Calculable Composite Higgs Models from a Warped Extra Dimension

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Plan

General motivations

Review of 5D Gauge-Higgs-Unification Models
(Composite Higgs Models)

Concrete Model with Dark Matter

Probably SUSY is still the most promising paradigm for physics beyond the SM.

Yet, it is interesting to look for alternative scenarios to solve the hierarchy problem

Essentially most of the alternatives involve strong coupling at a few TeV

Little Higgs, extra dimensions, Technicolor, etc.

Strongly coupled theories can be studied:

- Bottom-up approach (``Chiral Lagrangian") [Little Higgs] very effective and flexible, flavour problems difficult to address

- Top-down approach (``Quarks") [Technicolor] calculability very hard

Desirable to have a bottom-up framework where EWSB and flavour are calculable and UV insensitive

This is exactly what warped extra dimensions provide for us!

Why warped ?

- **They solve the Big Hierarchy problem** [Randall & Sundrum]
- **Natural explanation of the Yukawa coupling hierarchy and avoidance of FCNC (RS-GIM mechanism)**
- **Calculable way of approaching certain strongly coupled Large N QFT (AdS/CFT correspondence)** [Maldacena]

Warp factor is the holographic dual of dimensional transmutation.

Do not even need to assume the existence of any extra dimension !

A particularly interesting class of RS theories is obtained by assuming Higgs is the fifth component of a 5d field gauge field (Gauge-Higgs-Unification framework)

[Manton; Fairlie; Forgacs & Manton; Krasnikov; Hosotani; ...]

Electroweak SB = Wilson line SB

Higgs potential V(H) is radiatively generated and non-local in the extra dimension
V(H) is finite to all orders in perturbation theory

In warped space, it corresponds to a perturbative description of a strongly coupled composite Higgs of a softly broken large N CFT [Agashe, Contino, Pomarol]

Technicolor versus Composite Higgs Models

[Weinberg; Susskind] [Kaplan & Georgi; Agashe-Contino-Pomarol]

Both constructions assume new strongly coupled physics and Goldstone modes associated to W and Z are composite of the strongly coupled sector

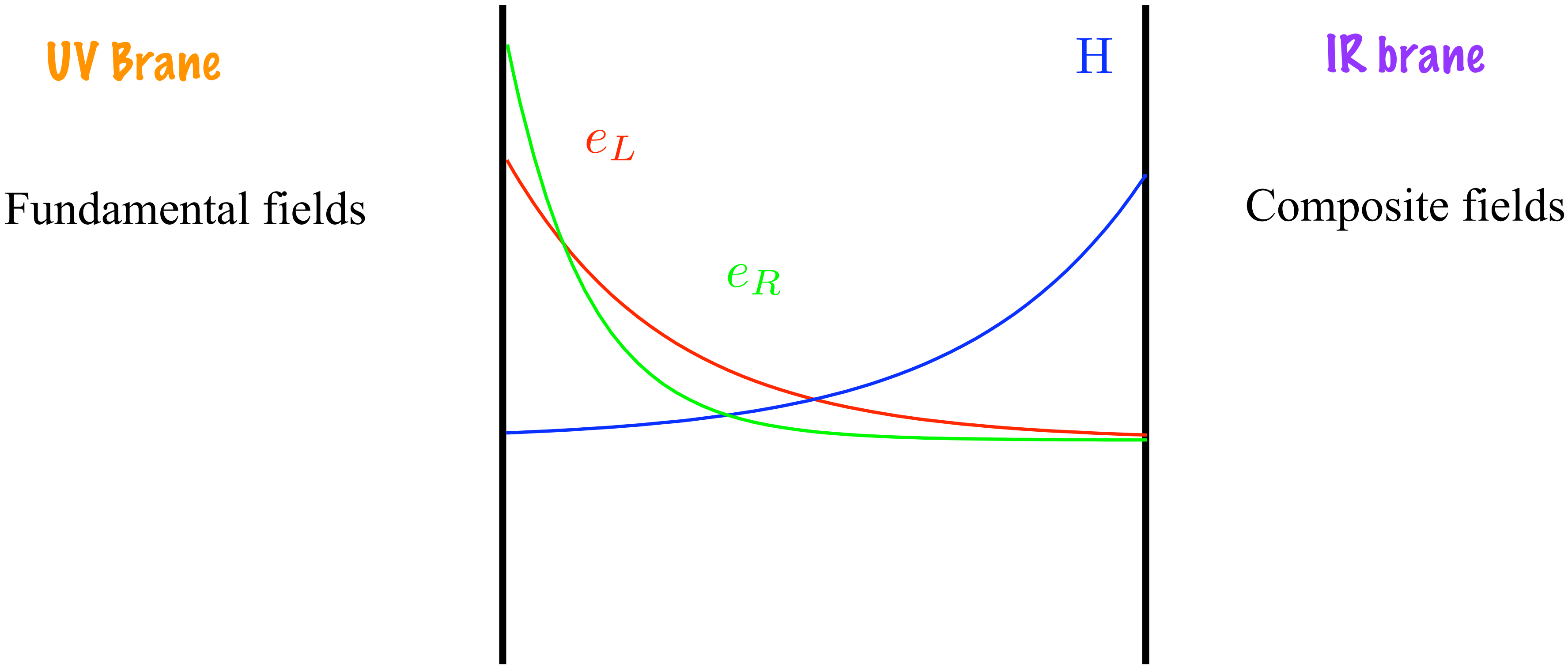
But

Technicolor: Higgs scalar degree of freedom (composite) not necessary and harmless as far as EWSB is concerned

Composite Higgs Models: Higgs scalar degree of freedom (composite), as in the Standard Model, responsible for EWSB

5D RS Composite Higgs Models (as any RS models with fermions in the bulk) implement in a calculable and incredibly simple way an old idea by Kaplan that SM fermions are partially composite

Cut-off Λ: $M_{Pl} \Longrightarrow M_{TeV}$



It is important to recall that 5D models provide for us the IR ``Chiral Lagrangian'' of the 4D dual only, not the ``QCD'' UV theory

It is not usual stringy AdS/CFT where we know both sides of the correspondence

This is clear from the 5D perspective. 5D theory is non-renormalizable. We expect, using NDA, the it becomes strongly coupled at energies of a few 10 TeV (we expect that strings close to the IR brane very light, so probably UV completion is some string theory)

However, strong coupling arises only close to the IR brane and hence light SM fields screened and essentially unaffected

⇒ Flavour physics perturbatively accessible!

Basic Properties of such models:

- EWSB (and Higgs mass) calculable
- Yukawa couplings are effective, not fundamental, couplings. Easy and natural to have hierarchical Yukawa's

Large tree-level contributions to the T-parameter and tension between non-universal Zbb coupling and top Yukawa coupling can be solved by a suitable choice of a custodial symmetry group

[Agashe, Delgado, May, Sundrum; Agashe, Contino, Da Rold, Pomarol]

Problem: no viable DM in warped models so far

There is no a natural discrete symmetry in warped space, like KK parity in Universal Extra Dimensions

With no viable geometric symmetry we have to rely on extra discrete symmetries to get a stable DM candidate.

Simple possibility: assume a Z2 exchange symmetry

$$\phi_1 \leftrightarrow \phi_2$$

$$\mathbf{Z}_2(\phi_\pm = \phi_1 \pm \phi_2) = \pm\phi_\pm$$

Lightest Z2 odd particle absolutely stable

Consider 5D model with gauge group $G \times U(1)_1 \times U(1)_2$ and two fermions ψ_1 and ψ_2 coupled to X_1 and X_2, respectively.

$$\mathcal{L} = \sum_{i=1,2} \left[-\frac{1}{4} F_i^2 + \bar{\psi}_i \Big(\mathrm{i}(\mathcal{D} + \mathrm{i} Q_X g_X X_i) - m \Big) \psi_i \right]$$

$$= -\frac{1}{4}(F_+^2 + F_-^2) + \bar{\psi}_+(\mathrm{i}\mathcal{D} - m)\psi_+ + \bar{\psi}_-(\mathrm{i}\mathcal{D} - m)\psi_-$$
$$-g_X Q_X (\bar{\psi}_+ X_+ \psi_+ + \bar{\psi}_- X_+ \psi_- + \bar{\psi}_+ X_- \psi_- + \bar{\psi}_- X_- \psi_+)$$

With suitable boundary conditions (+,-), lightest X_- KK mode has a mass $M_- \simeq M_+/10$. If $g_X \sim 1$, X_- viable DM candidate.

Possible problem: if **all** fermions are "doubled", Lightest $\mathbf{Z}_2$-Odd Particle (LOP) is a fermion with unacceptable masses and couplings $\Longrightarrow$

double only a subset of the whole fermion spectrum

Notice: **no** new parameters have been introduced with respect to the "undoubled" theory

Interestingly enough, this simple construction allows to have viable DM candidates in essentially all warped models: higgsless, RS with bulk fields and models with Gauge-Higgs-Unification (GHU)

By far most interesting scenario is the GHU one, where the DM and EWSB are correlated and calculable

The Model we consider is an extension of one introduced by Contino, Da Rold & Pomarol

$$G = SO(5) \times U(1)_+ \times U(1)_-$$

$$H_{IR} = SO(4) \times U(1)_+ = SU(2)_L \times SU(2)_R \times U(1)_+$$
$$H_{UV} = SU(2)_L \times U(1)_Y \times U(1)_-$$

5D fermions are all in **5** of SO(5)

In terms of $SU(2)_L \times SU(2)_R$, **5**=(**2**,**2**)+**1**

For each quark generation, 2 5's are needed to get 1 SM LH doublet and 2 SM RH singlets.

In order to have correct EWSB pattern, 2 extra 5's are needed, which have only massive KK excitations

Our ``doubling procedure'' will only involve 1 of these massive multiplets

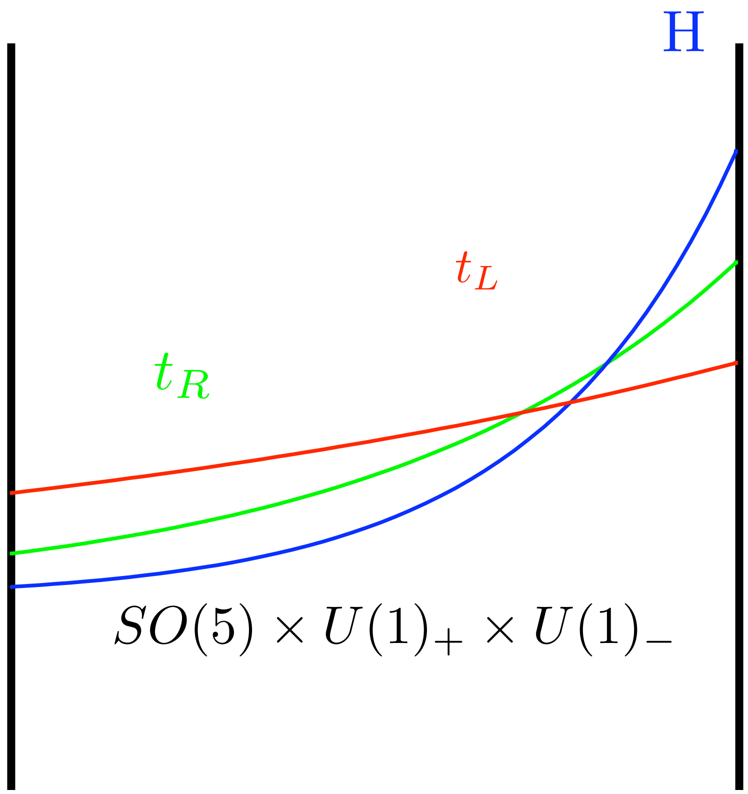
The extra contribution to V(H) is welcome. It drives EWSB in the region of parameter space where EWPT are more easily satisfied !

UV Brane

Fundamental fields

$SU(2)_L \times U(1)_Y \times U(1)_-$

Yukawa's given by the 5D geography



IR brane

Composite fields

$SU(2)_L \times SU(2)_R \times U(1)_+$

Fermion profile depends on 5D mass parameter c

There are 2 interesting regions, parametrized by the mass of doubled 5d multiplet:

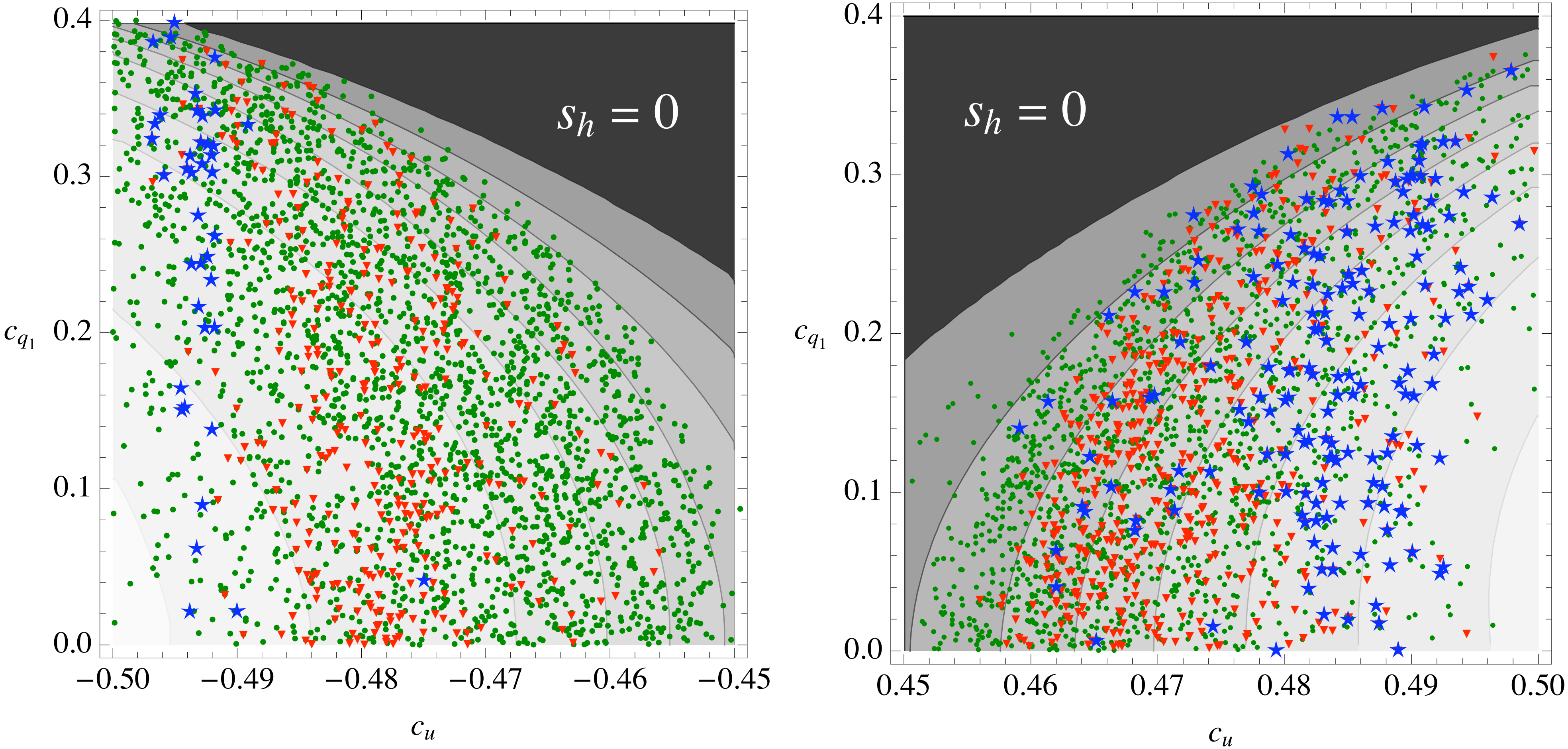
- $c_u \simeq 1/2$:bidoublet light

$$\bar{Q}_L X_- \psi_{NLOP,L} \subset \overline{(2,2)}^+_L X_- (2,2)^-_L$$

- $c_u \simeq -1/2$:singlet light

$$\bar{t}_R X_- \psi_{NLOP,R} \subset \overline{(1,1)}^+_R X_- (1,1)^-_R$$

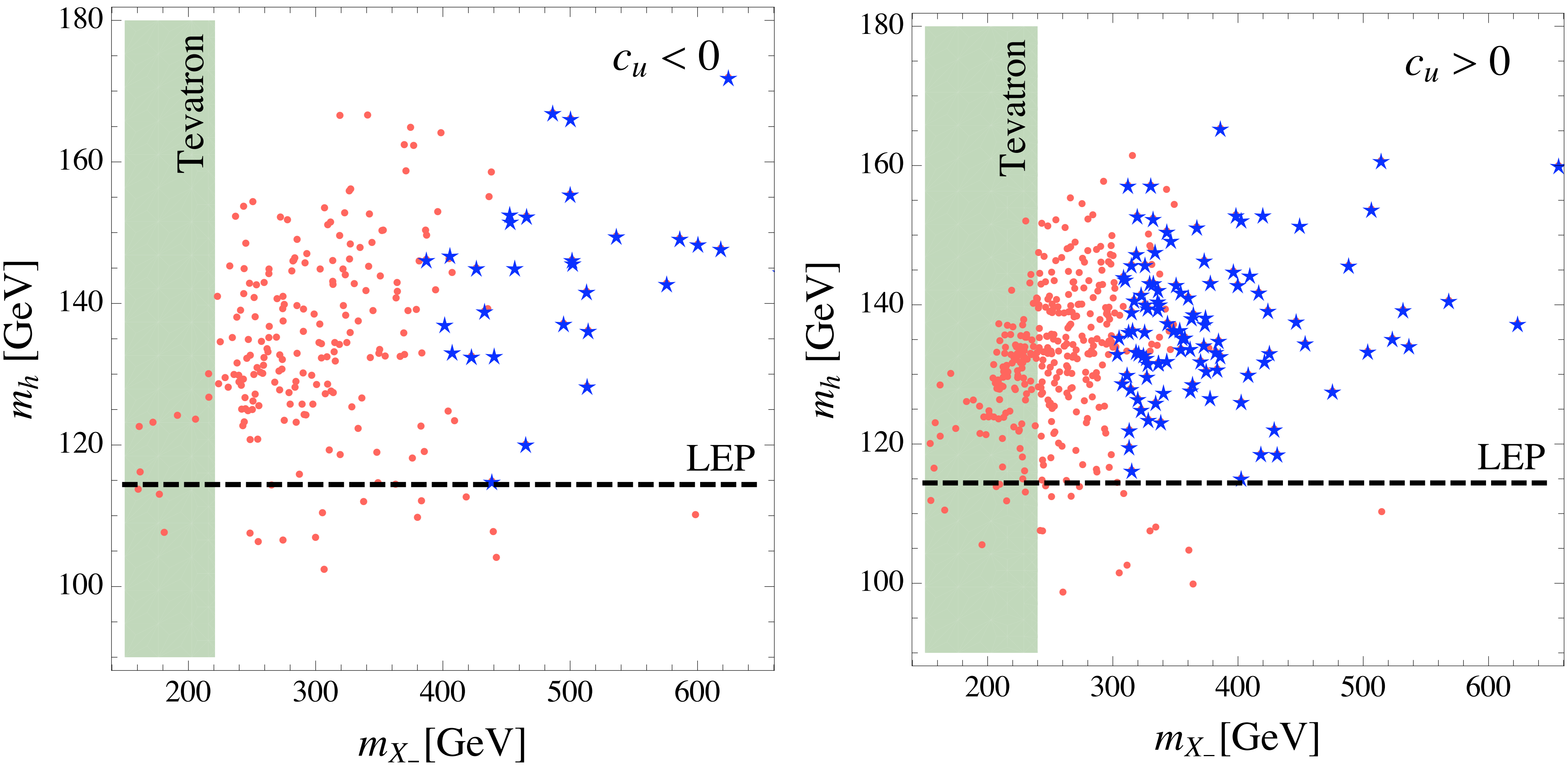
In these regions $m_{NLOP} \simeq m_{LOP}$ and coannihilations have to be taken into account



Green dots: mtop ok

Red triangles: DM ok

Blue stars: EWPT ok



Red dots: DM & mtop ok

Blue stars: DM & mtop & EWPT ok

Phenomenology

- Direct DM searches not promising. No Higgs coupling exchange, nor coupling to valence quarks

$$\sigma^{p,n}_{scalar} \simeq 2 \times 10^{-10} \mathrm{pb}$$

- Collider phenomenology more exciting. New colored exotic particles (both Z2 even and odd) with mass ~ 350- 400 GeV. Particular signature: charge 5/3 state, probably detectable at LHC [Contino & Servant]

Conclusions

- 5D GHU Models in warped spaces are one of the most promising alternatives of new physics beyond the SM

- Dark Matter in Warped Spaces is no problem

- Implementation in GHU (Composite Higgs) models particularly appealing. DM, EWPT and EWSB all point to a common region in parameter space, leading to a realistic and quite interesting model.

The end