The ILC Higgs White Paper for Snowmass

Tim Barklow SLAC May 28, 2013

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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 | $^{\gamma\gamma}_{125~{ m GeV}}$ |
|--------------------------------|-----------------|-------------------|---------------------|-------------------|----------------------|----------------------------------|
| spin-2 Grav. | $\sim 10\sigma$ | \gg 10 σ | ? | ? | ? | ? |
| | | | | | | |
| f_{CP} in VVH | ± 0.08 | ±0.03 (?) | ? | ? | ? | ? |
| $f_{C\!P}$ in $	au	au H$ | ? | ? | ? | ? | ? | ? |
| f_{CP} in ttH | ? | ? | _ | ? | — | — |
| f_{CP} in $\mu\mu H$ | — | _ | — | _ | ? | — |
| $f_{C\!P}$ in $\gamma\gamma H$ | — | (?) | — | _ | — | ? |

ZZH, WWH (SM g_1), Z γ 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 $g_i = 1 \leftrightarrow \sigma_i$):

$$f_{CP} = f_{g4} = \frac{|g_4|^2 \sigma_4}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4}; \quad \phi_{g4} = \arg\left(\frac{g_4}{g_1}\right)$$
$$f_{g2} = \frac{|g_2|^2 \sigma_2}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4}; \quad \phi_{g2} = \arg\left(\frac{g_2}{g_1}\right)$$

$$\begin{aligned} \tau^{+}\tau^{-}H, \mu^{+}\mu^{-}H, b\bar{b}H, t\bar{t}H\\ A_{f\bar{f}} \propto \frac{m_{f}}{v}\bar{u}_{2}\left(\rho_{1}+\rho_{2}\gamma_{5}\right)v_{1} &= \frac{m_{f}}{v}\bar{u}_{2}\rho\left(\cos\theta+e^{i\phi_{\rho^{2}}}\sin\theta\gamma_{5}\right)v_{1}\\ f_{CP} &= f_{\rho^{2}} = \frac{|\rho_{2}|^{2}\sigma_{2}}{|\rho_{1}|^{2}\sigma_{1}+|\rho_{2}|^{2}\sigma_{2}} = \frac{1}{|\rho_{1}/\rho_{2}|^{2}\sigma_{1}/\sigma_{2}+1} = \frac{1}{|\cot\theta|^{2}\sigma_{1}/\sigma_{2}+1}\\ \phi_{\rho_{2}} &= \arg\left(\frac{\rho_{2}}{\rho_{1}}\right)\end{aligned}$$

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Full simulation (DBD-like) ILC studies of $e^+e^- \rightarrow Zh$, $v_e\overline{v_e}h$ with M_h =125 GeV at $\sqrt{s} = 250, 350, \& 500$ GeV including $\Delta M_h, \Delta \sigma (e^+e^- \rightarrow Zh)$ --being done with SiD

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

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

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

- 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.

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Suggested table from Snowmass Higgs Conveners
 General coupling fits+ fits within specific models

| | LHC300 | LHC3000 | ILC250 | ILC500 | ILC1TeV | CLIC 3 TEV | μμ |
|------------------|--------|---------|--------|--------|---------|------------|----|
| Δ_{H} | | | | | | | |
| $\Delta_{\sf V}$ | | | | | | | |
| Δ_{f} | | | | | | | |
| Δ_{b} | | | | | | | |
| Δ_{τ} | | | | | | | |
| $\Delta_{\sf V}$ | | | | | | | |
| | | | | | | | |

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

When calculating $\kappa_{\rm H}^2(\kappa_i, m_{\rm H})$ in a benchmark parametrization, the final states $c\overline{c}$, $s\overline{s}$ 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:

$$\frac{\Gamma_{c\overline{c}}}{\Gamma_{c\overline{c}}^{SM}(m_{\rm H})} = \kappa_{\rm c}^2 = \kappa_{\rm t}^2$$
(28)

$$\frac{\Gamma_{\rm s\overline{s}}}{\Gamma_{\rm s\overline{s}}^{\rm SM}(m_{\rm H})} = \kappa_{\rm s}^2 = \kappa_{\rm b}^2$$
(29)

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\rm SM}_{\mu^-\mu^+}(m_{\rm H})} = \kappa_{\mu}^2 = \kappa_{\tau}^2$$
(30)

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

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

| | | | | | | | ILC TDR |
|--|------------------------|-----|------|---------|-----------------------|------------------------|------------------------|
| | | LHC | LHC | ILC TDR | ILC TDR | ILC TDR | +Lumi Upgr |
| | | 300 | 3000 | 250 | $\int dL \ 250 - 500$ | $\int dL \ 250 - 1000$ | $\int dL \ 250 - 1000$ |
| $\overline{\kappa(=\kappa_t=\kappa_b=\kappa_\tau)}$ | Common scale | | | | | | |
| $=\kappa_{_W}=\kappa_{_Z})$ | factor (= Δ_H) | | | | | | |
| | Boson and | | | | | | |
| $\kappa_{V}(=\kappa_{W}=\kappa_{Z})$ | fermion scale | | | | | | |
| $\underline{\kappa_t}(=\kappa_t=\kappa_b=\kappa_\tau)$ | factors | | | | | | |
| $\kappa_{VV}(=\kappa_V^2 / \kappa_H)$ | | | | | | | |
| $\lambda_{_{fV}} (= \kappa_{_f} / \kappa_{_V})$ | | | | | | | |
| | Custodial | | | | | | |
| K _Z | symmetry | | | | | | |
| $\lambda_{WZ} (= \kappa_Z / \kappa_W)$ | | | | | | | |
| $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$ | | | | | | | |
| $\kappa_{ZZ} (= \kappa_Z^2 / \kappa_H)$ | | | | | | | |
| $\lambda_{WZ} (= \kappa_Z / \kappa_W)$ | | | | | | | |
| $\lambda_{fZ} (= \kappa_f / \kappa_Z)$ | | | | | | | |

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

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

| | | | | | | | ILC TDR |
|---|---------------------|-----|------|---------|-----------------------|------------------------|------------------------|
| | | LHC | LHC | ILC TDR | ILC TDR | ILC TDR | +Lumi Upgr |
| | | 300 | 3000 | 250 | $\int dL \ 250 - 500$ | $\int dL \ 250 - 1000$ | $\int dL \ 250 - 1000$ |
| | Loop | | | | | | |
| ĸ _g | structure | | | | | | |
| κ _γ | | | | | | | |
| К _g | | | | | | | |
| κ_{γ} | | | | | | | |
| BR _{inv,undet} | | | | | | | |
| | Loop | | | | | | |
| K _g | structure | | | | | | |
| κ _γ | with floating | | | | | | |
| $\kappa_V (= \kappa_W = \kappa_Z)$ | boson and | | | | | | |
| $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$ | fermion κ 's | | | | | | |
| $\kappa_{gV}(=\kappa_g\bullet\kappa_V/\kappa_H)$ | | | | | | | |
| $\lambda_{Vg}(=\kappa_V / \kappa_g)$ | | | | | | | |
| $\lambda_{\gamma V} (= \kappa_{\gamma} / \kappa_{V})$ | | | | | | | |
| $\lambda_{fV} (= \kappa_f / \kappa_V)$ | | | | | | | |

| | | | | | | | ILC TDR |
|---|------------------|-----|------|---------|-----------------------|------------------------|----------------------|
| | | LHC | LHC | ILC TDR | ILC TDR | ILC TDR | +Lumi Upgr |
| | | 300 | 3000 | 250 | $\int dL \ 250 - 500$ | ∫ <i>dL</i> 250 – 1000 | ∫ <i>dL</i> 250–1000 |
| | Most general | | | | | | |
| $\kappa_{gZ} (= \kappa_g \cdot \kappa_Z / \kappa_H)$ | parameterization | | | | | | |
| $\lambda_{\gamma Z} (= \kappa_{\gamma} / \kappa_{Z})$ | in | | | | | | |
| $\lambda_{_{WZ}}(=\kappa_{_W}/\kappa_{_Z})$ | arXiv:1209.0040 | | | | | | |
| $\lambda_{bZ} (= \kappa_b / \kappa_Z)$ | | | | | | | |
| $\lambda_{tZ} (= \kappa_t / \kappa_Z)$ | | | | | | | |
| $\lambda_{Zg} (= \kappa_Z / \kappa_g)$ | | | | | | | |
| $\lambda_{tg}(=\kappa_t / \kappa_g)$ | | | | | | | |

| | | | | | | | ILC TDR |
|-----------------------|----------------------|-----|------|---------|-----------------------|------------------------|------------------------|
| | | LHC | LHC | ILC TDR | ILC TDR | ILC TDR | +Lumi Upgr |
| | | 300 | 3000 | 250 | $\int dL \ 250 - 500$ | $\int dL \ 250 - 1000$ | $\int dL \ 250 - 1000$ |
| | Model independent | | | | | | |
| κ _b | coupling | | | | | | |
| κ _w | determination | | | | | | |
| Kg | in κ notation | | | | | | |
| K_{τ} | | | | | | | |
| K _c | | | | | | | |
| κ _z | | | | | | | |
| K_{γ} | | | | | | | |
| $\kappa_{(\gamma Z)}$ | | | | | | | |
| κ_{μ} | | | | | | | |
| $BR_{inv,undet}$ | | | | | | | |
| κ _t | | | | | | | |
| $\kappa_{(HHH)}$ | | | | | | | |
| K | | | | | | | |

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| | | | |

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.

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|----|------|---|----|
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| | | | |

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 | 5 | | Baseline | 1st Stage | L Upgrade | TeV U A | pgrade B |
|--------------------------------------|---------------------|--|---------------------|------------------------|-----------|------------|-------------|
| Centre-of-mass energy | E_{CM} | ${\rm GeV}$ | 500 | 250 | 500 | 1000 | 1000 |
| Collision rate | frep | Hz | 5 | 5 | 5 | 4 | 4 |
| Electron linac rate | flinac | 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) | eta_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 | $\times 10^{34} \mathrm{~cm}^{-2} \mathrm{s}^{-2}$ | -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 |
| 14 March, 2013 | | | 500 GeV Baseline | Initial 'Hig Factor | gg's y | 22 | |



- Concept: increase n_b from
 - Reduce linac bunch spacing
 - Increase pulse current
 - Increase number of klystrons by

- $\begin{array}{c} 1312 \rightarrow 2625 \\ \textbf{554 ns} \rightarrow \textbf{336 ns} \\ \textbf{5.8} \rightarrow \textbf{8.8 mA} \\ \textbf{\sim50\%} \end{array}$
- Doubles beam power $\rightarrow \times 2 L (3.6 \times 10^{34} \text{cm}^{-2} \text{s}^{-1})$
- Damping ring:

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- Electron ring doubles current ($389mA \rightarrow 778mA$)
- Positron ring: possible 2nd (stacked) ring (e-cloud limit)
- AC power: 161 MW \rightarrow 204 MW (est.)
 - AC power increased by ×1.5
 - shorter fill time and longer beam pulse results in higher RFbeam efficiency (44% → 61%)

Staging and Upgrades:

ilr



ILC at low/high Ecm

• Low E_{cm} operation of upgraded ILC:

- L₂₅₀ ~ 3e34; Wall plug 200 MW
- Higgs Factory Option
- High E_{cm} ~ 1.5 TeV

- L₁₅₀₀ ~ 6e34; Wall plug 340 MW

Assumes 2x improved efficiency; 2450 bunches



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

| Ecm(GeV) | ILC | ILC | ILC |
|----------|---------------------|-------------|-------------|
| | TDR Baseline | Lum Upgrade | 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
 - Additional 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.