Flavors in DEWSB

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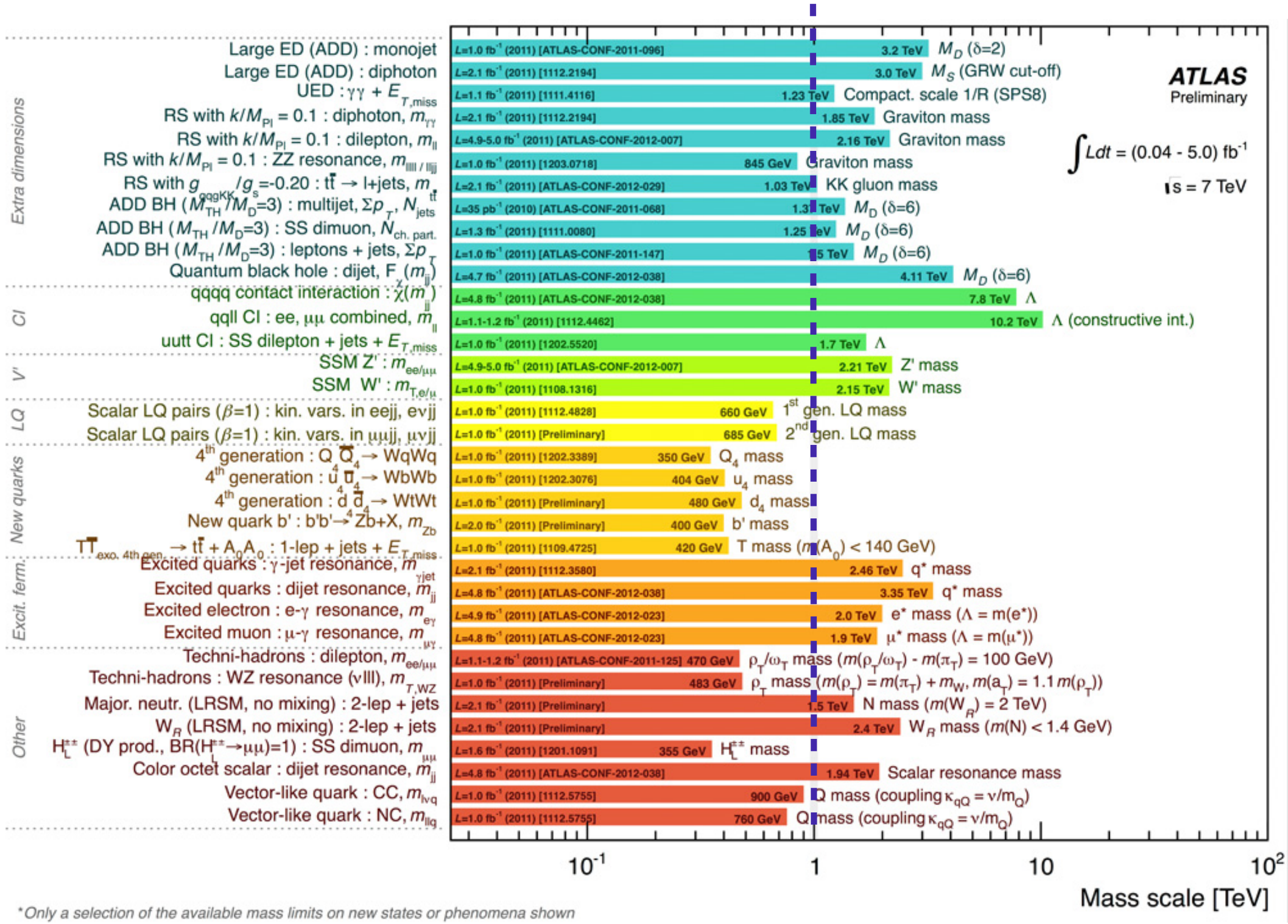
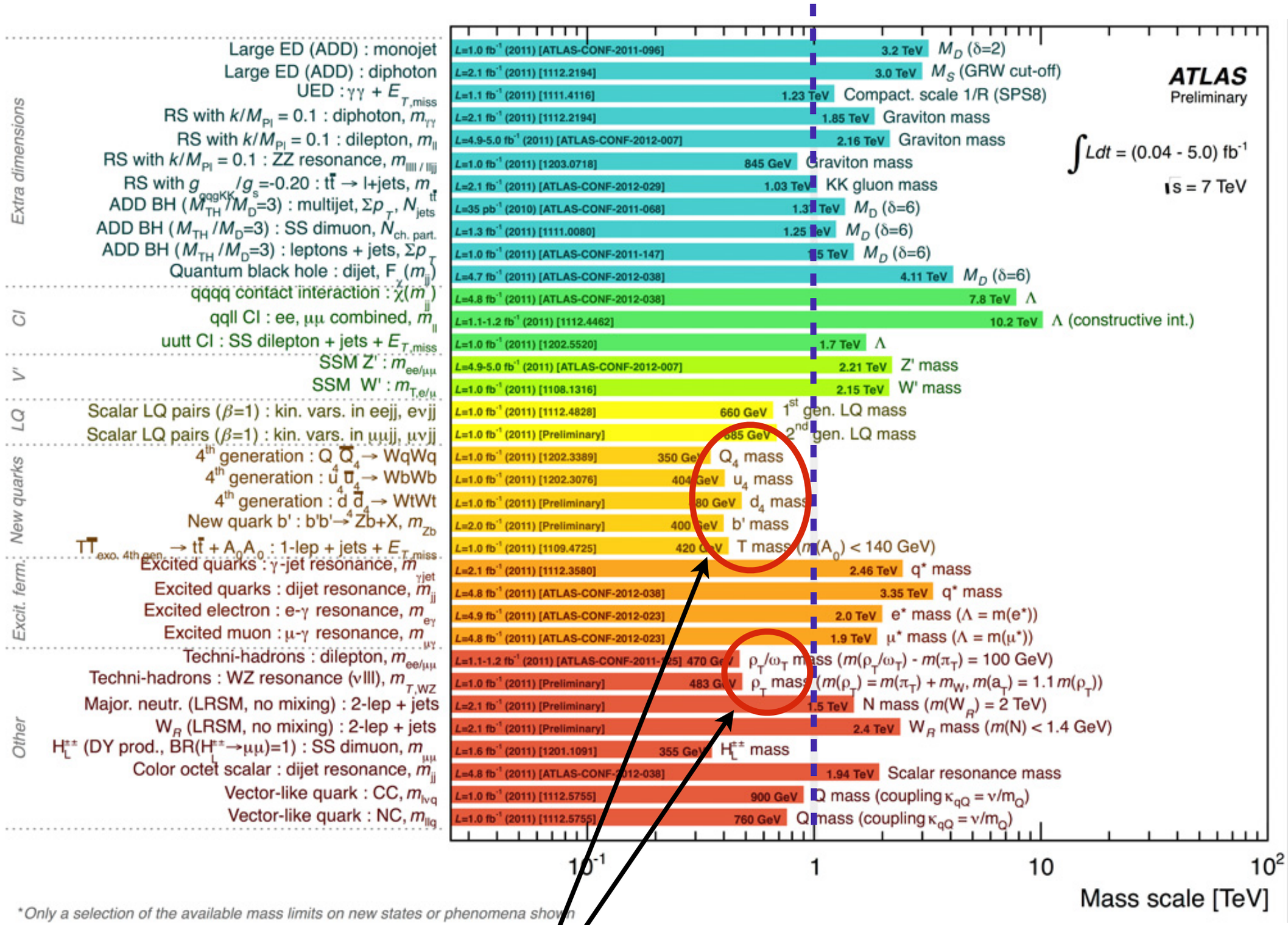
New physics around 1 TeV scale?



*Only a selection of the available mass limits on new states or phenomena shown

New physics around 1 TeV scale?

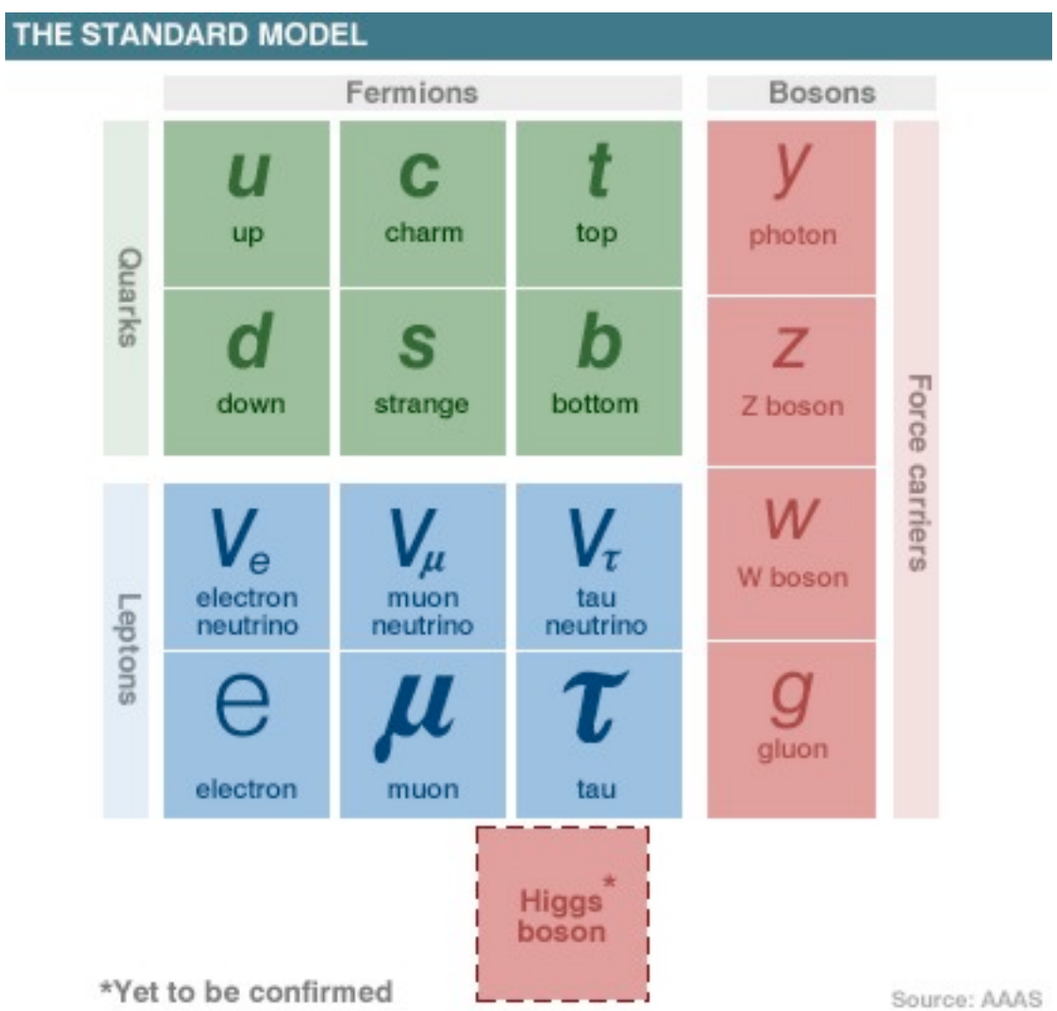


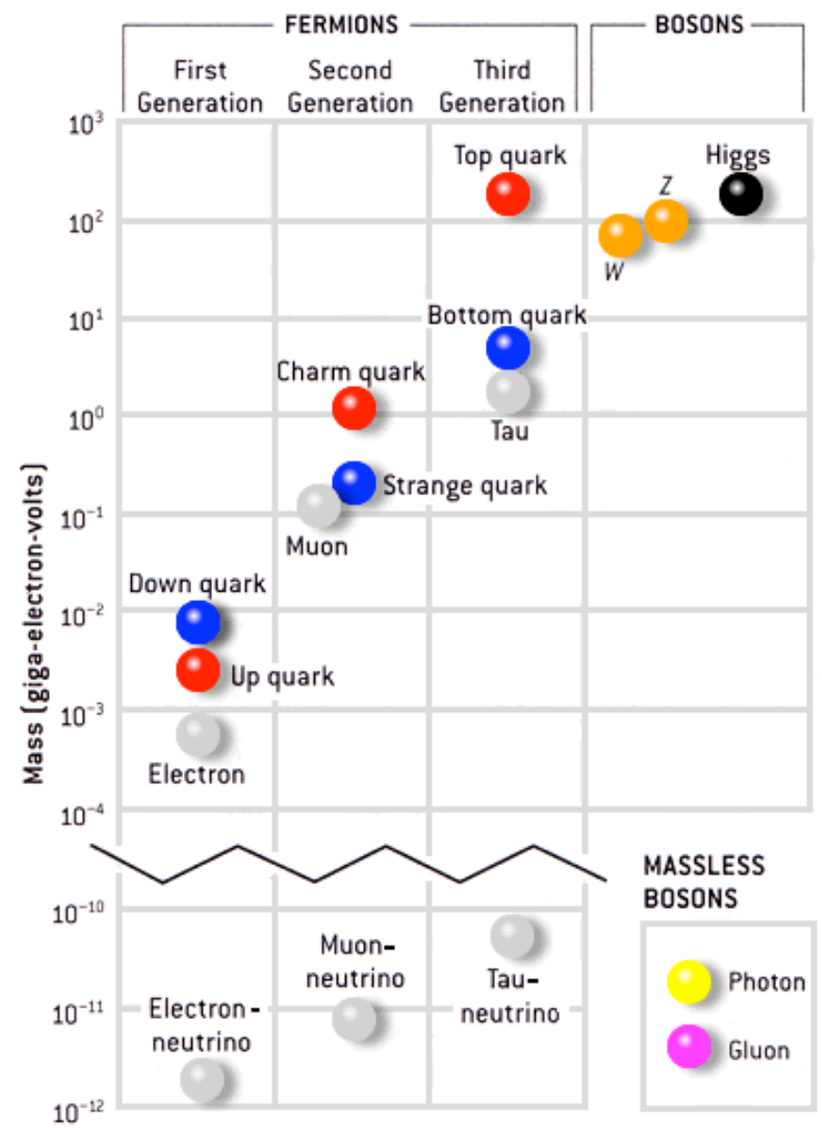
Paradigm choice: Technicolor

Two aspects of flavor:

1. Adding matter fields to SM

2. Generating fermion masses





Weinberg '79,
Susskind '79

Vintage Technicolor: replicate QCD

$SU(3)_{\rm TC} \times SU(3)_c \times SU(2)_L \times U(1)_Y$

$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \to \mathrm{SU}(2)_V$ $\qquad \langle \bar{Q}_L Q_R \rangle = \Lambda_{\rm TC}^3, \quad \Lambda_{\rm TC} \simeq 1 \text{ TeV}$

No hierarchy problem

SSB+gauge symm. $\qquad$ Higgs mechanism

$\pi^\pm, \pi^0 \to W_L^\pm, Z_L \qquad M_W = \dfrac{g F_{\rm TC}}{2}, \qquad F_{\rm TC} \simeq 250\,\text{GeV}$

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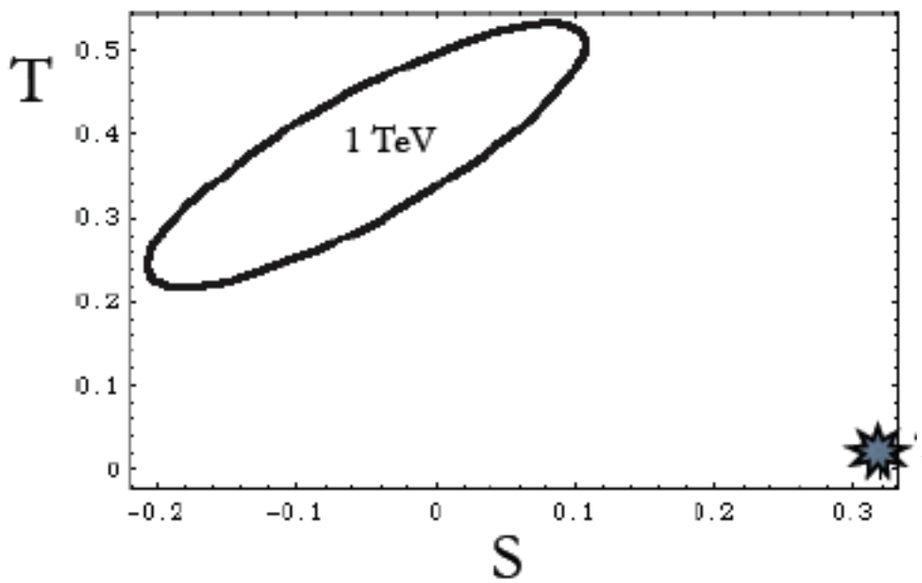
Analogous to superconductivity:

SM is the effective Ginzburg-Landau theory

Technicolor is the microscopic BCS theory

We simply have not
yet broken the
Cooper pairs!

Vintage TC is dead



The showstopper: S-parameter

(Peskin, Takeuchi '90)

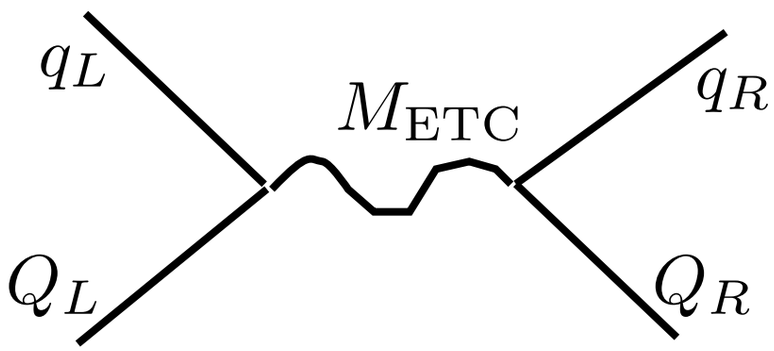
$N_f = 2 \quad \mathrm{SU}(3)$

fundamental rep. technifermions

Suggests non QCD-like dynamics instead

Also fermion masses are problematic...

Traditional approach: Extended TC (ETC)



$$\to \frac{g_{\rm ETC}^2}{M_{\rm ETC}^2}(\bar{q}_L Q_R)(\bar{Q}_L q_R) \to m_q \approx \frac{g_{\rm ETC}^2}{M_{\rm ETC}^2}\langle \bar{Q}Q\rangle_{\rm ETC}$$

$$\langle \bar{U}U\rangle_{\rm ETC} = \langle \bar{U}U\rangle_{\rm TC} \exp\left(\int_{\Lambda_{\rm TC}}^{\Lambda_{\rm ETC}} \frac{d\mu}{\mu}\gamma_m(\mu)\right)$$

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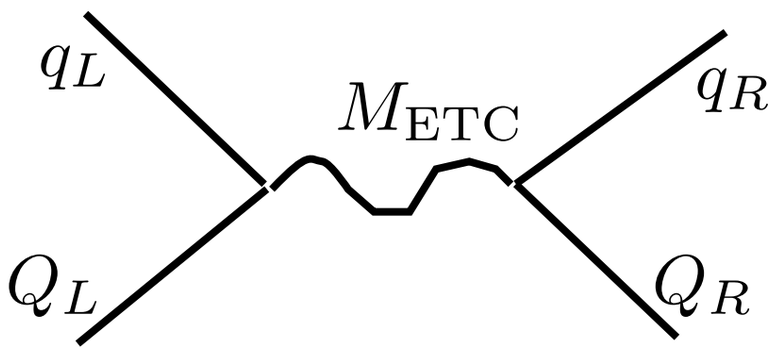

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$$\beta(g) \simeq 0, \quad \gamma_m \simeq 1$$

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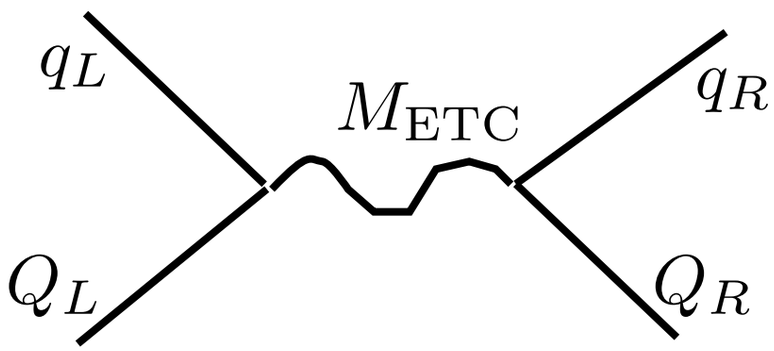

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$$\beta(g) \simeq 0, \quad \gamma_m \simeq 1$$

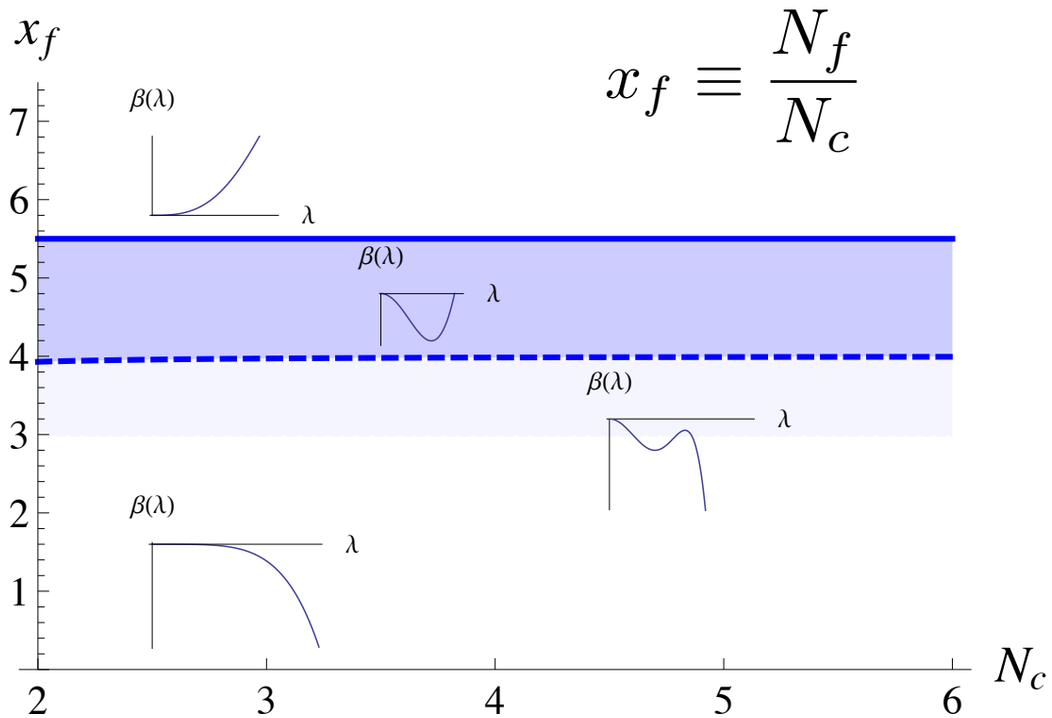
Again, non QCD-like dynamics needed,

<u>Walking Technicolor</u>

(Holdom, Yamawaki et al, Appelquist & Wijewardhana)

How to arrange $\beta(g) \simeq 0$?

Study gauge theory vacuum phase diagrams:



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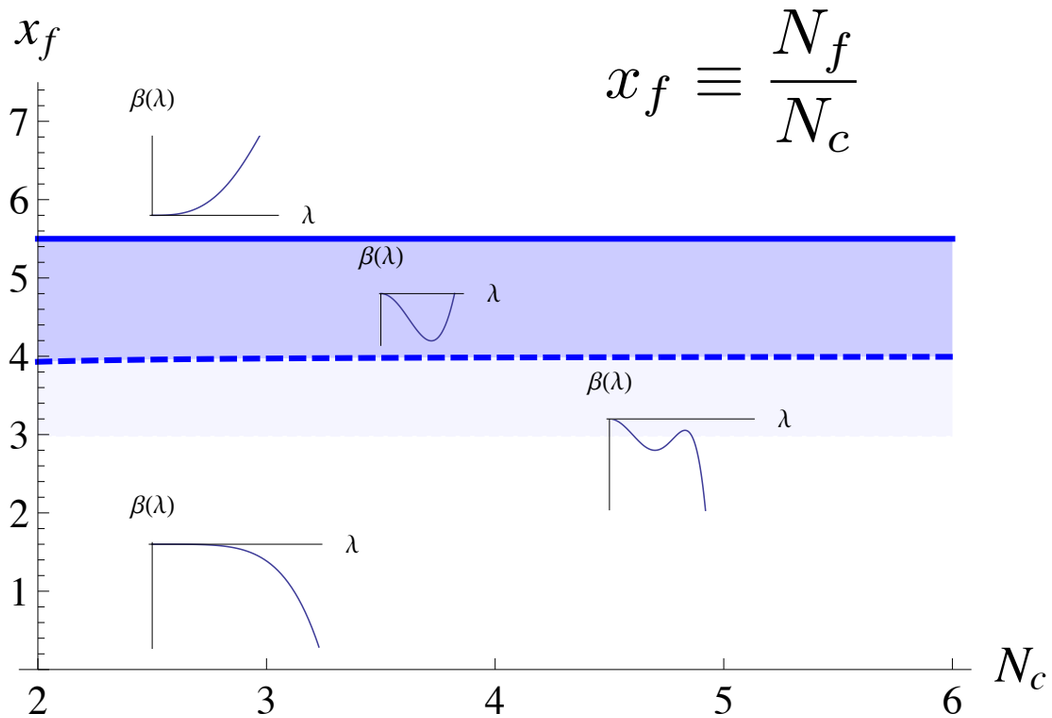
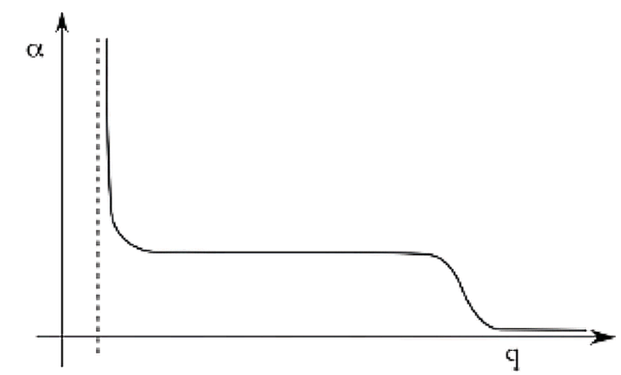


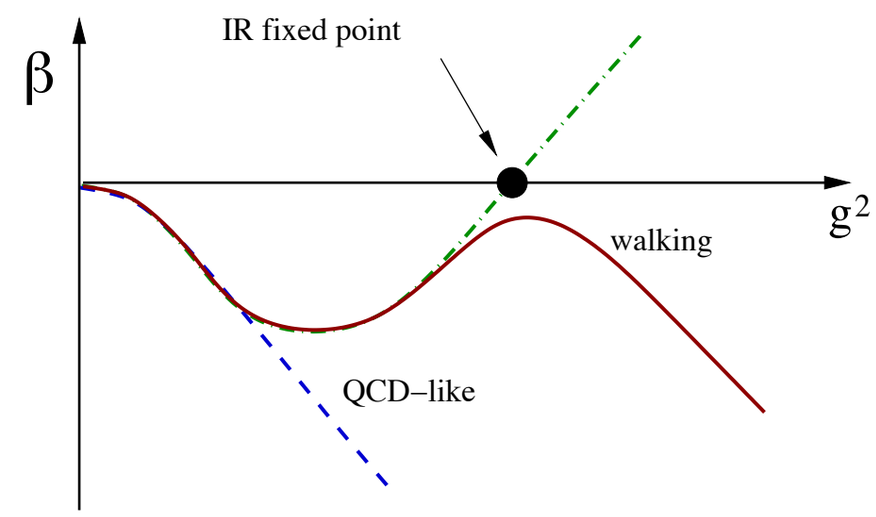
$$x_f \equiv \frac{N_f}{N_c}$$



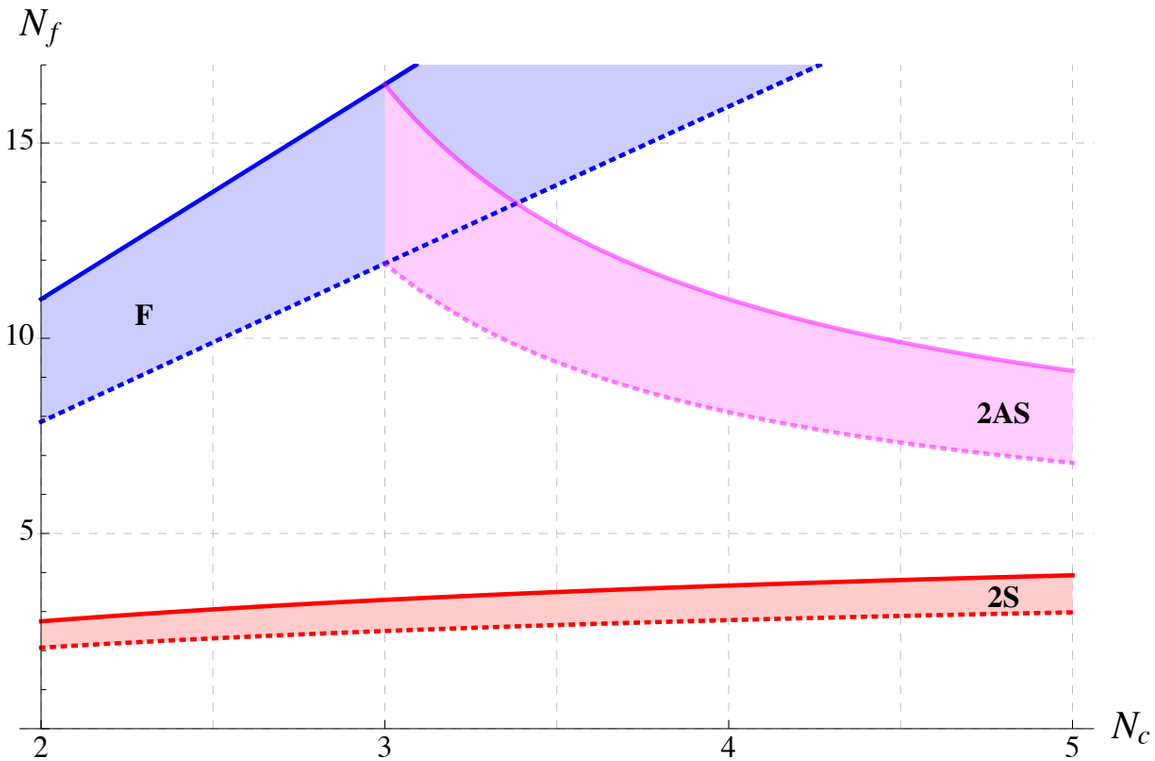
Fixed point from 2-loop betaf. $\alpha^* = -\frac{\beta_0}{\beta_1}$

Critical coupling for chiral breaking from SD-equ. $\alpha_c = \frac{\pi}{3C_2(R)}$

Conformal window: $\alpha^* \leq \alpha_c$



Higher reps. (Sannino, Tuominen '04)



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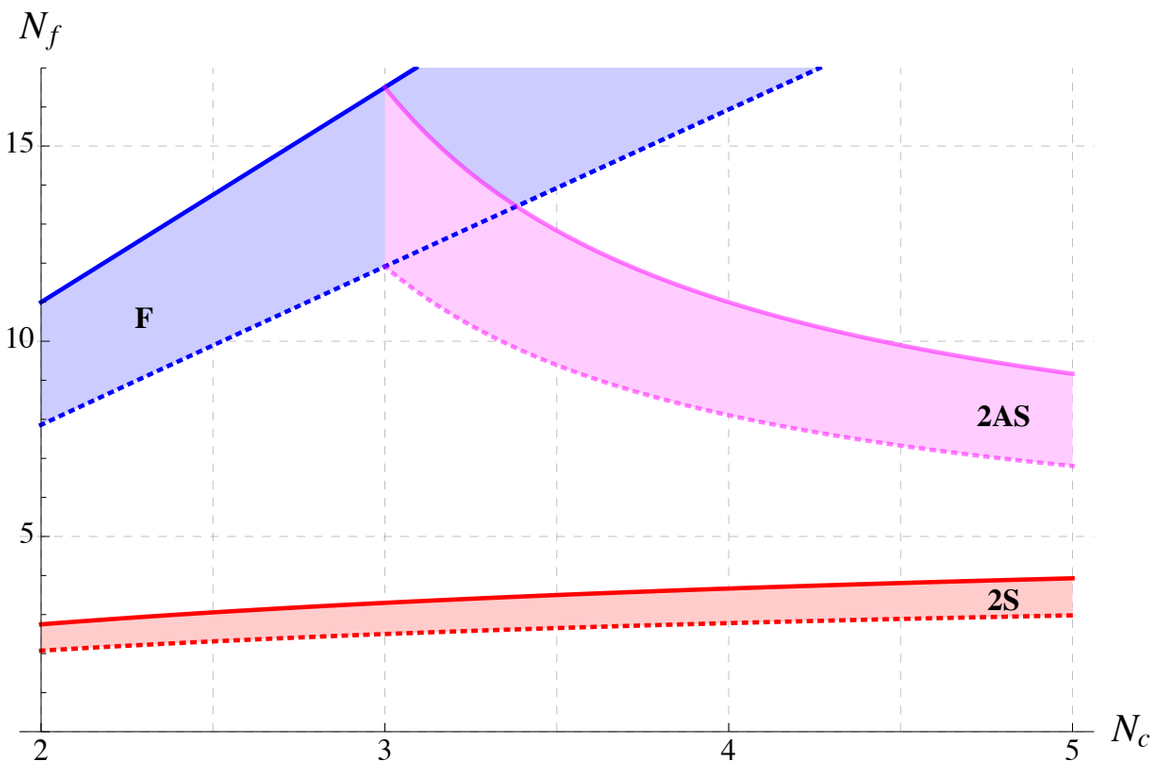
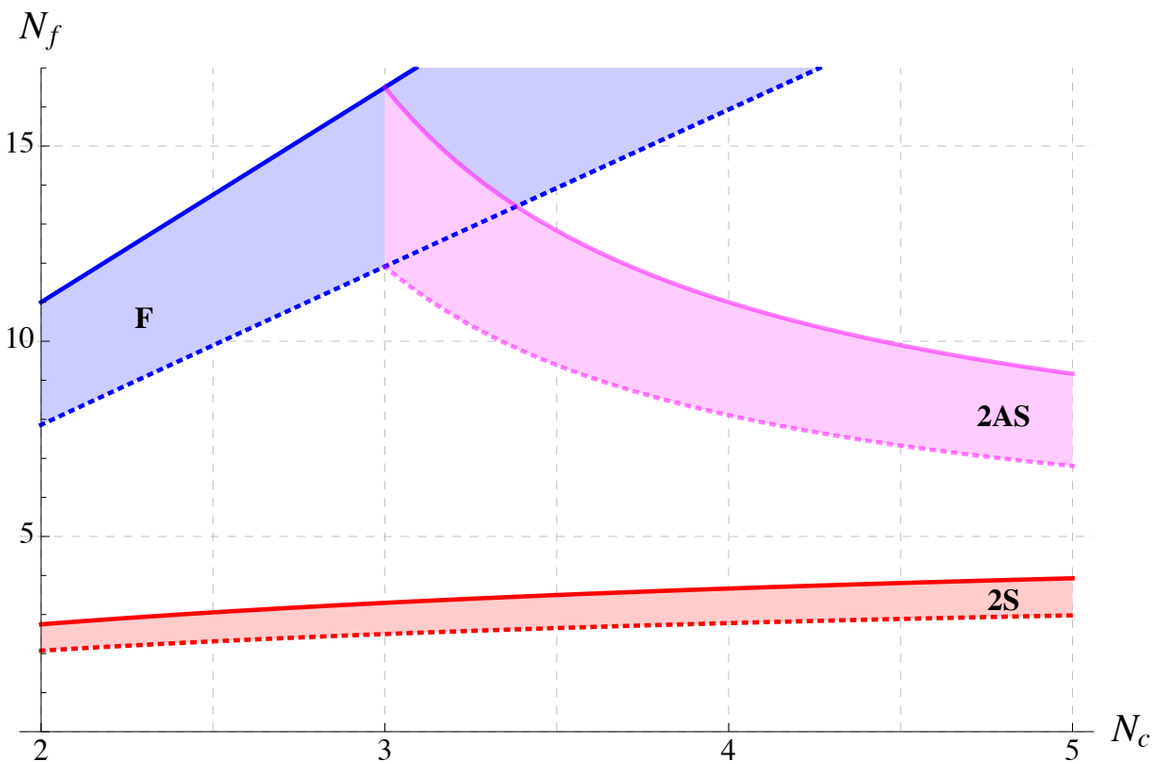


- Study on the lattice

Lots of efforts during last 4...5 years.

SU(2) adjoint:
(Catteral et al., Hietanen et al., Del Debbio et al.,...)
SU(2) fundamental: (Del Debbio et al., Karavirta et al.
SU(3) fundamental:
(Appelquist et al., Kuti et al.,...)
SU(3) sextet: (De Grand et al.,...)

Higher reps. (Sannino, Tuominen '04)



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SU(3) fundamental:
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SU(3) sextet: (De Grand et al.,...)

SU(2) + 2 adjoint flavors:
Minimal walking Technicolor (MWT)

-Walking with less flavors:
phenomenologically viable
Technicolor models

SU(3)+2 sextet flavors: NMWT

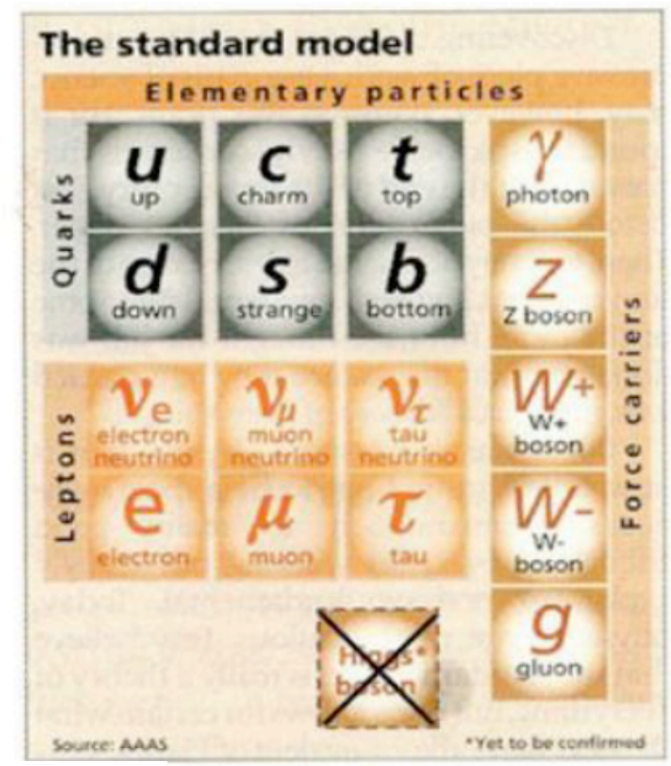
Minimal walking Technicolor

One weak doublet in 3 of SU(2): Witten anomaly.

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \qquad U_R^a , \quad D_R^a , \qquad a = 1, 2, 3$$

Cure by introducing one doublet of TC/QCD singlet fermions

$$L_L = \begin{pmatrix} N \\ E \end{pmatrix}_L , \qquad N_R , \; E_R$$



U(1)

SU(2)

SU(3)

SU(2)

N Extra Neutrino

E Extra Electron

U t-up

D t-down

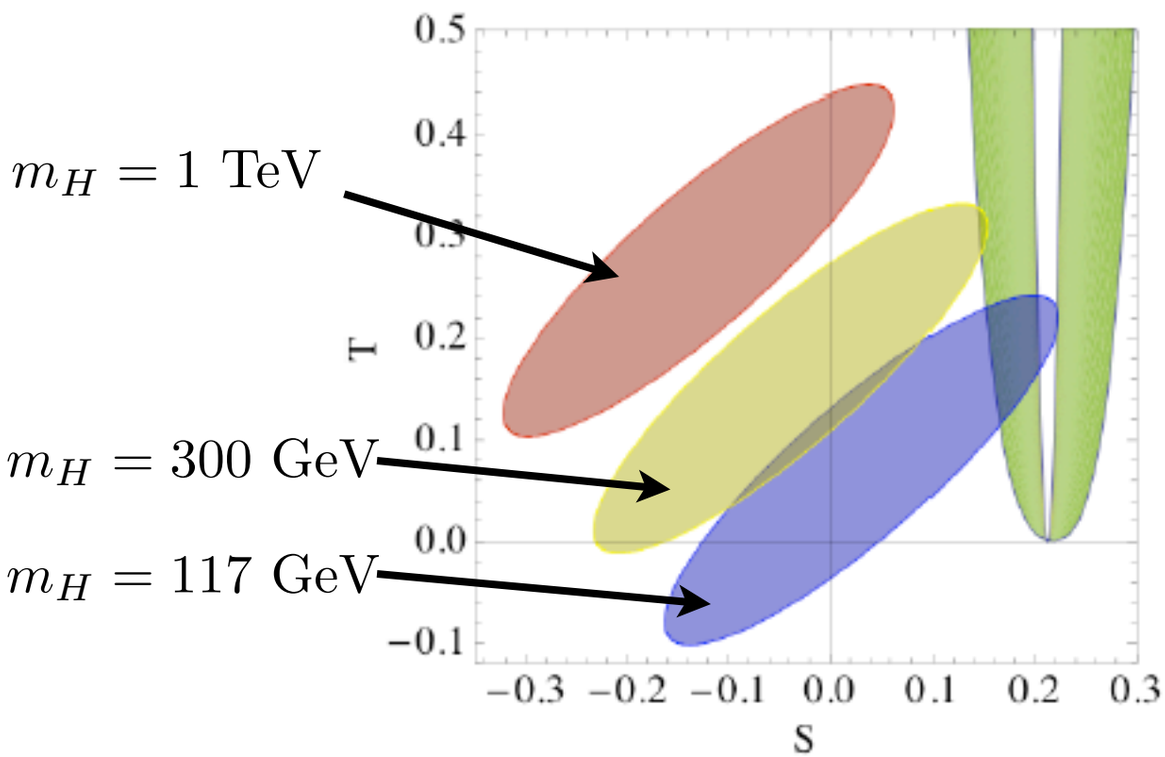
G t-glue

$$Y(Q_L) = \frac{y}{2} , \qquad Y(U_R, D_R) = \left(\frac{y+1}{2}, \frac{y-1}{2} \right) ,$$

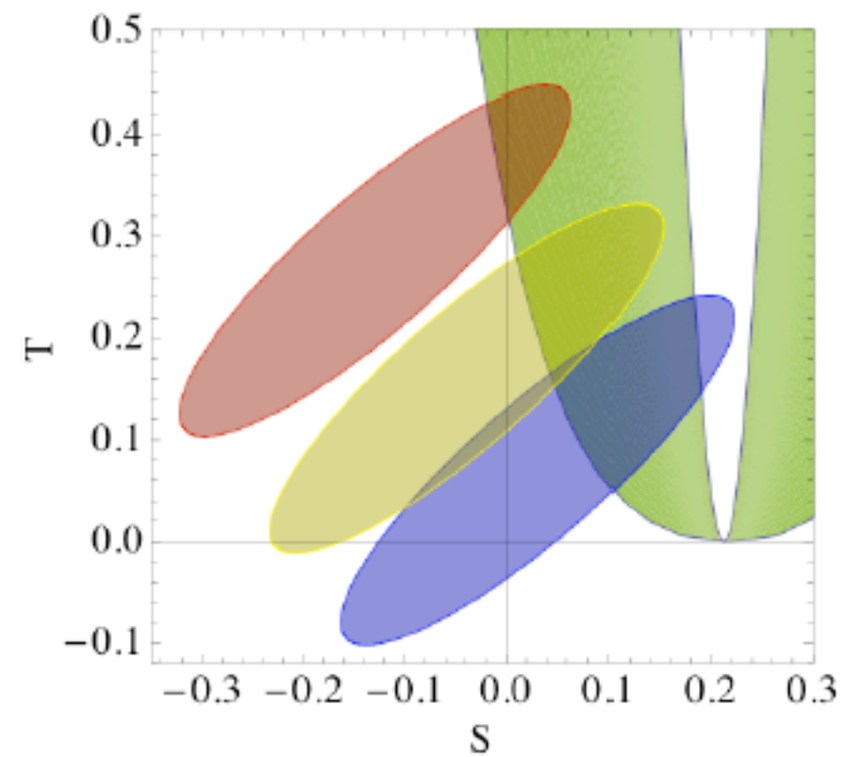
$$Y(L_L) = -3\frac{y}{2} , \qquad Y(N_R, E_R) = \left(\frac{-3y+1}{2}, \frac{-3y-1}{2} \right)$$

Precision data:

$$
\begin{aligned}
S &= -16\pi \Pi'_{3Y}(0), \\
T &= \frac{4\pi}{s_w^2 c_w^2 M_Z^2}(\Pi_{11}(0) - \Pi_{33}(0))
\end{aligned}
$$



$y = 1/3$



$y = 1$

From Technicolor: $S = \dfrac{N_f d(R)}{6\pi}, \quad T = 0$

What about fermion masses?

Traditional ETC

very ambitious: explain hierarchies between generations with a UV complete theory.

Bosonic TC

Add a new scalar: SM-like Yukawa patterns.

TopColor, Top-seesaw,

Dynamical, but more modest: explain top and bottom masses.

Build a bosonic TC model starting with NMWT (SU(3) gauge + 2 fermions in the sextet rep.)

(M. Antola et al. '09)

$$SU(3)_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \qquad U_R^a , \quad D_R^a , \qquad a = 1...6, \qquad Y(U_L) = Y(D_L) = 0, Y(U_R) = \frac{1}{2}, Y(D_R) = -\frac{1}{2}.$$

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$$\mathcal{L}_{TC} = \frac{1}{2}\mathrm{Tr}\left[DM^\dagger DM\right] + \frac{1}{2}m_M^2\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda_M}{4!}\mathrm{Tr}\left[M^\dagger M\right]^2$$

$$M = \frac{1}{\sqrt{2}}\left(sI_{2\times 2} + 2i\pi_M\right) \propto Q_L\bar{Q}_R, \qquad \langle s\rangle \equiv f,$$

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+

$$\mathcal{L}_{\mathrm{Higgs}} = \frac{1}{2}\mathrm{Tr}\left[DH^\dagger DH\right] - V_H,\ V_H = \frac{1}{2}m_H^2\mathrm{Tr}\left[H^\dagger H\right] + \frac{\lambda_H}{4!}\mathrm{Tr}\left[H^\dagger H\right]^2$$

$$H = \frac{1}{\sqrt{2}}\left(hI_{2x2} + 2i\pi_H\right), \quad \langle h\rangle \equiv v.$$

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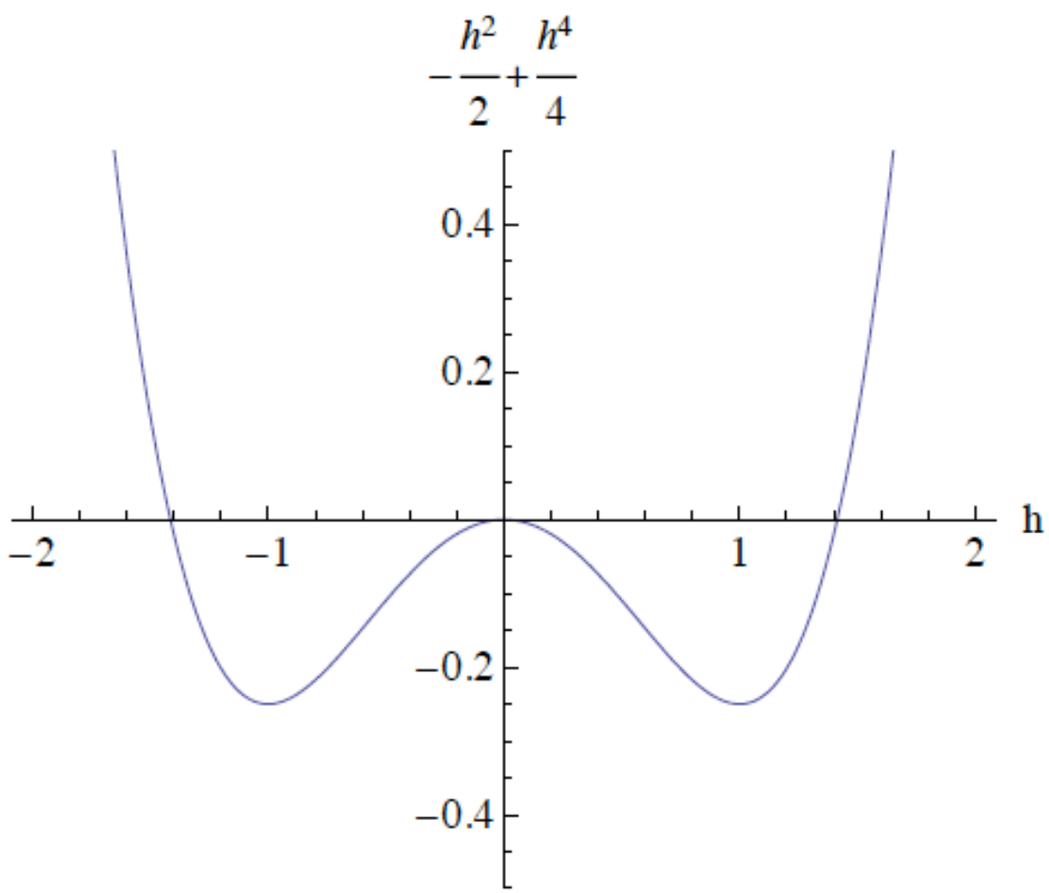
+

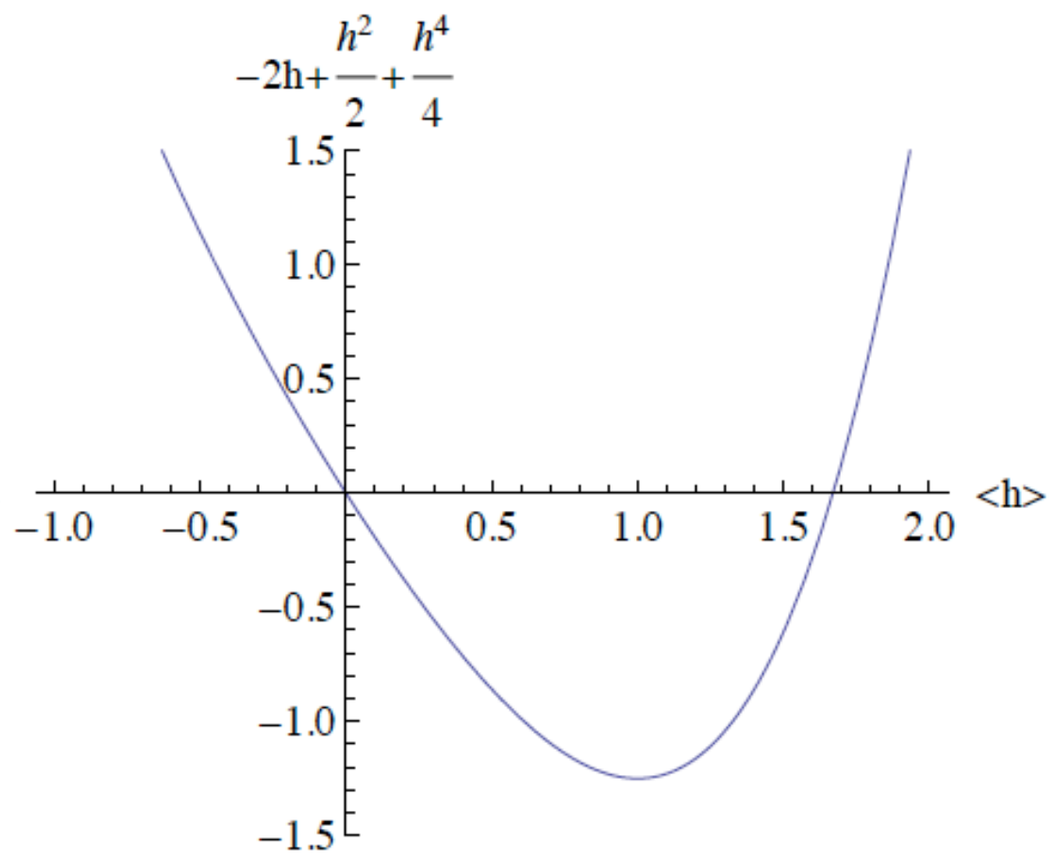
$$\mathcal{L}_{\mathrm{Yukawa}} \sim -\bar{Q}_L H Y_Q Q_R$$

$$\mathcal{L}_{BTC} = \mathcal{L}_{SM}\Big|_{Higgs=0} + \mathcal{L}_{TC} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

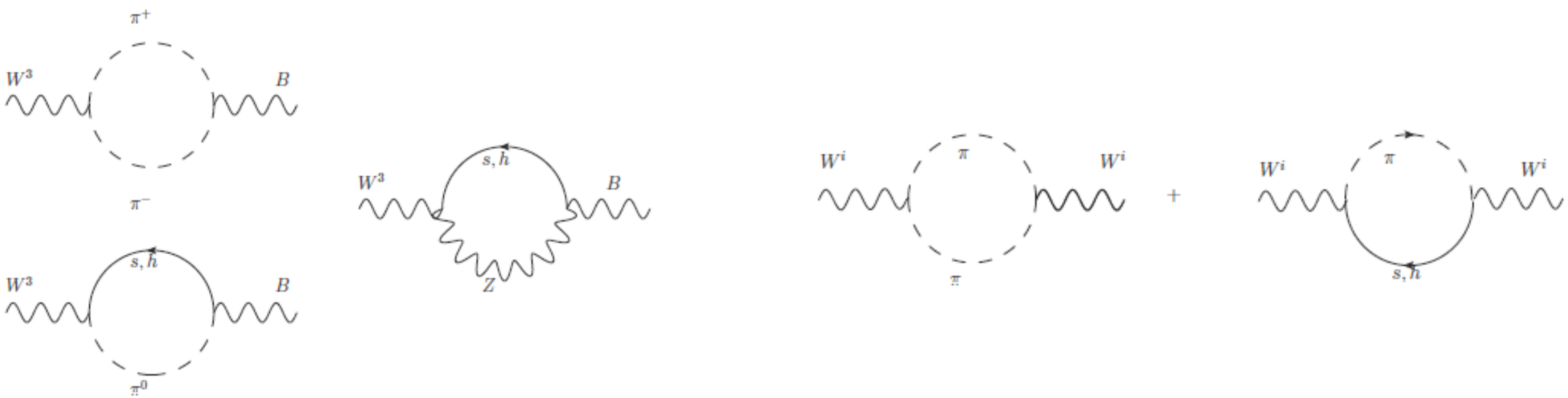
$$y_Q \bar{Q} H Q$$

$$V = -m_M^2 s^2 + \lambda_M s^4 + c_1 y_Q s h + m_H^2 h^2 + \lambda h^4.$$

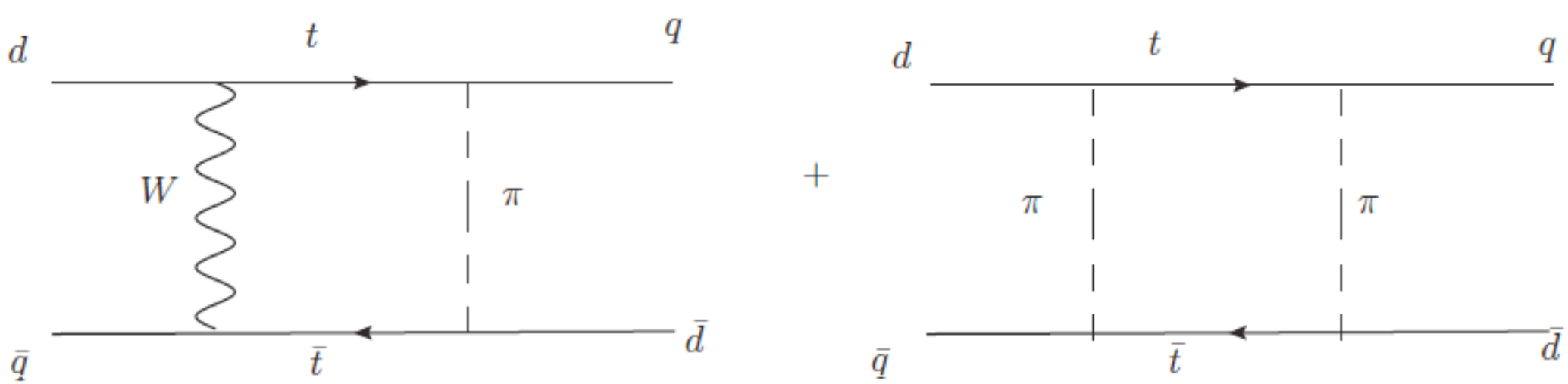




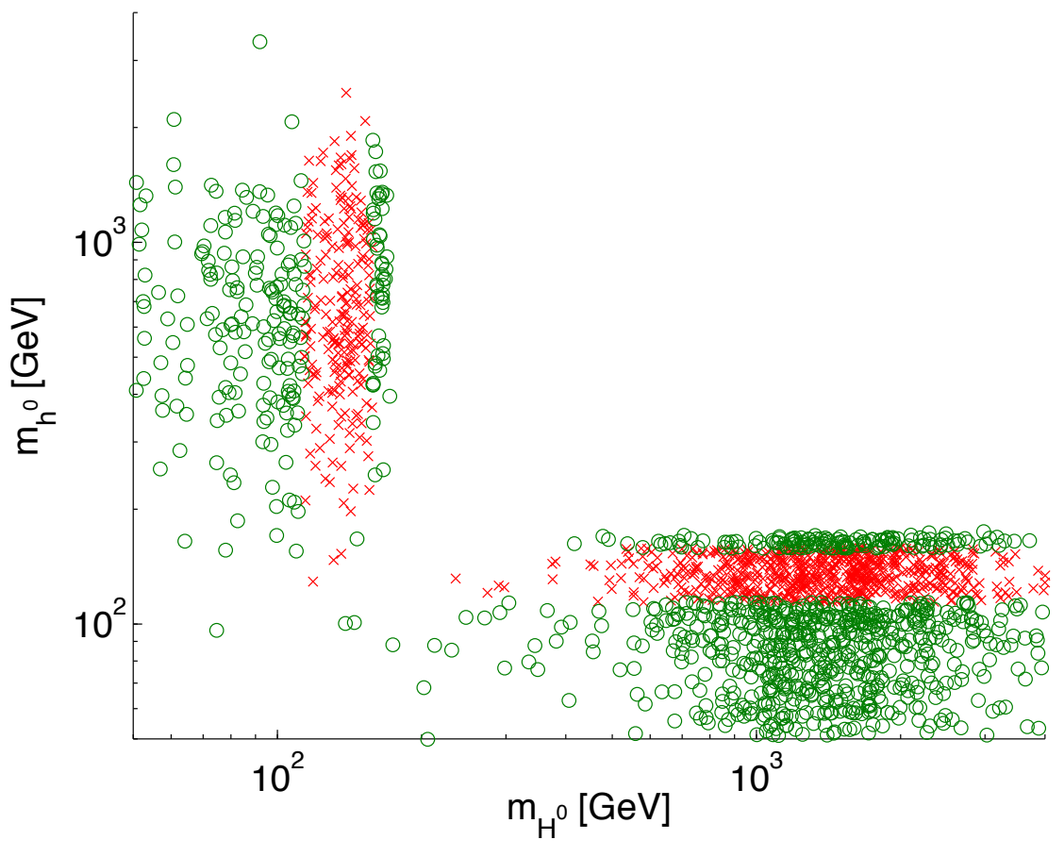
S and T...



FCNC interactions...



Main conclusion: the model is viable. Favored parameter space with one scalar heavy and the other light.



Also: additional contributions to FCNC's from Technivectors

(Fukano et. al)

Of course, a (fundamental) scalar is
unnatural. Naturalize with SUSY-TC.

Interesting recent model building addressing:

1) solution of the little hierarchy problem
2) providing a large top Yukawa

(M. Antola et al. 1001.2040, 1009.1624, 1111.1009, also Luty et al.)

Clearly, top is special.

Topcolor,
TC assisted Topcolor,

The challenge is to explain b-t splitting, and avoid large contributions to T-parameter

Top seesaw accomplishes this, but runs into trouble with R_b

Technicolor assisted top-seesaw

(Fukano, Tuominen '12)

MWT

field	$SU(2)_{TC}$	$SU(3)_1$	$SU(3)_2$	$SU(2)_L$	$U(1)_{Y1}$	$U(1)_{Y2}$
$\mathcal{Q}_L$	$\square\square$	1	1	2	0	1/6
$\mathcal{T}_R$	$\square\square$	1	1	1	0	2/3
$\mathcal{B}_R$	$\square\square$	1	1	1	0	-1/3
$L_L^{(4)}$	1	1	1	2	0	-1/2
$N_R^{(4)}$	1	1	1	1	0	0
$E_R^{(4)}$	1	1	1	1	0	-1
$Q_L^{(3)}$	1	3	1	2	1/6	0
$U_R^{(3)}$	1	1	3	1	0	2/3
$D_R^{(3)}$	1	1	3	1	0	-1/3
$L_L^{(3)}$	1	1	1	2	-1/2	0
$N_R^{(3)}$	1	1	1	1	0	0
$E_R^{(3)}$	1	1	1	1	-1	0
$U_L^{(4)}$	1	1	3	1	0	2/3
$U_R^{(4)}$	1	3	1	1	2/3	0
$D_L^{(4)}$	1	1	3	1	0	-1/3
$D_R^{(4)}$	1	3	1	1	-1/3	0
$Q^{(1,2)}$	1	1	3	SM	0	SM
$L^{(1,2)}$	1	1	1	SM	0	SM

$$SU(2)_{\rm TC} \times SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_1 \times U(1)_2$$

$$\downarrow$$

$$SU(2)_{\rm TC} \times SU(3)_{\rm QCD} \times SU(2)_L \times U(1)_Y$$

Technicolor assisted top-seesaw

(Fukano, Tuominen '12)

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$\mathcal{Q}_L$	$\square\square$	1	1	2	0	1/6
$\mathcal{T}_R$	$\square\square$	1	1	1	0	2/3
$\mathcal{B}_R$	$\square\square$	1	1	1	0	-1/3
$L_L^{(4)}$	1	1	1	2	0	-1/2
$N_R^{(4)}$	1	1	1	1	0	0
$E_R^{(4)}$	1	1	1	1	0	-1
$Q_L^{(3)}$	1	3	1	2	1/6	0
$U_R^{(3)}$	1	1	3	1	0	2/3
$D_R^{(3)}$	1	1	3	1	0	-1/3
$L_L^{(3)}$	1	1	1	2	-1/2	0
$N_R^{(3)}$	1	1	1	1	0	0
$E_R^{(3)}$	1	1	1	1	-1	0
$U_L^{(4)}$	1	1	3	1	0	2/3
$U_R^{(4)}$	1	3	1	1	2/3	0
$D_L^{(4)}$	1	1	3	1	0	-1/3
$D_R^{(4)}$	1	3	1	1	-1/3	0
$Q^{(1,2)}$	1	1	3	SM	0	SM
$L^{(1,2)}$	1	1	1	SM	0	SM

Weak singlet quarks, mix with the SM top gauge eigenstate:

$$(\bar{U}_L^{(3)}, \bar{U}_L^{(4)}) \begin{pmatrix} 0 & \mu \\ M_U^{(43)} & M_U^{(44)} \end{pmatrix} \begin{pmatrix} U_R^{(3)} \\ U_R^{(4)} \end{pmatrix}$$

$$SU(2)_{\rm TC} \times SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_1 \times U(1)_2$$

$$\downarrow$$

$$SU(2)_{\rm TC} \times SU(3)_{\rm QCD} \times SU(2)_L \times U(1)_Y$$

Λ $SU(2)_{\mathrm{TC}} \times SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_1 \times U(1)_2$

8 massive "colorons", G'
1 massive Z'.

v_{weak} $SU(2)_{\mathrm{TC}} \times SU(3)_{\mathrm{QCD}} \times SU(2)_L \times U(1)_Y$

Λ $\quad SU(2)_{\mathrm{TC}} \times SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_1 \times U(1)_2$

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1 massive Z'.

v_{weak} $\quad SU(2)_{\mathrm{TC}} \times SU(3)_{\mathrm{QCD}} \times SU(2)_L \times U(1)_Y$

$$\Lambda^2 \mathcal{L}^{4f} \sim g_U^{(34)} (\bar{U}_R^{(4)} Q_L^{(3)})^2 + g_D^{(34)} (\bar{D}_R^{(4)} Q_L^{(3)})^2 + g_E^{(33)} (\bar{E}_R^{(3)} L_L^{(3)})^2$$

Λ $\quad SU(2)_{\rm TC} \times SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_1 \times U(1)_2$

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NJL gap-equ:
$g > 1$ for dynamical condensate $\qquad g_U^{(34)}, g_D^{(34)} > 1, g_E^{(33)} < 1$

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NJL gap-equ:
$g > 1$ for dynamical condensate $\qquad g_U^{(34)}, g_D^{(34)} > 1, g_E^{(33)} < 1$

$$\mathcal{L}_{\rm mass} = -M_U^{(43)} \bar{U}_L^{(4)} U_R^{(3)} - M_U^{(44)} \bar{U}_L^{(4)} U_R^{(4)} + \cdots$$

Seesaw: $\quad (\bar{U}_L^{(3)}, \bar{U}_L^{(4)}) \begin{pmatrix} 0 & \mu \\ M_U^{(43)} & M_U^{(44)} \end{pmatrix} \begin{pmatrix} U_R^{(3)} \\ U_R^{(4)} \end{pmatrix}$

$\mathcal{L}^{4f} + \mathcal{L}_{\rm mass}$ has an axial U(1) symmetry.

But this is broken by the $SU(3)_1$ instantons.

$$\Phi_1 \sim \bar{D}_R^{(4)} Q_L^{(3)} \qquad \Phi_2 \sim \bar{U}_R^{(4)} Q_L^{(3)} \qquad + \text{Technicolor sector}$$

A three doublet model. Simplify by decoupling the TC Higgs and PNGBs. But TC still enters through $v_1^2 + v_2^2 + v_{\rm TC}^2 = v_{\rm weak}^2$

The spectrum, (masses of 4th generation quarks, Higgses)

Precision constraints, $S = S_{N,E} + S_{q4} + S_{\rm TC} + S_{\rm Higgs} + S_{G',Z'} + \Delta_S$

$S_{\rm TC} \sim 1/(2\pi)$

The model parameters: $g_U^{(34)} = g_D^{(34)} = 1.2$ to trigger condensation

$U(1)_A$ breaking parameter $\xi \sim 10^{-3}$

$\tan\beta = \frac{v_1}{v_2}$

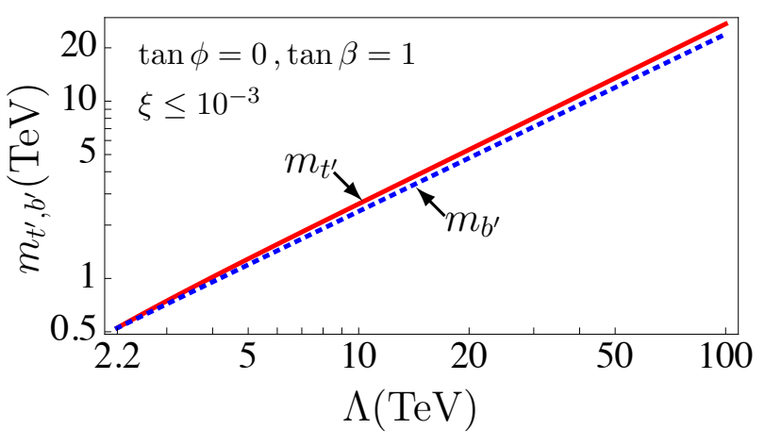
$\tan^2\phi = \frac{v_{\rm TC}^2}{v_1^2+v_2^2}$

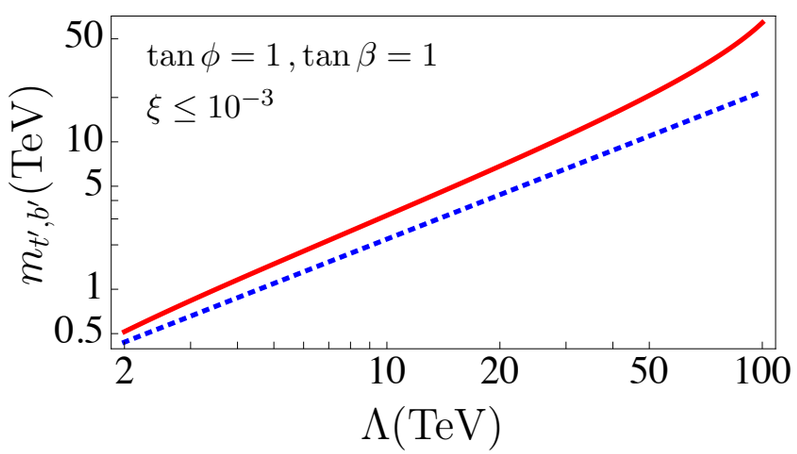
Λ, cutoff $\sim$ mass of G', Z'

$$v_{\rm TC} = 0$$

(He, Hill, Tait '01)

$$v_{\rm TC}^2 = v_1^2 + v_2^2$$



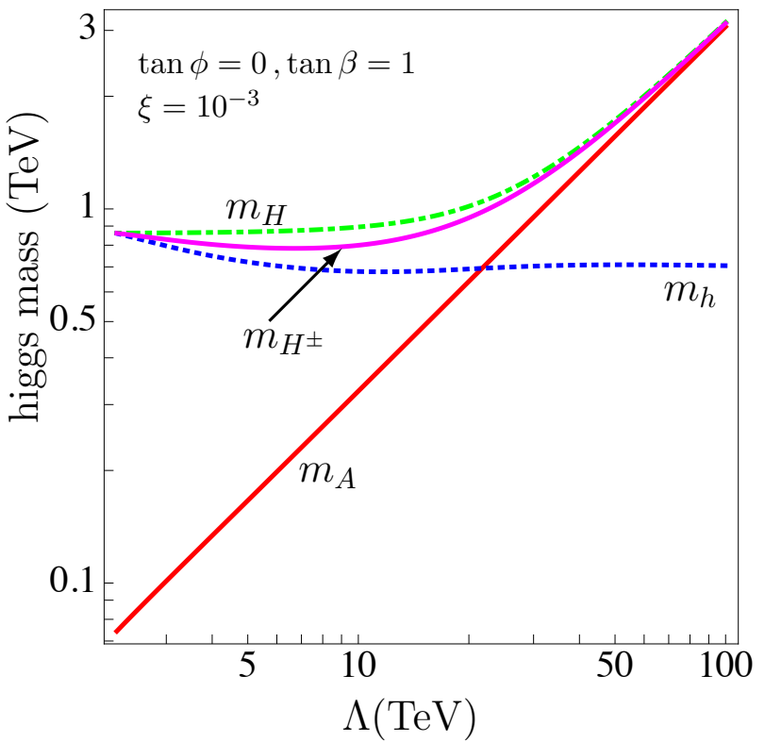


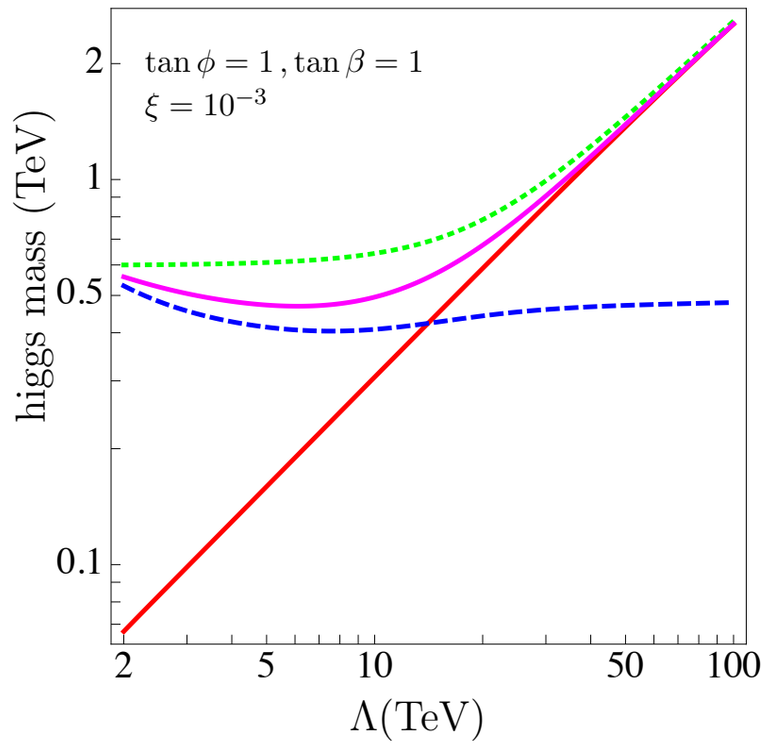
Larger t'-b' splitting

$v_{\rm TC} = 0$

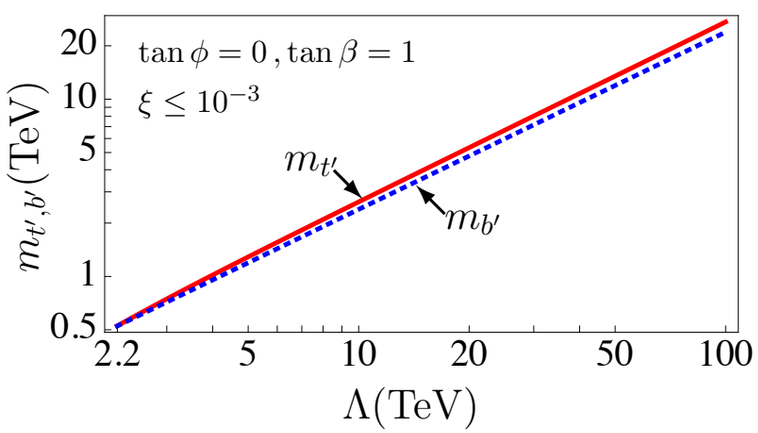
(He, Hill, Tait '01)

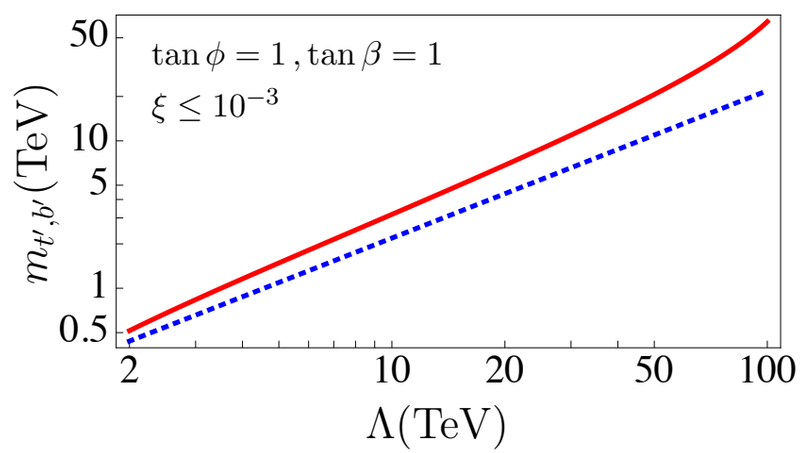
$v_{\rm TC}^2 = v_1^2 + v_2^2$





Lighter Higgs





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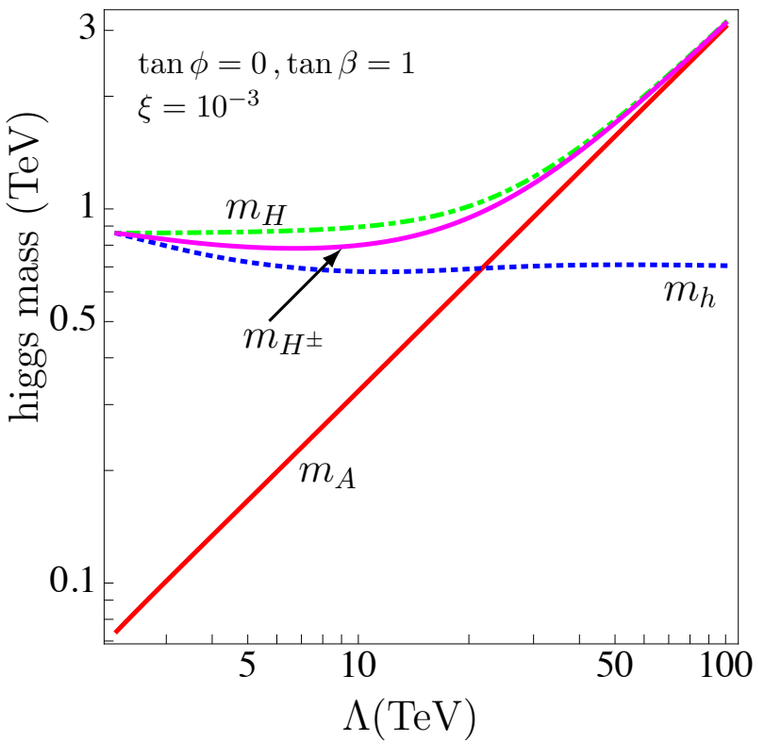
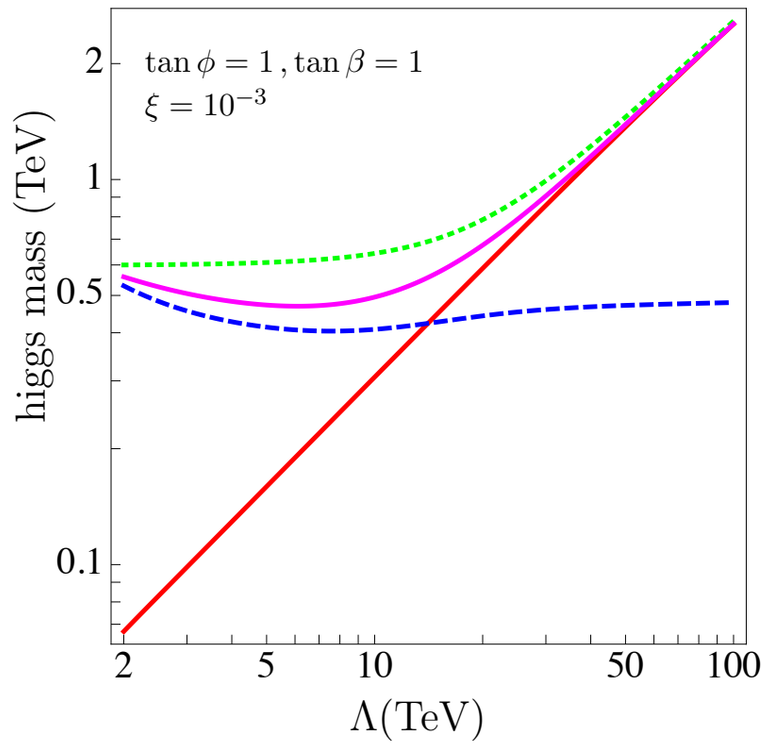
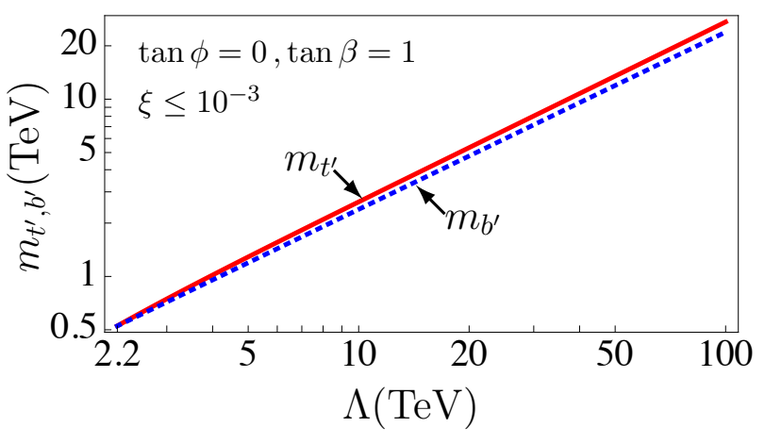


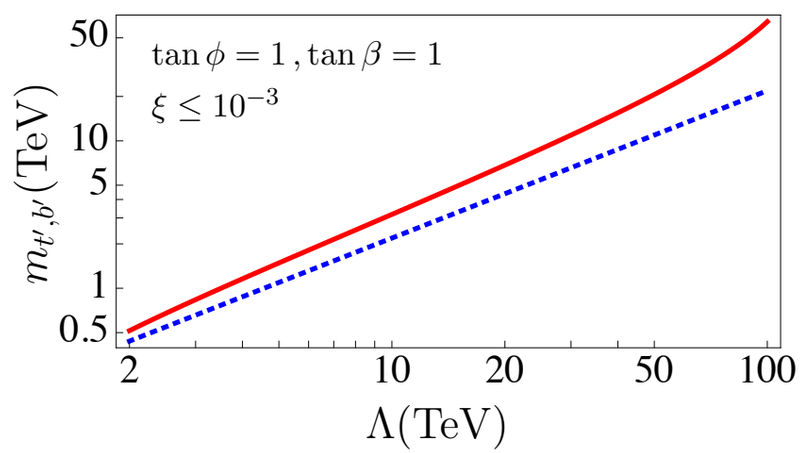


Lighter Higgs

Old school:
Higgs is heavy in TC

New school:
use TC to get light Higgs





Larger t'-b' splitting

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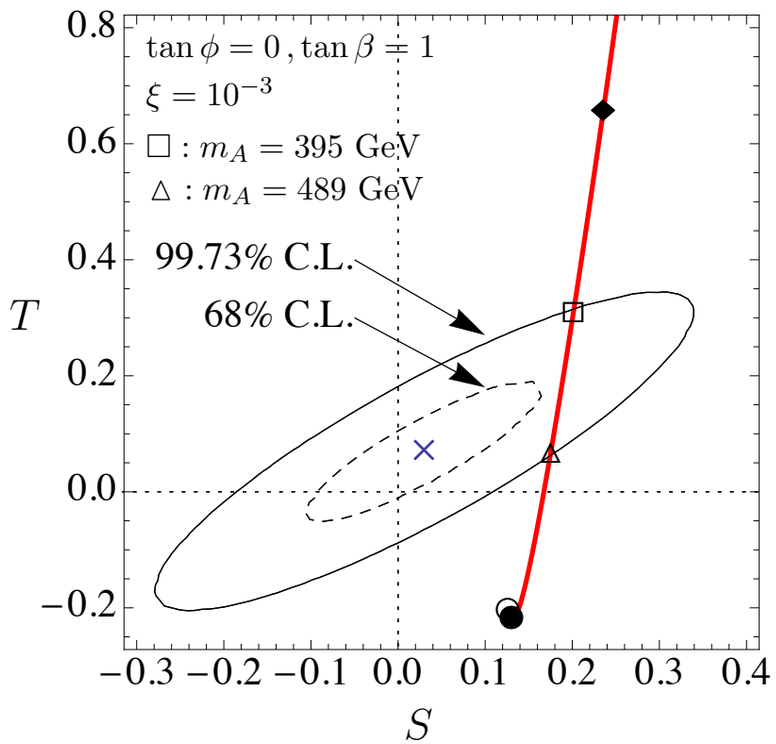
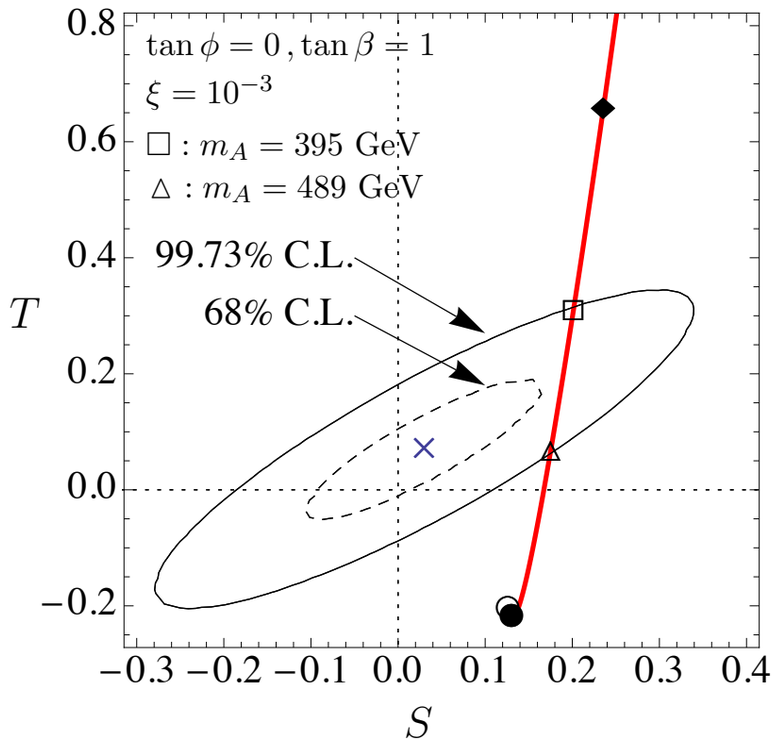


$$12 \text{ TeV} \leq \Lambda \leq 15 \text{ TeV}$$

But from Zbb vertex $R_b : \Lambda > 30 \text{ TeV}$

$v_{\rm TC} = 0$



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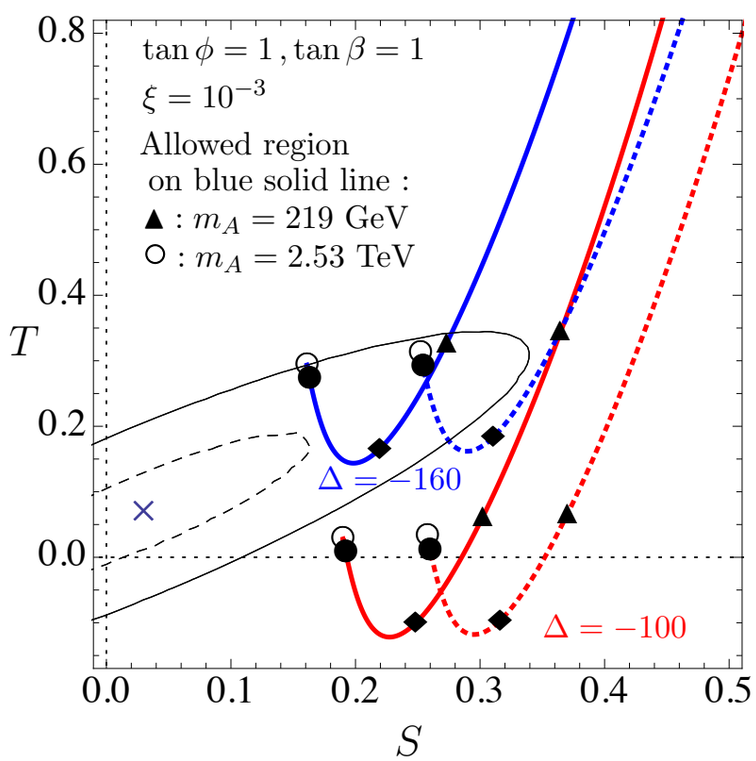
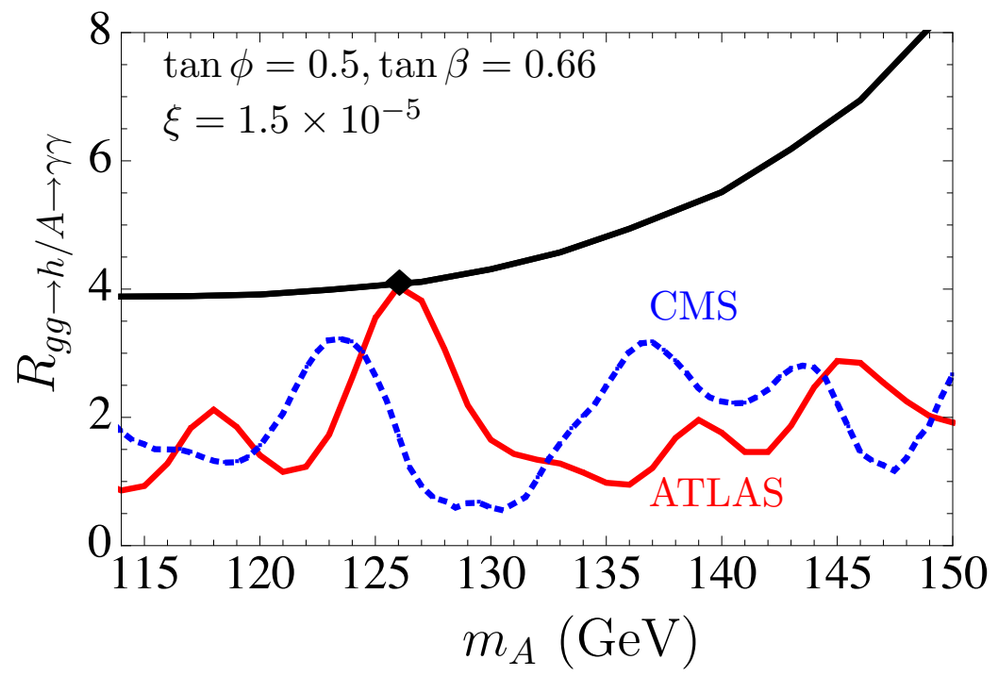
$v_{\rm TC}^2 = v_1^2 + v_2^2$

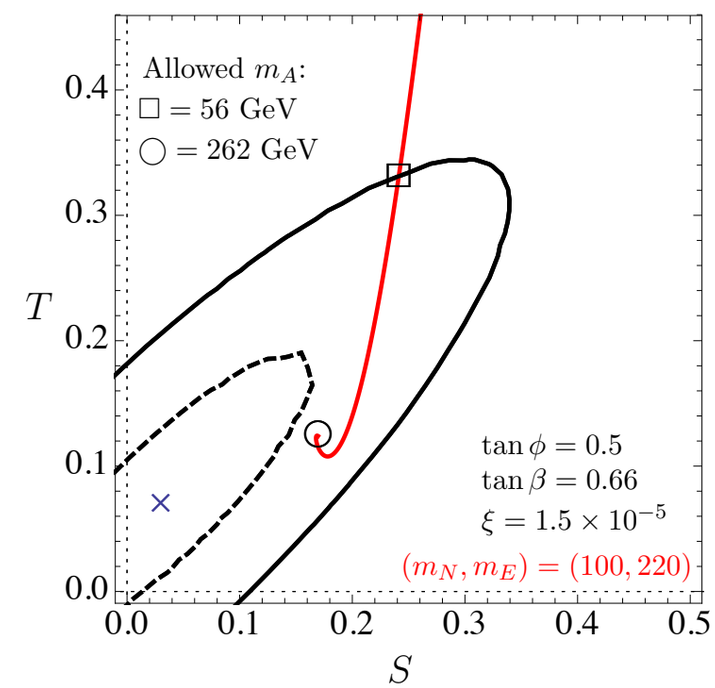


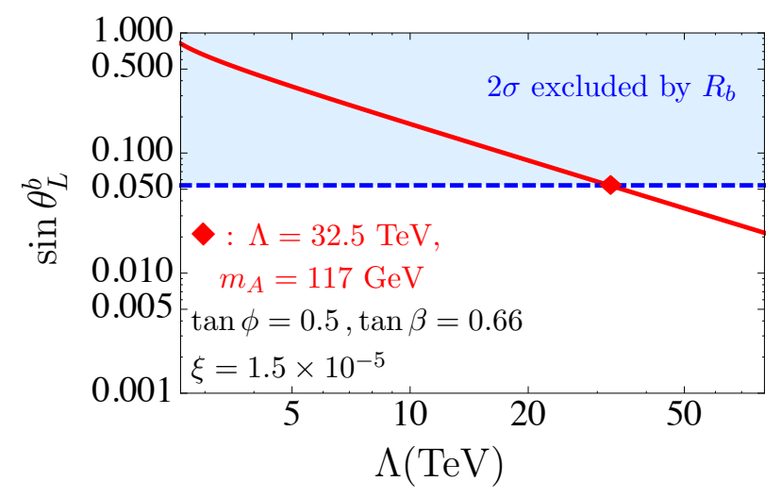
$$7 \text{ TeV} \leq \Lambda \leq 100 \text{ TeV}$$

$$R_b : \Lambda > 20 \text{ TeV}$$

Maybe the LHC signal is due to a light pseudoscalar?







Light CP-even higgs is also possible with full three doublet mixing.

Conclusions

Technicolor is viable, but needs to be extended.

ETC,
BosonicTC, (SUSY-TC),
topColor, top-seesaw,...

Intriguing and accessible connections:

new non-TC matter fields.
generations,
Origin of some/all fermion masses

LHC should be able to shed some light on some of these issues