(review of) Radion Physics at the LHC

by

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Outline

- Introduction
- The radion in RS1
- radion with matter in bulk
- Higgs-radion mixing
- Some preliminary results
- Conclusions

Introduction

Is it the Higgs?

- Radion couplings are higgs-like (except to gluons and photons)
- Radion might be the lightest new particle in warped scenarios
- When matter in the bulk, KK modes are constrained to be at ~ 3 TeV. The radion could be the only accessible mode from these models, or perhaps could even be used as a discovery channel for some of the heavy KK modes (1st KK graviton?).
- Radion can in principle mix with the Higgs

[Randall,Sundrum,('98)]

[Charmousis,Gregory,Rubakov('99)]

[Golberger,Wise('99)]

[Csaki,Graesser,LisaRandall,Terning(99)]

[Giudice,Rattazzi,Wells(00)]

[Csaki,Graesser,Kribs(00)]

[Han,Kribs,McElrath(01)]

[Rizzo,Hewett(02)]

[Dominici,Gunion,Grzadkowski,MT(02)],

[Gunion,MT,Wells(03)]

...

[Csaki,Hubisz,Lee(07)]

The Radion and its interactions

In the RS1 model [Randall, Sundrum, ('98)] the background metric g^{o}_{AB} is defined by

$$ds^2 \;=\; e^{-2\sigma}\eta_{\mu\nu}\, dx^\mu dx^\nu + dy^2$$

with $\sigma(y) = ky$ and such that a hierarchy is created between the two boundaries at $y = 0$ and $y = \pi r_0$ is created.

The linear metric perturbations $h_{AB}(x, y)$ can be reduced to

$$ds^2 = \left(e^{-2\sigma}\eta_{\mu\nu} \; + \left[e^{-2\sigma} h^{TT}_{\mu\nu}(x, y) - \eta_{\mu\nu} r(x)\right]\right) dx^\mu dx^\nu + \left(1 + 2e^{2\sigma} r(x)\right) dy^2$$

[Charmousis, Gregory, Rubakov ('99)]

$\Rightarrow$ linear interactions of radion and gravitons with matter but NOT quadratic i.e.

r-ψ-ψ , r-V-V but NOT r-r-V-V

We propose the metric perturbations (only radion)

$$ds^2 = \eta_{\mu\nu} \left(e^{-2\sigma} - r(x) + \frac{1}{4}\, e^{2\sigma} r^2(x) \right) dx^\mu dx^\nu$$

$$+ \left(1 + 2\, e^{2\sigma} r(x) + 2 e^{4\sigma} r^2(x)\right) dy^2$$

such that in the gravity Lagrangian there are NO $r \partial r \partial r$ terms

[Gunion, MT, Wells (03), MT (04)]

($r(x)$ does not have a potential. A stabilization mechanism is actually required for example [Golberger, Wise ('99)])

INTERACTIONS

Computing radion interactions is computing graviton interactions:

We write the previous metric as

$$g_{AB} = g^{(0)}_{AB}(y) + g^{(1)}_{AB}(y)\, r(x) + g^{(2)}_{AB}(y)\, r^2(x)$$

Matter-gravity interactions come from the matter action

$$S_{mat} = \int dx^5 \sqrt{-g}\ \mathcal{L}_{mat}$$

To expand this action in powers of the metric perturbations, we use

$$\frac{\delta S_{mat}}{\delta g^{AB}} \ = \ \frac{1}{2}\int dx^5 \sqrt{-g}\ T_{AB}$$

and

$$\frac{\delta^2 S_{mat}}{\delta g^{CD}\delta g^{AB}} \ = \ \frac{1}{2}\int dx^5 \sqrt{-g}\left(\frac{\delta T_{AB}}{\delta g^{CD}} - \frac{1}{2}\ T_{AB} g_{CD} \right)$$

And obtain

$$S_{mat}(r^0) = \int dx^5 \sqrt{-g^{(0)}}\mathcal{L}_{mat}$$

$$S_{int}(r) = -\frac{1}{2}\int dx^5 \sqrt{-g^{(0)}} e^{2\sigma} \left(-T^{\mu}_{\mu} + 2T_{55}\right) r(x)$$ [Rizzo(02),Csaki,Hubisz,Lee(07)]

$$S_{int}(r^2) = \frac{1}{2}\int dx^5 \sqrt{-g^{(0)}} \left[e^{4\sigma}\left(4T_{55} - \frac{1}{4}T^{\mu}_{\mu}\right) + g^{AB}_{(1)}(y)\ g^{CD}_{(1)}(y)\frac{\delta T_{AB}}{\delta g^{CD}}\right] r^2(x)$$

where $g^{AB}_{(1)} = e^{2\sigma}\left(-g^{AB}_{(0)} + 3\ \delta^A_5 \delta^B_5\right)$

But the radion $r(x)$ is NOT canonically normalized (canonical kinetic term).

The canonically normalized radion is $\phi_r(x)\frac{2}{\Lambda_r} = e^{2k\pi r_0} r(x)$

where $\Lambda_r = \sqrt{6} M_{Pl} e^{-k\pi r_0}$

RS1 - Matter on the brane

Single radion interaction becomes

$$S_{int}(r) = \frac{1}{\Lambda_r} \int dx^4 T^{\mu}_{\ \mu} \, \phi_0(x)$$

$\Rightarrow$ Higgs-like couplings!

For vector fields we have

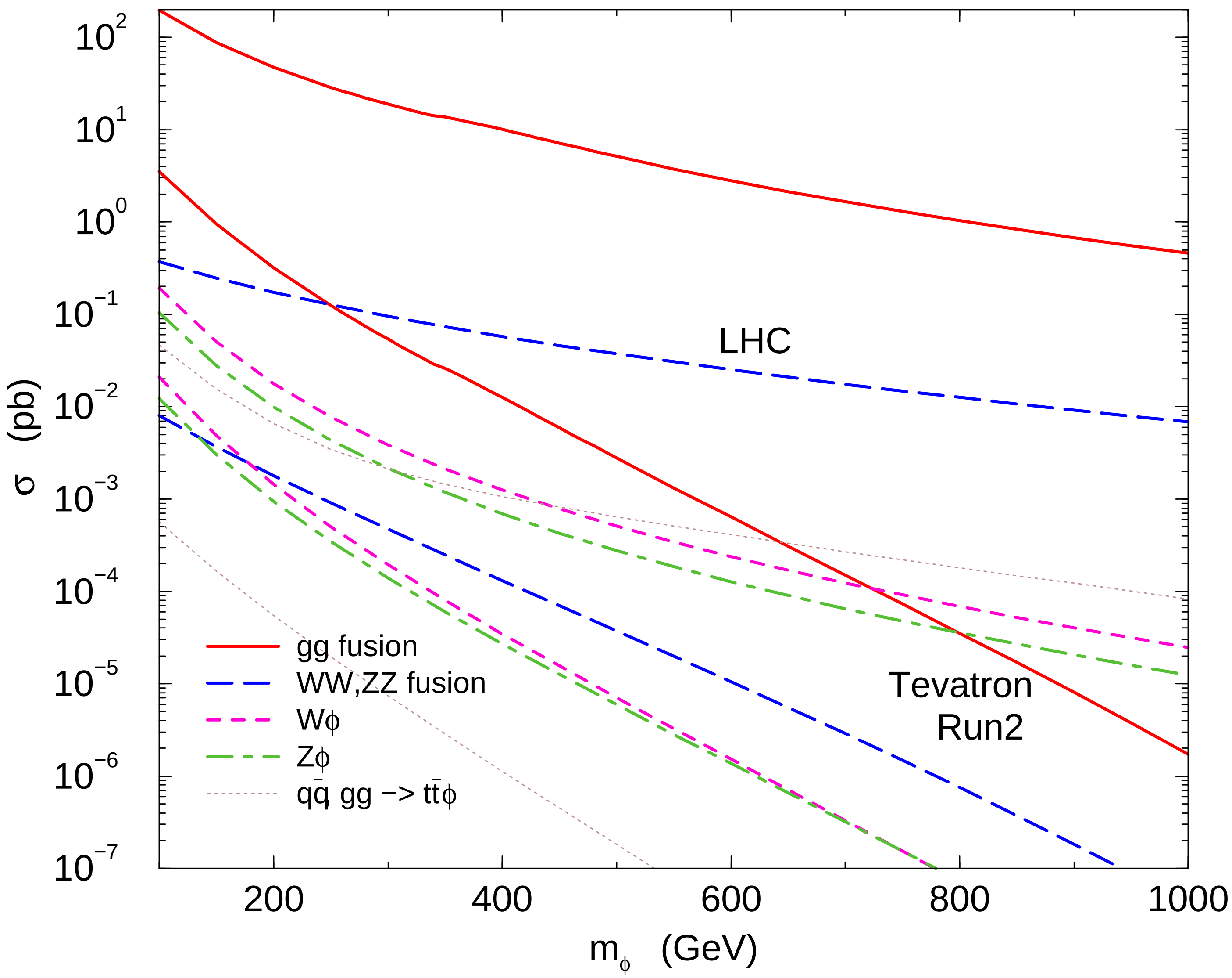
$$\mathcal{L}_{int} = \frac{1}{\Lambda_r} \phi_0(x) \left[M_V^2 V^\alpha V_\alpha + \epsilon \left(\frac{F^{\alpha\beta} F_{\alpha\beta}}{4} - \frac{M_V^2}{2} V^\alpha V_\alpha \right) \right]$$

Dimensional regularization $D = 4 - \epsilon$. Here ϵ comes from the trace.

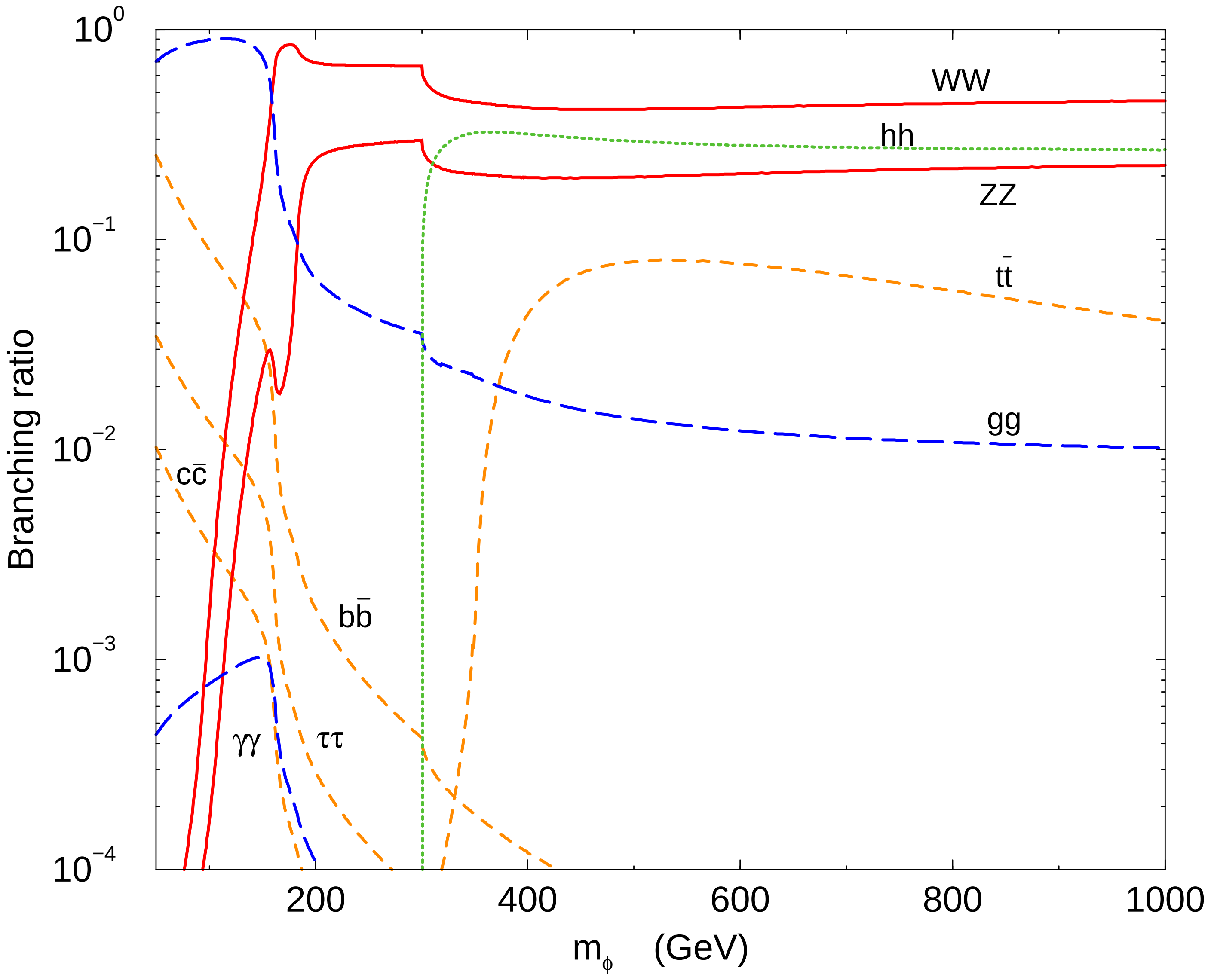
$\Rightarrow$ If $M_V = 0$ (gluons, photons) the ϵ term will cancel with the $\frac{1}{\epsilon}$ divergent terms from loops of charged fields.

$\Rightarrow$ Interactions with massless gauge bosons: The higgslike 1-loop contribution + this trace anomaly

gluons	$-\frac{\alpha_s}{8\pi}\left[\sum_i F_{1/2}(\tau_i)/2 - b_3\right]\ \frac{\phi_0}{\Lambda_r}\ G_{\mu\nu}G^{\mu\nu}$
photons	$-\frac{\alpha}{8\pi}\left[\sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y)\right]\ \frac{\phi_0}{\Lambda_r}\ F_{\mu\nu}F^{\mu\nu}$
massive bosons	$\frac{\phi_0}{\Lambda_r} M_V^2 V^\alpha V_\alpha$
fermions	$\frac{\phi_0}{\Lambda_r} m_f \bar{f} f$



(from K.Cheung ('00))



(from K.Cheung ('00))

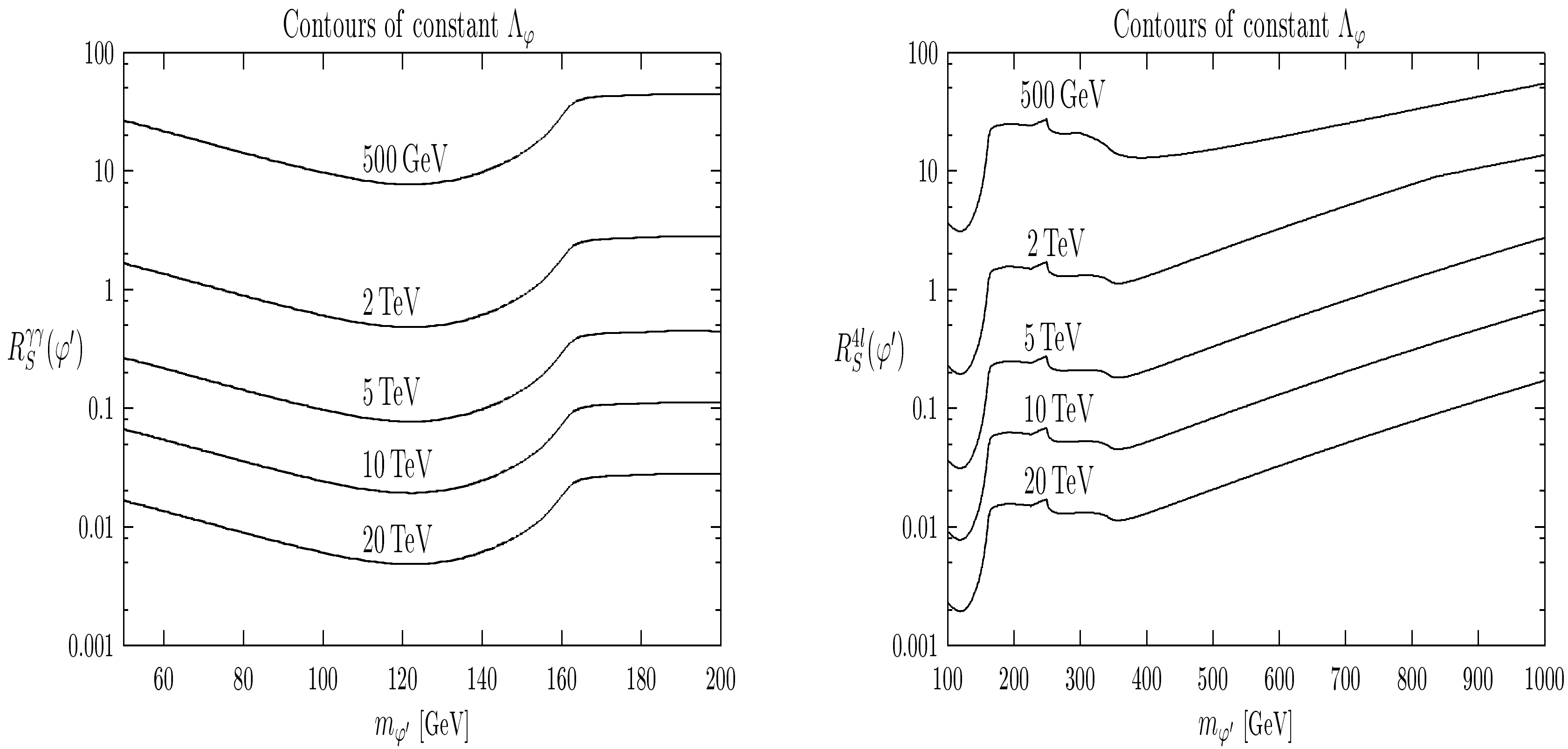


Figure 1: Ratio of signal significance in the $\gamma\gamma$ and ZZ channels between the radion and a SM higgs of same mass

(from Giudice,Rattazzi,Wells('00))

The Radion and Matter in the bulk [Csaki,Hubisz,Lee(07)]

With gauge fields and fermions in the bulk (but Higgs on the TeV brane) we need the new interactions with the radion.

$$S_{int}(r) = -\frac{1}{2}\int dx^5 \sqrt{-g^{(0)}} e^{2\sigma} \left(-T^{\mu}_{\ \mu} + 2T_{55}\right) r(x)$$

For Massless gauge fields:

- The T_{55} term $\Rightarrow$ tree level coupling r-glu-glu and r-γ-γ.
- Brane localized kinetic terms for gauge fields.
- Trace anomaly effect
- Loop contributions (tops and W's)

$$\left[\frac{1-4\pi\alpha(\tau^0_{UV}+\tau^0_{IR})}{4k\pi r_0} + \frac{\alpha}{8\pi}\left(b - \sum_i \kappa_i F_i(\tau_i)\right)\right] \frac{\phi}{\Lambda_r} F_{\mu\nu}F^{\mu\nu}$$

- Radion interaction with Massive Gauge bosons maintains its main contribution from the boson mass
- Interaction with fermions, although model dependent remains proportional to the mass of the fermion with an $\mathcal{O}(1)$ coefficient
- Interaction with the higgs is computed as in RS1 since Higgs localized

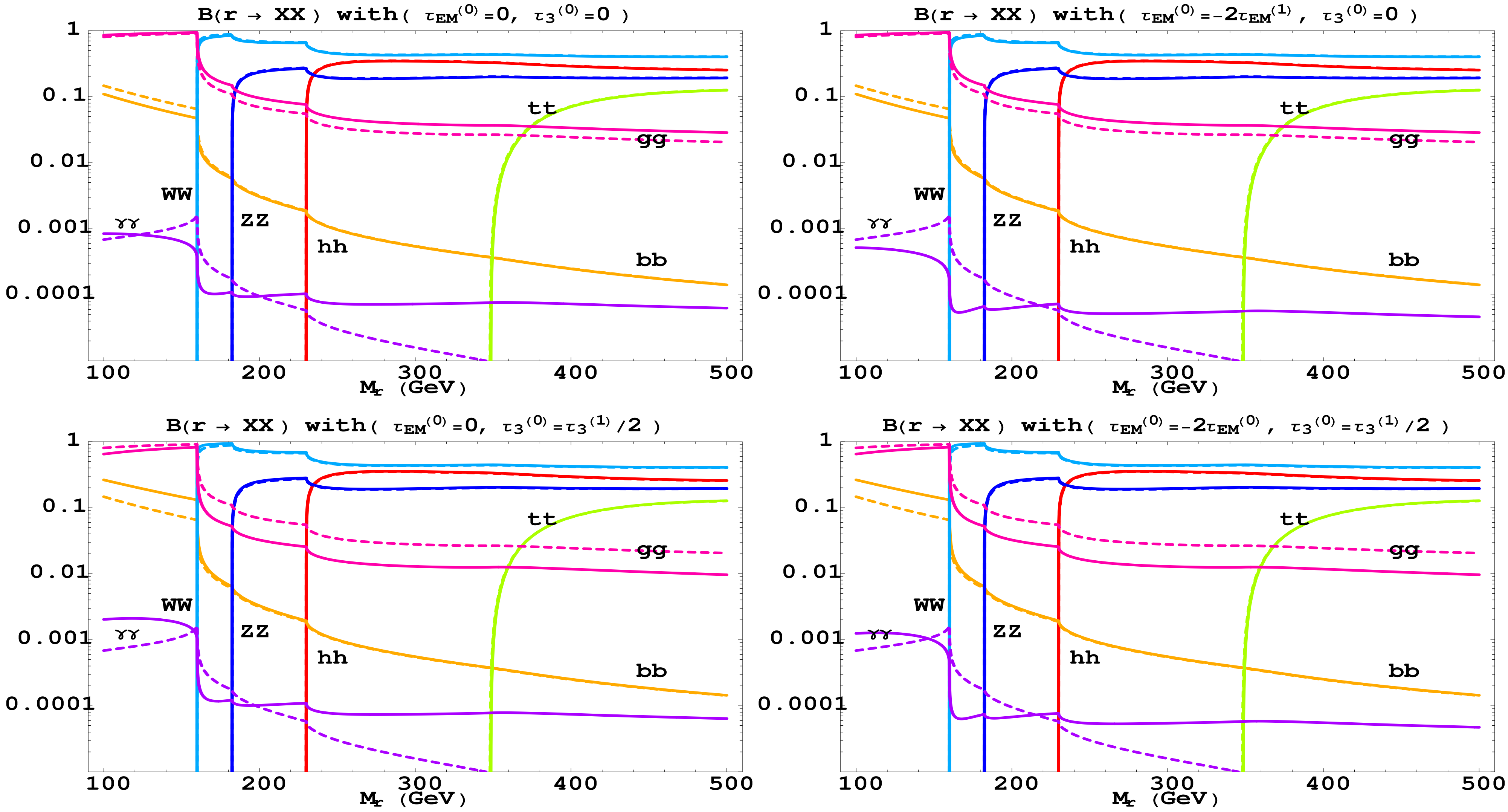


Figure 2:

(from Csaki,Hubisz,Lee('07))

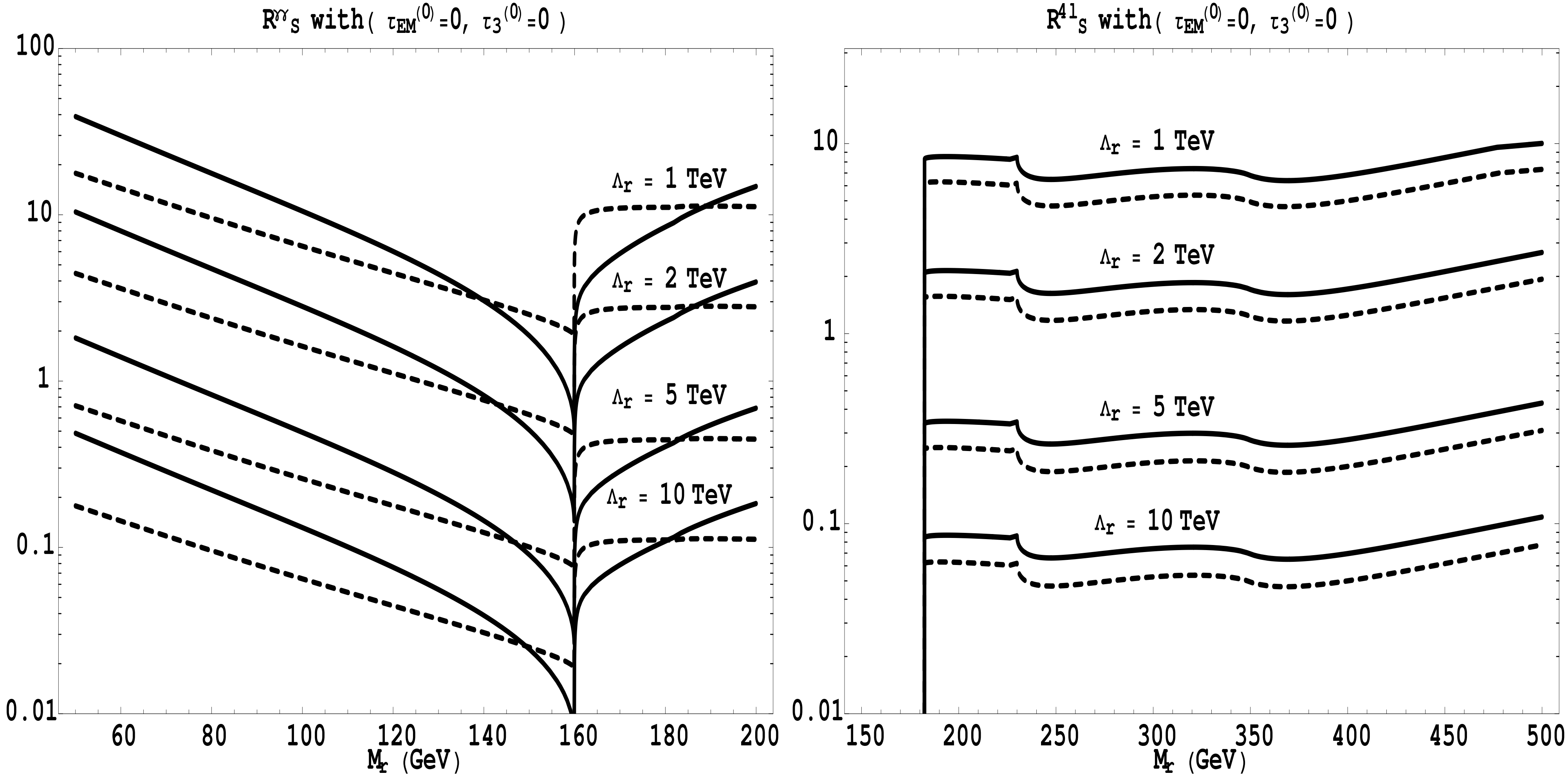


Figure 3: Ratio of signal significance in the $\gamma\gamma$ and ZZ channels between the radion and a SM higgs of same mass

(from Csaki,Hubisz,Lee('07))

Higgs-radion mixing

[Giudice,Rattazzi,Wells(00), Csaki,Graesser,Kribs(00), Han,Kribs,McElrath(01), Rizzo,Hewett(02), Dominici,Gunion,Grzadkowski,MT(02)], Gunion,MT,Wells(03)]...

We now consider the brane operator:

$$S_\xi = \xi \int d^4x \sqrt{g_{ind}} R(g_{ind}) \; H_0^\dagger H_0 \, .$$

$$\begin{aligned} \mathcal{L}_{scalar} &= -\frac{1}{2}\left\{1 + 6\xi\left(\frac{v_0}{\Lambda_r}\right)^2\right\}\phi_0 \Box \phi_0 - \frac{1}{2}\phi_0 m_{\phi_0}^2 \phi_0 \\ & -\frac{1}{2} h_0(\Box + m_{h_0}^2) h_0 - \frac{6\xi v}{\Lambda_r} \; h_0 \Box \phi_0 \end{aligned}$$

Radion mass added "by hand".

NORMALIZED HIGGS AND RADION PHYSICAL FIELDS

$$h_0 = \left(\cos\theta - \frac{6\xi\gamma}{Z}\sin\theta\right) h + \left(\sin\theta + \frac{6\xi\gamma}{Z}\cos\theta\right)\phi \equiv d\, h + c\, \phi$$

$$\phi_0 = \left(-\cos\theta\, \frac{1}{Z}\right)\phi + \left(\sin\theta\, \frac{1}{Z}\right) h \equiv a\, \phi + b\, h$$

with $$\tan 2\theta \equiv 12\gamma\xi Z \frac{m_{h0}^2}{m_{\phi_0}^2 - m_{h_0}^2(Z^2 - 36\xi^2\gamma^2)},$$

and

$$Z^2 \equiv 1 + 6\xi\gamma^2(1-6\xi) \qquad \textbf{and} \qquad \gamma \equiv \frac{v_0}{\Lambda_r}.$$

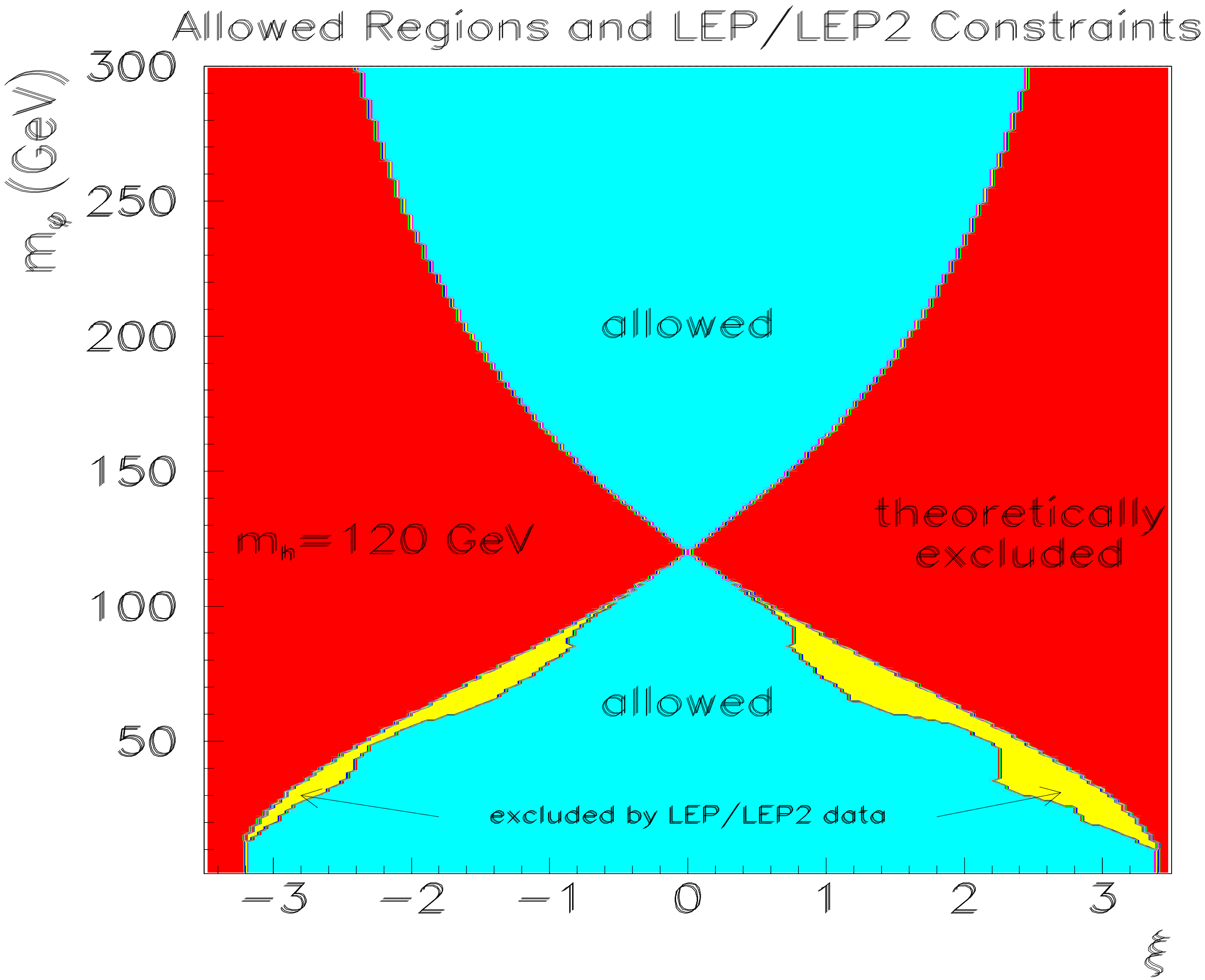


Figure 4:

(from Dominici,Gunion,Grzadkowski,M.T. ('02))

VV and ff COUPLINGS

$$g_{ZZh} = \frac{g\, M_z}{c_W}(d + \gamma b) \qquad g_{ZZ\phi} = \frac{g\, M_z}{c_W}(c + \gamma a)$$

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

Very interesting property of the ξ-mixing: the different couplings of the physical radion to matter photons, gluons, fermions and massive bosons can vanish at different points in parameter space.

$\Rightarrow \phi$ can be photon-fobic, gluon-fobic or massive-fobic

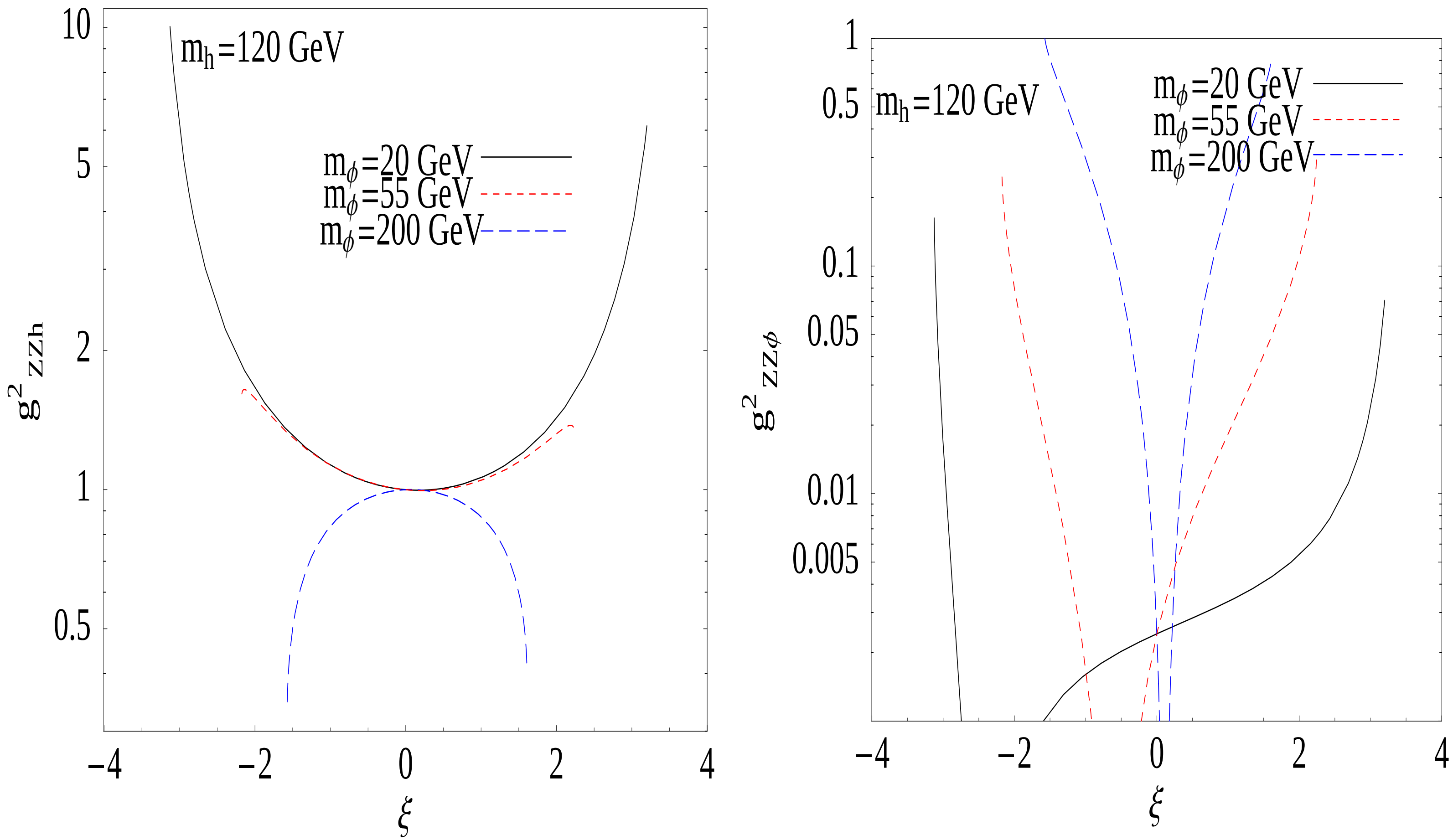
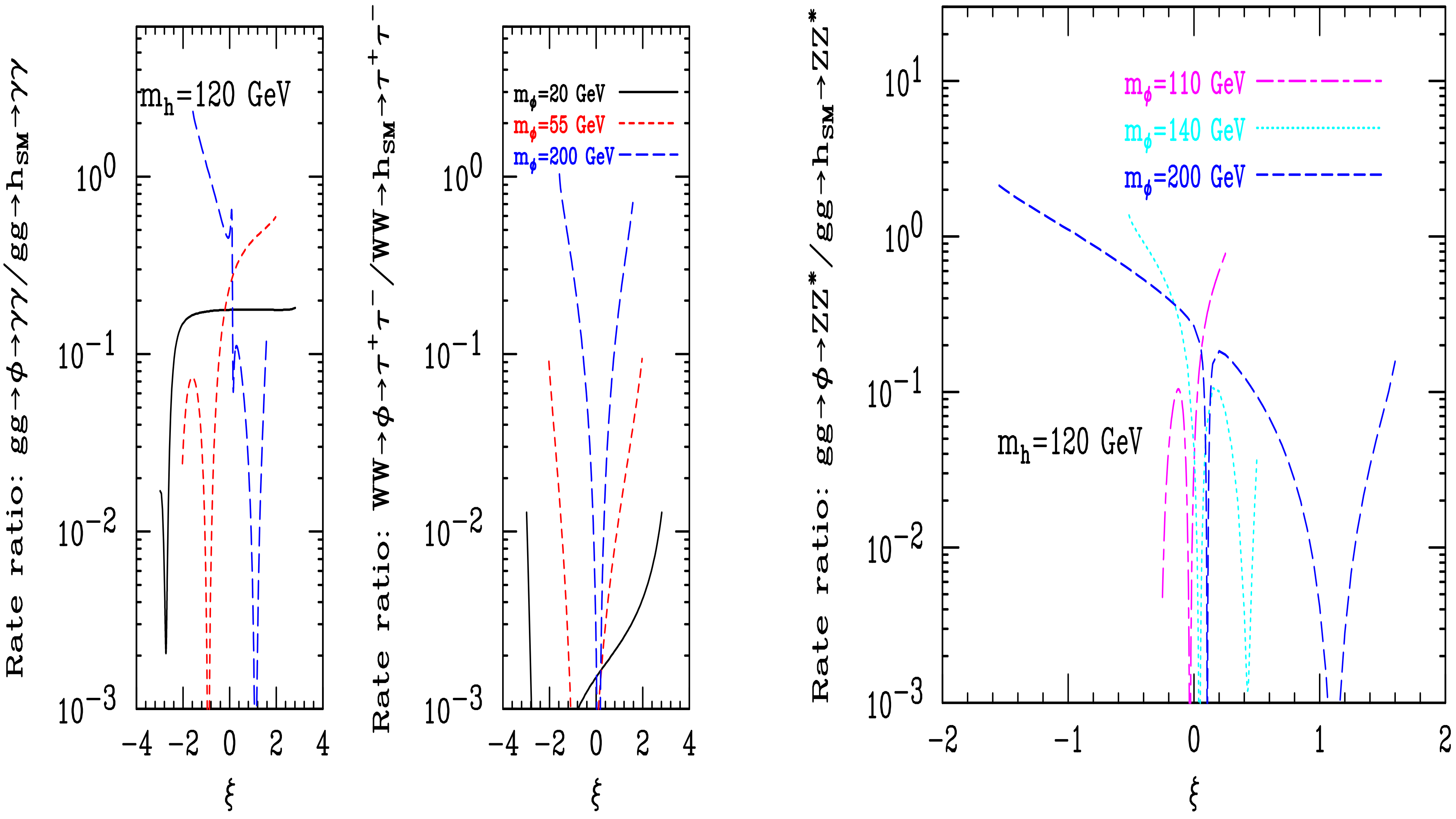


Figure 5:

(from Dominici,Gunion,Grzadkowski,M.T. ('02))



(from Dominici,Gunion,Grzadkowski,M.T.('02))

Precision EW constraints

[Csaki,Graesser,Kribs(00), Gunion,MT,Wells(03)]

COMPUTATION OF S AND T:

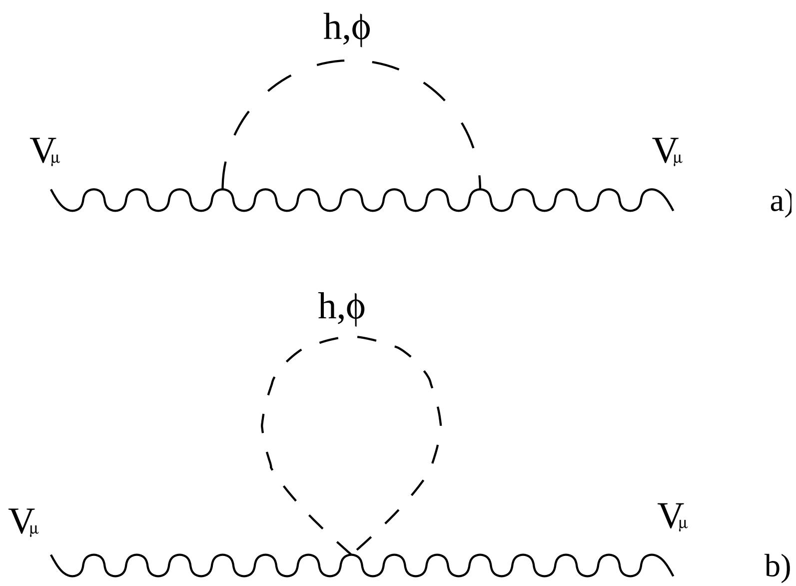


Figure 6: One-loop contributions to S_h and S_ϕ

$$S = -S_{h_{SM}^{ref}} + S_h + S_\phi + S^A + S^{ren}$$

$$T = -T_{h_{SM}^{ref}} + T_h + T_\phi + T^A + T^{ren}$$

- S^A finite anomalous contribution from the trace anomaly
- T^A finite anomalous contribution from the trace anomaly
- S^{ren} from the running of operators like: $\frac{1}{\Lambda^2}\ H^+ W_{\mu\nu} B^{\mu\nu} H$
- T^{ren} from the running of operators like: $\frac{1}{\Lambda^2}\ |H^+ D_\mu H|^2$

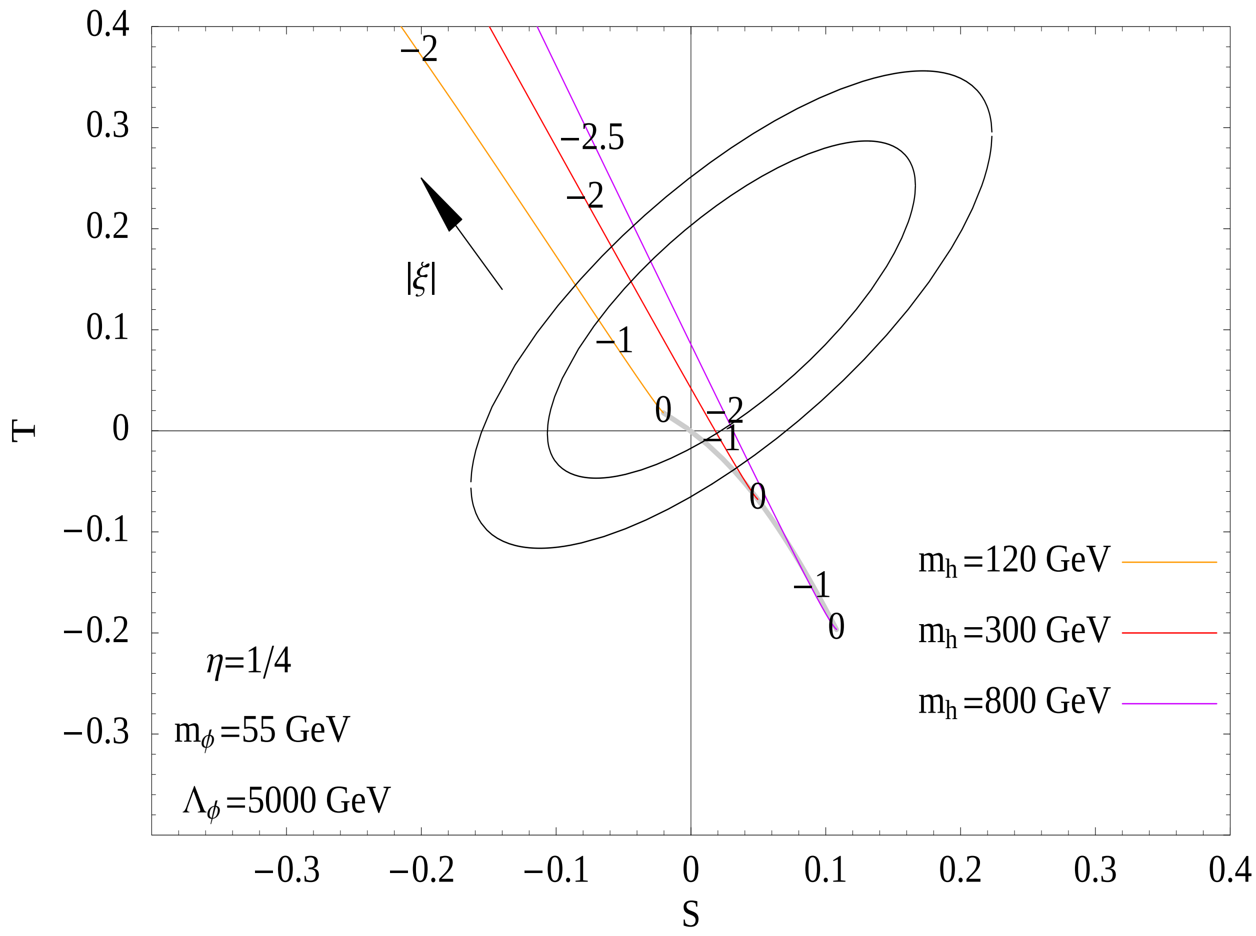


Figure 7: S-T dependence on ξ and Higgs Mass

(from M.T. ('04))

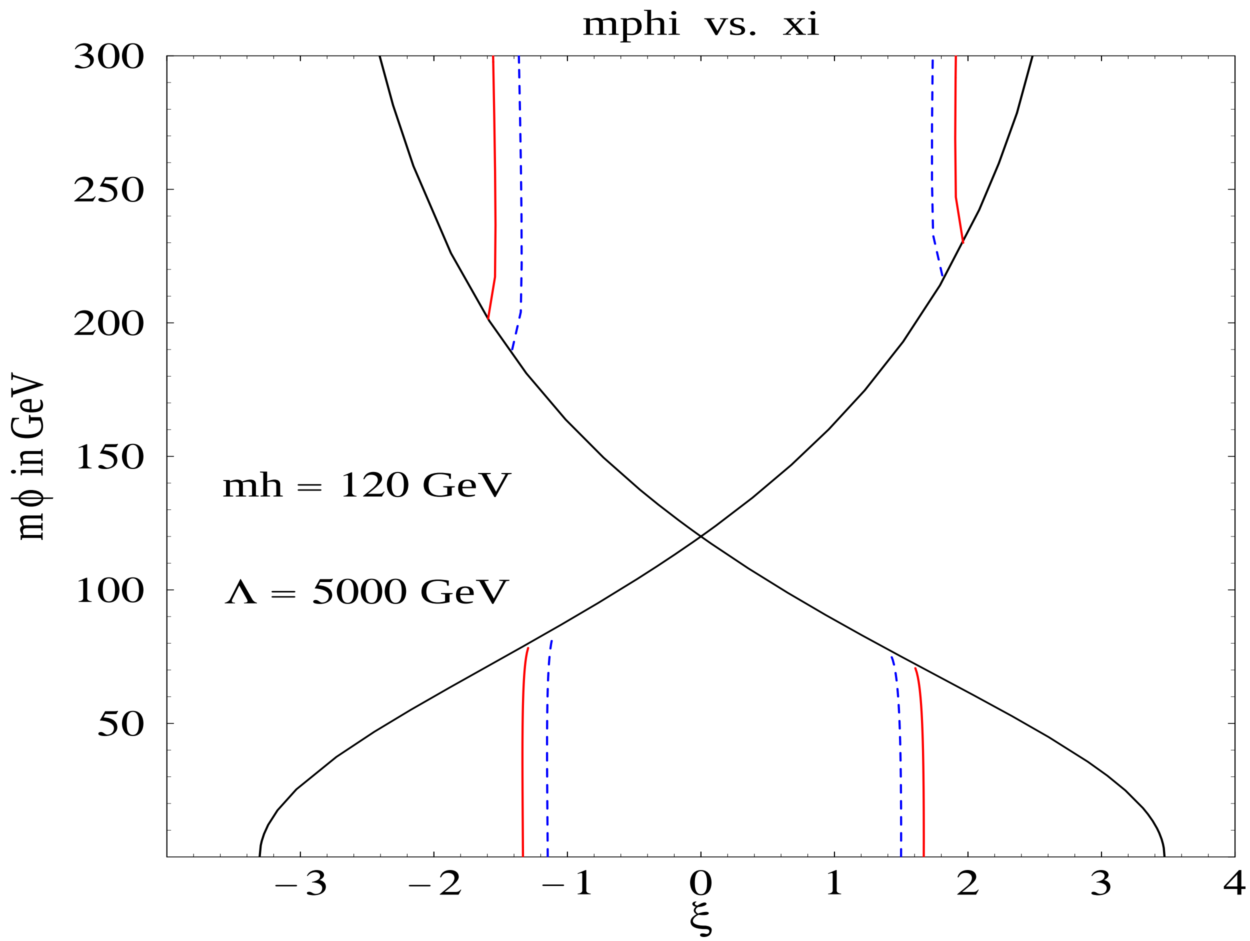


Figure 8:

(from Gunion,M.T.,Wells ('03))

Higgs-radion mixing & Matter in the bulk (Preliminary)

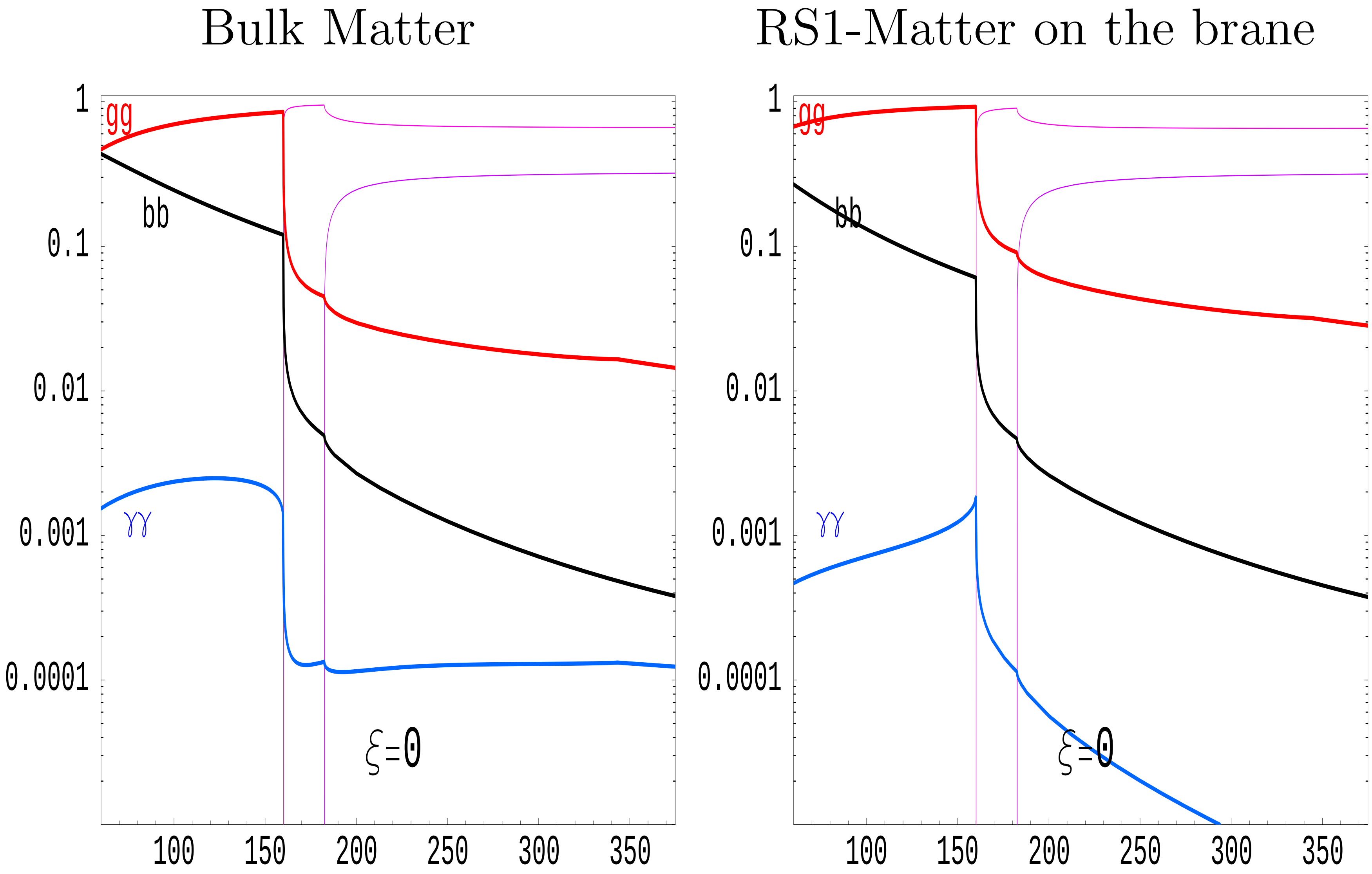


Figure 9: Branchings of the radion vs. its mass M_ϕ

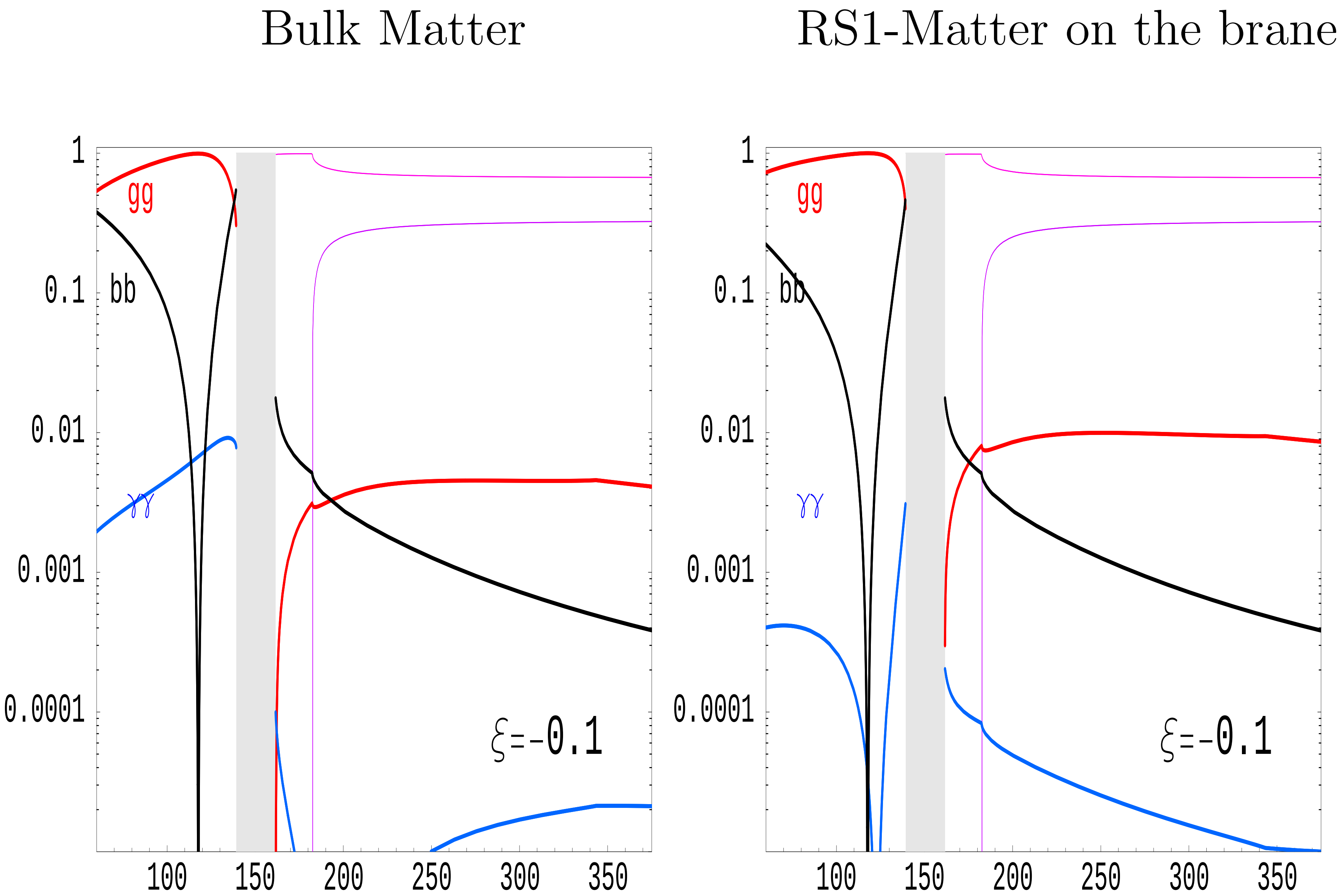


Figure 10: Branchings of the radion vs. its mass M_ϕ

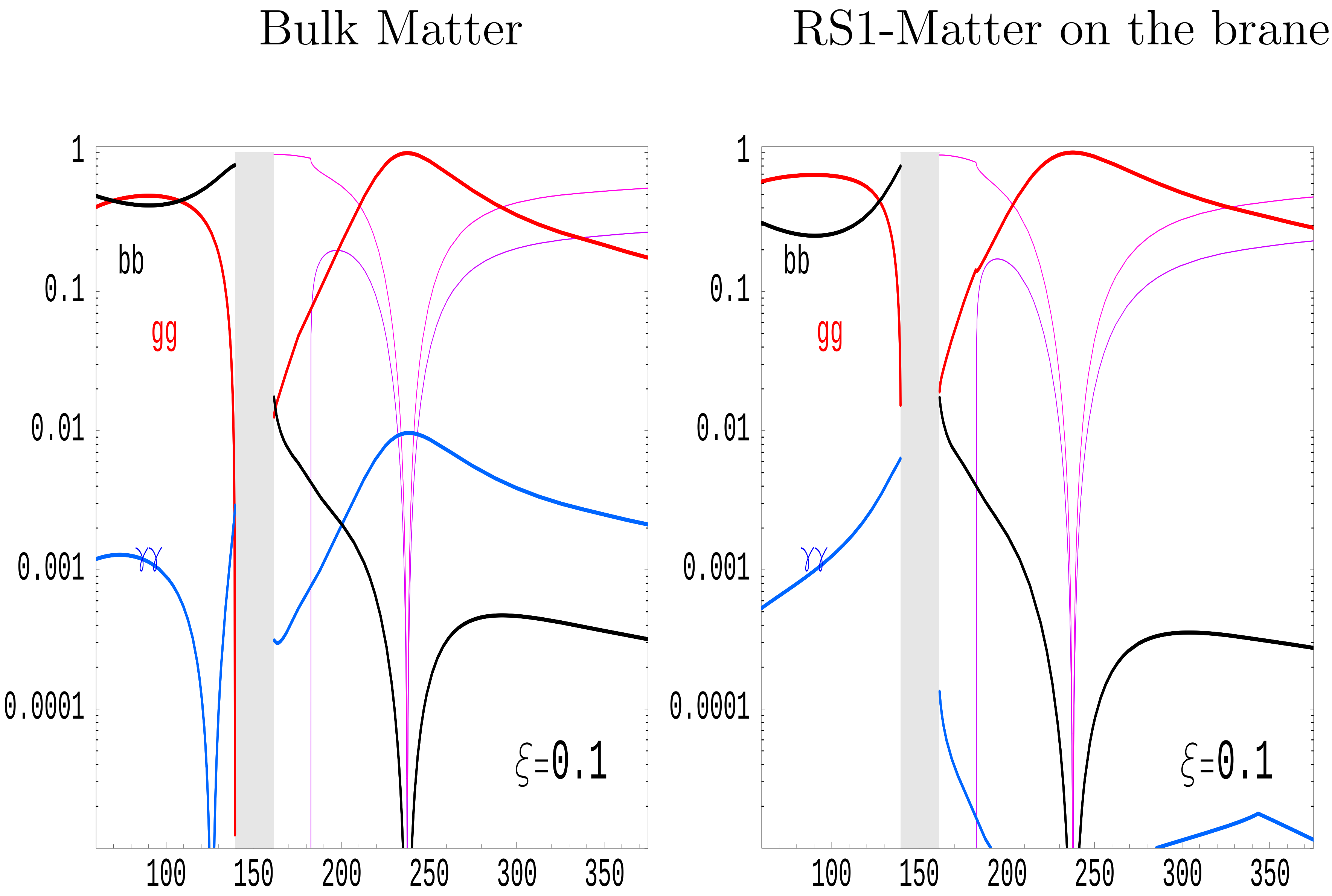


Figure 11: Branchings of the radion vs. its mass M_ϕ

Conclusions

- radion phenomenology is very similar to higgs search
- RS1 radion is simple and well studied
- Higgs-radion mixing adds interesting properties to the radion (fobic couplings)
- Bulk matter has interesting effects in radion pheno
- more so if in conjuction with some radion-higgs mixing (preliminary). A thorough scan of parameter space should be done, as well as perhaps a new estimate of effects on oblique corrections by the ξ mixing in the bulk fields scenario.
- a "non-standard" scalar, hypothesized to be the radion, could be used as an alternative search channel for elusive heavy KK modes..