Improving Naturalness in Warped EWSB

Planck 2011: From the Planck Scale to the EW Scale
30 May-3 June, 2011, Lisbon, Portugal

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Based on work with J. A. Cabrer and G. v. Gersdorff:
arXiv:0907.5361; arXiv:1011.2205; arXiv:1103.1388;
arXiv:1104.3149; arXiv:1104.5253

Outline

The outline of this talk is

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- Introduction
- Some general results
- RS model
- Our model
- Conclusion

Introduction

- The SM of EW interactions suffers from a naturalness problem as the Higgs mass is sensitive to UV physics scale Λ
- In particular the coupling of the top quark generates

Quadratic divergence $\Rightarrow$ sensitivity δ

$$\Delta m_H^2 \sim (3/4\pi^2)\Lambda^2 \Rightarrow \delta = 3\Lambda^2/(4\pi^2 m_H^2)$$

- Naturalness of the theory

$$\delta \sim 1 \Rightarrow \Lambda \lesssim 3.6\, m_H$$

$$M_H = [115, 600]\ GeV \Rightarrow \Lambda \lesssim [400, 2000]\ GeV$$

- In view of negative searches at LEP2, and the increasing bounds imposed by ongoing LHC searches it is thus interesting to consider possible solutions to the hierarchy problem able to accommodate a heavy Higgs

- Although the effective SM below a multi-TeV cutoff is more natural with a heavy Higgs, the present EWPT point towards a light Higgs
- In particular a χ^2 fit of all SM EWPO drives the 95% CL upper limit of the Higgs mass to $m_H \lesssim 150$ GeV
- It would then be necessary to introduce new physics to compensate for the contribution of a heavy Higgs

In fact...

we can consider the Higgs mass measurement at LHC as a good test for new physics: if LHC finds a heavy Higgs the SM would be excluded and new physics would be required motivating an upgrade of the LHC and/or the construction of other colliders

- We will consider models where EWPT are saved by the UV physics solving the hierarchy problem
- Since a heavy Higgs contributes negatively to the T parameter an obvious requirement is the presence of new states that violate custodial symmetry in such a way as to give a positive contribution to T
- Such states are naturally provided by the KK modes of the hypercharge gauge boson in 5D warped compactifications
- Warped models were originally proposed by Randall and Sundrum [1] for

AdS metric

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

and UV and IR boundaries located at $y = 0$ and $y = y_1$

[1] L. Randall and R. Sundrum, arXiv:hep-ph/9905221

General results

- We will then consider the SM propagating in a 5D space with an arbitrary metric $A(y)$
- 5D gauge fields $W^i_M(x,y)$ and $B_M(x,y)$ propagating in the bulk
- A stabilizing field $\phi(x,y)$ fixing the value of $A(y_1)$

A bulk SM Higgs

$$H(x,y)=\frac{1}{\sqrt{2}}e^{i\chi(x,y)}\begin{pmatrix}0\\ h(y)+\xi(x,y)\end{pmatrix}$$

- $\chi(x,y)$ contains the 4D Goldstone bosons
- $h(y)$ is the 5D Higgs background
- $\xi(x,y)$ describes the Higgs fluctuations

- We will consider for the moment an arbitrary background $h(y)$

The effective SM-like Lagrangian for the Higgs

$$\mathcal{L}_{\rm eff} = -|D_\mu \mathcal{H}|^2 + \mu^2 |\mathcal{H}|^2 - \lambda |\mathcal{H}|^4$$
$$\mu^2 \sim Z^{-1} \rho^2 , \qquad \lambda \sim Z^{-2}$$

- The IR scale ρ and dimensionless quantity Z are

Z is Higgs wave function renormalization

$$\rho = k e^{-A(y_1)} , \qquad Z = k \int_0^{y_1} dy \frac{h^2(y)}{h^2(y_1)} e^{-2A(y)+2A(y_1)}$$

- The physical Higgs mass is $m_H^2 = 2\mu^2 \sim 2Z^{-1}\rho^2$
- Radiative corrections in the effective theory below the scale $\Lambda \sim m_{KK}$ will tend to destabilize light Higgs masses: some degree of fine-tuning is needed to not spoil EWSB and to keep the Higgs light

- Electroweak precision measurements are commonly mapped to the set (T, S, W, Y) [2]
- They are defined as

Oblique observables

$$\alpha T = m_W^{-2}\left[c_W^2 \Pi_Z(0) - \Pi_W(0)\right]$$

$$\alpha S = 4 s_W^2 c_W^2 \left[\Pi'_Z(0) - \Pi'_\gamma(0)\right]$$

$$2 m_W^{-2} Y = s_W^2 \Pi''_Z(0) + c_W^2 \Pi''_\gamma(0)$$

$$2 m_W^{-2} W = c_W^2 \Pi''_Z(0) + s_W^2 \Pi''_\gamma(0)$$

- Associated with the coefficients of

Effective operators (d=6)

$$|H^\dagger D_\mu H|^2\,, \quad H^\dagger W_{\mu\nu} H B^{\mu\nu}\,, \quad (\partial_\rho B_{\mu\nu})^2\,, \quad (D_\rho W_{\mu\nu})^2$$

[2] R. Barbieri et al. hep-ph/0405040

- These observables can be computed as

Oblique observables

$$\alpha T = s_W^2 m_Z^2 \frac{I_2}{\rho^2} \frac{k y_1}{Z^2}$$

$$\alpha S = 8 s_W^2 c_W^2 m_Z^2 \frac{I_1}{\rho^2} \frac{1}{Z}$$

$$Y = W = c_W^2 m_Z^2 \frac{I_0}{\rho^2} \frac{1}{k y_1}$$

- where

$$I_n = k^3 \int_0^{y_1} (y_1 - y)^{2-n} u^n(y) e^{2A(y)-2A(y_1)}$$

$$I_n/\rho^2 = \mathcal{O}(1/m_{KK}^2)$$

- T is volume enhanced and Z^2 suppressed
- S is Z suppressed and $W = Y$ is volume suppressed

RS MODEL

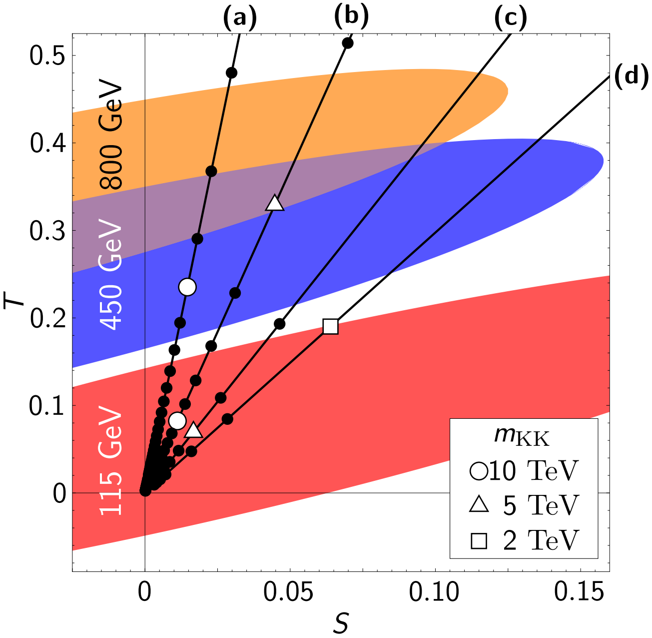
- In the RS model one introduces a 5D bulk Higgs mass: $M^2 = a(a-4)k^2$
- Holographic interpretation $a = \dim(\mathcal{O}_H)$
- Solution to the EOM: $h(y) \propto e^{aky}$
- No fine-tuning for $a > 2$: hierarchy solved with a composite Higgs
- $Z = \frac{1}{2(a-1)} < 1/2$ provides no suppression $\Rightarrow$ large m_{KK} & heavy Higgs & 5D Higgs as IR delocalized as possible
- For instance for $m_H = 450$ GeV the 95% CL window is

For localized 5D Higgs: $a \to \infty$

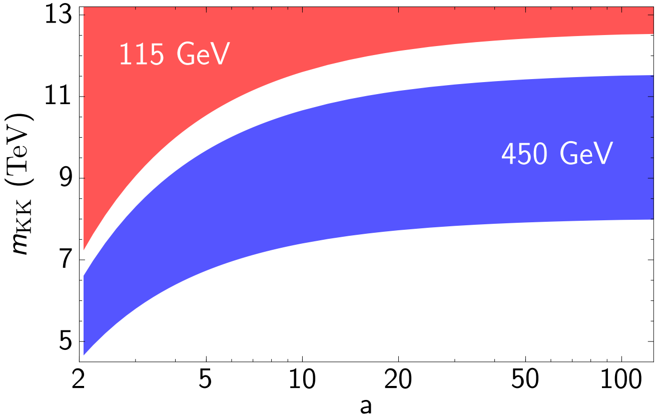
$$8 \lesssim m_{KK}/TeV \lesssim 11.5$$

For delocalized 5D Higgs: $a = 2.1$

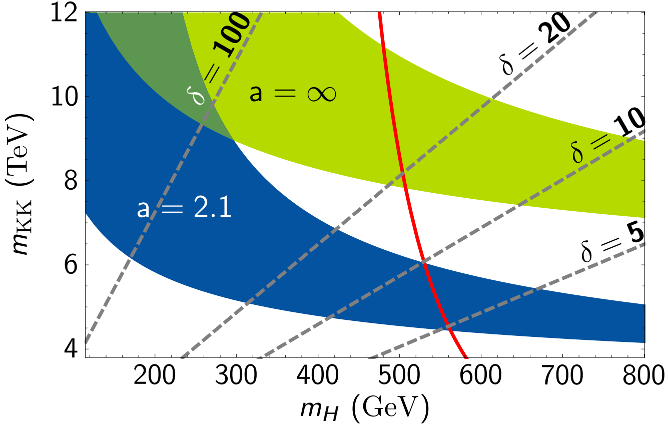
$$4.5 \lesssim m_{KK}/TeV \lesssim 6.5$$



95% CL regions. Ray (a) [(b)] is RS with a localized [bulk with a=2.1] Higgs



95% CL regions in the (a, m_{KK}) plane for RS and different values of the Higgs mass



95% CL regions in the (m_H, m_{KK}) plane for RS and the cases of a localized and a bulk Higgs with $a = 2.1$. Solid line is the perturbativity bound $\beta_\lambda^{(2)} = 0.5\ \beta_\lambda^{(1)}$

Our model

- We will consider a model with a conformal deformation in the IR
- It contains a stabilizing field ϕ which leads to

The metric

$$A(y) = ky - \frac{1}{\nu^2}\log\left(1 - y/(y_1+\Delta)\right), \quad \nu \in \mathbb{R}$$

- The metric has a spurious singularity located at $y_s = y_1 + \Delta$ outside the physical interval
- The dynamics of ϕ fixes y_1 $[A(y_1)]$ and Δ as in GW
- A 5D bulk Higgs mass: $M^2(\phi) = k^2[a(a-4) - be^{\nu\phi}]$ where a and b are arbitrary constants
- b can be absorbed by a shift of ϕ_0 at the UV: we fix it to $b = 1$

- The holographic interpretation of a is now a bit different from RS

In the IR

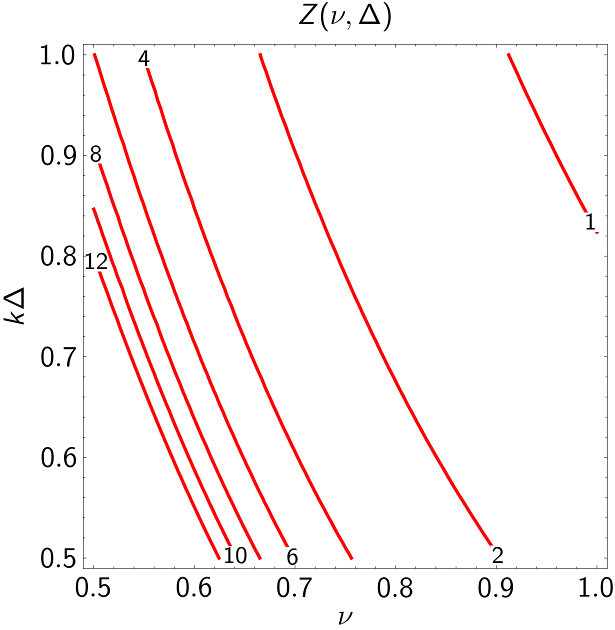
$$\dim(\mathcal{O}_H)^{IR} = \frac{a}{1 + \frac{1}{k\Delta\nu^2}}$$

- The solution to the EOM $h(y) = c_1 e^{aky} + c_2 \int^y e^{4A(y')-2aky'}$ imposes the constraint

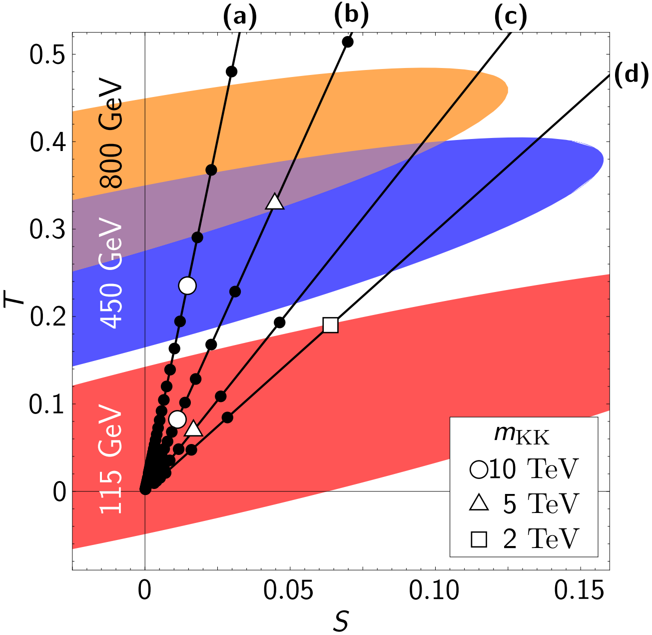
Hierarchy condition ($a > 2$ for RS)

$$a \gtrsim a_0 = 2A_1/ky_1$$

- In many cases $Z \gg 1$ which softens the bounds on EWPO



Contour lines of fixed $Z(\nu,\Delta)$ where $a = a_0(\nu,\Delta)$ and $A(y_1) = 35$



95% CL regions. Ray (c) [(d)] is our model with $k\Delta = 1$ and $\nu = 0.7$ [$\nu = 0.6$]

- For instance for $m_H = 450$ GeV and $a = a_0$ the 95% CL window is

For $k\Delta = 1$, $\nu = 0.7$

$$2.1 \lesssim m_{KK}/TeV \lesssim 2.9$$

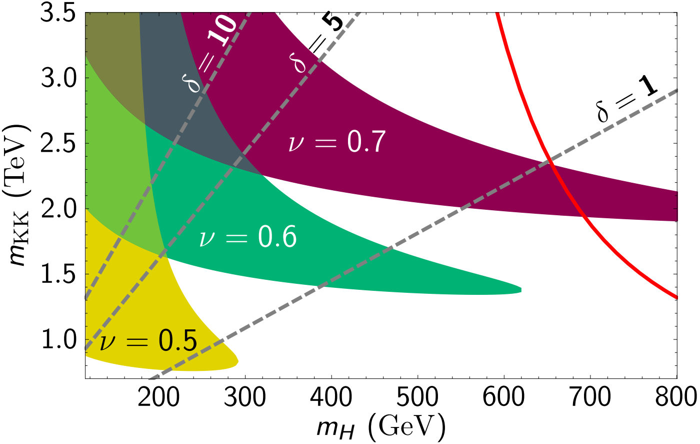
For $k\Delta = 1$, $\nu = 0.6$

$$1.4 \lesssim m_{KK}/TeV \lesssim 1.7$$

This shows that :

  - A heavy Higgs can be consistent with KK-modes accessible at LHC energies
  - The measurement of the Higgs mass at LHC should constrain the model parameters

- These two features are exhibited in the next plot



95% CL regions in the (m_H, m_{KK}) plane for our model with $k\Delta = 1$ and $\nu = 0.7, 0.6, 0.5$. Solid line corresponds to the perturbativity bound $\beta_\lambda^{(2)} = 0.5\ \beta_\lambda^{(1)}$

Conclusions

- We have considered models where the 5D SM gauge and Higgs bosons propagate in the bulk
- In the RS model a heavy Higgs is more natural than a light one and EWPT are satisfied for lighter values of the KK mass

RS window for $m_H = 450$ GeV

$$4.5\ \mathrm{TeV} \lesssim m_{KK} \lesssim 6.5\ \mathrm{TeV}$$

- In the model with an IR deformation of the conformal symmetry the KK spectrum can be accessible to LHC both for light and heavy Higgs and satisfying the naturalness condition
- In most of the parameter space the fine-tuning is better than 10%
- The Higgs discovery at LHC will just constrain the model parameters

- Fermion localized in the bulk with 5D masses can be localized towards the UV/IR brane in a way similar to RS models
- A careful consideration of quarks in the bulk should enable us to describe non-oblique observables and fit e.g. [3]

Third generation quark observables

$$R_b, \quad A^b_{FB}\ (LEP), \quad A^t_{FB}\ (CDF), \ldots$$

[3] Work in preparation