Implications of Vector Boson Scattering Unitarity in Composite Higgs Models

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arXiv:1705.02787, DBF, Piero Ferrarese

Outline

- Introduction
- Unitarity implications
- Experimental signatures
- 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.

- 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.
- Perturbative unitarity is a powerful tool to assess the scale of strong effects and properties of the composite spectrum.

Fundamental 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 et al. 0902.1483, Barnard et al. 1311.6562, Cacciapaglia, Sannino 14'

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

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

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

- In general the possible SB patterns from fermions G/H:
  SU(N)$\times$ SU(N)$\to$ SU(N), SU(2N)$\to$ SO(2N) or Sp(2N) Peskin 80

Effective Chiral Lagrangian

- The direction of the vacuum can be parametrized by the vacuum misalignment angle (determined by explicit breaking interactions)

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

$E_Q^{\pm}$: vacua that leave the EW symmetry intact.
E_Q^{B}: vacuum breaking EW symmetry to $\mathrm{U}(1)_{\mathrm{EM}}$

- After condensations, the **(pseudo-)Goldstone bosons** can be described by the CCWZ Effective Field Theory construction

$$\xi = \exp\left[\sqrt{2}\, i\left(\frac{\Pi_Q}{f}\right)\right], \Pi_Q = \sum_{i=1}^{5} \Pi_Q^i X_Q^i\,, \quad \omega^\mu = \xi^\dagger D^\mu \xi,\; x^\mu = 2\mathrm{Tr}\left[\omega^\mu X^a\right] X^a$$

- The leading order Lagrangian ($d = 2$)

$$\mathcal{L}_2 = \frac{1}{2} f^2 \langle x_\mu x^\mu \rangle$$

- generates the vev relation

$$v = f \sin\theta$$

- and the Higgs couplings modifications ($h \equiv \Pi^4_Q\,, \quad \eta \equiv \Pi^5_Q$)

$$\kappa_V \approx \cos\theta \gtrsim 0.98 \to \sin\theta \lesssim 0.2$$

Bounds from EWPO and Higgs coupling measurements.

- *The interplay with heavy composite states might relax this bound.
- To analyze perturbative unitarity it is imperative to include higher order terms → together with high dimensional operators. At $d = 4$,

$$\begin{aligned} \mathcal{L}_4 &= L_0 \langle x^\mu x^\nu x_\mu x_\nu \rangle + L_1 \langle x^\mu x_\mu \rangle \langle x^\nu x_\nu \rangle \\ &+ L_2 \langle x^\mu x^\nu \rangle \langle x_\mu x_\nu \rangle + L_3 \langle x^\mu x_\mu x^\nu x_\nu \rangle \end{aligned}$$

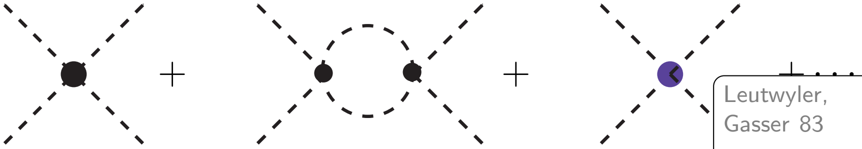
Unitarity of GBS amplitudes

- Consider $\pi^a\pi^b \to \pi^c\pi^d$ scattering amplitude in SU(4)/Sp(4). Expand in Sp(4) channels $\mathbf{5}\otimes\mathbf{5} = \mathbf{1}\oplus\mathbf{10}\oplus\mathbf{14} \equiv \mathbf{A}\oplus\mathbf{B}\oplus\mathbf{C}$ and partial waves, J
- Example scalar A $J=0$ channel
- In this basis, elastic unitarity condition read

$$\mathrm{Im}\,a_J(s) = |a_J(s)|^2$$

$$\mathrm{Im}\,a_J^{(1)}(s) = |a_J^{(0)}(s)|^2$$

$$
\begin{aligned}
a_{A0}(s) &= a_{A0}^{(0)}(s) + a_{A0}^{(1)}(s) + \cdots \\
a_{A0}^{(0)}(s) &= \frac{s}{16\pi f^2} \\
a_{A0}^{(1)}(s) &= \frac{s^2}{32\pi f^4}\left[\frac{1}{16\pi^2}\left(\frac{29}{12}+\frac{46}{18}\log\left(\frac{s}{\mu^2}\right)+2\pi i\right)+\frac{2}{3}\widehat{L_A}(\mu)\right]
\end{aligned}
$$

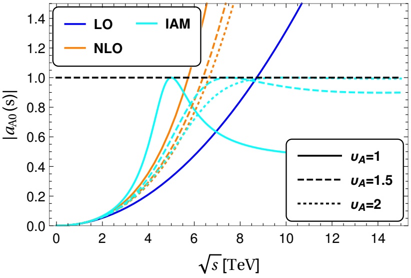


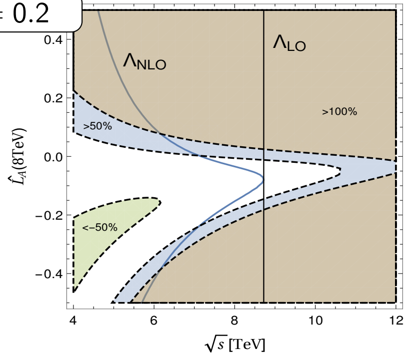
Leutwyler, Gasser 83

Bijnens, Lu 11

- **Unitarity/Perturbativity test** $|a(s)| < 1$.
- LO prediction is conservative. NLO corrections anticipate unitarity violation.
- Unitarity implies an eventual resonance is lighter than $M_\sigma \equiv v_A/\sin\theta$ TeV $\lesssim 1.75/\sin\theta$ TeV.
- Lattice results $M_\sigma = 4.7(2.6)/\sin\theta$ TeV (2 Dirac fermions in fundamental of SU(2), Arthur, Drach, Hansen, Hietanen, Pica, Sannino 16')
- IAM is an Unitarization Model (Dobado, Herrero, Pelaez 99'). Guidance for how the full non-perturbative amplitude could look like.

$\sin\theta = 0.2$





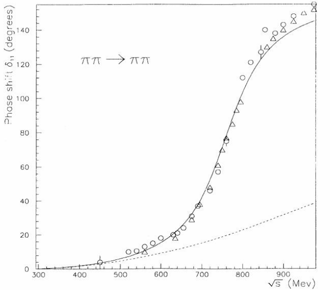


FIG. 1. (1,1) phase shift for $\pi\pi$ scattering. The solid line corresponds to our fit using Eq. (15). The dashed line is the result coming from nonunitarized ChPT with the $\bar{l}_i$ parameters proposed in [11]. The experimental data come from [12] (○) and [13] (△).

$$a_{IJ}^{IAM}(s) = \frac{a_{IJ}^{(0)}}{1 - a_{IJ}^{(1)}/a_{IJ}^{(0)}}$$

- Projection of perturbative amplitude into unitarity circle.
- Derived from dispersion relations (right cut exact, left cut approximate)
- Fits light resonances in $\pi\pi$ and πK scattering

- Generate poles interpreted as dynamically generated resonances in each channel, *e.g.*

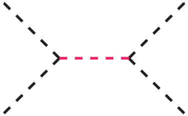
$$M_A^2 = \frac{2f^2}{\frac{1}{16\pi^2}\left(\frac{29}{12}\right) + \frac{2}{3}\widehat{L_A}(M_A)}, \quad \Gamma_A = \frac{M_A^3}{16\pi f^2}$$

- Not a QFT, violates crossing symmetry.

The σ resonance

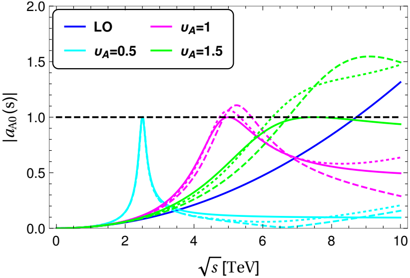
- Well defined QFT

$$\mathcal{L}_\sigma = \frac{1}{2}\kappa(\sigma) f^2 \langle x_\mu x^\mu \rangle + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}M_\sigma^2\sigma^2$$



$$a_{A0}^{\sigma}(s) = \frac{g_\sigma^2}{32\pi f^2}\left(\frac{5s^2}{m_\sigma^2 - i\Gamma_\sigma m_\sigma - s} - 2m_\sigma^2 + \frac{2m_\sigma^4 \log\left(\frac{s}{m_\sigma^2}+1\right)}{s} + s\right)$$

$$\upsilon_A \equiv \frac{m_\sigma \sin\theta}{\mathrm{TeV}}, \qquad \Gamma_\sigma \sim 5\frac{g_\sigma^2 m_\sigma^3}{32\pi f^2}, \qquad \kappa(\sigma) = 1 + \kappa'\sigma/f + \kappa''\sigma^2/(2f) + \cdots.$$



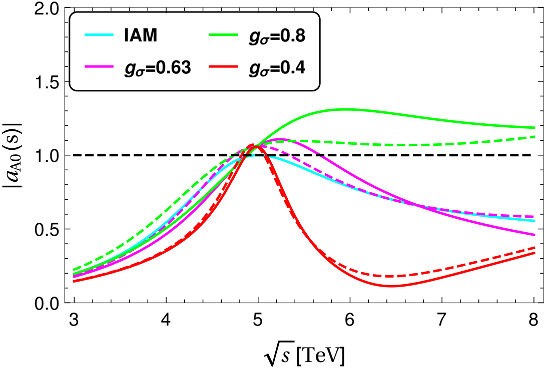
$g_\sigma \equiv \kappa'/2 \sim \sqrt{2/5} \sim 0.63$

Dashed: Fixed width

Dotted: Running width

Solid: IAM

$\sin\theta = 0.2$



$v = 1$
Solid: Fixed width
Dashed: Running width
$\sin\theta = 0.2$

- Unitarity and perturbativity give further information about the effective Lagrangian beyond pure dimensional analysis:

$$g_\sigma \lesssim 0.8 \text{ and } M_\sigma \lesssim \frac{1.2}{\sin\theta} \text{ TeV}$$

- The full resumation of the self-energy is better described by a "running" width lineshape - singlet case trivial (see DBF, Maltoni, Zhang 12 for a scalar doublet case)

Composite vector states

- **Hidden Local Symmetry:** enhance the symmetry group $\mathrm{SU}(4)_0 \times \mathrm{SU}(4)_1$. SM gauge bosons in SU(4)$_0$ and the heavy resonances in SU(4)$_1$. $\mathrm{SU}(4)_i \to \mathrm{Sp}(4)_i$. $\mathrm{Sp}(4)_0 \times \mathrm{Sp}(4)_1 \to \mathrm{Sp}(4)$ by a sigma field K DBF, Cacciapaglia, Cai, Deandrea, Frandsen (1605.01363)

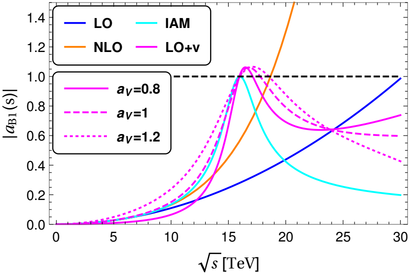
$$\begin{aligned}\mathcal{L}_v &= -\frac{1}{2\widetilde{g}^2}\langle \boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu}\rangle + \frac{1}{2}f_0^2\,\langle x_{0\mu}x_0^\mu\rangle + \frac{1}{2}f_1^2\,\langle x_{1\mu}x_1^\mu\rangle \\ &+ r\,f_1^2\,\langle x_{0\mu}Kx_1^\mu K^\dagger\rangle + \frac{1}{2}f_K^2\,\langle D^\mu K\; D_\mu K^\dagger\rangle\ .\end{aligned}$$

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

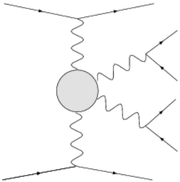
$$\pi_a(p_1)\pi_b(p_2)\mathcal{V}^c_\mu : ig_V(p_1-p_2)\Xi^{abc},\; g_V = -\frac{M_V}{2f}a_V = -\frac{M_V^2(1-r^2)}{\sqrt{2}\tilde{g}f^2}\,,$$

$$a^v_{B1}(s) = \frac{g_V^2}{32\pi}\left[\frac{s}{3(s-M_V^2)} - \frac{s}{2M_V^2} - \left(\frac{M_V^2}{s}+2\right)\left(2-\left(2\frac{M_V^2}{s}+1\right)\log\left(1+\frac{s}{M_V^2}\right)\right)\right].$$

- $M_V = 13f = 3.2\,\text{TeV}/\sin\theta$ from lattice (SU(2) gauge theory)
- $|a_V| \approx 1$



Experimental Signatures



GBS is embedded in more complicated processes

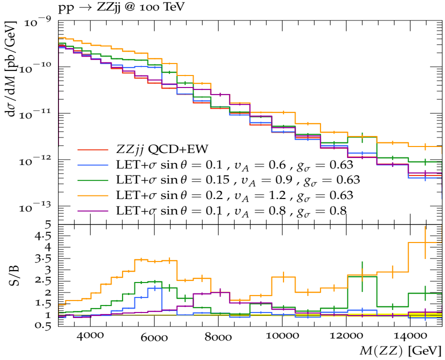
- VBS: $pp \to jjVV$, $V = W^{\pm}, Z$ (Equivalence Theorem)
- Double Higgs via VBS: $pp \to jjhh$ (effects also from trilinear Higgs modification, Arganda, Garcia-Garcia, Herrero 18)
- Double pNGB production: $pp \to jj\eta\eta$ (and other pNGB in larger cosets)

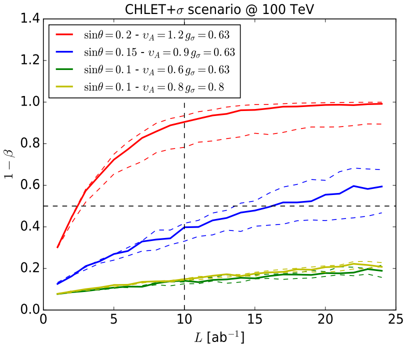
Other ways to produce the resonances

- DY for vector
- gluon fusion for scalar, if *e.g.* there is a link to the top sector

Strong VBS in $pp \to jjZZ \to jj4\ell$

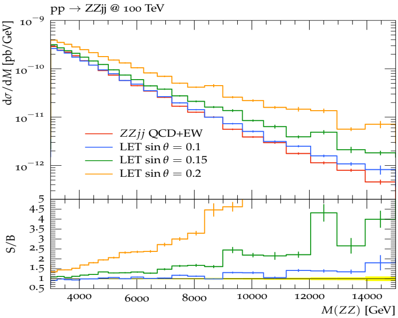
- High compositeness scale $f \gtrsim 1.2\,\text{TeV}$: **Scalar σ resonance at 100 TeV**
- Events generated with SHERPA with typical VBS cuts.
- Probability assumed to be a smeared Poisson distribution with $\epsilon = 0, 20, 40\%$
- Mixing $h - \sigma$ very small $\alpha \sim \frac{2m_h^2}{m_\sigma^2}$, suppressed gluon fusion.

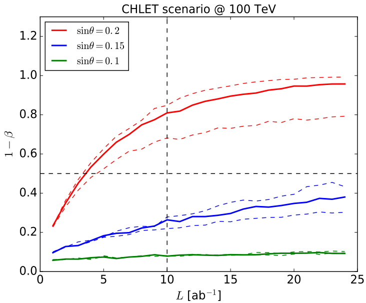




LET non-resonant enhancement at 100 TeV:

- Unitarity violation suppressed for $\sin\theta < 0.2$
- For larger deviations unitarized amplitudes should be used, implemented *e.g.* in WHIZARD(Alboteanu, Kilian, Reuter 08) and PHANTOM (Ballestrero, DBF, Oggero, Maina 11)

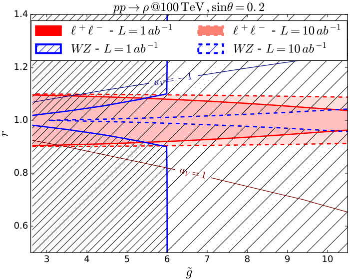


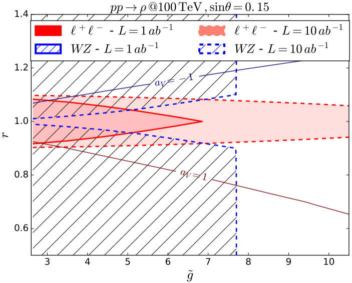


For **low scales** even **LHC** could be able to see the effects, *e.g.* for $\sin\theta = 1/\sqrt{2}$ ($f = 350\,\mathrm{GeV}$) we found $1-\beta \gtrsim 50\%$ combining channels $3\ell\nu + 2j$, $\ell^+\ell^- + 4j$ and $\ell\nu + 4j$ an $L = 200/fb$ with a parton level analysis (Ballestrero, Bevilacqua, DBF, Maina 09).

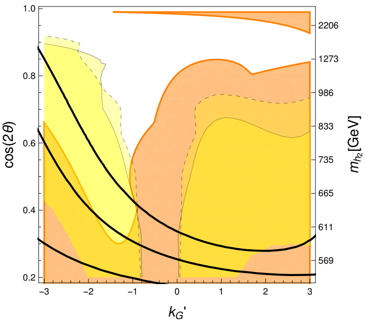
Search for Heavy Vector

- Search for techni-ρ via DY (mixing) and VBF for $M_\rho = 16\,\text{TeV}$ ($\sin\theta = 0.2$) and $M_\rho = 21.3\,\text{TeV}$ ($\sin\theta = 0.15$) model from DBF, Cacciapaglia, Cai, Deandrea, Frandsen, 1605.01363; σ bounds from Thamm, Torre, Wulzer 1502.01701





A final consideration: Low scale CH



The bound $f \gtrsim 1.2\,\text{TeV}$ is pessimistic (and unnatural). Higgs interplay with heavy composite states might alleviate the bounds to DBF, Cacciapaglia, Deandrea 1809.09146

$$f \gtrsim 550\,\text{GeV}$$

The mechanism requires top quark partial compositeness and unitarity inspired composite states.

- **A specific model:** Sp(4) gauge theory, $4Q$ in F + 6χ in AS. It predicts a $\mathcal{O}(\text{ TeV})$ scalar decaying mostly to $t\bar{t}$ and a light pseudo-scalar η
- A promising process: GBS $pp \to jj\eta\eta$ where η decays predominantly to $Z\gamma$ via anomalous interactions
  A first estimate for $m_\eta = 100\,\text{GeV}$, $f = 554\,\text{GeV}$:
  $\sigma(pp \to jj\eta\eta) = 0.6\text{fb}$ and very distinct signature!

Conclusion

- Perturbative unitarity gives valuable information about spectrum and couplings of composite sector in CH models. Beyond simple dimensional analysis.
- Scalar sector: σ resonance, $k'_G \lesssim 1.2$ and $M_\sigma \lesssim 1.2/\sin\theta$ TeV or *continuum* dominates.
- For high compositeness scale main process is VBS - 100 TeV collider more appropriate to observe strong effects.
- Low scale feasible $f \gtrsim 550\,\mathrm{GeV}$: larger LET effect ($\sin\theta \approx 0.45$) + $\mathcal{O}(\,\mathrm{TeV})$ scalar (though decaying mostly into $t\bar{t}$)
- Other light pNGBs might give smoking gun signatures in this kind of scenario, *e.g.* $pp \to jj\eta\eta$.

CCWZ

- Vacuum $\Sigma_0 = \cos\theta\Sigma_B + \sin\theta\Sigma_H$.
- Minimization $\cos\theta_{min} = \frac{2C_m}{y_t' C_t}$, for $y_t' C_t > 2|C_m|$.
- Generators

$$
\begin{aligned}
V^a \cdot \Sigma_0 + \Sigma_0 \cdot V^{a\,T} &= 0\,, \qquad & S^a \cdot \Sigma_B + \Sigma_B \cdot S^{a\,T} &= 0\,,\\
Y^a \cdot \Sigma_0 - \Sigma_0 \cdot Y^{a\,T} &= 0\,. \qquad & X^a \cdot \Sigma_B - \Sigma_B \cdot X^{a\,T} &= 0\,,
\end{aligned}
$$

$$
U = \exp\left[\frac{i\sqrt{2}}{f}\sum_{a=1}^{5}\pi^a Y^a\right]\,,
$$

$$
\begin{aligned}
\omega_\mu &= U^\dagger D_\mu U,\\
D_\mu &= \partial_\mu - igW^i_\mu S^i - ig' B_\mu S^6,\\
x_\mu &= 2\mathrm{Tr}\left[Y_a\omega_\mu\right] Y^a\ ,\\
s_\mu &= 2\mathrm{Tr}\left[V_a\omega_\mu\right] V^a\ .
\end{aligned}
$$

Hidden Local Symmetry (HLS)

- Enhance the symmetry group $\mathrm{SU}(4)_0 \times \mathrm{SU}(4)_1$, and embed the SM gauge bosons in $SU(4)_0$ and the heavy resonances in $SU(4)_1$. $\mathrm{SU}(4)_i \to \mathrm{Sp}(4)_i$. $\mathrm{Sp}(4)_0 \times \mathrm{Sp}(4)_1 \to \mathrm{Sp}(4)$ by a sigma field K

$$U_0 = \exp\left[\frac{i\sqrt{2}}{f_0}\sum_{a=1}^{5}(\pi_0^a Y^a)\right], \quad U_1 = \exp\left[\frac{i\sqrt{2}}{f_1}\sum_{a=1}^{5}(\pi_1^a Y^a)\right]. \tag{1}$$

$$\begin{aligned} D_\mu U_0 &= (\partial_\mu - igW_\mu^i S^i - ig' B_\mu S^6)U_0 , \\ D_\mu U_1 &= (\partial_\mu - i\widetilde{g}\mathcal{V}_\mu^a V^a - i\widetilde{g}\mathcal{A}_\mu^b Y^b)U_1 . \end{aligned} \tag{2}$$

$$\begin{aligned} K &= \exp\left[ik^a V^a / f_K\right] , \\ D_\mu K &= \partial_\mu K - i v_{0\mu} K + i K v_{1\mu} \end{aligned} \tag{3}$$

$$\boldsymbol{\mathcal{F}}_\mu = \boldsymbol{\mathcal{V}}_\mu + \boldsymbol{\mathcal{A}}_\mu = \sum_{a=1}^{d_H} \mathcal{V}_\mu^a V_a + \sum_{a=1}^{d_G - d_H} \mathcal{A}_\mu^a Y_a,$$

$$\begin{aligned} \mathcal{L}_v &= -\frac{1}{2\widetilde{g}^2} \langle \boldsymbol{\mathcal{F}}_{\mu\nu} \boldsymbol{\mathcal{F}}^{\mu\nu} \rangle + \frac{1}{2} f_0^2 \, \langle x_{0\mu} x_0^\mu \rangle + \frac{1}{2} f_1^2 \, \langle x_{1\mu} x_1^\mu \rangle \\ &+ r f_1^2 \, \langle x_{0\mu} K x_1^\mu K^\dagger \rangle + \frac{1}{2} f_K^2 \, \langle D^\mu K \; D_\mu K^\dagger \rangle . \end{aligned}$$

GBS amplitudes

- $\pi\pi \to \pi\pi$ scattering amplitudes expanded in partial wave amplitudes

$$\mathcal{A}(s,t) = 32\pi \sum_{J=0}^{\infty} a_J(s)(2J+1)P_J(\cos\theta)$$

- In order to force elasticity (at least below new heavy states appear), decompose amplitude in conserved quantum number
- **Template: SU(4)/Sp(4), FMCHM**, decompose in multiplets of Sp(4) (very good symmetry at high energy)

$$\mathbf{5} \otimes \mathbf{5} = \mathbf{1} \oplus \mathbf{10} \oplus \mathbf{14} \equiv \mathbf{A} \oplus \mathbf{B} \oplus \mathbf{C}$$

$pp \to ZZjj$ analysis

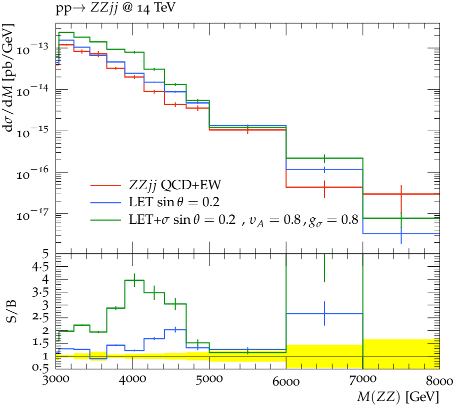
Cuts:

cut	100 TeV	14 TeV
2 jets	$p_T > 30$ GeV , $\|\eta\| > 3.5$, $\eta_1 \cdot \eta_2 < 0$	$p_{T,j} > 30$ GeV , $\|\eta_j\| > 3.$, $\eta_{j_1} \cdot \eta_{j_2} < 0$
ZZ invariant mass	$m_{ZZ} > 3$TeV	$m_{ZZ} > 3$TeV
di-jet invariant mass	$m_{jj} > 1$ TeV	$m_{jj} > 1$ TeV
Zs centrality	$\|\eta_{Z_i}\| < 2.$	$\|\eta_{Z_i}\| < 2.$
Zs momentum	$p_{T,Z_i} > 1$ TeV	$p_{T,Z_i} > 0.5$ TeV

Probability distribution:

$$\mathcal{P}(k;\lambda,\epsilon) = \frac{1}{2\epsilon}\int_{1-\epsilon}^{1+\epsilon} \mathrm{d}x\, e^{-x\lambda}\frac{(x\lambda)^k}{k!}$$

σ resonance at the LHC



- $\sigma \sim 2.9 \times 10^{-4}$ ab very small.
- Other VBS channels imperative for this search.
- Gluon fusion contribution could help.

Effective Chiral Lagrangian

- After condensation composite degrees of freedom
- 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

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

Top-quark Partial Compositeness

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

$$
\begin{array}{cccccccc}
V(\theta) & = & V_{top}(\theta) & + & V_{gauge}(\theta) & + & V_{mass}(\theta) \\
 & & \text{ETC: } s_\theta^2 \to 1 & & s_\theta^2 \to 0 & & \\
 & & \text{PC: } s_\theta^2 \to 1/2 & & & &
\end{array}
$$

- 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.

- Top-quark PC generates mass via a mixing $t\Psi$ where Ψ is a fermionic composite state with same quantum numbers of the top.
- Composite sector needs to be extended: QCD colored, asymptotic freedom, ...

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

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

	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}
$Q\sigma^\mu Q$	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

- Top partners can be integrated out from Lagrangian (assuming they are heavy)

$\sigma - h$ mix

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

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

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

...and modify Higgs couplings

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

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;

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

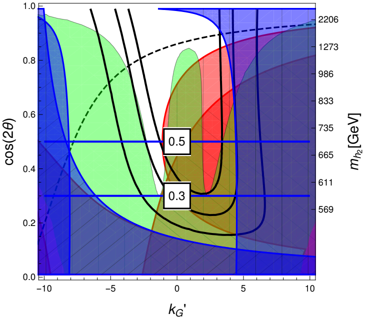
iii - EWPOs;

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

DBF, Cacciapaglia, et al. 16'

iv - Direct search of the heavy scalar.

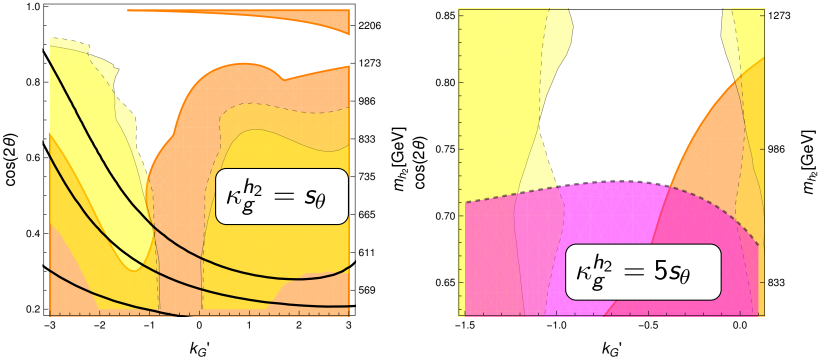
- Perturbativity, $|k_i'| < 4\pi$, pert. unitarity $\gamma = \frac{m_{h_2}}{4\sqrt{\pi f}} \lesssim 1$ ($\gamma = 0.2$ in the plot), $\Gamma/m_{h_2} \lesssim 1$ (black curves, 0.3, 0.5, 1)
- EWPO, σ creates the valleys and vectors shift and broaden them.



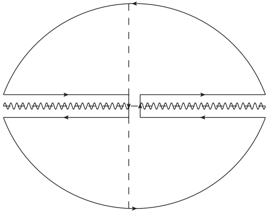
- Higgs measurements, $\kappa_{t,V}$. $\Gamma(h \to \eta\eta)$ (dashed line) for $m_\eta = 0$ - larger masses (m_ψ or **A** rep.) opens parameters space and interesting experimental signatures.
- Dynamically inspired composite resonance profile works nicely. σ: $|k_G'| \sim 1.2$. v_μ: $r = 1.1 \to |a_V|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



Dispersion for IAM



Three subtracted dispersion relation to ensure the function vanish at the infinity circle. Then for $G(s) = a^{(0)2}/a$.

$$G(s) = G_0 + G_1 s + G_2 s^2 + \frac{s^3}{\pi} \int_0^\infty \frac{\mathrm{Im}\, G(s') ds'}{s'^3(s' - s - i\epsilon)} + LC(G) + PC$$

$$\mathrm{Im}\, G = a^{(0)2} \mathrm{Im}(1/a) = -a^{(0)2} \mathrm{Im}\, a/|a|^2 \begin{cases} = -a^{(0)2}, & \text{if } s > 0 \\ \approx \mathrm{Im}\, a^{(1)}, & \text{if } s < 0 \end{cases}$$

Neglecting pole contributions (PC),

$$G \approx a^{(0)} - a^{(1)} \rightarrow a \approx \frac{a^{(0)2}}{a^{(0)} - a^{(1)}}$$

Right cut is exact,but the left cut (LC) is approximated.