The Scalar Sector of the Randall-Sundrum Model

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Outline

- Is the vacuum unique?
- Understanding the parameter space
- Basics of the couplings
- Phenomenology
- Conclusions

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, especially if the $\xi R \widehat{H}^\dagger \widehat{H}$ mixing term is present in $\mathcal{L}$. Previous work:

- $\xi = 0$:

1. Bae:2000pk S. B. Bae, P. Ko, H. S. Lee and J. Lee, Phys. Lett. B 487, 299 (2000) [arXiv:hep-ph/0002224].

2. Davoudiasl:1999jd H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. Lett. 84, 2080 (2000) [arXiv:hep-ph/9909255].
3. Cheung:2000rw K. Cheung, Phys. Rev. D 63, 056007 (2001) [arXiv:hep-ph/0009232].
4. Davoudiasl:2000wi H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. D 63, 075004 (2001) [arXiv:hep-ph/0006041].
5. Park:2000xp S. C. Park, H. S. Song and J. Song, Phys. Rev. D 63, 077701 (2001) [arXiv:hep-ph/0009245].

- $\xi \neq 0$:

1. wellsmix G. Giudice, R. Rattazzi, J. Wells, Nucl. Phys. B595 (2001), 250, hep-ph/0002178.
2. csakimix C. Csaki, M.L. Graesser, G.D. Kribs, Phys. Rev. D63 (2001), 065002-1, hep-th/0008151.
3. Han:2001xs T. Han, G. D. Kribs and B. McElrath, Phys. Rev. D 64, 076003 (2001) [arXiv:hep-ph/0104074].
4. Chaichian:2001rq M. Chaichian, A. Datta, K. Huitu and Z. h. Yu, Phys. Lett. B 524, 161 (2002) [arXiv:hep-ph/0110035].
5. Hewett:2002nk J. L. Hewett and T. G. Rizzo, hep-ph/0202155.
6. Csaki:1999mp C. Csaki, M. Graesser, L. Randall and J. Terning, Phys. Rev. D 62, 045015 (2000) [arXiv:hep-ph/9911406].

Randal-Sundrum Review

Some possibly very dramatic changes in phenomenology.

- We consider the usual two-brane (one visible, one hidden) RS 5D warped space scenario.

- The model is defined by the 5D action:

$$
\begin{aligned}
S &= -\int d^4x\,dy\sqrt{-\widehat{g}}\left(\frac{R}{2\widehat{\kappa}^2}+\Lambda\right) \\
&\quad + \int d^4x\,\sqrt{-g_{hid}}(\mathcal{L}_{hid}-V_{hid}) + \int d^4x\,\sqrt{-g_{vis}}(\mathcal{L}_{vis}-V_{vis}), \qquad (1)
\end{aligned}
$$

where $\widehat{g}^{\widehat{\mu}\widehat{\nu}}$ ($\widehat{\mu},\widehat{\nu}=0,1,2,3,y$) is the bulk metric and $g_{hid}^{\mu\nu}(x)\equiv\widehat{g}^{\mu\nu}(x,y=0)$ and $g_{vis}^{\mu\nu}(x)\equiv\widehat{g}^{\mu\nu}(x,y=1/2)$ ($\mu,\nu=0,1,2,3$) are the induced metrics on the branes.

- If $\Lambda/m_0=-V_{hid}=V_{vis}=-6m_0/\hat{\kappa}^2$ and if periodic boundary conditions identifying (x,y) with $(x,-y)$ are imposed, then the 5D Einstein equations

$\Rightarrow$

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

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

- Fluctations of $g_{\mu\nu}$ relative to $\eta_{\mu\nu}$ are the KK excitations $h^n_{\mu\nu}$.
- Fluctations of $b(x)$ relative to b_0 define the radion field.
- In addition, we place a Higgs doublet $\widehat{H}$ on the visible brane.

Including the ξ mixing term

- **We begin with**

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H} \,, \tag{3}$$

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

- **A crucial parameter is the ratio**

$$\gamma \equiv v_0 / \Lambda_\phi \,. \tag{4}$$

where Λ_ϕ 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 ϕ_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.

$$h_0 = \left(\cos\theta - \frac{6\xi\gamma}{Z}\sin\theta\right) h + \left(\sin\theta + \frac{6\xi\gamma}{Z}\cos\theta\right)\phi$$
$$\equiv dh + c\phi \qquad (5)$$
$$\phi_0 = -\cos\theta\frac{\phi}{Z} + \sin\theta\frac{h}{Z} \equiv a\phi + bh\,. \qquad (6)$$

- The mixing angle θ is given by

$$\tan 2\theta \equiv 12\gamma\xi Z \frac{m_{h_0}^2}{m_{\phi_0}^2 - m_{h_0}^2(Z^2 - 36\xi^2\gamma^2)}\,. \qquad (7)$$

- In the above equations

$$Z^2 \equiv 1 + 6\xi\gamma^2(1 - 6\xi)\,. \qquad (8)$$

$Z^2 > 0$ is required to avoid tachyonic situation.

This can be reexpressed as the requirement:

$$\frac{1}{12}\left(1-\sqrt{1+\frac{4}{\gamma^2}}\right) \leq \xi \leq \frac{1}{12}\left(1+\sqrt{1+\frac{4}{\gamma^2}}\right) \tag{9}$$

- **The corresponding mass-squared eigenvalues are**

$$m^2_{\pm} = \frac{1}{2Z^2}\left(m^2_{\phi_0} + \beta m^2_{h_0} \pm \left\{[m^2_{\phi_0} + \beta m^2_{h_0}]^2 - 4Z^2 m^2_{\phi_0} m^2_{h_0}\right\}^{1/2}\right), \tag{10}$$

with $\beta \equiv 1 + 6\xi\gamma^2$ **and** $\mathrm{Max}[m_h, m_\phi] = m_+$.

- **The process of inversion is very critical to the phenomenology and somewhat delicate.**

- **One finds:**

$$[\beta m^2_{h_0}, m^2_{\phi_0}] = \frac{Z^2}{2}\left[m^2_+ + m^2_- \pm \left\{(m^2_+ + m^2_-)^2 - \frac{4\beta m^2_+ m^2_-}{Z^2}\right\}^{1/2}\right]. \tag{11}$$

- For the quantity inside the square root appearing in Eq. (11) to be positive, we require that:

$$\frac{m_+^2}{m_-^2} > 1 + \frac{2\beta}{Z^2}\left(1 - \frac{Z^2}{\beta}\right) + \frac{2\beta}{Z^2}\left[1 - \frac{Z^2}{\beta}\right]^{1/2}, \quad (12)$$

where $1 - Z^2/\beta = 36\xi^2\gamma^2/\beta > 0$.

I.e. since we will identify m_+ with either m_h or m_ϕ, the physical states h and ϕ cannot be too close to being degenerate in mass, depending on the precise values of ξ and γ; extreme degeneracy is allowed only for small ξ and/or γ.

- A two-fold ambiguity remains in solving for $\beta m_{h_0}^2$ and $m_{\phi_0}^2$, corresponding to which we take to be the larger.

  We resolve this ambiguity by requiring that $m_{h_0}^2 \to m_h^2$ in the $\xi \to 0$ limit. This means that for $\beta m_{h_0}^2$ we take the $+$ $(-)$ sign in Eq. (11) for $m_h > m_\phi$ $(m_h < m_\phi)$, *i.e.* for $m_h = m_+$ $(m_h = m_-)$, respectively.

- Given this choice, we complete the inversion by writing out the kinetic energy of Eq. (??) using the substitutions of Eqs. (5) and (6) 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_ϕ^2.

It is easy to show that these requirements are equivalent and imply

$$\sin 2\theta = \frac{12\gamma\xi m_{h_0}^2}{Z\left(m_\phi^2 - m_h^2\right)}. \tag{13}$$

Note that the sign of $\sin 2\theta$ depends upon whether $m_h^2 > m_\phi^2$ or vice versa. It is convenient to rewrite the result for $\tan 2\theta$ of Eq. (7)

$$\tan 2\theta = \frac{12\gamma\xi m_{h_0}^2}{Z\left(m_\phi^2 + m_h^2 - 2m_{h_0}^2\right)}. \tag{14}$$

In combination, Eqs. (13) and (14) are used to determine $\cos 2\theta$. Together, $\sin 2\theta$ and $\cos 2\theta$ give a unique solution for θ.

Using this inversion, for given ξ, γ, m_h and m_ϕ we compute

- Z^2 from Eq. (8),

- $m^2_{h_0}$ and $m^2_{\phi_0}$ from Eq. (11),
- and then θ from Eq. (7).
- With this input, we can then obtain a, b, c, d as defined in Eqs. (5) and (6).
- **Net result**

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

$$\xi\,, \quad \Lambda_\phi\,, \quad m_h\,, \quad m_\phi\,, \tag{15}$$

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

  Two additional parameters will be required to completely fix the phenomenology of the scalar sector, including all possible decays. These are

$$\widehat{\Lambda}_W\,, \quad m_1\,, \tag{16}$$

  where $\widehat{\Lambda}_W$ will determine KK-graviton couplings to the h and ϕ and m_1 is the mass of the first KK graviton excitation.

We recall the earlier formulae:

$$
\begin{aligned}
\widehat{\Lambda}_W &\equiv \frac{2\sqrt{b_0}}{\epsilon\chi^n(1/2)} \simeq \sqrt{2} M_{Pl}\Omega_0\,, \\
m_n &= m_0 x_n \Omega_0\,, \\
\Lambda_\phi &= \sqrt{6} M_{Pl}\Omega_0 = \sqrt{3}\widehat{\Lambda}_W\,,
\end{aligned} \tag{17}
$$

where $\Omega_0 M_{Pl} = e^{-m_0 b_0/2} M_{Pl}$ should be of order a TeV to solve the hierarchy problem. In Eq. (17), the x_n are the zeroes of the Bessel function J_1 ($x_1 \sim 3.8$, $x_2 \sim 7.0$). A useful relation following from the above equations is:

$$
m_1 = x_1 \frac{m_0}{M_{Pl}} \frac{\Lambda_\phi}{\sqrt{6}}\,. \tag{18}
$$

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 RunI Tevatron constraints are $\Lambda_\phi = 5~\mathrm{TeV}$ ($\Rightarrow \widehat{\Lambda}_W \sim 3~\mathrm{TeV}$) and $m_0/M_{Pl} = 0.1$.

  We will also consider a marginal scenario with $\Lambda_\phi = 1~\mathrm{TeV}$.

- **For m_h and m_ϕ we will consider a range of possibilities, but with some prejudice towards $m_\phi < m_h$. There are theoretical arguments in favor of this.**

  A light radion ϕ eigenstate presents a particularly rich phenomenology.

The Couplings

The $f\overline{f}$ and VV couplings

The VV couplings

- The h_0 has standard ZZ coupling while the ϕ_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:

$$g_{ZZh} = \frac{g\,m_Z}{c_W}(d+\gamma b)\ , \quad g_{ZZ\phi} = \frac{g\,m_Z}{c_W}(c+\gamma a)\ . \tag{19}$$

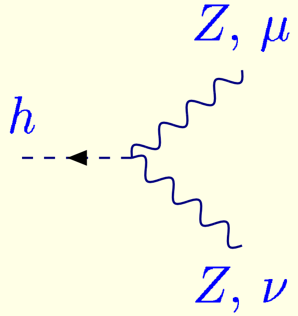
  g and c_W denote the $SU(2)$ gauge coupling and $\cos\theta_W$, respectively. The WW couplings are obtained by replacing gm_Z/c_W by gm_W.

- Additional contributions to the ZZh and $ZZ\phi$ couplings come from $-\frac{\phi_0}{\Lambda_\phi}T_\mu^\mu$ for the gauge fixing portions of $T_{\mu\nu}$. These terms vanish when contracted with on-shell W or Z polarizations, which is the physical situation we are interested in. In addition, these extra couplings vanish in the unitary gauge.

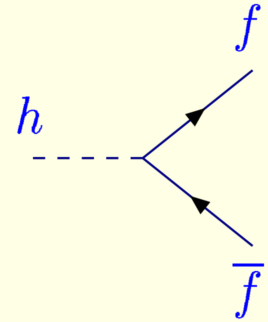
- The $f\overline{f}$ couplings
  - The h_0 has standard fermionic couplings.
  - The fermionic couplings of the ϕ_0 derive from $-\frac{\phi_0}{\Lambda_\phi}T_\mu^\mu$ using the Yukawa interaction contributions to T_μ^μ.
  - One obtains results in close analogy to the VV couplings just considered:

$$g_{f\bar{f}h} = -\frac{g\,m_f}{2\,m_W}(d+\gamma b)\,, \quad g_{f\bar{f}\phi} = -\frac{g\,m_f}{2\,m_W}(c+\gamma a)\,. \qquad (20)$$

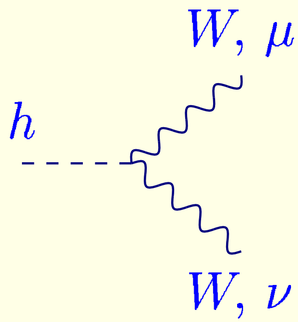
- Note same factors for WW and $f\bar{f}$ couplings.



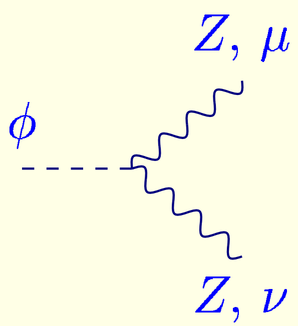
$$i\frac{g m_Z}{c_W}(d+\gamma b)\eta^{\mu\nu}$$



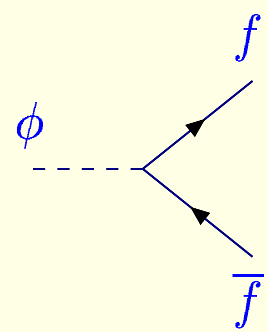
$$-i\frac{g}{2}\frac{m_f}{m_W}(d+\gamma b)$$



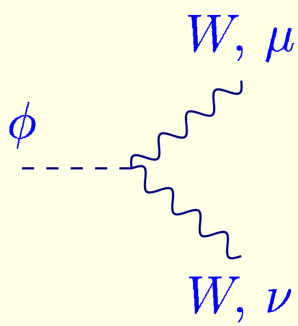
$$i g m_W(d+\gamma b)\eta^{\mu\nu}$$



$$i\frac{g m_Z}{c_W}(c+\gamma a)\eta^{\mu\nu}$$



$$-i\frac{g}{2}\frac{m_f}{m_W}(c+\gamma a)$$



$$i g m_W(c+\gamma a)\eta^{\mu\nu}$$

The gg and $\gamma\gamma$ couplings

- There are the standard loop contributions, except rescaled by $f\overline{f}/VV$ strength factor.

  For c_γ, the $\sum_i$ comprises all charged fermions (including quarks, with $N_c^i = 3$ and $e_i = 2/3$ or $-1/3$, and leptons, with $e_i = -1$ and $N_c^i = 1$) and the W boson (with $e_i = 1$ and $N_c^i = 1$).

  For c_g, the $\sum_i$ is over all colored fermions (assumed to have $N_c^i = 3$).

  The auxiliary functions are:

$$F_{1/2}(\tau) = -2\tau[1 + (1-\tau)f(\tau)]\,, \tag{21}$$

$$F_1(\tau) = 2 + 3\tau + 3\tau(2-\tau)f(\tau)\,, \tag{22}$$

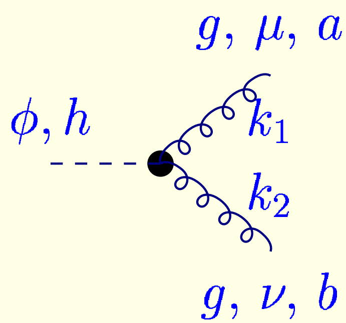
  for spin-1/2 and spin-1 loop particles, respectively, with

$$f(\tau) = -\tfrac{1}{4}\ln\left[-\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right]^2 \tag{23}$$

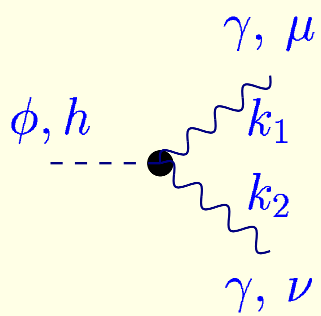
$\tau \equiv 4m^2/M^2$, where m is the mass of the internal loop particle and M is the mass of the scalar state, h or ϕ.

- Must include the anomalous contributions, which are expressed in terms of the SU(3)×SU(2)×U(1) β function coefficients $b_3 = 7$, $b_2 = 19/6$ and $b_Y = -41/6$.

- For the h, $g_{fV} = d + \gamma b$ and $g_r = \gamma b$. For the ϕ, $g_{fV} = c + \gamma a$ and $g_r = \gamma a$.



$$ic_g\delta^{ab}[k_1\cdot k_2\eta^{\mu\nu}-k_1^\nu k_2^\mu]:\ c_g=-\frac{\alpha_s}{4\pi v}[g_{fV}\sum_i F_{1/2}(\tau_i)-2b_3g_r]$$



$$ic_\gamma[k_1\cdot k_2\eta^{\mu\nu}-k_1^\nu k_2^\mu]:\ c_\gamma=-\frac{\alpha}{2\pi v}[g_{fV}\sum_i e_i^2N_c^iF_i(\tau_i)-(b_2+b_Y)g_r]$$

$Zh\phi$ tree level couplings are absent.

The cubic interactions

1. First, we have

$$\mathcal{L} \ni -V(H_0) = -\lambda(H_0^\dagger H_0 - \frac{1}{2}v_0^2)^2 = -\lambda(v_0^2 h_0^2 + v_0 h_0^3 + \frac{1}{4}h_0^4)\,, \quad (24)$$

after substituting $H_0 = \frac{1}{\sqrt{2}}(v_0 + h_0)$. Expressing λ in terms of m_{h_0} as in Eq. (??), the h_0^3 term of Eq. (24) becomes

$$\mathcal{L} \ni -\frac{m_{h_0}^2}{2v_0} h_0^3\,. \quad (25)$$

2. The interaction of ϕ_0 with $T_\mu^\mu(h_0)$:

$$-\frac{\phi_0}{\Lambda_\phi} T_\mu^\mu(h_0) = -\frac{\phi_0}{\Lambda_\phi}\left(-\partial^\rho h_0 \partial_\rho h_0 + 4\lambda v_0^2 h_0^2\right)\,. \quad (26)$$

3. The interaction of the KK-gravitons with $T^{\mu\nu}(h_0)$:

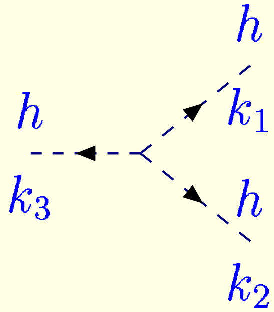
$$-\frac{\epsilon}{2}h_{\mu\nu}(x,y=1/2)T^{\mu\nu} \ni -\frac{1}{\widehat{\Lambda}_W}\sum_n h^n_{\mu\nu}\partial^\mu h_0 \partial^\nu h_0\,, \tag{27}$$

where we keep only the derivative contributions and we have dropped (using the gauge $h_\mu^{\mu\,n}=0$) the $\eta^{\mu\nu}$ parts of $T^{\mu\nu}$.

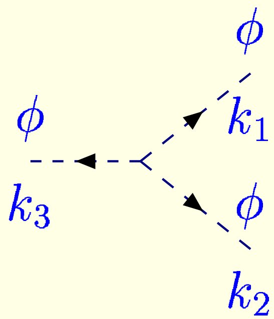
4. The ξ-dependent tri-linear components of Eq. (??):

$$\begin{aligned}
&6\xi\Omega(x)\left(-\Box\Omega(x)+\epsilon h_{\mu\nu}(x,y=1/2)\partial^\mu\partial^\nu\Omega(x)\right)H_0^\dagger H_0\\
&\ni \Big[-3\frac{\xi}{\Lambda_\phi}h_0^2\Box\phi_0 - 6\xi\frac{v_0}{\Lambda_\phi^2}h_0\phi_0\Box\phi_0\\
&-12\xi\frac{v_0}{\widehat{\Lambda}_W\Lambda_\phi}\sum_n h^n_{\mu\nu}\partial^\mu\phi_0\partial^\nu h_0 - 6\xi\frac{v_0^2}{\widehat{\Lambda}_W\Lambda_\phi^2}\sum_n h^n_{\mu\nu}\partial^\mu\phi_0\partial^\nu\phi_0\Big]
\end{aligned} \tag{28}$$

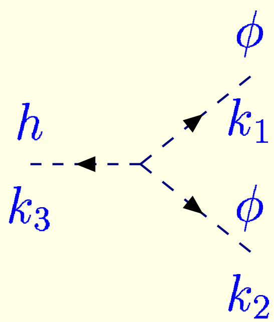
where we have employed the expansion of $h_{\mu\nu}(x,y=1/2)$ in terms of the $h^n_{\mu\nu}$, used the gauge conditions $\partial^\mu h^n_{\mu\nu}=0$ and $h_\mu^{\mu\,n}=0$, and also used the symmetry of $h_{\mu\nu}$.



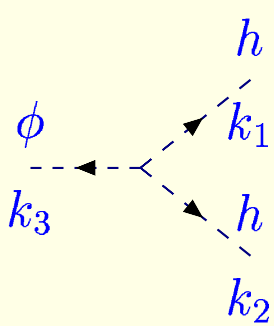
$$i\frac{g_{hhh}}{\Lambda_\phi} \equiv \frac{i}{\Lambda_\phi}\left[bd\Big\{[12b\gamma\xi + d(6\xi+1)]\,(k_1^2+k_2^2+k_3^2) - 12dm_{h_0}^2\Big\} - 3\gamma^{-1}d^3m_{h_0}^2\right]$$



$$i\frac{g_{\phi\phi\phi}}{\Lambda_\phi} \equiv \frac{i}{\Lambda_\phi}\left[ac\Big\{[12a\gamma\xi + c(6\xi+1)]\,(k_1^2+k_2^2+k_3^2) - 12cm_{h_0}^2\Big\} - 3\gamma^{-1}c^3m_{h_0}^2\right]$$



$$i\frac{g_{\phi\phi h}}{\Lambda_\phi} \equiv \frac{i}{\Lambda_\phi}\left[\Big\{6a\xi(\gamma(ad+bc)+cd)+bc^2\Big\}(k_1^2+k_2^2) \right.$$
$$\left. + c\Big\{12ab\gamma\xi + 2ad + bc(6\xi-1)\Big\}k_3^2 - 4c(2ad+bc)m_{h_0}^2 - 3\gamma^{-1}c^2dm_{h_0}^2\right]$$



$$i\frac{g_{\phi hh}}{\Lambda_\phi} \equiv \frac{i}{\Lambda_\phi}\left[\Big\{6b\xi(\gamma(ad+bc)+cd)+ad^2\Big\}(k_1^2+k_2^2) \right.$$
$$\left. + d\Big\{12ab\gamma\xi + 2bc + ad(6\xi-1)\Big\}k_3^2 - 4d(ad+2bc)m_{h_0}^2 - 3\gamma^{-1}cd^2m_{h_0}^2\right]$$

Constraints from LEP/LEP2

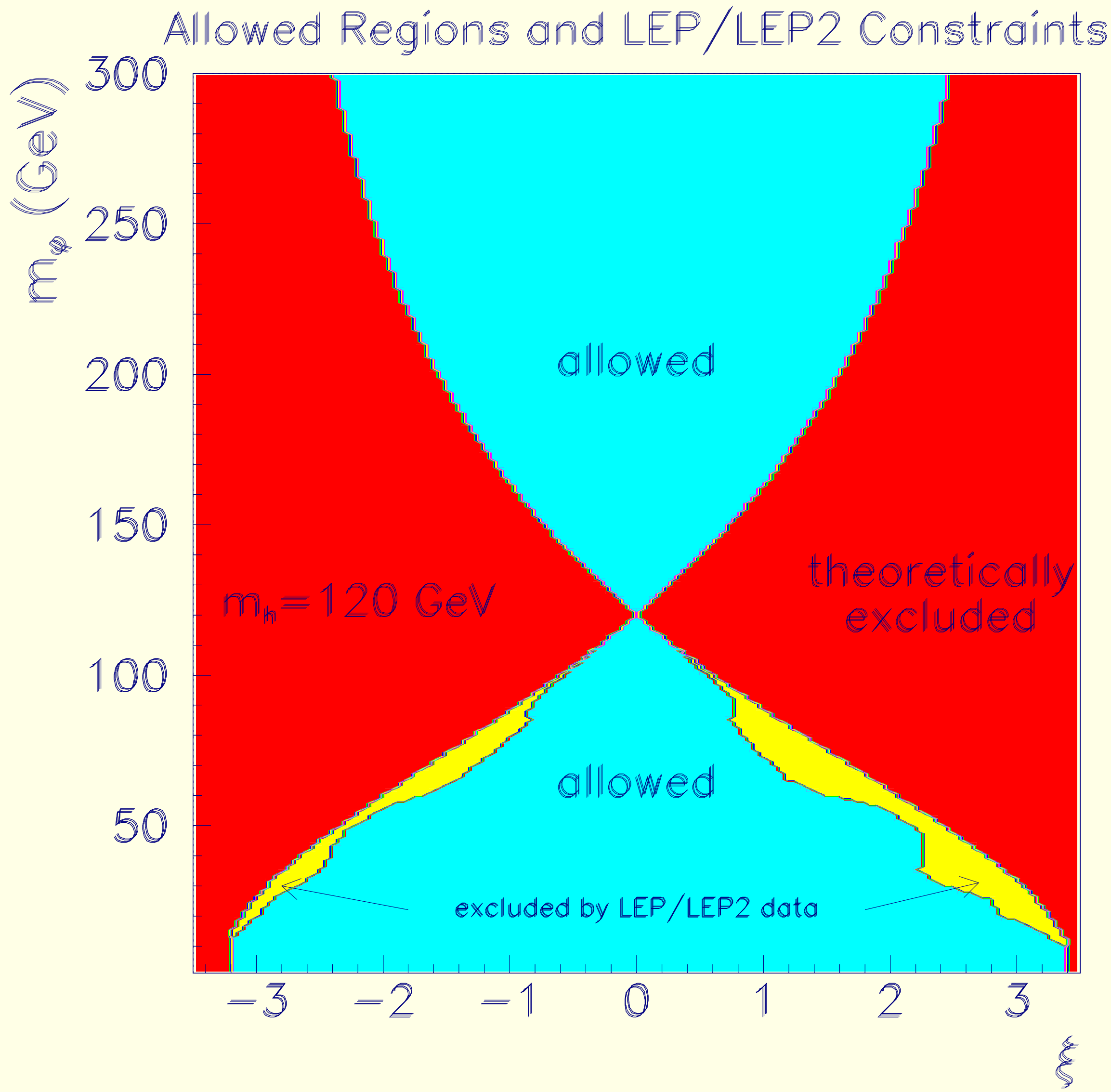
- Choose $\Lambda_\phi = 5~\mathrm{TeV}$. The $Z^2 > 0$ gives ξ constraint.

- LEP/LEP2 provides an upper limit on ZZs ($s = h$ or ϕ) from which we can exclude regions in the (m_h, m_ϕ) plane for a given choice of R^2.

  Use upper limits on the ZZs coupling in both with and without b tagging, with computed branching ratios into b and non-b final states.

- **Conclusion:**

  Small m_ϕ relative to m_h is entirely possible given current data so long as $m_h \gtrsim 115~\mathrm{GeV}$. (The $ZZ\phi$ coupling does not blow up.)

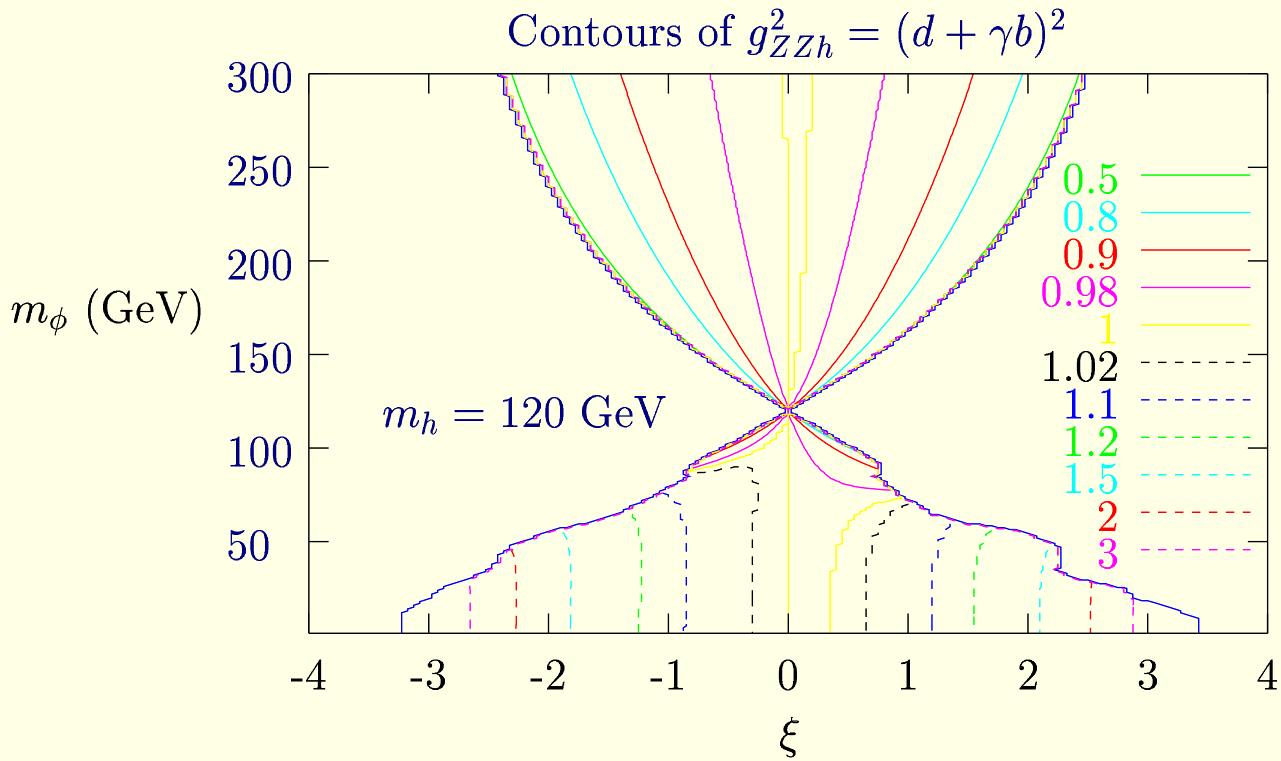

Allowed Regions and LEP/LEP2 Constraints
m_φ (GeV)
300
250
200
150
100
50
allowed
m_h=120 GeV
theoretically
excluded
allowed
excluded by LEP/LEP2 data
−3
−2
−1
0
1
2
3
ξ

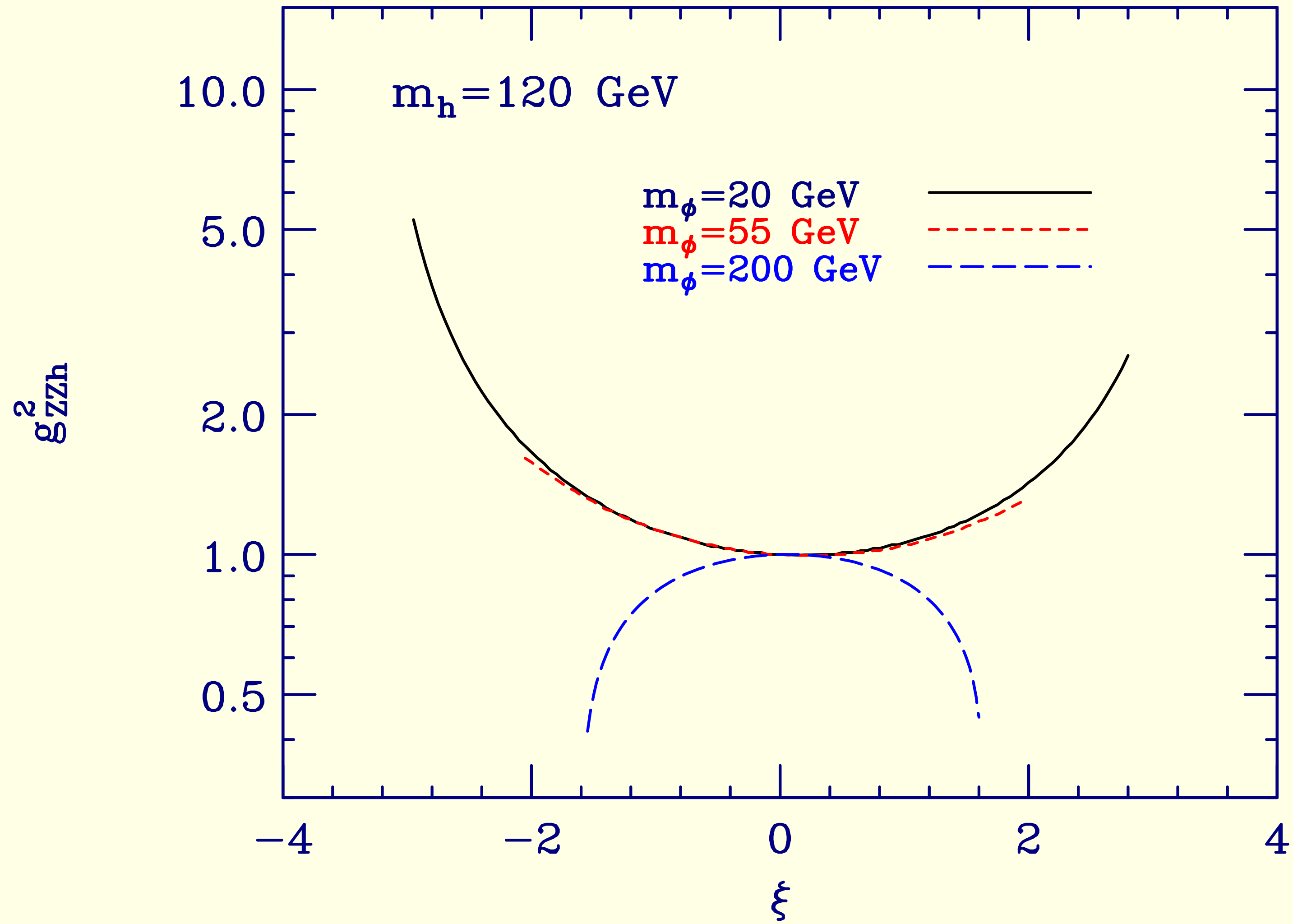
Couplings

- **First, consider the $f\overline{f}/VV$ couplings of h and ϕ relative to SM, taking $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV.**

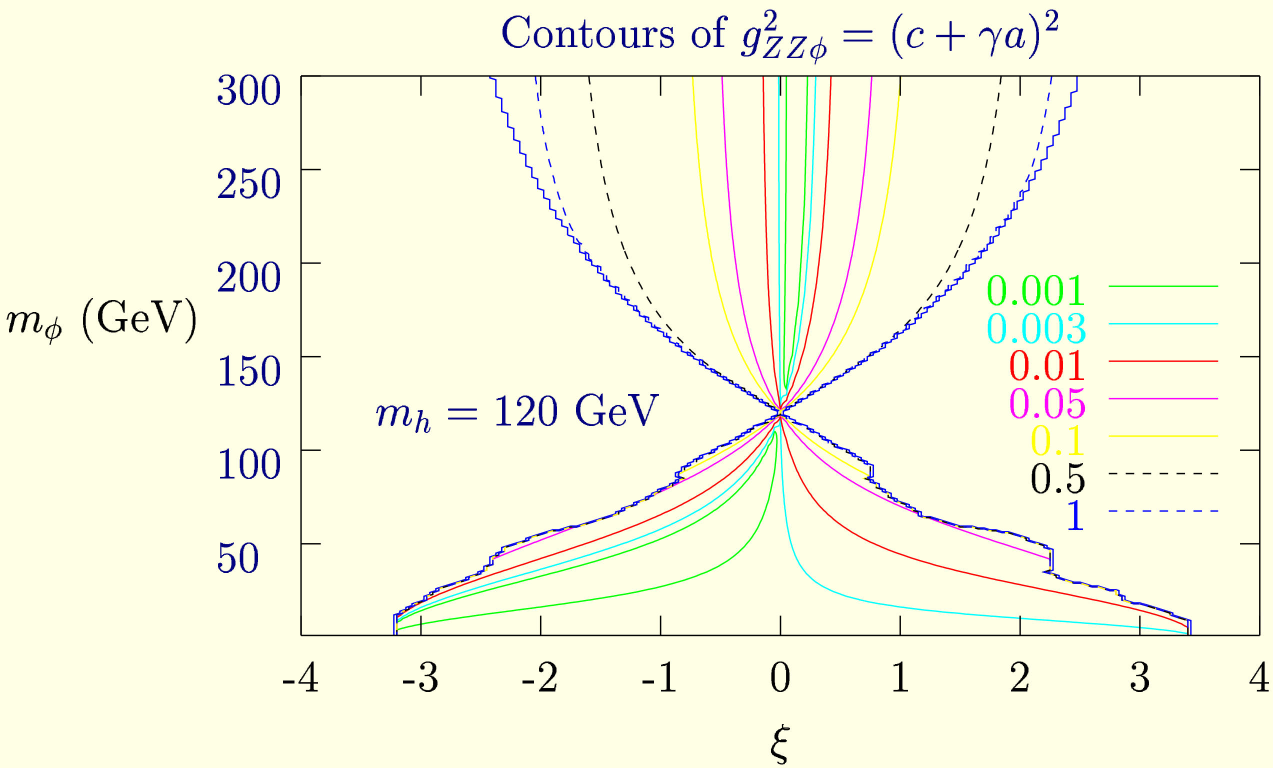
- **Next, the h^3 and ϕ^3 couplings relative to $h^3_{\rm SM}$ taking $m_{h_{\rm SM}} = m_h$ or m_ϕ, respectively.**

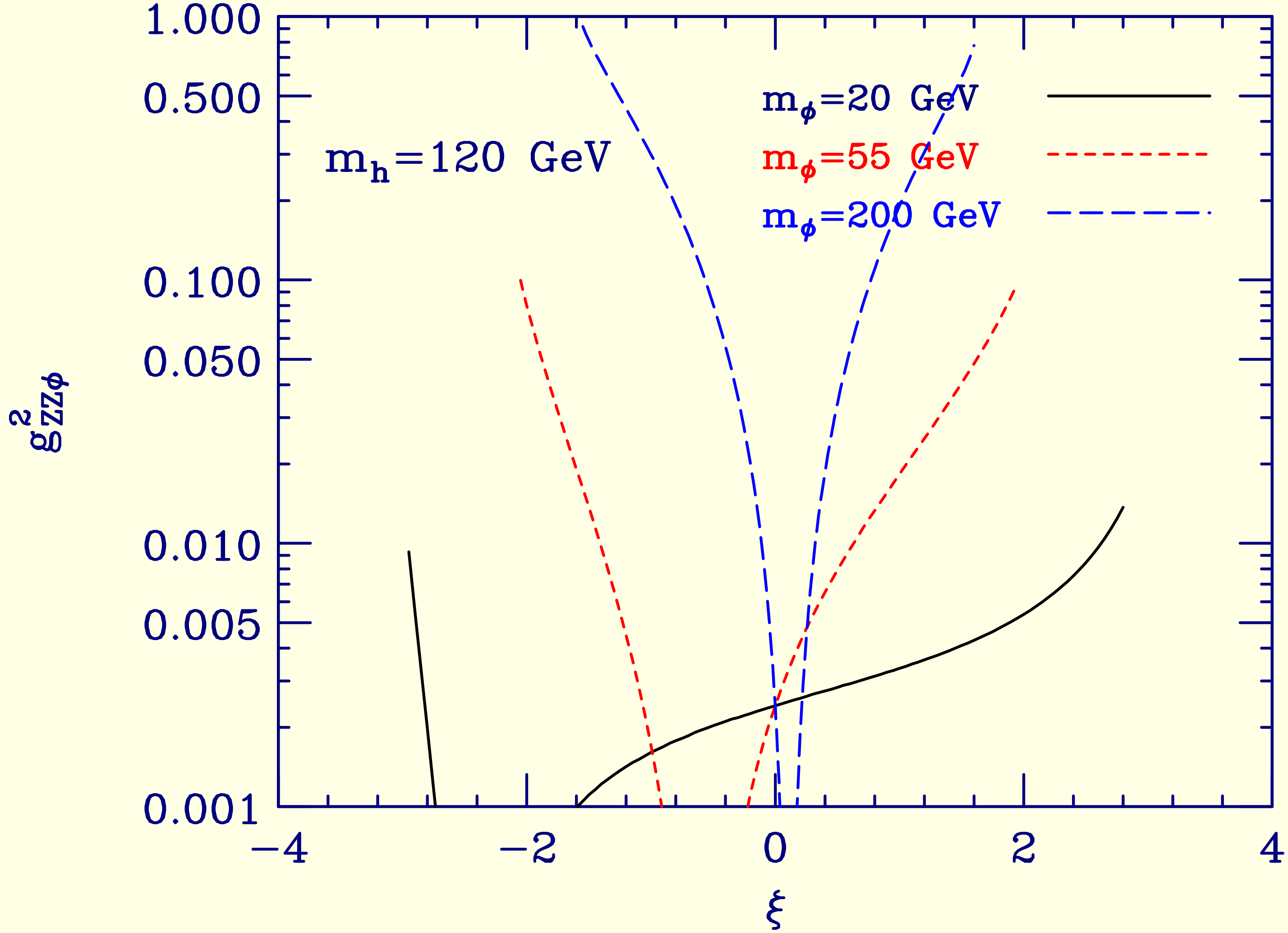
  Deviations shown should be readily explorable at an LC for the h^3 coupling, but the ϕ^3 coupling may be difficult to probe except where it gets near 1 (relative to SM comparison).

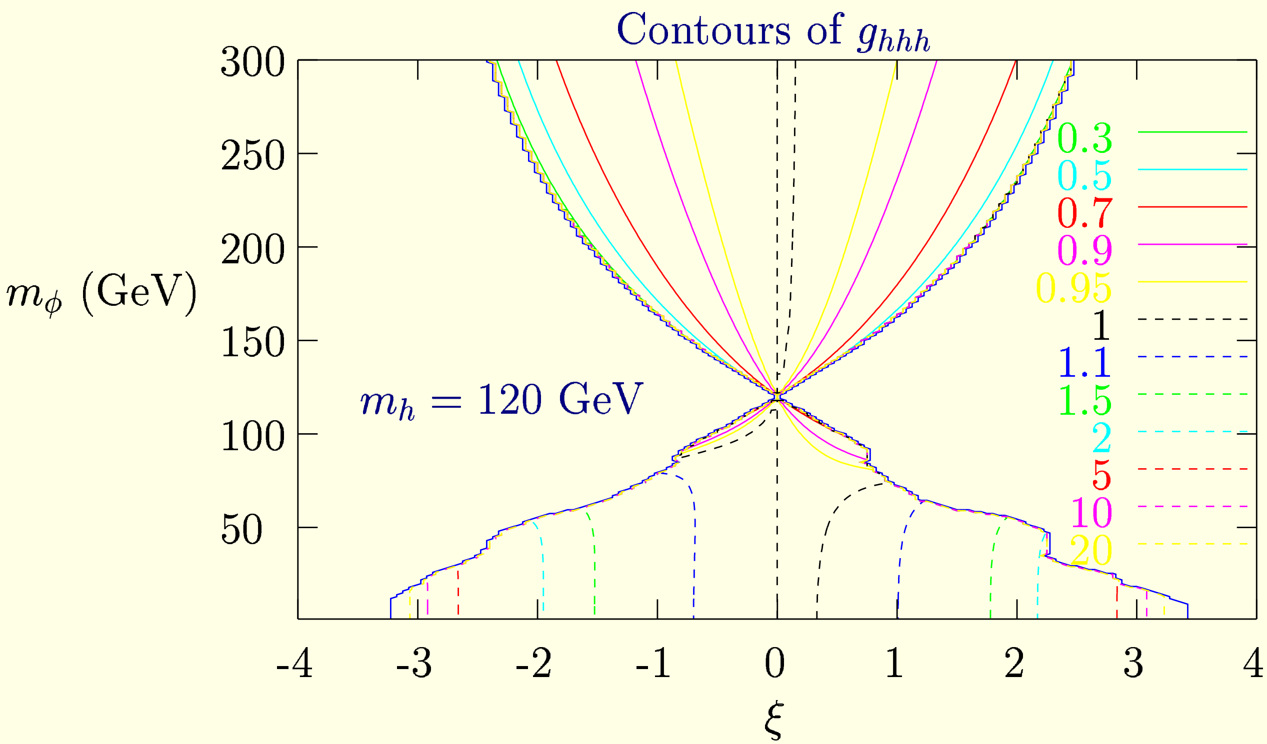

Contours of $g^2_{ZZh} = (d + \gamma b)^2$
300
250
200
150
100
50
m_ϕ (GeV)
$m_h = 120$ GeV
0.5
0.8
0.9
0.98
1
1.02
1.1
1.2
1.5
2
3
-4
-3
-2
-1
0
1
2
3
4
ξ



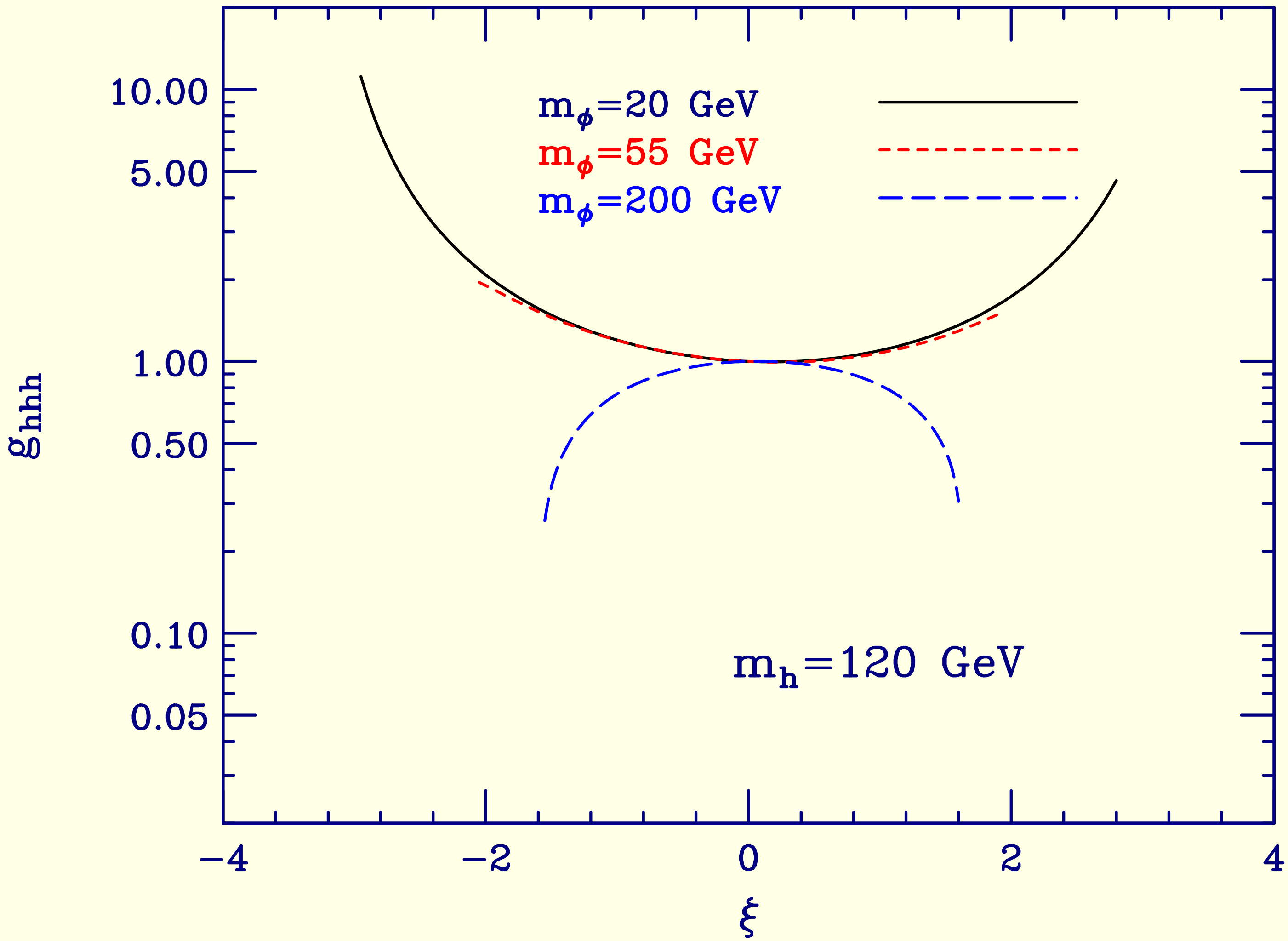
m_h=120 GeV
m_ϕ=20 GeV
m_ϕ=55 GeV
m_ϕ=200 GeV
10.0
5.0
2.0
1.0
0.5
g^2_{ZZh}
−4
−2
0
2
4
ξ


Contours of $g^2_{ZZ\phi} = (c + \gamma a)^2$
300
250
200
150
100
50
m_ϕ (GeV)
$m_h = 120$ GeV
0.001
0.003
0.01
0.05
0.1
0.5
1
-4
-3
-2
-1
0
1
2
3
4
ξ

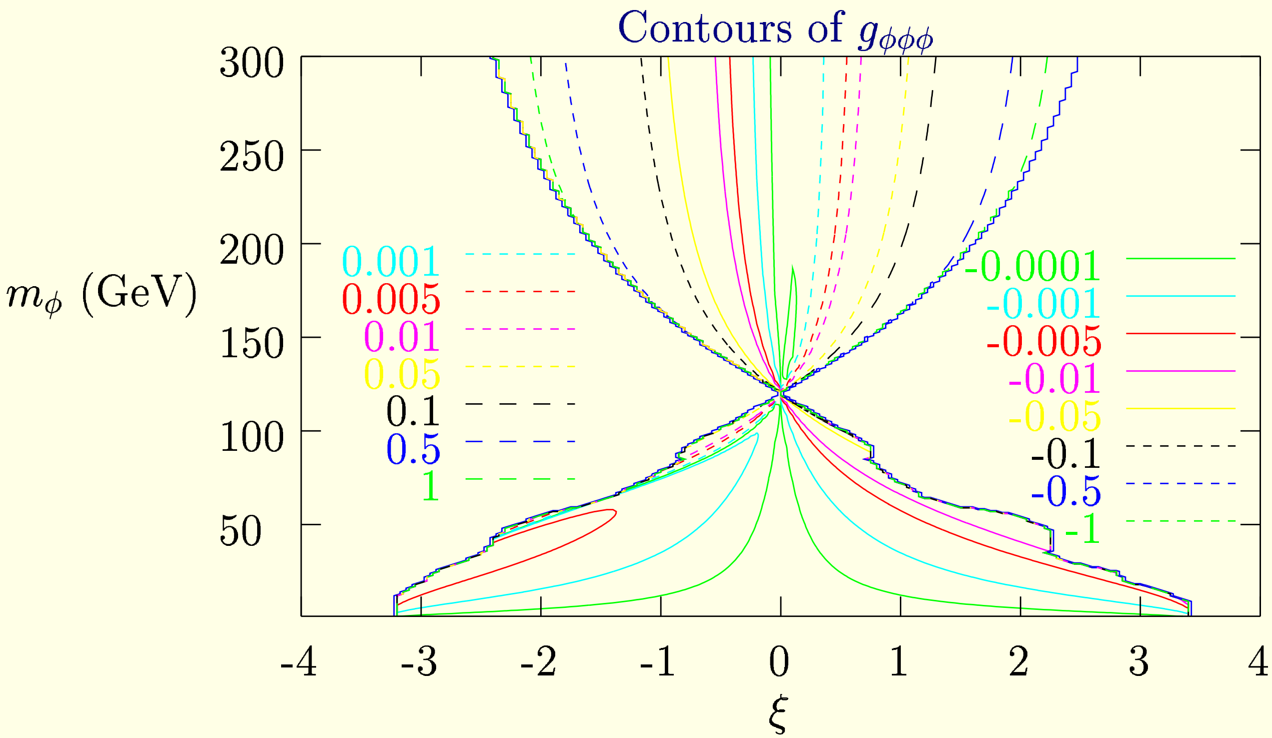

1.000
0.500
0.100
0.050
0.010
0.005
0.001
−4
−2
0
2
4
ξ
$g^2_{ZZ\phi}$
m_h=120 GeV
m_ϕ=20 GeV
m_ϕ=55 GeV
m_ϕ=200 GeV

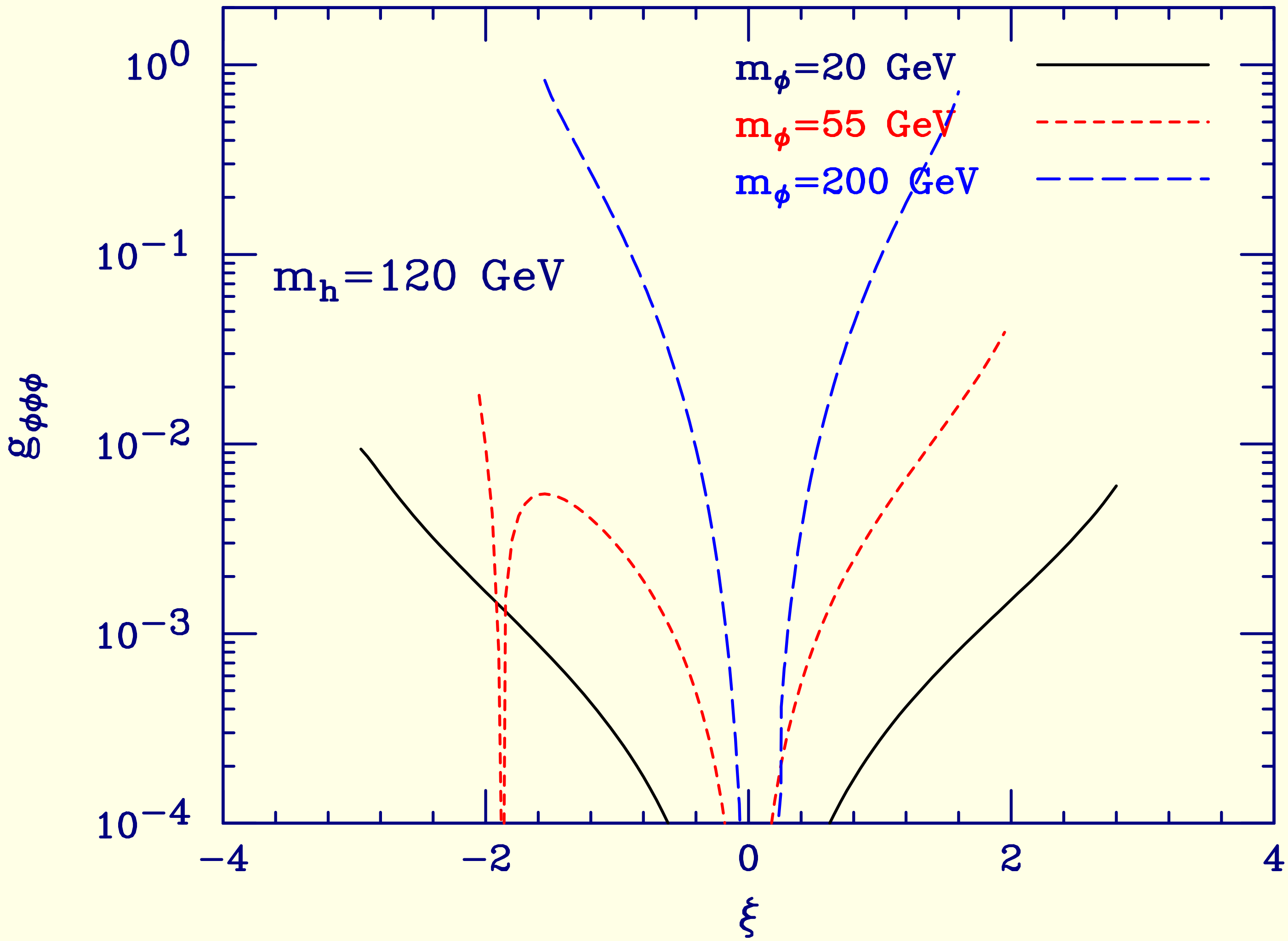


Contours of g_{hhh}
300
250
200
150
100
50
m_ϕ (GeV)
$m_h = 120$ GeV
0.3
0.5
0.7
0.9
0.95
1
1.1
1.5
2
5
10
20
-4
-3
-2
-1
0
1
2
3
4
ξ



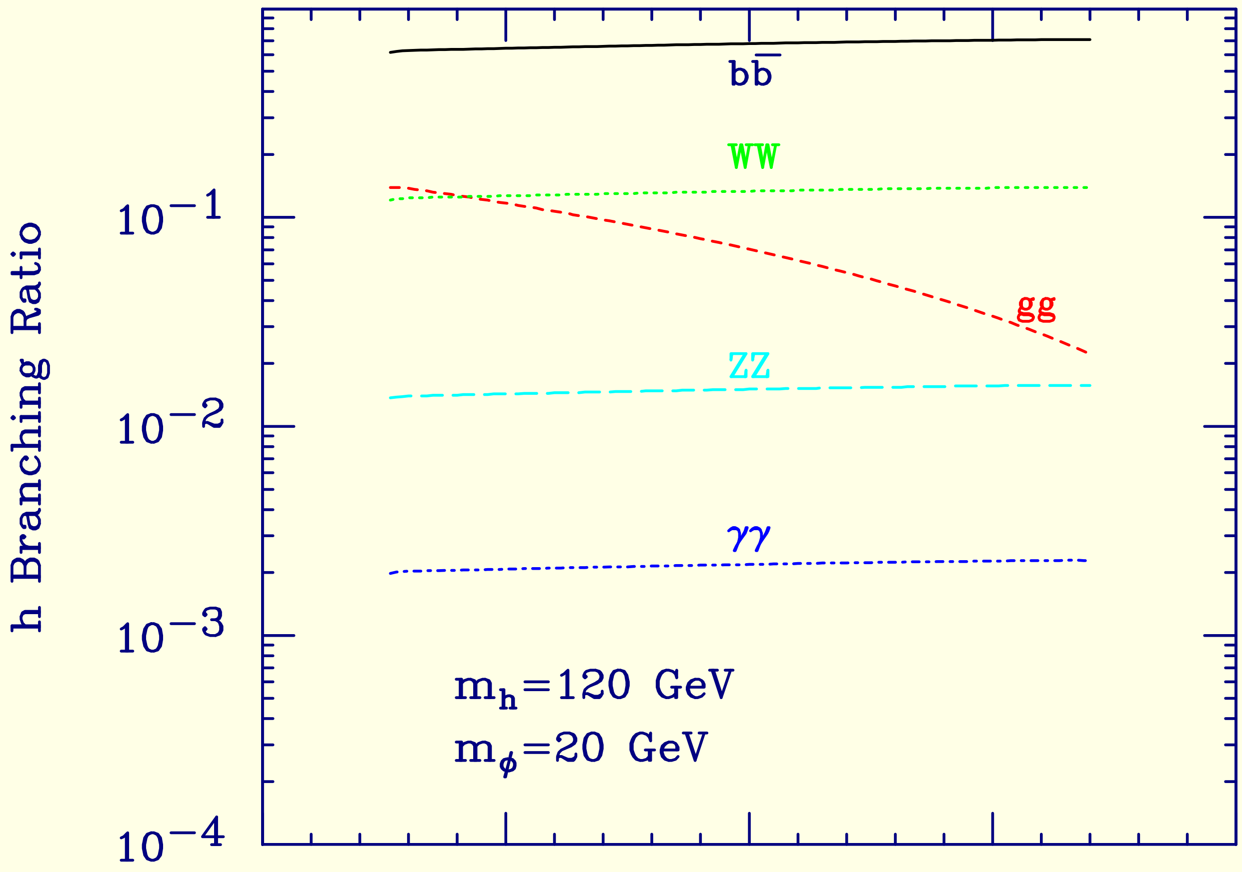
10.00
5.00
1.00
0.50
0.10
0.05
g_{hhh}
m_ϕ=20 GeV
m_ϕ=55 GeV
m_ϕ=200 GeV
m_h=120 GeV
−4
−2
0
2
4
ξ


Contours of $g_{\phi\phi\phi}$
300
250
200
150
100
50
m_ϕ (GeV)
-4
-3
-2
-1
0
1
2
3
4
ξ
0.001
0.005
0.01
0.05
0.1
0.5
1
-0.0001
-0.001
-0.005
-0.01
-0.05
-0.1
-0.5
-1

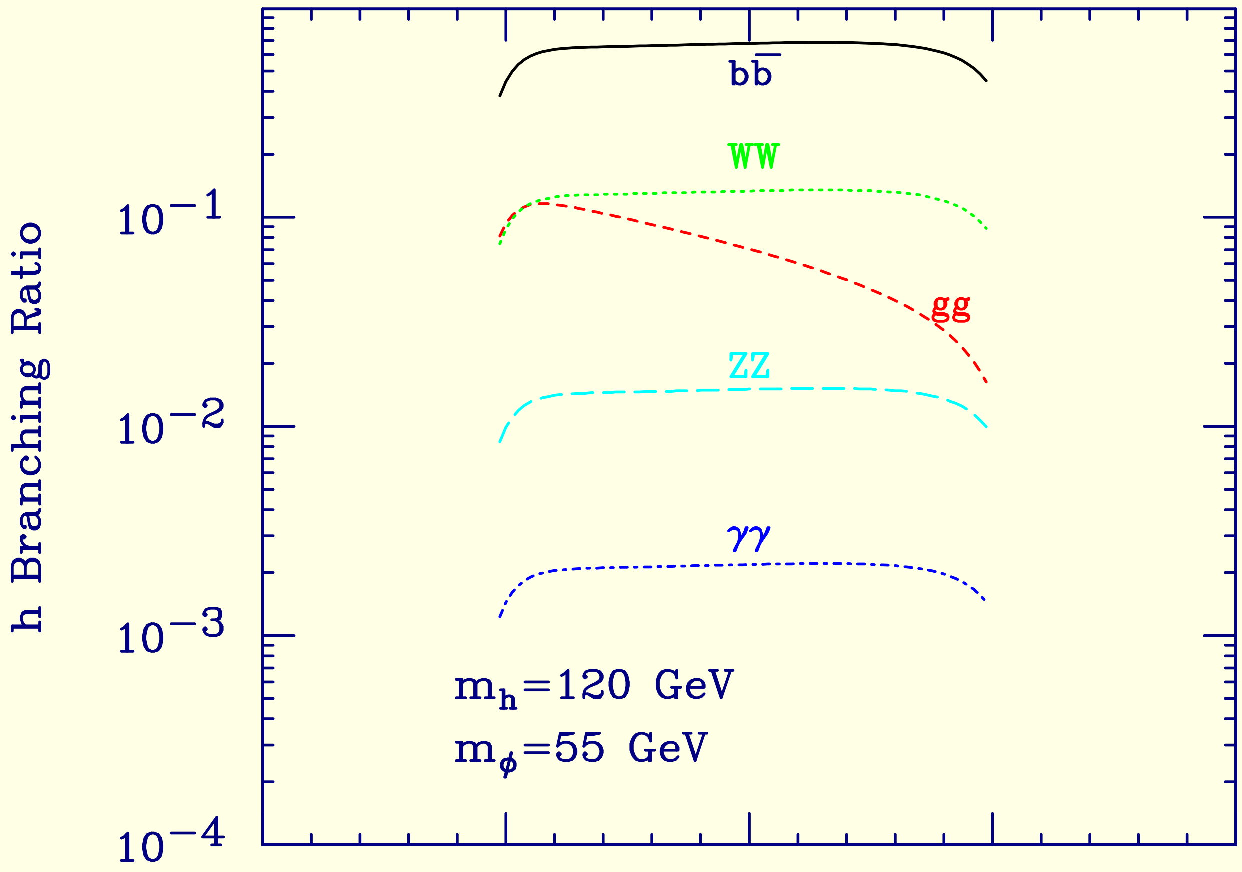


m_ϕ=20 GeV
m_ϕ=55 GeV
m_ϕ=200 GeV
m_h=120 GeV
$g_{\phi\phi\phi}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−4
−2
0
2
4
ξ

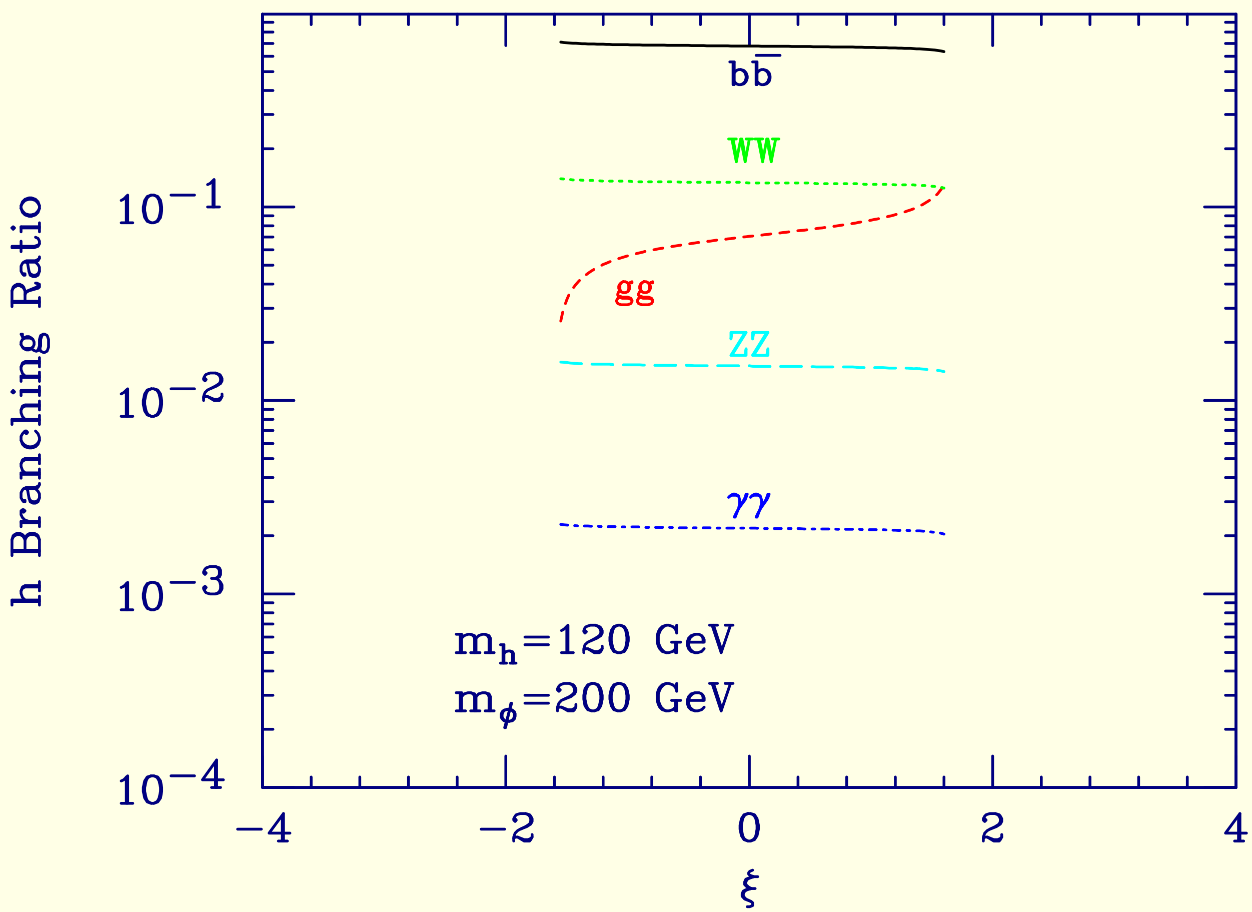
Physics Implications



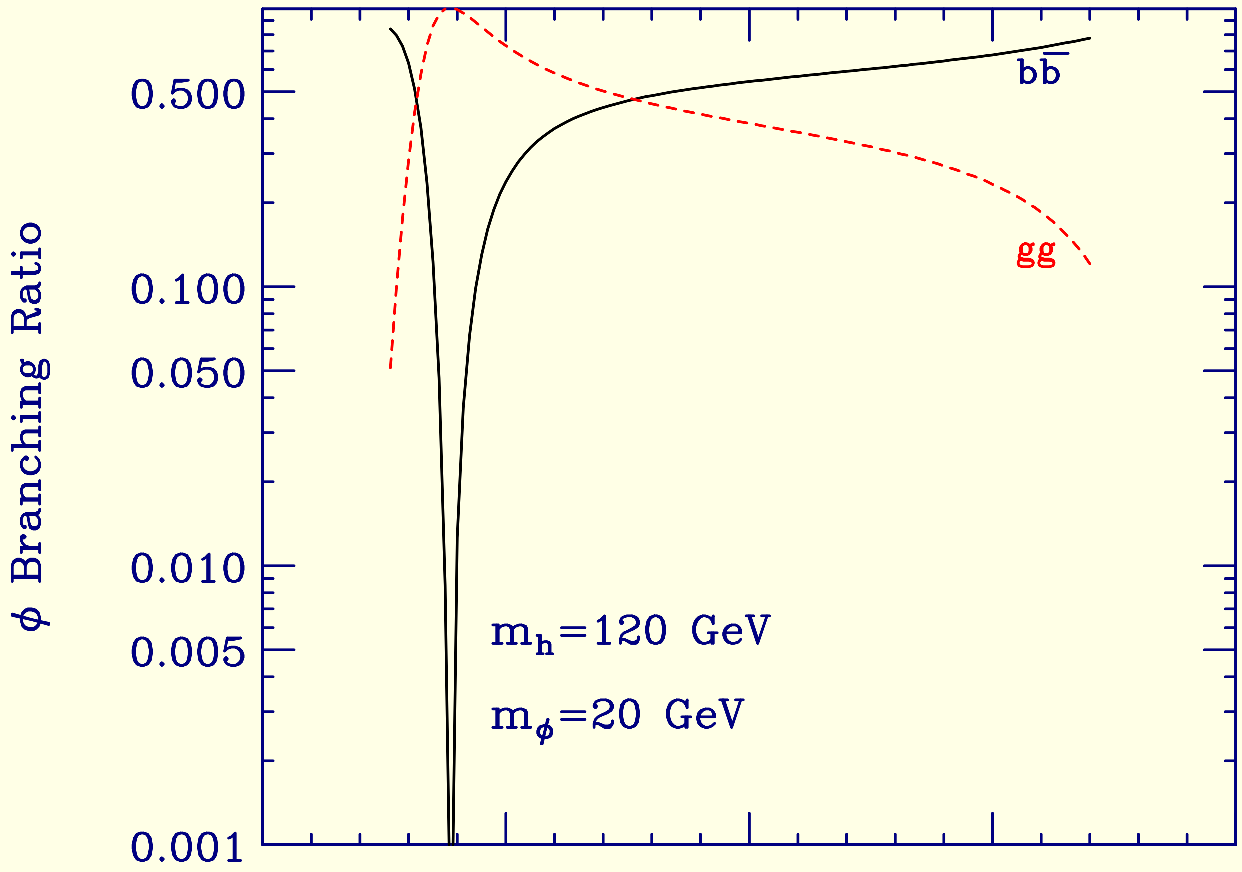
h Branching Ratio
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
WW
gg
ZZ
$\gamma\gamma$
m_h=120 GeV
m_ϕ=20 GeV

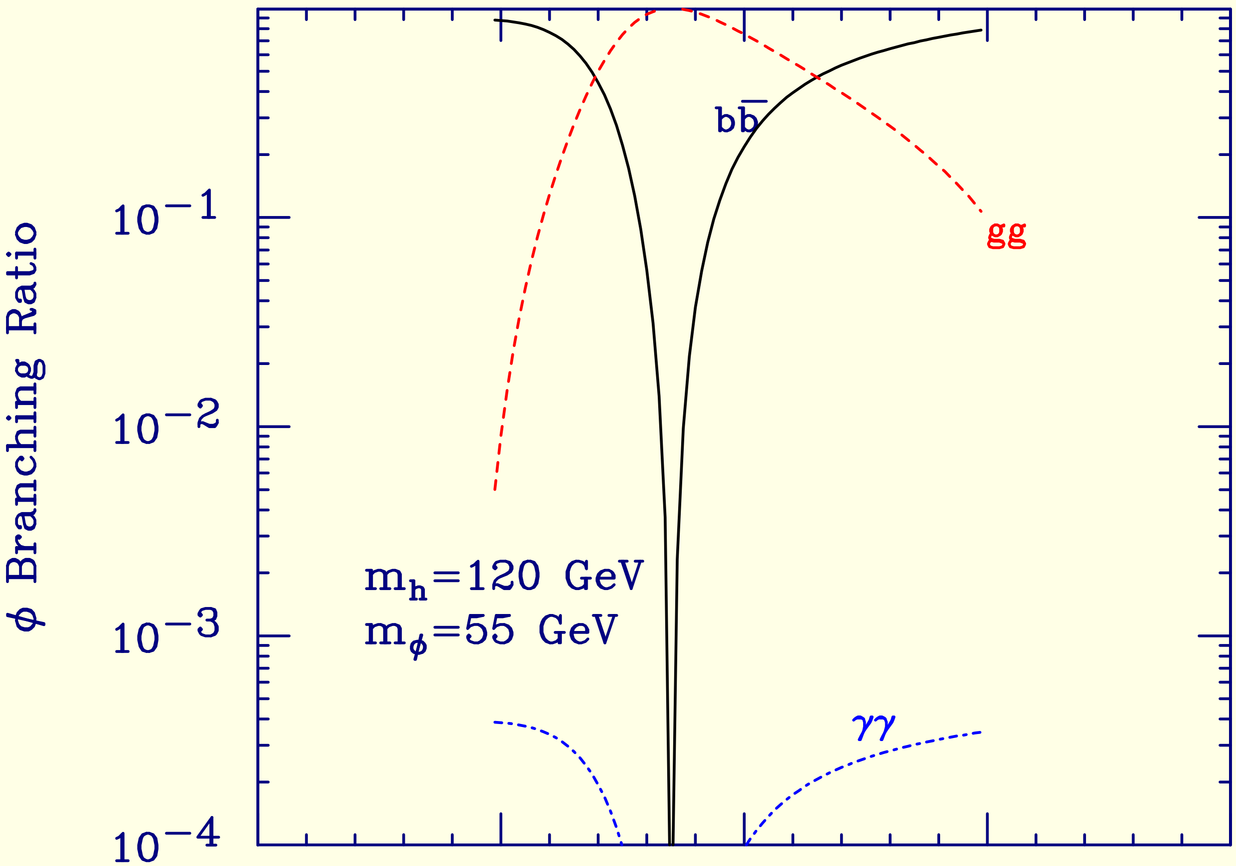


h Branching Ratio
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
WW
gg
ZZ
$\gamma\gamma$
m_h=120 GeV
m_ϕ=55 GeV

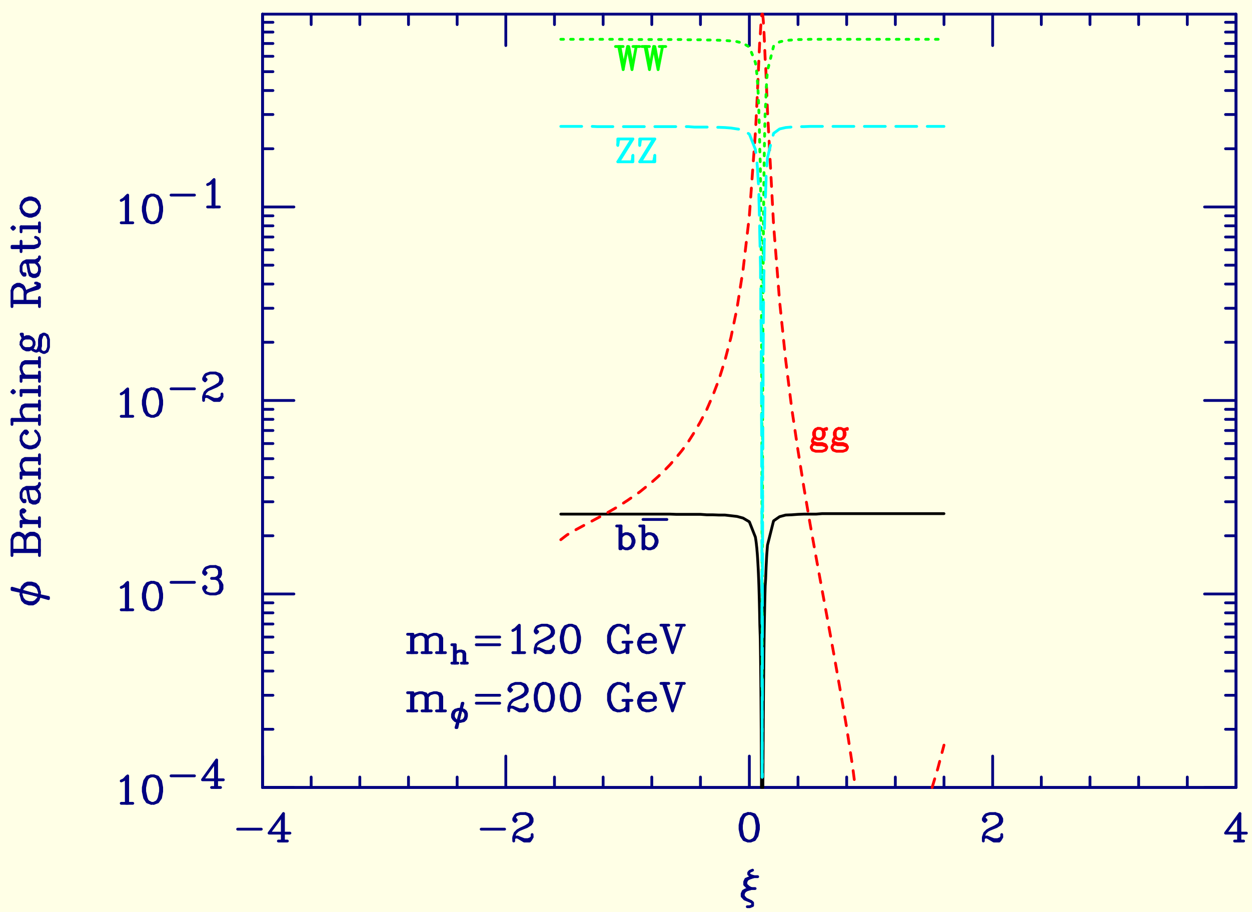


h Branching Ratio
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
WW
gg
ZZ
$\gamma\gamma$
m_h=120 GeV
m_ϕ=200 GeV
−4
−2
0
2
4
ξ

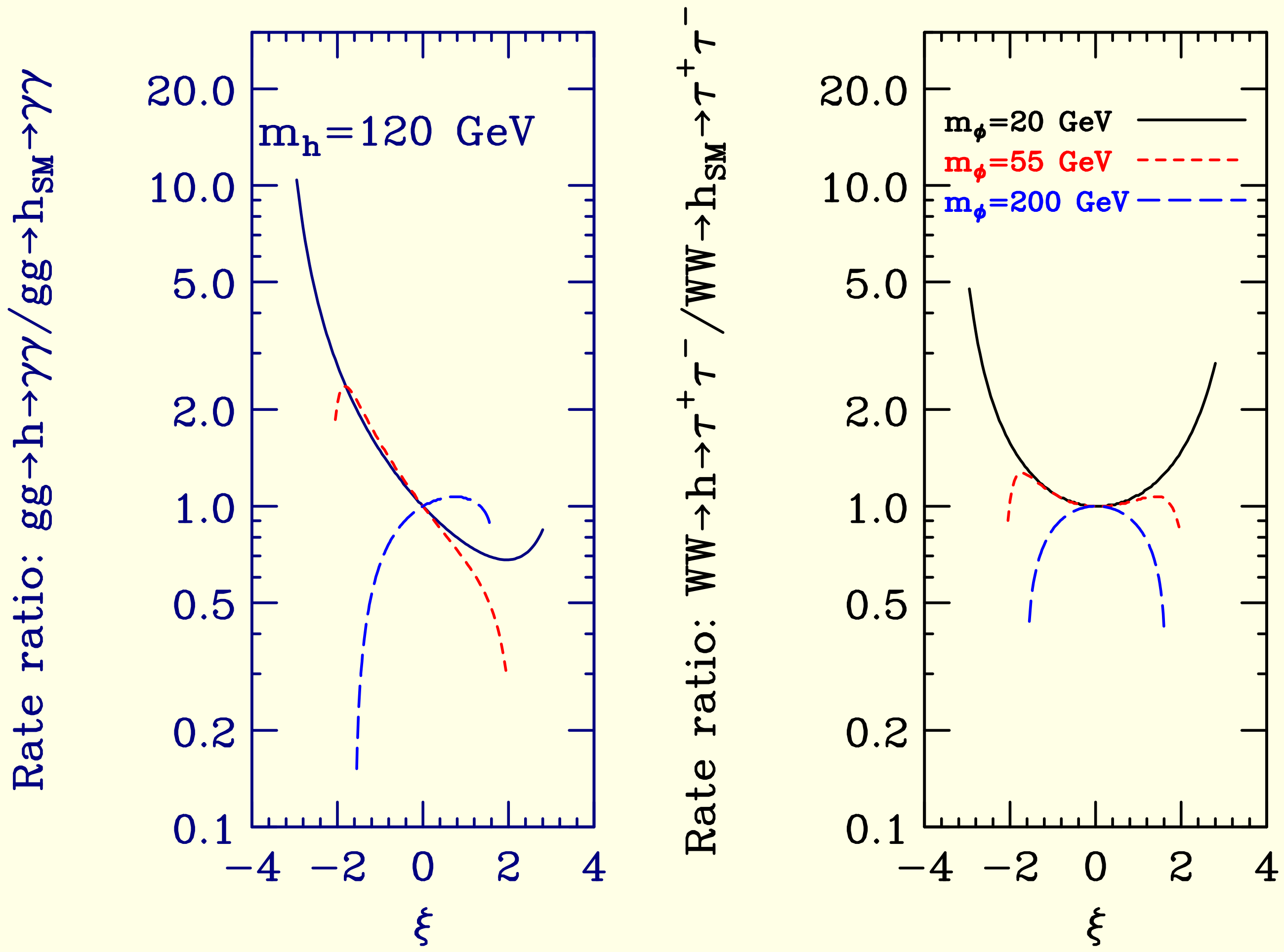

0.500
0.100
0.050
0.010
0.005
0.001
φ Branching Ratio
$b\bar{b}$
gg
m_h=120 GeV
m_ϕ=20 GeV



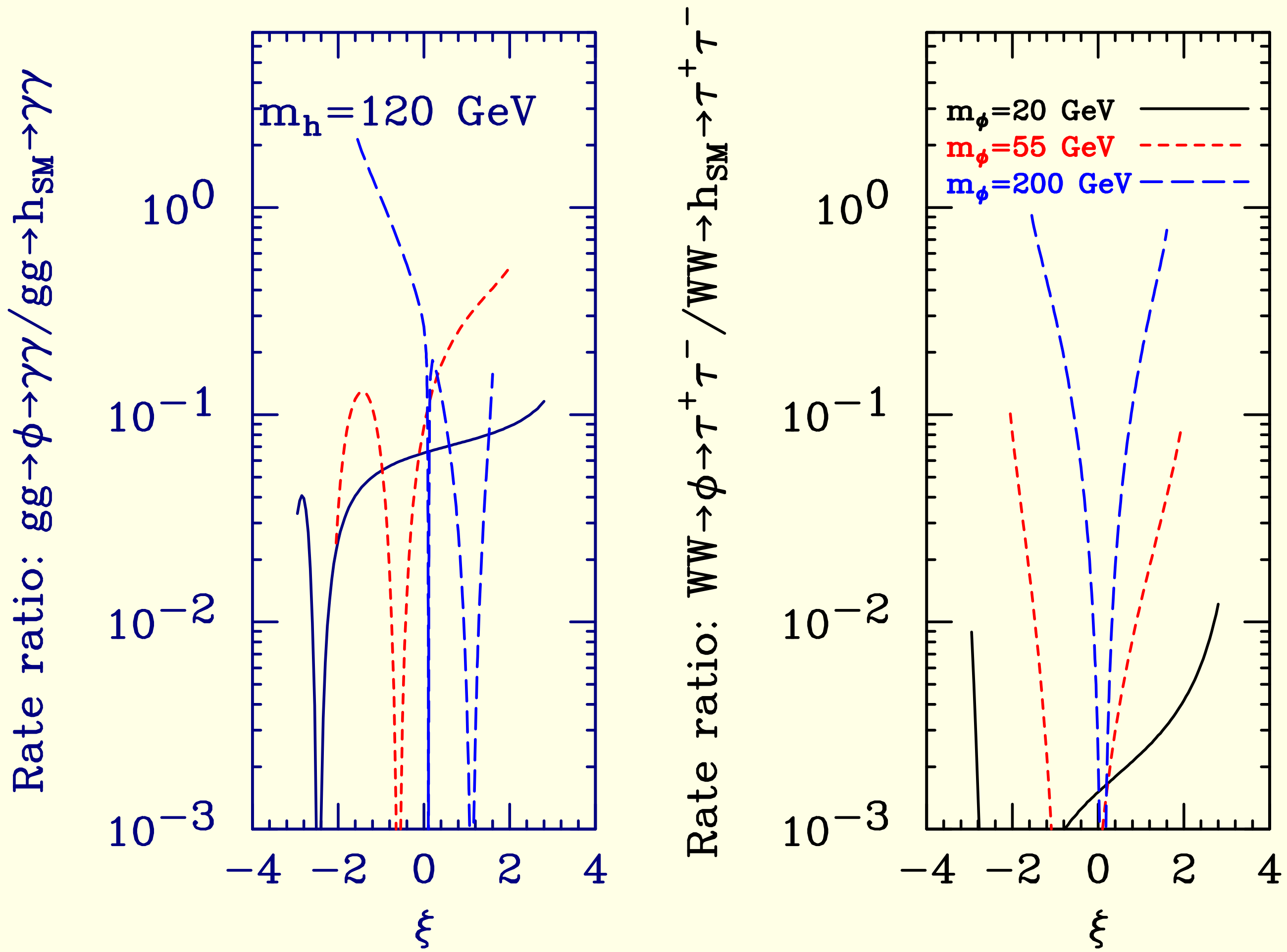
ϕ Branching Ratio
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
gg
$\gamma\gamma$
m_h=120 GeV
m_ϕ=55 GeV



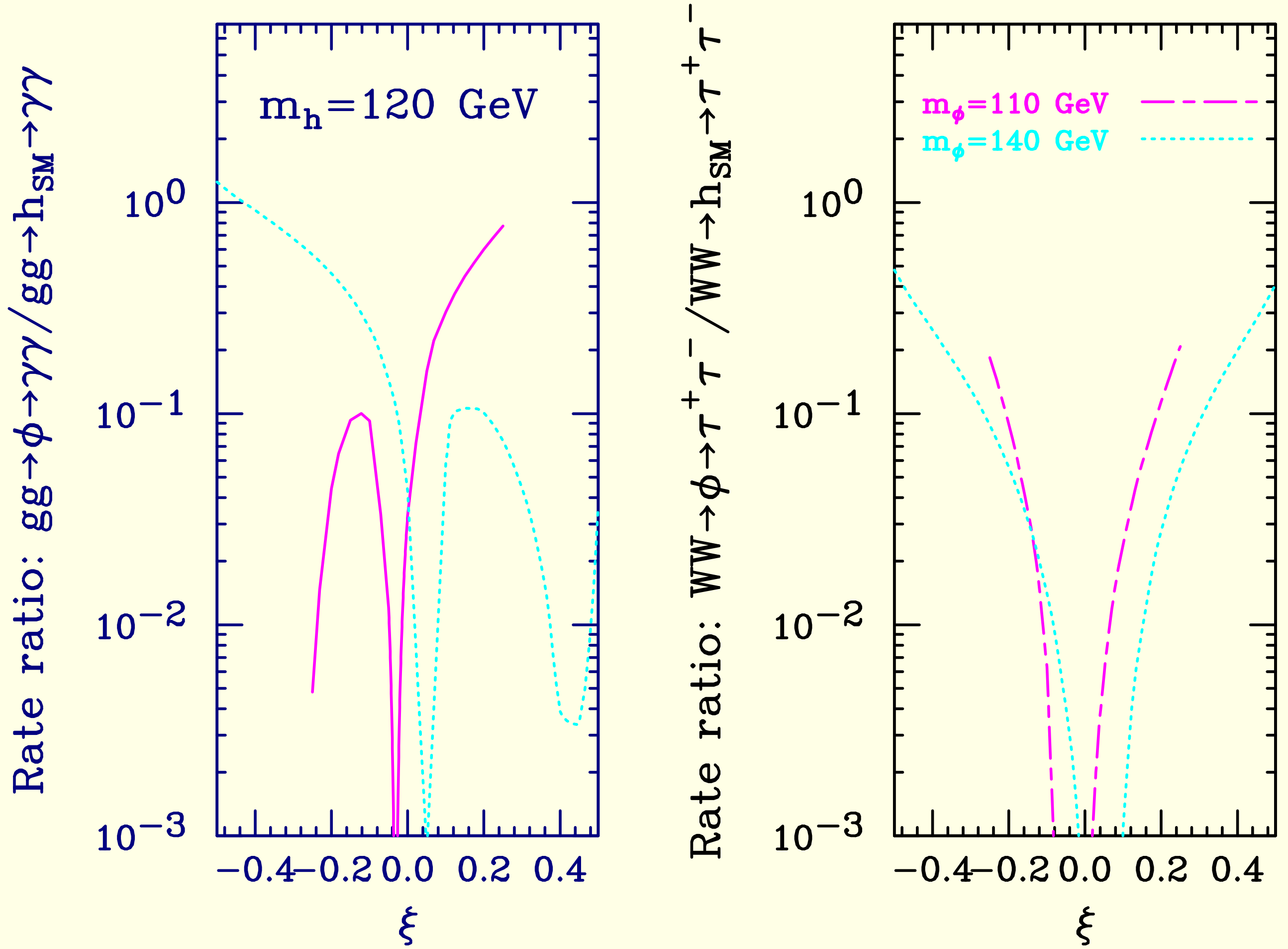
WW
ZZ
gg
$b\bar{b}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ϕ Branching Ratio
m_h=120 GeV
m_ϕ=200 GeV
−4
−2
0
2
4
ξ



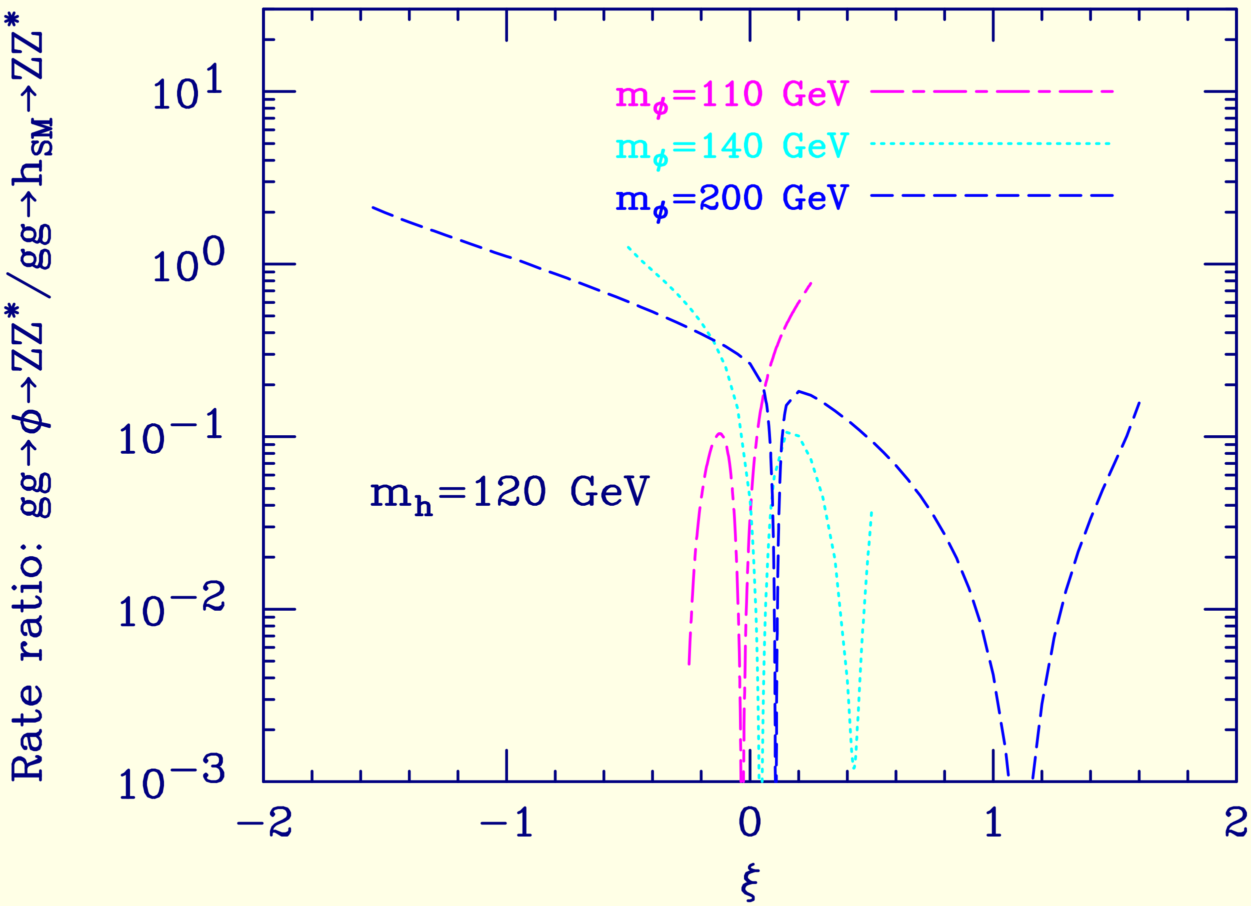
Rate ratio: gg→h→γγ/gg→h_SM→γγ
m_h=120 GeV
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
−4 −2 0 2 4
ξ
Rate ratio: WW→h→τ+τ−/WW→h_SM→τ+τ−
m_φ=20 GeV
m_φ=55 GeV
m_φ=200 GeV



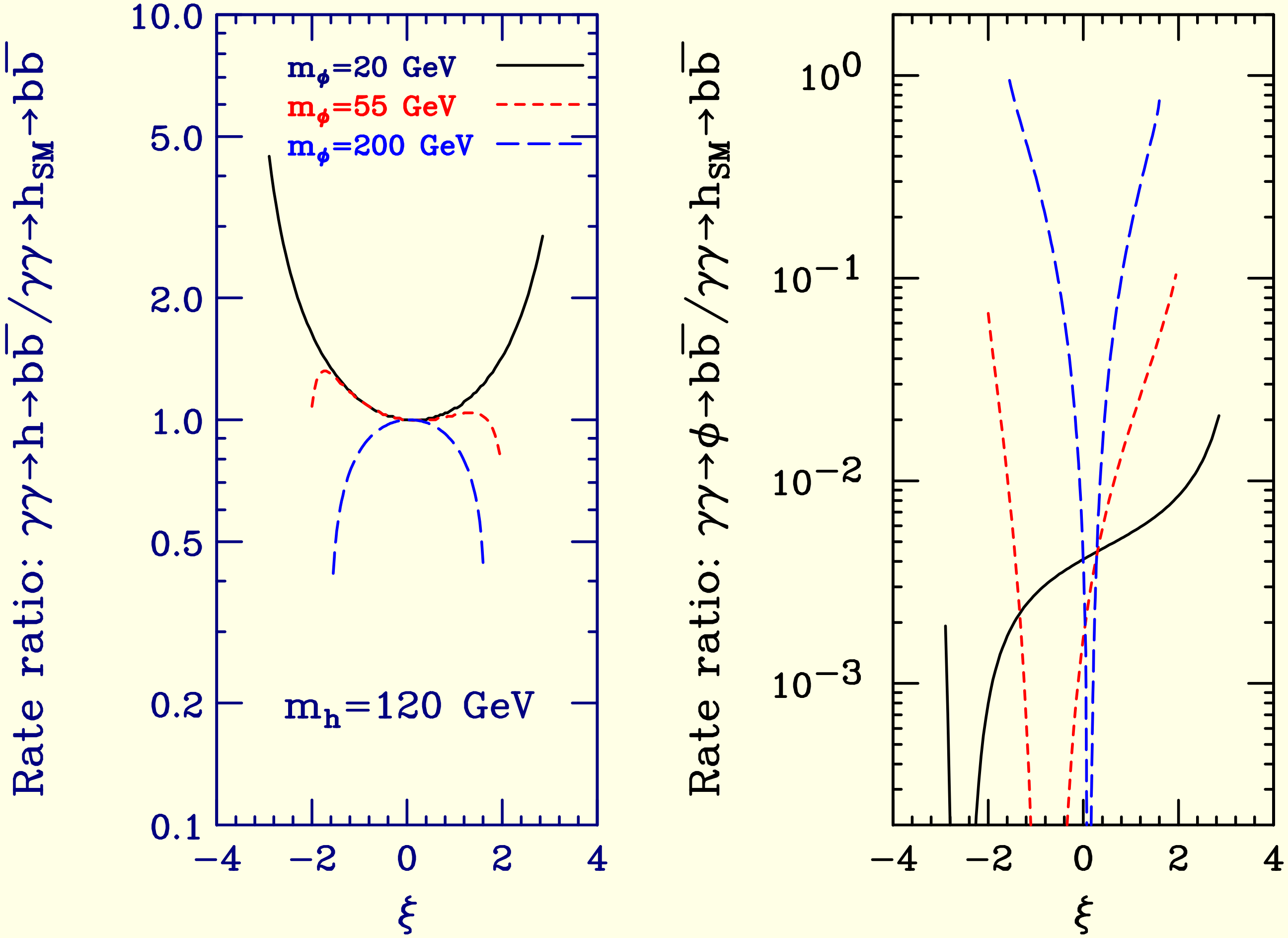
Rate ratio: gg→φ→γγ/gg→h_SM→γγ
m_h=120 GeV
10^0
10^-1
10^-2
10^-3
−4 −2 0 2 4
ξ
Rate ratio: WW→φ→τ^+τ^-/WW→h_SM→τ^+τ^-
m_φ=20 GeV
m_φ=55 GeV
m_φ=200 GeV
10^0
10^-1
10^-2
10^-3
−4 −2 0 2 4
ξ



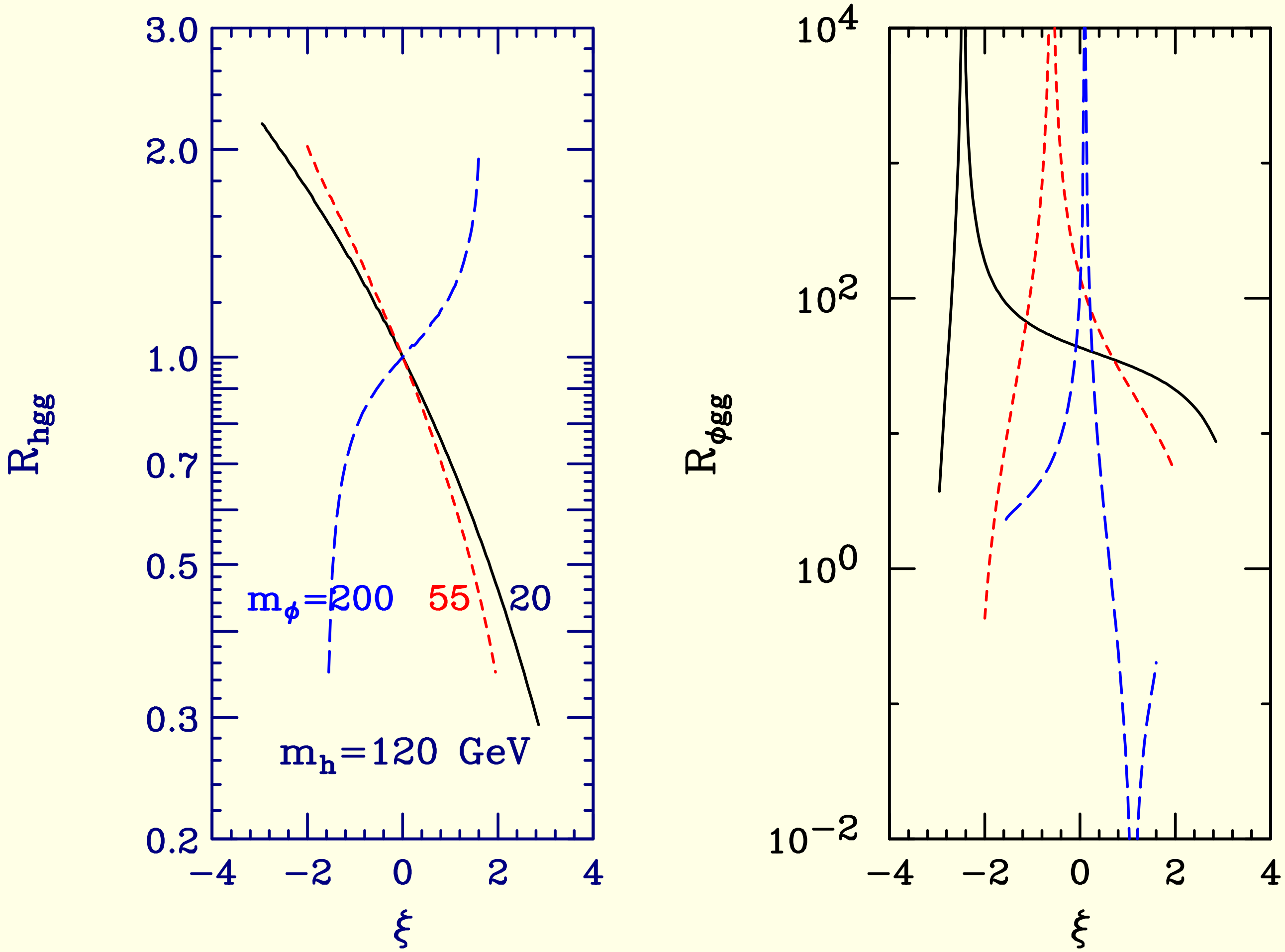
Rate ratio: gg→φ→γγ/gg→h_SM→γγ
m_h=120 GeV
10^0
10^−1
10^−2
10^−3
−0.4 −0.2 0.0 0.2 0.4
ξ
Rate ratio: WW→φ→τ+τ−/WW→h_SM→τ+τ−
m_φ=110 GeV
m_φ=140 GeV
10^0
10^−1
10^−2
10^−3
−0.4 −0.2 0.0 0.2 0.4
ξ

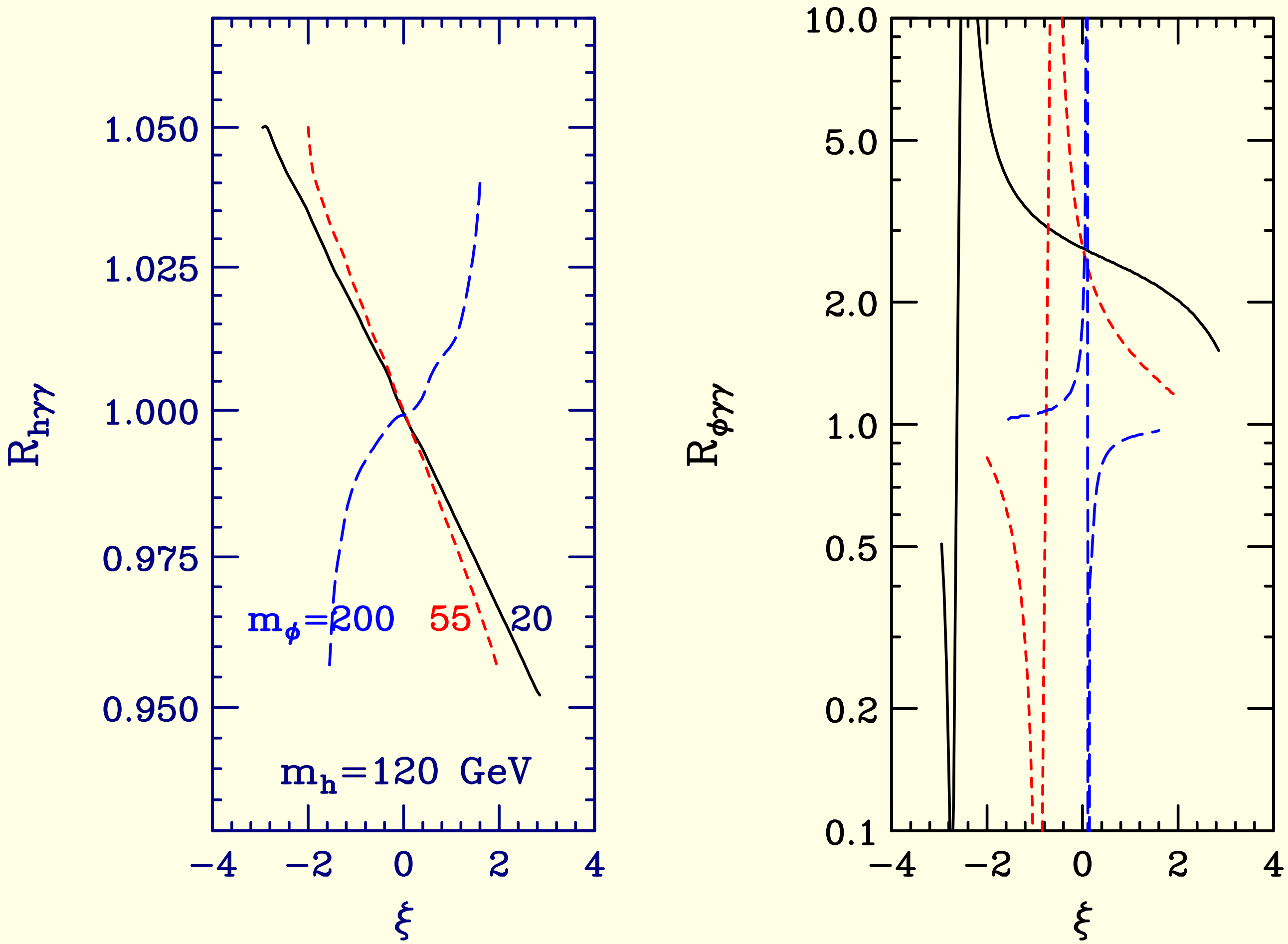


Rate ratio: gg→φ→ZZ*/gg→h_SM→ZZ*
m_ϕ=110 GeV
m_ϕ=140 GeV
m_ϕ=200 GeV
m_h=120 GeV
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
−2
−1
0
1
2
ξ



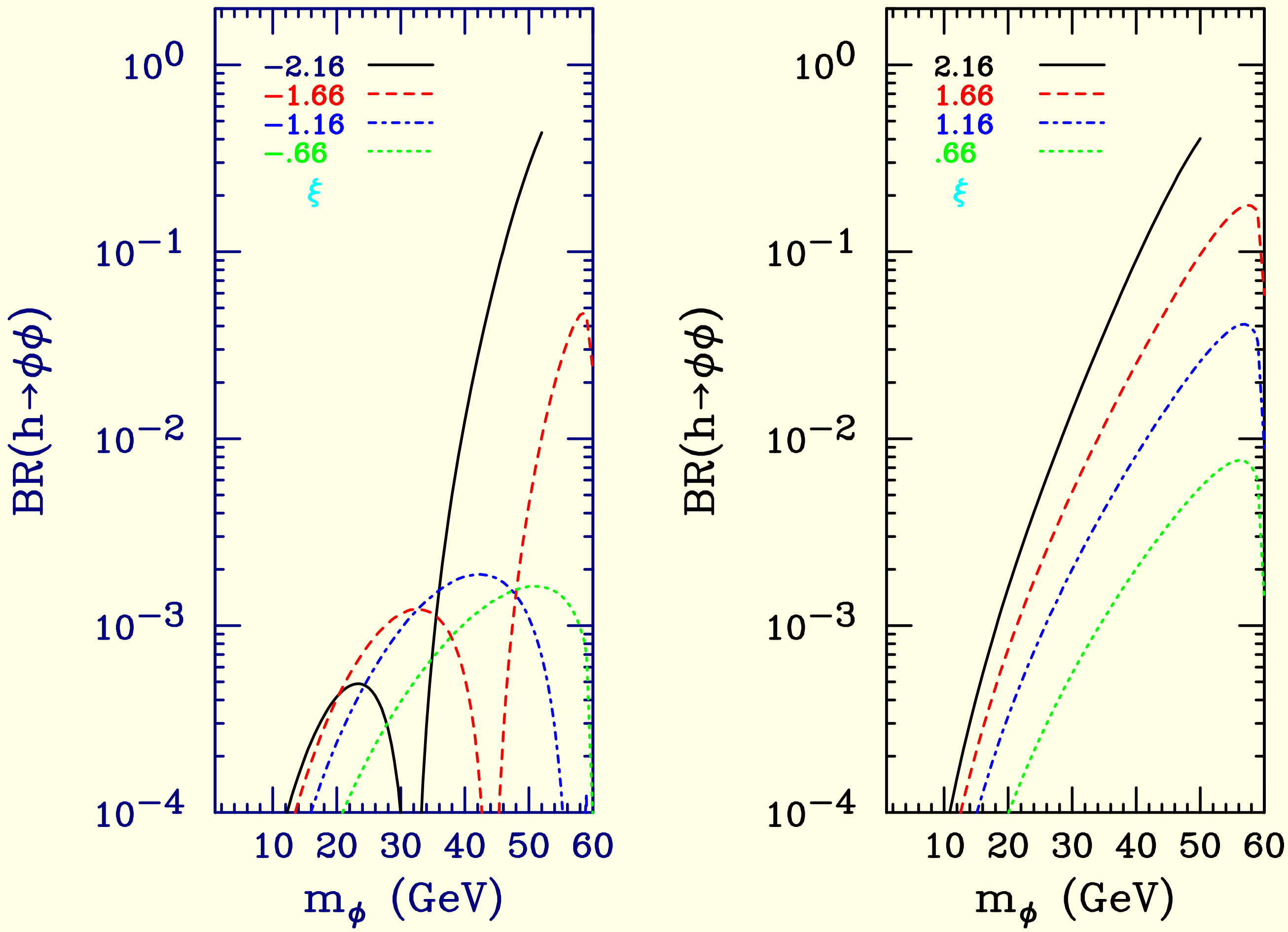
Rate ratio: $\gamma\gamma\to h\to b\bar{b}/\gamma\gamma\to h_{SM}\to b\bar{b}$
m_ϕ=20 GeV
m_ϕ=55 GeV
m_ϕ=200 GeV
m_h=120 GeV
10.0
5.0
2.0
1.0
0.5
0.2
0.1
−4
−2
0
2
4
ξ
Rate ratio: $\gamma\gamma\to\phi\to b\bar{b}/\gamma\gamma\to h_{SM}\to b\bar{b}$
10^0
10^{-1}
10^{-2}
10^{-3}

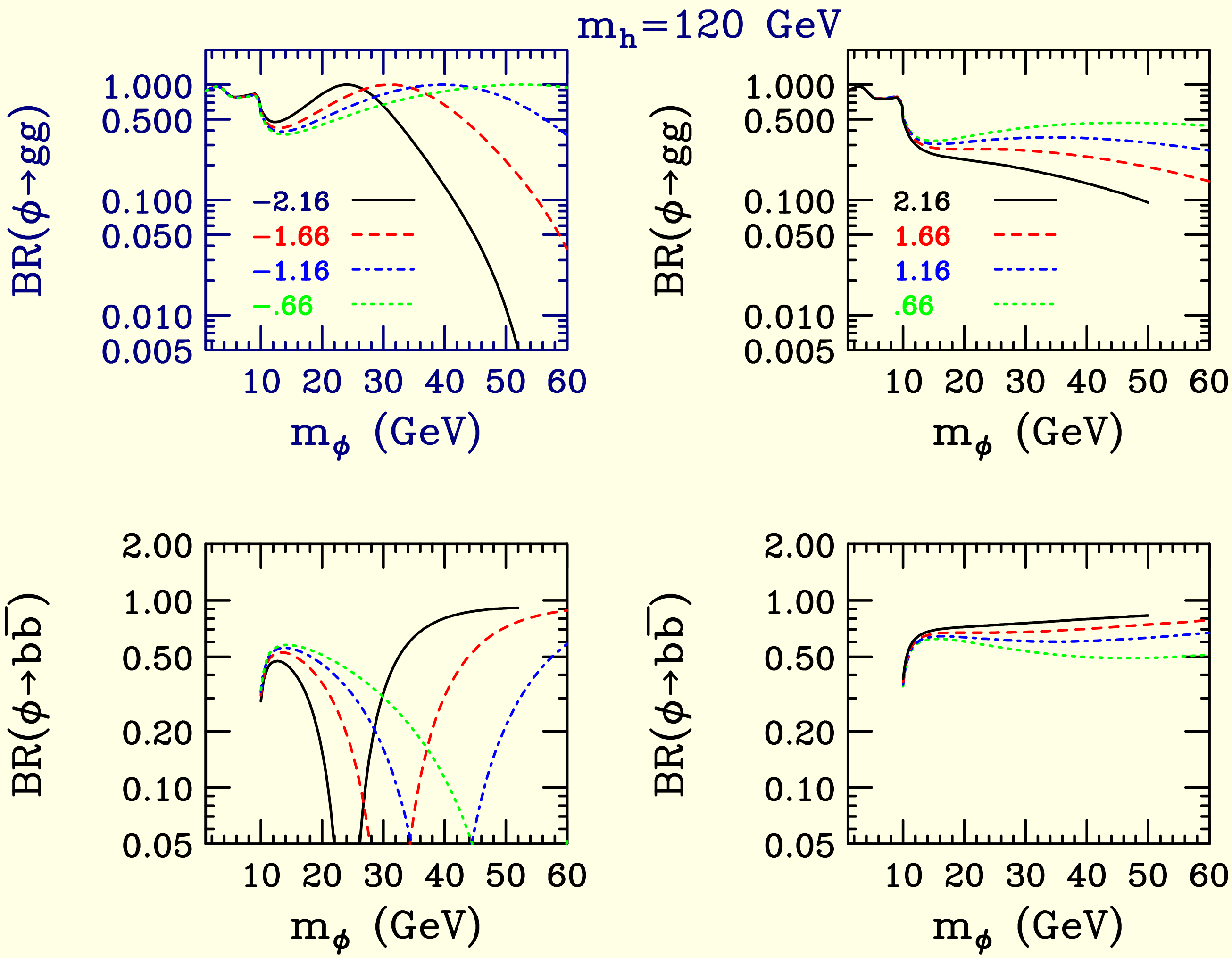

3.0
2.0
1.0
0.7
0.5
0.3
0.2
−4
−2
0
2
4
ξ
R_hgg
m_φ=200
55
20
m_h=120 GeV
10^4
10^2
10^0
10^−2
−4
−2
0
2
4
ξ
R_φgg



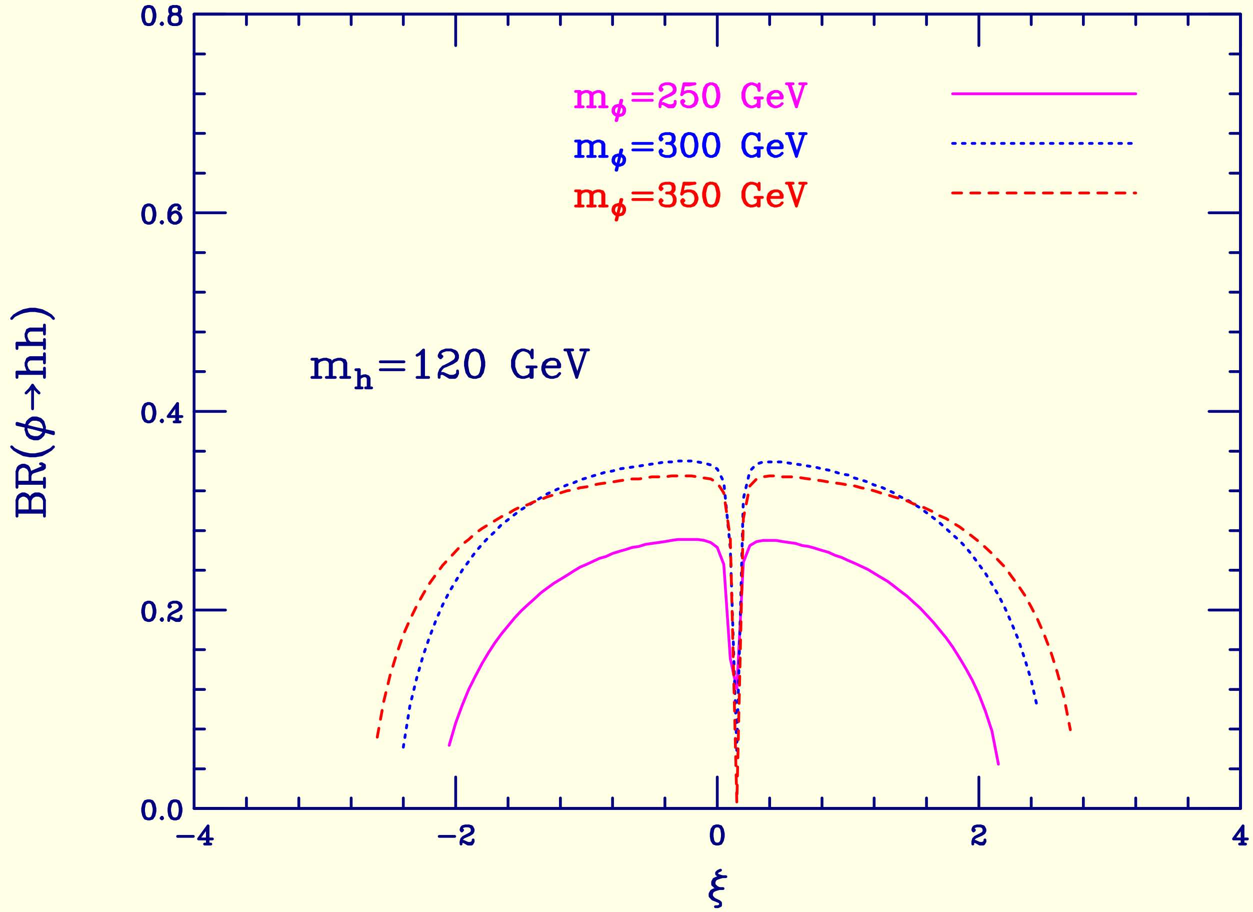
1.050
1.025
1.000
0.975
0.950
$R_{h\gamma\gamma}$
m_ϕ=200 55 20
m_h=120 GeV
−4 −2 0 2 4
ξ
10.0
5.0
2.0
1.0
0.5
0.2
0.1
$R_{\phi\gamma\gamma}$
−4 −2 0 2 4
ξ

m_h=120 GeV



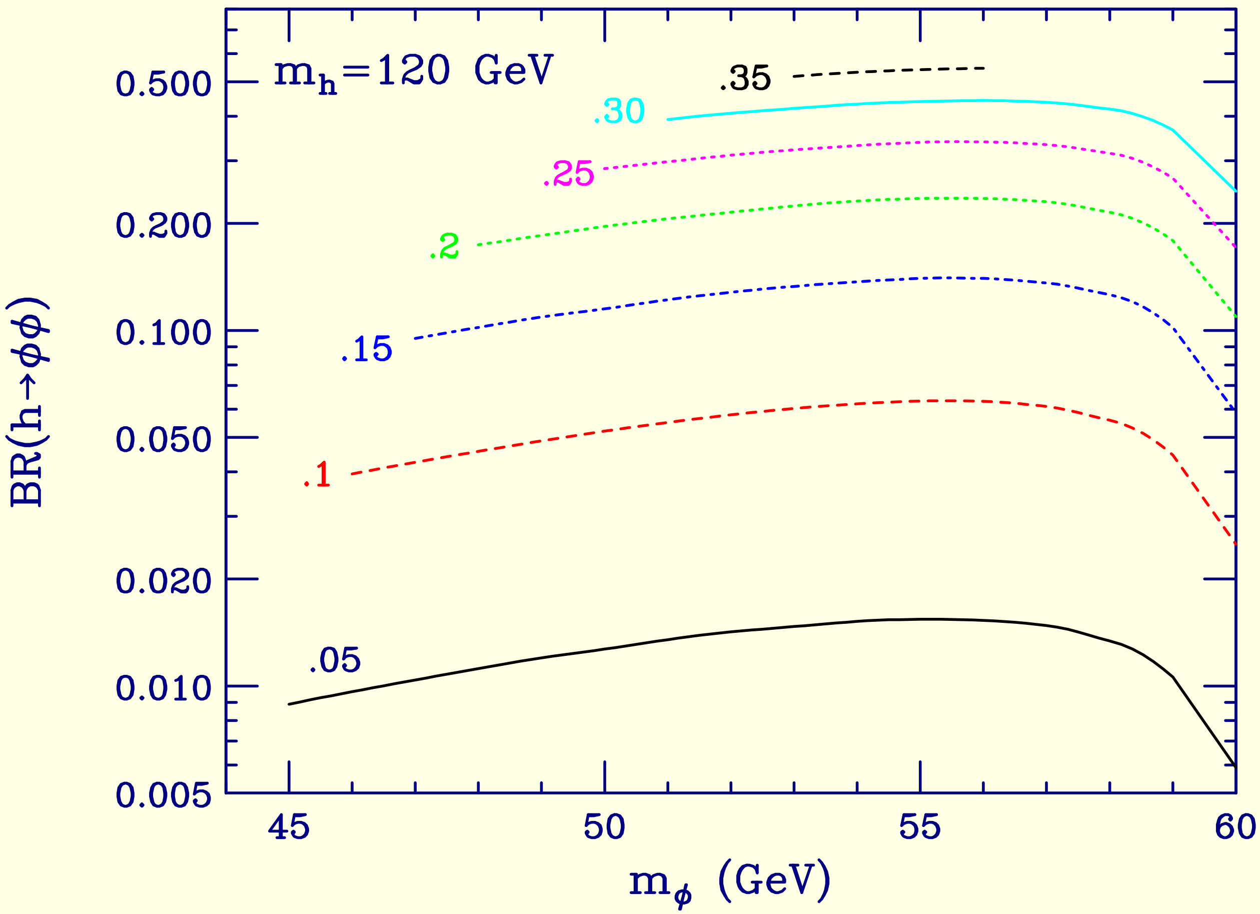


m_h=120 GeV
BR(ϕ→gg)
1.000
0.500
0.100
0.050
0.010
0.005
−2.16
−1.66
−1.16
−.66
10 20 30 40 50 60
m_ϕ (GeV)
BR(ϕ→gg)
2.16
1.66
1.16
.66
m_ϕ (GeV)
BR(ϕ→b$\bar{b}$)
2.00
1.00
0.50
0.20
0.10
0.05
m_ϕ (GeV)
BR(ϕ→b$\bar{b}$)
m_ϕ (GeV)

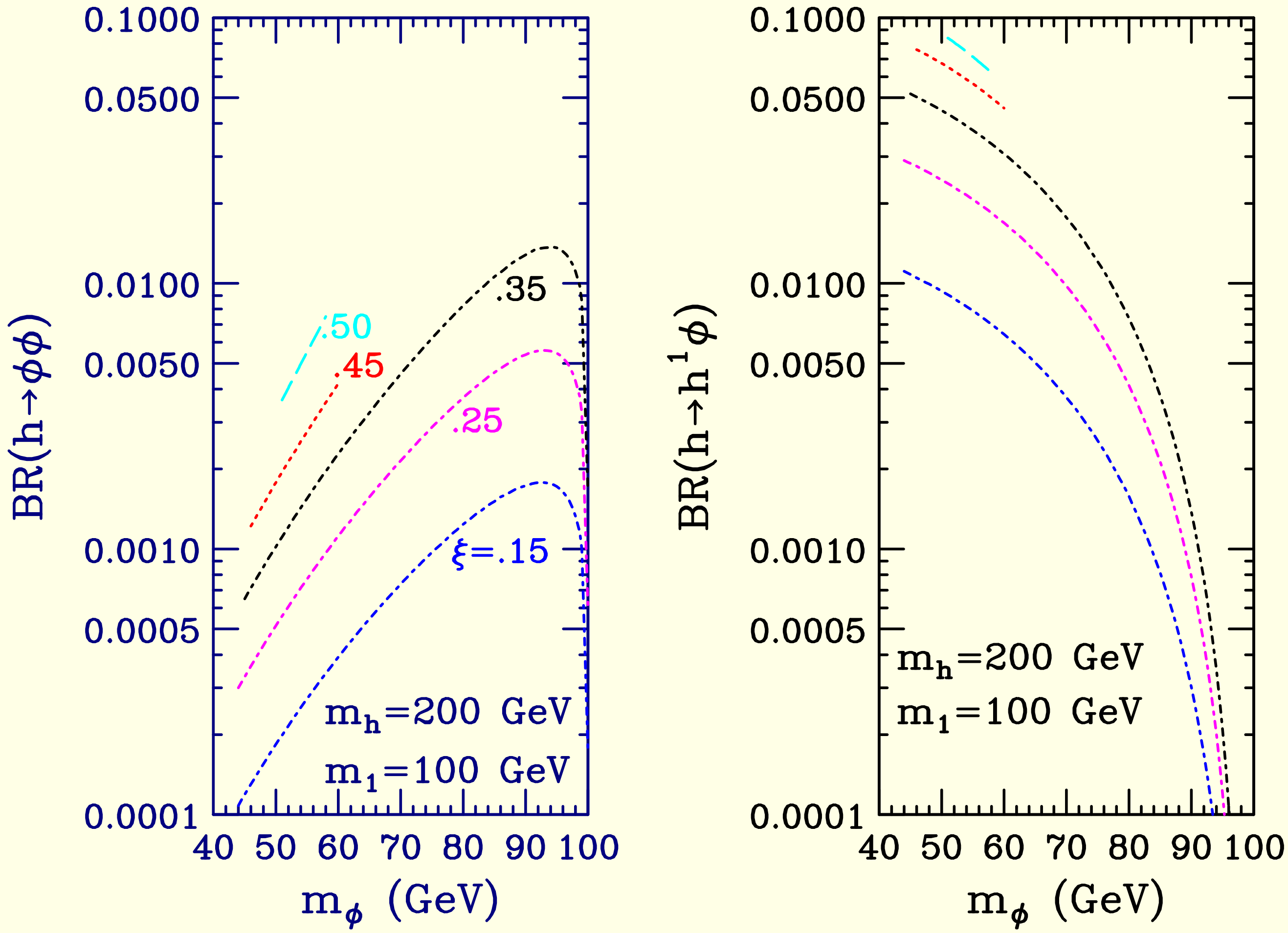


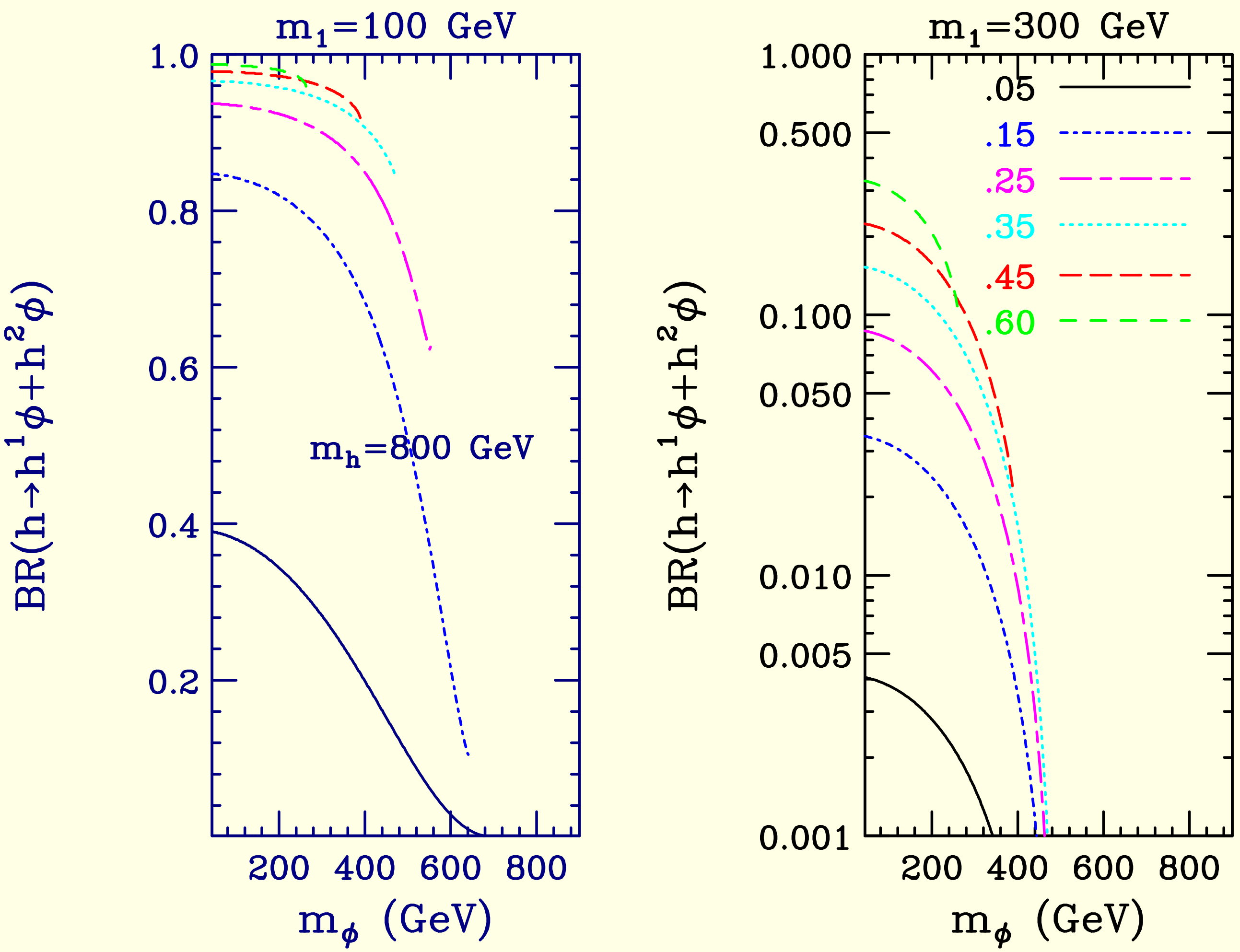
m_φ=250 GeV
m_φ=300 GeV
m_φ=350 GeV
m_h=120 GeV
BR(φ→hh)
ξ
0.8
0.6
0.4
0.2
0.0
−4
−2
0
2
4

More marginal case: $\Lambda_\phi = 1$ TeV



m_h=120 GeV
.35
.30
.25
.2
.15
.1
.05
0.500
0.200
0.100
0.050
0.020
0.010
0.005
45
50
55
60
BR(h→φφ)
m_ϕ (GeV)


0.1000
0.0500
0.0100
0.0050
0.0010
0.0005
0.0001
40 50 60 70 80 90 100
BR(h→φφ)
m_φ (GeV)
.50
.45
.35
.25
ξ=.15
m_h=200 GeV
m_1=100 GeV
BR(h→h^1 φ)
m_h=200 GeV
m_1=100 GeV


m1=100 GeV
1.0
0.8
0.6
0.4
0.2
mh=800 GeV
BR(h→h1φ+h2φ)
200
400
600
800
mφ (GeV)
m1=300 GeV
1.000
0.500
0.100
0.050
0.010
0.005
0.001
.05
.15
.25
.35
.45
.60
BR(h→h1φ+h2φ)
200
400
600
800
mφ (GeV)

CONCLUSIONS

- **The Higgs-radion sector will certainly be very revealing, and for some parameter choices may prove quite challenging to fully explore.**
- **In fact, at the LHC one can miss both the ϕ and the h for the most difficult parameter choices: $m_\phi = 200$ GeV and substantially negative ξ.**
- **$\Rightarrow$ keep improving and working on every possible signature.**
- **The large deviations of h properties with respect to $h_{\rm SM}$ properties is not really surprising given the nearness of the $\Lambda_\phi = 1$ TeV scale to the Higgs mass scales being considered.**
- **It would be nice to rule out the very light ϕ possibility.**
- **The decays (such as $h \to \phi\phi$ and $h \to h^n\phi$) which are only present if $\xi \neq 0$ can have large branching ratios and would provide an incontrovertible signature for mixing.**