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The role of composite resonances in the EW chiral Lagrangian

…with a light Higgs

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Work in progress
PRL 110 (**2013**) 181801 [arXiv:1212.6769]
JHEP 01 (**2014**) 157 [arXiv:1310.3121]

OUTLINE

1) Low-energy theory: The EW Chiral Lagrangian+Higgs (ECLh)

2) ECLh + Resonances: custodial inv. Lagrangian for light+R

3) Basic examples: tree-level and 1-loop

The Program:

Custodial symmetry

+

Resonance Lagrangian

+

UV completion hypothesis

⇓

Extract predictions for EFT Wilson coef.'s → Tree-level / Loops

⇓

Extract prediction for low-energy observables

•In this talk, no explicit reference to

- 100 TeV colliders
- tops
- flavour

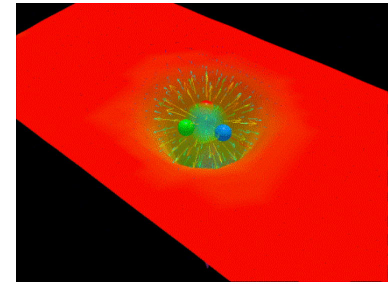
•However, we will see they are closely related issues to this talk:

- 100 TeV → Resonance direct searches
- tops → Fermion sector in the EFT
- flavour → Fermion families in the EFT

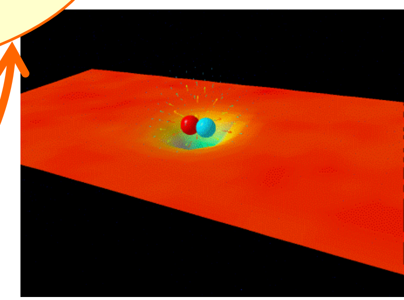
Non-linear low-energy EFT:

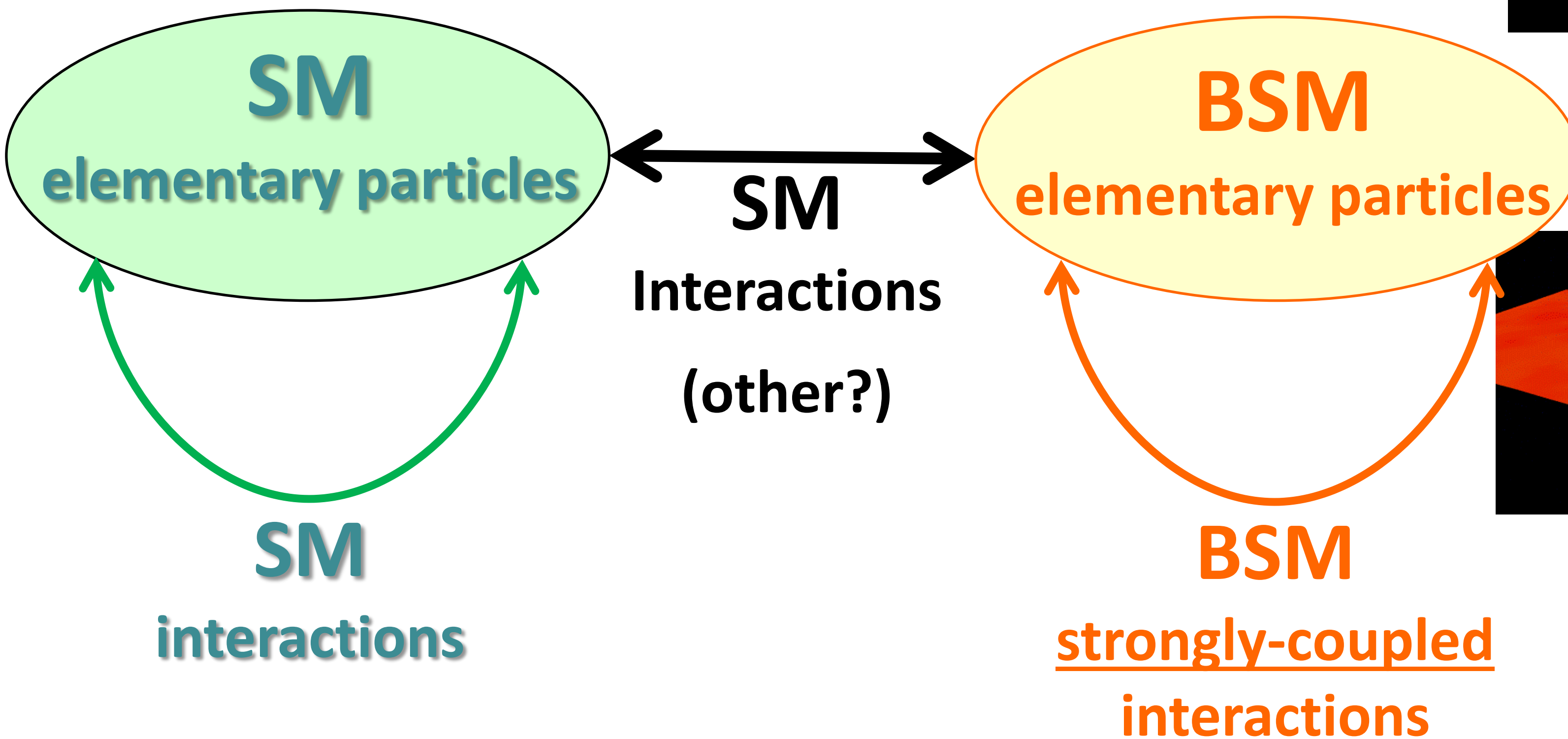
EW Chiral Lagrangian + h   (ECLh)

Strongly coupled BSM



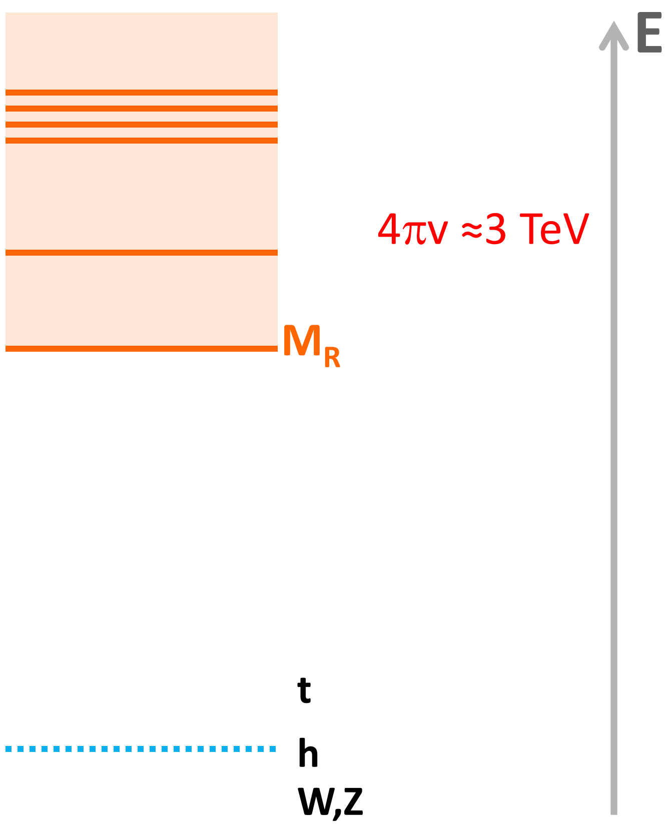
COMPOSITE STATES





• **Inspired/similar to SM and the QCD sector:** EW & leptons (weakly int.) ⇔ quarks & gluons (strongly int.)

Energy scales?



Naïve rescaling
from QCD to EW scale

QCD		EW
$F_\pi=0.090$ GeV	→	$v=0.246$ TeV
$\Lambda_{\chi PT}=4\pi F_\pi \approx 1.2$ GeV	→	$\Lambda_{EW}=4\pi v \approx 3.1$ TeV
$M_\rho=0.770$ GeV	→	$M_{V1}=2.1$ TeV
$M_{a1}=1.260$ GeV	→	$M_{A1}=3.4$ TeV
~~$m_S= 0.05$ GeV~~	→	$m_S= 0.126$ TeV !!

EFT general considerations

1. "SM" content: - Bosons χ: Higgs h + EW Golsdtones $\omega^{\pm}$,z + gauge bosons A^a_μ,B_μ,

   - Fermions ψ: (t,b)-type doublets

2. Applicability: $E \ll \Lambda_{ECLh} \sim \min\{4\pi v,\ M_R\}$ ($4\pi v \sim 3$ TeV)

3. EW would-be Goldston bosons ➔ Non-linear realization $U(\omega^a)$

4. **Custodial symmetry:** $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ pattern

5. Gauge symmetry: $SU(2)_L \otimes U(1)_Y$

Additionally it is appropriate to work with

6. Renormalizable R_ξ gauge: Landau gauge convenient *($m_{\omega\pm,z} = 0$)*

BOSONIC SECTOR : χ

- Building blocks with bosons χ (x):

EW Goldstones (ω^a) →

$$D_\mu U = \partial_\mu U - i\hat{W}_\mu U + iU\hat{B}_\mu\,,$$
$$u^\mu = iu_R^\dagger(\partial_\mu - i\hat{B}_\mu)u_R - iu_L^\dagger(\partial_\mu - i\hat{W}_\mu)u_L = iu(D^\mu U)^\dagger u\,,$$

EW gauge bosons (B, W^a) →

$$\hat{W}_{\mu\nu} = \partial_\mu\hat{W}_\nu - \partial_\nu\hat{W}_\mu - i[\hat{W}_\mu,\hat{W}_\nu]\,, \qquad \hat{B}_{\mu\nu} = \partial_\mu\hat{B}_\nu - \partial_\nu\hat{B}_\mu - i[\hat{B}_\mu,\hat{B}_\nu]\,,$$
$$f_\pm^{\mu\nu} = u_L^\dagger\hat{W}^{\mu\nu}u_L \pm u_R^\dagger\hat{B}^{\mu\nu}u_R\,.$$

Higgs (singlet h) → **h** via polynomials **$\mathcal{F}$(h/v)** & derivatives

soft-scale!!!

- "Chiral" counting*,**:

$$\partial_\mu\,,\quad m_W\,,\quad m_Z\,,\quad m_h \quad\sim\quad \mathcal{O}(p)$$
$$D_\mu U\,,\quad V_\mu\,,\quad g'v\,\mathcal{T}\,,\quad \hat{W}_\mu\,,\quad \hat{B}_\mu \quad\sim\quad \mathcal{O}(p)\,,$$
$$\hat{W}_{\mu\nu}\,,\quad \hat{B}_{\mu\nu} \quad\sim\quad \mathcal{O}(p^2)\,.$$

(x) Apelquist,Bernard '80
(x) Longhitano '80, '81
(x) Herrero,Morales '95
(x) Pich,Rosell,SC '12 '13
(x) Alonso et al., PLB722 (2013) 330
...etc

* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Urech '95

FERMIONIC SECTOR: ψ

- Custodial $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ framework [(+)]

- (t,b)-type doublets ψ: $\quad \psi_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}\,, \qquad \psi_R = \begin{pmatrix} t_R \\ b_R \end{pmatrix}$

  turned into a covariant doublet ξ with the help of Goldstones u(x)

$$\xi^a_m = \frac{1}{2}(\delta^{ab} - \gamma_5^{ab}) u_{mn}\psi^b_n + \frac{1}{2}(\delta^{ab} + \gamma_5^{ab}) (u^\dagger)_{mn}\psi^b_n$$

$$\left[\begin{array}{lll} \xi & = & \xi_L + \xi_R\,, \\ \xi_L & = & u_L^\dagger\,\psi_L = u\,\psi_L\,, \qquad \xi_R = u_R\,\psi_R = u^\dagger\psi_R \end{array}\right]$$

- Breaking down to $SU(2)_L \otimes U(1)_Y$ in $d_\mu\xi$ only through spurions

$$\boxed{\begin{array}{lll} \hat{W}_\mu & = & -\frac{g}{2}W^a_\mu\sigma^a\,, \\ \hat{B}_\mu & = & -\frac{g'}{2}B_\mu\sigma^3\,, \\ X_\mu & = & -B_\mu\,, \end{array}}$$

- More general EFT based on $SU(2)_L \otimes U(1)_Y$ also possible *

(+) Pich,Rosell,Santos,SC, forthcoming

* Buchalla,Catà,Krause ‘13
* Hirn,Stern ‘05

'CHIRAL' COUNTING

- "Chiral" counting *

$$\frac{\chi}{v} \sim \mathcal{O}(p^0)\,, \qquad \frac{\psi}{v} \sim \mathcal{O}\left(p^{\frac{1}{2}}\right)\,, \qquad \partial_\mu,\, m_\chi,\, m_\psi \sim \mathcal{O}(p)$$

and for the building blocks,

$$u(\varphi/v),\, U(\varphi/v),\, \frac{h}{v},\, \frac{W^a_\mu}{v},\, \frac{B_\mu}{v} \sim \mathcal{O}(p^0)\,,$$

$$D_\mu U,\, u_\mu,\, \hat{W}_\mu,\, \hat{B}_\mu \sim \mathcal{O}(p)\,,$$

$$\hat{W}_{\mu\nu},\, \hat{B}_{\mu\nu},\, f_{\pm\,\mu\nu} \sim \mathcal{O}(p^2)\,,$$

$$\partial_{\mu_1}\partial_{\mu_2}...\partial_{\mu_n}\,\mathcal{F}(h/v) \sim \mathcal{O}(p^n)\,,$$

$$\frac{\xi}{v} \sim \mathcal{O}\left(p^{\frac{1}{2}}\right)$$

- Assignment of the 'chiral' dimension: *

$$\mathcal{L}_{p^{\hat{d}}} \sim a_{(\hat{d})}\; p^{\hat{d}-N_F/2}\left(\frac{\overline{\psi}\psi}{v^2}\right)^{N_F/2}\sum_j\left(\frac{\chi}{v}\right)^j$$

* Manohar,Georgi, NPB234 (1984) 189
* Hirn,Stern '05
* Buchalla,Catà,Krause '13
* Pich,Rosell,Santos,SC, forthcoming

'CHIRAL' expansion in ECLh

- EFT Lagrangian at LO and NLO in chiral exp. *

$$\mathcal{L}_{ECLh} = \mathcal{L}_{p^2} + \mathcal{L}_{p^4} + \ldots$$

SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Examples of BSM terms:

$$\mathcal{L}_{p^2}^{\rm BSM} = \frac{(a-1)\,h}{2v} \mathrm{Tr}\{D_\mu U^\dagger D^\mu U\} + \ldots$$

$$\mathcal{L}_{p^4}^{\rm BSM} = \frac{i}{2}(a_2 - a_3)\,\mathrm{Tr}\{f_+^{\mu\nu}[u_\mu, u_\nu]\} + \mathcal{F}_{X\psi\psi}\,\mathrm{Tr}\{f_{+\,\mu\nu} d^\mu J_V^\nu\} + \ldots$$

which leads to a chiral exp. in the sctatering

$$T(2\to 2) = \frac{p^2}{v^2} + \underbrace{\frac{a_{(4)} p^4}{v^4}}_{tree-NLO} + \underbrace{\frac{p^4}{16\pi^2 v^4}}_{1\ell oop-NLO} + \ldots$$

* Weinberg '79
* Manohar,Georgi, NPB234 (1984) 189
* Urech '95
* Georgi,Manohar NPB234 (1984) 189
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149
* Pich,Rosell,Santos,SC, forthcoming

EW Chiral Lagrangian + h + R:

Models, assumptions, completions…

RESONANCE LAGRANGIAN

- Introduce light dof **+ Resonances** *,**

- Lightest SU(2) triplets V, A, S, P and singlets V1, A1, S1, P1 **,(x)

*(antisymetric-tensor formalism $R_{\mu\nu}$ for spin-1 Resonances *)*

- To extract their contribution to $\mathcal{L}_{p4}$

(NOTICE that this avoids contributions to $\mathcal{L}_{p2}$, avoiding large low-energy corrections to SM)

➔ We need only **R operators O(p²)**

$$\mathcal{L}_R = \frac{1}{2}\langle \nabla^\mu R \nabla_\mu R - M_R^2 R^2 \rangle + \langle R \chi_R \rangle \qquad (R = S,\, P)\,,$$

$$\mathcal{L}_R = -\frac{1}{2}\langle \nabla^\lambda R_{\lambda\mu} \nabla_\sigma R^{\sigma\mu} - \frac{1}{2} M_R^2 R_{\mu\nu} R^{\mu\nu} \rangle + \langle R_{\mu\nu} \chi_R^{\mu\nu} \rangle \qquad (R = V,\, A)\,,$$

$$\mathcal{L}_{R_1} = \frac{1}{2}\left(\partial^\mu R_1 \partial_\mu R_1 - M_{R_1}^2 R_1^2\right) + R_1 \chi_{R_1} \qquad (R_1 = S_1,\, P_1)\,,$$

$$\mathcal{L}_{R_1} = -\frac{1}{2}\left(\partial^\lambda R_{1\,\lambda\mu} \partial_\sigma R_1^{\sigma\mu} - \frac{1}{2} M_{R_1}^2 R_{1\,\mu\nu} R_1^{\mu\nu}\right) + R_{1\,\mu\nu} \chi_{R_1}^{\mu\nu} \qquad (R_1 = V_1,\, A_1)\,,$$

* Ecker et al. ’89
** Cirigliano et al., NPB753 (2006) 139
** Pich,Rosell,SC ‘12, ‘13
** Pich,Rosell,Santos,SC, forthcoming

(x) Caveats from higher resonances. See e.g. Marzocca,Serone,Shu, JHEP 1208 (2012) 013

Integrating out the RESONANCES

$$e^{iS[\chi,\psi]_{\rm EFT}} = \int [dR]\; e^{iS[\chi,\psi,R]}$$

- **At the practical level, ***

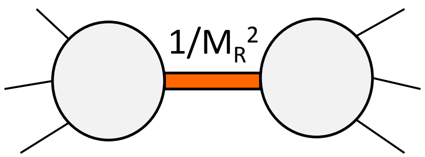
1.) Compute the Resonance EoM for p<<M_R:

$$R_{c\ell} = \frac{1}{M_R^2}\left(\chi_R - \frac{1}{N}\langle\chi_R\rangle\right) + \dots \qquad (R=S,\,P)\,,$$

$$R^{\mu\nu}_{c\ell} = -\frac{2}{M_R^2}\left(\chi_R^{\mu\nu} - \frac{1}{N}\langle\chi_R^{\mu\nu}\rangle\right) + \dots \qquad (R=V,\,A)\,,$$

$$R_{1\;c\ell} = \frac{1}{M_{R_1}^2}\chi_{R_1} + \dots \qquad (R_1=S_1,\,P_1)\,,$$

$$R^{\mu\nu}_{1\;c\ell} = -\frac{2}{M_{R_1}^2}\chi^{\mu\nu}_{R_1} + \dots \qquad (R=V,\,A)\,,$$



2.) Tree-level contribution to the O(p^4) ECLh for p<<M_R:

$$\boxed{S[\chi,\psi]_{\rm EFT} = S[\chi,\psi,R_{c\ell}]}$$

$$\Delta\mathcal{L}_R^{\mathcal{O}(p^4)} = \frac{1}{2M_R^2}\left(\langle\chi_R\chi_R\rangle - \frac{1}{N}\langle\chi_R\rangle^2\right) \qquad (R=S,\,P)\,,$$

$$\Delta\mathcal{L}_R^{\mathcal{O}(p^4)} = -\frac{1}{M_R^2}\left(\langle\chi_R^{\mu\nu}\chi_{R\,\mu\nu}\rangle - \frac{1}{N}\langle\chi_R^{\mu\nu}\rangle^2\right) \qquad (R=V,\,A)\,,$$

$$\Delta\mathcal{L}_{R_1}^{\mathcal{O}(p^4)} = \frac{1}{2M_{R_1}^2}(\chi_{R_1})^2 \qquad (R_1=S_1,\,P_1)\,,$$

$$\Delta\mathcal{L}_{R_1}^{\mathcal{O}(p^4)} = -\frac{1}{M_{R_1}^2}(\chi^{\mu\nu}_{R_1}\chi_{R_1\,\mu\nu}) \qquad (R_1=V_1,\,A_1)\,.$$

* Ecker et al. '89
* Cirigliano et al., NPB753 (2006) 139
* Colangelo,SC,Zuo, JHEP1211 (2012) 012

Basic predictions:

at tree-level

& 1 loop

• I could show you this,

$$
\begin{aligned}
\chi_V^{\mu\nu} \; = \;& \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} \;+\; \frac{iG_V}{2\sqrt{2}} [u^\mu, u^\nu] \\
&+\; c_{V0} v J_T^{\mu\nu} \\
&+\; \frac{c_{V1}}{2} \left(\nabla^\mu J_V^\nu - \nabla^\nu J_V^\mu\right) \;+\; \frac{ic_{V2}}{2} \left([J_A^\mu, u^\nu] - [J_A^\nu, u^\mu]\right) \\
&+\; \frac{c_{V3}}{2} \left(\frac{(\partial^\mu h)}{v} J_V^\nu - \frac{(\partial^\nu h)}{v} J_V^\mu \right) \\
&+\; c_{V4} \epsilon^{\mu\nu\alpha\beta} \{ J_{V\,\alpha}, u_\beta \} \;+\; c_{V5} \epsilon^{\mu\nu\alpha\beta} J_{A'\,\alpha\beta} \, ,
\end{aligned}
$$

$$
\begin{aligned}
\chi_A^{\mu\nu} \; = \;& \frac{F_A}{2\sqrt{2}} f_-^{\mu\nu} \;+\; \frac{\lambda_1^{hA}}{\sqrt{2}} \left((\partial^\mu h) u^\nu - (\partial^\nu h) u^\mu\right) \\
&+\; \frac{c_{A1}}{2} \left(\nabla^\mu J_A^\nu - \nabla^\nu J_A^\mu\right) \;+\; \frac{ic_{A2}}{2} \left([J_V^\mu, u^\nu] - [J_V^\nu, u^\mu]\right)
\end{aligned}
$$

...

etc.

BASIC TREE-LEVEL EXAMPLE

CP and P-even theories

- But it is more instructive to focus on a case (full R Lagrangian in *)

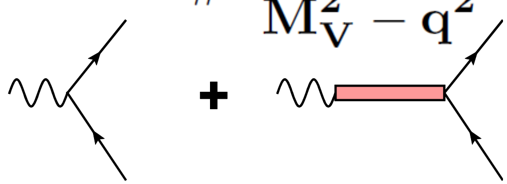
$$\mathcal{L}_V = Tr\{V_{\mu\nu}\ \underbrace{\left(\frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{iG_V}{2\sqrt{2}}[u^\mu, u^\nu] + c_{V1}\nabla^\mu J_V^\nu + \dots\right)}_{\chi_{\mathbf{V}}^{\mu\nu}}\}$$

- Integrate out V:

$$\mathcal{L}_{\mathcal{O}(p^4)}^{\mathrm{from\ V}} = \underbrace{-i\frac{F_V G_V}{4M_V^2}}_{i\,(a_2-a_3)/2} Tr\{f_+^{\mu\nu}[u^\mu, u^\nu]\} \quad \underbrace{- \frac{F_V c_{V1}}{\sqrt{2}M_V^2}}_{\mathfrak{F}_{X\psi\psi}} Tr\{f_+^{\mu\nu}\nabla_\mu J_{V\,\nu}\} + \dots$$

$$\mathbf{F(q^2)} \sim \mathbf{1} + \# \frac{\mathbf{q^2}}{\mathbf{M_V^2 - q^2}} \sim 1/q^2$$

- UV constraints:



$$\boxed{\begin{aligned} (a_2-a_3) &= -v^2/(2M_V^2) \\ \mathfrak{F}_{X\psi\psi} &= 1/(2M_V^2) \end{aligned}}$$

* Pich,Rosell,Santos,SC, forthcoming

Full Higgsless result
(Longhitano [(x)])

Higgsless part   CP conserving
But P-even & P-odd terms

- Higgsless R Lagrangian with only bosons

*(general custodial R Lagrangian in *)*

$$\chi_V^{\mu\nu} = \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{iG_V}{2\sqrt{2}}[u^\mu, u^\nu] + \frac{\widetilde{F}_V}{2\sqrt{2}} f_-^{\mu\nu}$$

$$\chi_A^{\mu\nu} = \frac{F_A}{2\sqrt{2}} f_-^{\mu\nu} + \frac{\widetilde{F}_A}{2\sqrt{2}} f_+^{\mu\nu} + \frac{i\widetilde{G}_A}{2\sqrt{2}}[u^\mu, u^\nu],$$

$$\chi_{S_1} = \frac{c_d}{\sqrt{2}}\langle\, u_\mu u^\mu \,\rangle$$

P-odd

- Integrate out V and A:

$$\begin{aligned}\mathcal{L}_4 \supset\ & \frac{1}{4} a_1 \langle\, f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu} \,\rangle \\ & + \frac{i}{2}(a_2 - a_3)\langle\, f_+^{\mu\nu}[u_\mu, u_\nu]\,\rangle + \frac{i}{2}(a_2 + a_3)\langle\, f_-^{\mu\nu}[u_\mu, u_\nu]\,\rangle \\ & + a_4 \langle\, u_\mu u_\nu \,\rangle \langle\, u^\mu u^\nu \,\rangle + a_5 \langle\, u_\mu u^\mu \,\rangle^2 \\ & + \frac{1}{2} H_1 \langle\, f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu} \,\rangle + \widetilde{H}_1 \langle\, f_+^{\mu\nu} f_{-\,\mu\nu} \,\rangle\,.\end{aligned}$$

$$\begin{aligned} a_1 &= -\frac{F_V^2}{4M_V^2} + \frac{\widetilde{F}_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2} - \frac{\widetilde{F}_A^2}{4M_A^2} \\ a_2 - a_3 &= -\frac{F_V G_V}{2M_V^2} - \frac{\widetilde{F}_A \widetilde{G}_A}{2M_A^2} \\ a_2 + a_3 &= -\frac{\widetilde{F}_V G_V}{2M_V^2} - \frac{F_A \widetilde{G}_A}{2M_A^2} \\ a_4 &= \frac{G_V^2}{4M_V^2} + \frac{\widetilde{G}_A^2}{4M_A^2} \\ a_5 &= \frac{c_{d\,1}^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} - \frac{\widetilde{G}_A^2}{4M_A^2} \\ H_1 &= -\frac{F_V^2}{8M_V^2} - \frac{\widetilde{F}_V^2}{8M_V^2} - \frac{F_A^2}{8M_A^2} - \frac{\widetilde{F}_A^2}{8M_A^2} \\ \widetilde{H}_1 &= -\frac{F_V \widetilde{F}_V}{4M_V^2} - \frac{F_A \widetilde{F}_A}{4M_A^2} \end{aligned}$$

(x) Longhitano '80, '81

* Pich,Rosell,Santos,SC,1501.07249 [hep-ph] (proceedings); forthcoming

PREDICTIONS:

TREE-LEVEL results + UV-constraint

Higgsless part CP conserving
Only P-even

- Higgsless R Lagrangian with only bosons

*(general custodial R Lagrangian in *)*

$$\chi_V^{\mu\nu} = \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{iG_V}{2\sqrt{2}}[u^\mu, u^\nu] + \cancel{\frac{\widetilde{F}_V}{2\sqrt{2}}} f_-^{\mu\nu}$$

$$\chi_A^{\mu\nu} = \frac{F_A}{2\sqrt{2}} f_-^{\mu\nu} + \cancel{\frac{\widetilde{F}_A}{2\sqrt{2}} f_+^{\mu\nu}} + \cancel{\frac{i\widetilde{G}_A}{2\sqrt{2}}[u^\mu, u^\nu]},$$

$$\chi_{S_1} = \frac{c_d}{\sqrt{2}} \langle\, u_\mu u^\mu \,\rangle$$

- Integrate out V and A:

$$\gamma^* \to \omega^+\omega^- \ \mathbf{EM-FF:} \qquad \mathbf{F_V G_V = v^2}$$

$$\mathbf{1 + 2\,WSR\,on\,\Pi_{W_3B}:} \qquad \mathbf{F_V^2 - F_A^2 = v^2,\ F_V^2 M_V^2 - F_A^2 M_A^2 = 0}$$

$$a_1 = -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2},$$

$$(a_2 - a_3) = -\frac{F_V G_V}{2M_V^2},$$

$$a_4 = \frac{G_V^2}{4M_V^2},$$

$$a_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2},$$

$$\boxed{\begin{aligned} a_1 &= -\frac{v^2}{4}\left(\frac{1}{M_V^2} + \frac{1}{M_A^2}\right), \\ (a_2 - a_3) &= -\frac{v^2}{2M_V^2}, \\ a_4 &= \frac{v^2}{4}\left(\frac{1}{M_V^2} - \frac{1}{M_A^2}\right), \\ a_5 &= -\frac{v^2}{4}\left(\frac{1}{M_V^2} - \frac{1}{M_A^2}\right) + \frac{c_d^2}{4M_{S_1}^2}, \\ H_1 &= -\frac{v^2}{8}\left(\frac{1}{M_V^2} - \frac{1}{M_A^2} + \frac{2}{M_A^2 - M_V^2}\right) \end{aligned}}$$

(x) Longhitano '80, '81

* Pich,Rosell,Santos,SC,1501.07249 [hep-ph] (proceedings); forthcoming

PREDICTIONS:
ONE-LOOP results + UV-constraint

Higgsless
C & P-even

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

$$S = \underbrace{\boxed{4\pi v^2\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)}}_{\text{LO}} + \frac{1}{12\pi}\left[\left(\log\frac{M_V^2}{m_H^2}-\frac{11}{6}\right) - \kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{11}{6}-\frac{M_A^2}{M_V^2}\log\frac{M_A^2}{M_V^2}\right)\right]$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]

(k_W=a)

✓ 1st and 2nd WSRs at LO and NLO + ππ-VFF:

→ 2nd WSR: $0 < a = M_V^2/M_A^2 < 1$

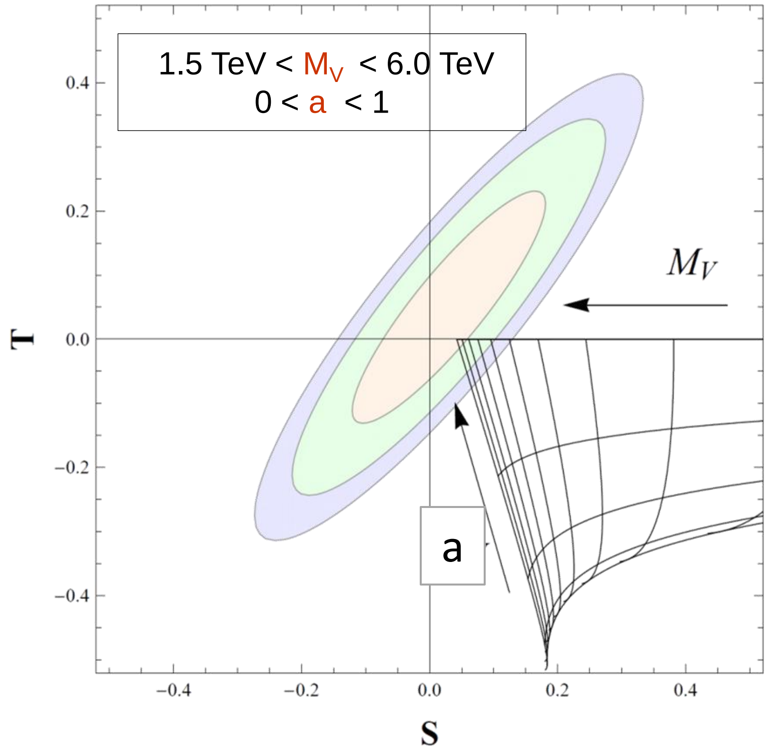
* Pich,Rosell, SC, PRL 110 (2013) 181801; JHEP 01 (2014) 157

PREDICTIONS:
ONE-LOOP results + UV-constraint

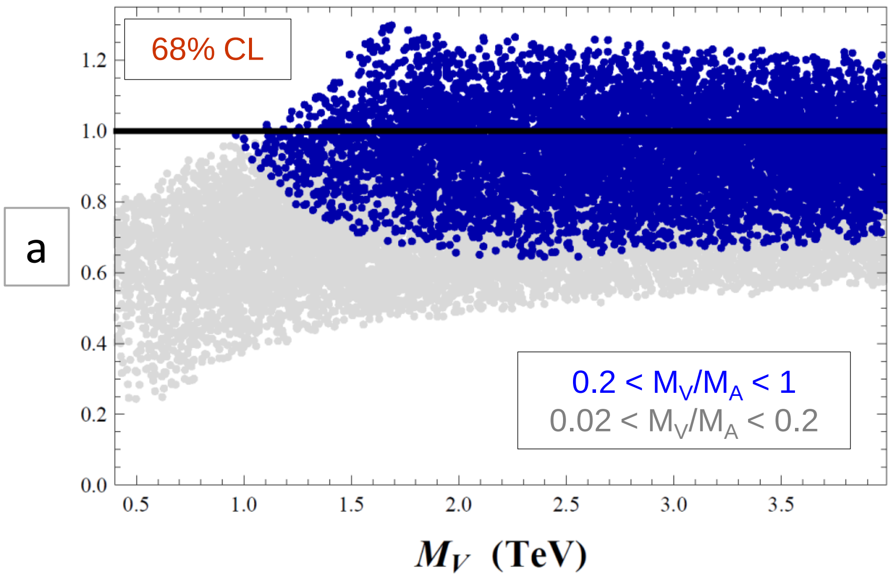
Higgsless
C & P-even

ii) NLO results: 1st and 2nd WSRs*

$1 > a > 0.94$
$M_A \approx M_V > 4$ TeV
(95%CL)



iii) NLO results: 1st WSR and $M_V < M_A$*



Similar conclusions, but softened

For $M_V<M_A$:

- ✓ A moderate resonance-mass splitting implies $a \approx 1$.
- ✓ M_V < 1 TeV implies large resonance-mass splitting.
- ✓ M_A > 1.5 TeV at 68% CL.

* Pich,Rosell, SC, PRL 110 (2013) 181801; JHEP 01 (2014) 157

Conclusions

- **Chiral power counting** in the low-energy non-linear EFT (ECLh)
- Build **custodial**-invariant Lagrangian w/ light dof + R
- **Low-energy matching:** contributions from R to the ECLh at $\mathcal{O}(p^4)$
- **UV-completion assumptions:** further constraints on the predictions

✓ **Tree-level** predictions of the O(p4) Wilson coefficients

✓ **1-loop applications:**

- Resonances perfectly allowed by S & T at $M_R \sim 4\pi v \approx 3$ TeV
- Resonances perfectly compatible with LHC $a \approx 1$

BACKUP SLIDES

$SU(2)_L \otimes SU(2)_R$ / $SU(2)_{L+R}$ Resonance Theory (P-even)

$$\mathcal{L} = \mathcal{L}_{\rm EW}^{(2)} + \mathcal{L}_{\rm GF} + \mathcal{L}_V + \mathcal{L}_A + \mathcal{L}_{VV}^{\rm kin} + \mathcal{L}_{AA}^{\rm kin} + \ldots$$

w/ field content: $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ EW Goldstones + SM gauge bosons

+ one $SU(2)_L \otimes SU(2)_R$ singlet Higgs-like scalar S_1 with m_{S1}=126 GeV ***

+ lightest V and A resonances -triplets- *(antisym. tensor formalism)* (x)

•Relevant resonance Lagrangian (x), **

$$\mathcal{L} = \frac{v^2}{4}\langle u_\mu u^\mu\rangle\left(1+\frac{2\,a}{v}\,h\right) \quad \longleftarrow \text{h + ω sector}$$

$$+\frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu}f_+^{\mu\nu}\rangle + \frac{i\,G_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu,u^\nu]\rangle \quad \longleftarrow \text{V + ω sector}$$

$$+\frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu}f_-^{\mu\nu}\rangle + \sqrt{2}\,\lambda_1^{hA}\,\partial_\mu h\,\langle A^{\mu\nu}u_\nu\rangle \quad \longleftarrow \text{A+h+ω sector}$$

NOTATIONS:
$\omega = \mathbf{a} = \kappa_{\mathbf{W}} = \kappa_{\mathbf{Z}}$

We will have 7 resonance parameters:
F_V, G_V, F_{AW}, κ_W, λ_1^{SA}, M_V and M_A

$\Rightarrow$ High-energy constraints will be crucial

(x) SD constraints: Ecker et al. '89
(x) EoM simplifications: Xiao, SC '07
(x) EoM simplifications: Georgi '91
(x) EoM simplification: Pich,Rosell,SC '13

** Appelquist, Bernard '80
** Longhitano '80 '81
** Dobado,Espriu,Herrero '91
** Dobado et al. '99
** Espriu,Matias '95 …

*** Alonso et al. '13
*** Manohar et al. '13
*** Elias-Miro et al. '13…

	P	C	CP	h.c.
S	S	S^T	S^T	S
P	$-P$	P^T	$-P^T$	P
$V^{\mu\nu}$	$V_{\mu\nu}$	$-V^{\mu\nu\,T}$	$-V_{\mu\nu}^T$	$V^{\mu\nu}$
$A^{\mu\nu}$	$-A_{\mu\nu}$	$A^{\mu\nu\,T}$	$-A_{\mu\nu}^T$	$A^{\mu\nu}$

	P	C	CP	h.c.
U	$U^\dagger$	U^t	U^*	$U^\dagger$
u	$u^\dagger$	u^t	u^*	$u^\dagger$
u^μ	$-u_\mu$	$u^{\mu\ t}$	$-u_\mu^t$	u^μ
$(d^\mu X)$	$(d_\mu X')$	$(d^\mu X)'$	$(d_\mu X)'$	$(d^\mu X^\dagger)$
$f_\pm^{\mu\nu}$	$\pm f_{\pm\,\mu\nu}$	$\mp f_\pm^{\mu\nu\ t}$	$-f_{\pm\,\mu\nu}^t$	$f_\pm^{\mu\nu}$
$\partial^\mu h$	$\partial_\mu h$	$\partial^\mu h$	$\partial_\mu h$	$\partial^\mu h$

$$
\begin{aligned}
(J_S)_{mn} &\equiv -Tr_D\{\xi_m\bar{\xi}_n\} \;=\; \bar{\xi}_n\xi_m\,,\\
(J_P)_{mn} &\equiv -i\,Tr_D\{\xi_m\bar{\xi}_n\gamma_5\} \;=\; i\,\bar{\xi}_n\gamma_5\xi_m\,,\\
(J_V^\mu)_{mn} &\equiv -Tr_D\{\xi_m\bar{\xi}_n\gamma^\mu\} \;=\; \bar{\xi}_n\gamma^\mu\xi_m\,,\\
(J_A^\mu)_{mn} &\equiv -Tr_D\{\xi_m\bar{\xi}_n\gamma^\mu\gamma_5\} \;=\; \bar{\xi}_n\gamma^\mu\gamma_5\xi_m\,,\\
(J_T^\mu)_{mn} &\equiv -Tr_D\{\xi_m\bar{\xi}_n\sigma^{\mu\nu}\} \;=\; \bar{\xi}_n\sigma^{\mu\nu}\xi_m\,,\\
(J_{V'}^{\mu\nu})_{mn} &\equiv -iTr_D\{(d^\mu\xi)_m\bar{\xi}_n\gamma^\nu - \xi_m(d^\mu\bar{\xi})_n\gamma^\nu\}\,,\\
(J_{A'}^{\mu\nu})_{mn} &\equiv -iTr_D\{(d^\mu\xi)_m\bar{\xi}_n\gamma^\nu\gamma_5 - \xi_m(d^\mu\bar{\xi})_n\gamma^\nu\gamma_5\}\,,\\
(J_{S'})_{mn} &\equiv -iTr_D\{(d_\mu\xi)_m\bar{\xi}_n\gamma^\mu - \xi_m(d_\mu\bar{\xi})_n\gamma^\mu\} \;=\; J^\mu_{V'\,\mu}\,,\\
(\tilde{J}_{S'})_{mn} &\equiv -iTr_D\{(d_\mu\xi)_m\bar{\xi}_n\gamma^\mu\gamma_5 - \xi_m(d_\mu\bar{\xi})_n\gamma^\mu\gamma_5\} \;=\; J^\mu_{A'\,\mu}
\end{aligned}
$$

2.1. Oblique Electroweak Observables

✓ Universal oblique corrections via the EW boson self-energies (transverse in the Landau gauge)

$$\mathcal{L}_{\text{v.p.}} \doteq -\frac{1}{2} W^3_\mu \, \Pi^{\mu\nu}_{33}(q^2) W^3_\nu - \frac{1}{2} B_\mu \, \Pi^{\mu\nu}_{00}(q^2) B_\nu - W^3_\mu \, \Pi^{\mu\nu}_{30}(q^2) B_\nu - W^+_\mu \, \Pi^{\mu\nu}_{WW}(q^2) W^-_\nu$$

✓ S parameter*: new physics in the difference between the Z self-energies at $Q^2=M_Z^2$ and $Q^2=0$.

$$e_3 = \frac{g}{g'} \, \widetilde{\Pi}_{30}(0) \, , \qquad \Pi_{30}(q^2) = q^2 \, \widetilde{\Pi}_{30}(q^2) + \frac{g^2 \tan\theta_W}{4} \, v^2 \, , \qquad S = \frac{16\pi}{g^2} \left(e_3 - e_3^{\rm SM} \right) .$$

✓ T parameter*: custodial symmetry breaking

$$e_1 = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{M_W^2} \overset{**}{=} \frac{Z^{(+)}}{Z^{(-)}} - 1 \qquad\qquad T = \frac{4\pi}{g'^2 \cos^2\theta_W} \left(e_1 - e_1^{\rm SM} \right)$$

✓ We follow the useful dispersive representation introduced by Peskin and Takeuchi* for S and a dispersion relation for T (checked for the lowest cuts):

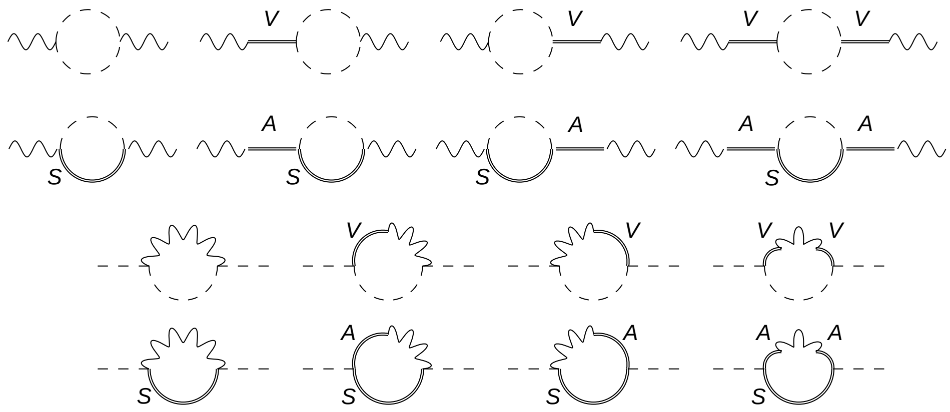
$$S = \frac{16\pi}{g^2 \tan\theta_W} \int_0^\infty \frac{{\rm d}t}{t} \left(\rho_S(t) - \rho_S(t)^{\rm SM} \right)$$

$$T = \frac{16\pi}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{{\rm d}t}{t^2} \left(\rho_T(t) - \rho_T(t)^{\rm SM} \right)$$

- ✓ $\rho_S(t)$ and $\rho_T(t)$ are the sectral functions of the W^3B and of the difference of the neutral and charged Goldstone boson self-energies, respectively.
- ✓ They need to be well-behaved at short-distances to get the convergence of the integral.
- ✓ S and T parameters are defined for a reference value for the SM Higgs mass.

* Peskin and Takeuchi '92.
** Barbieri et al. '93

iii) At next-to-leading order (NLO)*



- ✓ Dispersive relations
- ✓ Only lightest two-particles cuts have been considered, since higher cuts are supposed to be suppressed**.

iv) High-energy constraints

- ✓ We have seven resonance parameters: importance of short-distance information.
- ✓ In contrast to QCD, the underlying theory is ignored
- ✓ Weinberg Sum-Rules (WSR)***:

$$\Pi_{30}(s) = \frac{g^2 \tan\theta_W}{4}\, s\, [\Pi_{VV}(s) - \Pi_{AA}(s)] \quad \left\{ \begin{array}{lcl} \frac{1}{\pi}\int_0^\infty \mathrm{d}t\ [\mathrm{Im}\Pi_{VV}(t) - \mathrm{Im}\Pi_{AA}(t)] & = & v^2 \\ \frac{1}{\pi}\int_0^\infty \mathrm{d}t\ t\ [\mathrm{Im}\Pi_{VV}(t) - \mathrm{Im}\Pi_{AA}(t)] & = & 0 \end{array} \right.$$

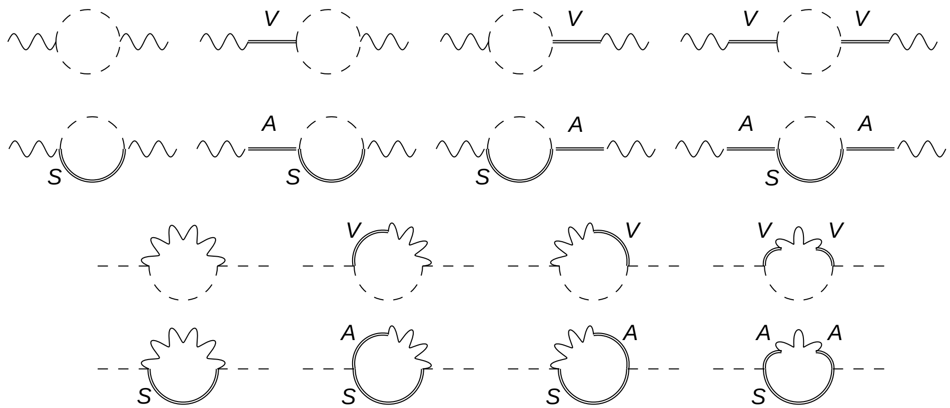
- ✓ We have 7 resonance parameters and up to 5 constraints:
  - ✓ With both, the 1st and the 2nd WSR: κ_W and M_V as free parameters
  - ✓ With only the 1st WSR: κ_W, M_V and M_A as free parameters

* Barbieri et al.'08
* Cata and Kamenik '08
* Orgogozo and Rynchov '11 '12

** Pich, IR and Sanz-Cillero '12

*** Weinberg '67
*** Bernard et al. '75.

iii) At next-to-leading order (NLO)*



- ✓ Dispersive relations
- ✓ Only lightest two-particles cuts have been considered, since higher cuts are supposed to be suppressed**.

iv) High-energy constraints

- ✓ We have seven resonance parameters: importance of short-distance information.
- ✓ In contrast to QCD, the underlying theory is ignored
- ✓ Weinberg Sum-Rules (WSR)***:

1st WSR at LO: $F_V^2\, M_V^2 \;-\; F_A^2\, M_A^2 \;=\; 0$

1st WSR at NLO (= VFF^ and AFF^^): $F_V G_V = v^2$, $F_A \lambda_1^{SA} = \kappa_W v$

2nd WSR at LO: $F_V^2 \;-\; F_A^2 \;=\; v^2$

2nd WSR at NLO: $\kappa_W = \dfrac{M_V^2}{M_A^2}$

- ✓ We have 7 resonance parameters and up to 5 constraints:
  - ✓ With both, the 1st and the 2nd WSR: κ_W and M_V as free parameters
  - ✓ With only the 1st WSR: κ_W, M_V and M_A as free parameters

* Barbieri et al.'08
* Cata and Kamenik '08
* Orgogozo and Rynchov '11 '12

** Pich, IR and Sanz-Cillero '12

*** Weinberg '67
*** Bernard et al. '75.

^ Ecker et al. '89

^^Pich, IR and Sanz-Cillero '08

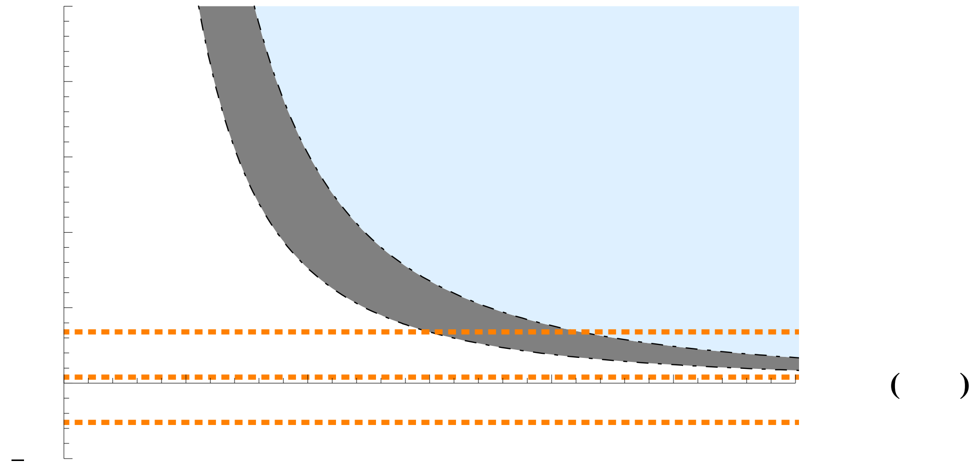
S = 0.03 ± 0.10 * (M_H=0.126 TeV)
T = 0.05 ± 0.12 * (M_H=0.126 TeV)

i) LO results

i.i) 1st and 2nd WSRs**

$$S_{\rm LO} \; = \; \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right)$$

$$\boxed{\frac{4\pi v^2}{M_V^2} < S_{\rm LO} < \frac{8\pi v^2}{M_V^2}}$$



i.ii) Only 1st WSR***

$$S_{\rm LO} \; = \; 4\pi\left\{\frac{v^2}{M_V^2}+F_A^2\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)\right\}$$

$$\boxed{S_{\rm LO} > \frac{4\pi v^2}{M_V^2}}$$

At LO $M_A > M_V > 1.5$ TeV at 95% CL

* Gfitter ** Peskin and Takeuchi '92 *** Pich, IR and Sanz-Cillero '12
* LEP EWWG
* Zfitter

3.1. Matching the theories*

✓ Once we have constrained the Resonance Theory by using short-distance constraints and the Phenomenology, we want to use it to determine the Low-Energy Constants (LECs).

✓ Two strongly coupled Lagrangians for two energy regions:

  ✓ Electroweak Effective Theory at low energies* (without resonances)
  ✓ Resonance Theory at high energies** (with resonances)

✓ The LECs contain information from heavier states.

✓ Steps:

1. Building the resonance Lagrangian
2. Matching the two effective theories
3. Requiring a good short-distance behaviour

✓ This program works in QCD: estimation of the LECs (Chiral Perturbation Theory) by using Resonance Chiral Theory

✓ As a preliminary example we show this game in the purely bosonic Lagrangian

* Pich, IR, Santos and Sanz-Cillero '14 [in progress]

4. Summary

1. What? **Electroweak Strongly Coupled Models**

2. Why? **What if this new particle around 125 GeV is not a SM Higgs bosson?**

- ✓ We should look for alternative ways of mass generation: strongly-coupled models.
- ✓ They should fulfilled the existing phenomenological tests.
- ✓ They can be used to determine the LECs

3. Where? **Effective approach**

a) EWSB: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$: similar to ChSB in QCD: ChPT.

b) Strongly-coupled models: similar to resonances in QCD: RChT.

c) General Lagrangian with at most two derivatives and short-distance information.

4. How?

Determination of S and T at NLO

1. Dispersive representation for S and T
2. Short-distance constraints

Determination of the LECs

1. Integrating out the resonances
2. Short-distance constraints

Constraining strongly-coupled models by considering S and T

- ✓ Strongly coupled scenarios are allowed by the current experimental data.
- ✓ The Higgs-like boson must have a WW coupling close to the SM one (κ_W=1):
  - ✓ With the 2nd WSR κ_W in [0.94, 1] at 95% CL
  - ✓ For larger departures from κ_W=1 the 2nd WSR must be dropped.
  - ✓ A moderate resonance-mass splitting implies $\kappa_W \approx 1$
- ✓ Resonance masses above the TeV scale:
  - ✓ At LO $M_A > M_V > 1.5$ TeV at 95% CL.
  - ✓ With the 2nd WSR $M_V > 4$ TeV at 95% CL.
  - ✓ With only the 1st WSR $M_V < 1$ TeV implies large resonance-mass splitting.

Determining the LECs in terms of resonance couplings

- ✓ Matching the Resonance Theory and the Electroweak Effective Theory.
- ✓ Similar to the QCD case.
- ✓ Short-distance constraints are fundamental.

A Warm-up example:
S & T parameters at O(p^4)

•Do oblique parameters exclude strongly-coupled models?

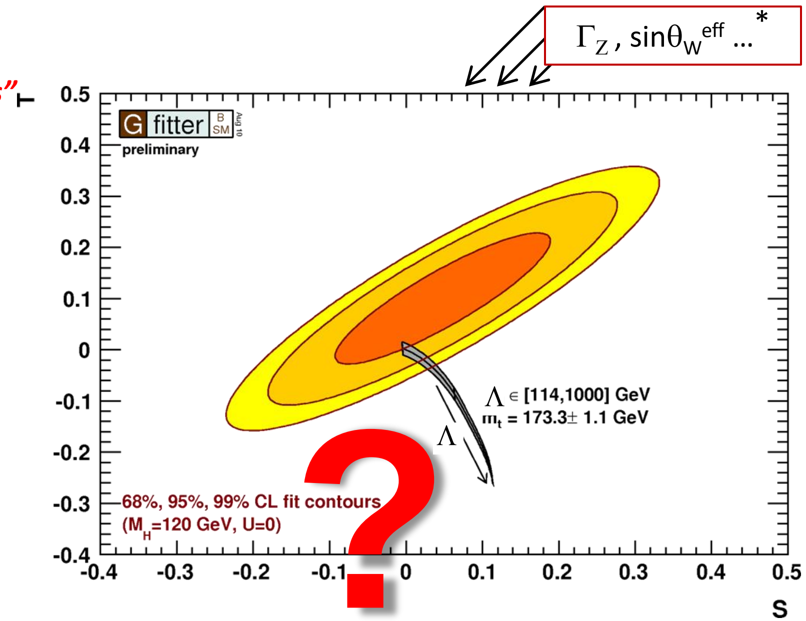
❑ ***The EWPO Oblique Parameters***

don't exclude them at all

- Dangerous naïve cut-offs at some $\Lambda^{\text{"phys"}}$

$$S \approx \frac{1}{12\pi}\ln\frac{\Lambda^2}{m^2_{H,ref}}\,,$$
$$T \approx -\frac{3}{16\pi\cos^2\theta_W}\ln\frac{\Lambda^2}{m^2_{H,ref}}$$

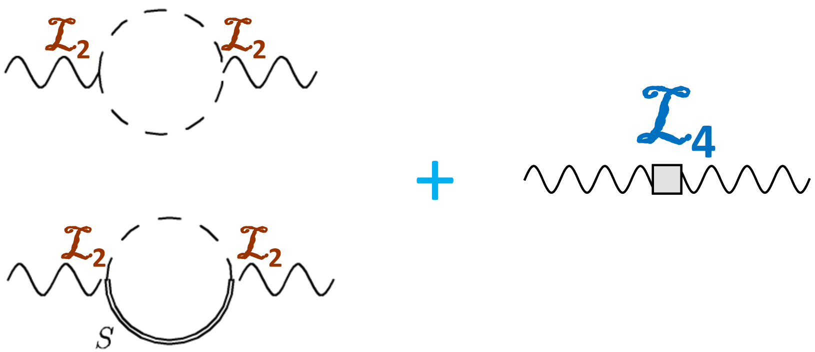
E.g. for Higgsless



-EFT: Loops + effective couplings

* Peskin,Takeuchi '92

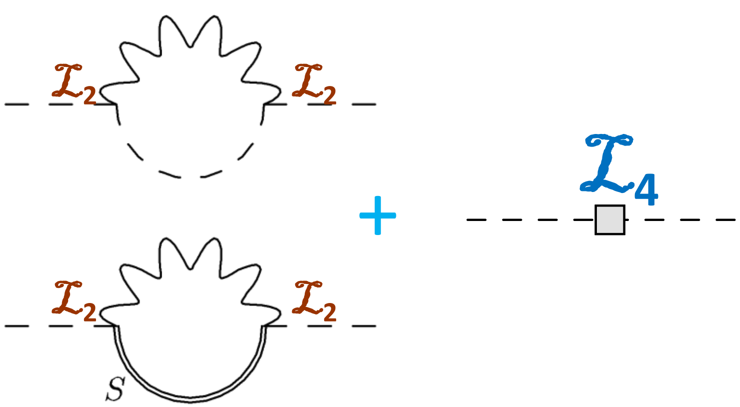
→W^3B correlator*



$$S \;=\; -16\pi\, \mathbf{a_1^r}(\mu) \;+\; \frac{(1-a^2)}{12\pi}\left(\frac{5}{6}+\ln\frac{\mu^2}{m_h^2}\right)$$

3 eff. couplings

→NGB self-energy *



$$T \;=\; \frac{8\pi}{c_W^2}\, \mathbf{a_0^r}(\mu) \;-\; \frac{3\,(1-a^2)}{16\pi c_W^2}\left(\frac{5}{6}+\ln\frac{\mu^2}{m_h^2}\right)$$

* Dobado et al. ‘99
* Pich, Rosell, SC ‘12, ‘13
* Delgado,Dobado,Herrero,SC [in prep]

→Similar in linear models:
Masso,Sanz,PRD87 (2013) 3, 033001
Chen,Dawson,Zhang,PRD89 (2014) 015016

• More observables* can over-constrain the $a_i(\mu)$

BUT not (S,T) alone!!!

• Taking just tree-level is incomplete $\longrightarrow$ $\left[\quad S = -16\pi\, a_1(\mu?)\,, \qquad T = \frac{8\pi}{c_W^2} a_0(\mu?) \quad\right]$

and similar if only loops $\longrightarrow$ $\left[\quad S = \frac{(1-a^2)}{12\pi}\ln\frac{\mu^2}{m_h^2}\,, \qquad T = -\frac{3\,(1-a^2)}{16\pi c_W^2}\ln\frac{\mu^2}{m_h^2} \quad\right]$

•Otherwise, one may resource to models**:

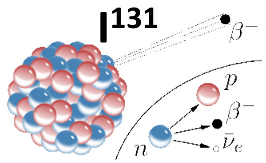
→Resonances *(lightest V + A)*

→ UV-completion assumptions *(high-energy constraints)*

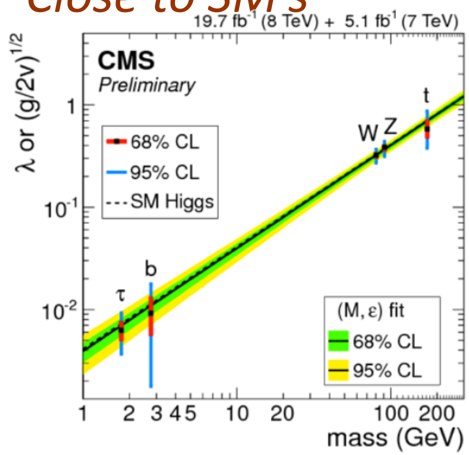
* Delgado,Dobado,Herrero,SC [in prep.] ** Pich, Rosell, SC '12, '13

- A Higgs-like boson discovered at LHC two years ago

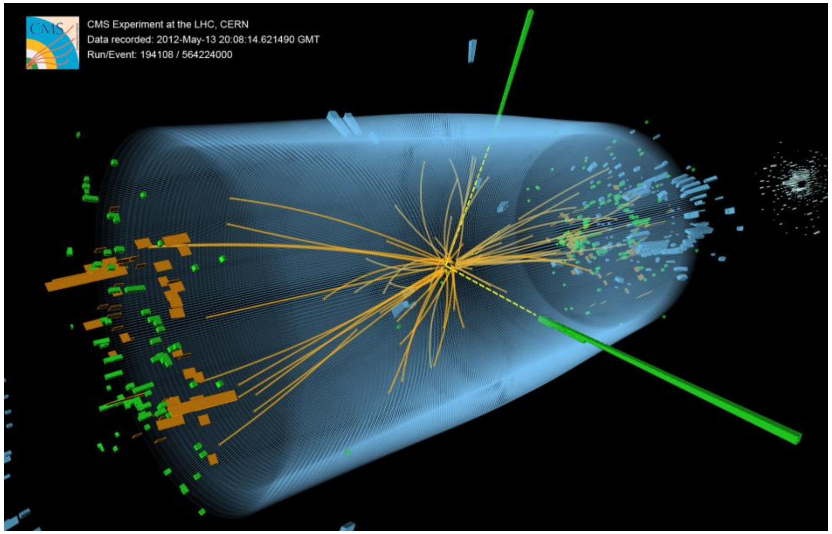
- M_H=125.64 ± 0.35 GeV ≈

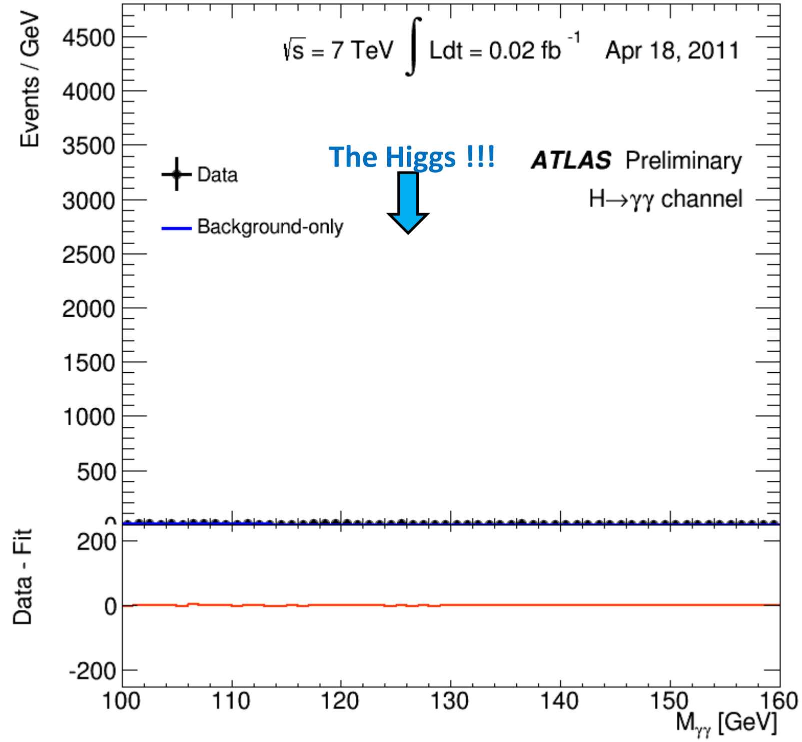


- Still many questions:
  - Spin? *0^+ most likely* $[\cancel{0^-}, \cancel{1^\pm}, \cancel{2^+}]$
  - Couplings? *Close to SM's*



  - Decay width, etc.
  - **SM Higgs?** ***Compatible so far***





[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Animations

What are we needing?

MOST PESIMISTIC SCENARIO:

NO BSM low-mass states

- **Observables!!**

★ We need more observables

sensitive to small deviations in the couplings *(e.g. $\Delta a = a - 1$)*

hWW coupling

- **Precise & *accurate* theoretical calculation!!**

★ **Just eff. vertices** → Not enough (dangerous)

★ **Low-energy EFT's** to relate observables

★ BOTH: counter-terms (couplings) + loops (logs)

★ **Full computations** (w/ finite parts)

Optimal Tool → EFT *(EW Chiral Lagrangians + h)*

(small devs. + mass gap)

Additional EFT considerations

1. Equivalence Theorem: E.g.

$$\begin{aligned}\mathcal{M}(\gamma\gamma\to W_L^+W_L^-) &\simeq -\mathcal{M}(\gamma\gamma\to w^+w^-)\\ \mathcal{M}(\gamma\gamma\to Z_LZ_L) &\simeq -\mathcal{M}(\gamma\gamma\to zz)\end{aligned}$$

for $m_{W,Z} << E$

Pheno ➔ $m_h \sim m_{W,Z} << E$ *(full calculation also possible)*

2. Renormalizable R_ξ gauge: Landau gauge convenient ($m_{\omega\pm,z} = 0$)

•**In summary:*** **RANGE OF VALIDITY (of our analysis)**

$$\mathbf{m_h^2 \sim m_W^2,\ m_Z^2 \overset{Eq.Th.}{\ll} s,\ t,\ u \overset{EFT}{\ll} \Lambda_{ECLh}^2}$$

(in practice we neglect m_W, m_Z and m_h)

* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

also notice the subtlety*,** $g^{(')} \sim m_{W,Z}/v \sim p/v$ *[notice $e \sim p/v$ too]*

* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Urech '95

(x) Apelquist,Bernard '80
(x) Longhitano '80, '81
(x) Herrero,Morales '95
(x) Pich,Rosell,Sc '12 '13
(x) Brivio et al. '13
(x) Gavela,Kanshin,Machado,Saa '14, etc.

Consider the relevant ECLh Lagrangian

• EFT Lagrangian up to NLO *[i.e. up to O(p⁴)]*:

$$\mathcal{L}_{\rm ECLh} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP}$$

Other notations:

$a=\kappa_V=\kappa_W=c_W=\omega=$etc.

➔ LO Lagrangian*,**:

$$\mathcal{L}_2 = -\frac{1}{2g^2}\mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}) - \frac{1}{2g'^2}\mathrm{Tr}(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}) + \frac{v^2}{4}\left(1 + 2a\,\frac{h}{v} + b\left(\frac{h^2}{v^2}\right)\right)\mathrm{Tr}(D^\mu U^\dagger D_\mu U) + \frac{1}{2}\partial^\mu h\,\partial_\mu h + \ldots$$

➔ NLO Lagrangian*,**:

$$\mathcal{L}_4 = a_1\mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger\hat{W}^{\mu\nu}) + i\,a_2\mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger[V^\mu,V^\nu]) - ia_3\mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu,V^\nu]) \boxed{- c_W\,\frac{h}{v}\,\mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}) - c_B\,\frac{h}{v}\,\mathrm{Tr}(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu})} + \ldots$$

$$-\frac{c_\gamma}{2}\frac{h}{v}e^2 A_{\mu\nu}A^{\mu\nu} + \ldots$$

* Apelquist,Bernard ‘80
* Longhitano ‘80, ‘81

** Buchalla,Catà ‘12
** Alonso,Gavela,Merlo,Rigolin,Yepes ‘12
** Brivio,Corbett,Eboli,Gavela,Gonzalez–Fraile,Gonzalez–Garcia,Merlo,Rigolin ’13
(list of operators in $\mathcal{L}_4$)

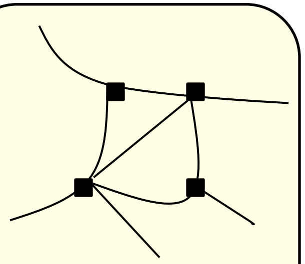
Counting, loops & renormalization

•In general, the $O(p^d)$ Lagrangian has the symbolic form (χ=W,B,π,h),

$$\mathcal{L}_d \;=\; \sum_k f_k^{(d)}\, p^d \left(\frac{\chi}{v}\right)^k$$

$$f_k^{(2)} \sim v^2$$
$$f_k^{(4)} \sim a_i$$
...

leading to a general scaling* of a diagram with
- *L loops*
- *E external legs*
- *N_d vertices of $\mathcal{L}_d$*



E.g.: L=2, E=5

$$\mathcal{M} \;\sim\; \left(\frac{\mathbf{p^2}}{\mathbf{v^{E-2}}}\right) \left(\frac{\mathbf{p^2}}{\mathbf{16\pi^2 v^2}}\right)^{\mathbf{L}} \prod_{\mathbf{d}} \left(\frac{\mathbf{f_k^{(d)} p^{(d-2)}}}{\mathbf{v^2}}\right)^{\mathbf{N_d}}$$

[scaling of individual diagrams; cancellations & higher suppressions for the total amplitude]

• $O(p^d)$ loop divergence + $O(p^d)$ chiral coupling = UV-finite

<u>**E.g. W_LW_L-scat**:**</u>

LO $O(p^2)$➔ $\frac{\mathbf{p^2}}{\mathbf{v^2}}$ (tree)

NLO $O(p^4)$➔ $\mathbf{a_i}\frac{\mathbf{p^4}}{\mathbf{v^4}}$ (tree) + $\frac{\mathbf{p^4}}{\mathbf{16\pi^2 v^4}}\left(\frac{1}{\epsilon}+\log\right)$ (1-loop)

* Weinberg '79
* Urech '95
* Georgi,Manohar NPB234 (1984) 189
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Espriu,Mescia,Yencho '13
** Delgado,Dobado '13

Relevant ECLh Lagrangian for $\gamma\gamma \to W_L^a W_L^b$

• EFT Lagrangian up to NLO *[i.e. up to $O(p^4)$]*:

$$\mathcal{L}_{\rm ECLh} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP}$$

Other notations:
$a=\kappa_V=\kappa_W=c_W=\omega=$etc.

→ LO Lagrangian*,**:

$$\mathcal{L}_2 = -\frac{1}{2g^2}\mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}) - \frac{1}{2g'^2}\mathrm{Tr}(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}) + \frac{v^2}{4}\left(1 + 2a\,\frac{h}{v} + b\left(\frac{h^2}{v^2}\right)\right)\mathrm{Tr}(D^\mu U^\dagger D_\mu U) + \frac{1}{2}\partial^\mu h\,\partial_\mu h + \ldots$$

→ NLO Lagrangian*,**:

$$\mathcal{L}_4 = a_1\mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger\hat{W}^{\mu\nu}) + i\,a_2\mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger[V^\mu,V^\nu]) - ia_3\mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu,V^\nu]) - c_W\,\frac{h}{v}\,\mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}) - c_B\,\frac{h}{v}\,\mathrm{Tr}(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}) + \ldots$$

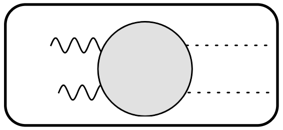
$$-\frac{c_\gamma}{2}\,\frac{h}{v}\,e^2 A_{\mu\nu}A^{\mu\nu} + \ldots$$

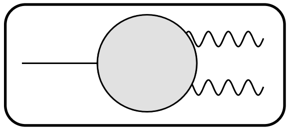
* Apelquist,Bernard ‘80
* Longhitano ‘80, ‘81

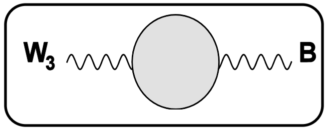
** Buchalla,Catà ‘12
** Alonso,Gavela,Merlo,Rigolin,Yepes ‘12
** Brivio,Corbett,Eboli,Gavela,Gonzalez–Fraile,Gonzalez–Garcia,Merlo,Rigolin ’13
(list of operators in $\mathscr{L}_4$)

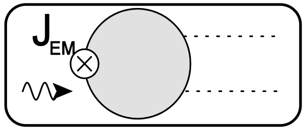
Related observables

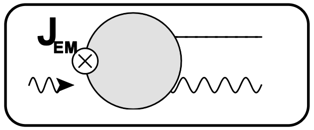
•How can we determine these ECLh couplings? *











Observables	ECLh couplings from $\mathcal{L}_2$	ECLh couplings from $\mathcal{L}_2$
$\mathcal{M}(\gamma\gamma \to zz)$	a	c_γ^r
$\mathcal{M}(\gamma\gamma \to \omega^+\omega^-)$	a	$c_\gamma^r,\, a_1^r,\, (a_2^r - a_3^r)$
$\Gamma(h \to \gamma\gamma)$	a	c_γ^r
S–parameter	a	a_1^r
$\gamma^* \to \omega^+\omega^-$ EM-FF	a	$(a_2^r - a_3^r)$
$\gamma^* \to \gamma h$ EM-FF	–	c_γ

• OVERDETERMINATION → EFT PREDICTIVITY:

6 observables vs. 4 combinations of parameters { a, c_γ, a_1,(a_2-a_3) }

* Delgado,Dobado,Herrero,SC '14

ECLh running at O(p^4)

- This 6 observables overdetermine the 4 combinations of couplings a, c_γ, a_1, $(a_2\text{-}a_3)$

  and provide their running:

a=0

		ECLh	ECL (Higgsless) (+)
*	$\Gamma_{a_1-a_2+a_3}$	0	0
*	Γ_{c_γ}	0	-
*	Γ_{a_1}	$-\frac{1}{6}(1-a^2)$	$-\frac{1}{6}$
* (x)	$\Gamma_{a_2-a_3}$	$-\frac{1}{6}(1-a^2)$	$-\frac{1}{6}$
**	Γ_{a_4}	$\frac{1}{6}(1-a^2)^2$	$\frac{1}{6}$
**	Γ_{a_5}	$\frac{1}{8}(b-a^2)^2 + \frac{1}{12}(1-a^2)^2$	$\frac{1}{12}$

* Delgado,Dobado,Herrero,SC '14

** Espriu,Mescia,Yencho '13
** Delgado,Dobado '13

(+) Herrero,Morales '95

(x) In agreement with Ametller,Talavera '14

Oblique EWPO's

✓ Universal oblique corrections via the EW boson self-energies (transverse in the Landau gauge) *, +

$$\mathcal{L}_{\text{vac-pol}} = -\frac{1}{2} W^3_\mu \Pi^{\mu\nu}_{33}(q^2) W^3_\nu - \frac{1}{2} B_\mu \Pi^{\mu\nu}_{00}(q^2) B_\nu - W^3_\mu \Pi^{\mu\nu}_{30}(q^2) B_\nu - W^+_\mu \Pi^{\mu\nu}_{WW}(q^2) W^-_\nu ,$$

with the subtracted definition,

$$\Pi_{30}(q^2) = q^2\, \widetilde{\Pi}_{30}(q^2) + \frac{g^2 \tan\theta_W}{4}\, v^2$$

$$\mathbf{e_1} = \frac{\mathbf{1}}{\mathbf{m_W^2}} \Big(\mathbf{\Pi_{33}(0) - \Pi_{WW}(0)} \Big) \stackrel{**}{=} \frac{\mathbf{Z^{(+)}}}{\mathbf{Z^{(0)}}} - \mathbf{1}$$

$$\mathbf{e_3} = \frac{\mathbf{1}}{\tan\theta_{\mathbf{W}}}\, \mathbf{\widetilde{\Pi}_{30}(0)}$$

$$\boxed{\varepsilon_1^{\rm SM} \approx -\frac{3g'^2}{32\pi^2} \log\frac{M_H}{M_Z} + \text{const}, \qquad \varepsilon_3^{\rm SM} \approx \frac{g^2}{96\pi^2} \log\frac{M_H}{M_Z} + \text{const}'}$$

$$T = \frac{4\pi}{g'^2 \cos^2\theta_W} \left(e_1 - e_1^{\rm SM}\right)$$

$$S = \frac{16\pi}{g^2} \left(e_3 - e_3^{\rm SM}\right),$$

We find that

strongly-coupled models **are**

perfectly/naturally allowed

* Peskin and Takeuchi '91, '92

** Barbieri et al.'93

\+ Gfitter
\+ LEP EWWG
\+ Zfitter

S-parameter sum-rule *

✓ In this work, dispersive representation introduced by Peskin and Takeuchi*.

$$S = \frac{16}{g^2 \tan\theta_W} \int_0^\infty \frac{\mathrm{d}t}{t} \left(\mathrm{Im}\widetilde{\Pi}_{30}(t) - \mathrm{Im}\widetilde{\Pi}_{30}(t)^{\mathrm{SM}} \right)$$

$$= \int_0^\infty \frac{\mathrm{d}t}{t} \left(\frac{16}{g^2 \tan\theta_W} \mathrm{Im}\widetilde{\Pi}_{30}(t) - \frac{1}{12\pi} \left[1 - \left(1 - \frac{m^2_{H,ref}}{t} \right)^3 \theta(t - m^2_{H,ref}) \right] \right)$$

→ The convergence of the integral requires $\rho_{\mathbf{S}}(\mathbf{t}) \equiv \frac{\mathbf{1}}{\pi} \mathrm{Im}\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{t}) \quad \xrightarrow{\mathbf{t}\to\infty} \quad \mathbf{0}$

→ S-parameter defined for an arbitrary reference value $m_{H,ref}$

→ Higher threshold cuts in $\mathrm{Im}\Pi_{30}$ will be suppressed in the dispersive integral

→ At tree-level: $S_{\mathrm{LO}} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right)$

* Peskin and Takeuchi ’92.

High-energy constraints

- ✓ We will have 7 resonance parameters: F_V, G_V, F_A, κ_W, λ_1^{SA}, M_V and M_A.
- ✓ The number of unknown couplings can be reduced by using short-distance information.
- ✓ In contrast with the QCD case, we ignore the underlying dynamical theory.

0) Once-subtracted dispersion* relation for $\Pi_{30}(s) \; = \; \dfrac{g^2 \tan\theta_W}{4} \; s \; \left[\Pi_{VV}(s) - \Pi_{AA}(s) \right]$

- ✓ Once-subtract. dispersive relation from tree+1-loop spectral function**

  $\pi\pi$, $h\pi$ … (higher cuts suppressed) $\quad \Pi_{30}(s) = \Pi_{30}(0) + \dfrac{s}{\pi} \displaystyle\int_0^\infty \dfrac{\mathrm{d}t}{t\,(t-s)} \mathrm{Im}\Pi_{30}(t)$

- ✓ F_R^r and M_R^r are *renormalized* couplings which define the resonance poles at the one-loop level.

$$\Pi_{30}(s)|_{\mathrm{NLO}} \; = \; \frac{g^2 \tan\theta_W}{4} \; s \; \left(\frac{v^2}{s} + \frac{F_V^{r\,2}}{M_V^{r\,2} - s} - \frac{F_A^{r\,2}}{M_A^{r\,2} - s} \; + \; \overline{\Pi}(s) \right)$$

* Peskin,Takeuchi ‘90, ‘91

** Pich, Rosell, SC ‘08

i) Weinberg Sum Rules (WSR)*

$$\Pi_{30}(s) = \frac{g^2 \tan\theta_W\, s}{4}\,[\,\mathbf{\Pi_{VV}(s)} - \mathbf{\Pi_{AA}(s)}\,] = \frac{g^2 v^2 \tan\theta_W}{4} + s\, \widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s})$$

1ST WSR:

$$\left| \mathbf{s} \times \mathbf{\Pi_{V-A}(s)} \right| \stackrel{\mathbf{s}\to\infty}{\longrightarrow} \mathbf{0} \quad \Longrightarrow \quad \int_{\mathbf{0}}^{\infty} \mathbf{dt}\; \rho_{\mathbf{S}}(\mathbf{t}) = \frac{\mathbf{g^2 v^2} \tan\theta_{\mathbf{W}}}{\mathbf{4}}$$

2ND WSR:

$$\left| \mathbf{s^2} \times \mathbf{\Pi_{V-A}(s)} \right| \stackrel{\mathbf{s}\to\infty}{\longrightarrow} \mathbf{0} \quad \Longrightarrow \quad \int_{\mathbf{0}}^{\infty} \mathbf{dt\;t}\; \rho_{\mathbf{S}}(\mathbf{t}) = \mathbf{0}$$

* Weinberg'67
* Bernard et al.'75.

$$\rho_{\mathbf{S}}(\mathbf{s}) = \frac{\mathbf{1}}{\pi}\mathrm{Im}\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s})$$

i.i) LO

$$\begin{aligned} F_V^2 - F_A^2 &= v^2 \\ F_V^2 M_V^2 - F_A^2 M_A^2 &= 0 \end{aligned}$$

(1 / 2 constraints)

i.ii) Imaginary NLO

$$\mathrm{Im}\Pi_{V-A}(s) \sim \mathcal{O}\left(\frac{1}{s^{\Delta/2}}\right)$$

(1 / 2 constraints)

i.iii) Real NLO: fixing of $F_{V,A}^r$ or lower bounds**

$$F_V^{r\,2} - F_A^{r\,2} = v^2\,(1 + \delta_{\rm NLO}^{(1)})$$
$$F_V^{r\,2} M_V^{r\,2} - F_A^{r\,2} M_A^{r\,2} = v^2 M_V^{r\,2} \delta_{\rm NLO}^{(2)}$$

(constraints on $F_{V,A}^r$)

F_R^r and M_R^r are *renormalized* couplings which define the resonance poles at the one-loop level**

$$\Pi_{30}(s) = \Pi_{30}(0) + \frac{s}{\pi}\int_0^\infty \frac{\mathrm{d}t}{t\,(t-s)}\mathrm{Im}\Pi_{30}(t)$$

$$\Pi_{30}(s)|_{\rm NLO} = \frac{g^2\tan\theta_W}{4}\, s\, \left(\frac{v^2}{s} + \frac{F_V^{r\,2}}{M_V^{r\,2}-s} - \frac{F_A^{r\,2}}{M_A^{r\,2}-s} + \overline{\Pi}(s)\right)$$

* Weinberg'67
* Bernard et al.'75.

** Pich, Rosell, SC '08

ii) Additional short-distance constraints

ii.i) $\omega\omega$ Vector Form Factor**

$$\frac{\mathbf{F_V G_V}}{\mathbf{v^2}} = \mathbf{1}$$

+ NO HIGHER DERIV. OPERATORS for W,B→$\omega\omega$

ii.ii) hω Axial-vector Form Factor**

(equivalent to VFF + vanishing $\rho_S(t)$ at $t \to \infty$)

$$\frac{\mathbf{F_A \lambda_1^{SA}}}{\kappa_\mathbf{W} \mathbf{v}} = \mathbf{1}$$

+ NO HIGHER DERIV. OPERATORS for W,B→hω

** Ecker et al.'89

*** Pich, Rosell, SC '12

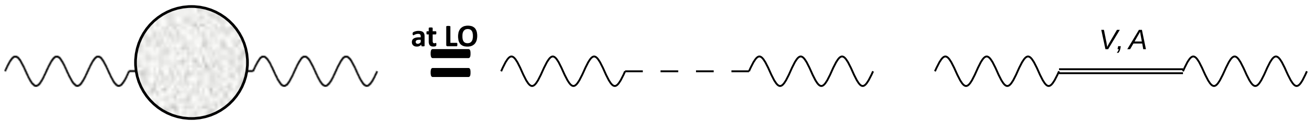
* Barbieri et al.'08
* Guo, Zheng, SC '07
* Pich, Rosell, SC '11

S and T *at LO*

S-parameter *

- New physics in the difference between the Z self-energies at $q^2=M_Z^2$ and $q^2=0$.

➔ *W^{3}B correlator* *(transverse in Landau gauge)*



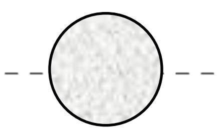
$$\Pi_{30}(s)|_{\rm LO} = \frac{g^2\tan\theta_W}{4}\, s\left(\frac{v^2}{s} + \frac{F_V^2}{M_V^2-s} - \frac{F_A^2}{M_A^2-s}\right)$$

$$S_{\rm LO} = 4\pi\left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2}\right)$$

T-parameter *

- It parametrizes the Custodial Symmetry breaking *(W^+W^- vs. ZZ)*

➔ *NGB self-energies*



$= 0$

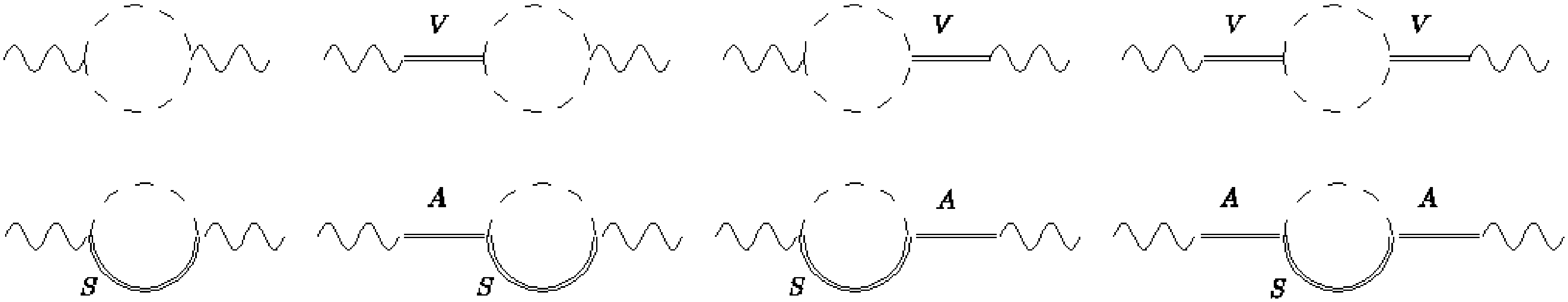
$$\Sigma(s)^{(0)} - \Sigma(s)^{(+)} = 0$$

$$T_{\rm LO} = 0$$

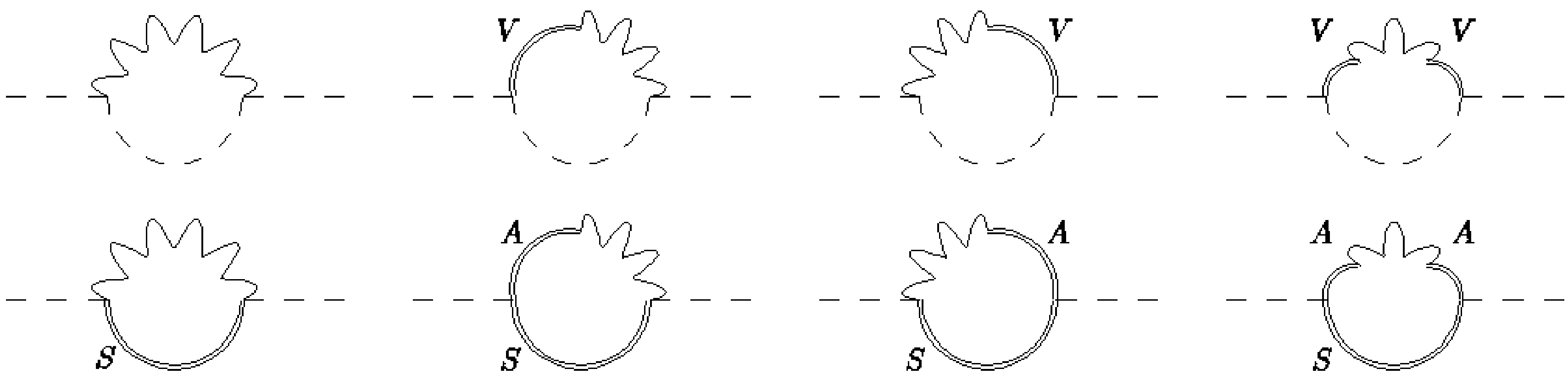
* Peskin and Takeuchi '92.

S and T *at NLO*

➔ W^3B correlator*



➔ NGB self-energy *

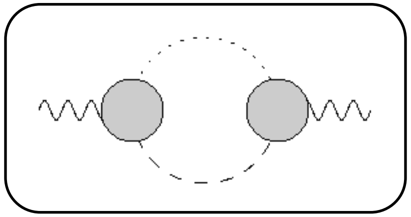


* Barbieri et al.'08
* Cata and Kamenik '10
* Orgogozo, Rychkov '11, '12

High-energy constraints + *Dispersion relations*

➔ W^{3}B correlator ⟶ **S-parameter sum-rule** (+)

$$S = \frac{16}{g^2 \tan\theta_W} \int_0^\infty \frac{dt}{t} \left[\rho_S(t) - \rho_S(t)^{SM} \right]$$

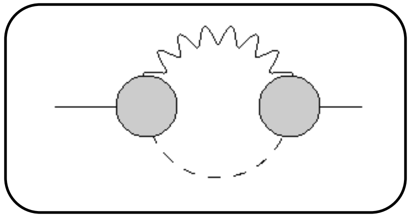


$$\rho_S(s) = \frac{1}{\pi} \mathrm{Im}\widetilde{\Pi}_{30}(s) \begin{cases} \rho_S|_{\pi\pi} = \frac{gg'\,\theta(s)}{192\pi} \left(1 + \frac{F_V G_V}{v^2} \frac{s}{M_V^2 - s}\right)^2 \xrightarrow{\text{VFF + WSR}} \frac{gg'\,\theta(s)}{192\pi} \left(\frac{M_V^2}{M_V^2 - s}\right)^2 \\ \rho_S|_{S\pi} = -\frac{gg'\,\kappa_W^2\,\sigma_{S\pi}^3 \theta(s - m_S^2)}{192\pi} \left(1 + \frac{F_A \lambda_1^{SA}}{\kappa_W v} \frac{s}{M_A^2 - s}\right)^2 \xrightarrow{\text{VFF + WSR}} -\frac{gg'\,\kappa_W^2\,\sigma_{S\pi}^3 \theta(s - m_S^2)}{192\pi} \left(\frac{M_A^2}{M_A^2 - s}\right)^2 \end{cases}$$

➔ NGB self-energies ⟶ **Convergent dispersion relation for T** (x)

for the lightest absorptive diagrams with Bπ + BS

$$T = \frac{4}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{dt}{t^2} \left[\rho_T(t) - \rho_T(t)^{SM} \right]$$



*

$$\rho_T(s) = \frac{1}{\pi} \mathrm{Im}[\Sigma(s)^{(0)} - \Sigma(s)^{(+)}] \begin{cases} \rho_T(s)|_{B\pi} \xrightarrow{s\to\infty} -\frac{3g'^2 s}{64\pi^2} \left(1 - \frac{F_V G_V}{v^2}\right)^2 + \mathcal{O}(s^0) \\ \rho_T(s)|_{BS_1} \xrightarrow{s\to\infty} \frac{3g'^2 \kappa_W^2 s}{64\pi^2} \left(1 - \frac{F_A \lambda_1^{SA}}{\kappa_W v}\right)^2 + \mathcal{O}(s^0) \end{cases}$$

+ Peskin ,Takeuchi '92

x Pich,Rosell,SC '13

* Orgogozo,Rychkov '11

$1^{st} + 2^{nd}$ WSR determination:

- ✓ 7 parameters (only lowest cuts $\pi\pi$+hπ): **M_V, M_A, F_V, F_A & G_V, κ_W, λ_1^{SA}**
- ✓ 2 + 2 + 1 constraints: **F_V, F_A & M_A, ($F_V G_V$), ($F_A \lambda_1^{SA}$)** $\Longrightarrow$ 2 free parameters: **M_V, κ_W**

Only 1^{st} WSR lower bound for $M_V < M_A$:

- ✓ 6 parameters (only lowest cuts $\pi\pi$+hπ / Bπ+Bh): **M_V, M_A, F_V & ($F_V G_V$), κ_W, ($F_A \lambda_1^{SA}$)**
- ✓ 1 + 1 + 1 constraints: **F_V & ($F_V G_V$), ($F_A \lambda_1^{SA}$)** $\Longrightarrow$ 3 free parameters: **M_V, M_A, κ_W**

LO results***

i.i) 1st and 2nd WSRs **

$$S_{\rm LO} = \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right)$$

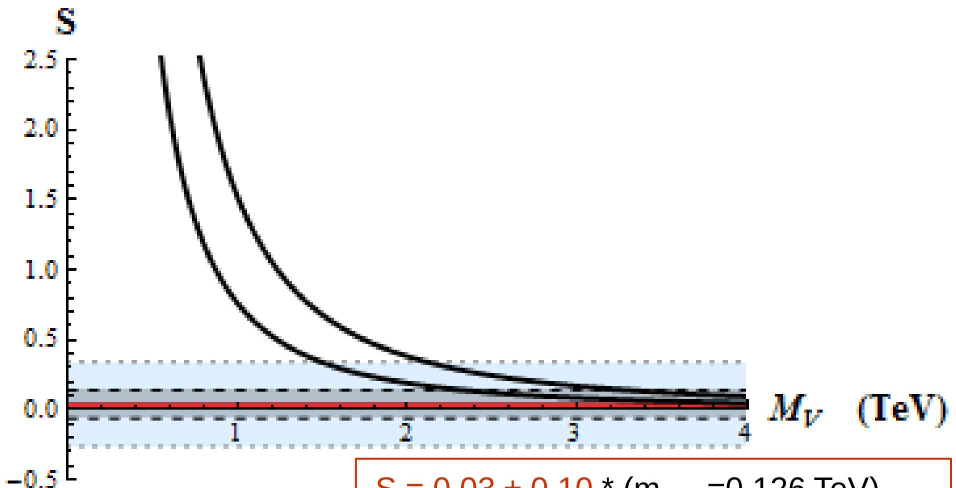
$$\boxed{\frac{4\pi v^2}{M_V^2} < S_{\rm LO} < \frac{8\pi v^2}{M_V^2}}$$

$$S_{\rm LO} = 4\pi\left(\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right), \qquad T_{\rm LO}=0$$

i.ii) Only 1st WSR *** (lower bound for $M_A > M_V$)

$$S_{\rm LO} = 4\pi\left\{\frac{v^2}{M_V^2}+F_A^2\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)\right\}$$

$$\boxed{S_{\rm LO} > \frac{4\pi v^2}{M_V^2}}$$



S = 0.03 ± 0.10 * ($m_{H,ref}$=0.126 TeV)

At LO M_V > 2.4 TeV at 68% CL

(M_V > 3.6 TeV if T_{LO}=0 also considered)

* Gfitter
* LEP EWWG
* Zfitter

** Peskin and Takeuchi '92.

*** Pich, Rosell, SC '12

*NLO results:** 1st and 2nd WSRs in Π_{30}

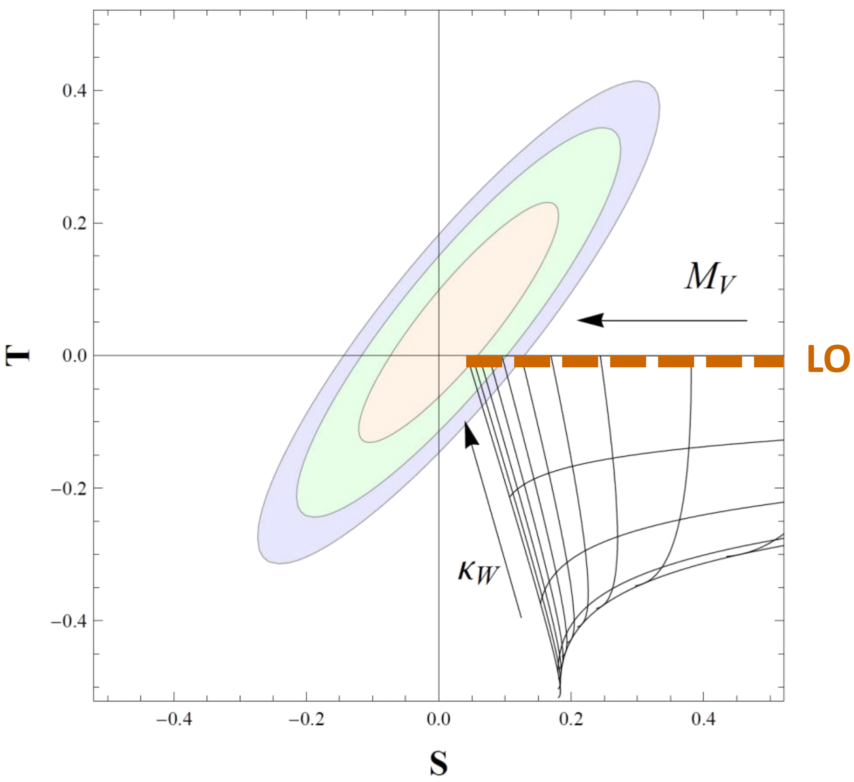
$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S = \boxed{4\pi v^2\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)} + \frac{1}{12\pi}\left[\left(\log\frac{M_V^2}{m_H^2}-\frac{11}{6}\right) - \kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{11}{6}-\frac{M_A^2}{M_V^2}\log\frac{M_A^2}{M_V^2}\right)\right]$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]

(*asymptotically-free theories*)



✓ 1st and 2nd WSRs at LO and NLO + ππ-VFF:

→ 2nd WSR: $0 < \kappa_W = M_V^2/M_A^2 < 1$

At NLO with the 1st and 2nd WSRs

$M_V > 5.4$ TeV, $0.97 < \kappa_W < 1$ at 68% CL

Small splitting $(M_V/M_A)^2 = \kappa_W$

* Pich,Rosell,SC '12, '13

NLO Results:* Only 1st WSRs in Π_{30}

(*walking & conformal TC, extra dimensions,…*)**

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2}-\kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S > \boxed{\frac{4\pi v^2}{M_V^2}} + \frac{1}{12\pi}\left[\left(\ln\frac{M_V^2}{m_H^2}-\frac{11}{6}\right)-\kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{17}{6}+\frac{M_A^2}{M_V^2}\right)\right]$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]

- ✓ **Assumption** $M_A > M_V$ for the S lower-bound
- ✓ Only 1st WSR at LO and NLO + ππ-VFF:

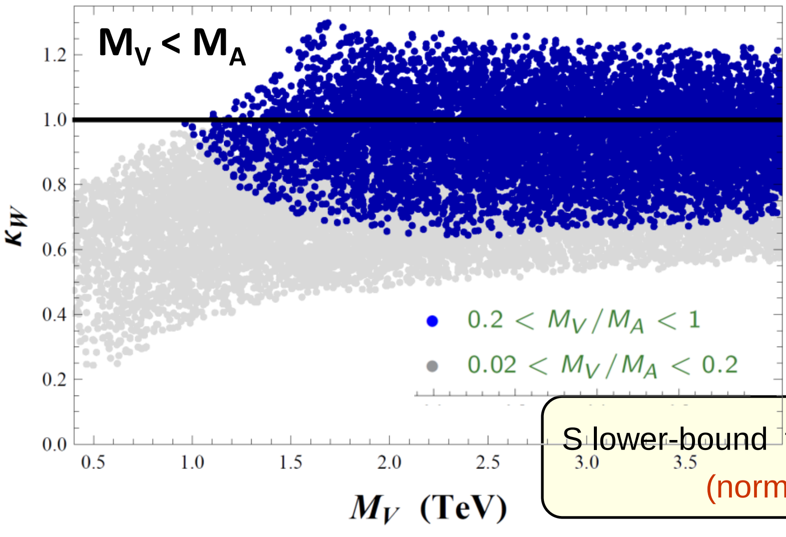
→ Free parameters: M_V, M_A and κ_W

* Pich,Rosell,SC '12, '13

** Orgogozo,Rychkov '11

*NLO Results:** Only 1st WSRs in Π_{30}

(*walking & conformal TC, extra dimensions,…*)**



S lower-bound for $M_A > M_V$ (normal hierarchy)

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2}-\kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S > \boxed{\frac{4\pi v^2}{M_V^2}} + \frac{1}{12\pi}\left[\left(\ln\frac{M_V^2}{m_H^2}-\frac{11}{6}\right)-\kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{17}{6}+\frac{M_A^2}{M_V^2}\right)\right]$$

At NLO with only 1st WSRs

$M_V > 1$ TeV, $\kappa_W \in (0.6\ ,\ 1.3)$ at 68% CL

for moderate splitting $0.2 < M_V/M_A < 1$

$\kappa_W = g_{HWW}/g_{HWW}^{SM}$

very different from the SM

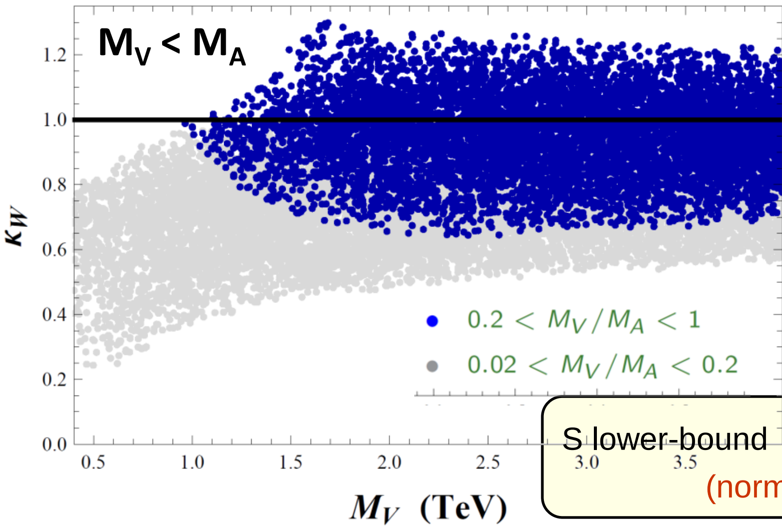
if one requires large (unnatural) splittings

* Pich,Rosell,SC '12, '13

** Orgogozo,Rychkov '11

*NLO Results:** Only 1st WSRs in Π_{30}

(*walking & conformal TC, extra dimensions,…*)**



S lower-bound for $M_A > M_V$
(normal hierarchy)

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S > \boxed{\frac{4\pi v^2}{M_V^2}} + \frac{1}{12\pi}\left[\left(\ln\frac{M_V^2}{m_H^2} - \frac{11}{6}\right) - \kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2} - \frac{17}{6} + \frac{M_A^2}{M_V^2}\right)\right]$$

At NLO with only 1st WSRs

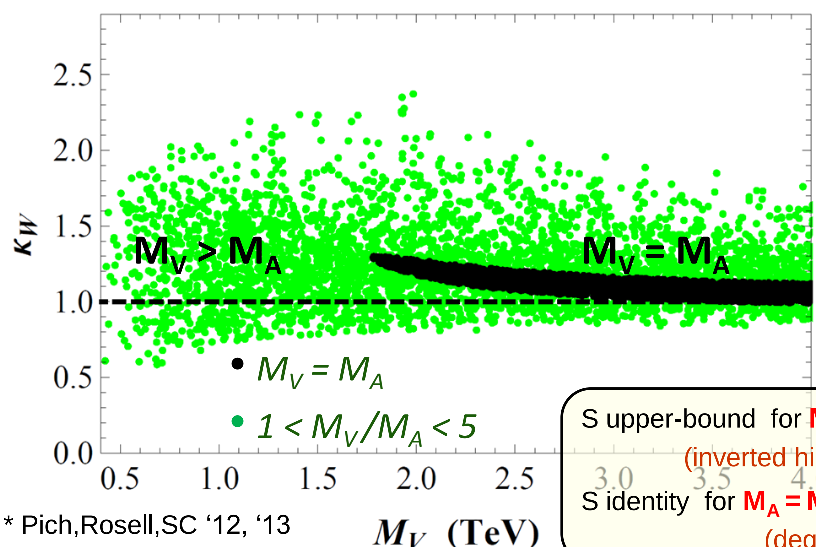
$M_V > 1$ TeV, $\kappa_W \in (0.6\,,\,1.3)$ at 68% CL

for moderate splitting $0.2 < M_V/M_A < 1$

$\kappa_W = g_{HWW}/g_{HWW}^{SM}$

very different from the SM

if one requires large (unnatural) splittings



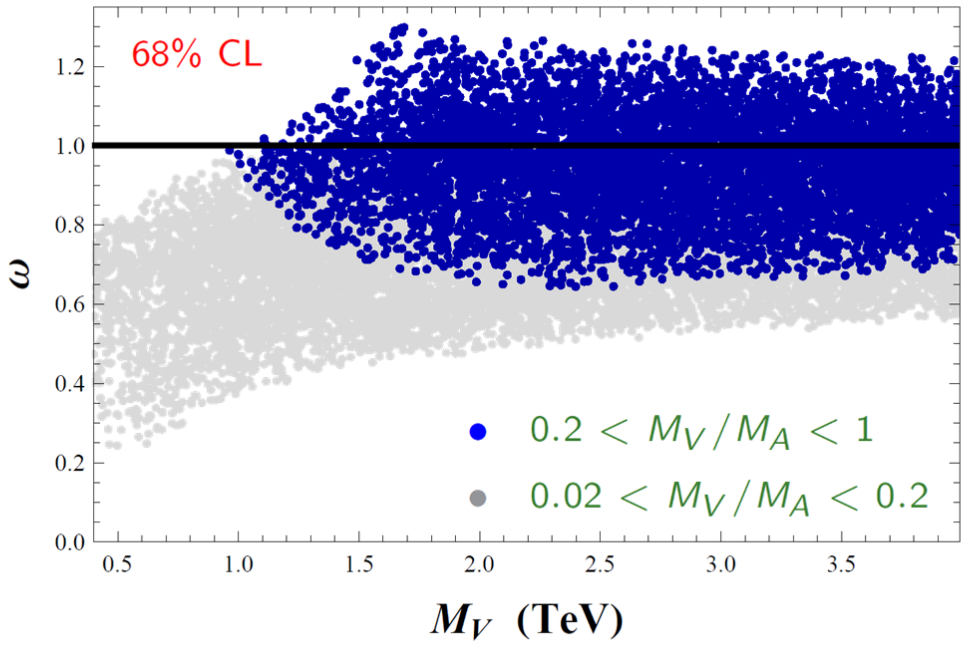
S upper-bound for $M_A < M_V$
(inverted hierarchy)

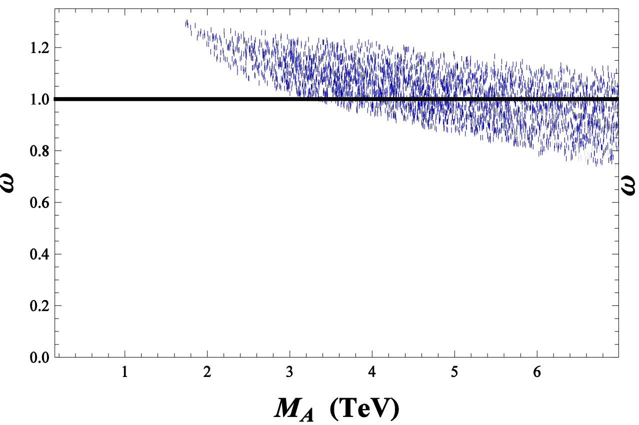
S identity for $M_A = M_V$
(degenerate)

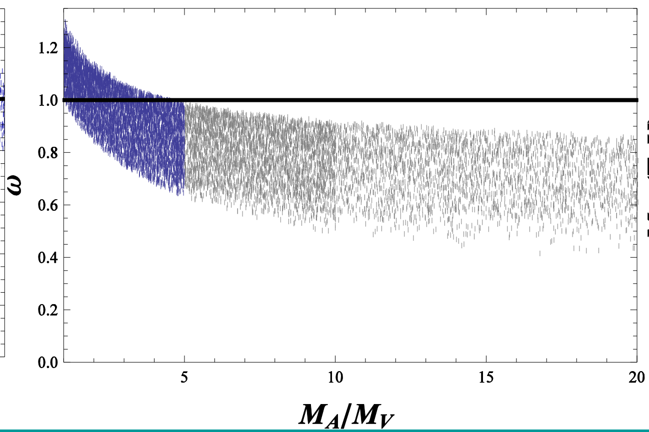
* Pich,Rosell,SC '12, '13

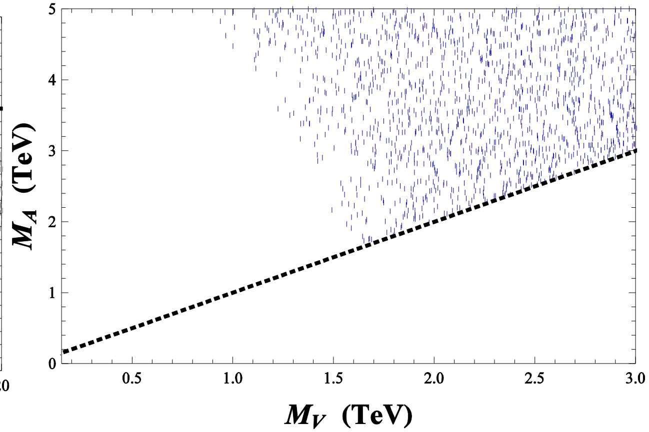
** Orgogozo,Rychkov '11

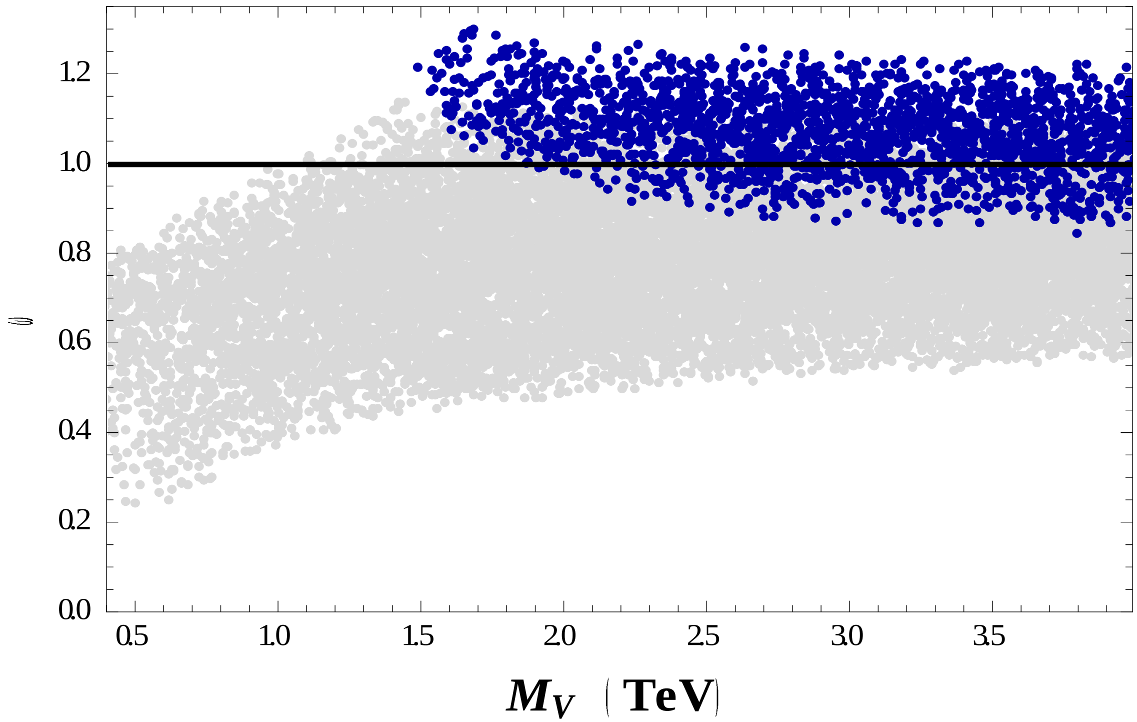
BACKUP PLOTS



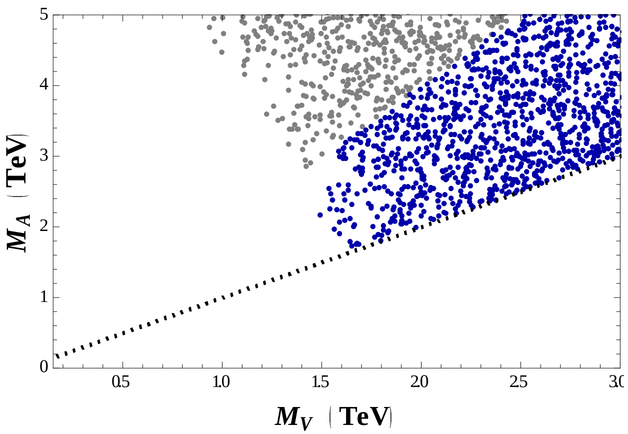


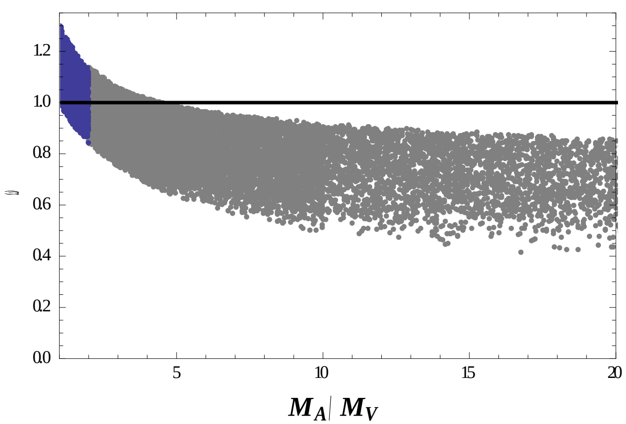


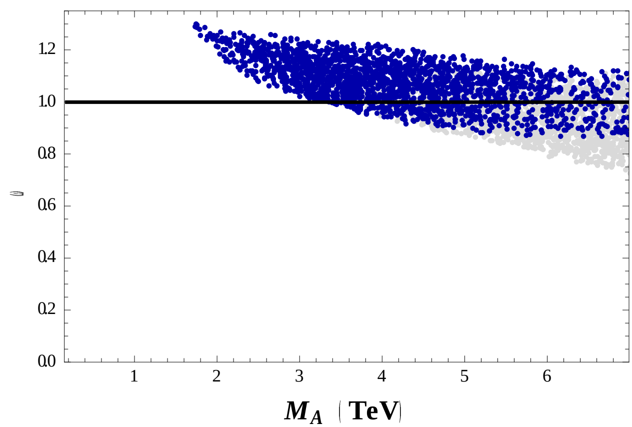




- **0.5 < M_V/M_A < 1**
- 0.02< M_V/M_A < 0.5







Further comments:

- 1< M_A/M_V< 2 yields **M_V > 1.5 TeV**, **$\kappa_W \in$[0.84 , 1.30]**

- The limit $\kappa_W \to 0$ only reached for $M_V/M_A \to 0$

  κ_W=0 incompatible with data *(independently of whether 1st+2nd WSR's or just 1st WSR)*

- Predictions for ECLh low-energy couplings

1st+2nd WSRs →
$$a_1(\mu) \;=\; \underbrace{\boxed{-\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)}}_{\text{LO}} + \frac{1}{192\pi^2}\left(\frac{8}{3}+\ln\frac{\mu^2}{M_V^2}\right) - \frac{\kappa_W^2}{192\pi^2}\left(\frac{8}{3}+\ln\frac{\mu^2}{M_A^2}\right) + \kappa_W \ln \kappa_W^2$$

$$a_0(\mu) \;=\; \frac{3}{128\pi^2}\left(\frac{11}{6}+\ln\frac{\mu^2}{M_V^2}\right) - \frac{3\,\kappa_W^2}{128\pi^2}\left(\frac{11}{6}+\ln\frac{\mu^2}{M_A^2}\right)$$

- Calculation valid for particular models with this symmetry:

  E.g., in SO(5)/SO(4) with κ_W=cosθ < 1 *

* Agashe,Contino,Pomarol '05
* Barbieri et al '12
* Marzocca,Serone,Shu '12 ...

Conclusions

✓ **Framework (I):** - $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ EFT w/ NGB's + <u>Higgs</u>

[ECL + h] - Power counting for individual contributions (<u>loops</u> + <u>tree</u>)

- Important cancellations in the full amplitude (stronger suppression $4\pi f$)

✓ **Framework (II):** - NGB's + <u>Higgs</u> + <u>Resonances</u>

[ECL + h + V + A] - High-energy constraints + 1 loop dispersive calculation

i) ECL + h:

- $\gamma\gamma \to w^a w^b$ up to NLO within ECLh: χ power counting → (NLO tree ~ NLO loops)

  - a_1, a_2, a_3, c_γ running and RGI combinations
  - Combine $\gamma\gamma$-scattering + S-parameter + $\Gamma(h\to\gamma\gamma)$ + $w^+w^-\gamma^*$ VFF + $h\gamma\gamma^*$ TFF

    BOTH $\gamma\gamma \to zz$ & $\gamma\gamma \to w^+w^-$ to separate c_γ & $(a_1-a_2+a_3)$

- Various possible signal origins: $a \neq 1$ or $c_\gamma \neq 0$ or $(a_1-a_2+a_3) \neq 0$

- Photon polarizations may allow a clean separation of BSM effects:

  UNPOLARIZED → Potential BSM signal in some scenarios

  POLARIZED → SM bg decreasing & BSM signal enhancement

- Use cuts to maximize the BSM signal and decrease SM bg

- Look for BSM in $\gamma\gamma \to Z_L Z_L$ better than $\gamma\gamma \to W_L^+ W_L^-$: similar BSM signal, less SM

ii) ECL + h + V + A:

✓ 1^{st} + 2^{nd} WSR's: Tiny splitting *(68% CL)* $0.97 < (M_V/M_A)^2 = \kappa_W < 1$, $M_V > 5.4$ TeV

✓ *Only* 1^{st} WSR: For a moderate mass splitting $M_A \sim M_V$ (lighter) , $\kappa_W \sim 1$, $M_V > 1$ TeV

✓ **FINAL CONCLUSIONS:**

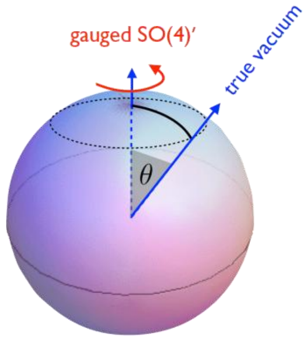
- Resonances perfectly allowed by S & T at $M_R \sim 4\pi v \approx 3$ TeV
- Resonances perfectly compatible with LHC $\kappa_W \approx 1$
- Conclusions applicable to more specific models *(e.g. SO(5)/SO(4) MCHM)*

Constraining strongly-coupled models by considering S and T

- ✓ Strongly coupled scenarios are allowed by the current experimental data.
- ✓ The Higgs-like boson must have a WW coupling close to the SM one (κ_W=1):
  - ✓ With the 2nd WSR κ_W in [0.94, 1] at 95% CL
  - ✓ For larger departures from κ_W=1 the 2nd WSR must be dropped.
  - ✓ A moderate resonance-mass splitting implies $\kappa_W \approx 1$
- ✓ Resonance masses above the TeV scale:
  - ✓ At LO $M_A > M_V > 1.5$ TeV at 95% CL.
  - ✓ With the 2nd WSR $M_V > 4$ TeV at 95% CL.
  - ✓ With only the 1st WSR $M_V < 1$ TeV implies large resonance-mass splitting.

Determining the LECs in terms of resonance couplings

- ✓ Matching the Resonance Theory and the Electroweak Effective Theory.
- ✓ Similar to the QCD case.
- ✓ Short-distance constraints are fundamental.



The Light Higgs as a Goldstone:

MCHM SO(5)/SO(4) *

* Agashe,Contino,Pomarol '05
* Barbieri et al '12
* Marzocca,Serone,Shu '12 ...

$$\frac{SO(5)}{SO(4)} \longrightarrow$$ 4 NGBs transforming as a (2,2) of SO(4)

[3 NGB (→ $W^{\pm}$,Z) + Higgs as 1 pNGB]

1. $O(v^2/f^2)$ shifts in tree-level Higgs couplings. Ex: $a = 1 - c_H \left(\frac{v}{f}\right)^2 + \ldots$

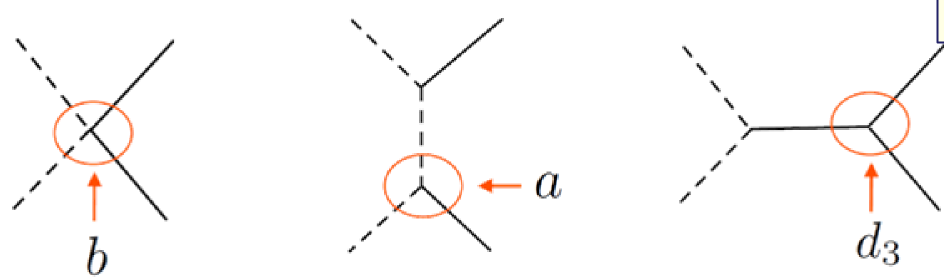
PRECISION FRONTIER

[Contino 'EPS-HEP-2013]

2. Scatterings involving the Higgs also grow with energy

ENERGY FRONTIER

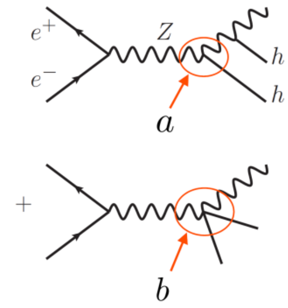
$$A(WW \to hh) \sim \frac{s}{v^2}(a^2 - b)$$



<u>Deviations from SM:</u> BSM's

❖ Different models → Different deviations from SM

($a=\kappa_W=\kappa_V$)



•O(p^2) Lagrangian in particular models:

$$a^2 = b = 0 \qquad \text{(Higgsless ECL)}$$
$$a^2 = b = 1 \qquad \text{(SM)},$$
$$a^2 = 1 - \frac{v^2}{f^2}\,, \quad b = 1 - \frac{2v^2}{f^2} \qquad \text{(SO(5)/SO(4) MCHM)},$$
$$a^2 = b = \frac{v^2}{\hat{f}^2}\,, \qquad \text{(Dilaton)}.$$

•O(p^4) Lagrangian in particular models:

$$c_W = c_B = c_\gamma = ... = 0 \qquad \text{(Higgsless ECL)},$$
$$a_i = c_W = c_B = c_\gamma = ... = 0 \qquad \text{(SM)},$$

❖ Measuring SM couplings up to (Δa) precision → Tests NP scale up to $\Lambda^2 \sim 16\pi^2 f^2 = \frac{\mathbf{16\pi^2 v^2}}{\mathbf{1-a^2}}$

Higgsless (Δa=100%) ➔ Loop scale at $\Lambda = 4\pi v$ = 3 TeV

Δa=15% ➔ Testing scales up to Λ= 6 TeV

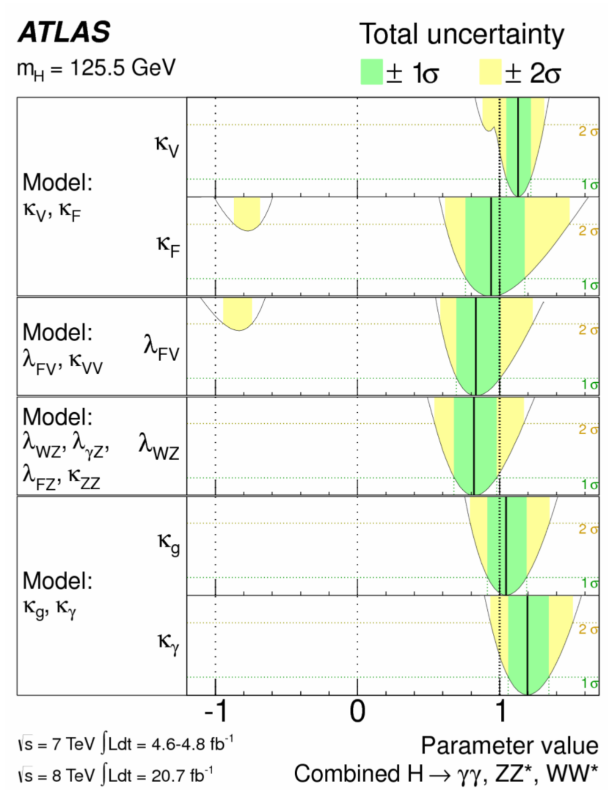
Δa=5% ➔ Testing scales up to Λ= 10 TeV …

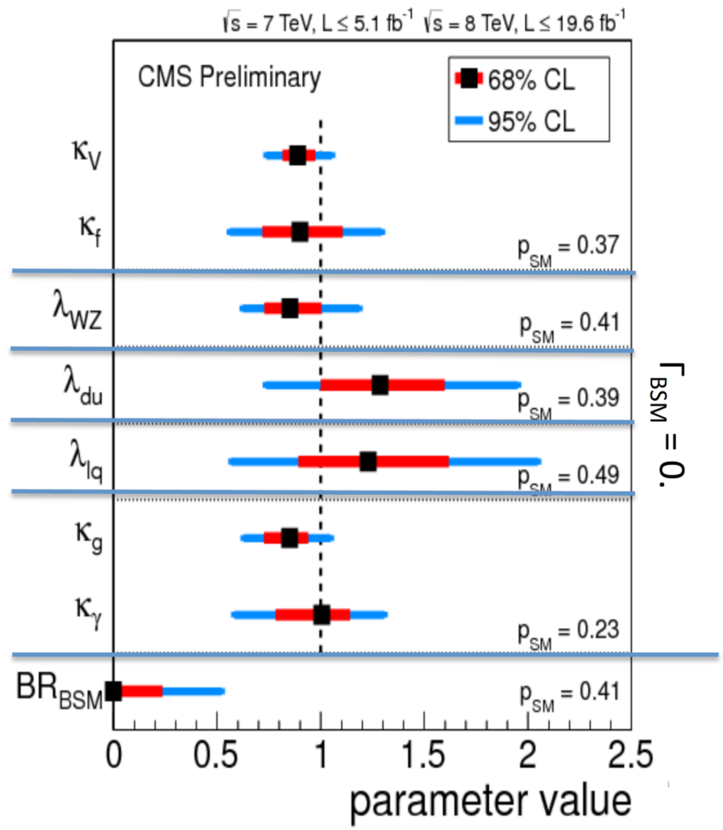
[Espinosa et al. '12]

[Delgado,Dobado,Herrero, SC 'in preparation]

Summary of all searches for coupling deviations

C. Moratti [ATLAS]

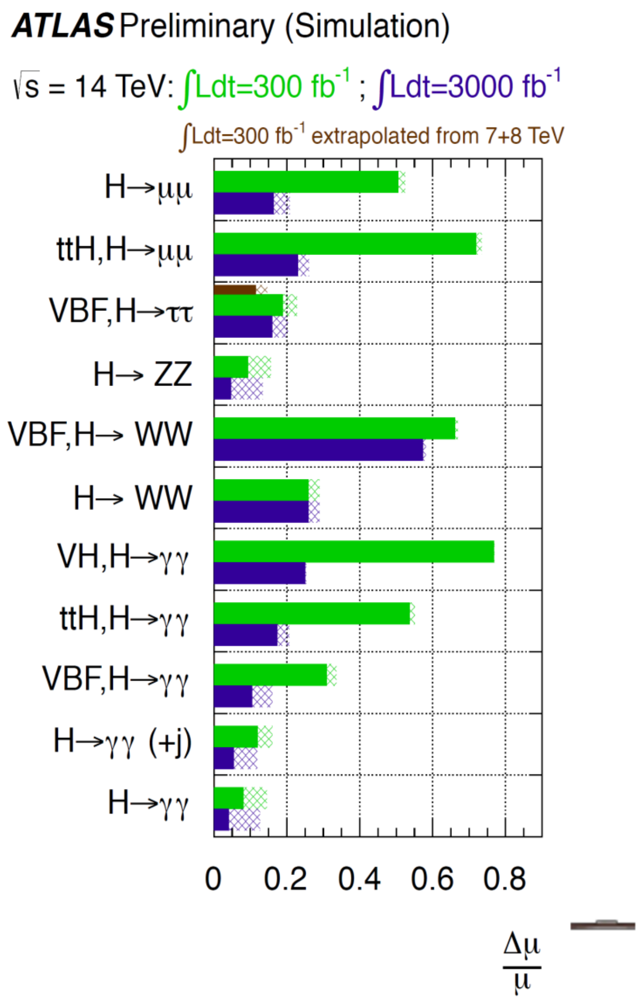


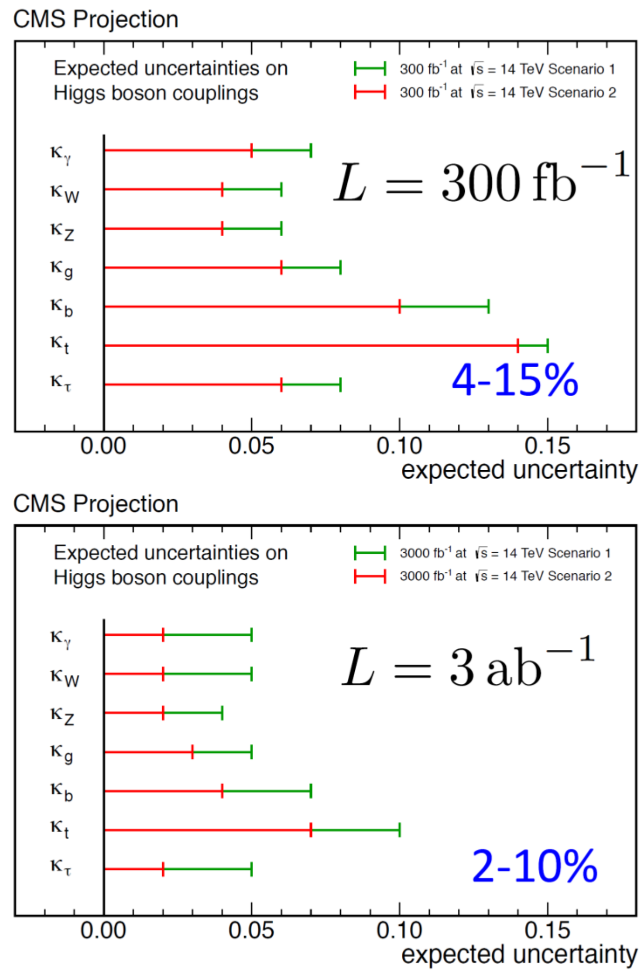


- **Compatibility with the SM**
- **Best uncertainties $\mathcal{O}$(10%)**

LHC prospects for next years

[1307.7135 [hep-ex]]





A Warm-up example:
S & T parameters at O(p^4)

•Do oblique parameters exclude strongly-coupled models?

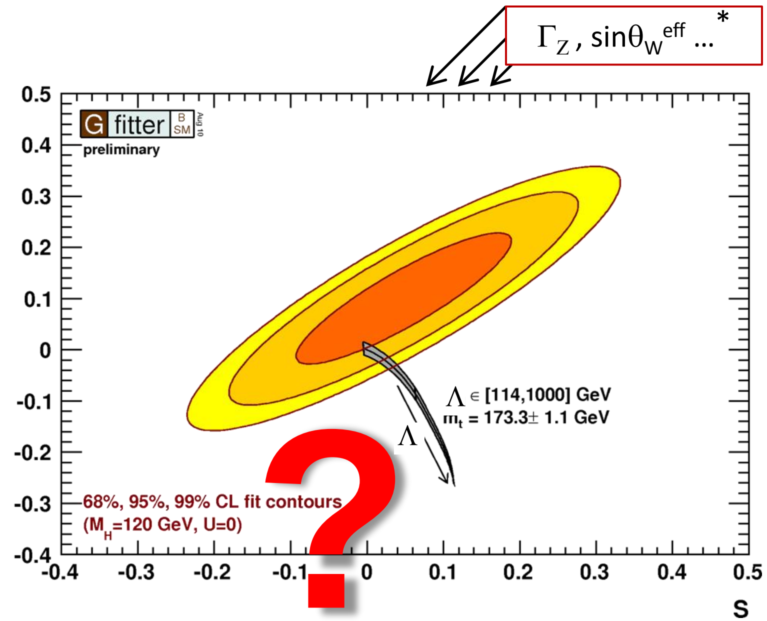
❑ ***The EWPO Oblique Parameters***

don't exclude them at all

- Dangerous naïve cut-offs at some $\Lambda^{\text{“phys”}}$

$$S \approx \frac{1}{12\pi}\ln\frac{\Lambda^2}{m^2_{H,ref}}\,,$$
$$T \approx -\frac{3}{16\pi\cos^2\theta_W}\ln\frac{\Lambda^2}{m^2_{H,ref}}$$

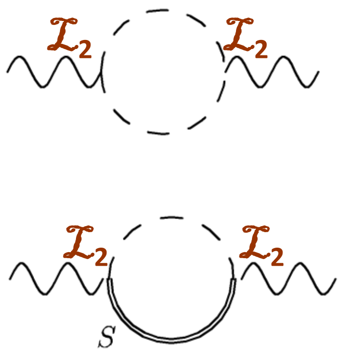
E.g. for Higgsless



-EFT: Loops + effective couplings

* Peskin,Takeuchi ‘92

➔ W^3B correlator*



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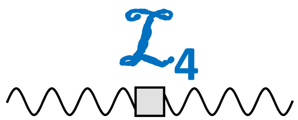
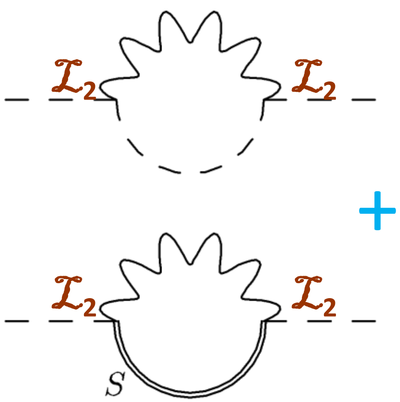


$$S \;=\; -16\pi\, \mathbf{a_1^r}(\mu) \;+\; \frac{(1-a^2)}{12\pi}\left(\frac{5}{6}+\ln\frac{\mu^2}{m_h^2}\right)$$

➔ NGB self-energy *



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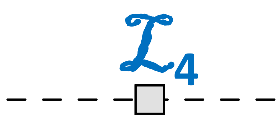


3 eff. couplings

$$T \;=\; \frac{8\pi}{c_W^2}\,\mathbf{a_0^r}(\mu) \;-\; \frac{3\,(1-a^2)}{16\pi c_W^2}\left(\frac{5}{6}+\ln\frac{\mu^2}{m_h^2}\right)$$

* Dobado et al. '99
* Pich, Rosell, SC '12, '13
* Delgado,Dobado,Herrero,SC [in prep]

→Similar in linear models:
Masso,Sanz,PRD87 (2013) 3, 033001
Chen,Dawson,Zhang,PRD89 (2014) 015016

• More observables* can over-constrain the $a_i(\mu)$

BUT not (S,T) alone!!!

• Taking just tree-level is incomplete $\longrightarrow$ $\left[\; S = -16\pi\, a_1(\mu?)\,, \qquad T = \frac{8\pi}{c_W^2} a_0(\mu?) \;\right]$

and similar if only loops $\longrightarrow$ $\left[\; S = \frac{(1-a^2)}{12\pi} \ln\frac{\mu^2}{m_h^2}\,, \qquad T = -\frac{3\,(1-a^2)}{16\pi c_W^2} \ln\frac{\mu^2}{m_h^2} \;\right]$

•Otherwise, one may resource to models**:

→Resonances *(lightest V + A)*

→ UV-completion assumptions *(high-energy constraints)*

* Delgado,Dobado,Herrero,SC [in prep.]   ** Pich, Rosell, SC ‘12, ‘13

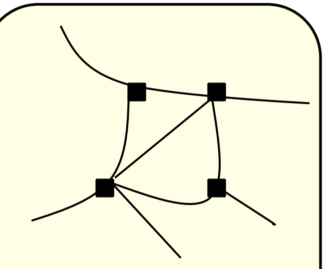
Counting, loops & renormalization

•In general, the $O(p^d)$ Lagrangian has the symbolic form (χ=W,B,π,h),

$$\mathcal{L}_d \;=\; \sum_k f_k^{(d)}\, p^d \left(\frac{\chi}{v}\right)^k$$

$$f_k^{(2)} \sim v^2$$
$$f_k^{(4)} \sim a_i$$
…

leading to a general scaling* of a diagram with
- *L loops*
- *E external legs*
- *N_d vertices of $\mathcal{L}_d$*



$$\mathcal{M} \;\sim\; \left(\frac{\mathbf{p^2}}{\mathbf{v^{E-2}}}\right)\left(\frac{\mathbf{p^2}}{\mathbf{16\pi^2 v^2}}\right)^{\mathbf{L}} \prod_{\mathbf{d}} \left(\frac{\mathbf{f_k^{(d)} p^{(d-2)}}}{\mathbf{v^2}}\right)^{\mathbf{N_d}}$$

[scaling of individual diagrams; cancellations & higher suppressions for the total amplitude]

• $O(p^d)$ loop divergence + $O(p^d)$ chiral coupling = UV-finite

E.g. W_LW_L-scat:**

LO $O(p^2)$➔ $\frac{\mathbf{p^2}}{\mathbf{v^2}}$ (tree)

NLO $O(p^4)$➔ $\mathbf{a_i}\,\frac{\mathbf{p^4}}{\mathbf{v^4}}$ (tree) + $\frac{\mathbf{p^4}}{\mathbf{16\pi^2 v^4}}\left(\frac{\mathbf{1}}{\epsilon}+\log\right)$ (1-loop)

* Weinberg '79
* Urech '95
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC '14

** Filipuzzi,Portoles,Ruiz-Femenia '12
** Espriu,Mescia,Yencho '13
** Delgado,Dobado '13

• $O(p^d)$ loop divergence + $O(p^d)$ chiral coupling = UV-finite

• In OUR case, renormalization at O(p4): $a_1, a_2, a_3, c_\gamma \to a_1^r, a_2^r, a_3^r, c_\gamma^r$

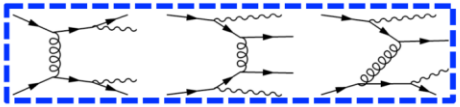
$$\boxed{\begin{aligned} C^r(\mu) &= C^{(B)} + \frac{\Gamma_C}{32\pi^2}\,\frac{1}{\hat\epsilon} \\ \frac{dC^r}{d\ln\mu} &= -\frac{\Gamma_C}{16\pi^2} \end{aligned}}$$

• Naively, our EFT range of validity given by $\mathbf{p^2} \ll \min\left\{\mathbf{16\pi^2 v^2}\,,\ \frac{\mathbf{v^2}}{\mathbf{a_i}}\right\}$

•**Previous May:** WW-scattering

[ATLAS 1405.6241: $W^{\pm}W^{\pm}jj$]

strong production



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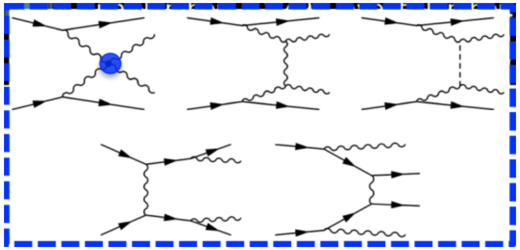
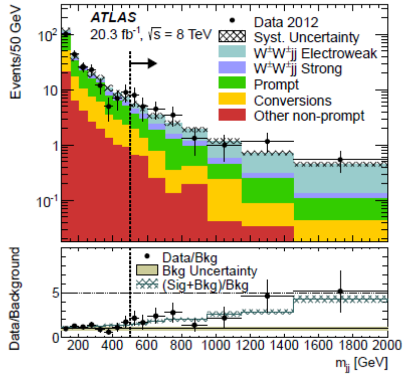
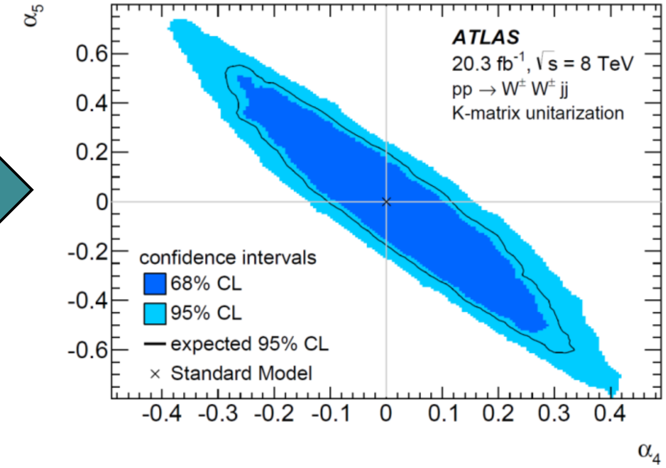
electroweak production







Theory side: ** Espriu,Mescia,Yencho '13
** Delgado,Dobado '13

•**Bounds on eff. vertices** ⟶

(stronger than LEP & Tevatron)

More experiment!!

+

More theory!!

JUST EFF. VERTICES

NOT ENOUGH

Low-energy EFT calculation

EFTs and the composite option

- **Large mass gap + small coupling deviations from SM:**

An appropriate tool → Effective theories:

Non-linear “Chiral” Lagrangians

w/ EW Goldstones +Higgs

Full NLO computations necessary

- **Strongly interacting models? Composite states?**

Technicolor (or relatives, heirs)

Composite Higgs [e.g., SO(5)/SO(4)]

Extra Dimensions (also)

…

Strong dynamics: tower of composite resonances* (QCD-like)

* Arkani-Hamed et al. ‘01
* Csaki et al. ’04
* Cacciapaglia et al. ’04
* Agashe,Contino,Pomarol ‘05
* Hirn,Sanz ’06 …

Final comment on EFT's validity:

or "How EFT break-down can mean good news"

•Criticism on EFT's * ➔

* They break down beyond some energy
* Is it justified to use them at "many"-TeV colliders?

•Reply:

* EFT's provide an expansion $\mathcal{M} \approx 1 + E/\Lambda + E^2/\Lambda^2 + \ldots$

(Λ fully unknown a priori)

* EFT breaks down when LO ~ NLO ~ NNLO …

* Large NLO effects **are good news!!** ➔ Large BSM effects

* Just cut-off regions with NLO $\geq$ LO (e.g. large p_T, large $M_{\gamma\gamma}$…)

(NO ad-hoc "vertex form-factors", please;

it spoils all you did Ok with the EFT)

* Biekötter,Knochel,Krämer,Liu,Riva, [1406.7320]

ii) Additional short-distance constraints

ii.i) $\pi\pi$ Vector Form Factor**

$$\frac{F_V G_V}{v^2} = 1$$

+ NO HIGHER DERIV. OPERATORS for W,B→$\pi\pi$

ii.ii) Sπ Axial-vector Form Factor**

(equivalent to VFF + vanishing $\rho_S(t)$ at $t\to\infty$)

$$\frac{F_A \lambda_1^{SA}}{\kappa_W v} = 1$$

+ NO HIGHER DERIV. OPERATORS for W,B→Sπ

ii.iii) $W_L W_L \to W_L W_L$ scattering*

*(NOT CONSIDERED HERE, studied in a previous work***)*

[$\kappa_W > 0$ + WSRs + VFF] ➔ $M_V/M_A > 0.8$

$$\frac{3G_V^2}{v^2} + \kappa_W^2 = 1$$

** Ecker et al.'89

*** Pich, Rosell, SC '12

* Barbieri et al.'08
* Guo, Zheng, SC '07
* Pich, Rosell, SC '11

1. Motivation

i) The Standard Model (SM) provides an extremely succesful description of the electroweak and strong interactions.

ii) A key feature is the particular mechanism adopted to break the electroweak gauge symmetry to the electroweak subgroup, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{QED}$, so that the W and Z bosons become massive. The LHC discovered a new particle around 125 GeV*. → Higgs Physics

iii) What if this new particle is not a standard Higgs boson? Or a scalar resonance? We should look for alternative mechanisms of mass generation. → Strongly Coupled Scenarios

iv) Strongly-coupled models: usually they do contain resonances. Similar to Chiral Symmetry Breaking in QCD. → Resonance Theory

v) They should fulfilled the existing phenomenological tests. → Oblique Electroweak Observables**

vi) They can be used to estimate the Low Energy Couplings (LECs) of the Electroweak Effective Theory → Estimation of the LECs

* CMS and ATLAS Collaborations.

** Peskin and Takeuchi '92.

Similarities to Chiral Symmetry Breaking in QCD

i) Neglecting the g' coupling, the Lagrangian is invariant under global $SU(2)_L \times SU(2)_R$ transformations. The Electroweak Symmetry Breaking (EWSB) turns out to be $SU(2)_L \times SU(2)_R$ ➔ $SU(2)_{L+R}$ (custodial symmetry).

ii) Absolutely similar to the Chiral Symmetry Breaking (ChSB) occuring in QCD. So the same pion Lagrangian describes the Goldstone boson dynamics associated with the EWSB, being replaced f_π by $v=1/\sqrt{(2G_F)}=246$ GeV. Similar to Chiral Perturbation Theory (ChPT)*^.

$$\Delta\mathcal{L}^{(2)}_{\mathrm{ChPT}} = \frac{f_\pi^2}{4}\langle u_\mu u^\mu\rangle \quad \rightarrow \quad \Delta\mathcal{L}^{(2)}_{\mathrm{EW}} = \frac{v^2}{4}\langle u_\mu u^\mu\rangle$$

iii) We can introduce the resonance fields needed in strongly-coupled models in a similar way as in ChPT: Resonance Chiral Theory (RChT)**.

✓ Note the implications of a naïve rescaling from QCD to EW:

$$\left\{\begin{array}{rcl} f_\pi = 0.090\,\mathrm{GeV} & \longrightarrow & v = 0.246\,\mathrm{TeV} \\ M_\rho = 0.770\,\mathrm{GeV} & \longrightarrow & M_V = 2.1\,\mathrm{TeV} \\ M_{a1} = 1.260\,\mathrm{GeV} & \longrightarrow & M_A = 3.4\,\mathrm{TeV} \end{array}\right.$$

iv) The estimations of the S and T parameters in strongly-coupled EW models are similar to the determination of L_{10} and $f_{\pi+}^2 - f_{\pi 0}^2$ in ChPT***.

v) The determination of the Electroweak LECs is similar to the ChPT case**.

* Weinberg '79
* Gasser and Leutwyler '84 '85
* Bijnens et al. '99 '00

^Dobado, Espriu and Herrero '91
^Espriu and Herrero '92
^Herrero and Ruiz-Morales '94

**Ecker et al. '89
** Cirigliano et al. '06

*** Pich, IR and Sanz-Cillero '08.

What?

Why?

How?

$$U(w^{\pm}, z) = 1 + iw^a\tau^a/v + \mathcal{O}(w^2) \quad \in \quad SU(2)_L \times SU(2)_R/SU(2)_{L+R},$$
$$D_\mu U = \partial_\mu U + i\,\hat{W}_\mu\, U - i\, U\, \hat{B}_\mu\,,$$
$$\hat{W}_{\mu\nu} = \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu + i[\hat{W}_\mu, \hat{W}_\nu] \ , \ \hat{B}_{\mu\nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu\,,$$
$$\hat{W}_\mu = g\,\vec{W}_\mu \vec{\tau}/2 \ , \ \hat{B}_\mu = g'\, B_\mu \tau^3/2\,,$$
$$V_\mu = (D_\mu U)\, U^\dagger \ , \ \mathcal{T} = U\,\tau^3\, U^\dagger\,,$$

$$\Big(\partial_\mu - i\hat{W}_\mu P_L - i\hat{B}_\mu P_R - ig' y_1 X_\mu\Big)\,\psi$$

$$\begin{aligned}
d_\mu \xi &= d_\mu^R \xi_R + d_\mu^L \xi_L\,, \\
d_\mu^L \xi_L &= \left(\partial_\mu + \Gamma_\mu^L - i\,g'\,y_1\,X_\mu\right)\xi_L = u_L^\dagger\left[\Big(\partial_\mu - i\hat{W}_\mu - i\,g'\,y_1\,X_\mu\Big)\,\psi_L\right] \\
d_\mu^R \xi_R &= \left(\partial_\mu + \Gamma_\mu^R - i\,g'\,y_1\,X_\mu\right)\xi_R = u_R^\dagger\left[\Big(\partial_\mu - i\hat{B}_\mu - i\,g'\,y_1\,X_\mu\Big)\,\psi_R\right]
\end{aligned}$$

* Buchalla,Catà,Krause ‘13
* Hirn,Stern ‘05

Consider the relevant ECLh Lagrangian

• EFT Lagrangian up to NLO *[i.e. up to O(p^4)]*:

$$\mathcal{L}_{\rm ECLh} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP}$$

Other notations:
a=κ_V=κ_W=c_W=ω=etc.

➔ LO Lagrangian*,**:

$$\mathcal{L}_2 = -\frac{1}{2g^2}{\rm Tr}(\hat W_{\mu\nu}\hat W^{\mu\nu}) - \frac{1}{2g'^2}{\rm Tr}(\hat B_{\mu\nu}\hat B^{\mu\nu}) + \frac{v^2}{4}\left(1+2a\frac{h}{v}+b\left(\frac{h^2}{v^2}\right)\right){\rm Tr}(D^\mu U^\dagger D_\mu U) + \frac{1}{2}\partial^\mu h\,\partial_\mu h + \ldots$$

➔ NLO Lagrangian*,**:

$$\mathcal{L}_4 = a_1{\rm Tr}(U\hat B_{\mu\nu}U^\dagger \hat W^{\mu\nu}) + i\,a_2{\rm Tr}(U\hat B_{\mu\nu}U^\dagger[V^\mu,V^\nu]) - ia_3{\rm Tr}(\hat W_{\mu\nu}[V^\mu,V^\nu]) \boxed{- c_W\frac{h}{v}{\rm Tr}(\hat W_{\mu\nu}\hat W^{\mu\nu}) - c_B\frac{h}{v}{\rm Tr}(\hat B_{\mu\nu}\hat B^{\mu\nu})} + \ldots$$

$$-\frac{c_\gamma}{2}\frac{h}{v}e^2 A_{\mu\nu}A^{\mu\nu} + \ldots$$

* Apelquist,Bernard '80
* Longhitano '80, '81

** Buchalla,Catà '12
** Alonso,Gavela,Merlo,Rigolin,Yepes '12
** Brivio,Corbett,Eboli,Gavela,Gonzalez–Fraile,Gonzalez–Garcia,Merlo,Rigolin '13
(list of operators in $\mathscr{L}_4$)

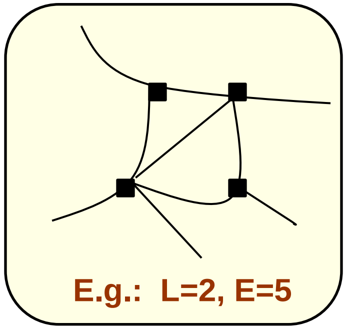
Counting, loops & renormalization

•In general, the $O(p^d)$ Lagrangian has the symbolic form (χ=W,B,π,h),

$$\mathcal{L}_d \;=\; \sum_k f_k^{(d)}\, p^d \left(\frac{\chi}{v}\right)^k$$

$$f_k^{(2)} \sim v^2$$
$$f_k^{(4)} \sim a_i$$
…

leading to a general scaling* of a diagram with
- *L loops*
- *E external legs*
- *N_d vertices of $\mathcal{L}_d$*



$$\mathcal{M} \;\sim\; \left(\frac{p^2}{v^{E-2}}\right)\left(\frac{p^2}{16\pi^2 v^2}\right)^L \prod_d \left(\frac{f_k^{(d)}\, p^{(d-2)}}{v^2}\right)^{N_d}$$

[scaling of individual diagrams; cancellations & higher suppressions for the total amplitude]

• $O(p^d)$ loop divergence + $O(p^d)$ chiral coupling = UV-finite

E.g. $W_L W_L$-scat:**

LO $O(p^2)$ ➔ $\frac{p^2}{v^2}$ (tree)

NLO $O(p^4)$ ➔ $a_i\,\frac{p^4}{v^4}$ (tree) + $\frac{p^4}{16\pi^2 v^4}\left(\frac{1}{\epsilon}+\log\right)$ (1-loop)

* Weinberg '79
* Urech '95
* Georgi,Manohar NPB234 (1984) 189
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Espriu,Mescia,Yencho '13
** Delgado,Dobado '13

BOSONIC SECTOR

$$
\begin{aligned}
\hat{W}_{\mu\nu} &= \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu - i[\hat{W}_\mu, \hat{W}_\nu]\,, \qquad \hat{B}_{\mu\nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu - i[\hat{B}_\mu, \hat{B}_\nu]\,, \\
D_\mu U &= \partial_\mu U - i\hat{W}_\mu U + iU\hat{B}_\mu\,, \\
u^\mu &= iu_R^\dagger(\partial_\mu - i\hat{B}_\mu)u_R - iu_L^\dagger(\partial_\mu - i\hat{W}_\mu)u_L \quad = \quad iu(D^\mu U)^\dagger u\,, \\
f_\pm^{\mu\nu} &= u_L^\dagger \hat{W}^{\mu\nu} u_L \pm u_R^\dagger \hat{B}^{\mu\nu} u_R\,.
\end{aligned}
$$

$$
\hat{W}_\mu = -g\frac{\vec{\sigma}}{2}\vec{W}_\mu\,, \qquad \hat{B}_\mu = -g'\frac{\sigma^3}{2}B_\mu
$$

$$
\begin{aligned}
\nabla_\mu \mathcal{X} &= \partial_\mu \mathcal{X} + [\Gamma_\mu, \mathcal{X}]\,, \qquad \Gamma_\mu = \frac{1}{2}\Gamma_\mu^R + \frac{1}{2}\Gamma_\mu^L\,, \\
\Gamma_\mu^L &= u_L^\dagger(\partial_\mu - i\hat{W}_\mu)u_L\,, \qquad \Gamma_\mu^R = u_R^\dagger(\partial_\mu - i\hat{B}_\mu)u_R
\end{aligned}
$$

Full Higgsless result
(Longhitano's Ops.)

- But it is more instructive to focus on a case (full R Lagrangian in *)

$$\mathcal{L}_{\mathbf{V}} = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{iG_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu]\rangle + \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle$$

- Integrate out V and A:

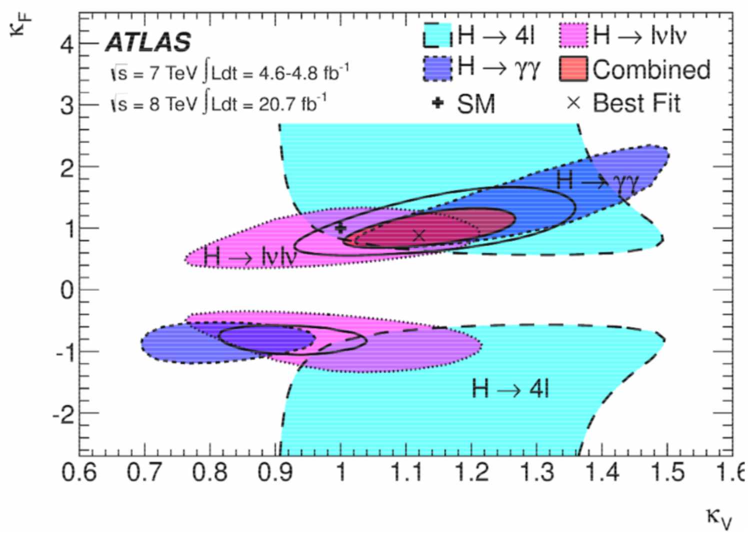
$$\begin{aligned}\mathcal{L}_4 \supset\; & \frac{1}{4}a_1\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle \\ & + \frac{i}{2}(a_2 - a_3)\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle + \frac{i}{2}(a_2 + a_3)\langle f_-^{\mu\nu}[u_\mu, u_\nu]\rangle \\ & + a_4\langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle + a_5\langle u_\mu u^\mu\rangle^2 \\ & + \frac{1}{2}H_1\langle f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu}\rangle + \widetilde{H}_1\langle f_+^{\mu\nu} f_{-\,\mu\nu}\rangle\,.\end{aligned}$$

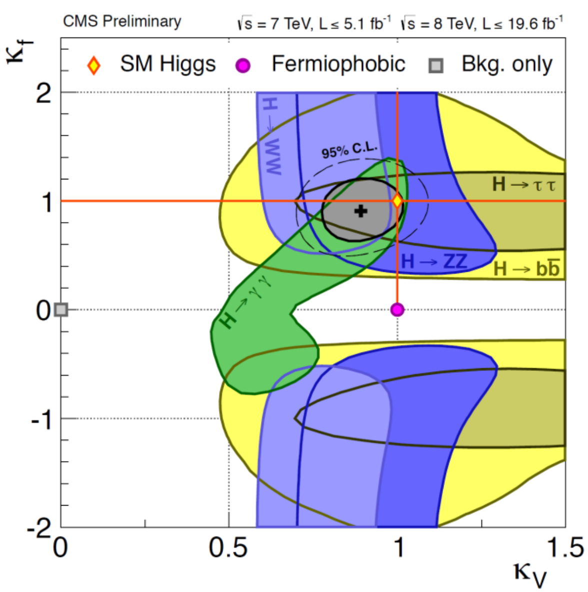
$$a_1 = -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2}\,, \qquad (a_2 - a_3) = -\frac{F_V G_V}{2M_V^2}\,, \qquad a_4 = -a_5 = \frac{G_V^2}{4M_V^2}\,, \qquad H_1 = -\frac{F_V^2}{8M_V^2} - \frac{F_A^2}{8M_A^2}\,,$$

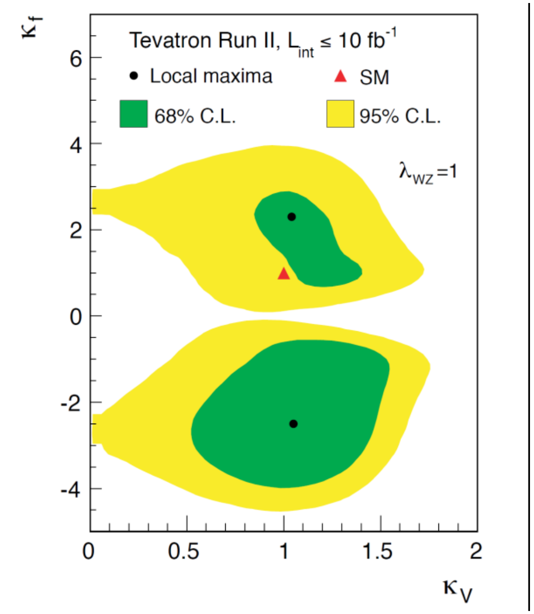
* Pich,Rosell,Santos,SC,1501.07249 [hep-ph] (proceedings); forthcoming

Higgs couplings

- κ_V: $h \rightarrow WW, ZZ$ ($\kappa_V^{SM}=1$)
- κ_F: $h \rightarrow f\bar{f}$ ($\kappa_F^{SM}=1$)







- ATLAS: κ_V [1.05,1.22] at 68% CL - κ_F [0.76,1.18] at 68% CL
- CMS: κ_V [0.74,1.06] at 95% CL - κ_F [0.61,1.33] at 95% CL

[F. Cerutti]

[1307.1427 [hep-ex]]

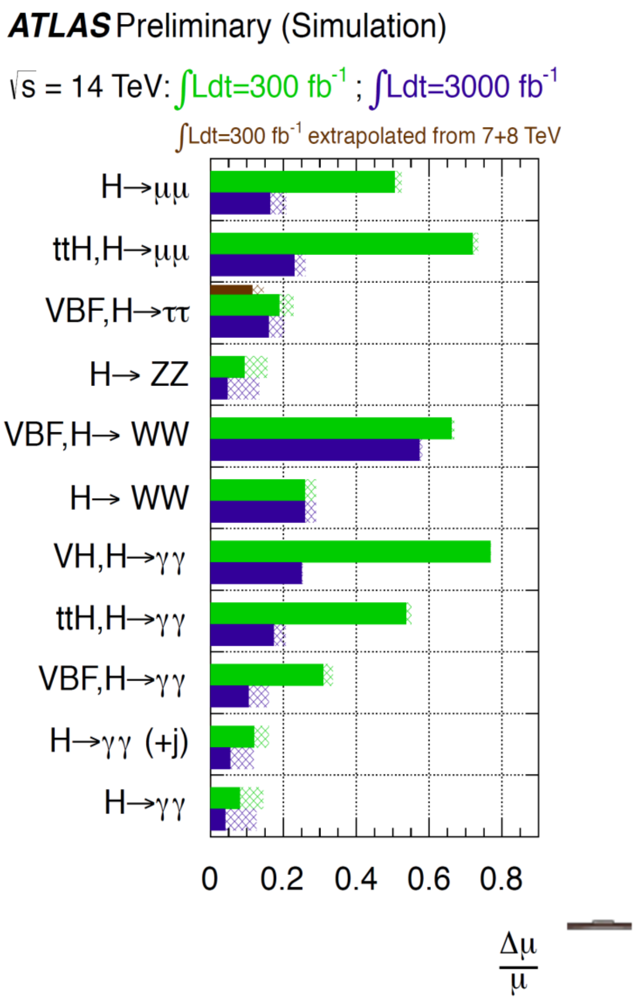
[1303.4571 [hep-ex]]

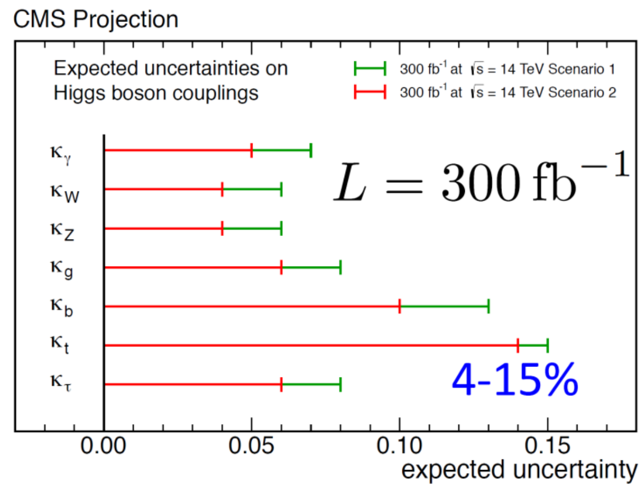
- **Compatibility with the SM**
- **Best uncertainties $\mathcal{O}$(10%)**

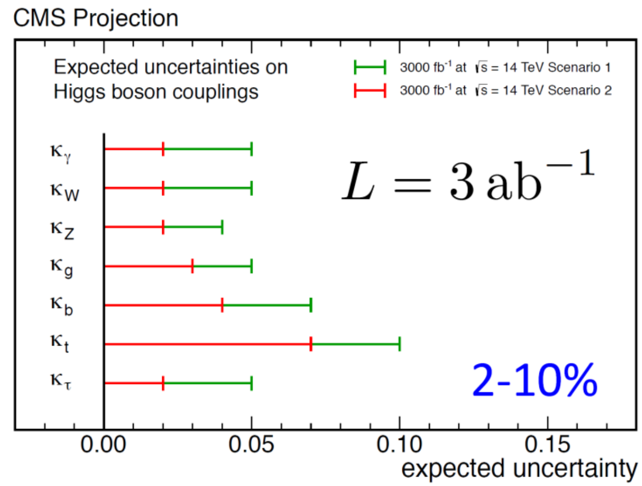
Many other similar analyses (2012-2013): Espinosa et al.; Carni et al.; Azatov et al; Ellis,You…

LHC prospects for next years

[1307.7135 [hep-ex]]





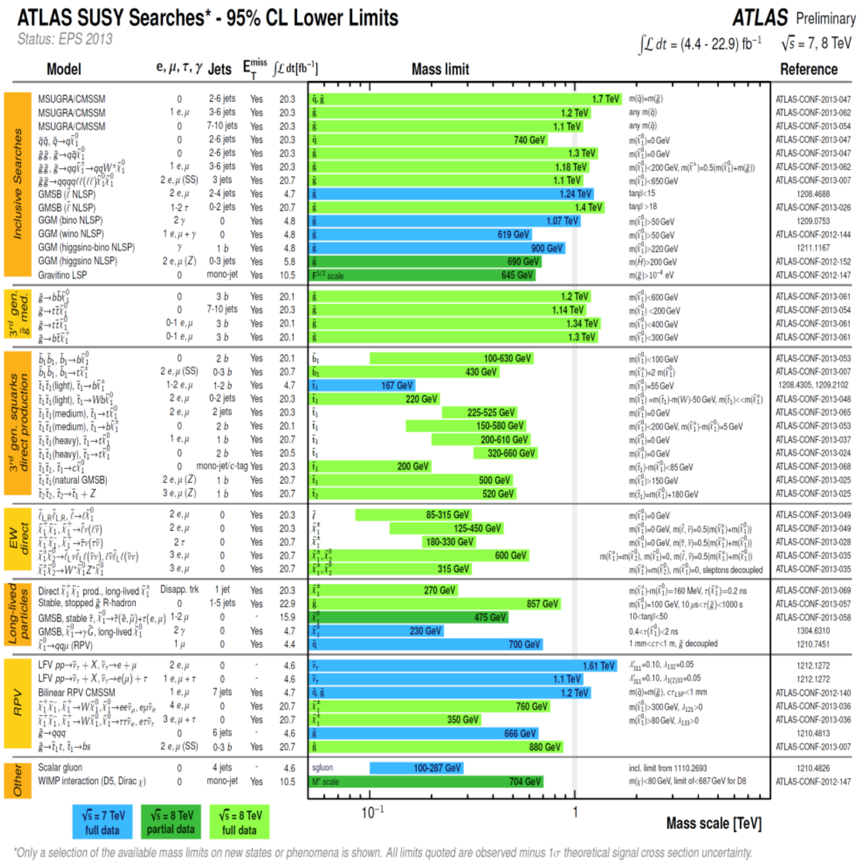


Spectrum below 1 TeV

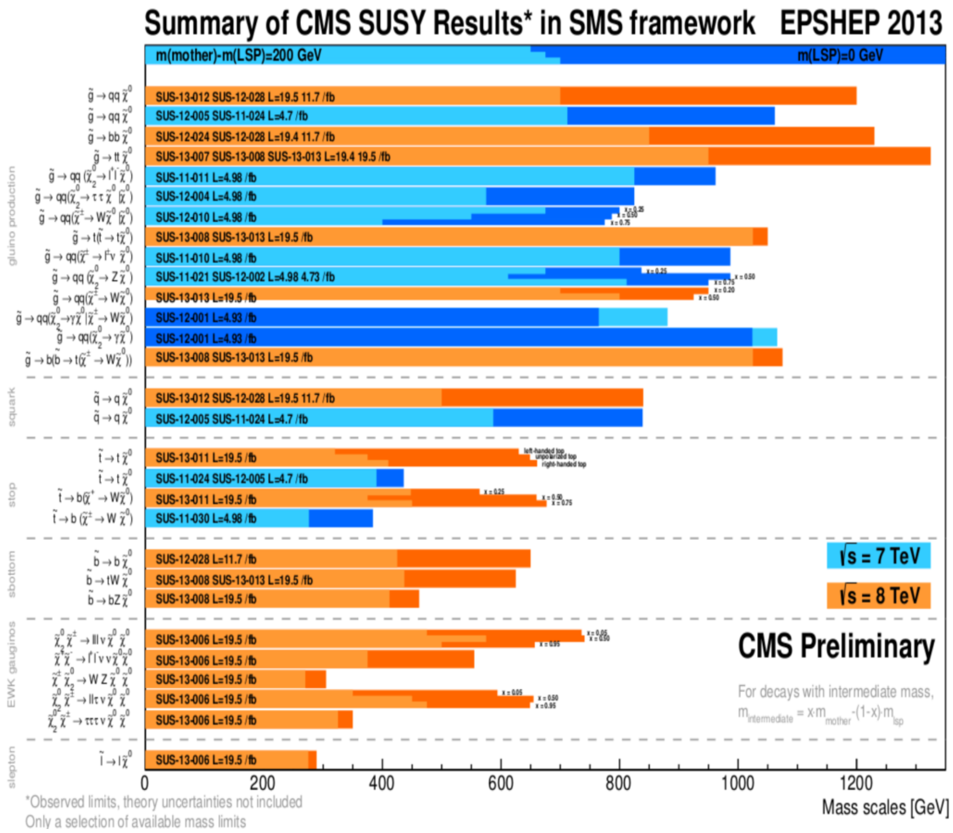
SM particles… and nothing else below the TeV

(e.g. SUSY exclusion limits)

ATLAS Summary



CMS Summary



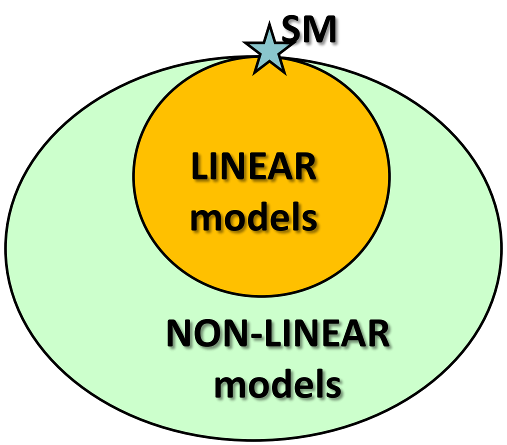
Mass gap + small deviations:
the non-linear EFT approach

→It describes any theory with a given symmetry pattern and light particle content

→Inspiration: *h=pNGB*

→1 model= 1 set of Wilson coef.'s:

$a^2 = b = 0$	Higgsless ECL
$a^2 = b = 1$	SM,
$a^2 = 1 - \frac{v^2}{f^2}\,, \quad b = 1 - \frac{2\,v^2}{f^2}$	SO(5)/SO(4) MCHM
$a^2 = b = \frac{v^2}{\hat{f}^2}\,,$	Dilaton



→Goldstones non-linearly realized

(most general framework)

[M.Trott's picture ©]

Constraining strongly-coupled models by considering S and T

- ✓ Strongly coupled scenarios are allowed by the current experimental data.
- ✓ The Higgs-like boson must have a WW coupling close to the SM one (κ_W=1):
  - ✓ With the 2nd WSR κ_W in [0.94, 1] at 95% CL
  - ✓ For larger departures from κ_W=1 the 2nd WSR must be dropped.
  - ✓ A moderate resonance-mass splitting implies $\kappa_W \approx 1$
- ✓ Resonance masses above the TeV scale:
  - ✓ At LO $M_A > M_V >$ 1.5 TeV at 95% CL.
  - ✓ With the 2nd WSR $M_V >$ 4 TeV at 95% CL.
  - ✓ With only the 1st WSR $M_V <$ 1 TeV implies large resonance-mass splitting.

Determining the LECs in terms of resonance couplings

- ✓ Matching the Resonance Theory and the Electroweak Effective Theory.
- ✓ Similar to the QCD case.
- ✓ Short-distance constraints are fundamental.