Title: Revisiting the scalar sector in Warped Extra Dimensions

Date: Mar 06, 2009 01:00 PM

URL: http://pirsa.org/09030025

Abstract: I will revisit the phenomenology of the radion graviscalar in warped extra dimensions. This particle could be the lightest 'new physics' state to be discovered at the LHC in this type of models. Its phenomenology is very similar to the Standard Model (SM) Higgs, another potentially light scalar particle with which it could actually mix. When SM fields are moved from the boundary to the bulk of the extra dimension, new interesting effects appear in the scalar sector of the model. With a little bit of Higgs-radion mixing, it is possible to enhance importantly some decay channels of the mostly-radion scalar. Moreover, both the Higgs and the radion can now typically mediate Flavor Changing Neutral Currents at tree level. These will impose bounds on the flavor structure of the model, but also allow for interesting probes in current and future collider experiments.

Revisiting the Scalar Sector in Warped Extra Dimensions (radion physics).[a]

by

Manuel Toharia

(University of Maryland)

at

Perimeter Institute, March 2009

[a]Based on

- Phys.Rev.D79 (2009), *M.T.*
- arXiv:0812.2489 *A.Azatov, M.T., L.Zhu*
- Work in Progress

Outline

- Introduction
- The radion in RS1
- radion with matter in bulk
- Higgs-radion mixing
- Radion and flavor
- Conclusions

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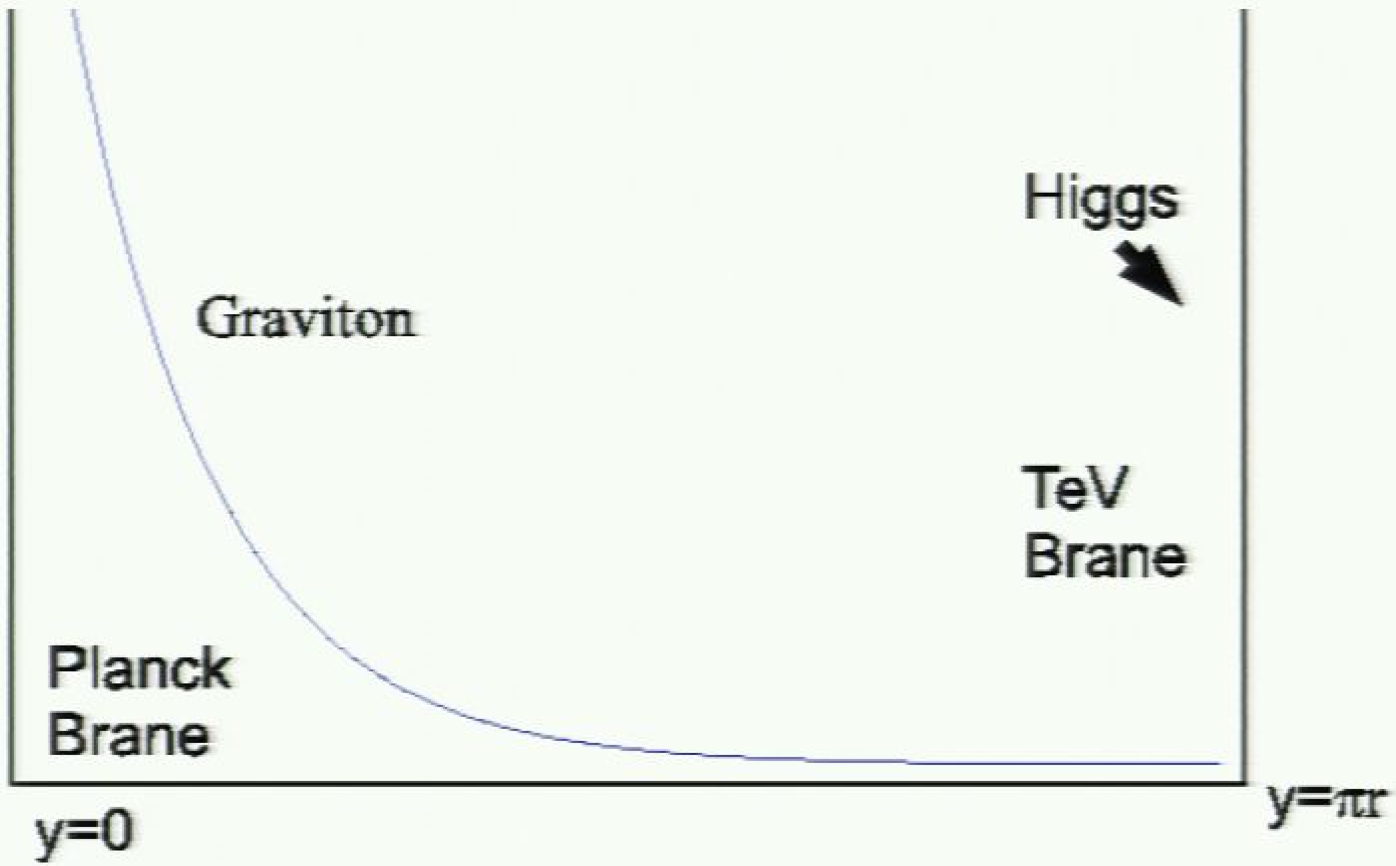
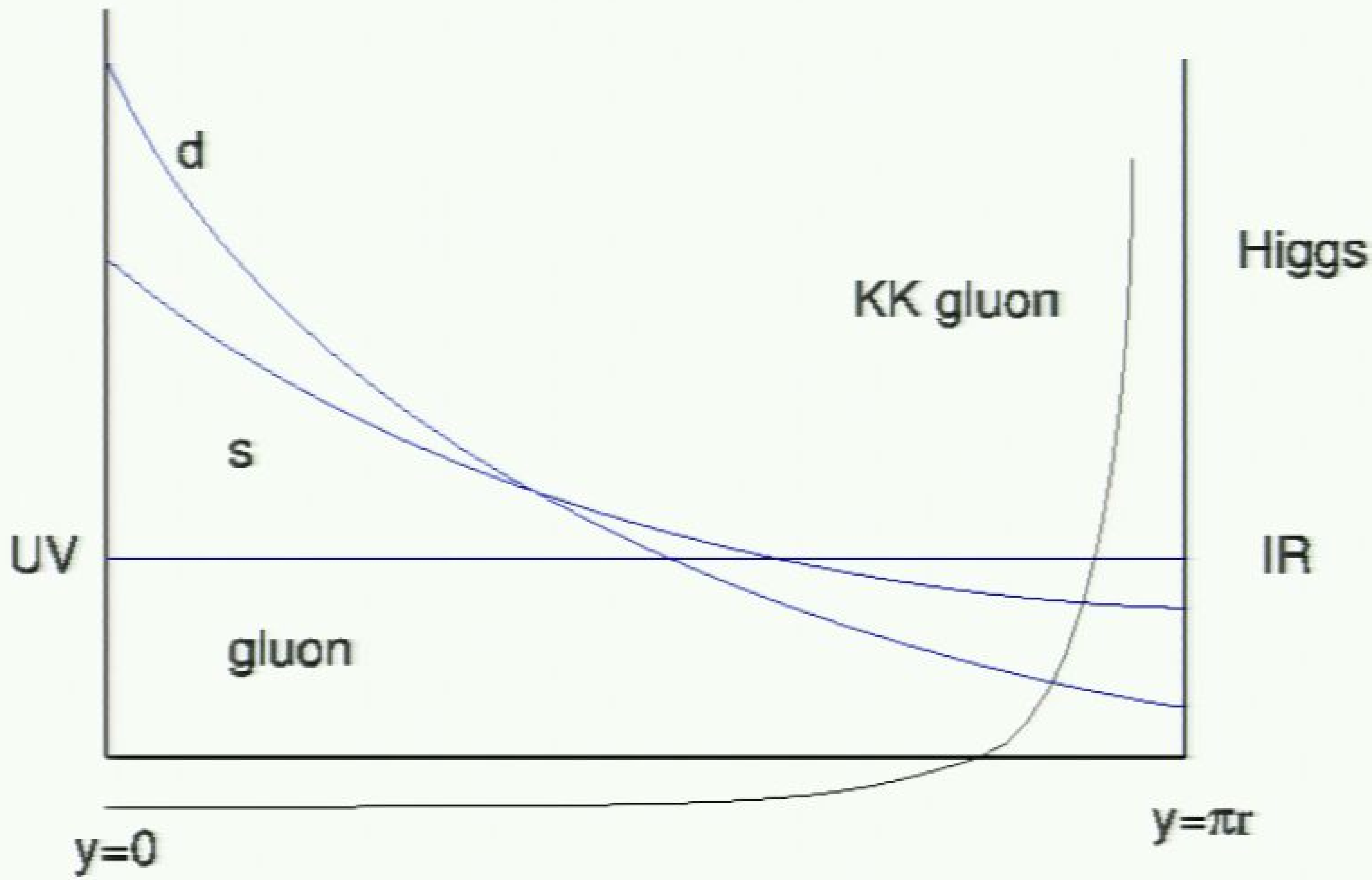
- Warped Extra Dimensions: One compact extra dimension with warped geometry.
- Original setup: Two branes as boundaries and all SM fields on the TeV Brane → RS1.
  - Towers of KK gravitons
  - Radion graviscalar


Higgs
Graviton
TeV
Brane
Planck
Brane
y=0
y=πr

Introduction

- Warped Extra Dimensions: One compact extra dimension with warped geometry.
- Original setup: Two branes as boundaries and all SM fields on the TeV Brane → RS1.
  - Towers of KK gravitons
  - Radion graviscalar
- More recent setups: Two branes, Higgs field on TeV brane, SM fields in the "bulk".
  - Towers of KK gravitons
  - Towers of KK SM fields
  - Radion graviscalar


d
Higgs
KK gluon
s
UV
IR
gluon
y=πr
y=0

What about the radion?

- Radion couplings are higgs-like (except to gluons and photons)
- Radion might be the lightest new particle in warped scenarios
- When SM matter in the bulk, KK modes are constrained to be at ~ 3 TeV. The radion could be the only accessible mode from these models.
- 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

$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}\, dx^\mu dx^\nu + dy^2 = \frac{R^2}{z^2}\left(\eta_{\mu\nu}\, dx^\mu dx^\nu + dz^2\right)$$

with $\sigma(y) = ky$ (and $R = 1/k$). Hierarchy created between the two boundaries at $y = 0$ and $y = \pi r_0$ ($z = R$ and $z = R'$).

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

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

(the graviscalar $r(x)$ is massless. A stabilization mechanism providing it with mass is assumed for example[Golberger,Wise('99)])

INTERACTIONS

Matter-gravity interactions come from the matter action

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

We expand this action in powers of the radion perturbation

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

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

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

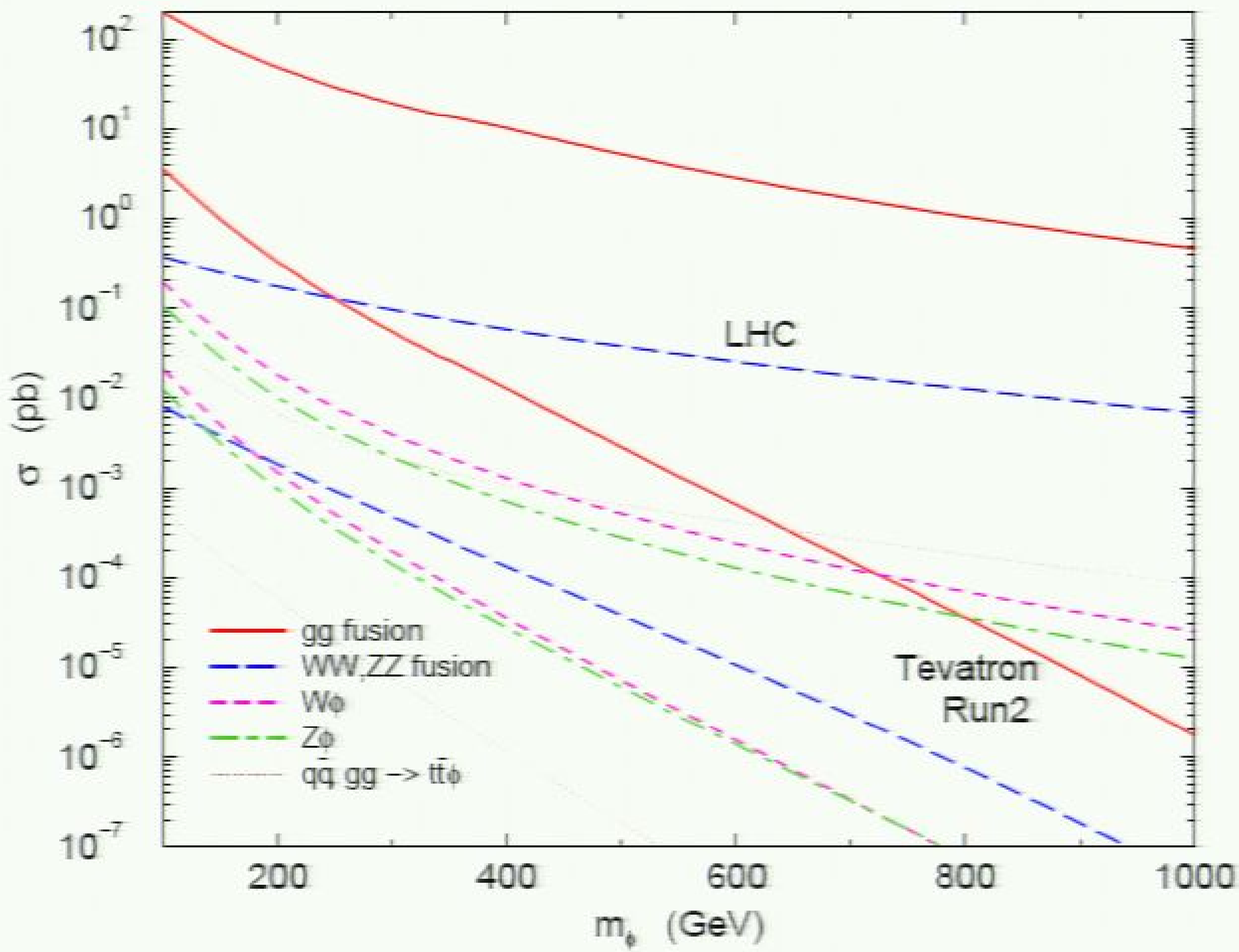
RS1 - Matter on the brane

Single radion interaction becomes

$$S_{int}(r) = \frac{1}{\Lambda_r} \int dx^4 T^\mu_{\ \mu}\ \phi_0(x) \qquad \Rightarrow \text{Higgs}-\text{like couplings!}$$

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	$\frac{\phi_0}{\Lambda_r} m_f \bar{f} f$

Radion Production



(from K.Cheung ('00), here $\Lambda_\phi = 1$ TeV)

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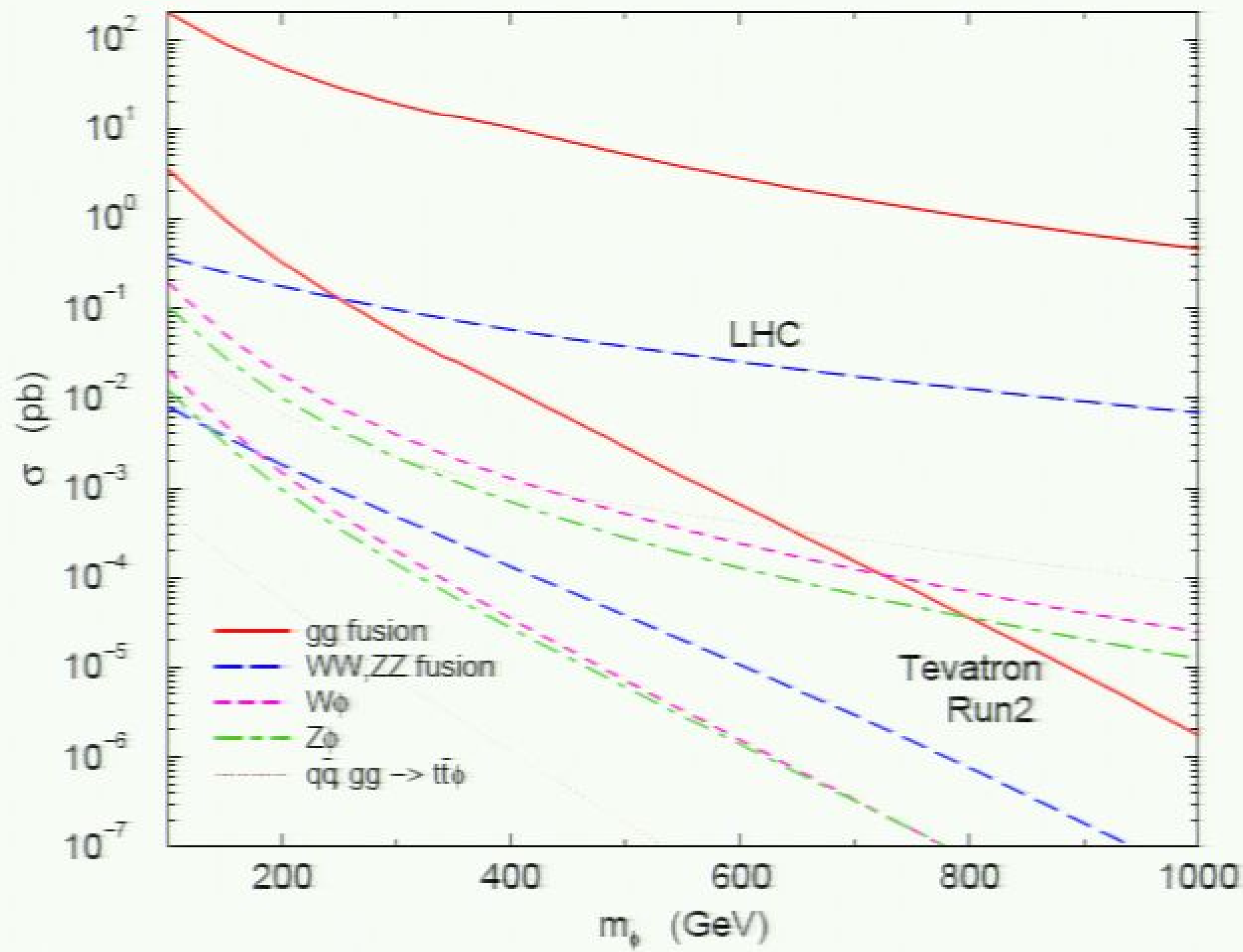

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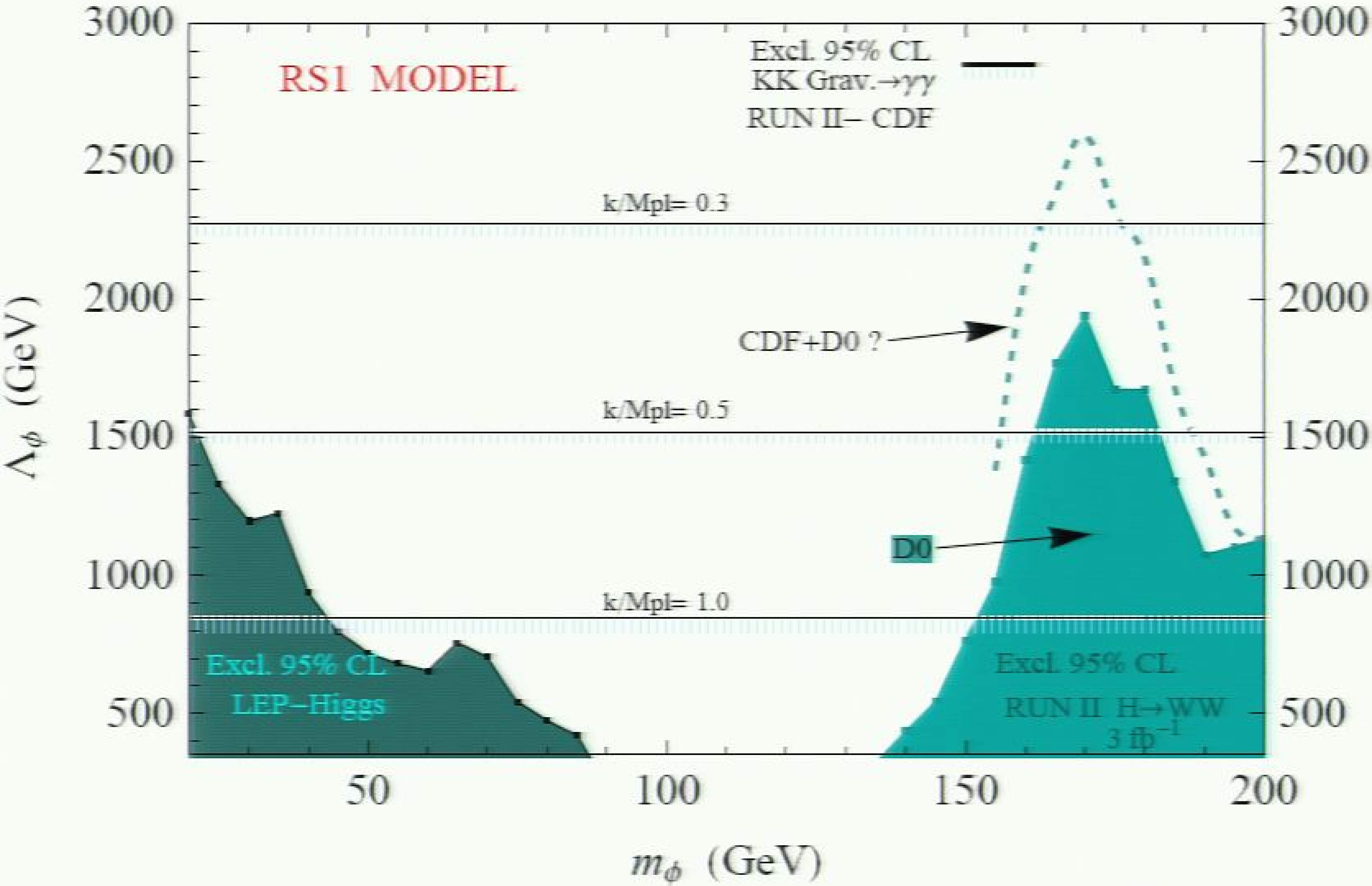
Experimental Bounds in $(m_\phi - \Lambda_\phi)$ (with Nobu Okada)



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)

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

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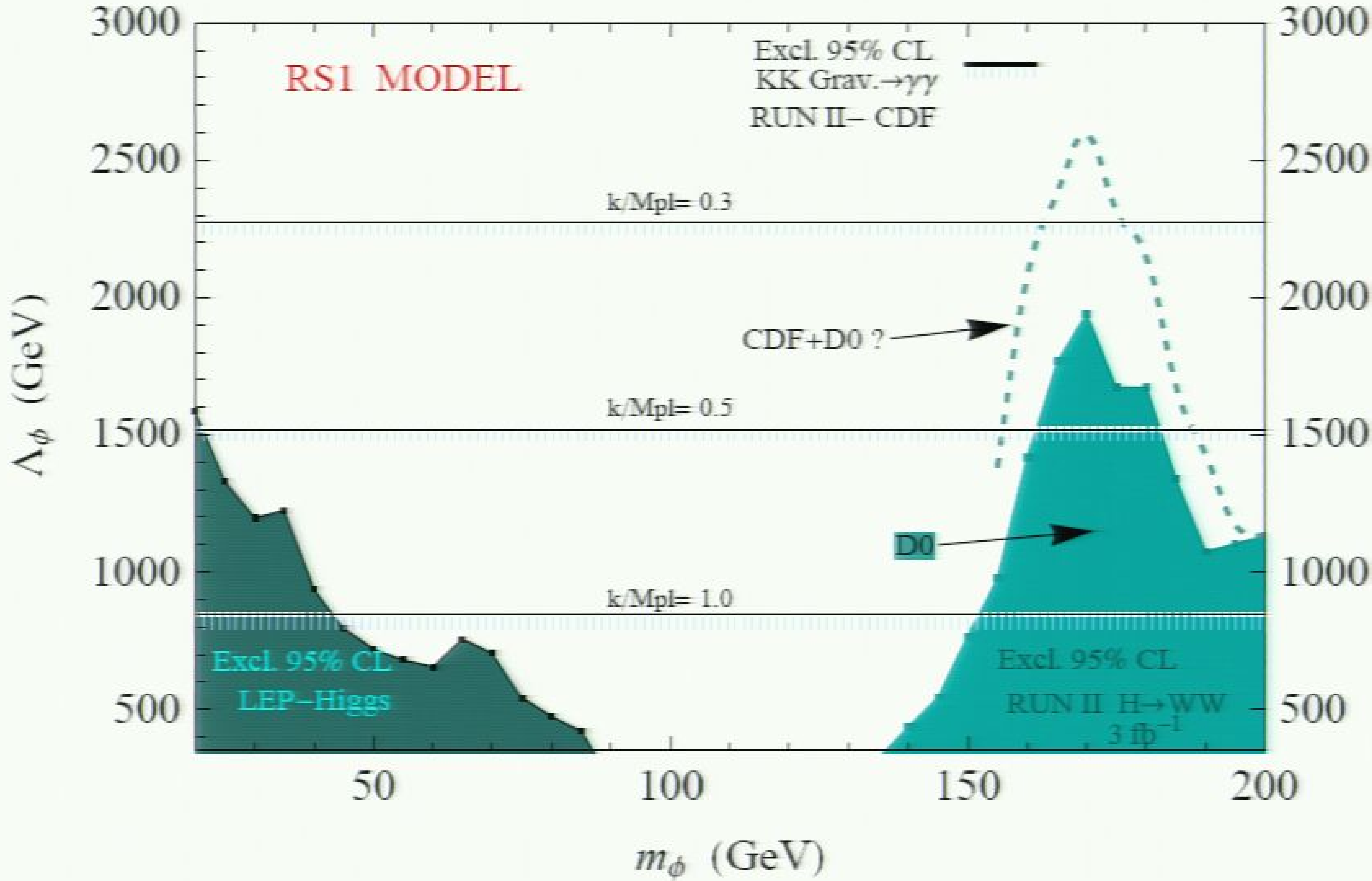

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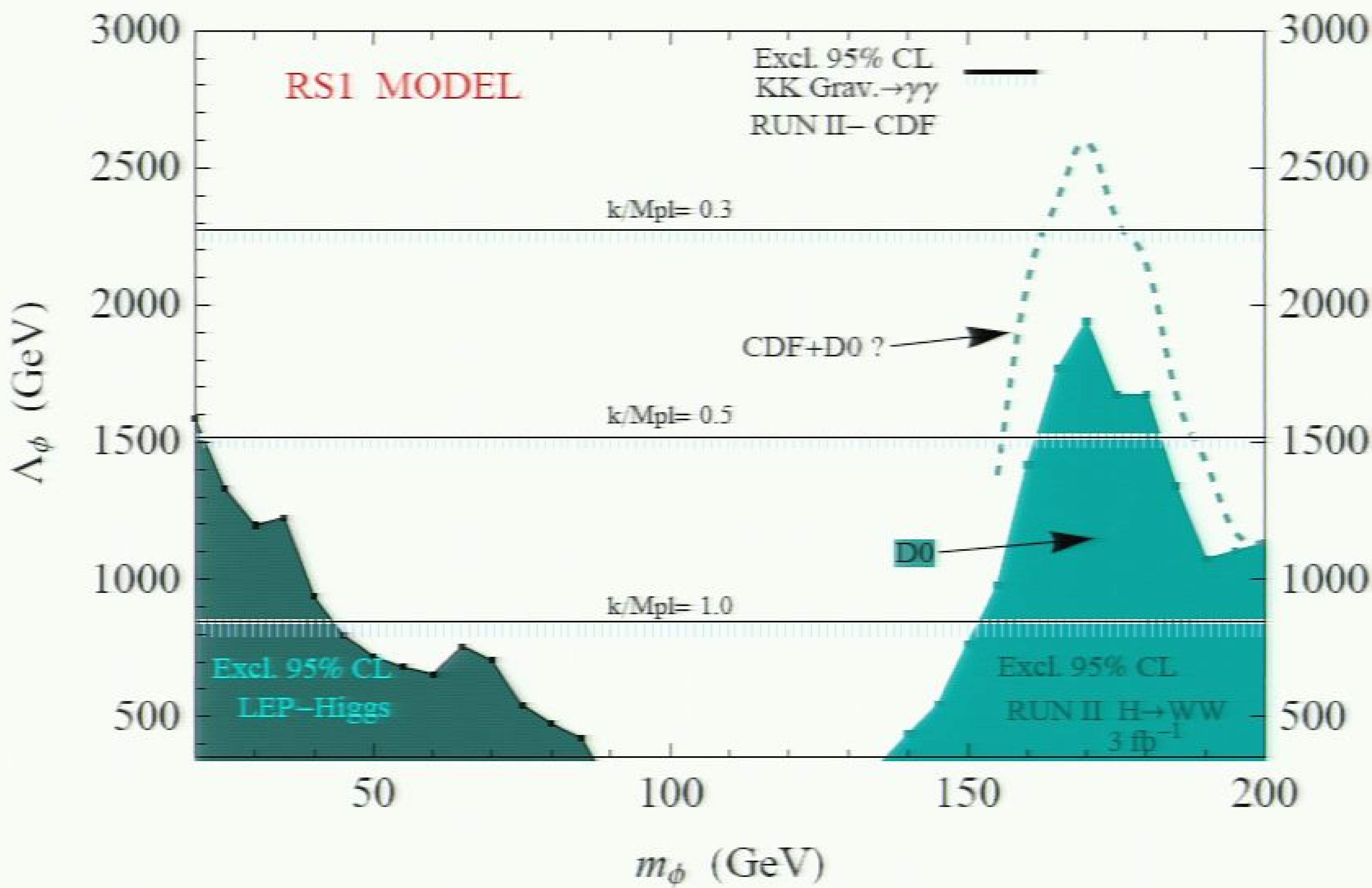

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- Interaction with fermions, although model dependent remains proportional to the mass of the fermion with an $\mathcal{O}(1)$ coefficient
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Bulk Matter vs. RS1-Matter on the brane

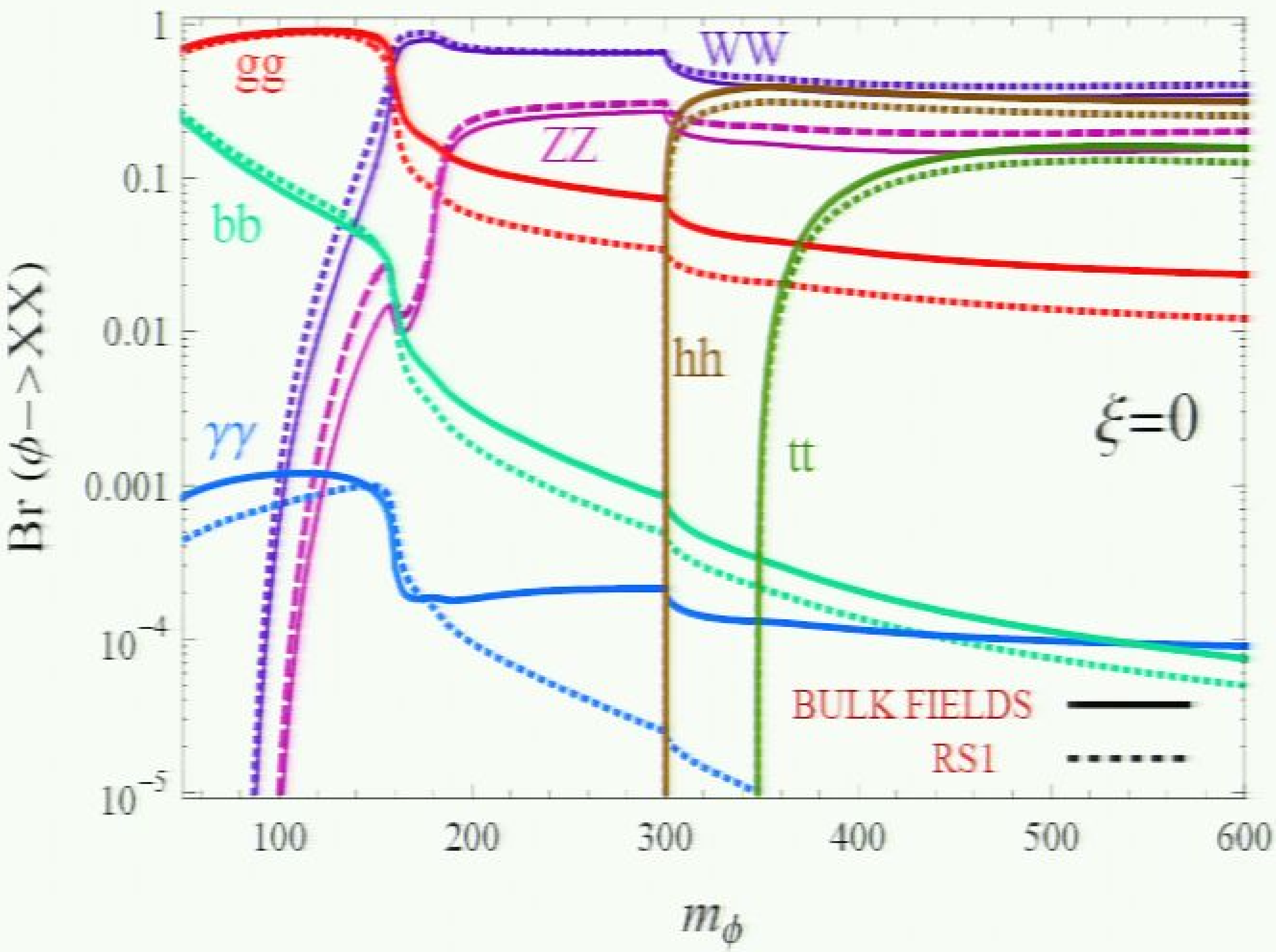

Figure 1: Branchings of the radion vs. its mass m_ϕ

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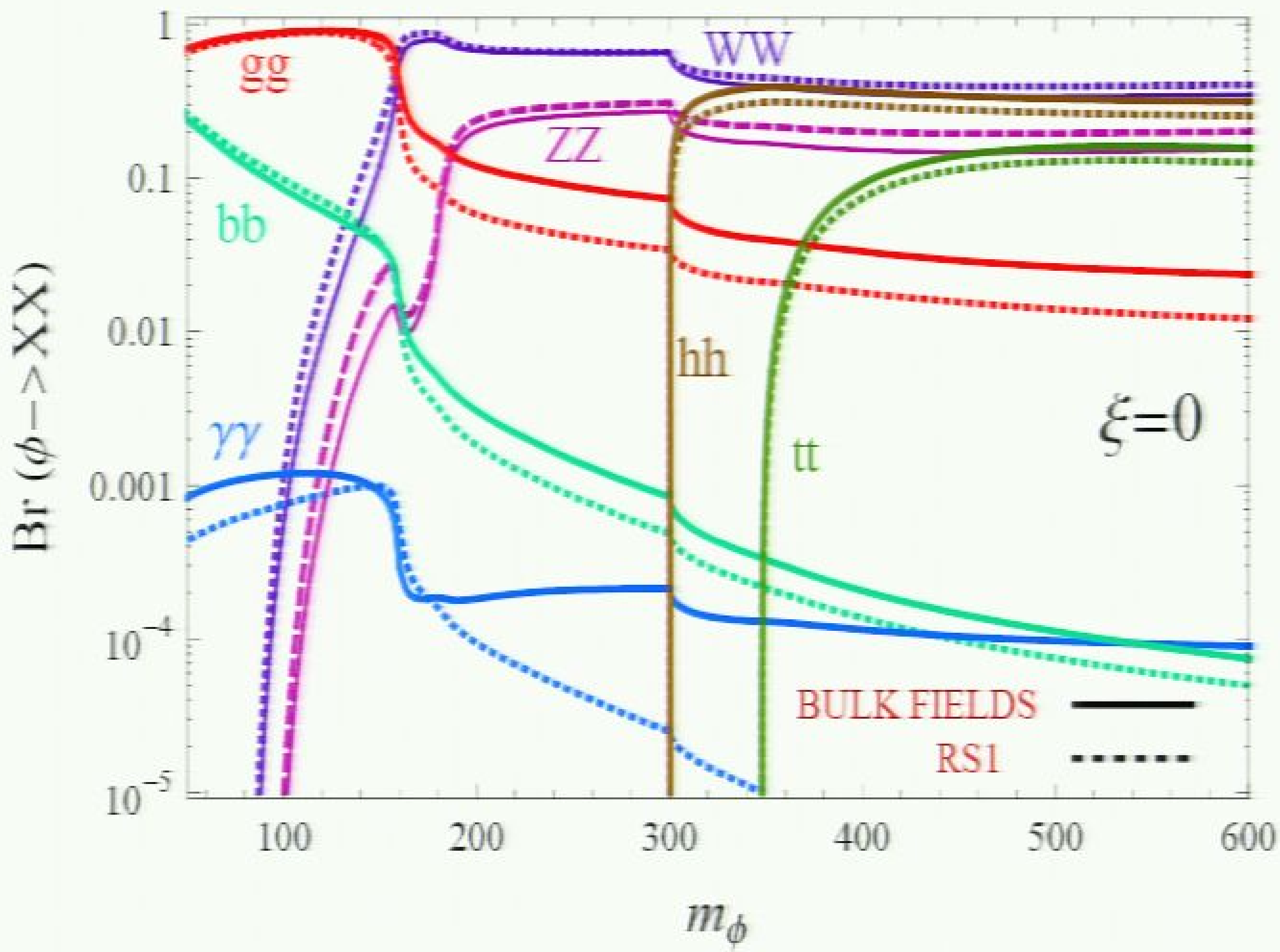

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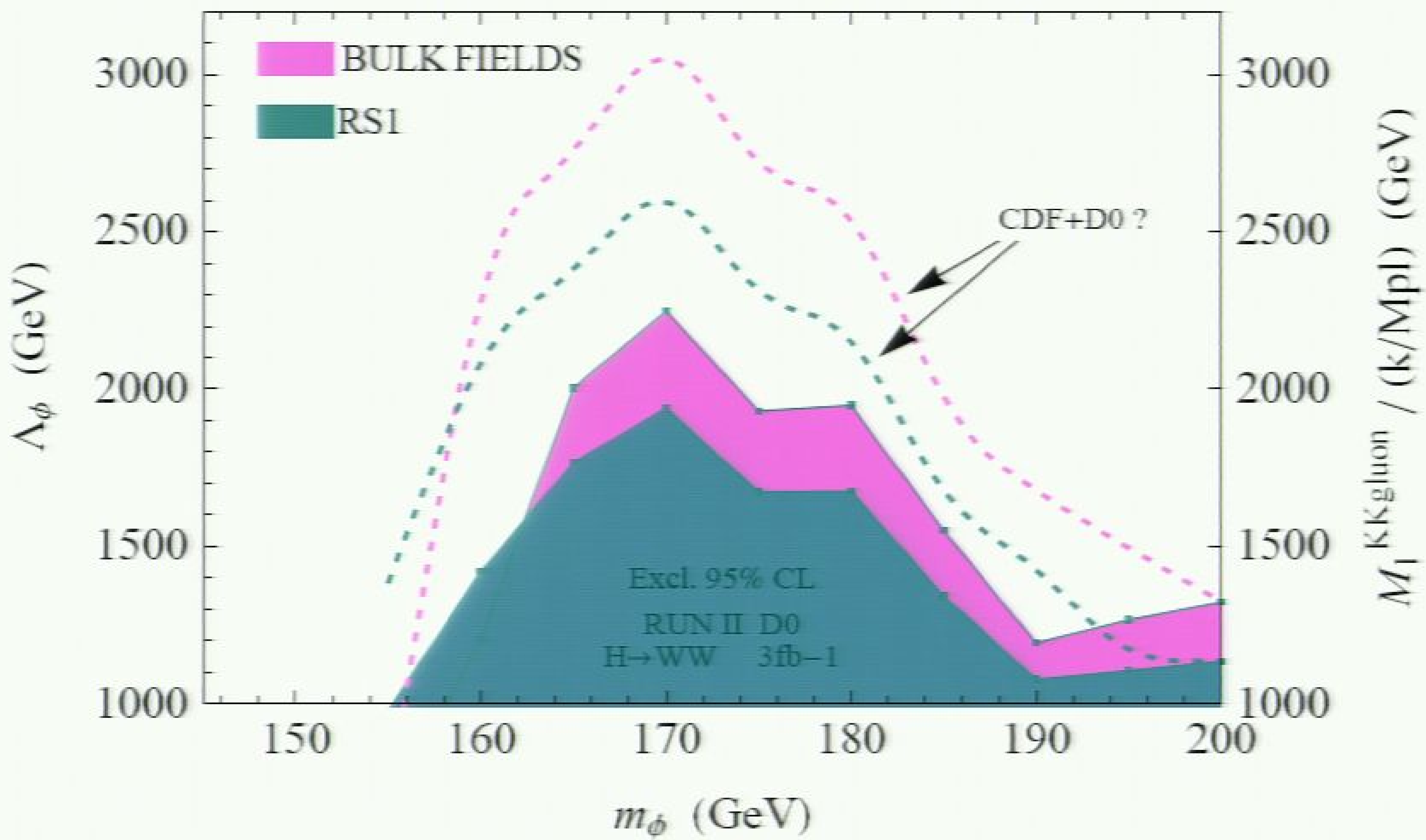
Tevatron Bounds in $(m_\phi - \Lambda_\phi)$ (with Nobu Okada)



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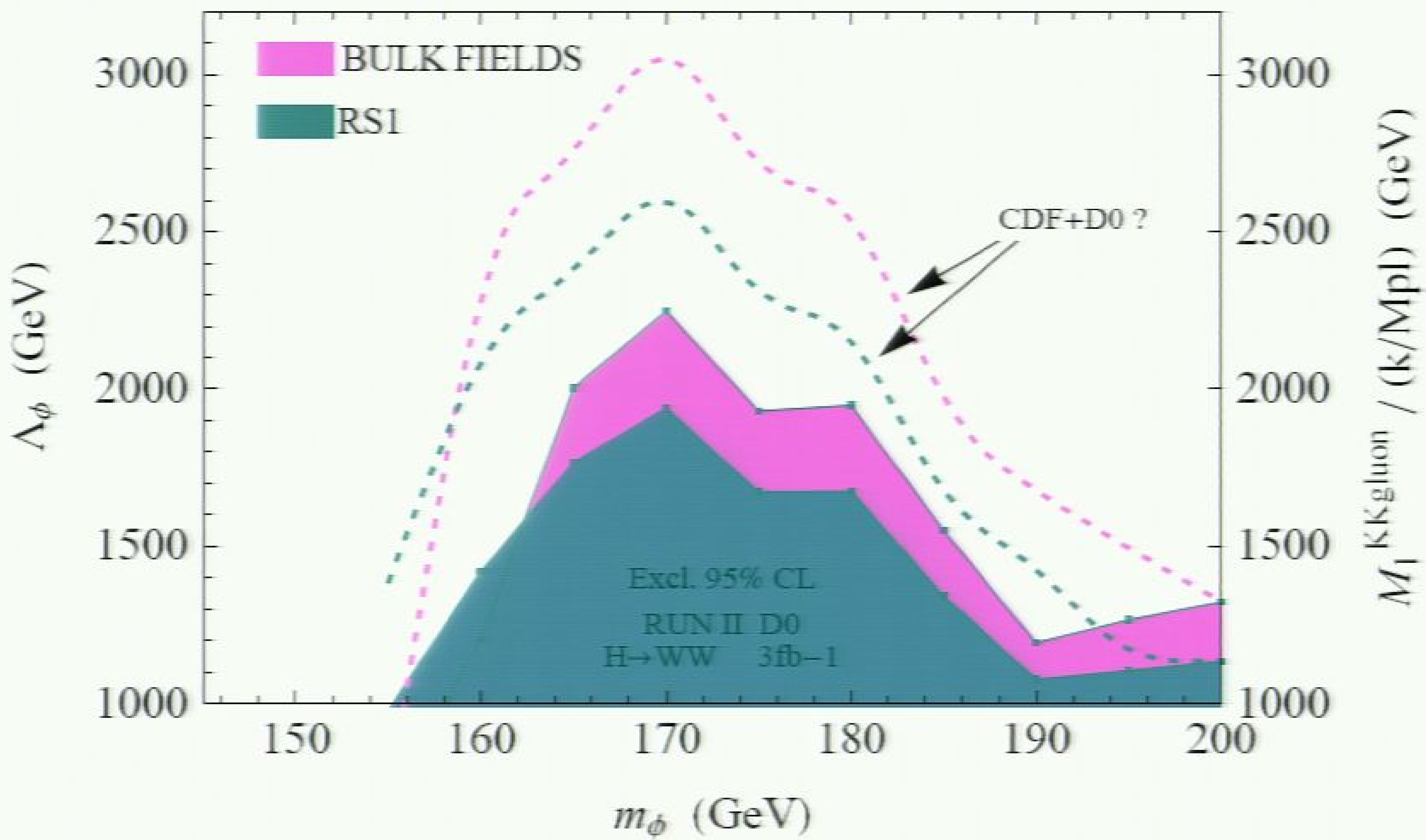

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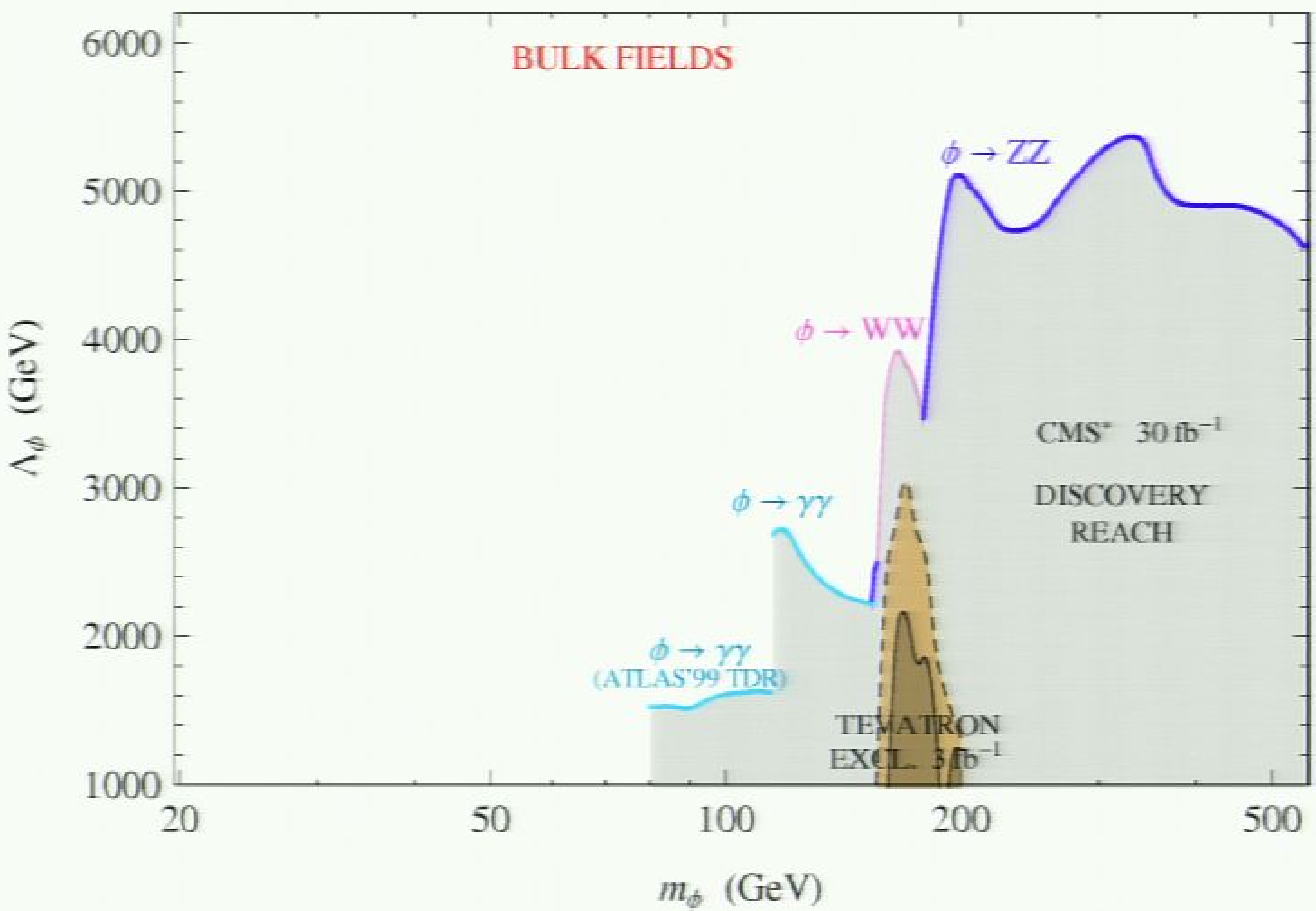

Higgs-radion mixing

[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:

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

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

Radion mass added “by hand”.

NORMALIZED HIGGS AND RADION PHYSICAL FIELDS

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with $\gamma = \frac{v}{\Lambda}$ and Z and θ depend on m_ϕ, m_h, Λ and ξ.

$\Rightarrow$ 4 parameters in Higgs-radion sector: m_ϕ , m_h , Λ_ϕ and ξ

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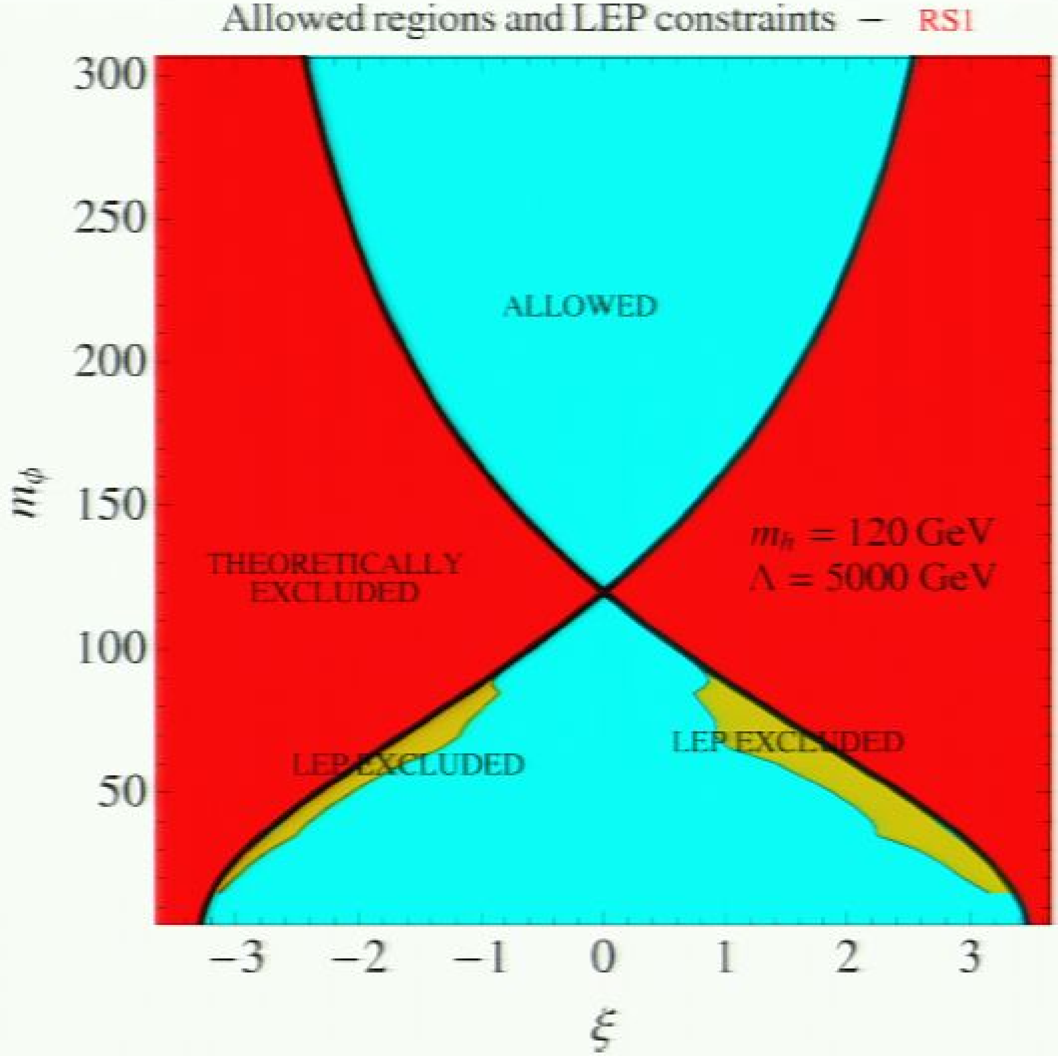

Figure 2: Allowed m_ϕ and ξ for $m_h = 120$GeV and $\Lambda = 5$TeV

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

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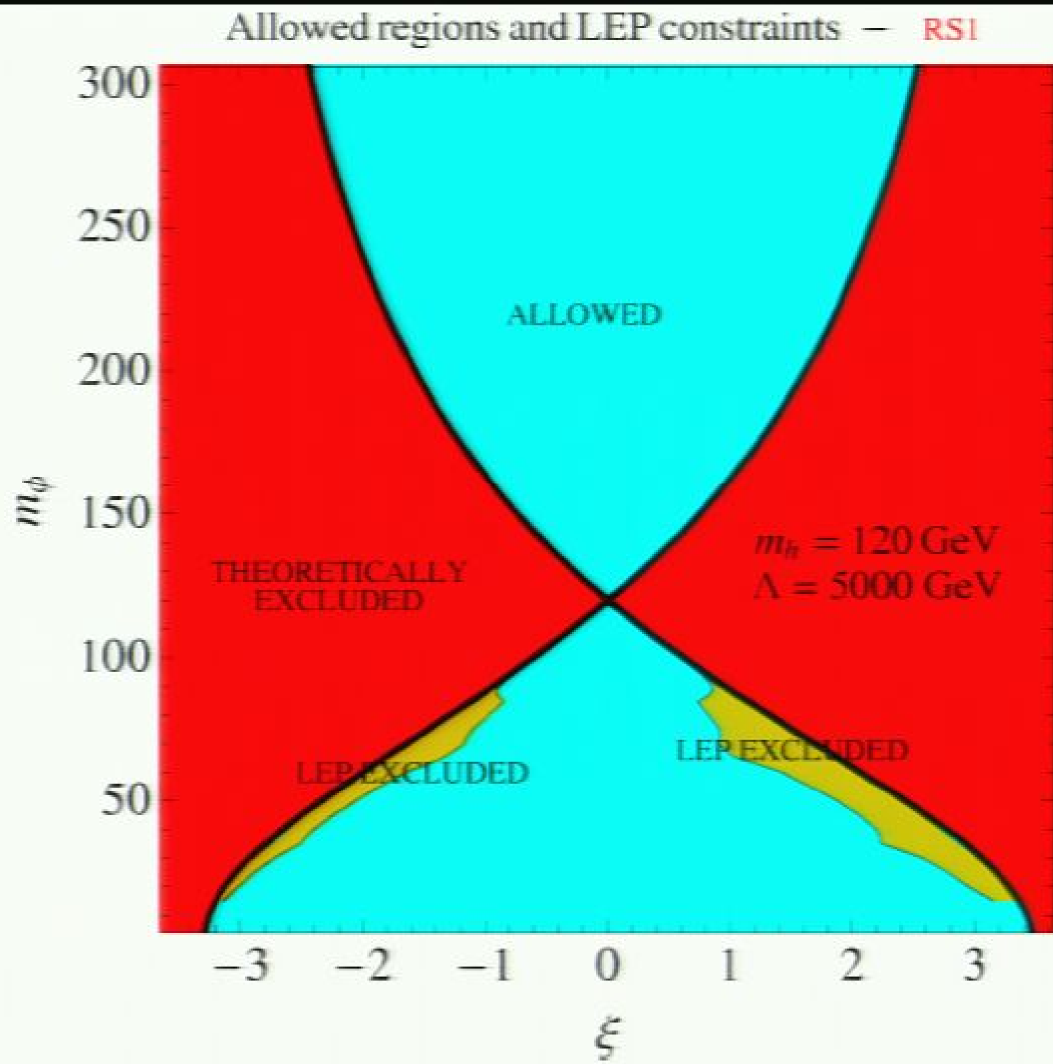

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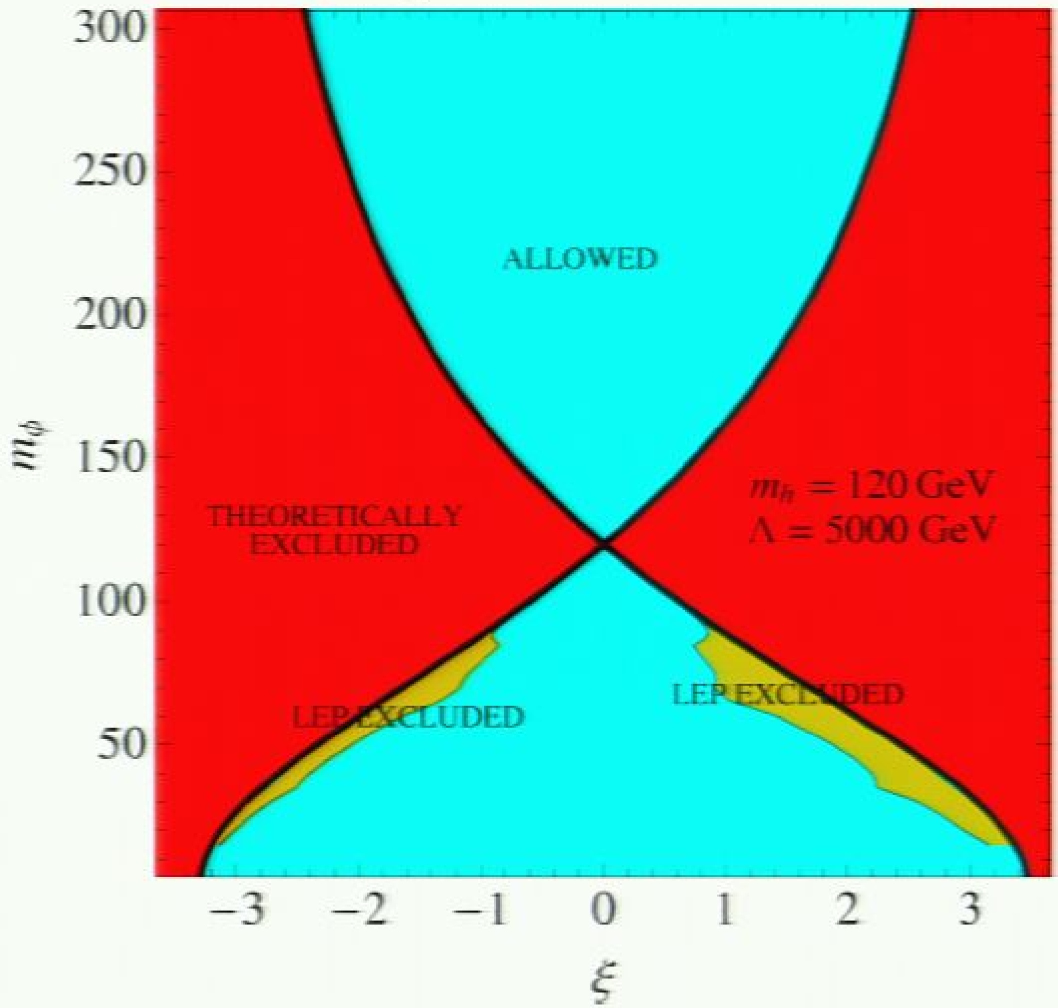
Allowed regions and LEP constraints – RS1



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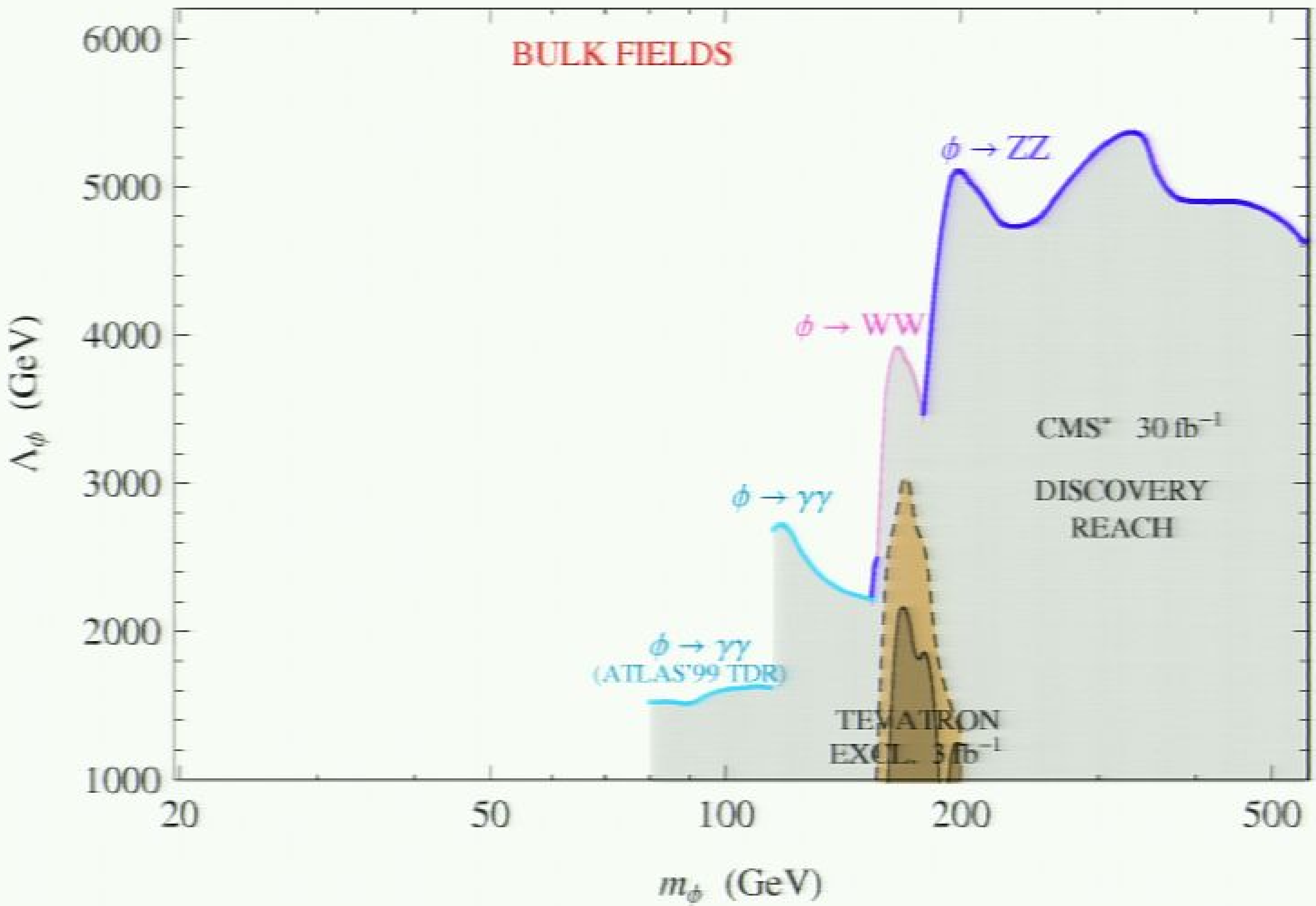

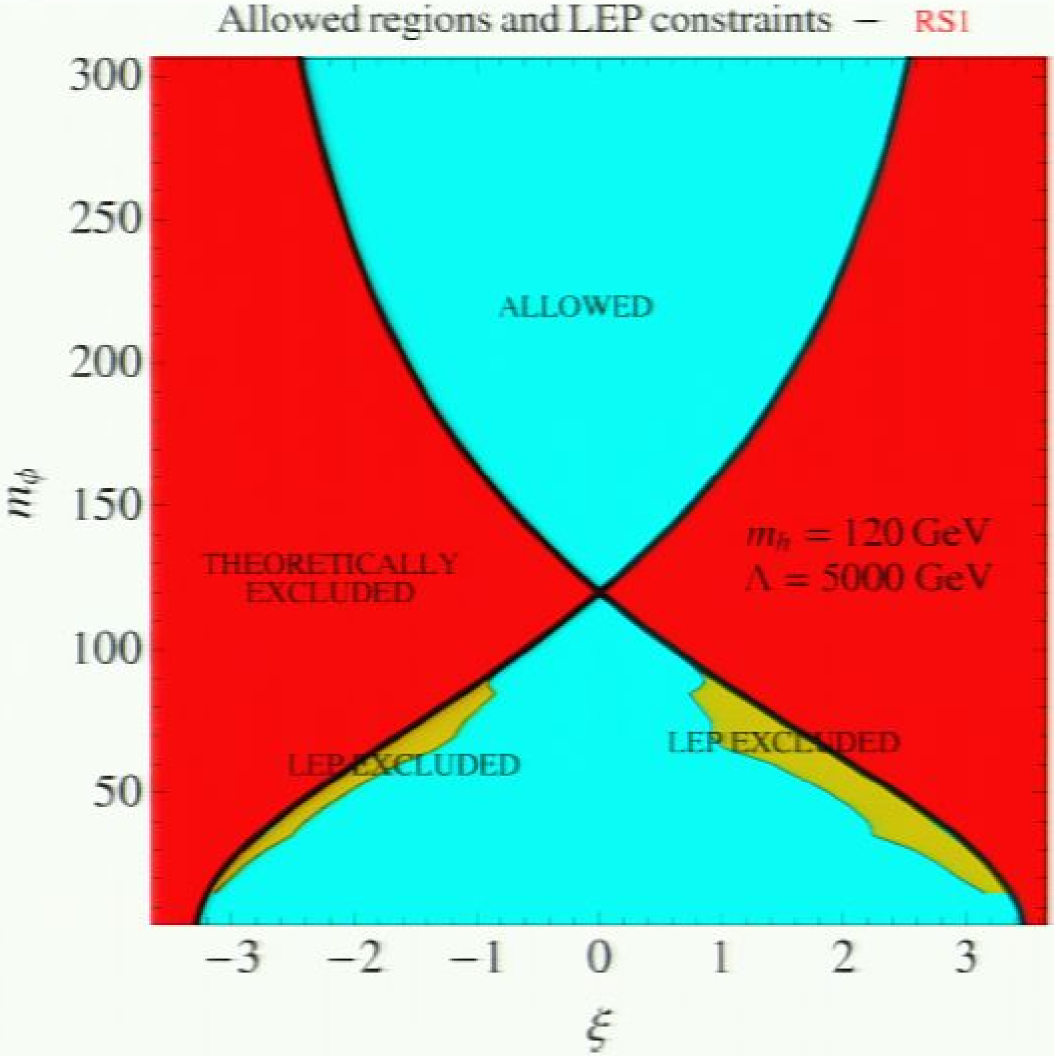

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Let g^0_{hii} and $g^0_{\phi ii}$ be the 'bare' Higgs and Radion couplings to the fields "i", then the couplings of the physical fields are

$$\begin{aligned} g_{hii} &= d\, g^0_{hii} + b\, g^0_{\phi ii} \\ g_{\phi ii} &= c\, g^0_{hii} + a\, g^0_{\phi ii} \end{aligned}$$

for couplings of the physical fields.

But we showed that $g^0_{\phi ii} \sim \frac{v}{\Lambda_\phi} g^0_{hii}$ and for small ξ mixing, the parameters $d \sim a \sim 1$ while b and c must be small.

$$\begin{aligned} g_{hii} &\sim g^0_{hii}(1 + b\frac{v}{\Lambda_\phi}) \\ g_{\phi ii} &\sim g^0_{hii}(c + \frac{v}{\Lambda_\phi}) \end{aligned}$$

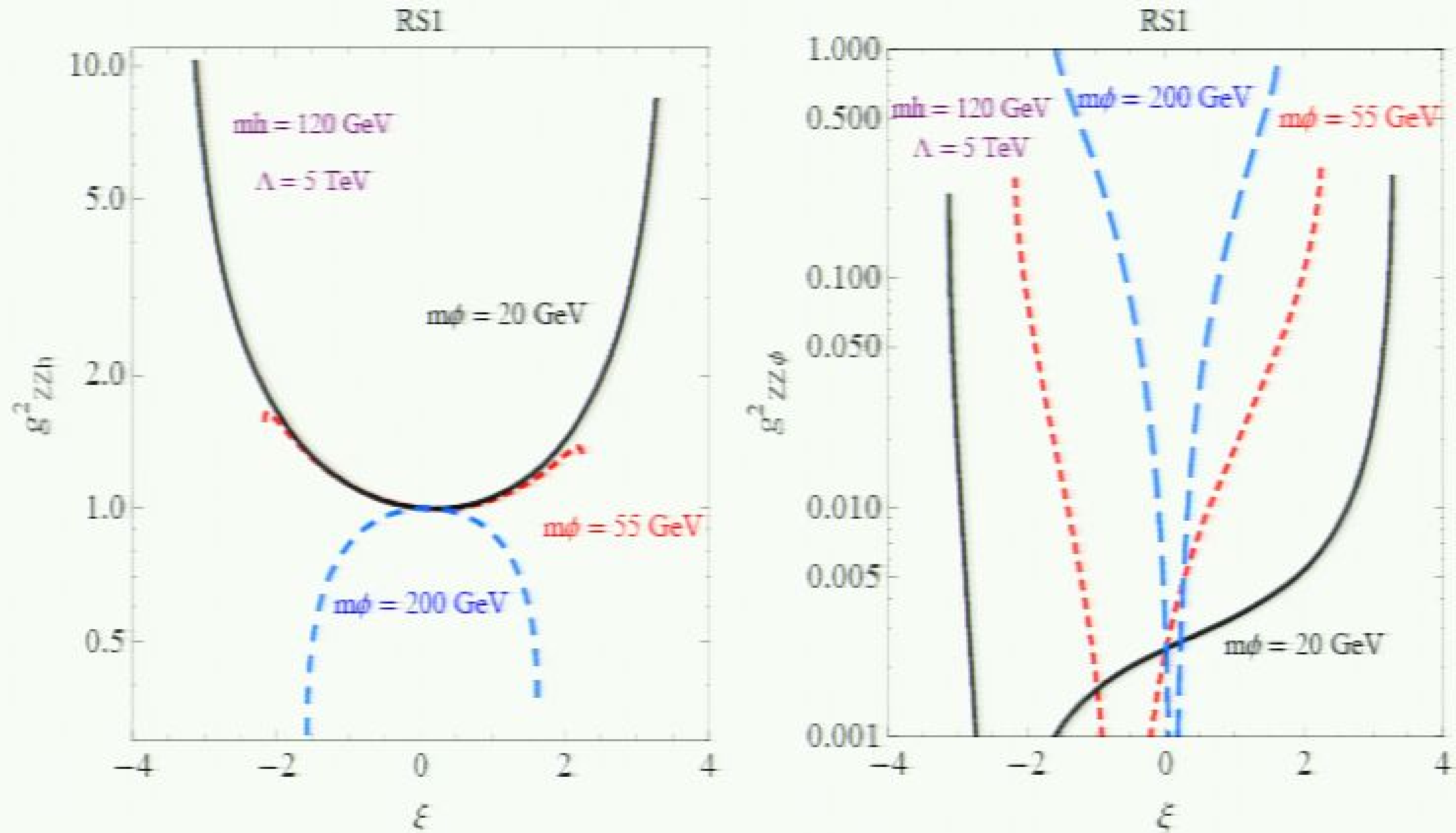

Figure 3:

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

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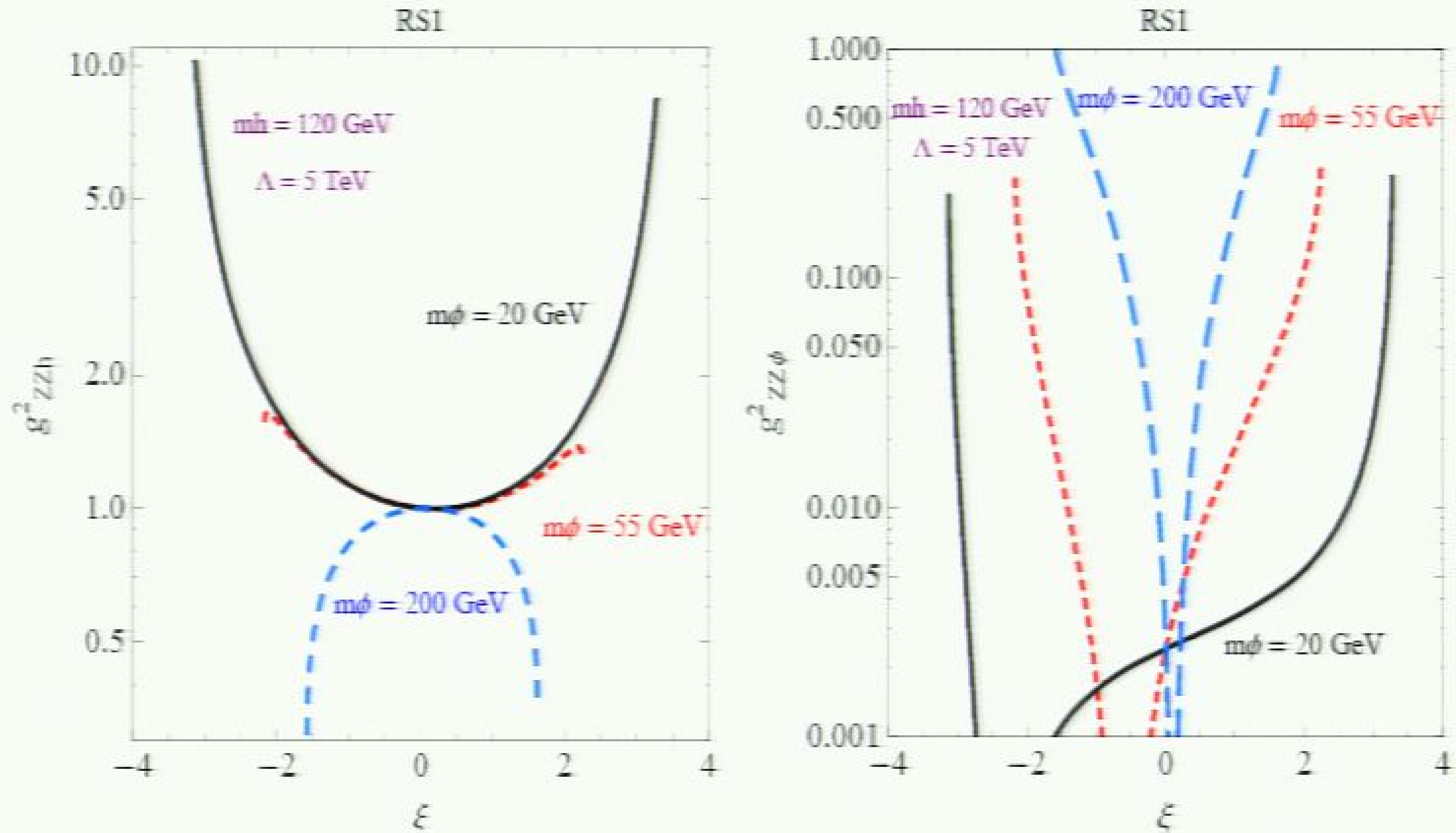


Figure 3:

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

Higgs-radion mixing & Matter in the bulk

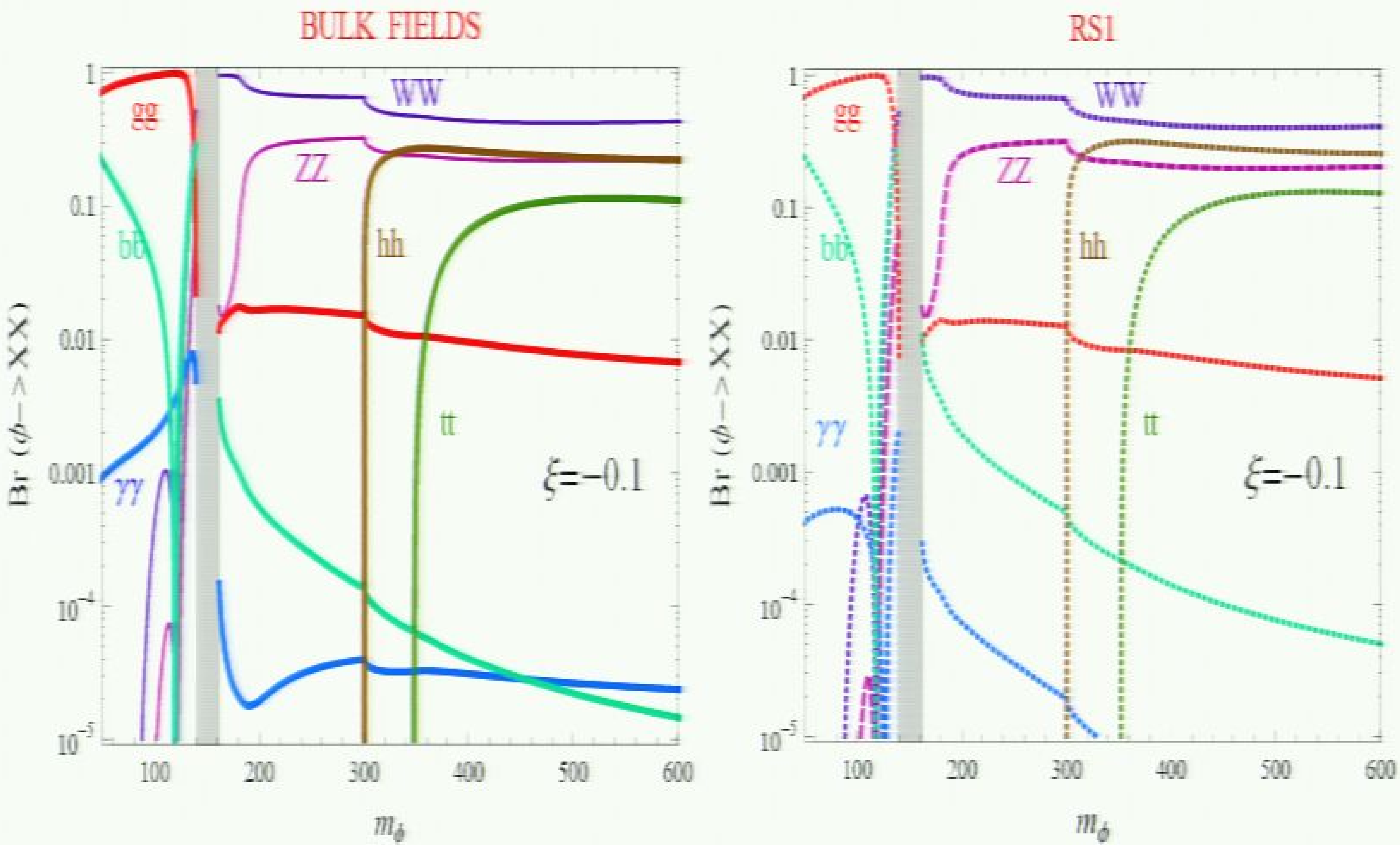
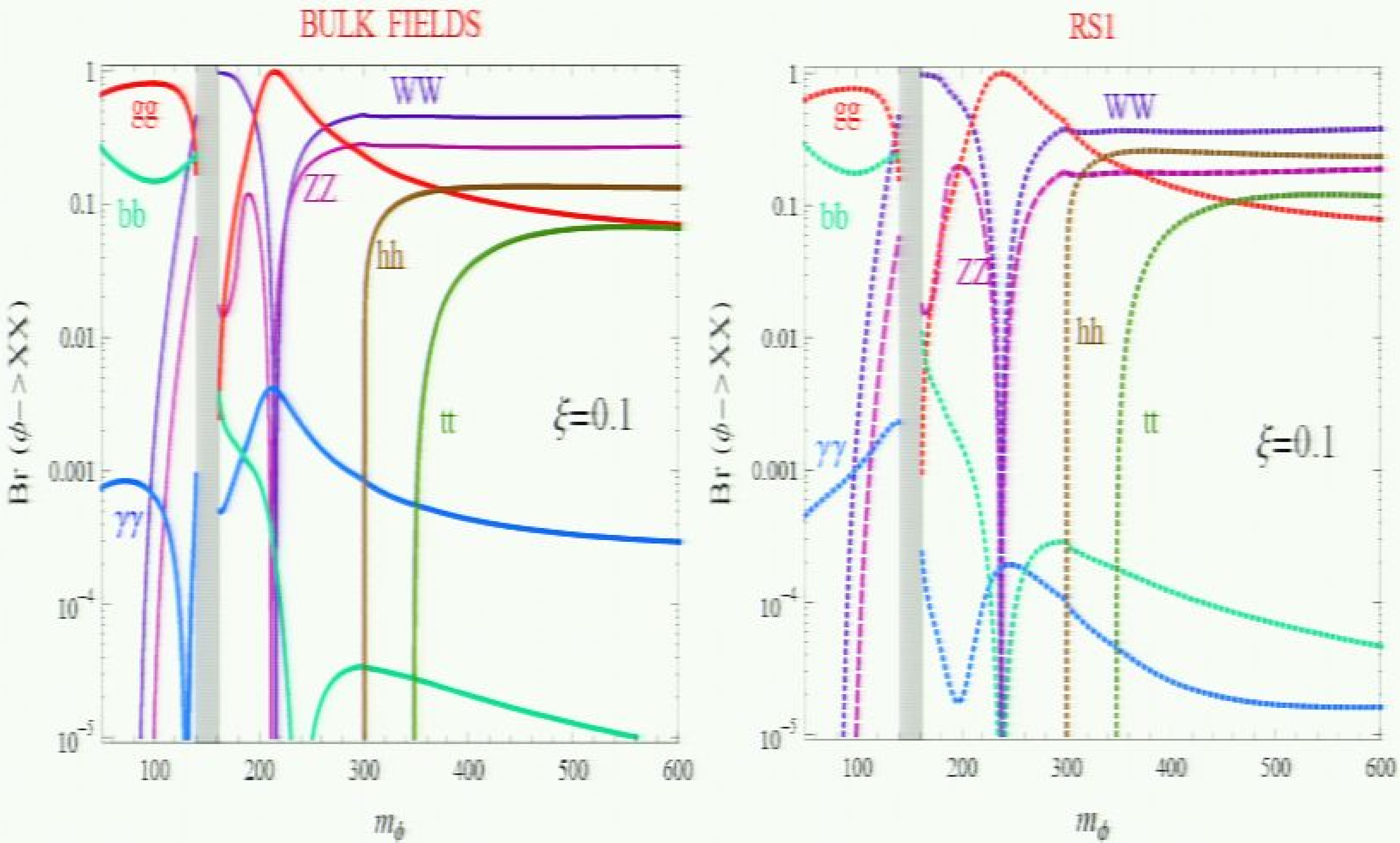


Figure 4: Branchings of the radion vs. its mass m_ϕ. Here we fix $m_h = 150$ GeV and $\Lambda = 2000$ GeV.



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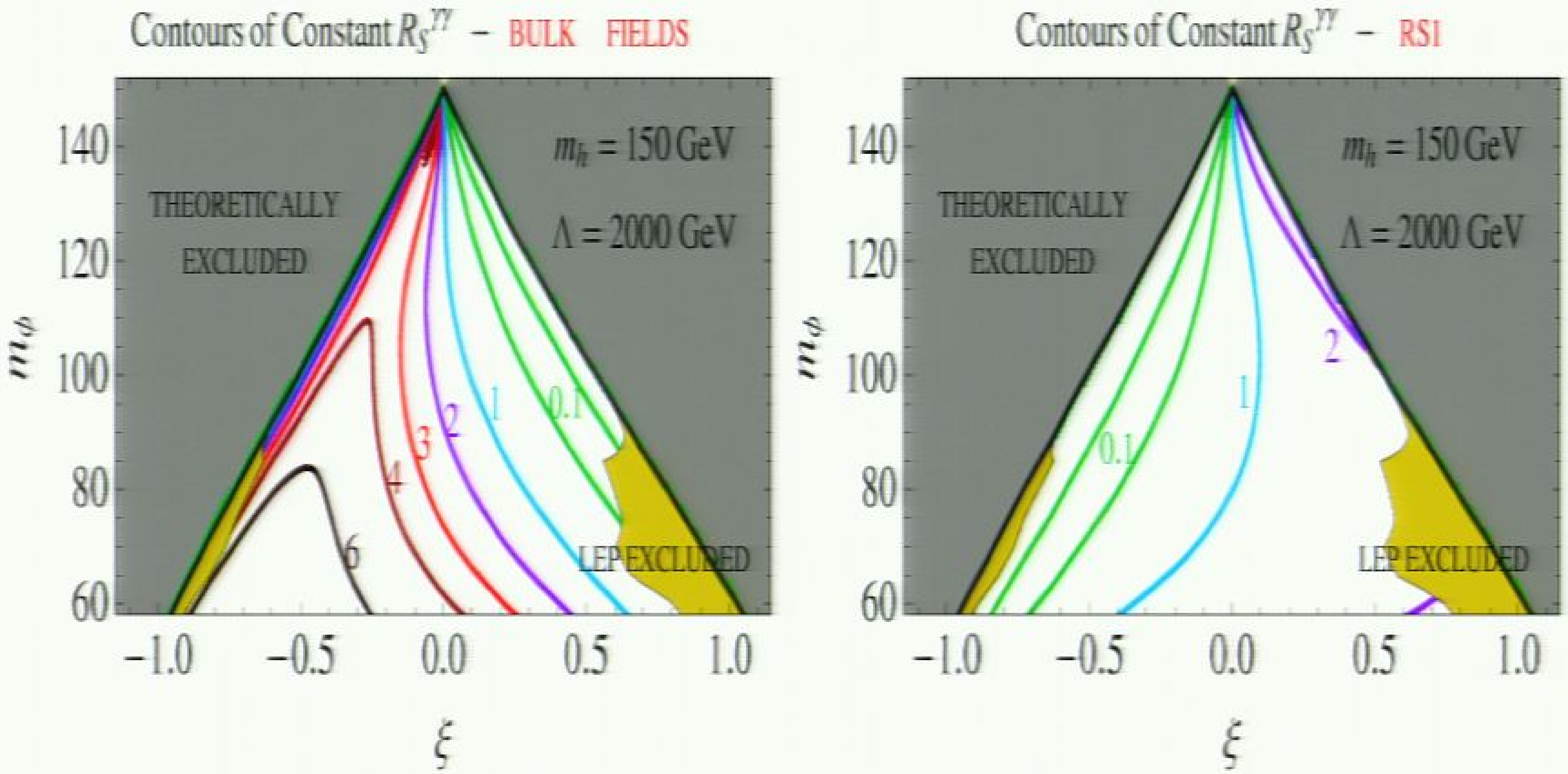

Figure 6: Contours of the Ratio $R_S^{\gamma\gamma}$ between the discovery significance (in $\gamma\gamma$ channel) of a radion and that of a SM Higgs of same mass.

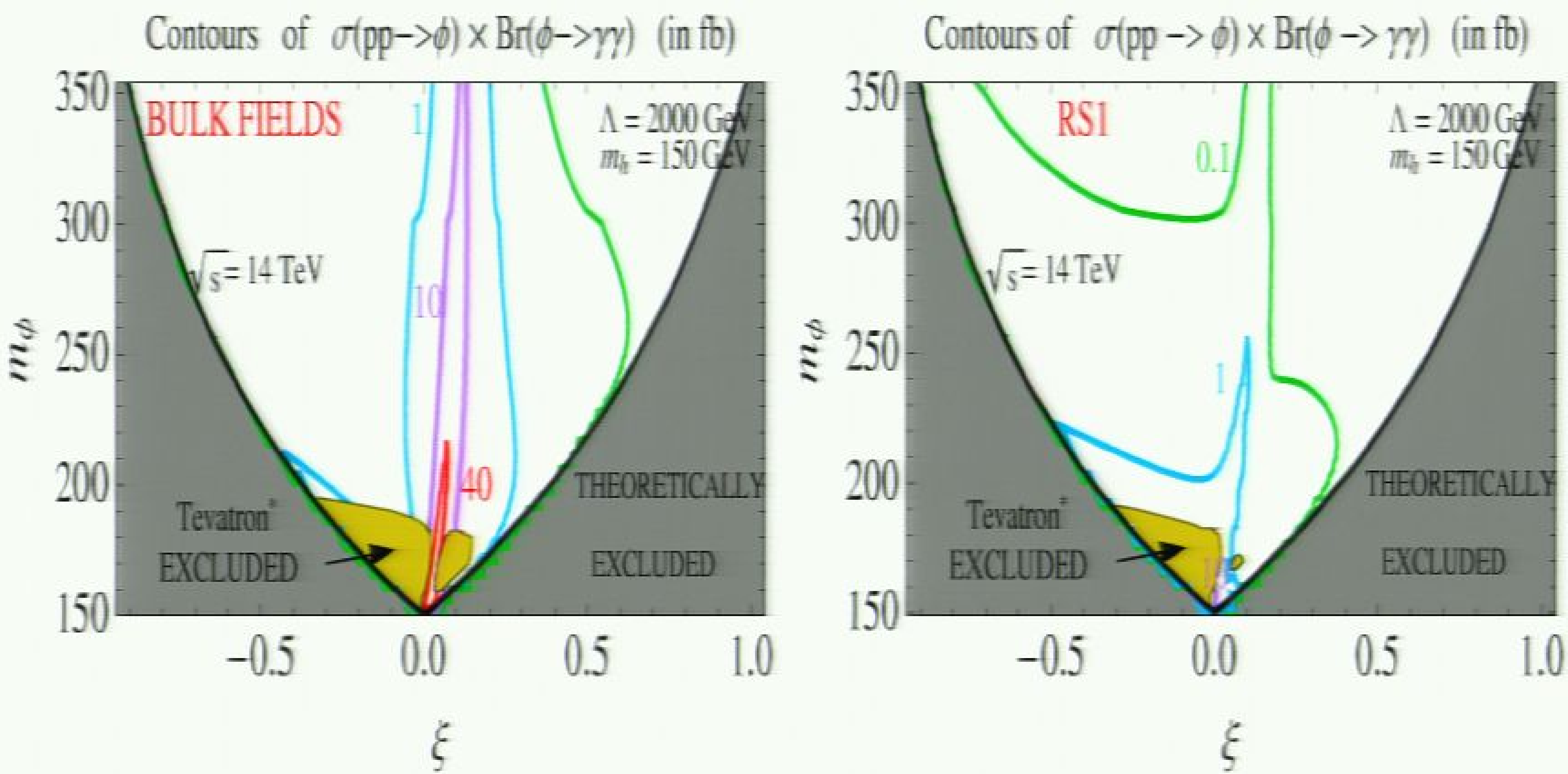

Figure 7: Contours of the cross section for $pp \to \phi \to \gamma\gamma$ at LHC for a heavier radion (using CTEQ5L pdf's and no QCD corrections..).

Radion couplings to 5D fermions

Let's consider two bulk fermions Q and U

$$Q \equiv \begin{pmatrix} q_L^{++} \\ q_R^{--} \end{pmatrix} \quad \text{and} \quad U \equiv \begin{pmatrix} u_L^{--} \\ u_R^{++} \end{pmatrix}$$

with action an

$$\begin{aligned} S &= \int d^4x dz \sqrt{g} \Big[\frac{i}{2} \left(\bar{Q} \Gamma^A \mathcal{D}_A Q - D_A \bar{Q} \Gamma^A Q \right) + \frac{c_Q}{R} \bar{Q} Q + \\ & \frac{i}{2} \left(\bar{U} \Gamma^A \mathcal{D}_A U - \mathcal{D}_A \bar{U} \Gamma^A U \right) + \frac{c_U}{R} \bar{U} U \; + \; \left(Y \; \bar{Q} \mathcal{H} U + h.c. \right) \Big] \end{aligned}$$

In the absence of Yukawas we have zero mode wave functions in z:

$$q_L^{++}(z) \;=\; Q_L \; z^{2-c_Q} \quad \text{with} \quad q_L^{++}(R') \;=\; \frac{R'^{3/2}}{R^2} \, f_Q$$

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The f_i profiles at the IR brane are

$$f_Q = \sqrt{\frac{1-2c_Q}{1-(R/R')^{1-2c_Q}}} \qquad f_U = \sqrt{\frac{1+2c_U}{1-(R/R')^{1+2c_U}}}$$

$\Rightarrow m_u \sim vY\ f_Q f_U$

$$\Rightarrow \quad \text{Mass matrices hierachical} \quad \mathbf{m} \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

If $U_d\, \mathbf{m_d}\, W_d^\dagger = \mathbf{m_d^{diag}}$ THEN

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with $\lambda \sim .22$ cabibbo angle (similar for up-sector)

- 1 family of bulk fermions and a Brane Higgs: [Csaki,Hubisz,Lee(07)]

$$\frac{\phi_0}{\Lambda_r}(c_Q - c_U) m_u \bar{u} u$$

Computation slightly involved, but a way to understand it is look at R' dependance in fermion mass term:

$$m_f \sim Y v (R/R')^{1+c_Q-c_U} \sim (1/R')^{c_Q-c_U}$$

Radion can be understood as perturbation in the interbrane distance L, or in $1/R'$ scale in the conformal frame. So we can write $1/R' \to 1/R' \ (1 + \phi/\Lambda_r)$

Then include it in mass term and expand linearly in the radion

$$(c_Q - c_U) \ \phi/\Lambda_r \ (1/R')^{c_Q-c_U} \Rightarrow (c_Q - c_U) \ \phi/\Lambda_r \ m_f$$

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- We extend to 3 families and allow for bulk Higgs (localized towards IR brane) [A. Azatov, M.T., L. Zhu (arXiv:0812.2489)]

$$\frac{\phi_0}{\Lambda_r}(c_Q^i - c_D^j)\ m_d^{ij}\ \bar{d^i}_L d_R^j + h.c$$

$$\frac{\phi_0}{\Lambda_r}\ \bar{\mathbf{d}}_\mathbf{L}(\mathbf{c_Q m_d} - \mathbf{m_d c_D})\mathbf{d_R}$$

where $\mathbf{m_d}$ is not in the diagonal physical basis and $\mathbf{c_{Q,D}}$ are diagonal matrices.

Diagonalize fermion mass matrix means here

$$\frac{\phi_0}{\Lambda_r}\ \bar{\mathbf{d}}_\mathbf{L}^\mathbf{phys}\left[(U^\dagger \mathbf{c_Q} U)\ \mathbf{m^d_{diag}} - \mathbf{m^d_{diag}}\ (W^\dagger \mathbf{c_D} W)\right] \quad \mathbf{d_R^{phys}}$$

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Tree level RADION exchange will induce $s_L d_R s_R d_L$ with coefficient

$$C_4 = a_{ds} a_{sd} m_d m_d \frac{1}{m_\phi^2 \Lambda_r^2} \quad \Rightarrow K - \bar{K} \text{ mixing and } \epsilon_K \text{ put tight bounds}$$

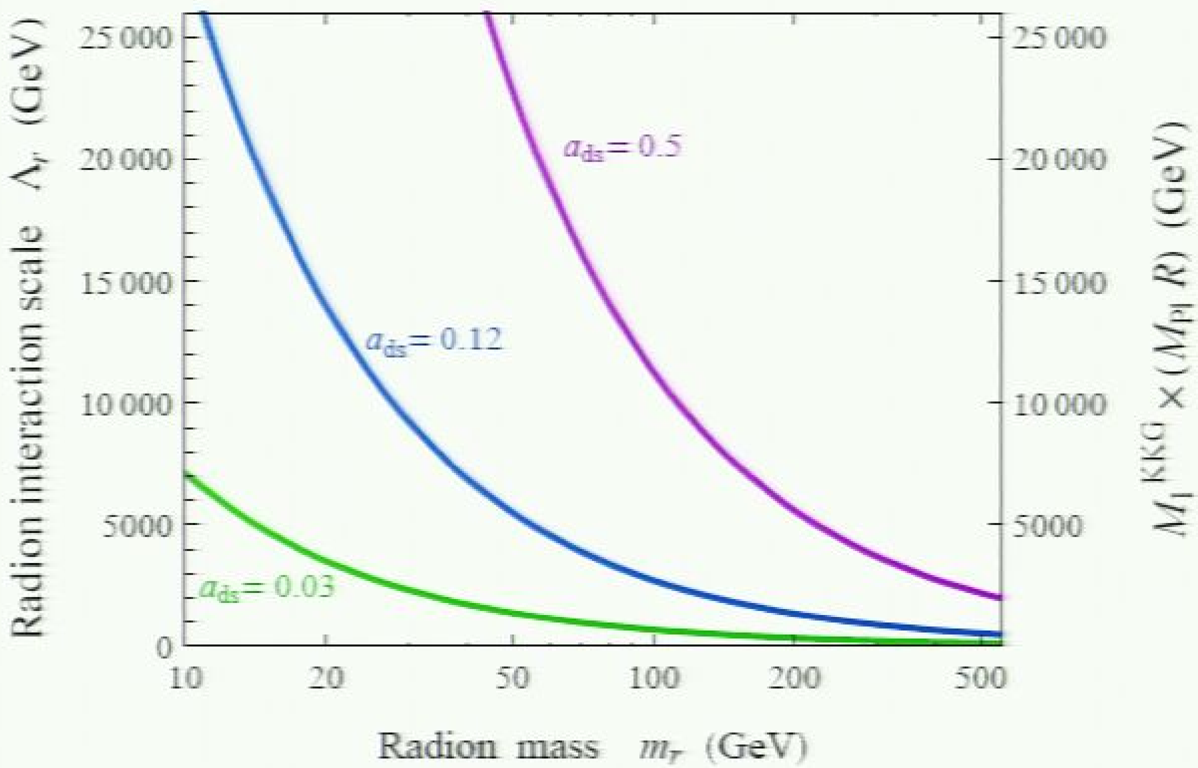

Figure 8: Bounds in $m_\phi - \Lambda_r$ plane from ϵ_K. Here we have called $a_{ds} \equiv \sqrt{|a_{ds} a_{sd}^*|}$

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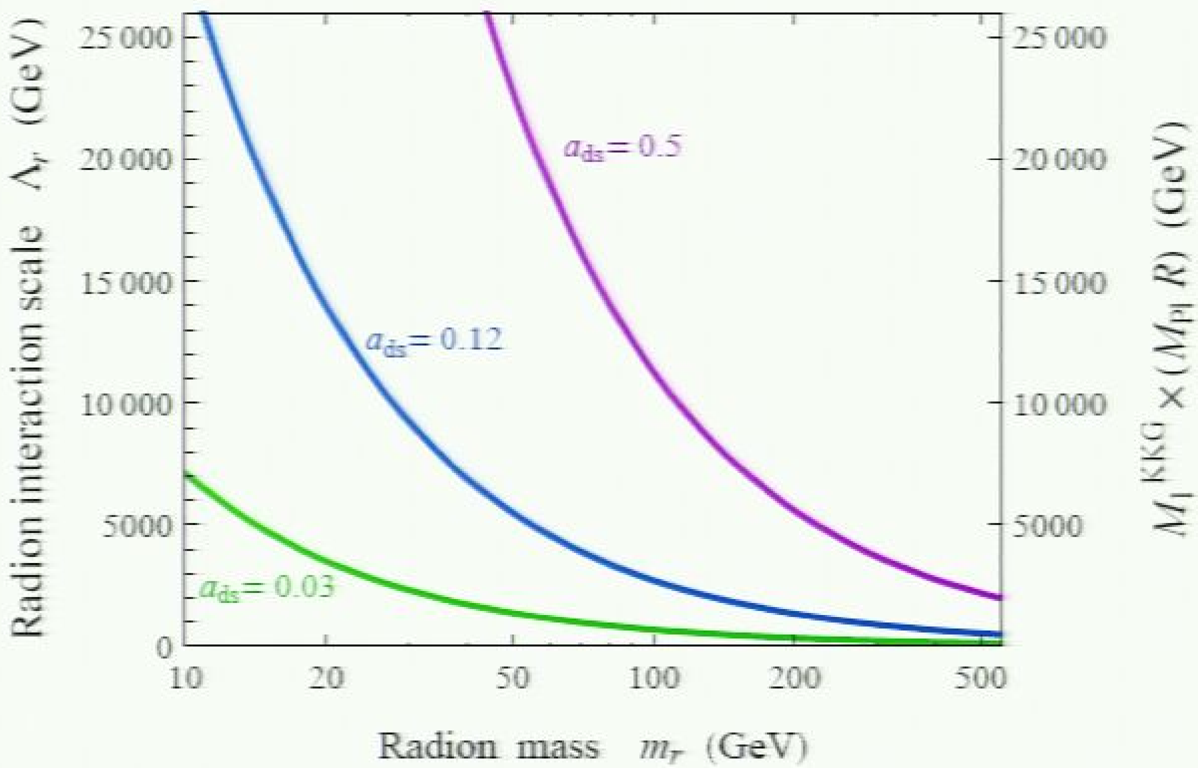

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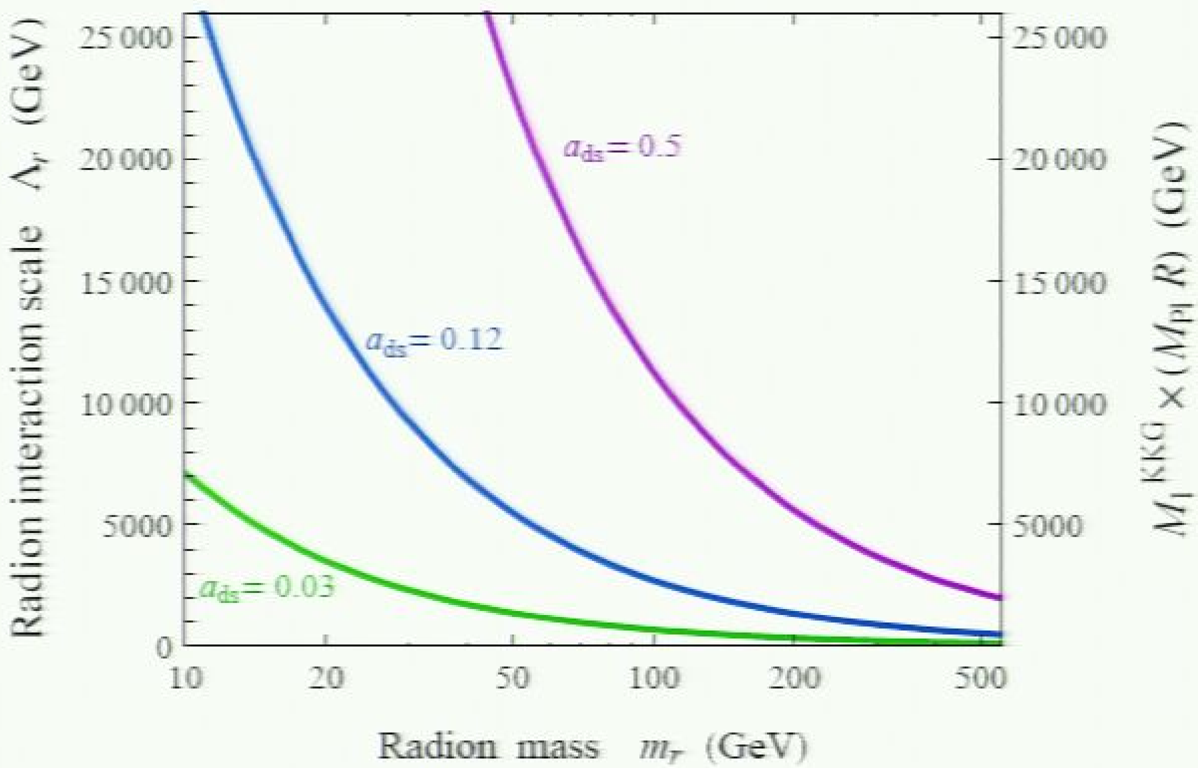

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What about LHC? (Heavier Radion)

We decided to estimate the feasibility of $\phi \to tc$

The "normalized" coupling a_{tc} is estimated to be $\sim .1$

- Signal: $\phi \to tc \to l\nu bc$
- Background: $t + j \to l\nu bj$; $W + jj \to l\nu jj$; $W + bb \to l\nu bb$;

m_r	250 GeV	300 GeV	350 GeV
Signal	$a_{tc}^2 \times 21$ fb	$a_{tc}^2 \times 15$ fb	$a_{tc}^2 \times 9$ fb
Background	280 fb	199 fb	136 fb

Table 1: Signal and background for different Radion masses with $\Lambda_r = 2$ TeV (and no Higgs-Radion mixing).

Very hard...

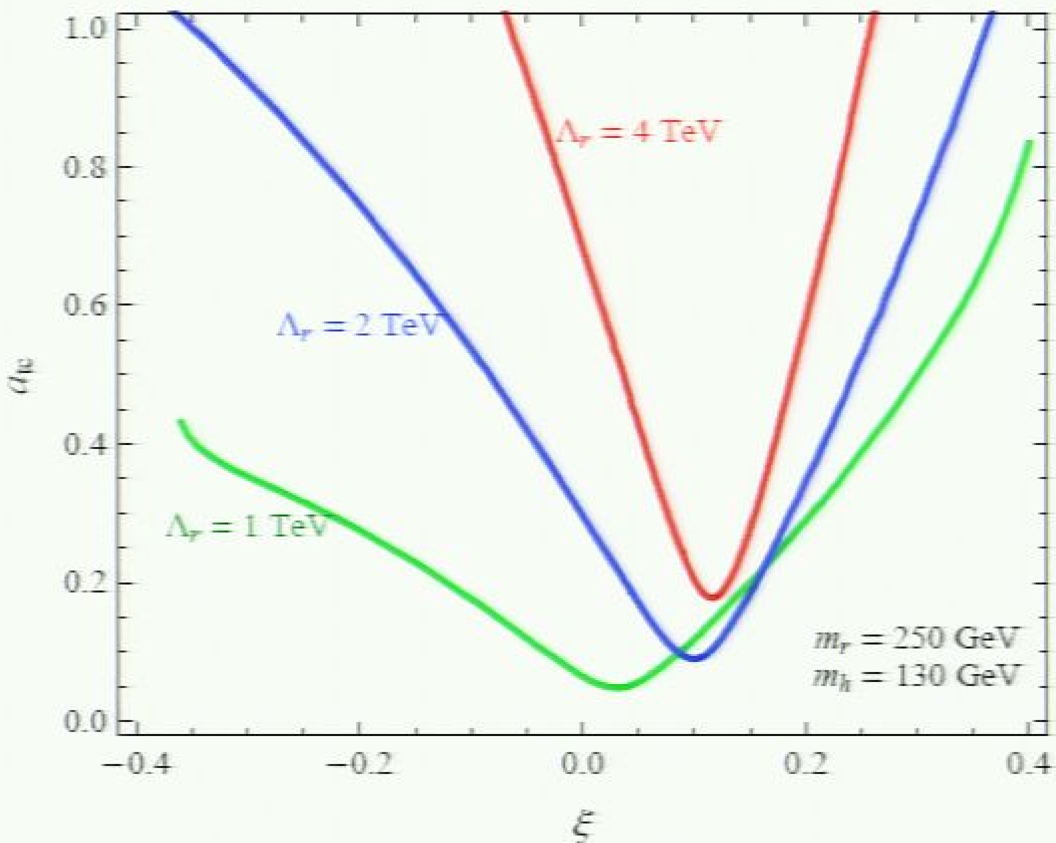

Figure 9: Contours in the $(\xi - a_{tc})$ plane of the signal significance $S/\sqrt{B} = 3$, for $300 fb^{-1}$ of data at the LHC

Conclusions - Outlook

- Radion phenomenology is generically very similar to the Higgs
- Higgs-radion mixing adds interesting properties to both the radion (phobic couplings) and the Higgs (suppressed/enhanced couplings)
- $\gamma\gamma$ signal can be importantly enhanced in Radion-higgs mixing with Bulk matter $\rightarrow$ maybe help differentiate between RS1 and Bulk-Fields scenario?
- radion couplings to bulk fermions: $\frac{\phi}{\Lambda}(c_L^i - c_R^j)m_{ij}$
  $\Rightarrow$ radion mediated FCNC's.
- Bulk Higgs-radion mixing?
- Tree level Higgs FCNC's (with no radion mixing) WORK IN PROGRESS