

Implementation of polarized $e^+e^- \rightarrow \gamma\gamma$ process in MCSANC

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Modern Problems in Nuclear and Elementary Particle Physics

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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 μ 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 $\leq 10^{-3}$

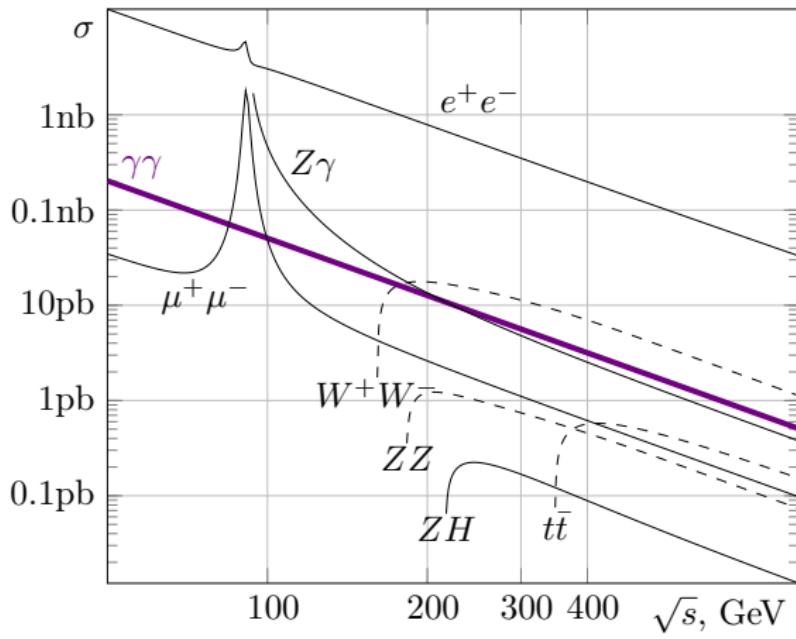
Beam polarization

- Desired (?)

MCSANC_{ee}: 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](#))
 - $e^+e^- \rightarrow ZH$ ([arXiv:1812.10965](#))
 - $e^+e^- \rightarrow \mu^+\mu^-$ (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)

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.

Historical overview: Radiative corrections to Compton scattering

For the first time the process

$$e^+(p_1) + e^-(p_2) \longrightarrow \gamma(p_3) + \gamma(p_4), \quad (1)$$

was considered in the classical papers:

- 1) L. M. Brown and R. P. Feynman, Radiative corrections to Compton scattering, Phys. Rev., 85, 1952
- 2) I. Harris and L. M. Brown, Radiative Corrections to Pair Annihilation, Phys. Rev., 105, 1 957

Later on revised

- 3) Berends, Frits A. and Gastmans, R., Hard photon corrections for $e^+ e^- \rightarrow \text{gamma gamma}$, Nucl. Phys., B61, 1973.

MC generators at 1-loop level without polarization:

- Eur Phys J.(2011) 71:1597
Monte-Carlo generator photon jets for the process $e^+ e^- \rightarrow \gamma\gamma$
S.I. Eidelman 1,2 , G.V. Fedotovich 1,2,a , E.A. Kuraev 3 , A.L. Sibidanov.
- Report “ $e^+ e^- \rightarrow \gamma\gamma$ for FCCee lumi” C.M. Carloni Calame, M.Chiesa, G. Montagna, O. Nicrosini, F. Piccinini, in 11 FCC-ee workshop: Theory & Experiment

MC generators with polarization:

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

Motivation: an additional tool to measure luminosity

- Precise determination of luminosity is a key ingredient in all experiments.

- **two-gamma-quantum annihilation**

$$e^+ e^- \rightarrow \gamma + \gamma,$$

- **Bhabha scattering**

$$e^+ e^- \rightarrow e^+ e^-$$

- **annihilation into a muon pair**

$$e^+ e^- \rightarrow \mu^+ \mu^-$$

Motivation: large cross section & no $\Pi_{\gamma\gamma}$ at NLO

- The cross section value estimated for large angles is **large enough**.

Events of this process have two collinear photons at large angles providing **a clean signature** for their selection among other detected particles.

- **No vacuum polarization effects.**

No source of uncertainty $\Pi_{\gamma\gamma}$.

Required accuracy

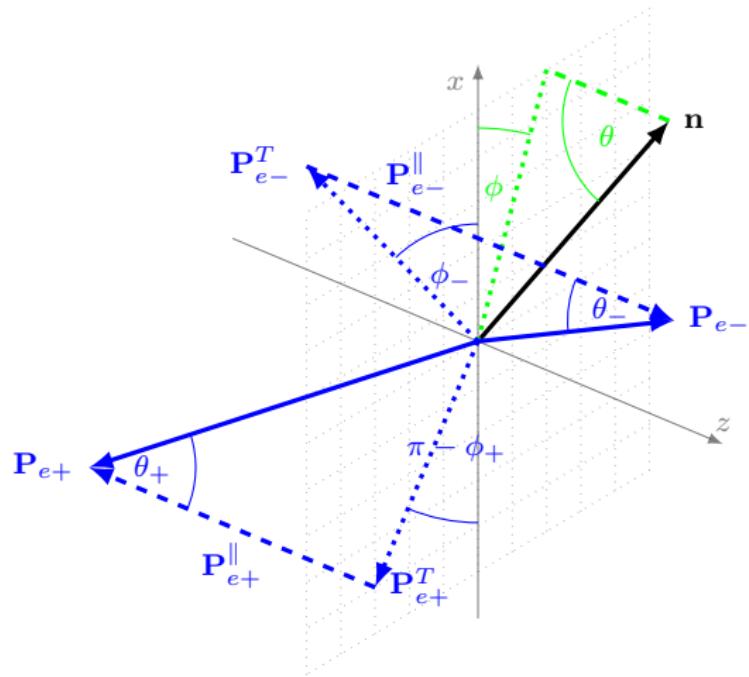
Cross section with radiative corrections (RC) at the level of per mill accuracy is needed (**or even 10^{-4}**):

- 1-loop level+polarization – done
- matching, $e^+e^- \rightarrow \gamma\gamma + n\gamma$ – soon Implementation of works:
 - Frits A. Berends, R. Kleiss, et al., Nucl. Phys., B239, (1984)
 - E.A. Kuraev, V.S. Fadin, Sov.J.Nucl.Phys, **41**, 466 (1985)
- **NNLO corrections**

SANC: basics, procedures

- Covariant amplitudes (CA) — \mathcal{CA}
- Scalar Form Factors (FF) — \mathcal{F}_i
- Helicity Amplitudes (HA) — $\mathcal{H}_{\{\lambda_i\}}(\mathcal{F}_i)$
standard approach: $\sigma \propto |\mathcal{CA}|^2$
while in terms of HA: $\sigma \propto \sum_{\{\lambda_i\}} |\mathcal{H}_{\{\lambda_i\}}|^2$
- Bremsstrahlung using HA: (BR)
- Analytical computing modules: FF, HA, BR

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

- 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 $\xi \equiv \xi_W$.
- To parameterize the ultraviolet divergences used dimensional regularization.
- 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:

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

where σ^{Born} — Born level cross-section,

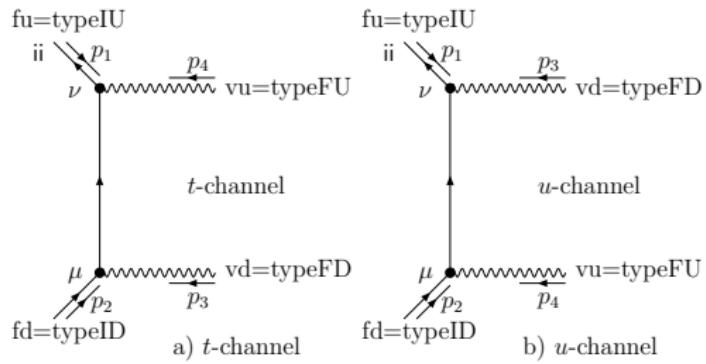
σ^{virt} — virtual(loop) corrections,

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.

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



$fu=\text{typeIU} \dots$ - “types” of external particles

$$\begin{aligned}
 s &= -(p_1 + p_2)^2, t = -(p_2 + p_3)^2, u = -(p_2 + p_4)^2, \\
 s' &= -(p_3 + p_4)^2, t' = -(p_1 + p_4)^2, u' = -(p_1 + p_3)^2, \\
 Z_1 &= -2p_1 p_5, Z_2 = -2p_2 p_5, Z_3 = -2p_3 p_5, Z_4 = -2p_4 p_5.
 \end{aligned}$$

Covariant amplitude

$$\mathcal{CA} = \sum_{i=1}^8 Str(\mathcal{F}_{V_i})\mathcal{F}_{V_i}(s, t, u) + \sum_{i=1}^4 Str(\mathcal{F}_{A_i})\mathcal{F}_{A_i}(s, t, u).$$

Massive basis

We introduce massive analogs of massless X,Y operators (14.58-14.59) and write structures using them.

- **CP-even**

$$\begin{aligned}
 X_{\pm\alpha\beta}^1 &= \frac{1}{\sqrt{s}} \bar{v} \gamma_{\pm} \gamma_{\alpha} (\not{p}_+ + \not{q}_+) \gamma_{\beta} u, & X_{\pm\alpha\beta}^2 &= \frac{1}{\sqrt{s}} \bar{v} \gamma_{\pm} \not{q}_- u \delta_{\alpha\beta}, \\
 X_{\pm\alpha\beta}^3 &= \frac{1}{\sqrt{s}} \bar{v} \gamma_{\pm} (\gamma_{\alpha} q_{+\beta} - \gamma_{\beta} q_{-\alpha}) u, & X_{\pm\alpha\beta}^4 &= \frac{1}{\sqrt{s}} \bar{v} \gamma_{\pm} (\gamma_{\alpha} p_{-\beta} - \gamma_{\beta} p_{+\alpha}) u, \\
 X_{\pm\alpha\beta}^5 &= \frac{1}{s\sqrt{s}} \bar{v} \gamma_{\pm} \not{q}_- q_{-\alpha} q_{+\beta} u, & X_{\pm\alpha\beta}^6 &= \frac{1}{s\sqrt{s}} \bar{v} \gamma_{\pm} \not{q}_- p_{+\alpha} p_{-\beta} u, \\
 X_{\pm\alpha\beta}^7 &= \frac{1}{s\sqrt{s}} \bar{v} \gamma_{\pm} \not{q}_- (q_{-\alpha} p_{-\beta} + p_{+\alpha} q_{+\beta}) u.
 \end{aligned} \tag{14.58}$$

- **CP-odd**

$$\begin{aligned}
 Y_{\pm\alpha\beta}^1 &= \frac{1}{\sqrt{s}} \bar{v} \gamma_{\pm} (\gamma_{\alpha} q_{+\beta} + \gamma_{\beta} q_{-\alpha}) u, & Y_{\pm\alpha\beta}^2 &= \frac{1}{\sqrt{s}} \bar{v} \gamma_{\pm} (\gamma_{\alpha} p_{-\beta} + \gamma_{\beta} p_{+\alpha}) u, \\
 Y_{\pm\alpha\beta}^3 &= \frac{1}{s\sqrt{s}} \bar{v} \gamma_{\pm} \not{q}_- (q_{-\alpha} p_{-\beta} - p_{+\alpha} q_{+\beta}) u.
 \end{aligned} \tag{14.59}$$

D. Bardin and G. Passarino book 'The Standard Model in the Making'

Vector structures general view

$$\begin{aligned} Str(\mathcal{F}_{V_0}) &= (iK_2 - m_l)\gamma^\mu\gamma^\nu \\ &+ 2i\frac{m_l^2 - t}{s} \left(\gamma^\mu p_4^\nu - \gamma^\nu p_3^\mu + \frac{1}{2}(\not{p}_3 - \not{p}_4)\delta^{\mu\nu} \right). \end{aligned}$$

$$K_2 = \frac{1}{2} (\not{p}_3 - \not{p}_4 + \not{p}_2 - \not{p}_1).$$

Vector structures: minimized view

$$\begin{aligned}
 Str(\mathcal{F}_{V_1}) &= (iK_2 - m_l) \tau_7^{\mu\nu} - 2i \frac{m_l^2 - t}{s} \left(\tau_9^{\mu\nu} - \tau_{11}^{\mu\nu} + \frac{1}{2} (\not{p}_3 - \not{p}_4) \tau_{12}^{\mu\nu} \right), \\
 Str(\mathcal{F}_{V_2}) &= iK_2 \tau_3^{\mu\nu}, \\
 Str(\mathcal{F}_{V_3}) &= -\frac{1}{2} \frac{m_l^2 - t}{s} [i\tau_1^{\mu\nu} + 2\tau_4^{\mu\nu} + 2m_l (\tau_5^{\mu\nu} - (m_l^2 - t)\tau_{12}^{\mu\nu})] \\
 &\quad + iK_2 \tau_6^{\mu\nu}, \\
 Str(\mathcal{F}_{V_4}) &= \frac{i}{2} \tau_1^{\mu\nu} + iK_2 2\tau_4^{\mu\nu} + (iK_2 + m_l) \tau_5^{\mu\nu} - m_l(m_l^2 - t)\tau_{12}^{\mu\nu},
 \end{aligned}$$

Vector structures: minimized view

$$Str(\mathcal{F}_{V_5}) = 4i \frac{m_l}{m_l^2 - t} K_2 \tau_4^{\mu\nu} + \frac{1}{2} s \tau_7^{\mu\nu} + \not{p}_4 \tau_9^{\mu\nu} + \not{p}_3 \tau_{11}^{\mu\nu} - (m_l^2 + t) \tau_{12}^{\mu\nu},$$

$$\begin{aligned} Str(\mathcal{F}_{V_6}) &= \frac{2}{s} \left[(m_l^2 - t) \left(\tau_5^{\mu\nu} + \frac{s}{4} \tau_7^{\mu\nu} - \frac{3m_l^2 - t}{2} \tau_{12}^{\mu\nu} \right) \right. \\ &\quad \left. + im_l (\tau_1^{\mu\nu} + 2K_2 \tau_4^{\mu\nu}) \right] + \not{p}_4 \tau_8^{\mu\nu} + \not{p}_3 \tau_{10}^{\mu\nu}, \end{aligned}$$

$$Str(\mathcal{F}_{V_7}) = \frac{1}{2} s \tau_3^{\mu\nu},$$

$$Str(\mathcal{F}_{V_8}) = \tau_6^{\mu\nu} + \frac{m_l^2 - t}{s} \left[\tau_5^{\mu\nu} - \frac{1}{2} (m_l^2 - t) \tau_{12}^{\mu\nu} \right].$$

Axial structures: minimized view

$$\begin{aligned}
 Str(\mathcal{F}_{A_1}) &= -iK_2 (\tau_4^{\mu\nu} - \tau_7^{\mu\nu}) \\
 &+ \frac{2i}{s} [(m_l^2 - t - im_l) \tau_9^{\mu\nu} + (m_l^2 - t + im_l) \tau_{11}^{\mu\nu}] \\
 Str(\mathcal{F}_{A_2}) &= iK_2 \frac{s}{m_l^2 - t} \tau_3^{\mu\nu}, \\
 Str(\mathcal{F}_{A_3}) &= -\frac{1}{2} \tau_2^{\mu\nu} - iK_2 (\tau_4^{\mu\nu} - \tau_6^{\mu\nu}), \\
 Str(\mathcal{F}_{A_4}) &= \frac{1}{2} \frac{s}{m_l^2 - t} \tau_2^{\mu\nu} + i (2\tau_4^{\mu\nu} + \tau_5^{\mu\nu}).
 \end{aligned}$$

Strings

$$\begin{aligned}
 \tau_1^{\mu\nu} &= \gamma^\mu \left[(m_l^2 - u)p_2^\nu - (m_l^2 - t)(p_1^\nu + p_3^\nu) \right] \\
 &\quad - \gamma^\nu \left[(m_l^2 - u)p_1^\mu - (m_l^2 - t)(p_2^\mu + p_4^\mu) \right], \\
 \tau_2^{\mu\nu} &= (m_l K_2 - it) \gamma_\nu \left(p_1^\mu + \frac{m_l^2 - t}{s} p_3^\mu \right) \\
 &\quad + (m_l K_2 + it) \gamma_\mu \left(p_2^\nu + \frac{m_l^2 - t}{s} p_4^\nu \right), \\
 \tau_3^{\mu\nu} &= \delta^{\mu\nu} + 2 \frac{p_3^\mu p_4^\nu}{s}, & \tau_8^{\mu\nu} &= \gamma^\nu p_1^\mu, \\
 \tau_4^{\mu\nu} &= \frac{m_l^2 - t}{s} p_3^\mu p_4^\nu, & \tau_9^{\mu\nu} &= \gamma^\nu p_3^\mu, \\
 \tau_5^{\mu\nu} &= p_1^\mu p_4^\nu + p_2^\nu p_3^\mu, & \tau_{10}^{\mu\nu} &= \gamma^\mu p_2^\nu, \\
 \tau_6^{\mu\nu} &= p_1^\mu p_2^\nu, & \tau_{11}^{\mu\nu} &= \gamma^\mu p_4^\nu, \\
 \tau_7^{\mu\nu} &= \gamma^\mu \gamma^\nu, & \tau_{12}^{\mu\nu} &= \delta^{\mu\nu}.
 \end{aligned}$$

Helicity amplitudes

Amplitudes combine to 4 sets:

Set 1

$$\mathcal{H}_{-++-}, \mathcal{H}_{+-+-}, \mathcal{H}_{-+-+}, \mathcal{H}_{+-+-}.$$

Set 2

$$\mathcal{H}_{+-+-}, \mathcal{H}_{-+++}, \mathcal{H}_{-+--}, \mathcal{H}_{+---}.$$

Set 3

$$\mathcal{H}_{--+-}, \mathcal{H}_{++++}, \mathcal{H}_{+++-}, \mathcal{H}_{--+-}.$$

Set 4

$$\mathcal{H}_{++++}, \mathcal{H}_{-----}, \mathcal{H}_{--++}, \mathcal{H}_{+-+-}.$$

Helicity amplitudes $l^+l^- \rightarrow \gamma Z$. Example: set 1

$$\mathcal{H}_{-+-+} = N_1 c_+ [-V_{11} + A_{11}],$$

$$\mathcal{H}_{+-+-} = N_1 c_+ [V_{11} + A_{11}],$$

$$\mathcal{H}_{-++-} = N_1 c_- [V_{12} + A_{12}],$$

$$\mathcal{H}_{+--+} = N_1 c_- [-V_{12} + A_{12}].$$

$$N_1 = \frac{1}{8} s \beta \sin \theta_\gamma,$$

$$V_{11} = 4 \frac{s}{z_1 z_2} \mathcal{F}_{v_1} + \frac{s}{2} (2 - \beta c_+) \mathcal{F}_{v_3} - 2s \mathcal{F}_{v_4} + 4m_f \mathcal{F}_{v_6},$$

$$A_{11} = 4\beta \mathcal{F}_{a_1} - \frac{s}{2} [(\beta_-^2 - \beta^2 c_-) \mathcal{F}_{a_3} + (\beta_-^2 - 2\beta^2 c_-) \mathcal{F}_{a_4}],$$

$$V_{12} = 4 \frac{s}{z_1 z_2} \mathcal{F}_{v_1} + \frac{s}{2} (2 + \beta c_-) \mathcal{F}_{v_3} - 2s \mathcal{F}_{v_4} + 4m_f \mathcal{F}_{v_6},$$

$$A_{12} = -4\beta \mathcal{F}_{a_1} - \frac{s}{2} [(\beta_+^2 - \beta^2 c_+) \mathcal{F}_{a_3} + (\beta_+^2 - 2\beta^2 c_+) \mathcal{F}_{a_4}].$$

Helicity amplitudes $l^+l^- \rightarrow \gamma Z$. Example: set 2

$$\mathcal{H}_{+-+-} = \mathcal{H}_{+---} = N_2(V_2 + A_2),$$

$$\mathcal{H}_{-+++} = \mathcal{H}_{-+--} = N_2(-V_2 + A_2).$$

$$N_2 = \frac{1}{8}s \sin \theta_\gamma,$$

$$V_2 = -4\mathcal{F}_{v_2}$$

$$+ s\beta \left[(\beta_-^c - \frac{1}{2}\beta c_+ c_-) \mathcal{F}_{v_3} + 2 \cos \theta_\gamma \left(\mathcal{F}_{v_4} - 2\frac{m_f}{s} \mathcal{F}_{v_6} \right) \right],$$

$$A_2 = s\beta \left[-\frac{1}{s} (k_1 \mathcal{F}_{a_1} + \mathcal{F}_{a_2}) + \frac{1}{2} k_1^2 \mathcal{F}_{a_3} + \frac{1}{2} (k_1^2 - \beta^2 c_- c_+) \mathcal{F}_{a_4} \right].$$

HA, example for interplay

$$e^+(p_1) + e^-(p_2) \longrightarrow \gamma(p_3) + \gamma(p_4) + \gamma(p_5)$$

C, P, Bose and crossing between final and initial symmetries:

$$\mathcal{H}^{+--+--} = 2e^3 p_2 \cdot p_4 \sqrt{\frac{p_3 \cdot p_4}{p_1 \cdot p_3 \ p_1 \cdot p_4 \ p_3 \cdot p_5 \ p_4 \cdot p_5}}$$

$$\mathcal{H}^{+-+-+-} = \mathcal{H}^{+--+--}, (P + \text{Bose})$$

$$\mathcal{H}^{+-+--+} = \mathcal{H}^{+--+--}, (C)$$

$$\mathcal{H}^{+---+-} = \mathcal{H}^{+--+--}, (CP + \text{Bose})$$

$$\mathcal{H}^{+++-+-} = \mathcal{H}^{+--+--}, (C + \text{crossing})$$

$$\mathcal{H}^{+++-+-} = \mathcal{H}^{+++-+-}, (C)$$

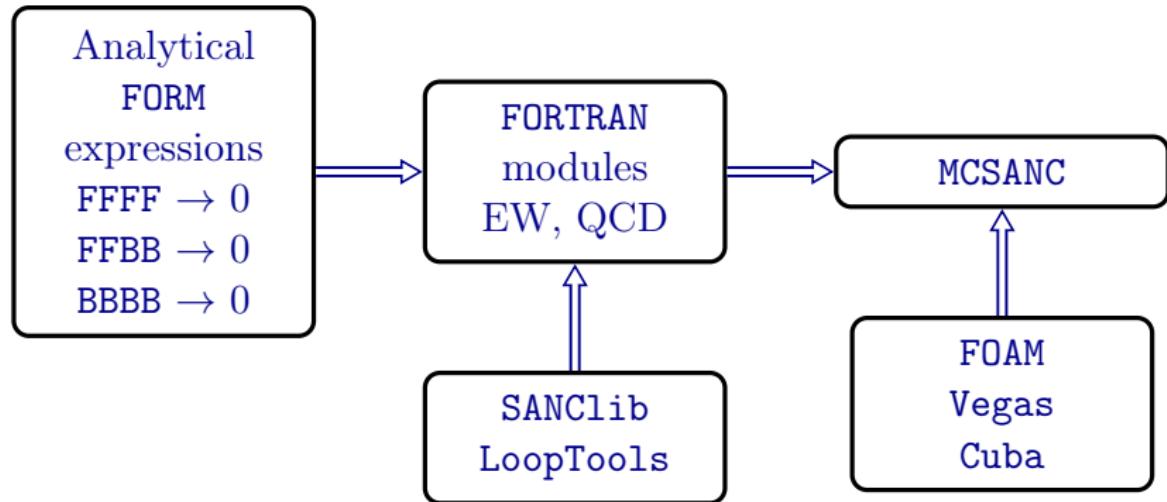
$$\mathcal{H}^{+++++-} = \mathcal{H}^{-----}, (P)$$

Hard: $e^+e^- \rightarrow \gamma\gamma\gamma$

Descriptions of the pure QED reaction $\gamma\gamma \rightarrow e^+e^-\gamma$ using method of helicity amplitudes are:

- S. Dittmaier, Phys Rev D59, (1999), 016007, hep-ph/9805445
- T.V. Shishkina, V.V. Makarenko, (2003), hep-ph/0212409

The SANC/ARIeL framework and MCSANC generator



We created Monte Carlo generator of unweighted events for the polarized events with NLO EW corrections stored in standard Les Houches format.

This generator uses adaptive algorithm [mFOAM](#) (CPC 177:441-458,2007) which is part of ROOT program.

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

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

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

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

$e^+e^- \rightarrow \gamma\gamma:$ CalcHep vs MCSANCee (Born), fb

 $\sqrt{s}=250 \text{ GeV}$

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
WHIZARD	4262	4262	2216	6307
CalcHEP	4262	4262	2216	6307
MCSANCee	4261	4261	2216	6307

 $\sqrt{s}=500 \text{ GeV}$

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
WHIZARD	1065	1065	554.0	1577
CalcHEP	1065	1065	554.0	1577
MCSANCee	1065	1065	554.0	1577

 $\sqrt{s}=1000 \text{ GeV}$

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
WHIZARD	266.3	266.3	138.5	394.2
CalcHEP	266.4	266.4	138.5	394.2
MCSANCee	266.3	266.3	138.5	394.2

$e^+e^- \rightarrow \gamma\gamma:$ CalcHep vs MCSANCee (**Hard**), fb

 $\sqrt{s}=250 \text{ GeV}$

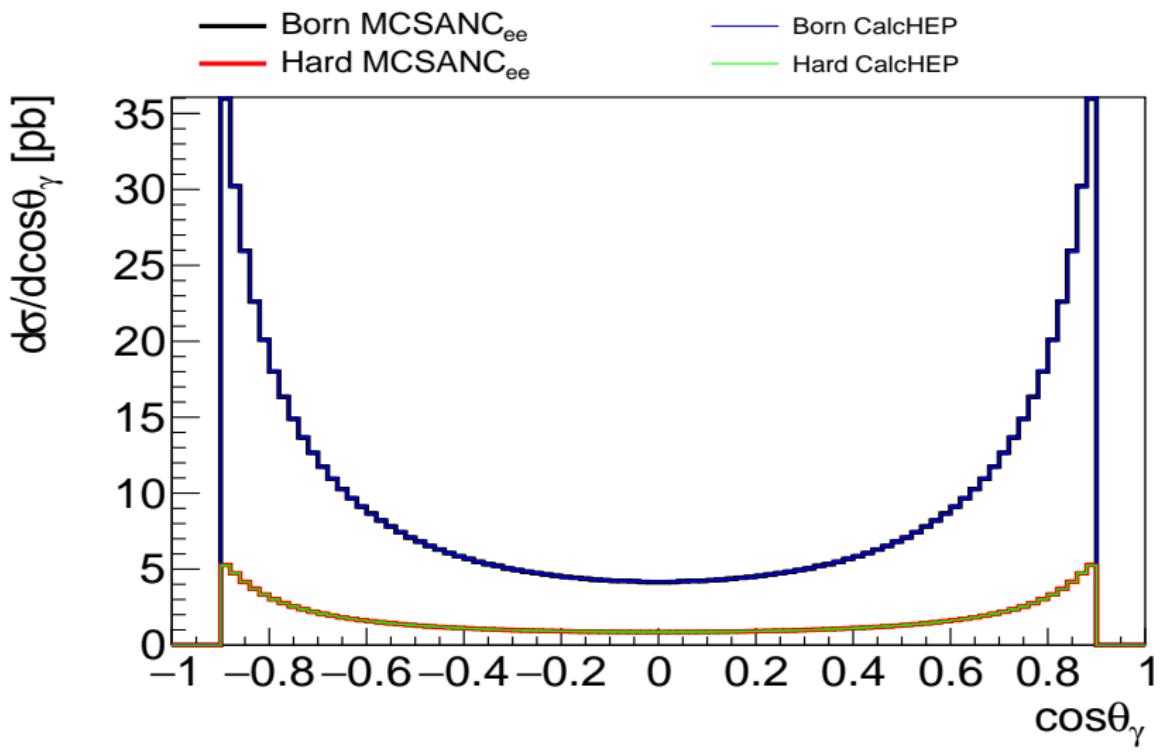
P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
WHIZARD	594.1	594.1	308.9	879.2
CalcHEP	594.0	593.8	308.8	879.2
MCSANCee	594.0	594.2	308.9	879.1

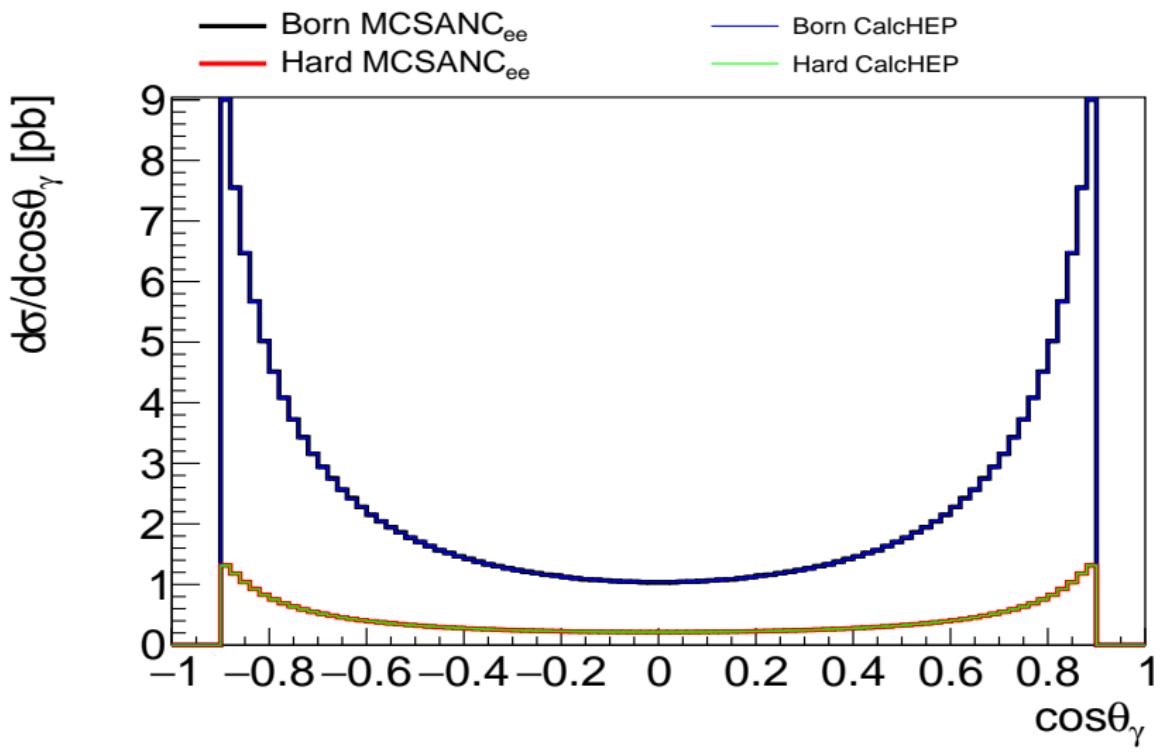
 $\sqrt{s}=500 \text{ GeV}$

P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
WHIZARD	158.6	158.5	82.50	234.5
CalcHEP	158.7	158.6	82.50	234.8
MCSANCee	158.7	158.7	82.50	234.8

 $\sqrt{s}=1000 \text{ GeV}$

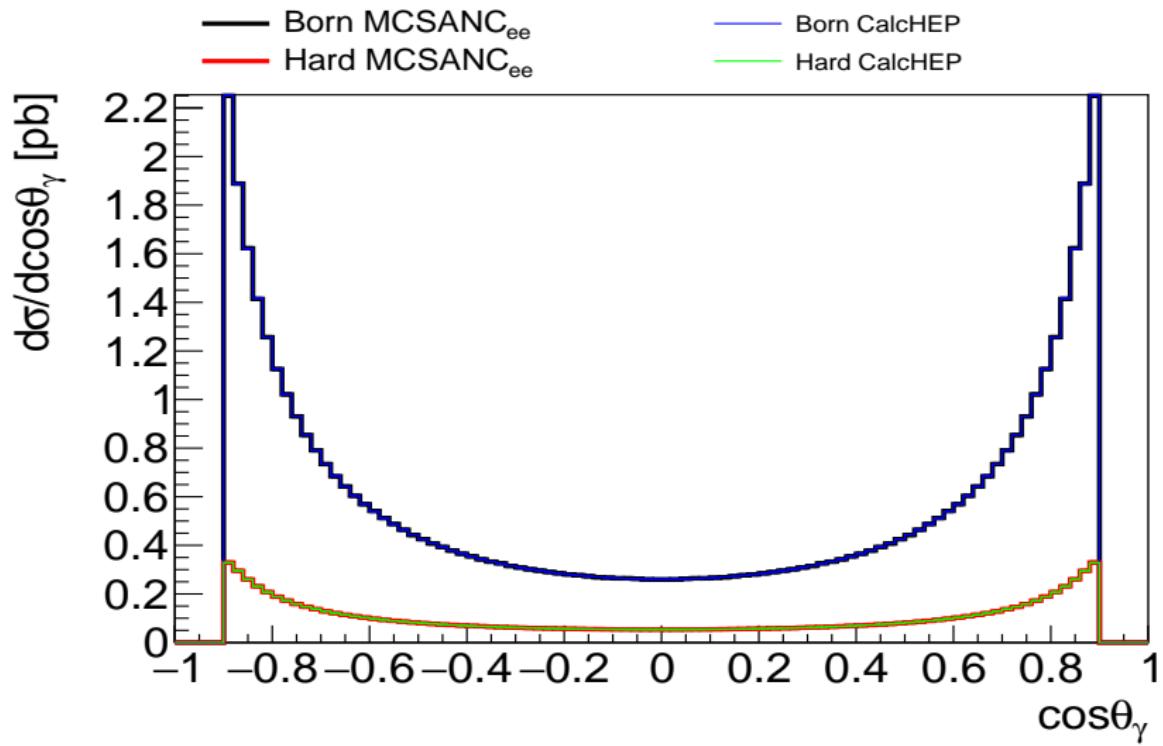
P_{e^-}, P_{e^+}	0, 0	-0.8, 0	-0.8, -0.6	-0.8, 0.6
WHIZARD	42.18	42.20	21.95	62.43
CalcHEP	42.19	42.18	21.94	62.45
MCSANCee	42.17	42.20	21.94	62.44

$e^+e^- \rightarrow \gamma\gamma$: σ distributions on $\cos(\theta)$. $\sqrt{s}=250$ GeV

$e^+e^- \rightarrow \gamma\gamma$: σ distributions on $\cos(\theta)$. $\sqrt{s}=500$ GeV

$e^+e^- \rightarrow \gamma\gamma$: σ distributions on $\cos(\theta)$.

$\sqrt{s}=1000\text{GeV}$



$e^+e^- \rightarrow \gamma\gamma$: Preliminary NLO results (QED)

P_{e^-}, P_{e^+}	0, 0	0.8, 0.3	-0.8, 0.3
$\sqrt{s} = 500 \text{ GeV}$			
$\sigma^{\text{Born}}, \text{fb}$	1065	809.7	1321
$\sigma^{\text{1-loop}}, \text{fb}$	1365	864.1	1408
$\delta, \%$	6.67	6.72	6.62

Angle cut $|\cos(\theta)_{CM}| < 0.9$ for at least two photons.

RESUME: MCSANC_{ee}

Started implementation into Monte Carlo generator MCSANC_{ee} of polarized $e^+e^- \rightarrow \gamma\gamma$ scattering with complete one-loop EW corrections and with possibility to produce events in Standard Les Houches Format.

Two schemes: $\alpha(M_Z), G_F$.

Generator uses adaptive algorithm `mFOAM` (CPC 177:441-458,2007) which is a part of the `ROOT` program.