A global view on the Higgs self-coupling

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DESY - IFAE

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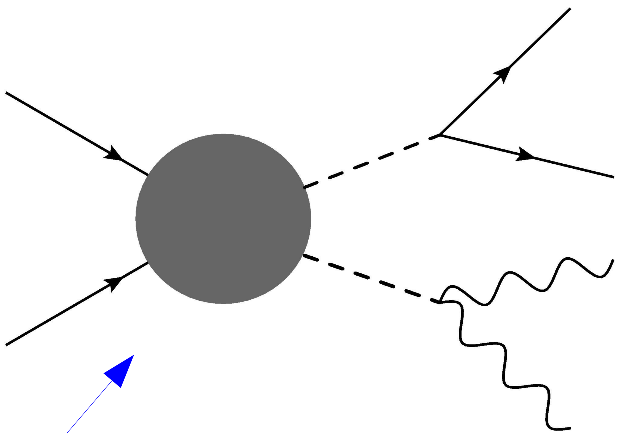
Introduction



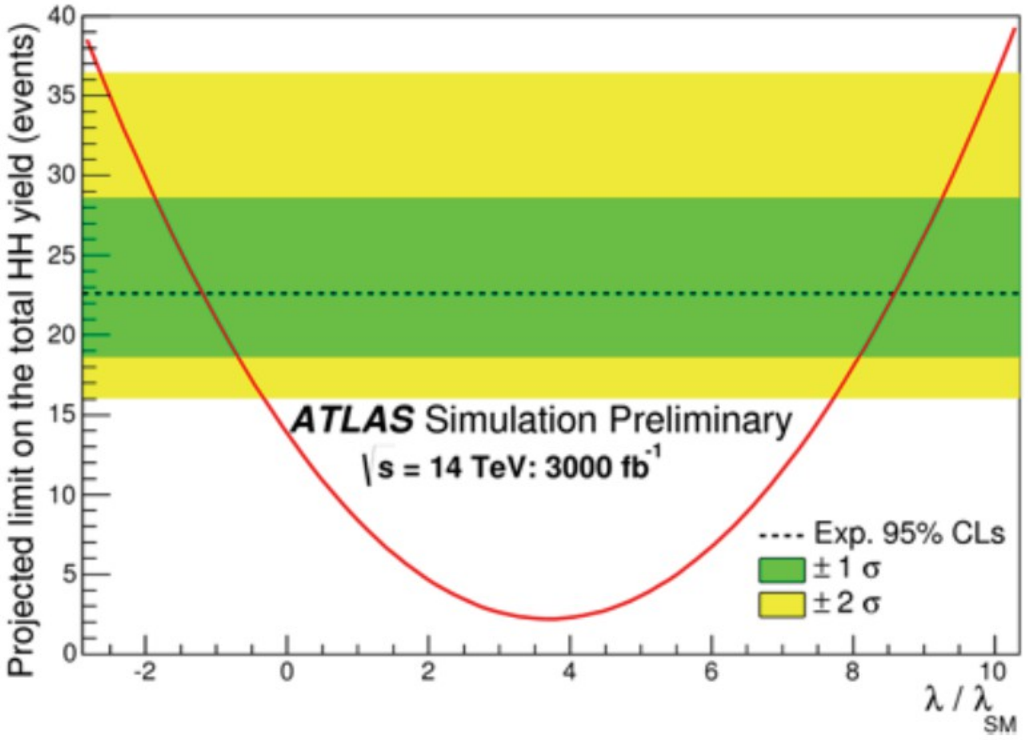
$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3}$$

$$\mathrm{Br}(h \to b\bar{b}) \cdot \mathrm{Br}(h \to \gamma\gamma) \sim 60\% \cdot 0.1\%$$

Very challenging for the LHC, suffers from low production cross section and small *visible* branching ratio.

The Higgs trilinear interferes destructivelly and decreases the cross section by 50%.

Introduction



- with no syst. error:

$$\boxed{-1.3 < \lambda_{HHH} / \lambda_{SM} < 8.7}$$

ATL-PHYS-PUB-2014-019, plot taken from **V. Martin, ECFA, HL-LHC workshop 2016**

Introduction

With the present knowledge, even at the HL-LHC phase a trilinear 10xSM will not be excluded!

Idea: given this loose bound, perhaps effects in single higgs at NLO can help.

McCullough, 1312.3322
Gorbahn, Haisch 1607.03773
Degrassi, et al. 1607.04251
Bizon, et al. 1610.05771
Degrassi, et al. 1702.01737

See Giardino's talk!

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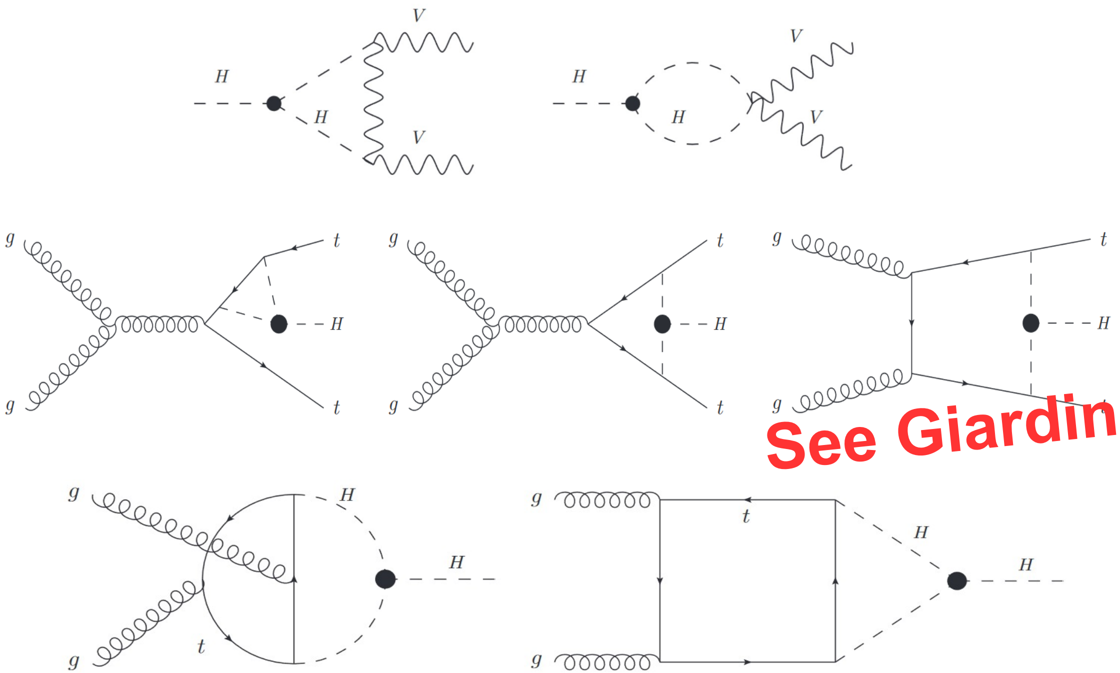

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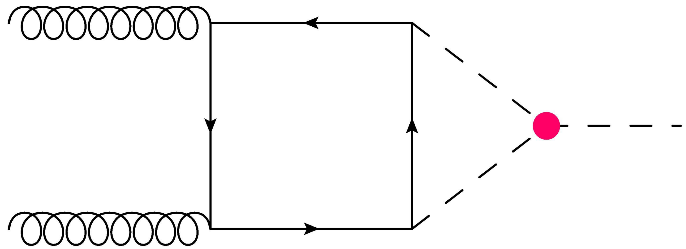
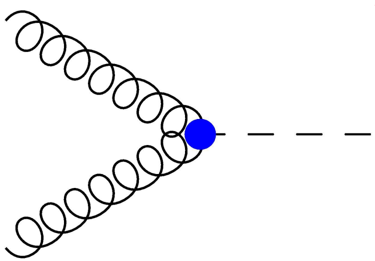
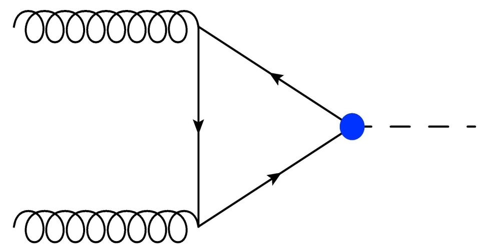
Introduction

However, it is interesting to ask what happens to this picture in a general setup



Given a bound on h to gg rate, can we disentangle the different contributions?





Already hard to separate

Higgs basis

Most general parametrization of BSM effects in Higgs couplings:

So called Higgs basis is becoming a standard:
- **As easy to interpret as the kappa framework,**
- **But still capable to correlate different physics (e.g. LEP constraints to Higgs physics)**

9 parameters:

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

+1:

$$\kappa_\lambda$$

Two combinations are probed by TGCs

$$\delta g_{1,z} \quad \delta\kappa_\gamma$$

Flat direction

ATLAS + CMS combination

Production process		$H \to \gamma\gamma$ [fb] Best fit value	Uncertainty Stat	Syst	$H \to ZZ$ [fb] Best fit value	Uncertainty Stat	Syst	$H \to WW$ [pb] Best fit value	Uncertainty Stat	Syst	$H \to \tau\tau$ [fb] Best fit value	Uncertainty Stat	Syst	$H \to bb$ [pb] Best fit value	Uncertainty Stat	Syst
ggF	Measured	$48.0^{+10.0}_{-9.7}$	$^{+9.4}_{-9.4}$	$^{+3.2}_{-2.3}$	580^{+170}_{-160}	$^{+170}_{-160}$	$^{+40}_{-40}$	$3.5^{+0.7}_{-0.7}$	$^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	1300^{+700}_{-700}	$^{+400}_{-400}$	$^{+500}_{-500}$	–		
		$\left(^{+9.7}_{-9.5}\right)$	$\left(^{+9.4}_{-9.4}\right)$	$\left(^{+2.5}_{-1.6}\right)$	$\left(^{+150}_{-130}\right)$	$\left(^{+140}_{-130}\right)$	$\left(^{+30}_{-20}\right)$	$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+700}_{-700}\right)$	$\left(^{+400}_{-400}\right)$	$\left(^{+500}_{-500}\right)$	–		
	Predicted	44 ± 5			510 ± 60			4.1 ± 0.5			1210 ± 140			11.0 ± 1.2		
	Ratio	$1.10^{+0.23}_{-0.22}$	$^{+0.22}_{-0.21}$	$^{+0.07}_{-0.05}$	$1.13^{+0.34}_{-0.31}$	$^{+0.33}_{-0.30}$	$^{+0.09}_{-0.07}$	$0.84^{+0.17}_{-0.17}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	$1.0^{+0.6}_{-0.6}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.4}$	–		
VBF	Measured	$4.6^{+1.9}_{-1.8}$	$^{+1.8}_{-1.7}$	$^{+0.6}_{-0.5}$	3^{+46}_{-26}	$^{+46}_{-25}$	$^{+7}_{-7}$	$0.39^{+0.14}_{-0.13}$	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.05}$	125^{+39}_{-37}	$^{+34}_{-32}$	$^{+19}_{-18}$	–		
		$\left(^{+1.8}_{-1.6}\right)$	$\left(^{+1.7}_{-1.6}\right)$	$\left(^{+0.5}_{-0.4}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+8}_{-5}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+39}_{-37}\right)$	$\left(^{+34}_{-32}\right)$	$\left(^{+19}_{-18}\right)$	–		
	Predicted	3.60 ± 0.20			42.2 ± 2.0			0.341 ± 0.017			100 ± 6			0.91 ± 0.04		
	Ratio	$1.3^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$^{+0.2}_{-0.1}$	$0.1^{+1.1}_{-0.6}$	$^{+1.1}_{-0.6}$	$^{+0.2}_{-0.2}$	$1.2^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+0.2}_{-0.2}$	$1.3^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$	–		
WH	Measured	$0.7^{+2.1}_{-1.9}$	$^{+2.1}_{-1.8}$	$^{+0.3}_{-0.3}$	–			$0.24^{+0.18}_{-0.16}$	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.08}$	-64^{+64}_{-61}	$^{+55}_{-50}$	$^{+32}_{-34}$	$0.42^{+0.21}_{-0.20}$	$^{+0.17}_{-0.16}$	$^{+0.12}_{-0.11}$
		$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.08}_{-0.07}\right)$	$\left(^{+67}_{-64}\right)$	$\left(^{+60}_{-54}\right)$	$\left(^{+30}_{-32}\right)$	$\left(^{+0.22}_{-0.21}\right)$	$\left(^{+0.18}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
	Predicted	1.60 ± 0.09			18.8 ± 0.9			0.152 ± 0.007			44.3 ± 2.8			0.404 ± 0.017		
	Ratio	$0.5^{+1.3}_{-1.2}$	$^{+1.3}_{-1.1}$	$^{+0.2}_{-0.2}$	–			$1.6^{+1.2}_{-1.0}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$	$^{+1.2}_{-1.1}$	$^{+0.7}_{-0.8}$	$1.0^{+0.5}_{-0.5}$	$^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$
ZH	Measured	$0.5^{+2.9}_{-2.4}$	$^{+2.8}_{-2.3}$	$^{+0.5}_{-0.2}$	–			$0.53^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$^{+0.10}_{-0.07}$	58^{+56}_{-47}	$^{+52}_{-44}$	$^{+20}_{-16}$	$0.08^{+0.09}_{-0.09}$	$^{+0.08}_{-0.08}$	$^{+0.04}_{-0.04}$
		$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+49}_{-40}\right)$	$\left(^{+46}_{-38}\right)$	$\left(^{+16}_{-12}\right)$	$\left(^{+0.10}_{-0.09}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.05}_{-0.04}\right)$
	Predicted	0.94 ± 0.06			11.1 ± 0.6			0.089 ± 0.005			26.1 ± 1.8			0.238 ± 0.012		
	Ratio	$0.5^{+3.0}_{-2.5}$	$^{+3.0}_{-2.5}$	$^{+0.5}_{-0.2}$	–			$5.9^{+2.6}_{-2.2}$	$^{+2.3}_{-2.1}$	$^{+1.1}_{-0.8}$	$2.2^{+2.2}_{-1.8}$	$^{+2.0}_{-1.7}$	$^{+0.8}_{-0.6}$	$0.4^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$
ttH	Measured	$0.64^{+0.48}_{-0.38}$	$^{+0.48}_{-0.38}$	$^{+0.07}_{-0.04}$	–			$0.14^{+0.05}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	-15^{+30}_{-26}	$^{+26}_{-22}$	$^{+15}_{-15}$	$0.08^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.06}_{-0.06}$
		$\left(^{+0.45}_{-0.34}\right)$	$\left(^{+0.44}_{-0.33}\right)$	$\left(^{+0.10}_{-0.05}\right)$	–			$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.02}_{-0.02}\right)$	$\left(^{+31}_{-26}\right)$	$\left(^{+26}_{-22}\right)$	$\left(^{+16}_{-13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.06}_{-0.05}\right)$
	Predicted	0.294 ± 0.035			3.4 ± 0.4			0.0279 ± 0.0032			8.1 ± 1.0			0.074 ± 0.008		
	Ratio	$2.2^{+1.6}_{-1.3}$	$^{+1.6}_{-1.3}$	$^{+0.2}_{-0.1}$	–			$5.0^{+1.8}_{-1.7}$	$^{+1.5}_{-1.5}$	$^{+1.0}_{-0.9}$	$-1.9^{+3.7}_{-3.3}$	$^{+3.2}_{-2.7}$	$^{+1.9}_{-1.8}$	$1.1^{+1.0}_{-1.0}$	$^{+0.5}_{-0.5}$	$^{+0.8}_{-0.8}$

Flat direction

Since we are measuring signal strengths, in the linear regime we are not measuring 10 quantities but 9:

$$\mu_i^f \simeq 1 + \delta\mu_i + \delta\mu^f$$

Are invariant under

$$\mu_i \to \mu_i + \delta \qquad\qquad \mu^f \to \mu^f - \delta$$

So we can obtain the flat direction as a function of the trilinear:

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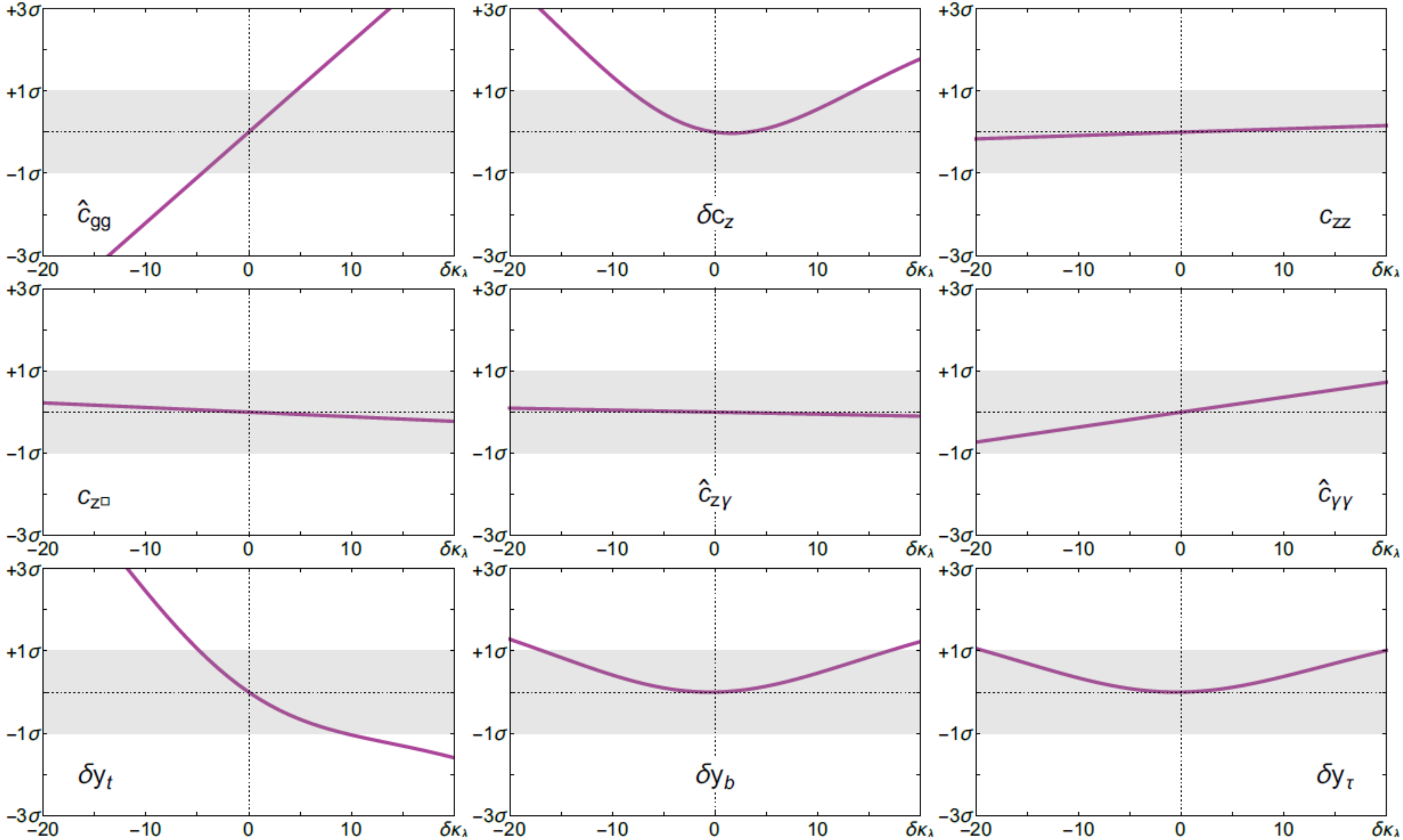
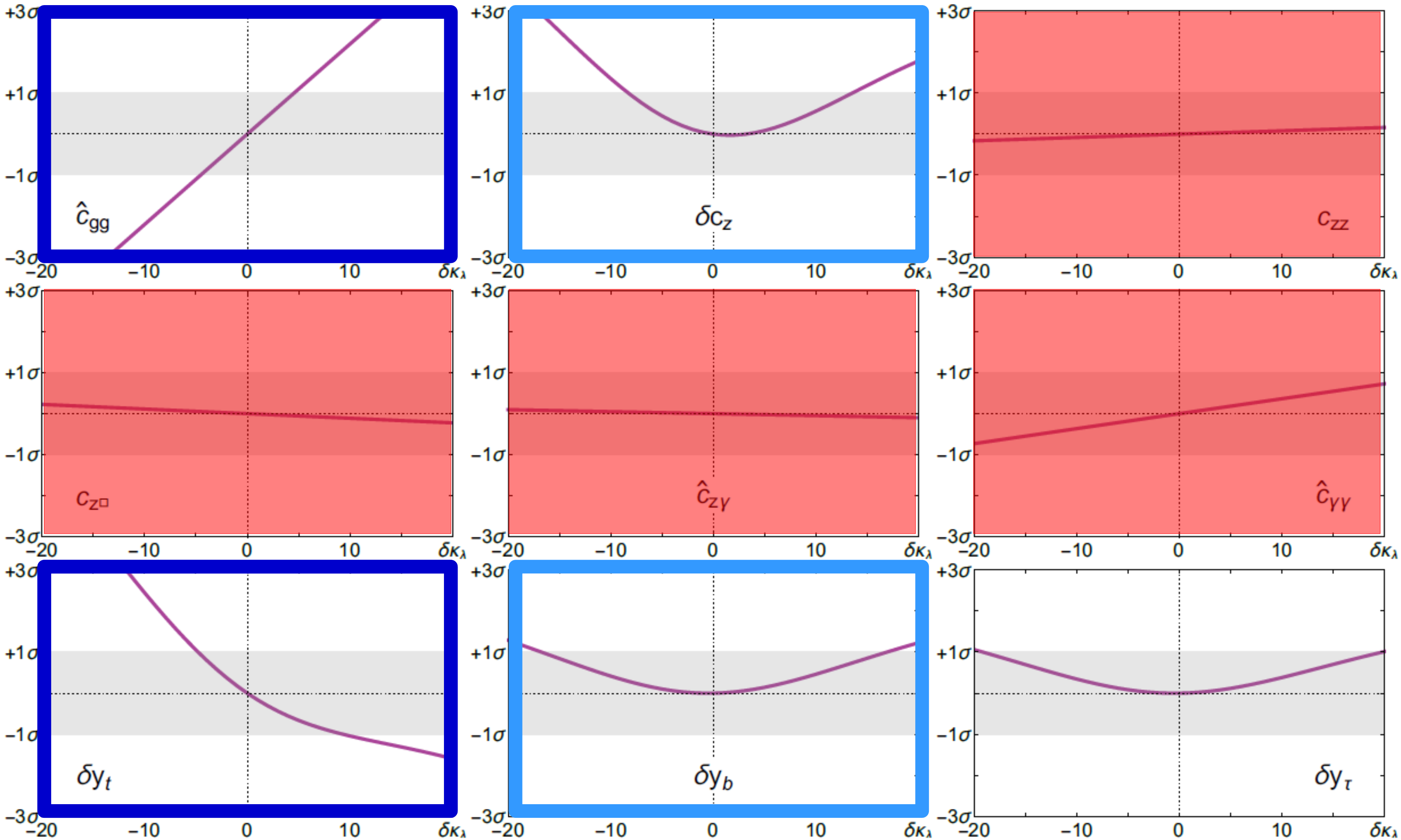


Flat direction



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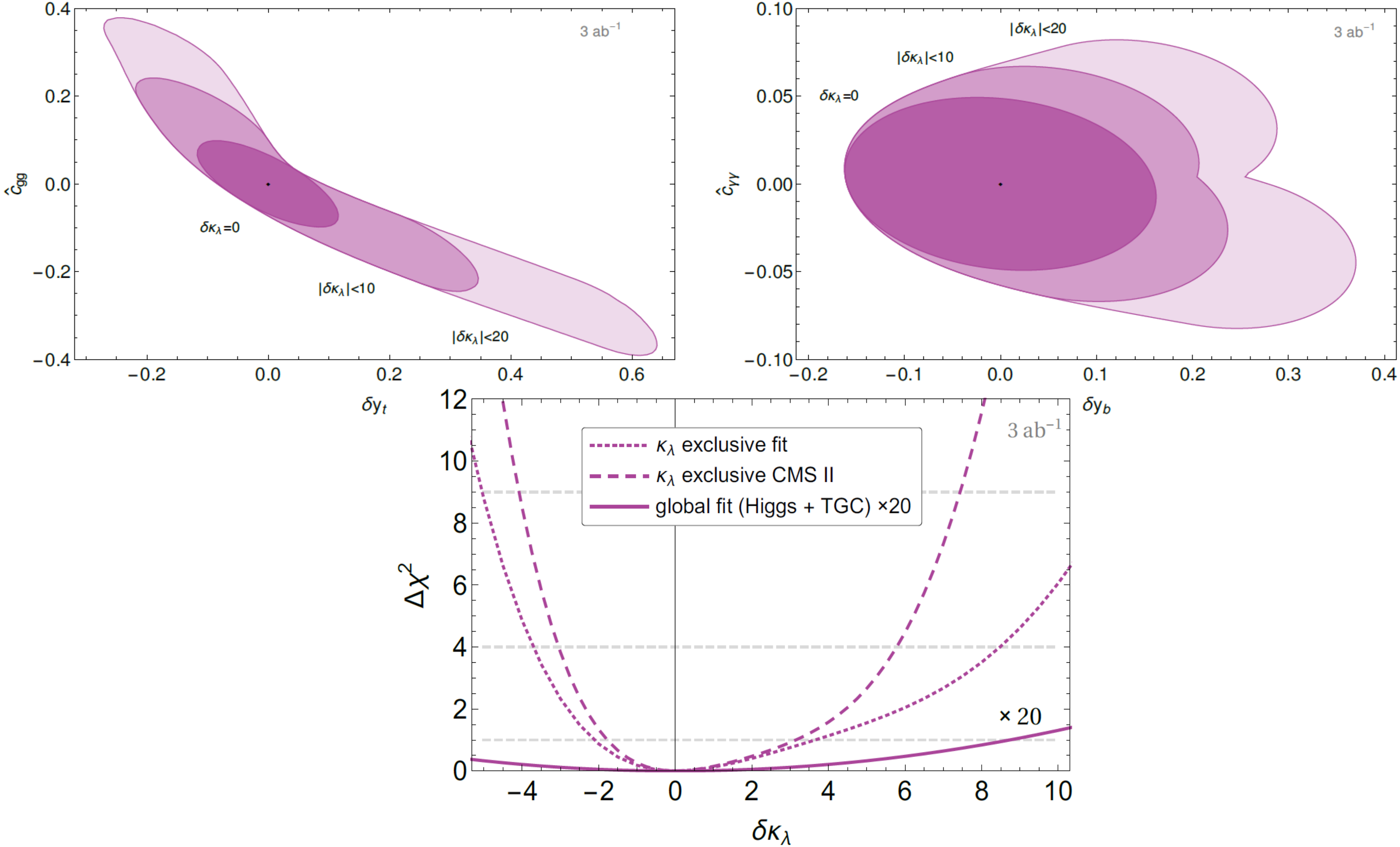


Single Higgs studies validity

This does not mean that we shoud throw to the trash the single Higgs fits done up to now.

All interpretations of the data carry some degree of assumptions.
What matters here is how large the trilinear can be, and in a large class of models is expected to be not too large.

e.g., - SUSY protects the quartic relating it to gauge couplings
- Goldstone Higgs scenarios (SILH) protects it via shift symmetry.

This means that the breakdown of single Higgs studies only happens for particular scenarios, e.g. Higgs portal

Higgs portal example

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

$$\delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_*^2} \qquad \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2}$$

$$\delta\kappa_\lambda \sim \theta g_*^2 / \lambda_3^{SM} \delta c_z \longrightarrow$$

Compare with SILH:

$$\delta\kappa_\lambda \sim \delta c_z$$

But $\frac{m_H^2}{2v^2} \sim 0.13$ **, so we need a tunning of** $\Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}}$ **.**

$$\delta\kappa_\lambda \sim \frac{1}{\theta} \Delta \, \delta c_z$$

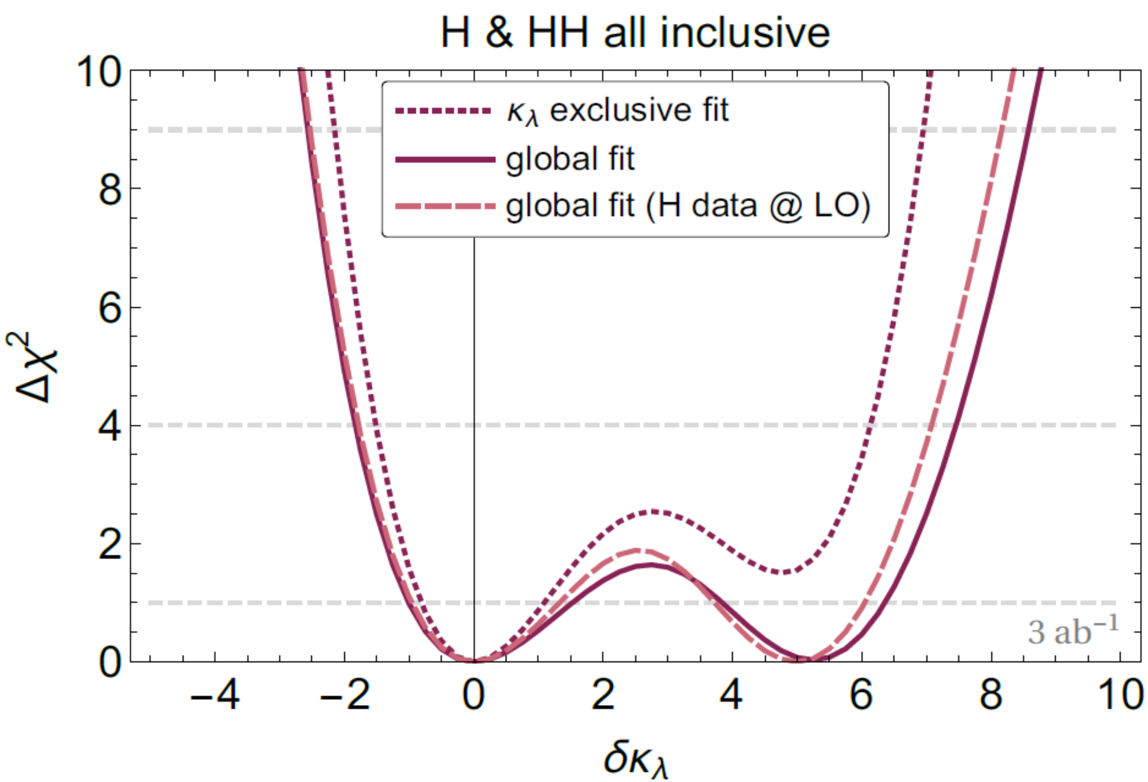
Higgs portal example

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

$$\Downarrow$$

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

Double Higgs observables



- Precision on single Higgs parameters comparable to single Higgs observables when neglecting the trilinear.
- Impact of trilinear NLO corrections negligible.

Differential observables

- Inclusive single Higgs observables do not maximize the information one can extract from data.

- This is even more crucial in our analysis since it presents a flat direction.

- Effects of the trilinear are virtual corrections that are large at threshold, when particles in the loop go onshell.

- Effects of the EFT are typically larger at large invariant masses.

- Thus, we expect qualitative changes by including differential information.

- We will include differential information in the invariant mass of the system for HW, HZ, ttH.

Differential observables

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- Effects of the trilinear are virtual corrections that are large at threshold

Disclaimer: The total invariant mass of the system is not always reconstructible. One should view our procedure as a realistic way to parametrize the de-correlations due to the differential information

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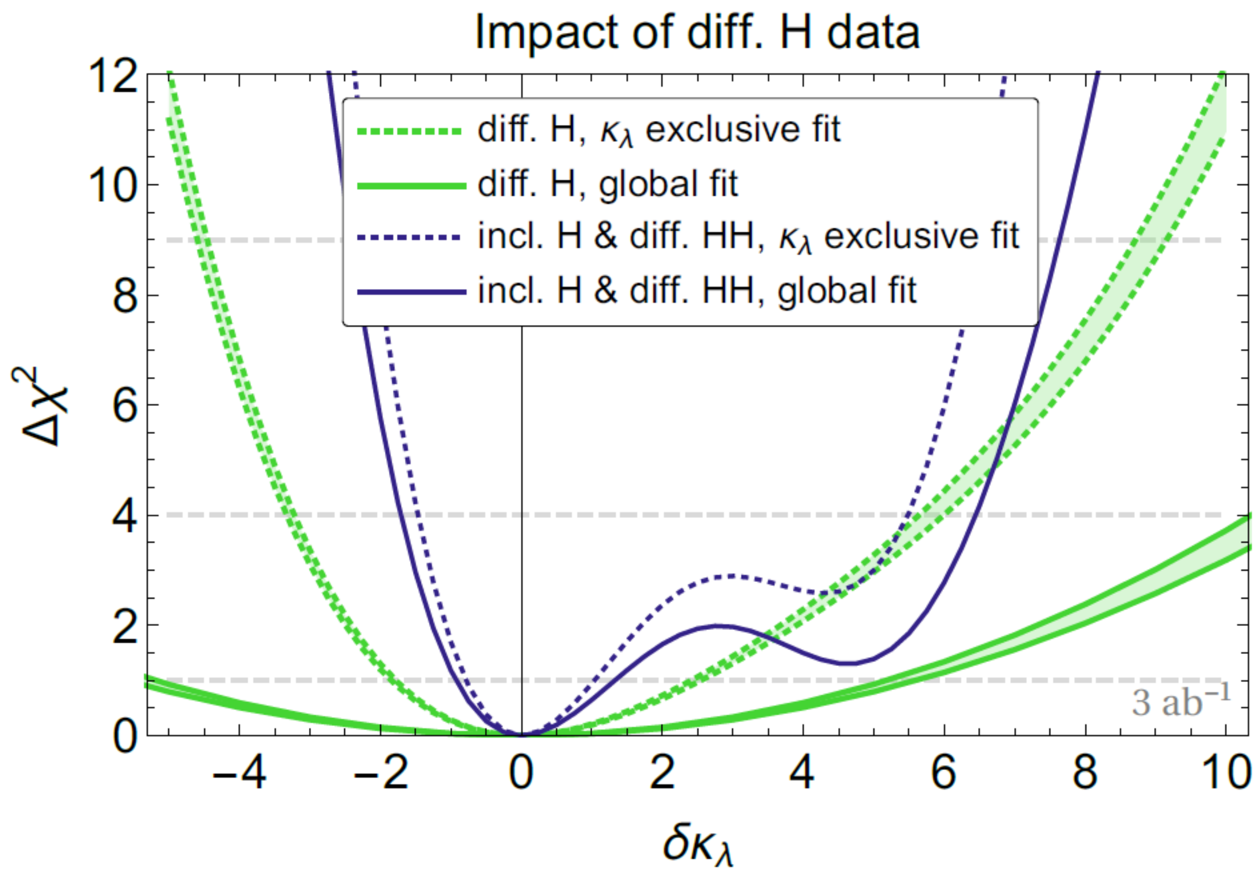
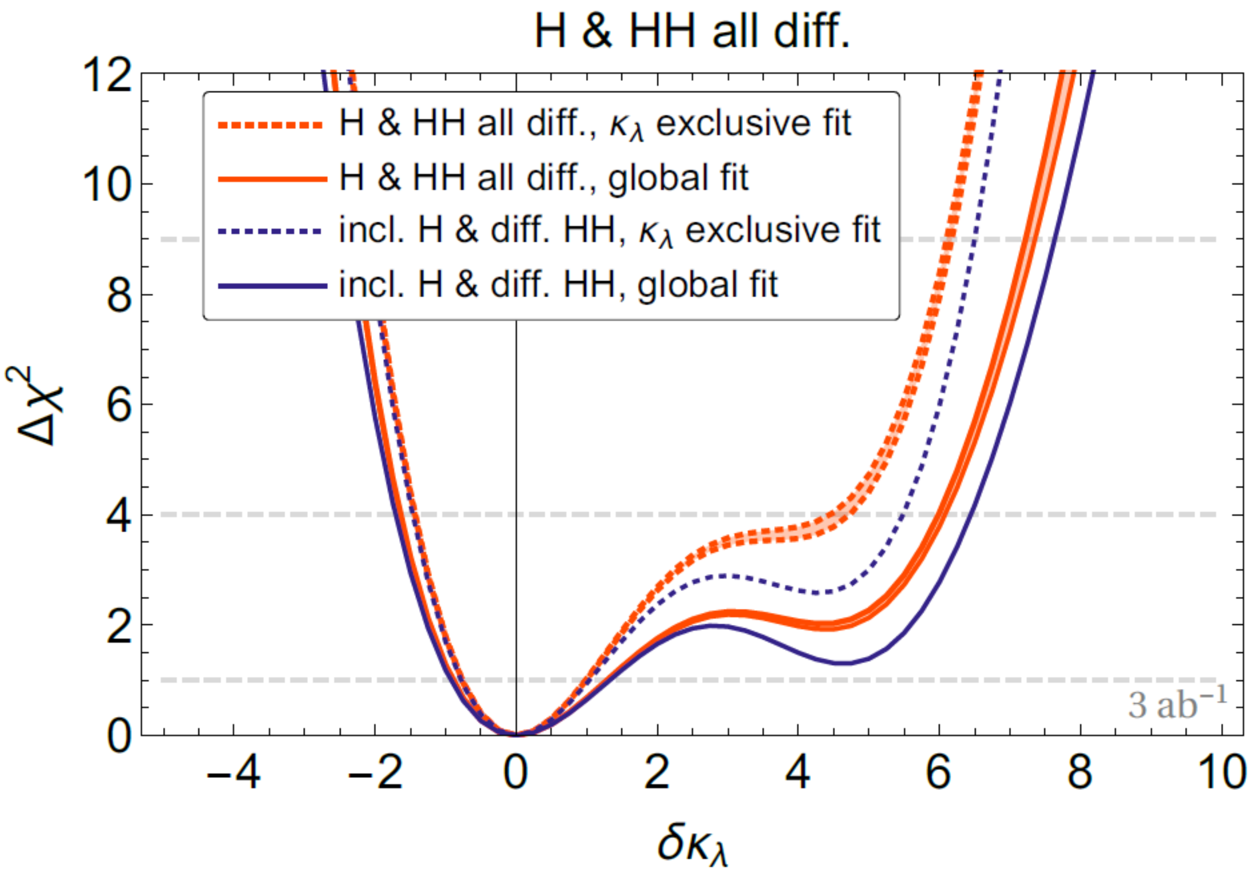
- We will include differential information in the invariant mass of the system for HW, HZ, ttH.

Differential observables



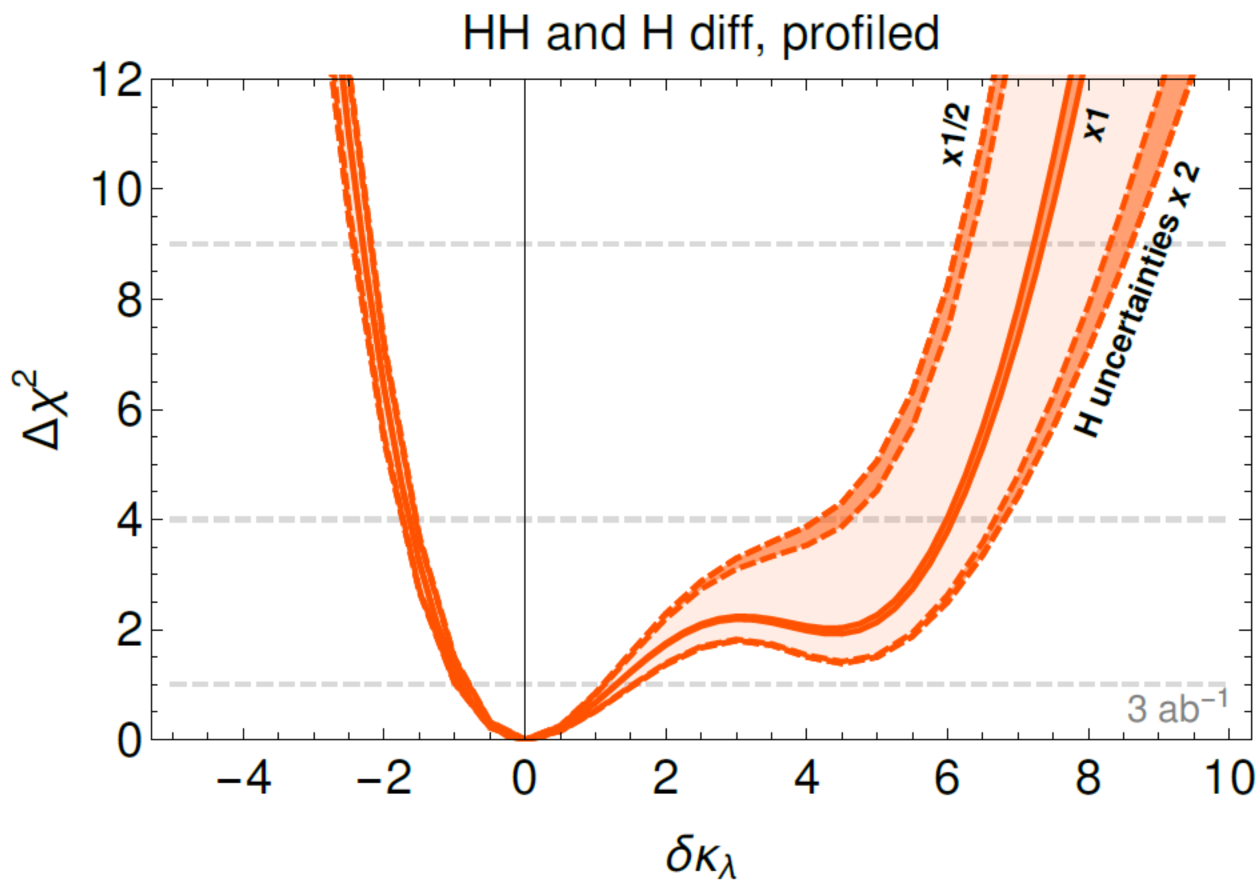
- Differential information in single Higgs allows to remove the flat direction

Differential observables



- The combined fit improves the "blind spot" of double Higgs searches

Robustness of the fit



- **Rescaling a factor of 2 the full expected uncertainties on single Higgs does not change the picture much.**

Conclusions

- Probing the Higgs trilinear via single Higgs processes is an intriguing idea that deserves to be further explored.

- Since the trilinear only affects the single Higgs rates at NLO, its effects can be easily overwhelmed by deviations on single Higgs couplings.

- A naive global fit does not work, and one must consider differential information.

- The set of models affected by this flat direction is limited, and more theoretical insight is needed.

- Although unrealistic, the scenario where one only considers the trilinear might be a good benchmark to devote experimental effort. One must keep in mind that a global fit is needed to extract reliable information.

- Further improvements: Come up with optimized observables, new channels to resolve the flat direction (h+jet, offshell Higgs...)

Thank you