# Polarized photon-photon collisions in ReneSANCe Monte Carlo generator

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# Motivation

- New opportunities for physics of photon-photon collisions are associated with the future high-energy linear *ee* collider (`CLIC`, `ILC`) operated in $\gamma\gamma$ mode through Compton backscattering of laser photons
- Photon colliders have high potential in:
    - Higgs physics
    - Gauge boson physics
    - Hadron physics and QCD
    - New physics beyond SM
- The direct observation of collisions of real photons is expected at photon collider with collision energy $\sim 1$ MeV (`Genie` collider in Shenzhen, China)
- Polarization effects can be studied by varying polarization states of initial electron and laser photon beams

# Cross sections

[V. Serbo. arXiv:hep-ph/0510335]
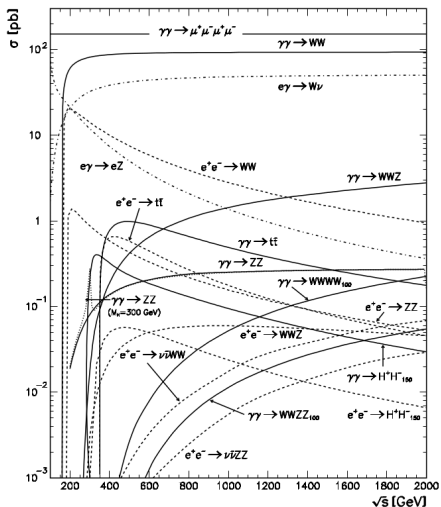
# The SANC framework and products family
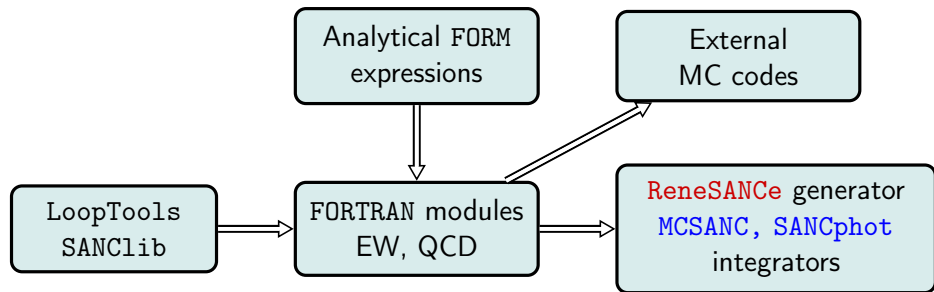


Publications:
SANC – CPC 174 (2006), 481-517;
MCSANC – CPC 184 (2013), 2343-2350; JETP Letters 103 (2016), 131-136;
SANCphot – CPC 294 (2024) 108929;
ReneSANCe – CPC 256 (2020), 107445 (ee-mode);
CPC 285 (2023) 108646 (pp-mode).

SANC products are available at http://sanc.jinr.ru/download.php
ReneSANCe is also available at http://renesance.hepforge.org

# ReneSANCe **generator**

ReneSANCe (Renewed SANC Monte Carlo event generator)
is a Monte Carlo event generator for simulation of processes at
$ee$ and $pp(p\bar{p})$ colliders.

- The following processes are fully implemented:
  - $e^+e^- \to e^-e^+, ZH, \mu^+\mu^-, \tau^+\tau^-, Z\gamma, \gamma\gamma, t\bar{t}$
  - $e^-e^- \to e^-e^-$, $\mu^+\mu^+ \to \mu^+\mu^+$, $\mu^+e^- \to \mu^+e^-$
  - $pp(p\bar{p}) \to \ell^+\ell^- X, \ell^+\nu_\ell X, \ell^-\bar{\nu}_\ell X$
  - $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$
- Based on the SANC (Support for Analytic and Numeric Calculations for experiments at colliders) modules
- Complete one-loop and some higher-order electroweak radiative corrections
- All the particle masses and polarizations
- Effectively operates in the collinear region and in wide $\sqrt{s}$ range
- New processes can be easily added

# Helicity density matrix for photons

- Circular polarization

$$\rho_\gamma^{circ} = 1/2 \begin{pmatrix} 1+\xi_2 & 0 \\ 0 & 1-\xi_2 \end{pmatrix} = 1/2 \begin{pmatrix} 1+\mathcal{P}^{circ} & 0 \\ 0 & 1-\mathcal{P}^{circ} \end{pmatrix}$$

$\mathcal{P}^{circ} = \xi_2 \in [-1;1]$ is the *circular polarization degree* ($\mathcal{P}^{circ} = +1$ corresponds to photon with positive helicity $\lambda = +1$)

- Linear polarization

$$\rho_\gamma^{lin} = 1/2 \begin{pmatrix} 1 & -\xi_3+i\xi_1 \\ -\xi_3-i\xi_1 & 1 \end{pmatrix} = 1/2 \begin{pmatrix} 1 & -\mathcal{P}^{lin}e^{-2i\phi} \\ -\mathcal{P}^{lin}e^{2i\phi} & 1 \end{pmatrix}$$

$\xi_1, \xi_3 \in [0;1]$, $\mathcal{P}^{lin} = \xi_{13} = \sqrt{\xi_1^2 + \xi_3^2} \in [0;1]$ is the *linear polarization degree*, $\phi = \frac{1}{2}Arg(\xi_1 - i\xi_3) \in [0;\pi]$ is the *linear polarization angle*.

# Helicity density matrix for photons

- Mixed polarization

$$\rho^{\gamma} = 1/2 \begin{pmatrix} 1 + \xi_2 & -\xi_3 + i\xi_1 \\ -\xi_3 - i\xi_1 & 1 - \xi_2 \end{pmatrix} = 1/2 \begin{pmatrix} 1 + \mathcal{P}^{circ} & -\mathcal{P}^{lin} e^{-2i\phi} \\ -\mathcal{P}^{lin} e^{2i\phi} & 1 - \mathcal{P}^{circ} \end{pmatrix}$$

$\xi_1^2 + \xi_2^2 + \xi_3^2 = (\mathcal{P}^{circ})^2 + (\mathcal{P}^{lin})^2 \leqslant 1$, $\mathcal{P}^{lin} \geqslant 0$.
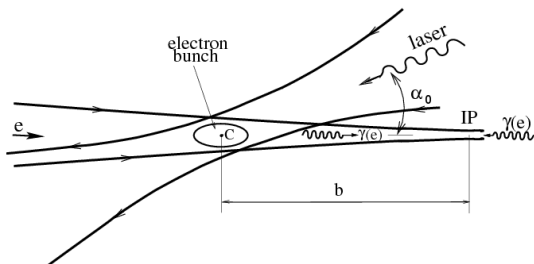
- The cross section for the process $\gamma\gamma \to X$ with polarized initial photons can be written as

$$d\sigma = \sum_{\lambda_1 \lambda_2 \lambda_1' \lambda_2'} \rho^{\gamma_1}_{\lambda_1 \lambda_1'} \rho^{\gamma_2}_{\lambda_2 \lambda_2'} \mathcal{H}_{\lambda_1 \lambda_2} \mathcal{H}^*_{\lambda_1' \lambda_2'} d\Phi,$$

where $\mathcal{H}_{\lambda_1 \lambda_2}$ - helicity amplitudes for generic process $\gamma\gamma \to X$.

# Photon collider based on linear *ee* collider

$e \to \gamma$ conversion through the Compton scattering of laser light on high-energy electrons (I.F. Ginzburg, G.L. Kotkin, V.G. Serbo and V.I. Telnov. ZhETF Pis'ma. 34 (1981) 514):



Basic parameters:

- $x_0 = \frac{4E\omega_0}{m_e^2}$, where $E$ - electron energy, $\omega_0$ - the laser photon energy

- $P_e$ - electron beam long. polarization, $P_\gamma$ - laser beam long. polarization, $P_t$ - laser beam linear polarization, $\Phi$ - azimuthal angle of lazer photon linear polarization

- $y = \frac{\omega}{E} \leqslant \frac{x_0}{1+x_0}$, where $\omega$ - energy of the back-scattered photon

# Density matrices for backscattered photons

$$\rho \quad = 1/2 \begin{pmatrix} 1 + \xi_2(y) & -\xi_{13}(y)e^{-2i(\Phi-\phi)} \\ -\xi_{13}(y)e^{2i(\Phi-\phi)} & 1 - \xi_2(y) \end{pmatrix},$$

$$\rho' \quad = 1/2 \begin{pmatrix} 1 + \xi_2'(y') & -\xi_{13}'(y')e^{2i(\Phi'-\phi)} \\ -\xi_{13}'(y')e^{-2i(\Phi'-\phi)} & 1 - \xi_2'(y') \end{pmatrix}$$

$$\xi_2(y) = \frac{P_e f_2(y) + P_\gamma f_3(y)}{C(y)}, \quad \xi_{13}(y) = \frac{2r^2(y)P_t}{C(y)}, \quad C(y) = f_0(y) + P_e P_\gamma f_1(y)$$

$$f_0(y) = \frac{1}{1+y} + 1 - y - 4r(1-r),$$

$$f_1(y) = \frac{y}{1-y}(1-2r)(2-y),$$

$$f_2(y) = x_0 r[1 + (1-y)(1-2r)^2],$$

$$f_3(y) = (1-2r)(\frac{1}{1-y} + 1 - y),$$

$$r(y) = \frac{y}{x_0(1-y)}$$

# Cross sections for $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$

$$\frac{d\sigma}{dy\,dy'\,d\cos\theta^*\,d\phi} = \frac{d\mathcal{L}_{\gamma\gamma}}{dy\,dy'}\left(\frac{d\bar{\sigma}_0}{d\cos\theta^*} + \langle\xi_2\xi_2'\rangle\frac{d\bar{\sigma}_{22}}{d\cos\theta^*} + \langle\xi_{13}\rangle\cos 2(\Phi - \phi)\frac{d\bar{\sigma}_3}{d\cos\theta^*}\right.$$

$$+\langle\xi_{13}'\rangle\cos 2(\Phi' - \phi)\frac{d\bar{\sigma}_3'}{d\cos\theta^*} + \langle\xi_{13}\xi_{13}'\rangle\cos 2(\Phi + \Phi' - 2\phi)\frac{d\bar{\sigma}_{33}}{d\cos\theta^*}$$

$$+\langle\xi_{13}\xi_{13}'\rangle\cos 2(\Phi - \Phi')\frac{d\bar{\sigma}_{33}'}{d\cos\theta^*} + \langle\xi_2\xi_{13}'\rangle\sin 2(\Phi' - \phi)\frac{d\bar{\sigma}_{23}}{d\cos\theta^*}$$

$$\left.+\langle\xi_{13}\xi_2'\rangle\sin 2(\Phi - \phi)\frac{d\bar{\sigma}_{23}'}{d\cos\theta^*}\right)$$

Luminosity distribution of colliding photons $\frac{d\mathcal{L}_{\gamma\gamma}}{dy\,dy'}$ depends on the reduced distance $\rho$ between conversion and collision points and aspect ratio $A$ of horizontal $\sigma_{ye}$ and vertical $\sigma_{xe}$ sizes of electron beams (Ginzburg I. F., Kotkin G. L. Phys. J. C. 2000. V. 13. P. 295):

$$\rho^2 = \left(\frac{b}{(E/m_e)\sigma_{xe}}\right)^2 + \left(\frac{b}{(E/m_e)\sigma_{ye}}\right)^2, \quad A = \frac{\sigma_{xe}}{\sigma_{ye}}$$

# Luminosity of backscattered photons

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dydy'} = \frac{1}{(2\pi)^2} \int d\phi_1 d\phi_2 f(x_0, y) f(x_0, y') \exp\left[-\frac{\rho^2 \Psi}{4(1 + A^2)}\right],$$

$$\Psi = A^2 \left(g(x_0, y)\cos\phi_1 + g(x_0, y')\cos\phi_2\right)^2 + \left(g(x_0, y)\sin\phi_1 + g(x_0, y')\sin\phi_2\right)^2,$$

$$g(x_0, y) = \sqrt{\frac{x_0}{y} - x_0 - 1},$$

$$f(x_0, y) = N(x_0)\left[f_0(y) + P_e P_\gamma f_1(y)\right].$$

# Cross sections for $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$

$$\frac{d\bar{\sigma}_0}{d\cos\theta^*} = \frac{N}{64\pi\hat{s}}\left(|\mathcal{H}_{++}|^2 + |\mathcal{H}_{+-}|^2\right),$$

$$\frac{d\bar{\sigma}_{22}}{d\cos\theta^*} = \frac{N}{64\pi\hat{s}}\left(|\mathcal{H}_{++}|^2 - |\mathcal{H}_{+-}|^2\right),$$

$$\frac{d\bar{\sigma}_3}{d\cos\theta^*} = -\frac{N}{32\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{++}\mathcal{H}_{-+}^*\right),$$

$$\frac{d\bar{\sigma}_3'}{d\cos\theta^*} = -\frac{N}{32\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{++}\mathcal{H}_{+-}^*\right),$$

$$\frac{d\bar{\sigma}_{33}}{d\cos\theta^*} = \frac{N}{64\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{+-}\mathcal{H}_{-+}^*\right),$$

$$\frac{d\bar{\sigma}_{33}'}{d\cos\theta^*} = \frac{N}{64\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{++}\mathcal{H}_{--}^*\right),$$

$$\frac{d\bar{\sigma}_{23}}{d\cos\theta^*} = \frac{N}{32\pi\hat{s}}\mathfrak{Im}\left(\mathcal{H}_{++}\mathcal{H}_{+-}^*\right),$$

$$\frac{d\bar{\sigma}_{23}'}{d\cos\theta^*} = \frac{N}{32\pi\hat{s}}\mathfrak{Im}\left(\mathcal{H}_{++}\mathcal{H}_{-+}^*\right)$$

$N = \frac{1}{2}$ for $\gamma\gamma \to \gamma\gamma$, $N = 1 - \frac{M_Z^2}{\hat{s}}$ for $\gamma\gamma \to \gamma Z$, $N = \frac{1}{2}\sqrt{1 - \frac{4M_Z^2}{\hat{s}}}$ for $\gamma\gamma \to ZZ$

# Cross sections for $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$

The $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$ SM processes through fermion and boson loops were calculated within the SANC framework:

- $\gamma\gamma \to \gamma\gamma$: Physics of Atomic Nuclei, 2010, Vol. 73, No. 11, pp. 1878–1888
- $\gamma\gamma \to \gamma Z$: Physics of Atomic Nuclei, 2013, Vol. 76, No. 11, pp. 1339–1344
- $\gamma\gamma \to ZZ$: Physics of Particles and Nuclei Letters, 2017, Vol. 14, No. 6, pp. 811–816

# Numerical results: input parameters

We performed numerical calculations in the $\alpha(0)$-scheme at $\sqrt{s} = 500$ GeV.
The results for $\rho = 0$ were cross-checked with SANCphot program.
Input parameters:

$$x_0 = 4.83,$$
$$\alpha = 1/137.035990996,$$

| | | |
|---|---|---|
| $M_Z = 91.1867$ GeV, | $M_W = 80.45149$ GeV, | $M_H = 125$ GeV, |
| $m_e = 0.51099907$ MeV, | $m_\mu = 0.105658389$ GeV, | $m_\tau = 1.77705$ GeV, |
| $m_d = 0.083$ GeV, | $m_s = 0.215$ GeV, | $m_b = 4.7$ GeV, |
| $m_u = 0.062$ GeV, | $m_c = 1.5$ GeV, | $m_t = 173.8$ GeV. |

Polarization configurations:

- Set 1: $P_e = P'_e = 0.8, P_\gamma = P'_\gamma = -1, P_t = P'_t = 0$
- Set 2: $P_e = P'_e = 0, P_\gamma = P'_\gamma = 0, P_t = P'_t = 1, \Phi = \Phi'$
- Set 3: $P_e = 0.8, P'_e = 0, P_\gamma = -1, P'_\gamma = 0, P_t = 0, P'_t = 1$

Cuts: $30° < \theta < 150°, M_{\gamma\gamma} > 20$ GeV, $M_{\gamma Z} > 100$ GeV, $M_{ZZ} > 200$ GeV.

# Cross sections for $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$ at $\sqrt{s} = 500$ GeV

|  | $\rho$ | 0 | 1 | 5 |
|---|---|---|---|---|
| $\gamma\gamma \to \gamma\gamma$ | $\sigma$, fb [Set 1] | 9.4420(1) | 1.9820(1) | 0.2232(1) |
|  | $\sigma$, fb [Set 2] | 8.0452(2) | 1.5473(1) | 0.1448(1) |
|  | $\sigma$, fb [Set 3] | 8.0134(2) | 1.6429(1) | 0.1647(1) |

|  | $\rho$ | 0 | 1 | 5 |
|---|---|---|---|---|
| $\gamma\gamma \to \gamma Z$ | $\sigma$, fb [Set 1] | 21.528(1) | 8.884(1) | 1.247(1) |
|  | $\sigma$, fb [Set 2] | 19.373(1) | 7.196(1) | 0.818(1) |
|  | $\sigma$, fb [Set 3] | 17.015(1) | 6.426(1) | 0.750(1) |

|  | $\rho$ | 0 | 1 | 5 |
|---|---|---|---|---|
| $\gamma\gamma \to ZZ$ | $\sigma$, fb [Set 1] | 32.326(1) | 13.520(1) | 1.898(1) |
|  | $\sigma$, fb [Set 2] | 21.802(1) | 8.361(1) | 0.975(1) |
|  | $\sigma$, fb [Set 3] | 24.312(1) | 9.599(1) | 1.176(1) |

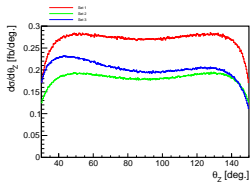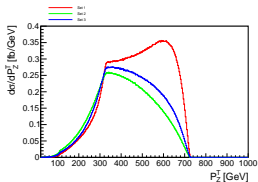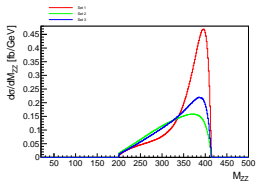# Distributions for $\gamma\gamma \to \gamma\gamma$ $(\rho = 0, 1, 5)$
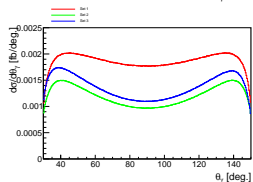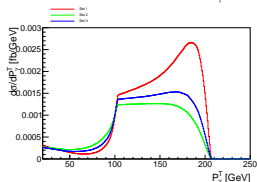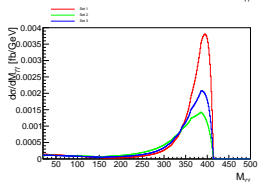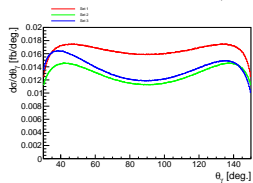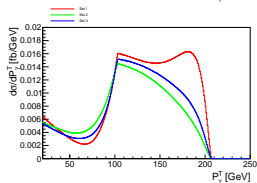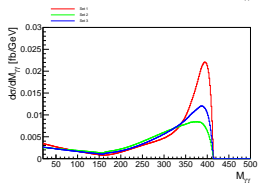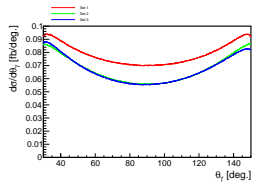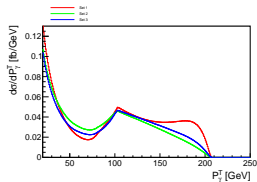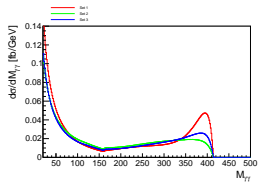
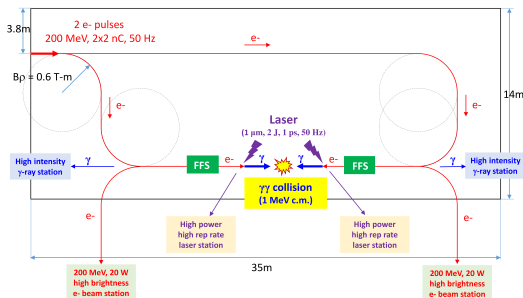# Distributions for $\gamma\gamma \to \gamma Z$ $(\rho = 0, 1, 5)$
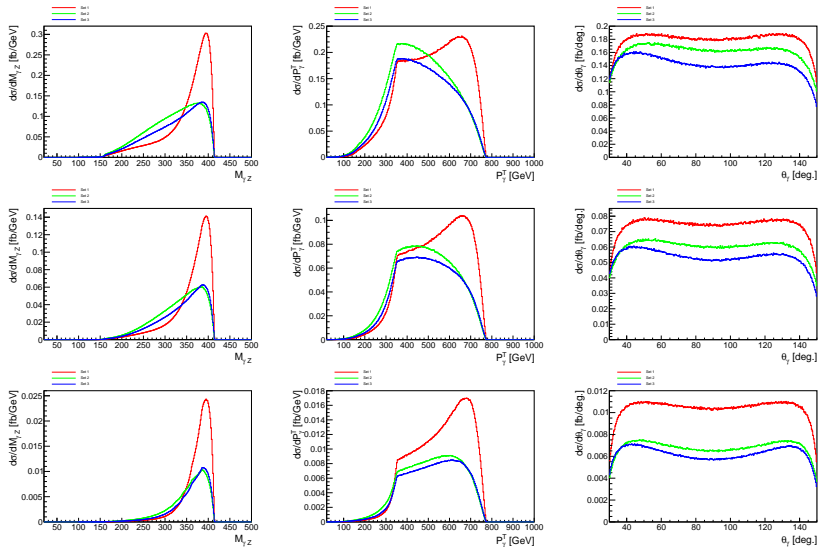
# Distributions for $\gamma\gamma \to ZZ$ $(\rho = 0, 1, 5)$
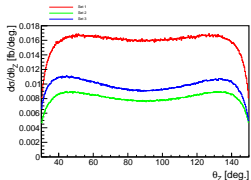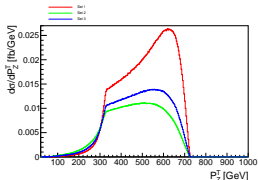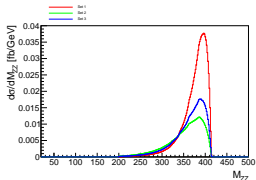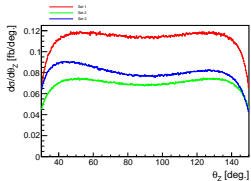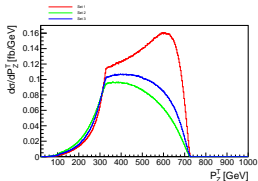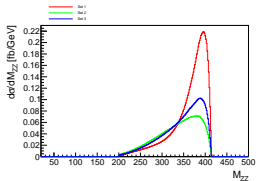
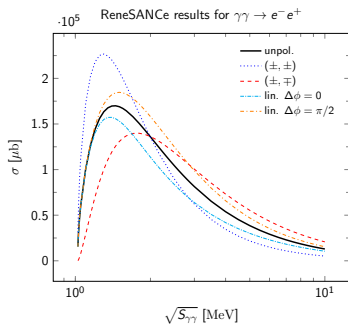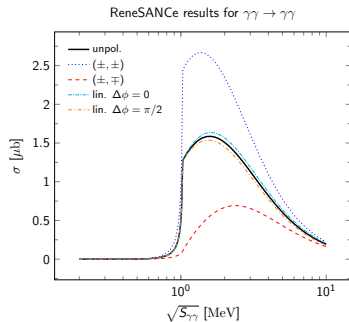# Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

The photon collider `Genie (Qini)` is proposed with $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV
T. Takahashi et.al. Eur. Phys. J. C (2018) 78:893



Picture from Huang Yongshen presentation DOI:10.13140/RG.2.2.11301.88806
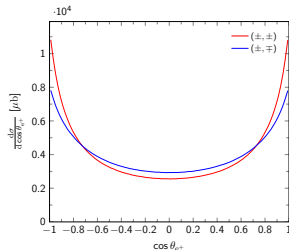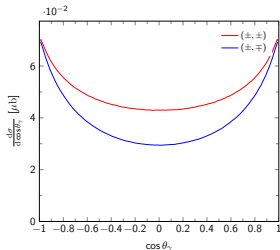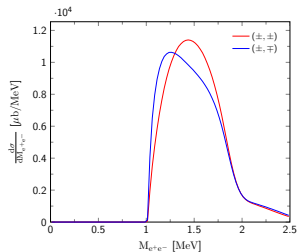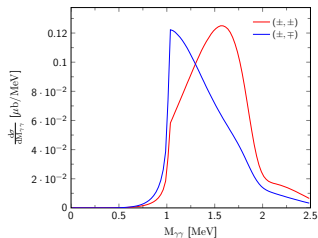
# Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

Cross sections of $\gamma\gamma \to \gamma\gamma$ and $\gamma\gamma \to e^+ e^-$ processes for different polarization of initial photons:

# Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

The photon spectrum is simulated by `CAIN 2.42` program and interfaced to `ReneSANCe` generator

# Summary and plans

$\gamma\gamma$ **collisions implemented in Monte Carlo event generator** `ReneSANCe`

- $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ, e^+e^-$ with arbitrary polarization of initial photons
- Events with unit weights, output in `LHE`, `HepMC`, `HEPEVT` and `root` formats
- Different options for $\gamma\gamma$ spectrum:
    - Simple model for polarized $\gamma\gamma$ collisions at future photon collider based on linear *ee* colliders
    - Interface to `CAIN` program
    - EPA spectrum in ultraperipheral heavy-ion collisions

**Plans**:

- New processes: $\gamma\gamma \to \nu\bar{\nu}, \ell^+\ell^-, t\bar{t}, W^+W^-, ZH$
- Massive two-loop QCD and QED corrections to $\gamma\gamma \to \gamma\gamma$
- Virtual photons

# Thank you!