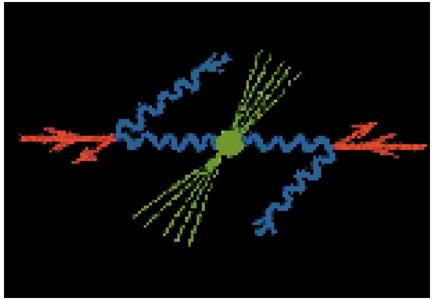
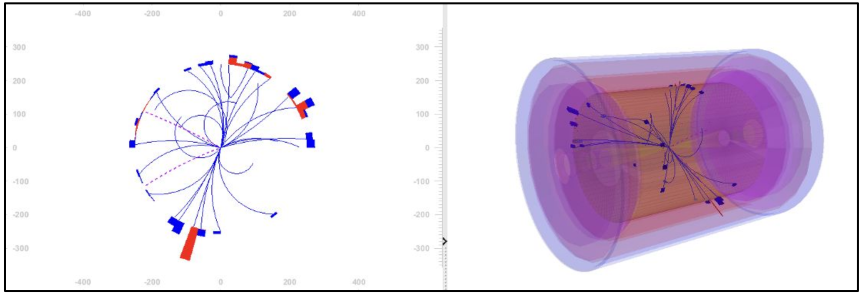
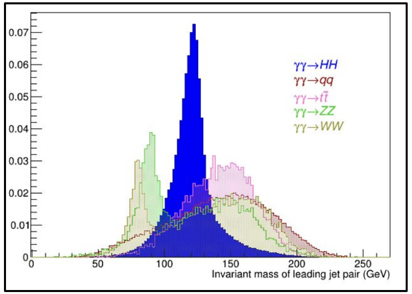






Physics Potential of an Alternative Gamma-Gamma Collider Mode

Gudrid Moortgat-Pick, Ariel Schwartzman

CERN Linear Collider Vision Community Event 2025
CERN 08-Jan-2025

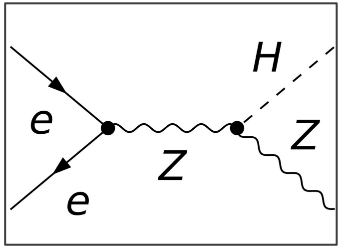
DESY.
SLAC NATIONAL ACCELERATOR LABORATORY

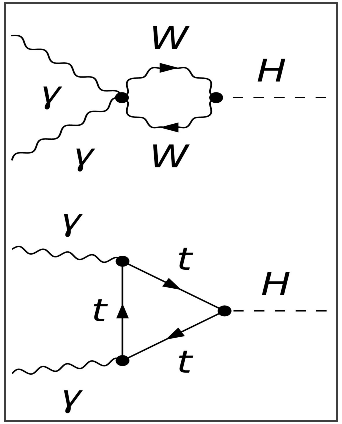
Introduction

High energy photons collisions (γγ and $e^-γ$) offer a complementary physics program to e^+e^-:

e.g. Tesla TDR, Part VI, JLC 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
  - γγ can directly couple to spin-0 resonances whereas e+e- require the production of another spin-1 particle
    - complementary probe of the scalar sector
- **Polarization of both electrons and photons**
  - Allows for a rich study of CP violation in the scalar sector





Ginzburg et al. 1983

e^+e^- / $\gamma\gamma$ Complementarity

Yokoya 2000

- $\gamma\gamma$ 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^-:
  - $e^-\gamma \to$ ~e □^{0}

Kanemura 2001, Nauenberg 2001, Mühlleitner 2006,....

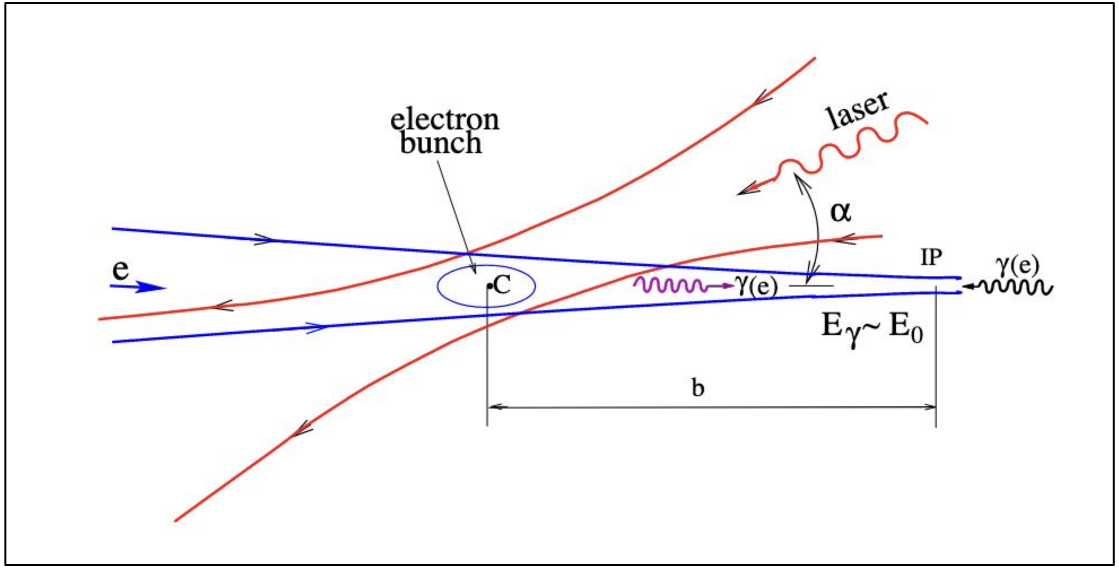
- Since $\gamma\gamma \to H$ is a loop-induced process, it can probe new physics contributions to the Higgs photon coupling: **sensitive to BSM particles in loops**

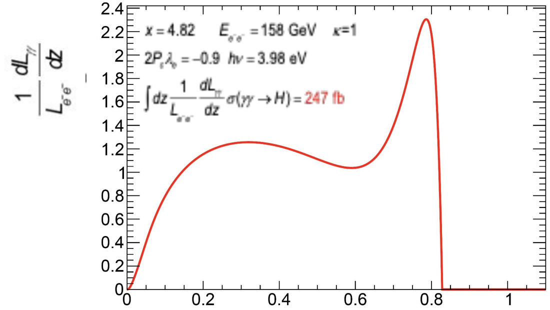
Grzadkowski, Gunion 1992, , Krämer et al. 1994, Godbole, Kraml, et al. 2006

- 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 $\gamma\gamma$ 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

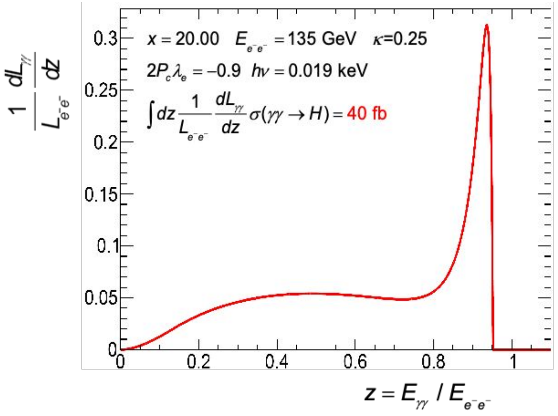
Telnov 2020, 2023

Photon Collider Mode





T. Barklow 2023



$x = \frac{4E_{e^-}\omega_0}{m_e^2}$ determines luminosity spectra

ω_0 = laser photon energy

maximum Compton photon energy $\omega_m = \frac{x}{x+1}E_{e^-}$

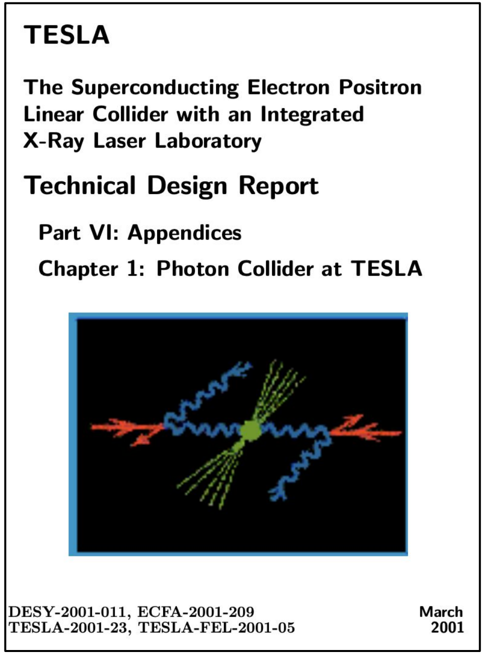
Important threshold in x:

At $x = 4.82$ $\gamma\gamma_{laser} \to e^+e^-$ opens up which depletes the high energy photon beam.

For increasing values of x the high energy photon spectrum becomes more peaked towards maximum energies. **The value x ≈ 4.8 has been the choice for previous optical photon collider concepts**

Photon Collider Concepts

- Optical photon colliders concepts developed in the 2000's can produce similar number of Higgs bosons per year than e^+e^-, but with higher backgrounds
- Recent innovation in photon science, particularly in XFELs can lead to enhanced capabilities


TESLA

The Superconducting Electron Positron Linear Collider with an Integrated X-Ray Laser Laboratory

Technical Design Report

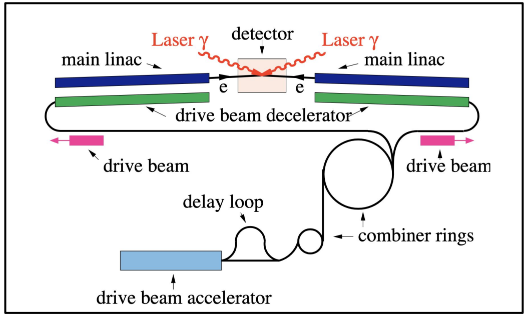
Part VI: Appendices

Chapter 1: Photon Collider at TESLA

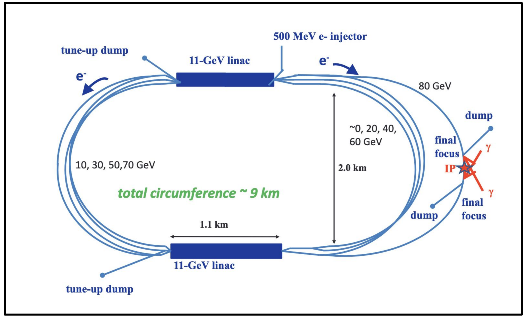
DESY-2001-011, ECFA-2001-209
TESLA-2001-23, TESLA-FEL-2001-05

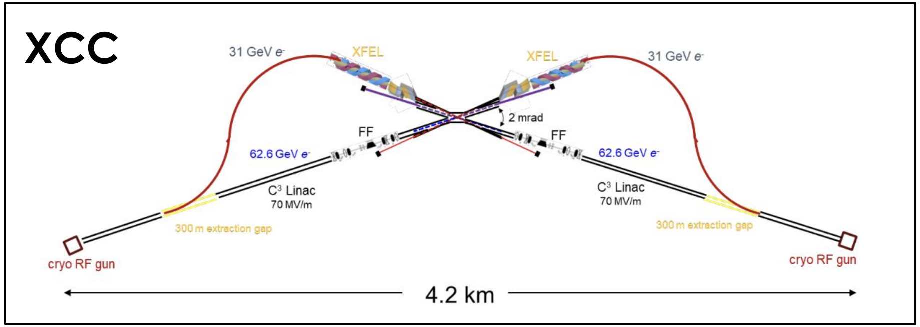
March 2001

CLICHE



SAPPHiRE





T. Barklow 2022

Physics Opportunities

e.g. Tesla TDR, Part VI

Jikia, 1994, Bharucha et al, 2021, Berger, Braathen, GMP, Weiglein

- Di-Higgs production and measurement of trilinear couplings
- Enhanced production cross sections of any charged particles by factor of ~10 compared to e^+e^- (e.g. SUSY, etc.)

Mühlleitner 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 which is particularly sensitive to new heavy charged particles beyond the kinematic range

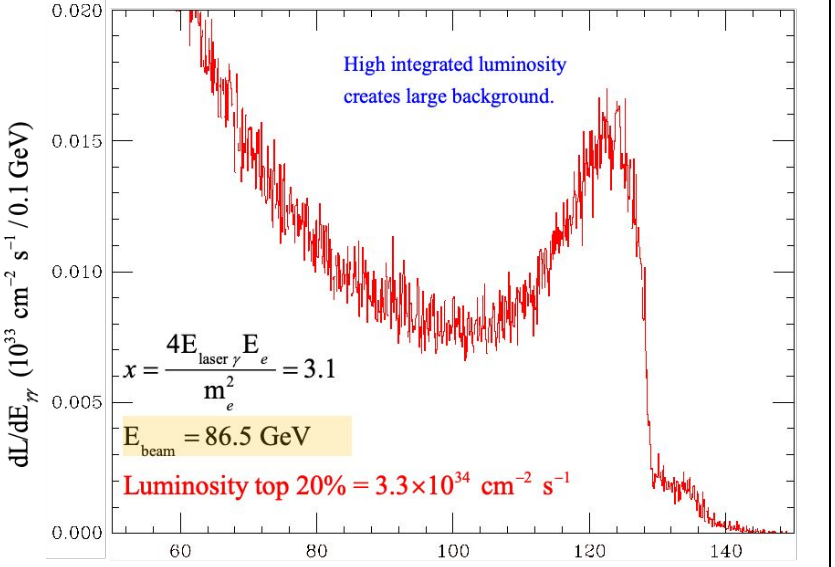
Gunion et al. 1997

- Spectroscopy of C-even resonances (e.g. in multi-quark states, glueballs)

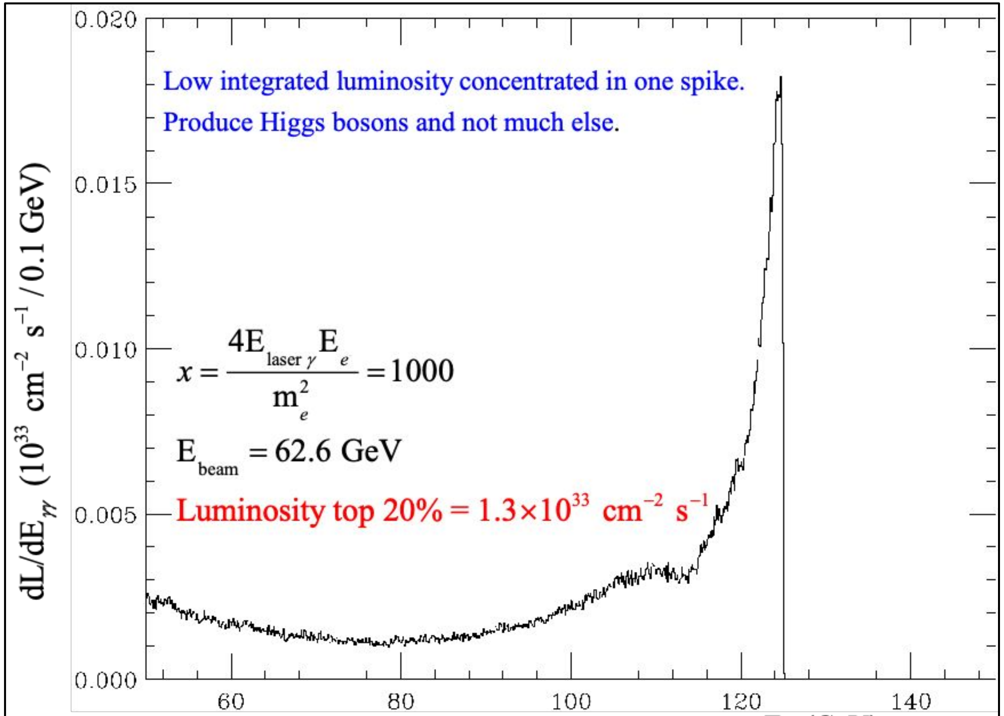
Telnov et al., 2023

X-ray FEL based Photon Collider

Machine	E_{e^-} (GeV)	Polarization	N_H/yr	N_{Bgnd}/N_H	$N_{pileup/BX}$
XCC	62.8	90% e^-	80,000	170	1.3
2.4 eV laser	86.5	90% e^-	52,000	1310	6.8
ILC	125	−80% e^- +30% e^+	98,000	130	1.3
ILC	125	+80% e^- −30% e^+	65,000	50	1.3



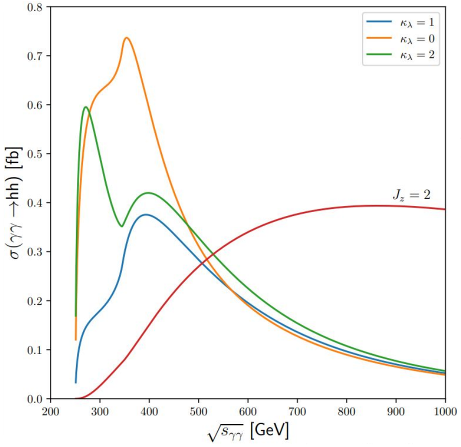
2.4 eV optical laser



XCC 1 keV X-ray laser

Di-Higgs Production

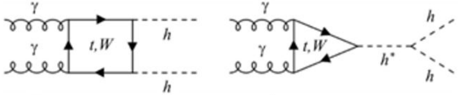
$\gamma\gamma \rightarrow HH$ cross section at 380 GeV centre of mass energy is almost double that of e^+e^- at 500 GeV, with a simpler hadronic final state (4 jets)



Berger, Braathen, GMP, Weiglein

	$\sqrt{s}$ (GeV)	polarization	σ (fb)
$\gamma\gamma \rightarrow HH$	380	$+100\%\ \gamma\ \ +100\%\ \gamma$	0.40
$e^+e^- \rightarrow ZHH$	500 / 550	$-80\%\ e^-\ \ +30\%\ e^+$	0.20 / 0.22

XCC



Initiated an effort to update physics case of a Photon Collider mode at 126 GeV and 380 GeV centre of mass energies

Data sets were produced utilizing Pythia8 and Cain $\sqrt{\hat{s}}$ spectra:

$\gamma\gamma \rightarrow HH$ $\quad \gamma\gamma \rightarrow qq$ $\quad \gamma\gamma \rightarrow tt$

$\gamma\gamma \rightarrow ZZ$ $\quad \gamma\gamma \rightarrow W^+W^-$

Cain $(x1, x2)$ spectra is now interfaced to Whizard 3.14 . Background data sets such as the following are being produced:

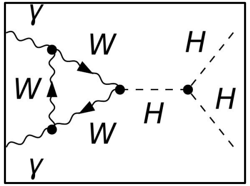
$e^-\gamma \rightarrow \nu W$ $\quad e^-\gamma \rightarrow \nu q\bar{q}W$ $\quad e^-\gamma \rightarrow e^- q\bar{q}W$

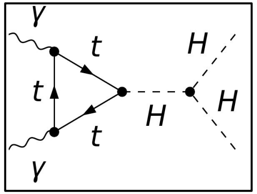
$e^-\gamma \rightarrow e^- Z$ $\quad e^-\gamma \rightarrow \nu q\bar{q}Z$ $\quad e^-\gamma \rightarrow e^- q\bar{q}Z$

$e^-\gamma \rightarrow e^- H$ $\quad e^-\gamma \rightarrow \nu q\bar{q}H$ $\quad e^-\gamma \rightarrow e^- q\bar{q}H$

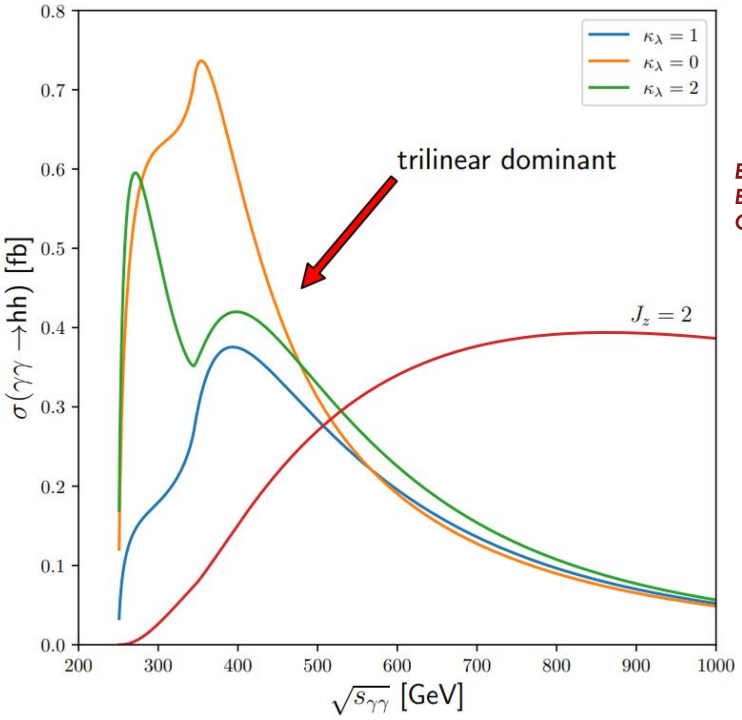
Di-Higgs Production

- Complementary to e^+e^-
- Depends on total angular momentum J_z
- Trilinear coupling only for $J_z = 0$





- Choice of laser photon helicity to maximise $J_z = 0$ in the luminosity distribution

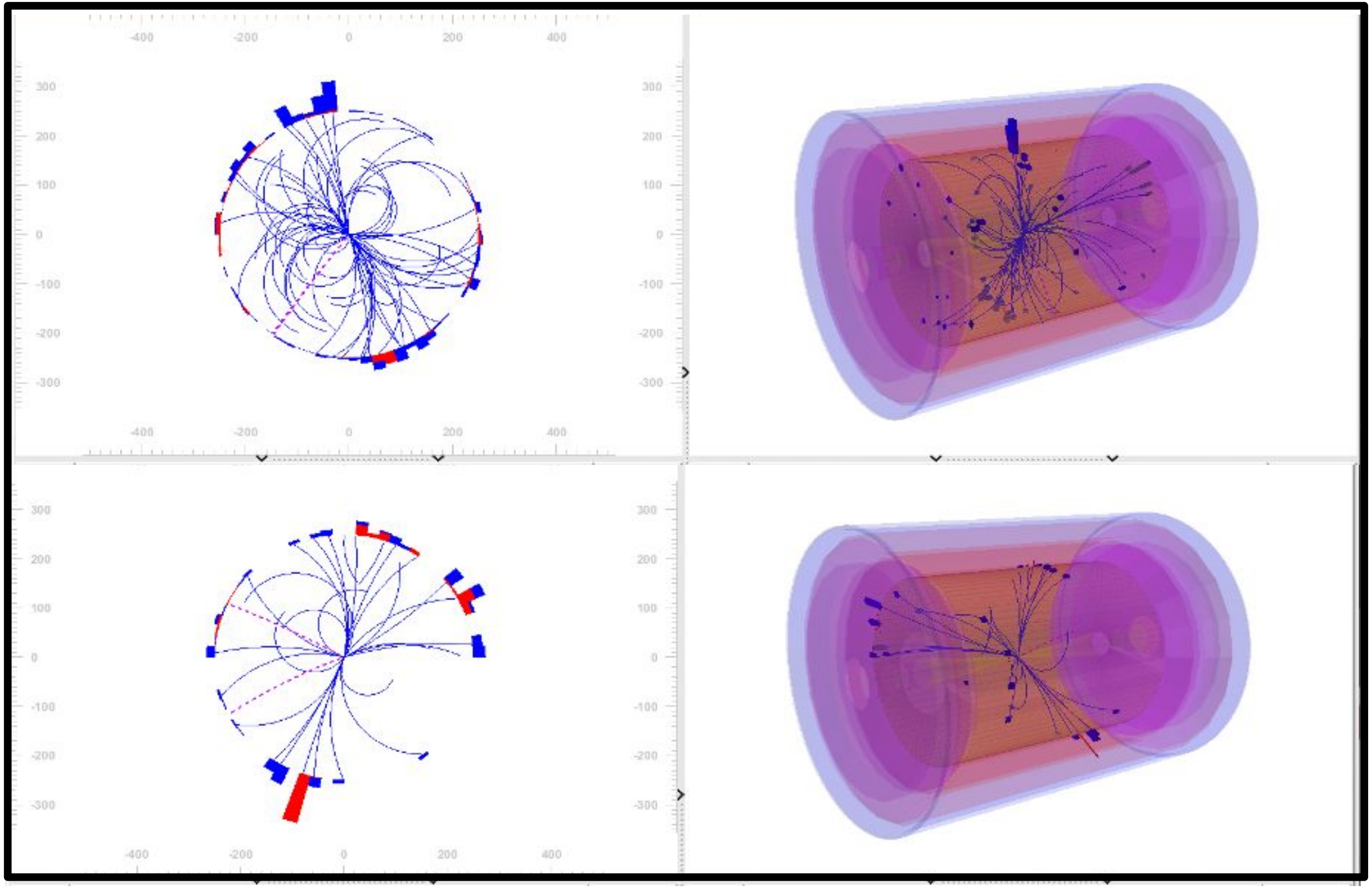


Berger, Braathen, GMP, Weiglein

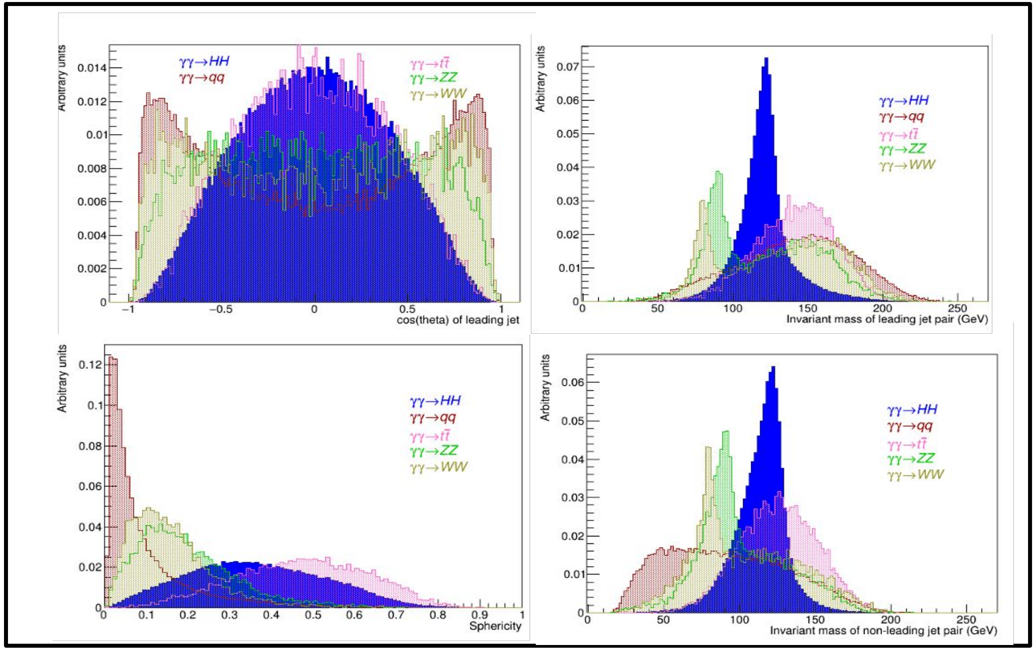
Delphes Event Displays

$e^+e^- \to ZHH$
$\to qqbbbb$
$\sqrt{s} = 550$ GeV

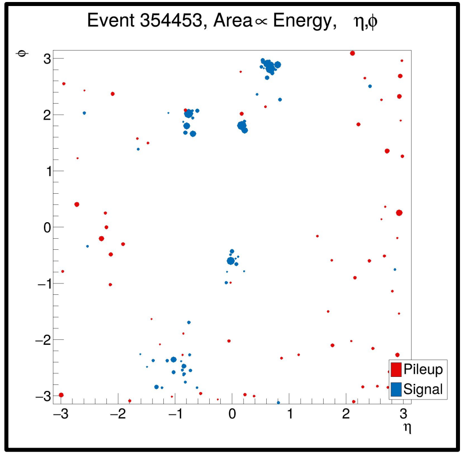
$\gamma\gamma \to HH$
$\to bbbb$
$\sqrt{s} = 380$ GeV



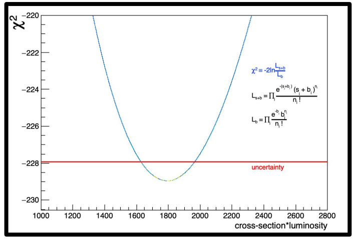
Di-Higgs at 380 GeV



Several BDTs trained to separate signal from various backgrounds. No kinematic fit yet



Pileup mostly forward: can be suppressed using constituent subtraction techniques before jet clustering. Studies ongoing



Kinematic fit being implemented. Aim at full comparison with e^+e^- at 550 GeV

Next steps/Outlook

e.g. with CAIN, Yokoya

- Update simulation studies for single and double Higgs using various laser configurations
- Include studies of polarization in simulations
- More precise studies on light-by-light for different energy stages
  - Allows direct access to light-by-light scattering, i.e. a new plethora of ‘old’ and ‘new’ physics as Born-Infeld, constraints for non-linear extensions of QED, dark matter candidates, ALPS etc. …

Ellis et al. 2024

Ginzburg et al. 1984

- Evaluation photon-photon IP region challenges
  - crossing angle, …

Summary

- The addition of $\gamma\gamma$ and $e^-\gamma$ collision modes to a e^+e^- linear collider program can provide complementary physics capabilities, driven by s-channel Higgs production and polarization, enabling CP violation measurements, higher mass reach for BSM Higgs, and Di-Higgs measurements at 380 GeV

T. Barklow, 2022

- XFELs provide new opportunities to enhance the physics capabilities of a photon-photon collider mode. Need R&D to address technical challenges and prototypes, e.g. EuroXFEL

Telnov 2020, 2023

- The next first step is to update the photon collider physics case using new simulations

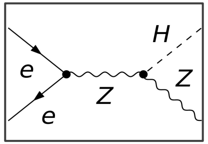
CAIN, Yokoya

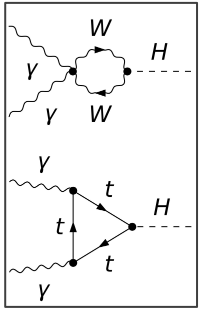
Backup

Reaction	Remarks
$\gamma\gamma \to h^0 \to b\bar{b}$	SM (or MSSM) Higgs, $M_{h^0} < 160\,\mathrm{GeV}$
$\gamma\gamma \to h^0 \to WW(WW^*)$	SM Higgs, $140\,\mathrm{GeV} < M_{h^0} < 190\,\mathrm{GeV}$
$\gamma\gamma \to h^0 \to ZZ(ZZ^*)$	SM Higgs, $180\,\mathrm{GeV} < M_{h^0} < 350\,\mathrm{GeV}$
$\gamma\gamma \to H, A \to b\bar{b}$	MSSM heavy Higgs, for intermediate $\tan\beta$
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-,\ H^+H^-$	large cross sections, possible observations of FCNC
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium
$\gamma e \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma\gamma \to W^+W^-$	anomalous W interactions, extra dimensions
$\gamma e^- \to W^-\nu_e$	anomalous W couplings
$\gamma\gamma \to WWWW, WWZZ$	strong WW scatt., quartic anomalous W, Z couplings
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions
$\gamma e^- \to \bar{t}b\nu_e$	anomalous Wtb coupling
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section
$\gamma e^- \to e^-X$ and $\nu_e X$	$\mathcal{NC}$ and $\mathcal{CC}$ structure functions (polarised and unpolarised)
$\gamma g \to q\bar{q},\ c\bar{c}$	gluon distribution in the photon
$\gamma\gamma \to J/\psi\, J/\psi$	QCD Pomeron

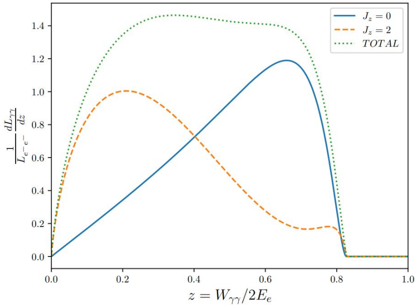
CP-Comparison e^+e^- vs $\gamma\gamma$

- **Higgs boson production**
  - e^+e^--collider via Higgsstrahlung (250 GeV)
  - γγ-collider via top-loop and W-boson-loop (125 GeV)

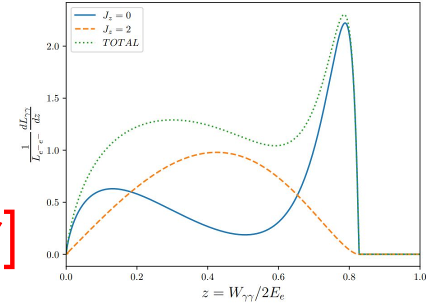




- Single resonance hadron production at e^+e^--collider for $J^{PC}=1^{--}$
- γγ-collider allows for C = + states with (even J)$^-$ and J^+ apart from J = 1
- J_z = 0, 2 is chosen via laser photon helicity



left-handed electrons



laser photon helicity opposite (top) same (bottom)

[V. I. Telnov] [M. Berger]