Polarized photon-photon collisions in the ReneSANCe event generator

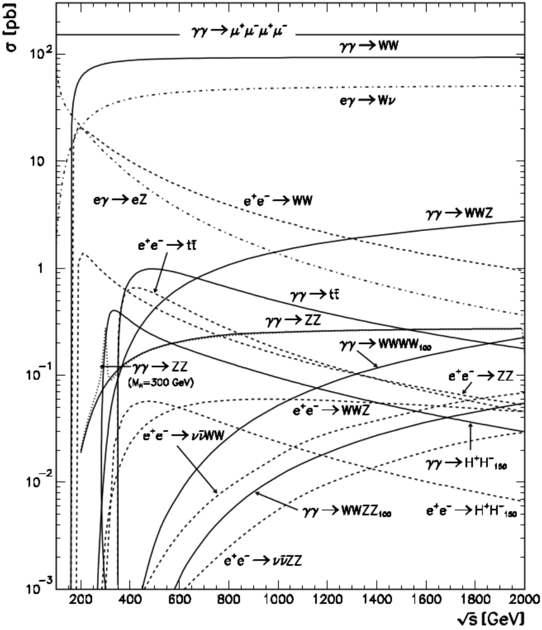
Renat Sadykov
(DLNP JINR)
on behalf of the SANC team

CEPC International Workshop
Guangzhou, November 8th, 2025

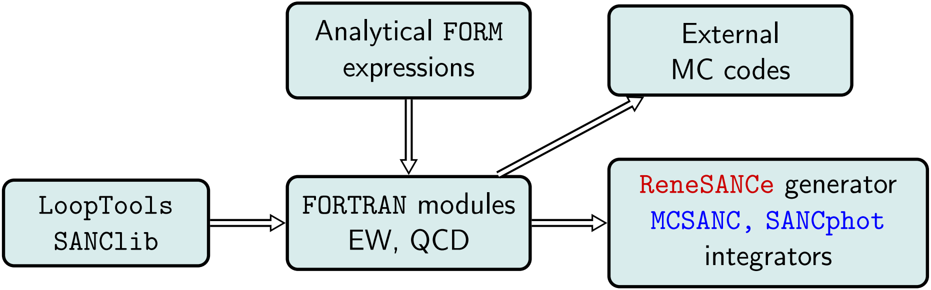
Motivation

- 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 ~ 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

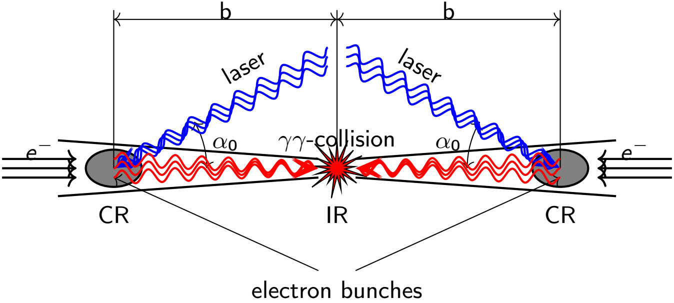
ReneSANCe **generator**

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:
  - $e^+e^- \to e^-e^+, ZH, \mu^+\mu^-, \tau^+\tau^-, Z\gamma, \gamma\gamma, t\bar{t}$
  - $e^-e^- \to e^-e^-$, $\mu^+\mu^+ \to \mu^+\mu^+$, $\mu^+e^- \to \mu^+e^-$
  - $pp(p\bar{p}) \to \ell^+\ell^-X, \ell^+\nu_\ell X, \ell^-\bar{\nu}_\ell X$
  - $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ, e^-e^+$
- 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

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 circ. polarization, P_t – laser beam linear polarization, Φ – azimuthal angle of lazer photon linear polarization
- $x = \frac{\omega}{E} \leqslant \frac{x_0}{1+x_0}$, where ω – energy of the back-scattered photon

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

$$d\sigma = \sum_{\lambda_1 \lambda_2 \lambda_1' \lambda_2'} \rho^{\gamma_1}_{\lambda_1 \lambda_1'} \rho^{\gamma_2}_{\lambda_2 \lambda_2'} \mathcal{H}^{\gamma\gamma\to X}_{\lambda_1 \lambda_2} \left(\mathcal{H}^{\gamma\gamma\to X}_{\lambda_1' \lambda_2'} \right)^{\dagger} d\Phi,$$

where $\mathcal{H}_{\lambda_1 \lambda_2}$ – helicity amplitudes for generic process $\gamma\gamma \to X$ summed over the helicities of the final particles:

$$\mathcal{H}^{\gamma\gamma\to X}_{\lambda_1 \lambda_2} \left(\mathcal{H}^{\gamma\gamma\to X}_{\lambda_1' \lambda_2'} \right)^{\dagger} = \sum_{\lambda_i} \mathcal{H}^{\gamma\gamma\to X}_{\lambda_1 \lambda_2 \ldots \lambda_i \ldots} \left(\mathcal{H}^{\gamma\gamma\to X}_{\lambda_1' \lambda_2' \ldots \lambda_i \ldots} \right)^{\dagger}$$

Density matrices for backscattered photons

$$\rho^{\gamma_1} = 1/2 \begin{pmatrix} 1+\xi_2^1(x_1) & -\xi_{13}^1(x_1)e^{-2i(\Phi_1-\phi)} \\ -\xi_{13}^1(x_1)e^{2i(\Phi_1-\phi)} & 1-\xi_2^1(x_1) \end{pmatrix},$$

$$\rho^{\gamma_2} = 1/2 \begin{pmatrix} 1+\xi_2^2(x_2) & -\xi_{13}^2(x_2)e^{2i(\Phi_2-\phi)} \\ -\xi_{13}^2(x_2)e^{-2i(\Phi_2-\phi)} & 1-\xi_2^2(x_2) \end{pmatrix}.$$

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

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

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

$$f_2(x_i) = x_0 r(x_i)\left[1+(1-x_i)(1-2r(x_i))^2\right],$$

$$f_3(x_i) = (1-2r(x_i))\left(\frac{1}{1-x_i} + 1 - x_i\right),$$

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

Cross sections for $2 \to 2$ process

$$\frac{d\sigma_{\gamma\gamma\to X}}{dx_1\, dx_2\, d\cos\theta^*\, d\phi} = \frac{d\mathcal{L}_{\gamma\gamma}}{dx_1\, dx_2} \frac{d\hat{\sigma}_{\gamma\gamma\to X}}{d\cos\theta^*\, d\phi},$$

$$\frac{d\hat{\sigma}_{\gamma\gamma\to X}}{d\cos\theta^*\, d\phi} = \frac{N_{\gamma\gamma\to X}}{64\pi\hat{s}} \sum_{\lambda_1\lambda_2\lambda_1'\lambda_2'} \rho^{\gamma_1}_{\lambda_1\lambda_1'} \rho^{\gamma_2}_{\lambda_2\lambda_2'} \mathcal{H}^{\gamma\gamma\to X}_{\lambda_1\lambda_2} \left(\mathcal{H}^{\gamma\gamma\to X}_{\lambda_1'\lambda_2'}\right)^\dagger,$$

$$N_{\gamma\gamma\to\gamma\gamma} = \frac{1}{2},$$

$$N_{\gamma\gamma\to Z\gamma} = 1 - \frac{M_Z^2}{\hat{s}},$$

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

$$N_{\gamma\gamma\to e^-e^+} = \frac{1}{2}\sqrt{1 - \frac{4m_e^2}{\hat{s}}}.$$

Luminosity of backscattered photons

Luminosity distribution of colliding photons $\frac{d\mathcal{L}_{\gamma\gamma}}{dx_1 dx_2}$ 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):

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

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dx_1 dx_2} = \frac{1}{(2\pi)^2}\int d\phi_1 d\phi_2 f^1(x_0, x_1) f^2(x_0, x_2) \exp\left[-\frac{\rho^2\Psi}{4(1+A^2)}\right],$$

$$\Psi = A^2\left(g(x_0, x_1)\cos\phi_1 + g(x_0, x_2)\cos\phi_2\right)^2 + \left(g(x_0, x_1)\sin\phi_1 + g(x_0, x_2)\sin\phi_2\right)^2,$$

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

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

Cross sections for $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ, e^- e^+$ in SANC

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

The $\gamma\gamma \to e^- e^+ (\gamma)$ process at 1-loop EW

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: $P_e^1 = P_e^2 = 0.8, P_\gamma^1 = P_\gamma^2 = -1, P_t^1 = P_t^2 = 0$
- Set 2: $P_e^1 = P_e^2 = 0, P_\gamma^1 = P_\gamma^2 = 0, P_t^1 = P_t^2 = 1, \Phi^1 = \Phi^2$
- Set 3: $P_e^1 = 0.8, P_e^2 = 0, P_\gamma^1 = -1, P_\gamma^2 = 0, P_t^1 = 0, P_t^2 = 1$

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

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)

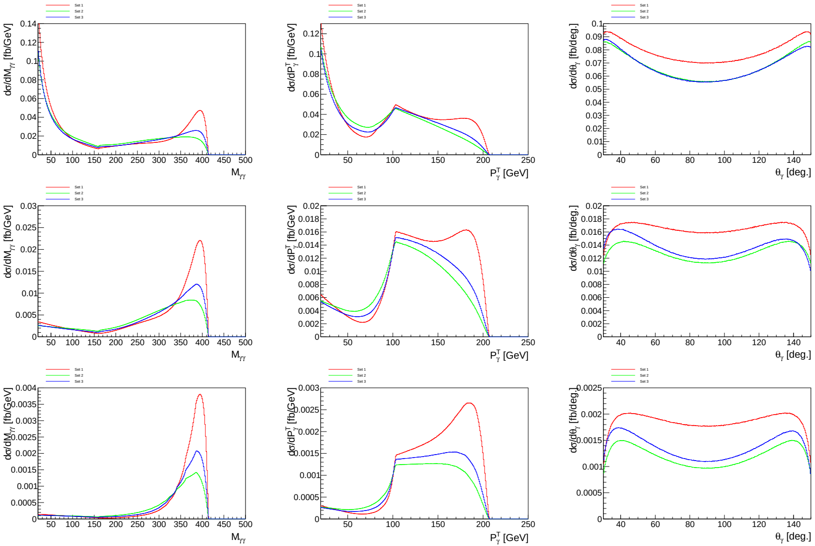
$\gamma\gamma \to \gamma Z$

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)

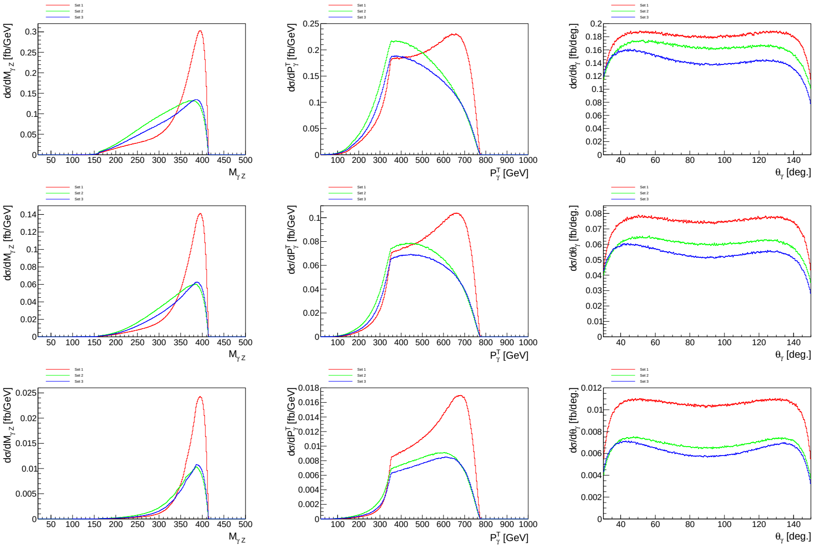
$\gamma\gamma \to ZZ$

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)

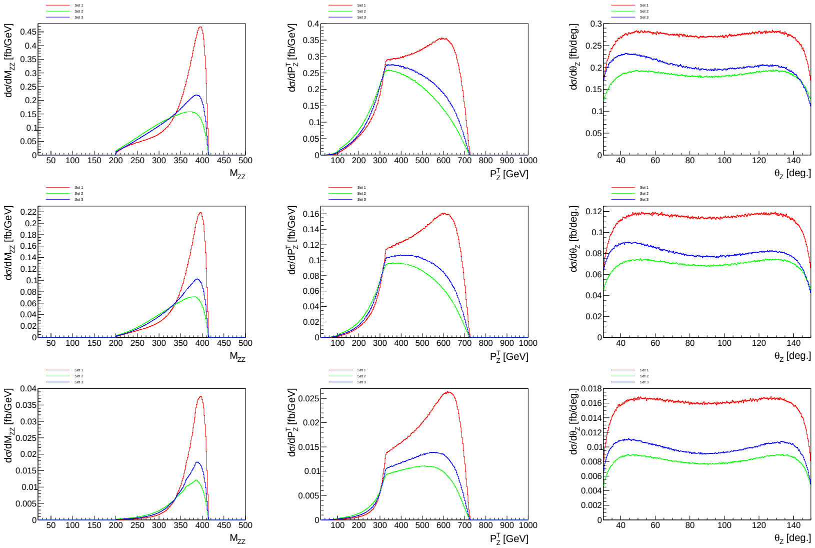
Distributions for $\gamma\gamma \to \gamma\gamma$ $(\rho = 0, 1, 5)$



Distributions for $\gamma\gamma \to \gamma Z$ $(\rho = 0, 1, 5)$

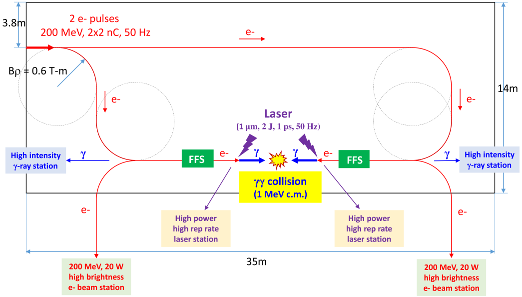


Distributions for $\gamma\gamma \to ZZ$ ($\rho = 0, 1, 5$)



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

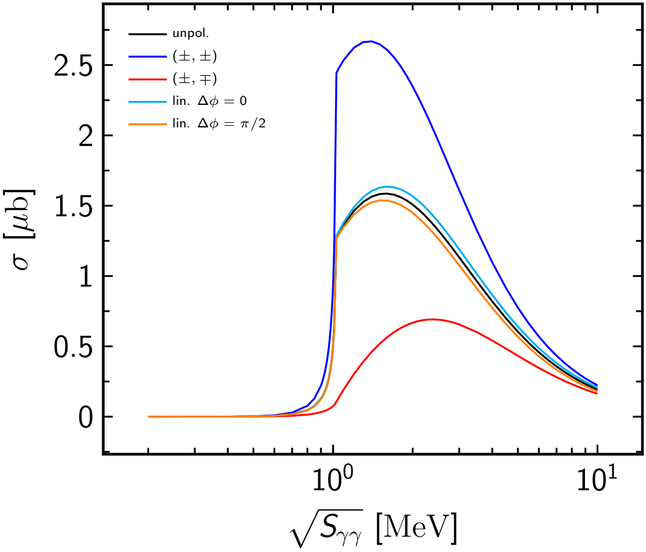
The photon collider Genie is proposed with $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV
T. Takahashi et.al. Eur. Phys. J. C (2018) 78:893



Picture from Huang Yongshen presentation DOI:10.13140/RG.2.2.11301.88806

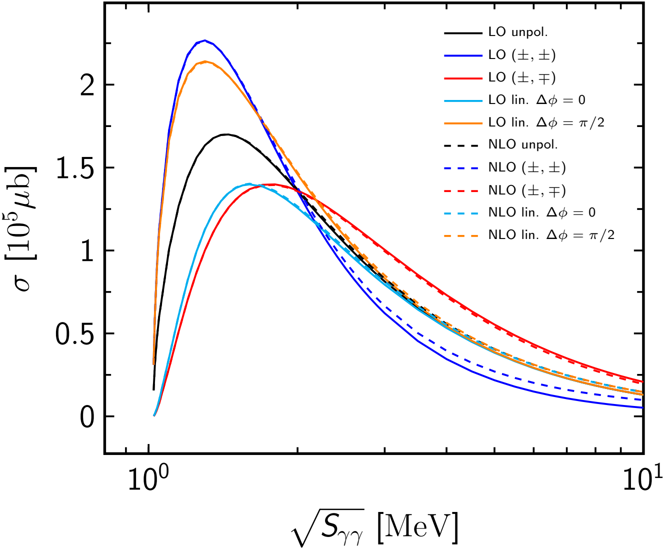
Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

$\gamma\gamma \to \gamma\gamma$ cross sections for different polarization



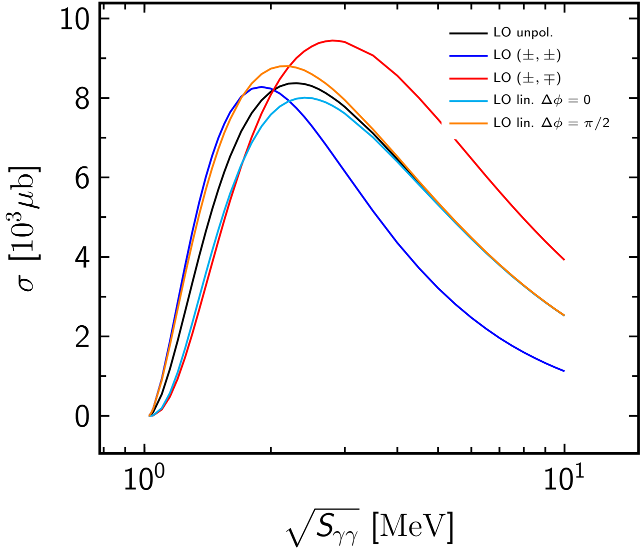
Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

$\gamma\gamma \to e^+e^-$ cross sections for different polarization



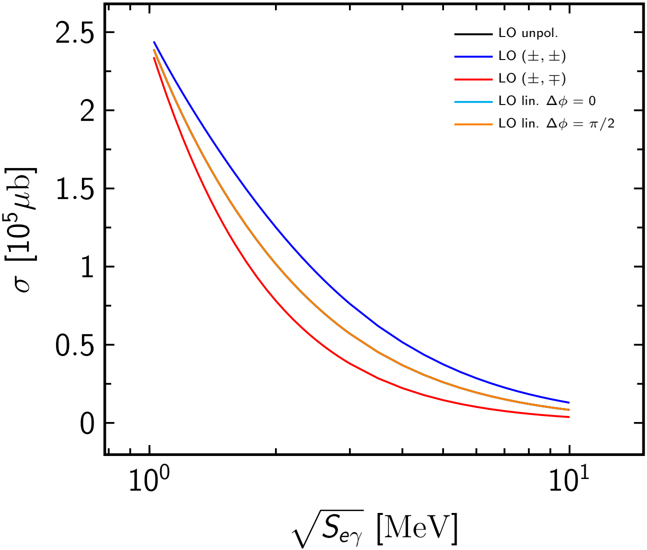
Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

$\gamma\gamma \to e^+e^-\gamma$ cross sections for different polarization



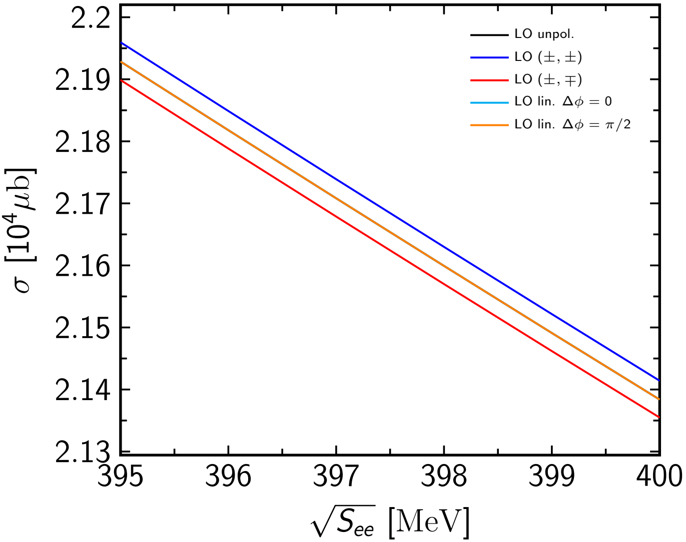
Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

$e^-\gamma \to e^-\gamma$ cross sections for different polarization



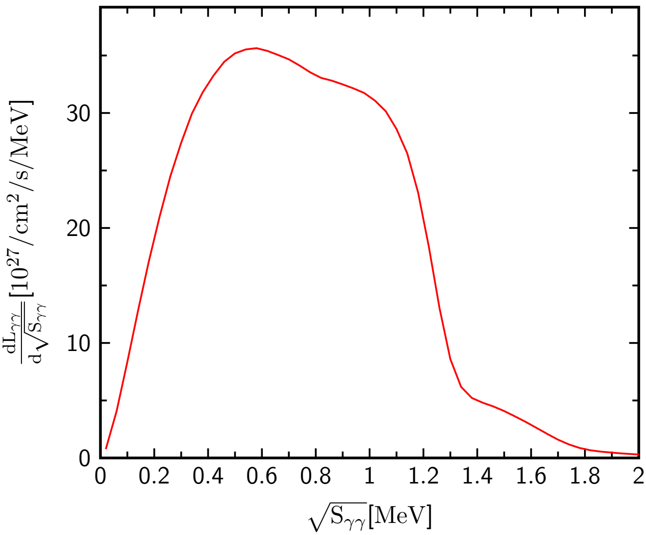
Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

$e^- e^- \to e^- e^-$ cross sections for different polarization



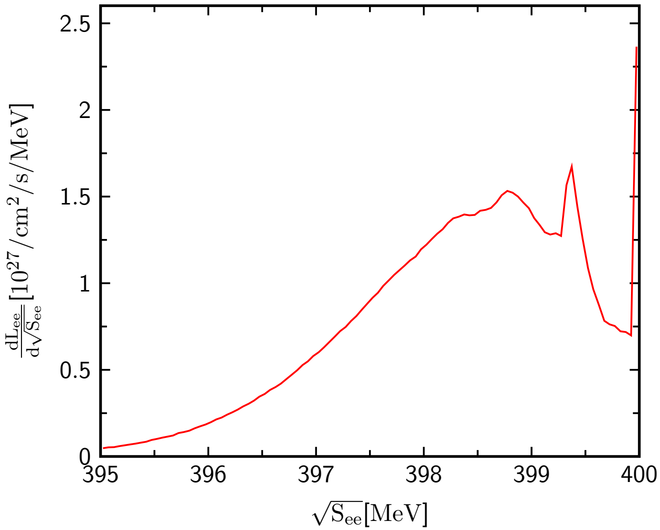
Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

$\gamma\gamma$ luminosity $\mathcal{L}_{\gamma\gamma}$ simulated with `CAIN 2.42`



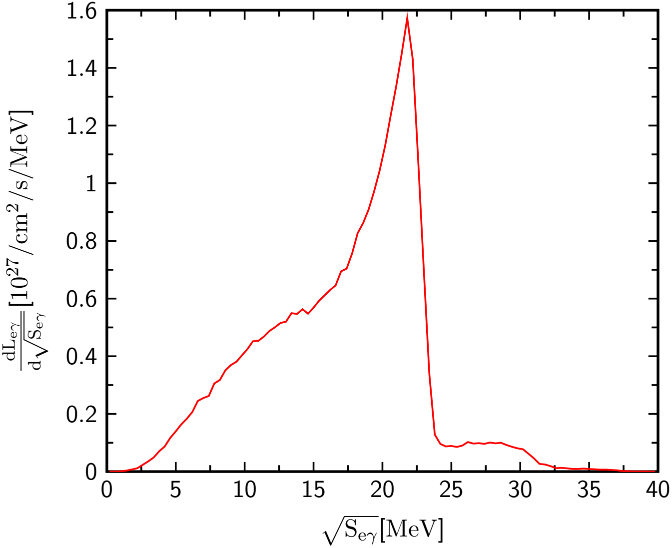
Application for photon collider at $\sqrt{S_{ee}} \sim 1$ MeV

$e^- e^-$ luminosity $\mathcal{L}_{ee}$ simulated with `CAIN 2.42`



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

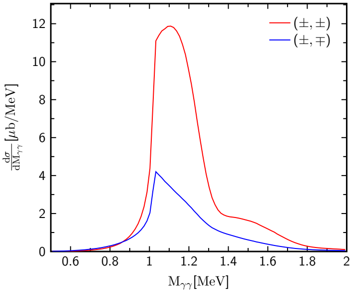
$e^-\gamma$ luminosity $\mathcal{L}_{e\gamma}$ simulated with CAIN 2.42

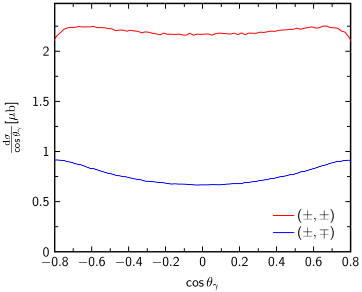


Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

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

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

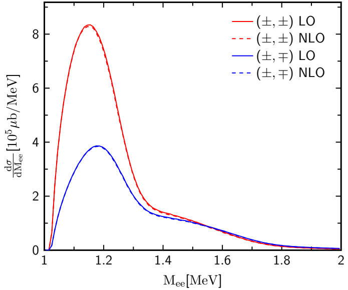


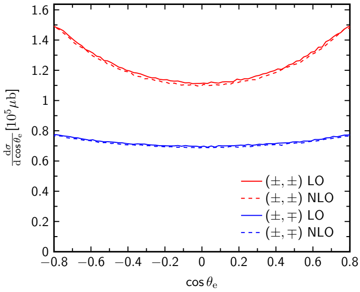


Application for photon collider at $\sqrt{S_{\gamma\gamma}} \sim 1$ MeV

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

$$\gamma\gamma \to e^+e^-(\gamma)$$





Summary and plans

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

- $\gamma\gamma \to \gamma\gamma, \gamma Z, ZZ, e^+e^-$,
  $e^-e^- \to e^-e^-$, $e^-\gamma \to e^-\gamma$ with arbitrary polarization of initial photons and electorns
- 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!