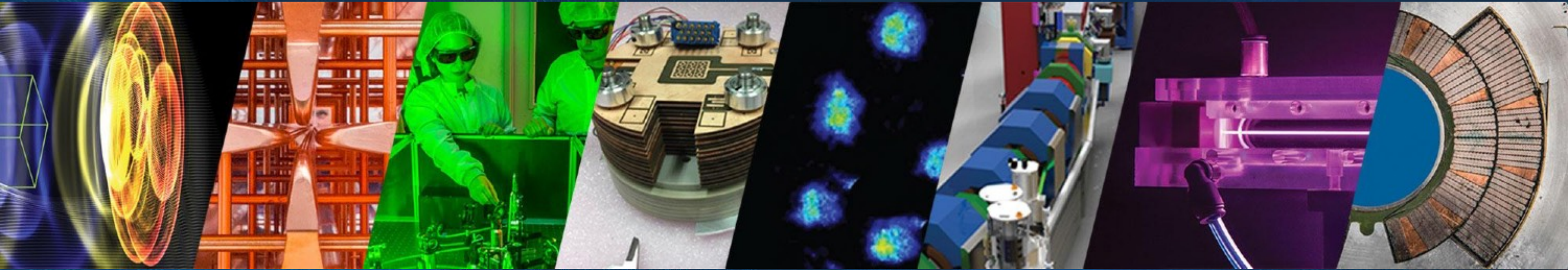
On the design of a 10 TeV $\gamma\gamma$-collider



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

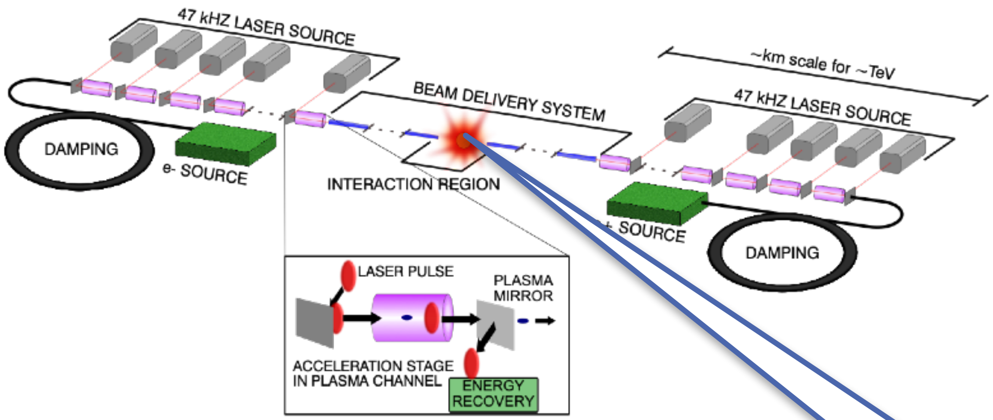
T. Barklow, S. Gessner, and A. Schwartzman
SLAC National Accelerator Laboratory, Menlo Park, California, USA

BERKELEY LAB

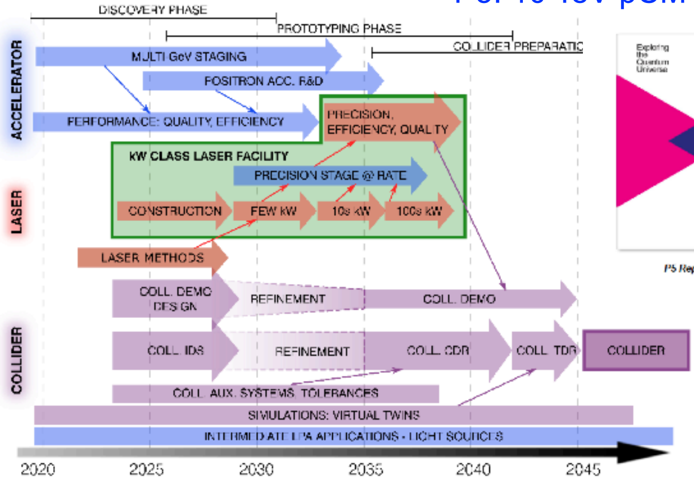
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

Basic configuration of a laser-plasma linear collider



P5: 10 TeV pCM collider



P5 Report (2023)

Leemans & Esarey Phys. Today (2009)

Linear collider based on laser-plasma accelerators, C.B. Schroeder, et al., JINST, 2023

Report of Snowmass 21 accelerator frontier topical group 6 on advanced accelerators: C. Geddes, M. Hogan, P. Musumeci, and R. Assmann, arXiv:2208.13279

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

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

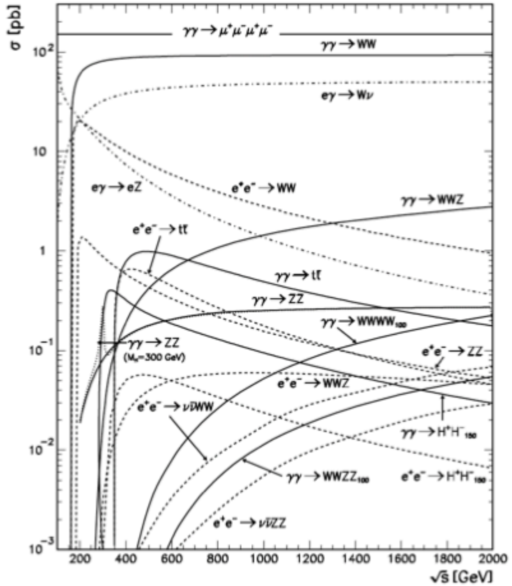
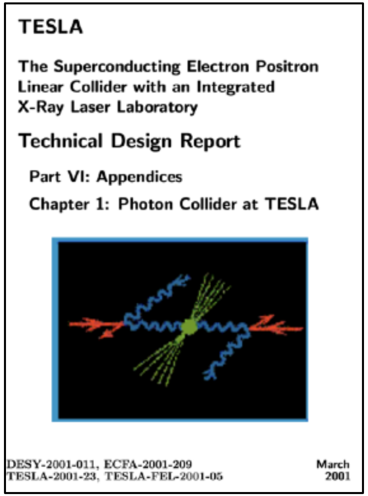


Fig. 2. Typical cross-sections in $\gamma\gamma$, γe and e^+e^- collisions. The polarization is assumed to be zero. Solid, dash-dotted and dashed curves correspond to $\gamma\gamma$, γe and e^+e^- modes respectively. Unless indicated otherwise the neutral Higgs mass was taken to be 100 GeV. For charged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

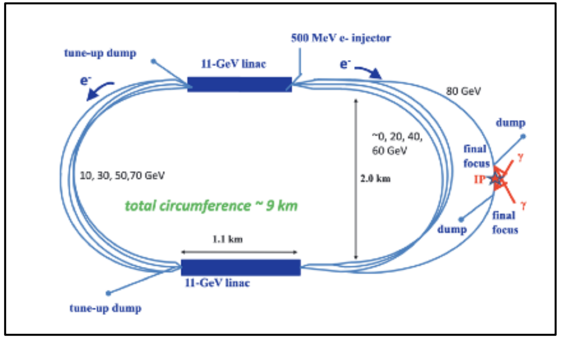
Part VI: Appendices

Chapter 1: Photon Collider at TESLA

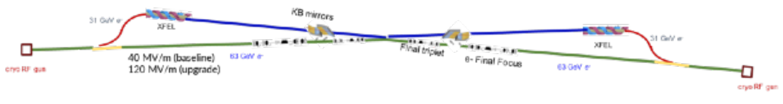
DESY-2001-011, ECFA-2001-209 TESLA-2001-23, TESLA-FEL-2001-05

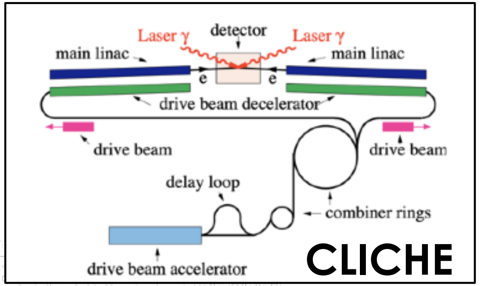
March 2001

SAPPHiRE

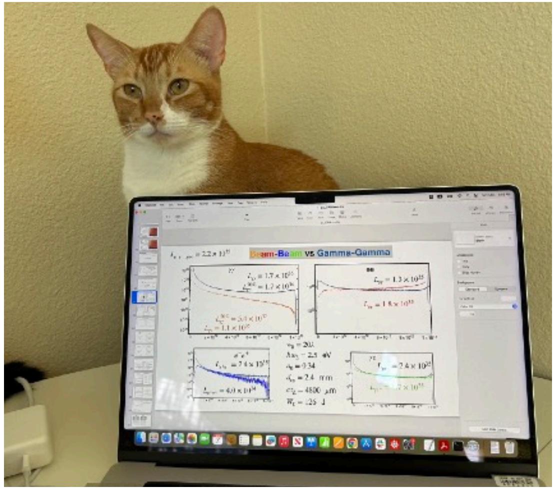


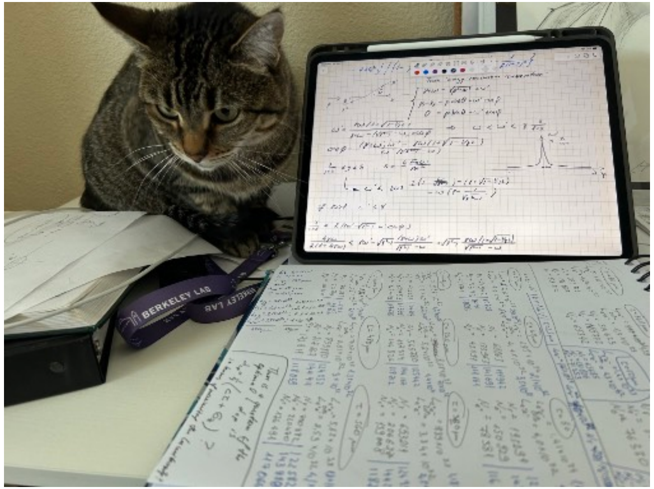
XFEL Compton Collider XCC





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





We should not be afraid of this outcome!

“Notice all the computations, theoretical scribblings, and lab equipment, Norm. ... Yes, curiosity killed these cats.”

Two of my cats are quite skeptical about the whole gamma-gamma design endeavor,

but we do not need to be!

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?

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

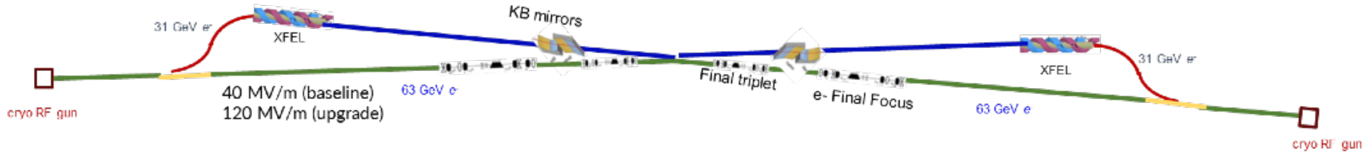
What questions need to be addressed before starting the 10 TeV $\gamma\gamma$-collider design?

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 s
   luminos

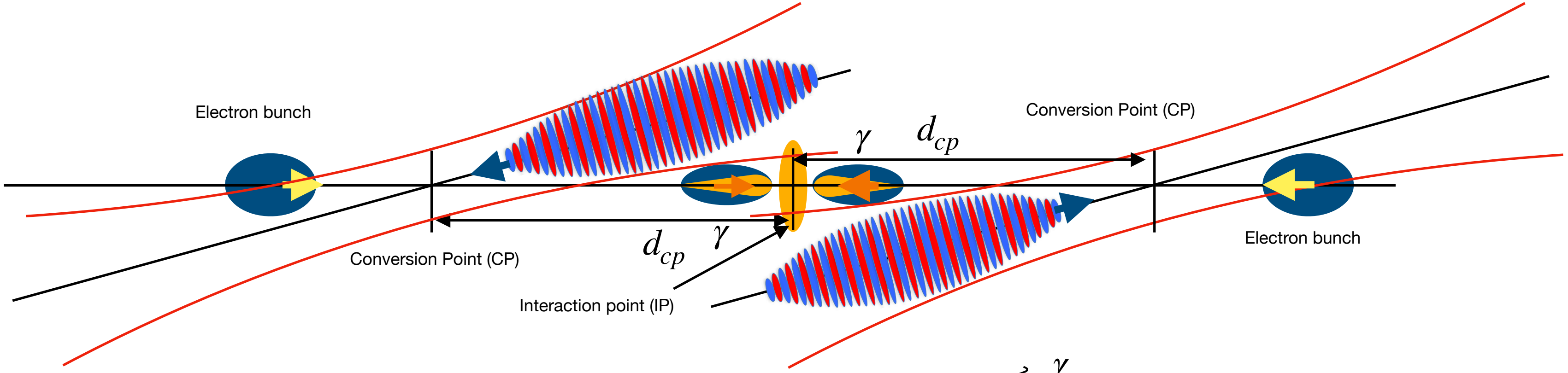
3. What a
   partial g

XFEL Compton Collider XCC



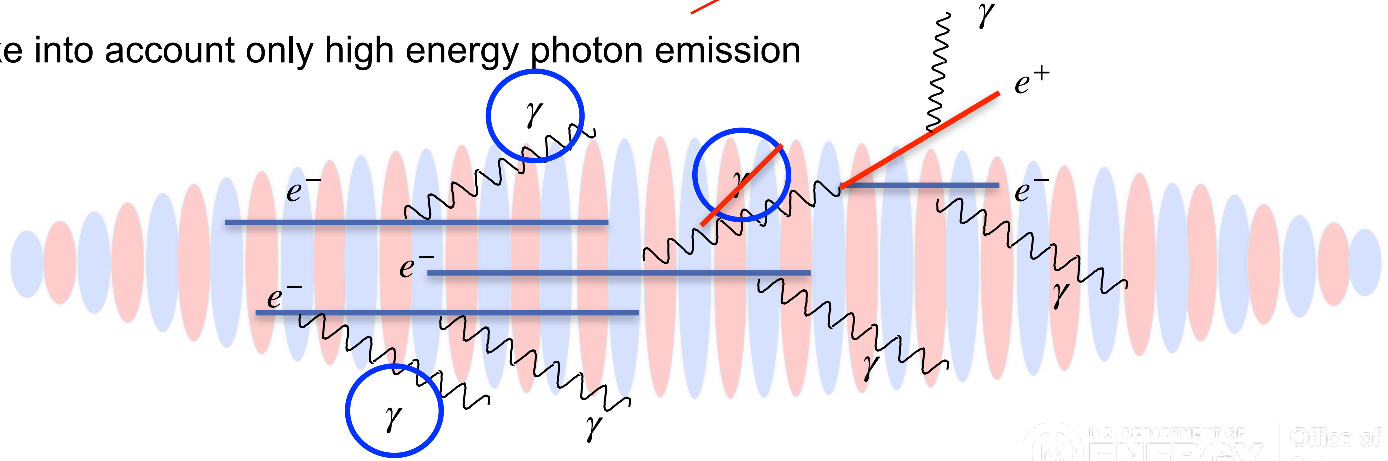
T. Barklow, C. Emma, Z. Huang, A. Naji, E. Nanni, A. Schwartzman, S. Tantawi, and G. White, Xcc: an x-ray fel-based compton collider higgs factory, Journal of Instrumentation 18 (07), P07028, 2023

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?

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

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

$$n_\gamma = n_0(\kappa - 1)^{-1}\left(e^{-\tilde{t}} - e^{-\kappa\tilde{t}}\right)$$

$$n_\gamma^{max} = n_0\ \kappa^{\frac{\kappa}{1-\kappa}} \qquad \tilde{t} = W_C t$$

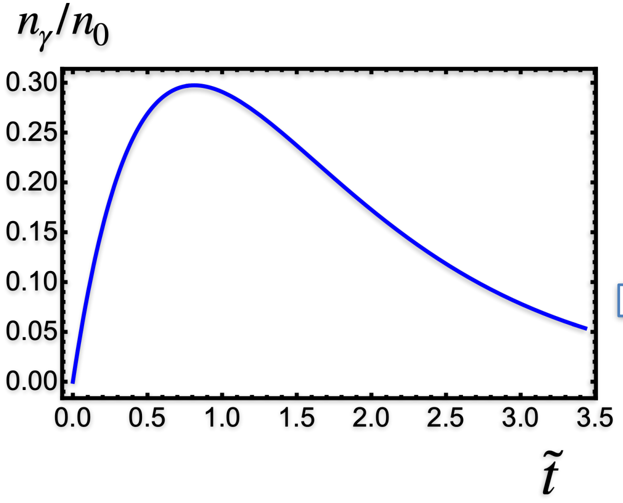
$$\tilde{t}_{max} = \ln(\kappa)/(\kappa - 1) \qquad \kappa = W_{BW}/W_C$$

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

$$\omega_m' = \frac{x}{x+1}E_0$$

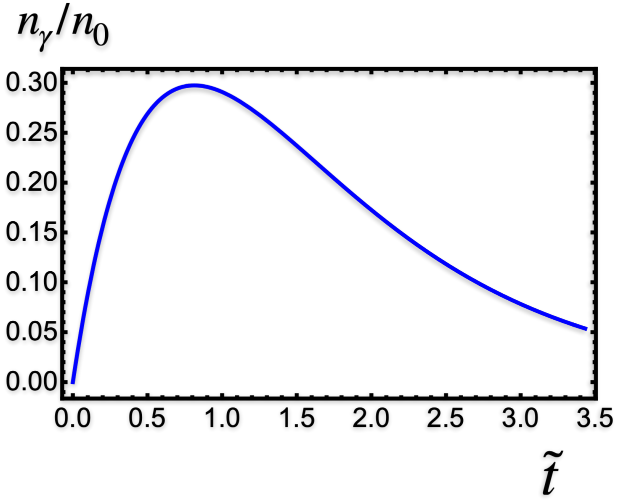
Simple 1D model for high energy photon ($\hbar\omega' > 0.5E_0$) production:

Compton+Breit-Wheeler



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

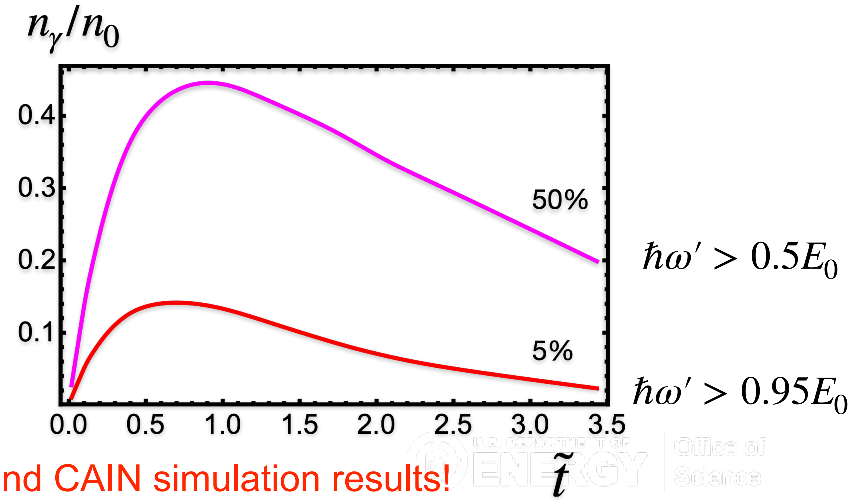
$a_0 = 0.3$

$x \approx 200$

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

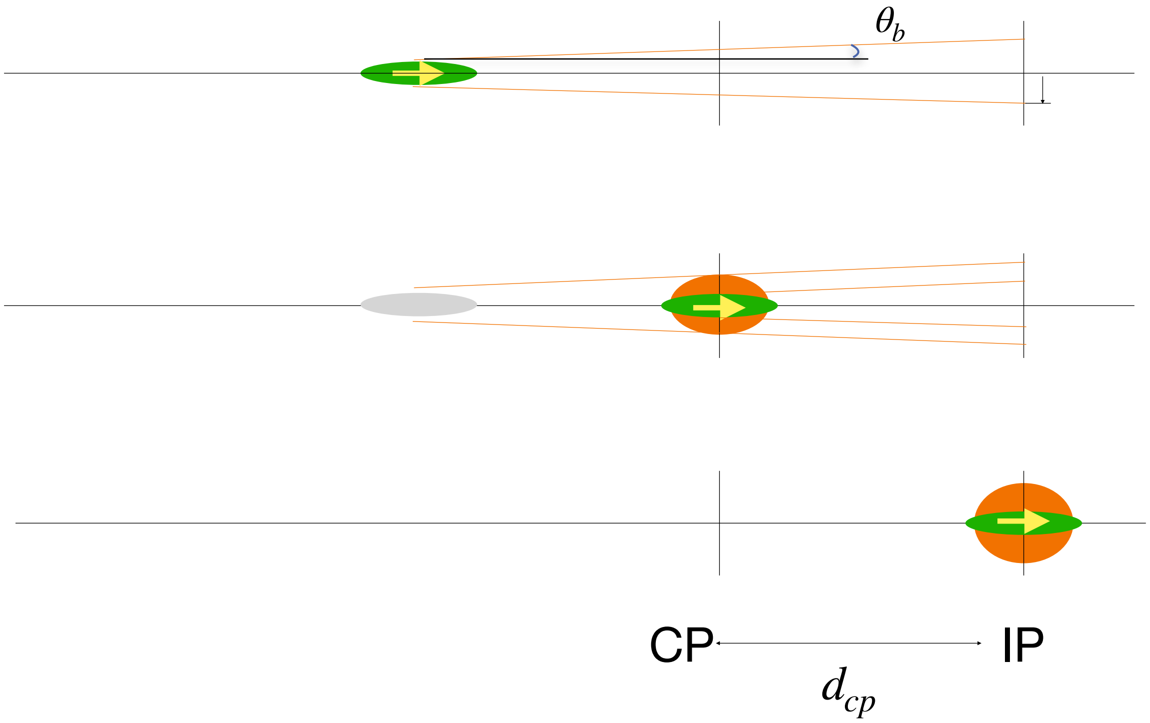
$$L_{\gamma\gamma} \sim 10^{-1} L_{ee}^{geo}$$

<u>CAIN: Simulation results</u>



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

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



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

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

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

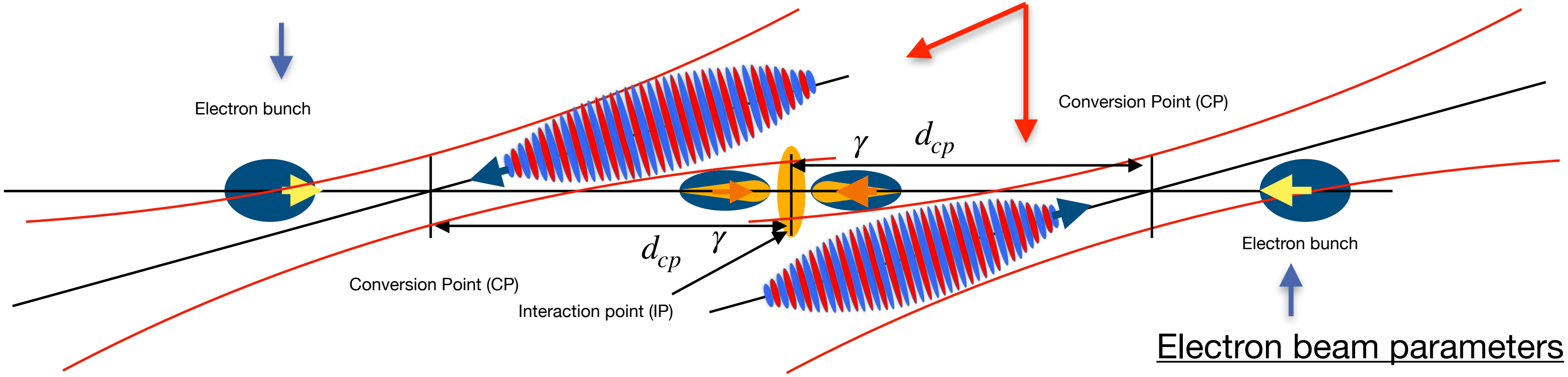
$w_L = 20\lambda_0$

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

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

$a_0 = 0.3$

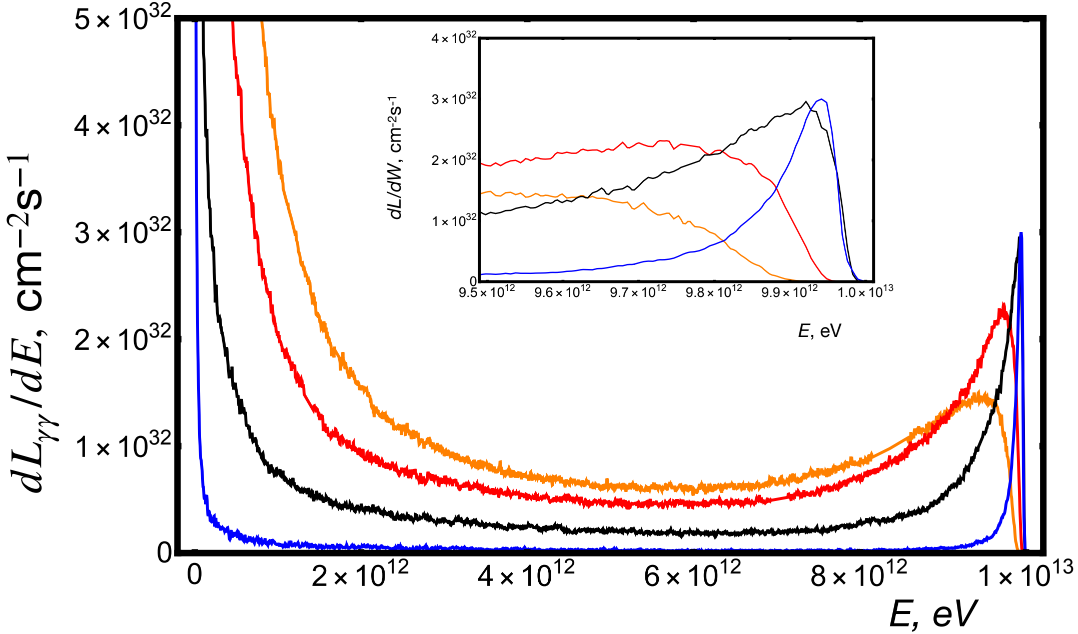
$L_{e^-e^-,\ geo} = 5.5 \times 10^{35}\ cm^{-2}s^{-1}$

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

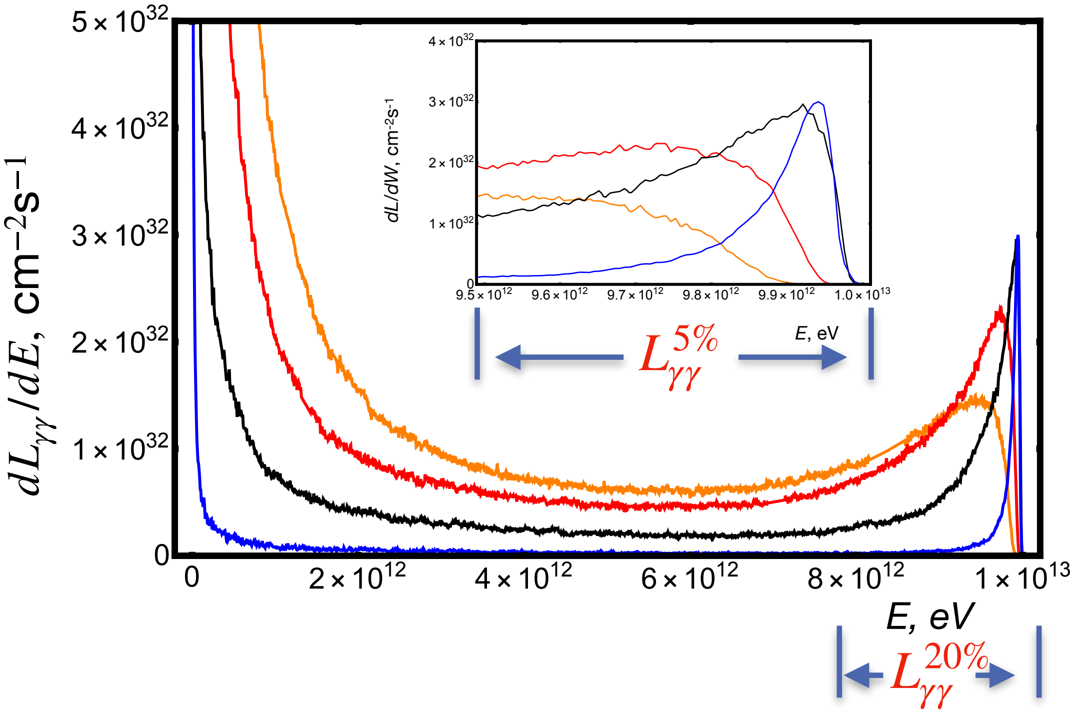
2.5 eV $x = 190$, $c\tau = 6$ mm

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

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



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

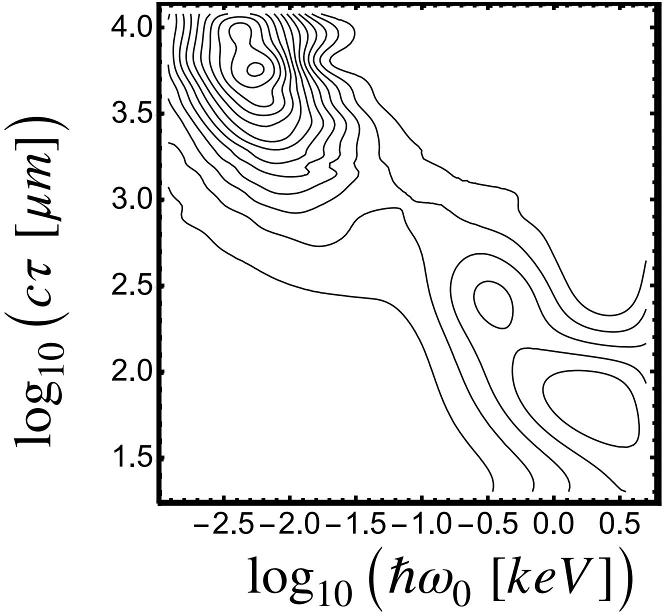
7.5 eV $x = 575, \ c\tau = 5.3$ mm

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

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

$L_{\gamma\gamma}^{5\%}$ $(\hbar\omega' > 0.95E_0)$

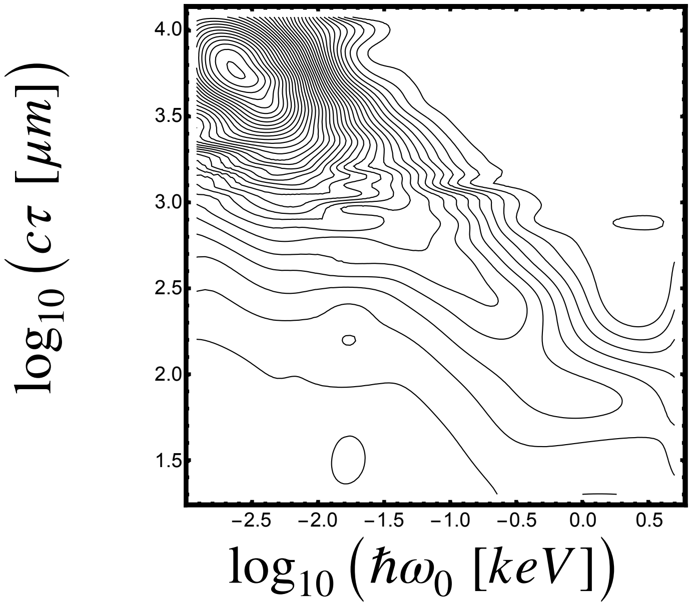
$Max[L_{\gamma\gamma}^{5\%}]/L_{\gamma\gamma,\ geo} = 2.4 \times 10^{-2}$



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

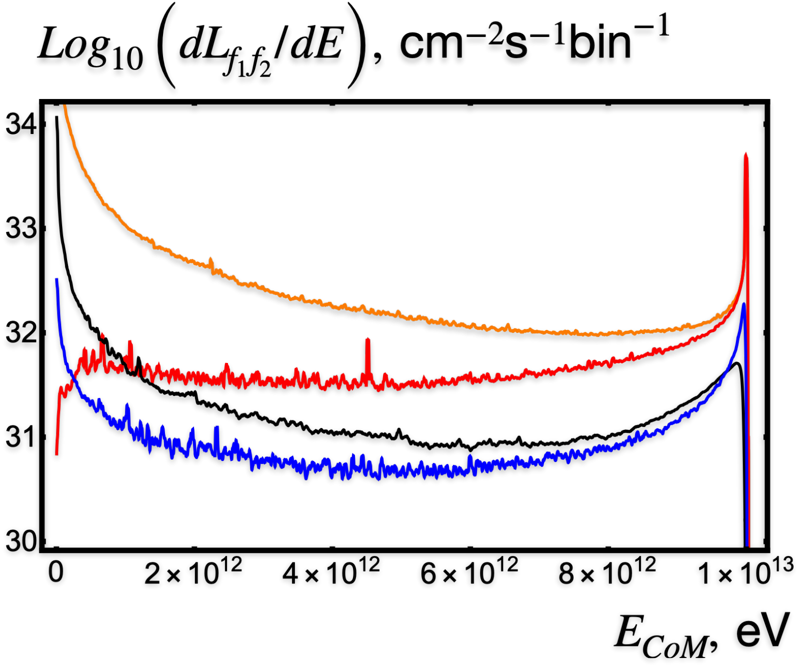
$L_{\gamma\gamma}^{20\%}$ $(\hbar\omega' > 0.8E_0)$

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



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

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

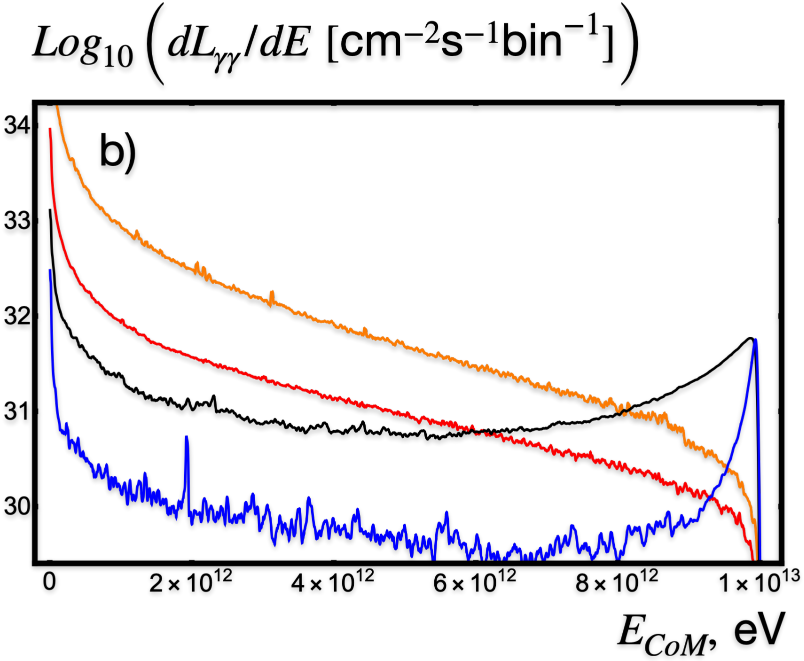


Electron-positron collider: $f_1 = e^-$, $f_2 = e^+$

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

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

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 $L_{\gamma\gamma}^{5\%}$

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!