

*Composite resonance effects
on the EW chiral lagrangian
at NLO*

PRELIMINARY

J.J. Sanz-Cillero (UAM/CSIC-IFT)

In collaboration with:
A.Pich, J.Santos, I.Rosell
[1501.07249]; forthcoming

PRL 110 (2013) 181801 [arXiv:1212.6769]
JHEP 01 (2014) 157 [arXiv:1310.3121]
[arXiv:1501.07249 [hep-ph]]



Claude Monet 82

OUTLINE

1) Compositeness, non-linearity, chiral low-E counting

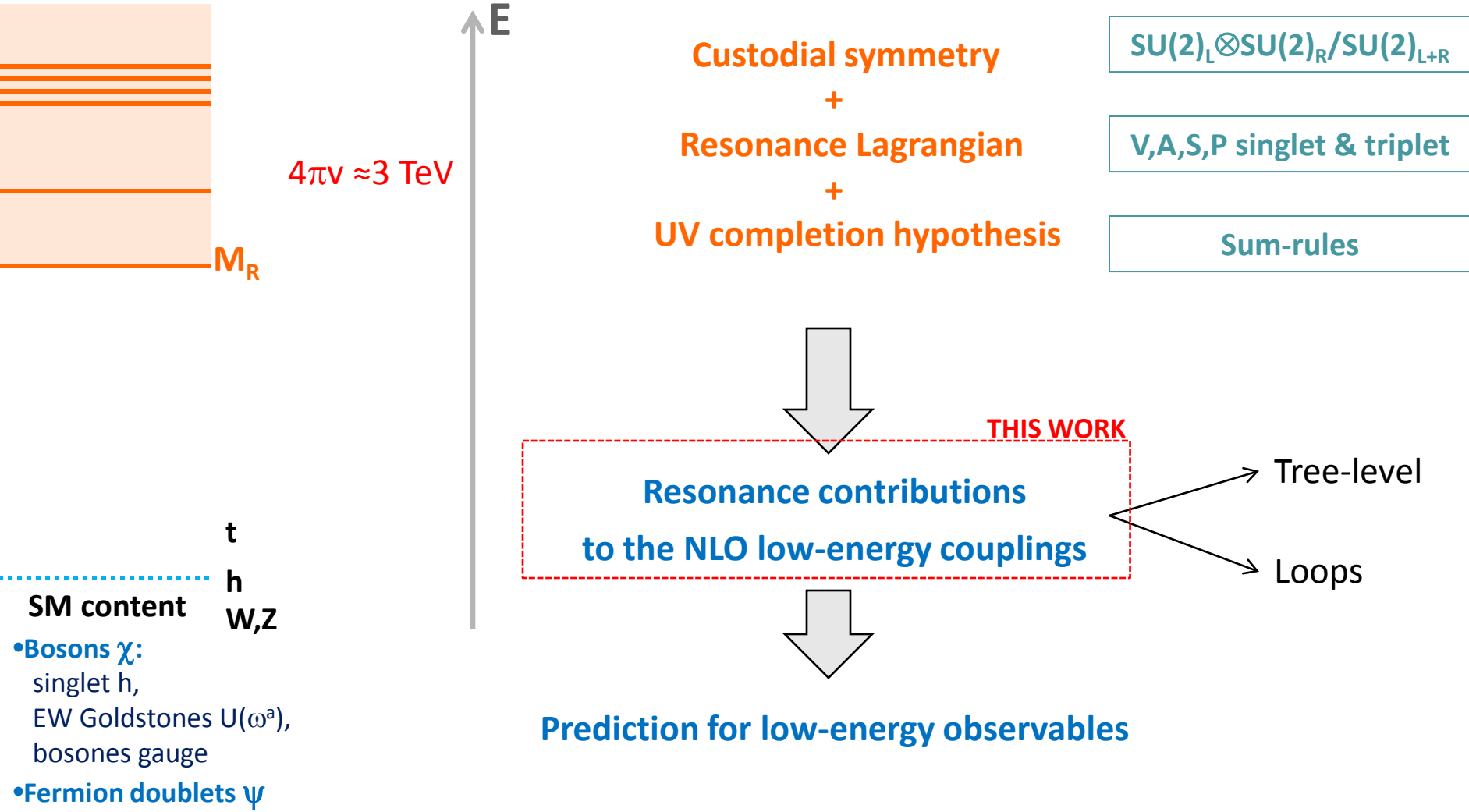
2) Custodial sym. & Resonances:

Contribution to the EFT @ NLO, i.e., \mathcal{L}_{p4}

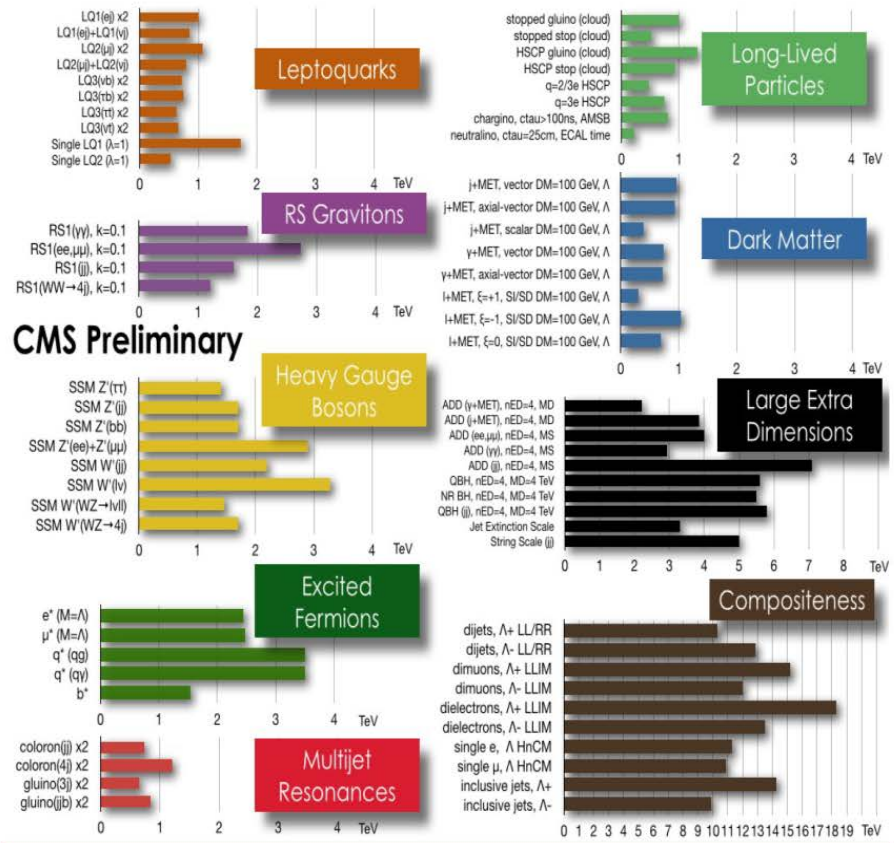
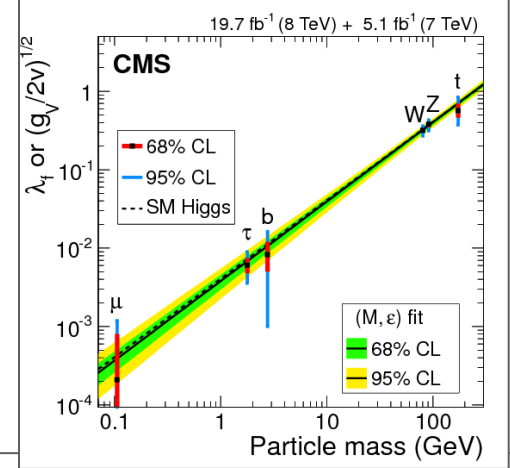
3) Simple pheno:

Easy to avoid bounds with $M_R \sim 4\pi v \approx 3 \text{ TeV}$

Composite theories: the Resonance + EFT program



Close to the SM



CMS Exotica Physics Group Summary – Moriond, 2015

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

Model	ℓ, γ	Jets	E_{miss}^+	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit	Reference
Extra dimensions	ADD $G_{XX} + g/\lambda$	$\geq 1j$	Yes	203	$M_{*} \geq 5.25 \text{ TeV}$	1502.01518
	ADD non-resonant ll	$2e, \mu$	—	203	$M_{*} \geq 4.7 \text{ TeV}$	1407.2410
	ADD OBH $- \ell q$	$1e, \mu$	$1j$	203	$M_{*} \geq 5.2 \text{ TeV}$	1311.2006
	ADD OSH	—	$2j$	203	$M_{*} \geq 5.82 \text{ TeV}$	1407.1376
	ADD BH high N_{ch}	2μ (SS)	—	203	$M_{*} \geq 4.7 \text{ TeV}$	1306.4025
	ADD BH high $2j$	$\geq 1e, \mu$	$\geq 2j$	203	$M_{*} \geq 3.8 \text{ TeV}$	1405.4254
	ADD BH high multijet	—	$\geq 2j$	203	$M_{*} \geq 5.8 \text{ TeV}$	Preliminary
	RSI $G_{XX} \rightarrow \ell\ell$	$2e, \mu$	—	203	$M_{*} \geq 2.88 \text{ TeV}$	1405.4120
	RSI $G_{XX} \rightarrow \gamma\gamma$	2γ	—	203	$M_{*} \geq 2.88 \text{ TeV}$	Preliminary
	Bulk RS $G_{XX} \rightarrow ZZ \rightarrow qq\ell\ell$	$2e, \mu$	$2j/1j$	203	$M_{*} \geq 740 \text{ GeV}$	1409.6190
	Bulk RS $G_{XX} \rightarrow WW \rightarrow qq\ell\nu$	$1e, \mu$	$2j/1j$	Yes 203	$M_{*} \geq 700 \text{ GeV}$	1500.0657
	Bulk RS $G_{XX} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	—	4b	195	$M_{*} \geq 590 \text{ TeV}$	ATLAS-COM-2015-005
	Bulk RS $G_{XX} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1LQ$	Yes 203	$M_{*} \geq 2.2 \text{ TeV}$	ATLAS-COM-2015-009
	2UED / RPP	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes 203	$M_{*} \geq 360 \text{ GeV}$	Preliminary
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	—	203	$M_{*} \geq 2.9 \text{ TeV}$	1405.4120
	SSM $Z' \rightarrow \tau\tau$	2τ	—	195	$M_{*} \geq 2.92 \text{ TeV}$	1500.0717
	SSM $W' \rightarrow \ell\nu$	$1e, \mu$	Yes	203	$M_{*} \geq 3.24 \text{ TeV}$	1407.2594
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell\ell$	$3e, \mu$	Yes	203	$M_{*} \geq 1.52 \text{ TeV}$	1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	$2e, \mu$	$2j/1j$	203	$M_{*} \geq 1.59 \text{ TeV}$	1409.6190
	HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$	$1e, \mu$	$2b$	Yes 203	$M_{*} \geq 1.47 \text{ TeV}$	Preliminary
	LRSM $W_2 \rightarrow tb$	$1e, \mu$	$2b, 0j$	Yes 203	$M_{*} \geq 1.92 \text{ TeV}$	1416.4100
	LRSM $W_2 \rightarrow tb$	$0e, \mu$	$\geq 1b, 1j$	203	$M_{*} \geq 1.76 \text{ TeV}$	1403.0886
CI	CI $qqqq$	—	$2j$	173	$M_{*} \geq 120 \text{ TeV}$	Preliminary
	CI $qq\ell\ell$	$2e, \mu$	—	203	$M_{*} \geq 21.6 \text{ TeV}$	1407.2410
	CI $qqttt$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes 203	$M_{*} \geq 4.35 \text{ TeV}$	Preliminary
DM	EFT D5 operator (Dirac)	$0e, \mu$	$\geq 1j$	Yes 203	$M_{*} \geq 974 \text{ GeV}$	1500.01518
	EFT D9 operator (Dirac)	$0e, \mu$	$1j, \geq 1j$	Yes 203	$M_{*} \geq 2.4 \text{ TeV}$	1309.4017
LO	Scalar LQ 1 st gen	$2e, \mu$	$\geq 2j$	10	$M_{*} \geq 660 \text{ GeV}$	1112.4898
	Scalar LQ 2 nd gen	$2\mu, \tau$	$\geq 2j$	10	$M_{*} \geq 685 \text{ GeV}$	1205.3172
	Scalar LQ 3 rd gen	$1e, \mu, 1\tau$	$1b, 1j$	47	$M_{*} \geq 594 \text{ GeV}$	1205.0286
Heavy quarks	VLO $TT \rightarrow Ht + X, Wb + X$	$1e, \mu, 1\gamma$	$\geq 1b, \geq 3j$	Yes 203	$M_{*} \geq 785 \text{ GeV}$	isospin singlet
	VLO $TT \rightarrow Zt + X$	$2b, 3e, \mu$	$\geq 2b, 1b$	203	$M_{*} \geq 785 \text{ GeV}$	T in (1,0) doublet
	VLO $BB \rightarrow Zb + X$	$2b, 3e, \mu$	$\geq 2b, 1b$	203	$M_{*} \geq 755 \text{ GeV}$	B in (3,Y) doublet
	VLO $BB \rightarrow Wt + X$	$1e, \mu, 1\tau$	$\geq 1b, \geq 5j$	Yes 203	$M_{*} \geq 640 \text{ GeV}$	isospin singlet
	$T_{3/2} \rightarrow Wt$	$1e, \mu, 1\tau$	$\geq 1b, \geq 5j$	Yes 203	$M_{*} \geq 840 \text{ GeV}$	isospin singlet
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$	203	$M_{*} \geq 3.5 \text{ TeV}$	only d^* and d^* , $A = m(q^*)$
	Excited quark $q^* \rightarrow qg$	—	$2j$	203	$M_{*} \geq 4.99 \text{ TeV}$	only d^* and d^* , $A = m(q^*)$
	Excited quark $b^* \rightarrow Wt$	1τ or $2e, \mu, 1b, 2j$ or $1j$	Yes	47	$M_{*} \geq 870 \text{ GeV}$	left-handed coupling
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	—	130	$M_{*} \geq 2.2 \text{ TeV}$	$A = 2.2 \text{ TeV}$
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	$3e, \mu, \tau$	—	203	$M_{*} \geq 5.8 \text{ TeV}$	$A = 1.6 \text{ TeV}$
Other	LSTC $\beta\beta \rightarrow W\gamma$	$1e, \mu, 1\gamma$	—	Yes 203	$M_{*} \geq 960 \text{ GeV}$	1407.8150
	LRSM Majorana ν	$2e, \mu$	$2j$	21	$M_{*} \geq 1.5 \text{ TeV}$	$m(\tilde{\nu}_1) = 2 \text{ TeV}$, no mixing
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	—	203	$M_{*} \geq 551 \text{ GeV}$	DM production, BR($H^{\pm\pm} \rightarrow \ell\ell$) = 1
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3e, \mu, \tau$	—	203	$M_{*} \geq 494 \text{ GeV}$	DM production, BR($H^{\pm\pm} \rightarrow \ell\tau$) = 1
	Monopole (non-res prod)	$1e, g$	$1b$	Yes 203	$M_{*} \geq 697 \text{ GeV}$	$\alpha_{EM} = 0.2$
	Multi-charged particles	—	—	203	$M_{*} \geq 785 \text{ GeV}$	DM production, $ q = 5e$
	Magnetic monopoles	—	—	20	$M_{*} \geq 862 \text{ GeV}$	DM production, $ q = 1e_0$

*Only a selection of the available mass limits on new states or phenomena is shown.

J. Alcaraz @ Blois 2015

What is the meaning of “close to the SM”?

• If Higgs (pseudo) Goldstone boson → **Non-linearity for $h + \omega^a$**

• **Chiral expansion** in non-linear EFT's: *

$$\mathcal{M}(2 \rightarrow 2) \approx \frac{p^2}{v^2} \left[\underbrace{1}_{\text{LO (tree)}} + \underbrace{\left(\frac{c_k^r p^2}{v^2} - \frac{\Gamma_k p^2}{16\pi^2 v^2} \ln \frac{p}{\mu} + \dots \right)}_{\text{NLO (tree) + NLO (1-loop)}} + \mathcal{O}(p^4) \right]$$

Finite pieces from loops
(amplitude dependent) ⁽⁺⁾

LO (tree)

NLO (tree)

NLO (1-loop)

Typical tree suppression

$\sim 1/M_R^2$

(other states)

Typical loop suppression

$\sim 1/(16\pi^2 v^2)$

(non-linearity)

THIS WORK

** Catà, EPJC74 (2014) 8, 2991

** Pich,Rosell,Santos,SC, [1501.07249]; 'forthcoming

** Pich,Rosell and SC, JHEP 1208 (2012) 106;

PRL 110 (2013) 181801

(x) Contino,Salvareza, [1504.02750]

(x) Contino,Marzocca,Pappadopulo,Rattazzi,
JHEP 1110 (2011) 081

- Espriu,Yencho, PRD 87 (2013) 055017

- Espriu,Mescia, Yencho, PRD88 (2013) 055002

- Delgado,Dobado,Llanes-Estrada, JHEP1402 (2014) 121

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

- Gavela,Kanshin,Machado,Saa, JHEP 1503 (2015) 043

- Guo,Ruiz-Femenia,SC, [1506.04204]

- Azatov, Contino,Di Iura,Galloway, PRD88 (2013) 7, 075019

- Azatov,Grojean,Paul,Salvioni, Zh.Eksp.Teor.Fiz. 147 (2015) 410,

J.Exp.Theor.Phys. 120 (2015) 354

* 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

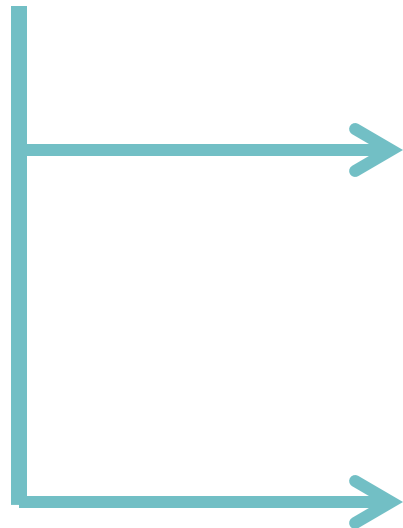
* Pich,Rosell,Santos,SC, forthcoming

- Values of the NLO low-energy couplings?
- Resonances at $M_R \sim 4\pi v \approx 3 \text{ TeV}$ compatible with

→ LHC narrow resonance searches $M_R \gtrsim 1-2 \text{ TeV}$

→ Strong limits on low-energy EFT operators $\Lambda_{\text{eff}} \gtrsim 10 \text{ TeV}$ (???)

Meaning?



Suppression
of the EFT couplings



Suppression
of the EFT operators



Chiral expansion
(non-linear EFT)



Relaxed bounds $M_R \gtrsim 1 \text{ TeV}$

‘CHIRAL’ COUNTING

- Assignment of the ‘chiral’ dimension: * $\mathcal{L}_{p^{\hat{d}}} \sim a_{(\hat{d})} p^{\hat{d}-N_F/2} \left(\frac{\bar{\psi}\psi}{v^2}\right)^{N_F/2} \sum_j \left(\frac{\chi}{v}\right)^j$
- with the low-energy scaling* $\frac{\chi}{v} \sim \mathcal{O}(p^0)$, $\frac{\psi}{v} \sim \mathcal{O}(p^{1/2})$, $\partial_\mu, m_\chi, m_\psi \sim \mathcal{O}(p)$

- **Low-energy EFT (ECLh) *** → Classification of the operators according to ‘chiral’ dimension:

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

$\supset \mathcal{L}^{\text{SM}}$

- **High-energy theory for Resonances + χ + ψ**

→ General $\Delta\mathcal{L}_R$ ‘of $\mathcal{O}(p^2)$ ’ **

$\Delta\mathcal{L}_R = \boxed{\text{F}_R \text{ R } \mathcal{O}_{p^2}[\chi, \psi]} + \dots$

* Weinberg, 79; Manohar,Georgi, NPB234 (1984) 189
 * Gasser,Leutwyler ‘84 ‘85
 * Hirn,Stern ‘05
 * Buchalla,Catà,Krause ‘13
 * Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149
 * Henning,Lu,Murayama, [1412.1837]
 * Pich,Rosell,Santos,SC, [1501.07249]; forthcoming

* Apelquist,Bernard ‘80
 * Longhitano ‘80, ‘81
 * Alonso,Gavela,Merlo,Rigolin,Yepes ‘12
 * Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile,Gonzalez-Garcia,Merlo,Rigolin ‘13

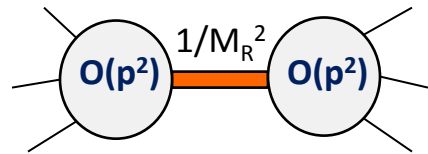
** Ecker et al. ‘89
 ** Cirigliano et al., NPB753 (2006) 139
 ** Pich,Rosell,Santos,SC, [1501.07249]; forthcoming

Res. contributions to the $O(p^4)$ EFT couplings

1.) Only R operators $O(p^2)$: ** singlets V_1, A_1, S_1, P_1 + triplets V, A, S, P + ...

*[antisymmetric-tensor formalism $R_{\mu\nu}$
for spin-1 Resonances **]*

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



$$e^{i S[\chi, \psi]_{\text{EFT}}} = \int [dR] e^{i S[\chi, \psi, R]}$$

tree-level \equiv $e^{i S[\chi, \psi, R_{\text{cl.}}]}$

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

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

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

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

** Ecker et al. '89

** Cirigliano et al., NPB753 (2006) 139

** Pich, Rosell, Santos, SC, [1501.07249]; forthcoming

BASIC TREE-LEVEL EXAMPLE: form-factors & $Z \rightarrow \psi\bar{\psi}$

- Triplet V contribution in C & P-even strongly couple theories (full R Lagrangian in *)

$$\mathcal{L}_V = Tr\{V_{\mu\nu} \underbrace{\left(\frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{iG_V}{2\sqrt{2}} [u^\mu, u^\nu] + c_1^V \nabla^\mu J_V^\nu / v^2 + \dots \right)}_{O_V^{\mu\nu}}\}$$

- Contribution from V,

to the EFT @ NLO: $\mathcal{L}_{p^4}^{\text{from V}} = -i \frac{F_V G_V}{4M_V^2} Tr\{f_+^{\mu\nu} [u^\mu, u^\nu]\} - \frac{F_V c_1^V}{\sqrt{2}M_V^2} Tr\{f_+^{\mu\nu} \nabla_\mu J_{V\nu} / v^2\} + \dots$

\downarrow $i(a_2 - a_3)/2$ \downarrow $C^{\Psi 2h_0}_{10}$

- Impose UV constraints on \mathcal{L}_R , predict in the EFT: *, **

$$\mathcal{F}_{\omega\omega}^v(q^2) = 1 + \frac{F_V G_V}{v^2} \frac{q^2}{M_V^2 - q^2}$$

$$\mathcal{F}_{\psi\bar{\psi}}^v(q^2) = 1 - \frac{\sqrt{2} F_V c_1^V}{v^2} \frac{q^2}{M_V^2 - q^2}$$

$\left. \begin{array}{l} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right\} \xrightarrow{q^2 \rightarrow \infty} 0$

$(a_2 - a_3) = -v^2 / (2M_V^2)$

$C^{\Psi 2h_0}_{10} = v^2 / (2M_V^2)$

** Peskin, Takeuchi, PRL65 (1990) 96; PRD46 (1992) 381

** Orgozo, Rychkov, JHEP1203 (2012) 046; 1306 (2013) 014

** Pich, Rosell, SC, PRL110 (2013) 181801; JHEP01 (2014) 157

* Pich, Rosell, Santos, SC, [1501.07249]; forthcoming

- Contributions to $Z \rightarrow \psi\bar{\psi}$ (with $\psi = t, b$)

- Ruled by the previous couplings

$$|\delta g^{Z\psi}| \stackrel{\text{EFT}}{=} \frac{\cos(2\theta) c_{10}^{\psi^2 h^0} m_Z^2}{v^2}$$

$$\stackrel{\text{from V}}{=} -\cos(2\theta) \frac{F_V c_1^V}{\sqrt{2}v^2} \frac{m_Z^2}{M_V^2}$$

$$\stackrel{\text{UV-complet.}}{=} \frac{\cos(2\theta) m_Z^2}{2M_V^2}$$

- How strong are the bounds? Not difficult to make them* small enough**

$$M_V \gtrsim 1.5 \text{ TeV} \quad \longrightarrow \quad |\delta g^{Z\psi}| \lesssim 10^{-3}$$

* Pich, Rosell, Santos, SC, forthcoming
 ** Agashe, Contino, Da Rold, Pomarol, PLB641 (2006) 62
 ** Efrati, Falkowski, Soreq, [1503.07872]
 ** LEP [0511027]

**(S , T) oblique parameters:
ONE-LOOP results + UV-constraint**

C & P-even

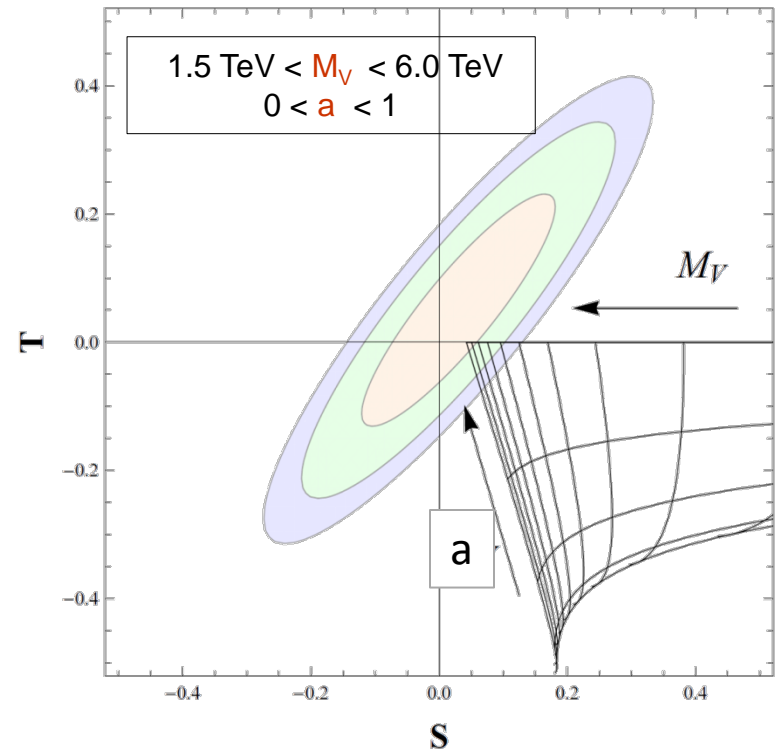
ii) NLO results: 1st and 2nd WSRs*

$$1 > a > 0.94$$

$$M_A \approx M_V > 4 \text{ TeV}$$

(95%CL)

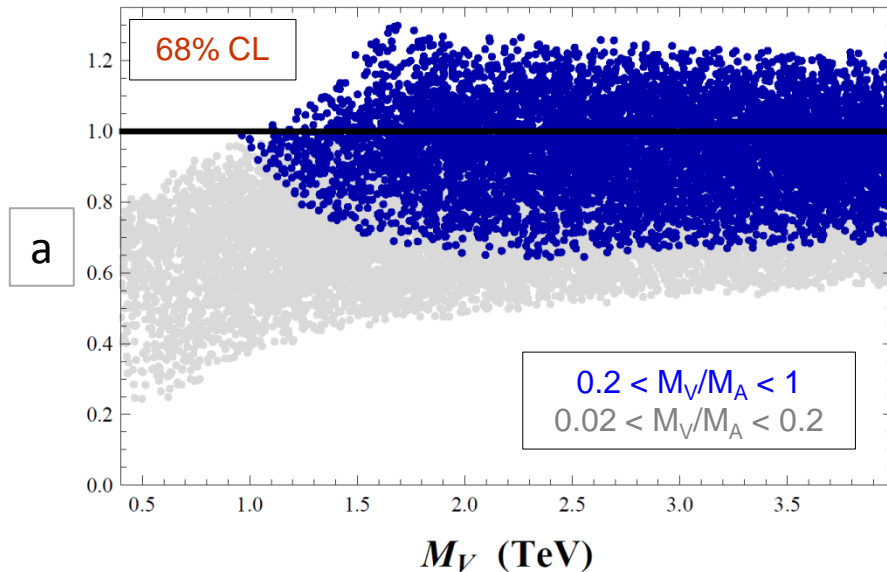
iii) NLO results: 1st WSR and $M_V < M_A^*$



Similar conclusions, but softened

For $M_V < M_A$:

✓ $M_A > 1 \text{ TeV}$ 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 $\chi + \psi + \mathbf{R}$
 - Low-energy matching: Res. contributions to the EFT @ $O(p^4)$
 - UV-completion assumptions: further constraints on the predictions
- ✓ Tree-level predictions of the $O(p^4)$ low-energy couplings
- ✓ Natural suppression in low-energy observables for $M_R \sim 4\pi v \approx 3 \text{ TeV}$ _
- $Z \rightarrow b\bar{b}$: Ok for $M_V > 1.5 \text{ TeV}$
 - S & T param: Ok for $a \approx 1$ $M_V > 4 \text{ TeV}$ (1 TeV) for 1st+2nd WSR (only 1st WSR)