The XFEL Compton Collider (XCC) Higgs Factory

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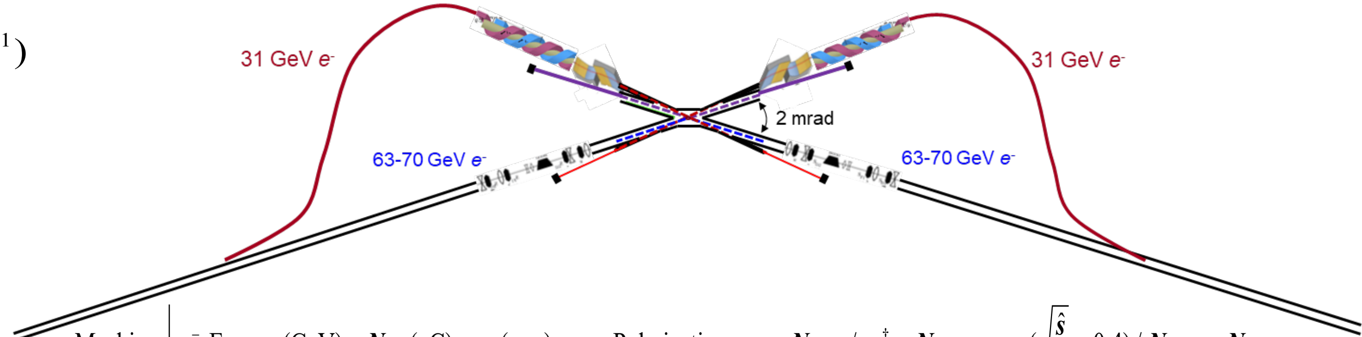
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

XCC – XFEL Compton Collider

Process	Luminosity ($10^{34}\text{cm}^{-2}\ \text{s}^{-1}$)	
	Total	$\sqrt{\hat{s}} > 100$ GeV
$\gamma\gamma$	2.1	0.12
$e^-\gamma$	2.5	0.42
$e^+\gamma$	0.47	0.0059
e^+e^-	0.48	0.049
e^-e^-	0.23	0.18



Machine	e^- Energy (GeV)	N_{e^-} (nC)	$\sigma_z(\mu m)$	Polarization	N_{Higgs} / yr†	$N_{\text{Hadronic Events}}(\sqrt{\frac{\hat{s}}{s}} > 0.4) / N_{\text{Higgs}}$	$N_{\text{minbias/BX}}$
XCC	62.5	1.0	20	90% e^-	32,000	165	9.5
ILC	125	3.2	300	$-80\%\ e^-\ \ +30\%\ e^+$	42,000	138	1.3
ILC	125	3.2	300	$+80\%\ e^-\ \ -30\%\ e^+$	28,000	55	1.3

†1 yr $= 1.0\times10^7$ s

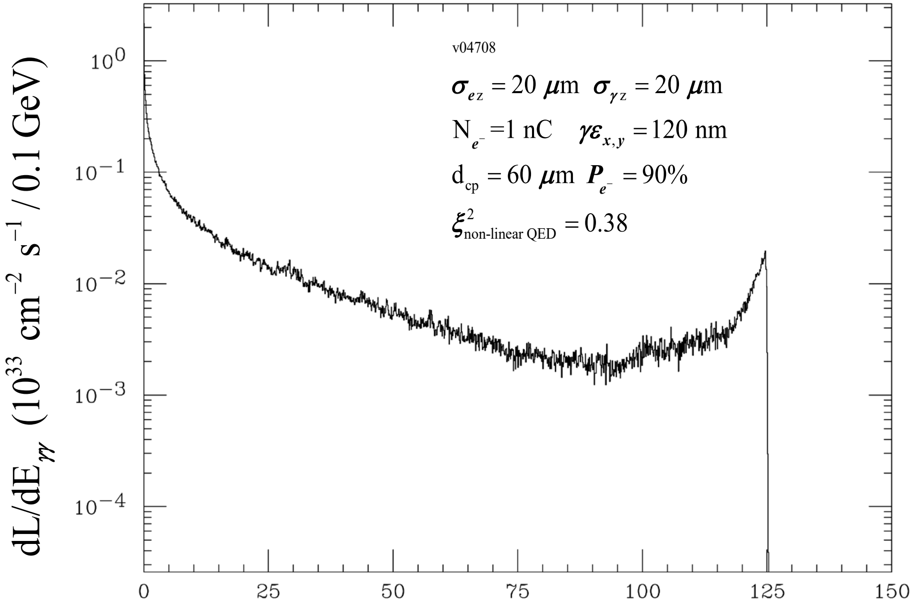
Run $\gamma\gamma \to H$ at $\sqrt{s_{\gamma\gamma}} = 125$ GeV 30% of the time

and $e^-\gamma \to e^- H$ at $\sqrt{s_{e\gamma}} = 140$ GeV 70% of the time

to calibrate the $\sigma \times$ BR measurements at $\sqrt{s_{\gamma\gamma}} = 125$ GeV.

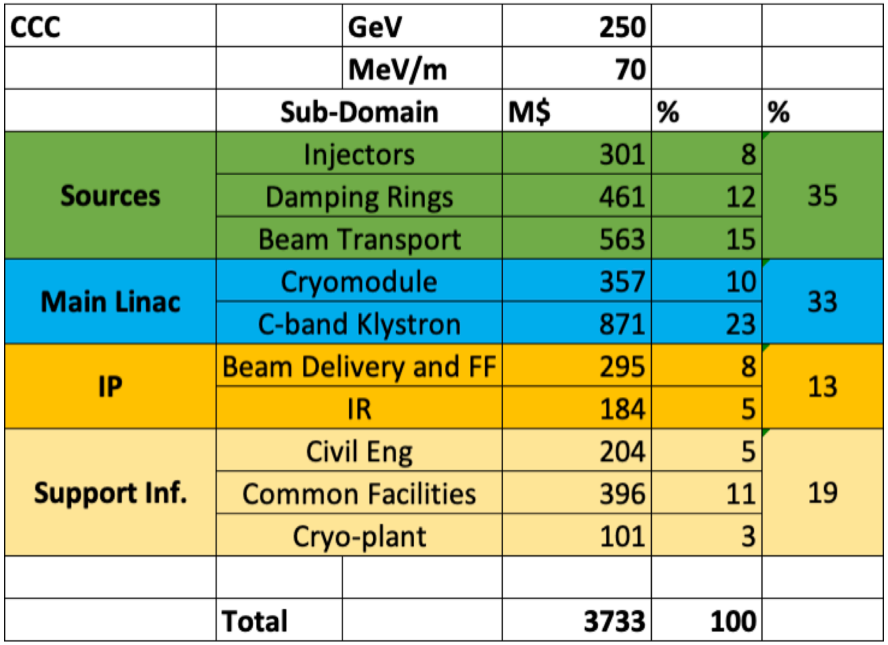
This produces model independent Higgs coupling measurements, just like the ILC.

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.*



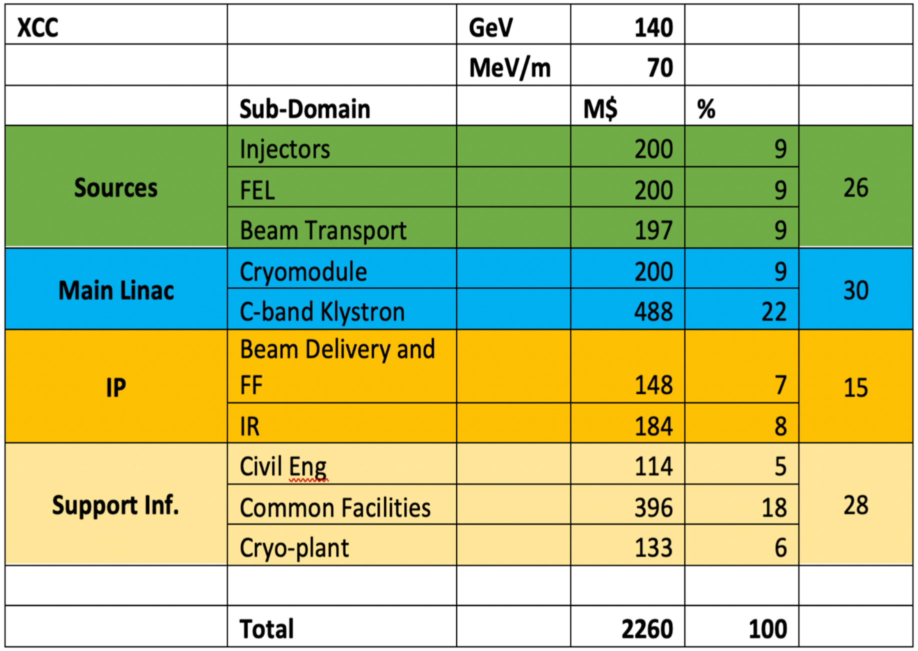
Potential Cost Savings with the XCC

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**	

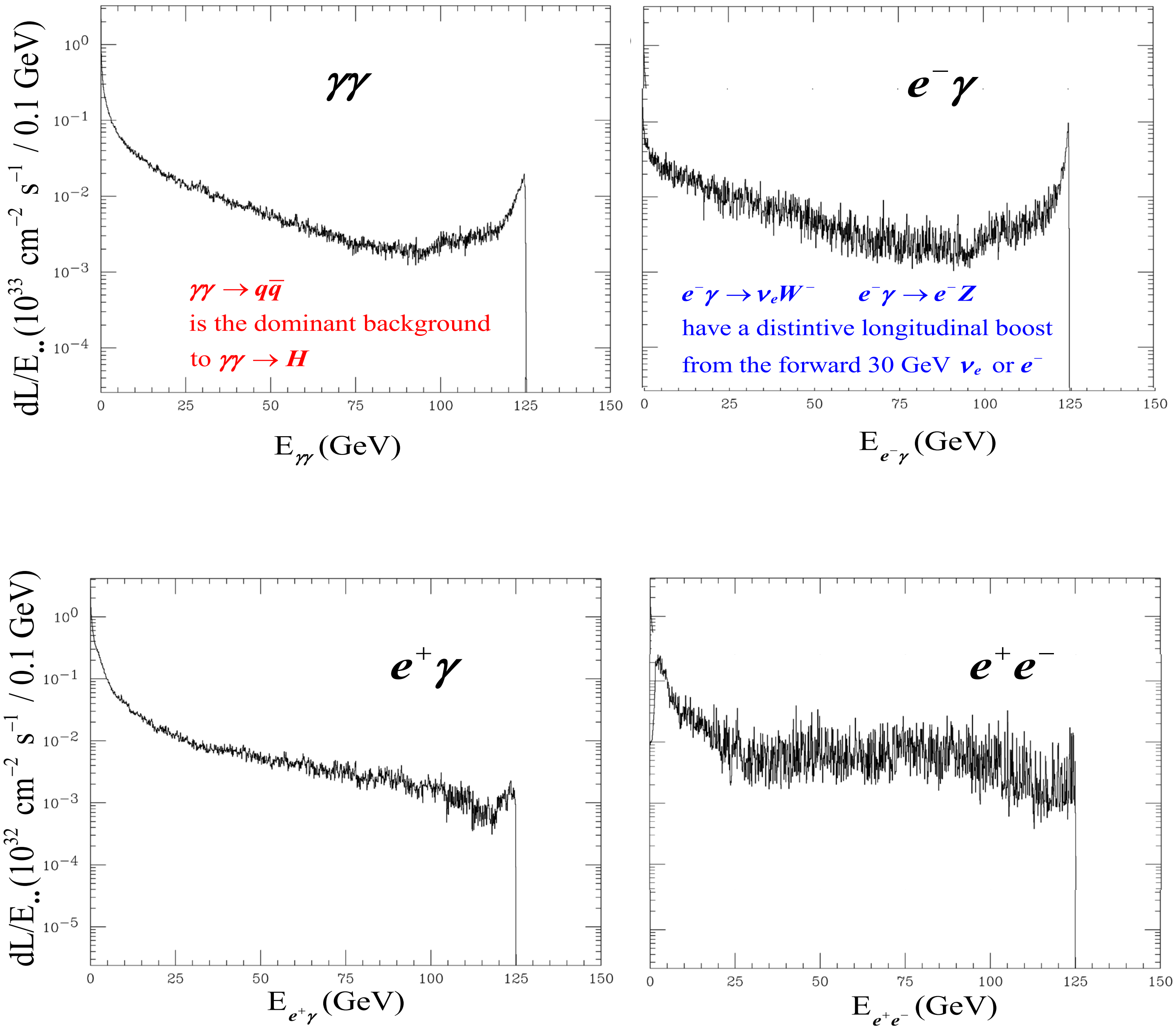
XCC 140 GeV Capital Cost Estimate



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. ***But we can't seriously make this claim at this time.*** *There are still too many components of the XCC machine that need work -- such as the focusing optics to take the x-ray beam from the end of the undulator to the Compton interaction point.*

XCC physics backgrounds



$\gamma\gamma \to q\bar{q}$
is the dominant background
to $\gamma\gamma \to H$

$e^-\gamma \to \nu_e W^-$ $e^-\gamma \to e^- Z$
have a distintive longitudinal boost
from the forward 30 GeV ν_e or e^-

	Luminosity (10^{34}cm^{-2} s^{-1})	
Process	Total	$\sqrt{\hat{s}} > 100$ GeV
$\gamma\gamma$	2.1	0.12
$e^-\gamma$	2.5	0.42
$e^+\gamma$	0.47	0.0059
e^+e^-	0.48	0.049
e^-e^-	0.23	0.18

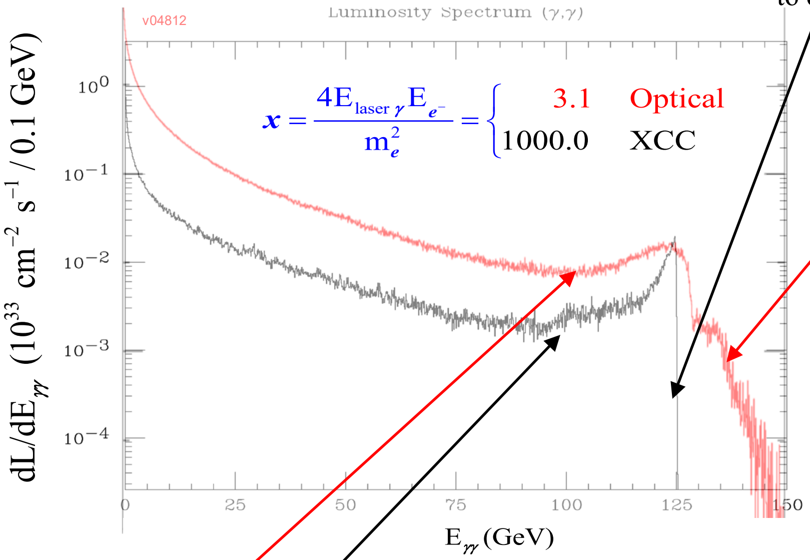
Due to the narrow Higgs resonance the Higgs rate at XCC is that of a 10^{34}cm^{-2} s^{-1} e^+e^- collider even though the $\gamma\gamma$ and $e^-\gamma$ luminosity for $\sqrt{\hat{s}} > 100$ GeV is $\sim 10^{33}$cm^{-2} s^{-1}

The background is not resonant and so background will be typical of a 10^{33}cm^{-2} s^{-1} e^+e^- collider

XCC and ILC physics background comparison

In lieu of CAIN+WHIZARD MC production and analysis, use hadronic production with $\sqrt{\hat{s}/s} > 0.4$ as a measure of the Higgs background

Non-linear QED included in XCC Simulation.
Use 45 MeV leading edge width (set by e^- σ_E)
to directly detect $\Gamma_H \geq 10$ MeV with energy scan.



$$x = \frac{4E_{\text{laser}\,\gamma}E_{e^-}}{m_e^2} = \begin{cases} 3.1 & \text{Optical} \\ 1000.0 & \text{XCC} \end{cases}$$

Non-linear QED included in Optical Compton Simulation

n_γ	$E_{\gamma\gamma\ \max}$ (GeV) XCC	Optical
1	125.04	129.1
2	125.12	147.9
3	125.16	155.4

With Optical, luminosity dominated by beamstahlung γ's for $\sqrt{s_{\gamma\gamma}} < 105$ GeV

At XCC, luminosity dominated by beamstahlung γ's for $\sqrt{s_{\gamma\gamma}} < 115$ GeV

Use comparable XCC and ILC backgrounds to justify using ILC σXBR measurement errors in EFT analysis

Machine	e^- Energy (GeV)	N_{e^-} (nC)	$\sigma_z(\mu m)$	Polarization	N_{Higgs} / yr†	$N_{\text{Hadronic Events}}(\sqrt{\hat{s}/s} > 0.4) / N_{\text{Higgs}}$	$N_{\text{minbias/BX}}$
Optical	86.5	1.0	20	90% e^-	30,000	536	50
XCC	62.5	1.0	20	90% e^-	32,000	165	9.5
ILC	125	3.2	300	$-80\%\ e^-$ $+30\%\ e^+$	42,000	138	1.3
ILC	125	3.2	300	$+80\%\ e^-$ $-30\%\ e^+$	28,000	55	1.3

$^\dagger 1\ \text{yr} = 1.0 \times 10^7$ s

Can beamstrahlung be suppressed with a shorter bunch length?

Beamstrahlung suppression depends on bunch charge and length

Quantum Parameter

$$\chi_{av} \approx \frac{5}{12}\frac{N\alpha \lambda\!\!\!^{-}{}_c^2}{\sigma_r \sigma_z^*}$$

$$\alpha\chi^{2/3} \gtrsim 1$$

reaching fully non-perturbative regime

Radiation Probability

$$W \approx \alpha\chi_{av}^{2/3}\frac{\sigma_z^*}{\lambda\!\!\!^{-}{}_c}$$

$$W < 1$$

acceptable radiation loss

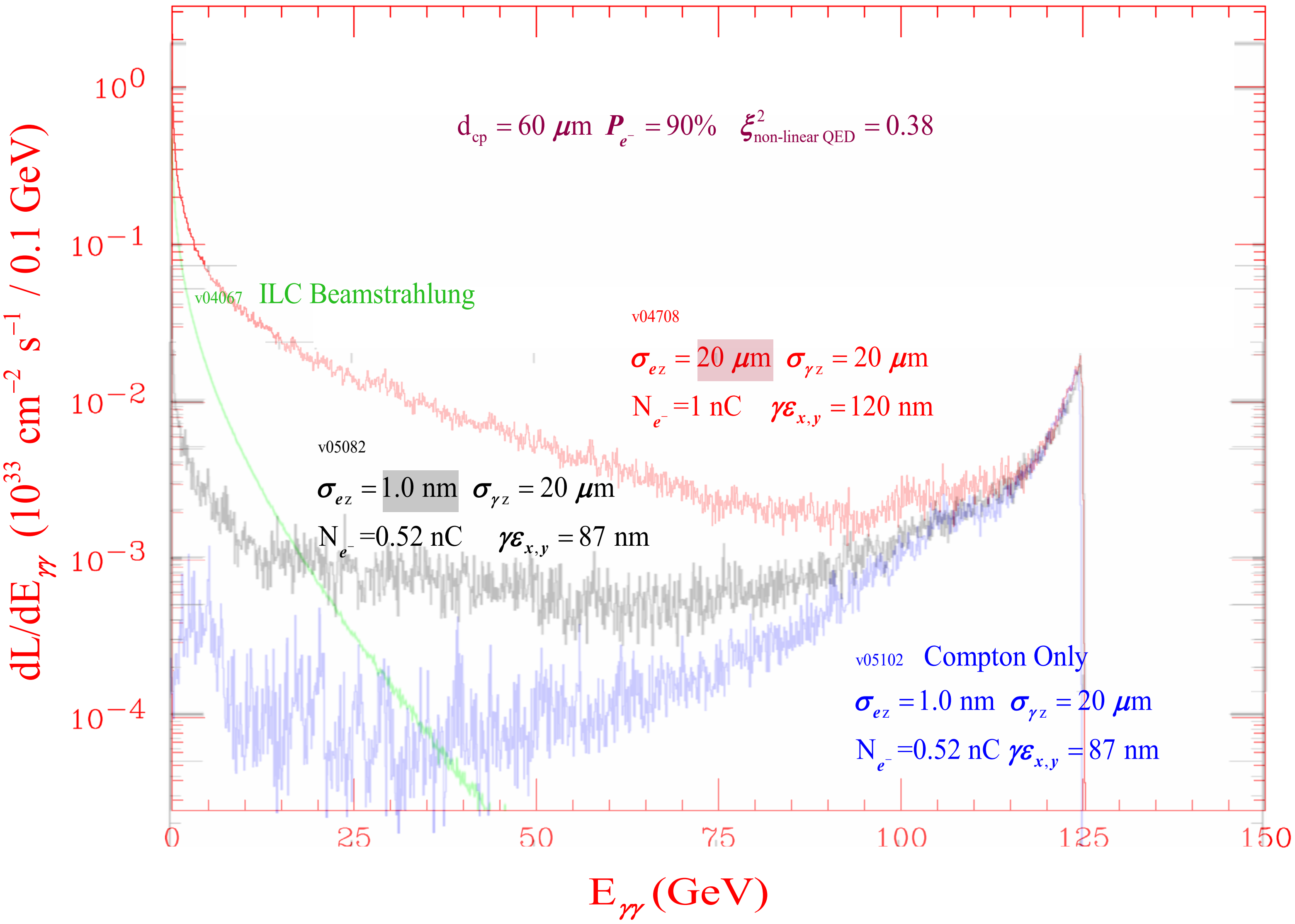
$$W \propto N^{\frac{2}{3}}\sigma_x^{-\frac{2}{3}}\sigma_z^{\frac{1}{3}}$$

To achieve beamstrahlung suppression we need

$$(\eta N)^{\frac{2}{3}}\sigma_x^{-\frac{2}{3}}\sigma_z^{\frac{1}{3}} = (0.14\ \mathrm{nC})^{\frac{2}{3}}(9.27\ \mathrm{nm})^{-\frac{2}{3}}(10\ \mathrm{nm})^{\frac{1}{3}} \quad , \quad \eta = \text{Compton conv. eff.} \approx 0.5$$

$$\Rightarrow \quad \sigma_z = 0.27\ \mathrm{nm} \quad \text{for}\ \ \mathrm{N} = 1\mathrm{nC}\ \ , \sigma_x = 5.42\ \mathrm{nm}$$

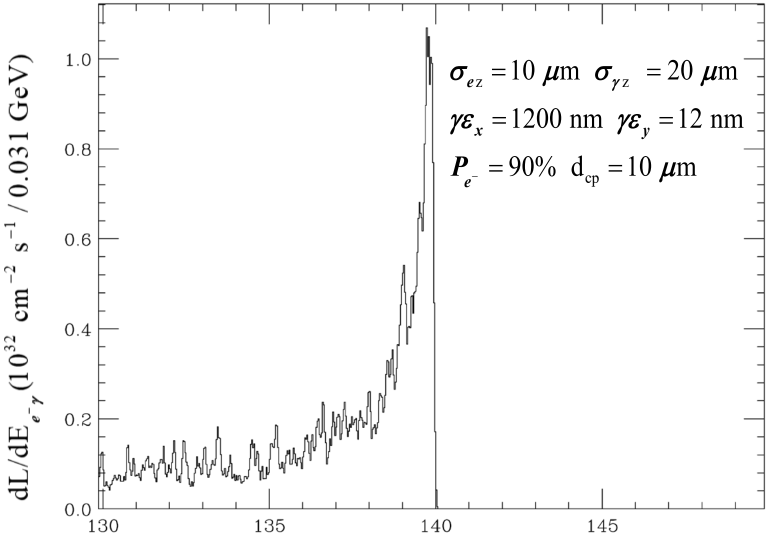
1 nC , σ_z=20 μm vs 0.52 nC , σ_z=1 nm

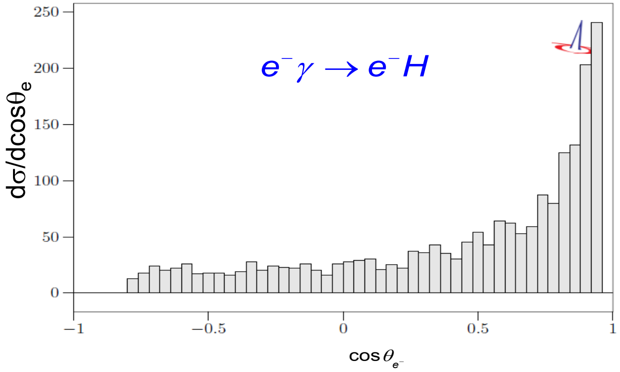


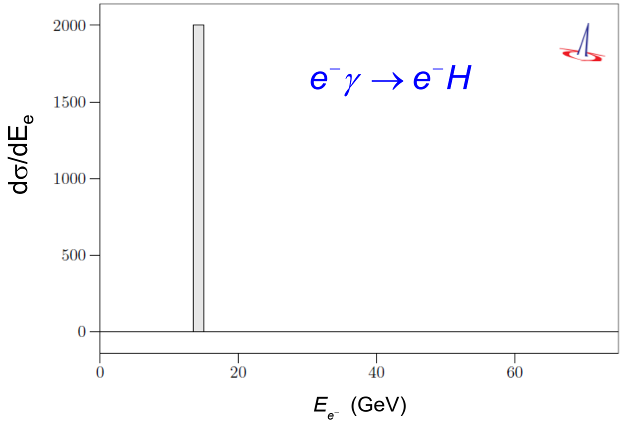
Extreme short bunch suppresses beamstrahlung luminosity – but high field (as high as 10% of Schwinger) kicks e+e- pairs and degraded energy electrons to very large angles - don't see how we can extract beam. We have traded one form of background for another.

Luminosity for $e^- \gamma \rightarrow e^- H$ at E_{cm}=140 GeV

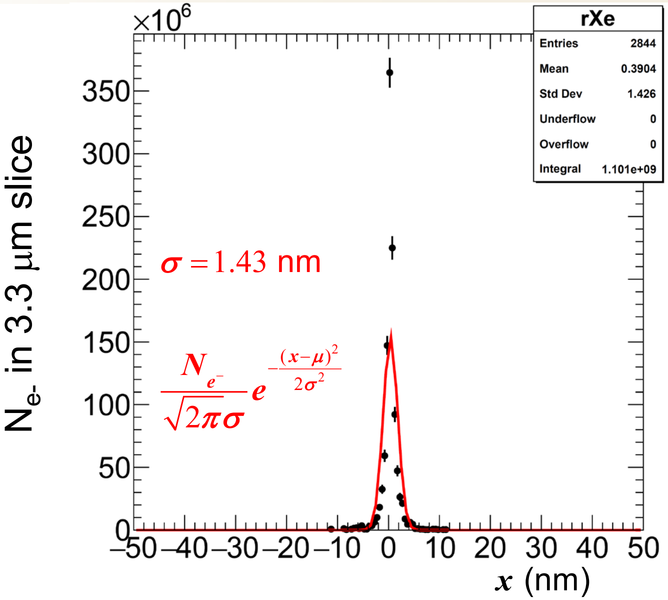
To match the ILC Higgs coupling precision the XCC must detect 1 $e^-\gamma \to e^- H$ event at 140 GeV per $50-100$ $\gamma\gamma \to H$ events produced at 125 GeV





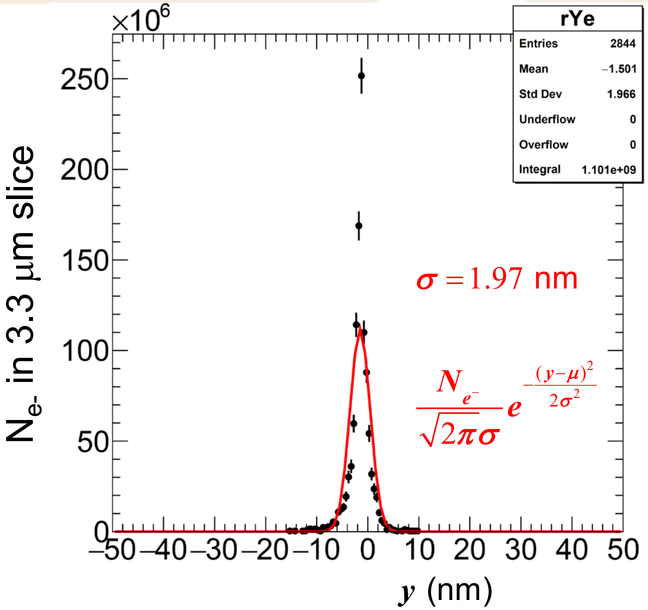


Pinching in $e^-\gamma$ collisions due to e^+ from pair production; I.P. geometric e^- σ_x,σ_y=5.1 nm



$\sigma = 1.43$ nm

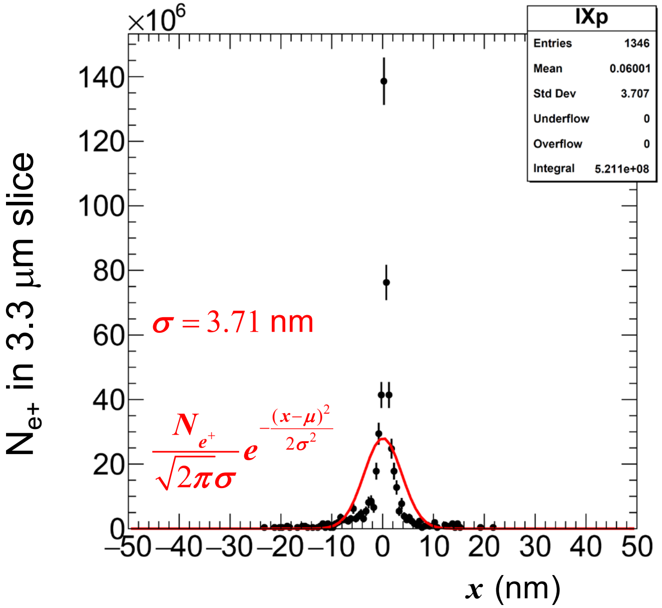
$$\frac{N_{e^-}}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



$\sigma = 1.97$ nm

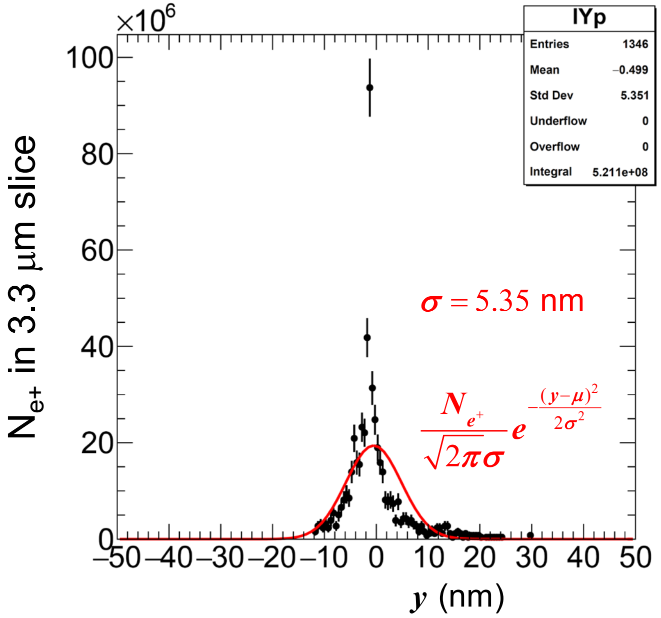
$$\frac{N_{e^-}}{\sqrt{2\pi\sigma}} e^{-\frac{(y-\mu)^2}{2\sigma^2}}$$

Narrow non-Gaussian cores with widths << σ



$\sigma = 3.71$ nm

$$\frac{N_{e^+}}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



$\sigma = 5.35$ nm

$$\frac{N_{e^+}}{\sqrt{2\pi\sigma}} e^{-\frac{(y-\mu)^2}{2\sigma^2}}$$

This pinching creates very high fields $\Rightarrow$ prob. to radiate γ in time slice >1 and CAIN program terminates

For $e^- \gamma$ go to asymmetric e^- ε_x ε_y to handle debilitating beamstrahlung

job	σ_z (μm)	ε_x (nm)	ε_y (nm)	a_{γ_x} (nm)	a_{γ_y} (nm)	$L_{e^-\gamma\ \mathrm{max}}$ (10^{32} cm^{-2} s^{-1} /bin)	$L_{e^-\gamma\ \mathrm{tot}}$ (10^{34} cm^{-2} s^{-1})	E_{max} (10^{18} V/m)
4918	10	120	120	10.2	10.2	0.9	244	4.0×10^{-3}
4923	20	120	120	10.2	10.2	0.7	16.02	4.8×10^{-4}
4951	20	1200	12	32.4	10.2	1.2	1.33	3.8×10^{-5}

Fields as high as $E_{\mathrm{Schwinger}}/250$

Scan parameter space in search of maximum $e^-\gamma \to e^- H$ events / yr

job	d_{cp} (μm)	σ_z (μm)	ε_x (nm)	ε_y (nm)	$L_{e^-\gamma}$ / yr, (fb^{-1})	$e^-\gamma \to e^- H$ events / yr
					$139 < E_{e^-\gamma} < 140$ GeV	$\theta_{e^-} > 3$ mrad
4992	60	10	120	120	8.5	35
4993	60	20	120	120	5.1	21
4965	60	10	1200	12	17.3	70
4955	60	20	1200	12	17.1	69
5240	10	10	1200	12	32.2	131

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 program

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

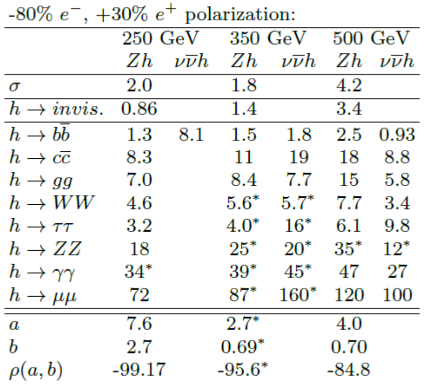
4000 $e^{-}\gamma \to e^{-}$ H events

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

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

assuming $n_{\text{bunch}} = 76 \to 290$

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	

What is required to fully match ILC precision?

	ILC	XCC
coupling a	Δa (%)	Δa (%)
HZZ	0.57	0.94
HWW	0.55	0.95
Hbb	1.0	1.0
$H\tau\tau$	1.2	1.1
Hgg	1.6	1.3
Hcc	1.8	1.3
$H\gamma\gamma$	1.1	0.33
$H\gamma Z$	9.1	10.0
$H\mu\mu$	4.0	3.6
Γ_{tot}	2.4	2.3
$\Gamma_{\text{inv}}{}^{\dagger}$	0.36	–
$\Gamma_{\text{other}}{}^{\dagger}$	1.6	1.2

†95% C.L. limit

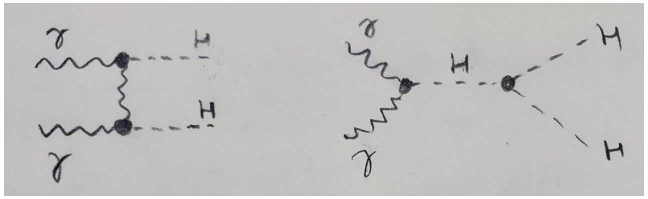
ILC: 0.5×10^6 $e^+e^- \to$ ZH events
full 2 ab^{-1} $\sqrt{s}=250$ GeV program

XCC: 1.0×10^6 $\gamma\gamma \to$ H events
20,000 $e^-\gamma \to e^-$ H events

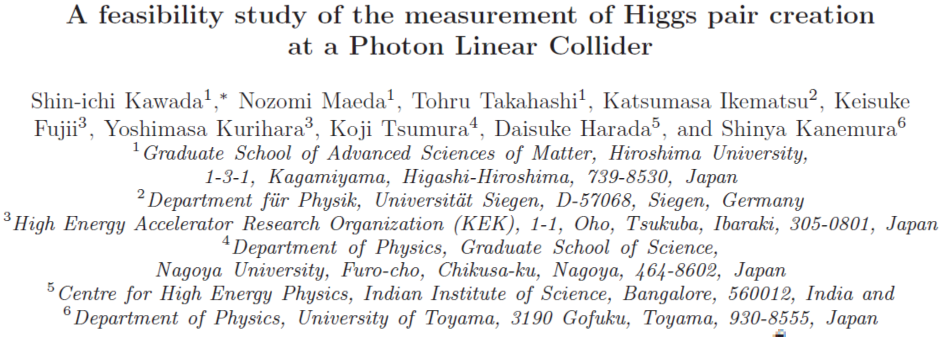
The $\gamma\gamma \to$ H sample only requires 3 more years @ $\sqrt{s}=125$ GeV with no change to the machine.

The 20,000 $e^-\gamma \to e^-$ H sample, however, is problematic. A dedicated 30 GeV accelerator for the one FEL in the $e^-\gamma$ mode would double the rate for $e^-\gamma \to e^-$ H from 500 to 1000 events/year. An additional luminosity upgrade is needed, however, to acquire 20,000 $e^-\gamma \to e^-$ H events in a reasonable time ---*unsolved problem*.

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



2012 Study



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

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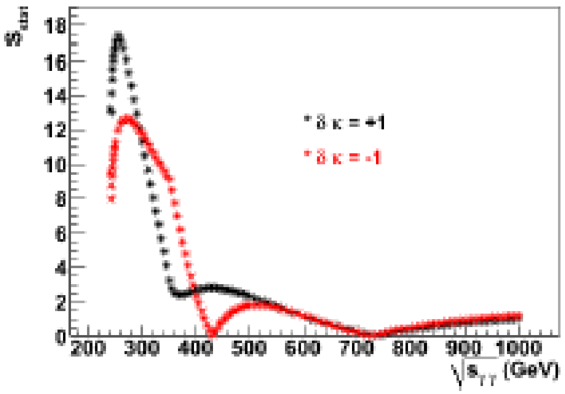
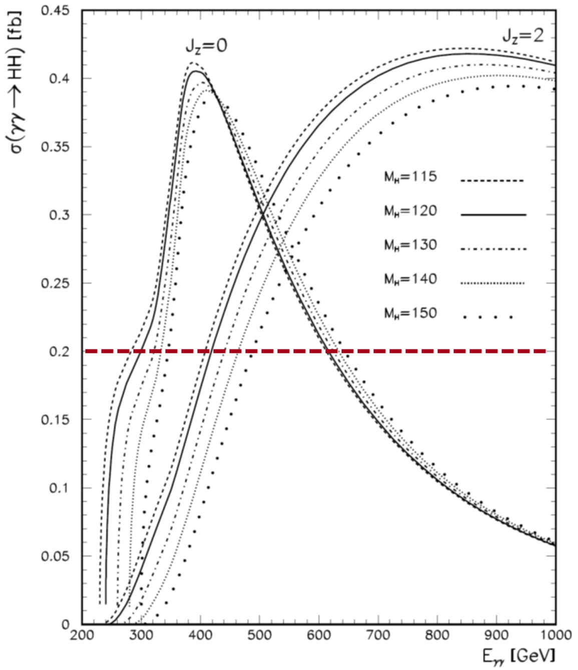


FIG. 3. Statistical sensitivity (S_{stat}) as a function of $\gamma\gamma$ collision energy. Black and red dots show the $\delta\kappa = +1$ and $\delta\kappa = -1$ cases.

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

Used optical laser for Compton scattering



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

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

Compton Collision Point

electron beam	
Energy (GeV)	62.6
β_{ex} / β_{ey} (mm)	0.03 / 0.03
$\gamma\varepsilon_{ex}$ / $\gamma\varepsilon_{ey}$ (μm)	0.12 / 0.12
σ_{ex} / σ_{ey} at IP (nm)	5.4 / 5.4
σ_{ez} (μm)	20
N (10^{10})	0.63
Rep Rate (Hz)	120x76
L_{geom} (10^{34} cm^{-2} s^{-1})	9.7
CP - IP distance (mm)	0.06
σ_{ex} / σ_{ey} at CP (nm)	12.1 / 12.1

laser beam	
Laser λ (nm)	1.19
Laser ω_0 (keV)	1.04
a_γ (nm)	15.3
non-linear QED ξ^2	0.38
Laser pulse length = $2\beta_\gamma$ (μm)	40.0
Laser pulse energy (J)	0.72

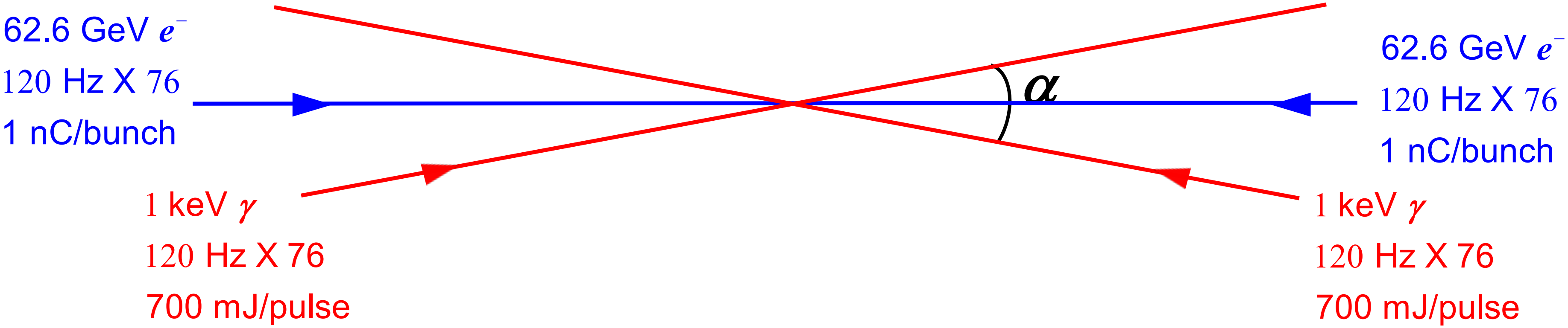
We need to reliably focus a a_γ=1 μm transverse radius 720 mJ/pulse x-ray laser beam down to a point with a_γ=15 nm .

If we backed off to a Compton collision point 100 μm from the primary IP, the required laser beam radius would grow to a_γ=24 nm but with a 30% loss in $\gamma\gamma$ luminosity (the angular spread of the Compton photons produces this sensitivity to Compton IP - primary IP distance).

Currently working on x-ray beam layout near IP

Luminosity dependence of laser angle α assuming 2 mrad crossing angle for e⁻ beams

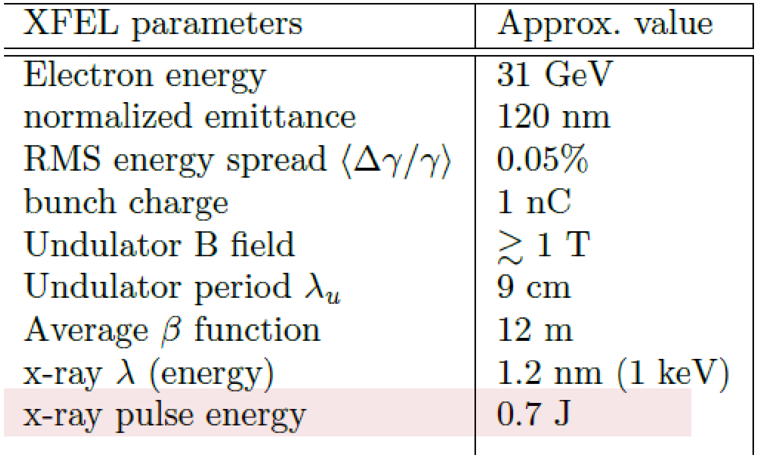
job	Laser α (mrad)	d_{cp} (μm)	σ_z (μm)	$\varepsilon_{x,y}$ (nm)	a_γ (nm)	N_{Higgs}/yr
5014	0	60	20	120	15.3	32,000
5015	2	60	20	120	15.3	32,000 .
5016	14	60	20	120	15.3	25,000
5017	28	60	20	120	15.3	12,000



XFEL for XCC

XFEL Parameters

Zhirong Huang and Adham Naji

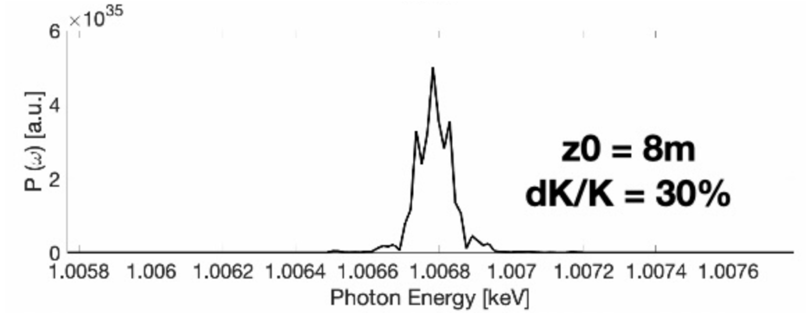


XFEL parameters	Approx. value
Electron energy	31 GeV
normalized emittance	120 nm
RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
bunch charge	1 nC
Undulator B field	$\gtrsim 1$ T
Undulator period λ_u	9 cm
Average β function	12 m
x-ray λ (energy)	1.2 nm (1 keV)
x-ray pulse energy	0.7 J

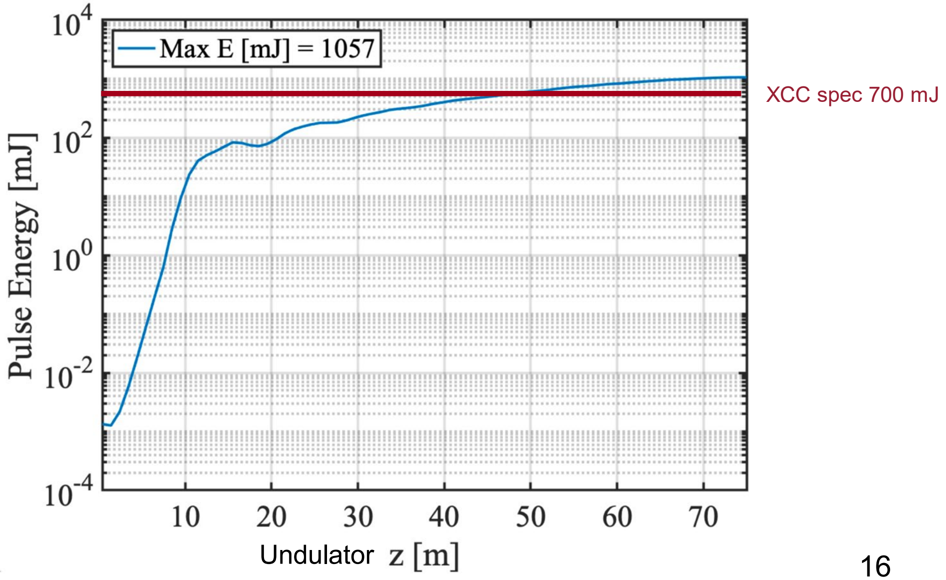
- Due to high B field and electron energy, quantum diffusion energy spread must be properly included in the design.
- With permanent magnet undulator, peak B field slightly above 1 Tesla, <β>=12m, 1 keV X-rays with pulse energy ~ 0.07 J can be produced with negligible diffusion
- With seeded helical FEL and taper of undulator K parameter after saturation, pulse energy of 0.7 J can be achieved
- Overall length of XFEL is ~ 100 m

GENESIS Simulation of XCC XFEL Design

Claudio Emma



Time-dependent

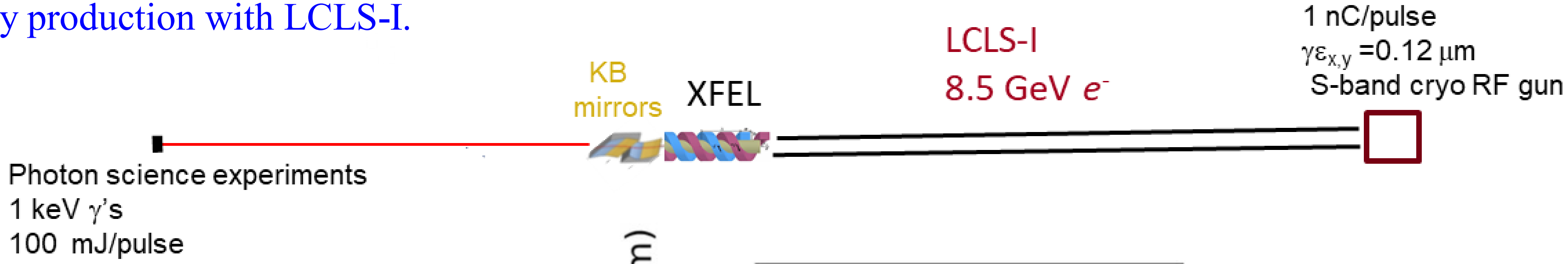


C^3-injector/XCC/BES Demonstration Project

Current soft x-ray (~1 keV) FEL's operate at a few mJ/pulse maximum, while XCC calls for 700 mJ/pulse

To actually test the production and focussing of soft x-rays with >> few mJ per pulse, Joe Frisch has suggested that we look into adding a 1nC/pulse, 120 nm emittance cryo RF gun injector to LCLS-I to see if that change alone could produce a soft x-ray beam with >> few mJ/pulse.

This could be more than just an XCC/C^3 demonstration project -- there have been indications of interest in the photon science community for a ~100 mJ/pulse soft x-ray beam. The low ε gun could also enhance hard x-ray production with LCLS-I.



1 nC/pulse
$\gamma\varepsilon_{x,y}$ =0.12 µm
S-band cryo RF gun

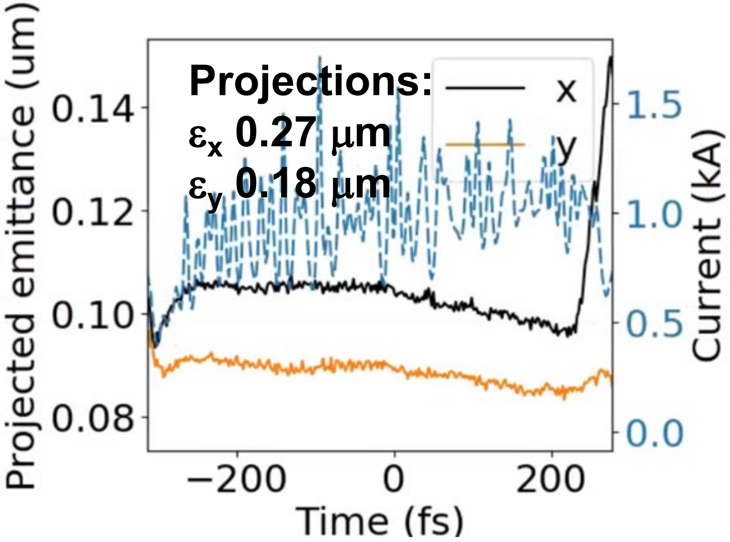
LCLS-I
8.5 GeV e^-

XFEL

KB mirrors

Photon science experiments
1 keV γ's
100 mJ/pulse

Initial study transport of nC/pulse $\gamma\varepsilon_{x,y} = 0.12\ \mu$m beam down LCLS-I linac: (Joe Duris)



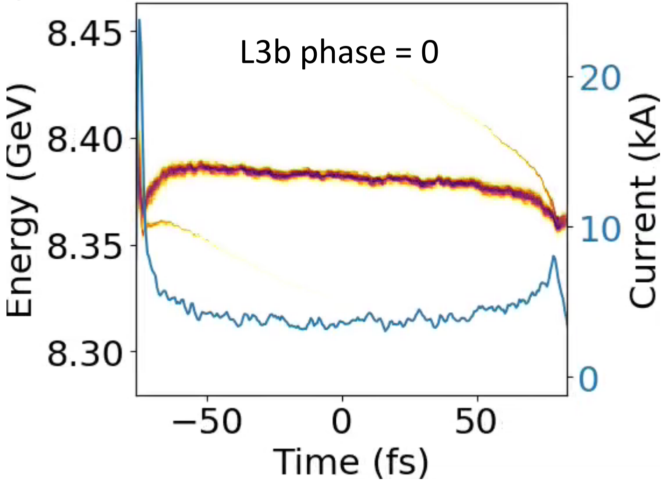
SXRSS with low emittance 1 nC beam from LCLS

Resistive wall wake fields added

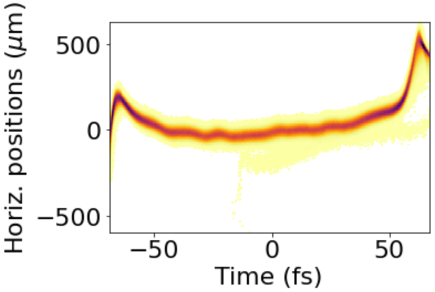
Joe Duris

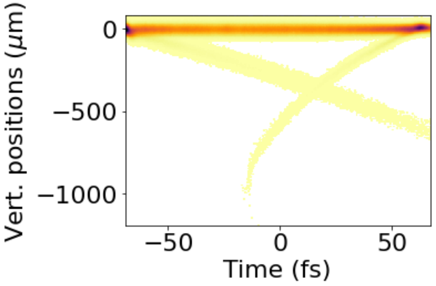
Nov 24,2021

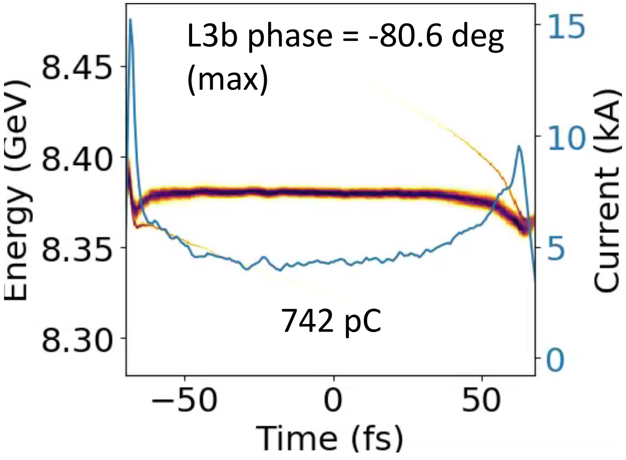
Elegant simulation of LINAC



- Collimate to 742 pC
- L1 phase: -16 deg
- L1X phase: -160 deg
- L2 phase: -39 deg
- L3a (26-27) phase: 0 deg
- L3b (28-30) phase: -80.6 deg (remove chirp)



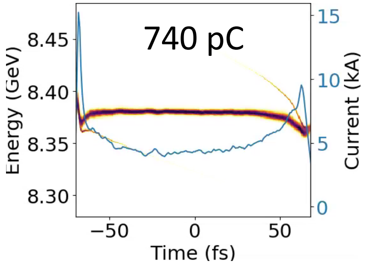


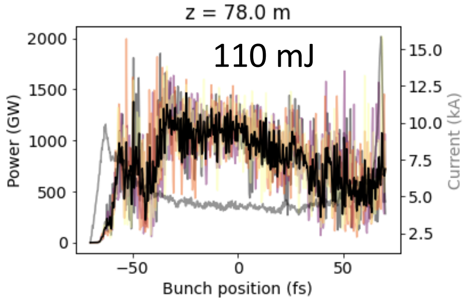


Undulator line focusing optics

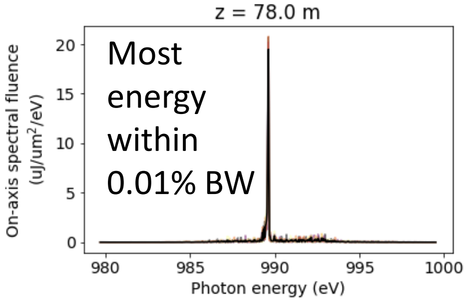
- 8400 MeV and 0.12 um emittance
- Normal lattice
  - E-beam transverse rms 11 um => X-ray waist of ~22 um => Rayleigh length of ~ 1 m => significant diffraction within a gain length (0.8 m). Also affects mode quality?
- Shot noise power of 7 kW (compared to 800W with 1 kA, 4 GeV beam leading to 10% SASE breakthrough)
- Reduce FODO quad gradients to 21% of normal
  - E-beam x-rms 22 um => 42 um waist => Rayleigh range of 5 m (1.2 m gain length)
  - Shot noise ~ 2.5 kW
- Seeding
  - ~50 kW limit to seed power (significantly exceeding this can damage spectral collimating optics in SXRSS monochromator)
  - FEL Pierce parameter rho ~ 0.18%

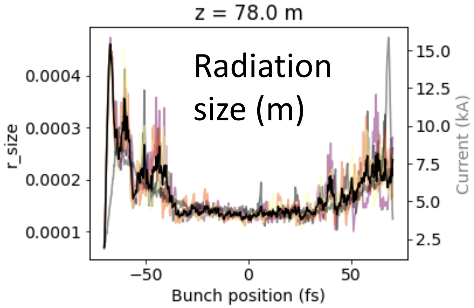
LCLS Low ε Summary





- 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





XCC Summary

- The XCC at E_{cm}=125-140 GeV can measure absolute Higgs couplings with an accuracy of order 1% . This is pretty close to the ILC precision (see slide 12 to judge for yourself). To fully match the ILC Higgs coupling accuracy, a way must be found to increase [production X detection eff.] for $e^- \gamma \rightarrow e^- H$ at E_{cm}=140 GeV by about a factor of 5.
- The Higgs self coupling can be studied via $\gamma\gamma \rightarrow HH$ if the XCC energy is upgraded to E_{cm}=300 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. Hence the XCC at E_{cm}=140-300 GeV could provide the same Higgs physics program as the ILC at E_{cm}=250-550 GeV, with the exception that the XCC would not measure the top Yukawa coupling.
- The XCC at E_{cm}=140 GeV might provide a significant cost saving with respect to C^3 at 250 GeV; perhaps the same can be said about XCC at E_{cm}=140-300 GeV versus C^3 at E_{cm}= 250-550 GeV. Further study is required to determine if this is actually the case.
- The XCC design for a 700 mJ/pulse 1keV XFEL by Zhirong Huang and Adham Naji has been validated by Claudio Emma using the GENESIS program. This energy/pulse is more than two orders of magnitude larger than current XFEL's.
- As a step in the direction of larger pulse energies, Joe Duris has demonstrated that the LCLS-I soft x-ray undulator could deliver ~100 mJ/pulse with < 0.01% FWHM bandwidth if LCLS-I can be outfitted with a 1nC/pulse, 120 nm emittance gun. Such a project would serve XCC, C^3, and BES.