XCC

C3 Workshop

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SLAC NATIONAL ACCELERATOR LABORATORY

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$\gamma\gamma$ Collider Basics

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 $|\xi_i| \le 1$

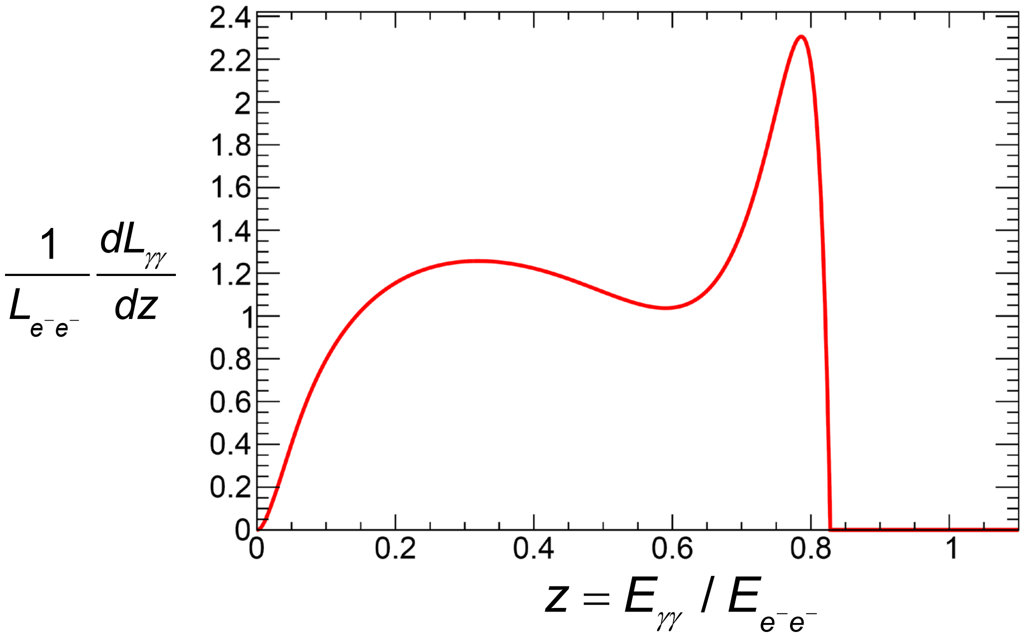
The thresholds for two important physics processes are crossed as *x* is varied:

At $x = 4.82$ $\gamma\gamma_{\text{laser}} \to e^+e^-$ opens up which depletes the high energy photon beam

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.

Both of these effects are included in the CAIN MC simulation.

Nominal configuration with optical laser



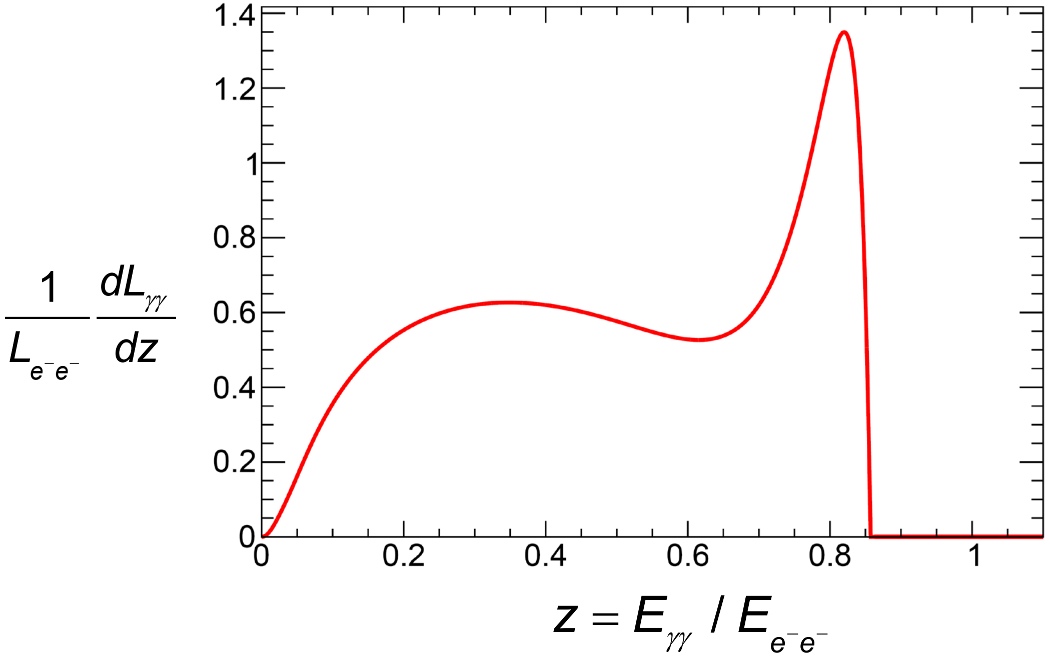
$x = 4.82$ $E_{e^-e^-} = 158$ GeV $\kappa = 1$

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

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

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

Start increasing photon energy (x value) ...

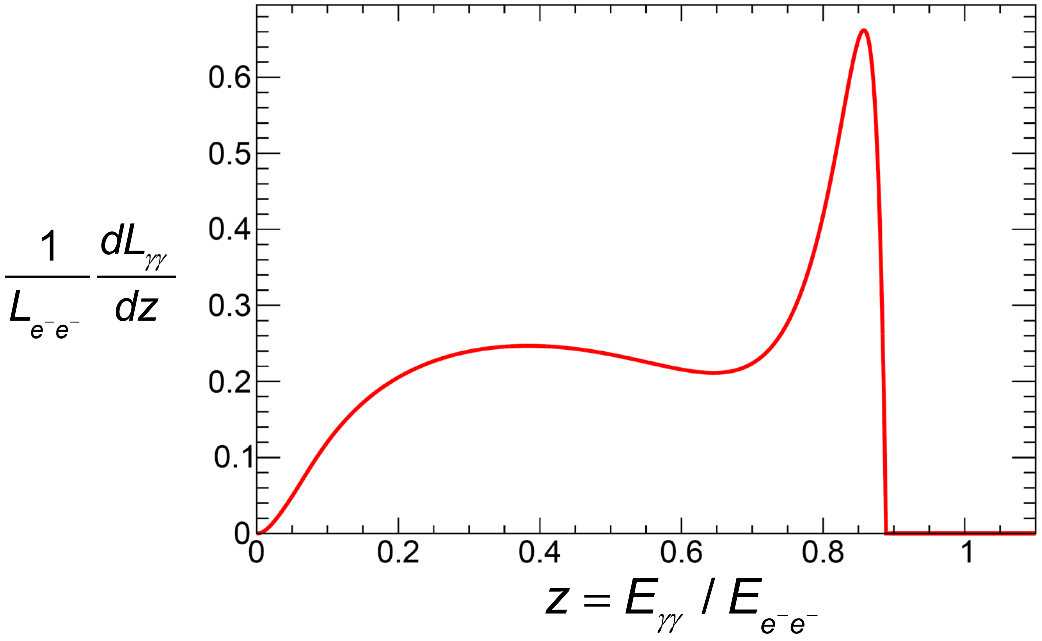


$x = 6.00$ $E_{e^-e^-} = 150$ GeV $\kappa = 0.73$

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

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

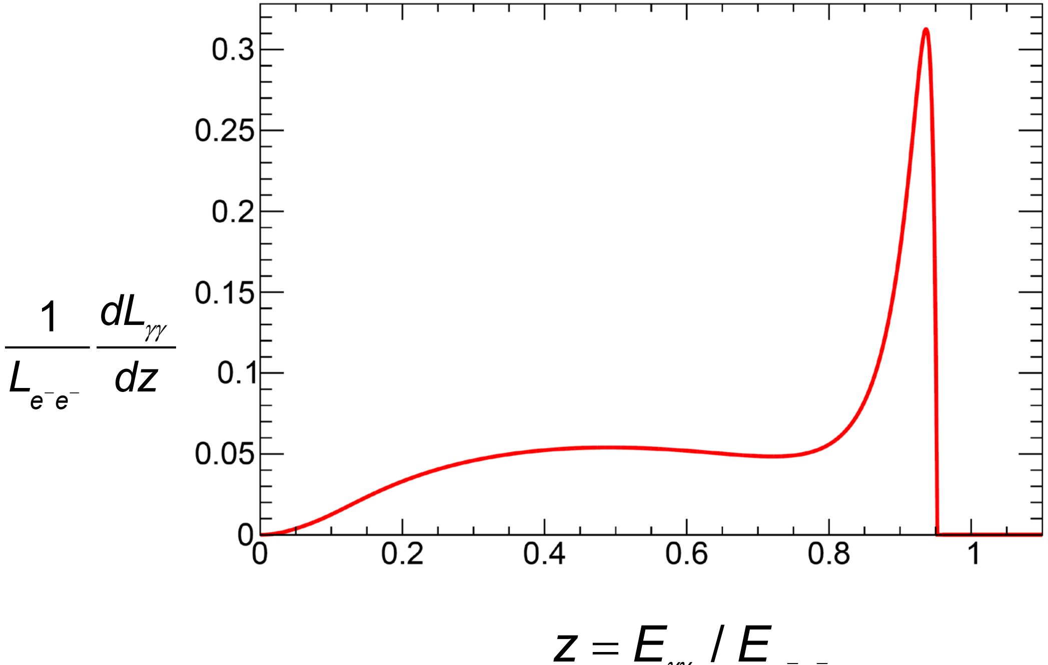
Keep increasing photon energy (x value) ...



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

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

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

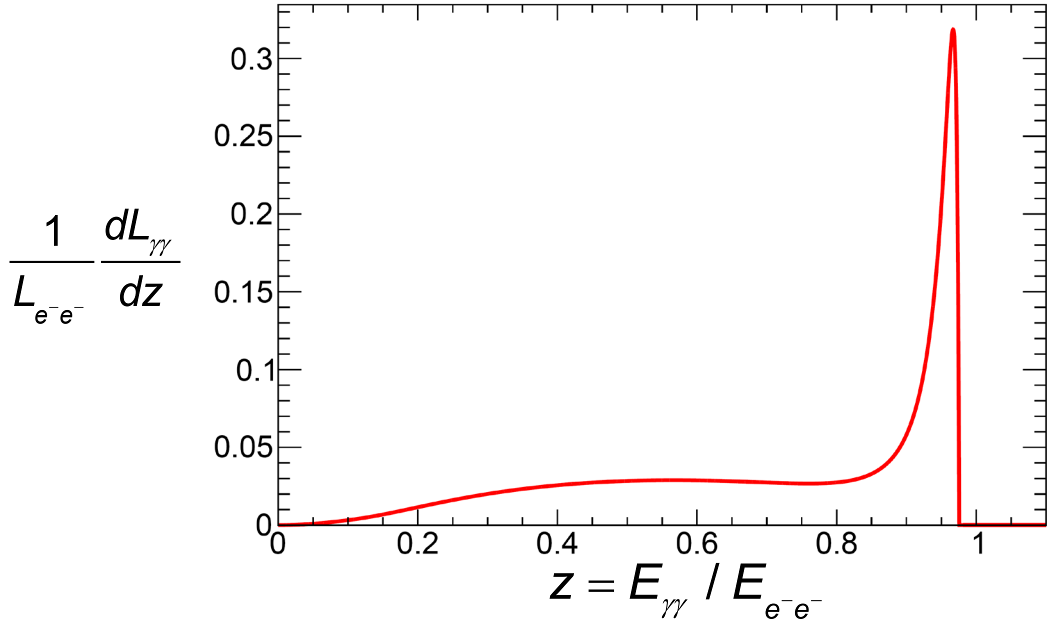


$x = 20.00 \quad E_{e^-e^-} = 134.8\ \text{GeV} \quad \kappa = 0.25$

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

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

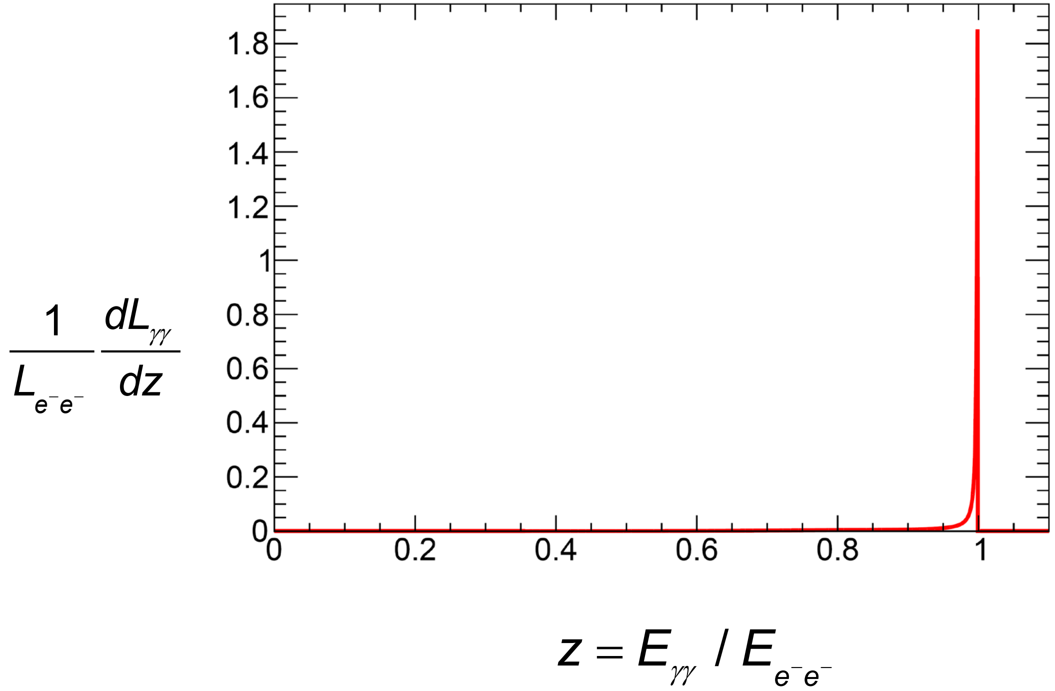
Keep increasing photon energy (x value) ...



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

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

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

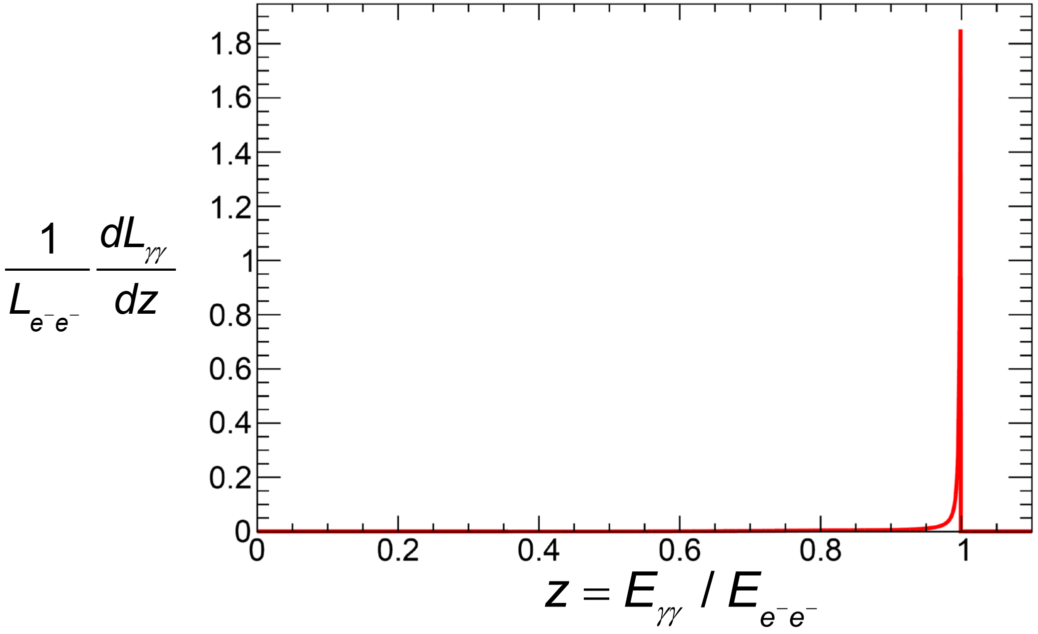


$x = 1000. \quad E_{e^-e^-} = 126.2$ GeV $\quad \kappa = 0.11$

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

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

At large x values the opposite $e^-\gamma$ helicity product sign also gives peaked lumi spectrum

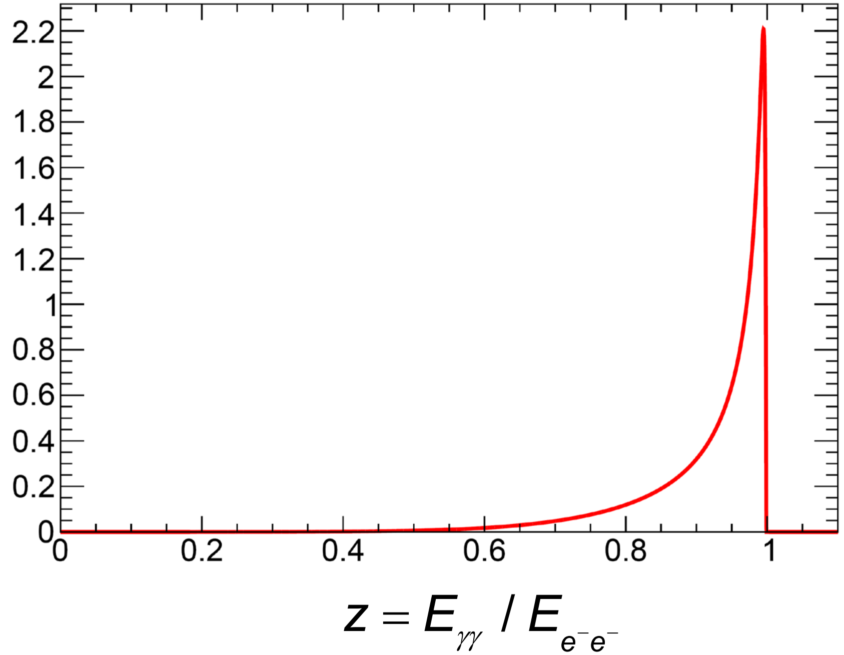


$x = 1000.$ $E_{e^-e^-} = 125.2$ GeV κ=0.11

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

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

$x = 1000$ with $2P_c\lambda_e = +0.9$ is baseline XCC due to higher Higgs rate. Detailed detector/physics studies will determine which of $2P_c\lambda_e = \pm 0.9$ is better.



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

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

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

$2P_c\lambda_e = +0.9$ 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 $2P_c\lambda_e$)

XCC

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

An $e^- e^-$ collider using 70 MV/m C3 accelerator technology operating at $\sqrt{s} = 125$ GeV upgradeable to $\sqrt{s} = 380$ GeV using 120 MV/m -- it is an alternative C3 acceleratory technology Higgs factory

Compton collision points 60 μm upstream of the IP convert 20% of the 62.5 GeV electrons to 62.5 GeV photons using 1 keV XFEL photons.

Electron beam and XFEL parameters chosen to give $\gamma\gamma \rightarrow$ Higgs rate and backgrounds comparable to $e^+ e^-$ Higgs factory rates. This leads to comparable XCC Higgs physics precision but also many electron beam and XFEL technical challenges.

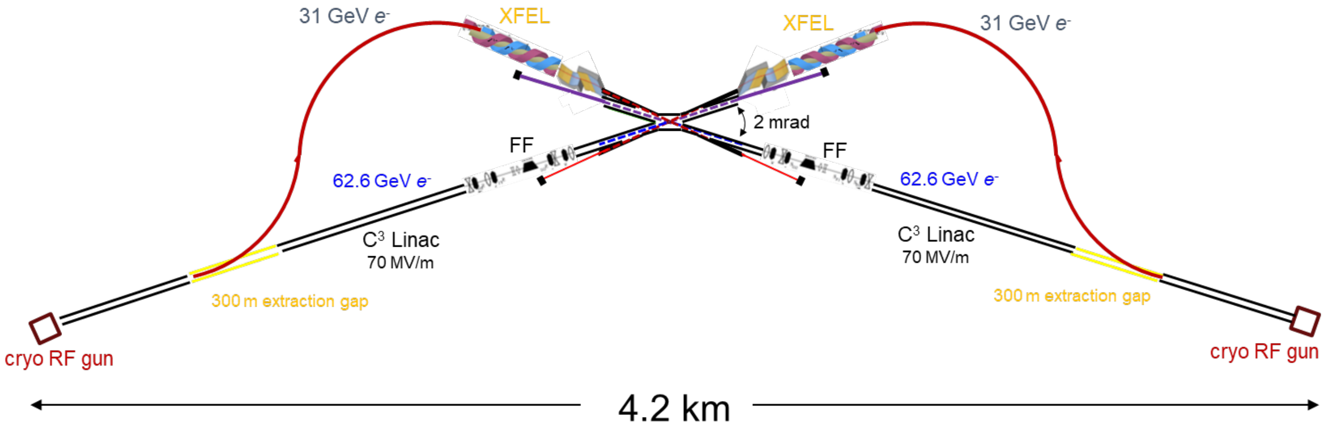
The operation of XCC is relatively simple since $L_{\gamma\gamma} = \kappa^2 L_{e^- e^-}$, where κ=Compton eff:

- Optimize $L_{e^- e^-}$ using $e^- e^-$ beam-beam deflection and beamstrahlung monitors (just like $e^+ e^-$ colliders)
- Maximize Compton conversion efficiency with stable XFEL and X-ray mirror operation.

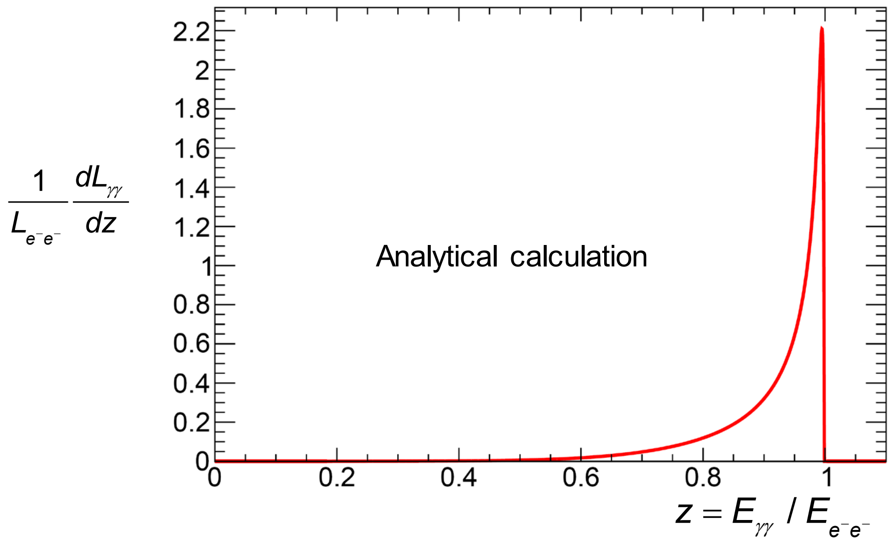
XCC

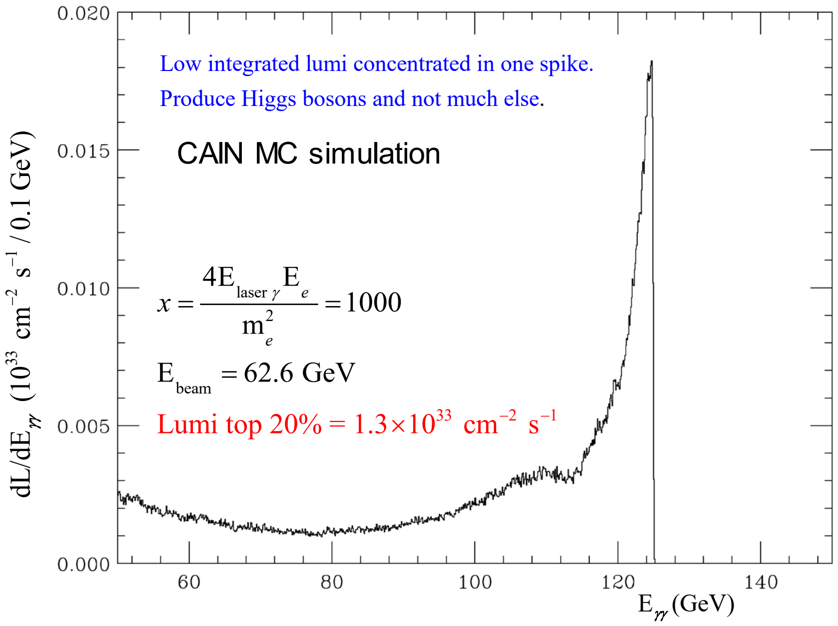
XCC s-channel $\gamma\gamma \to H$ @ $\sqrt{s} = 125$ GeV

$\gamma\gamma \to HH$ @ $\sqrt{s} = 380$ GeV



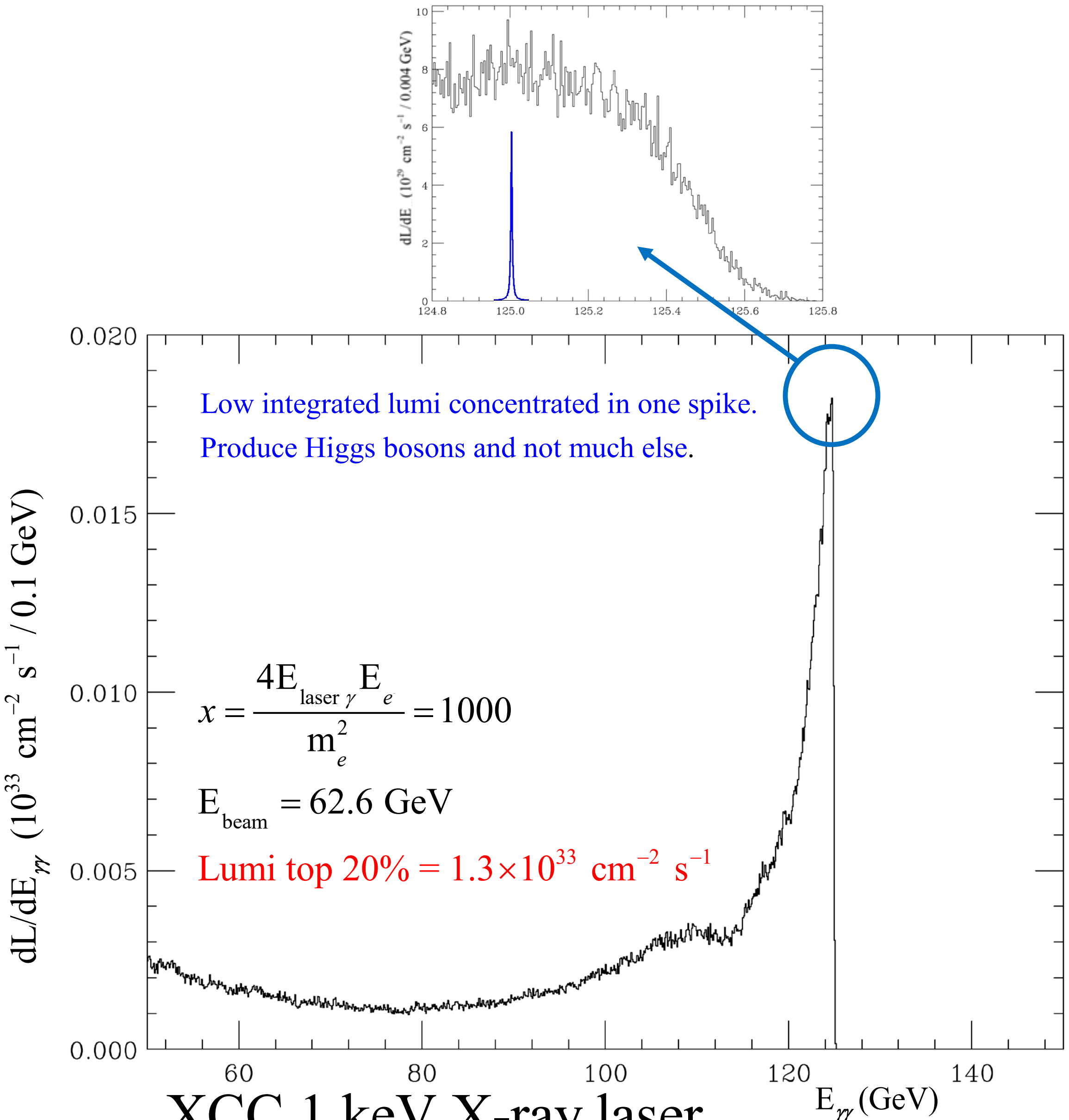
Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$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



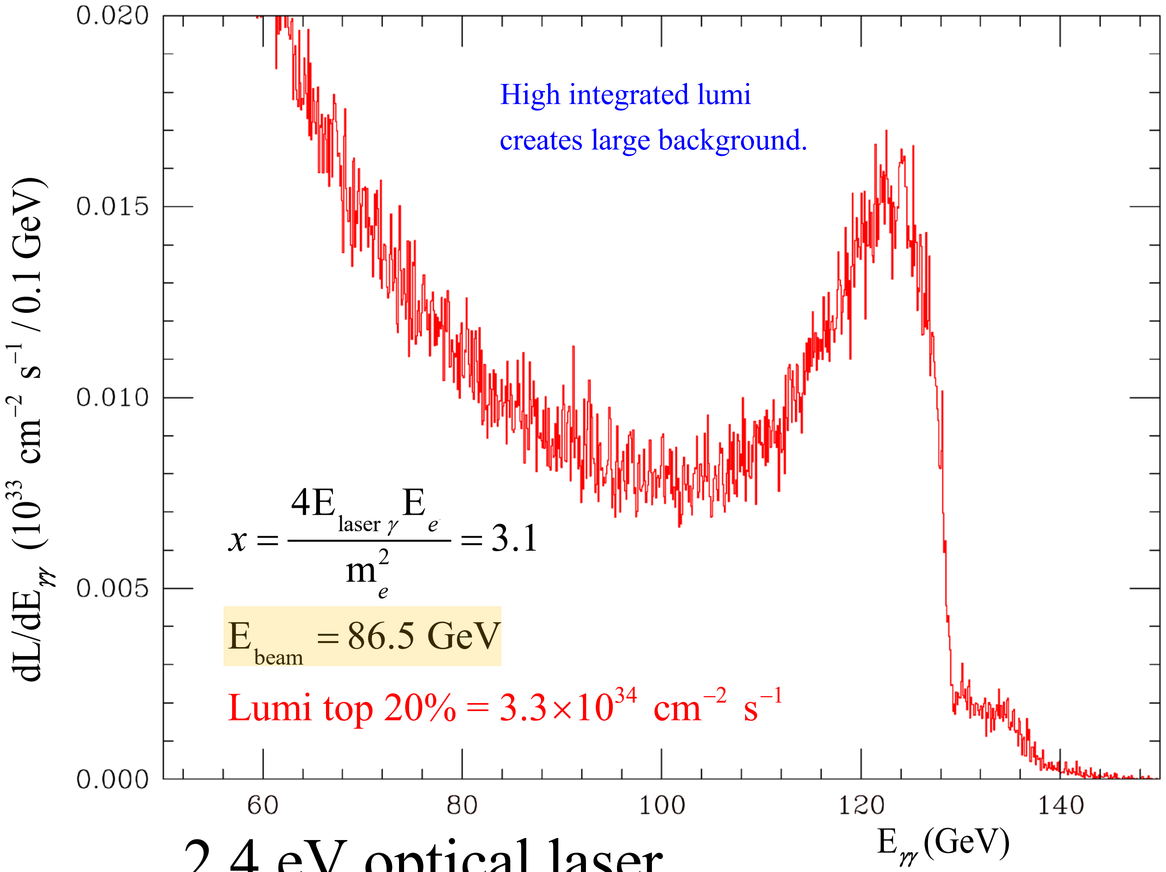


The XCC is very different from previous $\gamma\gamma$ collider concepts

Machine	E_{e^-} (GeV)	Polarization	N_H/yr	N_{Bgnd}/N_H	$N_{pileup/BX}$
XCC	62.8	90% e^-	80,000	170	1.3
2.4 eV laser	86.5	90% e^-	52,000	1310	6.8
ILC	125	−80% e^- +30% e^+	98,000	130	1.3
ILC	125	+80% e^- −30% e^+	65,000	50	1.3



XCC 1 keV X-ray laser



2.4 eV optical laser

ILC/C^3 vs. XCC Physics Comparison

Stage I & II Parameters

Colliding Particles	ILC/C^3 e^+e^-	XCC $\gamma\gamma$
Stage I:		
$\sqrt{s}$ (GeV)	250	125
Luminosity (fb^{-1})	2000	460
Beam Power (MW)	5.3 / 4.0	4.0
Run Time (yr)	10	10
# Single Higgs	0.5×10^6	1.3×10^6
Stage II:		
$\sqrt{s}$ (GeV)	550	380
Luminosity (fb^{-1})	4000	4900
Beam Power (MW)	11 / 4.9	4.9
Run Time (yr)	10	10
# Single Higgs (I+II)	1.5×10^6	1.3×10^6
# Double Higgs	840	1800
# $t\bar{t}$	2.0×10^6	2.9×10^6

Stage I, 10 years

κ framework $\mathrm{BR}_{\mathrm{BSM}} = 0$

coupling a	HL-LHC† Δa (%)	ILC/C^3 Δa (%)	XCC Δa (%)
HZZ	2.4	0.46	0.83
HWW	2.6	0.44	0.84
Hbb	6.0	0.83	0.85
$H\tau\tau$	2.8	0.98	0.89
Hgg	4.0	1.6	1.1
Hcc	-	1.8	1.2
$H\gamma\gamma$	2.9	1.1	0.10
$H\gamma Z$	-	-	1.5
$H\mu\mu$	6.7	4.0	3.5
Γ_{tot}	5	1.6	1.7

† S1 from Table 36 in arXiv:1902.00134 [hep-ph]

Stage I+II, 20 years

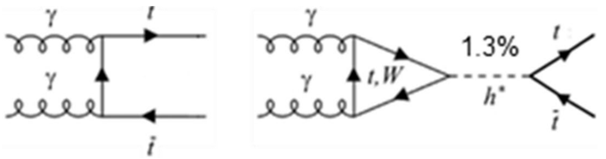
Model Independent EFT

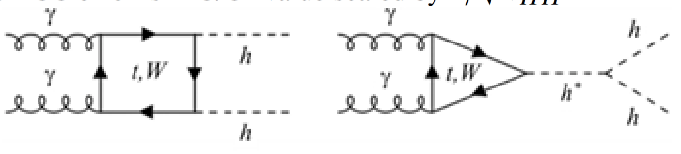
coupling a	ILC/C^3 Δa (%)	XCC$^{\#}$ Δa (%)
HZZ	0.38	0.94
HWW	0.37	0.94
Hbb	0.60	0.95
$H\tau\tau$	0.77	0.99
Hgg	0.96	1.2
Hcc	1.2	1.2
$H\gamma\gamma$	1.0	0.44
$H\gamma Z$	4.0	1.5
$H\mu\mu$	3.8	3.5
Htt	2.8	4.6
HHH	20	14*
Γ_{tot}	1.6	2.4
$\Gamma_{\mathrm{inv}}{}^\dagger$	0.32	–
$\Gamma_{\mathrm{other}}{}^\dagger$	1.3	1.5

† 95% C.L. limit

*assumes XCC error is ILC/C^3 value scaled by $1/\sqrt{N_{HH}}$

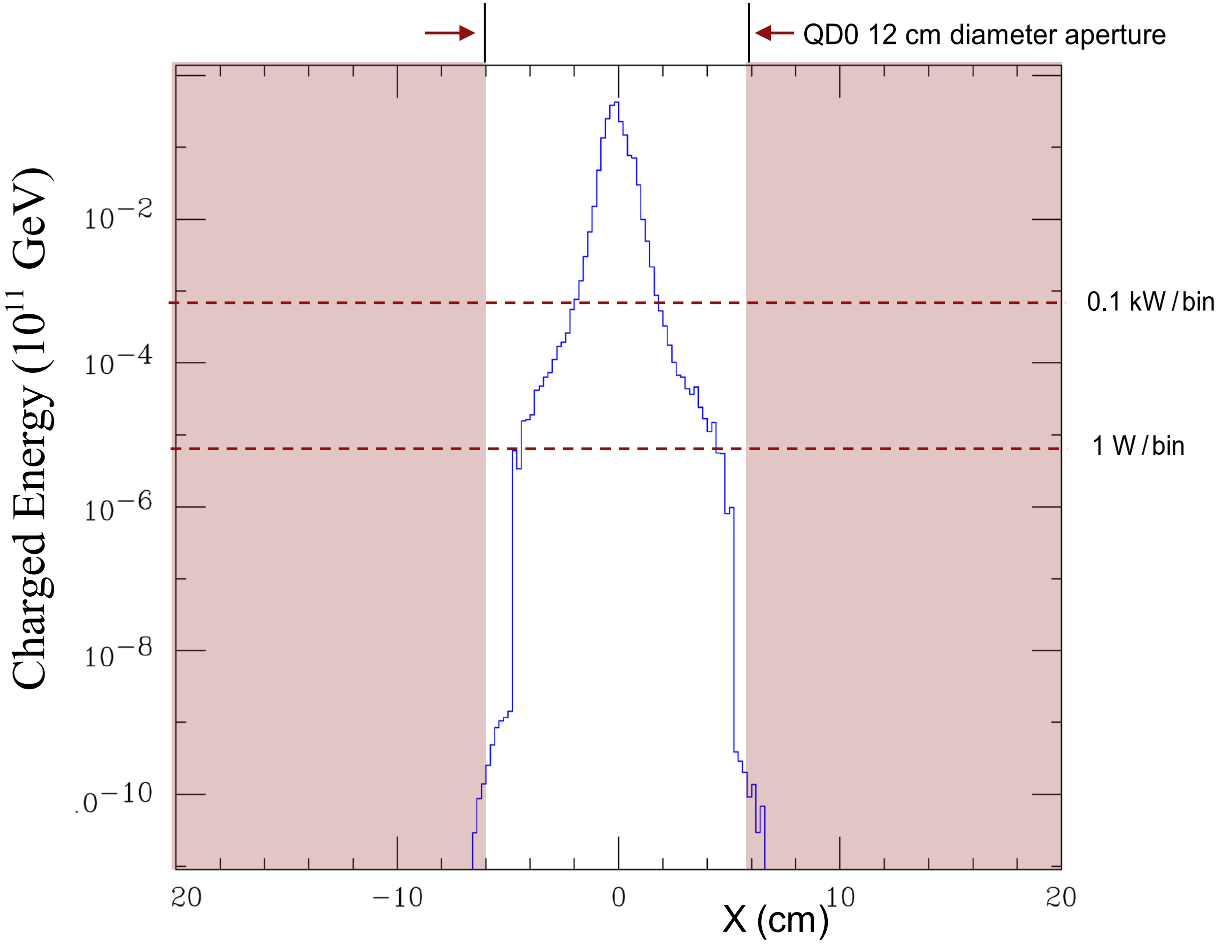
$^{\#}$XCC achieves model independence through measurement of $\Gamma_{\gamma\gamma}$ using monochomatic electron in $e^-\gamma \to e^- H$ during $\sqrt{s} = 380$ GeV $\gamma\gamma$ run.

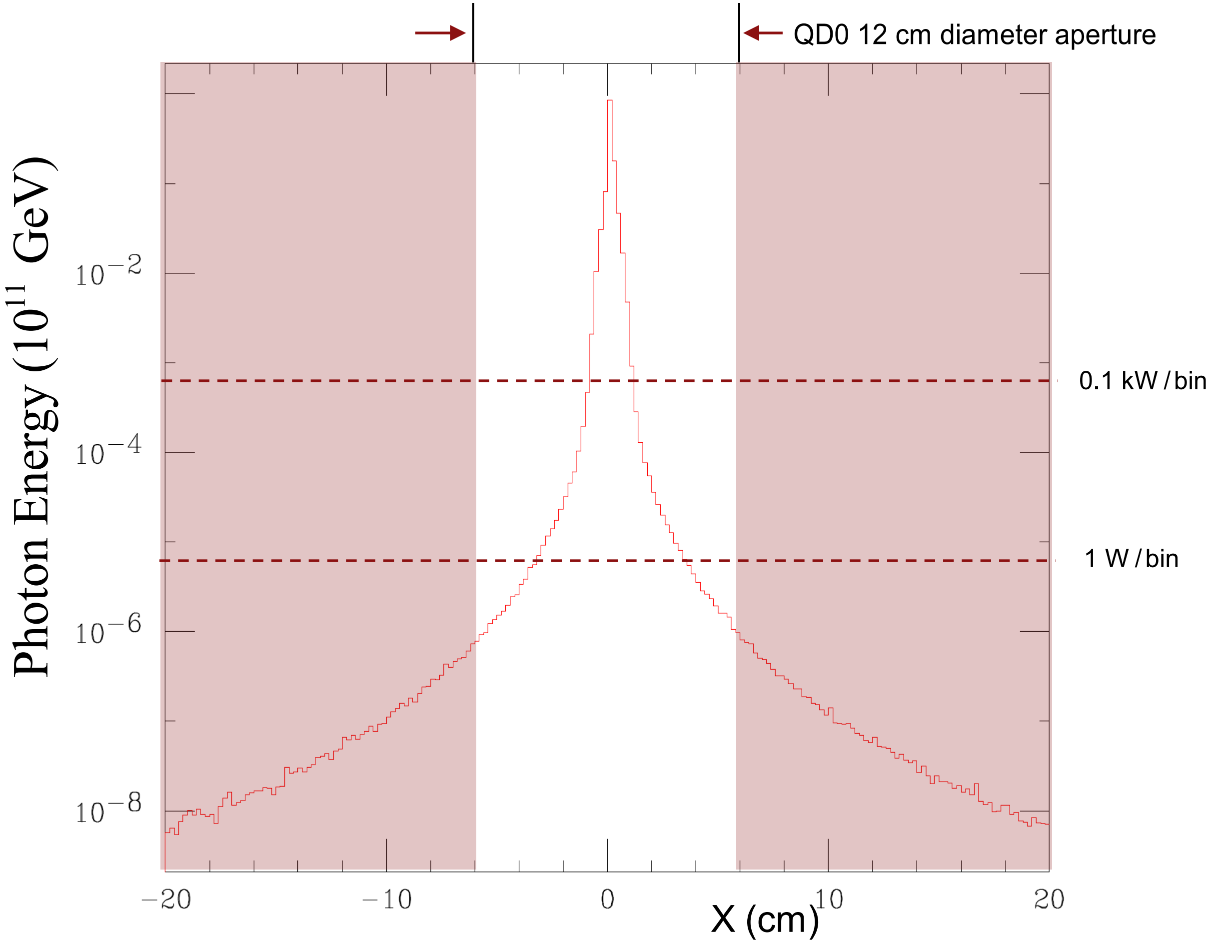




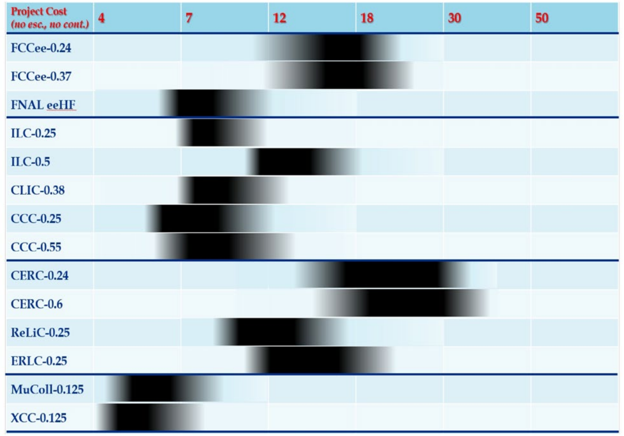
Final Quad Aperture

CAIN Simulation from IP to Face of Quad, Assume 5 T Solenoid

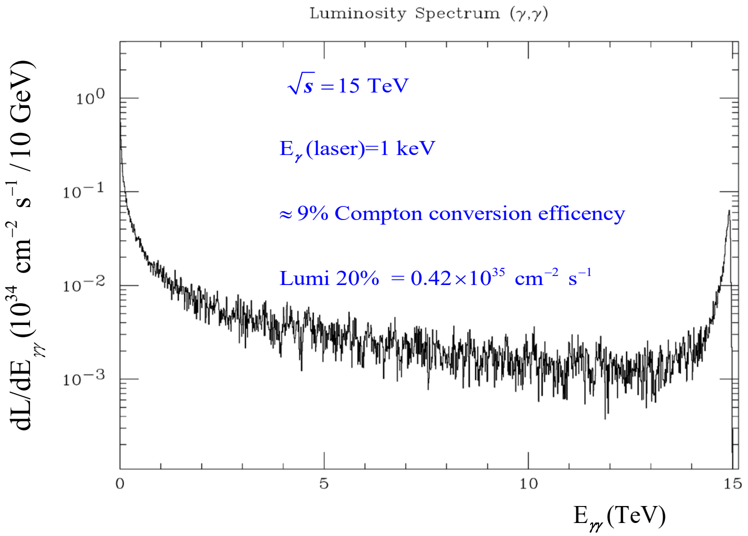




XCC advantages:



ITF

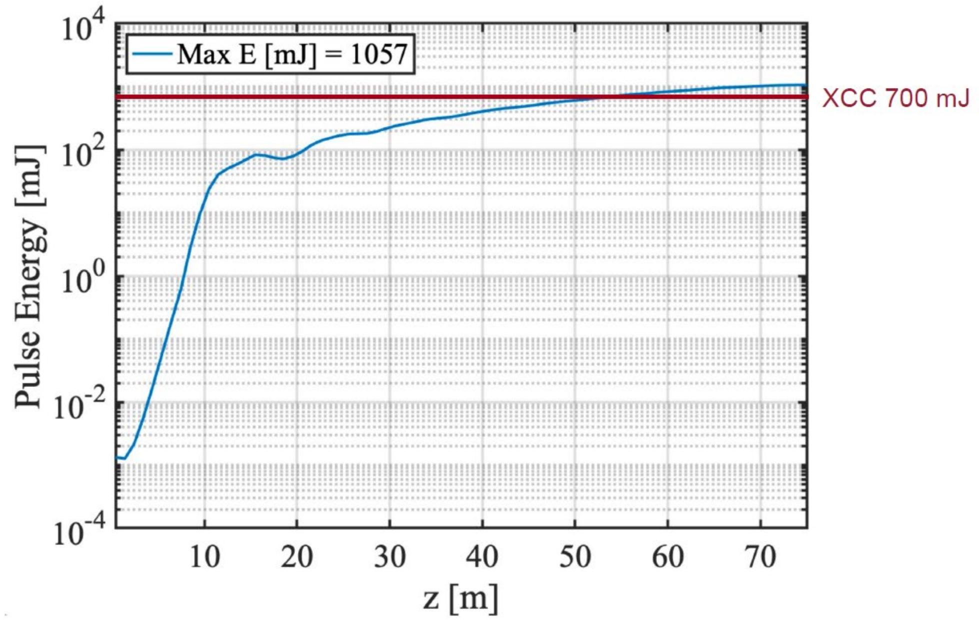


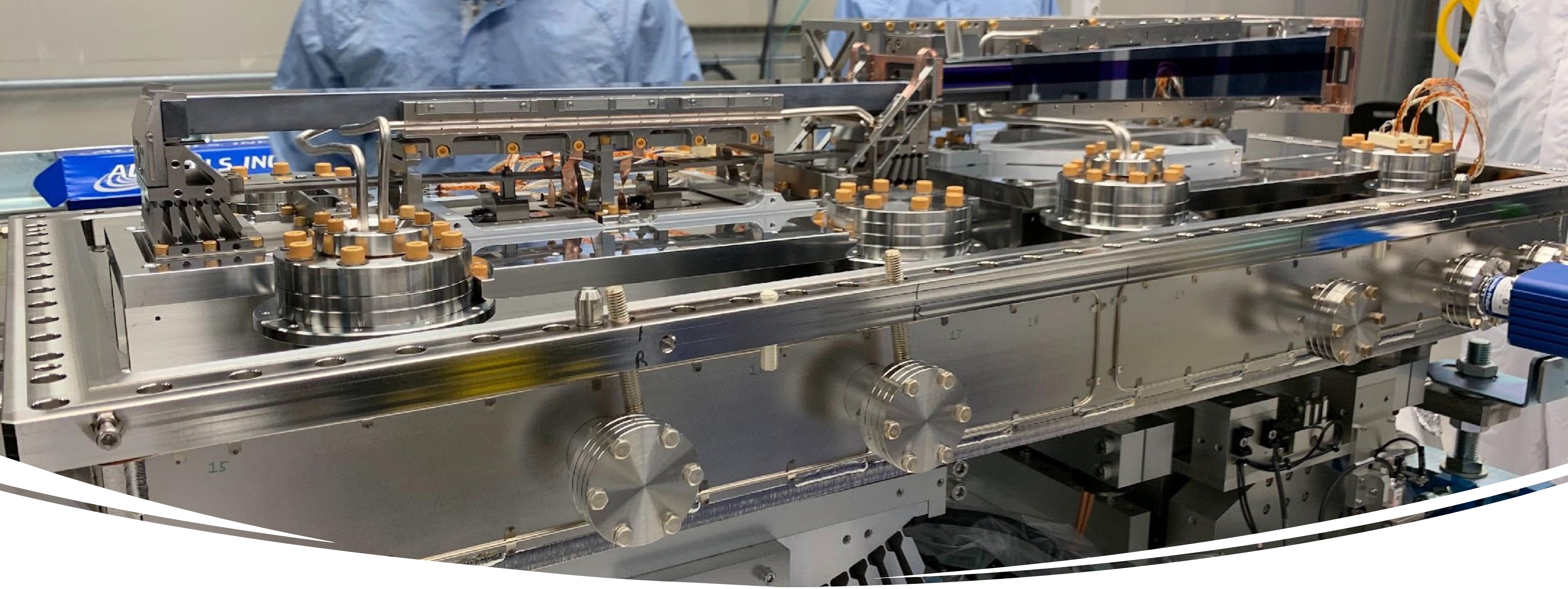
- $\approx$ 40% lower cost w.r.t C3 e^+e^- collider
- Highly synergistic with SLAC XFEL program.
- XCC has a factor of 2 statistical advantage w.r.t. ILC/C^3 in double Higgs production, and may have additional advantages in the triple Higgs coupling measurement due to the simplicity of the HH final state vs. ZHH.
- Physics would be more complementary to CEPC than ILC/C^3, generally due to a different initial state, and specifically due to enhanced $\Delta H\gamma\gamma$, $\Delta H\gamma Z$ & ΔHHH precision.
- If positron acceleration is a show stopper for a 15 TeV PWFA e^+e^- collider then the PWFA must be operated in $\gamma\gamma$ mode, in which case XCC would serve as a $\gamma\gamma$ collider prototype. There are some indications that a soft x-ray laser might be the optimum laser wavelength for a 15 TeV PWFA $\gamma\gamma$ collider

XCC challenges:

- e^- accelerator with $70-120$ MV/m (common with C^3 e^+e^- collider)
- Polarized low emittance e^- injector (common with C^3 e^+e^- , except flat beams not needed)
- Focusing of round e^- beams to $\sigma_{x,y} = 5.5$ nm
- Production and focusing of 1 keV γ XFEL with 700 mJ/pulse to 70 nm FWHM waist *
- XFEL and e^- beamline layouts around the IP
- Timing and position stability of the XFEL laser beam and e^- beam at Compton IP.

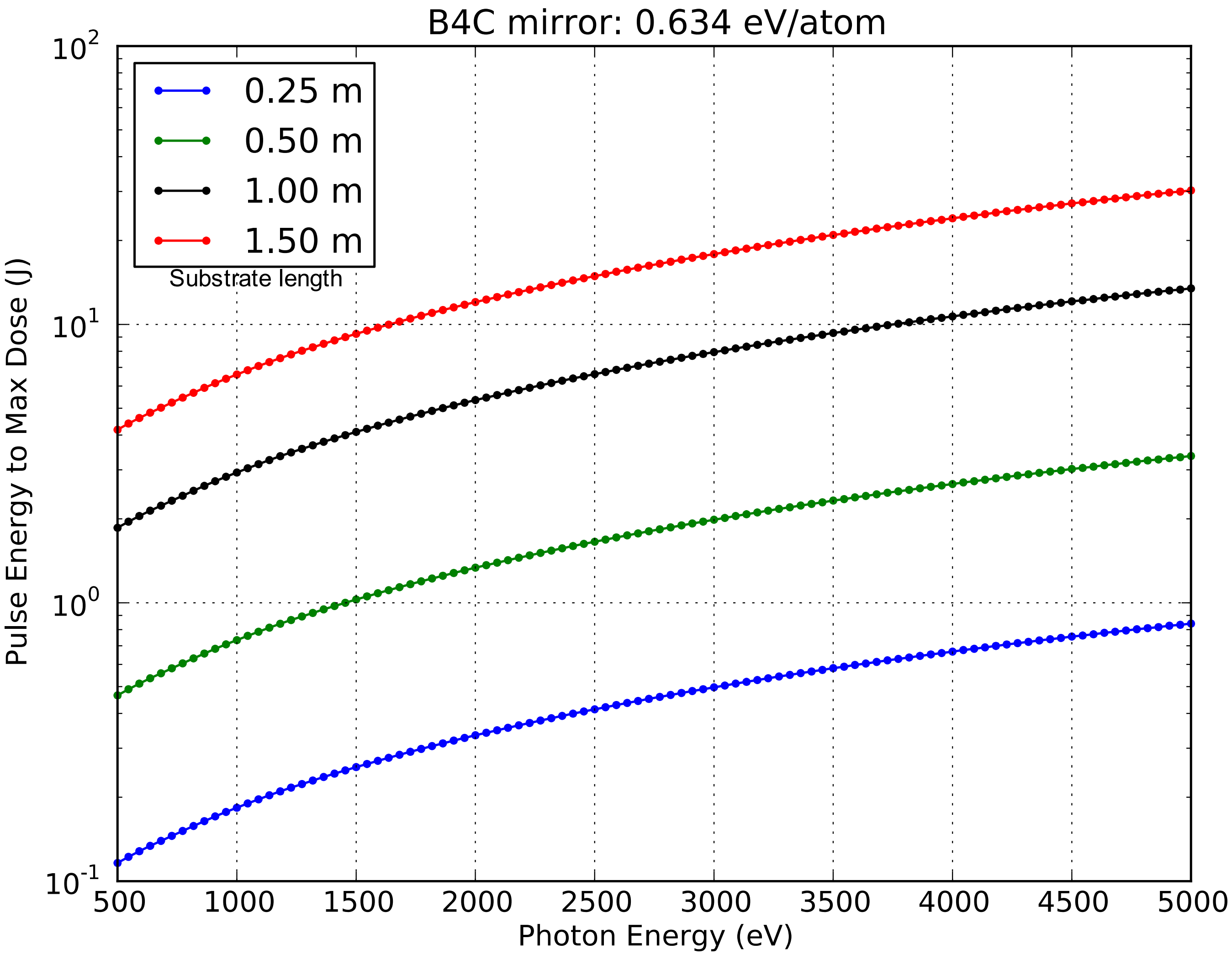
*Design for production of 1 keV γ XFEL with 700 mJ/pulse has been validated with Genesis program.





KB Mirror Focusing for $\gamma\gamma$ Collider

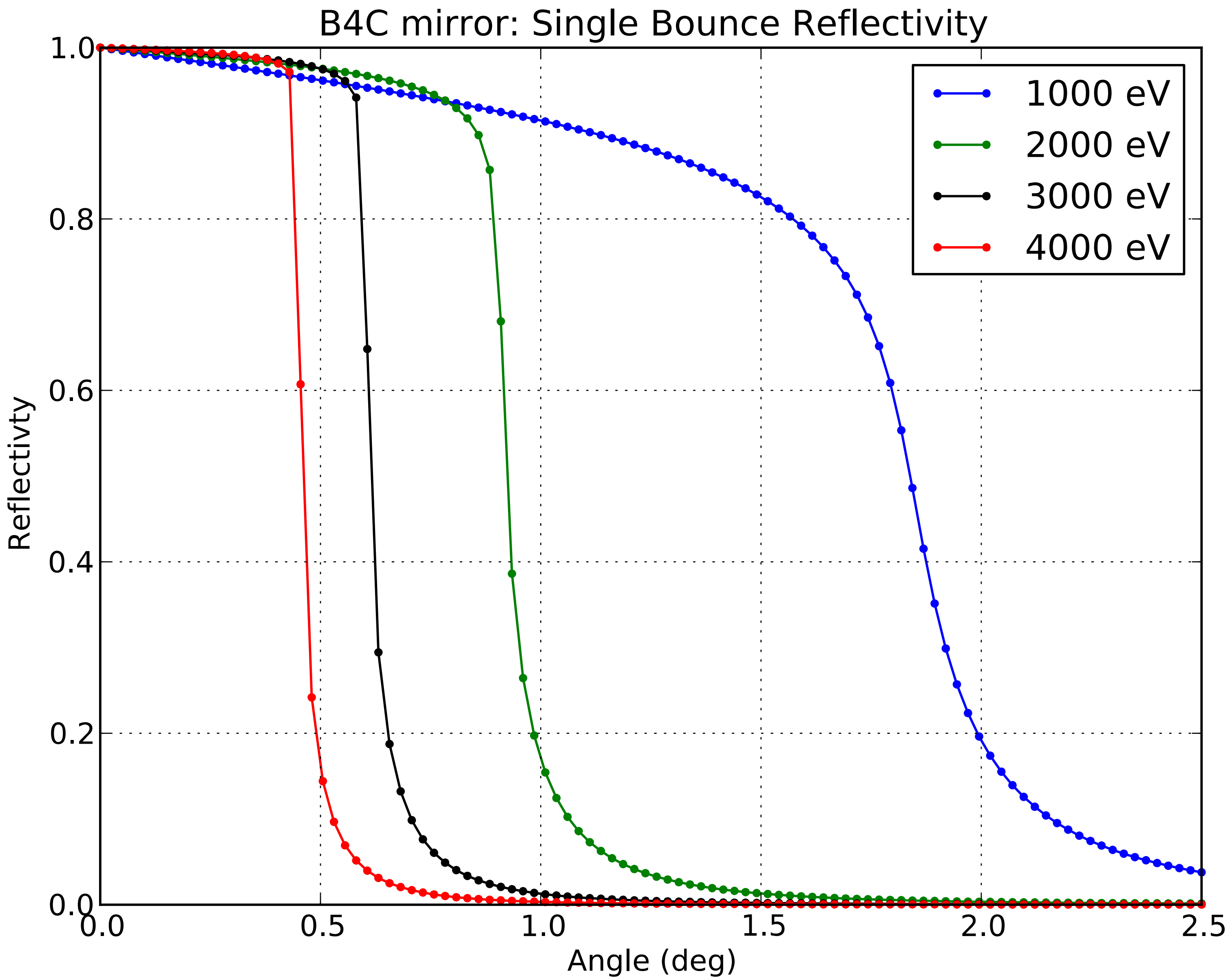
Mirror Damage Limit (single pulse)



- Boron carbide is the highest damage threshold coating and is used for this calculation
- Assumes the incident fwhm beam size is ½ the substrate length
- No safety factor is included in these calculations – 5-10x below this value should be planned for
- Calculation is weakly dependent on incident angle below the mirror cutoff (0.3 deg AOI used)

A large mirror (> 1 m) is needed to survive ~ 1 J pulse energies

Mirror Reflectivity



Some Possibilities for ≤70 nm FWHM Focal Size (Round Equivalent)

Focal Size (nm)	Photon Energy (eV)	Rayleigh Range (um)	RMS Source Size (um)	AOI (deg)	Max E w/ 10x SF (J)	Substrate Length (m)	Unfocused Beam Size (mm)	Source Distance (m)	Reflectivity	Focal Length (m)	IP Distance from Mirror (m)
50	1000	4.5	10	1.30	0.31	1.00	11.34	487	0.872	1.032	0.532
100	1000	18.2	10	0.90	0.68	1.50	11.78	505	0.926	2.144	1.394
50	2000	9.1	10	0.80	0.54	1.00	6.98	600	0.933	1.27	0.770
100	2000	36.4	10	0.60	1.05	1.40	7.33	629	0.967	2.668	1.968
50	2000	9.1	10	0.65	1.21	1.50	8.51	731	0.962	1.548	0.798
100	2000	36.4	10	0.50	2.14	2.00	8.73	750	0.976	3.176	2.176
40	4000	11.6	10	0.4	1.06	1.13	3.93	675	0.982	1.143	0.581
70	4000	35.7	10	0.3	2.40	1.50	3.93	675	0.992	2.001	1.251
40	4000	11.6	10	0.4	2.39	1.50	5.24	899	0.982	1.525	0.775
70	4000	35.7	10	0.3	4.27	2.00	5.24	899	0.992	2.668	1.668

- KB pairs are needed to focus the beam
- If source is round, then KB mirrors will create an elliptical focus
- Round equivalent = $\sqrt{vert * horizontal}$
- Things improve with photon energy for the KB optics:
  - Damage
  - Reflectivity --> less absorbed power
  - Focal size
  - Rayleigh range

Initial KB Mirror study summary

- Large mirrors (> 1 m) are needed for 1 J per pulse energy
  - 1 m FEL quality substrates produced today
  - 1.5 m substrates produced for synchrotrons
  - > 1 m FEL quality substrates would require development with industry but not R&D
- > 1 km source to KB optic distance is desirable
- FEL average power is a new regime (6.5 kW)
  - This requires an engineering study
  - Very grazing angles help since the most straight forward approach is to absorb less in the substrate
  - Another reason to consider beyond state-of-the-art substrates sizes (e.g. 2 m or beyond)

Post initial KB mirror study comments:

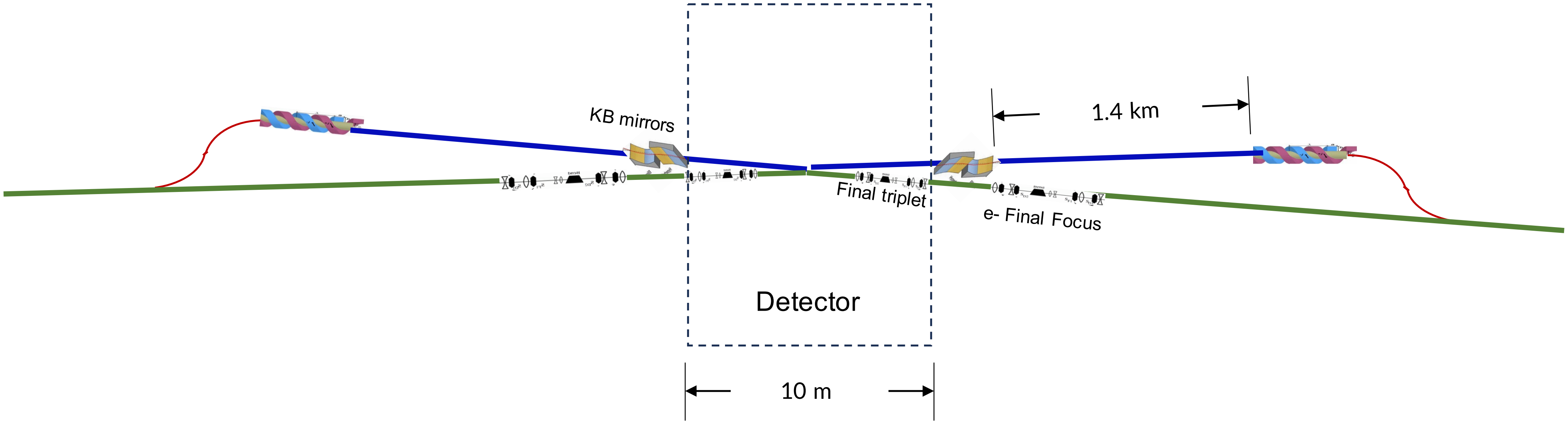
Need for 5 m focal length implies even longer substrates of at least 5 m.

Reflectivity issues (heating and Compton conversion eff.) may force us to switch from 1 keV to 2 keV photons

Example beam layout of KB mirror and electron final triplet QD0

At least 1.4 km distance from XFEL to KB mirror required

XCC Schematic with 1.4 km line between XFEL and KB mirrors



LCLS-I Summary of ELEGANT simulation of Linac Plus 120 nm 1 nC injector

100 mJ/pulse great for XCC R&D. Is there genuine synergy with photon science for other applications of low emittance injector?

- Preliminary results:
  - >110 mJ of 1 keV X-rays within 20 undulators
  - <0.01% FWHM bandwidth (0.18% rms)
- Caveats:
  - Simulation done with pure seed so FWHM bandwidth may be a bit larger with a full simulation (full sim: first stage, clean spectrum, second stage)
- Resistive wall wake fields
  - increased FWHM bandwidth by 40%
  - decreased pulse energy by 12%
  - Increasing undulator chamber gap from 5 to 7 mm could halve wake field strength.
  - Shaping the beam (shortening) may shape space charge wake