Goldstone Boson Scattering in Composite Higgs Models

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Multi-Boson-Interaction
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Outline

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 → dynamical EW symmetry breaking (hierarchy problem)
  (Weinberg 76, Susskind 79)

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

- 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

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

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

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

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

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

- Spontaneously breaks $G \to H$

$$\mathrm{SU}(4) \to \mathrm{Sp}(4)$$

CCWZ formalism Callan, Coleman, Wess, Zumino 69

- 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

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

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

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

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

$$\begin{aligned} \omega_\mu &= \xi^\dagger \nabla_\mu \xi \quad \nabla_\mu \xi = (\partial_\mu - igW^a_\mu T^a_L - ig' B_\mu T^3_R)\xi \\ \omega_\mu &= \tilde{\omega}_\mu + \hat{\omega}_\mu \equiv x_\mu + s_\mu \quad \text{Proj. to } X^A, S^A \\ x_\mu &\to hx_\mu h^\dagger, \quad s_\mu \to hs_\mu h^\dagger + h\partial_\mu h^\dagger \end{aligned}$$

- 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

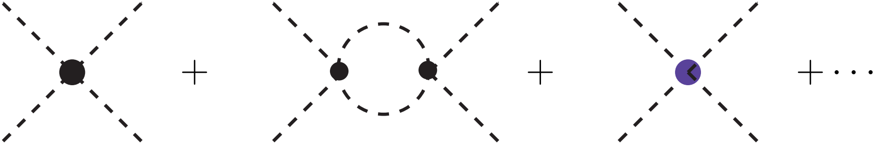
$$\begin{aligned} \mathcal{L}_4 \quad = \quad & L_0\langle x^\mu x^\nu x_\mu x_\nu\rangle + L_1\langle x^\mu x_\mu\rangle\langle x^\nu x_\nu\rangle + L_2\langle x^\mu x^\nu\rangle\langle x_\mu x_\nu\rangle + L_3\langle x^\mu x_\mu x^\nu x_\nu\rangle \\ + \quad & L_4\langle x^\mu x_\mu\rangle\langle\tilde{\chi}\rangle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

2 - Unitarity of GBS amplitudes DBF, Ferrarese 17'

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

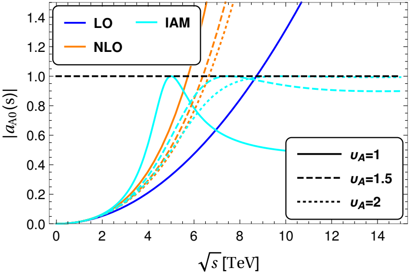
$$\mathrm{Im} a_J(s) = |a_J(s)|^2$$

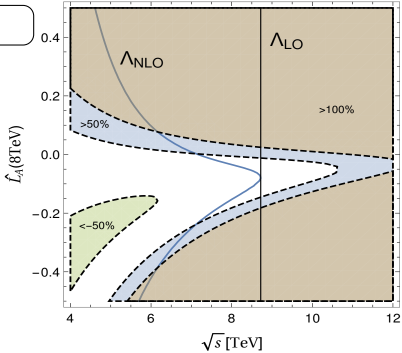
$$\begin{aligned} a_{A0}(s) &= a^{(0)}_{A0}(s) + a^{(1)}_{A0}(s) + \cdots \\ a^{(0)}_{A0}(s) &= \frac{s}{16\pi f^2} \quad \text{Low Energy Theorem (LET)} \\ a^{(1)}_{A0}(s) &= \frac{s^2}{32\pi f^4}\left[\frac{1}{16\pi^2}\left(\frac{29}{12} + \frac{46}{18}\log\left(\frac{s}{\mu^2}\right) + 2\pi i\right)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



- **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'

$\sin\theta = 0.2$





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

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

$$O_1 = \langle x_\mu x^\mu \rangle^2, \quad O_2 = \langle x_\mu x^\mu \rangle^2, \quad O_3 = \langle E^{L\,2}_{\mu\nu} \rangle - \langle E^{R\,2}_{\mu\nu} \rangle \ ,$$

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

Linearization and Universal relations Liu, Low, Yin 1809.09126

- "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.

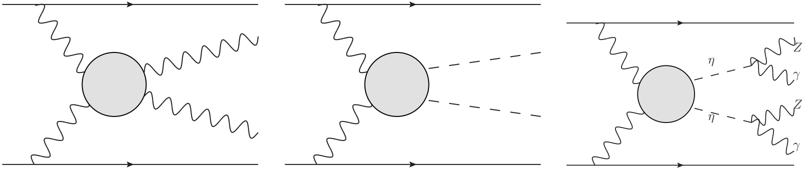
$f^2\mathcal{O}_3$	$f^2\mathcal{O}_4^+$	$f^2\mathcal{O}_4^-$
$-4(\mathcal{O}_W - \mathcal{O}_B)$	$2(\mathcal{O}_{HW} + \mathcal{O}_{HB})$	$2(\mathcal{O}_{HW} - \mathcal{O}_{HB})$
$f^2\mathcal{O}_5^+$	$f^2\mathcal{O}_5^-$	
$4\left[\mathcal{O}_W + \mathcal{O}_B - (\mathcal{O}_{HW} + \mathcal{O}_{HB})\right]$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

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

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 decribes 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

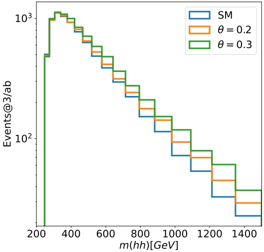
$$q_1 q_2 \;\rightarrow\; q_1' q_2' hh$$

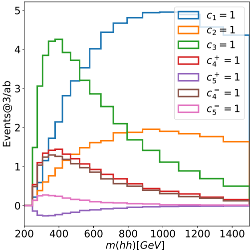
- Di-pNGBs via VBF:

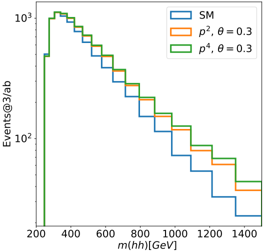
$$q_1 q_2 \;\rightarrow\; q_1' q_2' \eta\eta, \quad q_1 q_2 \;\rightarrow\; q_1' q_2' \pi^0 \pi^0, \cdots$$

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

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







Selection cuts

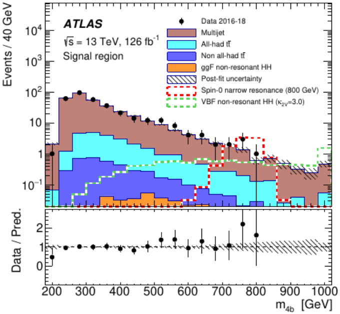
$p_T(j) > 20\,\text{GeV}, \quad |\eta(j)| < 5 \quad M(jj) > 200\,\text{GeV}$

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

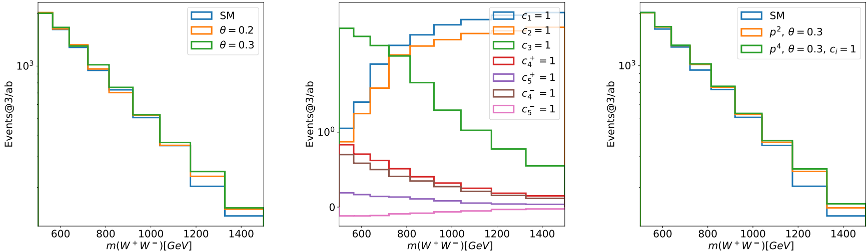
- Will ATLAS show an excess at high energy *hh*? JHEP07(2020)108
- Non-resonant scenario parametrized “only” by k_V and k_{2V} Bishara, Contino, Rojo 1611.03860
- Other Lorentz structures are present - Other observables?

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

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



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

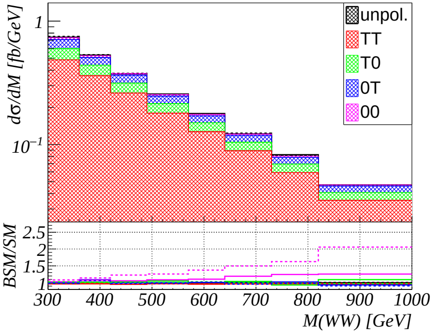


Selection cuts

$p_T(j) > 20$ GeV, $\quad |\eta(j)| < 5$
$M(jj) > 250$ GeV, $\quad \Delta\eta(jj) > 2.5$,
$|\eta(W^\pm)| < 3.5\,. \quad p_T(W^\pm) > 30$ GeV,
$M(W^+W^-) > 500$ GeV,

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

VBS Polarization Analysis DBF, Mattelaer, Ruiz, Shil 1912.01725



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

Selection cuts

$p_T(j) > 20$ GeV, $|\eta(j)| < 5$

$M(jj) > 250$ GeV, $\Delta\eta(jj) > 2.5$,

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

$M(W^+W^-) > 300$ GeV,

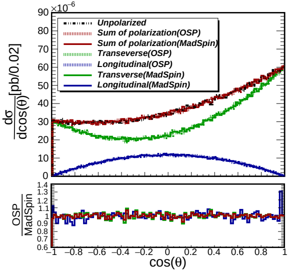
Very hard to distinguish from SM.

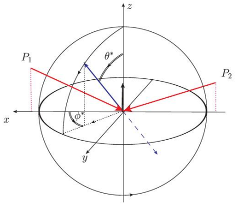
	p-CM SM ($a = 1$)		p-CM CH ($a = 0.8$)			p-CM CH ($a = 0.9$)		
Process	σ [fb]	$f_{\lambda\lambda'}$	σ [fb]	$f_{\lambda\lambda'}$	$\sigma^{\text{CH}}/\sigma^{\text{SM}}$	σ [fb]	$f_{\lambda\lambda'}$	$\sigma^{\text{CH}}/\sigma^{\text{SM}}$
jjW^+W^-	171	. . .	173	. . .	1.00	172	. . .	1.00
$jjW_T^+W_T^-$	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.

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

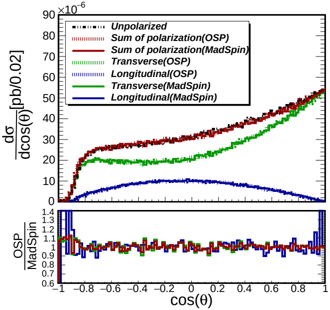




- Can be used as tool to extract polarization fractions (see Carlos Cid talk)

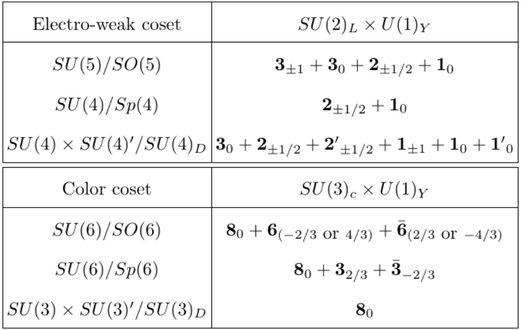
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} \approx \frac{3}{8}(1+\cos\theta)^2 f_L + \frac{3}{8}(1-\cos\theta)^2 f_R + \frac{3}{4}\sin^2\theta\, f_0$$

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



- 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

Other pNGBs



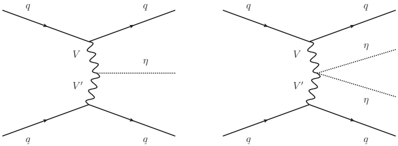
Electro-weak coset	$SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm 1} + \mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4) \times SU(4)'/SU(4)_D$	$\mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{2'}_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0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

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.

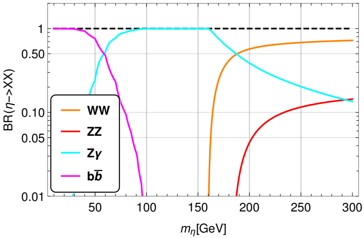
η production via VBF and double-η-strahlung

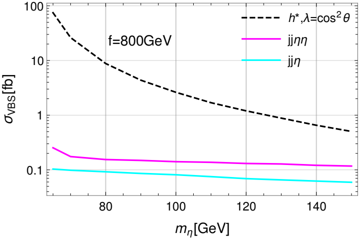


- Double-η production via kinetic term (VBF, 2η-strahlung) DBF, Ferretti, Li, Shu 2005.13578

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

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

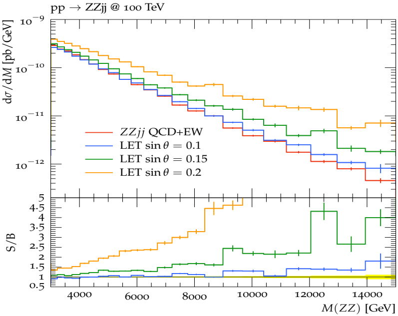


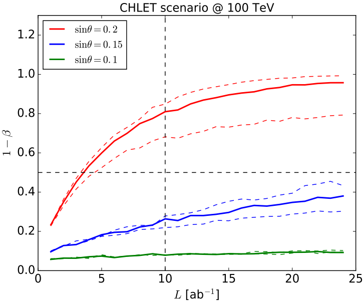


LET non-resonant enhancement FCC-hh 100 TeV

- No cancellations in EWPO $s_\theta \lesssim 0.2$ (unknown alignment mechanism)
- $pp \to jjZZ \to jje^+e^-\mu^+\mu^-$ 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(Alboteanu, Kilian, Reuter 08) and PHANTOM (Ballestrero, DBF, Oggero, Maina 11)

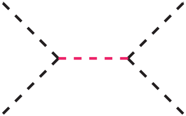
DBF, Ferrarese 1705.02787





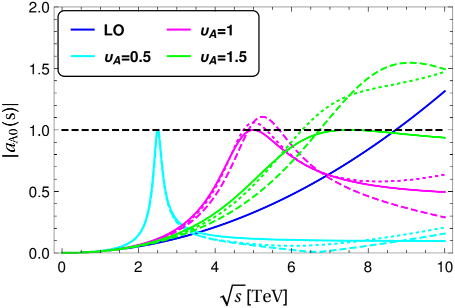
4 - $E \sim m_\sigma$: the scalar excitation

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



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

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



DBF, Ferrarese 17

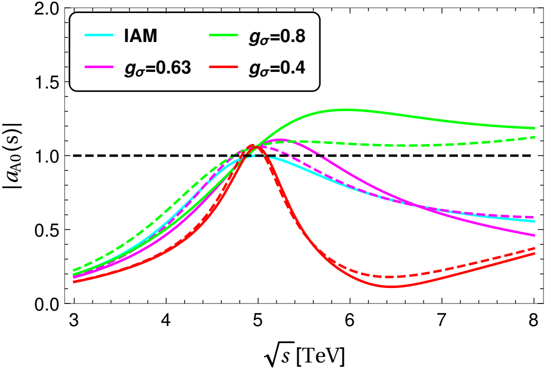
$g_\sigma \equiv \kappa'/2 \sim \sqrt{2/5} \sim 0.63$

Dashed: Fixed width

Dotted: Running width

Solid: IAM

$\sin\theta = 0.2$



$v = 1$

Solid: Fixed width

Dashed: Running width

$\sin\theta = 0.2$

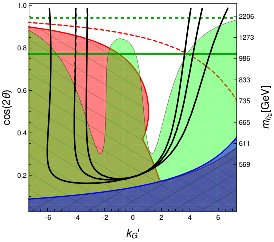
Unitarity and perturbativity give further information about effective Lagrangian beyond pure dimensional analysis:

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

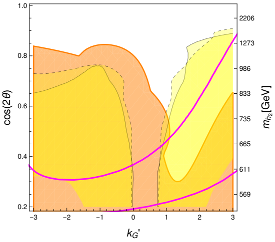
Lightish 0^+ DBF, Cacciapaglia, Deandrea 1809.09146

- 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

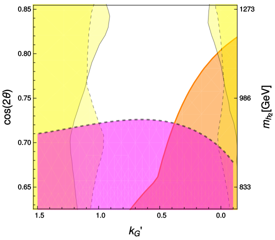
EWPO+Higgs



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

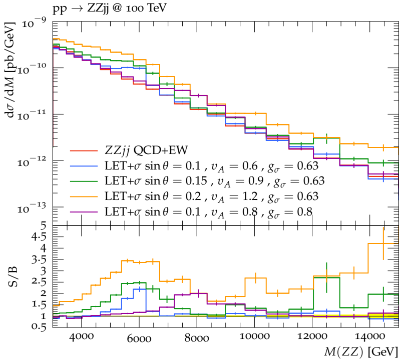


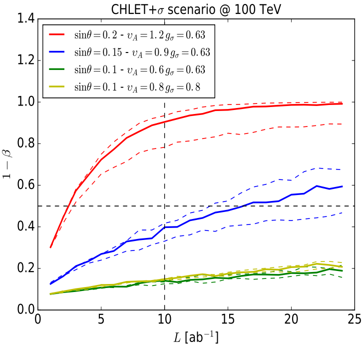
$\sigma \to ZZ$, tt



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

- 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)
$\binom{\psi_1}{\psi_2}$	$\square$	**1**	**2**	0	**4**	**1**
$\psi_{3,4}$	$\square$	**1**	**1**	$\pm 1/2$		**1**
$\chi_{1,2,3}$	$\begin{array}{c}\square\\ \square\end{array}$	**3**	**1**	X	**1**	**6**
$\chi_{4,5,6}$	$\begin{array}{c}\square\\ \square\end{array}$	$\bar{3}$	**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

6 - Conclusions

- CH + PC continues to be a promising alternative to the SM.
- It has striking predictions easily distinguible from other BSM models,
- that will be observed at the energy and/or precision frontiers of our experimental aparatus.
- 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

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

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

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$$

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

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

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

Example of couplings table from Liu, Low, Yin 1809.09126

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

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

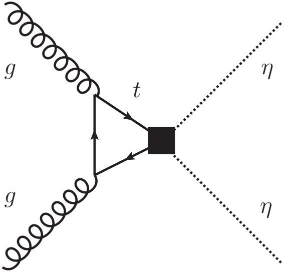
$\mathcal{I}_i^{2h}$	C_i^{2h} (NL)	C_i^{2h} (D6)
(1) $\frac{h^2}{v^2} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu$	$\frac{2c_{2w}}{c_w^2}\left(-2c_3 + c_4^-\right)\cos\theta$ $+\frac{2}{c_w^2}\, c_4^+ \cos 2\theta$	$\frac{1}{2}\,C_1^h$
(2) $\frac{h^2}{v^2} Z_{\mu\nu} Z^{\mu\nu}$	$-\frac{c_{2w}}{c_w^2}\left(c_4^- + 2c_5^-\right)\cos\theta$ $-\frac{1}{c_w^2}\left(c_4^+ - 2c_5^+\right)\cos 2\theta$	$\frac{1}{2}\,C_2^h$
(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) $\frac{h^2}{v^2} W^+_\mu \mathcal{D}^{\mu\nu} W^-_\nu + h.c.$	$2(-2c_3 + c_4^-)\cos\theta$ $+2c_4^+ \cos 2\theta$	$\frac{1}{2}\,C_5^h$
(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) $\frac{\partial^\mu h \partial^\nu h}{v^2} W^+_\mu W^-_\nu$	$16c_2 \sin^2\theta$	×

DBF, Ferretti, Shu, Huang (2005.13578)

- 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**	$\cos\theta$	$1/2$	$1/2$	$\cos\theta$	
6	**15**	$\cos\theta$	$1/2$	$1/2$	$\cos\theta$	$T^3_R = 0$ of $(1,3)$
6	**6**	$\cos(2\theta)/\cos\theta$	2	1	$\cos\theta$	$\alpha_R = 0$
15	**6**	$\cos\theta$	$1/2$	$1/2$	$\cos\theta$	



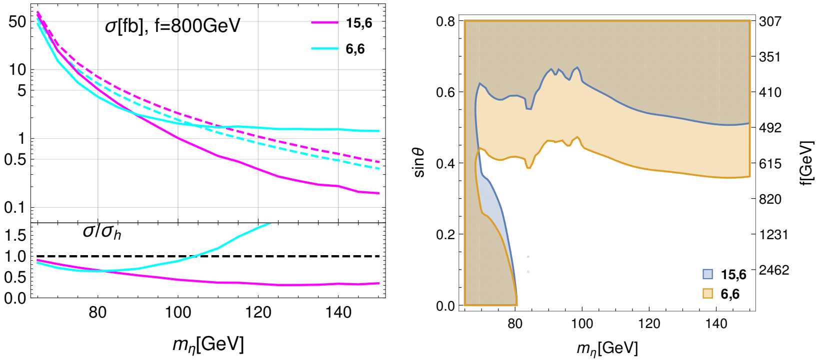


Figure: *Left:* Total η pair production cross section at 14 TeV LHC for Q_L, t_R^c in the **15, 6** (cyan) and **6, 6** (magenta) including the coherent sum of contact and off-shell Higgs contributions in solid lines, and only the off-shell Higgs in dashed lines. *Right:* Excluded region in $(m_\eta,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