LHC and $\gamma C$ Probes of the Scalar Sector of the Randall-Sundrum Model

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Cornell LC Workshop, 7/13/2003
Previous work:

• $\xi = 0$:
  

• $\xi \neq 0$:
  

5. J. L. Hewett and T. G. Rizzo, hep-ph/0202155. As pointed out in their recent revision of this work dated July 2, 2003, our paper (hep-ph/0206192) appeared 4 months after their original hep-ph submission. However, their results at that time, in their previous presentations, and in all but the most recent presentations, were incorrect except at rather small $\xi$ values due to the fact that they employed the small $\xi$ approximations to the mixing/diagonalization procedures that were given in Giudice etal., hep-ph/0002178. The revision of July 2, 2003 comes some 12 months after our hep-ph/0206192 preprint. Their results now appear to be in accord with ours. Our work was, of course, performed completely independently of their work and was fully in progress at the time of their earliest presentation.

Presuming the new physics scale to be close to the TeV scale, there can be a rich new phenomenology in which Higgs and radion physics intermingle if the $\xi R \hat{H}^\dagger \hat{H}$ mixing term is present in $\mathcal{L}$.

References:


Some possibly very dramatic changes in phenomenology.

- There are two branes, separated in the 5th dimension ($y$) and $y \to -y$ symmetry is imposed. With appropriate boundary conditions, the 5D Einstein equations

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu - b_0^2 dy^2,$$

(1)

where $\sigma(y) \sim m_0 b_0 |y|$.

- $e^{-2\sigma(y)}$ is the warp factor; scales at $y = 0$ of order $M_{Pl}$ on the hidden brane are reduced to scales at $y = 1/2$ of order TeV on the visible brane.

- Fluctuations of $g_{\mu\nu}$ relative to $\eta_{\mu\nu}$ are the KK excitations $h_{\mu\nu}^n$.

- Fluctuations of $b(x)$ relative to $b_0$ define the radion field.

- In addition, we place a Higgs doublet $\tilde{H}$ on the visible brane. After various rescalings, the properly normalized quantum fluctuation field is called $h_0$. 

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Including the $\xi$ mixing term

• We begin with

$$S_\xi = \xi \int d^4x \sqrt{g_{\text{vis}}} R(g_{\text{vis}}) \hat{H}^\dagger \hat{H},$$

(2)

where $R(g_{\text{vis}})$ is the Ricci scalar for the metric induced on the visible brane.

• A crucial parameter is the ratio

$$\gamma \equiv v_0/\Lambda_\phi.$$

(3)

where $\Lambda_\phi$ is vacuum expectation value of the radion field.

• After writing out the full quadratic structure of the Lagrangian, including $\xi \neq 0$ mixing, we obtain a form in which the $h_0$ and $\phi_0$ fields for $\xi = 0$ are mixed and have complicated kinetic energy normalization.

We must diagonalize the kinetic energy and rescale to get canonical
normalization.

\[ h_0 = \left( \cos \theta - \frac{6\xi \gamma}{Z} \sin \theta \right) h + \left( \sin \theta + \frac{6\xi \gamma}{Z} \cos \theta \right) \phi \]
\[ \equiv dh + c\phi \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \Quad
The result found is that the physical mass eigenstates $h$ and $\phi$ cannot be too close to being degenerate in mass, depending on the precise values of $\xi$ and $\gamma$; extreme degeneracy is allowed only for small $\xi$ and/or $\gamma$.

Using this inversion, for given $\xi$, $\gamma$, $m_h$ and $m_\phi$ we compute $Z^2$, $m^2_{h_0}$ and $m^2_{\phi_0}$, $\theta$ to obtain $a, b, c, d$ in Eqs. (4) and (5).

- **Net result**

4 independent parameters to completely fix the mass diagonalization of the scalar sector when $\xi \neq 0$. These are:

$$\xi, \gamma, m_h, m_\phi,$$

where we recall that $\gamma \equiv v_0/\Lambda_\phi$ with $v_0 = 246$ GeV.

The quantity $\hat{\Lambda}_W = \frac{1}{\sqrt{3}}\Lambda_\phi$ fixes the KK-graviton couplings to the $h$ and $\phi$ and

$$m_1 = x_1 \frac{m_0 \Lambda_\phi}{M_{Pl} \sqrt{6}}$$

is the mass of the first KK graviton excitation ($x_1$ is the first zero of the Bessel function $J_1$ ($x_1 \sim 3.8$))
\( m_0/M_{Pl} \) is related to the curvature of the brane and should be a relatively small number for consistency of the RS scenario.

- Sample parameters that are safe from precision EW data and Run1 Tevatron constraints are \( \Lambda_\phi = 5 \text{ TeV} \) \( (\Rightarrow \Lambda_W \sim 3 \text{ TeV}) \) and \( m_0/M_{Pl} = 0.1 \).

The latter \( \Rightarrow m_1 \sim 780 \text{ GeV} \); i.e. \( m_1 \) is typically too large for KK graviton excitations to be present, or if present, important, in \( h, \phi \) decays.

But, KK excitations in this mass range (and much higher) will be observed and well measured at the LHC.

- Given this choice, we complete the inversion by writing out the kinetic energy terms of the complete Lagrangian using the substitutions of Eqs. (4) and (5) and demanding that the coefficients of \(-\frac{1}{2}h^2\) and \(-\frac{1}{2}\phi^2\) agree with the given input values for \( m_h^2 \) and \( m_\phi^2 \).

Results shown take \( m_0/M_{Pl} = 0.1 \).

- KK excitation probably observable at LHC

Will provide important information.
1. Mass gives $m_1$ in above notation.
2. Excitation spectrum as a function of $m_{jj}$ determines $m_0/M_{Pl}$.
3. Combine ala Eq. (8) to get $\Lambda_{\phi}$.
   This will really help in LHC-only study of Higgs sector.
The $f\bar{f}$ and $VV$ couplings

- **The $VV$ couplings**
  
  - The $h_0$ has standard $ZZ$ coupling.
  - The $\phi_0$ has $ZZ$ coupling deriving from the interaction $-\frac{\phi_0}{\Lambda_\phi} T^\mu_\mu$ using the covariant derivative portions of $T^\mu_\mu(h_0)$.

  The result for the $\eta_{\mu\nu}$ portion of the $ZZ$ couplings is:

  \[
g_{ZZh} = \frac{g m_Z}{c_W} (d + \gamma b) , \quad g_{ZZ\phi} = \frac{g m_Z}{c_W} (c + \gamma a) . \tag{9}
  \]

  $g$ and $c_W$ denote the $SU(2)$ gauge coupling and $\cos \theta_W$, respectively. The $WW$ couplings are obtained by replacing $gm_Z/c_W$ by $gm_W$.

- **The $f\bar{f}$ couplings**
  
  - The $h_0$ has standard fermionic couplings.
– The fermionic couplings of the $\phi_0$ derive from $-\frac{\phi_0}{\Lambda_\phi} T^\mu_\mu$ using the Yukawa interaction contributions to $T^\mu_\mu$.
– One obtains results in close analogy to the $VV$ couplings just considered:

$$g_{f\bar{f}h} = -\frac{g m_f}{2 m_W} (d + \gamma b), \quad g_{f\bar{f}\phi} = -\frac{g m_f}{2 m_W} (c + \gamma a). \quad (10)$$

• Note same factors for $WW$ and $f\bar{f}$ couplings.

The $gg$ and $\gamma\gamma$ couplings

• There are the standard loop contributions, except rescaled by $f\bar{f}/VV$ strength factors $g_{fVh}$ or $g_{fV\phi}$.

• In addition, there are anomalous contributions, which are expressed in terms of the $SU(3) \times SU(2) \times U(1)$ $\beta$ function coefficients $b_3 = 7, b_2 = 19/6$ and $b_Y = -41/6$.

• The anomalous couplings of $h$ and $\phi$ enter only through their radion admixtures, $g_h = \gamma b$ for the $h$, and $g_\phi = \gamma a$ for the $\phi$. 
First, consider the $f\bar{f}/VV$ couplings of $h$ and $\phi$ relative to SM, taking $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV.

For the chosen value of $m_0/M_{Pl} = 0.1$, once $m_h$ and $\Lambda_\phi$ are fixed, the remaining free parameters are $m_\phi$ and $\xi$. The plots give the couplings in the $m_\phi, \xi$ parameter space.

Note the hourglass shape that defines the theoretically allowed region.

The most important points

If $g_{fVh}^2 < 1$ is observed then $m_\phi > m_h$, and vice versa, except for small region near $\xi = 0$.

In cases where $g_{fV\phi}$ is small, prior indirect knowledge of, or constraints on, $m_\phi$ could be crucial.

At large $|\xi|$, if $m_\phi > m_h$ the $ZZ\phi$ couplings can become sort of SM strength, implying SM type discovery modes could become relevant.
Figure 1: Contours of \( g_{\tilde{f}Vh}^2 = (d + \gamma b)^2 \) (relative to SM) for \( \Lambda_\phi = 5 \) TeV, \( m_h = 120 \) GeV.

- Observe suppression if \( m_\phi > m_h \) and vice versa.
Figure 2: \( \frac{g_{ZZh}^2}{g_{ZZh}^{SM}} = \frac{g_{ffh}^2}{g_{ffh}^{SM}} \) as a function of \( \xi \) for several \( m_\phi \) values.
Figure 3: Contours of $g^2_{ZZ\phi} = (c + \gamma a)^2$ for $\Lambda_\phi = 5$ TeV, $m_h = 120$ GeV

- Substantial $g^2_{fV\phi}$ is possible if $m_\phi > m_h$ and $\xi$ is not too small.
Figure 4: $g_{ZZ\phi}^2/g_{ZZh_{SM}}^2 = g_{\bar{f}f\phi}^2/g_{\bar{f}fh_{SM}}^2$ as a function of $\xi$ for several $m_\phi$ values.
Some important points are:

- \( h \) branching ratios are quite SM-like (even if partial widths are different) except that \( h \rightarrow gg \) can be bigger than normal, especially when \( g_{fV}^2 h \) is suppressed.

- For \( m_\phi < 2m_W \), \( \phi \rightarrow gg \) is very possibly the dominant mode in the substantial regions near zeroes of \( g_{fV}^2 \).

  For \( m_\phi > 2m_W \), \( \phi \) branching ratios are sort of SM-like (except at \( \xi \simeq 0 \)) but total and partial widths are rescaled.
At the LHC, we (Battaglia, Dominici, de Curtis, de Roeck, JFG) focused on the case of a relatively light Higgs boson, $m_h = 120$ GeV for example.

- The precision EW studies suggest that some of the larger $|\xi|$ range is excluded, but we studied the whole range just in case.

- We rescaled the statistical significances predicted for the SM Higgs boson at the LHC using the $h$ and $\phi$ couplings predicted relative to the $h_{SM}$.

A modified version of HDECAY was employed.

- The most important modes are $gg \to h \to \gamma\gamma$ and $gg \to \phi \to ZZ^{(*)} \to 4\ell$.

  Also useful are $t\bar{t}h$ with $h \to b\bar{b}$ and $h \to ZZ^* \to 4\ell$.  

Figure 5: SM Higgs search capabilities at the LHC for ATLAS and CMS.

- An example of the type of effect that will be observed is that the \( h \to \gamma \gamma \) mode becomes unobservable if \( |\xi| \) is large and \( m_\phi > m_h \) (which together imply suppressed \( hWW \) coupling and hence suppressed \( W \)-loop...
contribution to the $\gamma\gamma h$ couplings).

One interesting graph is below. Note how we lose the $h \rightarrow \gamma\gamma$ mode if $m_\phi > m_h$, especially if $\xi < 0$. If $m_\phi < m_h$, $h \rightarrow \gamma\gamma$ will be strong if $\xi < 0$, but can be considerably weakened if $\xi > 0$.

![Graph](image)

**Figure 6:** $gg \xrightarrow{\xi} h \rightarrow \gamma\gamma/gg \xrightarrow{\xi} h_{SM} \rightarrow \gamma\gamma$ and $WW \rightarrow h \rightarrow \tau^+\tau^-/WW \rightarrow h_{SM} \rightarrow \tau^+\tau^-$ (same as for $gg \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$) for $m_{h_{SM}} = m_h$; $\Lambda_\phi = 5$ TeV.
Figure 7: The ratio of the rate for $gg \to \phi \to ZZ$ to the corresponding rate for a SM Higgs boson with mass $m_\phi$ assuming $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as a function of $\xi$ for $m_\phi = 110$, 140 and 200 GeV. Recall that the $\xi$ range is increasingly restricted as $m_\phi$ becomes more degenerate with $m_h$. Note: for $m_\phi > m_h$ the mode approaches SM strength if $\xi < 0$ and is nearing SM strength if $\xi > 0$ and near maximal.
Figure 8: $L = 30\text{fb}^{-1}$ illustration of mode complementarity at the LHC for $m_h = 120$ GeV. The cyan regions show where the $gg \rightarrow h \rightarrow \gamma\gamma$ mode (or not very important at this $m_h$ value, $gg \rightarrow h \rightarrow 4\ell$ mode) yields a $> 5\sigma$ signal. The regions between dark blue curves define the regions where $gg \rightarrow \phi \rightarrow 4\ell$ is $> 5\sigma$. The graphs are for $\Lambda_\phi = 2.5$ TeV (left) $\Lambda_\phi = 5$ TeV (center) and $\Lambda_\phi = 7.5$ TeV (right).
The LHC can find either the $h$ or $\phi$ except for the $m_\phi < m_h$, $\xi > 0$ and large, region.

But, some portion of this difficult region is disfavored by the precision electroweak data — e.g. $|\xi| \lesssim 1.5$ is preferred in the $\Lambda_\phi = 5$ TeV case.

Figure 9: As in previous figure. The graphs are for $\Lambda_\phi = 5$ TeV and $m_h = 115$ GeV (left) $m_h = 140$ GeV (center) and $m_h = 180$ GeV (right).

Above, we see that the region where neither the $h$ nor the $\phi$ can be
detected grows (decreases) as $m_h$ decreases (increases). It diminishes as $m_h$ increases since the $gg \rightarrow h \rightarrow 4\ell$ increases in strength at higher $m_h$.

Figure 10: The cyan regions are those where $h$ discovery is not possible for $\Lambda_\phi = 5$ TeV and $m_h = 120$ GeV case assuming LHC $L = 30 fb^{-1}$ (left) or $L = 100 fb^{-1}$ (right).

The regions where the $h$ is not observable are reduced by considering either a larger data set or $qqh$ Higgs production, in association with forward jets. An integrated luminosity of $100 \text{ fb}^{-1}$ would remove the regions at large positive $\xi$ in the $\Lambda_\phi = 5$ and 7.5 TeV plots of Fig. 8. Similarly,
including the $qqh$, $h \rightarrow WW^* \rightarrow \ell\ell\nu\bar{\nu}$ channel in the list of the discovery modes removes the same two regions and reduces the large region of $h$ non-observability at negative $\xi$ values.

- Figures 8 and 9 also exhibit regions of $(m_h, \xi)$ parameter space in which both the $h$ and $\phi$ mass eigenstates will be detectable.

In these regions, the LHC will observe two scalar bosons somewhat separated in mass, with the lighter (heavier) having a non-SM-like rate for the $gg$-induced $\gamma\gamma$ ($Z^0Z^0$) final state.

Additional information will be required to ascertain whether these two Higgs bosons derive from a multi-doublet or other type of extended Higgs sector or from the present type of model with Higgs-radion mixing.

- What about an LC?

An $e^+e^-$ LC should guarantee observation of both the $h$ and the $\phi$ in the region of low $m_\phi$, large $\xi > 0$ within which detection of either at the LHC might be difficult. This is because the $ZZ\phi$ coupling-squared is $\gtrsim 0.01$ relative to the SM for most of this region.

But, what if there is no LC?
Let’s remind ourselves about the results for the SM Higgs boson obtained in the CLIC study of hep-ex/0111056. There, a SM Higgs boson with $m_{h_{SM}} = 115$ GeV was examined. After the cuts, one obtains about $S = 3280$ and $B = 1660$ in the $\gamma\gamma \rightarrow h_{SM} \rightarrow b\bar{b}$ channel, corresponding to $S/\sqrt{B} \sim 80$ !!!

We will assume that these numbers do not change significantly for a Higgs mass of 120 GeV.

After mixing, the $S$ rate for the $h$ will be rescaled relative to that for the $h_{SM}$. Of course, $B$ will not change.

The rescaling is shown in the figure.

The $S$ for the $\phi$ can also be obtained by rescaling if $m_{\phi} \sim 115$ GeV.

For $m_{\phi} < 120$ GeV, the $\phi \rightarrow b\bar{b}$ channel will continue to be the most relevant for $\phi$ discovery, but studies have not yet been performed to obtain the $S$ and $B$ rates for low masses.
Figure 11: The rates for $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow \phi \rightarrow b\bar{b}$ relative to the corresponding rate for a SM Higgs boson of the same mass. Results are shown for $m_h = 120$ GeV and $\Lambda_{\phi} = 5$ TeV as functions of $\xi$ for $m_{\phi} = 20$, 55 and 200 GeV.
Observe that for $m_\phi < m_h$ we have either little change or enhancement, whereas significant suppression of the $gg \rightarrow h \rightarrow \gamma\gamma$ rate was possible in this case for positive $\xi$.

Also note that for $m_\phi > m_h$ and large $\xi < 0$ (where the LHC could not see the $h$) there is much less suppression of $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$ than for $gg \rightarrow h \rightarrow \gamma\gamma$ — at most a factor of 2 vs a factor of 8 (at $m_\phi = 200$ GeV).

This is no problem since $S/\sqrt{B} \sim \frac{1}{2}80 \sim 40$ is still a very strong signal.

- In fact, we can afford a reduction by a factor of 16 before we hit the 5$\sigma$ level!

- Thus, the $\gamma\gamma$ collider will allow $h$ discovery (for $m_h = 120$) throughout the entire hourglass, which is something the LHC cannot do.

- Using the factor of 16 mentioned above, the $\phi$ with $m_\phi < 120$ GeV is very likely to elude discovery at the $\gamma\gamma$ collider. (Recall that it also eludes discovery at the LHC for this region.)

The only exceptions to this statement occur at the very largest $|\xi|$ values for $m_\phi \geq 55$ GeV where $S_\phi > S_{h_{SM}}/16$.

- Of course, we need to have signal and background results after cuts for
these lower masses to know if the factor of 16 is actually the correct factor to use.

To get the best signal to background ratio we would want to lower the machine energy (relatively easy for CLIC case) and readjust cuts and so forth.

This study should be done.

- For the $m_\phi > m_h$ region, we will need results for the $WW$ and $ZZ$ modes that are being worked on.
Conclusions

• The $\gamma C$ is more than competitive with the LHC for $h$ discovery. The $\gamma C$ can see the $h$ where the LHC can’t, although the “bad” LHC regions are not very big for full $L$.

• Of course, there is a big part of the hourglass where the $h$ will be seen at both colliders. This is most of the hourglass when $L$ at the LHC is $> 100 fb^{-1}$. This will certainly increase our knowledge about the $h$ since the two rates measure different things.

The ratio of the rates gives us $\frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow bb)}$, in terms of which we may compute

$$R_{h,gg} \equiv \left[ \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow bb)} \right] \left[ \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow bb)} \right]_{SM}^{-1}.$$  

(11)

This is a very!!!! interesting number since it directly probes for the presence of the anomalous $ggh$ coupling.
In particular, \( R_{hgg} = 1 \) if the only contributions to \( \Gamma(h \rightarrow gg) \) come from quark loops and all quark couplings scale in the same way.

**Figure 12:** In the left two plots, we give the ratios \( R_{hgg} \) and \( R_{\phi gg} \) of the \( hgg \) and \( \phi gg \) couplings-squared including the anomalous contribution to the corresponding values expected in its absence. Results for the the analogous ratios \( R_{h\gamma\gamma} \) and \( R_{\phi\gamma\gamma} \) are presented in the two plots on the right. Results are shown for \( m_h = 120 \text{ GeV} \) and \( \Lambda_\phi = 5 \text{ TeV} \) as functions of \( \xi \) for \( m_\phi = 20, 55 \) and \( 200 \text{ GeV} \). (The same type of line is used for a given \( m_\phi \) in the right-hand figure as is used in the left-hand figure.)
We can estimate the accuracy with which $R_{hgg}$ can be measured as follows. Assuming the maximal reduction of $1/2$ for the $S$ rescaling at the $\gamma\gamma$ CLIC collider, we find that $\Gamma(h \to \gamma\gamma)\Gamma(h \to b\bar{b})/\Gamma_h^{tot}$ can be measured with an accuracy of about $\sqrt{S + B}/S \sim \sqrt{3200}/1600 \sim 0.035$. The dominant error will then be from the LHC which will typically measure $\Gamma(h \to gg)\Gamma(h \to \gamma\gamma)/\Gamma_h^{tot}$ with an accuracy of between 0.1 and 0.2 (depending on parameter choices and available $L$). From Fig. 12, we see that 0.2 fractional accuracy will reveal deviations of $R_{hgg}$ from 1 for all but the smallest $\xi$ values.

- The ability to measure $R_{hgg}$ may be the strongest reason in the Higgs context for having the $\gamma C$ as well as the LHC.

Almost all non-SM Higgs theories predict $R_{hgg} \neq 1$ for one reason another, unless one is in the decoupling limit.

- Depending on $L$ at the LHC, there is a somewhat smaller part of the hourglass (large $|\xi|$ with $m_\phi > m_h$) where only the $\phi$ will be seen at the LHC and the $h$ will only be seen at the $\gamma C$.

(We don’t know for sure about the $\phi$ at the $\gamma C$ until $WW, ZZ$ final states are studied, but I am not all that optimistic.)
This is a nice example of complementarity between the two machines. By having both machines we maximize the chance of seeing both the $h$ and $\phi$.

- Thus, there is a strong case for the $\gamma C$ in the RS model context!, especially if a Higgs boson is seen at the LHC that has non-SM-like rates, ...