The Littlest Higgs boson at a photon collider

Heather Logan
(University of Wisconsin, Madison)

Victoria Linear Collider Workshop
July 28-31, 2004

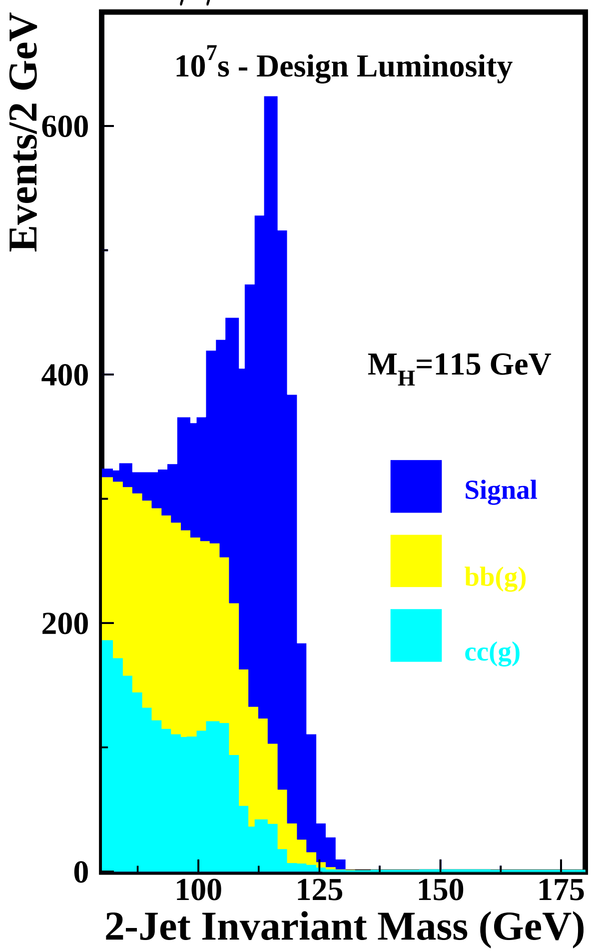
Based on:
T.Han, H.L., B.McElrath, L-T.Wang, PRD 67, 095004 (2003)
T.Han, H.L., B.McElrath, L-T.Wang, PLB 563, 191 (2003)
H.L., hep-ph/0405072

Higgs production at a photon collider

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

Asner et al, 2001

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



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

Expt.	M_H	$b\bar{b}$	WW^*	$\gamma\gamma$
CLICHE	115	2%	5%	22%
NLC	120	2.9%	–	–
TESLA	120	1.7–2%	–	–
	130	1.8%	–	–
	140	2.1%	–	–

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

$\gamma\gamma \to H$ 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 $\gamma\gamma \to H$?

$$C/\Lambda^2 \longrightarrow C_{SM}/\Lambda_{SM}^2 + C_{new}/\Lambda_{new}^2$$

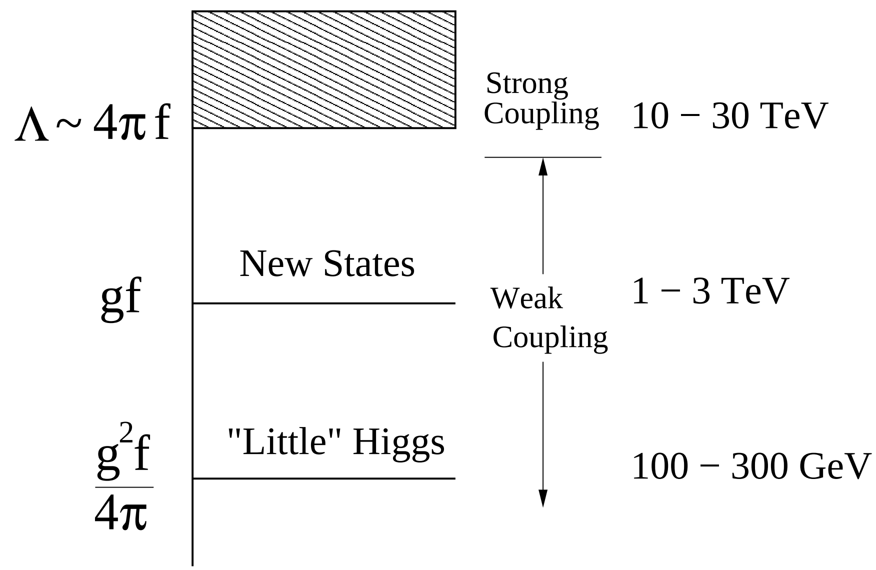
		95% CL,	5σ
If $C_{new} = C_{SM}$ (weakly coupled new physics):	$\Lambda_{new} =$	1.2 TeV,	0.74 TeV
If $C_{new} = 1$ (strongly coupled new physics):	$\Lambda_{new} =$	48 TeV,	31 TeV

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: $[SU(2)]^2 \times [U(1)]^2 \longrightarrow SU(2)_L \times U(1)_Y$
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)

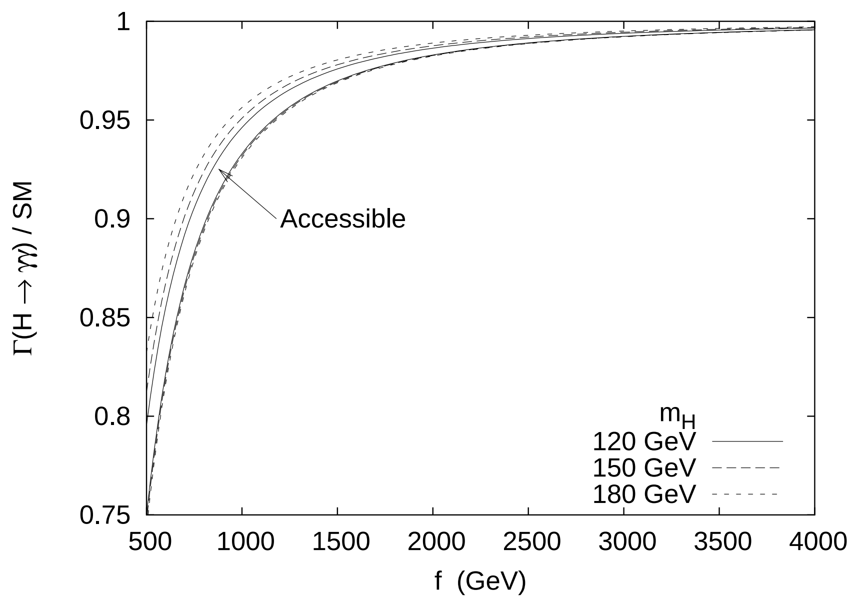
c' – $\mathrm{U}(1)_{1,2}$ gauge boson mixing angle [EW precision favors only one U(1) $\to c' = 1/\sqrt{2}$]

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.

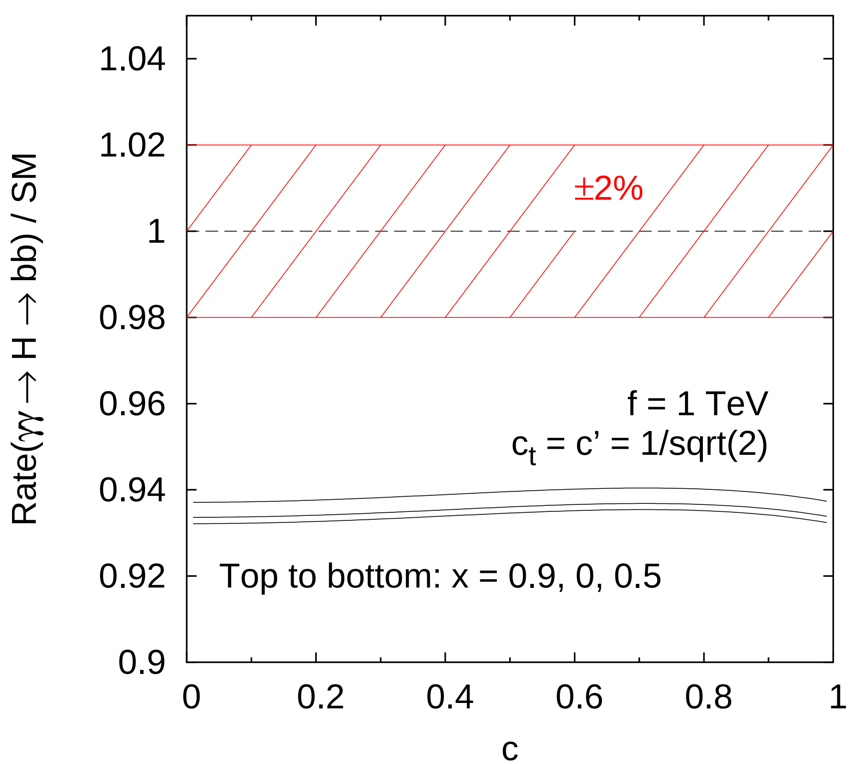
**(bug fixed in code)

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: $H \to b\bar{b}$.



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

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

$\longrightarrow$ 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.

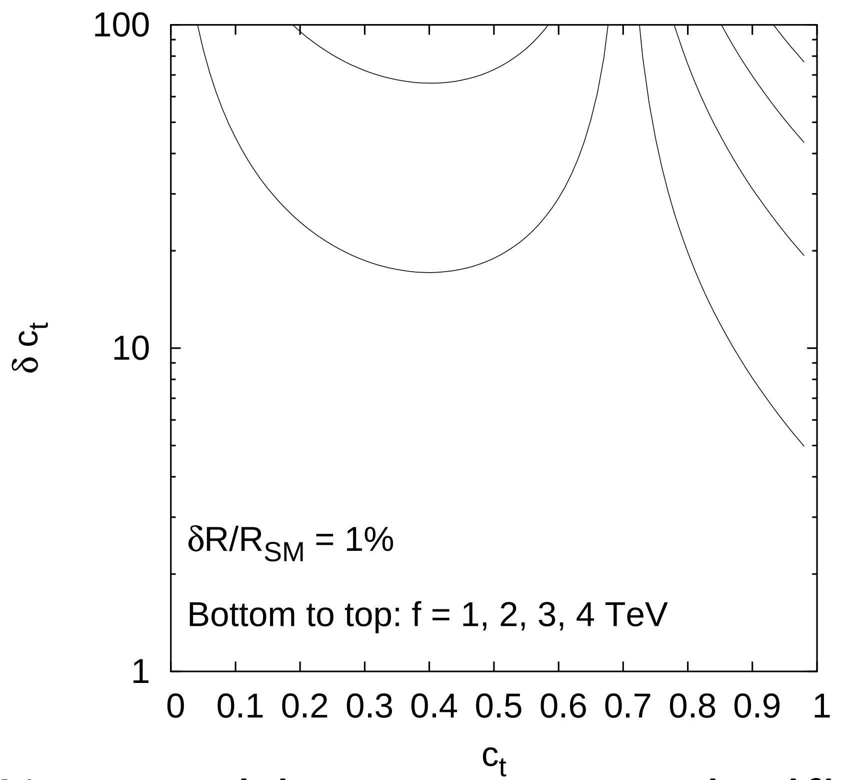
Must predict the rate $R = R_{SM} + R_{LH}$ for $\gamma\gamma \to H \to b\bar{b}$ with precision comparable to the 2% photon collider expt uncertainty.

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 ~10%. Feasible with hadron collider data.

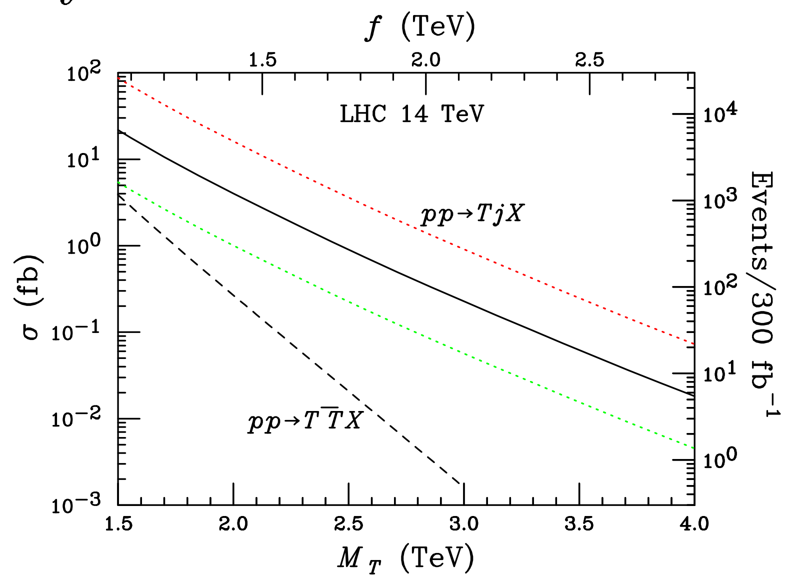
Input precisions: c_t

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



Not sensitive to c_t at a significant level.
$\rightarrow$ Don't need a measurement of this parameter.

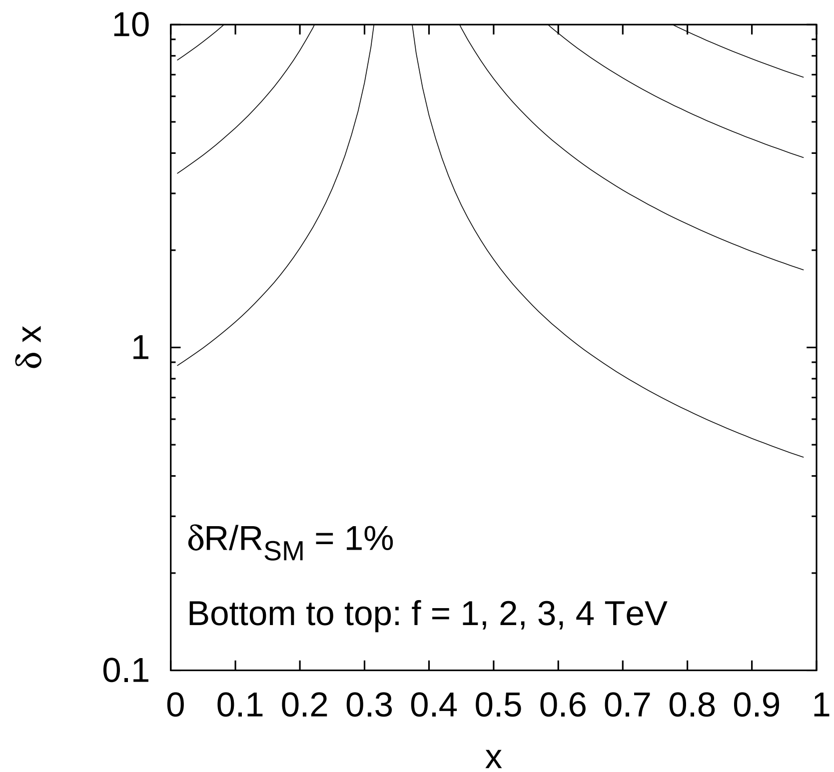
Measure c_t from the $Wb \to T$ cross section:
($c_t^2 =$ 0.8, 0.5, 0.2)

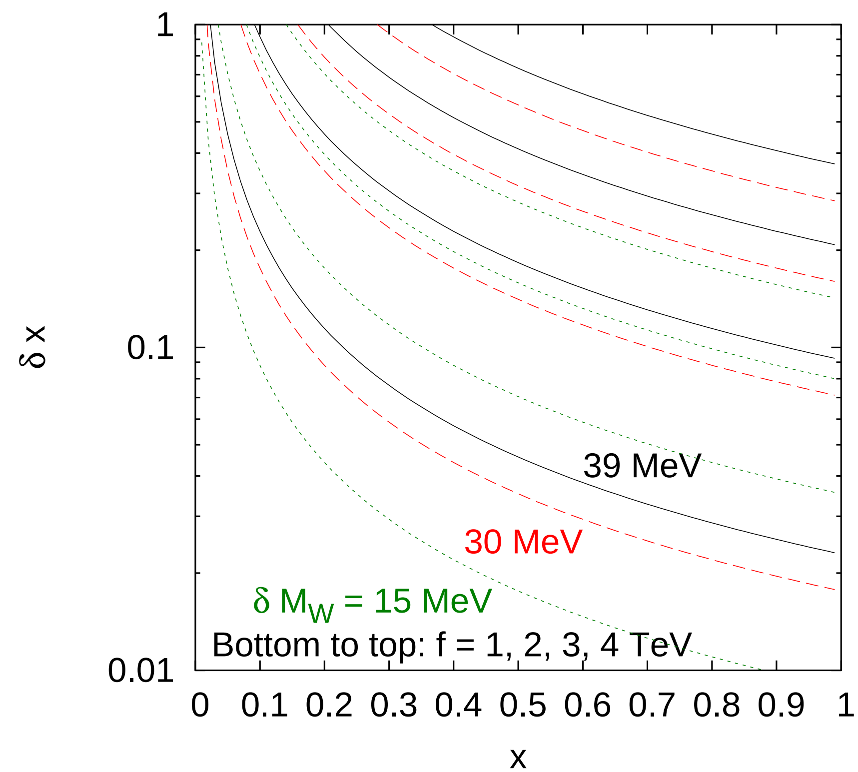


or extract from T mass:
$M_T = m_t f / v s_t c_t$

Input precisions: x

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





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 Φ 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.

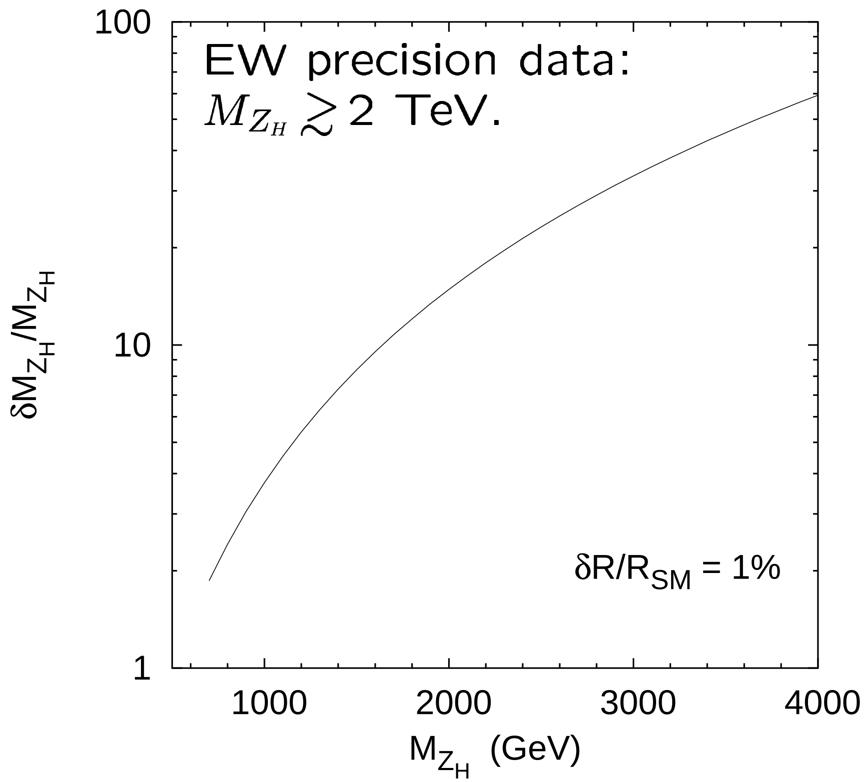
Input precisions: M_{Z_H} and M_{A_H}

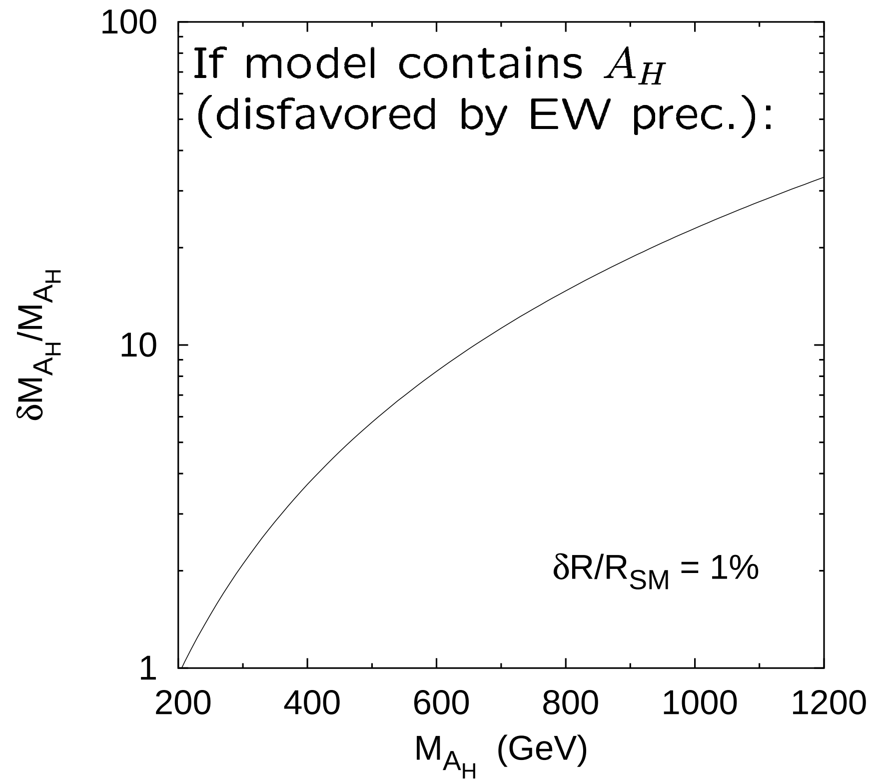
Trade $c \to M_{Z_H}$, $c' \to M_{A_H}$: more easily measured (dileptons).

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

Sensitivity comes from:

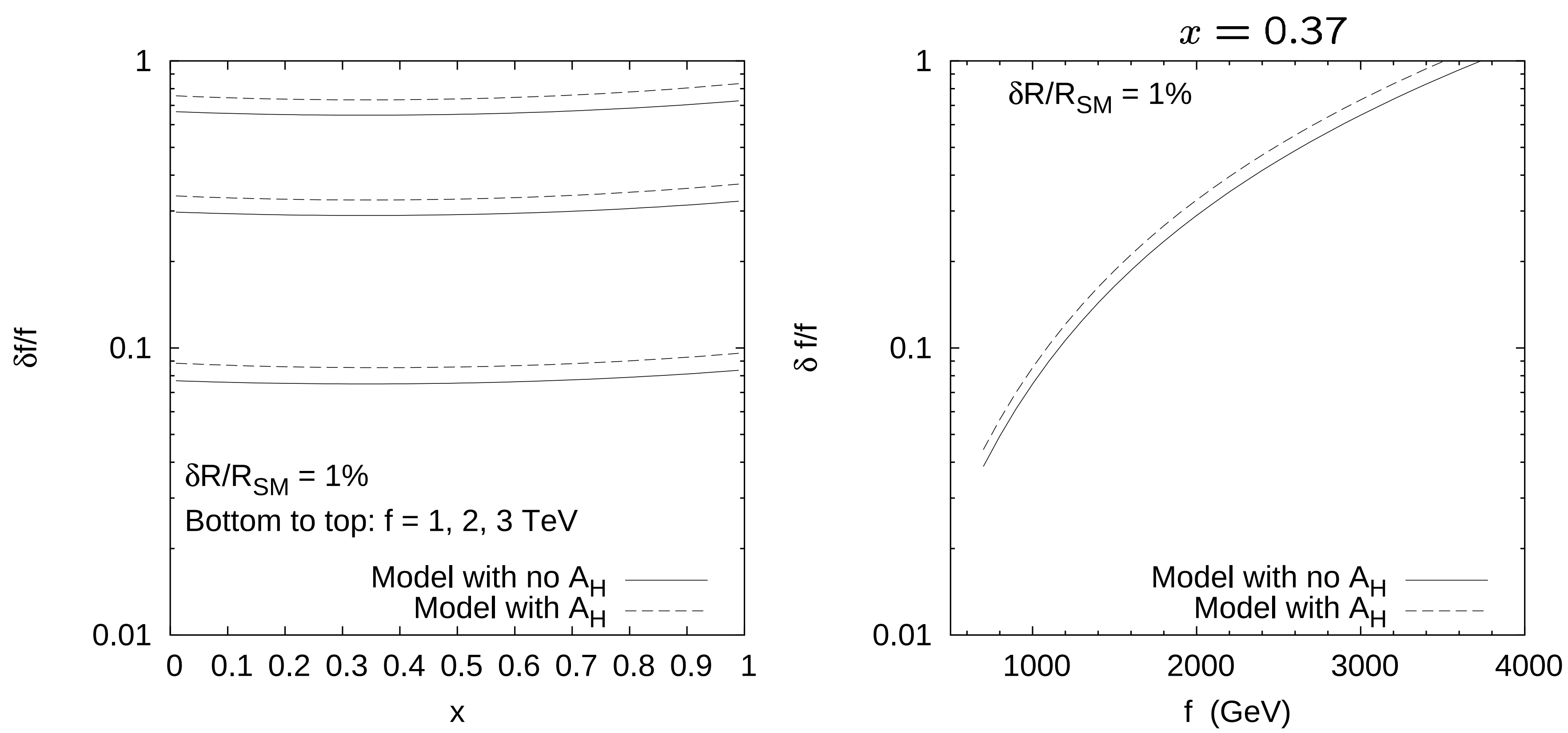
M_{Z_H}: corrections to EW inputs (M_W, M_Z, G_F), $W_H^{\pm}$ in loop.
M_{A_H}: corrections to EW inputs (M_Z, G_F).





Input precisions: f

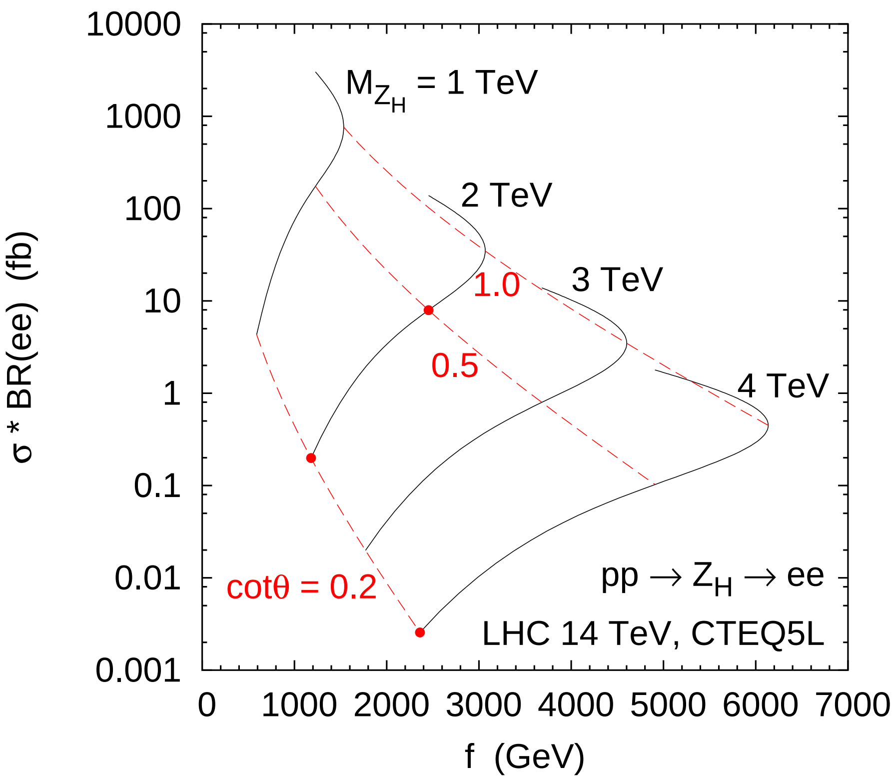
Overall scale parameter: new effects go like v^2/f^2.



EW precision constraints: $f \gtrsim 1$ TeV $\rightarrow$ want $\gtrsim 7\%$ precision.

Input precisions: f, continued

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

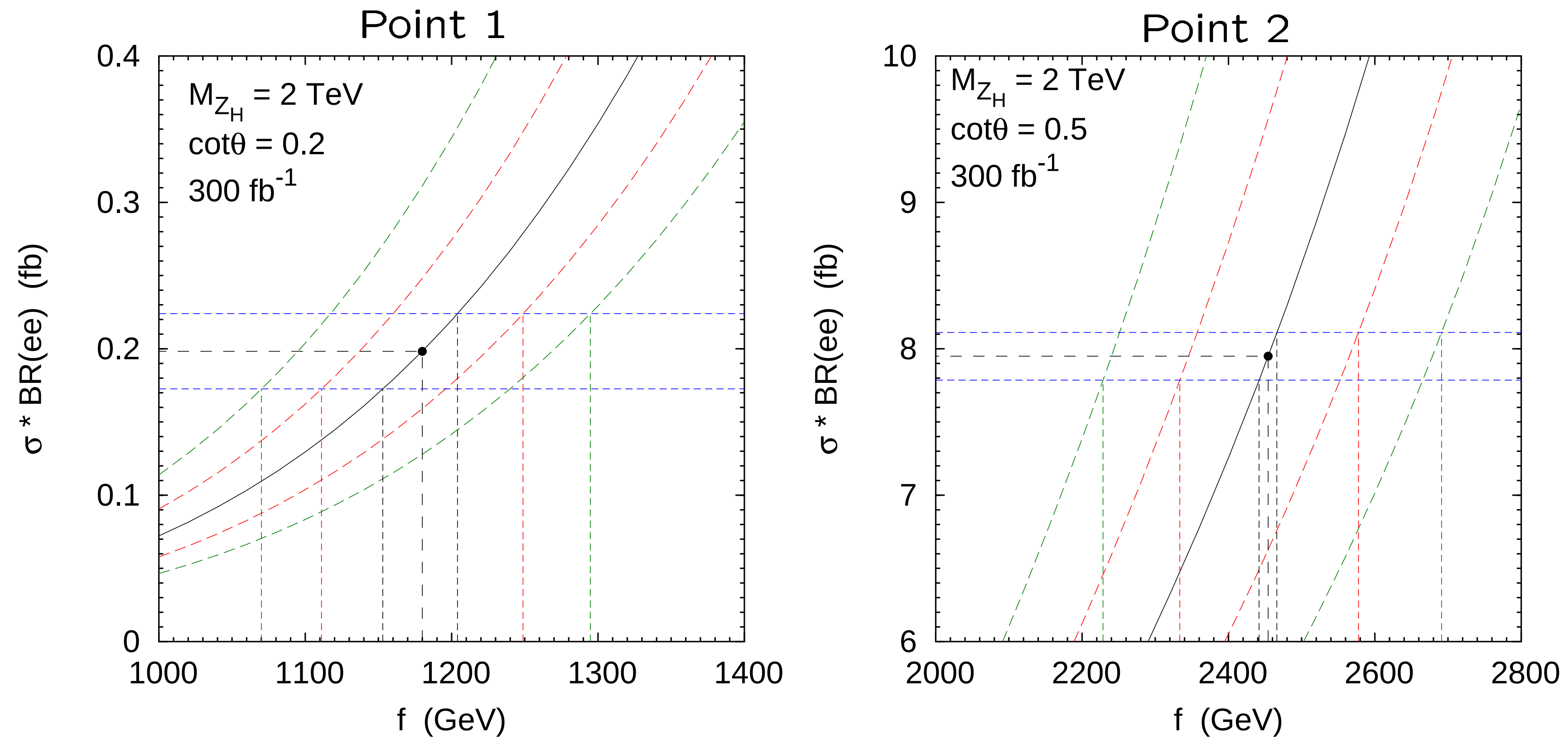


Three benchmark points:

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	1180	13% (59 evts)	2%	6%	10%	10% / 12%
2	2454	2.0% (2380 evts)	0.5%	5%	9%	43% / 49%
3	2360	– (0.8 evts)	–	–	–	40% / 45%

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 NLΣM 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 ~ 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 $\gamma\gamma \to H \to b\bar{b}$?

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

• "Resolved photons": photon has a PDF containing quarks, gluons, etc. $\longrightarrow$ Higgs production via gluon fusion, $b\bar{b}$ fusion: part of cross section not due to Γ_γ; also $e^-e^- \to \nu\nu H$: 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:
$\longrightarrow$ Need to calculate R_{SM} at the 1% level.

- Radiative corrections to $\gamma\gamma \to H$

– 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 BR($H \to b\bar{b}$)

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

- Parametric uncertainty in BR($H \to b\bar{b}$) from m_b (and α_s)

– $m_b(m_b) = 4.17 \pm 0.05$ GeV (and $\alpha_s = 0.1185 \pm 0.0020$) give δ[BR($H \to b\bar{b}$)] $\simeq 1.4\%$ for $M_H = 120$ GeV: lattice (thy) and CLEO bottomonium spectroscopy (expt) should improve m_b

Summary

Photon collider can measure $\gamma\gamma \to H \to b\bar{b}$ to 2% for 115 GeV $\leq M_H \lesssim$ 140 GeV.

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

- Strongly coupled UV completion contributes at same order as TeV-scale particles: $\sim$ several percent for $f \sim 1-3$ TeV.
- Weakly coupled UV completion should not affect $\gamma\gamma \to H$ at an observable level: $\longrightarrow$ 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 $\longrightarrow$ 1% precision goal