Probing the Higgs trilinear self-coupling via single Higgs production and precision physics

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Roma “La Sapienza”, May 8th 2017

Based on: P.P. Giardino, F. Maltoni, D. Pagani, G. D. JHEP 1612 (2016) 080
M. Fedele, P.P. Giardino, G.D JHEP 1704 (2017) 155

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Outline

- Status of the Higgs sector of the SM
- Getting information on the trilinear Higgs self-coupling looking at loop effects in:
  i) single Higgs production and decay processes
  ii) Precision Observables
- Perspective for the future
- Conclusions

Present view: the Standard Model

Strong, electromagnetic and weak interactions (not gravity) are described with very good accuracy by a remarkably simple renormalizable theory:

The Standard Model

$$\mathcal{L}_{SM} = \underbrace{-\frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu} + i\bar{\psi}\not{D}\psi}_{\text{gauge}} + \underbrace{(\lambda_{ij}\bar{\psi}_i\psi_j\phi + h.c)}_{\text{flavor}} + \underbrace{|D^\mu\phi|^2 - V(\phi)}_{\text{EWSB}} + \bar{N}_i M_{ij} N_j$$

ν -mass (Majorana)

Symmetry principle
Gauge + flavor symmetry

$SU(3)_c \times SU(2)_W \times U(1)_Y$
local symmetry

Needed to describe data

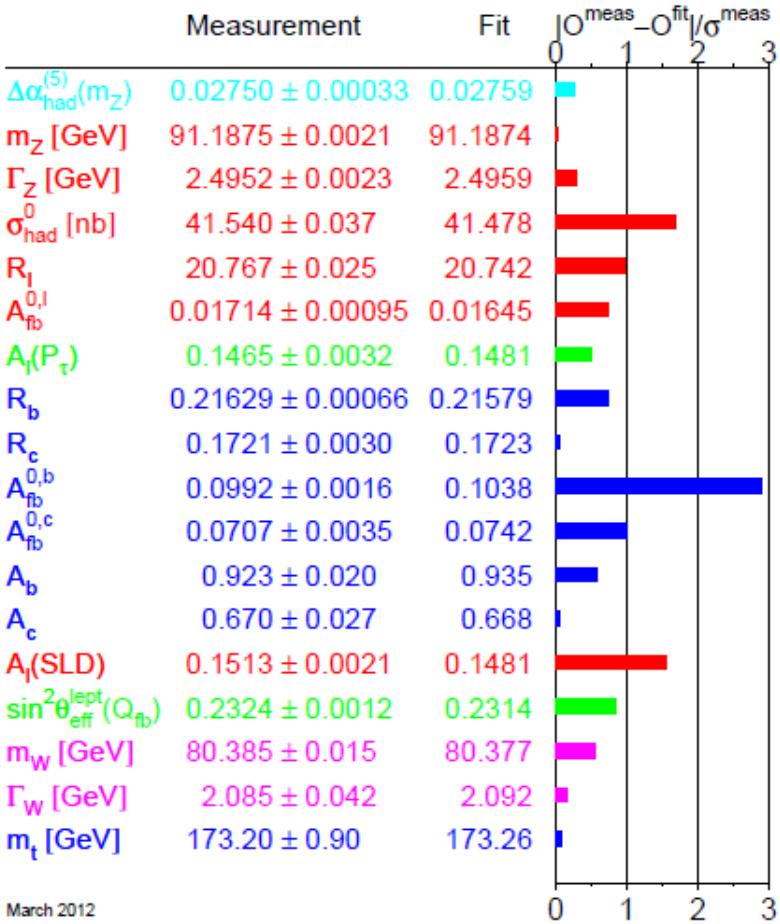
Renormalizable interactions
~~Principle~~ of minimality

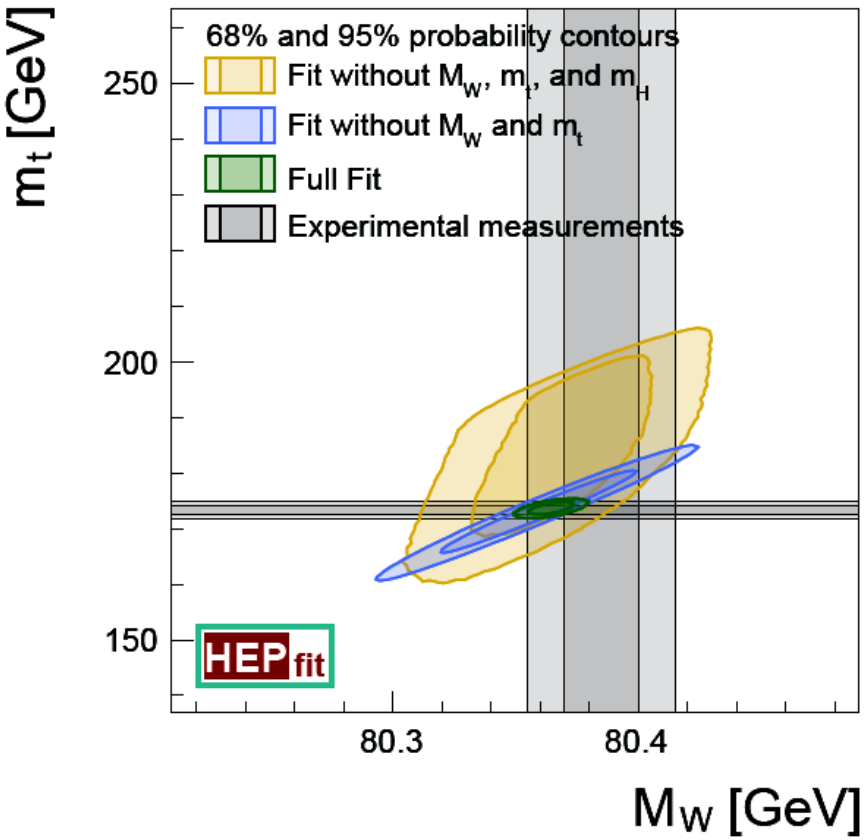
Gauge: Experimentally tested with high accuracy (room for NP?)

Flavor: exp. tested with accuracy (room for NP?)

EWSB: we just started (room for NP)

Gauge sector well tested (W and Z physics)





Precision ~ $5\text{-}1\cdot10^{-3}$

M_W = 80.385 ± 0.015 GeV (w.a.)

M_W = 80.370 ± 0.019 GeV (ATLAS, 16)

M_W = 80.357 ± 0.010 GeV (SM)

Higgs sector, what we know

EWSB is achieved in the SM via the Higgs mechanism realized in the most economical and simple way, i. e. with the introduction of a single elementary $SU(2)_L$ scalar doublet with a Φ^4 potential

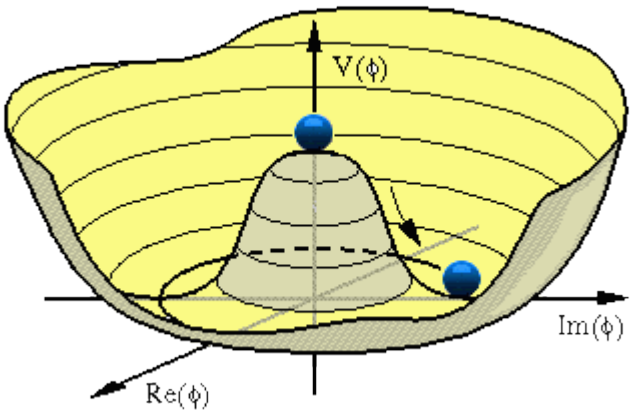
$$\mathcal{L}_{Higgs} = (\lambda_{ij}\bar{\psi}_i\psi_j\phi + h.c) + |D^\mu\phi|^2 - V(\phi)$$

EWSB: m_f, $h\bar{f}f$ $\quad$ $m_{w,z}$, HVV, HHVV $\quad$ m_H, HHH, HHHH,...

The ground state of the potential known since long time

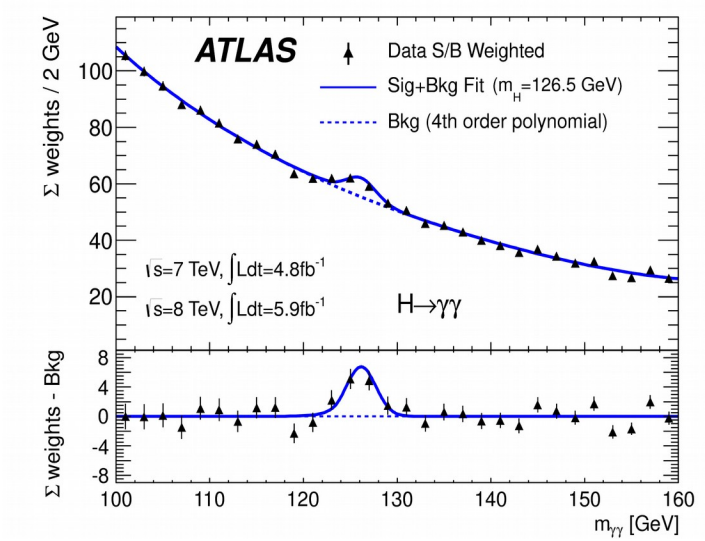
$$G_\mu = \frac{1}{2v^2} \qquad v = \langle\phi^\dagger\phi\rangle^{1/2} \sim 246\ \mathrm{GeV}$$

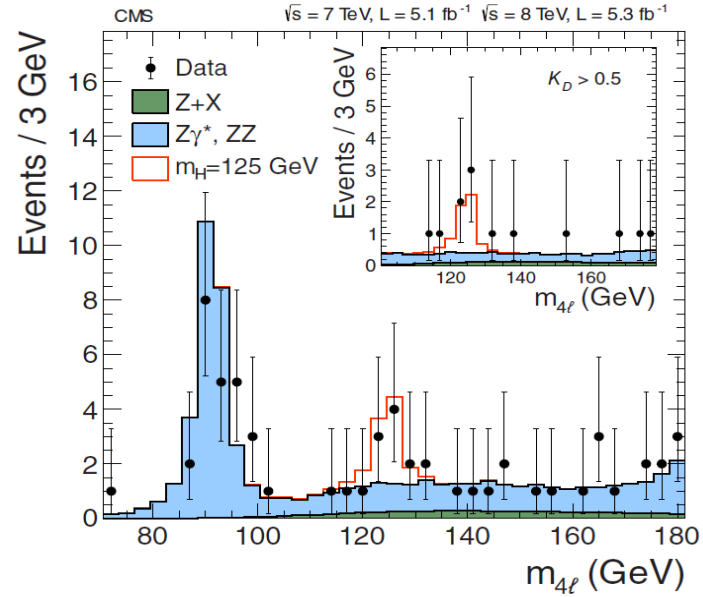
$$V^{SM}(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

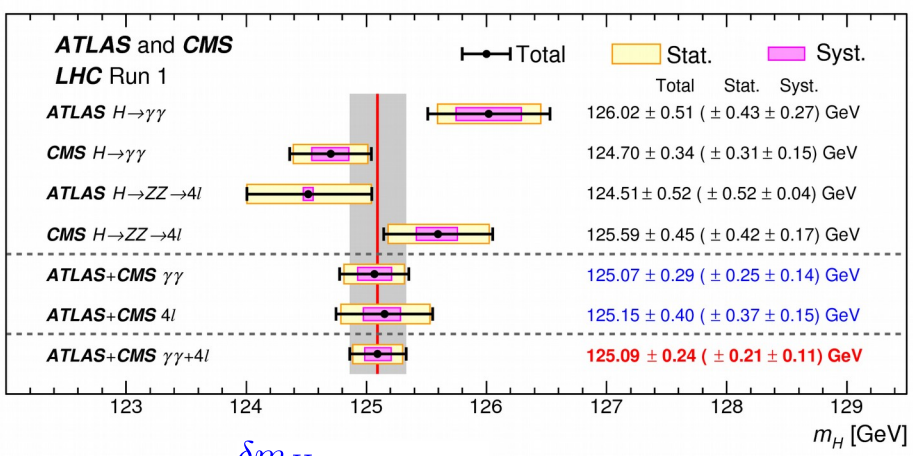


Testing $\mathcal{L}_{Higgs}$: m_H

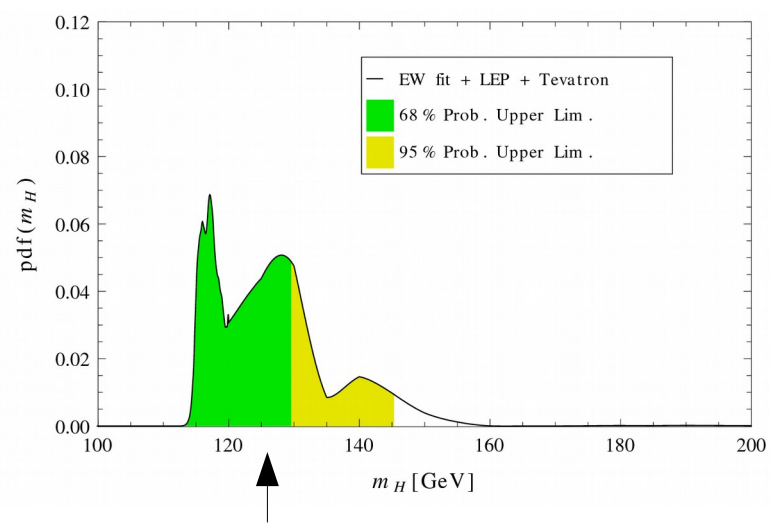
4th July 2012





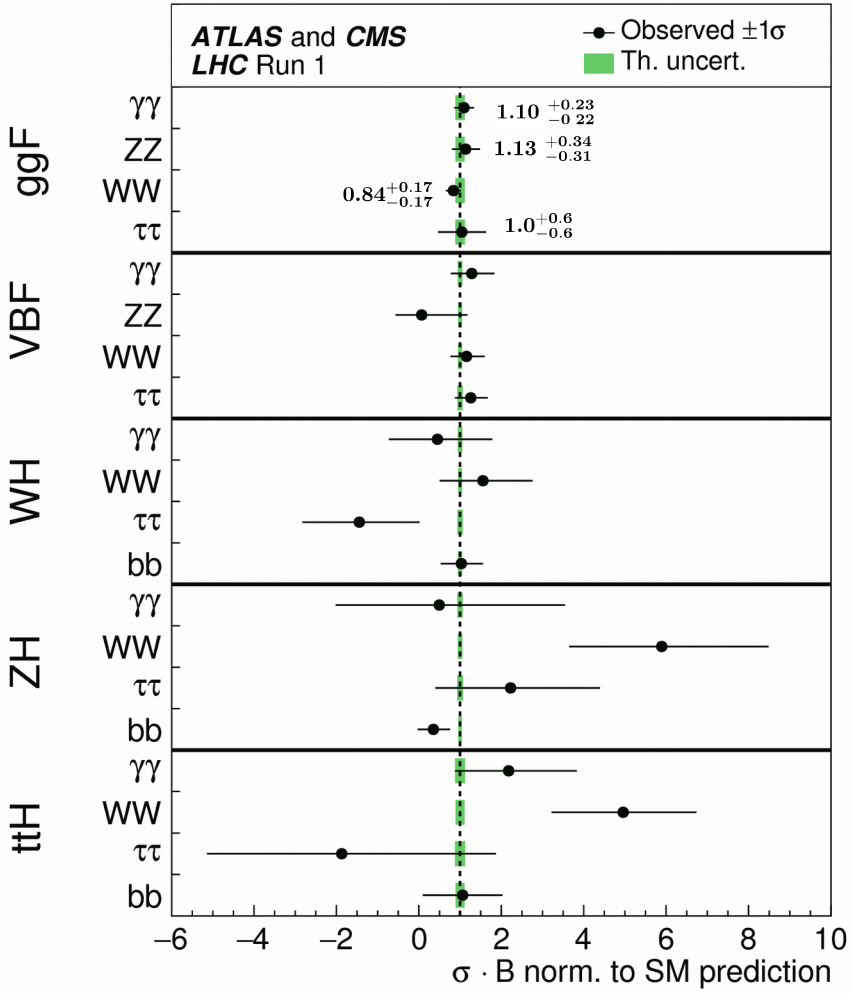


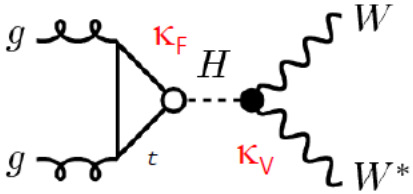
$$\frac{\delta m_H}{m_H} \sim 2 \cdot 10^{-3}$$

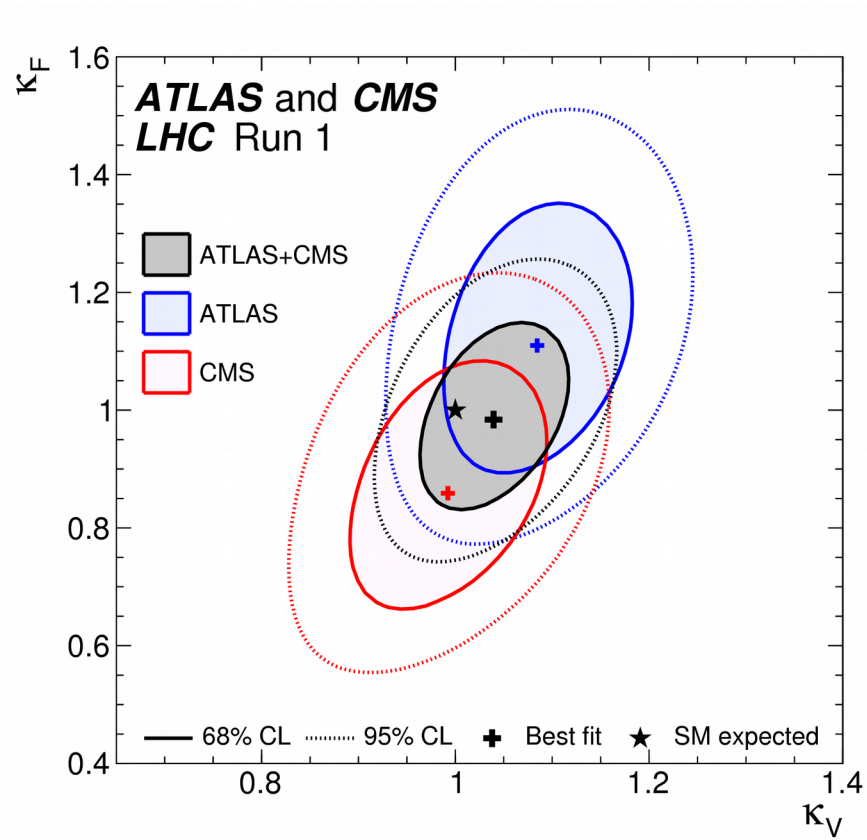


Testing $\mathcal{L}_{Higgs}$: $(\lambda_{ij}\bar{\psi}_i\psi_j\phi + h.c) + |D^\mu\phi|^2$

HVV ($H\bar{f}f$) couplings



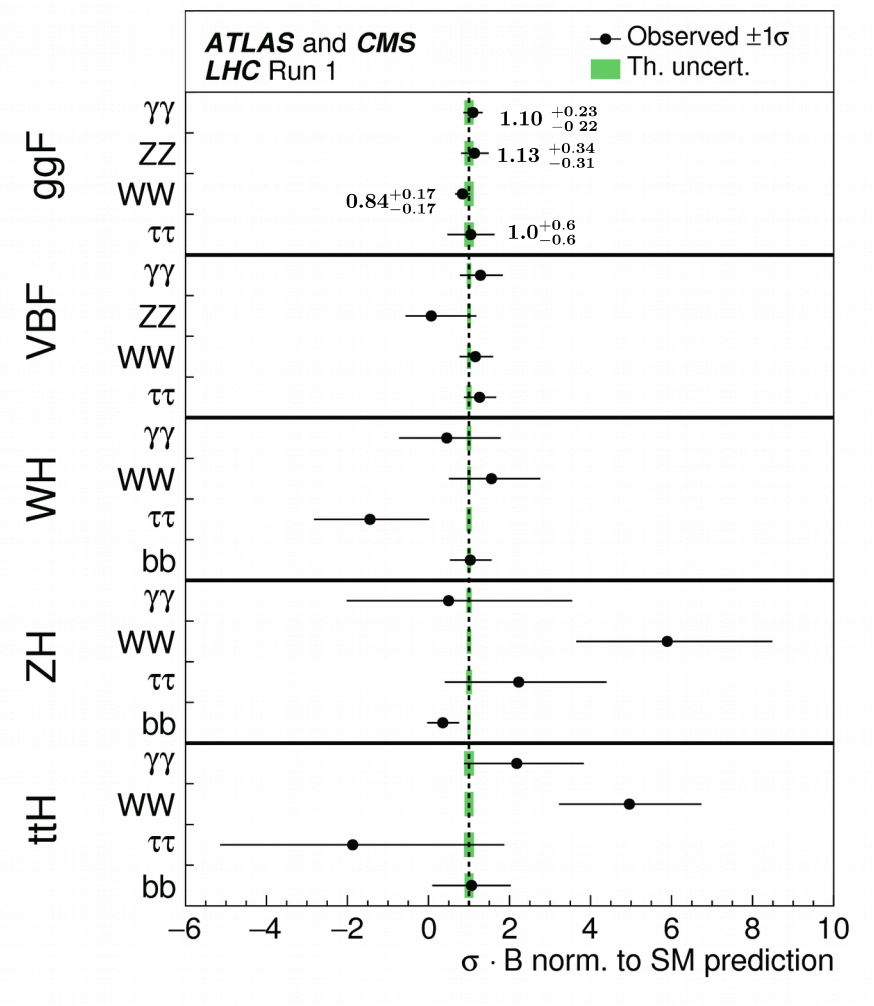




$$\mu_i \equiv \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \qquad \mu^f \equiv \frac{B^f}{(B^f)_{SM}} \qquad \mu_i^f = \mu_i \times \mu^f$$

HVV, $H\bar{f}f$ couplings perspectives

Run I



HL-LHC: 14 TeV 3/ab int. luminosity

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

Estimated relative uncertianties

Di Vita et al. (17) arXiv 1704.01953

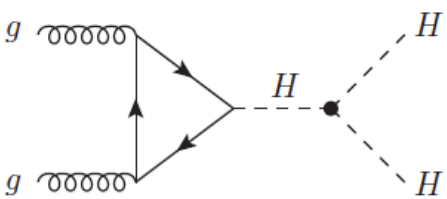
Testing $\mathcal{L}_{Higgs}$: $V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots$

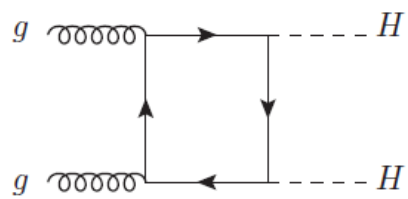
The shape of V(H): Higgs self couplings

n-Higgs production probes (n+1)-Higgs self-coupling

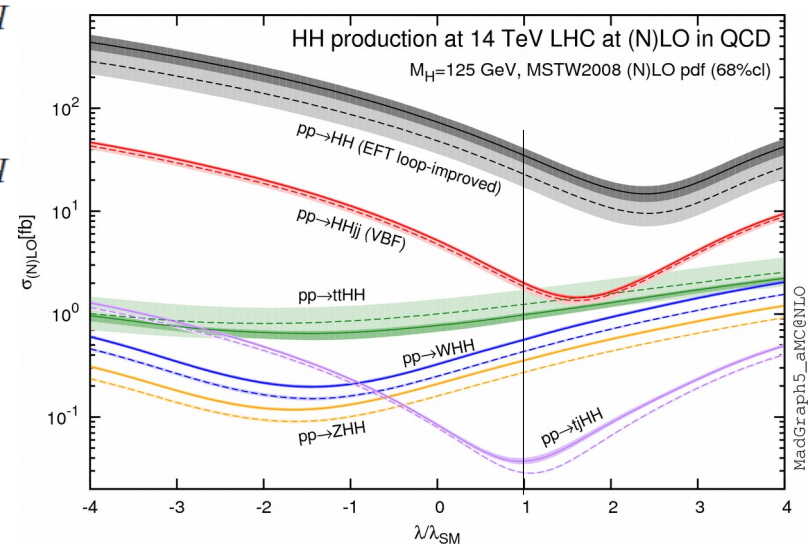
In the SM at tree-level only λ_3 and λ_4 fixed by: $\lambda_3 = \lambda_4 = \lambda = m_H^2/(2v^2) \quad v = \left(\sqrt{2}G_\mu\right)^{-1/2}$

λ_3: double Higgs production





Frederix et al. (14)



destructive interference, small cross section

$$\sigma(pp \to HH)_{SM} \sim 35\, fb$$

4 particles in the final state

$$\kappa_{gg} = 1, \; \kappa_t = 1$$

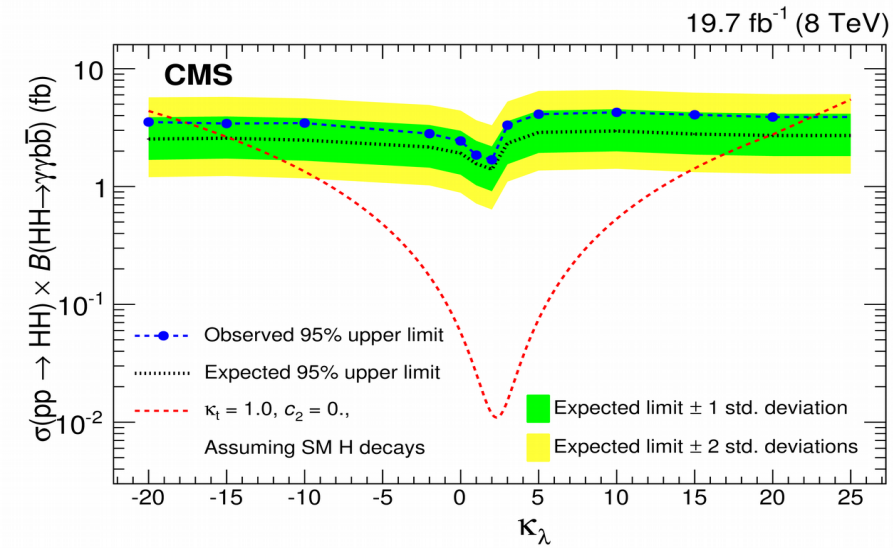
λ_4: triple Higgs production

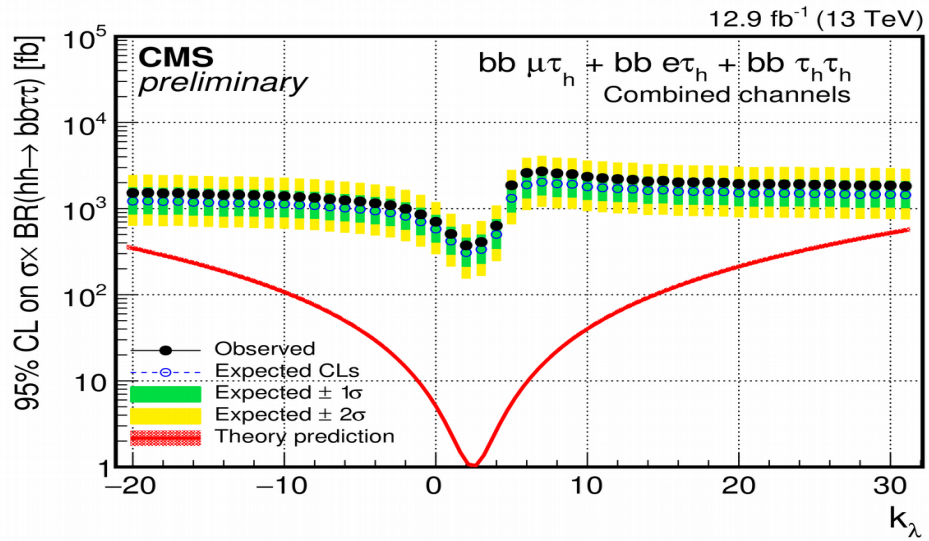
$$\cancel{\sigma(pp \to HHH)_{SM} \sim 0.1\, fb}$$

λ_3 status : "best" channels $gg \to HH \to bb\gamma\gamma,\ gg \to HH \to bb\tau\tau$

$$\lambda_3 = \kappa_\lambda \lambda_3^{SM} = \kappa_\lambda \frac{G_\mu}{\sqrt{2} m_H^2}$$

$\kappa_{gg} = 1,\ \kappa_t = 1$





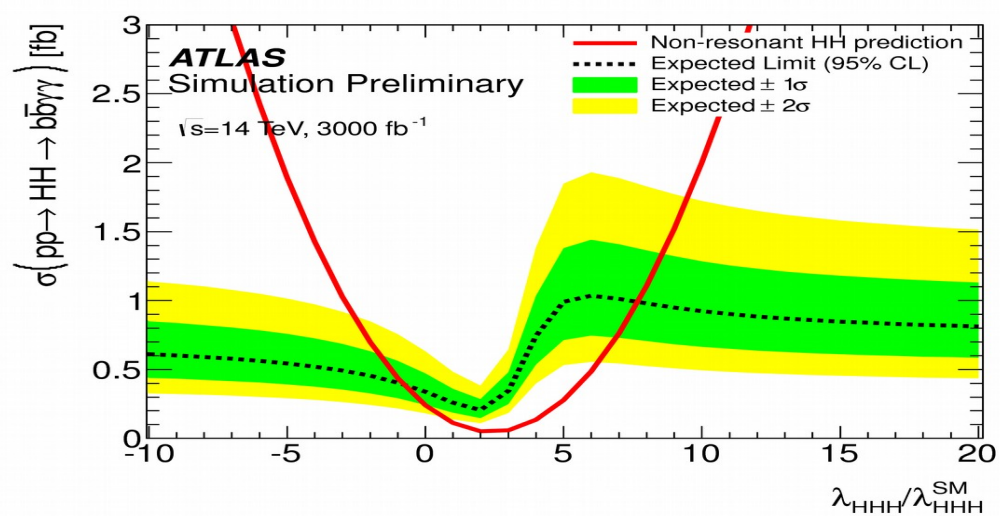
$\sigma(gg \to HH) \sim 70\, \sigma^{SM}(gg \to HH) \quad \kappa_\lambda = [-17.5,\ 22.5]$

λ_3 perspective :

HL-LHC, 3000 fb^{-1}, <μ>=200

No systematic

$$\kappa_\lambda = [-0.8,\ 7.7]$$



Present status:

- SM has been extremely successful in describing all low and high-energy results. The Higgs mass value prediction is the last success of an impressive series, M_W, m_t, m_H

- We know that physics beyond the SM must exist (neutrino masses, dark matter, barion asymmetry)

- We do not know at which energy scale New Physics should appear and LHC is pushing the scale higher up. Long standing theoretical argument (naturalness) are “suffering”.

- Models addressing the naturalness problems, like supersymmetry, makes predictions for the ~1 TeV scale, but can survive LHC because they are constructed to enforce the decoupling. “They cannot be ruled out, they can be only be abandoned”.

- Many New Physics models can be constructed and, a part theoretical argument, there is no way to prefer one with respect to another.

Outcome

Use a “model independent” approach to NP in which the SM is the starting point
“Standard Model Effective Field Theory Approach”
(SM EFT)

SM EFT Approach

Basic assumption: Sizable gap between the mass scale of NP (Λ) and the Energy scale (E) presently probed $\Lambda >> E$. Deviations from the SM results are expressed in powers of E/Λ.

Framework employed: Effective Field Theory in which the SM Lagrangian is augmented by higher dimensional operators, constructed used only SM fields, that respect the $SU(3)_C x SU(2)_L x U(1)_Y$ symmetry

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \cancel{\frac{1}{\Lambda^4}\mathcal{L}^{D=8}}$$

Lepton number or B-L violating
Very constrained

Starting point is generally OK, bur for V(H)

$$\mathcal{L}_{EFT} = \cdots - m^2 \left(\frac{H+v}{\sqrt{2}}\right)^2 + \lambda \left(\frac{H+v}{\sqrt{2}}\right)^4 + \frac{c_6}{\Lambda^2}\left(\frac{H+v}{\sqrt{2}}\right)^6 + \ldots$$

$$\kappa_\lambda = 1 + c_6 \frac{2\,v^2}{m_H^2}\frac{v^2}{\Lambda^2} \sim \mathcal{O}(\pm 5)$$

We are far from probing this case

Remark: we can envisage a scenario such that at the end of the HL-LHC program the couplings of the Higgs to gauge fields and fermions will be known O(≤ 10%) while λ_3 will be known O(1)

QUESTION

Can we use alternative information with respect to double Higgs production in order to constraint λ_3 <u>today?</u>

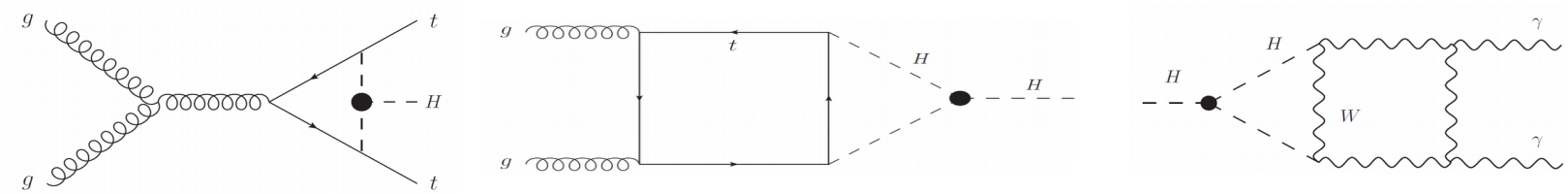
(Obviously some assumptions are needed)

Notice: $$\frac{\sigma(pp \to H)_{SM}}{\sigma(pp \to HH)_{SM}} = \frac{\sim 50\,pb}{\sim 35\,fb} \sim \frac{1}{1400} \sim \mathcal{O}\left(\frac{\alpha}{4\pi}\right)$$

Idea

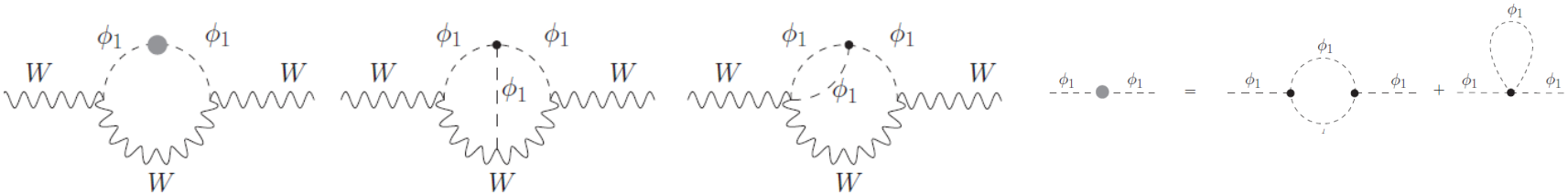
Constrain λ_3 via loop effects:

Exploit the dependence of single Higgs (total and differential) cross sections and decay rates upon the trilinear Higgs self coupling at NLO EW



See also: M. McCullough (13) $(e^+e^- \to ZH)$; M. Gorbahn, U. Haisch (16) $(gg \to H,\ H \to \gamma\gamma)$;
W. Bizon, M. Gorbahn, U. Haisch, G. Zanderighi (1610.05771), (WH, ZH, VBF)

Use the sensitivity of precision observables to λ_3 at NNLO EW



See also: Kribs et al. (1702.07678)

Working assumption: only the Higgs self-couplings are modified or, equivalently, any modification of the Higgs coupling to fermion and bosons is much smaller.

Not the most general assumption, but can be relaxed in the future when information on the other Higgs couplings will become more accurate.

It is the best we can do today.

Related problems:

- How I identify the contribution proportional to λ_3 ?
  What about λ_4, λ_5 etc.?

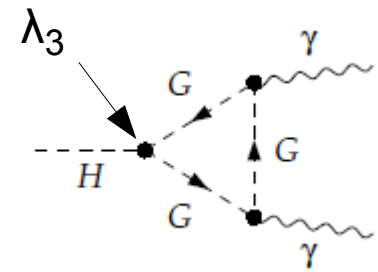
- If I "deform" $\lambda_3^{SM} \to \lambda_3 = \kappa_\lambda \lambda_3^{SM}$ the theory become not renormalizable.
  I expect a dependence on Λ, the scale of NP .

- I expect to be able to probe large values of κ_λ . My scenario is not a standard EFT. Does it have a limit to an EFT?

Identifying λ_3 contributions

In the SM in an R_ξ gauge not only the *HHH* vertex is proportional to λ_3 but also the vertices with unphysical scalars $H\,\phi^+\phi^-,\ H\,\phi_2\phi_2$
Identification of the λ_3 is not straightforward.

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{v+H+i\phi_2}{\sqrt{2}} \end{pmatrix}$$



Solution: Go to the Unitary gauge
Gauge-dependent result? See later

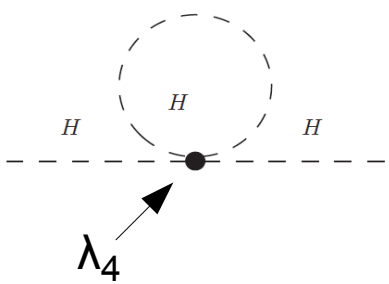
λ_4, λ_5 .....

At the level of (N)NLO EW corrections, i.e.:

1-loop corrections for $\sigma_{VBF},\ \sigma_{VH},\ \sigma_{t\bar{t}H}, \Gamma_{VV},\ \Gamma_{f\bar{f}}$

2-loop corrections for: $\sigma_{gg},\ \Gamma_{gg},\ \Gamma_{\gamma\gamma},\ M_W, \sin^2\theta_{\rm eff}^{\rm lep}$

the Higgs quartic self interaction enters only through the Higgs mass correction diagram



Canceled by the Higgs mass counterterm
No dependence on λ_4

At the (N)NLO level λ_5, λ_6 .... interactions do not contribute

Technical remark:

The unitary gauge is a tricky gauge: one is interchanging

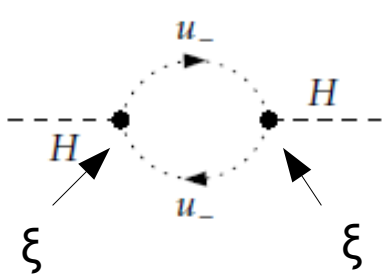
$$\lim_{\xi\to\infty}\int d^n k \longrightarrow \int d^n k \lim_{\xi\to\infty}$$

Vector boson propagator: $\dfrac{-i}{k^2 - M_V^2 + i\epsilon}\left[g^{\mu\nu} + (\xi - 1)\dfrac{k^\mu k^\nu}{k^2 - \xi M_V^2}\right] \longrightarrow -i\dfrac{g^{\mu\nu} - k^\mu k^\nu / M_V^2}{k^2 - M_V^2 + i\epsilon}$

Ghost, unphysical scalar propagator $\dfrac{-i}{k^2 - \xi M_V^2 + i\epsilon} \longrightarrow 0$

No ghosts, no unphysical in an UG calculation

However, in R_ξ , in principle, there can be residues from the ξ in the denominators from the propagators and the one in the numerators from vertices of higgses with ghosts



$$\lim_{\xi\to\infty}\int d^n k \frac{\xi^2}{(k^2 - \xi\, m_W^2)^2} = \int d^n k \frac{1}{m_W^4} = 0$$

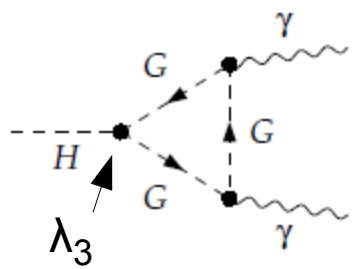
DR

Finiteness of κ_λ

Although our theory is not renormalizable the result for κ_λ at the level of (N)NLO EW corrections is finite, i.e. it does not depend on Λ

Reason: the "Born" results do not depend upon λ_3. Renormalization of λ_3 is not needed

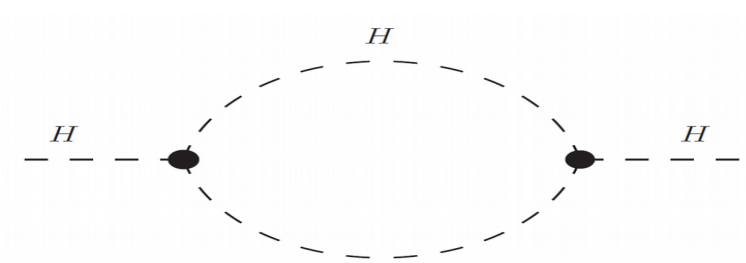
What about



?

In UG is not there; you are trading a coupling for a kinematical mass

NLO λ_3-dependent diagram:



Finite after Higgs mass renormalization

What is my scenario?

My scenario is described by the SM Lagrangian with a modified scalar potential:

$$V^{NP} = \sum_{n=1}^{N} c_{2n} (\Phi^\dagger \Phi)^n \qquad \Phi = \begin{pmatrix} \phi^+ \\ \frac{v+H+i\phi_2}{\sqrt{2}} \end{pmatrix}$$

N unspecified. C_{2n} arbitrary

Limit to EFT:

N=3,4.. $c_{2n+2} \sim c_{2n}/\Lambda^2$

$$m_H^2 = v^2 \sum_{n=1}^{N} c_{2n}\, n(n-1) \left(\frac{v^2}{2}\right)^{n-2}$$

$$\begin{aligned} V_{4\phi}^{NP} &= \frac{m_H^2}{2v^2}\left[\phi^+\phi^-(\phi^+\phi^- + \phi_2^2) + \frac{1}{4}\phi_2^4\right] + \left(\frac{m_H^2}{2v^2} + d\lambda_4\right)\frac{1}{4}H^4 \\ &+ \left(\frac{m_H^2}{2v^2} + 3\,d\lambda_3\right) H^2 \left[\phi^+\phi^- + \frac{1}{2}\phi_2^2\right] + \left(\frac{m_H^2}{2v} + v\,d\lambda_3\right) H^3 \\ &+ \frac{m_H^2}{2v} H\left(\phi_2^2 + 2\phi^+\phi^-\right) + \frac{1}{2} m_H^2 H^2 \end{aligned}$$

$$\kappa_\lambda = 1 + 2v^2/m_H^2\, d\lambda_3$$

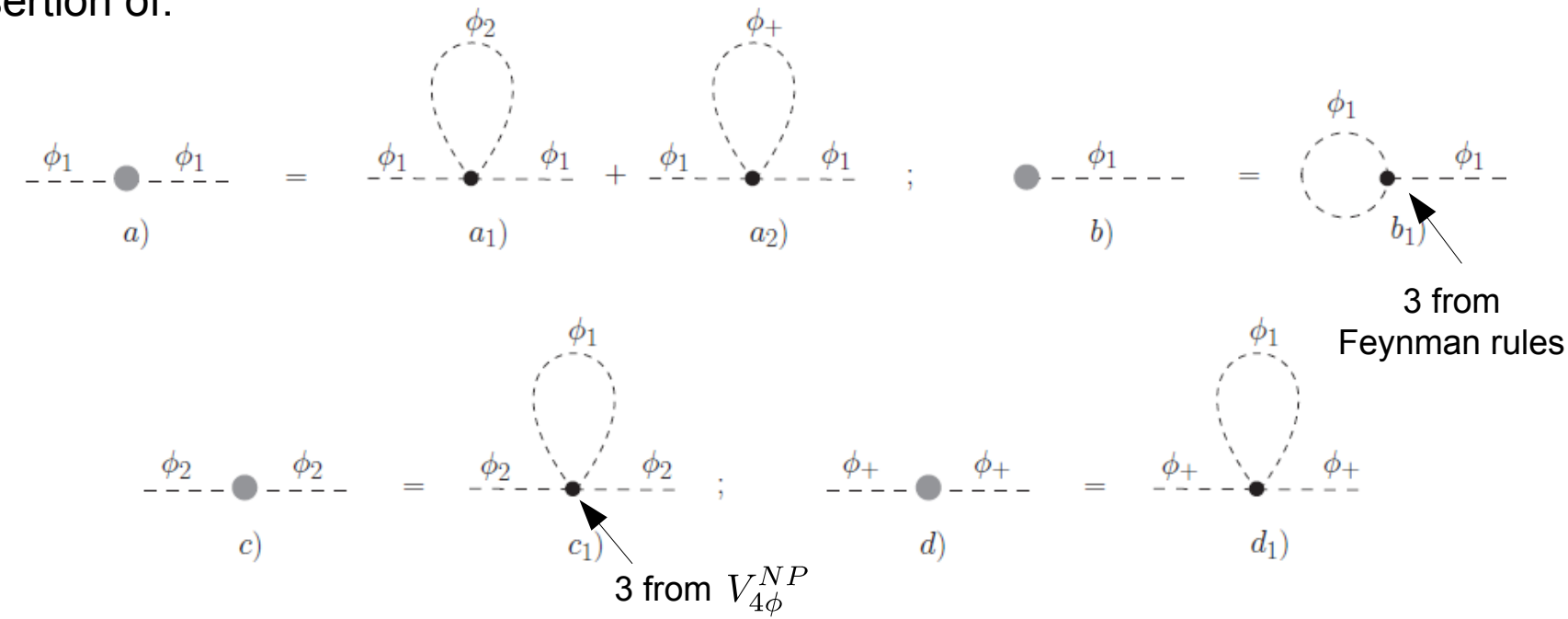
Few couplings modified with respect to the SM and there are correlations

$$d\lambda_3 = \frac{1}{3}\sum_{n=3}^{N} c_{2n}\, n(n-1)(n-2)\left(\frac{v^2}{2}\right)^{n-2},$$

$$d\lambda_4 = \frac{2}{3}\sum_{n=3}^{N} c_{2n}\, n^2(n-1)(n-2)\left(\frac{v^2}{2}\right)^{n-2}$$

Diagrams that in R_ξ can give additional contributions with respect to the UG result

Insertion of:



All these contributions are canceled by the mass renormalization counterterms

$$\delta m_\phi^2 = \delta m_V^2 + \delta T$$

Tadpole contribution

What is my scenario?

- I am dealing with “large” couplings, but they cannot be too large otherwise I have problem with perturbativity.

- Although I find a finite result at the (N)NLO level my theory is not renormalizable. Λ-dependent contributions will appear in higher order of perturbation theory.

- To estimate the cutoff scale of this scenario one can look at

$$V_L\, V_L \longrightarrow V_L\, V_L\, H^n$$

$$\Lambda \lesssim \frac{4\pi v}{\sqrt{|\kappa_\lambda - 1}}\sqrt{\frac{32\pi}{15}}\frac{v}{m_H} \rightarrow \Lambda \lesssim 3\ \mathrm{TeV},\ |\kappa_\lambda| \lesssim 20$$

A. Falkowski, R. Rattazzi in preparation

Single Higgs processes

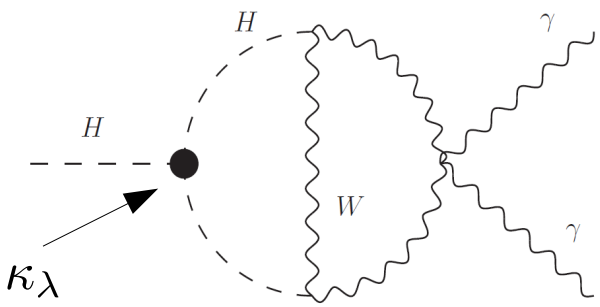
Master Formula

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

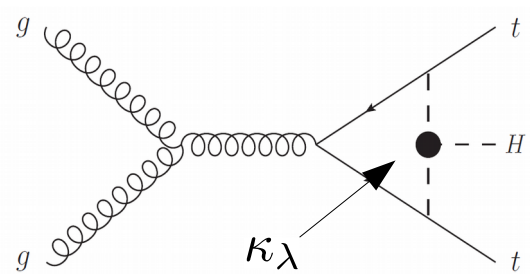
dressed with QCD

process dependent

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



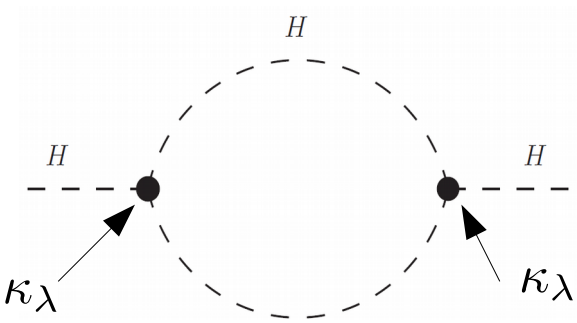
$$C_1^\sigma = \frac{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, 2\Re\left(\mathcal{M}^{0*}_{ij}\mathcal{M}^1_{,ij}\right) d\Phi}{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, |\mathcal{M}^0_{ij}|^2 d\Phi}$$



Master Formula

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

universal



$$= \kappa_\lambda^2 \delta Z_H\,, \qquad \delta Z_H = -\frac{9}{16}\,\frac{G_\mu\, m_H^2}{\sqrt{2}\,\pi^2}\left(\frac{2\pi}{3\sqrt{3}}-1\right)$$

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

Resummation requires $|\kappa_\lambda| \lesssim 25$

$$\delta\Sigma \equiv \frac{\Sigma_{\rm NLO}-\Sigma_{\rm NLO}^{\rm SM}}{\Sigma_{\rm LO}} = (\kappa_\lambda^2-1)\boxed{C_2} + (\kappa_\lambda-1)\boxed{C_1}$$

overall and universal

process dependent

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

Results: total cross sections

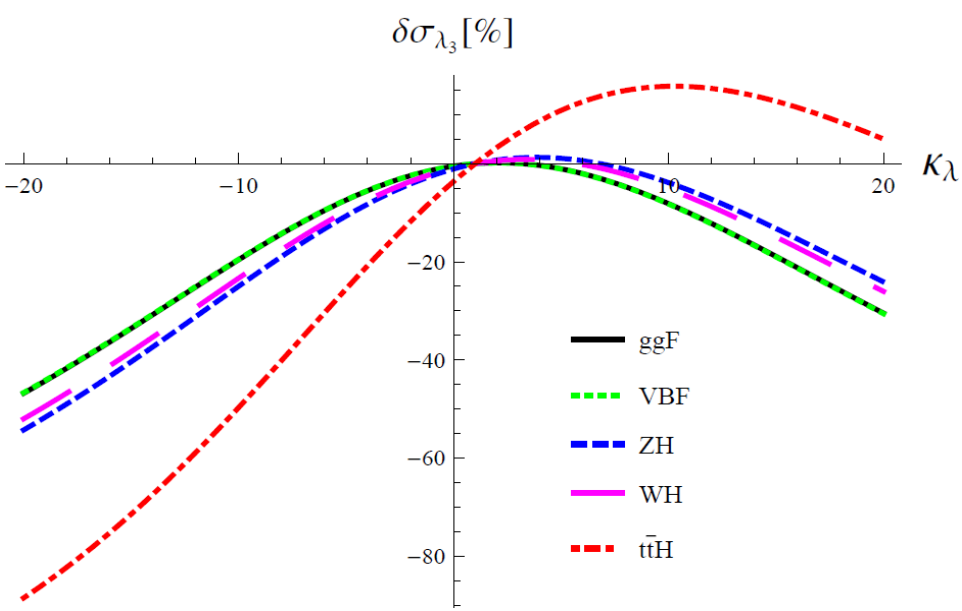
$$\delta\sigma = (\kappa_\lambda^2 - 1)C_2 + (\kappa_\lambda - 1)C_1$$

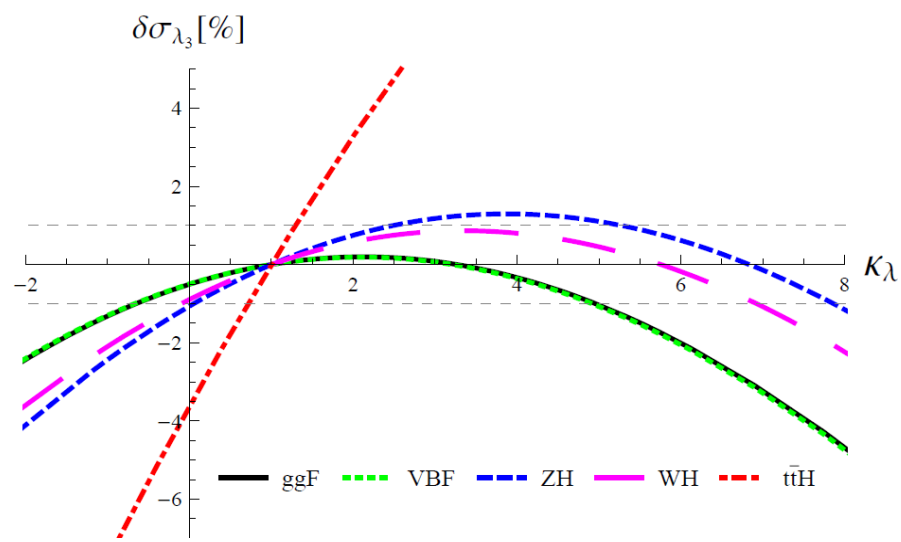
$$C_2 = -9.14 \cdot 10^{-4}, \quad \kappa_\lambda = \pm 20$$

$$C_2 = -1.53 \cdot 10^{-3}, \quad \kappa_\lambda = \pm 1$$

C_1^σ [%]	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

Largest effects in $t\bar{t}H$ and VH





Only $t\bar{t}H$ receive sizable positive corrections

Results: differential cross sections

Kinematical dependence of the C_1 coefficient.

C_1^σ [%]	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)

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

Table 1: C_1^σ at 13 TeV obtained by imposing the cut $p_T(H) < p_{T,\ \mathrm{cut}}$, for several values of $p_{T,\mathrm{cut}}$. In parentheses the fraction of events left after the quoted cut is applied.

C_1^σ [%]	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)

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

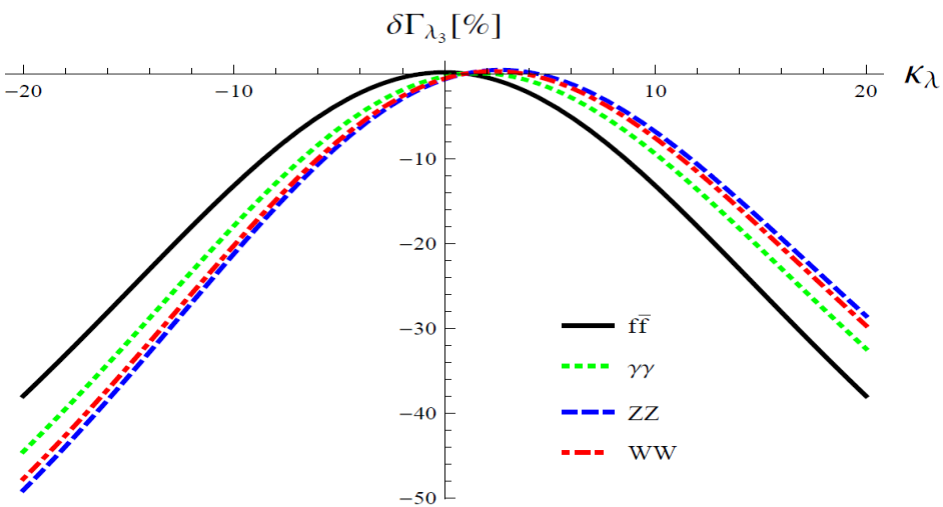
Table 1: C_1^σ at 13 TeV obtained by imposing the cut $m_{\mathrm{tot}} < K\ tm_{\mathrm{thr}}$, for several values of K. In parentheses the fraction of even ts left after the quoted cut is applied.

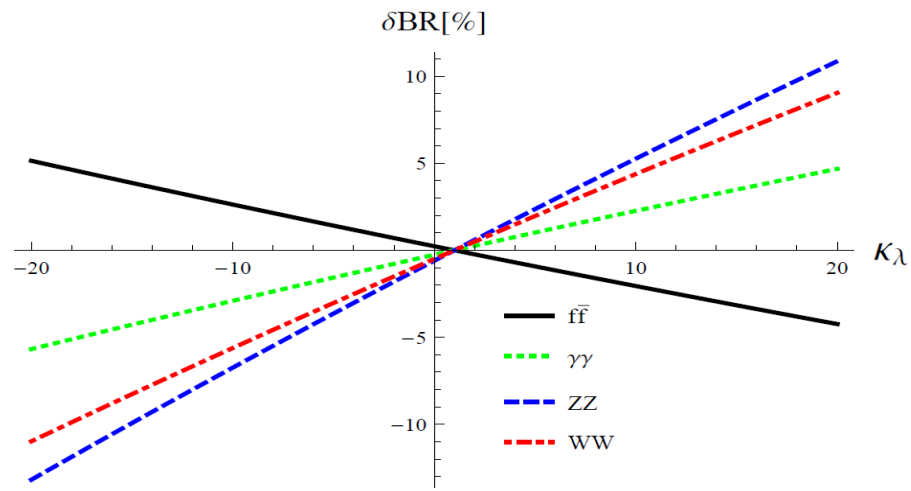
Results: decay rates

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

$$C_1^{\Gamma_{\rm tot}} \equiv \sum_j \mathrm{BR}^{\rm SM}(\ j) C_1^\Gamma(j) = 2.3 \cdot 10^{-3}$$

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





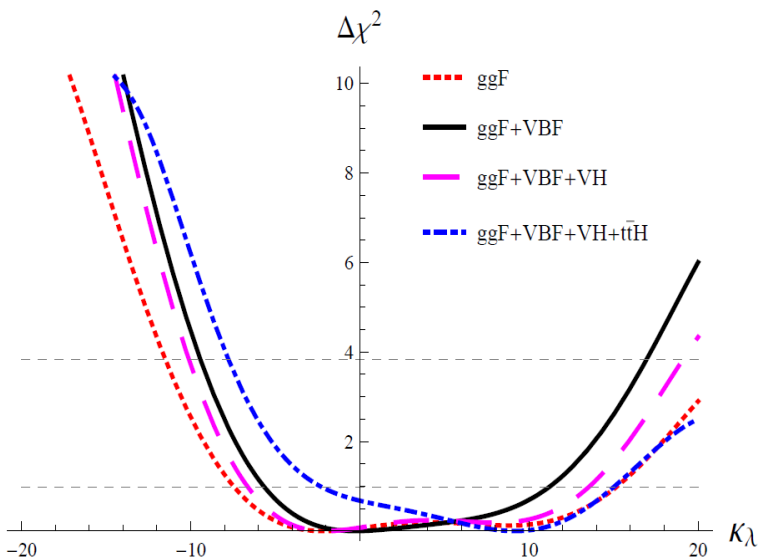
Much milder dependence on κ_λ in the BR because no C_2 contribution

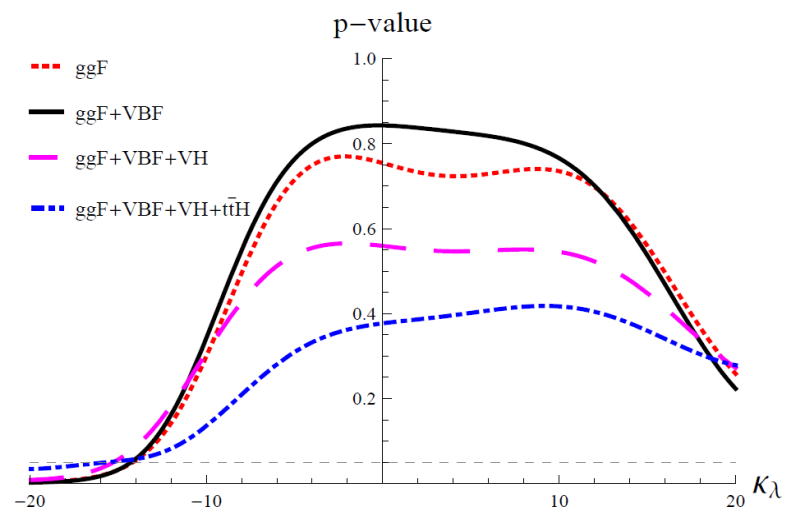
Constraints on λ_3 from 8 TeV data

Using signal strength results from the combination of ATLAS and CMS we can make a one-parameter fit to estimate the limit that can be set on κ_λ

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

$$\begin{aligned} \mu_i^f(\kappa_\lambda) &= \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda) \\ \mu_i(\kappa_\lambda) &= 1 + \delta\sigma_{\lambda_3}(i) \\ \mu^f(\kappa_\lambda) &= 1 + \delta\mathrm{BR}_{\lambda_3}(f) \end{aligned}$$





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

$$p\text{-value}(\kappa_\lambda) = 1 - F_{\chi^2_{(n)}}(\chi^2(\kappa_\lambda))\,, \qquad p > 0.05 \qquad \kappa_\lambda > -14.3$$

Precision Observables

λ_3-dependent contributions in m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$

m_W and the effective sine are obtained from α, G_μ and m_Z via

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

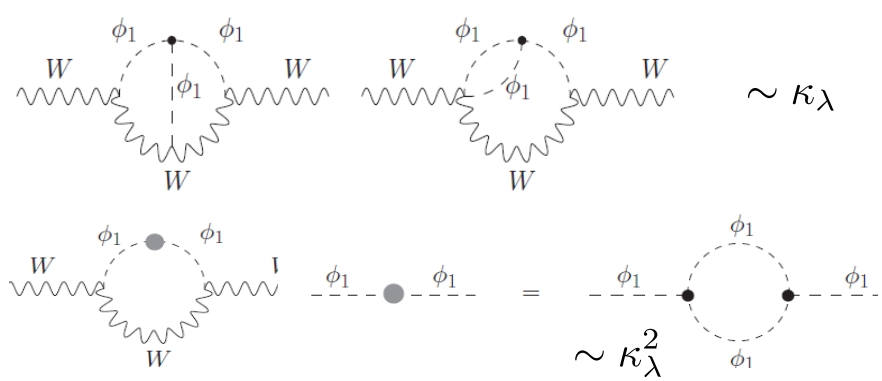
$$\sin^2\theta_{\rm eff}^{\rm lep} \sim \frac{1}{2}\left\{1-\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

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

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

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

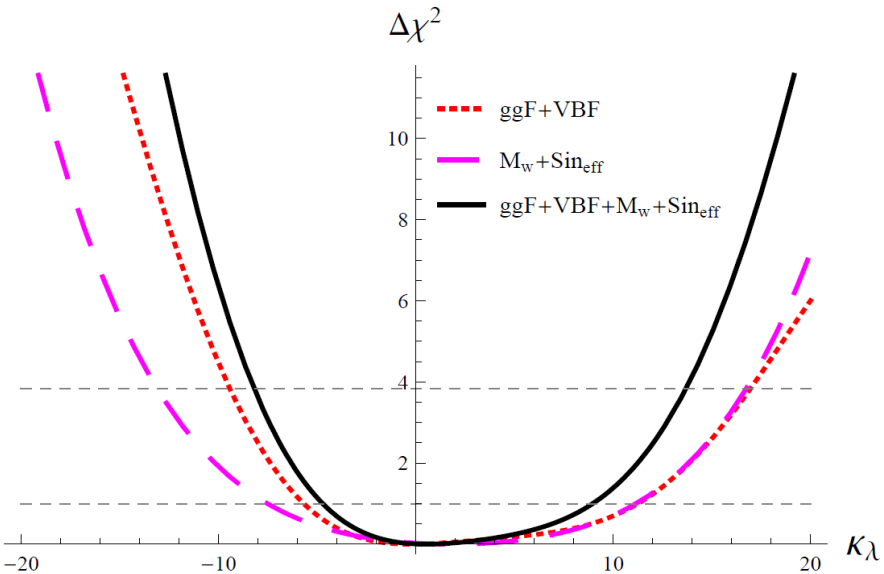
$$Y_{\overline{MS}}^{(2)} = {\rm Re}\left[\frac{A_{WW}^{(2)}(m_W^2)}{m_W^2} - \frac{A_{ZZ}^{(2)}(m_Z^2)}{m_Z^2}\right] + \ldots$$

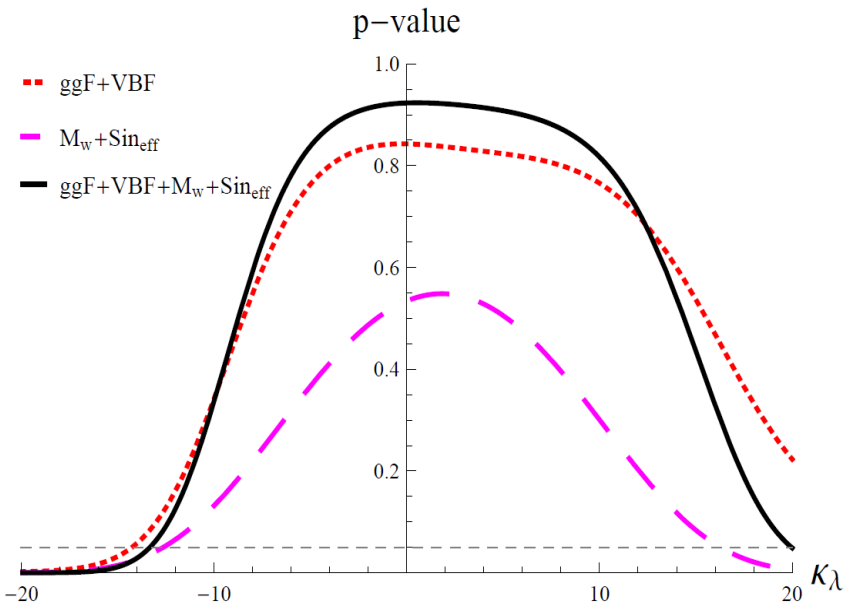


Constraints on λ_3 from P.O. and 8 TeV data

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

	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}





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

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

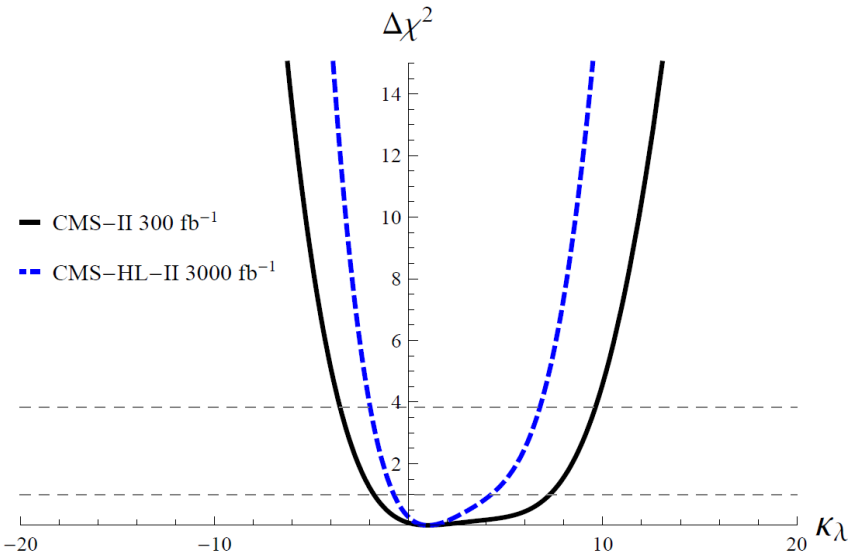
ggF + VBF $\quad \kappa_\lambda^{\rm best} = -0.24\,, \quad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \quad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

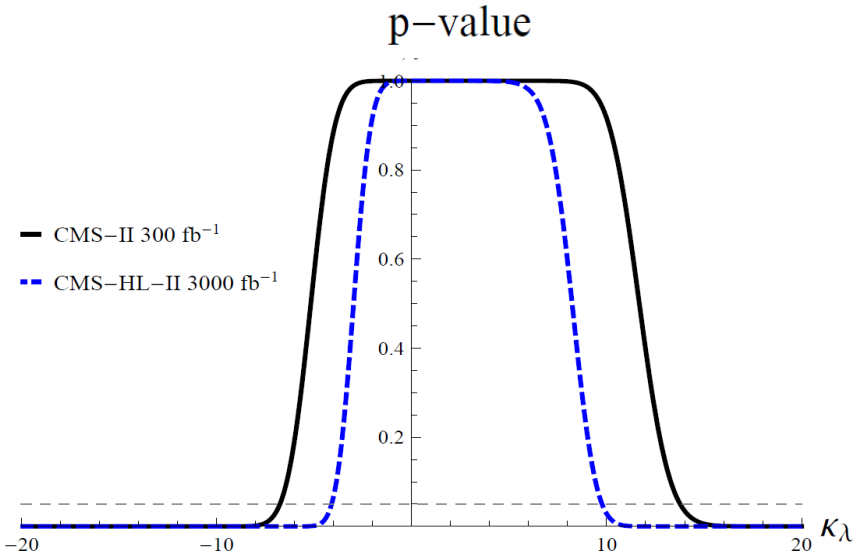
$p > 0.05 \quad \kappa_\lambda > -14.3$

Perspectives for the future

Exercise: $\mu_i^f = 1 \longrightarrow \kappa_\lambda^{\rm best} = 1$ central values are SM

Relative uncertainties as estimated in Peskin arXiv: 1312.4974





CMS-II (300 fb^{-1}) $\kappa_\lambda^{1\sigma} = [-1.8, 7.3]\,,$ $\kappa_\lambda^{2\sigma} = [-3.5, 9.6]$ $\kappa_\lambda^{p>0.05} = [-6.7,\ 13.8]$

CMS-HL-II (3000 fb^{-1}) $\kappa_\lambda^{1\sigma} = [-0.7, 4.2]\,,$ $\kappa_\lambda^{2\sigma} = [-2.0, 6.8]$ $\kappa_\lambda^{p>0.05} = [-4.1,\ 9.8]$

Conclusions

- The shape of the Higgs potential is presently very poorly known and the bounds on the trilinear self couplings from double Higgs production do not allow to test weakly coupled models.

- I presented the idea of using the sensitivity to the Higgs trilinear coupling of single Higgs processes and precision observables in order to gather information on the Higgs potential.

- These kind of studies can be competitive and complementary to the direct double Higgs measuremets

- Our studies rely on some assumptions (some of which are in common with the double Higgs analyses) that can be in the future progressively relaxed.