Phenomenological considerations for top-quark partial compositeness: anomalous dimensions, resonances and form factors

Diogo Buarque Franzosi

The LIO international workshop on Vector-like Fermions

July 24, 2019

Outline

1. UV considerations from Anomalous dimensions of potential top-partners
2. Composite states
   - Vacuum, pNGB, σ, ρ
   - A light top-partners?
3. How do partially composite top quarks interact with gluons?
4. Conclusions

1 - UV considerations on Partial Compositeness (PC)

A model example

Gripaios, Pomarol, Riva, Serra 0902.1483, Ferretti, Karateev 1312.5330

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	$-3(N_c-1)q_\chi$
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			
χ_1 χ_2 χ_3	$\boxminus$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\boxminus$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

- Technicolor (TC): 4D confining gauge theory G_{HC} with fermionic matter $\rightarrow$ dynamical EW symmetry breaking (hierarchy problem)
- Composite Higgs (CH): Vacuum misalignment (Higgs is a pNGB) (Little-hierarchy problem and doublet nature of Higgs)

$$v = f \sin\theta$$

- Top-quark PC: Top-quark mass generated via mixing with composite operators $\mathcal{O} \sim Q\chi Q,\ \chi Q\chi \ldots$

$$\delta\mathcal{L} = \frac{g_F^2}{\Lambda_F^2}(Q_L\mathcal{O}_R + \bar{t}_R\mathcal{O}_L + \text{h.c.}), \quad Q_L = (t_L, b_L)^T$$

Fermion masses

- The SM works pretty neatly.

$$\mathcal{L}_y = -yH\bar{q}_L u_R + \cdots$$

- Yukawas are the only relevant operators $\rightarrow$ suppression of FCNC via the GIM mechanism. Extra source of FCNC suppressed automatically by v^2/Λ_{UV}^2
- In TC, flavour scale $\Lambda_F > 10^4$ TeV $\gg \Lambda_{TC}$ generates low energy 4-fermion interactions, *schematically:*

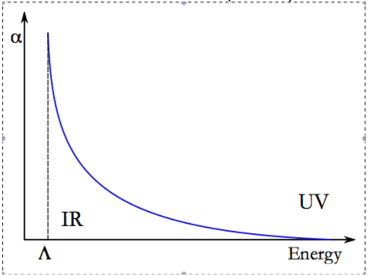
$$\alpha\frac{\bar{Q}Q\bar{Q}Q}{\Lambda_F^2} + \underbrace{\boxed{\beta\frac{\bar{Q}Q\bar{\psi}\psi}{\Lambda_F^2}}}_{\text{ETC}} + \underbrace{\boxed{\kappa\frac{QQQ\psi}{\Lambda_F^2} + h.c.}}_{\text{PC}} + \underbrace{\boxed{\gamma\frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda_F^2}}}_{\text{FCNC}}$$

- Extended Technicolor (ETC) (Dimopoulos, Susskind 79, Eichten, Lane 80)
- Partial Compositeness (PC) Kaplan 91
- Yukawa is NOT the only relevant operator. Is it enhanced w.r.t. 4-fermion FCNC operators? $\rightarrow$ Walking Technicolor

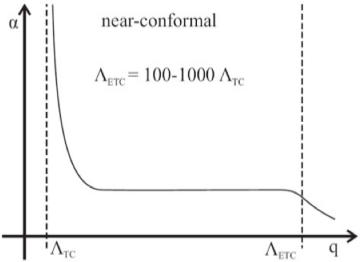
Walking Technicolor

Presence of the IR (near-)fixed point.

$$\langle \bar{Q}Q_{ETC} \rangle \sim ln \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma} \langle \bar{Q}Q_{TC} \rangle$$



$$\sim \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma(\alpha^*)} \langle \bar{Q}Q_{TC} \rangle$$



- For ETC, $H = \bar{Q}Q$, $\Delta_S = [H^\dagger H]$ is bounded by $d = [H]$ and a large enough Δ_S infers d close to 1 which revive the SM hierarchy problem Ratazzi, Rychkov, Tonni, Vichi 08, 10.
- In principle, PC does not have this problem, but still a large anomalous dimension is necessary.

Anomalous dimensions of potential top-partners

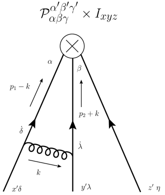
DBF, Ferretti 1905.08273

- Even before understanding the dynamics, more fundamental symmetry-related requirements to construct PC models are important
  Ferretti, Karateev 13
- A list of most promising candidates with fermions in 2 representations of G_{HC} is

Name	Gauge group	ψ	χ	Baryon type
M1	$SO(7)$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$\psi\chi\chi$
M2	$SO(9)$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$\psi\chi\chi$
M3	$SO(7)$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$\psi\psi\chi$
M4	$SO(9)$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$\psi\psi\chi$
M5	$Sp(4)$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$\psi\chi\chi$
M6	$SU(4)$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$\psi\chi\chi$
M7	$SO(10)$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$\psi\chi\chi$
M8	$Sp(4)$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$\psi\psi\chi$
M9	$SO(11)$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$\psi\psi\chi$
M10	$SO(10)$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$\psi\psi\chi$
M11	$SU(4)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$\psi\psi\chi$
M12	$SU(5)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$\psi\psi\chi$, $\psi\chi\chi$

- We are interested in objects like $\langle X_\alpha Y_\beta Z_\gamma \rangle$ and $\langle X_\alpha Y^\dagger_{\dot\beta} Z^\dagger_{\dot\gamma} \rangle$, X a Weyl fermion and $\langle ... \rangle$ an G_{HC} invariant.
- The anomalous dimension has a wave renormalization piece and a piece from diagrams like below

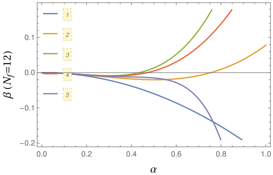
$$\gamma^{IJ}(g) = \frac{g^2}{16\pi^2}\left(a^{IJ} - \frac{1}{2}\delta^{IJ}(a_X + a_Y + a_Z)\right).$$

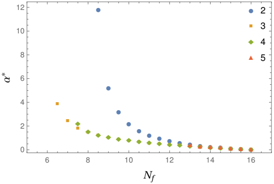


- We can construct now ψ^3 hyper-color singlets with opposite quantum number of third family q_L and t_R^c
- and compute the coefficient A, $\gamma = \frac{g^2}{16\pi^2} A$

	potential top-partners $(1/2, 0)$	other $(1/2, 0)$	$(1/2, 1)$	$(3/2, 0)$	$\psi \overset{(\sim)}{\psi}$	$\chi \overset{(\sim)}{\chi}$
M1	-27/8, - 9/2	-39/8	9/8, 3/2	33/8	-9	-63/8
M2	-11/2, -6	-15/2	5/2, 2	13/2	-12	-27/2
M3	-39/8, -9/2, -27/8		9/8, 3/2	33/8	-63/8	-9
M4	-11/2, -6, -15/2		5/2, 2	13/2	-27/2	-12
M5	-3/2, -6	-15/2	1/2, 2	9/2	-12	-15/2
M6	-15/4, -15/2	-35/4	5/4, 5/2	25/4	-15	-45/4
M7	-45/8, -27/4	-81/8	27/8, 9/4	63/8	-27/2	-135/8
M8	-15/2, -6, -3/2		1/2, 2	9/2	-15/2	-12
M9	-45/8, -15/2	-105/8	35/8, 5/2	75/8	-165/8	-15
M10	-45/8, -27/4, -81/8		27/8, 9/4	63/8	-135/8	-27/2
M11	-35/4, -15/2, -15/4		5/4, 5/2	25/4	-45/4	-15
M12	-66/5, -54/5, -18/5 -24/5, -36/5	-72/5	6/5, 18/5 24/5 12/5	42/5 48/5	-72/5 -108/5	-108/5 -72/5

Position of IR fixed point



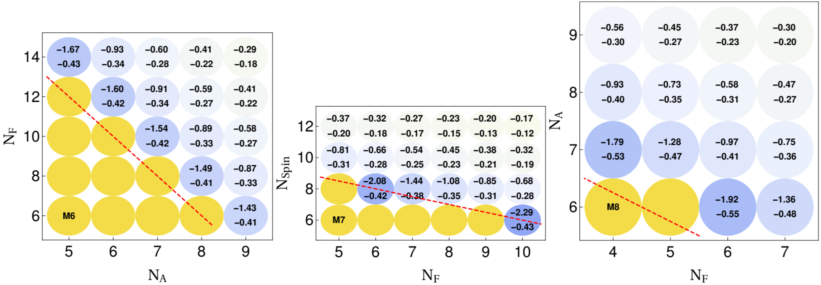


$SU(3)$:

- Perturbative expansion not very reliable.
- Disagreement in the Lattice community.
- 2-loop seems to reproduce better lattice results.
- 4 loop over-estimate the conformal window and give small g^* - result in Pica, Sannino 16 based on 4-loop.
- We use a more conservative approach g^* between 2-loop and 4-loop Zoller 16
- More sophisticated methods to use perturbative expansion exist e.g. Antipin, Maiezza, Vasquez 18

Results

- Free dimension $[XXX] = 9/2$. A $\gamma^* \approx -2$ would make a good enhancement.
- Showing the largest absolute (negative) anomalaous dimension



- Can identify promising model candidates (most studied models M6, M8 are not promising!)
- and the specific most promising top-partner candidate.

2 - Composite states

- Below chiral symmetry breaking scale $\Lambda = 4\pi f$, hyper-quarks condensate into composite states that can be described by Chiral Lagrangians

M8 as example
Symmetry breaking pattern SU(4)/Sp(4)

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\bar{Q}\bar{Q}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\bar{Q}\sigma^\mu Q$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\bar{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

Ferretti et al. 1312.5330, Ferretti et al. 1604.06467, Cacciapaglia et al. 1507.02283, Bizot et al. 1803.00021

- What are the phenomenological implications of IR physics from this PC framework?

Effective Chiral Lagrangian

- Let's start assuming heavy (integrated out) fermions.
- Including (pseudo-)NGB and a scalar techni-sigma excitation

$$\Sigma = \exp\left[2\sqrt{2}\, i \left(\frac{\Pi_Q}{f}\right)\right] E_Q\,, \quad \Pi_Q = \sum_{i=1}^{5} \Pi_Q^i X_Q^i\,, \quad h \equiv \Pi_Q^4\,, \quad \eta \equiv \Pi_Q^5$$

$$\begin{aligned} \mathcal{L} &= k_G(\sigma)\frac{f^2}{8} D_\mu \Sigma^\dagger D^\mu \Sigma - \frac{1}{2}(\partial_\mu \sigma)^2 - V_M(\sigma) \\ &+ k_t(\sigma)\,\frac{y_L y_R f C_y}{4\pi}(Q_\alpha t^c)^\dagger\, \mathrm{Tr}\,[(P_Q^\alpha \Sigma^\dagger P_t \Sigma^\dagger)] + \text{h.c.} \\ &- k_t^2(\sigma) V_t - k_G^2(\sigma) V_g - k_m(\sigma) V_m\,, \end{aligned}$$

Loop induced and techniquark induced potential

$$\begin{aligned} \text{top-quark PC: } V_t &= \frac{C_t}{(4\pi)^2} k_t(\sigma/f)^2 (y_L^2 y_R^2 \mathrm{Tr}\,[P_Q^\alpha \Sigma^\dagger P_t \Sigma^\dagger]\mathrm{Tr}\,[\Sigma P_{Q\alpha}^\dagger \Sigma P_t^\dagger] \\ \text{Gauge: } V_g &= C_g k_G(\sigma/f)^2 f^4 (g^2 \mathrm{Tr}\,[S^i\Sigma(S^i\Sigma)^*] + g'^2 \mathrm{Tr}\,[S^6\Sigma(S^6\Sigma)^*]) \\ \text{techniquark mass: } V_m &= C_m k_m(\sigma/f) f^3 m_Q \mathrm{Tr}\,[E_B \Sigma]\,. \end{aligned}$$

Sigma-assisted natural composite Higgs

DBF, Cacciapaglia, Deandrea (1809.09146)

Typically, the top interactions dominates the misalignment dynamics ($\partial V/\partial\theta = 0$)

$$V(\theta) = \underbrace{V_{top}(\theta)}_{\substack{\text{ETC: } s_\theta^2 \to 1 \\ \text{PC: } s_\theta^2 \to 1/2}} + \underbrace{V_{gauge}(\theta)}_{s_\theta^2 \to 0} + V_{mass}(\theta)$$

- In Partial Compositeness (PC), $m_t \propto f s_{2\theta}$, so top loops give $V \sim f^2 m_t^2$ which minimizes for $\theta = \pi/4$
- PC provides a natural EWSB+CH mechanism,
- However, a large θ leads to large modifications in the Higgs couplings, EWPO and coupling measurement problems

$$\kappa_V = \frac{\partial_\theta v}{v} = c_\theta \to \sqrt{2}/2\,, \qquad \kappa_t = \frac{v}{f m_t}\partial_\theta m_t = \frac{c_{2\theta}}{c_\theta} \to 0.$$

with the top coupling specially severe, since $c_{2\theta} \to 0$ in the PC dominated case.

The role of heavy composite states

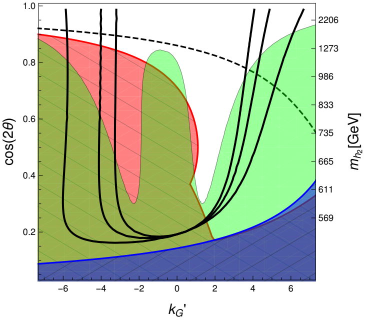
The problem

The common lore is that CH needs high scale $f \gtrsim 1.2\,\text{TeV}$ to avoid EWPO and Higgs coupling constraints, which requires fine-tuning.

Our claim

- The ubiquitous presence of scalar and vector excitations help alleviating these constraints.
- The expected masses and couplings of these states, from unitarity arguments and from lattice calculations, provide the correct parameters to evade the bounds.
- We predict novel signatures not yet fully explored that can be searched for at the LHC.

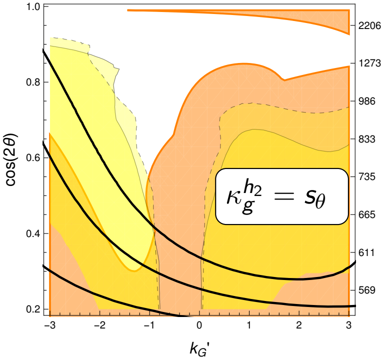
- Perturbativity, $|k_i'| < 4\pi$, pert. unitarity $\gamma = \frac{m_{h_2}}{4\sqrt{\pi f}} \lesssim 1$ ($\gamma = 0.2$ in the plot), $\Gamma/m_{h_2} \lesssim 1$ (black curves, 0.3, 0.5, 1)
- EWPO, σ creates the valleys and vectors shift and broaden them.

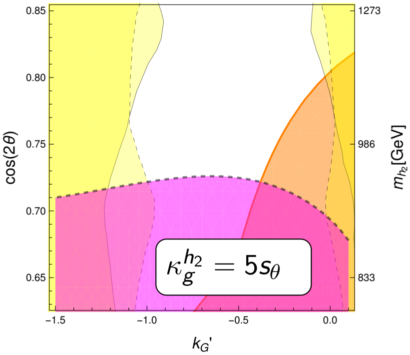


- Higgs measurements, $\kappa_{t,V}$. $\Gamma(h \to \eta\eta)$ (dashed line) for $m_\eta = 0$ - larger masses (m_ψ or **A** rep.) opens parameters space and interesting experimental signatures.
- Dynamically inspired composite resonance profile works nicely. σ: $|k_G'| \sim 1.2$. v_μ: $r = 1.1 \to |a_V| = 1$, with $M_V = 4\pi f$, $\widetilde{g} = 3$.

Direct searches

- $pp \to h_2 \to ZZ$ (CMS 18') and $pp \to h_2 \to t\bar{t}$ (from DBF, Fabbri, Schumman 17')
- $\sigma = \sigma_0^{gg} \frac{|\kappa_t^{h_2} A_F(\tau_t) + \kappa_g^{h_2}|^2}{|A_F(\tau_t)|^2} + \sigma_0^{VBF} (\kappa_V^{h_2})^2$ gg: Anastasiou et al. 16', VBF: Bolzoni, Maltoni, Moch, Zaro 11'





One nice top partner

	Sp(4)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	SU(4)	SU(6)
$\binom{\psi_1}{\psi_2}$	$\square$	**1**	**2**	0	**4**	**1**
$\psi_{3,4}$	$\square$	**1**	**1**	$\pm 1/2$		**1**
$\chi_{1,2,3}$	$\boxminus$	**3**	**1**	$2/3$	**1**	**6**
$\chi_{4,5,6}$	$\boxminus$	$\bar{\mathbf{3}}$	**1**	$-2/3$	**1**	

- ψ sector condensates SU(4)$\to$ Sp(4): EWSB, 5 (p)NGB (Higgs doublet (H) + singlet η)
- χ sector condensates SU(6)$\to$ SO(6): 20 (p)NGB ($\pi_c \sim \mathbf{8}+\mathbf{6}+\bar{6}$)
- $U(1)^2 \to$ 2 abelian pNGB: a, η' (anomalous)
- Bunch of fermionic states, $\chi\psi^2$, **1, 5, 10** of Sp(4) $\to$ top partners and top mass via PC
- + vector states, σ, and higher spin stuff...

Low energy spectrum

1. $\Psi_5 \ni \binom{T}{B}_{1/6} + \binom{X_{5/3}}{X_{2/3}}_{7/6} + \tilde{T}_5$

Assumptions:

- Only one Ψ (much lighter than others)
- Ψ lighter than π_c and vectors (might be motivated)

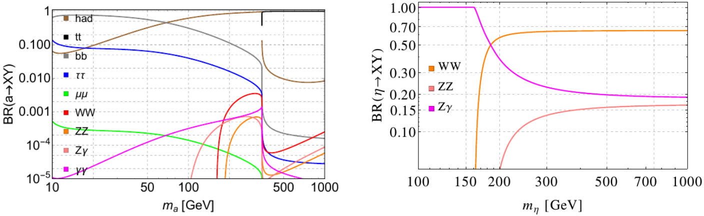
Lagrangian:

$$\mathcal{L} = -y_L f \bar{Q}_L \widetilde{\Psi}_R - y_R f \bar{\widetilde{\Psi}}_L t_R - M \bar{\Psi}_L \Psi_R + \mathrm{h.c.} + s \frac{g_V^2 K_V^s}{16\pi^2 f_s} V_{\mu\nu} \tilde{V}^{\mu\nu} - is \frac{C_f^s m_f}{f_s} \bar{f} \gamma_5 f$$

- Top partner (Ψ) sector, 3 free parameters: f, y_R, M (Use y_L to fix m_t)
- Scalar $(s = a, \eta)$ couplings quite fixed

Scalars

- a, η decays



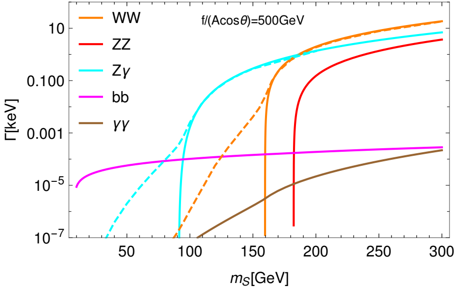
Bizot, Cacciapaglia, Flacke 18

- Small mass expected $m_\eta \propto m_\psi$ completely generated by technifermion masses $\rightarrow$ small to avoid fine-tuning.

$$m_\eta^2 = \tilde{m}_\eta^2 + \frac{\epsilon_{\mathbf{A}}}{4}(m_h^2/c_\theta^2 - \tilde{m}_\eta^2 t_\theta^2), \quad \tilde{m}_\eta^2 = m_h^2 \frac{(\delta - c_{2\theta})}{s_\theta^2(\delta - 3c_{2\theta} - 2)}$$

$$\frac{\partial V}{\partial \theta} = 2f^3 s_\theta \left(f C_t'(c_{2\theta} - \delta)c_\theta - 2C_m m_\psi \right) = 0 \, .$$

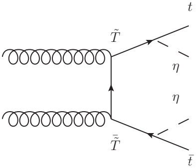
- Decay $\eta \rightarrow Z\gamma$ dominates in the range $65\,\text{GeV} \lesssim m_\eta \lesssim 170\,\text{GeV}$ using Bauer, Neubert, Thamm 17



Pheno Ψ_5

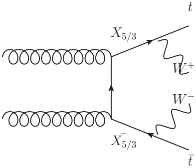
- T, $X_{2/3}$, t' mix to mass eigenstates t, $T_{1,2}$.
  b', $B \to b$, B_1
  $\tilde{T}$, $X_{5/3}$ remain unmixed.
- 3 light top partners, $M_{\tilde{T}} = M_{X_{5/3}} = M$
- Competition BSM *vs* SM decay

$BR(\tilde{T} \to t\eta) = 100\%$



=100%

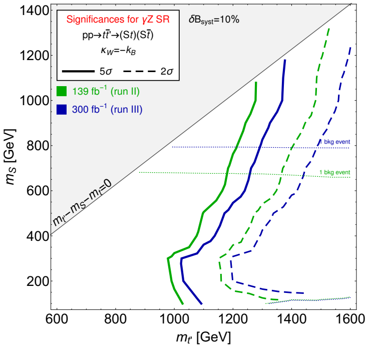
$BR(X_{5/3} \to tW) = 100\%$



=100%

- T_1 a bit heavier $M_{T_1} = M + \mathcal{O}(v^2/f)$ and decays more democratically and model dependent
- T_2, B much heavier $M^2 \sim M^2 + y_L f^2$

- $pp \to \tilde{T}\bar{\tilde{T}} \to t\bar{t}\eta\eta \to t\bar{t}2\gamma 2Z$ is a quite striking signature, can it compete with the SM decay $pp \to \bar{X}_{5/3}X_{5/3} \to t\bar{t}W^+W^-$ ($M > 1.3$ TeV pair-prod. ~ 1.6 for k=1 incl. single prod.)? Try to answer in 1907.05929.



- For large masses M, single production might become competitive. In this case the couplings are relevant and might enhance the singlet production.

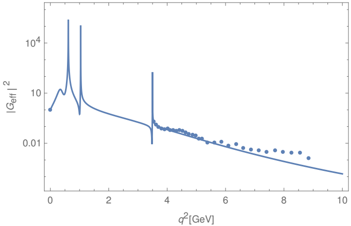
- Analysis not optimized. Limited by MC statistics. Could look at 2 branchings.
- Neutrino channel could be interesting
  $pp \to \eta\eta t\bar{t} \to ZZ\gamma\gamma tt \to \ell^+\ell^-\nu\nu+$ jets
- Relax assumption, *e.g.* lighter vectors and π_c

3 - Gluon interactions to top partners and top quarks

DBF, Tonero 1907.XXXXX

- A composite state interact very differently than a point-like particle.
- Our goal is to estimate the typical scales and effects of these modified interactions for
  1. top partner production;
  2. partially composite top quark production.

The proton inspiration

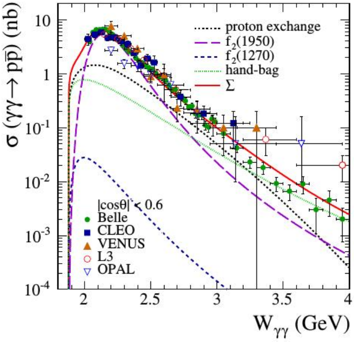


$e^+e^- \to p\,\bar{p}$ Bijker, Iachello 04

$$\sigma \simeq \frac{4\pi\alpha^2}{3s} C_N(s)\sqrt{1-\frac{4M^2}{s}}\left(1+\frac{2M^2}{s}\right)|G_{\rm eff}(s)|^2$$

$$|G_{\rm eff}(s)|^2 = \frac{\left(|G_M(s)|^2+\frac{2M^2}{s}|G_E(s)|^2\right)}{\left(1+\frac{2M^2}{s}\right)}$$

Point-like: $|G_{\rm eff}(s)|^2 = 1$



$\gamma\gamma \to p\bar{p}$ (Kłusek-Gawenda, Lebiedowicz, Nachtmann, Szczurek 17)

Exponentially suppressed w.r.t. point-like case.

One-gluon form factors

- Elementary t' and composite T' states mix to form the mass eigenstates (t, T) (simplified model with a $SU(2)_L$ singlet T)

$$t_{L,R} = c_{L,R}\, t'_{L,R} + s_{L,R}\, T'_{L,R}\,.$$

- In fully analogy with the nucleons EM interactions, the interaction of T' with a single gluon can be parametrized at tree level by the form factors

$$(J_{T'})^{\mu,a} = g_s\, \bar{T}'\, T^a \left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(q^2)\right] T'$$

$$F_1(q^2) = 1 + \frac{q^2}{M^2} f_1(q^2)\,, \quad F_1(0) = 1\,, \quad F_2(0) = \kappa_g$$

- The top quark acquires non-standard interactions from the mixing

$$(J_t)^{\mu,a} = g_s \bar{t}\, T^a \left[\gamma^\mu F_1^{tg}(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2^{tg}(q^2)\right] t$$

$$F_1^{tg}(q^2) = 1 + (s_L^2 P_L + s_R^2 P_R)\frac{q^2}{M^2} f_1(q^2)\,, \quad F_2^{tg}(q^2) = s_L s_R F_2(q^2)\,.$$

Phenomenological parametrization of the form factors

- Data from several proton scattering experiments are well fitted by the so-called dipole approximation

$$G_E^p(q^2) = \mu^{-1} G_M^p(q^2) = G_D^p(q^2) = \left(1 - \frac{q^2}{m_D^2} e^{i\theta\Theta(q^2)}\right)^{-2}$$

$$G_E^N(q^2) = F_1^N(q^2) + \frac{q^2}{4M_p^2} F_2^N(q^2), \; G_M^N(q^2) = F_1^N(q^2) + F_2^N(q^2)$$

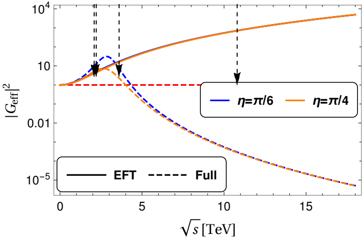
- In the time-like region an extra absortive factor and resonances eventually appear (with more sophisticated models)

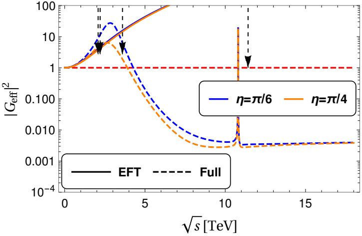
A similar behavior is expected for the top partner. We use the dipole approximation to parametrize the gluonic form factors of T' for $\mu < m_\rho$

$$F_1(q^2) = G_D(q^2)\left(1 + \frac{\kappa_g}{1 - 4M^2/q^2}\right), \quad F_2(q^2) = G_D(q^2)\left(\frac{\kappa_g}{1 - q^2/(4M^2)}\right).$$

Probing form factors in $q\bar{q} \to T\bar{T}$

$$\sigma_{q\bar{q}\to T\bar{T}} = \frac{8\alpha_s^2\pi}{27s}\sqrt{1-\frac{4m_T^2}{s}}\left(1+\frac{2m_T^2}{s}\right)|G_{\text{eff},T}(s)|^2$$





pure case $(c_L = c_R = 1)$ top-partner (simp. model $\lambda = 3$)

- Scales (arrows): $\Lambda_{c,1}$, $\Lambda_{c,2}$, $m_\rho = 6f$ and $2m_T$.
- Parameters: $M = 9f$, $M_D = 5f$, $f = 0.6\,\text{TeV}$ and $\kappa_g = 2$. Inspired by SU(4) lattice calculations Ayyar, Degrand, Hackett, Jay, Neil, Shamir, Svetitsky 18

Effective low energy expansion

- The Pauli and Dirac interactions can be derived from the EFT

$$\mathcal{L}_{EFT} = \frac{g_s}{M^2}\bar{t}\gamma^\mu T_a(s_L^2 P_L + s_R^2 P_R)tf_1(-D^2)D^\nu G^a_{\mu\nu} + \frac{g_s}{4M}s_L s_R \bar{t}\sigma^{\mu\nu}T_a t F_2(-D^2)G^a_{\mu\nu}$$

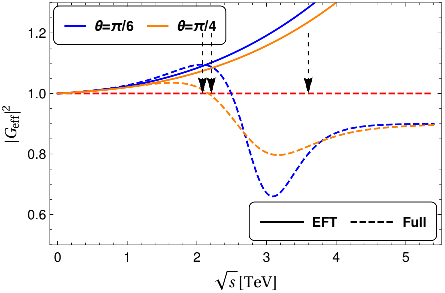
$$= \frac{g_s}{\Lambda^2_{c,1}}\bar{t}\gamma^\mu T_a(s_L^2 P_L + s_R^2 P_R)tD^\nu G^a_{\mu\nu} + \frac{g_s\kappa_g}{4M}s_L s_R \bar{t}\sigma^{\mu\nu}T_a t G^a_{\mu\nu} + \cdots$$

$$\to \frac{g_s R}{6}\bar{t}\gamma^\mu T_a t D^\nu G^a_{\mu\nu} + \frac{g_s\tilde{\kappa}_g}{4M}\bar{t}\sigma^{\mu\nu}T_a t G^a_{\mu\nu}$$

- Leading dimension (last line) is the typical framework for the study of top-quark structure, Englert, Freitas, Spira, Zerwas 12, Englert, Gonçalves, Spannowsky 14, Fabbrichesi, Pinamonti, Tonero 13, ... - based on the assumption that new physics sits at high scales.
- This is generally not justified. E.g. proton $\Lambda_c \sim 600$ MeV. Nonrelativisitc quark model (NRQM) (Manohar, Georgi 83) $\to$ intermediate scales where pions and quarks coexist $\Lambda_c < \mu < \Lambda_\chi$.
- **PC might present a low compositeness scale with small coefficients, not well described by the leading dimension Lagrangian**

$$\Lambda^{-2}_{c,1} = \frac{2}{M_D^2} - \frac{\kappa_g}{4M^2} \qquad \Lambda^{-2}_{c,2} = \frac{2}{M_D^2} + \frac{1}{4M^2}.$$

Probing form factors in $q\bar{q} \to t\bar{t}$



$|G_{eff}|^2$.

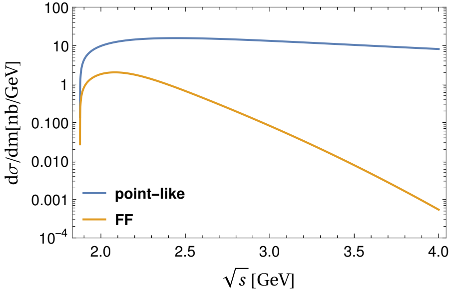
- Parameters: $M = 9f$, $M_D = 5f$, $f = 0.6\,\text{TeV}$, $\kappa_g = 2$ and $\lambda = 3$ ($s_L = 0.091$ and $s_R = 0.313$).
- Scales (arrows): $\Lambda_{c,1}$, $\Lambda_{c,2}$ and $m_\rho = 6f$.
- Mixing angles enter only linearly $\to$ higher dimension operators are relatively more relevant than naively expected
- Chromomagnetic moment more suppressed than Dirac-like interaction: $s_L s_R$ and helicity suppression.

Results for $q\bar{q} \to g^* \to \cdots$

- Large suppression in $q\bar{q} \to T\bar{T}$.
- Enhancement in the total cross section of $q\bar{q} \to t\bar{t} \sim 1\%$, with $m(t\bar{t}) > 1\,\text{TeV} \sim 4\%$.
- A new single production mechanism. Energy dependent $g^* \to t\bar{T}$ (parametrization more complicated due to different spinor masses)

Two-gluon form factors

- To describe $gg \to T\bar{T}$ we can get hints from $\gamma\gamma \to p\bar{p}$ process in ultra-peripheral ion collision.
- The main contribution near threshold can be modeled by the proton exchange mechanism and the $f_2(1950)$ resonance (the handbag mechanism contributes at high energies) Kłusek-Gawenda, Lebiedowicz, Nachtmann, Szczurek 17



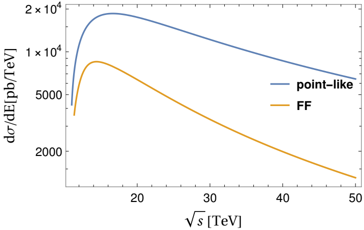
$\gamma\gamma \to p\bar{p}$
proton exchange contribution
$|\cos\theta| < 0.6$.

$gg \to T\bar{T}$

- A similar suppression is expected for the top partner production.
- Only $F_2(q^2)$ contributes. Dirac operator ($f_1(q^2)$) equivalent to 4f operators at tree-level
- We assume no resonance near threshold.
- The soften of the cross section can be parametrized by an overall exponential form factor $F(t,u,s)$.

$$\mathcal{M}_T = \mathcal{M}_{T,bare} F(t,u,s)$$

$$F(t,u,s) = \frac{F(t,u,s)^2 + F(u,t,s)^2}{1+\tilde{F}(t,u,s)^2}, \quad F(t,u,s) = \exp\left(-\frac{s+u-t}{\Lambda_T^2}\right), \quad \tilde{F}(t,u,s) = \exp\left(-\frac{s+2t+2u}{\Lambda_T^2}\right).$$

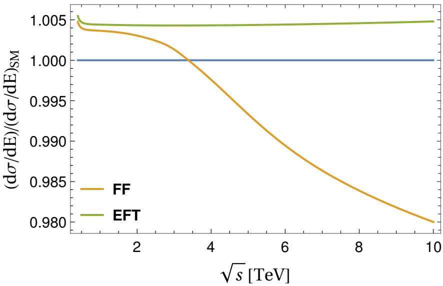


$m_T = 9f,\ m_D = 5f,\ \kappa = 2,\ \Lambda_T = 11f,\ f = 0.6\,\text{TeV},\ |\cos\theta| < 1.$

$gg \to t\bar{t}$

- Pauli-type interaction is doubly suppressed (Helicity and $s_L s_R$).
- Details of the form factors form not *extremelly* relevant. We use the *ansatz*

$$F_t(t,u,s) = (1/2)[(c_L^2 + c_R^2) + (s_L^2 + s_R^2)F(t,u,s)]\,.$$



$m_T = 9f$, $m_D = 5f$, $\kappa = 2$, $\Lambda_T = 7f$, $f = 0.6$ TeV.

Conclusion

- PC is a promising alternative to give mass to the top quark in models of DEWSB.
- We can estimate best model candidates and top partners from largest anomalous dimensions.
- Composite resonances may play a role in experimental constraints, even in EWPO,
- and have phenomenological implications.
- Top partners from composite completion may have interesting experimental signatures.
- The existence of compositeness effects before the appearence of resonances is well motivated.
- We expect a large suppression in the production of the top partner pair, that might be relevant for current and future searches.
- The deviations in $t\bar{t}$ production are expected mostly in $q\bar{q}$ initiated production.
- New energy dependent single production channel is a possibility.

Backup

Simplified model:

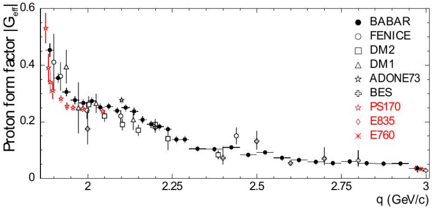
$$\mathcal{L} \supset -M\bar{T}'_L T'_R - y\bar{Q}'_L \widetilde{H} T'_R - \lambda f\,\bar{T}'_L t'_R + \text{h.c.}$$

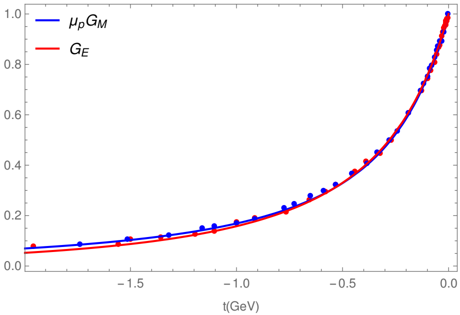
Bounds on operators:
With QCD corrections at NLO DBF, Zhang 15

$$-0.0099 < s_L s_R \frac{m_t}{4M}\kappa_g < 0.0123$$

Barducci, Fabbrichesi, Tonero 17

$$-0.018 < (s_L^2 + s_R^2) m_t^2 \left(\frac{2}{M_D^2} - \frac{\kappa_g}{4M^2}\right) < 0.017\,.$$


Proton form factor $|G_{eff}|$
0.6
0.4
0.2
0
2
2.25
2.5
2.75
3
q (GeV/c)
BABAR
FENICE
DM2
DM1
ADONE73
BES
PS170
E835
E760


$\mu_p G_M$
G_E
1.0
0.8
0.6
0.4
0.2
0.0
−1.5
−1.0
−0.5
0.0
t(GeV)

Composite Higgs

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(4)$	$\mathrm{SU}(6)$	$\mathrm{U}(1)$
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	$-3(N_c-1)q_\chi$
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			

A model example: Gripaios,Pomarol, Riva, Serra 0902.1483

$$\mathcal{L}_{\mathrm{UV}} = \bar{Q}\mathrm{i}\not{D}Q + \delta\mathcal{L}_m + \delta\mathcal{L}\,,$$

- Global symmetry SU(4) spontaneously breaks to Sp(4) via the condensate SU(4)/Sp(4)

$$\langle Q^I_{\alpha,c} Q^J_{\beta,c'} \epsilon^{\alpha\beta}\epsilon^{cc'}\rangle \sim f^3 E^{IJ}_Q$$

- The direction of the vacuum can be parametrized by the vacuum misalignment angle

$$E_Q = \cos\theta E_Q^- + \sin\theta E_Q^{\mathrm{B}}$$

- $E_Q^{\pm}$: vacua that leave the EW symmetry intact.
  E_Q^{B}: vacuum breaking EW symmetry to $\mathrm{U}(1)_{\mathrm{EM}}$
- Generates hierarchy between compositeness scale f and EW vev v

$$v = f \sin\theta$$

- Higgs = pNGB EW doublet of spontaneous SB G/H.

Partial Compositeness, Kaplan 91

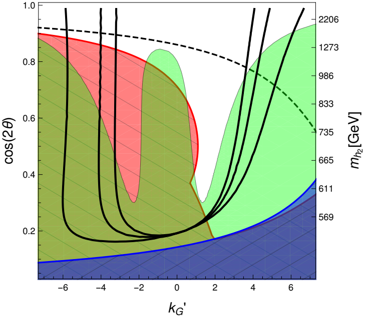
	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(4)$	$\mathrm{SU}(6)$	$\mathrm{U}(1)$
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	$-3(N_c-1)q_\chi$
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

A model example: Ferretti, Karateev 1312.5330

- Top-quark mass generated via mixing with composite operators $\mathcal{O} \sim Q\chi Q,\ \chi Q\chi \ldots$

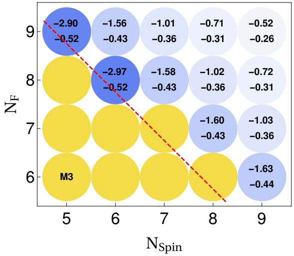
$$\delta\mathcal{L} = \frac{g_F^2}{\Lambda_F^2}(Q_L\mathcal{O}_R + \bar{t}_R\mathcal{O}_L + \text{h.c.}), \quad Q_L = (t_L, b_L)^T$$

- Typically top interactions dominates the misalignment dynamics.
- In Partial Compositeness (PC), $m_t \propto f s_{2\theta}$, so top loops give $V \sim f^2 m_t^2$ which minimizes for $s_\theta^2 = 1/2$ (different in ETC, $s_\theta \to 1$)
- PC provides a natural EWSB+CH mechanism.
- Large s_θ leads to modifications in Higgs physics and EWPO, which can be alleviated by the effects of composite resonances, $f \gtrsim 600\,\text{GeV}$.



DBF, Cacciapaglia, Deandrea 18

- This framework relies on the presence of an approximate IR fixed point and a large anomalous dimensions γ^* of $\mathcal{O}$.
- Defied by low values of γ^*, Pica, Sannino 16. Their results however rely on the 4-loop β-function.
- No agreement in the lattice community either about the presence and magnitude of IRFP in some theories.
- **A more modest and conservative estimate still allows for a large anomalous dimension and regards PC as a promising alternative to the SM.**

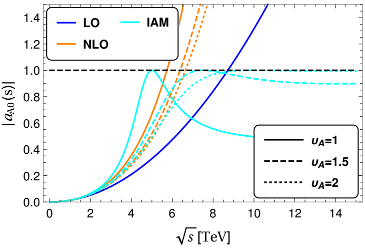


Example SO(7), more comprehensive study in DBF, Ferretti 1905.XXXX

Techni-σ unitarity implications (DBF, Ferrarese, 1705.02787)

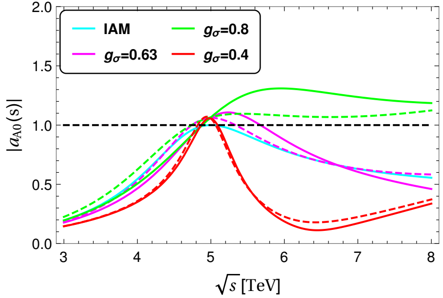
- A striking evidence of strong dynamics is the growing (with E^2) behavior of **Goldstone Boson Scattering (GBS)** amplitudes

$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{f^2} = \frac{s}{v^2}\sin^2\theta\,,$$



- controlled by strong effects at high energies, broad continuum or composite resonances, saturating unitarity - similar to hadron physic the scalar excitation is therefore its unavoidal consequence.
- IAM unitarization, based on dispersion relations, predict very well hadronic spectrum and give us a guidance.

- Unitarity implies that a eventual resonance lighter than $\gamma \equiv \frac{m_\varphi}{4\sqrt{\pi}f} \lesssim 1$, and the closer it is to this limit, broad/continuum excess take place.



$\gamma = 0.86$
Solid: Fixed width
Dashed: Running width
$\sin\theta = 0.2$

- The above analysis assume $f \gg v$ and neglect low energy interactions.
- Unitarity indicates also reasonable values for the coupling $g_\sigma \equiv k'_G/2 \approx 0.63$, which approaches the unitarized amplitudes.
- Increasing evidence of the presence of a light scalar state in theories with an infra-red conformal phase from lattice and gravity duals Athenodorou et al 16, Aoki et al 17, Elander et al, 17

$\sigma - h$ mix

$$
\begin{aligned}
m^2_{h\sigma} &= A m_h^2 + B\tilde{m}_\eta^2 \\
A &= \frac{c_{2\theta}}{2 s_{2\theta}}(k'_G - 2k'_t)\,, \\
B &= \frac{s_{2\theta}}{4}[2(k'_m + k'_t) - 3k'_G] + \frac{t_\theta}{4}(k'_G - 2k'_t)
\end{aligned}
$$

...and modify Higgs couplings

$$
\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \left(\begin{array}{cc} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{array} \right) \begin{pmatrix} h \\ \sigma \end{pmatrix}
$$

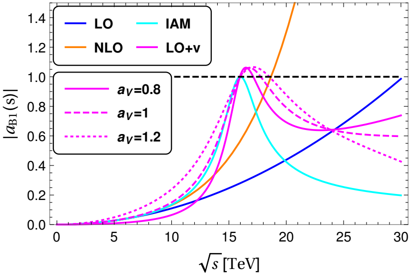
$$
\tan 2\alpha = -2\frac{A m_h^2 + B\tilde{m}_\eta^2}{m_\sigma^2 - m_h^2}
$$

$$
\begin{aligned}
\kappa_V^{h_1} &= c_\theta c_\alpha + (k'_G/2) s_\theta s_\alpha \\
\kappa_V^{h_2} &= -c_\theta s_\alpha + (k'_G/2) s_\theta c_\alpha \\
\kappa_t^{h_1} &= \frac{c_{2\theta}}{c_\theta} c_\alpha + k'_t s_\theta s_\alpha \\
\kappa_t^{h_2} &= -\frac{c_{2\theta}}{c_\theta} s_\alpha + k'_t s_\theta c_\alpha
\end{aligned}
$$

Vector composite states

- Unitarity and dispersion relation arguments can also be applied to the vector resonances leading to $|a_\rho \equiv \frac{\sqrt{2}M_\rho(1-r^2)}{f\tilde{g}}| \approx 1$ (DBF, Ferrarese, 17')

.



- Similar result from width bounds DBF, Cacciapaglia, Cai, Deandrea, Frandsen 16'

Constraints

i - Consistency of the theory, which includes perturbativity of the couplings and perturbative unitarity of pNGB scattering;

ii - Higgs property measurements, namely its couplings and total width;

$$\begin{aligned} \kappa_V &= 1.035 \pm 0.095 \\ \kappa_t &= 1.12^{+0.14}_{-0.12} \\ B_{\rm BSM} &< 0.32 \quad \text{Higgs will decay to } \eta \text{ if } m_\eta < m_h/2 \end{aligned}$$

iii - EWPOs;

$$\begin{aligned} \Delta S &= \frac{1-(\kappa_V^{h_1})^2}{6\pi} \log\frac{\Lambda}{m_{h_1}} - \frac{(\kappa_V^{h_2})^2}{6\pi} \log\frac{\Lambda}{m_{h_2}} + \Delta S_\rho \\ \Delta S_\rho &= \frac{16\pi(1-r^2)s_\theta^2}{2(g^2+\tilde{g}^2) - g^2(1-r^2)s_\theta^2} \end{aligned}$$

DBF, Cacciapaglia, et al. 16'

iv - Direct search of the heavy scalar.

$$|G_{\mathrm{eff},T}(s)|^2 = 1 + \left(1 + \frac{2m_T^2}{s}\right)^{-1} \left\{ \frac{2m_T^2 + s}{M^2}(c_R^2 + c_L^2)\mathrm{Re}f_1(s) + \frac{3m_T}{M} c_R c_L \mathrm{Re}F_2(s) \right.$$
$$+ \frac{s^2}{2M^4}\left[(c_R^4 + c_L^4)\left(1 - \frac{m_T^2}{s}\right) + 6c_R^2 c_L^2 \frac{m_T^2}{s}\right] |f_1(s)|^2 + \frac{8m_T^2 + s}{8M^2} c_R^2 c_L^2 |F_2(s)|^2$$
$$\left. + \frac{3m_T s}{2M^3} c_R c_L (c_R^2 + c_L^2)\mathrm{Re}f_1(s)F_2^*(s) \right\}. \quad (1)$$

$$\mathcal{L}_{T'} \quad = \quad \bar{T}' i\gamma^\mu D_\mu T' + \frac{g_s}{M^2}\bar{T}'\gamma^\mu T_a T' f_1(-D^2) D^\nu G^a_{\mu\nu} + \frac{g_s}{4M}\bar{T}'\sigma^{\mu\nu} T_a T' F_2(-D^2) G^a_{\mu\nu} \tag{2}$$

$$\mathcal{L}_{t'} = \bar{t}' i\gamma^\mu D_\mu t' \tag{3}$$

$$\mathcal{L} = \mathcal{L}_{T'} + \mathcal{L}_{t'} + \mathcal{L}_{\mathrm{mass}}$$

$$\begin{aligned}
\mathcal{L} \quad = \quad & \bar{T} i\gamma^\mu D_\mu T + \bar{t} i\gamma^\mu D_\mu t - m_T \bar{T} T - m_t \bar{t} t \\
& + \frac{g_s}{M^2}\bar{t}\gamma^\mu T_a (s_L^2 P_L + s_R^2 P_R) t f_1(-D^2) D^\nu G^a_{\mu\nu} - \frac{g_s}{4M} s_L s_R \bar{t}\sigma^{\mu\nu} T_a t F_2(-D^2) G^a_{\mu\nu} \\
& + \frac{g_s}{M^2}\bar{T}\gamma^\mu T_a (c_L^2 P_L + c_R^2 P_R) T f_1(-D^2) D^\nu G^a_{\mu\nu} + \frac{g_s}{4M} c_L c_R \bar{T}\sigma^{\mu\nu} T_a T F_2(-D^2) G^a_{\mu\nu} \\
& + \frac{g_s}{M^2}\bar{t}\gamma^\mu T_a (s_R c_R P_R - s_L c_L P_L) T f_1(-D^2) D^\nu G^a_{\mu\nu} + (t \leftrightarrow T) \\
& + \frac{g_s}{4M}\bar{t}\sigma^{\mu\nu} T_a (-s_L c_R P_R + s_R c_L P_L) T F_2(-D^2) G^a_{\mu\nu} + \frac{g_s}{4M}\bar{T}\sigma^{\mu\nu} T_a (c_L s_R P_R - c_R s_L P_L) t F_2(-D^2) G^a_{\mu\nu} \\
& + \ldots
\end{aligned} \tag{4}$$

$$\mathcal{H} \oplus S \equiv \begin{pmatrix} H^{0*} & H^{+} \\ -H^{+*} & H^{0} \end{pmatrix} \oplus S \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) = \mathbf{5}. \tag{5}$$

$$\Psi \equiv \begin{pmatrix} T & X \\ B & T' \end{pmatrix} \oplus \widetilde{T} \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) = \mathbf{5}. \tag{6}$$

$$\Sigma = \exp\left(\frac{i\sqrt{2}}{f}\Pi\right), \text{ transforming as: } \Sigma \to g\Sigma h^{-1}, \text{ for } g \in \mathrm{SU}(4),\ h \in \mathrm{Sp}(4), \tag{7}$$

$$\mathcal{L} = y_L f \mathrm{Tr}\left(\bar{Q}_L \Sigma \Psi_R \Sigma^T\right) + y_R f \mathrm{Tr}\left(\Sigma^* \bar{\Psi}_L \Sigma^\dagger \widetilde{t}_R\right) - M \mathrm{Tr}\left(\bar{\Psi}_L \Psi_R\right) + \text{ h.c.} \tag{8}$$

$$\mathcal{L}_{\rm tops} = -\begin{pmatrix} \bar{\tilde{t}}_L & \bar{T}_L & \bar{T'}_L & \bar{\tilde{T}}_L \end{pmatrix} \left(\mathcal{M} + h\mathcal{I}_h + S\mathcal{I}_S\right) \begin{pmatrix} \tilde{t}_R \\ T_R \\ T'_R \\ \tilde{T}_R \end{pmatrix} + \text{ h.c.} \tag{9}$$

$$\mathcal{M} = \begin{pmatrix} 0 & y_L f \cos^2\left(\frac{\theta}{2}\right) & -y_L f \sin^2\left(\frac{\theta}{2}\right) & 0 \\ \frac{y_R f}{\sqrt{2}} \sin\theta & M & 0 & 0 \\ \frac{y_R f}{\sqrt{2}} \sin\theta & 0 & M & 0 \\ 0 & 0 & 0 & M \end{pmatrix}$$

$$\mathcal{I}_h = \begin{pmatrix} 0 & -\frac{1}{2} y_L \sin\theta & -\frac{1}{2} y_L \sin\theta & 0 \\ \frac{y_R}{\sqrt{2}} \cos\theta & 0 & 0 & 0 \\ \frac{y_R}{\sqrt{2}} \cos\theta & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{10}$$

$$\mathcal{I}_S = \begin{pmatrix} 0 & 0 & 0 & \frac{i y_L}{\sqrt{2}} \sin\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ i y_R \cos\theta & 0 & 0 & 0 \end{pmatrix}.$$

$$m_t = \frac{y_L y_R f v}{\sqrt{2}\widehat{M}} + \mathcal{O}\left(\frac{v^2}{f^2}\right), \quad m_{t'} = M, \quad m_{t''} = M + \mathcal{O}\left(\frac{v^2}{f^2}\right), \quad m_{t'''} = \widehat{M} + \mathcal{O}\left(\frac{v^2}{f^2}\right). \tag{11}$$

$$\tilde{t}_L = -\frac{M}{\widehat{M}} t_L + \frac{y_L f}{\widehat{M}} t_L''', \quad T_L = \frac{y_L f}{\widehat{M}} t_L + \frac{M}{\widehat{M}} t_L''', \quad T_L' = t_L'', \quad \tilde{T}_L = t_L' \tag{12}$$

$$\tilde{t}_R = t_R + \frac{y_R v}{\sqrt{2}M} t_R'' + \frac{y_R v M}{\sqrt{2}\widehat{M}^2} t_R''', \quad T_R = t_R''' - \frac{y_R v M}{\sqrt{2}\widehat{M}^2} t_R, \quad T_R' = t_R'' - \frac{y_R v}{\sqrt{2}M} t_R, \quad \tilde{T}_R = t_R'.$$