Electroweak Symmetry Breaking and Extra Dimensions

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Large extra dimensions can address the "hierarchy problem" by reducing the fundamental M_{Pl}, to be close to M_{weak}

[Extra dim with only gravity can be as big as ~O(mm)]

* What is the mechanism for EW breaking?

[Why $H(1, 2, \frac{1}{2})$, $m_H^2 < 0$?]

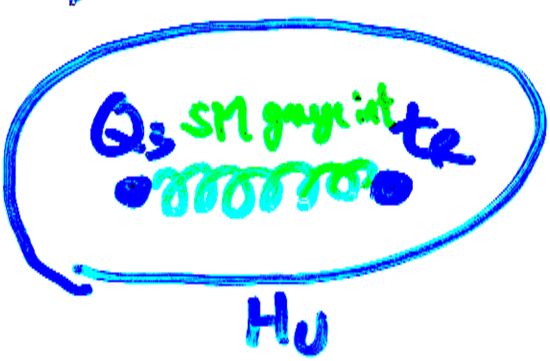
If Standard Model fields also propagate in some extra dimensions, [these dimensions have to be $\lesssim O(\text{TeV}^{-1})$] Higgs can arise as a bound state of the SM fermions, bound by SM gauge interactions in extra dimensions

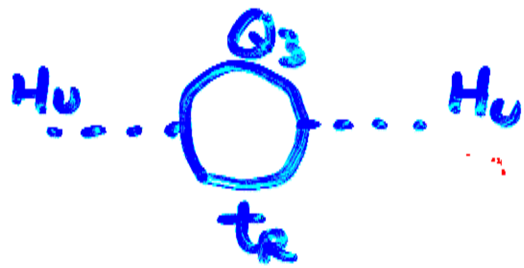
Gauge theories in D(>4)-dim are non-renormalizable, gauge interactions become strong rapidly at high energies (therefore needs a physical cutoff M_s)

Dimensionless expansion parameter

$$\propto g_D \cdot E^{\delta/2} \; (= g_4 \times N_{KK}) \uparrow \text{ as } E \uparrow$$

They can bind SM fermions into bound states





$$H_u \sim \bar{Q}_3 t_R \; (1, 2, \tfrac{1}{2})$$

Bound state mass^2 decreases as interaction strength increases, becomes negative for interaction strength exceeding some critical value (large enough cutoff M_s compared with M_{comp})

Ex. A one (3rd) generation model in 6D

$M_c \, (=R^{-1})$: Compactification scale of the 2 extra dimensions $\sim$ TeV

M_s : Cutoff scale for the higher-dim theory
$M_s/M_c \sim 5$ for gauge interactions become strong

Fermions in 6D (4-comp chiral spinors) : Q_+, L_+ (SU(2) doublets)
U_-, D_-, E_- (SU(2) singlets)

$\pm$: 6D chirality (eigenstates of Γ_7)

Imposing orbifold projection to project out half of the zero-mode components

$\Rightarrow$ 4D massless chiral fermions $Q_+^{(0)} = (t, b)_L$

$U_-^{(0)} = t_R$, $D_-^{(0)} = b_R$ $L_+^{(0)} = (\nu_\tau, \tau)_L$ $E_-^{(0)} = \tau_R$

The 6D composite scalars are of the form

$\bar{\Psi}_+ \chi_-$ or $\bar{\Psi}^c_+ \chi_-$

(Note that in 4k+2 dim, charge conjugation does not change chirality $C\,\psi_+ \to \psi^c_+$)

Find the symmetry breaking pattern by identifying the <u>most attractive scalar channel</u>

Using one-gauge-boson-exchange approximation

binding strength $\propto \sum_{i=1}^{N_{KK}-1} \hat{g}_i^2 \, T^i_{\bar{\Psi}} \, T^i_{\chi}$

$$T_{\bar{\Psi}} \cdot T_{\chi} = \frac{1}{2}\left[C_2(\bar{\Psi}) + C_2(\chi) - C_2(\bar{\Psi}\chi)\right]$$

(All $\hat{g}_i$ become comparable at M_s due to power-law running)

Composite scalar	constituents	$SU(3) \times SU(2) \times U(1)$ representation	binding strength	relative binding for $\hat{g}_1 = \hat{g}_2 = \hat{g}_3$
$H_{\mathcal{U}}$	$\overline{\mathcal{Q}}_+\mathcal{U}_-$	$(\mathbf{1}, \mathbf{2}, +1/2)$	$\frac{4}{3}\hat{g}_3^2 + \frac{1}{15}\hat{g}_1^2$	1
$H_{\mathcal{D}}$	$\overline{\mathcal{Q}}_+\mathcal{D}_-$	$(\mathbf{1}, \mathbf{2}, -1/2)$	$\frac{4}{3}\hat{g}_3^2 - \frac{1}{30}\hat{g}_1^2$	0.93
$\tilde{q}$	$\overline{\mathcal{Q}}_+\mathcal{D}_-^c$	$(\mathbf{3}, \mathbf{2}, +1/6)$	$\frac{2}{3}\hat{g}_3^2 + \frac{1}{30}\hat{g}_1^2$	0.5
X	$\overline{\mathcal{Q}}_+\mathcal{U}_-^c$	$(\mathbf{3}, \mathbf{2}, -5/6)$	$\frac{2}{3}\hat{g}_3^2 - \frac{1}{15}\hat{g}_1^2$	0.43
$H_{\mathcal{E}}$	$\overline{\mathcal{L}}_+\mathcal{E}_-$	$(\mathbf{1}, \mathbf{2}, -1/2)$	$\frac{3}{10}\hat{g}_1^2$	0.21
$\tilde{q}'$	$\overline{\mathcal{L}}_+^c\mathcal{U}_-$	$(\mathbf{3}, \mathbf{2}, +1/6)$	$\frac{1}{5}\hat{g}_1^2$	0.14
$\tilde{q}''$	$\overline{\mathcal{L}}_+\mathcal{D}_-$	$(\mathbf{3}, \mathbf{2}, +1/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07
X'	$\overline{\mathcal{Q}}_+^c\mathcal{E}_-$	$(\mathbf{3}, \mathbf{2}, -5/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07

Attractive scalar channels in six dimensions with chiral fermions

- H_u is MAC, $M_{H_u}^2$ turns negative first when increasing the binding strength
  Need to tune M_s/M_c to have H_u channel just above criticality
- H_D is also strongly bound, can be light
  Other channels are not sufficiently strongly bound to form light bound states
  $\Rightarrow$ 2 Higgs doublet model at low energies

Advantages compared with usual 4-dim dynamical EW breaking models:

- No need for new interations or new fermions

  Higgs is a bound state of SM fermions bound by SM interactions in extra dimensions

- Good prediction for the top quark mass

  $\lambda_t \sim 1 \quad \left(\sim g_4 , \quad \frac{\text{strong coupling}, O(4\pi)}{\text{volume suppression}, N_{KK}} \right)$

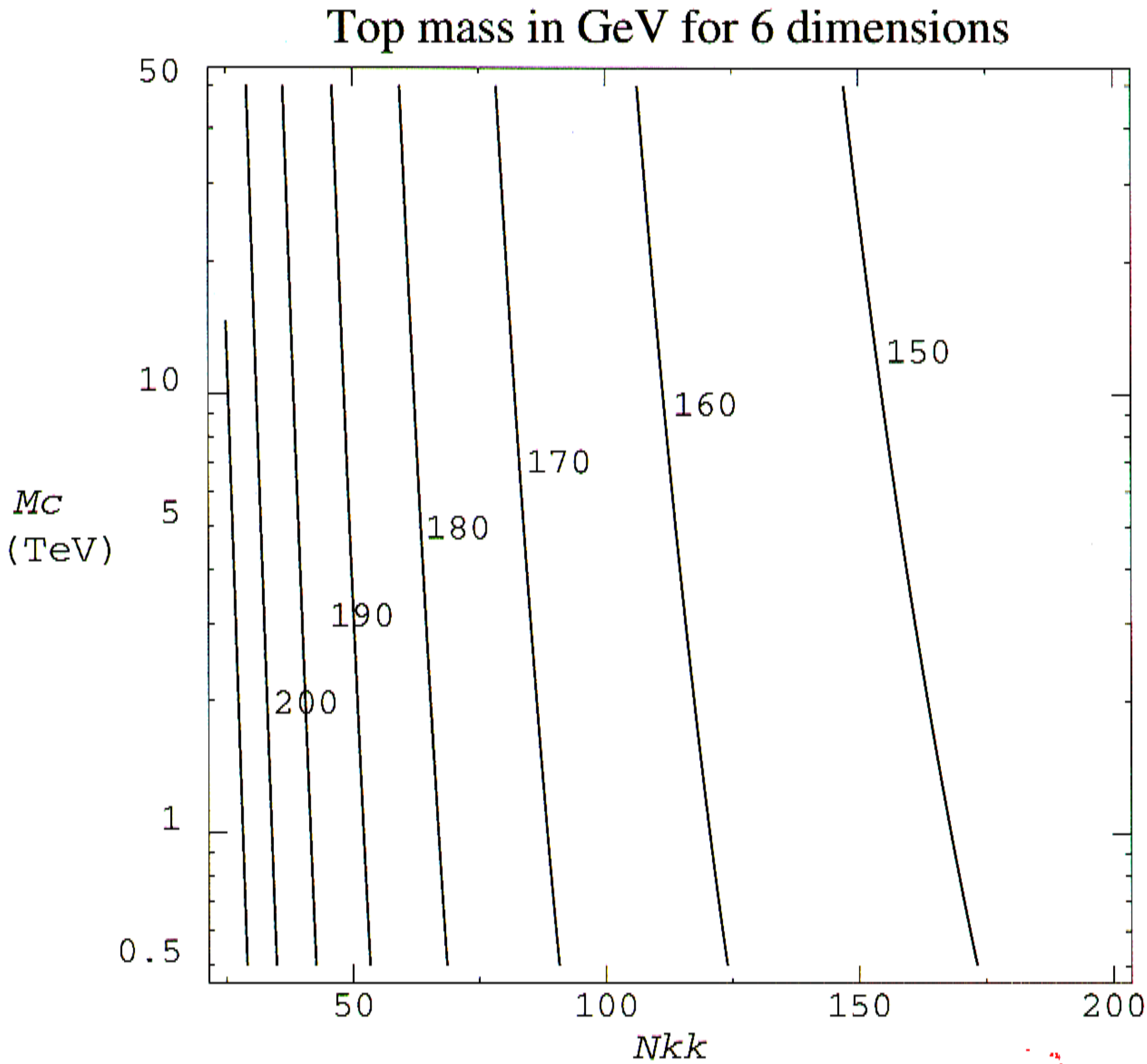
  cf. 4-dim top condensate model

  $m_t \sim 600$ GeV for compositeness scale $\sim$ TeV

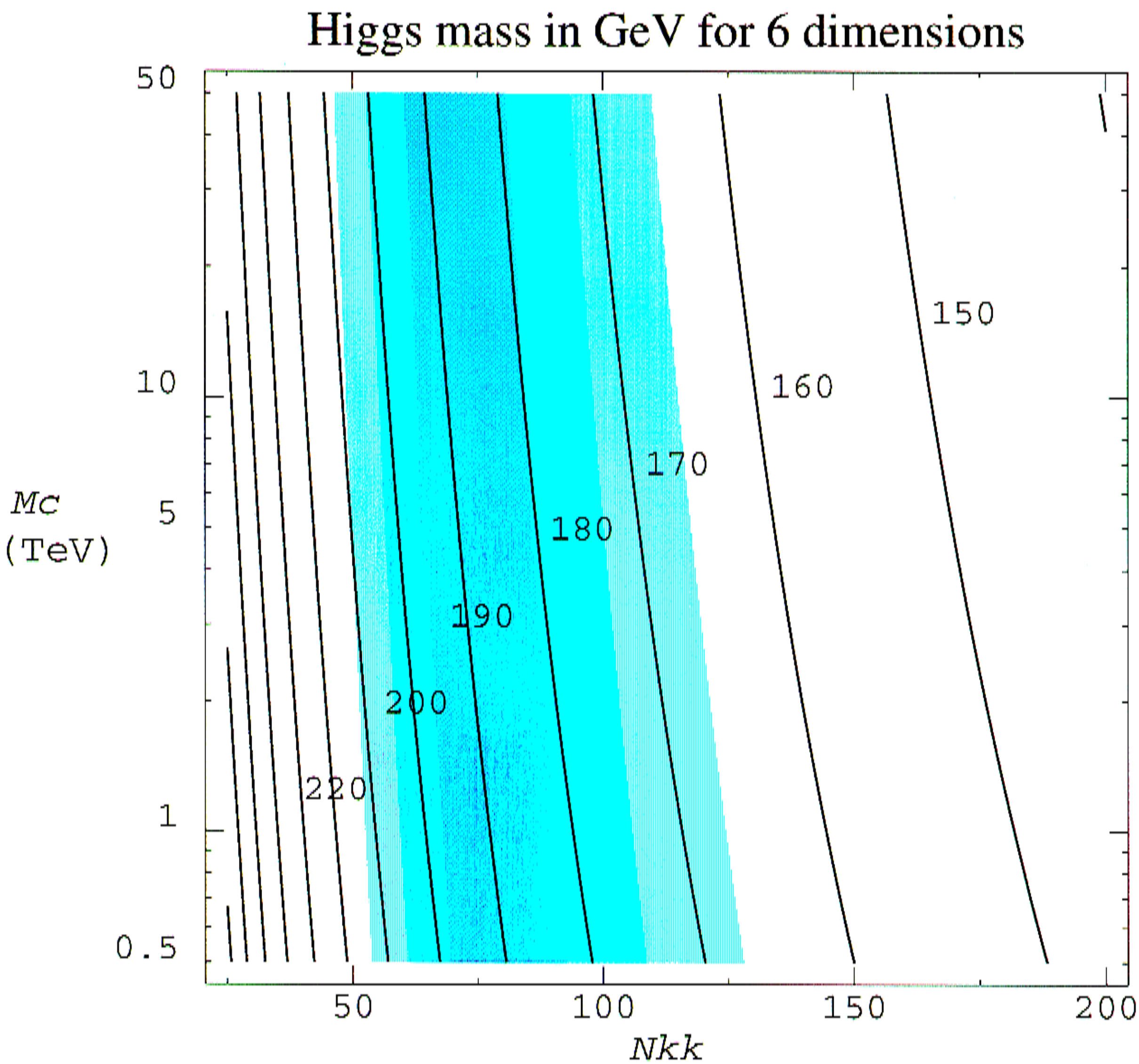
  Similarly, Higgs is also relatively light

  $\lambda_H \sim 1 \Rightarrow m_h \sim 200$ GeV

In fact, m_t, m_h can be predicted from RG IR fixed points, quite insensitive to cutoff M_s



The predicted top mass as a function of the number of KK modes, $N_{\rm KK}$, and the compactification scale, M_c, in the six-dimensional theory.



The predicted Higgs mass as a function of N_{KK} and M_c in the six-dimensional theory. The shaded regions correspond to the top mass lying within 1–3 σ (dark to light) of the experimental value.

165 GeV $\leq m_h \lesssim$ 210 GeV (for 6D)

for $m_t = 174.3 \pm 5.1 (\times 3)$ GeV

Composite scalar	constituents	$SU(3)\times SU(2)\times U(1)$ representation	binding strength	relative binding for $\hat{g}_1=\hat{g}_2=\hat{g}_3$
$H_{\mathcal{U}}$	$\overline{\mathcal{Q}}_+\mathcal{U}_-$	$(\mathbf{1},\mathbf{2},+1/2)$	$\frac{4}{3}\hat{g}_3^2+\frac{1}{15}\hat{g}_1^2$	1
$H_{\mathcal{D}}$	$\overline{\mathcal{Q}}_+\mathcal{D}_-$	$(\mathbf{1},\mathbf{2},-1/2)$	$\frac{4}{3}\hat{g}_3^2-\frac{1}{30}\hat{g}_1^2$	0.93
$\tilde{b}$	$\overline{\mathcal{Q}}_+\mathcal{Q}_-^c$	$(\mathbf{3},\mathbf{1},-1/3)$	$\frac{2}{3}\hat{g}_3^2+\frac{3}{4}\hat{g}_2^2-\frac{1}{60}\hat{g}_1^2$	$1-\epsilon$
$\tilde{b}'$	$\overline{\mathcal{U}}_-\mathcal{D}_+^c$	$(\mathbf{3},\mathbf{1},-1/3)$	$\frac{2}{3}\hat{g}_3^2+\frac{2}{15}\hat{g}_1^2$	0.57
$\tilde{b}''$	$\overline{\mathcal{Q}}_-^c\mathcal{L}_+$	$(\mathbf{3},\mathbf{1},-1/3)$	$\frac{3}{4}\hat{g}_2^2+\frac{1}{20}\hat{g}_1^2$	0.57
$\tilde{b}'''$	$\overline{\mathcal{U}}_+^c\mathcal{E}_-$	$(\mathbf{3},\mathbf{1},-1/3)$	$\frac{2}{5}\hat{g}_1^2$	0.29
$H_{\mathcal{E}}$	$\overline{\mathcal{L}}_+\mathcal{E}_-$	$(\mathbf{1},\mathbf{2},-1/2)$	$\frac{3}{10}\hat{g}_1^2$	0.21
$\tilde{q}$	$\overline{\mathcal{L}}_+\mathcal{D}_-$	$(\mathbf{3},\mathbf{2},+1/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07

Attractive scalar channels in eight dimensions with chiral fermions. We include an $\epsilon>0$ in the $\tilde{b}$ channel to account for the lifting of the degeneracy due to the running coupling effect below M_s.

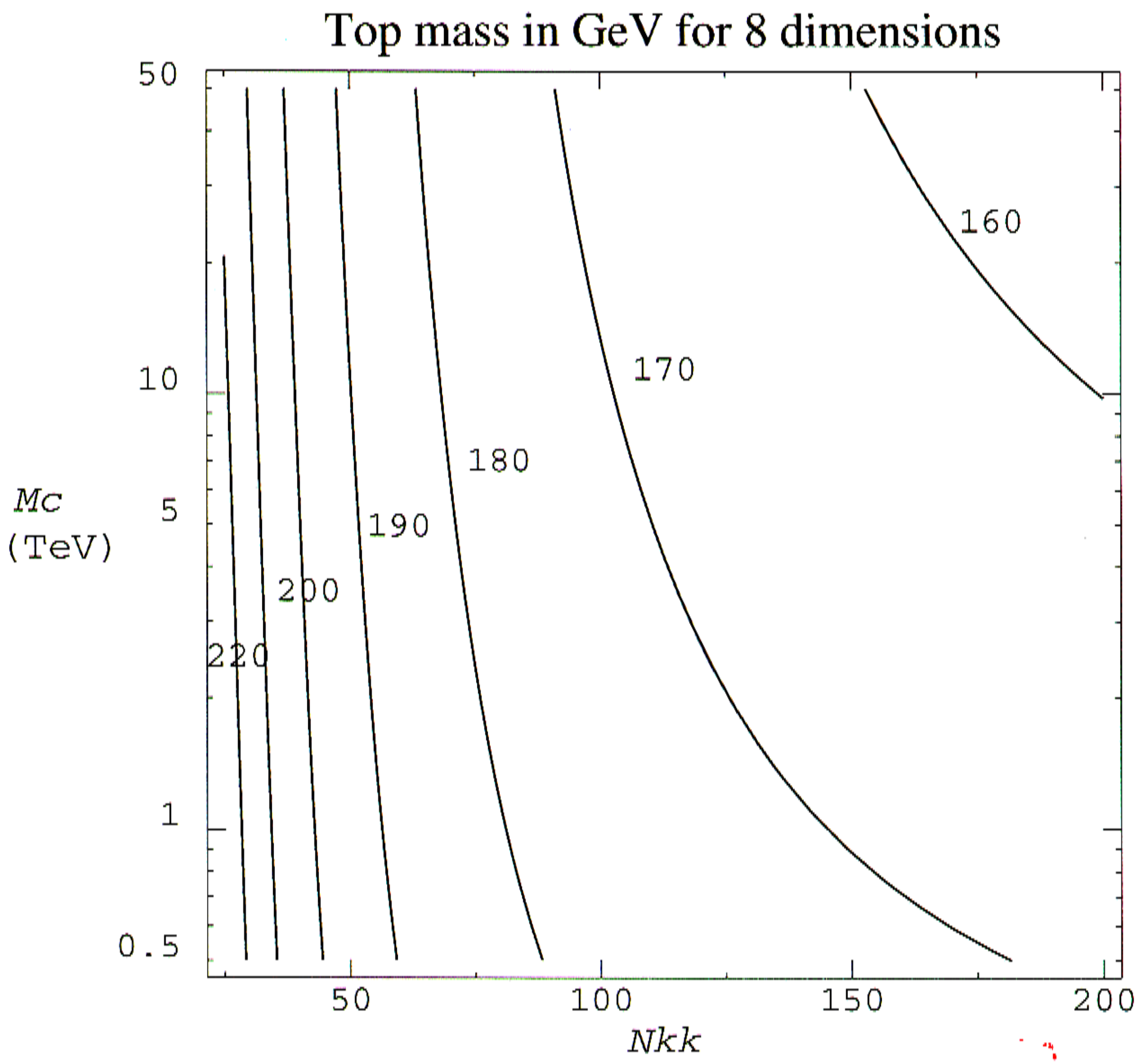
- In 8 (4k) dim, charge conjugation flips the chirality $C\,\psi_+ \to \psi_-^c$

  ⇒ Different bound states (from 6D) involving C

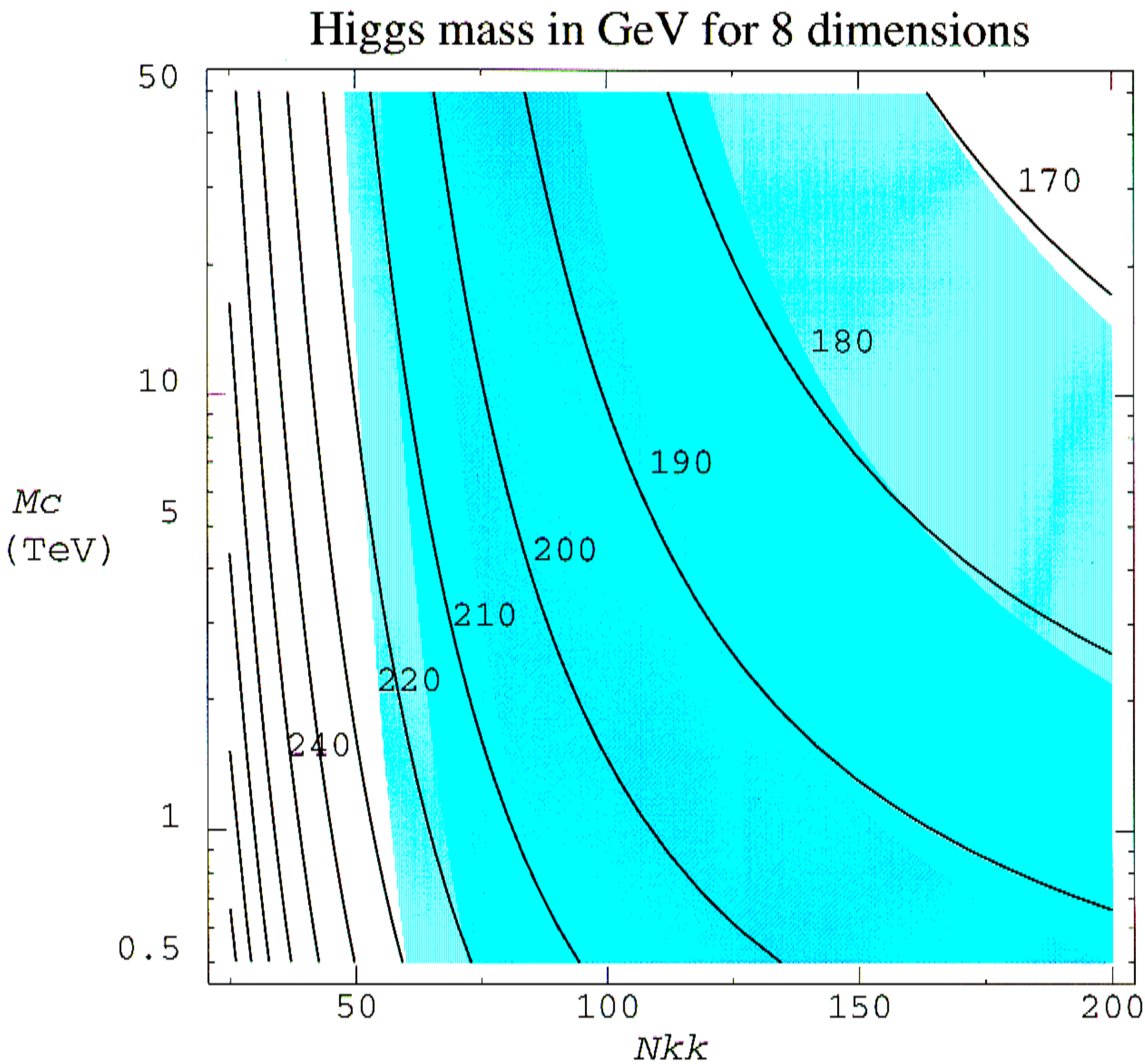
- $\tilde{b}=\overline{Q}_+Q_-^c$ is also strongly bound because $\hat{g}_2$(8D) becomes strong too

  ⇒ light color-triplet scalar

  (in addition to H_U H_D)



The predicted top mass as a function of N_{KK} and M_c in the eight-dimensional theory.



The predicted Higgs mass as a function of N_{KK} and M_c in the eight-dimensional theory. The shaded regions correspond to the top mass lying within 1–3 σ (dark to light) of the experimental value.

170 GeV $\leq m_h \leq$ 230 GeV (8D)

Flavor

1. First 2 gen. are 4-dimensional, localized at some points in extra dimensions
   $\Rightarrow$ There can be 4-dimensional bound states

2. All 3 gen. in the bulk : gauge interactions preserve $U(3)^5$. $H_U \sim (3,\bar{3})$ under $U(3)_Q \times U(3)_U$
   Without flavor breaking $\langle H_U \rangle$ breaks $U(3)_Q \times U(3)_U$ to $U(3)$ $\Rightarrow$ 8 goldstone bosons
   Explicit flavor breaking can come from operators induced at M_S, e.g. $\frac{\eta_{ij}}{M_S^{D-2}} (\bar{Q}_+^i U_-^j)(\bar{U}_-^j Q_+^i)$
   Assume only $H_U^{3,3}$ is supercritical $\langle H_U^{3,3} \rangle \neq 0$
   after tilting, other light fermions can get masses from $(\bar{Q}_+^3 U_-^3)(\bar{Q}_+^3 D_-^3)$
   $(\bar{Q}_+^3 U_-^3)(\bar{U}_-^i Q_+^j)$, $(\bar{Q}_+^3 D_-^3)(\bar{D}^i Q_+^j)$, $(\bar{Q}_+^3 D_-^3)(\bar{E}_+^i L_-^j)$.

Phenomenology for future experiments

- $m_h \sim 200$ GeV

$$h \to WW$$
$$\hookrightarrow ZZ$$

- Possible other bound states

e.g.

- $H_D \sim \bar{Q} D$
- $\tilde{b} \sim \bar{Q}\, \tilde{Q}^c$ $(3, 1, -\frac{1}{3})$ in the 8-dim model

$$\tilde{b} \to \bar{t}\bar{b}$$

$$\left(\begin{array}{ll} \text{SUSY with } \not{R}_p \ U_3 D_3 D_2, & \tilde{s} \to \bar{t}\bar{b} \\ \text{Charged Higgs} & H^+ \to t\bar{b} \end{array} \right)$$

- Different bound states for various setups

(Mimic SUSY?)

- KK excitations of SM fields:
  - Non-universal extra dimensions: If only some of the SM fields live in extra dimensions.
    EW precision constraints ar strong $M_c \gtrsim 2-5$ TeV
  - Universal extra dimensions: all SM fields live in same extra dimensions. The constraints are much weaker because of KK number (momentum in extra dim) conservation
    Direct production: KK excitations have to be pair produced $M_c > O(100\,\text{GeV})$
    EW precision observables: No tree-level contribution, loop contributions require $M_c \gtrsim 300\,\text{GeV}\ (D=5)$, $\gtrsim 600\,\text{GeV}\ (D \geq 6)$
    If no extra-dim momentum conservation violating int. (Most) KK states are stable (Cosmological problem)
    Int. localized on 3-branes violates KK # conservation
    $\Rightarrow$ KK states decay according to these interactions
    e.g. $e^{(1)} \to e\gamma, 3e$

Conclusions

Extra dimensions with SM fields can provide an explanation for the EW symmetry breaking. SM gauge interactions become strong in higher dimensions and naturally form a composite Higgs from SM fermions (top), breaking $SU(2)_W \times U(1)_Y$ to $U(1)_{EM}$

Top mass is predicted in agreement with the experimental value. and Higgs mass is predicted to be $O(200\,\mathrm{GeV})$

There are a lot of exciting new states to be discovered at future experments

Varions bound states. KK excitations.