The Littlest Higgs boson at a photon collider

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Based on:
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The Higgs is produced via the loop-induced $\gamma\gamma H$ coupling. 
→ Sensitive to new physics running in the loop.

Expected precisions: $\gamma\gamma \rightarrow H \rightarrow XX$

<table>
<thead>
<tr>
<th>Expt.</th>
<th>$M_H$</th>
<th>$bb$</th>
<th>$WW^*$</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLICHE</td>
<td>115</td>
<td>2%</td>
<td>5%</td>
<td>22%</td>
</tr>
<tr>
<td>NLC</td>
<td>120</td>
<td>2.9%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TESLA</td>
<td>120</td>
<td>1.7–2%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>1.8%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>2.1%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

• Rate for $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ can be measured to about 2% for $115 \text{ GeV} \leq M_H \lesssim 140 \text{ GeV}$.
• $b\bar{b}$ will be the best-measured decay mode for this Higgs mass range in $\gamma\gamma$ collisions.
• Compare LHC or LC: $\Gamma_\gamma$ to 15–20%.
\[ \gamma \gamma \to H \text{ in the Standard Model and beyond} \]

\[ \gamma \gamma \to H \text{ comes from the gauge-invariant dim-6 operator} \]

\[ \mathcal{L} = \frac{C}{\Lambda^2} H^T H F_{\mu \nu} F^{\mu \nu} \]

induced by \( W \) boson and top quark loops in the SM.

Taking \( C = e^2/16\pi^2 \) (electromagnetic, loop-induced), \( M_H = 115 \) GeV and \( \Gamma_\gamma^{SM} \) calculated using HDECAY, we find \( \Lambda_{SM} \simeq 170 \) GeV. Right scale for \( W \) and \( t \) loops.

How high a \( \Lambda_{\text{new}} \) can be probed with a 2% measurement of \( \gamma \gamma \to H? \]

\[ \frac{C}{\Lambda^2} \longrightarrow \frac{C_{SM}}{\Lambda_{SM}^2} + \frac{C_{\text{new}}}{\Lambda_{\text{new}}^2} \]

If \( C_{\text{new}} = C_{SM} \)

(weakly coupled new physics): \( \Lambda_{\text{new}} = 1.2 \text{ TeV}, \ 0.74 \text{ TeV} \)

If \( C_{\text{new}} = 1 \)

(strongly coupled new physics): \( \Lambda_{\text{new}} = 48 \text{ TeV}, \ 31 \text{ TeV} \)
The little Higgs models are a new approach to stabilize the weak scale against radiative corrections, thereby solving the naturalness problem of a light Higgs boson.

**New particles** at the TeV scale cancel off the SM quadratic divergence of the Higgs mass from top, gauge and Higgs loops.

- Higgs is a pseudo-Goldstone boson from global symmetry breaking at scale \( \Lambda \sim 4\pi f \sim 10 - 30 \text{ TeV} \);
- Quadratic divergences cancelled at one-loop level by new states \( M \sim gf \sim 1 - 3 \text{ TeV} \);
- Higgs acquires a mass radiatively at the EW scale \( v \sim \frac{g^2 f}{4\pi} \sim 100 - 300 \text{ GeV} \).
The Littlest Higgs model is a nonlinear sigma model broken by a condensate $f \sim \text{TeV}$.

**Global symmetry:** $\text{SU}(5) \rightarrow \text{SO}(5)$
Nonlinear sigma model field $\Sigma$ ($5 \times 5$) contains $H$ (plus extra scalars). $H$ is a Nambu-Goldstone boson of the global symmetry breaking.

**Gauge symmetry:** $[\text{SU}(2)]^2 \times [\text{U}(1)]^2 \rightarrow \text{SU}(2)_L \times \text{U}(1)_Y$
Embedded in the $\text{SU}(5)$ global symmetry $\rightarrow$ Explicitly breaks global symmetry; makes $H$ a pseudo-Nambu-Goldstone boson.

**Yukawa interactions:** Extra $\text{SU}(2)$-singlet vector-like pair of quarks $T, \bar{T}$ added to top sector.
$\rightarrow$ Explicitly breaks global symmetry; makes $H$ a pseudo-Nambu-Goldstone boson.
The Littlest Higgs model, continued

New particle content at the TeV scale:
\( Z_H, W_H^\pm \) – SU(2) triplet of gauge bosons from the breaking \([SU(2)]^2 \rightarrow SU(2)_L\). Cancels the Higgs mass divergence from \( W^\pm, W^3 \).
\( T \) – vectorlike charge-2/3 quark. Cancels the Higgs mass divergence from the top quark.
\( \Phi^{0,+,++} \) – SU(2) triplet of scalars. Cancels the Higgs mass divergence from the Higgs self-interaction.
\( A_H \) – U(1) gauge boson from the breaking \([U(1)]^2 \rightarrow U(1)_Y\). Cancels the Higgs mass divergence from \( B_Y \). [EW precision favors only one \( U(1) \rightarrow \) no \( A_H \) particle]

Model parameters:
\( f \) – new physics scale \( \sim \) TeV
\( c \) – SU(2)\(_{1,2}\) gauge boson mixing angle \([Z_H, W_H^\pm]\)
\( c_t \) – top sector parameter \([T]\)
\( x \) – Higgs sector parameter (controls \( \Phi \) vev)
\( c' \) – U(1)\(_{1,2}\) gauge boson mixing angle [EW precision favors only one \( U(1) \rightarrow c' = 1/\sqrt{2} \)]
Corrections to $\gamma\gamma \rightarrow H$ in the Littlest Higgs model

- $\gamma\gamma \rightarrow H$ is loop induced: TeV-scale charged particles $W^\pm_H$, $T$, $\Phi^\pm$, $\Phi^{\pm\pm}$ can run in the loops.

- Higgs couplings to SM particles are modified due to mixing between SM and TeV-scale particles and corrections to SM parameters.

Accessible range found by scanning over model parameters. Corrections are of order $v^2/f^2$.

**(bug fixed in code)**
Higgs decays in the Littlest Higgs model

Corrections to Higgs decays all $\mathcal{O}(v^2/f^2)$:

$$\frac{\text{Rate}}{\text{SM}} = 1 + \frac{v^2}{f^2} \text{fn}(x, x^2, c_t^2) + a \frac{M_W^2}{M_{Z_H}^2} + b \frac{M_W^2}{M_{A_H}^2}$$

- Corrections about the same size in each channel.
- Best channel from experimental side: $H \rightarrow b\bar{b}$.

Model parameters:
- $f$ – new physics scale $\sim$ TeV
- $c \leftrightarrow M_{Z_H} - \text{SU(2)}_{1,2}$ gauge boson mixing angle $[Z_H, W^{\pm}_H]$
- $c_t$ – top sector parameter $[T]$
- $x$ – Higgs sector parameter (controls $\Phi$ vev)
- $c' \leftrightarrow M_{A_H} - \text{U(1)}_{1,2}$ gauge boson mixing angle $[\text{one U(1)} \rightarrow c' = 1/\sqrt{2}]$

![Graph showing rate of $\gamma H \rightarrow b\bar{b}$ as a function of $c$ for $x = 0.9, 0, 0.5$]
Using $\gamma \gamma \to H \to b \bar{b}$ to probe the Littlest Higgs

$\rightarrow$ Test the model: probe $\Lambda_{new} \sim 1 - 3$ TeV.

$\rightarrow$ Search for strongly-coupled UV completion:
  probe $\Lambda_{new} \sim 10-30$ TeV.

- A strongly coupled UV completion should affect $\gamma \gamma \to H$ at the same level as the TeV-scale weakly-coupled new physics.

- A weakly coupled UV completion should affect $\gamma \gamma \to H$ at $\sim v^2/\Lambda^2$ compared to the SM coupling: too small to observe.

Must predict the rate $R = R_{SM} + R_{LH}$ for $\gamma \gamma \to H \to b \bar{b}$ with precision comparable to the 2% photon collider expt uncertainty.

We therefore compute how well each model parameter must be measured (at the LHC) in order to contribute no more than 1% uncertainty to $R$ (i.e., $|\delta R/R_{SM}| \leq 1$).

Since $R_{LH}/R_{SM} \sim \mathcal{O}(10\%)$, only need to compute $R_{LH}$ to $\sim 10\%$. Feasible with hadron collider data.
Input precisions: $c_t$

Sensitivity comes from: $t$ coupling to Higgs, $T$ loop.

Measure $c_t$ from the $Wb \rightarrow T$ cross section:

$$\left( c_t^2 = 0.8, 0.5, 0.2 \right)$$

or extract from $T$ mass:

$$M_T = m_t f / v s_t c_t$$

Not sensitive to $c_t$ at a significant level.
→ Don’t need a measurement of this parameter.
Input precisions: $x$

Sensitivity comes from: $H-\Phi^0$ mixing, corrections to EW inputs $(M_W, M_Z, G_F)$, $\Phi^+\Phi^-$ loop.

Need to measure $x$ at low $f$.

- Triplet scalar sector:
  \[ M_{\Phi} = \sqrt{2} M_H f / v \sqrt{1 - x^2} \]
  \[ W^+W^+ \to \Phi^{++} \to W^+W^+ \propto x^2 \]
  Unfortunately $\Phi$ prod. too small!

- Shift in $M_W$:
  Current $\delta M_W = 39$ MeV good enough except for $x \lesssim 0.05$ for $f = 1$ TeV.
  Tev Run II: 30 MeV, LHC: 15 MeV.
Input precisions: $M_{ZH}$ and $M_{AH}$

Trade $c \rightarrow M_{ZH}$, $c' \rightarrow M_{AH}$: more easily measured (dileptons).

$$M_{ZH} = M_{WH} = g f / 2 s c,$$

$$M_{AH} = g' f / 2 \sqrt{5} s' c'$$

Sensitivity comes from:

- $M_{ZH}$: corrections to EW inputs ($M_W$, $M_Z$, $G_F$), $W^\pm_H$ in loop.
- $M_{AH}$: corrections to EW inputs ($M_Z$, $G_F$).

EW precision data: $M_{ZH} \gtrsim 2$ TeV.

If model contains $A_H$ (disfavored by EW prec.):

- $\delta R / R_{SM} = 1\%$
Input precisions: $f$

Overall scale parameter: new effects go like $v^2/f^2$.

EW precision constraints: $f \gtrsim 1$ TeV $\rightarrow$ want $\gtrsim 7\%$ precision.
Input precisions: $f$, continued

Extract $f$ from $M_{ZH} = gf/2sc$ and $pp \to Z_H$ cross section $\propto c^2/s^2$.

Three benchmark points:
1. $M_{ZH} = 2$ TeV, $\cot \theta = 0.2$
2. $M_{ZH} = 2$ TeV, $\cot \theta = 0.5$
3. $M_{ZH} = 4$ TeV, $\cot \theta = 0.2$

- Uncertainty on $M_{ZH}$ from dilepton mass reconstruction.
- Uncertainty on cross section from statistics: $\delta \sigma/\sigma = 1/\sqrt{N_S}$. 
**Input precisions: \( f \), continued**

\[
\delta M_{ZH} = 0, \ 2\%, \ 4\%.
\]

<table>
<thead>
<tr>
<th>Point</th>
<th>( f ) (GeV)</th>
<th>Statistical uncert. on ( \sigma \times \text{BR}(ee) )</th>
<th>( \delta f / f ) (( \delta M_{ZH} )) (0%) (2%) (4%)</th>
<th>Desired ( \delta f / f ) (no ( A_H )/with ( A_H ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1180</td>
<td>13% (59 evts)</td>
<td>2% (2%) (4%)</td>
<td>10% / 12%</td>
</tr>
<tr>
<td>2</td>
<td>2454</td>
<td>2.0% (2380 evts)</td>
<td>0.5% (5%) (9%)</td>
<td>43% / 49%</td>
</tr>
<tr>
<td>3</td>
<td>2360</td>
<td>− (0.8 evts)</td>
<td>−</td>
<td>40% / 45%</td>
</tr>
</tbody>
</table>

\( M_{ZH} = 2 \text{ TeV} \)

\( \cot \theta = 0.2 \)

\( 300 \text{ fb}^{-1} \)

\( M_{ZH} = 2 \text{ TeV} \)

\( \cot \theta = 0.5 \)

\( 300 \text{ fb}^{-1} \)
Other uncertainties: parameter extraction

Parameter extraction from LHC data looks good in most of parameter space. But there are other sources of uncertainty:

- Higher order terms in NL$\Sigma$M $v^2/f^2$ expansion for $c, c' \leftrightarrow M_{Z_H}, M_{A_H}$: Few-percent; straightforward to include (thy)

- $Z_H$ cross section:
  - QCD corrections to Drell-Yan: NLO K-factor $\sim 1.4$; differential NNLO calc done: under control
  - LHC lumi uncertainty $\sim 5\%$: small enough

- $Z_H$ mass measurement: $\sim 4\%$ wanted
  - Electroweak radiative corrections to $M_{Z_H} \leftrightarrow$ model params: more work needed! (thy)
  - TeV-momentum leptons at LHC: good energy resolution and energy scale calibration needed: apparently not yet studied! (expt)
Other uncertainties: Photon collider issues

How solid is the 2% measurement of the rate for $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$?

- $\gamma\gamma$ luminosity and polarization spectra must be measured to normalize the cross section. $\gamma\gamma \rightarrow e^+e^-$ (and $e^+e^-\gamma$?) for lumi spectrum; $e\gamma \rightarrow e\gamma$, $e\gamma \rightarrow W\nu$ for pol spectrum: further study needed! (expt)

- "Resolved photons": photon has a PDF containing quarks, gluons, etc. $\rightarrow$ Higgs production via gluon fusion, $b\bar{b}$ fusion: part of cross section not due to $\Gamma_\gamma$; also $e^-e^- \rightarrow \nu\nu H$: quantitative estimate needed (thy)

- Background normalization must be under control to subtract from signal: what is BG uncertainty? Can it be measured? (expt)
Other uncertainties: SM Higgs coupling calculation

To detect a new-physics effect, we need solid control of the SM prediction:

→ Need to calculate $R_{SM}$ at the 1% level.

- Radiative corrections to $\gamma\gamma \rightarrow H$
  - QCD: NLO $\sim 2\%$, NNLO negligible: under control.
  - Electroweak: light-fermion loops $\sim -(1-2)\%$; 3rd-gen loops $\mathcal{O}(G_F m_t^2) \sim -2.5\%$: under control? at the 1–2% level (thy)

- Radiative corrections to $\text{BR}(H \rightarrow b\bar{b})$
  - $H \rightarrow b\bar{b}$ QCD, EW corrections under control
  - $H \rightarrow WW, ZZ$ offshell effects, EW and QCD corrections under control (though EW/QCD RCs $\lesssim 2\%$ not yet in HDECAY) (thy)

- Parametric uncertainty in $\text{BR}(H \rightarrow b\bar{b})$ from $m_b$ (and $\alpha_s$)
  - $m_b(m_b) = 4.17 \pm 0.05$ GeV (and $\alpha_s = 0.1185 \pm 0.0020$) give $\delta[\text{BR}(H \rightarrow b\bar{b})] \simeq 1.4\%$ for $M_H = 120$ GeV: lattice (thy) and CLEO bottomonium spectroscopy (expt) should improve $m_b$
Photon collider can measure $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ to 2% for $115 \text{ GeV} \leq M_H \lesssim 140 \text{ GeV}$.

$\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ can be reliably calculated from LHC data on model parameters in much of the Littlest Higgs model parameter space.

**Probe the UV completion at $\sim 10 \text{ TeV}$!**
- Strongly coupled UV completion contributes at same order as TeV-scale particles: $\sim$ several percent for $f \sim 1 - 3 \text{ TeV}$.
- Weakly coupled UV completion should not affect $\gamma\gamma \rightarrow H$ at an observable level: $\rightarrow$ Measurement is a test of model consistency.

**Work needed on both thy and expt sides:**
- TeV-scale dilepton invariant mass measurement
- Photon collider lumi/pol spectra measurements, resolved photon contribution to Higgs prod, $b\bar{b}$ background uncertainty
- SM Higgs coupling calculation $\rightarrow 1\%$ precision goal