Photon-photon collisions with arbitrary polarization in ReneSANCe Monte Carlo generator

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November 1st 2023, IHEP, Beijing

Outline

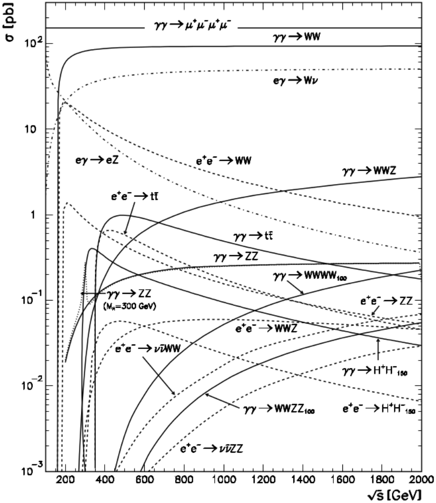
- Motivation
- SANC framework and ReneSANCe Monte Carlo generator
- Polarized photon-photon collisions at future *ee* colliders
- Results for polarized $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$
- Summary and plans

Motivation

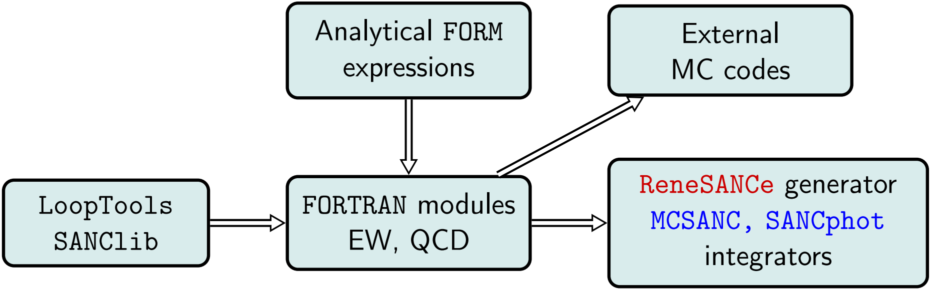
- New opportunities for physics of photon-photon collisions are associated with the future high-energy *ee* collider
- Photon colliders have high potential in:
  - Higgs physics
  - Gauge boson physics
  - Hadron physics and QCD
  - New physics beyond SM

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 – arXiv:2201.04350;

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

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

$\xi_1^2 + \xi_2^2 + \xi_3^2 = (\mathcal{P}^{circ})^2 + (\mathcal{P}^{lin})^2 \leqslant 1$, $\mathcal{P}^{lin} \geqslant 0$.

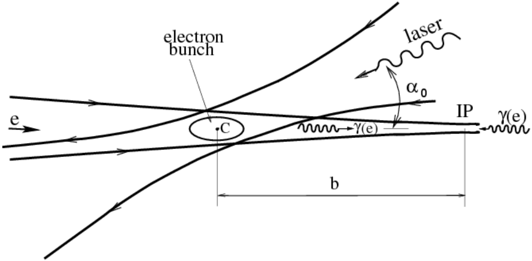
- The cross section for the process $\gamma\gamma \to X$ with polarized initial photons can be written as

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

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, ω_0 - the laser photon energy
- P_e - electron beam long. polarization, P_γ - laser beam long. polarization, P_t - laser beam linear polarization, Φ - azimuthal angle of lazer photon linear polarization
- $y = \frac{\omega}{E} \leqslant \frac{x_0}{1+x_0}$, where ω - energy of the back-scattered photon

Density matrices for backscattered photons

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

$$\rho' = 1/2 \begin{pmatrix} 1+\xi'_2(y') & -\xi'_{13}(y')e^{2i(\Phi'-\phi)} \\ -\xi'_{13}(y')e^{-2i(\Phi'-\phi)} & 1-\xi'_2(y') \end{pmatrix}$$

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

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

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

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

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

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

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

$$
\begin{aligned}
\frac{d\sigma}{dydy'\,d\cos\theta^* d\phi} = & \frac{d\mathcal{L}_{\gamma\gamma}}{dydy'}\Bigg(\frac{d\bar{\sigma}_0}{d\cos\theta^*} + \langle\xi_2\xi_2'\rangle\frac{d\bar{\sigma}_{22}}{d\cos\theta^*} + \langle\xi_{13}\rangle\cos 2(\Phi-\phi)\frac{d\bar{\sigma}_3}{d\cos\theta^*} \\
& + \langle\xi_{13}'\rangle\cos 2(\Phi'-\phi)\frac{d\bar{\sigma}_3'}{d\cos\theta^*} + \langle\xi_{13}\xi_{13}'\rangle\cos 2(\Phi+\Phi'-2\phi)\frac{d\bar{\sigma}_{33}}{d\cos\theta^*} \\
& + \langle\xi_{13}\xi_{13}'\rangle\cos 2(\Phi-\Phi')\frac{d\bar{\sigma}_{33}'}{d\cos\theta^*} + \langle\xi_2\xi_{13}'\rangle\sin 2(\Phi'-\phi)\frac{d\bar{\sigma}_{23}}{d\cos\theta^*} \\
& + \langle\xi_{13}\xi_2'\rangle\sin 2(\Phi-\phi)\frac{d\bar{\sigma}_{23}'}{d\cos\theta^*}\Bigg)
\end{aligned}
$$

Luminosity distribution of colliding photons $\frac{d\mathcal{L}_{\gamma\gamma}}{dydy'}$ depends on the reduced distance ρ between conversion and collision points and aspect ratio A of horizontal σ_{ye} and vertical σ_{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 $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$

$$
\begin{aligned}
\frac{d\bar{\sigma}_0}{d\cos\theta^*} &= \frac{N}{64\pi\hat{s}}\left(|\mathcal{H}_{++}|^2+|\mathcal{H}_{+-}|^2\right), \\
\frac{d\bar{\sigma}_{22}}{d\cos\theta^*} &= \frac{N}{64\pi\hat{s}}\left(|\mathcal{H}_{++}|^2-|\mathcal{H}_{+-}|^2\right), \\
\frac{d\bar{\sigma}_3}{d\cos\theta^*} &= -\frac{N}{32\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{++}\mathcal{H}^*_{-+}\right), \\
\frac{d\bar{\sigma}_3^{'}}{d\cos\theta^*} &= -\frac{N}{32\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{++}\mathcal{H}^*_{+-}\right), \\
\frac{d\bar{\sigma}_{33}}{d\cos\theta^*} &= \frac{N}{64\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{+-}\mathcal{H}^*_{-+}\right), \\
\frac{d\bar{\sigma}_{33}^{'}}{d\cos\theta^*} &= \frac{N}{64\pi\hat{s}}\mathfrak{Re}\left(\mathcal{H}_{++}\mathcal{H}^*_{--}\right), \\
\frac{d\bar{\sigma}_{23}}{d\cos\theta^*} &= \frac{N}{32\pi\hat{s}}\mathfrak{Im}\left(\mathcal{H}_{++}\mathcal{H}^*_{+-}\right), \\
\frac{d\bar{\sigma}_{23}^{'}}{d\cos\theta^*} &= \frac{N}{32\pi\hat{s}}\mathfrak{Im}\left(\mathcal{H}_{++}\mathcal{H}^*_{-+}\right)
\end{aligned}
$$

$N = \frac{1}{2}$ 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:

$$x_0 = 4.83,$$
$$\alpha = 1/137.035990996,$$
$$M_Z = 91.1867 \text{ GeV}, \quad M_W = 80.45149 \text{ GeV}, \quad M_H = 125 \text{ GeV},$$
$$m_e = 0.51099907 \text{ MeV}, \quad m_\mu = 0.105658389 \text{ GeV}, \quad m_\tau = 1.77705 \text{ GeV},$$
$$m_d = 0.083 \text{ GeV}, \quad m_s = 0.215 \text{ GeV}, \quad m_b = 4.7 \text{ GeV},$$
$$m_u = 0.062 \text{ GeV}, \quad m_c = 1.5 \text{ GeV}, \quad m_t = 173.8 \text{ GeV}.$$

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: $30^\circ < \theta < 150^\circ, M_{\gamma\gamma} > 20$ 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

$\gamma\gamma \to \gamma\gamma$

ρ	0	1	5
σ, fb [Set 1]	9.4420(1)	1.9820(1)	0.2232(1)
σ, fb [Set 2]	8.0452(2)	1.5473(1)	0.1448(1)
σ, fb [Set 3]	8.0134(2)	1.6429(1)	0.1647(1)

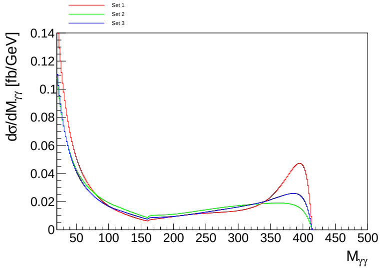
$\gamma\gamma \to \gamma Z$

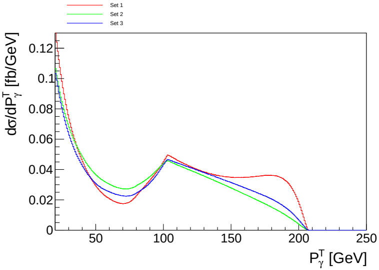
ρ	0	1	5
σ, fb [Set 1]	21.528(1)	8.884(1)	1.247(1)
σ, fb [Set 2]	19.373(1)	7.196(1)	0.818(1)
σ, fb [Set 3]	17.015(1)	6.426(1)	0.750(1)

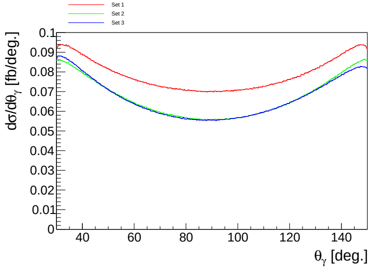
$\gamma\gamma \to ZZ$

ρ	0	1	5
σ, fb [Set 1]	32.326(1)	13.520(1)	1.898(1)
σ, fb [Set 2]	21.802(1)	8.361(1)	0.975(1)
σ, fb [Set 3]	24.312(1)	9.599(1)	1.176(1)

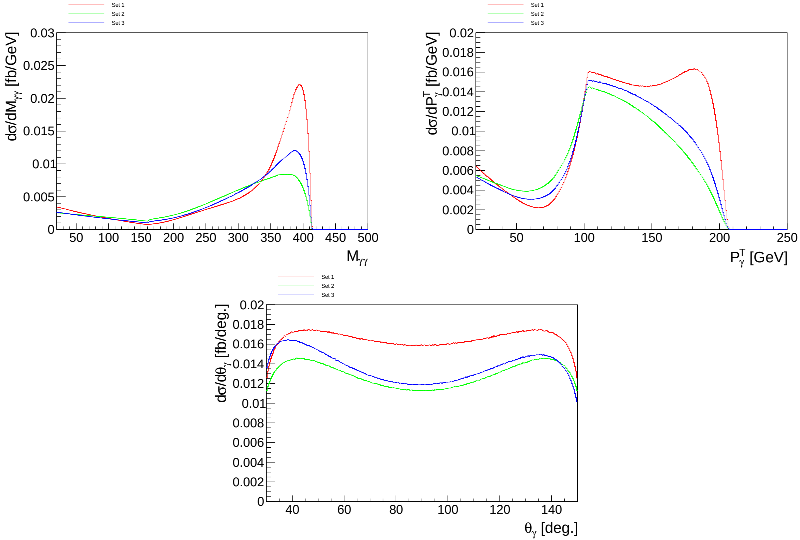
Distributions for $\gamma\gamma \to \gamma\gamma$ $(\rho = 0)$



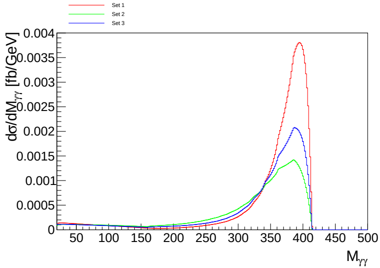


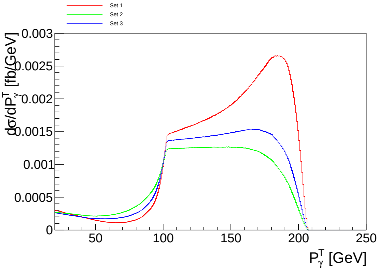


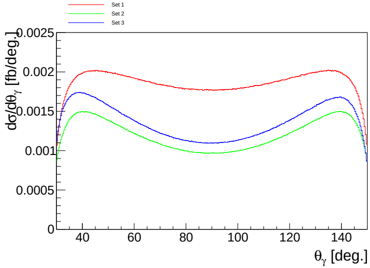
Distributions for $\gamma\gamma \to \gamma\gamma$ $(\rho = 1)$



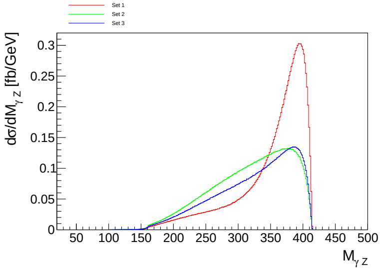
Distributions for $\gamma\gamma \to \gamma\gamma$ ($\rho = 5$)

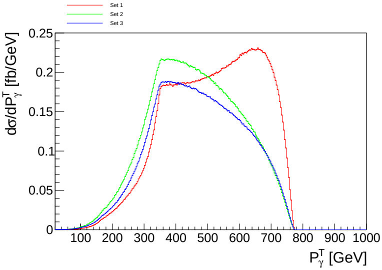


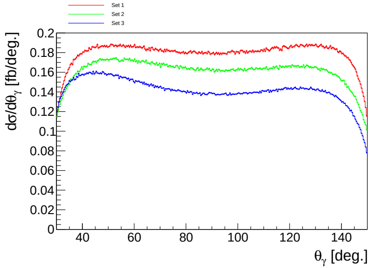




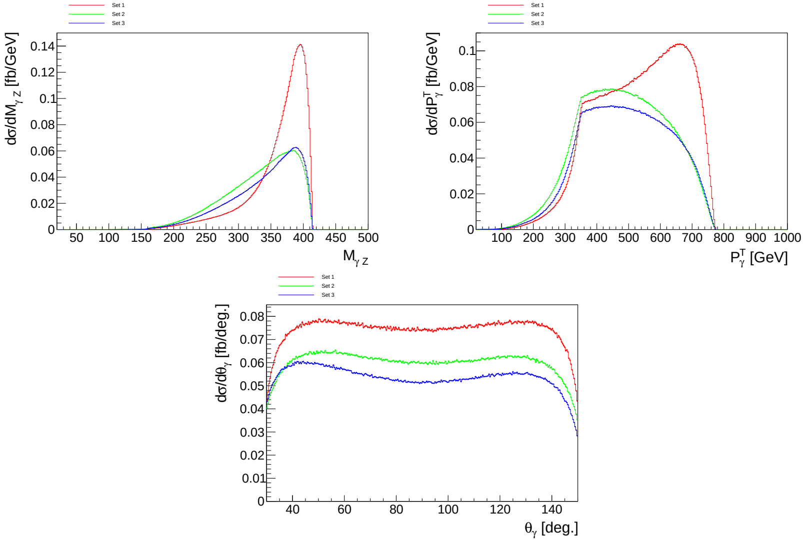
Distributions for $\gamma\gamma \to \gamma Z$ ($\rho = 0$)



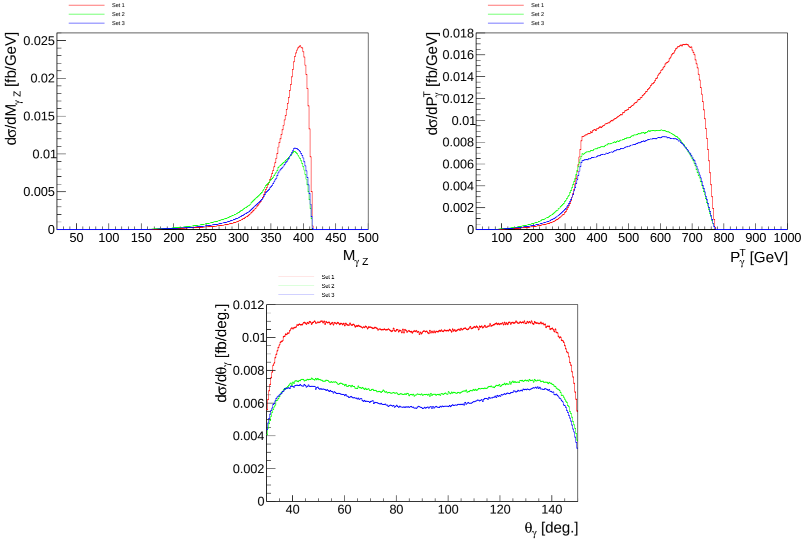




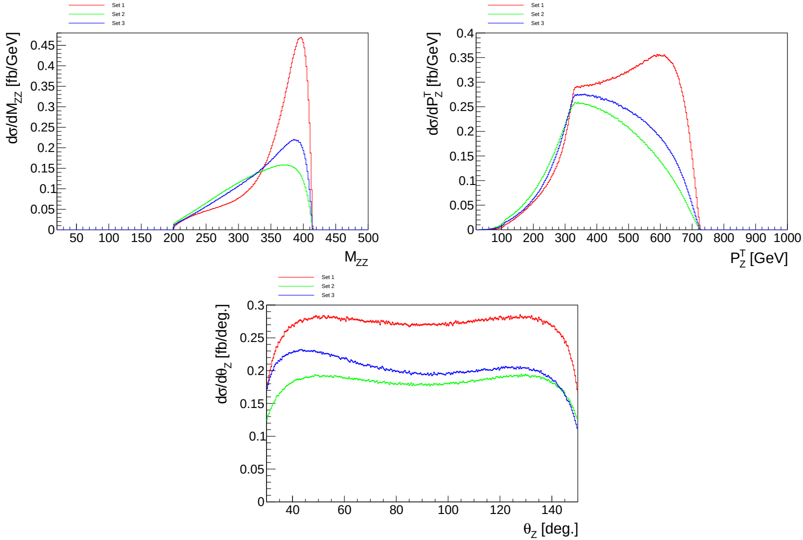
Distributions for $\gamma\gamma \to \gamma Z$ $(\rho = 1)$



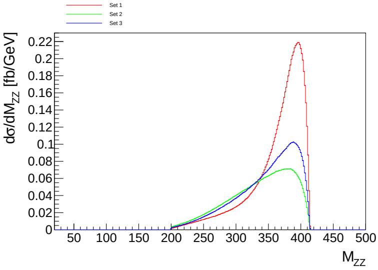
Distributions for $\gamma\gamma \to \gamma Z$ ($\rho = 5$)

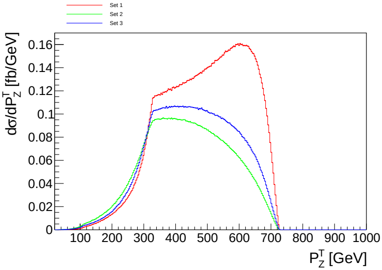


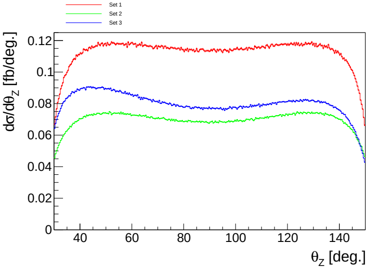
Distributions for $\gamma\gamma \to ZZ$ $(\rho = 0)$



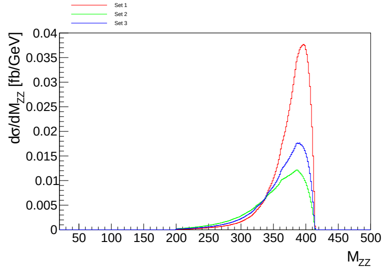
Distributions for $\gamma\gamma \to ZZ$ ($\rho = 1$)

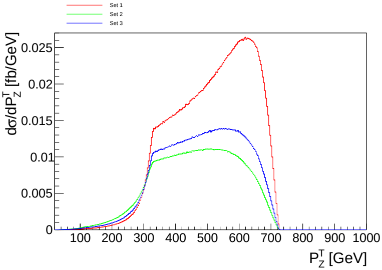


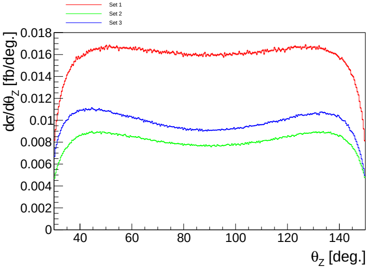




Distributions for $\gamma\gamma \to ZZ$ $(\rho = 5)$







Summary and plans

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

- $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ$ with arbitrary polarization of initial photons
- Events with unit weights, output in `LHE` and `root` formats
- Simple model for polarized $\gamma\gamma$ collisions at future photon collider based on linear ee colliders

Plans:

- New processes: $\gamma\gamma \to \nu\bar{\nu}, \ell^+\ell^-(\ell = e, \mu, \tau), t\bar{t}, W^+W^-, ZH$
- Virtual photons
- More precise description of the incoming photon spectrum

Thank you!