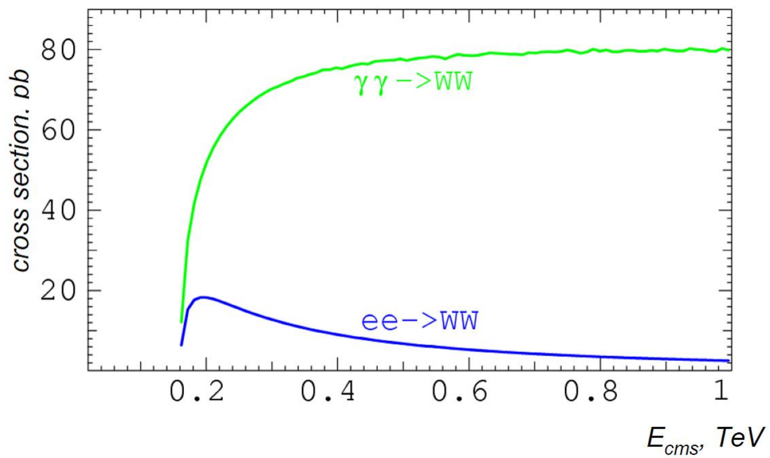
Electron radius from ee→γγ

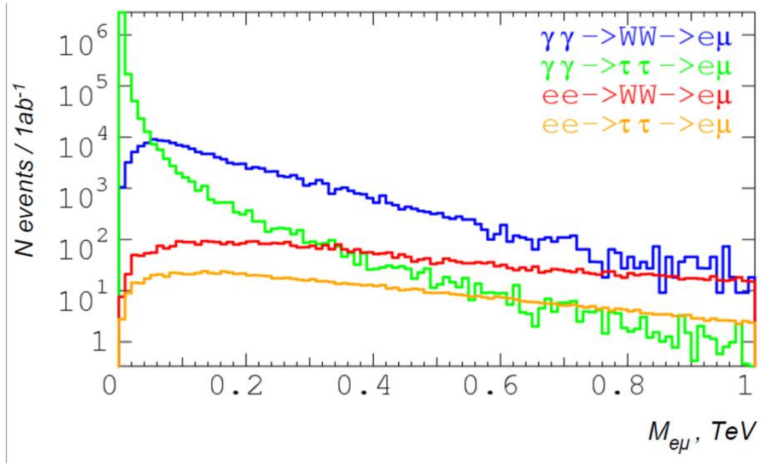


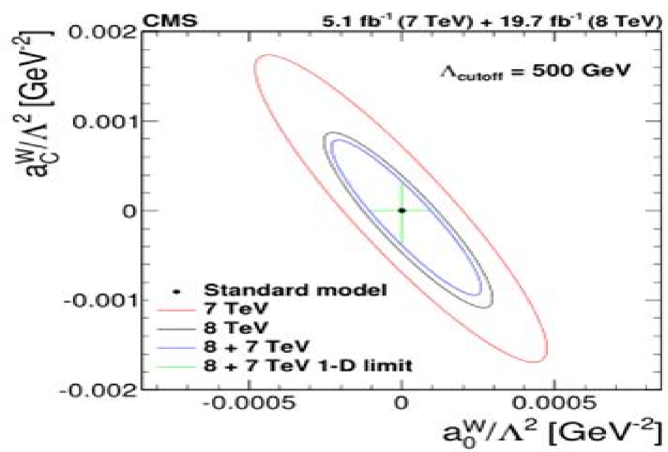


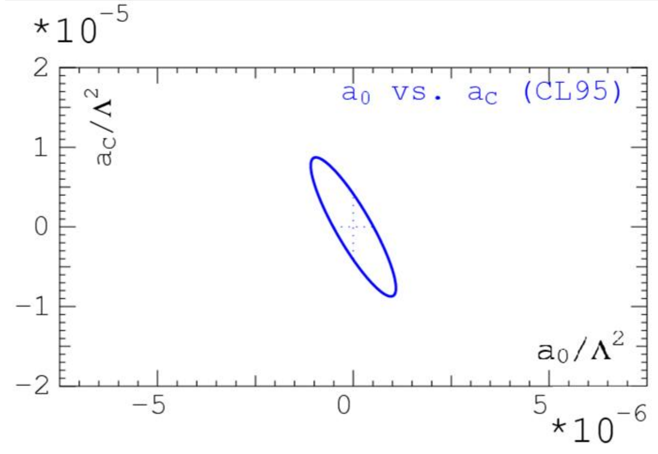
	LEP limit	CLIC expectation
$\Lambda_{\pm}$ (QED cut-off) Electron radius	364 GeV 4.6×10^{-17} cm	6-6.5 TeV $(3-3.5) \times 10^{-18}$ cm
Λ' (contact interactions)	831 GeV	18-20 TeV
M_s (extra dimensions)	933 GeV	15-17 TeV
M_{e^*} (excited electron)	248 GeV	4.5-5.0 TeV

$\gamma\gamma \to$ WW at 3000 GeV





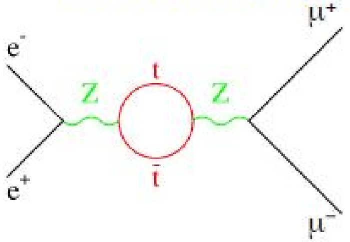


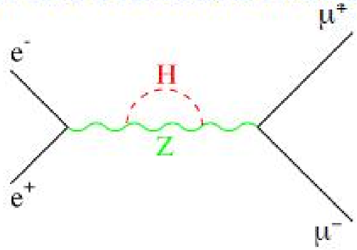


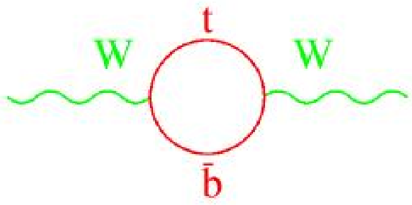
Precision means discovery!

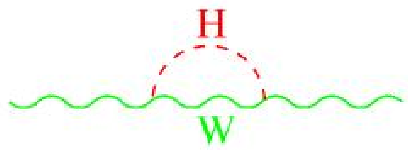
Electroweak observables are sensitive to heavy particles in "loops"

- For example, in the standard model: $\Gamma(Z \to \mu^+\mu^-)$ or m_W









$$\Gamma_{ll} = \frac{G_F}{\sqrt{2}} \frac{m_Z^3}{24\pi}\left(1 + \left[\frac{1}{4} - \sin^2\theta_W^{eff}\right]^2\right) \times (1+\Delta\rho)$$

$$m_W^2 = \frac{\pi\alpha_{QED}(m_Z^2)}{\sqrt{2}G_F \sin^2\theta_W^{eff}} \times \frac{1}{1-\Delta r}$$

$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

$$\Delta r = -\frac{\cos^2\vartheta_W}{\sin^2\vartheta_W}\Delta\rho + \frac{\alpha}{3\pi}\left[\frac{1}{2} - \frac{1}{3}\frac{\sin^2\vartheta_W}{1-\tan^2\vartheta_W}\right]\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

- With precise measurements of the Z mass, Z width, and Weinberg angle [+ $\alpha_{QED}(m_Z)$]
  - LEP was able to predict m_{top} and m_W (with uncertainty for unknown m_H)
- With the discovery of the top (Tevatron) at the right mass
  - LEP was able to predict m_H

Precision of theory

- At the next-generation e^+e^- colliders the experimental precision will be improved by 1-2 orders of magnitude
- The measurements must be confronted to theoretical calculations
- Corresponding improvement of calculations is an absolute necessity

- After LEP

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo}$$

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo}$$

Precision of theory

- At the next-generation e^+e^- colliders the experimental precision will be improved by 1-2 orders of magnitude
- The measurements must be confronted to theoretical calculations
- Corresponding improvement of calculations is an absolute necessity

- After FCC-ee

$$M_W = 80.3593 \pm 0.0002\ _{m_t} \pm 0.0001\ _{M_Z} \pm 0.0004\ _{\Delta\alpha_{\rm had}} \pm 0.0001\ _{\alpha_S} \pm 0.0000\ _{M_H} \pm 0.0040_{\rm theo}$$

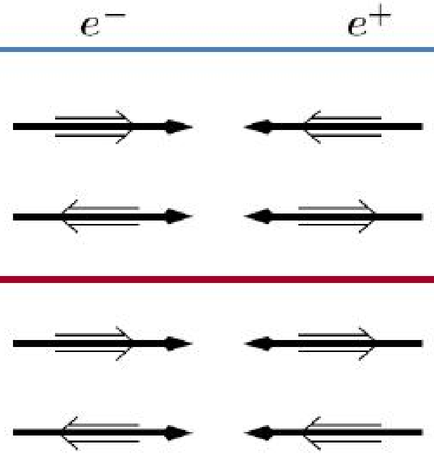
0.0005

$$\sin^2\theta^\ell_{\rm eff} = 0.231496 \pm 0.0000015\ _{m_t} \pm 0.000001\ _{M_Z} \pm 0.000006\ _{\Delta\alpha_{\rm had}} \pm 0.0000014\ _{\alpha_S} \pm 0.000000\ _{M_H} \pm 0.000047_{\rm theo}$$

0.000006

Beam polarization

Consider s-channel processes (ee→ff)



		Contibution due to polarization
$J_Z = 0$	σ_{RR}	$\frac{1+P_{e^-}}{2}\frac{1+P_{e^+}}{2}$
	σ_{LL}	$\frac{1-P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
$J_Z = 1$	σ_{RL}	$\frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
	σ_{LR}	$\frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}$

P_{e-} = -1:
100% left-polarized e-
P_{e+} = -1:
100% right-polarized e+

$$\sigma_{ij}^{meas} = \sigma_0 (1 - P_{e-} P_{e+})(1 + A_{LR} P_{eff})$$

$$P_{eff} = \frac{P_{e-} - P_{e+}}{1 - P_{e-} P_{e+}}$$

σ_0 - unpolarized cross section

Most sensitive to weak mixing angle: A_{LR}

$$A_{LR} = \frac{A_{LR}^{meas}}{P} = A_e = \frac{2 v_e a_e}{v_e^2 + a_e^2}$$

(independent of the final state)

$$\frac{v_e}{a_e} = 1\text{-}4 \sin^2 \theta_{eff}^{lept}$$

Full treatment of polarization

$$|\mathcal{M}|^2 = \frac{1}{4}\Big\{(1-P^{||}_{e-})(1+P^{||}_{e+})|\mathcal{H}_{-+}|^2 + (1+P^{||}_{e-})(1-P^{||}_{e+})|\mathcal{H}_{-+}|^2$$
$$+ (1-P^{||}_{e-})(1-P^{||}_{e+})|\mathcal{H}_{--}|^2 + (1+P^{||}_{e-})(1-P^{||}_{e+})|\mathcal{H}_{++}|^2$$
$$- 2P^T_{e-}P^T_{e+}\Big[\cos(\phi_- - \phi_+)\,\mathrm{Re}(\mathcal{H}_{++}\mathcal{H}^*_{--}) + \cos(\phi_- + \phi_+ - 2\phi)\,\mathrm{Re}(\mathcal{H}_{-+}\mathcal{H}^*_{+-})$$
$$+ \sin(\phi_- + \phi_+ - 2\phi)\,\mathrm{Im}(\mathcal{H}_{-+}\mathcal{H}^*_{+-}) + \sin(\phi_- - \phi_+)\,\mathrm{Im}(\mathcal{H}_{++}\mathcal{H}^*_{--})\Big]$$
$$+ 2P^T_{e-}\Big[\cos(\phi_- - \phi)\Big((1-P^{||}_{e+})\,\mathrm{Re}(\mathcal{H}_{+-}\mathcal{H}^*_{--}) + (1+P^{||}_{e+})\,\mathrm{Re}(\mathcal{H}_{++}\mathcal{H}^*_{-+})\Big)$$
$$+ \sin(\phi_- - \phi)\Big((1-P^{||}_{e+})\,\mathrm{Im}(\mathcal{H}_{+-}\mathcal{H}^*_{--}) + (1+P^{||}_{e+})\,\mathrm{Im}(\mathcal{H}_{++}\mathcal{H}^*_{-+})\Big)\Big]$$
$$- 2P^T_{e+}\Big[\cos(\phi_+ - \phi)\Big((1-P^{||}_{e-})\,\mathrm{Re}(\mathcal{H}_{-+}\mathcal{H}^*_{--}) + (1+P^{||}_{e-})\,\mathrm{Re}(\mathcal{H}_{++}\mathcal{H}^*_{+-})\Big)$$
$$- \sin(\phi_+ - \phi)\Big((1-P^{||}_{e-})\,\mathrm{Im}(\mathcal{H}_{-+}\mathcal{H}^*_{--}) + (1+P^{||}_{e-})\,\mathrm{Im}(\mathcal{H}_{++}\mathcal{H}^*_{+-})\Big)\Big]\Big\},$$

where $\mathcal{H}_{++}$, $\mathcal{H}_{--}$,$\mathcal{H}_{+-}$,$\mathcal{H}_{-+}$ — helicity amplitudes.

G. Moortgat-Pick et al. Phys. Rept. 460 (2008) 131–243

MC generator with polarization

- Currently there is no MC generator with polarization at complete 1-loop level
- Our group plans to create a generator with polarization for the most important e^+e^- processes at complete 1-loop EW level, with leading EW contributions up to 3 loops and leading QCD contributions up to 4 loops
- For Bhabha this work is already at a rather advanced stage

$$\sigma^{\text{1-loop}} = \sigma^{\text{Born}} + \sigma^{\text{virt}}(\lambda) + \sigma^{\text{soft}}(\lambda, \omega) + \sigma^{\text{hard}}(\omega)$$

Our background

- We participated in the following precision calculation projects:
  - ZFITTER (LEP1, LEP2)
  - HECTOR (HERA)
  - SANC (LHC)
- We participate(d) in the following HEP experiments:
  - DELPHI (LEP1, LEP2)
  - BES3 (BEPCII)
  - ATLAS and CMS (LHC)
- 2 doctoral and 9 candidate dissertations defended
- More than 50 publications by our group alone (and more than 1000 within collaborations)

Our manpower

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	70	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 Zbigniev	d		INP, Krakow, Poland
32.	Jadach Stanislav	d		INP, Krakow, Poland

- Total 32 persons
- 18 from Dubna
- Equivalent FTE: 11 persons (Dubna only)
- Doctor nauk / professor: 8
- PhD/candidat: 15
- Researcher: 4
- Postgraduates: 2
- Students: 3

Our spendings

- At current stage, our main hardware tool is a computer.
  – We plan to buy ½ PC per 3 years per 1 FTE (Dubna people only)
- At current stage, our main activity is computation and data analysis, that must be widely presented and discussed. So, our main spendings:
  – Travels to collaboration meetings
  – Visiting our colleagues and co-authors in Hamburg, Cracow, Minsk, Novosibirsk, etc
  – Participations in international conferences
  – Hosting our colleagues here in Dubna

Requested budget

Expenditures ($)	3 years	2019	2020	2021
Computer equipment	9000	3000	3000	3000
Foreign travels	93000	31000	31000	31000
Travels in Russia	12000	4000	4000	4000
Total	114000	38000	38000	38000

Summary

- We are building a powerful team of experimentalists and theoreticians that will prepare the physics research at the next generation e^+e^- collider
- We are seeking for your approval of our project