A natural partially composite top Goldstone Higgs aided by techni-σ

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work in progress

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Outline

- Introduction
- Techni-σ and unitarity implications
- Low energy and vacuum alignment
- EWPT and Higgs couplings
- Top partner and vector resonances
- Conclusions

Introduction

- Despite its incredible success, the SM is plagued by several problems.
- Composite Higgs (CH) models are among the most promising alternatives,
- dynamically generating the EW scale through a vacuum condensate misaligned with the vacuum that breaks EW symmetry

$$v = f \sin\theta$$

- and at the same time explaining the mass gap between the Higgs and the other composite states $\rightarrow$ Higgs = Goldstone boson of spontaneous symmetry G/H.

- The explicit G breaking terms in the effective potential are responsible for aligning the vacuum.

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

- Partial Compositeness (PC) provides a natural EWSB+CH mechanism,
- besides alleviating the flavour problem - with near-conformal dynamics (see *e.g.* Gripaios, 0910.1789) .
- However, the Higgs couplings in PC are extremely suppressed,

$$\kappa_V^h = c_\theta \to \sqrt{2}/2 \qquad \kappa_t^h = c_{2\theta}/c_\theta \to 0$$

- and data (EWPO and Higgs measurements) implies $s_\theta \lesssim 0.2$, requiring a conspiracy among interactions ("fine tuning")

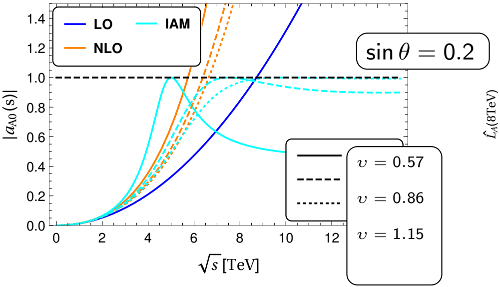
A heavy scalar techni-σ might help in attenuating these constraints by mixing with h. Arbey, Cacciapaglia, Cai, Deandrea, Le Corre, Sannino (1502.04718)

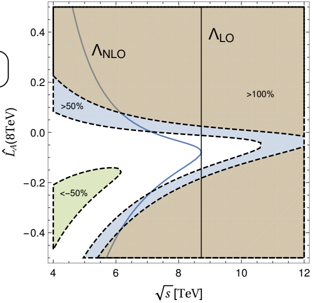
Techni-σ: unitarity implications (DBF, Ferrarese, 1705.02787)

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

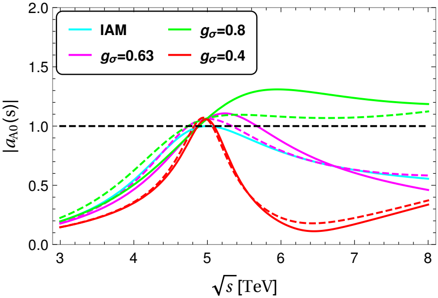
$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{f^2} = \frac{s}{v^2} \sin^2\theta \,,$$

- controlled by strong effects at high energies, broad continuum or composite resonances, saturating unitarity - similar to hadron physics.
- The scalar excitation is therefore its unavoidable consequence.





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



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

- The above analysis assume $f \gg v$ and neglect low energy interactions.

Low energy and vacuum alignment

- A minimal PC model:
  G_{FCD} =Sp(4) gauge theory with $4Q$ (spin rep.), 6χ (2 index A.S rep), realizing SU(4)/Sp(4)$\times$SU(6)/SO(6) breaking
  see e.g. Cacciapaglia, Cai, Deandrea, Flacke, Lee, Parolini (1507.02283)
- Introducing the techni-σ

$$\begin{aligned}\mathcal{L} &= k_G(\sigma/f) f^2 D_\mu \Sigma^\dagger D_\mu \Sigma - \frac{1}{2}(\partial_\mu \sigma)^2 - k_M(\sigma/f)\frac{M^2}{2}\sigma^2 \\ &+ k_t(\sigma/f)\frac{y_L y_R f C_y}{4\pi}(Q_\alpha t^c)^\dagger \,\mathrm{Tr}\,[(P_Q^\alpha \cdot P_t^T)\Sigma^\dagger] + \mathrm{h.c.}\end{aligned}$$

- Loop induced potential

$$\begin{aligned}V(\theta,\sigma) &\sim -\frac{k_t(\sigma/f)^2 C_t}{(4\pi)^2} f^4 (y_L^2 y_R^2) s_\theta^2 (s_\theta^2 - 1 + \delta(\sigma/f)) \\ \delta(\sigma/f) &\sim \frac{-(4\pi)^2 C_g (3g^2 + g'^2)}{C_t y_L^2 y_R^2}\frac{k_G(s)}{k_t(s)^2}\end{aligned}$$

- EWSB+CH+PC minimization solution: $s_\theta^2 = \frac{1-\delta}{2}$

- Mass mixing structure

$$
\begin{aligned}
m_\varphi^2 &= M^2 + \delta M^2 \\
m_h^2 &= -8(C_t/C_y^2)m_t^2 \\
m_{h\varphi}^2 &= \frac{m_h^2}{2}(k'_G - 2k'_t)\frac{\delta}{\sqrt{1-\delta^2}}
\end{aligned}
$$

Lighest mass eigenstate identified as the discovered Higgs,

$$m_{h_1} = 125\,\text{GeV}.$$

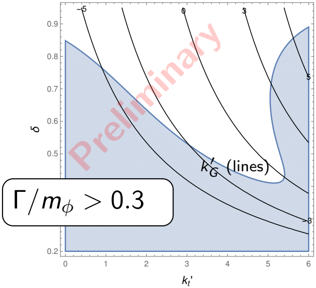
- From $\pi\pi \to \pi\pi$ unitarity $\upsilon \equiv \frac{m_\varphi}{4\sqrt{\pi}f} \lesssim 1\,,$

we set a motivated region for the couplings:

$\Gamma/m_\varphi \simeq \frac{5(2s_\theta k'_G)^2}{8}\upsilon^2 + (s_\theta k'_t)^2 \frac{N_c m_t^2}{8\pi v^2}\left(1 - \frac{4m_t^2}{m_\varphi^2}\right)^{3/2} \lesssim 0.3.$

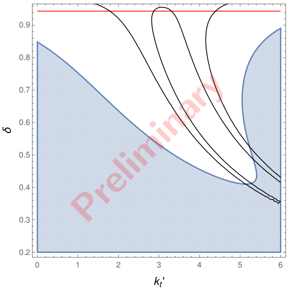
Benchmark scenario:

$\upsilon = 0.2,\ m_h = m_t.$

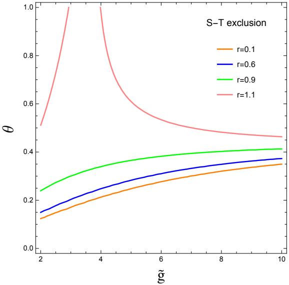


EWPT

- Without σ, $s_\theta \lesssim 0.17 \to \delta > 0.94$@95%CL.
- The techni-σ state helps alleviating EWPT (1502.04718), in particular in the motivated unitary region.

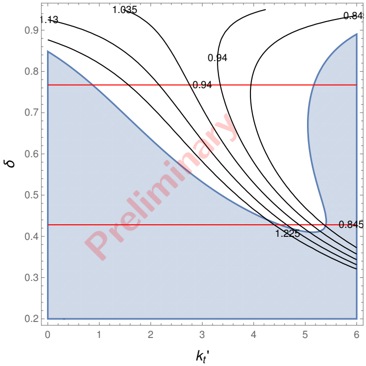


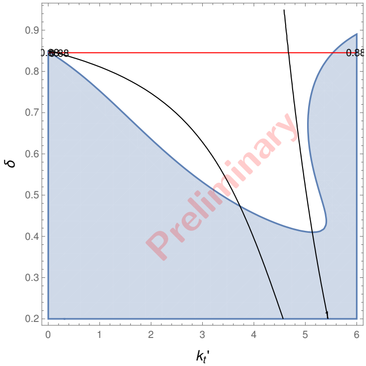
- Vector resonances also contribute to oblique parameters and might cancel tensions.
- Analysis made using the Local Hidden Symmetry construction and VMD DBF, Cacciapaglia, Cai, Deandrea, Frandsen (1605.01363)



Higgs couplings

- ATLAS+CMS, (1606.02266): $\kappa_V = 1.03 \pm 0.09$.
- CMS $t\bar{t}H$ measurement, (1804.02610): $\kappa_t = 1.12^{+0.14}_{-0.12}$



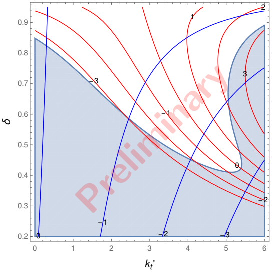


Despite initial low values of κ_V and specially κ_t, the mixing with σ in the motivated region of parameter space pushes the coupling into allowed region

- The heavy scalar h_2 will be produced at the LHC via ggF and VBF.
- Estimate of strong sector loop induced ggF delicate.

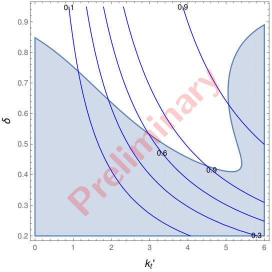
Couplings

$\kappa^{V}_{h_2}$, $\kappa^{t}_{h_2}$,

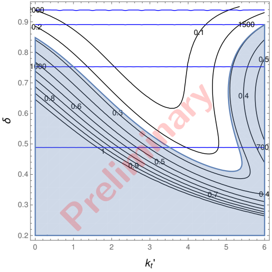


BR

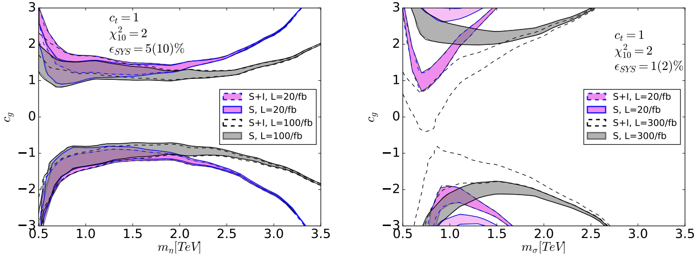
$h_2 \to \pi\pi$, $h_2 \to t\bar{t}$,



m_{h_2}, Γ_{h_2}/m_{h_2}

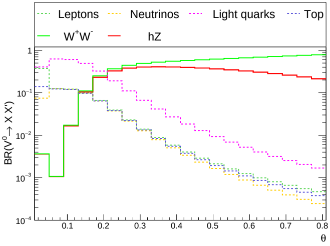


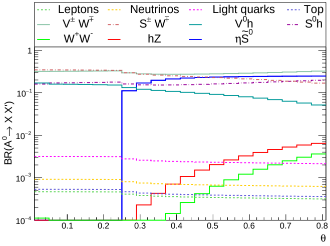
- Main channel $pp \to h_2 \to t\bar{t}$.
- Gluon effective coupling must be estimated.
- For larger values of κ_t and width large interference effects come into play.



- Vector states of SU(4)/Sp(4) offer a rich phenomenology.
- Reference mass from lattice (do not apply to this model): Sp(2) gauge theory, $M_V \simeq 13f$ (1602.06559).

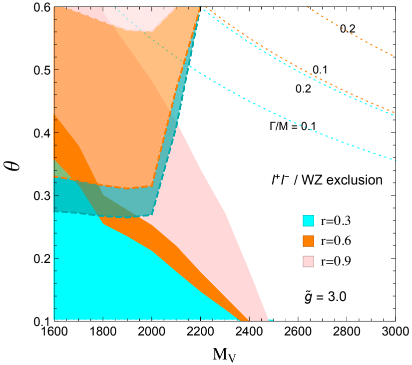
		$SU(2)_V$	$SU(2)_L \times SU(2)_R$	TC	CH
$\mathcal{V}$	$v_\mu^{0,\pm}$	3	(3,1)$\oplus$(1,3)	$\vec{\rho}_\mu$	$\vec{\rho}_\mu$
	$s_\mu^{0,\pm}$	3			$\vec{a}_\mu$
	$\tilde{s}_\mu^{0,\pm}$	3	(2,2)		
	$\tilde{v}_\mu^{0}$	1			
$\mathcal{A}$	$a_\mu^{0,\pm}$	3	(2,2)	$\vec{a}_\mu$	
	x_μ^{0}	1			
	$\tilde{x}_\mu^{0}$	1	(1,1)		





$\tilde{g} = 3$
$r = 0.6$
$M_V = 2.5$ TeV
$M_A = 3$ TeV

- Excluded region (superseded analyses $L = 3.2/fb$), e.g. dilepton ATLAS 1707.02424 from 3.5 to 4.5 TeV in Z' SSM.



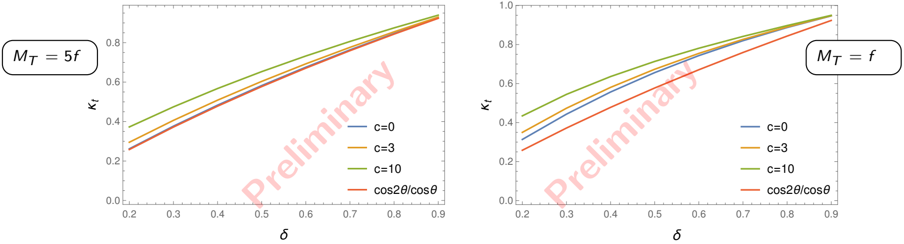
$M_V = M_A$

Top partner

- There are finite mass effects due to mixing between top partner and top, e.g. increasing of κ_t^h
- Derivative interaction present can also increase effective coupling.

$$ic_{L,R}\bar{\psi}_{5L,R}d_\mu\gamma^\mu\psi_{1L,R} = c_{L,R}\frac{\partial_\mu h}{2f}(\bar{T}_{L,R} + \bar{X}_{2/3L,R})\gamma^\mu\tilde{T}_{1L,R}$$

- Reference mass from lattice (do not apply to this model): SU(4) gauge theory with $5Q$(real rep)+3χ(comp rep), $M_T \simeq 32f$



Conclusion

to see...

- SU(6)/SO(6) colored sector, $f_6 \simeq \sqrt{N_c} f_4 = \sqrt{2} f_4$ (details in 1507.02283).
- Top partner pheno and σ interplay, $M_T \gtrsim 1.3\,\text{TeV}$ (1805.04758) model dependent.
- Loop induced couplings, gg, $\gamma\gamma$.

Conclusion:

- CH with natural low scales is still a possibility in PC paradigm.
- We provided a specific realization with predictions testable at the LHC.

Backup

Details in 1507.02283

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
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	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

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

$$M_T = \begin{pmatrix} 0 & \frac{y_{5L}}{2} f(1+c_\theta) & \frac{y_{5L}}{2} f(1-c_\theta) & \frac{y_{1L}}{2} f s_\theta \\ \frac{y_{5R}}{\sqrt{2}} f s_\theta & M_5 & 0 & 0 \\ -y_{5R} f s_\theta & 0 & M_5 & 0 \\ y_{1L} f c_\theta & 0 & 0 & M_5 \end{pmatrix} .$$

EWPT

$$\Delta S = \frac{1}{6\pi}\left((1-(\kappa_V^{h_1})^2)\log\frac{\Lambda}{m_{h_1}} - (\kappa_V^{h_2})^2\log\frac{\Lambda}{m_{h_2}} + N_D s_\theta\right)$$

$$\Delta T = \frac{-3}{8\pi\cos^2\theta_W}\left((1-(\kappa_V^{h_1})^2)\log\frac{\Lambda}{m_{h_1}} - (\kappa_V^{h_2})^2\log\frac{\Lambda}{m_{h_2}} + N_D s_\theta\right)$$

$$\hat{S} = -\frac{g^2\left(r^2-1\right)s_\theta^2}{2\tilde{g}^2 + g^2\left[2+(r^2-1)s_\theta^2\right]}\,, \tag{1}$$

$$W = \frac{g^2 M_W^2\left[s_\theta^2\left(r^2M_V^2 - M_A^2\right) + 2M_A^2\right]}{M_A^2 M_V^2\left\{g^2\left[\left(r^2-1\right)s_\theta^2+2\right] + 2\tilde{g}^2\right\}}\,, \tag{2}$$

$$Y = \frac{g'^2 M_W^2\left[s_\theta^2\left(r^2M_V^2 - M_A^2\right) + 2M_A^2\right]}{M_A^2 M_V^2\left\{2\tilde{g}^2 + g'^2\left[\left(r^2-1\right)s_\theta^2+2\right]\right\}}\,, \tag{3}$$

$$X = \frac{gg' s_\theta^2 M_W^2\left(M_A^2 - r^2M_V^2\right)}{M_A^2 M_V^2\sqrt{\left\{g^2\left[\left(r^2-1\right)s_\theta^2+2\right]+2\tilde{g}^2\right\}\left\{2\tilde{g}^2 + g'^2\left[\left(r^2-1\right)s_\theta^2+2\right]\right\}}}\,, \tag{4}$$

Spin-1 spectrum

DBF, Cacciapaglia, Cai, Deandrea, Frandsen

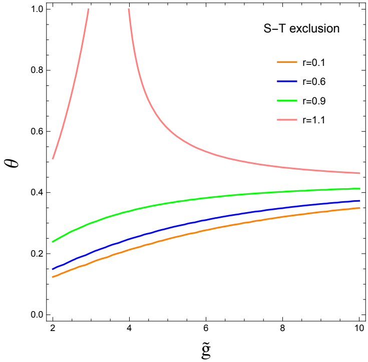
Follow Hidden Local Symmetry approach

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{2g^2}\,\mathrm{Tr}\,\widetilde{\mathbf{W}}_{\mu\nu}\widetilde{\mathbf{W}}^{\mu\nu} - \frac{1}{2g'^2}\,\mathrm{Tr}\,\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{\kappa_F(\sigma)}{2\widetilde{g}^2}\,\mathrm{Tr}\,\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu} \\
&+ \frac{1}{2}\kappa_{G_0}(\sigma) f_0^2\,\mathrm{Tr}\,p_{0\mu}p_0^{\mu} + \frac{1}{2}\kappa_{G_1}(\sigma) f_1^2\,\mathrm{Tr}\,p_{1\mu}p_1^{\mu} + r(\sigma) f_1^2\,\mathrm{Tr}\,p_{0\mu}K p_1^{\mu} K^{\dagger} \\
&+ \frac{1}{2}\kappa_K(\sigma) f_K^2\,\mathrm{Tr}\,\mathcal{D}^{\mu}K\,\mathcal{D}_{\mu}K^{\dagger} + \frac{1}{2}\partial_{\mu}\sigma\partial^{\mu}\sigma - \mathcal{V}(\sigma) \\
&+ \mathcal{L}_{fermions}
\end{aligned}
$$

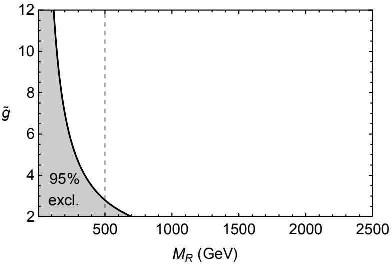
EWPT

- the vectors can cancel the contribution from Higgs modified couplings
- note that fo $r \sim 1$ higher momenta EW parameters W, Y have to be considered, but in this case EWPT is not constraining, as in Custodial Vector Model (CVM Becciolini, DBF, Foadi, Frandsen, Hapola, Sannino 14')
- $\theta \lesssim 0.2$, $f \gtrsim 1$ TeV.
- Similar bounds from Higgs physics.

FCH

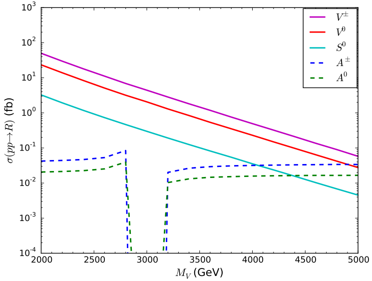


CVM



Cross sections - LHC Run II

DY



VBF