Natural composite Higgs via Universal Boundary Conditions

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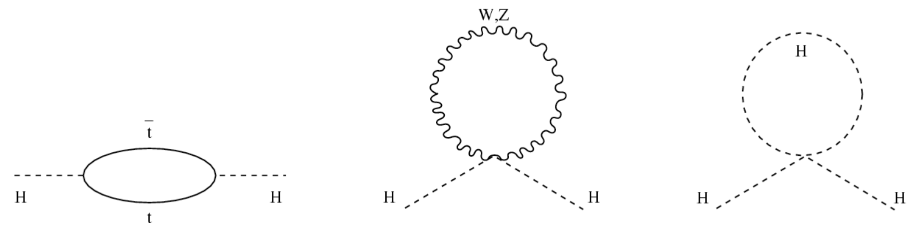
Hierarchy problem

All elementary scalars expected to be **ultra heavy**

$$\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$$



Mass of Higgs not protected by symmetries (like fermion, gauge boson)

- Sensitive to any UV scale physics - Λ a stand-in for mass of whatever new physical particle appears there

Composite Higgses

- One simple way to solve hierarchy: Higgs NOT elementary, but composite.

- Most naive assumption: scale of compositeness $\mathbf{\Lambda}$ ~ 10 TeV. At that scale lots of resonances giving $1/\Lambda^2$ dim 6 operators. To avoid LEP bounds need $\mathbf{\Lambda}$>~ 5-10 TeV

- Expected Higgs mass $\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$

- For $\mathbf{\Lambda}$~10 TeV this is still ~ (1 TeV)^2 about 100 times too large… little hierarchy

The pNGB Composite Higgses

- To further lower Higgs mass make Higgs also a pNGB

- Strong dynamics producing composites has a global symmetry G

- During confinement G→H breaking, which produces GB's. Some of these will be identified with SM Higgs

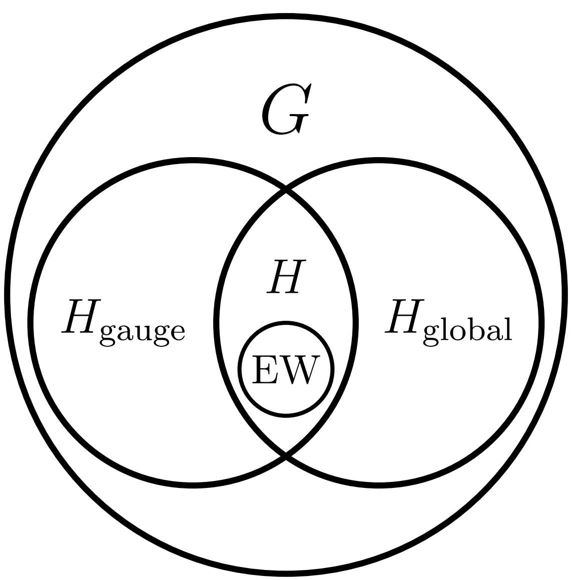
- Global symmetry breaking scale: f

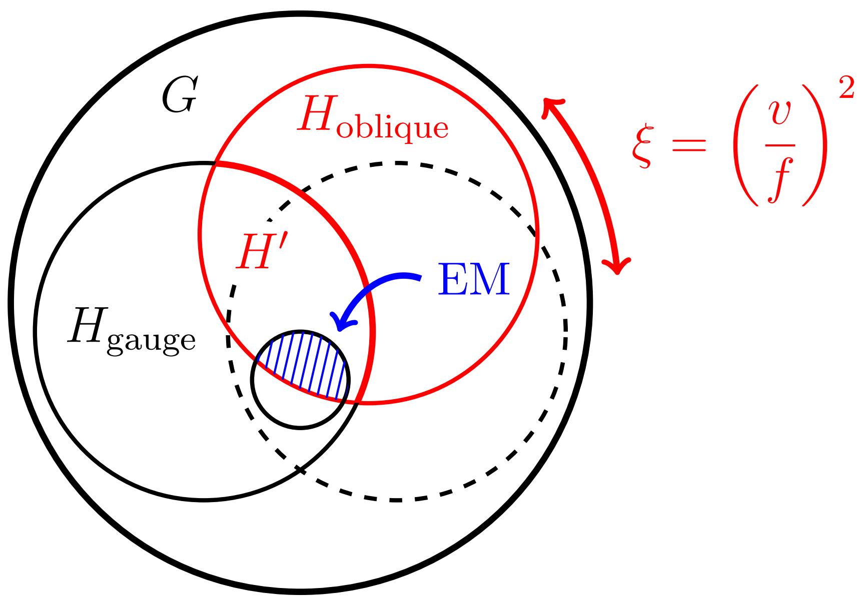
- Cutoff scale (scale of generic composites): Λ

$$\Lambda \sim 4\pi f$$

The pNGB Composite Higgses

- For Λ~10 TeV we find f~1 TeV, and IF corrections given by $f^2/(4\pi)^2$ then Higgs mass can be natural…
- New particles at f~1 TeV (top and spin 1 partners)
- This is eventually what is called ``composite Higgs model”





Collective symmetry breaking

- Generically explicit breaking reintroduces the quadratic divergence of the Higgs potential!

- Explicit breaking has to have a very special form to avoid quadratically divergent corrections!

- Basic idea: No single explicit breaking term itself will completely break the global symmetry

- Need 2 (or more) explicit breaking terms simultaneously to given mass to Higgs

- Presence of several insertions usually softens divergence and makes potential finite (or log div)

Simplest example of collective breaking

- Take SU(3)/SU(2) coset - will produce a doublet GB (+singlet - ignore for simplicity)

$$\mathcal{H} = \exp\left[\frac{i}{f}\left(\begin{array}{c|c} 0_{2\times 2} & H \\ \hline H^\dagger & 0 \end{array}\right)\right]\begin{pmatrix} 0 \\ 0 \\ \hline f \end{pmatrix} = \begin{pmatrix} iH \\ f \end{pmatrix} - \frac{1}{2f}\begin{pmatrix} \\ H^+H \end{pmatrix}$$

- Enlarge SM fermion doublet to triplet $Q \to \Psi = \begin{pmatrix} Q \\ T \end{pmatrix}$

- T is top partner, and we need two right handed tops now (one for SM, one top partner)

- Yukawa coupling: $\mathcal{L}_{Yuk} = \lambda_1 \Psi \mathcal{H} t_c^1 + \lambda_2 f T t_c^2$

Simplest example of collective breaking

$$\mathcal{L}_{Yuk} = \lambda_1 \Psi \mathcal{H} t_c^1 + \lambda_2 f T t_c^2$$

• First term SU(3) invariant. Second term does not contain Higgs field. Need BOTH terms to make Higgs a pNGB and generate potential!

• Let us expand now $\mathcal{H}$ to get form of Yukawa coupling

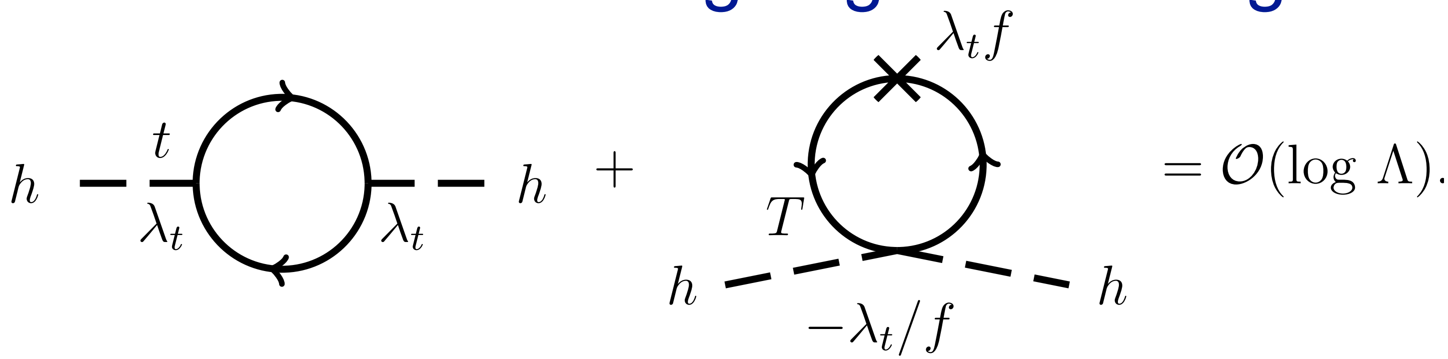
$$\lambda_1 H(iQ) t_c^1 + \left(f - \frac{H^\dagger H}{2f} \right) T \lambda_1 t_c^1 + \lambda_2 f T t_c^2$$

• One loop quadratic divergence will cancel by collective breaking of SU(3) symmetry!

Simplest example of collective breaking

$$\lambda_1 H(iQ)t_c^1 + \left(f - \frac{H^\dagger H}{2f}\right) T\lambda_1 t_c^1 + \lambda_2 f T t_c^2$$

- Easiest to do WITHOUT going to mass eigenbasis



- Leading pieces of two diagrams cancel - seems like a miracle but really governed by underlying symmetry

Minimal Composite Higgs (MCH)

- Most commonly used example. Reason: minimal setup where so called T-parameter is protected.

- G=SO(5), H=SO(4) = $SU(2)_L$ x $SU(2)_R$

$\mathrm{SO}(5) \to \mathrm{SO}(4)$ breaking via VEV of SO(5) vector

$$\langle \Sigma \rangle = (0,0,0,0,1)^T$$

- 4 Goldstone bosons - identified with Higgs

$$\Sigma = e^{ih^{\hat{a}}(x)T^{\hat{a}}/f}\langle\Sigma\rangle = \frac{\sin(h/f)}{h}\left(h^1, h^2, h^3, h^4, h\cot(h/f)\right).$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} h^1 + ih^2 \\ h^3 + ih^4 \end{pmatrix}.$$

Partial compositeness

- Best way to introduce fermionic partners: they will be assumed to be composite fermions from the strong sector.

- To couple them (for flavor physics): small mixing between SM (elementary) and heavy fermions

$$\Delta\mathcal{L} \sim \bar{Q}_L \mathcal{O}_{Q_L}$$

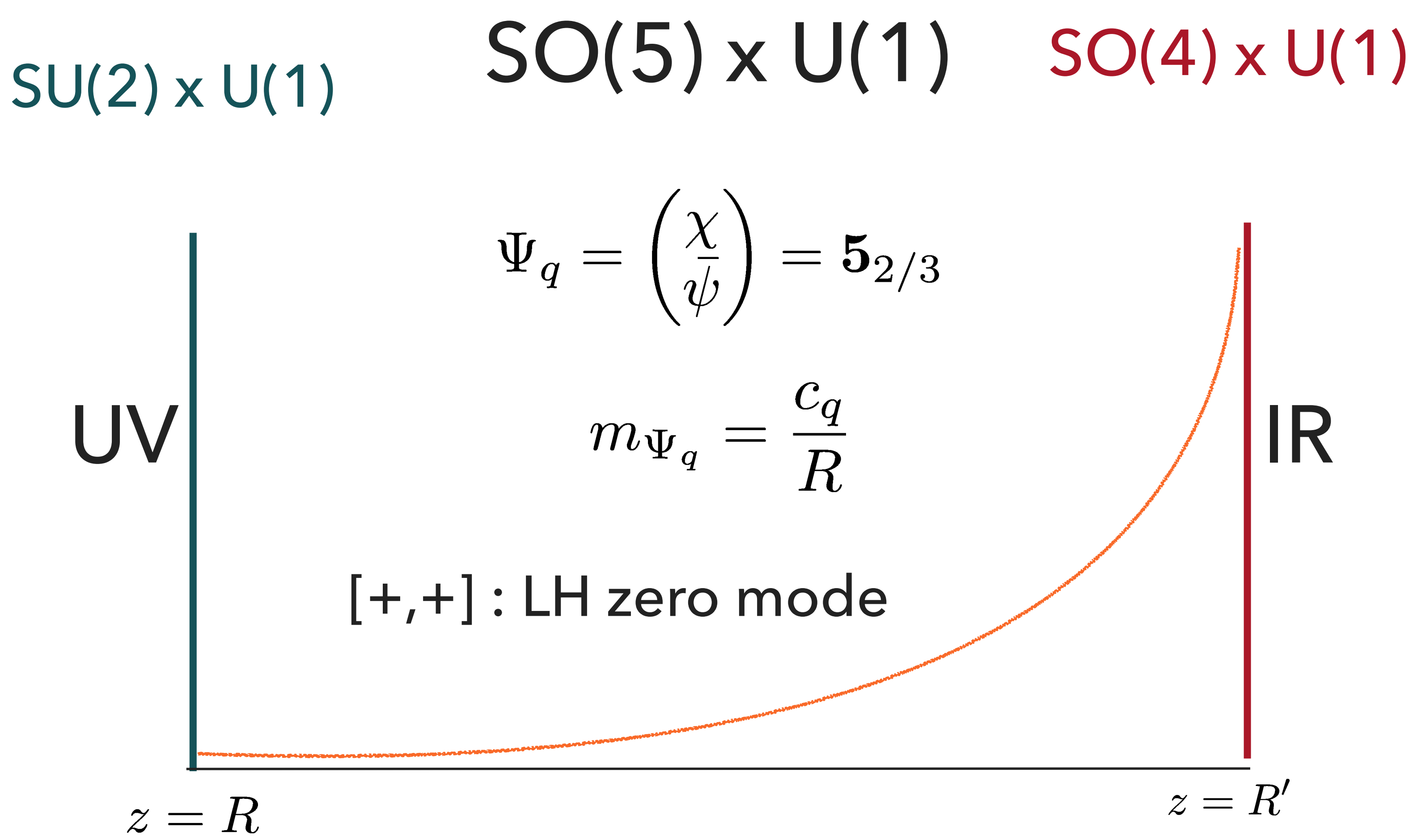
- Will result in

$$|\text{observed particle}\rangle \sim |\text{elementary}\rangle + \epsilon|\text{composite}\rangle.$$

- ε will control the flavor properties of the model - has wonderful automatic RS GIM mechanism (separate talk needed for that)

5D implementation

- Using AdS/CFT has a nice interpretation in warped space



$$\Psi_q = \begin{pmatrix} \chi \\ \bar{\psi} \end{pmatrix} = \mathbf{5}_{2/3}$$

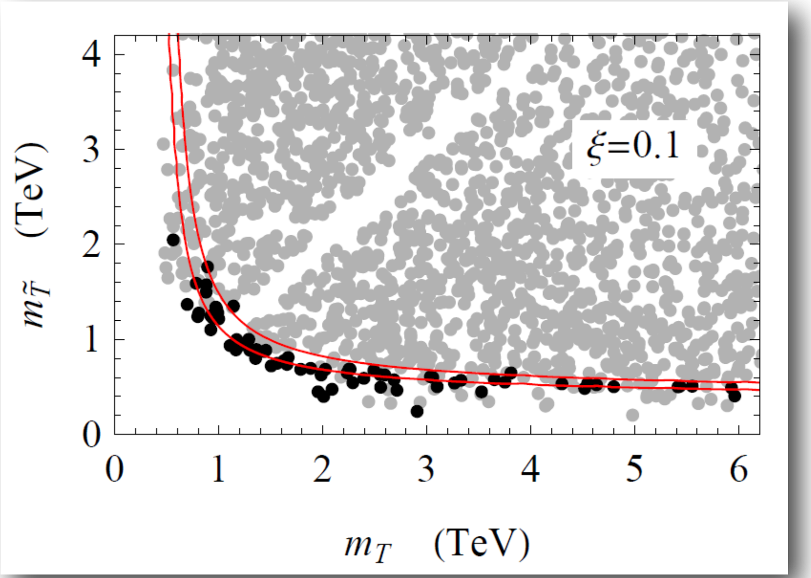
$$m_{\Psi_q} = \frac{c_q}{R}$$

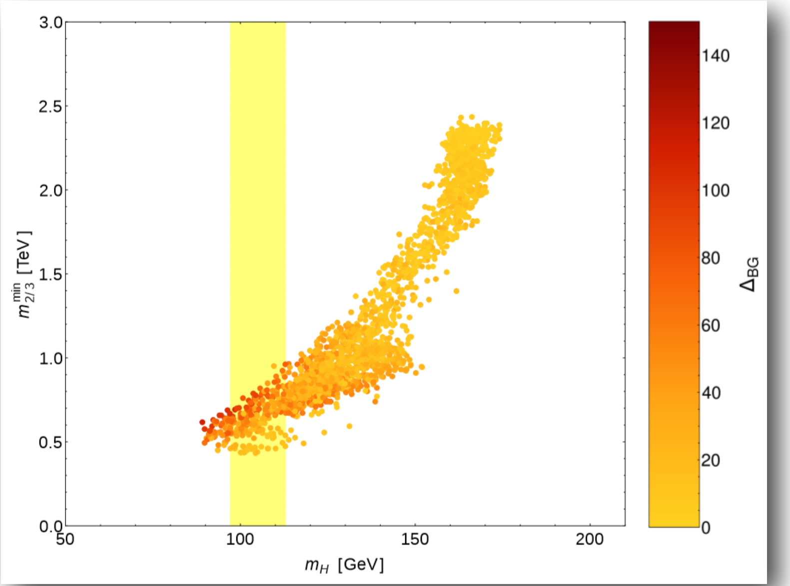
5D implementation

- Strong correlation between light Higgs and light top partner in minimal models

$$m_h \sim \frac{m_T}{f} m_t$$

- Usual prediction: light top partners



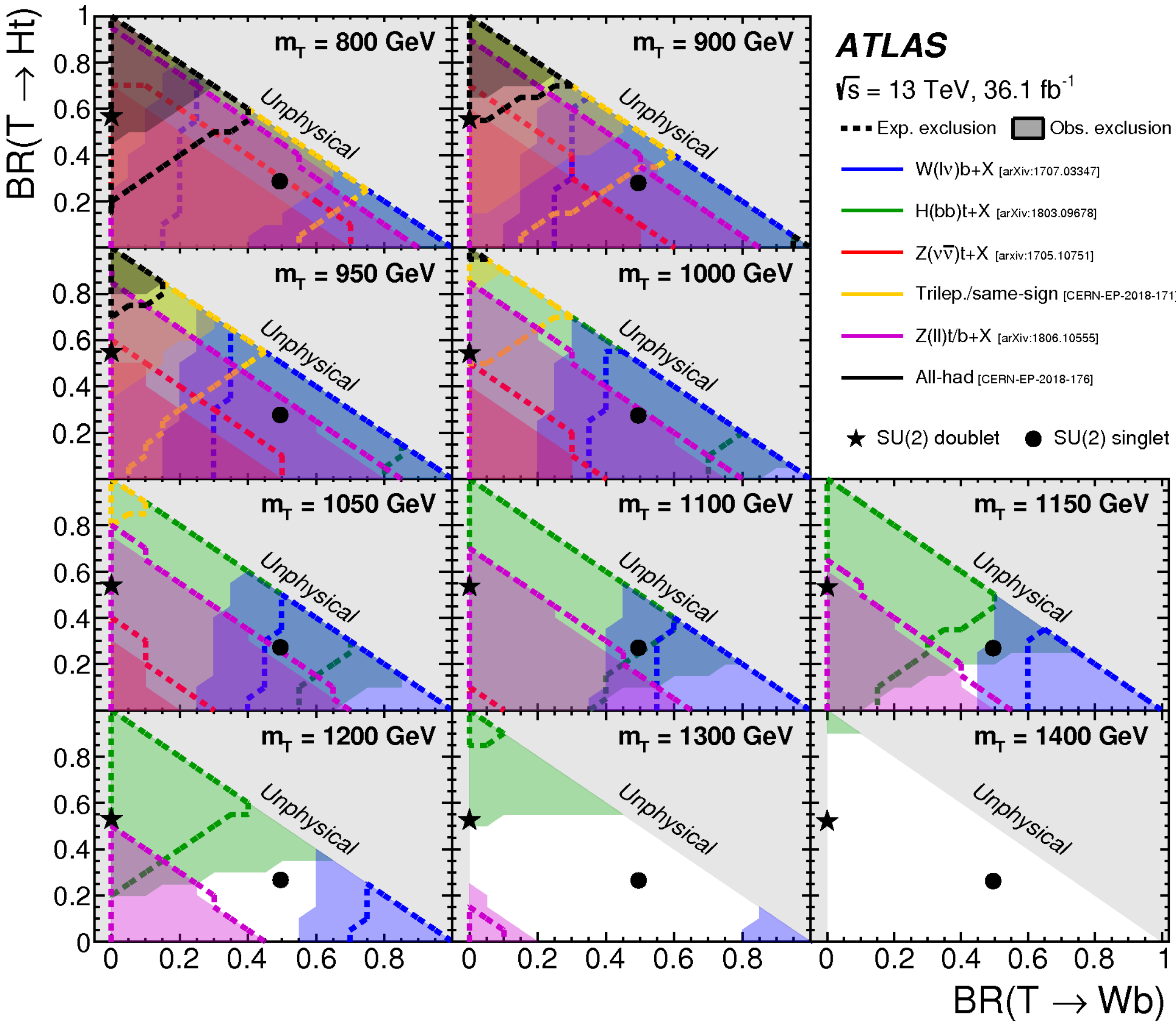


Matsedonskyi, Panico, Wulzer 2012
4D effective theory

Carmona, Goertz 2015
Holographic 5D theory

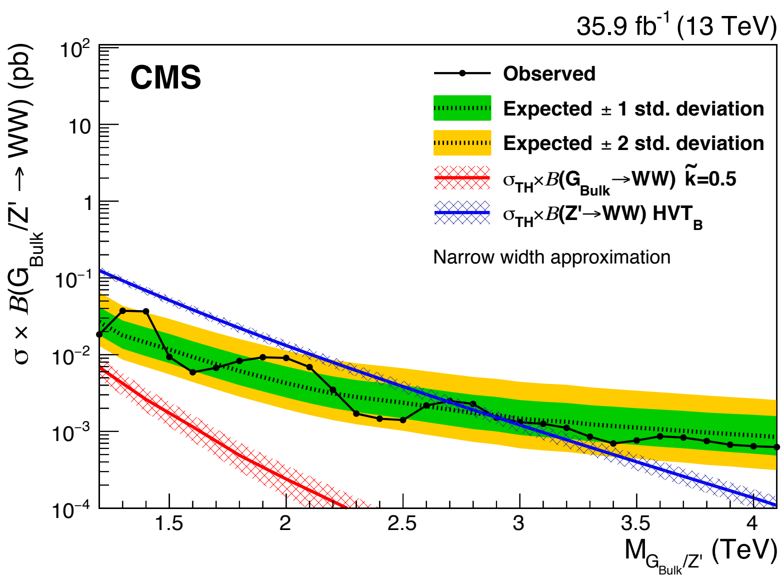
• Direct bounds

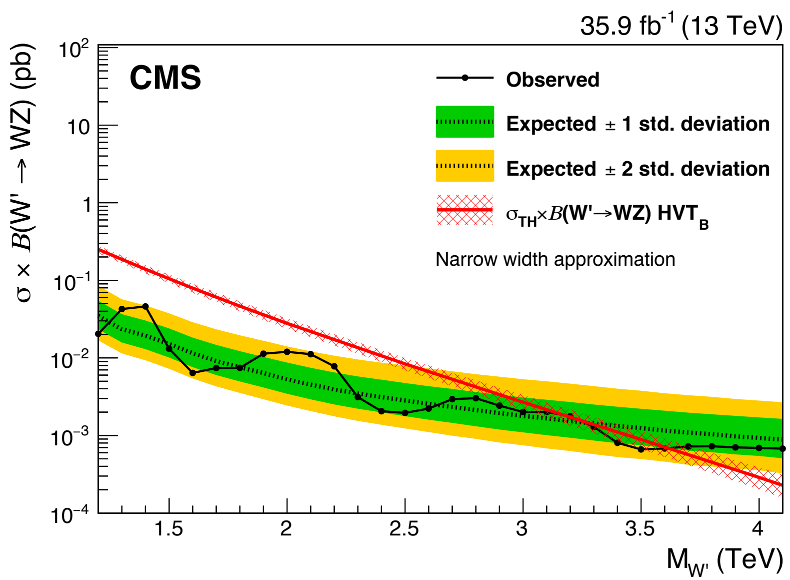
Spin 1/2 top partners



• **Direct bounds**

Spin 1 partners W', Z'





Tuning in CHM's

- Leading contribution to Higgs potential from top sector

- Structure of Higgs potential: $V(h) = -\gamma s_h^2 + \beta s_h^4$
  where $\xi \equiv s_h^2 = \frac{\gamma}{2\beta}$

- Minimal tuning - if **β** and **γ** of same order:

$$\Delta_{\text{min}} = 1/\xi$$

- From EWP, Higgs couplings we know $\xi < 0.1$

- However in actual models usually turns out larger

Tuning in CHM's

- ``Double tuning'': in simplest holographic models

$$\gamma \sim \frac{1}{16\pi^2}\frac{y_t^2}{g_*^2} \qquad\qquad \beta \sim \frac{1}{16\pi^2}\frac{y_t^4}{g_*^4}$$

- Both finite at one loop, but different order in $\frac{y_t^2}{g_*^2}$

- Actual tuning $\Delta \sim \frac{g_*^2}{y_t^2}\frac{1}{\xi} \sim 1\%$

- Using $m_h \sim \frac{m_T}{f} m_t$

- Numerical expression of tuning: $\Delta \sim 90 \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$

- Already pretty bad for $m_T \sim 1\,\mathrm{TeV}$ and grows quadratically with top partner mass

Tuning in CHM's

- To find natural CHM

1. Need to eliminate double tuning - Maximal symmetry

2. Remove quadratic dependence on top partner mass - soft breaking

3. Combined version has very simple 5D implementation, not at all more involved than original holographic CHM's

Maximal symmetry

(Teng Ma, Jing Shu, C.C. + JiangHaoYu)

- Maximal symmetry is an enhanced global symmetry of (part of) the composite sector
- Will render Higgs potential finite, minimize tuning and give very specific form of the Higgs potential
- Generically $G \to H$ breaking composite sector has only H symmetry
- Composites in general don't even have to form complete G multiplets

Emergence of Maximal Symmetry

- It is possible that the composite sector itself has a global symmetry bigger than H - an emerging accidental symmetry: maximal symmetry

- Key object: U Goldstone matrix $U = \exp\left(\frac{ih^{\hat{a}}T^{\hat{a}}}{f}\right)$

- Transforms as $U \to gUh(h^{\hat{a}}, g)^{\dagger}$

- Best interpretation: U connects elementary and composite sector symmetries $SO(5)_{el} \times SO(5)_{co}$

- Where composite sector breaks $SO(5)_{co}$ to $SO(4)$ (assumed G=SO(5) and H=SO(4) for concreteness)

Emergence of Maximal Symmetry

- When some remnant of $SO(5)_{el} \times SO(5)_{co}$ remains unbroken - can protect/restrict form of Higgs potential

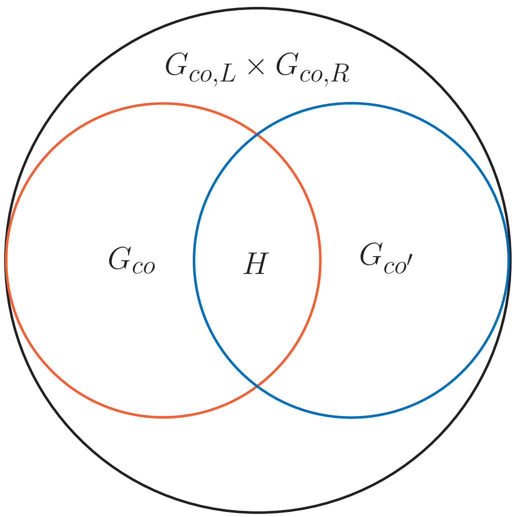
- If either $SO(5)_{el}$ or $SO(5)_{co}$ itself unbroken - no Higgs potential at all! U will disappear from the effective Lagrangian no potential.

- Need to break these symmetries but such that some remnant is left over

Maximal Symmetry

- Standard assumption: q_L and t_R both embedded into the elementary sector. This embedding breaks the $SO(5)_{el}$ elementary global symmetries

- Composite sector: need to preserve an SO(5) that does NOT coincide with $SO(5)_{co}$



Maximal Symmetry

- Simplest possibility: assume matter content of composites fills out full SO(5): Q - 4, S - 1 under SO(4) combine to SO(5).

- Vectorlike matter has chiral $SO(5)_L x SO(5)_R$ (without mass terms). Mass term can break

$$M_Q - M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R/SO(5)_V$$
$$M_Q + M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R/SO(5)_{V'}$$
$$|M_Q| \neq |M_S| \Rightarrow SO(5)_L \times SO(5)_R/SO(4)_V$$

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- Full $SO(5)_{co}$ unbroken - no Higgs potential

Maximal Symmetry

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- An SO(5) different from the original $SO(5)_{co}$ is left unbroken. Potential will be generated BUT symmetry will impose restrictions (maximal symmetry)

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$$\boxed{|M_Q| \neq |M_S| \Rightarrow SO(5)_L \times SO(5)_R / SO(4)_V}$$

- No enhanced symmetry of the composite sector - usual divergent Higgs potential

Consequence of Maximal Symmetry

- Kinetic term of effective Lagrangian can not have non-trivial Higgs dependence
- Will not generate $\bar{\Psi}_{q_L} \not{p} \Sigma' \Psi_{q_L}$ type terms - these are exactly the ones responsible for double tuning
- Form of Higgs potential will be $c_{LR} \frac{N_c M_f^4}{16\pi^2} \left(\frac{y_t}{g_f}\right)^2 [-s_h^2 + s_h^4]$
- Both **β**, **γ** originate from same term
- ``Trigonometric parity" $\sin \frac{h}{f} \leftrightarrow \cos \frac{h}{f}$ unbroken

Consequence of Maximal Symmetry

- No double tuning! Wants to sit at $\xi = \frac{1}{2}$ need to invoke cancellation of the order of minimal tuning with gauge sector to ensure realistic model
- Resulting tuning $$\Delta \sim \frac{1}{\xi} \sim 9 \left(\frac{m_T}{1\,\mathrm{TeV}} \right)^2$$
- Double tuning removed, minimal tuning
- But still quadratically dependent on top partner mass

Soft symmetry breaking

(Simone Blasi + Florian Goertz)

- Makes SM fermions also complete SO(5) multiplets

- Breaks the link between the Higgs mass and the top partner mass

$$\Delta_L^\dagger q_L = \begin{pmatrix} q_L \\ 0 \\ 0 \end{pmatrix} \to \psi_L = \begin{pmatrix} q_L \\ w_L \\ s_L \end{pmatrix} \qquad \Delta_R^\dagger t_R = \begin{pmatrix} 0 \\ 0 \\ t_R \end{pmatrix} \to \psi_R = \begin{pmatrix} v_R \\ w_R \\ t_R \end{pmatrix}$$

- Add explicit masses for additional elementary vector-like fermions $\mathcal{L}_{\mathrm{el}} = m_v \bar{v} v + m_w \bar{w} w + m_s \bar{s} s$

$$= m_v \bar{v}_L \Delta_L \psi_R + m_w \bar{\psi}_L \Gamma_w \psi_R + m_s \bar{s}_R \Delta_R \psi_L$$

- Usual partial compositeness $-\mathcal{L}_{\mathrm{mass}} = m_4 \bar{Q}_L Q_R + m_1 \bar{\tilde{T}}_L \tilde{T}_R$

$$+ \; y_L f \, \bar{\psi}^t_{LI} \left(a_L U_{Ii} Q^i_R + b_L U_{I5} \tilde{T}_R \right) + \; y_R f \, \bar{\psi}^t_{RI} \left(a_R U_{Ii} Q^i_L + b_R U_{I5} \tilde{T}_L \right) + \mathrm{h.c.}$$

Soft symmetry breaking

- Now origin of explicit breaking no longer in the interactions between composites and elementary fields, but rather in the explicit elementary masses!

- Two limits:

1. Vector masses >> f - complete decoupling (usual CHM)
2. Vector masses << f - No Higgs potential generated

- In between - relation between Higgs and top partner masses broken

$$m_T \simeq 2.2 \frac{m_h}{m_t} \frac{1-\epsilon/4}{\sqrt{\epsilon}} f$$

- Where $\epsilon \equiv 1 - \frac{M}{m_s}$ and M composite mass scale

Successfully combining maximal symmetry and soft breaking

(Simone Blasi, Florian Goertz, CC)

- The soft sector has left and right fields separated (otherwise trigonometric parity badly broken)

$$\psi_L = \begin{pmatrix} q_L \\ w_L \\ s_L \end{pmatrix} \qquad \psi_R = \begin{pmatrix} v_R \\ w'_R \\ t_R \end{pmatrix}$$

- All new fermions have their own partners to make them massive

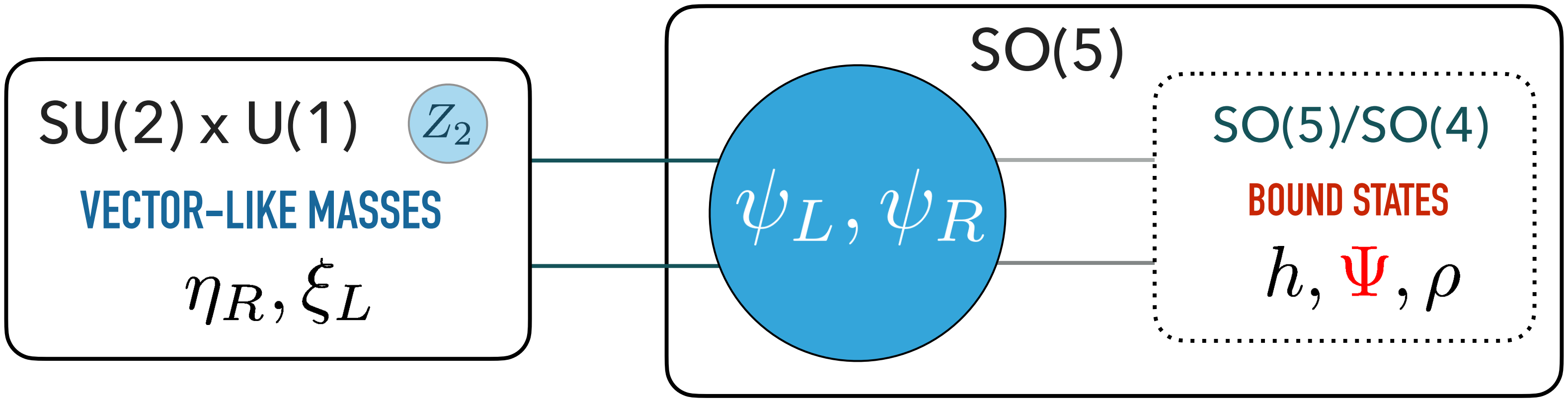
$$\begin{aligned} -\mathcal{L}_{\text{el}} = & \, m_{w_1}(\bar{w}_{1L}w_{1R} + \bar{w}_{1R}w_{1L}) + m_{w_2}(\bar{w}_{2L}w_{2R} + \bar{w}_{2R}w_{2L}) \\ & + m_v(\bar{v}_L v_R + \bar{v}_R v_L) + m_s(\bar{s}_L s_R + \bar{s}_R s_L) \ . \end{aligned}$$

- Can group the non-interacting helicities

$$\eta_R \equiv (w_{1R}, s_R), \quad \xi_L \equiv (w_{2L}, v_L)$$

Successfully combining maximal symmetry and soft breaking

- Summary of the successful model



$$\mathcal{L}_{\rm el} = \bar{\eta}_R M_R \psi_L + \bar{\xi}_L M_L \psi_R \qquad \mathcal{L}_{\rm linear} = \lambda_L \bar{\psi}_L U \Psi_R + \lambda_R \bar{\psi}_R U \Psi_L \qquad \mathcal{L}_{\rm mass} = M \bar{\Psi}_L V \Psi_R$$

UV-BRANE LOCALIZED SPINORS | SO(5)-SYMMETRIC PARTIAL COMP. | SO(5)' MAXIMAL SYMMETRY

$$\eta_R = (w_R, s_R) \quad \xi_L = (w'_L, v_L)$$

Successfully combining maximal symmetry and soft breaking

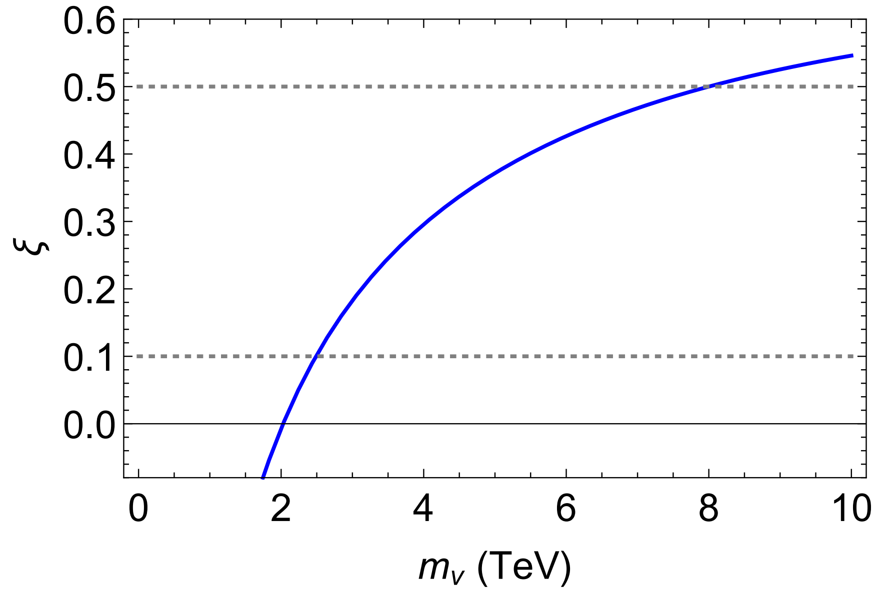
- The resulting potential: $V_{\rm LO}(h) = c_{LR} \sum_{i,j=1}^{\infty} a_{ij}\, {\rm Tr}(\Sigma^\dagger \Gamma_L^i \Sigma\, \Gamma_R^j)$
- Trigonometric parity broken, but various terms allow for non-trivial minimum. Eg.

$$V_{\rm LO}^{(1,1)}(h) \propto \left(m_s^2 m_v^2 + m_s^2 m_{w2}^2 - 2 m_{w1}^2 m_{w2}^2\right)\, \sin^2(h/f) + (m_v^2 m_{w1}^2 - m_s^2 m_v^2 + m_{w1}^2 m_{w2}^2 - m_s^2 m_{w2}^2)\sin^4(h/f),$$

- Get easily away from $\xi = 0.5$ except if $(m_v^2 - m_{w_2}^2) m_{w_1}^2 = 0$ when trigonometric parity is restored
- For example $\xi = 0.1$ for $m_s = 2.4$ TeV, $m_{w1} = 3$ TeV, $m_{w2} = 4$ TeV and $m_v = 5$ TeV

Successfully combining maximal symmetry and soft breaking

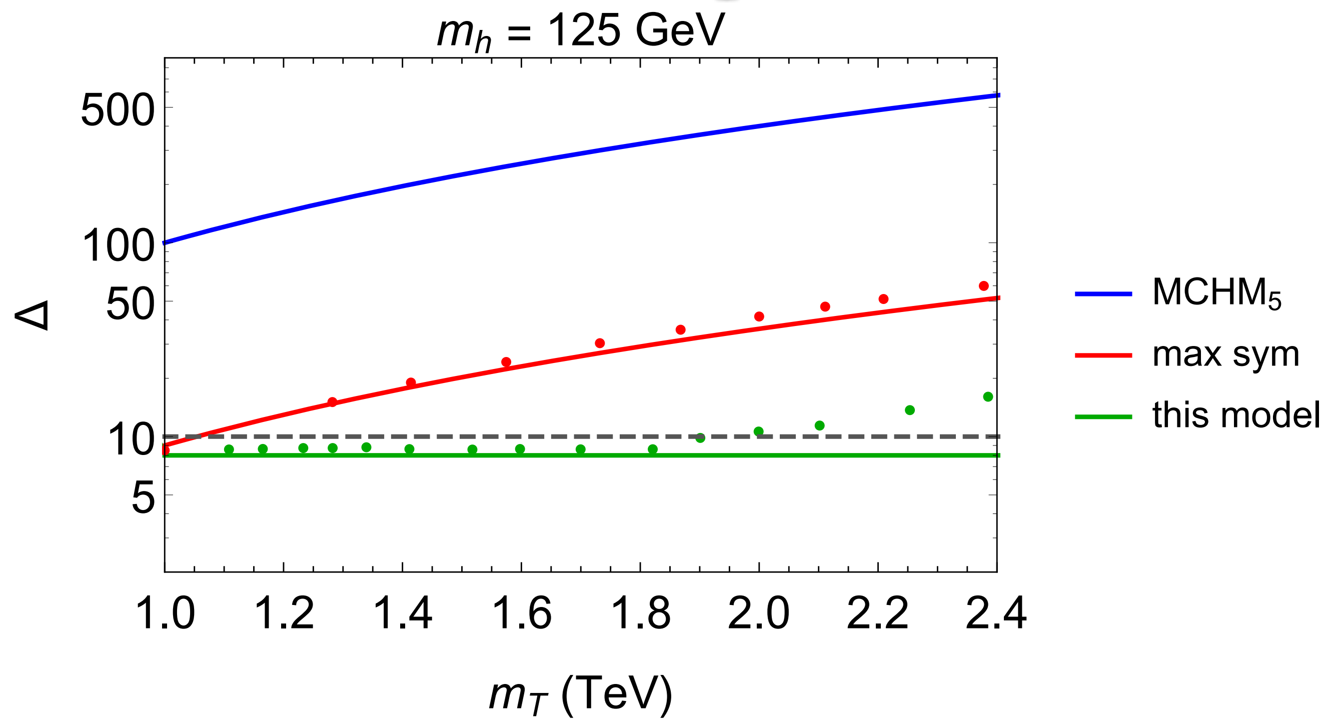
- An illustration



$$M = 2.6 \text{ TeV},\ m_{w_1} = m_{w_2} = 8 \text{ TeV},\ m_s = 2.4\,\text{TeV}$$

Successfully combining maximal symmetry and soft breaking

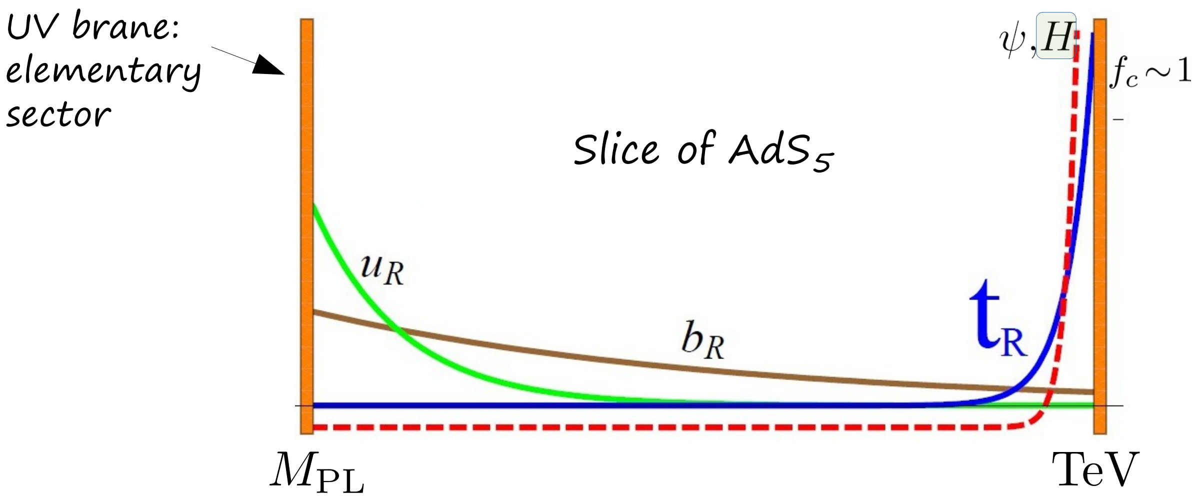
- The tuning



- To leading order: minimal tuning independent of the top partner mass (Can raise top partner mass - to a point - without raising f) $\Delta \simeq \frac{1}{\xi} - 2 \simeq 8$

Implementation in 5D extremely simple!

- Simply use UNIVERSAL BC's for all fermions - IR will ensure maximal symmetry, UV will ensure elementary partners



MCHM5

$$\psi_L = \begin{pmatrix} w_1^1[-,+] & t[+,+] \\ w_1^2[-,+] & b[+,+] \end{pmatrix} \oplus s[-,+]$$

sMCHM5

$$\psi_L = \begin{pmatrix} w_1^1[+,+] & t[+,+] \\ w_1^2[+,+] & b[+,+] \end{pmatrix} \oplus s[+,+]$$

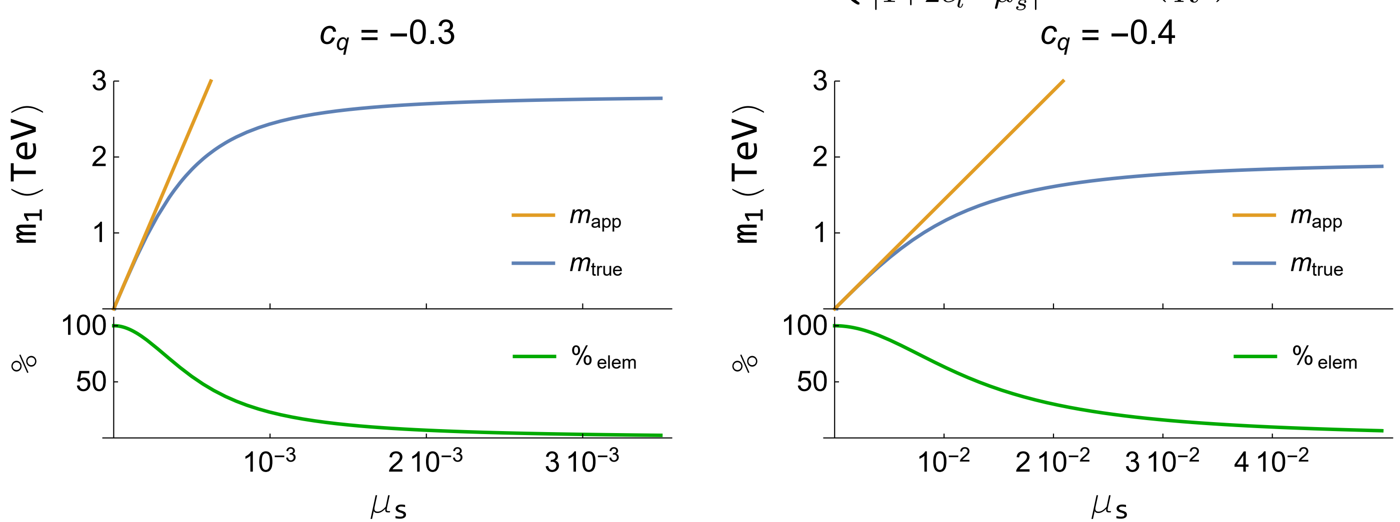
Implementation in 5D extremely simple!

- To remove extra DOF's add elementary partners as UV brane localized fields

$$S_{\rm UV}=\int \mathrm{d}^4x\Big\{-i\eta_R\sigma^\mu\partial_\mu\bar\eta_R-i\bar\xi_L\bar\sigma^\mu\partial_\mu\xi_L+\frac{1}{\sqrt{R}}\chi_l(R)\,M_R^\dagger\,\eta_R+\frac{1}{\sqrt{R}}\psi_r(R)\,M_L^\dagger\,\xi_L+\text{h.c.}\Big\}$$

- If field IR localized, UV mass naturally very small! Happens automatically for 3rd generation (which is exactly what we need)

$$m_1^2\sim\begin{cases}(2c_l-1)\mu_s^2R^{-2} & c_l>1/2\Rightarrow\text{UV}\\ \frac{(1-4c_l^2)\mu_s^2}{|1+2c_l-\mu_s^2|}R'^{-2}\left(\frac{R}{R'}\right)^{-1-2c_l} & c_l<1/2\Rightarrow\text{IR}\end{cases}$$



Conclusions

- Composite Higgs models solve hierarchy but under stress from LHC
- Top partner bound now above TeV, tuning ~ 1%
- Maximal symmetry eliminates double tuning
- Soft breaking removes quadratic dependence on top mass - easy to combine with maximal symmetry
- Extra dimensional version very natural
- Resulting tuning ~ 10% - back to pre-LHC era. Heavy top partners ideal target for FCC.