Radion-Higgs mixing @ LHC

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PRD 2012

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24/04/2012

Outline

- Introduction: scale invariance and the dilaton
- EWSB
- Higgs-dilaton mixing
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- Radion phenomenolgy
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Introduction

Consider the following general lagrangian:

$$\mathcal{L} = \sum_i \underbrace{g_i(\mu)}_{\text{coupling}} \underbrace{\mathcal{O}_i(x)}_{\text{operator with scaling dimension } d_i}$$

Scale transformation (dilatations):

$$x \to e^{\alpha} x \qquad \mathcal{O}_i(x) \to e^{\alpha d_i} \mathcal{O}_i(e^{\alpha} x)$$

Associated current:

$$j^\mu = x_\nu T^{\mu\nu}$$

$$\delta\mathcal{L} = \partial_\mu j^\mu = T^\mu_\mu$$

Variation of lagrangian under an infinitesimal scale transformation:

$$\delta\mathcal{L} = \sum_i \left[g_i(\mu)(d_i - 4) - \beta(g_i)\right] \mathcal{O}_i(x)$$

Theory is scale invariant if operators have dimension 4 (dimensionless couplings) and couplings don't run.

Broken scale invariance can be realized nonlinearly by introducing a scalar field

$$\chi(x) = f e^{\phi(x)/f} \approx f + \phi(x) + \frac{1}{2f}\phi(x)^2 + \cdots$$

symmetry breaking scale

$$\delta\phi = x^\mu \partial_\mu \phi + f$$

Nambu-Golstone boson – the dilaton

Scale invariant lagrangian

$$\mathcal{L} = \sum_i g_i \left(\frac{\chi}{f}\mu\right) \left(\frac{\chi}{f}\right)^{4-d_i} \mathcal{O}_i(x) + \mathcal{L}_\chi$$

Expanding field χ in lagrangian:

$$\mathcal{L} = \mathcal{L}(\chi = f) + \left(\frac{\phi(x)}{f} + \frac{\phi^2(x)}{2f^2} + \cdots\right) \overbrace{\sum_i \left[g_i(\mu)(d_i - 4) - \beta(g_i)\right] \mathcal{O}_i}^{T^\mu_\mu} + \mathcal{L}_\chi$$

Dilaton couples to the trace of the energy-momentum tensor (which is the source of scale symmetry breaking)

Examples:

Does this look familiar??

- coupling to W's and Z's (dim=2)

$$\left(\frac{\phi(x)}{f} + \frac{\phi^2(x)}{2f^2} + \cdots\right)\left(2M_W^2 W_\mu W^\mu + M_Z^2 Z_\mu Z^\mu\right)$$

- coupling to fermions (dim=3)

$$\left(\frac{\phi(x)}{f} + \cdots\right)\left(m_f \bar{f} f\right)$$

- coupling to massless gauge bosons (dim=4)

$$\left(\frac{\phi(x)}{f} + \cdots\right)\left(\beta(g)\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right)$$

Dilaton couplings = Higgs couplings (with f=v)

Important exception: coupling to massless gauge bosons

$$\mathcal{L}_{hgg} = \frac{h}{v}\beta(g)_{\text{heavy}}\left(G_{\mu\nu}\right)^2 \qquad \mathcal{L}_{\phi gg} = \frac{\phi}{f}\beta(g)_{\text{light}}\left(G_{\mu\nu}\right)^2$$

$$b_0^{\text{top}} = 2/3 \qquad b_0^{\text{light}} = -11 + 2n_f/3 = -23/3$$

factor ~10

Dilaton ≠ Higgs (dilaton is singlet)

Dilaton can mimick a Higgs (Higgs impersonator)

Golberger, Grinstein and Skiba (2008); Fan, Goldberger, Ross and Skiba (2009)

Dilaton can mix with a Higgs (change “Higgs” couplings)

EWSB

Idea: EWSB (or maybe whole SM) is embedded in a conformal invariant, strongly interacting sector.

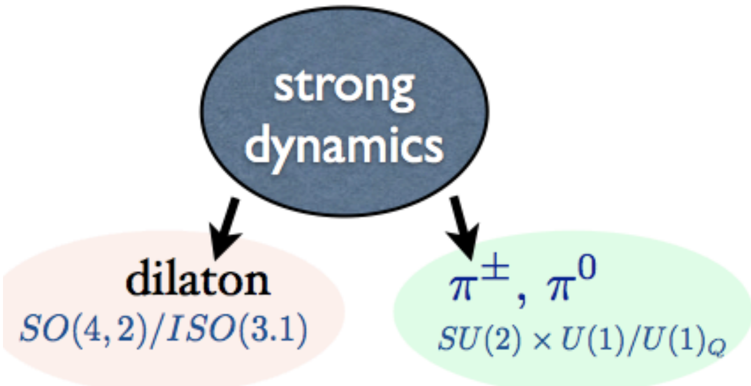
At some high energy scale f there is a breaking of scale invariance that triggers EWSB at a lower energy scale v.

A dilaton is generated at f and a Higgs doublet (PNGB) is generated at scale v.

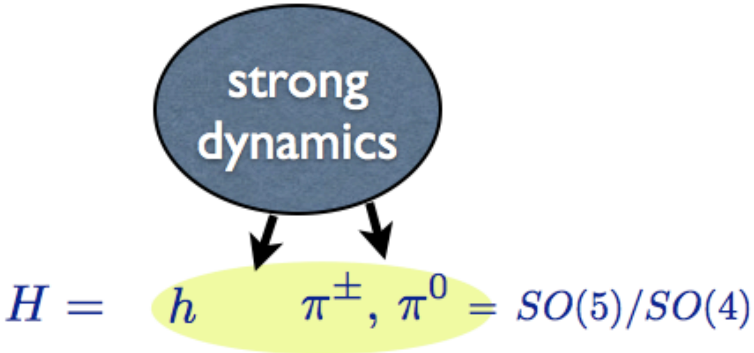
Agashe, Contino, Pomarol '04

Rattazzi, Planck 2010

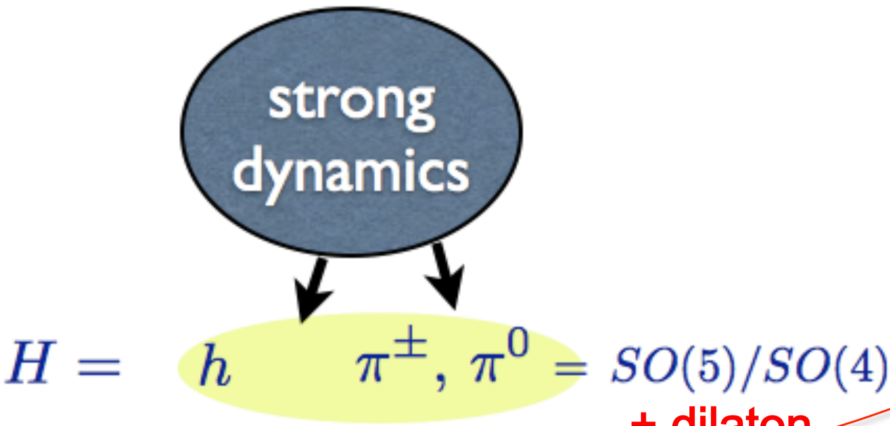
Higgsless with Light dilaton



Pseudo-Goldstone Higgs doublet



Pseudo-Goldstone Higgs doublet + dilaton



+ dilaton

Higgs-dilaton mixing

Scalar fields contribution to the canonical $T^{\mu\nu}$ violate scale invariance even at the classical level.

Example: free scalar field $$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m^2 h^2$$

$$T_{\mu\nu} = \partial_\mu h \partial_\nu h - g_{\mu\nu}\mathcal{L} \Longrightarrow T^\mu_\mu = -(\partial_\mu h)^2 + m^2 h^2$$

Nonzero in the conformal m=0 limit!

Need to "improve" definition of energy-momentum tensor

Callan, Coleman and Jackiw (1970)

$$\Theta_{\mu\nu} = T_{\mu\nu} - \xi\left(\partial_\mu \partial_\nu - g_{\mu\nu}\Box\right) h^2$$

$$(\Theta^\mu_\mu = m^2 h^2 \ \ \text{for} \ \ \xi = 1/6)$$

Higgs coupling to dilaton:

$$\mathcal{L}_{h-d} = \frac{\phi}{f}\Theta^{\mu}_{\mu}$$

$$\Theta_{\mu\nu} = T_{\mu\nu} - \xi\left(\partial_\mu\partial_\nu - g_{\mu\nu}\Box\right)\underbrace{H^\dagger H}_{\frac{(h+v)^2}{2}}$$

SSB + improved $T^{\mu\nu}$: Higgs-dilaton kinetic mixing

$$\mathcal{L}_{h-d} \sim \frac{v}{f}\phi\Box h$$

Schematic Higgs-dilaton mixing:

$$\mathcal{L} = -\frac{1}{2}\tilde{\phi}\left[(1+\kappa)\Box + m^2_{\tilde{\phi}}\right]\tilde{\phi} - \frac{1}{2}\tilde{h}\left[\Box + m^2_{\tilde{h}}\right]\tilde{h} - \mu^2\tilde{\phi}\tilde{h} - \zeta\tilde{\phi}\Box\tilde{h}$$

$$\begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & \alpha \\ 0 & \beta \end{pmatrix}}_{} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

re-scaling the kinetic terms
to their canonical forms

Physical fields are obtained from a non-orthogonal transformation

Does a dilaton exist?

Theories can be scale invariant at the classical level but symmetry is broken at the quantum level:

- Spontaneous breaking (1-loop effective potential)
- Explicit breaking (non-zero beta functions)

It is not clear if a dilaton exists in quasi-conformal walking technicolor models

Yamawaki et al (1986, ..., 2012); Holdom and Terning (1986,87), Appelquist and Bai (2010),...

Radion in WED models

WED is a concrete implementation of a scale invariant model. Scale invariance is broken by the presence of the IR and UV branes in the extra 5th dimension.

Radion is the scalar mode of the metric fluctuation.
It may be the lightest new particle in these models (depends on the stabilization mechanism).

We follow the realistic implementation of WED by Csáki, Hubisz and Lee (2007) –fermions and gauge fields in the bulk.

It can be shown that the radion r(x) couplings are set by:

$$\mathcal{L} = \frac{r(x)}{\Lambda_r} T^{\mu}_{\mu}$$

Radion vev: size of extra-d

Hardly surprising... but there are some subtleties due to extra dimensional wave functions and other details that must be taken into account.

Radion phenomenology

Radion production and decay has same experimental efficiency and acceptance as the SM higgs of same mass. Production cross section:

$$\sigma(pp \stackrel{gg}{\to} r \to X)(s) = \int d\tau \mathcal{L}_{gg}(\tau)\hat{\sigma}(\tau s)$$

In the narrow width approximation

$$\frac{\sigma(pp \stackrel{gg}{\to} r \to X)}{\sigma(pp \stackrel{gg}{\to} h \to X)_{SM}} = \frac{\Gamma_h^{SM}}{\Gamma_r} \frac{\Gamma(r \to gg)}{\Gamma(h \to gg)_{SM}} \frac{\Gamma(r \to X)}{\Gamma(h \to X)_{SM}}$$

$$X = VV^*, \bar{f}f, \gamma\gamma$$

Phenomenology is determined by radion couplings and the mixing matrix

Giudice et al (2001); Csáki et al (2001); Dominici et al (2003), ...

$$\begin{pmatrix} \tilde{r} \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} r \\ h \end{pmatrix}$$

For instance,

radion component

Higgs component

$$\frac{\Gamma(r \to VV^*, \bar{f}f)}{\Gamma(h \to VV^*, \bar{f}f)_{SM}} = (c + \gamma a)^2$$

$$\gamma \equiv \frac{v}{\Lambda_r}$$

Similarly we can compute

$$\frac{\Gamma(r \to gg)}{\Gamma(h \to gg)_{SM}} \qquad \frac{\Gamma(r \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \qquad \Gamma(r \to hh)$$

Free parameters: radion mass, mixing and scale

$$m_r,\ \xi,\ \Lambda_r$$

Not all values of mixing are allowed – too large values lead to imaginary masses

Results

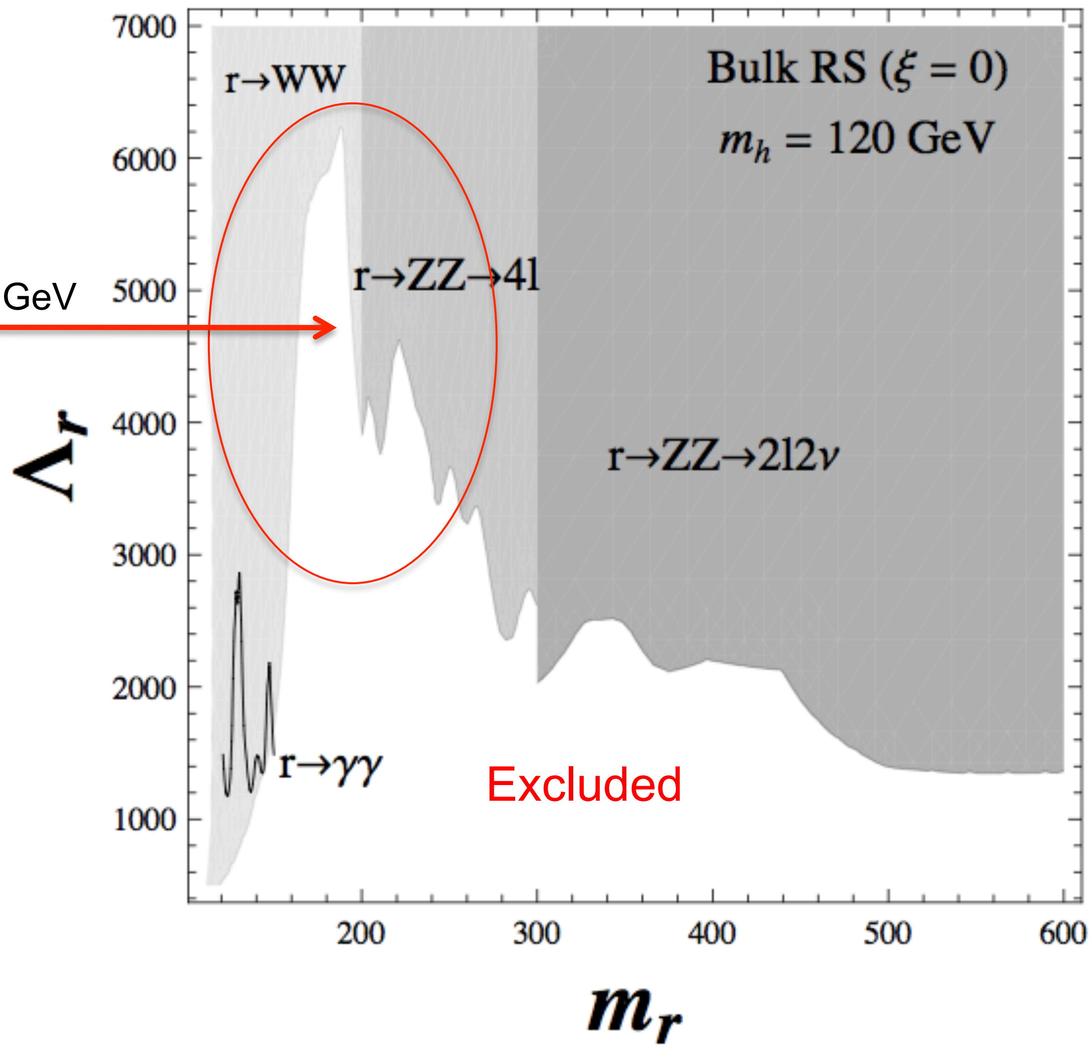
We used CMS data with "signal strength modifier"

$$\mu = \frac{\sigma(pp \stackrel{gg}{\to} r \to X)}{\sigma(pp \stackrel{gg}{\to} h \to X)_{SM}}$$

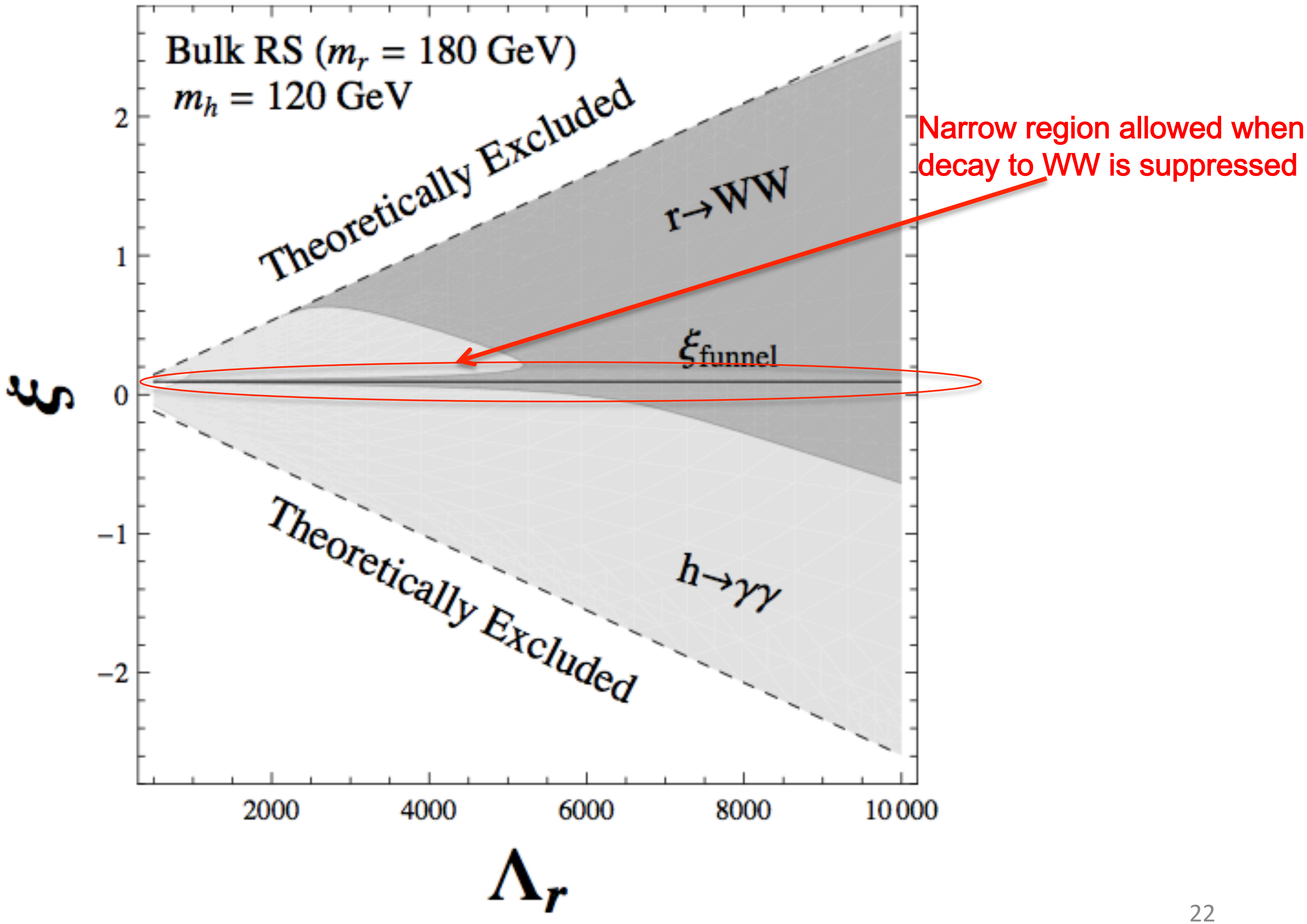
to constrain radion models using Higgs search data.

Exclusion plots

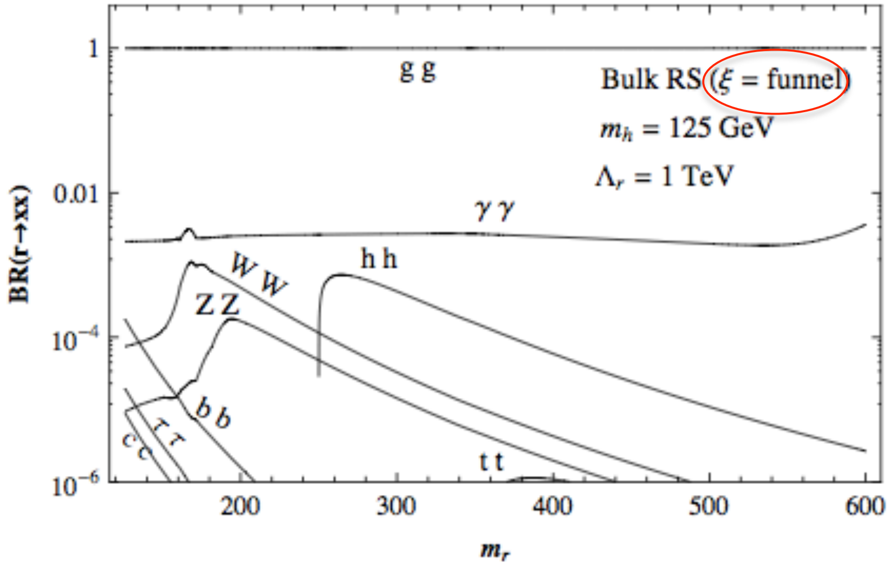
Large sensitivity at ~180 GeV

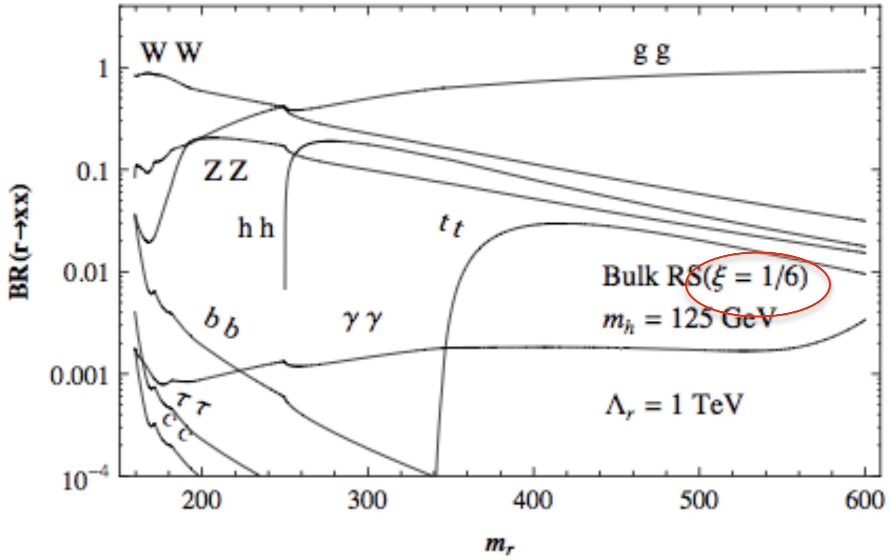


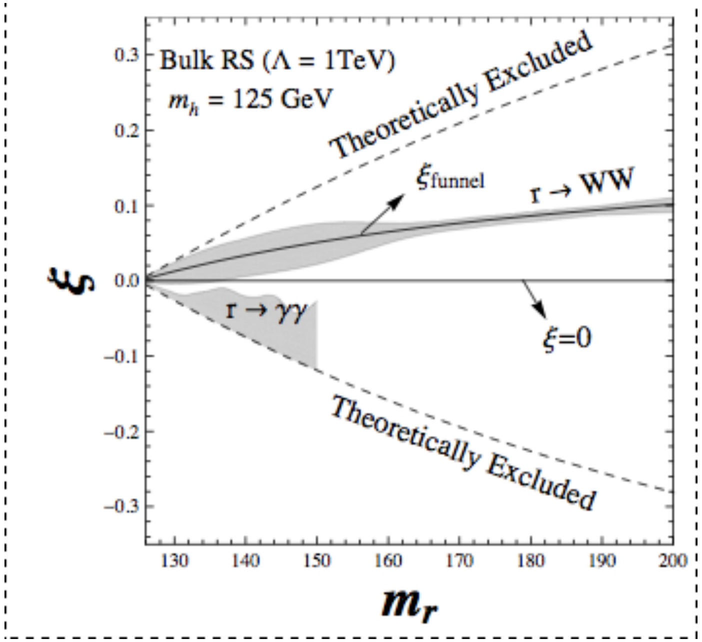
Effect of mixing: bounds are loosened



Branching ratios can be substantially modified







Also “real” Higgs can be hidden

$$S^r_{VV} = \frac{\Gamma^r(H \to gg)\Gamma^r(H \to VV)/\Gamma^r(H)}{\Gamma^{SM}(H \to gg)\Gamma^{SM}(H \to VV)/\Gamma^{SM}(H)} < 1$$

Conclusions

• If the EWSB sector is embedded in a conformal sector there could be a dilaton-like particle in the spectrum

• If there is no Higgs boson, the dilaton can mimick one

• If there is a light Higgs boson, the dilaton can mix and change phenomenology

• Get ready for 2012 data!