Strong Dynamics Confronts The Top

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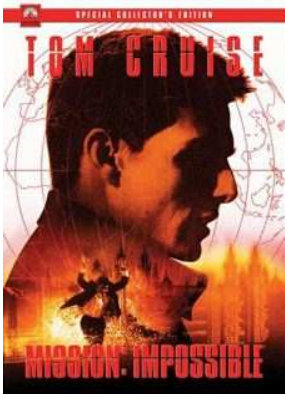
Image by Prof. Jan-Henrik Andersen, University of Michigan.

1. Introduction

Previously on the Strong Dynamics Channel:

- a) Chiral symmetry breaking in QCD and applications to EWSB
- b) Using strong dynamics to create light fermion masses (extended technicolor)
- c) Experimental signatures of strong dynamics and constraints on model-building from light flavor physics (walking)



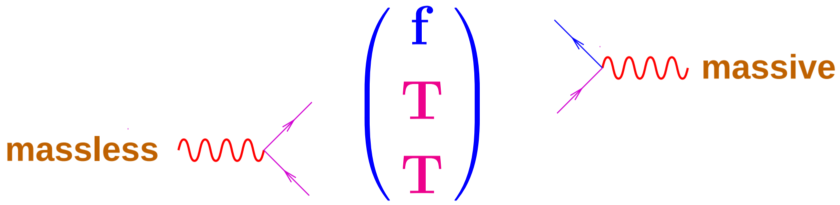
Today's Mission:

the LARGE mass
of the top quark

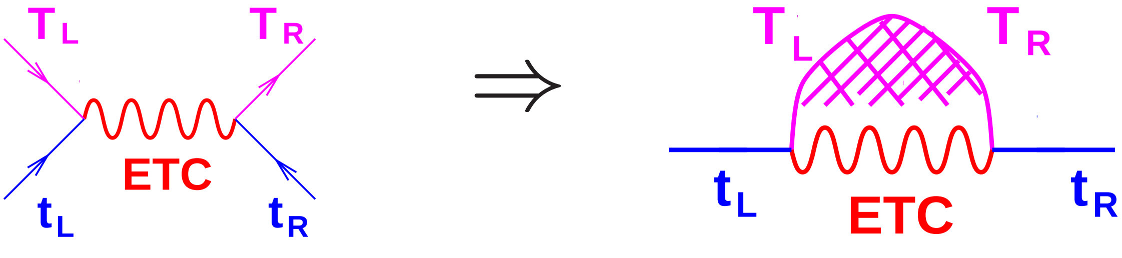
- How is it created?
- Why is it so much heavier than its weak partner? than other up-type quarks?
- What guidance does experiment provide?

In extended technicolor (ETC) models, fermion masses arise because heavy gauge bosons couple the quarks and leptons to the condensing technifermions that break the EW symmetry

- larger ETC gauge group subsumes TC
- all fermions carry ETC charge
- ETC breaks to TC at scale $\mathbf{M} > \mathbf{\Lambda_{TC}}$.



The top quark's mass comes from exchange of an ETC boson among t_L, t_R and technifermions



and its size is $\mathbf{m_t \approx (g^2/M^2)\langle \bar{T}T\rangle \approx (g^2/M^2)(4\pi v^3)}$

This works well in principle – but it is difficult to accommodate a large m_t while remaining consistent with precision EW data.

Two key challenges have led model-building in new directions:

The dynamics causing large m_t couples to b_L

How to keep R_b consistent with experiment? This leads to models in which the weak interactions of top are non-standard - as discussed in Section 2.

$m_t \gg m_b$ but $\Delta\rho \approx 1$

How to accommodate large weak isospin violation in the $t-b$ sector without producing a large shift in M_W? This has led to models in which the strong (color) interactions of t are modified - as covered in Sections 3 and 4

2. New Weak Interactions for Top

In classic ETC models, the large value of $\mathbf{m_t}$ is thought to come from ETC dynamics at a relatively low scale $\mathbf{M}$ ($\sim$ few TeV)

However note that
- $SU(2)_W$ is intact at the ETC scale (M)
- the CKM element $|V_{tb}| \approx 1$

Therefore the dynamics generating $\mathbf{m_t}$ must couple equally to t_L and b_L.

While many properties of t are only loosely constrained, the b has been far more closely studied. In particular, the $Zb\bar{b}$ coupling has been well-measured at LEP.

That coupling could be affected by ETC since
- ETC couples ordinary fermions like t_L, b_L to technifermions
- the W and Z acquire mass from condensing technifermions

$Zb\bar{b}$ in extended technicolor

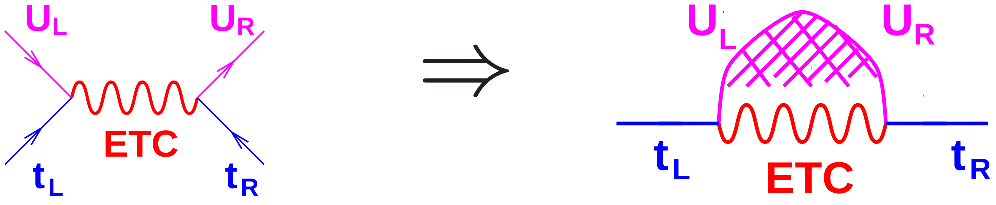
Simplest way to build an ETC model: make the SM and ETC gauge sectors independent

- ETC & weak groups commute: $G_{ETC} \times SU(2)_W$
- ETC gauge bosons carry no weak charge

The ETC boson responsible for m_t couples to:

$$\xi \left(\bar{\psi}^i_L \; \gamma^\mu \; T^{ik}_L \right) \; + \; \xi^{-1} \left(\bar{t}_R \; \gamma^\mu \; U^k_R \right)$$

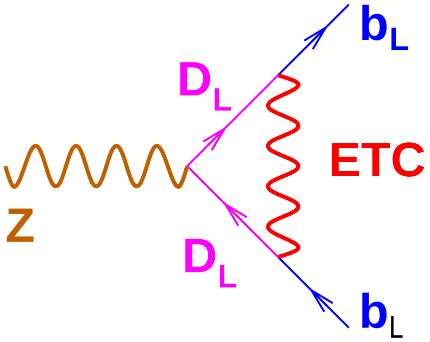
Recall, the top quark mass comes from:



its size is $m_t \approx (g^2/M^2)(4\pi v^3)$, so that

$$\frac{g^2 v^2}{M^2} \approx \frac{m_t}{4\pi v}$$

Exchange of the same ETC boson among purely LH states causes a direct correction to Z decay



$I_3^D = -\frac{1}{2}$

which reduces the $\mathbf{Zb\bar{b}}$ coupling strength by

$$\delta g_L = \frac{-e}{2\sin\boldsymbol{\theta}\cos\boldsymbol{\theta}}\, I_3^D \left(\frac{g^2v^2}{M^2}\right)$$

Where can this be seen ?

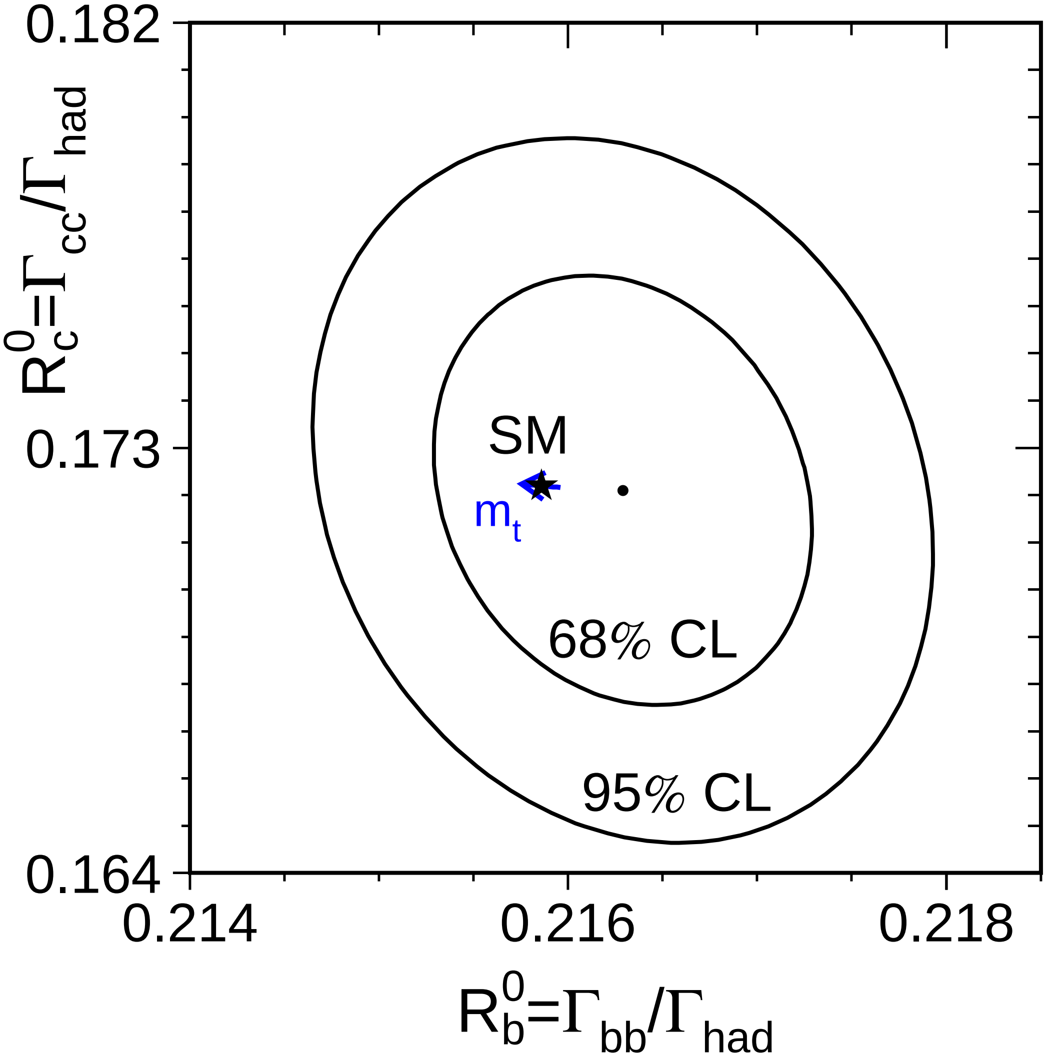
- $\Gamma(Z \to b\bar{b})$ has direct & oblique corrections: $\Gamma_b^{corr.} = (1+\Delta\rho)(\Gamma_b + \delta\Gamma_b)$
- consider $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$
  - oblique, QCD corrections cancel in ratio
  - direct correction proportional to δg_L

$$\boxed{\frac{\delta R_b}{R_b} \approx -5.1\% \cdot \xi^2 \cdot \left(\frac{m_t}{175\text{GeV}}\right)}$$

Let's compare to results of the LEP Electroweak Working Group...

Data on R_b **and** R_c (LEPEWWG, 2005)

- R_b^{SM} and $R_b^{expt,central}$ match to within 0.5%
- 1σ in R_b is about 0.5%



This effectively excludes our simple commuting ETC model for the origin of the top mass.

A New Kind of ETC

What about ‘non-commuting’ ETC models ?

- weak group $\mathbf{SU(2)_W}$ is embedded in $\mathbf{G_{ETC}}$
- the ETC gauge bosons carry weak charge

Must balance requirements

- wide range of quark masses
- weak interactions ‘universal’ at low scales

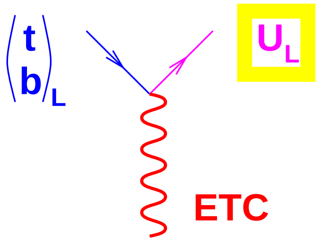
This leads to the symmetry-breaking pattern:

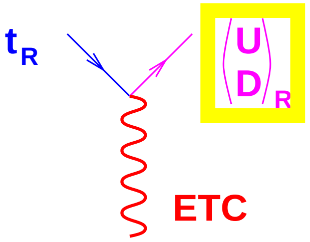
$$\begin{tikzcd}
ETC \times SU(2)_{light} \times U(1) \arrow[d, "f"] \\
TC \times SU(2)_{heavy} \times SU(2)_{light} \times U(1)_Y \arrow[d, "u"] \\
TC \times SU(2)_{weak} \times U(1)_Y \arrow[d, "v"] \\
TC \times U(1)_{EM}
\end{tikzcd}$$

The result is two non-SM contributions to $\mathbf{R_b}$

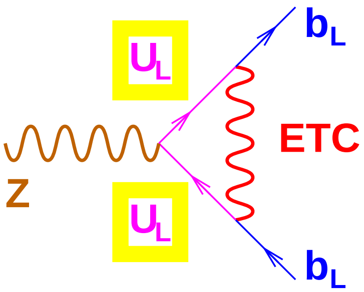
- the dynamics that generates m_t
- the mixing of the two $\mathbf{Z}$ bosons

The ETC boson responsible for $\mathbf{m_t}$ couples to:





It gives a direct correction to Z decay:



that enlarges the $\mathbf{Zb\bar{b}}$ coupling by

$$\delta g_L = \frac{-e}{2\sin\theta\cos\theta} I_3^U \frac{g^2v^2}{M^2} \qquad\qquad I_3^U = \frac{1}{2}$$

thereby altering $\mathbf{R_b}$ by

$$\frac{\delta \mathrm{R_b}}{\mathrm{R_b}} \approx +5\%$$

But this is not the only effect on $\mathbf{R_b}$ now.

The $SU(2)_h \times SU(2)_\ell \times U(1)_Y$ gauge bosons mix to form mass eigenstates

- γ coupling to $Q = T_{3h} + T_{3\ell} + Y$

$$A^\mu = \sin\theta[\sin\phi\, W^\mu_{3\ell} + \cos\phi\, W^\mu_{3h}] + \cos\theta X^\mu$$

- W^L, Z^L resembling standard W and Z
- W^H, Z^H coupling mainly to 3rd generation

To understand the mass eigenstates, use a rotated gauge basis $(s \equiv \sin\phi\,,\ c \equiv \cos\phi)$

$$D^\mu = \partial^\mu + ig\left(T^\pm_\ell + T^\pm_h\right) W_1^{\pm\,\mu} + ig\left(\tfrac{c}{s}T^\pm_\ell - \tfrac{s}{c}T^\pm_h\right) W_2^{\pm\,\mu}$$

$$W^\pm_1 = s\,W^\pm_\ell + c\,W^\pm_h \qquad W^\pm_2 = c\,W^\pm_\ell - s\,W^\pm_h$$

$$D^\mu = \partial^\mu + i\tfrac{g}{\cos\theta}\left(T_{3\ell} + T_{3h} - \sin^2\theta Q\right) Z^\mu_1 + ig\left(\tfrac{c}{s}T_{3\ell} - \tfrac{s}{c}T_{3h}\right) Z^\mu_2$$

$$Z_1 = \cos\theta(s\,W_{3\ell} + c\,W_{3h}) - \sin\theta X \qquad Z_2 = c\,W_{3\ell} - s\,W_{3h}$$

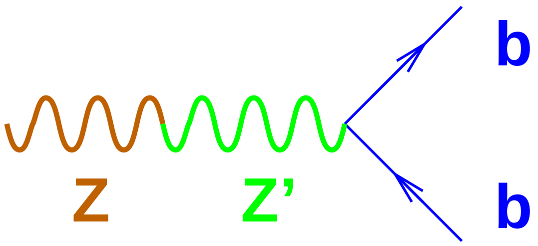
Mass eigenstates are $(v^2/u^2 \equiv 1/x << 1)$

$$W^L \approx W_1 - \frac{c^3 s}{x} W_2\ , \qquad W^H \approx W_2 + \frac{c^3 s}{x} W_1$$

$$Z^L \approx Z_1 - \frac{c^3 s}{x\cos\theta} Z_2\ , \qquad Z^H \approx Z_2 + \frac{c^3 s}{x\cos\theta} Z_1$$

Heavy boson masses are : $M_{W^H} \approx M_{Z^H} \approx \frac{\sqrt{x}}{sc} M_W$

Due to the ZZ' mixing, the Z^L coupling to quarks differs from the SM value for the Z^0



$$\delta \mathbf{g_L} = \frac{c^3 s}{x}\left(\frac{c}{s}\mathbf{T_{3\ell}} - \frac{s}{c}\mathbf{T_{3h}}\right)$$

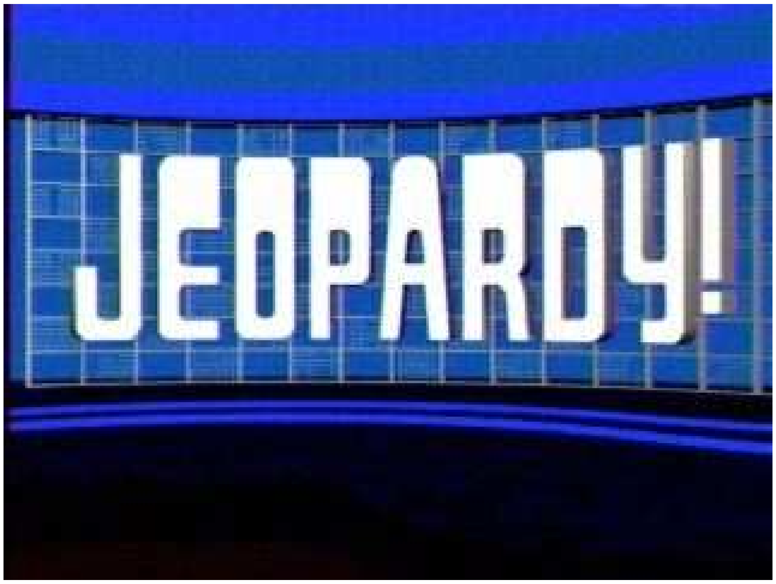
$$\frac{\delta \mathbf{R_b}}{\mathbf{R_b}} \approx -\mathbf{5.1\%} \cdot \quad \underbrace{\sin^2\phi \cdot \frac{f^2}{u^2}}_{\mathrm{O(1)}}$$

Competing effects of same size, opposite sign ⇒ net size of R_b is consistent with experiment

What produces a large m_t without causing a shift in R_b is non-standard weak interactions for the top quark

- this makes non-commuting ETC work where commuting ETC failed
- the idea has been incorporated into other models too (topflavor, seesaw)

This suggests some immediate questions



DOES the top quark have distinct weak interactions?

ARE the weak interactions REALLY

$$\mathrm{SU}(2)_{\mathrm{heavy}} \times \mathrm{SU}(2)_{\mathrm{light}}?$$

HOW can we tell?

Available Approaches:

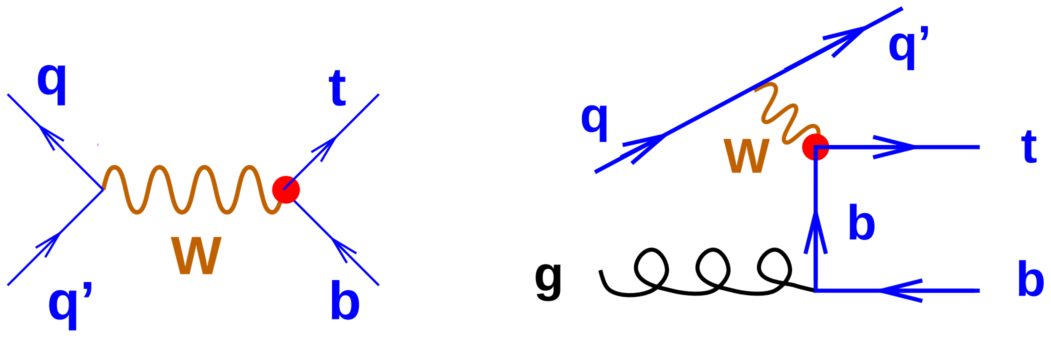
Direct measurement of the top quark's weak interaction strength. Single top production is sensitive to the $\mathbf{Wtb}$ coupling.

Direct search for new $\mathbf{W}'$ and $\mathbf{Z}'$ resonances. Look at collider production of $\mathbf{b\bar{b}}, \tau^+\tau^-$.

Indirect test: fit to electroweak observables. Modified weak interactions affect Z and τ decays, the value of M_W, atomic parity violation...

Single Top Production

Production of a single top quark in $\mathbf{p\bar{p}}$ collisions at Fermilab is sensitive to the $\mathbf{Wtb}$ coupling:



As in the $\mathbf{Z} \rightarrow \mathbf{b\bar{b}}$ case, two effects contribute.

- $\mathbf{W}$ - $\mathbf{W}'$ mixing alters the coupling.
- $\mathbf{W}'$ exchange adds to cross-section, $\sigma_{\mathbf{tb}}$.

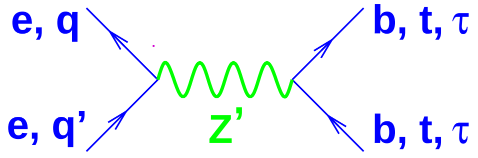
Tevatron may measure $\mathbf{R}_\sigma \equiv \sigma_{\mathbf{tb}}/\sigma_{\ell\nu}$ to ±8%.

- Structure function uncertainties cancel in the ratio for the $\mathbf{W}*$ process.
- Non-standard top weak interactions increase $\mathbf{R}_\sigma$, unlike most kinds of new physics

Deviations in the $\mathbf{Wtb}$ coupling corresponding to $\mathbf{W}'$ masses up to ~1.5 TeV could be visible.

Searches for W' or Z'

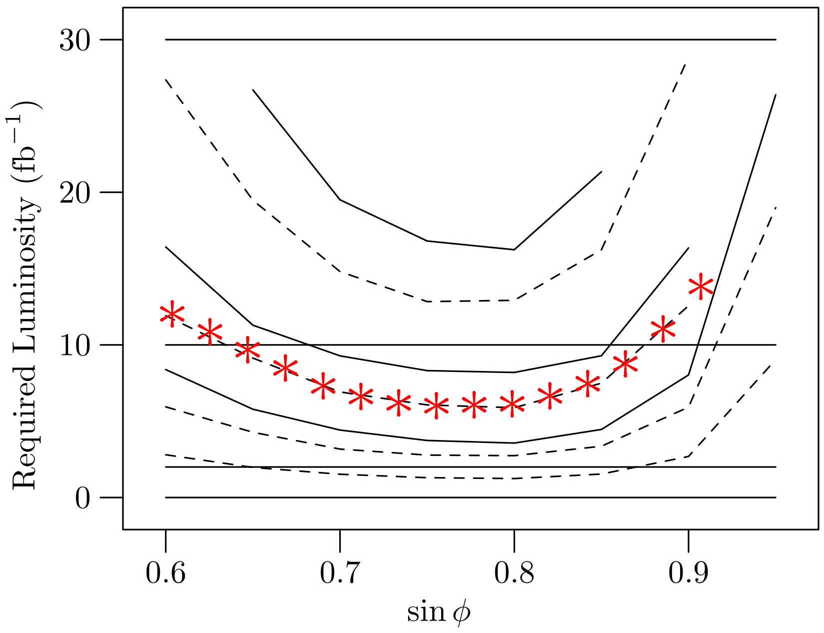
Extra electroweak bosons would affect heavy fermion pair production at LEP II and FNAL



LEP II data on $\mathbf{e^+e^- \to b\bar{b}}$, and $\mathbf{e^+e^- \to \tau^+\tau^-}$ already require $\mathbf{M_{Z'} > 400\,GeV}$

FNAL Run II can search for $\mathbf{p\bar{p} \to Z' \to \tau\tau \to e\mu X}$

- Z' events topologically distinct from SM
- Z' bosons up to 650 GeV likely to be visible

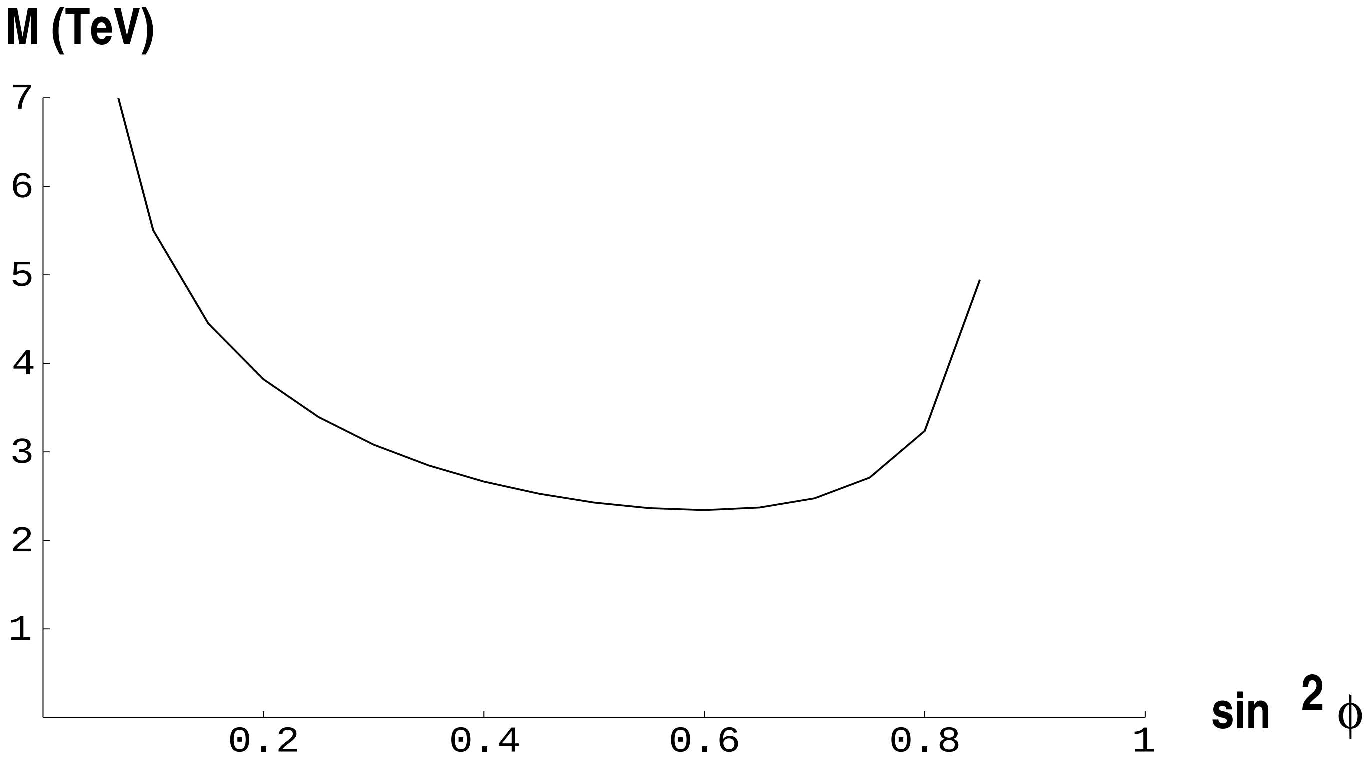


← $10fb^{-1}$

← $2fb^{-1}$

Low-Energy Precision Tests

Altered $\mathbf{Z^L}$, $\mathbf{W^L}$ couplings and $\mathbf{Z^H}$, $\mathbf{W^H}$ exchange would affect precision electroweak observables. A global fit yields lower bounds on $\mathbf{M_{W'}}$ as a function of the extra $\mathbf{SU(2)}$ mixing angle $\sin\phi$



Z',W' prefer
3rd family

N.B.: Additional new physics can shift limits.

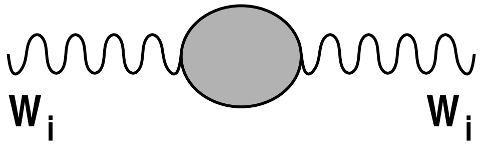
3. New Strong Interactions for Top

In the tree-level SM, $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$ due to a “custodial” global SU(2) symmetry relating members of a weak isodoublet.

The fact that the two fermions in each isodoublet have different masses and hypercharges causes “oblique” radiative corrections to the W and Z propagators to pull ρ away from 1.

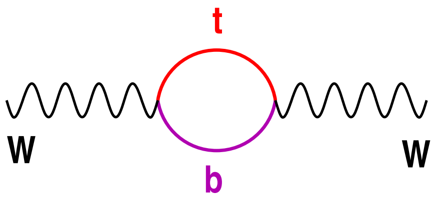
Conventionally, one speaks of $\Delta\rho \equiv \rho - 1$

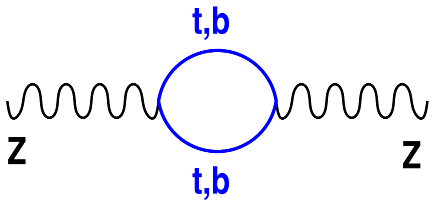
$$\Delta\rho(0) \equiv \frac{e^2}{\sin^2\theta_W \cos^2\theta_W M_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)]$$



$$= i\Pi_{ii} g^{\mu\nu} + \ldots$$

The one-loop correction from the (t, b) doublet is large because $m_t \gg m_b$. (What if $m_t = m_b$?)





Experiment finds $|\Delta\rho| \leq 0.4\%$, which constrains physics beyond the SM.

E.g., a new doublet of heavy ($\gg M_Z$) leptons (N, E) with standard weak couplings gives

$$\Delta\rho_{N,E} \approx \frac{\alpha_{EM}}{16\pi \sin^2\theta_W \cos^2\theta_W M_Z^2}$$
$$\cdot[m_N^2 + m_E^2 - \frac{2m_N^2 m_E^2}{m_N^2 - m_E^2} log(\frac{m_N^2}{m_E^2})]$$

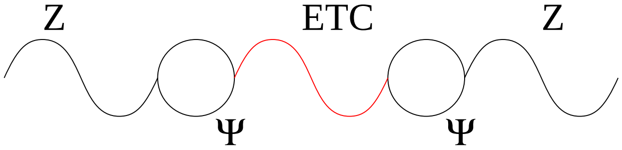
A new quark doublet gives 3x as much.

Dynamical theories of mass like ETC must break weak isospin to produce $m_t \gg m_b$. But the new dynamics may cause new contributions to $\Delta\rho$. This realization has had a dramatic effect on model-building.

Let's examine how ETC dynamics affects $\Delta\rho$.

“Direct” Contributions to $\Delta\rho$

ETC *must* violate weak-isospin to make $\mathbf{m_t} \gg \mathbf{m_b}$. Then ETC boson mixing with Z through technifermion loops can induce dangerous contributions to $\Delta\rho$



$$\Delta\rho \approx 12\% \cdot \left(\frac{\sqrt{N_D}F_{TC}}{250\ \text{GeV}}\right)^2 \cdot \left(\frac{1\ \text{TeV}}{M_{ETC}/g_{ETC}}\right)^2$$

How to satisfy experimental constraint: $\boldsymbol{\Delta\rho \leq 0.4\%}$?

- make ETC boson heavy ?

$$\frac{M_{ETC}}{g_{ETC}} > 5.5\ \text{TeV} \cdot \left(\frac{\sqrt{N_D}F_{TC}}{250\ \text{GeV}}\right)^2$$

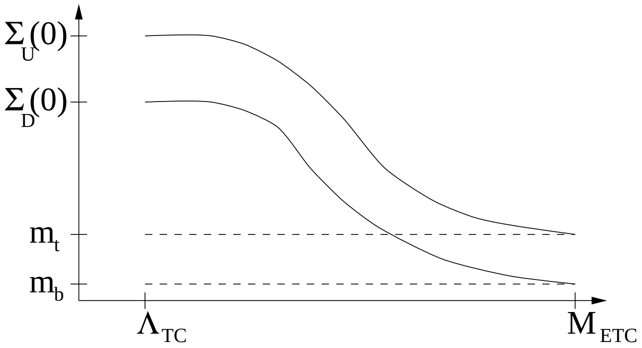
too heavy to provide $m_t \simeq 178 GeV$

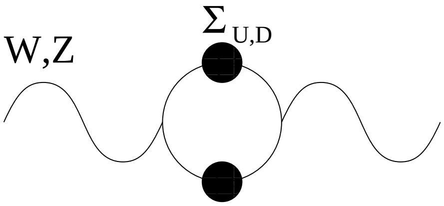
- arrange for $N_D F_{TC}^2 \ll (250 GeV)^2$?

  e.g. separate sectors for m_t and
  EW symmetry breaking (more later)

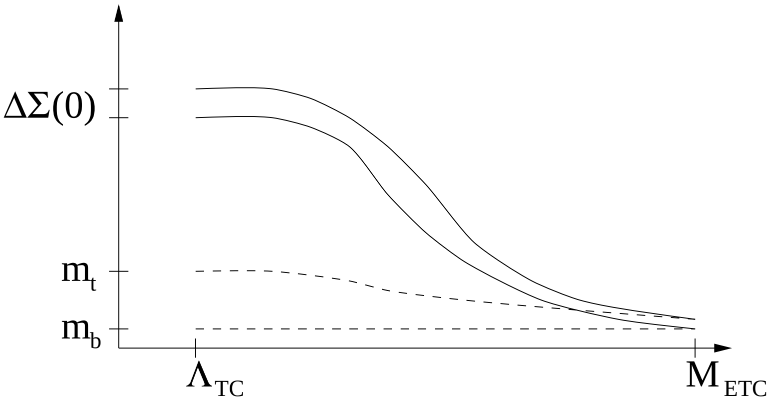
“Indirect” Contributions to $\Delta\rho$

What about isospin violation in the technifermion dynamical masses? $\Delta\rho \sim (\Sigma_U(0) - \Sigma_D(0))^2/M_Z^2$





Again, one solution is having t, b get only part of their mass from technicolor:



$$\Delta\Sigma(0) \simeq m_t(M_{ETC}) - m_b(M_{ETC}) \ll m_t$$

Then t,b must feel a strong interaction not felt by light fermions or technifermions.

If top feels a new strong interaction, perhaps

- some (topcolor, TC2)
- or even all (top mode, top seesaw)

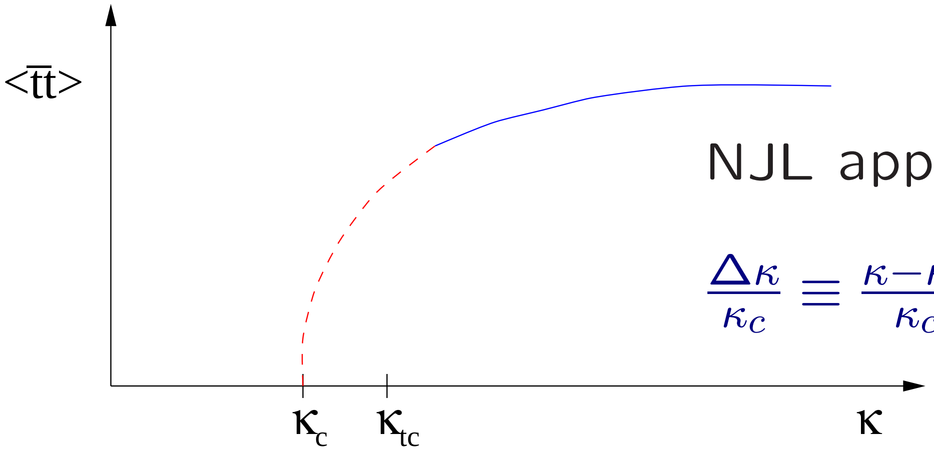
of EWSB due to $\langle \bar{t}t \rangle \neq 0$.

One physical realization of a new interaction for t is a (spontaneously broken) extended color gauge group called topcolor:

$SU(3)_h \times SU(3)_\ell \xrightarrow{M} SU(3)_{QCD}$
where (t,b) feel the first SU(3)
and (u,d,c,s) feel the second

Below the scale M

- massive topgluons exchanged by top quarks
- $\mathcal{L} \supset -\frac{4\pi\kappa}{M^2}\left(\bar{t}\gamma_\mu \frac{\lambda^a}{2} t\right)^2$



NJL approximation

$$\frac{\Delta\kappa}{\kappa_c} \equiv \frac{\kappa-\kappa_c}{\kappa_c} \propto \frac{\langle \bar{t}t \rangle}{M^3}$$

Note: $M \gg 1TeV$ ⇒ fine tuning.

Sample Model: Topcolor-Assisted Technicolor

$$G_{TC} \times \overset{(g_h > g_\ell)}{SU(3)_h \times SU(3)_\ell} \times SU(2)_W \times \overset{(g_h > g_\ell)}{U(1)_h \times U(1)_\ell}$$

$$\downarrow \quad M \gtrsim 1 \text{ TeV}$$

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

$$\downarrow \quad \Lambda_{TC} \sim 1 \text{ TeV}$$

$$G_{TC} \times SU(3)_{QCD} \times U(1)_{EM}$$

Below M, new effective interactions for $\boldsymbol{\psi} \equiv (t, b)$:

$$-\frac{4\pi\kappa_{\color{blue}\bullet}}{M^2}\left[\overline{\psi}\gamma_\mu \frac{\lambda^a}{2}\psi\right]^2$$

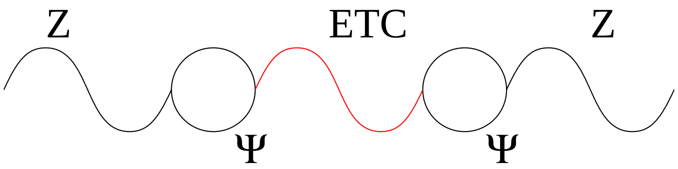
$$-\frac{4\pi\kappa_{\color{green}\bullet}}{M^2}\left[\frac{1}{3}\overline{\psi_L}\gamma_\mu\psi_L + \frac{4}{3}\overline{t_R}\gamma_\mu t_R - \frac{2}{3}\overline{b_R}\gamma_\mu b_R\right]^2$$

Result is large $\langle \bar{t}t \rangle$ & m_t , but not $\langle \bar{b}b \rangle$ & m_b:

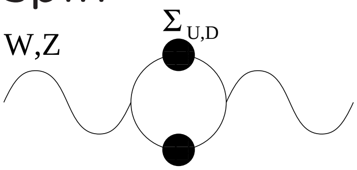
$$\kappa^t = \kappa_{\color{blue}\bullet} + \frac{1}{3}\kappa_{\color{green}\bullet} > \underbrace{\kappa_C}_{\left(=\frac{3\pi}{8}\right)_{\mathbf{NJL}}} > \kappa_{\color{blue}\bullet} - \frac{1}{6}\kappa_{\color{green}\bullet} = \kappa^b$$

Benefits of new strong top dynamics in topcolor-assisted technicolor

- technicolor responsible for most of EW symmetry breaking ⇒ $\boldsymbol{\Delta}\rho \approx 0$
  - $\langle \bar{\mathbf{t}}\mathbf{t} \rangle$ responsible for only $f \sim 60\ GeV$
    - fixes



  - technifermion $\mathbf{U(1)_h}$ charges can preserve weak isospin
    - avoids



- $\langle \bar{t}t \rangle$ provides large m_t
- ETC dynamics at $M >> 1 TeV$
  - generates light m_f (no large FCNC)
  - contributes ~ 1 GeV to heavy $\mathbf{m_f}$

    ⇒ no large shift in R_b

4. Phenomenology of Strong Top Dynamics

Models with new strong top dynamics continue to proliferate. Three classes of models with distinctive spectra and phenomenology have emerged.

- topcolor
- flavor-universal extended color
- top seesaw

They include a variety of new states that are potentially accessible to experiment

- colored gauge bosons: topgluons, colorons
- color singlet gauge bosons: Z'
- composite scalars: top-pions, q-pions

Topcolor Models*

color sector $\mathbf{SU(3)_h \times SU(3)_\ell \rightarrow SU(3)_{QCD}}$

- only t, b transform under strong $\mathbf{SU(3)_h}$
- heavy topgluons couple strongly to t, b

hypercharge sector $\mathbf{U(1)_h \times U(1)_\ell \rightarrow U(1)_Y}$

- third generation feels strong $\mathbf{U(1)_h}$
- heavy Z' couples mainly to 3rd generation

weak sector $\mathbf{SU(2)_W}$

- standard

composite scalars $\mathbf{t\bar{t}}$, $\mathbf{b\bar{b}}$, $\mathbf{t\bar{b}}$, $\mathbf{b\bar{t}}$

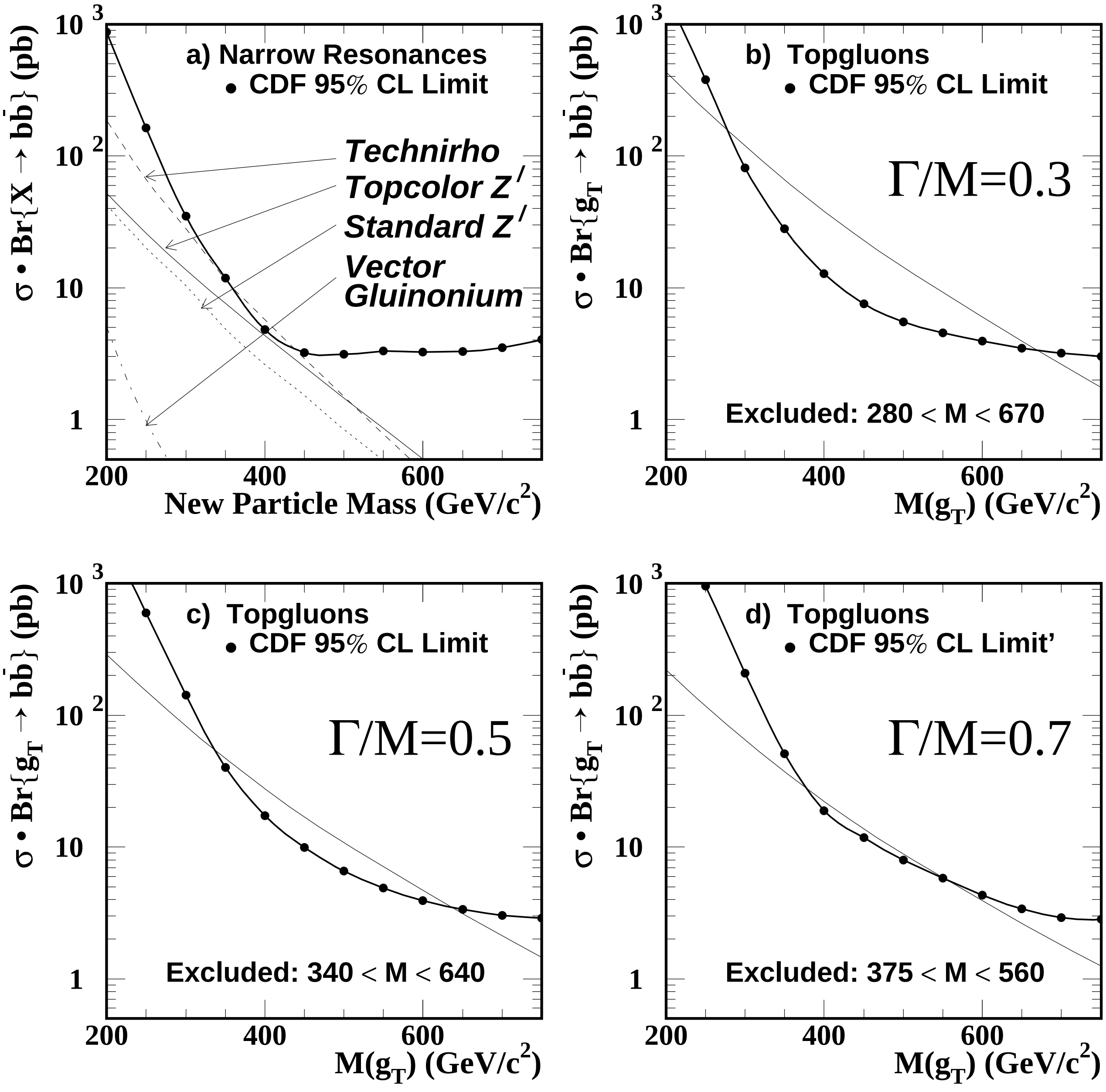
fermion gauge charges

	$\mathbf{SU(3)_h}$	$\mathbf{SU(3)_\ell}$	$\mathbf{SU(2)}$	$\mathbf{U(1)_h}$	$\mathbf{U(1)_\ell}$
I	1	SM	SM	0	SM
II	1	SM	SM	0	SM
III	SM	1	SM	SM	0

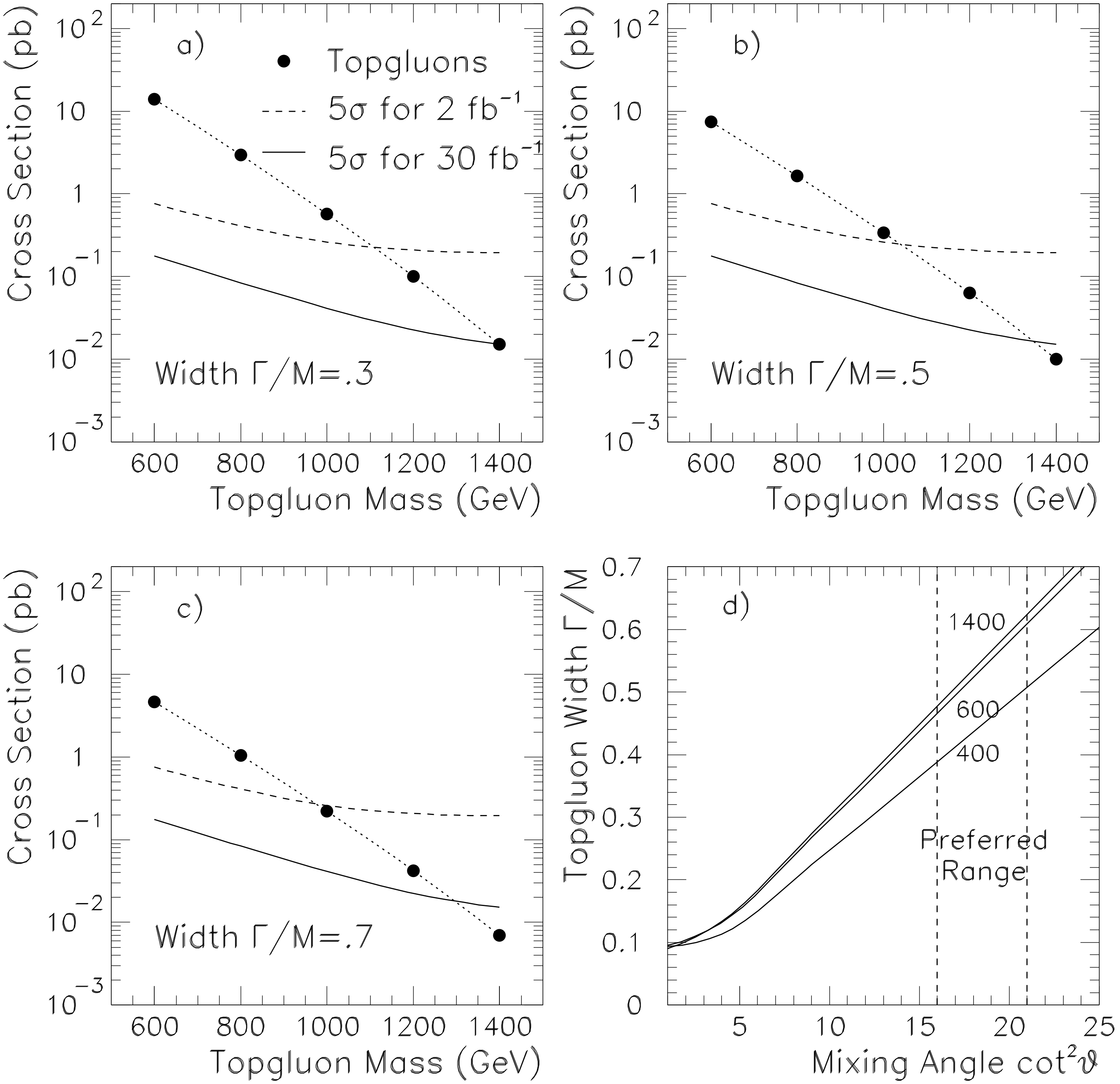
* Hill hep-ph/9411426

CDF Run I search for topgluons in $b\bar{b}$

Note: strong coupling makes resonance broad

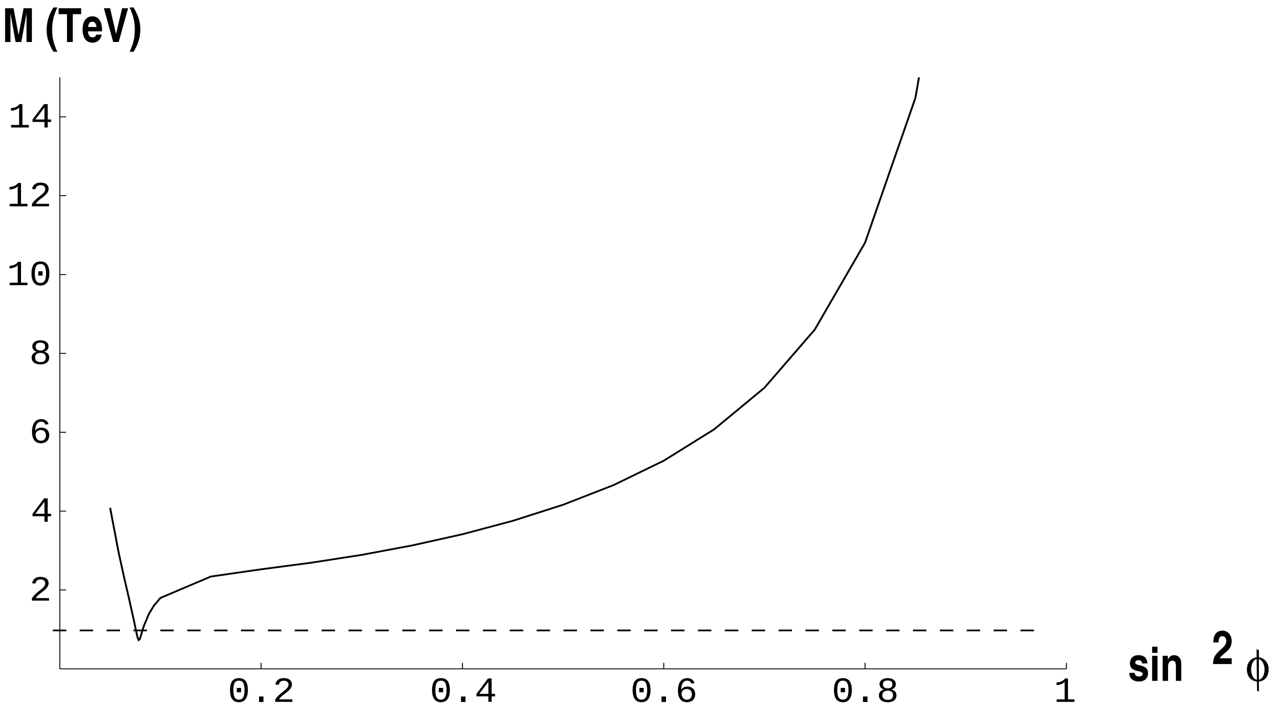


Run II & LHC can also seek topgluons in $t\bar{t}$



Precision EW limits on topcolor Z'

(Chivukula & Simmons, hep-ph/0205064)

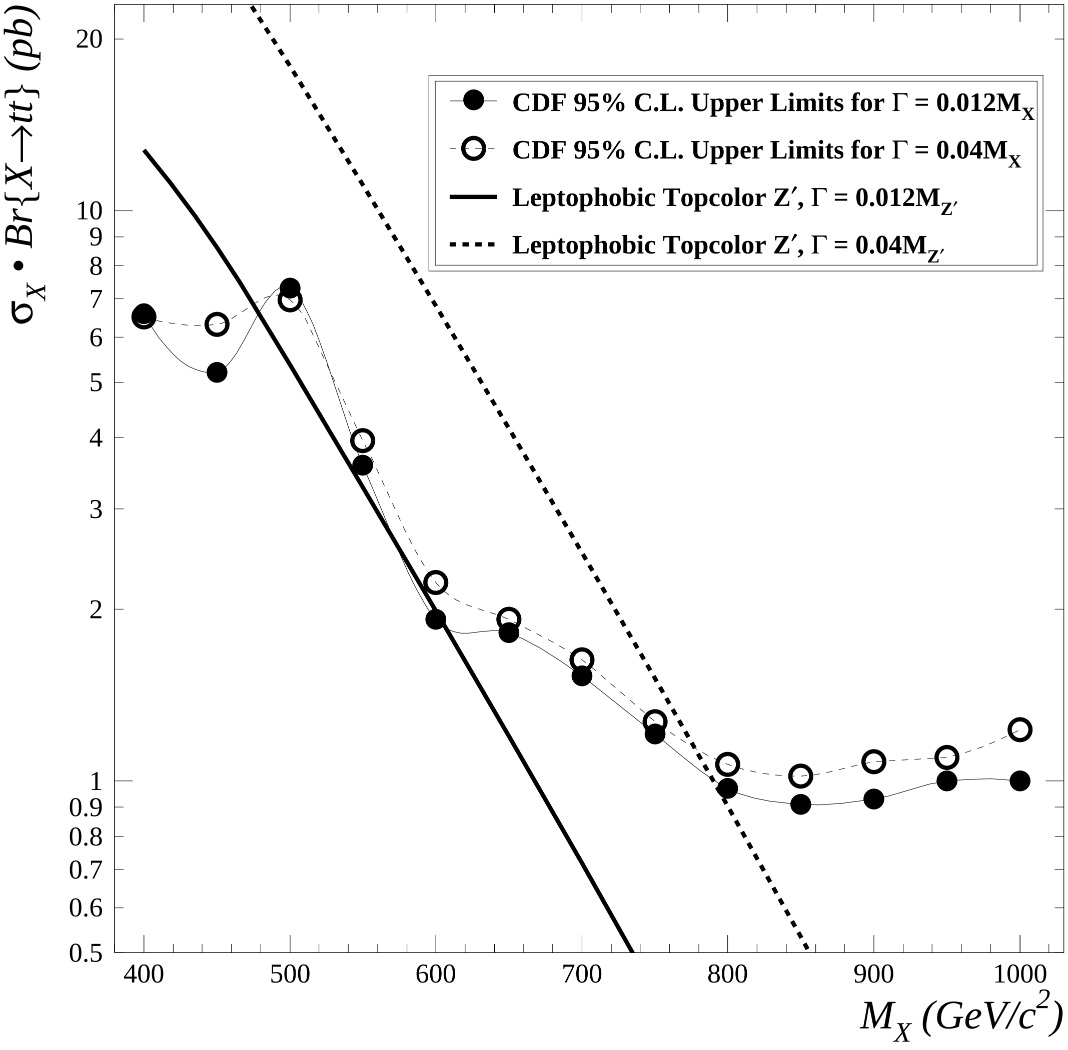


Z' prefers
3rd family

Future Collider Limits:

- Run II can exclude 500-600 GeV Z' in $Z' \to \tau\tau \to e\mu$
- NLC can find 3-6 TeV Z' in $\tau\tau$ production

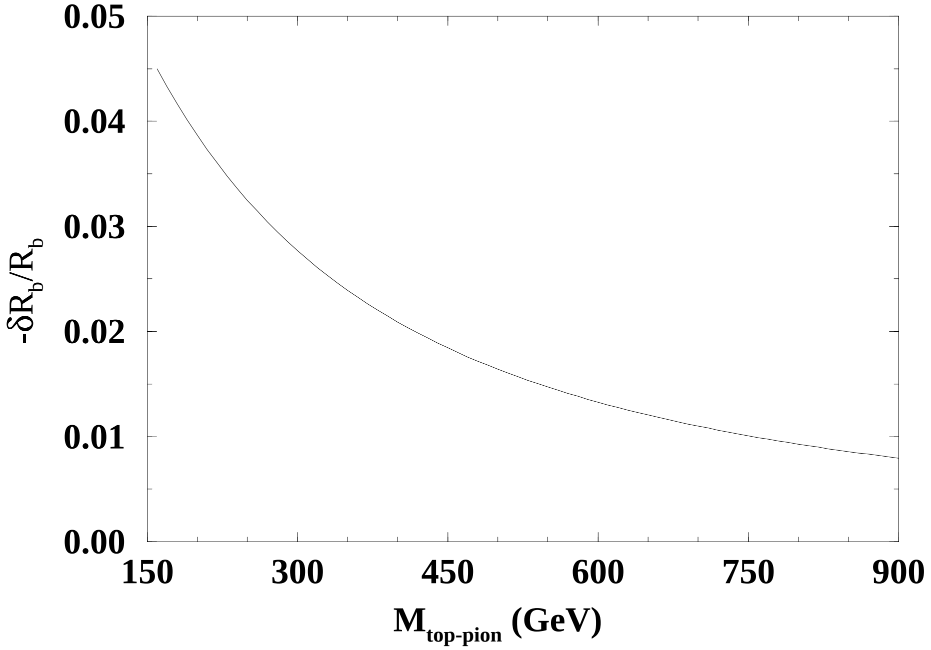
CDF search for leptophobic topcolor Z' in $t\bar{t}$



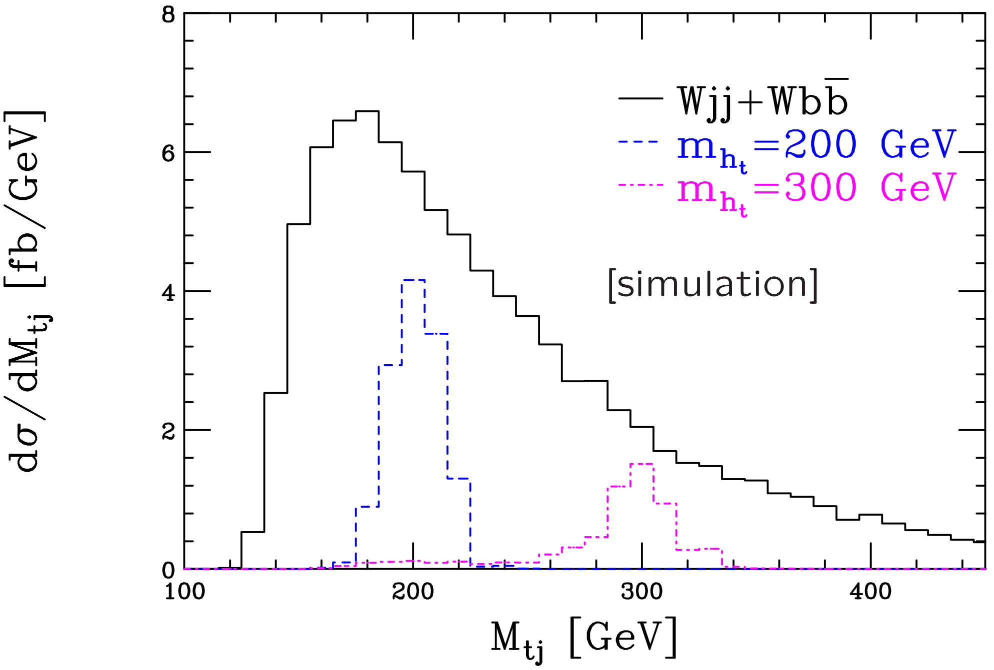
excluded $M_{Z'} < 480$ GeV for $\Gamma_{Z'} = .012\, M_{Z'}$
excluded $M_{Z'} < 780$ GeV for $\Gamma_{Z'} = .04\, M_{Z'}$

Constraints on top-pions

Top-pion exchange significantly[%] decreases R_b



At Run II, neutral top-higgs (σ) can be singly produced and detected in decay to tc [†]



Charged top-pions visible in single top production up to 350 GeV at Run II (1 TeV, LHC)[*]

[%] hep-ph/9702265
[†] hep-ph/9905347
[*] hep-ph/9810367

Flavor-Universal Coloron Models*

color sector $SU(3)_h \times SU(3)_\ell \rightarrow SU(3)_{QCD}$

- all quarks transform under $SU(3)_h$
- heavy colorons couple strongly to all quarks

hypercharge sector $U(1)_h \times U(1)_\ell \rightarrow U(1)_Y$

- third generation feels strong $U(1)_h$
- heavy Z' couples mainly to 3rd generation

weak sector $SU(2)_W$

- standard

composite scalars $\mathbf{t\bar{t}}$ and full set of $\mathbf{q\bar{q}}'$

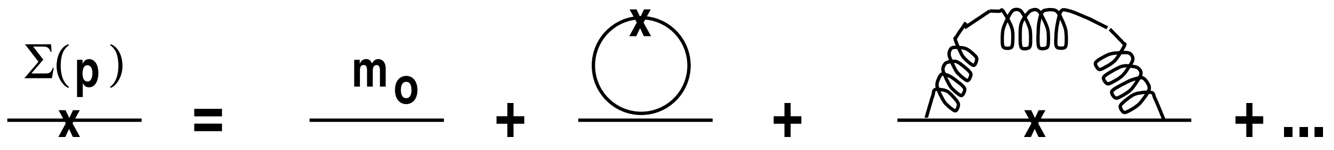
fermion gauge charges

	$SU(3)_h$	$SU(3)_\ell$	$SU(2)$	$U(1)_h$	$U(1)_\ell$
I	SM	1	SM	0	SM
II	SM	1	SM	0	SM
III	SM	1	SM	SM	0

* Popovic/Simmons hep-ph/9806287

Gauge coupling limits [$\kappa_3 \equiv \alpha_s \cot^2\theta_3\,, \quad \kappa_1 \equiv \alpha_Y \cot^2\theta_1$]

constraints from gauged NJL gap equations



$$\kappa_3 + \tfrac{2}{27}\kappa_1 \geq \tfrac{2\pi}{3} - \tfrac{4}{3}\alpha_s - \tfrac{4}{9}\alpha_Y \qquad \langle t\bar{t}\rangle \neq 0$$

$$\kappa_3 + \tfrac{2}{27}\tfrac{\alpha_Y^2}{\kappa_1} < \tfrac{2\pi}{3} - \tfrac{4}{3}\alpha_s - \tfrac{4}{9}\alpha_Y \qquad \langle c\bar{c}\rangle = 0$$

$$\kappa_1 \;\; < 2\pi - 6\alpha_Y \qquad \langle \tau\tau\rangle = 0$$

constraint from $Z \to \tau\tau$

$Z\,Z'$ mixing alters $Z\tau\tau$ coupling

$$\delta g_{\tau_L} = \tfrac{1}{2}\delta g_{\tau_R} = \sin^2\theta_W \frac{M_Z^2}{M_{Z'}^2}[1 - \frac{f_t^2}{v^2}(\frac{\kappa_1}{\alpha_Y} + 1)]$$

where the top-pion decay constant is

$$f_t^2 = \frac{3}{8\pi^2} m_t^2 \ln\left(\frac{\Lambda^2}{m_t^2}\right) \quad \text{[NJL approx.]}$$

bounds from $\delta\rho$ [$Z\,Z'$ mixing, coloron exchange]

$$\Delta\rho_*^{(C)} \approx \frac{16\pi^2\alpha_Y}{3\sin^2\theta_W}\left(\frac{f_t^2}{M_C M_Z}\right)^2 \kappa_3$$

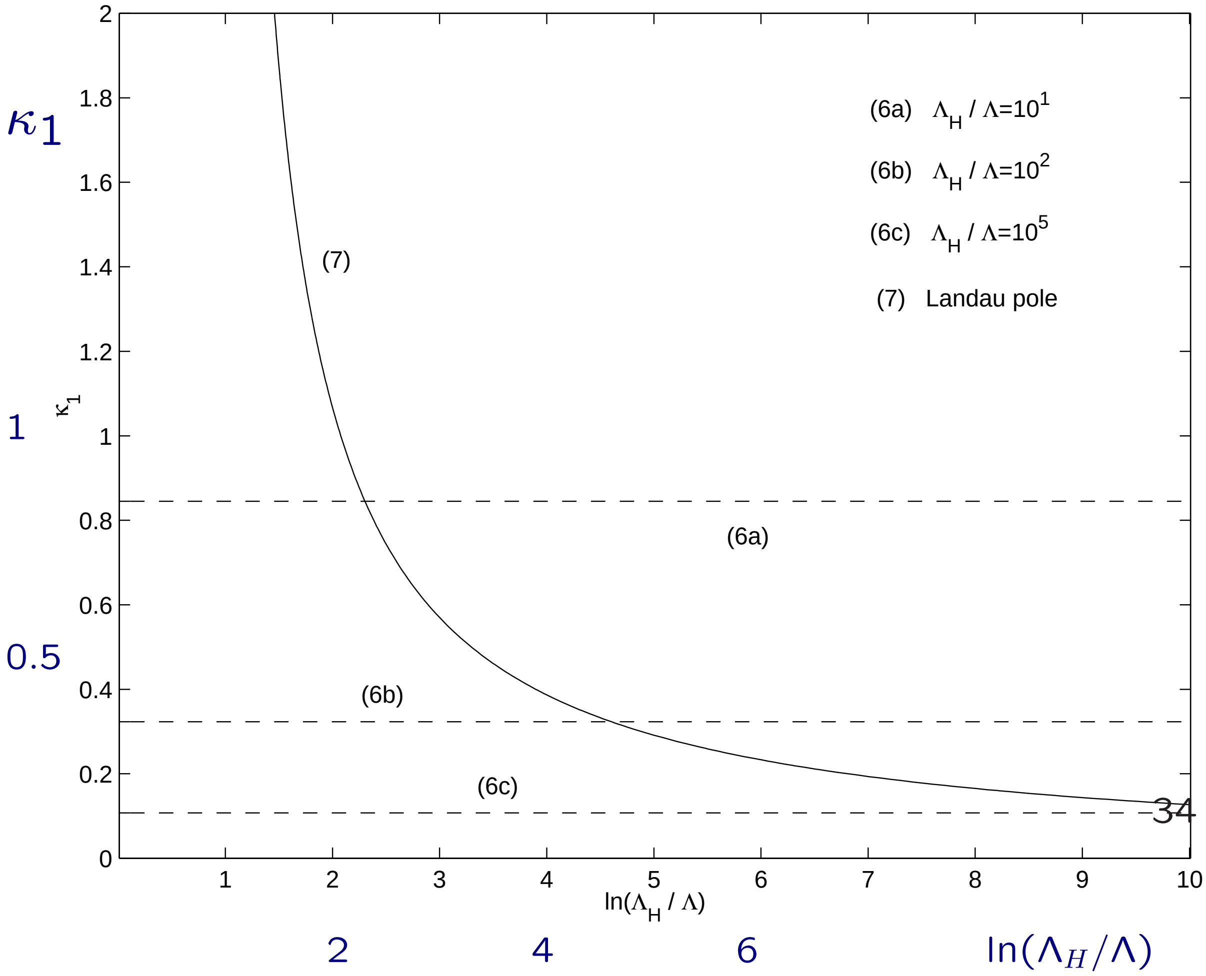
$$\Delta\rho_*^{(Z')} \approx \frac{\alpha_Y \sin^2\theta_W}{\kappa_1}\frac{M_Z^2}{M_{Z'}^2}[1 - \frac{f_t^2}{v^2}(\frac{\kappa_1}{\alpha_Y} + 1)]^2$$

constraint from UV behavior of $U(1)_1$

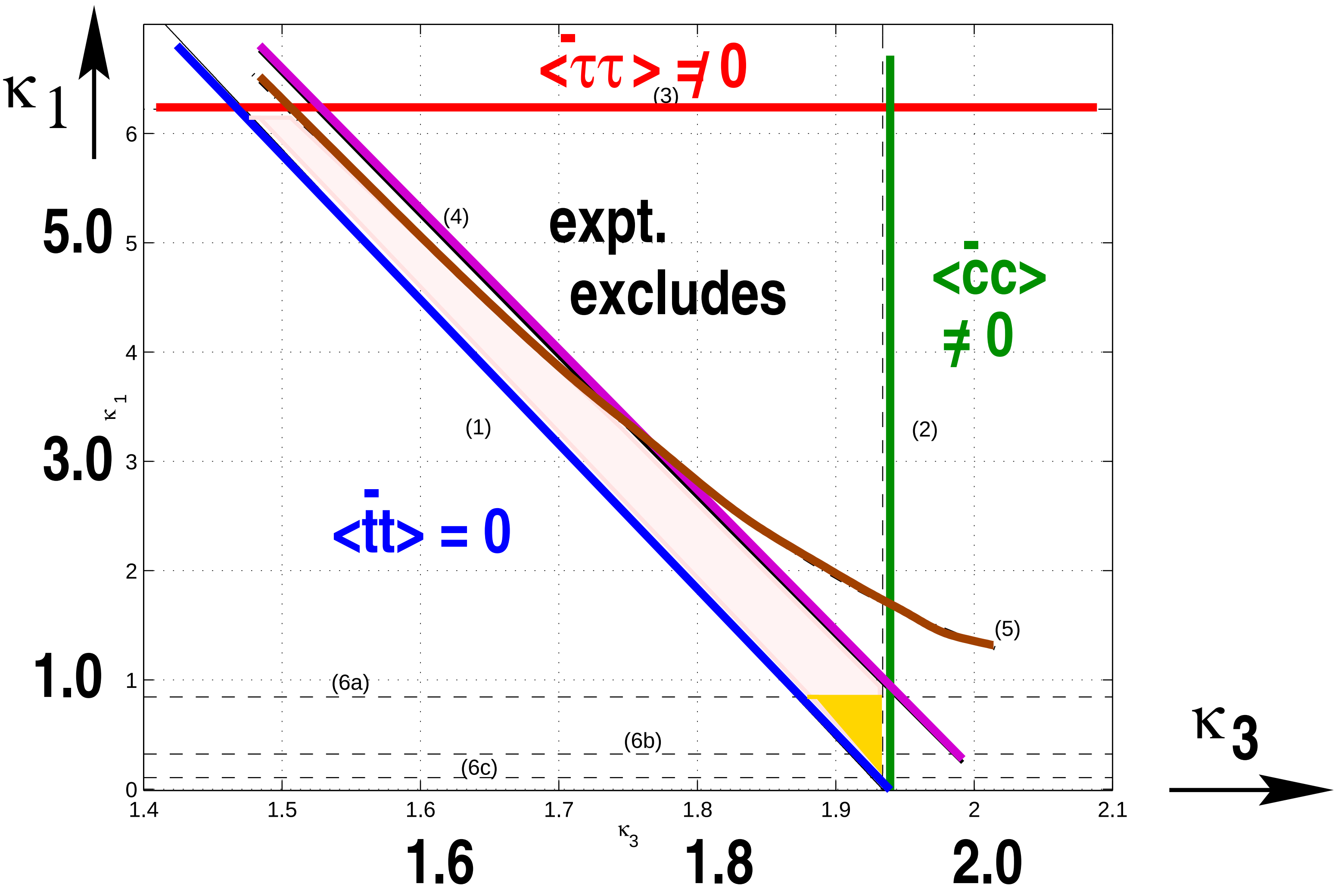
- strongly-coupled $U(1)_1$ tilts the vacuum
- Landau pole (Λ_H) of $U(1)_1$ found from RGE result [$A \equiv exp(5/3)$, $C = 15/4$]

$$\frac{g_{1(1)}^{2}}{4\pi}\Big|_{\Lambda_H} = \frac{\frac{g_{1(1)}^{2}}{4\pi}\big|_{\Lambda}}{1-\left(\frac{g_{1(1)}^{2}}{4\pi}\right)\big|_{\Lambda}\frac{C}{3\pi}\ln\left(\frac{\Lambda_H^2}{A\Lambda^2}\right)}$$

if Λ of symmetry-breaking is to lie below Λ_H then κ_1 cannot be too large:



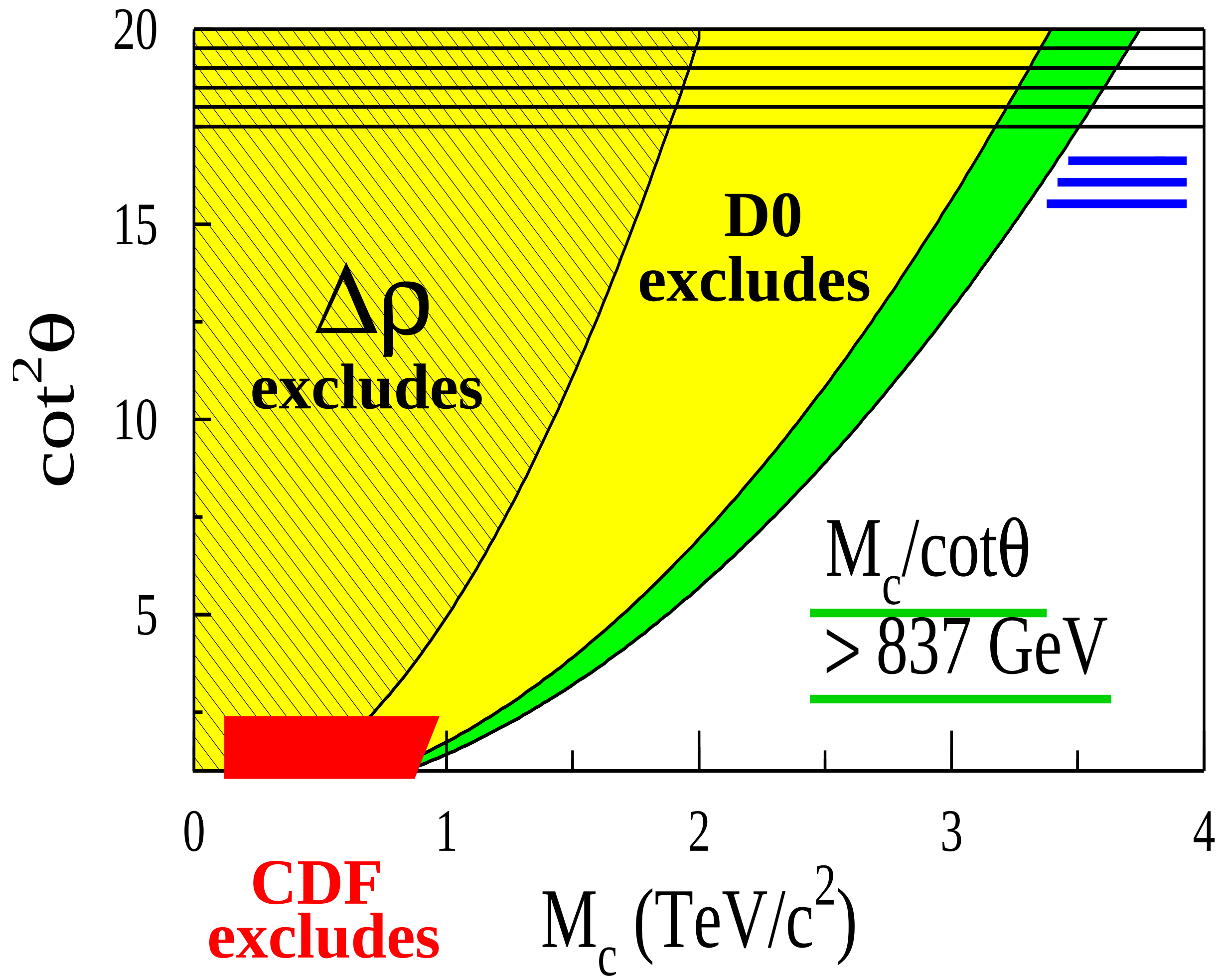
Plot of limits on strong and hypercharge couplings in flavor-universal coloron models



Limits on topcolor models are very similar

Flavor-universal coloron limits*

- as $\Gamma \approx \kappa_3 M_c$, coloron is generally broad; seek excess, not bump in dijet spectrum
- DØ dijet mass spectrum would show excess at high invariant mass $\Rightarrow$ $M_c/\cot\theta > 837 GeV$
- this implies $M_c \gtrsim 3.4$ TeV in dynamical models where coloron coupling is strong



* Bertram/Simmons hep-ph/9809472

Top Seesaw Models* Summarized

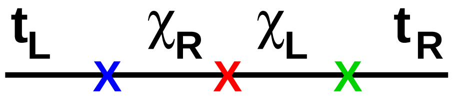
color sector: $SU(3)_h \times SU(3)_\ell \to SU(3)_{QCD}$

weak + hypercharge sectors: standard

3rd family fermions: regular (t, b), exotic (χ)
t_L, b_L and χ_R transform under $SU(3)_h$
t_R, b_R and χ_L transform under $SU(3)_\ell$

	$SU(3)_h$	$SU(3)_\ell$	$SU(2)$
$(t,\ b)_L$	3	1	2
$t_R,\ b_R$	1	3	1
χ_L	1	3	1
χ_R	3	1	1

seesaw mass for top



$$\begin{pmatrix} \bar{t}_L & \bar{\chi}_L \end{pmatrix} \begin{pmatrix} 0 & \mu \\ m_o & M_\chi \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix}$$

composite scalars: $\bar{t}_L \chi_R$

unlike topcolor: $(\bar{3}, 3, 1, 0)$ condensate breaking color symmetry must couple t_L to χ_R

---

* Hill/Dobrescu hep-ph/9712319

Context of Top Seesaw Models

Earlier ideas:

Form composite Higgs bosons as $T\bar{T}$ bound states in strongly-coupled (walking) ETC and have them break electroweak symmetry

OR

Form composite top-Higgs as $t\bar{t}$ bound state of spontaneously broken topcolor to make top heavy in TC2 models, while the TC sector breaks electroweak symmetry

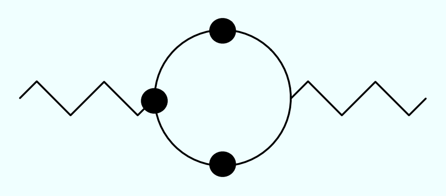
More economical:

Make composite Higgs from top quarks* using strong topcolor interaction. In contrast to TC2 models, EWSB can be due to $\langle t\bar{t}\rangle \neq 0$, without technicolor.

... but can a $t\bar{t}$ bound state play both roles?

* Bardeen, Hill, Lindner, 1990

Recall Pagels-Stokar relationship of v to dynamical fermion mass $\Sigma(p)$



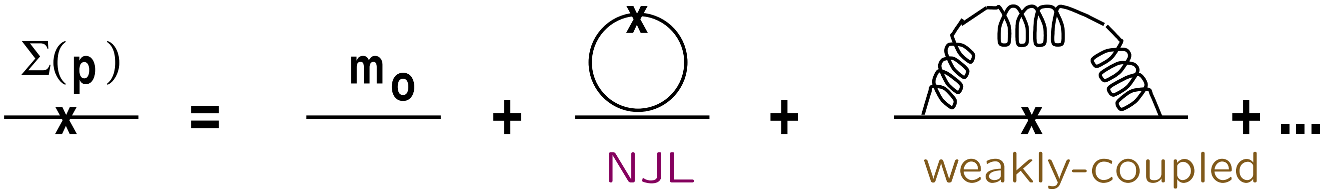
$$v^2 = \frac{N}{16\pi^2}\int_0^\infty dk^2\, \frac{4k^2\Sigma^2+\Sigma^4}{(k^2+\Sigma^2)^2}$$

Approximate topgluon exchange by a 4-fermion interaction. This NJL (Nambu– Jona-Lasinio†) model is equivalent to a large N_c expansion.

$$\frac{g^2}{2}\left(\bar\psi\gamma_\mu\frac{\lambda^A}{2}\psi\right)\frac{g^{\mu\nu}}{q^2-M^2}\left(\bar\psi\gamma_\nu\frac{\lambda^A}{2}\psi\right)\supset$$

$$\frac{g^2}{M^2}(\bar\psi^a_L\psi_{Ra})(\bar\psi^b_R\psi_{Lb})$$

In this "fermion bubble" approximation, $\Sigma(p)$ is constant; call it just m_t.



Then the Pagels-Stokar formula reduces to

$$v^2 \approx \frac{N_c}{8\pi^2}m_t^2(\log\frac{M^2}{m_t^2} + k).$$

† Nambu, Jona-Lasinio, 1961

Applying this result to topcolor ($k \sim 1$, $N_c = 3$)

$$v^2 \approx \frac{N_c}{8\pi^2} m_t^2 (\log \frac{M^2}{m_t^2} + k).$$

yields a dilemma

- To produce $v = 246$ GeV from dynamics at $M \sim 1$TeV, one is forced to generate $m_t \sim 600$ GeV.
- If we pin $m_t \sim 178$ GeV ($v = 246$ GeV), we require $M \sim 10^{15}$ GeV.
  What problem results?

Pure top condensation will not suffice for EWSB. But what if top is a bit less "standard"?

Here's where the "seesaw" idea enters.

Seesaw: If top mixes with (e.g. weak-singlet) partner fermion "χ", the top we see is a mass (not gauge) eigenstate. Seesaw mixing pattern

$$\begin{pmatrix} \bar{t}_L & \bar{\chi}_L \end{pmatrix} \begin{pmatrix} 0 & \mu \\ m_o & M_\chi \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix}$$

yields two mass eigenstates;

- one is mostly top (LH weak doublet):

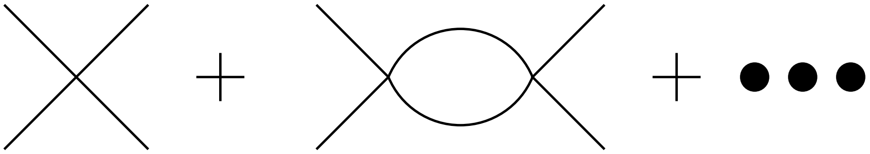
$$m_t^{expt} \approx \frac{m_o \mu}{M_\chi} \approx 178\text{GeV}$$

- complementary state (mostly χ) is heavy, with mass $\sim M_\chi$.
- As $\mu \approx 600$ GeV appears in Pagels-Stokar, seesaw makes top-generated EWSB viable.

Can rewrite NJL interaction as composite Higgs

$$\frac{g^2}{M^2}(\bar{\psi}_L^a \psi_{Ra})(\bar{\psi}_R^b \psi_{Lb}) \rightarrow (g\overline{\psi}_L \psi_R H + h.c.) - M^2 H^\dagger H$$

- Fermion bubble approximation: $M_H \approx 2m_t$.



- Consistent with EW data? (stay tuned)

Dynamical Issues

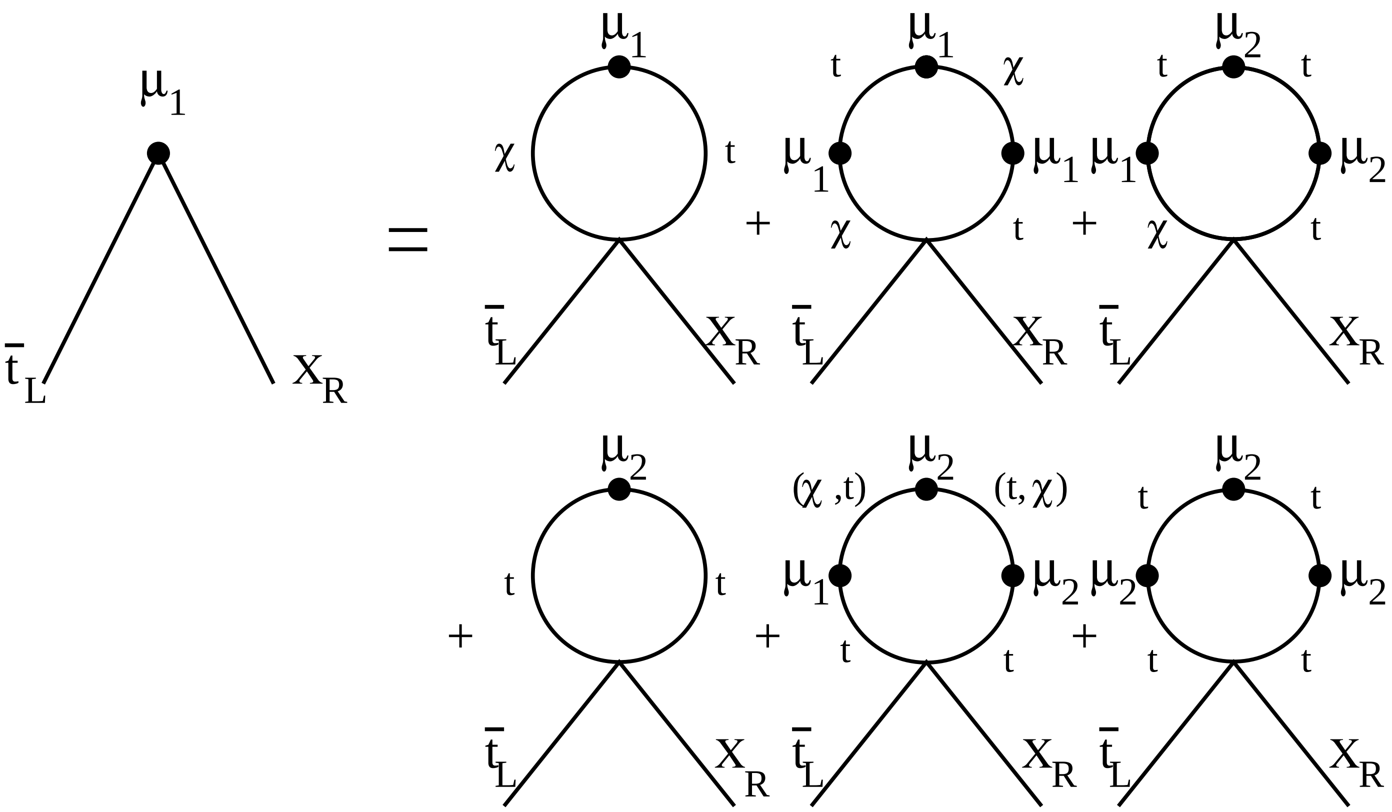
Since M_χ and m_o link only weak-singlet fermions, they are allowed by unbroken $SU(2) \times U(1)$. But μ involves weak-charged t_L and must be dynamically generated.

Can the topcolor/seesaw Lagrangian do this?

$$\mathcal{L} \supset -(M_\chi \overline{\chi_L}\,\chi_R + m_0\,\overline{\chi_L}\,t_R + \text{h.c.})$$
$$+\frac{h_1^2}{M^2}(\overline{\psi_L}\,\chi_R)\,(\overline{\chi_R}\,\psi_L) \qquad \text{NJL}$$

- Rotate (t_R, χ_R) basis by $\tan\phi_R \equiv m_o/M_\chi$ so the d=3 terms $\mathcal{L}$ are diagonal
- Postulate dynamical mass terms $\mu_1 \bar{t}_L \chi_R$ and $\mu_2 \bar{t}_L t_R$ (cf. $\mu_1 = \mu\cos\phi_R, \quad \mu_2 = \mu\sin\phi_R$)
- Solve gap equations...

E.g. dynamical μ_1 is (nontrivial) solution of

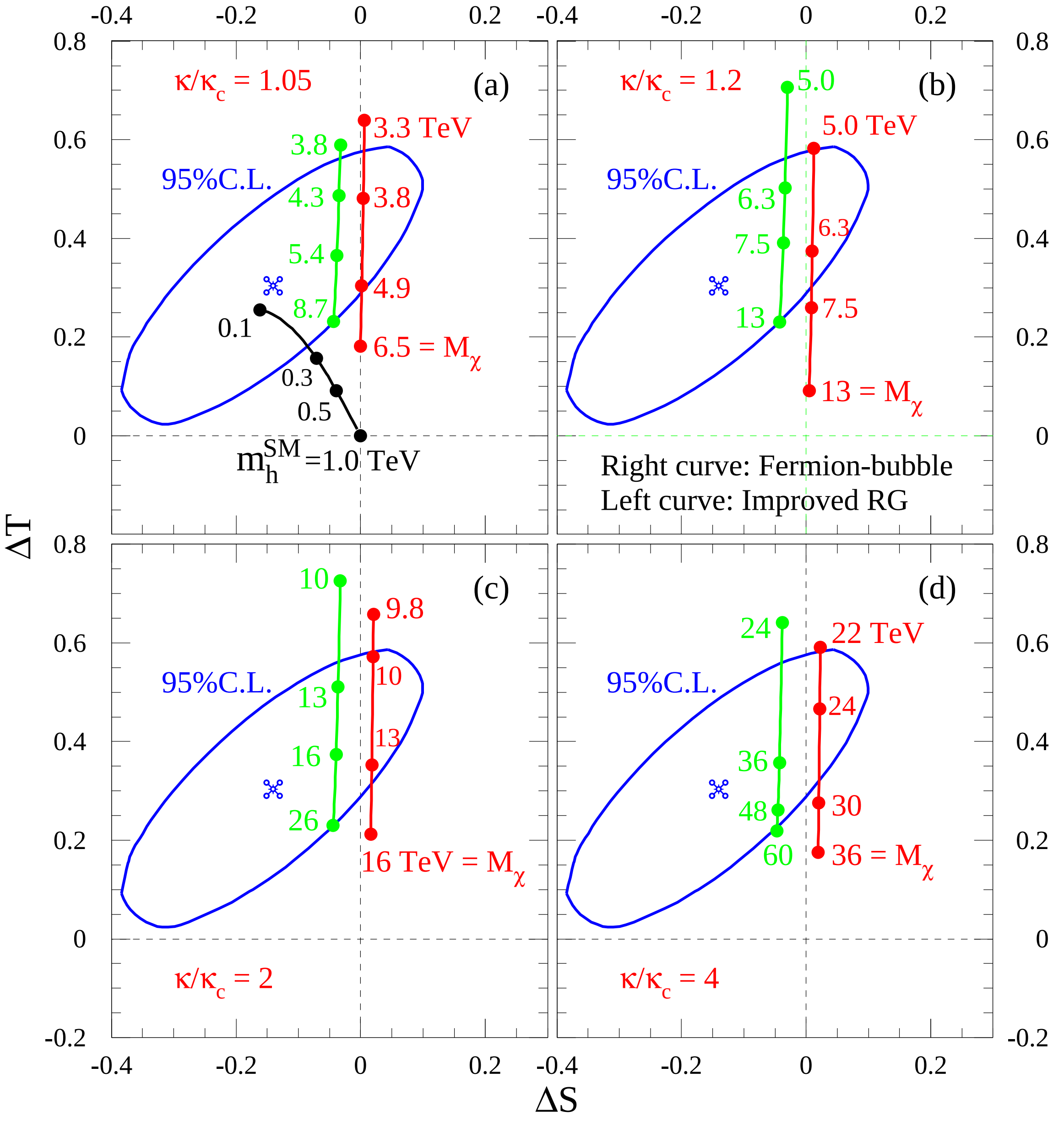


Solutions for do exist above a critical NJL coupling strength: $h_1^2/4\pi \equiv \kappa > \kappa_c \equiv 2\pi/3$.

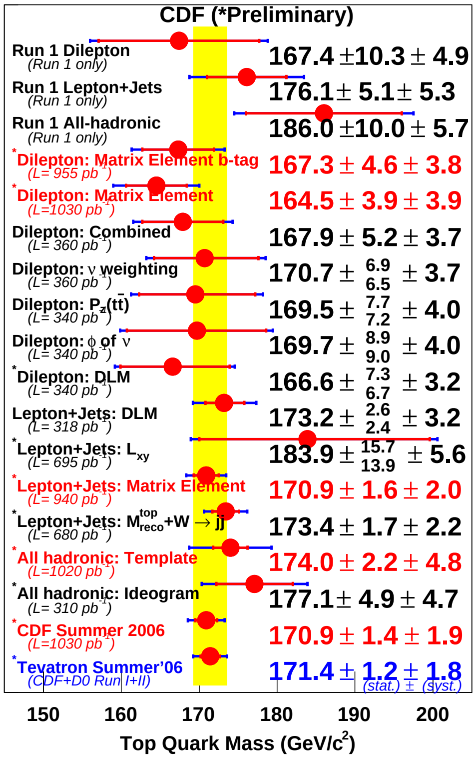
Success!

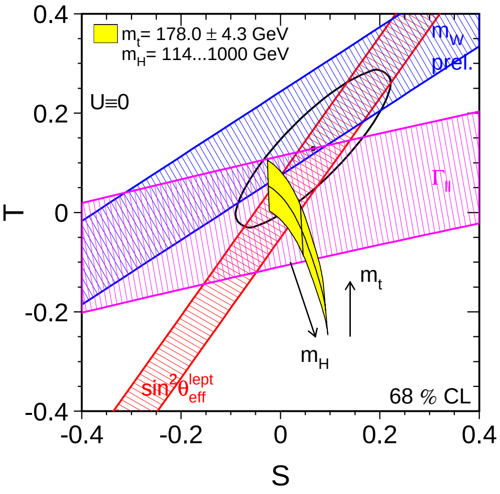
Precision Electroweak Constraints on Top Seesaw

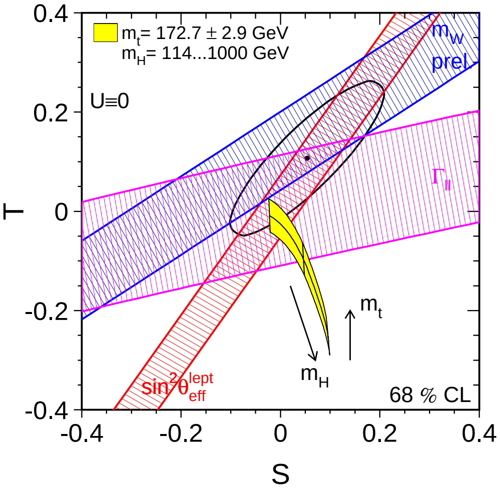
Data favors ellipse in $S-T$ plane, bounding M_χ as a function of topcolor coupling κ.



Shifts* in central m_t value affect S-T ellipse.







What does this imply for M_χ constraints in top seesaw models?

LEPEWWG: upper (lower) S-T plot early (late) summer 2005

Top/Bottom Seesaw and beyond

Gauge group: $SU(3)_1 \times SU(3)_2 \times SU(2)_W \times U(1)_Y$

Add partner ω for bottom quark:

$SU(3)_1$	$SU(3)_2$
$\left(\begin{array}{l} \begin{pmatrix} t \\ b \end{pmatrix}_L \; I = \frac{1}{2} \\ \begin{pmatrix} \chi \\ \omega \end{pmatrix}_R \; I = 0 \;\; or \;\; \frac{1}{2} \end{array} \right)$	$\left(\begin{array}{l} \begin{pmatrix} t \\ b \end{pmatrix}_R \; I = 0 \\ \begin{pmatrix} \chi \\ \omega \end{pmatrix}_L \; I = 0 \;\; or \;\; \frac{1}{2} \end{array} \right)$

Seesaw mass forms for b

$$\begin{pmatrix} \bar{b}_L & \bar{\omega}_L \end{pmatrix} \begin{pmatrix} 0 & \mu_\omega \\ m_\omega & M_\omega \end{pmatrix} \begin{pmatrix} b_R \\ \omega_R \end{pmatrix}$$

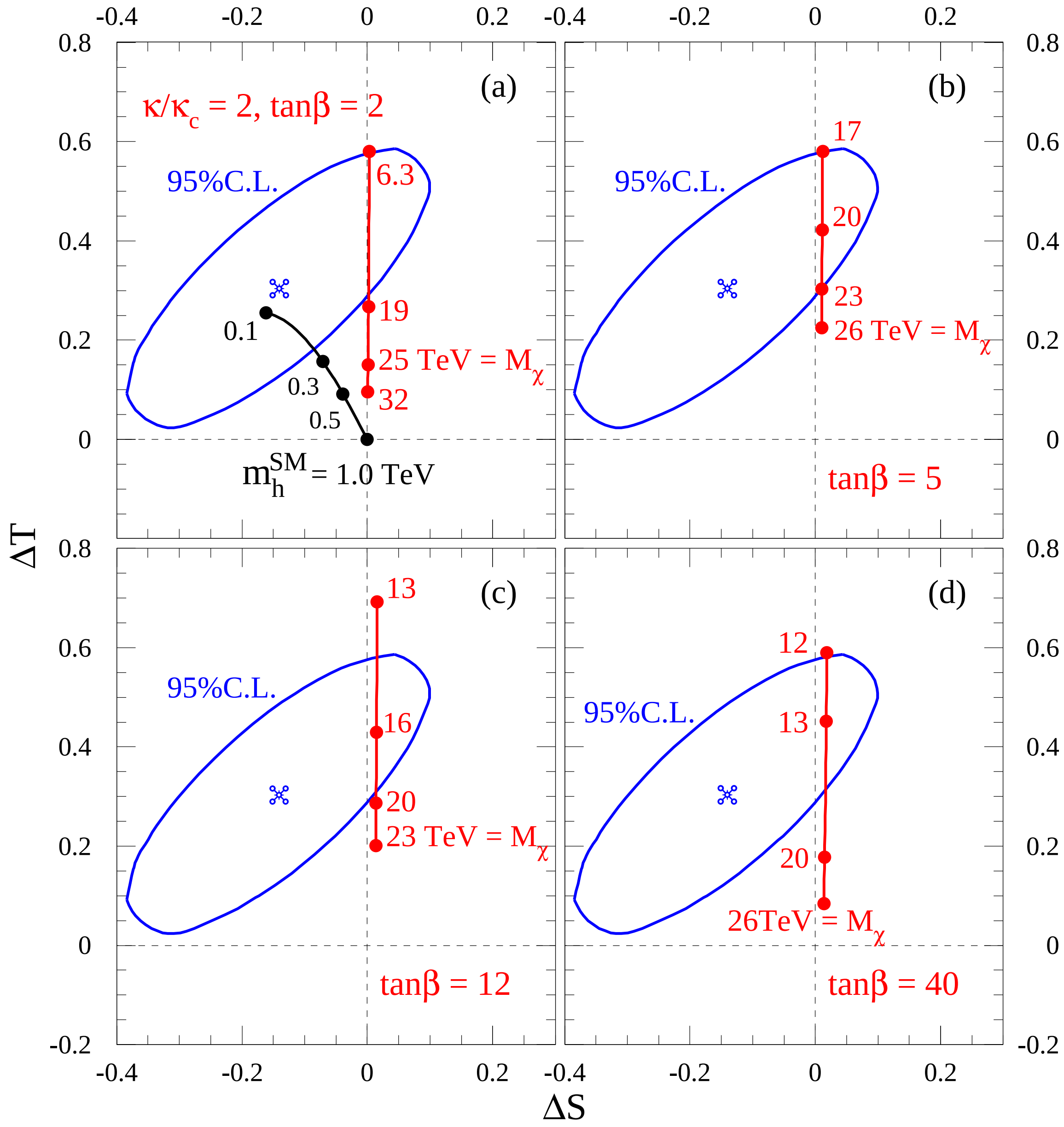
small m_ω suppresses m_b (cost?)

New composite scalars created:
neutral $\overline{b_L}\omega_R$; charged $\overline{t}_L\omega_R$, $\overline{b}_L\chi_R$

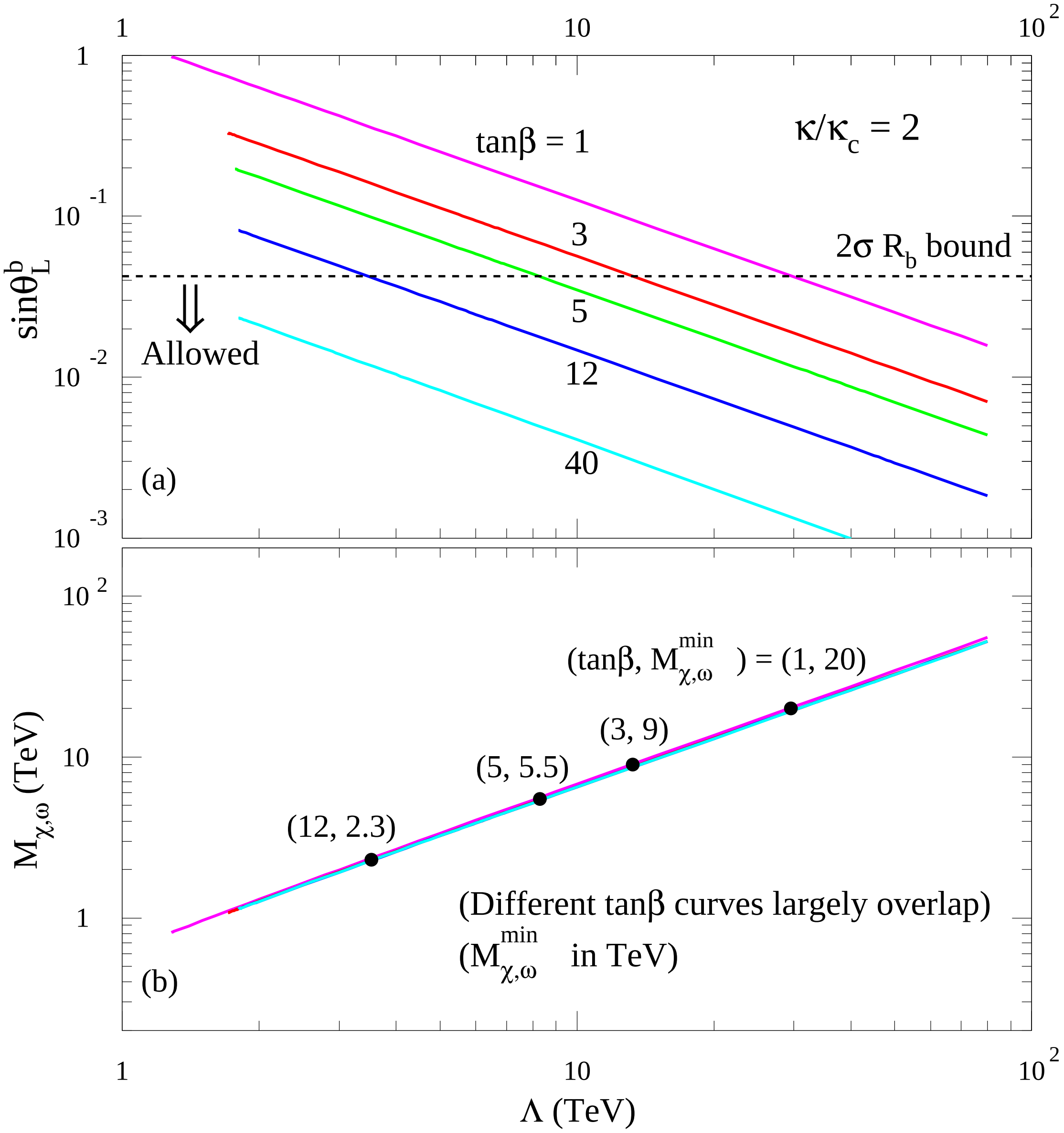
precision signatures: shifts in S, T, R_b

ambitious extensions: flavor-universal models

Precision Electroweak Constraints on Top/Bottom Seesaw



Top-Bottom Seesaw and R_b

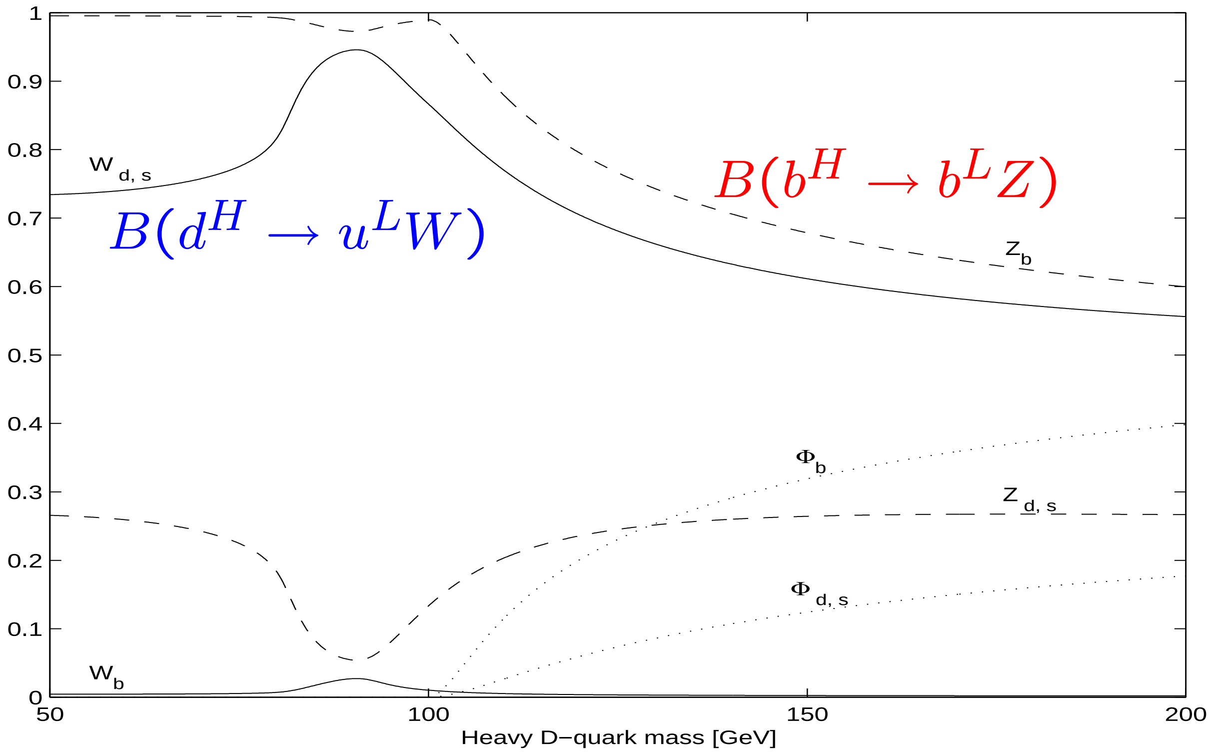


DØ/CDF pair-production limits* on weak-singlet quarks mixing with ordinary quarks

(a) Seek excess in top-search dilepton events

$$p\bar{p} \to q^H \bar{q}^H \to q^L W \bar{q}^L W \to q^L \bar{q}^L \ell \nu_\ell \ell' \nu_{\ell'}$$

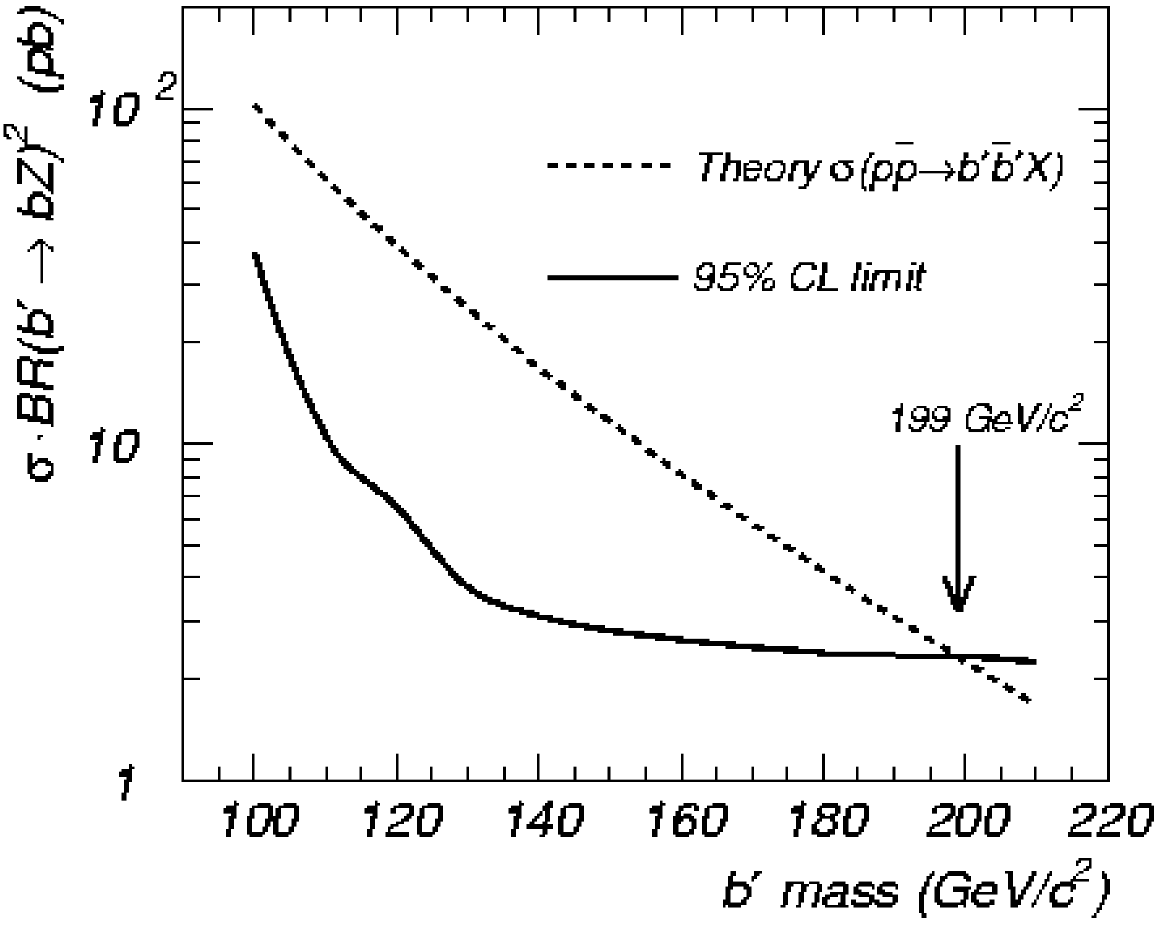
Flavor-conserving neutral-current decays and Cabbibo suppression lower $B(q^H \to q^L W)$



- $M_{s',d'} \gtrsim$ 140 GeV
- $M_{b'} \gtrsim$ 160 GeV [if d,s,b all partnered]

* Popovic/Simmons hep-ph/0001302

(b) CDF search for $p\bar{p} \to b^H \bar{b}^H$ excludes 100 GeV $< M_{b^H} <$ 199 GeV if $B(b^H \to b^L Z) \sim 1$.



Note: LHC can see pair-produced χ quarks via $\chi \to ht \to t\bar{t}t$ in 6-top final states. $\sigma \sim 1pb^{-1}$.

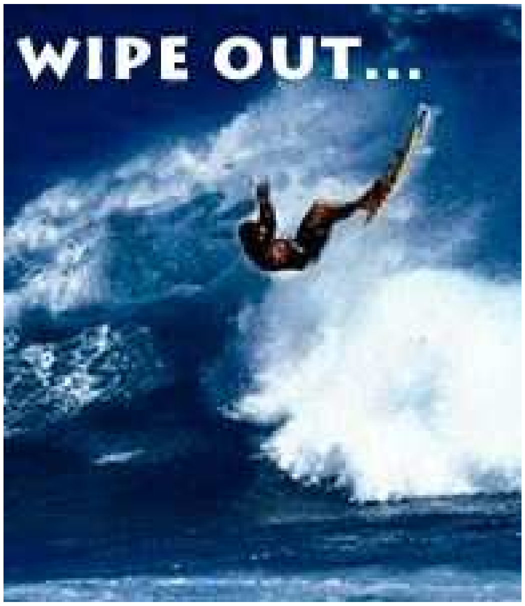
5. Summary

Creating a large mass for the top quark - and only the top quark - is a challenge in models of dynamical electroweak symmetry breaking.

It is necessary to maintain a delicate balance

between several kinds of experimental constraints.

Some early models like (commuting) Extended Technicolor or Top-Mode Standard Model foundered



under the opposing forces of the large top mass and the low scale of electroweak dynamics.

Data on the $Zb\bar{b}$ coupling and weak isospin violation have been the impetus for creation of models in which the top's large mass is provided by gauge interactions specific to the third generation.

So far, models like Non-Commuting ETC, TopFlavor, Topcolor-Assisted Technicolor, and Top Seesaw are still in play.

These models have a rich phenomenology that should afford clear signals...

…for ongoing and future experiments to pursue

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Experiments' websites:

    CDF: www-cdf.fnal.gov

    DØ : www-d0.fnal.gov

    LEP EW Working Group: lepewwg.web.cern.ch/LEPEWWG/