Montpellier, March 11th 2014

EW chiral Lagrangians and the Higgs properties at the one-loop level

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A. Pich, I. Rosell and JJ SC, JHEP 1208 (2012) 106;
PRL 110 (2013) 181801;
JHEP 1401 (2014) 157;
R. Delgado, A. Dobado, M.J. Herrero and JJ SC [in preparation]

OUTLINE

1) Introduction: searching for tiny deviations from SM

2) The EW Chiral Lagrangian+Higgs (ECLh)

   S and T phenomenology (?)

3) ECLh + Resonances

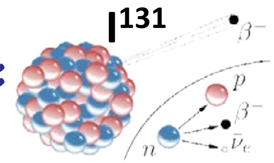
   S and T phenomenology

Introduction:

Deviations from SM?

- A new Higgs-like boson discovered at LHC

- $M_H = 125.64 \pm 0.35$ GeV $\approx$



- Still many questions:

  - Spin?

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

  - Coupling to gauge bosons?

    Very close to SM's

  - Invisible decays vs SM?

    – ATLAS: **$BR_{inv} < 0.60$** @ 95% CL (0.84 exp.)

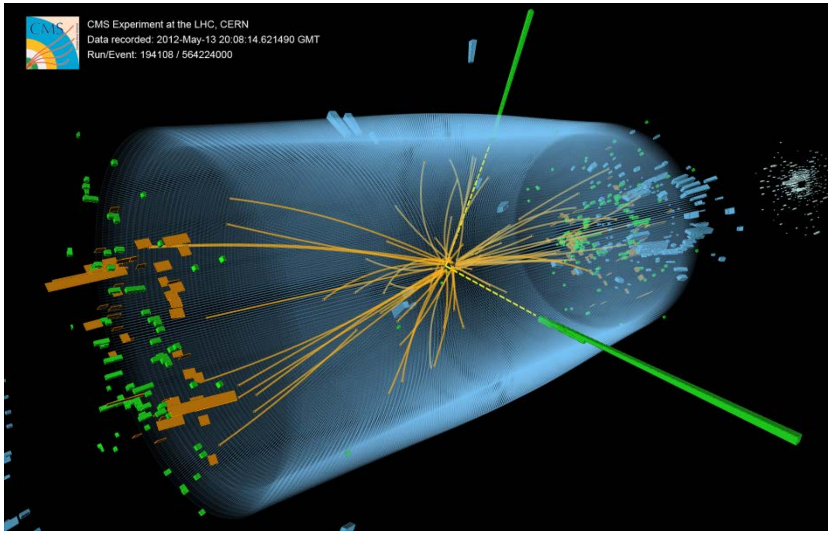
    – CMS: **$BR_{inv} < 0.75$** @ 95% CL (0.91 exp.)

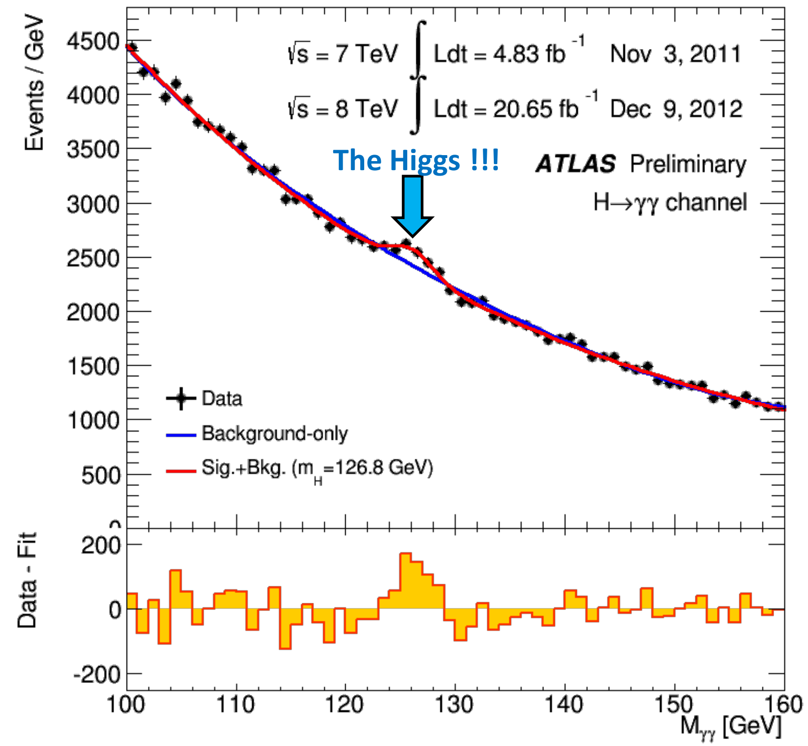
    From $\gamma\gamma$: $\Gamma_H < 6.9$ GeV at 95% CL (direct)

  - SM Higgs?

    Compatible so far

...

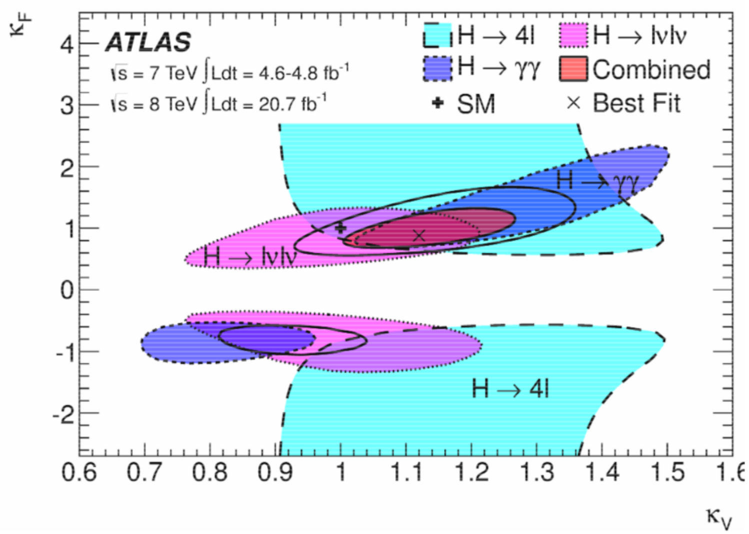


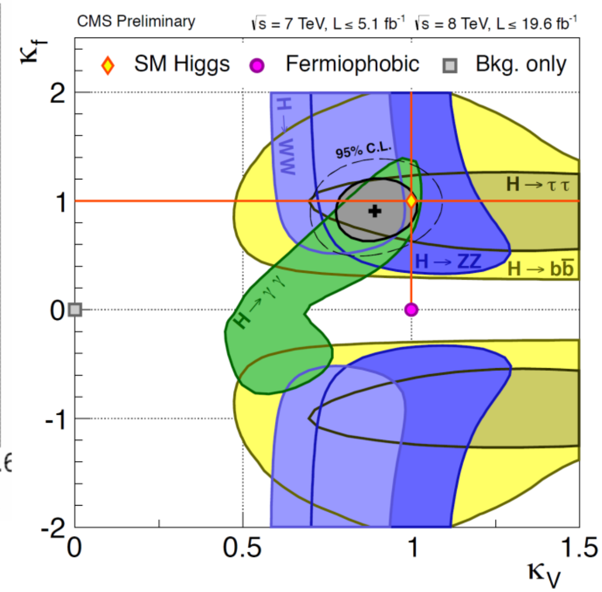


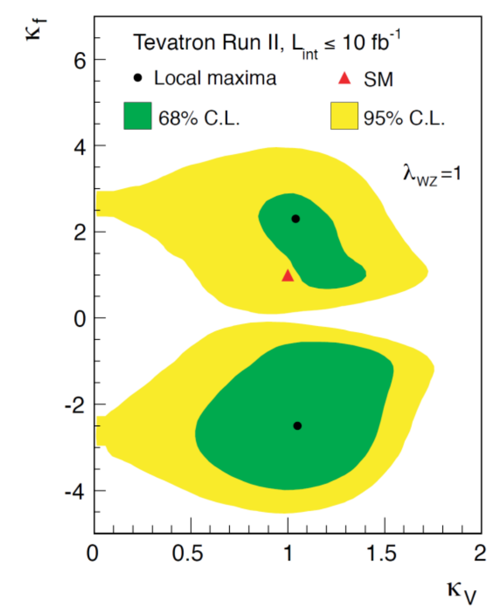
[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Animations

Higgs couplings

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







– **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]

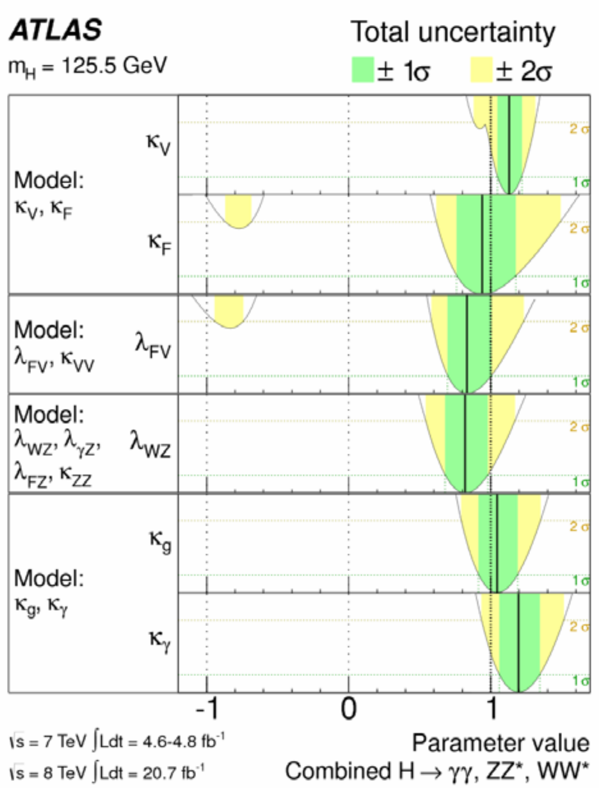
[1307.1427 [hep-ex]]

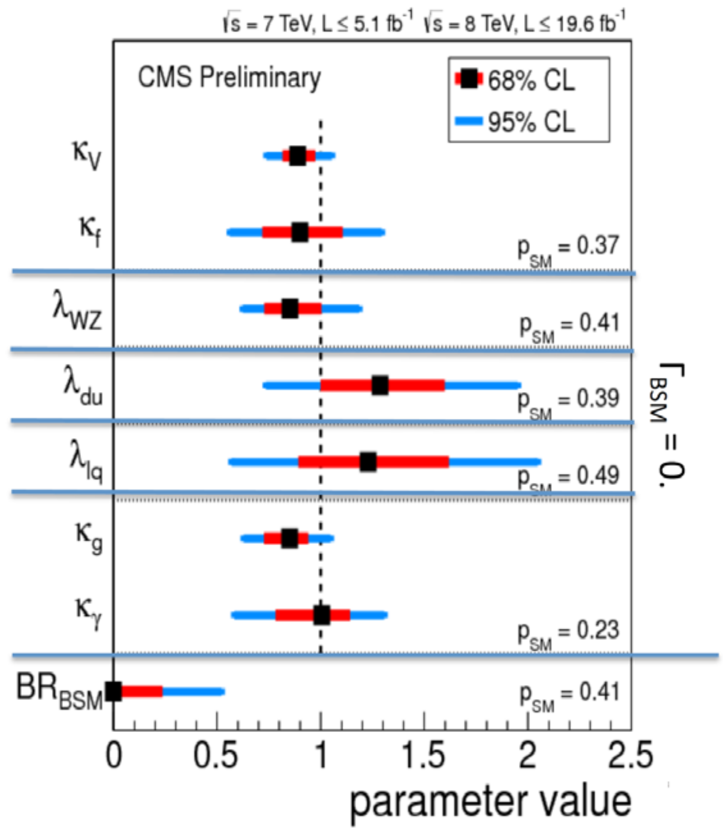
[1303.4571 [hep-ex]]

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]

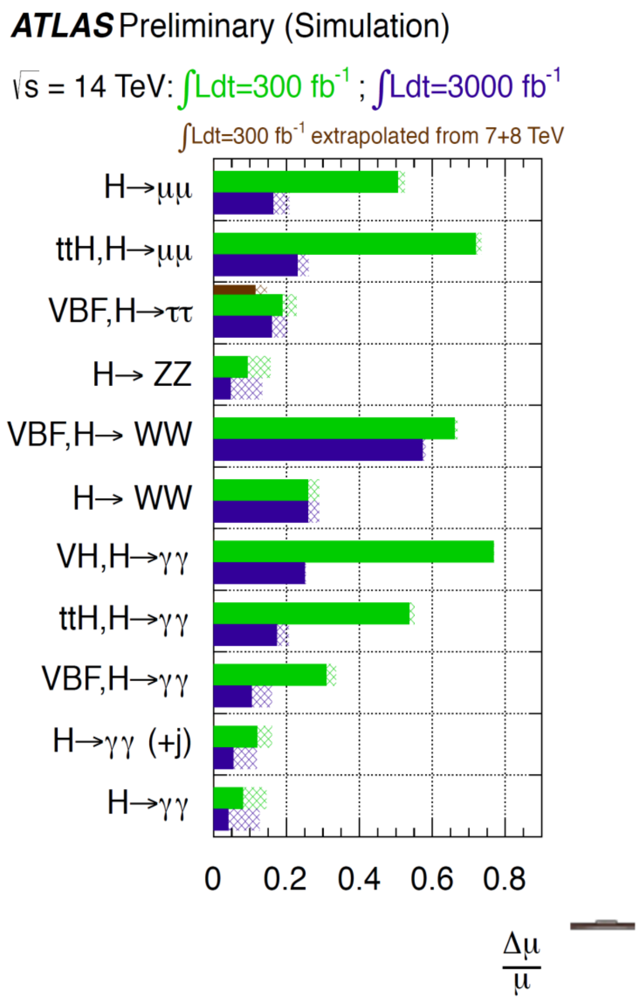


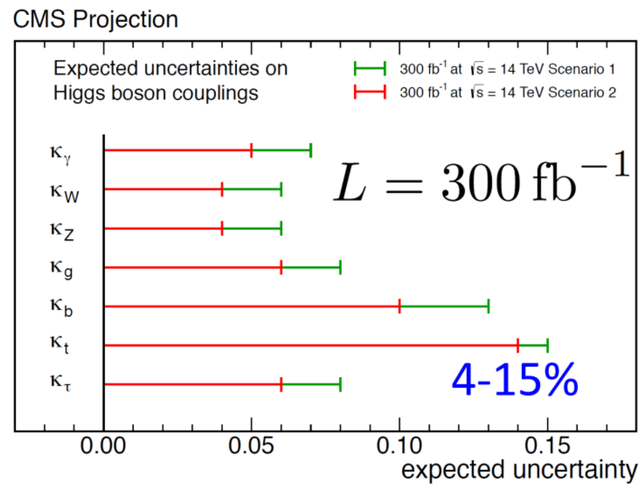


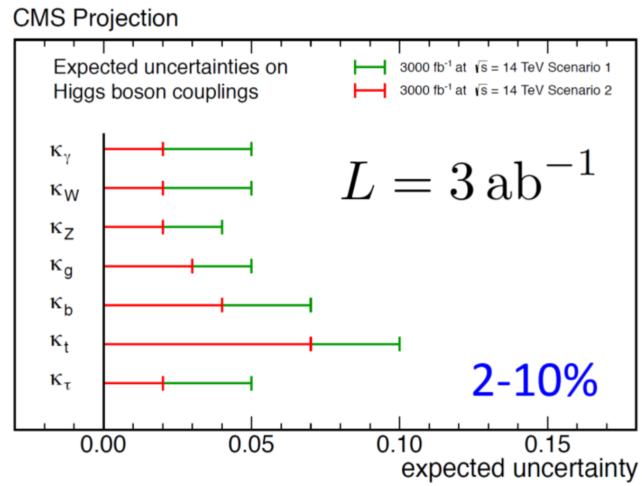
- **Compatibility with the SM**
- **Best uncertainties $\mathcal{O}$(10%)**

LHC prospects for next years

[1307.7135 [hep-ex]]





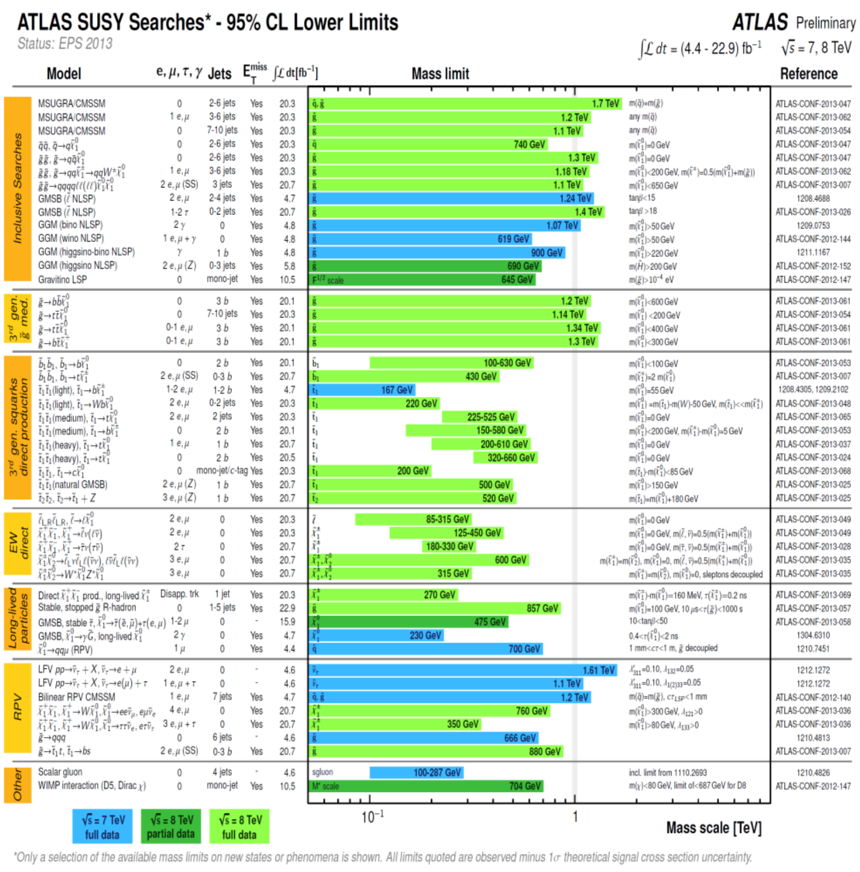


Spectrum below 1 TeV

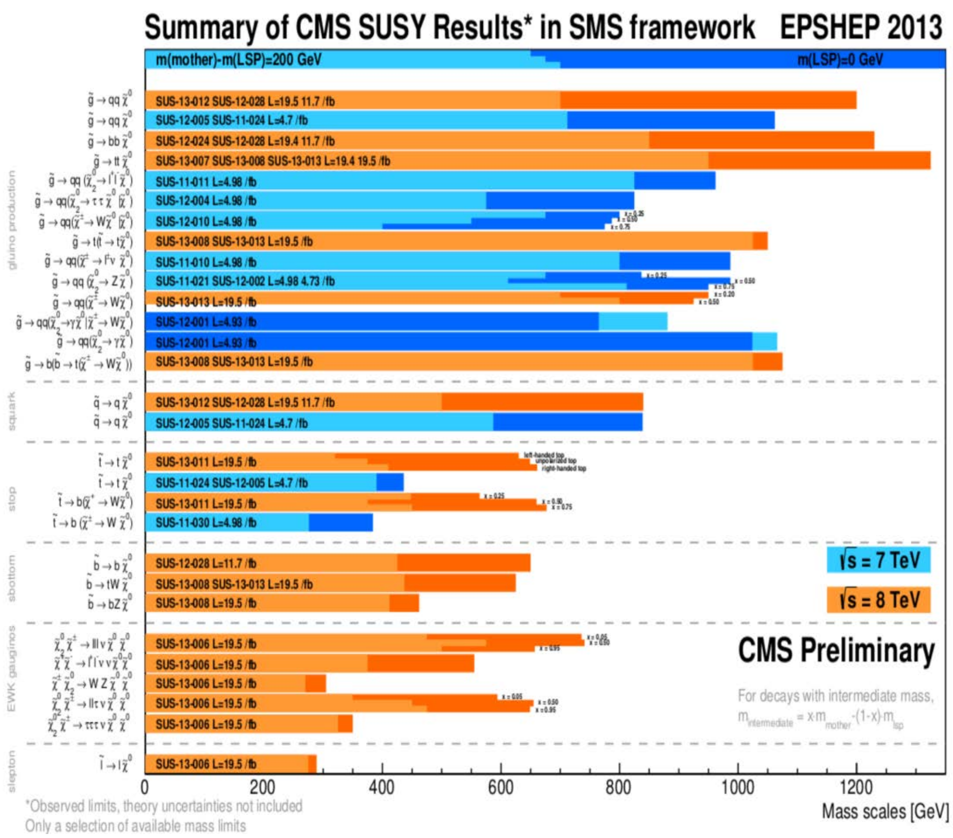
SM particles… and nothing else below the TeV

(e.g. SUSY exclusion limits)

ATLAS Summary



CMS Summary



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 …

EW Chiral Lagrangian + Higgs   (ECLh):

Low-energy EFT

•EFT assumptions:

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

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

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

•Building blocks:

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

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

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

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

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

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

soft-scale!!!

•“Chiral” counting*:

$$\partial_\mu\,,\quad m_W\,,\quad m_Z\,,\quad m_h \quad \sim \quad \mathcal{O}(p)$$

$$D_\mu U\,,\quad V_\mu\,,\quad g' v\,\mathcal{T}\,,\quad \hat{W}_\mu\,,\quad \hat{B}_\mu \quad \sim \quad \mathcal{O}(p)\,,$$

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

also notice the subtlety*,** $g^{(\prime)} \sim m_{W,Z}/v \sim p/v$

* Buchalla,Catà,Krause ‘13
* Hirn,Stern ‘05
* Delgado,Dobado,Herrero,SC [in prep.] ** Urech ‘95

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

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

➔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

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

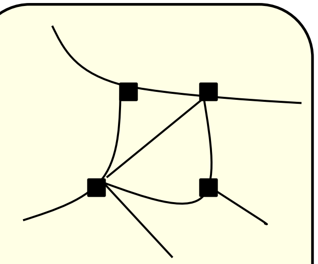
Counting, loops & renormalization

•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 $\mathcal{L}_d$*



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

* Weinberg '79
* Urech '95
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC [in prep.]

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

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

Example: S & T parameters at $O(p^4)$

More complicated/interesting examples coming soon
[Delgado,Dobado,Herrero,SC 'in preparation]

STAY TUNED

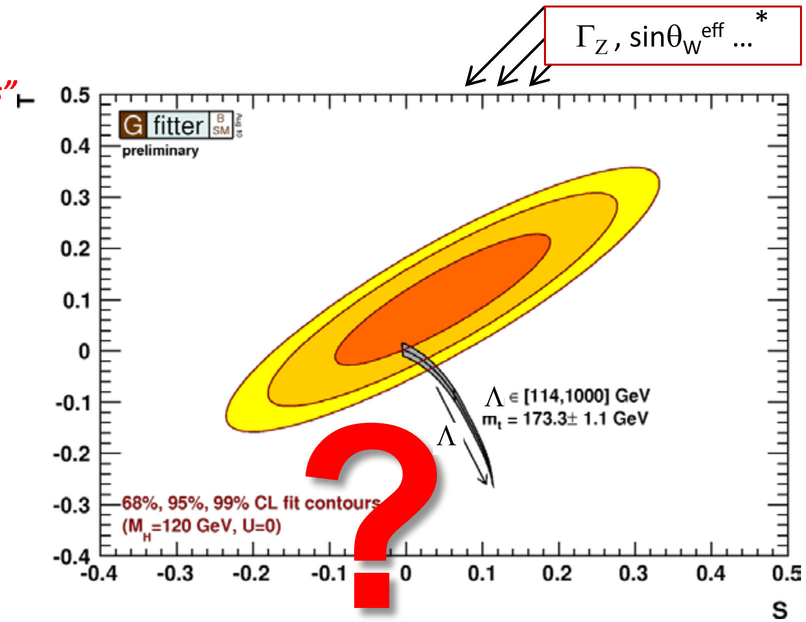
•Do oblique parameters exclude strongly-coupled models?

❑ ***The EWPO Oblique Parameters***

don't exclude them at all

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

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

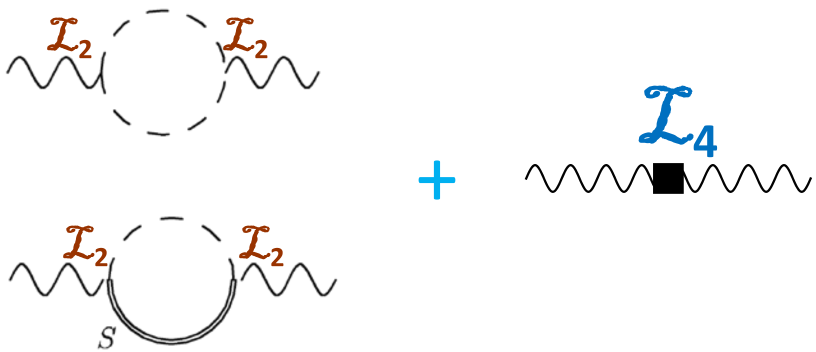


-EFT: Loops + effective couplings

(ALWAYS!!!)

* Peskin,Takeuchi '92

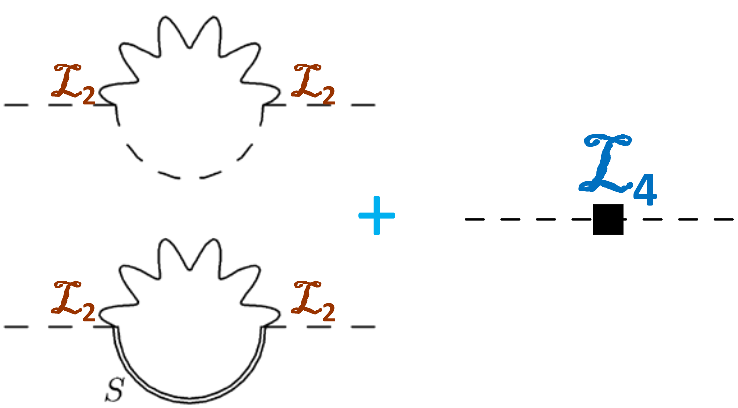
➔ W^3B correlator*



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

➔ 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 $\longrightarrow \left[\ S = -16\pi\, a_1(\mu?)\,, \qquad T = \frac{8\pi}{c_W^2} a_0(\mu?)\ \right]$

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)*

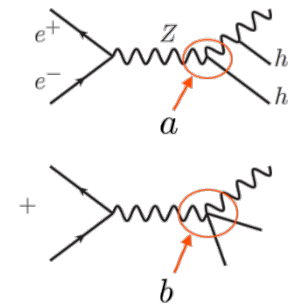
* Delgado,Dobado,Herrero,SC [in prep.]

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

Deviations from SM: BSM's

❖ Different models → Different deviations from SM

($a=\kappa_W=\kappa_V$)



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

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

•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 Λ= 4πv = 3 TeV

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

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

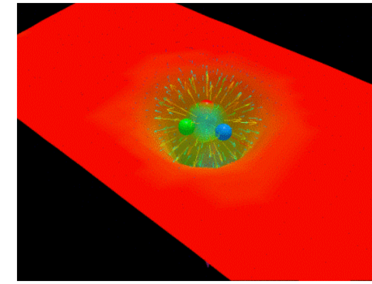
[Espinosa et al. '12]

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

EW Chiral Lagrangian + h + V + A:

Models, assumptions, completions…

Strongly coupled BSM



SM

elementary particles

SM

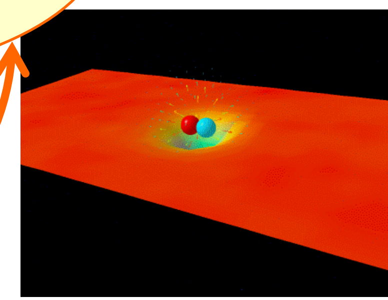
Interactions

(other?)

BSM

elementary particles

COMPOSITE STATES



SM

interactions

BSM

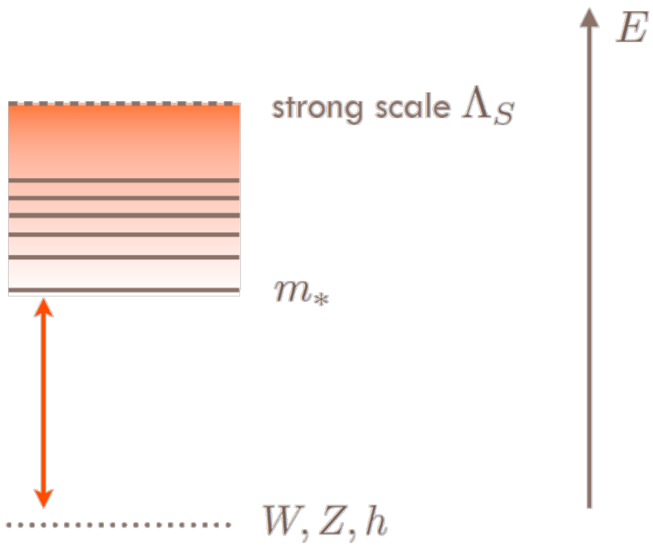
strongly-coupled

interactions

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

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

Energy scales?



[Contino EPS-HEP'14 ©]

Rescaling
from QCD to EW scale

QCD	$\rightarrow$	**EW**
$F_\pi = 0.090$ GeV	$\rightarrow$	$v = 0.246$ TeV
$\Lambda_{\chi PT} = 4\pi F_\pi \approx 1.2$ GeV	$\rightarrow$	$\Lambda_{EW} = 4\pi v \approx 3.1$ TeV
$M_\rho = 0.770$ GeV	$\rightarrow$	$M_{V1} = 2.1$ TeV
$M_{a1} = 1.260$ GeV	$\rightarrow$	$M_{A1} = 3.4$ TeV
$\cancel{m_S = 0.65\ \text{GeV}}$	$\rightarrow$	$m_S = 0.126$ TeV **!!**

- ***AIM*** **of this work**:**
  - Bounds on M_R
  - Bounds on couplings 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) * , +

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

with the subtracted definition,

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

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

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

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

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

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

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*.

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

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

→ 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.

What? One-loop calculation of the oblique (S,T)-parameters in strongly-coupled EWSB *, **

Why? Study of composite models

How? 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: Resonances like in QCD → RChT (+)

c) General Lagrangian + EoM + short-distance cond. (+)

d) Just the lightest two-particle absorptive cuts.

\+

Dispersive representation for S * ← $\pi\pi$ + $h\pi$

\+

Dispersion relation for T *(for the lightest cuts)* (x) ← $B\pi$ + Bh

(impact of heavier channels neglected (x))

*** Apelquist '80
*** Longhitano '80, '81
*** Weinberg '79
*** Gasser & Leutwyler '84 '85
*** Bijnens et al. '99 '00

** Gfitter
** LEP EWWG
** Zfitter

(+) Ecker et al. '89
(+) Cirigliano et al. '06
(+) Pich, Rosell, SC '08

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

* Peskin,Takeuchi '92

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

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

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), **

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

$$\mathcal{L} = \left\{ \frac{v^2}{4} \boxed{+ \kappa_W \frac{v}{2} S_1} \right\} \langle u_\mu u^\mu \rangle \quad \longleftarrow \text{h} + \pi \text{ sector}$$

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

$$+ \frac{F_A}{2\sqrt{2}} \langle A_{\mu\nu} f_-^{\mu\nu} \rangle + \sqrt{2} \lambda_1^{SA}\, \partial_\mu S_1 \langle A^{\mu\nu} u_\nu \rangle \quad \text{A+h+}\pi \text{ sector}$$

We will have 7 resonance parameters:

F_V, G_V, F_{AW}, κ_W, λ_1^{SA}, M_V and M_A

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…

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 $\Pi_{30}(s) = \frac{g^2 \tan\theta_W}{4}\, s\, [\Pi_{VV}(s) - \Pi_{AA}(s)]$

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

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

- ✓ 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)***

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

1ST WSR:

$$\left| \mathbf{s} \times \mathbf{\Pi_{V-A}(s)} \right| \stackrel{\mathbf{s}\to\infty}{\longrightarrow} \mathbf{0} \quad\Longrightarrow\quad \int_0^\infty \mathbf{dt}\ \rho_{\mathbf{S}}(\mathbf{t}) = \frac{\mathbf{g^2 v^2} \tan\theta_{\mathbf{W}}}{\mathbf{4}}$$

2ND WSR:

$$\left| \mathbf{s^2} \times \mathbf{\Pi_{V-A}(s)} \right| \stackrel{\mathbf{s}\to\infty}{\longrightarrow} \mathbf{0} \quad\Longrightarrow\quad \int_0^\infty \mathbf{dt\ t}\ \rho_{\mathbf{S}}(\mathbf{t}) = \mathbf{0}$$

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

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

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**

$$F_V^{r\,2} - F_A^{r\,2} = v^2\,(1 + \delta^{(1)}_{\rm NLO})$$

$$F_V^{r\,2}\, M_V^{r\,2} - F_A^{r\,2} M_A^{r\,2} = v^2 M_V^{r\,2} \delta^{(2)}_{\rm NLO}$$

(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) $\pi\pi$ Vector Form Factor**

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

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

ii.ii) $S\pi$ 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 $W,B \to S\pi$

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

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

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

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

** Ecker et al.'89

*** Pich, Rosell, SC '12

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

These are

my principles.

If you don't like

them,

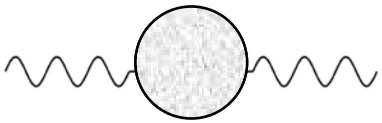
I have others

S and T *at LO*

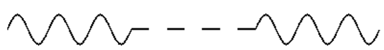
S-parameter *

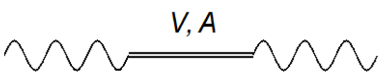
❖ New physics in the difference between the Z self-energies at $q^2=M_Z^2$ and $q^2=0$.

➔ *W³B correlator* *(transverse in Landau gauge)*



at LO =





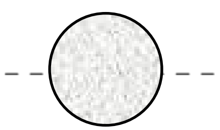
$$\Pi_{30}(s)|_{\rm LO} = \frac{g^2\tan\theta_W}{4}\, s\left(\frac{v^2}{s} + \frac{F_V^2}{M_V^2-s} - \frac{F_A^2}{M_A^2-s}\right)$$

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

T-parameter *

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

➔ *NGB self-energies*



= 0

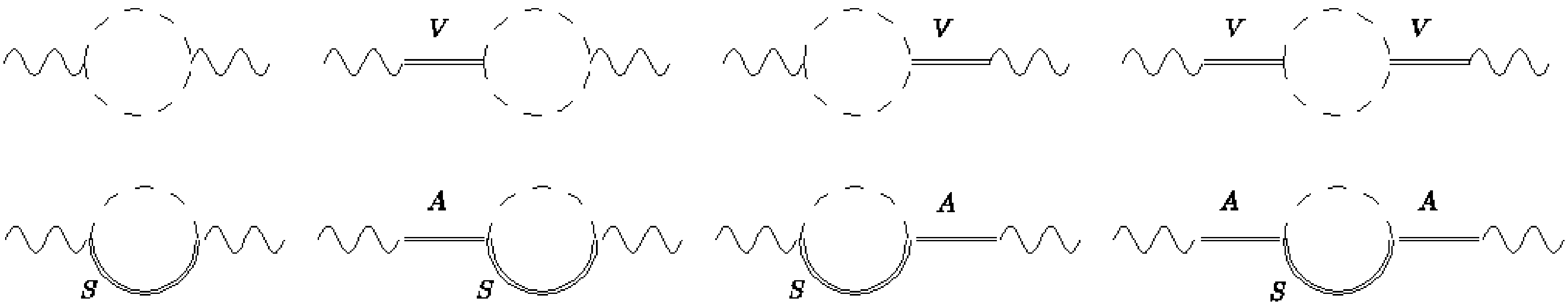
$$\Sigma(s)^{(0)} - \Sigma(s)^{(+)} = 0$$

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

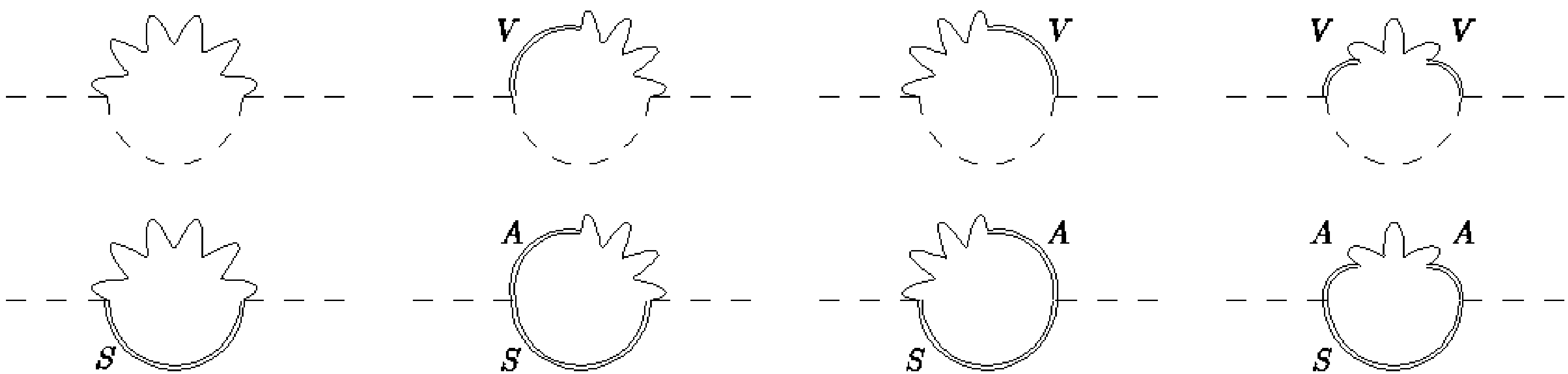
* Peskin and Takeuchi '92.

S and T *at NLO*

➔ W^{3}B correlator*



➔ NGB self-energy *

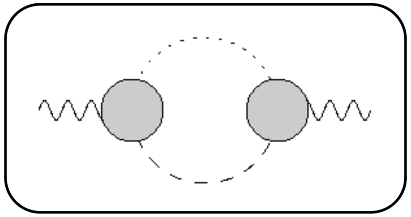


* Barbieri et al.'08
* Cata and Kamenik '10
* Orgogozo, Rychkov '11, '12

High-energy constraints + *Dispersion relations*

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

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

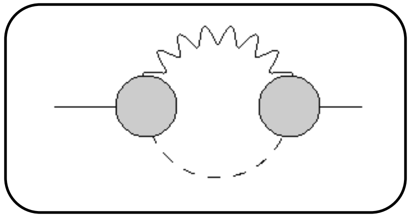


$$\rho_{\mathbf{S}}(\mathbf{s}) \;=\; \frac{1}{\pi}\mathrm{Im}\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s}) \quad \left\{ \begin{array}{l} \rho_S|_{\pi\pi} \;=\; \dfrac{gg'\,\theta(s)}{192\pi}\left(1+\dfrac{F_VG_V}{v^2}\dfrac{s}{M_V^2-s}\right)^2 \;\xrightarrow[\text{WSR}]{\text{VFF +}}\; \dfrac{gg'\,\theta(s)}{192\pi}\left(\dfrac{M_V^2}{M_V^2-s}\right)^2 \\ \\ \rho_S|_{S\pi} \;=\; -\,\dfrac{gg'\,\kappa_W^2\,\sigma_{S\pi}^3\theta(s-m_S^2)}{192\pi}\left(1+\dfrac{F_A\lambda_1^{SA}}{\kappa_W v}\dfrac{s}{M_A^2-s}\right)^2 \;\xrightarrow[\text{WSR}]{\text{VFF +}}\; -\,\dfrac{gg'\,\kappa_W^2\,\sigma_{S\pi}^3\theta(s-m_S^2)}{192\pi}\left(\dfrac{M_A^2}{M_A^2-s}\right)^2 \end{array} \right.$$

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

for the lightest absorptive diagrams with $B\pi$ + BS

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



*

$$\rho_{\mathbf{T}}(\mathbf{s}) \;=\; \frac{1}{\pi}\mathrm{Im}[\mathbf{\Sigma}(\mathbf{s})^{(0)} - \mathbf{\Sigma}(\mathbf{s})^{(+)}] \left\{ \begin{array}{l} \rho_{\mathbf{T}}(\mathbf{s})|_{\mathbf{B}\pi} \;\xrightarrow{\mathbf{s}\to\infty}\; -\,\dfrac{\mathbf{3g'^2 s}}{\mathbf{64\pi^2}}\left(\mathbf{1}-\dfrac{\mathbf{F_VG_V}}{\mathbf{v^2}}\right)^{\mathbf{2}} \;+\; \mathcal{O}(\mathbf{s^0}) \\ \\ \rho_{\mathbf{T}}(\mathbf{s})|_{\mathbf{BS_1}} \;\xrightarrow{\mathbf{s}\to\infty}\; \dfrac{\mathbf{3g'^2\kappa_W^2 s}}{\mathbf{64\pi^2}}\left(\mathbf{1}-\dfrac{\mathbf{F_A\lambda_1^{SA}}}{\mathbf{\kappa_W v}}\right)^{\mathbf{2}} \;+\; \mathcal{O}(\mathbf{s^0}) \end{array} \right.$$

+ 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

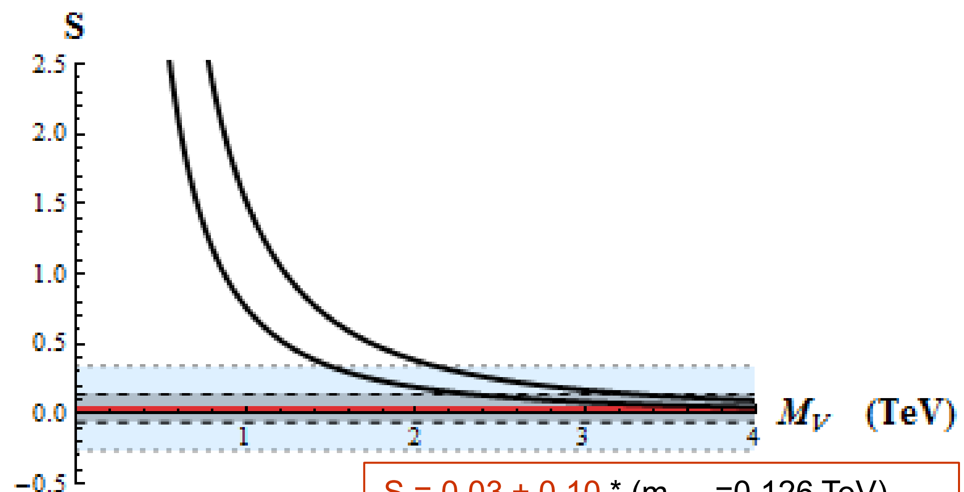
LO results***

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

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

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

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



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

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

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

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

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}

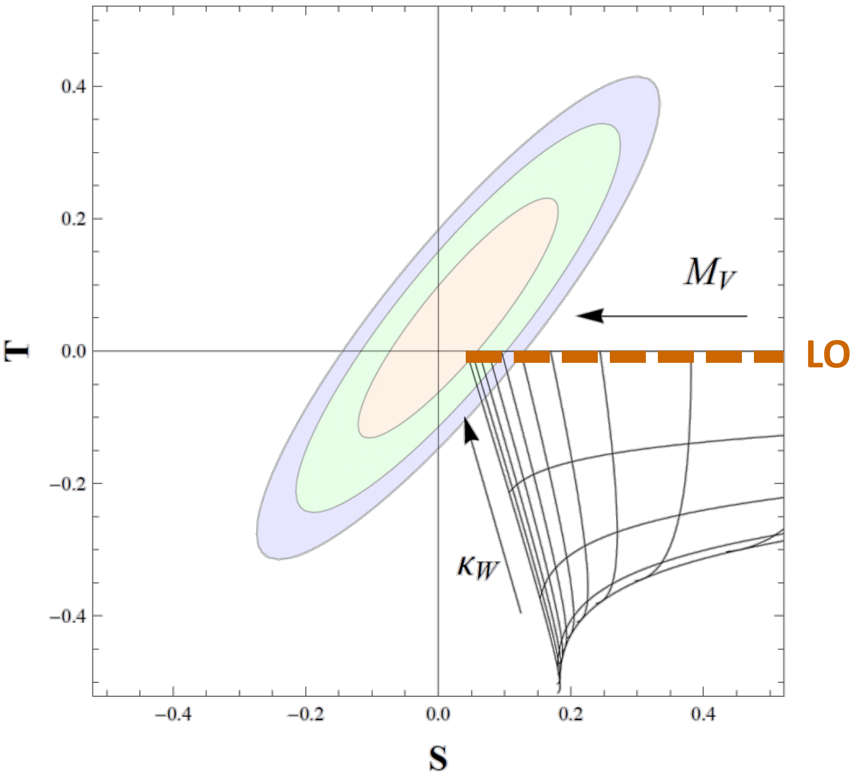
$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

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 + $\pi\pi$-VFF:

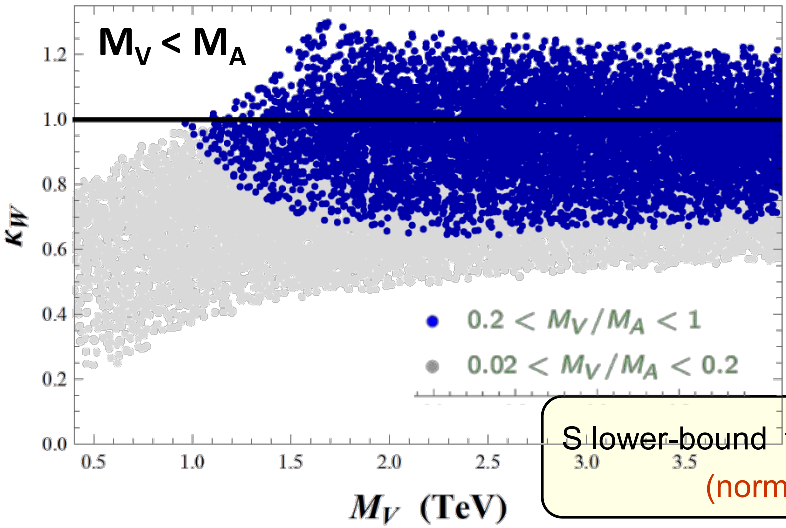
→ Free parameters: M_V, M_A and κ_W

* Pich,Rosell,SC '12, '13

** Orgogozo,Rychkov '11

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

(*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

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

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

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

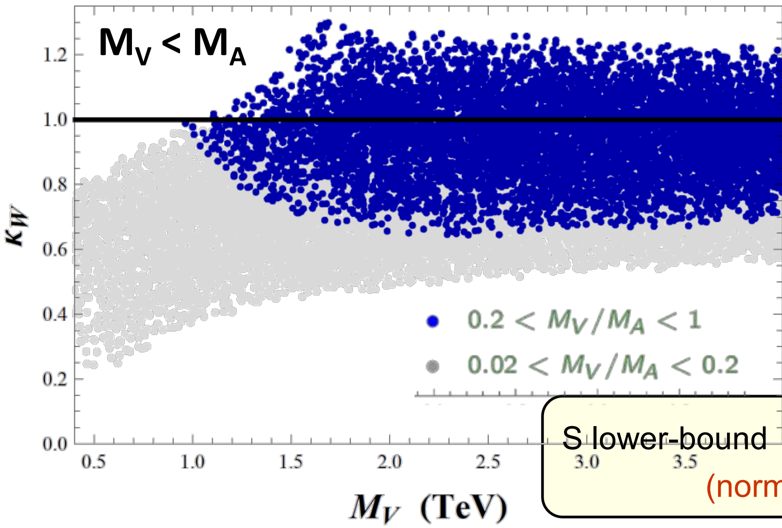
if one requires large (unnatural) splittings

* 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)

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

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

At NLO with only 1st WSRs

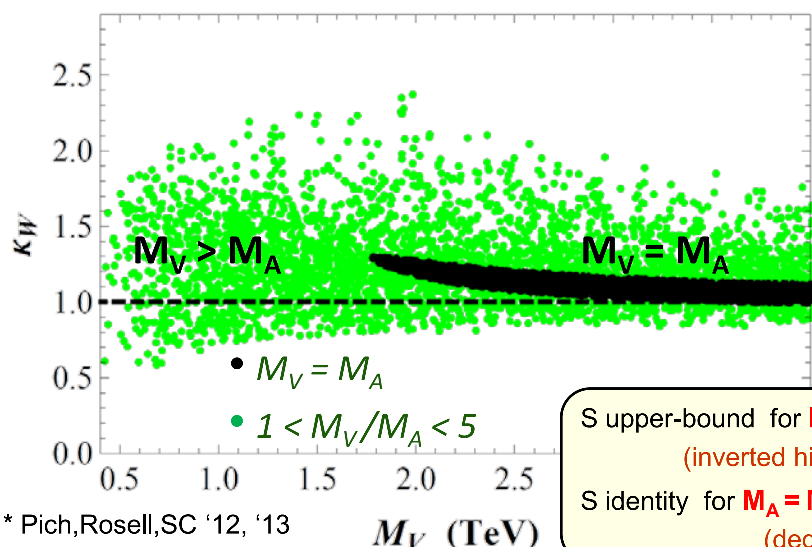
$M_V > 1$ TeV, $\kappa_W \in (0.6\,,\,1.3)$ at 68% CL

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



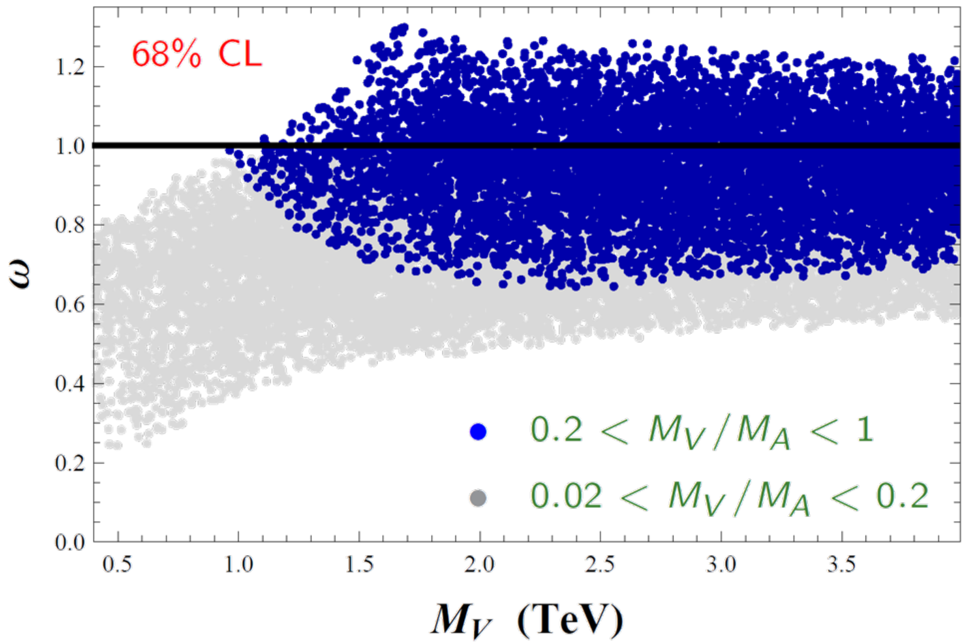
S upper-bound for $M_A < M_V$
(inverted hierarchy)

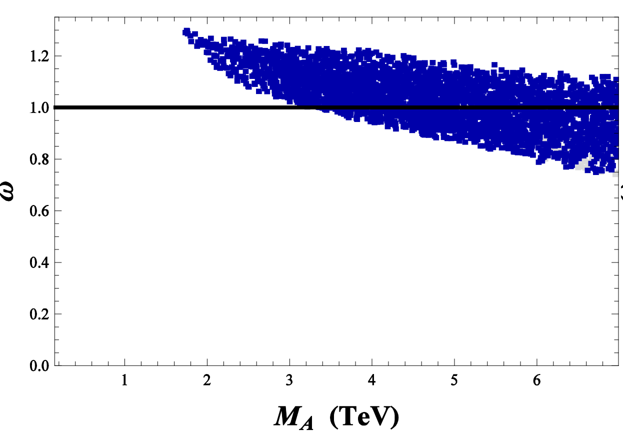
S identity for $M_A = M_V$
(degenerate)

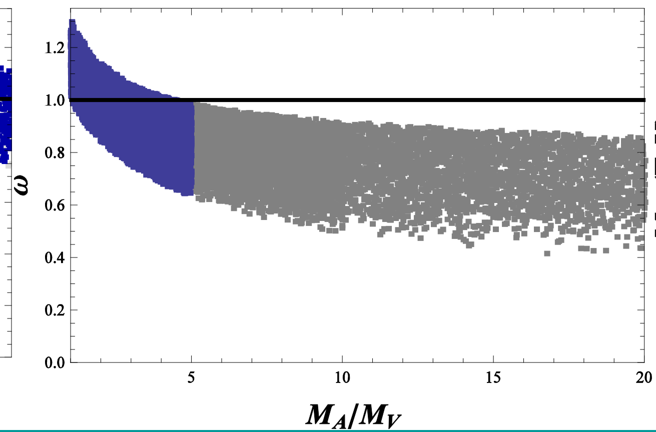
* Pich,Rosell,SC '12, '13

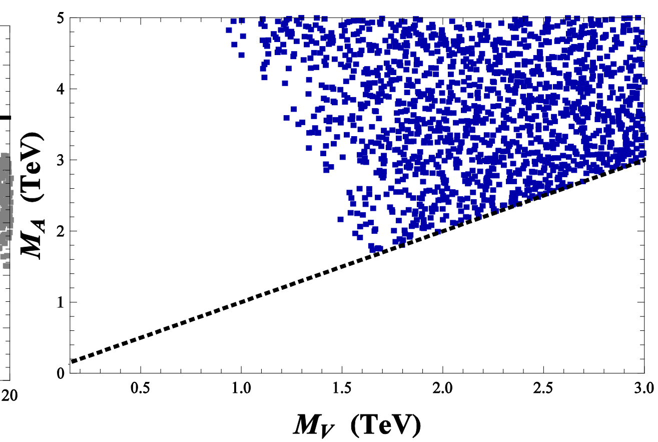
** Orgogozo,Rychkov '11

BACKUP PLOTS

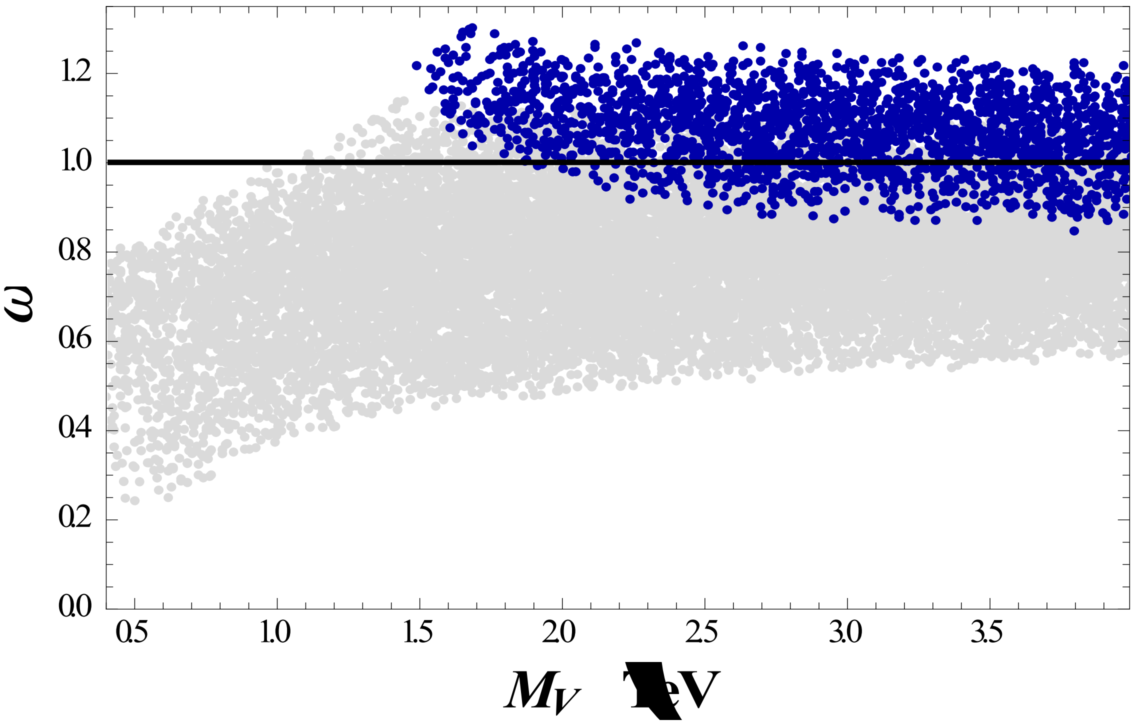




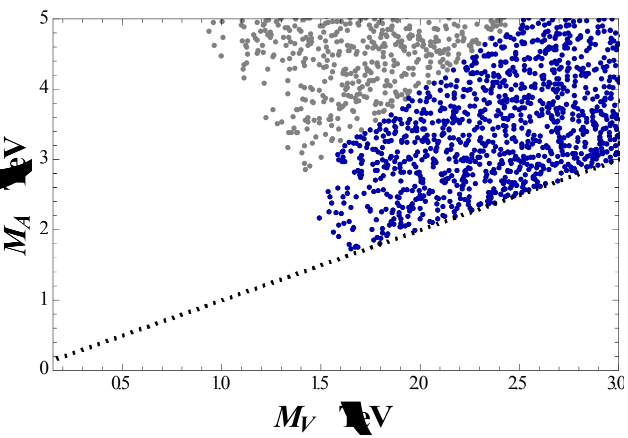


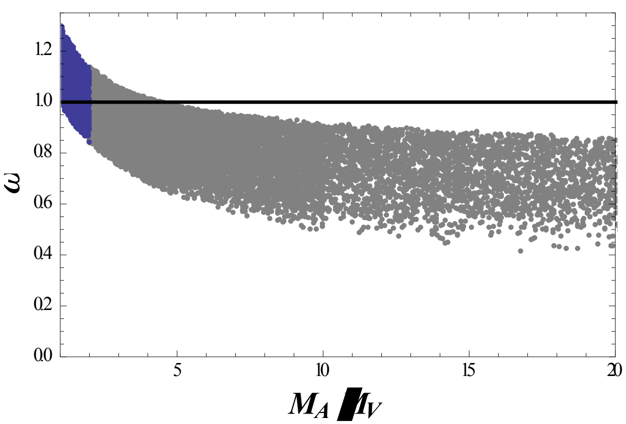


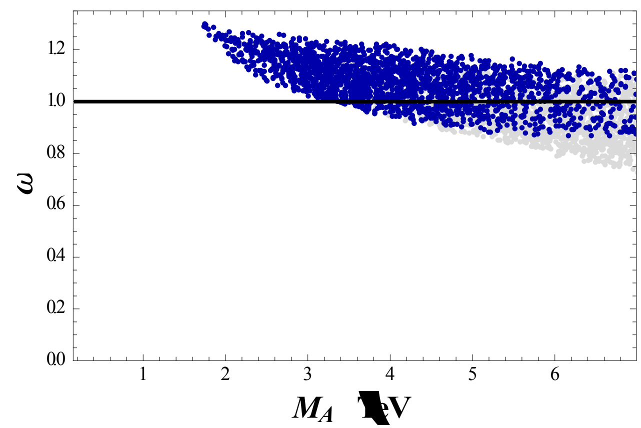
BACKUP PLOTS



- **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 → LO

$$a_1(\mu) = \boxed{-\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)} + \frac{1}{192\pi^2}\left(\frac{8}{3}+\ln\frac{\mu^2}{M_V^2}\right) - \frac{\kappa_W^2}{192\pi^2}\left(\frac{8}{3}+\ln\frac{\mu^2}{M_A^2}\right) + \kappa_W \ln\kappa_W^2$$

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

✓ Calculation valid for particular models with this symmetry:

E.g., in SO(5)/SO(4) with $\kappa_W=\cos\theta < 1$ *

* 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> (ECLh)

- 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>

- High-energy constraints + 1 loop dispersive calculation

✓ **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

✓ <u>**FINAL CONCLUSIONS:**</u>

- Resonances perfectly allowed by S & T at $M_R \sim 4\pi v \approx 3$ TeV
- Resonances perfectly compatible with LHC $\kappa_W \approx 1$
- Only some slight issues below TeV *(large splitting, inv. hierarchy…)*
- Conclusions applicable to more specific models *(e.g. SO(5)/SO(4) MCHM)*

BACKUP SLIDES

- Field content of the theory:

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

+ one $SU(2)_L \otimes SU(2)_R$ singlet scalar S_1

+ lightest resonances *(e.g., V and A ; optional)*

- Building blocks: $SU(2)_L \otimes SU(2)_R$ transformation properties

$$u(\varphi) \longrightarrow g_L\, u(\varphi)\, h^\dagger(\varphi,g) = h(\varphi,g)\, u(\varphi)\, g_R^\dagger$$

$$\hat{W}^\mu \to g_L\, \hat{W}^\mu g_L^\dagger + i\, g_L\, \partial^\mu g_L^\dagger\,, \qquad \hat{B}^\mu \to g_R\, \hat{B}^\mu g_R^\dagger + i\, g_R\, \partial^\mu g_R^\dagger$$

$$R \longrightarrow h(\varphi,g)\, R\, h^\dagger(\varphi,g)\,, \qquad R_1 \longrightarrow R_1$$

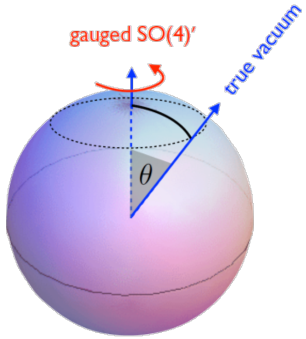
NOTATION:

$$U = u^2 = \exp\{i\vec{\sigma}\vec{\pi}/v\}$$

$$f_\pm^{\mu\nu} = u^\dagger\, \hat{W}^{\mu\nu} u \pm u\, \hat{B}^{\mu\nu} u^\dagger \qquad \hat{W}^\mu = -g\, \frac{\vec{\sigma}}{2}\vec{W}^\mu\,, \qquad \hat{B}^\mu = -g'\, \frac{\sigma_3}{2} B^\mu$$

$$\hat{W}^{\mu\nu} = \partial^\mu \hat{W}^\nu - \partial^\nu \hat{W}^\mu - i\,[\hat{W}^\mu, \hat{W}^\nu]\,, \qquad \hat{B}^{\mu\nu} = \partial^\mu \hat{B}^\nu - \partial^\nu \hat{B}^\mu - i\,[\hat{B}^\mu, \hat{B}^\nu]\,,$$

$$u^\mu = i\, u\, D^\mu U^\dagger\, u = -i\, u^\dagger D^\mu U\, u^\dagger = u^{\mu\dagger}\,, \qquad D^\mu U = \partial^\mu U - i\, \hat{W}^\mu U + i\, U\, \hat{B}^\mu\,.$$



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: $a = 1 - c_H \left(\frac{v}{f}\right)^2 + \ldots$

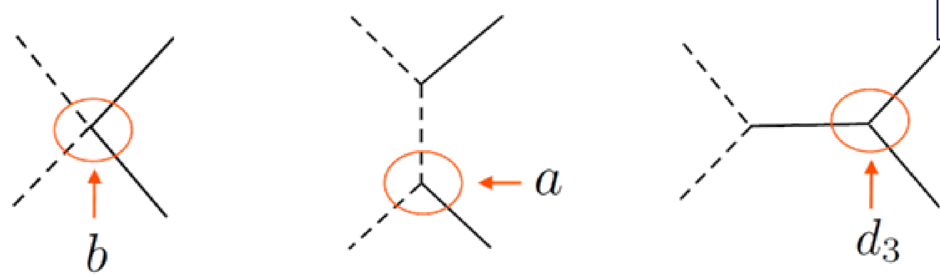
PRECISION FRONTIER

[Contino 'EPS-HEP-2013]

2. Scatterings involving the Higgs also grow with energy

ENERGY FRONTIER

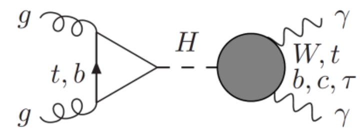
$$A(WW \to hh) \sim \frac{s}{v^2}(a^2 - b)$$

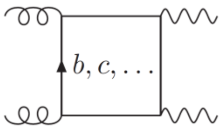


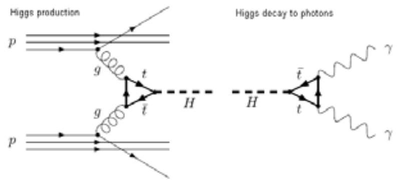
$H \to \gamma\gamma$

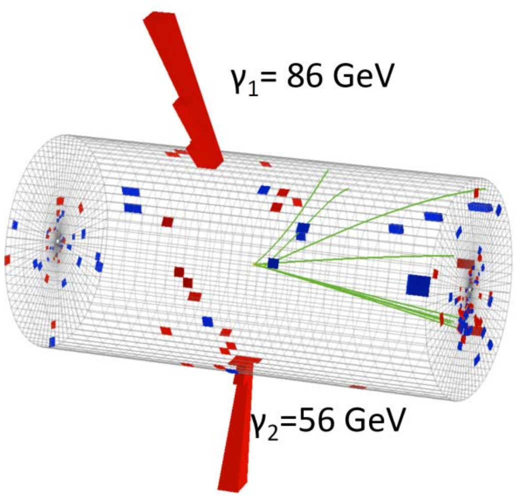
- Higgs decay through a top loop

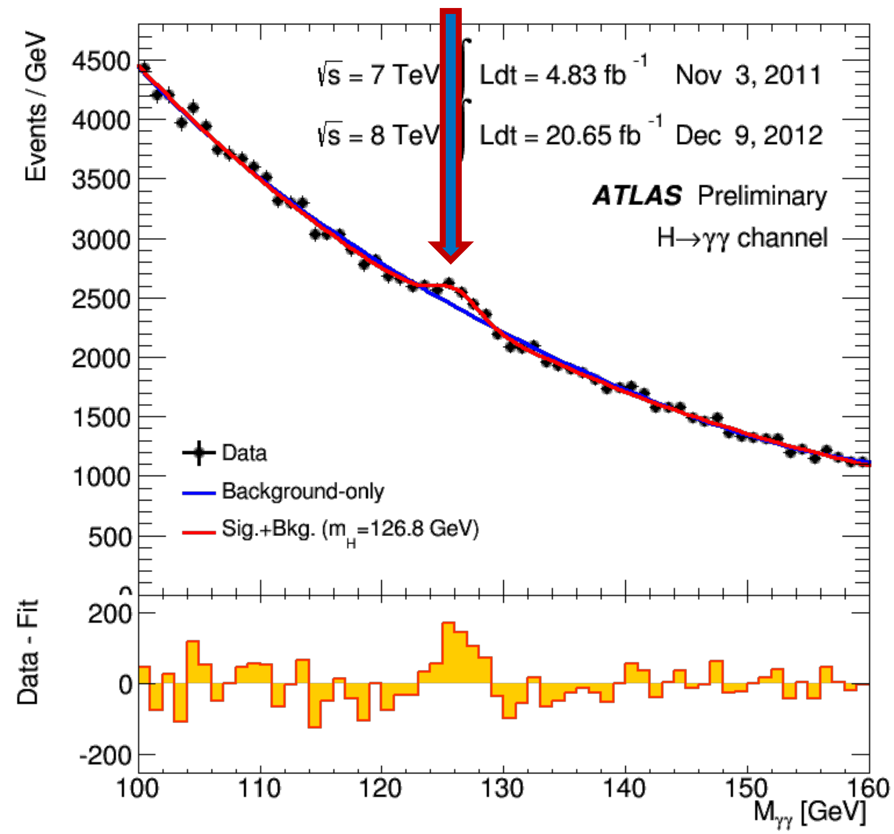
  (mainly enhanced by $H \to tt$ coupling; prop. to m_t)







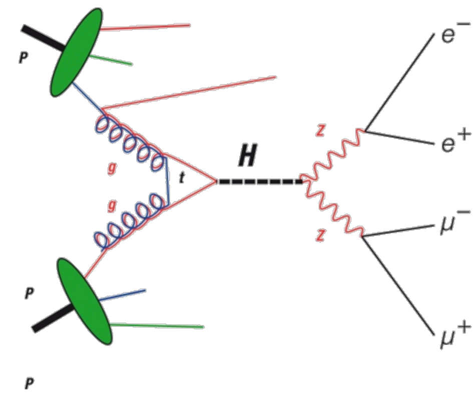




Signature: 2 energetic, isolated γ, a narrow mass peak on top of a steeply falling spectrum

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

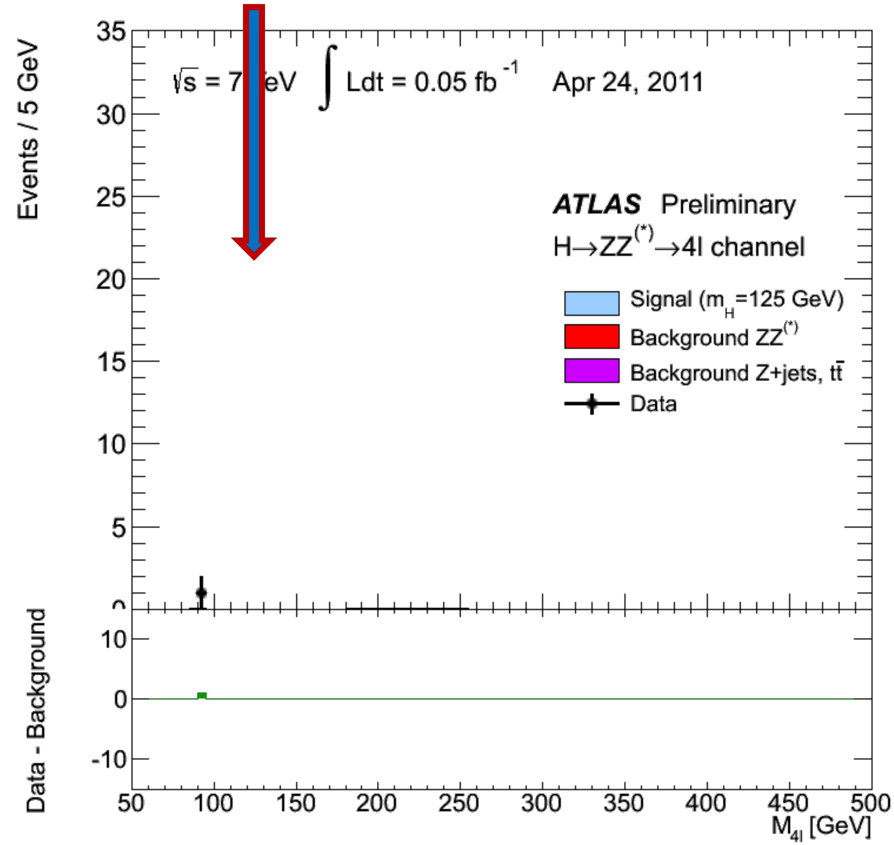
$H \to ZZ^* \to 4\ell$

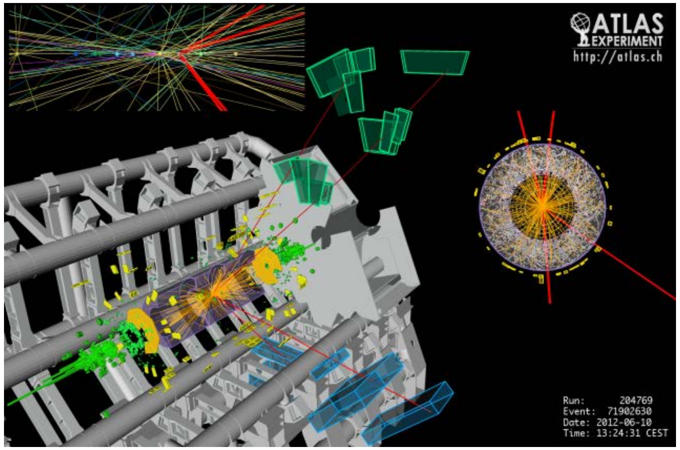


The final states considered are 4μ, 4e, 2e2μ

Very clean final state:
- 4 leptons of high p_T,
- isolated
- coming from the primary vertex

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





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