Photon colliders: simulation and di-Higgs production as physics case

Marten Berger

In cooperation with
Johannes Braathen, Gudrid Moortgat-Pick
Georg Weiglein, Monika Alexandra Wüst

Contents

- Gamma-gamma collider
- Di-Higgs
- Light-by-Light

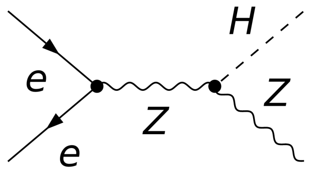
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

11.04.2025

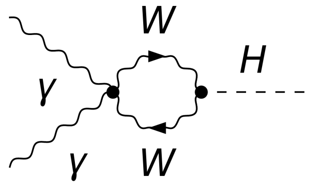
Introduction

- High energy photons collisions (ɣɣ and e-ɣ) offer a complementary physics program to e+e-:

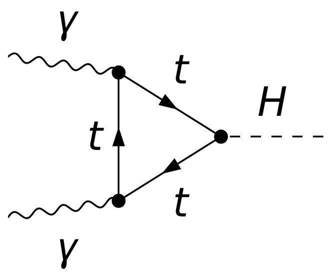
TESLA TDR 2001, JLC TDR 1998



- **The Higgs boson is produced in the s channel**
  - The electron beam energy is lower than what is required in e+e- collisions (65-80 GeV vs 125 GeV)
  - At higher center of mass energies, all phase space is available for producing the Higgs boson → higher mass reach for heavy Higgs bosons than e^+e^- at the same center of mass energy
  - ɣɣ can couple to spin-0 resonances whereas e+e- require the production of another spin-1 particle
    - complementary probe of the scalar sector



Ginzburg et al. 1983



- **Polarization of both electrons and photons**
  - Allows for a rich study of CP properties in the scalar sector

Complementarity ee vs γγ

- γγ collisions can produce **heavy Higgs bosons** with masses >1.5 times higher than e^+e^-:
  - $e^+e^- \to HA$ vs. $\gamma\gamma \to H$, $\gamma\gamma \to A$

Mühlleitner, Zerwas 2006

- $e^-\gamma$ collisions can produce **charged particles** with masses higher than pair-production in e^+e^-:
  - $e^-\gamma \to \tilde{e}\tilde{\chi}^0$

Kanemura 2001, Nauenberg 2001, Mühlleitner 2006

- Since $\gamma\gamma \to H$ is a loop-induced process, it can probe new physics contributions to the Higgs photon coupling: **sensitive to BSM particles in loops**

Grzadkowski,Gunion 1992, Krämer et al. 1994

Godbole, Kraml et al. 2006

- Ability to control the photon polarizations provides a powerful tool for the **exploration of CP properties** of any single neutral Higgs boson
  - The J_z=0 γγ initial state can form a CP-even or a CP-odd state using linear polarizations of the laser beams
  - CP-even Higgs bosons (h^0, H^0) couple to linearly polarized photons with maximum strength for parallel polarisation vectors
  - CP-odd Higgs boson (A^0) couple to linearly polarized photons with perpendicular polarization vectors

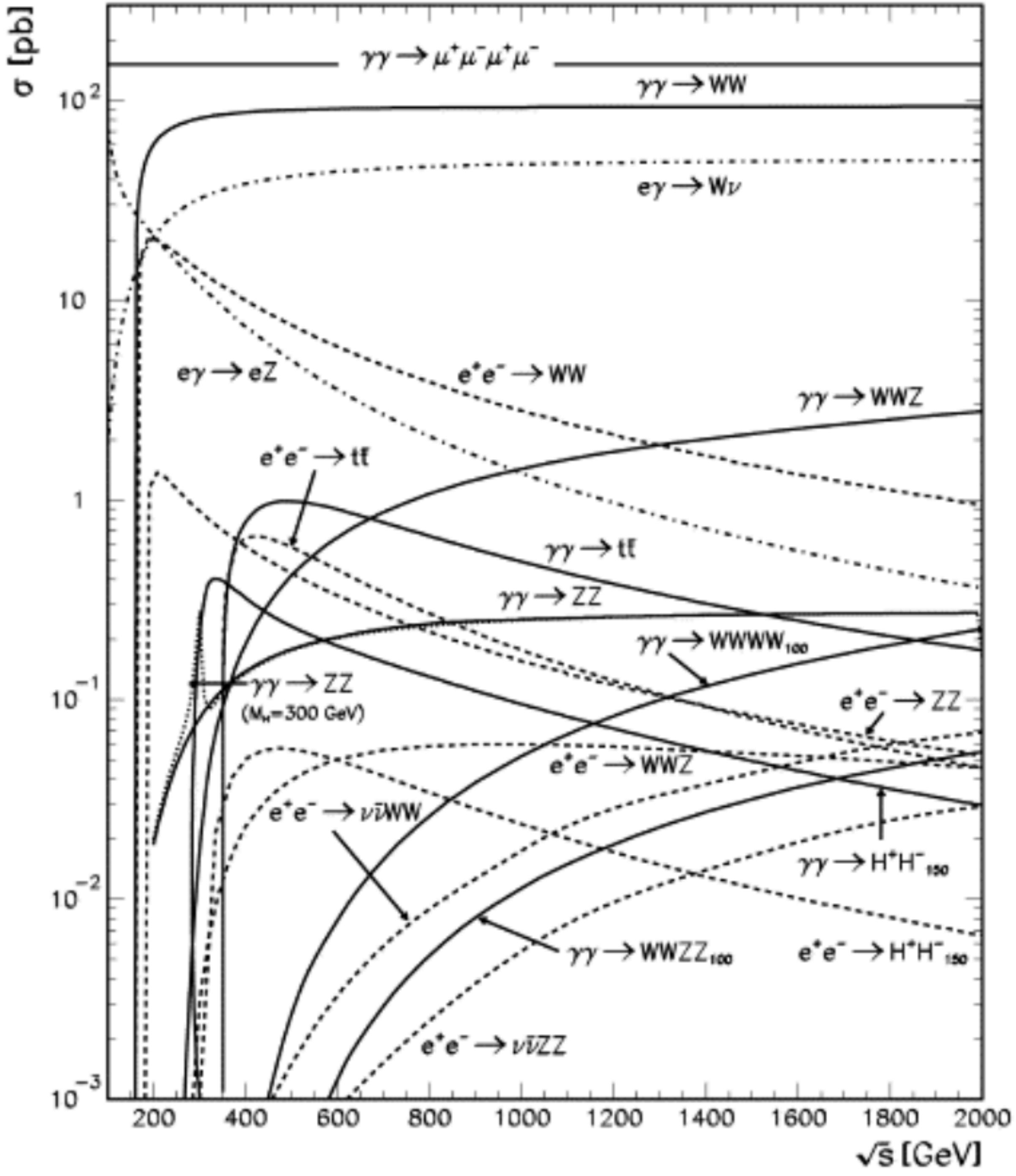
Telnov 2020, 2023

Physics Opportunities

- Di-Higgs production and measurement of trilinear couplings *Jikia 1994, Bharucha et al. 2021* *MB, Braathen, Weiglein, Moortgat-Pick*
- Enhanced production cross sections of any charged particles by a factor of ~10 compared to e^+e^- (e.g. SUSY, etc.) *Mühlleitner et al. 2006, Kanemura 2001*
- $e^-\gamma$-options extends kinematic reach for charged particles (BSM, SUSY, heavy Higgs, etc.)
- Access to hadronic and electromagnetic structure of photons via photon-photon and photon-electron scattering
- Access to precise measurement of the two-photon decay width of the Higgs boson due to the higher rates *Gunion et al. 1997*
- Searches for BSM particles in light-by-light scattering *İnan, Kisselev 2020* *MB, Moortgat-Pick*
- Spectroscopy of C-even resonances (e.g. in multi-quark states, glueballs) *Telnov et al. 2023*

Physi

- Di-Higgs
- Enhance compare
- e-ɣ-optio ... gs, etc.)
- Access t ... d photon-e
- Access t ... due to the hig beyond t
- Spectros

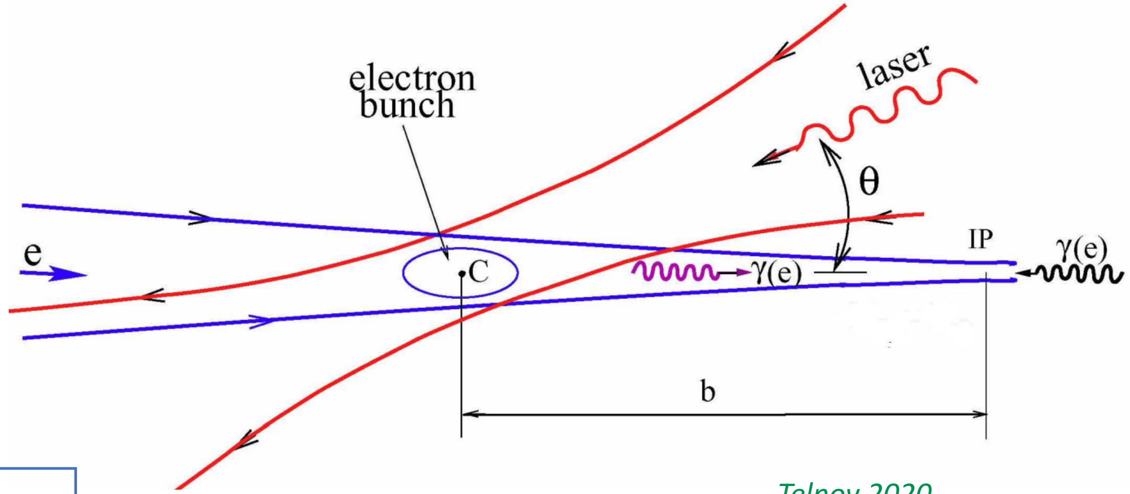


see also Balazs et al., arXiv 2503.19983

...t al. 2001
...glein, GMP
...2001
...997
...l. 2023

Photon collider

- Addition to e^+e^- colliders
- Compton backscattering
- Getting access to $\gamma\gamma$ and γe processes



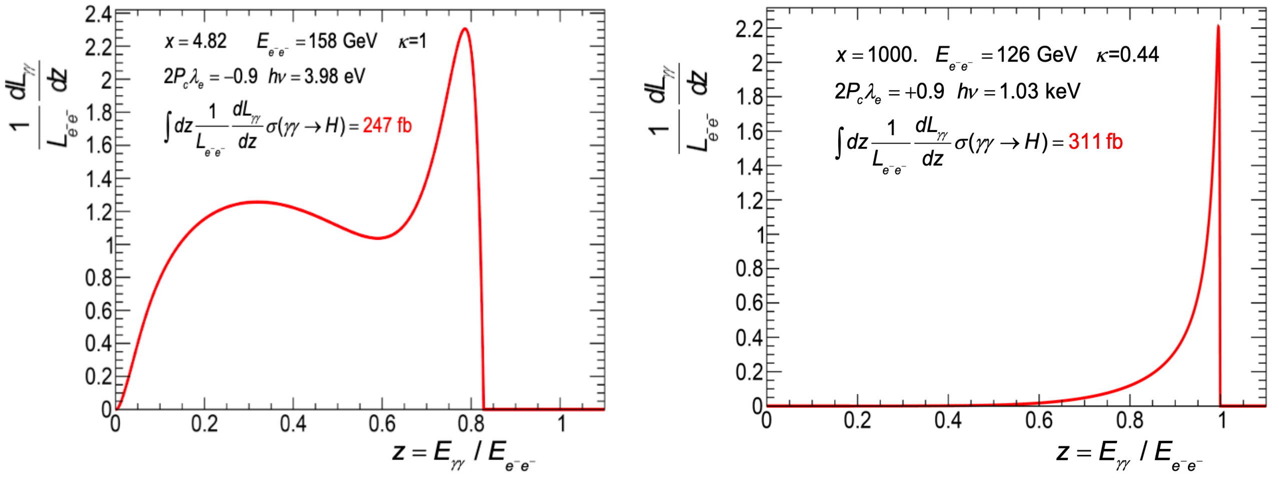
Telnov 2020

$$\omega_m \approx \frac{x}{x+1}E_0 \qquad x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\omega_0}{\text{eV}}\right] = 19\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\mu\text{m}}{\lambda}\right]$$

Barklow 2024

Laser is decisive:

a) optical
b) XFEL-like



How to get the beams?

Ilya Ginzburg '83

- Compton backscattering $\sigma_c = \sigma_c^{np} + \lambda_e P_c \sigma_c^1$

$$\sigma_c^{np} = \frac{2\pi\alpha^2}{x m_e^2}\left[\left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2}\right]$$

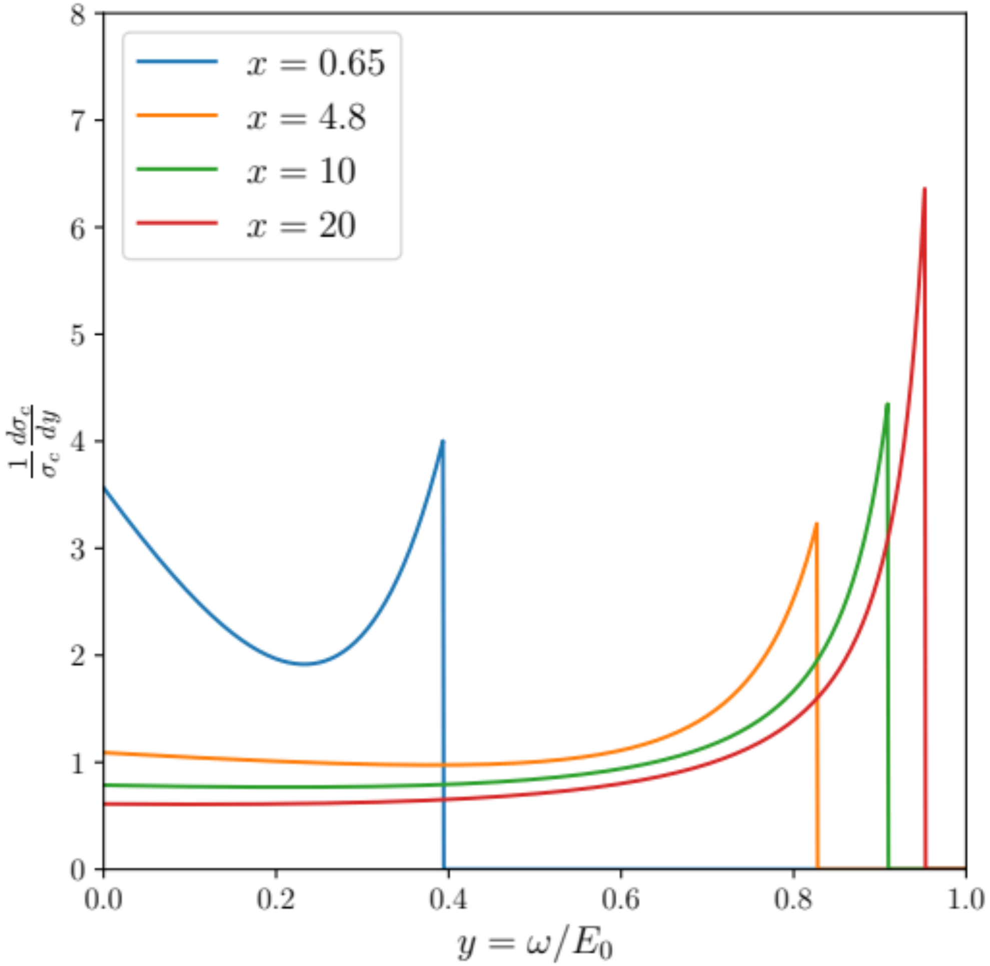
$$\sigma_c^1 = \frac{2\pi\alpha^2}{x m_e^2}\left[\left(1 + \frac{2}{x}\right)\ln x + 1 - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right]$$

- Energy spectrum

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} \equiv f(x,y)$$

$$= \frac{2\pi\alpha^2}{\sigma_c x m_e^2}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) - \lambda_e P_c r x (2r-1)(2-y)\right]$$

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



How to get the beams?

Ilya Ginzburg '83

- Compton backscattering $\sigma_c = \sigma_c^{np} + \lambda_e P_c \sigma_c^1$

$$\sigma_c^{np} = \frac{2\pi\alpha^2}{xm_e^2}\left[\left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2}\right]$$

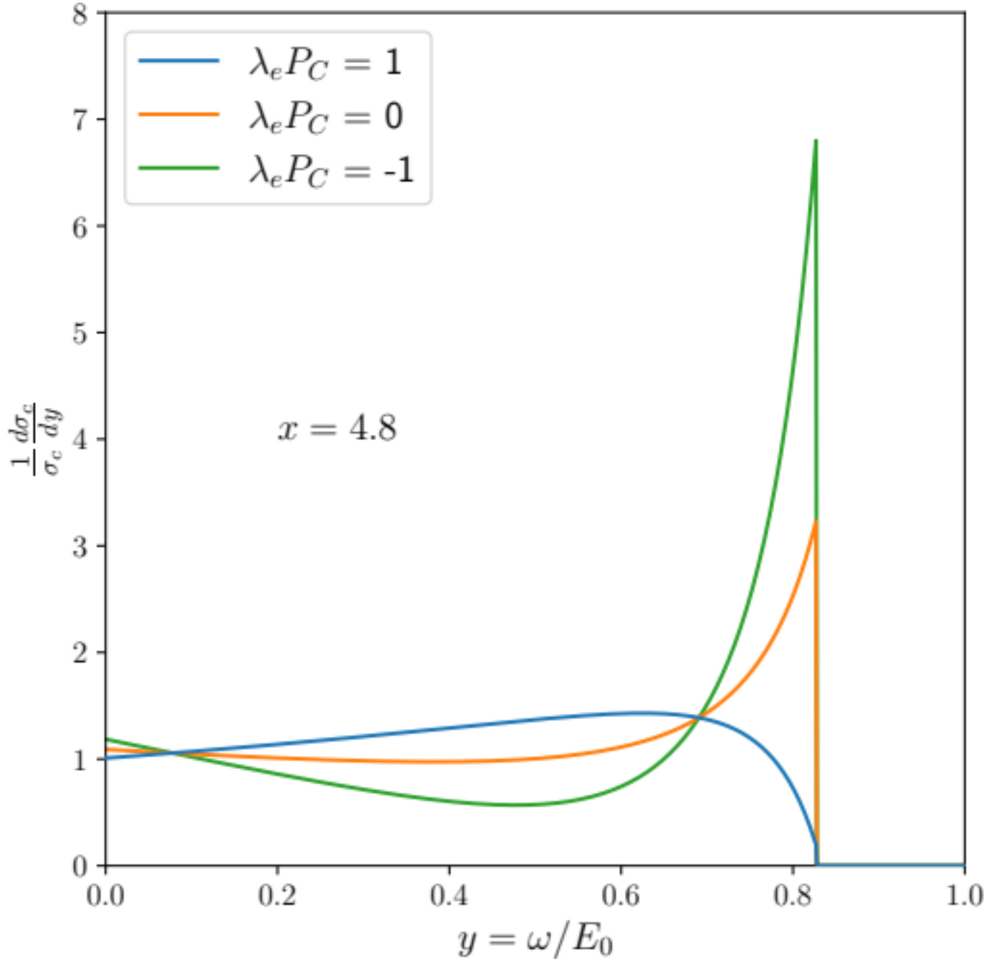
$$\sigma_c^1 = \frac{2\pi\alpha^2}{xm_e^2}\left[\left(1 + \frac{2}{x}\right)\ln x + 1 - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right]$$

- Energy spectrum

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} \equiv f(x,y)$$

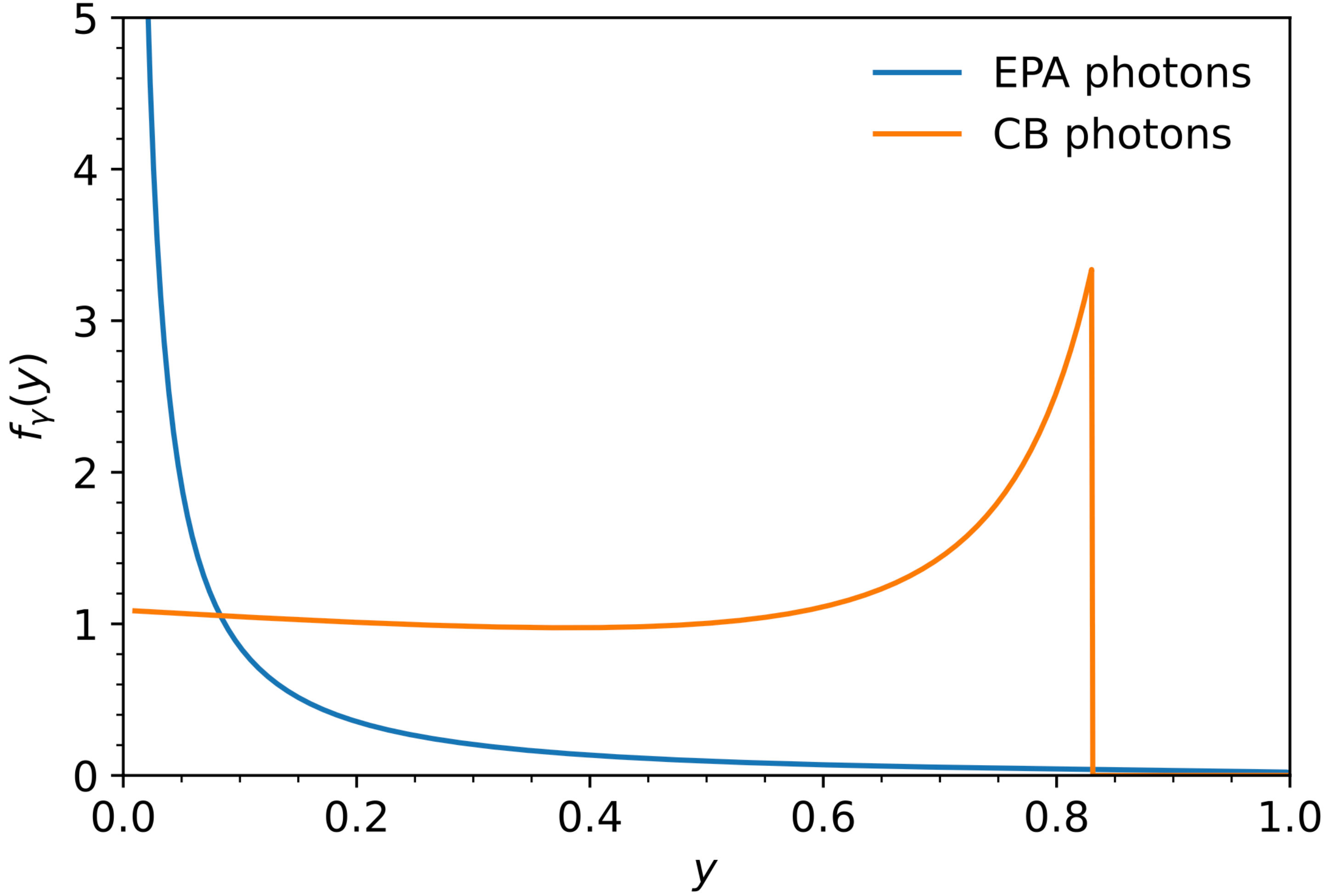
$$= \frac{2\pi\alpha^2}{\sigma_c x m_e^2}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) - \lambda_e P_c r x (2r-1)(2-y)\right]$$

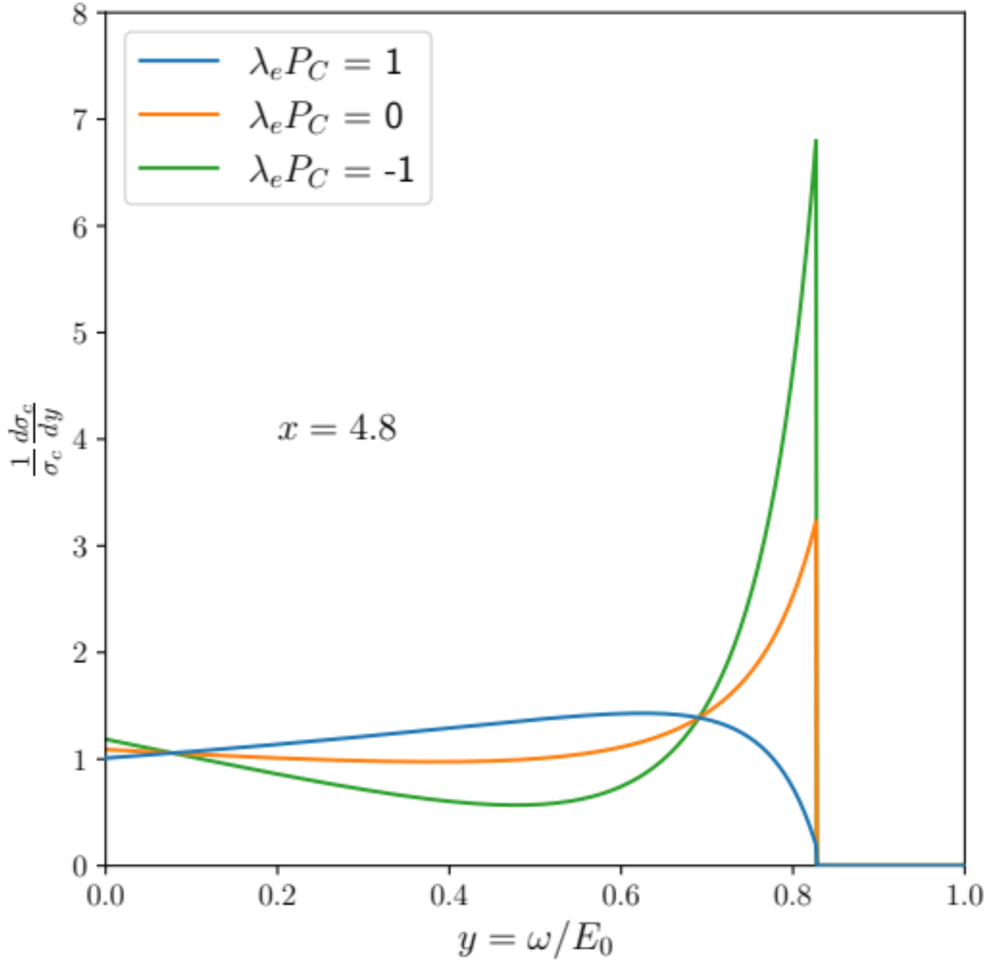
$$r = \frac{y}{x(1-y)} \leq 1$$



Compared to EPA photons

Wüst

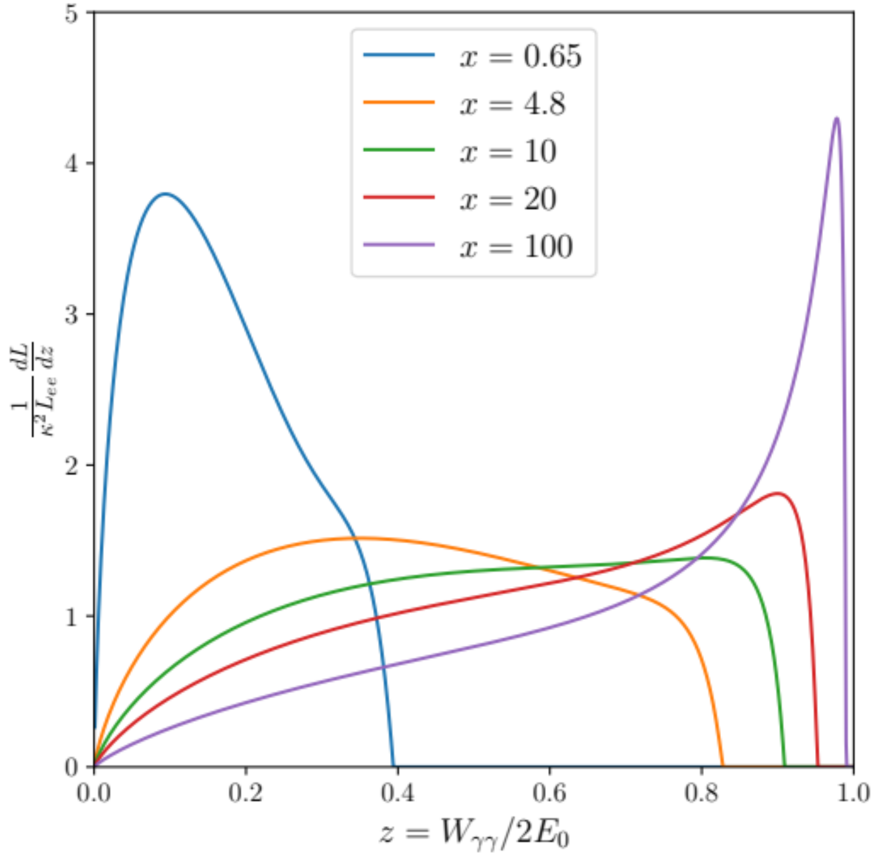




Spectral Luminosity

$$\frac{1}{k^2 L_{ee}} \frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = 2z \int_{z^2/y_{max}}^{y_{max}} \frac{\mathrm{d}y}{y} f(x,y) f\left(x, \frac{z^2}{y}\right) I_0\left(\rho^2 \sqrt{\left(\frac{y_{max}}{y} - 1\right)\left(\frac{y_{max} y}{z^2} - 1\right)}\right) \exp\left[-\frac{\rho^2}{2}\left(\frac{y_{max}}{y} + \frac{y_{max} y}{z^2} - 2\right)\right]$$

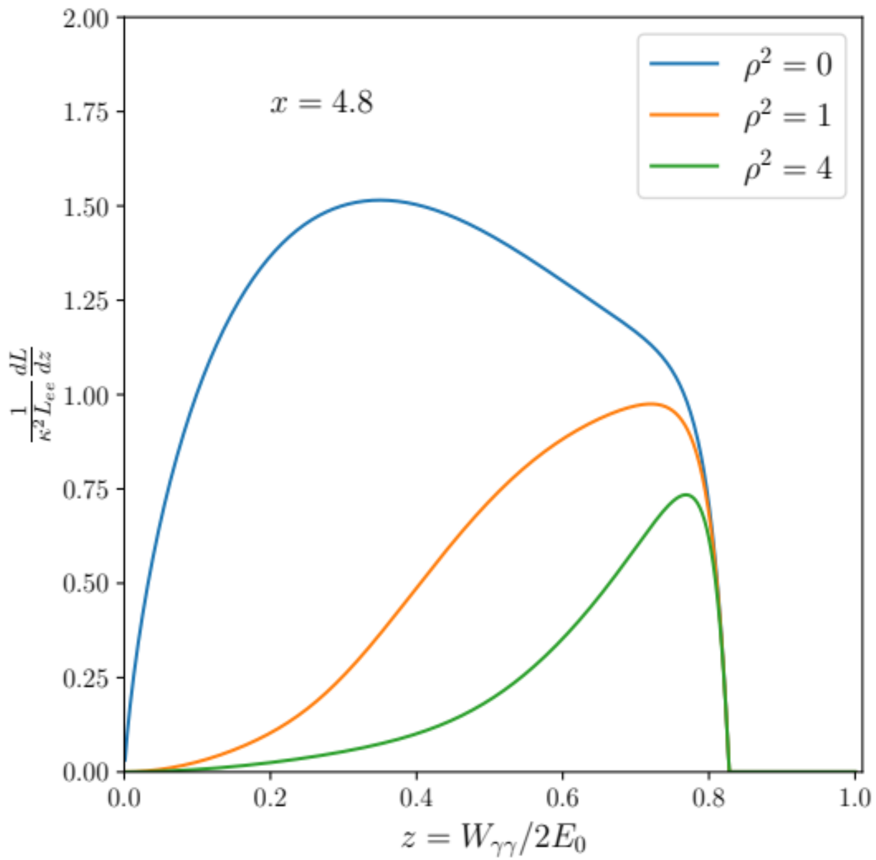
$$\rho^2 = \left(\frac{b}{\gamma \sigma_x}\right)^2 + \left(\frac{b}{\gamma \sigma_y}\right)^2$$



Spectral Luminosity

$$\frac{1}{k^2 L_{ee}}\frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = 2z\int_{z^2/y_{max}}^{y_{max}} \frac{\mathrm{d}y}{y} f(x,y) f\left(x, \frac{z^2}{y}\right)$$
$$I_0\left(\rho^2\sqrt{\left(\frac{y_{max}}{y}-1\right)\left(\frac{y_{max}y}{z^2}-1\right)}\right)$$
$$\exp\left[-\frac{\rho^2}{2}\left(\frac{y_{max}}{y}+\frac{y_{max}y}{z^2}-2\right)\right]$$

$$\rho^2 = \left(\frac{b}{\gamma\sigma_x}\right)^2 + \left(\frac{b}{\gamma\sigma_y}\right)^2$$



Polarization at photon collider

- Polarization effects
  - Mean helicity of the beams

$$\langle\lambda_\gamma\rangle = \frac{\lambda_e xr[1+(1-y)(2r-1)^2] - P_c(2r-1)[(1-y)^{-1}+1-y]}{(1-y)^{-1}+1-y-4r(1-r)-\lambda_e P_c xr(2-y)(2r-1)}$$

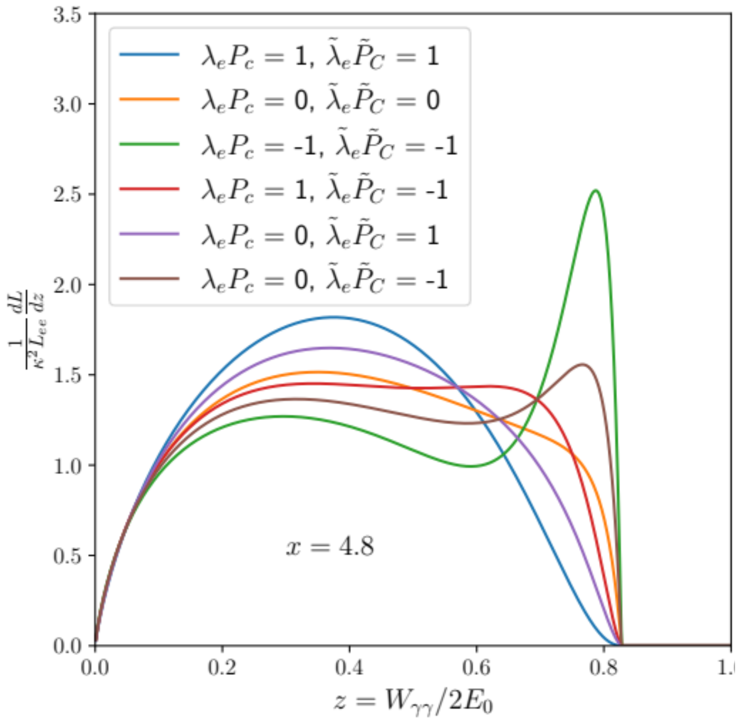
  - Effect on the luminosity

$$\frac{1}{k^2 L_{ee}}\frac{\mathrm{d}L_{\gamma\gamma}^{+\pm}}{\mathrm{d}z} = 2z\int_{z^2/y_{max}}^{y_{max}}\frac{\mathrm{d}y}{y}\left(\frac{1\pm\lambda_{\gamma,1}\lambda_{\gamma,2}}{2}\right) f(x,y) f\left(x,\frac{z^2}{y}\right) F(\rho),$$

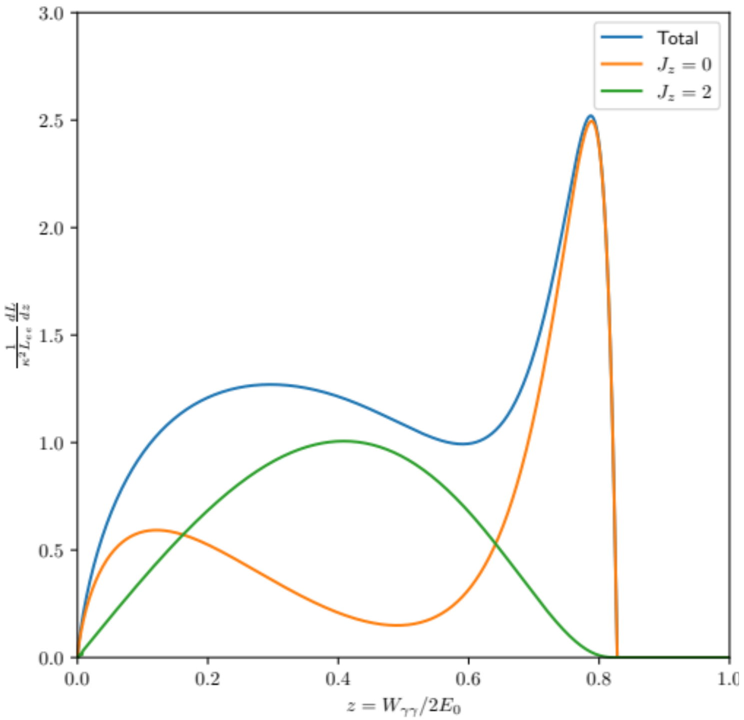
$$L_{\gamma\gamma} = L_{\gamma\gamma}^{++} + L_{\gamma\gamma}^{+-}$$

Polarization at photon collider

Flipping of the $J_z = 0$, 2 contribution, with same total spectrum

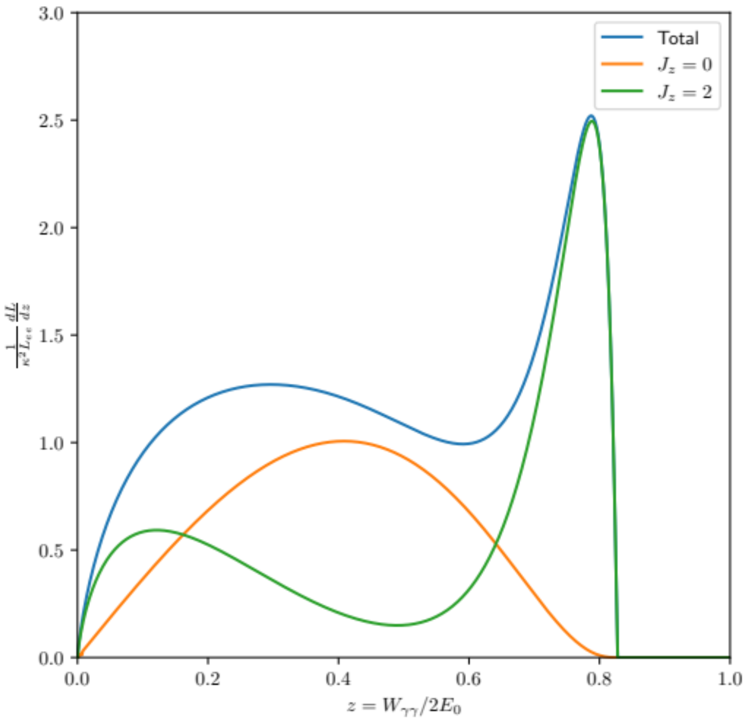


Include polarization in energy spectrum



Beam polarization included with

$$\lambda_e = 1, \quad P_c = -1, \quad \tilde{\lambda}_e = 1, \quad \tilde{P}_c = -1$$



Beam polarization included with

$$\lambda_e = 1, \quad P_c = -1, \quad \tilde{\lambda}_e = -1, \quad \tilde{P}_c = 1$$

Realistic spectrum

- CAIN includes important effects *Yokoya et al.*
  - Breit-Wheeler and Bethe-Heitler
  - Needs fine-tuning of laser and electron beam parameters to optimize spectrum

- Possible to use 2D-Spectrum *Kilian, Ohl, Reuter, et al.*
  - Used with other codes like WHIZARD
  - Also gain information on boost

Designs

Optical

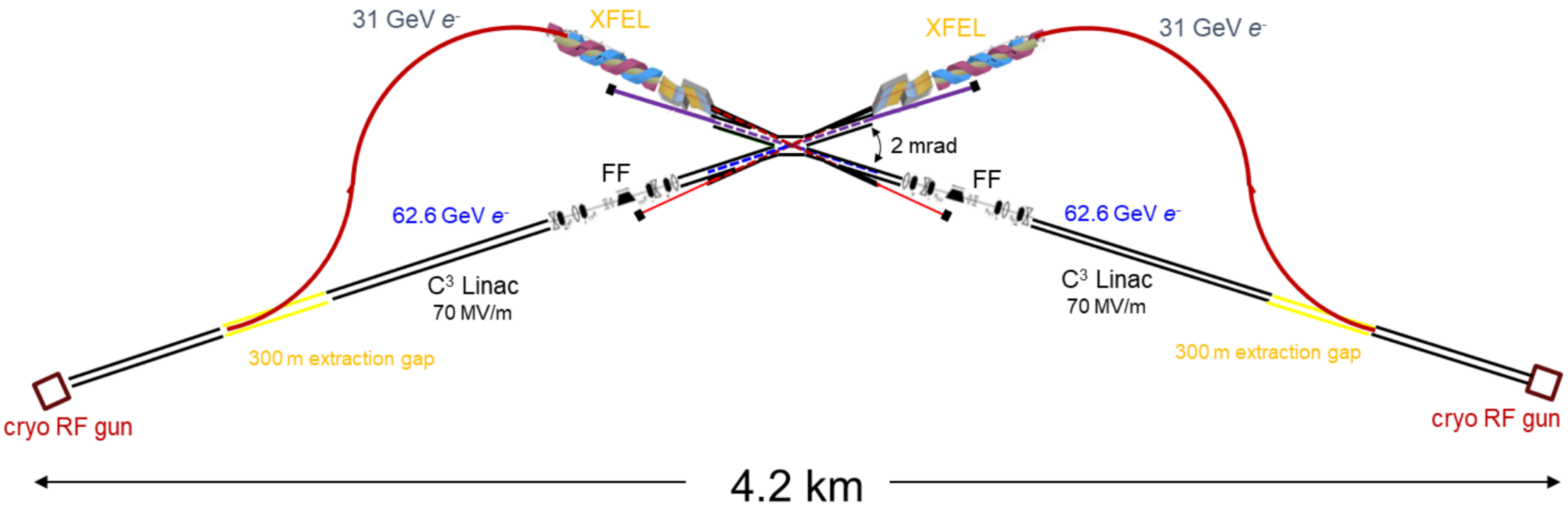
- Laser for x = 4.82
- Energy of up to ~80% E_e
- Broad spectrum
- 100% of electrons
- h-production at E_e = 108 GeV
- di-Higgs at E_e = 250 GeV
- $\lambda_e P_c$ = -0.9

XCC

- XFEL for x = 1000
- Energy of close to 100% E_e
- Peaked spectrum
- 20% of electrons converted
- h-production at E_e = 62.8 GeV
- di-Higgs at E_e = 190 GeV
- $\lambda_e P_c$ = 0.9

Design for XCC cms = 125 GeV

Barklow et al. 2023



Parameters for cms = 380 GeV

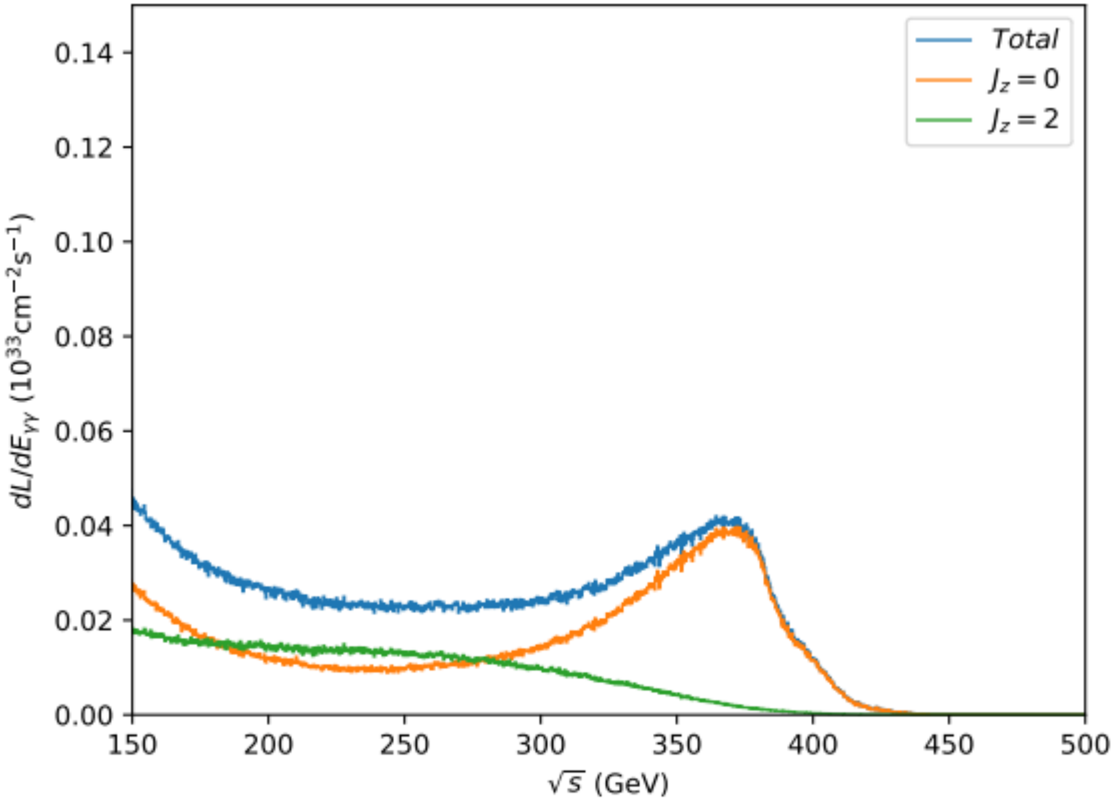
LCVision, Balazs et al., arXiv 2503.19983

Final Focus parameters	SCRF + Optical Laser	C3 + XFEL
Electron energy [GeV]	250	190
Electron beam power [MW]	10.5	2.1
β_x/β_y [mm]	1.5/0.3	0.01/0.01
$\gamma\epsilon_x/\gamma\epsilon_y$ [nm]	2500/30	60/60
σ_x/σ_y at e^-e^- IP [nm]	88/4.3	1.3/1.3
σ_z [μm]	300	10
Bunch charge [$10^{10} e^-$]	2	0.62
Bunches/train at IP	2625	93
Train Rep. Rate at IP [Hz]	5	120
Bunch spacing at IP [ns]	366	5.2
σ_x/σ_y at IPC [nm]	176/37.5	5,2/5.2
$\mathscr{L}_{\text{geometric}}$ [$10^{34}\text{cm}^2\ \text{s}^{-1}$]	12	180
δ_E/E [%]		0.1
L^* (QD0 exit to e^-e^- IP) [m]	3.8	1.5 or 3.0
d_{cp} (IPC to IP) [μm]	2600	40
crossing angle [mrad]	20	2 or 20

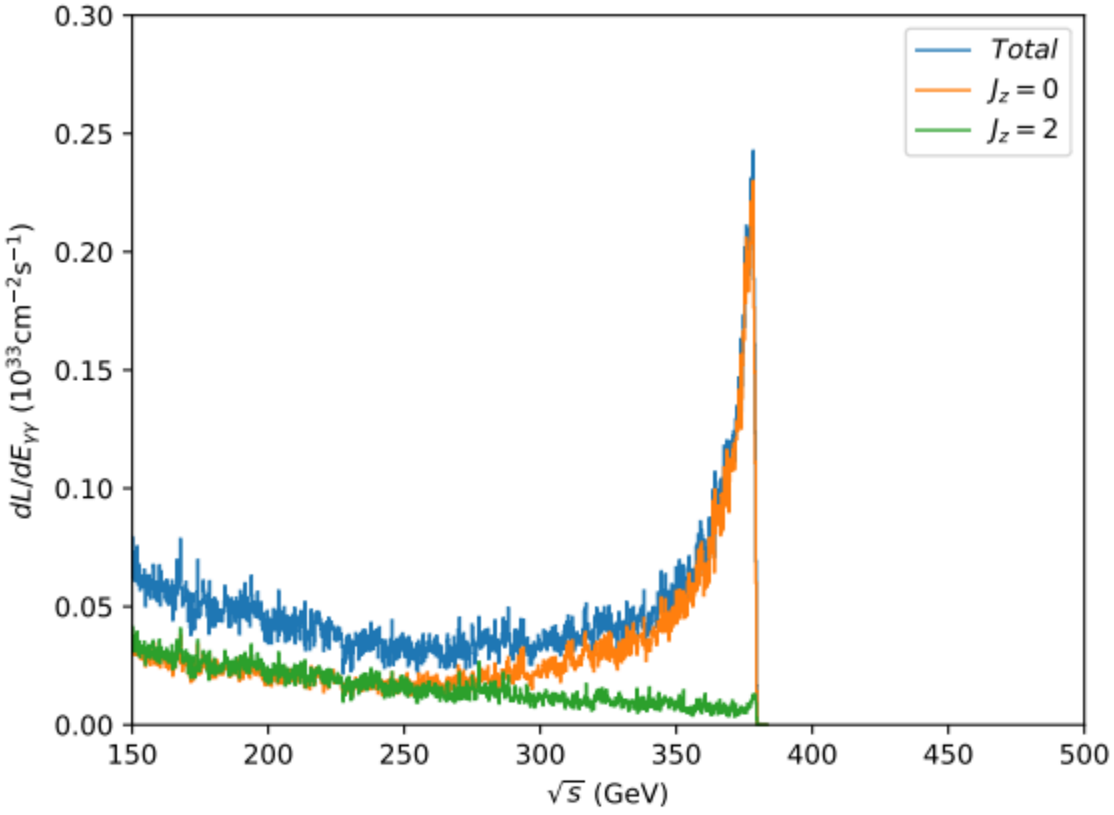
Laser parameters	SCRF + Optical Laser	C3 + XFEL
Electron energy [GeV]	n.a.	31
Normalized emittance [nm]	n.a.	60
RMS energy spread $\langle\Delta\gamma/\gamma\rangle$ [%]	n.a.	0.05
Bunch charge [nC]	n.a.	1
Undulator B field [T]	n.a.	-
Undulator period λ_u [cm]	n.a.	-
Average β function [m]	n.a.	-
photon λ (energy) [nm (keV)]	1056 (0.0012)	2.5 (0.05)
photon pulse energy [J]	2.4	1.0
rms pulse length [μm]	450	20
$a_{\gamma x}/a_{\gamma y}$ (x/y waist) [nm]	5000/5000	21/21
non-linear QED ξ^2	0.21	1.1

Optical and XCC

Optical laser with x = 4.82

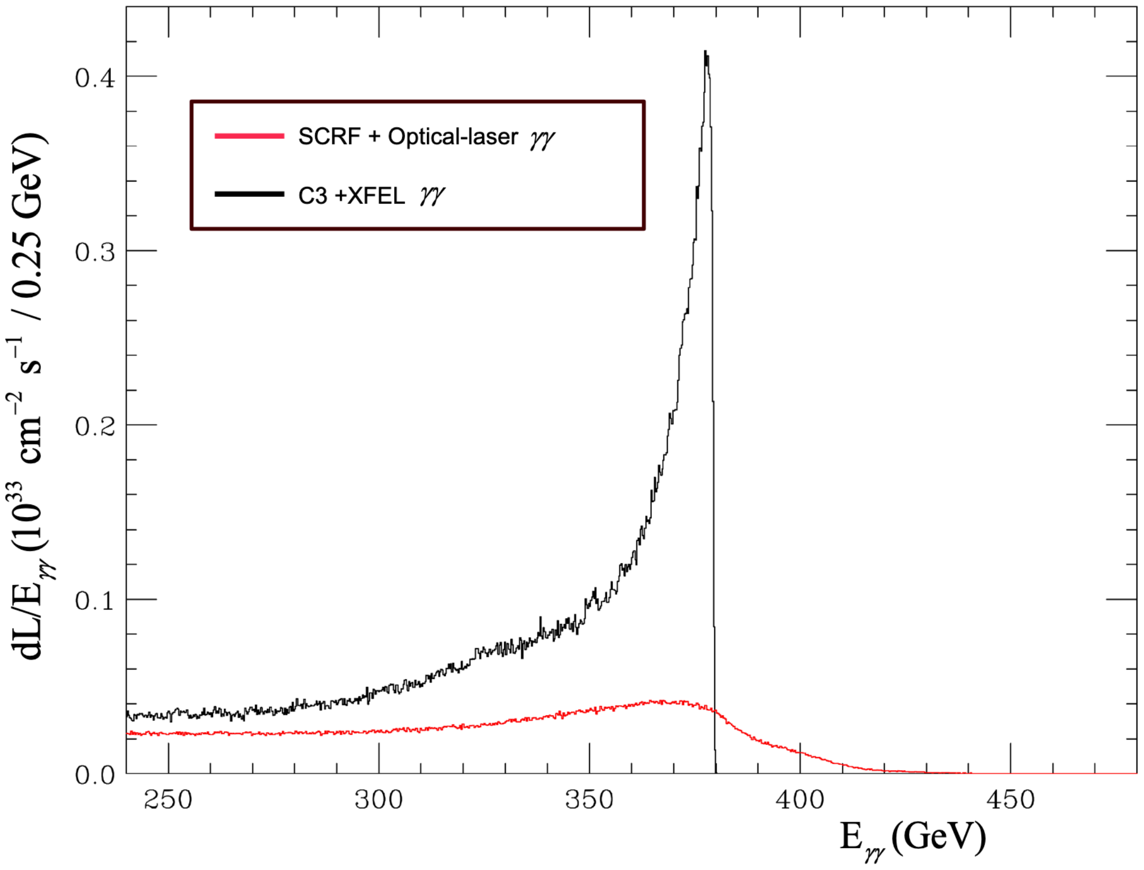


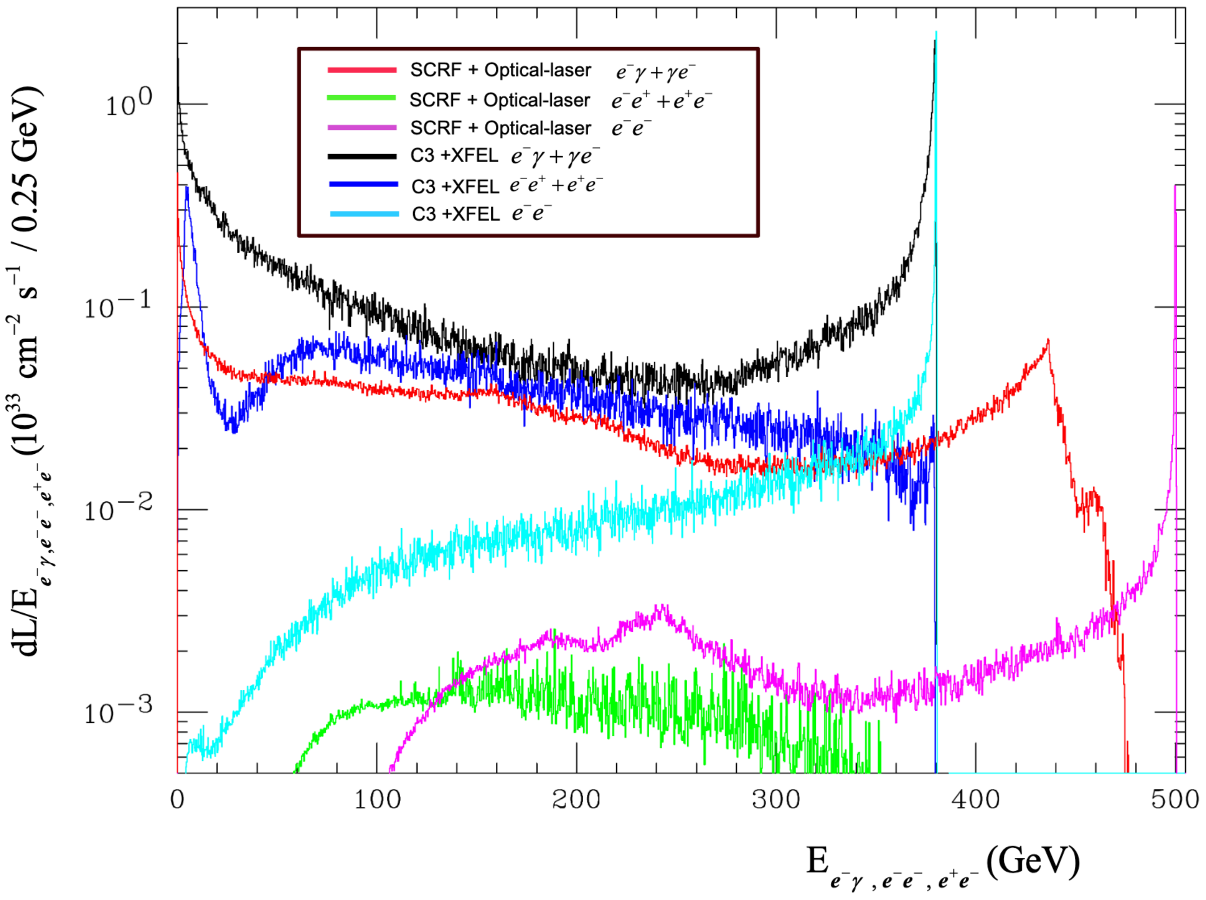
XCC with x = 1000



Additional processes in $\gamma\gamma$ mode

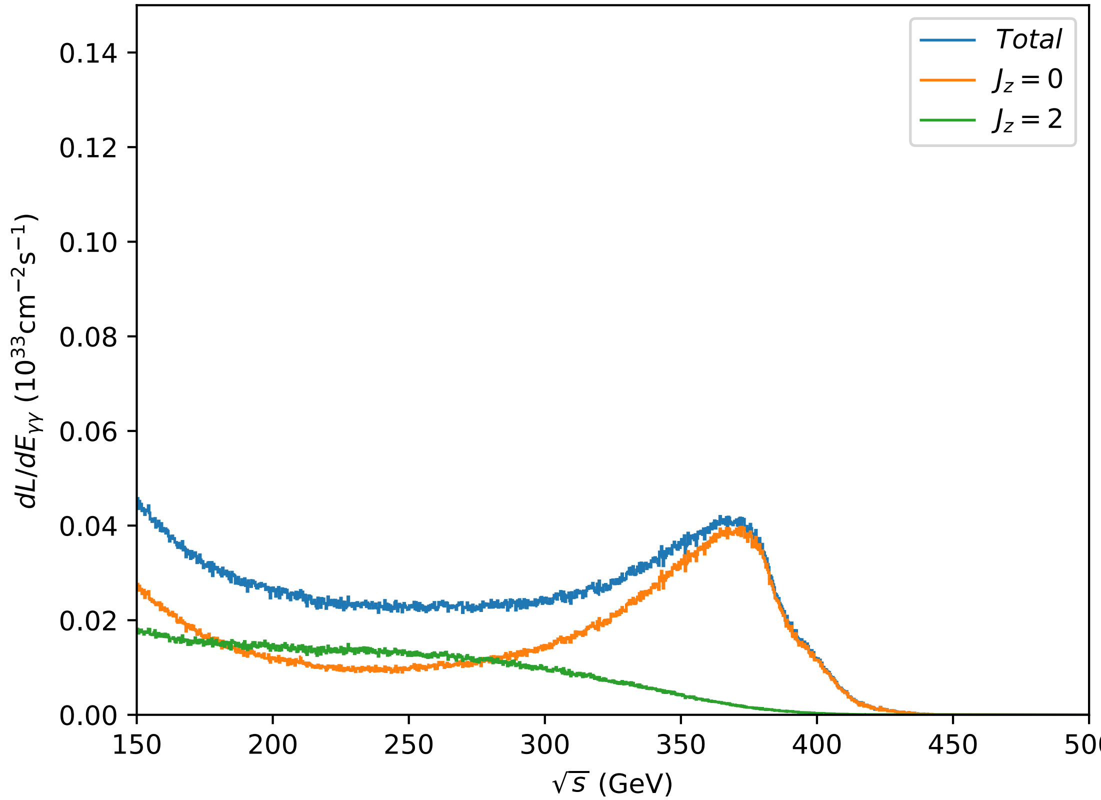
LCVision, Balazs et al., arXiv 2503.19983



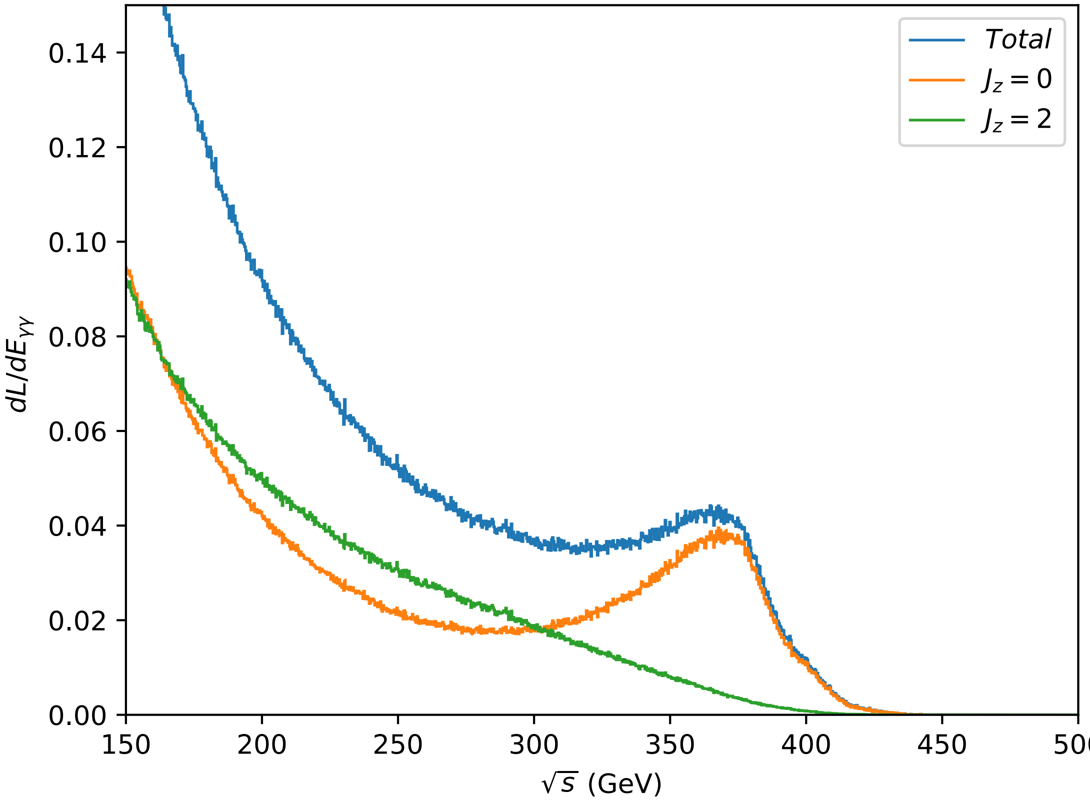


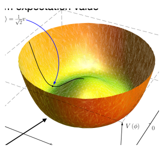
Comparison between e⁻e⁻ and e⁺e⁻

e⁻e⁻-mode

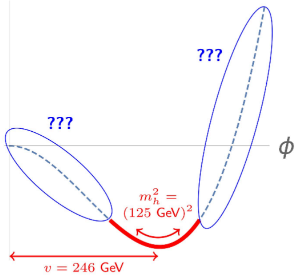


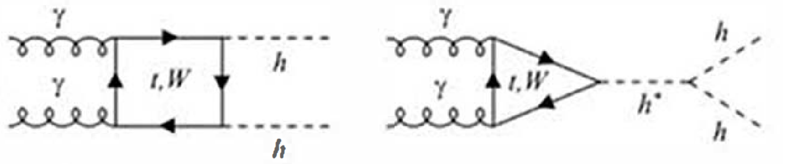
e⁺e⁻-mode



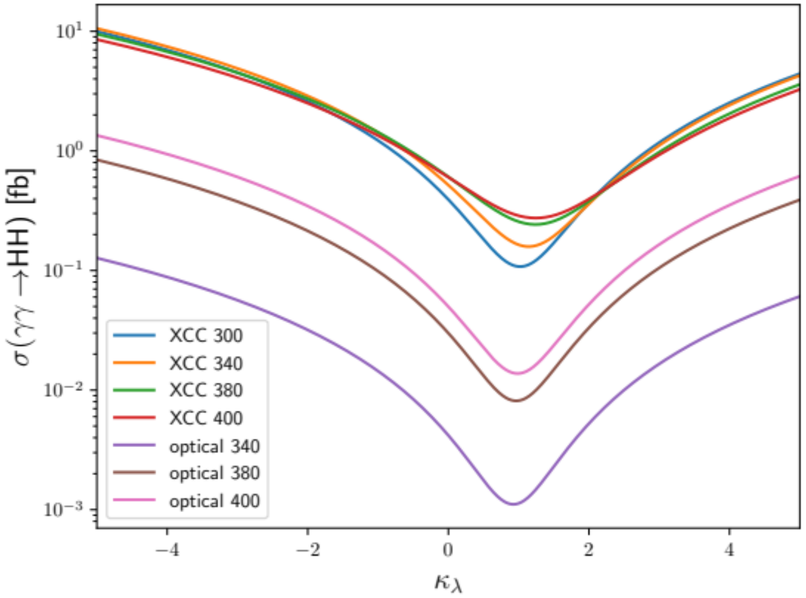


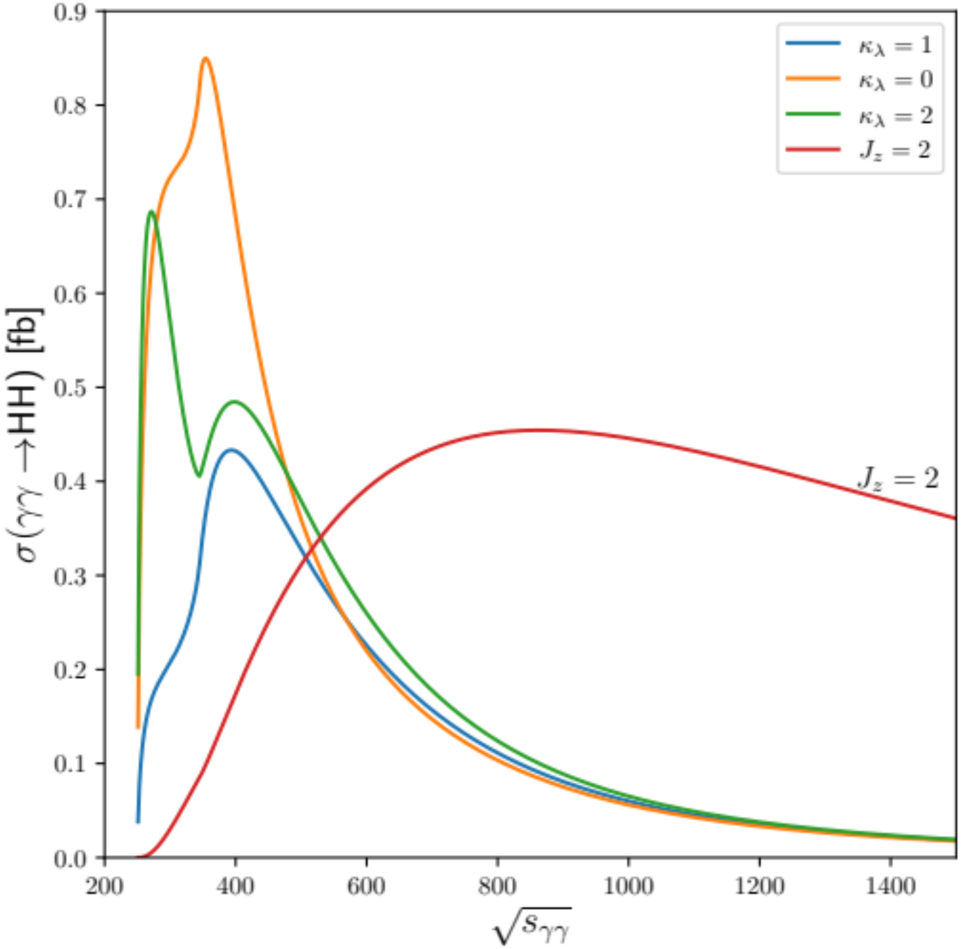
Di-Higgs production

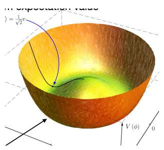




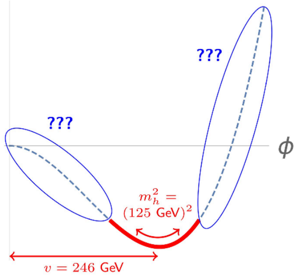
- Triangle contribution only for J_z=0
- Highly depending on trilinear Higgs-coupling

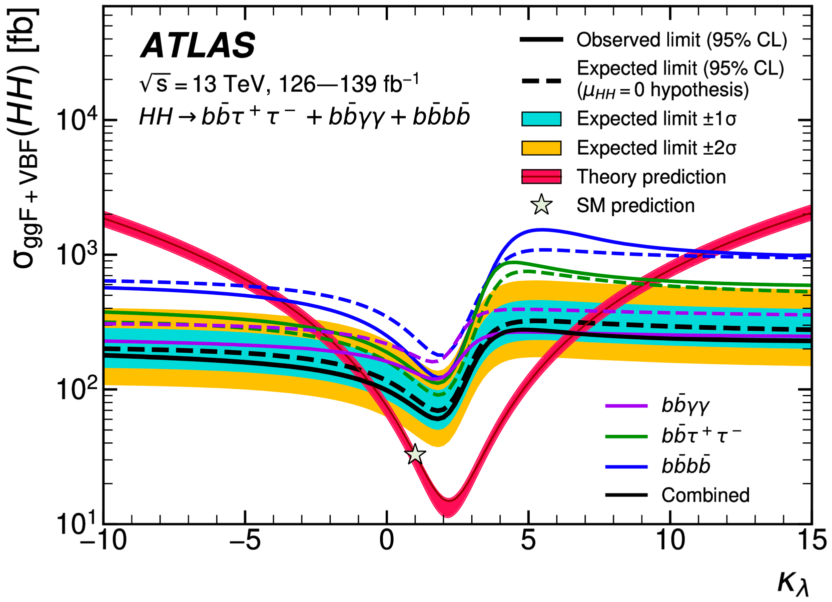




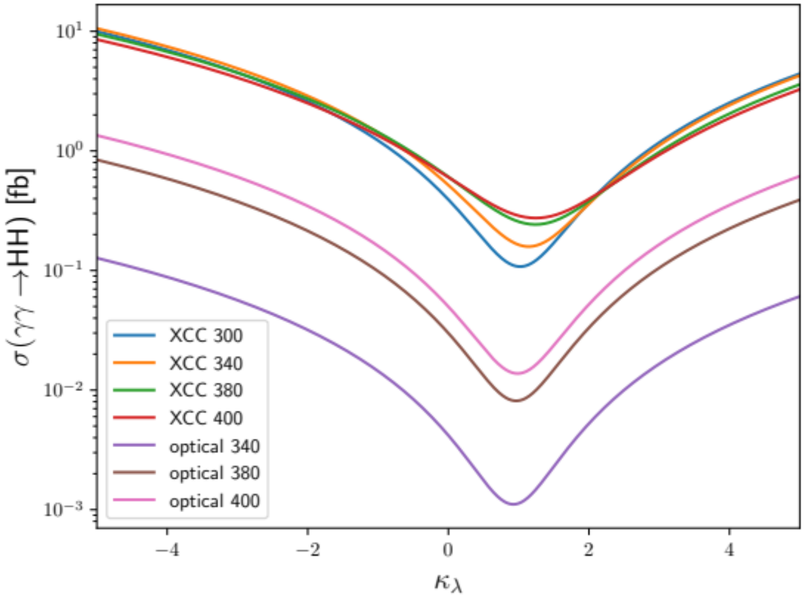


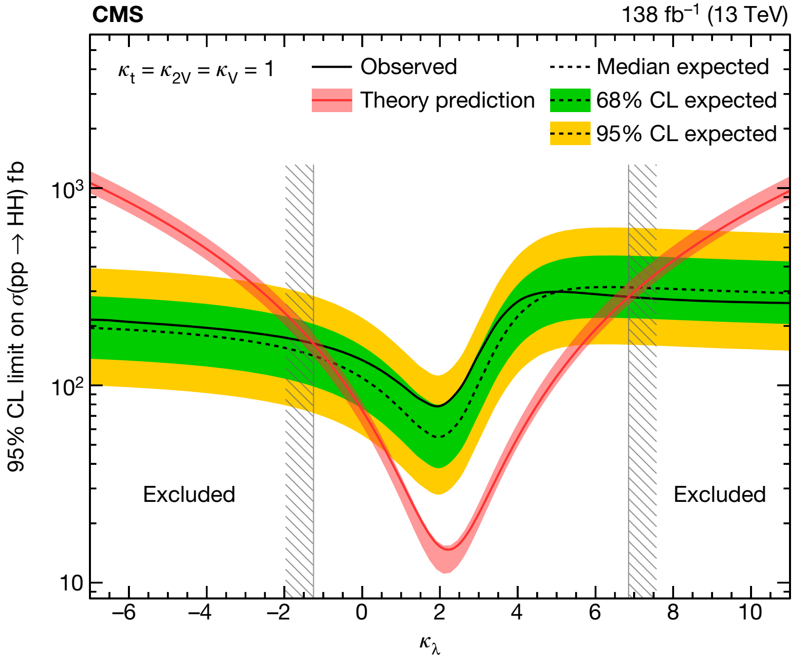
Di-Higgs production





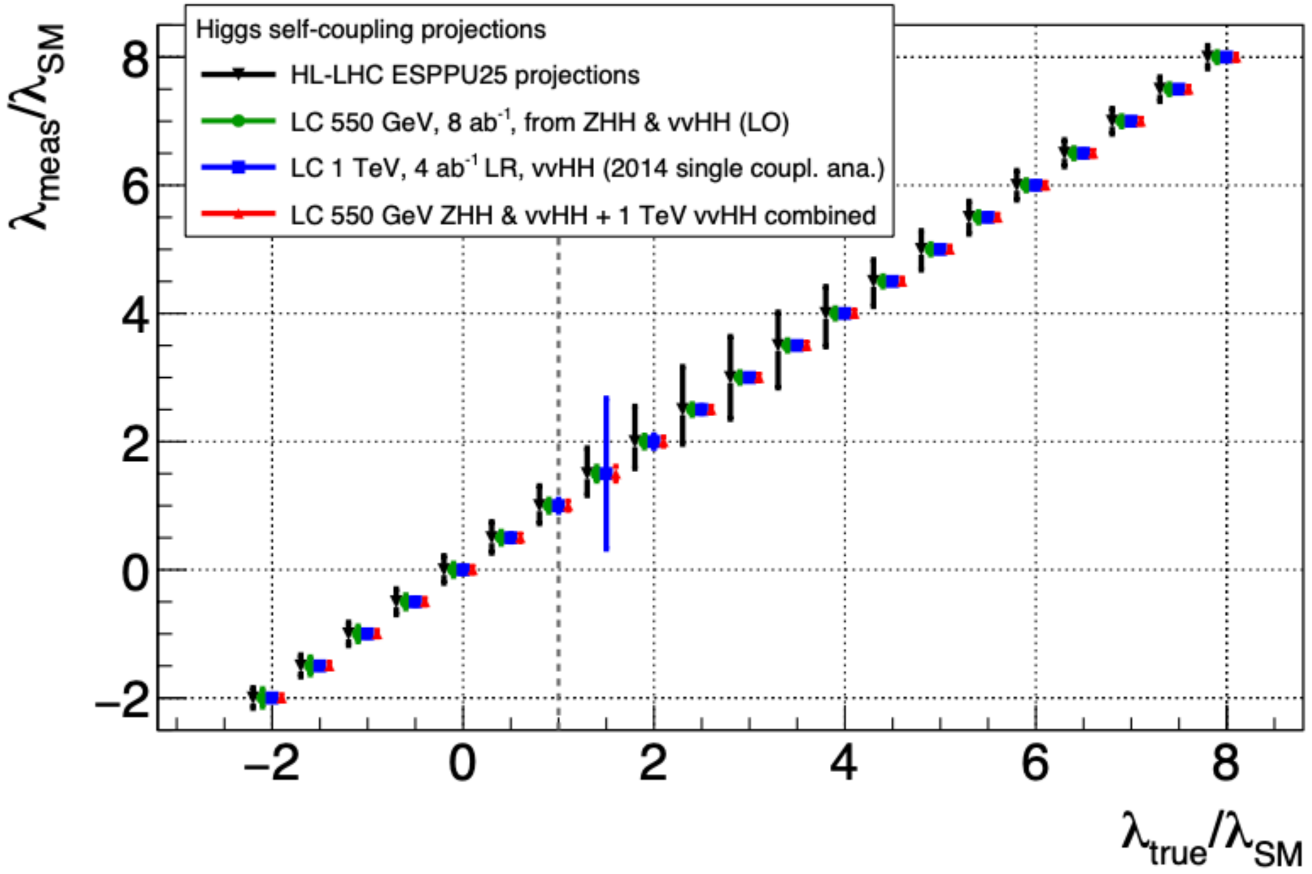
- Minimum around $\kappa_\lambda = 1$
- Compared to LHC minimum around $\kappa_\lambda = 2$

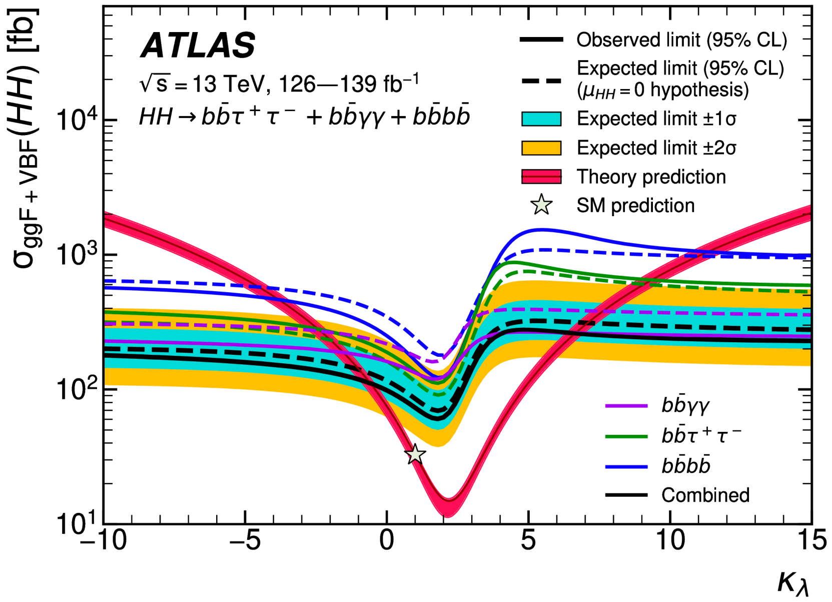


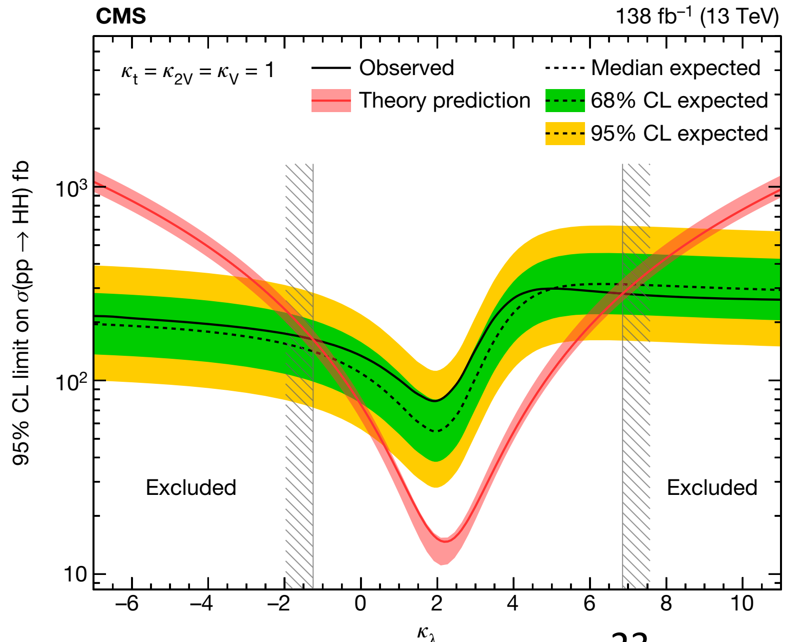


Bound on the trilinear Higgs self-coupling: κ_λ

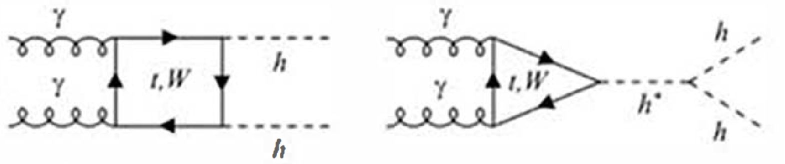
LCvision, C. Balazs, arXiv: 2503.19983

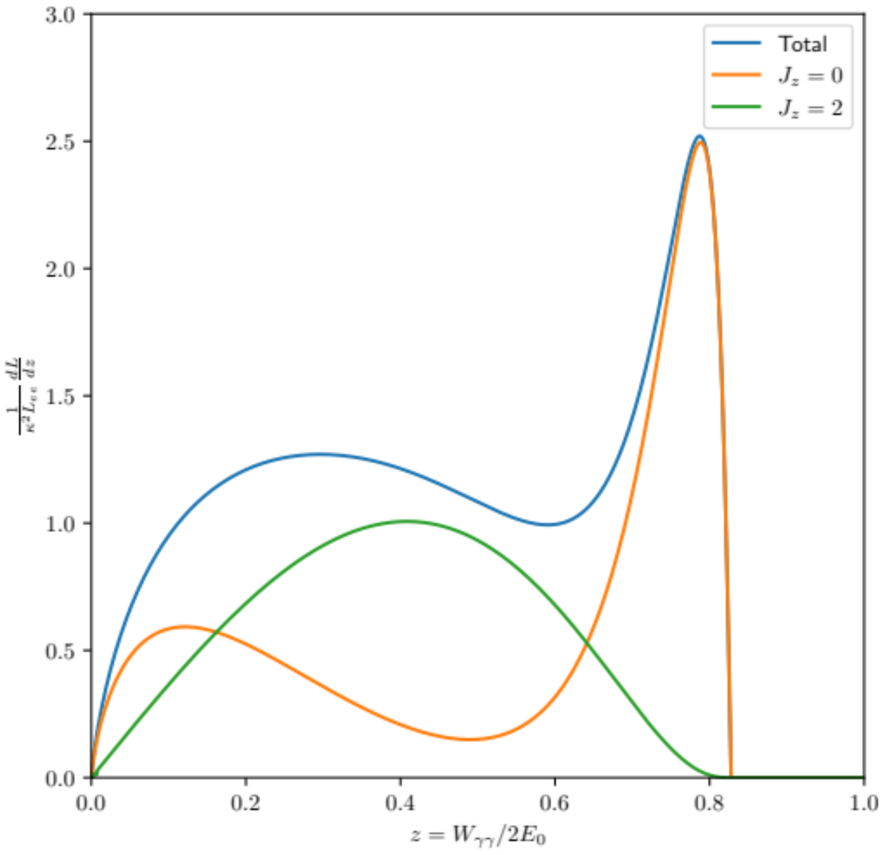




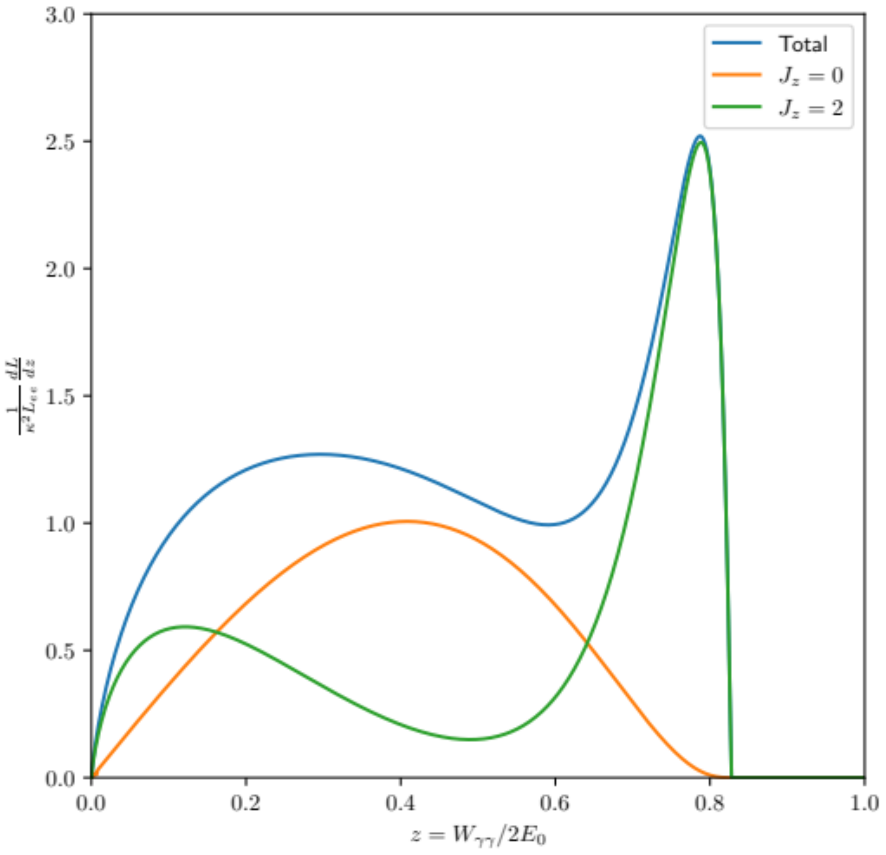


Di-Higgs production





$\lambda_e = 1, \quad P_c = -1, \quad \tilde{\lambda}_e = 1, \quad \tilde{P}_c = -1$

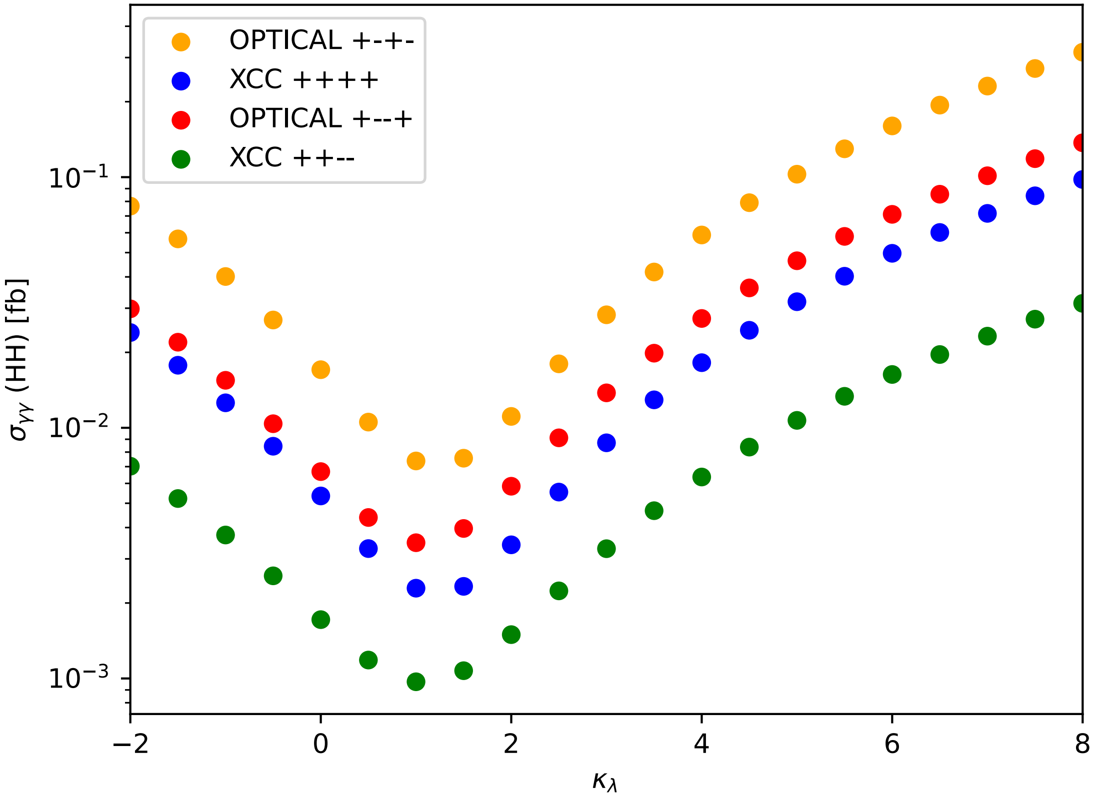


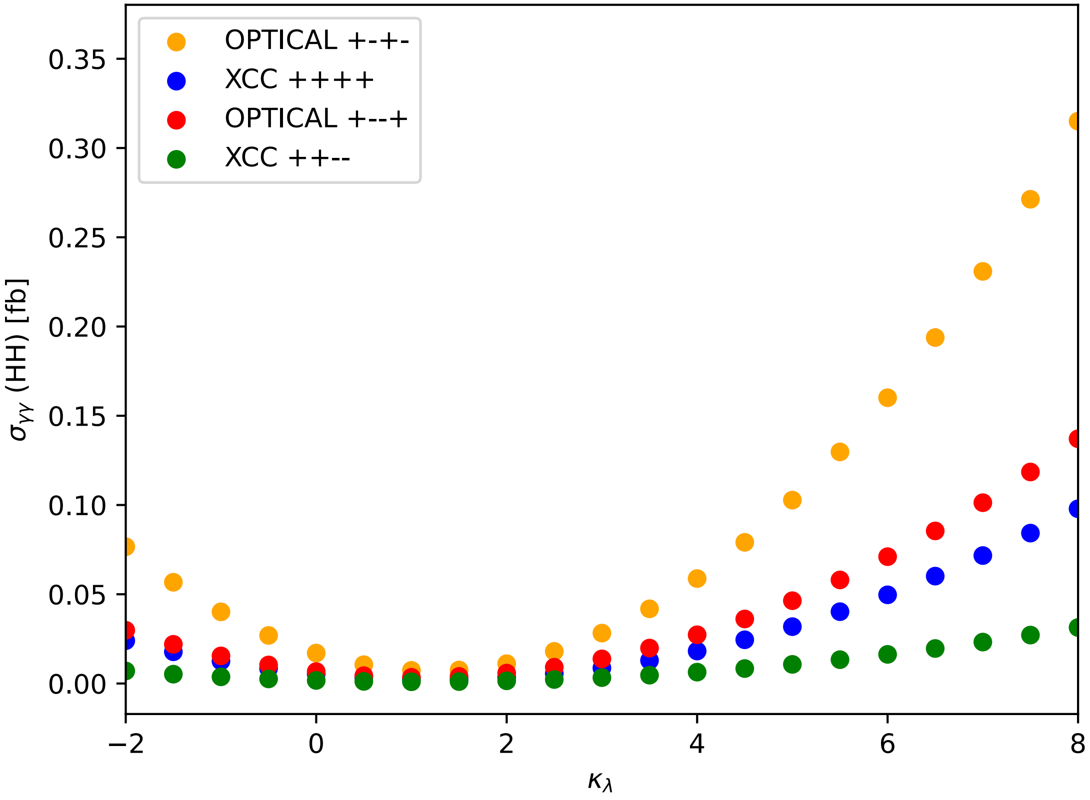
$\lambda_e = 1, \quad P_c = -1, \quad \tilde{\lambda}_e = -1, \quad \tilde{P}_c = 1$

M_{++} = Triangle + Box(++)

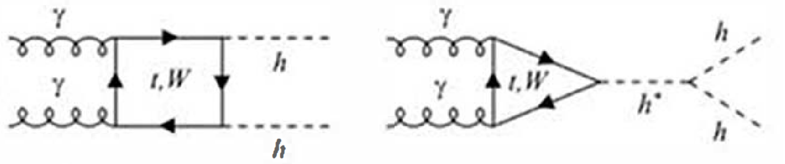
M_{+-} = Box(+-)

Di-Higgs production





Di-Higgs production



- CAIN spectrum
- Optical

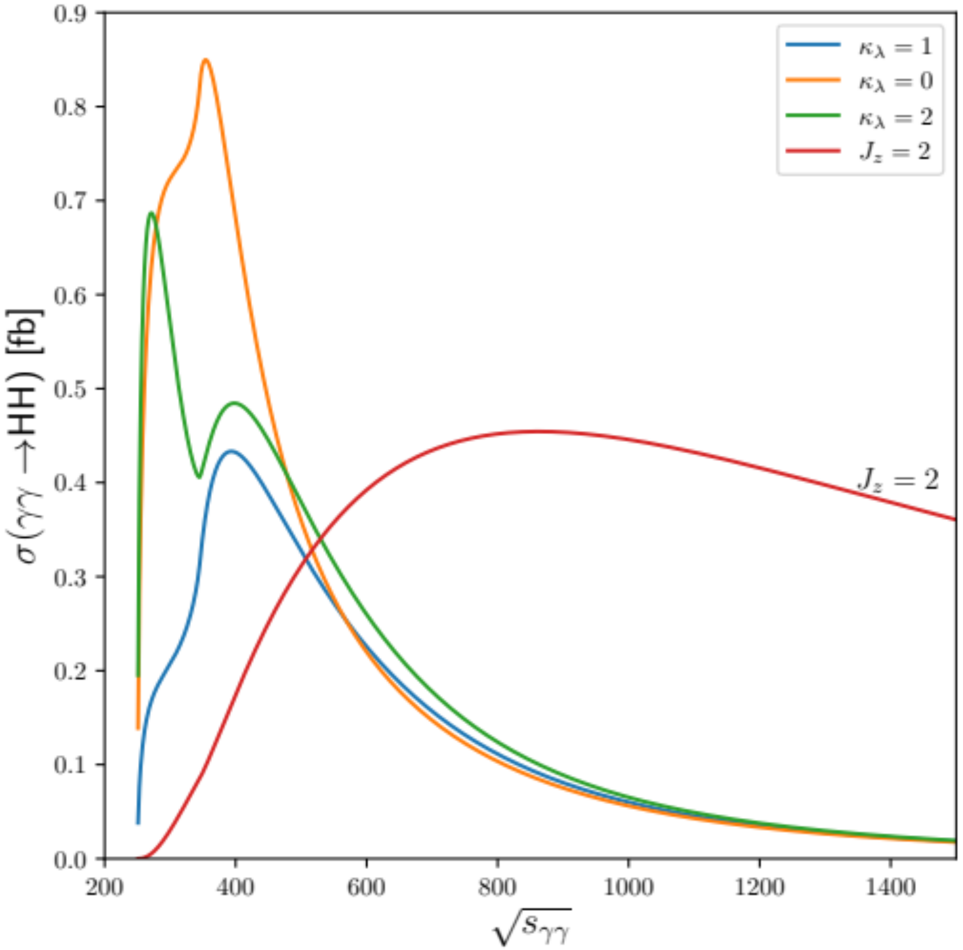
$$L_{\gamma\gamma} = 7.30735 * 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

  – 34 events per year

- XCC

$$L_{\gamma\gamma} = 3.96267 * 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

  – 58 events per year



Photon collider at XFEL

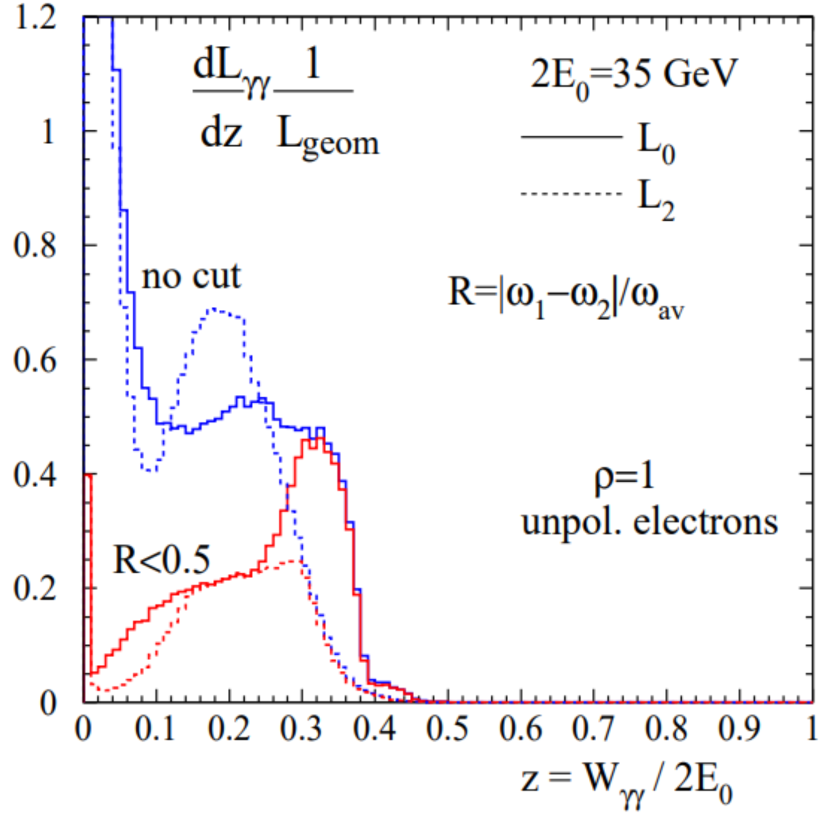
Telnov 2020

$$\omega_m \approx \frac{x}{x+1} E_0$$

$$x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\mathrm{TeV}}\right] \left[\frac{\omega_0}{\mathrm{eV}}\right] = 19 \left[\frac{E_0}{\mathrm{TeV}}\right] \left[\frac{\mu\mathrm{m}}{\lambda}\right]$$

- Use European XFEL (E_0 = 17.5 GeV)
- At the beam dump, splitting the beam
- 12 GeV peak
- Excellent for $b\bar{b}$ and $c\bar{c}$ range

$2E_0$	GeV	35
N per bunch	10^{10}	0.62
Collision rate	kHz	13.5
σ_z	μm	70
$\varepsilon_{x,n}/\varepsilon_{y,n}$	mm · mrad	1.4/1.4
β_x/β_y at IP	μm	70/70
σ_x/σ_y at IP	nm	53/53
Laser wavelength λ	μm	0.5
Parameters x and ξ^2		0.65, 0.05
Laser flash energy	J	3
Laser pulse duration	ps	2
f# $\equiv F/D$ of laser system		27
Crossing angle	mrad	$\sim$ 30
b (CP–IP distance)	mm	1.8
$\mathcal{L}_{ee,\mathrm{geom}}$	10^{33} cm^{-2}s^{-1}	1.45
$\mathcal{L}_{\gamma\gamma}$ ($z > 0.5z_m$)	10^{33} cm^{-2}s^{-1}	0.19
$W_{\gamma\gamma}$ (peak)	GeV	12



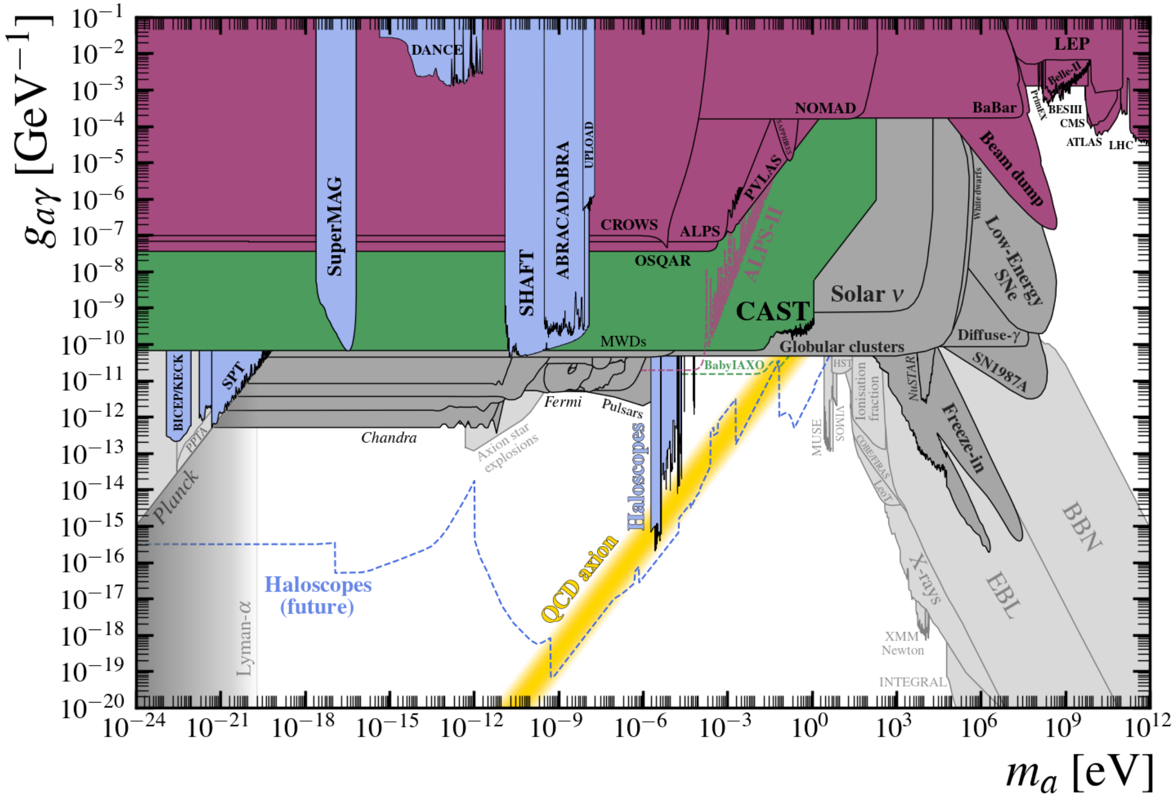
[V. I. Telnov 2020]

BSM Searches at photon colliders

- Additional hadronic resonances
- Possible four-quark states

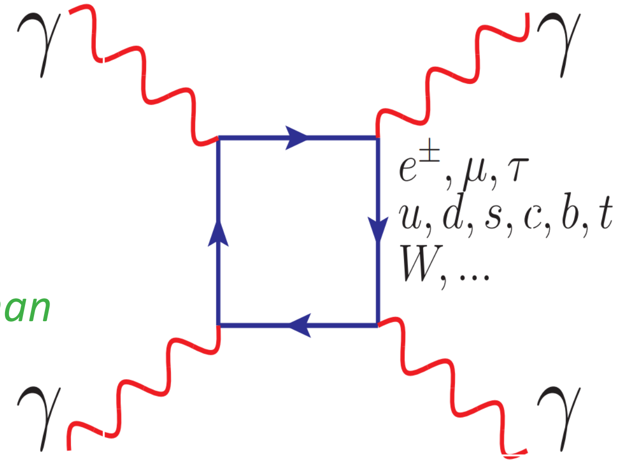
- Looking for BSM particles
  - ALPs
  - Mixed models
- Indirect tests of SM physics
  - Precision observables

Telnov 2020

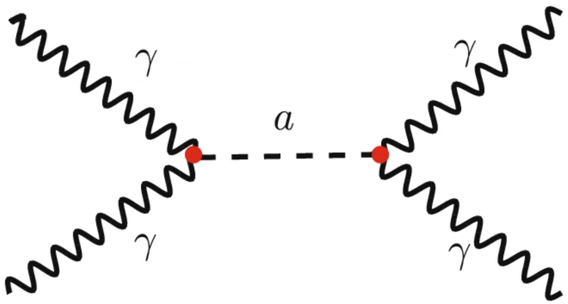


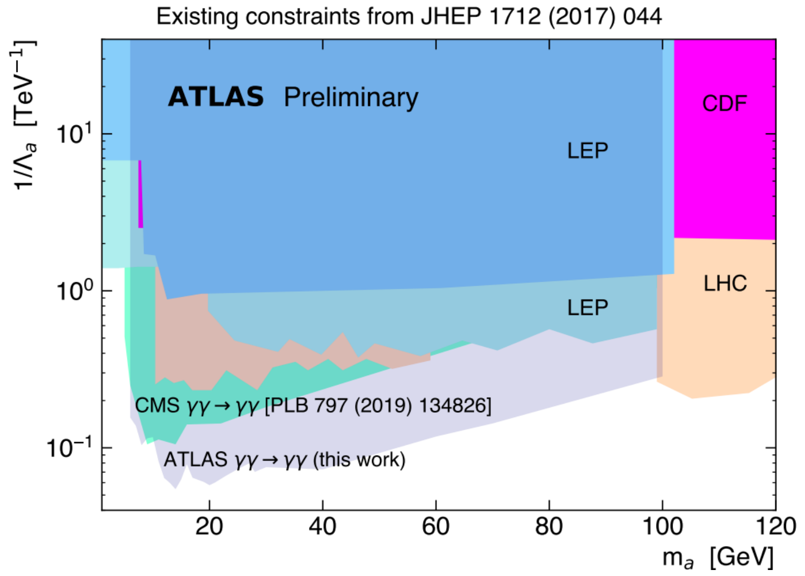
[FIPS Workshop 2022]

Light-by-light scattering



- Has been done for a long time *Lifshitz, De Tollis, Karplus, Neuman*
- So far observed by ATLAS
  - recent results from 2020
- Possibility to observe BSM contributions

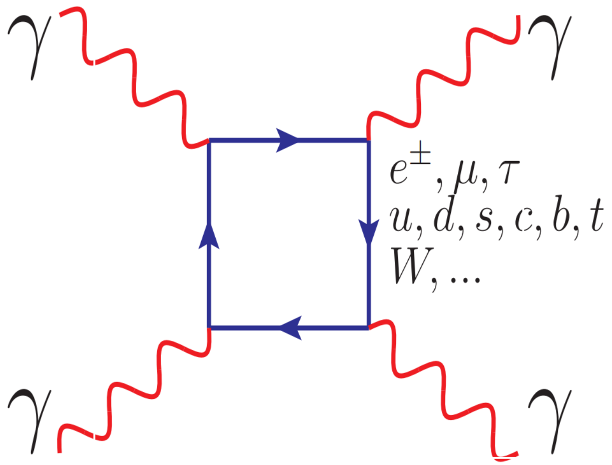




ATLAS Collaboration 2020

[FIPS Workshop 2022]

Light-by-light scattering



$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{1}{4\omega^2} |M_{fi}|^2$$

- Helicity amplitudes

$$|M_{fi}|^2 \to \frac{1}{2}\{2|M_{++++}|^2 + 2|M_{++--}|^2 + 2|M_{+-+-}|^2 + 2|M_{+--+}|^2 + 8|M_{+++-}|^2\}$$

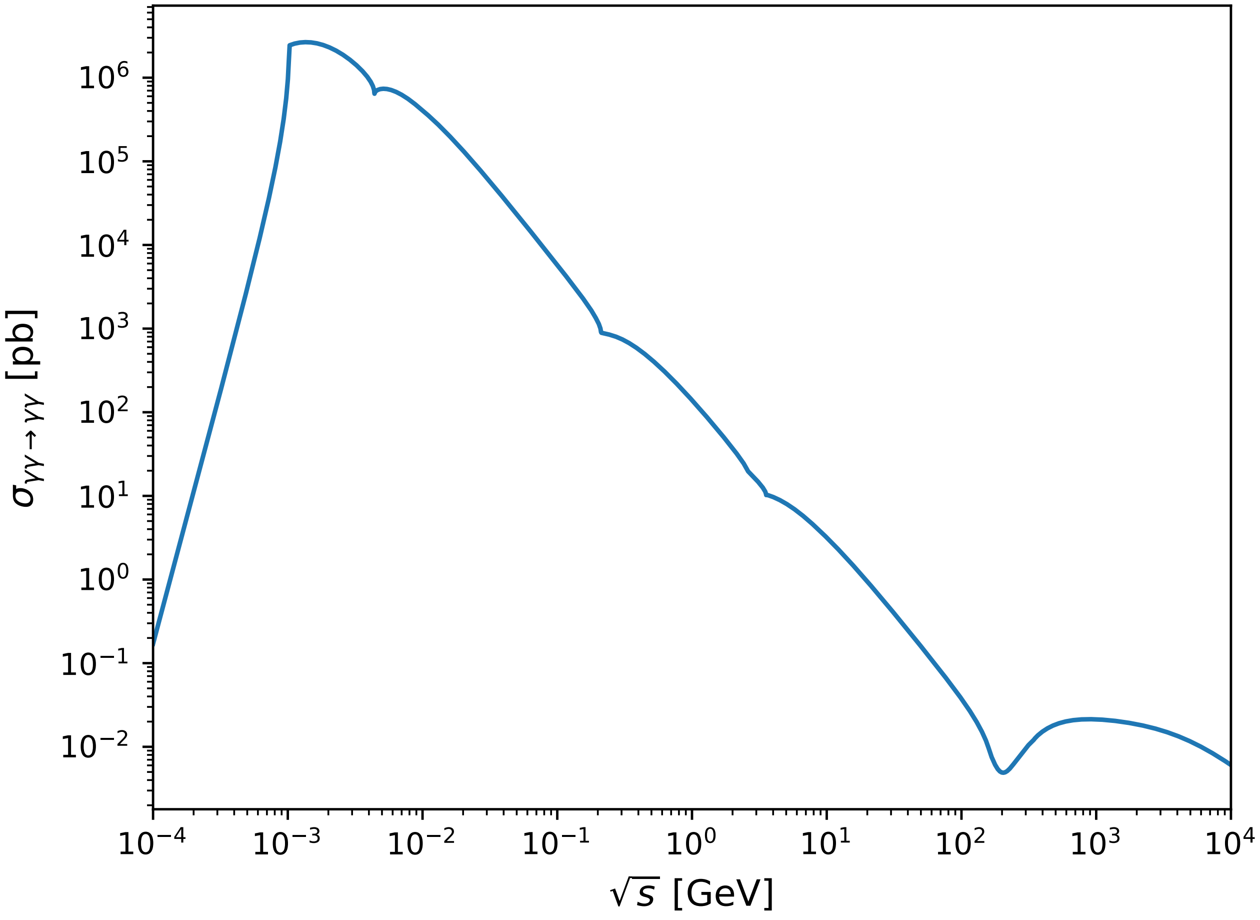
$$M_{++++} \ , M_{++--} \ \text{und} \ M_{+++-}$$

Light-by-light scattering

- Only fermionic contributions

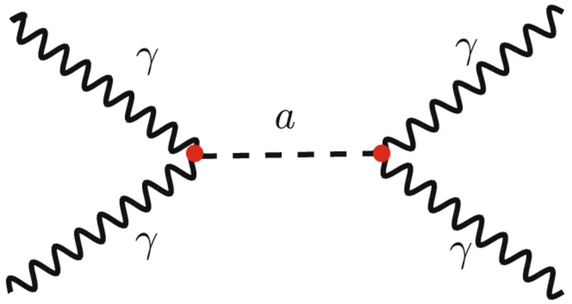
- Electron contribution dominant

$$\mathrm{d}\sigma = \int_0^{z_{max}} \mathrm{d}z \int_{z^2/y_{max}}^{y_{max}} \mathrm{d}y \frac{1}{L_{\gamma\gamma}} \frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} \mathrm{d}\sigma_{\gamma\gamma\to\gamma\gamma}$$



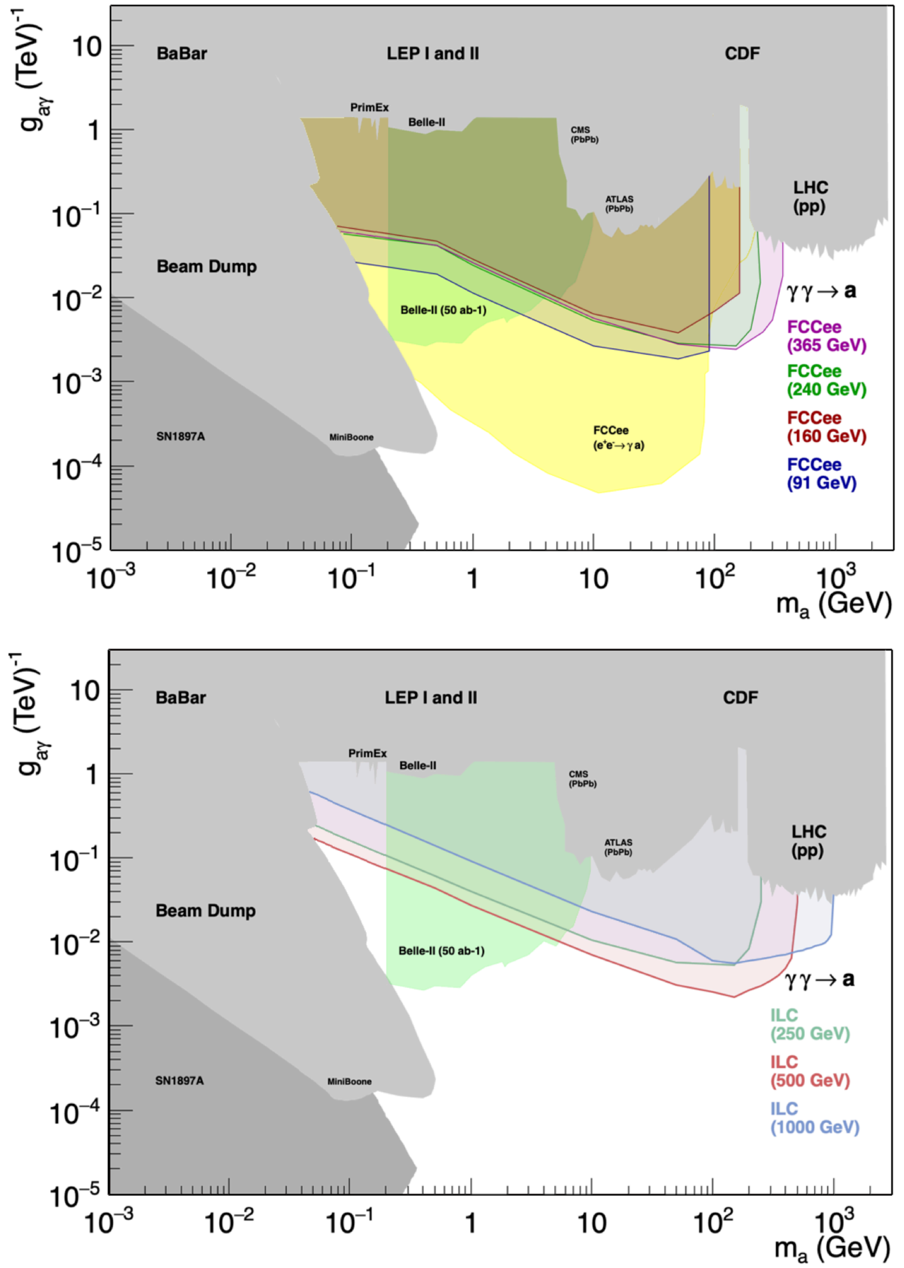
Axion-Like Particles

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



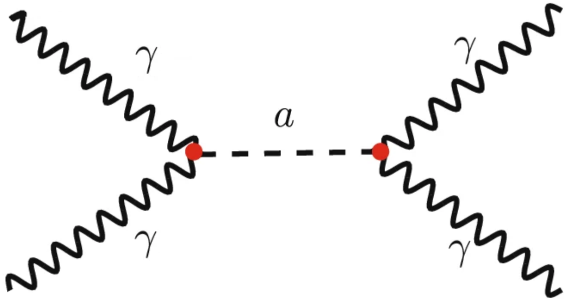
- Main contribution from s-channel

$$\mathcal{M}_{ALPs} = -\frac{1}{2}\frac{g_{a\gamma\gamma}^2 s^2}{s - m_a^2 + im_a\Gamma}$$



Teles et al. 2024

Axion-Like Particles



- With helicity amplitudes *Baldenegro et al. 2018*

$$\frac{d\sigma}{d\Omega}^{\gamma\gamma\to\gamma\gamma} = \frac{1}{128\pi^2 s}(|\mathcal{M}_{++++}|^2 + |\mathcal{M}_{+-+-}|^2 + |\mathcal{M}_{+--+}|^2 + |\mathcal{M}_{++--}|^2)$$

$$|M_{fi}|^2 \to \frac{1}{2}\{2|M_{++++}|^2 + 2|M_{++--}|^2 + 2|M_{+-+-}|^2 + 2|M_{+--+}|^2 + 8|M_{+++-}|^2\}$$

- Final cross-section dependent on photon luminosity

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

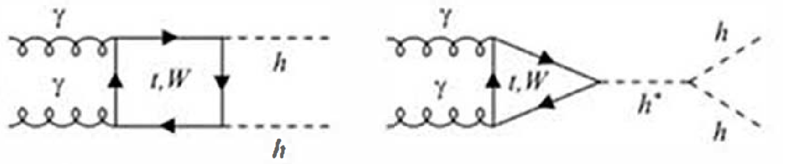
Conclusions

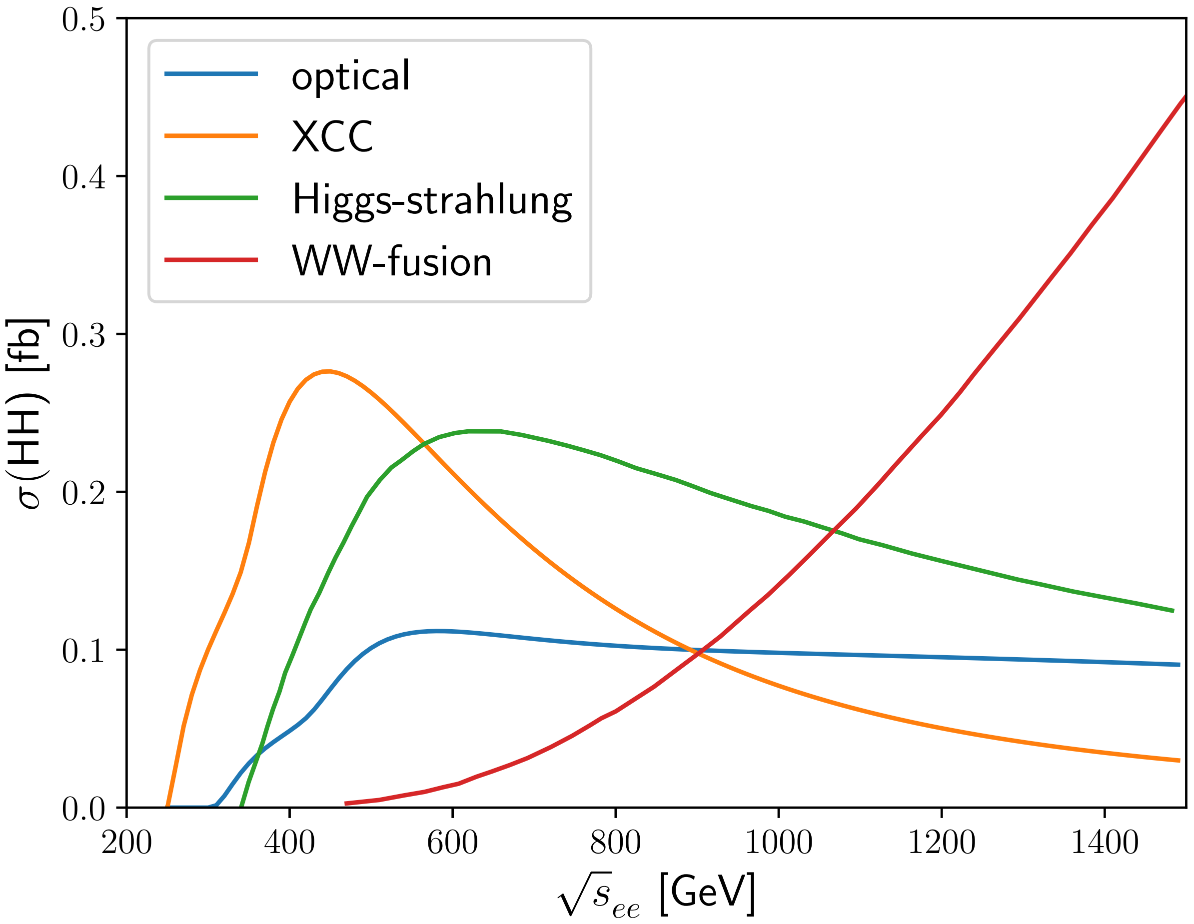
- Gamma-gamma colliders are great additions to e^+e^- colliders
  - e^+ not needed, main concept with e^-e^-
- At European XFEL first look at the technology for future colliders
- $b\bar{b}$ and $c\bar{c}$ production range is covered

Ongoing Work

- Determination of trilinear Higgs Couplings for (B)SM Higgs
- SM Light-by-Light vs different BSM contributions
- Full ALPs check with CAIN luminosity

Di-Higgs production





Barklow et al. 2023

Costs for XCC

- For XCC 125 GeV
- Very early stage
- Using C^3-250 cost model

	Sub-Domain	%	%
Sources	Injectors	9	26
	FEL	9	
	Beam Transport	9	
Main Linac	Cryomodule	9	30
	C-band Klystron	22	
BDS	Beam Delivery and Final Focus	7	15
	IR	8	
Support Infrastructure	Civil Engineering	5	28
	Common Facilities	18	
	Cryo-plant	6	
Total	2.3B$	100	100

"Dark Axion model"

[K. Kaneta, H. Lee, S. Yun `17]

- KSVZ-type axion [Kim, Shifman, Vainshtein, Zakharov]
  - (Very) heavy quark and (nearly) sterile axion
- With dark photon

$$\mathcal{L}_{\text{axion portal}} = \frac{G_{agg}}{4} a G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$

$$\mathcal{L}_{\text{vector portal}} = \frac{\epsilon}{2} F_{\mu\nu}F'^{\mu\nu}$$

$$\mathcal{L}_{\text{dark axion portal}} = \frac{G_{a\gamma'\gamma'}}{4} a F'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{G_{a\gamma\gamma'}}{4} a F_{\mu\nu}\tilde{F}'^{\mu\nu}$$