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

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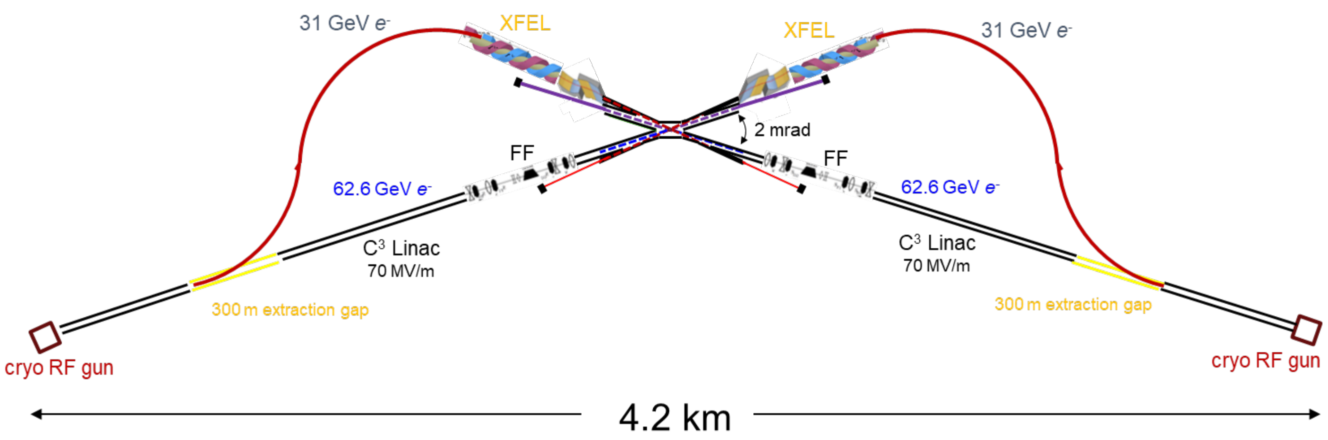
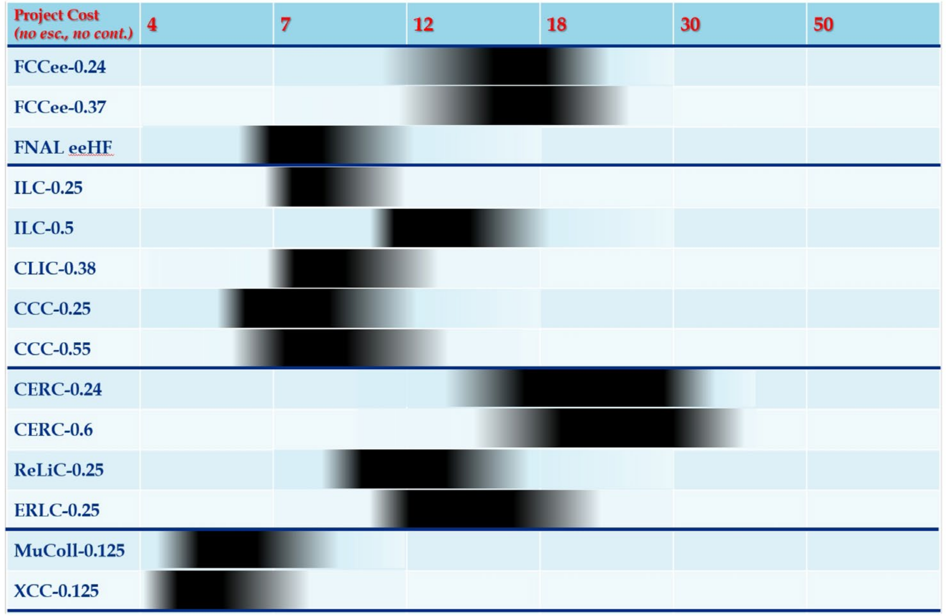
XCC s-channel $\gamma\gamma \rightarrow H$ @ $\sqrt{s} = 125$ GeV



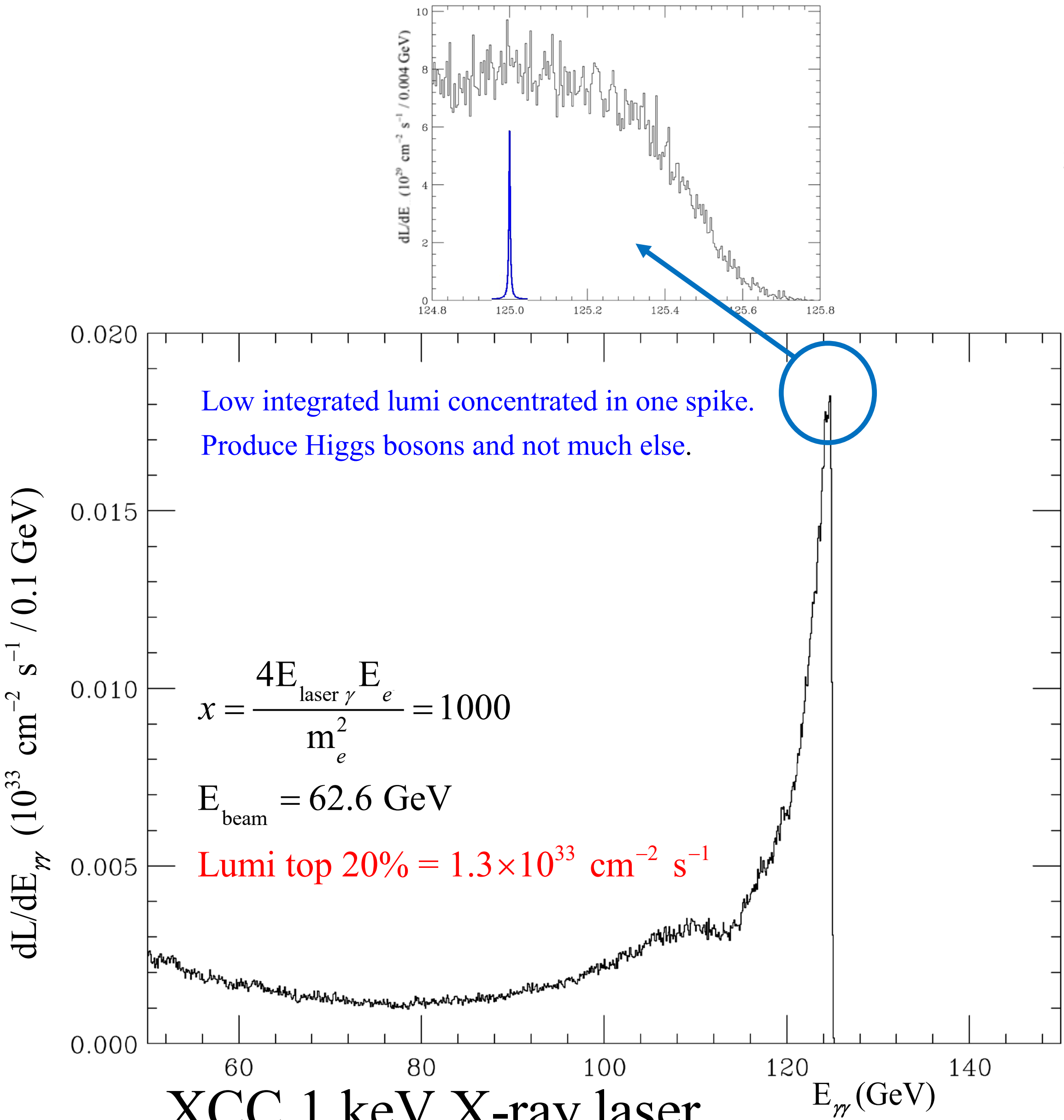


ITF

- Staging an e^+e^- collider with an intial $\gamma\gamma$ collider at the Higgs resonance is not a new idea.
  Such a suggestion by H. Sugawara in 2009 for the ILC was rejected in part due to a weak physics case.
- With an X-ray laser in place of an optical laser, the physics case for a 1st stage $\gamma\gamma$ collider Higgs factory is strengthened considerably. The optimum 2nd stage could again be a $\gamma\gamma$ collider, at $\sqrt{s}$=380 GeV to produce $\gamma\gamma \rightarrow H^* \rightarrow HH$.
- The XCC could begin operation on an earlier time scale than an e^+e^- Higgs factory due to its lower cost and smaller footprint.

The XCC is very different from previous γγ collider concepts

Machine	E_{e^-} (GeV)	Polarization	N_{H}/yr	$N_{\mathrm{Bgnd}}/N_{\mathrm{H}}$	$N_{\mathrm{minbias/BX}}$
XCC	62.8	90% e^-	80,000	170	9.5
2.4 eV laser	86.5	90% e^-	70,000	540	50
ILC	125	-80% e^- +30% e^+	98,000	140	1.3
ILC	125	+80% e^- -30% e^+	65,000	60	1.3



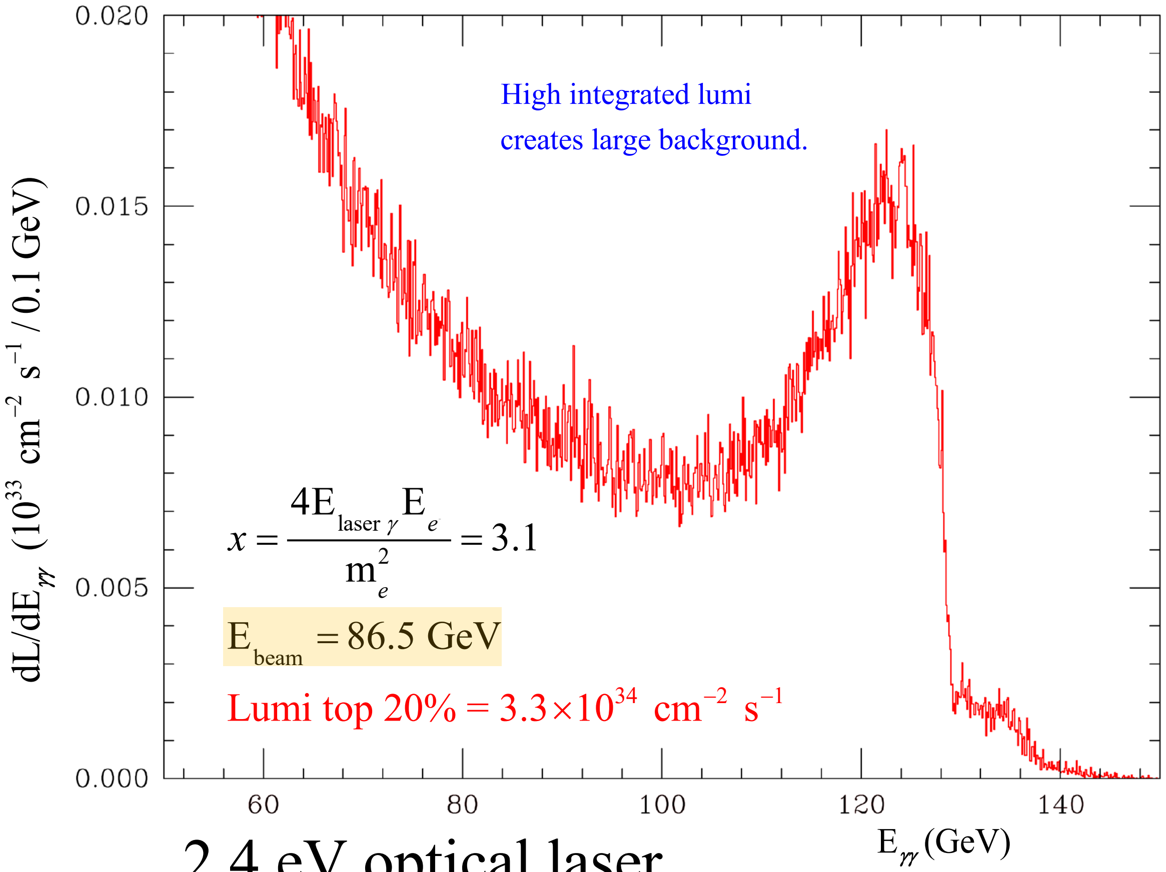
Low integrated lumi concentrated in one spike.
Produce Higgs bosons and not much else.

$$x = \frac{4E_{\mathrm{laser}\ \gamma} E_e}{m_e^2} = 1000$$

$E_{\mathrm{beam}} = 62.6$ GeV

Lumi top 20% = 1.3×10^{33} cm^{-2} s^{-1}

XCC 1 keV X-ray laser



High integrated lumi
creates large background.

$$x = \frac{4E_{\mathrm{laser}\ \gamma} E_e}{m_e^2} = 3.1$$

$E_{\mathrm{beam}} = 86.5$ GeV

Lumi top 20% = 3.3×10^{34} cm^{-2} s^{-1}

2.4 eV optical laser

Machine Detector Interface at XCC

Backgrounds from e^+, e^-, γ produced at Compton IP's and primary IP:

(1) Vertex detector inner radius (incoherent e^+e^- pairs from primary IP - same situation as e^+e^- linear colliders)

(2) Beampipe X_0 (moderate soft X-ray flux from Compton IP's $|\cos\theta| < 0.95$)

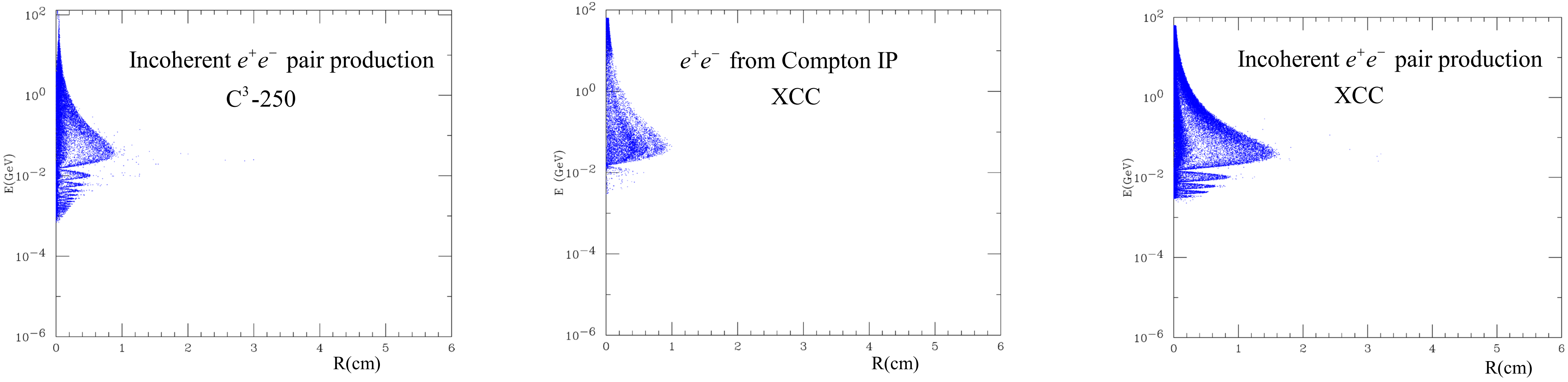
(3) Forward boundaries of the main tracker/calorimeter and solid angle coverage of forward detector (large hard X-ray flux from Compton IP's $|\cos\theta| > 0.95$)

(4) Aperture of final quad (e^+, e^-, γ from primary & Compton IP's must pass through this aperture)

Vertex Detector Inner Radius

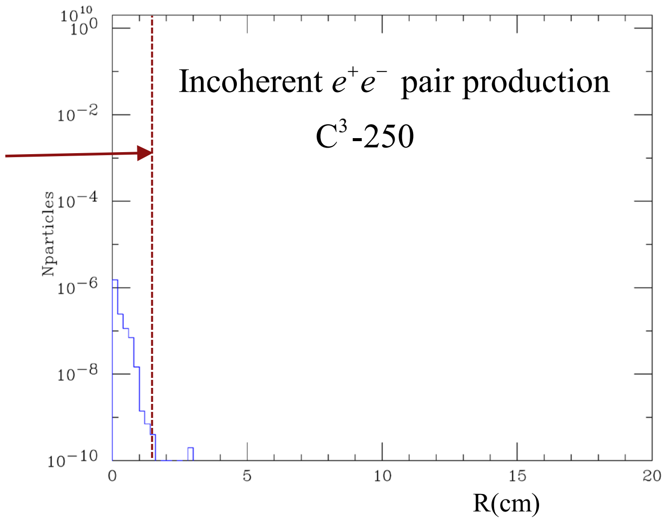
CAIN Simulation assuming 5 T Solenoid

$E(e^{\pm})$ vs. R at $z = 6.25$ cm

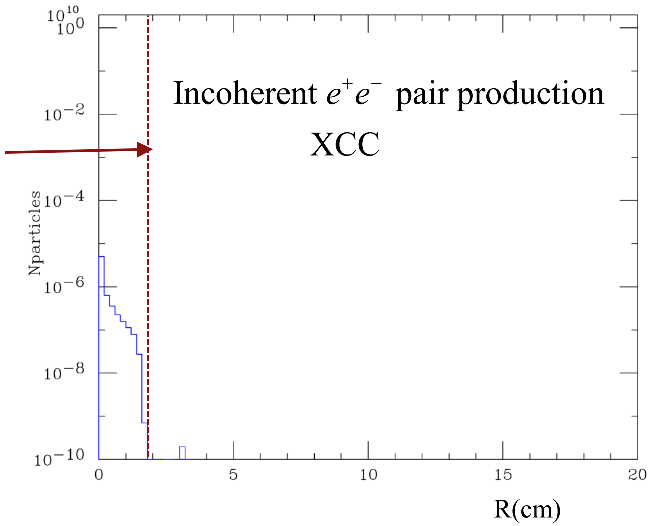


$N(e^{\pm})$ vs. R at $z = 6.25$ cm

SiD Vtx Inner Rad=1.5 cm



XCC Vtx Inner Rad=1.9 cm
should be OK

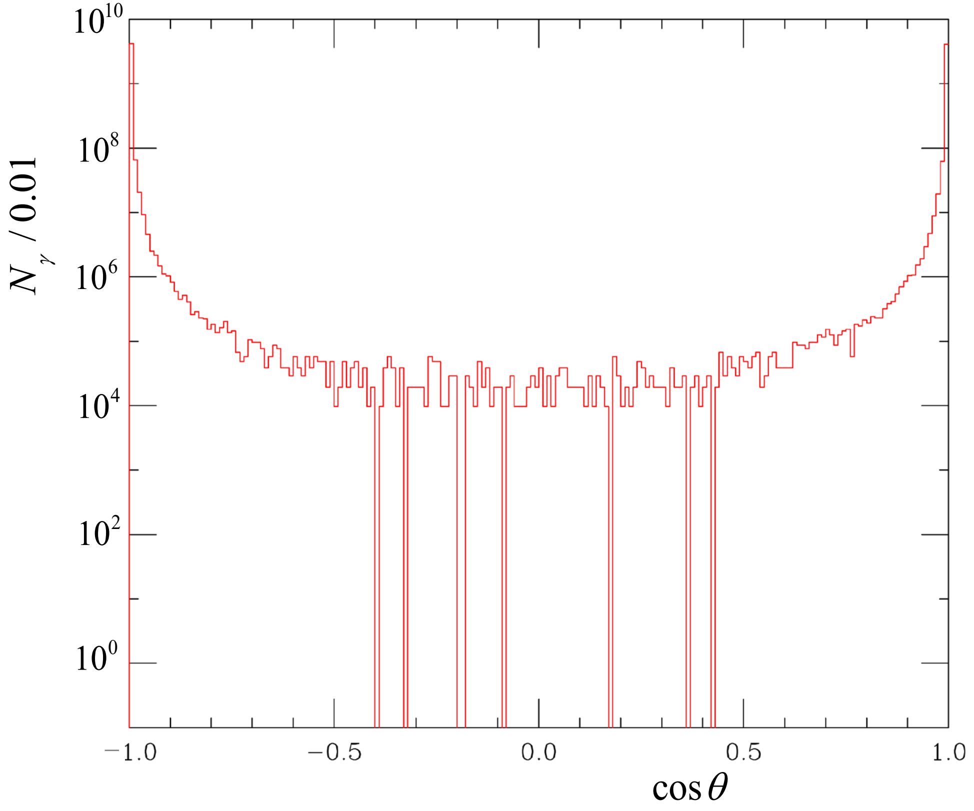


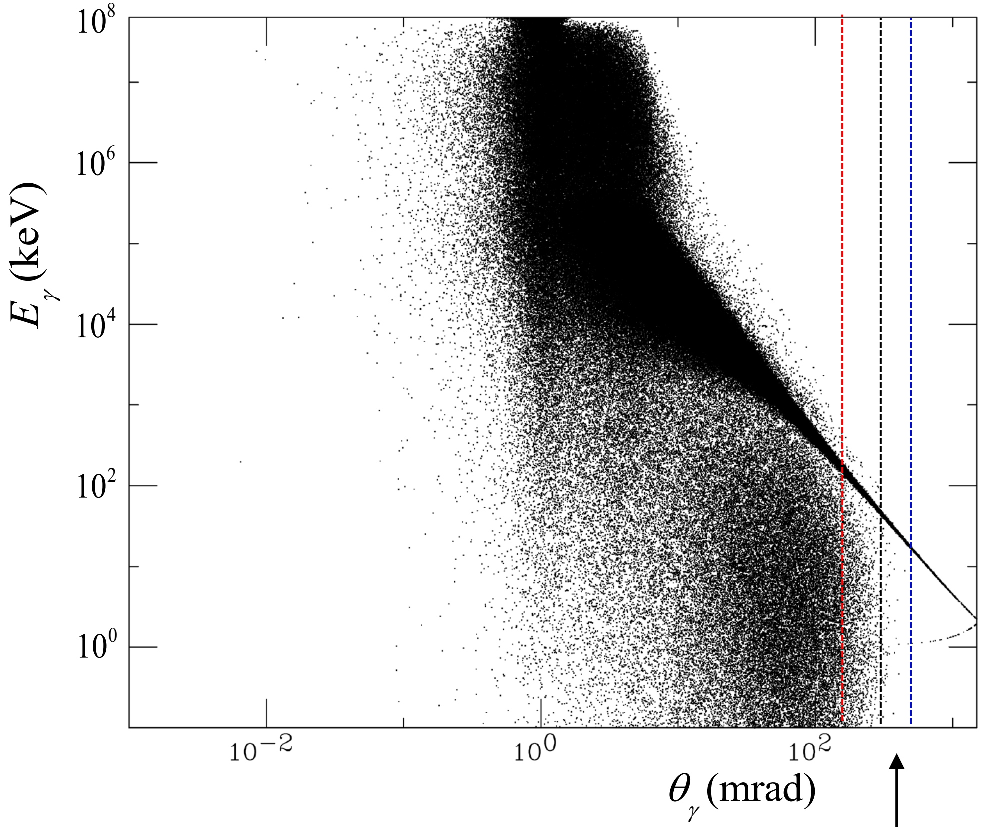
X-rays from Compton IP's

CAIN Simulation

Moderate flux of soft (few keV) X-rays in central region

Number and energy of Compton IP X-rays increases rapidly in the forward region





$|\cos\theta| = (0.99, 0.95, 0.90)$

X-rays handled by adding 0.1% - 1.0% X_0 heavy element to Beampipe for $|\cos\theta| < 0.8$

Required absorber increases to 5.0% X_0 at $|\cos\theta| = 0.93$

Complicated design for $0.95 < |\cos\theta| < 0.99$; probably can't instrument for $|\cos\theta| > 0.99$

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

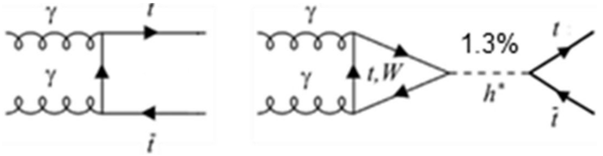
Model Independent EFT

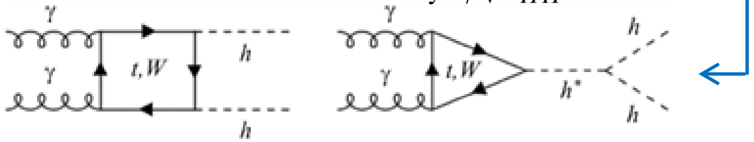
coupling a	ILC/C^3 Δa (%)	XCC[#] Δa (%)
HZZ	0.38	0.94
HWW	0.37	0.94
Hbb	0.60	0.95
$H\tau\tau$	0.77	0.99
Hgg	0.96	1.2
Hcc	1.2	1.2
$H\gamma\gamma$	1.0	0.44
$H\gamma Z$	4.0	1.5
$H\mu\mu$	3.8	3.5
Htt	2.8	4.6
HHH	20	14*
Γ_{tot}	1.6	2.4
Γ_{inv}[†]	0.32	–
Γ_{other}[†]	1.3	1.5

[†] 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.



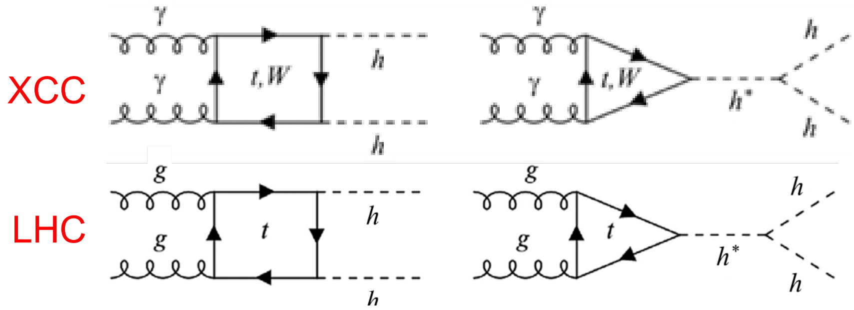


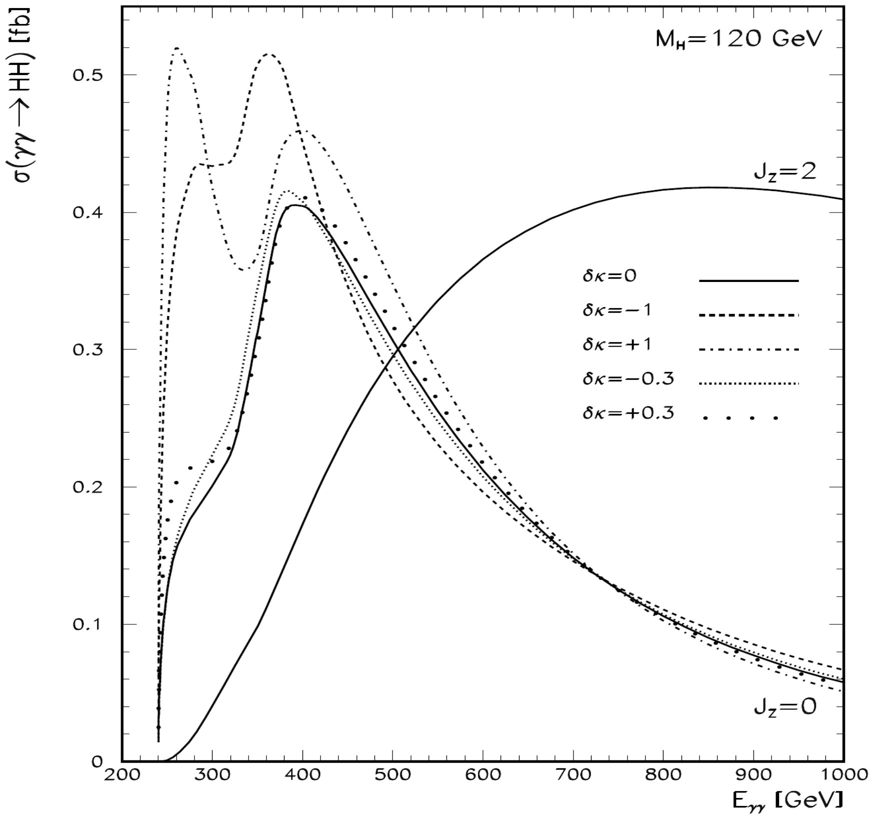
$\gamma\gamma \to HH$ at $\sqrt{s} = 380$ GeV

- At 0.4 fb, the cross section for $\gamma\gamma \to HH$ at $\sqrt{s}$=380 GeV is twice that of $e^+e^- \to ZHH$ at $\sqrt{s}$=500 GeV, so that the XCC Higgs self-coupling measurement starts out with a $\sqrt{2}$ statistical advantage over 500 GeV e^+e^- colliders.

- The HH final state is simpler than ZHH. N.B., the associated Z boson in e^+e^- production of the Higgs is great for measurements such as Γ_{ZZ} & $\Gamma_{\text{invisible}}$, but can be a complication in other instances.

- Interesting interference between box diagram and s-channel: constructive at XCC vs. destructive at LHC





XCC Technical Challenges + Going Forward

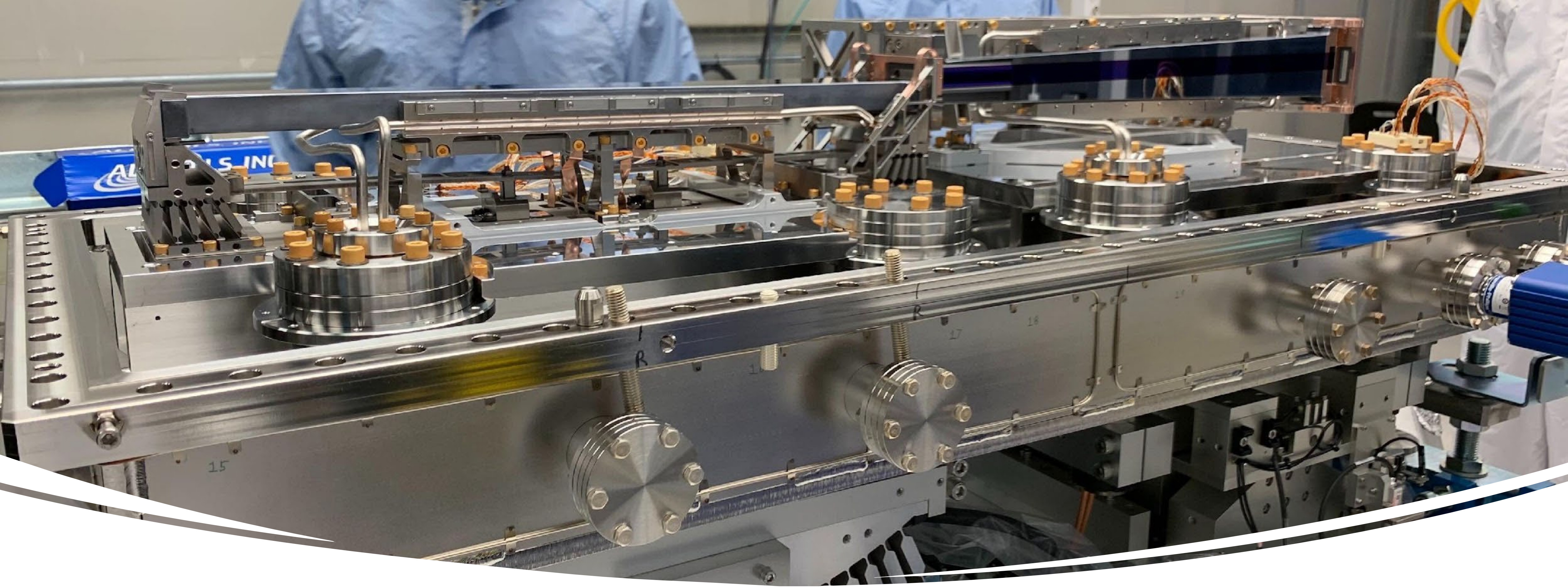
Technical Challenges

- e^- accelerator with $70-120$ MV/m (common with C^3 e^+e^- collider)
- Focusing of round e^- beams to $\sigma_{x,y} = 5.5$ nm
- Focusing of 1 keV γ XFEL with 700 mJ/pulse to 70 nm FWHM waist
- XFEL and e^- beamline layouts around the IP
- Timing stability of the XFEL laser beam and e^- beam at Compton IP.

Going Forward

- Hope to obtain support for an XCC CDR (such support is required as the XCC work cannot detract from the C^3 demo and e^+e^-collider design efforts.)
- Due to common accelerator technology, the XCC CDR could be incorporated into the C^3 CDR as a 2nd collider configuration option, with the choice between e^+e^- and $\gamma\gamma$ to be made at a later date (much like a CDR might contain several site options).

Backup Slides



KB Mirror Focusing for $\gamma\gamma$ Collider

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: *(probably forces 1 keV → 2 keV)*
  - Damage
  - Reflectivity --> less absorbed power
  - Focal size
  - Rayleigh range

Summary of Initial $\gamma\gamma$ Collider KB Mirror Study

- 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)

Final Quad Aperture

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