$\mathbf{MCSANC_{ee}}$ – Monte Carlo Generator for polarized e^+e^- scattering at one-loop EW

Renat Sadykov

DLNP JINR, Dubna

for the SANC/ARIeL team

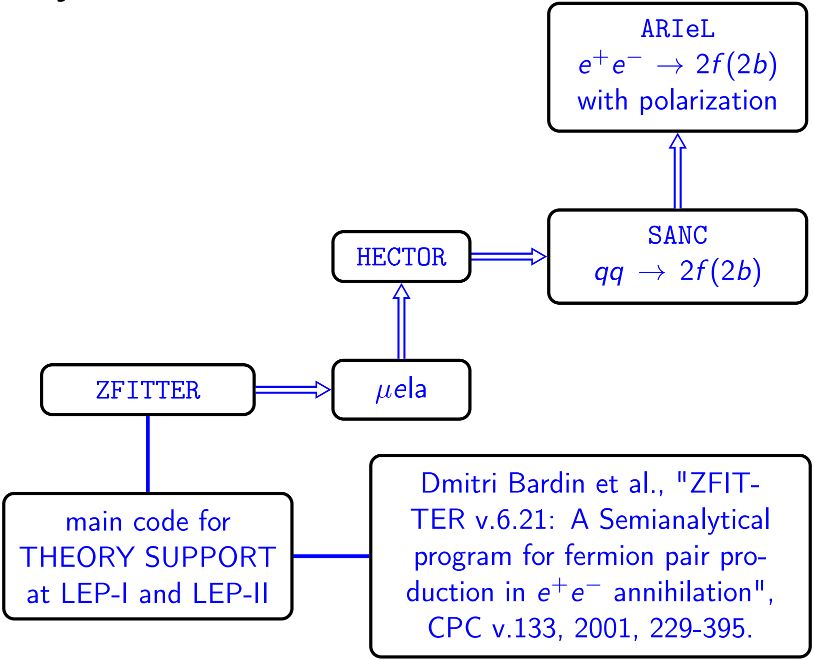
CEPC Topical Workshop

4th April 2019, IHEP, Beijing

Outline

- History overview
- ARIeL project
- Polarization effects
- Cross section at one-loop
- High order (HA) corrections through $\Delta\rho$
- Results
- Conclusions and plans
- Demonstration of the generator for $e^+e^- \to ZH$

History overview



Why ARIeL?

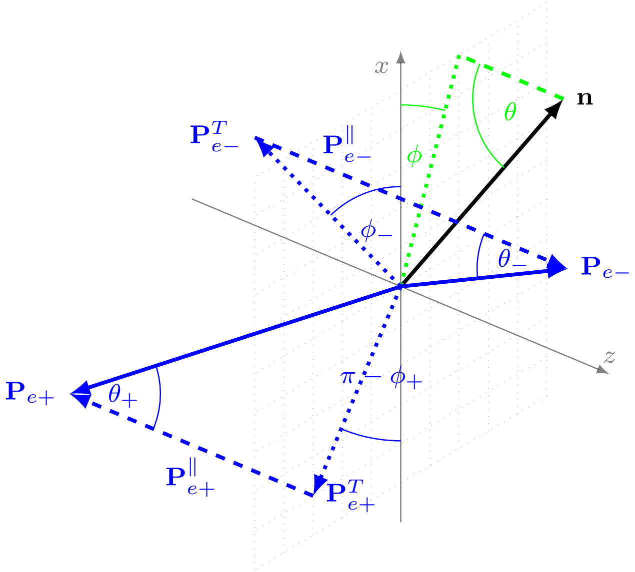
- **Advanced**
- **Research of**
- **Interactions in**
- e^+e^-
- **coLlisions**

Goals

- Preparation of research program fo future e^+e^- colliders:
  - 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 to parton shower MC (`PYTHIA8` etc.)
  - 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

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



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

Matrix element squared

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

where

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

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

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

Scheme of FF calculation

- One-loop accuracy level with using the renormalization scheme on the mass surface in R_ξ calibration with three calibration parameters ξ_A, ξ_Z and $\xi \equiv \xi_\mathsf{W}$
- Dimensional regularization to parameterize the ultraviolet divergences
- Loop integrals are expressed in terms of standard scalar Passarino-Veltman functions: A_0, B_0, C_0, D_0
- The error criterion is the absence of ξ dependencies

Cross-section structure

The cross-section of this processes at one-loop can be devided into four parts:

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

Contributions due to:
σ^{Born} — Born level cross-section,
σ^{virt} — virtual(loop) corrections,
σ^{soft} — soft photon emission,
σ^{hard} — hard photon emission (with energy $E_\gamma > \omega$).
Auxiliary parameters λ ("photon mass") and ω cancel out after summation.

Helicity Amplitudes (HA) approach

We count all contributions through HA approach.

The cross section of the generic $2 \to 2(\gamma)$ process $e^+e^- \to X_3X_4(\gamma)$ $(X_3X_4 = e^-e^+, \mu^-\mu^+, ZH, \gamma Z, \gamma\gamma, ...)$

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\sum_{\chi_1,\chi_2}(1+\chi_1 P_{e^-})(1+\chi_2 P_{e^+})\sigma_{\chi_1\chi_2},$$

where $\chi_i = -1(+1)$ corresponds to lepton with left (right) helicity state.

The virt(Born) cross section:

$$\frac{d\sigma^{\text{virt(Born)}}_{\chi_1\chi_2}}{d\cos\theta} = \frac{\sqrt{\lambda(s, M_3^2, M_4^2)}}{2^5\pi s^2}\left|\mathcal{H}^{\text{virt(Born)}}_{\chi_1\chi_2}\right|^2,$$

where

$$\left|\mathcal{H}^{\text{virt(Born)}}_{\chi_1\chi_2}\right|^2 = \sum_{\chi_3,\chi_4}\left|\mathcal{H}^{\text{virt(Born)}}_{\chi_1\chi_2\chi_3\chi_4}\right|^2.$$

Helicity Amplitudes (HA) approach

The soft term is factorized to Born-level cross section:

$$\frac{d\sigma^{\text{soft}}_{\chi_1\chi_2}}{d\cos\theta} = \frac{d\sigma^{\text{Born}}_{\chi_1\chi_2}}{d\cos\theta} \cdot \frac{\alpha}{2\pi} K^{soft}(\omega, \lambda).$$

The cross section for hard Bremsstrahlung

$$\frac{d\sigma^{\text{hard}}_{\chi_1\chi_2}}{ds' d\cos\theta_4 d\phi_4 d\cos\theta_5} = \frac{s-s'}{8(4\pi)^4 ss'} \frac{\sqrt{\lambda(s', M_3^2, M_4^2)}}{\sqrt{\lambda(s, m_e^2, m_e^2)}} \left|\mathcal{H}^{\text{hard}}_{\chi_1\chi_2}\right|^2,$$

where $s = (p_1 + p_2)^2$, $s' = (p_3 + p_4)^2$ and

$$\left|\mathcal{H}^{\text{hard}}_{\chi_1\chi_2}\right|^2 = \sum_{\chi_3,\chi_4,\chi_5} \left|\mathcal{H}^{\text{hard}}_{\chi_1\chi_2\chi_3\chi_4\chi_5}\right|^2.$$

HA for Bhabha

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

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

where

$$\chi_Z^s = \frac{1}{4s_W^2c_W^2}\,\frac{s}{s-M_Z^2+iM_Z\Gamma_Z},\quad \chi_Z^t = \frac{1}{4s_W^2c_W^2}\,\frac{t}{t-M_Z^2},\quad \delta_e = v_e - a_e = 2s_W^2,$$

$$\mathcal{F}_{QQ}^{(\gamma,Z)}(a,b,c) = \mathcal{F}_{QQ}^{\gamma}(a,b,c) + \chi_Z^a\delta_e^2\mathcal{F}_{QQ}^Z(a,b,c).$$

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

HO corrections through $\Delta\rho$

We follow the recipe introduced in J. Fleischer et al. Phys.Lett. B319 (1993) 249-256.

The ρ parameter is defined as the ratio of the neutral current to charged current amplitudes at zero momentum transfer:

$$\rho = \frac{G_{NC}(0)}{G_{CC}(0)} = \frac{1}{1 - \Delta\rho}\,,$$

where $G_{CC}(0) = G_\mu$ is the Fermi constant defined from the μ-decay width.

Perturbatively

$$\Delta\rho = \Delta\rho^{(1)} + \Delta\rho^{(2)} + \ldots$$

Expanding ρ up to quadratic terms $\Delta\rho^2$, we have

$$\rho = 1 + \Delta\rho + \Delta\rho^2\,.$$

HO corrections through $\Delta\rho$

The leading in $G_\mu m_t^2$ NLO EW contribution to $\Delta\rho$ is explicitly given by

$$\Delta\rho^{(1)}\Big|^{G_\mu} = 3x_t = \frac{3\sqrt{2}G_\mu m_t^2}{16\pi^2}\,.$$

At the two-loop level, quantity $\Delta\rho$ contains two contributions:

$$\Delta\rho = 3x_t\,\left[1+\rho^{(2)}\,\left(M_H^2/m_t^2\right)\,x_t\right]\,\left[1-\frac{2\alpha_s(M_Z^2)}{9\pi}(\pi^2+3)\right].$$

They consist of the following:

- two-loop EW part at $\mathcal{O}(G_\mu^2)$.
- mixed two-loop EW$\otimes$QCD at $\mathcal{O}(G_\mu\alpha_s)$

HO corrections through $\Delta\rho$

The leading in $G_\mu m_t^2$ universal higher order (h.o.) corrections may be taken into account via the replacements, [Dittmaier et al., JHEP 1001 (2010) 060]:

$$
\begin{aligned}
s_W^2 &\to \bar{s}_W^2 \equiv s_W^2 + \Delta\rho\, c_W^2\,, \\
c_W^2 &\to \bar{c}_W^2 \equiv 1 - \bar{s}_W^2 = (1 - \Delta\rho)\, c_W^2\,, \\
\alpha_{G_\mu} &\to \alpha_{G_\mu} \frac{\bar{s}_W^2}{s_W^2}
\end{aligned}
$$

in the LO expression for the cross section.

This approach correctly reproduces terms up to $\mathcal{O}(\Delta\rho^2)$.

Given these replacements, we get the contributions of h.o. corrections to the scalar form factors of the invariant amplitude

HO corrections through $\Delta\rho$

A large group of dominant radiative corrections can be absorbed into the shift of the ρ parameter from its lowest order value $\rho_{Born} = 1$.

These groups of radiative corrections are:

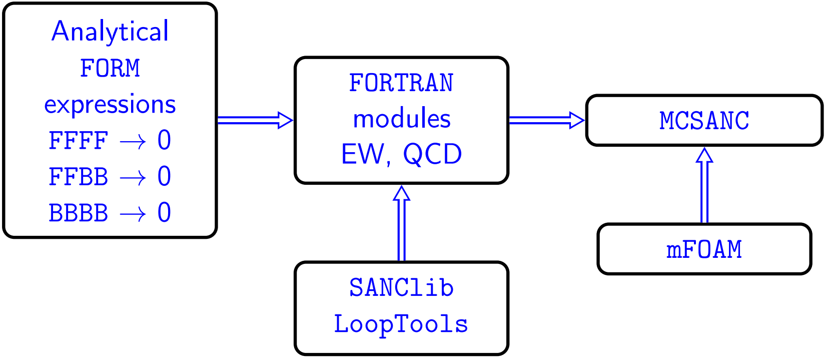
$$\begin{aligned} \Delta\rho &= \Delta\rho_{x_t} + \Delta\rho_{\alpha\alpha_s} + \Delta\rho_{x_t\alpha_s} + \Delta\rho_{x_t^3 + x_t^2\alpha_s} \\ &\quad + \Delta\rho_{x_t\alpha_s^2} + \Delta\rho_{x_t^2} + \Delta\rho_{x_t\alpha_s^3} + \Delta\rho_{x_t^2(bos)} + \Delta\rho_{x_t^3}. \end{aligned}$$

HO corrections through $\Delta\rho$

- $\Delta\rho_{x_t}$ — 1-loop EW at $\mathcal{O}(x_t)$
- $\Delta\rho_{\alpha\alpha_s}$ — 2-loop mixed QCD-EW at $\mathcal{O}(\alpha\alpha_s)$
- $\Delta\rho_{x_t\alpha_s}$ — 2-loop large top-mass at $\mathcal{O}(x_t\alpha_s)$
- $\Delta\rho_{x_t^3+x_t^2\alpha_s}$ — leading 3-loop large top-mass contributions
- $\Delta\rho_{x_t\alpha_s^2}$ — 3-loop mixed at $\mathcal{O}(x_t\alpha_s^2)$
- $\Delta\rho_{x_t^2}$ — 2-loop EW at $\mathcal{O}(x_t^2)$
- $\Delta\rho_{x_t\alpha_s^3}$ — 4-loop mixed at $\mathcal{O}(x_t\alpha_s^3)$
- $\Delta\rho_{x_t^2(bos)}$ — 2-loop EW bosonic corrections at $\mathcal{O}(x_t^2)$
- $\Delta\rho_{x_t^3(bos)}$ — 3-loop EW corrections at $\mathcal{O}(x_t^3)$

All of these corrections that were computed by different groups in the past will be included in the generator

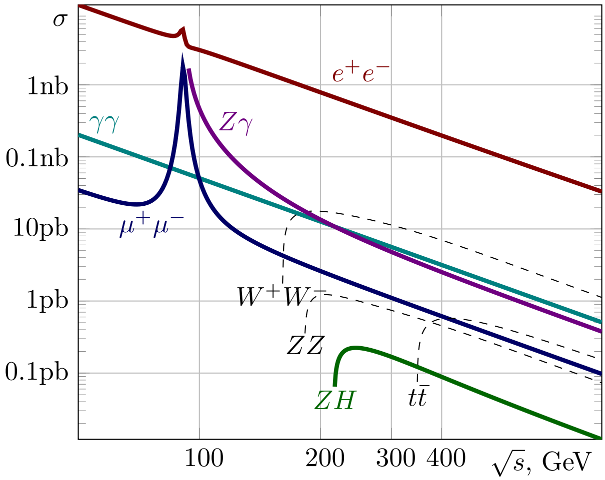
MCSANC$_{\text{ee}}$ generator



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

This generator uses adaptive Monte Carlo algorithm mFOAM [S. Jadach and P. Sawicki. CPC 177:441-458,2007] which is a part of ROOT [https://root.cern.ch] program.

Basic processes of SM for e^+e^- annihilation



The cross sections are given for polar angles between $10^o < \theta < 170^o$ in the final state

Setup for tuned comparison

Input parameters:

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

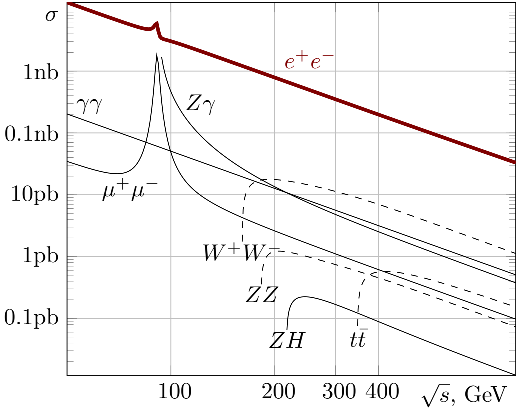
Cuts:

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

Tuned comparison of our results for polarized Born and hard Bremsstrahlung with the results WHIZARD [Eur.Phys.J.C71 (2011) 1742] and CalcHEP [CPC 184(2013) 1729-1769] programs shows agreement within statistical errors.

Unpolarized Soft + virtual contribution agree with the results of aİTALC [CPC 174 (2006) 71-82] (for $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$) and Grace-Loop [Phys.Rept. 430 (2006) 117-209] (for $e^+e^- \to ZH$)

$e^+e^- \to e^+e^-$



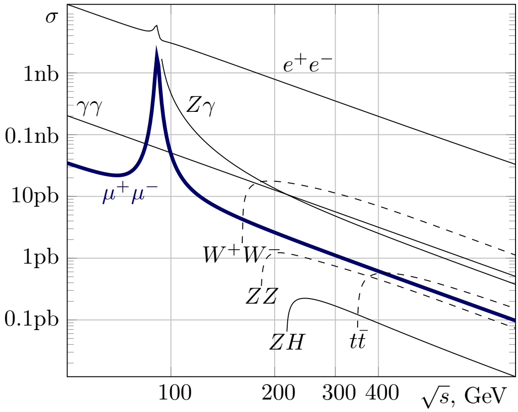
For details, see the talk by Andrej Arbuzov

$e^+e^- \to e^+e^-$: 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				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	56.676(1)	57.774(1)	56.273(1)	59.275(1)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	61.73(1)	62.59(1)	61.88(1)	63.29(1)
δ, %	8.92(1)	8.33(1)	9.96(1)	6.77(1)
$\sqrt{s} = 500$ GeV				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	14.379(1)	15.031(1)	12.706(1)	17.355(1)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	15.47(1)	15.87(1)	13.86(1)	17.88(1)
δ, %	7.56(1)	5.59(1)	9.09(1)	3.05(1)
$\sqrt{s} = 1000$ GeV				
$\sigma^{\text{Born}}_{e^+e^-}$, pb	3.6792(1)	3.9057(1)	3.0358(1)	4.7756(1)
$\sigma^{\text{1-loop}}_{e^+e^-}$, pb	3.864(1)	3.945(1)	3.233(1)	4.654(1)
δ, %	5.02(1)	0.99(1)	6.50(1)	-2.54(1)

$$e^+e^- \to \mu^-\mu^+$$

$$e^+e^- \to \tau^-\tau^+$$



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

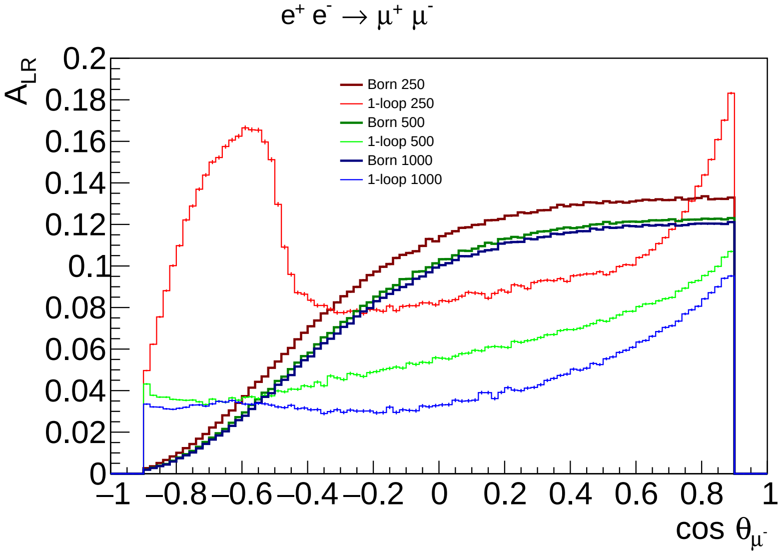
P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
$\sigma^{\rm Born}_{\mu^+\mu^-}$, pb	1.417(1)	1.546(1)	0.7690(2)	2.323(1)
$\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb	2.397(1)	2.614(1)	1.301(1)	3.927(1)
δ,%	69.1(1)	69.1(1)	69.2(1)	69.1(1)
$\sqrt{s} = 500$ GeV				
$\sigma^{\rm Born}_{\mu^+\mu^-}$, pb	0.3436(1)	0.3716(1)	0.1857(1)	0.5575(1)
$\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb	0.4696(1)	0.4953(1)	0.2506(1)	0.7399(1)
δ,%	36.7(1)	33.3(1)	35.0(1)	32.7(1)
$\sqrt{s} = 1000$ GeV				
$\sigma^{\rm Born}_{\mu^+\mu^-}$, pb	0.08535(1)	0.09213(1)	0.04608(1)	0.1382(1)
$\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb	0.1163(1)	0.1212(1)	0.06169(1)	0.1807(1)
δ,%	36.2(1)	31.6(1)	33.9(1)	30.8(1)

$e^+e^- \to \tau^+\tau^-$: 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				
$\sigma^{\rm Born}_{\tau^+\tau^-}$, pb	1.417(1)	1.546(1)	0.7692(1)	2.324(1)
$\sigma^{\rm 1-loop}_{\tau^+\tau^-}$, pb	2.360(1)	2.575(1)	1.298(1)	3.850(1)
δ,%	66.5(1)	66.5(1)	68.8(1)	65.7(1)
$\sqrt{s} = 500$ GeV				
$\sigma^{\rm Born}_{\tau^+\tau^-}$, pb	0.3436(1)	0.3715(1)	0.1857(1)	0.5575(1)
$\sigma^{\rm 1-loop}_{\tau^+\tau^-}$, pb	0.4606(1)	0.4861(1)	0.2466(1)	0.7257(1)
δ,%	34.0(3)	30.8(1)	32.8(1)	30.1(1)
$\sqrt{s} = 1000$ GeV				
$\sigma^{\rm Born}_{\tau^+\tau^-}$, pb	0.08534(2)	0.09213(1)	0.04608(1)	0.1382(1)
$\sigma^{\rm 1-loop}_{\tau^+\tau^-}$, pb	0.1134(1)	0.11885(2)	0.06067(1)	0.1770(1)
δ,%	33.6(1)	29.0(1)	31.7(1)	28.1(1)

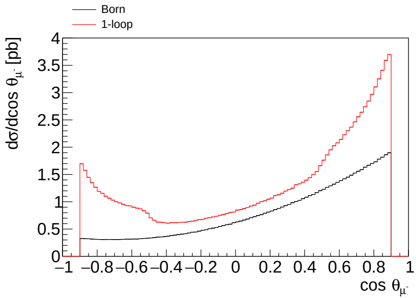
$e^+e^- \to \mu^+\mu^-$: A_{LR} distributions in $\cos\theta$

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

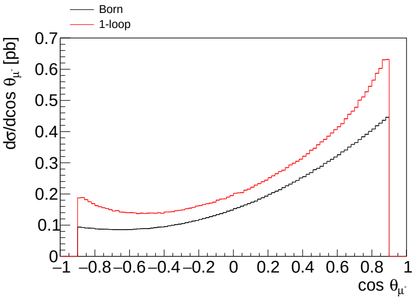


$e^+e^- \to \mu^+\mu^-$: distributions in $\cos\theta$

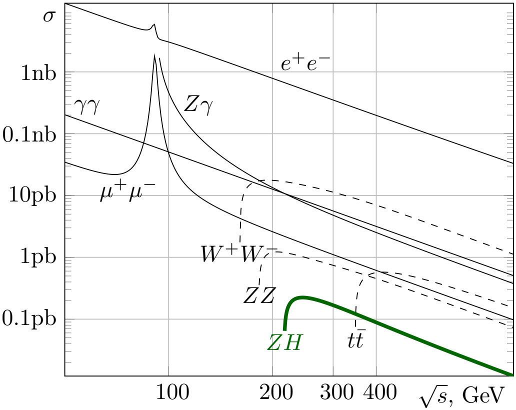
250 GeV:



500 GeV:



$e^+e^- \to ZH$



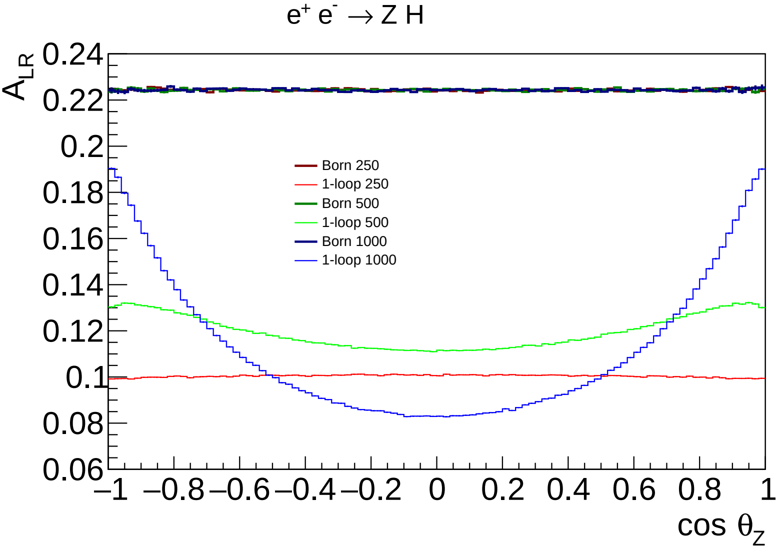
σ
1nb
0.1nb
10pb
1pb
0.1pb
e^+e^-
$\gamma\gamma$
$Z\gamma$
$\mu^+\mu^-$
W^+W^-
ZZ
ZH
$t\bar{t}$
100
200
300
400
$\sqrt{s}$, GeV

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

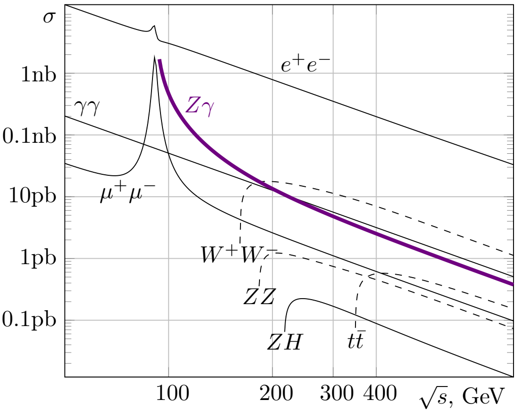
P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
σ^{Born}, fb	205.64(1)	242.55(1)	116.16(1)	368.93(1)
$\sigma^{\text{1-loop}}$, fb	186.6(1)	201.5(1)	100.8(1)	302.2(1)
δ,%	-9.24(1)	-16.94(1)	-13.25(1)	-18.10(1)
$\sqrt{s} = 500$ GeV				
σ^{Born}, fb	51.447(1)	60.680(1)	29.061(1)	92.299(1)
$\sigma^{\text{1-loop}}$, fb	57.44(1)	62.71(1)	31.25(1)	94.17(2)
δ,%	11.65(1)	3.35(2)	7.54(1)	2.03(2)
$\sqrt{s} = 1000$ GeV				
σ^{Born}, fb	11.783(1)	13.898(1)	6.6559(1)	21.140(1)
$\sigma^{\text{1-loop}}$, fb	12.92(1)	13.91(1)	6.995(1)	20.83(1)
δ,%	9.68(1)	0.10(2)	5.09(2)	-1.47(2)

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

.



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



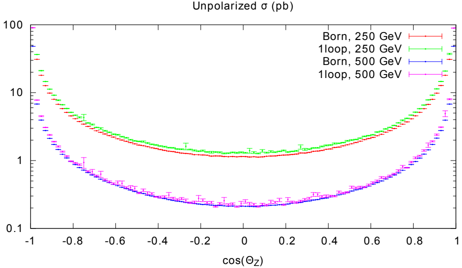
σ
1nb
0.1nb
10pb
1pb
0.1pb
e^+e^-
$Z\gamma$
$\gamma\gamma$
$\mu^+\mu^-$
W^+W^-
ZZ
ZH
$t\bar{t}$
100
200
300
400
$\sqrt{s}$, GeV

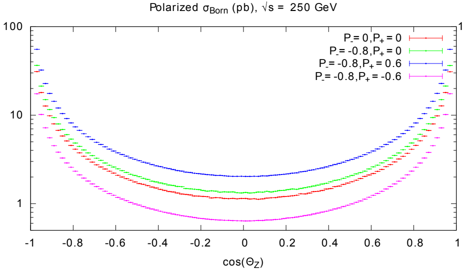
$e^+e^- \to Z\gamma$: Born vs 1-loop (preliminary)

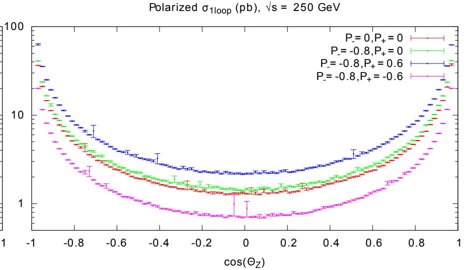
$\sqrt{s}$, GeV	250	500	1000
$\sigma^{\text{Born}}_{Z\gamma}$, pb	15.7038(6)	3.3858(3)	0.81958(3)
$\sigma^{\text{1-loop}}_{Z\gamma}$, pb	24.37(1)	5.23(6)	1.237(3)
δ, %	55.20(6)	54.4(2)	50.9(4)

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

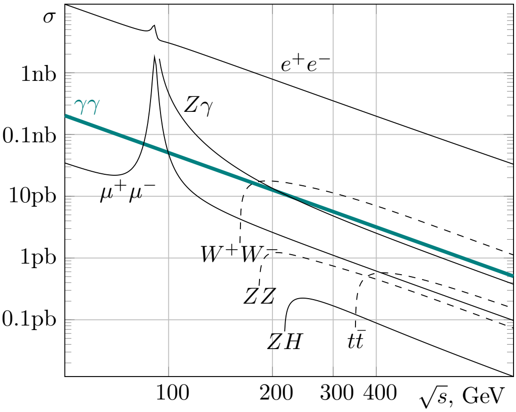
$e^+e^- \to Z\gamma$: distributions in $\cos\theta_Z$ (preliminary)







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

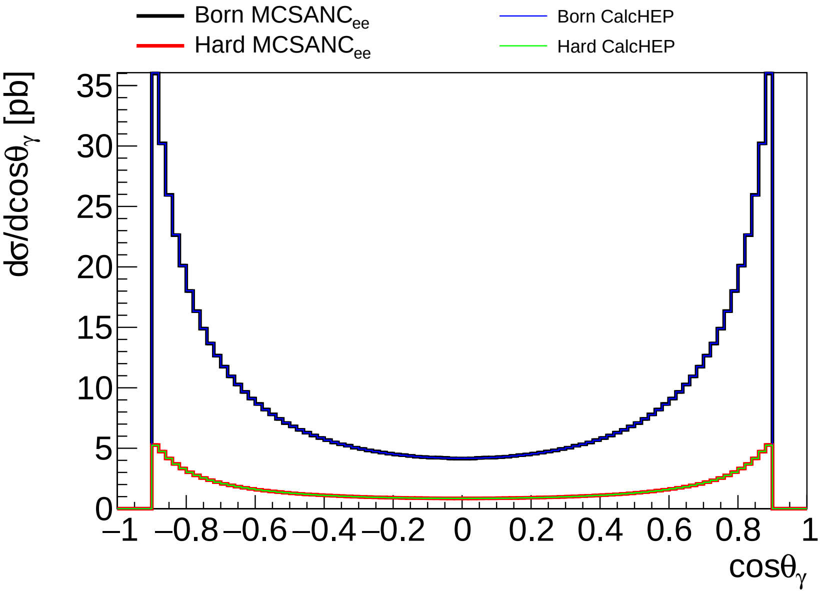


$e^+e^- \to \gamma\gamma$: WHIZARD vs CalcHEP vs MCSANCee

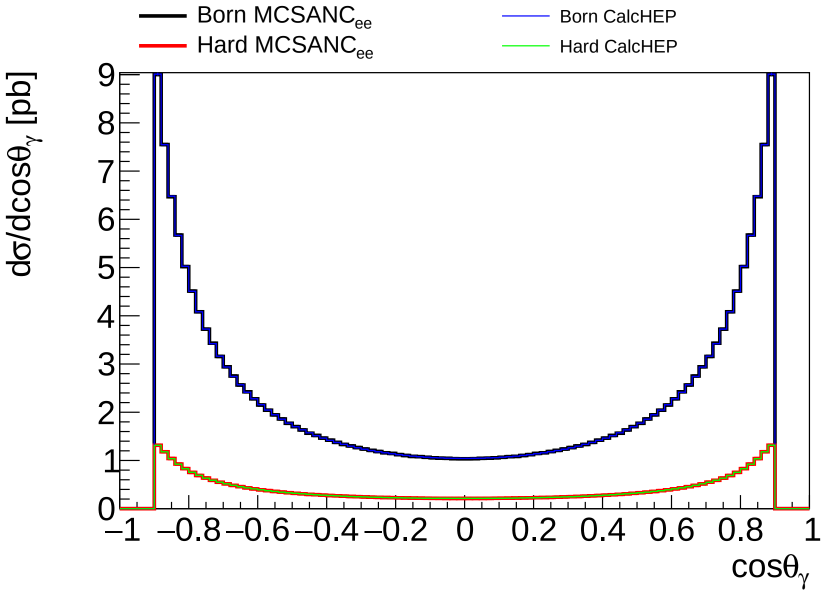
P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
$\sqrt{s} = 250$ GeV				
σ^{hard}, fb	594.1(1)	594.1(1)	308.9(1)	879.2(1)
σ^{hard}, fb	594.0(1)	593.8(1)	308.8(1)	879.2(1)
σ^{hard}, fb	594.0(1)	594.2(1)	308.9(1)	879.1(1)
$\sqrt{s} = 500$ GeV				
σ^{hard}, fb	158.6(1)	158.5(1)	82.50(1)	234.5(1)
σ^{hard}, fb	158.7(1)	158.6(1)	82.50(1)	234.8(1)
σ^{hard}, fb	158.7(1)	158.7(1)	82.50(1)	234.8(1)
$\sqrt{s} = 1000$ GeV				
σ^{hard}, fb	42.18(1)	42.20(1)	21.95(1)	62.43(1)
σ^{hard}, fb	42.19(1)	42.18(1)	21.94(1)	62.45(1)
σ^{hard}, fb	42.17(1)	42.20(1)	21.94(1)	62.44(1)

Cuts: $|\cos\theta_\gamma| < 0.9$, $E_\gamma > 0.0025$ GeV for each of the final photons

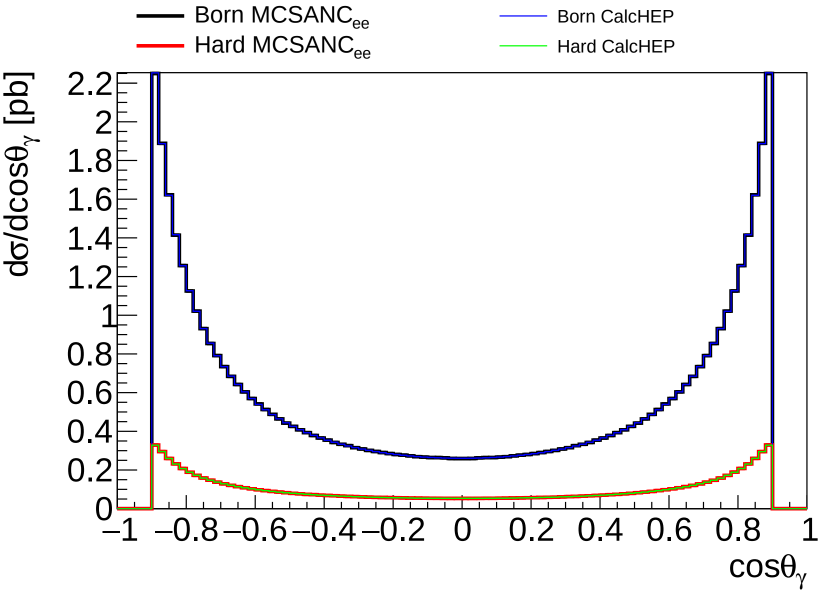
$e^+e^- \to \gamma\gamma$: distribution in $\cos\theta$, $\sqrt{s}$=250 GeV



$e^+e^- \to \gamma\gamma$: distribution in $\cos\theta$, $\sqrt{s}$=500 GeV



$e^+e^- \to \gamma\gamma$: distribution in $\cos\theta$, $\sqrt{s}$=1000GeV



Summary

- We created Monte Carlo generator of unweighted events $\texttt{MCSANC}_{\text{ee}}$ for polarized e^+e^- scattering with complete one-loop EW corrections
- Now it includes the following processes:
  - $e^+e^- \to e^+e^-$ (`Phys.Rev.D 98, 013001`)
  - $e^+e^- \to ZH$ (arXiv:1812.10965)
  - $e^+e^- \to \mu^+\mu^-$(or $\tau^+\tau^-$) (preliminary)
  - $e^+e^- \to Z\gamma$ (preliminary)
  - $e^+e^- \to \gamma\gamma$ (preliminary)
- Support of Les Houches format for events

Plans

- to include in $\texttt{MCSANC}_{\mathsf{ee}}$ the following processes:
  - $e^+e^- \to t\bar{t}$
  - $e^+e^- \to ZZ$
  - $e^+e^- \to H\gamma$
  - $e^+e^- \to f\bar{f}\gamma$
  - $e^+e^- \to f\bar{f}H$
  - $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to e^+e^-$, $\gamma\gamma \to HZ$, $\gamma\gamma \to Z\gamma$, $\gamma\gamma \to ZZ$
  - $e^\pm\gamma \to e^\pm\gamma$
- to extend the functionality of the generator with actual energy spectrum of initial particles, leading multi-loop corrections, and with transverse polarization
- Public pre-release: June 2019