Photon Collider H(125) Factory

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Let's look at H(125) production through s-channel annihilation of the colliding beam particles e^+e^- , $\mu^+\mu^-$, $\gamma\gamma$

For SM Higgs, $M_H = 125$ GeV

$\Gamma_{tot} = 4.03$ MeV

$\Gamma_{\gamma\gamma} = 9.33$ KeV

$\Gamma_{\mu^+\mu^-} = 0.89$ KeV

$\Gamma_{e^+e^-} = 0.02$ eV

A measurement of $\sigma(e^+e^- \to H(125))$ is mentioned in FCC-ee Higgs studies as a means to access the electron Yukawa coupling, but e^+e^- s-channel Higgs production certainly can't be used as a Higgs factory.

Muon collider Higgs factories have been discussed that operate with $\Delta E_{beam}/E_{beam} < 0.01\%$ in order to match $\Gamma_{tot} = 4.03$ MeV. However, there are a lot of technical challenges (muon beam emittance, neutrino radiation hazard, background from electrons produced in beam muon decay, ...).

The SM $\gamma\gamma$ partial width is 10 times the $\mu^+\mu^-$ partial width. Is there any way to operate a $\gamma\gamma$ collider with a very small $\gamma\gamma$ center of mass energy spread to take advantage of the relatively large $\gamma\gamma$ partial width? With a total width of 4 MeV, the smaller you make the $\gamma\gamma$ center of mass energy spread the greater your Higgs production rate

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 $x = 4.82$ $\gamma\gamma_{\text{laser}} \rightarrow e^+e^-$ 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 $x = 8$ $e^-\gamma_{\text{laser}} \rightarrow e^+e^-e^-$ opens up. This process smears the electron energy and hence smears the high energy photon spectrum. The effects of this process are not included.

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

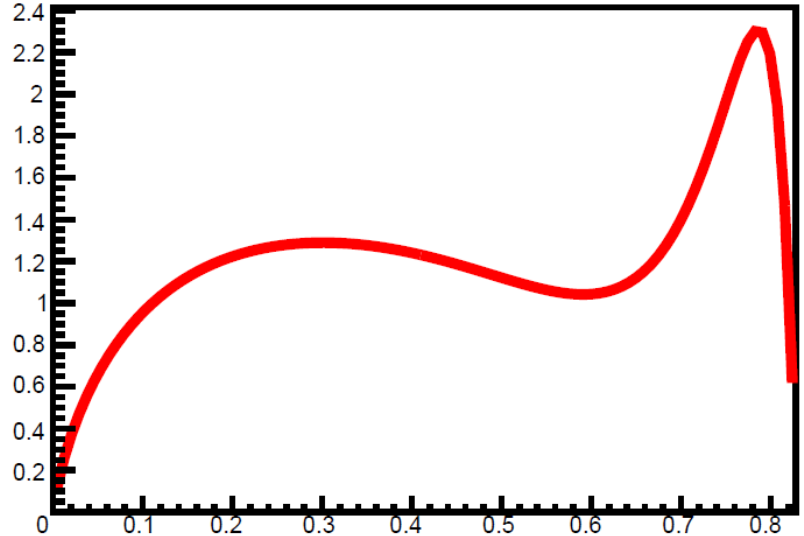
$\xi_i =$ mean helicity of the high energy photon beam i, i=1,2 $|\xi_i| \leq 1$

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

Strong field nonlinear effects are not included unless otherwise noted

Nominal configuration

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



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

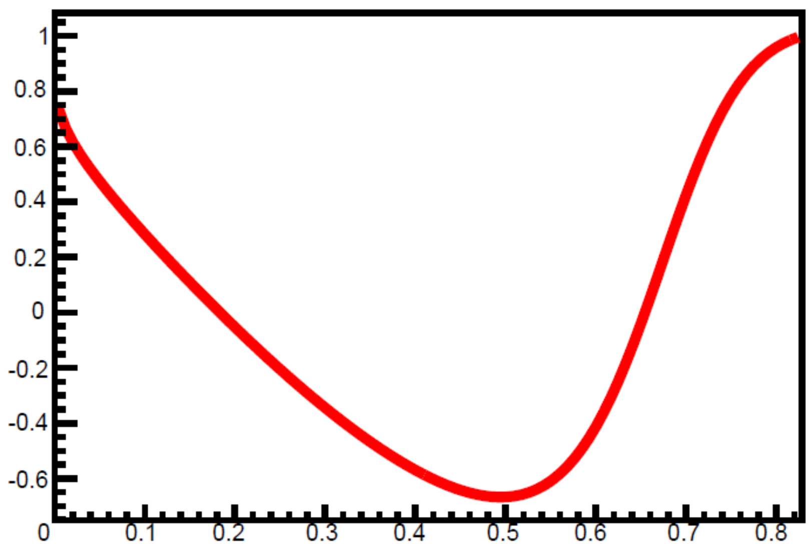
$x = 4.82 \quad E_{e^-e^-} = 158\ \text{GeV} \quad \kappa = 1$

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

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

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

$$< \xi_1\ \xi_2 >$$



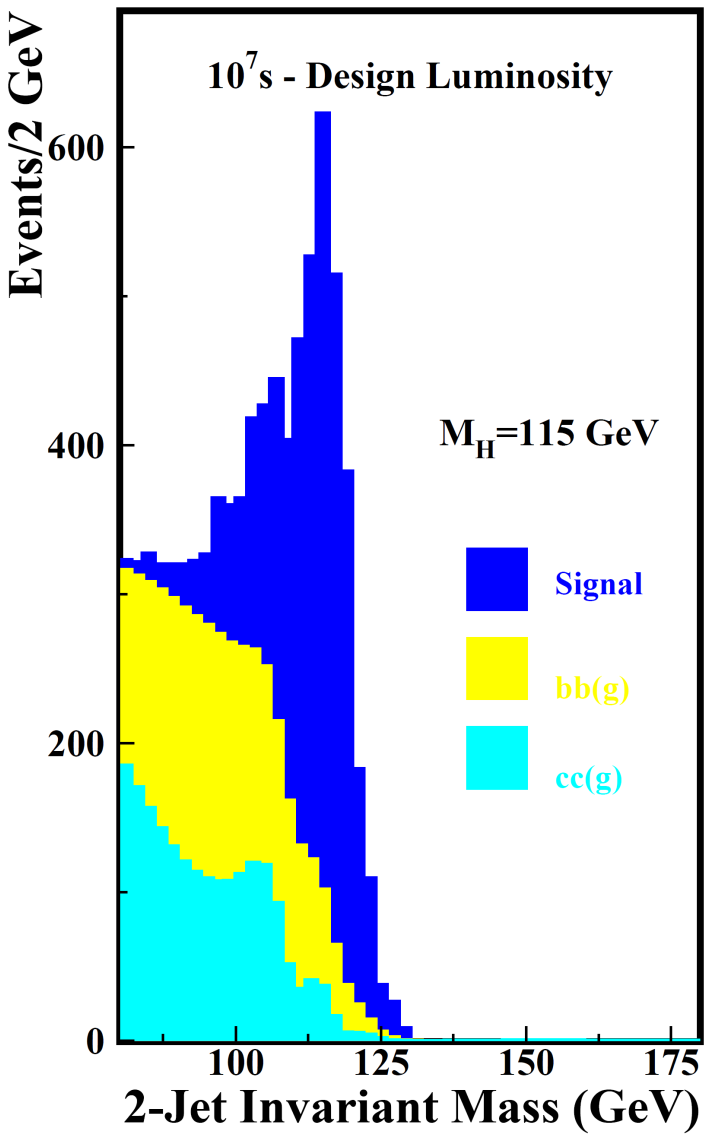
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

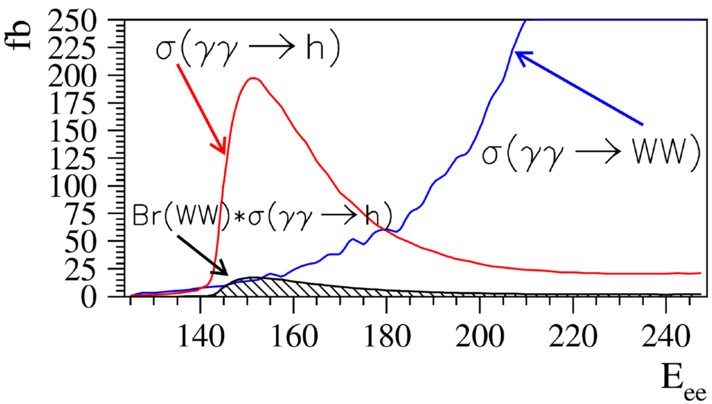
$$\sigma(\gamma\gamma \to H) = \frac{8\pi\,\Gamma_{\gamma\gamma}\Gamma_{tot}}{(s - M_H^2)^2 + \Gamma_{tot}^2 M_H^2}(1 + \xi_1\,\xi_2)$$

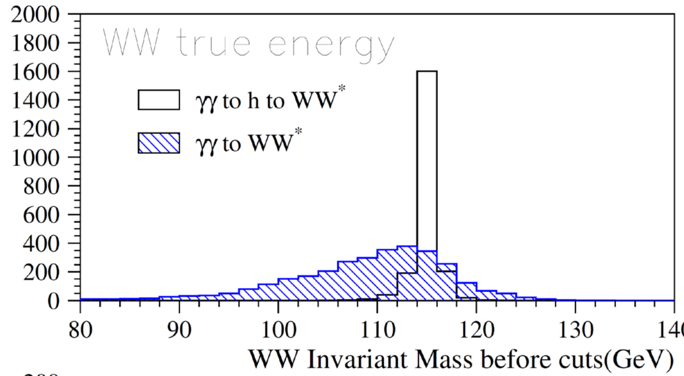
$$\approx \frac{4\pi^2\Gamma_{\gamma\gamma}}{M_H^3}(1 + \xi_1\,\xi_2) z_H \delta(z - z_H)$$

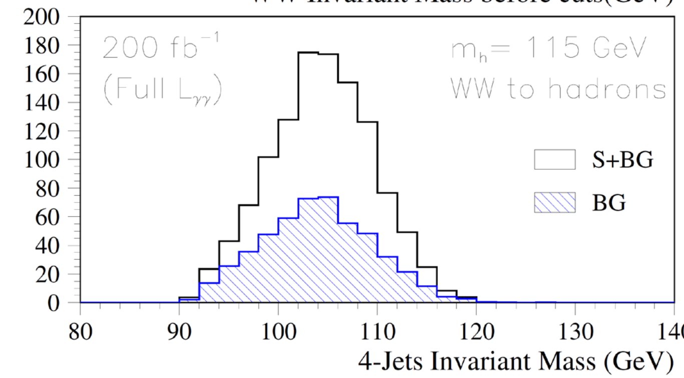
CLICHE Study x=4.1 200 fb^{-1} $\gamma\gamma$ luminosity arXiv:hep-ex/0111056

Full Compton collision simulation with CAIN. Fast MC Detector Simulation



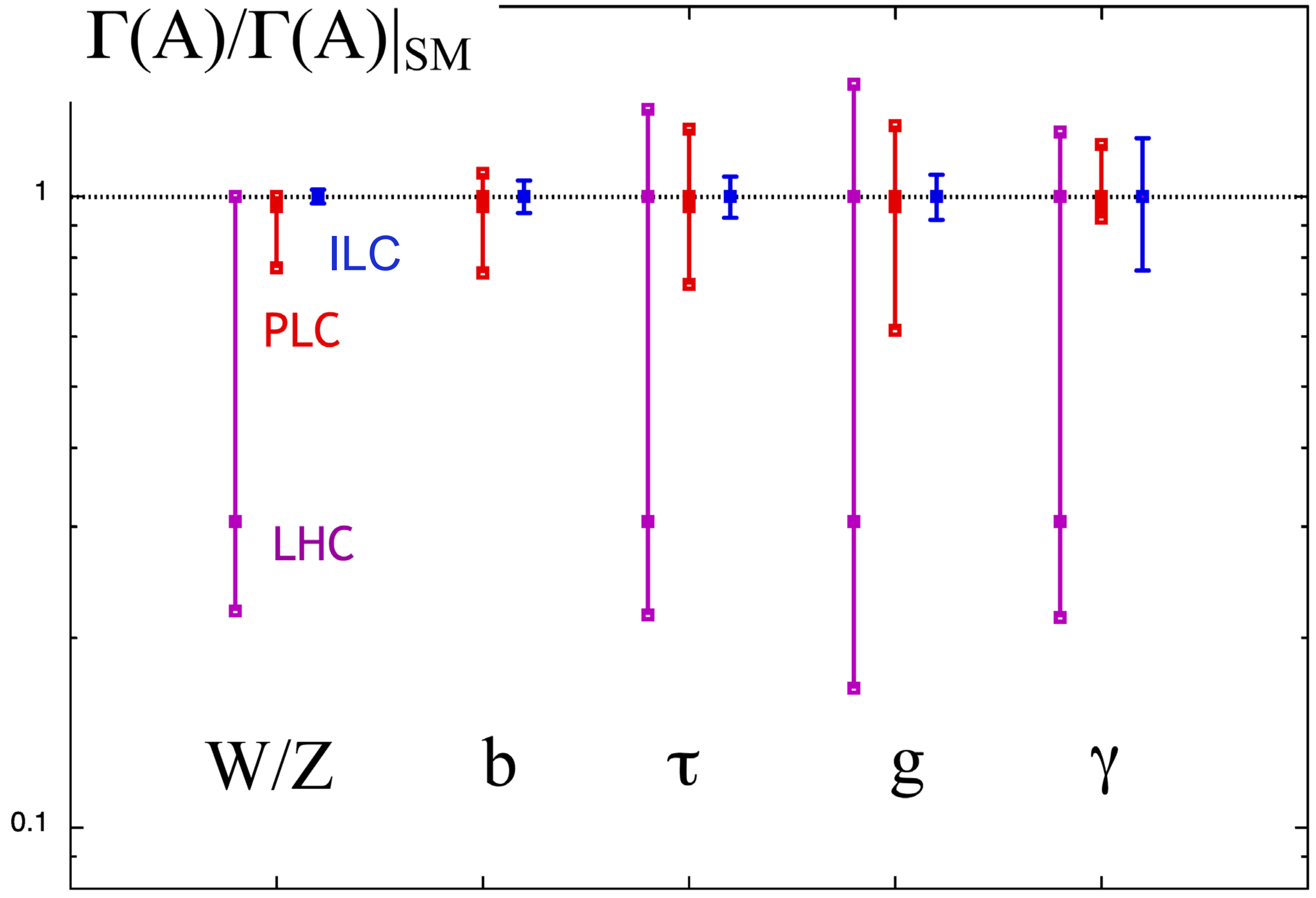






observable	relative error
$\sigma(\gamma\gamma) \cdot BR(b\bar{b})$	4%
$\sigma(\gamma\gamma) \cdot BR(WW)$	9%
$\sigma(\gamma\gamma) \cdot BR(ZZ)$	20%
$\sigma(\gamma\gamma) \cdot BR(\gamma\gamma)$	40%

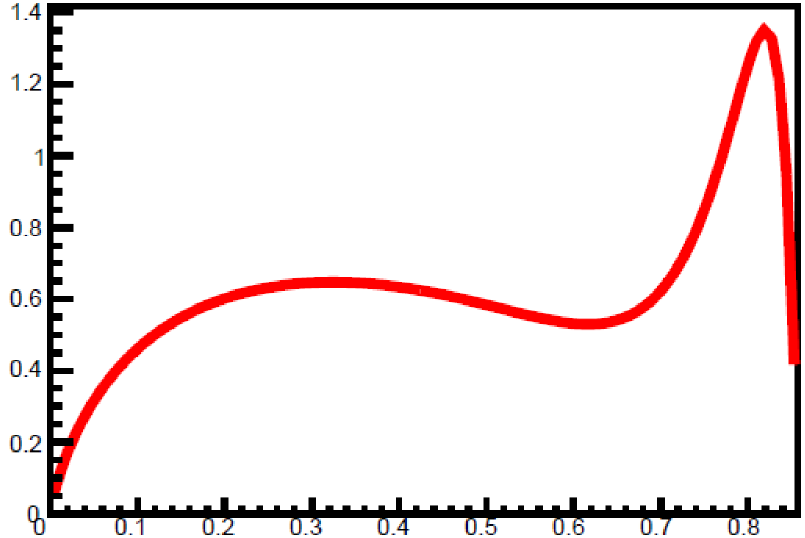
Observables of the Higgs boson that should be measured by the PLC experiment with 60 fb^{-1} of data, for $m_h = 120$ GeV. The errors are given as a fraction of the Standard Model prediction.



Allowed ranges (1σ confidence) for the Higgs boson partial widths to WW, $b\bar{b}$, gg, and $\gamma\gamma$, using the analysis described in the text. We indicate in magneta the constraints from the LHC with 100 fb^{-1} of data per experiment, in red, the limits from the PLC with 60 fb^{-1} total $\gamma\gamma$ luminosity, and, in blue, the expected results from the ILC with 250 fb^{-1}.

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

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



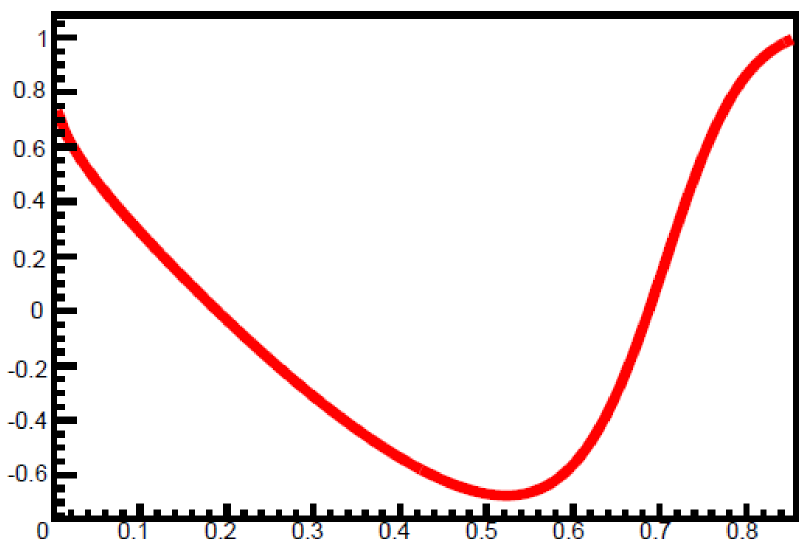
$z = E_{\gamma\gamma} / E_{e^-e^-}$

$x = 6.00 \quad E_{e^-e^-} = 150$ GeV $\quad \kappa = 0.73$

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

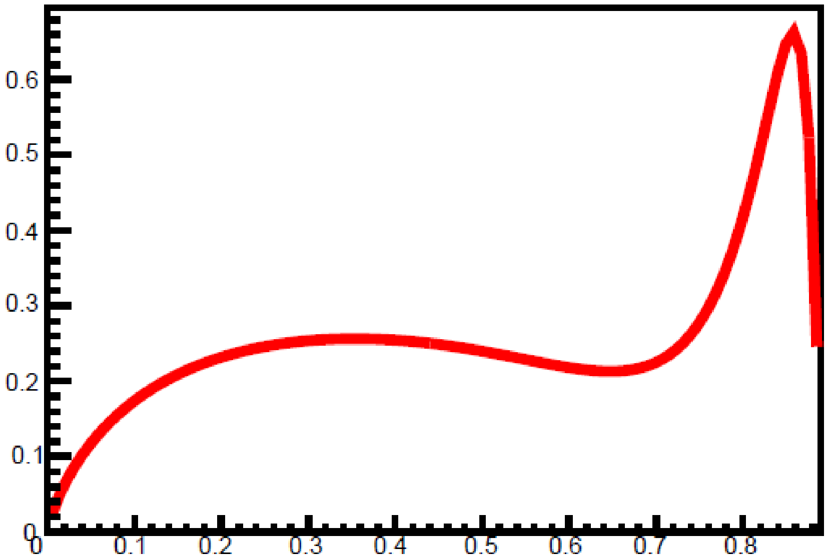
$$\int dz \frac{1}{L_{e^-e^-}} \frac{dL_{\gamma\gamma}}{dz} \sigma(\gamma\gamma \to H) = 130 \text{ fb}$$

$< \xi_1 \, \xi_2 >$



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

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



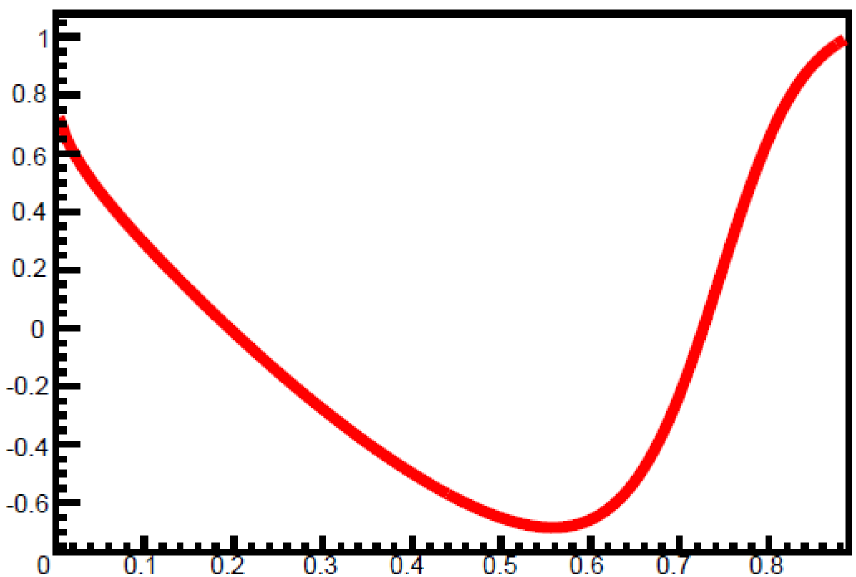
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

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

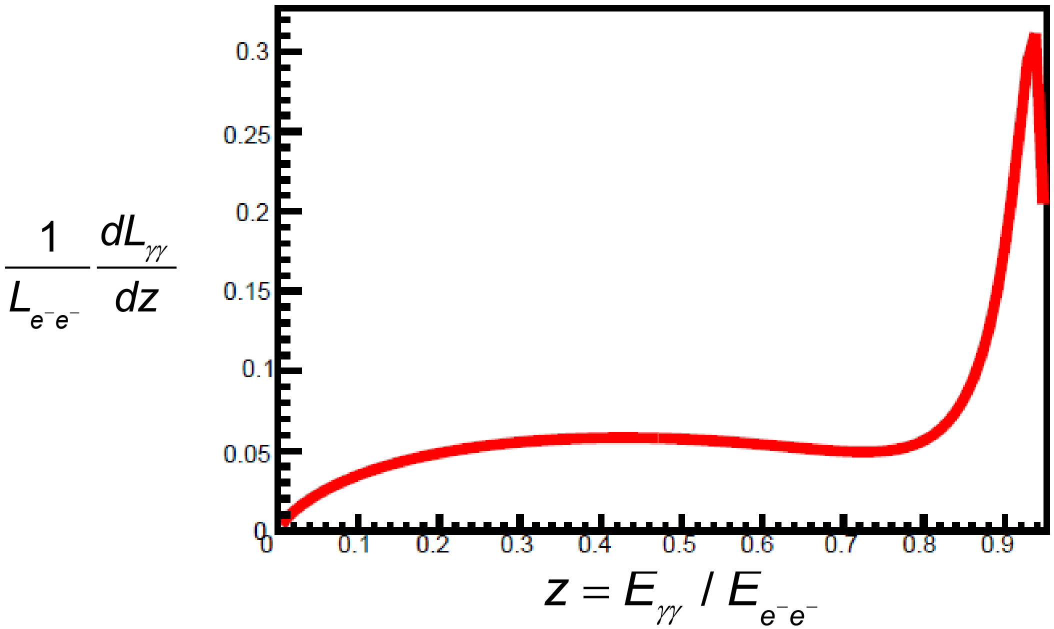
$\text{pol}(e^-) = 90\% \quad 2P_c\lambda_e = -0.9$

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

$$< \xi_1\ \xi_2 >$$



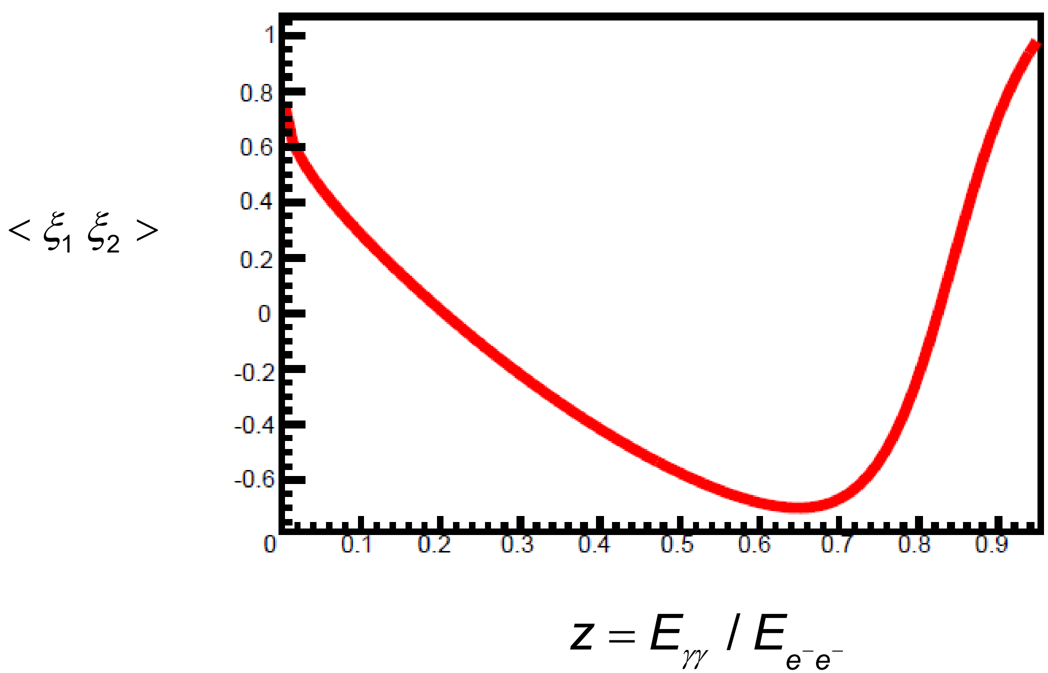
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$



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

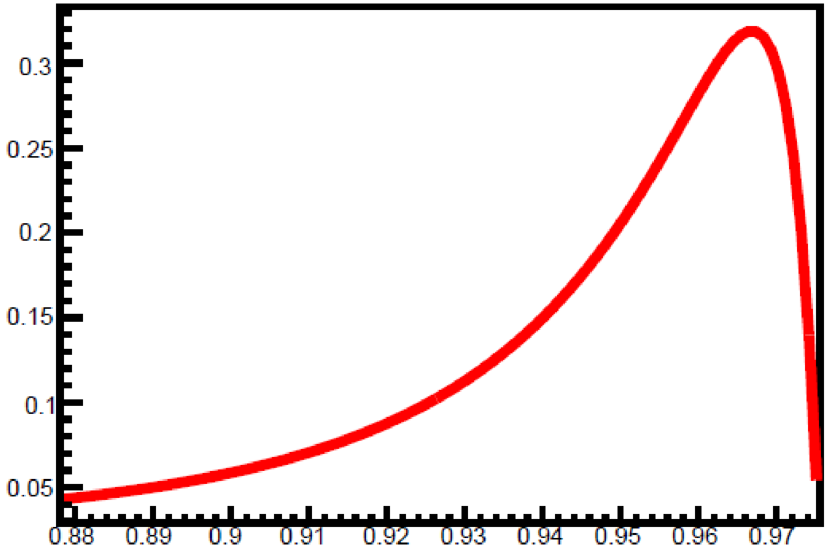
pol(e^-) = 90% $\quad 2P_c\lambda_e = -0.9$

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



11

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



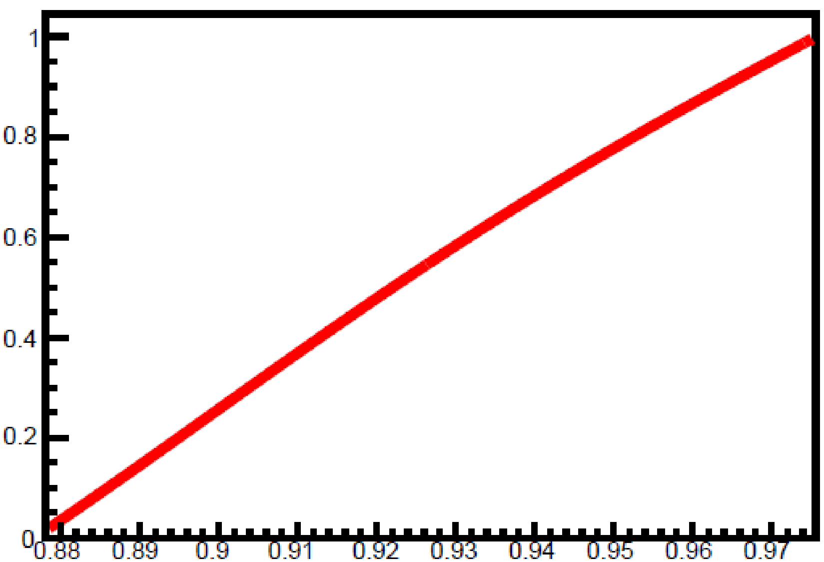
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

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

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

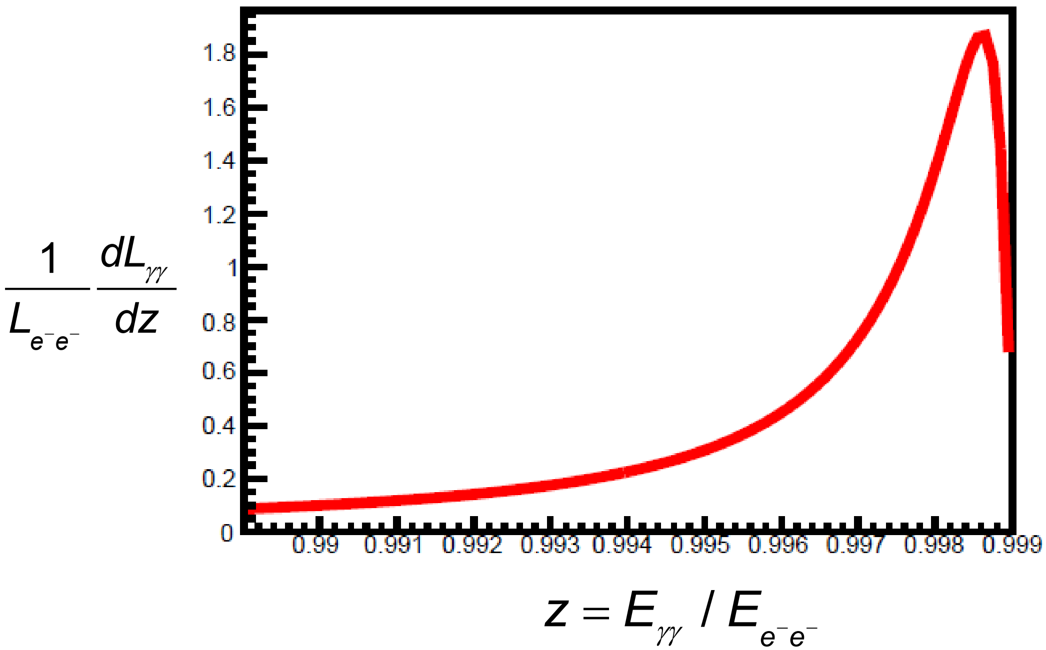
$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 42 \text{ fb}$$

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



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

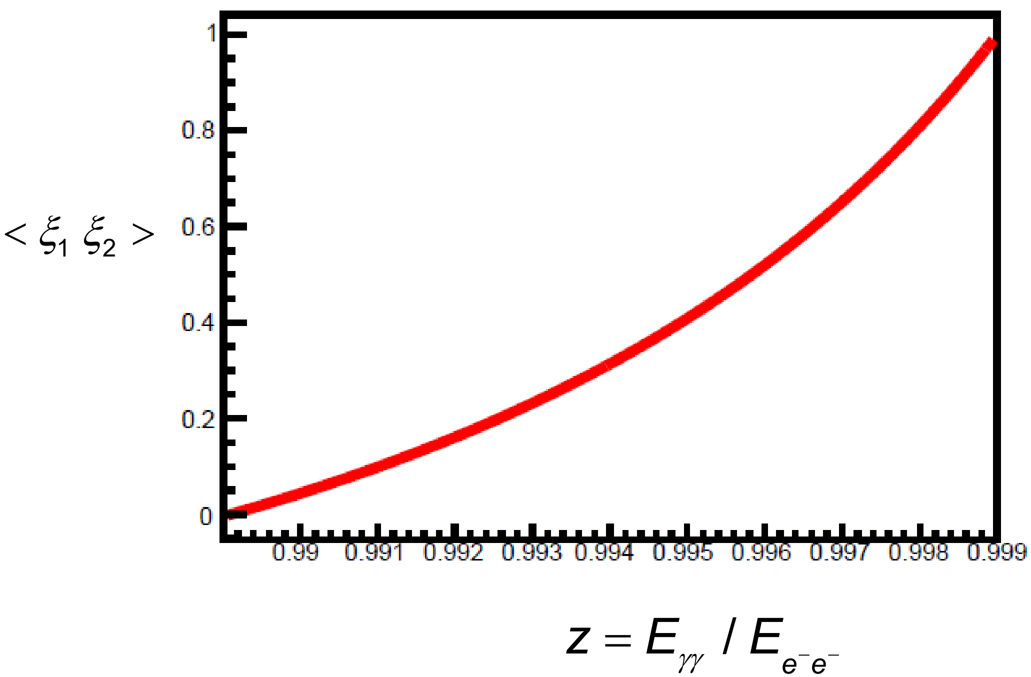
12



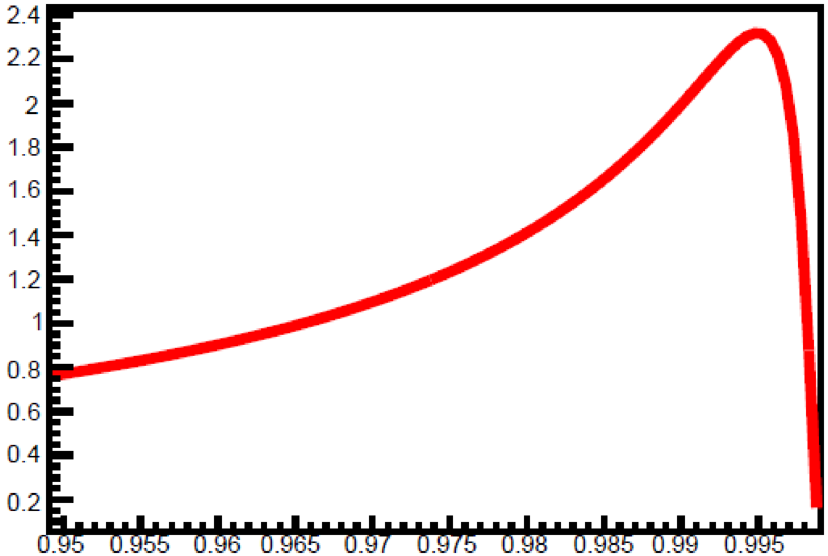
$x = 1000. \quad E_{e^-e^-} = 126.2 \text{ GeV} \quad \kappa = 0.11$

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

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



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



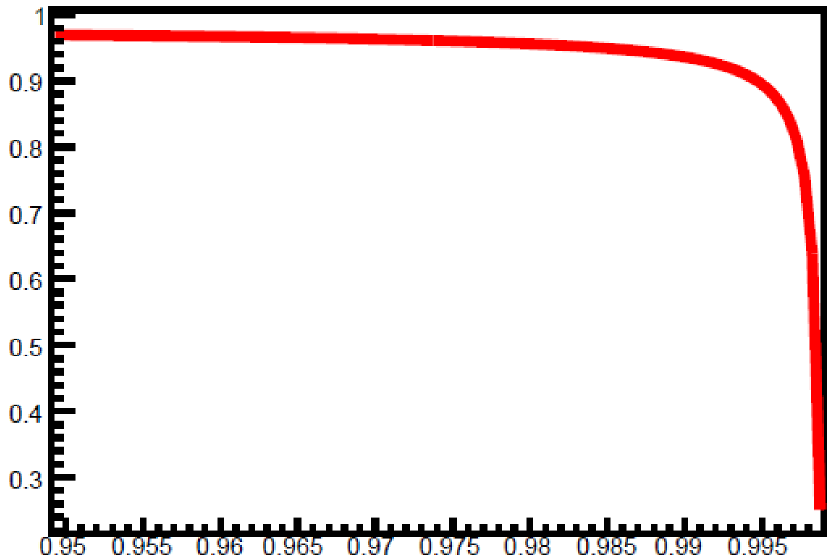
$$z = E_{\gamma\gamma} \,/\, E_{e^-e^-}$$

$x = 1000.$ $E_{e^-e^-} = 126.6$ GeV κ=0.44

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

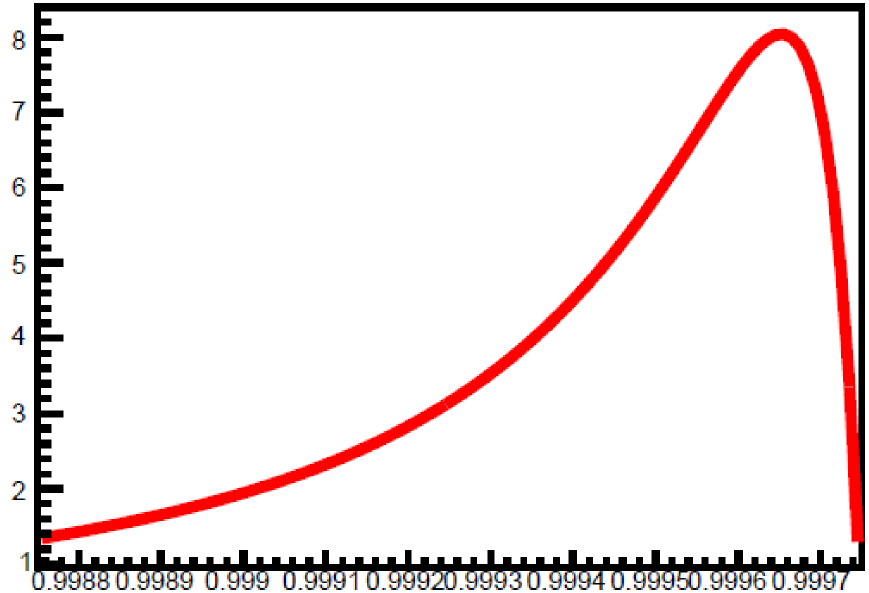
$$\int dz \frac{1}{L_{e^-e^-}}\frac{dL_{\gamma\gamma}}{dz}\sigma(\gamma\gamma \to H) = 311 \text{ fb}$$

$$< \xi_1 \; \xi_2 >$$



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

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



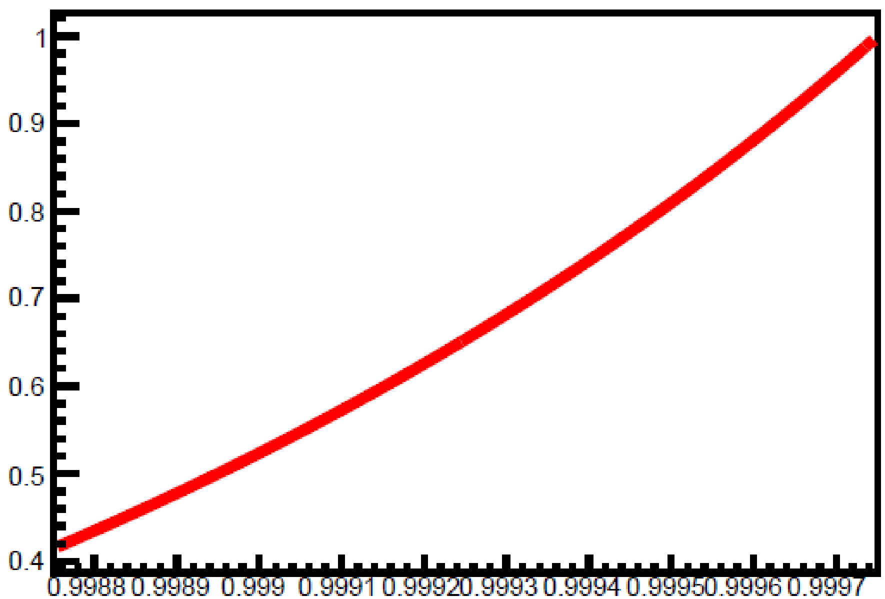
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

$x = 4000.$ $E_{e^-e^-} = 126$ GeV κ=0.12

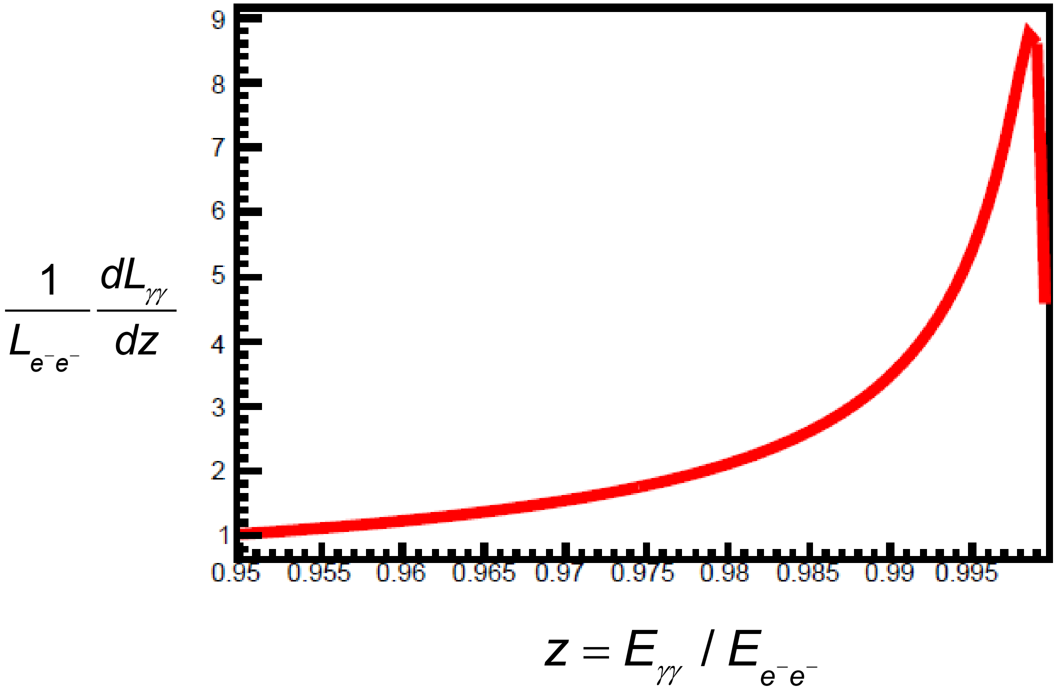
pol$(e^-) = 90\%$ $2P_c\lambda_e = -0.9$

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

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



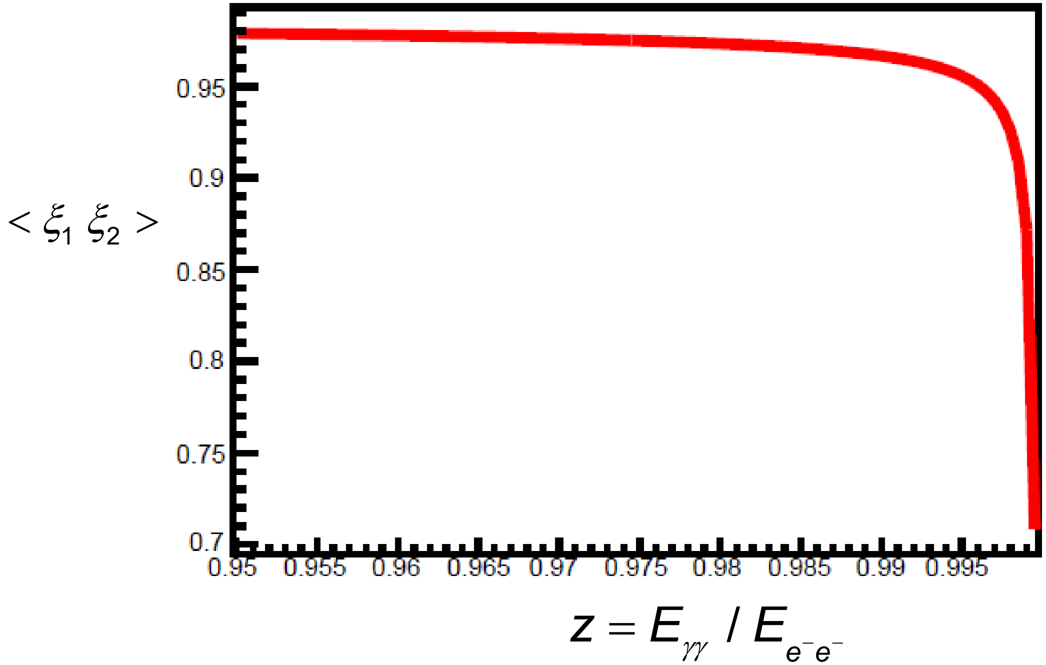
$$z = E_{\gamma\gamma} / E_{e^-e^-}$$

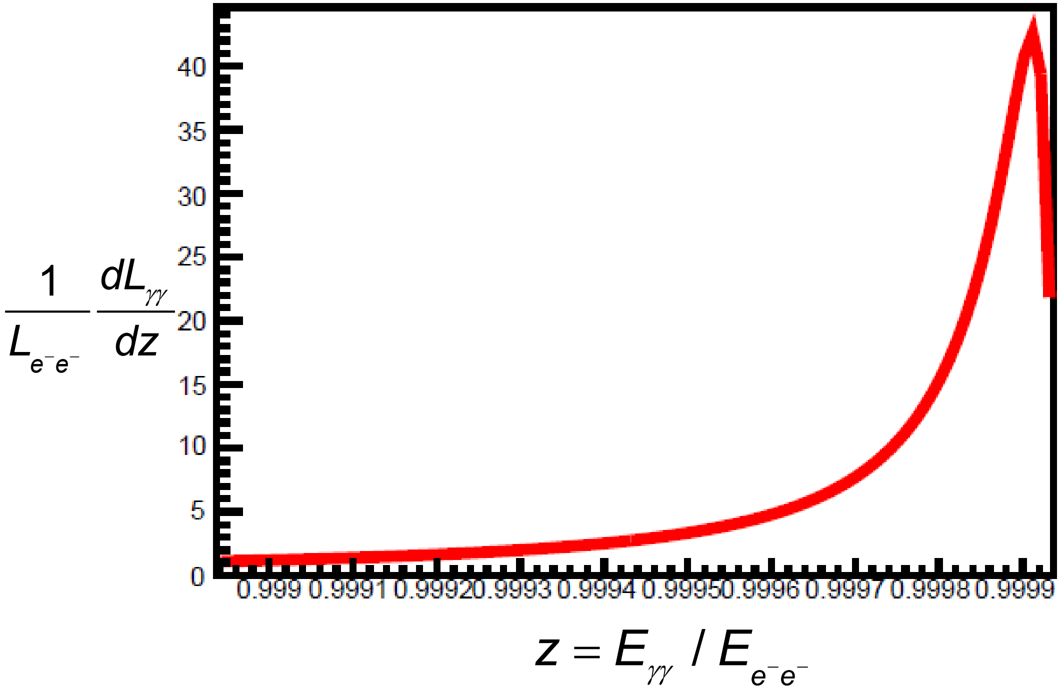


$x = 4000.$ $E_{e^-e^-} = 126.2$ GeV κ=0.53

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

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

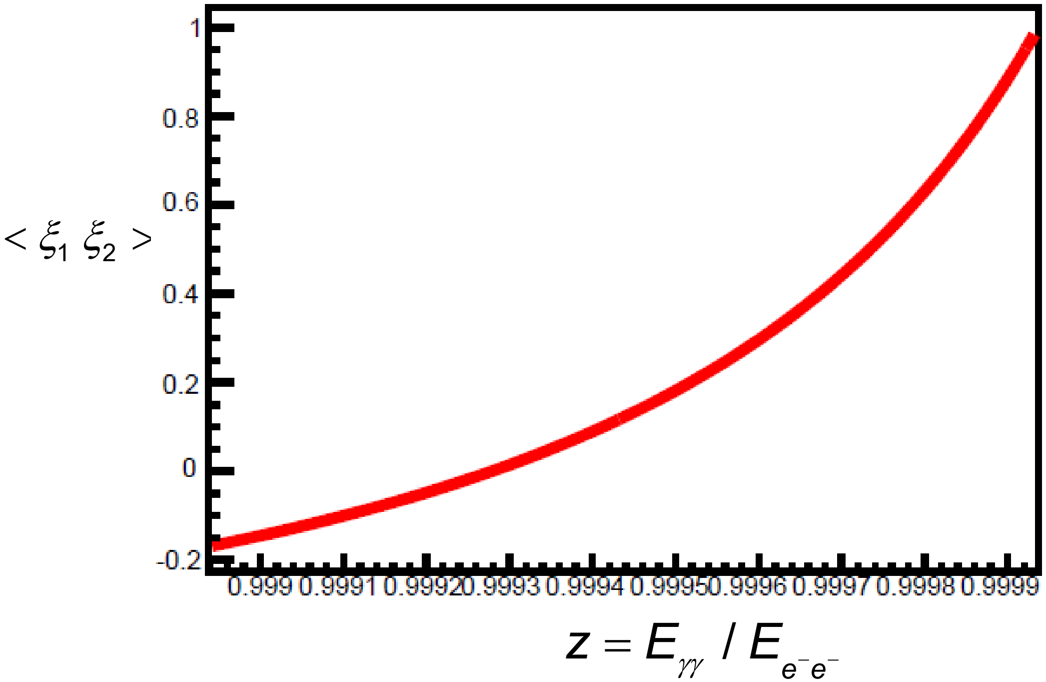


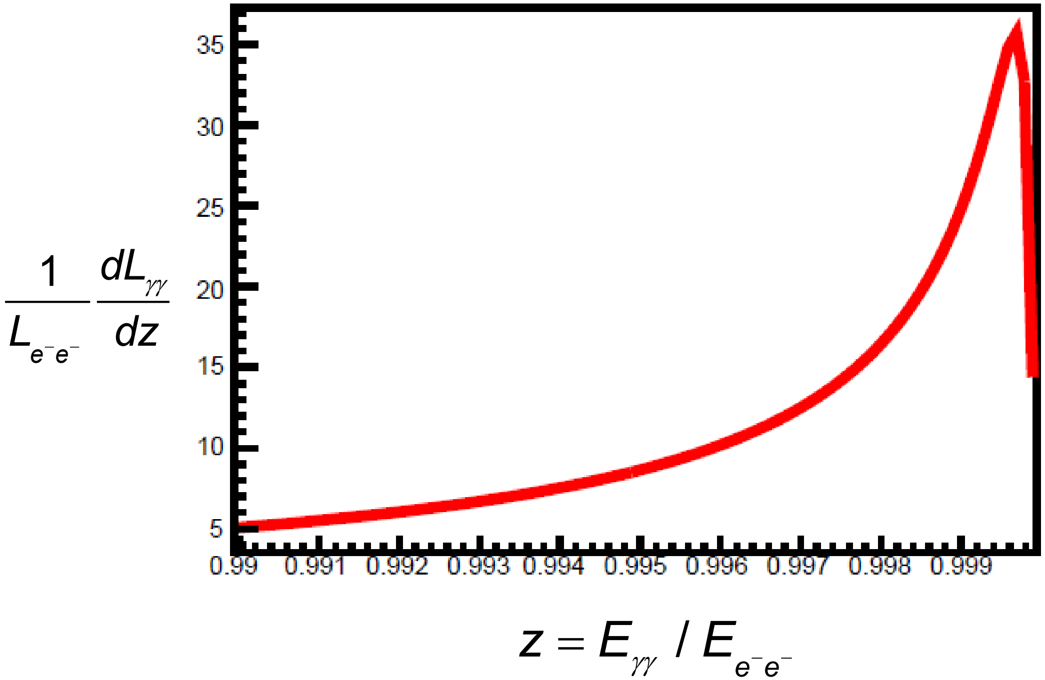


$x = 15870.$ $E_{e^-e^-} = 126$ GeV κ=0.15

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

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

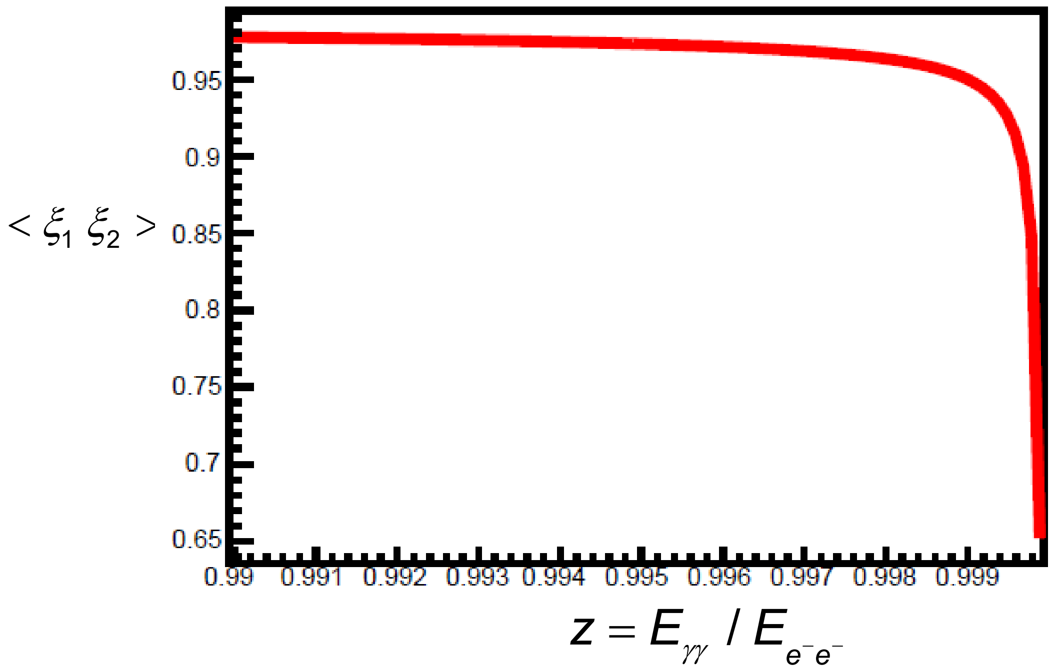




$$x = 15870. \quad E_{e^-e^-} = 126 \text{ GeV} \quad \kappa = 0.64$$

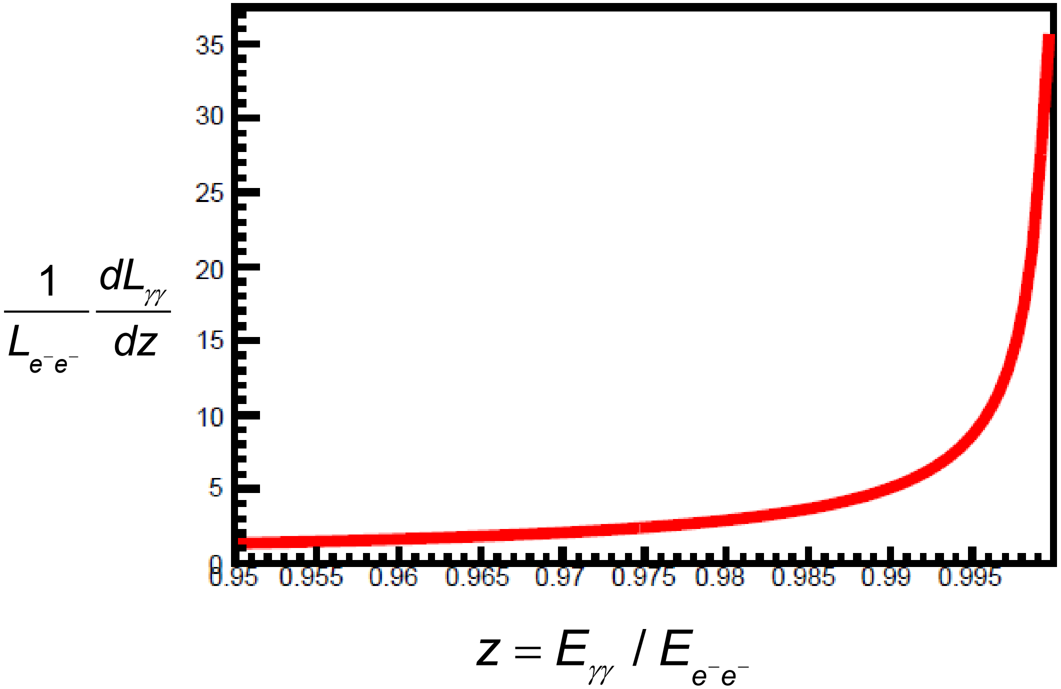
$$\text{pol}(e^-) = 90\% \quad 2P_c\lambda_e = +0.9$$

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



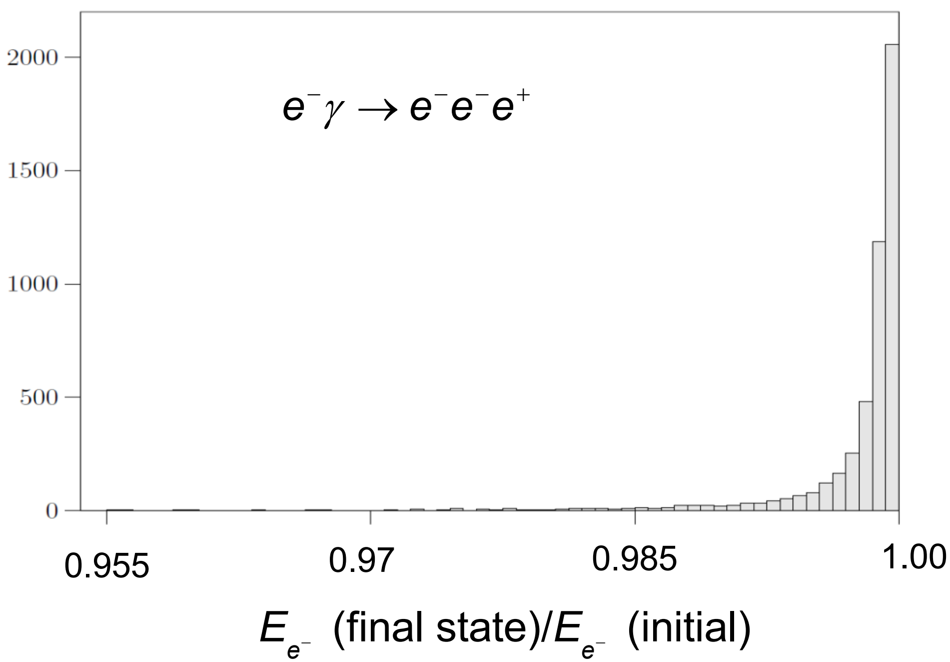
$2P_c\lambda_e = +0.9$ is a better match to $\Delta E_{beam} / E_{beam} \approx 0.1\%$ than $2P_c\lambda_e = -0.9$ for this large x value.

18



$x = 15870.$ $E_{e^-e^-} = 126$ GeV κ=0.64

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



Lab electron energy spectrum following single Bethe-Heitler interaction $e^-\gamma \to e^-e^-e^+$ for E_{e^-}(initial)=63 GeV, $E_\gamma = 15$ keV

Problem:

$\sigma(e^-\gamma \to e^-e^-e^+) = 20 \times \sigma(e^-\gamma \to e^-\gamma)$

for E_{e^-}=63 GeV, $E_\gamma = 15$ keV

Summary of Compton Collision Parameter Study

Existing compton collision parameters are optimal for a $\gamma\gamma$ Higgs factory unless you go to very large values of x where the lumi spectrum is sharply peaked and $\gamma\gamma \to e^+e^-$ is suppressed via polarization.

Assuming electron energy spread is dominated by accelerator energy spread, and disregarding the extreme laser technical challenges the optimal x value was x=16000 with $2P_c\lambda_e = +0.9$. The Higgs production rate in this configuration was 20 times the nominal $\gamma\gamma$ collider rate.

Unfortunately, it appears that at large x values the electron energy spread is not dominated by the accelerator but rather by the Bethe-Heitler process $e^-\gamma_{\text{laser}} \to e^-e^-e^+$. This needs to be investigated. CAIN documentation indicates that it can simulate this process, but this has to be verified.

Nonlinear strong field effects have to be incorporated into this study. CAIN can simulate nonlinear $\gamma\gamma_{\text{laser}} \to e^+e^-$ and $e^-\gamma_{\text{laser}} \to \gamma e^-$.

To Do for Snowmass 2020 p.1

Using an x-ray laser at the Compton collision point and the gamma/e^- polarizations shown on the previous slides, a $\sqrt{s}$=125 GeV e^-e^- collider operating in $\gamma\gamma$ mode could produce $\approx$ 1M Higgs bosons in a 5 year period with a $\gamma\gamma$ center-of-mass energy spread of $\approx$ 200 MeV.

We need to use the CAIN MC program to determine how the $\gamma\gamma$ properties are affected by non-linear QED effects, the Bethe-Heiler process $e^-\gamma_{\text{laser}} \rightarrow e^-e^-e^+$, electron energy spread, and X-ray laser energy spread.

These affects will increase the $\gamma\gamma$ center of mass energy spread and reduce the Higgs production rate. The question is by how much.

To Do for Snowmass 2020 p.2

With a more realistic simulation of the $\gamma\gamma$ beam conditions then we would use a fast MC simulation of SiD to estimate σXBR for various Higgs final states, perhaps with different sets of initial state gammma polarizations.
How much, if anything, a gamma-gamma center-of-mass energy scan can tell us about the total Higgs width will depend on the $\gamma\gamma$ center-of-mass energy spread predicted by the full CAIN simulation.

We need to then address the question of the physics reach under various scenarios (gamma-gamma colider with or without a 250 GeV e+e- collider, with or without FCC-hh, etc.)