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

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&
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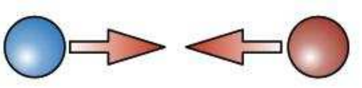
Outline

- Motivation and goals
- Description of the project
- Polarized Bhabha scattering $e^+e^- \to e^+e^-$ at NLO EW
- Preliminary results at NLO EW for other processes with polarized e^+e^- beams
- Conclusions and plans

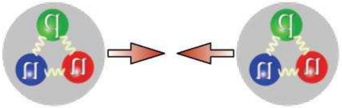
Motivation: choice of collider types

e^+e^- collisions



- Point-like particles
- Total annihilation: initial state known
- Decent background
- Limited in energy, but — precision!

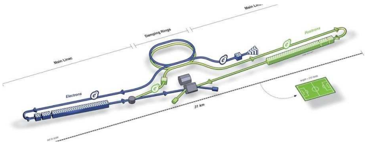
$pp(\bar{p})$ collisions



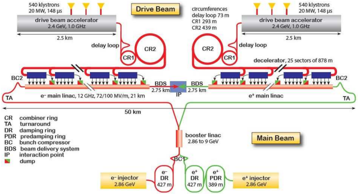
- Composite particles
- Random energy of the hard interaction
- High background
- High energy — discovery!

Projects of e^+e^- collider

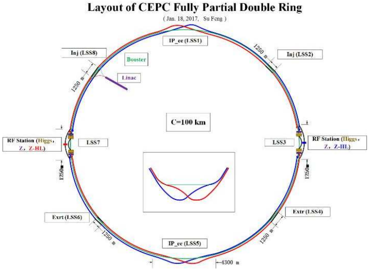
ILC (2030) 250 GeV



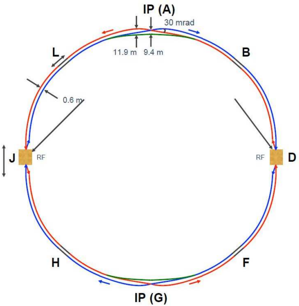
CLIC (2035) 380-3000 GeV



CEPC (2030) 240 GeV



FCC-ee (2039) 350 GeV



Why ARIeL?

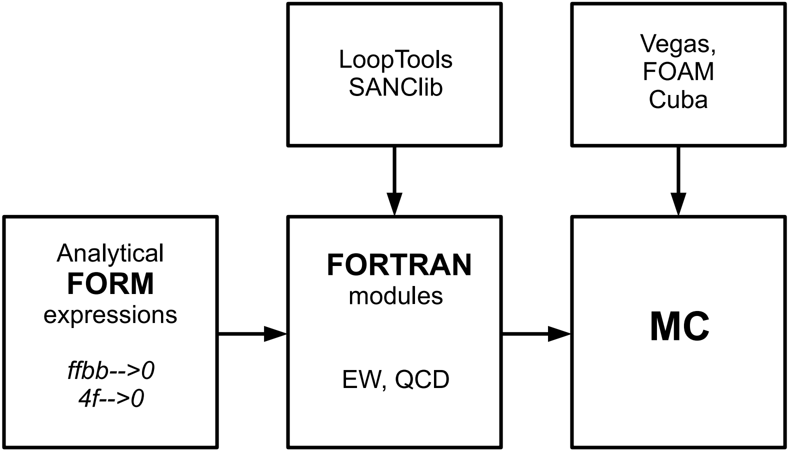
- **Advanced**
- **Research of**
- **Interactions in**
- e^+e^-
- **coLlisions**

Goals

- Preparation of CLIC research program:
  - Precision study of $e^+e^- \to \gamma\gamma$ and setting limits on the NP models
  - Precision measurement of the Higgs boson mass M_H
  - Determination of top quark polarization
  - Measurement of $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to ZZ$ and search for anomalous quarting coupling

- Theoretical support:
  - Create e^+e^- Monte Carlo generator with polarization at complete one-loop EW and leading multiloop for processes $e^+e^- \to e^+e^-$ $(\mu\mu, \tau\tau, tt, HZ, H\gamma, Z\gamma, ZZ, H\nu\nu, H\mu\mu, ff\gamma, \gamma\gamma)$
  - Interface NLO EW RC to PYTHIA8
  - Implement a single-resonance approach to complex processes
  - Elaborate the standard procedure for $2 \to 3, 4$ helicity amplitudes
  - Create building blocks for complete EW 2-loops and QCD 3-loops, plus leading EW 3-loops and QCD 4-loops

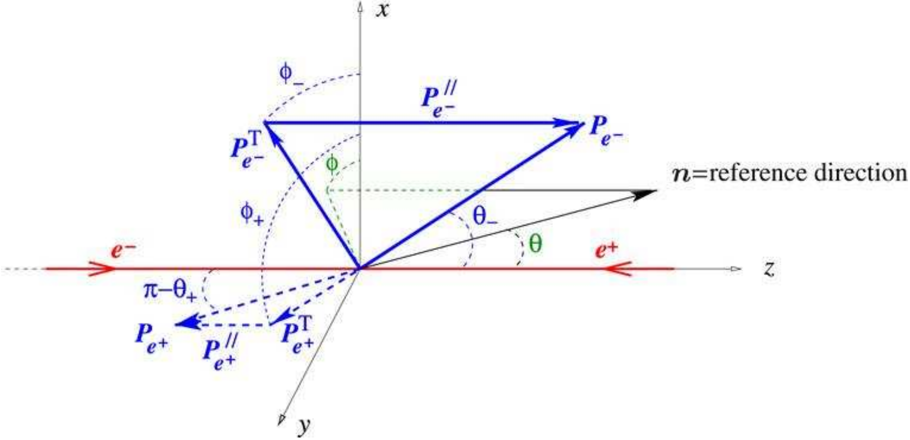
The calculation framework scheme



Processes with polarized beams in MCSANC

- NLO EW corrections for polarized e^+e^- scattering:
  - Bhabha scattering (D.Bardin et al. Phys.Rev. D98 (2018) no.1, 013001)
  - $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$ (preliminary results)
  - $e^+e^- \to Z\gamma$ (preliminary results)
  - $e^+e^- \to t\bar{t}$ (in progress)
  - $e^+e^- \to ZH$ (in progress)
  - $e^+e^- \to \gamma\gamma$ (in progress)
  - $e^+e^- \to ZZ$ (in progress)
  - $e^+e^- \to f\bar{f}\gamma$ (future plans)
  - $e^+e^- \to f\bar{f}H$ (future plans)
- NLO EW corrections for polarized $\gamma\gamma$ scattering:
  - $\gamma\gamma \to \gamma\gamma$ (future plans)
  - $\gamma\gamma \to Z\gamma$ (future plans)
  - $\gamma\gamma \to ZZ$ (future plans)

Decomposition of the $e^{\pm}$ polarization vector



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

Matrix element squared

$$
\begin{aligned}
|\mathcal{M}|^2 = \quad & L^{||}_{e-} R^{||}_{e+} |\mathcal{H}_{-+}|^2 + R^{||}_{e-} L^{||}_{e+} |\mathcal{H}_{+-}|^2 + L^{||}_{e-} L^{||}_{e+} |\mathcal{H}_{--}|^2 + R^{||}_{e-} R^{||}_{e+} |\mathcal{H}_{++}|^2 \\
& - \frac{1}{2} P^T_{e-} P^T_{e+} Re\left[e^{i(\Phi_+ - \Phi_-)} \mathcal{H}_{++} \mathcal{H}^*_{--} + e^{i(\Phi_+ + \Phi_-)} \mathcal{H}_{+-} \mathcal{H}^*_{-+} \right] \\
& + P^T_{e-} Re\left[e^{i\Phi_-} \left(L^{||}_{e+} \mathcal{H}_{+-} \mathcal{H}^*_{--} + R^{||}_{e+} \mathcal{H}_{++} \mathcal{H}^*_{-+} \right) \right] \\
& - P^T_{e+} Re\left[e^{i\Phi_+} \left(L^{||}_{e-} \mathcal{H}_{-+} \mathcal{H}^*_{--} + R^{||}_{e-} \mathcal{H}_{++} \mathcal{H}^*_{+-} \right) \right],
\end{aligned}
$$

where

$$
L^{||}_{e\pm} = \frac{1}{2}(1 - P^{||}_{e\pm}), \quad R^{||}_{e\pm} = \frac{1}{2}(1 + P^{||}_{e\pm}), \quad \Phi_\pm = \phi_\pm - \phi,
$$

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

Longitudinally-polarized beams

With longitudinally-polarized beams, cross-sections at an e^+e^- collider can be subdivided into four parts:

$$\sigma_{P_{e^-}P_{e^+}} = R_{e^-}R_{e^+}\sigma_{RR} + L_{e^-}L_{e^+}\sigma_{LL} + R_{e^-}L_{e^+}\sigma_{RL} + L_{e^-}R_{e^+}\sigma_{LR},$$

where σ_{RL} stands for the cross-section if the e^- beam is completely right-handed polarized ($P_{e^-} = +1$) and the e^+ beam is completely left-handed polarized ($P_{e^+} = -1$). The cross-sections σ_{LR}, σ_{RR} and σ_{LL} are defined analogously.

Polarized Bhabha scattering at one-loop

Here we present complete one-loop EW corrections to Bhabha scattering $e^+e^- \to e^+e^-$ with longitudinally polarized initilal particles.

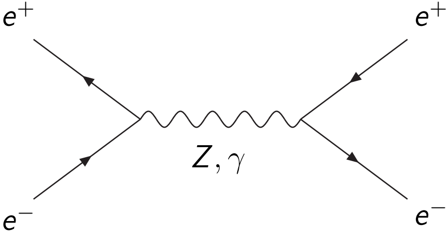
The cross-section of this process at one-loop can be divided into four parts:

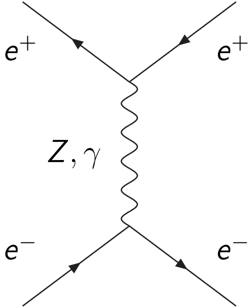
$$\sigma^{\text{1-loop}} = \sigma^{\text{Born}} + \sigma^{\text{virt}}(\lambda) + \sigma^{\text{soft}}(\lambda, \omega) + \sigma^{\text{hard}}(\omega),$$

where σ^{Born} — Born level cross-section, σ^{virt} — contribution of virtual(loop) corrections, σ^{soft} — contribution due to soft photon emission, σ^{hard} — contribution due to hard photon emission (with energy $E_\gamma > \omega\frac{\sqrt{s}}{2}$).

Auxiliary parameters λ ("photon mass") and ω cancel out after summation.

Bhabha scattering: Born-level diagrams





Polarized Bhabha scattering: HA for Born and Virtual parts

At one-loop level we have six non-zero HAs (four independent):

$$\mathcal{H}_{++++} = \mathcal{H}_{----} = -2e^2\,\frac{s}{t}\Big(\mathcal{F}^{(\gamma,Z)}_{QQ}(t,s,u) - \chi^t_Z\delta_e\mathcal{F}^Z_{QL}(t,s,u)\Big),$$

$$\mathcal{H}_{+-+-} = \mathcal{H}_{-+-+} = -2e^2\,\frac{t}{s}\Big(\mathcal{F}^{(\gamma,Z)}_{QQ}(s,t,u) - \chi^s_Z\delta_e\mathcal{F}^Z_{QL}(s,t,u)\Big),$$

$$\mathcal{H}_{+--+} = 2e^2\left(\frac{u}{s}\Big[\mathcal{F}^{(\gamma,Z)}_{QQ}(s,t,u) + \chi^s_Z\left(\mathcal{F}^Z_{LL}(s,t,u) - 2\delta_e\mathcal{F}^Z_{QL}(s,t,u)\right)\Big]\right.$$
$$\left.+\frac{u}{t}\Big[\mathcal{F}^{(\gamma,Z)}_{QQ}(t,s,u) + \chi^t_Z\left(\mathcal{F}^Z_{LL}(t,s,u) - 2\delta_e\mathcal{F}^Z_{QL}(t,s,u)\right)\Big]\right),$$

$$\mathcal{H}_{-++-} = 2e^2\left(\frac{u}{s}\mathcal{F}^{(\gamma,Z)}_{QQ}(s,t,u) + \frac{u}{t}\mathcal{F}^{(\gamma,Z)}_{QQ}(t,s,u)\right),$$

where

$$\chi^s_Z = \frac{1}{4s^2_W c^2_W}\,\frac{s}{s - M^2_Z + iM_Z\Gamma_Z},\quad \chi^t_Z = \frac{1}{4s^2_W c^2_W}\,\frac{t}{t - M^2_Z},\quad \delta_e = v_e - a_e = 2s^2_W,$$

$$\mathcal{F}^{(\gamma,Z)}_{QQ}(a,b,c) = \mathcal{F}^{\gamma}_{QQ}(a,b,c) + \chi^a_Z\delta^2_e\mathcal{F}^Z_{QQ}(a,b,c).$$

We get the Born level HAs by replacing $\mathcal{F}^Z_{LL} \to 1$, $\mathcal{F}^Z_{QL} \to 1$, $\mathcal{F}^Z_{QQ} \to 1$ and $\mathcal{F}^{\gamma}_{QQ} \to 1$.

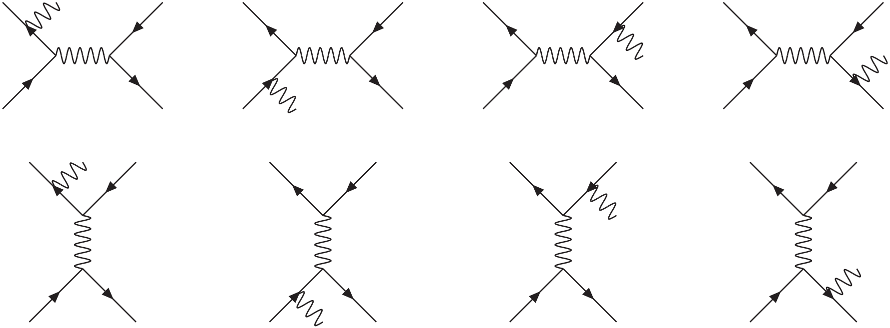
Polarized Bhabha scattering: soft photon contribution

The soft photon contribution contains the infrared divergences which compensate the infrared divergences of the one-loop QED corrections.

This soft photon correction can be calculated analytically and to be factorized to Born cross section. The polarization dependence is contained in σ^{Born}.

$$\begin{aligned}
\sigma^{\text{soft}}(\lambda,\omega) \qquad &= -\sigma^{\text{Born}}\frac{\alpha}{\pi}\Bigg\{\left(1+\ln\left(\frac{m_e^2}{s}\right)\right)^2+\ln\left(-\frac{u}{s}\right)^2-\ln\left(-\frac{t}{s}\right)^2 \\
&-2\mathrm{Li}_2\left(-\frac{u}{s}\right)+2\mathrm{Li}_2\left(-\frac{t}{s}\right)+4\mathrm{Li}_2\left(1\right) \\
&-1+2\ln\left(\frac{4\omega^2}{\lambda}\right)\left[1+\ln\left(\frac{m_e^2}{s}\right)-\ln\left(\frac{t}{u}\right)\right]\Bigg\}.
\end{aligned}$$

Polarized Bhabha scattering: hard photon contribution



For HA for hard bremsstrahlung see presentation by Yahor Dydyshka

Polarized Bhabha scattering: Monte Carlo generator

We created Monte Carlo generator of unweighted events for the polarized Bhabha scattering $e^+e^- \to e^+e^-$ with complete one-loop EW corrections.

This generator uses adaptive algorithm `mFOAM` [CPC 177:441-458,2007] which is a part of `ROOT` [https://root.cern.ch] program.

It will be interfaced to `PYTHIA8` [CPC 178 (2008) 852–867] program.

Setup for tuned comparison

We performed a tuned comparison of our results for polarized Born and hard Bremsstrahlung with the results WHIZARD [Eur.Phys.J.C71 (2011) 1742] program. The contributions of soft and virtual parts were compared with the results of aÎTALC [CPC 174 (2006) 71-82] program

Input parameters:

$$\alpha^{-1}(0) = 137.03599976,$$
$$M_W = 80.4514958 \text{ GeV}, \quad M_Z = 91.1876 \text{ GeV}, \quad \Gamma_Z = 2.49977 \text{ GeV},$$
$$m_e = 0.51099907 \text{ MeV}, \quad m_\mu = 0.105658389 \text{ GeV}, \quad m_\tau = 1.77705 \text{ GeV},$$
$$m_d = 0.083 \text{ GeV}, \quad m_s = 0.215 \text{ GeV}, \quad m_b = 4.7 \text{ GeV},$$
$$m_u = 0.062 \text{ GeV}, \quad m_c = 1.5 \text{ GeV}, \quad m_t = 173.8 \text{ GeV}.$$

Cuts:

$$|\cos\theta| < 0.9,$$
$$E_\gamma > 1 \text{ GeV} \quad \text{(for comparison of hard Bremsstrahlung)}.$$

$e^+e^- \to e^+e^-$: WHIZARD vs MCSANC (Born)

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	56.677(1)	57.774(1)	56.272(1)	59.276(1)
$\sigma^{\text{Born}}_{e^+e^-}$, pb	56.677(1)	57.775(1)	56.272(1)	59.275(1)
$\sqrt{s} = 500$ GeV				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	14.379(1)	15.030(1)	12.706(1)	17.355(1)
$\sigma^{\text{Born}}_{e^+e^-}$, pb	14.379(1)	15.030(1)	12.706(1)	17.354(1)
$\sqrt{s} = 1000$ GeV				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	3.6792(1)	3.9057(1)	3.0358(1)	4.7756(1)
$\sigma^{\text{Born}}_{e^+e^-}$, pb	3.6792(1)	3.9057(1)	3.0358(1)	4.7755(1)

$e^+e^- \to e^+e^-$: WHIZARD vs MCSANC (hard)

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
$\sigma^{\text{hard}}_{e^+e^-}$, pb	48.62(1)	49.58(1)	48.74(1)	50.40(1)
$\sigma^{\text{hard}}_{e^+e^-}$, pb	48.65(1)	49.56(1)	48.78(1)	50.44(1)
$\sqrt{s} = 500$ GeV				
$\sigma^{\text{hard}}_{e^+e^-}$, pb	15.14(1)	15.81(1)	13.54(1)	18.07(1)
$\sigma^{\text{hard}}_{e^+e^-}$, pb	15.12(1)	15.79(1)	13.55(1)	18.11(2)
$\sqrt{s} = 1000$ GeV				
$\sigma^{\text{hard}}_{e^+e^-}$, pb	4.693(1)	4.976(1)	3.912(1)	6.041(1)
$\sigma^{\text{hard}}_{e^+e^-}$, pb	4.694(1)	4.975(1)	3.913(1)	6.043(1)

$e^+e^- \to e^+e^-$: aİTALC vs MCSANC (virtual+soft)

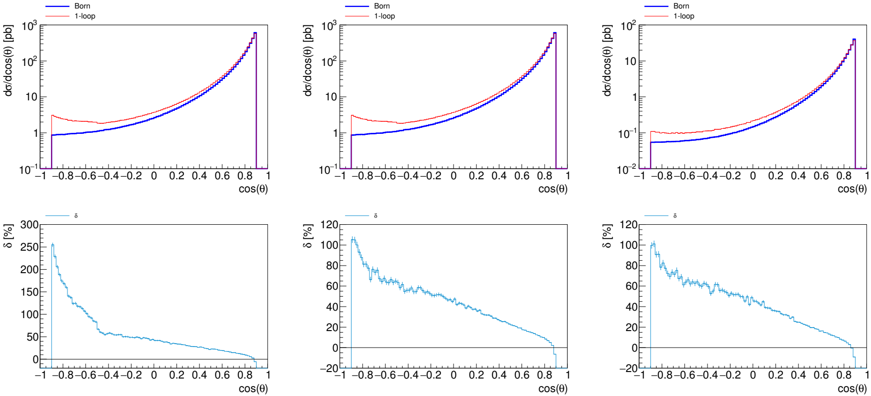
$\cos\theta$	$\sigma^{\text{Born}}_{e^+e^-}$, pb	$\sigma^{\text{Born+virt+soft}}_{e^+e^-}$, pb
-0.9	$2.16999 \cdot 10^{-1}$ $2.16999 \cdot 10^{-1}$	$1.93445 \cdot 10^{-1}$ $1.93445 \cdot 10^{-1}$
-0.5	$2.61360 \cdot 10^{-1}$ $2.61360 \cdot 10^{-1}$	$2.38707 \cdot 10^{-1}$ $2.38707 \cdot 10^{-1}$
0	$5.98142 \cdot 10^{-1}$ $5.98142 \cdot 10^{-1}$	$5.46677 \cdot 10^{-1}$ $5.46677 \cdot 10^{-1}$
$+0.5$	$4.21273 \cdot 10^{0}$ $4.21273 \cdot 10^{0}$	$3.81301 \cdot 10^{0}$ $3.81301 \cdot 10^{0}$
$+0.9$	$1.89160 \cdot 10^{2}$ $1.89160 \cdot 10^{2}$	$1.72928 \cdot 10^{2}$ $1.72928 \cdot 10^{2}$
$+0.99$	$2.06556 \cdot 10^{4}$ $2.06555 \cdot 10^{4}$	$1.90607 \cdot 10^{4}$ $1.90607 \cdot 10^{4}$
$+0.999$	$2.08236 \cdot 10^{6}$ $2.08236 \cdot 10^{6}$	$1.91624 \cdot 10^{6}$ $1.91624 \cdot 10^{6}$
$+0.9999$	$2.08429 \cdot 10^{8}$ $2.08429 \cdot 10^{8}$	$1.91402 \cdot 10^{8}$ $1.91402 \cdot 10^{8}$

$e^+e^- \to e^+e^-$: Born vs 1-loop

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
$\sigma^{\rm Born}_{e^+e^-}$, pb	56.6763(1)	57.7738(1)	56.2725(4)	59.2753(5)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	61.731(6)	62.587(6)	61.878(6)	63.287(7)
δ, %	8.92(1)	8.33(1)	9.96(1)	6.77(1)
$\sqrt{s} = 500$ GeV				
$\sigma^{\rm Born}_{e^+e^-}$, pb	14.3789(1)	15.0305(1)	12.7061(1)	17.3550(2)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	15.465(2)	15.870(2)	13.861(1)	17.884(2)
δ, %	7.56(1)	5.59(1)	9.09(1)	3.05(1)
$\sqrt{s} = 1000$ GeV				
$\sigma^{\rm Born}_{e^+e^-}$, pb	3.67921(1)	3.90568(1)	3.03577(3)	4.77562(5)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	3.8637(4)	3.9445(4)	3.2332(3)	4.6542(7)
δ, %	5.02(1)	0.99(1)	6.50(1)	-2.54(1)

$e^+e^- \to e^+e^-$: distributions in $\cos\theta$

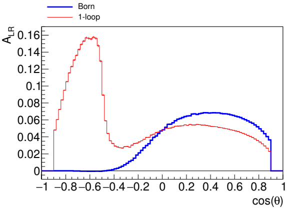
$\sqrt{s} = 250$ GeV $\quad\quad$ $\sqrt{s} = 500$ GeV $\quad\quad$ $\sqrt{s} = 1000$ GeV



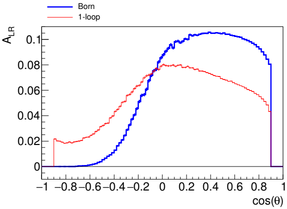
$e^+e^- \to e^+e^-$: A_{LR} distributions in $\cos\theta$

$$A_{LR} = \frac{\sigma_{LR}-\sigma_{RL}}{\sigma_{LR}+\sigma_{RL}}$$

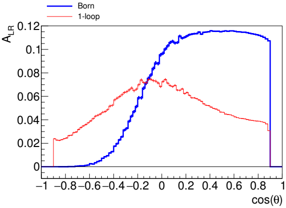
$\sqrt{s} = 250$ GeV



$\sqrt{s} = 500$ GeV



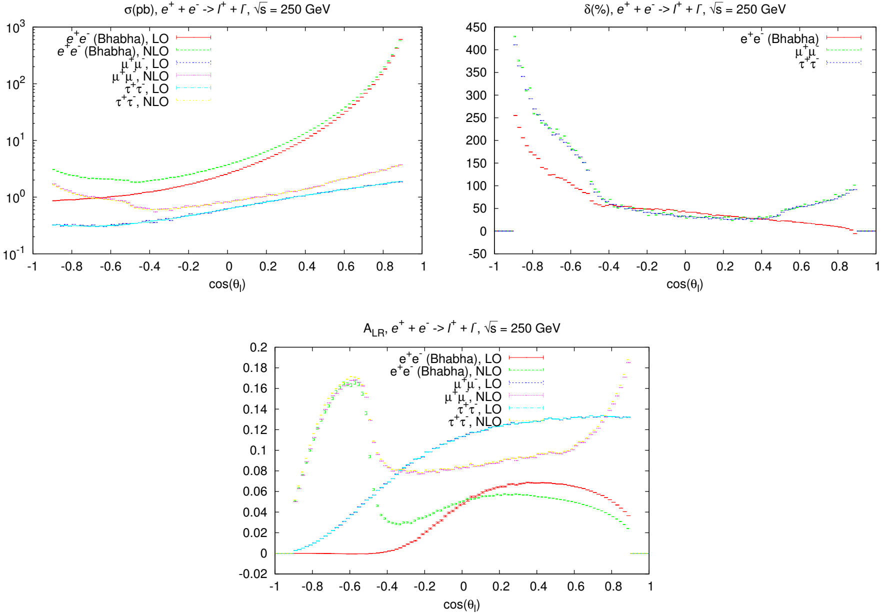
$\sqrt{s} = 1000$ GeV



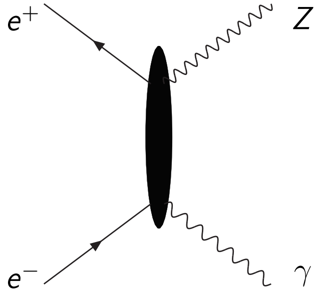
$e^+e^- \to \ell^+\ell^-$: Born vs 1-loop (preliminary)

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
$e^- + e^+ \to e^- + e^+$ (Bhabha)				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	56.6763(1)	57.7738(1)	56.2725(4)	59.2753(5)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	61.731(6)	62.587(6)	61.878(6)	63.287(7)
δ, %	8.92(1)	8.33(1)	9.96(1)	6.77(1)
$e^- + e^+ \to \mu^- + \mu^+$				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	1.4174(1)	1.5462(1)	0.7690(2)	2.3231(2)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	2.3987(2)	2.616(2)	1.3015(1)	3.929(1)
δ, %	69.22(2)	69.13(1)	69.18(2)	69.12(1)
$e^- + e^+ \to \tau^- + \tau^+$				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	1.4174(1)	1.5461(1)	0.7692(1)	2.3230(1)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	2.3609(1)	2.5773(1)	1.2817(1)	3.8728(2)
δ, %	66.56(1)	66.69(1)	66.62(1)	66.71(1)

$e^+e^- \to \ell^+\ell^-$: distributions in $\cos\theta_\ell$ (preliminary)



$e^+e^- \to Z\gamma$



The expressions fo HA and the results for unpolarized case were published in Eur.Phys.J.C54:187-197,2008

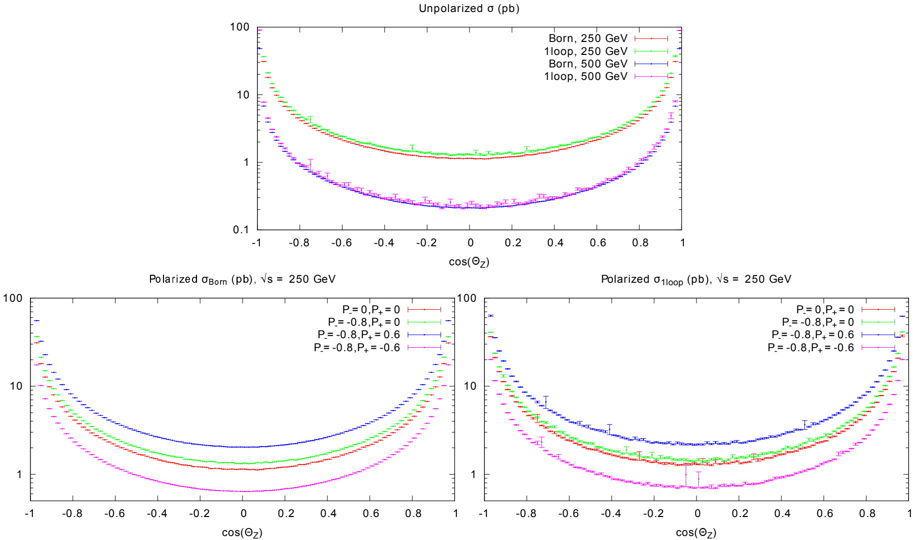
Here we present the preliminary results for 1-loop corrections taking into account the effect of polarization of e^+e^- beams.

$e^+e^- \to Z\gamma$: Born vs 1-loop (preliminary)

$\sqrt{s}$	250	500	1000
$\sigma_{Z\gamma}^{\text{Born}}$, pb	15.7038(6)	3.3858(3)	0.81958(3)
$\sigma_{Z\gamma}^{\text{1-loop}}$, pb	24.37(1)	5.23(6)	1.237(3)
δ, %	55.20(6)	54.4(2)	50.9(4)

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, 0.6	-0.8, -0.6
$\sqrt{s} = 250$ GeV				
$\sigma_{Z\gamma}^{\text{Born}}$, pb	15.7038(6)	18.520(4)	28.174(2)	8.870(3)
$\sigma_{Z\gamma}^{\text{1-loop}}$, pb	24.37(1)	28.00(1)	42.13(2)	13.53(1)
δ, %	55.20(6)	51.11(8)	49.55(7)	52.57(9)

$e^+e^- \to Z\gamma$: distributions in $\cos\theta_Z$ (preliminary)



Conclusions and plans

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

- We created the `FORTRAN` modules for polarized Bhabha scattering with complete one-loop EW corrections. Based on these modules Monte Carlo generator [Phys.Rev. D98 (2018) no.1, 013001] of unweighted events was created with possibility to produce events in Les Houches Event format

- Preliminary results for polarized $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to Z\gamma$ were presented. More processes will be included in MC generator in the future