XFEL Compton Collider (XCC) $\gamma\gamma$ Higgs Factory

LCWS 2024

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Jul 08, 2024

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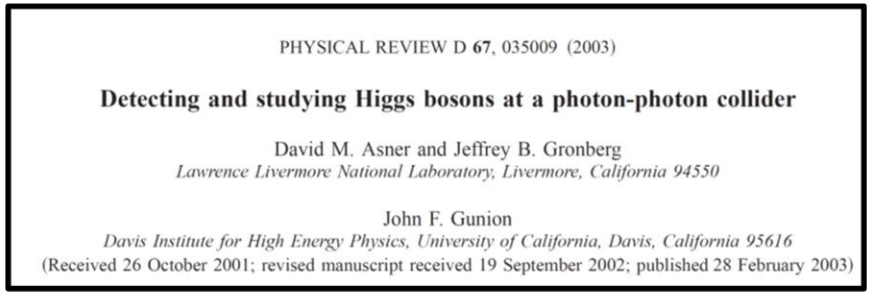
Introduction

$\gamma\gamma$ colliders provide complementary physics to e^+e^- colliders at potentially reduced cost. $\gamma\gamma$ colliders have been considered as initial, supplemental, or follow-on stages of e^+e^- colliders for more than 20 years. Recent innovations in photon science, particularly in XFEL technology, can lead to enhanced $\gamma\gamma$ collider capabilities beyond those of previous concepts.

- Previous $\gamma\gamma$ collider concepts were limited to optical wavelength lasers due to the nascent status of XFEL's and an underappreciation of the particle physics advantages of $\gamma\gamma$ colliders with shorter wavelength lasers.

- e^+e^- collider proposals continue to be bedeviled by cost. $\gamma\gamma$ Higgs factories have a smaller footprint than any e^+e^- Higgs factory because there is no need to produce an associated Z boson. Smaller footprint translates directly to lower cost.

- The $\gamma\gamma$ configuration of a 10 TeV PWFA collider may provide the best opportunity for particle physics with such a machine. A $\gamma\gamma$ collider Higgs factory would serve as a prototype for such a collider.



PHYSICAL REVIEW D **67**, 035009 (2003)

Detecting and studying Higgs bosons at a photon-photon collider

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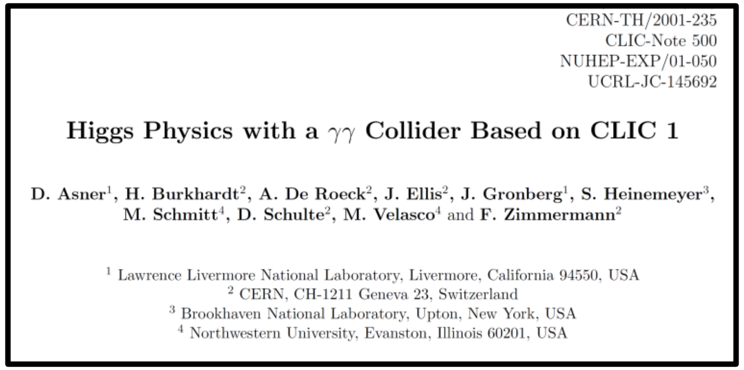
(Received 26 October 2001; revised manuscript received 19 September 2002; published 28 February 2003)



CERN-TH/2001-235
CLIC-Note 500
NUHEP-EXP/01-050
UCRL-JC-145692

Higgs Physics with a $\gamma\gamma$ Collider Based on CLIC 1

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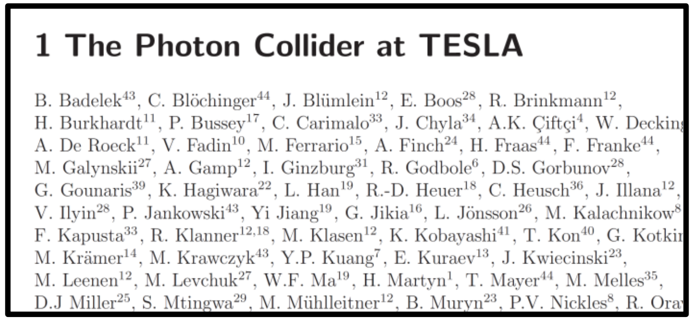
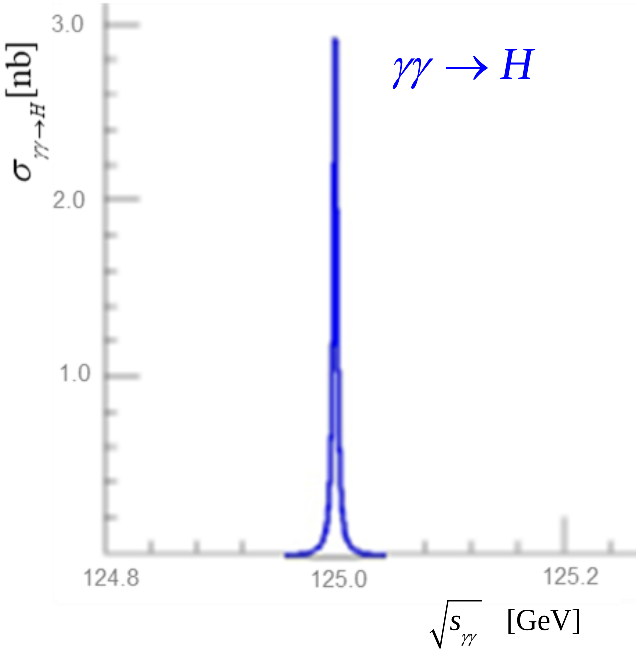
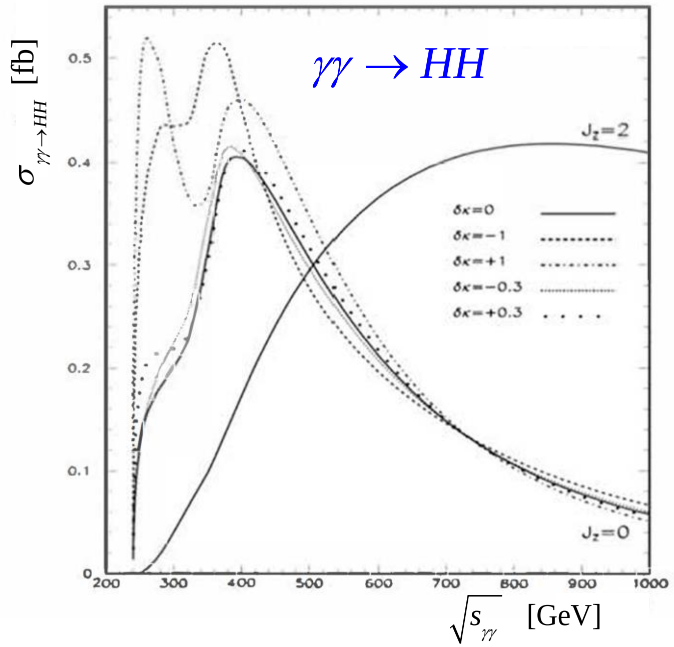


1 The Photon Collider at TESLA

B. Badelek[43], C. Blöchinger[44], J. Blümlein[12], E. Boos[28], R. Brinkmann[12],
H. Burkhardt[11], P. Bussey[17], C. Carimalo[33], J. Chyla[34], A.K. Çiftçi[4], W. Deckin
A. De Roeck[11], V. Fadin[10], M. Ferrario[15], A. Finch[24], H. Fraas[44], F. Franke[44],
M. Galynskii[27], A. Gamp[12], I. Ginzburg[31], R. Godbole[6], D.S. Gorbunov[28],
G. Gounaris[39], K. Hagiwara[22], L. Han[19], R.-D. Heuer[18], C. Heusch[36], J. Illana[12],
V. Ilyin[28], P. Jankowski[43], Yi Jiang[19], G. Jikia[16], L. Jönsson[26], M. Kalachnikow[8]
F. Kapusta[33], R. Klanner[12,18], M. Klasen[12], K. Kobayashi[41], T. Kon[40], G. Kotki
M. Krämer[14], M. Krawczyk[43], Y.P. Kuang[7], E. Kuraev[13], J. Kwiecinski[23],
M. Leenen[12], M. Levchuk[27], W.F. Ma[19], H. Martyn[1], T. Mayer[44], M. Melles[35],
D.J Miller[25], S. Mtingwa[29], M. Mühlleitner[12], B. Muryn[23], P.V. Nickles[8], R. Ora

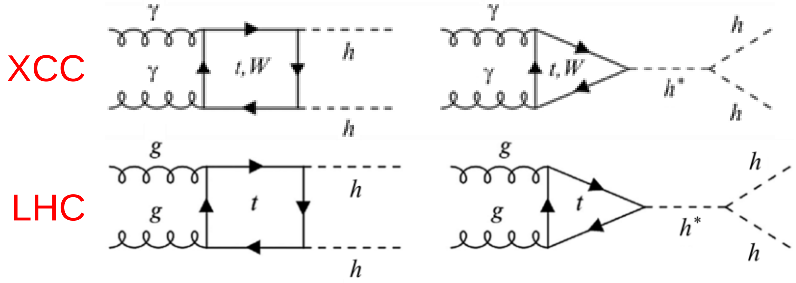
Higgs Production Cross Sections for $\gamma\gamma$, e^+e^- , $\mu^+\mu^-$ Initial States





	$\sqrt{s}$ (GeV)	polarization	σ (fb)
$e^+e^- \to ZH$	250	$-80\%\ e^-$ $+30\%\ e^+$	310
$\gamma\gamma \to H$	125	$+100\%\ \gamma$ $+100\%\ \gamma$	3×10^6
$\mu^+\mu^- \to H$	125	$0\%\ \mu^-$ $0\%\ \mu^+$	7×10^4
$e^+e^- \to H$	125	$0\%\ e^-$ $0\%\ e^+$	1.64

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



[†] Can't take full advantage of $\sigma_{\gamma\gamma}$ =3 nb because $\gamma\gamma$ beam width < 4 MeV is impossible. But in general, narrower $\gamma\gamma$ beam width $\Rightarrow$ higher Higgs rate

Optical $\to$ X-ray Laser Produces Narrower $\gamma\gamma$ Luminosity Spectra

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

$\omega_0 =$ laser photon energy

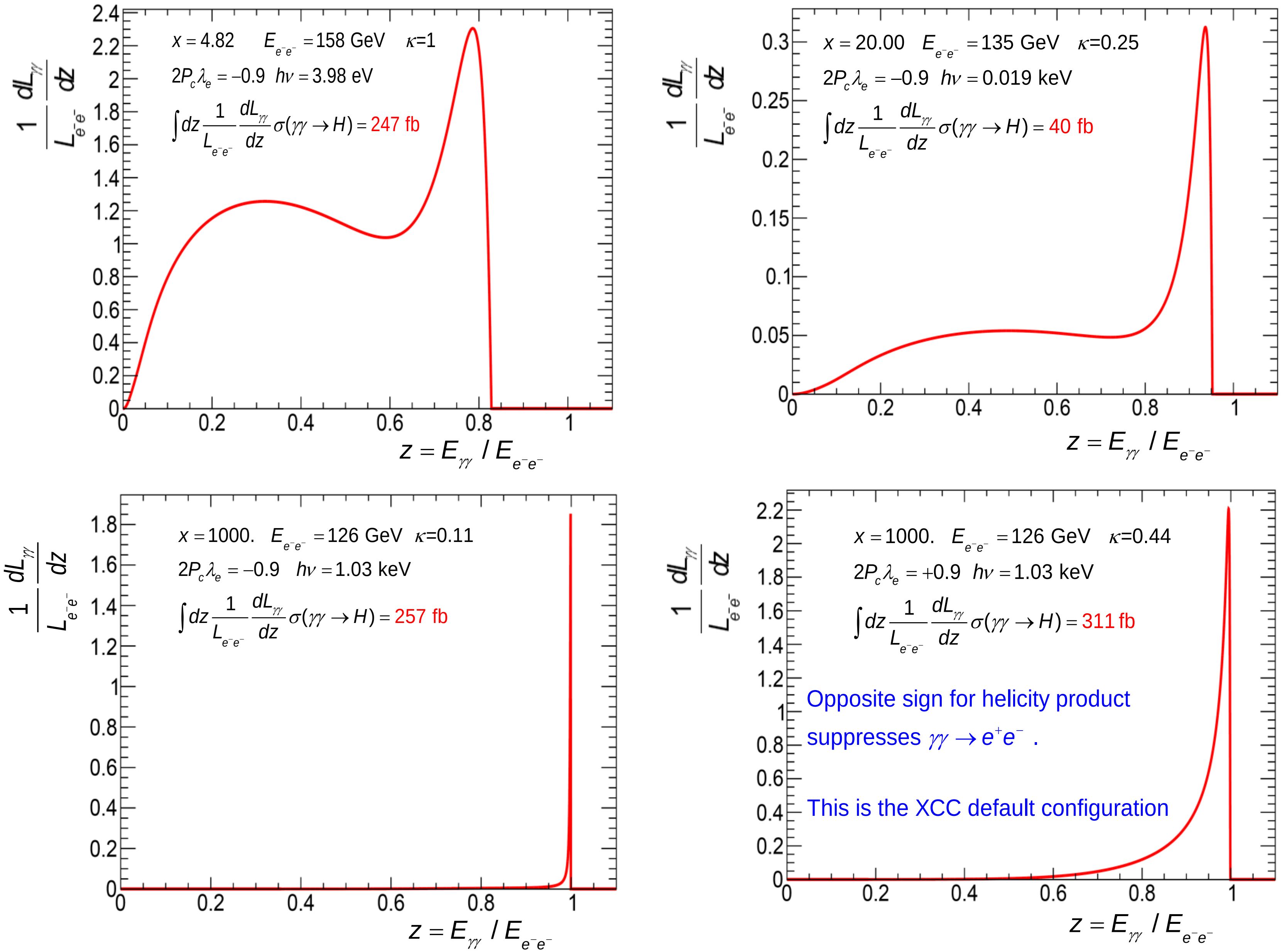
maximum Compton photon energy $\omega_m = \dfrac{x}{x+1}E_{e^-}$

Important threshold in x:

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

$\kappa = 1 -$ prob that Compton γ annihilates with laser γ

$$\sigma(\gamma\gamma \to H) = \frac{8\pi\Gamma_{\gamma\gamma}\Gamma_{tot}}{(s-M_H^2)^2+\Gamma_{tot}^2 M_H^2}(1+\xi_1\xi_2)$$
$$\approx \frac{4\pi^2\Gamma_{\gamma\gamma}}{M_H^3}(1+\xi_1\xi_2)z_H\delta(z-z_H)$$



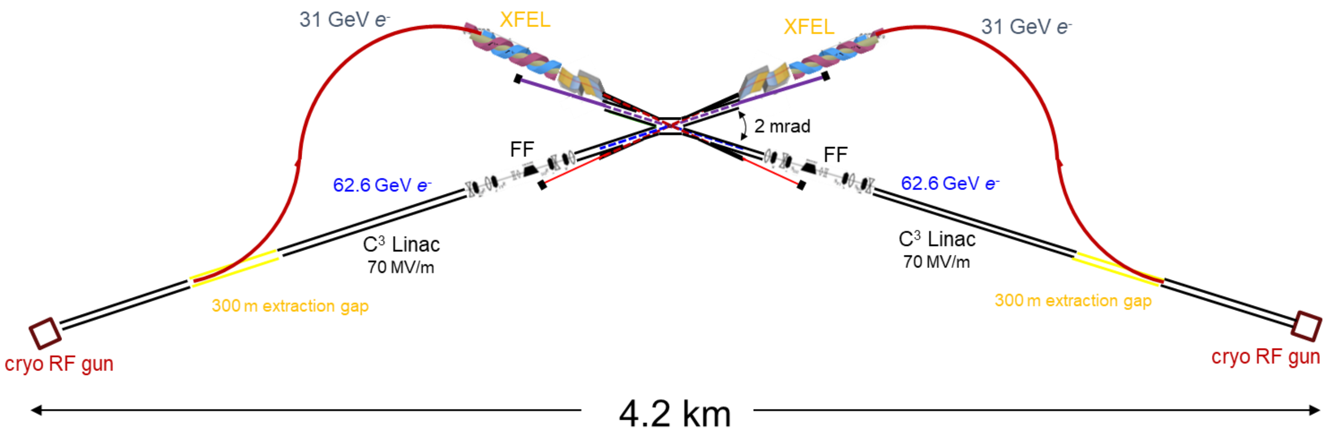
Opposite sign for helicity product suppresses $\gamma\gamma \to e^+e^-$.

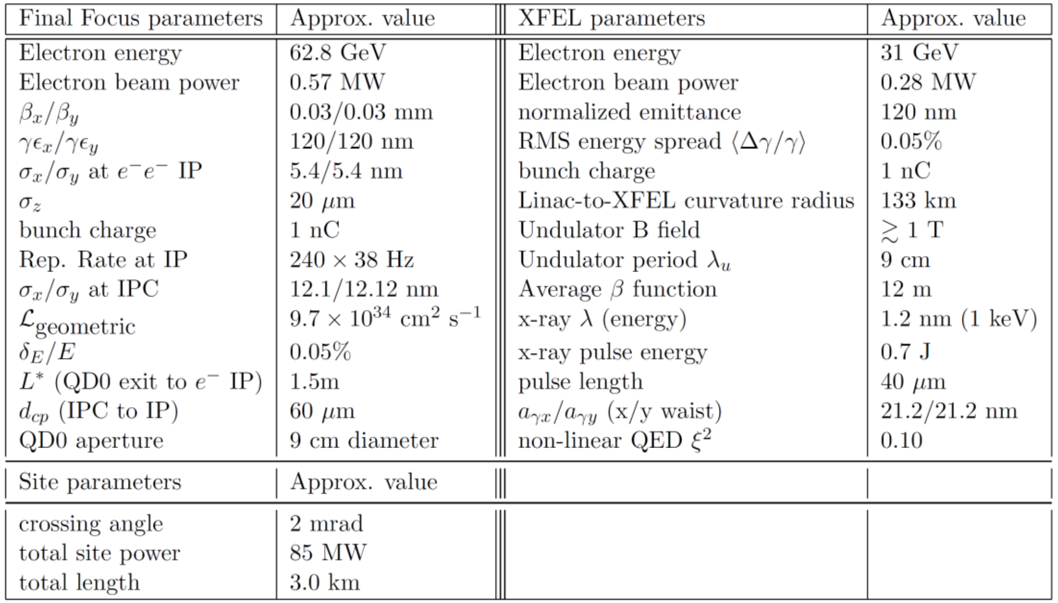
This is the XCC default configuration

XCC Schematic, 125 GeV Design Parameters, Full Cain Simulation

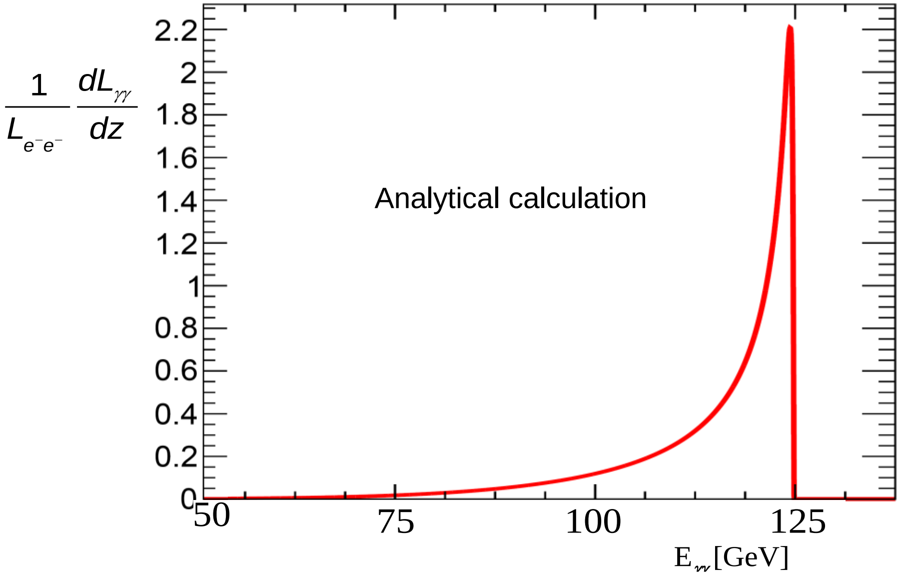
$$\text{XCC s-channel } \gamma\gamma \to H \quad @ \quad \sqrt{s} = 125 \text{ GeV}$$

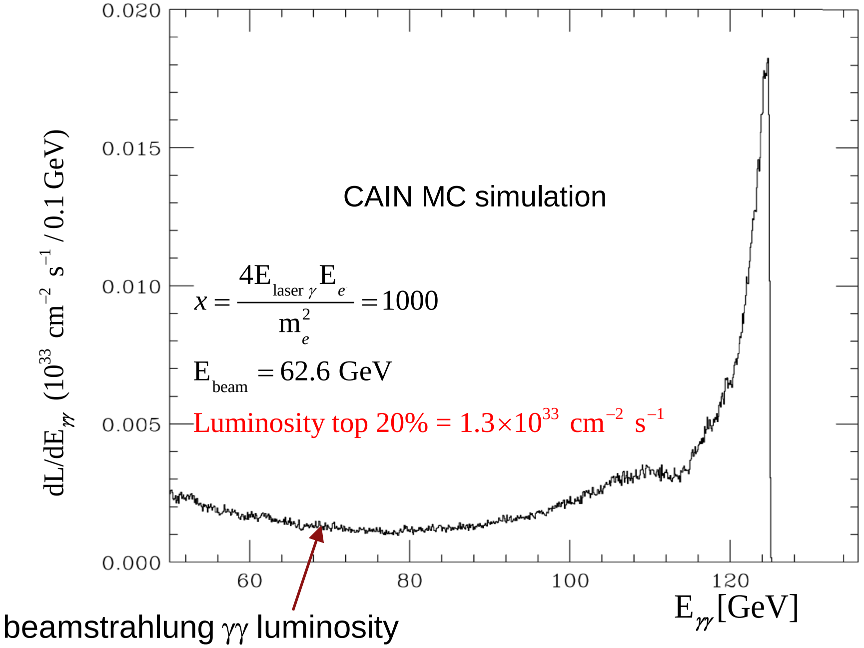
$$\gamma\gamma \to HH \quad @ \quad \sqrt{s} = 380 \text{ GeV}$$





Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	5.4/5.4 nm	bunch charge	1 nC
σ_z	20 μm	Linac-to-XFEL curvature radius	133 km
bunch charge	1 nC	Undulator B field	$\gtrsim$ 1 T
Rep. Rate at IP	240 × 38 Hz	Undulator period λ_u	9 cm
σ_x/σ_y at IPC	12.1/12.12 nm	Average β function	12 m
$\mathcal{L}_{\text{geometric}}$	9.7×10^{34} cm^2 s^{-1}	x-ray λ (energy)	1.2 nm (1 keV)
δ_E/E	0.05%	x-ray pulse energy	0.7 J
L^* (QD0 exit to e^- IP)	1.5m	pulse length	40 μm
d_{cp} (IPC to IP)	60 μm	$a_{\gamma x}/a_{\gamma y}$ (x/y waist)	21.2/21.2 nm
QD0 aperture	9 cm diameter	non-linear QED ξ^2	0.10
Site parameters	**Approx. value**		
crossing angle	2 mrad		
total site power	85 MW		
total length	3.0 km		



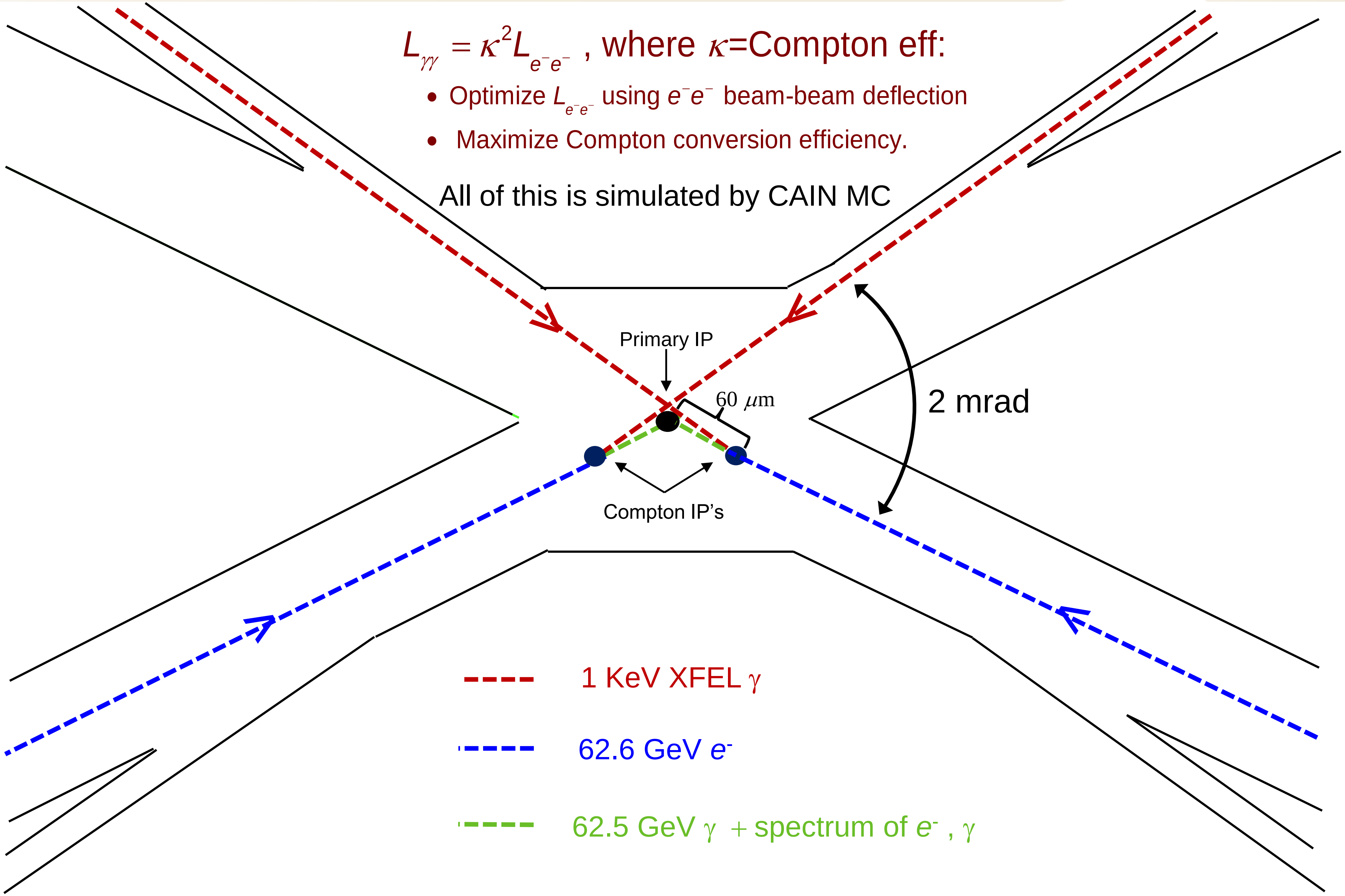


XCC layout of 1 keV XFEL , 63 GeV e^- Beams near Interaction Point

$L_{\gamma\gamma} = \kappa^2 L_{e^-e^-}$, where κ=Compton eff:

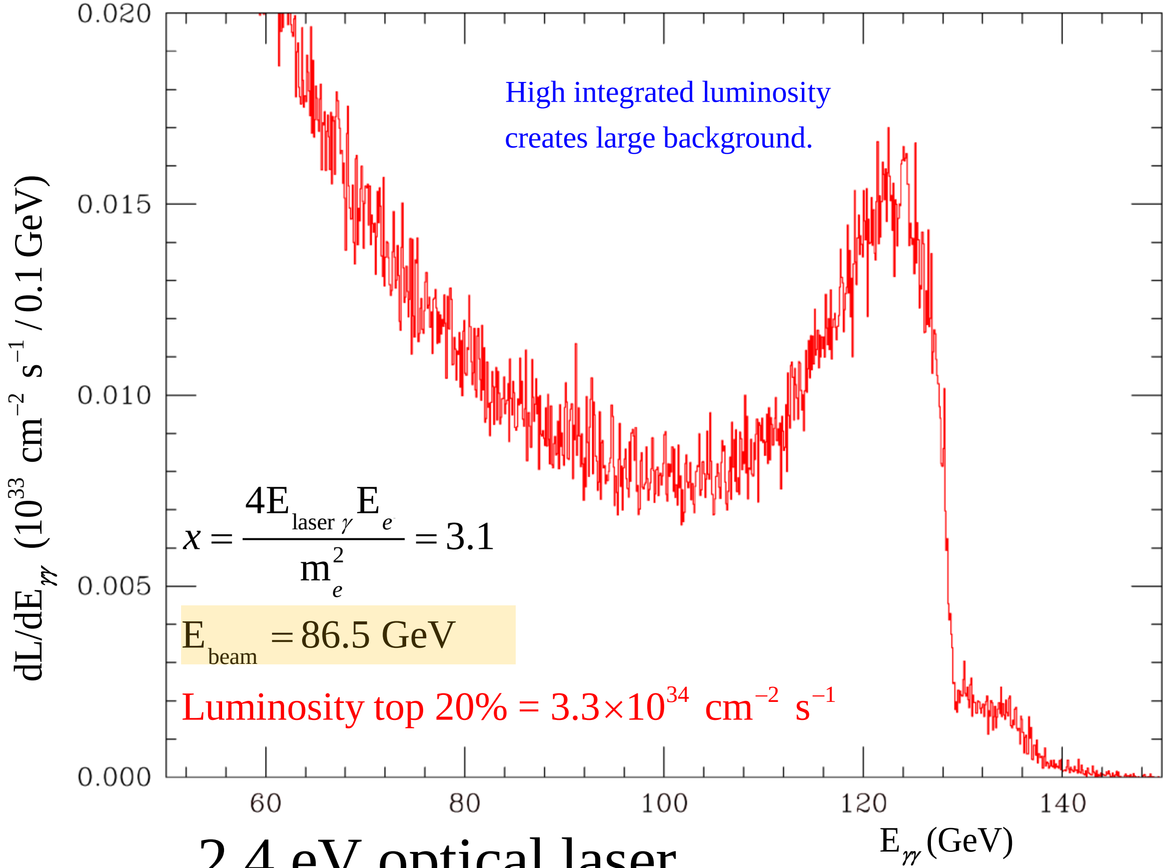
- Optimize $L_{e^-e^-}$ using e^-e^- beam-beam deflection
- Maximize Compton conversion efficiency.

All of this is simulated by CAIN MC



The XCC experimental environment is qualitatively different from optical laser γγ – more like e^+e^-

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



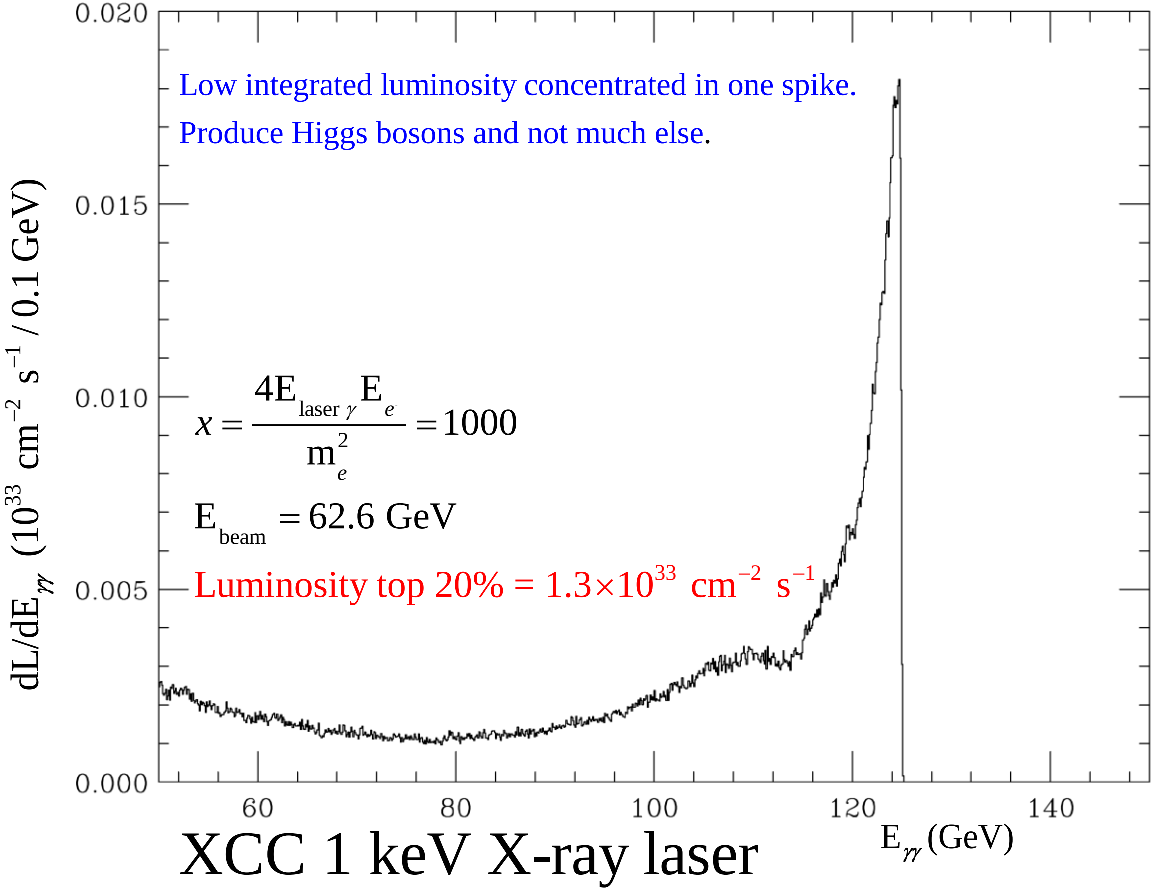
High integrated luminosity creates large background.

$$x = \frac{4E_{\text{laser}\,\gamma}E_e}{m_e^2} = 3.1$$

$E_{\text{beam}} = 86.5$ GeV

Luminosity top 20% = 3.3×10^{34} cm^{-2} s^{-1}

2.4 eV optical laser



Low integrated luminosity concentrated in one spike.
Produce Higgs bosons and not much else.

$$x = \frac{4E_{\text{laser}\,\gamma}E_e}{m_e^2} = 1000$$

$E_{\text{beam}} = 62.6$ GeV

Luminosity top 20% = 1.3×10^{33} cm^{-2} s^{-1}

XCC 1 keV X-ray laser

Tools are being Developed for Delphes Analyses of $\gamma\gamma \to H$, $\gamma\gamma \to HH$ assuming SiD Detector and Full Suite of Backgrounds

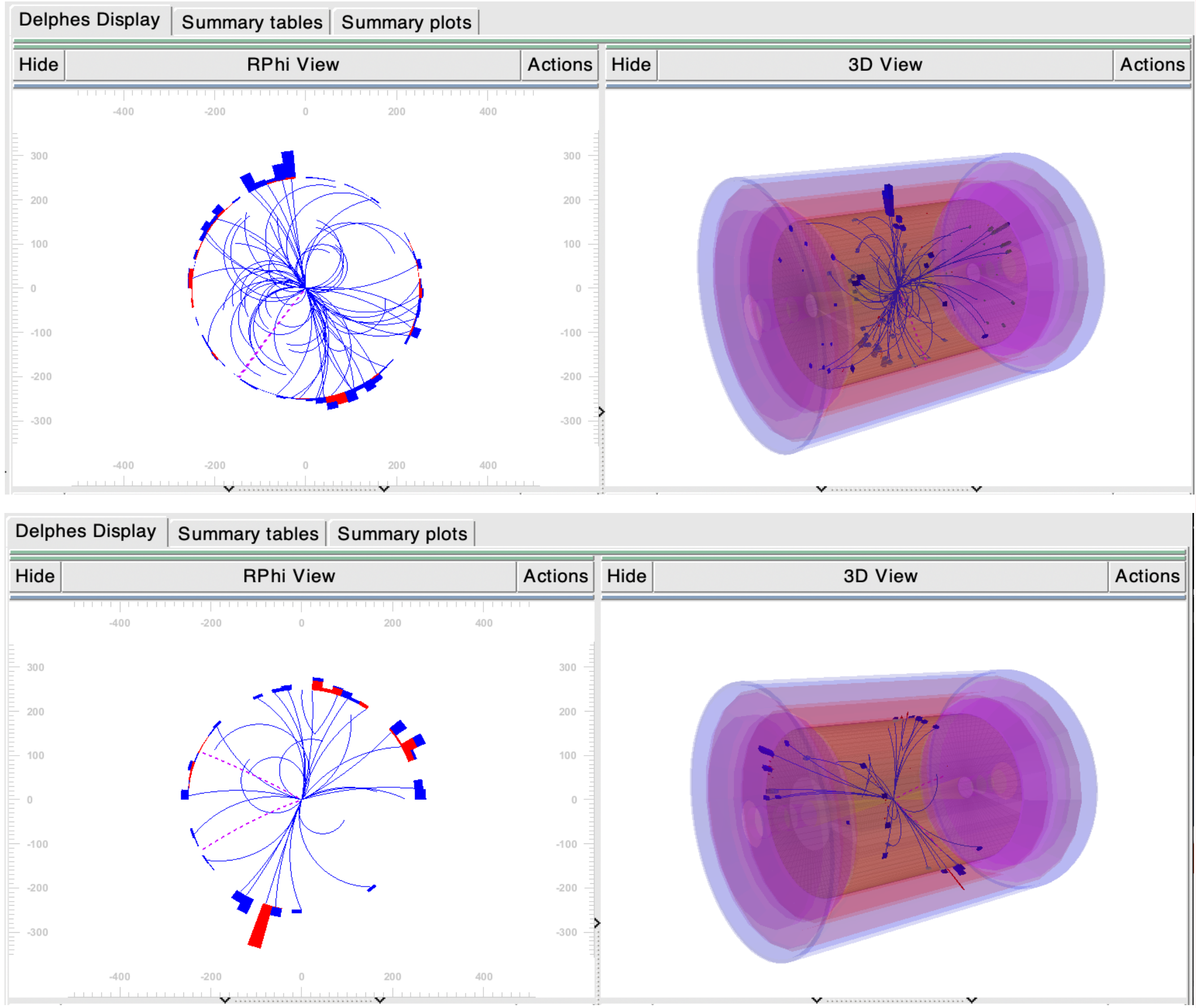
Higgs self-couping analysis

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

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

$\gamma\gamma \to HH$ $\gamma\gamma \to qq$ $\gamma\gamma \to tt$

$\gamma\gamma \to ZZ$ $\gamma\gamma \to W^+W^-$



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

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

Delphes Event Displays of $e^+e^- \to ZHH \to qqbbbb$ and $\gamma\gamma \to HH \to bbbb$

Tools are being Developed for Delphes Analyses of $\gamma\gamma \to H$, $\gamma\gamma \to HH$ assuming SiD Detector and Full Suite of Backgrounds

Higgs self-couping analysis

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

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

$\gamma\gamma \to HH$ $\quad\gamma\gamma \to qq$ $\quad\gamma\gamma \to tt$

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

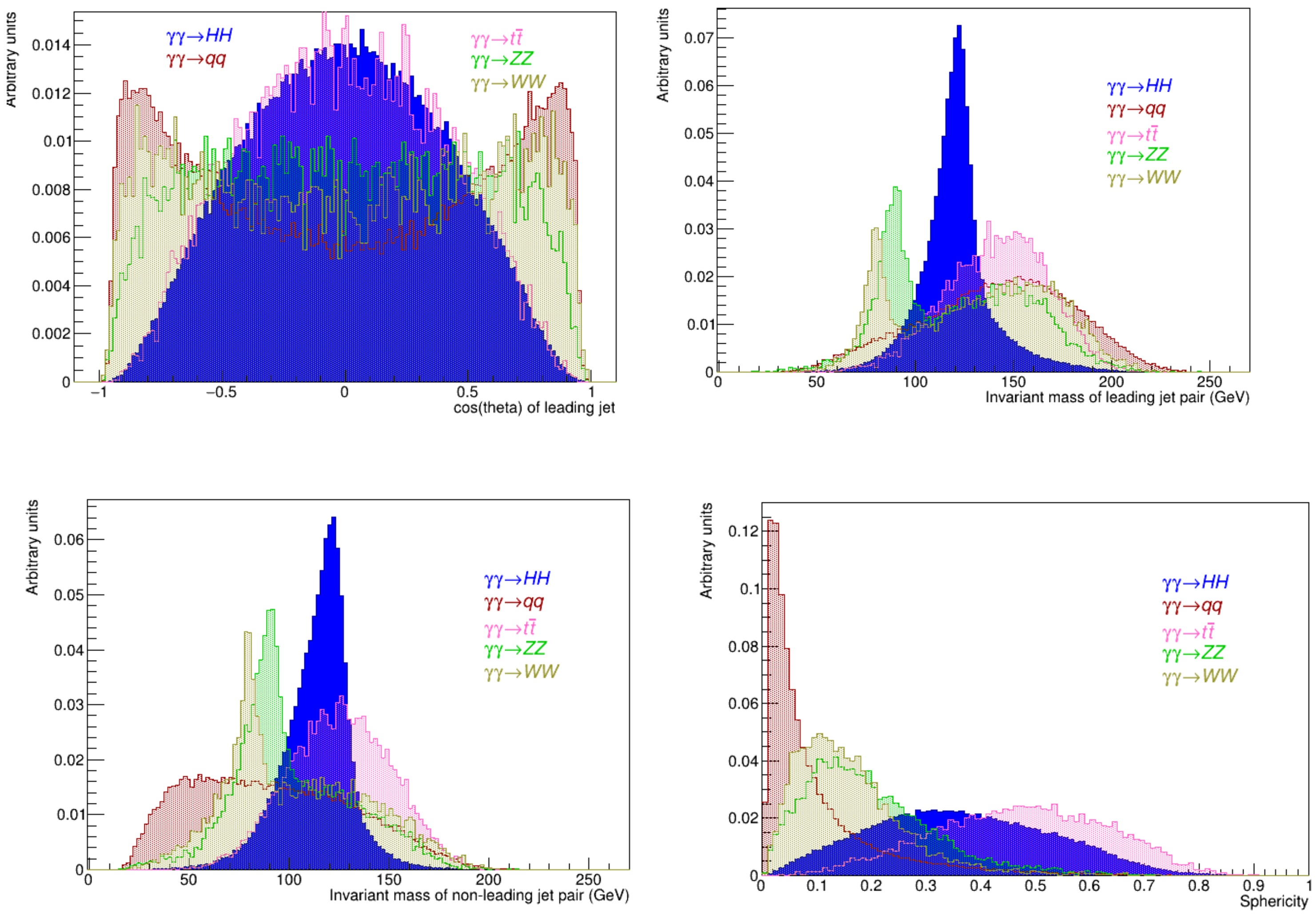
Cain $(x1, x2)$ spectra is now interfaced to Whizard 3.14 . Background data sets such as the following are being produced:

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

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

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

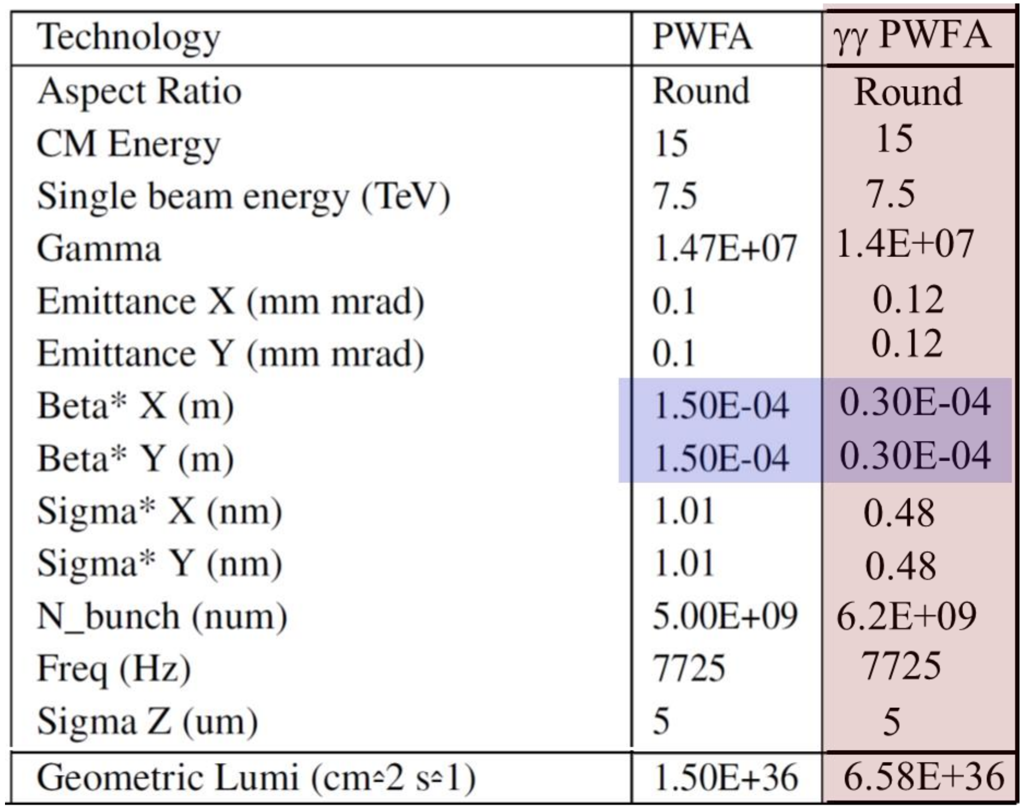
In addition the $\gamma\gamma \to$ *hadrons* simulation used with Whizard 1.95 has now been interfaced to Whizard 3.14 so pileup will also be included.



Examples of variables used in analysis of $\gamma\gamma \to HH \to bbbb$

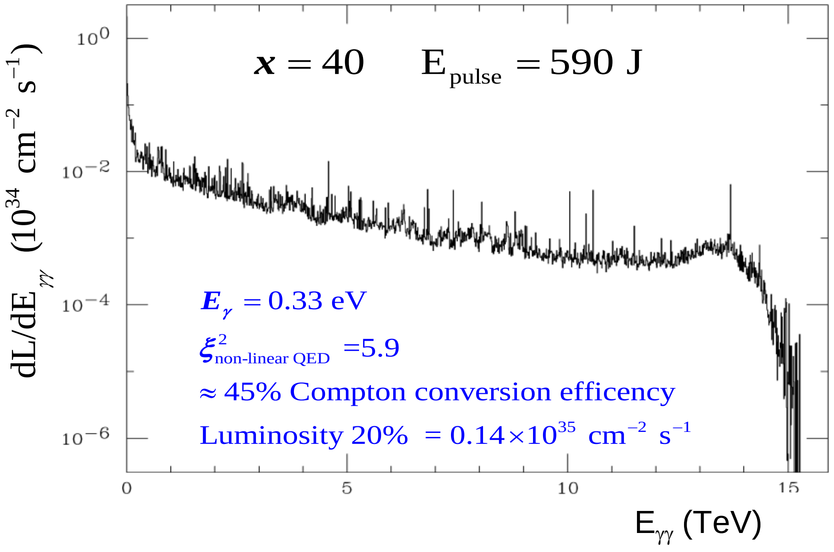
Each distribution normalized to 1. No kinematic fit (yet).

10 TeV PWFA $\gamma\gamma$ Collider

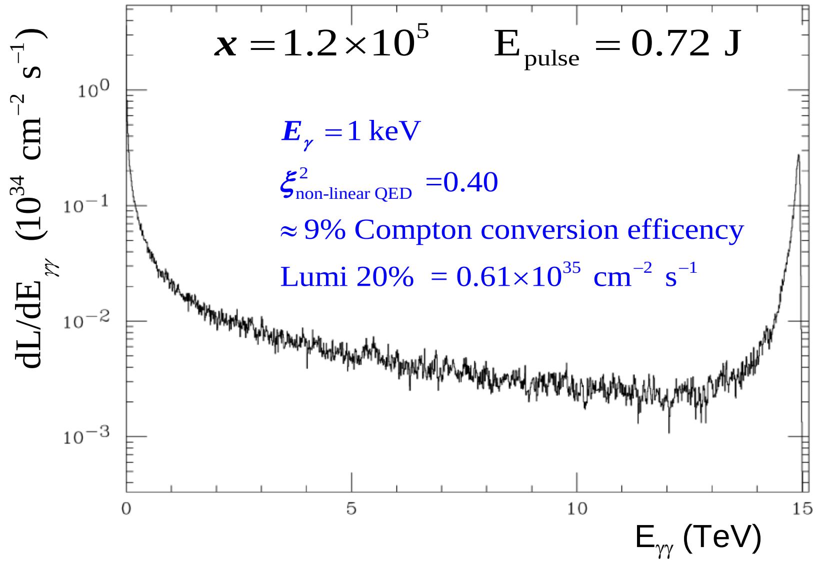


Technology	PWFA	$\gamma\gamma$ PWFA
Aspect Ratio	Round	Round
CM Energy	15	15
Single beam energy (TeV)	7.5	7.5
Gamma	1.47E+07	1.4E+07
Emittance X (mm mrad)	0.1	0.12
Emittance Y (mm mrad)	0.1	0.12
Beta* X (m)	1.50E-04	0.30E-04
Beta* Y (m)	1.50E-04	0.30E-04
Sigma* X (nm)	1.01	0.48
Sigma* Y (nm)	1.01	0.48
N_bunch (num)	5.00E+09	6.2E+09
Freq (Hz)	7725	7725
Sigma Z (um)	5	5
Geometric Lumi (cm^{-2} s^{-1})	1.50E+36	6.58E+36

In limited survey of configs, XFEL lasers give the best luminosity spectra for multi-TeV PWFA $\gamma\gamma$ colliders.



Unscattered e^- from Compton IP have full beam energy. Runaway coherent e^+e^- pair-production due to positrons pinching the electron beams: fields as high as 0.6 ×Schwinger

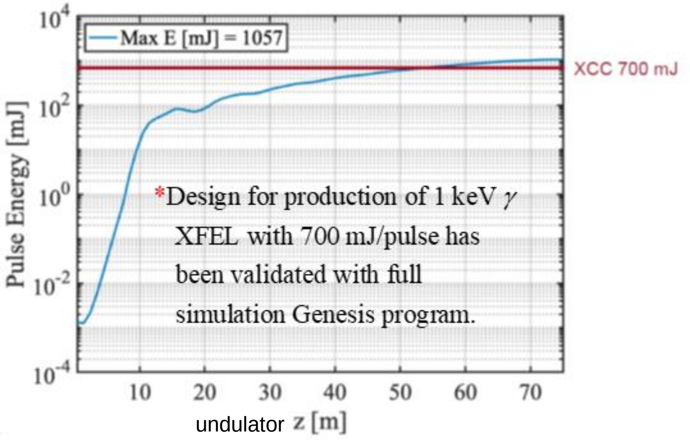


e^- from Compton IP have much reduced energy due to multiple trident $e^-\gamma \rightarrow e^-e^+e^-$. EM fields are 3 orders of magnitude smaller.

XCC Accelerator Challenges

Electron beam:

- e^- accelerator with $70-120$ MV/m (common with C^3 e^+e^- collider)
- Polarized low emittance e^- injector (common with C^3 e^+e^- , except flat beams not needed)
- Focusing of round e^- beams to $\sigma_{x,y} = 5.5$ nm



*Design for production of 1 keV γ XFEL with 700 mJ/pulse has been validated with full simulation Genesis program.

XFEL beam and Compton IP:

- Production of 1 keV γ XFEL with 700 mJ/pulse
- Focusing of 1 keV , 700 mJ/pulse XFEL beam to 70 nm FWHM waist
- XFEL and e^- beamline layouts around the IP
- Timing and position stability of the XFEL laser beam and e^- beam at Compton IP.

Table of XCC KB mirror parameters

Focal Size (nm)	Photon Energy (eV)	Rayleigh Range (um)	RMS Source Size (um)	AOI (deg)	Max E w/ 10x SF (J)	Substrate Length (m)	Unfocused Beam Size (mm)	Source Distance (m)	Reflectivity	Focal Length (m)	IP Distance from Mirror (m)
50	1000	4.5	10	1.30	0.31	1.00	11.34	487	0.872	1.032	0.532
100	1000	18.2	10	0.90	0.68	1.50	11.78	505	0.926	2.144	1.394
50	2000	9.1	10	0.80	0.54	1.00	6.98	600	0.933	1.27	0.770
100	2000	36.4	10	0.60	1.05	1.40	7.33	629	0.967	2.668	1.968
50	2000	9.1	10	0.65	1.21	1.50	8.51	731	0.962	1.548	0.798
100	2000	36.4	10	0.50	2.14	2.00	8.73	750	0.976	3.176	2.176
40	4000	11.6	10	0.4	1.06	1.13	3.93	675	0.982	1.143	0.581
70	4000	35.7	10	0.3	2.40	1.50	3.93	675	0.992	2.001	1.251
40	4000	11.6	10	0.4	2.39	1.50	5.24	899	0.982	1.525	0.775
70	4000	35.7	10	0.3	4.27	2.00	5.24	899	0.992	2.668	1.668

Summary

- In contrast to optical laser-based $\gamma\gamma$ colliders, the experimental environment at an XFEL-based collider is somewhat closer to that of an e^+e^- collider.
- The XCC Higgs factory has a smaller footprint than its e^+e^- counterparts, and therefore costs less.
- Past estimates of XCC Higgs coupling precision based on equal XCC and ILC detection efficienes are in the process of being replaced by Delphes analyses of $\gamma\gamma \to H$ and $\gamma\gamma \to HH$ using a complete set of CAIN+Whizard signal & background data sets.
- A $\gamma\gamma$ configuration may be optimal for particle physics with a 10 TeV PWFA collider. The XCC could therefore serve as a prototype for a 10 TeV collider.

Significant R&D is required to address XCC's accelerator challenges:

- With the exception of round beam focusing, the required XCC electron accelerator R&D is common with that of the C^3 e^+e^- collider
- The accelerator R&D unique to XCC -- production and focusing of 1 Joule/pulse XFEL beams -- is unique not only within particle physics, but also within the broader x-ray science community. XCC is the first science project to require 1 Joule/pulse soft x-ray beams, which could ultimately have broader applications.