

ECLh
and $\gamma\gamma \rightarrow Z_L Z_L, W_L^+ W_L^-$
at the one-loop level



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R. Delgado, A. Dobado, M.J. Herrero and JJ SC [forthcoming]

OUTLINE

- 1) Introduction: searching for tiny deviations from SM
- 2) The EW Chiral Lagrangian+Higgs (ECLh): Power counting
- 3) $\gamma\gamma \rightarrow W_L^a W_L^b$ scattering up to NLO [$O(e^2 p^2)$; 1 loop]

Discussion:

Related observable and (future) pheno

UV-finiteness and running

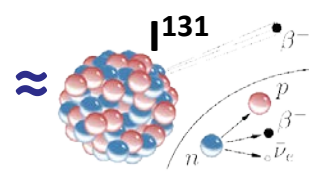
Understanding the simplicity: $SO(5)/SO(4)$ MCHM

Introduction:

Deviations from SM?

•A new Higgs-like boson discovered at LHC

• $M_H = 125.64 \pm 0.35 \text{ GeV}$



•Still many questions:

- Spin?

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

- Coupling to gauge bosons?

Very close to SM's

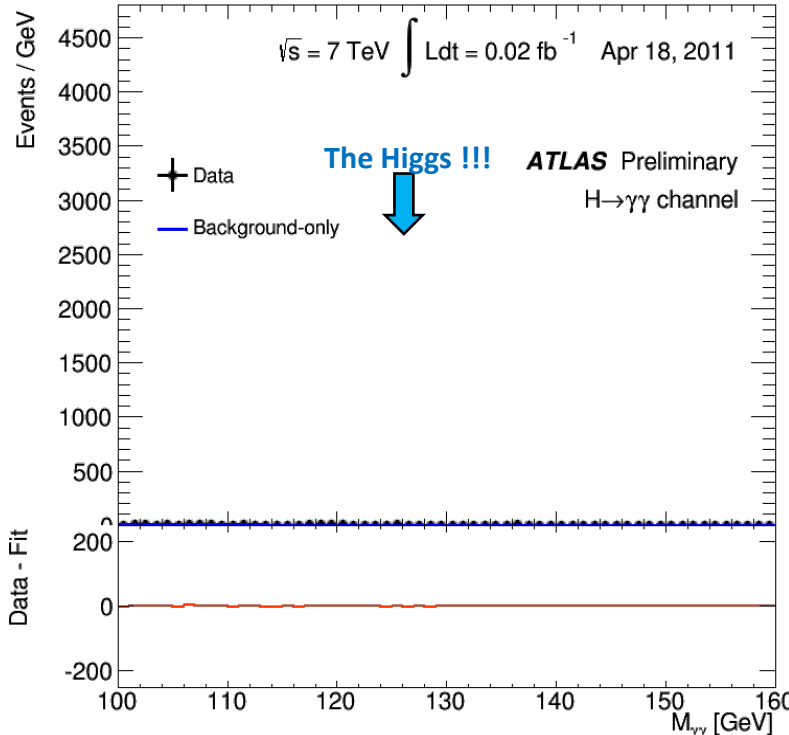
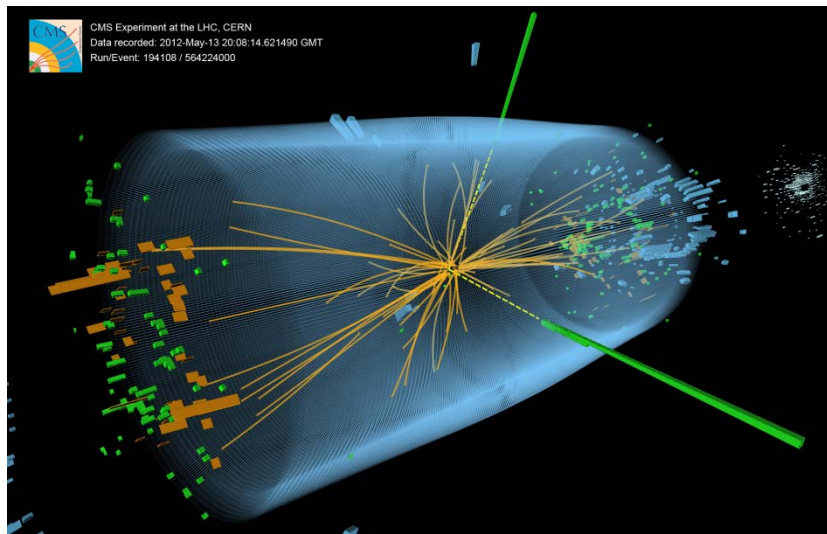
- Invisible decays vs SM?

- 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

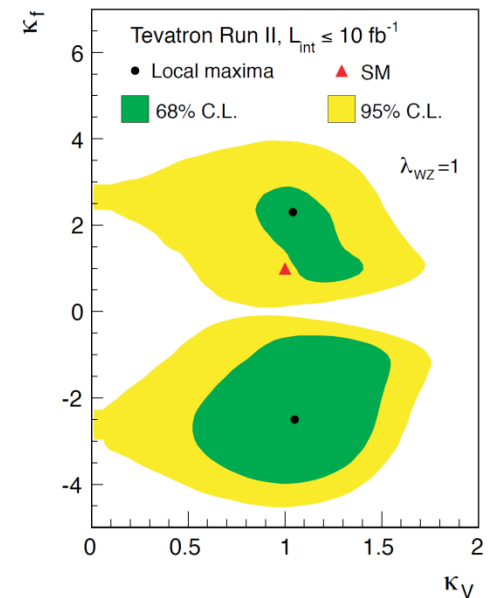
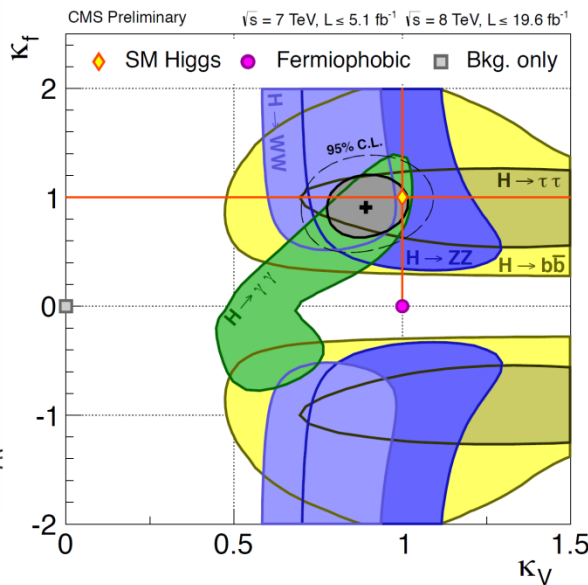
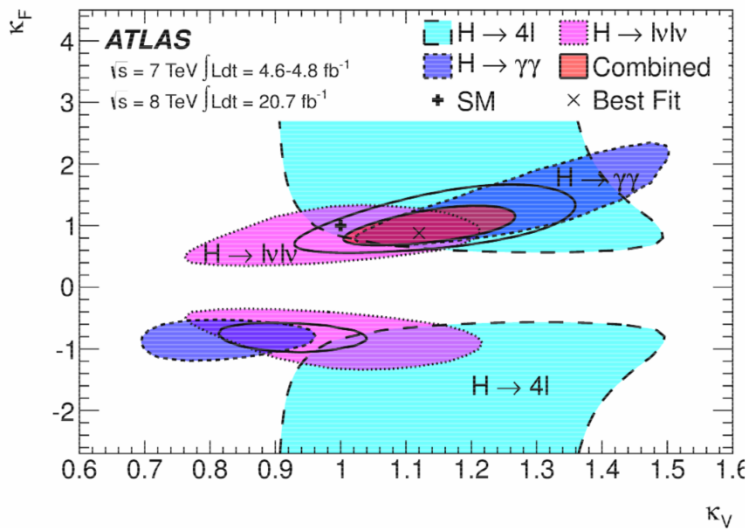
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[<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Animations>]

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]

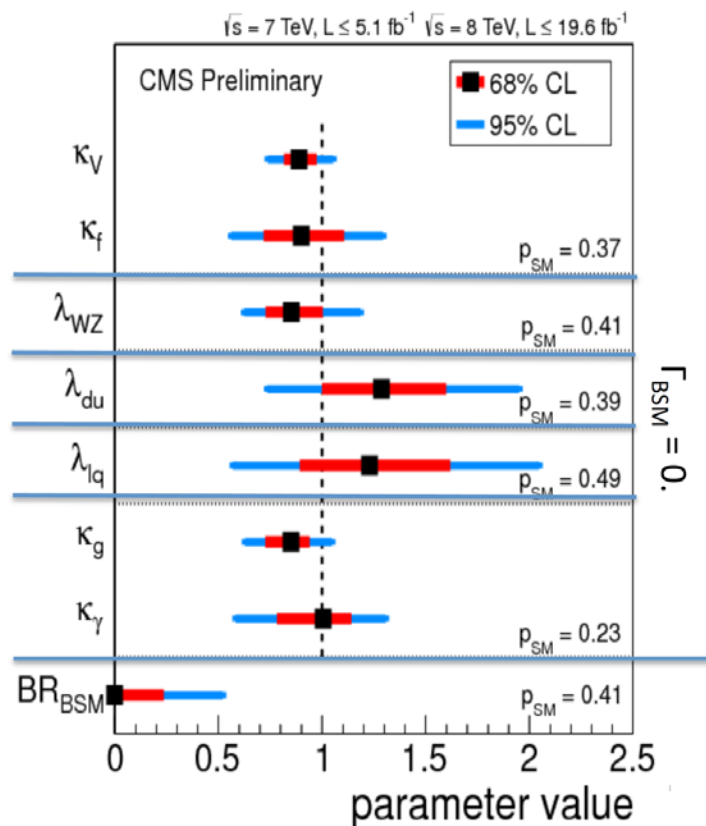
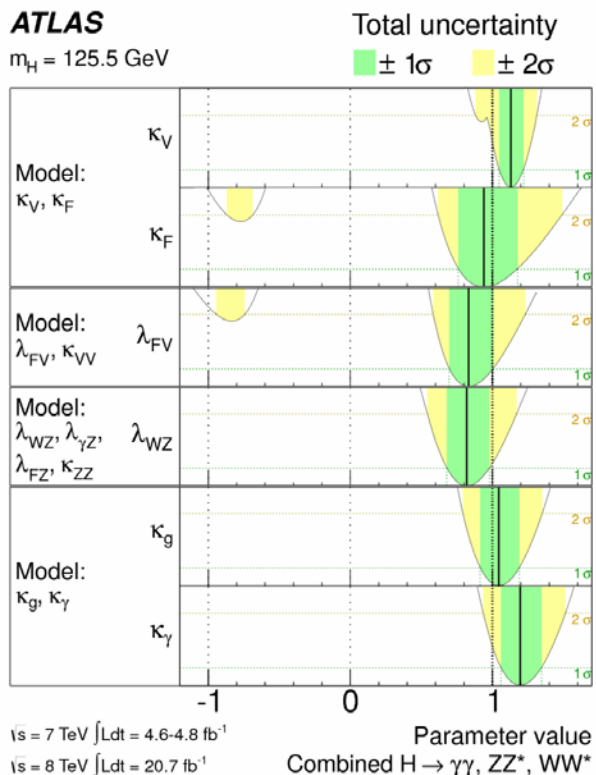
[1307.1427 [hep-ex]]

[1303.4571 [hep-ex]]

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

Summary of all searches for coupling deviations

C. Moratti [ATLAS]



- Compatibility with the SM
- Best uncertainties ($\alpha \approx 10\%$)

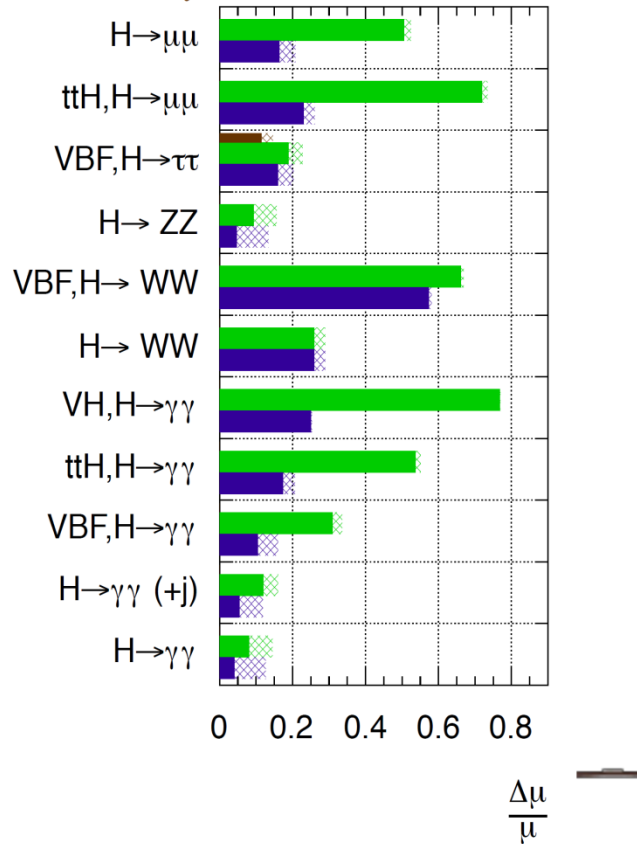
LHC prospects for next years

[1307.7135 [hep-ex]]

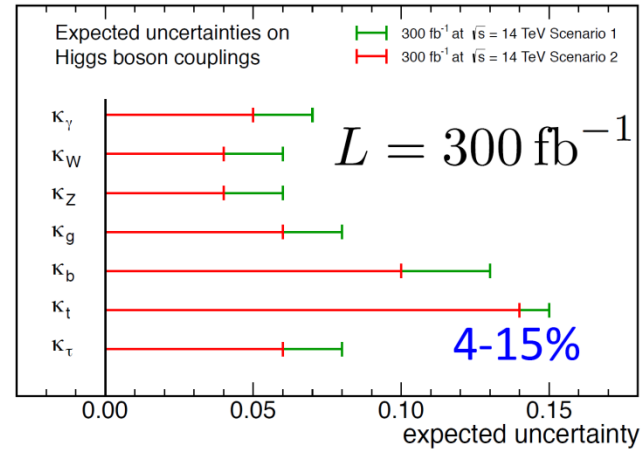
ATLAS Preliminary (Simulation)

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

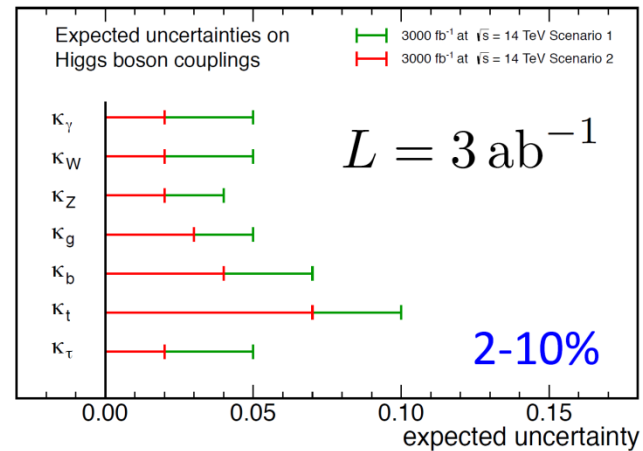
$\int L dt = 300 \text{ fb}^{-1}$ extrapolated from 7+8 TeV



CMS Projection



CMS Projection



Spectrum below 1 TeV

SM particles... and nothing else below the TeV

(e.g. SUSY exclusion limits)

ATLAS Summary

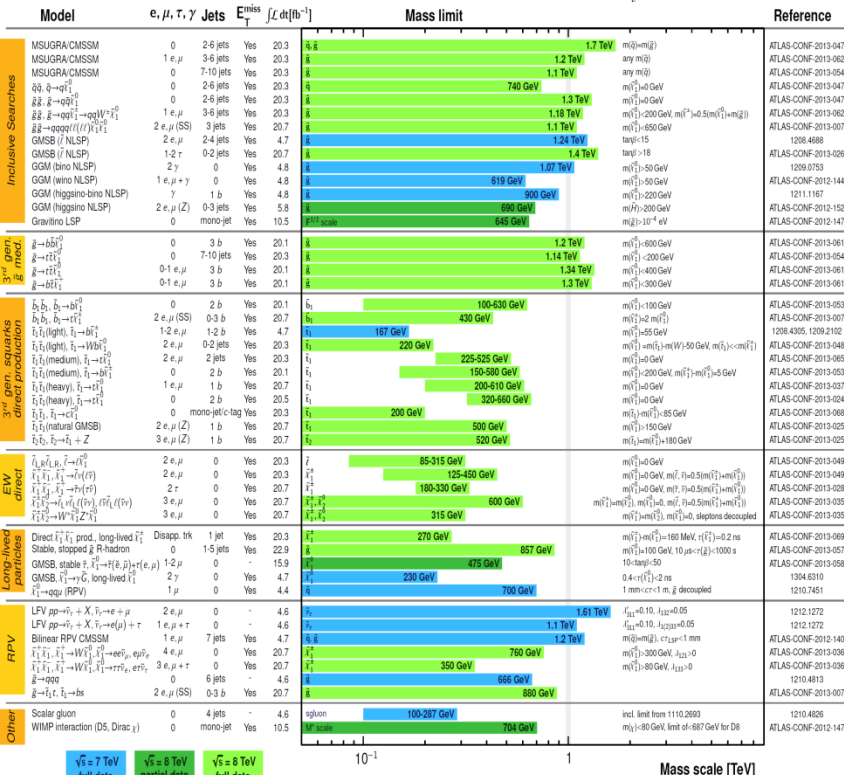
CMS Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

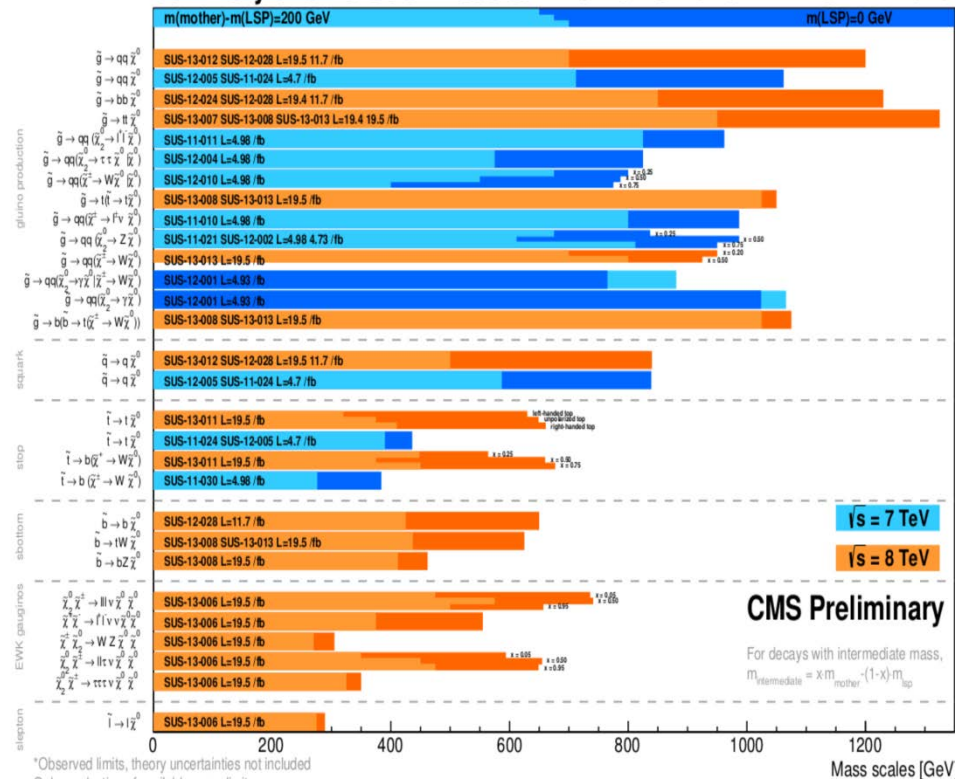
Status: EPS 2013

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$
 $\int \mathcal{L} dt = (4.4 - 22.9) \text{ fb}^{-1}$



Summary of CMS SUSY Results* in SMS framework EPSHEP 2013



CMS Preliminary

For decays with intermediate mass,
 $m_{\text{intermediate}} = x m_{\text{mother}} - (1-x) m_{\text{lep}}$

*Observed limits, theory uncertainties not included
Only a selection of available mass limits

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

EFTs and the composite option

- Large mass gap + small coupling deviations from SM:

An appropriate tool $\rightarrow$ 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)

...

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

EW Chiral Lagrangian + Higgs (ECLh):

Low-energy EFT

•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: $m_{W,Z} \ll E$

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

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 $g, g' \rightarrow 0$

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

RANGE OF VALIDITY

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

•Building blocks^(x):

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

$$\mathcal{F}(h) = 1 + 2a \frac{h}{v} + b \left(\frac{h}{v} \right)^2 + \dots,$$

$$D_\mu U = \partial_\mu U + i \hat{W}_\mu U - i U \hat{B}_\mu,$$

$$\hat{W}_{\mu\nu} = \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu + i [\hat{W}_\mu, \hat{W}_\nu], \quad \hat{B}_{\mu\nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu,$$

$$\hat{W}_\mu = g \vec{W}_\mu \vec{\tau} / 2, \quad \hat{B}_\mu = g' B_\mu \tau^3 / 2,$$

$$V_\mu = (D_\mu U) U^\dagger, \quad \mathcal{T} = U \tau^3 U^\dagger,$$

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^{*,**}

$$g^{(\prime)} \sim m_{W,Z} / v \sim p / v$$

[notice $e \sim p / v$ too]

(x) Appelquist, 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 [in prep.]

** 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=κ_V=κ_W=c_W=ω=etc.

→NLO Lagrangian^{*,**}:

$$\begin{aligned} \mathcal{L}_4 = & a_1 \text{Tr}(U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu}) + i a_2 \text{Tr}(U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu]) - i a_3 \text{Tr}(\hat{W}_{\mu\nu} [V^\mu, V^\nu]) \\ & - c_W \frac{h}{v} \text{Tr}(\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}) - c_B \frac{h}{v} \text{Tr}(\hat{B}_{\mu\nu} \hat{B}^{\mu\nu}) + \dots \\ & - \frac{c_\gamma}{2} \frac{h}{v} e^2 A_{\mu\nu} A^{\mu\nu} + \dots \end{aligned}$$

* Apelquist,Bernard '80
* Longhitano '80, '81
** $\mathcal{L}_4$ conventions from Brivio et al. '13

- The ECLh is a general low-energy EFT
- 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

$$a_i = 0, \quad c_\gamma = 0,$$

SM

Counting, loops & renormalization

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

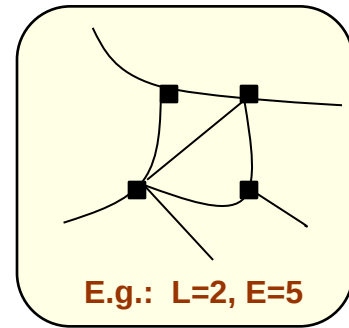
$$\mathcal{L}_d = \sum_k f_k^{(d)} p^d \left(\frac{\chi}{v} \right)^k$$

$$\begin{aligned} f_k^{(2)} &\sim v^2 \\ f_k^{(4)} &\sim a_i \\ &\dots \end{aligned}$$

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 [in prep.]
 ** 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)

Any # of $\mathcal{L}_2$
vertices

loops

of $\mathcal{L}_4$
vertices

- In OUR case, $\mathcal{M}(\gamma\gamma \rightarrow w^a w^b)$ up to NLO:

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

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

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

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

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

- In OUR case, renormalization at $O(p^4)$: $a_1, a_2, a_3, c_\gamma \rightarrow a_1^r, a_2^r, a_3^r, c_\gamma^r$

$$C^r(\mu) = C^{(B)} + \frac{\Gamma_C}{32\pi^2} \frac{1}{\hat{\epsilon}}$$

$$\frac{dC^r}{d\ln\mu} = -\frac{\Gamma_C}{16\pi^2}$$

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

** Espriu, Mescia, Yengo '13

** Delgado, Dobado '13

The calculation:

$$\gamma\gamma \rightarrow zz \text{ and } \gamma\gamma \rightarrow w^+w^-$$

- 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 (aka by hand)
- 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

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

$$\gamma(k_1, \epsilon_1) \gamma(k_2, \epsilon_2) \rightarrow z(p_1) z(p_2)$$

can be described by 2 scalar functions A & B:

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

(similar for the w+w- channel)

with the Lorentz structures and Mandelstam variables

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

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

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

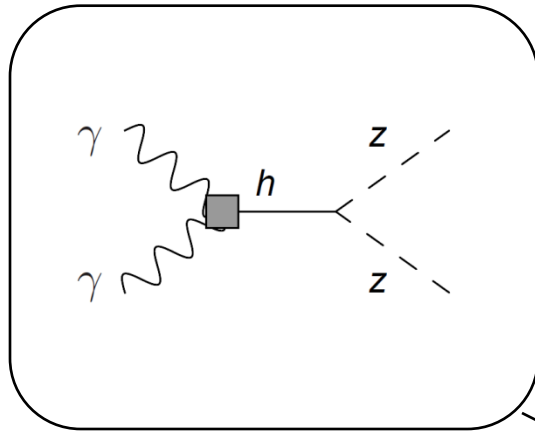
$$s = (k_1 + k_2)^2, \quad t = (k_1 - p_1)^2, \quad u = (k_1 - p_2)^2$$

$\gamma\gamma \rightarrow zz$

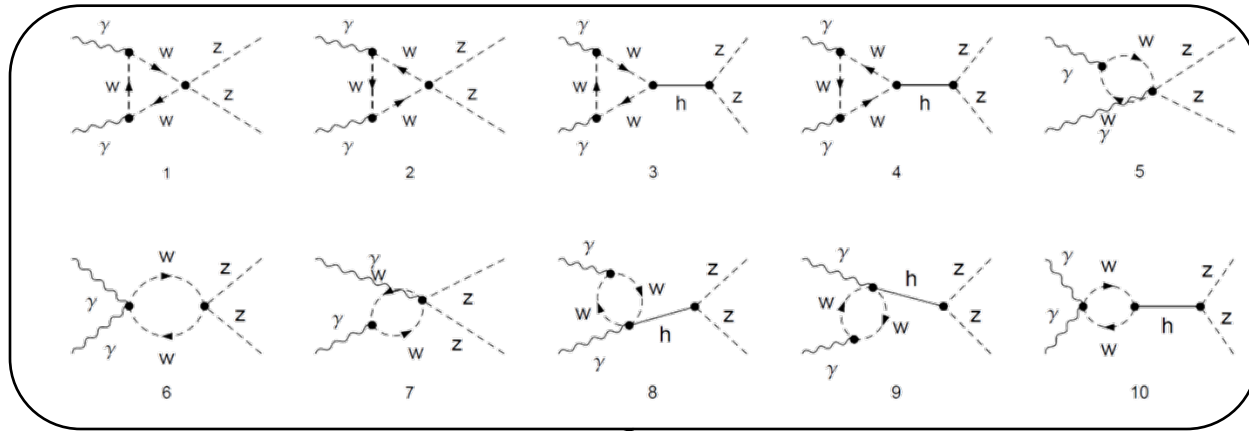
•LO (no contribution): $\mathcal{M}(\gamma\gamma \rightarrow zz)_{\text{LO}} = 0$

•NLO:

→ Tree-level



→ One-loop *



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

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

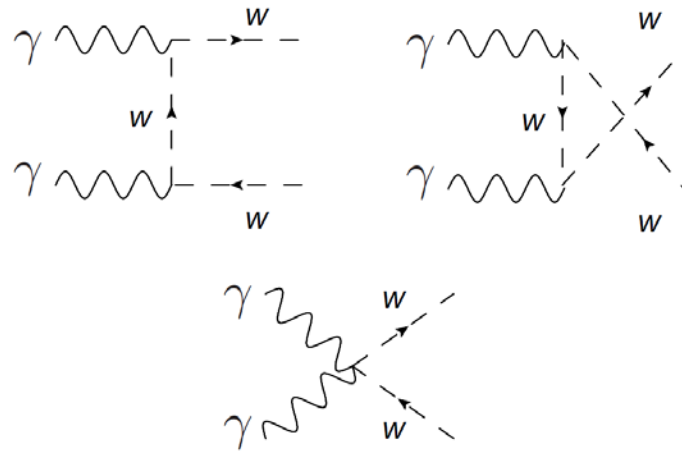
* In agreement with Ametller, Talavera '14

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

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

$$\gamma\gamma \rightarrow w^+w^-$$

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



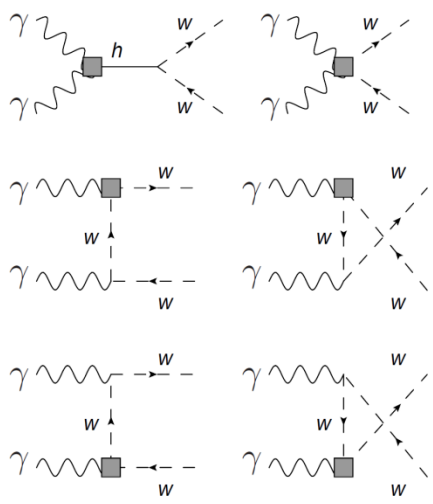
[Born term]

•NLO:

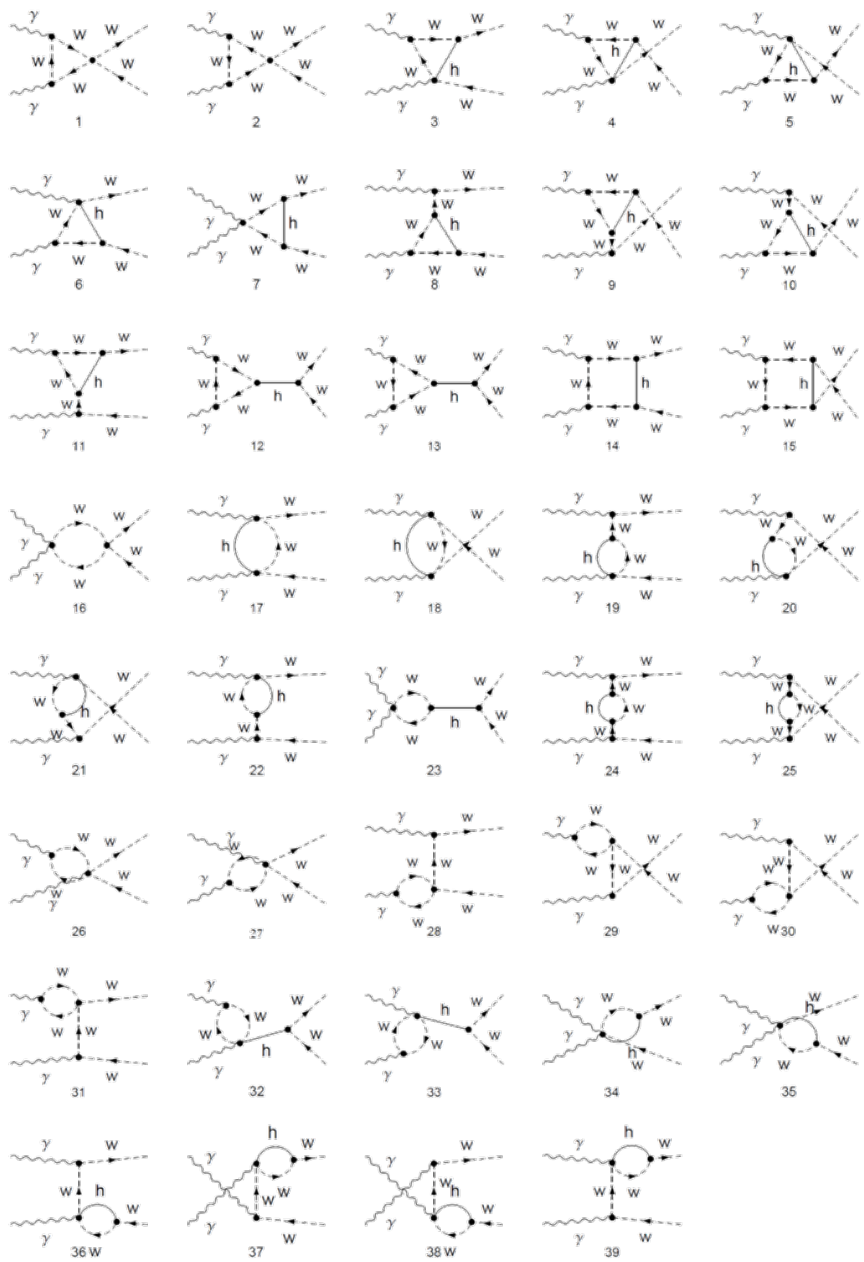
→ Tree-level

→ One-loop

•NLO: ➔Tree-level



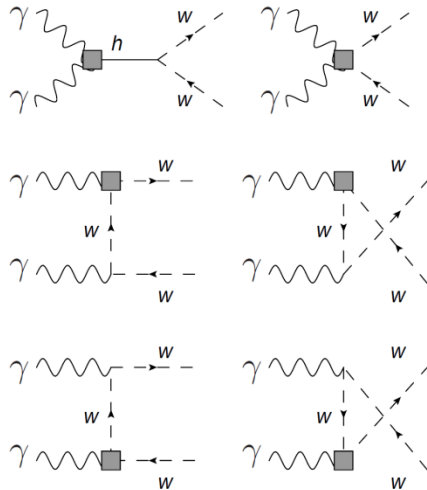
➔One-loop



It may look complicated

•NLO: →Tree-level

→One-loop



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

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

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

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

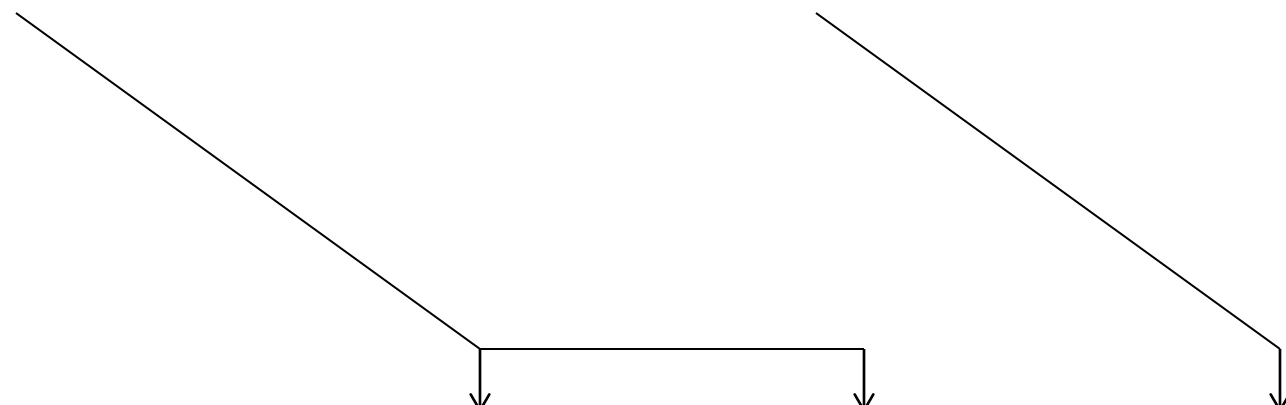
$$\mathcal{M}^5 = \frac{ia^2 e^2}{288\pi^2 v^2} \left(3B_0(u,0,0)(2(\epsilon_1 \epsilon_2) u - 5((\epsilon_1 \Delta) - (\epsilon_1 k_2))((\epsilon_2 \Delta) + (\epsilon_2 k_1))) \right. \\ \left. - (\epsilon_1 \Delta)((\epsilon_2 \Delta) + (\epsilon_2 k_1)) + (\epsilon_1 k_2)((\epsilon_2 \Delta) + (\epsilon_2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

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!!!

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

- Renormalization (or lack of it) + $\gamma\gamma\rightarrow zz$ result:

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

- 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 $f^2 = \frac{v^2}{|1 - a^2|}$]

Discussion:

Related observables, running,
and simplicity

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	$(a_1^r - a_2^r + a_3^r), \quad c_\gamma^r$
$\Gamma(h \rightarrow \gamma\gamma)$	a	c_γ^r
S -parameter	a	a_1^r
$\mathcal{F}_{\gamma^*ww}$	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 $\{a, c_\gamma, a_1, (a_2 - a_3)\}$

ECLh running at $O(p^4)$

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

**RG
INVARIANTS**

	ECLh	ECL ⁽⁺⁾ (Higgsless)
$\rightarrow \Gamma_{a_1 - a_2 + a_3}$	0	0
$\rightarrow \Gamma_{c_\gamma}$	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 [forthcoming]

** Espriu, Mescia, Yencho '13

** Delgado, Dobado '13

* Herrero, Morales '95

(x) In agreement with Ametller, Talavera '14

Why so simple? SO(5)/SO(4) MCHM

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

- Usual CCWZ formalism*
$$\Phi_0 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \sin \theta \\ f \cos \theta \end{pmatrix} \longrightarrow \Phi(\omega^\alpha) = U(\omega^\alpha) \Phi_0$$

- 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

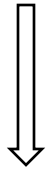
** Contino et al. '12

- However, in the S^4 spherical parametrization**

$$\Phi = \begin{pmatrix} \omega^1 \\ \omega^2 \\ \omega^3 \\ c\omega^4 + s\chi \\ -s\omega^4 + c\chi \end{pmatrix} \quad \chi = \left(f^2 - \sum_{\alpha} (\omega^{\alpha})^2 \right)^{1/2}$$

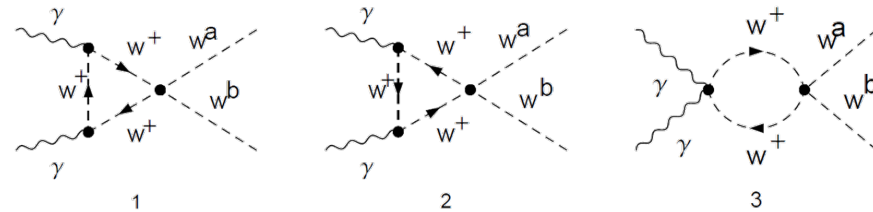
with $s = \sin \theta$, $c = \cos \theta$ and θ being the misalignment angle.

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



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

- 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]

Conclusions

- ✓ **Framework:**
 - $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ EFT w/ NGB's + Higgs (ECLh)
 - Power counting for individual contributions (loops + tree)
 - Important cancellations in the full amplitude (stronger suppression $4\pi f$)
 - Full $\gamma\gamma \rightarrow W^a W^b$ up to NLO for the range $m_W, m_Z, m_h \ll E \ll \Lambda_{ECLh}$

- ✓ **Optimal tool to discern new physics** (under minimal assumptions)

- ✓ **Renormalization, UV-finiteness and (no) running:** RG invariants

→ Partial understanding through $SO(5)/SO(4)$ MCHM

[a possible enlarged symmetry in the massless Higgs limit]

- ✓ **Phenomenological proposal for $\{a, c_\gamma, a_1, (a_2 - a_3)\}$:**

$\gamma\gamma$ -scattering + S-parameter + $\Gamma(h \rightarrow \gamma\gamma)$ + $w^+ w^- \gamma^*$ VFF + $h\gamma\gamma^*$ TFF

BACKUP SLIDES

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 $\Lambda^{\text{“phys”}}$*



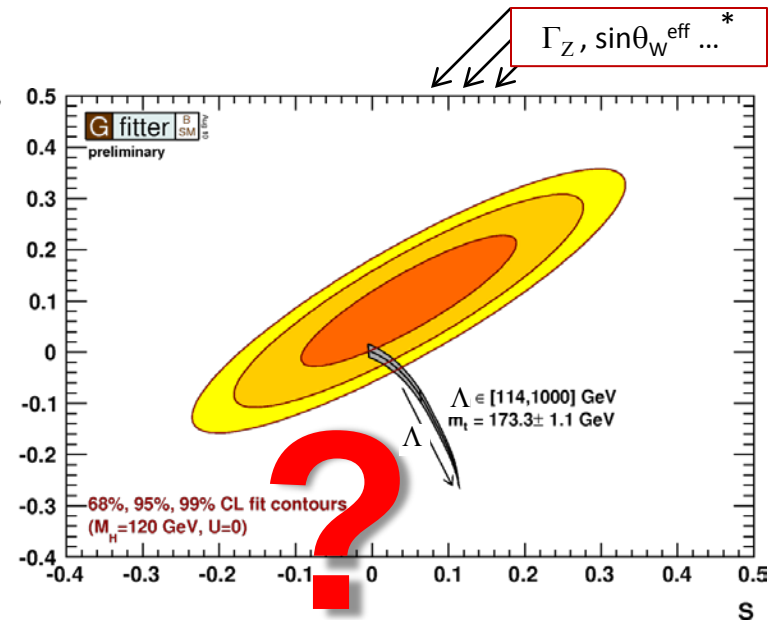
$$S \approx \frac{1}{12\pi} \ln \frac{\Lambda^2}{m_{H,ref}^2},$$

$$T \approx -\frac{3}{16\pi \cos^2 \theta_W} \ln \frac{\Lambda^2}{m_{H,ref}^2}$$



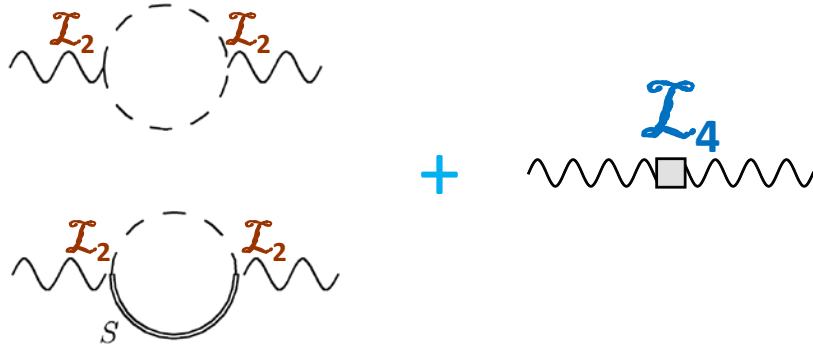
-EFT: Loops + effective couplings

(ALWAYS!!!)



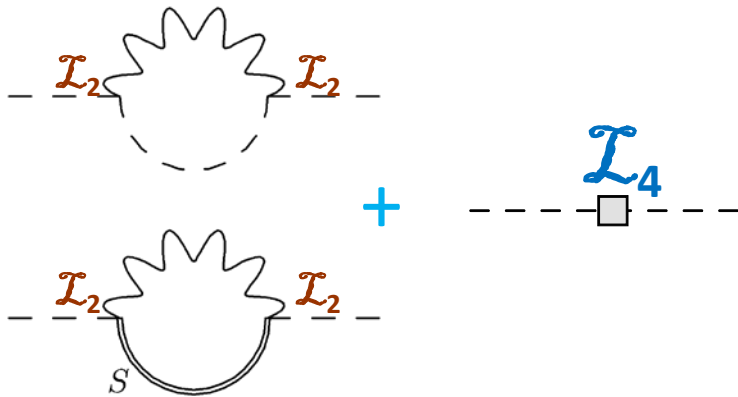
* Peskin, Takeuchi '92

→ W^3B correlator*



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

→ NGB self-energy*



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

- Otherwise, one may resource to models**:

$\rightarrow$ Resonances

(lightest $V + A$)

$\rightarrow$ 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:

$$a^2 = b = 0$$

$$a^2 = b = 1$$

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

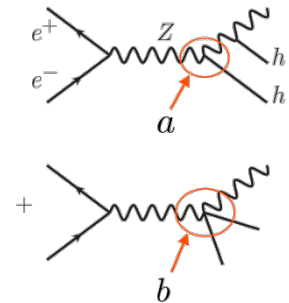
$$a^2 = b = \frac{v^2}{f^2},$$

(Higgsless ECL)

(SM),

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

(Dilaton).



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

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

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

(Higgsless ECL),

(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 $\Lambda = 4\pi v = 3 \text{ TeV}$

$\Delta a = 15\%$

→ Testing scales up to $\Lambda = 6 \text{ TeV}$

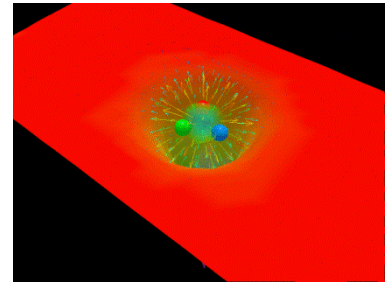
$\Delta a = 5\%$

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

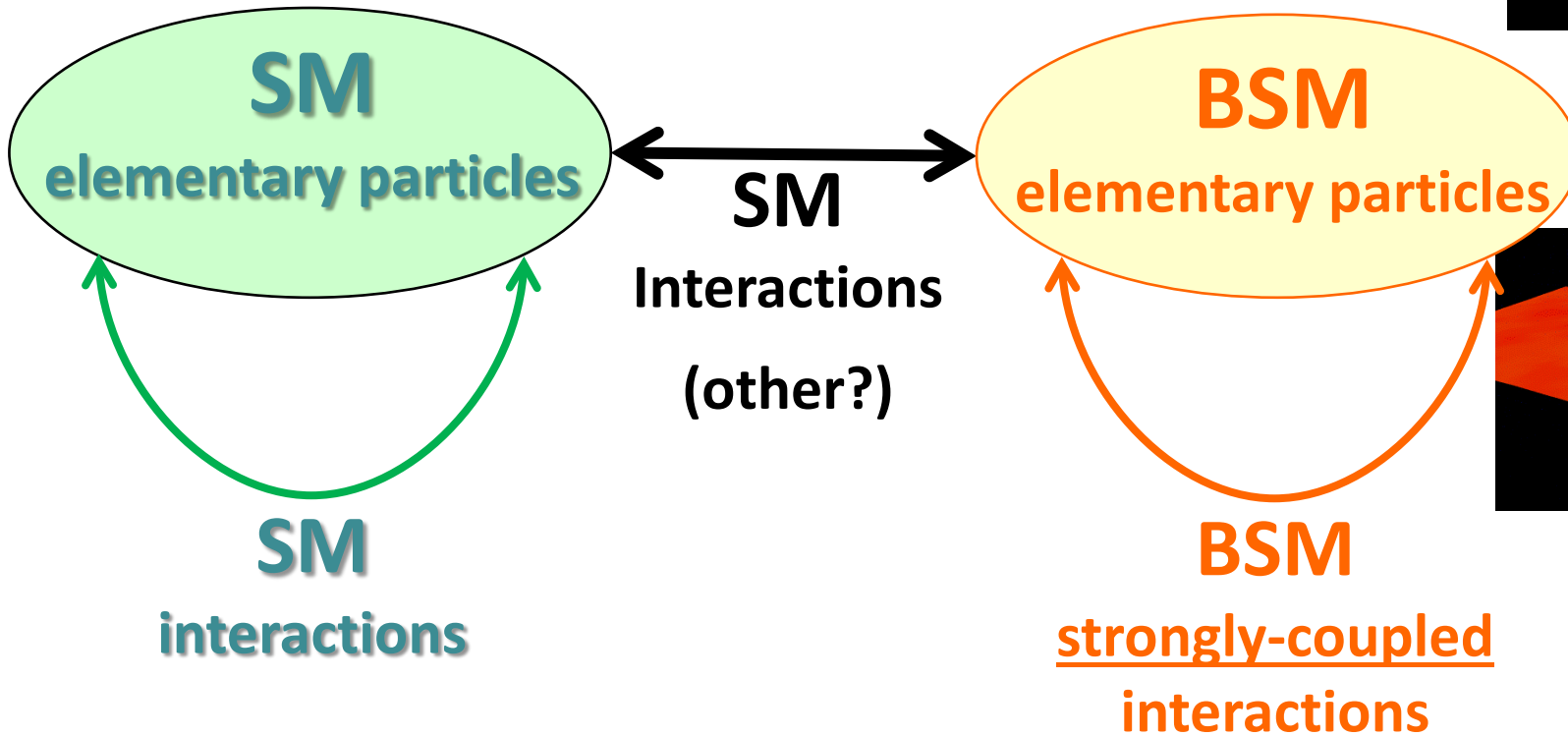
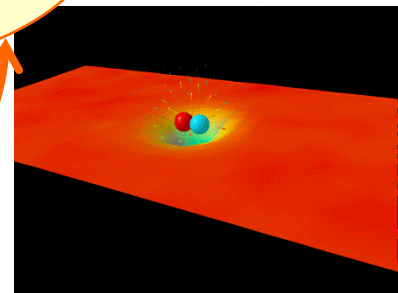
[Espinosa et al. '12]

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

Strongly coupled BSM



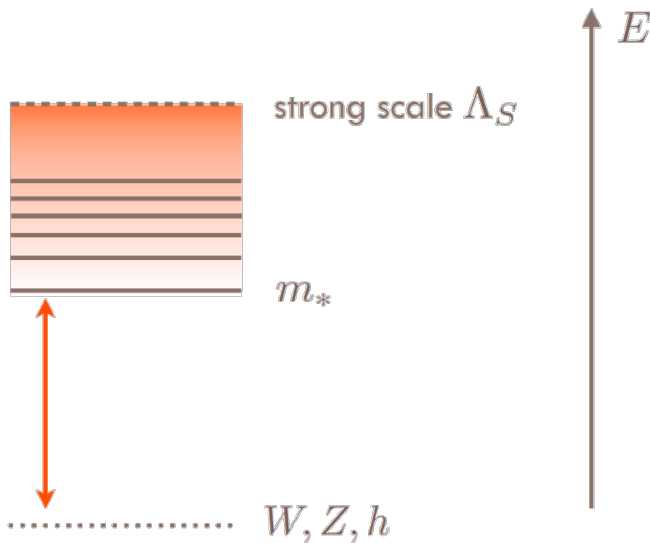
COMPOSITE
STATES



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

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

Energy scales?



Rescaling
from QCD to EW scale

QCD

EW

$$F_\pi = 0.090 \text{ GeV}$$

$$\rightarrow v = 0.246 \text{ TeV}$$

$$\Lambda_{\chi\text{PT}} = 4\pi F_\pi \approx 1.2 \text{ GeV}$$

$$\rightarrow \Lambda_{EW} = 4\pi v \approx 3.1 \text{ TeV}$$

$$M_\rho = 0.770 \text{ GeV}$$

$$\rightarrow M_{V1} = 2.1 \text{ TeV}$$

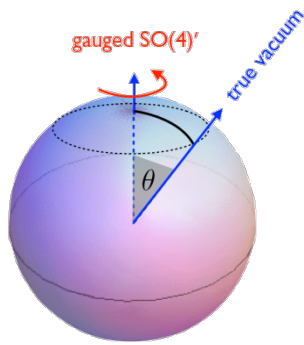
$$M_{a1} = 1.260 \text{ GeV}$$

$$\rightarrow M_{A1} = 3.4 \text{ TeV}$$

~~$$m_S = 0.05 \text{ GeV}$$~~

$$\rightarrow m_S = 0.126 \text{ TeV} \quad !!$$

[Contino EPS-HEP'14 ©]



The Light Higgs as a Goldstone:

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

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

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

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

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

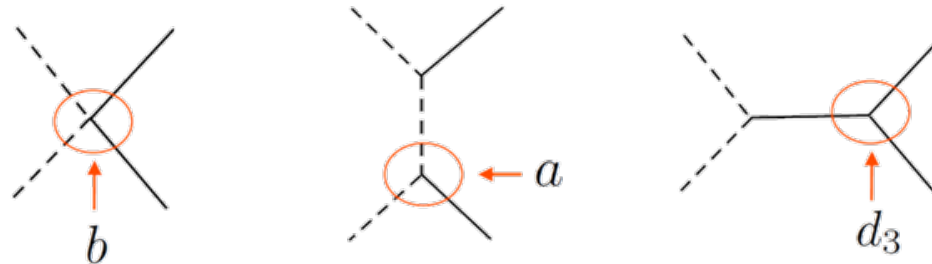
**PRECISION
FRONTIER**

[Contino 'EPS-HEP-2013]

2. Scatterings involving the Higgs also grow with energy

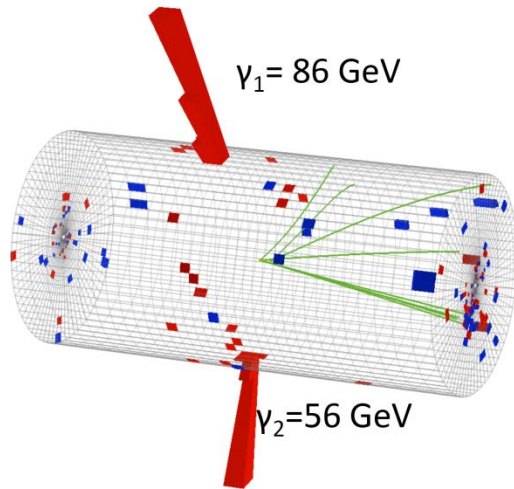
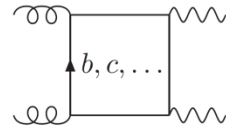
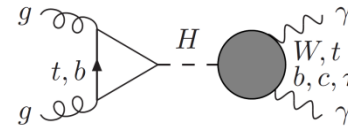
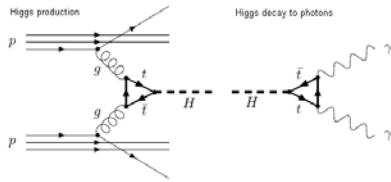
**ENERGY
FRONTIER**

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

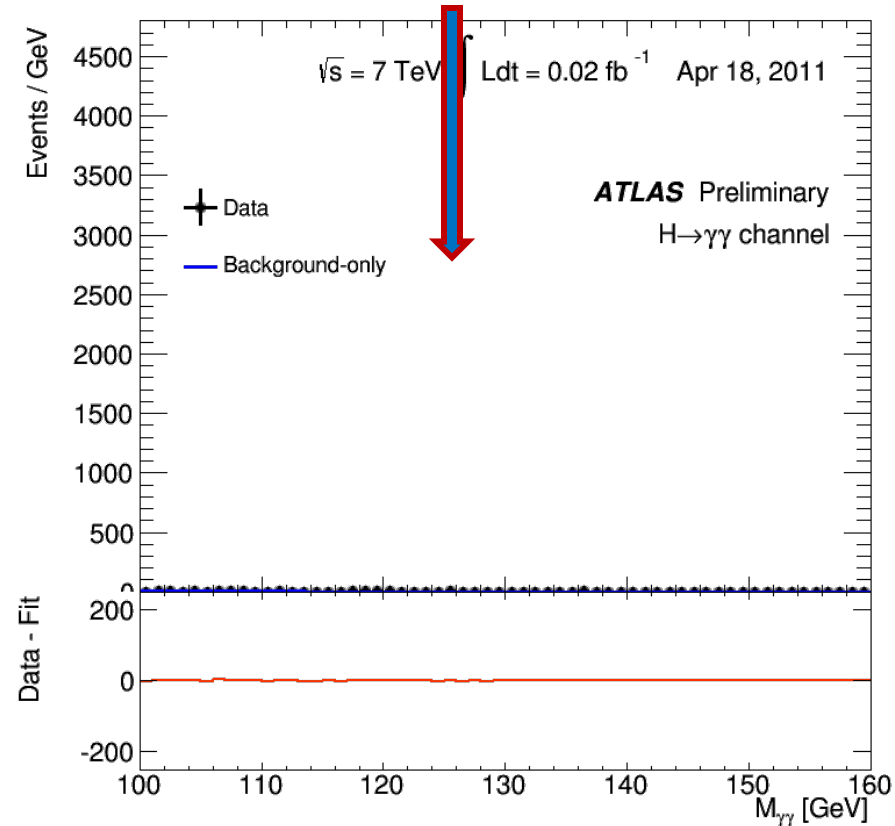


$$H \rightarrow \gamma\gamma$$

- 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>]

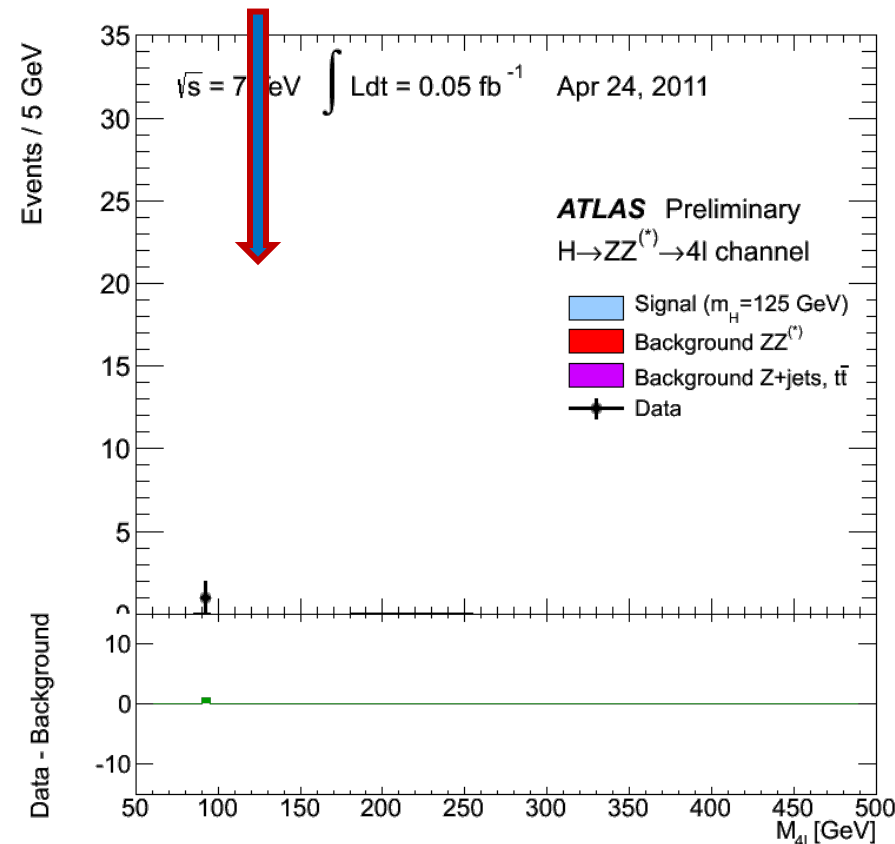
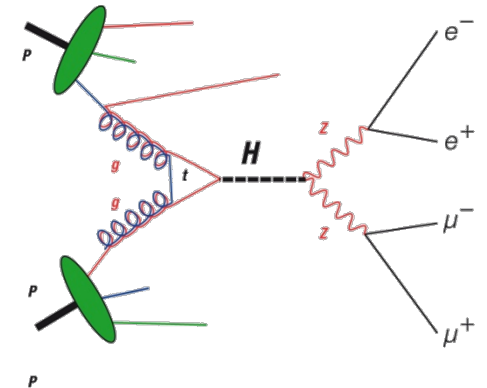
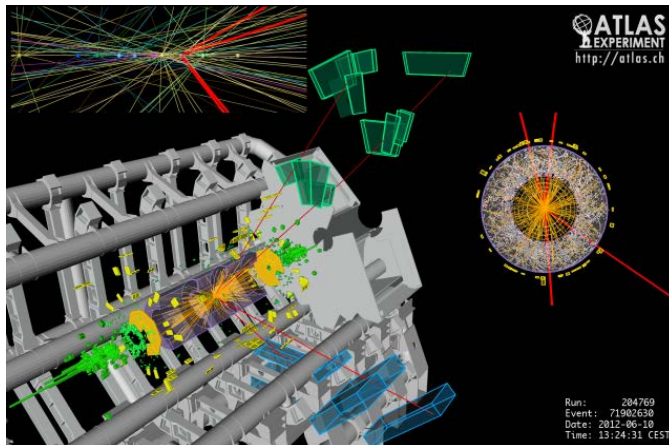
$$H \rightarrow ZZ^* \rightarrow 4\ell$$

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

Very tiny cross section $\rightarrow$ **But a clear distinctive signal**



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