EW constraints on warped scenarios with custodial protection

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Based on work with M. Carena, J. Santiago and C. Wagner
hep-ph/0607106, hep-ph/0701055 and work in progress

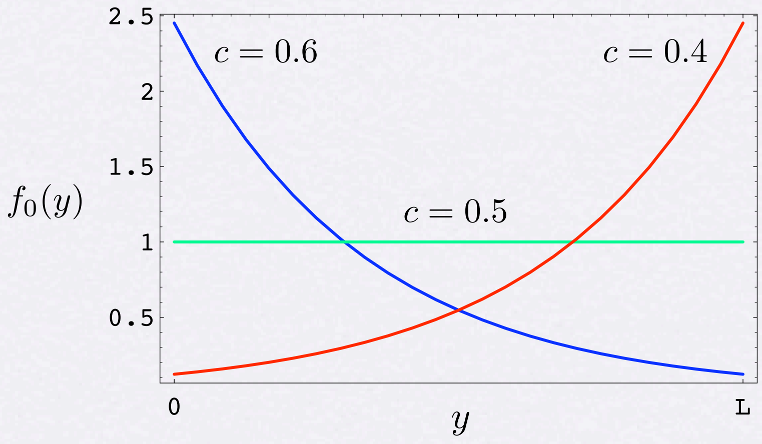
The RS scenario: scales

Randall-Sundrum proposal (1999)

UV brane IR brane

Slice of AdS: $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$ $\quad y \in [0, L]$

- Non-supersymmetric solution to the hierarchy problem
- Multiple scales through localization along the 5th dimension
  - EW symmetry breaking on IR brane $\longrightarrow$ "TeV scale"
  - Delocalized SM fermions as a solution to RS1 flavor problem



- Suppression of FCNC's due to higher dimension operators
- SM fermion mass hierarchies (exponential hierarchies natural)

The RS scenario and EWSB

New physics at a scale of order $\tilde{k} \equiv k\, e^{-kL}$, although radiative corrections to Higgs potential generically cutoff at $\Lambda \gg \tilde{k}$

$\longrightarrow$ little hierarchy problem: why $m_h^2 \ll \Lambda^2$?

strong coupling scale

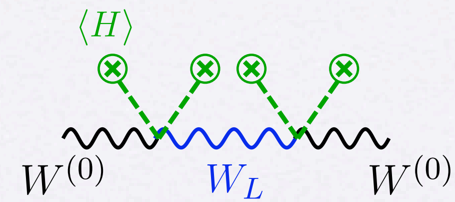
However, in a "gauge-Higgs unification" scenario, i.e. Higgs as A_5, loop contributions to m_h are really cutoff at $\tilde{k}$

In fact, Higgs potential is calculable $\longrightarrow$ can *explain* EWSB!

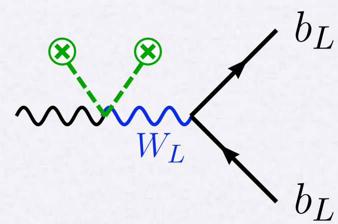
But how light the new physics?

Tree level corrections to SM observables $\longrightarrow$ stringent constraints

Large contributions to oblique parameters, e.g. T



Shifts in fermion-gauge boson couplings



... or other fermions

These constraints can put the new physics beyond the reach of the LHC

In this talk I will consider models that tame the large tree-level corrections by

- Imposing a custodial SU(2) symmetry **(Agashe,Delgado,May,Sundrum)**
- Quantum numbers such that bottom couplings are protected **(Agashe,Contino,DaRold,Pomarol)**

S parameter remains as source of most important constraints...

... however, protected parameters can still be important

Custodial Symmetry: $SU(2)_L \times SU(2)_R$

Unlike in SM with Higgs doublet, large custodial violation due to KK of hypercharge and top quark: $g'\sqrt{2kL}$ and $y_t\sqrt{2kL}$ with $\sqrt{2kL} \sim 8$.

1. Possible solution: soften couplings with BKT′ (Davoudiasl,Hewett and Rizzo) (Carena,Delgado,E.P., Tait and Wagner)

2. Make $SU(2)_R$ exact: (Agashe,Delgado,May,Sundrum)

Gauge

$$SU(2)_L \times \underbrace{SU(2)_R \times U(1)_X}_{U(1)_Y}$$

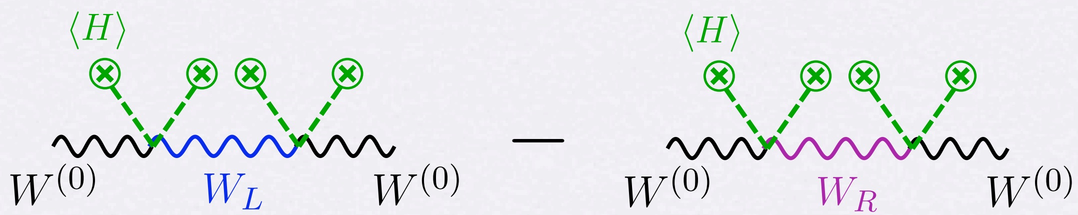
... and brake it minimally (at UV brane only)

$$W^a_{L\,\mu} \sim (+,+)\ , \quad B_\mu \sim (+,+) \qquad a = 1,2,3$$
$$W^b_{R\,\mu} \sim (-,+)\ , \quad Z'_\mu \sim (-,+) \qquad b = 1,2$$

$$B_\mu = \frac{g_{5\,X} W^3_{R\,\mu} + g_{5\,R} X_\mu}{\sqrt{g^2_{5\,R} + g^2_{5\,X}}}$$

Custodial violation due to small KK-mode splittings: $M_{W^n_L} \neq M_{W^n_R}$, $g_{W^n_L} \neq g_{W^n_R}$

Schematically, the T parameter at tree-level:



Tower with 0-mode **Tower with no 0-mode**

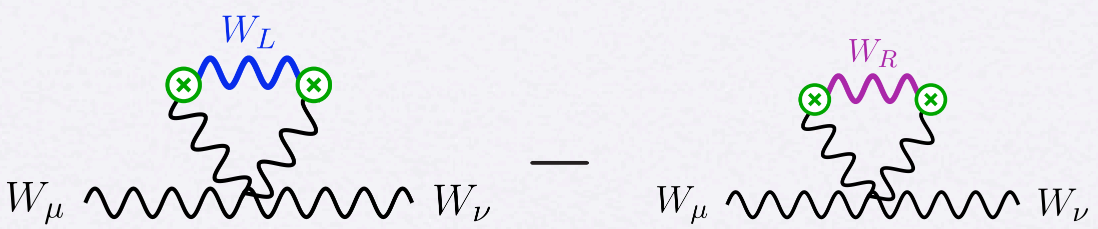
$$= \Delta_{++} - \Delta_{-+} \approx 0$$

The T-parameter at one-loop

Non-local breaking of custodial $SU(2) \quad \longrightarrow \quad T \neq 0,$ calculable

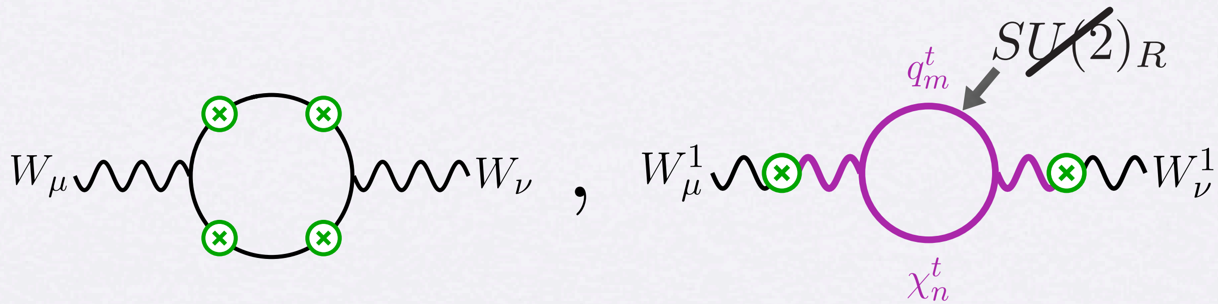
Types of contributions discussed by Agashe, Delgado, May, Sundrum

Gauge:
(Schematic)



$\sim$ small

Fermions:



(subdominant)

These depend on various localization parameters!

Why one-loop interesting?

Localization towards IR brane $\longrightarrow$ better custodial protection

But in SM, top gives (1-loop)

$$T_{\rm top} = \frac{N_c m_{\rm top}^2}{16\pi s^2 c^2 m_Z^2} \sim 1 \quad \longrightarrow$$

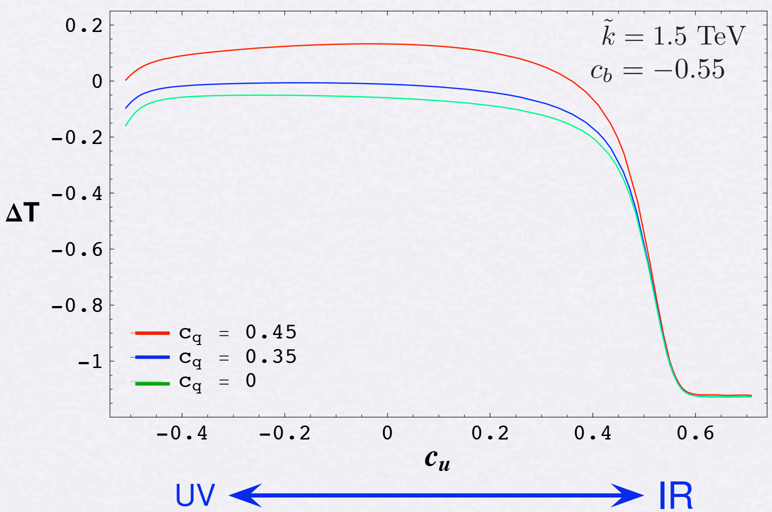
Expect some degree of cancellation in this limit

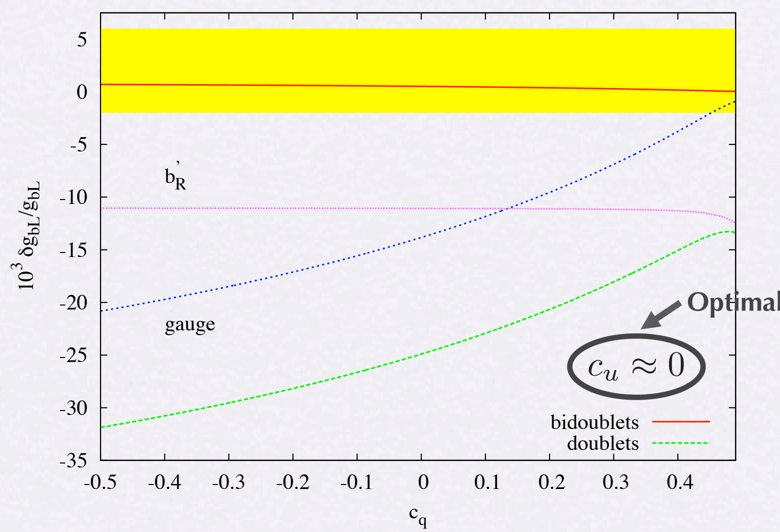
New physics may contribute $\Delta T < 0$ (top sector)

Example: Simplest implementation of $SU(2)_R$ in fermion sector

$SU(2)_L$ doublet $\qquad$ $SU(2)_R$ doublet $\qquad$ $c_Q > 1/2$

$$q_L = \begin{pmatrix} t_L(+,+) \\ b_L(+,+) \end{pmatrix}, \qquad Q_R = \begin{pmatrix} t_R(+,+) \\ b'_R(-,+) \end{pmatrix} \qquad \to b'_R \text{ ultralight}$$





Large corrections to $Zb\bar{b}$ anyway!

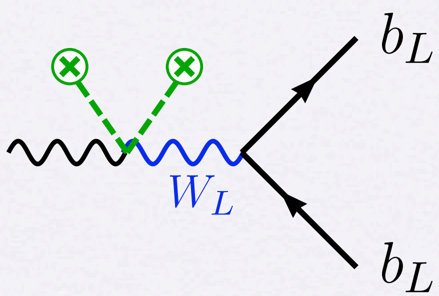
(mixing of b_L and b'_R)

$$m_{KK}^{\rm gauge} > 9 \text{ TeV}$$

Coupling of Z to bottom and custodial protection

(Agashe,Contino, DaRold,Pomarol)

If $g_L = g_R$ and $T^3_L(b_L) = T^3_R(b_L)$:



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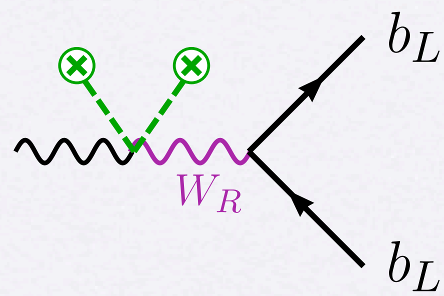
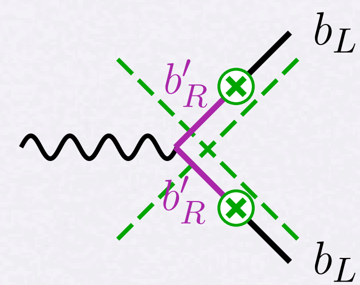


$$= G^{b_L}_{++} - G^{b_L}_{-+} \approx 0$$

$$SU(2)_R \; \longleftrightarrow$$

$$SU(2)_L \updownarrow \begin{pmatrix} \chi^u_L(-,+) & q^t_L(+,+) \\ \chi^d_L(-,+) & q^b_L(+,+) \end{pmatrix} \sim (2,2)_{2/3} \sim \begin{pmatrix} 5/3 & 2/3 \\ 2/3 & -1/3 \end{pmatrix}$$



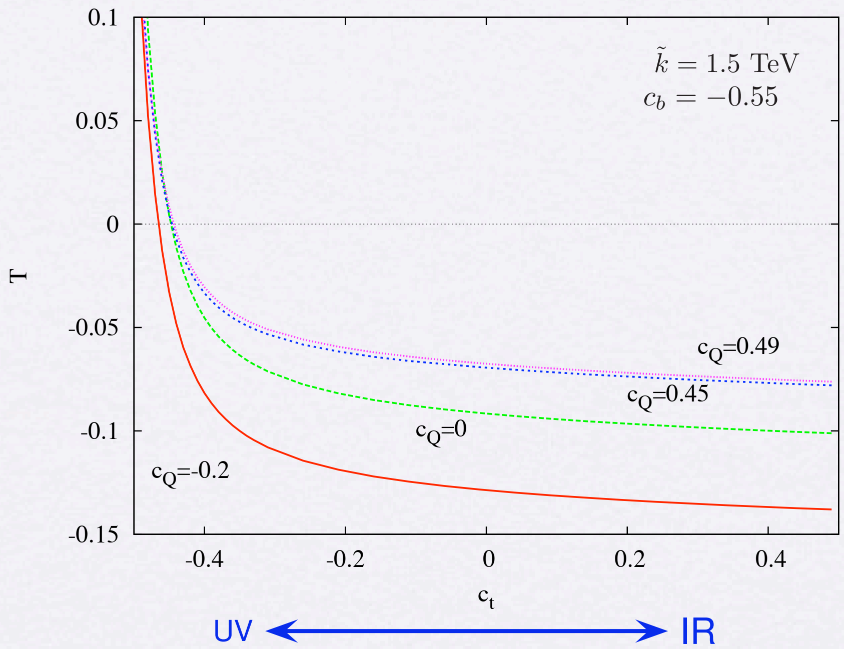
Impose discrete P_{LR} and choose quantum numbers of b_L

(No counterterms that correct $Zb_L\bar{b}_L$ vertex allowed!)

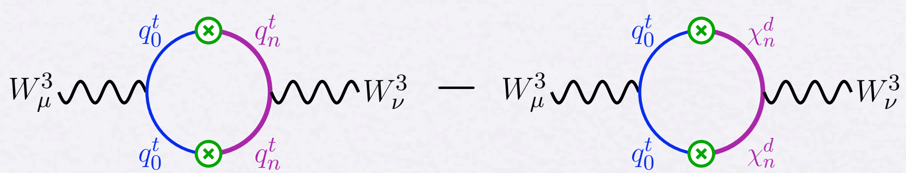
T and custodial protection of $Zb_L\bar{b}_L$

When $Q_L = \begin{pmatrix} \chi_L^u(-,+) & q_L^t(+,+) \\ \chi_L^d(-,+) & q_L^b(+,+) \end{pmatrix} \oplus t_R(+,+)$, b_R from $SU(2)$ triplets

(Carena,E.P,Santiago,Wagner)

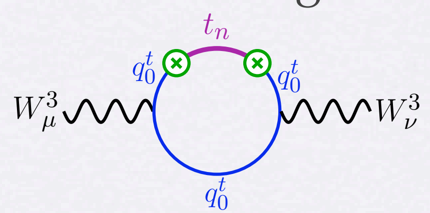


Negative contribution: EWSB mixing of bidoublet KK modes with t_R



χ's lighter and more strongly coupled to Higgs than q's

Positive T from mixing with singlet!



Together with S > 0 $\rightarrow t_R$ far from IR brane seems preferred

Light singlet states that mix strongly with the top quark

Global fit to EW observables

(Carena,E.P.,Santiago,Wagner)

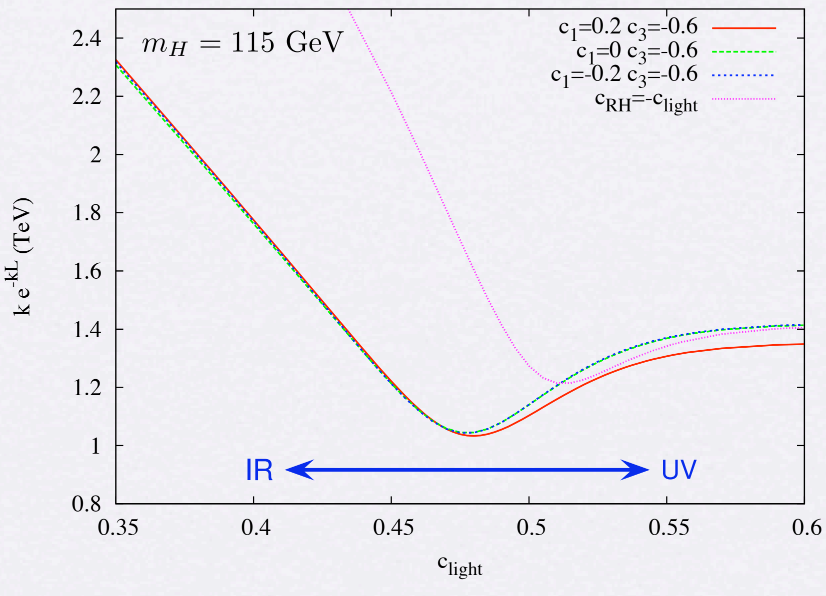
We would like to address the following, in the context of the previous models:

- Localizing the light fermions near the "conformal" point can decouple the tower of KK modes of the SM gauge bosons

  $\longrightarrow$ Can one get rid of the bounds from the "S parameter"?

- How important are the 1-loop contributions to T and the $Zb_L\bar{b}_L$ vertex ?

"S,T,U" analysis insufficient, global fit is required (use Han, Skiba fit based on dim-6 ops)



Non-trivial constraints remain due to

- Couplings to W_R non-universal
- Shifts in up- and down-type couplings different
- Positive T preferred: constraints on localization parameters of 3rd generation quark sector

$$\tilde{k} \equiv ke^{-kL} \gtrsim 1 \text{ TeV } (95\% \text{ C.L.})$$

$$\Longrightarrow \quad M_{\rm KK}^{\rm gauge} \gtrsim 2.5 \text{ TeV}$$

Global fit to EW observables

- New measurements of m_t and m_W may generate some tension in SM
- Interestingly, tension relaxed in the presence of the new physics

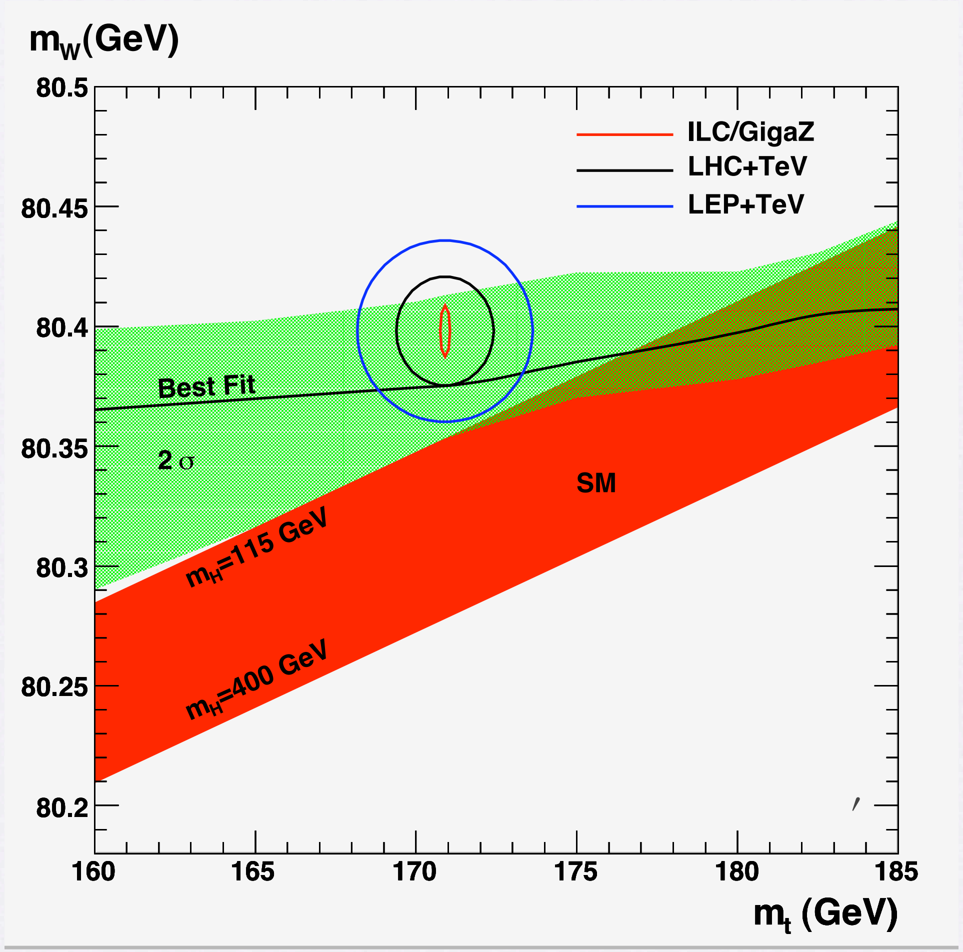
Green region: *predicted* m_W at 95% CL (global fit with m_W excluded, $m_h = 115\ \mathrm{GeV}$)

68% C.L. based on combined CDF/D0 top mass,

$$m_t = 170.9 \pm 1.8\ \mathrm{GeV}$$

plus newest combined LEP and Tevatron measurement of

$$M_W = 80.398 \pm 0.025\ \mathrm{GeV}$$



Application: Gauge-Higgs Unification

Bulk gauge symm: $SU(3)_c \times SO(5) \times U(1)_X \quad \longrightarrow SO(5) \supset SU(2)_L \times SU(2)_R$

UV: $SU(2)_L \times U(1)_Y$ IR: $SO(4) \times U(1)_X \simeq SU(2)_L \times SU(2)_R \times U(1)_X$

Extra gauge bosons have the quantum numbers of the Higgs

$$SO(5)/SO(4) \longrightarrow A_\mu^{\hat{a}}(-,-) \quad A_5^{\hat{a}}(+,+)$$

Identify with H

No tree-level Higgs potential $\longrightarrow$ induced at one-loop (calculable)

The fermion sector is more model dependent. Built out of

$$5 \sim (2,2) \oplus 1 \;\; \text{and} \;\; 10 \sim (2,2) \oplus (3,1) \oplus (1,3)$$

Since Yukawa's $\longleftrightarrow$ gauge coupling: flavour from IR localized mass terms

$$\mathcal{L}_m = \delta(y-L)\left[\bar{u}'_L \tilde{M}_u u_R + \bar{Q}_{1L} M_u Q_{2R} + \bar{Q}_{1L} M_d Q_{3R} + \text{h.c.}\right]$$

Other parameters relevant the for EW fit: $\longrightarrow$ c_L, c_R localization of $1^{st}, 2^{nd}$ gen.
c_1, c_2, c_3 localization of 3^{rd} gen.

The Higgs Potential

Falkowski
Medina, Shah and Wagner

Coleman-Weinberg potential:

$$V(h) = \sum_r \pm \frac{N_r}{(4\pi)^2} \int_0^\infty dp\, p^3 \log \rho(-p^2)$$

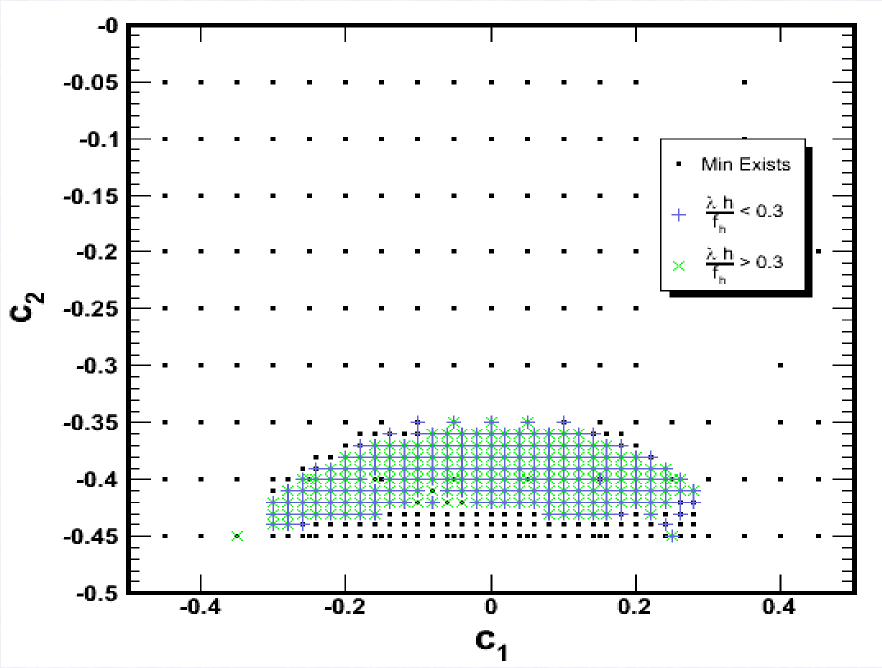
Quartic from top spectral function:

Higgs is NGB

$$\rho_t(z^2) = 1 + F_{t1}(z^2) \sin^2\left(\frac{h}{\sqrt{2} f_h}\right) + F_{t2}(z^2) \sin^4\left(\frac{h}{\sqrt{2} f_h}\right)$$

$f_h \propto \tilde{k}/\sqrt{kL}$

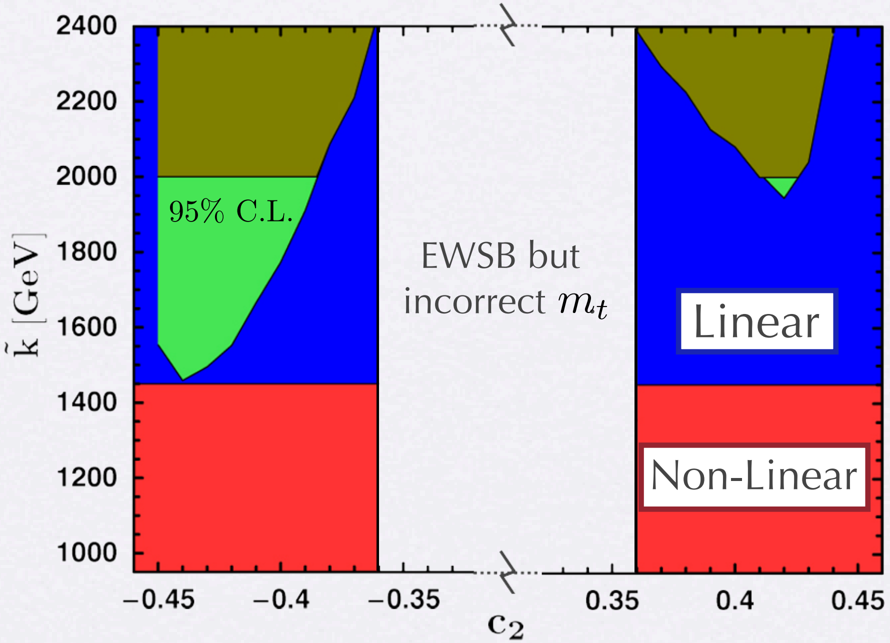
- Correct EWSB pattern (i.e. $m_Z\,, m_W$) for any $c_1\,, c_2$
- Correct top (and bottom) masses for either:
  - t_R mostly composite $(c_2 \sim 0.4)$
  - t_R mostly fundamental $(c_2 \sim -0.4)$
- t_L cannot be very flat $(|c_1| \leq 0.3)$



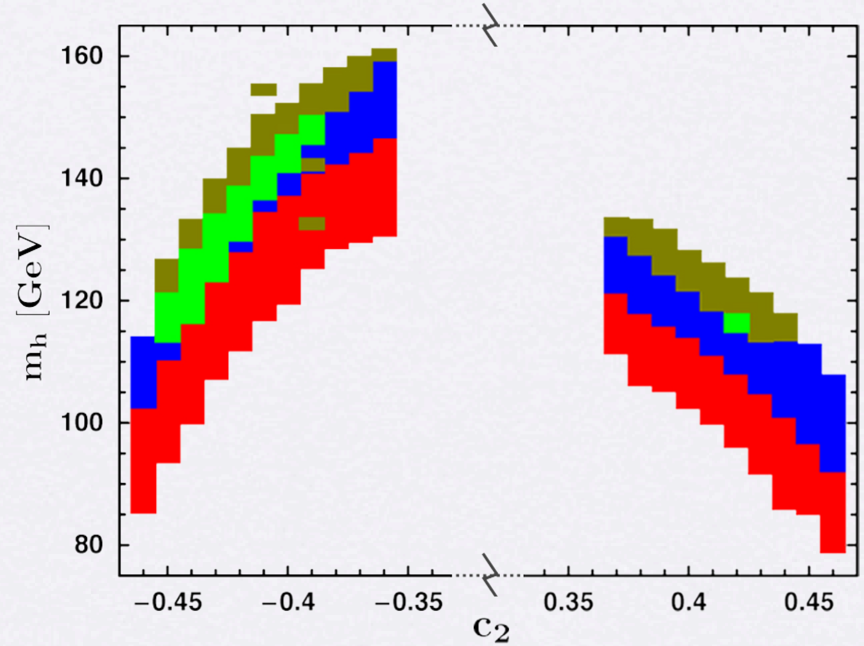
EW constraints on Gauge-Higgs scenario

(E.P. and Santiago)

- Restric to "linear" regime: $\frac{h}{\sqrt{2}f_h} \approx \sin\left(\frac{h}{\sqrt{2}f_h}\right) < 0.3$
- Consider "oblique region" with light fermions far from IR brane (fit unlikely to improve significantly in other regions)
- Green region: EWSB, linear approx holds, correct m_t, m_b, m_h above LEP bound, and $\tilde{k} < 2$ TeV $(M_{\rm KK}^{\rm gauge} < 5$ TeV$)$



t_R ~ "fundamental" **composite**

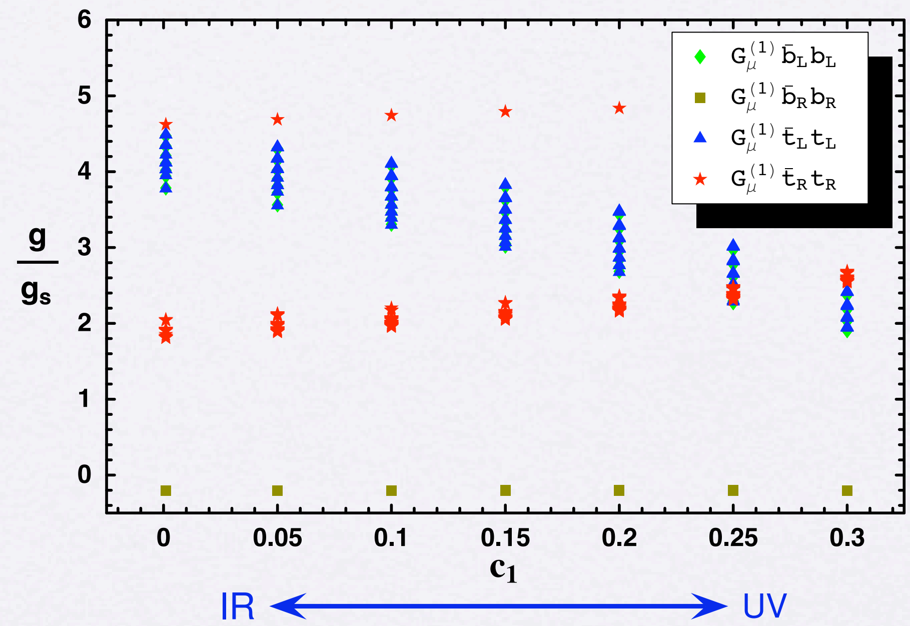


Some properties of fermionic states

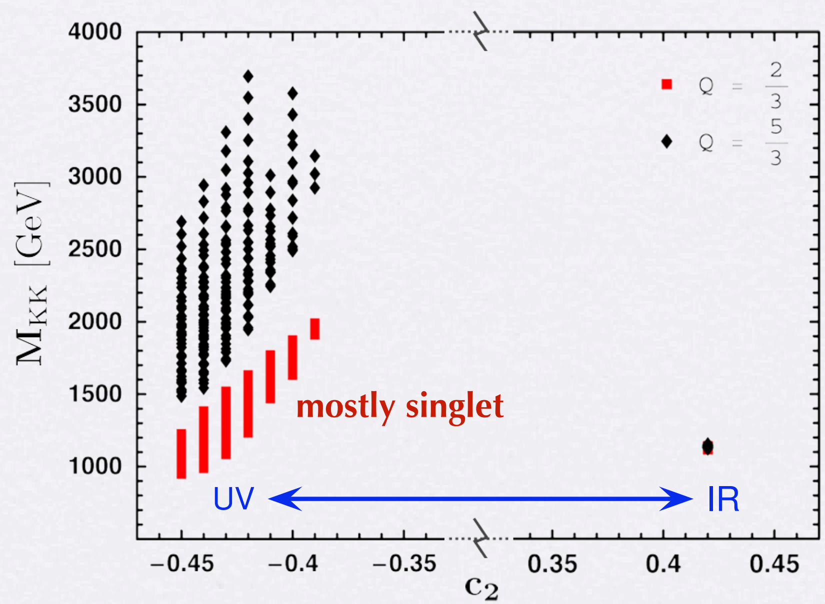
All points obey conditions of green region in previous two figures

Couplings to KK gluons of LH (t,b) comparable to those of RH top

Couplings of G'_μ to 3^{rd} gen. in units of g_s



Lightest KK fermion states



- Light vector-like SM singlets (that can give T > 0)
- Exotic states can be light if they do not violate custodial symmetry (naturally present in gauge-Higgs scenarios)

$\longrightarrow$ degenerate vector-like fermions

Conclusions

- Possible to build fully realistic RS scenarios, that
  - pass EW constraints
  - have gauge boson KK resonances likely accessible at the LHC
  - require KK fermion resonances lighter than gauge KK modes
  - dynamical EW symmetry breaking
- Calculability at loop level can constraint the parameter space and suggest interesting consequences for the collider phenomenology:
  - Couplings of (t_L, b_L) to new physics need not be suppressed compared to those of t_R.
  - Lightest states likely to have a large singlet component
  - Lightest bidoublet KK fermion states likely to be fairly degenerate
  - Expect non-trivial decay chains of KK gluons

Details of fermion sector

The fermion sector is more model dependent. Built out of

$$5 \sim (2,2) \oplus 1 \quad \text{and} \quad 10 \sim (2,2) \oplus (3,1) \oplus (1,3)$$

In gauge-Higgs unification scenarios Yukawa's arise from gauge coupl.

Flavour structure from mixing via IR localized mass terms

$$\xi^i_{1L} \sim Q^i_{1L} = \begin{pmatrix} \chi^{u_i}_{1L}(-,+) & q^{u_i}_{L}(+,+) \\ \chi^{d_i}_{1L}(-,+) & q^{d_i}_{L}(+,+) \end{pmatrix} \oplus u'^i_L(-,+) \,,$$

$$\xi^i_{2R} \sim Q^i_{2R} = \begin{pmatrix} \chi^{u_i}_{2R}(-,+) & q'^{u_i}_{R}(-,+) \\ \chi^{d_i}_{2R}(-,+) & q'^{d_i}_{R}(-,+) \end{pmatrix} \oplus u^i_R(+,+) \,,$$

$$\xi^i_{3R} \sim T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+) \\ U'^i_R(-,+) \\ D'^i_R(-,+) \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+) \\ U''^i_R(-,+) \\ D^i_R(+,+) \end{pmatrix} \oplus Q^i_{3R} = \begin{pmatrix} \chi^{u_i}_{3R}(-,+) & q''^{u_i}_{R}(-,+) \\ \chi^{d_i}_{3R}(-,+) & q''^{d_i}_{R}(-,+) \end{pmatrix}$$

$$\mathcal{L}_m = \delta(y-L)\left[\bar{u}'_L \tilde{M}_u u_R + \bar{Q}_{1L} M_u Q_{2R} + \bar{Q}_{1L} M_d Q_{3R} + \text{h.c.}\right]$$

Other parameters relevant the for EW fit: $\longrightarrow$

c_L, c_R localization of $1^{st}, 2^{nd}$ gen.

c_1, c_2, c_3 localization of 3^{rd} gen.

Observables used in global fit

(bottom treated independently)

(Han,Skiba)

	Standard Notation	Measurement	Reference
Atomic parity violation	$Q_W(Cs)$	Weak charge in Cs	[21]
	$Q_W(Tl)$	Weak charge in Tl	[22]
DIS	g_L^2, g_R^2	ν_μ-nucleon scattering from NuTeV	[23]
	R^ν	ν_μ-nucleon scattering from CDHS and CHARM	[24, 25]
	κ	ν_μ-nucleon scattering from CCFR	[26]
	$g_V^{\nu e}, g_A^{\nu e}$	ν-e scattering from CHARM II	[27]
Z-pole	Γ_Z	Total Z width	[20]
	σ_h^0	e^+e^- hadronic cross section at Z pole	[20]
	$R_f^0(f = e, \mu, \tau, b, c)$	Ratios of decay rates	[20]
	$A_{FB}^{0,f}(f = e, \mu, \tau, b, c)$	Forward-backward asymmetries	[20]
	$\sin^2\theta_{eff}^{lept}(Q_{FB})$	Hadronic charge asymmetry	[20]
	$A_f(f = e, \mu, \tau, b, c)$	Polarized asymmetries	[20]
Fermion pair production at LEP2	$\sigma_f(f = q, \mu, \tau)$	Total cross sections for $e^+e^- \to f\overline{f}$	[20]
	$A_{FB}^f(f = \mu, \tau)$	Forward-backward asymmetries for $e^+e^- \to f\overline{f}$	[20]
	$d\sigma_e/d\cos\theta$	Differential cross section for $e^+e^- \to e^+e^-$	[28]
W pair	$d\sigma_W/d\cos\theta$	Differential cross section for $e^+e^- \to W^+W^-$	[29]
	M_W	W mass	[20, 30]

TABLE I: Relevant measurements