Higgs self couplings in single H and HH production

Fabio Maltoni
Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain

`Work in collaboration with: G.Degrassi,PP.Giardino,D.Pagani`

The Higgs potential

A low-energy parametrisation of the Higgs potential

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4 + \ldots$$

In the Standard Model:

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda/4 \end{cases}$$

i.e., fixing v and m_H , uniquely determines both λ_3 and λ_4 .

That means that by measuring λ_3 and λ_4 one can test the SM, yet to interpret deviations, one needs to "deform it", i.e. needs to consider a well-defined BSM extension. Such extensions will necessarily depend on TH assumptions.

The Higgs potential

To go Beyond the SM, one can parametrise a generic potential by expanding it in series:

$$V^{\mathrm{BSM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{v^2}{2})^n$$

so that the basic relations remain the same as in the SM:

$$\begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases}$$

while the λ_3 and λ_4 are modified with respect to the SM values:

$$\begin{cases} \lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}} \\ \lambda_4 = \kappa_{\lambda_4} \lambda_4^{\mathrm{SM}} \end{cases}$$

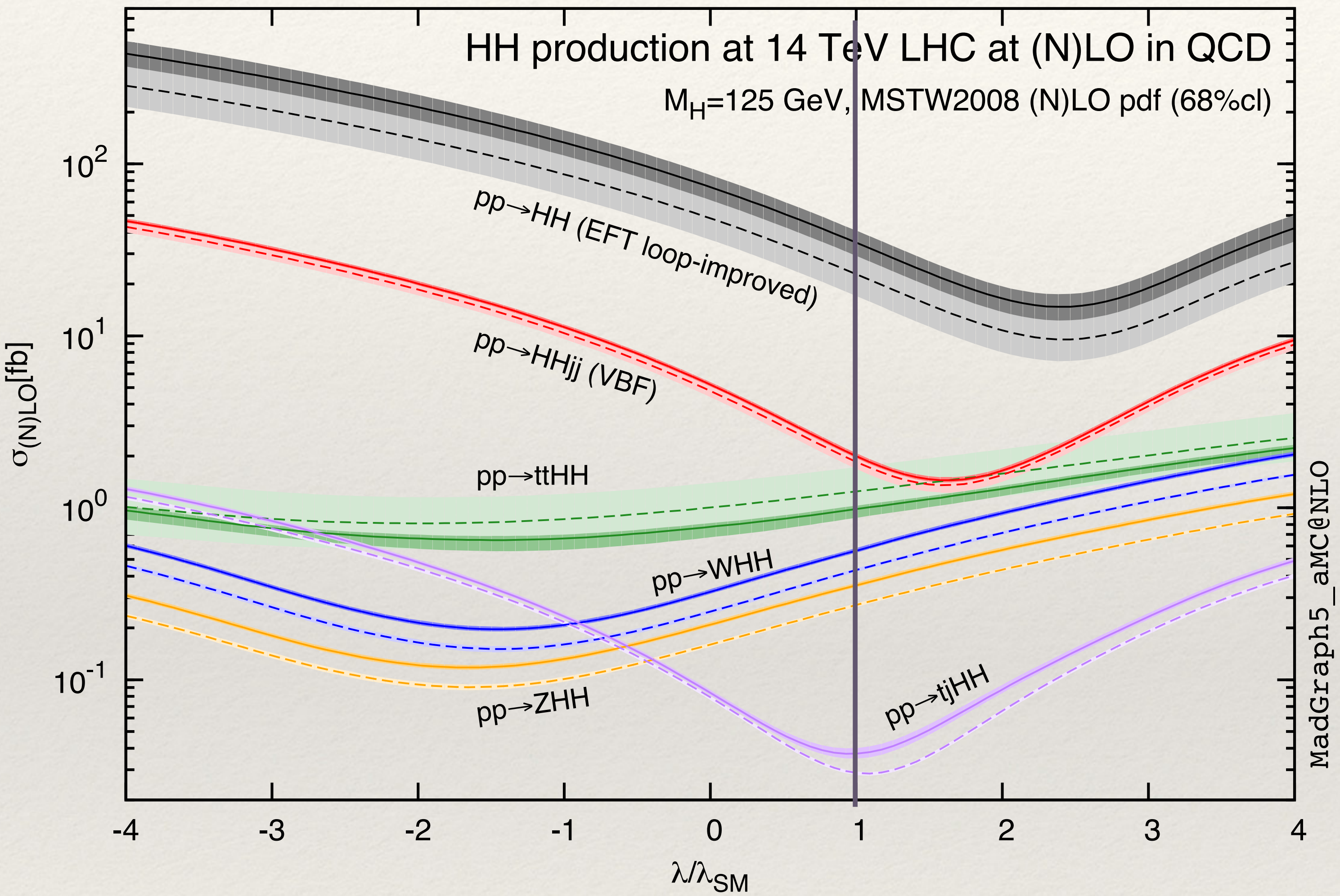
So for example: adding c_6 only

$$\begin{cases} \kappa_\lambda = 1 + \dfrac{c_6 v^2}{\lambda\Lambda^2} \\ \kappa_{\lambda_4} = 1 + \dfrac{6 c_6 v^2}{\lambda\Lambda^2} \end{cases}$$

i.e., in this case λ_3 and λ_4 are related.

HH at the LHC

[Frederix et al. '14]



Many channels, but small cross sections.

Current limits are on σ_{SM} (gg→HH) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 74$ (bbγγ)
ATLAS : $\sigma/\sigma_{SM} < 30$ (bbbb)

Remarks:

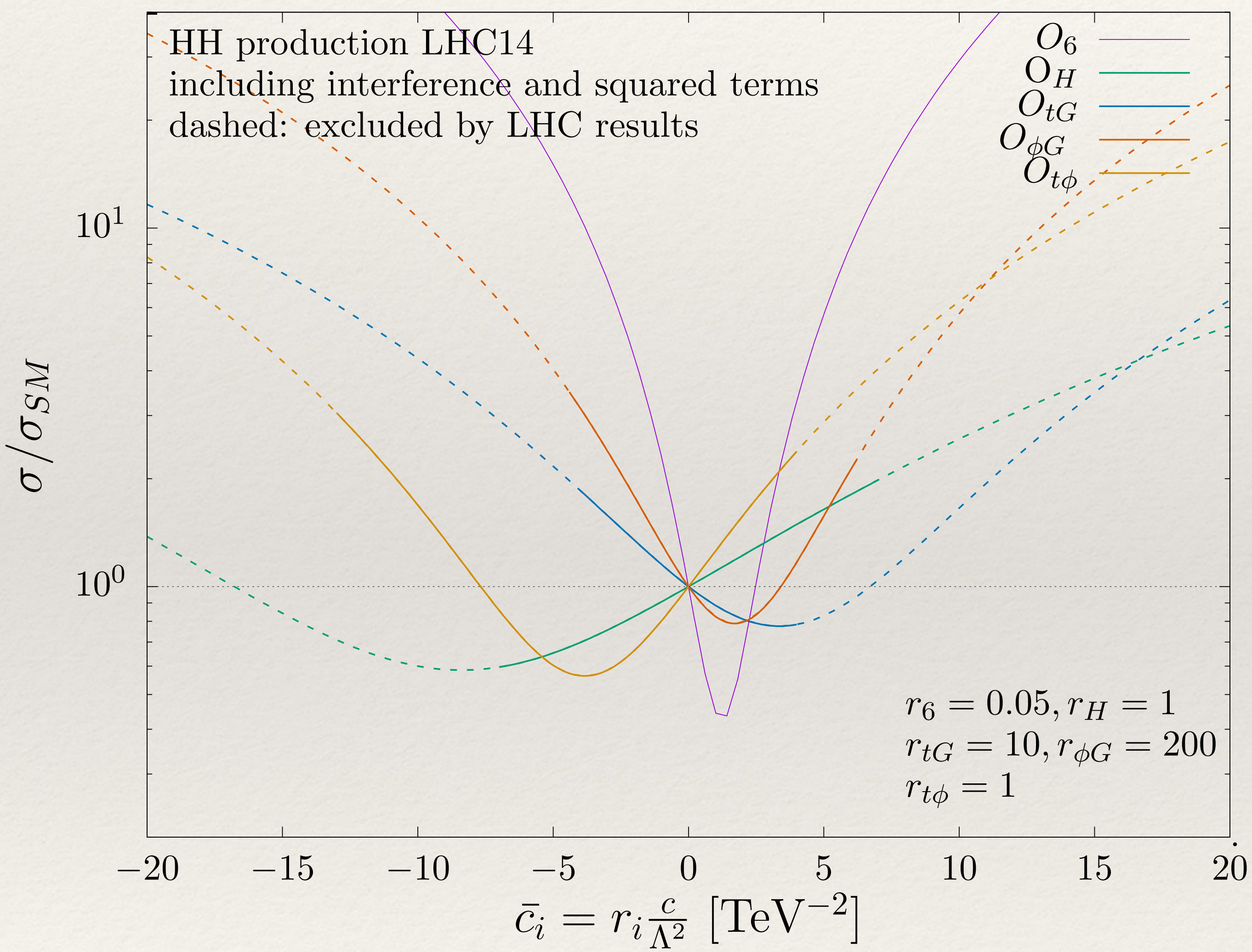
1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of λ_3 which leads to a change in σ as well as of distributions:

$$\sigma = \sigma_{SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

Note: due to shape changes, it is not straightforward to infer a bound on λ_3 from σ(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

HH sensitivity in the SMEFT

Eleni Vryonidou®



Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable. The range of c_6 is commensurate to that of $k_{\lambda 3}$.

Main observations:

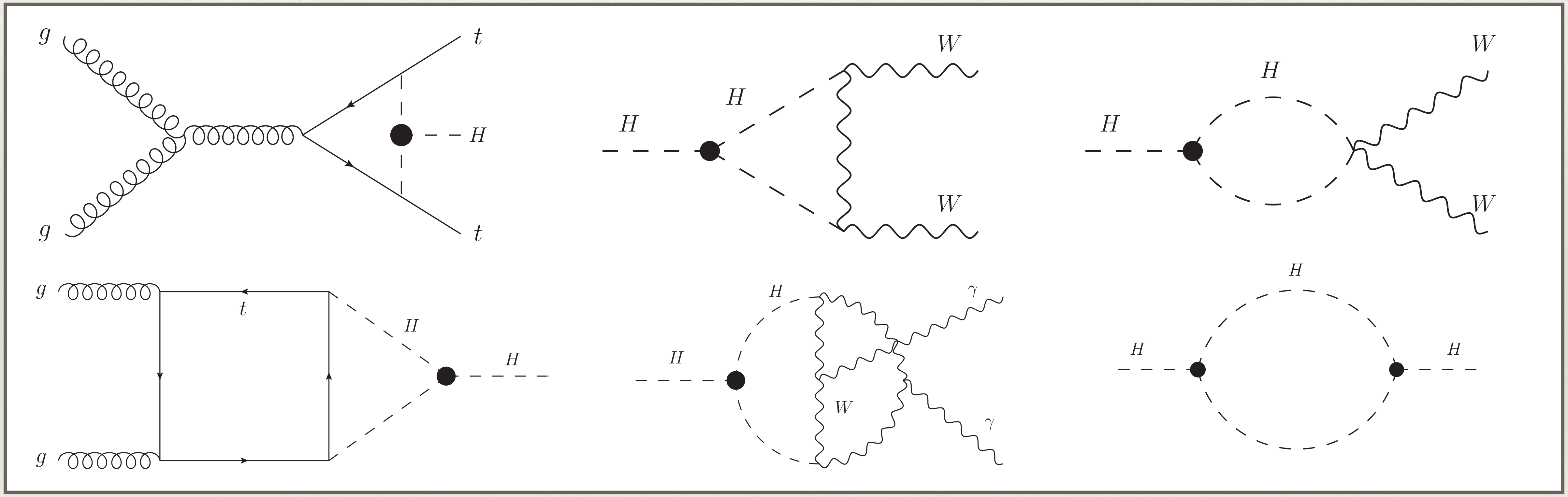
1. An accurate measurement of the Higgs self-couplings will depend on our ability to bound several (top-related) SMEFT operators: O_{tG},$O_{\varphi G}$,$O_{t\varphi}$.
2. Given the current constraints on σ(HH), the Higgs self-coupling can be constrained "ignoring" the other EFT couplings.
3. The current "EFT-relevant" range corresponds to values around -2 ≲ k_λ ≲ 4.
4. A theoretically meaningfully way of interpreting models with quite large values for λ_i is assumed in closing down at "EFT-consistent" and "EFT-relevant" regions.

Question

Is there any other way of getting independent (and useful) information on the Higgs self-interactions at the LHC?

The idea

1) Exploit the dependence of single-Higgs (total and differential) cross sections and decay rates on the self couplings at NLO (EW) level:



2) Combine all the information (rates and distributions) coming from the relevant single Higgs channels in a global way.

Available calculations

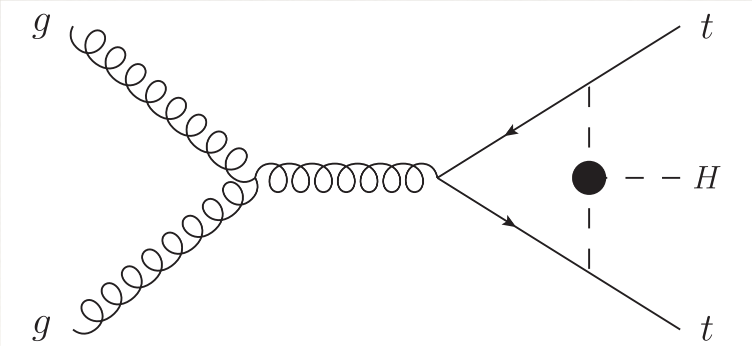
Ref	Authors	Processes	Comments
1312.3322	M.McCullough	$e^+e^- \to ZH$	applications at future colliders
1607.03773	M.Gorbahn, U.Haisch	$gg \to H$ $H \to \gamma\gamma$	approx. two-loop results $m_h \to 0$
1607.04251	G.Degrassi, P.P. Giardino, F.M., D.Pagani	$gg \to H$,WH,ZH,VBF, ttH $H \to \gamma\gamma, WW^*/ZZ^* \to 4l$, gg	total and diff.
1610.05771	W.Bizon, M.Gorbahn, U.Haisch, G.Zanderighi	WH,ZH,VBF	total and diff. + effects of QCD corrections

Master formula

$$\delta\sigma \equiv \frac{\sigma_{\rm NLO} - \sigma^{\rm SM}_{\rm NLO}}{\sigma_{\rm LO}} = (\kappa_\lambda - 1) C_1 + (\kappa_\lambda^2 - 1) C_2$$

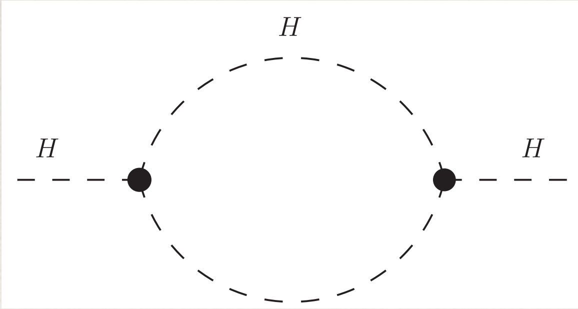
Process and kinetic dependent

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



overall and universal

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



Similar (but simpler) formula for C_1 of decay widths.
Note that branching ratios do not depend on C_2

Technical intermezzo

- We remind that **in general** in renormalisable gauge theories is not possible to meaningfully isolate effects of specific couplings, at the tree-level or at higher orders. Even more troublesome can be to arbitrary "deform" the SM by arbitrary changes of couplings and compute loops.
- A consistent and safe framework to perform higher-order computations is that of an EFT, where several NLO (QCD and EW) results are now available.
- In the case of the processes (single Higgs) and the order (NLO) considered here, however, we have explicitly verified that the results obtained by rescaling λ_3 are not only **gauge invariant and finite**, but also equivalent to those obtained, for example, by adding the O_6 operator of the SMEFT.

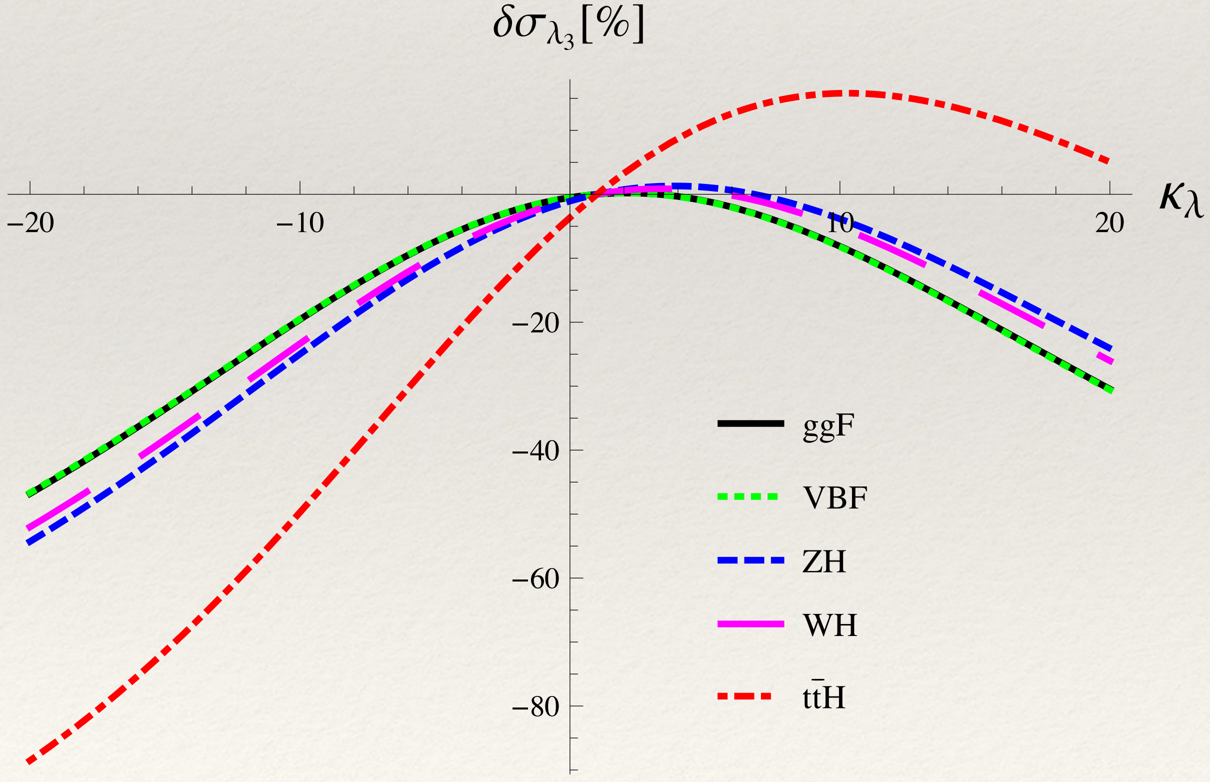
Results : total cross sections

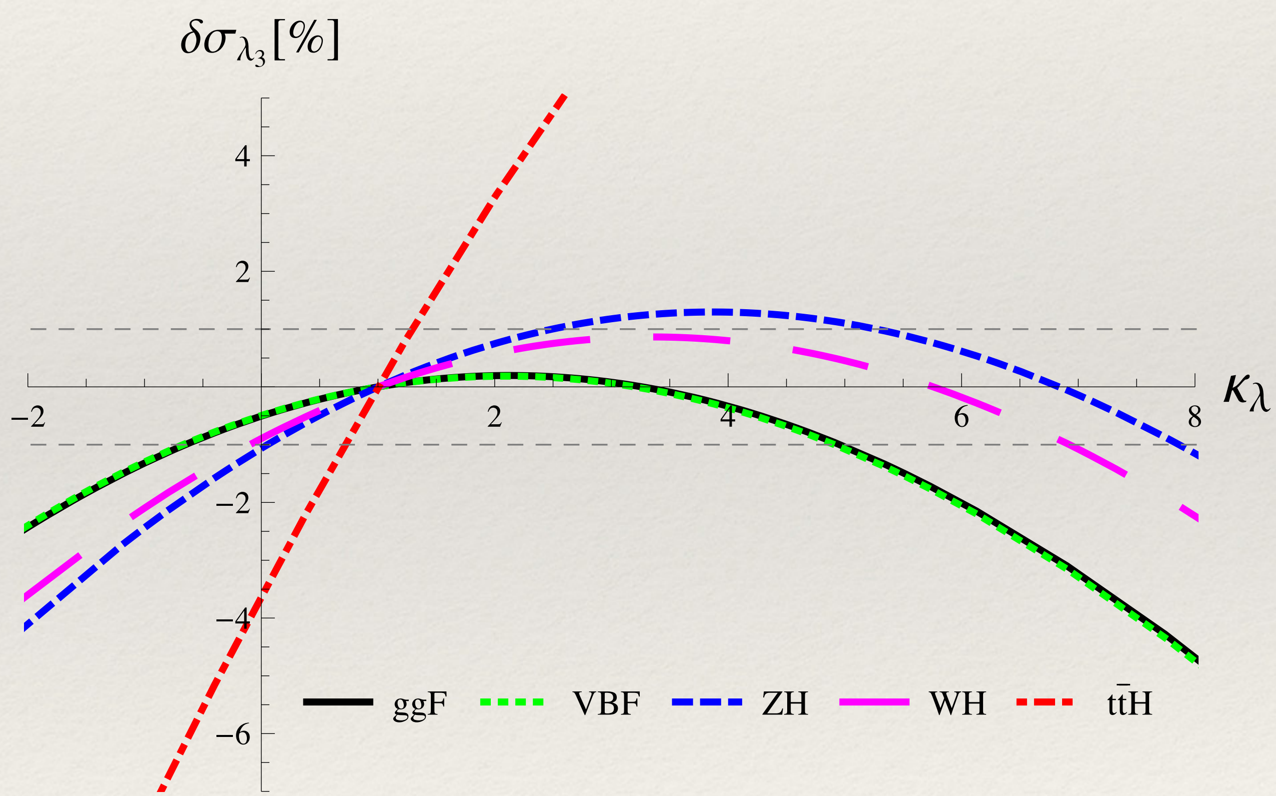
$$\delta\sigma = (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2$$

$C_1^\sigma[\%]$	ggF	VBF	WH	ZH	$t\bar{t}H$
8 TeV	0.66	0.65	1.05	1.22	3.78
13 TeV	0.66	0.64	1.03	1.19	3.51

$C_2 = -9.514 \cdot 10^{-4}$ for $\kappa_\lambda = \pm 20$

$C_2 = -1.536 \cdot 10^{-3}$ for $\kappa_\lambda = 1$





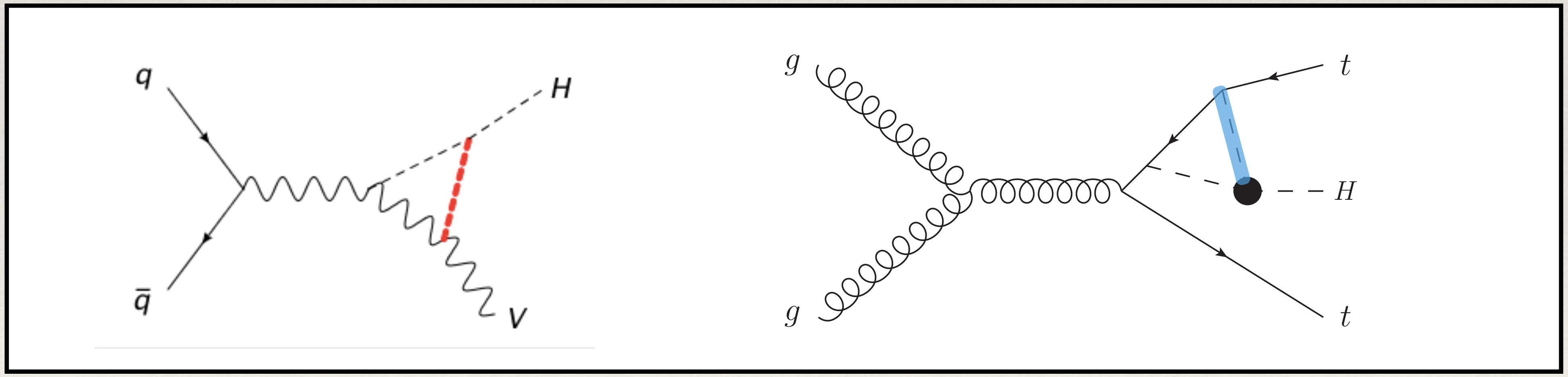
Results : differential production

$C_1^\sigma[\%]$	25 GeV	50 GeV	100 GeV	200 GeV	500 GeV
WH	1.71 (0.11)	1.56 (0.34)	1.29 (0.72)	1.09 (0.94)	1.03 (0.99)
ZH	2.00 (0.10)	1.83 (0.33)	1.50 (0.71)	1.26 (0.94)	1.19 (0.99)
$t\bar{t}H$	5.44 (0.04)	5.14 (0.17)	4.66 (0.48)	3.95 (0.84)	3.54 (0.99)

$$p_T(H) < p_{T,\text{cut}}$$

$C_1^\sigma[\%]$	1.1	1.2	1.5	2	3
WH	1.78 (0.17)	1.60 (0.36)	1.32 (0.70)	1.15 (0.89)	1.06 (0.97)
ZH	2.08 (0.19)	1.86 (0.38)	1.51 (0.72)	1.31 (0.90)	1.22 (0.98)
$t\bar{t}H$	8.57 (0.02)	7.02 (0.10)	5.11 (0.43)	4.12 (0.76)	3.64 (0.94)

$$m_{\text{tot}} < K \cdot m_{\text{thr}}$$

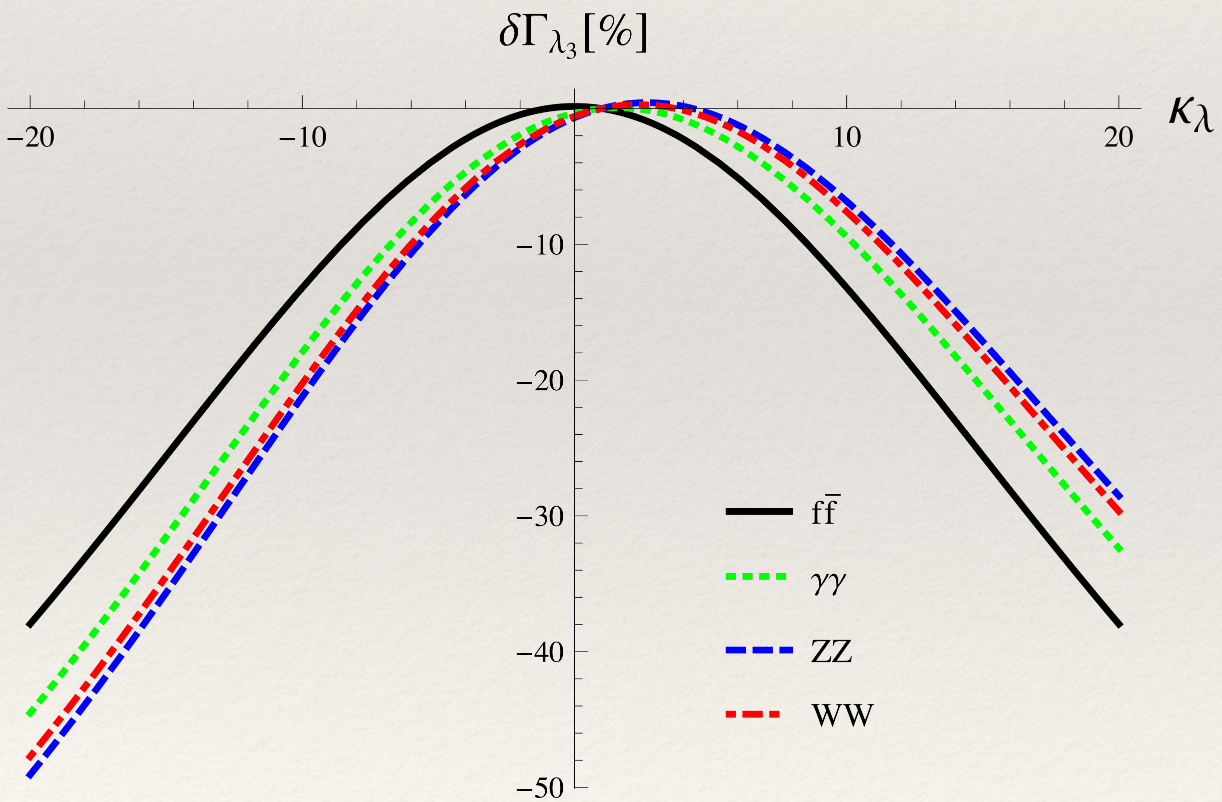


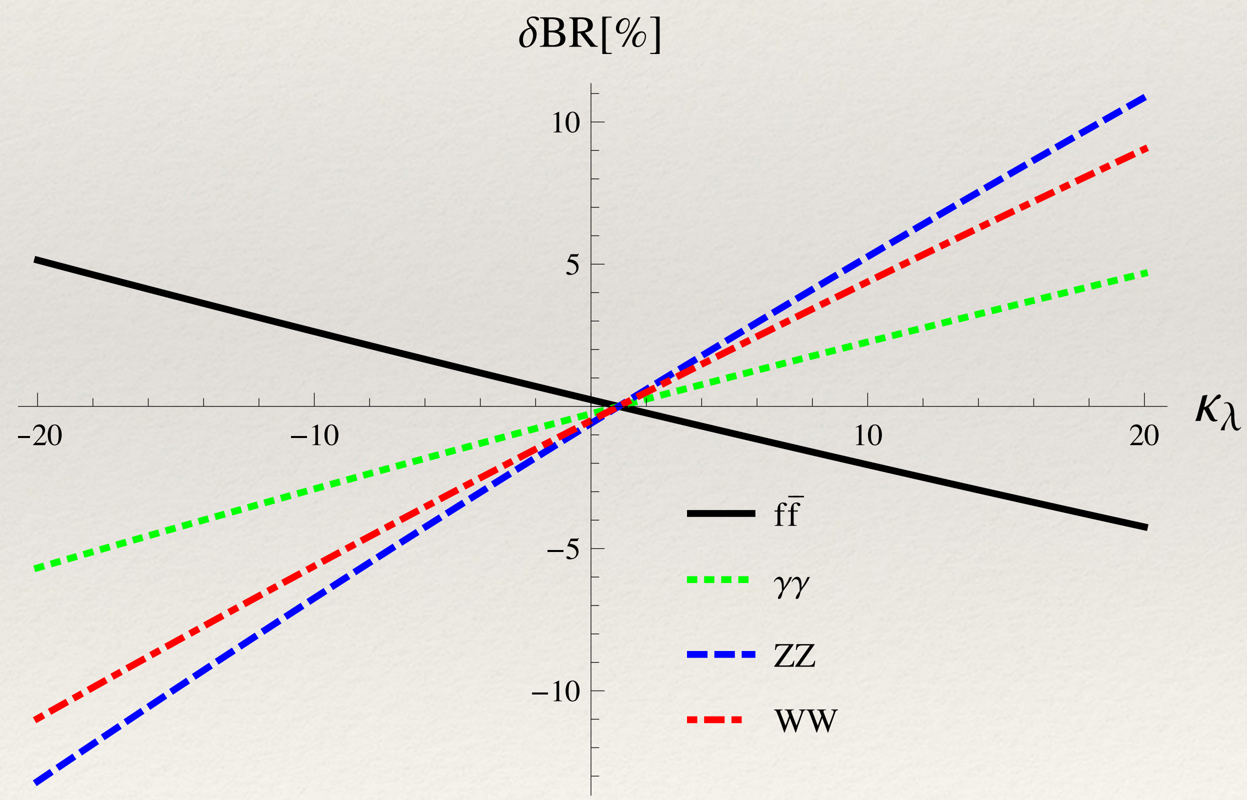
The largest effects are **non-local** and **at threshold**: corrections to ttH and HV processes can be seen as induced by a Yukawa potential, giving a Sommerfeld enhancement when the final states are non relativistic.

Results: Decay rates

$$\delta \mathrm{BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^\Gamma(i) - C_1^{\Gamma_{\rm tot}})}{1 + (\kappa_\lambda - 1)C_1^{\Gamma_{\rm tot}}}$$

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

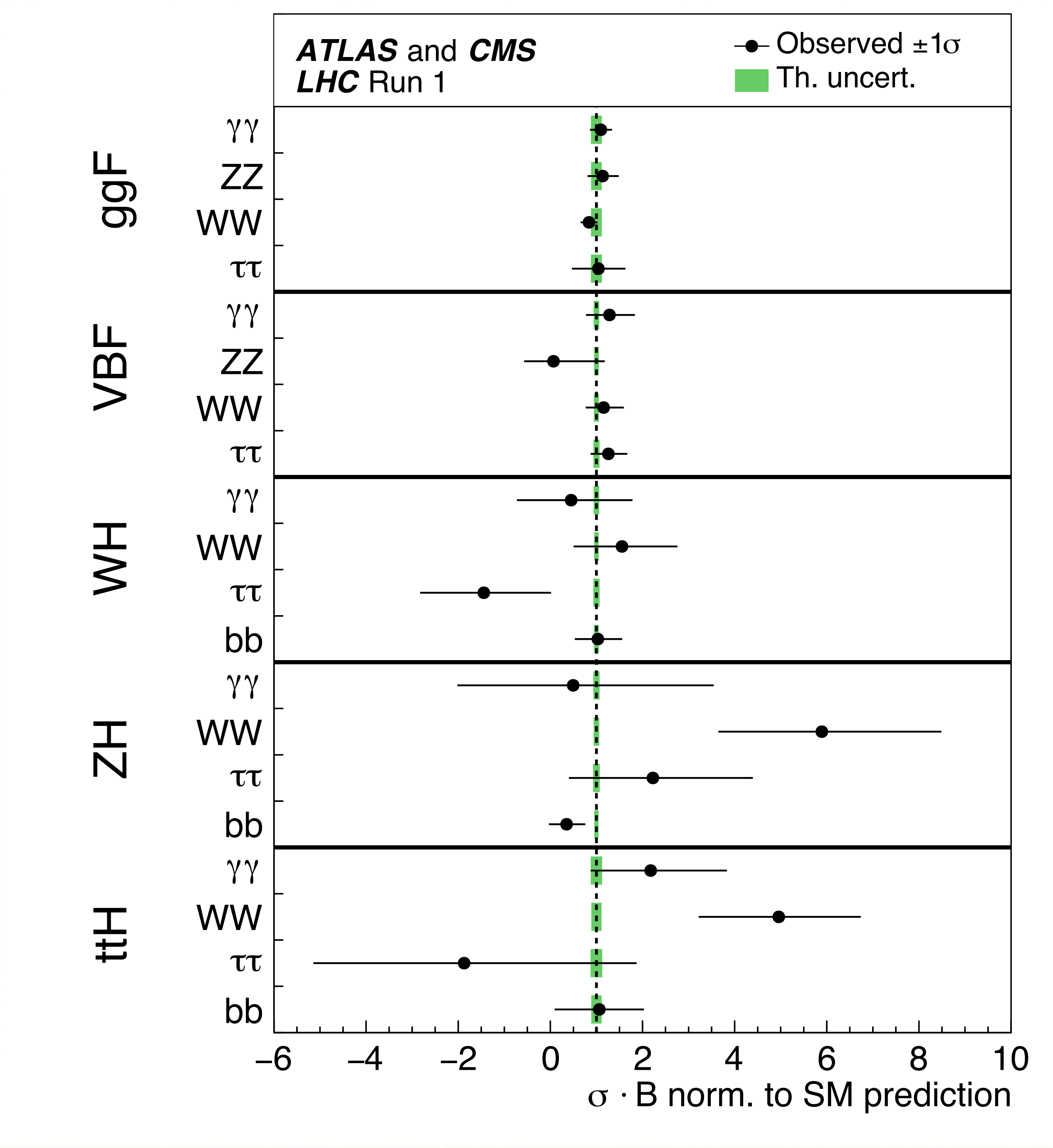




Further questions

- Is the sensitivity of the various processes large enough to set constraints?
- Can we start to exploit such a sensitivity **now**, to close the gap between the current bounds ($|k_\lambda| \lesssim$ 10-20) and the EFT-relevant region ($-2 \lesssim k_\lambda \lesssim 4$)?
- What are the minimal theoretical assumptions that are needed to guarantee that the interpretations at large values of k_λ are robust?

The first global sensitivity study



We have performed a first sensitivity study using the 8 TeV data on rates and projecting on the future LHC measurements.

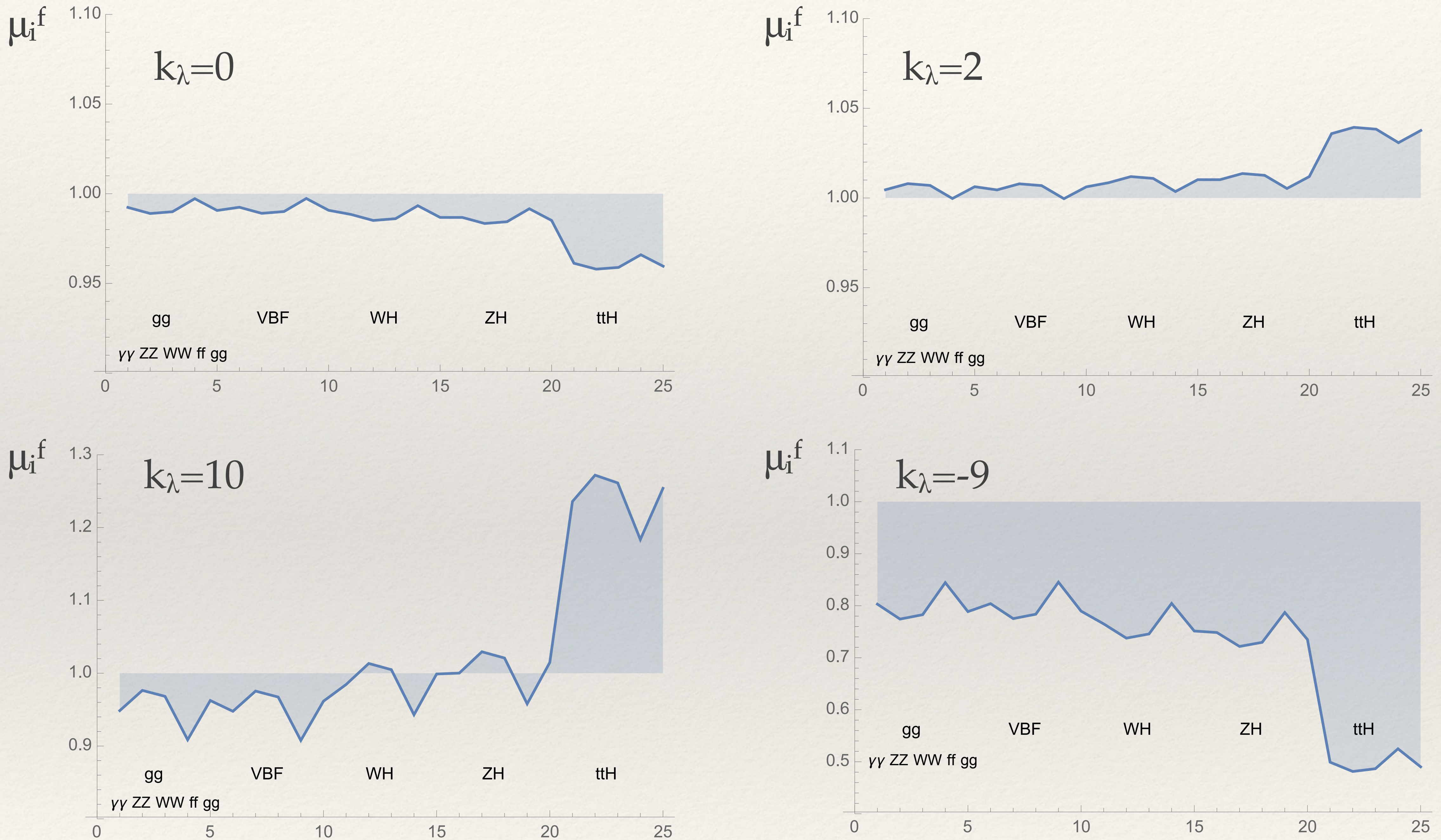
We performed a one-parameter fit, assuming the other Higgs couplings to be SM like.

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$

$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$

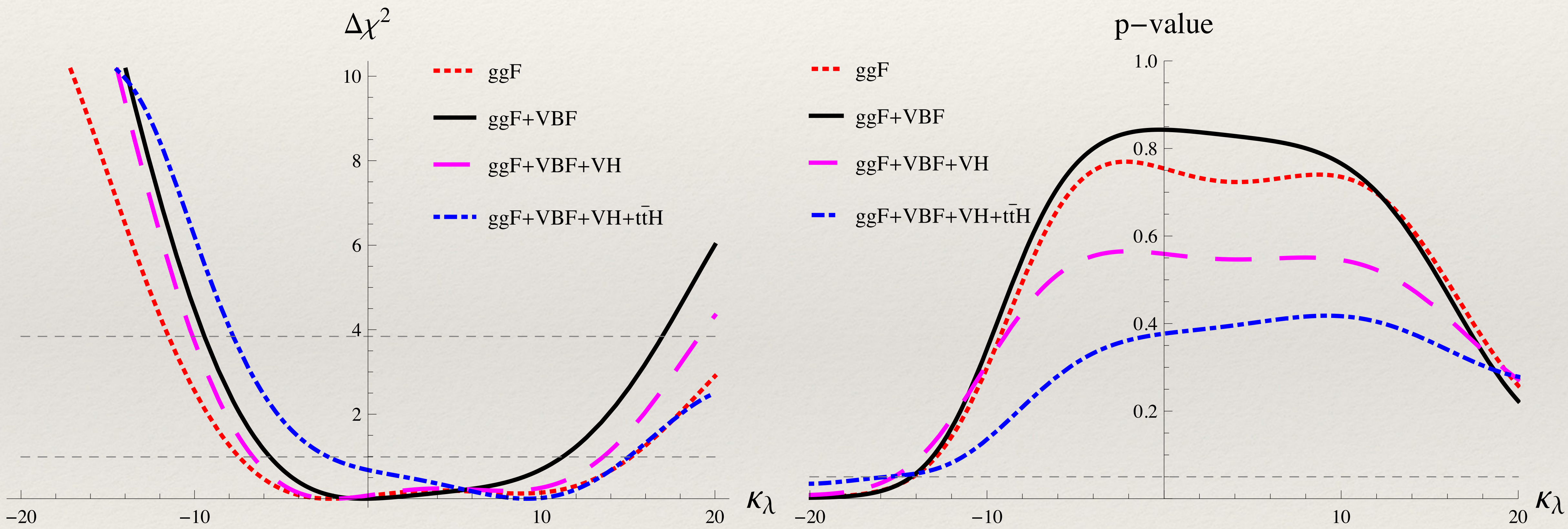
Rates: $\mu_i^f(k_\lambda)$



An animation can be found here

The first global sensitivity study

Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$



P_2: ggF+VBF ➡ $\kappa_\lambda^{\mathrm{best}} = -0.24\,, \quad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \quad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

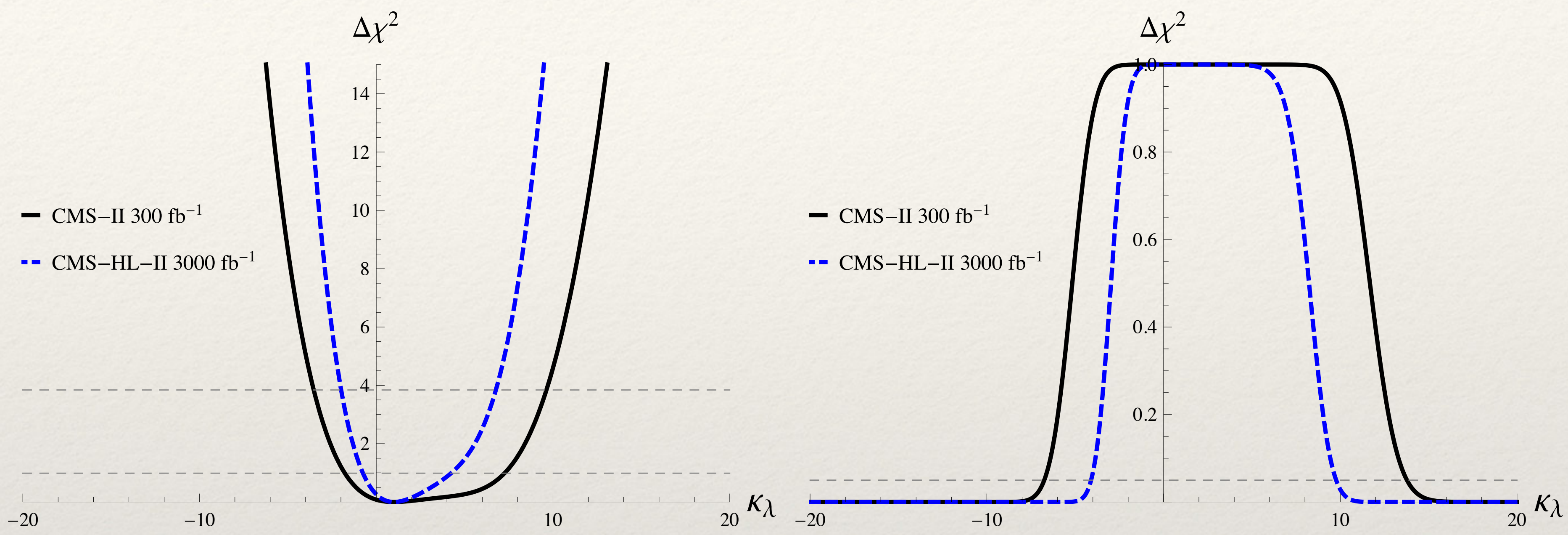
$p\text{-value}(\kappa_\lambda) = 1 - F_{\chi^2_{(n)}}(\chi^2(\kappa_\lambda))$ ➡ $\kappa_\lambda < -14.3$ Excluded at more than 2σ

Future runs

Exercise 0:

$$\bar{\mu}_i^f = 1$$

$$\kappa_\lambda^{\text{best}} = 1$$



"CMS-II" (300 fb^{-1})

$$\kappa_\lambda^{1\sigma} = [-1.8, 7.3]\,, \qquad \kappa_\lambda^{2\sigma} = [-3.5, 9.6]\,, \qquad \kappa_\lambda^{p>0.05} = [-6.7, 13.8]$$

"CMS-HL-II" (3000 fb^{-1})

$$\kappa_\lambda^{1\sigma} = [-0.7, 4.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-2.0, 6.8]\,, \qquad \kappa_\lambda^{p>0.05} = [-4.1, 9.8]$$

A few comments

- Our first sensitivity study **using only total rates at 8 TeV** indicates the possibility of exploiting the precision of single Higgs measurements to independently bound the trilinear self coupling.
- The structure of the corrections in ggH, ZH,WH, ttH and in the decays, shows that a sensitivity would remain in principle even if the SM assumption for the other Higgs couplings, for example in case k_V and k_t , is lifted.
- The importance of studying threshold regions for VH and ttH has been highlighted to provide further information.
- Our calculations are per-se independent of the interpretational framework (k-framework, linear EFT, non-linear EFT) and can be used in any of them. However, one should keep in mind that the validity of the loop expansion and the maximal acceptable range of k_λ depend on the assumptions inherent in the interpretations.
- The reliability of the interpretations at the current limits on k_λ is a model-dependent matter, common to single-H and HH studies. Models exist in the literature (portal models, accidentally light Higgs [Da liu et al, 1603.03064]) where effects in the Higgs potential can be sizeable and parametrically larger than those on the other couplings.

Conclusions and Outlook

- We have put forward the idea (and performed the corresponding calculations) of using the sensitivity of single-Higgs processes at NLO to the Higgs trilinear coupling to gather information on the Higgs potential.
- Our first exploration on the sensitivity shows that the method is promising and could become complementary to that of the direct HH measurements. Other recent studies support this conclusion.
- More work is needed on several important aspects: methodological (the use of distributions, progressively relaxing SM assumptions on other couplings,…), experimental (insertion and verification of sensitivity in the global fits,…) and theoretical (range of validity of the EFT expansions, relevance for actual models, …).

Thanks

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  - Andre David
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  - …