Exploring dark sector physics at a high energy photon-photon collider

IMPRS Recruiting Workshop

Monika Wüst
in collaboration with Marten Berger & Prof. Gudrid Moortgat-Pick

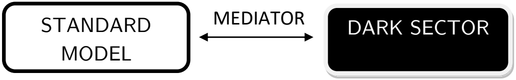
July 24, 2024

Table of contents

Motivation

Why a dark sector?

- Standard Model (SM) is incomplete:
  - Conceptual problems: Strong CP, Naturalness etc
  - Empirical facts: Neutrino masses, Dark Matter, matter-antimatter asymmetry
- Dark sector: Consists of particles not charged under SM gauge groups



Motivation

Why a dark sector?

- Standard Model (SM) is incomplete:
    - Conceptual problems: Strong CP, Naturalness etc
    - Empirical facts: Neutrino masses, Dark Matter, matter-antimatter asymmetry
- Dark sector: Consists of particles not charged under SM gauge groups

Why a Photon Photon collider?

- Complementary option for high energy linear colliders: $\gamma\gamma$ and γe collisions
- Variable polarization, luminosity comparable to e^+e^-
- New physics accessible in two-photon interaction
- Precision Tests for SM, e.g. Higgs factory

$$\boxed{\text{STANDARD MODEL}} \xleftrightarrow{\text{MEDIATOR}} \boxed{\text{DARK SECTOR}}$$

Basics of a Photon-Photon Collider

- High energy photons are produced via Compton backscattering (CB)
- Photon with energy $E_0 = \hbar\omega_0$ is scattered on electron with Energy E_e at small angle θ
- Maximum photon energy

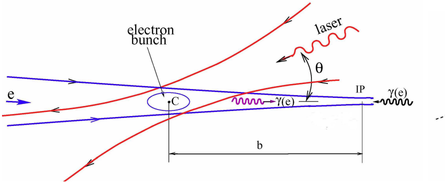
$$E_\gamma^{max} \approx 0.83 E_e \quad \text{for} \quad x \approx 4.8$$

- Study $\gamma\,\gamma$ or $\gamma\,e$ collisions with real photons

Maximum energy of scattered photons

$$E_\gamma^{max} = \frac{x}{x+1} E_e$$

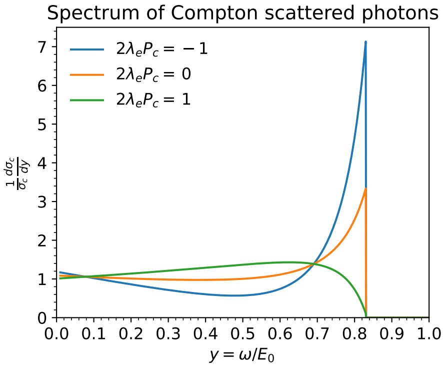
$$x \approx \frac{4 E_e \omega_0}{m_e^2 c^4} = 15.3 \left[\frac{E_e}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right]$$



[V. Telnov: arXiv:2007.14003]

Energy spectrum, Luminosity and Nonlinear Effects

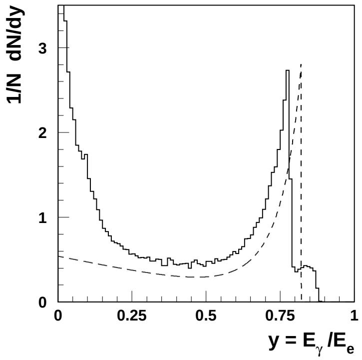
- Photon energy spectrum (CB) has strong dependence on polarization
- Realistic photon energy spectrum taken into account beam and laser system
  - Multiple Compton Scattering
  - Nonlinear effects: Effective increase in electron mass
- Luminosity spectrum simulation with CAIN [K. Yokoya et al.]



Spectrum of Compton-scattered photons for $x = 4.8$

Energy spectrum, Luminosity and Nonlinear Effects

- Photon energy spectrum (CB) has strong dependence on polarization
- Realistic photon energy spectrum taken into account beam and laser system
  - Multiple Compton Scattering
  - Nonlinear effects: Effective increase in electron mass
- Luminosity spectrum simulation with CAIN [K. Yokoya et al.]

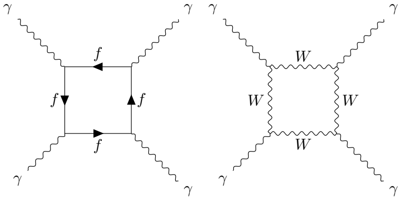


Realistic photon energy distribution compared to simple Compton spectrum [Zarnecki arXiv:0207021]

Light-by-Light scattering

in Theory

- Proceeds at leading order via box diagram $\mathcal{O}(\alpha^4)$
- Use Computation Tools like FormCalc [1604.04611] to reduce tensor integrals to scalar integrals
- Helicity amplitudes: $M_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}$, $\lambda_i = \pm$ for circular polarized photons



Cross section in helicity amplitude approach:

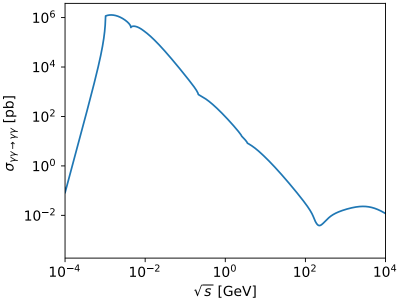
$$\frac{d\sigma}{d\Omega} = \frac{1}{128\pi^2 s}\left(|M_{++++}|^2 + |M_{++--}|^2 + |M_{+--+}|^2 + 4|M_{+++-}|^2\right)$$

Advantage: Use symmetries of the process to reduce number of independent amplitudes

Light-by-Light scattering

in Theory

- Proceeds at leading order via box diagram $\mathcal{O}(\alpha^4)$
- Use Computation Tools like FormCalc [1604.04611] to reduce tensor integrals to scalar integrals
- Helicity amplitudes: $M_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}$, $\lambda_i = \pm$ for circular polarized photons



Cross section in helicity amplitude approach:

$$\frac{d\sigma}{d\Omega} = \frac{1}{128\pi^2 s}\left(|M_{++++}|^2 + |M_{++--}|^2 + |M_{+--+}|^2 + 4|M_{+++-}|^2\right)$$

Advantage: Use symmetries of the process to reduce number of independent amplitudes

Light-by-Light Scattering

in Experiment

> Indirectly tested in electron and muon magnetic moments

> First direct observation: Heavy ion collisions (Pb-Pb), recorded by ATLAS in 2016 [arXiv: 1702.01625]

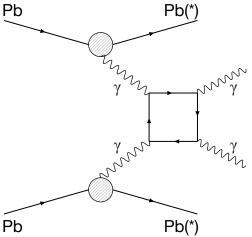
> Z^4 photon flux enhancement for ions compared to protons

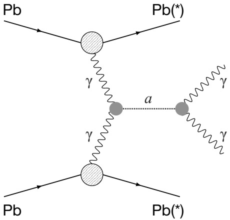
Why LbL to study BSM?

> Quartic anomalous gauge couplings

> Supersymmetry

> Axion-Like Particles





Light-by-Light through Axion Like Particles

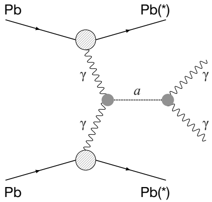
- Axion-Like Particles (ALPs): Pseudoscalar particles appearing in theories with broken global symmetry
- Effective interaction of ALPs with photons:

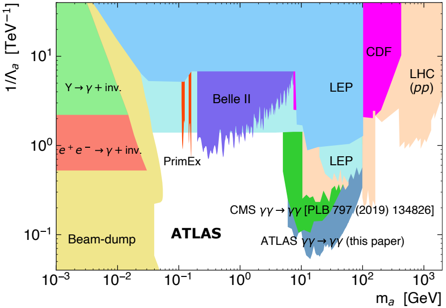
$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 - \frac{1}{4}g_{a\gamma\gamma}\,aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Decay Width of ALP into Photons:

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

$\Longrightarrow$ Competitive Limits through LbL at a Photon Collider?





Limits on ALP parameter space [ATLAS arXiv:2008.05355]

Light-by-Light through ALP's

- Helicity amplitudes of pure ALP LbL (computed with FormCalc), e.g.

$$M_{++++} = -\frac{g_{a\gamma\gamma}^2}{16} \frac{s^2}{s - m_a^2 + i m_a \Gamma_a}$$

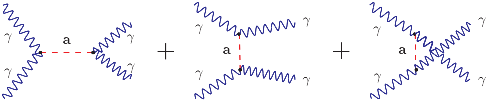
- Each helicity amplitude: $M = M_{alp} + M_{SM}$
- Resonance region $s \sim m_a^2$ in s-channel, for narrow resonance

$$\sigma_{\gamma\gamma\to a\to\gamma\gamma} \propto g_{a\gamma\gamma}^2 \mathcal{B}_{a\to\gamma\gamma}$$

- Full cross section with CB photons:

$$\frac{d\sigma}{d\Omega} = \int \frac{d\mathcal{L}}{d\hat{s}} \frac{d\hat{\sigma}^{\gamma\gamma}}{d\Omega} d\hat{s}$$

- Differential luminosity spectrum calculation with CAIN



Light-by-Light virtual production of ALP [S.C. Inan, A.V. Kisselev: arXiv:2007.01693]

Conclusions and Outlook (Work in Progress)

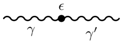
- High physics potential for a $\gamma\gamma$-collider to probe a dark sector: Complementary to e^+e^--colliders and LHC
- ALP parameter space can be constrained at future high energy colliders such as CLIC

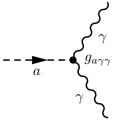
Outlook

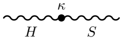
- Optimize photon luminosity
- Investigate dark sector phenomenology
  - Dark Higgs and Dark Photon
  - Dark Axion Portal

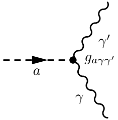
Backup - Overview Dark Sector Portals

Portal	Particle	Interaction
Vector	Dark photon γ'	$\frac{\epsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$
Axion	Pseudoscalar a	$\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{g_{a\gamma\gamma}}{4} \partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$
Higgs	Dark scalar S	$\lambda_{HS} \lvert S \rvert^2 \lvert H \rvert^2$
Dark Axion	Mixed a and γ'	$\frac{g_{a\gamma\gamma'}}{4} a F_{\mu\nu} \tilde{Z}'^{\mu\nu} + \frac{g_{a\gamma'\gamma'}}{4} a Z'_{\mu\nu} \tilde{Z}'^{\mu\nu}$









and Neutrino portal, mixed scenarios etc.

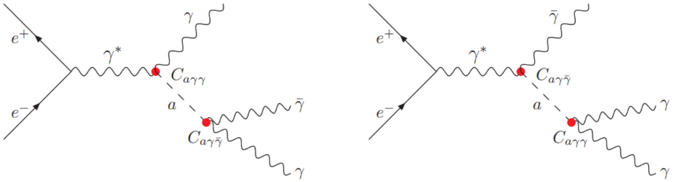
Backup - Dark Axion Portal

> Interaction Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{g_{a\gamma\gamma'}}{2} a F^{\mu\nu} \tilde{F}'_{\mu\nu}$$

> Fermions in triangle loop can have both charges $U(1)_{PQ}$ and $U(1)_{Dark}$

> Dark Axion Portal couplings are not just product of two individual portals ($\epsilon G_{a\gamma\gamma}$ would be greatly suppressed since $\epsilon^2 \ll 1$)



Feynman diagrams for $e^+ e^- \to \gamma\gamma\gamma'$

Backup - Compton Scattering

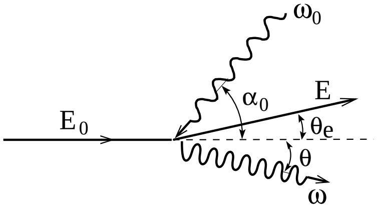
Compton Cross Section:

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} = \frac{2\sigma_0}{x\sigma_c}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda_e P_c r x(1-2r)(2-y)\right]$$

- $r = y/(x(1-y))$
- Kinematics of backward Compton scattering is characterized by

$$x = \frac{2p_0 k_0}{m^2 c^2} \approx \frac{4E_0\omega_0}{m^2 c^4}\cos^2\frac{\alpha_0}{2}$$

- Photon emission angle is very small, $\theta \sim 1/\gamma_e = 2 \cdot 10^{-6}$
- Photons with maximum energy scatter at zero angle



Backup - Vector boson fusion (VBF)

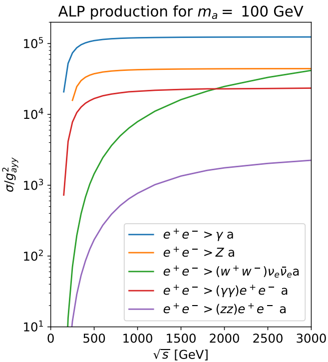
at electron-positron vs gamma-gamma collider

- Assume now coupling of ALP to electroweak gauge bosons

$$\mathcal{L}_{int} = C_{WW}\frac{a}{f_a} W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + C_{BB}\frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$\Longrightarrow$ Generate UFO-File with Feynrules

- At e^+e^--collider: Main production channels at low energies (ALP Strahlung) flatten out
- VBF depend only logarithmically on s but can reach sizeable cross section at high energies [C.X Yue et al: arXiv:2112.11604]
- VBF at gamma-gamma collider: Access to dark Higgs and ALPs



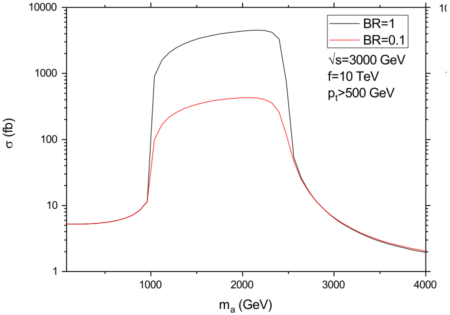
Simulated with MadGraph5 aMC@ NLO

Backup - ALP LbL at a Photon Collider

- Full cross section with CB photons:

$$\frac{d\sigma}{d\Omega} = \int \frac{d\mathcal{L}}{d\hat{s}} \frac{d\hat{\sigma}^{\gamma\gamma}}{d\Omega} d\hat{s}$$

- Differential luminosity spectrum calculation with CAIN
- Compact linear collider (CLIC): proposed future e^+e^--collider with 3 stages ($\sqrt{s} = 380, 1500, 3000$ GeV) $\rightarrow$Limits on ALP mass in range $m_a = 1000 - 2400$ GeV
- Cross sections much smaller for EPA photons in e^+e^- collision
- Use initial-state photon polarization



[S.C. Inan, A.V. Kisselev: arXiv:2007.01693]

Backup - Realistic photon energy spectrum

Nonlinear QED effects:

- Very strong laser field in conversion region $\rightarrow$ electron can interact simultaneously with several laser photons
- Characterized by parameter

$$\xi^2 = \frac{e^2 \bar{F}^2 h^2}{m_e^2 c^2 \omega_0^2} = \frac{2 n_\gamma r_e^2 \lambda}{\alpha}$$

  where $\bar{F}$ is strength of electric field in laser wave and n_γ the density of laser photons
- Leads to effective increase in the electron mass, maximum energy of scattered photons descreases:

$$E_\gamma^{max} = \frac{x}{x + 1 + \xi^2} E_e$$

Backup - ILC and CLIC Parameters

Optical parameters resulting from an optimisation of the $\gamma\gamma$ luminosity

laser pulse energy E_{pulse}	≈ 9.0 J	
average laser power $< P_{laser} >_t$	≈ 130 kW	for one pass collisions at the TESLA bunch-structure
pulse duration τ_{pulse}	3.53 ps FWHM ($\sigma = 1.5$ ps)	
Rayleigh length z_R	≈ 0.63 mm	
beam waist w_0	$\approx 14.3\,\mu$m $(1/e^2)$ ($\sigma = 7.15\,\mu$m)	
laser-e$^-$ crossing-angle α_L	≈ 56 mrad	
normalised mirror-size $a_{cc}/w_{cc,G}$	0.75	
laser wavelength λ	1.064 μm	
nonlinearity parameter ξ^2	0.30	
total luminosity $L_{\gamma\gamma}$	$1.1 \cdot 10^{34}$ cm^{-2}s^{-1}	

$2E_0$ GeV	3000
λ_L [μm]/x	4.4/6.5
t_L [λ_{scat}]	1.
$N/10^{10}$	0.4
σ_z [mm]	0.03
$f_{rep} \times n_b$ [kHz]	15.4
$\gamma\epsilon_{x/y}/10^{-6}$ [m·rad]	0.68/0.02
$\beta_{x/y}$ [mm] at IP	8/0.15
$\sigma_{x/y}$ [nm]	43/1
b [mm]	3
L_{ee}(geom) [10^{34}] cm^{-2}s^{-1}	4.5
$L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma})[10^{34}]$	0.45
$L_{\gamma e}(z > 0.8 z_{m,\gamma e})[10^{34}]$	0.9
$L_{ee}(z > 0.65)[10^{34}]$	0.6

Laser Parameters ILC ($E_b = 250$ GeV) [Bechtel et al arXiv:0601204] and CLIC ($E_b = 1500$ GeV) [Burckhardt 2020]

Backup - Helicity amplitudes (SM)

Use discrete symmetries to reduce number of indendent amplitudes:

- Parity

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,t,u) = M_{-\lambda_1-\lambda_2-\lambda_3-\lambda_4}(s,t,u).$$

- Time reversal

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,t,u) = M_{\lambda_3\lambda_4\lambda_1\lambda_2}(s,t,u)$$

- Bose symmetry

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,t,u) = M_{\lambda_2\lambda_1\lambda_4\lambda_3}(s,t,u)$$

Use crossing symmetry, only 3 amplitudes have to be calculated, e.g.

$$M_{++++}(s,t,u), \quad M_{++--}(s,t,u), \quad M_{+++-}(s,t,u)$$

Backup - Helicity amplitudes (ALP)

$$M_{++++} = -\frac{g^2_{a\gamma\gamma}}{4}\frac{s^2}{s - m_a^2 + i m_a \Gamma_a}$$
$$M_{++--} = -\frac{g^2_{a\gamma\gamma}}{4}\left(\frac{s^2}{s - m_a^2 + i m_a \Gamma_a} + \frac{t^2}{t - m_a^2} + \frac{u^2}{u - m_a^2}\right)$$
$$M_{+++-} = 0$$

where

$$M_{+-+-}(s,t,u) = M_{++++}(u,t,s)$$
$$M_{+--+}(s,t,u) = M_{++++}(t,s,u)$$

and differential cross section

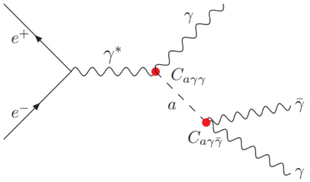
$$\frac{d\sigma}{d\Omega} = \frac{1}{128\pi^2}(|M_{++++}|^2 + |M_{+-+-}|^2 + |M_{+--+}|^2 + |M++--|^2)$$

Backup - Dark Axion Portal

- Interaction Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{g_{a\gamma\gamma'}}{2} a F^{\mu\nu} \tilde{F}'_{\mu\nu}$$

- Fermions in triangle loop can have both charges $U(1)_{PQ}$ and $U(1)_{Dark}$
- Dark Axion Portal couplings are not just product of two individual portals ($\epsilon G_{a\gamma\gamma}$ would be greatly suppressed since $\epsilon^2 \ll 1$)



Feynman diagrams for $e^+e^- \to \gamma\gamma\gamma'$

Backup - EPA and photon flux

Full $\gamma\gamma$ production cross section

$$\sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) = \int dw_1\, dw_2 \frac{f_{\gamma/A}(w_1)}{w_1} \frac{f_{\gamma/B}(w_2)}{w_2} \sigma_{\gamma\gamma\to\gamma\gamma}(\sqrt{s_{\gamma\gamma}})$$

with

$\sqrt{s_{\gamma\gamma}} = \sqrt{4\omega_1\omega_2}$ two photon cms energy

$\omega_{1/2}$ two photon energies

$f_{A/B}(\omega)$ photon flux at energy ω radiated of by the hadrons A/B