Goldstone Boson Scattering in Composite Higgs Models

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BSM models in Vector Boson Scattering processes

Lisbon, December 5, 2019

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Outline

- Introduction
- Scenario 1: GBS in CH with low compositeness scale $f \gtrsim 550\,\text{GeV}$
  - Polarization studies in VBS
  - other GBS
  - a lightish TeV scalar
- Scenario 2: $f \gtrsim$ TeV at FCC-hh
- 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.

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)

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

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

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

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

- The leading order kinetic term ($d = 2$)

$$\mathcal{L}_2 = \frac{f^2}{8} D_\mu \Sigma^\dagger D^\mu \Sigma$$

- generates the vev relation

$$v = f \sin\theta$$

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

$$\kappa_V \approx \cos\theta \gtrsim \begin{cases} 0.98 \text{ (EWPO, indirect) Scenario 2} \\ 0.9 \text{ (Higgs couplings meas.) Sce.1} \end{cases}$$

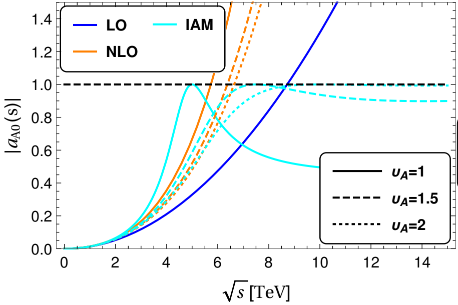
(EWPO constraints might be relaxed by the contributions of composite vectors and scalars DBF, Cacciapaglia, Deandrea 18)

Goldstone Boson Scattering

- and the associated 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.



$\sin\theta = 0.2$

DBF, Ferrarese 17

A natural (and optimistic) scenario (1)

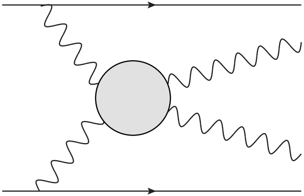
- A natural vacuum misalignment $\sin\theta \lesssim 0.45$ ($c_\theta \gtrsim 0.9$)

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

- I - Non resonant scenario: Saturation of unitarity bounds by resonances require $m_\sigma \lesssim 4\,\text{TeV}$ and $m_\rho \lesssim 13\,\text{TeV}$ ($c_\theta = 0.9$), or continuum.
- II - Resonant σ, 0^+ scenario, $m_\sigma \approx 1\,\text{TeV}$ Bounds don't need to be saturated - indication of light 0^+ scalar in near conformal dynamics
  e.g. Hasenfratz, Rebbi, Witzel 16, Elander, Piai, 17
- Let us assume other composite states, vectors, fermions,... are heavy.
- pNGBs: h, η, a (abelian pNGBs), + other pNGBs in larger cosets. (back to that later)
- Low energy effects small (anomaly: loop suppressed) $\rightarrow$ try to use the power of energy growing.

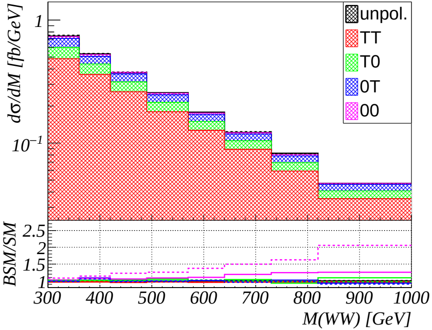
Vector Boson Scattering $VV \to VV$ (I)

Polarization studies in VBS DBF, Mattelaer, Ruiz, Shil 1912.01725



- Longitudinal weak bosons are manifestations of the NGB from the EWSB and will present an enhancement at high energy in CH models
  Long list of references
- Let us use the new feature of `MadGraph_aMC@NLO` to decompose the different polarizations in

$$q_1 q_2 \;\to\; q_1' q_2' W_\lambda^+ W_{\lambda'}^-$$



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,

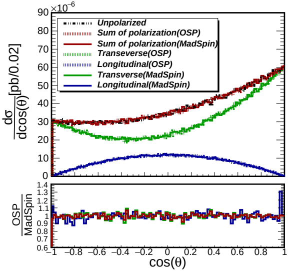
Very hard to distinguish from SM.

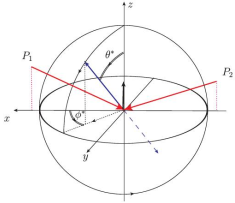
	p-CM SM ($a = 1$)		p-CM CH ($a = 0.8$)			p-CM CH ($a = 0.9$)		
Process	σ [fb]	$f_{\lambda\lambda'}$	σ [fb]	$f_{\lambda\lambda'}$	$\sigma^{\rm CH}/\sigma^{\rm SM}$	σ [fb]	$f_{\lambda\lambda'}$	$\sigma^{\rm CH}/\sigma^{\rm SM}$
jjW^+W^-	171	. . .	173	. . .	1.00	172	. . .	1.00
$jjW_T^+W_T^-$	119	70%	116	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 .
- Polarized decays implemented in `Phantom` MC Ballestrero, Maina, Pellicciolí 18, 19
- Now independently in `MadGraph_aMC@NLO` DBF, Mattelaer, Ruiz, Shil 1912.01725.

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



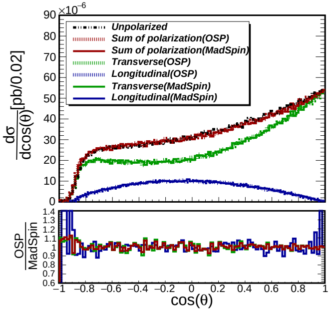


- Can be used as tool to extract polarization fractions (see Long talk, CMS PAS FTR-18-038,...)

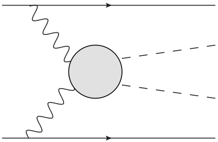
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos\theta)^2 f_L + \frac{3}{8}(1-\cos\theta)^2 f_R + \frac{3}{4}\sin^2\theta f_0$$

$f_L = 0.5264, f_R = 0.2658, f_0 = 0.2077.$

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

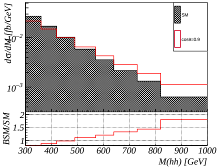


$VV \to hh$ scattering (I)

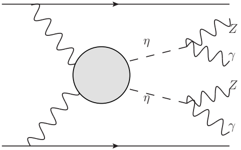


- As a pNGB, the $V_L V_L \to hh$ amplitudes will also manifest growing energy behavior (same origin)
- Couplings approx. fixed $c_V = c_\theta$, $c_{2V} = \cos 2\theta$, $\lambda/\lambda_{SM} \sim c_\theta$ in the language of Bishara, Contino, Rojo 16
  $\to c_\theta = 0.9$ approx. equivalent to benchmark $c_{2V} = 0.8$ of 1611.03860
- Complicated analysis, but HL-LHC could eventually reach required sensitivity (ATLAS current sensitivity worse, ATLAS-CONF-2019-030)

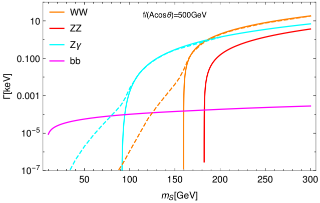
	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\text{bkg}}$	$3 \times \sigma_{\text{bkg}}$
LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC_{100}	$[0, 0.01]$	$[-0.01, 0.01]$



$VV \to \eta\eta$ (I)



- Consider the example model in PC presented before
- η is expected to be very light $m_\eta \lesssim m_h$ (different than ETC case considered in Arbey, Cacciapaglia, Cai, Deandrea, Le Corre, Sannino 15)
- It has suppressed coupling to fermions
- Its anomaly coefficients makes it a photophobic ALP (Neubert et al.) $\to$ dominant decay $\eta \to Z\gamma$.



- All same origin.
- $pp \to \eta\eta jj$ has a striking signature.
- $m_\eta = 80\,\text{GeV}$, $\sigma \approx 0.4\text{fb}$

Extra sectors and abelian pNGB

	$SU(2)_{TC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
(U_L, D_L)	$\square$	1	$\square$	0
$\widetilde{U}_L$	$\square$	1	1	$-1/2$
$\widetilde{D}_L$	$\square$	1	1	$+1/2$
λ_L	Adj	1	1	0
$\widetilde{\lambda}_L$	Adj	1	1	0
$\chi_{1,2,3}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\square$	1	$1/2$
$\chi_{4,5,6}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\overline{\square}$	1	$-1/2$

- Extra sectors e.g. dark matter Alane, DBF, Frandsen, Rosenlyst 18 and/or top-quark partial compositeness (PC) Ferretti, Karateev 13
- give rise to extra light non-anomalous abelian light scalars.
- In PC they might be directly produced via gluon fusion Cacciapaglia, Ferretti, Flacke, Serôdio 19

Rich phenomenology

2-sector PC model candidates Ferretti, Karateev 13

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

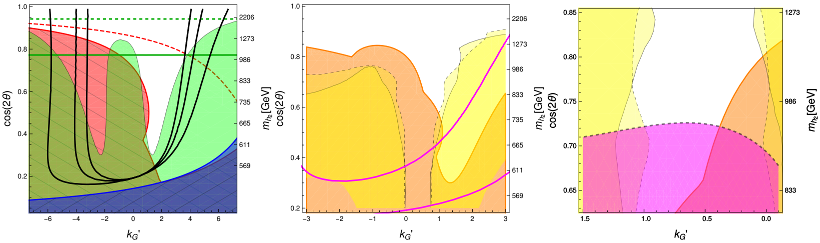
- and their pNGB spectra Cacciapaglia, Ferretti, Flacke, Serôdio 19

Model	EW coset					QCD coset					a	η'
	$\mathbf{2}_{\pm 1/2}$	$\mathbf{3}_0$	$\mathbf{3}_{\pm 1}$	$\mathbf{1}_0$	$\mathbf{1}_{\pm 1}$	$\mathbf{8}_0$	$\bar{\mathbf{3}}_{2/3}$	$\bar{\mathbf{3}}_{4/3}$	$\mathbf{6}_{2/3}$	$\mathbf{6}_{4/3}$		
M1	1	1	1	1	-	1	-	-	1	-	1	1
M2	1	1	1	1	-	1	-	-	1	-	1	1
M3	1	1	1	1	-	1	-	-	-	1	1	1
M4	1	1	1	1	-	1	-	-	-	1	1	1
M5	1	1	1	1	-	1	1	-	-	-	1	1
M6	1	1	1	1	-	1	-	-	-	-	1	1
M7	1	1	1	1	-	1	-	-	-	-	1	1
M8	1	-	-	1	-	1	-	-	-	1	1	1
M9	1	-	-	1	-	1	-	-	-	1	1	1
M10	2	1	-	2	1	1	-	-	-	1	1	1
M11	2	1	-	2	1	1	-	-	-	1	1	1
M12	2	1	-	2	1	1	-	-	-	-	1	1

- η states might decay diversely.
- a states have QCD charged constituents $\rightarrow$ production via gluon fusion from WZW anomaly $\rightarrow$ can give stringent bounds (see Giacomo's talk).
- QCD pNGB expected to be $\sim$ 10x heavier ($m \sim g_s^2 f$)

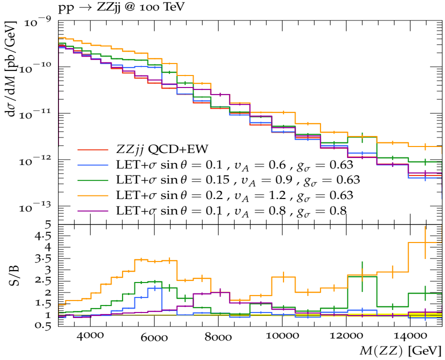
Scenario II: Lightish 0^+

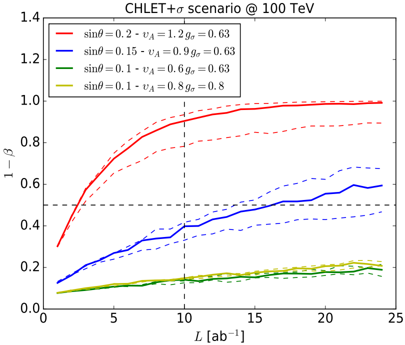
- The ubiquitous presence of a scalar composite state σ (and vector) might alleviate EWPO bounds DBF, Cacciapaglia, Deandrea 1809.09146
- Ingredients: PC and typical couplings (unitarity and dimensional inspired) of composite resonances (no fine-tuning) (DBF, Ferrarese 17)
- σ must be light $\sim$ TeV, does not saturate unitarity $\rightarrow$ indications from lattice and gravity dual of a light state in near conformal dynamics



Pessimistic scenario, $f \gtrsim 1.2$ TeV

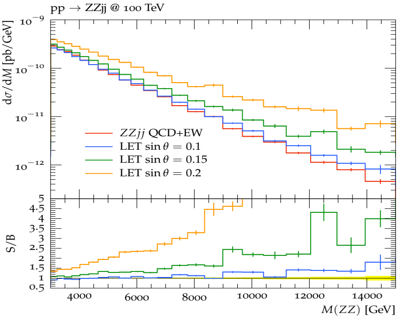
- No cancellations in EWPO $s_\theta \lesssim 0.2$ (unknown alignment mechanism)
- **Scalar σ resonance at 100 TeV** DBF, Ferrarese 17
- Events generated with SHERPA with typical VBS cuts.
- Probability assumed to be a smeared Poisson distribution with $\epsilon = 0, 20, 40\%$
- Mixing $h - \sigma$ very small $\alpha \sim \frac{2m_h^2}{m_\sigma^2}$, suppressed gluon fusion.

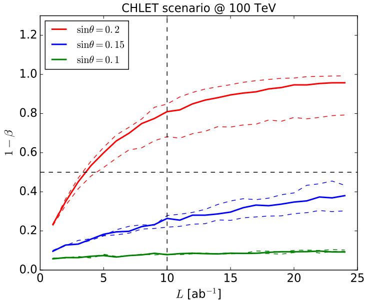




LET non-resonant enhancement at 100 TeV:

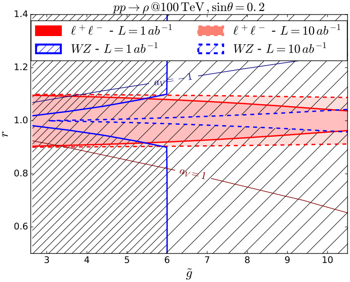
- Unitarity violation suppressed for $\sin\theta < 0.2$
- For larger deviations unitarized amplitudes should be used, implemented *e.g.* in WHIZARD(Alboteanu, Kilian, Reuter 08) and PHANTOM (Ballestrero, DBF, Oggero, Maina 11)

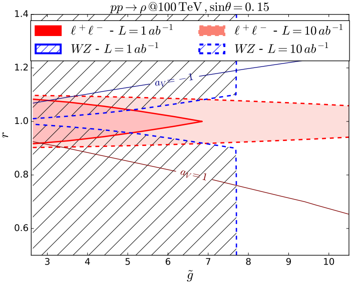




Search for Heavy Vector

- 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





Conclusion

- CH provides a dynamical mechanism to EWSB, possibly helping addressing other mysteries of Nature like DM.
- It contains a rich collider phenomenology, with light weakly coupled pNGBs and other heavy composite states.
- Scenario 1: cancellations in EWPO, $f \gtrsim 550\,\text{GeV}$, $c_\theta \gtrsim 0.9$ **(HL-LHC)**
  - 1.I: **non resonant GBS**, VBS, double-Higgs via VBS and other unexplored processes like $pp \to jj\eta\eta \to jjZ\gamma Z\gamma$.
  - 1.II: **lightish TeV scalar** produced via gluon fusion and VBF and decaying to VV and $t\bar{t}$.
- Scenario 2: EWPO constrains $f \gtrsim 1.2\,\text{TeV}$
  - 2.I: **FCC-hh** needed to see VBS
  - **LHC** could possibly see abelian pNGBs with QCD charged constituents
- **No Retreat, No Surrender!**

- 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 ($h \equiv \Pi_Q^4\,, \quad \eta \equiv \Pi_Q^5$)

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

  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 $d = 4$,

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

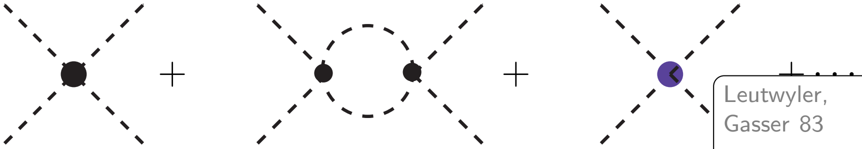
Unitarity of GBS amplitudes

- 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

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

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

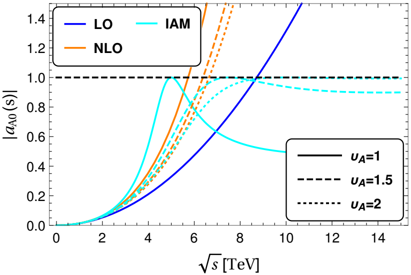
$$\begin{aligned}
a_{A0}(s) &= a_{A0}^{(0)}(s) + a_{A0}^{(1)}(s) + \cdots \\
a_{A0}^{(0)}(s) &= \frac{s}{16\pi f^2} \\
a_{A0}^{(1)}(s) &= \frac{s^2}{32\pi f^4}\left[\frac{1}{16\pi^2}\left(\frac{29}{12} + \frac{46}{18}\log\left(\frac{s}{\mu^2}\right) + 2\pi i\right) + \frac{2}{3}\widehat{L_A}(\mu)\right]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



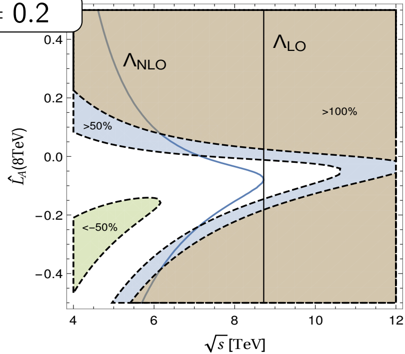
Leutwyler, Gasser 83

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.



$\sin\theta = 0.2$



Inverse Amplitude Method (IAM) Dobado, Peláez 9301276

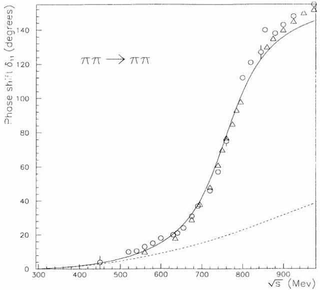


FIG. 1. (1,1) phase shift for $\pi\pi$ scattering. The solid line corresponds to our fit using Eq. (15). The dashed line is the result coming from nonunitarized ChPT with the $\bar{l}_i$ parameters proposed in [11]. The experimental data come from [12] (○) and [13] (△).

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

- 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.*

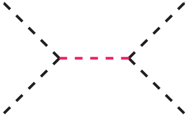
$$M_A^2 = \frac{2f^2}{\frac{1}{16\pi^2}\left(\frac{29}{12}\right) + \frac{2}{3}\widehat{L_A}(M_A)}, \quad \Gamma_A = \frac{M_A^3}{16\pi f^2}$$

- Not a QFT, violates crossing symmetry.

The σ resonance

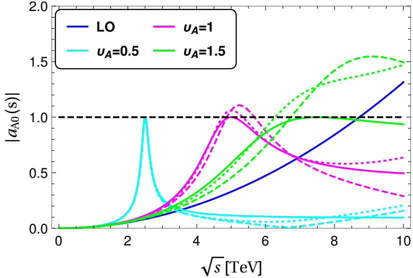
- Well defined QFT

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



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

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



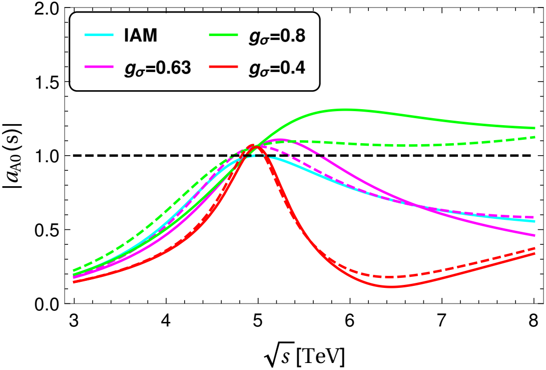
$g_\sigma \equiv \kappa'/2 \sim \sqrt{2/5} \sim 0.63$

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)

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

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

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

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

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

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

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

$$\begin{aligned} K &= \exp\left[ik^a V^a/f_K\right]\,, \\ D_\mu K &= \partial_\mu K - iv_{0\mu}K + iKv_{1\mu} \end{aligned} \qquad (3)$$

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

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

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

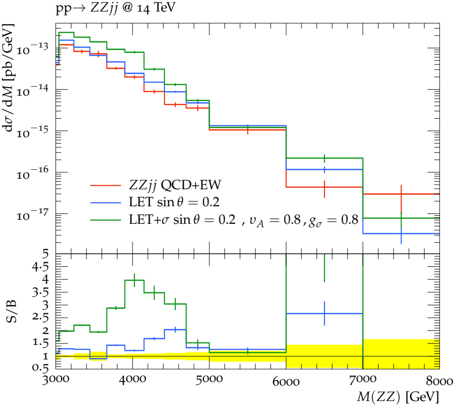
Cuts:

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 ($\partial V/\partial\theta = 0$)

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

- 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, ...

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

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

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

...and modify Higgs couplings

$$
\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ \sigma \end{pmatrix}
$$

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

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

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;

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

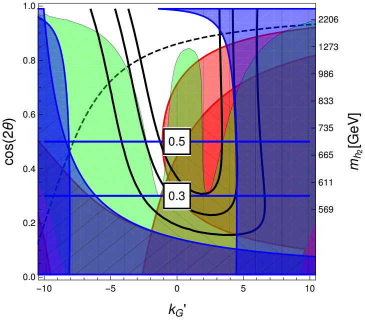
iii - EWPOs;

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

DBF, Cacciapaglia, et al. 16'

iv - Direct search of the heavy scalar.

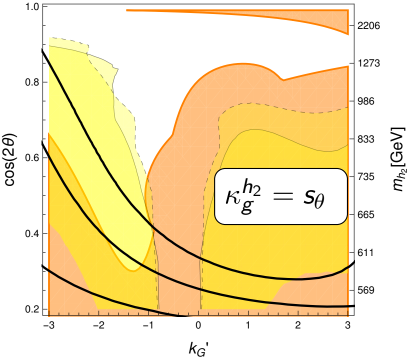
- Perturbativity, $|k_i'| < 4\pi$, pert. unitarity $\gamma = \frac{m_{h_2}}{4\sqrt{\pi f}} \lesssim 1$ ($\gamma = 0.2$ in the plot), $\Gamma/m_{h_2} \lesssim 1$ (black curves, 0.3, 0.5, 1)
- EWPO, σ creates the valleys and vectors shift and broaden them.

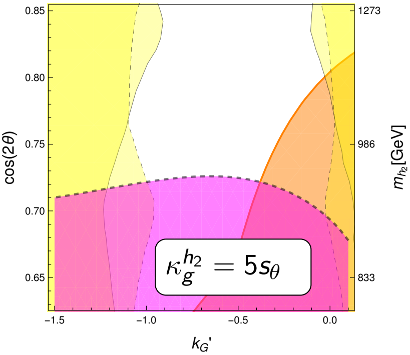


- Higgs measurements, $\kappa_{t,V}$. $\Gamma(h \to \eta\eta)$ (dashed line) for $m_\eta = 0$ - larger masses (m_ψ or **A** rep.) opens parameters space and interesting experimental signatures.
- Dynamically inspired composite resonance profile works nicely. σ: $|k_G'| \sim 1.2$. v_μ: $r = 1.1 \to |a_V|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

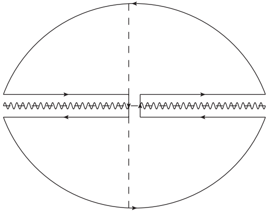
Direct searches

- $pp \to h_2 \to ZZ$ (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.