XCC Physics Case

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SLACmass Summary Retreat
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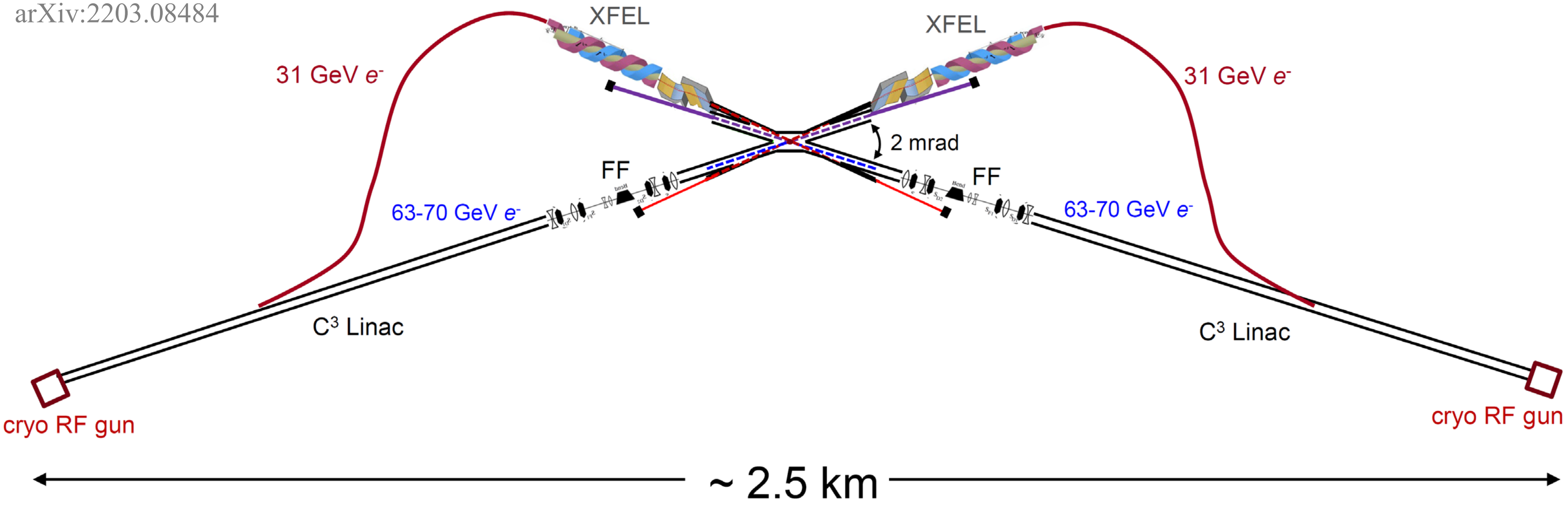
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

XCC – XFEL Compton Collider

arXiv:2203.08484



Run $\gamma\gamma \rightarrow H$ at $\sqrt{s_{\gamma\gamma}} = 125$ GeV 30% of the time
and $e^-\gamma \rightarrow e^- H$ at $\sqrt{s_{e\gamma}} = 140$ GeV 70% of the time
to calibrate the $\sigma \times \text{BR}$ measurements at $\sqrt{s_{\gamma\gamma}} = 125$ GeV.
This produces model independent Higgs coupling measurements, just like the ILC.

$$\sigma_{ez} = 20\ \mu\text{m} \quad \sigma_{\gamma z} = 20\ \mu\text{m}$$

$$\text{N}_{e^-} = 1\ \text{nC} \quad \gamma\varepsilon_{x,y} = 120\ \text{nm}$$

$$\text{d}_{\text{cp}} = 60\ \mu\text{m} \quad P_{e^-} = 90\%$$

$$a_{\gamma FWHM} = 70\ \text{nm} \quad \xi^2_{\text{non-linear QED}} = 0.10$$

$\gamma\gamma$ mode $\sqrt{s} = 125$ GeV		
	Luminosity $(10^{34}\ \text{cm}^{-2}\ \text{s}^{-1})$	
Process	Total	$\sqrt{\hat{s}} > 100$ GeV
$\gamma\gamma$	2.1	0.12
e^-e^-	0.23	0.18
$e^-\gamma + \gamma e^-$	2.5	0.42
$e^+e^- + e^-e^+$	0.48	0.05
$e^+\gamma + \gamma e^+$	0.47	0.01

The XCC is presented as a possible lower cost ***alternative*** *to the ILC and C³ 250 GeV e⁺e⁻ Higgs factories. It is being pursued because every e⁺e⁻ linear collider proposal to date has been rejected due to its high cost. That said, it should be noted that strong synergies between XCC and the SLAC XFEL program also serve to motivate this concept.*

Potential Cost Savings with the XCC

C^3 250 GeV Capital Cost Estimate

CCC		GeV	250		
		MeV/m	70		
	Sub-Domain		M$	%	%
Sources	Injectors		301	8	35
	Damping Rings		461	12	
	Beam Transport		563	15	
Main Linac	Cryomodule		357	10	33
	C-band Klystron		871	23	
IP	Beam Delivery and FF		295	8	13
	IR		184	5	
Support Inf.	Civil Eng		204	5	19
	Common Facilities		396	11	
	Cryo-plant		101	3	
	Total		**3733**	**100**	

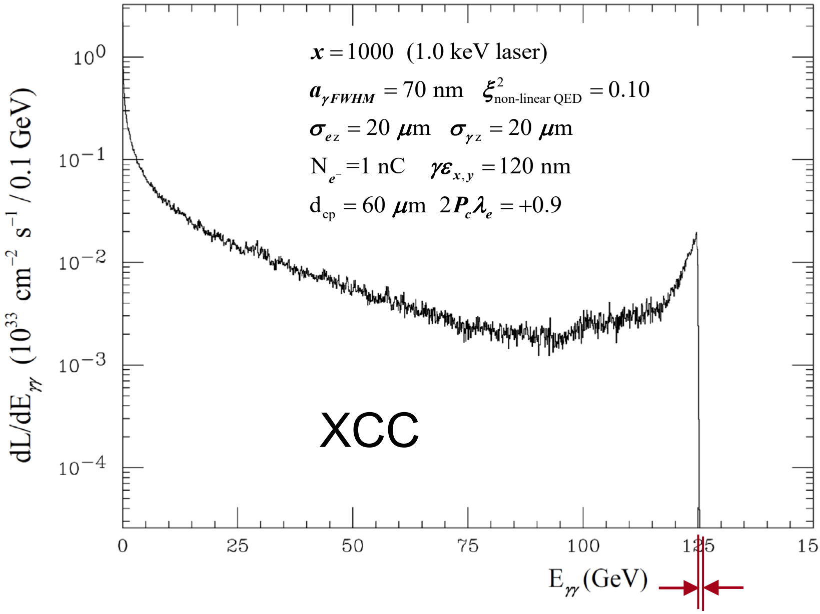
XCC 140 GeV Capital Cost Estimate

XCC		GeV	140		
		MeV/m	70		
	Sub-Domain		M$	%	
Sources	Injectors		200	9	26
	FEL		200	9	
	Beam Transport		197	9	
Main Linac	Cryomodule		200	9	30
	C-band Klystron		488	22	
IP	Beam Delivery and FF		148	7	15
	IR		184	8	
Support Inf.	Civil Eng		114	5	28
	Common Facilities		396	18	
	Cryo-plant		133	6	
	Total		**2260**	**100**	

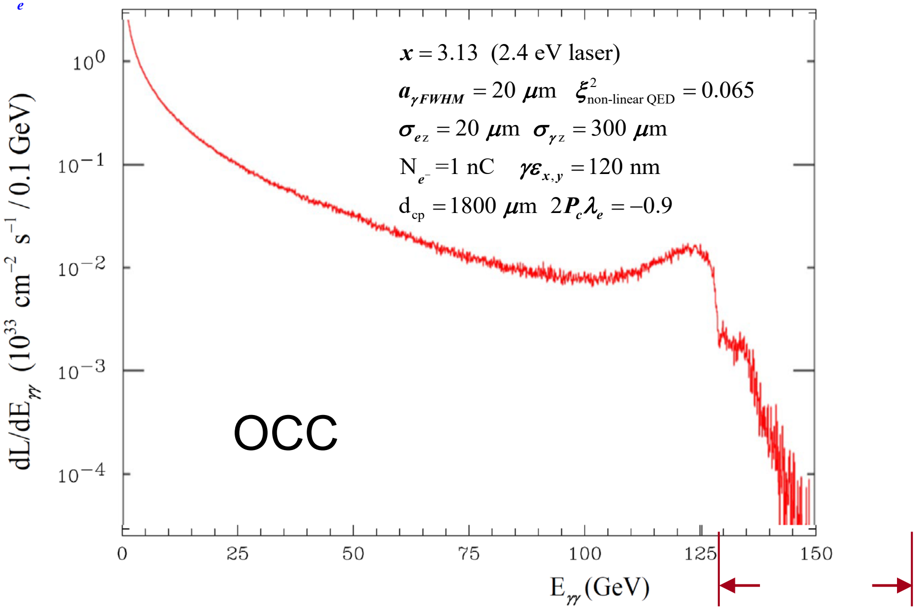
With these estimates the XCC would be 60% of the cost of C^3 250 GeV. Given the very early stage of the XCC design and the many XFEL technical challenges, it is important that these tables are viewed as illustrative, providing insight into the *potential* cost savings of the XCC.

Higgs Rate and Background for XCC vs Optical $\gamma\gamma$ Collider (OCC) & ILC

$$x = \frac{4E_e E_\gamma^{Laser}}{m_e^2}$$



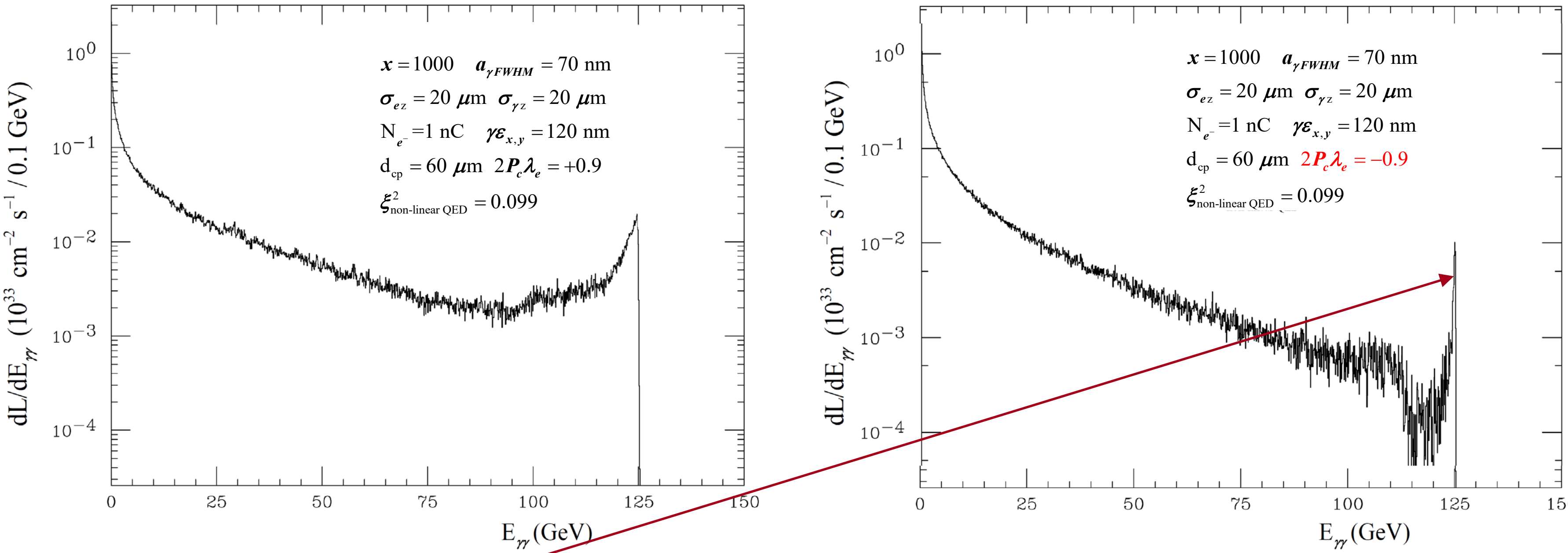
$2\max(E_\gamma^{\text{non-linear QED}}) - 2\max(E_\gamma^{\text{linear}}) = \frac{2E_e}{x+1} = 0.13$ GeV



$2\max(E_\gamma^{\text{non-linear QED}}) - 2\max(E_\gamma^{\text{linear}}) = \frac{2E_e}{x+1} = 42$ GeV

Machine	E_{e^-} (GeV)	N_{e^-} (nC)	Polarization	$N_{\rm H}/{\rm yr}$	$N_{\rm Hadronic}/N_{\rm H}$	$N_{\rm minbias/BX}$
XCC	62.8	1.0	90% e^-	34,000	170	9.5
OCC	86.5	1.0	90% e^-	30,000	540	50
ILC	125	3.2	-80% e^- +30% e^+	42,000	140	1.3
ILC	125	3.2	+80% e^- -30% e^+	28,000	60	1.3

Alternative Polarization for Scanning Higgs Resonance



Narrower leading edge width (45 MeV) at cost of lower Higgs rate. Width dominated by 0.05% e^- energy spread.

A Higgs resonance scan can measure the total width to 4.5 MeV, i.e., a 112% measurement if the width has the SM value.

A total Higgs width $\gg$ 4 MeV is not ruled out by LHC data, but would require, for example, a conspiracy of a universal kappa scale factor $\kappa_0 > 1$ combined with $B_{BSM} \approx 1 - \kappa_0^{-2}$ assuming LHC kappa ratios $\rightarrow 1$ with ever greater precision:

κ_0	B_{BSM} (%)	Γ_H (MeV)
1.4	49	15
1.2	31	8
1.0	0	4

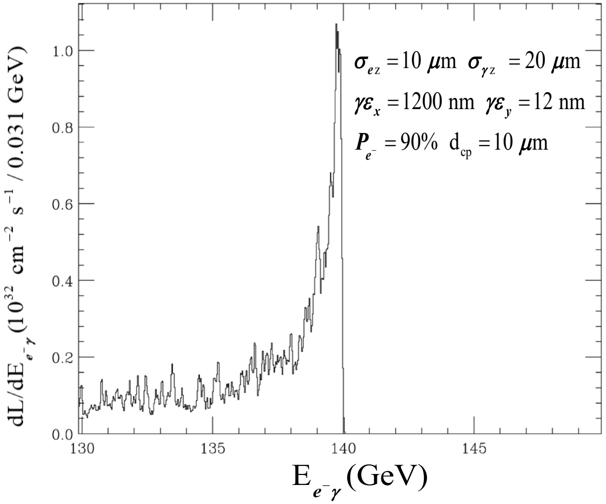
$$\Leftarrow \Gamma_H \text{ assuming universal } \kappa_0 \text{ , } B_{BSM} = 1 - \kappa_0^{-2} \text{ , } \frac{\kappa_g \kappa_Z}{\kappa_H} = \frac{\kappa_W}{\kappa_Z} = \frac{\kappa_\gamma}{\kappa_Z} = \frac{\kappa_g}{\kappa_Z} = \cdots = 1$$

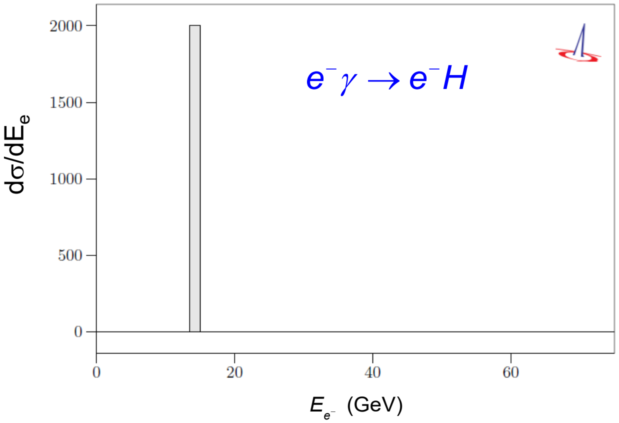
(also LHC off-shell H* $\rightarrow$ ZZ measurements would have to be addressed)

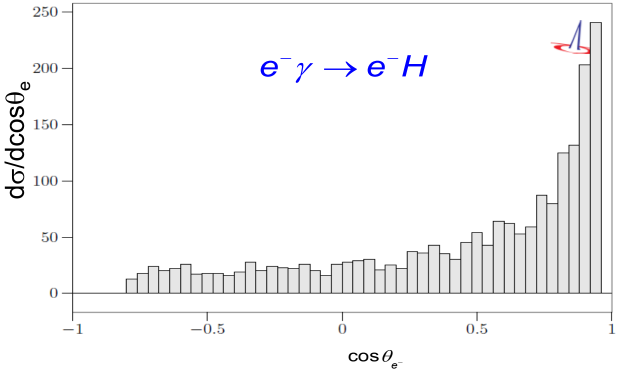
Another possible application of the alternative polarization is improved signal-to-background. Detailed studies are required to determine if this improvement can compensate for the loss in signal statistics.

Measurement of Γ_γ using $e^-\gamma \to e^-H$ at E_{cm}=140 GeV

If, as is likely, a direct 5 MeV measurement of the Higgs width corresponds to a large fractional error, then individual Higgs partial widths and the total Higgs width will have to be extracted at XCC by measuring Γ_γ through $e^-\gamma \to e^-H$ at $\sqrt{s} = 140$ GeV. This is the XCC analog of the e^+e^- Higgs factory measurement of Γ_Z through Higgs recoil in $e^+e^- \to ZH$.







The signal is a monochromatic 14.2 GeV electron, predominantly in the forward direction. In order to achieve model independent ILC-like precision for Higgs couplings and the total Higgs width, about 1 $e^-\gamma \to e^-H$ event must be detected at 140 GeV per 125 $\gamma\gamma \to H$ events collected at 125 GeV. $\sigma(e^-\gamma \to e^-H) = 4.1$ fb at 140 GeV assuming forward detector coverage down to $\theta > 3$ mrad (there is no Compton scatter background on this side of the IP in $e^-\gamma$ collisions).

With the current $e^-\gamma$ collider design, the yearly luminosity with $\sqrt{\hat{s}}$ within 1% of the 140 GeV peak is 32 fb^{-1} $\Rightarrow$ for every year collecting Higgs events at $\sqrt{s} = 125$ GeV, two years must be spent producing $e^-\gamma \to e^-H$ at 140 GeV.

XCC Coupling Errors Using EFT Higgs Program

	ILC	XCC
coupling a	Δa (%)	Δa (%)
HZZ	0.57	1.2
HWW	0.55	1.2
Hbb	1.0	1.4
$H\tau\tau$	1.2	1.4
Hgg	1.6	1.7
Hcc	1.8	1.8
$H\gamma\gamma$	1.1	0.77
$H\gamma Z$	9.1	10.0
$H\mu\mu$	4.0	3.8
Γ_{tot}	2.4	3.8
$\Gamma_{\text{inv}}{}^{\dagger}$	0.36	–
$\Gamma_{\text{other}}{}^{\dagger}$	1.6	2.7

†95% C.L. limit

ILC: 0.5×10^6 $e^+e^- \to$ ZH events

full 2 ab^{-1} $\sqrt{s} = 250$ GeV

10 year program

XCC: 0.5×10^6 $\gamma\gamma \to$ H events

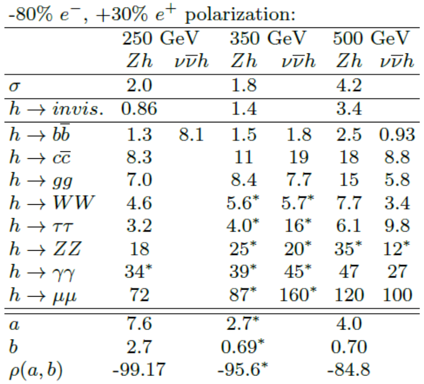
4000 $e^-\gamma \to e^-$ H events

4 years $\gamma\gamma \to$ H @ $\sqrt{s} = 125$ GeV

8 years $e^-\gamma \to e^-$ H @ $\sqrt{s} = 140$ GeV

assuming $\text{n}_{\text{bunch}} = 76 \to 290$

Use ILC σXBR measurement errors for XCC:



-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	2.0		1.8		4.2	
$h \to invis.$	0.86		1.4		3.4	
$h \to b\bar{b}$	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$	8.3		11	19	18	8.8
$h \to gg$	7.0		8.4	7.7	15	5.8
$h \to WW$	4.6		5.6*	5.7*	7.7	3.4
$h \to \tau\tau$	3.2		4.0*	16*	6.1	9.8
$h \to ZZ$	18		25*	20*	35*	12*
$h \to \gamma\gamma$	34*		39*	45*	47	27
$h \to \mu\mu$	72		87*	160*	120	100
a	7.6		2.7*		4.0	
b	2.7		0.69*		0.70	
$\rho(a,b)$	-99.17		-95.6*		-84.8	

The $e^-\gamma$ Luminosity Problem

With the current $e^-\gamma$ collider design, the Higgs rate in $e^-\gamma$ collisions at $\sqrt{s} = 140$ GeV is 0.8% of the rate in $\gamma\gamma$ collisions at $\sqrt{s} = 125$ GeV. This is an unsatisfactory situation as 2/3 of the running time is spent waiting for $e^-\gamma \rightarrow e^- H$ events to dribble in at $\sqrt{s} = 140$ GeV. Another related issue is the factor of 3.8 increase in the number of bunches per train required to achieve ILC-like Higgs precision over 12 years. Only a factor of 2 increase in the number of bunches per train at XCC is required to match the ILC's count of 0.5×10^6 Higgs bosons over a decade (note that ILC also assumes a 2x luminosity upgrade).

The e^-e^- geometric luminosity for $e^-\gamma$ collisions is 11×10^{34} cm^{-2} s^{-1} and yet the $e^-\gamma$ luminosity within 1% of the 140 GeV peak is only 0.09×10^{34} cm^{-2} s^{-1} for symmetric x and y emttiances.

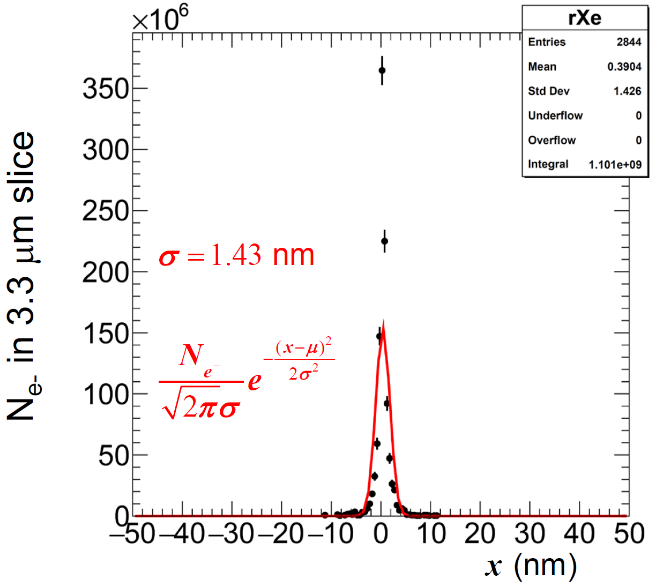
Large coherent e^+e^- pair production leads to pinching of the opposite e^- beam which further increases the E_{field} leading to more positron production and pinching in a feedback manner (new effect discovered in XCC study).

$\gamma\varepsilon_x = 120$ nm $\gamma\varepsilon_y = 120$ nm

$e^-\gamma$ mode $\sqrt{s} = 140$ GeV

Process	Luminosity (10^{34} cm^{-2} s^{-1}) Total	$\sqrt{\hat{s}} > 139$ GeV
$e^-\gamma$	139	0.09
$\gamma\gamma$	292	-
e^-e^+	173	-
γe^+	171	-
γe^-	4.5	-
e^-e^-	0.9	-
$e^+\gamma$	3.0	-
e^+e^-	0.06	-

geometric $\sigma_x = 5.1$ nm



The e$^{-}\gamma$ Luminosity Problem

Solution for now is to go to asymmetric emittances

$\gamma\varepsilon_x = 120$ nm $\quad \gamma\varepsilon_y = 120$ nm

$e^-\gamma$ mode $\sqrt{s} = 140$ GeV

	Luminosity (10^{34} cm^{-2} s^{-1})	
Process	Total	$\sqrt{\hat{s}} > 139$ GeV
$e^-\gamma$	139	0.09
$\gamma\gamma$	292	-
e^-e^+	173	-
γe^+	171	-
γe^-	4.5	-
e^-e^-	0.9	-
$e^+\gamma$	3.0	-
e^+e^-	0.06	-

$\Rightarrow$

$\gamma\varepsilon_x = 1200$ nm $\quad \gamma\varepsilon_y = 12$ nm

$e^-\gamma$ mode $\sqrt{s} = 140$ GeV

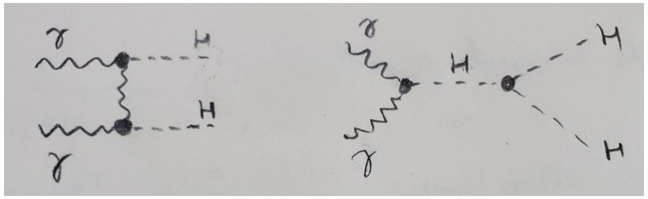
	Luminosity (10^{34} cm^{-2} s^{-1})	
Process	Total	$\sqrt{\hat{s}} > 139$ GeV
$e^-\gamma$	11.5	0.32
$\gamma\gamma$	14.5	-
e^-e^+	13.4	-
γe^+	11.3	-
γe^-	0.92	-
e^-e^-	0.43	0.07
$e^+\gamma$	0.09	-
e^+e^-	0.01	-

Ultimately we would like to suppress the E_{field}

- Introduce a plasma to neutralize the IP (suggestion by F. Zimmerman to reduce the anti-pinch in e^-e^- collisions)

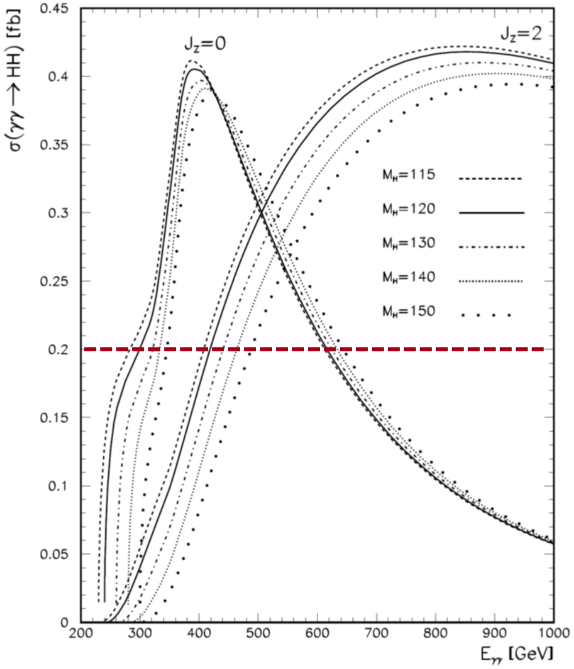
- Studies using CAIN indicate that the introduction of an additional 10 GeV e^- beam with suitable timing and location could deflect the Compton-scattered beam just enough to significantly suppress beamstrahlung and coherent e^+e^- pair-production.

Energy upgrade to Ecm=280 GeV for Higgs Self Coupling Study



2.8 km footprint

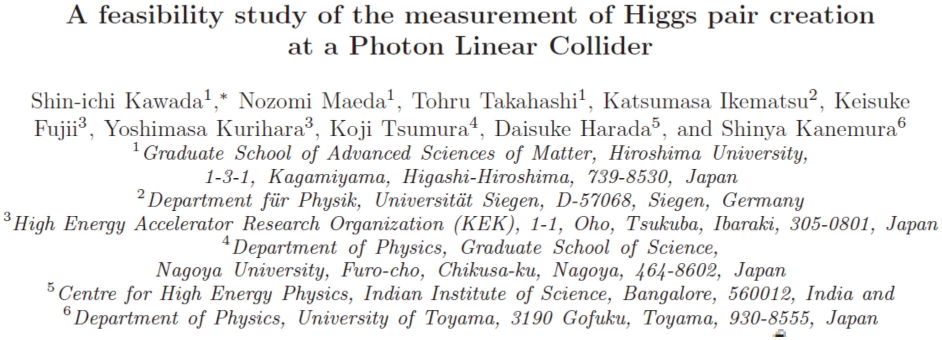
assuming gradient 70 MeV/m → 120 MeV/m
(C^3 uses assumes this gradient upgrade to get from E_{cm}=250 → 500 GeV)



$\sigma(\gamma\gamma \to HH)$ @ $\sqrt{s} = 280$ GeV $\approx$ $\sigma(e^+e^- \to ZHH)$ @ $\sqrt{s} = 500$ GeV

Need to redo the KEK $\gamma\gamma \to HH$ study with the XCC $\gamma\gamma$ spectrum.

2012 Study



A feasibility study of the measurement of Higgs pair creation
at a Photon Linear Collider

Shin-ichi Kawada[1],* Nozomi Maeda[1], Tohru Takahashi[1], Katsumasa Ikematsu[2], Keisuke Fujii[3], Yoshimasa Kurihara[3], Koji Tsumura[4], Daisuke Harada[5], and Shinya Kanemura[6]

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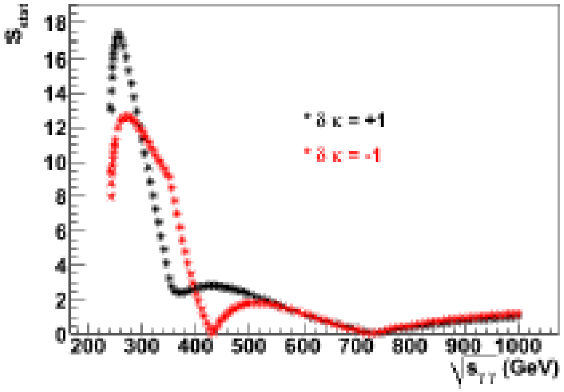
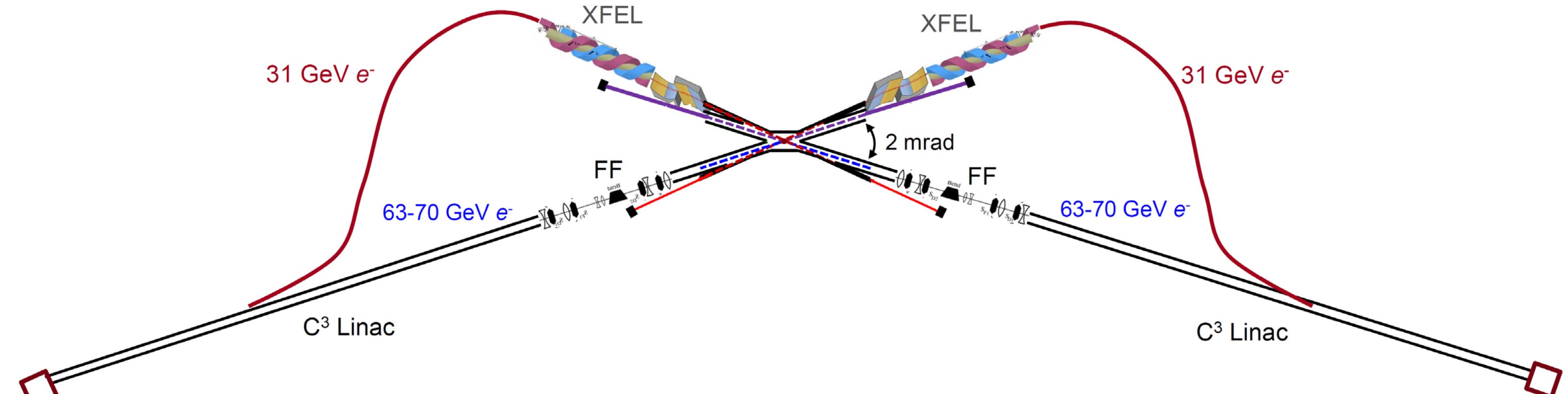


FIG. 3. Statistical sensitivity (S_{stat}) as a function of $\gamma\gamma$ collision energy. Black and red dots show the $\delta\kappa = +1$ and $\delta\kappa = -1$ cases.

Optimum sensitivity at $\sqrt{s_{\gamma\gamma}} = 280$ GeV

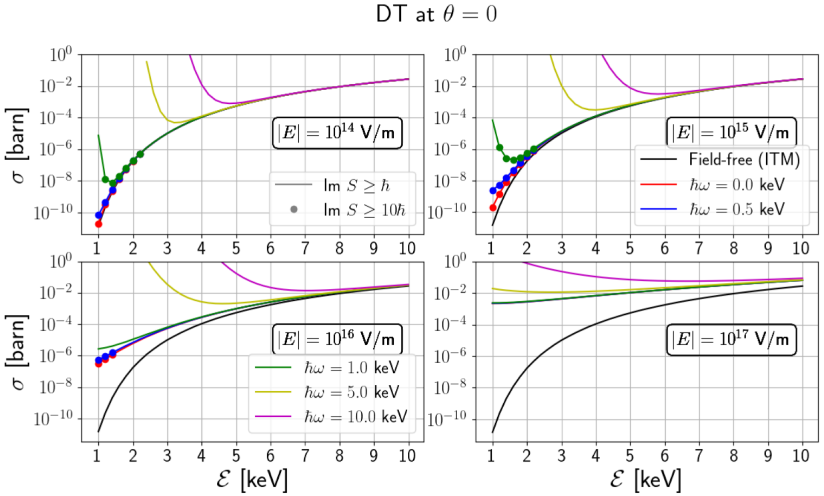
Used optical laser for Compton scattering

Photon Science at XCC - HEDS Fusion Example



$\sigma(^2H\,^3H \rightarrow {}^4H_e\, n)$ enhanced in presence of $E_{field} > 10^{16}$ V/m

"Applicability of semiclassical methods for modeling laser-enhanced fusion rates in a realistic setting"
Phys. Rev. C **105**, 054001 – 10 May 2022



$$E_{field} \propto E_{pulse}^{\frac{1}{2}}\; a_{\gamma FWHM}^{-1}\; \sigma_{\gamma z}^{-\frac{1}{2}} \qquad E_{pulse} = 0.7 \text{ J}$$

$2\sigma_{\gamma z}$ (μm)	$2\sigma_{\gamma z}$ (fs)	$a_{\gamma FWHM}$ (nm)	E_{field} (V/m)	I_{peak} (W cm^{-2})	P (TW)	Validity
10	33	71	1.6×10^{15}	7.1×10^{23}	21	Soft X-rays
10	33	12	1.0×10^{16}	2.8×10^{25}	21	Hard X-rays

XCC Physics Summary

- The XCC at E_{cm}=125-140 GeV can measure absolute Higgs couplings in a model independent manner with an accuracy of order 1% . This is pretty close to the ILC precision. To fully match or exceed the ILC Higgs coupling accuracy, a way must be found to increase the top 1% e-γ luminosity at E_{cm}=140 GeV.

- The Higgs self coupling can be studied via $\gamma\gamma \rightarrow HH$ if the XCC energy is upgraded to E_{cm}=280 GeV. Given that $\sigma(\gamma\gamma \rightarrow HH) \sim \sigma(e^+e^- \rightarrow ZHH)$, the Higgs self coupling sensitivity for XCC will probably be comparable to ILC at E_{cm}=550 GeV

- There are strong synergies between XCC and the XFEL program at SLAC. Solutions to high energy/pulse XFEL production and focusing issues at XCC will lead to new opportunities in XFEL photon science.