

Goldstone Boson Scattering in Composite Higgs Models

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- 1 Composite Higgs (CH) in the CCWZ framework
- 2 Unitarity in Goldstone Boson Scattering (GBS)
- 3 $v \lesssim E \lesssim m_\sigma$: LET, $\mathcal{O}(p^4)$ corrections and GBS at colliders.
- 4 $E \sim m_\sigma$: the scalar excitation.
- 5 Comments on Partial Compositeness (PC)
- 6 Conclusions

1 - Composite Higgs (CH)

- **Technicolor (TC):** 4D confining gauge theory G_{HC} with fermionic matter \rightarrow dynamical EW symmetry breaking (**hierarchy problem**)
(Weinberg 76, Susskind 79)

$$\langle \psi\psi \rangle \sim f^3 \rightarrow f = v$$

- **Composite Higgs (CH):** Vacuum misalignment (Higgs is a pNGB) (**Little-hierarchy problem and doublet nature of Higgs**)
(Peskin 80, Preskill 80, Georgi, Kaplan 84', Agashe, Contino, Pomarol 05)

$$v = f \sin \theta$$

Model example (Gripaios, Pomarol, Riva, Serra 0902.1483):

	Sp(4)	SU(3) _c	SU(2) _L	U(1) _Y	SU(4)	SU(6)
$\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$	□	1	2	0	4	1
$\psi_{3,4}$	□	1	1	$\pm 1/2$		1

Condensation: the raise of electroweak scale and pNGBs

- UV Lagrangian

$$\mathcal{L}_{UV} = \bar{\psi}^I i \not{D} \psi^I + \delta \mathcal{L}_m + \delta \mathcal{L}$$

- Global symmetry at quantum level (from kinetic terms) (U(1) is explicitly broken by gauge anomaly)

$$G = \text{SU}(4)$$

- Gauge interactions, fermion masses and other interactions might break the global symmetry
- **Condensation** at scale $\Lambda \sim 4\pi f$

$$\langle \psi_{\alpha,c}^I \psi_{\beta,c'}^J \epsilon^{\alpha\beta} \epsilon^{cc'} \rangle \sim f^3 E_{\psi}^{IJ}$$

- Spontaneously breaks $G \rightarrow H$

$$\text{SU}(4) \rightarrow \text{Sp}(4)$$

- Below condensation scale, the d.o.f. are the composite states,
- including the (pseudo-)NGB π from the symmetry breaking manifesting its non-linearity properties

$$\xi(\pi) = e^{i\pi^A X^A}, \quad \xi(\pi) \rightarrow \xi(\pi') = g\xi h(g, \pi)^\dagger$$

- The custodial group $SU(2)_L \times SU(2)_R$ “rotates” with the Higgs (or pNGBs) vev

$$\Omega = e^{i\langle \tilde{h} \rangle X_h / f}, \quad T_{L/R}^i = \Omega \hat{T}_{L/R}^i \Omega^\dagger \quad SU(2)_V \text{ left unbroken}$$

- Chiral expansion in ∂^μ / f with the gauged Maurer-Cartan one-forms

$$\omega_\mu = \xi^\dagger \nabla_\mu \xi \quad \nabla_\mu \xi = (\partial_\mu - igW_\mu^a T_L^a - ig' B_\mu T_R^3) \xi$$

$$\omega_\mu = \tilde{\omega}_\mu + \hat{\omega}_\mu \equiv x_\mu + s_\mu \quad \text{Proj. to } X^A, S^A$$

$$x_\mu \rightarrow hx_\mu h^\dagger, \quad s_\mu \rightarrow hs_\mu h^\dagger + h\partial_\mu h^\dagger$$

- The leading order kinetic term $\mathcal{O}(p^2)$

$$\mathcal{L}_2 = \frac{f^2}{N^2} \langle x^\mu x_\mu + \tilde{\chi} \rangle$$

- generates the vev relation

$$v = f \sin \theta$$

- the Higgs- VV couplings modifications

$$\kappa_V \approx \cos \theta \gtrsim \begin{cases} 0.98 \text{ (EWPO, indirect)} \\ 0.90 \text{ (Higgs couplings meas.)} \\ 0.96 \text{ (SMEFT fit individual } c_{\varphi D})^* \end{cases}$$

*Ethier, Ambrosio, Magni, Rojo 2101.03180

- $\tilde{\chi}$ depict spurionic G -breaking terms contributing to the pNGB potential
- At $\mathcal{O}(p^4)$ Gasser, Leutwyler 84, Bijjnens, Ecker 14

$$\begin{aligned} \mathcal{L}_4 = & L_0 \langle x^\mu x^\nu x_\mu x_\nu \rangle + L_1 \langle x^\mu x_\mu \rangle \langle x^\nu x_\nu \rangle + L_2 \langle x^\mu x^\nu \rangle \langle x_\mu x_\nu \rangle + L_3 \langle x^\mu x_\mu x^\nu x_\nu \rangle \\ & + L_4 \langle x^\mu x_\mu \rangle \langle \tilde{\chi} \rangle + L_5 \langle x^\mu x_\mu \tilde{\chi} \rangle + L_6 \langle \tilde{\chi} \rangle^2 + L_7 \langle \hat{\chi} \rangle^2 + \frac{1}{2} L_8 \langle \tilde{\chi}^2 + \hat{\chi}^2 \rangle \\ -i & L_9 \langle \tilde{f}_{\mu\nu} x^\mu x^\nu \rangle + 1/4 L_{10} \langle \tilde{f}_{\mu\nu}^2 - \hat{f}_{\mu\nu}^2 \rangle + K_1 f^2 \langle x^\mu x_\mu \rangle \langle \tilde{\chi}^2 + \hat{\chi}^2 \rangle - \frac{1}{4} \langle f^{\mu\nu} f_{\mu\nu} \rangle \end{aligned}$$

2 - Unitarity of GBS amplitudes DBF, Ferrarese 17'

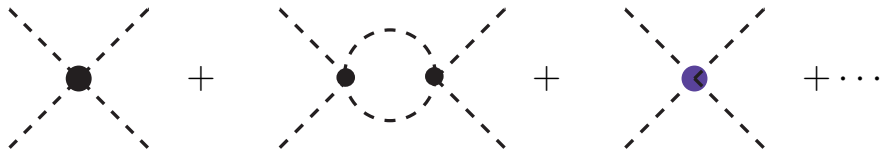
- $\pi^a \pi^b \rightarrow \pi^c \pi^d$ scattering amplitude in exact $SU(4)/Sp(4)$. $Sp(4)$ channels $5 \otimes 5 = 1 \oplus 10 \oplus 14 \equiv A \oplus B \oplus C$ and partial waves, J
- Elastic unitarity condition read

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

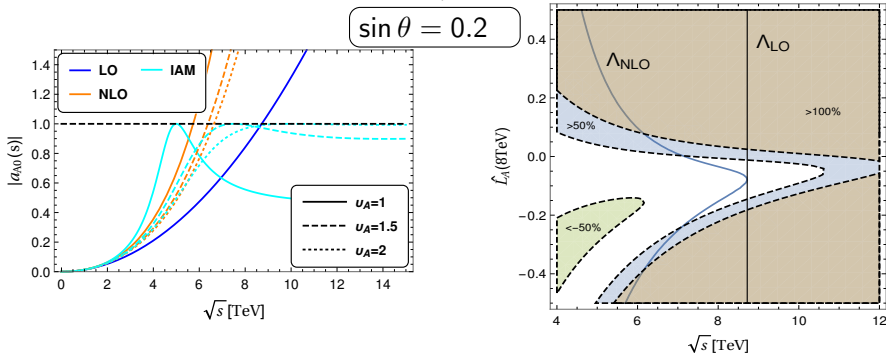
$$a_{A0}(s) = a_{A0}^{(0)}(s) + a_{A0}^{(1)}(s) + \dots$$

$$a_{A0}^{(0)}(s) = \frac{s}{16\pi f^2} \quad \text{Low Energy Theorem (LET)}$$

$$a_{A0}^{(1)}(s) = \frac{s^2}{32\pi f^4} \left[\frac{1}{16\pi^2} \left(\frac{29}{12} + \frac{46}{18} \log \left(\frac{s}{\mu^2} \right) + 2\pi i \right) + \frac{2}{3} \widehat{L}_A(\mu) \right]$$



- **Unitarity/Perturbativity test** $|a(s)| < 1$.
- LO prediction is conservative. NLO corrections anticipate unitarity violation.
- Unitarity implies an eventual resonance is lighter than $M_\sigma \lesssim 1.75/\sin\theta$ TeV. (Similar bounds for vector channel).
- Values of L_i : $1/(4\pi)^2$ (NDA), specific combinations bounded by unitarity and positivity Zhang, Zhou et. al. 18, 20
- **Inverse Amplitude Method (IAM)** unitarization model derived from dispersion relations, describes ρ hadron Dobado, Herrero, Pelaez 99'



3 - $v \lesssim E \lesssim f$: LET, $\mathcal{O}(p^4)$, GBS at colliders

- The minimal $SO(5)/SO(4)$ is a peculiar coset because $SO(4) \sim SU(2) \times SU(2)$. The unbroken projectors and operators can all be split in independent terms
- Neglecting CP-odd and terms with χ Contino, Marzocca, Pappadopulo, Rattazzi 1109.1570

$$\mathcal{L}_4 = c_i O_i$$

$$O_1 = \langle x_\mu x^\mu \rangle^2, \quad O_2 = \langle x_\mu x^\mu \rangle^2, \quad O_3 = \langle E_{\mu\nu}^{L2} \rangle - \langle E_{\mu\nu}^{R2} \rangle,$$

$$O_4^\pm = -i \langle x_\mu x_\nu [f_{\mu\nu}^{+L} \pm f_{\mu\nu}^{+R}] \rangle, \quad O_5^+ = \langle (f_{\mu\nu}^-)^2 \rangle, \quad O_5^- = \langle [(f_{\mu\nu}^{+L})^2 - (f_{\mu\nu}^{+R})^2] \rangle$$

- “Linearization” to SMEFT in the SILH basis (Giudice, Grojean, Pomarol, Rattazzi, 07) with extra dim-8 subset

$$\mathcal{L} = \sum_{i=H,T,y,6} \frac{c_i}{f^2} \mathcal{O}_i + \sum_{i=W,B,HW,HB} \frac{c_i}{m_\rho^2} \mathcal{O}_i + \frac{c_i^8}{f^2 m_\rho^2} (H^\dagger H) \mathcal{O}_i$$

- Universal relations from couplings due to the non-linear nature of the symmetry realization can only be respect by including dim-6 and dim-8 operators of the linear framework, e.g. the couplings $Z_{\mu\nu} A^{\mu\nu} [C_4^h h/v + C_4^{2h} (h/v)^2]$ respect

$$\frac{C_4^{2h}}{C_4^h} = \frac{1}{2} \cos \theta \approx \frac{1}{2} \left(1 + \frac{C_{HW}^8 - C_{HB}^8}{C_{HW} - C_{HB}} (v/f)^2 \right)$$

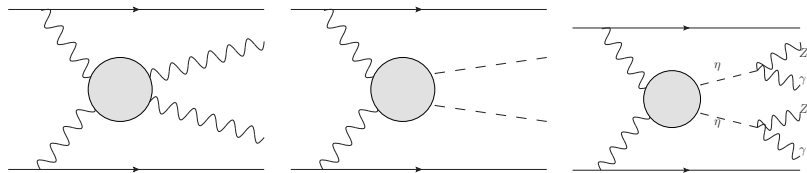
- Moreover, leading operators in strong VBS $\mathcal{O}_{1,2}$ appear only at dim-8 in the SMEFT.

$f^2 \mathcal{O}_3$	$f^2 \mathcal{O}_4^+$	$f^2 \mathcal{O}_4^-$
$-4(\mathcal{O}_W - \mathcal{O}_B)$	$2(\mathcal{O}_{HW} + \mathcal{O}_{HB})$	$2(\mathcal{O}_{HW} - \mathcal{O}_{HB})$
$f^2 \mathcal{O}_5^+$	$f^2 \mathcal{O}_5^-$	
$4[\mathcal{O}_W + \mathcal{O}_B - (\mathcal{O}_{HW} + \mathcal{O}_{HB})]$	$-4[\mathcal{O}_W - \mathcal{O}_B - (\mathcal{O}_{HW} - \mathcal{O}_{HB})]$	
$c_H = 1, \quad c_Y = -1/3, \quad c_6 = -4/3$		

Feynrules/UFO implementation (work in progress)

- Implementation of CCWZ framework in FeynRules/UFO at $\mathcal{O}(p^4)$ to describe CH collider phenomenology.
- FeynRules/UFO provides a flexible tool to simulate collider events e.g. in MadGraph, using all its features like polarization selection, possibility to include radiative corrections.
- Would allow e.g. a more robust test of the Universal relations.
- Difference of the CCWZ/CH framework w.r.t. SMEFT and HEFT:
 - Universal relations from non-linear symmetry
 - Natural inclusion of other pNGBs (in non-minimal cosets - **minimal coset is NOT realizable by a fundamental gauge theory.**)
 - and other heavy resonances e.g. spin-1 DBF, Cacciapaglia, Cai, Deandrea, Frandsen 1605.01363
- HEFT describes CH, with a set of Higgs expansion coefficients (Higgs is treated as a singlet) e.g. Delgado, Dobado, Llanes-Estrada 1408.1193; Alonso, Brivio, Gavela, Merlo, Rigolin 1409.1589, and resonances e.g. Dobado, Llanes-Estrada, Sanz-Cillero 1711.10310

GBS at Colliders



- GBS are embedded in more complicated processes at colliders.
- Longitudinal weak bosons are manifestations of the GBs (equivalence theorem)
- Polarized scattering with MadGraph_aMC@NLO DBF, Mattelaer, Ruiz, Shil 1912.01725

$$q_1 q_2 \rightarrow q'_1 q'_2 W_\lambda^+ W_{\lambda'}^-, \quad \lambda = 0, T$$

- Di-Higgs via VBF

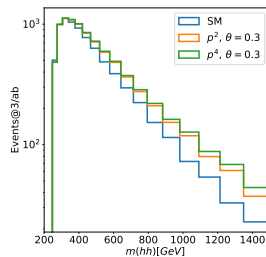
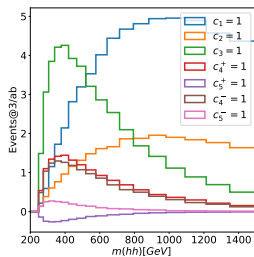
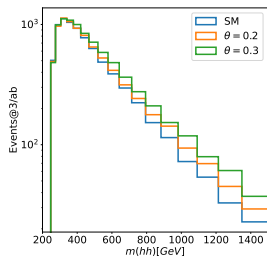
$$q_1 q_2 \rightarrow q'_1 q'_2 hh$$

- Di-pNGBs via VBF:

$$q_1 q_2 \rightarrow q'_1 q'_2 \eta \eta, \quad q_1 q_2 \rightarrow q'_1 q'_2 \pi^0 \pi^0, \dots$$

$pp \rightarrow jjhh$ at $\mathcal{O}(p^4)$ (Preliminary)

- Trilinear coupling has to be added (from potential) - suppressed.



Selection cuts

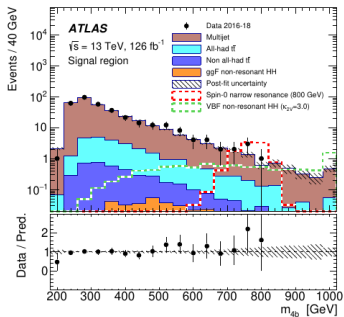
$$p_T(j) > 20 \text{ GeV}, \quad |\eta(j)| < 5 \quad M(jj) > 200 \text{ GeV}$$

$$|\eta(h)| < 3.5. \quad p_T(h) > 30 \text{ GeV},$$

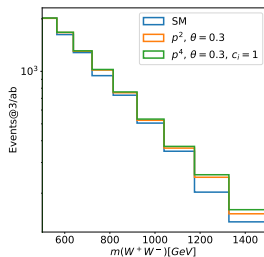
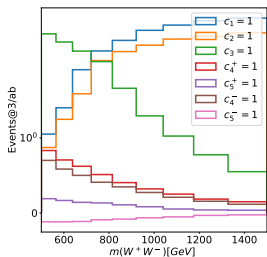
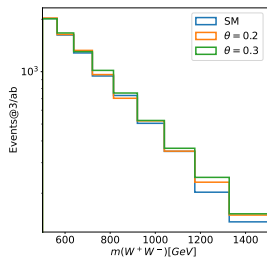
- Will ATLAS show an excess at high energy hh ? JHEP07(2020)108
- Non-resonant scenario parametrized “only” by k_V and k_{2V} Bishara, Contino, Rojo 1611.03860
- Other Lorentz structures are present - **Other observables?**

$$Z_\mu \mathcal{D}^{\mu\nu} Z_\nu \left(C_1^h \frac{h}{v} + C_1^{2h} \frac{h^2}{v^2} \right), \quad Z^{\mu\nu} Z_{\mu\nu} \left(C_2^h \frac{h}{v} + C_2^{2h} \frac{h^2}{v^2} \right)$$

$$\mathcal{D}^{\mu\nu} = \partial^\mu \partial^\nu - g^{\mu\nu} \partial^2$$



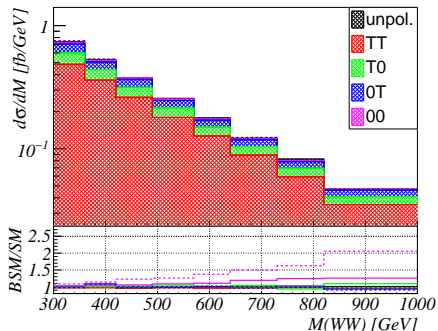
$pp \rightarrow jjW_0^+ W_0^-$ at $\mathcal{O}(p^4)$ (Preliminary)



Selection cuts

$$\begin{aligned}
 p_T(j) &> 20 \text{ GeV}, & |\eta(j)| &< 5 \\
 M(jj) &> 250 \text{ GeV}, & \Delta\eta(jj) &> 2.5, \\
 |\eta(W^\pm)| &< 3.5, & p_T(W^\pm) &> 30 \text{ GeV}, \\
 M(W^+W^-) &> 500 \text{ GeV},
 \end{aligned}$$

- Same-sign WW has been studied in the HEFT context Kozów, Merlo, Pokorsky, Szeleper 1905.03354



BSM scenarios $c_\theta = 0.8$, $c_\theta = 0.9$

Selection cuts

$$p_T(j) > 20 \text{ GeV}, \quad |\eta(j)| < 5$$

$$M(jj) > 250 \text{ GeV}, \quad \Delta\eta(jj) > 2.5,$$

$$|\eta(W^\pm)| < 2.5. \quad p_T(W^\pm) > 30 \text{ GeV},$$

$$M(W^+W^-) > 300 \text{ GeV},$$

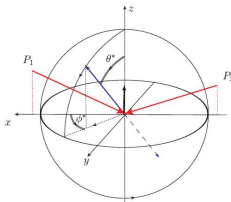
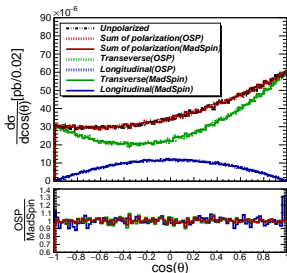
Very hard to distinguish from SM.

Process	p-CM SM ($a = 1$)		p-CM CH ($a = 0.8$)			p-CM CH ($a = 0.9$)		
	σ [fb]	$f_{\lambda\lambda'}$	σ [fb]	$f_{\lambda\lambda'}$	$\sigma^{\text{CH}}/\sigma^{\text{SM}}$	σ [fb]	$f_{\lambda\lambda'}$	$\sigma^{\text{CH}}/\sigma^{\text{SM}}$
jjW^+W^-	171	...	173	...	1.00	172	...	1.00
$jjW_T^+W_T^-$	119	70%	116	69%	0.98	115	69%	0.96
$jjW_0^+W_T^-$	20.6	12%	21.5	13%	1.05	22.0	13%	1.07
$jjW_T^+W_0^-$	23.8	14%	24.1	14%	1.01	23.9	14%	1.01
$jjW_0^+W_0^-$	5.45	3%	7.17	4%	1.31	6.01	4%	1.10

Polarization variables

- One can use polarization variables beyond typical VBS cuts to e.g. extract the longitudinal component e.g. Mirkes 92, Bern, Diana, Dixon 11, Stirling, Vryonidou 12, Belyaev, Ross 13 .
- In MadGraph_aMC@NLO DBF, Mattelaer, Ruiz, Shil 1912.01725.

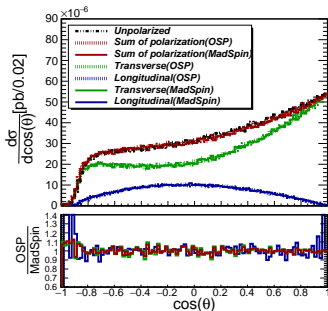
$$pp \rightarrow jjW^+W_\lambda^-, \quad \text{with } W^+ \rightarrow \mu^+\nu_\mu \quad \text{and } W_\lambda^- \rightarrow e^-\bar{\nu}_e,$$



- Can be used as tool to extract polarization fractions (see Carlos Cid talk)

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta} \approx \frac{3}{8}(1 + \cos\theta)^2 f_L + \frac{3}{8}(1 - \cos\theta)^2 f_R + \frac{3}{4}\sin^2\theta f_0$$

- and assess other useful variables, including selection cuts on decay products, e.g. $p_T(e^-) > 20 \text{ GeV}$, $|\eta(e^-)| < 2.5$, $\Delta R(j e^-) > 0.4$



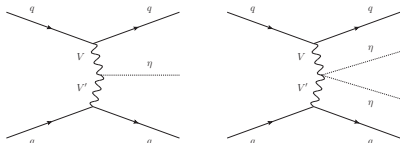
- Very hard measurement. f_0 with DNN $\rightarrow c_\theta \sim 0.9$ at $L = 3/ab$ 4% systematics. Jinmian Li, Shuo Yang, Rao Zhang, 2010.13281
- Current f_0 measurement at CMS: uncertainty $\sim 130\%$ CMS 2009.09429

Electro-weak coset	$SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm 1} + \mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4) \times SU(4)' / SU(4)_D$	$\mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{2}'_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0 + \mathbf{1}'_0$
Color coset	$SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{8}_0 + \mathbf{6}_{(-2/3 \text{ or } 4/3)} + \bar{\mathbf{6}}_{(2/3 \text{ or } -4/3)}$
$SU(6)/Sp(6)$	$\mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)' / SU(3)_D$	$\mathbf{8}_0$

Ferretti 1604.06467

- At low energy VBS competes with other production mechanisms,
- Offshell Higgs and top contact interaction DBF, Ferretti, Li, Shu 2005.13578
- DY for charged pions.

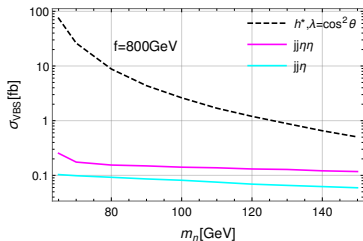
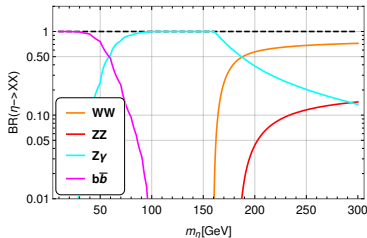
η production via VBF and double- η -strahlung



- Double- η production via kinetic term (VBF, 2 η -strahlung) DBF, Ferretti, Li, Shu 2005.13578

$$\mathcal{L} \supset \frac{f^2}{8} D_\mu U D^\mu U^\dagger \supset \left(M_W^2 W^{+\mu} W_\mu^- + \frac{M_Z^2}{2} Z^\mu Z_\mu \right) \left(1 + \frac{2 \cos \theta}{v} h - \frac{\sin^2 \theta}{v^2} \eta^2 \right)$$

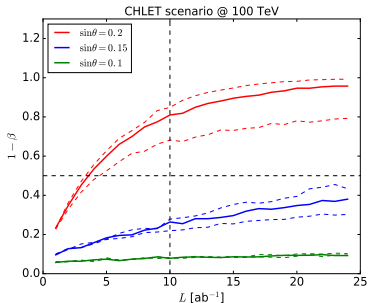
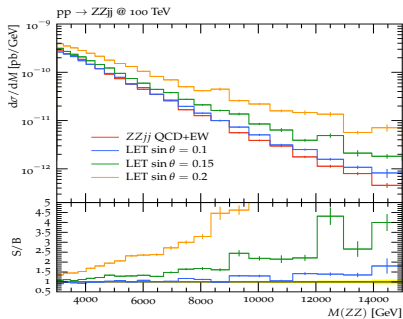
- Single- η via WZW anomalous interaction (VBF, η -strahlung)



LET non-resonant enhancement FCC-hh 100 TeV

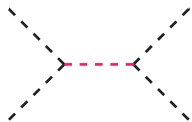
- No cancellations in EWPO $s_\theta \lesssim 0.2$ (unknown alignment mechanism)
- $pp \rightarrow jjZZ \rightarrow jje^+e^-\mu^+\mu^-$ events, SHERPA with typical VBS cuts.
- Probability assumed to be a smeared Poisson distribution
- Unitarity violation suppressed for $\sin \theta < 0.2$ (Otherwise use unitarized amplitudes WHIZARD(Alboreanu, Kilian, Reuter 08) and PHANTOM (Ballestrero, DBF, Oggero, Maina 11))

DBF, Ferrarese 1705.02787



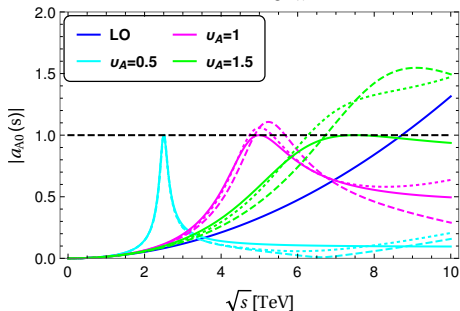
4 - $E \sim m_\sigma$: the scalar excitation

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



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

$$v_A \equiv \frac{m_\sigma \sin\theta}{\text{TeV}}, \quad \Gamma_\sigma \sim 5 \frac{g_\sigma^2 m_\sigma^3}{32\pi f^2}, \quad \kappa(\sigma) = 1 + \kappa'\sigma/f + \kappa''\sigma^2/(2f) + \dots$$



DBF, Ferrarese 17

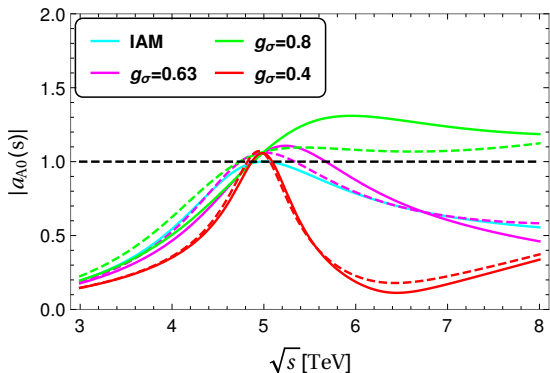
$$g_\sigma \equiv \kappa'/2 \sim \sqrt{2/5} \sim 0.63$$

Dashed: Fixed width

Dotted: Running width

Solid: IAM

$\sin\theta = 0.2$



$v = 1$

Solid: Fixed width

Dashed: Running width

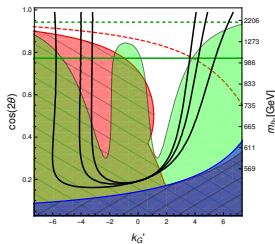
$\sin \theta = 0.2$

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

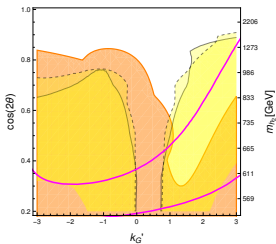
$$g_\sigma \lesssim 0.8 \text{ and } M_\sigma \lesssim \frac{1.2}{\sin \theta} \text{ TeV}$$

- The ubiquitous presence of a scalar composite state σ (and vector) might alleviate EWPO bounds
- **Ingredients:** Partial Compositeness and typical couplings
- Indication of light 0^+ scalar in near conformal dynamics e.g. Hasenfratz, Rebbi, Witzel 16, Elander, Piai, 17

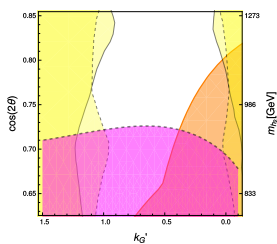
EWPO+Higgs



$\sigma \rightarrow ZZ$ (gg+VBF)

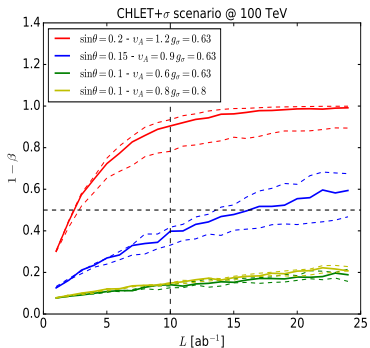
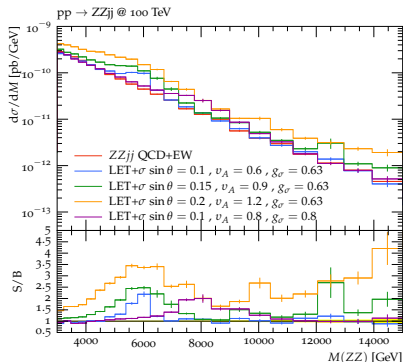


$\sigma \rightarrow ZZ, tt$



Scalar resonance at the FCC-hh, $f \gtrsim 1.2$ TeV

- Mixing $h - \sigma$ very small $\alpha \sim \frac{2m_h^2}{m_\sigma^2}$, suppressed gluon fusion.



5 - Comments on Partial Compositeness (PC)

- One must address SM fermion in the CH context, in particular the top-quark mass.
- **Partial Compositeness (PC)**: top mass from mixing with composite top partner Kaplan 91 and large anomalous dimension from **Walking dynamics** Holdom 81 Example with 2 rep. of G_{HC} : EW ψ , and QCD-charged χ . Barnard, Gherghetta, Ray 13, Ferretti, Karateev 13, Ferretti 16

	Sp(4)	SU(3) _c	SU(2) _L	U(1) _Y	SU(4)	SU(6)
$\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$	□	1	2	0	4	1
$\psi_{3,4}$	□	1	1	$\pm 1/2$		1
$\chi_{1,2,3}$	□	3	1	X	1	6
$\chi_{4,5,6}$	□	$\bar{3}$	1	-X	1	

- Typical pheno consequences:
 - A light ALP associated to the non-anomalous U(1) e.g. 1610.06591, at LHCb: 2106.12615
 - QCD charged pNGBs (heavier than EW pNGBs) e.g. 1507.02283
 - Heavy fermionic states (top partners and others) e.g. 1907.05929
 - Contributions of top loops in pNGB productions → **competing with GBS**

- CH + PC continues to be a promising alternative to the SM.
- It has striking predictions easily distinguishable from other BSM models,
- that will be observed at the energy and/or precision frontiers of our experimental apparatus.
- GBS, including VBS, di-Higgs, di-pNGB production are very important processes in this context
- The CCWZ formalism is the most appropriate to describe the CH physics

Backup

$$\mathcal{O}_H = \frac{1}{2} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H), \quad \mathcal{O}_T = \frac{1}{2} (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger \overleftrightarrow{D}_\mu H)$$

$$\mathcal{O}_6 = \lambda (H^\dagger H)^3, \quad \mathcal{O}_y = y_f H^\dagger H \bar{f}_L H f_R$$

$$\mathcal{O}_W = \frac{ig}{2} (H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W_{\mu\nu}^a, \quad \mathcal{O}_B = \frac{ig'}{2} (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig (D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a, \quad \mathcal{O}_{HB} = ig' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}.$$

$$c_H = 1, \quad c_y = -1/3, \quad c_6 = -4/3$$

$f^2 \mathcal{O}_3$	$f^2 \mathcal{O}_4^+$	$f^2 \mathcal{O}_4^-$
$-4(\mathcal{O}_W - \mathcal{O}_B)$	$2(\mathcal{O}_{HW} + \mathcal{O}_{HB})$	$2(\mathcal{O}_{HW} - \mathcal{O}_{HB})$
$f^2 \mathcal{O}_5^+$	$f^2 \mathcal{O}_5^-$	
$4[\mathcal{O}_W + \mathcal{O}_B - (\mathcal{O}_{HW} + \mathcal{O}_{HB})]$	$-4[\mathcal{O}_W - \mathcal{O}_B - (\mathcal{O}_{HW} - \mathcal{O}_{HB})]$	

Example of couplings table from Liu, Low, Yin 1809.09126

\mathcal{I}_i^h	C_i^h (NL)	C_i^h (D6)
(1) $\frac{\hbar}{v} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu$	$\frac{4c_{2W}}{c_W^2} \left(-2c_3 + c_4^- \right) + \frac{4}{c_W^2} c_4^+ \cos \theta$	$2(c_W + c_{HW}) + 2t_w^2 (c_B + c_{HB})$
(2) $\frac{\hbar}{v} Z_{\mu\nu} Z^{\mu\nu}$	$-\frac{2c_{2W}}{c_W^2} \left(c_4^- + 2c_5^- \right) - \frac{2}{c_W^2} \left(c_4^+ - 2c_5^+ \right) \cos \theta$	$-(c_{HW} + t_w^2 c_{HB})$
(3) $\frac{\hbar}{v} Z_\mu \mathcal{D}^{\mu\nu} A_\nu$	$8 \left(-2c_3 + c_4^- \right) t_w$	$2t_w(c_W + c_{HW}) - 2t_w(c_B + c_{HB})$
(4) $\frac{\hbar}{v} Z_{\mu\nu} A^{\mu\nu}$	$-4 \left(c_4^- + 2c_5^- \right) t_w$	$-t_w(c_{HW} - c_{HB})$
(5) $\frac{\hbar}{v} W_\mu^+ \mathcal{D}^{\mu\nu} W_\nu^- + h.c.$	$4 \left(-2c_3 + c_4^- \right) + 4c_4^+ \cos \theta$	$2(c_W + c_{HW})$
(6) $\frac{\hbar}{v} W_{\mu\nu}^+ W^{-\mu\nu}$	$-4 \left(c_4^- + 2c_5^- \right) - 4 \left(c_4^+ - 2c_5^+ \right) \cos \theta$	$-2c_{HW}$

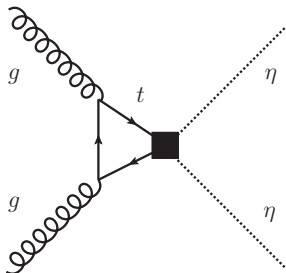
$$\mathcal{D}^{\mu\nu} = \partial^\mu \partial^\nu - g^{\mu\nu} \partial^2$$

\mathcal{I}_i^{2h}	C_i^{2h} (NL)	C_i^{2h} (D6)
(1) $\frac{h^2}{v^2} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu$	$\frac{2c_{2W}}{c_W^2} \left(-2c_3 + c_4^- \right) \cos \theta$ $+ \frac{2}{c_W^2} c_4^+ \cos 2\theta$	$\frac{1}{2} C_1^h$
(2) $\frac{h^2}{v^2} Z_{\mu\nu} Z^{\mu\nu}$	$-\frac{c_{2W}}{c_W^2} \left(c_4^- + 2c_5^- \right) \cos \theta$ $-\frac{1}{c_W^2} \left(c_4^+ - 2c_5^+ \right) \cos 2\theta$	$\frac{1}{2} C_2^h$
(3) $\frac{h^2}{v^2} Z_\mu \mathcal{D}^{\mu\nu} A_\nu$	$4t_w \left(-2c_3 + c_4^- \right) \cos \theta$	$\frac{1}{2} C_3^h$
(4) $\frac{h^2}{v^2} Z_{\mu\nu} A^{\mu\nu}$	$-2t_w \left(c_4^- + 2c_5^- \right) \cos \theta$	$\frac{1}{2} C_4^h$
(5) $\frac{h^2}{v^2} W_\mu^+ \mathcal{D}^{\mu\nu} W_\nu^- + h.c.$	$2 \left(-2c_3 + c_4^- \right) \cos \theta$ $+ 2c_4^+ \cos 2\theta$	$\frac{1}{2} C_5^h$
(6) $\frac{h^2}{v^2} W_{\mu\nu}^+ W^{-\mu\nu}$	$-2 \left(c_4^- + 2c_5^- \right) \cos \theta$ $-2 \left(c_4^+ - 2c_5^+ \right) \cos 2\theta$	$\frac{1}{2} C_6^h$
(7) $\frac{(\partial_\nu h)^2}{v^2} Z_\mu Z^\mu$	$\frac{8}{c_W^2} c_1 \sin^2 \theta$	×
(8) $\frac{\partial_\mu h \partial_\nu h}{v^2} Z^\mu Z^\nu$	$\frac{8}{c_W^2} c_2 \sin^2 \theta$	×
(9) $\frac{(\partial_\nu h)^2}{v^2} W_\mu^+ W^{-\mu}$	$16c_1 \sin^2 \theta$	×
(10) $\frac{\partial^\mu h \partial^\nu h}{v^2} W_\mu^+ W_\nu^-$	$16c_2 \sin^2 \theta$	×

- Although $\eta - t - \bar{t}$ vanishes, $\eta^2 t \bar{t}$ is always present,

$$\mathcal{L} \supset -m_t \left(1 + \frac{h}{v} \kappa_t - \frac{h^2}{f^2} \kappa_{th^2} - \frac{\eta^2}{f^2} \kappa_{t\eta^2} \right) \bar{t} t$$

Q_L	t_R	κ_t	κ_{th^2}	$\kappa_{t\eta^2}$	λ_η	comments
6	1	$\cos \theta$	1/2	1/2	$\cos \theta$	$T_R^3 = 0$ of (1, 3) $\alpha_R = 0$
6	15	$\cos \theta$	1/2	1/2	$\cos \theta$	
6	6	$\cos(2\theta)/\cos \theta$	2	1	$\cos \theta$	
15	6	$\cos \theta$	1/2	1/2	$\cos \theta$	



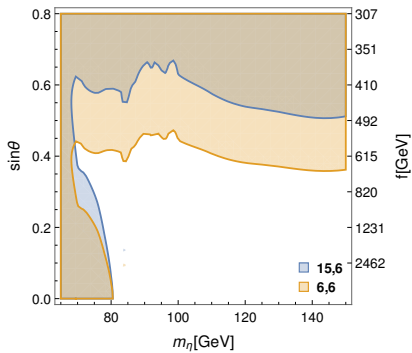
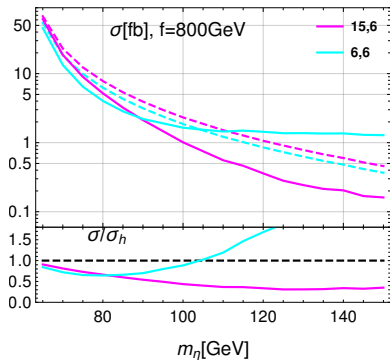


Figure: Left: Total η pair production cross section at 14 TeV LHC for Q_L, t_R^c in the **15, 6** (cyan) and **6, 6** (magenta) including the coherent sum of contact and off-shell Higgs contributions in solid lines, and only the off-shell Higgs in dashed lines. Right: Excluded region in $(m_\eta, \sin\theta)$ space for the same choice of spurions, using the leptonic selection.