Luminosity Spectra at a 15 TeV Plasma Wakefield $\gamma\gamma$ Collider

Advance Accelerator Concepts Parallel Session, LCWS23

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May 18, 2023

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Photon Collider Basics

Photons from a high powered laser are scattered off the high energy beam electrons of a linear collider between the final quadrupole and the interaction point. The compton scattered photons acquire the momenta of the high energy electrons and collide at the i.p. with the compton scattered photons from the opposing beam. The $\gamma\gamma$ luminosity will be given by the geometric e^+e^- luminosity times the compton conversion efficiency squared.

$$x = \frac{4E_{e^-}\omega_0}{m_e^2} \qquad \omega = \frac{\omega_m}{1+\left(\theta/\theta_0\right)^2} \qquad \omega_m = \frac{x}{x+1}E_{e^-} \qquad \theta_0 = \frac{m_e}{E_{e^-}}\sqrt{x+1}$$

$m_e^2(x+1) =$ center of mass energy squared of electron and laser photon

$\omega_0 =$ laser photon energy

$\omega =$ compton scattered (high energy) photon energy

$\theta =$ angle of compton scattered (high energy) photon w.r.t. electron

In the following slides I calculate the Higgs production rate while varying x, P_c , and λ_e, where

P_c = mean helicity of laser beam $|P_c| \leq 1$

λ_e = mean helicity of electron beam $|\lambda_e| \leq \frac{1}{2}$

The thresholds for two important physics processes are crossed as x is varied

At $x = 4.82$ $\gamma\gamma_{\text{laser}} \to e^+e^-$ opens up which depletes the high energy photon beam; this effect is included in the Higgs cross section calculation and is given by the variable κ

At $x = 8$ $e^-\gamma_{\text{laser}} \to e^+e^-e^-$ opens up. This process smears the electron energy and hence smears the high energy photon spectrum. The effects of this process are not included in the following analytical plots (they are included in the CAIN MC simulation).

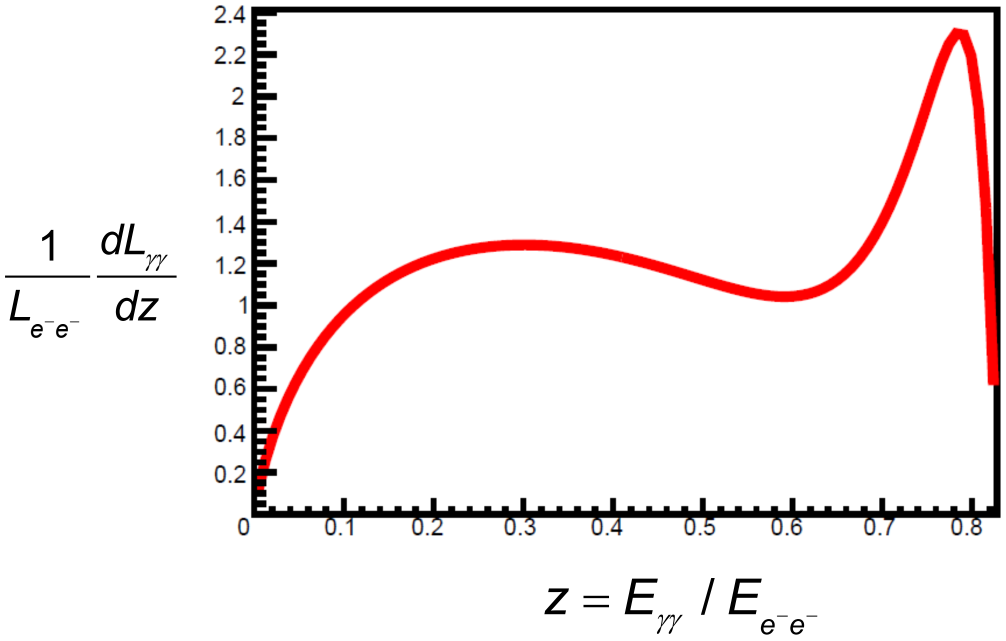
The $\gamma\gamma$ luminosity spectrum is plotted, along with $\langle \xi_1 \xi_2 \rangle$ where

$\xi_i =$ mean helicity of the high energy photon beam i, i=1,2 $|\xi_i| \leq 1$

Note: All $\gamma\gamma$ luminosities must be multiplied by the $e^-\gamma_{\text{laser}}$ conversion probability squared

Strong field nonlinear effects are not included in the following analytical calculation plots (they are included in the CAIN MC simulations).

Nominal configuration

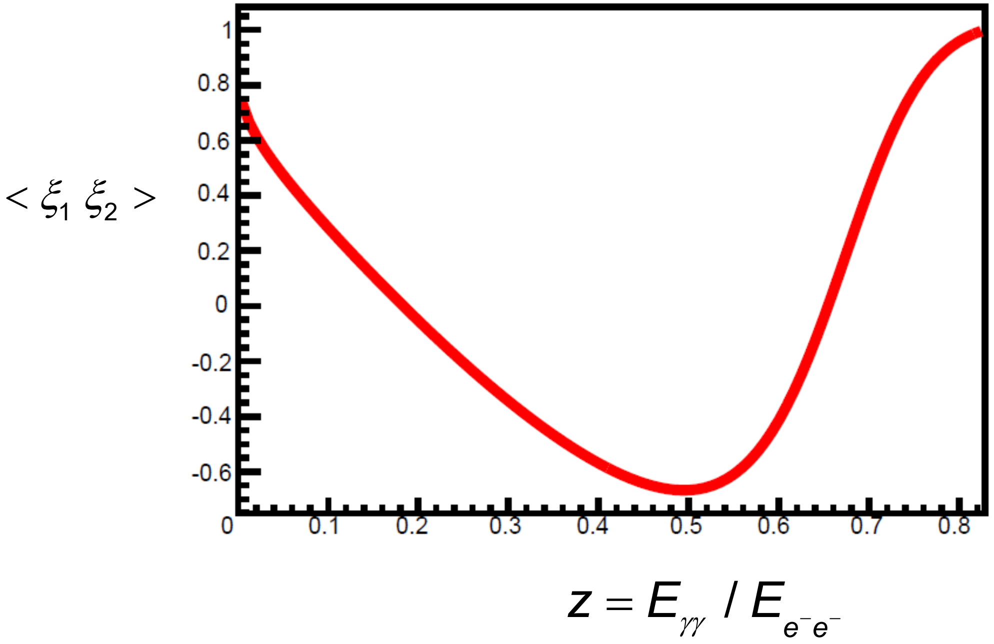


$x = 4.82 \quad E_{e^-e^-} = 158\ \text{GeV} \quad \kappa = 1$

$\text{pol}(e^-) = 90\% \quad 2P_c\lambda_e = -0.9 \quad h\nu = 3.98\ \text{eV}$

(κ= 1 – prob that γ annihilates with laser γ)

$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 247\ \text{fb}$$

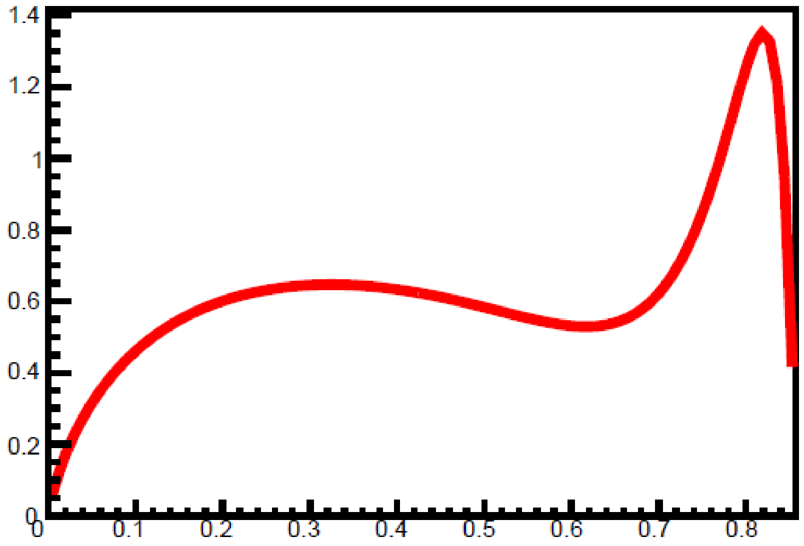


$$\sigma(\gamma\gamma \to H) = \frac{8\pi\,\Gamma_{\gamma\gamma}\Gamma_{tot}}{(s - M_H^2)^2 + \Gamma_{tot}^2 M_H^2}(1 + \xi_1\,\xi_2)$$

$$\approx \frac{4\pi^2\Gamma_{\gamma\gamma}}{M_H^3}(1 + \xi_1\,\xi_2) z_H \delta(z - z_H)$$

Now let's start increasing x (the energy of the Compton photon)

$$\frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}$$



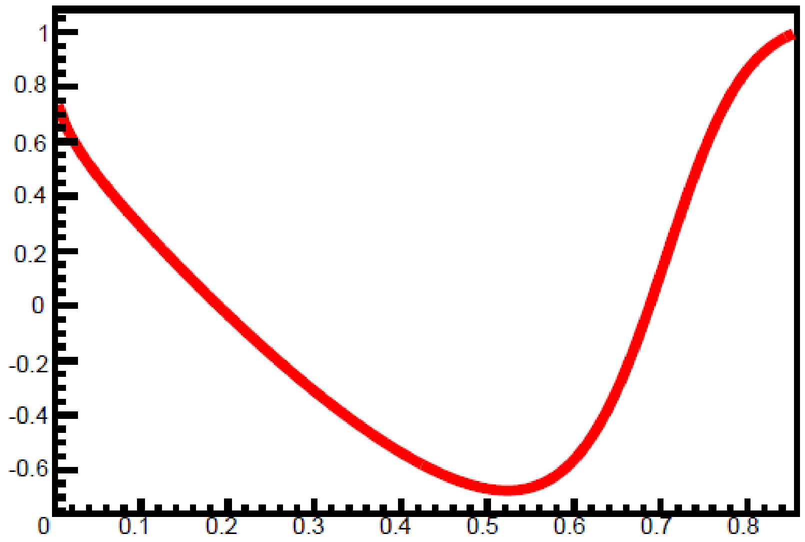
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

$x = 6.00$ $E_{e^-e^-} = 150$ GeV κ=0.73

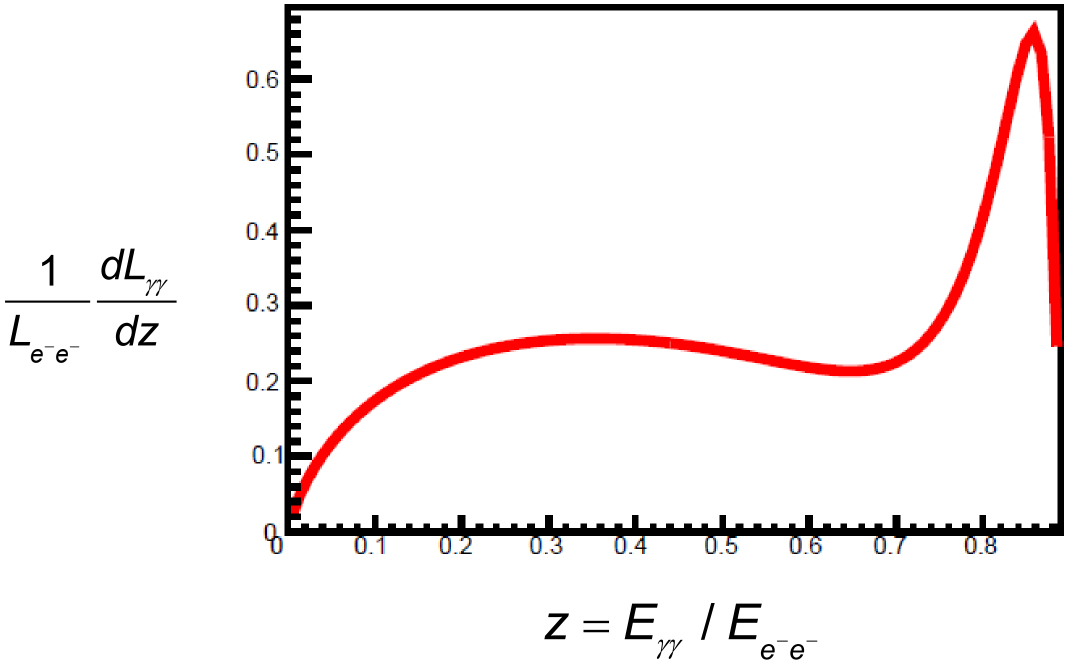
$\text{pol}(e^-) = 90\%$ $2P_c\lambda_e = -0.9$ $h\nu = 5.22$ eV

$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 130 \text{ fb}$$

$$< \xi_1 \, \xi_2 >$$



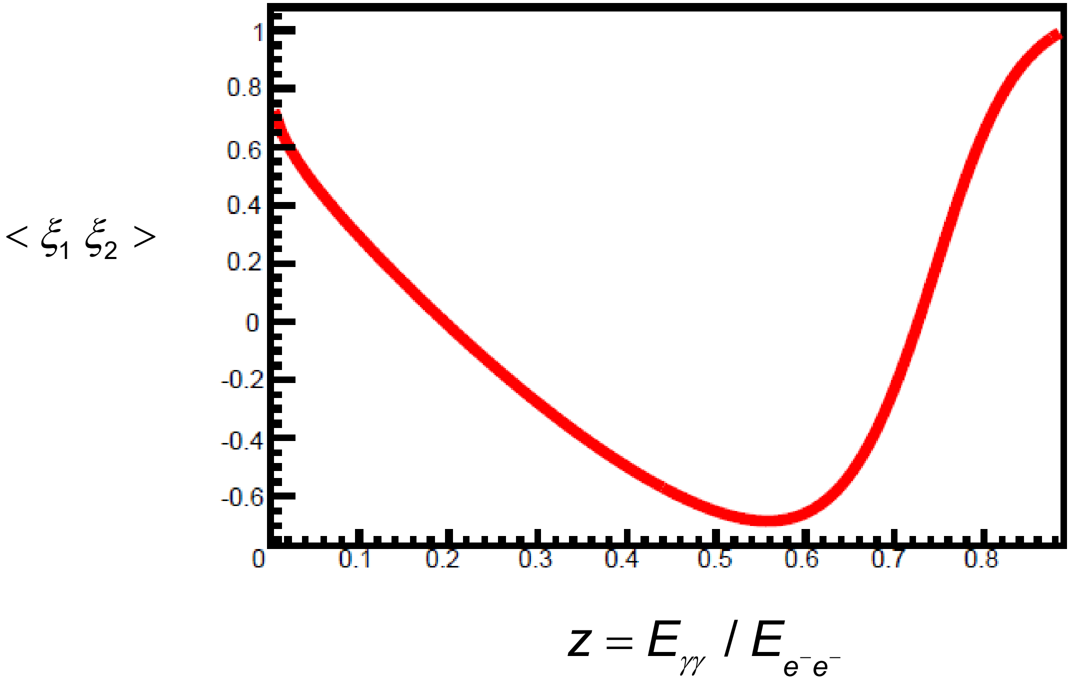
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

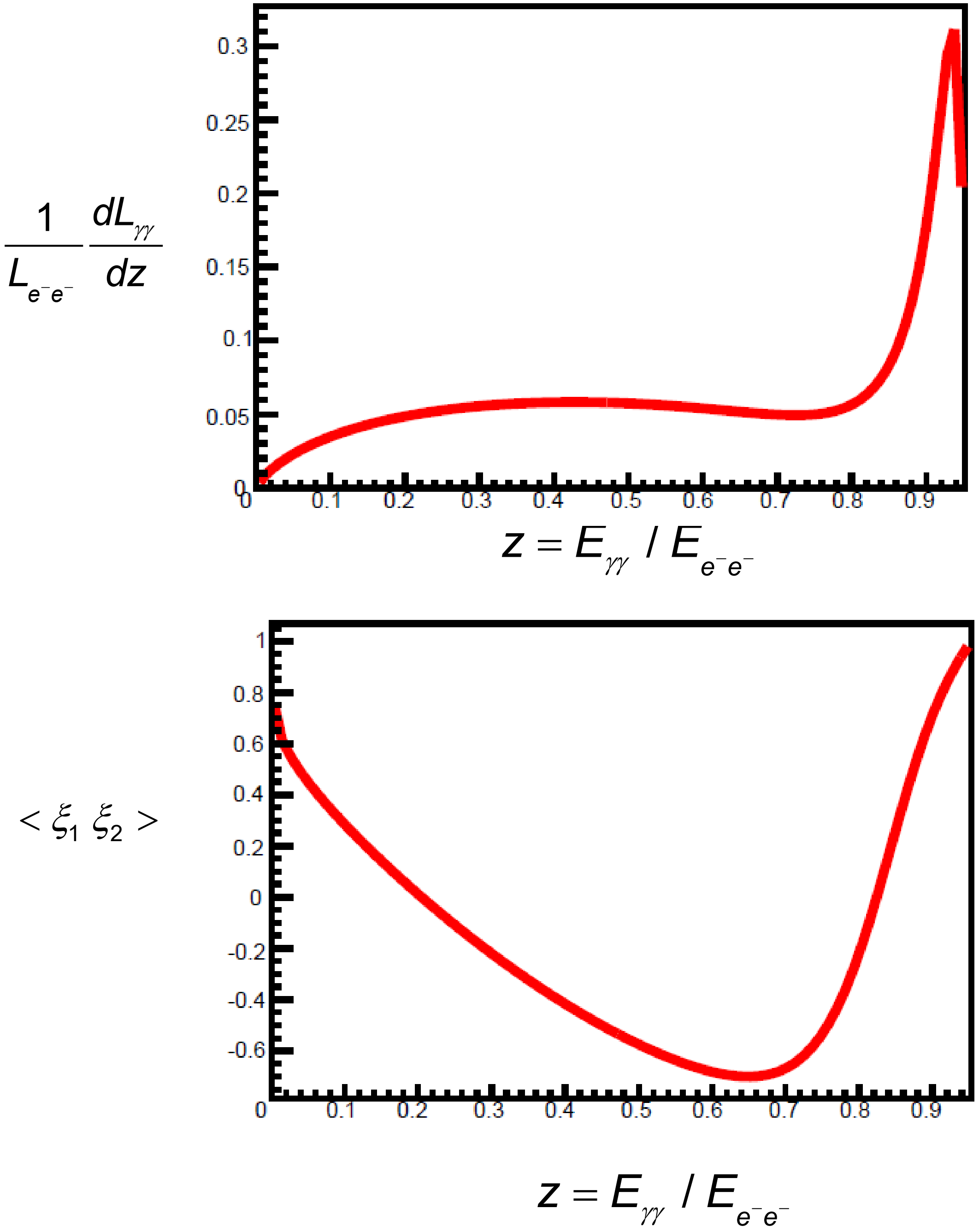


$x = 8.00 \quad E_{e^-e^-} = 146.5\ \mathrm{GeV} \quad \kappa = 0.48$

$\mathrm{pol}(e^-) = 90\% \quad 2P_c\lambda_e = -0.9 \quad h\nu = 7.13\ \mathrm{eV}$

$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 78\ \mathrm{fb}$$

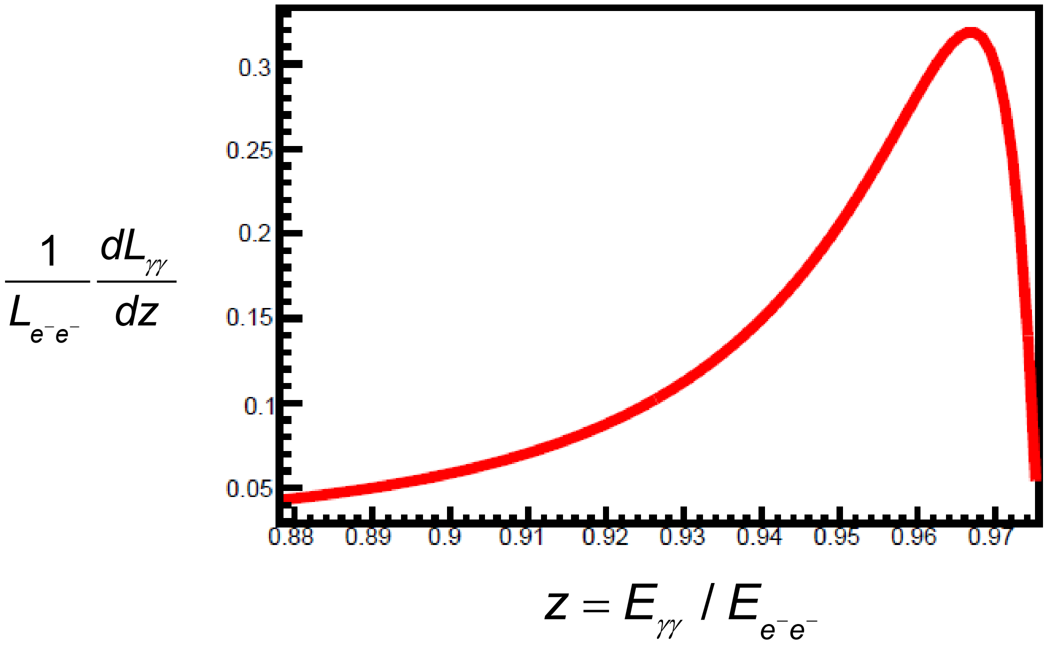




$x = 20.00 \quad E_{e^-e^-} = 134.8 \text{ GeV} \quad \kappa = 0.25$

$\text{pol}(e^-) = 90\% \quad 2P_c\lambda_e = -0.9 \quad h\nu = 19.4 \text{ eV}$

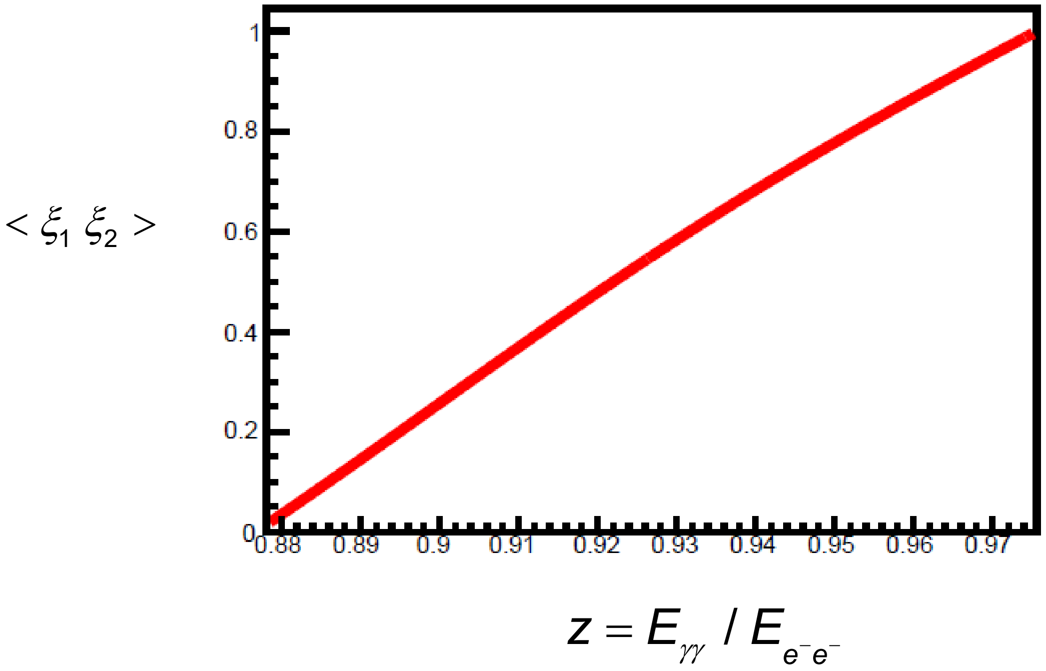
$$\int dz \frac{1}{L_{e^-e^-}} \frac{dL_{\gamma\gamma}}{dz} \sigma(\gamma\gamma \to H) = 40 \text{ fb}$$

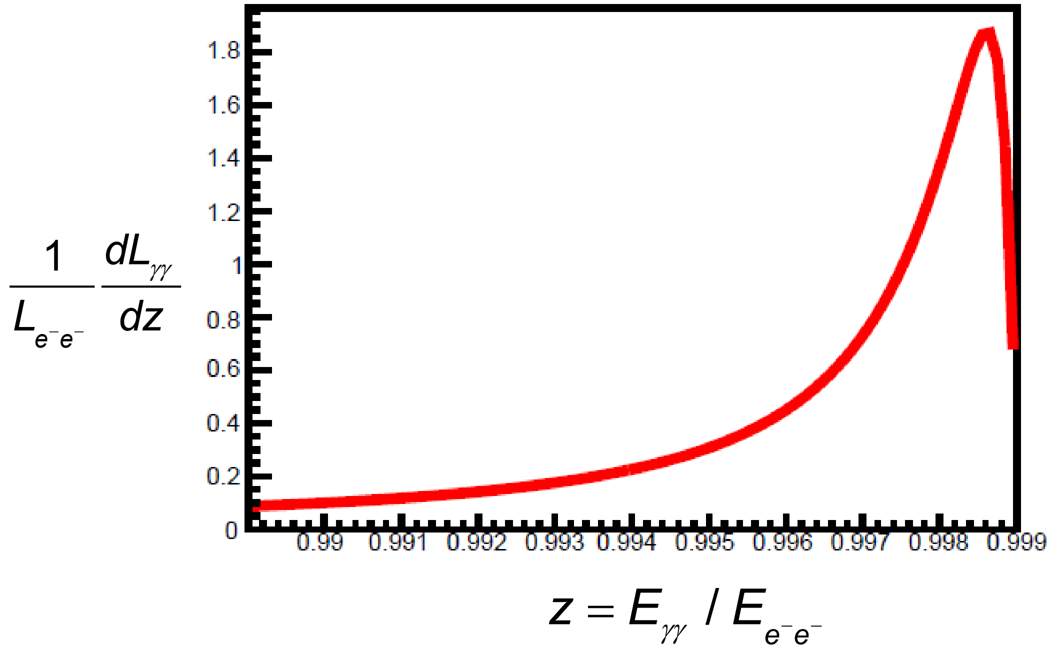


$x = 40.00 \quad E_{e^-e^-} = 130.3 \text{ GeV} \quad \kappa = 0.19$

$\text{pol}(e^-) = 90\% \quad 2P_c\lambda_e = -0.9 \quad h\nu = 40.1 \text{ eV}$

$$\int dz \frac{1}{L_{e^-e^-}} \frac{dL_{\gamma\gamma}}{dz} \sigma(\gamma\gamma \to H) = 42 \text{ fb}$$

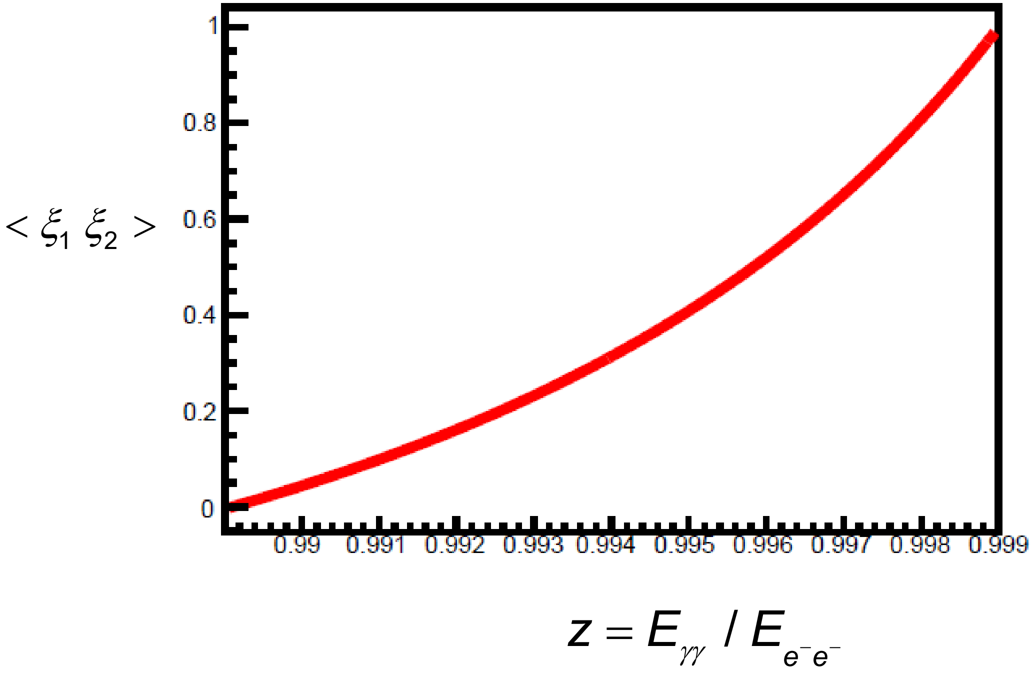




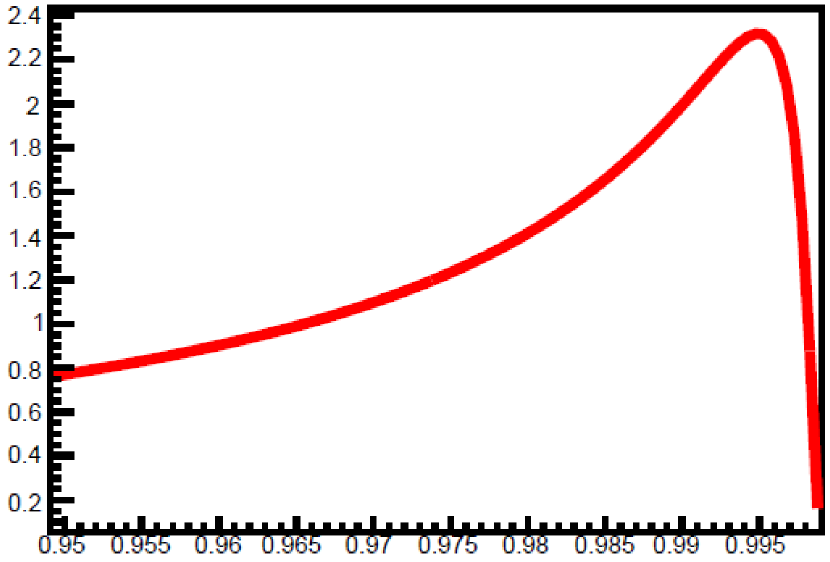
$x = 1000.$ $E_{e^-e^-} = 125.2$ GeV $\kappa = 0.11$

$\mathrm{pol}(e^-) = 90\%$ $2P_c\lambda_e = -0.9$ $h\nu = 1.03$ keV

$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 257 \text{ fb}$$



$$\frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}$$



$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

$x = 1000.$ $\quad E_{e^-e^-} = 125.6$ GeV $\quad \kappa$=0.44

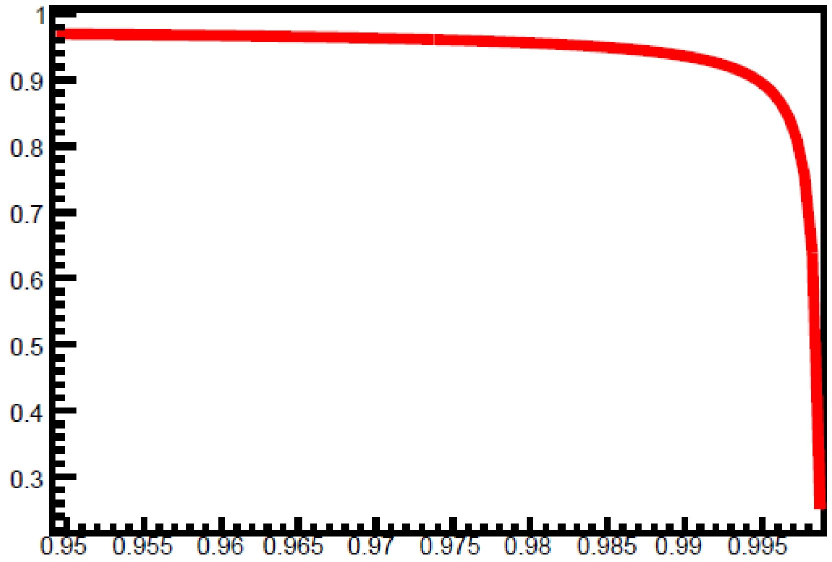
pol(e^-) = 90% $\quad 2P_c\lambda_e = +0.9$ $\quad h\nu = 1.03$ keV

$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 311 \text{ fb}$$

c.f. $\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}^{x=4.82}}{dz}\sigma(\gamma\gamma \to H) = 247$ fb

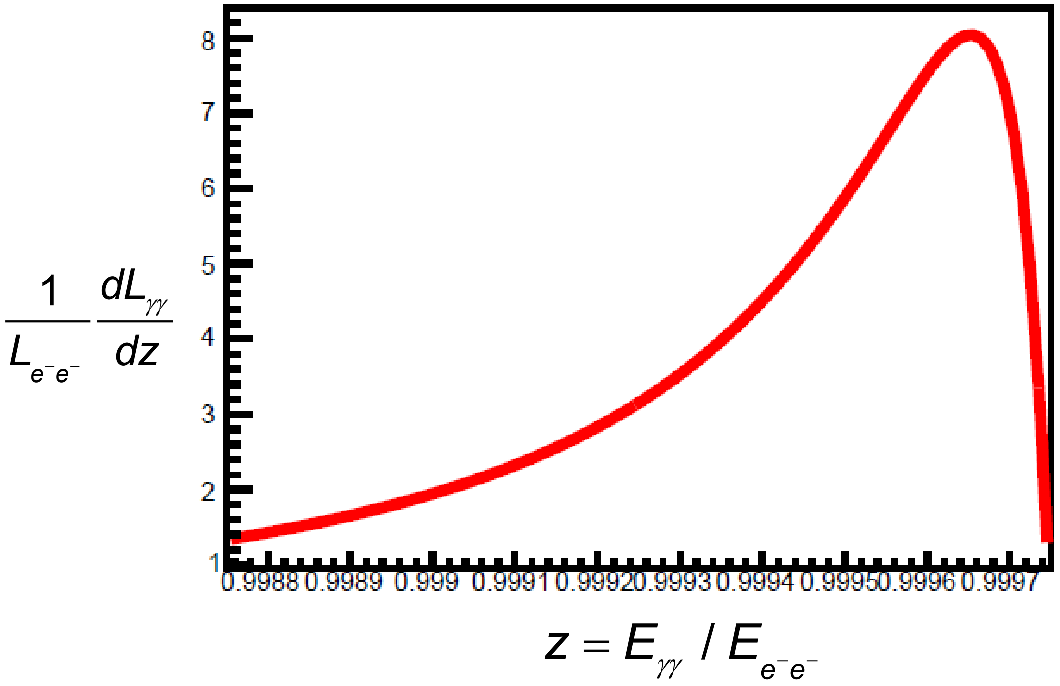
$\sigma^{\text{peak}}(e^+e^- \to ZH \ \& \ \nu_e\bar{\nu}_e H)$ = 218 fb

$$< \xi_1 \ \xi_2 >$$



$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

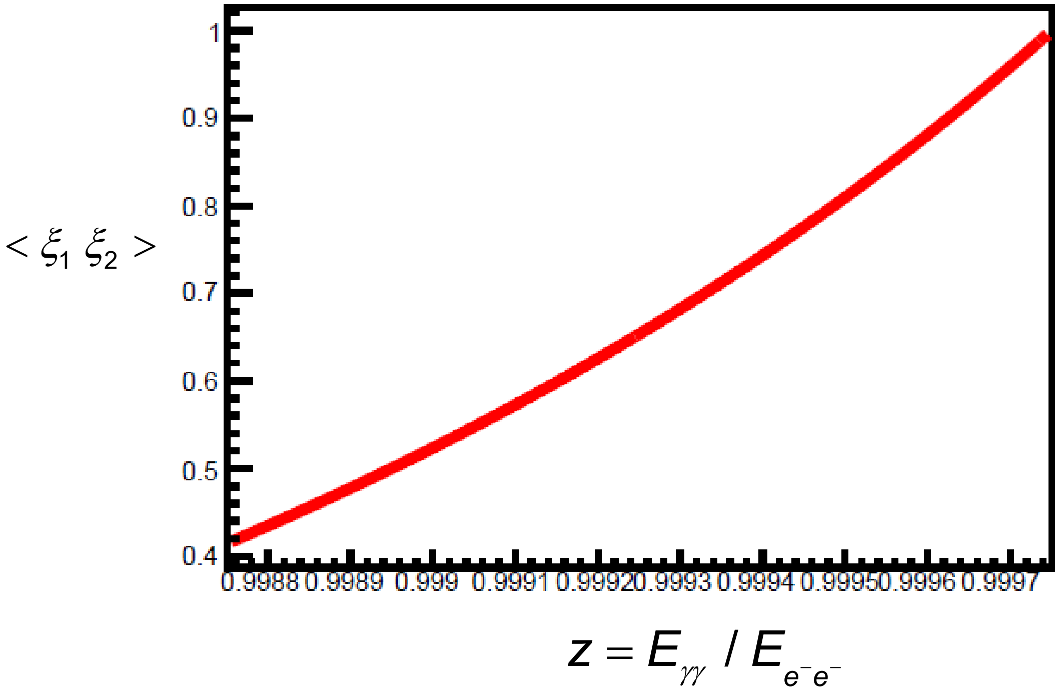
$2P_c\lambda_e = +0.9$ gives broader spectrum in $E_{\gamma\gamma}$
but this is compensated by suppression
of $\gamma\gamma \to e^+e^-$ (κ=0.44 vs 0.11 for opposite
sign of $2P_c\lambda_e$)

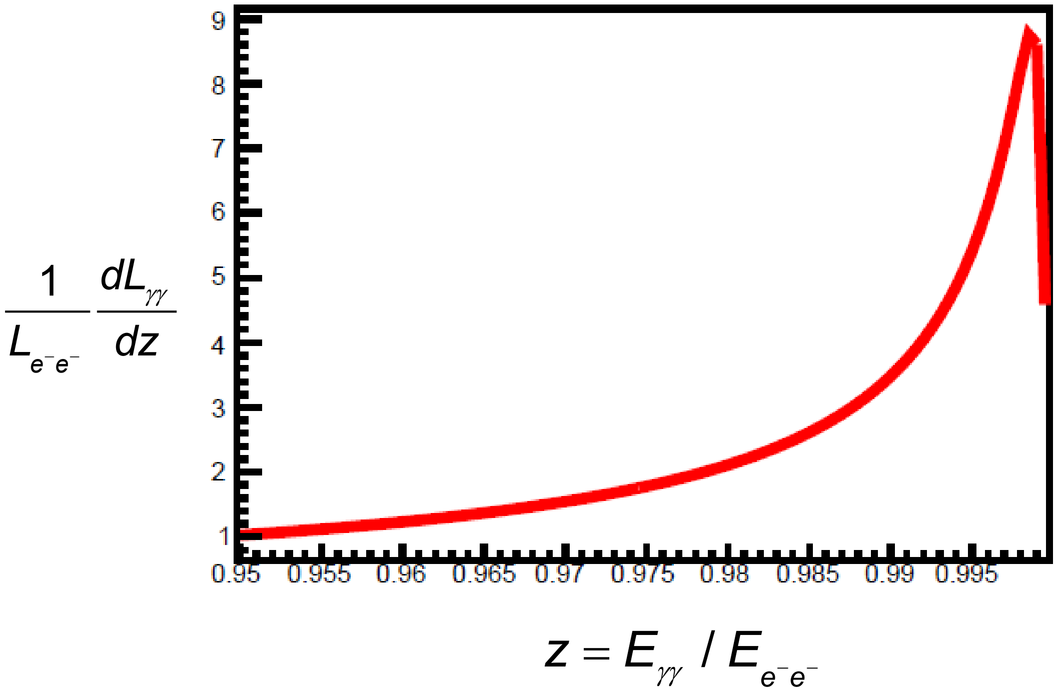


$x = 4000.$ $E_{e^-e^-} = 125.2$ GeV κ=0.12

pol(e^-) = 90% $2P_c\lambda_e = -0.9$ $h\nu = 4.17$ keV

$$\int dz \frac{1}{L_{e^-e^-}} \frac{dL_{\gamma\gamma}}{dz} \sigma(\gamma\gamma \to H) = 1099 \text{ fb}$$

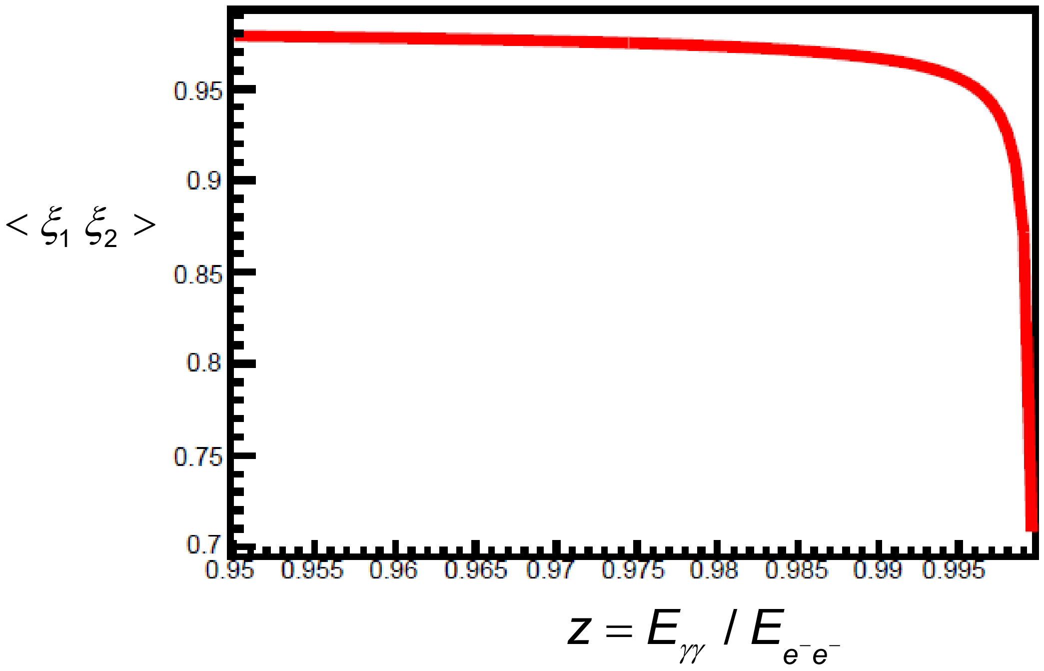


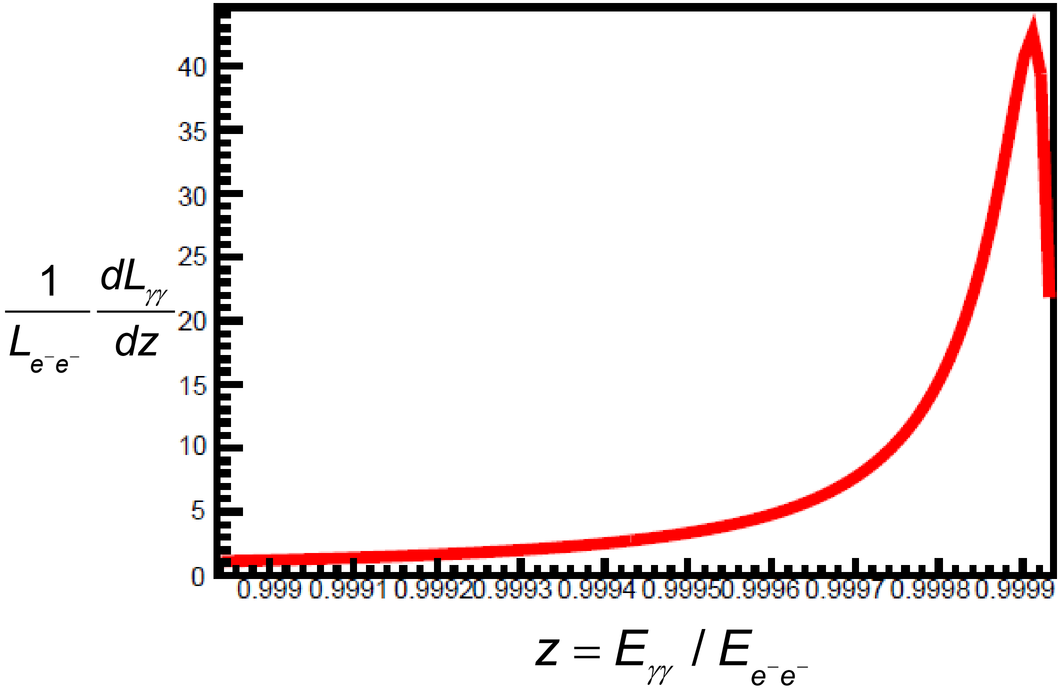


$x = 4000.$ $E_{e^-e^-} = 125.2$ GeV κ=0.53

pol(e^-) = 90% $2P_c\lambda_e = +0.9$ $h\nu = 4.17$ keV

$$\int dz \frac{1}{L_{e^-e^-}} \frac{dL_{\gamma\gamma}}{dz} \sigma(\gamma\gamma \to H) = 1188 \text{ fb}$$

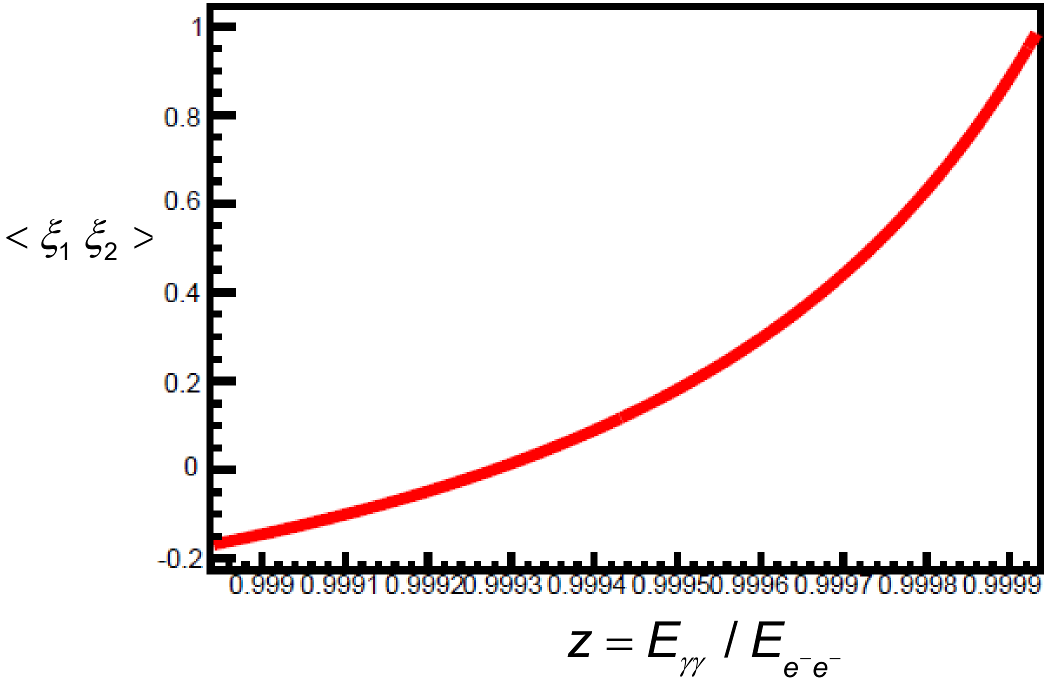


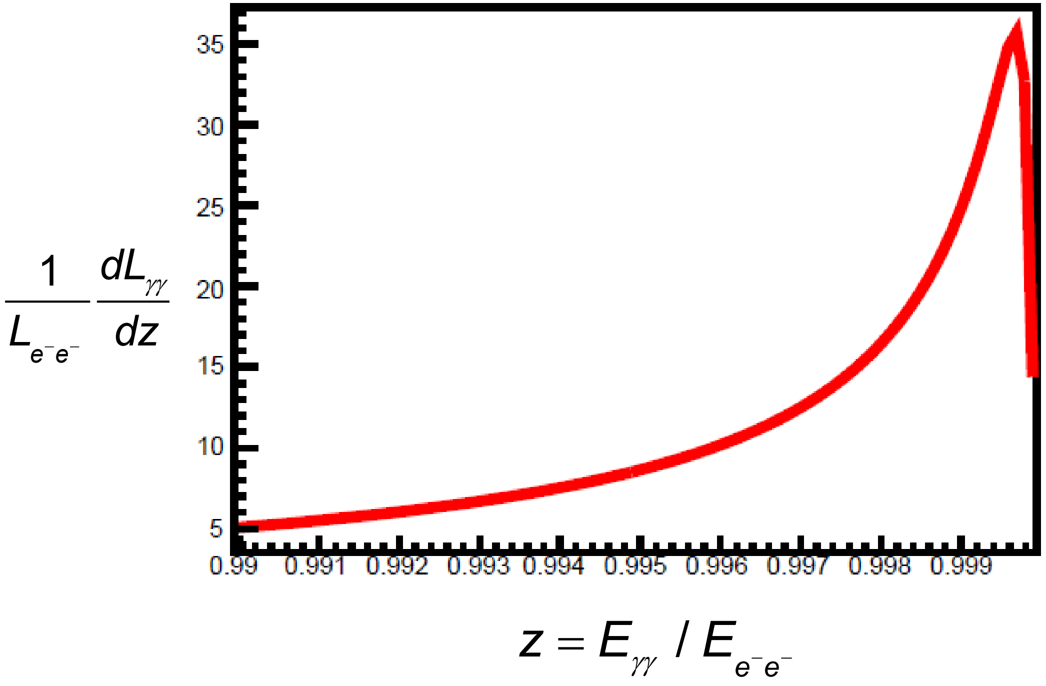


$x = 15870.$ $E_{e^-e^-} = 125$ GeV κ=0.15

pol(e^-) = 90% $2P_c\lambda_e = -0.9$ $h\nu = 16.6$ keV

$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 5614 \text{ fb}$$

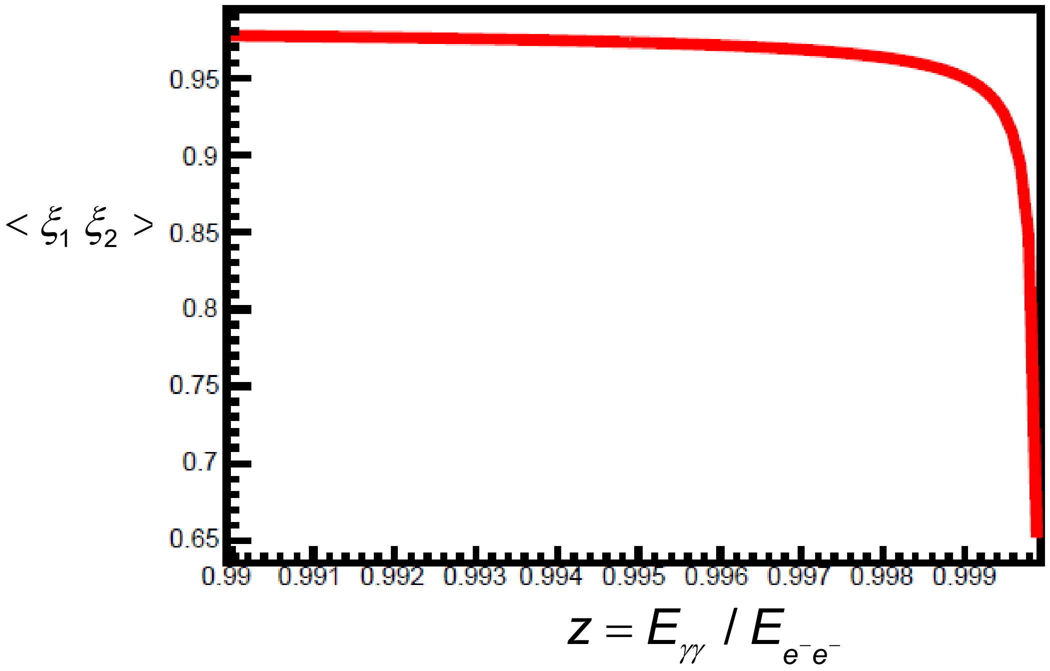




$x = 15870.$ $E_{e^-e^-} = 125$ GeV κ=0.64

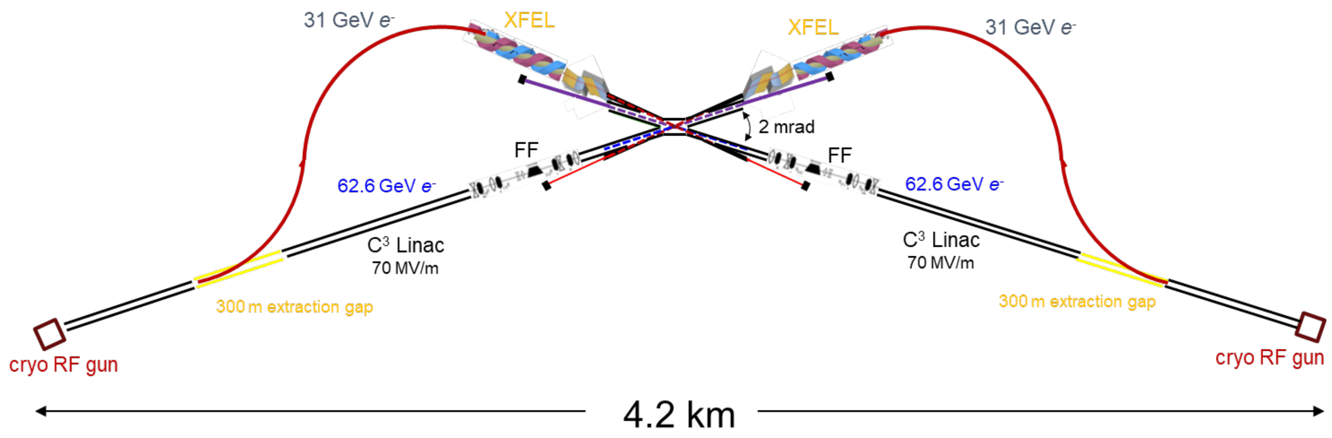
pol(e^-) = 90% $2P_c\lambda_e = +0.9$ $h\nu = 16.6$ keV

$$\int dz \frac{1}{L_{e^-e^-}} \frac{dL_{\gamma\gamma}}{dz} \sigma(\gamma\gamma \to H) = 4792 \text{ fb}$$

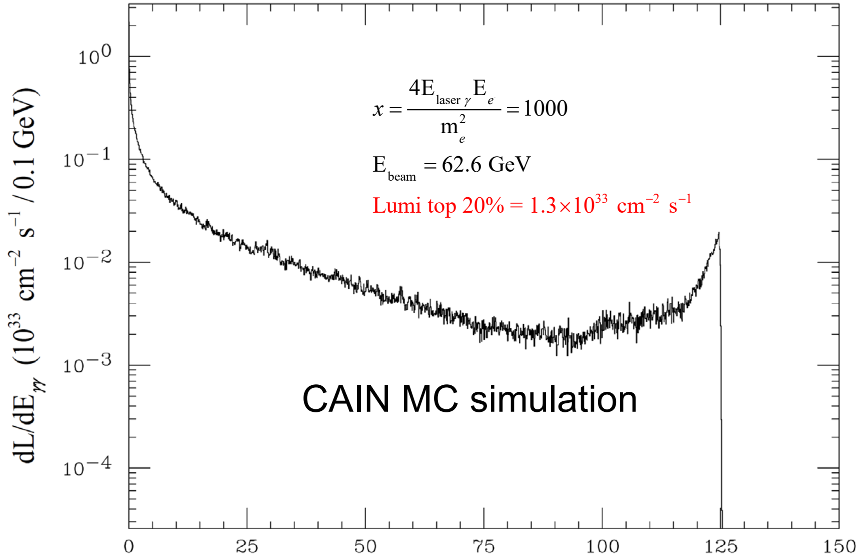


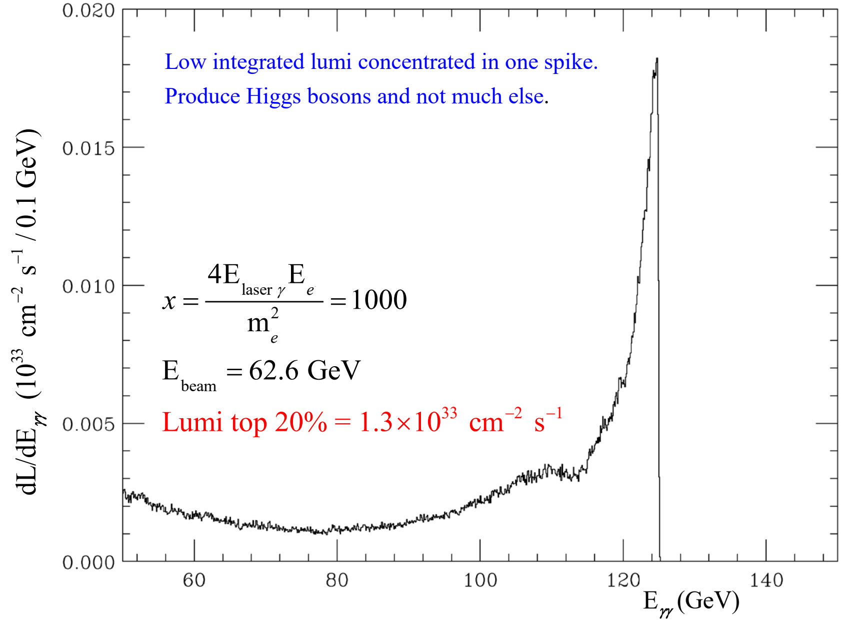
XCC: XFEL Compton $\gamma\gamma$ Collider Higgs Factory

XCC s-channel $\gamma\gamma \rightarrow H$ @ $\sqrt{s} = 125$ 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		





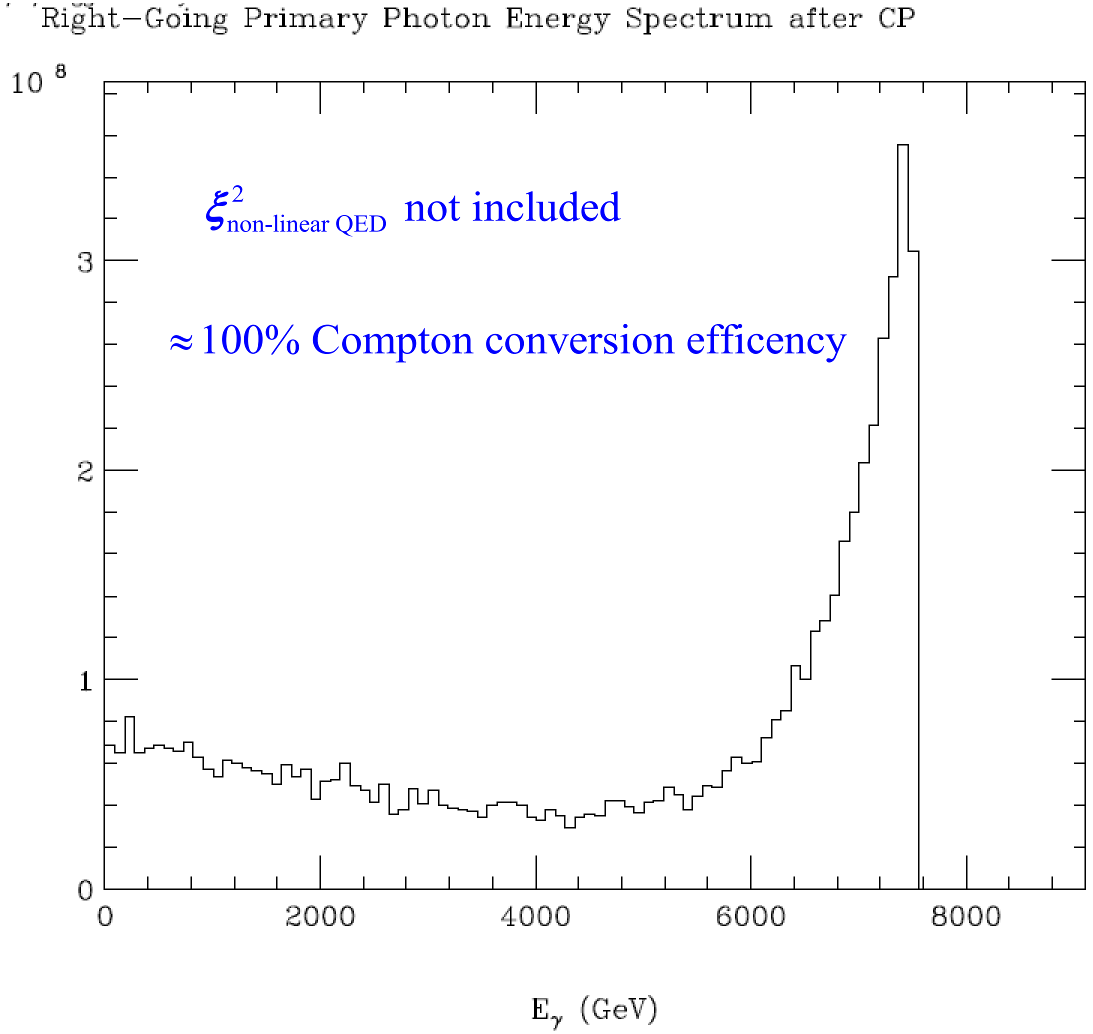
Replace 62.5 GeV C^3 e- beam w/ 7500 GeV PWFA e- beam and simulate γγ Collisions using CAIN MC

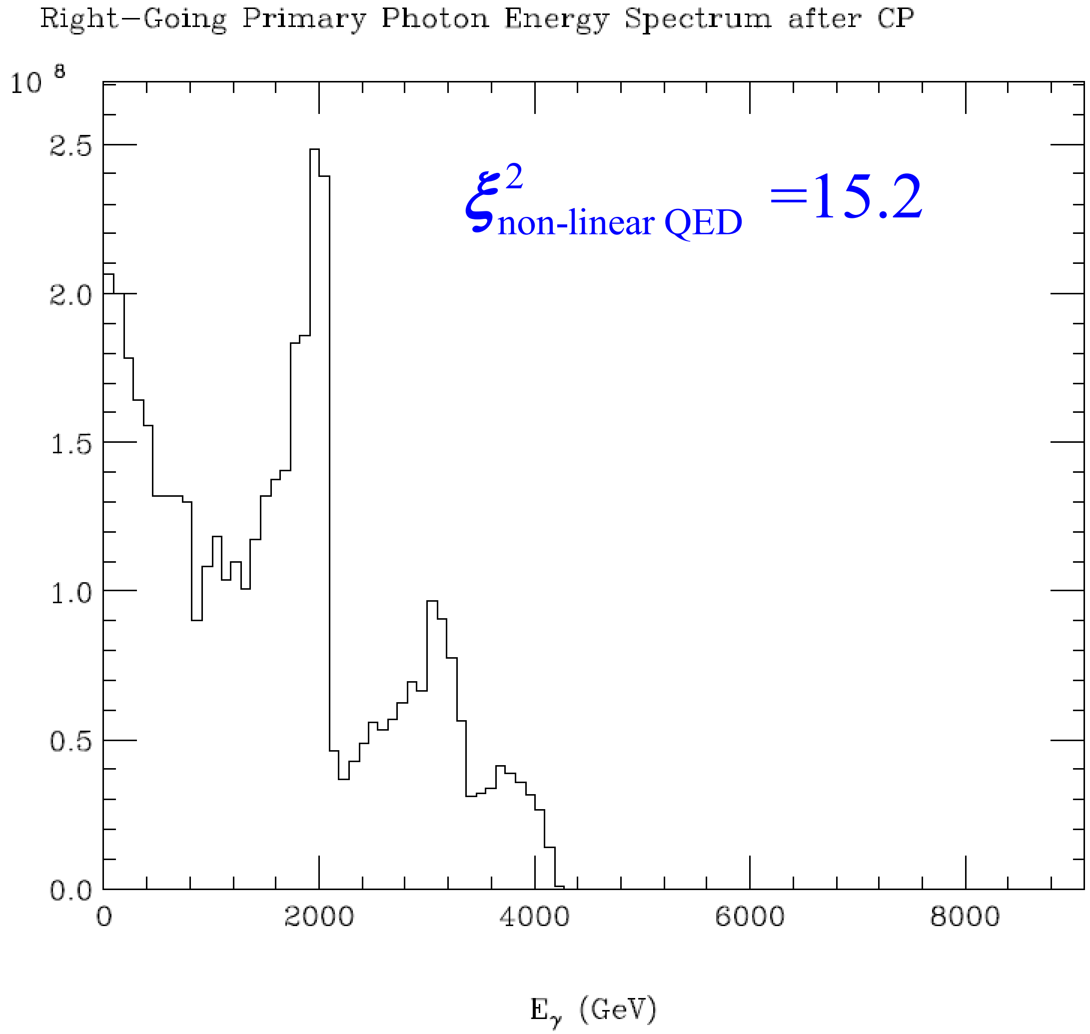
Technology	PWFA	γγ PWFA
Aspect Ratio	Round	Round
CM Energy	15	15
Single beam energy (TeV)	7.5	7.5
Gamma	1.47E+07	1.4E+07
Emittance X (mm mrad)	0.1	0.12
Emittance Y (mm mrad)	0.1	0.12
Beta* X (m)	1.50E-04	0.30E-04
Beta* Y (m)	1.50E-04	0.30E-04
Sigma* X (nm)	1.01	0.48
Sigma* Y (nm)	1.01	0.48
N_bunch (num)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

x=4.8 adjust parameters to get ~ 100 % conversion w/ linear QED

$x = 4.8 \;\Rightarrow\; 9100 \text{ GeV } e^- + 0.034 \text{ eV } \gamma \;\; (\lambda = 36\ \mu\text{m})$ $\quad a_{\gamma FWHM} = 2.1 \text{ mm} \quad \sigma_{\gamma z} = 0.79 \text{ mm} \quad d_{cp} = 2.4 \text{ mm}$

$\sigma_{ez} = 5\ \mu\text{m} \quad N_{e^-} = 1 \text{ nC} \quad \gamma\varepsilon_{x,y} = 120 \text{ nm} \quad 2P_c\lambda_e = -0.9 \quad E_{pulse} = 4400 \text{ J}$

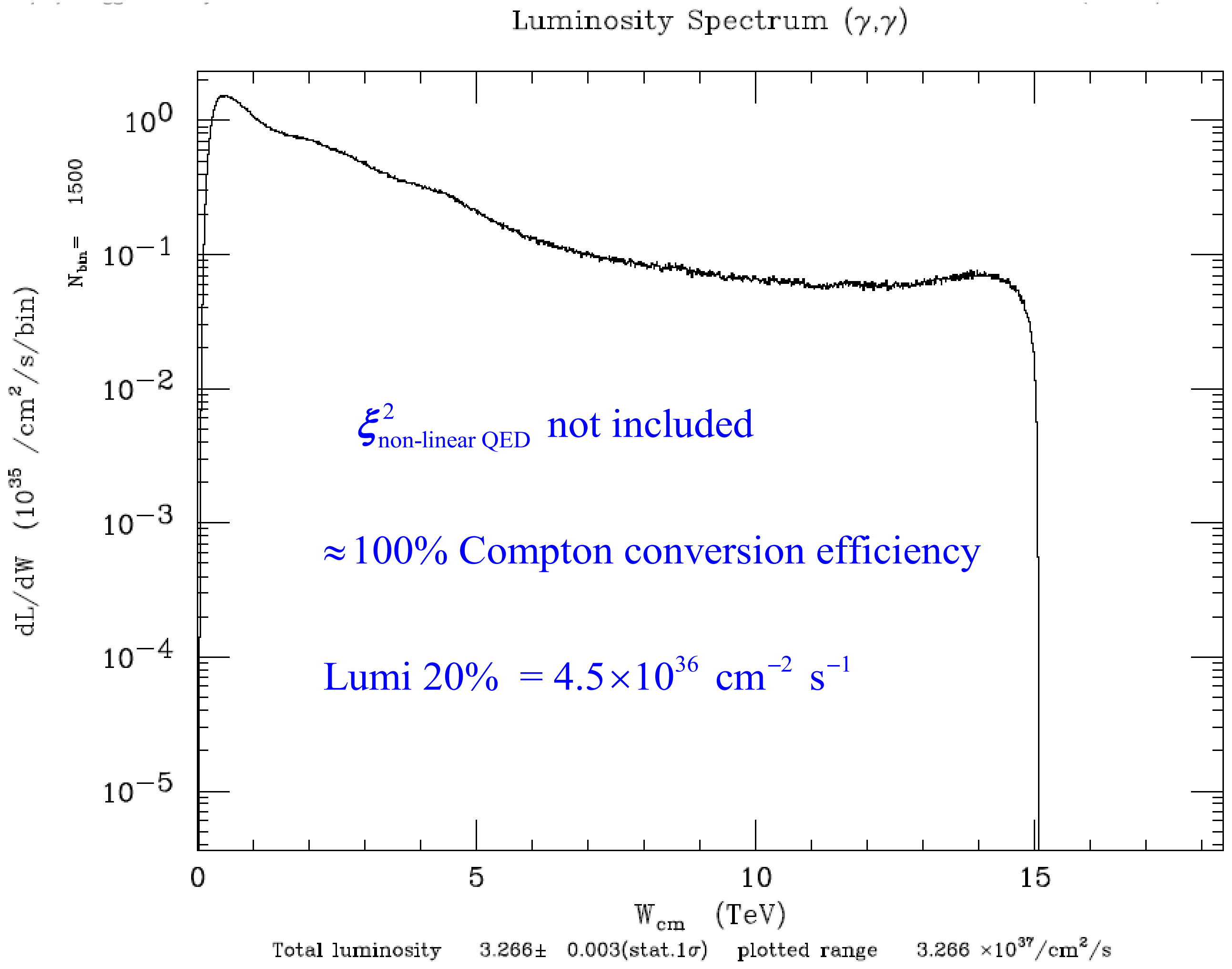




x=4.8 adjust parameters to get ~ 100 % conversion w/ linear QED

$x = 4.8 \Rightarrow$ 9100 GeV $e^- +$ 0.034 eV γ (λ=36 μm) $a_{\gamma FWHM} = 2.1$ mm $\sigma_{\gamma z} = 0.79$ mm $d_{cp} = 2.4$ mm

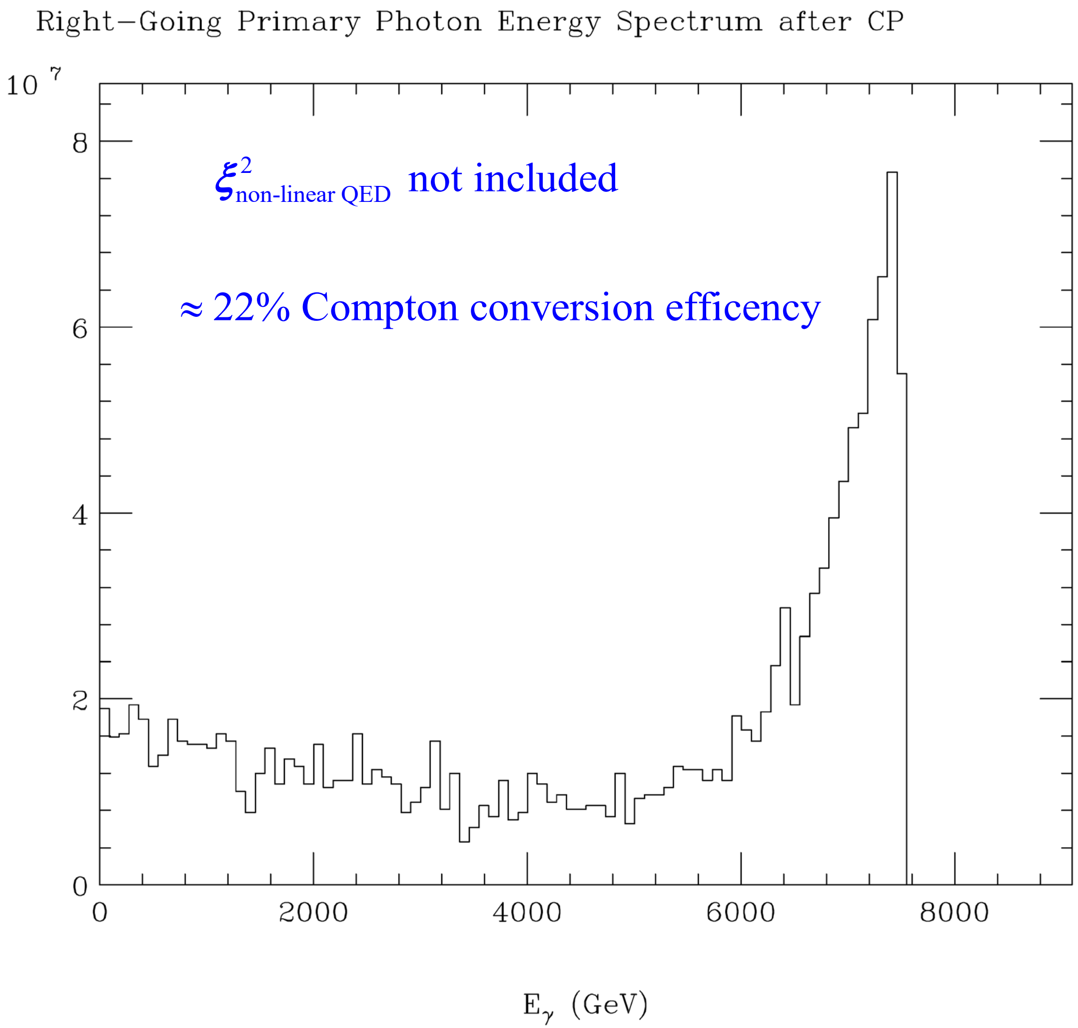
$\sigma_{ez} = 5\ \mu$m $N_{e^-} = 1$ nC $\gamma\varepsilon_{x,y} = 120$ nm $2P_c\lambda_e = -0.9$ $E_{pulse} = 4400$ J

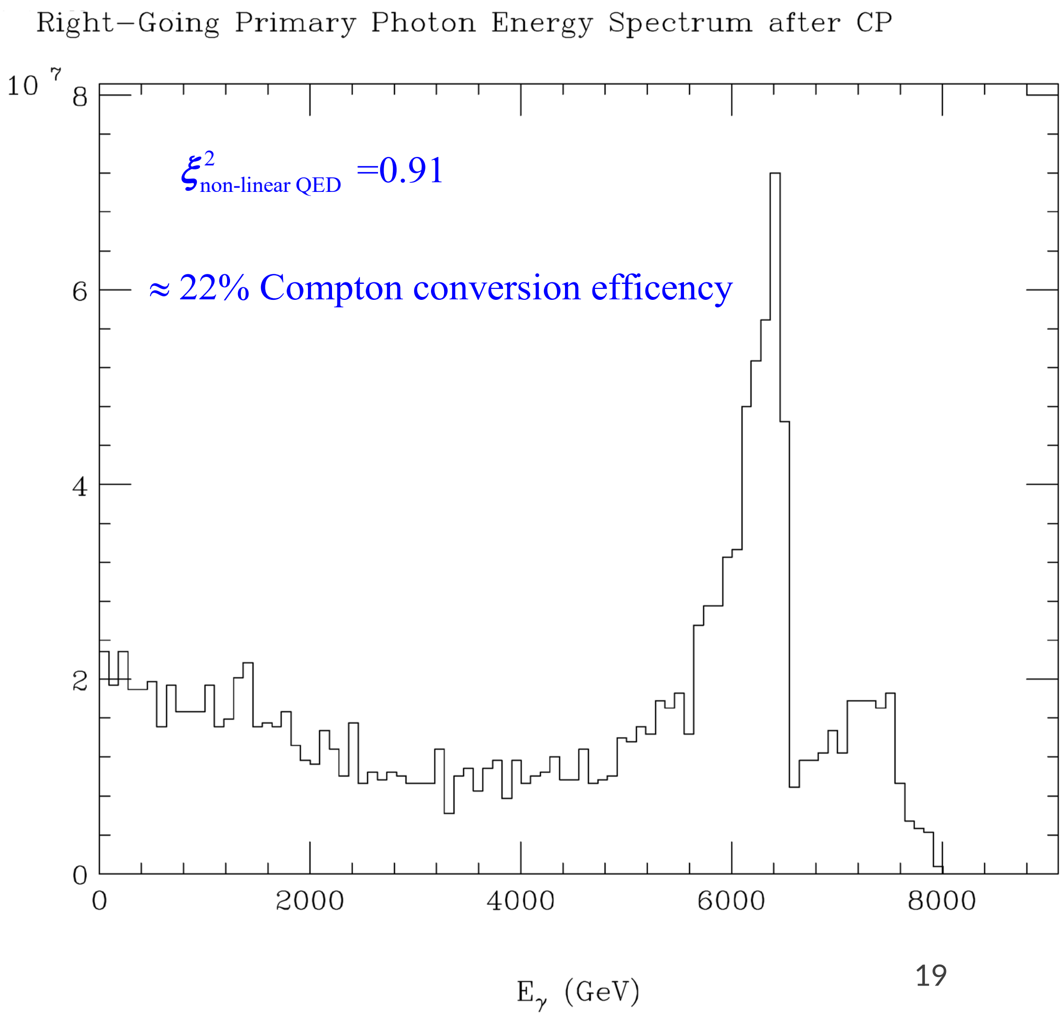


x=4.8 dial back E_{pulse} to get $\xi^2 < 1$

$x = 4.8 \Rightarrow 9100\text{ GeV } e^- + 0.034\text{ eV } \gamma$ (λ=36 μm) $a_{\gamma FWHM} = 2.1$ mm $\sigma_{\gamma z} = 0.79$ mm $d_{cp} = 2.4$ mm

$\sigma_{ez} = 5\ \mu$m $N_{e^-} = 1$ nC $\gamma\varepsilon_{x,y} = 120$ nm $2P_c\lambda_e = -0.9$ $E_{pulse} = 260$ J

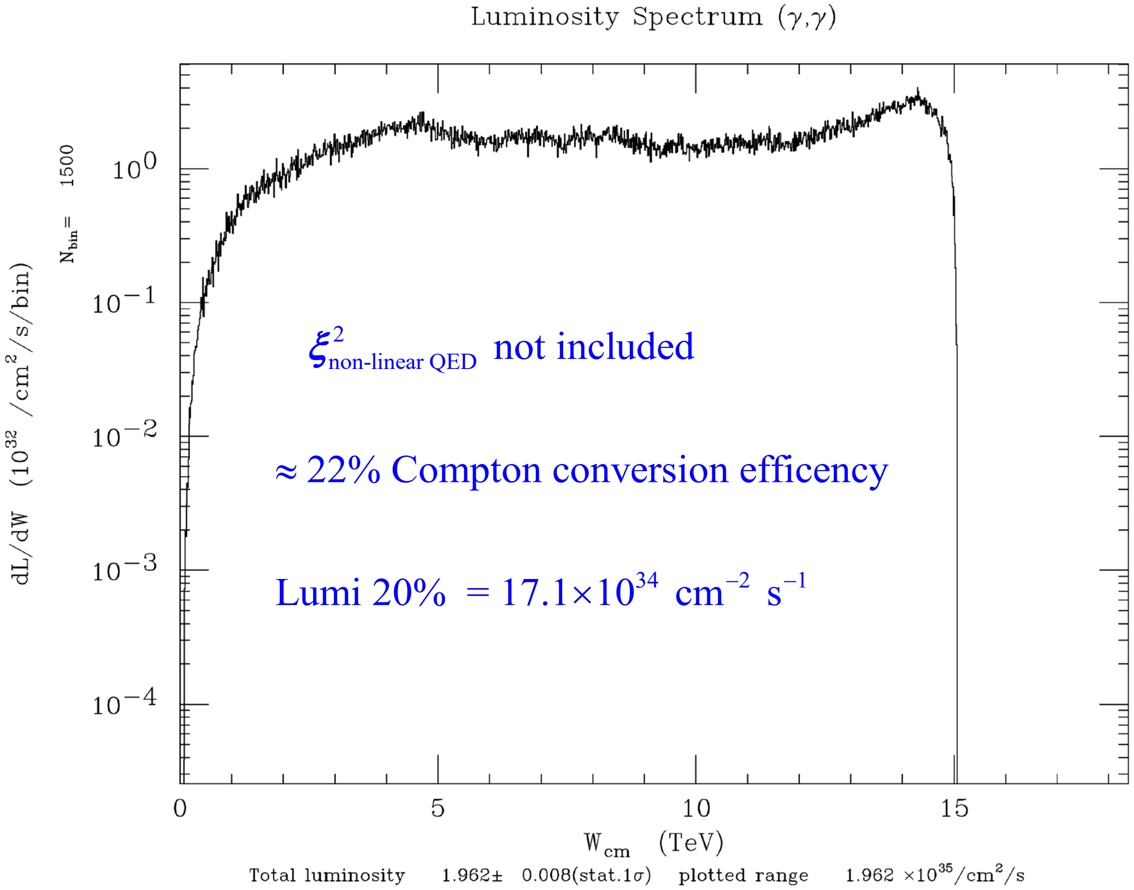


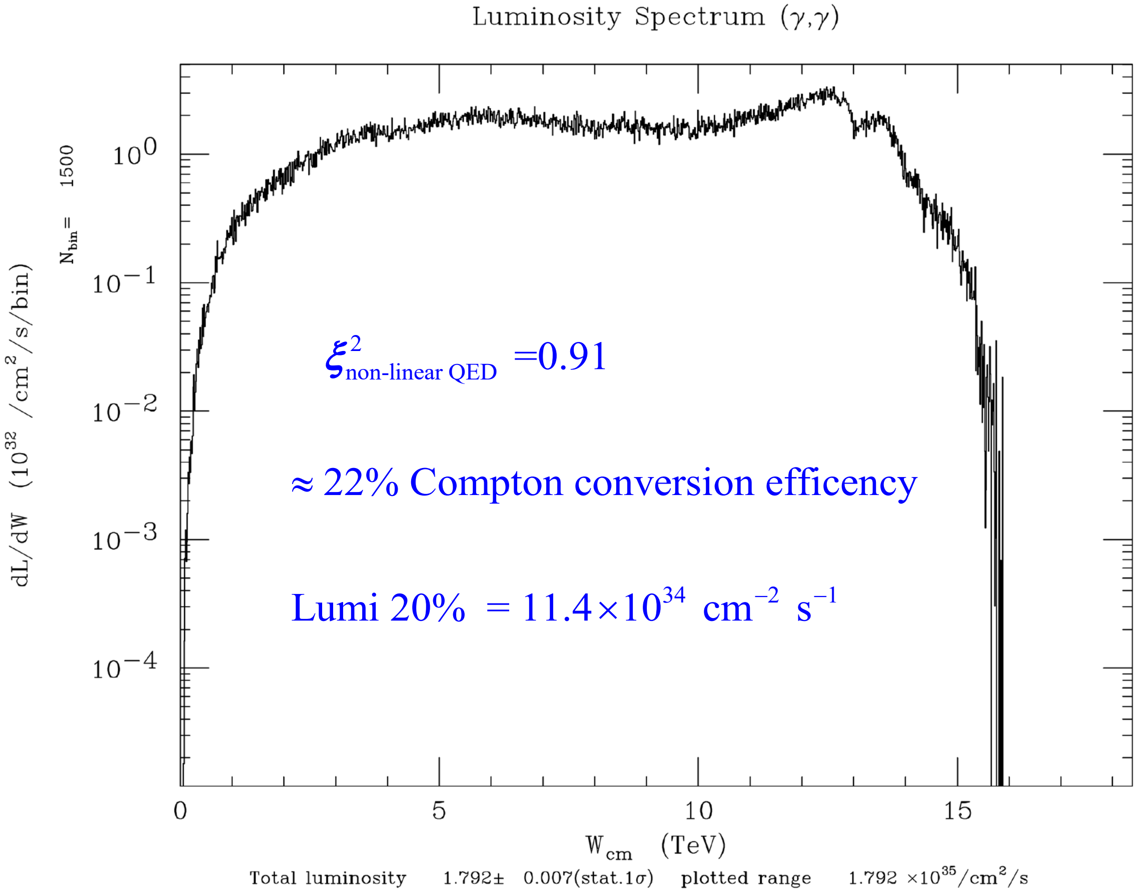


x=4.8 dial back E_{pulse} to get $\xi^2 < 1$

$x = 4.8 \Rightarrow$ 9100 GeV $e^- + 0.034$ eV γ (λ=36 μm) $a_{\gamma FWHM} = 2.1$ mm $\sigma_{\gamma z} = 0.79$ mm $d_{cp} = 2.4$ mm

$\sigma_{ez} = 5\ \mu$m $N_{e^-} = 1$ nC $\gamma\varepsilon_{x,y} = 120$ nm $2P_c\lambda_e = -0.9$ $E_{pulse} = 260$ J

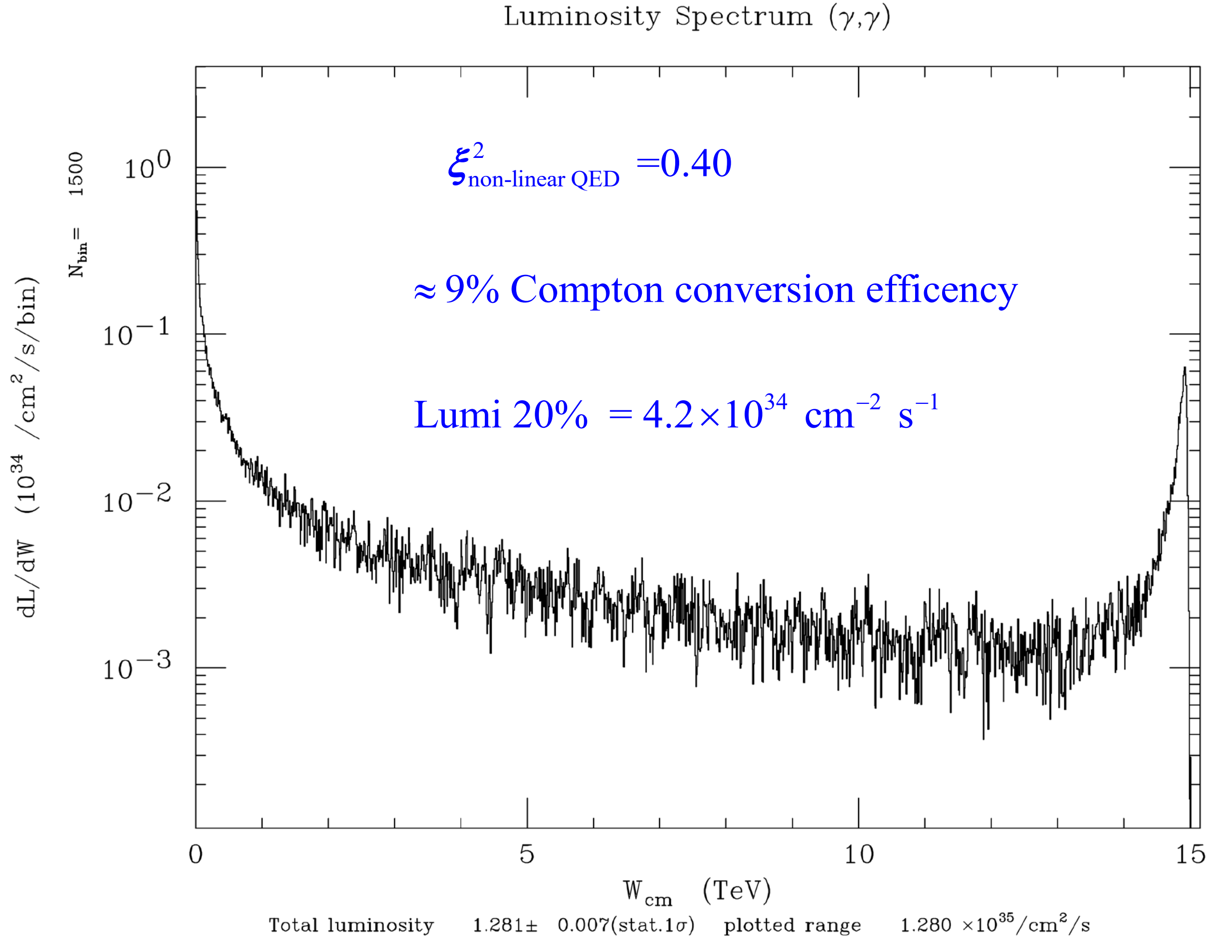




x=1.2 x 10^5 (try 1 keV XCC XFEL laser)

$x = 1.2\times10^5 \Rightarrow$ 7500 GeV $e^- + 1$ keV γ (λ=1.2 nm) $a_{\gamma FWHM} = 70$ mm $\sigma_{\gamma z} = 5\ \mu$m $d_{cp} = 15\ \mu$m

$\sigma_{ez} = 5\ \mu$m $N_{e^-} = 1$ nC $\gamma\varepsilon_{x,y} = 120$ nm $2P_c\lambda_e = +0.9$ $E_{pulse} = 0.72$ J



Abandon this config because

$\gamma\gamma \to N\times e^+e^-$, $e^-\gamma \to e^- + N\times e^+e^-$, $N = 2,3, \ldots$

are not simulated by CAIN. These processes can be ignored for $x \le 1000$, but not for $x = 1.2\times10^5$

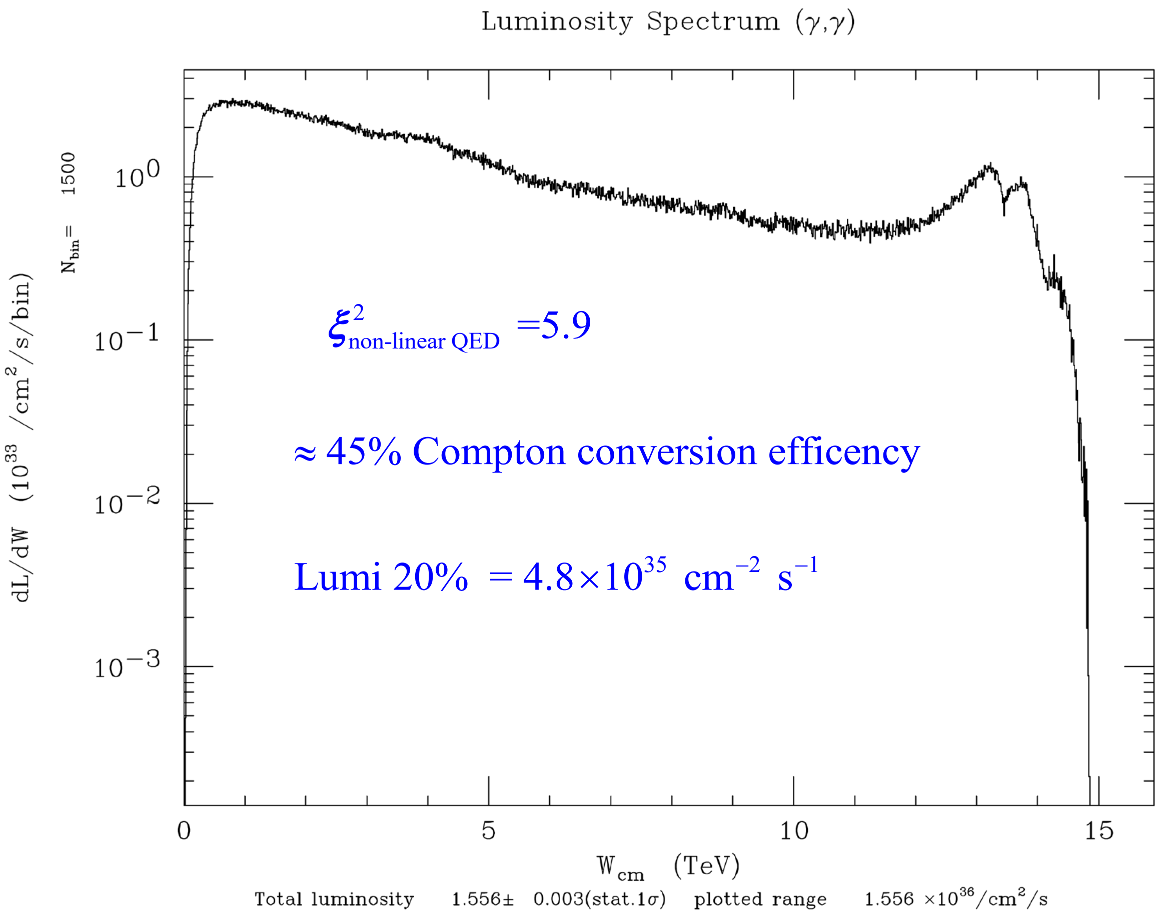
x	$\frac{\sqrt{s_{e^-\gamma}}}{m_e} = \sqrt{x+1}$	$\frac{\sqrt{s_{e^-\gamma}}}{m_e} m_W$ (TeV)
4.82	2.4	0.2
1000	32	2.5
1.2×10^5	350	28

Ignoring these processes would be the equivalent of ignoring multiple 4,5,... W boson production in e^+e^- or $\gamma\gamma$ collisions. This is OK at 0.2 TeV & 2.5 TeV due to phase space suppression, but not OK at 28 TeV.

x=40

$\boldsymbol{x} = 40 \;\Rightarrow\; 7875\ \text{GeV}\ \boldsymbol{e}^- + 0.33\ \text{eV}\ \boldsymbol{\gamma}\quad (\boldsymbol{\lambda}=3.7\ \boldsymbol{\mu}\text{m}) \quad \boldsymbol{a}_{\gamma FWHM} = 0.24\ \text{mm} \quad \boldsymbol{\sigma}_{\gamma z} = 270\ \boldsymbol{\mu}\text{m} \quad \text{d}_{\text{cp}} = 0.82\text{mm}$

$\boldsymbol{\sigma}_{e z} = 5\ \boldsymbol{\mu}\text{m} \quad \text{N}_{e^-} = 1\ \text{nC} \quad \gamma\varepsilon_{x,y} = 120\ \text{nm} \quad 2\boldsymbol{P}_c\boldsymbol{\lambda}_e = -0.9 \quad \text{E}_{\text{pulse}} = 590\ \text{J}$



$\xi^2_{\text{non-linear QED}} = 5.9$

$\approx$ 45% Compton conversion efficency

Lumi 20% $= 4.8\times10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$

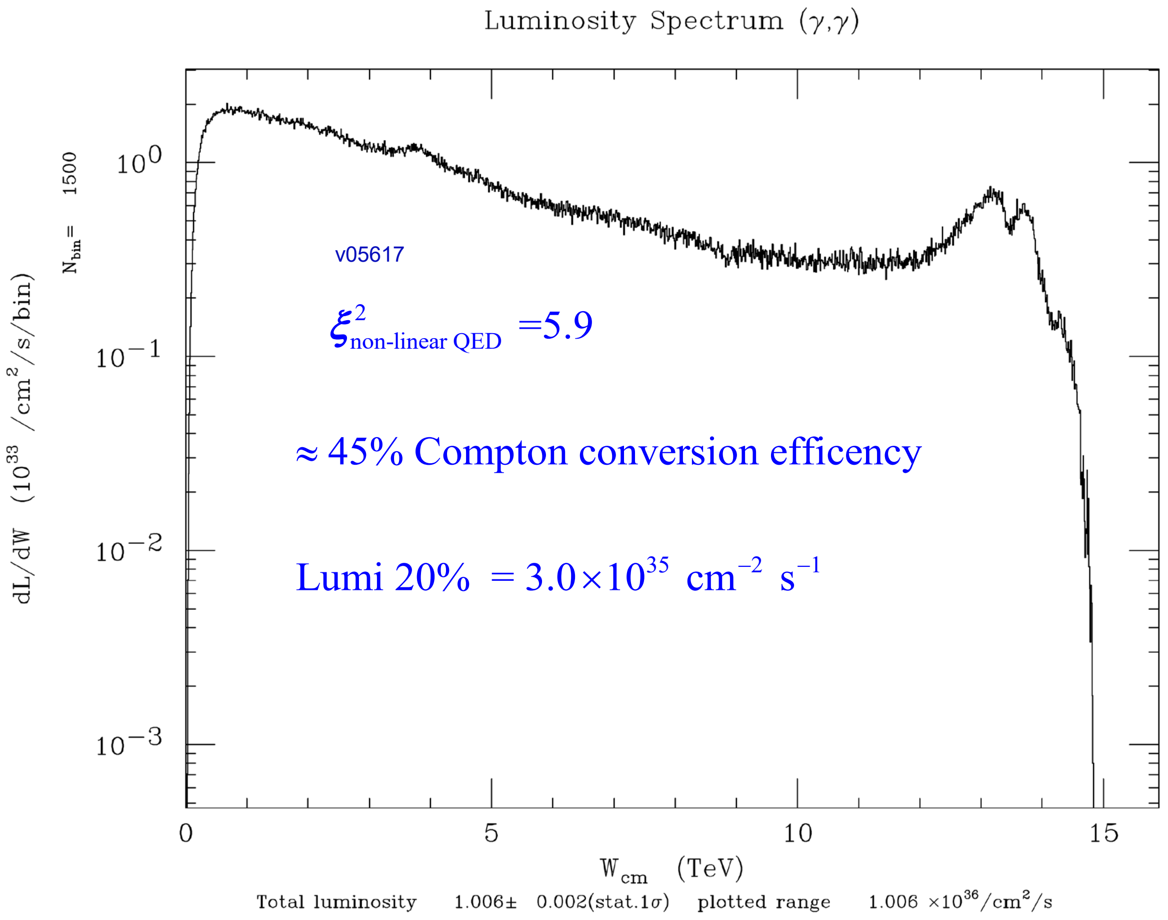
In contrast to the $\text{E}_{\text{beam}} = 63$ GeV, $\boldsymbol{x} = 1000$ XCC, there is an incompatiblity between the longer laser wavelengths required for $\text{E}_{\text{beam}} = 7500$, $\boldsymbol{x} = 1000$ and the short distance that must be maintained between the Compton IP and the $\boldsymbol{\gamma\gamma}$ IP at $\boldsymbol{x} = 1000$ ($< 100\ \boldsymbol{\mu}$m). This is due to the angular divergence of the Compton scattered photon, which grows as $\sqrt{\boldsymbol{x}+1}$.

Hence, we try instead moderate $\boldsymbol{x}$ values such as $\boldsymbol{x} = 40$.

x=40 use spreadsheet bunch charge of N_e=5x10^9

$x = 40 \Rightarrow$ 7875 GeV $e^- +$ 0.33 eV γ (λ=3.7 μm) $a_{\gamma FWHM} = 0.24$ mm $\sigma_{\gamma z} = 270\ \mu$m $d_{cp} = 0.82$mm

$\sigma_{ez} = 5\ \mu$m $N_{e^-} = 5\times10^9$ $\gamma\varepsilon_{x,y} = 120$ nm $2P_c\lambda_e = -0.9$ $E_{pulse} = 590$ J



x=40 Now turn on coherent processes

$\boldsymbol{x} = 40 \quad \Rightarrow \quad 7875 \text{ GeV } \boldsymbol{e}^- + 0.33 \text{ eV } \boldsymbol{\gamma} \quad (\lambda{=}3.7\ \mu\text{m}) \quad \boldsymbol{a}_{\gamma FWHM} = 0.24 \text{ mm} \quad \boldsymbol{\sigma}_{\gamma z} = 270\ \mu\text{m} \quad \text{d}_{\text{cp}} = 0.82\text{mm}$

$\boldsymbol{\sigma}_{ez} = 5\ \mu\text{m} \quad \text{N}_{e^-} = 5 \times 10^9 \quad \gamma\varepsilon_{x,y} = 120 \text{ nm} \quad 2\boldsymbol{P}_c\boldsymbol{\lambda}_e = -0.9 \quad \text{E}_{\text{pulse}} = 590 \text{ J}$

Halfway through the collision CAIN complains:

(SUBR.COHPAR) Algorithm of coherent pair generation wrong.
Call the programmer prob,pmaxco= 8.309E-01 8.000E-01

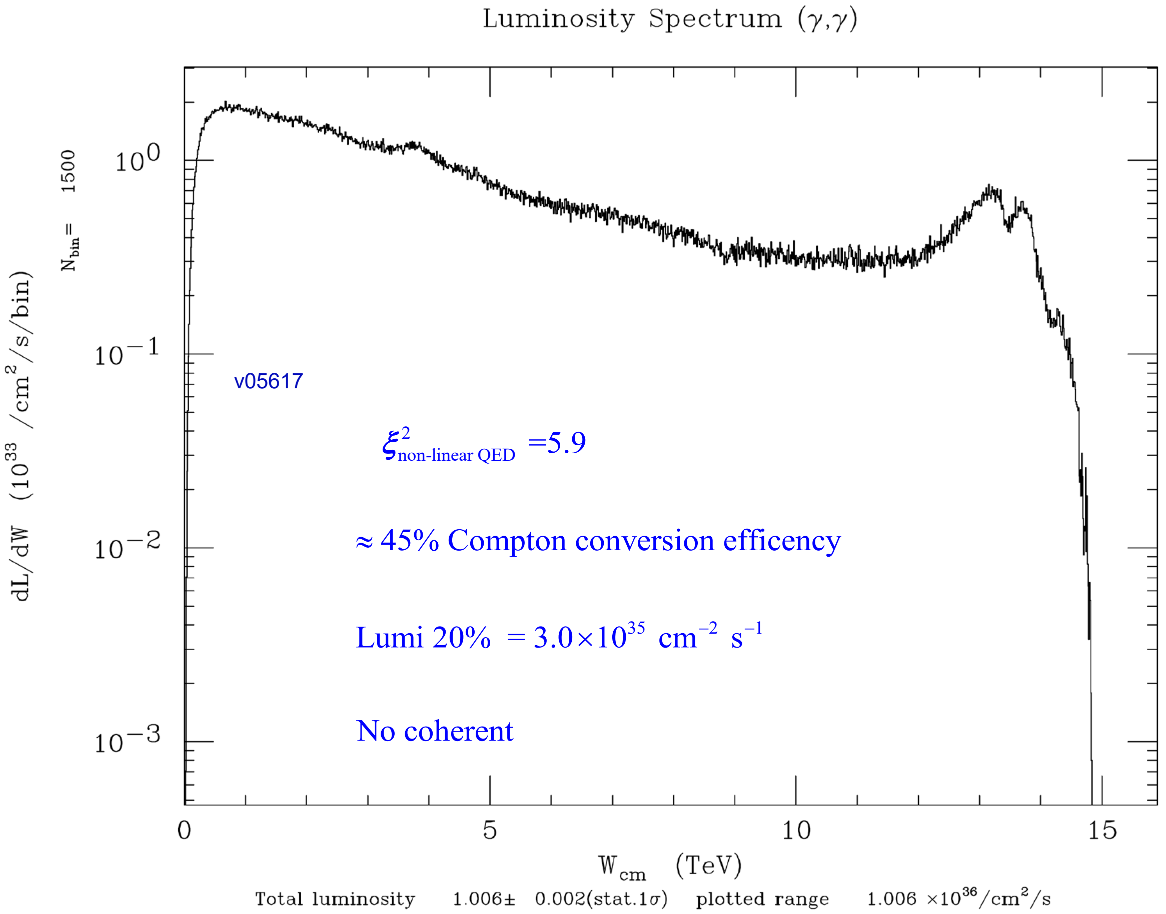
Solution:

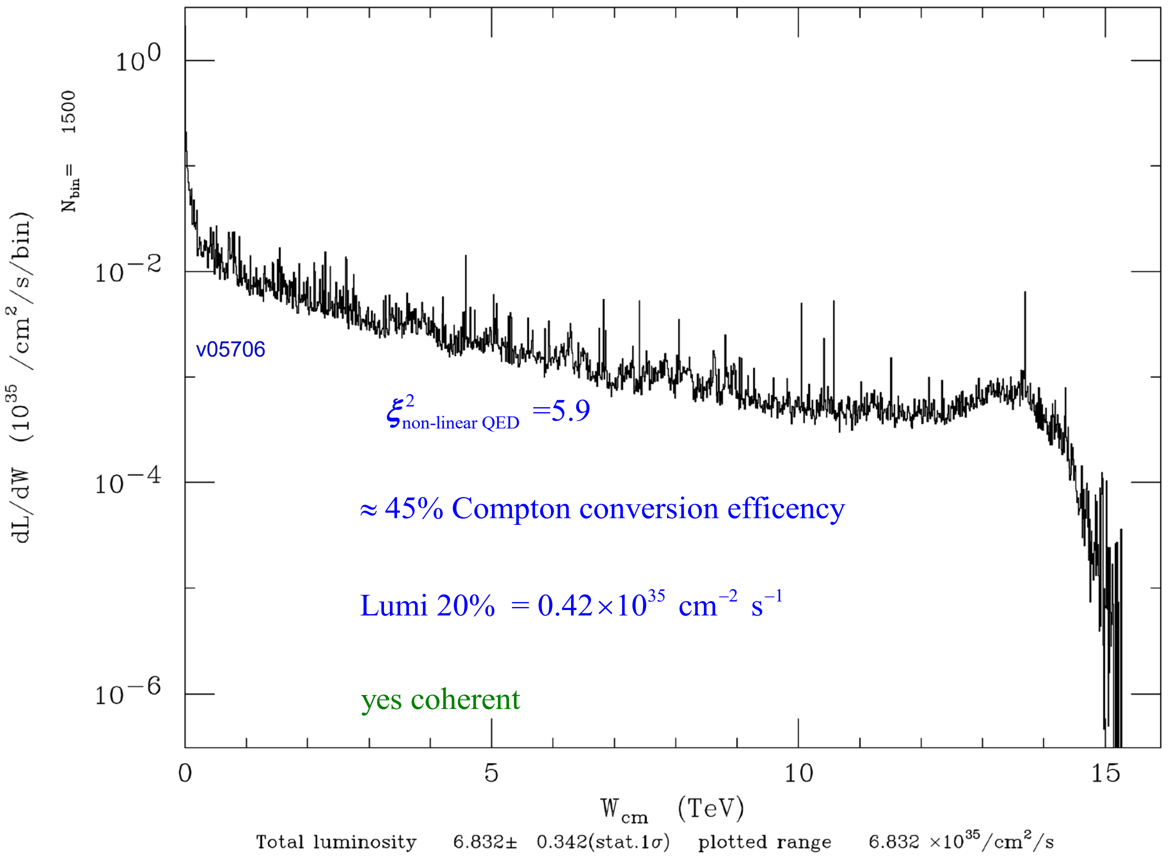
number of macro particles produced per coherent beamstrahlung photon = 1 → 0.01
number of pairs of macro particles produced per coherent e+e- pair = 1 → 0.0001
number of macro particles produced per incoherent particle = 1 → 0.01

x=40 Now turn on coherent processes

$x = 40 \Rightarrow 7875\text{ GeV } e^- + 0.33\text{ eV } \gamma \quad (\lambda=3.7\ \mu\text{m}) \quad a_{\gamma FWHM} = 0.24\text{ mm} \quad \sigma_{\gamma z} = 270\ \mu\text{m} \quad d_{cp} = 0.82\text{mm}$

$\sigma_{ez} = 5\ \mu\text{m} \quad N_{e^-} = 5\times10^9 \quad \gamma\varepsilon_{x,y} = 120\text{ nm} \quad 2P_c\lambda_e = -0.9 \quad E_{pulse} = 590\text{ J}$





Coherent pair production eats up the 7.5 TeV photons and produces many e+ that pinch the e- beam leading to higher fields and even more coherent pair production.

γγ Collider Ecm=15 TeV

κ=Compton Conv Eff. = 44% for all configs   Freq = 7725 Hz

config	σ_x (nm)	σ_y (nm)	$\frac{\sigma_y}{\sigma_x}$	coherent	L_{ee}^{geo} $(10^{34}$ cm^{-2} s$^{-1})$	$\kappa^2 L_{ee}^{geo}$ $(10^{34}$ cm^{-2} s$^{-1})$	$L_{\gamma\gamma}^{total}$ $(10^{34}$ cm^{-2} s$^{-1})$	$L_{\gamma\gamma}^{top\ 20\%}$ $(10^{34}$ cm^{-2} s$^{-1})$
v05617	0.483	0.483	1.00	N	657.9	127.5	301.8	29.9
v05706	0.483	0.483	1.00	Y	657.9	127.5	204.9	4.05
v05831	1.53	0.153	10.0	Y	657.9	127.5	107.4	4.32
v05832	4.83	0.153	31.6	Y	207.9	40.2	102.6	4.62
v05833	6.84	0.153	44.7	Y	147.0	28.5	102.3	3.69
v05834	8.37	0.153	54.7	Y	120.0	23.1	38.4	2.22
v05835	9.67	0.153	63.2	Y	104.1	20.1	52.8	2.22
v05836	10.8	0.153	70.6	Y	124.0	18	14.1	0.81
v05837	11.8	0.153	77.1	Y	84.9	16.5	47.4	2.19
v05838	12.8	0.153	83.7	Y	78.6	15.3	40.2	2.10

Bit surprised we didn't get better results with asymmetric beams

Summary

- Not surprisingly, it is not straightforward to extrapolate a Compton $\sqrt{s} = 125$ GeV $\gamma\gamma$ collider to 15 TeV
- The high EM fields produced by the tightly focused e^- beams lead to significant coherent beamstrahlung and e^+e^- pair-production. This is excaberated by the produced e^+ which pinch the e^- beams leading to even higher EM fields. These effects serve to wipe out the $\gamma\gamma$ luminosity in the top 20% of the $\sqrt{\hat{s}}$ distribution.
- First attempts at exploration of parameter space have not produced a satisfactory configuration at $\sqrt{s} = 15$ TeV
- Next steps include:
    - Back off $\beta^* = 0.03$ mm $\rightarrow$ 0.15 mm
    - Pay attention to same sign electron - photon helicity: same (opposite) sign decreases (increases) $\gamma\gamma \rightarrow e^+e^-$
    - Revisit x values $10^2 < x < 10^5$; at what value of x do the processes

      $\gamma\gamma \rightarrow N \times e^+e^-$, $e^-\gamma \rightarrow e^- + N \times e^+e^-$, $N = 2, 3, \ldots$ become relevant?