

CMS general H combination

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Introduction

The discovery of a new boson with mass of 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV is compatible to the one predicted by the Standard Model (SM):

- Yukawa couplings are free parameters in the SM
- There is still not explanation for the observed values of fermion masses
- The detailed structure of the Higgs sector is still unclear
- Several direct searches for additional Higgs bosons have been carried out Beyond the SM (BSM) excluding a large part of phase space
- Precision measurements of the properties of the Higgs boson are an important test for the SM and Beyond
- Measurements of the Higgs boson properties are more accurate in Run2
 - Coupling measurements are crucial since BSM can manifest as percent-level deviations
 - Couplings affect both production and decay therefore the best constrain comes from the combination of all the accessible channels

- **Higgs production modes and decay channels**
- **Measurements of the signal strength and fiducial cross sections [1]**
- **Coupling modifier models [1]**
- **Constraints on BSM from coupling modifiers [1] and differential cross sections [2]**
- **Summary and outlook**

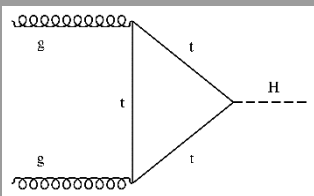
CMS papers taken as reference:

1. Combined measurements of the Higgs couplings with 2016 dataset [arXiv1809.10733]
2. Combination of fiducial differential cross-sections with 2016 dataset [arXiv 1812.06504]

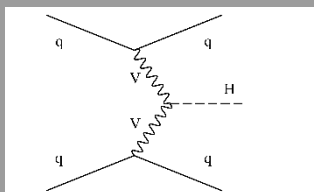
Higgs production and decay modes

Production

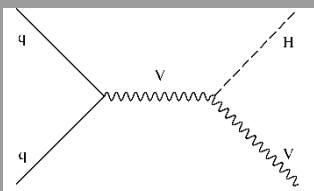
ggH



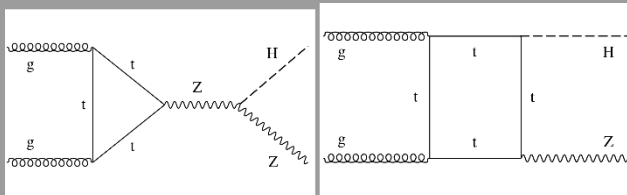
VBF



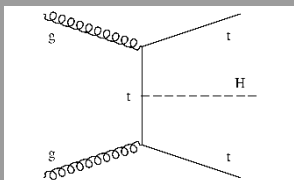
VH



ZH



ttH



Decay

$\gamma\gamma$

ZZ

WW

bb

$\tau\tau$

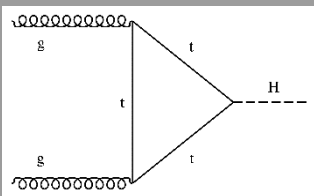
$\mu\mu$

inv

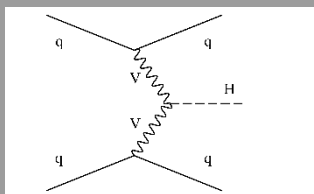
Higgs production and decay modes

Production

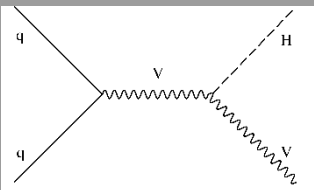
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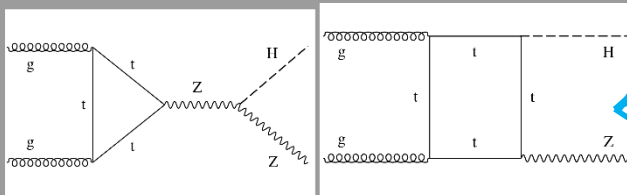
VBF



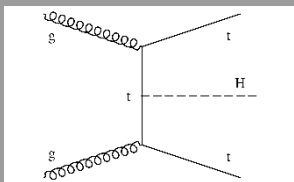
VH



ZH



ttH



Decay

$\gamma\gamma$

ZZ

WW

bb

$\tau\tau$

$\mu\mu$

inv

Several categories per each analysis:

- Sensitive to all the different possible final state decays
- Further categorization to enhance the production mode
- Negligible overlap of events amongst the 256 categories (5500 nuisance parameters to account for the systematic uncertainties)

Signal strength measurements

The **signal strength modifier** μ can be experimentally extracted only for combined production and decay:

$$\mu_i = \frac{\sigma_i}{\sigma_{i,\text{SM}}} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f} \quad \mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

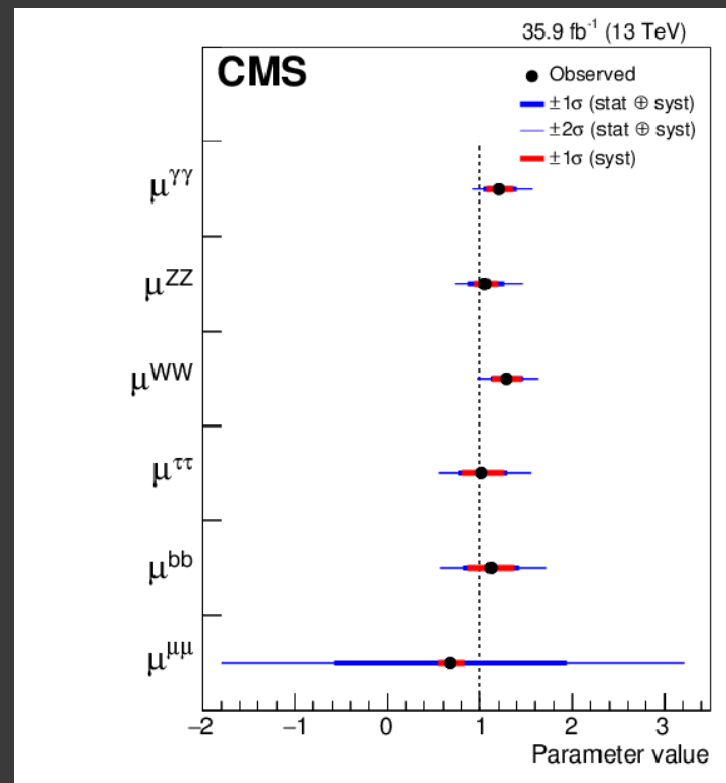
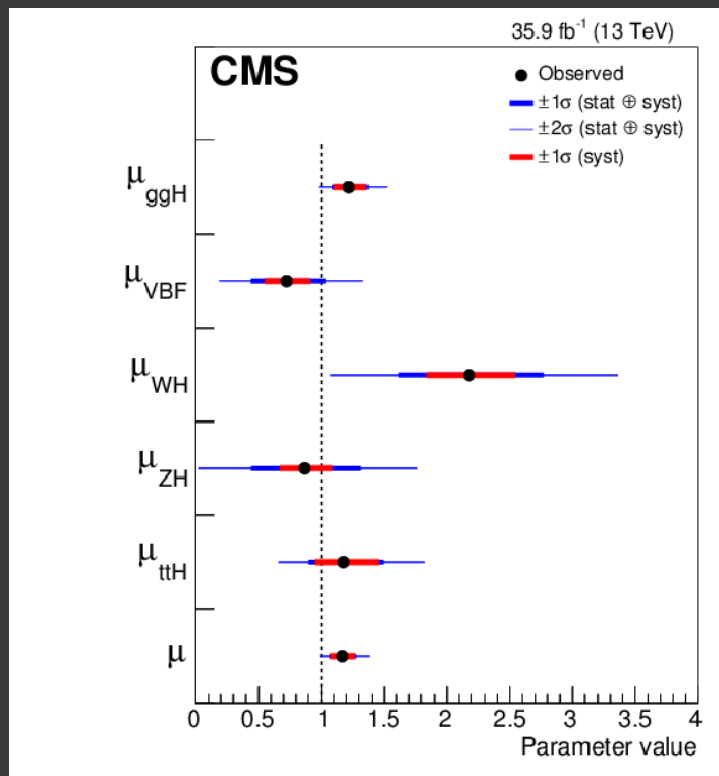
- this parametrization assumes a narrow width approximation
- global signal strength obtained with 35.9 fb⁻¹ of data at 13 TeV (2016) is

$$\mu = 1.17_{-0.10}^{+0.10} = 1.17 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (sig theo)} \pm 0.06 \text{ (other syst)}$$

- the largest experimental systematic uncertainty is the integrated luminosity 2.5% correlated amongst the categories.
- improved relative precision compared to the Run-1 result (ATLAS + CMS combination of 7 and 8 TeV data)

Signal strength measurements

Relaxing the assumption of a common signal strength modifier
per production mode

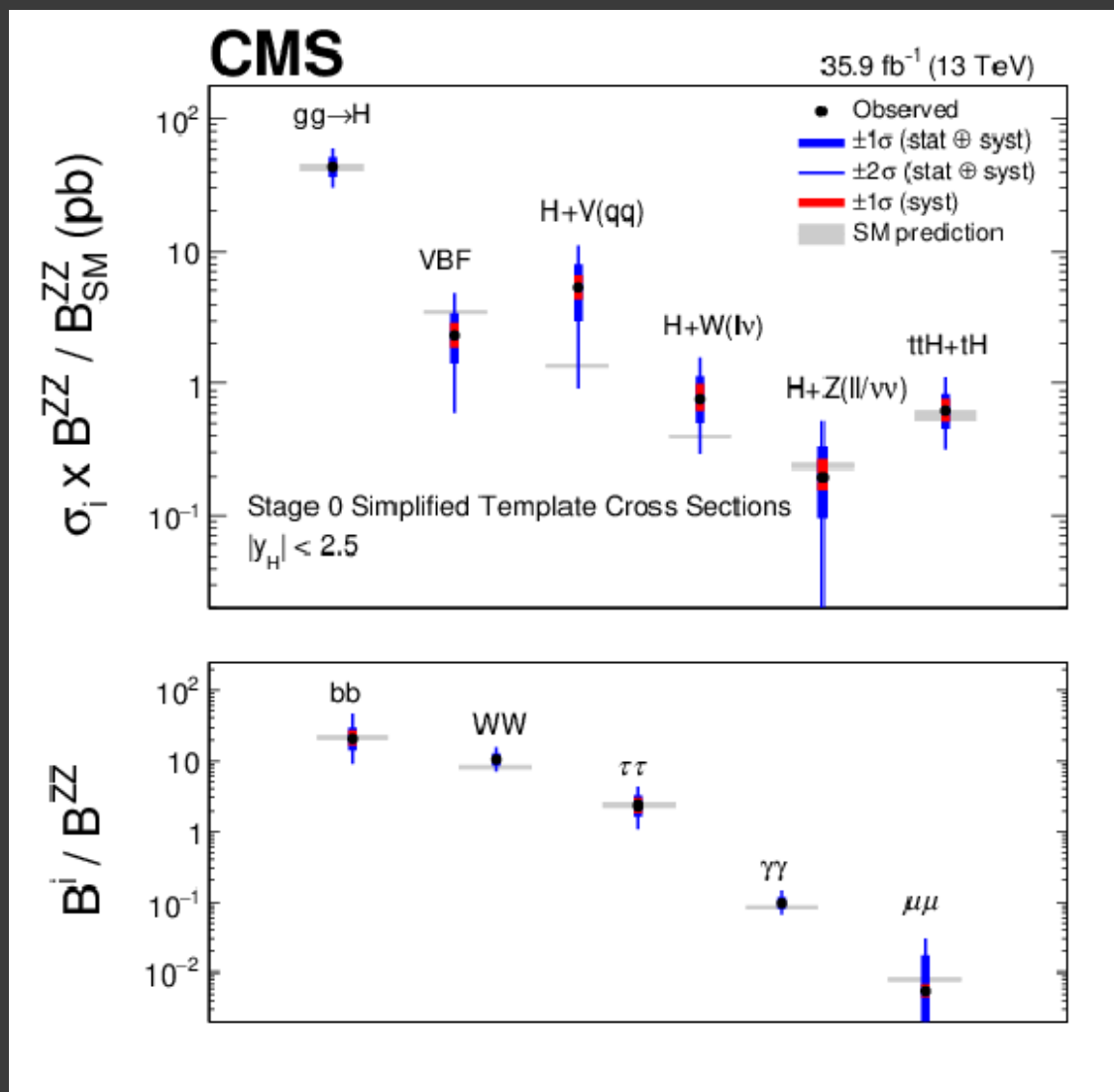


- Increased cross sections at 13 TeV, reduction of the theoretical uncertainties, and addition of some categories w.r.t. the Run1 results give:
 - 20% of improvement in VBF and VH
 - 50% of uncertainty reduction in ttH
 - 30% of improvement in the ggH measurement w.r.t. Run1 combination

Fiducial cross sections

Cross section measurements are done for processes defined according to the simplified cross section template:

- defined in the fiducial region of $|\eta_H| < 2.5$ – stage 0 –
- fitted cross sections (not affected by the theoretical uncertainties)
 - floating Branching fractions defined w.r.t. the B_{ZZ}
- no theoretical uncertainties on the SM predicted cross sections enter in this calculation (grey bands)



Higgs boson coupling modifiers

Deviations from the SM can be measured as deviation in the LO couplings between Higgs and fermions and/or bosons

$$\sigma_i \cdot \text{BR}^f = \frac{\sigma_i(\vec{k}) \cdot \Gamma^f(\vec{k})}{\Gamma_H}$$

To measure the coupling modifiers assumption on the Higgs total width are needed

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\kappa_H^2}{1 - (\text{BR}_{\text{undet.}} + \text{BR}_{\text{inv.}})}$$

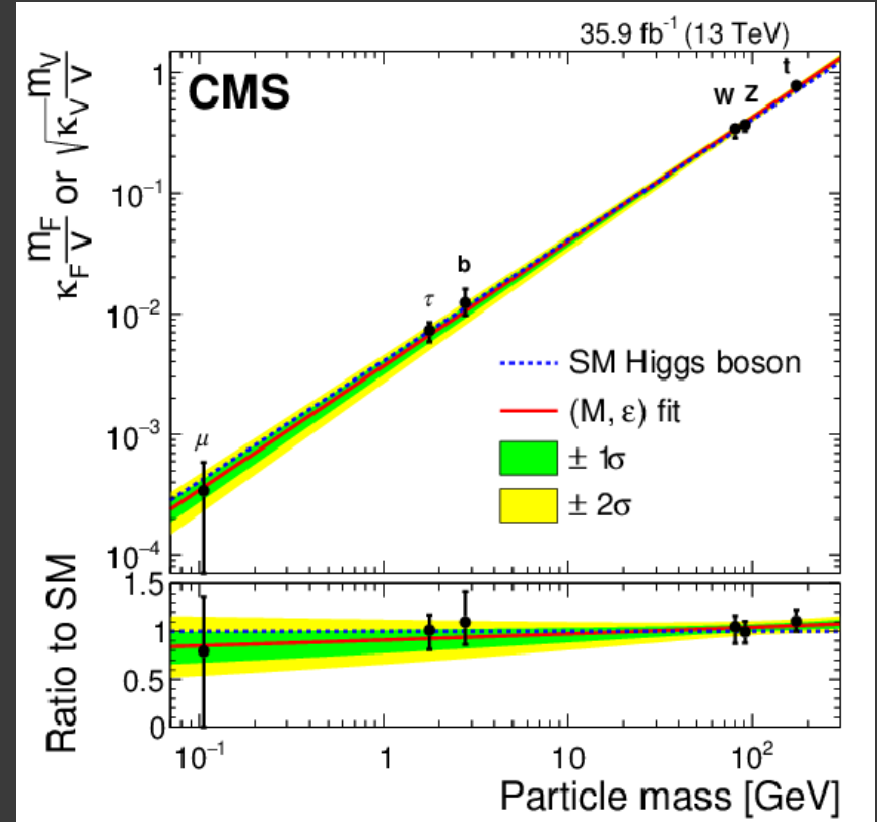
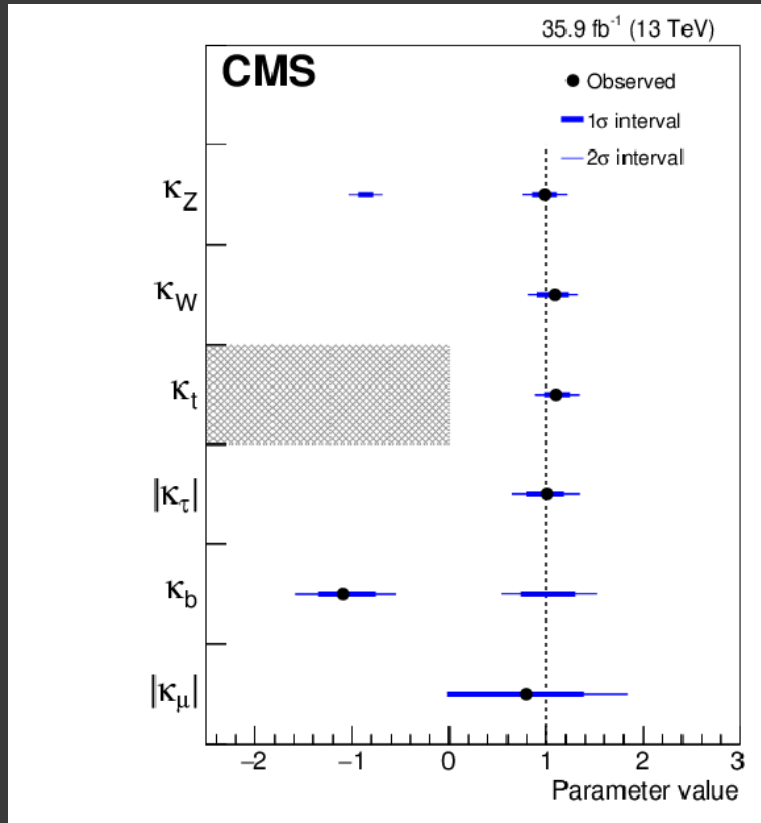
$$\kappa_H^2 = \sum_j \text{BR}_{\text{SM}}^j \kappa_j^2$$

Different parametrizations depending on the BSM contributions

κ -framework with resolved loops

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\kappa_H^2}{1 - (\cancel{\text{BR}_{\text{undet.}}} + \cancel{\text{BR}_{\text{inv.}}})}$$

Assuming the SM width and no BSM particles contributing to the ggH and H $\gamma\gamma$ loops



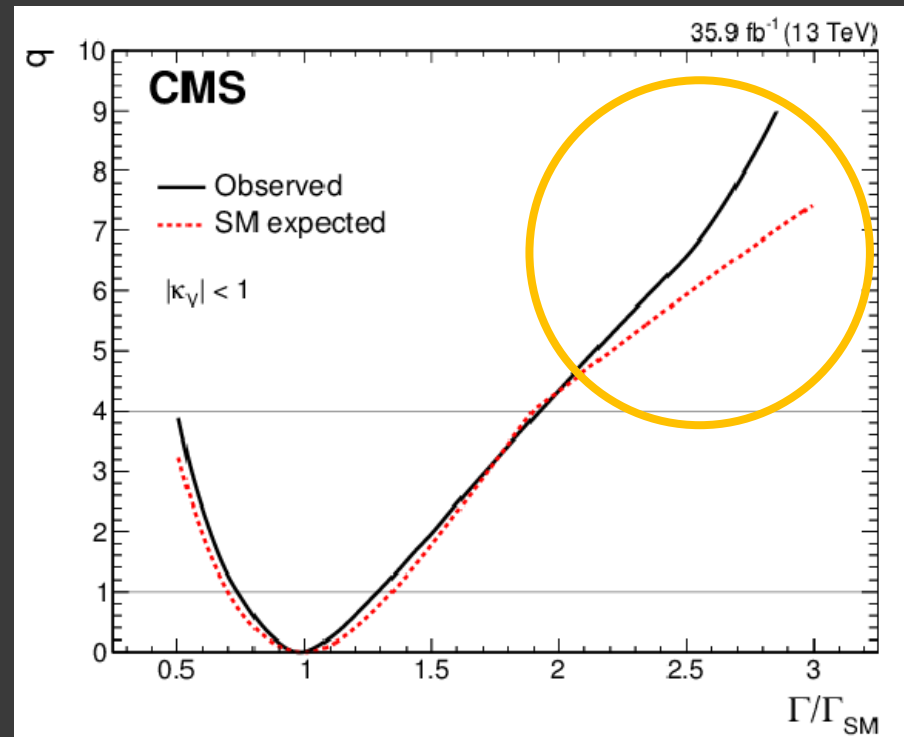
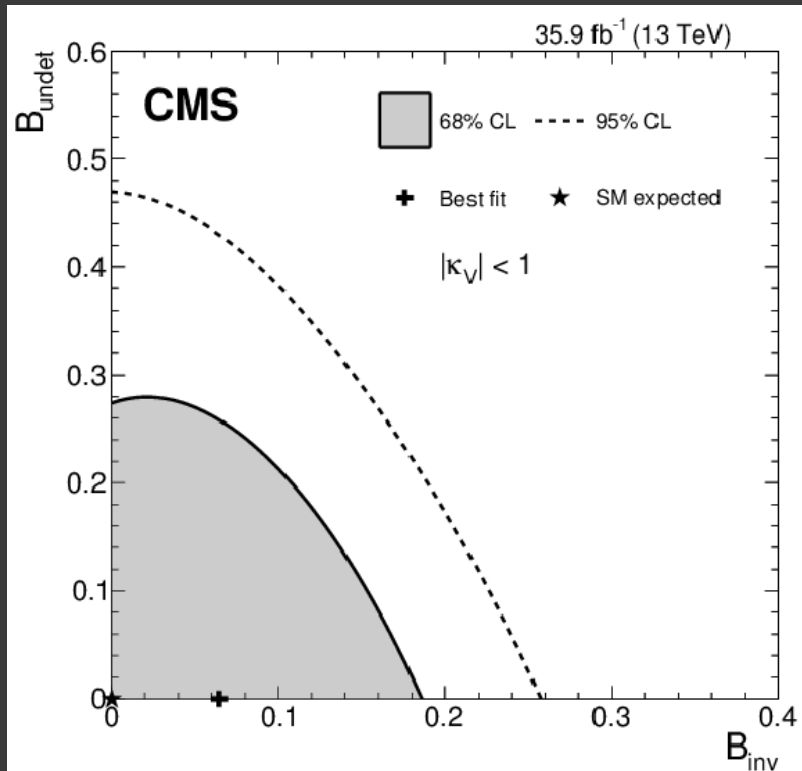
- 6 free parameters
- Loop diagrams resolved in terms of κ_W κ_Z κ_τ κ_b

Phenomenological parametrization relating the mass of the fermions and vector bosons to the coupling modifiers

κ -framework with effective loops

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\kappa_H^2}{1 - (\text{BR}_{\text{undet.}} + \text{BR}_{\text{inv.}})}$$

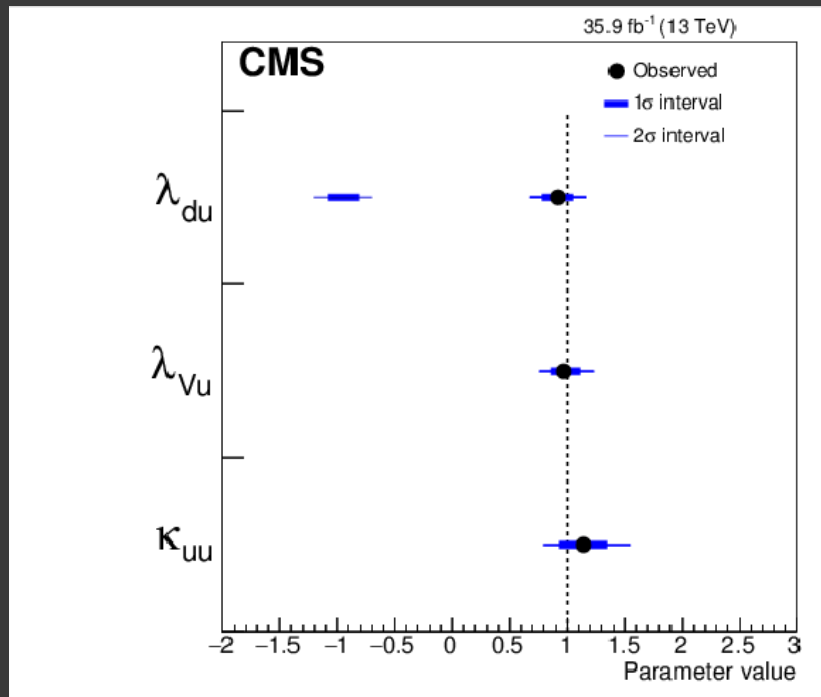
Allowing BSM particles to contribute to the ggH and H $\gamma\gamma$ loops



- H \rightarrow inv results included in the combination
- **Difference due to preferred $\kappa_w \kappa_t < 0$**

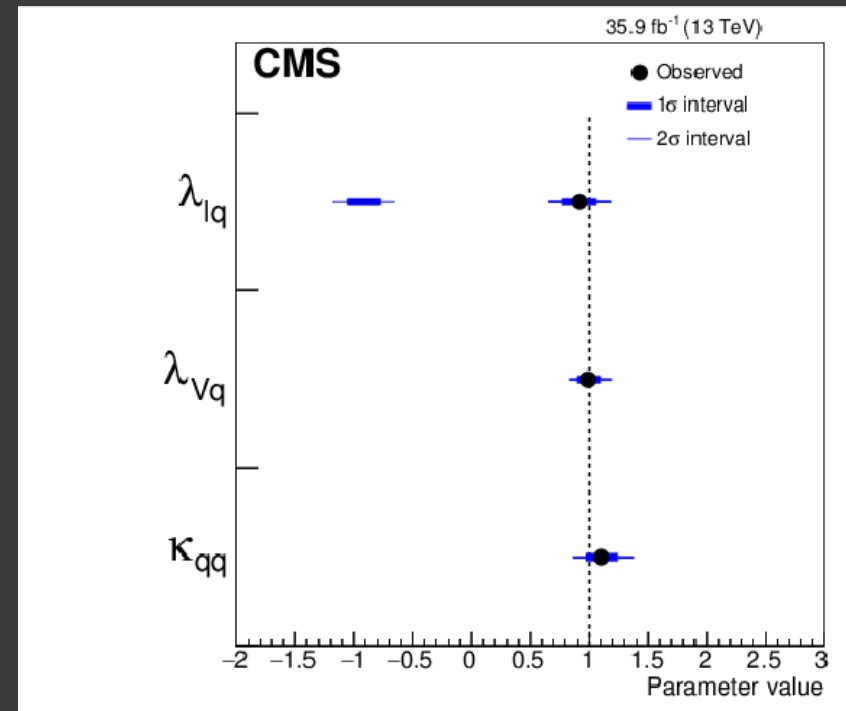
Benchmark models with resolved loops

Allows to constrain the BSM from the symmetry of the coupling modifiers



$$\Lambda_{du} = \kappa_d / \kappa_u$$

Up-type vs Down-type fermions

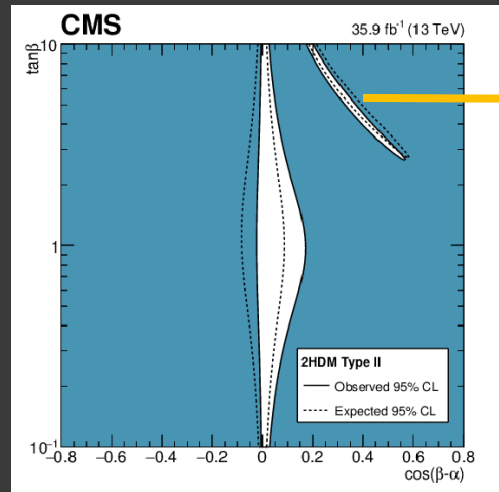
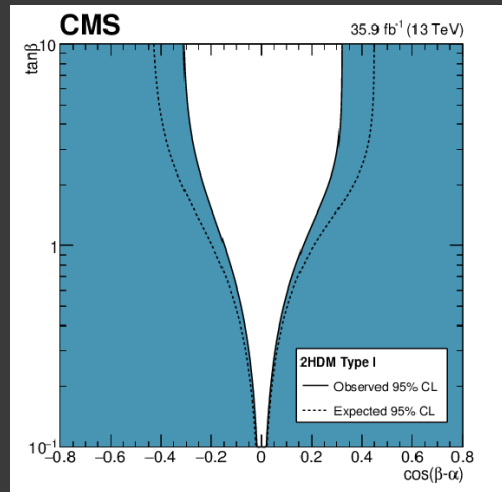


$$\Lambda_{du} = \kappa_l / \kappa_q$$

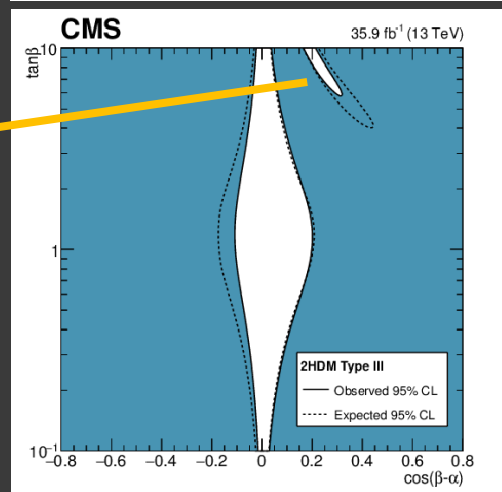
Leptons vs Quarks

Direct constraints on the parameters of 2HDM

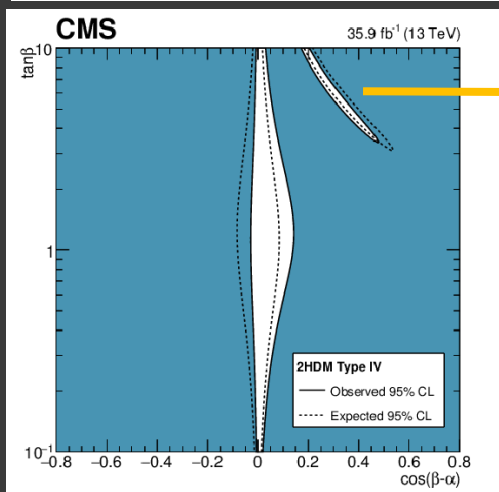
Type I, II, III, and IV differ by the couplings of the Higgs to the fermions, while coupling to vector bosons is modified by a factor of $\sin(\beta-\alpha)$ for all the types



negative
 K_d



negative
 K_τ



negative
 K_b

Differential cross sections

Study of the cross sections of Higgs process binned in a differential observable:

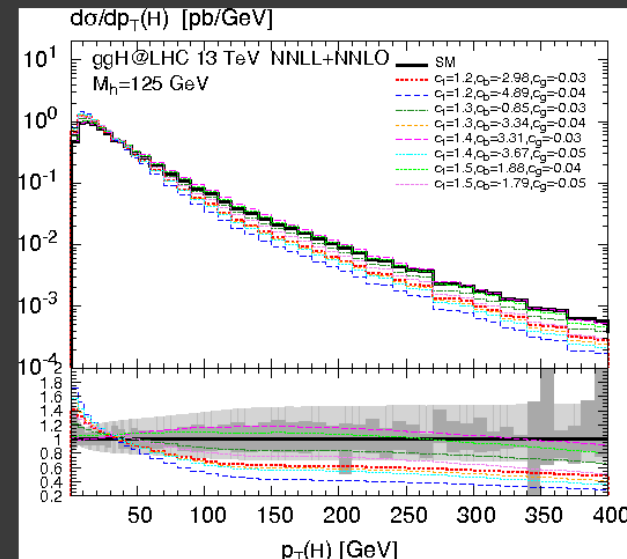
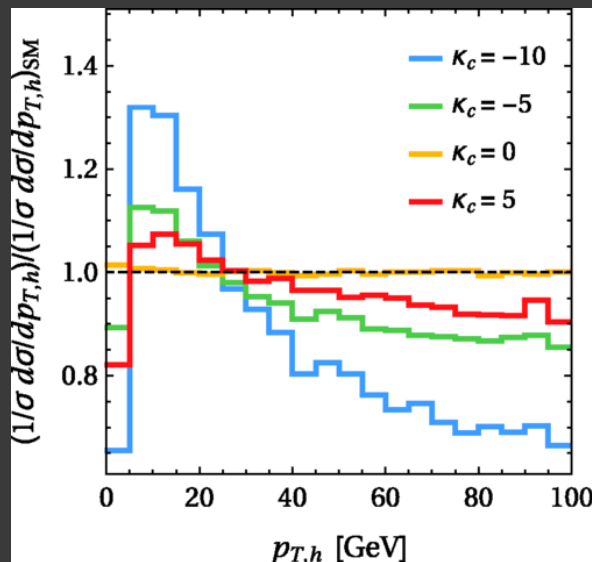
- Higgs pt, Leading Jet pt, Jet multiplicity and Higgs rapidity

Distortions in the shape of differential cross sections are expected by varying the coupling modifiers:

- even if the inclusive cross section agrees with the SM expectation
- several models parametrizing the SM modifications in Higgs coupling modifiers

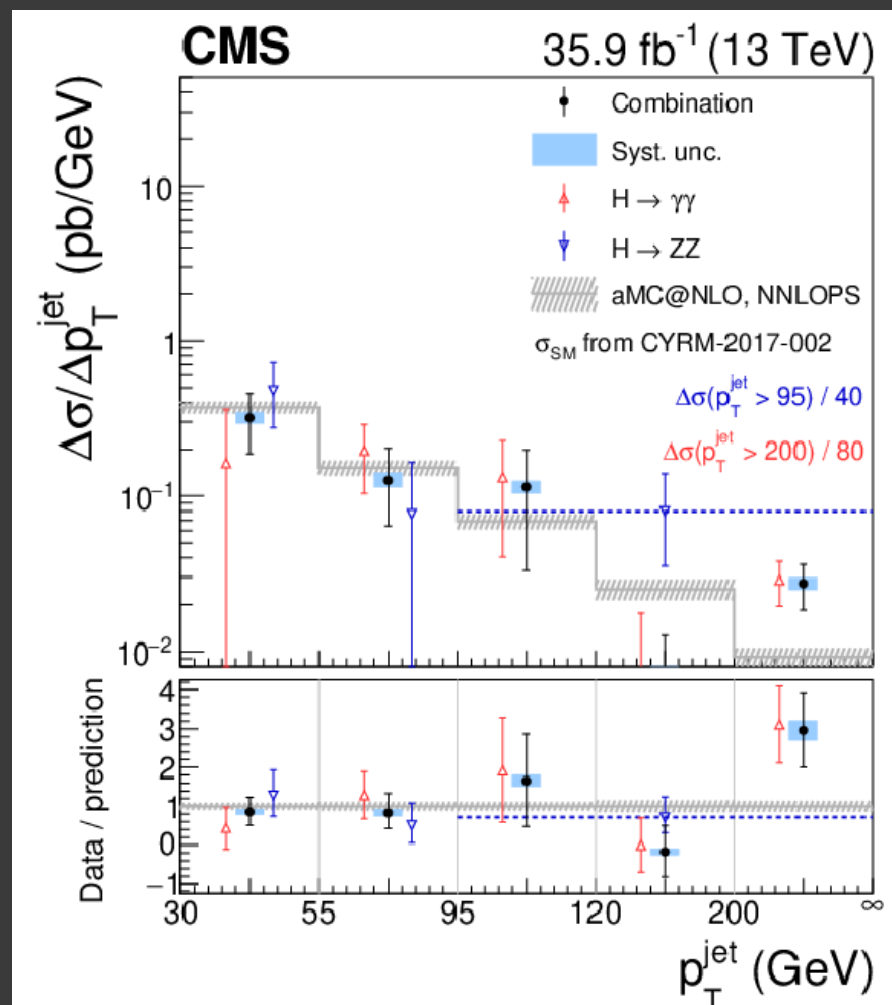
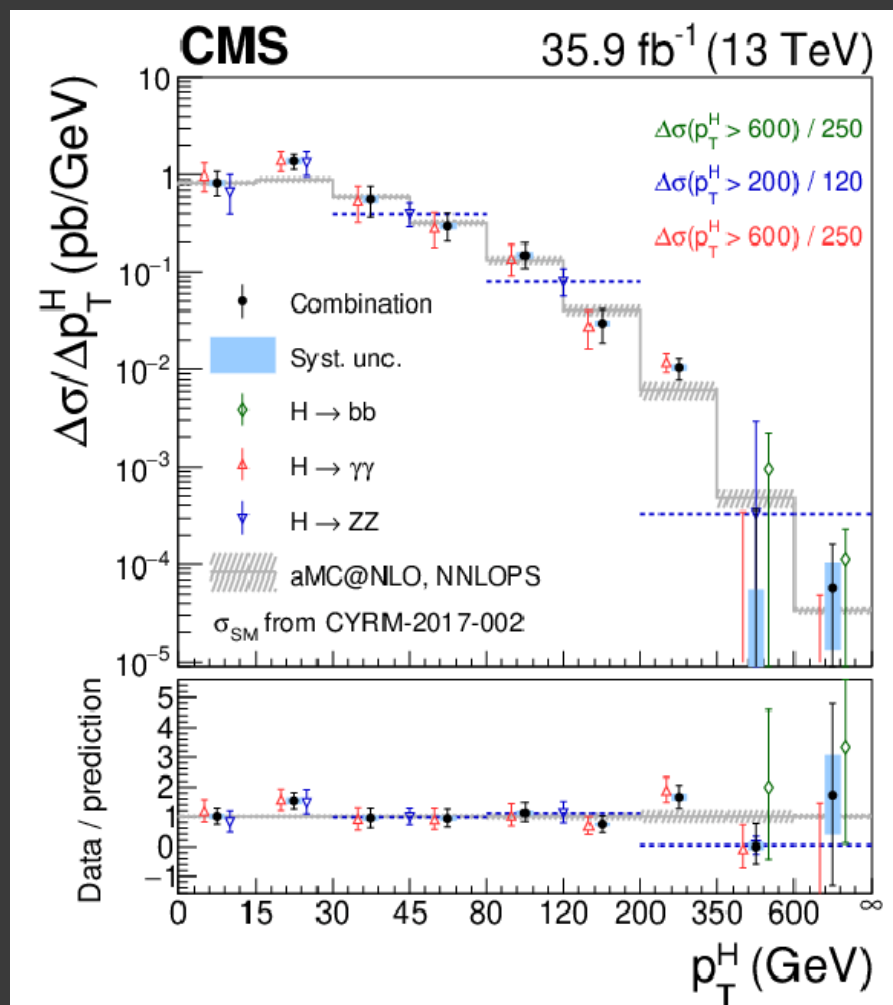
Low p_T region sensitive to $\kappa_b - \kappa_c$ deviations
 Bishara, Haisch, Monni, Re (2016)
 [1606.09253]

EFT-based parametrization in κ_b , κ_t and c_g
 Grazzini, Ilnicka, Spira, Wiesenmann (2017)
 [1705.05143]



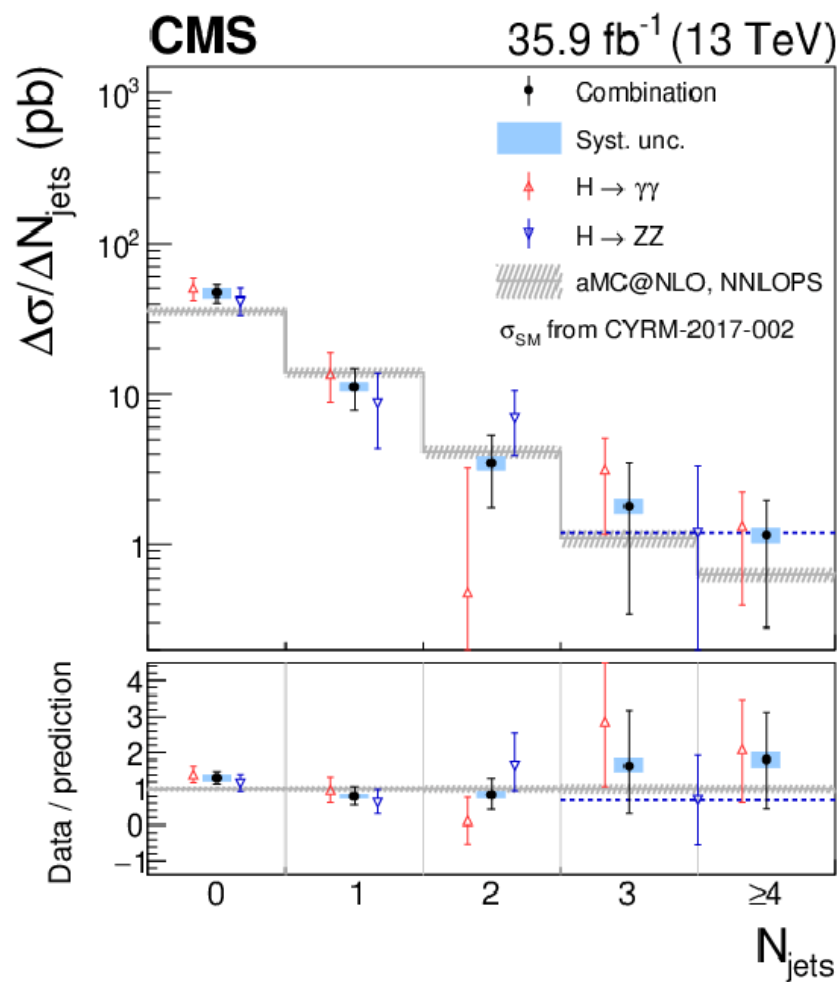
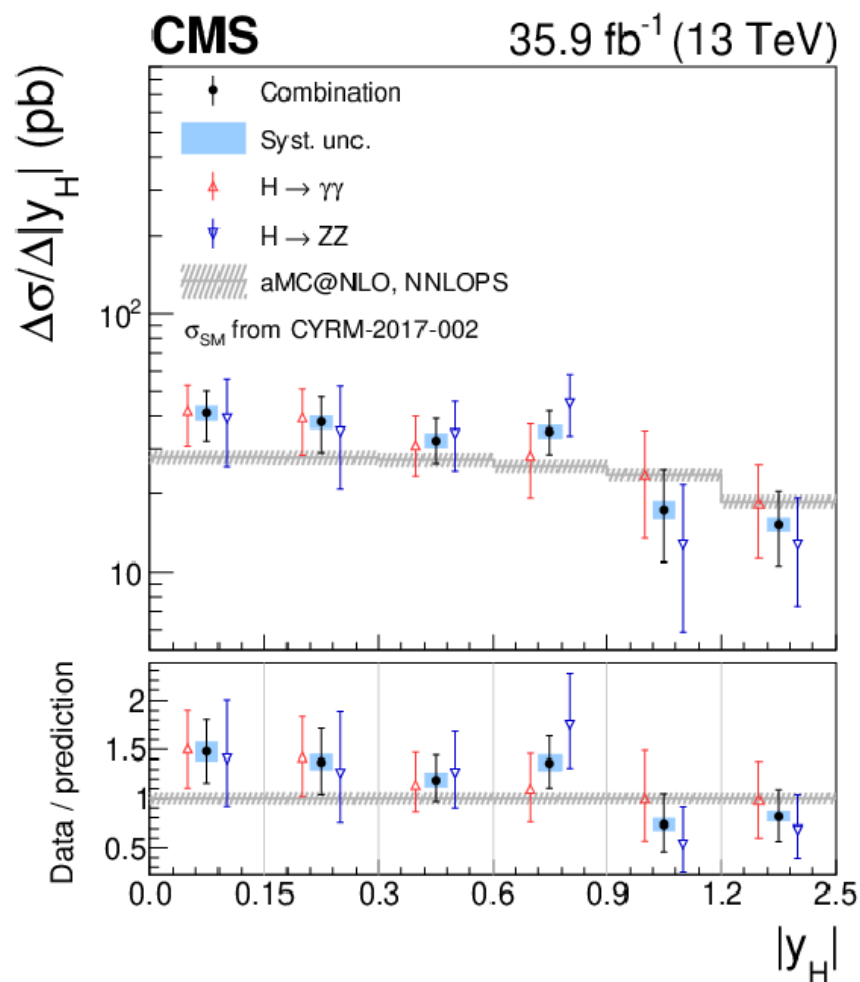
Differential cross sections

Only a subset of analyse is used: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and $H \rightarrow bb$ (only for the last two bins of H p_T)



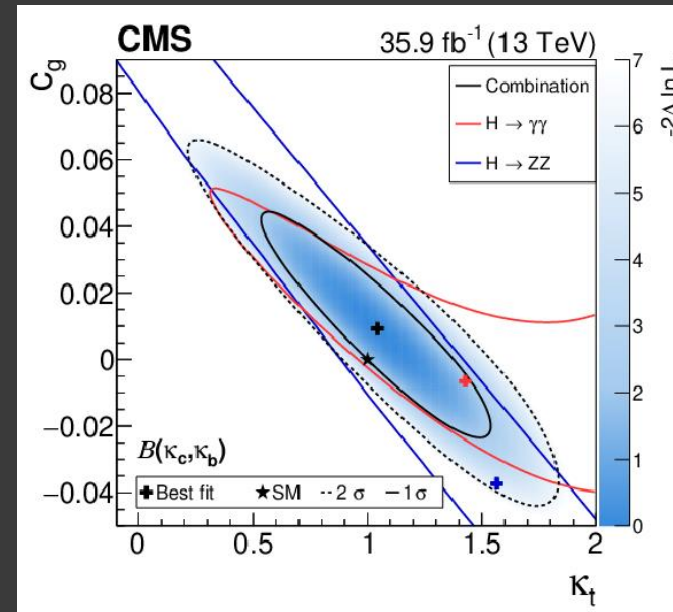
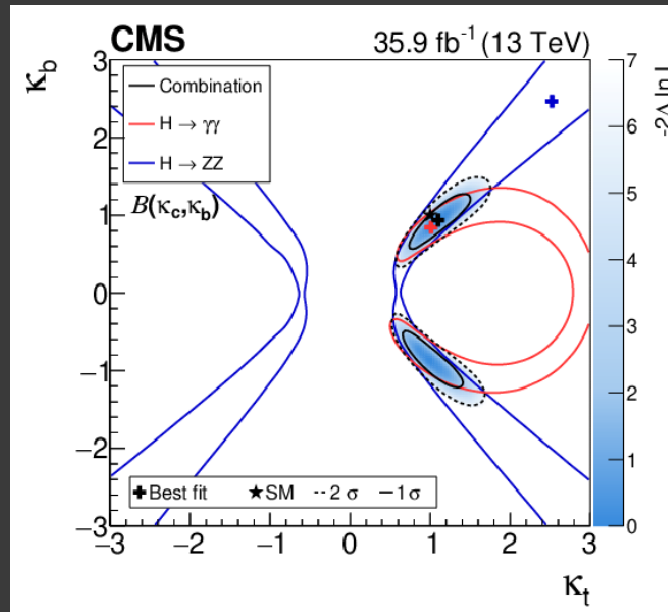
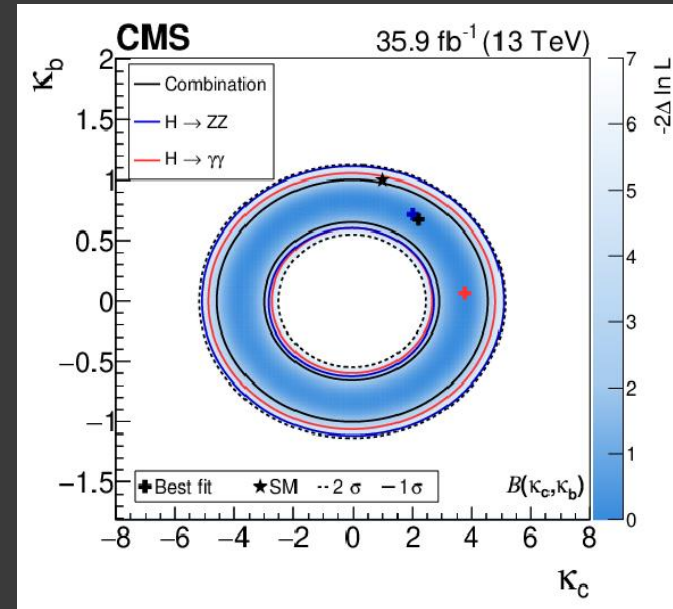
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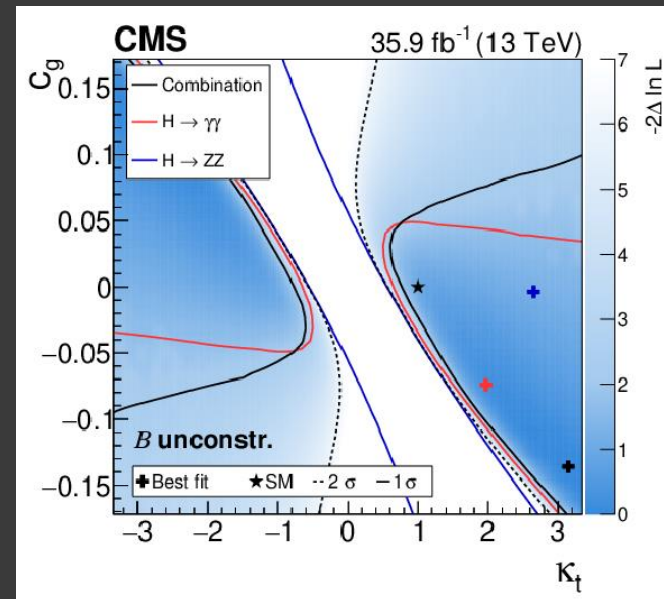
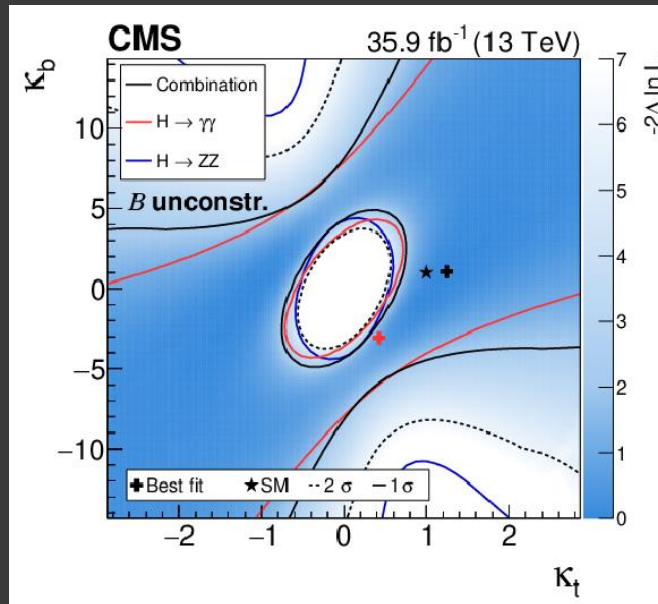
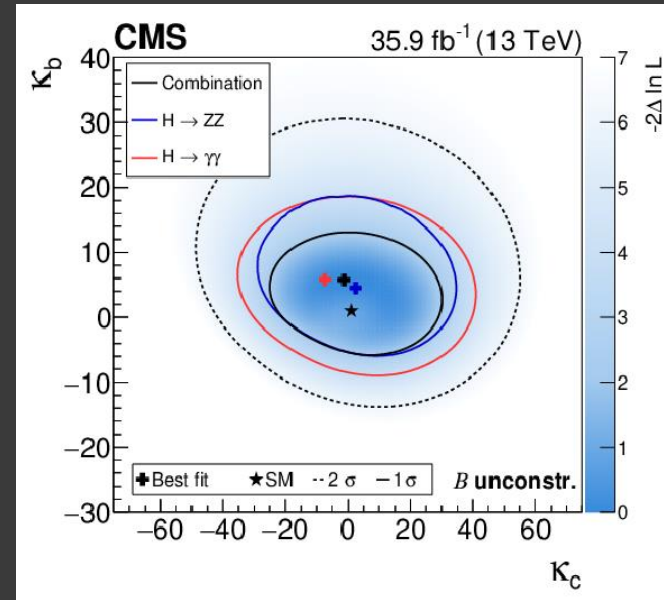
Constraints on the coupling modifiers

Assuming a
coupling-dependent BR
Resolved loops



Constraints on the coupling modifiers

Allowing BR to float
Constraint from shape only





Summary and outlook

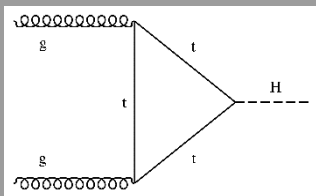
- **Combined measurements of the Higgs production and decay channels have been performed at CMS using 35 fb^{-1} of data at 13 TeV:**
 - **higher precision in the measurements**
 - **larger excluded BSM parameter space**
 - **used as input to make projections for HL-LHC (E. Fontanesi's talk)**
- **An improved combination is expected with the full Run2 dataset**
 - **higher statistics and ongoing efforts to improve systematics in each analysis**

Back-up

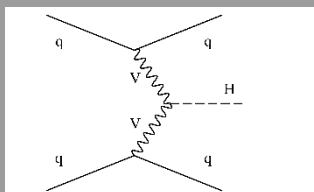
Higgs production and decay modes

Production

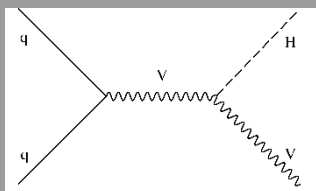
ggH



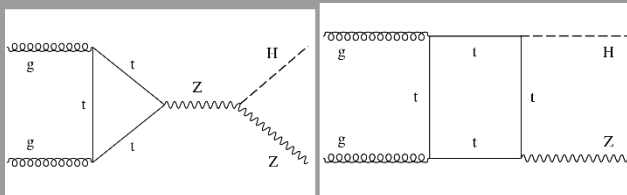
VBF



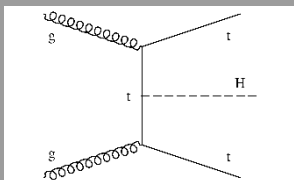
VH



ZH



ttH



Decay

$\gamma\gamma$

ZZ

WW

bb

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$\mu\mu$

inv

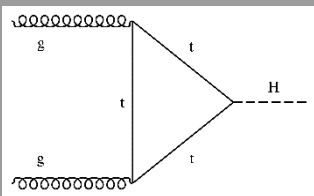
Several categories per each analysis:

- Sensitive to all the different possible final state decays
- Further categorization to enhance the production mode

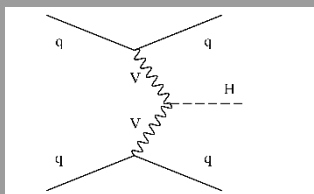
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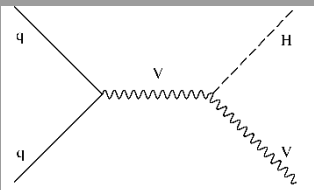
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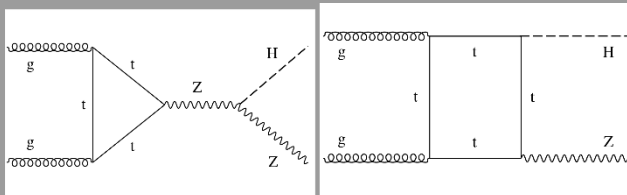
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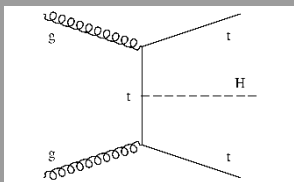
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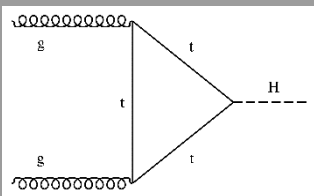
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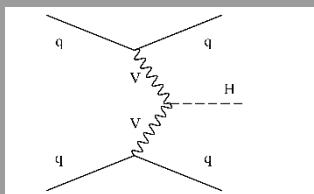
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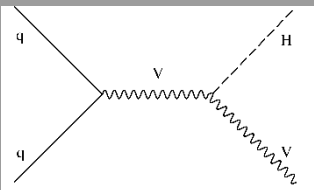
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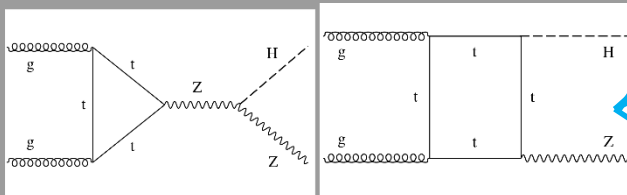
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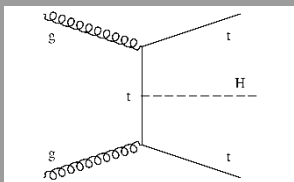
VH



ZH



ttH



Decay

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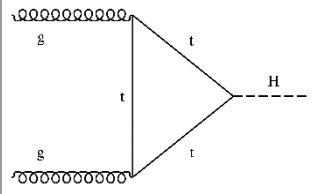
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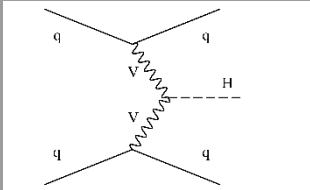
Higgs production and decay modes

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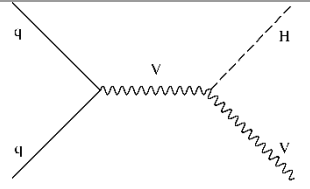
ggH



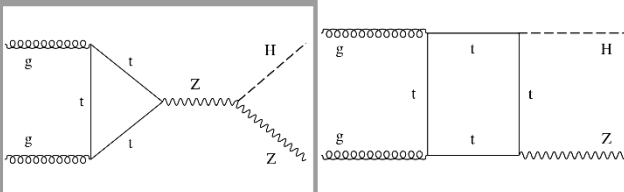
VBF



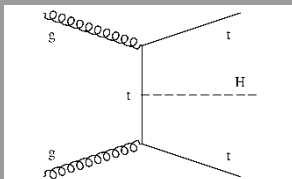
VH



ZH



ttH



Decay

$\gamma\gamma$

ZZ

WW

bb

$\tau\tau$

$\mu\mu$

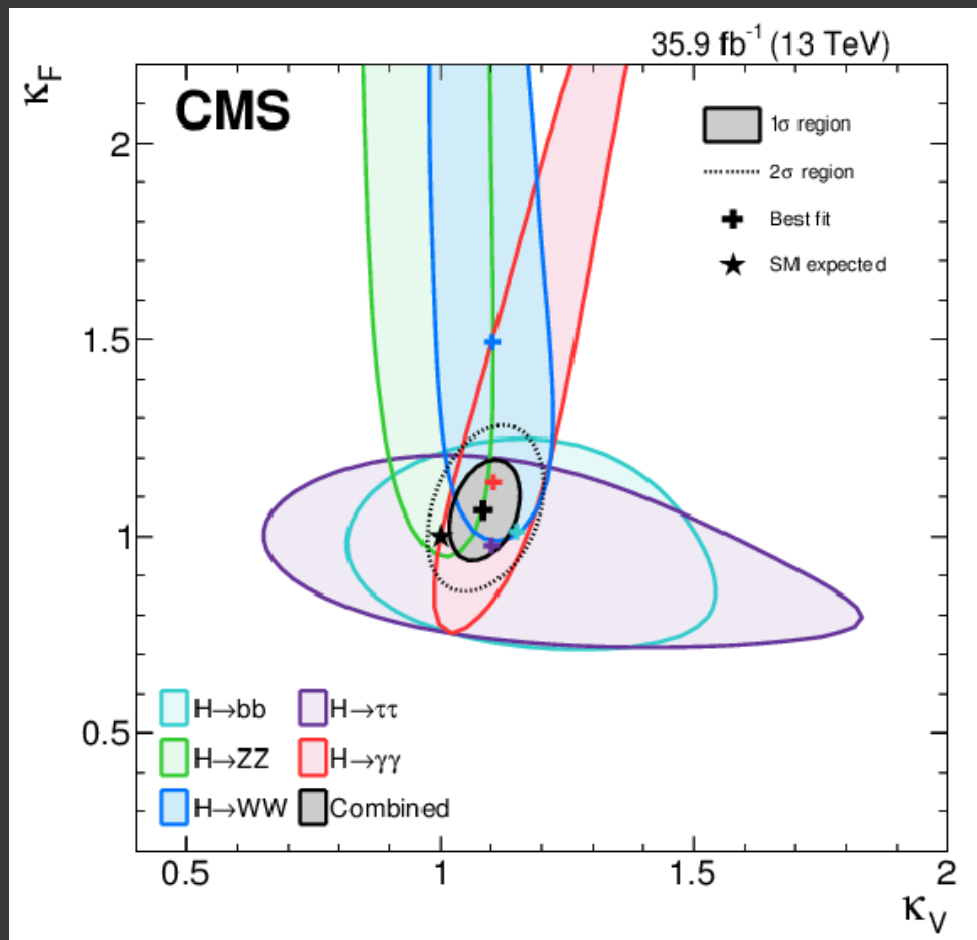
inv

Several categories per each analysis:

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Vector boson and fermion

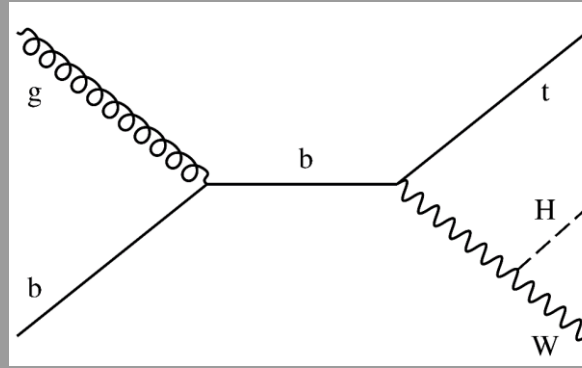
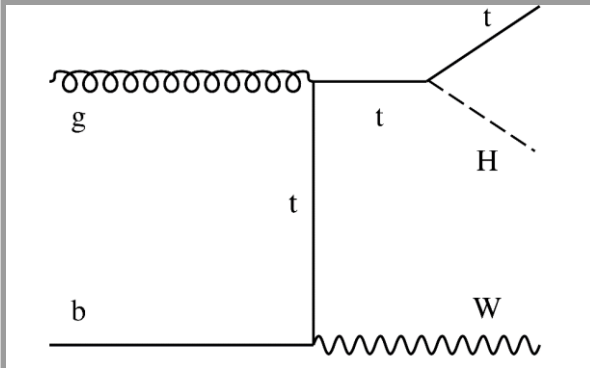
More constrained model assuming the same scaling for vector bosons and fermions



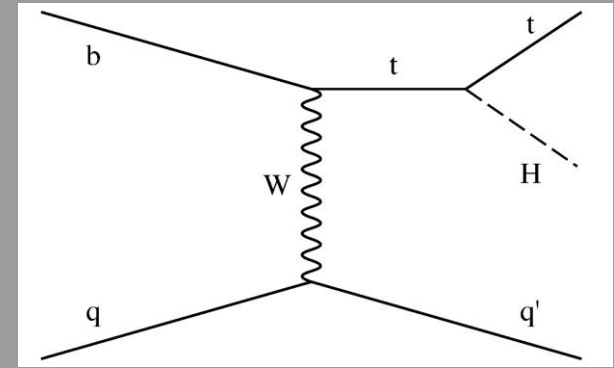
Interferences

- tH production suppressed in the SM (about 15% of ttH)
- Enhanced if the relative sign of HWW and ttH couplings is negative

tHW

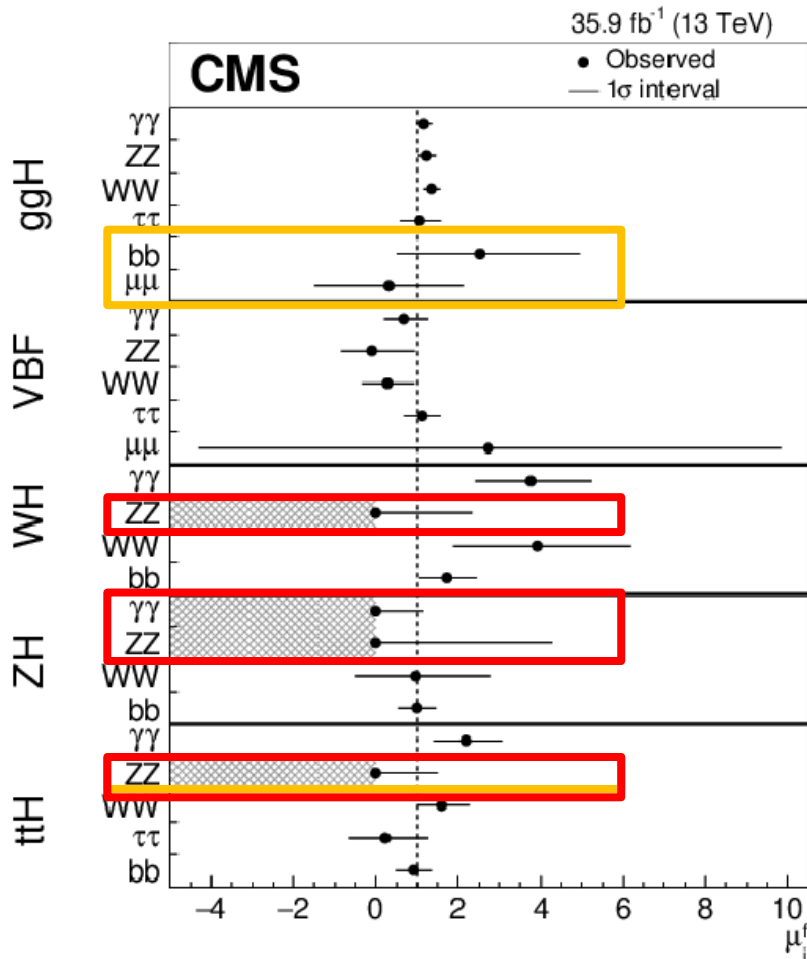


tHq



Signal strength measurements

Relaxing the assumption of a common signal strength modifier,
one μ for each $\sigma \times \text{BR}$ can be measured



Not all the decay channels are sensitive to
each production mode \rightarrow SM is assumed

Too small background contamination
resulting in negative signal strength: forced
to positive values

New w.r.t. Run1



Higgs boson coupling modifiers

Deviations from the SM can be measured as deviation in the LO couplings between Higgs and fermions and/or bosons

$$\kappa_j^2 = \sigma_j / \sigma_j^{\text{SM}} \quad \kappa_j^2 = \Gamma_j / \Gamma_j^{\text{SM}}$$

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To measure the coupling modifiers assumption on the Higgs total width are needed

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\kappa_H^2}{1 - (\text{BR}_{\text{undet.}} + \text{BR}_{\text{inv.}})}$$

$$\kappa_H^2 = \sum_j \text{BR}_{\text{SM}}^j \kappa_j^2$$

Done in different frameworks depending on the BSM contributions

Couplings in 2HDM

TypeI: small values of $\tan\beta$ produce large deviations of the couplings $\kappa_u = \kappa_d$. The same is true for coupling to the up-type fermions in TypeII (dominated by the constraints on the couplings higgs-top and higgs-tau).

Table 2: Modifications of the couplings of the h to up - (κ_u), $down$ -type (κ_d) fermions and vector bosons (κ_V), with respect to the SM expectation, in 2HDM's model of *type-I* (second column) and II (third column) and for the h MSSM (fourth column). The coupling modifications for the h MSSM are completed by the expressions for s_u and s_d as given in Equation (4).

	2HDM		hMSSM
	type I	type II/MSSM	
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\frac{s_d + s_u \tan \beta}{\sqrt{1 + \tan^2 \beta}}$
κ_u	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$s_u \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta}$
κ_d	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$s_d \sqrt{1 + \tan^2 \beta}$

$$s_u = \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2 \beta}{(m_Z^2 + m_A^2 \tan^2 \beta - m_h^2 (1 + \tan^2 \beta))^2}}}$$

$$s_d = s_u \cdot \frac{m_A^2 + m_Z^2 \tan \beta}{m_Z^2 + m_A^2 \tan^2 \beta - m_h^2 (1 + \tan^2 \beta)}$$