# Generator MCSANC$_{ee}$ for the polarized $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-, ZH$ scattering at one-loop EW level.

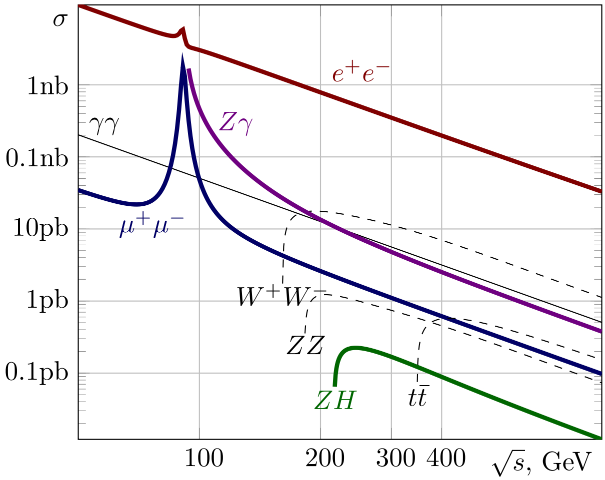
Y. Dydyshka[a], L. Kalinovskaya[a], L. Rumyantsev[a,b], R. Sadykov[a], V. Yermolchyk[a], A. Arbuzov[c], S. Bondarenko[c].

[a] *DLNP JINR, Dubna,* [c] *BLTP JINR, Dubna,*

[b] *IoP, Southern Federal University, Rostov-on-Don, Russia*

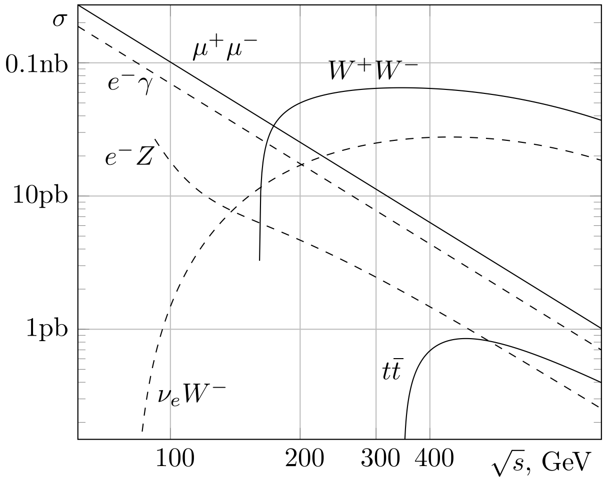
*presented by Igor Boyko[a].*

# 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.

# Basic processes of SM for $e^{\pm}\gamma$ and $\gamma\gamma$ initial state




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

# Polarized scattering $2 \to 2$, EW corrections, notations

**We consider a scattering of two polarized $e^+$ and $e^-$ beams with:**

- **four momentum of incoming $p_1$ and $p_2$, outgoing particles $p_3$ and $p_4$,**
- **in the massless case $m_e = 0$**
- **at the one-loop EW level**
- **with longitudinal polarization $P_{e^+}$ and $P_{e^-}$ of incoming beams:**

$$e^+(p_1) + e^-(p_2) \longrightarrow e^+(p_3) + e^-(p_4).$$

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

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

**where $\sigma^{\text{Born}}$ — Born level cross-section,**
**$\sigma^{\text{virt}}$ — contribution of virtual(loop) corrections,**
**$\sigma^{\text{soft}}$ — contribution due to soft photon emission,**
**$\sigma^{\text{hard}}$ — contribution due to hard photon emission (with energy $E_\gamma > \omega$).**
**Auxiliary parameters $\lambda$ ("photon mass") and $\omega$ cancel out after summation.**

# Polarized scattering: two approaches

For the longitudinally polarized, as example

- **First approach — covariant amplitude (CA) formalism.**
  The differential cross-section is proportional to square of the absolute value of covariant amplitude $\mathcal{A}$. For $2 \to 2$ kinematics

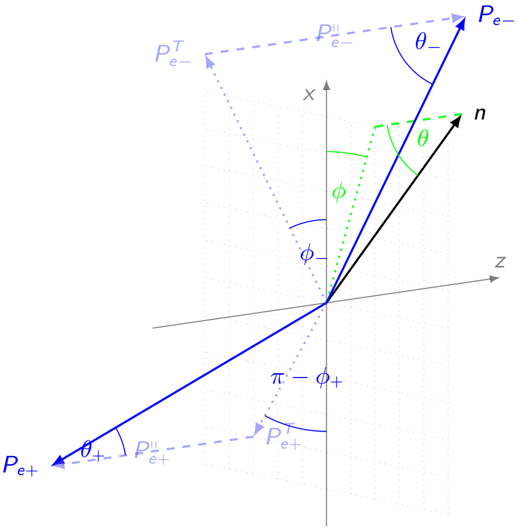
$$d\sigma = \frac{1}{32\pi s} |\mathcal{A}|^2 \, d\cos\theta,$$

$$d\sigma = d\sigma_0 + (P_{e^+} - P_{e^-}) d\sigma_1 + P_{e^+} P_{e^-} d\sigma_2$$

- **Second approach — helicity amplitude (HA) formalism.**
  To get the cross-section we sum squares of absolute values of non-interfering helicity amplitudes:

$$128\pi s \frac{d\sigma}{d\cos\theta}$$
$$= (1 - P_{e^-})(1 - P_{e^+}) \sum_{ij} |\mathcal{H}_{++ij}|^2 + (1 - P_{e^-})(1 + P_{e^+}) \sum_{ij} |\mathcal{H}_{+-ij}|^2$$
$$+ (1 + P_{e^-})(1 - P_{e^+}) \sum_{ij} |\mathcal{H}_{-+ij}|^2 + (1 + P_{e^-})(1 + P_{e^+}) \sum_{ij} |\mathcal{H}_{--ij}|^2$$

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




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

# Matrix element squared

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

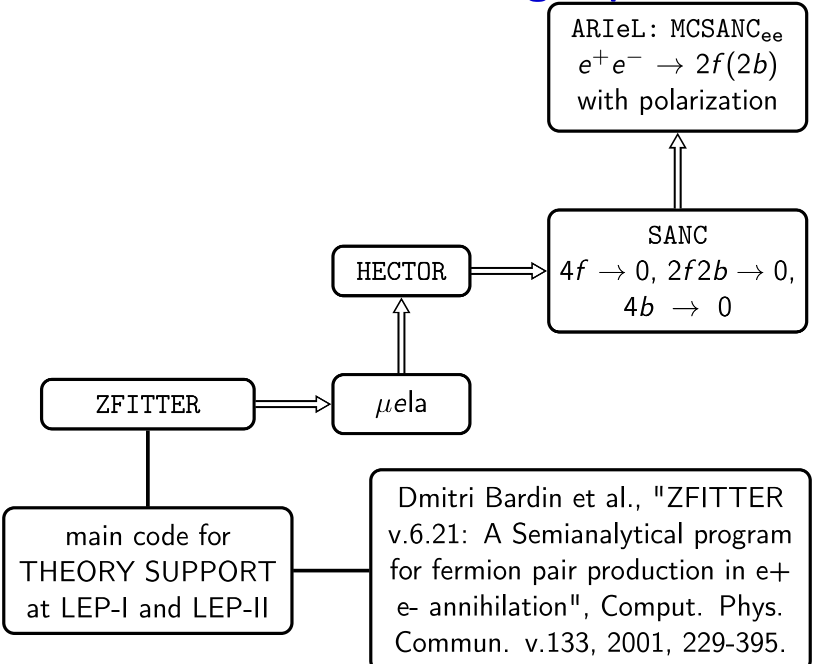
where

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

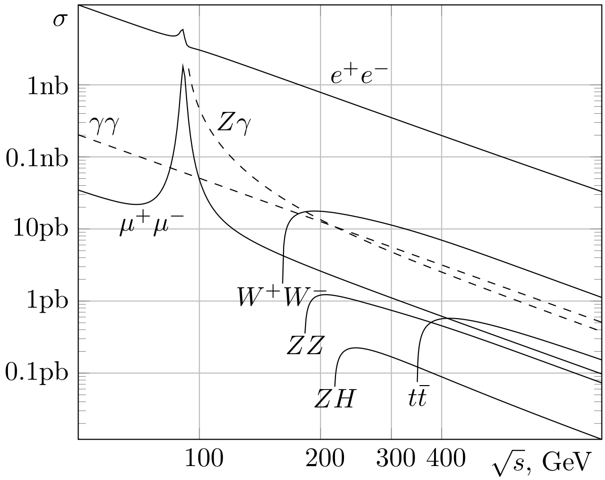
$\mathcal{H}_{--}$, $\mathcal{H}_{++}$,$\mathcal{H}_{-+}$,$\mathcal{H}_{+-}$ — helicity amplitudes.

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

# HISTORY OVERVIEW, SANC group



# 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.

# $\texttt{MCSANC}_{\text{ee}}$, March 2019

Monte Carlo generator of unweighted events for the polarized
$e^+e^- \to e^+e^-(\mu^+\mu^-, \tau^+\tau^-, Z\gamma, ZH, \gamma\gamma)$
scattering with complete one-loop EW corrections and with possibility to produce events in Standard Les Houches Format.
Different schemes: e.g. $\alpha(0), \alpha(M_z), G_F$.

Generator uses adaptive algorithm mFOAM (S. Jadach and P. Sawicki, CPC 177:441-458,2007) which is part of ROOT program.

# Status MCSANC$_{\text{ee}}$: NLO EW, polarized $e^+e^-$ scattering

— January 2018, CLIC, R. Sadykov, "NLO EW corrections for polarized $e^+e^-$ scattering: $e^+e^- \to e^+e^-$ (Bhabha)(Phys.Rev.D 98, 013001), $e^+e^- \to Z\gamma$."

— January 2019, CLIC, I. Boyko, "Status MCSANC$_{\text{ee}}$: $e^+e^- \to \mu^+\mu^-$(or $\tau^+\tau^-$) and $e^+e^- \to ZH$".

# Numerical results: Setup for tuned comparison

We performed a tuned comparison of our results for polarized Born and hard Bremsstrahlung with the results WHIZARD and CalcHEP programs.

## Initial parameters

$$\alpha^{-1}(0) = 137.03599976, \quad M_W = 80.451495 \text{ GeV}, \quad \Gamma_W = 2.0836 \text{ GeV},$$
$$M_H = 125.0 \text{ GeV}, \quad M_Z = 91.1876 \text{ GeV}, \quad \Gamma_Z = 2.49977 \text{ GeV},$$
$$m_e = 0.5109990 \text{ MeV}, \quad m_\mu = 0.105658 \text{ GeV}, \quad m_\tau = 1.77705 \text{ GeV},$$
$$m_d = 0.083 \text{ GeV}, \quad m_s = 0.215 \text{ GeV}, \quad m_b = 4.7 \text{ GeV},$$
$$m_u = 0.062 \text{ GeV}, \quad m_c = 1.5 \text{ GeV}, \quad m_t = 173.8 \text{ GeV}.$$

with cuts $|\cos\theta| < 0.9, \quad E_\gamma > 1$ GeV

## WHIZARD and CalcHEP

- W. Kilian, T. Ohl, J. Reuter, Eur.Phys.J.C71 (2011) 1742,
- A.Belyaev, N.Christensen,A.Pukhov, Comp. Phys. Comm. 184 (2013), pp. 1729-1769

## $e^+e^- \to \mu^+\mu^-$: **aǏTALC vs MCSANC$_{ee}$**, $\sqrt{s} = 500\,GeV$

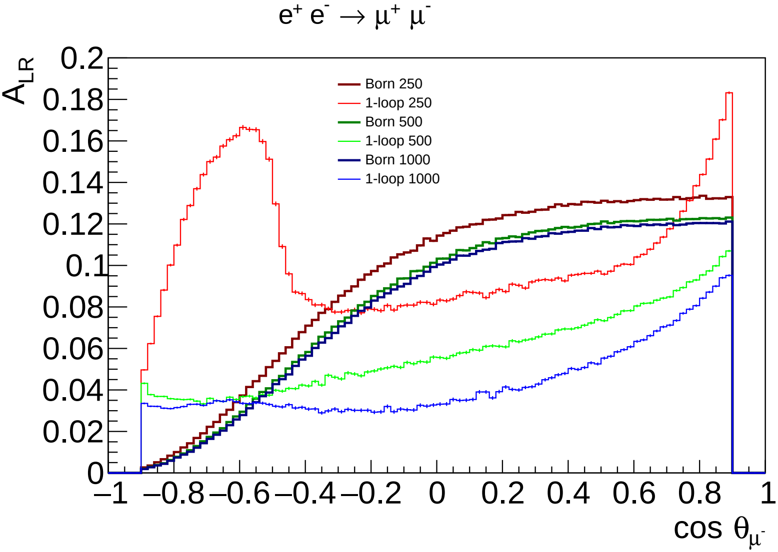
*Born&virt&soft*

| | $\cos\vartheta$ | $\sigma^{\text{Born}}_{\mu^+\mu^-}$, pb | $\sigma^{\text{virt}}_{\mu^+\mu^-}$, pb | $\sigma^{\text{soft}}_{\mu^+\mu^-}$, pb | $\sigma^{\text{Born+virt+soft}}_{\mu^+\mu^-}$, pb |
|---|---|---|---|---|---|
| a | -0.9 | 0.09458936 | 0.007074202 | -.01137770 | 0.09028587 |
| S | | 0.09458937 | 0.007074200 | -.01137770 | 0.09028587 |
| a | -0.5 | 0.08929449 | 0.01142066 | -.01603201 | 0.08468314 |
| S | | 0.08929448 | 0.01142066 | -.01603201 | 0.08468313 |
| a | 0.0 | 0.1503198 | 0.02280391 | -.03291616 | 0.1402075 |
| S | | 0.1503199 | 0.02280392 | -.03291616 | 0.1402075 |
| a | 0.5 | 0.2865049 | 0.06366626 | -.07403504 | 0.2761361 |
| S | | 0.2865049 | 0.06366627 | -.07403505 | 0.2761361 |
| a | 0.9 | 0.4495681 | 0.1596106 | -.1428113 | 0.4663674 |
| S | | 0.4495682 | 0.1596107 | -.1428113 | 0.4663675 |

Ref: aǏTALC, A. Lorca and T. Riemann, Comput. Phys. Commun. 174 (2006) 71-82, hep-ph/0412047

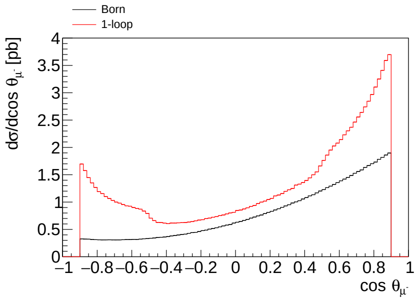
# $e^+e^- \to \mu^+\mu^-$: $A_{LR}$ distributions on $\cos\theta$

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

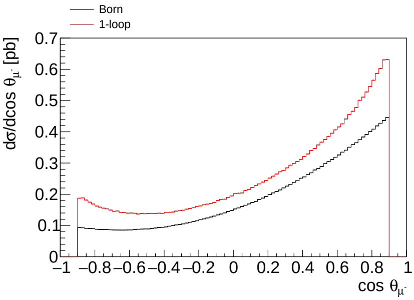


# $e^+e^- \to \mu^+\mu^-$: distributions $\frac{d\sigma}{d\cos\vartheta}$

250 GeV:




500 GeV:



# $e^+e^- \to \mu^+\mu^-$: NLO EW results, preliminary

| $P_{e^-}, P_{e^+}$ | 0, 0 | -0.8, 0 | -0.8, 0.6 | -0.8, -0.6 |
|---|---|---|---|---|
| $\sqrt{s} = 250$ GeV | | | | |
| $\sigma^{\rm Born}_{\mu^+\mu^-}$, pb | 1.4174(1) | 1.5462(1) | 2.3231(2) | 0.7690(2) |
| $\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb | 2.397(1) | 2.614(1) | 3.927(1) | 1.301(1) |
| $\delta$,% | 69.1(1) | 69.1(1) | 69.1(1) | 69.2(1) |
| $\sqrt{s} = 500$ GeV | | | | |
| $\sigma^{\rm Born}_{\mu^+\mu^-}$, pb | 0.34361(1) | 0.37159(1) | 0.55751(1) | 0.18567(1) |
| $\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb | 0.4696(1) | 0.4953(1) | 0.7399(1) | 0.2506(1) |
| $\delta$,% | 36.67(3) | 33.30(2) | 32.71(2) | 34.98(2) |
| $\sqrt{s} = 1000$ GeV | | | | |
| $\sigma^{\rm Born}_{\mu^+\mu^-}$, pb | 0.085354(1) | 0.09213(1) | 0.13818(1) | 0.04608(1) |
| $\sigma^{\rm 1-loop}_{\mu^+\mu^-}$, pb | 0.11627(2) | 0.12119(2) | 0.18069(3) | 0.061694(1) |
| $\delta$,% | 36.22(2) | 31.55(2) | 30.78(2) | 33.90(2) |

# $e^+e^- \to \tau^+\tau^-$: NLO EW results, preliminary

| $P_{e^-}, P_{e^+}$ | 0, 0 | -0.8, 0 | -0.8, 0.6 | -0.8, -0.6 |
|---|---|---|---|---|
| $\sqrt{s} = 250$ GeV | | | | |
| $\sigma^{\mathrm{Born}}_{\tau^+\tau^-}$, pb | 1.417(1) | 1.546(1) | 2.324(1) | 0.7692(1) |
| $\sigma^{\mathrm{1-loop}}_{\tau^+\tau^-}$, pb | 2.360(1) | 2.575(1) | 3.850(1) | 1.298(1) |
| $\delta$,% | 66.5(1) | 66.5(1) | 65.7(1) | 68.8(1) |
| $\sqrt{s} = 500$ GeV | | | | |
| $\sigma^{\mathrm{Born}}_{\tau^+\tau^-}$, pb | 0.3436(1) | 0.3715(1) | 0.5575(1) | 0.1857(1) |
| $\sigma^{\mathrm{1-loop}}_{\tau^+\tau^-}$, pb | 0.4606(1) | 0.4861(1) | 0.7257(1) | 0.2466(1) |
| $\delta$,% | 34.0(3) | 30.8(1) | 30.1(1) | 32.8(1) |
| $\sqrt{s} = 1000$ GeV | | | | |
| $\sigma^{\mathrm{Born}}_{\tau^+\tau^-}$, pb | 0.08534(2) | 0.09213(1) | 0.1382(1) | 0.04608(1) |
| $\sigma^{\mathrm{1-loop}}_{\tau^+\tau^-}$, pb | 0.11340(5) | 0.11885(2) | 0.1770(1) | 0.06067(1) |
| $\delta$,% | 33.6(1) | 29.0(1) | 28.1(1) | 31.7(1) |

## $e^+e^- \to ZH$: WHIZARD vs CalcHEP vs MCSANC$_{ee}$ (Born), fb

$\sqrt{s}$=250 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -1,-1 | -1,1 | 1,-1 | 1,1 |
|---|---|---|---|---|---|
| WHIZARD | 225.59 | 6.368E-8 | 552.34 | 350.01 | 6.368E-8 |
| CalcHEP | 225.59 | 4.411E-8 | 552.34 | 350.02 | 4.411E-8 |
| SANCee | 225.59 | 0 | 552.34 | 350.01 | 0 |

$\sqrt{s}$=500 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -1,-1 | -1,1 | 1,-1 | 1,1 |
|---|---|---|---|---|---|
| WHIZARD | 53.738 | 3.762E-7 | 131.57 | 83.377 | 3.762E-7 |
| CalcHEP | 53.738 | 5.994E-8 | 131.57 | 83.377 | 5.994E-8 |
| SANCee | 53.737 | 0 | 131.57 | 83.377 | 0 |

$\sqrt{s}$=1000 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -1,-1 | -1,1 | 1,-1 | 1,1 |
|---|---|---|---|---|---|
| WHIZARD | 12.054 | 4.801E-7 | 29.515 | 18.703 | 4.801E-7 |
| CalcHEP | 12.054 | 2.639E-8 | 29.515 | 18.703 | 2.639E-8 |
| SANCee | 12.054 | 0 | 29.515 | 18.703 | 0 |

## $e^+e^- \to ZH$: WHIZARD and CalcHEP vs SANC (hard), fb

$\sqrt{s}$=250 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -1,-1 | -1,1 | 1,-1 | 1,1 |
|---|---|---|---|---|---|
| WHIZARD | 82.00(1) | 0.009143(1) | 200.7(2) | 127.2(1) | 0.01470(1) |
| CalcHEP | 82.00(1) | 0.02596(1) | 200.8(1) | 127.2(1) | 0.02596(1) |
| SANCee | 82.00(1) | 0.02596(1) | 200.7(1) | 127.2(1) | 0.02597(1) |

$\sqrt{s}$=500 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -1,-1 | -1,1 | 1,-1 | 1,1 |
|---|---|---|---|---|---|
| WHIZARD | 38.96(1) | 0.1256(1) | 95.10(8) | 60.27(1) | 0.1169(1) |
| CalcHEP | 38.96(1) | 0.2201(1) | 95.12(1) | 60.27(1) | 0.2198(1) |
| SANCee | 38.96(1) | 0.2200(1) | 95.10(1) | 60.25(1) | 0.2199(1) |

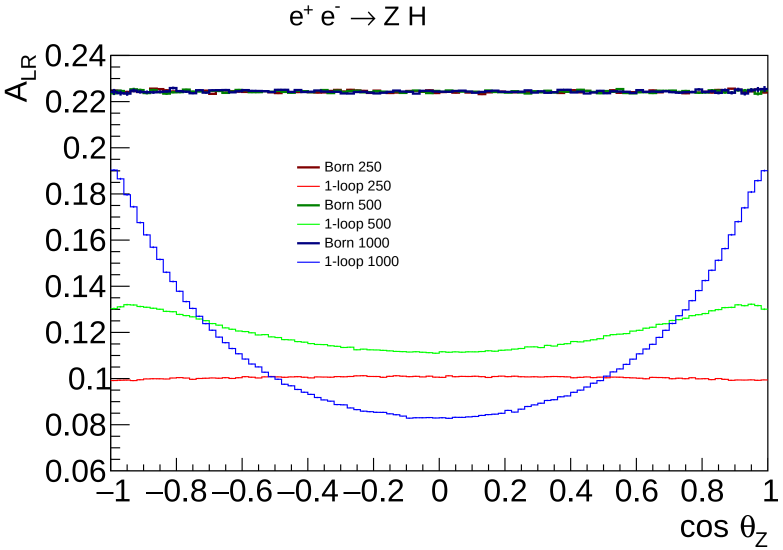
$\sqrt{s}$=1000 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -1,-1 | -1,1 | 1,-1 | 1,1 |
|---|---|---|---|---|---|
| WHIZARD | 11.67(1) | 0.07051(1) | 28.41(1) | 18.00(1) | 0.07018(1) |
| CalcHEP | 11.67(1) | 0.1326(1) | 28.41(1) | 18.00(1) | 0.1326(1) |
| SANCee | 11.67(1) | 0.1327(1) | 28.40(1) | 18.00(1) | 0.1326(1) |

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

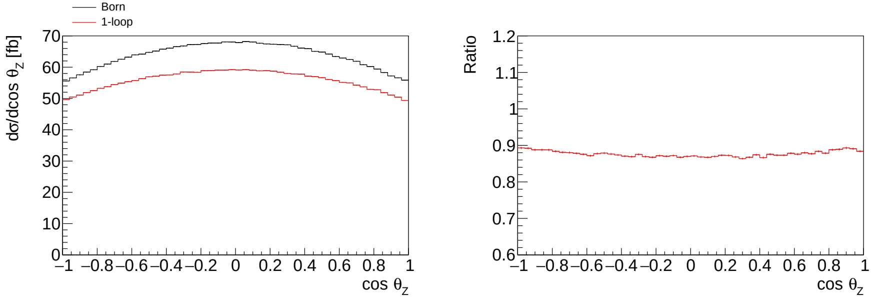
.

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



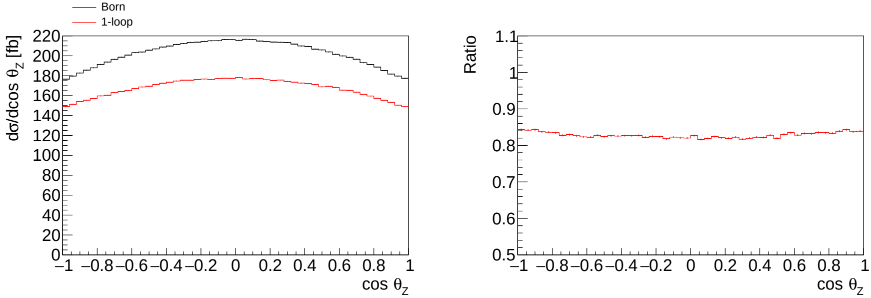
# $e^+e^- \to ZH$: $\sigma$ distributions on $\cos\theta$

$$\frac{d\sigma}{d\cos\vartheta_Z},\ (P_{e^-}, P_{e^+}) = (-0.8, -0.6),\ \sqrt{s} = 250\text{GeV}$$



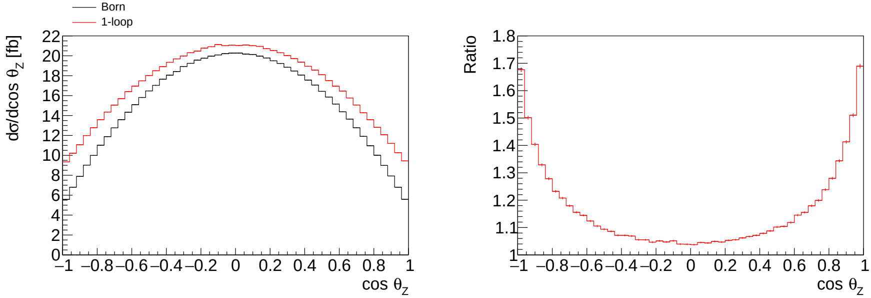
# $e^+e^- \to ZH$: $\sigma$ distributions on $\cos\theta$

$$\frac{d\sigma}{d\cos\vartheta_Z},\ (P_{e^-}, P_{e^+}) = (-0.8, +0.6),\ \sqrt{s} = 250\text{GeV}$$



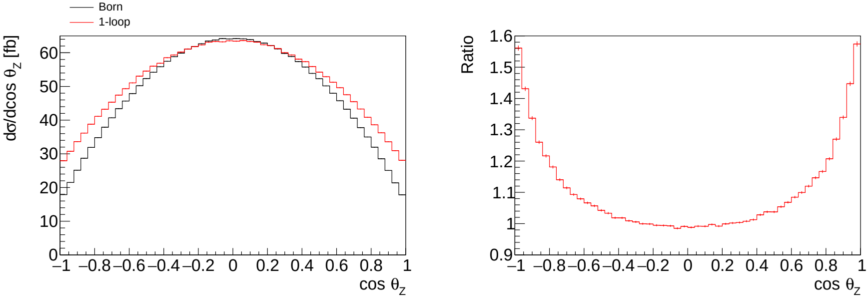
# $e^+e^- \to ZH$: $\sigma$ distributions on $\cos\theta$

$$\frac{d\sigma}{d\cos\vartheta_Z},\ (P_{e^-}, P_{e^+}) = (-0.8, -0.6),\ \sqrt{s} = 500\text{GeV}$$



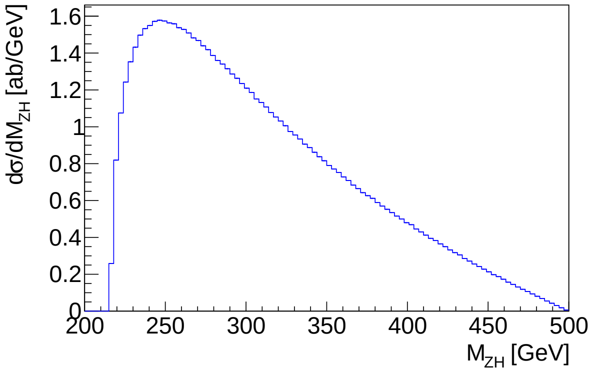
# $e^+e^- \to ZH$: $\sigma$ distributions on $\cos\theta$

$$\frac{d\sigma}{d\cos\vartheta_Z},\ (P_{e^-}, P_{e^+}) = (-0.8, +0.6),\ \sqrt{s} = 500\text{GeV}$$



## $e^+e^- \to ZH$: $\sigma$ distributions on $M_{ZH}$

$$\frac{d\sigma}{dM_{ZH}},\ (P_{e^-}, P_{e^+}) = (-1, -1),\ \sqrt{s} = 500\text{GeV}$$



# $e^+e^- \to ZH$: Preliminary MCSANC$_{ee}$ NLO EW results

$\sqrt{s}$=250 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -0.8,0 | -1,1 | 1,-1 | -0.8,-0.6 |
|---|---|---|---|---|---|
| $\sigma^{Born}$,pb | 0.22559(1) | 0.26605(1) | 0.55234(1) | 0.35001(1) | 0.12742(1) |
| $\sigma^{1-loop}$,pb | 0.20693(1) | 0.22353(1) | 0.45532(1) | 0.37227(1) | 0.11176 |
| $\delta$, % | -8.27(1) | -15.98(1) | -17.57(1) | -6.36(1) | -12.29(1) |

$\sqrt{s}$=500 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -0.8,0 | -1,1 | 1,-1 | -0.8,-0.6 |
|---|---|---|---|---|---|
| $\sigma^{Born}$,pb | 0.05373(1) | 0.06337(1) | 0.13157(1) | 0.08337(1) | 0.03035(1) |
| $\sigma^{1-loop}$,pb | 0.06242(1) | 0.06831(1) | 0.13937(1) | 0.10990(1) | 0.03404(1) |
| $\delta$, % | 16.15(1) | 7.78(1) | 5.493(1) | 31.81(1) | 12.16(1) |

$\sqrt{s}$=1000 GeV

| $P_{e^-}, P_{e^+}$ | 0,0 | -0.8,0 | -1,1 | 1,-1 | -0.8,-0.6 |
|---|---|---|---|---|---|
| $\sigma^{Born}$,pb | 0.01205(1) | 0.01421(1) | 0.02951(1) | 0.01870(1) | 0.00680(1) |
| $\sigma^{1-loop}$,pb | 0.01457(1) | 0.01582(1) | 0.03214(1) | 0.02590(1) | 0.00795(1) |
| $\delta$, % | 20.86(1) | 11.30(1) | 8.89(1) | 38.49(1) | 16.77(1) |

# MCSANC$_{ee}$, plans

- NLO EW corrections for polarized $e^+e^-$ scattering:
  - $e^+e^- \to e^+e^-$ (Bhabha) (Phys.Rev.D 98, 013001)
  - $e^+e^- \to \mu^+\mu^-$(or $\tau^+\tau^-$) (preliminary)
  - $e^+e^- \to Z\gamma$ (preliminary)
  - $e^+e^- \to t\bar{t}$ (in progress)
  - $e^+e^- \to ZH$ (arXiv:1812.10965)
  - $e^+e^- \to \nu\bar{\nu}H$ (in progress)
  - $e^+e^- \to ZZ$ (in progress)
  - $e^+e^- \to \gamma\gamma$ (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)

# RESUME: MCSANC$_{ee}$, March 2019

Monte Carlo generator of unweighted events for the polarized
$e^+e^- \to e^+e^-(\mu^+\mu^-, \tau^+\tau^-, Z\gamma, ZH, \gamma\gamma)$
scattering with complete one-loop EW corrections and with possibility to produce events in Standard Les Houches Format.
Different schemes: e.g. $\alpha(0), \alpha(M_z), G_F$