Probing the Higgs self coupling at the LHC: direct vs indirect determinations

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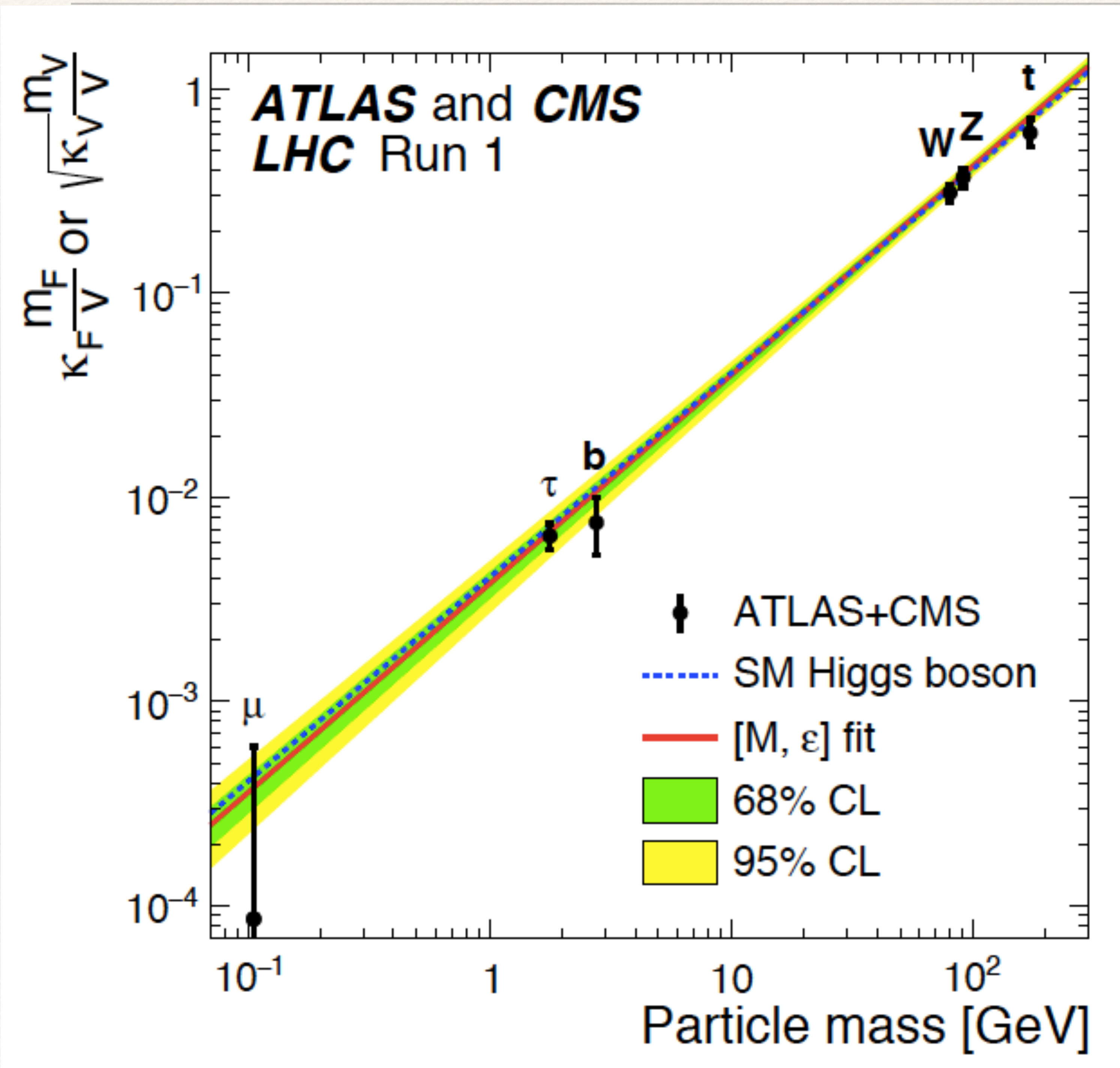
`on behalf of an increasing number of interested theorists…`

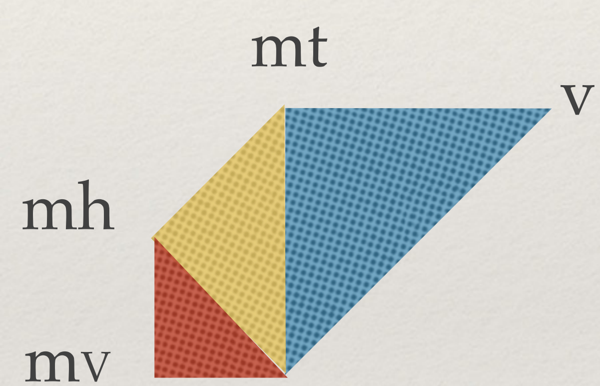
Indirect approach: relevant literature

Ref	Authors	Processes	Comments
1312.3322	M.McCullough	e+e- → ZH	applications at future colliders
1607.03773	M.Gorbahn, U.Haisch	gg→H, H→γγ	approx. two-loop results mh →0
1607.04251	G.Degrassi, P.P. Giardino, F.M., D.Pagani	gg→H,WH,ZH,VBF, ttH H→γγ,WW*/ZZ*→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
1702.01737	G. Degrassi, M. Fedele, P.P. Giardino	EWPO	two-loop effects
1702.07678	G. Kribs, A. Maier, H. Rzehak, M. Spannowksy, P. Waite	EWPO	two-loop effects
1704.01953	S. Di Vita, C. Grojean, G. Panico, M. Riembau, T. Vantalon	Direct+indirect	global fit in the EFT including differential
1707.XXXXX	F. Maltoni, D. Pagani, A. Shivaji, X. Zhao	VBF, VH, tHj ttH and H→4l.	Differential distributions with EW corrections. Release of MC

Higgs couplings



$$\frac{v}{m_t} = \frac{m_t}{m_h} = \frac{m_h}{\bar{m}_V} = \sqrt{2}$$



$$r = 2^{\frac{2\theta}{\pi}}$$

The Higgs potential

A low-energy parametrisation of the Higgs potential

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

In the Standard Model:

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

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:

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

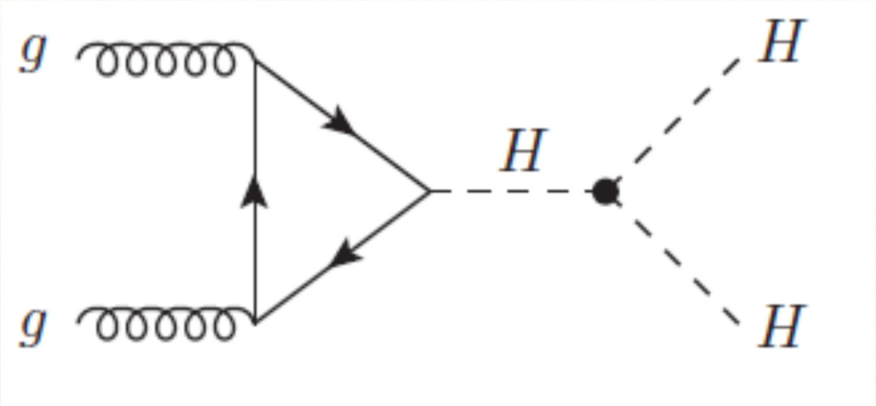
so that the basic relations remain the same as in the SM: $\begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases}$

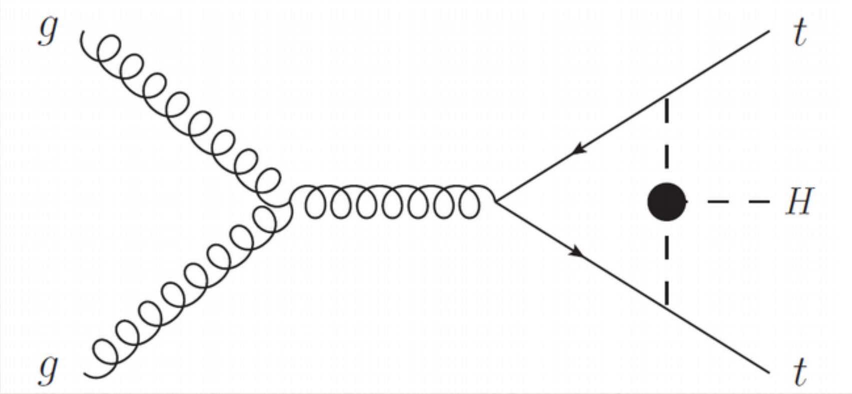
while the λ_3 and λ_4 are modified with respect to the SM values: $\begin{cases} \lambda_3 = \kappa_\lambda \lambda_3^{\rm SM} \\ \lambda_4 = \kappa_{\lambda_4} \lambda_4^{\rm SM} \end{cases}$

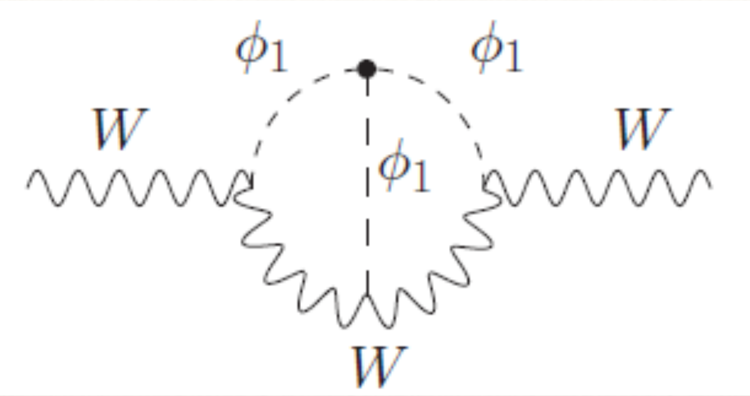
So for example: adding c_6 only $\begin{cases} \kappa_\lambda = 1 + \dfrac{c_6 v^2}{\lambda\Lambda^2} \\ \kappa_{\lambda_4} = 1 + \dfrac{6 c_6 v^2}{\lambda\Lambda^2} = 6\kappa_\lambda - 5 \end{cases}$ i.e., in this case λ_3 and λ_4 are related.

Note: to change λ_3 and λ_4 independently, one needs at least to go up to dim=8.

How to probe the trilinear coupling?







Tree-level	One-loop	Two-loop
"Direct"	"Indirect"	"Indirect^2"
2H	**1H**	**0H**

Comments:

1. For all the processes above and **at the corresponding order** , SMEFT calculations with O_6 or with a rescaling of λ_3 are equivalent (and gauge invariant!).
2. Model depedent assumptions are always implicitly xor explicitly made in interpreting the experimental constraints.

Model dependence and max size of the trilinear

Direct measurements are "by definition" less model dependent than indirect ones. It is therefore important to clearly assess what are the issues that impact both direct and indirect, and what are those impacting only or especially the indirect.

Questions:

1. What are the NP scenarios that can be probed via a given measurement?
2. How large can λ_3 be?
3. Is it possible to have λ_3 significantly different from the SM, with all other Higgs couplings being close to the SM values?

Answers to these questions frame all possible interpretations of direct and indirect measurements and need to be kept in mind when sensitivity comparisons are made.

Model dependence and max size of the trilinear

A few recent studies/results (note: each with its own theoretical assumptions):

- L. Di Luzio, R. Gröber, M. Spannowsky 1704.02311:

  hh → hh partial wave unitarity
  hhh one-loop $(\lambda_3)^3$ corrections $\Longrightarrow$ $|k_\lambda| \lesssim 6$

- If we start with $V^{SM}=0$, but couple the Higgs with a singlet scalar S, then CW potential would give (M. Perelstein) :

$$V^{\rm CW} = \frac{N_S \xi_0^2 h^4}{64\pi^2}\left(\log\frac{h^2}{v^2} - \frac{1}{2}\right) \Longrightarrow k_\lambda \lesssim 5/3$$

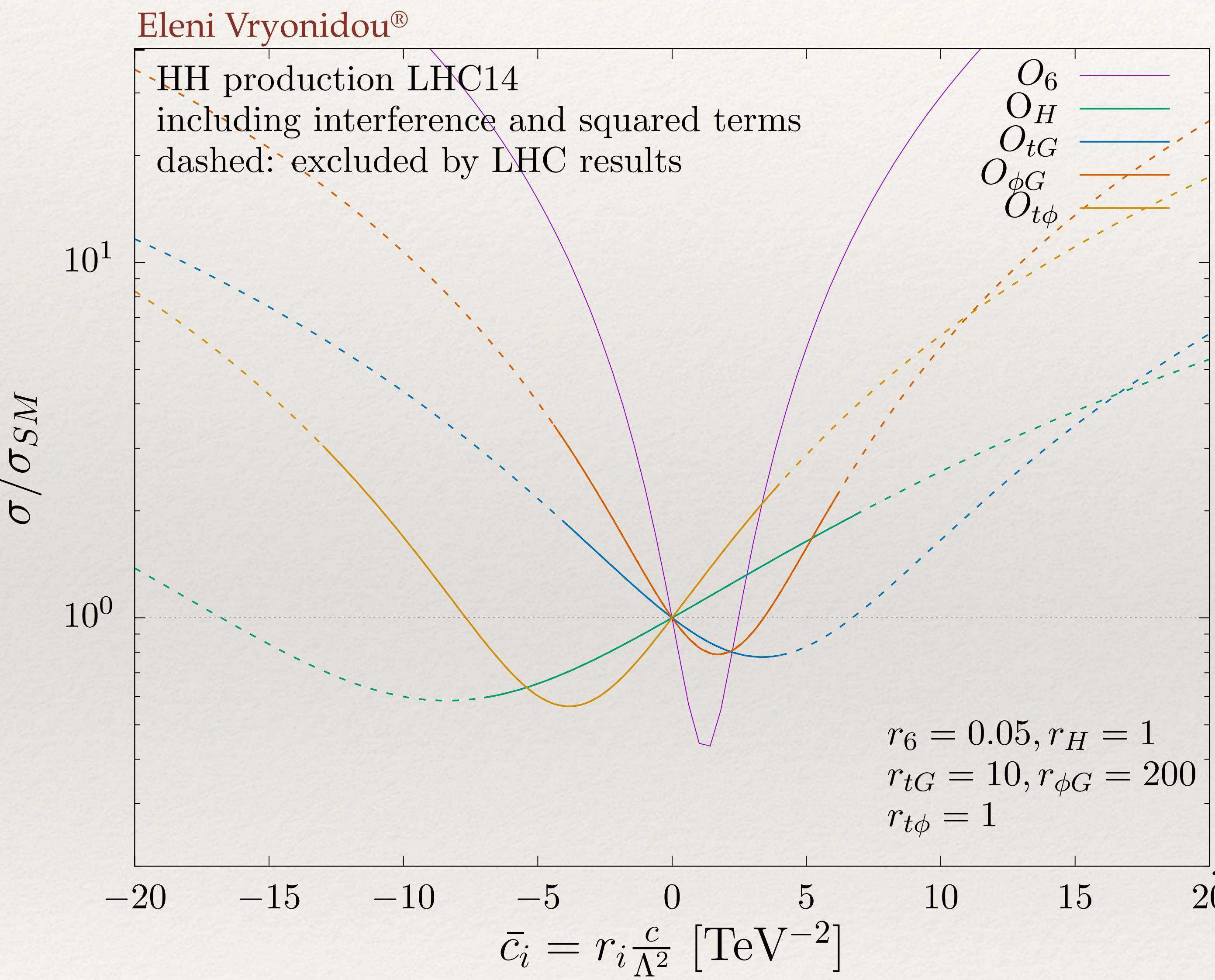
- Di Vita et al. 1704.01953:

  Higgs portal with tuning, leaves all H couplings close to the SM and allows $|k_\lambda| \lesssim 6$.

- Falkowski and Rattazzi (by now famous yet private note):

  Validity of a theory with ONLY self-coupling deformations is studied through unitarity and can be up to several TeV's for deformation of order $|k_\lambda| \lesssim 10$.

HH sensitivity in the SMEFT

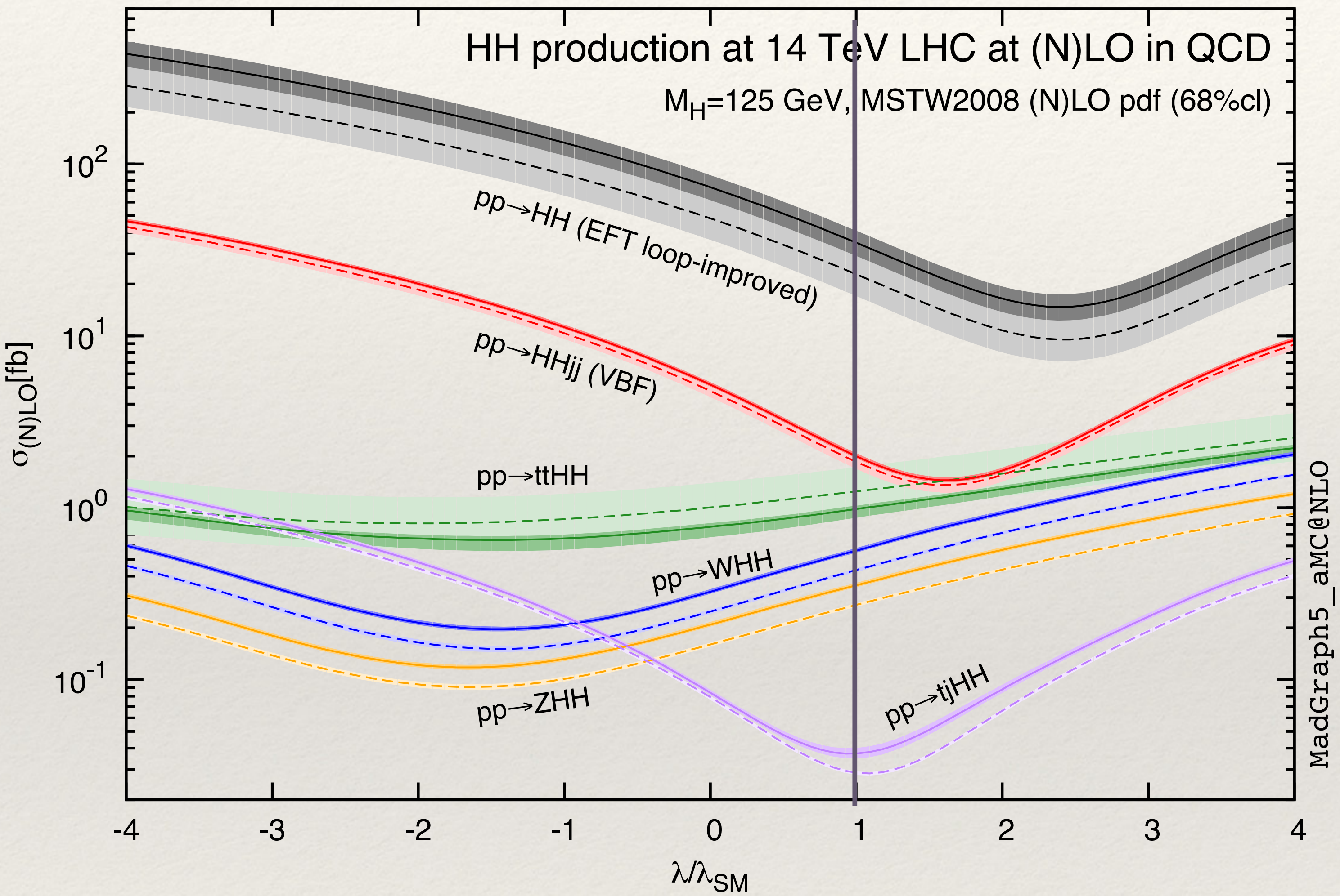


Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable. The range of c_6 is commensurate to that of $k_{\lambda 3}$.

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.

HH at the LHC

[Frederix et al. '14]



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.

Many channels, but small cross sections.

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

CMS : $\sigma/\sigma_{SM} < 19$ (bbɣɣ) [EPS2017]
ATLAS : $\sigma/\sigma_{SM} < 30$ (bbbb)
CMS : $\sigma/\sigma_{SM} < 28$ (bbtt)

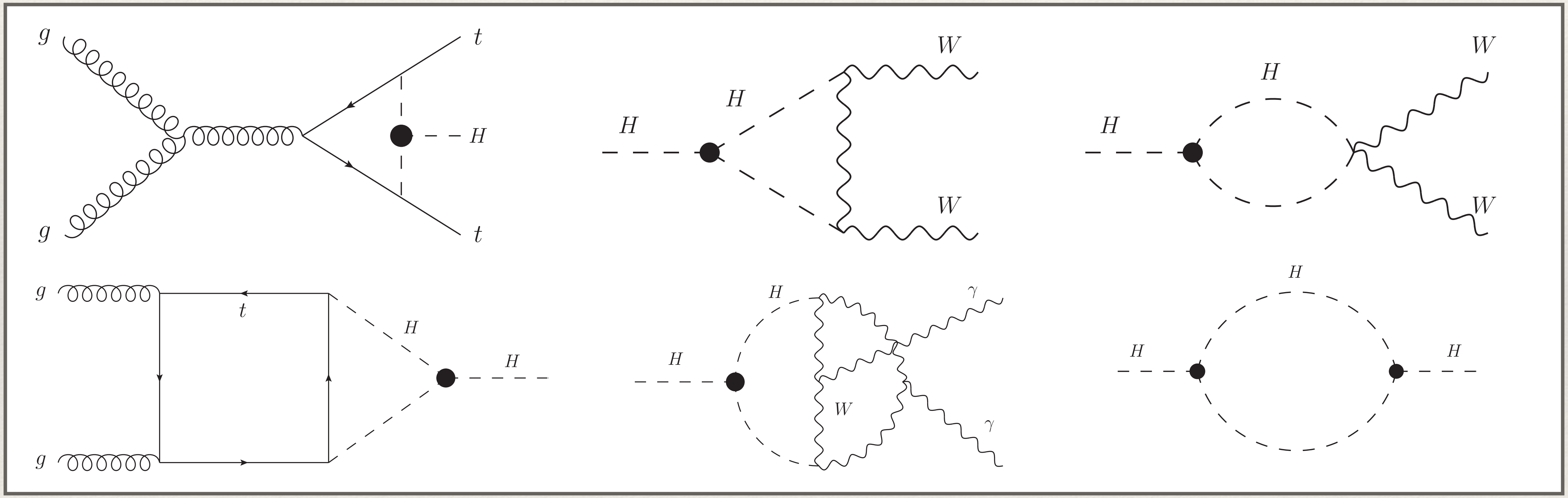
Remarks:

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:

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

Indirect measurement in single Higgs production

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.

Master formula

1607.04251

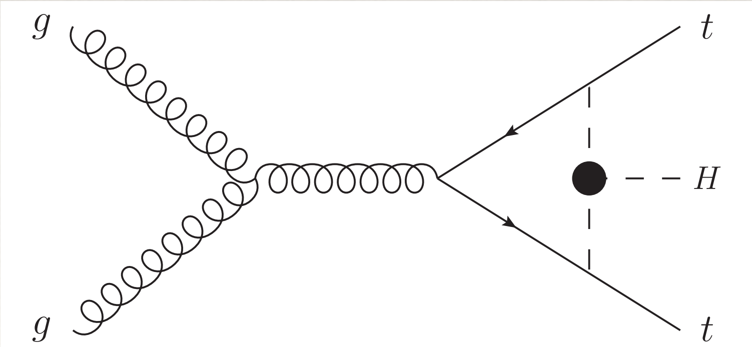
$$\delta\sigma \equiv \frac{\sigma_{\rm NLO} - \sigma^{\rm SM}_{\rm NLO}}{\sigma_{\rm LO}} = (\kappa_\lambda - 1) C_1 + (\kappa_\lambda^2 - 1) C_2$$

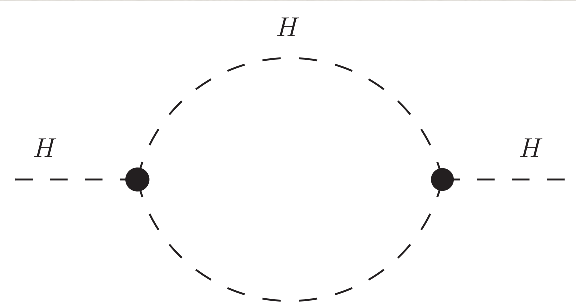
Process and kinematics dependent

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

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

Results : total cross sections

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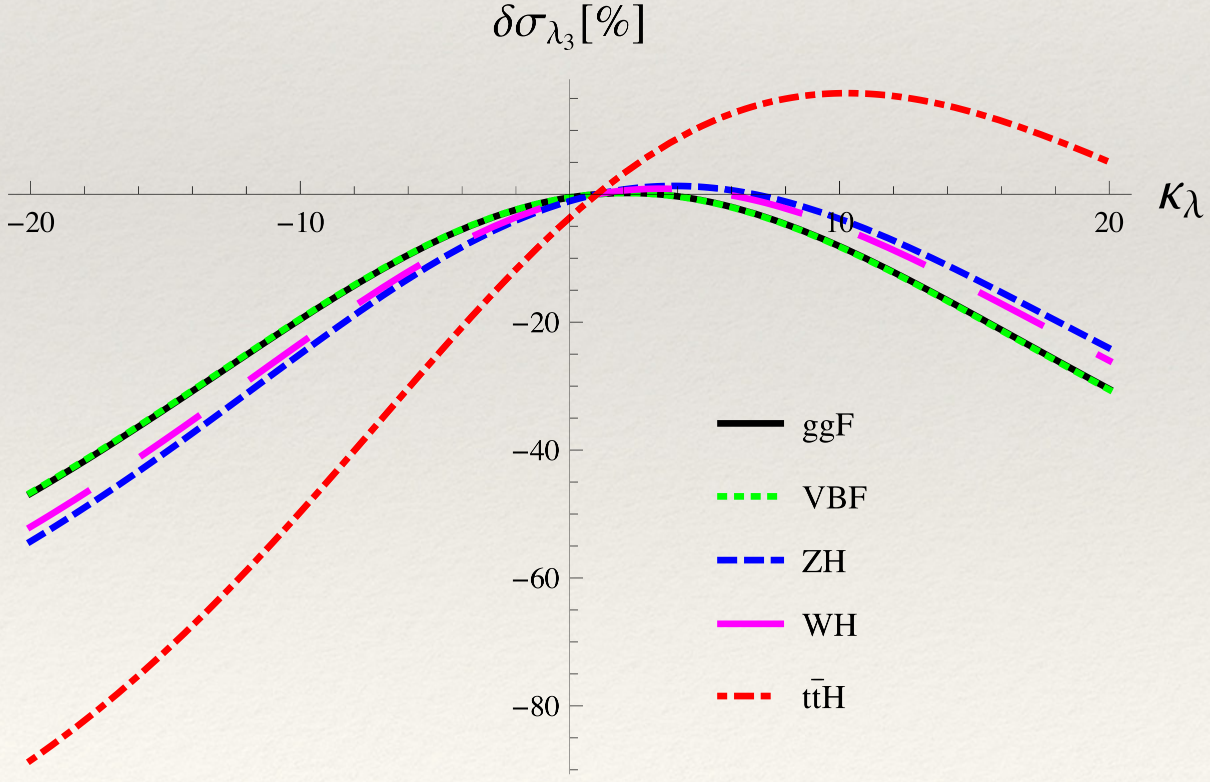
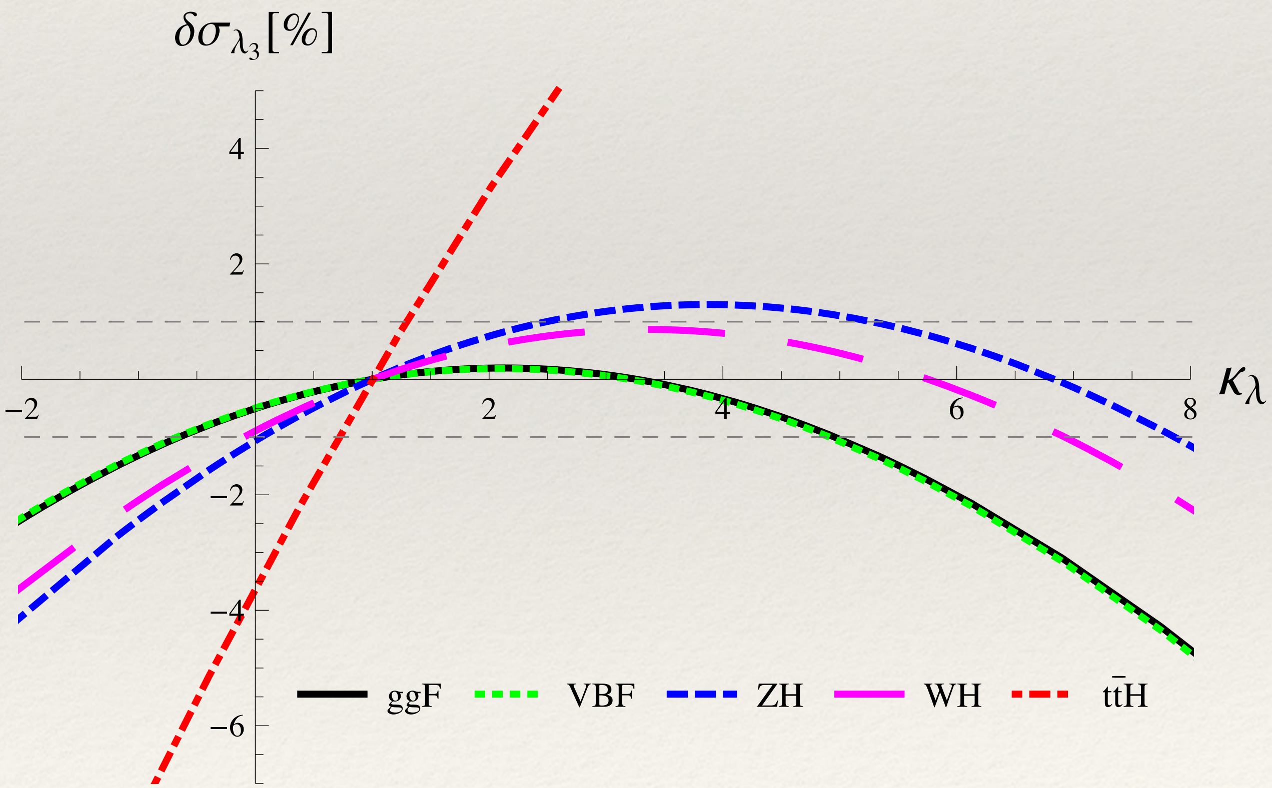
$$\delta\sigma = (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2$$

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

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

$C_1^\sigma[\%]$	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





Results: Decay rates

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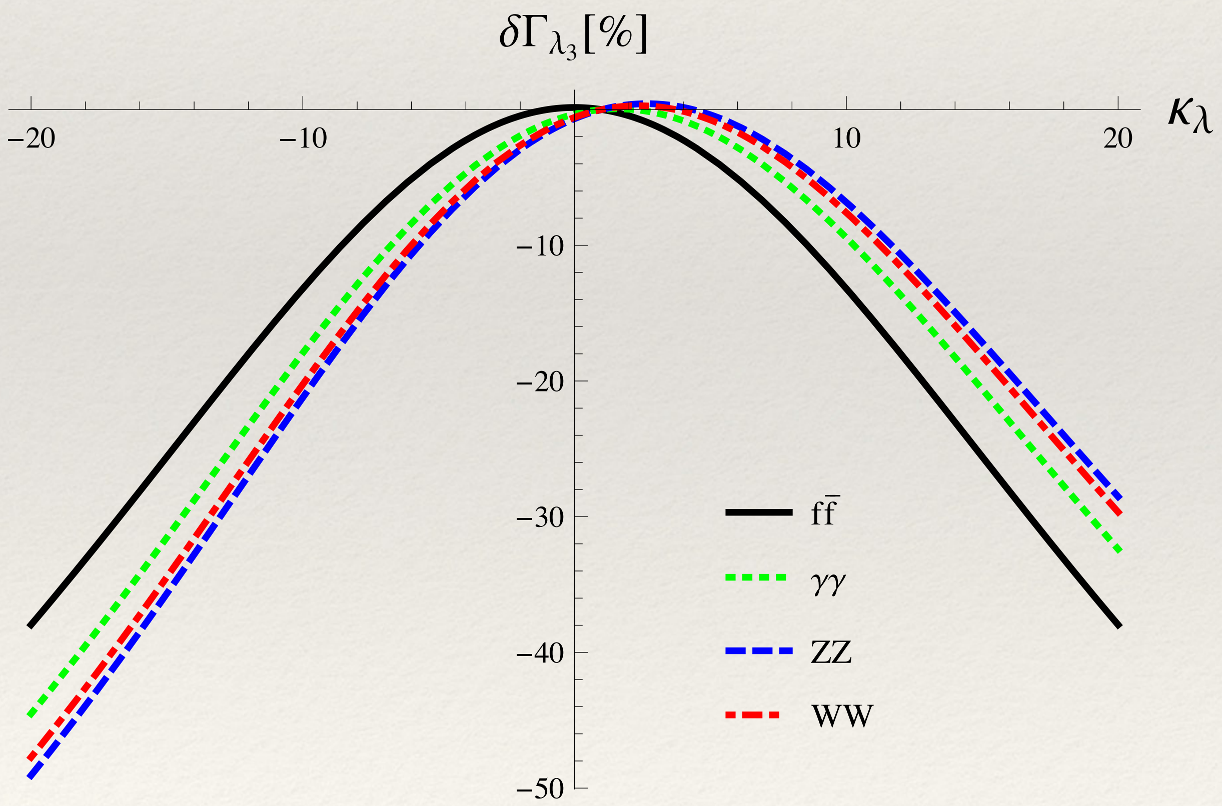
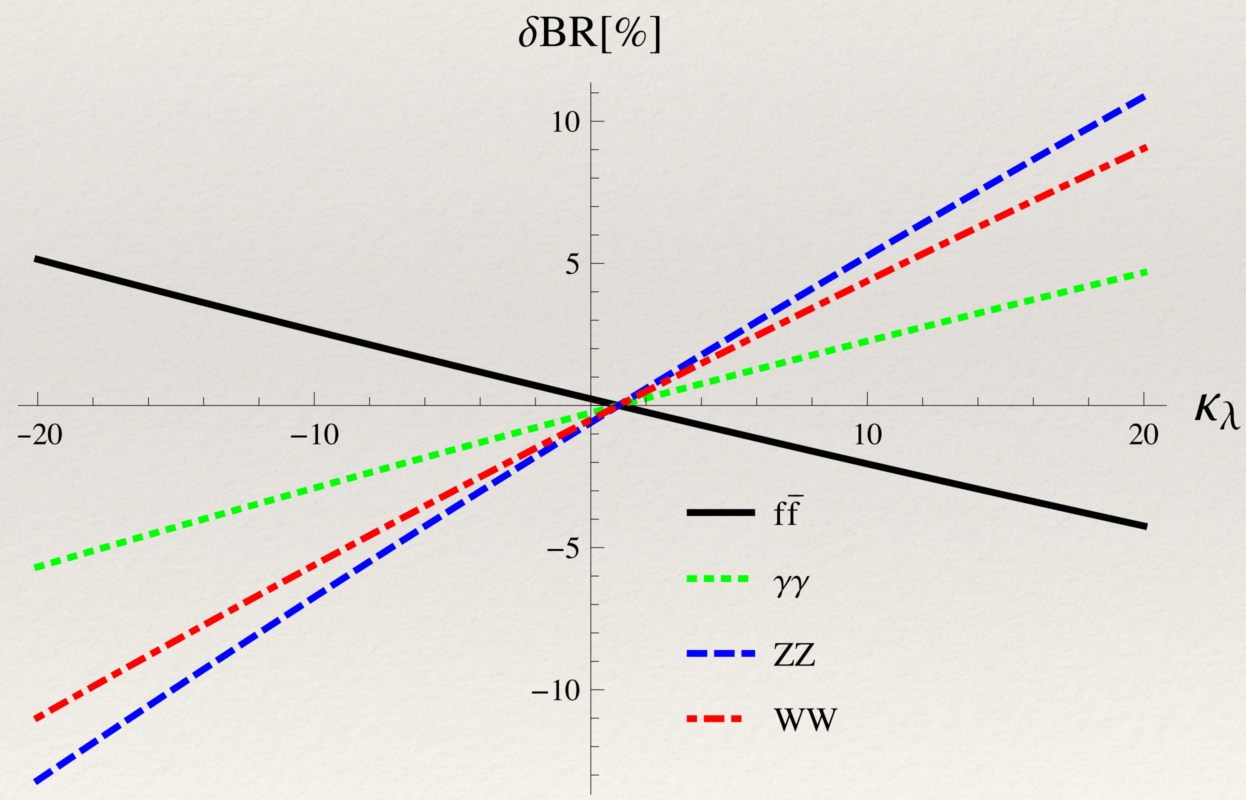
$$\delta \mathrm{BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^\Gamma(i) - C_1^{\Gamma_{\rm tot}})}{1 + (\kappa_\lambda - 1) C_1^{\Gamma_{\rm tot}}}$$

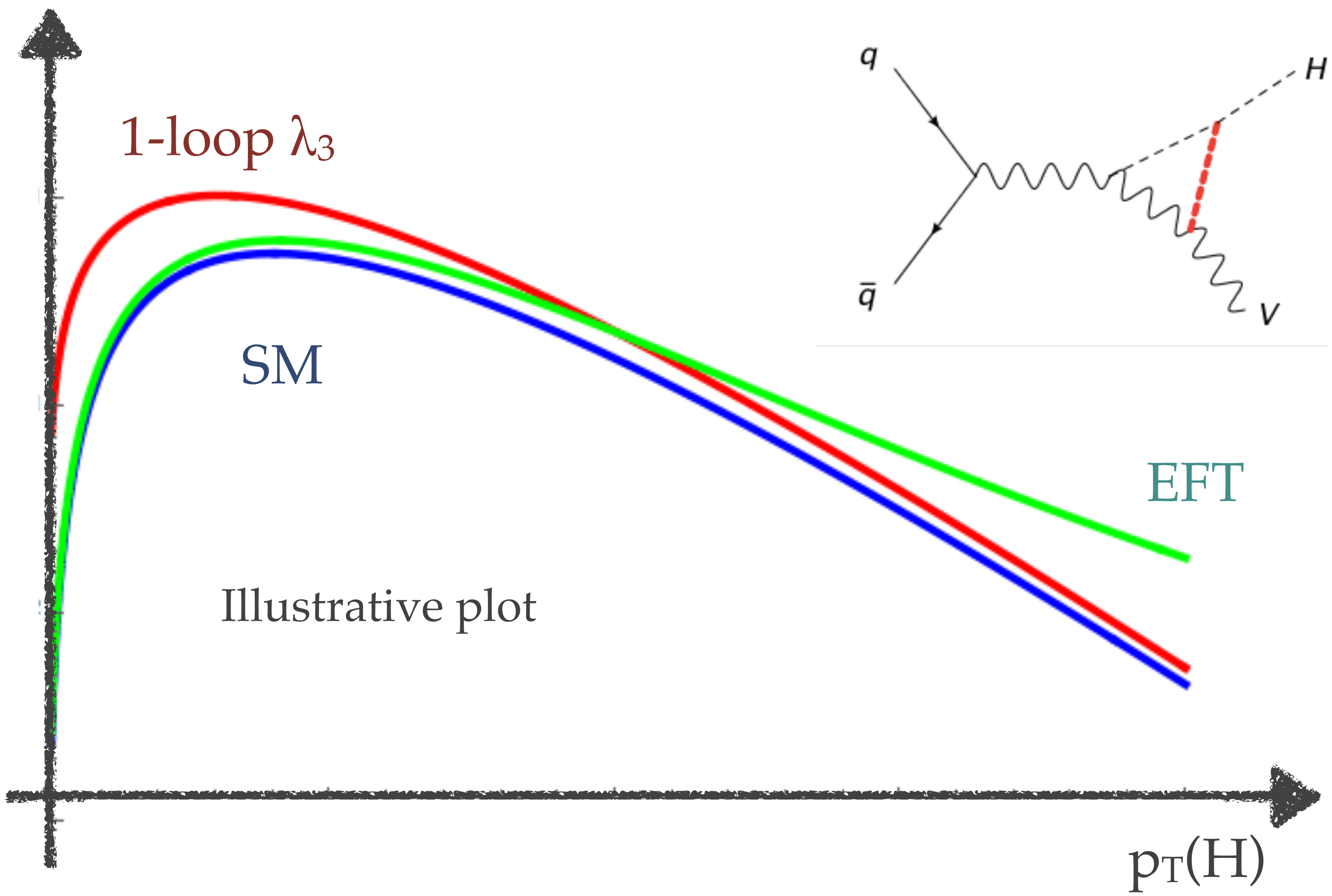
$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66



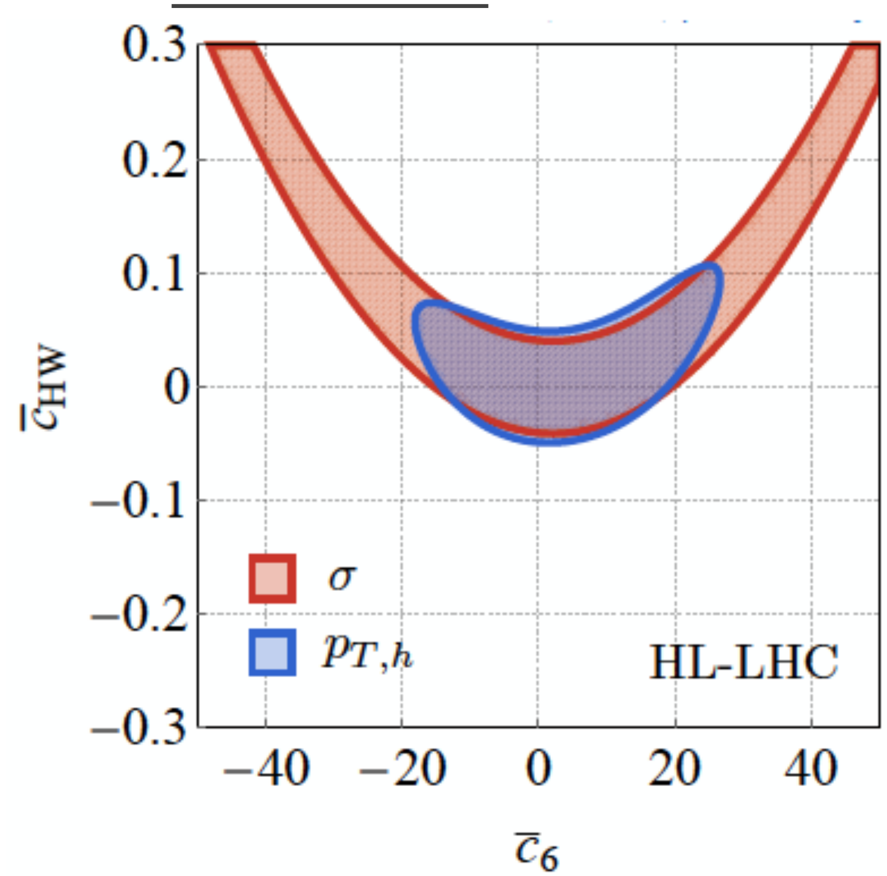


Differential information

Calculations: 1607.04251 1610.05771 1707.XXXX Use in the fit: 1704.01953 1707.XXXXX



1706.09730 U. Haisch



The largest effects are **non-local** and **at threshold**: corrections to ttH and HV processes can be seen as induced by a Yukawa potential. EFT (at LO) gives **local** effects and **in the tails.**

Differential information

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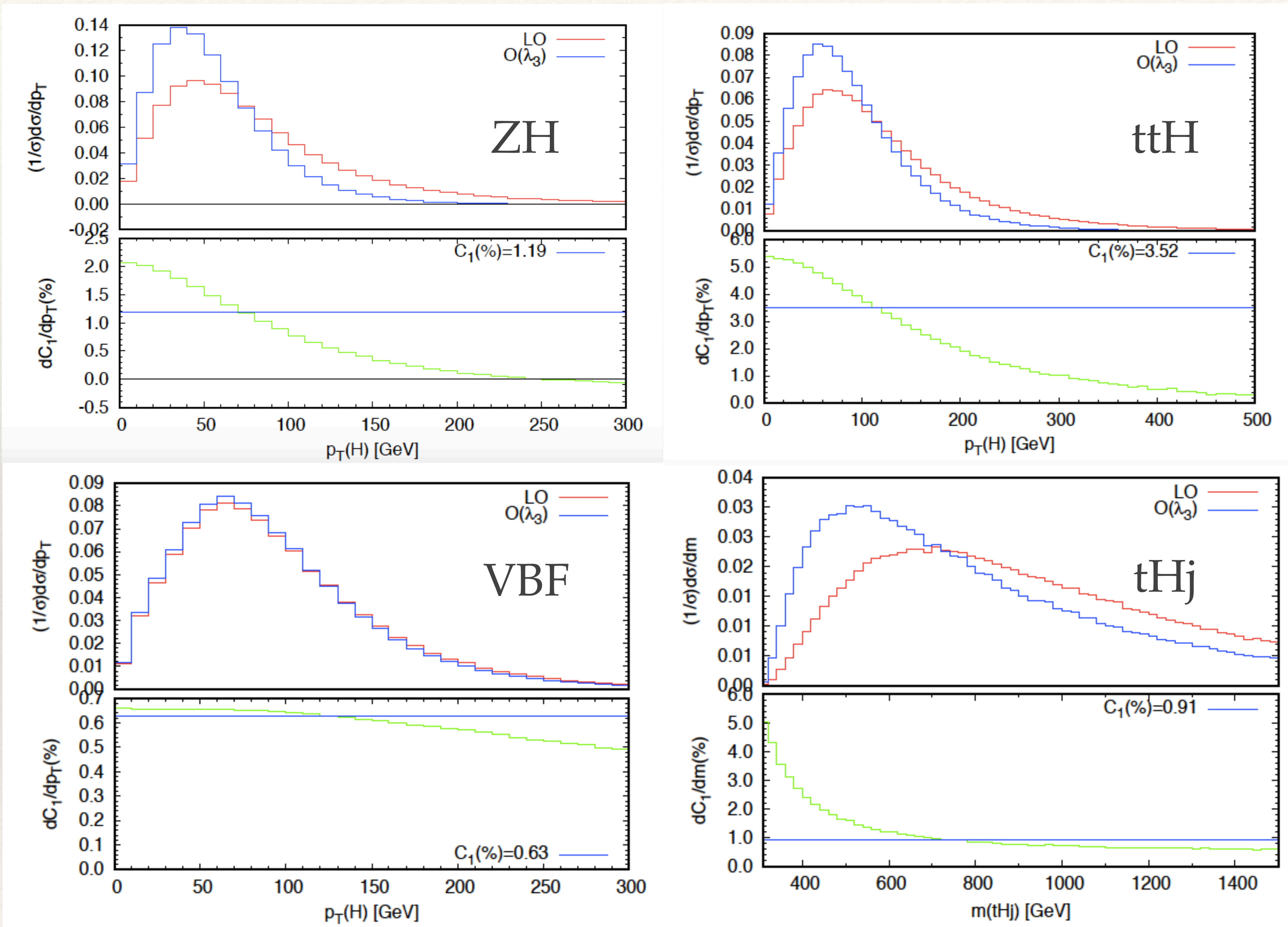

Codes to reweight SM events to include the 1-loop λ_3 in VH,VBF, ttH, tHj available HERE.

Differential information

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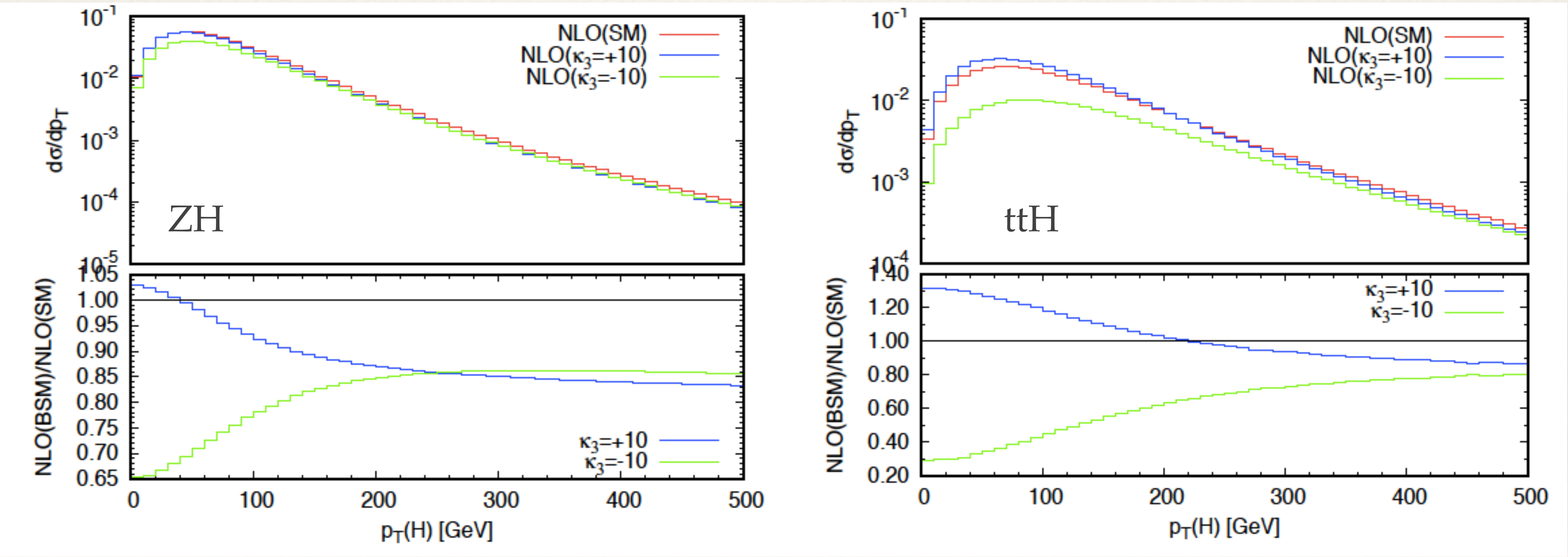
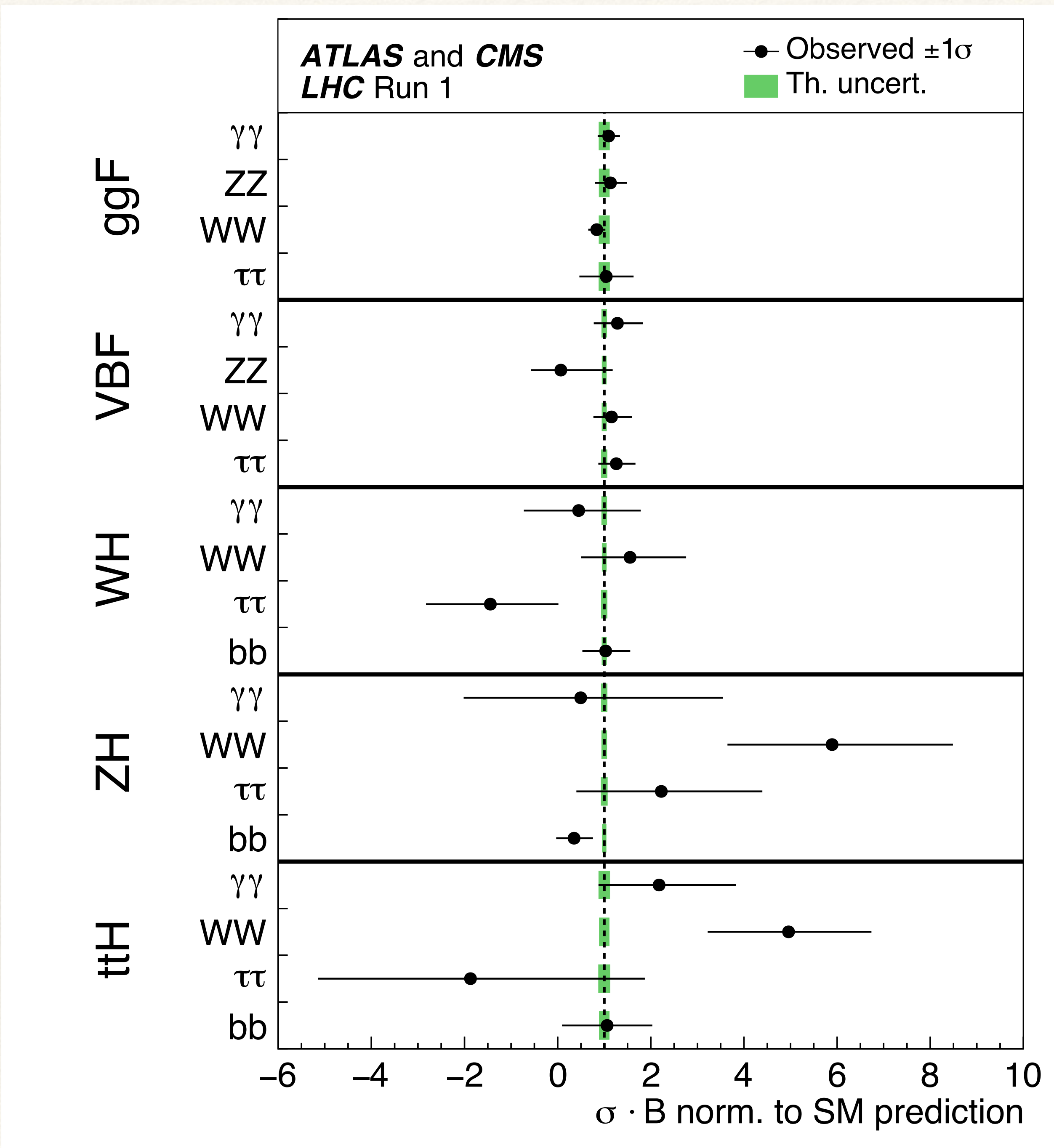
Inclusion of the EW corrections:



Note: Differential study for H→4l also including EW corrections, available. Differential effects in H→4l from λ_3 are very small

The first global sensitivity study at 8 TeV



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

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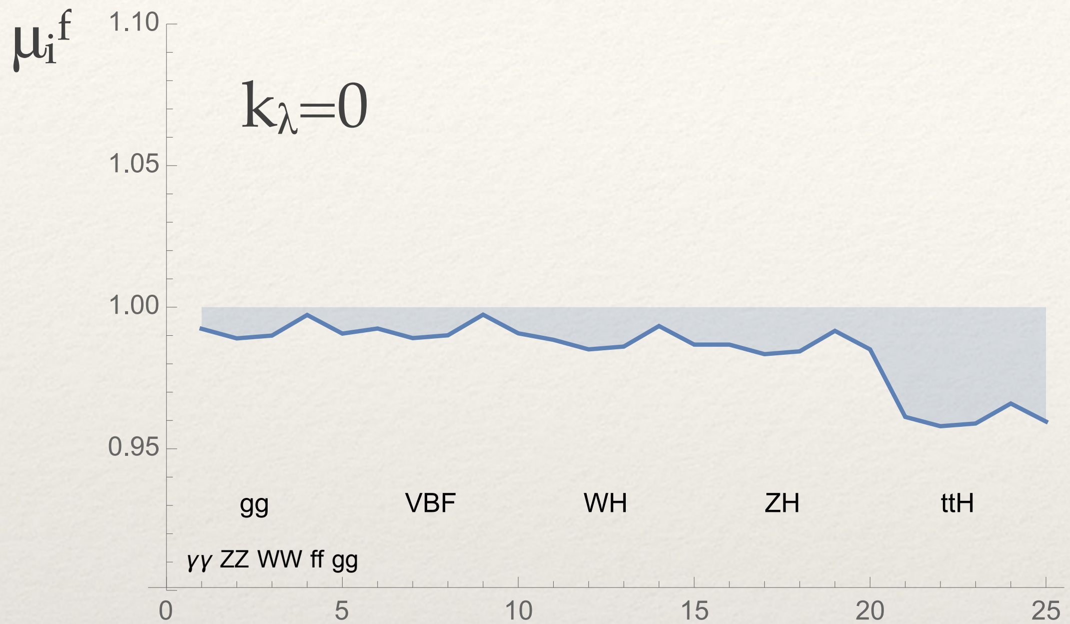
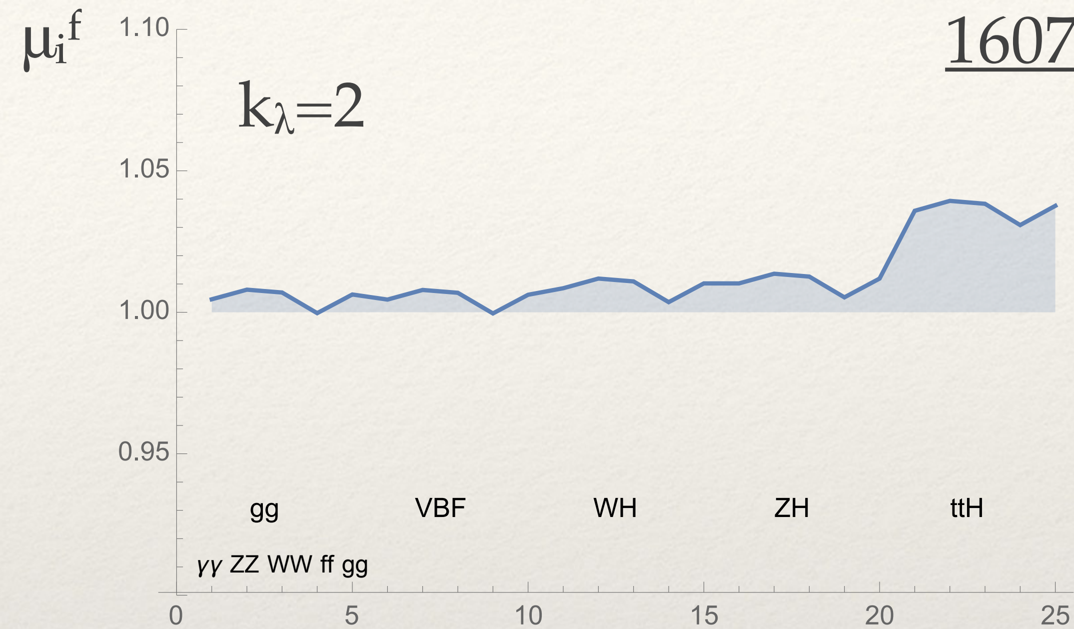
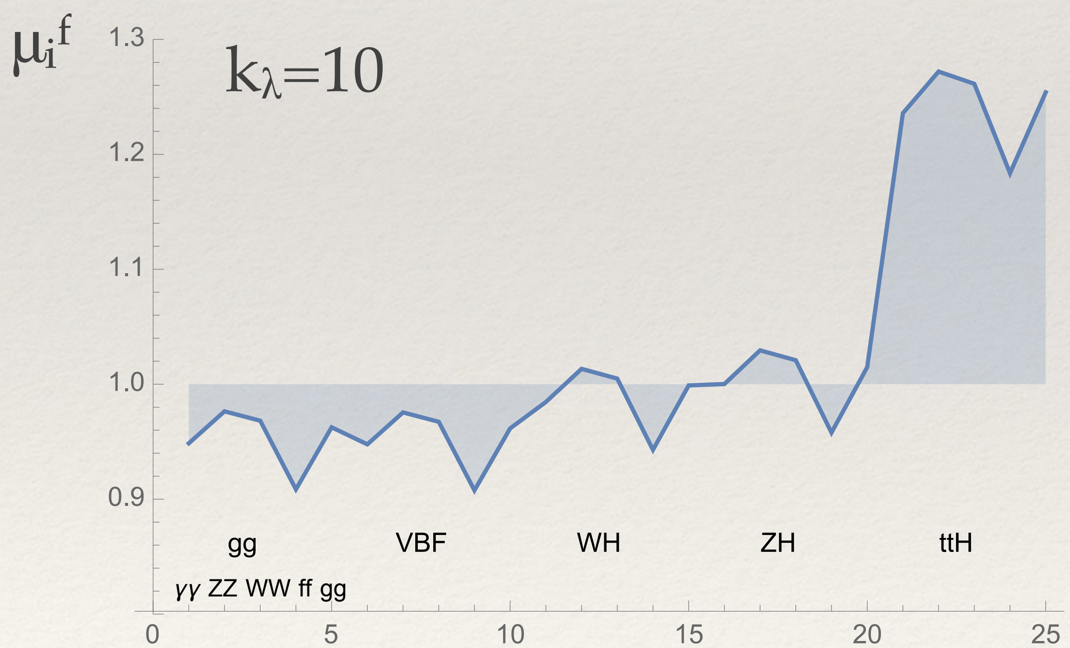
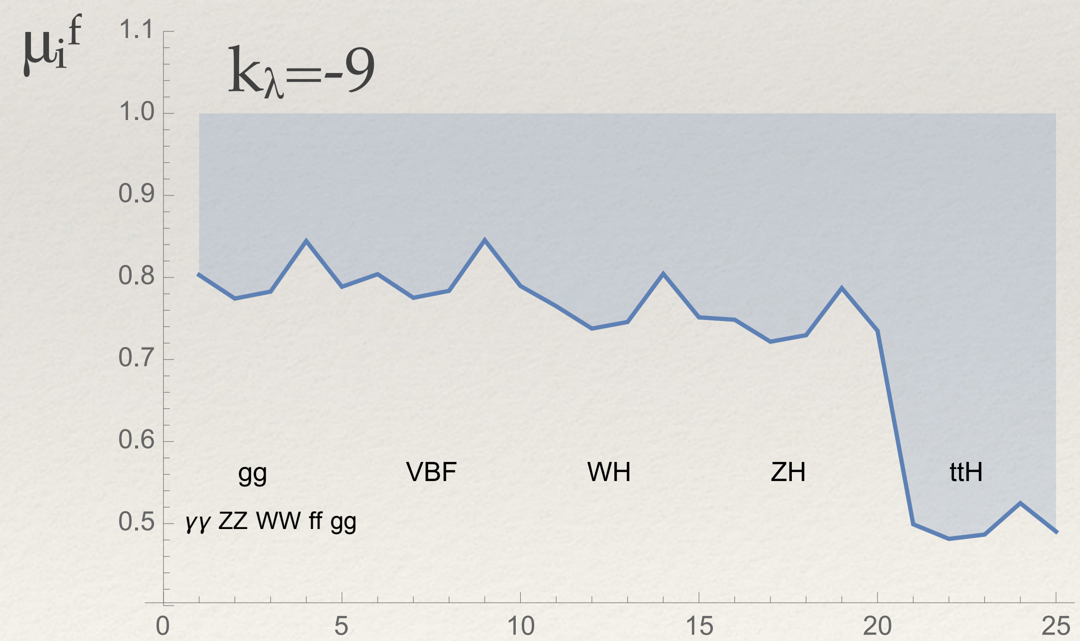






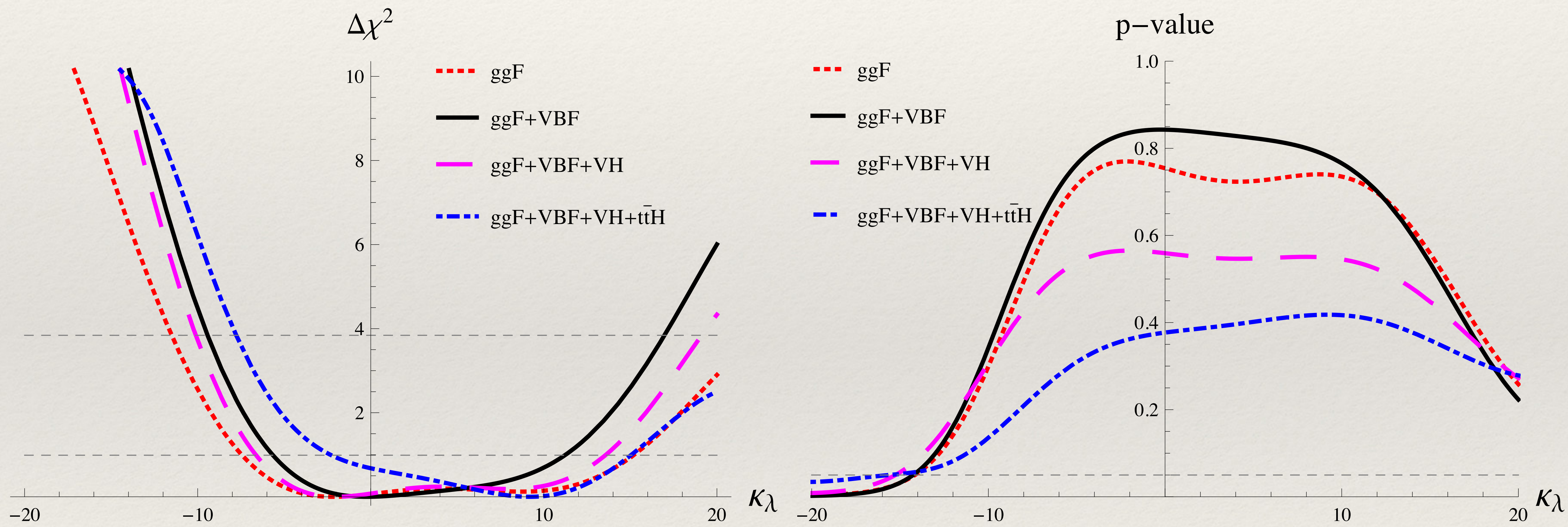


An animation can be found here

The first global sensitivity study at 8 TeV

1607.04251

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 → $\kappa_\lambda^{\text{best}} = -0.24\,, \quad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \quad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

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

The first global sensitivity study at 8 TeV: inclusion of EWPO

m_w and the effective sine are obtained from α, G_μ and m_z via

$$m_W^2 = \frac{\hat\rho\, m_Z^2}{2}\left\{1+\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

$$\sin^2\theta_{\rm eff}^{\rm lep} \sim \frac{1}{2}\left\{1-\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

$$\begin{aligned}\hat A &= (\pi\hat\alpha(m_Z)/(\sqrt{2}G_\mu))^{1/2}\\ \hat\alpha(m_Z) &= \frac{\alpha}{1-\Delta\hat\alpha(m_Z)}\\ \frac{G_\mu}{\sqrt{2}} &= \frac{\pi\hat\alpha(m_Z)}{2m_W^2\hat s^2}(1+\Delta\hat r_W)\\ \hat\rho &= \frac{1}{1-Y_{\overline{MS}}}\end{aligned}$$

[1702.01737](1702.01737)

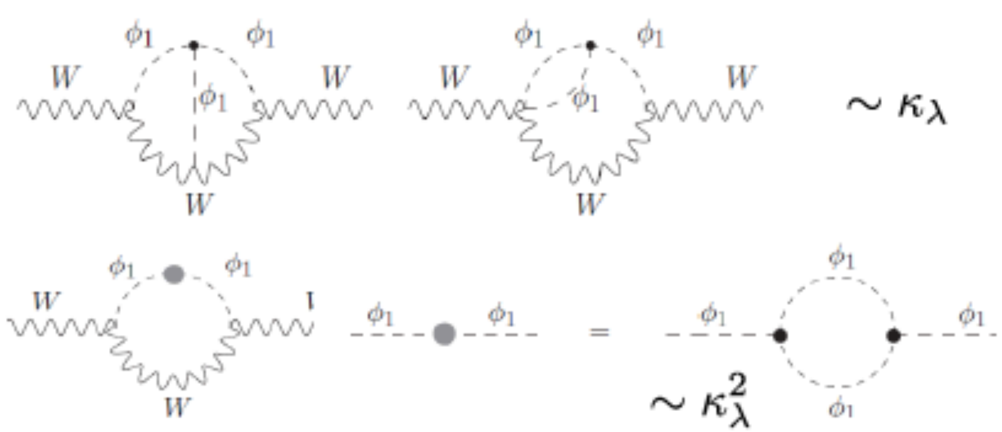
see also

1702.07678

λ_3-dependent contributions appear at two-loop in the W and Z self-energies

$$\Delta\hat r_W^{(2)} = \frac{{\rm Re}\,A_{WW}^{(2)}(m_W^2)}{m_W^2} - \frac{A_{WW}^{(2)}(0)}{m_W^2} + \ldots$$

$$Y_{\overline{MS}}^{(2)} = {\rm Re}\left[\frac{A_{WW}^{(2)}(m_W^2)}{m_W^2} - \frac{A_{ZZ}^{(2)}(m_Z^2)}{m_Z^2}\right] + \ldots$$



Talk by G. Degrassi at EPS

The first global sensitivity study at 8 TeV: inclusion of EWPO

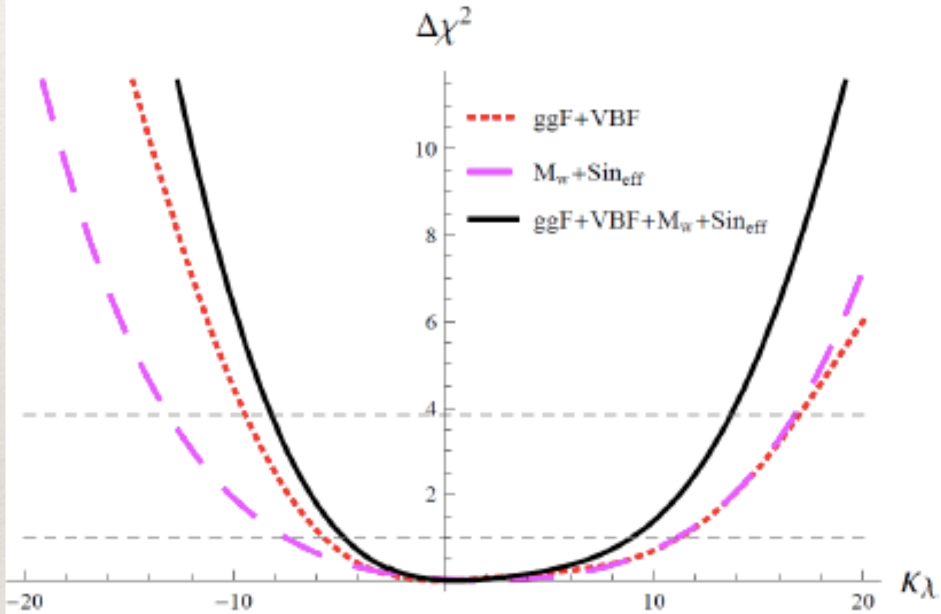
$$O = O^{\rm SM}\left[1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2\right]$$

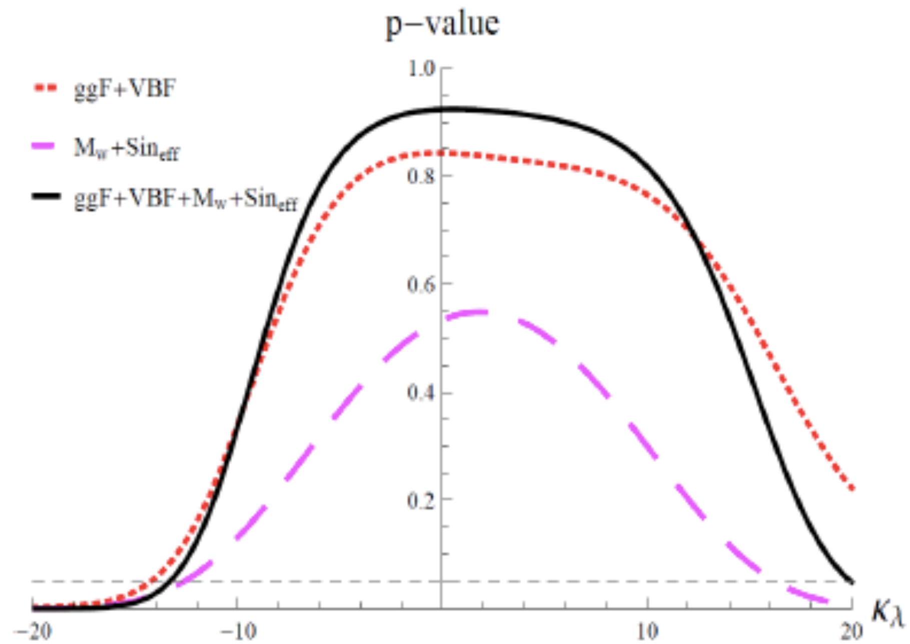
	C_1	C_2
m_W	6.27×10^{-6}	-1.72×10^{-6}
$\sin^2\theta_{\rm eff}^{\rm lep}$	-1.56×10^{-5}	4.55×10^{-6}

1702.01737

see also

1702.07678





P.O. + ggF +VBF $\kappa_\lambda^{\rm best} = 0.5\,,\quad \kappa_\lambda^{1\sigma} = [-4.7, 8.9]\,,\quad \kappa_\lambda^{2\sigma} = [-8.2, 13.7]$

$p > 0.05 \quad \kappa_\lambda > -13.3, \quad \kappa_\lambda < 20$

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

$p > 0.05 \quad \kappa_\lambda > -14.3$

Talk by G. Degrassi at EPS

Combining H (total+diff), HH and EWPO

1704.01953

SM Effective Field Theory framework

Write down all the possible operators, let H→h+v, write lagrangian in mass eigenstates basis performing field redefinitions and couplings shifts, … [see HXSWG YR4; Falkowski '14]

SM tensor structures

"SM" tensor structures

4 New tensor structures

10 Independent couplings

8 Dependent couplings

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

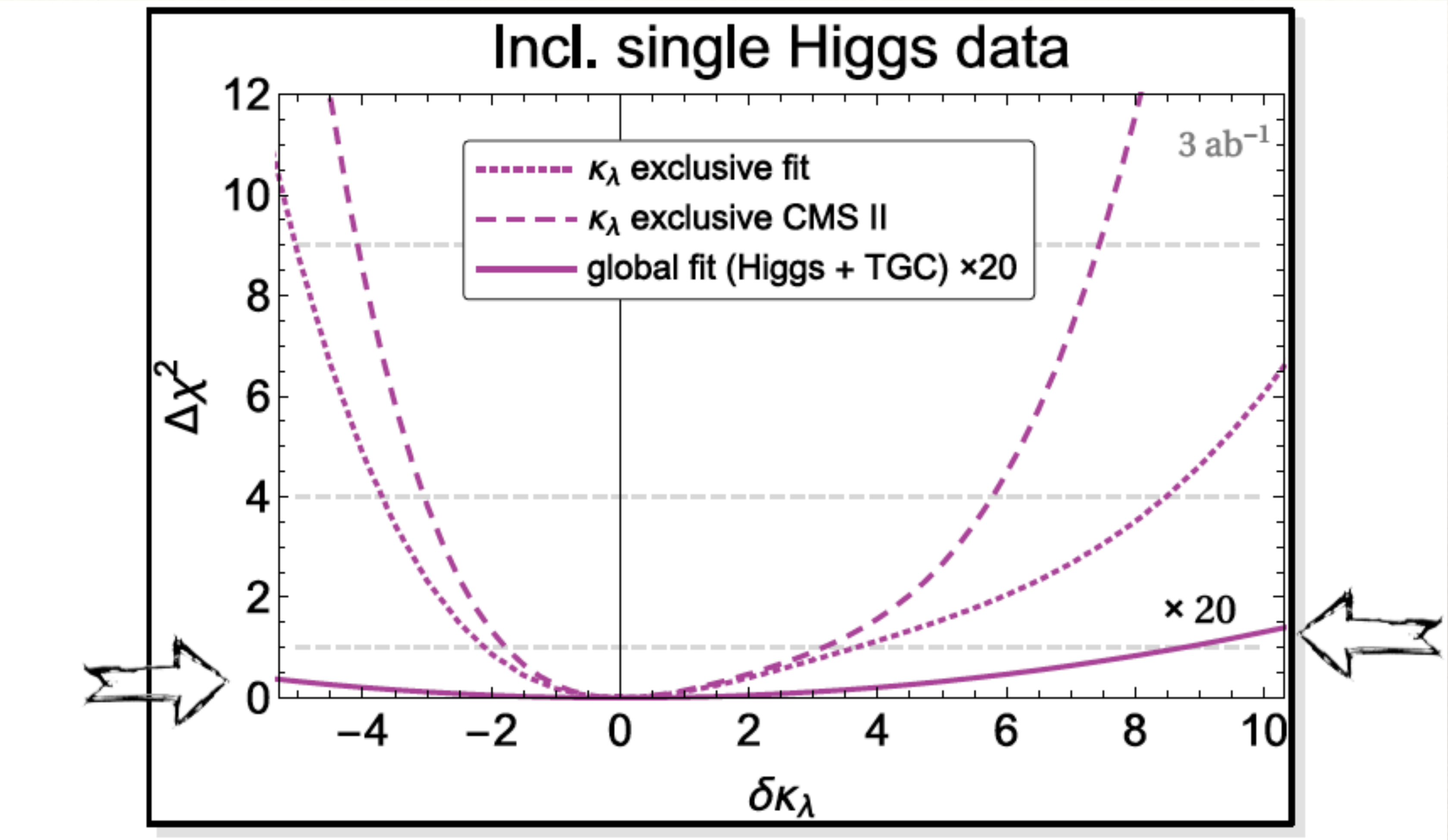
f=t,b,τ

Assuming for simplicity: only dim-6 operators, flavor universality, no CP-odd operators, no dipole operators and no Ψ⁴ operators involving light quarks

Talk by S. Di Vita in the kick-off WG2 meeting

Combining H (total+diff), HH and EWPO

1704.01953



One flat direction with inclusive observables.

Talk by S. Di Vita in the kick-off WG2 meeting

Combining H (total+diff), HH and EWPO

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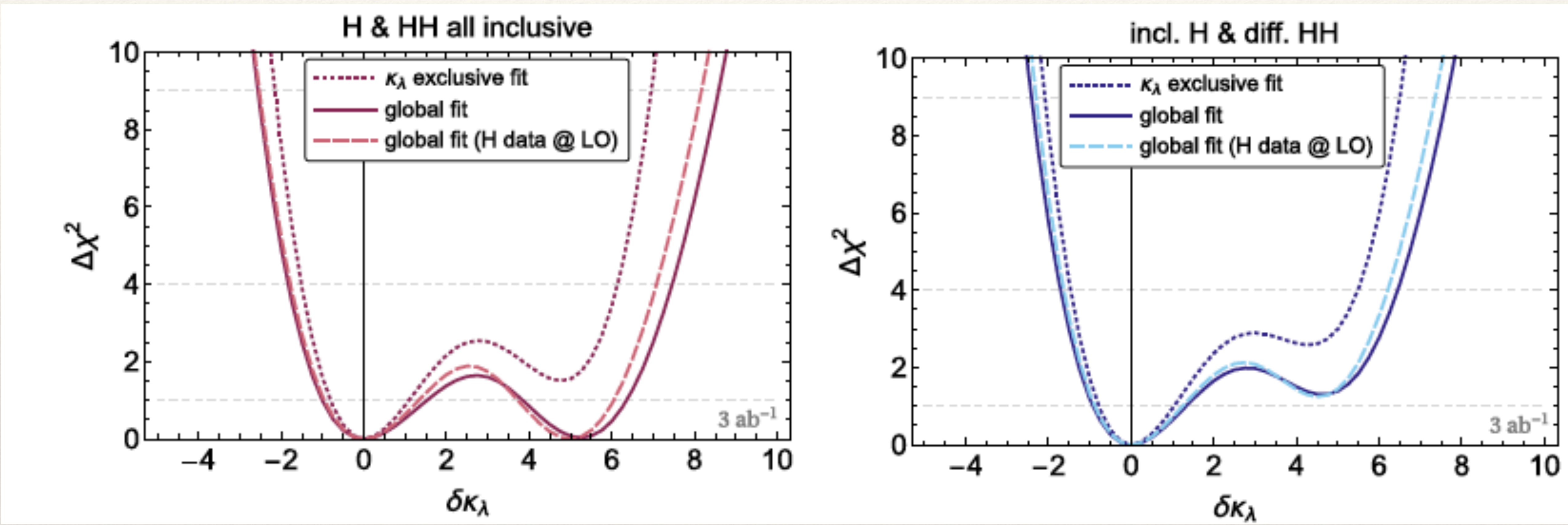

Double Higgs drives the bound on k_λ while, single-Higgs observables are essential to constrain the other coefficients deforming HH production.

Differential m(HH) removes the degeneracy with the second minimum

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Combining H (total+diff), HH and EWPO

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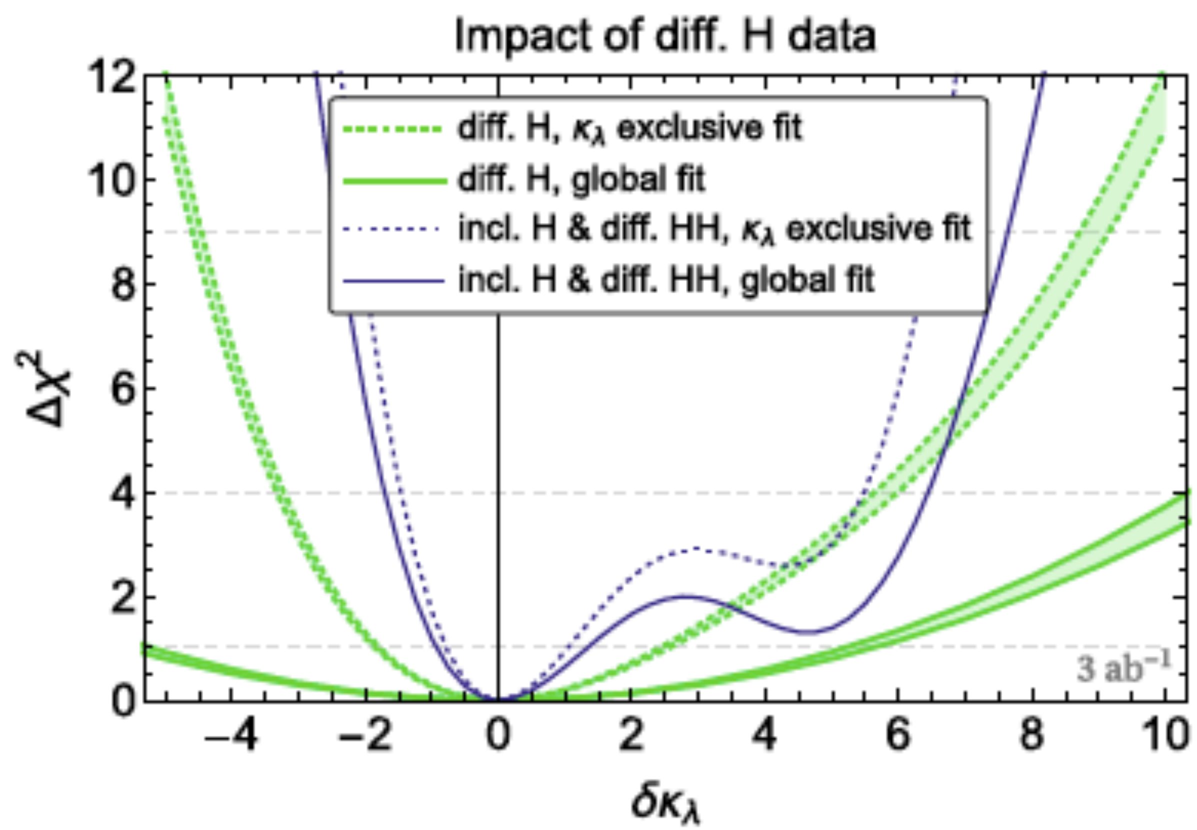

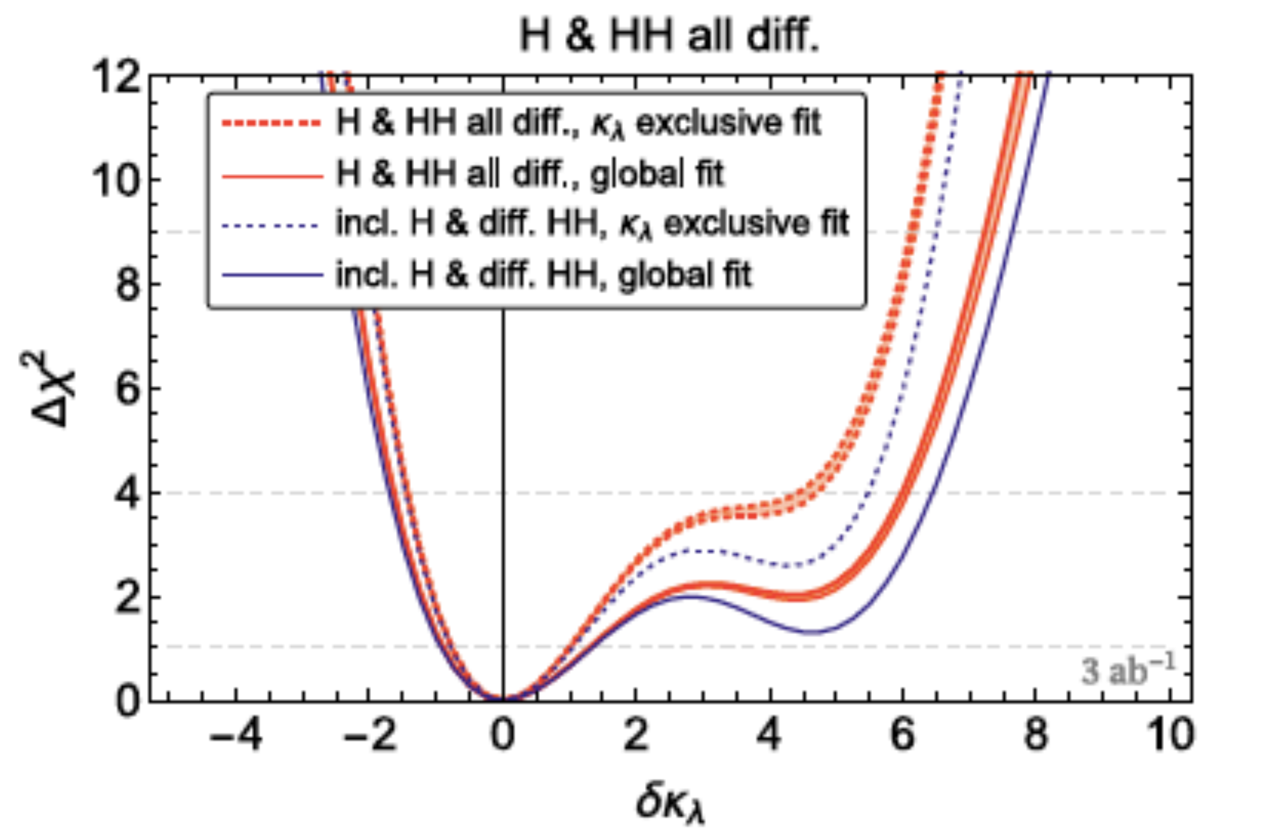

The inclusion of differential information in single-Higgs observables seems promising, but better experimental estimates are required

Combining differential information from single- and double-Higgs, the second minimum is futher lifted.

Talk by S. Di Vita in the kick-off WG2 meeting

Sentivity study: k_t, k_V,k_λ

1707.XXXXXX

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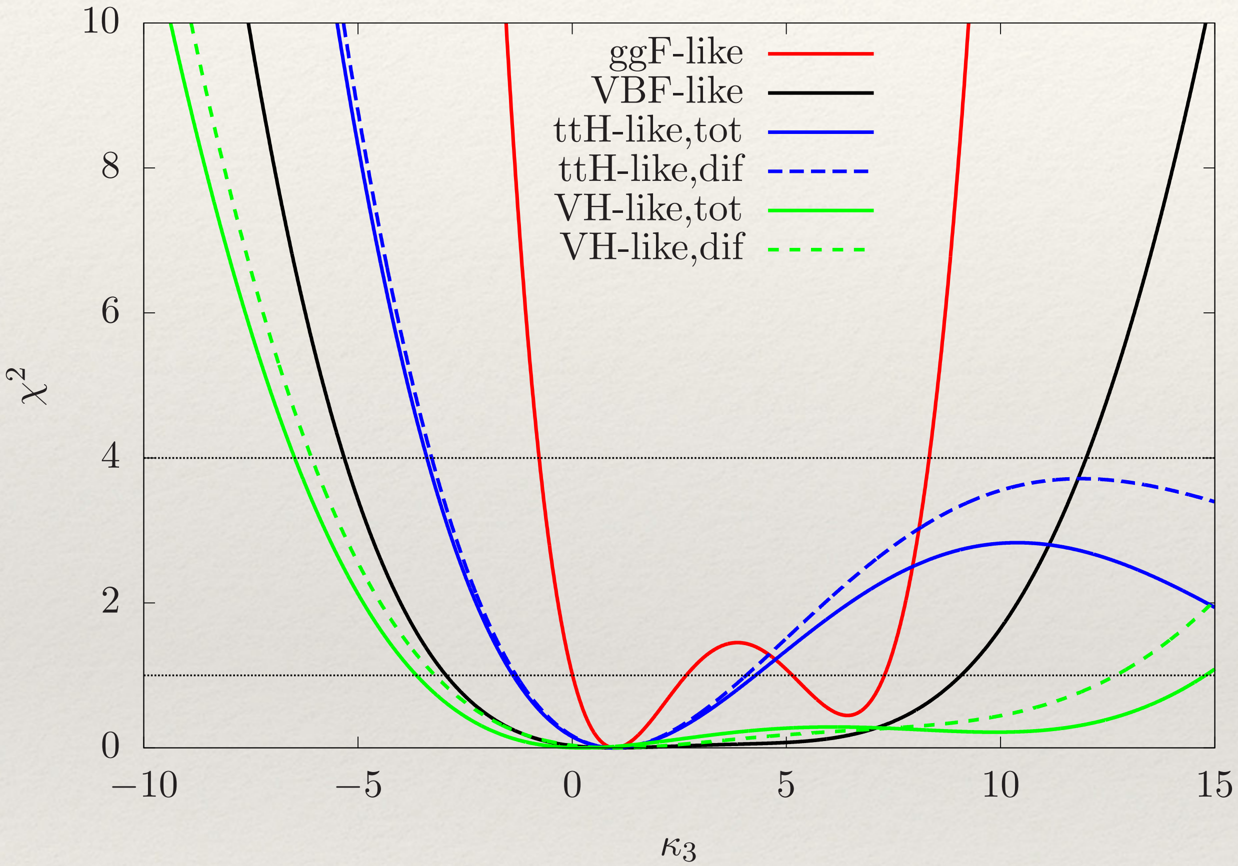

Sensitivity process-by-process to k_λ only

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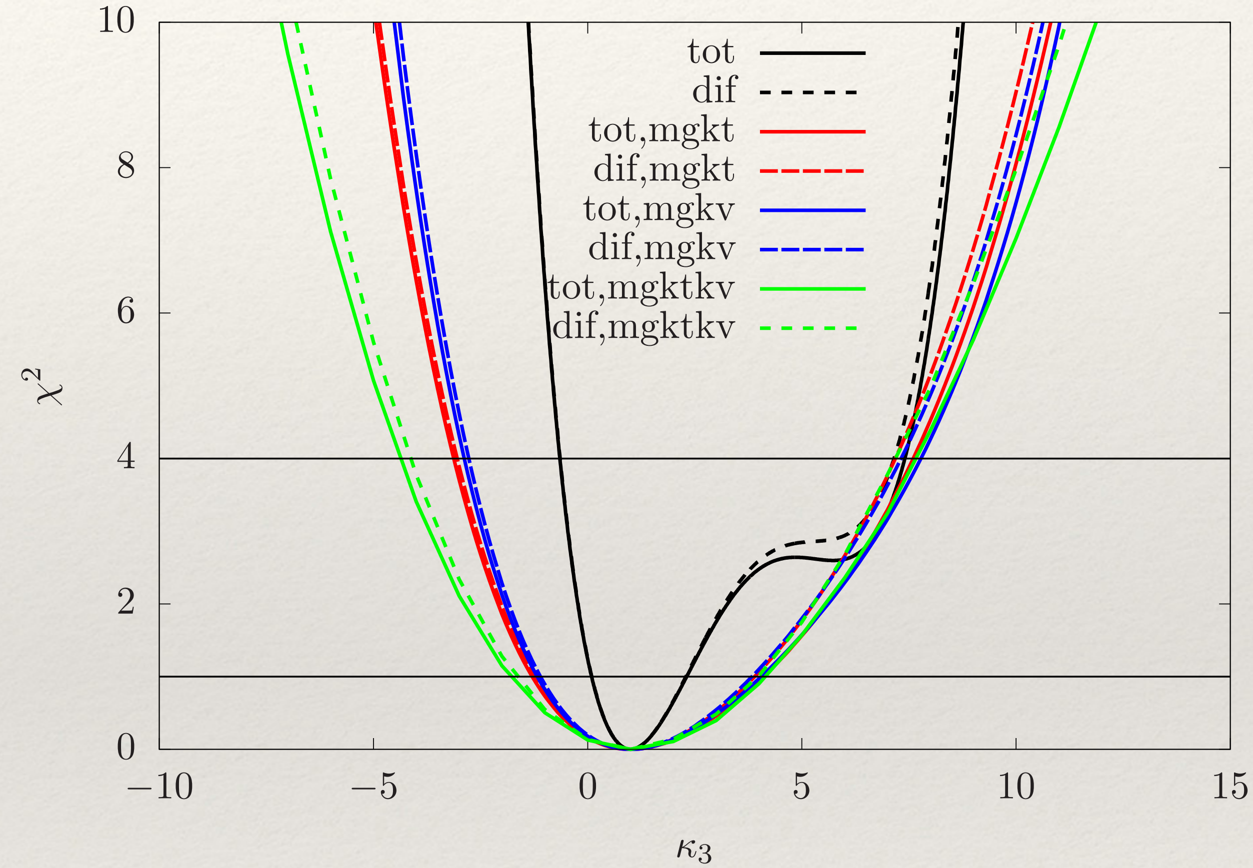

Black: Global on k_λ . Red: only, k_λ,k_t only. Blue: k_λ,k_V only. Green: all three.

Differential = 5 bins VH in pt(H) , 3 bins ttH in pt(H)

Summary and Outlook

- It is one year now that it has been proposed to use precision measurements in single Higgs at the LHC to gain complementary information on the trilinear self-coupling.
- Theory progress has been made on several fronts:
  - Understanding whether EFT vs anomalous coupling approaches differ (they don't for the calculations considered so far). More studies on going for other observables/computations.
  - Understanding the model dependence and how large $|\lambda_3|$ can be (with the other Higgs couplings staying close to SM values) in concrete models. Some of the results affect both direct and indirect interpretration of the measurements. More studies welcome and on going.
  - Covering all the set of single Higgs processes, improving the precision and identifying the most promising observables. MC codes for VBF, VH, ttH, tHj are now publicly available.
  - Studying the sensitivity of the global fits in the EFT and in simplified scenarios. Including also differential information and other measurements allows in principle to lift all degeneracies even in quite general cases. Justification of simplified scenarios?
- We are more then ready for experimental studies to kick-in and perform their sensitivity studies. Dedicated STXS at low $p_T(H)$? Top-down studies?