

# Процесс $e^+e^- \rightarrow Z\gamma$ с учетом продольной поляризации

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# Future lepton collider projects

## Linear collider (e+e-)

- ILC; CLIC
- ILC: technology at hand, realization in Japan??

$E_{cm}$

- 250GeV – 1TeV, 91GeV (ILC)
- 500GeV – 3TeV (CLIC)

$$L \approx 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} (\sim 500 \text{ fb}^{-1}/\text{year})$$

→ Stat. uncertainty  $\sim 10^{-3} \dots 10^{-2}$

### Beam polarization

e- beam  $P = 80\text{-}90\%$

e+ beam

ILC:  $P = 30\%$  baseline;  
60% upgrade

CLIC:  $P \geq 60\%$  upgrade

## Circular collider

- FCC-ee, TLEP  $\mu$  Collider
- CEPC Projects under study

$E_{cm}$

91 GeV, 160GeV, 240GeV, 350GeV

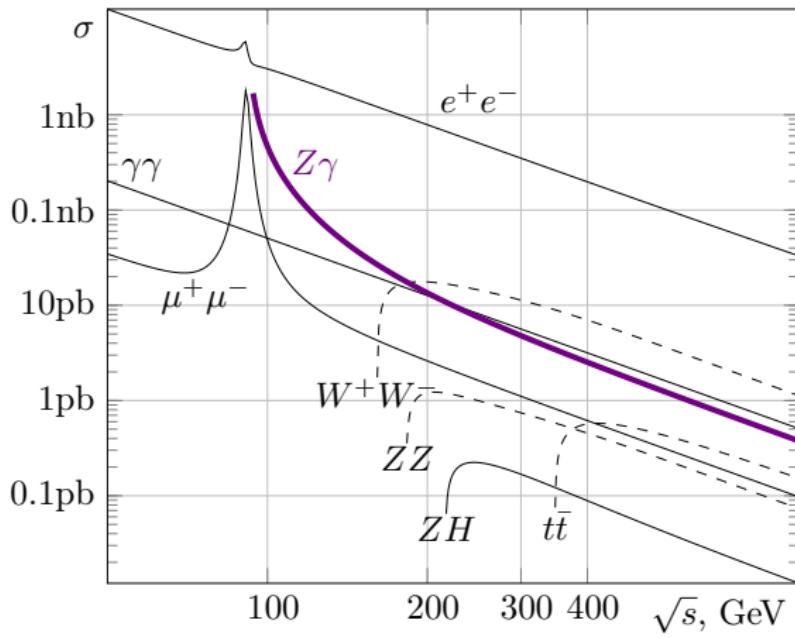
$$L \approx 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \text{ (4 experiments)}$$

→ Stat. uncertainty  $\leq 10^{-3}$

### Beam polarization

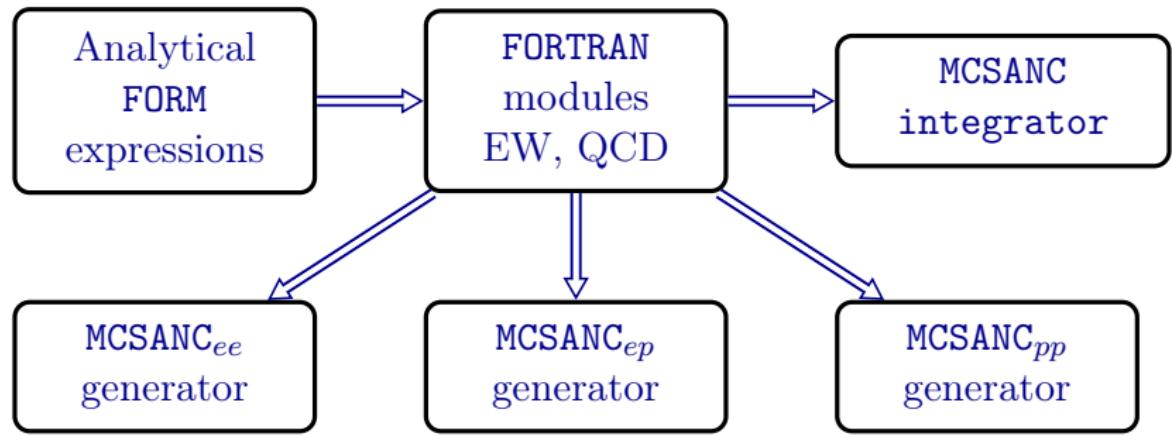
- Desired (?)

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

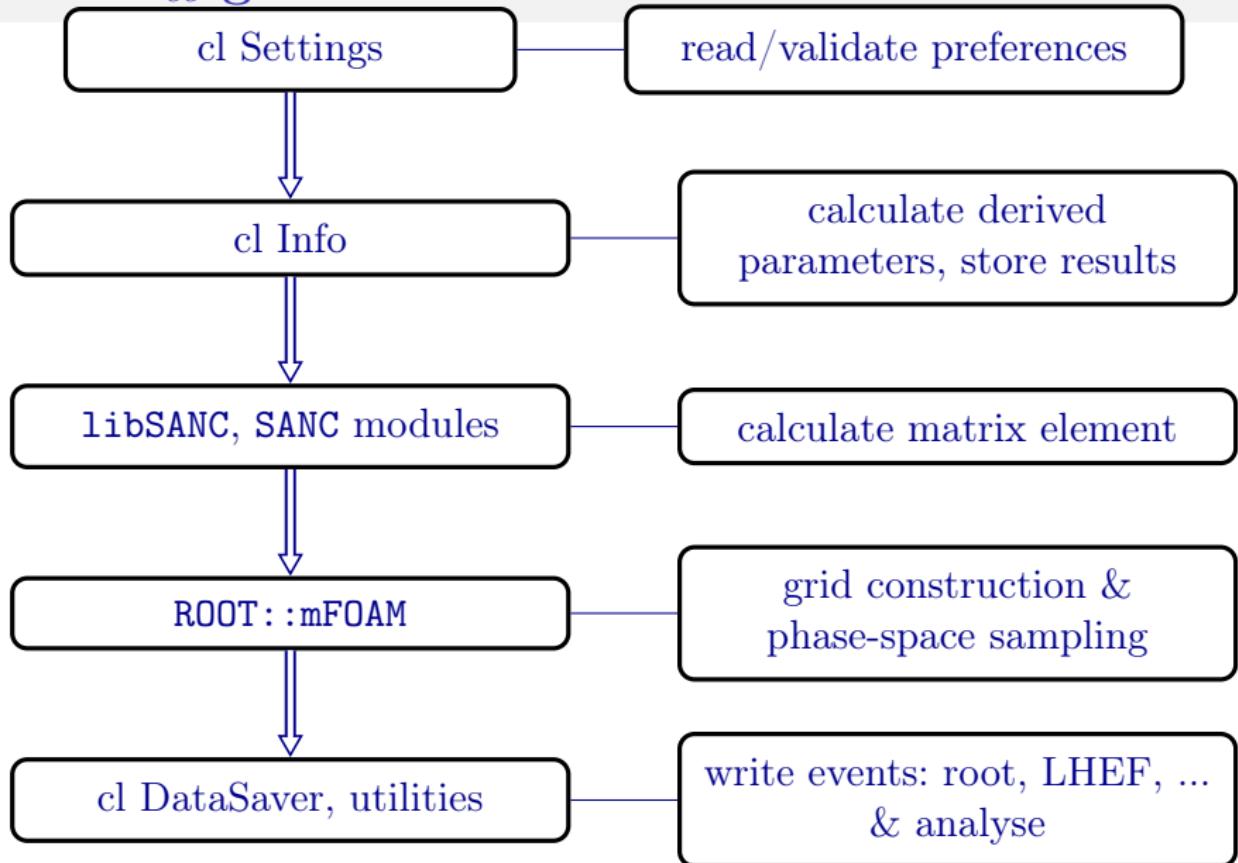


The cross sections are given for polar angles between  $10^\circ < \theta < 170^\circ$  in the final state.

# The SANC/ARIeL framework and products family



## MCSANC<sub>ee</sub> generator



# MCSANC<sub>ee</sub> generator

- CMAKE build system
- Modular architecture
- c++ & fortran
- For sampling used adaptive algorithm **mFOAM** (**CPC** 177:441-458,2007) which is part of **ROOT** program

# MCSANC<sub>ee</sub> settings

```

schema: {
properties: {
#!!!!!!!!!!!!!!!
# Process id:
pid : {type: integer, minimum: 101, maximum: 107}
    # 101 - e^+e^- --> e^-e^+
    # 102 - e^+e^- |--> mu^-mu^+
    # 103 - e^+e^- --> ZH
    # 104 - e^+e^- --> gamma gamma
#!!!!!!!!!!!!!!!
# ALR:
alr : {type: integer, minimum: 0, maximum: 2, default: 0}
# 0 - sigma, 1 - sigma RL-sigma LR, 2 - sigma RL+sigma LR
#!!!!!!!!!!!!!!!
# Process id:
pid : 103 # 101 - e^+e^- --> e^-e^+
    # 102 - e^+e^- --> mu^-mu^+
    # 103 - e^+e^- --> ZH
    # 104 - e^+e^- --> gamma gamma
#!!!!!!!!!!!!!!!
# ALR:
alr : 0 # 0 - sigma, 1 - sigma RL-sigma_LR, 2 - sigma RL+sigma_LR
#!!!!!!!!!!!!!!!
# Longitudinal polarization of initial particles:
lamep : 0 # e^+ polarization
lamem : -0.8 # e^- polarization
#!!!!!!!!!!!!!!!

```

**Validation of 'pid'=108' failed:**  
 'number is too big: 108.000, maximum is: 107.000'  
**Requirements:**  
 type = "integer";  
 minimum = 101;  
 maximum = 107;

# MCSANC<sub>ee</sub>: NLO EW RC for polarized scattering

- NLO EW corrections for polarized  $e^+e^-$  scattering:
  - $e^+e^- \rightarrow e^+e^-$  (Bhabha) ([Phys. Rev. D 98, 013001](#))
  - $e^+e^- \rightarrow ZH$  ([Phys. Rev. D 100, 073002](#))
  - $e^+e^- \rightarrow \mu^+\mu^-$  (or  $\tau^+\tau^-$ ) ([preliminary](#))
  - $e^+e^- \rightarrow Z\gamma$  ([preliminary](#))
  - $e^+e^- \rightarrow \gamma\gamma$  ([preliminary](#))
  - $e^+e^- \rightarrow t\bar{t}$  ([in progress](#))
  - $e^+e^- \rightarrow \nu\bar{\nu}H$  ([in progress](#))
  - $e^+e^- \rightarrow ZZ$  ([in progress](#))
  - $e^+e^- \rightarrow f\bar{f}\gamma$  ([future plans](#))
  - $e^+e^- \rightarrow f\bar{f}H$  ([future plans](#))
- NLO EW corrections for polarized  $\gamma\gamma$  scattering:
  - $\gamma\gamma \rightarrow e^+e^-$  ([in progress](#))
  - $\gamma\gamma \rightarrow \gamma\gamma$  ([future plans](#))
  - $\gamma\gamma \rightarrow Z\gamma$  ([future plans](#))
  - $\gamma\gamma \rightarrow ZZ$  ([future plans](#))

# Results for $e^+e^- \rightarrow e^+e^-$ (Bhabha)

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

Born and 1-loop cross sections of Bhabha scattering and the corresponding relative corrections  $\delta$  for  $\sqrt{s} = 250, 500$  and  $1000$  GeV.

# Results for $e^+e^- \rightarrow ZH$

$P_{e^-}$	$P_{e^+}$	$\sigma^{\text{hard}}, \text{fb}$	$\sigma^{\text{Born}}, \text{fb}$	$\sigma^{\text{1-loop}}, \text{fb}$	$\delta, \%$
0	0	82.0(1)	225.59(1)	206.91(1)	-8.28(1)
-0.8	0	47.6(1)	266.05(1)	223.52(2)	-15.99(1)
-0.8	-0.6	46.3(1)	127.42(1)	111.76(2)	-12.29(1)
-0.8	0.6	147.1(1)	404.69(1)	335.28(1)	-17.15(1)

Hard, Born and 1-loop cross sections in fb of the process  $e^+e^- \rightarrow ZH$  and relative correction  $\delta$  in percents for energy 250 GeV and various polarizations of initial particles produced by **MCSANC<sub>ee</sub>**.

# Results for $e^+e^- \rightarrow \tau^+\tau^-$

$P_{e^+}$	$P_{e^-}$	$\sigma^{\text{Born}}, \text{ pb}$	$\sigma^{\text{1-loop}}, \text{ pb}$	$\delta, \%$
0	0	2703.1(1)	2220(1)	-17.9(1)
-0.6	-0.8	1405.5(1)	1037(1)	-26.2(1)
0	-0.8	2702.6(1)	1747(1)	-35.4(1)
0.6	-0.8	3999.8(1)	2457(1)	-38.6(1)

Impact of 1-loop electroweak corrections on  $e^+e^- \rightarrow \tau^-\tau^+$  cross-section,  $\sqrt{S} = 5 \text{ GeV}$ ,  $|\cos\theta_{\tau^-}| < 0.9$ ,  $|\cos\theta_{\tau^+}| < 0.9$ .

# Historical overview: $Z\gamma$ production

For the first time the process

$$e^+ + e^- \rightarrow Z + \gamma, \quad (1)$$

was considered in the papers:

- 1) M. Capdequi Peyranere, Y. Loubatieres, M. Talon, Weak radiative corrections to  $e^+e^- \rightarrow Z\gamma$ , Nuovo Cimento, 90A, 63, 1985
- 2) F.A. Berends, G.J.H. Burgers, W.L. Van Neerven, QED radiative corrections to the reaction  $e^+e^- \rightarrow Z\gamma$ , Phys. Lett. B, 177, 191-194, 1986
- 3) M. Bohm and Th. Sack, Electroweak radiative corrections to  $e^+e^- \rightarrow \gamma Z^0$ , Z. Phys. C, 35, 119-128, 1987

### MC generators at tree level with polarization:

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

# Motivation: 1) anomalous neutral triple couplings

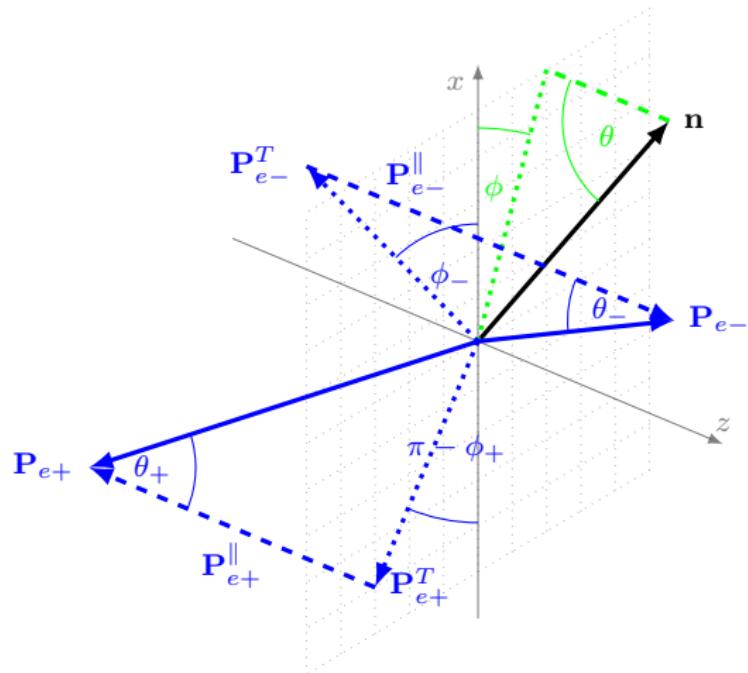
For the process  $e^+e^- \rightarrow Z\gamma$  it is convenient to study the anomalous neutral triple gauge couplings  $Z\gamma Z$  and  $Z\gamma\gamma$  which obey Lorentz and gauge invariance. Process  $e^+e^- \rightarrow Z\gamma$  is well suited to search for non-zero  $ZZ\gamma$  and  $Z\gamma\gamma$  couplings, which vanish in the Standard Model, and could thus provide a clean signal of new physics.

The constraints on the neutral gauge boson couplings,  $ZZ\gamma$  and  $Z\gamma\gamma$ , are investigated at linear  $e^+e^-$  collider energies through the  $Z\gamma$  production with longitudinal and transverse polarization states of the final  $Z$  boson.

## Motivation: 2) main background for Higgs boson

Also this process is a main background in the new method for Higgs boson measurements which is provided by the ILC. This method should identify Higgs boson events independently of the decay mode, allowing the measurement of the total cross section for Higgs production and the discovery of exotic and unanticipated Higgs decays. It is the measurement of the reaction  $eeZH$  at 250 GeV. At an  $e + e -$  collider at this energy, it is true to a first approximation that any  $Z$  boson observed with a lab energy of 110 GeV is recoiling against a Higgs boson. The backgrounds to this signature come from radiative  $e^+e^- \rightarrow Z\gamma$  and  $e^+e^- \rightarrow ZZ$ . We try to estimate contribution with the polarization effects.

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



# Matrix element squared

$$|\mathcal{M}|^2 = L_{e^-}^{\parallel} R_{e^+}^{\parallel} |\mathcal{H}_{-+}|^2 + R_{e^-}^{\parallel} L_{e^+}^{\parallel} |\mathcal{H}_{+-}|^2 + L_{e^-}^{\parallel} L_{e^+}^{\parallel} |\mathcal{H}_{--}|^2 + R_{e^-}^{\parallel} R_{e^+}^{\parallel} |\mathcal{H}_{++}|^2$$

$$- \frac{1}{2} P_{e^-}^{\perp} P_{e^+}^{\perp} \operatorname{Re} \left[ e^{i(\Phi_+ - \Phi_-)} \mathcal{H}_{++} \mathcal{H}_{--}^* + e^{i(\Phi_+ + \Phi_-)} \mathcal{H}_{+-} \mathcal{H}_{-+}^* \right]$$

$$+ P_{e^-}^{\perp} \operatorname{Re} \left[ e^{i\Phi_-} \left( L_{e^+}^{\parallel} \mathcal{H}_{+-} \mathcal{H}_{--}^* + R_{e^+}^{\parallel} \mathcal{H}_{++} \mathcal{H}_{-+}^* \right) \right]$$

$$- P_{e^+}^{\perp} \operatorname{Re} \left[ e^{i\Phi_+} \left( L_{e^-}^{\parallel} \mathcal{H}_{-+} \mathcal{H}_{--}^* + R_{e^-}^{\parallel} \mathcal{H}_{++} \mathcal{H}_{+-}^* \right) \right],$$

where

$$L_{e^{\pm}}^{\parallel} = \frac{1}{2}(1 - P_{e^{\pm}}^{\parallel}), \quad R_{e^{\pm}}^{\parallel} = \frac{1}{2}(1 + P_{e^{\pm}}^{\parallel}), \quad \Phi_{\pm} = \phi_{\pm} - \phi,$$

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

# SANC: basics, scheme of FF calculation

- All calculations at the one-loop precision level are realized in the  $R_\xi$  gauge with three calibration parameters:  $\xi_A$ ,  $\xi_Z$  and  $\xi \equiv \xi_W$  (checking cancellation of gauge parameter dependence).
- To parameterize the ultraviolet divergences used dimensional regularization (checking cancellation of UV poles).
- To test symmetry properties and validity of the Ward identities, all at the level of analytical expressions: vanishing of EWFF in front of CP-odd structures and Ward identities:  $A_{\mu\nu} \cdot (p_\gamma)_\nu = 0$  (transverse nature of photons).
- Loop integrals are expressed in terms of standard scalar Passarino-Veltman functions:  $A_0$ ,  $B_0$ ,  $C_0$ ,  $D_0$ .

# 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:

$\sigma^{\text{Born}}$  — Born level cross-section,

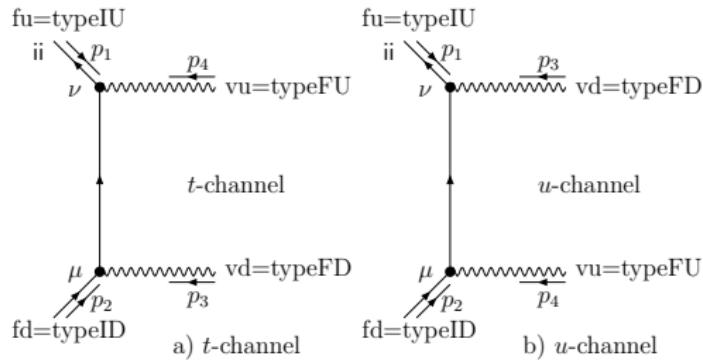
$\sigma^{\text{virt}}$  — virtual(loop) corrections,

$\sigma^{\text{soft}}$  — soft photon emission,

$\sigma^{\text{hard}}$  — hard photon emission (with energy  $E_\gamma > \omega$ ).

Auxiliary parameters  $\lambda$  ("photon mass") and  $\omega$  cancel out after summation.

## Born level, $e^+e^- \rightarrow Z\gamma$ , $t$ and $u$ channels



`fu=typeIU ...` - “types” of external particles

$$s = -(p_1 + p_2)^2, t = -(p_2 + p_3)^2, u = -(p_2 + p_4)^2,$$

$$s' = -(p_3 + p_4)^2, t' = -(p_1 + p_4)^2, u' = -(p_1 + p_3)^2,$$

$$Z_1 = -2p_1p_5, Z_2 = -2p_2p_5, Z_3 = -2p_3p_5, Z_4 = -2p_4p_5.$$

# Covariant amplitude

$$\mathcal{A}_{\bar{f}_1 f_1 Z \gamma} = \bar{v}(p_1) \left[ \text{Str}_{\mu\nu}^0 \left( v_f \mathcal{F}_v^0 + a_f \gamma_5 \mathcal{F}_a^0 \right) + \sum_{j=1}^{13} \text{Str}_{\mu\nu}^j \left( \mathcal{F}_v^j + \gamma_5 \mathcal{F}_a^j \right) \right] u(p_2) \varepsilon_\nu^\gamma(p_3) \varepsilon_\mu^Z(p_4),$$

$$\text{Str}_{\mu\nu}^0 = i \left[ \frac{1}{2} \left( \frac{1}{k_u} + \frac{1}{k_t} \right) \gamma_\mu \not{p}_3 \gamma_\nu + \frac{1}{k_u} (\not{p}_3 \delta_{\mu\nu} - \gamma_\nu p_{3\mu}) - \left( \frac{1}{k_u} p_{1\nu} - \frac{1}{k_t} p_{2\nu} \right) \gamma_\mu \right],$$

$$\text{Str}_{\mu\nu}^1 = i \gamma_\mu \not{p}_3 \gamma_\nu, \quad \text{Str}_{\mu\nu}^2 = \not{p}_3 \gamma_\nu p_{1\mu}, \quad \text{Str}_{\mu\nu}^4 = \gamma_\mu \left( \not{p}_3 p_{1\nu} - \frac{1}{2} k_u \gamma_\nu \right),$$

$$\text{Str}_{\mu\nu}^6 = i \left( \not{p}_3 p_{1\nu} - \frac{1}{2} k_u \gamma_\nu \right) p_{1\mu}, \quad \text{Str}_{\mu\nu}^8 = i \left( \not{p}_3 p_{1\nu} - \frac{1}{2} k_u \gamma_\nu \right) p_{2\mu},$$

$$\text{Str}_{\mu\nu}^{10} = i (\not{p}_3 \delta_{\mu\nu} - \gamma_\nu p_{3\mu}), \quad \text{Str}_{\mu\nu}^{11} = i \gamma_\mu [k_t p_{1\nu} - k_u p_{2\nu}],$$

$$\text{Str}_{\mu\nu}^{12} = p_{1\mu} p_{2\nu} + p_{2\mu} p_{2\nu} + \frac{1}{2} k_t \delta_{\mu\nu}, \quad \text{Str}_{\mu\nu}^{13} = [k_t p_{1\nu} - k_u p_{2\nu}] p_{2\mu}.$$

where  $k_i = m_e^2 - I$ ,  $I = t, u$ .

$\text{Str}_{\mu\nu}^{3,5,7,9}$  can be obtained from  $\text{Str}_{\mu\nu}^{2,4,6,8}$  by replacing  $p_{1j} \rightarrow p_{2j}$ ,  $u \rightarrow t$ .

# HA: virtual part

One-loop corrections for this process are symmetric in  $u \leftrightarrow t$   
( therefore no  $A_{fb}$ )

$$\begin{aligned} & \mathcal{H}_{\mp\mp\mp\mp}, \mathcal{H}_{\mp\mp\mp 0}, \mathcal{H}_{\mp\mp\mp\pm}, \mathcal{H}_{\mp\mp\pm\mp}, \mathcal{H}_{\mp\mp\pm 0}, \mathcal{H}_{\mp\mp\pm\pm}, \\ & \mathcal{H}_{\pm\mp\pm\pm}, \mathcal{H}_{\pm\mp\mp\mp}, \mathcal{H}_{\pm\mp\mp\pm}, \mathcal{H}_{\pm\mp\pm\mp}, \mathcal{H}_{\pm\mp\pm 0}, \mathcal{H}_{\mp\pm\pm 0}. \end{aligned}$$

# HA: virtual part, example

$$\begin{aligned}\mathcal{H}_{\pm\mp\pm 0} &= \frac{1}{8\sqrt{2}} \frac{\sqrt{s}}{M_Z} c_+ \left[ \frac{8M_Z^2}{Z_1(m_e)} \mathcal{F}_0^\pm + (t+u) \left( k_2 \mathcal{F}_6^\pm \right. \right. \\ &\quad \left. \left. + k_1 \mathcal{F}_8^\pm - 4 \mathcal{F}_{10}^\pm - 2k_+ c_- \mathcal{F}_{11}^\pm \right) \right], \\ \mathcal{H}_{\mp\pm\pm 0} &= -\frac{1}{8\sqrt{2}} \frac{\sqrt{s}}{M_Z} c_- \left[ \frac{8M_Z^2}{Z_2(m_e)} \mathcal{F}_0^\pm - (t+u) \left( 8 \mathcal{F}_1^\pm + k_2 \mathcal{F}_7^\pm \right. \right. \\ &\quad \left. \left. + k_1 \mathcal{F}_9^\pm - 4 \mathcal{F}_{10}^\pm + 2k_+ c_+ \mathcal{F}_{11}^\pm \right) \right].\end{aligned}$$

Here

$$\begin{aligned}\mathcal{F}^{\pm,0} &= v_f \mathcal{F}_v^0(s, t, u) \pm a_f \mathcal{F}_a^0(s, t, u), \quad \mathcal{F}^{\pm,j} = \mathcal{F}_v^j(s, t, u) \pm \mathcal{F}_a^j(s, t, u), \\ k_{1,2} &= sc_\pm - M_Z^2 c_\mp, \quad \text{with } c_\pm = 1 \pm \cos \theta_\gamma.\end{aligned}$$

# HA: hard photon Bremsstrahlung

$$\mathcal{H}_{+-h_3+h_5} = 2e^3 \frac{v_f + a_f}{M_Z^2} A_{h_3 h_5} \left( \begin{smallmatrix} 1, & 2, & 4, & \bar{4} \\ \bar{1}, & \bar{2}, & \bar{4}, & \underline{4} \end{smallmatrix} \right),$$

$$\mathcal{H}_{-+h_3+h_5} = 2e^3 \frac{v_f - a_f}{M_Z^2} A_{h_3 h_5} \left( \begin{smallmatrix} \bar{1}, & \bar{2}, & 4, & \bar{4} \\ -1, & -2, & \bar{4}, & \underline{4} \end{smallmatrix} \right),$$

$$\mathcal{H}_{-+h_3-h_5} = 2e^3 \frac{v_f - a_f}{M_Z^2} A_{h_3 h_5} \left( \begin{smallmatrix} \bar{1}, & \bar{2}, & \bar{4}, & -\bar{4} \\ -1, & -2, & -4, & \bar{\underline{4}} \end{smallmatrix} \right).$$

$$\mathcal{H}_{+-h_30h_5} = 2e^3 \frac{v_f + a_f}{M_Z^2} \left[ A_{h_3 h_5} \left( \begin{smallmatrix} 1, & 2, & 4, & -\bar{4} \\ \bar{1}, & \bar{2}, & \bar{4}, & \bar{\underline{4}} \end{smallmatrix} \right) + A_{h_3 h_5} \left( \begin{smallmatrix} 1, & 2, & \bar{4}, & \bar{4} \\ \bar{1}, & \bar{2}, & -4, & \underline{4} \end{smallmatrix} \right) \right].$$

$$A_{h_3 h_5} \left( \begin{smallmatrix} 1, & 2, & 4, & \bar{4} \\ \bar{1}, & \bar{2}, & \bar{4}, & \underline{4} \end{smallmatrix} \right) = \left\{ A_{-h_3,-h_5} \left( \begin{smallmatrix} 2, & 1, & 4, & \bar{4} \\ \bar{2}, & \bar{1}, & \bar{4}, & \underline{4} \end{smallmatrix} \right) \right\}^*.$$

# HA: Bremsstrahlung

$$\begin{aligned}
 A_{+-}\left(\frac{1}{\bar{1}}, \frac{2}{\bar{2}}, \frac{4}{\bar{4}}, \frac{4}{\bar{4}}\right) &= \frac{\langle 2 | 3 \rangle}{\langle 1 | 5 \rangle^3 \langle 4 | 2 \rangle^2 \langle 3 | 5 \rangle \langle 1 | \mathbf{23} | 4 | 3 \rangle} \times \\
 &\times \left[ \frac{\langle 1 | 3 \rangle \langle 1 | 5 \rangle^2 (\langle 4 | 2 \rangle \langle 4 | \mathbf{1} | 4 | 3 \rangle - s_{135} M_Z \langle 2 | 3 \rangle)^2}{s_{24} M_Z^2} + \right. \\
 &+ \frac{(\langle 1 | \mathbf{23} | 4 | 3 \rangle - s_{23} \langle 1 | 3 \rangle)}{s_{14} s_{23} s_{35}} \times \\
 &\times \left. (s_{35} M_Z \langle 1 | 5 \rangle \langle 2 | 3 \rangle + \langle 4 | 2 \rangle \langle 3 | 5 \rangle \langle 1 | \mathbf{3} | \mathbf{24} | 4 \rangle)^2 \right] + (3 \leftrightarrow 5) \\
 A_{++}\left(\frac{1}{\bar{1}}, \frac{2}{\bar{2}}, \frac{4}{\bar{4}}, \frac{4}{\bar{4}}\right) &= -\frac{\langle 4 | 2 \rangle^2}{\langle 2 | 3 \rangle \langle 3 | 5 \rangle \langle 5 | 1 \rangle} + (3 \leftrightarrow 5)
 \end{aligned}$$

with abbreviations:

$$u(p_k) \rightarrow k, \quad \bar{u}(p_k) \rightarrow \bar{k}, \quad \gamma_5 u(p_k) \rightarrow \underline{k}$$

$$s_{i\dots k} = (p_i + \dots + p_k)^2, \quad \hat{p}_i + \dots + \hat{p}_k \rightarrow \mathbf{i} \dots \mathbf{k}$$

# 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

$$\begin{aligned} \alpha^{-1}(0) &= 137.03599976, & M_W &= 80.451495 \text{ GeV}, & \Gamma_W &= 2.0836 \text{ GeV}, \\ M_H &= 125.0 \text{ GeV}, & M_Z &= 91.1867 \text{ GeV}, & \Gamma_Z &= 2.49977 \text{ GeV}, \\ m_e &= 0.5109990 \text{ MeV}, & m_\mu &= 0.105658 \text{ GeV}, & m_\tau &= 1.77705 \text{ GeV}, \\ m_d &= 0.083 \text{ GeV}, & m_s &= 0.215 \text{ GeV}, & m_b &= 4.7 \text{ GeV}, \\ m_u &= 0.062 \text{ GeV}, & m_c &= 1.5 \text{ GeV}, & m_t &= 173.8 \text{ GeV}. \end{aligned}$$

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

**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

# $e^+e^- \rightarrow Z\gamma$ : MCSANC<sub>ee</sub> vs CalcHep vs WHIZARD (Born), fb

MCSANC <sub>ee</sub>	WHIZARD	CalcHep
2.6976(1)	2.6976(1)	2.6976(1)

$$e^+e^- \rightarrow Z\gamma, \sqrt{S} = 1000 \text{ GeV}$$

# $e^+e^- \rightarrow Z\gamma$ : MCSANC<sub>ee</sub> vs CalcHep vs WHIZARD (Hard with cuts), fb

MCSANC <sub>ee</sub>	WHIZARD	CalcHep
6.016(1)	6.016(1)	6.03(1)

$e^+e^- \rightarrow Z\gamma$ ,  $\sqrt{S} = 250$  GeV,  $\omega = 10^{-4}$ ,  $1^\circ < \theta_{\gamma_{all}} < 179^\circ$ ,  
 $1^\circ < \theta_Z < 179^\circ$ .

# $e^+e^- \rightarrow Z\gamma$ : MCSANC<sub>ee</sub> vs WHIZARD (Hard), fb

$P_{e^+}$	$P_{e^-}$	code	$\sigma^{\text{hard}}$ , pb
-1	-1	MCSANC <sub>ee</sub>	2.51(1)
		WHIZARD	2.53(1)
-1	1	MCSANC <sub>ee</sub>	69.71(2)
		WHIZARD	69.75(1)
1	-1	MCSANC <sub>ee</sub>	110.04(3)
		WHIZARD	110.07(2)
1	1	MCSANC <sub>ee</sub>	2.45(1)
		WHIZARD	2.53(1)

$$e^+e^- \rightarrow Z\gamma, \sqrt{S} = 250 \text{ GeV}, \omega = 10^{-4}.$$

# $e^+e^- \rightarrow Z\gamma$ : MCSANC<sub>ee</sub> vs WHIZARD (Hard), fb

$P_{e^+}$	$P_{e^-}$	code	$\sigma^{\text{hard}}$ , pb
-1	-1	MCSANCee	0.73(1)
		WHIZARD	0.76(1)
-1	1	MCSANCee	17.03(1)
		WHIZARD	17.05(1)
1	-1	MCSANCee	26.88(1)
		WHIZARD	26.90(1)
1	1	MCSANCee	0.72(1)
		WHIZARD	0.76(1)

$$e^+e^- \rightarrow Z\gamma, \sqrt{S} = 500 \text{ GeV}, \omega = 10^{-4}.$$

# $e^+e^- \rightarrow Z\gamma$ : MCSANC<sub>ee</sub> vs WHIZARD (Hard), fb

$P_{e^+}$	$P_{e^-}$	code	$\sigma^{\text{hard}}$ , pb
-1	-1	MCSANCee	0.198(1)
		WHIZARD	1.032(2)
-1	1	MCSANCee	4.605(1)
		WHIZARD	16.63(3)
1	-1	MCSANCee	7.265(2)
		WHIZARD	26.43(3)
1	1	MCSANCee	0.196(3)
		WHIZARD	1.043(3)

$$e^+e^- \rightarrow Z\gamma, \sqrt{S} = 1000 \text{ GeV}, \omega = 10^{-4}.$$

$e^+e^- \rightarrow Z\gamma$ : MCSANC<sub>ee</sub>, ( $\sigma^{1\text{-loop}}$ , pb) vs ( $P_{e^+}$  &  $P_{e^-}$ )

$P_{e^+}$	$P_{e^-}$	$\sigma^{\text{Born}}, \text{pb}$	$\sigma^{1\text{-loop}}, \text{pb}$	$\delta, \%$
0	0	4.0698(3)	4.256(3)	4.6(1)
-0.6	-0.8	2.3050(2)	2.338(2)	1.4(1)
0	-0.8	4.8248(5)	4.752(5)	-1.5(1)
0.6	-0.8	7.3445(7)	7.166(7)	-2.4(1)

 $e^+e^- \rightarrow Z\gamma, \sqrt{S} = 250 \text{ GeV}, |\cos \theta_{\gamma hard}| < 0.9, |\cos \theta_Z| < 0.9.$

# RESUME: MCSANC<sub>ee</sub>

- Monte Carlo event generator MCSANC<sub>ee</sub> is under development.
  - Events with unit weights.
  - Polarized initial beams.
  - Complete one-loop EW corrections.
  - Possibility to produce events in Standard Les Houches Format.
  - Simple installation & usage.
  - Validation of input parameters.
- Polarized  $e^+e^- \rightarrow Z\gamma$  scattering implemented in MCSANC<sub>ee</sub>.
  - Good stability for Born and hard in wide phase space region.
  - Virt corrections still only work with cuts on scattering angle.