The Littlest Higgs boson at a photon collider

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Based on:

T.Han, H.L., B.McElrath, L-T.Wang, PRD 67, 095004 (2003)

T.Han, H.L., B.McElrath, L-T.Wang, PLB 563, 191 (2003)

H.L., hep-ph/0405072

Higgs boson coupling to photons

The Higgs coupling to photons is loop-induced.

$\longrightarrow$ Sensitive to new physics running in the loop

How to measure the $\gamma\gamma H$ coupling:

- LHC: $H \to \gamma\gamma$ decays
$\longrightarrow$ measure ratios of partial widths (Γ_γ/Γ_W, $\Gamma_\gamma/\Gamma_\tau$) to $\sim 15\%$
$\longrightarrow$ extract absolute partial width to $\sim 20\%$ (some theory assumptions necessary)

- LC: $H \to \gamma\gamma$ decays
$\longrightarrow$ measure BR($H \to \gamma\gamma$) to 15–20% (limited by low statistics since BR is small)

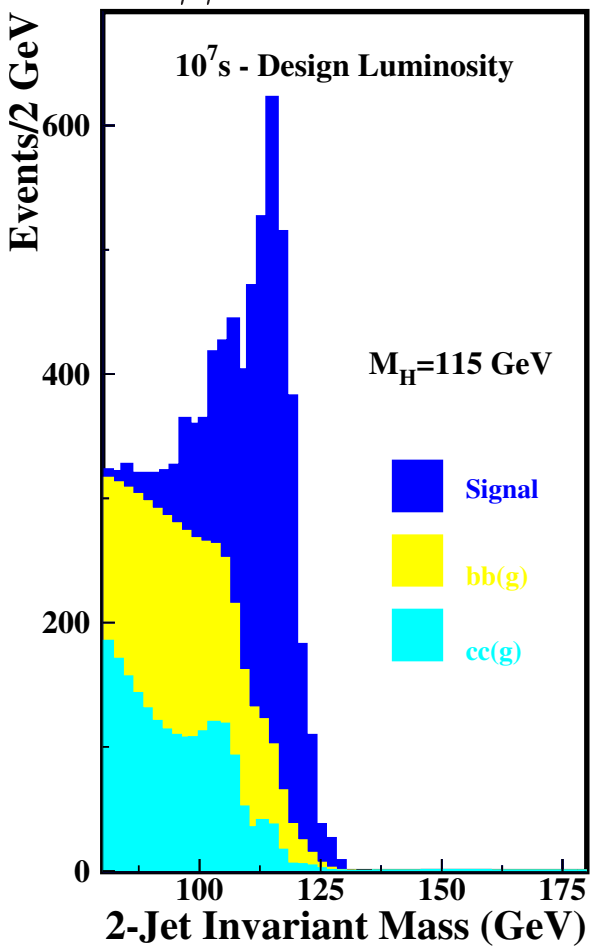
- Photon collider (next slide)

Higgs production at a photon collider

The Higgs boson is produced at a photon collider via the loop-induced $\gamma\gamma H$ coupling.

Asner et al, 2001

$\gamma\gamma \to H \to b\bar{b}$



Expected precisions:

Expt.	M_H	$b\bar{b}$	WW^*	$\gamma\gamma$
CLICHE	115	2%	5%	22%
NLC	120	2.9%	–	–
TESLA	120	1.7–2%	–	–

- Rate for $\gamma\gamma \to H \to b\bar{b}$ can be measured to about 2% for a 115-120 GeV Higgs.
- $b\bar{b}$ will be the best-measured decay mode for this Higgs mass in $\gamma\gamma$ collisions.

$\gamma\gamma \to H$ in the Standard Model and beyond

$\gamma\gamma \to H$ comes from the gauge-invariant dim-6 operator

$$\mathcal{L} = \frac{C}{\Lambda^2} H^\dagger H F_{\mu\nu} F^{\mu\nu}$$

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 Γ_γ^{SM} calculated using HDECAY, we find $\Lambda_{SM} \simeq 170$ GeV. Right scale for W and t loops.

How high a Λ_{new} can be probed with a 2% measurement of $\gamma\gamma \to H$?

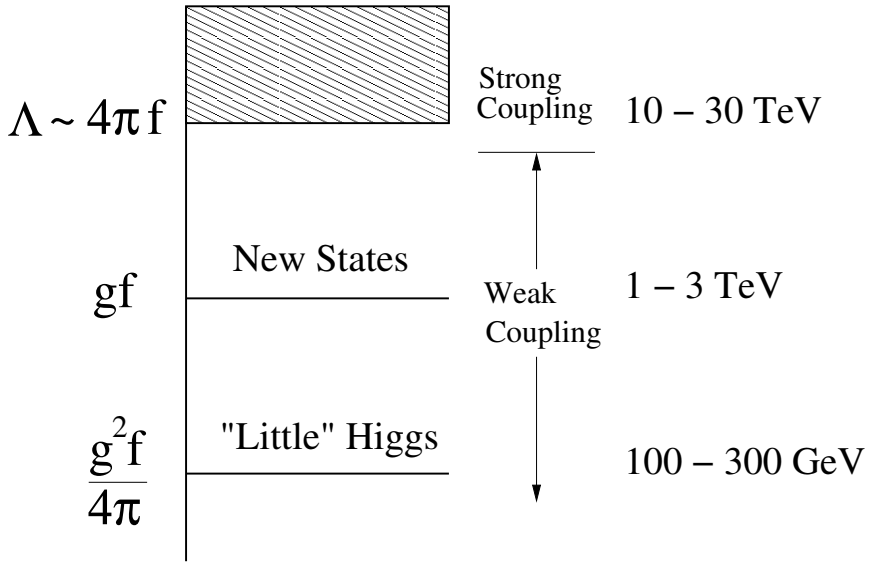
		95% CL,	5σ
If $C_{new} = C_{SM}$ (weakly coupled new physics):	$\Lambda_{new} =$	1.2 TeV,	0.74 TeV
If $C_{new} = 1$ (strongly coupled new physics):	$\Lambda_{new} =$	48 TeV,	31 TeV

The little Higgs models

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 $\Lambda \sim 4\pi f \sim 10 - 30$ TeV;
- Quadratic divergences cancelled at one-loop level by new states $M \sim gf \sim 1 - 3$ TeV;
- Higgs acquires a mass radiatively at the EW scale $v \sim g^2 f/4\pi \sim 100 - 300$ GeV.



The Littlest Higgs model

The Littlest Higgs model is a nonlinear sigma model broken by a condensate $f \sim$ TeV.

Global symmetry: SU(5) $\longrightarrow$ SO(5)
Nonlinear sigma model field Σ (5×5) contains H (plus extra scalars). H is a Nambu-Goldstone boson of the global symmetry breaking.

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

Yukawa interactions: Extra SU(2)-singlet vector-like pair of quarks T, $\bar{T}$ added to top sector.
$\longrightarrow$ 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 $[\mathrm{SU}(2)]^2 \to \mathrm{SU}(2)_L$. 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 $[\mathrm{U}(1)]^2 \to \mathrm{U}(1)_Y$. Cancels the Higgs mass divergence from B^Y. [EW precision favors only one U(1) $\to$ no A_H particle]

Model parameters:

f – new physics scale $\sim$ TeV

c – $\mathrm{SU}(2)_{1,2}$ gauge boson mixing angle [Z_H, $W_H^\pm$]

c_t – top sector parameter [T]

x – Higgs sector parameter (controls Φ vev)

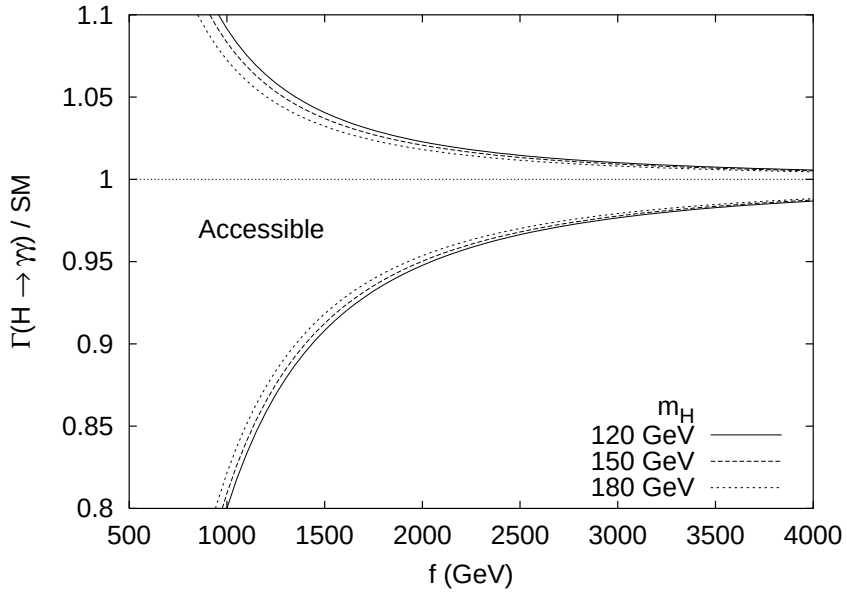
c' – $\mathrm{U}(1)_{1,2}$ gauge boson mixing angle [EW precision favors only one U(1) $\to c' = 1/\sqrt{2}$]

Corrections to $\gamma\gamma \to H$ in the Littlest Higgs model

- $\gamma\gamma \to H$ is loop induced: TeV-scale charged particles $W_H^{\pm}$, 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.

Han, Logan, McElrath, Wang '03



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

Corrections to Higgs partial widths

$$\Gamma_f/\Gamma_f^{\mathsf{SM}} = y_{G_F}^2 y_f^2, \qquad \Gamma_t/\Gamma_t^{\mathsf{SM}} = y_{G_F}^2 y_t^2$$

$$\Gamma_Z/\Gamma_Z^{\mathsf{SM}} = y_{G_F}^2 y_Z^2, \qquad \Gamma_W/\Gamma_W^{\mathsf{SM}} = y_{G_F}^2 y_W^2 \frac{y_{M_Z}^4}{y_{M_W}^4} y_{c_W}^4$$

$$\Gamma_\gamma/\Gamma_\gamma^{\mathsf{SM}} = y_{G_F}^2 \frac{\left|\sum_{i,\mathsf{LH}} y_i N_{ci} Q_i^2 F_i\right|^2}{\left|\sum_{i,\mathsf{SM}} N_{ci} Q_i^2 F_i\right|^2}, \qquad \Gamma_g/\Gamma_g^{\mathsf{SM}} = y_{G_F}^2 \frac{\left|\sum_{i,\mathsf{LH}} y_i F_{1/2}(\tau_i)\right|^2}{\left|\sum_{i,\mathsf{SM}} F_{1/2}(\tau_i)\right|^2}$$

Model with A_H:

$$\begin{aligned}
y_{G_F}^2 &= 1 + \frac{v^2}{f^2}\left[-\frac{5}{12} + \frac{1}{4}x^2\right] \\
y_f &= 1 + \frac{v^2}{f^2}\left[-\frac{2}{3} + \frac{1}{2}x - \frac{1}{4}x^2\right] \\
y_t &= 1 + \frac{v^2}{f^2}\left[-\frac{2}{3} + \frac{1}{2}x - \frac{1}{4}x^2 + c_t^2(1+c_t^2)\right] \\
y_Z &= 1 + \frac{v^2}{f^2}\left[-\frac{5}{3} + \frac{1}{4}x^2\right] + \frac{M_W^2}{M_{Z_H}^2} + \frac{s_W^2}{c_W^2}\frac{M_W^2}{M_{A_H}^2} \\
y_W &= 1 + \frac{v^2}{f^2}\left[\frac{7}{12} - x^2\right] - 3\frac{M_W^2}{M_{Z_H}^2} \\
y_{M_Z}^2 &= 1 + \frac{v^2}{f^2}\left[-\frac{5}{3} + \frac{1}{2}x^2\right] + \frac{M_W^2}{M_{Z_H}^2} + \frac{s_W^2}{c_W^2}\frac{M_W^2}{M_{A_H}^2}
\end{aligned}$$

$$
\begin{aligned}
y^2_{M_W} &= 1 + \frac{v^2}{f^2}\left[-\frac{5}{12} + \frac{1}{4}x^2\right] + \frac{M_W^2}{M_{Z_H}^2} \\
y^2_{c_W} &= 1 + \frac{v^2}{f^2}\frac{s_W^2}{c_W^2 - s_W^2}\left[-\frac{25}{12} + \frac{3}{4}x^2\right] + \frac{s_W^2}{c_W^2 - s_W^2}\left[\frac{M_W^2}{M_{Z_H}^2} + \frac{s_W^2}{c_W^2}\frac{M_W^2}{M_{A_H}^2}\right] \\
y_T &= -c_t^2(1 + c_t^2)\frac{v^2}{f^2} \\
y_{W_H} &= -\frac{M_W^2}{M_{Z_H}^2} \\
y_{\Phi^+} &= \frac{v^2}{f^2}\left[-\frac{1}{3} + \frac{1}{4}x^2\right] \\
y_{\Phi^{++}} &= 0
\end{aligned}
$$

Using the $\gamma\gamma H$ coupling to probe the Littlest Higgs

$\longrightarrow$ Probe for weakly-coupled new physics up to $\Lambda \sim$ TeV:
Test the Littlest Higgs model by seeing deviation in $\gamma\gamma H$ coupling.

$\longrightarrow$ Probe for strongly-coupled new physics up to $\Lambda \sim$ few $\times 10$ TeV:
Potential sensitivity to the UV completion of the Littlest Higgs model at the 10–30 TeV scale!

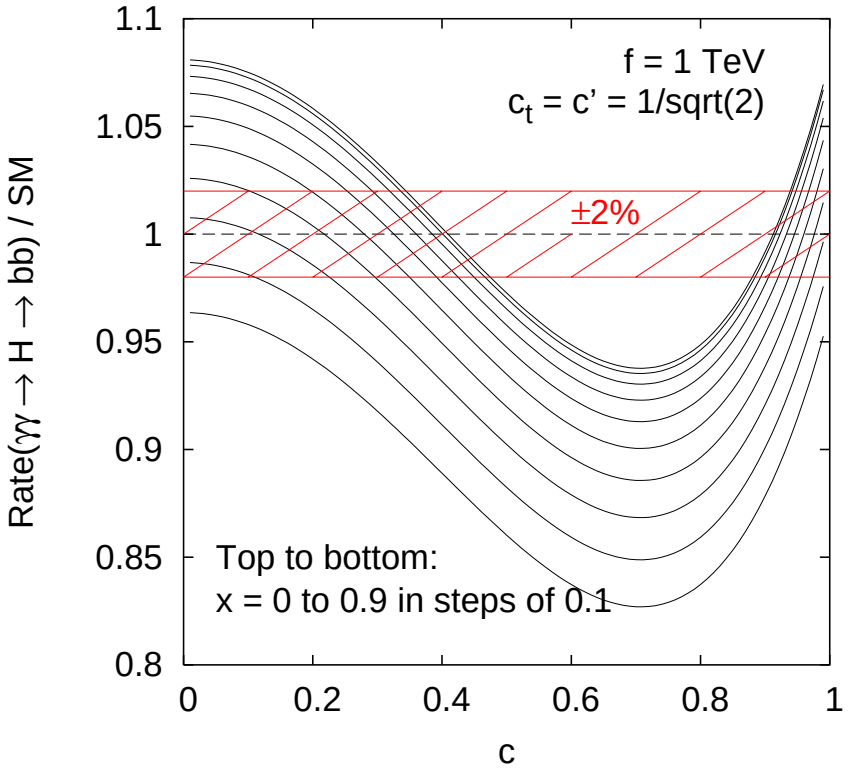
If the UV completion physics is strongly coupled, it should affect the $\gamma\gamma H$ coupling at the same level as the TeV-scale weakly-coupled new physics.

If the UV completion physics is weakly coupled, it should affect the $\gamma\gamma H$ coupling at a level suppressed by v^2/Λ^2 compared to the SM coupling; i.e., too small to be observable.

Higgs decays in the Littlest Higgs model

Corrections to Higgs decays [from mixing between SM and TeV-scale particles and corrections to couplings]: also $\mathcal{O}(v^2/f^2)$.

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



Model parameters:

f – new physics scale $\sim$ TeV

$c \leftrightarrow M_{Z_H}$ – SU(2)$_{1,2}$ gauge boson mixing angle [Z_H, $W_H^{\pm}$]

c_t – top sector parameter [T]

x – Higgs sector parameter (controls Φ vev)

$c' \leftrightarrow M_{A_H}$ – U(1)$_{1,2}$ gauge boson mixing angle [one U(1) $\to c' = 1/\sqrt{2}$]

Using $\gamma\gamma \to H \to b\bar{b}$ to probe the Littlest Higgs

What can be done with the $\gamma\gamma \to H \to b\bar{b}$ rate measurement?

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

$\longrightarrow$ Search for strongly-coupled UV completion:
probe $\Lambda_{new} \sim$ few$\times$10 TeV.

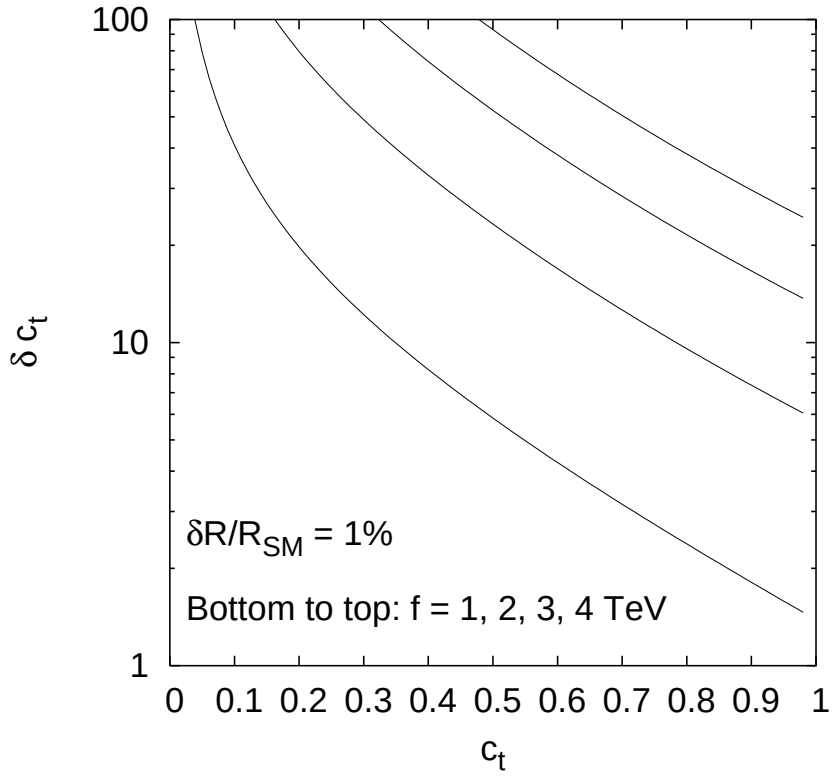
Must be able to predict the rate for $\gamma\gamma \to H \to b\bar{b}$, $R = R_{SM} + R_{LH}$, with a precision comparable to the photon collider experimental uncertainty of 2%.

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.

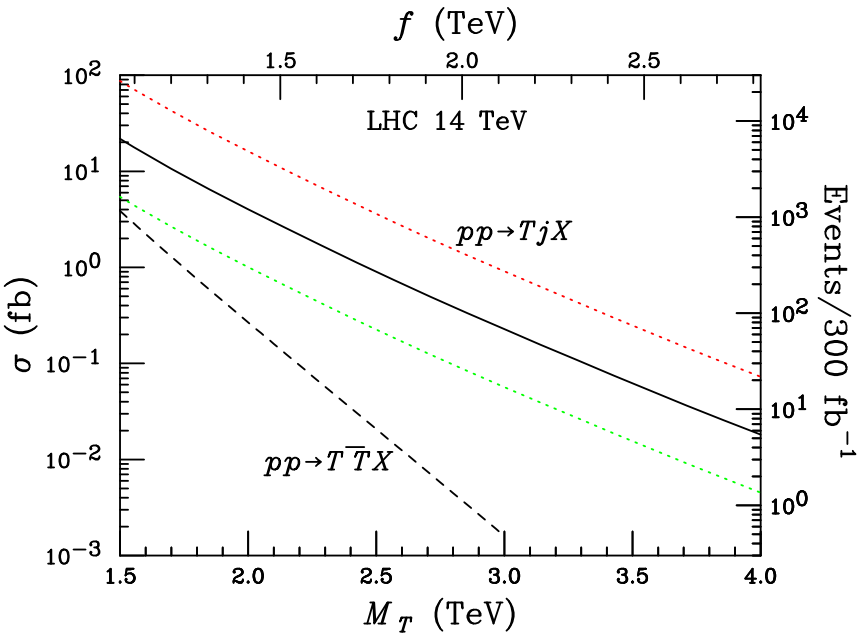


The $\gamma\gamma \to H \to b\bar{b}$ rate is not sensitive to c_t at a significant level.

$\to$ Don't need a measurement of this parameter.

Input precisions: c_t, continued

c_t can be measured from the $Wb \to T$ cross section:



$c_t^2 = 0.8,\ 0.5,\ 0.2$

or extracted from the T mass:

$$M_T = \frac{m_t f}{v s_t c_t}$$

Input precisions: x

Sensitivity comes from: H–Φ^0 mixing, corrections to EW inputs (M_W, M_Z, G_F), Φ^+ loop.

Ideal place to measure x is in the scalar triplet sector:

- Φ mass depends on x:

$$M_\Phi = \frac{\sqrt{2} M_H f}{v\sqrt{1-x^2}}$$

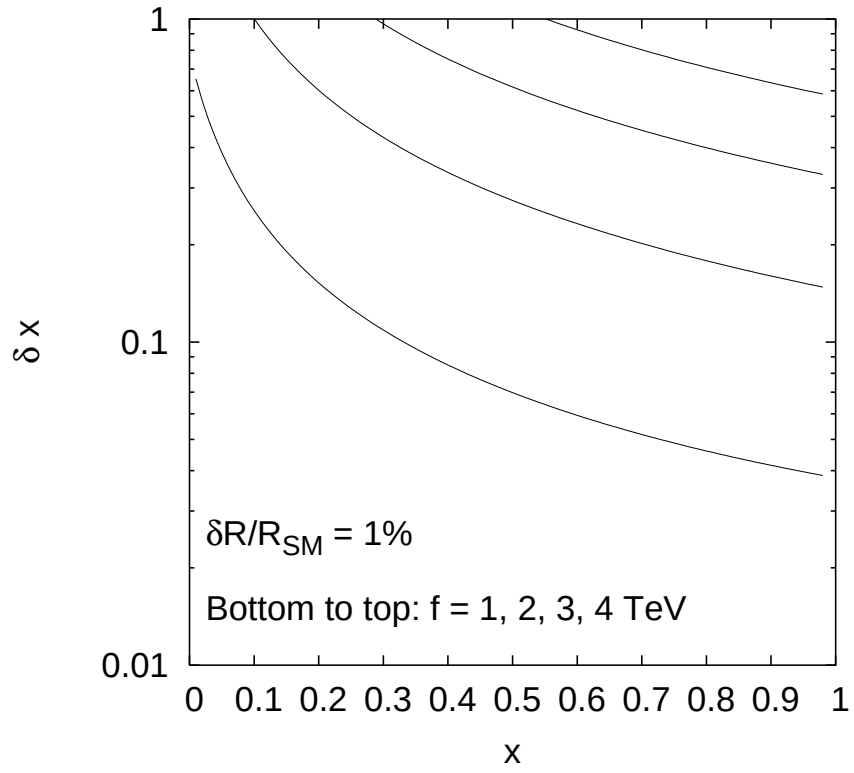
- Resonant $W^+W^+ \to \Phi^{++} \to W^+W^+$ scattering rate is proportional to x^2.

Unfortunately $W^+W^+ \to \Phi^{++} \to W^+W^+$ rate is too small (LHC) and Φ is too heavy for pair production to give a strong signal.

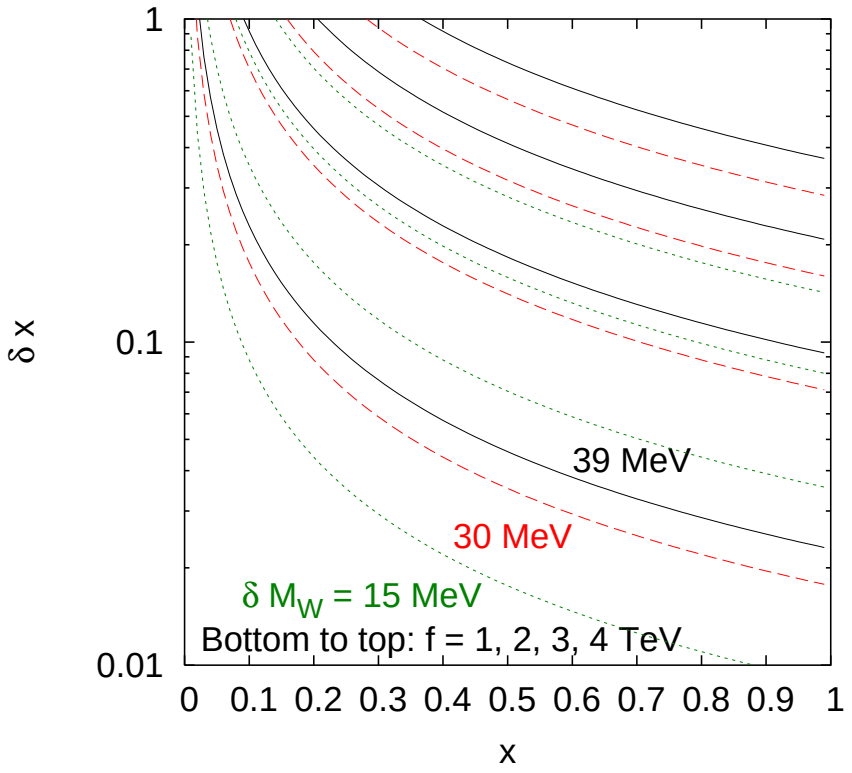
Input precisions: x, continued

If f, c and c' are known, then x can be extracted from M_W. Even the current $\delta M_W = 39$ MeV gives good enough precision on x (except for $x \lesssim 0.1$, $f = 1$ TeV).
[Tevatron Run II (2 fb^{-1}) goal: $\delta M_W = 30$ MeV; LHC 15 MeV.]

Precision wanted on x:



Precision on x from M_W measurement:



Input precisions: M_{Z_H} and M_{A_H}

Trade $c \to M_{Z_H}$, $c' \to M_{A_H}$: more easily measured.

$$M_{Z_H} = M_{W_H} = \frac{gf}{2sc}, \qquad M_{A_H} = \frac{g'f}{2\sqrt{5}s'c'}$$

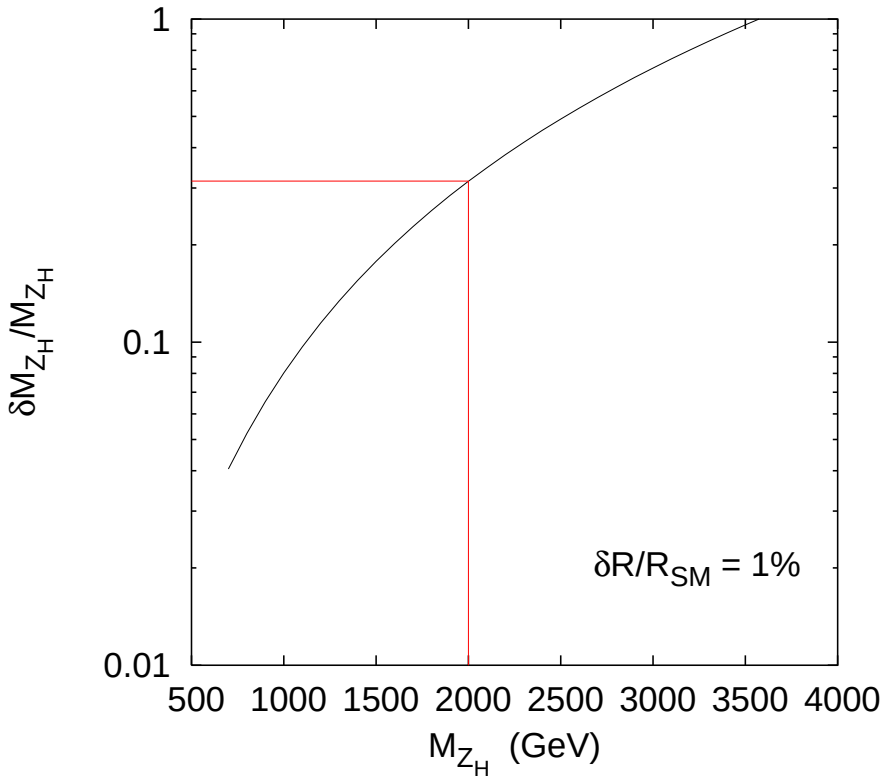
Sensitivity comes from:

M_{Z_H}: corrections to EW inputs (M_W, M_Z, G_F), $W_H^{\pm}$ in loop.

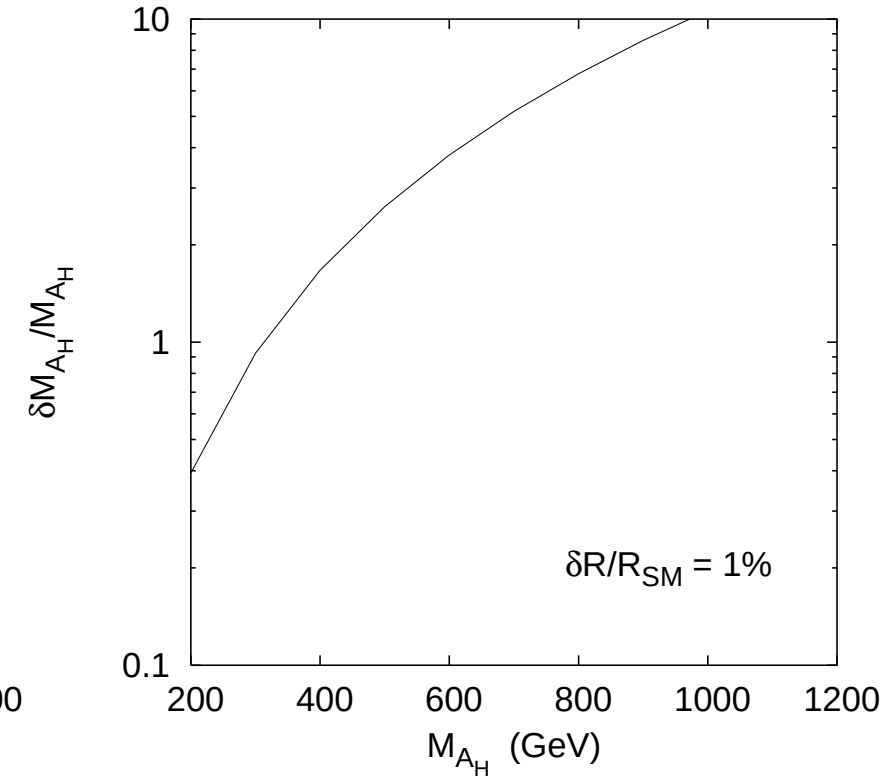
M_{A_H}: corrections to EW inputs (M_Z, G_F).

Input precisions: M_{Z_H} and M_{A_H}, continued

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



If model contains A_H
(disfavored by EW precision):

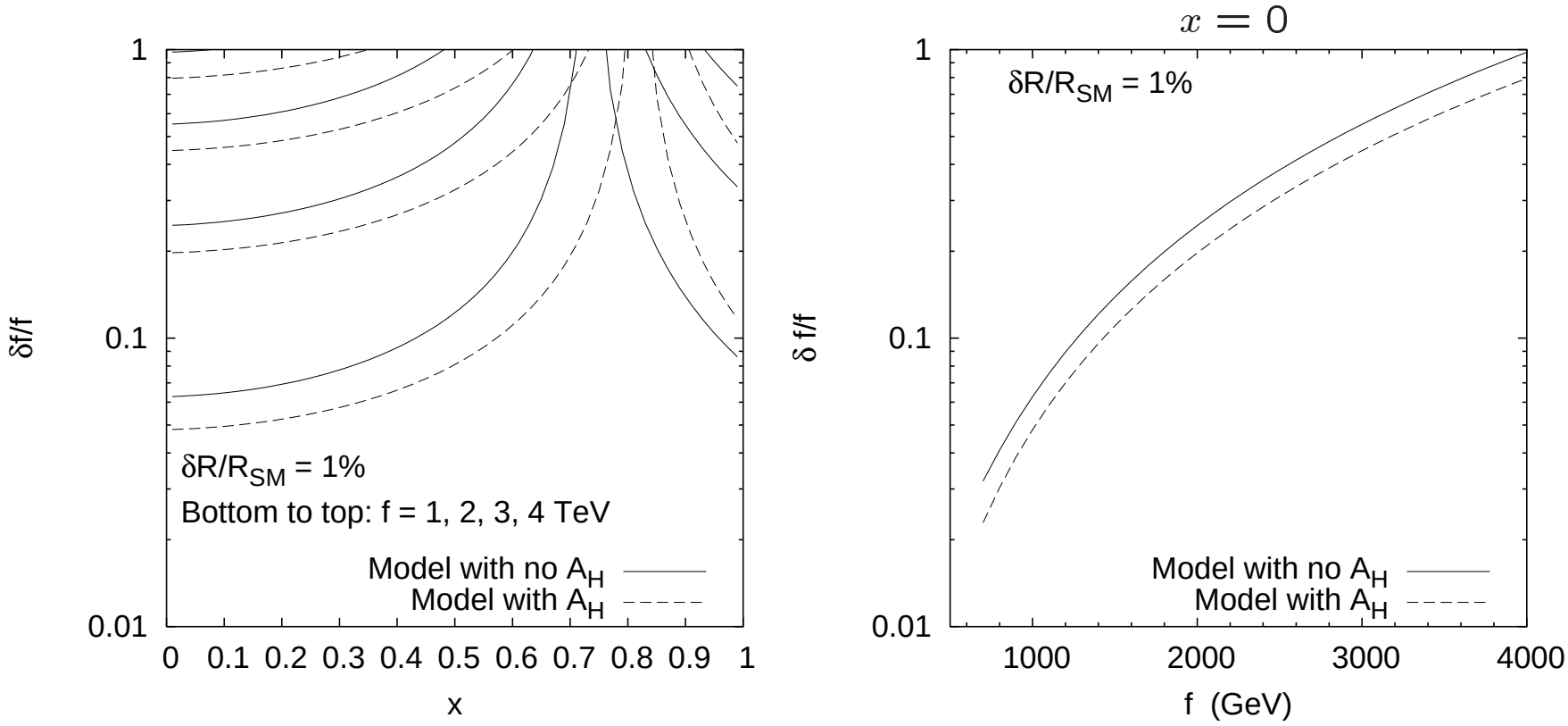


Measure Z_H $(A_H) \rightarrow$ dileptons.

Dilepton invariant mass resolution typically a few percent
$\rightarrow$ no problem.

Input precisions: f

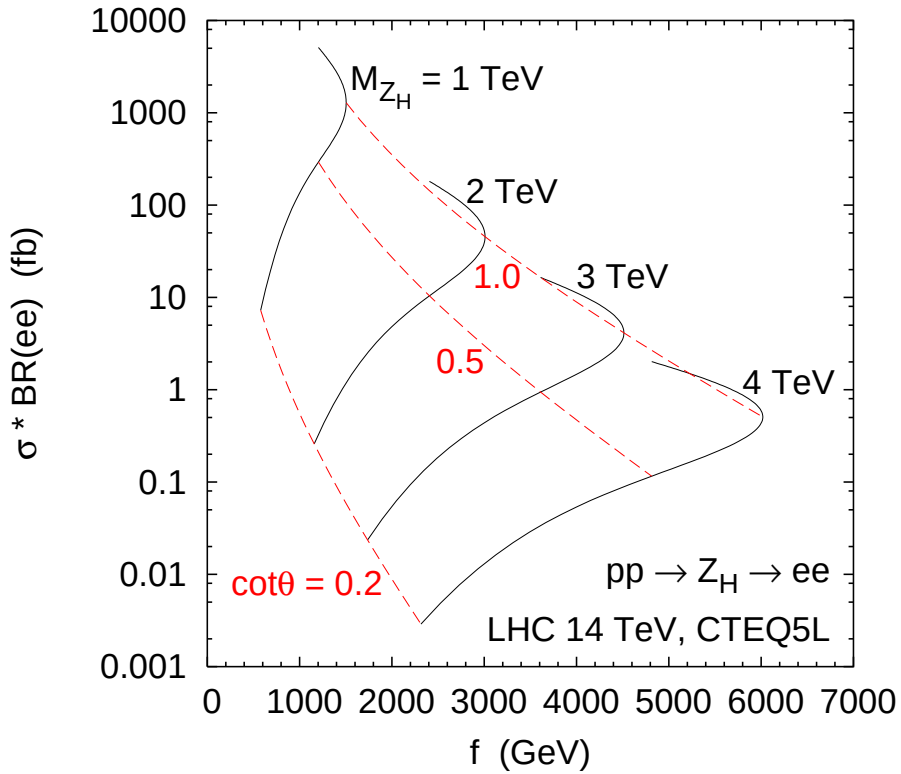
Overall scale parameter: new effects go like v^2/f^2.



EW precision constraints: $f \gtrsim 1$ TeV $\rightarrow$ want $\gtrsim 6\%$ precision.

Input precisions: f, continued

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



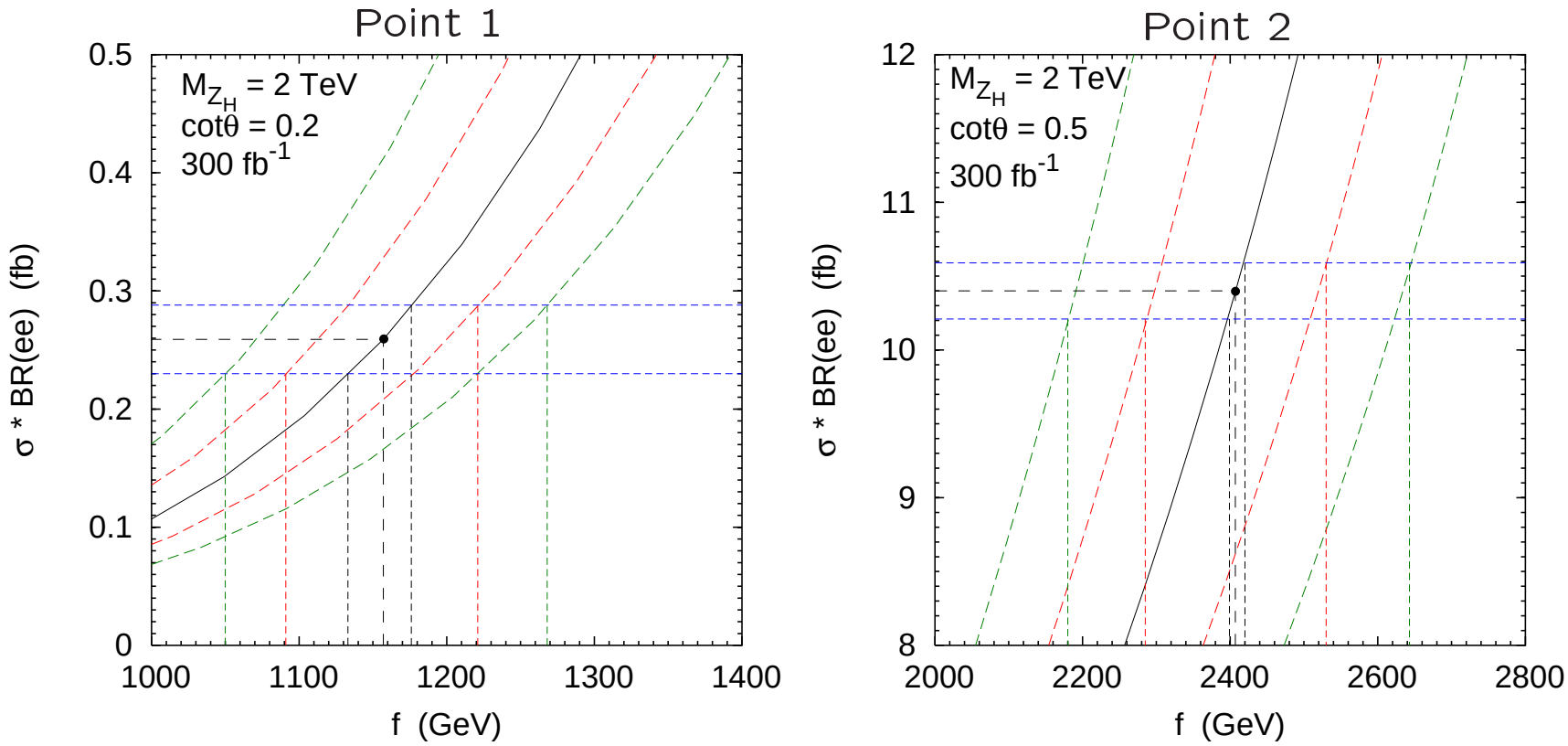
Three benchmark points:

1. $M_{Z_H} = 2$ TeV, $\cot\theta = 0.2$
2. $M_{Z_H} = 2$ TeV, $\cot\theta = 0.5$
3. $M_{Z_H} = 4$ TeV, $\cot\theta = 0.2$

Uncertainty on M_{Z_H} from dilepton mass reconstruction.

Uncertainty on cross section from statistics: $\delta\sigma/\sigma = 1/\sqrt{N_S}$.

Input precisions: f, continued



$\delta M_{Z_H} = 0$, 2%, 4%.

Point	f, GeV	Statistical uncert. on $\sigma \times$ BR(ee)	$\delta f/f$ (δM_{Z_H}) (0%)	(2%)	(4%)	Desired $\delta f/f$ (no A_H/with A_H)
1	1157	11% (78 evts)	2%	6%	10%	8.3%/6.5%
2	2407	1.8% (3120 evts)	0.5%	5%	10%	36%/29%
3	2315	– (0.9 evts)	–	–	–	33%/27%

Other Little Higgs parameter uncertainties

Rate for $\gamma\gamma \to H \to b\bar{b}$ in the Littlest Higgs model can be reliably calculated from LHC data on model parameters in a large part of the parameter space.

Are there other sources of uncertainty in the LH parameter extraction?

• We used leading-order relation between c, c' and M_{Z_H}, M_{A_H} in NLΣM v^2/f^2 expansion. Higher order terms straightforward to include; effects down by $v^2/f^2 \sim$ few percent; not very significant.

• Extraction of f depends on Z_H cross section measurement: must include QCD corrections to $pp \to Z_H \to \ell\ell$. NLO calc 25 years ago, $K_{DY} \sim 1.4$. How well is this known?

More uncertainties: Photon collider issues

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

• Background normalization must be under control to subtract from signal.

• $\gamma\gamma$ luminosity and polarization spectra must be measured to normalize the cross section.

• "Resolved photons": photon has a PDF containing quarks, gluons, etc. Resolved photon collisions give Higgs production via gluon fusion, $b\bar{b}$ fusion $\longrightarrow$ some (small) part of cross section is not due to Γ_γ.

These are under investigation.

More uncertainties: SM Higgs coupling calculation

To detect a new-physics effect, we need solid control of the SM prediction:
$\longrightarrow$ Need to calculate R_{SM} at the 1% level.

• 2-loop (=NLO) EW corrections to $\gamma\gamma H$ calculated last week (hep-ph/0405232): correction $\sim -2.5\%$, largely cancels known $\mathcal{O}(\alpha_s)$ correction.

• Parametric uncertainty in BR($H \to b\bar{b}$) from m_b, α_s:
$\alpha_s = 0.1185 \pm 0.0020$, $m_b(m_b) = 4.17 \pm 0.05$ GeV
$\longrightarrow \delta[\mathrm{BR}(H \to b\bar{b})] \simeq 1.4\%$ for $M_H = 120$ GeV.
Large BR suppresses uncertainty.
Other sources (QCD?) under investigation.

Summary

Photon collider can measure Rate($\gamma\gamma \to H \to b\bar{b}$) to 2% for $m_H = 115$–120 GeV.

Rate($\gamma\gamma \to H \to b\bar{b}$) in the Littlest Higgs model can be reliably calculated from LHC data on model parameters in a large part of the parameter space.

Probe the UV completion at ~ 10 TeV!

- A strongly coupled UV completion contributes at the same order as the TeV-scale particles:
  $\sim$ several percent for $f \sim 1 - 3$ TeV.

- A weakly coupled UV completion should not affect $\gamma\gamma \to H$ at an observable level:
  $\to$ Measurement is a test of model consistency.