

EW Chiral Lagrangians & the Higgs properties at the one loop



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



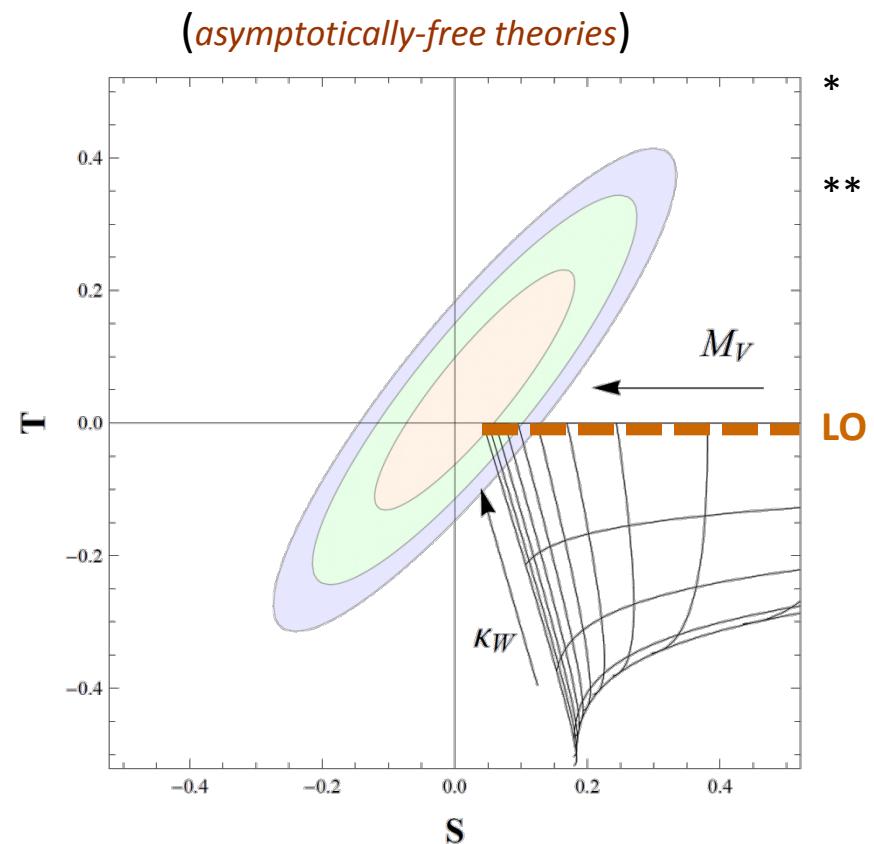
R. Delgado, A. Dobado, M.J. Herrero and JJ SC [arXiv:1404.2866 [hep-ph]] (JHEP accepted)
A. Pich, I. Rosell and JJ SC, JHEP 1208 (2012) 106; 1401 (2014) 157; PRL 110 (2013) 181801

OUTLINE

- 1) Introduction
- 2) Searching for Higgs-sensitive observables with EFT's
 - $\gamma\gamma \rightarrow W_L^a W_L^b$ scattering up to NLO [$O(e^2 p^2)$; 1 loop]
 - + related observables (S-parameter, form-factors, decay rates...)
 - Constraints on { hVV couplings, a_1, a_2-a_3 }
 - 3) Testing composite resonances:
 - (S,T) oblique parameters
 - Constraints on M_R & hWW coupling

And new look at old data...

Oblique
parameters
vs.
EW composite
resonance models



** Gfitter
** LEP EWWG
** Zfitter

* Pich,Rosell,SC '12, '13

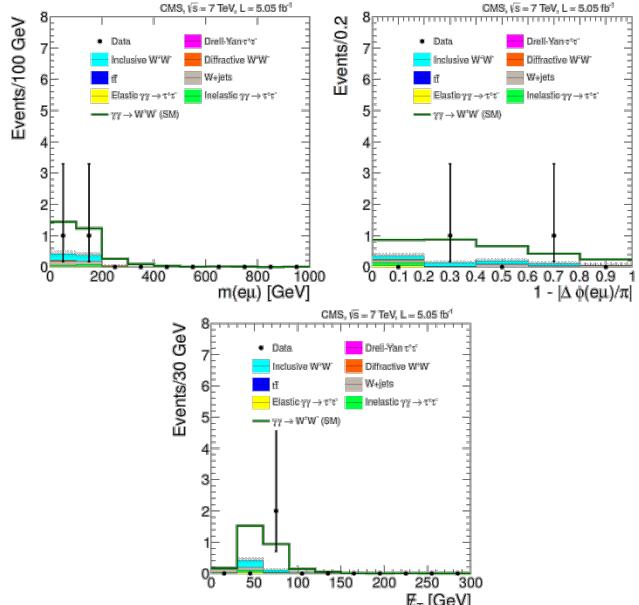
...and an old look at (forthcoming) new data

- Experimental results for $\gamma\gamma \rightarrow W^+W^-$: 2 events

[CMS JHEP 07 (2013) 116: $pp \rightarrow p W^+W^- p \quad p_T > 30\text{GeV}$]

So far,
only bounds
on eff. vertices

(stronger than LEP & Tevatron)



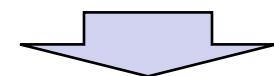
We need more experiment

+

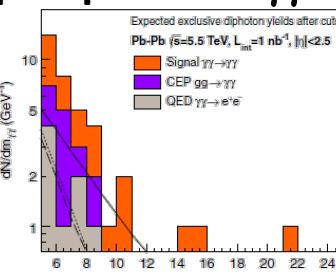
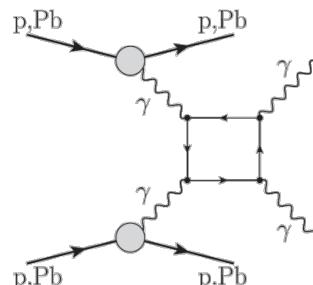
more theory:

JUST EFF. VERTICES

NOT ENOUGH



- Also experimental prospects for $\gamma\gamma \rightarrow \gamma\gamma$



18 events/y
expected in Pb-Pb
after cuts**

** Enterria, Silveira, PRL 11 (2013) 080405

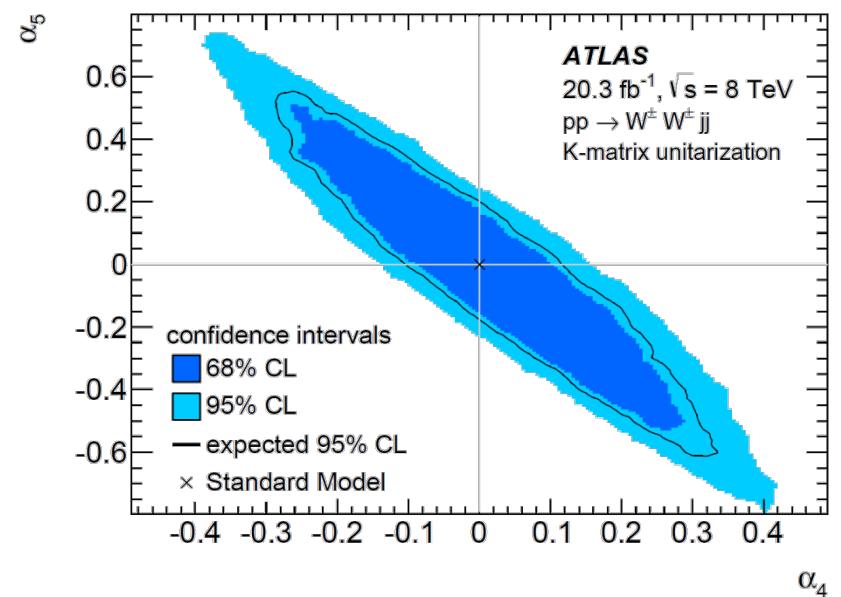
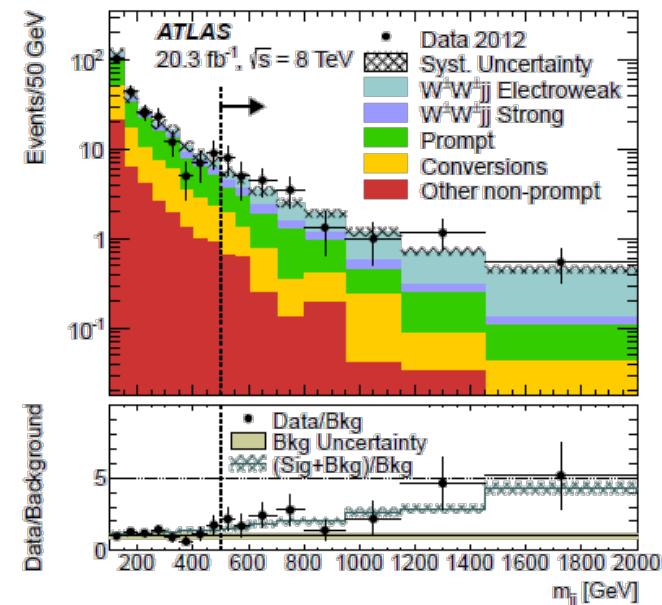
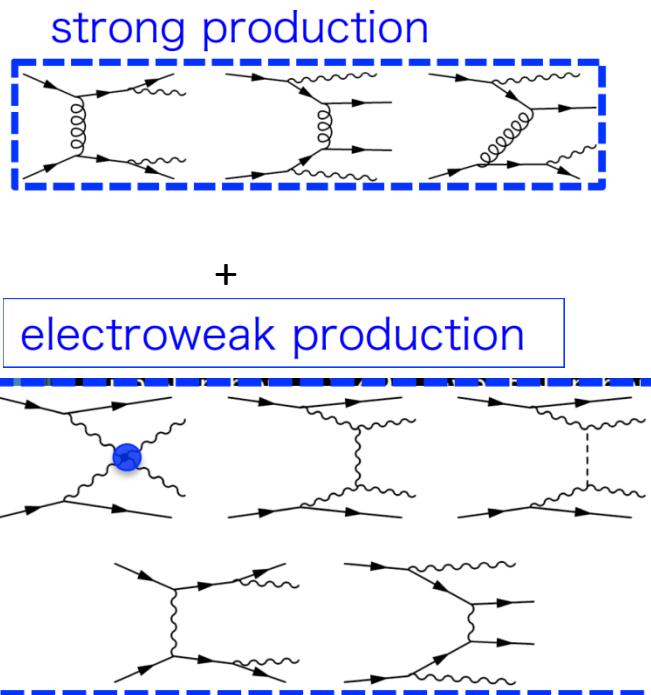
Low-energy EFT calculation

FORTHCOMING
FORW. DETECTORS @ LHC:
 CMS-TOTEM (2015!),
 ATLAS-AFP

•Last month:

WW-scattering

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

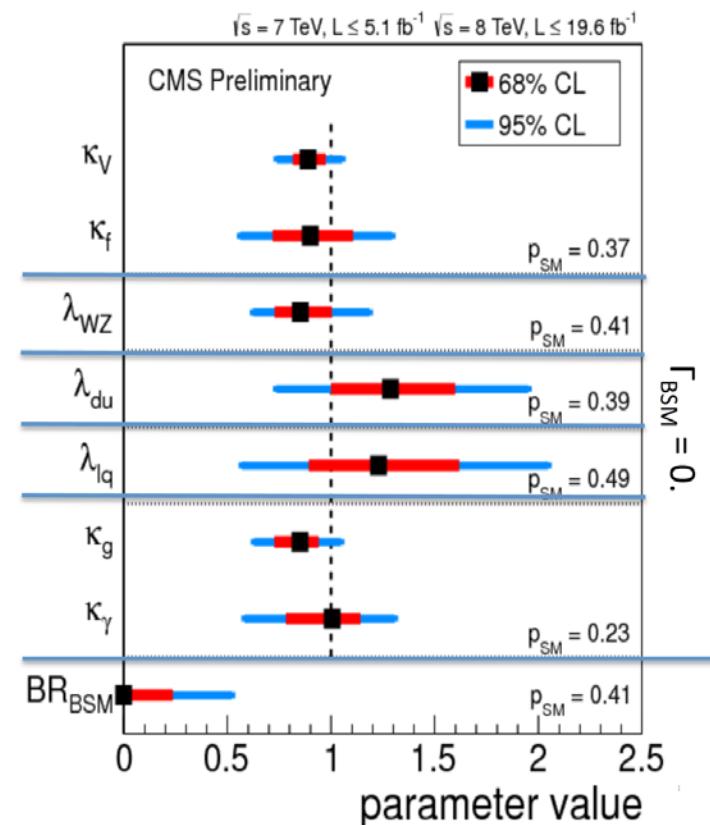
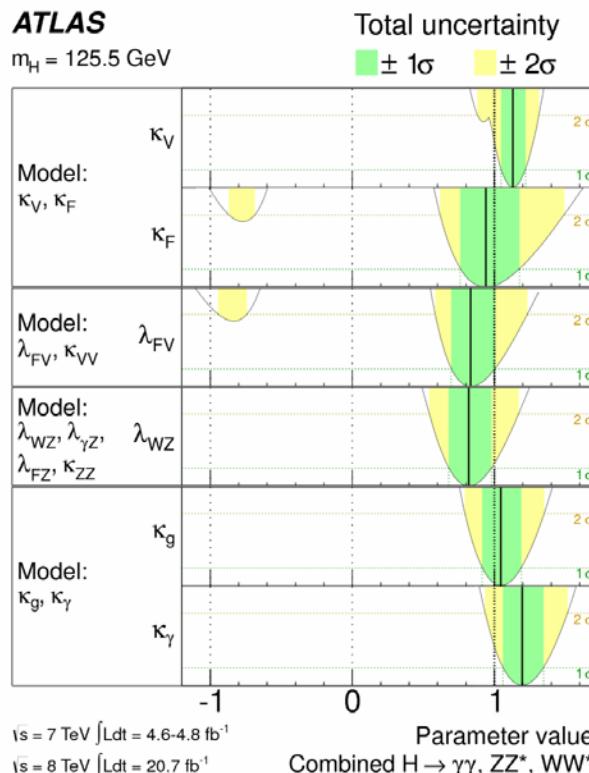


Summary of all searches for coupling deviations

C. Moratti [ATLAS]
EPS-HEP'13

ATLAS

$m_H = 125.5 \text{ GeV}$



- Compatibility with the SM

- Best uncertainties $\approx 10\%$

What are we needing?

- Observables!!

- ★ We need more observables
sensitive to small deviations in the couplings (e.g. $\Delta a = \tilde{a} - 1$)

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)



(I) EW Chiral Lagrangian + Higgs (ECLh):

Low-energy EFT;

$\gamma\gamma \rightarrow zz, w^+w^-$ & related obs.

•EFT approach:

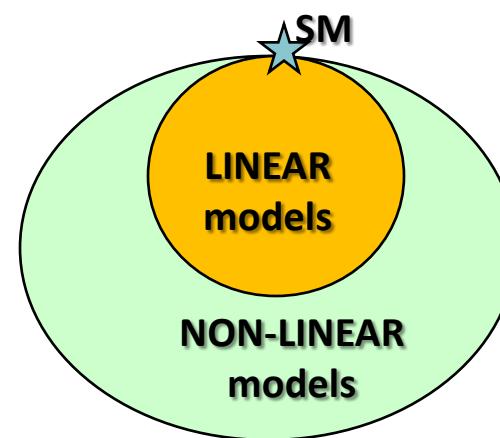
→ It describes any theory w/ the given symmetry pattern

→ In principle no ref to composite, dilaton, etc. *(though, $h=pNGB$ obvious inspiration)*
 (1model=1set of LECs; e.g. SM)

$a^2 = b = 0$	Higgsless ECL
$a^2 = b = 1$	SM,
$a^2 = 1 - \frac{v^2}{f^2}, \quad b = 1 - \frac{2v^2}{f^2}$	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 ©]

•EFT assumptions:

1. “SM” content: EW Goldstones+gauge bosons + h
2. Applicability: $E \ll \Lambda_{\text{ECLh}} = \min\{4\pi v, M_R\}$
3. Landau gauge *(for convenience; R_ξ renormalizable in any case)*
4. Equivalence Theorem: $m_{W,Z} \ll E$

$$\begin{aligned} \mathcal{M}(\gamma\gamma \rightarrow W_L^+ W_L^-) &\simeq -\mathcal{M}(\gamma\gamma \rightarrow w^+ w^-) \\ \mathcal{M}(\gamma\gamma \rightarrow Z_L Z_L) &\simeq -\mathcal{M}(\gamma\gamma \rightarrow z z) \end{aligned}$$
Pheno $\rightarrow m_h \sim m_{W,Z} \ll E$ *(full calculation also possible)*
5. Custodial symmetry: $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ pattern
6. A minor detail: gauge boson sector switched off when $g, g' \rightarrow 0$ *(through $g W^\mu_a$ & $g' B_\mu$)*

•OUR $\gamma\gamma \rightarrow W_L^a W_L^b$ ANALYSIS:*

RANGE OF VALIDITY

$$m_W^2, m_Z^2, m_h^2 \ll s, t, u \ll \Lambda_{\text{ECLh}}^2$$

* Delgado,Dobado,Herrero,SC '14

•Building blocks^(x):

$$U(w^\pm, z) = 1 + iw^a\tau^a/v + \mathcal{O}(w^2) \in SU(2)_L \times SU(2)_R / SU(2)_{L+R},$$

$$\begin{aligned} D_\mu U &= \partial_\mu U + i \hat{W}_\mu U - i U \hat{B}_\mu, \\ \hat{W}_{\mu\nu} &= \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu + i [\hat{W}_\mu, \hat{W}_\nu], \quad \hat{B}_{\mu\nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu, \\ \hat{W}_\mu &= g \vec{W}_\mu \vec{\tau}/2, \quad \hat{B}_\mu = g' B_\mu \tau^3/2, \\ V_\mu &= (D_\mu U) U^\dagger, \quad \mathcal{T} = U \tau^3 U^\dagger, \end{aligned}$$

soft-scale!!!

•“Chiral” counting*:

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

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

(x) Apelquist,Bernard '80

(x) Longhitano '80, '81

(x) Herrero,Morales '95

(x) Pich,Rosell,Sc '12 '13

(x) Brivio et al. '13

, etc.

* Buchalla,Catà,Krause '13

* Hirn,Stern '05

* Delgado,Dobado,Herrero,SC '14

** Urech '95

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

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

→ LO Lagrangian*,:**:

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

Various notations:

$a = \kappa_v = \kappa_w = c_w = \omega = \text{etc.}$

→ NLO Lagrangian*,:**:

$$\mathcal{L}_4 = a_1 \text{Tr}(U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu}) + i a_2 \text{Tr}(U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu]) - i a_3 \text{Tr}(\hat{W}_{\mu\nu} [V^\mu, V^\nu])$$

$$- c_W \frac{h}{v} \text{Tr}(\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}) - c_B \frac{h}{v} \text{Tr}(\hat{B}_{\mu\nu} \hat{B}^{\mu\nu}) + \dots$$

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

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

** \mathcal{L}_4 conventions from Brivio et al. '13

Counting, loops & renormalization

- In general, the $O(p^d)$ Lagrangian has the symbolic form ($\chi=W,B,\pi,h$),

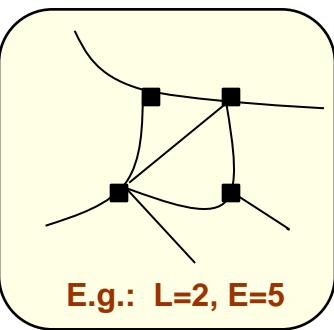
$$\mathcal{L}_d = \sum_k f_k^{(d)} p^d \left(\frac{\chi}{v}\right)^k$$

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

leading to a general scaling* of a diagram with

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

- L loops
- E external legs
- N_d vertices of \mathcal{L}_d



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

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

* 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

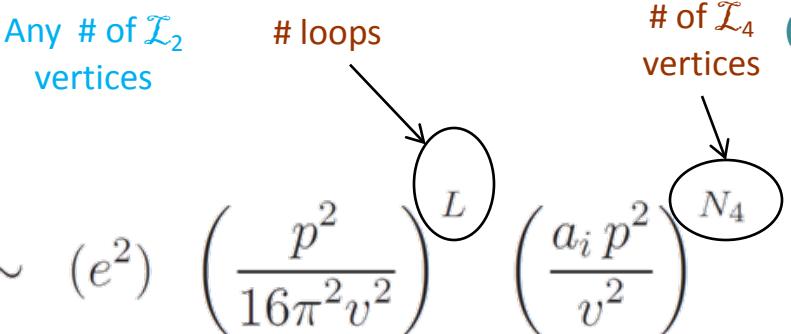
** Delgado,Dobado '13

E.g. $W_L W_L$ -scat**: LO $O(p^2) \rightarrow \frac{p^2}{v^2}$ (tree)

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

- $\mathcal{M}(\gamma\gamma \rightarrow w^a w^b)$ up to NLO: *

$$\mathcal{M} \sim \left(\frac{p^2}{v^2}\right) \left(\frac{p^2}{16\pi^2 v^2}\right)^L \left(\frac{a_i p^2}{v^2}\right)^{N_4}$$



- Summarizing up to NLO: $\mathcal{M} = \mathcal{M}_{\text{LO}} + \mathcal{M}_{\text{NLO}}$

- LO \rightarrow Tree-level ($L=0, N_4=0$): $\mathcal{M}_{\text{LO}} = \mathcal{M}_{\mathcal{O}(e^2)}^{\text{tree}} \sim e^2$

- NLO: $\mathcal{M}_{\text{NLO}} = \mathcal{M}_{\mathcal{O}(e^2 p^2)}^{\text{1-loop}} + \mathcal{M}_{\mathcal{O}(e^2 p^2)}^{\text{tree}}$

- \rightarrow One-loop ($L=1, N_4=0$): $\mathcal{M}_{\mathcal{O}(e^2 p^2)}^{\text{1-loop}} \sim e^2 \left(\frac{p^2}{16\pi^2 v^2}\right)$

- \rightarrow Tree-level ($L=0, N_4=1$): $\mathcal{M}_{\mathcal{O}(e^2 p^2)}^{\text{tree}} \sim e^2 \left(\frac{a_i p^2}{v^2}\right)$

- Renormalization at $\mathcal{O}(p^4)$: $a_1, a_2, a_3, c_\gamma \rightarrow a_1^r, a_2^r, a_3^r, c_\gamma^r$

* Weinberg '79

* Urech '95

* Buchalla,Catà,Krause '13

* Hirn,Stern '05

* Delgado,Dobado,Herrero,SC '14

- General gauge invariant Lorentz structure w/ on-shell transverse photons

$[w^{a,b} = w^\pm, z]$

$$\gamma(k_1, \epsilon_1) \gamma(k_2, \epsilon_2) \rightarrow w^a(p_1) w^b(p_2)$$

can be described by 2 scalar functions A & B: * , (x)

$$\mathcal{M} = ie^2(\epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}^{(1)}) A(s, t, u) + ie^2(\epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}^{(2)}) B(s, t, u)$$

with the Lorentz structures and Mandelstam variables

$$(\epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}^{(1)}) = \frac{s}{2}(\epsilon_1 \epsilon_2) - (\epsilon_1 k_2)(\epsilon_2 k_1),$$

$$(\epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}^{(2)}) = 2s(\epsilon_1 \Delta)(\epsilon_2 \Delta) - (t-u)^2(\epsilon_1 \epsilon_2) - 2(t-u)[(\epsilon_1 \Delta)(\epsilon_2 k_1) - (\epsilon_1 k_2)(\epsilon_2 \Delta)]$$

$$\Delta^\mu \equiv p_1^\mu - p_2^\mu$$

$$s = (k_1 + k_2)^2, \quad t = (k_1 - p_1)^2, \quad u = (k_1 - p_2)^2$$

* Bijnens,Cornet '88

* Bijnens,Dawson,Valencia '91

* Donoghue,Holstein '93

...

* Colangelo,Fen,SC '13

(x) Notation:

* Dai,Pennington '14, etc.

Burgi '96; Gasser et al. '05, '06

$$\gamma\gamma \rightarrow zz$$

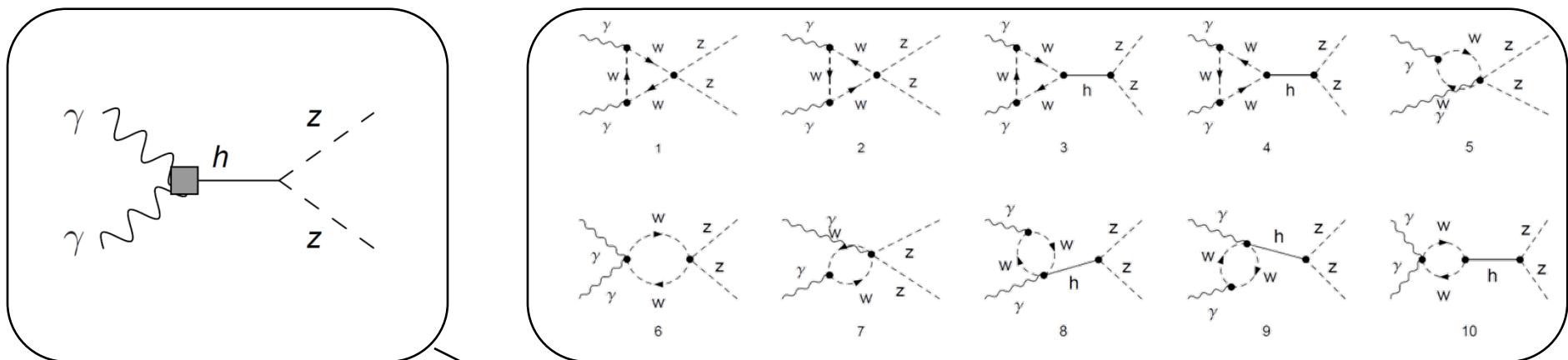
(14)

- LO (no contribution): $\mathcal{M}(\gamma\gamma \rightarrow zz)_{\text{LO}} = 0$

- NLO:

→ Tree-level

→ One-loop *



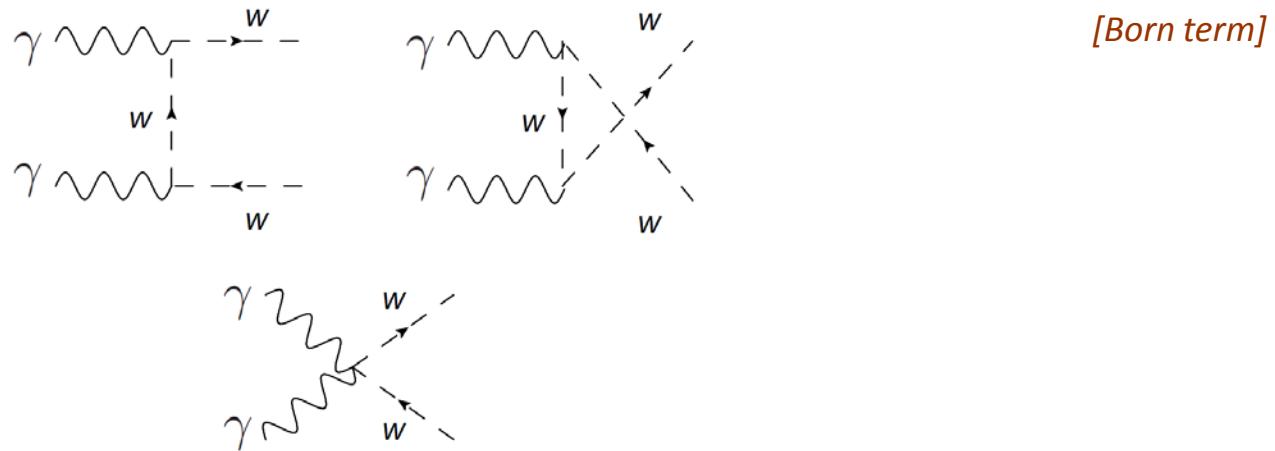
$$A(\gamma\gamma \rightarrow zz)_{\text{NLO}} = \frac{2 a c_\gamma^r}{v^2} + \frac{(a^2 - 1)}{4\pi^2 v^2},$$

$$B(\gamma\gamma \rightarrow zz)_{\text{NLO}} = 0,$$

* In agreement with Ametller,Talavera '14

$$\gamma\gamma \rightarrow W^+W^-$$

•LO (tree-level): $A(\gamma\gamma \rightarrow w^+w^-)_{\text{LO}} = 2s B(\gamma\gamma \rightarrow w^+w^-)_{\text{LO}} = -\frac{1}{t} - \frac{1}{u}$

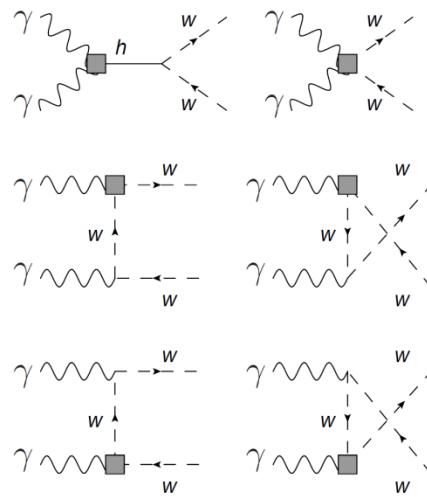


•NLO:

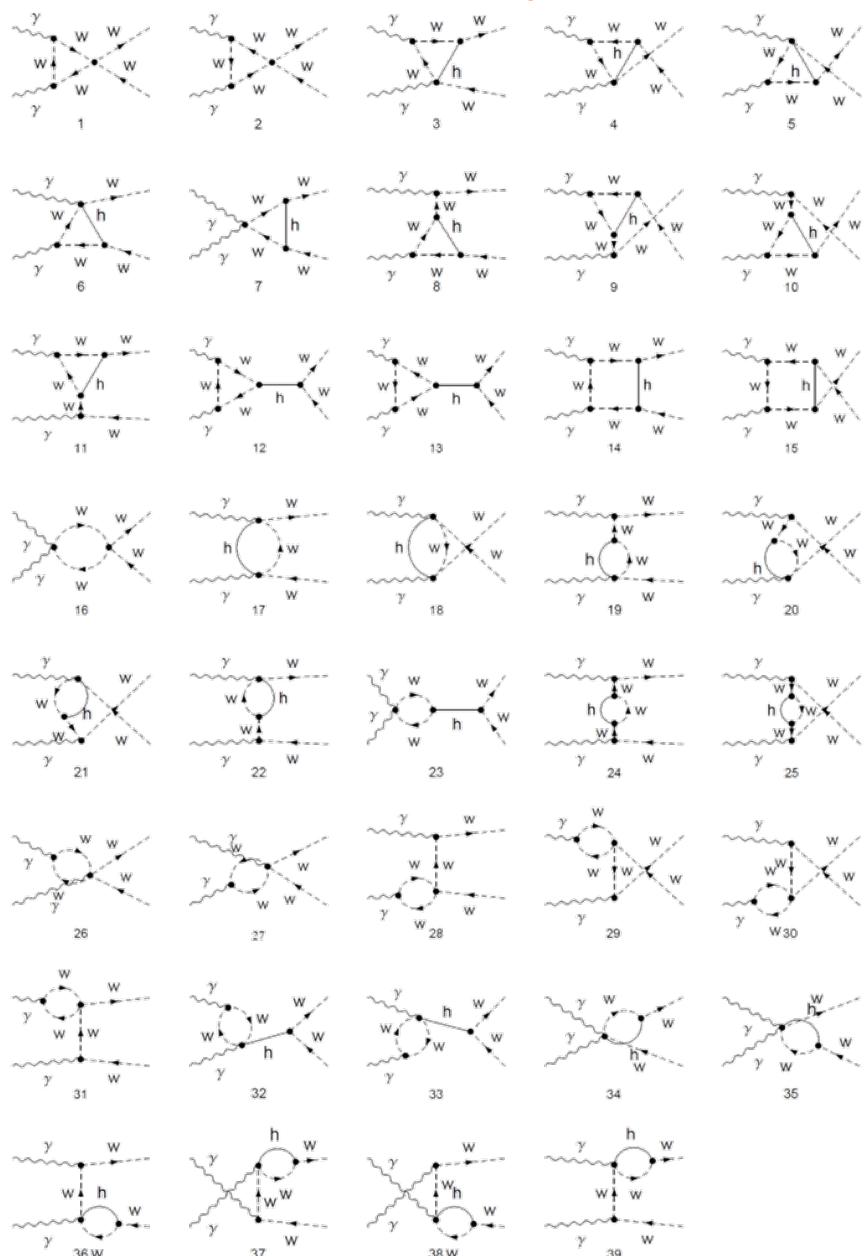
→ Tree-level

→ One-loop

•NLO*: →Tree-level



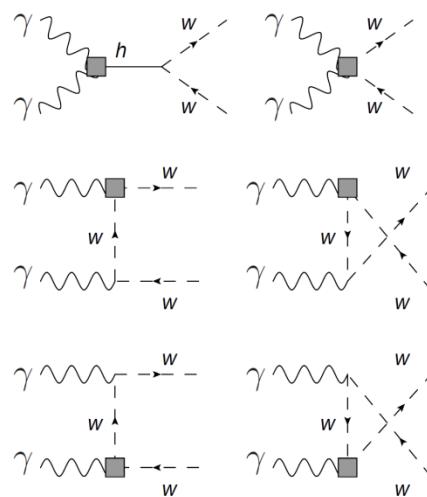
→One-loop



It may
look
complicated

•NLO: →Tree-level

→One-loop



$$\mathcal{M}^1 = -\frac{ie^2}{144\pi^2 sv^2} \left(3B_0(s,0,0)(t+u)(-(\epsilon_1\Delta)(\epsilon_2 k_1) + (\epsilon_1 k_2)(\epsilon_2\Delta) + (\epsilon_1\epsilon_2)t + 2(\epsilon_1\epsilon_2)u) + 2(\epsilon_1 k_2)((\epsilon_2\Delta)(t+u) + 3(\epsilon_2 k_1)(t+2u)) + (t+u)(-2(\epsilon_1\Delta)(\epsilon_2 k_1) + 2(\epsilon_1\epsilon_2)t + 7(\epsilon_1\epsilon_2)u) \right),$$

$$\mathcal{M}^2 = -\frac{ie^2}{144\pi^2 sv^2} \left(3B_0(s,0,0)(t+u)((\epsilon_1\Delta)(\epsilon_2 k_1) - (\epsilon_1 k_2)(\epsilon_2\Delta) + 2(\epsilon_1\epsilon_2)t + (\epsilon_1\epsilon_2)u) - 2(\epsilon_1 k_2)((\epsilon_2\Delta)(t+u) - 3(\epsilon_2 k_1)(2t+u)) + (t+u)(2(\epsilon_1\Delta)(\epsilon_2 k_1) + 7(\epsilon_1\epsilon_2)t + 2(\epsilon_1\epsilon_2)u) \right),$$

$$\mathcal{M}^3 = \frac{ia^2 e^2}{288\pi^2 v^2} \left(3B_0(t,0,0)(2(\epsilon_1\epsilon_2)t - 5((\epsilon_1\Delta) + (\epsilon_1 k_2))((\epsilon_2\Delta) - (\epsilon_2 k_1))) + (-(\epsilon_1\Delta) - (\epsilon_1 k_2))((\epsilon_2\Delta) - (\epsilon_2 k_1)) + 4(\epsilon_1\epsilon_2)t \right),$$

$$\mathcal{M}^4 = \frac{ia^2 e^2}{288\pi^2 v^2} \left(3B_0(u,0,0)(2(\epsilon_1\epsilon_2)u - 5((\epsilon_1\Delta) - (\epsilon_1 k_2))((\epsilon_2\Delta) + (\epsilon_2 k_1))) - (\epsilon_1\Delta)((\epsilon_2\Delta) + (\epsilon_2 k_1)) + (\epsilon_1 k_2)((\epsilon_2\Delta) + (\epsilon_2 k_1)) + 4(\epsilon_1\epsilon_2)u \right),$$

$$\mathcal{M}^5 = \frac{ia^2 e^2}{288\pi^2 v^2} \left(3B_0(u,0,0)(2(\epsilon_1\epsilon_2)u - 5((\epsilon_1\Delta) - (\epsilon_1 k_2))((\epsilon_2\Delta) + (\epsilon_2 k_1))) - (\epsilon_1\Delta)((\epsilon_2\Delta) + (\epsilon_2 k_1)) + (\epsilon_1 k_2)((\epsilon_2\Delta) + (\epsilon_2 k_1)) + 4(\epsilon_1\epsilon_2)u \right),$$

Each diagram
is
complicated

, etc...

•NLO: →Tree-level

→One-loop

$$A(\gamma\gamma \rightarrow w^+w^-)_{\text{NLO}} = \frac{8(a_1^r - a_2^r + a_3^r)}{v^2} + \frac{2a c_\gamma^r}{v^2} + \frac{(a^2 - 1)}{8\pi^2 v^2}$$

$$B(\gamma\gamma \rightarrow w^+w^-)_{\text{NLO}} = 0.$$

BUT, sum
is
simple!!!*

•Since $a^{\exp} \approx 1$, full one-loop amplitude not simply suppressed by $\frac{p^2}{16\pi^2 v^2}$

but stronger loop suppression by $\frac{(1-a^2)p^2}{16\pi^2 v^2}$

[we can rewrite our particular result for the suppression in the form $\frac{p^2}{16\pi^2 f^2}$ with $f^2 = \frac{v^2}{|1-a^2|}$]

* Delgado,Dobado,Herrero,SC '14

Related observables

- How can we determine these ECLh couplings? *

Observables	Relevant combinations of parameters	
	from \mathcal{L}_2	from \mathcal{L}_4
$\mathcal{M}(\gamma\gamma \rightarrow zz)$	a	c_γ^r
$\mathcal{M}(\gamma\gamma \rightarrow w^+w^-)$	a	$(a_1^r - a_2^r + a_3^r), c_\gamma^r$
$\Gamma(h \rightarrow \gamma\gamma)$	a	c_γ^r
S -parameter	a	a_1^r
\mathcal{F}_{γ^*ww}	a	$(a_2^r - a_3^r)$
$\mathcal{F}_{\gamma^*\gamma h}$	—	c_γ^r

- OVERDETERMINATION → EFT PREDICTIVITY:

6 observables vs. 4 combinations of parameters { $a, c_\gamma, a_1, (a_2-a_3)$ }

* Delgado,Dobado,Herrero,SC '14

ECLh running at $O(p^4)$

- This 6 observables overdetermine the 4 combinations of couplings $a, c_\gamma, a_1, (a_2-a_3)$ and provide their running:*

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

* Delgado,Dobado,Herrero,SC '14

** Espriu,Mescia,Yencho '13

** Delgado,Dobado '13

(+) Herrero,Morales '95

(x) In agreement with Ametller,Talavera '14

Further improvements: Theory and Pheno

- Inclusion of top loops (IMPORTANT)
- Beyond the Equivalence Theorem (refinement)
- Beyond $m_h = m_W = m_Z = 0$ (refinement)
- MC simulations of signals at LHC and ILC (IMPORTANT)
 - *Experimental selection of this subprocesses at LHC**, (x)
 - *Estimates of integrated event #*
 - *Energy dependence*
- Joined analysis of $\gamma\gamma$ -amplitudes + decay-rates + oblique-parameters + FF's (IMPORTANT)

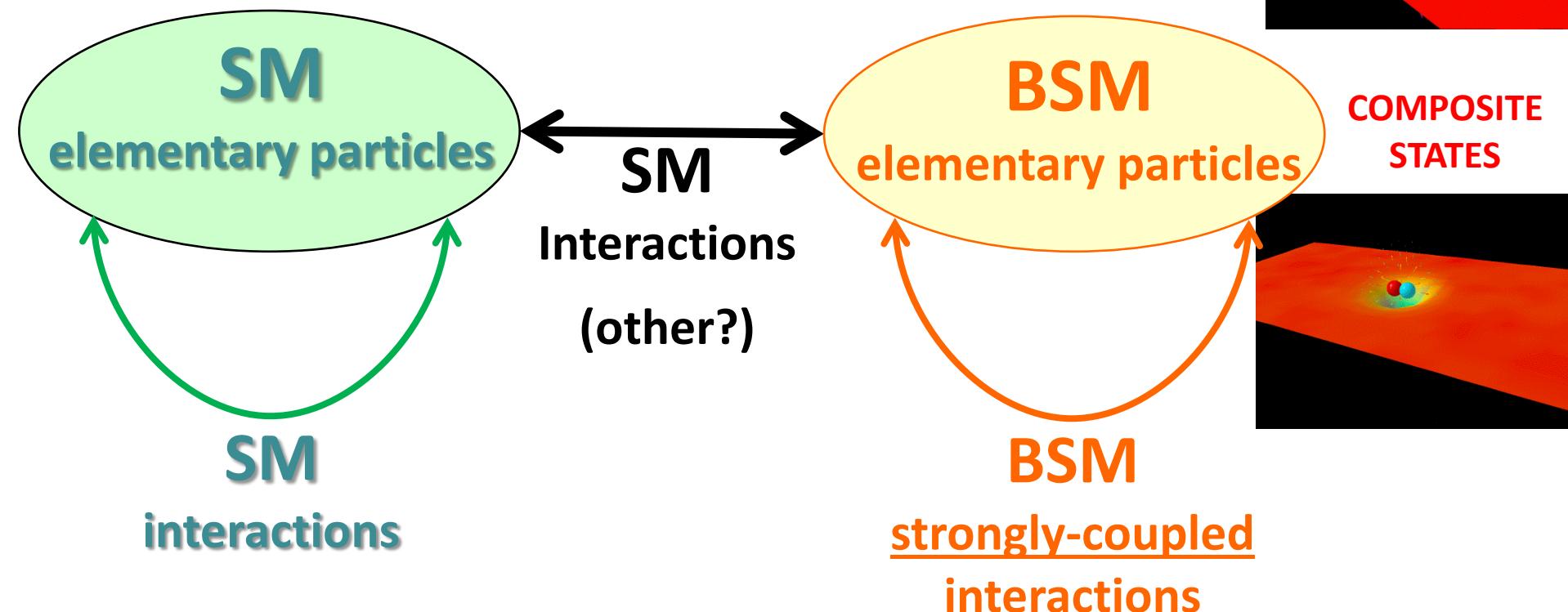
(x) Photon-LHC-2008 Workshop, NPB (Proc. Suppl.) 179+180 (2008)

(x) FP420 (Project for a Forward Detector at 420m) (→now CMS-TOTEM)

* CMS, JHEP 07(2013) 116

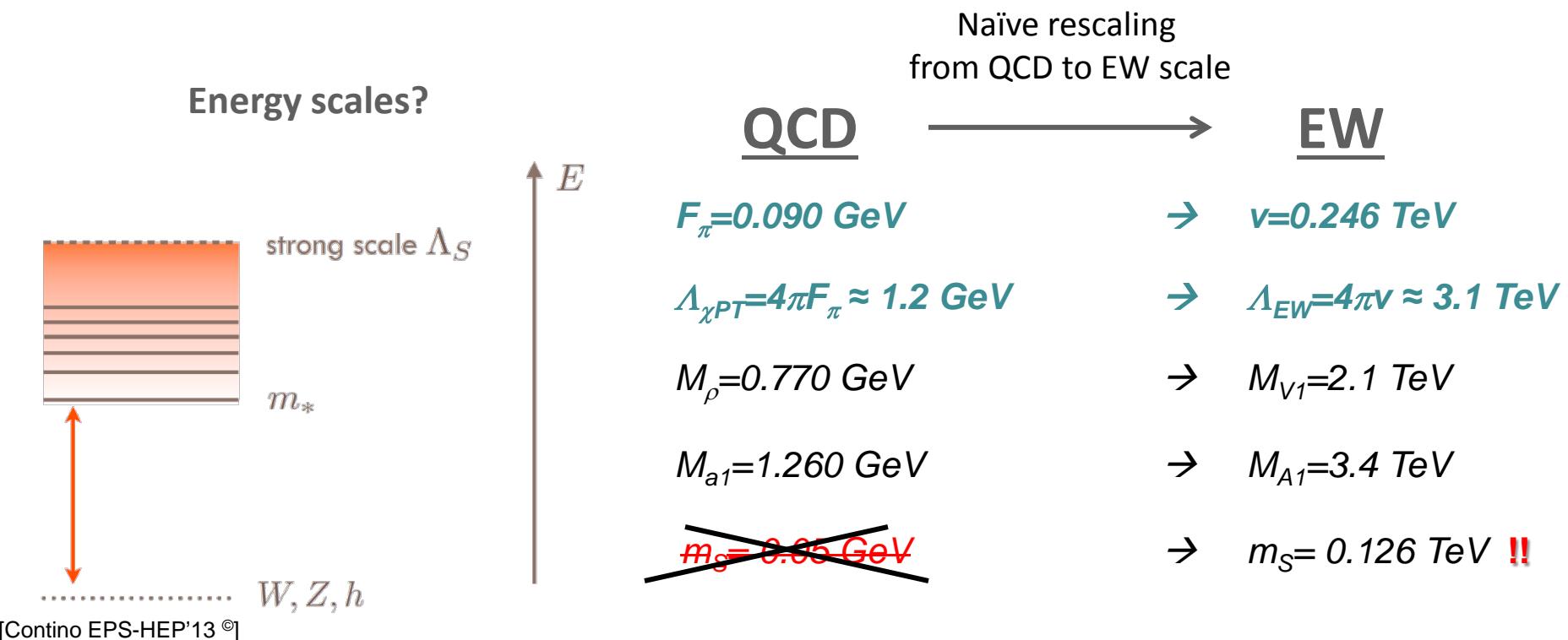
(II) Beyond low-energy EFTs: S & T parameters, composite resonance models, completions...

Strongly coupled BSM



- Inspired/similar to SM and the QCD sector: EW & leptons \leftrightarrow quarks & gluons

- However, it can't be just a copy of QCD:



- AIM of this work**:
 - Bounds on M_R
 - Bounds on hWW coupling from (S,T)

** Pich, Rosell, SC '12, '13

Oblique EWPO's

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

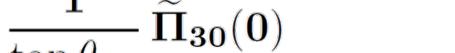
$$\mathcal{L}_{\text{vac-pol}} = -\frac{1}{2} W_\mu^3 \Pi_{33}^{\mu\nu}(q^2) W_\nu^3 - \frac{1}{2} B_\mu \Pi_{00}^{\mu\nu}(q^2) B_\nu - W_\mu^3 \Pi_{30}^{\mu\nu}(q^2) B_\nu - W_\mu^+ \Pi_{WW}^{\mu\nu}(q^2) W_\nu^-,$$

with the subtracted definition,

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



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



$$e_3 = \frac{1}{\tan \theta_W} \tilde{\Pi}_{30}(0)$$

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



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

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

- + Gfitter
- + LEP EWWG
- + Zfitter

* Peskin and Takeuchi '91, '92

** Barbieri et al.'93

We find that

strongly-coupled models are
perfectly/naturally allowed

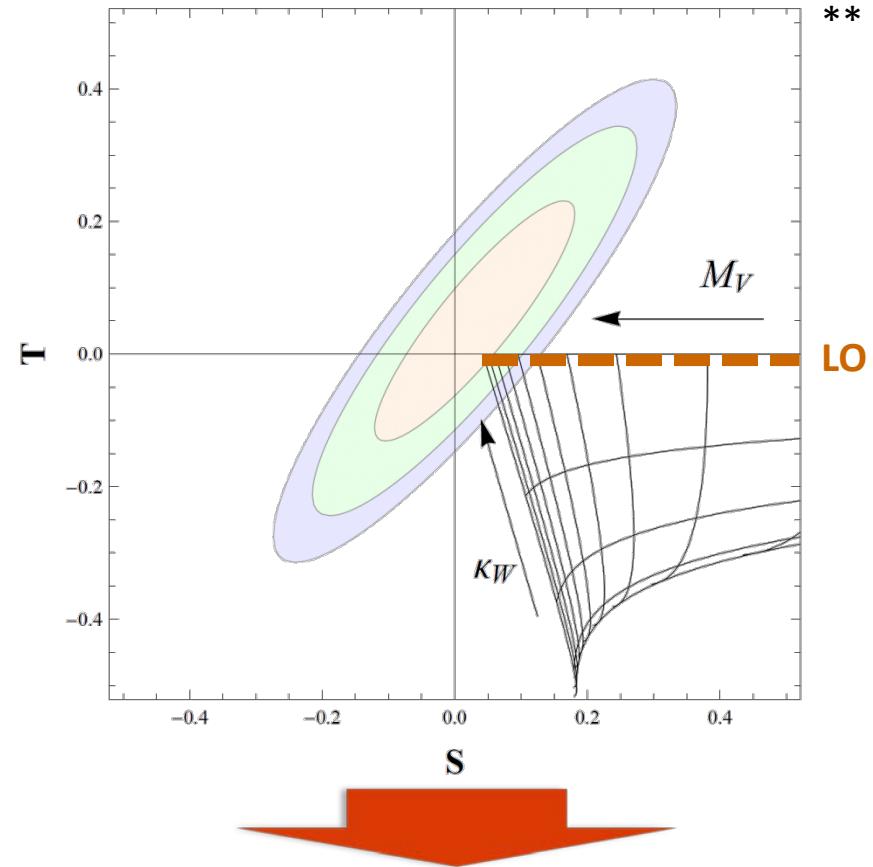
NLO results: ^{*} 1st and 2nd WSRs in Π_{30}

(asymptotically-free theories)

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

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

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



✓ 1st and 2nd WSRs at LO and NLO + $\pi\pi$ -VFF:

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

At NLO with the 1st and 2nd WSRs

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

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

** Gfitter

** LEP EWWG

** Zfitter

* Pich,Rosell,SC '12, '13

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

(walking & conformal TC, extra dimensions,...)^{**}

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

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

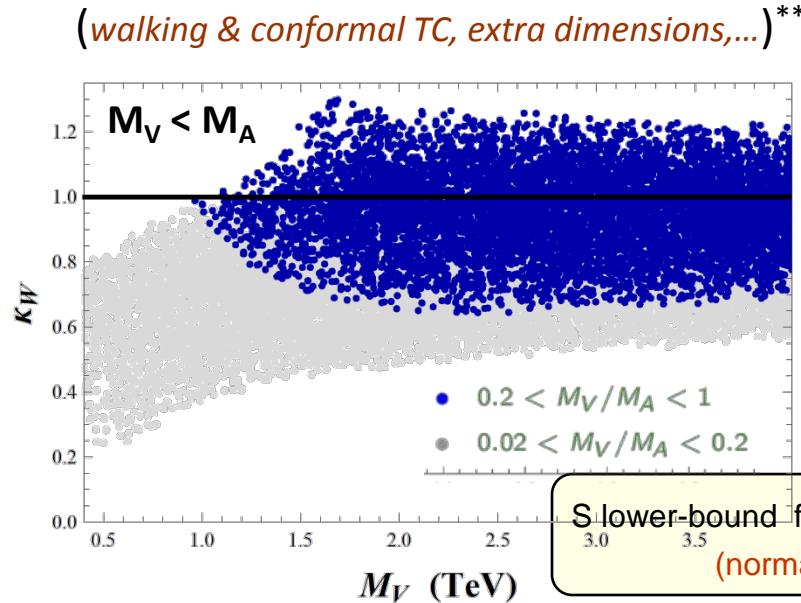
[terms $O(m_S^2/M_{V,A}^2)$ neglected]

- ✓ Assumption $M_A > M_V$ for the S lower-bound
- ✓ Only 1st WSR at LO and NLO + $\pi\pi$ -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}



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

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

At NLO with only 1st WSRs

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

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

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

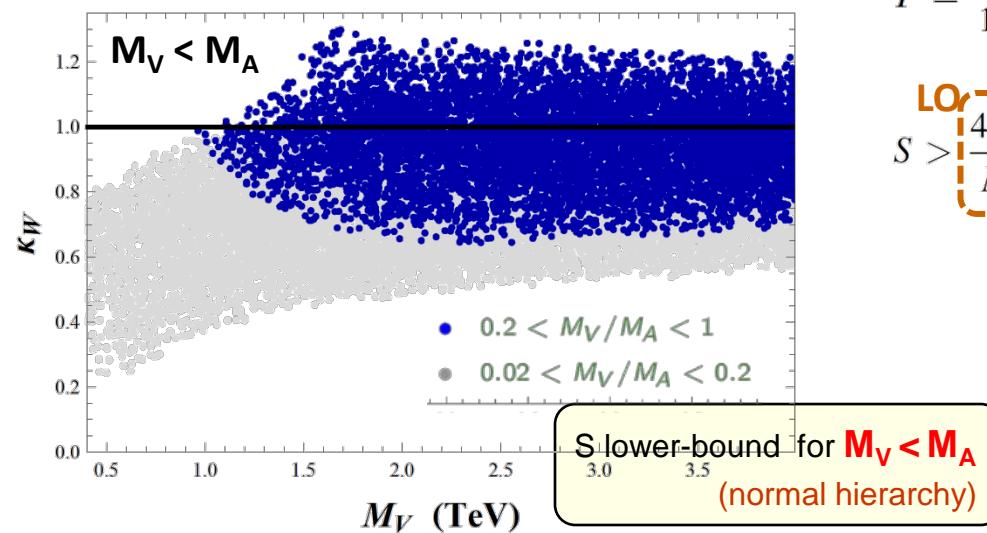
very different from the SM
if one requires large (unnatural) splittings

* Pich,Rosell,SC '12, '13

** Orgogozo,Rychkov '11

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

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



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

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

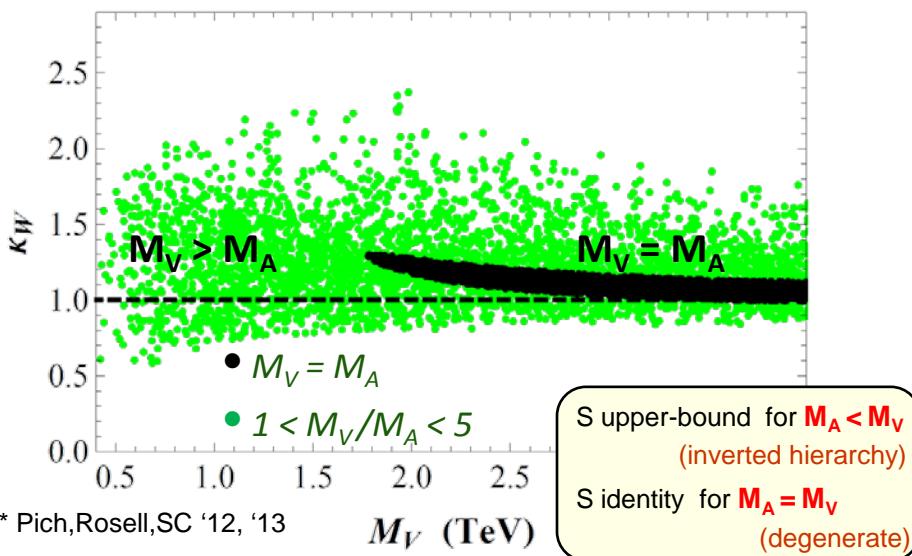
$M_V > 1 \text{ TeV}$, $\kappa_W \in (0.6, 1.3)$ at 68% CL

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

very different from the SM

if one requires large (unnatural) splittings



* Pich,Rosell,SC '12, '13

** Orgogozo,Rychkov '11

Conclusions

- Very close to SM + large mass gap → EFT's can be the safest choice
- Need for obs. sensitive to NP
- (I) Low-energy EFT: $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ w/ NGB's + Higgs (ECLh)
 - $\gamma\gamma \rightarrow w^a w^b$ up to NLO
 - Chiral power counting à la Weinberg (always tree+loops)
 - Important cancellations in the full amplitude (stronger suppression $4\pi f$)
 - Combine $\gamma\gamma$ -scattering + S-parameter + $\Gamma(h \rightarrow \gamma\gamma)$ + $w^+ w^- \gamma^*$ VFF + $h\gamma\gamma^*$ TFF
- (II) Compositeness: NGB's + h + R + High-energy constraints
 - ✓ 1st + 2nd WSR's: Tiny splitting (68% CL) $0.97 < (M_V/M_A)^2 = \kappa_W < 1$, $M_V > 5.4$ TeV
 - ✓ Only 1st WSR: For a moderate mass splitting $M_A \sim M_V$ (lighter), $\kappa_W \sim 1$, $M_V > 1$ TeV

BACKUP SLIDES

- A Higgs-like boson discovered at LHC

- $M_H = 125.64 \pm 0.35 \text{ GeV}$

- Still many questions:

- Spin?

0^+ most likely $[0^-, 1^\pm, 2^+]$

- Coupling to gauge bosons?

Very close to SM's

- Invisible decays vs SM?

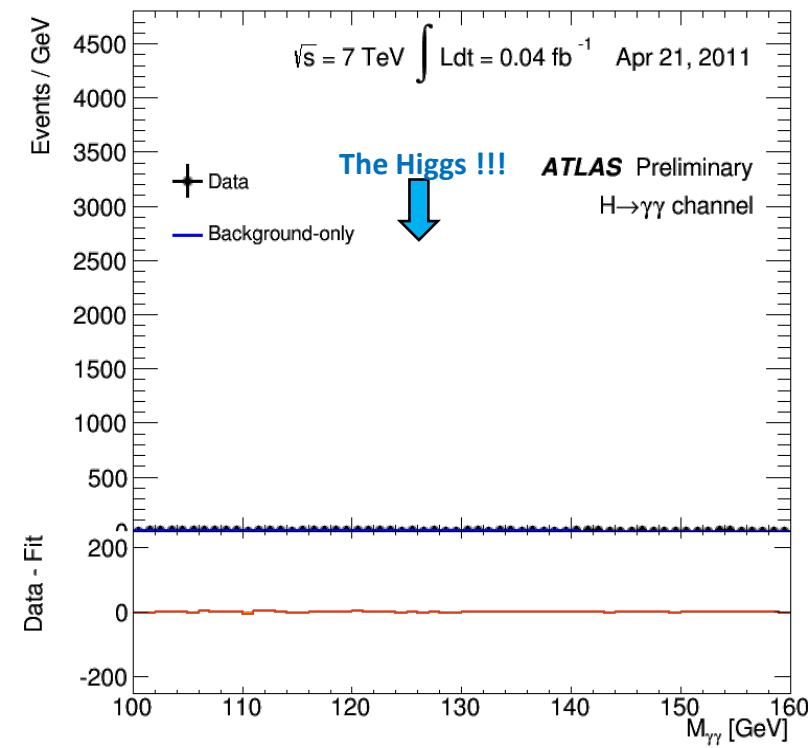
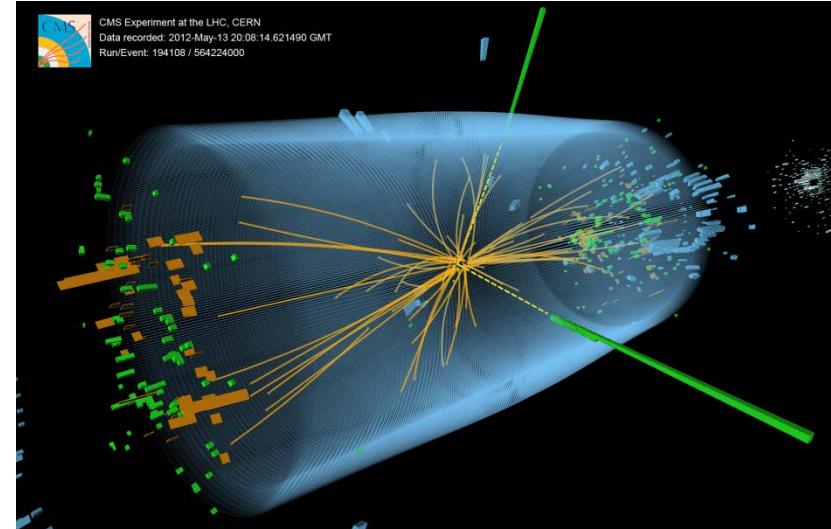
- ATLAS: $BR_{inv} < 0.60$ @ 95% CL (0.84 exp.)
- CMS: $BR_{inv} < 0.75$ @ 95% CL (0.91 exp.)

From $\gamma\gamma$: $\Gamma_H < 6.9 \text{ GeV}$ at 95% CL (direct)

- SM Higgs?

Compatible so far

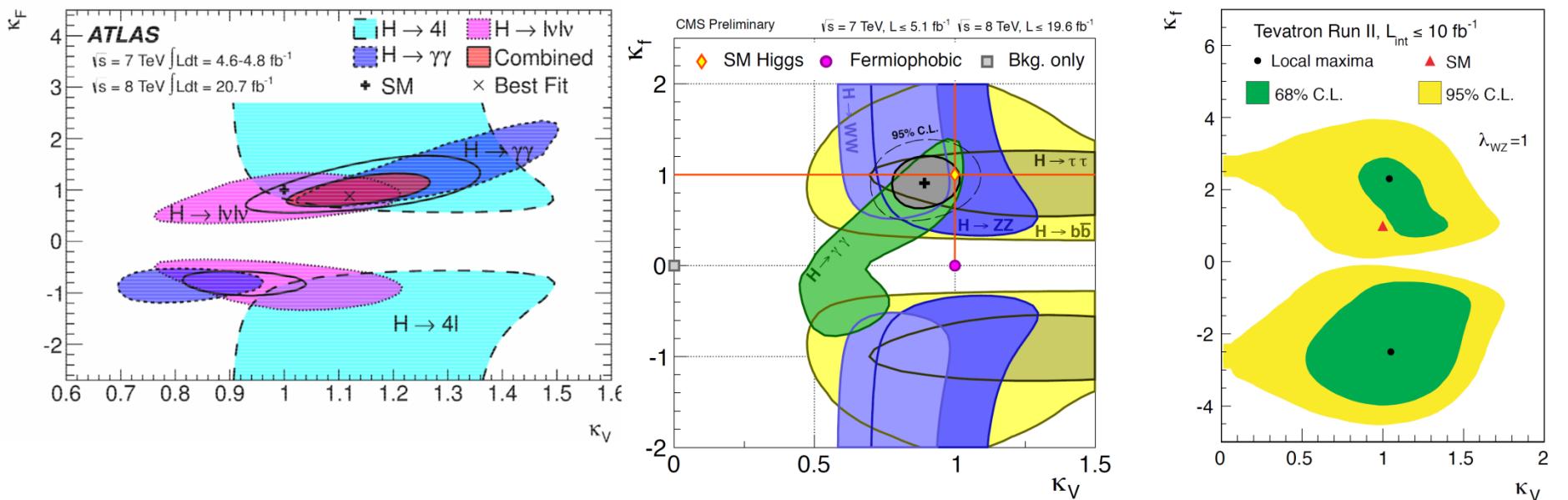
...



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

Higgs couplings

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



- 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]]

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

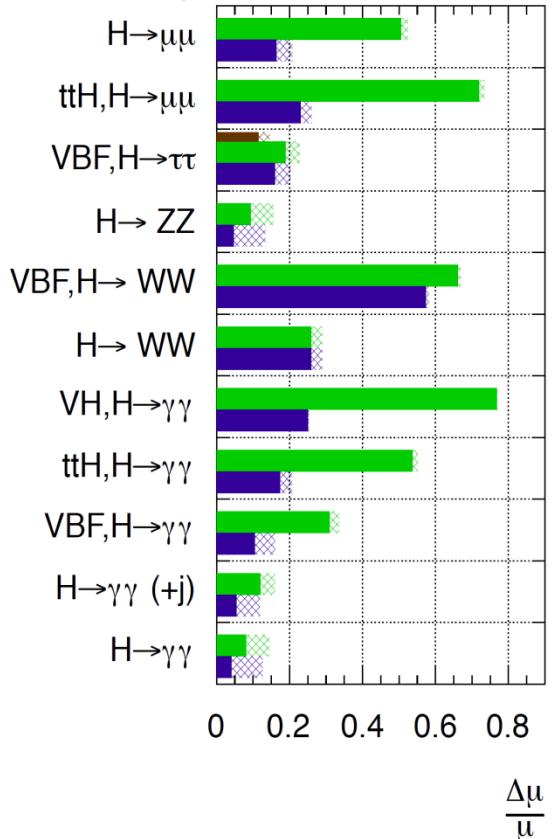
LHC prospects for next years

[1307.7135 [hep-ex]]

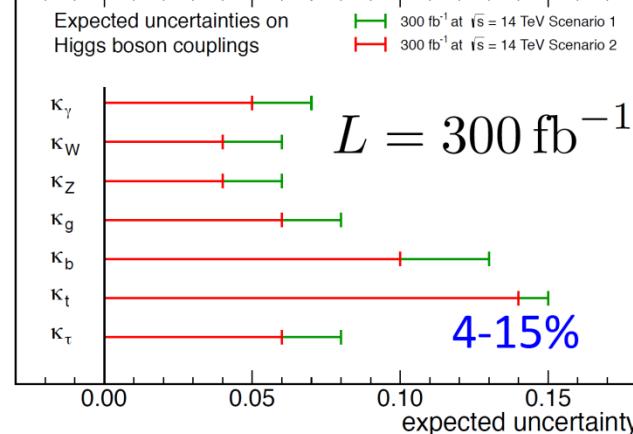
ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1}$

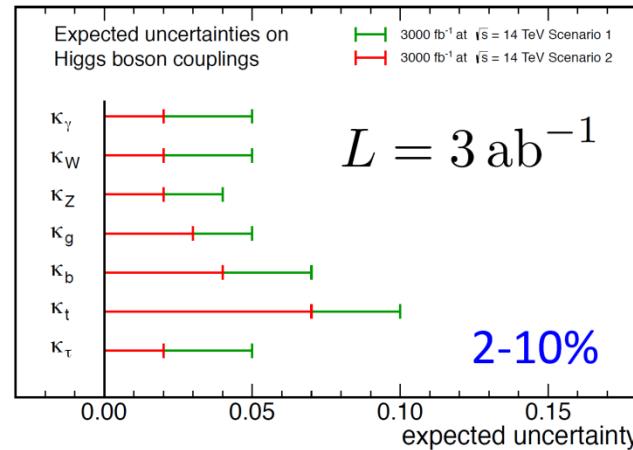
$\int L dt = 300 \text{ fb}^{-1}$ extrapolated from 7+8 TeV



CMS Projection



CMS Projection



Spectrum below 1 TeV

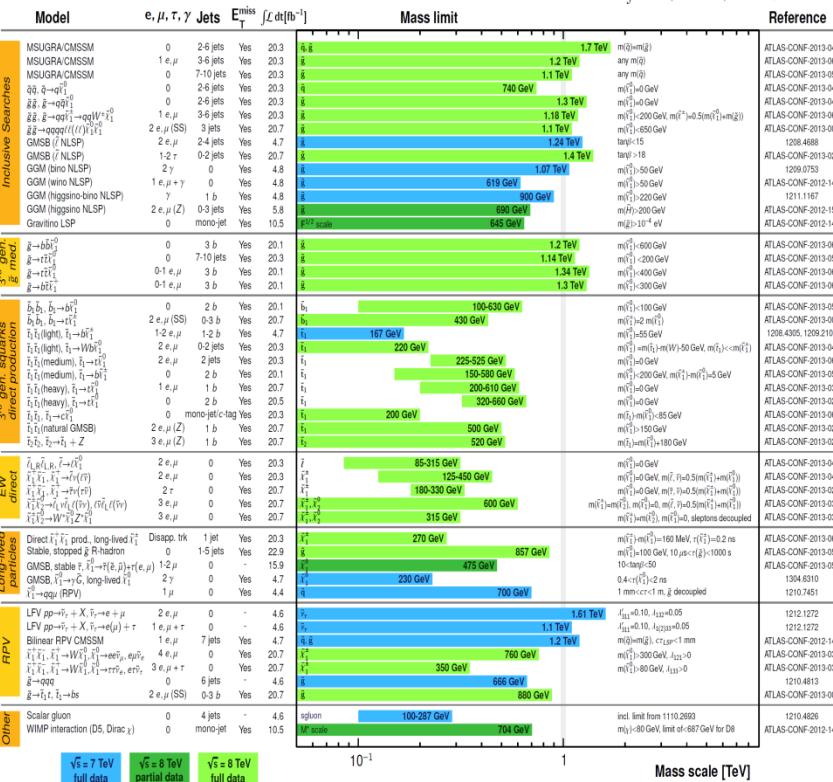
SM particles... and nothing else below the TeV

(e.g. SUSY exclusion limits)

ATLAS Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

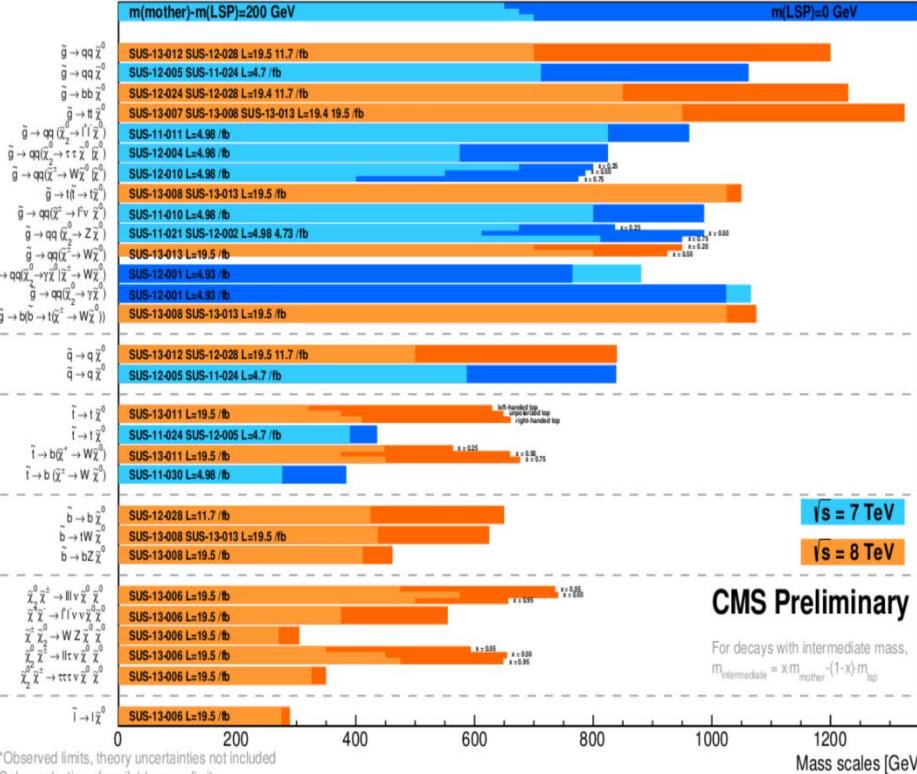
Status: EPS 2013



J.J. Sanz-Cillero

CMS Summary

Summary of CMS SUSY Results* in SMS framework EPSHEP 2013



- The ECLh is a general low-energy EFT *(even for non-composite models!!)*
- But for specific models one has specific predictions for the couplings

- For \mathcal{L}_2 (LO Lagrangian):

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

- For \mathcal{L}_4 (NLO Lagrangian): Less studied but

$c_\gamma = 0,$	Higgsles ECL
$a_i = 0, c_\gamma = 0,$	SM

- $O(p^d)$ loop divergence + $O(p^d)$ chiral coupling = UV-finite
- In OUR case, renormalization at $O(p^4)$: $a_1, a_2, a_3, c_\gamma \rightarrow a_1^r, a_2^r, a_3^r, c_\gamma^r$

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

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

- Calculation up to NLO
- Two different Goldstone coset parametrizations:
 - Exponential $U(x) = \exp i \frac{\tilde{\pi}}{v}$
 - Spherical $U(x) = \sqrt{1 - \frac{\omega^2}{v^2}} + i \frac{\tilde{\omega}}{v}$
- Two separate cross-checks: FeynArts+FeynRules & Analytical computation

- Masses neglected: $m_W, m_Z, m_h = 0$

[Their effects would enter as corrections proportional to m^2 .

E.g., the w^b wave-function renormalization would be]*

$$Z = 1 + \frac{(b-a^2)}{16\pi^2 v^2} A_0(m_h^2) - \frac{a^2 m_h^2}{32\pi^2 v^2}$$

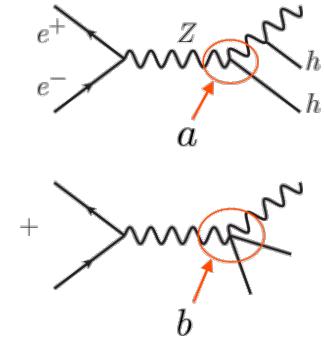
[More vertices and more couplings would be needed.

E.g., the b coupling for $hhWW$]

* Espriu,Mescia,Yencho '13

* Delgado,Dobado '13

Deviations from SM: BSM's



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

Higgsless ($\Delta a=100\%$) \rightarrow Loop scale at $\Lambda = 4\pi v = 3$ TeV

[Espinosa et al. '12]

[Delgado,Dobado,Herrero,SC '14]

$\Delta a=15\%$ \rightarrow Testing scales up to $\Lambda = 6$ TeV

$\Delta a=5\%$ \rightarrow Testing scales up to $\Lambda = 10$ TeV ...

Why so simple?

SO(5)/SO(4) MCHM

- SO(5) invariant model → Spontaneous breaking to SO(4) *[unspecified dynamics]*

- Usual CCWZ formalism*

$$\Phi_0 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \sin\theta \\ f \cos\theta \end{pmatrix} \longrightarrow \Phi(\omega^\alpha) = \mathbf{U}(\omega^\alpha) \Phi_0$$

- EFT construction in the exponential parametrization**

$$\mathcal{L}_2^{\text{MCHM}} = \frac{1}{2} D^\mu \Phi^\dagger D_\mu \Phi = \dots = \frac{1}{2} (\partial_\mu h)^2 + \frac{v^2}{4} \langle D^\mu U^\dagger D_\mu U \rangle \frac{f^2}{v^2} \sin^2 \left(\theta + \frac{h}{f} \right)$$



$$\mathcal{L}_2^{\text{MCHM}} = \frac{1}{2} (\partial_\mu h)^2 + \frac{v^2}{4} \langle D^\mu U^\dagger D_\mu U \rangle \left(1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \dots \right)$$

$$a^2 = \cos^2 \theta = 1 - \frac{v^2}{f^2},$$

$$b = \cos(2\theta) = 1 - 2 \frac{v^2}{f^2}.$$

* Coleman,Callan,Wess,Zumino '69

** Agashe,Contino,Pomarol '05

** Contino et al. '12

- However, in the S^4 spherical parametrization** $\Phi = \begin{pmatrix} \omega^1 \\ \omega^2 \\ \omega^3 \\ c\omega^4 + s\chi \\ -s\omega^4 + c\chi \end{pmatrix}$

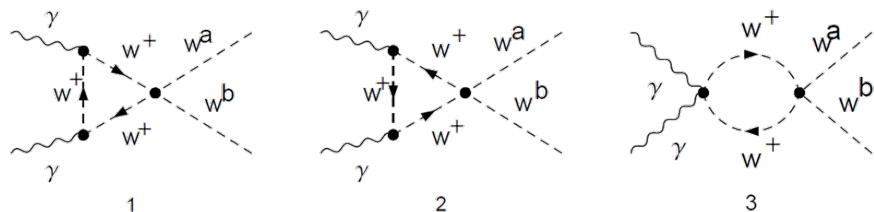
$$\chi = \left(f^2 - \sum_{\alpha} (\omega^{\alpha})^2 \right)^{1/2}$$

with $s = \sin \theta$, $c = \cos \theta$ and θ being the misalignment angle.

$$g_{\alpha\beta} = \delta_{\alpha\beta} + \frac{\omega^{\alpha}\omega^{\beta}}{f^2 - \sum_{\alpha} (\omega^{\alpha})^2}$$

$$\begin{aligned} \mathcal{L}_2^{\text{MCHM}} &= \frac{1}{2} g_{\alpha\beta}(\omega) D^{\mu}\omega^{\alpha} D_{\mu}\omega^{\beta} \\ &= \frac{1}{2} g_{\alpha\beta}(\omega) \partial^{\mu}\omega^{\alpha} \partial_{\mu}\omega^{\beta} + ieA_{\mu}(\omega^- \partial^{\mu}\omega^+ - \omega^+ \partial^{\mu}\omega^-) + e^2 A^2 \omega^+ \omega^- \end{aligned}$$

- The one-loop computations gets greatly simplified

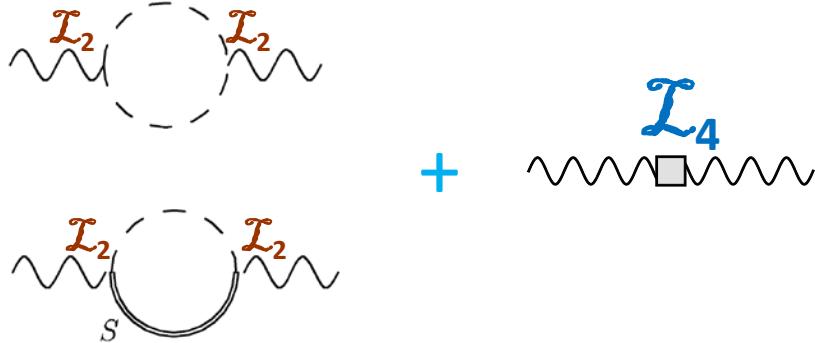


reproducing the previous (complicate) calculation

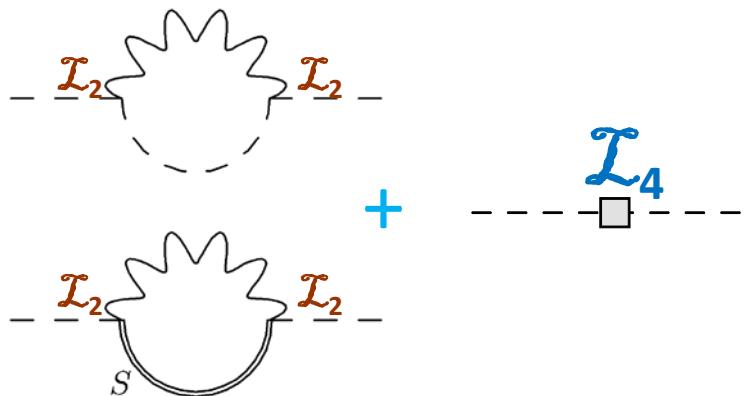
$$\begin{aligned} A(s, t, u)^{\gamma\gamma \rightarrow zz} &= -\frac{1}{4\pi^2 f^2} = -\frac{(1-a^2)}{4\pi^2 v^2} \\ A(s, t, u)^{\gamma\gamma \rightarrow w^+ w^-} &= -\frac{1}{8\pi^2 f^2} = -\frac{(1-a^2)}{8\pi^2 v^2} \end{aligned}$$

** Delgado,Dobado,Herrero,SC [forthcoming]

→ W^3B correlator*



→ NGB self-energy *



$$S = -16\pi \mathbf{a}_1^r(\mu) + \frac{(1-a^2)}{12\pi} \left(\frac{5}{6} + \ln \frac{\mu^2}{m_h^2} \right)$$

3 eff. couplings →

$$T = \frac{8\pi}{c_W^2} \mathbf{a}_0^r(\mu) - \frac{3(1-a^2)}{16\pi c_W^2} \left(\frac{5}{6} + \ln \frac{\mu^2}{m_h^2} \right)$$

* Dobado et al. '99

* Pich, Rosell, SC '12, '13

* Delgado,Dobado,Herrero,SC [in prep]

- More observables* can over-constrain the $a_i(\mu)$
BUT not (S,T) alone!!!

- Taking just tree-level is incomplete $\longrightarrow \left[\begin{array}{l} S = -16\pi a_1(\mu?) , \\ T = \frac{8\pi}{c_W^2} a_0(\mu?) \end{array} \right]$
- and similar if only loops $\longrightarrow \left[\begin{array}{l} S = \frac{(1-a^2)}{12\pi} \ln \frac{\mu^2}{m_h^2} , \\ T = -\frac{3(1-a^2)}{16\pi c_W^2} \ln \frac{\mu^2}{m_h^2} \end{array} \right]$

- 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

Deviations from SM: BSM's

- ❖ Different models → Different deviations from SM

$$(a = \kappa_W = \kappa_V)$$

- $\mathcal{O}(p^2)$ Lagrangian in particular models:

$$a^2 = b = 0$$

(Higgsless ECL)

$$a^2 = b = 1$$

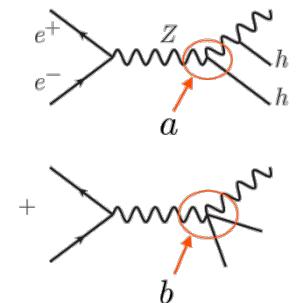
(SM),

$$a^2 = 1 - \frac{v^2}{f^2}, \quad b = 1 - \frac{2v^2}{f^2}$$

(SO(5)/SO(4) MCHM),

$$a^2 = b = \frac{v^2}{\hat{f}^2},$$

(Dilaton).



- $\mathcal{O}(p^4)$ Lagrangian in particular models:

$$c_W = c_B = c_\gamma = \dots = 0$$

(Higgsless ECL),

$$a_i = c_W = c_B = c_\gamma = \dots = 0$$

(SM),

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

Higgsless ($\Delta a=100\%$) → Loop scale at $\Lambda=4\pi v=3$ TeV

[Espinosa et al. '12]

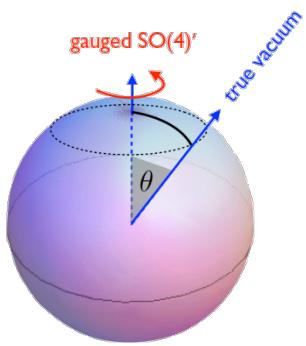
$\Delta a=15\%$

→ Testing scales up to $\Lambda=6$ TeV

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

$\Delta a=5\%$

→ Testing scales up to $\Lambda=10$ TeV ...



The Light Higgs as a Goldstone:

MCHM $SO(5)/SO(4)$ *

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

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

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

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

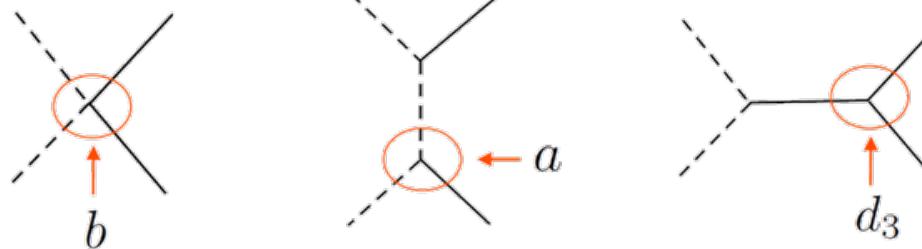
PRECISION FRONTIER

[Contino 'EPS-HEP-2013]

2. Scatterings involving the Higgs also grow with energy

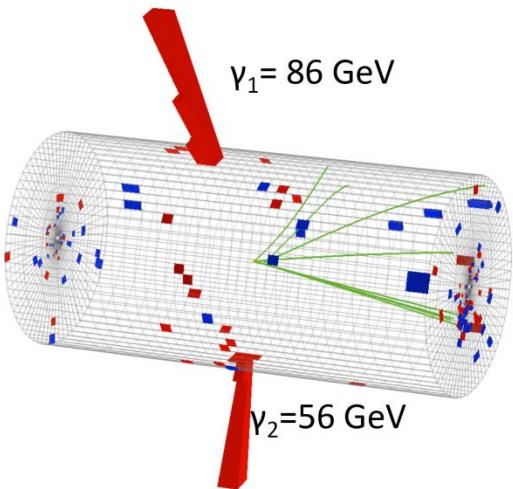
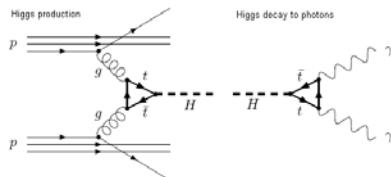
ENERGY FRONTIER

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

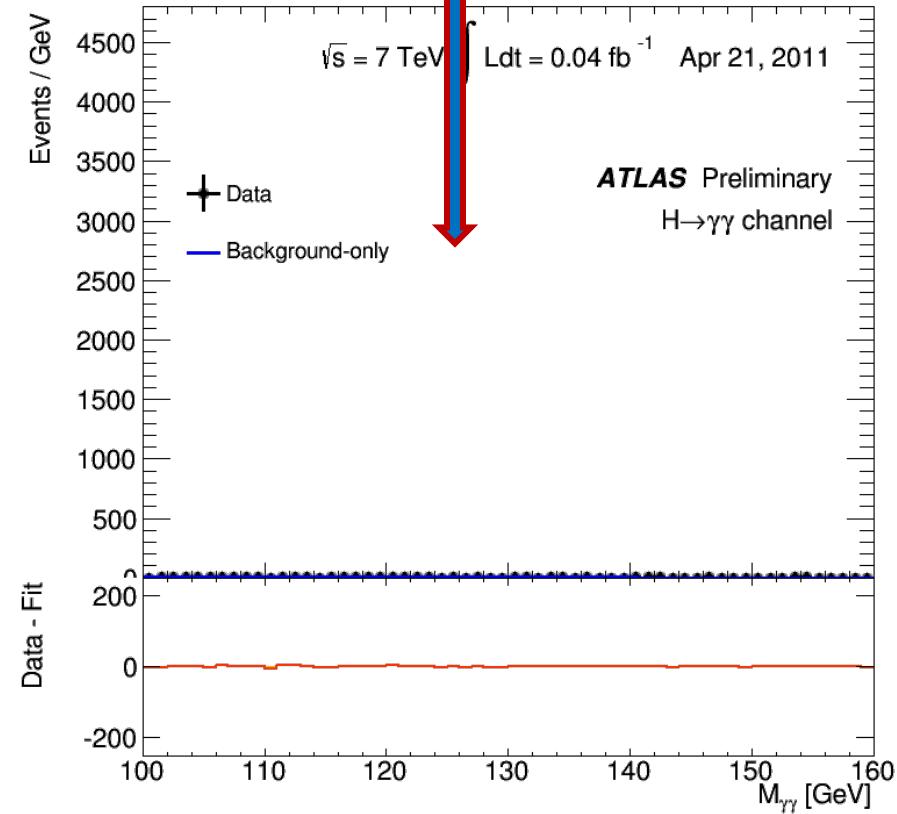
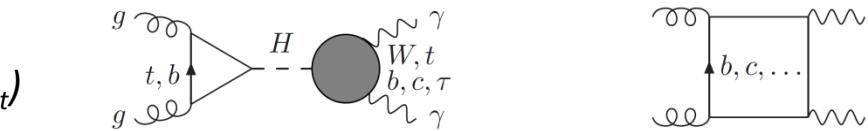
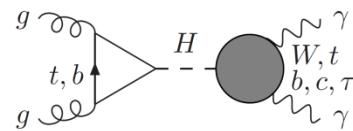


$H \rightarrow \gamma\gamma$

- Higgs decay through a top loop
(mainly enhanced by $H \rightarrow tt$ coupling; prop. to m_t)



Signature: 2 energetic, isolated γ ,
a narrow mass peak on top of a
steeply falling spectrum



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

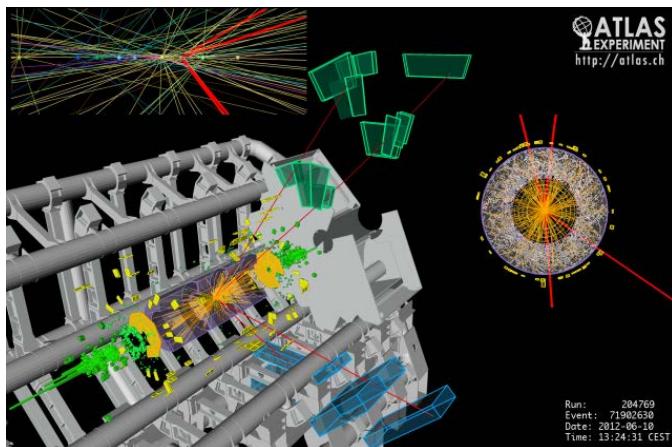
$$H \rightarrow ZZ^* \rightarrow 4\ell$$

The final states considered are 4μ , $4e$, $2e2\mu$

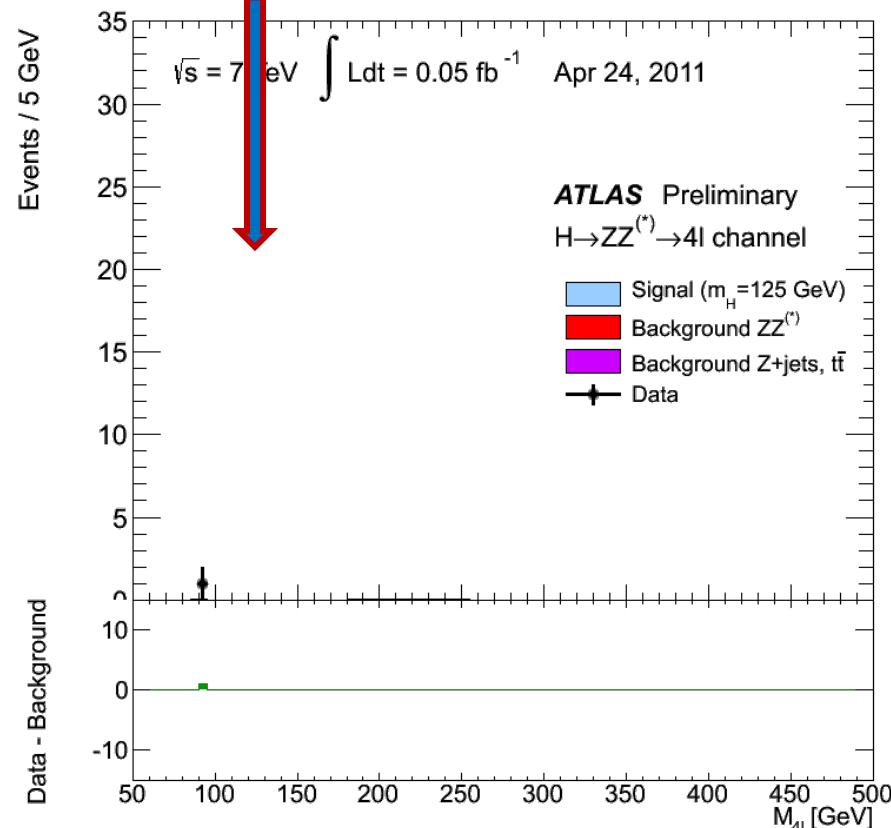
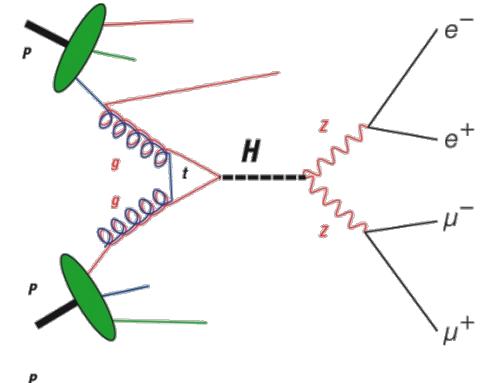
Very clean final state:

- 4 leptons of high p_T ,
- isolated
- coming from the primary vertex

**But a clear
Very tiny cross section → distinctive
signal**



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



EFTs and the composite option

- Large mass gap + small coupling deviations from SM:

An appropriate tool → Effective theories:

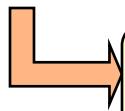
Non-linear “Chiral” Lagrangians
w/ EW Goldstones +Higgs

Full NLO
computations
necessary

- Strongly interacting models? Composite states?

Technicolor (and relatives)
Composite Higgs [e.g., $SO(5)/SO(4)$]
Extra Dimensions (also)

...



**Tower of composite
resonances* (QCD-like)**

* Arkani-Hamed et al. '01

* Csaki et al. '04

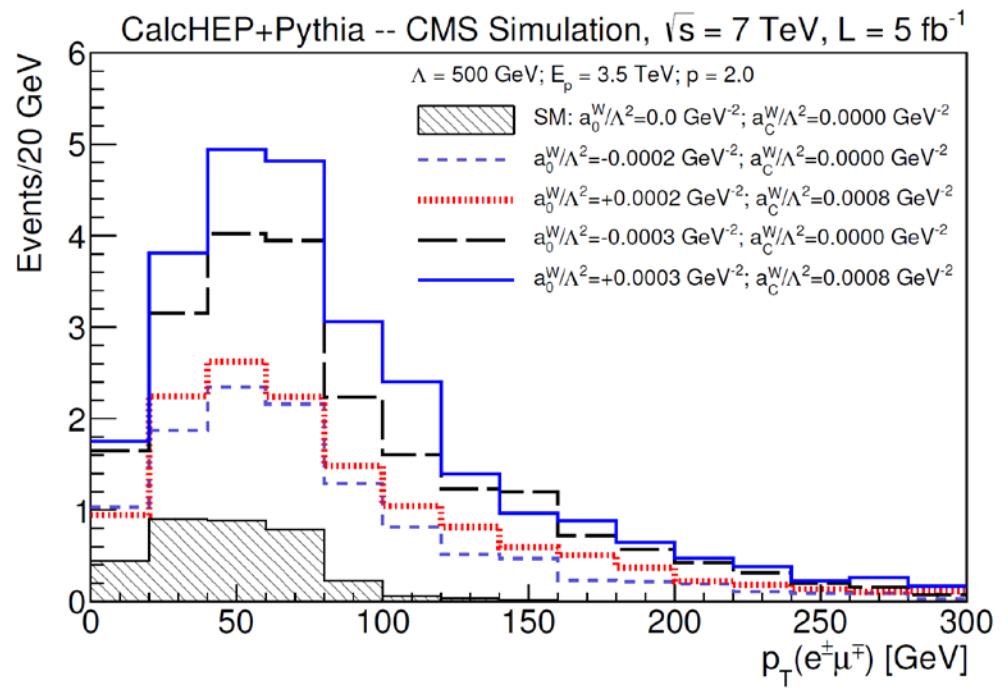
* Cacciapaglia et al. '04

* Agashe, Contino, Pomarol '05

* Hirn, Sanz '06 ...

- UV-finite also with Higgs (as in Higgsless ECL)

- Renormalization (or lack of it): $c_\gamma^r = c_\gamma$



* CMS, JHEP 07(2013) 116

$pT > 100 \text{ GeV}$

- Again, UV-finite also with Higgs (as in Higgsless ECL)
- Renormalization (or lack of it) + $\gamma\gamma \rightarrow zz$ result: $\gamma(k_1, \epsilon_1)\gamma(k_2, \epsilon_2) \rightarrow z(p_1)z(p_2)$

$$(a_1^r - a_2^r + a_3^r) = (a_1 - a_2 + a_3)$$

- Since $a^{\text{exp}} \approx 1$, full one-loop amplitude not simply suppressed by $\frac{p^2}{16\pi^2 v^2}$
 - but stronger loop suppression by $\frac{(1 - a^2) p^2}{16\pi^2 v^2}$
- [we can rewrite our particular result for the suppression in the form $\frac{p^2}{16\pi^2 f^2}$ with $f^2 = \frac{v^2}{|1 - a^2|}$]