(Indirect) measurements of the Higgs trilinear coupling

A global view

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Workshop on the physics of HL-LHC, and perspectives at HE-LHC

CERN, Oct 31, 2017

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

My working assumptions

- Scale "Λ" of new physics » typical energy of the process "E" ⇒ d=6 EFT
- linearly realized EW symmetry (h belongs to Higgs doublet) ⇒ SMEFT
- Operators O_i tested in processes w/o the Higgs assumed to be constrained
- Work in the Higgs basis ⇒ trilinear interaction $\lambda_3=\kappa_\lambda\lambda_{SM}=(1+\delta\kappa_\lambda)\lambda_{SM}$
- Further simplifying assumptions (just to limit # of O_i)
  - no CP,L,B-L, violating O_i
  - no dipole O_i
  - flavor universality
  - no ψ^4 (t^4,ttqq,q^4)

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

L violating   B-L violating   subleading wrt d=6

Focus on 10 O_i relevant at the LHC (not just SM tensor structures! EFT ≠ k-framework)

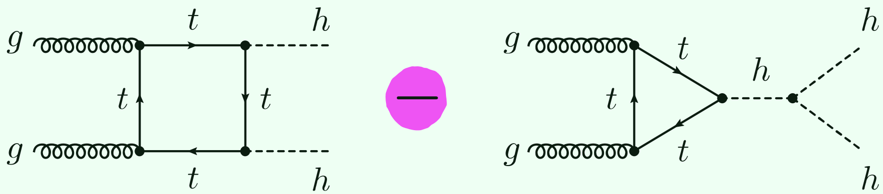
⇒ 10 independent deformations of hGG, hψψ, hWW, hZZ, hγγ, hZγ, hhGG, hhψψ, **hhh**

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

Double-Higgs deformation(s) [ggF]

(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} $\longrightarrow$ $\frac{\lambda}{\lambda_{\rm SM}} \in [\text{-}14.5,\ 19.1]$

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

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

4b, ATLAS-CONF-2016-049

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

2γ2b, ATL-PHYS-PUB-2017-001

1-param

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

EFT dim-6

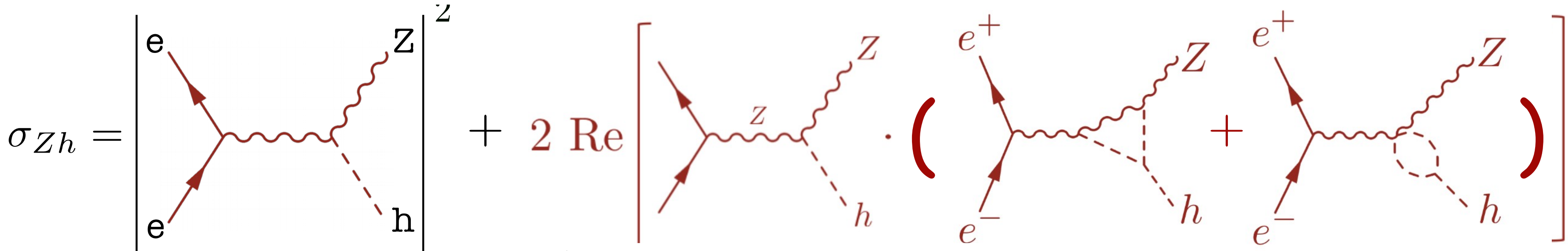
$$\begin{aligned}\frac{\sigma(pp \to hh)}{\sigma_{\rm SM}(pp \to hh)} = {} & A_1\,(1+\delta y_t)^4 + A_2\,(\delta y_t^{(2)})^2 + A_3\,\kappa_\lambda^2\,(1+\delta y_t)^2 + A_4\,\kappa_\lambda^2\,\hat{c}_{gg}^2 \\ & + A_5\,(\hat{c}_{gg}^{(2)})^2 + A_6\,(1+\delta y_t)^2\,\delta y_t^{(2)} + A_7\,\kappa_\lambda\,(1+\delta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

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

Self-coupling & single-Higgs @NLO

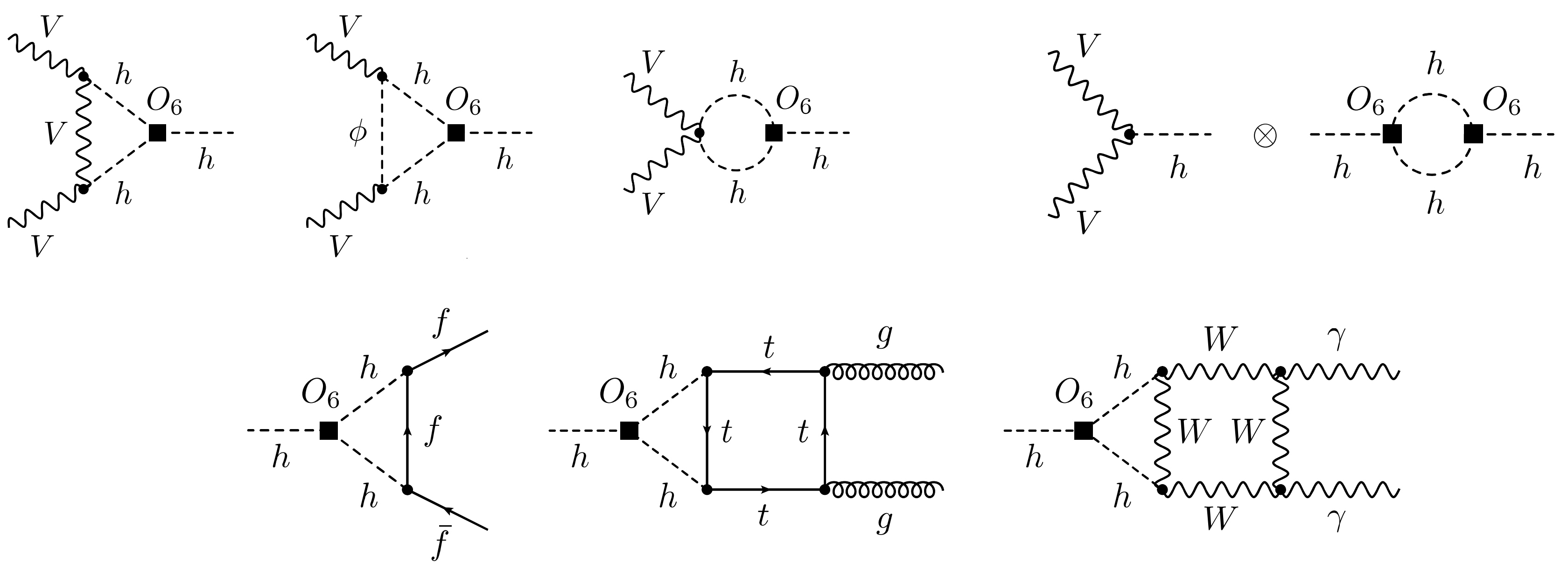
Idea: trilinear coupling affects also single-Higgs rates, but **@NLO. Still, if $\boldsymbol{\lambda_3}$ is large** ...

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



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. Can we really avoid performing **global fits** for BSM?
4. Is **bound** on λ_3 **stable** if we allow other BSM deformations?
5. Will it be **enough** to look at **inclusive rates**?
6. Can we "replace" pp$\to$hh with **single-H observables** for h^3?
7. If λ_3 is large, does it **spoil** the previous **single-Higgs fits**?*

* see backup

Only large anomalous λ_3? Not really…

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

- 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

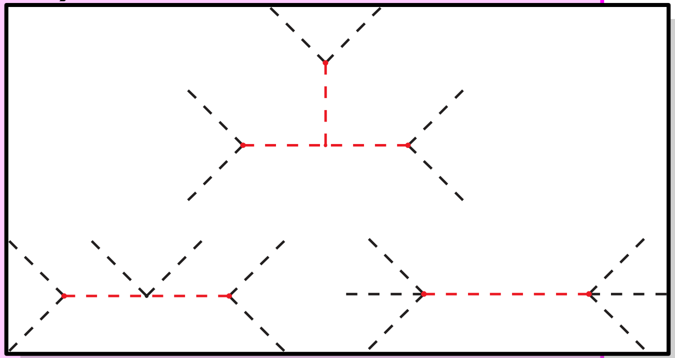
Modification of **h^3 only** leads to loss perturbative unitarity at low energy scales in processes like

$V_L V_L \to V_L V_L h^n$

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

Are there **classes** of BSM models that, in an EFT description:

- **Either deform just Higgs self-interactions (tree-level matching)**
  - e.g. SU(2) scalar quadruplets (not quite a "class")
  - still, 1-loop matching→ other single-Higgs couplings!
- **Or enhance $\delta\kappa_\lambda$** wrt the single-Higgs couplings?
  - e.g. **tuned** Higgs Portal can get $\delta\kappa_\lambda$~6 vs other couplings O(0.1)
- See also De Blas et al [1412.8480], Jiang, Trott [1612.02040], Di Luzio, Gröber, Spannowsky [1704.02311]



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Not in generic BSM scenarios

A global view on the Higgs self-coupling

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

HL-LHC prospects on $\delta\kappa_\lambda$ with ATLAS projections ($\sim$ CMS "Scenario 1")

14TeV, 3/ab, pile-up μ=140

ATL-PHYS-PUB-2014-016 + ATL-PHYS-PUB-2016-008 + ggF N^{3}LO uncertainty HXSWG YR4 + VH ($H\to ZZ$) split in WH,ZH

Keep only interference SM-BSM

Allow for NLO corrections due to κ_λ

With my assumptions, **10 parameters**

Perform χ^2 fit with SM signal ($\mu_i^f=1$)

Signal strength measurements

$\mu_i^f=\sigma_i \times BR^f/(\sigma_i \times BR^f)_{SM} \sim 1+\delta\sigma_i+\delta BR^f$

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

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

A fit of the "usual" inclusive rates is insensitive to simultaneous global shift

$\sigma_i \to \sigma_i + \Delta$ & $Br^f \to BR^f - \Delta$

In principle have 5x5=25 observables, in fact only 9 directions are independent

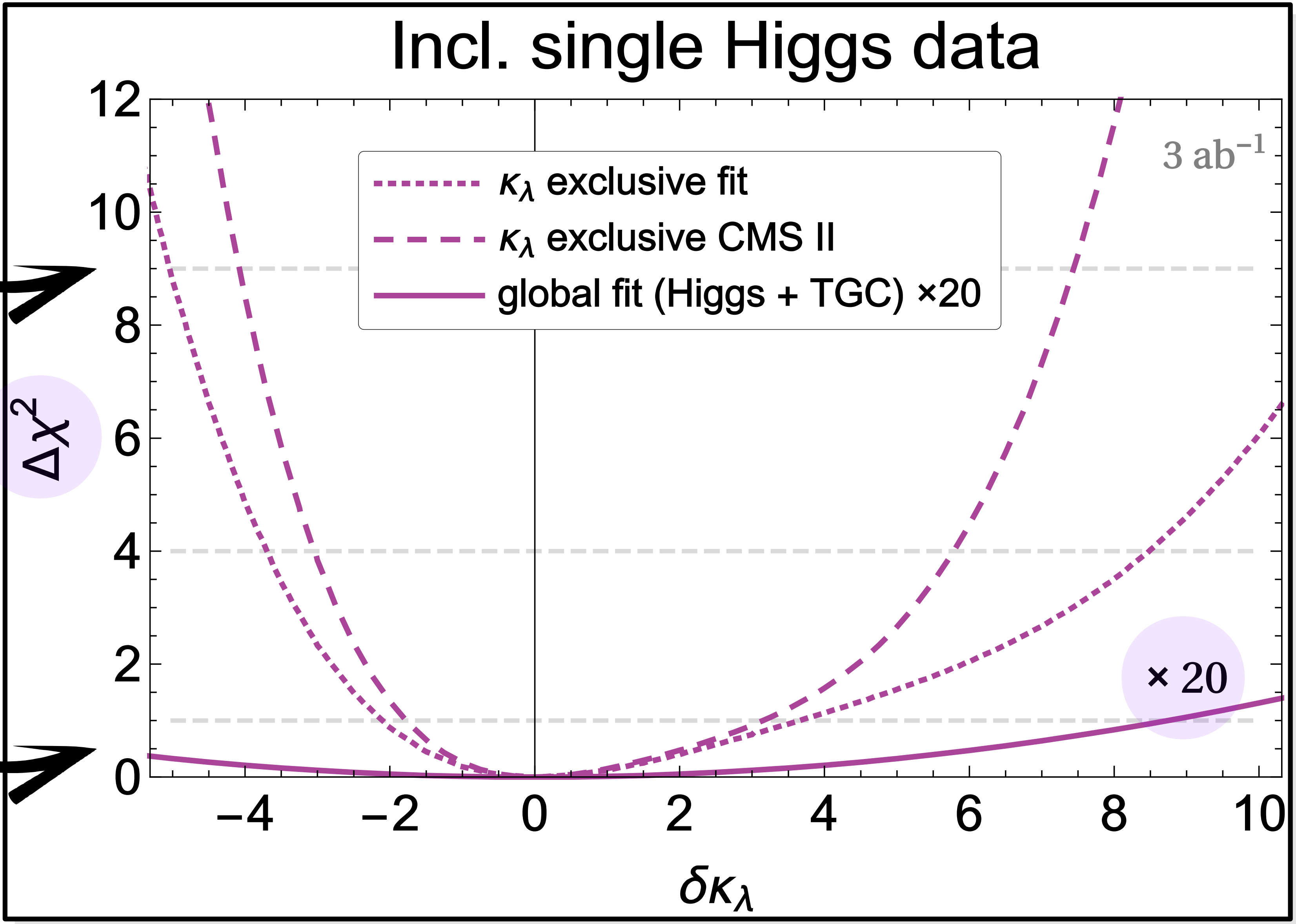
⇒ we expect 1 exact flat direction in a 10 parameters fit

Sorry: including Triple Gauge Couplings constraints, BR($h\to Z\gamma$), BR($h\to\mu\mu$) does not really help :(

Bound on $\delta\kappa_\lambda$ from inclusive rates

allow only $\delta\kappa_\lambda$

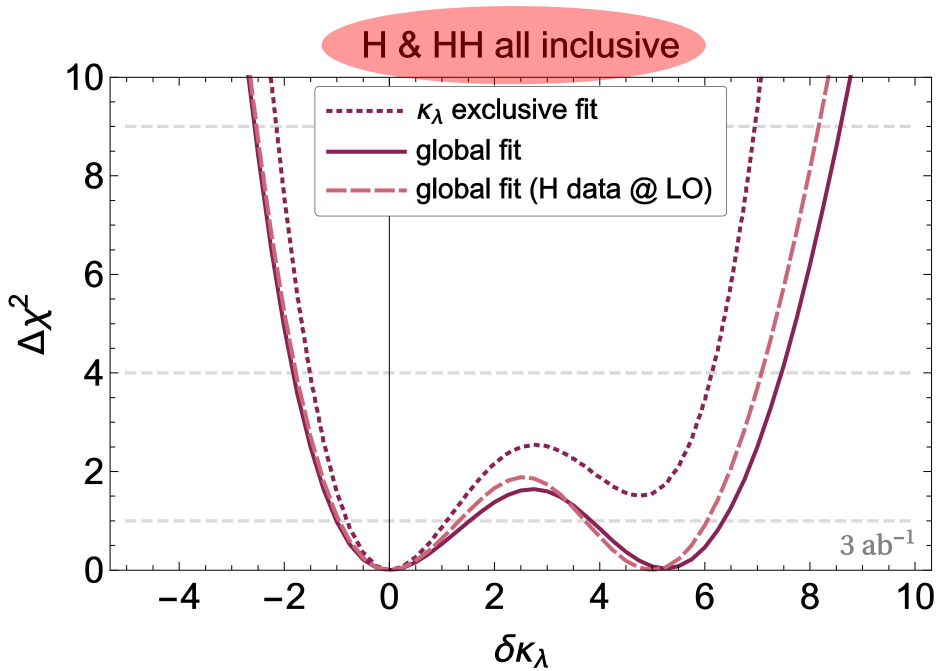
$\delta\kappa_\lambda$ & 7 single-Higgs deformations

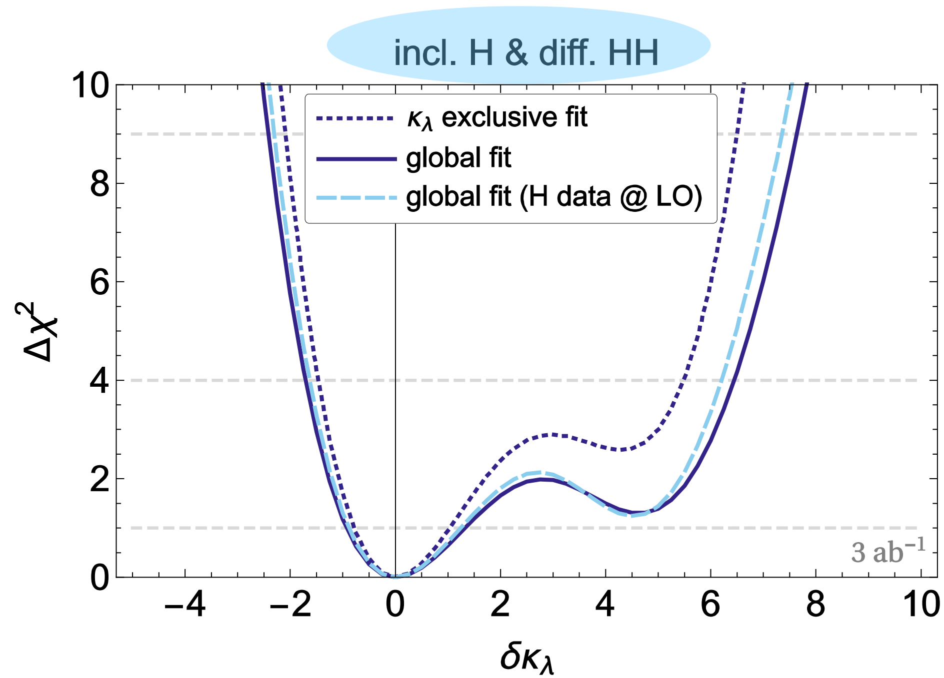


FLAT!

the flat direction is rather insensitive to the TGC constraint

Compare & combine w/double-Higgs





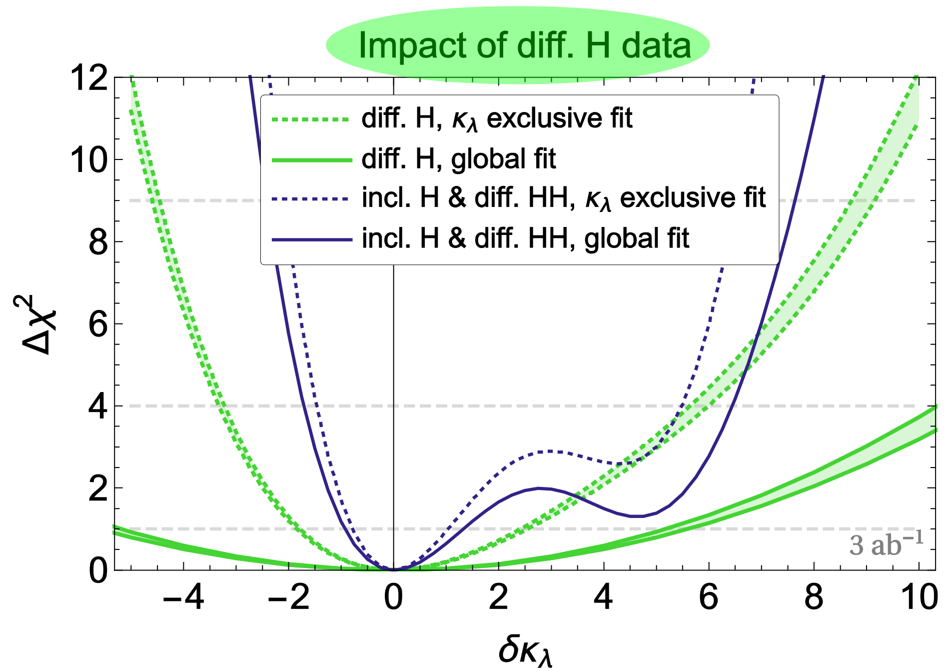
Double-Higgs drives the bound on κ_λ while, single-Higgs observables are essential in order to constrain the other coefficients deforming $\sigma(hh)$

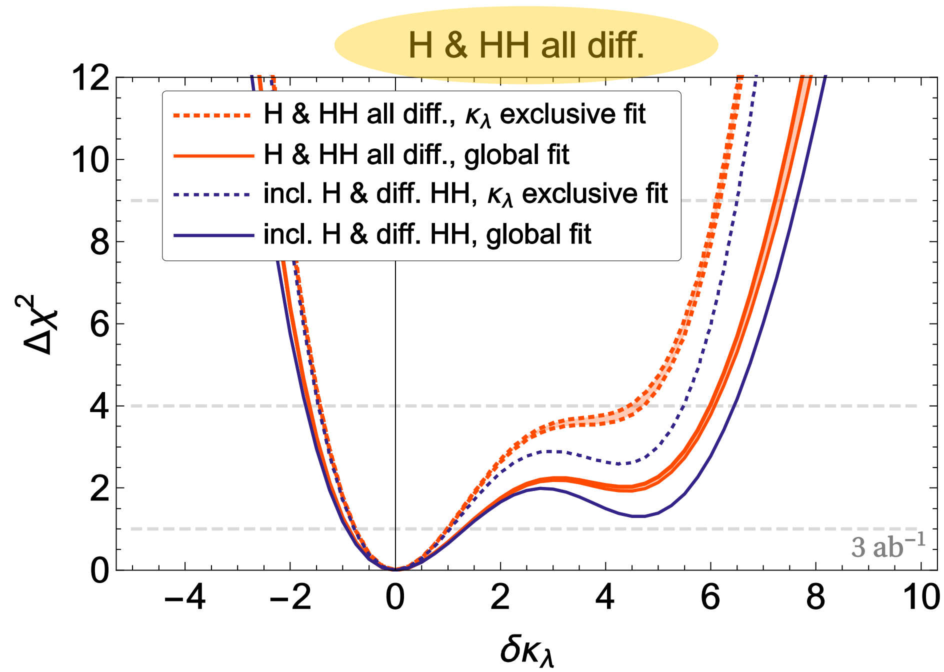
Differential (m_{hh}) double-Higgs removes degeneracy due to second minimum

"Exclusive" κ_λ fits benefit from NLO single-Higgs, global don't

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

Impact of differential VH and ttH





Inclusion of differential data ($d\sigma/dm_{inv}$) 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!

Bound from single-H not competitive but has totally different systematics ⇒ complementary to HH

See Maltoni, Pagani, Shivaji, Zhao [1709.08649] for the impact of $\delta\kappa_\lambda$ on single-Higgs differential distributions and for a simplified κ-framework analysis

Higgs self-coupling @ HL-LHC summary

& HE-LHC outlook

HL-LHC

14 TeV, 3/ab
σ(hh,ggF)~35fb

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

- Inclusive single-Higgs rates can't constrain $\delta\kappa_\lambda$ (w/ NLO effects) in generic BSM scenarios
- Double-Higgs production drives the bound (single-Higgs LO crucial for other deformations)
- Differential measurements of both h and hh help eliminate the extra minimum $\delta\kappa_\lambda \sim 5$
- HL-LHC is **the machine** for accurate differential Higgs measurements → explore prospects!

HE-LHC

33 TeV, 10/ab
σ(hh,ggF)~194fb

- Both high E and high lumi
- Probe BSM in distrib's tails
- Exploit non-SM tensor structures to disentangle flat directions in BSM fits
- Also VBF channel See e.g. Contino et al '10, '12
- Work to be done!

HE here is just naive extrapolation! (FCC=100TeV)

$\delta\kappa_\lambda$ bound / scenario	68%	95%
HL: h incl, hh incl	[-1, 1.5] U [3.9, 6.4]	[−1.8, 7.5]
HL: h incl, hh diff	[-1.1, 1.3]	[−1.7, 6.5]
HE: h incl, hh incl	[-0.3, 0.3] U [5.0, 6.0]	[-0.5, 0.7] U [4.5, 6.7]
HL + HE	[-0.3, 0.3]	[-0.5, 0.6] U [4.8, 6.0]
FCC 100 TeV 30/ab h incl, hh diff	[−0.03, 0.03]	[−0.06, 0.06]

- Uncertanties on single-H μ's: naively extrapolated from HL-LHC
- Double-H EFT: interpolation between HL-LHC and FCC of Azatov et al '15
- NLO $\delta\kappa_\lambda$ effect on single-H: courtesy of D.Pagani

Items for discussion

- Keep up with the hard work in measuring inclusive & diff rates
- 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

Bounds on κ_λ from simplified fits have a physical interpretation only in very non-generic scenarios

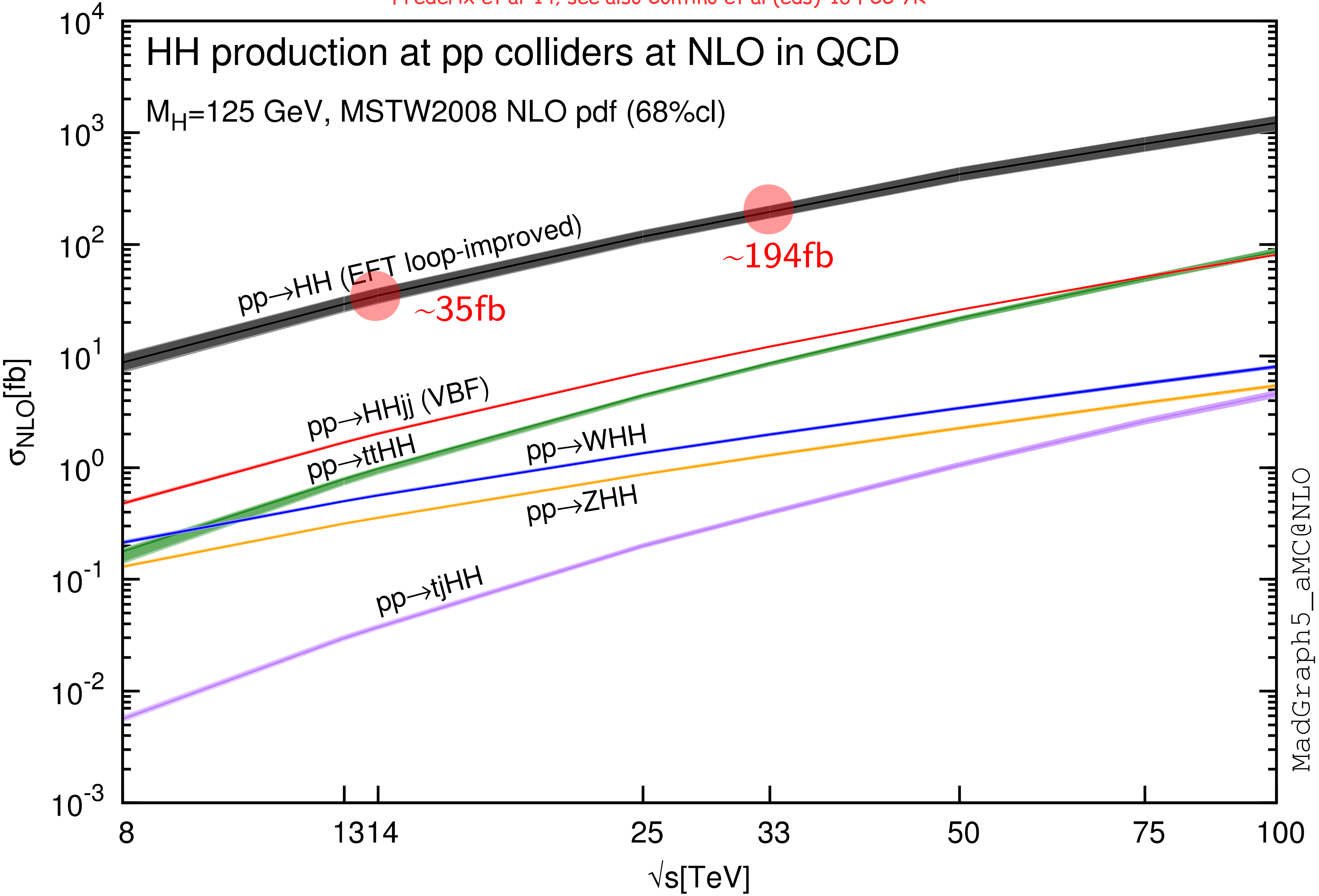
$\Rightarrow$ not at all model-independent statements on the Higgs self-coupling!

- Bounds on κ_λ from single-H can't compete w/ HH, but are complementary
- Come up with optimized observables (e.g. best differential distrib's)
- Include new channels to resolve flat directions (e.g. h+j, h+γ)
- Updated HL-LHC projections for inclusive rates and for differential distrib's
- Very welcome, in order to assess LHC potential to constrain BSM scenarios.
- Are there BSM scenarios that can be tested now? $\Rightarrow$ Model building effort?
- Is it reasonable to neglect the other operators in these extrapolations?

Backup

Double-Higgs at higher energies

Frederix et al '14; see also Contino et al (eds) '16 FCC YR



Higgs deformations in the Higgs basis

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

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

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

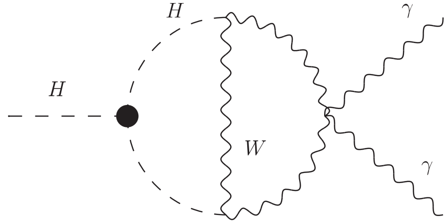
8 Dependent couplings

Self-coupling & single-Higgs @NLO

LO can include
QCD corrections

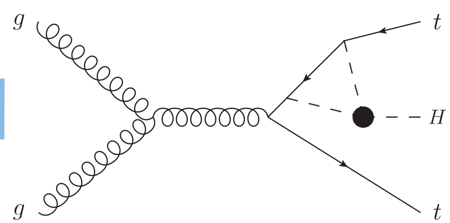
$$\Sigma_{\mathrm{NLO}} = Z_H \, \Sigma_{\mathrm{LO}} \left(1 + \kappa_\lambda \boxed{C_1}\right)$$

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



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

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



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

dΦ inclusive or differential

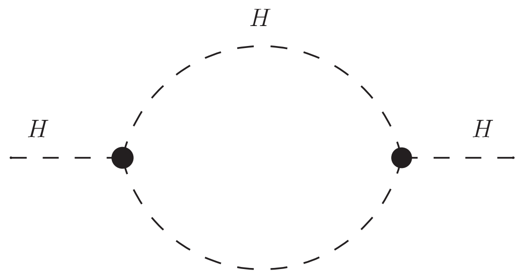
Courtesy of D. Pagani @ Turin '17

Self-coupling & single-Higgs @NLO

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

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

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



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

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.

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

For a sensible resummation

20

Courtesy of D. Pagani @ Turin '17

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

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

Process and kinetic dependent

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

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

$$\underset{21}{\mathcal{O}(\kappa_\lambda^3\, \alpha^2)} \simeq \kappa_\lambda^3 C_1 \delta Z_H \lesssim 10\% \quad \Rightarrow \quad |\kappa_\lambda| \lesssim 20$$

Courtesy of D. Pagani @ Turin '17

Large λ$_3$ in tuned Higgs Portal

1 dimensionless parameter

1 coupling

1 scale

singlet

potential

dimensionless argument

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

Linear EFT valid if

(expansion in h/v)

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

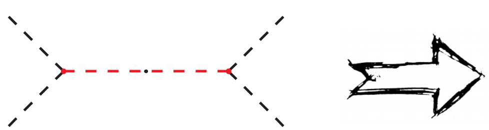
Otherwise only derivative expansion is allowed, many more couplings!!

Can achieve parametric enhancement of λ$_3$ at the price of some tuning

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

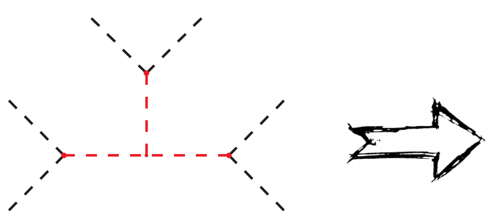
$$\varepsilon \simeq 0.1\,,\ 1/\Delta \simeq 1.5\%\,,\ \delta c_z \simeq 0.1\,,\ \delta\kappa_\lambda \simeq 6$$

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



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

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



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

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

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

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

NLO h^3 irrelevant

Partly Composite Higgs

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

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

NLO h^3 could be relevant

Bosonic Technicolor

Induced EWSB

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

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

NLO h^3 a priori relevant

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

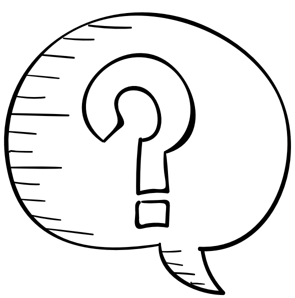
14TeV, 3/ab, μ=140

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 N³LO 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?**

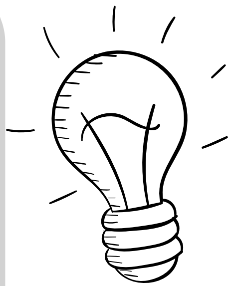


Would it be feasible to have HL-LHC **projections for (select) diff. distributions?**

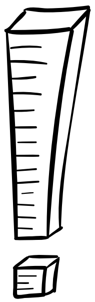
Will further constraints help?

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

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

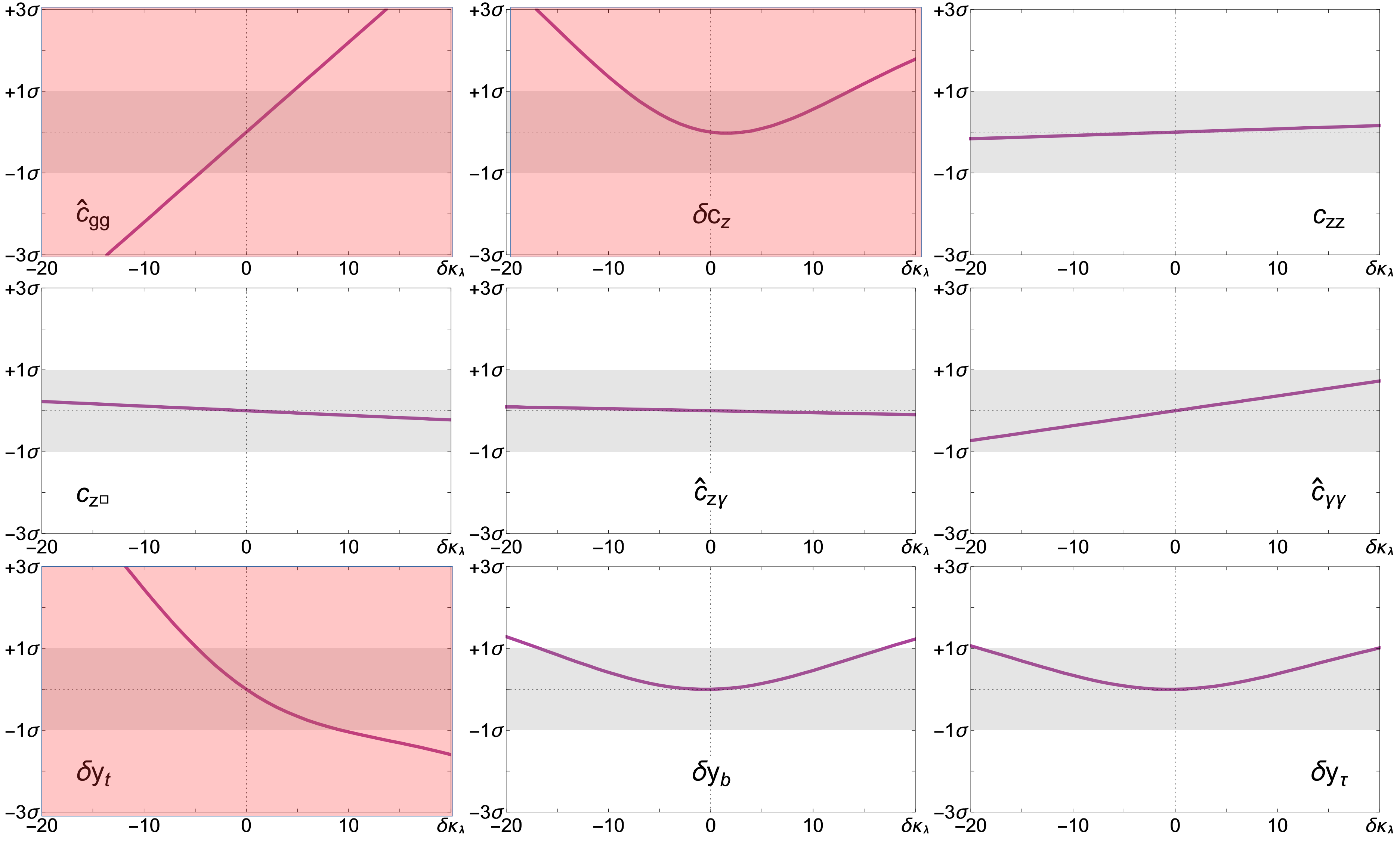


- BR(h$\to$Zγ)
  - Will be measured w/ 30% accuracy
  - Can be used to constrain $c_{z\gamma}$ $\to$ not relevant for κ_{λ}!
- BR(h$\to$μμ)
  - Either one extra parameter δy_μ
  - Or (w/ flavor universality) just helps to better bound δy_e



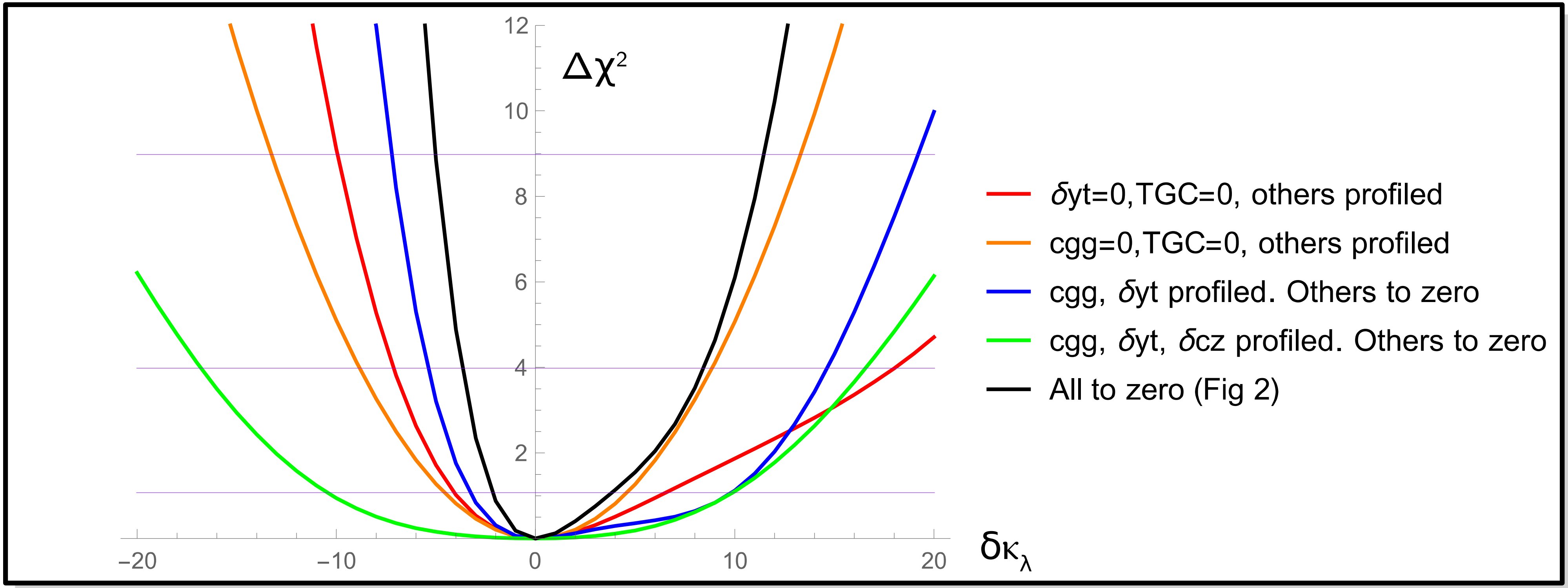
Exact flat direction in the global fit

Higgs couplings variation along the flat direction



Constrained "intermediate" scenarios

A game: let's pretend we have scenarios with some of (δy_t,c_{gg},δcz) switched off



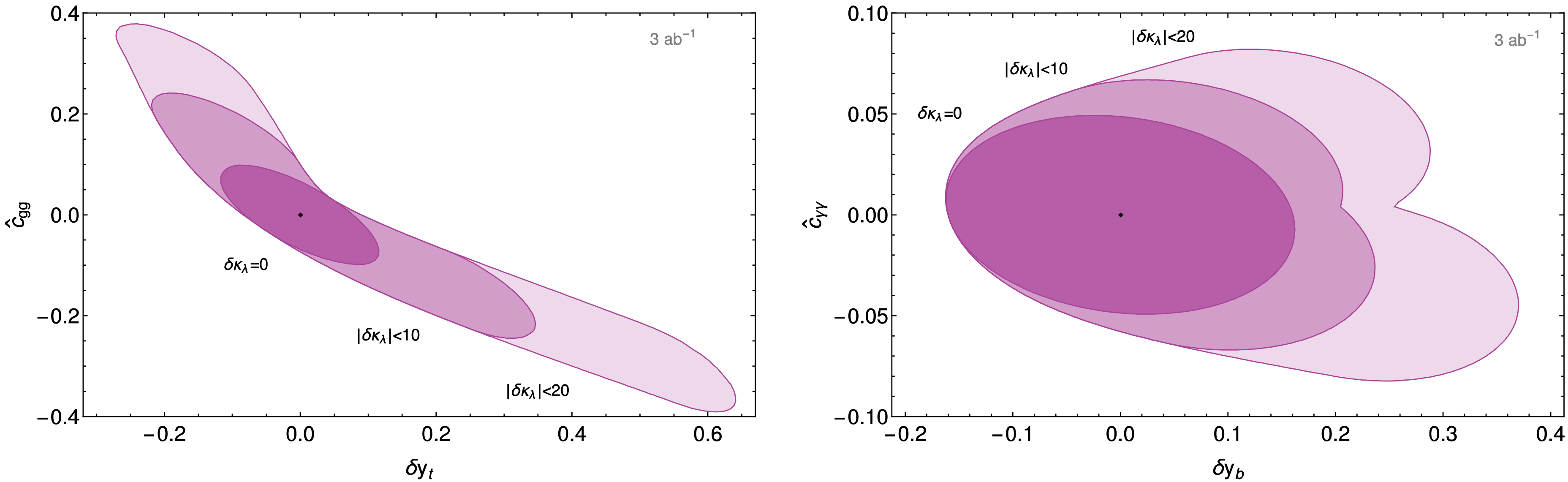
As expected, constraining "by hand" the coefficients that control the flat direction, the bound on κ_λ shrinks

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

Single-Higgs couplings fit w/κ_λ@NLO

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

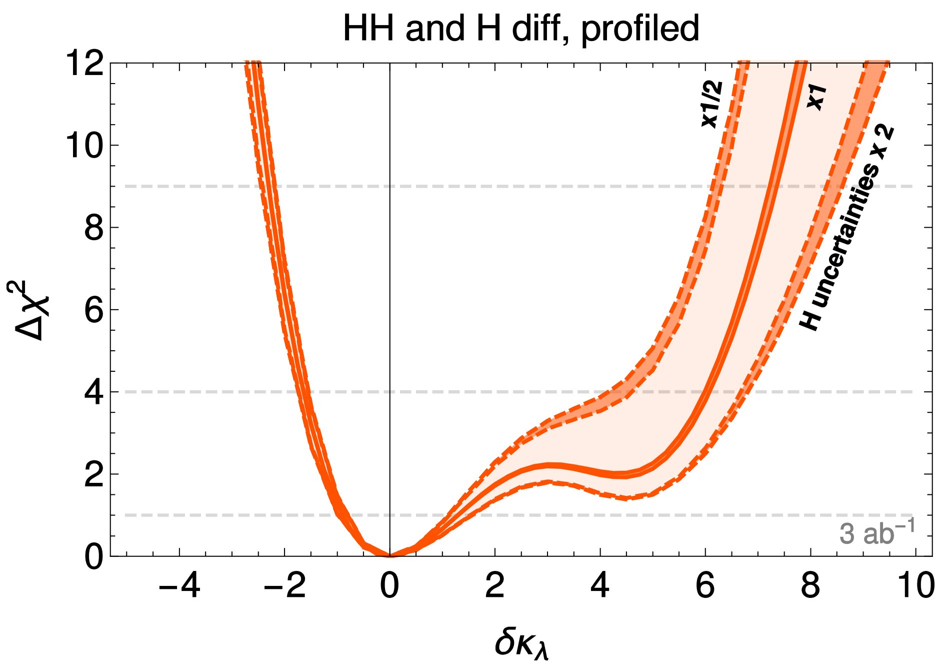
Incl. single Higgs data

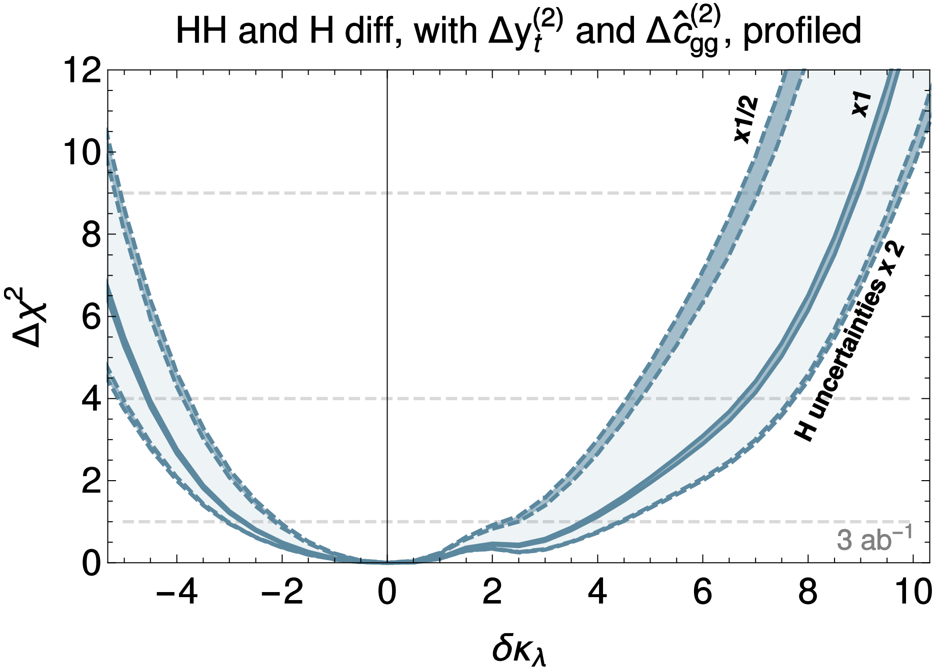


$\Delta\chi^2$=2.3 contours (68% CL in the gaussian limit)
[other 8 couplings profiled]

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

Some simple systematics





simple global rescaling of single-Higgs uncertainties

relaxing the assumption of linear EFT for double-Higgs

Triple gauge couplings – Higgs interplay

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

WWγ and WWZ data can constrain single-Higgs couplings

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

Gauge invariant operators in the Higgs basis

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