The ILC Higgs White Paper for Snowmass

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Convened by Jim Brau, the ILC Higgs White Paper Authors are:

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Goals of ILC Higgs White Paper

- Target audience is the Snowmass Higgs Subgroup Conveners and Others Gathered at the Snowmass Meeting in Minnesota
- Summarize Higgs physics potential of the ILC
- Utilize existing literature including LOI & DBD results from ILD & SiD
- Perform new studies to fill in gaps and to address issues raised by Snowmass Higgs conveners
- Include self-contained Higgs theory section

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***See following talk in this session by Stefan Berge**

Suggested table from Snowmass Higgs Conveners

	LHC 300/fb	LHC 3000/fb	e^+e^- 250 GeV	e^+e^- 1 TeV	$\mu^+\mu^-$ 125 GeV	$\gamma\gamma$ 125 GeV
spin-2 Grav. ...	$\sim 10\sigma$ ...	$\gg 10\sigma$ ...	? ...	? ...	? ...	? ...
f_{CP} in VVH	± 0.08	± 0.03 (?)	?	?	?	?
f_{CP} in $\tau\tau H$	?	?	?	?	?	?
f_{CP} in ttH	?	?	–	?	–	–
f_{CP} in $\mu\mu H$	–	–	–	–	?	–
f_{CP} in $\gamma\gamma H$	–	(?)	–	–	–	?

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ZZH, WWH (SM g_1), $Z\gamma H$, $\gamma\gamma H$, ggH (SM g_2), or 0^- (g_4)

$$A_{VV} \propto g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

When g_1 dominates, f_{g_4} is CP-violating fraction (here $g_i = 1 \leftrightarrow \sigma_i$):

$$f_{CP} = f_{g4} = \frac{|g_4|^2\sigma_4}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g4} = \arg\left(\frac{g_4}{g_1}\right)$$

$$f_{g2} = \frac{|g_2|^2\sigma_2}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g2} = \arg\left(\frac{g_2}{g_1}\right)$$

$$\tau^+\tau^- H, \mu^+\mu^- H, b\bar{b}H, t\bar{t}H$$

$$A_{f\bar{f}} \propto \frac{m_f}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1 = \frac{m_f}{v} \bar{u}_2 \rho \left(\cos\theta + e^{i\phi_{\rho 2}} \sin\theta\, \gamma_5\right) v_1$$

$$f_{CP} = f_{\rho 2} = \frac{|\rho_2|^2\sigma_2}{|\rho_1|^2\sigma_1 + |\rho_2|^2\sigma_2} = \frac{1}{|\rho_1/\rho_2|^2\, \sigma_1/\sigma_2 + 1} = \frac{1}{|\cot\theta|^2\, \sigma_1/\sigma_2 + 1}$$

$$\phi_{\rho_2} = \arg\left(\frac{\rho_2}{\rho_1}\right)$$

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New Studies

Full simulation (DBD-like) ILC studies of $e^+e^- \to Zh$, $\nu_e\bar{\nu}_e h$ with M_h=125 GeV at $\sqrt{s} =$ 250, 350, & 500 GeV including

ΔM_h, $\Delta\sigma(e^+e^- \to Zh)$ **--being done with SiD**

$BR(h \to ZZ^* \ Z\gamma, \ \mu^+\mu^-)$ **--being done with SiD**

$BR(h \to bb, cc, WW^*, gg, \tau^+\tau^-, \gamma\gamma)$ **-- being done with ILD, see talks by Shin-ichi Kawada and Hiroaki Ono in this morning's session 11:00 - 13:00**

$BR(h \to invisible)$ **--being done with SiD & ILD (previous talk in this session by Akimasa Ishikawa)**

New Studies

More Higgs self coupling studies at $\sqrt{s} =$ 500 and 1000 GeV

Repeat Higgs self coupling measurement with M_h=125 GeV and add WW^* final state to analysis

-- see talks by Junping Tian and Masakazu Kurata in the Wednesday 16:00 - 17:30 Higgs session.

Suggested table from Snowmass Higgs Conveners

- General coupling fits+ fits within specific models

	LHC300	LHC3000	ILC250	ILC500	ILC1TeV	CLIC 3 TEV	$\mu\mu$
Δ_H							
Δ_V							
Δ_f							
Δ_b							
Δ_τ							
Δ_V							
...							

See recommendations of LHC Higgs Cross Section Working Group

LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like Particle arXiv:1029.0040

κ_i coupling scaling factor examples, and some assumptions used in all parameterizations

3.2.4 Treatment of $\Gamma_{c\bar{c}}$, $\Gamma_{s\bar{s}}$, $\Gamma_{\mu^-\mu^+}$ and light fermion contributions to loop-induced processes

When calculating $\kappa_H^2(\kappa_i, m_H)$ in a benchmark parametrization, the final states $c\bar{c}$, $s\bar{s}$ and $\mu^-\mu^+$ (currently unobservable at the LHC) are tied to κ_i scale factors which can be determined from the data. Based on flavour symmetry considerations, the following choices are made:

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}(m_H)} = \kappa_c^2 = \kappa_t^2 \tag{28}$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}(m_H)} = \kappa_s^2 = \kappa_b^2 \tag{29}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}(m_H)} = \kappa_\mu^2 = \kappa_\tau^2 \tag{30}$$

Following the rationale of Ref. [61, Sec. 9], the widths of e^-e^+, $u\bar{u}$, $d\bar{d}$ and neutrino final states are neglected.

Through interference terms, these light fermions also contribute to the loop-induced $gg \to H$ and $H \to gg, \gamma\gamma, Z\gamma$ vertices. In these cases, the assumptions $\kappa_c = \kappa_t$, $\kappa_s = \kappa_b$ and $\kappa_\mu = \kappa_\tau$ are made.

		LHC 300	LHC 3000	ILC TDR 250	ILC TDR $\int dL$ 250 – 500	ILC TDR $\int dL$ 250 – 1000	ILC TDR +Lumi Upgr $\int dL$ 250 – 1000
$\kappa (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z)$	Common scale factor ($=\Delta_H$)						
$\kappa_V (= \kappa_W = \kappa_Z)$ $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$	Boson and fermion scale factors						
$\kappa_{VV} (= \kappa_V^2 / \kappa_H)$ $\lambda_{fV} (= \kappa_f / \kappa_V)$							
κ_Z $\lambda_{WZ} (= \kappa_Z / \kappa_W)$ $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$	Custodial symmetry						
$\kappa_{ZZ} (= \kappa_Z^2 / \kappa_H)$ $\lambda_{WZ} (= \kappa_Z / \kappa_W)$ $\lambda_{fZ} (= \kappa_f / \kappa_Z)$							

Note: $\kappa_H^2 \equiv \frac{\Gamma_H}{\Gamma_H^{SM}}$

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		LHC 300	LHC 3000	ILC TDR 250	ILC TDR $\int dL$ 250 – 500	ILC TDR $\int dL$ 250 – 1000	ILC TDR +Lumi Upgr $\int dL$ 250 – 1000
$\kappa_V (= \kappa_W = \kappa_Z)$ $\lambda_{du} (= \kappa_d / \kappa_u)$ $\kappa_u (= \kappa_t)$	up-type and down-type fermion symmetry						
$\kappa_{uu} (= \kappa_u^2 / \kappa_H)$ $\lambda_{du} (= \kappa_d / \kappa_u)$ $\lambda_{Vu} (= \kappa_V / \kappa_u)$							
$\kappa_V (= \kappa_W = \kappa_Z)$ $\lambda_{lq} (= \kappa_l / \kappa_q)$ $\kappa_q (= \kappa_t = \kappa_b)$	quark and lepton symmetry						
$\kappa_{qq} (= \kappa_q^2 / \kappa_H)$ $\lambda_{lq} (= \kappa_l / \kappa_q)$ $\lambda_{Vq} (= \kappa_V / \kappa_q)$							

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		LHC 300	LHC 3000	ILC TDR 250	ILC TDR $\int dL$ 250 – 500	ILC TDR $\int dL$ 250 – 1000	ILC TDR +Lumi Upgr $\int dL$ 250 – 1000
κ_g	Loop structure						
κ_γ							
κ_g							
κ_γ							
$BR_{inv,undet}$							
κ_g	Loop structure with floating boson and fermion κ's						
κ_γ							
$\kappa_V (= \kappa_W = \kappa_Z)$							
$\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$							
$\kappa_{gV} (= \kappa_g \bullet \kappa_V / \kappa_H)$							
$\lambda_{Vg} (= \kappa_V / \kappa_g)$							
$\lambda_{\gamma V} (= \kappa_\gamma / \kappa_V)$							
$\lambda_{fV} (= \kappa_f / \kappa_V)$							

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		LHC 300	LHC 3000	ILC TDR 250	ILC TDR $\int dL\ 250-500$	ILC TDR $\int dL\ 250-1000$	ILC TDR +Lumi Upgr $\int dL\ 250-1000$
$\kappa_{gZ}(=\kappa_g \bullet \kappa_Z / \kappa_H)$	Most general parameterization in arXiv:1209.0040						
$\lambda_{\gamma Z}(=\kappa_\gamma / \kappa_Z)$							
$\lambda_{WZ}(=\kappa_W / \kappa_Z)$							
$\lambda_{bZ}(=\kappa_b / \kappa_Z)$							
$\lambda_{tZ}(=\kappa_t / \kappa_Z)$							
$\lambda_{Zg}(=\kappa_Z / \kappa_g)$							
$\lambda_{tg}(=\kappa_t / \kappa_g)$							

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		LHC 300	LHC 3000	ILC TDR 250	ILC TDR $\int dL$ 250 – 500	ILC TDR $\int dL$ 250 – 1000	ILC TDR +Lumi Upgr $\int dL$ 250 – 1000
	Model independent						
κ_b	coupling						
κ_W	determination						
κ_g	in κ notation						
κ_τ							
κ_c							
κ_Z							
κ_γ							
$\kappa_{(\gamma Z)}$							
κ_μ							
$BR_{inv,undet}$							
κ_t							
$\kappa_{(HHH)}$							
κ_H							

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New Studies

Higgs physics with the $\gamma\gamma$ option at ILC

We do not have the resources to get the $\gamma\gamma$ event generation machinery up and running in a timely manner. Therefore we will take previous $\gamma\gamma$ studies of Higgs $\sigma \times BR$ and CP-violation, compare the results with those from e^+e^- ILC and high luminosity LHC, and attempt to quantify the additional physics provided by the $\gamma\gamma$ option.

New Studies

Investigate impact of ILC luminosity upgrades
on Higgs physics

In consultation with acc. physicists luminosity upgrade options have been explored (next slides).

We will scale existing measurement errors and identify important systematic errors.

ILC Parameters

			Baseline	1st Stage	L Upgrade	TeV Upgrade A	TeV Upgrade B
Centre-of-mass energy	E_{CM}	GeV	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	5	10	5	4	4
Number of bunches	n_b		1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	366	366	366
Pulse current	I_{beam}	mA	5.79	5.8	8.75	7.6	7.6
Average total beam power	P_{beam}	MW	10.5	5.2	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	162	128	205	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	11.0	13.0	11.0	22.6	11.0
IP vertical beta function (no TF)	β_y^*	mm	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	474	729	474	481	335
IP RMS veritcal beam size (no TF)	σ_y^*	nm	5.9	7.7	5.9	2.8	2.7
Luminosity (inc. waist shift)	L	$\times 10^{34}$ cm^{-2}s^{-1}	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	344.1	46.5	344.1	1338.0	3441.0

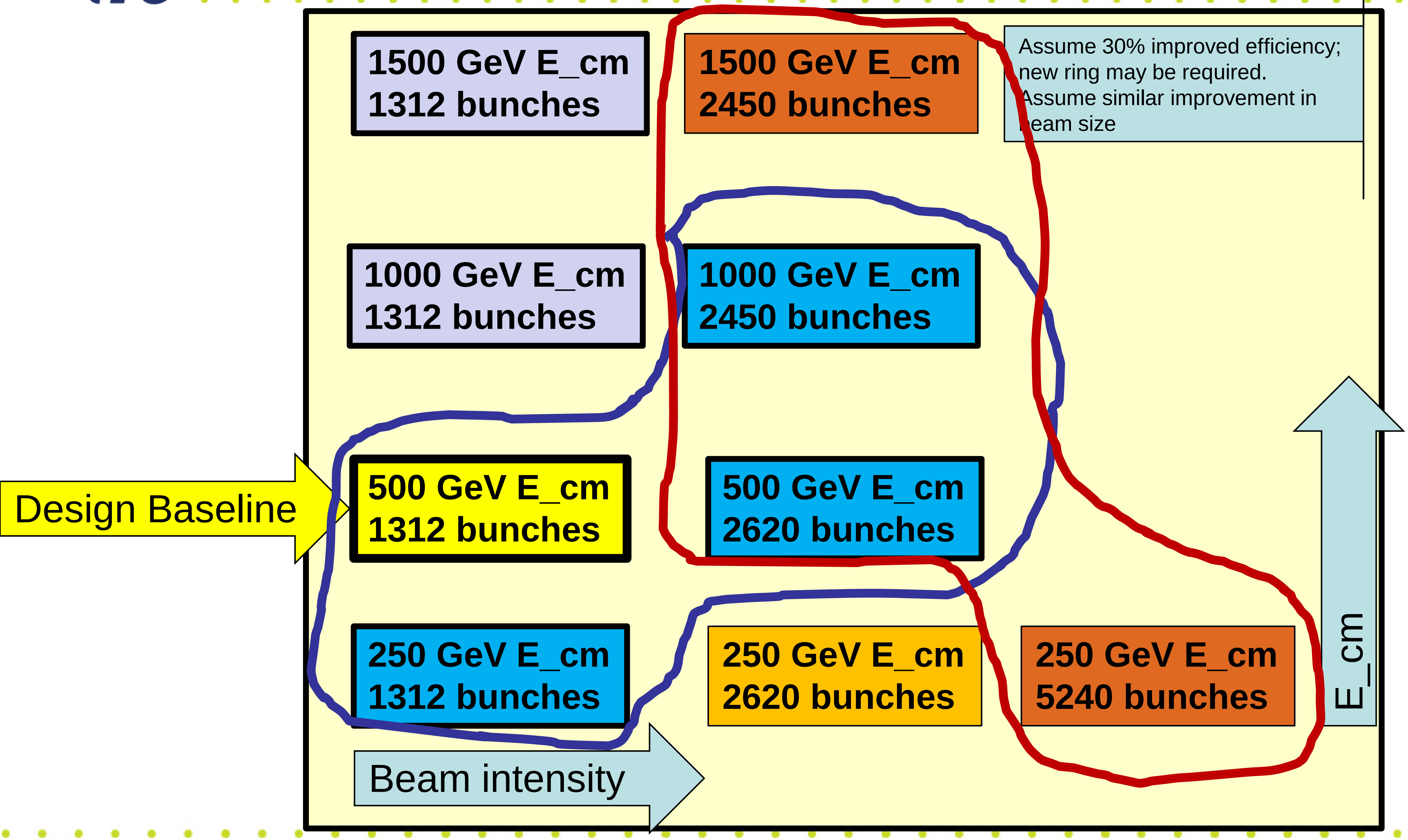
500 GeV Baseline

Initial 'Higg's Factory

ILC Luminosity Upgrade

- Concept: increase n_b from 1312 → 2625
  - **Reduce linac bunch spacing 554 ns → 336 ns**
  - **Increase pulse current 5.8 → 8.8 mA**
  - **Increase number of klystrons by ~50%**
- Doubles beam power → ×2 L ($3.6 \times 10^{34} cm^{-2} s^{-1}$)
- Damping ring:
  - **Electron ring doubles current (389mA → 778mA)**
  - **Positron ring: possible 2nd (stacked) ring (e-cloud limit)**
- AC power: 161 MW → 204 MW (est.)
  - **AC power increased by ×1.5**
  - **shorter fill time and longer beam pulse results in higher RF-beam efficiency (44% → 61%)**

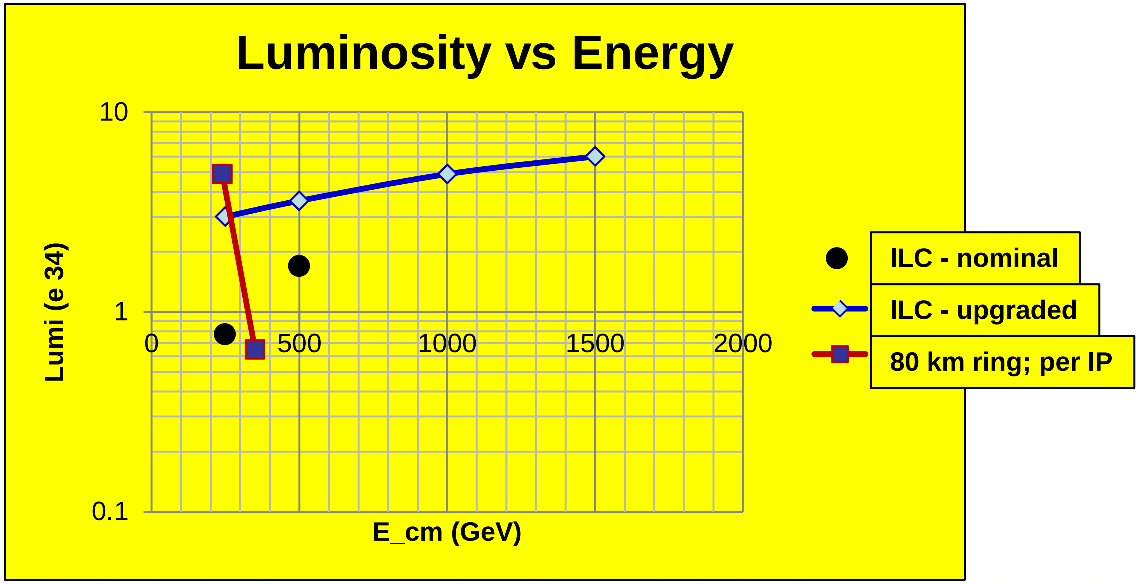
Staging and Upgrades:



ILC at low/high Ecm

- **Low E_{cm} operation of upgraded ILC:**
  - L_{250} ~ 3e34; Wall plug 200 MW
  - Higgs Factory Option
- **High E_{cm} ~ 1.5 TeV**
  - L_{1500} ~ 6e34; Wall plug 340 MW

Assumes 2x improved efficiency; 2450 bunches



Snowmass ILC Luminosity (fb^{-1}) based on 3×10^7 s running time for each stage of ILC

Ecm(GeV)	ILC TDR Baseline	ILC Lum Upgrade	ILC TDR+Upgrade
250	250	900	1150
350	300	950	1250
500	500	1100	1600
1000	1000	1500	2500

Summary

- Any suggestions for how we can improve the paper are welcome.
- The paper will be based mostly on existing literature but will contain some new results:
  - Updated full simulation Higgs BR studies with mH=125 GeV and Ecm=250-500
  - Full simulation study of the invisible Higgs width
  - Additonal Higgs self coupling studies
  - Consideration of a luminosity upgrade
- Event generation and DBD-like simulation and reconstruction for ILC Higgs studies with mH=125 GeV and Ecm=250-500 essentially complete. Analyses have started.
- Our self-imposed due date for a first draft is June 6. The draft to be used by the Snowmass Higgs Subgroup in creating their pre-Minnesota draft is due a little over three weeks later on June 30. We consider the June 30th version of our paper the most important one.
- Two additional dates of interest for revisions are the first day of the Minnesota meeting, July 29, and the absolute cutoff date for revisions, Sep 30.