A global view on the Higgs self-coupling

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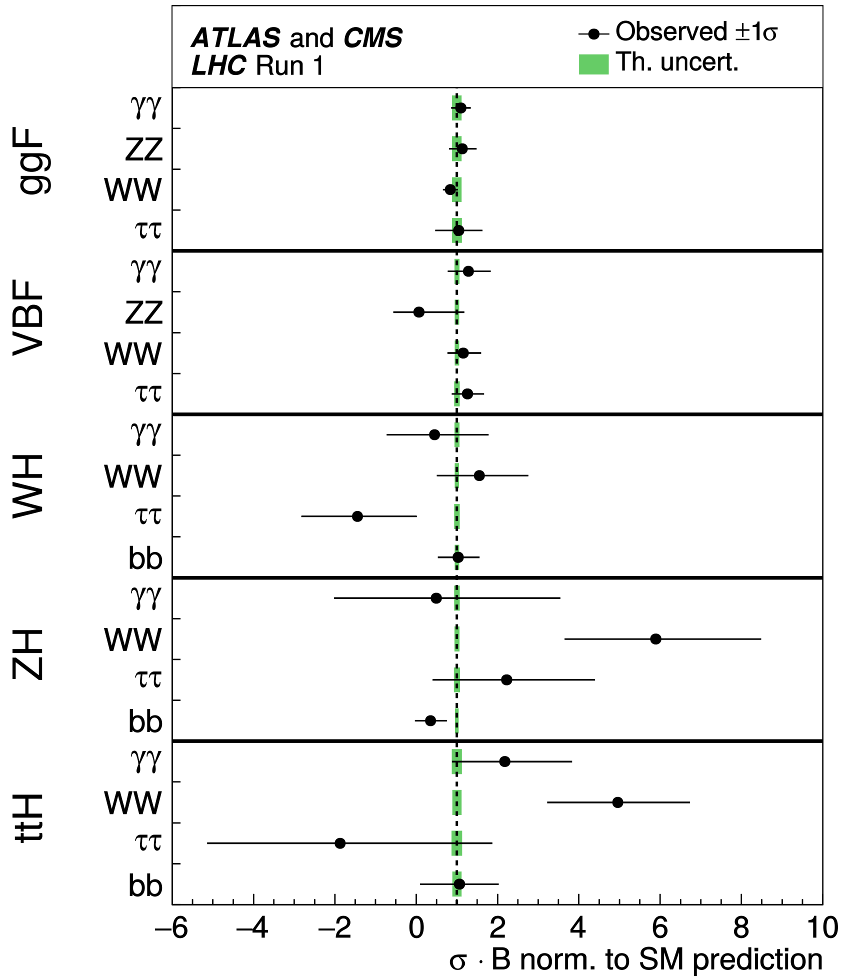
HEFT @ Durham 2017/05/22

Based on DV, Grojean, Panico, Riembau, Vantalon [1704.01953]

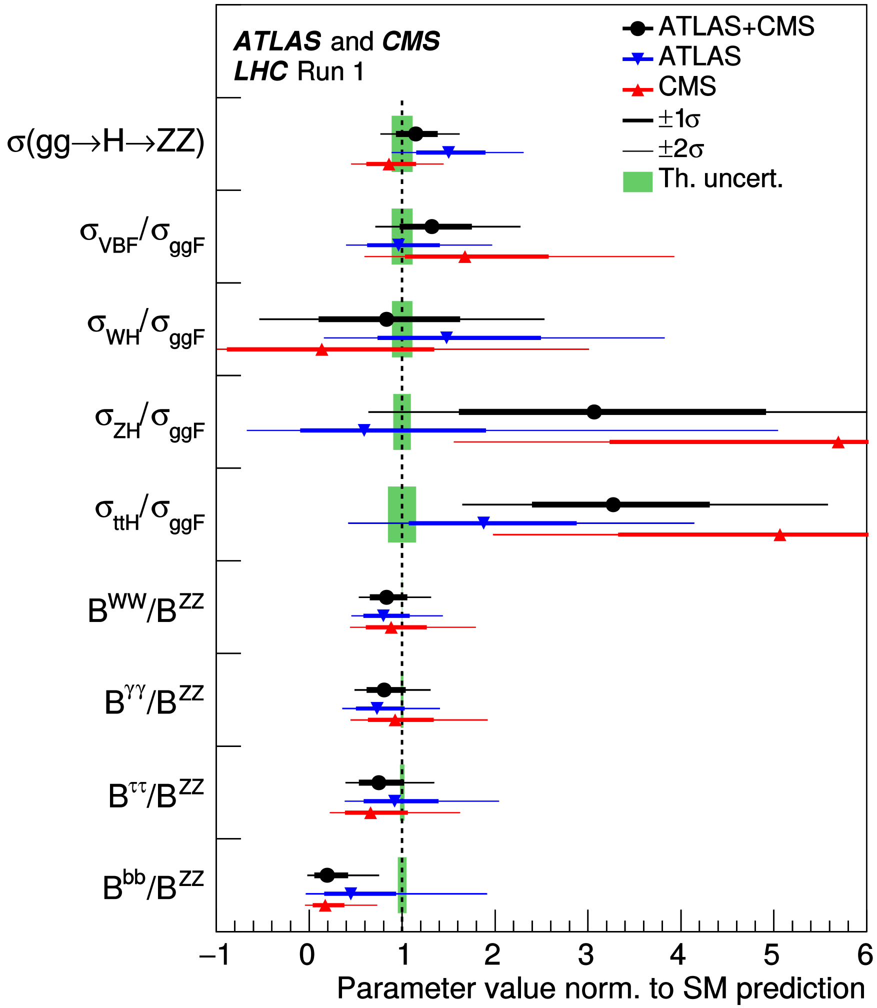
Precision single-Higgs physics @ LHC

ATLAS+CMS [1606.02266]

20x ($\sigma_i B^f$) (norm. to SM*)



Fit rates w/ 1x σ and 8x ratios*



***Hypothesis**: h is produced on-shell (σ_i) and then decays (BR^f)

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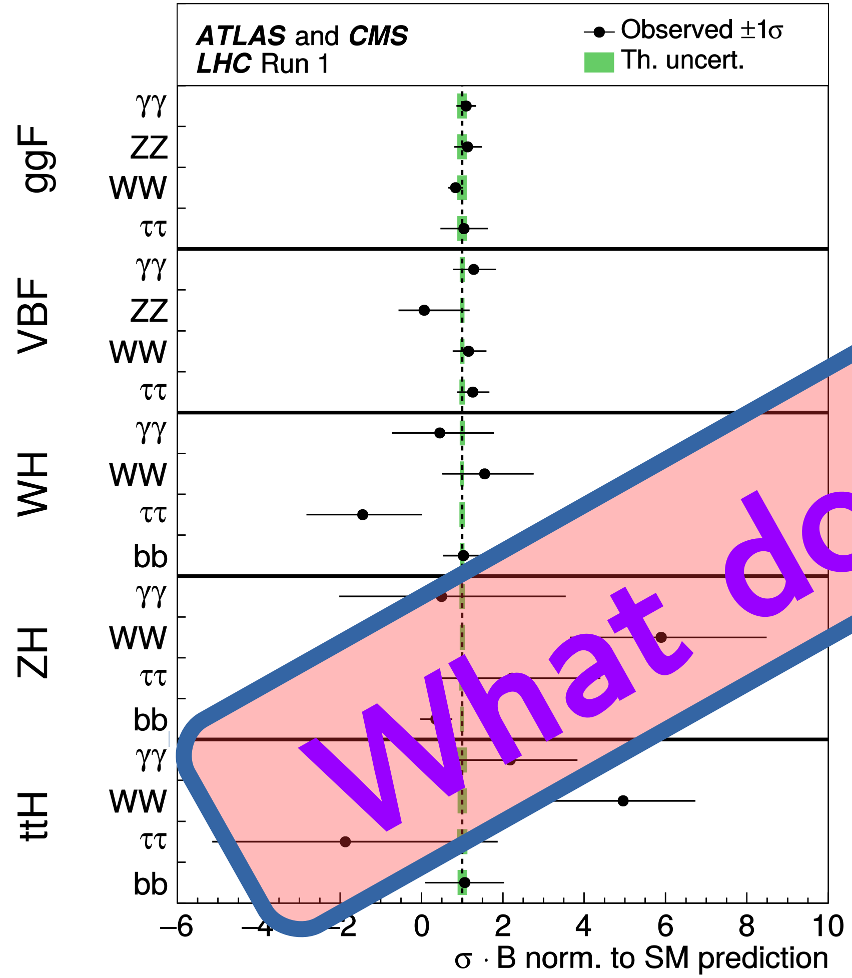

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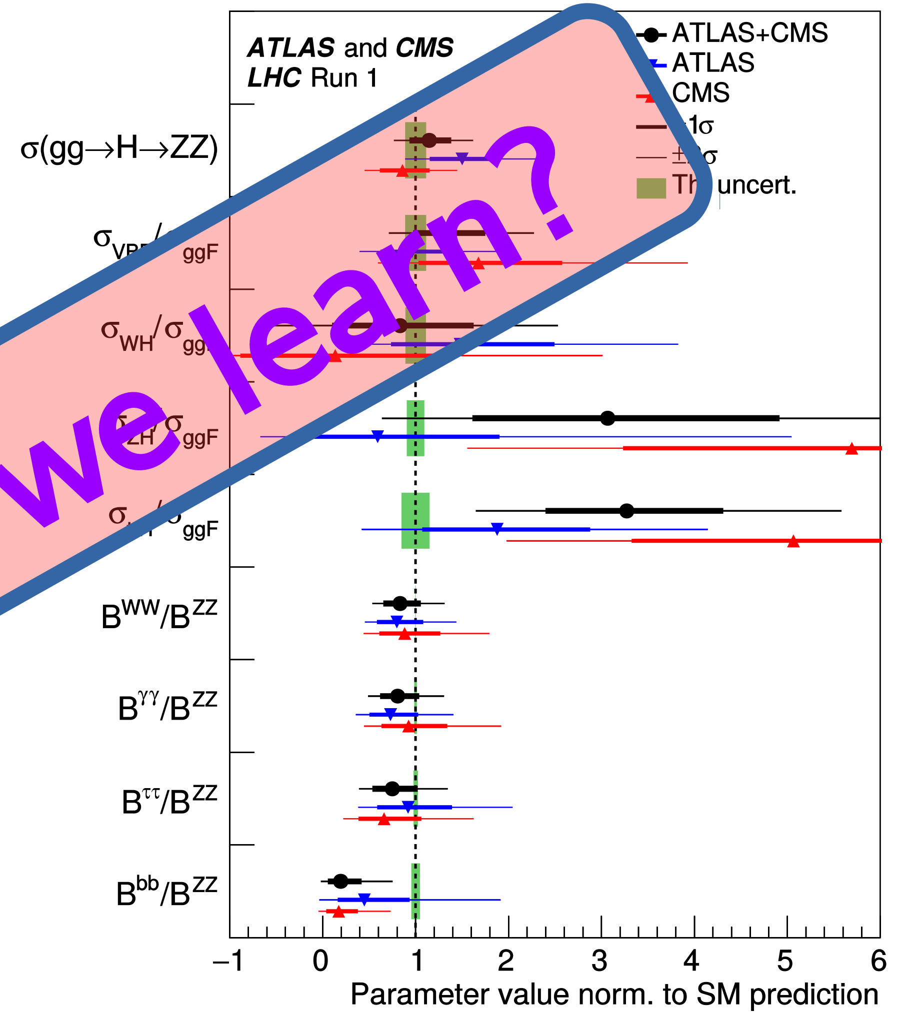


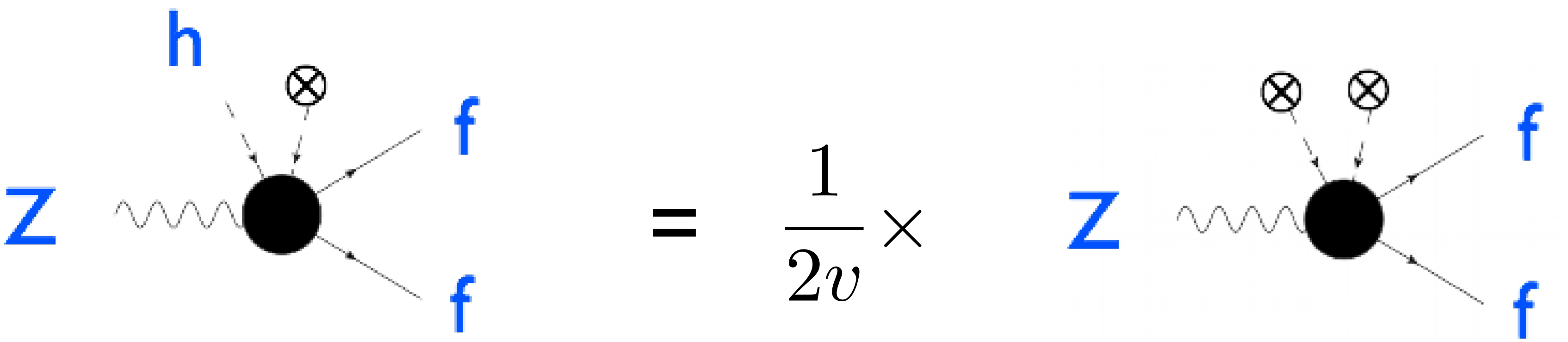
***Hypothesis**: h is produced on-shell (σ_i) and then decays (BR^f)

Constraining BSM deformations

Assume New Physics is **heavy** & EW symmetry is **linearly realized** → SMEFT

Potentially new BSM-effects in h physics could have been already tested in the vacuum

(courtesy of A. Pomarol@HiggsHunting2014)



$$= \frac{1}{2v} \times$$

$$H^\dagger D_\mu H \bar{f} \gamma^\mu f$$

(assuming that the Higgs boson is part of a doublet)

Modifications in h→Zff related to Z→ff

Already constrained at LEP

Constraining BSM deformations

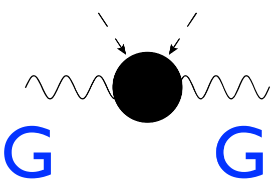
Assume: New Physics is **heavy** & EW symmetry is **linearly realized** $\rightarrow$ SMEFT

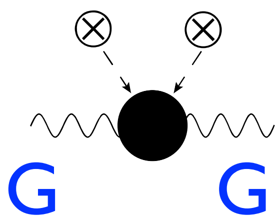
There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

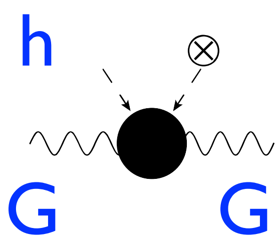
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \rightarrow \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

operator not visible in the vacuum
(redefinition of input parameter)





But can affect h physics:



affects GG $\rightarrow$ h!

My working assumptions

- SMEFT ⇒ Linearly realized EW symmetry (H doublet)
- Mass scale "Λ" of NP heavier than typical energy scale of the process "E" ⇒ expansion in E/Λ
- Further simplifying assumptions (to limit # of O's)
  - only CP-even d=6 O's
  - no O's tested in vacuum
  - flavor universality
  - no L,B-L violating O's
  - no dipole O's
  - no Ψ^4 O's (t^4,ttqq,q^4)

$$\mathcal{L} \supset \boxed{\mathcal{L}_{\rm SM}} + \cancel{\mathcal{L}_{d=5}} + \boxed{\mathcal{L}_{d=6}} + \cancel{\mathcal{L}_{d=7}} + \cancel{\mathcal{L}_{d=8}} + \dots$$

L violating — B-L violating — subleading wrt d=6

Higgs deformations in the Higgs basis

Pomarol '14; +Gupta,Riva '14; Falkowski '15; HXSWG YR4

$$
\begin{aligned}
\mathcal{L} \supset \frac{h}{v}\Big[& \delta c_w \frac{g^2 v^2}{2} W^+_\mu W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu \\
& + c_{ww}\frac{g^2}{2} W^+_{\mu\nu} W^{-\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu} \\
& + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu} \Big] \\
& + \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}^{(2)}_{gg}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f \left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right) \bar{f}_R f_L + \text{h.c.}\right] \\
& - (\kappa_\lambda - 1)\lambda_3^{SM} v h^3 ,
\end{aligned}
$$

f=t,b,τ

parametrize space of d=6 operators in a way more directly connected to observable quantities in Higgs physics

SM tensor structures

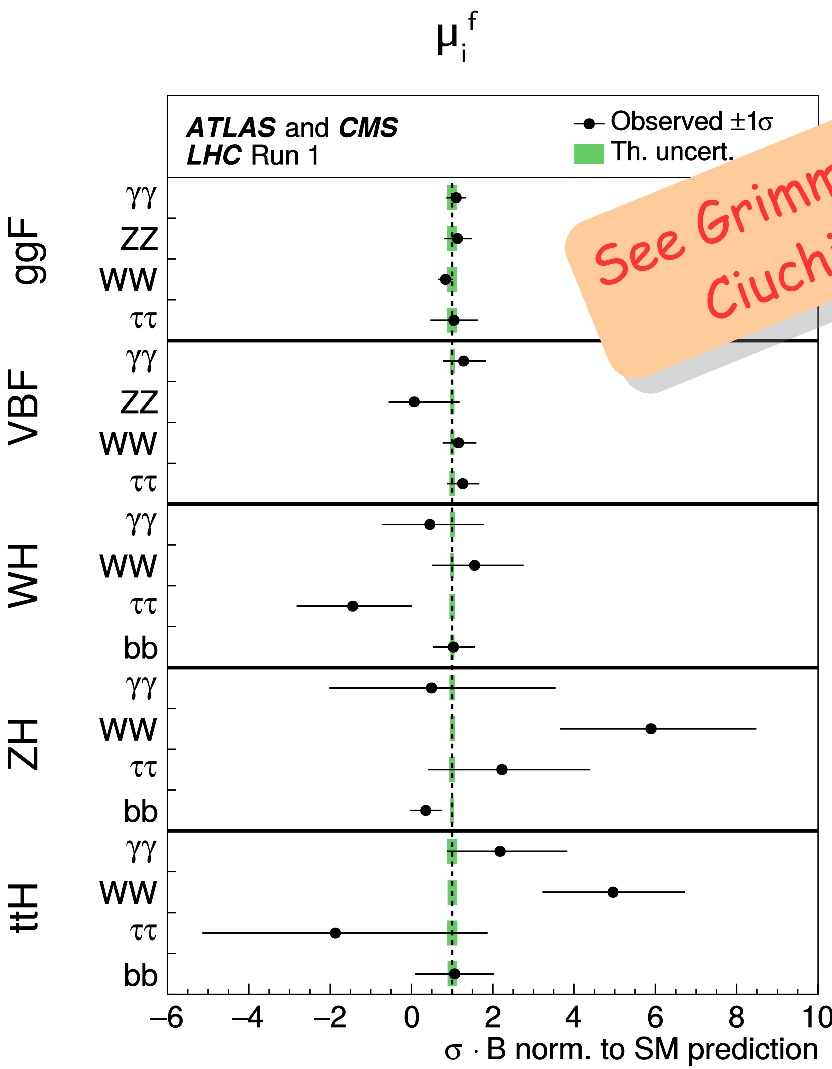
"SM" tensor structures

"New" tensor structures

10 Independent couplings

8 Dependent couplings

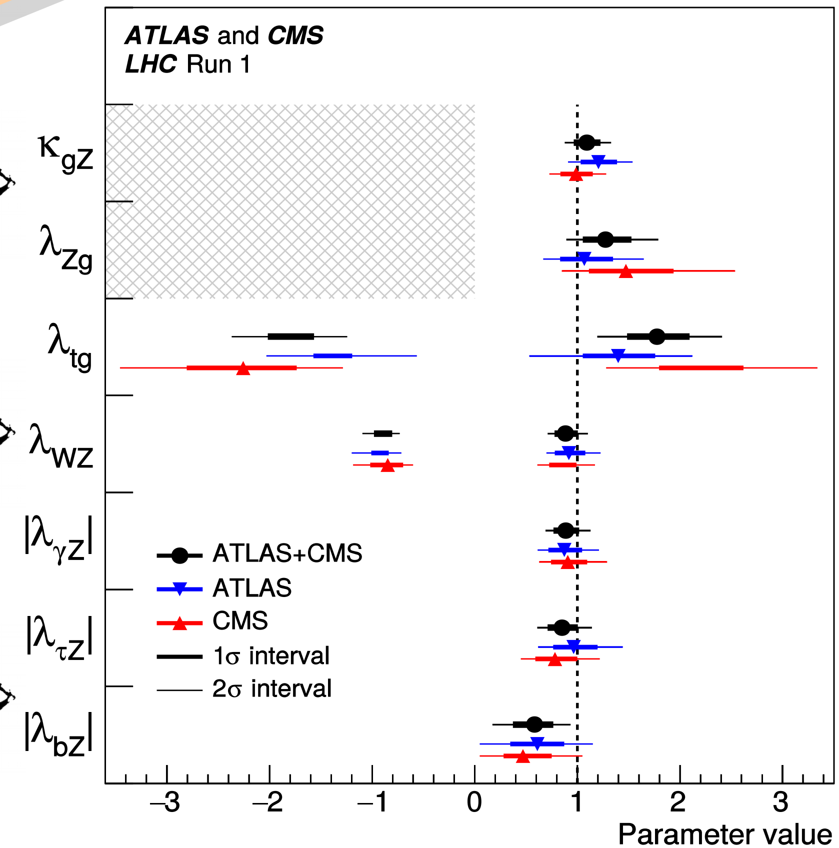
Interpretation of rates measurements



See Grimm's, Kolger's, Cuchini's talks

"κ-framework"

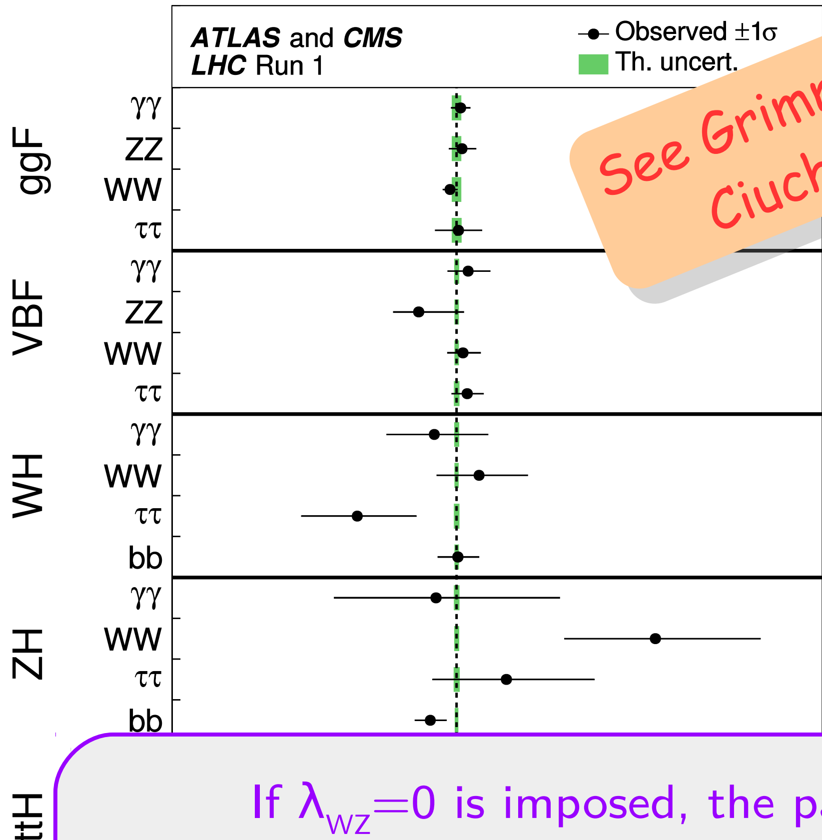
- Only total rates modified
- No new tensor structures



ATLAS+CMS [1606.02266]

Interpretation of rates measurements

μ_i^f



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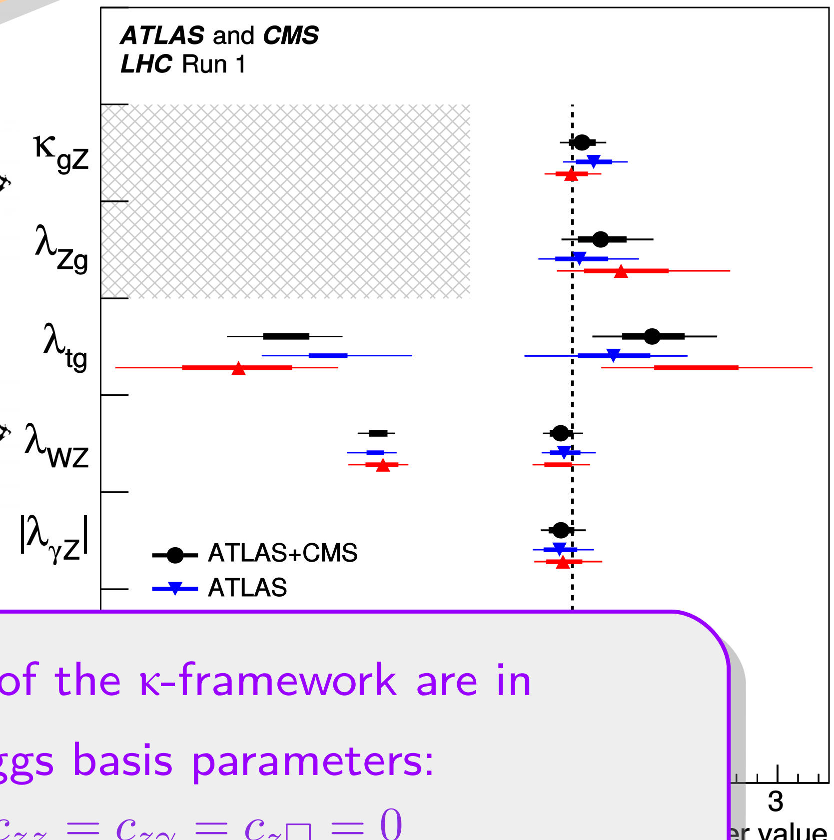


If $\lambda_{WZ}=0$ is imposed, the parameters of the κ-framework are in correspondence with 6 of the Higgs basis parameters:

$c_{gg}, \delta c_z, c_{\gamma\gamma}, \delta y_t, \delta y_b, \delta y_\tau$ while $c_{zz} = c_{z\gamma} = c_{z\Box} = 0$

(and the new tensor structures are allowed)

Still missing: Higgs self-coupling

$$V^{\rm SM}(h) = \frac{1}{2} m_h^2 h^2 + \lambda_3^{\rm SM} v h^3 + \lambda_4^{\rm SM} h^4$$

$$\lambda_3^{\rm SM} = \frac{m_h^2}{2v^2} \qquad \lambda_4^{\rm SM} = \frac{m_h^2}{8v^2}$$

See also Gorbahn's talk

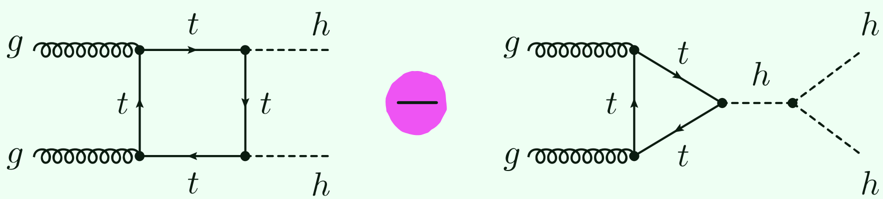
- Why important? In the SM, λ_3 and λ_4 control
  - stability of the EW vacuum
  - possibility of baryogenesis through 1st order EW phase transition

- λ_3 affects Higgs-pair production @LO
  - @LHC 13TeV, 35.9/fb, hh→bbττ, CMS bound is **$\sigma(hh)/\sigma_{SM}(hh)<28$ (exp 25)**
  [CMS PAS HIG-17-002]
- Assuming SM hVV & hff couplings
  - @HL-LHC, 14TeV, 3/ab, hh→bbγγ, ATLAS projection is **$-0.8<\lambda_3/\lambda_3^{SM}<7.7$**
  [ATL-PHYS-PUB-2017-001]

Double-Higgs deformation(s)

(U. Haisch@MoriondEW2017)

Anatomy of hh production



$$R = \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{\rm SM}} = 2.1 - 10.8\lambda + 17.2\lambda^2$$

$$R = 1 \implies \lambda_{1,2} = \{\lambda_{\rm SM}, 3.8\lambda_{\rm SM}\}$$

Limits on λ from hh production

LHC Run I, 20.3 fb^{-1} → $\frac{\lambda}{\lambda_{\rm SM}} \in [-14.5, 19.1]$

2γ2b, 1406.5053;
4b, 1506.00285;
2b2τ, 2γ2W, 1509.04670

LHC Run II, 13.3 fb^{-1} → $\frac{\lambda}{\lambda_{\rm SM}} \in [-8.4, 13.4]$

4b, ATLAS-CONF-2016-049

HL-LHC, 3 ab^{-1} → $\frac{\lambda}{\lambda_{\rm SM}} \in [-0.8, 7.7]$

2γ2b, ATL-PHYS-PUB-2017-001

1-param

$\lambda = \kappa_\lambda \lambda_3^{\rm SM}$

EFT dim-6

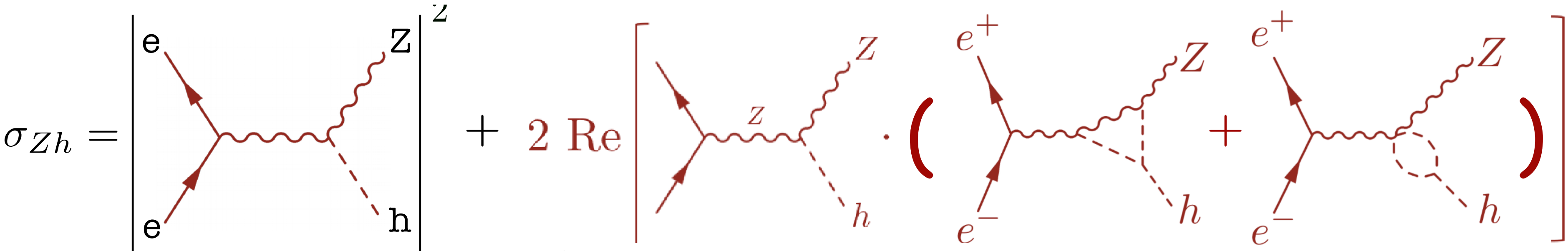
$$\begin{aligned}\frac{\sigma(pp \to hh)}{\sigma_{\rm SM}(pp \to hh)} = {} & A_1\,(1+\delta y_t)^4 + A_2\,(\delta y_t^{(2)})^2 + A_3\,\kappa_\lambda^2\,(1+\delta y_t)^2 + A_4\,\kappa_\lambda^2\,\hat{c}_{gg}^2 \\ & + A_5\,(\hat{c}_{gg}^{(2)})^2 + A_6\,(1+\delta y_t)^2\,\delta y_t^{(2)} + A_7\,\kappa_\lambda\,(1+\delta y_t)^3 \\ & + A_8\,\kappa_\lambda\,(1+\delta y_t)\,\delta y_t^{(2)} + A_9\,\kappa_\lambda\,\hat{c}_{gg}\,\delta y_t^{(2)} + A_{10}\,\hat{c}_{gg}^{(2)}\,\delta y_t^{(2)} \\ & + A_{11}\,\kappa_\lambda\,\hat{c}_{gg}\,(1+\delta y_t)^2 + A_{12}\,\hat{c}_{gg}^{(2)}\,(1+\delta y_t)^2 + A_{13}\,\kappa_\lambda^2\,\hat{c}_{gg}\,(1+\delta y_t) \\ & + A_{14}\,\kappa_\lambda\,\hat{c}_{gg}^{(2)}\,(1+\delta y_t) + A_{15}\,\kappa_\lambda\,\hat{c}_{gg}\,\hat{c}_{gg}^{(2)}\end{aligned}$$

Azatov et al '15 Goertz et al '15 Cao et al '15

Self-coupling & single-Higgs @NLO

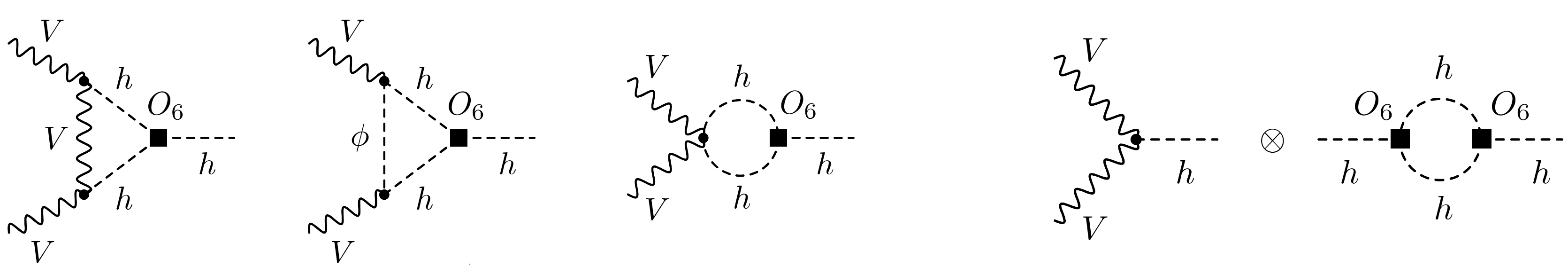
Idea: trilinear coupling affects also single-Higgs rates, but **@NLO. Still, if λ_3 is large** ...

McCullough '13

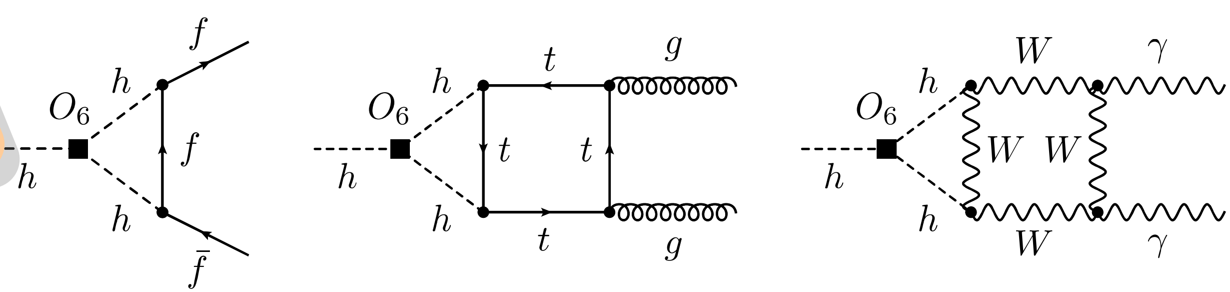


$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Gorbahn, Haisch '16 — Degrassi, Giardino, Maltoni, Pagani '16 — Bizon, Gorbahn, Haisch, Zanderighi '16



See also Gorbahn's talk



Self-coupling & single-Higgs @NLO

$$\Sigma_{\rm NLO} = Z_H \, \Sigma_{\rm LO} \, (1 + \kappa_\lambda C_1)$$

$$\Sigma_{\rm NLO}^{\rm SM} = \Sigma_{\rm LO} \, (1 + C_1 + \delta Z_H)$$

universal

$$\delta\Sigma_{\lambda_3} \equiv \frac{\Sigma_{\rm NLO} - \Sigma_{\rm NLO}^{\rm SM}}{\Sigma_{\rm LO}} = (\kappa_\lambda - 1) C_1 + (\kappa_\lambda^2 - 1) C_2 + \mathcal{O}(\kappa_\lambda^3 \, \alpha^2)$$

Process and kinetic dependent

(inclusive or differential in m_{inv} and p_T^H)

$$C_2 = \frac{\delta Z_H}{(1 - \kappa_\lambda^2 \delta Z_H)}$$

$$\mathcal{O}(\kappa_\lambda^3 \, \alpha^2) \simeq \kappa_\lambda^3 C_1 \delta Z_H \lesssim 10\% \quad \Rightarrow \quad |\kappa_\lambda| \lesssim 20$$

21

Courtesy of D. Pagani @ Turin '17

What can we learn from λ_3 analyses?

1. Is it theoretically motivated to **deform only $\boldsymbol{\lambda_3}$**?
2. How **large** can λ_3 be, from the theoretical point of view?
3. Is bound on λ_3 **stable** if we allow other BSM deformations?
4. If λ_3 is large, does it **spoil** the previous single-Higgs **fits**?
5. Will it be enough to look at **inclusive rates**?
6. Can we "replace" pp$\rightarrow$hh with **other observables**?
7. Can we really avoid performing **global fits** for BSM?
8. (fill w/ your own questions!)

Only an anomalous λ_3?

Note that, at NLO, single-Higgs observables are **insensitive to $h^4, h^5, \ldots$**

- They enter only at higher loop level
- Modifications of the full V(h) could still be allowed, in principle
- At NLO, κ_λ framework = EFT w/ O_6

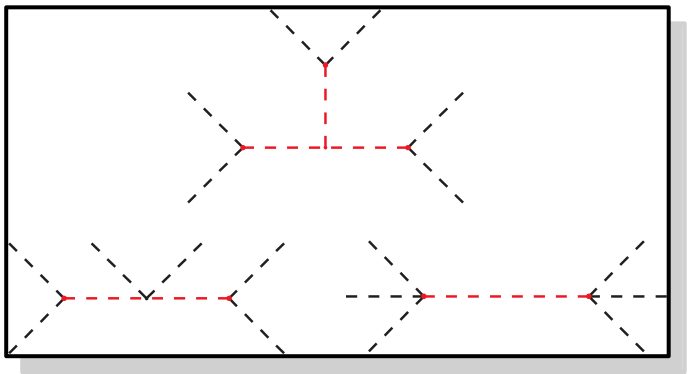
Modification of **h^3 only** leads to loss perturbative unitarity at low energy scales in processes like

$$V_L V_L \to V_L V_L h^n$$

- for $|\kappa_\lambda| < 10$ one gets $\Lambda \sim 5$TeV
  [Falkowski, Rattazzi (in progress)]
- see also Di Luzio, Gröber, Spannowsky [1704.02311

Look for extensions of the SM that, in an EFT description:

- **Only** affect h self-interactions at tree-level, eg SU(2) scalar quadruplets
  - still, 1-loop matching→ other single-Higgs couplings!
- Give **enhanced** modifications of the trilinear
- See e.g.
  - De Blas et al [1412.8480]
  - Jiang, Trott [1612.02040]
  - Di Luzio, Gröber, Spannowsky [1704.02311]



How large can λ_3 be?

DV, Grojean, Panico, Riembau, Vantalon [1704.01953]

A class of models:

Higgs portal, controlled by
- 1 coupling (g_*)
- 1 scale (m_*)

dimensionless parameter · singlet · dimensionless argument

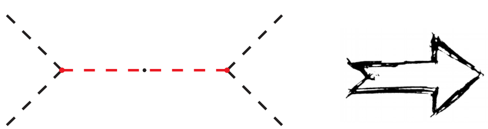
$$\mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_* \varphi / m_*)$$

potential

Linear EFT valid if
(expansion in h/v)

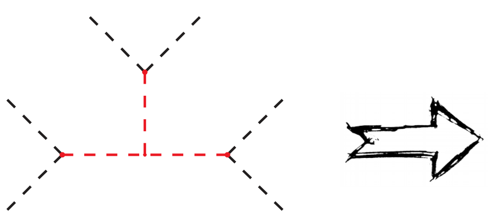
$$\varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2} \ll 1$$

Otherwise only derivative expansion is allowed, many more couplings!!



$$(H^\dagger H)^2 \qquad \Rightarrow \text{tuning of quartic } \Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{\rm SM}}$$

$$\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) \qquad \Rightarrow \delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_*^2} = \theta \varepsilon$$



$$(H^\dagger H)^3 \qquad \Rightarrow \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2} = \varepsilon \Delta$$

Can achieve parametric enhancement of λ_3 at the price of some tuning

$$\theta \simeq 1\,,\ g_* \simeq 3\,,\ m_* \simeq 2.5 \text{ TeV}$$

$$\varepsilon \simeq 0.1\,,\ 1/\Delta \simeq 1.5\%\,,\ \delta c_z \simeq 0.1\,,\ \delta\kappa_\lambda \simeq 6$$

How large can λ_3 be?

Think in terms of model classes

No analysis is truly model independent!

NLO w/ dominant h^3 ? > = < LO w/ subdominant other h

Courtesy of C. Grojean @ Portorož '17

Minimal Composite Higgs
SILH

$\frac{1}{f^2}\left(\partial_\mu |H|^2\right)^2$ $\quad$ $\frac{\lambda_4}{f^2}|H|^6$

$\xi = \frac{v^2}{f^2} \ll 1$ $\quad$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\xi$ $\quad$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\xi$

NLO h^3
irrelevant

Partly Composite Higgs

$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2$ $\quad$ $\frac{\varepsilon^6}{f^2}|H|^6$

$\xi = \frac{v^2}{f^2} \ll 1$ $\quad$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\varepsilon^4\xi$ $\quad$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\varepsilon^2 \frac{g_*^2 v^2}{m_h^2}\varepsilon^4\xi$

NLO h^3
could be relevant

Bosonic Technicolor
Induced EWSB

$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2$ $\quad$ $\frac{\varepsilon^6}{f^2}|H|^6$

$\varepsilon = \frac{f}{v} \ll 1$ $\quad$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\varepsilon^2$ $\quad$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\mathcal{O}(1)$

NLO h^3
a priori relevant

A global view on the Higgs self-coupling

DV, Grojean, Panico, Riembau, Vantalon [1704.01953]

ATLAS HL-LHC scenario

- Similar to CMS “Scenario 1”
- 14TeV, 5/ab, pile-up μ=140

Observables: $\mu_i^f = \sigma_i \times BR^f / (\sigma_i \times BR^f)_{SM}$

Production channels: ggF,WH,ZH,VBF,ttH

Decay modes: $\gamma\gamma$,WW,ZZ,bb,$\tau\tau$

Assume **SM signal (μ_i^f=1)**

- Keep only interference SM-BSM
- Allow for NLO corrections due to κ_λ
- With my assumptions, **10 parameters**
- Perform simple χ^2 fit

The fit is insensitive to global shift $\sigma_i \to \sigma_i + \Delta$ & $Br^f \to BR^f - \Delta$

high precision $\to$ $\mu_i^f = 1 + \delta\sigma_i + \delta BR^f$

In principle 5x5 observables, but **only 9 independent directions $\to$ 1 exact flat direction**

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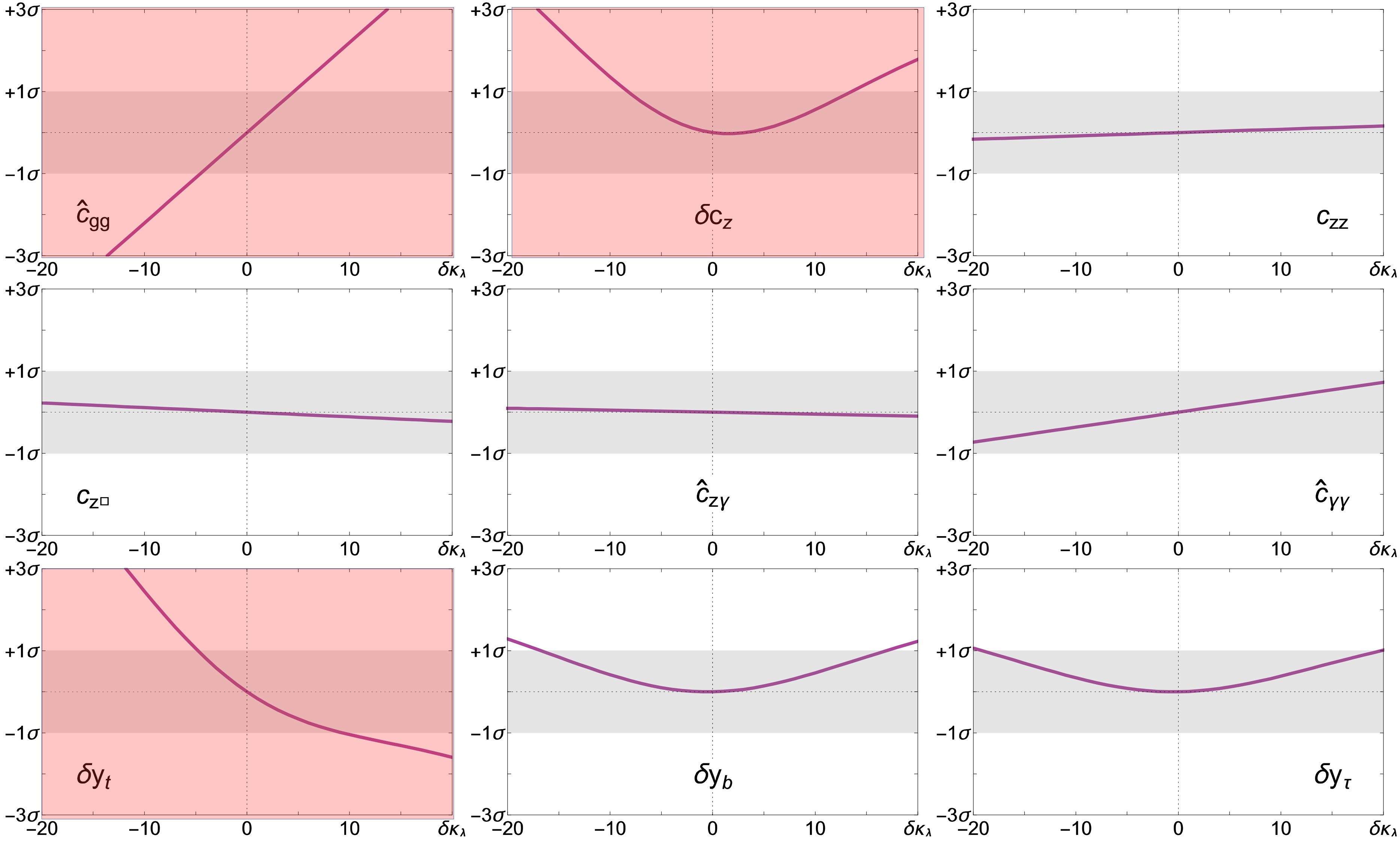
In principle 5x5 observables, but **only 9 independent directions** **$\to$ 1 exact flat direction**

- Impact of single-Higgs couplings on κ_λ
- Impact of κ_λ on single-Higgs couplings
- Compare & combine w/ double-Higgs production
- Crude analysis of the effect of single-Higgs differential distributions

Exact flat direction in the global fit

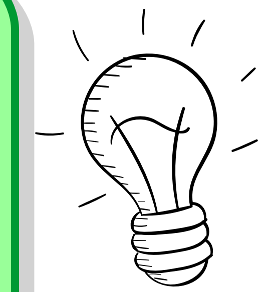
Higgs couplings variation along the flat direction



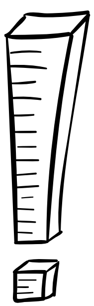
Will further constraints help?

- Triple Gauge Couplings
  - currently WWZ and WWγ tested at 5% → expect 1%
  - can be converted in constraints on 2 linear combinations of

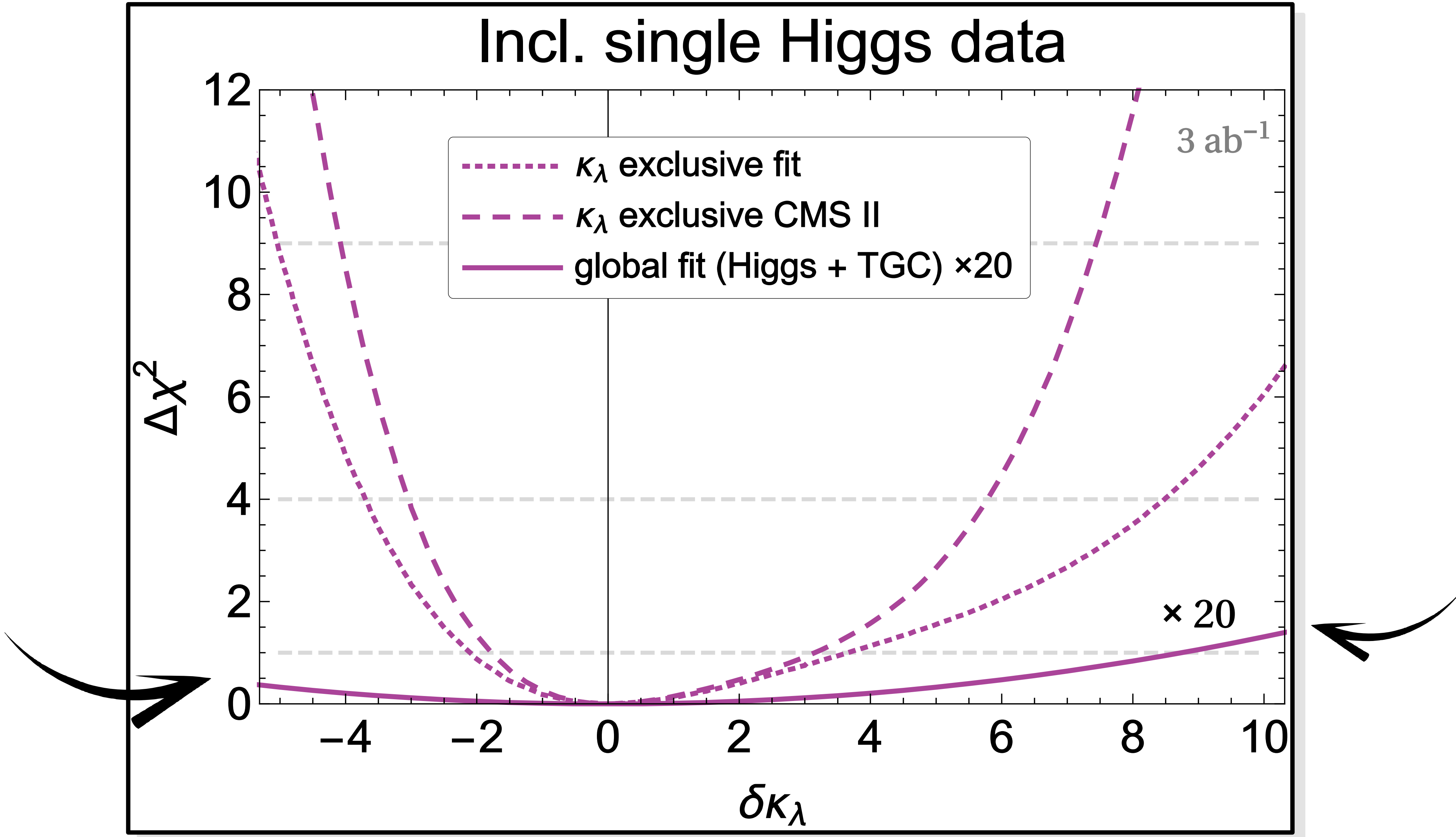
$$\hat{c}_{\gamma\gamma}, \hat{c}_{z\gamma}, c_{zz}, c_{z\Box}$$



- BR(h→Zγ)
  - Will be measured w/ 30% accuracy
  - Can be used to constrain $c_{z\gamma}$ → not relevant for κ_{λ}!
- BR(h→μμ)
  - Either one extra parameter δy_{μ}
  - Or (w/ flavor universality) just helps to better bound δy_{e}



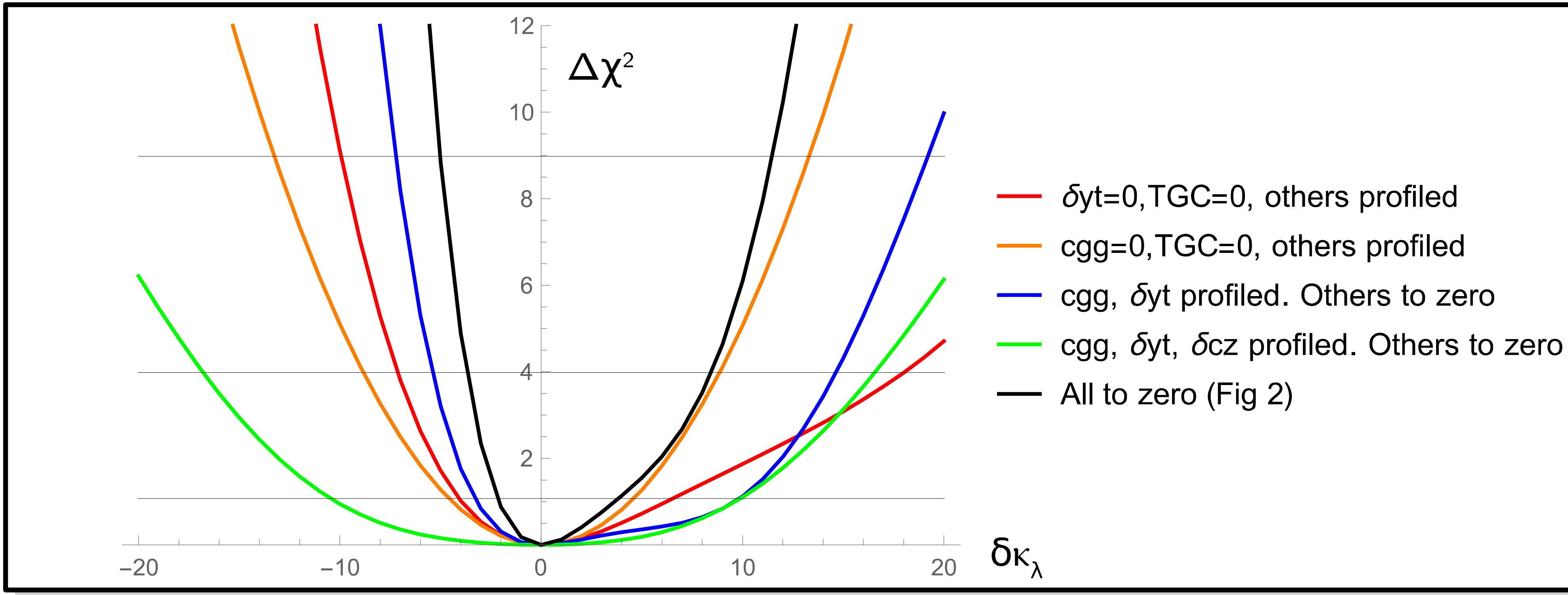
Bound on (κ_λ-1) in a global fit



As expected, the flat direction is rather insensitive to the TGC constraint

Constrained "intermediate" scenarios

A game: let's pretend we have scenarios with some of $(\delta y_t, c_{gg}, \delta cz)$ switched off

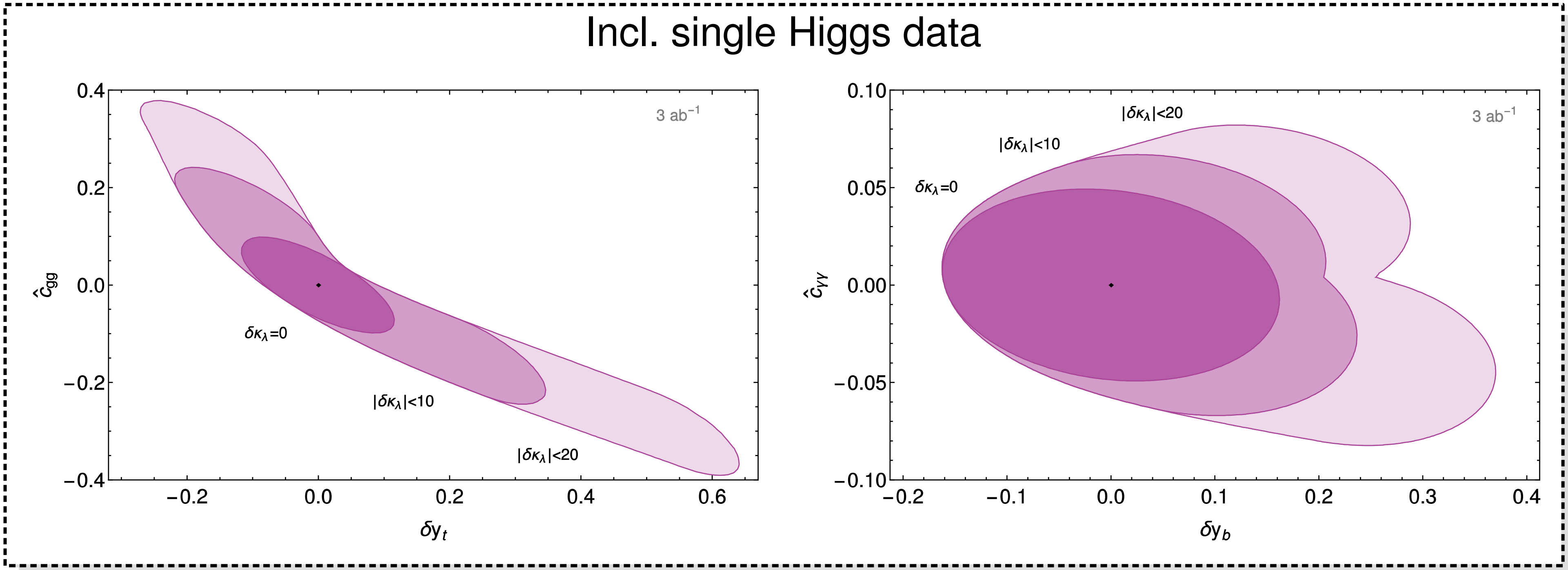


As expected, constraining "by hand" the coefficients that control the flat direction, the bound on κ_λ shrinks

Any model builder willing to explore how motivated such scenarios are?

Single-Higgs couplings fit w/κ_λ@NLO

$(\delta y_t, \hat{c}_{gg})$ $(\delta y_b, \hat{c}_{\gamma\gamma})$

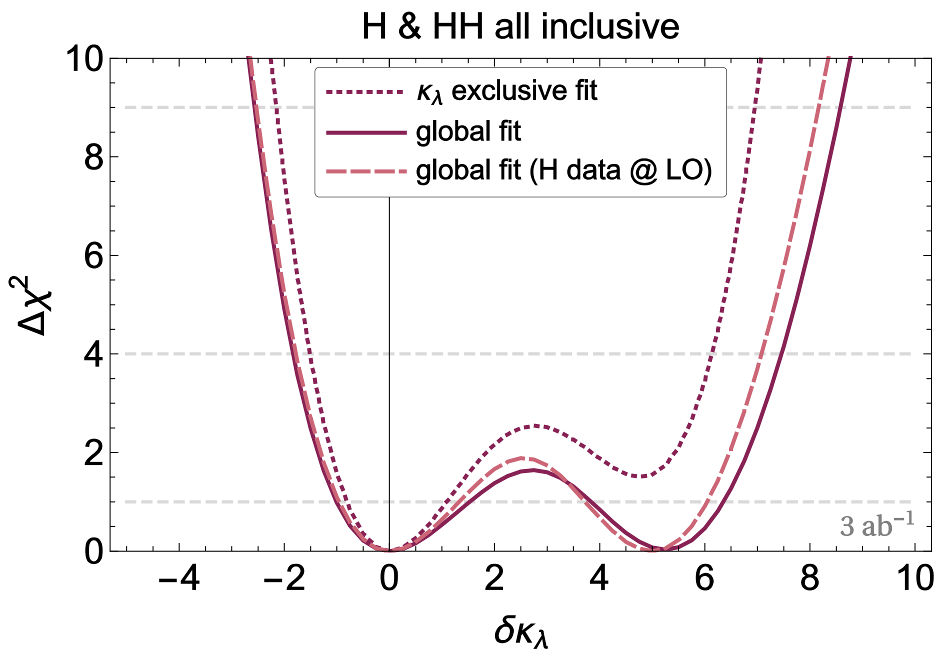


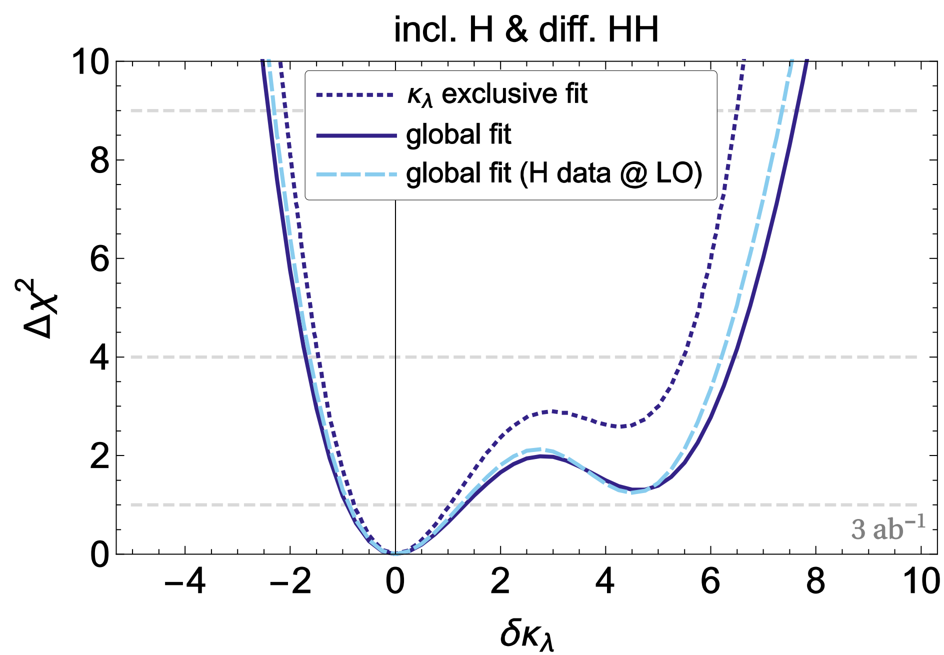
$\Delta\chi^2$=2.3 contours (68% CL in the gaussian limit)

[other 8 couplings profiled]

If large κ_λ is allowed, it feeds back into single-Higgs couplings fits

Compare & combine w/double-Higgs





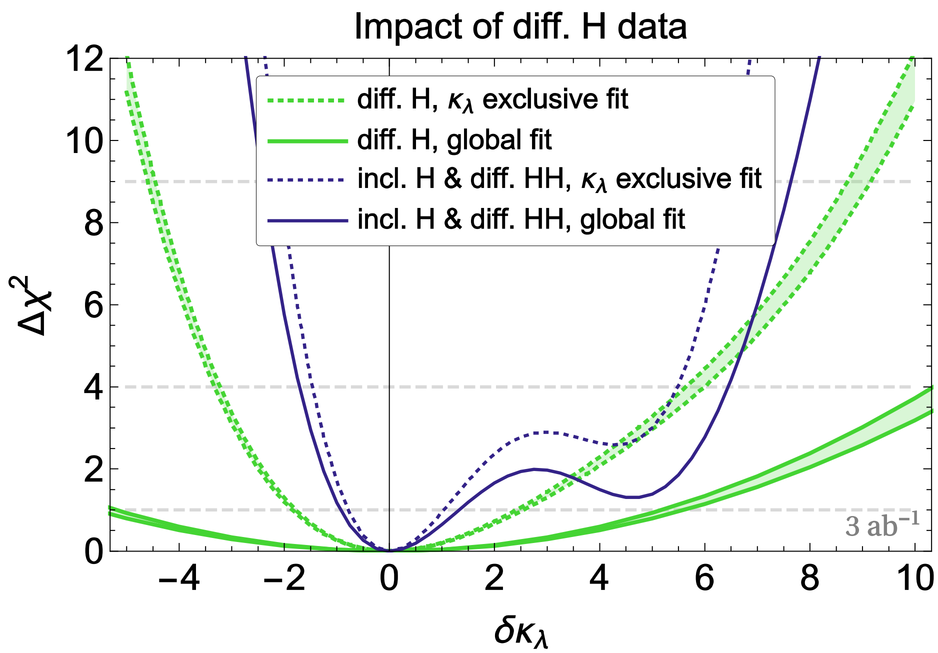
Double-Higgs drives the bound on κ_λ while, single-Higgs observables are essential in order to constrain the **other** coefficients deforming $\sigma(hh)$

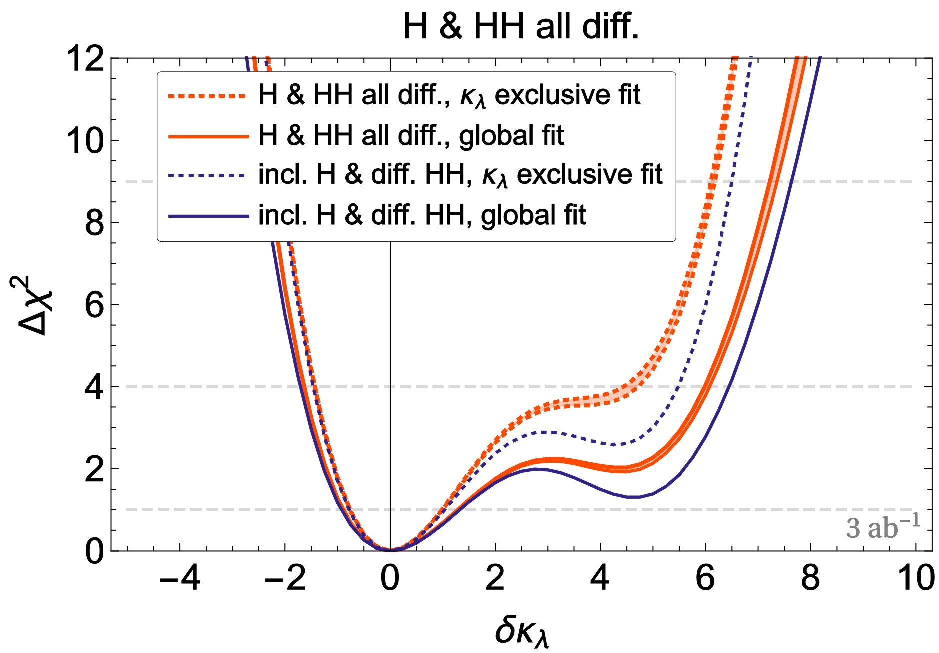
Differential (m_{hh}) double-Higgs removes degeneracy due to second minimum

"Exclusive" κ_λ fit benefits from single-Higgs

Warning: here the assumption is that of linearly realized EW symmetry.
Non-linear EFT$\Rightarrow\{1,h,h^2\}$X couplings unrelated$\Rightarrow$more parameters, global fit w/ EWPO!

Impact of differential single-Higgs





The inclusion of differential data for single-Higgs observables seems promising, but more detailed estimates of the experimental systematics are required, as well as more refined analyses.

Combining differential data from single- and double-Higgs, the minimum at large $\delta\kappa_\lambda$ is further lifted. Synergy!

Outlook

- Keep up with the hard work in **measuring inclusive & diff rates.**
  - **Remember that their interpretation is a 2nd step**..
- Suggestion: **use simplified frameworks with few parameters as a training ground, to push the combined experimental analyses and to show their limitations in such optimistic scenarios**

- **Caveat**: bounds on κ_λ obtained in this way, **will have a physical interpretation only in very specific scenarios, and will not represent model-independent statements on the self-coupling**

- How to move forward?
  - Come up with **optimized observables** (e.g. the best differential distributions)
  - Include **new channels to resolve flat directions in the BSM deformations** (e.g. **h+j, h+γ**)
  - Updated **HL-LHC projections** for inclusive rates, and possibly for (select) differential distributions would be welcome, in order to assess the LHC potential to constrain BSM scenarios.
  - Are there BSM scenarios that can be tested now? ⇒ **Model building effort?**

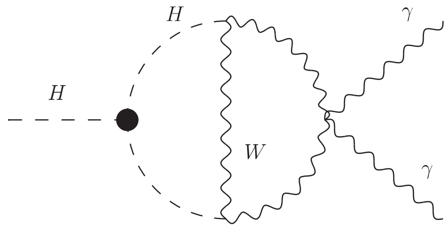
Backup

Self-coupling & single-Higgs @NLO

LO can include QCD corrections

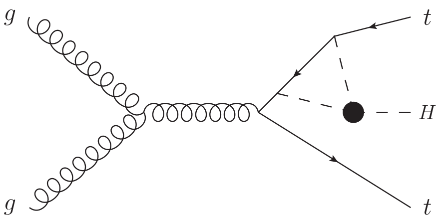
$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO} (1 + \kappa_\lambda C_1)$$

$$C_1^\Gamma = \frac{\int d\Phi \; 2\Re\left(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM}}\right)}{\int d\Phi \; |\mathcal{M}^0|^2}$$



$$= \mathcal{M}^1_{\lambda_3^{\rm SM}} \sim \kappa_\lambda$$

$$C_1^\sigma = \frac{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, 2\Re\left(\mathcal{M}^{0*}_{ij}\mathcal{M}^1_{\lambda_3^{\rm SM},ij}\right) d\Phi}{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, |\mathcal{M}^0_{ij}|^2 d\Phi}$$



$$= \mathcal{M}^1_{\lambda_3^{\rm SM}} \sim \kappa_\lambda$$

dΦ inclusive or differential

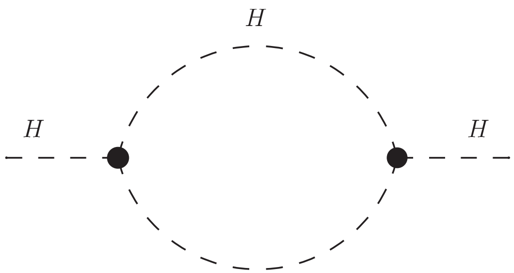
Courtesy of D. Pagani @ Turin '17

Self-coupling & single-Higgs @NLO

$$\Sigma_{\rm NLO} = Z_H\, \Sigma_{\rm LO}\left(1 + \kappa_\lambda C_1\right)$$

$$Z_H = \frac{1}{1 - \kappa_\lambda^2\, \delta Z_H}$$

$$\delta Z_H = -\frac{9}{16}\,\frac{2(\lambda_3^{\rm SM})^2}{m_H^2\,\pi^2}\left(\frac{2\pi}{3\sqrt{3}} - 1\right)$$



$$\sim \quad \kappa_\lambda^2$$

The wave-function normalization receives corrections that depend quadratically on λ_3.
For large κ_λ, the result cannot be linearized and must be resummed.

$$\kappa_\lambda^2\, \delta Z_H \lesssim 1 \quad \Rightarrow \quad |\kappa_\lambda| \lesssim 25$$

For a sensible resummation

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Courtesy of D. Pagani @ Turin '17

Projections at HL-LHC: $\Delta\mu_i^f/\mu_i^f$

14TeV, 3/ab, μ=140

Process		Combination	Theory	Experimental
$H \to \gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H \to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H \to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
$H \to Z\gamma$	incl.	0.30	0.13	0.27
$H \to b\bar{b}$	WH	0.37	0.09	0.36
	ZH	0.14	0.05	0.13
$H \to \tau^+\tau^-$	VBF	0.19	0.12	0.15

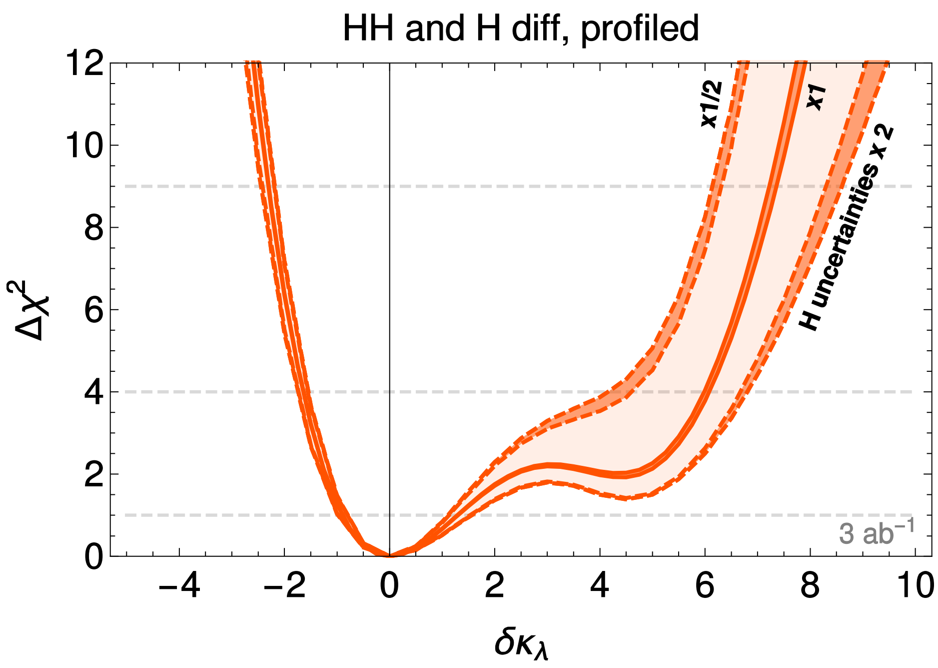
ATL-PHYS-PUB-2014-016
+ ATL-PHYS-PUB-2016-008
+ ggF N^{3}LO uncertainty
+ VH (H→ZZ) split in WH,ZH

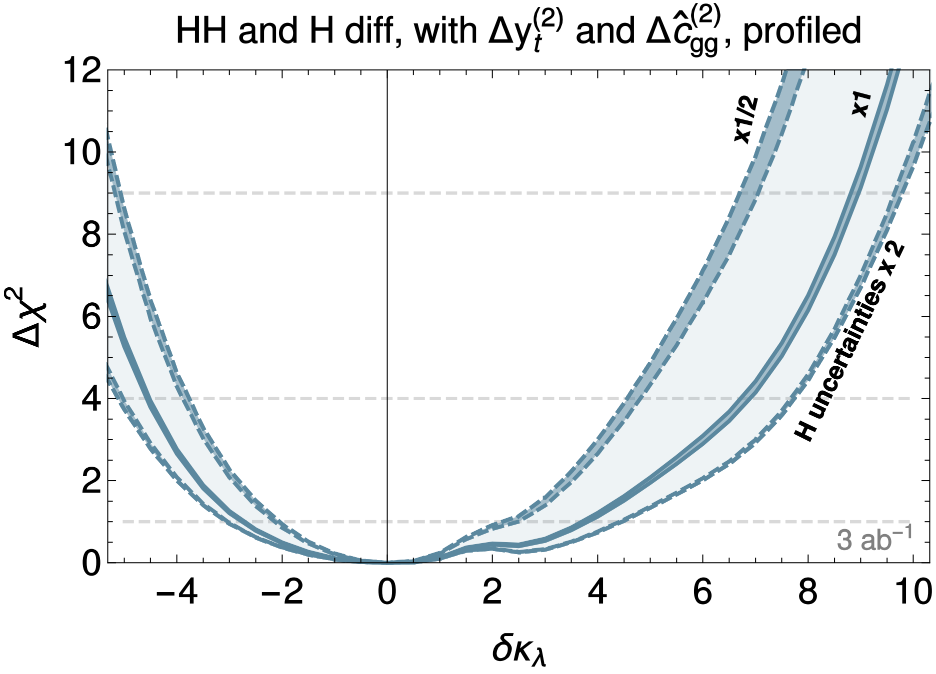
Any further effort on this side would be welcome!

- Updated simulations/projections
- Systematics
- Correlations (?)
- Theory $\to$ what to compute? **Differential?**

Would it be feasible to have HL-LHC **projections for (select) diff. distributions?**

Some simple systematics





Simple global rescaling of single-Higgs uncertainties

Relax assumption of linear EFT for double-Higgs

Triple gauge couplings – Higgs interplay

$$\begin{aligned}
\mathcal{L}_{\rm tgc} &= ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\left[(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu + \tilde\kappa_\gamma \tilde A_{\mu\nu}\,W^+_\mu W^-_\nu\right]\\
&+ igc_\theta\left[(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\delta\kappa_z)\,Z_{\mu\nu}\,W^+_\mu W^-_\nu + \tilde\kappa_z\,\tilde Z_{\mu\nu}\,W^+_\mu W^-_\nu\right]\\
&+ i\frac{e}{m_W^2}\left[\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \tilde\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}\tilde A_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu} + \tilde\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}\tilde Z_{\rho\mu}\right]\\
&- g_s f^{abc}\partial_\mu G^a_\nu G^b_\mu G^c_\nu + \frac{c_{3g}}{v^2}g_s^3 f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu} + \frac{\tilde c_{3g}}{v^2}g_s^3 f^{abc}\widetilde G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}.
\end{aligned}$$

WWγ and WWZ data can constrain single-Higgs couplings

$$\begin{aligned}
\delta g_{1,z} &= \frac{1}{2(g^2-g'^2)}\left[c_{\gamma\gamma}e^2g'^2 + c_{z\gamma}(g^2-g'^2)g'^2 - c_{zz}(g^2+g'^2)g'^2 - c_{z\Box}(g^2+g'^2)g^2\right]\\
\delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right),
\end{aligned}$$

Gauge invariant operators in the Higgs basis

$$
\begin{aligned}
O_{\delta\lambda_3} &= -\frac{1}{v^2}(H^\dagger H)^3, \\
O_{c_{gg}} &= \frac{g_s^2}{4v^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} \\
O_{\delta c_z} &= -\frac{1}{v^2}\left[\partial_\mu (H^\dagger H)\right]^2 + \frac{3\lambda}{v^2}(H^\dagger H)^3 + \left(\sum_f \frac{\sqrt{2} m_{f_i}}{v^3} H^\dagger H \bar{f}_{L,i} H f_{R,i} + \text{h.c.}\right), \\
O_{c_{z\Box}} &= \frac{ig^3}{v^2(g^2 - g'^2)}\left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu} - \frac{ig^2 g'}{v^2(g^2 - g'^2)}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)\partial_\nu B_{\mu\nu}, \\
O_{c_{zz}} &= \frac{ig(g^2+g'^2)}{2v^2(g^2 - g'^2)}\left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu} - \frac{ig'(g^2+g'^2)}{2v^2(g^2 - g'^2)}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)\partial_\nu B_{\mu\nu} \\
&- \frac{ig}{v^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} - \frac{ig'}{v^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}, \\
O_{c_{z\gamma}} &= -\frac{2igg'^2}{v^2(g^2+g'^2)}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} + \frac{2ig' g^2}{v^2(g^2+g'^2)}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}, \\
O_{c_{\gamma\gamma}} &= -\frac{igg'^4}{2v^2(g^4 - g'^4)}\left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu} + \frac{ig'^5}{2v^2(g^4 - g'^4)}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)\partial_\nu B_{\mu\nu} \\
&- \frac{igg'^4}{v^2(g^2+g'^2)^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} + \frac{ig'^3(2g^2+g'^2)}{(g^2+g'^2)^2 v^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu} + \frac{g'^2}{4v^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}, \\
[O_{\delta y_f}]_{ij} &= -\frac{\sqrt{2 m_{f_i} m_{f_j}}}{v^3} H^\dagger H \bar{f}_{L,i} H f_{R,j} + \text{h.c.},
\end{aligned}
$$