Composite Higgs boson from top dynamics

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Outline:

- **Composite Higgs models**
- $U(3)_L$**-symmetric Top-seesaw model**
- **Computation of the Higgs mass**
- **Signatures of vectorlike quarks**

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SM

Spin-1 fields:

$$\left\{ \begin{array}{rl} G^\mu & (8, 1, \ \ 0) \\ W^\mu & (1, 3, \ \ 0) \\ B^\mu & (1, 1, \ \ 0) \end{array} \right.$$

Spin-0 field: $H \ (1, 2, \ +1/2)$

Spin-1/2 fields:

$$3 \times \left\{ \begin{array}{rl} q_L & (3, 2, \ \ +1/6) \\ u_R & (3, 1, \ \ +2/3) \\ d_R & (3, 1, \ \ -1/3) \\ l_L & (1, 2, \ \ -1/2) \\ e_R & (1, 1, \ \ -1) \end{array} \right.$$

SM

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Spin-2 field: graviton with $M_{\rm Planck}$-suppressed interactions

(effective theory breaks down near 10^{16} TeV)

ν masses require:

$\frac{c}{M}HHl_Ll_L$ interactions, suppressed by $M/c \approx 10^{14}$ GeV

or

additional spin-1/2 fields: $3\times\nu_R(1,1,0)$ which together with the SM ν_L acquire Dirac masses.

SM

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SMνg

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- Dark matter requires particle(s) beyond the SM$\nu\mathcal{G}$

DM particle can be a fermion (Majorana or Dirac)
or a boson (spin 0 or 1).

DM particle may be part of a large hidden sector ...

- A 4th generation of chiral quarks and leptons is essentially ruled out by the LHC searches for new quarks.

Vectorlike quarks or leptons = fermions whose masses are gauge invariant; current limits on their masses around 700 GeV.

Only spin-0 particle of the SM$\nu\mathcal{G}$:

Higgs boson discovered by the ATLAS and CMS collaborations

mass near 125 GeV, SM-like couplings (so far).

Is the Higgs doublet a composite field?

If so, what are its constituents?

What binds them inside the Higgs field?

What are the experimental tests?

Composite Higgs models - Nambu-Goldstone bosons

• 1984 - 1985: Kaplan, Georgi, Dugan, Banks, Dimopoulos, ...

QCD-like theories with Nambu-Goldstone bosons transforming as the SM Higgs doublet

• 2003 - ... : Agashe, Contino, Pomarol, Nomura, Redi, ...

Require vectorlike quarks

Strongly coupled conformal Higgs sector

• 1999 - ... : Randall, Sundrum, Agashe, Delgado, May, ...

Warped extra dimension with bulk fields
$\rightarrow$ include vectorlike quarks.

Composite Higgs models - Top condensation

• 1989 - 1993: Nambu; Miransky, Tanabashi, Yamawaki; Marciano; Bardeen, Hill, Lindner; ...

Strongly-coupled 4-fermion interactions $\rightarrow$ Higgs doublet is a bound state of $\bar{t}_R$ and $(t, b)_L$.

• 1997 - 1999: Hill, Dobrescu, Chivukula, Georgi, Tait, He, ...

Top-seesaw mechanism $\rightarrow$ Higgs doublet is a bound state of a vectorlike quark and $(t, b)_L$.

Top condensation

$$\frac{g^2}{\Lambda}(\bar{t}_R \psi^3_L)(\bar{\psi}^3_L t_R) \qquad\qquad \psi^3_L = (t,b)_L$$

Similar to Nambu–Jona-Lasinio model 1961

$g \gg 1 \;\to\; \bar{t}_R \psi^3_L$ bound state

– same quantum numbers as the SM Higgs doublet!

Fermion loop gives mass term in the potential

$$M_H^2 = \Lambda^2 \left(1 - \frac{g^2 N_c}{8\pi^2}\right)$$

Criticality condition: $g > \pi\sqrt{8/N_c} \to$ bound state gets a VEV.

Second order phase transition:

$\left|M_H^2\right| \ll \Lambda$ **is possible if g is tuned to be only slighly above $g_{\rm critical}$.**

4-fermion interaction is not confining.

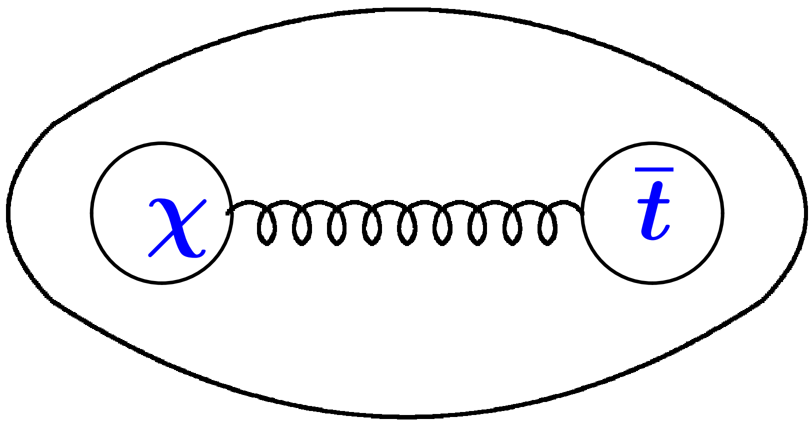
If Higgs doublet is a $\bar{t}_R \psi_L^3$ bound state, then top Yukawa coupling is large $\rightarrow m_t \approx 600$ GeV ... unless $\Lambda \rightarrow M_{\rm Planck}$

Top seesaw model

Higgs boson is a bound state of top quark with a new quark χ.

(BD, C. Hill, hep-ph/9712319, Chivukula et al, hep-ph/9809470)

Binding may be due to some strongly-interacting heavy gauge bosons



Scale of Higgs compositeness may be as low as a few TeV.

Minimal composite Higgs model (MCHM) with light scalars: B.D, hep-ph/9908391

Top seesaw: vectorlike quark χ, transforming as t_R.

H is a $\bar{\chi}_R \psi_L^3$ bound state.

$$- (\overline{t}_L, \overline{\chi}_L) \begin{pmatrix} 0 & \frac{\xi}{\sqrt{2}} v \\ m_{\chi t} & m_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix}$$

ξ at scale Λ, upon integrating out H, matches the coefficient of the 4-fermion interactions:

$$\xi^2 = \frac{8\pi^2}{N_c \ln(\Lambda/m_\chi)}$$

Composite scalars are $U(3)_L$ triplets:

$$\Phi_t = \begin{pmatrix} H_t \\ \phi_t \end{pmatrix} \sim \bar{t}_R \begin{pmatrix} \psi_L^3 \\ \chi_L \end{pmatrix} \quad , \quad \Phi_\chi = \begin{pmatrix} H_\chi \\ \phi_\chi \end{pmatrix} \sim \bar{\chi}_R \begin{pmatrix} \psi_L^3 \\ \chi_L \end{pmatrix}$$

Two Higgs doublets and two singlets:

$$H_t = \begin{pmatrix} \frac{1}{\sqrt{2}} \left(h_t + i A_t \right) \\ H_t^- \end{pmatrix} \quad , \quad H_\chi = \begin{pmatrix} \frac{1}{\sqrt{2}} \left(v + h_\chi + i A_\chi \right) \\ H_\chi^- \end{pmatrix}$$

$$\phi_t = \frac{1}{\sqrt{2}}(u s_\gamma + \varphi_t + i \pi_t) \quad , \quad \phi_\chi = \frac{1}{\sqrt{2}}(u c_\gamma + \varphi_\chi + i \pi_\chi)$$

$$\Phi = \left(\Phi_t \ , \ \Phi_\chi\right)$$

The scalar field Φ is a 3×2 complex matrix

$$V_\Phi = \frac{\lambda_1}{2}\,\mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] + \frac{\lambda_2}{2}\left(\mathrm{Tr}[\Phi^\dagger\Phi]\right)^2 + M_\Phi^2\Phi^\dagger\Phi$$

Explicit $U(2)_R$ breaking effects which distinguish t_R and χ_R:

$$\delta M_{tt}^2\ \Phi_t^\dagger\Phi_t + \delta M_{\chi\chi}^2\ \Phi_\chi^\dagger\Phi_\chi + (M_{\chi t}^2\Phi_\chi^\dagger\Phi_t + \mathrm{H.c.})$$

$$\mathcal{L}_{\rm mass} = -\mu_{\chi t}\bar{\chi}_L t_R - \mu_{\chi\chi}\bar{\chi}_L \chi_R + {\rm H.c.}$$

Below Λ, these fermion masses map to tadpole terms for the $SU(2)_W$-singlet scalars:

$$V_{\rm tadpole} = -(0,0,C_{\chi t})\Phi_t - (0,0,C_{\chi\chi})\Phi_\chi + {\rm H.c.}$$

Matching at the scale Λ gives

$$C_{\chi t} \approx \frac{\mu_{\chi t}}{\xi}\Lambda^2 \quad , \quad C_{\chi\chi} \approx \frac{\mu_{\chi\chi}}{\xi}\Lambda^2 \, .$$

Effective potential below the compositeness scale:

$$\begin{aligned} V_{\text{scalar}} &= \frac{\lambda_1+\lambda_2}{2}\left[(\Phi_t^\dagger\Phi_t)^2+(\Phi_\chi^\dagger\Phi_\chi)^2\right]+\lambda_1|\Phi_t^\dagger\Phi_\chi|^2+\lambda_2(\Phi_t^\dagger\Phi_t)(\Phi_\chi^\dagger\Phi_\chi) \\ & +M_{tt}^2\Phi_t^\dagger\Phi_t+M_{\chi\chi}^2\Phi_\chi^\dagger\Phi_\chi+(M_{\chi t}^2\Phi_\chi^\dagger\Phi_t+\text{H.c.}) \\ & -(0,0,2C_{\chi t})\text{Re}\,\Phi_t-(0,0,2C_{\chi\chi})\text{Re}\,\Phi_\chi \end{aligned}$$

In the large N_c limit, $\lambda_1 \gg \lambda_2$.

Mass-squared matrix of the CP-even neutral scalars (h_t, h_χ, φ_t, φ_χ):

$$\begin{pmatrix} M_{H^\pm}^2 + \frac{\lambda_1}{2} v^2 & 0 & -\frac{\lambda_1}{2} uvc_\gamma & -\frac{\lambda_1}{2} uvs_\gamma \\ 0 & \lambda_1 v^2 & 0 & \lambda_1 uvc_\gamma \\ -\frac{\lambda_1}{2} uvc_\gamma & 0 & M_{H^\pm}^2 + \frac{\lambda_1}{2}\left(1 + s_\gamma^2\right) u^2 & \frac{\lambda_1}{2} u^2 s_\gamma c_\gamma \\ -\frac{\lambda_1}{2} uvs_\gamma & \lambda_1 uvc_\gamma & \frac{\lambda_1}{2} u^2 s_\gamma c_\gamma & \lambda_1 \left(1 - \frac{s_\gamma^2}{2}\right) u^2 \end{pmatrix}$$

Keeping the leading order in v^2/u^2 and s_γ:

$$M_h^2 = \lambda_1 v^2 s_\gamma^2 \, \frac{M_{H^\pm}^2}{2M_{H^\pm}^2 + \lambda_1 u^2}$$

Higgs mass is suppressed by s_γ, because in the limit of $m_t \to 0$ the $U(3)_L$ breaking tadpole terms vanish and the H_χ and π_χ fields become Nambu-Goldstone bosons.

$$m_t \approx \frac{\xi}{\sqrt{2}} v\, s_\gamma$$

ξ and s_γ are related to the top Yukawa coupling $\quad s_\gamma \approx \frac{y_t}{\xi}$

ξ is expected to be between 3 and 4.5 $\rightarrow s_\gamma^2 \sim O(0.1)$.

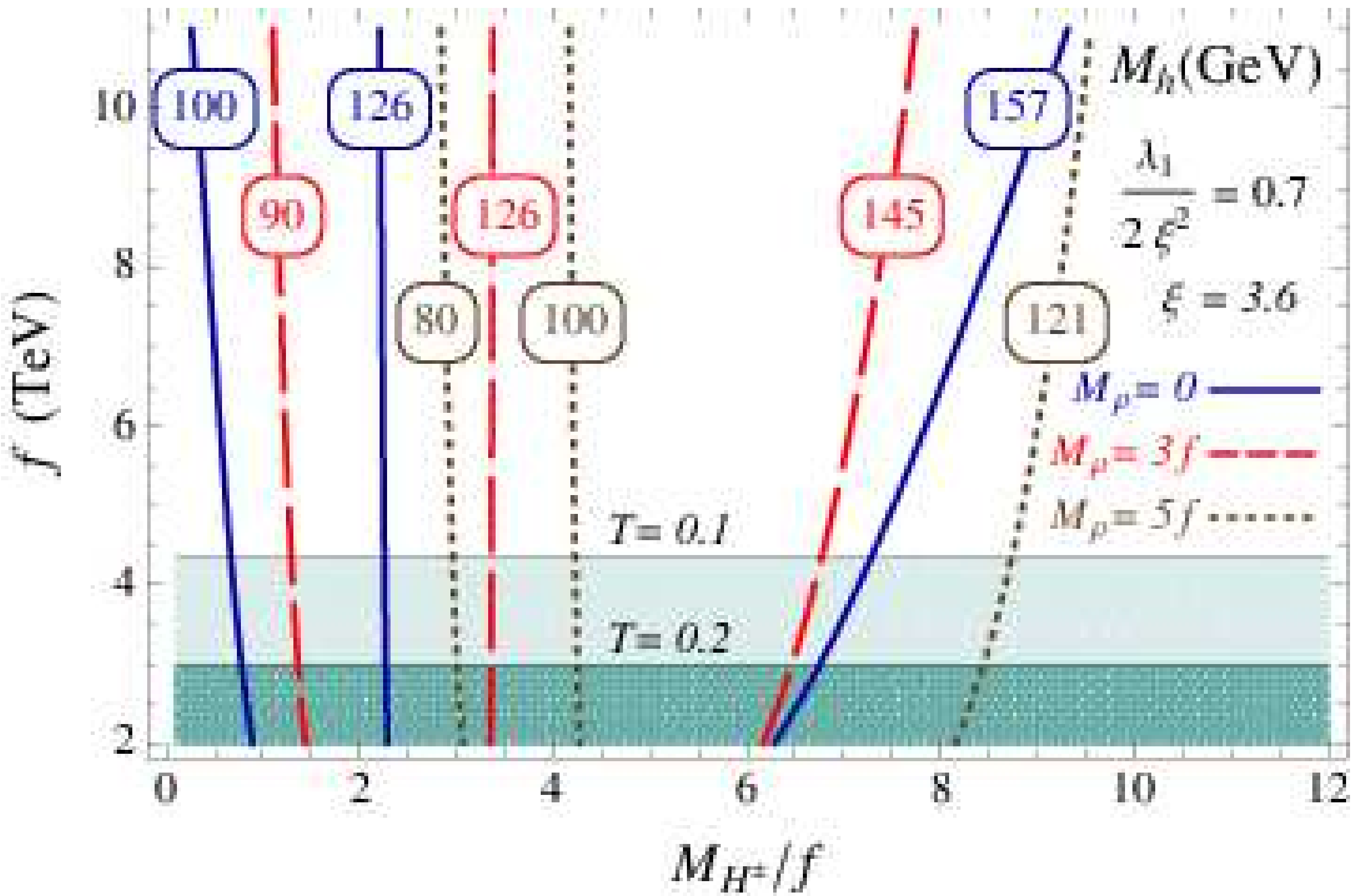
$$M_h^2 \approx \frac{\lambda_1}{2\xi^2} \left(1 + \frac{\lambda_1 m_{t'}^2}{\xi^2 M_{H^\pm}^2} \right)^{-1} y_t^2\, v^2$$

In the fermion-loop approximation of NJL the ratio of couplings $\lambda_1/(2\xi^2) = 1$. Scalar and gauge boson loops reduce this ratio:

$$0.4 \lesssim \frac{\lambda_1}{2\xi^2} \lesssim 1 \qquad \Rightarrow \qquad M_h < m_t$$

Additional $U(3)_L$ *breaking effects from* $SU(2)_W \times U(1)_Y$ *interactions.*
Higgs squared mass receives a correction:

$$\Delta M_h^2 \approx -(0.08\,v)^2 \frac{M_\rho^2}{f^2}$$



Custodial symmetry is broken by the $t - \chi$ mixing:

$$T \approx \frac{3}{16\pi^2 \alpha f^2}\left[\frac{v^2\xi^2}{2} + 4m_t^2 \ln\left(\frac{\xi f}{\sqrt{2}m_t}\right) - 2m_t^2\right]$$

$T < 0.15$ at 95% CL $\Rightarrow$ $f > 3.5$ TeV

Fine-tuning of order v^2/f^2 ...

Loopholes:

• higher-dimensional operators at the scale Λ may contribute to the T parameter. If they are negative, the limit on f decreases.

• additional states at the TeV scale may cancel the contribution of χ to the T parameter.

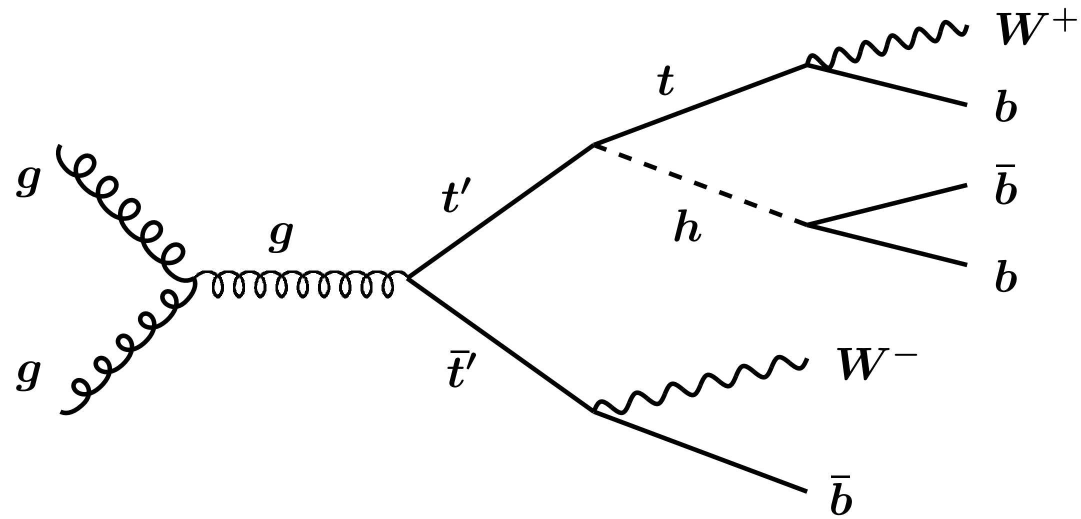
Example: H.C. Cheng, J. Gu: 1406.6689 custodial symmetry is preserved in the presence of a vectorlike quark transforming as (3,2,7/6) $\Rightarrow$ $f \gtrsim 1$ TeV

Mass of the new quark:

$$m_{t'} \approx \frac{\xi}{\sqrt{2}} f$$

$f > 3$ TeV $\Rightarrow$ $m_{t'} > 8$ TeV

$M_{H_1} > m_{t'}$ We need a VLHC!



"Light" CP-odd scalar: $M_A > 1$ TeV,

gluon fusion through χ loop ...

Story #2: Peculiar decays of vectorlike quarks

All Standard Model fermions are chiral: their masses are not gauge invariant, and arise from the Higgs coupling.

Vectorlike (*i.e.* non-chiral) fermions – *a new form of matter.*
Masses allowed by $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry,
$\Rightarrow$ naturally heavier than the t quark.

Usual LHC searches for vectorlike quarks rely on their decays into a SM quark and a $\boldsymbol{W}$ or $\boldsymbol{Z}$ or $\boldsymbol{h^0}$ boson.

Depending on some parameters, the vectorlike quarks may predominantly decay into 3 SM quarks,
or into one quark and two leptons,
or into one quark plus a g or γ.

A vectorlike t' quark

A vectorlike quark χ which transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the top quark:

$$\mathcal{L} = -\left(\overline{u}^3_L \; , \; \overline{\chi}_L\right) \begin{pmatrix} \lambda_t v_H & 0 \\ M_0 & M_\chi \end{pmatrix} \begin{pmatrix} u^3_R \\ \chi_R \end{pmatrix}$$

λ_t is the top Yukawa coupling
$v_H \simeq 174$ GeV is the Higgs vacuum expectation value
M_0 and M_χ are mass parameters

χ *is present in: Top-quark seesaw theory, Little Higgs models, ...*

Transform the gauge eigenstates u^3 and χ to the physical states t and t':

$$\begin{pmatrix} t_L \\ t'_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} u^3_L \\ \chi_L \end{pmatrix}$$

The three initial parameters λ_t, M_0, M_χ are replaced by physical parameters: m_t (measured!), $m_{t'}$ and $s_L \equiv \sin\theta_L$.

Decay widths of t':

$$\Gamma(t' \to W^+ b) = \frac{s_L^2\, m_{t'}^3}{32\pi v_H^2}\left[1 + O\left(\frac{M_W^4}{m_{t'}^4}\right)\right]$$

$$\Gamma(t' \to Zt) = \frac{s_L^2 c_L^2\, m_{t'}^3}{64\pi v_H^2}\left[1 + O\left(\frac{M_Z^4}{m_{t'}^4}\right)\right]$$

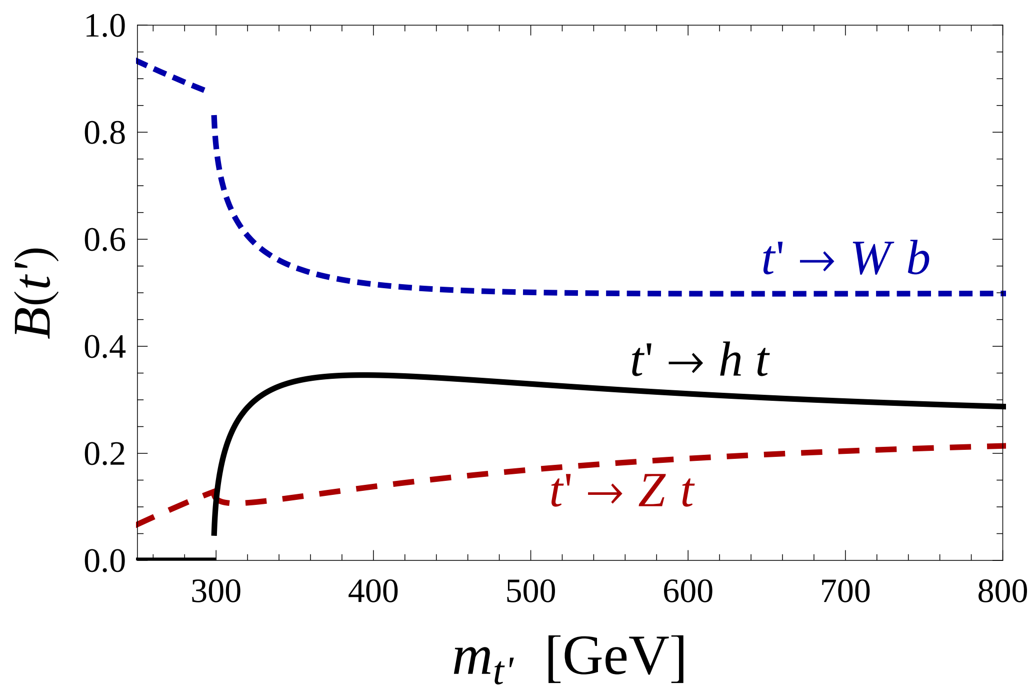
If $m_{t'} > M_h + m_t$:

$$\Gamma(t' \to ht) = \frac{s_L^2 c_L^2 m_{t'}^3}{64\pi v_H^2}\left[\left(1 + \frac{m_t^2 - M_h^2}{m_{t'}^2}\right)\left(1 + \frac{m_t^2}{m_{t'}^2}\right) + \frac{4m_t^2}{m_{t'}^2}\right]\left[\left(1 - \frac{m_t^2 + M_h^2}{m_{t'}^2}\right)^2 - 4\frac{m_t^2}{m_{t'}^2}\right]^{1/2}$$

(with K. Kong, R. Mahbubani, 0902.0792)

Branching fractions of t':

$$(s_L = 0.1)$$



QCD production of $t'\bar{t}'$, followed by t' decays, leads to various final states:

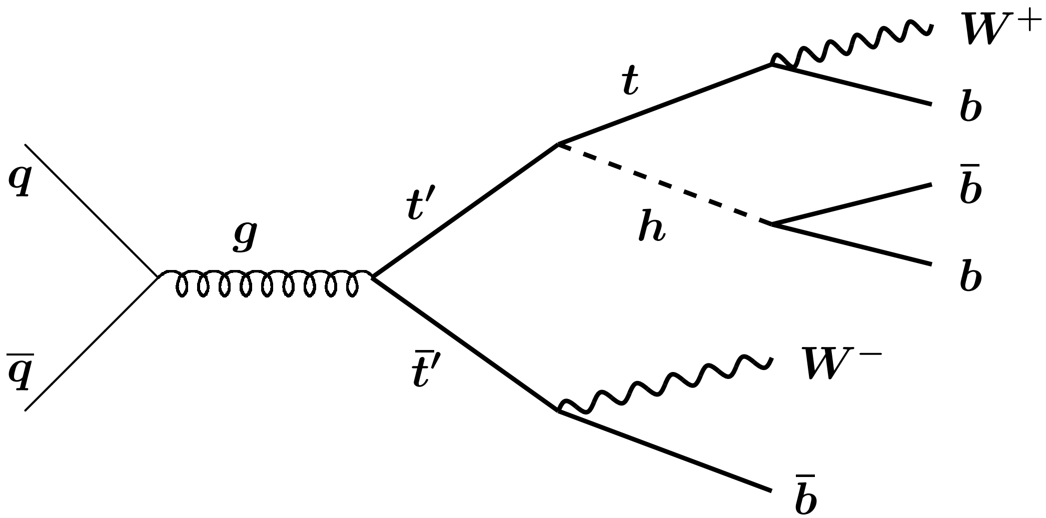
$(W^+b)(W^-\bar{b})$ usual "t' search"

$(Zt)(W^-\bar{b})$ or $(Z\bar{t})(W^+b)$

$(ht)(W^-\bar{b})$ or $(h\bar{t})(W^+b)$, with $h \to b\bar{b}$ or $h \to W^+W^-$

...

Example:



If $s_L \to 0$ then the widths for $t' \to Wb, Zt, ht$ vanish.

$\longrightarrow$ Decays via higher-dimensional operators may dominate.

Interactions of vectorlike quark χ with three SM quarks

Dimension-6 operators:

$Q_L = (t_L, b_L)$

$$\frac{1}{M_\phi^2}(\bar{\chi}_R Q_L)\left(\bar{Q}_L t_R + i\sigma_2 \bar{b}_R Q_L\right) \quad , \quad \frac{1}{M_{\tilde{d}}^2}(\bar{\chi}_R t_R^c)(\bar{t}_R^c t_R)$$

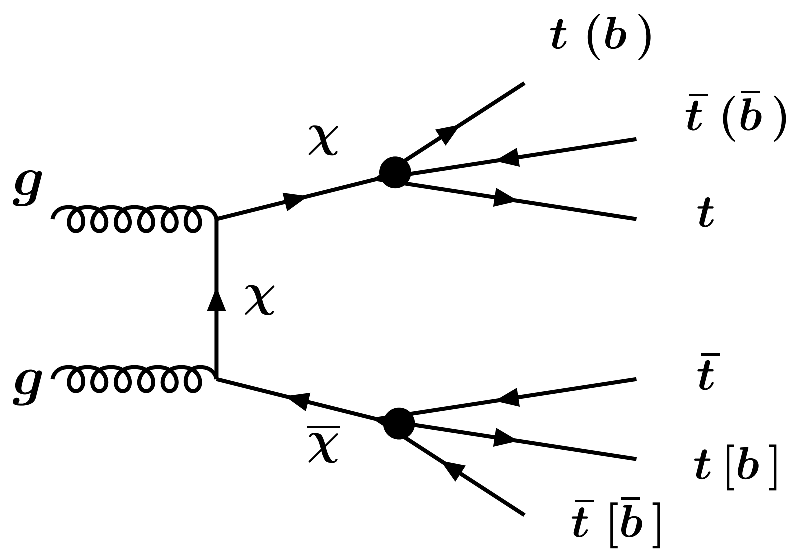
These may be induced by the exchange of a particle of mass $> O(5)$ TeV.

Simplest possibility: a scalar $\rightarrow$ couplings proportional to fermion masses

$\rightarrow$ 3rd generation fermions in the final state

Decay modes:

$\chi \rightarrow t\bar{t}t \ , \ b\bar{b}t$



Interactions of vectorlike quark χ with a SM quark and two leptons

Dimension-6 operators:

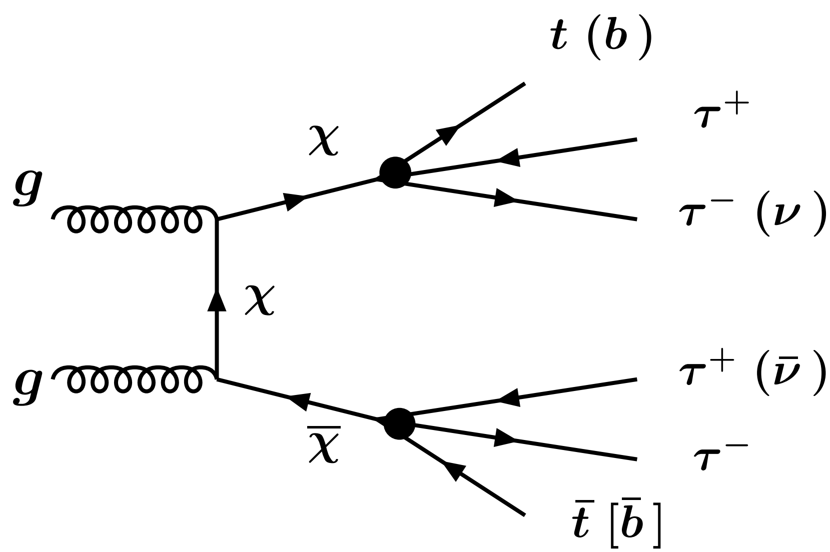
$L_L = (\nu_L, \tau_L)$

$$\frac{1}{M_\phi^2}(\bar{\chi}_R Q_L)\left(\bar{L}_L \tau_R + i\sigma_2 \bar{\tau}_R L_L\right) \;,$$

$$\frac{1}{M_S^2}(\bar{\chi}_R L_L)\left(\bar{L}_L t_R + i\sigma_2 \bar{\tau}_R Q_L\right) \;, \quad \frac{1}{M_R^2}(\bar{\chi}_R \tau_R^c)(\bar{\tau}_R^c t_R)$$

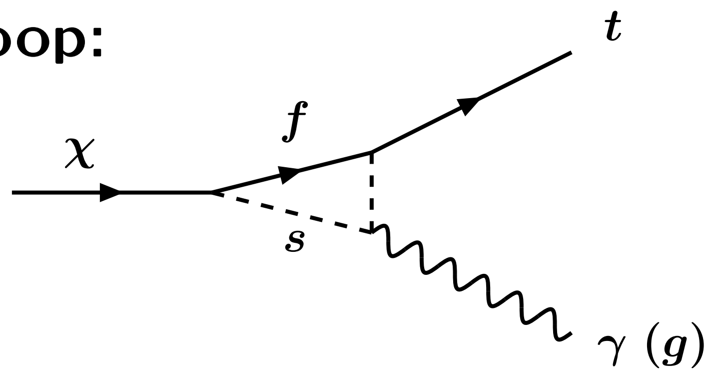
Decay modes:

$\chi \to \tau^+\tau^- t \;, \; \tau^+ \nu \, b$



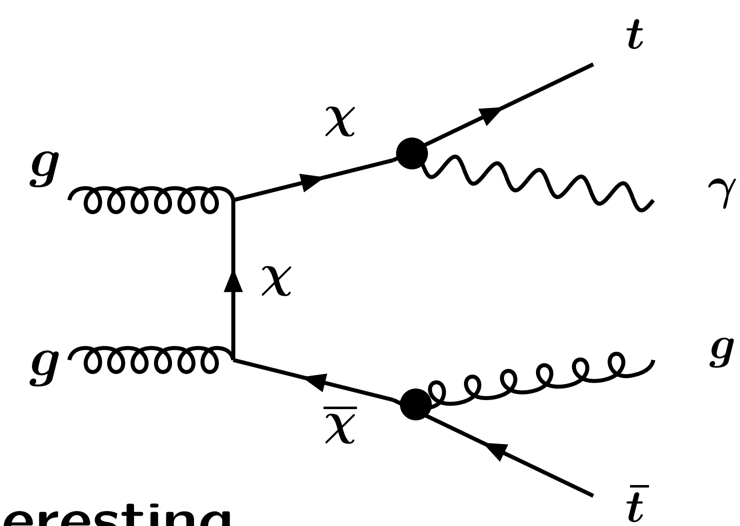
Decays of vectorlike quark χ into a SM quark and a γ or g

$\chi - t - \gamma$ coupling may arise at 1-loop:



If $\chi \to t\gamma$ is induced at one loop, then $\chi \to tg$ is also induced at one loop with a width larger by $O(\alpha_s/\alpha)$.

Branching fraction: $B(\chi \to t\gamma) \lesssim 10\%$.



$pp \to \chi\bar{\chi} \to t\bar{t}\gamma\gamma$ - too small signal

$\chi\bar{\chi} \to t\bar{t}\gamma j$ - promising

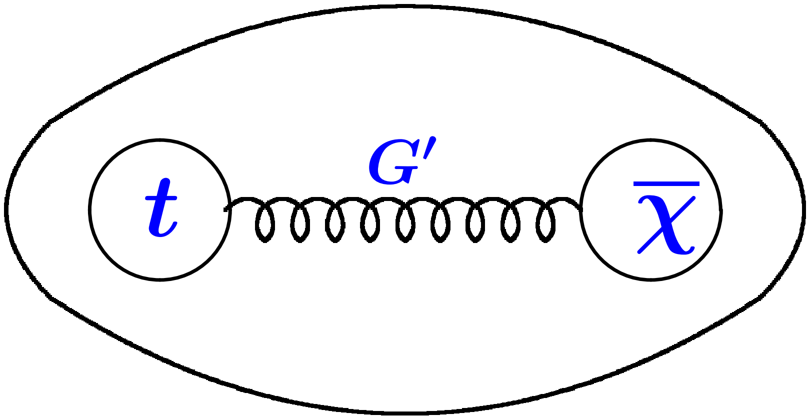
$\chi\bar{\chi} \to t\bar{t}jj$ - large background, still interesting

Conclusions

Higgs boson may be composite. $M_h \approx 125$ GeV arises naturally.

Composite Higgs field as a bound state of the top quark and a vectorlike quark

Binding due to some new strongly coupled interaction:



Electroweak constraints push the compositeness scale > 10 TeV.

Fine tuning (little hierarchy problem).

Searches for vectorlike quarks at the LHC and future hadron colliders are very important.