Simulations Luminosity Spectra of Multi-TeV PWFA $\gamma\gamma$ Colliders

Advanced Accelerator Concepts LCWS2024

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Simulation of 15 TeV $\gamma\gamma$ Collider

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

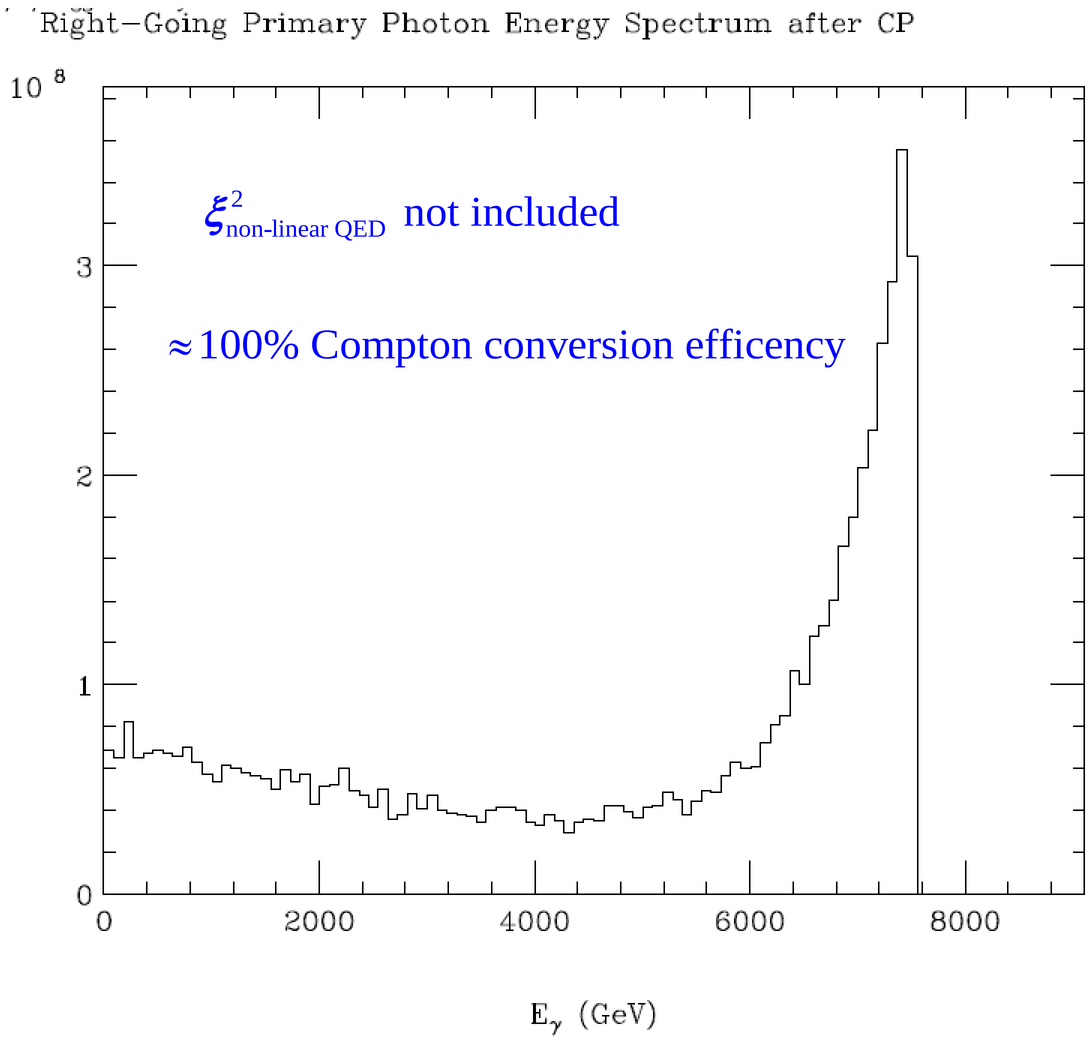
Technology	PWFA	$\gamma\gamma$ PWFA
Aspect Ratio	Round	Round
CM Energy	15	15
Single beam energy (TeV)	7.5	7.5
Gamma	1.47E+07	1.4E+07
Emittance X (mm mrad)	0.1	0.12
Emittance Y (mm mrad)	0.1	0.12
Beta* X (m)	1.50E-04	0.30E-04
Beta* Y (m)	1.50E-04	0.30E-04
Sigma* X (nm)	1.01	0.48
Sigma* Y (nm)	1.01	0.48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

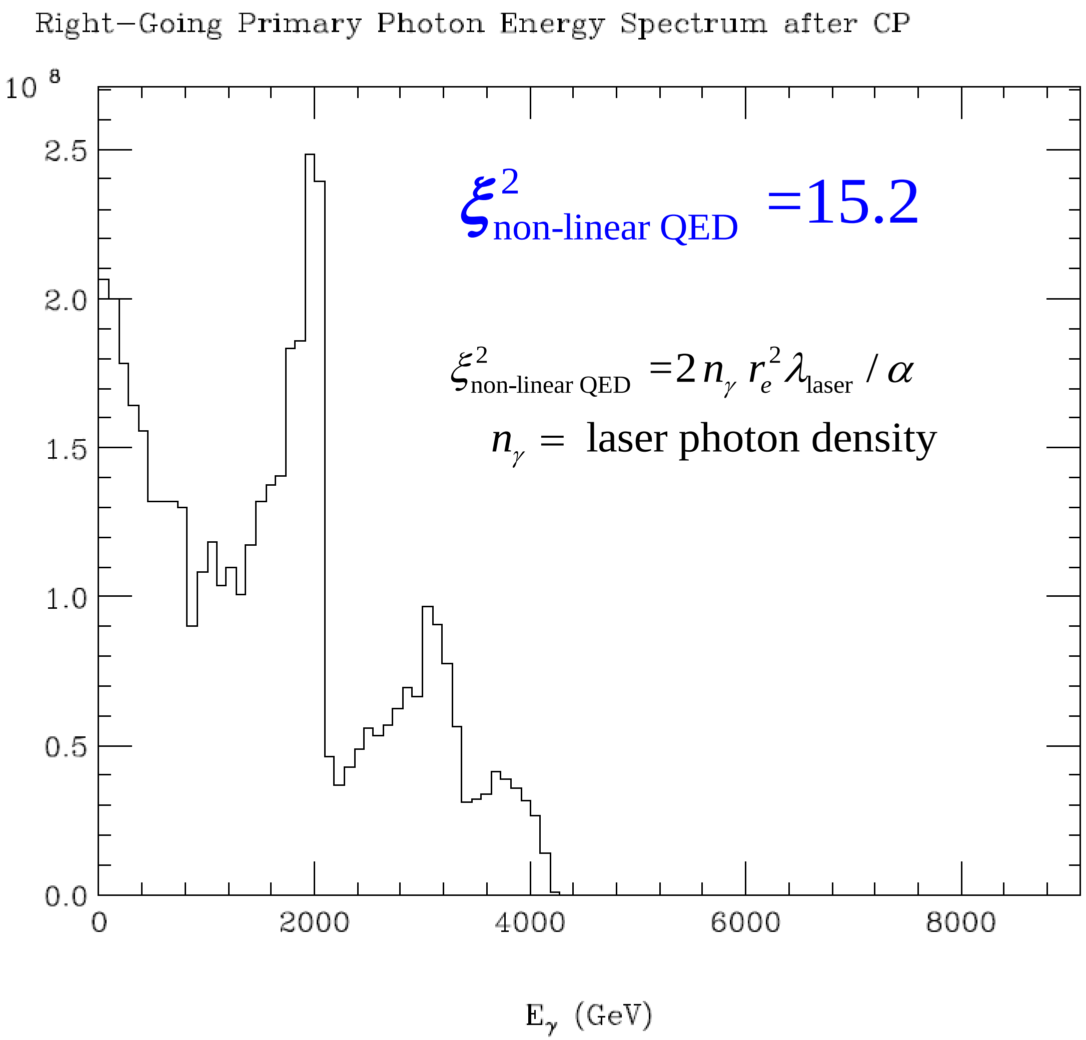
Start with x=4.8 because this was considered the typical $\gamma\gamma$ collider x value before this study was performed

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

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

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





x=4.8 , parameters with ~ 100 % conversion w/ linear QED

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

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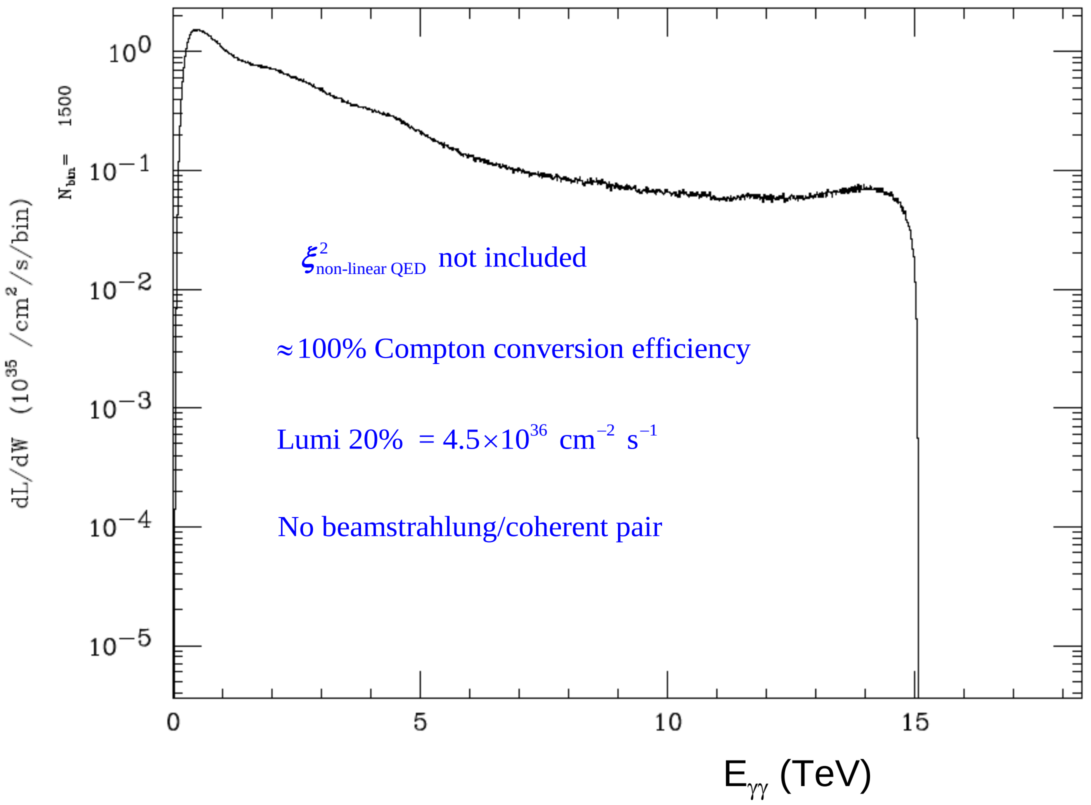
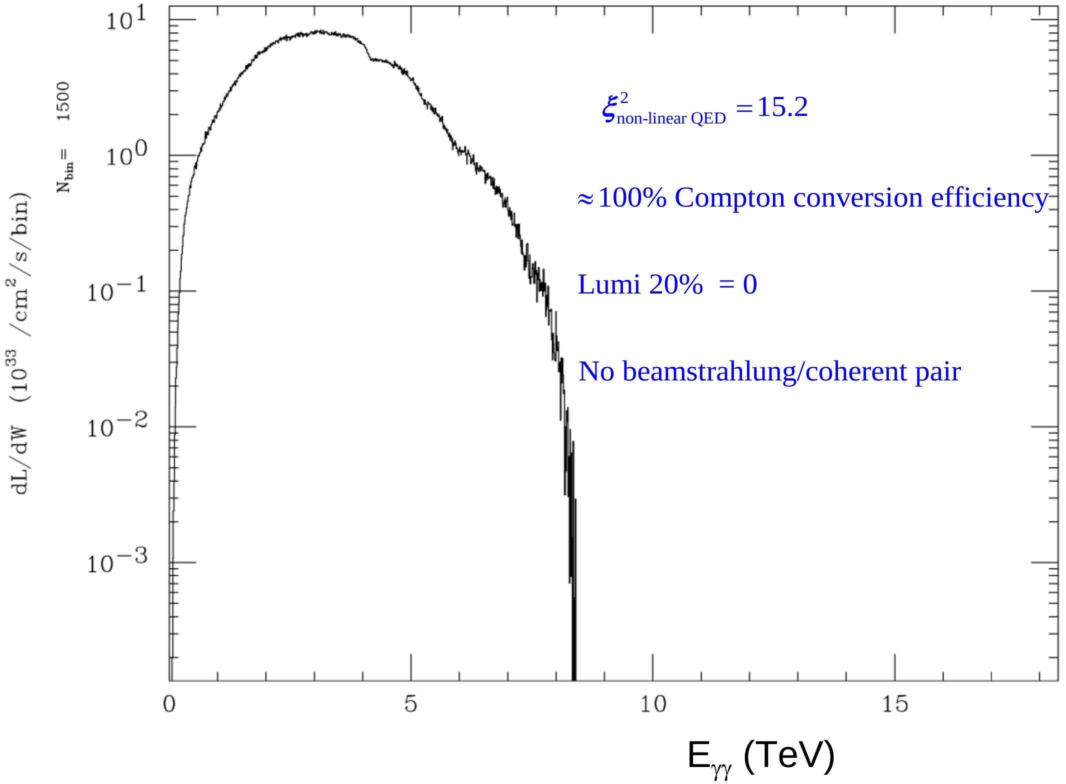
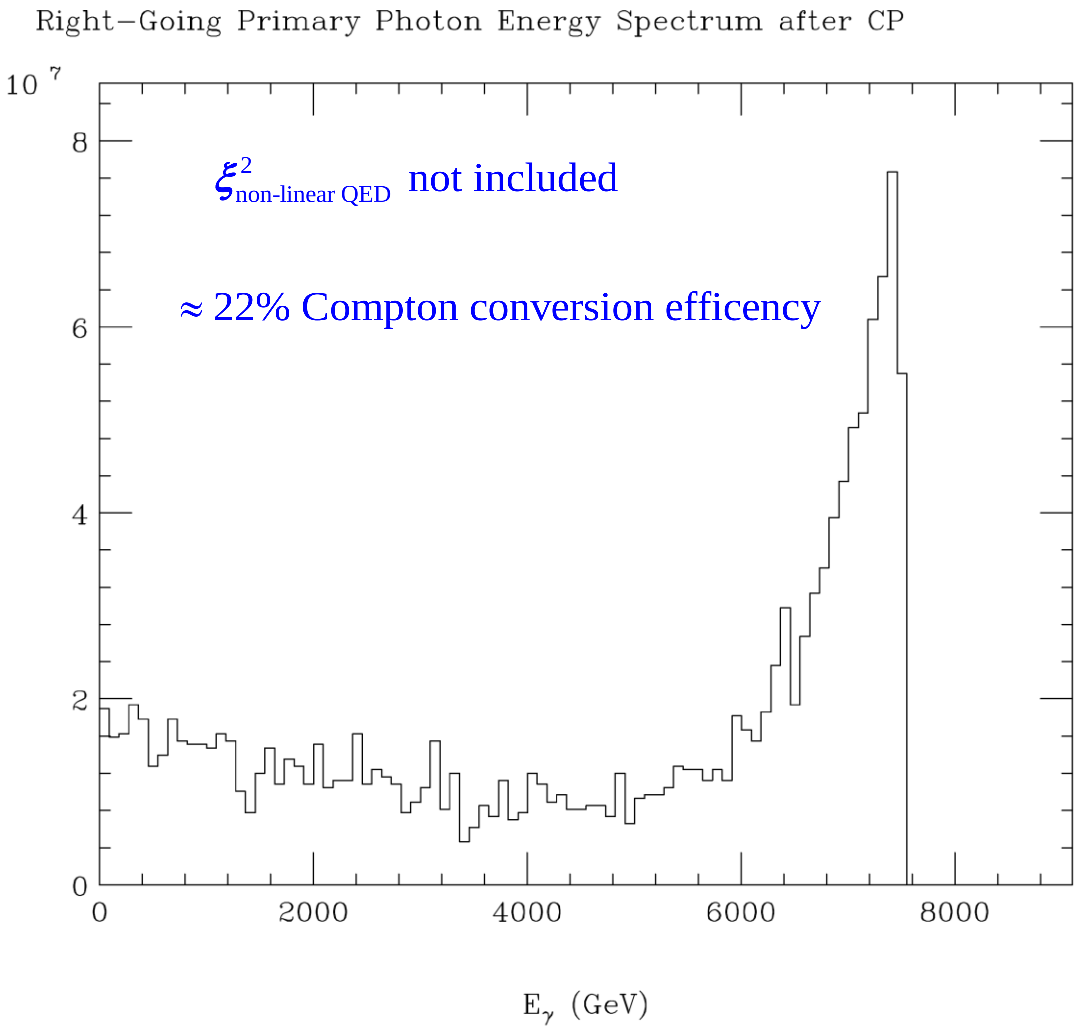


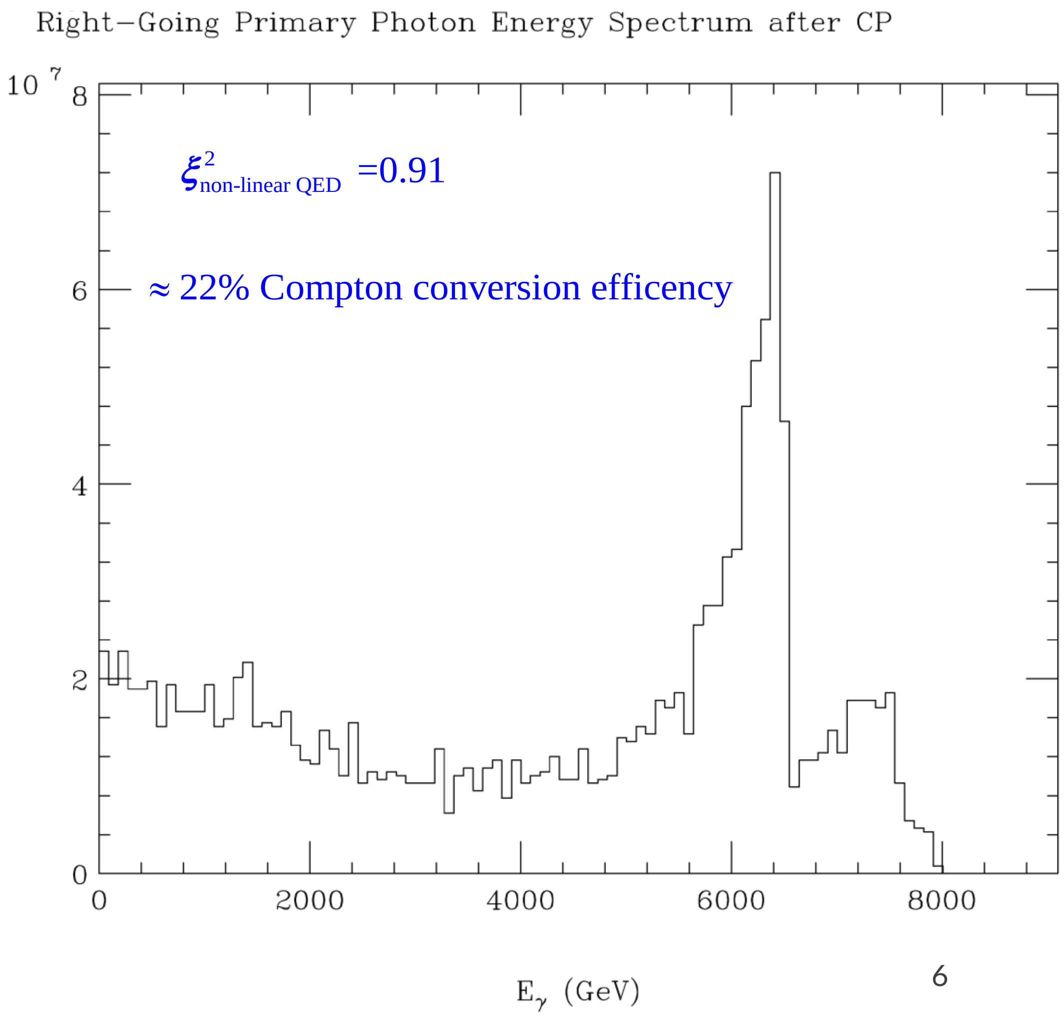


x=4.8 dial back E_{pulse} to get $\xi^2 < 1$

$x = 4.8 \Rightarrow$ 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





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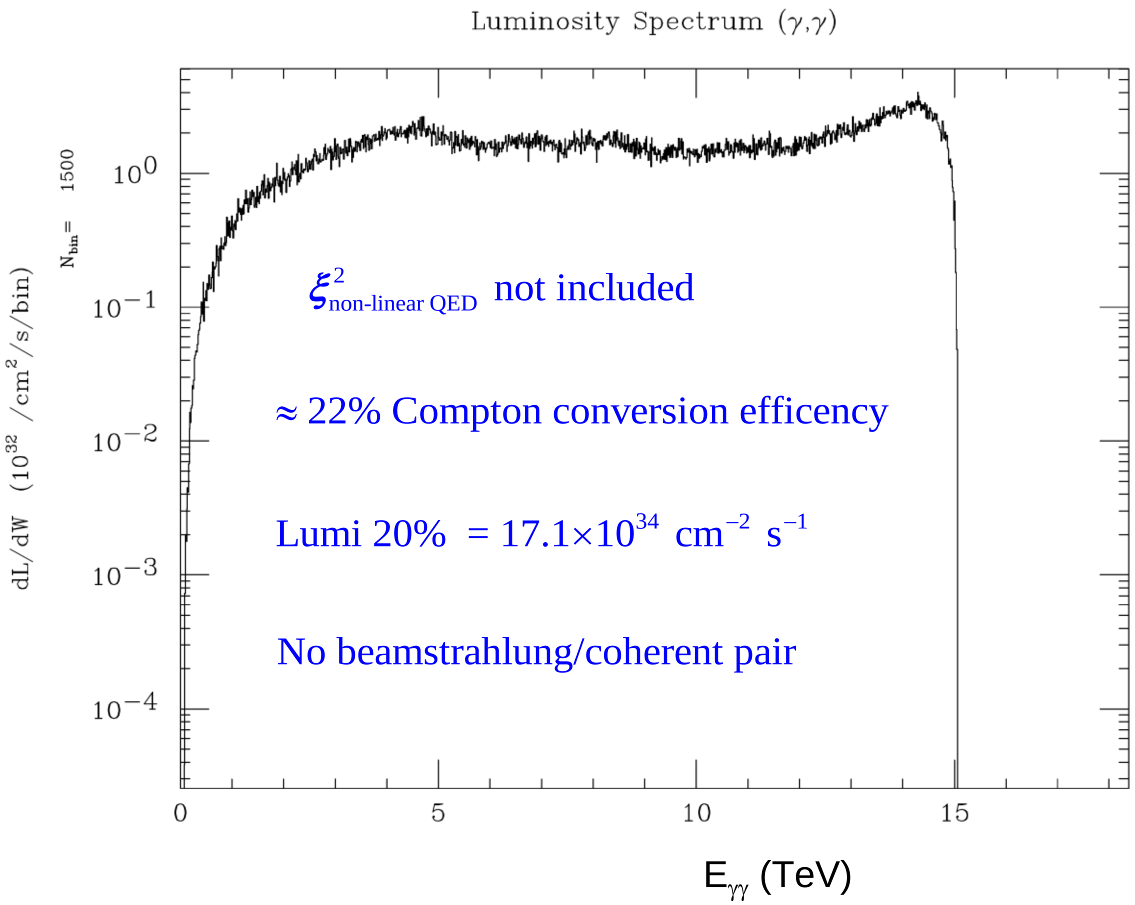
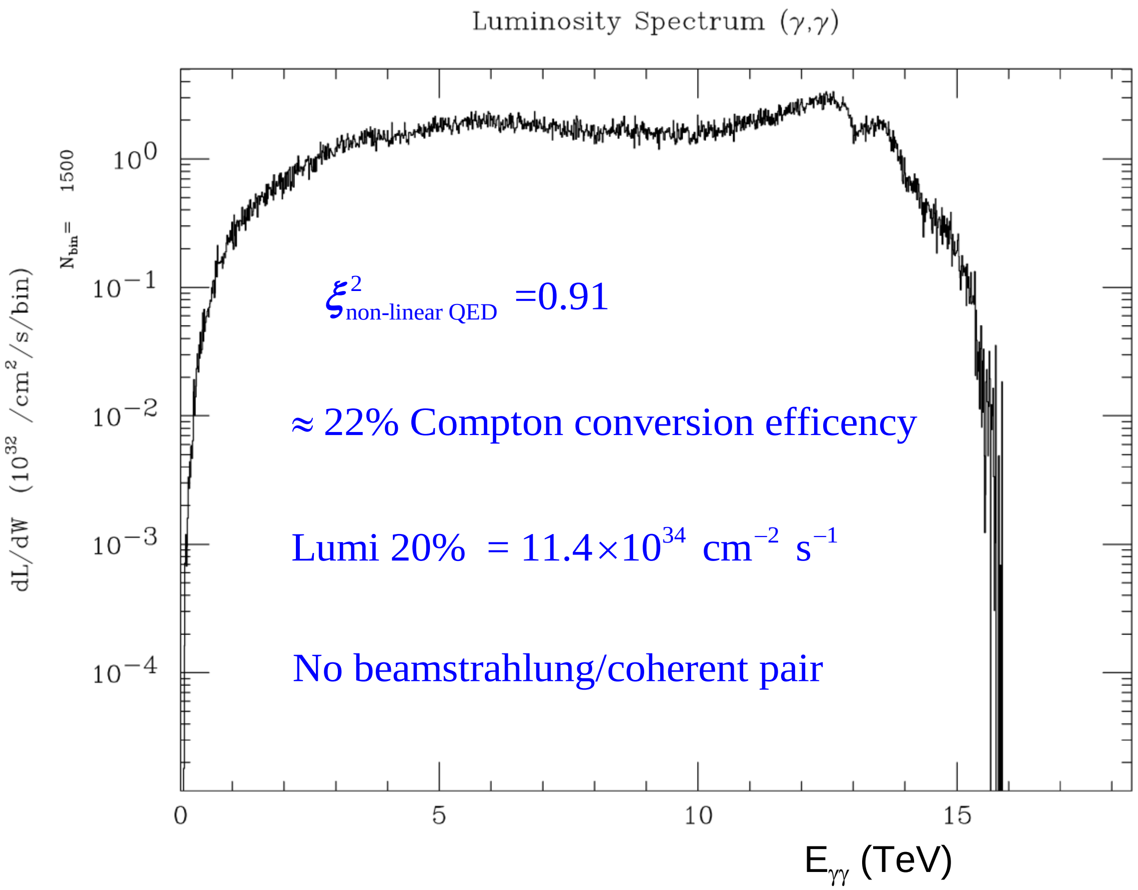
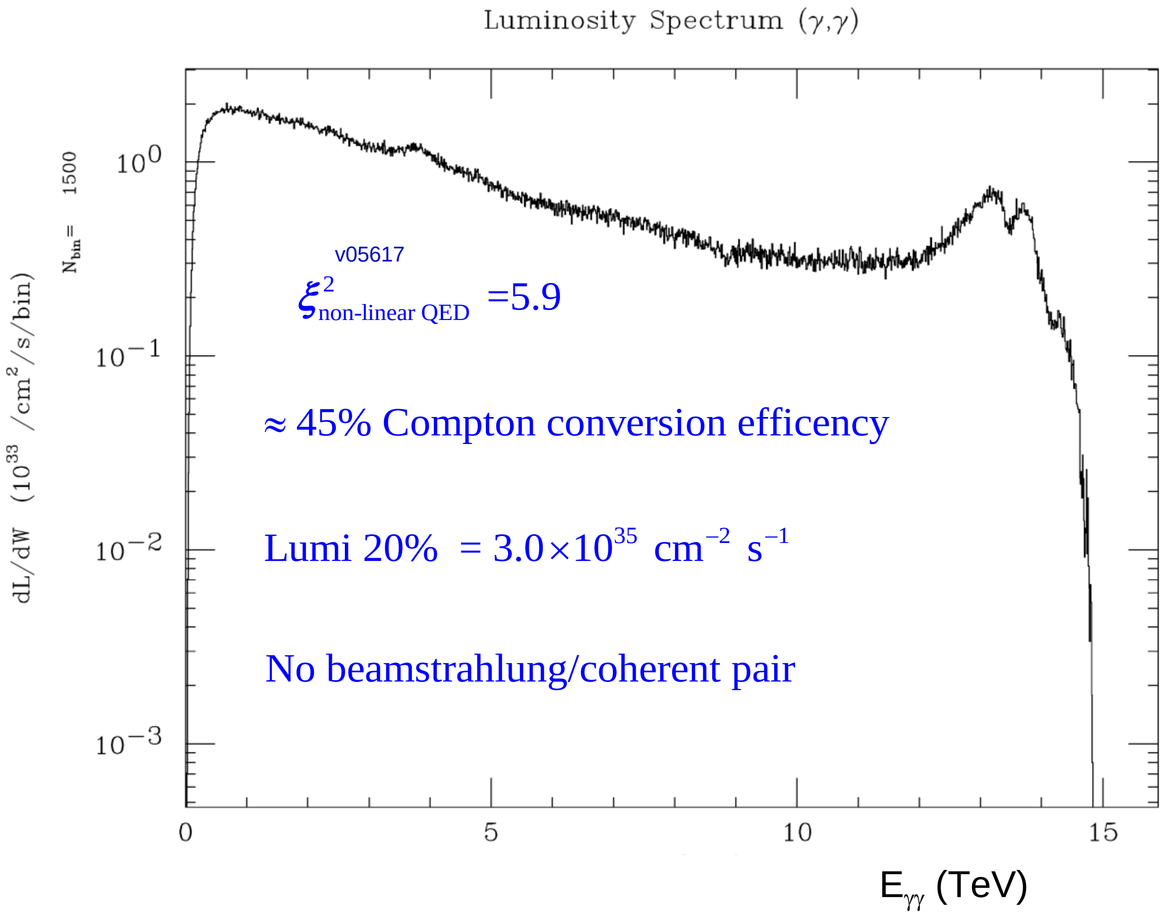




x=40 use spreadsheet bunch charge of N_e=5x10[9]

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

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



15 TeV and x=40 Turn on coherent processes

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

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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

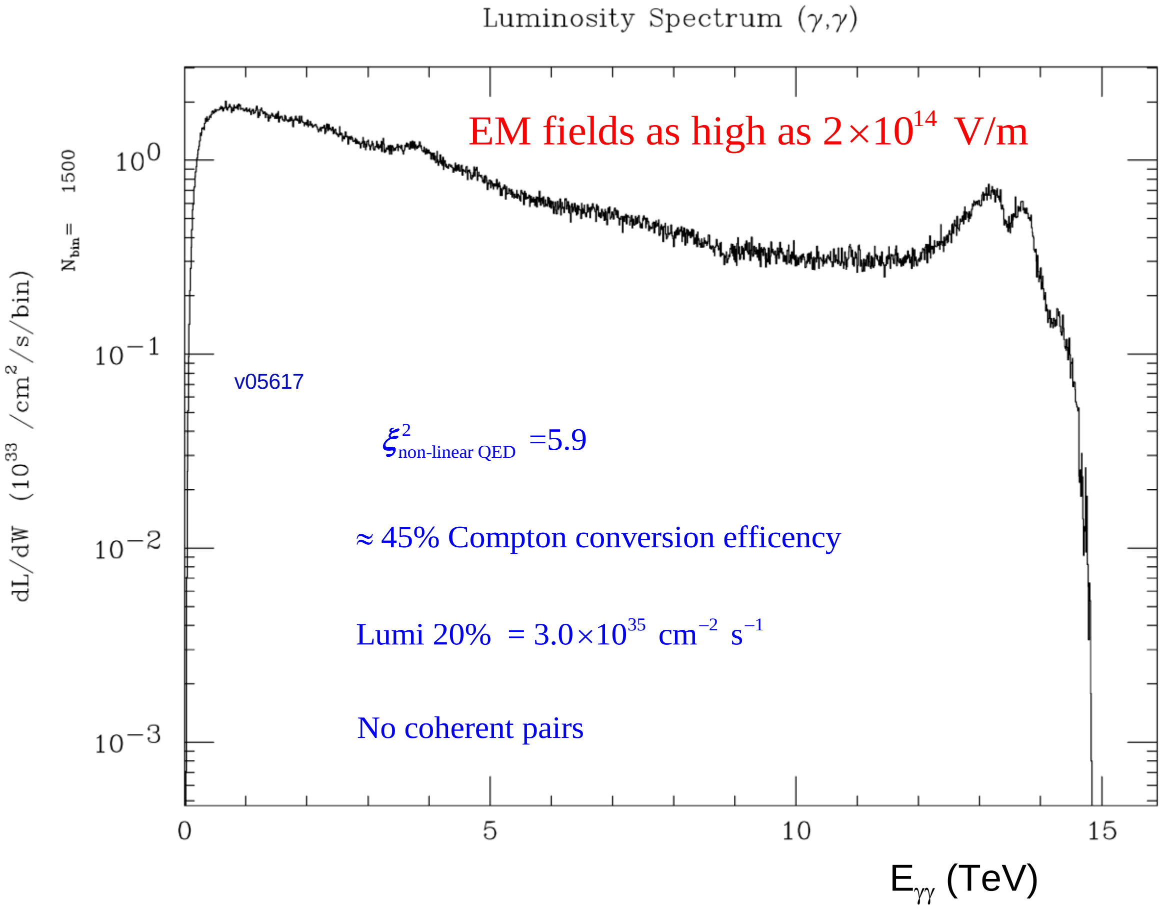
Solution:

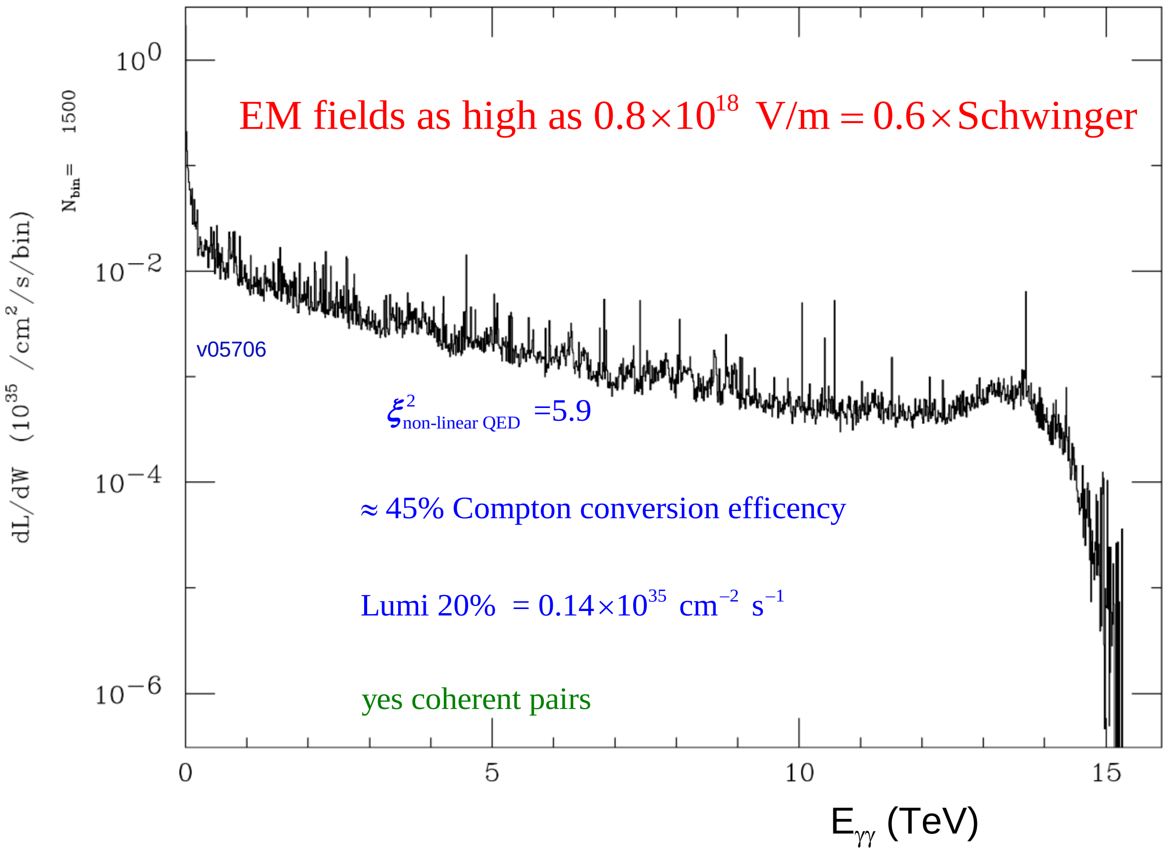
number of macro particles produced per coherent beamstrahlung photon = 1 → 0.01
number of pairs of macro particles produced per coherent e+e- pair = 1 → 0.0001
number of macro particles produced per incoherent particle = 1 → 0.01

15 TeV and x=40 Turn on coherent processes

$x = 40 \Rightarrow$ 7875 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

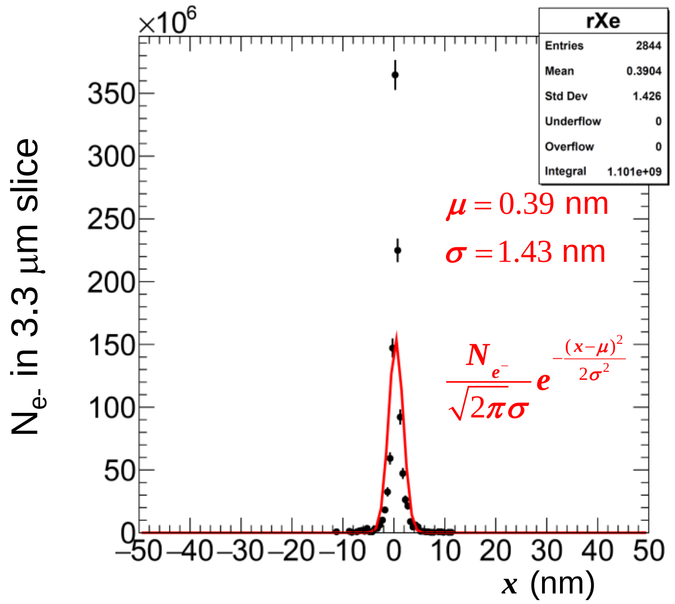
$\sigma_{ez} = 5\ \mu$m $N_{e^-} = 5\times10^9$ $\gamma\varepsilon_{x,y} = 120$ nm $2P_c\lambda_e = -0.9$ $E_{pulse} = 590$ J

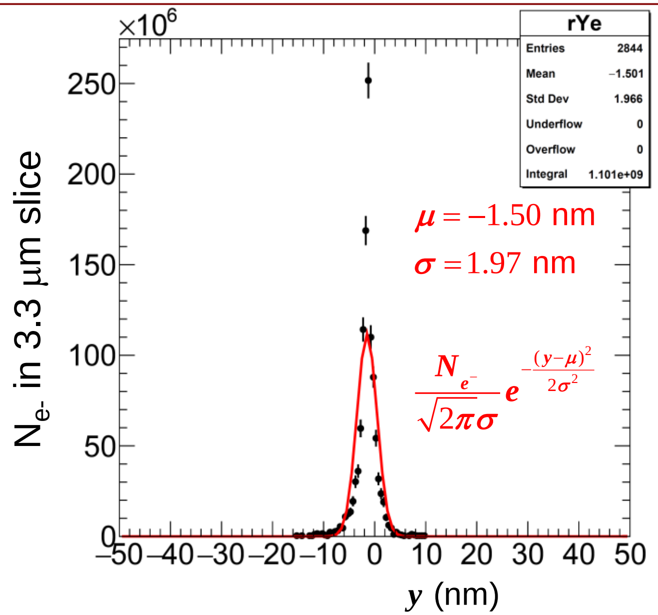


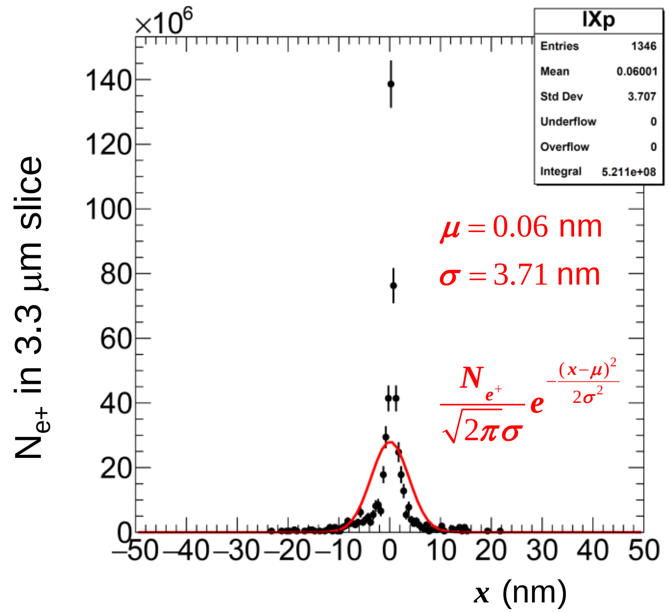


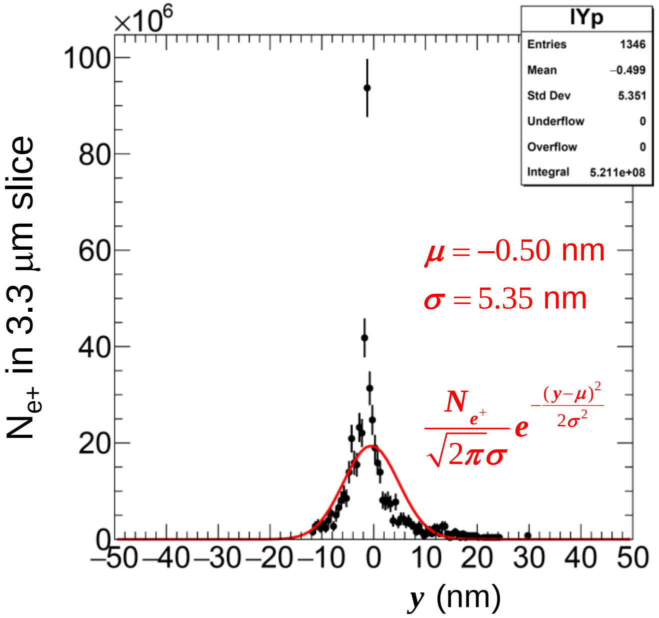
Coherent pair production eats up the 7.5 TeV photons and produces many e+ that pinch the e- beam leading to higher fields and even more coherent pair production.

$e^- \gamma$ 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.

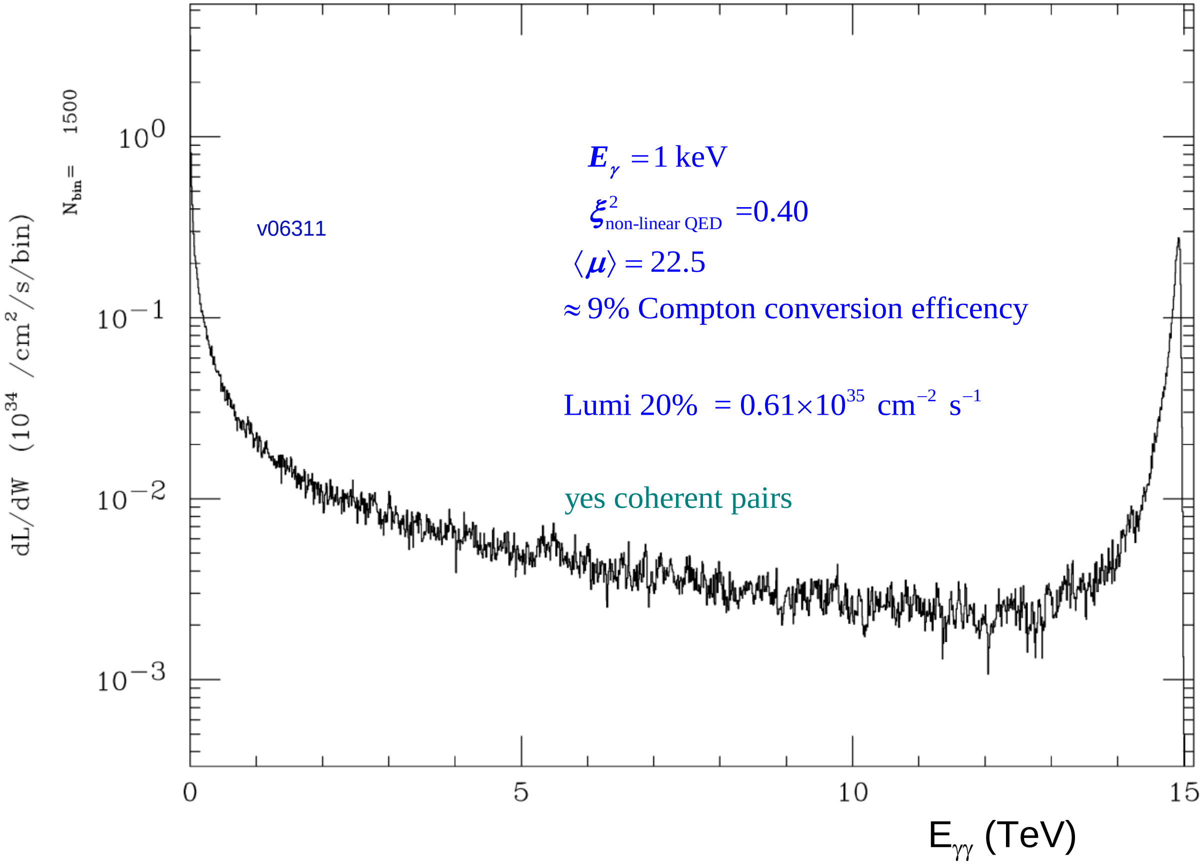
x=1.2x10^5 (1 keV γ) not affected as much by coherent processes

$x = 1.2\times10^5 \Rightarrow$ 7500 GeV $e^- +$ 1 keV γ (λ=1.2 nm)

$a_{\gamma FWHM} = 70$ mm $\quad \sigma_{\gamma z} = 5\ \mu$m $\quad d_{cp} = 15\ \mu$m

$\sigma_{ez} = 5\ \mu$m $\quad N_{e^-} = 6\times10^9 \quad \gamma\varepsilon_{x,y} = 120$ nm

$2P_c\lambda_e = +0.9 \qquad E_{pulse} = 0.72$ J



$x = 40 \Rightarrow$ 7875 GeV $e^- +$ 0.33 eV γ (λ=3.7 μm)

$a_{\gamma FWHM} = 0.24$ mm $\quad \sigma_{\gamma z} = 270\ \mu$m $\quad d_{cp} = 0.82$mm

$\sigma_{ez} = 5\ \mu$m $\quad N_{e^-} = 5\times10^9 \quad \gamma\varepsilon_{x,y} = 120$ nm

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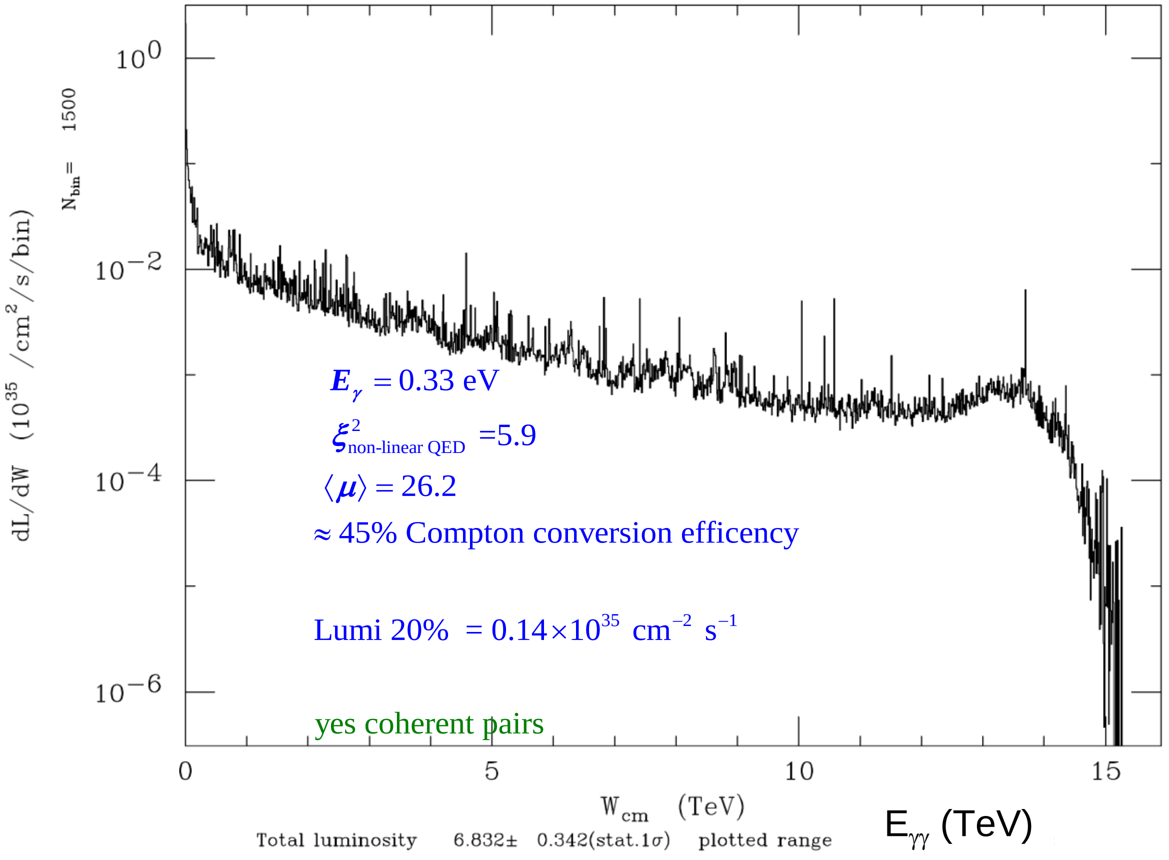
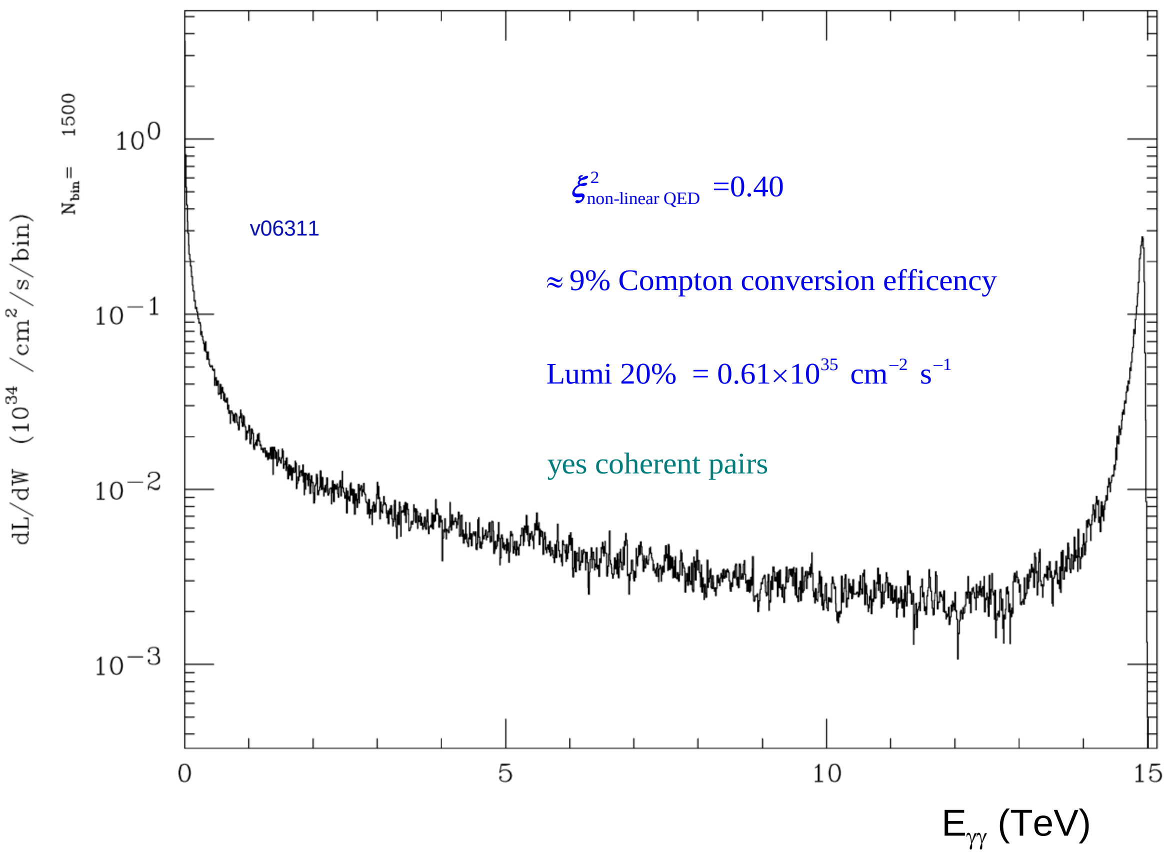


$\gamma\gamma \rightarrow N \times e^+e^-$, $e^-\gamma \rightarrow e^- + N \times e^+e^-$, $N = 2,3, \ldots$

$x = 1.2\times10^5 \Rightarrow$ 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



$\gamma\gamma \rightarrow N \times e^+e^-$, $e^-\gamma \rightarrow e^- + N \times e^+e^-$, $N = 2,3, \ldots$ are not simulated by CAIN.

$N \geq 2$ cross sections relatively small for $x \leq 1000$, but what about at $x \sim 10^5$?

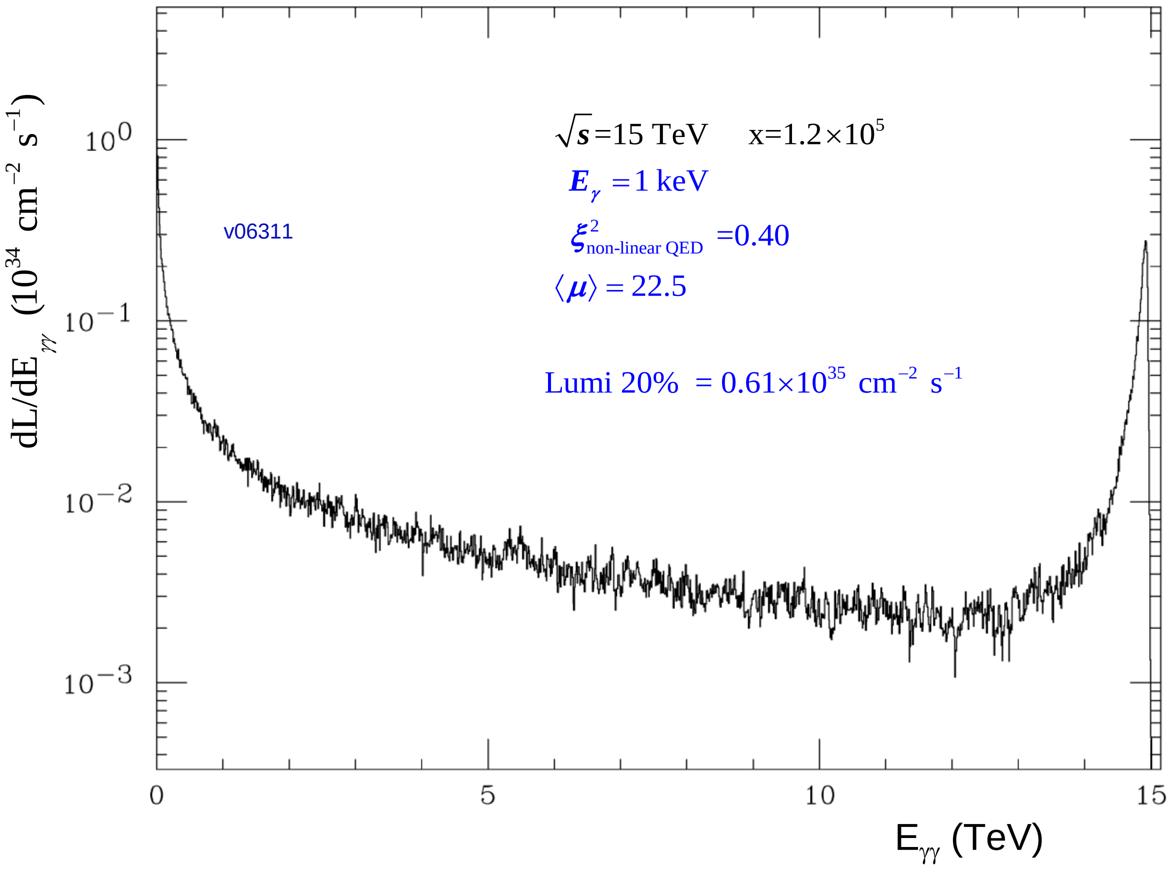
Cross section Table for 1 keV laser γ calculated using Tree-level MC Integration:

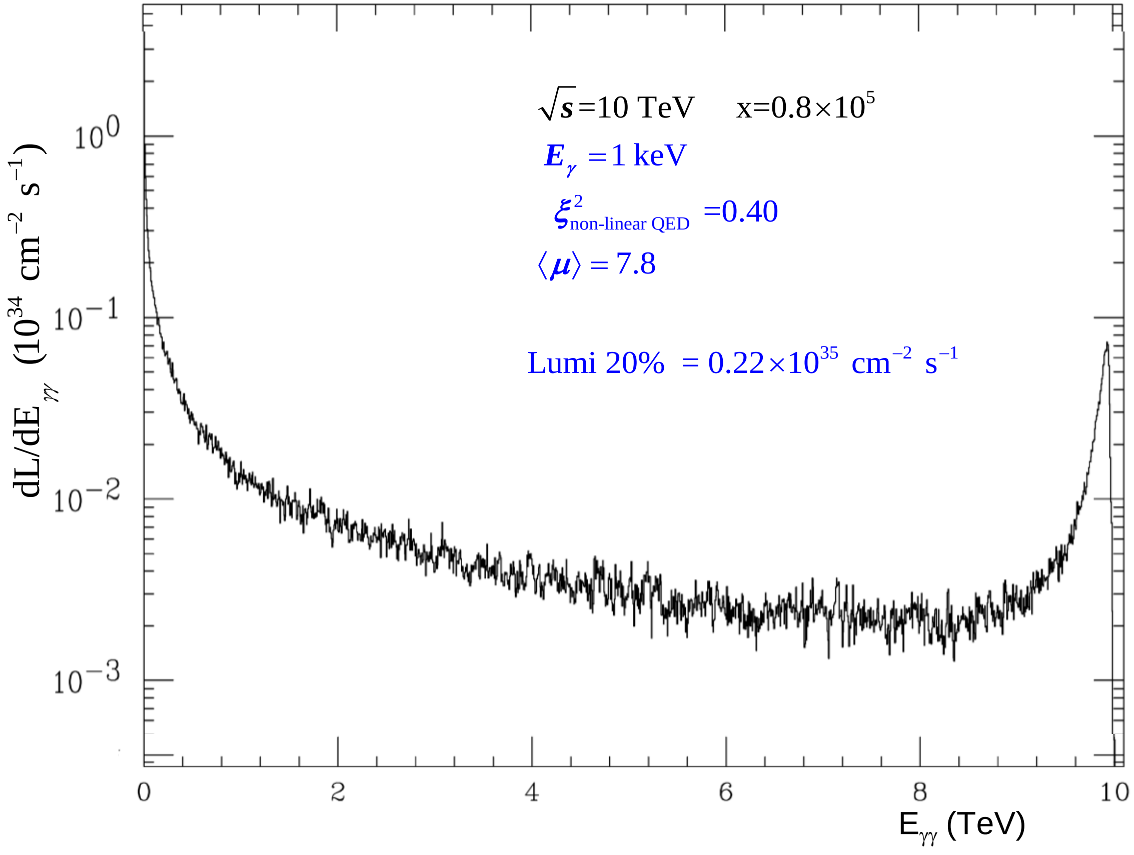
Note: processes colored red are included in the CAIN MC

process	E_{e^-} (GeV)/x = 62.6 / 1000	E_{e^-} (GeV)/x = 5000 / 80,000	E_{e^-} (GeV)/x = 7500 / 120,000
$\gamma\gamma \rightarrow e^+e^-$	$2.16\times10^{12} \pm 0.03\%$	$2.68\times10^{10} \pm 0.07\%$	
$\gamma\gamma \rightarrow e^+e^-e^+e^-$	$3.26\times10^{9} \pm 0.27\%$	$5.70\times10^{9} \pm 0.92\%$	
$\gamma\gamma \rightarrow e^+e^-e^+e^-e^+e^-$		$2.33\times10^{4} \pm 11.9\%$	
$e^-\gamma \rightarrow e^-e^+e^-$	$8.22\times10^{12} \pm 0.22\%$	$9.55\times10^{11} \pm 13.4\%$	$4.61\times10^{10} \pm 30.4\%$
$e^-\gamma \rightarrow e^-e^+e^-e^+e^-$	$1.63\times10^{7} \pm 0.78\%$	$5.68\times10^{6} \pm 21.1\%$	$7.47\times10^{5} \pm 17.4\%$

The relative MC integration statistical error increases for $x \sim 10^5$ but it is good enough to demonstrate that the $N = 1$ processes still dominate at $x \sim 10^5$ and therefore the current CAIN MC is valid.

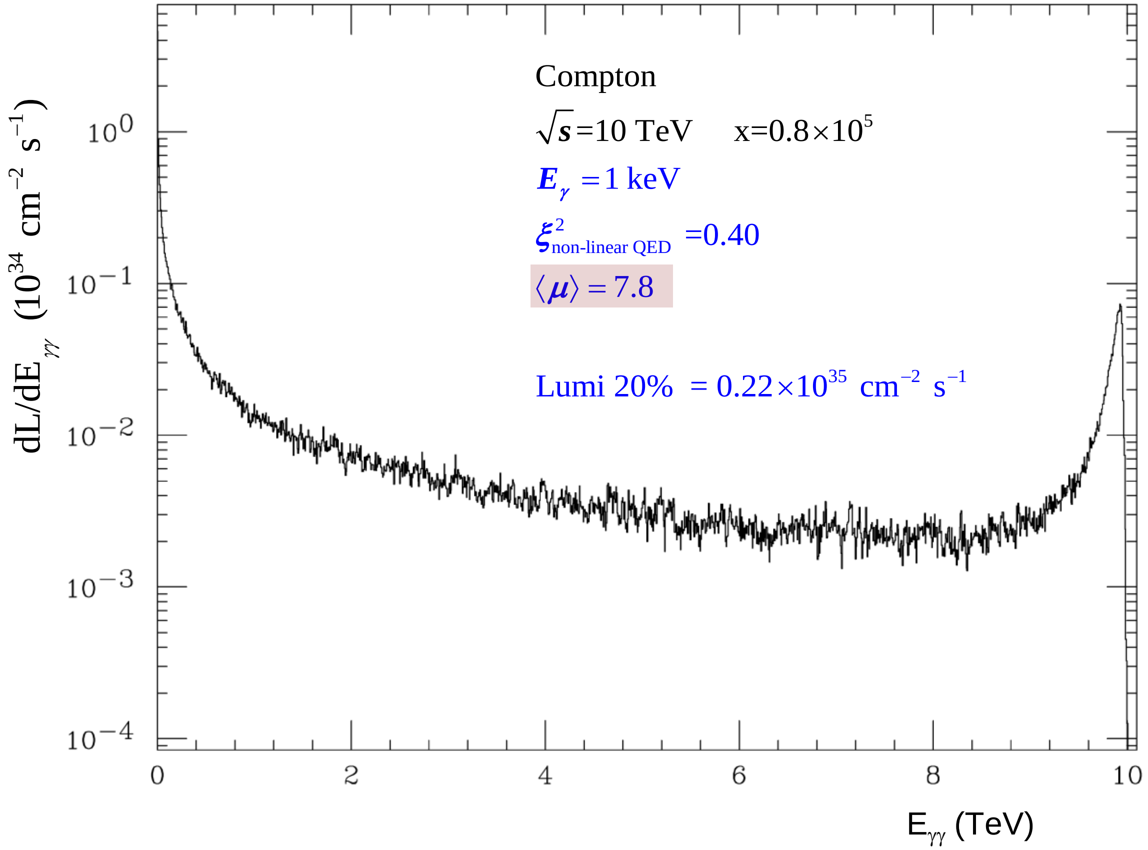
Compare 15 and 10 TeV



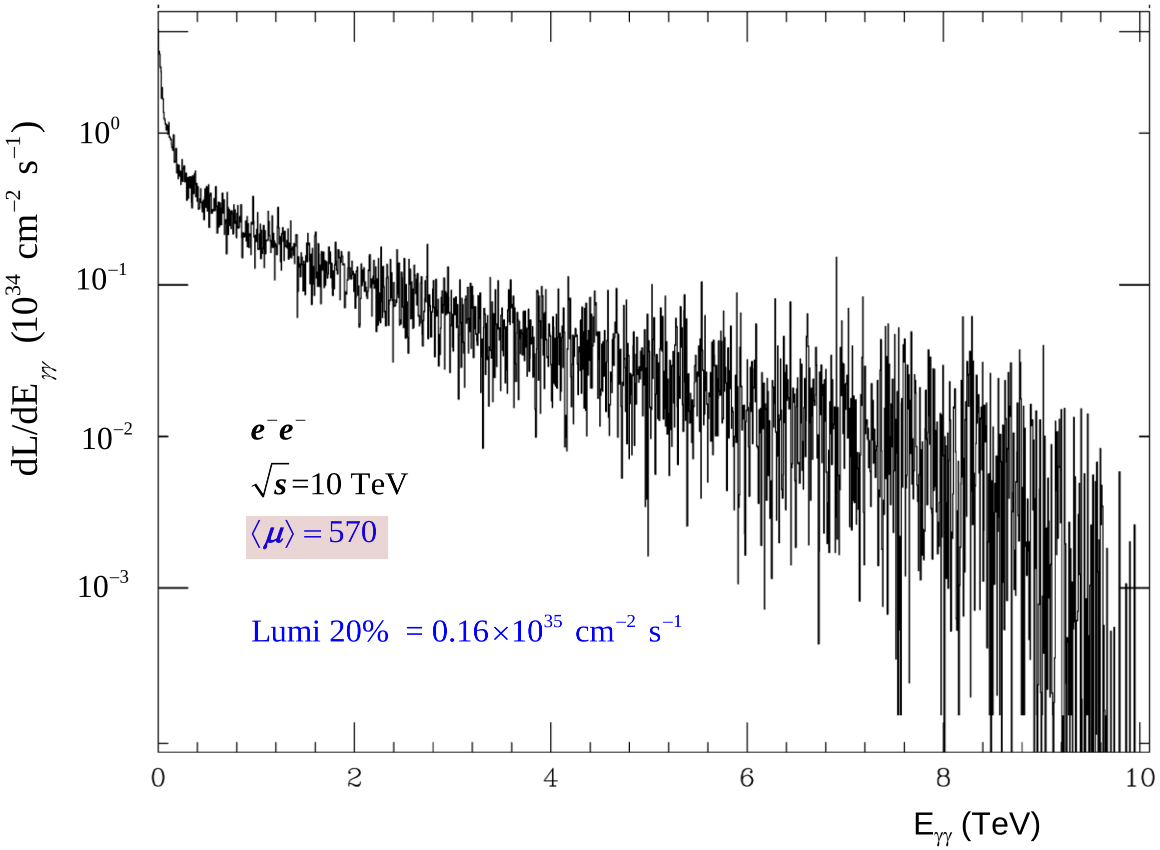


10 TeV $\gamma\gamma$ Luminosity: Compton vs e^-e^- Collider

Compton Collider



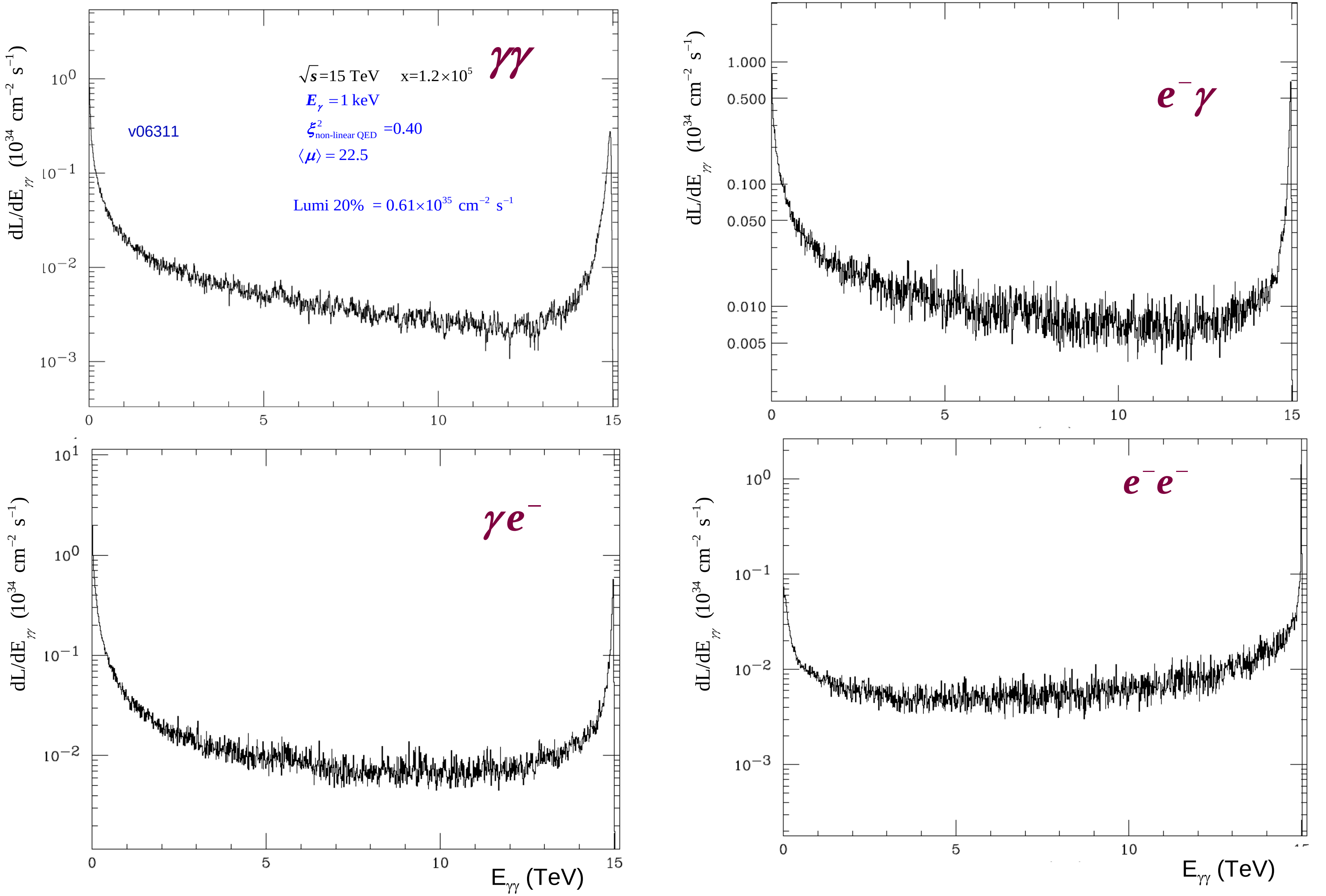
e^-e^- Collider



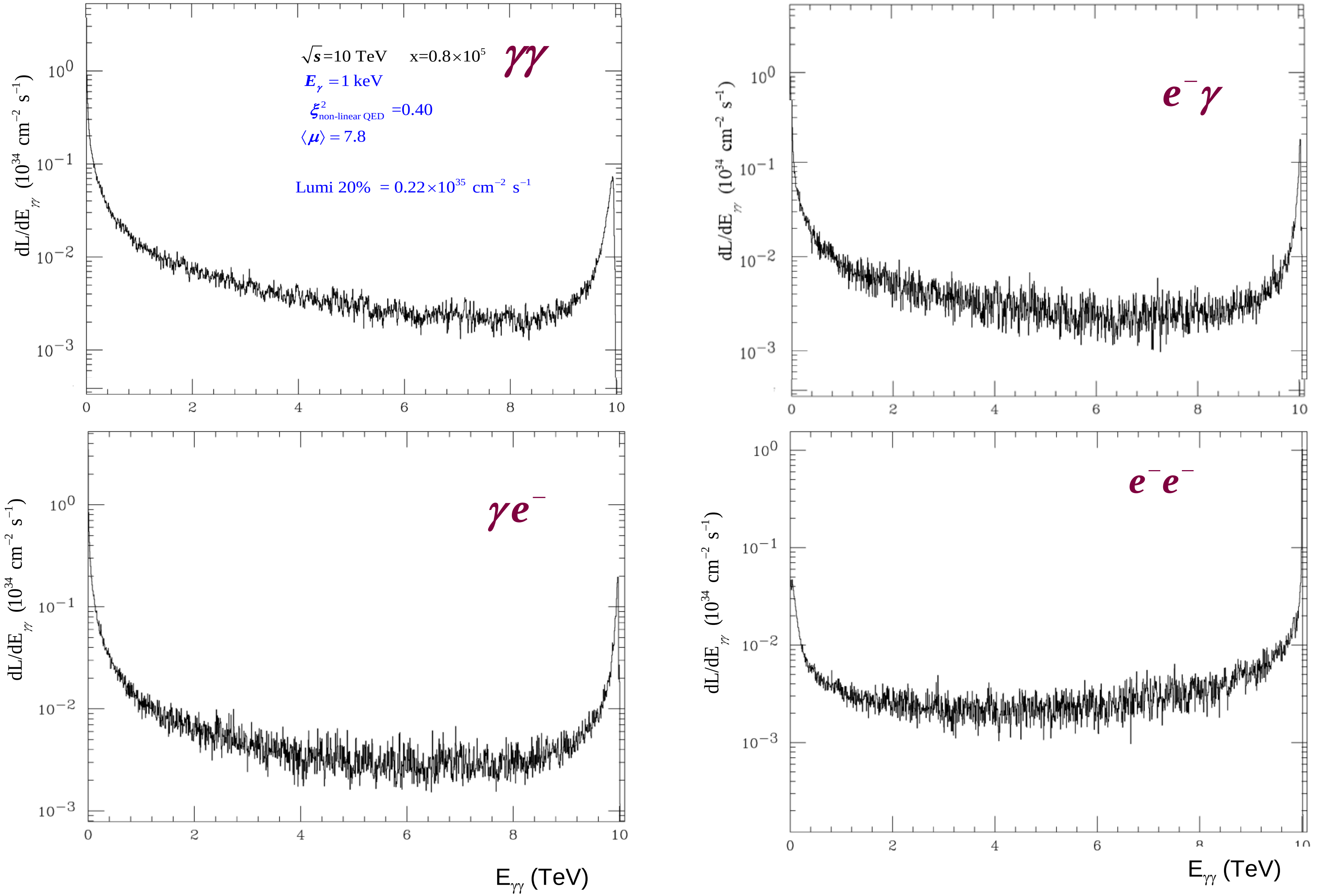
The top 20% Compton $\gamma\gamma$ Lumi is only 38% larger than the top 20% from e^-e^- beamstrahlung.

But the pileup for the e^-e^- is $\langle\mu\rangle = 570$ which is not too different from FCC-hh $\langle\mu\rangle = 1000$

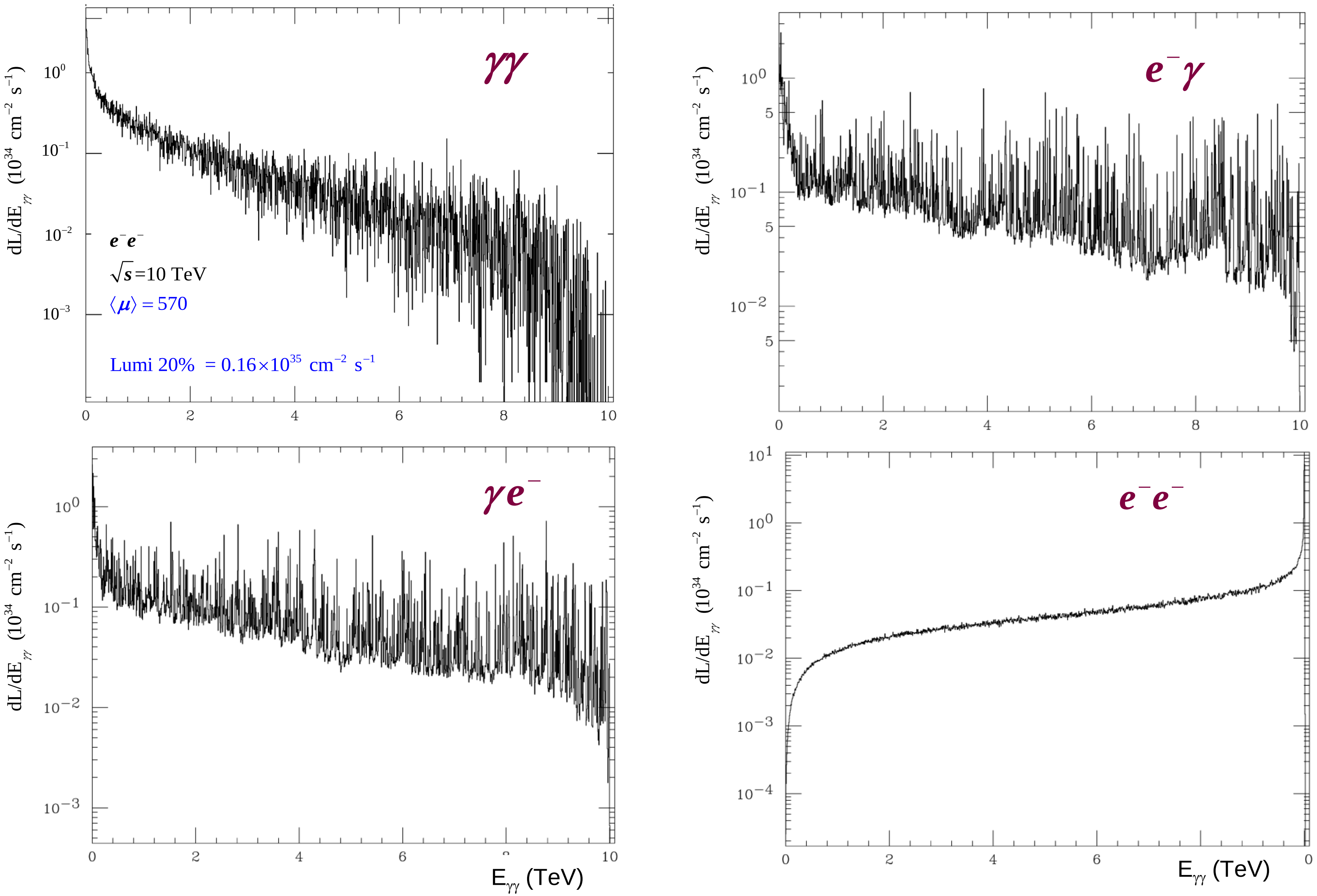
15 TeV Compton Collider $\gamma\gamma$ $e^-\gamma$ γe^- e^-e^-



10 TeV Compton Collider $\gamma\gamma$ $e^-\gamma$ γe^- e^-e^-



10 TeV e^-e^- Collider $\gamma\gamma$ $e^-\gamma$ γe^- e^-e^-



Summary

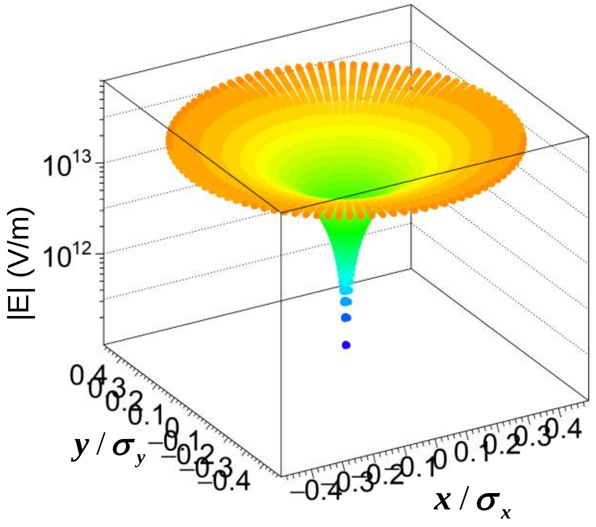
Working with a fixed, specific set of round electron beam parameters (varying only the beam energy as needed):

- Not surprisingly, it is not straightforward to extrapolate a Compton $\sqrt{s}=125$ GeV $\gamma\gamma$ collider to 10 or 15 TeV
- A value of $x = 4.8$ requires e^-e^- E_{cm}=18.2 TeV for E_{cm}=15 TeV $\gamma\gamma$ and has very broad lumi spectrum
- A value $x =$ 40 requires e^-e^- E_{cm}=15.6 TeV for E_{cm}=15 TeV $\gamma\gamma$. But when coherent processes are considered, EM fields produced by the tightly focused e^- beams lead to significant coherent beamstrahlung and e^+e^- pair-production for moderate values of x This is excaberated by the produced e^+ which pinch the e^- beams leading to even higher EM fields. These effects serve to diminish the $\gamma\gamma$ luminosity in the top 20% of the $\sqrt{\hat{s}}$ distribution. The mean number of pileup events is 26.2 (defined to include all events down to $\pi\pi$ threshold of $\sqrt{\hat{s}} = 0.3$ GeV).
- A multi-TeV $\gamma\gamma$ collider with extremely large values of $x \approx 10^5$, corresponding to soft x-ray Compton scattering, does not suffer as much from coherent processes. This is due to a larger number of trident processes $e^-\gamma \rightarrow e^-e^+e^-$ It also gives the largest top 20% luminosity among the configurations considered so far, and has an e^+e^-/XCC-like luminosity spectrum with a relatively narrow peak near the maximum center-of-mass energy. The mean number of pileup events is 22.5 (defined to include all events down to $\pi\pi$ threshold of $\sqrt{\hat{s}} = 0.3$ GeV).

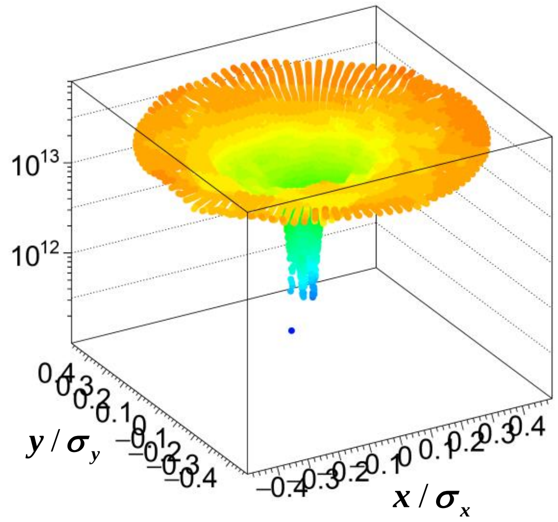
Backup

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

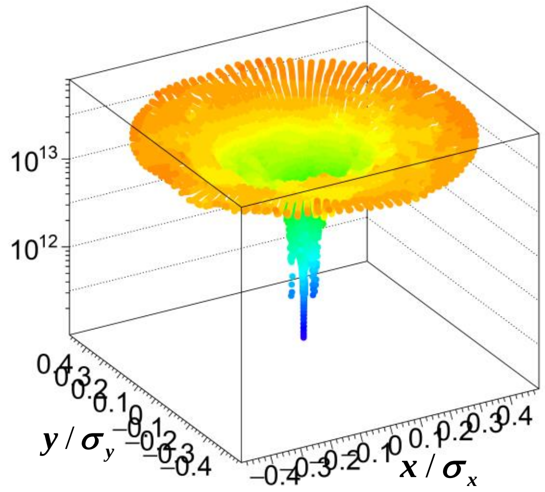
Bassetti-Erskine
$(0,0) =$ center of charge distribution



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

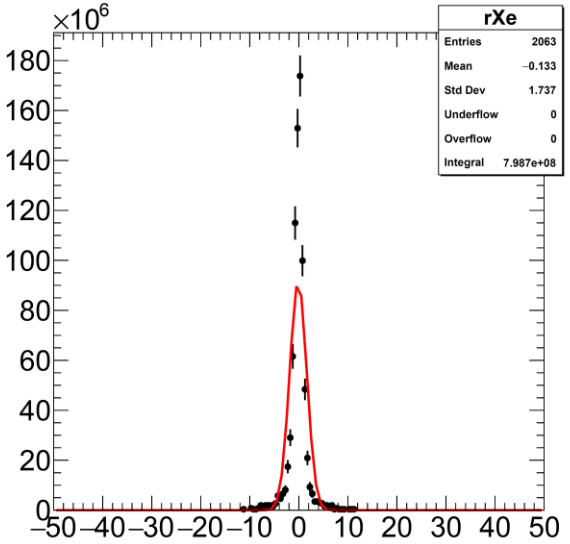


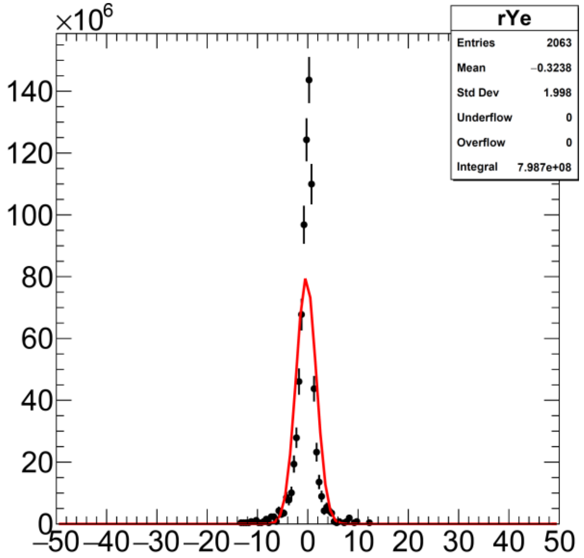
CAIN
$(0,0) =$ EM field minimum



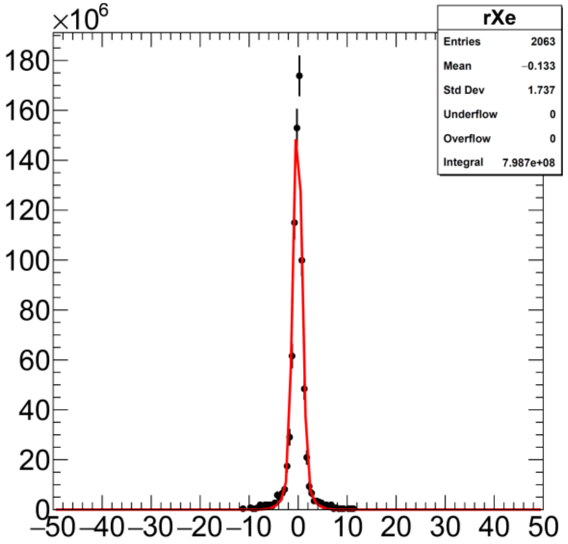
Replace CAIN EM FFT EM Field Calculation with Bassetti-Erskine 2d Gaussian Expression

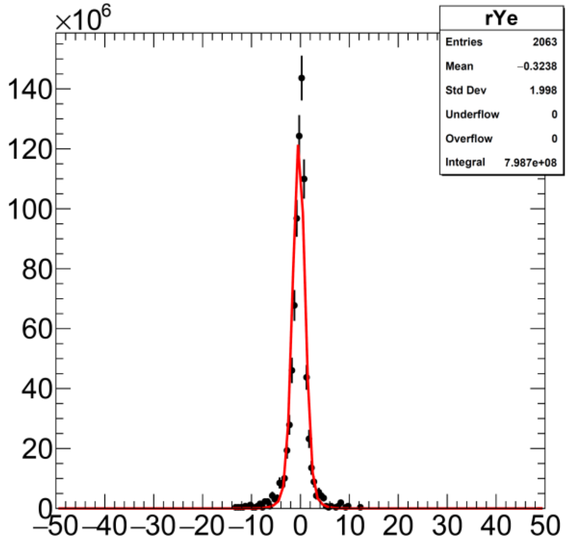
Bassetti-Erskine 1 Gaussian





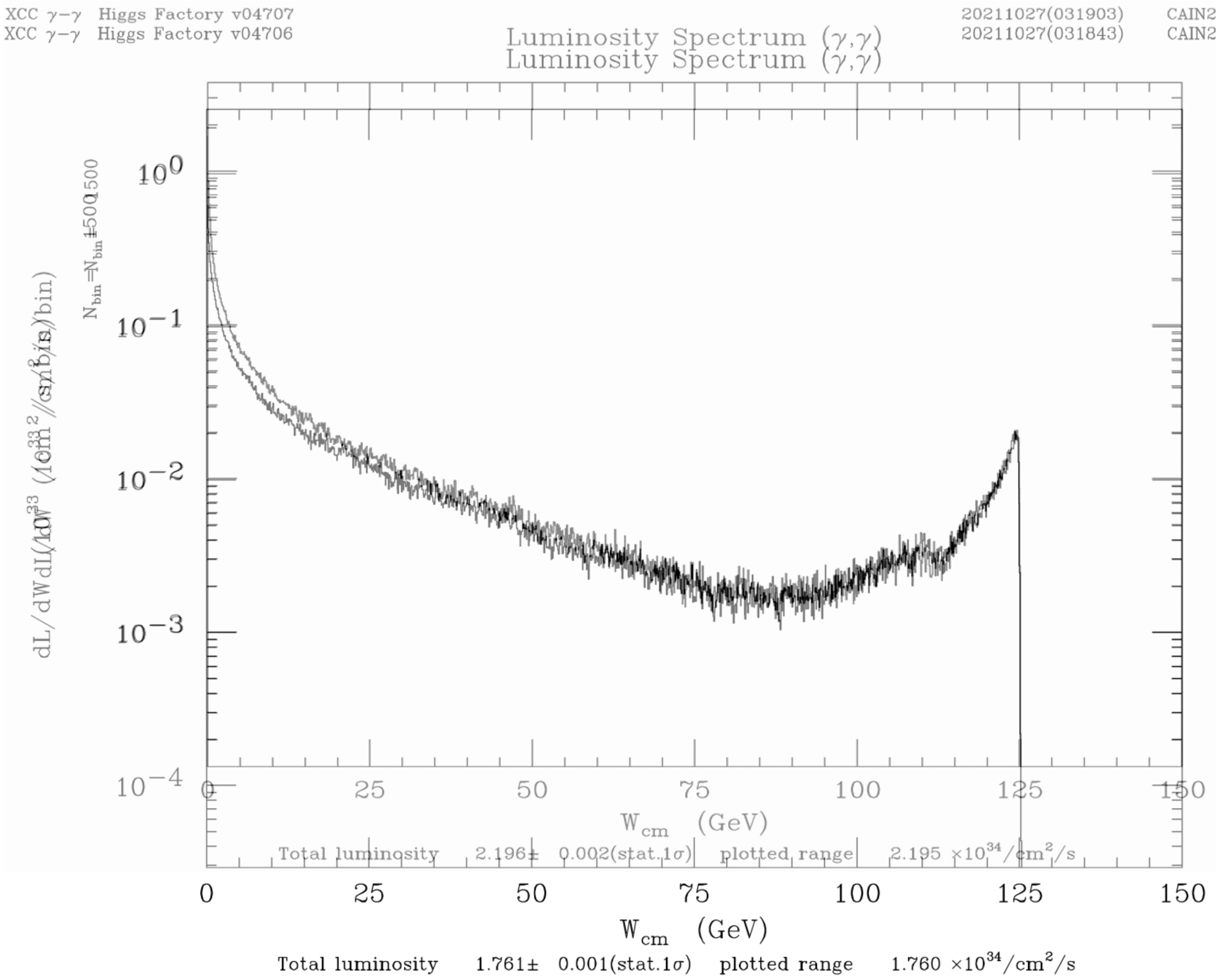
Bassetti-Erskine 2 Gaussians





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