$\gamma\gamma$ Collider Simulations with CAIN

15 TeV Beam-Beam Meeting

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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

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

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

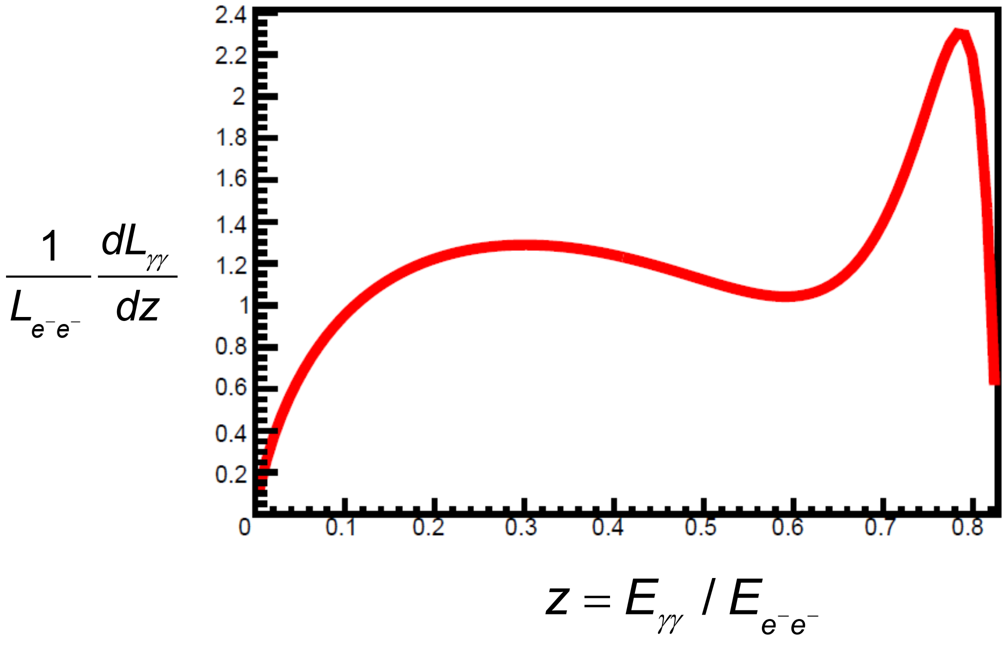
$\xi_i =$ mean helicity of the high energy photon beam i, i=1,2 $|\xi_i| \le 1$

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).

Nominal configuration

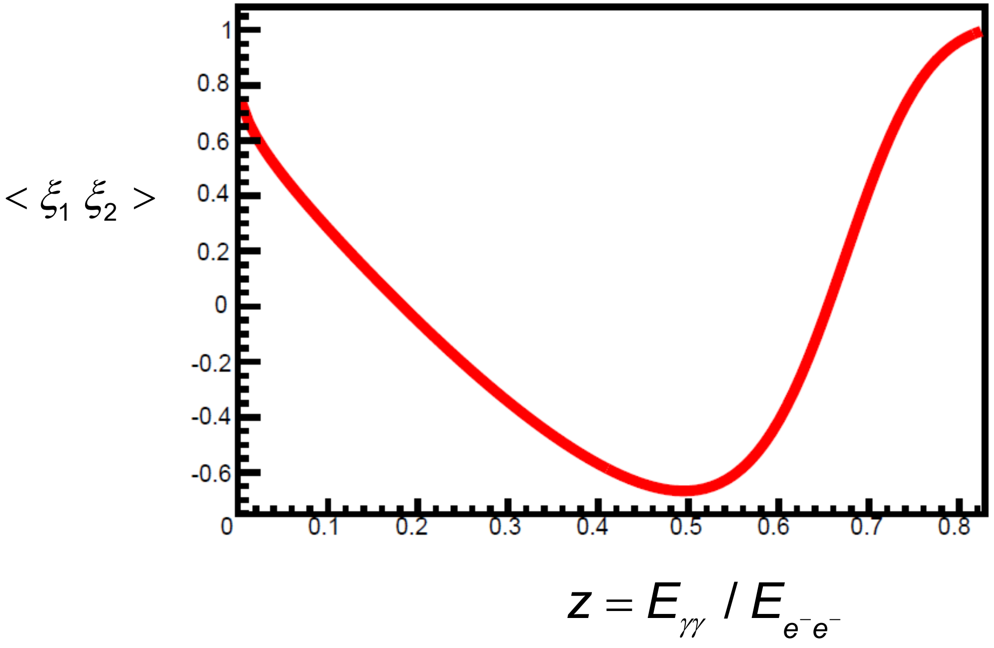


$x = 4.82 \qquad E_{e^-e^-} = 158$ GeV $\qquad \kappa=1$

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

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

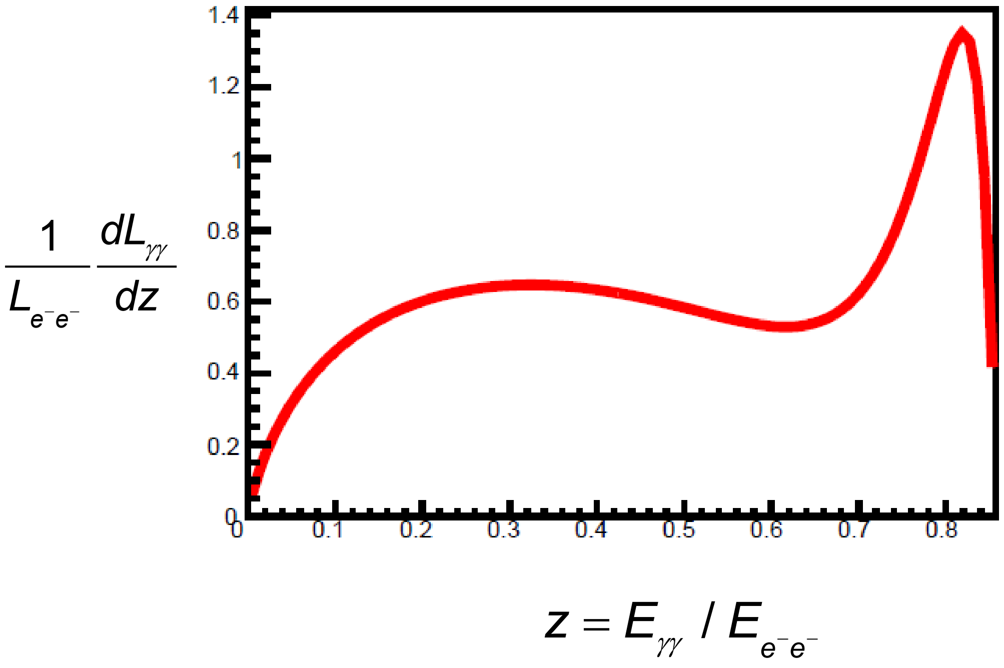
$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 247 \text{ fb}$$



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

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

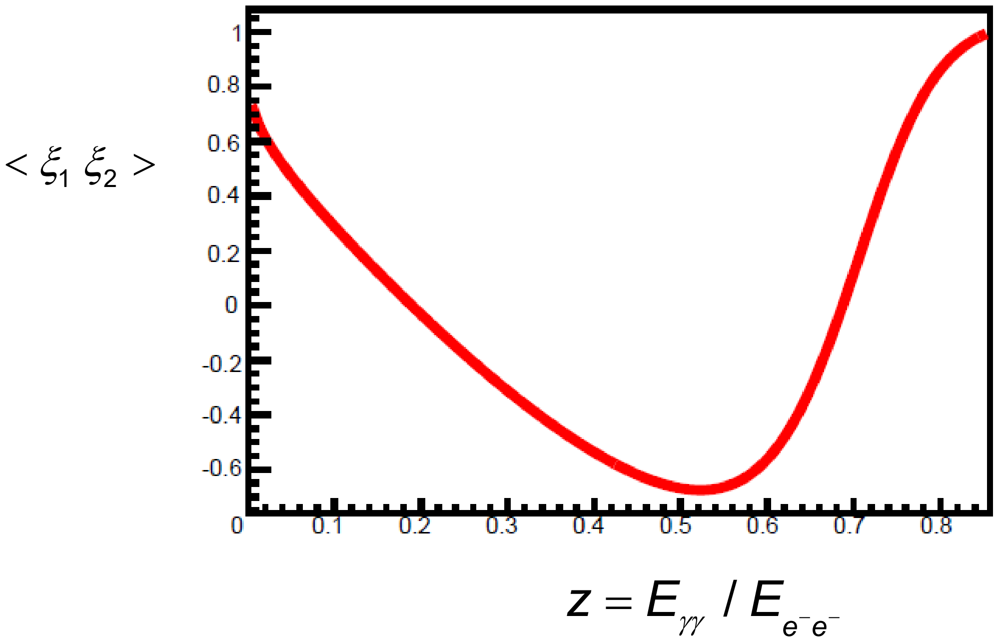
Now let's start increasing x (the energy of the Compton photon)

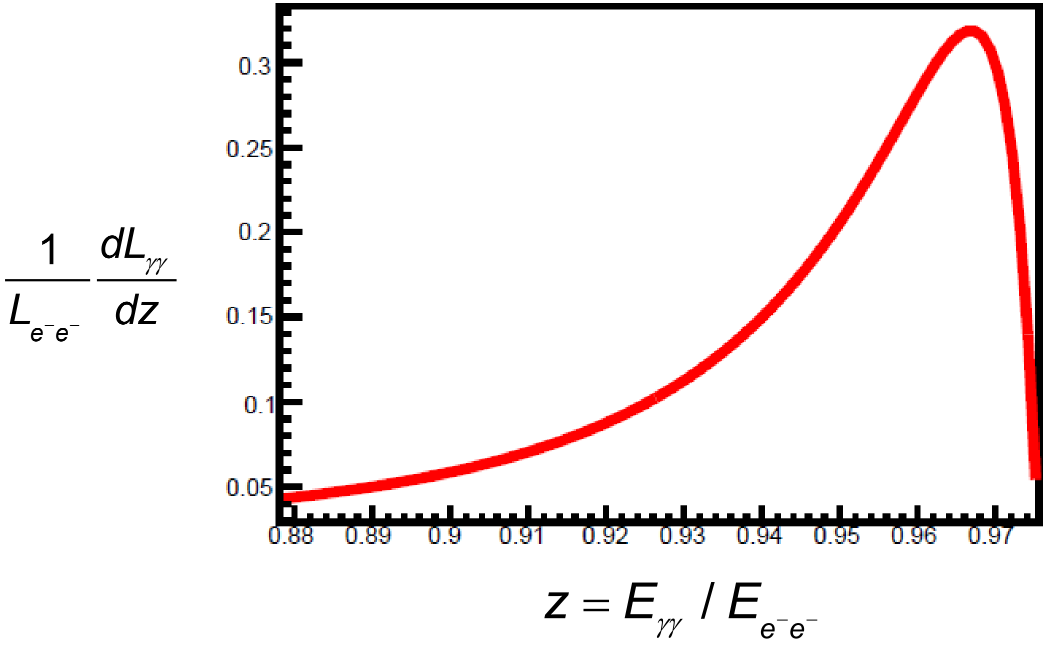


$x = 6.00$ $E_{e^-e^-} = 150$ GeV κ=0.73

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

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

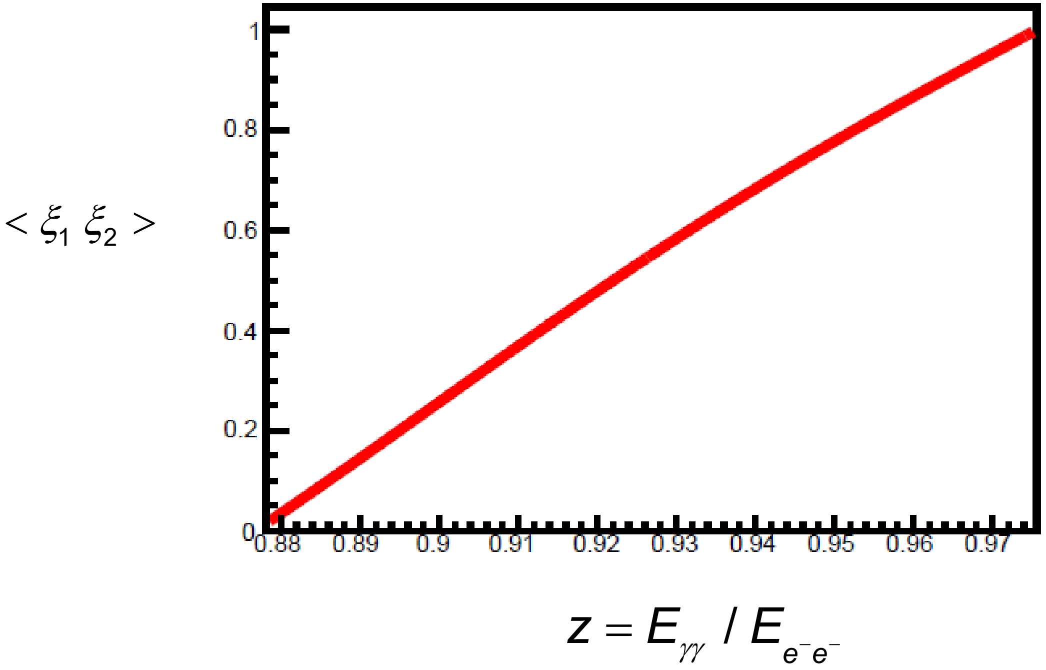


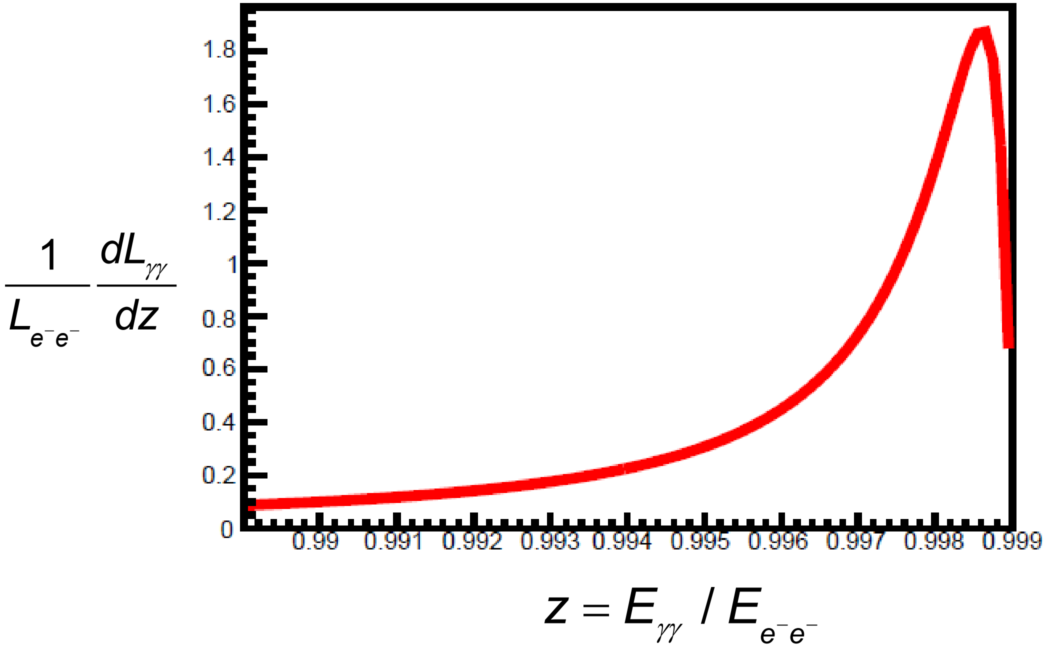


$x = 40.00$ $E_{e^-e^-} = 130.3$ GeV $\kappa = 0.19$

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

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

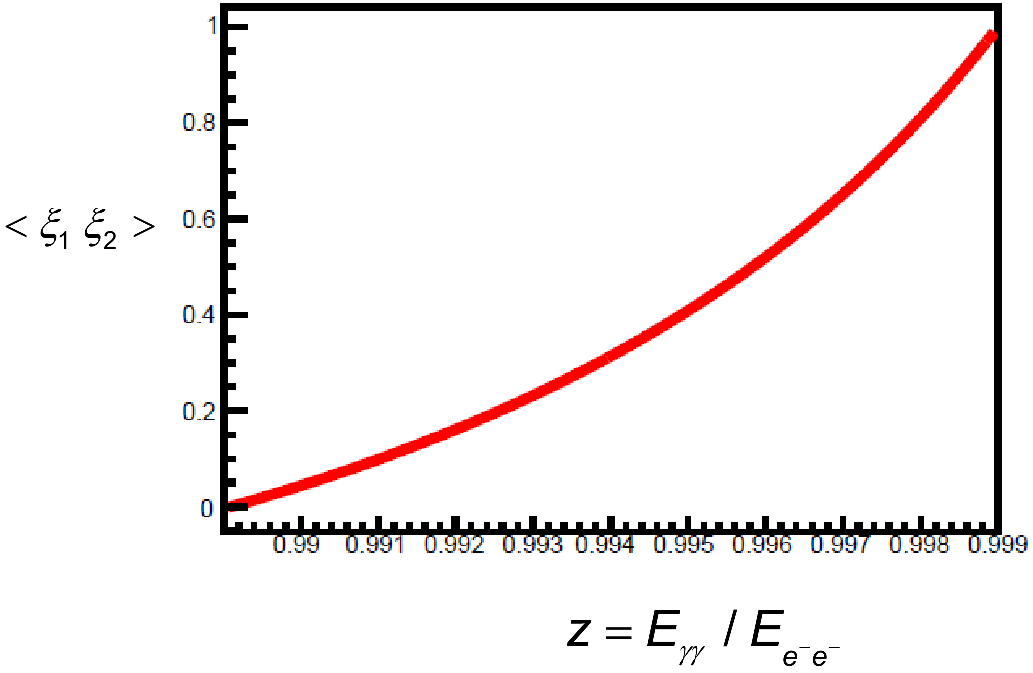


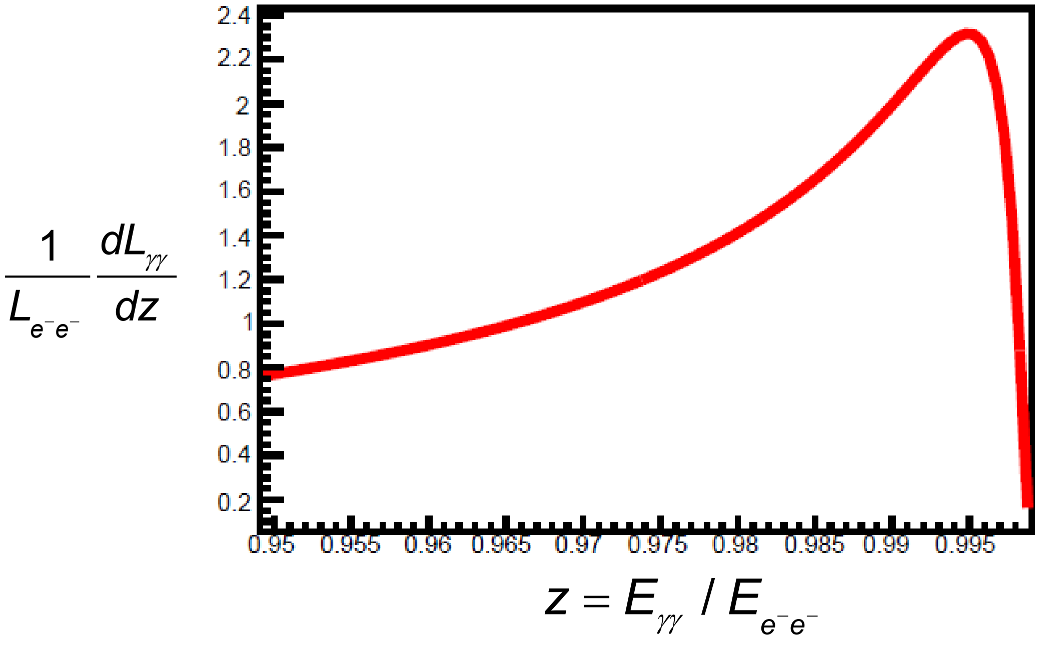


$x = 1000.$ $E_{e^-e^-} = 125.2$ GeV κ=0.11

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

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





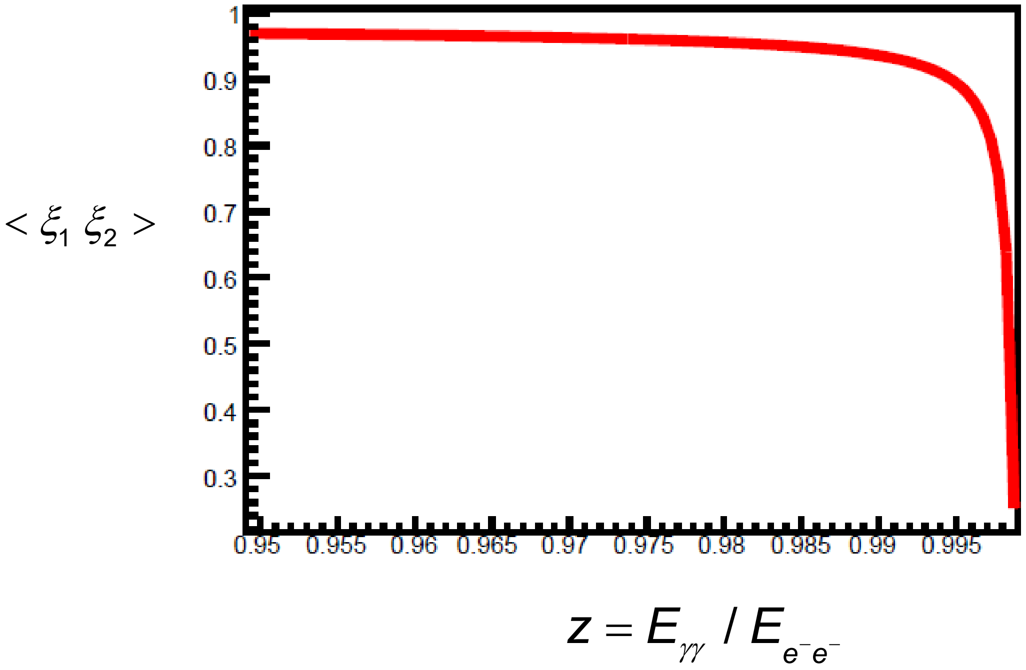
$x = 1000.$ $E_{e^-e^-} = 125.6$ GeV κ=0.44

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

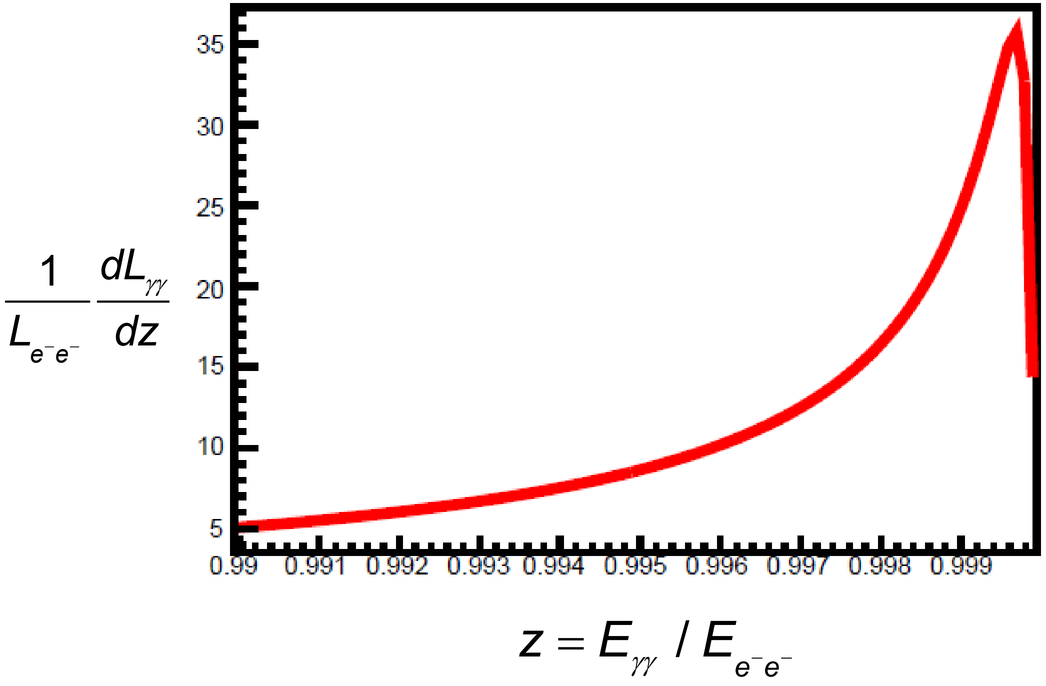
$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 311 \text{ fb}$$

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

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



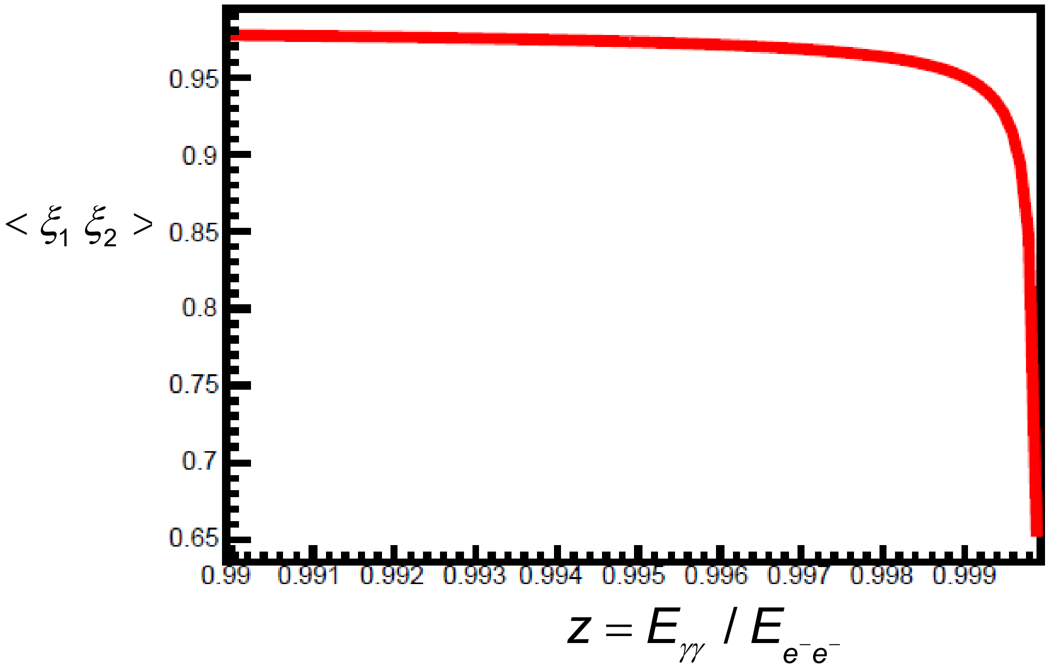
$2P_c\lambda_e = +0.9$ gives broader spectrum in $E_{\gamma\gamma}$ but this is compensated by suppression of $\gamma\gamma \to e^+e^-$ (κ=0.44 vs 0.11 for opposite sign of $2P_c\lambda_e$)



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

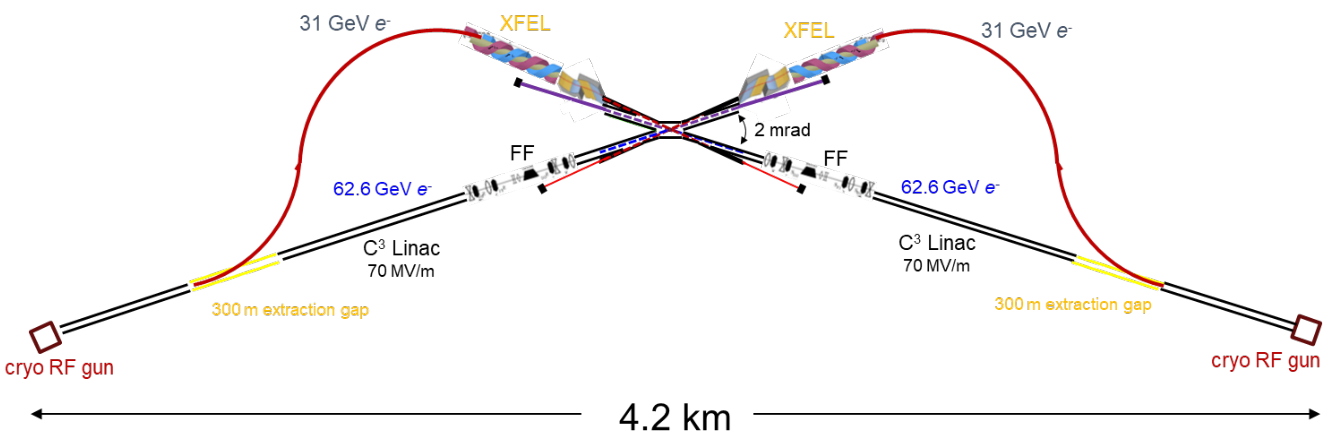
pol(e^-) = 90% $2P_c\lambda_e = +0.9$ $h\nu = 16.6$ keV

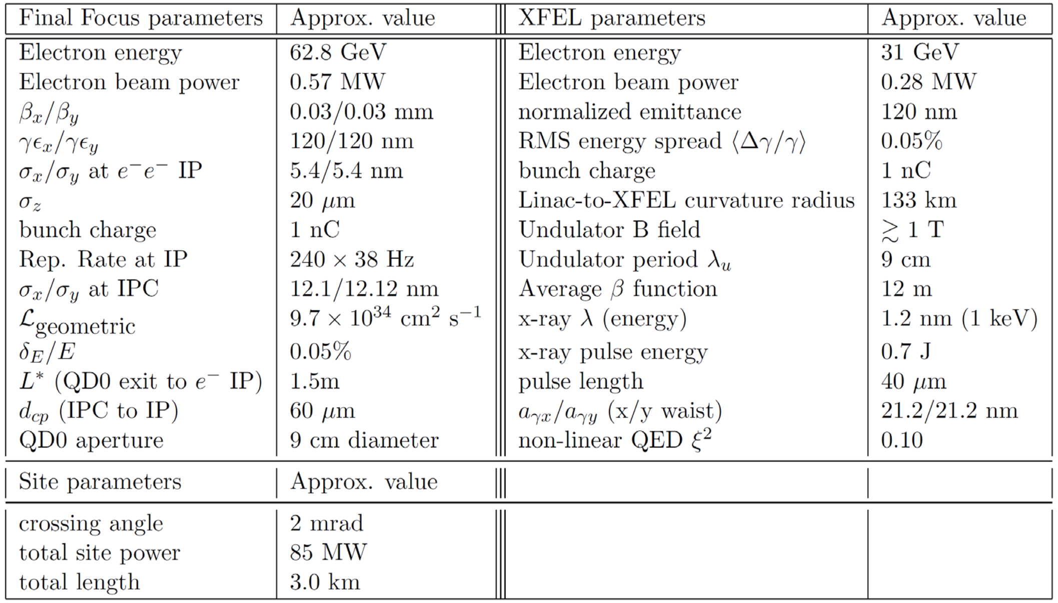
$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 4792 \text{ fb}$$



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

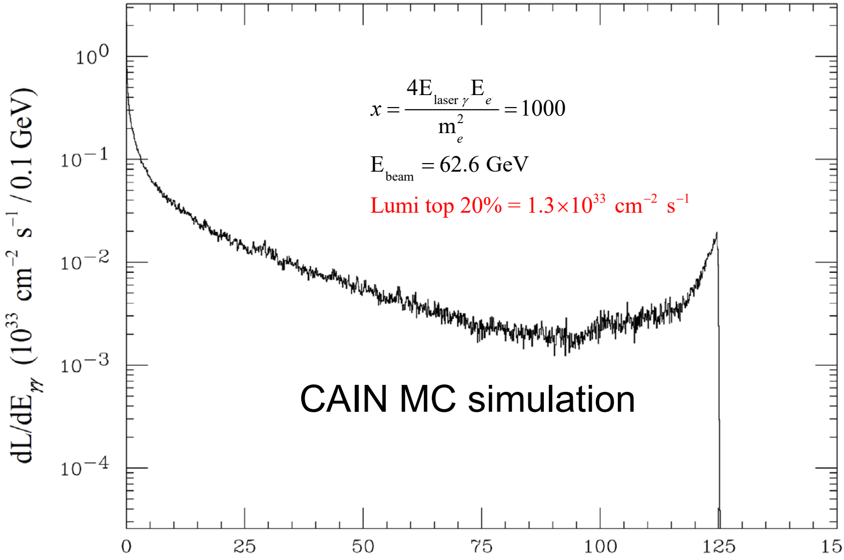
XCC s-channel $\gamma\gamma \to H$ @ $\sqrt{s} = 125$ GeV



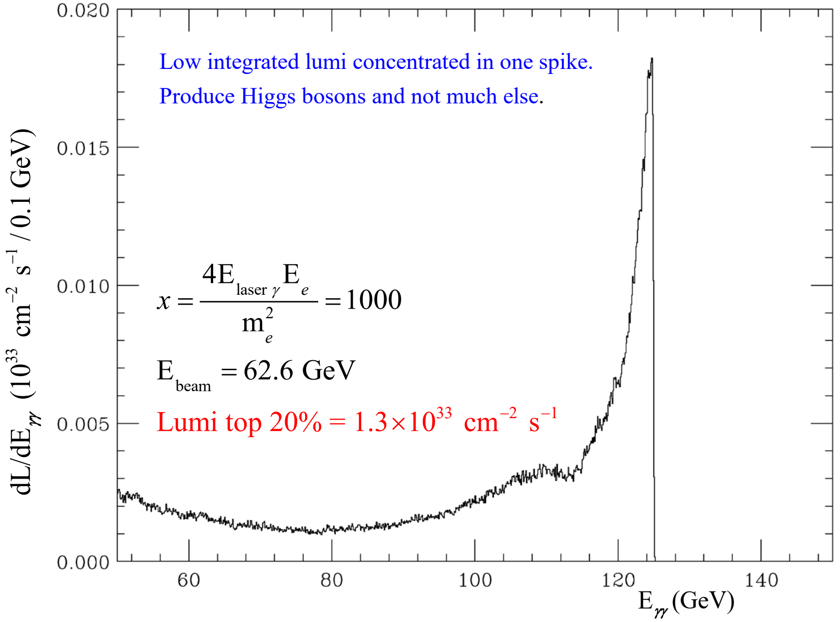


Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	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



CAIN MC simulation



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

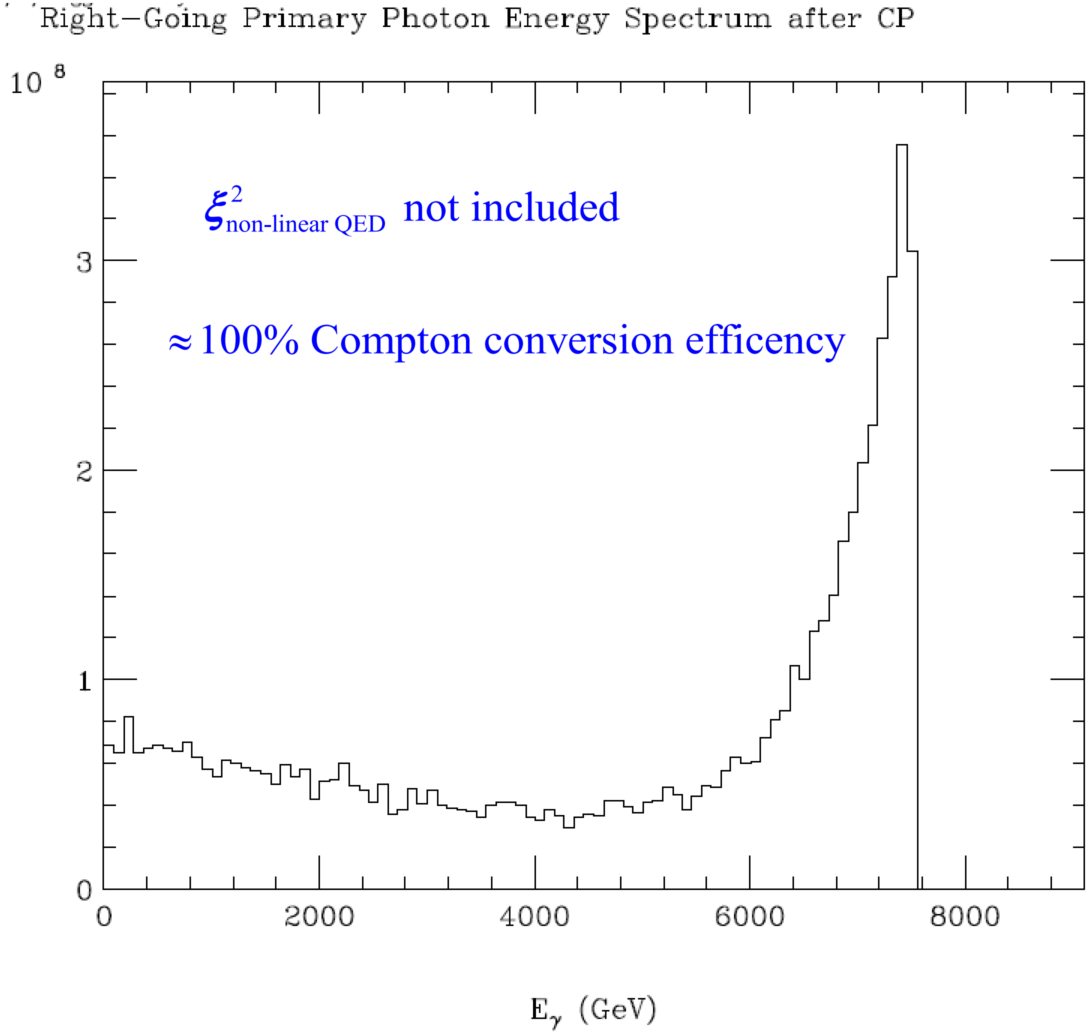
Replace 62.5 GeV C^3 e- beam w/ 7500 GeV PWFA e- beam and simulate $\gamma\gamma$ Collisions using CAIN MC

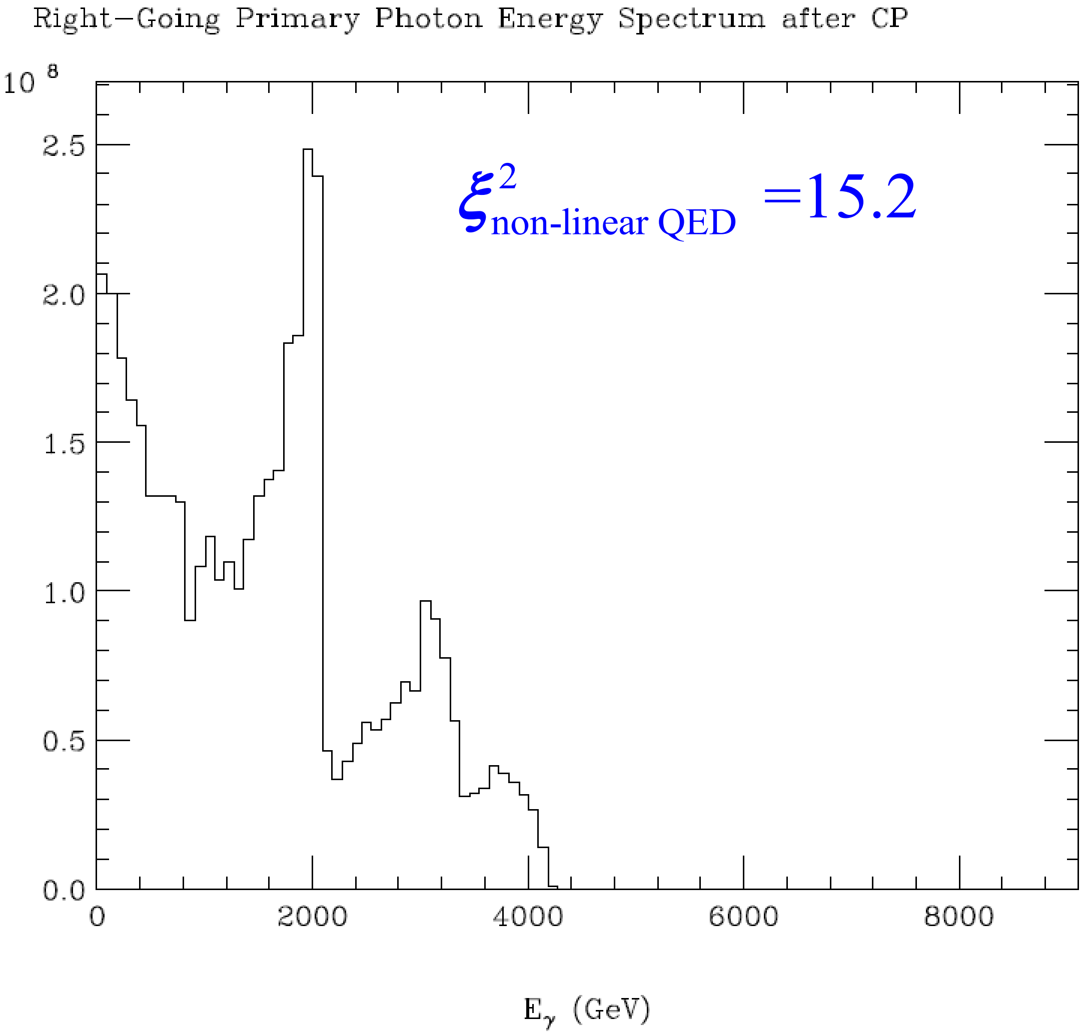
Technology	PWFA	$\gamma\gamma$ PWFA
Aspect Ratio	Round	Round
CM Energy	15	15
Single beam energy (TeV)	7.5	7.5
Gamma	1.47E+07	1.4E+07
Emittance X (mm mrad)	0.1	0.12
Emittance Y (mm mrad)	0.1	0.12
Beta* X (m)	1.50E-04	0.30E-04
Beta* Y (m)	1.50E-04	0.30E-04
Sigma* X (nm)	1.01	0.48
Sigma* Y (nm)	1.01	0.48
N_bunch (num)	5.00E+09	6.2E+09 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

$x = 4.8 \;\Rightarrow\; 9100$ 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

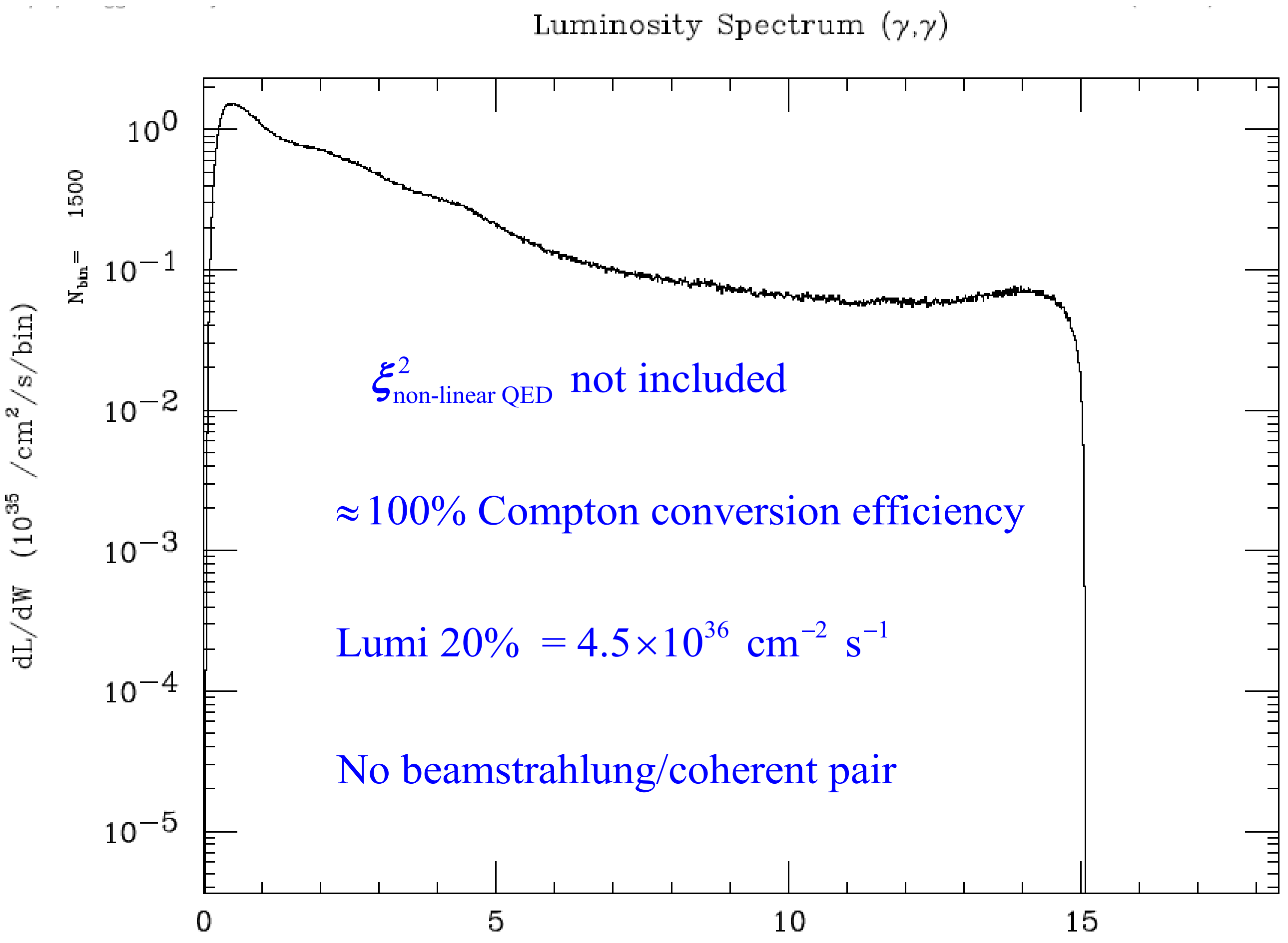




x=4.8 adjust parameters to get ~ 100 % conversion w/ linear QED

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

$\boldsymbol{\sigma}_{ez} = 5\ \mu\text{m}\quad \text{N}_{e^-} = 1\ \text{nC}\quad \gamma\boldsymbol{\varepsilon}_{x,y} = 120\ \text{nm}\quad 2\boldsymbol{P}_c\boldsymbol{\lambda}_e = -0.9\qquad \text{E}_{\text{pulse}} = 4400\ \text{J}$



$\xi^2_{\text{non-linear QED}}$ not included

$\approx$100% Compton conversion efficiency

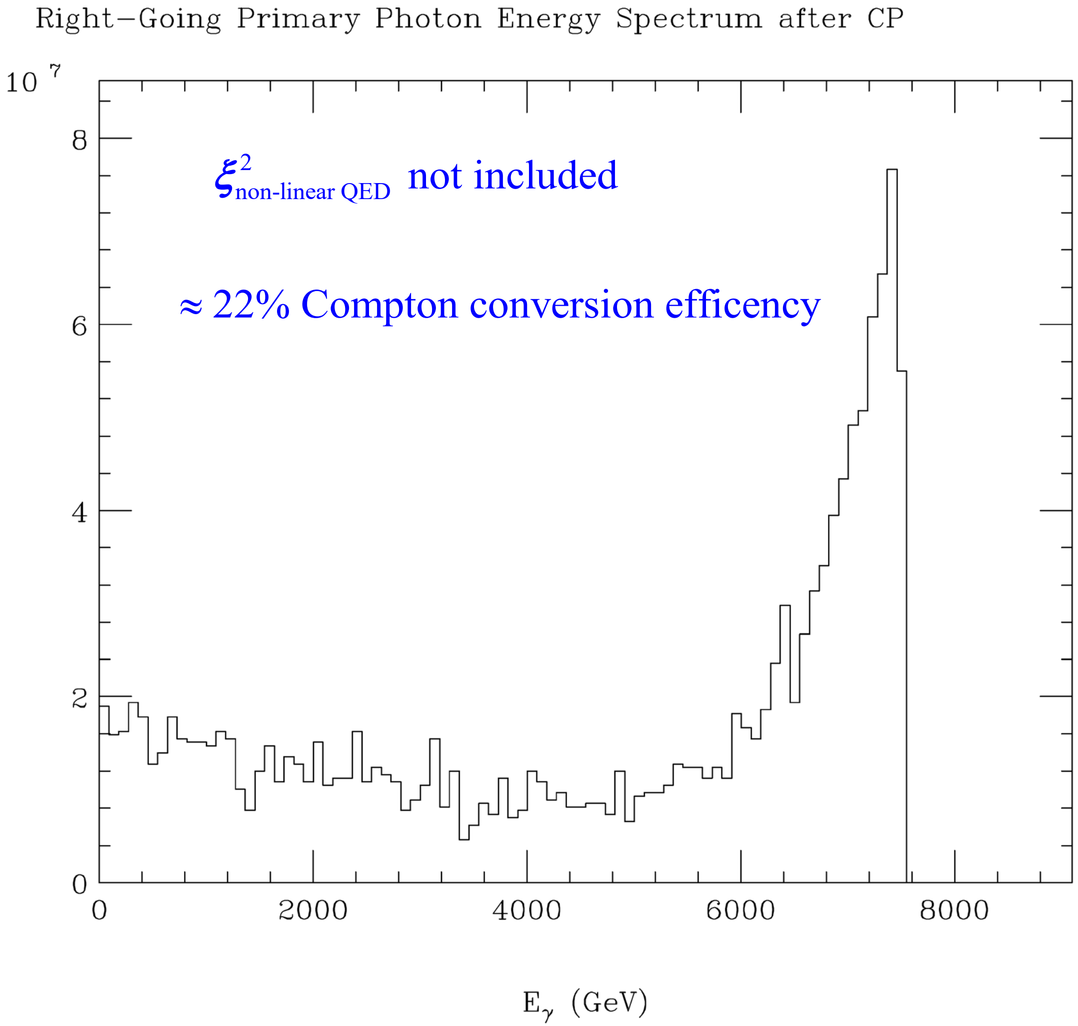
Lumi 20% $= 4.5\times10^{36}\ \text{cm}^{-2}\ \text{s}^{-1}$

No beamstrahlung/coherent pair

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

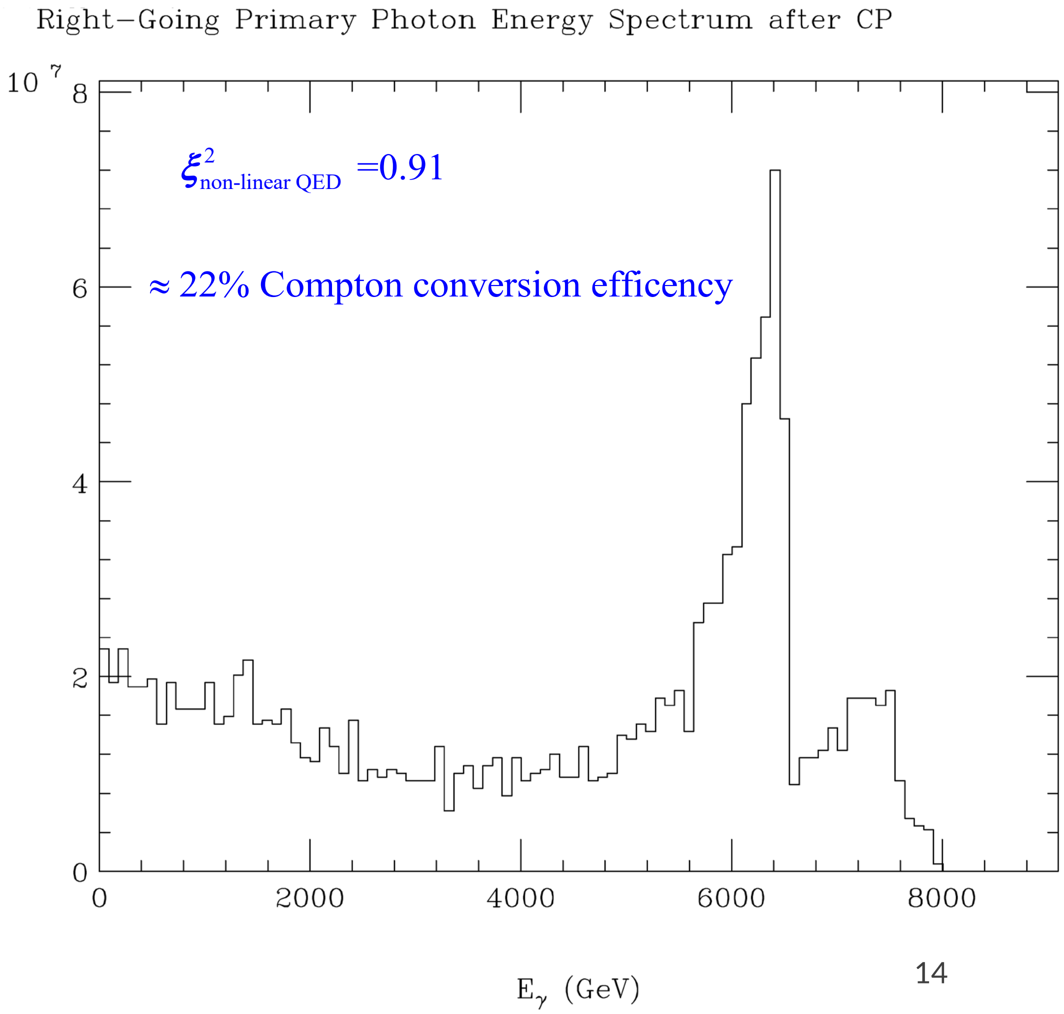
$x = 4.8 \Rightarrow$ 9100 GeV $e^- + 0.034$ eV γ (λ=36 μm) $a_{\gamma FWHM} = 2.1$ mm $\sigma_{\gamma z} = 0.79$ mm $d_{cp} = 2.4$ mm

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



$\xi^2_{\text{non-linear QED}}$ not included

≈ 22% Compton conversion efficency



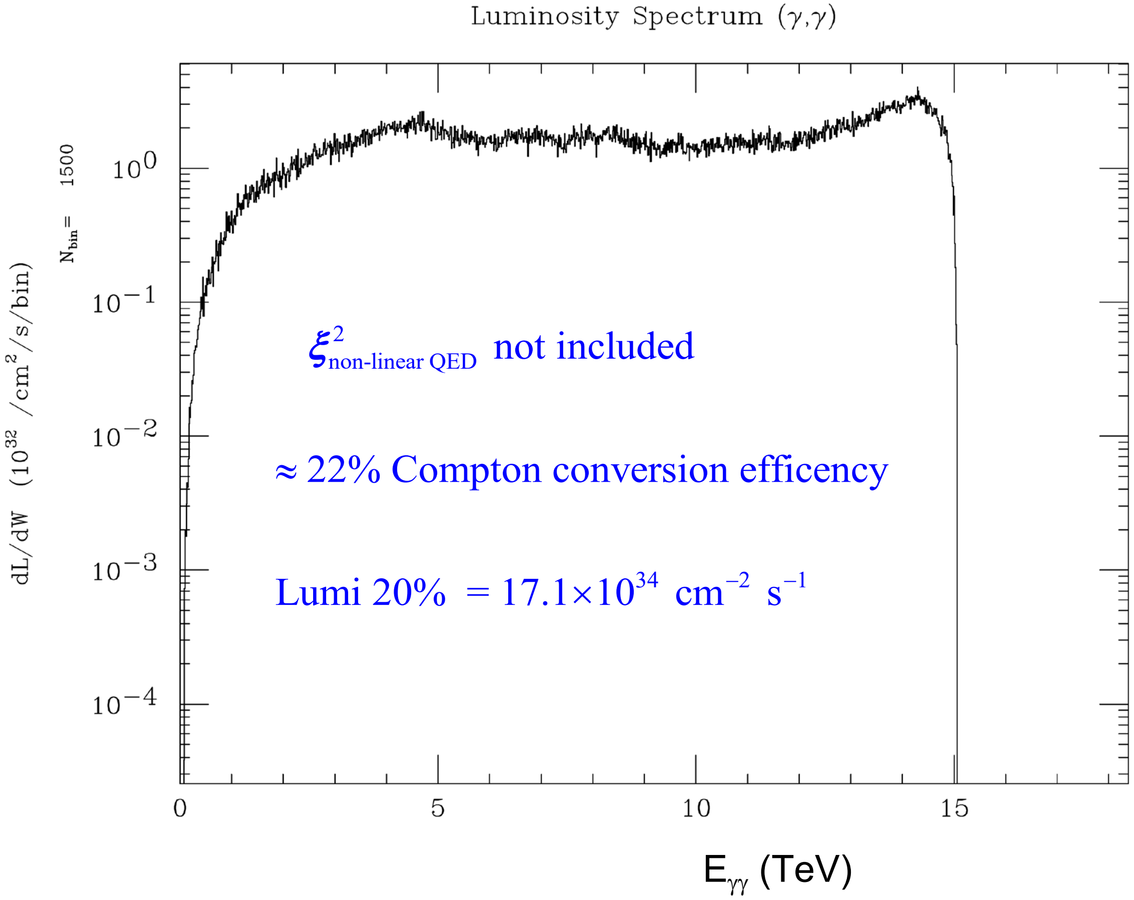
$\xi^2_{\text{non-linear QED}}$ =0.91

≈ 22% Compton conversion efficency

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

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

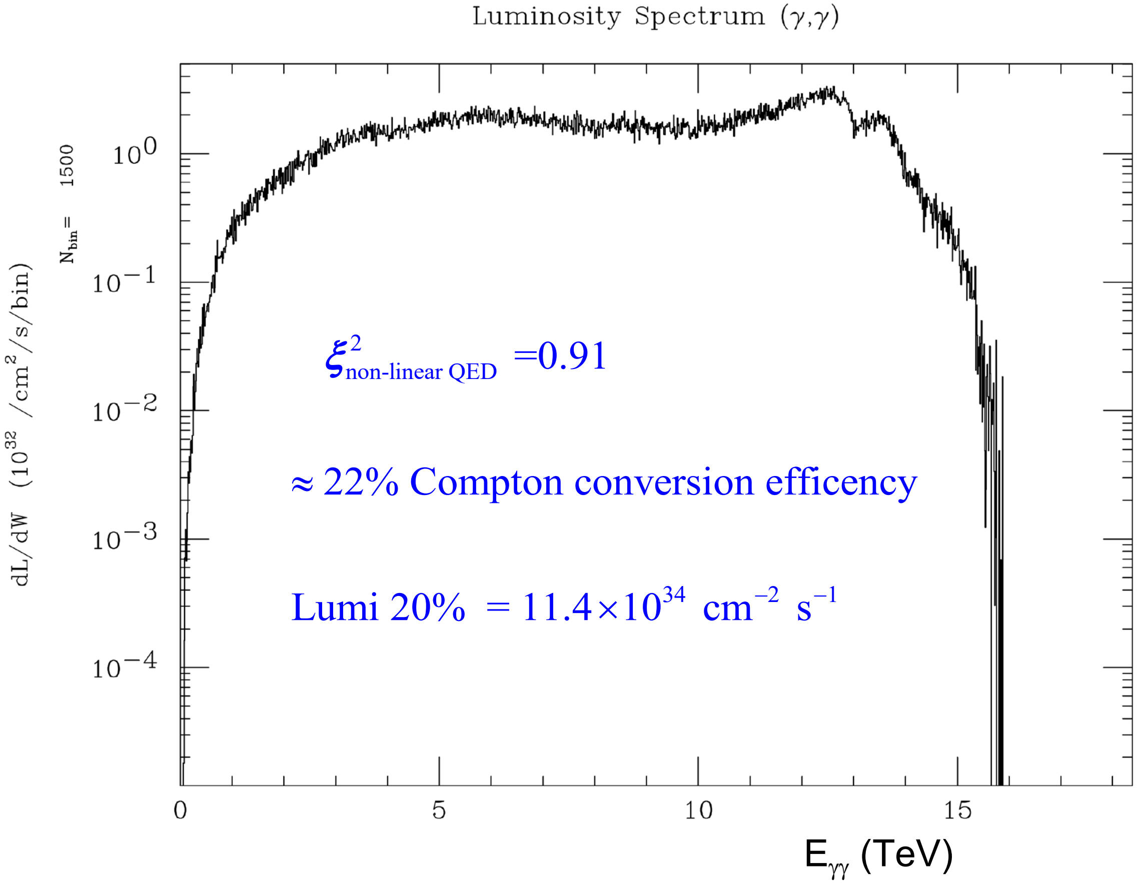
$\boldsymbol{\sigma}_{ez} = 5\ \mu\text{m} \quad \text{N}_{e^-} = 1\text{ nC} \quad \gamma\boldsymbol{\varepsilon}_{x,y} = 120\text{ nm} \quad 2\boldsymbol{P}_c\boldsymbol{\lambda}_e = -0.9 \qquad \text{E}_{\text{pulse}} = 260\text{ J}$



$\xi^2_{\text{non-linear QED}}$ not included

≈ 22% Compton conversion efficency

Lumi 20% $= 17.1\times10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$



$\xi^2_{\text{non-linear QED}} = 0.91$

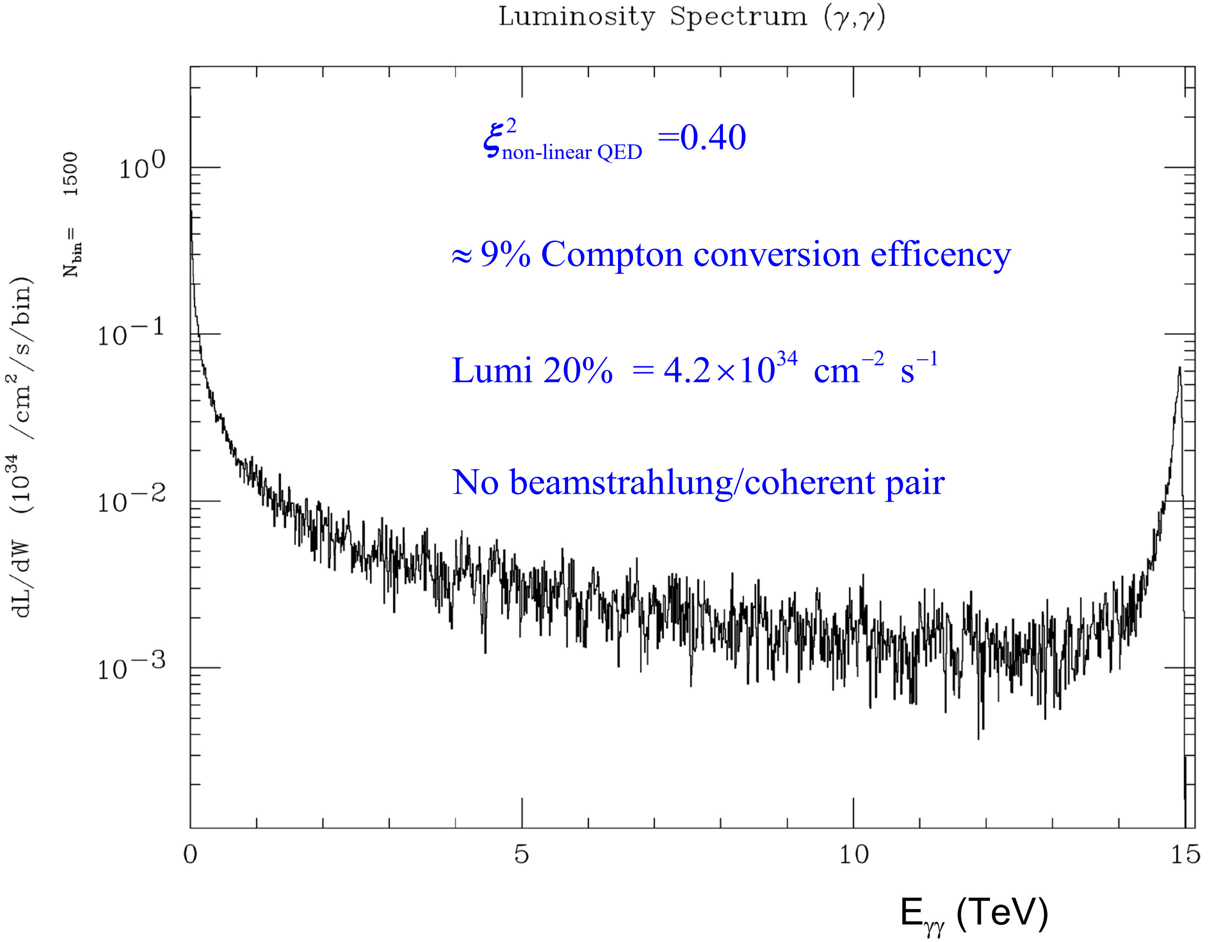
≈ 22% Compton conversion efficency

Lumi 20% $= 11.4\times10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

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

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

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

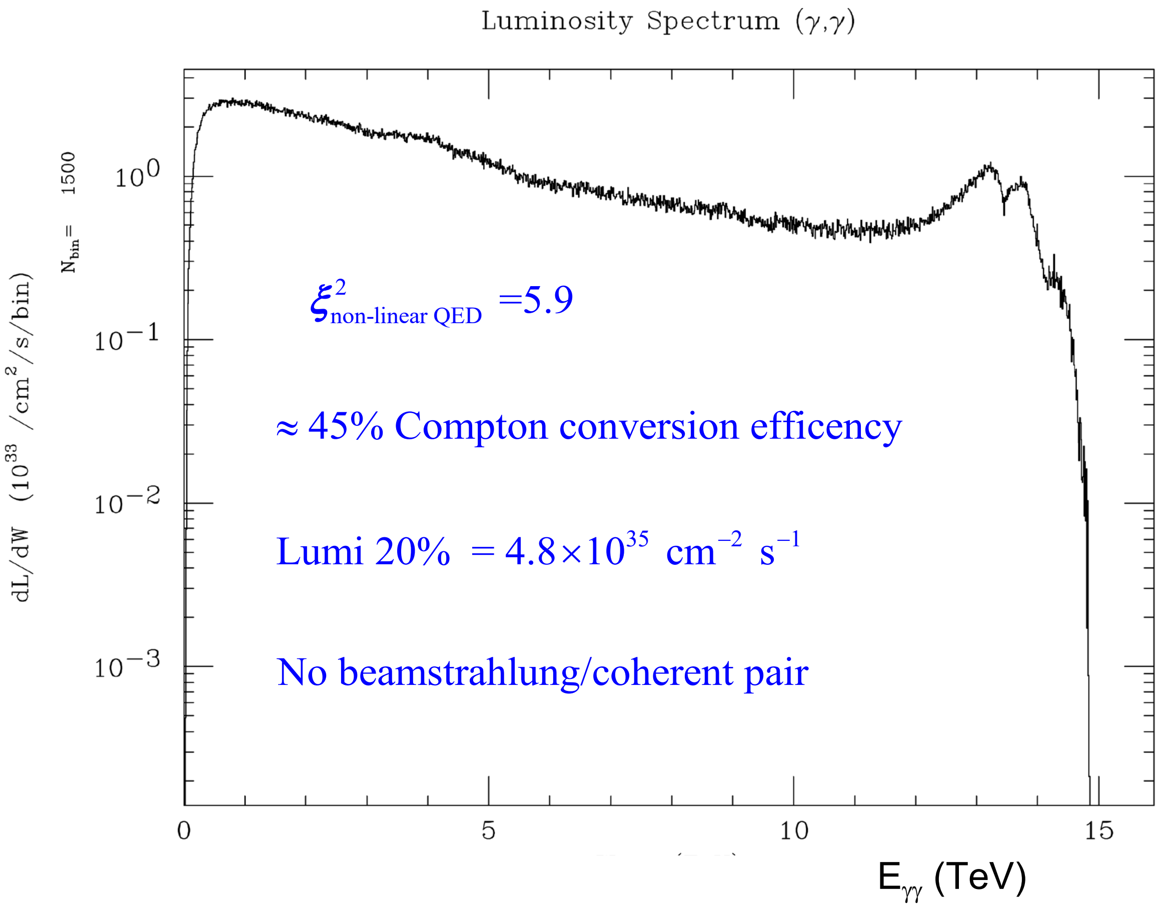
x	$\frac{\sqrt{s_{e^-\gamma}}}{m_e} = \sqrt{x+1}$	$\frac{\sqrt{s_{e^-\gamma}}}{m_e} m_W$ (TeV)
4.82	2.4	0.2
1000	32	2.5
1.2×10^5	350	28

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

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

$\sigma_{ez} = 5\ \mu\text{m} \quad \text{N}_{e^{-}} = 1\ \text{nC} \quad \gamma\varepsilon_{x,y} = 120\ \text{nm} \quad 2P_c\lambda_e = -0.9 \qquad \text{E}_{\text{pulse}} = 590\ \text{J}$



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

$\approx 45\%$ Compton conversion efficency

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

No beamstrahlung/coherent pair

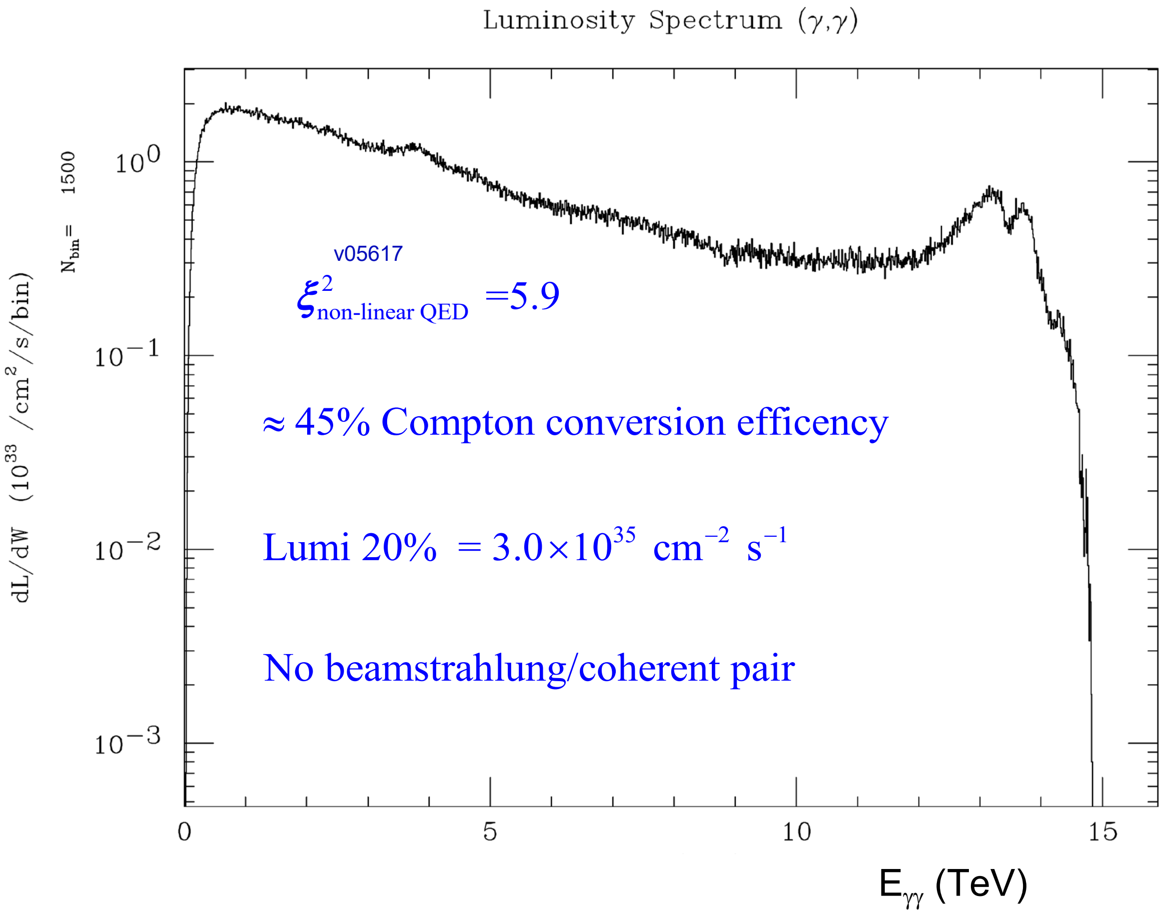
In contrast to the $\text{E}_{\text{beam}} = 63$ GeV, $x = 1000$ XCC, there is an incompatiblity between the longer laser wavelengths required for $\text{E}_{\text{beam}} = 7500$, $x = 1000$ and the short distance that must be maintained between the Compton IP and the $\gamma\gamma$ IP at $x = 1000$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

Hence, we try instead moderate x values such as $x = 40$.

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

$x = 40 \quad \Rightarrow \quad 7875$ 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



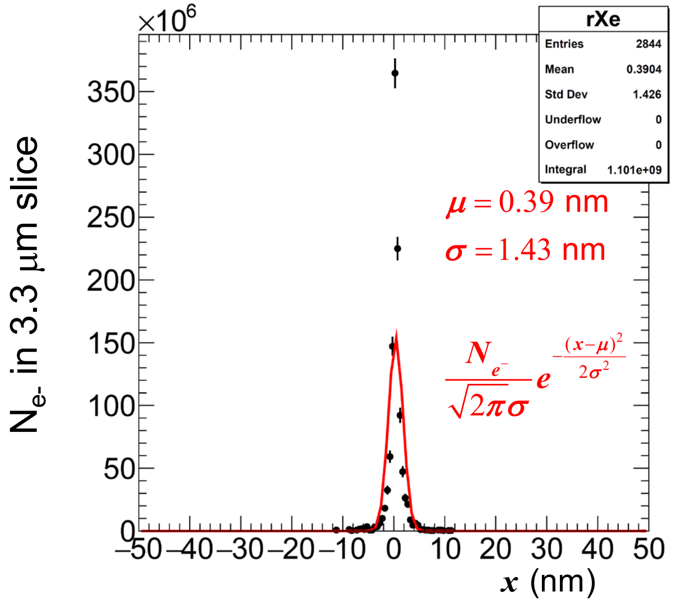
$\xi^2_{\text{non-linear QED}} = 5.9$

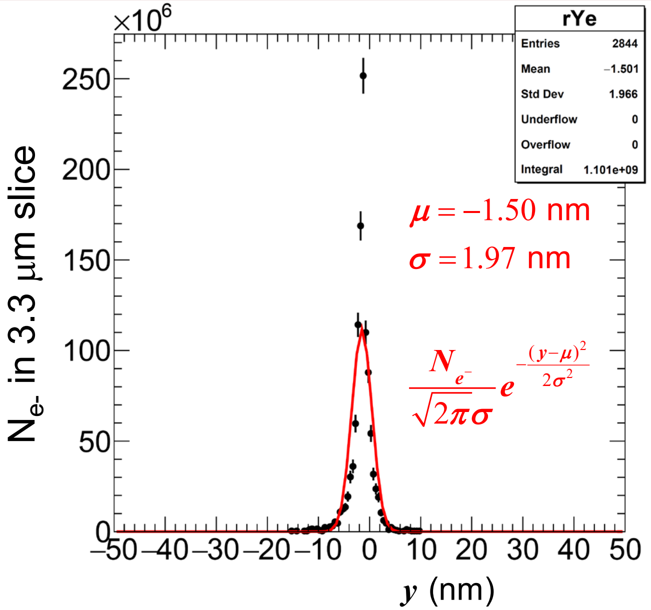
≈ 45% Compton conversion efficency

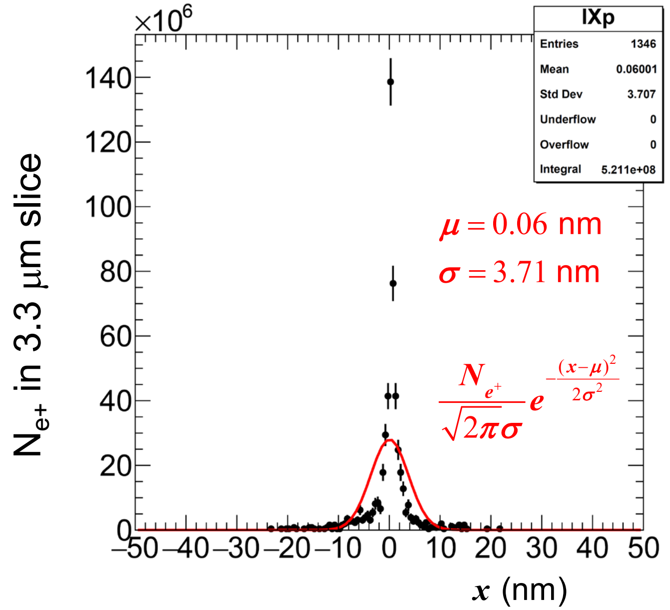
Lumi 20% $= 3.0\times10^{35}$ cm^{-2} s^{-1}

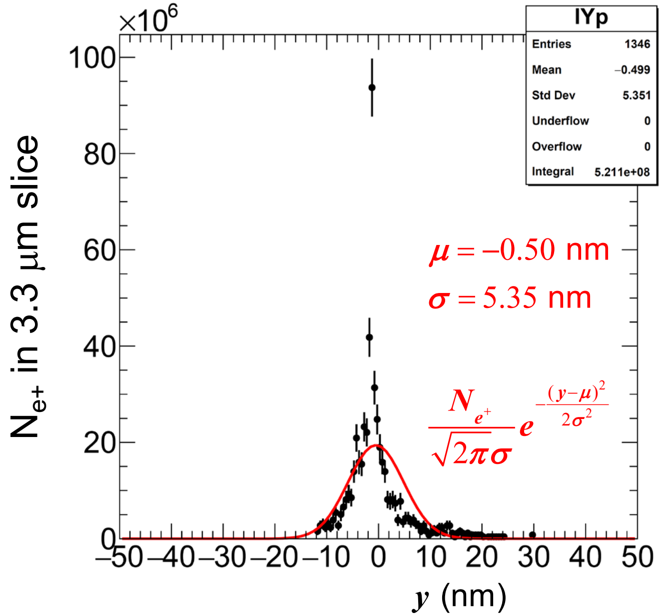
No beamstrahlung/coherent pair

$e^- \gamma$ collisions at $E_{e\gamma}$=140 GeV I.P. geometric e^- σ_x,σ_y=5.1 nm









During the collision, the e^+ from coherent e^+e^- production are focused by the EM field of the oncoming e^- beam. This leads to focusing (pinching) of the e^- beam.

This pinching creates very high fields which leads to even more coherent pair production and even higher fields.

Return to 15 TeV and x=40   Turn on coherent processes

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

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

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
```

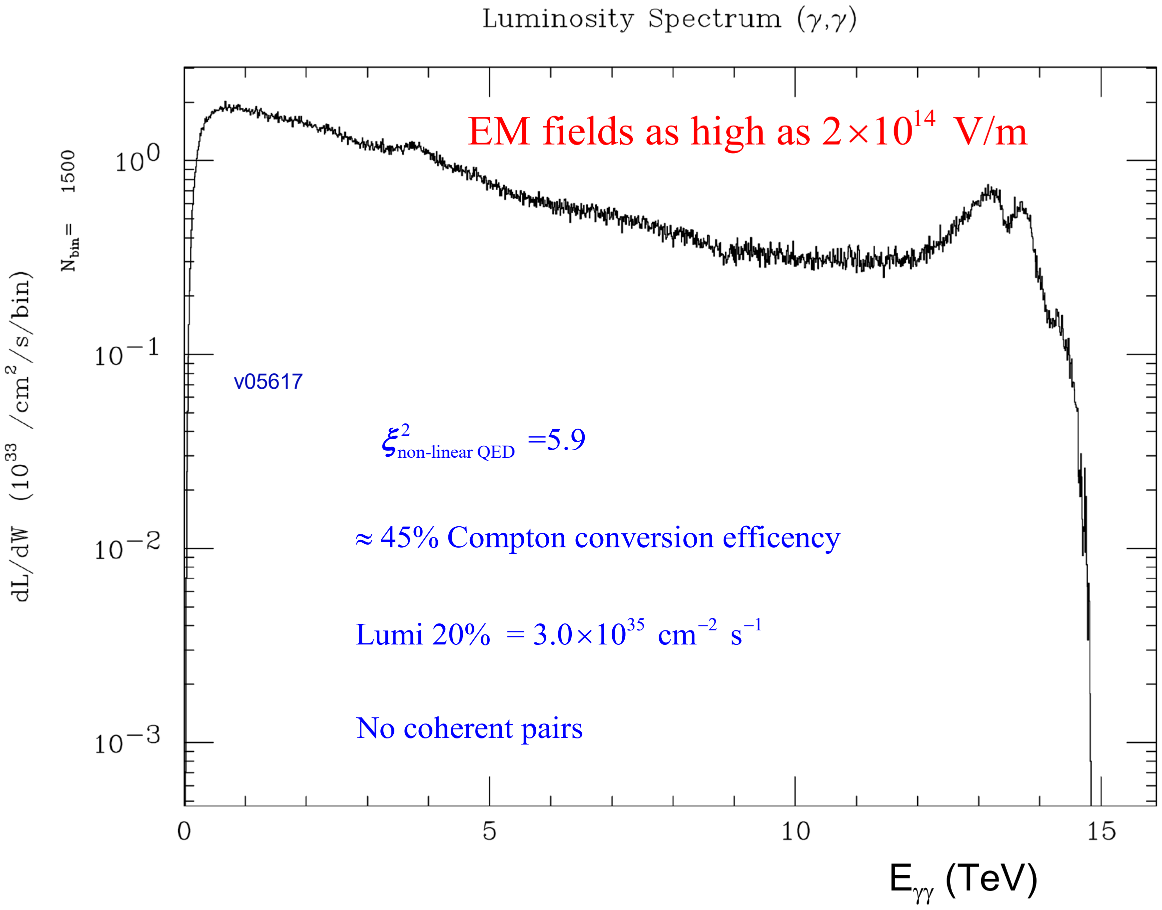
Solution:

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

15 TeV and x=40 Turn on coherent processes

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

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



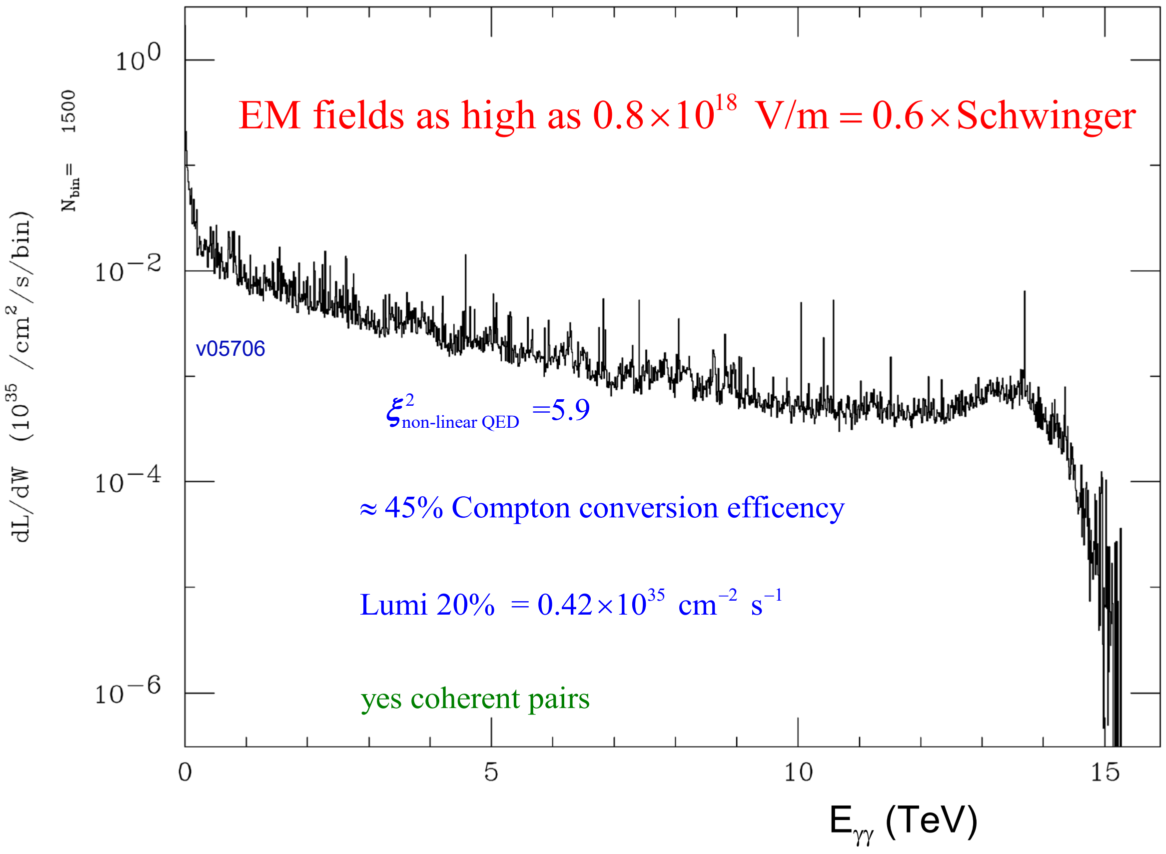
EM fields as high as 2×10^{14} V/m

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

≈ 45% Compton conversion efficency

Lumi 20% $= 3.0\times10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$

No coherent pairs



EM fields as high as 0.8×10^{18} V/m = 0.6×Schwinger

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

≈ 45% Compton conversion efficency

Lumi 20% $= 0.42\times10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$

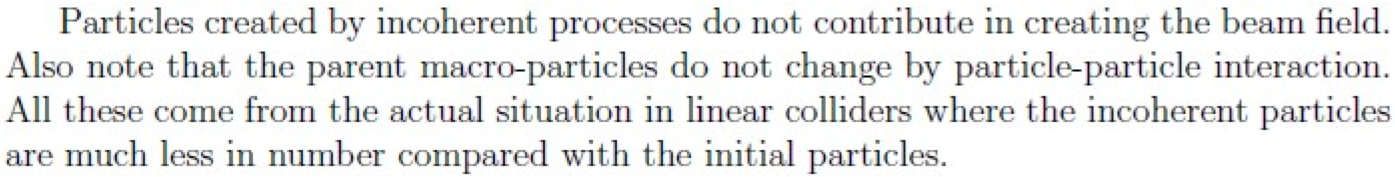
yes coherent pairs

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.

Does CAIN Simulate the Field of Coherent e^+e^- Pairs ?

- In recent private communication with Spencer, CAIN author K. Yokoya says NO.

- CAIN manual is silent on the issue w.r.t. coherent pairs, but does mention incoherent pairs:



> Particles created by incoherent processes do not contribute in creating the beam field. Also note that the parent macro-particles do not change by particle-particle interaction. All these come from the actual situation in linear colliders where the incoherent particles are much less in number compared with the initial particles.

- In the FORTRAN code, incoherently produced particles are given names such as ‘IBW ’, ‘IBH ’, ‘ILL ’ , ‘IBR ’ , whereas all other particles -- including coherently produced e^+e^- -- are given 4 spaces: ‘   ‘.

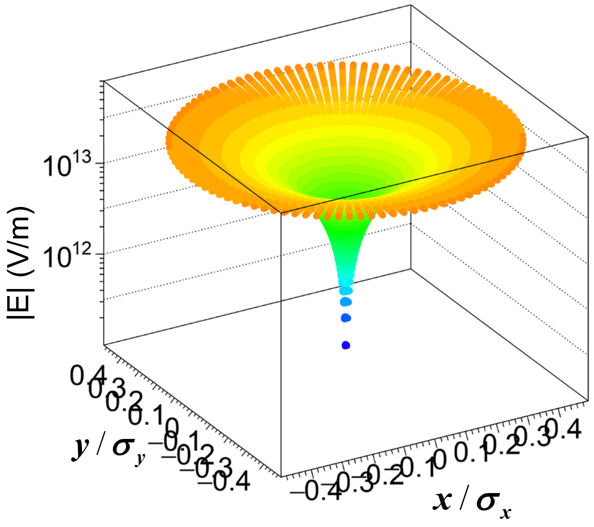
- The FORTAN code that calculates the EM field is filled with loops like this

```
DO 300 N=1,NP
      IF(ISBIN(N).NE.IS) GOTO 300
      IF(KIND(N).EQ.1) GOTO 300
      IF(LOST(N).NE.0) GOTO 300
      IF(PNAME(N).NE.'    ') GOTO 300
      IF(TXYS(0,N).GT.T) GOTO 300
```

Replace CAIN EM FFT EM Field Calculation with Bassetti-Erskine 2d Gaussian Expression

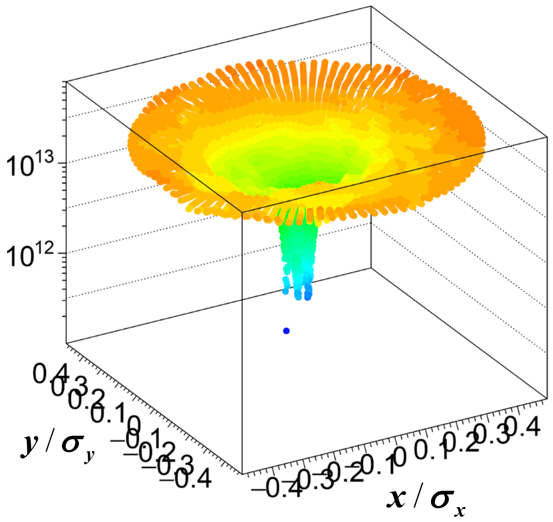
Bassetti-Erskine

$(0,0) =$ center of charge distribution



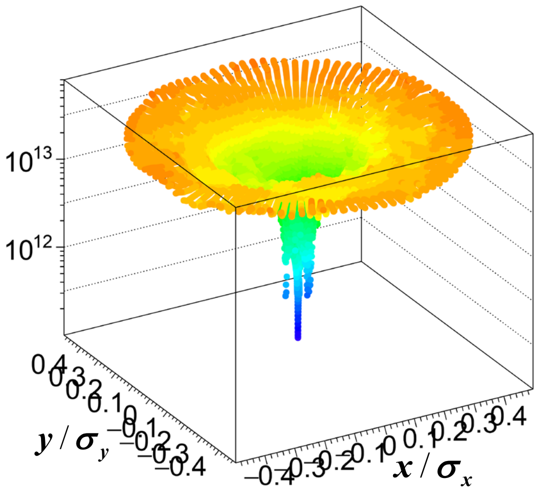
CAIN

$(0,0) =$ center of charge distribution



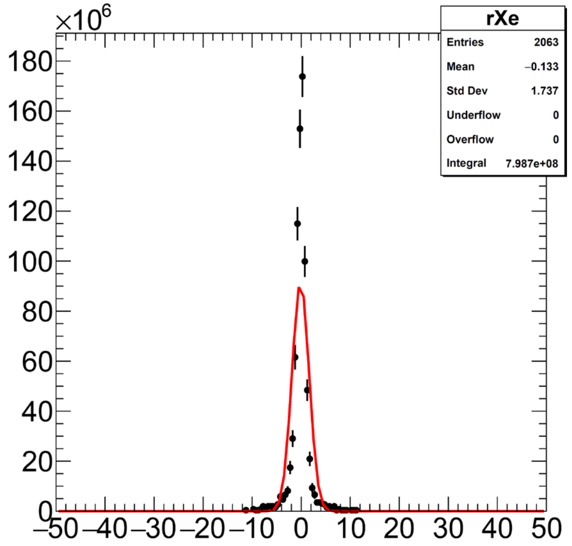
CAIN

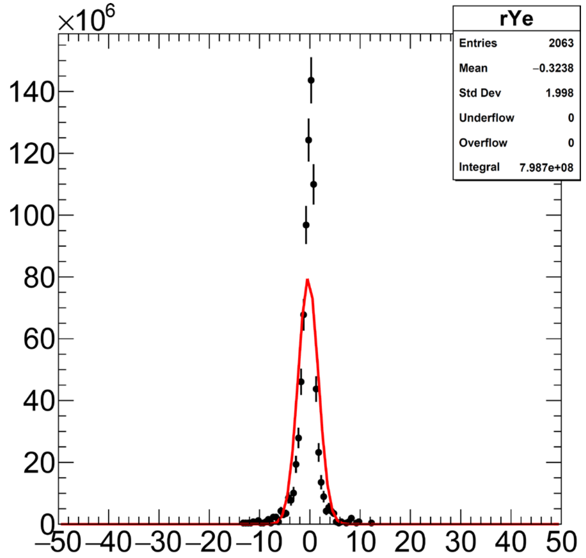
$(0,0) =$ EM field minimum



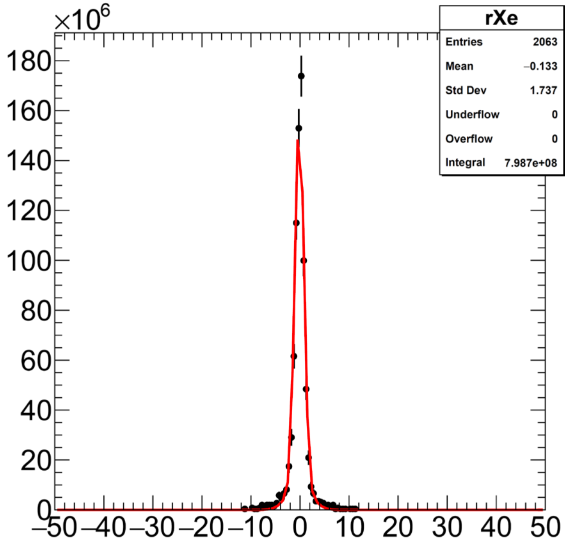
Replace CAIN EM FFT EM Field Calculation with Bassetti-Erskine 2d Gaussian Expression

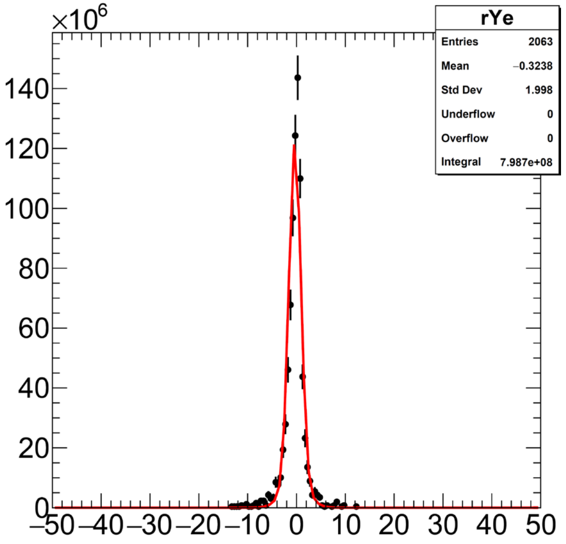
Bassetti-Erskine 1 Gaussian





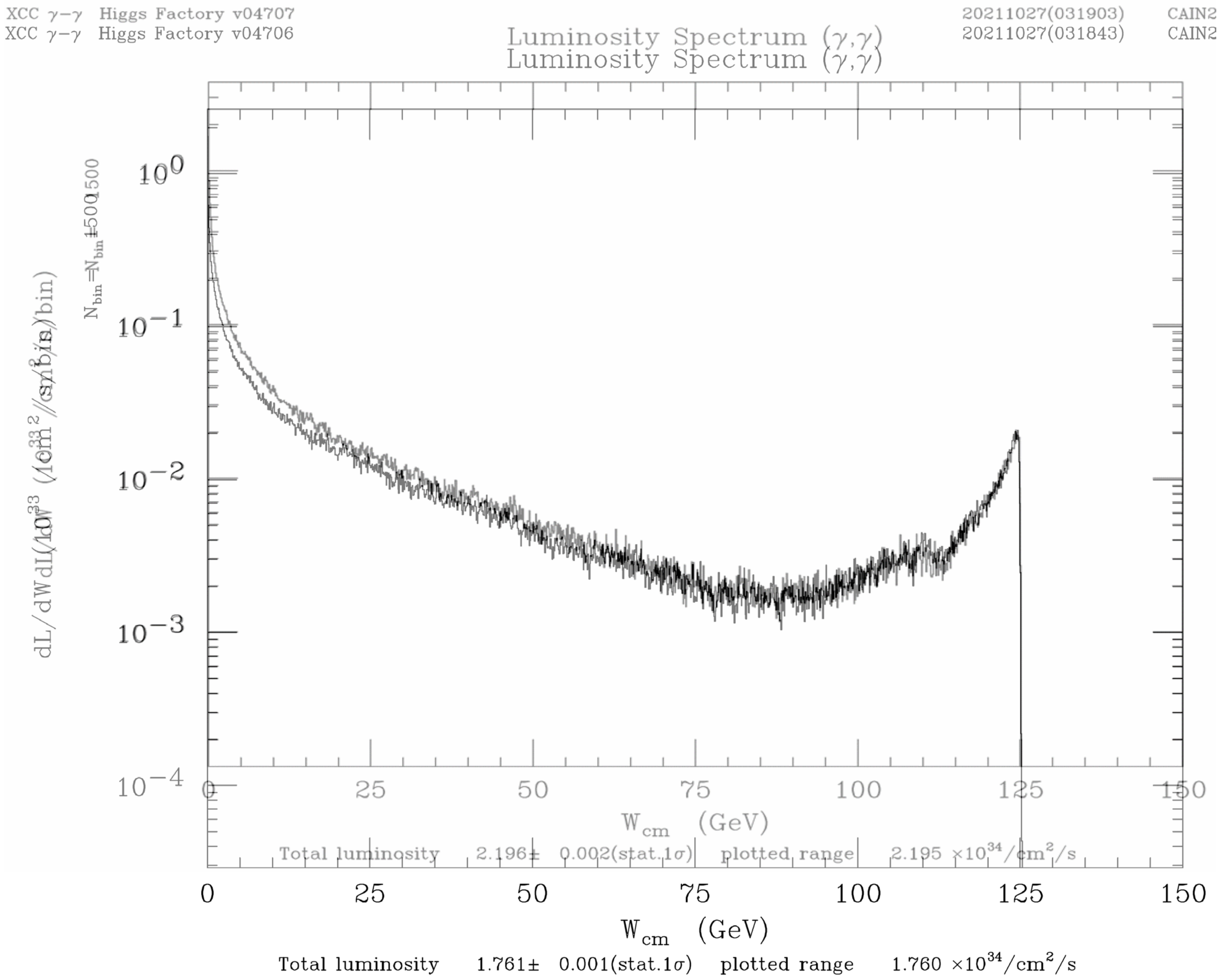
Bassetti-Erskine 2 Gaussians





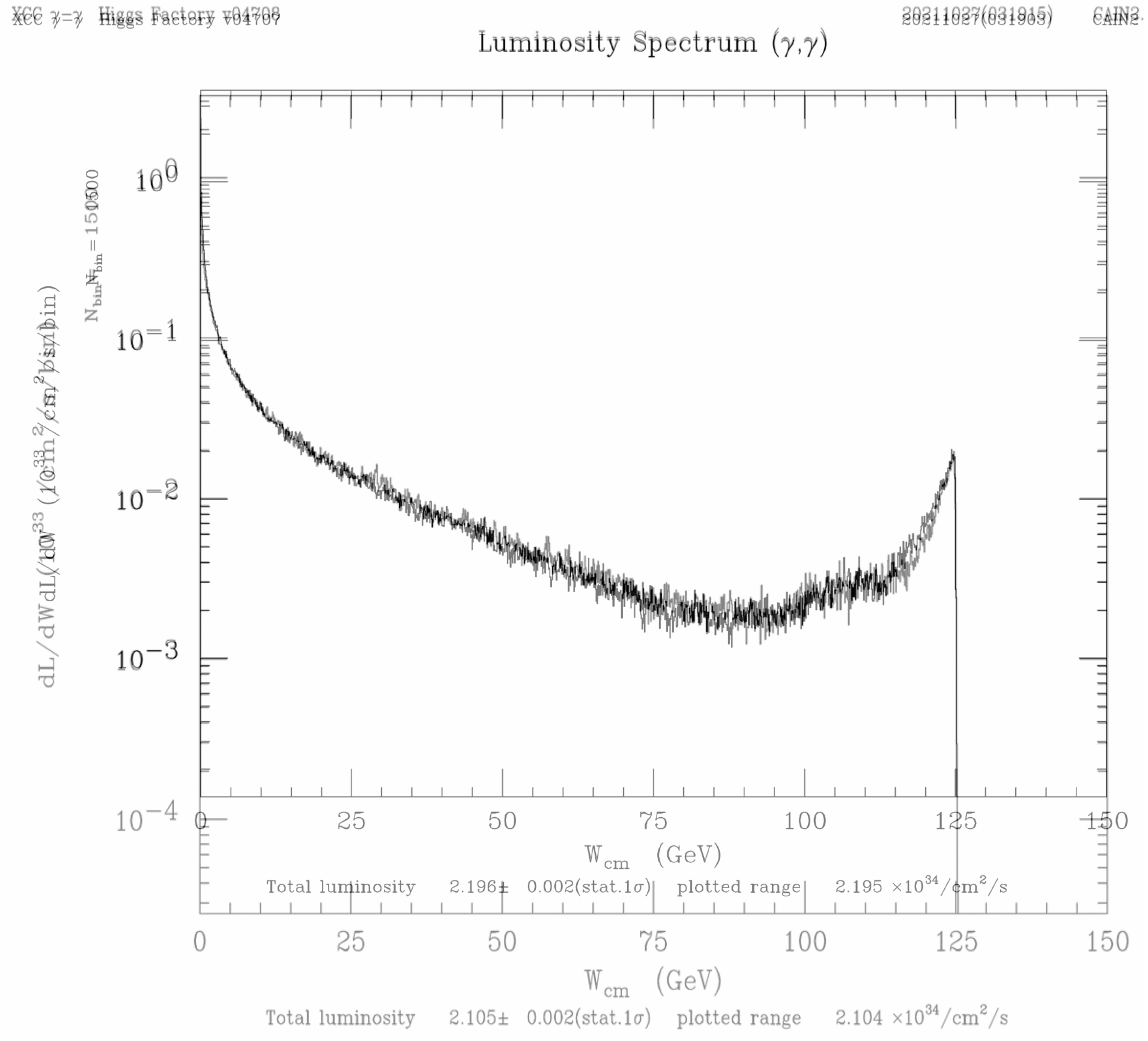
Replace CAIN EM FFT EM Field Calculation with Bassetti-Erskine 2d Gaussian Expression

Bassetti-Erskine 1 Gaussian vs Bassetti-Erskine 2 Gaussian for γγ collision

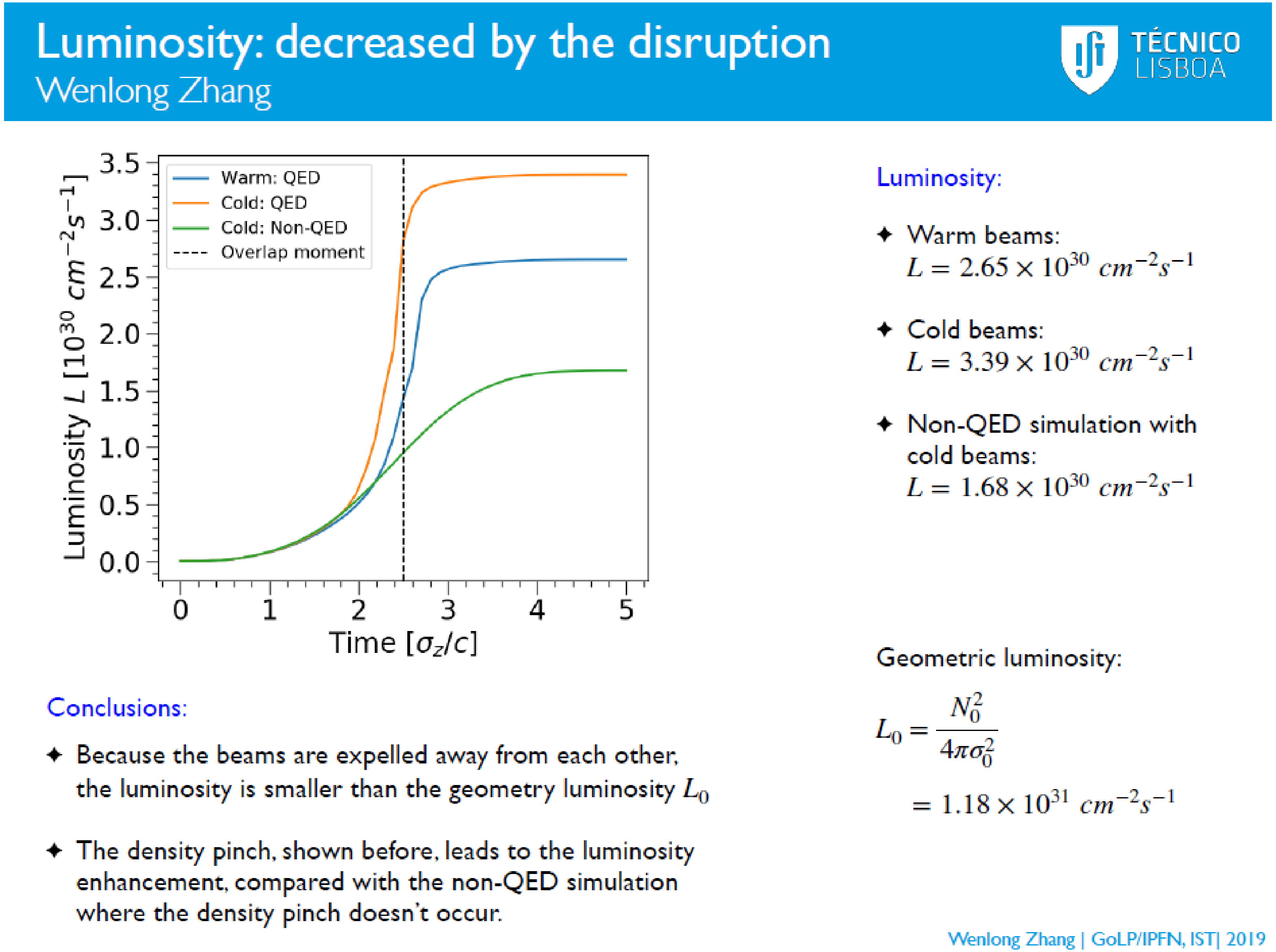


Replace CAIN EM FFT EM Field Calculation with Bassetti-Erskine 2d Gaussian Expression

2 Gaussian Bassetti-Erskine vs CAIN EM Field



Wenlong Zhang Also Sees Pinching in e^-e^- Collisions



Luminosity: decreased by the disruption

Wenlong Zhang

Luminosity:

- Warm beams: $L = 2.65 \times 10^{30}\ cm^{-2}s^{-1}$
- Cold beams: $L = 3.39 \times 10^{30}\ cm^{-2}s^{-1}$
- Non-QED simulation with cold beams: $L = 1.68 \times 10^{30}\ cm^{-2}s^{-1}$

Geometric luminosity:

$$L_0 = \frac{N_0^2}{4\pi\sigma_0^2}$$

$$= 1.18 \times 10^{31}\ cm^{-2}s^{-1}$$

Conclusions:

- Because the beams are expelled away from each other, the luminosity is smaller than the geometry luminosity L_0
- The density pinch, shown before, leads to the luminosity enhancement, compared with the non-QED simulation where the density pinch doesn't occur.

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
- I have presented evidence that the e^+e^- from coherent pair production are used in the EM field calculation in CAIN