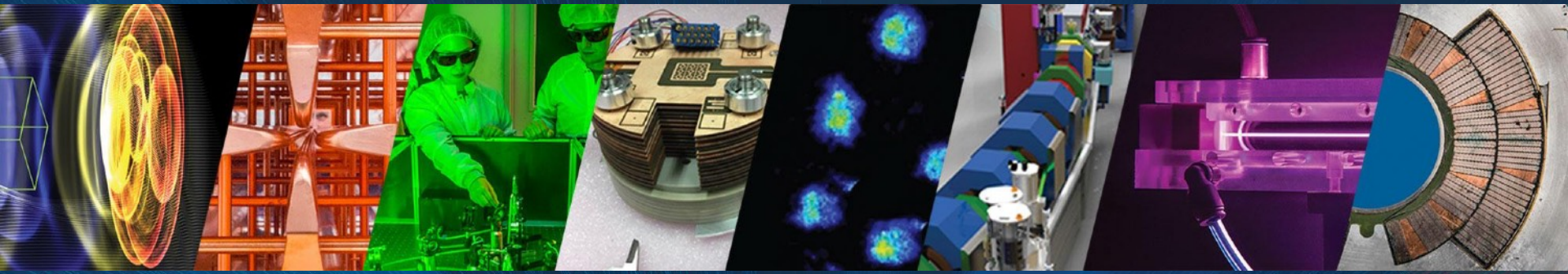
Enhancing 10 TeV gamma-gamma collider luminosity through scattering laser wavelength selection in the presence of prolific electron-positron pair production.



Stepan Bulanov, C. Benedetti, Arianna Formenti, Remi Lehe, Simon Knapen, Christiane Schreb, Simone Pagan Griso, Angira Rastogi, Carl Schroeder, Jens Osterhoff
Lawrence Berkeley National Laboratory, Berkeley, California, USA

T. Barklow, S. Gessner, and A. Schwartzman
SLAC National Accelerator Laboratory, Menlo Park, California, USA

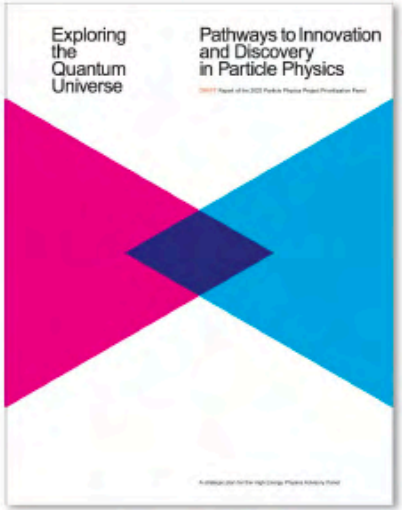
BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

Wakefield acceleration for 10 TeV pCM collider

P5 prioritizes accelerator R&D toward a future 10 TeV pCM collider



P5 Report (2023)

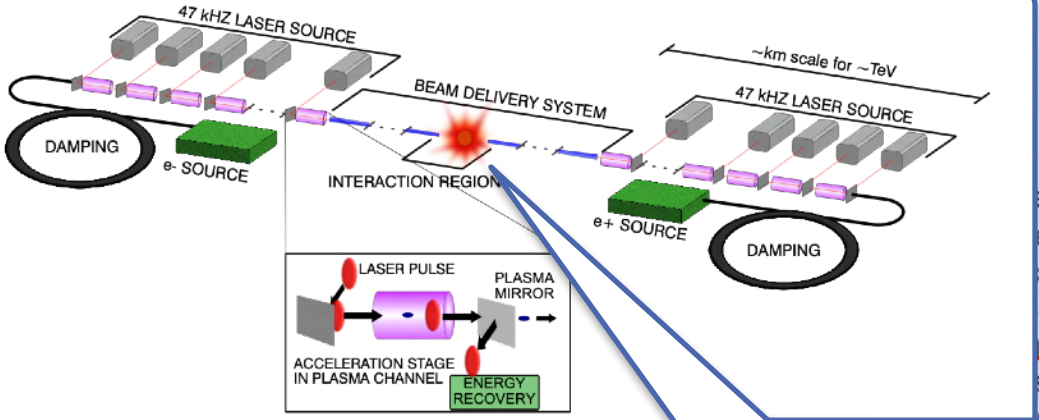
The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM) collider** to search for direct evidence and quantum imprints of new physics at unprecedented energies. Turning this concept into a cost-effective, realistic collider design demands that we aggressively develop multiple innovative accelerator and detector technologies. This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Investing in the future of the field to fulfill this vision requires the following:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5 and Recommendation 6).

Wakefield acceleration for 10 TeV pCM collider





P5 Report (2023)

a future 10 TeV pCM collider

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e collider concept: a **10 TeV parton center-of-mo-**
h for direct evidence and quantum imprints of new
. Turning this concept into a cost-effective, realistic
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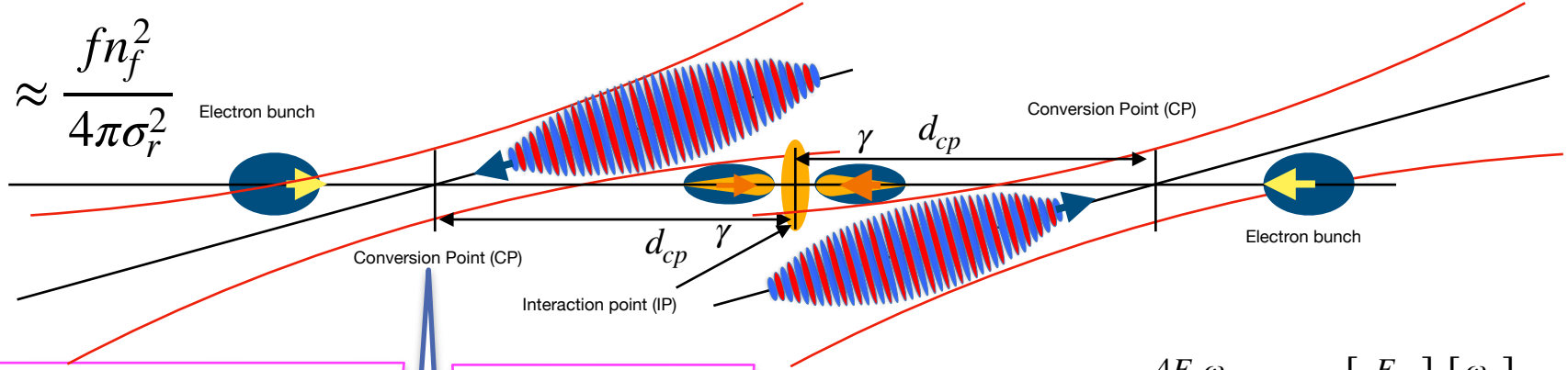
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A number of operational scenarios is being considered for a 10 TeV wake-field based energy frontier collider, namely, **electron-positron, electron-electron, and** $\gamma\gamma$ ones:

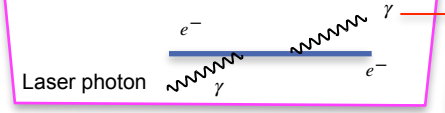
Gessner et.al., "Design Initiative for a 10 TeV pCM Wakefield Collider", arXiv:2503.20214

What is a gamma-gamma collider and how it operates?

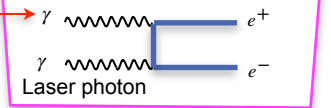
$$L_{geo}^{ff} \approx \frac{f n_f^2}{4\pi\sigma_r^2}$$

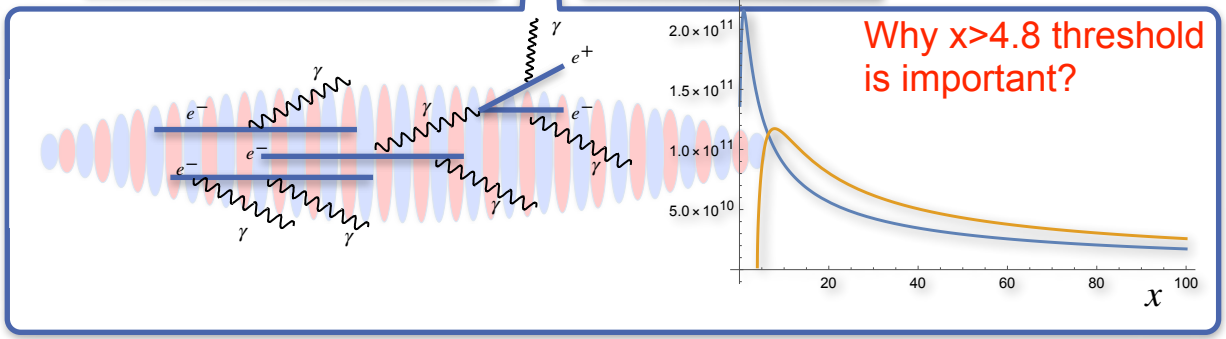


Compton Scattering and



Breit-Wheeler pair production (?)





Why x>4.8 threshold is important?

$$x \approx \frac{4E_0\omega_0}{m^2c^4} \approx 15.3\left[\frac{E_0}{TeV}\right]\left[\frac{\omega_0}{eV}\right]$$

$$\omega'_m = \frac{x}{x+1}E_0 \qquad \omega' = \frac{\omega'_m}{1+(\theta/\theta_0)^2}$$

$$\theta_0 = \frac{\sqrt{x+1}}{\gamma_e}$$

$E_0 = 250$ GeV

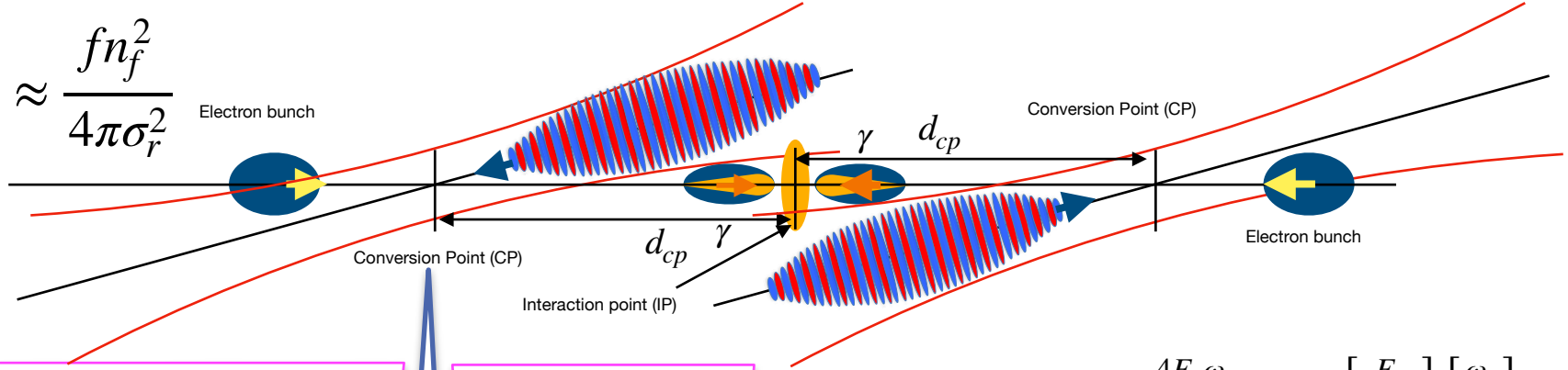
$\omega_0 = 1.17$ eV

$x = 4.5$

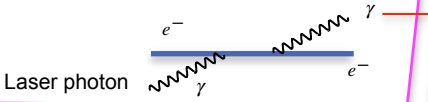
$\omega'_m/E_0 = 0.82$

What is a gamma-gamma collider and how it operates?

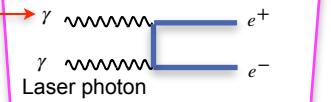
$$L_{geo}^{ff} \approx \frac{f n_f^2}{4\pi\sigma_r^2}$$

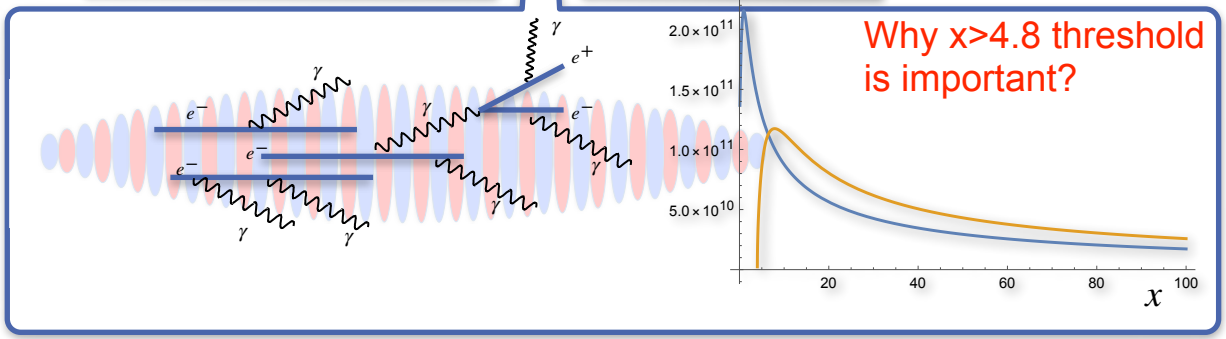


Compton Scattering and



Breit-Wheeler pair production (?)





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$$x \approx \frac{4E_0\omega_0}{m^2c^4} \approx 15.3\left[\frac{E_0}{TeV}\right]\left[\frac{\omega_0}{eV}\right]$$

$$\omega_m' = \frac{x}{x+1}E_0 \qquad \omega' = \frac{\omega_m'}{1+(\theta/\theta_0)^2}$$

$$\theta_0 = \frac{\sqrt{x+1}}{\gamma_e}$$

$E_0 = 5$ TeV

$\omega_0 = 1.17$ eV

$x = 90$

$\omega_m'/E_0 = 0.99$

Why $\gamma\gamma$-option is interesting?

I.Ginzburg, G.Kotkin, V.Serbo, V.Telnov, On possibility of obtaining gamma-gamma, gamma-electron beams with high energy and luminosity, Pizma ZhETF 34 (1981) 514; JETP Lett. 34 (1982) 91

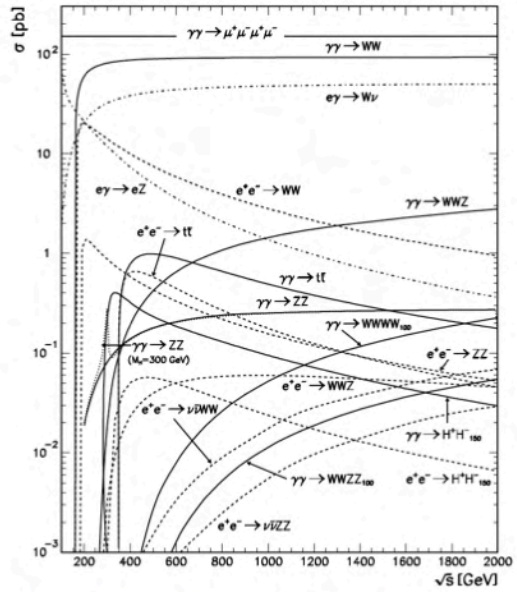


Fig. 2. Typical cross-sections in $\gamma\gamma$, γe and e^+e^- collisions. The polarization is assumed to be zero. Solid, dash-dotted and dashed curves correspond to $\gamma\gamma$, γe and e^+e^- modes respectively. Unless indicated otherwise the neutral Higgs mass was taken to be 100 GeV. For charged Higgs pair production, $M_{H^\pm} = 150$ GeV was assumed.

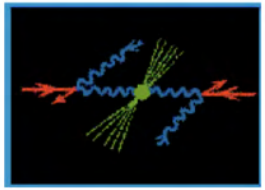
TESLA

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

Technical Design Report

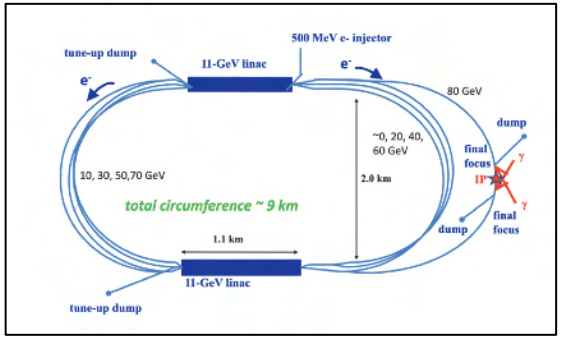
Part VI: Appendices

Chapter 1: Photon Collider at TESLA

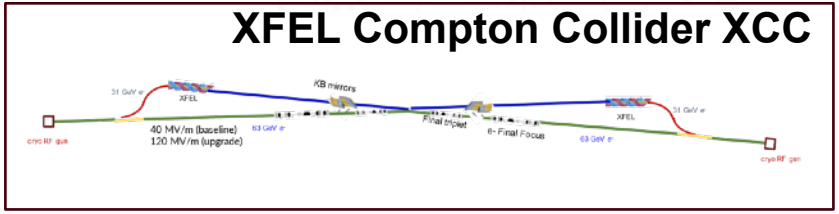


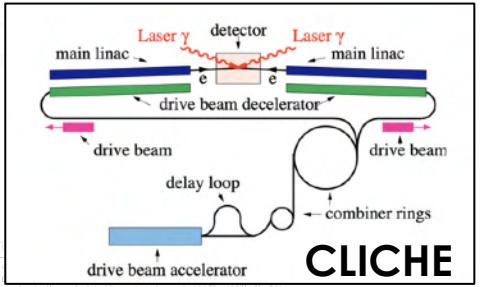
DESY-2001-011, ECFA-2001-209
TESLA-2001-23, TESLA-FEL-2001-05
March 2001

SAPPHiRE



XFEL Compton Collider XCC

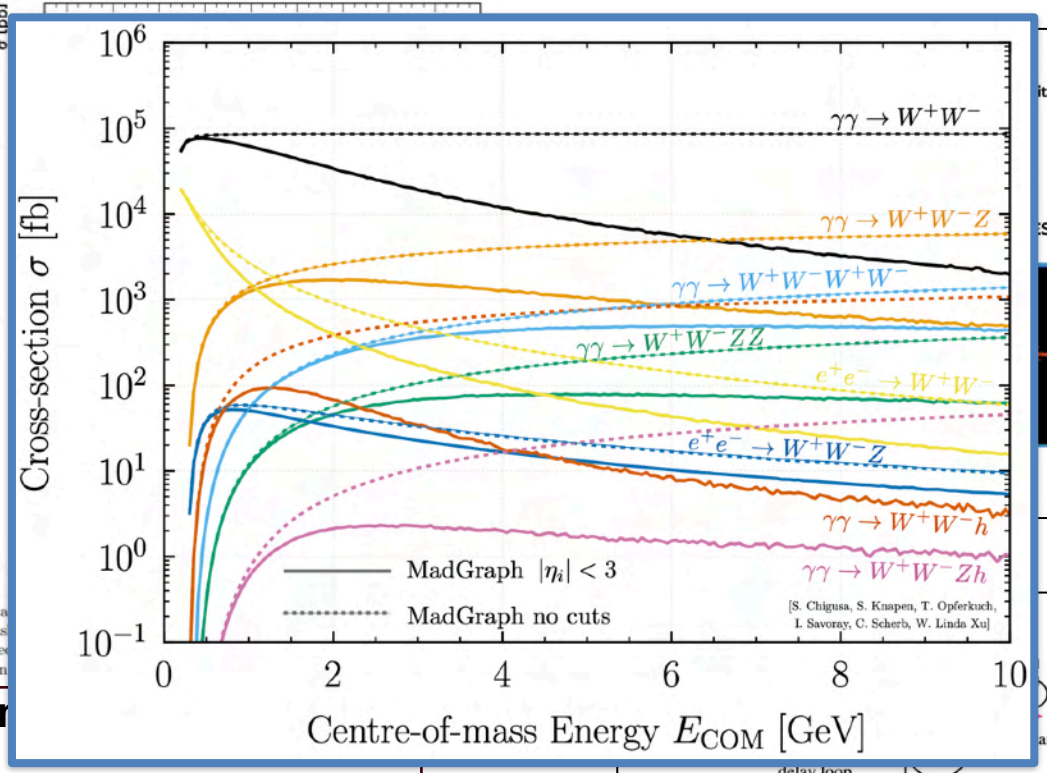


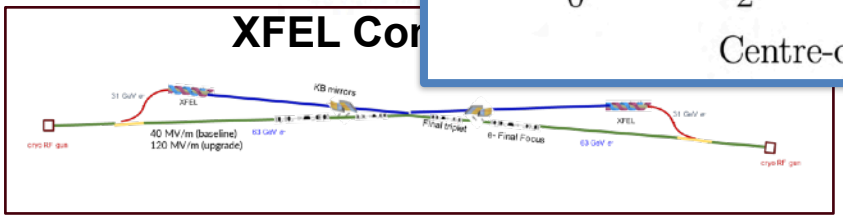


Why $\gamma\gamma$-option is interesting?

I.Ginzburg, G.Kotkin, V.Serbo, V.Telnov, On possibility of obtaining gamma-gamma, gamma-electron beams with high energy and luminosity, Pizma

- Vector boson fusion processes at 10TeV scale important, impact luminosity requirements at 10TeV pCM.
- Some processes may favor γγ; Impact on physics case being studied.





What questions need to be addressed before starting the 10 TeV $\gamma\gamma$-collider design?

1. Is gamma-gamma collider possible in the presence of electron-positron pair production during the conversion of the electron beam into high energy photons, i.e., for $x > 4.8$?

2. What scattering laser wavelengths can deliver required gamma-gamma luminosities?

3. What are the optimal scattering laser wavelength and duration to maximize partial gamma-gamma luminosities?

$$x \approx \frac{4E_0\omega_0}{m^2c^4} \approx 15.3\left[\frac{E_0}{TeV}\right]\left[\frac{\omega_0}{eV}\right] \qquad \omega_m' = \frac{x}{x+1}E_0$$

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2. What s
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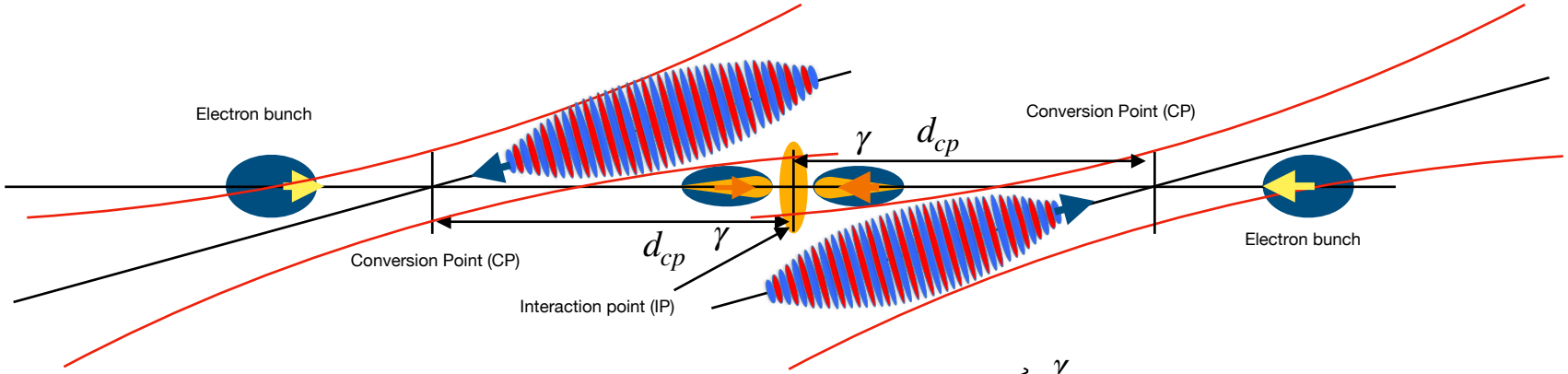
XFEL Compton Collider XCC



T. Barklow, C. Emma, Z. Huang, A. Naji, E. Nanni, A. Schwartzman, S. Tantawi, and G. White, Xcc: an x-ray fel-based compton collider higgs factory, Journal of Instrumentation 18 (07), P07028, 2023

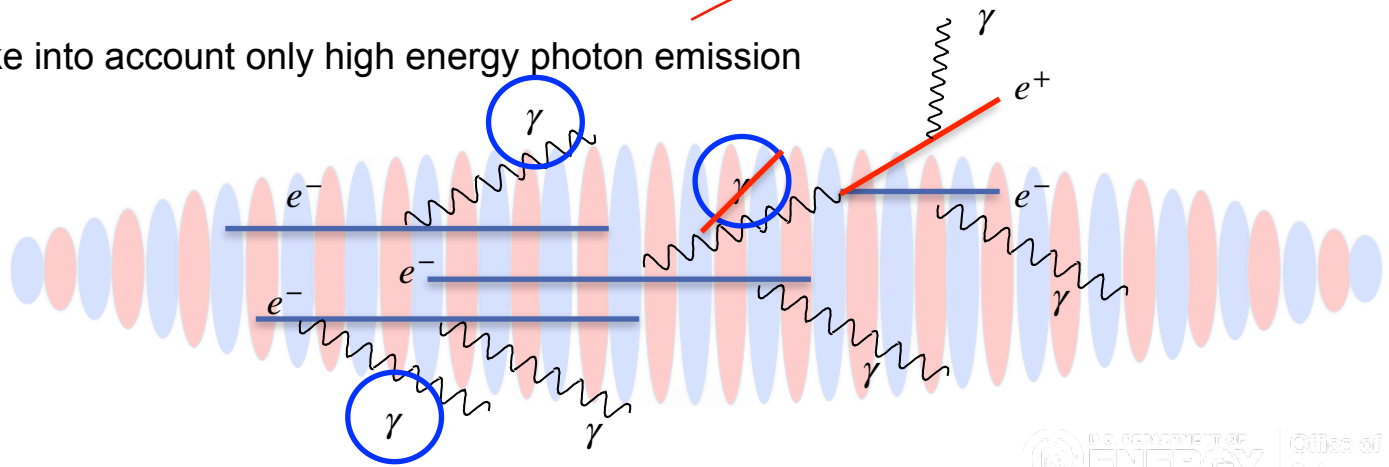
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Can one design a gamma-gamma collider in the presence of electron-positron pair production (x>4.8)?



1D Model: Take into account only high energy photon emission

$(\hbar\omega' > 0.5E_0)$



How many photons can be generated in the presence of electron-positron pair production?

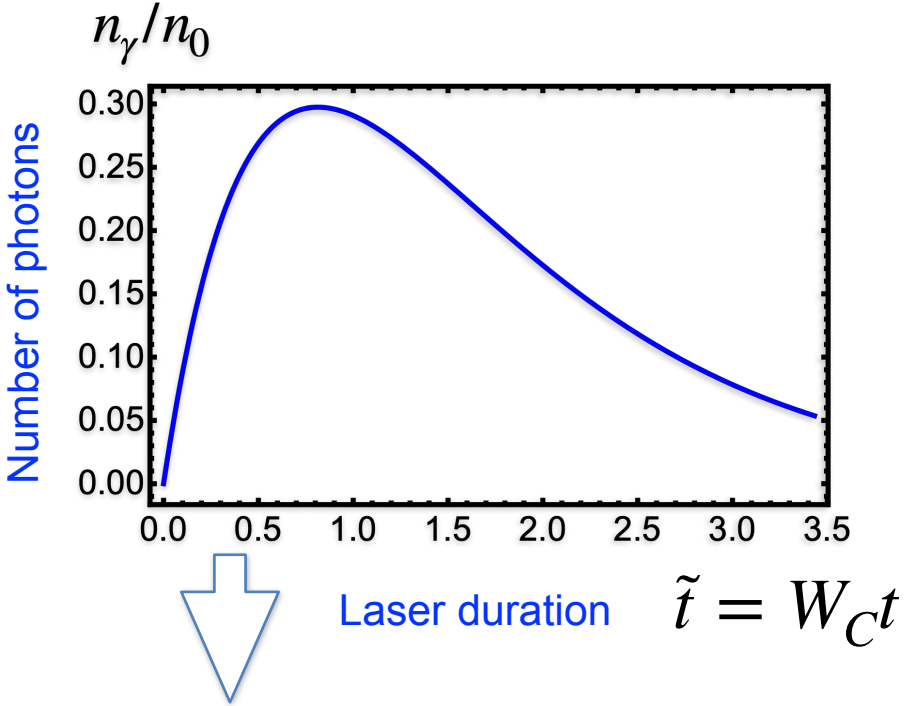
Simple 1D model for high energy photon production:

$(\hbar\omega' > 0.5E_0)$

Compton+Breit-Wheeler

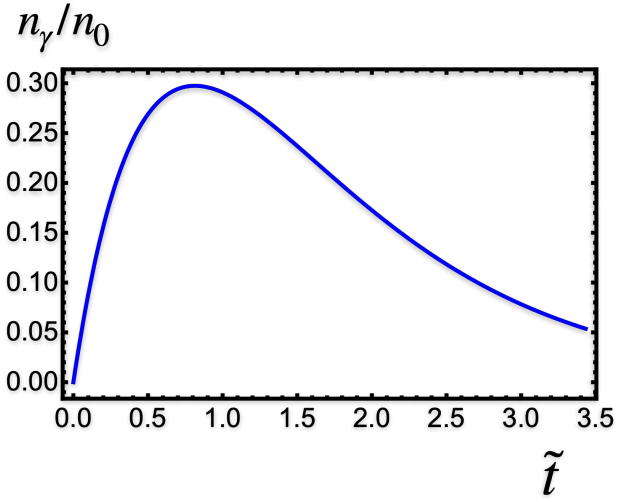
$$n_e'(t) = -n_e(t)W_C,$$

$$n_\gamma'(t) = n_e(t)W_C - n_\gamma(t)W_{BW}$$



A significant number of high energy photons can be produced in the presence of prolific electron-positron pair production

Will 1D estimates hold when compared to simulation results?



$E_0 = 5$ TeV

$\hbar\omega_L = 2.5$ eV

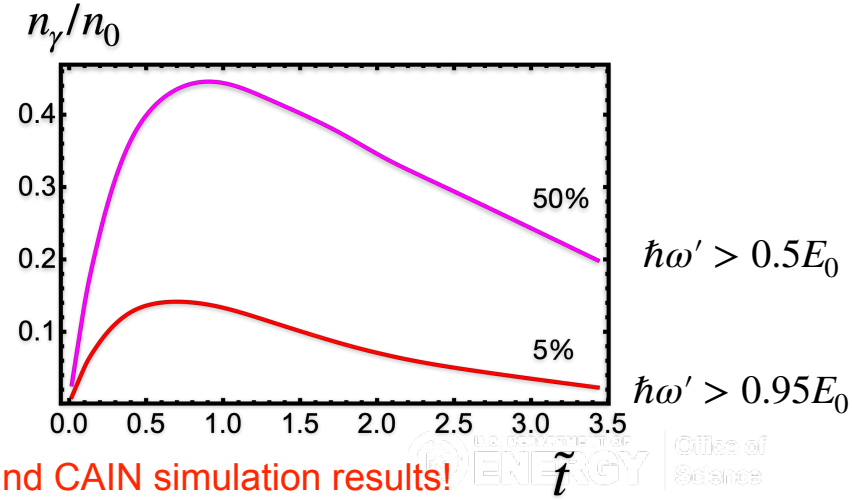
$a_0 = 0.3$

$x \approx 200$

$$n_\gamma^{max} = 0.3 n_0$$

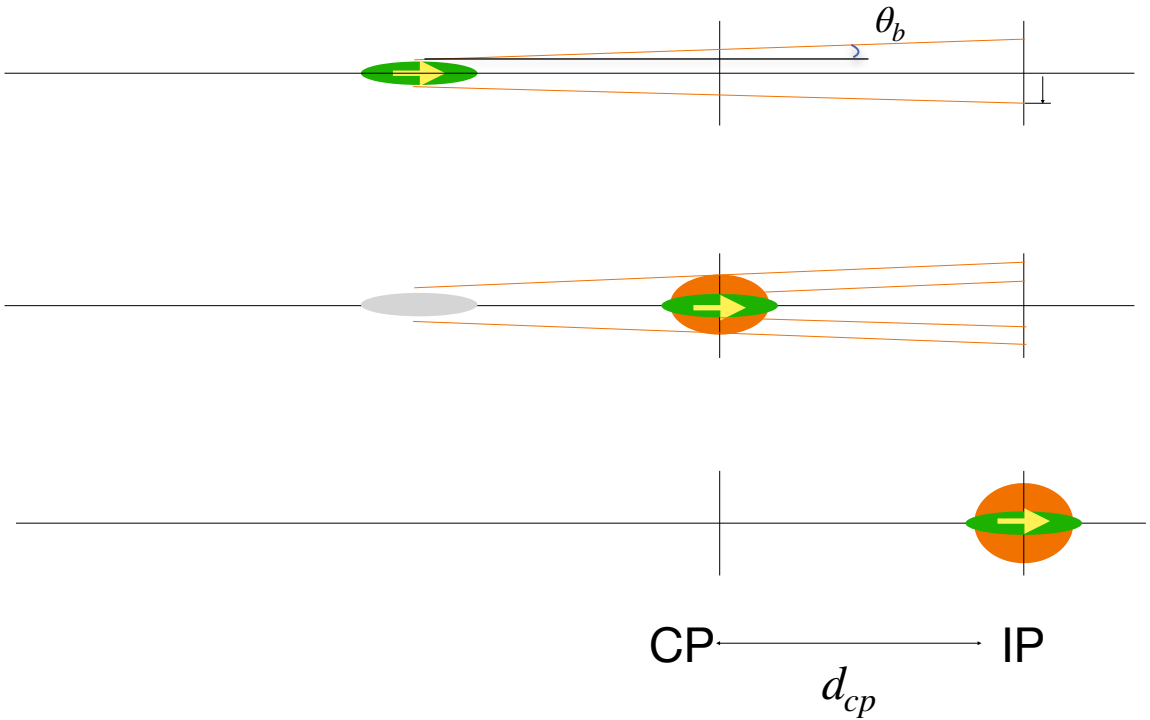
$$L_{\gamma\gamma} \sim 10^{-1} L_{ee}^{geo}$$

CAIN: Simulation results



Reasonable agreement between simple 1D model and CAIN simulation results!

Photon emission angle puts limit on the distance between conversion and interaction points .



$$d_{CP} < \frac{\sqrt{\epsilon\beta}}{\theta_b}$$

$$d_{CP} \sim c\tau_L/2$$

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Simulations using CAIN code: laser and electron beam parameters

Electron beam parameters

$E_0 = 5$ TeV

$N_e = 2.12 \times 10^9$

$d_{cp} = 0.01 - 6.0$ mm

$r_b \approx 1.7$ nm

$\sigma_z = 5\ \mu$m

Repetition Rate $= 47$ kHz

Laser beam parameters

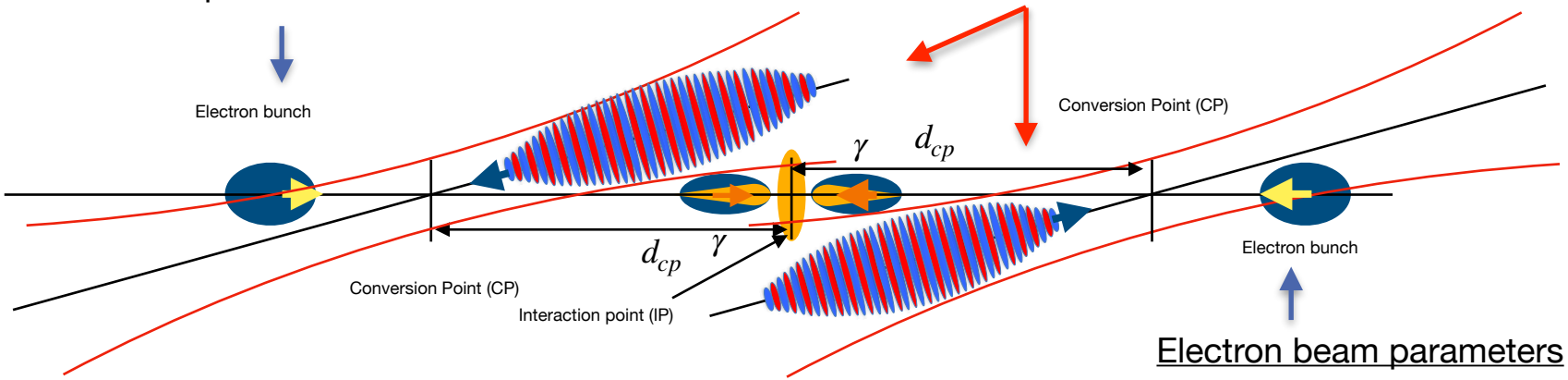
$w_L = 20\lambda_0$

$c\tau_L = 20 - 12000\ \mu$m

$\hbar\omega_L = 1.2 - 5 \times 10^3$ eV

$W_L = 0.4 - 160$ J

$a_0 = 0.3$



Electron beam parameters

$E_0 = 5$ TeV

…

$L_{e^-e^-,\,geo} = 5.5 \times 10^{35}\ cm^{-2}s^{-1}$

K. Yokoya, CAIN

Different photon-photon luminosity spectra can be generated by scattering lasers with different frequencies according to simulations using CAIN code

Electron beam parameters

$E_0 = 5$ TeV

$N_e = 2.12 \times 10^9$

$d_{cp} = 0.01 - 4.0$ mm

$r_b \approx 1.7$ nm

$\sigma_z = 5\ \mu$m

Repetition Rate $= 47$ kHz

$L_{e^-e^-,\,geo} = 5.5 \times 10^{35}\ cm^{-2}s^{-1}$

1.2 eV $x = 92,\ c\tau = 8$ mm

2.5 eV $x = 190,\ c\tau = 6$ mm

7.5 eV $x = 575,\ c\tau = 5.3$ mm

1 keV $x = 7.7 \times 10^4,\ c\tau = 80\ \mu$m

Laser beam parameters

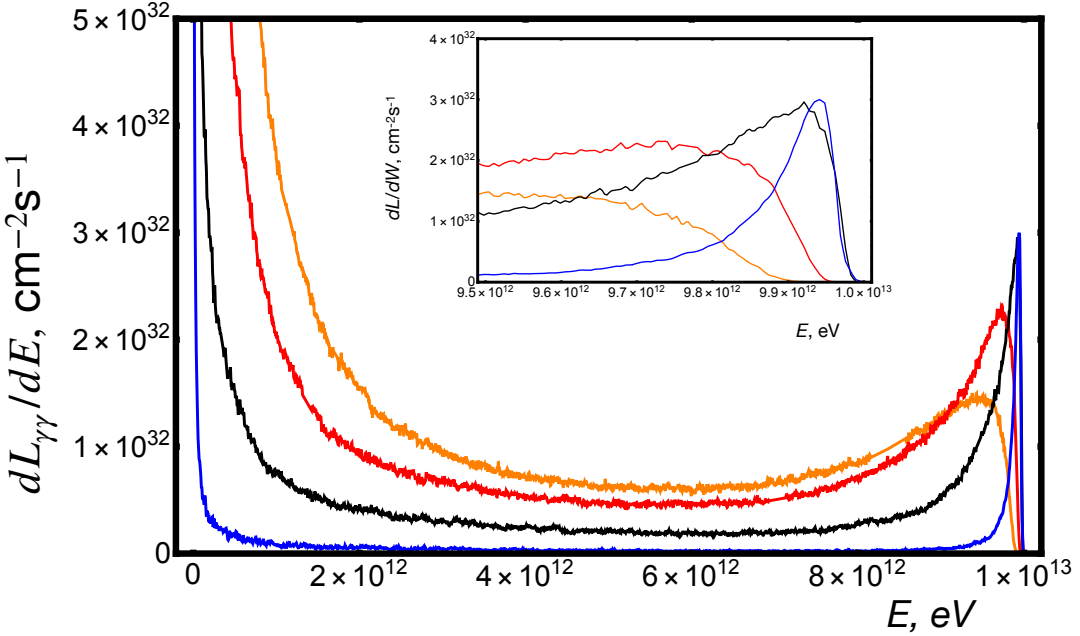
$w_L = 20\lambda_0$

$c\tau_L = 20 - 8000\ \mu$m

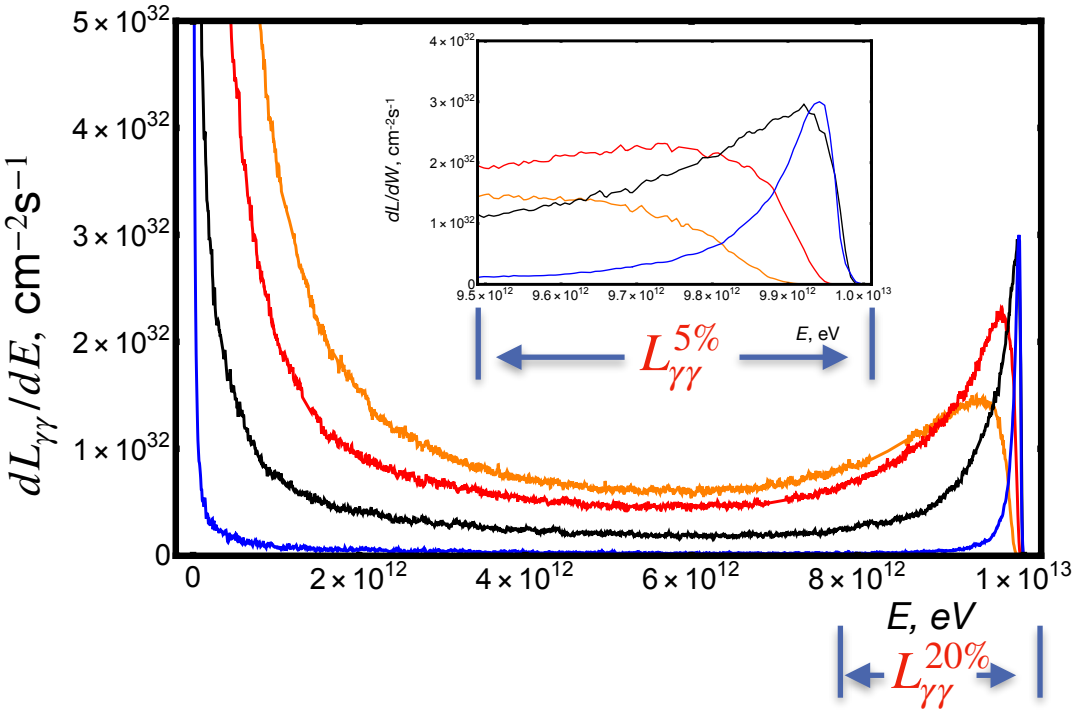
$\hbar\omega_L = 1.2 - 5 \times 10^3$ eV

$W_L = 0.4 - 160$ J

$a_0 = 0.3$



One way to characterize $\gamma\gamma$-collider performance is to consider partial luminosities



1.2 eV $x = 92,\ c\tau = 8$ mm

2.5 eV $x = 190,\ c\tau = 6$ mm

7.5 eV $x = 575,\ c\tau = 5.3$ mm

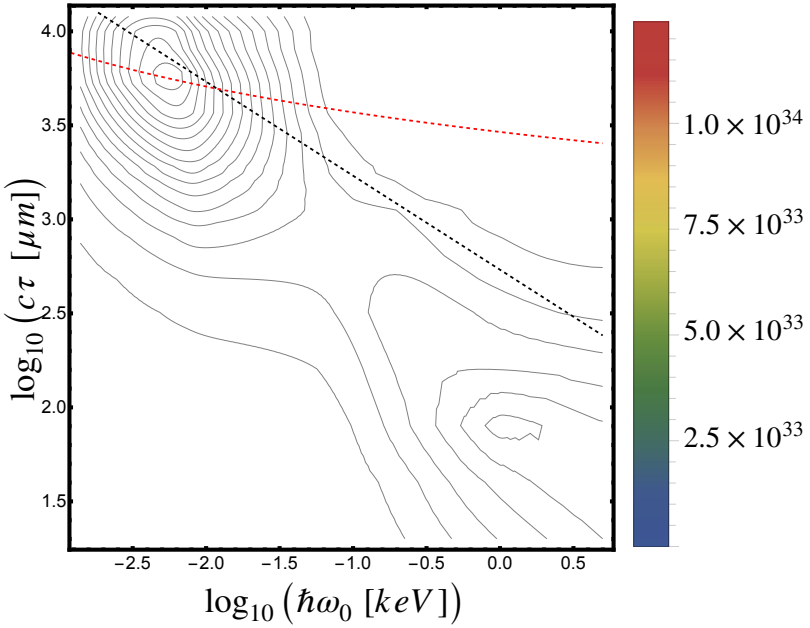
1 keV $x = 7.7 \times 10^4,\ c\tau = 80\ \mu$m

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The scattering laser parameter scan reveals laser wavelength and duration that optimize the luminosity of high energy gamma-gamma collisions

$Max[L_{\gamma\gamma}^{5\%}]/L_{\gamma\gamma,\,geo} = 2.4 \times 10^{-2}$

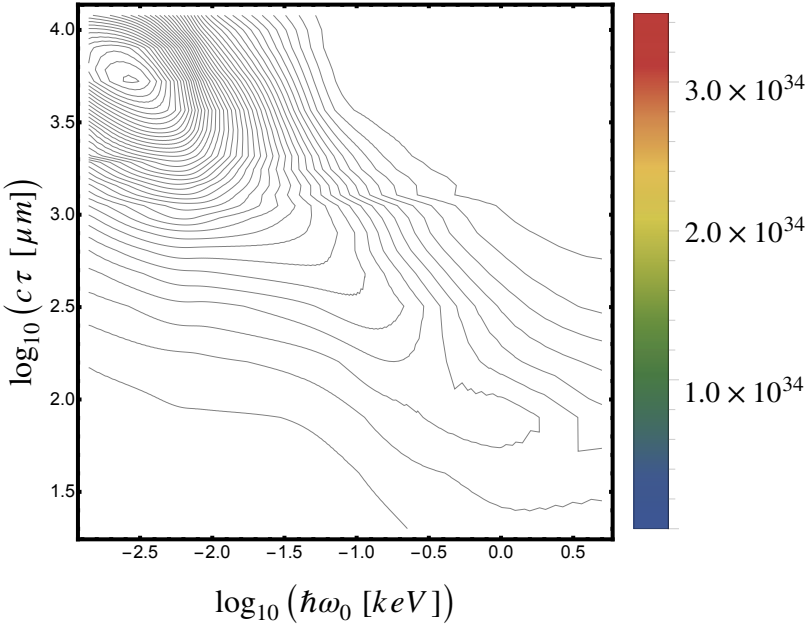
$L_{\gamma\gamma}^{5\%}$, $\mathrm{cm}^{-2}s^{-1}$



$L_{\gamma\gamma}^{5\%} = 1.3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\quad \hbar\omega_L \sim 5$ eV

$Max[L_{\gamma\gamma}^{20\%}]/L_{\gamma\gamma,\,geo} = 6.7 \times 10^{-2}$

$L_{\gamma\gamma}^{20\%}$, $\mathrm{cm}^{-2}s^{-1}$

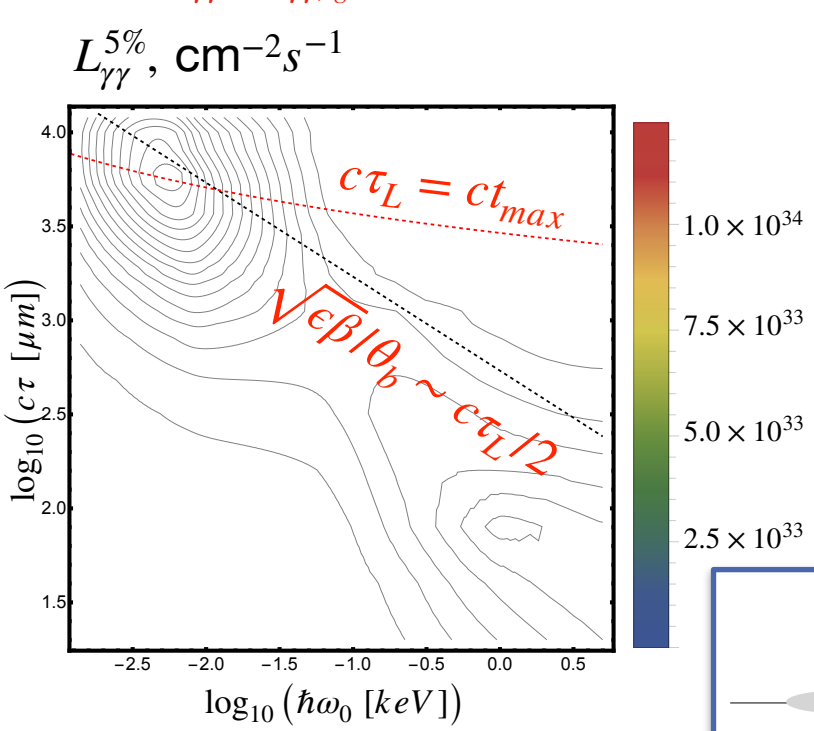


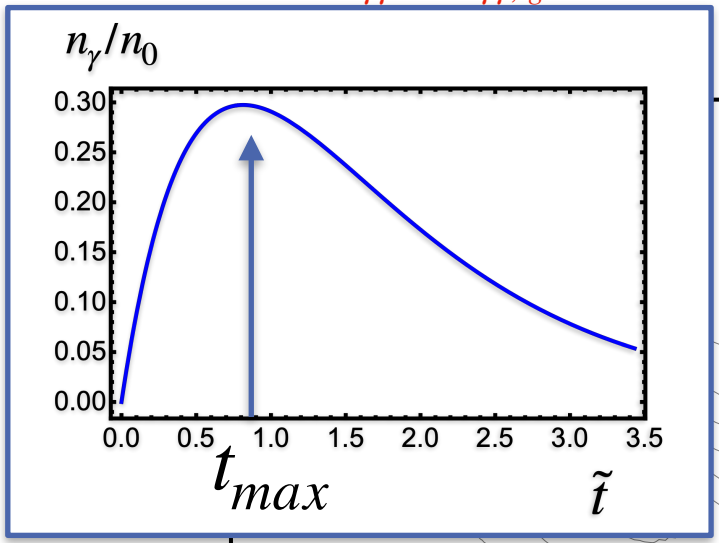
$L_{\gamma\gamma}^{20\%} = 3.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\quad \hbar\omega_L \sim 2.5$ eV

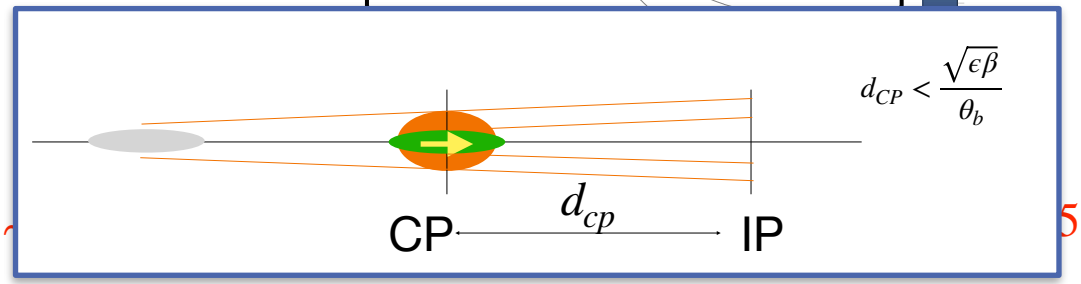
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$L_{\gamma\gamma}^{5\%} = 1.3 \times 10^{34}$ cm^{-2}s^{-1} $\hbar\omega_L$

What questions need to be addressed before starting the 10 TeV $\gamma\gamma$-collider design?

1. Is gamma-gamma collider possible in the presence of electron-positron pair production during the conversion of the electron beam into high energy photons, i.e., for $x > 4.8$? => **Yes**

2. What scattering laser wavelengths can deliver required $\gamma\gamma$ luminosities? => **from optical to X-rays:** $\hbar\omega_L = 1.2$ eV $-$ 5 keV

3. What are the optimal scattering laser wavelength and duration to maximize partial $\gamma\gamma$ luminosities? $\hbar\omega_L \sim 5$ eV , $c\tau = 6$ mm for both $L_{\gamma\gamma}^{5\%}$ and $L_{\gamma\gamma}^{20\%}$

$\hbar\omega_L \sim 5$ eV , $c\tau = 6$ mm and $\hbar\omega_L \sim 1$ keV , $c\tau = 80$ μm for $L_{\gamma\gamma}^{5\%}$

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Conclusions

- The design of a 10 TeV $\gamma\gamma$ collider is possible in the presence of electron-positron pair production during the conversion of the electron beam into high energy photons, i.e., for $x > 4.8$.

- The parameter scan shows that near-optical and X-ray scattering laser wavelengths maximize partial $\gamma\gamma$ luminosities, with near-optical lasers producing more broad luminosity spectra beneficial for the new particle searches.

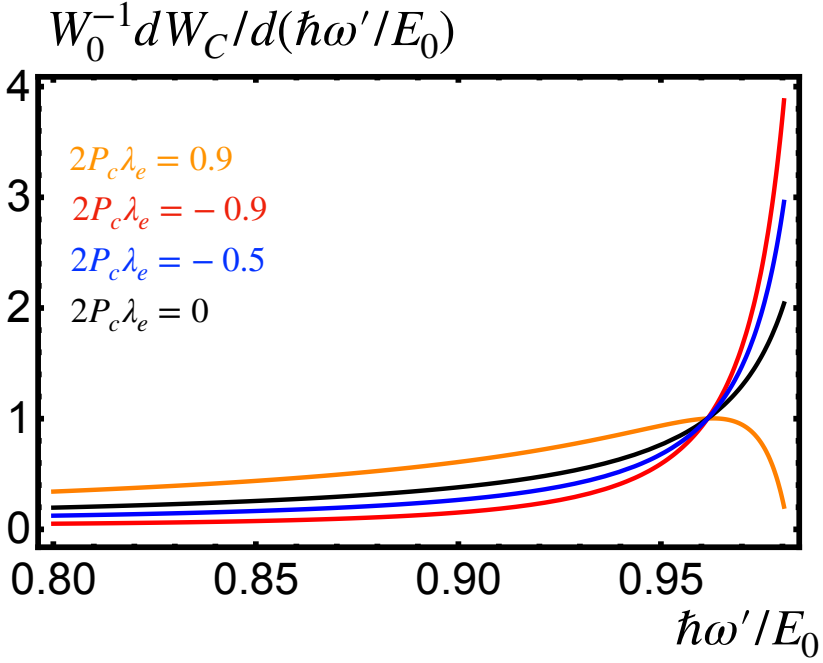
- The important parameters for a 10 TeV $\gamma\gamma$ collider design: (1) Laser pulse duration; (2) Distance between the conversion and interaction points.

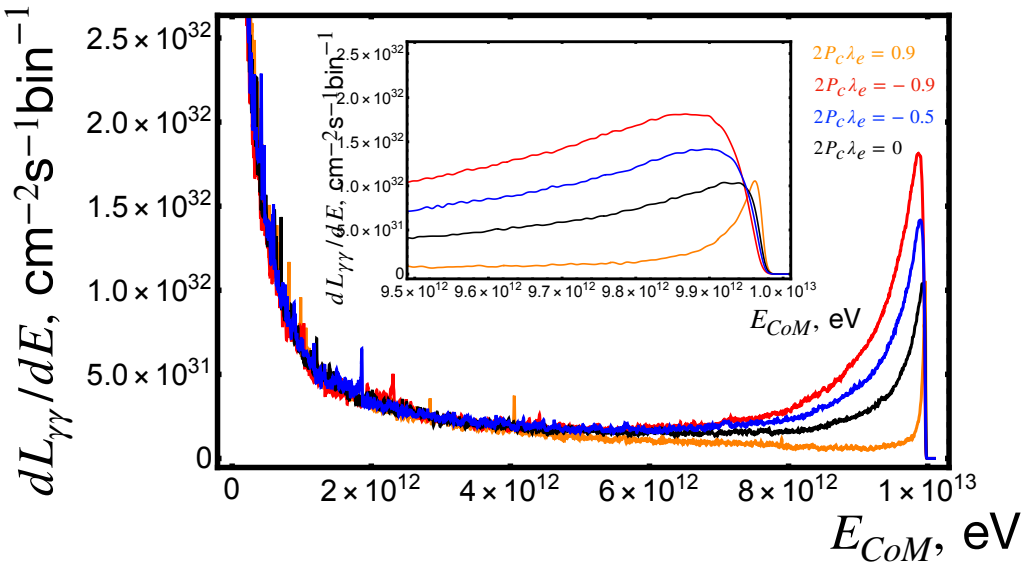
Thank you!

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Is the polarization important for the gamma-gamma collider design?

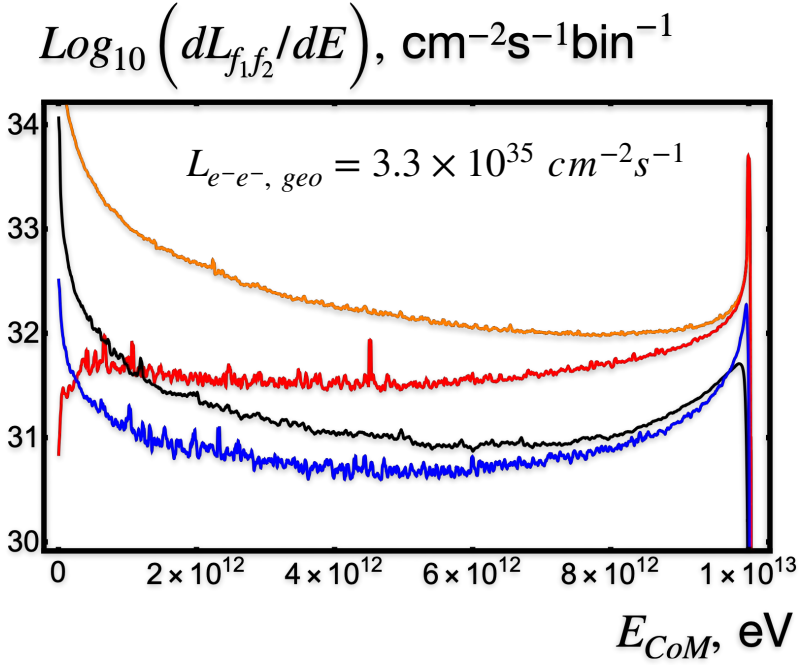
$$W_C = W_C^0 + 2\lambda_e P_c W_C^1 \qquad W_{BW} = W_{BW}^0 + \lambda_\gamma P_c W_{BW}^1$$

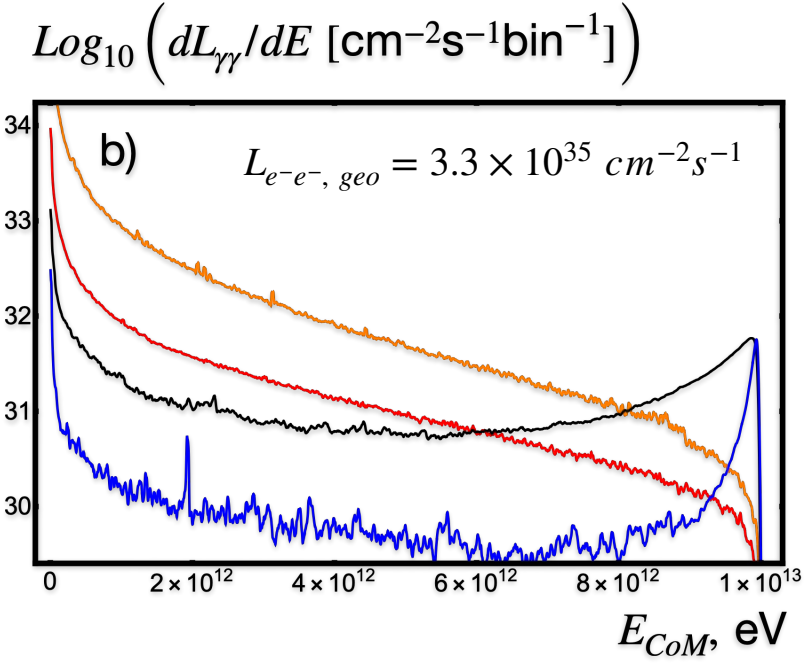




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How different operational scenarios for a 10 TeV collider compare in terms of luminosity spectra?





Electron-positron collider: $f_1 = e^-,\ f_2 = e^+$

Electron-electron collider: $f_1 = e^-,\ f_2 = e^-$

5 eV $\gamma\gamma$ collider: $f_1 = e^-,\ f_2 = \gamma$

1 keV $\gamma\gamma$ collider: $f_1 = \gamma,\ f_2 = \gamma$

Electron-positron collider

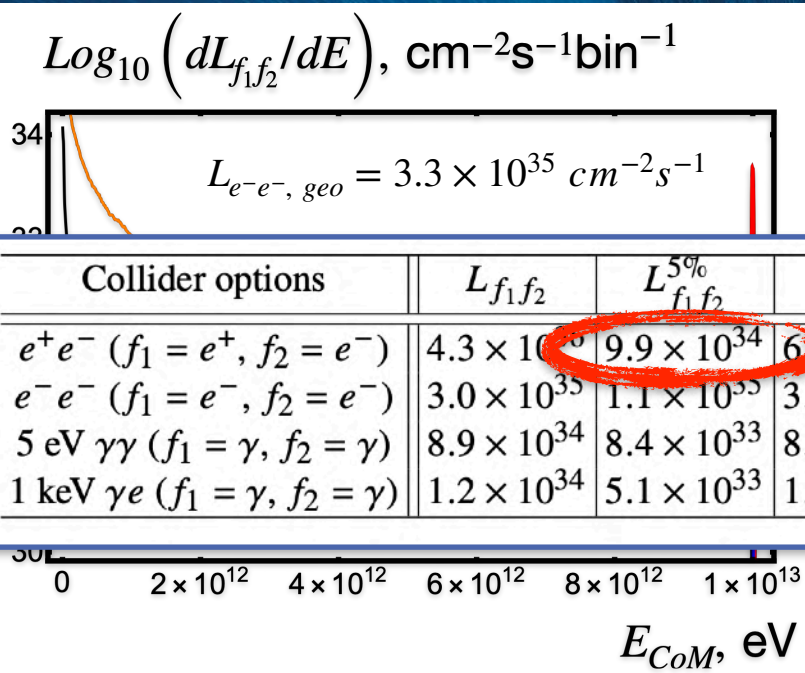
Electron-electron collider

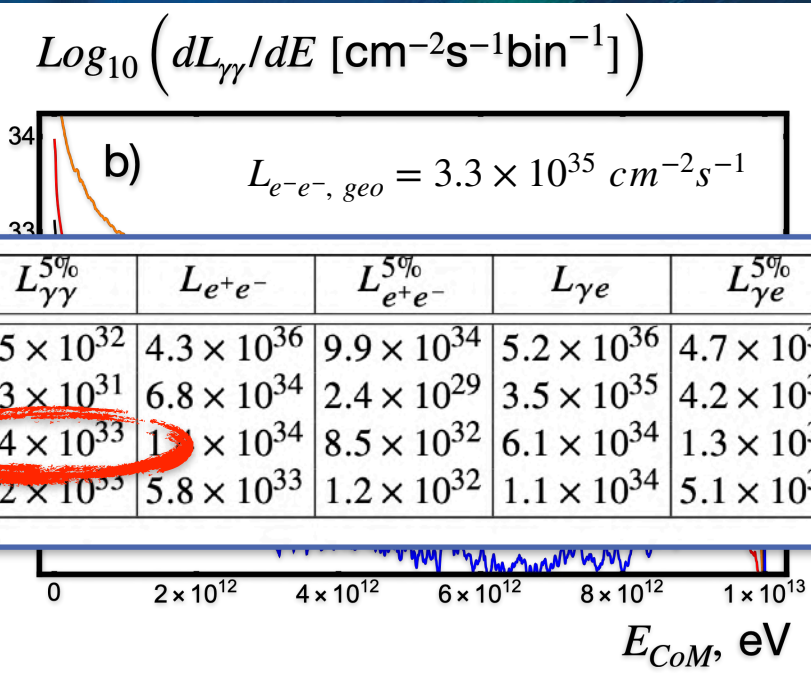
5 eV $\gamma\gamma$ collider

1 keV $\gamma\gamma$ collider

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How different operational scenarios for a 10 TeV collider compare in terms of luminosity spectra?





Collider options	$L_{f_1f_2}$	$L^{5\%}_{f_1f_2}$	$L_{\gamma\gamma}$	$L^{5\%}_{\gamma\gamma}$	$L_{e^+e^-}$	$L^{5\%}_{e^+e^-}$	$L_{\gamma e}$	$L^{5\%}_{\gamma e}$
e^+e^- ($f_1 = e^+$, $f_2 = e^-$)	4.3×10^{36}	9.9×10^{34}	$6.[illegible] \times 10^{36}$	2.5×10^{32}	4.3×10^{36}	9.9×10^{34}	5.2×10^{36}	4.7×10^{33}
e^-e^- ($f_1 = e^-$, $f_2 = e^-$)	3.0×10^{35}	1.1×10^{35}	3.0×10^{35}	9.3×10^{31}	6.8×10^{34}	2.4×10^{29}	3.5×10^{35}	4.2×10^{33}
5 eV $\gamma\gamma$ ($f_1 = \gamma$, $f_2 = \gamma$)	8.9×10^{34}	8.4×10^{33}	$8.9 \times 10^{[illegible]}$	8.4×10^{33}	$1.[illegible] \times 10^{34}$	8.5×10^{32}	6.1×10^{34}	1.3×10^{34}
1 keV γe ($f_1 = \gamma$, $f_2 = \gamma$)	1.2×10^{34}	5.1×10^{33}	1.1×10^{34}	3.2×10^{33}	5.8×10^{33}	1.2×10^{32}	1.1×10^{34}	5.1×10^{33}

Electron-positron collider: $f_1 = e^-$, $f_2 = e^+$

Electron-electron collider: $f_1 = e^-$, $f_2 = e^-$

5 eV $\gamma\gamma$ collider: $f_1 = e^-$, $f_2 = \gamma$

1 keV $\gamma\gamma$ collider: $f_1 = \gamma$, $f_2 = \gamma$

Electron-positron collider

Electron-electron collider

5 eV $\gamma\gamma$ collider

1 keV $\gamma\gamma$ collider

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