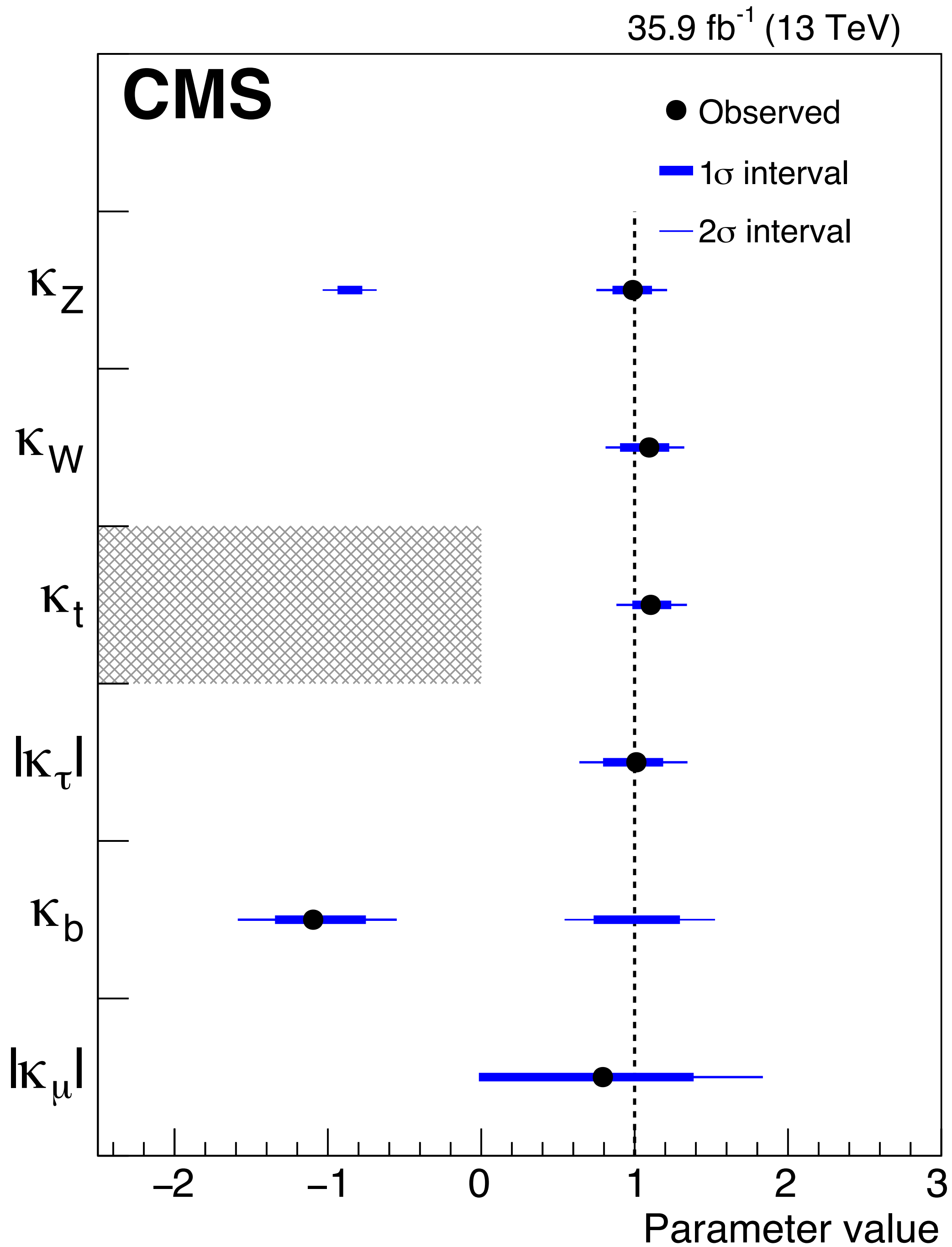
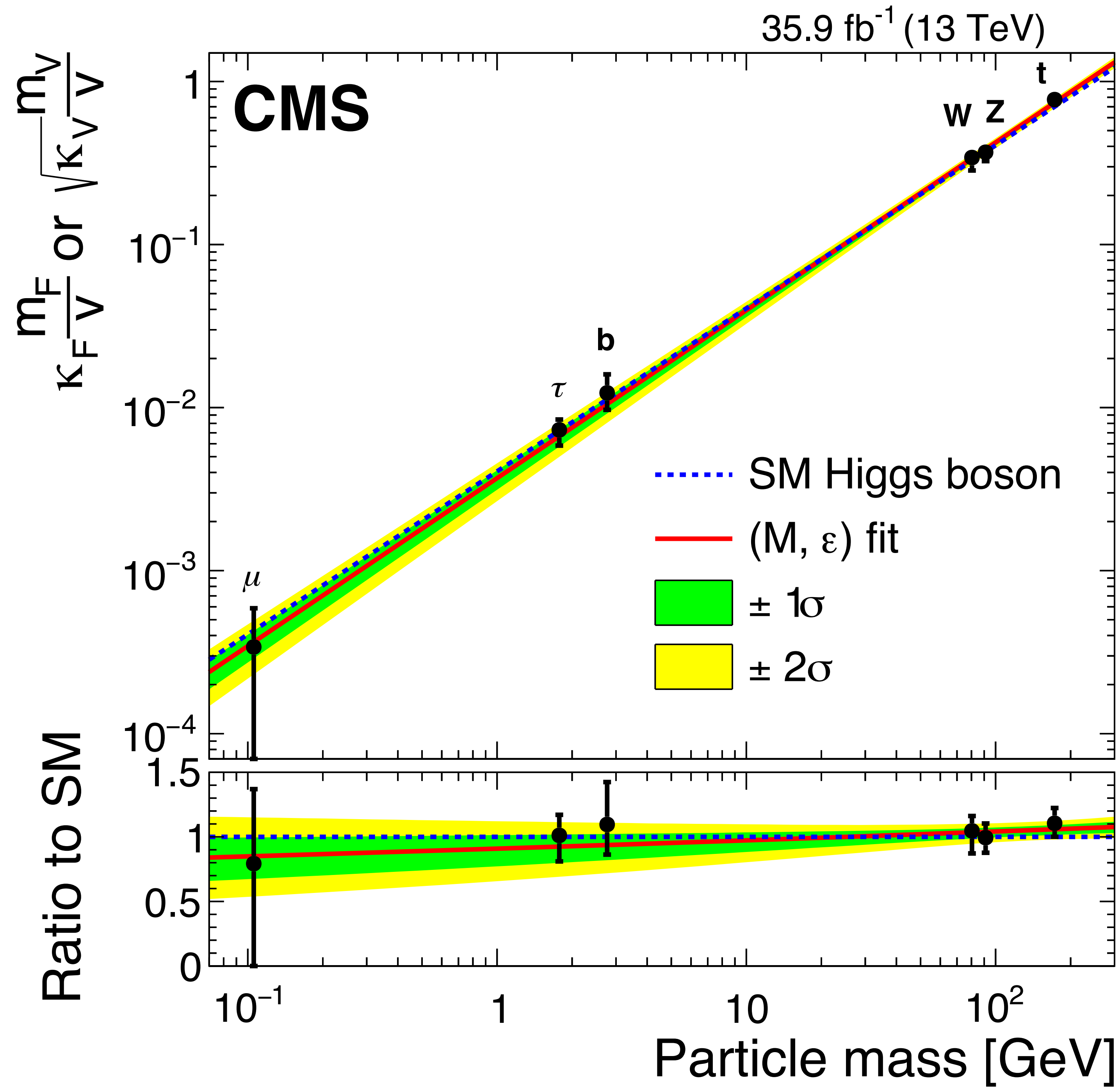
Trilinear Higgs self coupling from single Higgs production (and similar ideas)

Davide Pagani

Milan Xmas meeting 2018
Milano
20-12-2018

Higgs boson couplings now

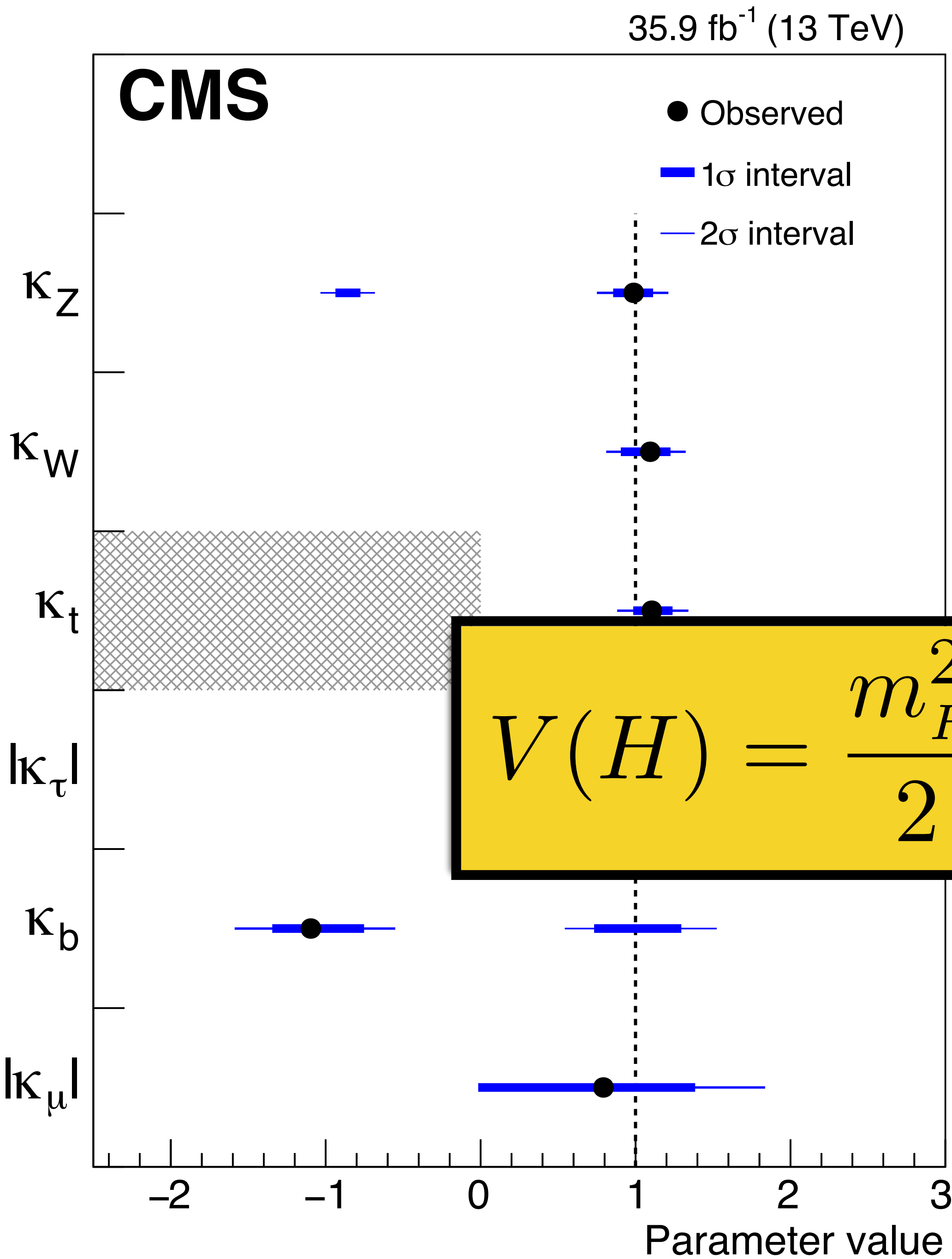


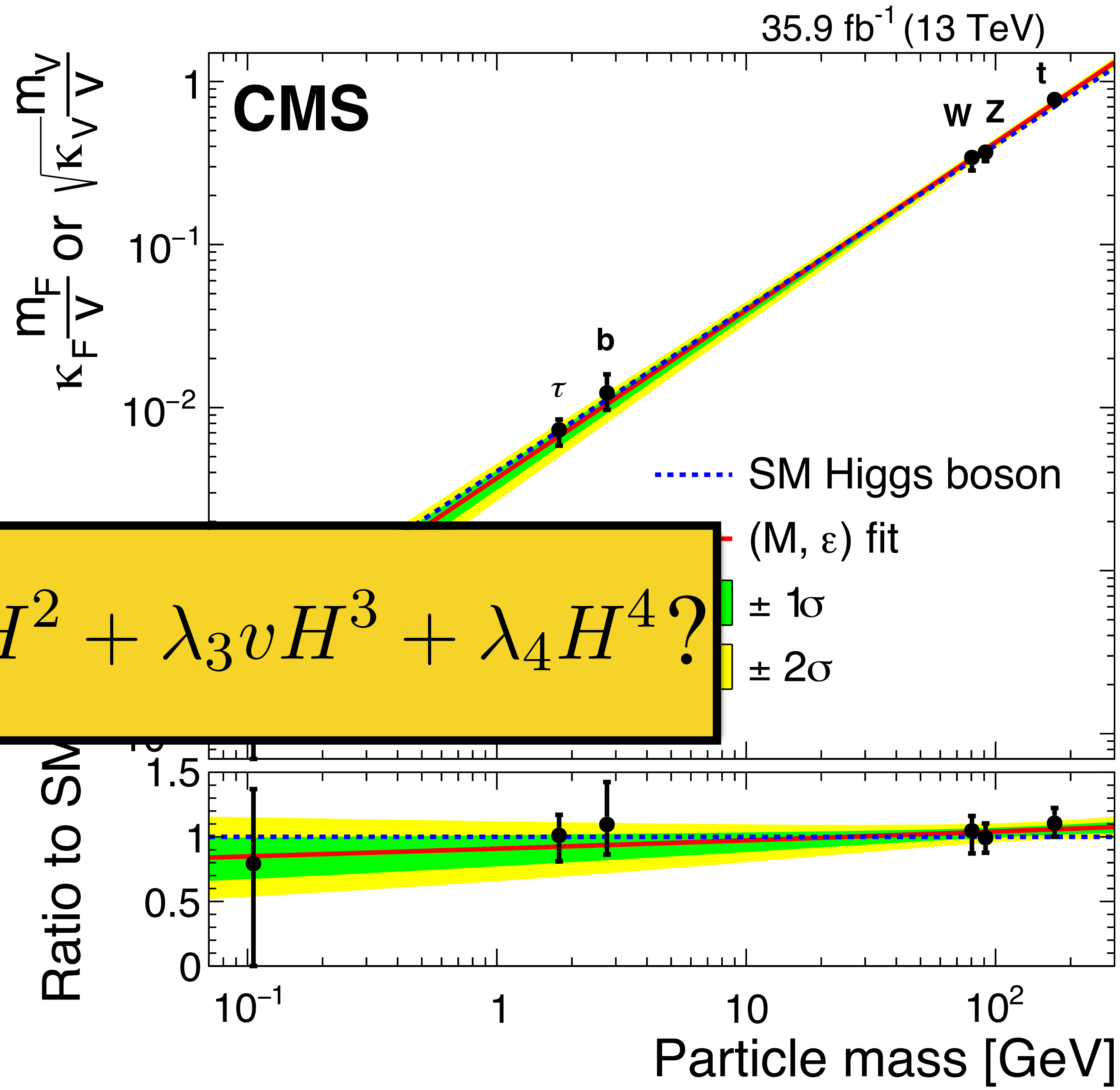


Interactions with vectors bosons and (heavy) fermions are already probed at $\mathcal{O}(10-30\%)$ level.

CMS-HIG-17-031

Higgs boson couplings now





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

Interactions with vectors bosons and (heavy) fermions are already probed at $\mathcal{O}(10-30\%)$ level.

CMS-HIG-17-031

The Higgs Potential

$$V^{\mathrm{SM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

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

$$v = (\sqrt{2}G_\mu)^{-1/2} \qquad \mu^2 = \frac{m_H^2}{2}$$

$$\lambda = \frac{m_H^2}{2v^2} \qquad \lambda_3^{\mathrm{SM}} = \lambda \qquad \lambda_4^{\mathrm{SM}} = \lambda/4$$

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The Higgs **self couplings** are **completely determined in the SM** by the vev and the Higgs mass. On the other hand, Higgs self interactions have not been measured yet.

The measurement of the Higgs self couplings is an **important SM test**, essential for the study of the **Higgs potential**.

Possible deviations need to be parametrised via **additional parameters**, without altering the value of the Higgs mass and the vev.

Interpretations of the additional parameters strongly **depend on the theory** assumptions!

EFT

$$V^{\mathrm{dim-6}}(\Phi) = V^{\mathrm{SM}}(\Phi) + \frac{c_6}{v^2}(\Phi^\dagger\Phi)^3 \quad \Rightarrow \quad V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \lambda_4 H^4 + \cdots$$

$$\lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}} \qquad \lambda_4 = \kappa_{\lambda_4} \lambda_4^{\mathrm{SM}}$$

$$\kappa_\lambda = 1 + \frac{2c_6 v^2}{m_H^2} \qquad \kappa_{\lambda_4} = 1 + \frac{12 c_6 v^2}{m_H^2} \qquad \kappa_{\lambda_4} = 6\kappa_\lambda - 5$$

Gauge invariant, valid up to the NP (implicit) scale Λ.
Interpretation as linear EFT expansion valid (in general) only for small c6.
Deformation of the trilinear and quartic couplings correlated.
Perturbativity imposes bounds on c6 and thus κ_λ .

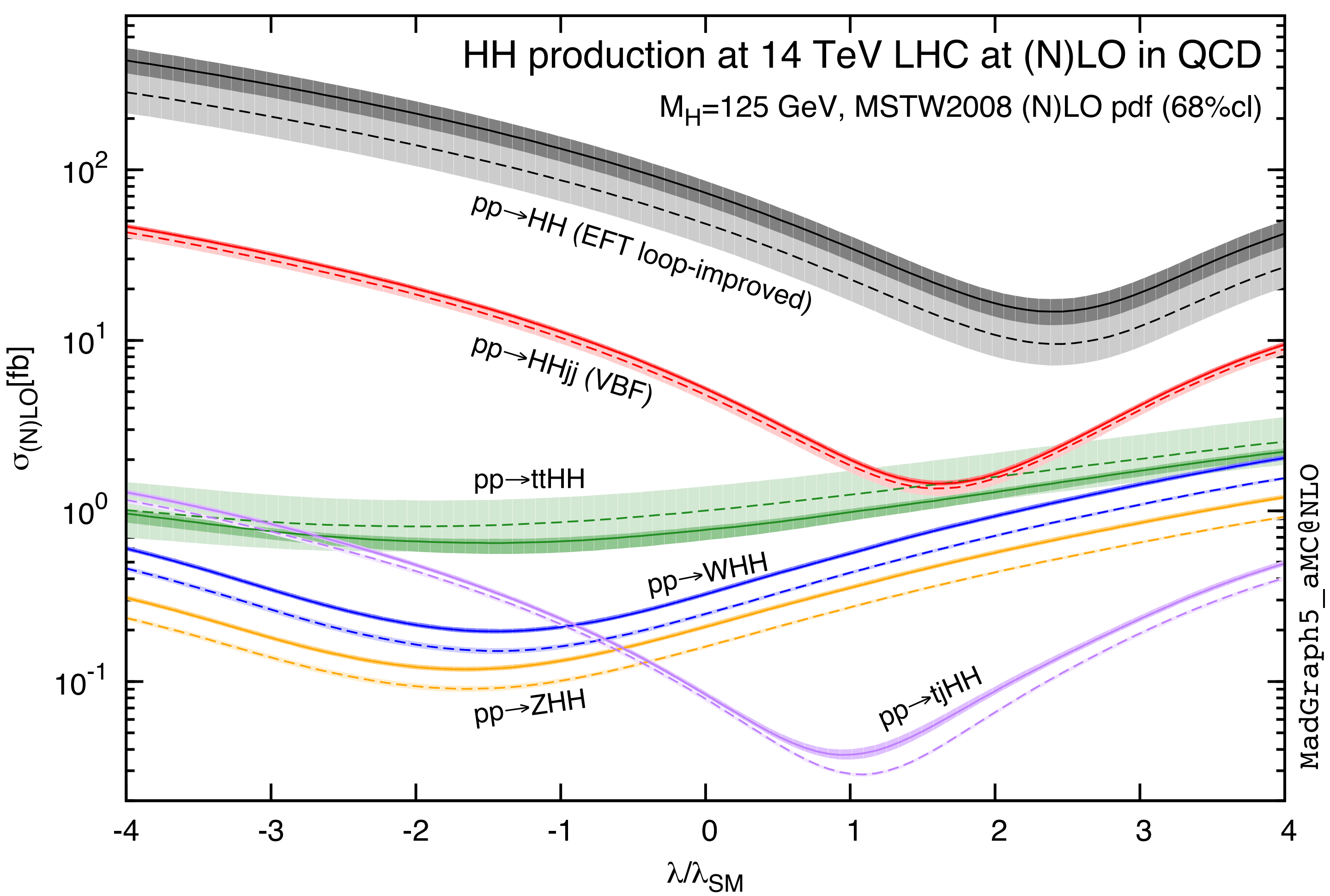
$$V^{\mathrm{dim-8}}(\Phi) = V^{\mathrm{SM}}(\Phi) + \frac{c_6}{v^2}(\Phi^\dagger\Phi)^3 + \frac{c_8}{v^4}(\Phi^\dagger\Phi)^4 \qquad \kappa_{\lambda_4} = 1 + \frac{(12c_6 + 32c_8)v^2}{m_H^2}$$

Trilinear and quartic couplings uncorrelated.

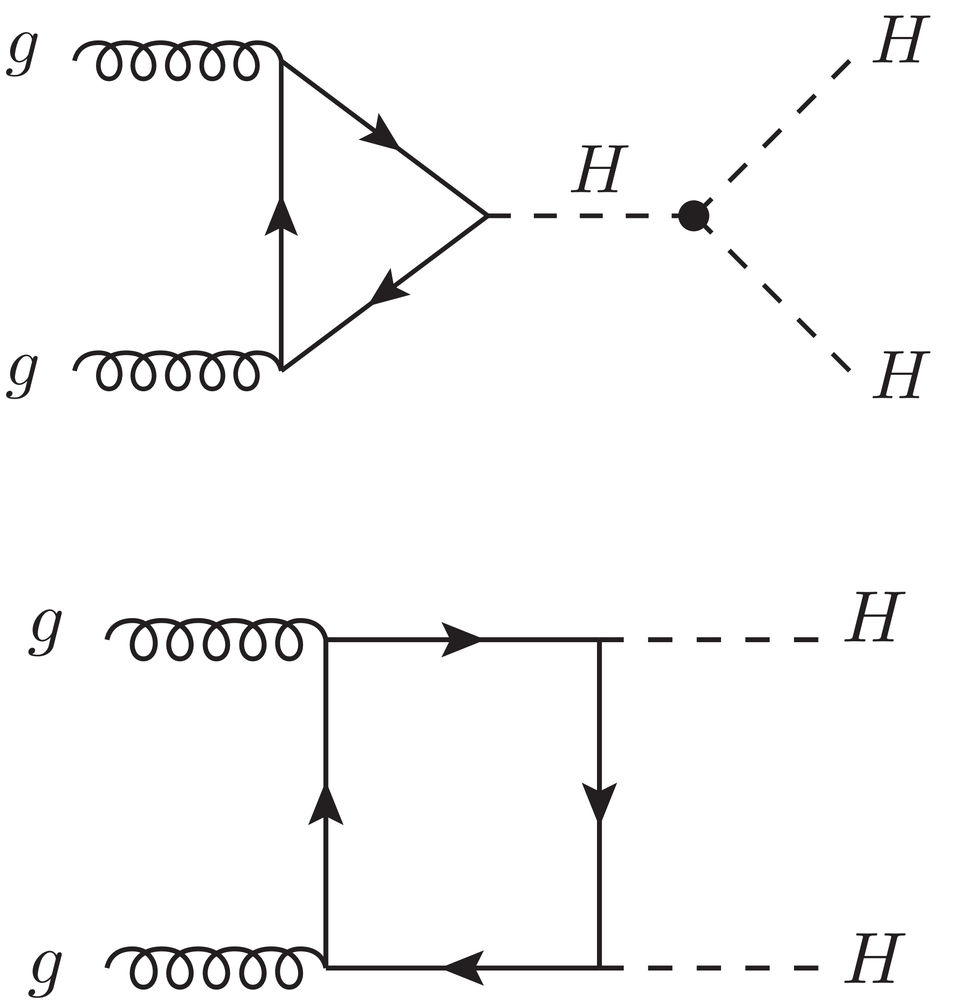
$$\kappa_\lambda = 1 + \frac{(2c_6 + 4c_8)v^2}{m_H^2}$$

How do we measure the Higgs self coupling?

Standard Answer: you need to produce **at least two** Higgs!



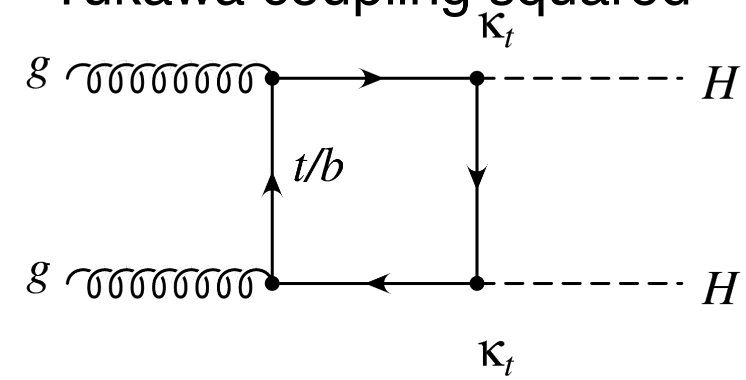
Frederix et al. '14



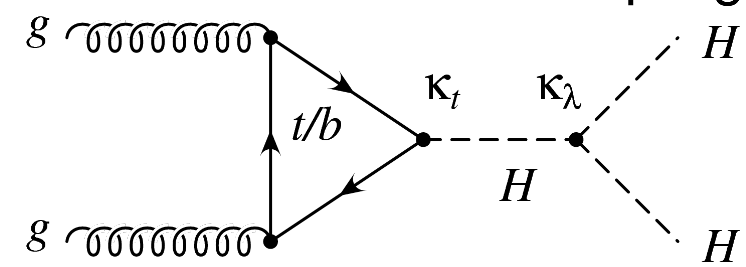
Di-Higgs production

- ATLAS: $\mu<6.7$ (exp 10.4) @95% CL
- CMS: $\mu<22$ (exp 13) @95% C.L.
- Limits at 95% CL on self-coupling scale factor κ_λ:
  - ATLAS: $-5.0<\kappa_\lambda<12.1$
  - CMS: $-11.8<\kappa_\lambda<18.8$

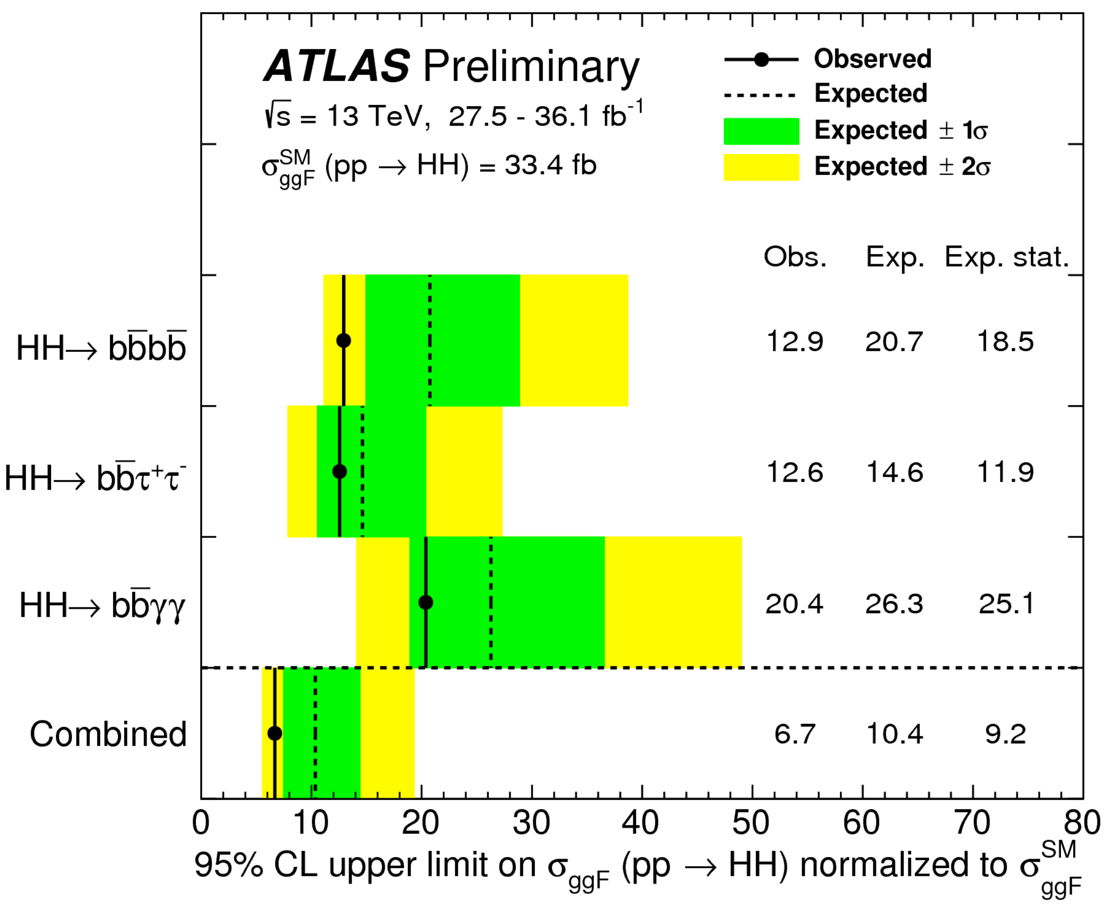
Yukawa coupling squared



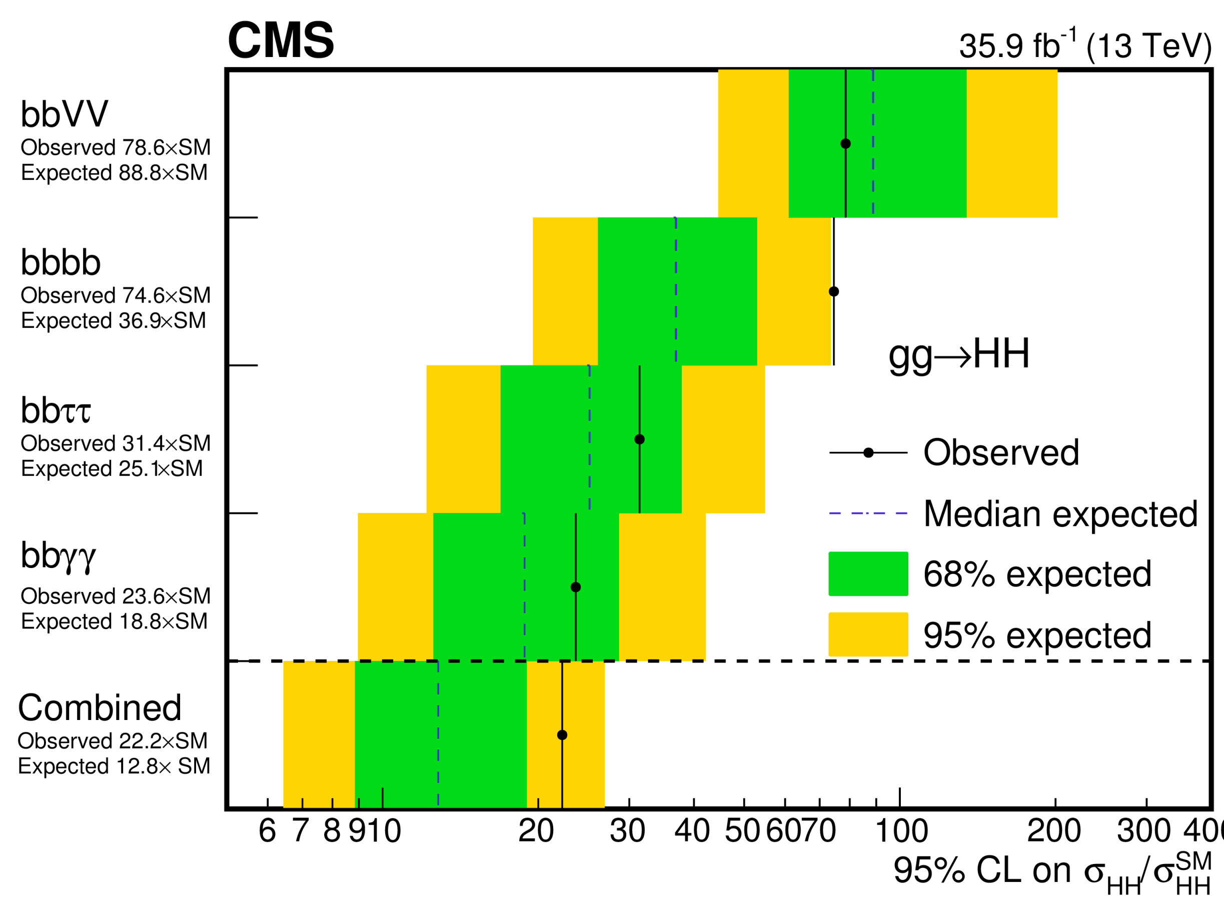
Yukawa and H self-coupling



ATLAS-CONF-2018-043



CMS-PAS-HIG-17-030



An additional and complementary strategy for the determination (at the LHC) of the Higgs self coupling is definitely useful.

We can exploit at the LHC the
"High Precision for Hard Processes"

HP^2

It is time for something new

Degrassi, Giardino, Maltoni, DP '16

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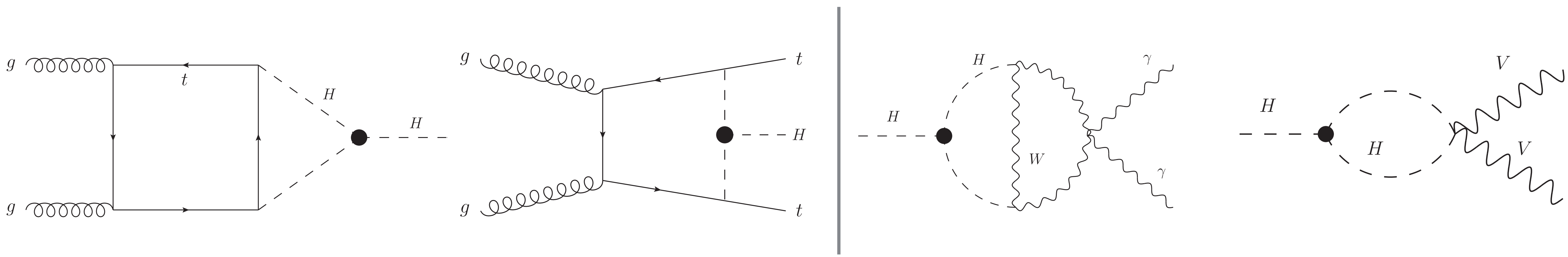
Degrassi, Giardino, Maltoni, DP '16

and ***probe*** the quantum effects (NLO EW) induced by the Higgs self coupling on single Higgs production and decay modes.



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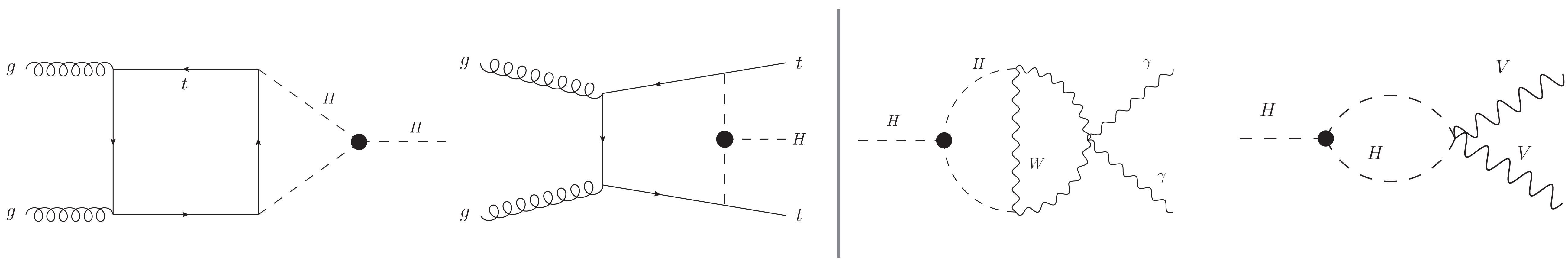

All the single Higgs production and decay processes are affected by an anomalous trilinear (**<u>not quartic</u>**) Higgs self coupling, parametrized by κ_λ.

All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.

Step 1:
only self couplings are anomalous, only total rates are considered

Calculation framework

We assume that the dominant New Physics effects involve the Higgs potential.
At **NLO EW** only the trilinear Higgs self coupling appears; the quartic-coupling dependence enters only at higher orders.

SM

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

$$m_H^2 = 2\lambda v^2, \lambda_3^{\rm SM} = \lambda, \lambda_4^{\rm SM} = \lambda/4$$

NP parameterised via

$$\lambda_3\, v\, H^3 \equiv \kappa_\lambda \lambda_3^{\rm SM}\, v\, H^3$$

Degrassi, Giardino, Maltoni, DP '16

The possible range of κ_λ, even before the comparison with data, depends on the underlying theory assumptions and it applies also to double-Higgs analyses.

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Degrassi, Giardino, Maltoni, DP '16

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Pioneering study for (only) ZH production at e+e- collider in *McCullough '14*

Similar studies in EFT approach for only gluon-fusion with decays into photons in *Gorbahn, Haisch '16,* and for VBF+VH in *Bizon, Gorbahn, Haisch, Zanderighi '16*

Besides minor differences, results can be translated via:

$$\kappa_\lambda = 1 + \frac{2 c_6 v^2}{m_H^2}$$

Numerical results

Degrassi, Giardino, Maltoni, DP '16

universal

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

Process and kinetic dependent

$C_2 = -9.514 \cdot 10^{-4}$ for $\kappa_\lambda = \pm 20$ $\qquad$ $C_2 = -1.536 \cdot 10^{-3}$ for $\kappa_\lambda = 1$

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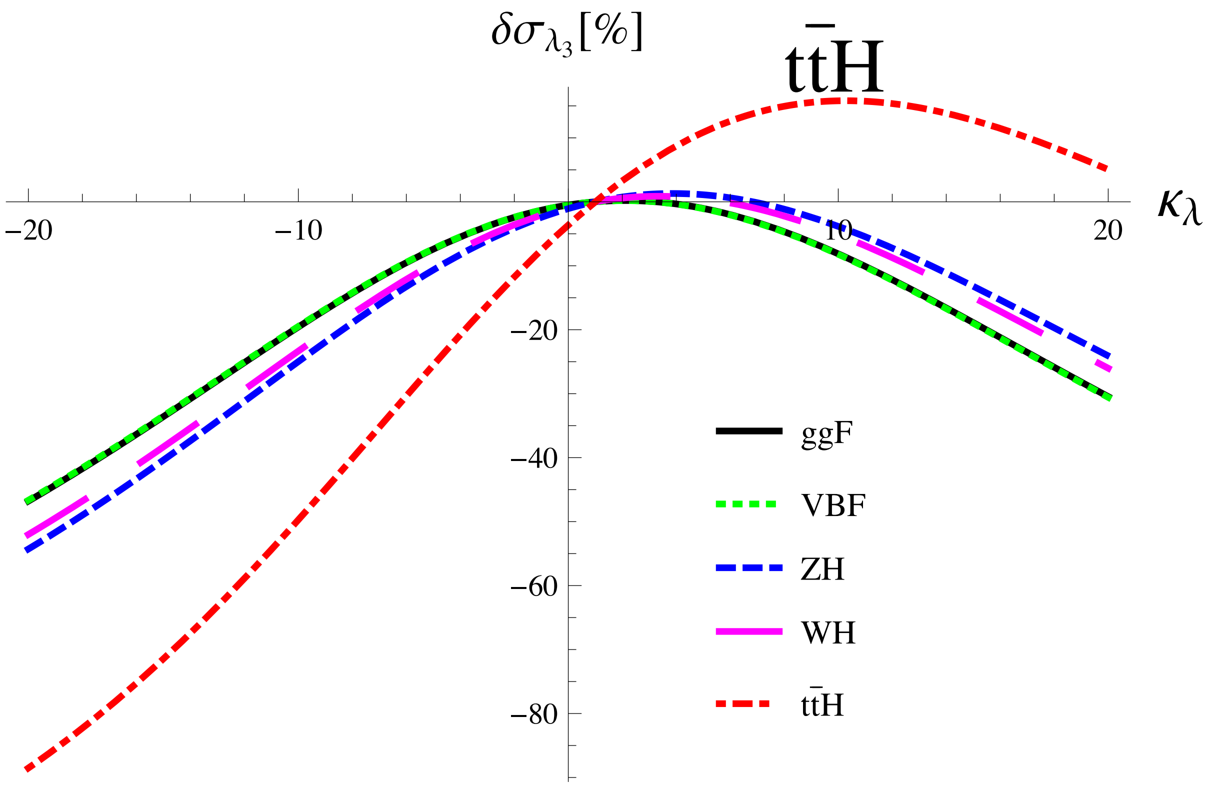
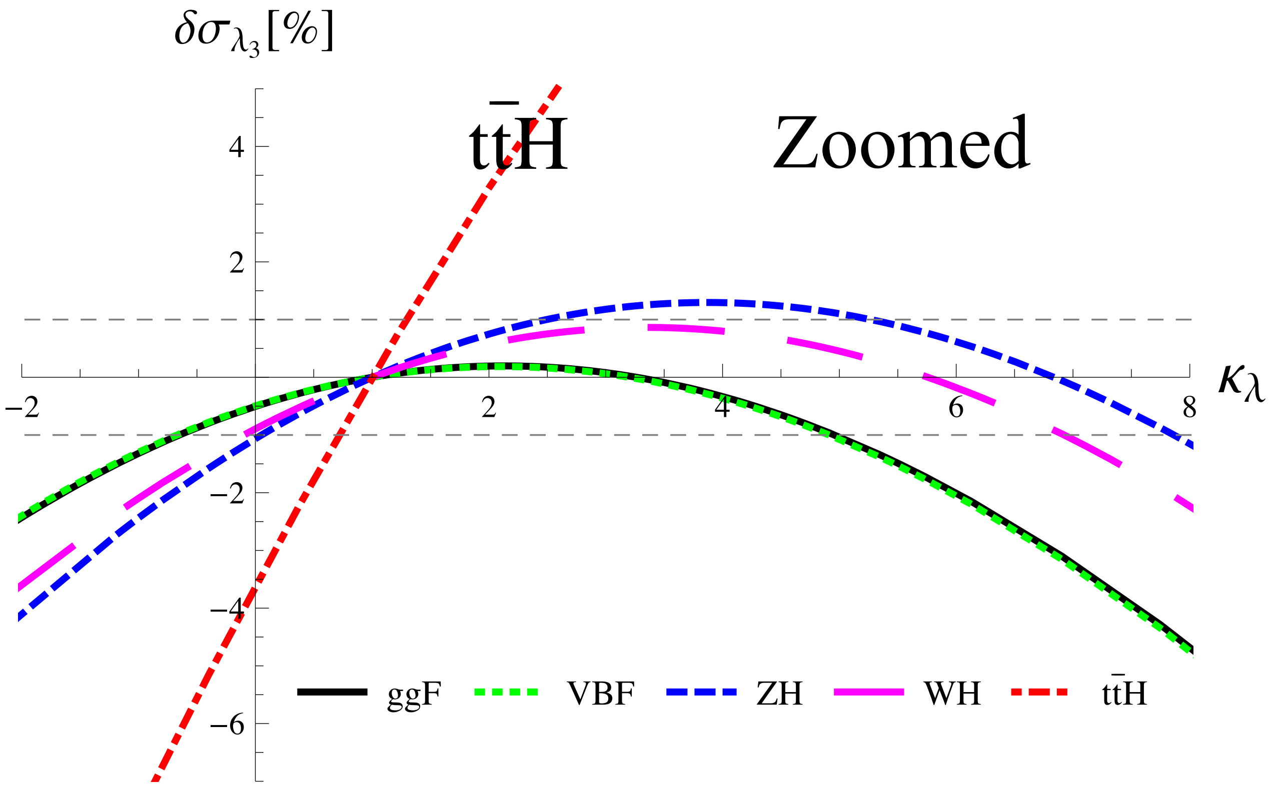
Production: $\delta\sigma_{\lambda_3}$

$C_1^\sigma[\%]$	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





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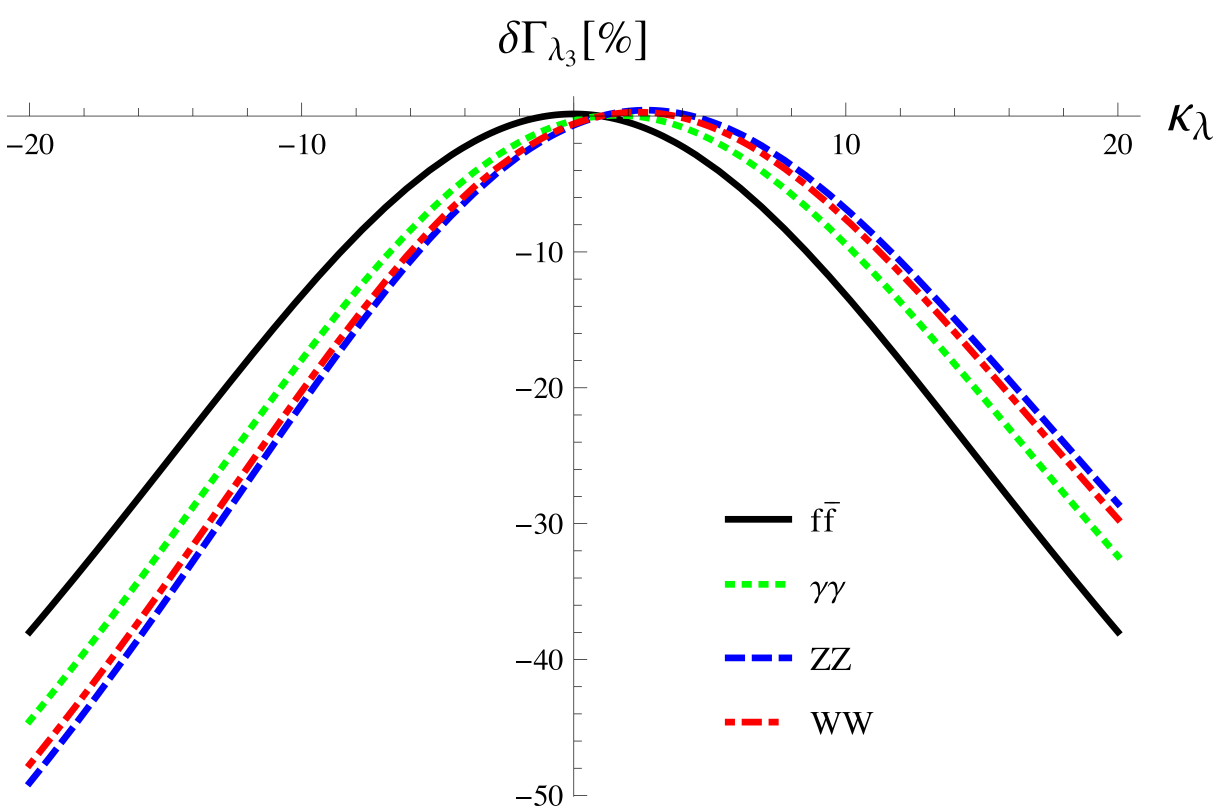
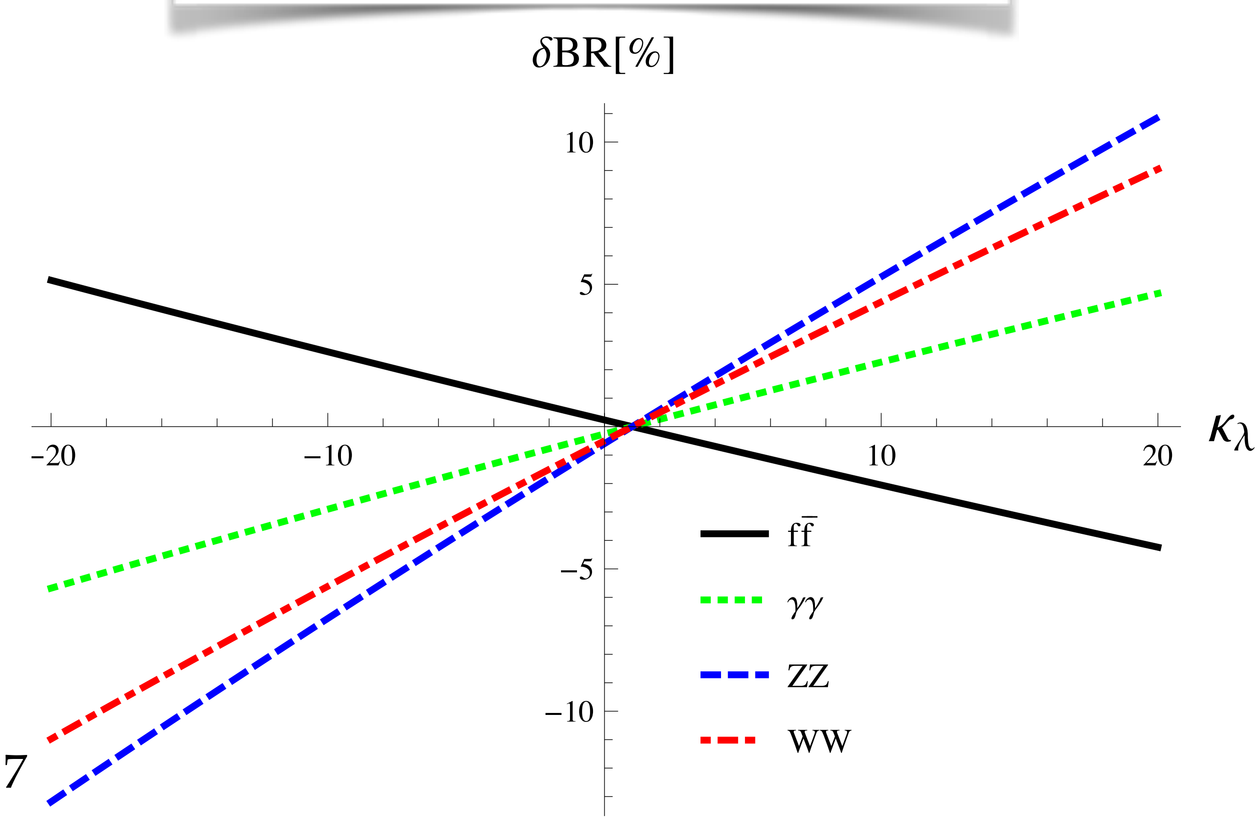
Decay: $\delta\Gamma_{\lambda_3}$ and $\delta \mathrm{BR}_{\lambda_3}$

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

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

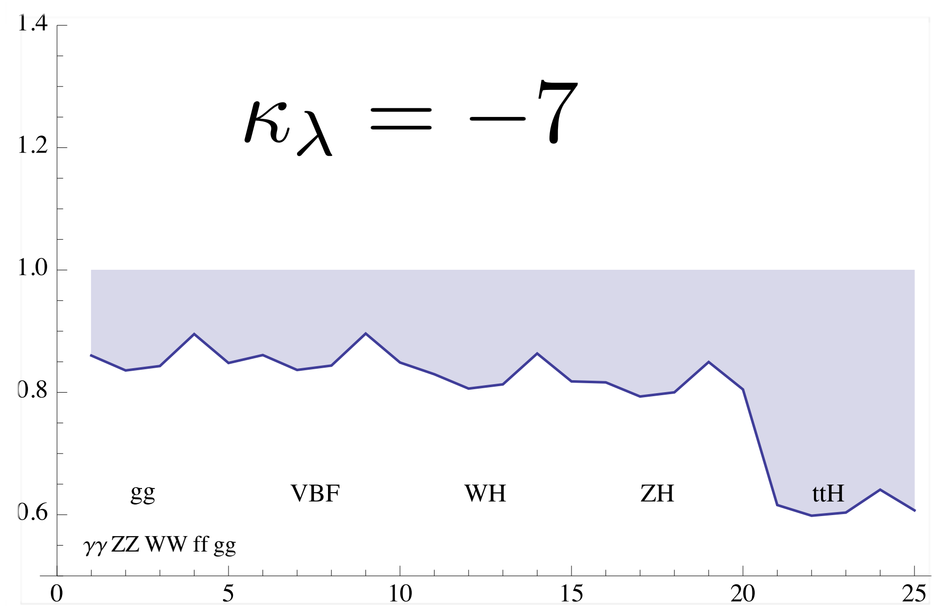




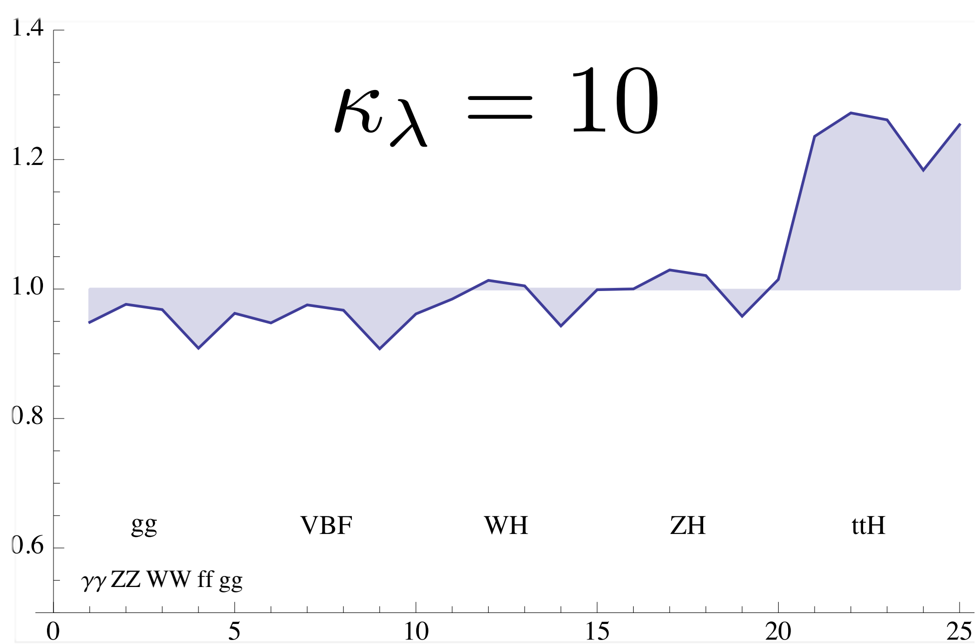
Fitting from LHC data (8 TeV)

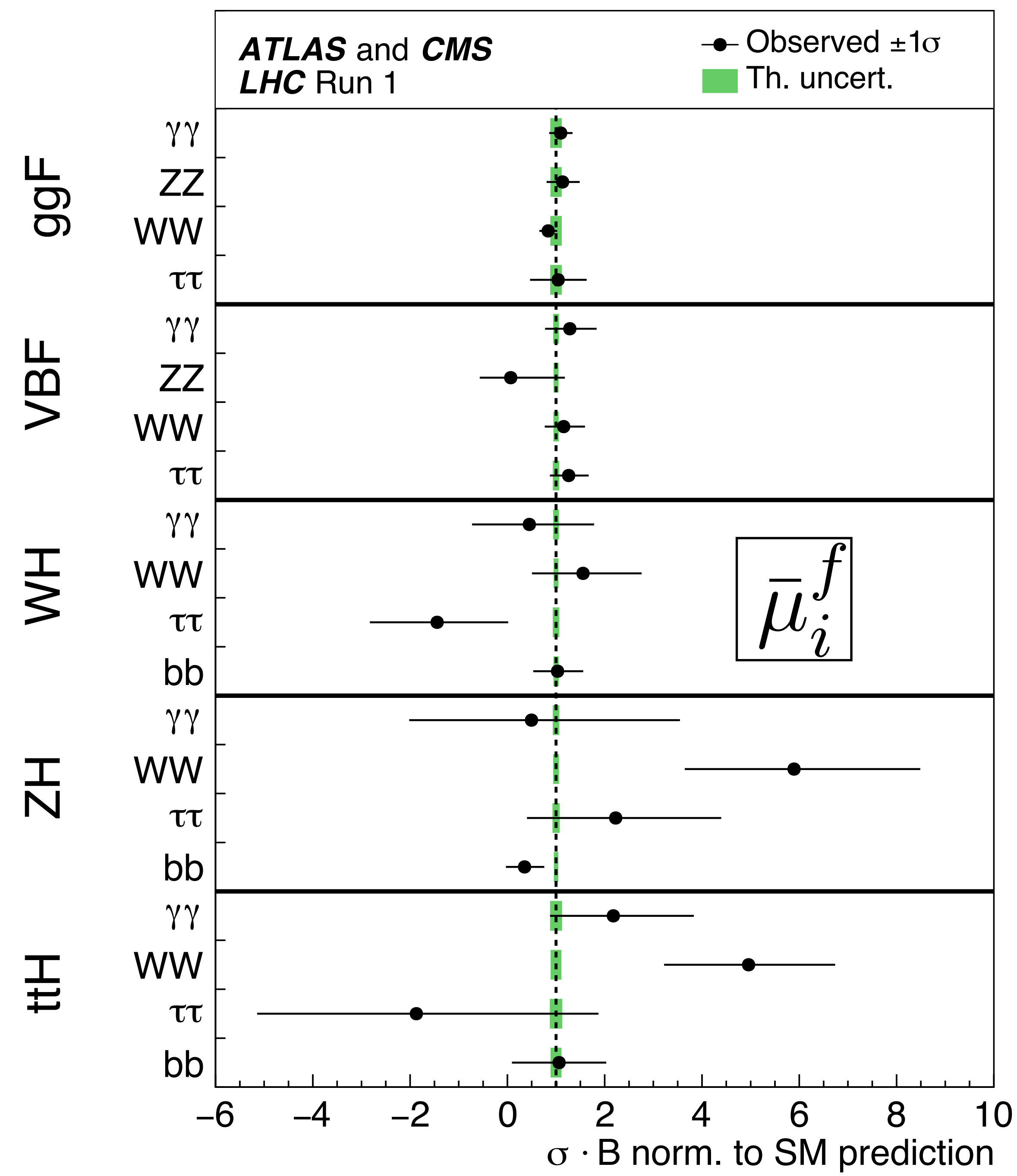
$$i \to H \to f \quad \Rightarrow \quad \mu_i^f \equiv \mu_i \times \mu^f$$

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



$\boxed{\mu_i^f(\kappa_\lambda)}$

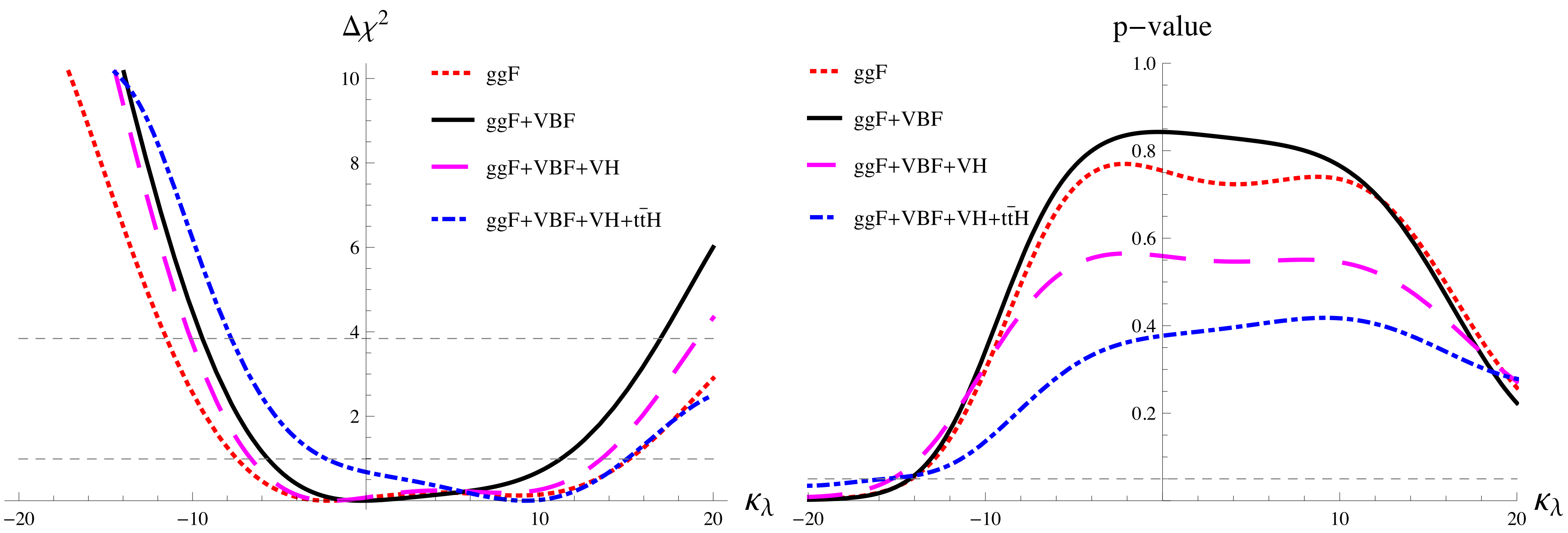




$\boxed{\bar{\mu}_i^f}$

Results for present data (8 TeV)

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

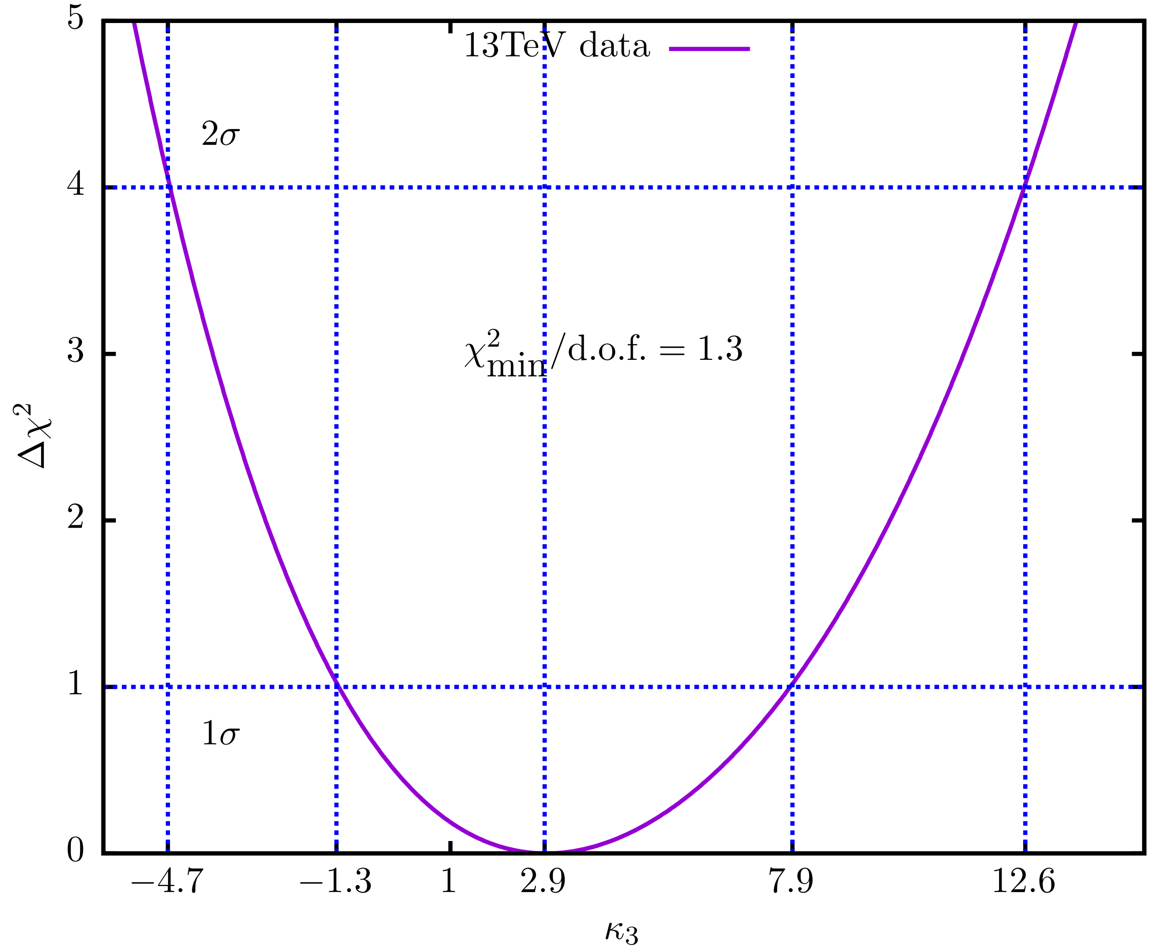


$$\kappa_\lambda^{\text{best}} = -0.24\,, \qquad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$$

Degrassi, Giardino, Maltoni, DP '16

Results for present data (13 TeV)

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



plot done by Xiaoran Zhao

based on CMS-HIG-17-031

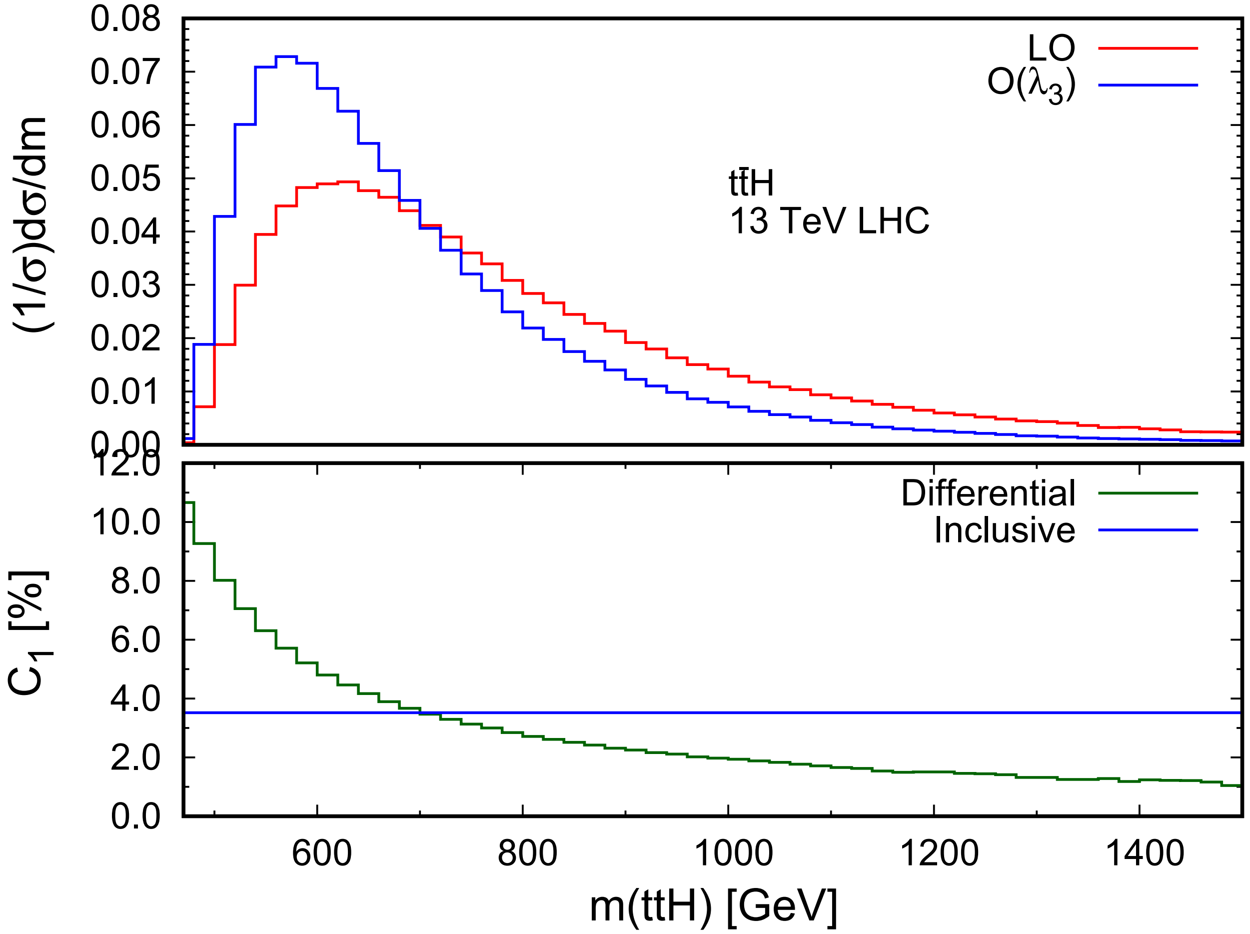
$$\kappa_\lambda^{\rm best} = 2.9\,, \qquad \kappa_\lambda^{1\sigma} = [-1.3, 7.9]\,, \qquad \kappa_\lambda^{2\sigma} = [-4.7, 12.6]$$

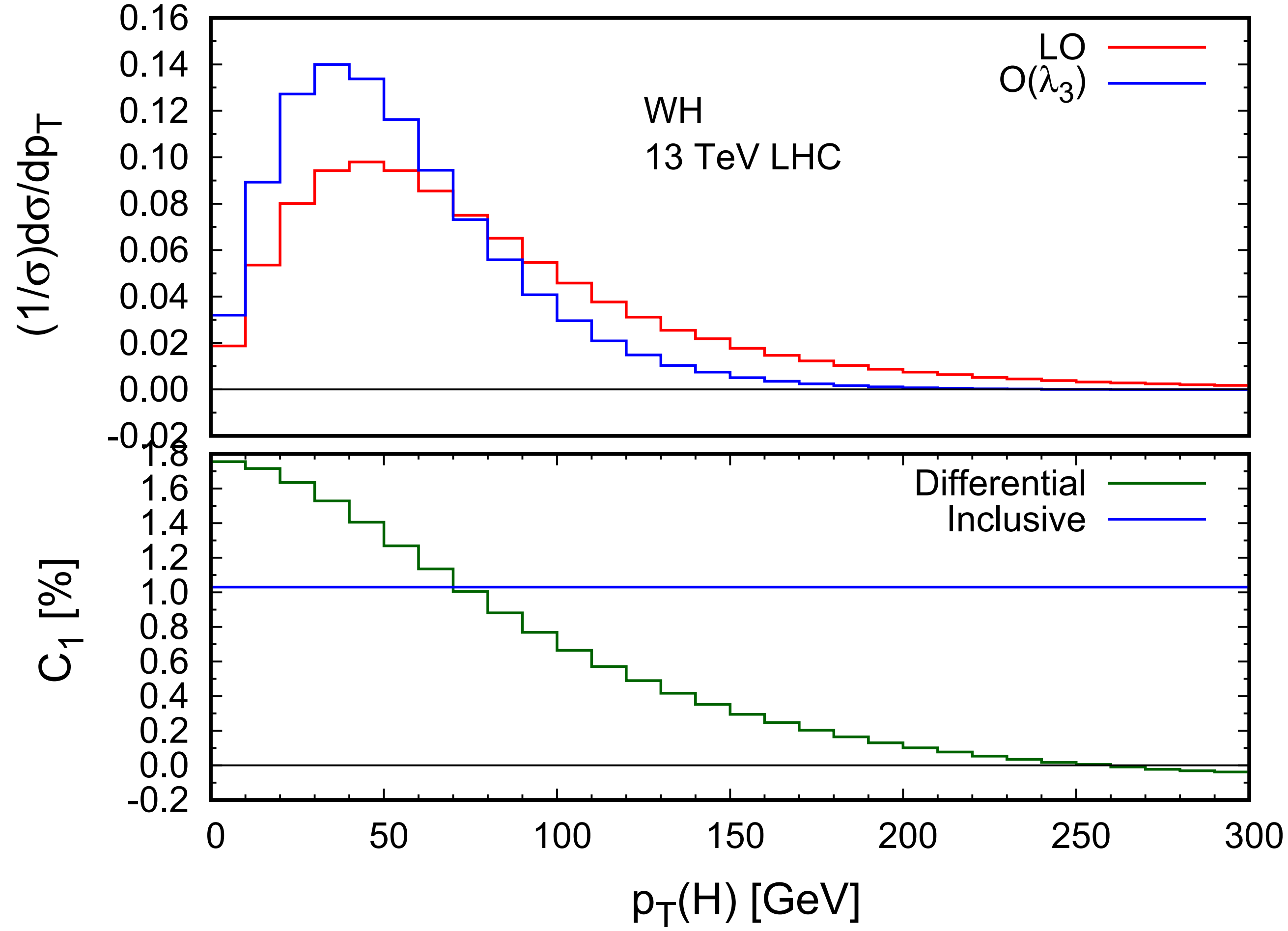
EXP double Higgs:

- ATLAS: $-5.0<\kappa_\lambda<12.1$
- CMS: $-11.8<\kappa_\lambda<18.8$

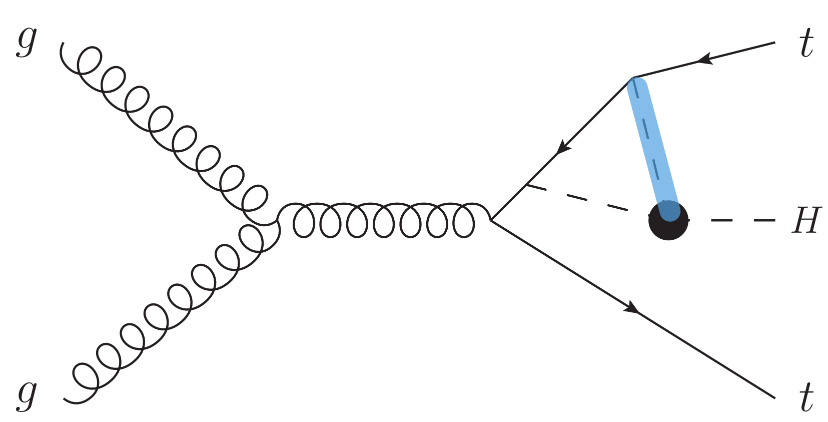
Step 2:
also other BSM interactions can be present,
differential distributions are considered

C1: kinematic dependence





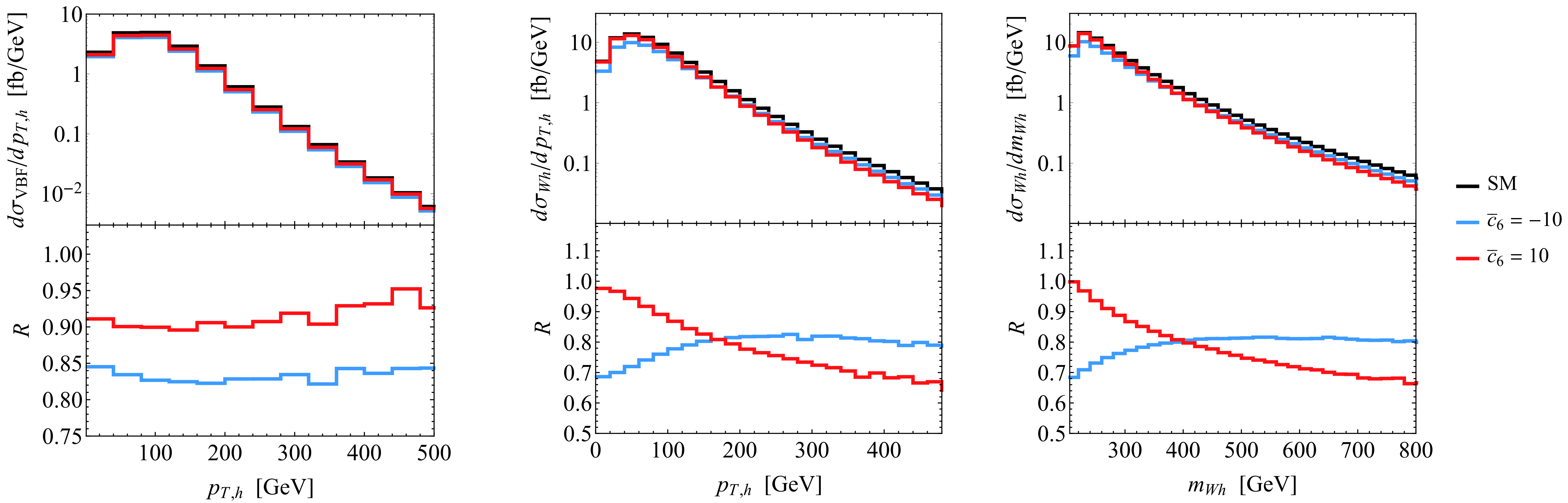
Maltoni, DP, Shivaji, Zhao '17



Contributions to ttH and HV processes can be seen as induced by a Yukawa potential, giving a Sommerfeld enhancement at the threshold.
NP at the threshold, not in the tails!

Kinematic dependence

VBF WH ZH

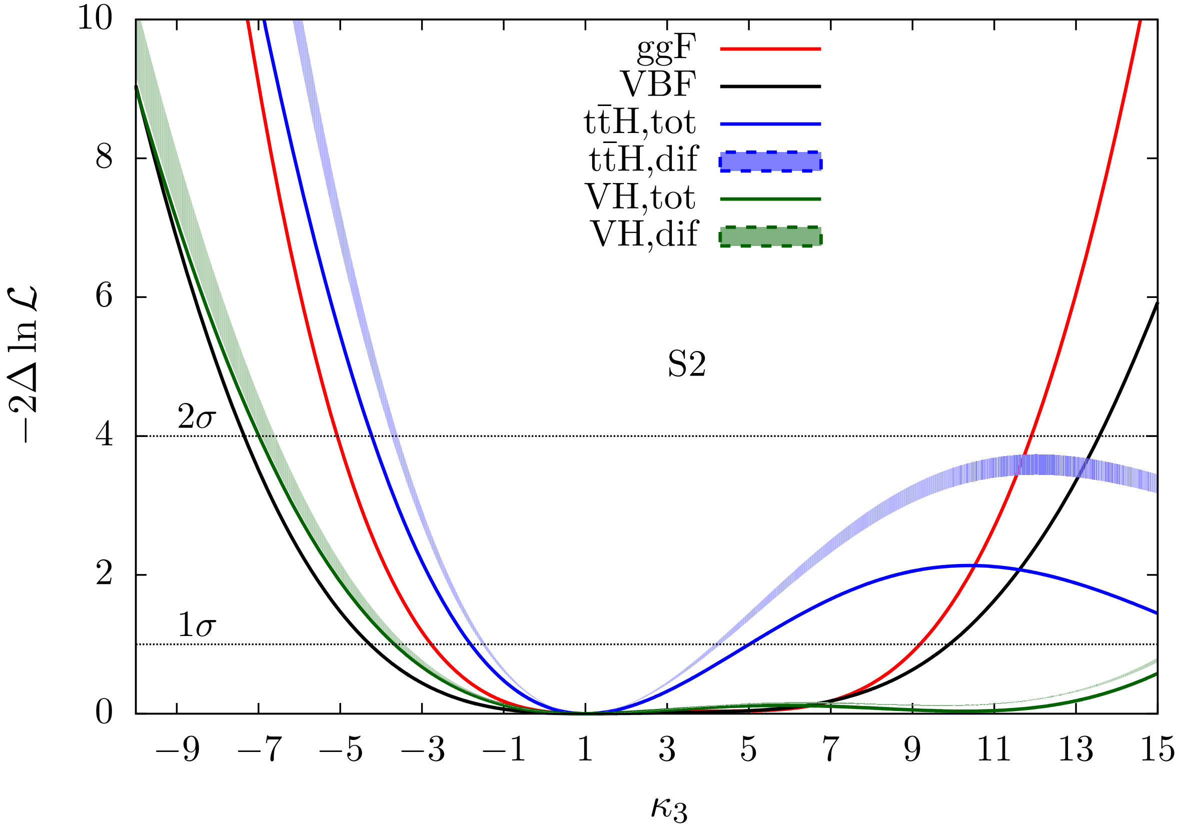


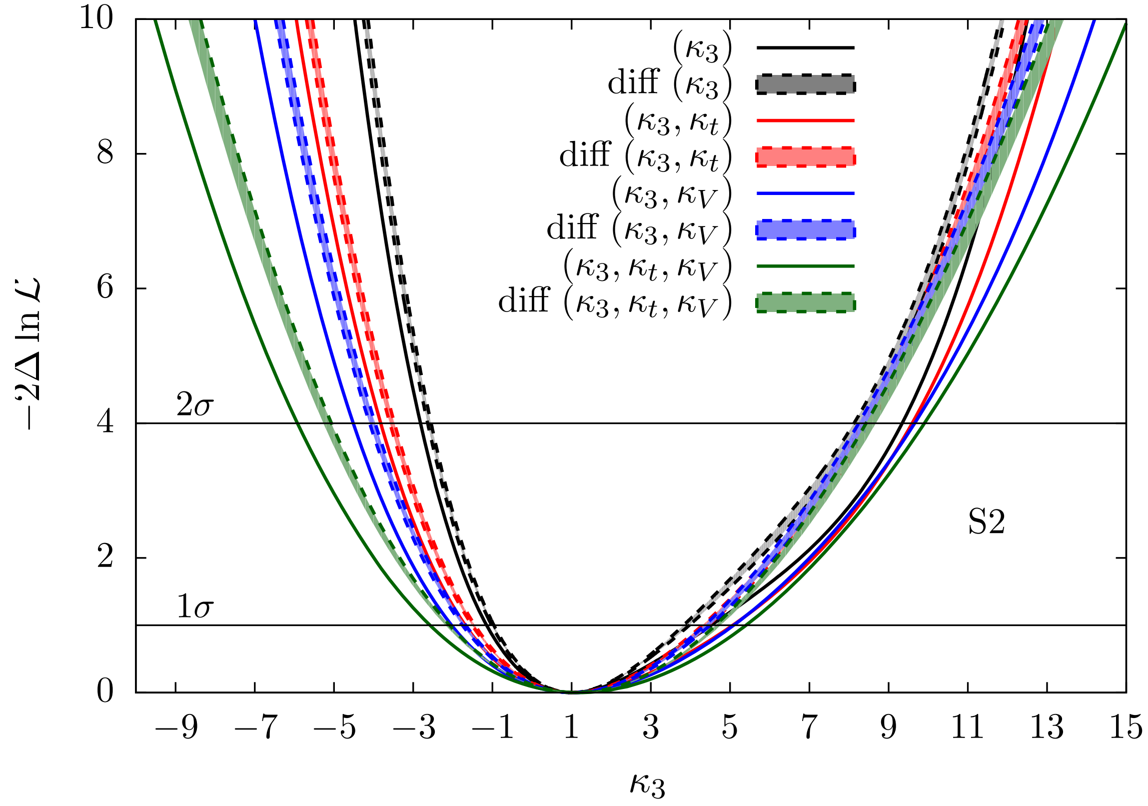
Bizon, Gorbahn, Haisch, Zanderighi '16

At variance with VH and ttH, in VBF the kinematic dependence is very small.

Gluon-fusion calculation is extremely complicated: EW corr. to $gg \to H + j$.

Differential information + other anomalous couplings



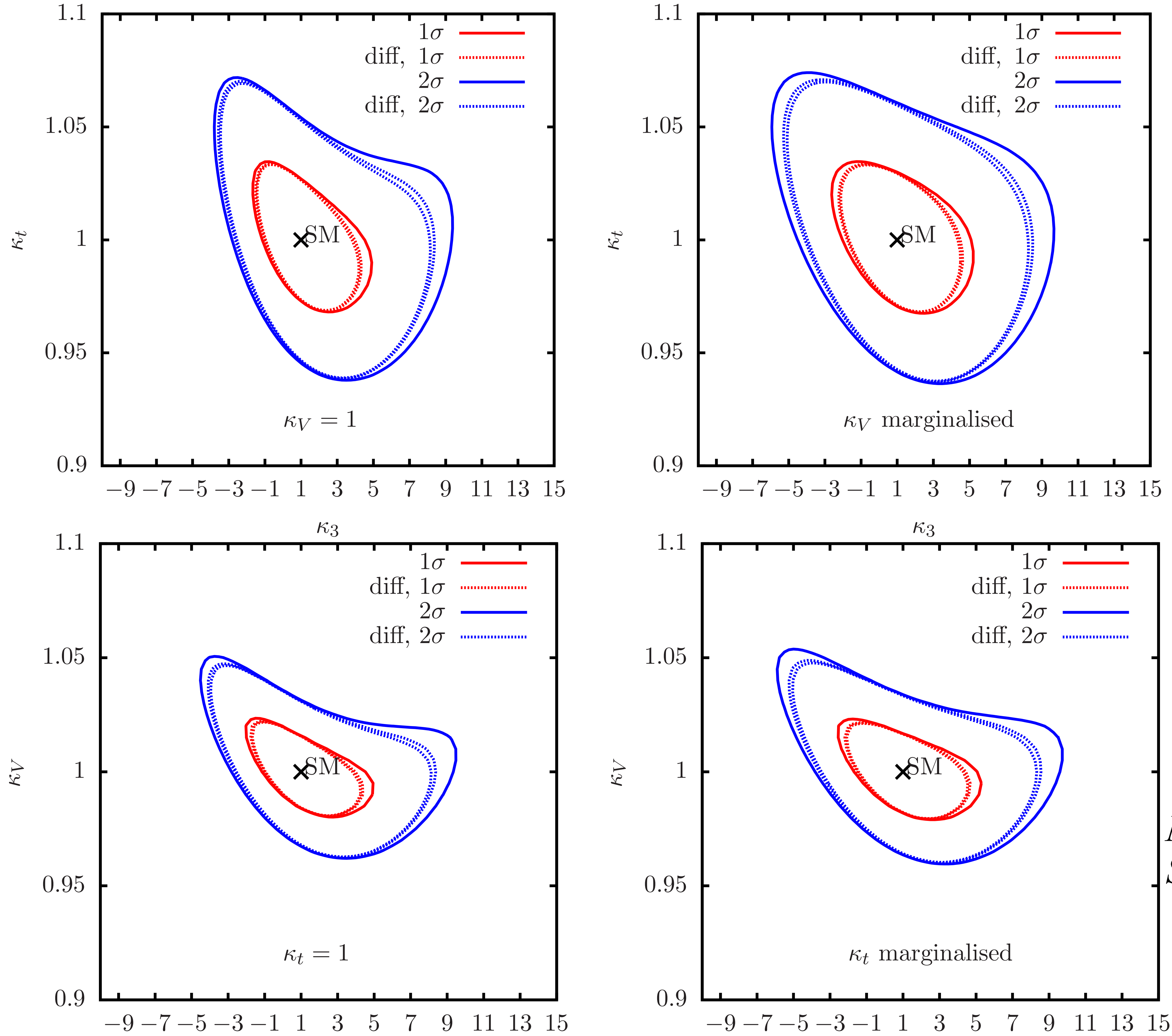


Maltoni, DP, Shivaji, Zhao '17

The interplay between additional possible couplings, experimental uncertainties and differential information lead to different results.

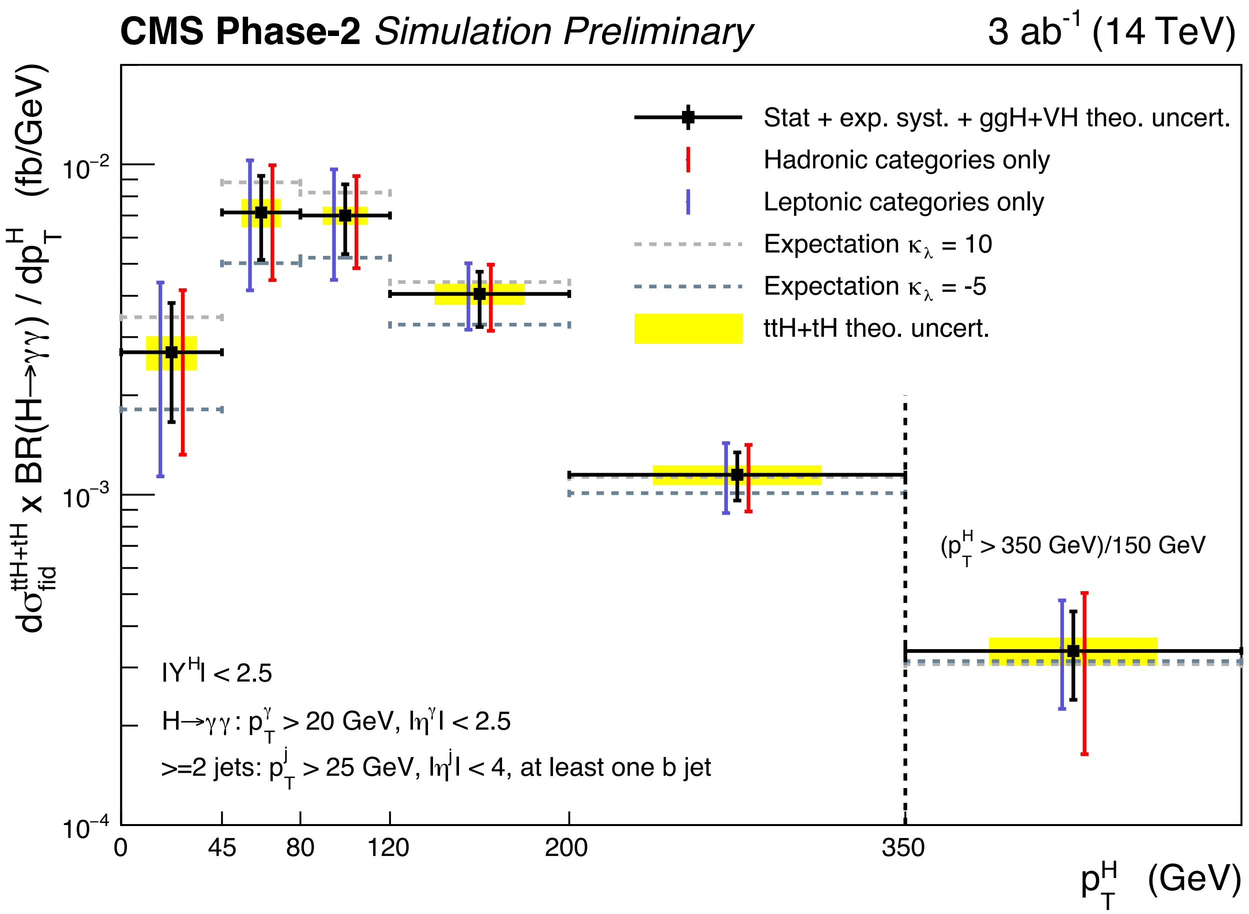
Differential information improves constraints, especially when additional anomalous couplings are considered.

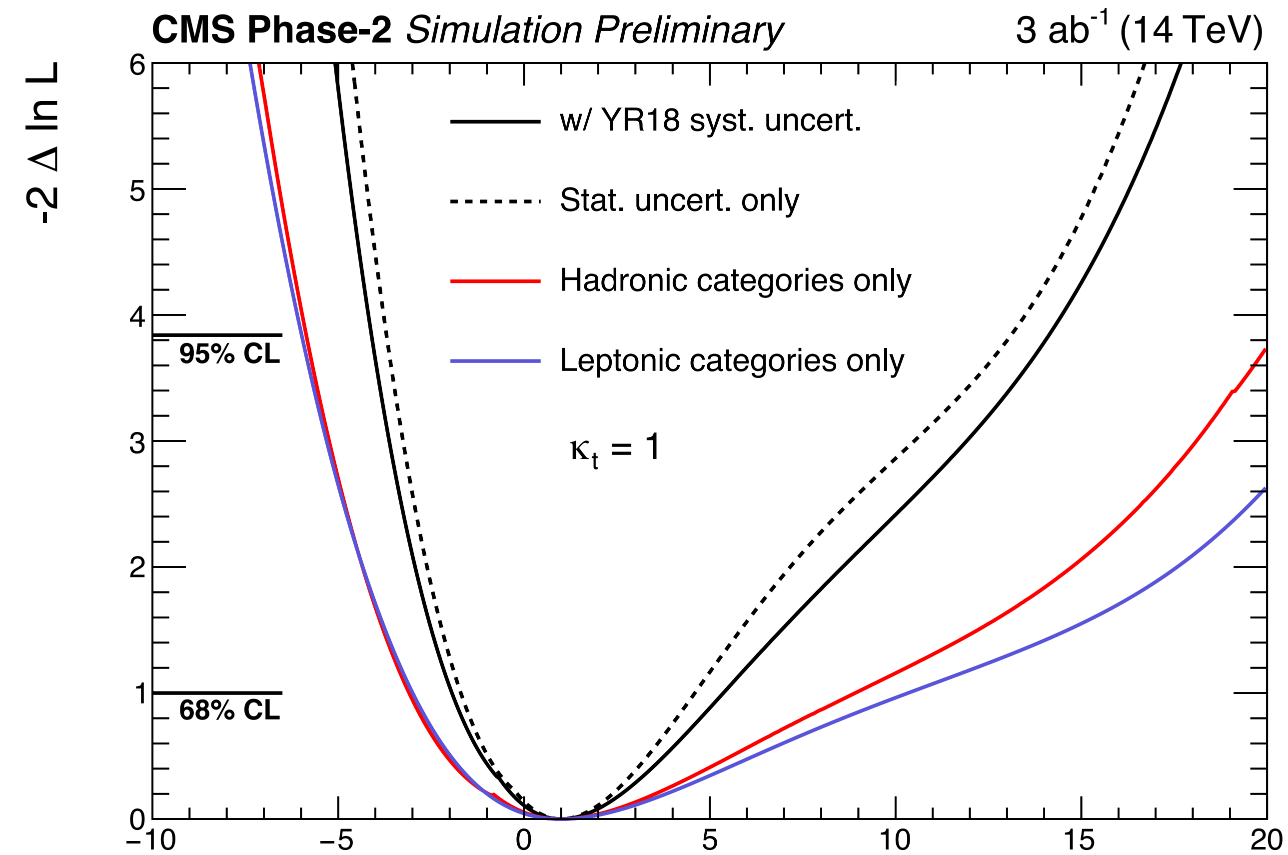
Differential information + other anomalous couplings



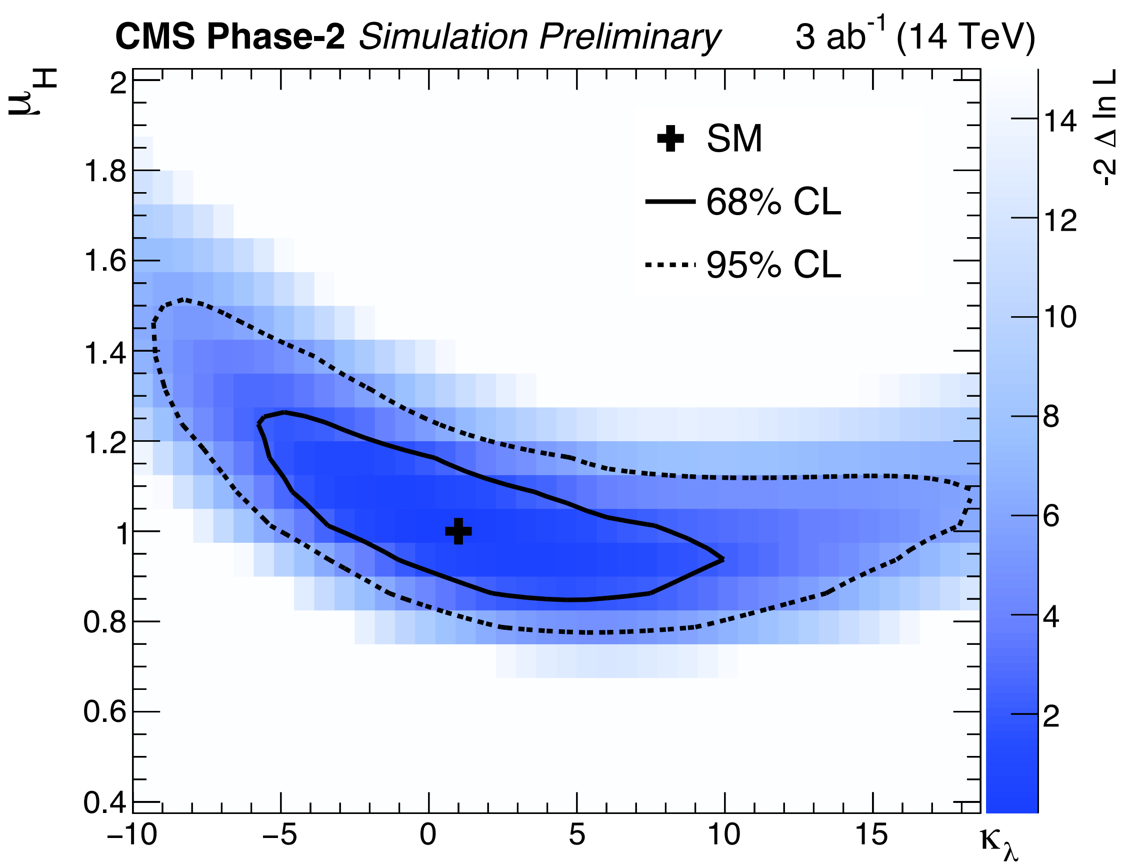
Maltoni, DP, Shivaji, Zhao '17

First experimental projections





$$-4.1 < \kappa_\lambda < 14.1$$



Only ttH+tH with H—>γγ.

Differential information is used. Including a free parameter for the global rescaling, bounds are not dramatically changed!

CMS PAS FTR-18-020

Step 2.b: general EFT

Combined fit with other EFT parameters

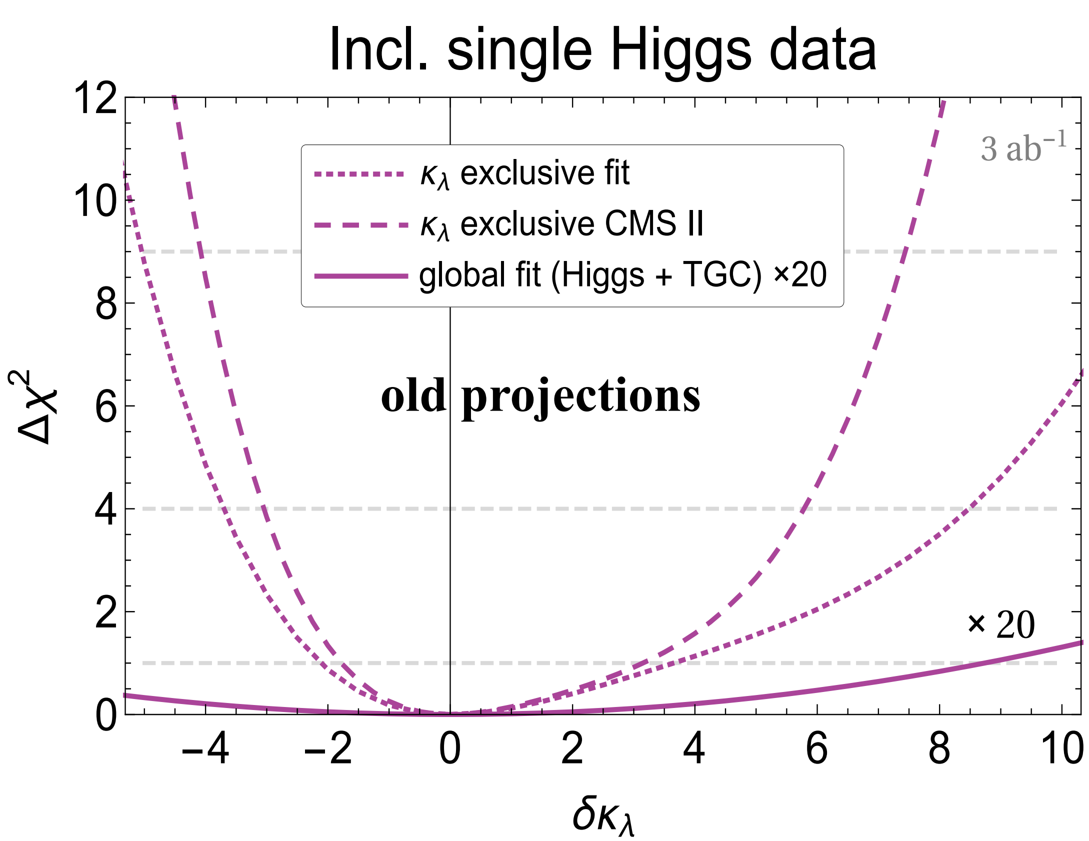
Assumptions:

Di Vita, Grojean, Panico, Riembau, Vantalon '17

- Consider **all** the possible EFT dimension-6 operators that enter **only** in single Higgs production and decay (10 independent parameters).

tree-level: $\delta c_z, c_{zz}, c_{z\Box}, \hat{c}_{z\gamma}, \hat{c}_{\gamma\gamma}, \hat{c}_{gg}, \delta y_t, \delta y_b, \delta y_\tau$ *loop:* κ_λ

- Consider **only *inclusive*** single-Higgs observable (9 independent constraints)

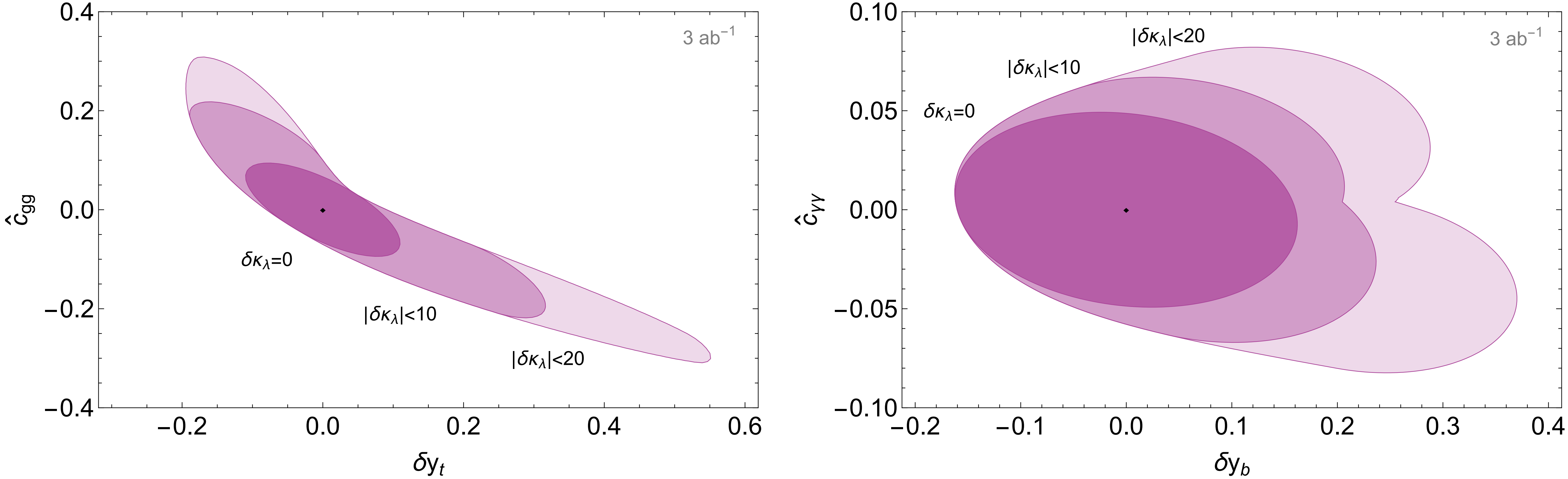


10 parameters vs 9 constraints —> 1 flat direction so no constraints for the weakest: κ_λ

9 constraints can become 10 (Higgs plus jet, Double Higgs ..), or many (look at distributions)

Combined fit with other EFT parameters

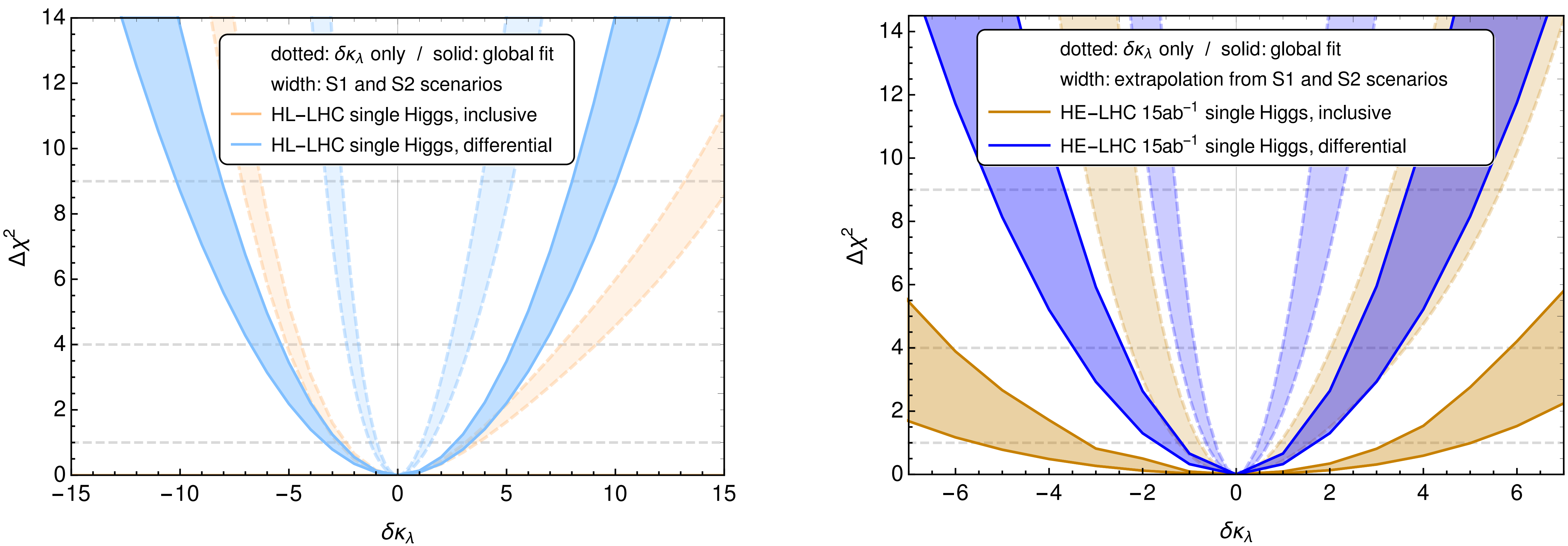
Incl. single Higgs data



Surprisingly, trilinear loop-induced contributions anyway affect the precision in the determination of the other parameters entering at the tree level.

Di Vita, Grojean, Panico, Riembau, Vantalon '17

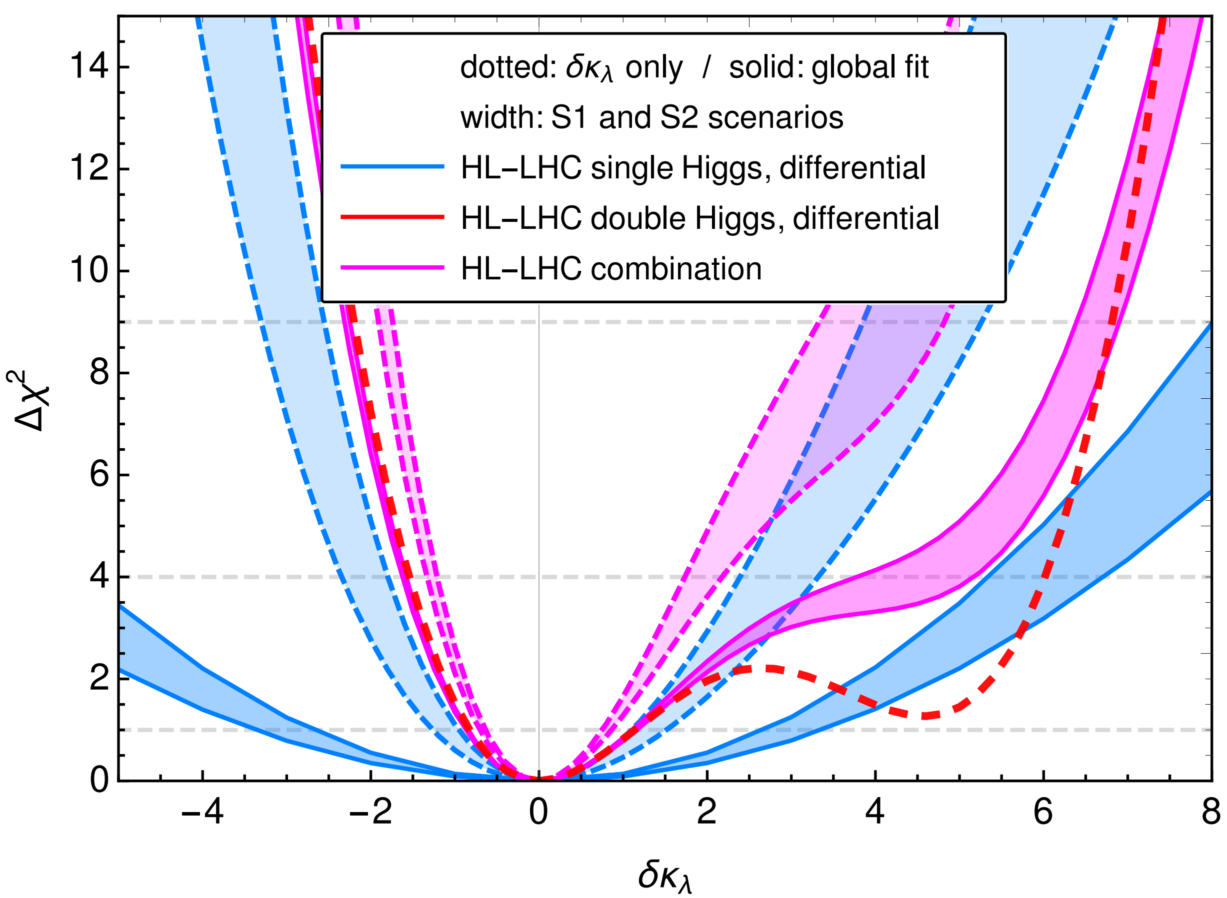
Combined fit with other EFT parameters

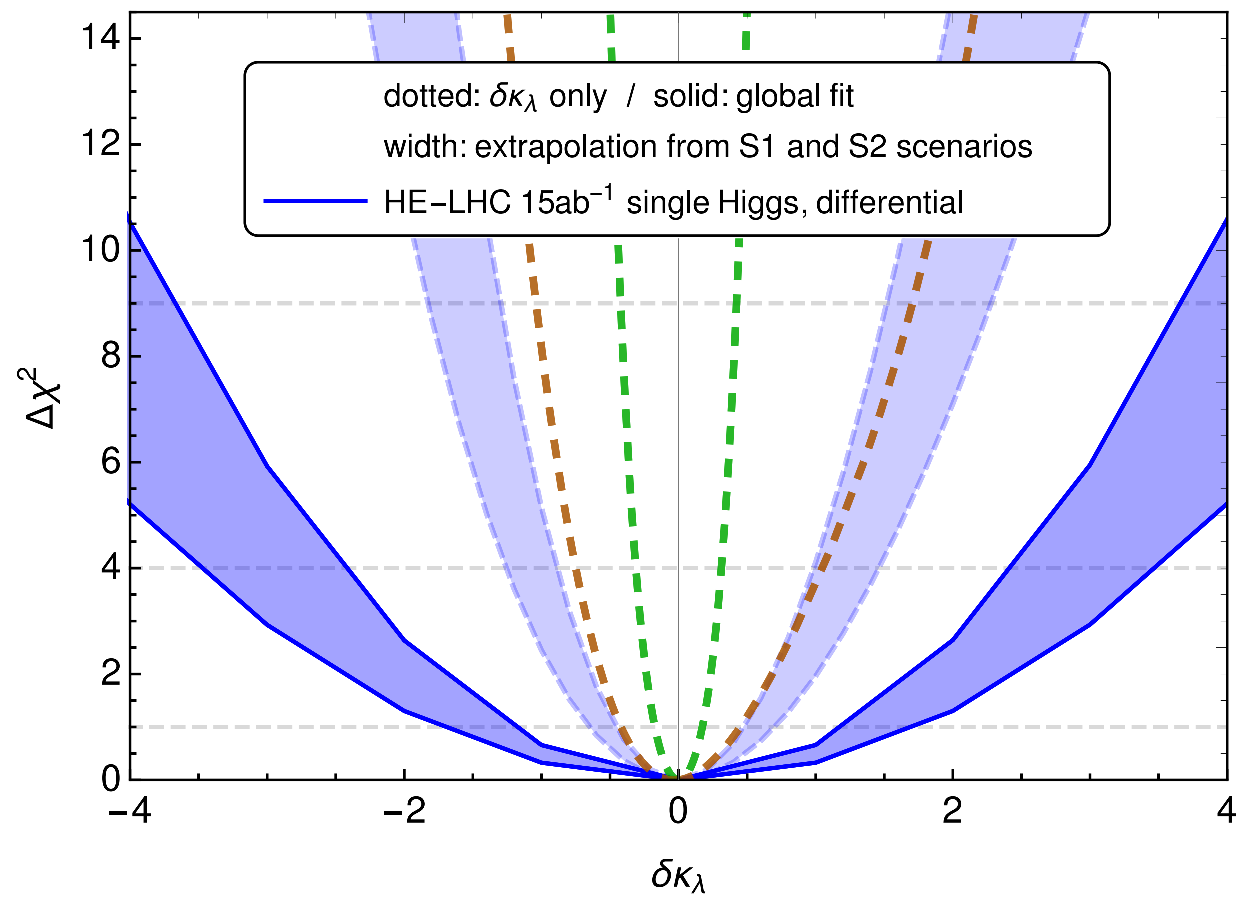


HL- HE-LHC Report WG2

With new projections, also in a global EFT competitive results can be obtained at the HL-LHC. At the HE-LHC, also tH and H—>Zgamma available: 11 constraints already at the inclusive level.

Combined fit with other EFT parameters

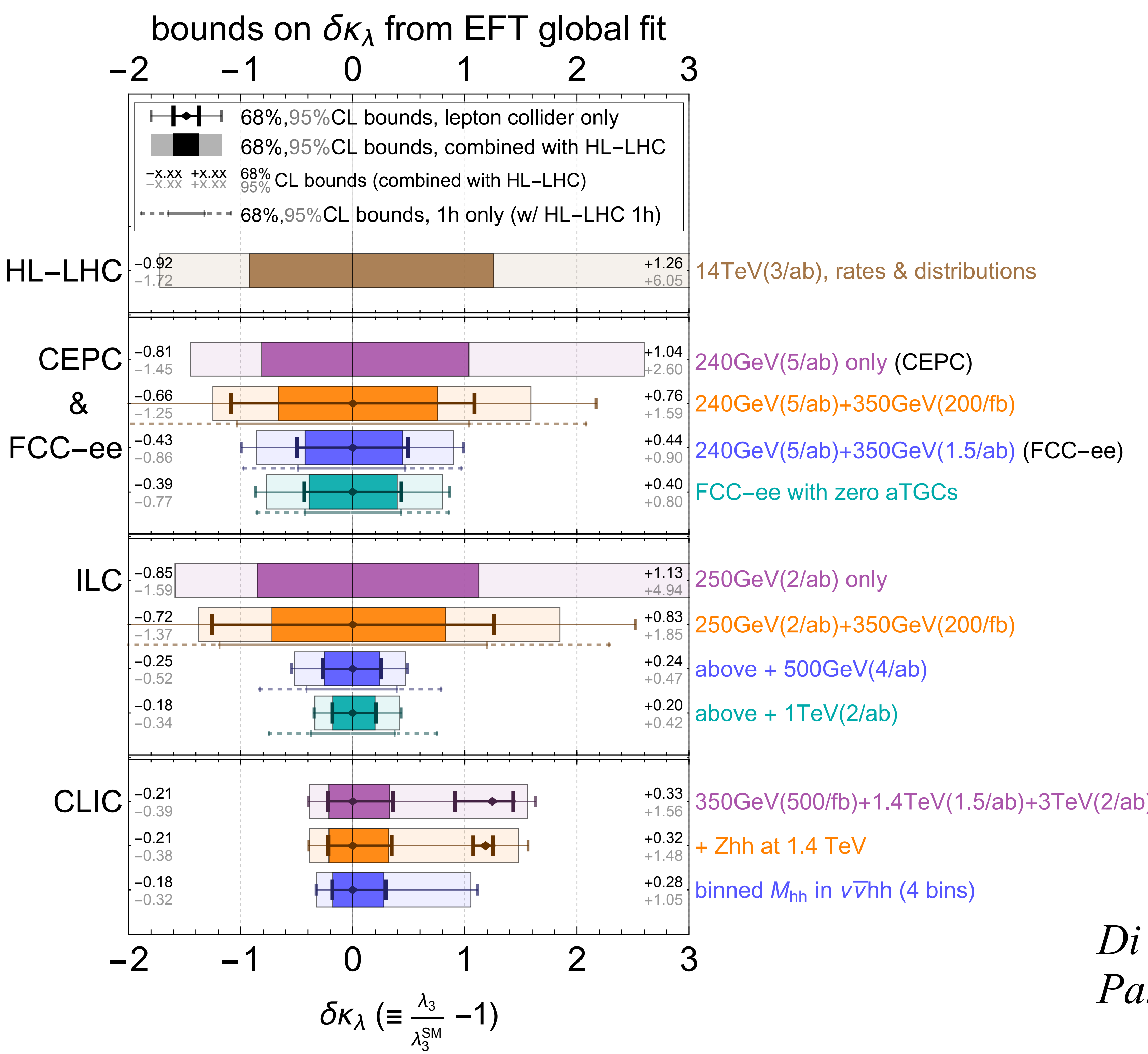


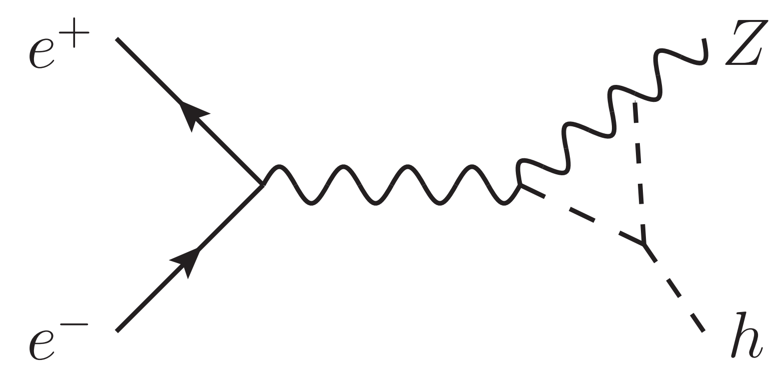


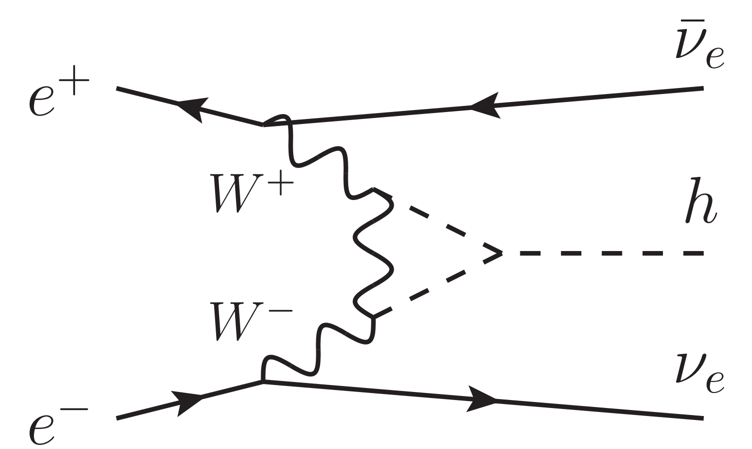
HL- HE-LHC Report WG2

Combination with HH improves final results.

Combined fit with other EFT parameters (e+e-)







Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17

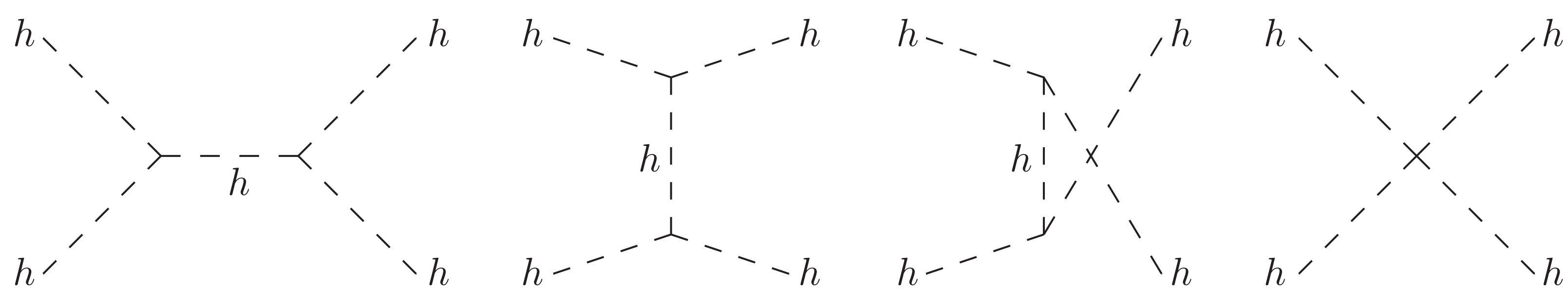
see also
Barklow, Fujii, Junga, Peskin, Tian '18

Additional related aspects

How large can be the self couplings?

Di Luzio, Gröber, Spannowsky '17

- EFT is not the right framework for extracting bounds on Higgs self couplings from the stability of the vacuum.
- General bounds can be extracted from **perturbativiy arguments**.

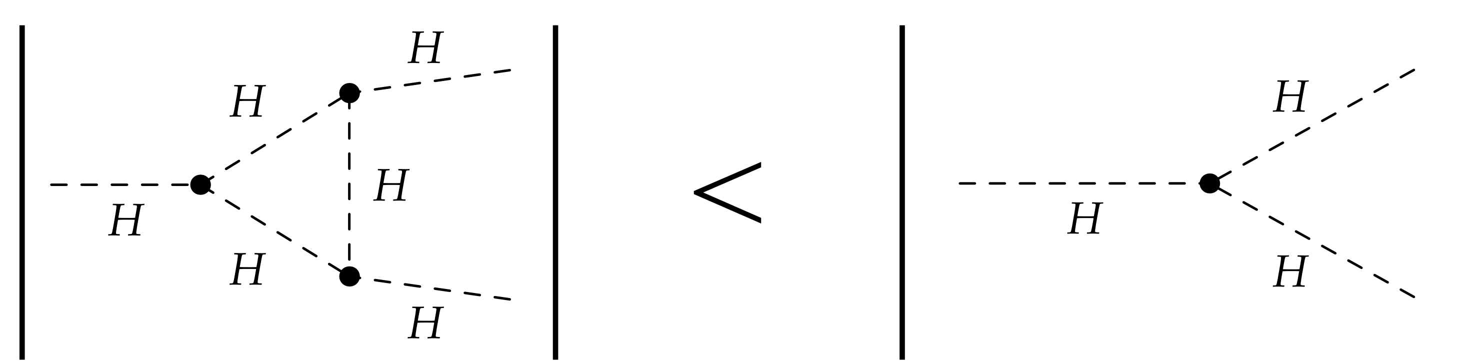


The $J = 0$ partial wave is found to be

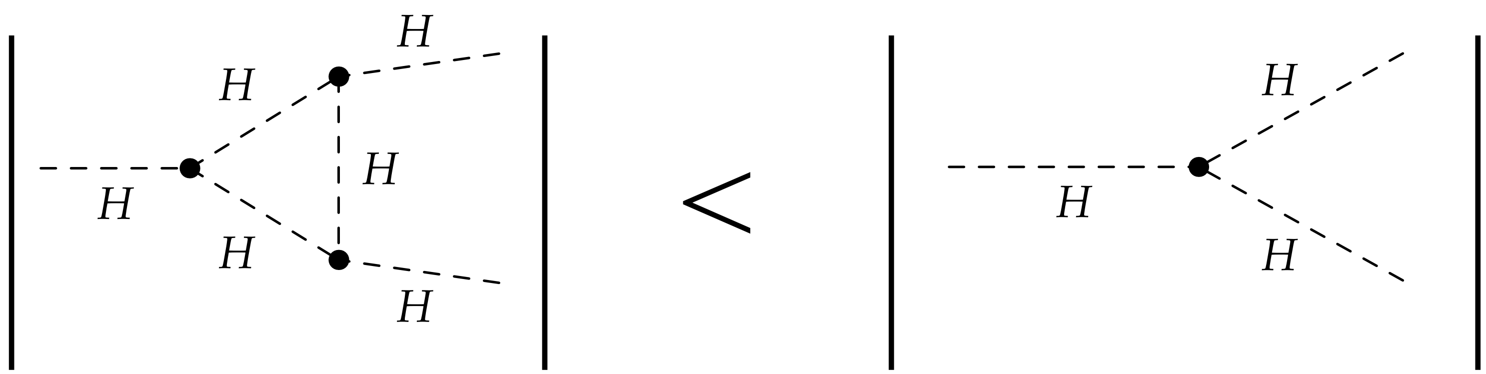
$$a^0_{hh\to hh} = -\frac{1}{2}\frac{\sqrt{s(s-4m_h^2)}}{16\pi s}\left[\lambda_{hhh}^2\left(\frac{1}{s-m_h^2} - 2\frac{\log\frac{s-3m_h^2}{m_h^2}}{s-4m_h^2}\right) + \lambda_{hhhh}\right]$$

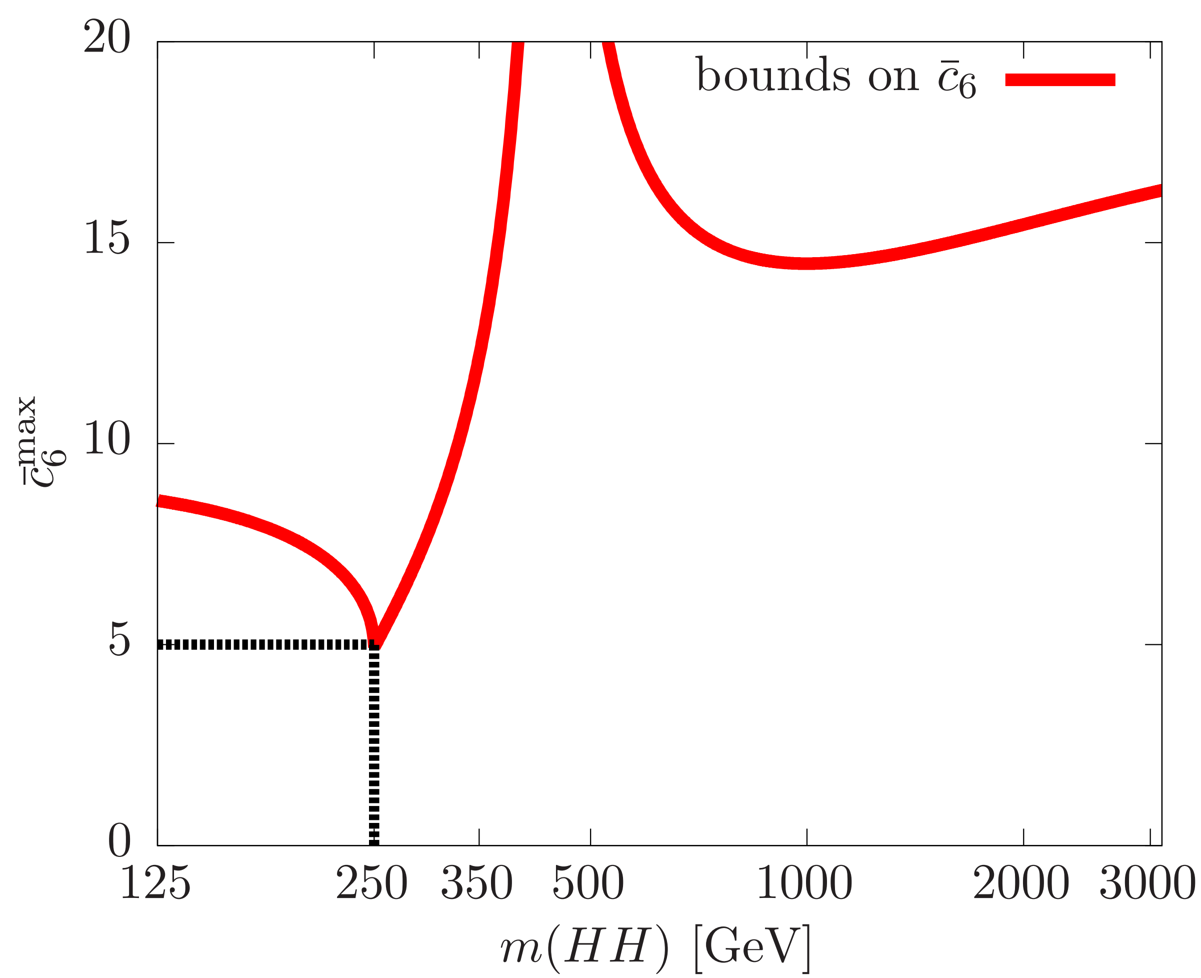
$$\left|\mathrm{Re}\, a^0_{hh\to hh}\right| < 1/2 \quad \Rightarrow \quad \left|\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}\right| \lesssim 6.5 \quad \text{and} \quad \left|\lambda_{hhhh}/\lambda_{hhhh}^{\mathrm{SM}}\right| \lesssim 65$$

Similar bounds on the trilinear by requiring for any external momenta:



How large can be the self couplings?





Strongest perturbativity bounds arise from the threshold configuration in double Higgs production, NOT present in single Higgs production.

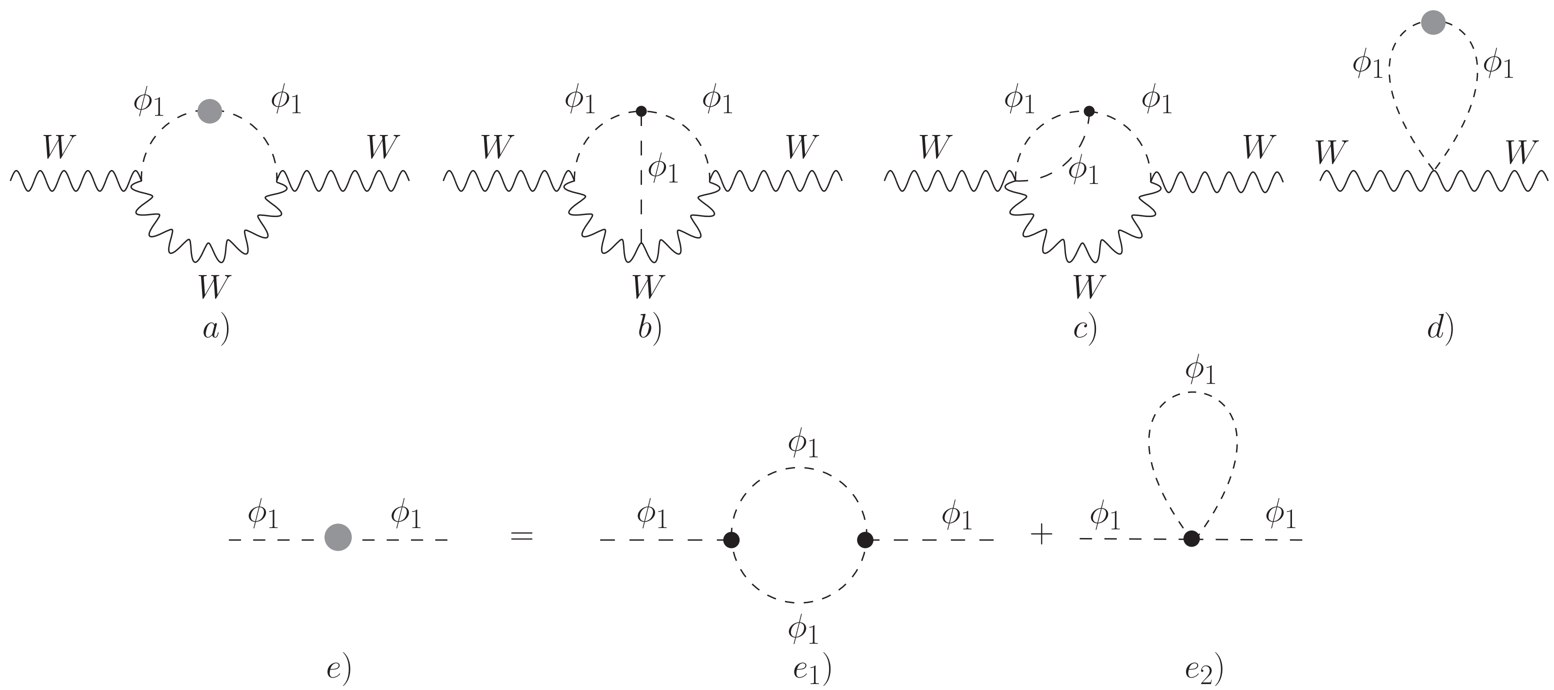
$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda \Lambda^2} \equiv 1 + \bar{c}_6$$

Maltoni, DP, Zhao '18

EWPO: dependence on the Higgs self coupling

The trilinear coupling enters the two-loop relations among m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$ and the EW input parameters. At two-loop, there is not dependence on the quadrilinear coupling.

Degrassi, Fedele, Giardino '17



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

$$\sin^2\theta_{\rm eff}^{\rm lep} = \hat k_\ell(m_Z^2)\hat s^2, \qquad \hat k_\ell(m_Z^2) = 1 + \delta\hat k_\ell(m_Z^2)$$

$$\hat A = (\pi\hat\alpha(m_Z)/(\sqrt{2}G_\mu))^{1/2}$$

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

$$\hat\rho \equiv \frac{m_W^2}{m_Z^2\hat c^2} = \frac{1}{1-\boxed{Y_{\overline{MS}}}}$$

Terms affected by κλ

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\hat\alpha(m_Z)}{2m_W^2\hat s^2}(1+\boxed{\Delta\hat r_W})$$

EWPO: dependence on the Higgs self coupling

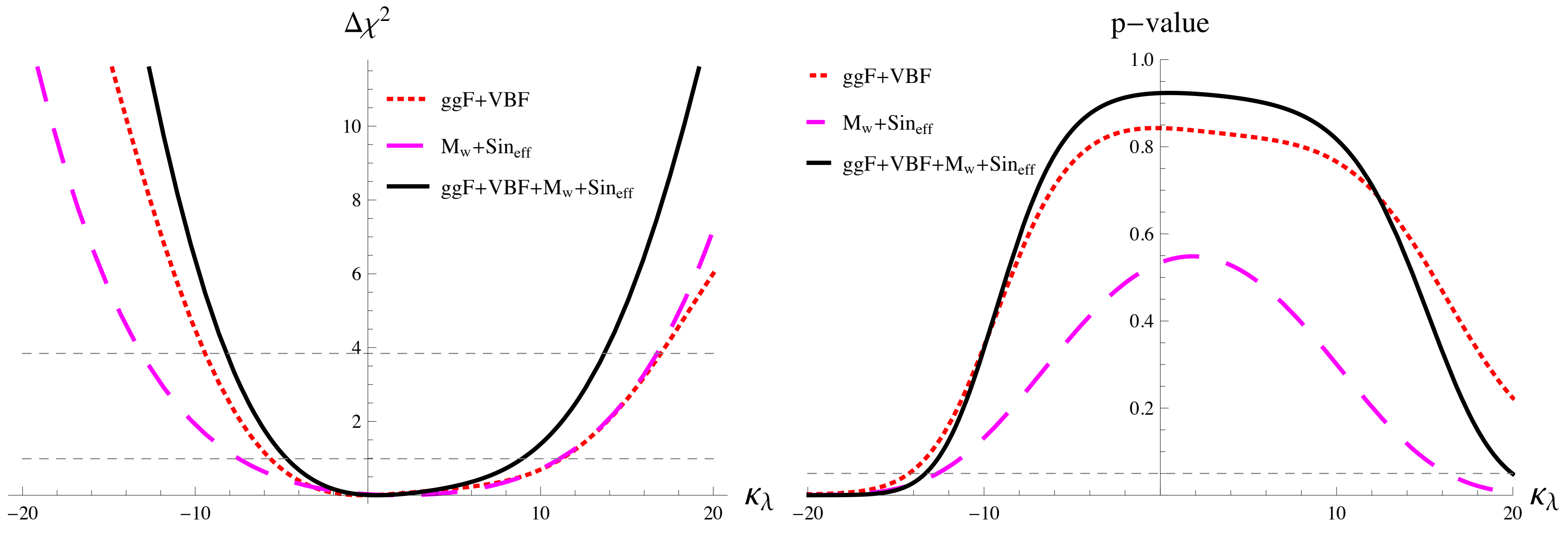
Denoting as O either m_W or $\sin^2\theta_{\rm eff}^{\rm lep}$ one can write

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

	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}

Degrassi, Fedele, Giardino '17

$$m_W = 80.370 \pm 0.019 \text{ GeV}$$
$$\sin^2\theta_{\rm eff}^{\rm lep} = 0.23185 \pm 0.00035$$



ggF+VBF (8TeV)

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

ggF+VBF (8TeV) + EWPO

$$\kappa_\lambda^{\rm best} = 0.5\,, \qquad \kappa_\lambda^{1\sigma} = [-4.7, 8.9]\,, \qquad \kappa_\lambda^{2\sigma} = [-8.2, 13.7]$$

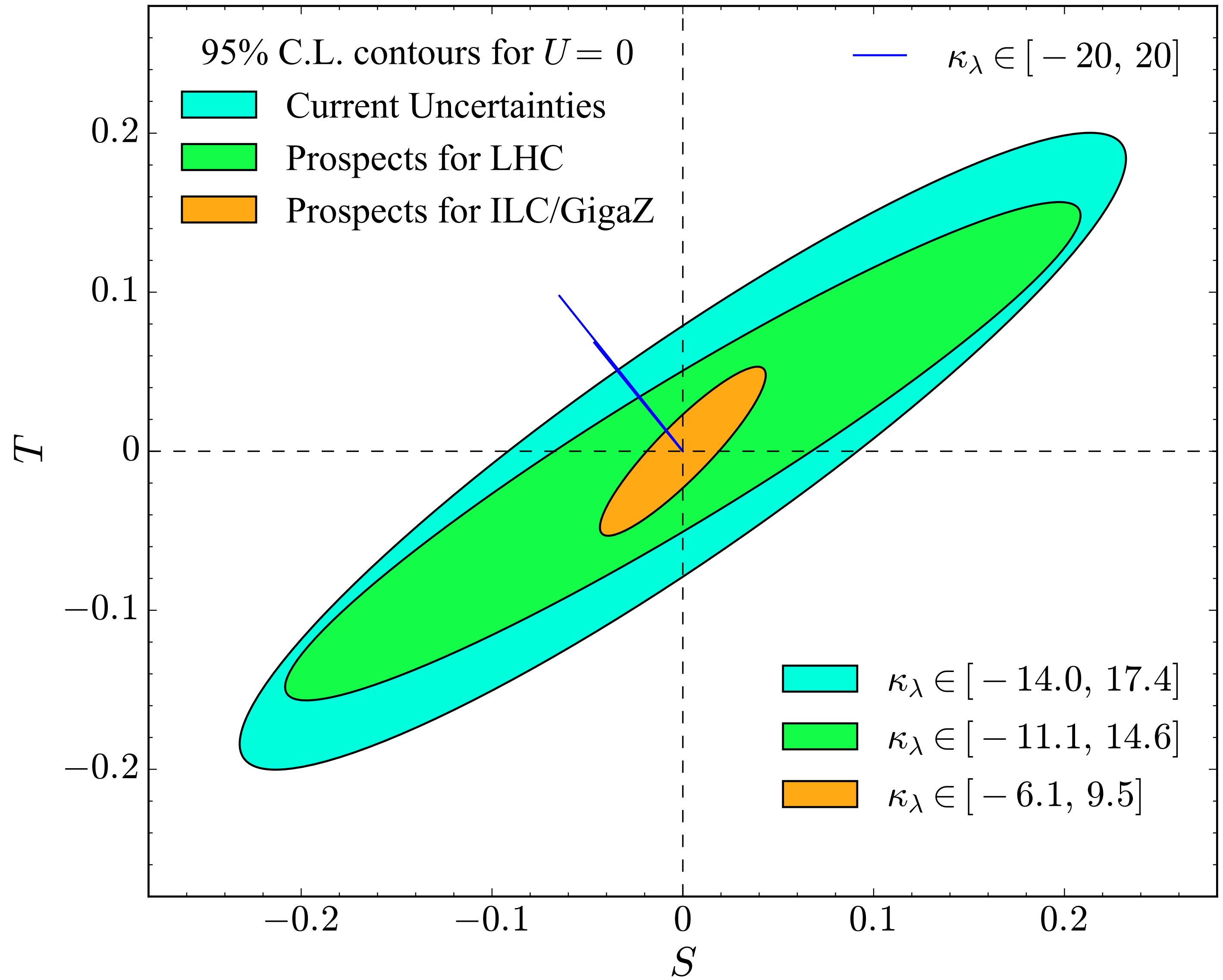
EWPO: dependence on the Higgs self coupling

Equivalent results can be also found looking at S and T oblique parameters.

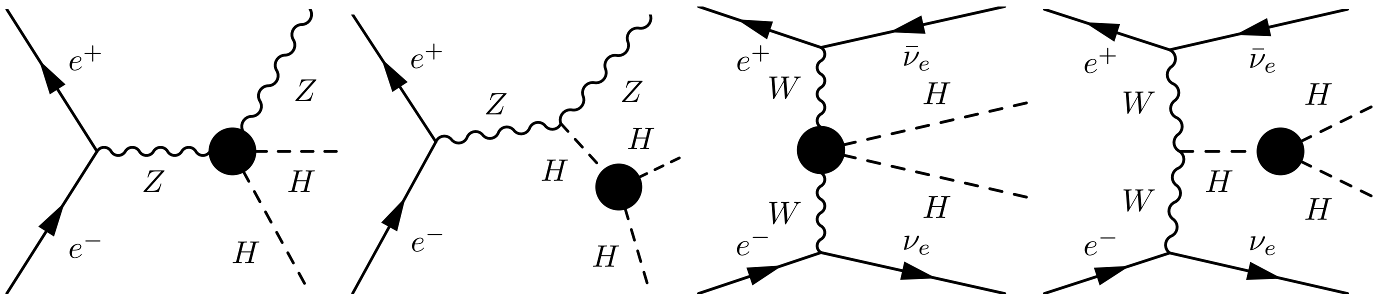
$$S = -0.000138\ (\kappa_\lambda^2 - 1) + 0.000456\ (\kappa_\lambda - 1)$$
$$T = \ \ 0.000206\ (\kappa_\lambda^2 - 1) - 0.000736\ (\kappa_\lambda - 1)$$

$$\Rightarrow \quad -14.0 \leq \kappa_\lambda \leq 17.4$$

Kribs, Maier, Rzehak, Spannowsky, Waite '17

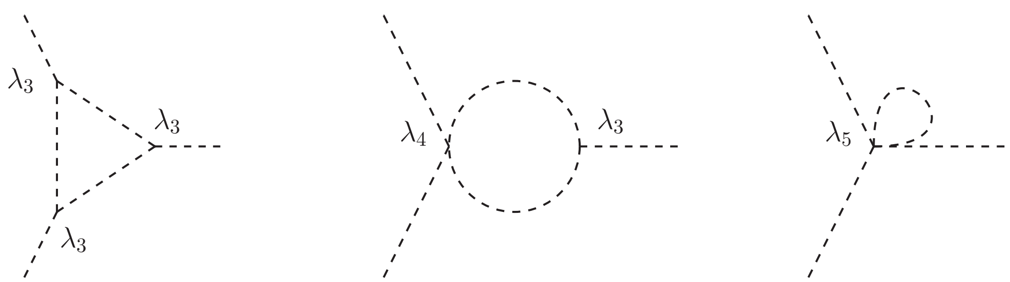


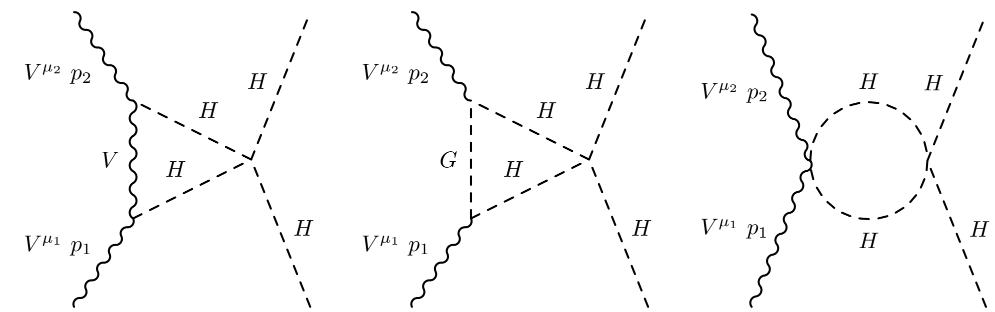
Quartic coupling at lepton colliders



from **triple** in **single** Higgs
to **quartic** in **double** Higgs

Maltoni, DP, Zhao ’18





EFT is mandatory, UV divergences have to be renormalised.

$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda \Lambda^2} \equiv 1 + \bar{c}_6 , \qquad \kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{\rm SM}} = 1 + \frac{6 c_6 v^2}{\lambda \Lambda^2} + \frac{4 c_8 v^4}{\lambda \Lambda^4} \equiv 1 + 6\bar{c}_6 + \bar{c}_8$$

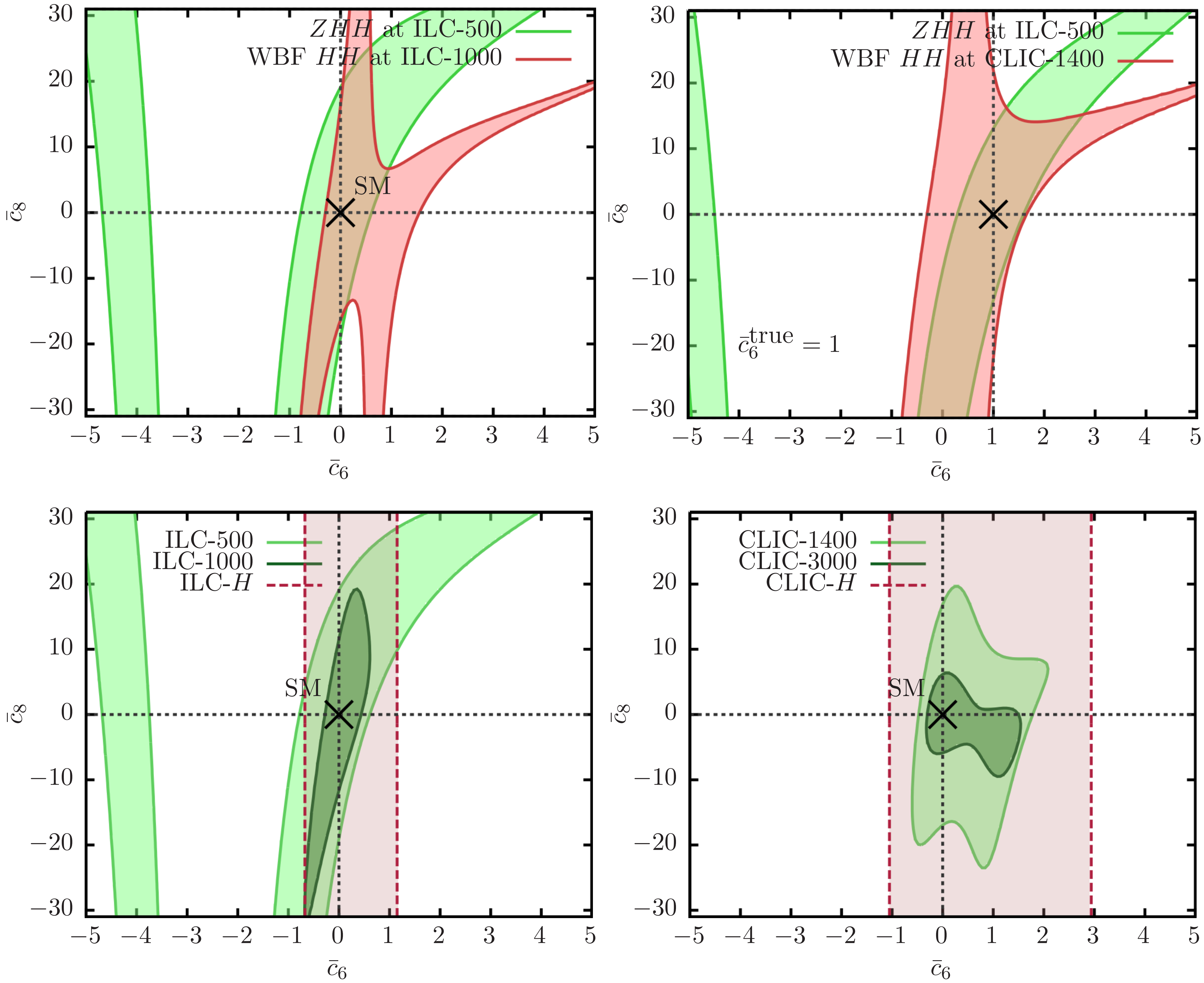
$$\sigma_{\rm NLO}^{\rm pheno}(HH) = \sigma_{\rm LO}(HH) + \Delta\sigma_{\bar{c}_6}(HH) + \Delta\sigma_{\bar{c}_8}(HH)\,,$$

$$\Delta\sigma_{\bar{c}_6}(HH) = \bar{c}_6^3 \Big[\sigma_{30} + \sigma_{40}\bar{c}_6 \Big]\,,$$ ⟵ Triple corrections to the triple

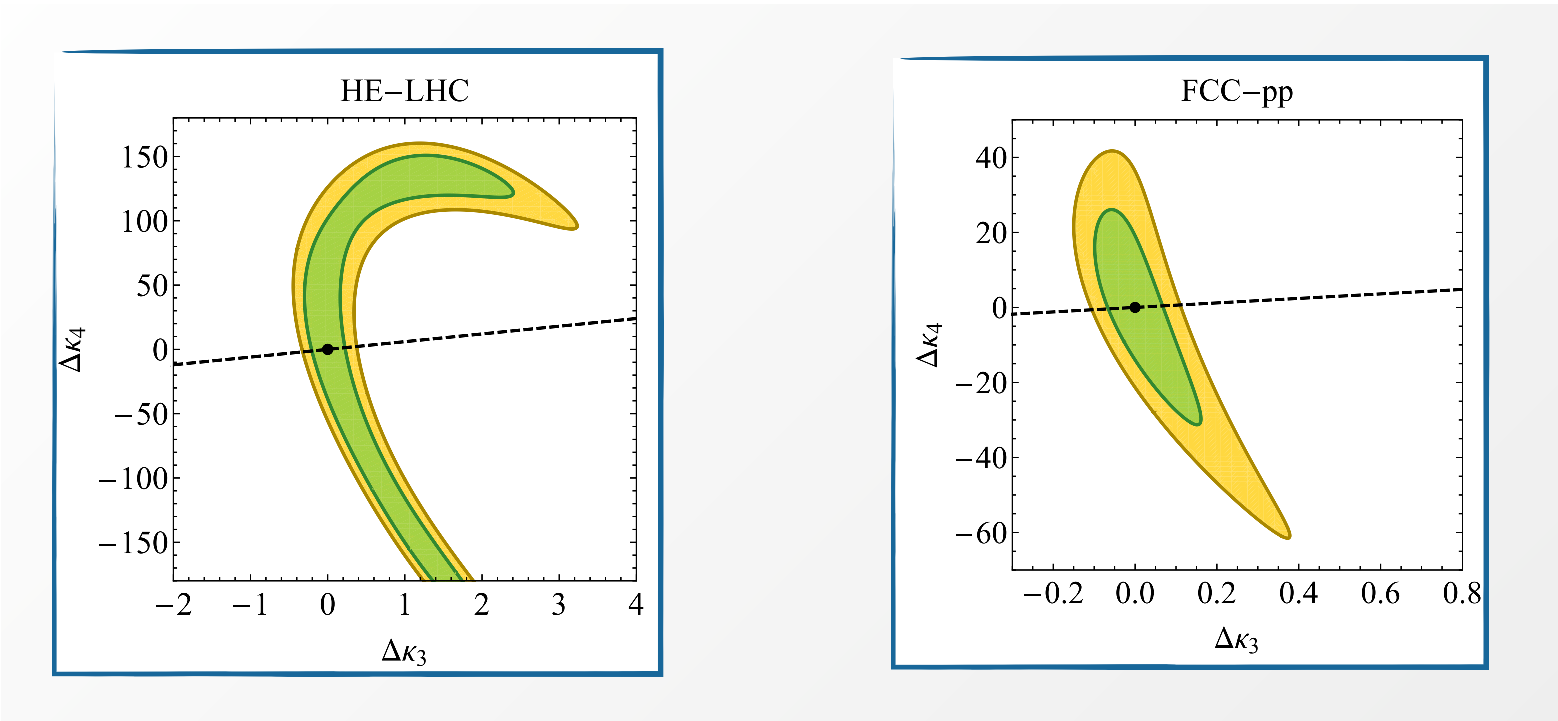
$$\Delta\sigma_{\bar{c}_8}(HH) = \bar{c}_8 \Big[\sigma_{01} + \sigma_{11}\bar{c}_6 + \sigma_{21}\bar{c}_6^2 \Big]\,.$$ ⟵ Sensitivity quartic

Quartic coupling at lepton colliders

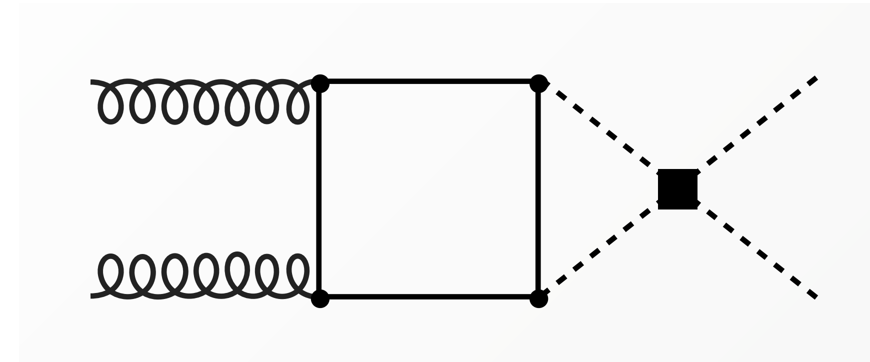
Maltoni, DP, Zhao '18

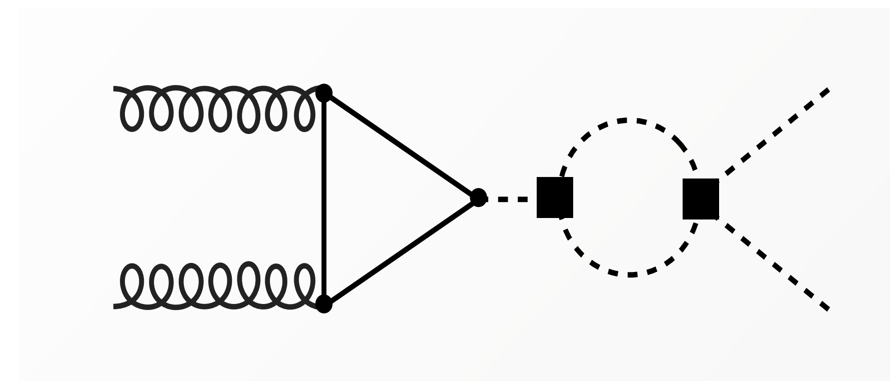


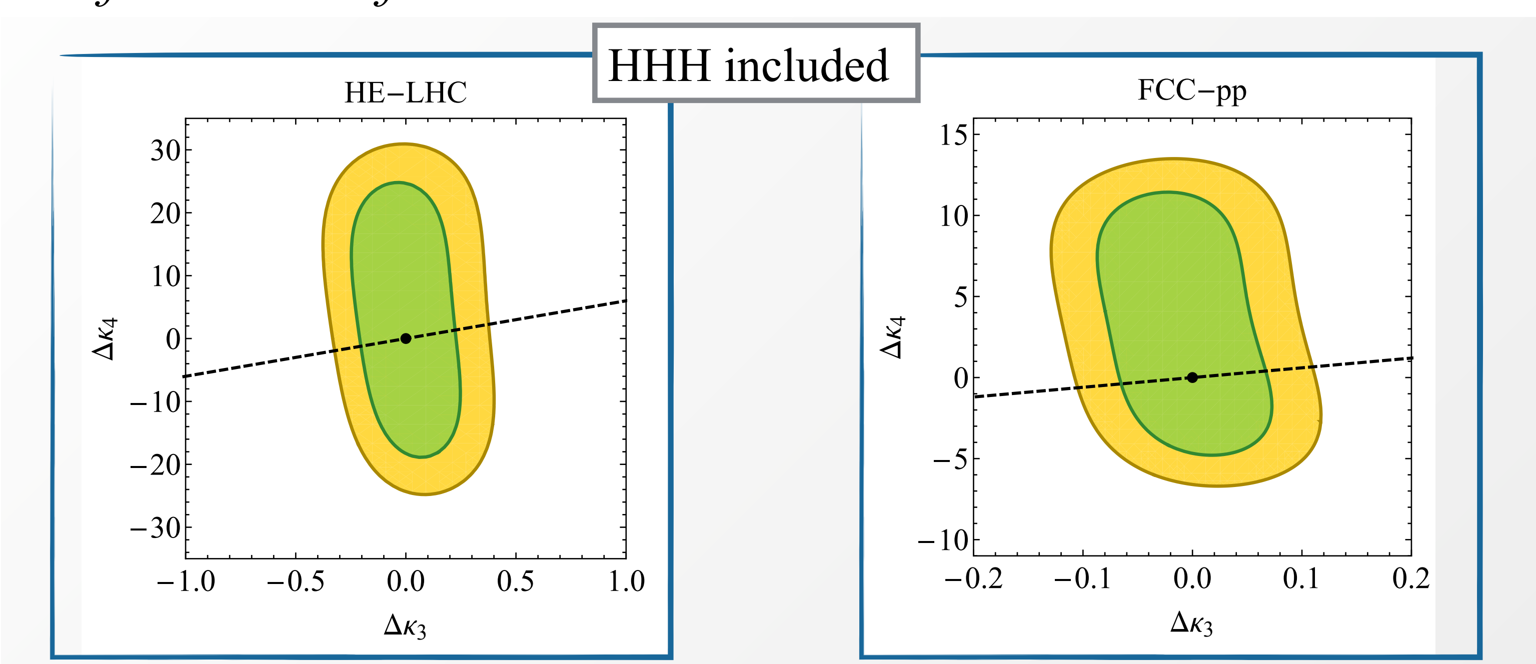
Quartic coupling at hadron colliders: first estimate



from talk of Luca Rottoli







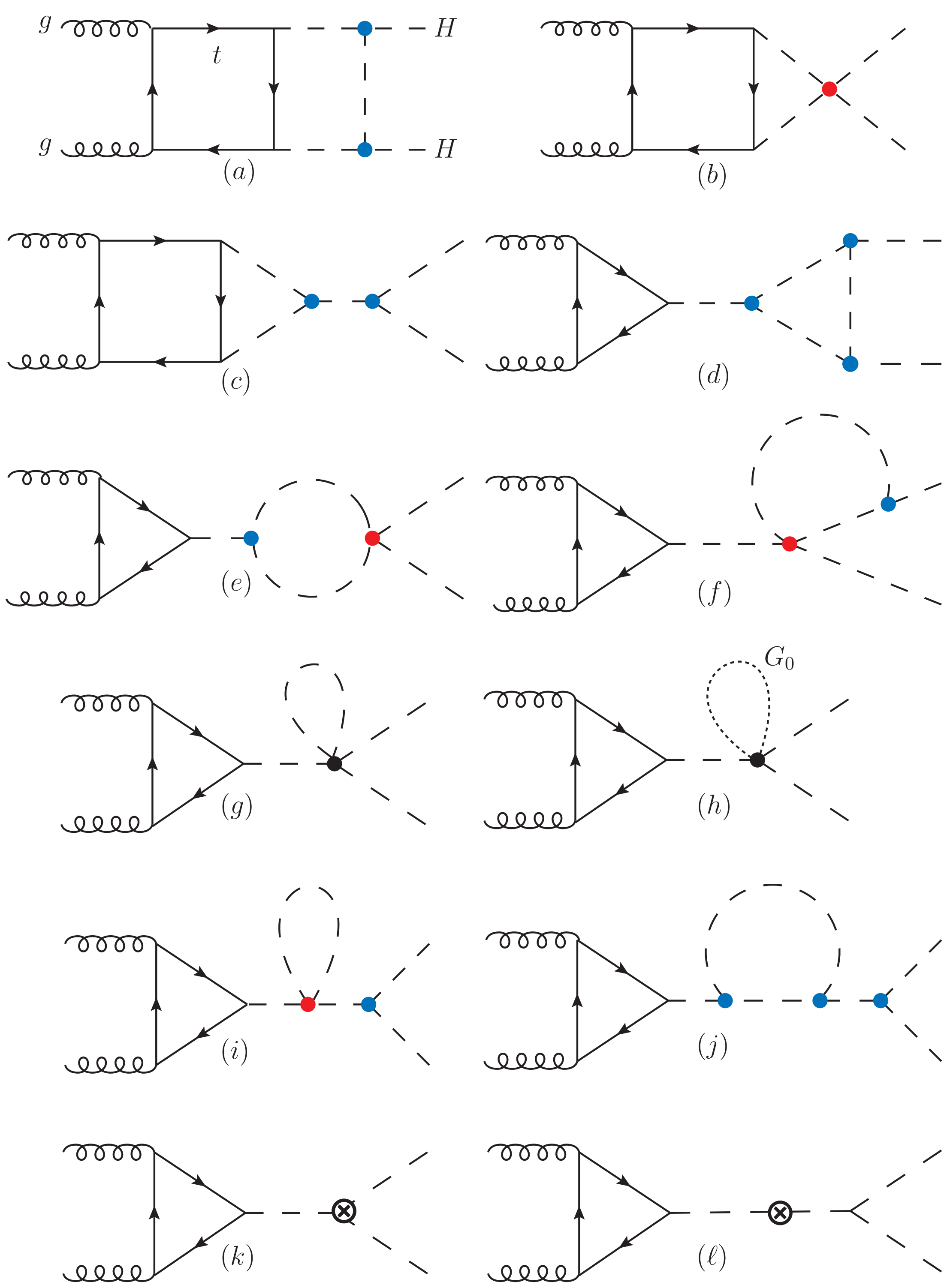
$\kappa_3 = 1$	$\kappa_4 \in [-20{,}29]$	$\kappa_3 = 1$	$\kappa_4 \in [-5{,}13]$
Profiling over κ_3	$\kappa_4 \in [-17{,}25]$	Profiling over κ_3	$\kappa_4 \in [-4{,}12]$

The m(HH) distribution is e in the analysis.

Bizon, Haisch, Rottoli '18

$\kappa_3 \sim 1 \rightarrow |\kappa_4| \lesssim 31$
for sensible results (perturbativity)

Quartic coupling at hadron colliders: full result

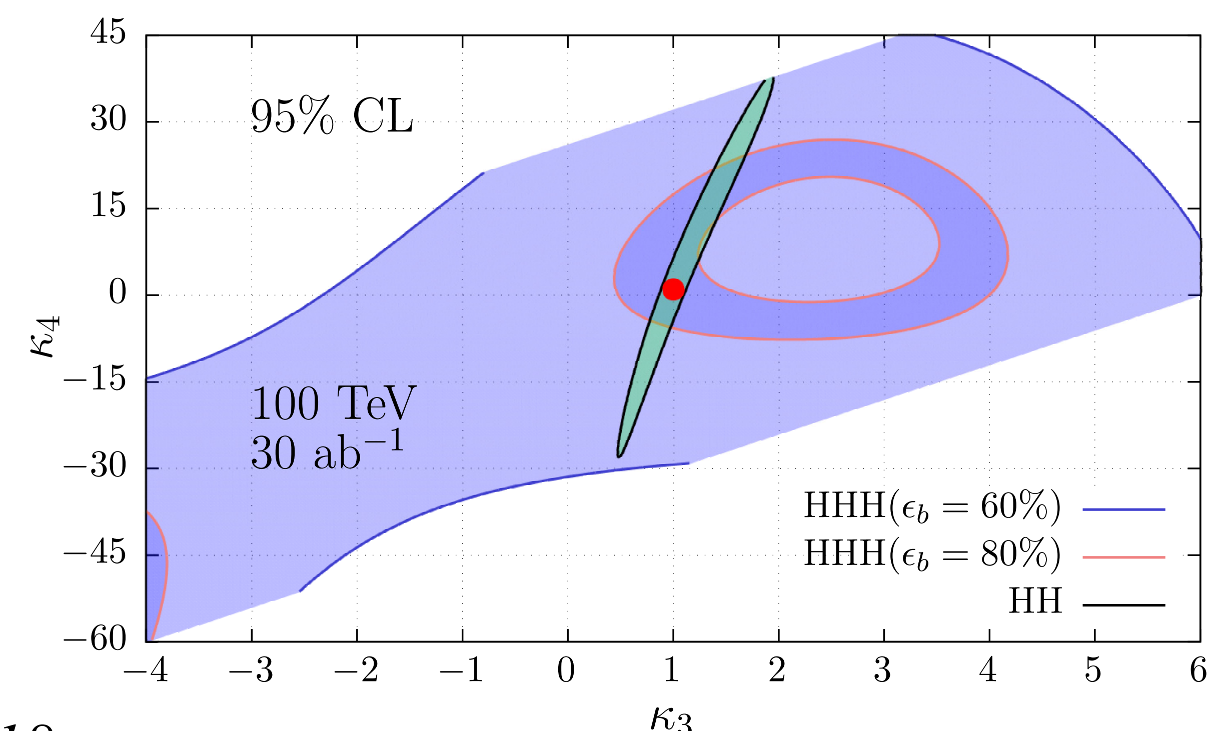


$$\sigma_{\rm NLO}^{\rm pheno} = \sigma_{\rm LO} + \Delta\sigma_{\bar{c}_6} + \Delta\sigma_{\bar{c}_8}$$

$$\Delta\sigma_{\bar{c}_6} = \bar{c}_6^2\left[\sigma_{30}\bar{c}_6 + \sigma_{40}\bar{c}_6^2\right] + \tilde{\sigma}_{20}\bar{c}_6^2\,,$$

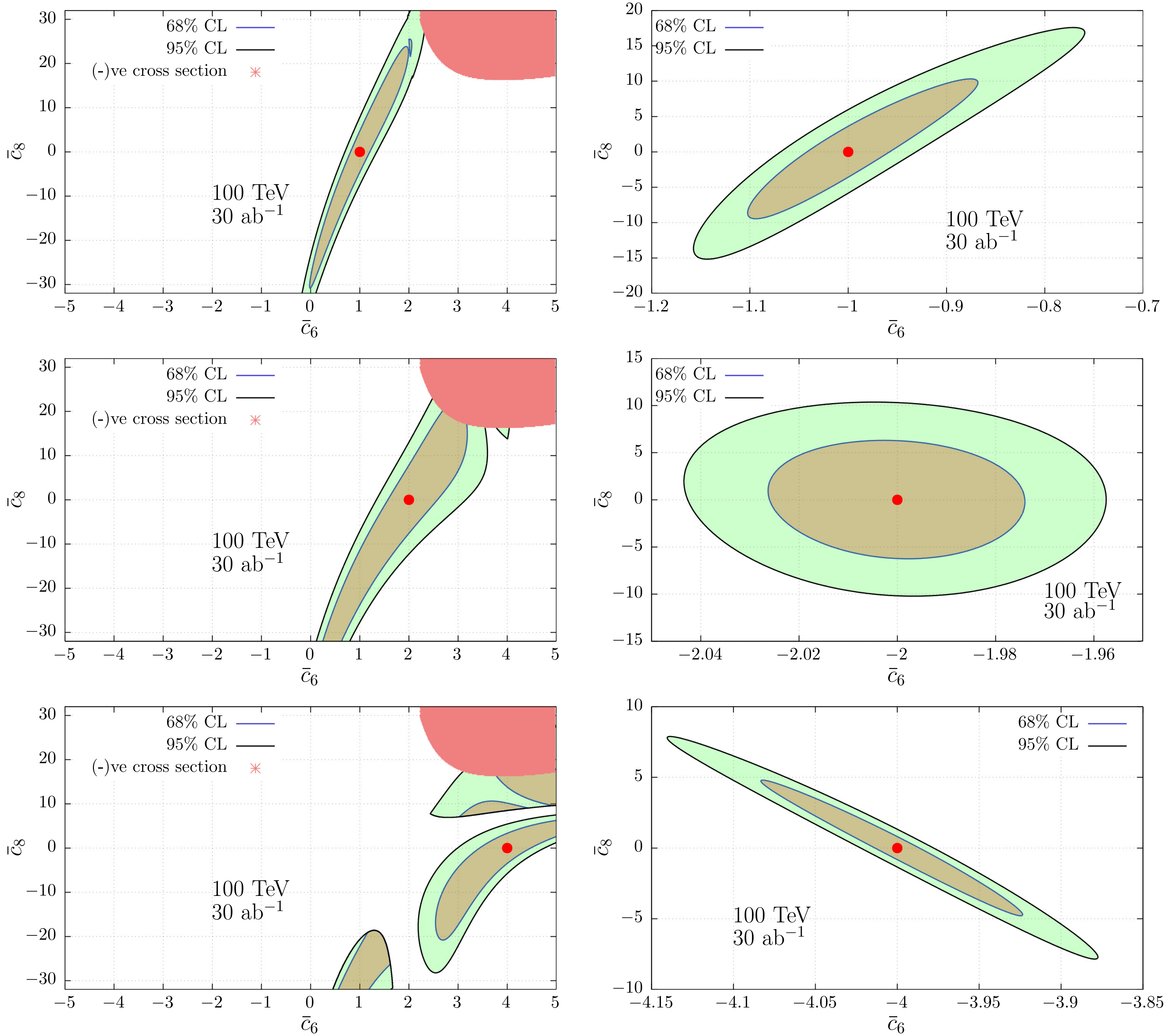
$$\Delta\sigma_{\bar{c}_8} = \bar{c}_8\left[\sigma_{01} + \sigma_{11}\bar{c}_6 + \sigma_{21}\bar{c}_6^2\right]$$

All 2-loop contributions from c8 and at c6^3 and c6^4 order are taken into account and renormalised.
The m(HH) distribution is exploited in the analysis.
Only $b\bar{b}\gamma\gamma$ signature is considered.



Duhr, Borowka, Maltoni, DP, Shivaji, Zhao ‘18

Quartic coupling at hadron colliders: full result



Constraints on c6 and c8 strongly depend on the true value of c6.

For large and negative true values of c6, constraints are much stronger.

Duhr, Borowka, Maltoni, DP, Shivaji, Zhao ‘18

Conclusion

An **alternative method** for the determination of the trilinear Higgs **self coupling** λ_3 is available. It relies on the effects that **loops** featuring λ_3 would imprint on **single Higgs production and decay** channels at the **LHC**.

The sensitivity to λ_3 via a **one-parameter fit** to the complete set of single Higgs inclusive measurements at the LHC 8 TeV and at 13 TeV with HL is **competitive with** those from **Higgs pair production.**

Including differential information, especially from the threshold, also in a general EFT approach single-Higgs is competitive with double-Higgs.

Perturbativity arguments suggest that $\kappa_\lambda < \sim 6$

We look forward to experimental studies, consistently taking into account correlations among different measurements and experimental errors.

A similar strategy is also possible for the quartic with double-Higgs at 100 TeV.

EXTRA SLIDES

The Master Formula

The term $\Sigma_{\rm NLO}$ is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\rm SM}$. LO is meant dressed by QCD corrections.

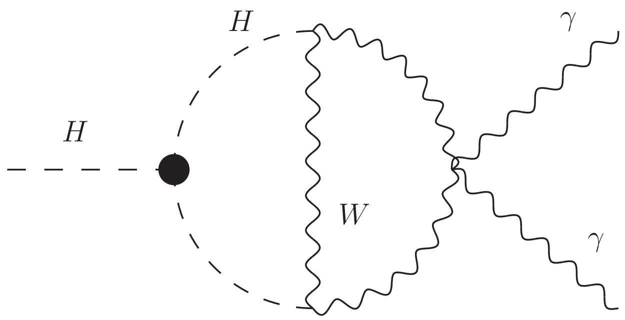
$$\Sigma_{\rm NLO} = Z_H \, \Sigma_{\rm LO} \left(1 + \kappa_\lambda C_1\right)$$

The Master Formula

The term Σ_{NLO} is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\mathrm{SM}}$. LO is meant dressed by QCD corrections.

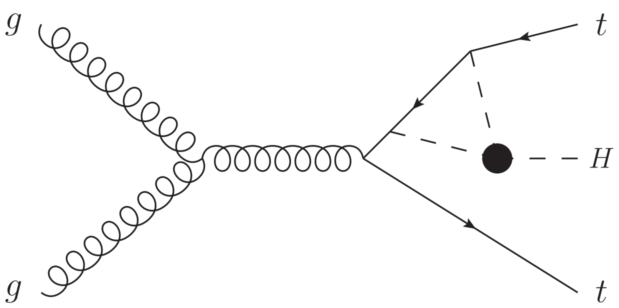
$$\Sigma_{\mathrm{NLO}} = Z_H\, \Sigma_{\mathrm{LO}}\, (1 + \kappa_\lambda \boxed{C_1})$$

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



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

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



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

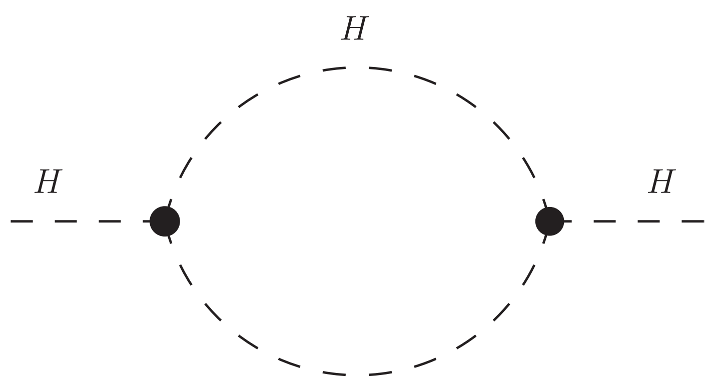
The Master Formula

The term $\Sigma_{\rm NLO}$ is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\rm SM}$. LO is meant dressed by QCD corrections.

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

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

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



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

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.

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

For a sensible resummation

The Master Formula

The term $\Sigma_{\rm NLO}$ is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\rm SM}$. LO is meant dressed by QCD corrections.

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

$$\Sigma_{\rm NLO}^{\rm SM} = \Sigma_{\rm LO} \left(1 + C_1 + \delta Z_H\right)$$

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

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

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

NLO EW and anomalous couplings

If we modify a SM coupling via $c_i^{\mathrm{SM}} \to c_i \equiv \kappa_i c_i^{\mathrm{SM}}$, do higher-order computations ***remain in general finite*** (UV cancellation)? **NO**

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Exceptions

The renormalization of c_i does not involve EW corrections

c_i is involved in the renormalization of other couplings, but it is not renormalized

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Exceptions

The renormalization of c_i does not involve EW corrections

Standard "kappa framework" (No EW corrections possible)

Double Higgs dependence on κ_λ (No EW corrections possible)

c_i is involved in the renormalization of other couplings, but it is not renormalized

Sensitivity of ttbar production on κ_t (NLO EW effect)

Kühn et al. '13; Beneke et al. '15

Sensitivity of single Higgs production on κ_λ (NLO EW effect)

NLO EW and anomalous couplings

If we modify a SM coupling via $c_i^{\rm SM} \to c_i \equiv \kappa_i c_i^{\rm SM}$, do higher-order computations ***remain in general finite*** (UV cancellation)? **NO**

Exceptions

The renormalization of c_i does not involve EW corrections

c_i is involved in the renormalization of other couplings, but it is not renormalized

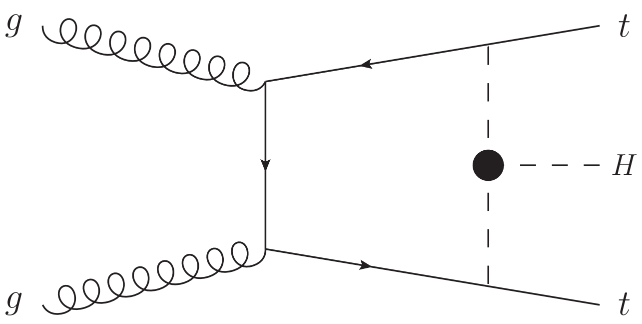
In all cases, $\Lambda_{\rm NP}$ has to be assumed to be not too large in order to have higher-order corrections under control.

In our case, linear EFT (c6) and anomalous coupling (κ_λ) are equivalent at NLO EW.

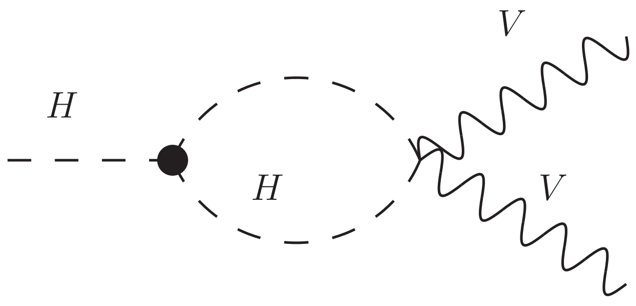
(NLO EW effect)

Calculation of C_1 coefficients

1 Loop Case : *FeynArts, FormCalc, Feyncalc*



ttH



decay and HV, VBF

Cannot be expressed via

κ_t κ_Z, κ_W

Standard "kappa framework" does not capture the full effect

Calculation of C_1 coefficients

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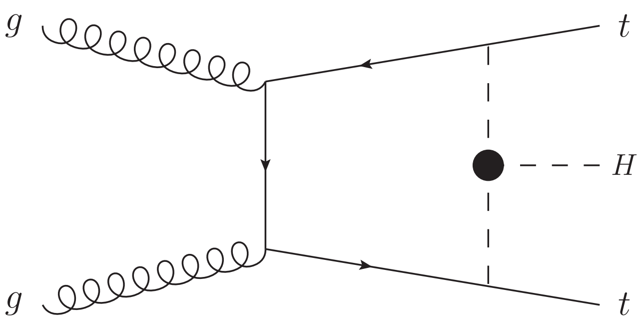

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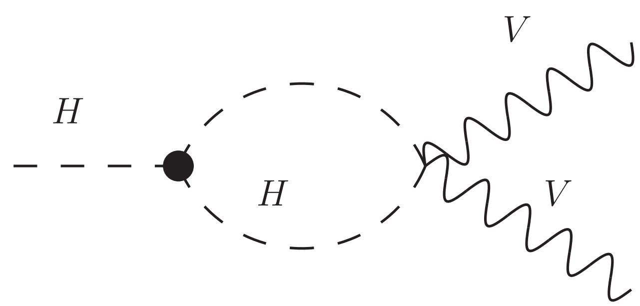


decay and HV, VBF

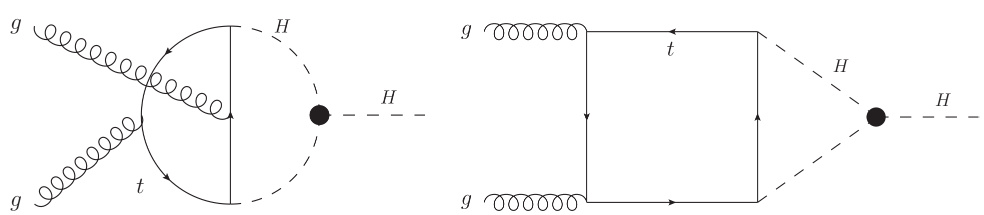
Cannot be expressed via

κ_t $\kappa_Z,\ \kappa_W$

Standard "kappa framework" does not capture the full effect

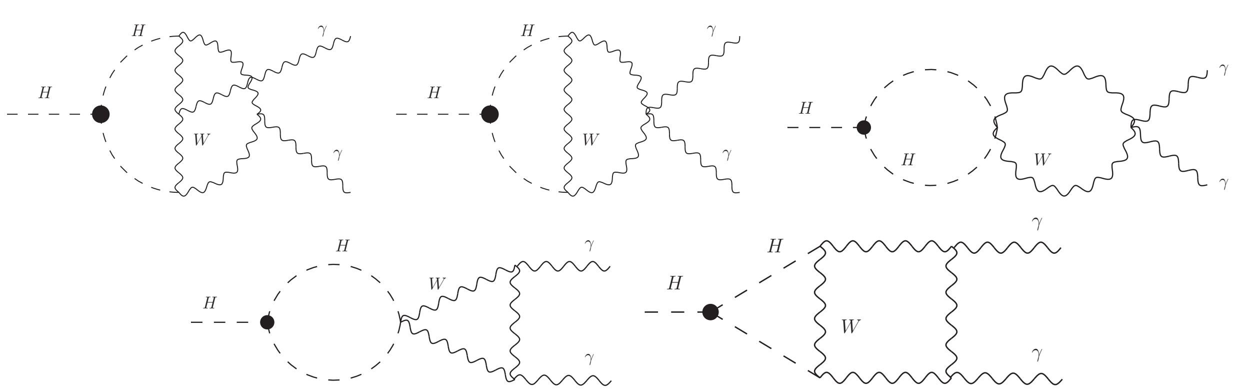
---

2 Loop Case : *FeynArts and expansions*



ggF

Large top-mass expansion with terms up to $\mathcal{O}(m_H^6/m_t^6)$



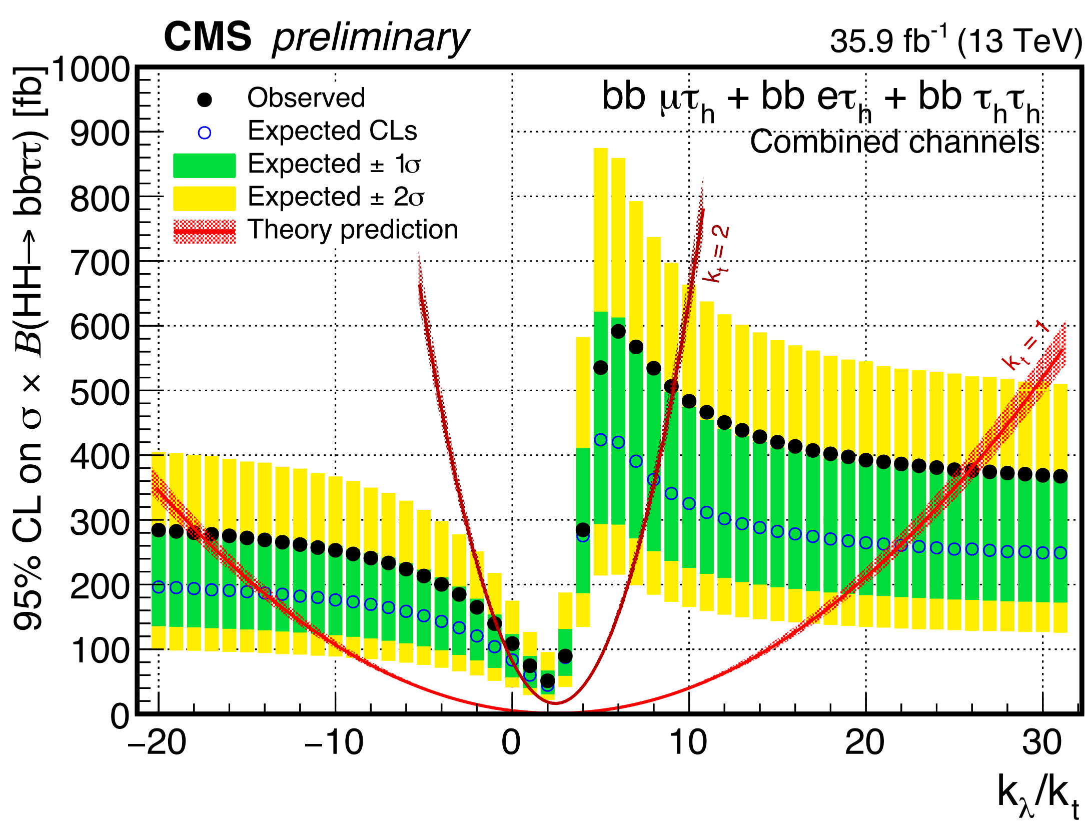
$H \to \gamma\gamma$

Taylor expansion in $q^2/(4m_W^2),\, q^2/(4m_H^2)$ up to $\mathcal{O}(q^6/m^6)$

Calculation performed in unitary gauge in order to identify genuine λ_3-dependence and keep only kinematic m_H-dependence

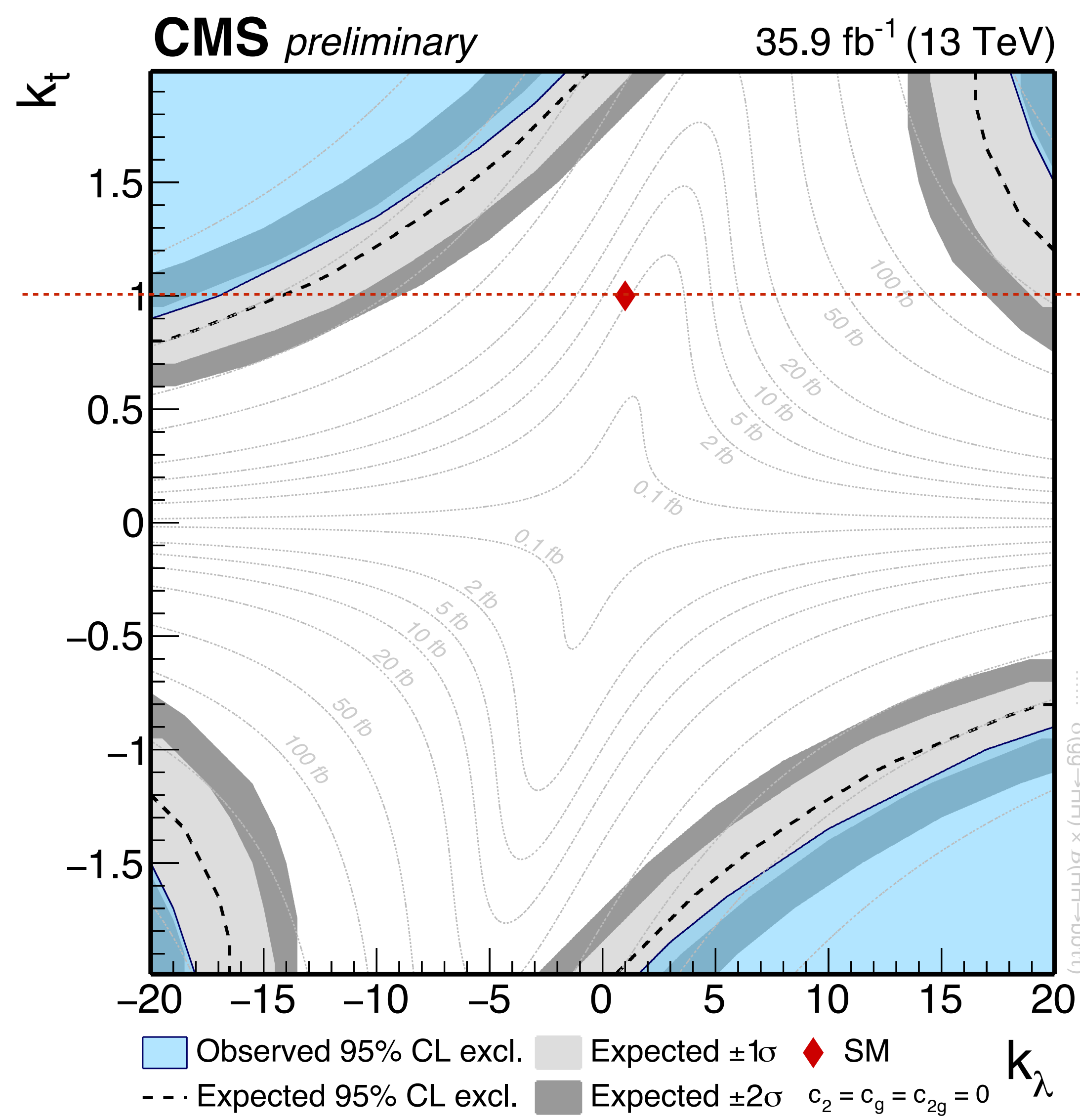
Double Higgs: top-yukawa and trilinear interplay

New experimental analyses including κ_t started to appear.
κ_λ exclusion limits are affected by κ_t value.
(No constraints from ggF and ttH in the figures below)



CMS PAS HIG-17-002

(a) k_λ / k_t scan



(b) Exclusion in (k_λ, k_t) plane

Combined fit with others EFT parameters

$$
\begin{aligned}
\mathcal{L} \supset \frac{h}{v}\Bigg[&\delta c_w \frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu \\
&+ c_{ww}\frac{g^2}{2} W^+_{\mu\nu} W_{-\mu\nu} + c_{w\Box} g^2 \left(W^+_\mu \partial_\nu W_{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu} \\
&+ c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu}\Bigg] \\
&+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}^{(2)}_{gg}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f\left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right] \\
&- (\kappa_\lambda - 1)\lambda_3^{SM} v h^3\,, \qquad (2.5)
\end{aligned}
$$

Di Vita, Grojean, Panico, Riembau, Vantalon '17

$$
\begin{aligned}
\delta c_w &= \delta c_z\,, \\
c_{ww} &= c_{zz} + 2\frac{\pi^2 g'^2}{g^2+g'^2}\hat{c}_{z\gamma} + \frac{9\pi^2 g'^4}{2(g^2+g'^2)^2}\hat{c}_{\gamma\gamma}\,, \\
c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\frac{\pi^2 g'^2}{g^2+g'^2}\hat{c}_{\gamma\gamma} - (g^2-g'^2)\frac{\pi^2 g'^2}{g^2+g'^2}\hat{c}_{z\gamma}\right], \\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + \left(g^2+g'^2\right)c_{zz} - \pi^2 e^2 \hat{c}_{\gamma\gamma} - \pi^2\left(g^2-g'^2\right)\hat{c}_{z\gamma}\right], \\
\hat{c}^{(2)}_{gg} &= \hat{c}_{gg}\,, \\
\delta y_f^{(2)} &= 3\delta y_f - \delta c_z\,.
\end{aligned}
$$

EWPO: trilinear dependence

$$\widehat{\alpha}(M_Z)T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2} \ ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}\,^2_Z\widehat{c}\,^2_Z}S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{M_Z^2} -$$

$$\frac{\widehat{c}\,^2_Z - \widehat{s}\,^2_Z}{\widehat{c}\,_Z\widehat{s}\,_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2} \ ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}\,^2_Z}(S+U) \equiv \frac{\Pi^{\rm new}_{WW}(M_W^2) - \Pi^{\rm new}_{WW}(0)}{M_W^2} -$$

$$\frac{\widehat{c}\,_Z}{\widehat{s}\,_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2} \ .$$

$$\Delta\hat{r}_W^{(2)} = \frac{\mathrm{Re}\,A^{(2)}_{WW}(m_W^2)}{m_W^2} - \frac{A^{(2)}_{WW}(0)}{m_W^2} + \ldots$$

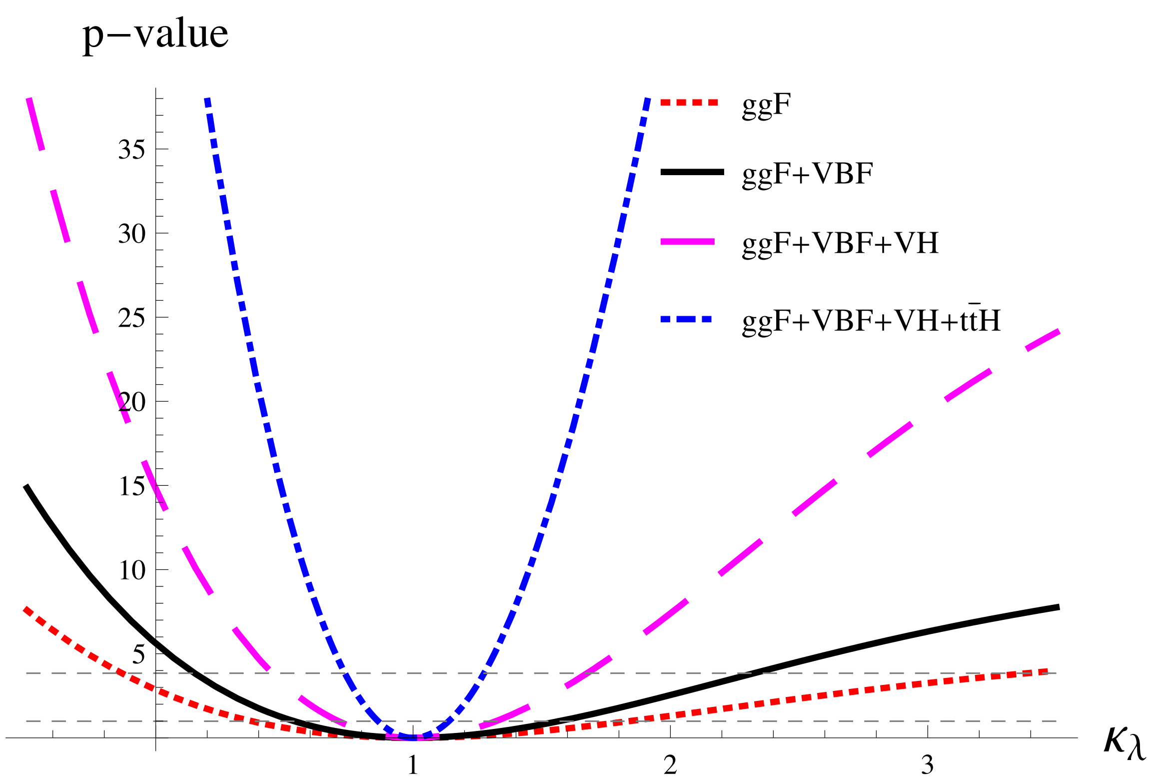
$$Y^{(2)}_{\overline{MS}} = \mathrm{Re}\left[\frac{A^{(2)}_{WW}(m_W^2)}{m_W^2} - \frac{A^{(2)}_{ZZ}(m_Z^2)}{m_Z^2}\right] + \ldots$$

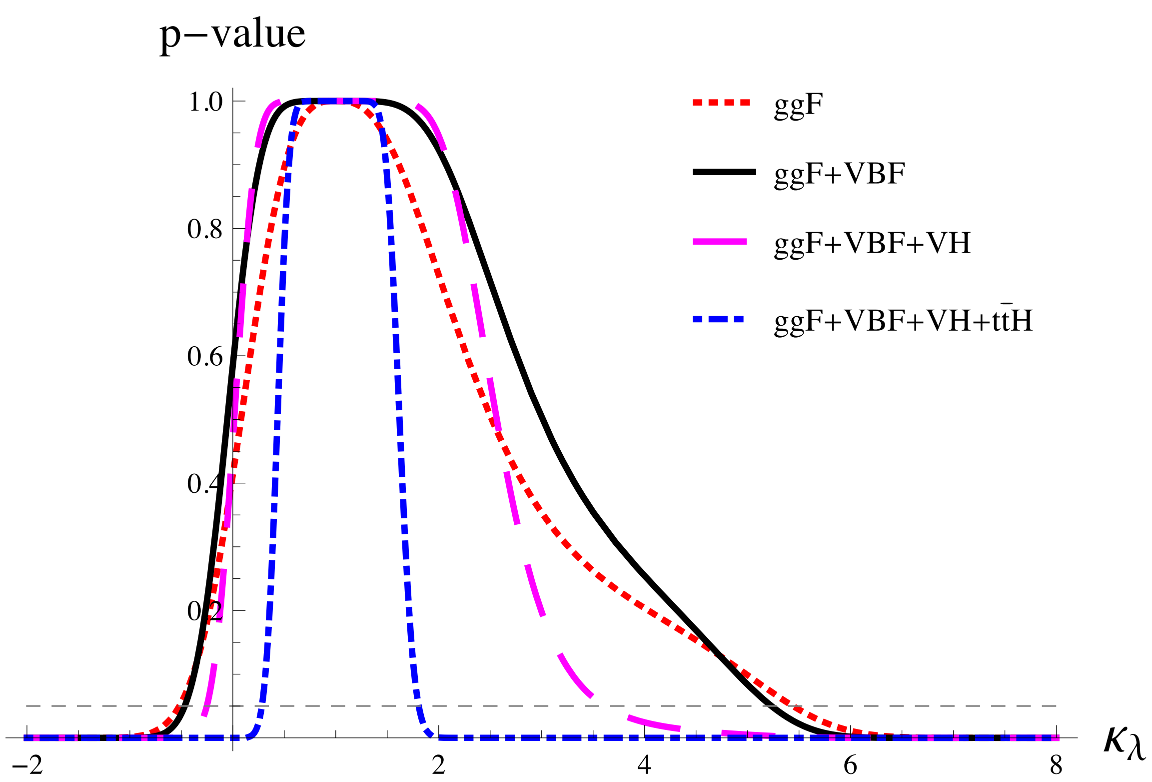
Fit procedure

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

Exercise: 1% errors

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





$$\kappa_\lambda^{1\sigma} = [0.86, 1.14]\,, \qquad \kappa_\lambda^{2\sigma} = [0.74, 1.28]\,, \qquad \kappa_\lambda^{p>0.05} = [0.28, 1.80]$$

The ttH process strongly improves (as expected) the determination of κ_λ.
The statistical analysis suggests also in this case the possibility of obtaining stronger bounds.