CMS Results of Higgs Boson Decaying to Bosons

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On behalf of CMS Collaboration

Higgs Hunting, Orsay, Paris, July 29, 2019

Outline

- Introduction
- H→ZZ
- H→ γγ
- H→WW
- Summary & Outlook

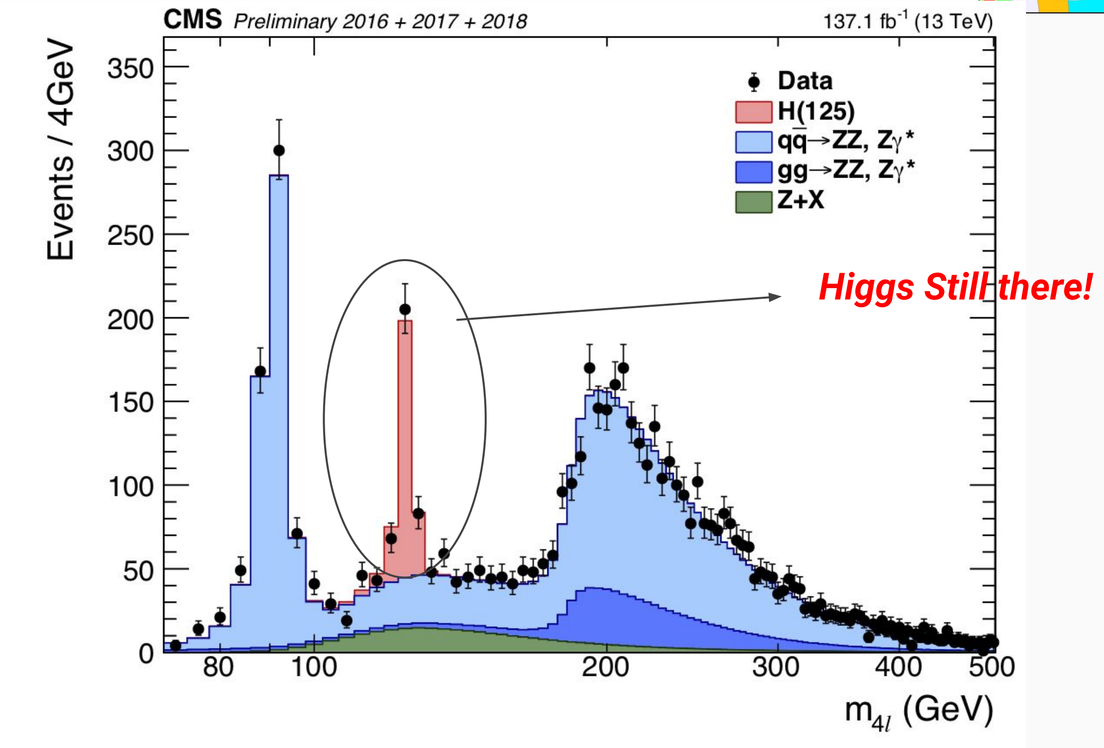
Introduction

- ➔ LHC has delivered more than expected performance in Run-II and CMS recorded data at very high efficiency.
- ➔ We have ~ 137 fb^{-1} pp dataset at hand → provides a great opportunity to look further in the properties of discovered Higgs boson@125GeV.
- ➔ Individual channels are becoming sensitive enough to measure various properties of Higgs :
  - ◆ Couplings and Signal strengths (inclusive and also per process), Simplified Template Cross-sections
  - ◆ Fiducial and Differential Cross-sections
  - ◆ Mass
  - ◆ Width (on-shell & off-shell production)
- ➔ Following the latest recommendations from LHC HXSWG

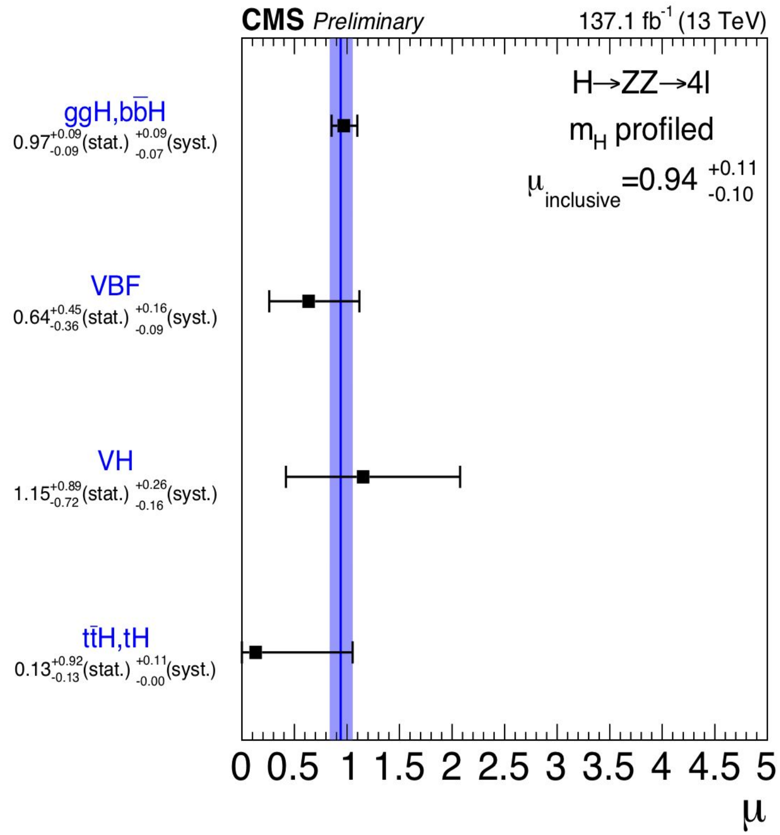
H⟶4l Overview

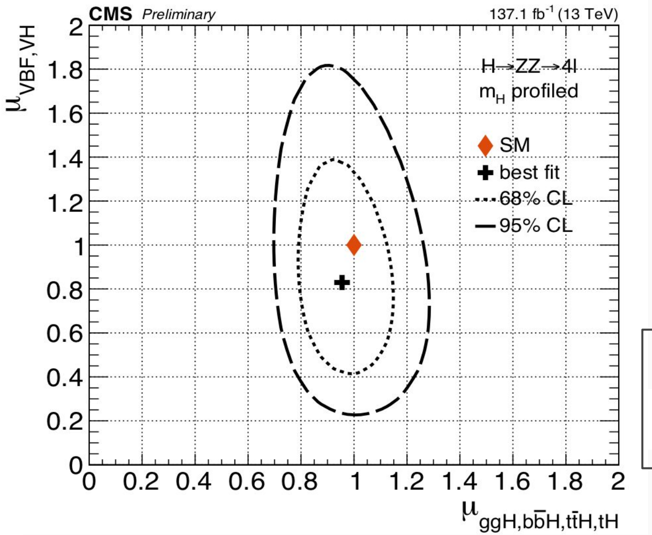
HIG-19-001

- ★ Clean signature with 4 identified & isolated leptons → high S/B
- ★ Results have been produced with full Run-II luminosity
- ★ signal strengths in STXS 1.1 are provided
- ★ Improved binning and new variable introduced for differential X-sec



H→4l : Signal Strengths





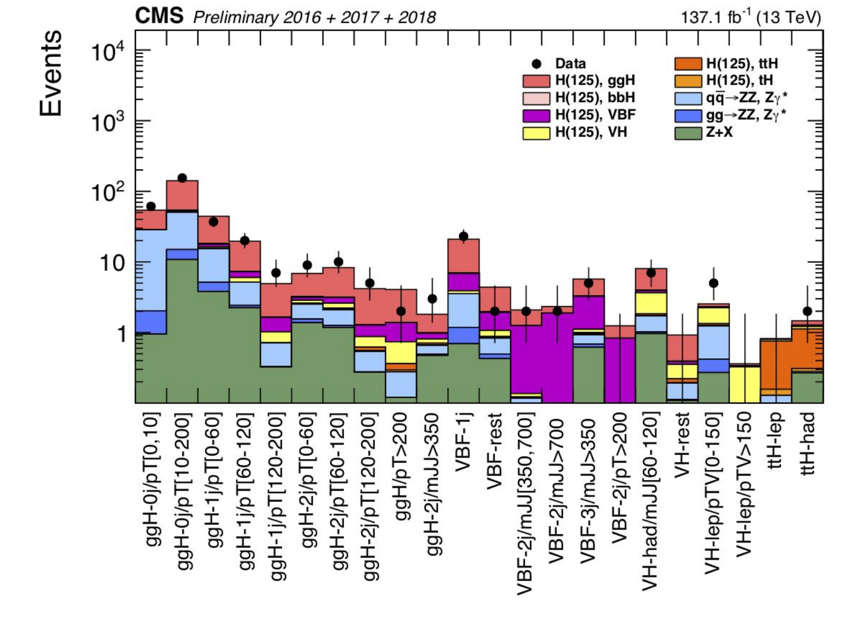
Multidimensional likelihood fit to (m_{4l},KD) templates in 66 channels (22 x 3)

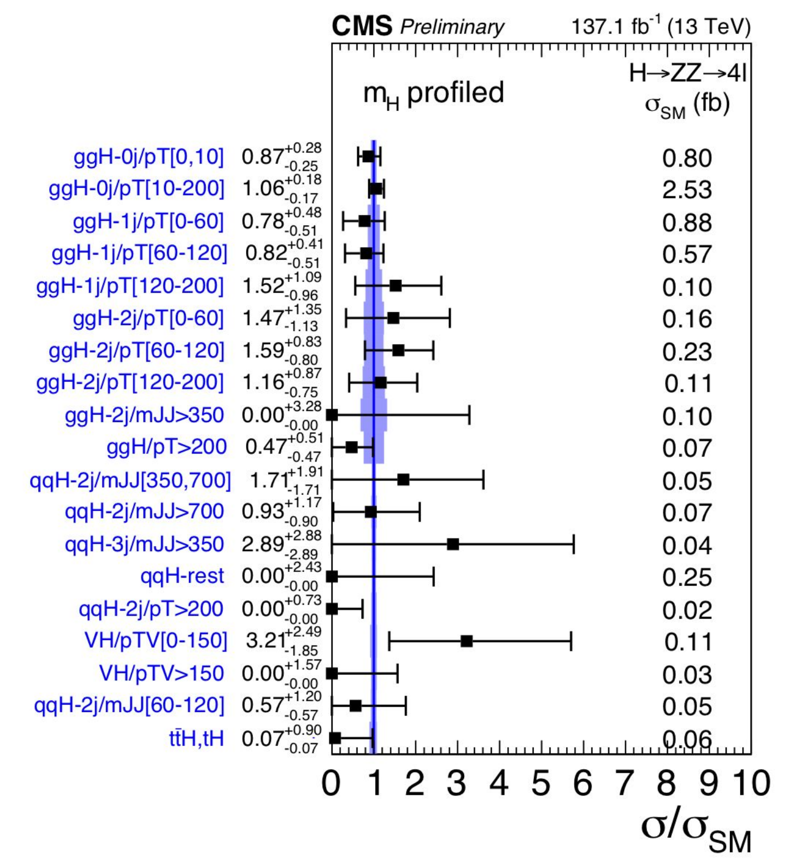
2D likelihood is defined :

$$\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}^{\rm kin}_{\rm bkg}) = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}^{\rm kin}_{\rm bkg}|m_{4\ell})$$

	Expected	Observed
$\mu_{\rm inclusive}$	$1.00^{+0.08}_{-0.08}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$
$\mu_{\rm ggH}$	$1.00^{+0.10}_{-0.10}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.97^{+0.09}_{-0.09}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$
$\mu_{\rm VBF}$	$1.00^{+0.54}_{-0.45}(\text{stat.})^{+0.27}_{-0.14}(\text{syst.})$	$0.64^{+0.45}_{-0.36}(\text{stat.})^{+0.16}_{-0.09}(\text{syst.})$
$\mu_{\rm VH}$	$1.00^{+0.91}_{-0.72}(\text{stat.})^{+0.29}_{-0.16}(\text{syst.})$	$1.15^{+0.89}_{-0.72}(\text{stat.})^{+0.26}_{-0.16}(\text{syst.})$
$\mu_{\rm t\bar{t}H,tH}$	$1.00^{+1.16}_{-0.73}(\text{stat.})^{+0.19}_{-0.04}(\text{syst.})$	$0.13^{+0.92}_{-0.13}(\text{stat.})^{+0.11}_{-0.00}(\text{syst.})$

H→4l : STXS 1.1





The primary goals of the STXS framework are to maximize the sensitivity of the measurements while at the same time to minimize their theory dependence.

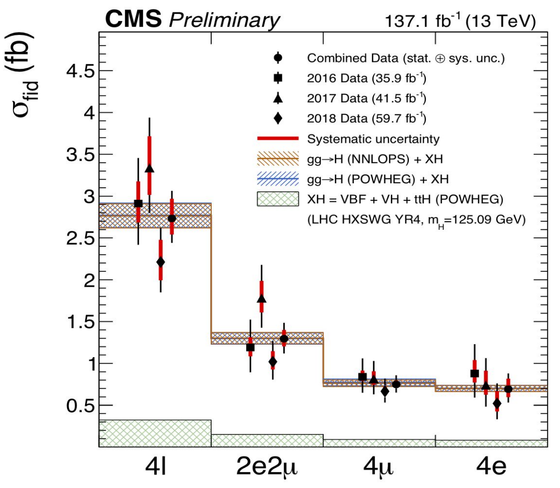
H→4l : Fiducial X-sec

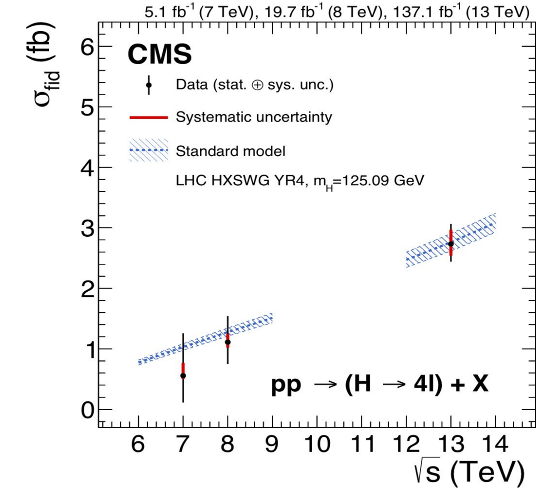
- ❑ fiducial volume is defined to match closely the reconstruction level selection
- ❑ 1D m_{4l} has been fitted to extract the fiducial cross-section
  - ❑ Inclusive fit without event categorization → min model independence

$$\sigma_{\text{fid.}} = 2.73^{+0.30}_{-0.29} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid.}} = 2.76 \pm 0.14\ \text{fb.}$$

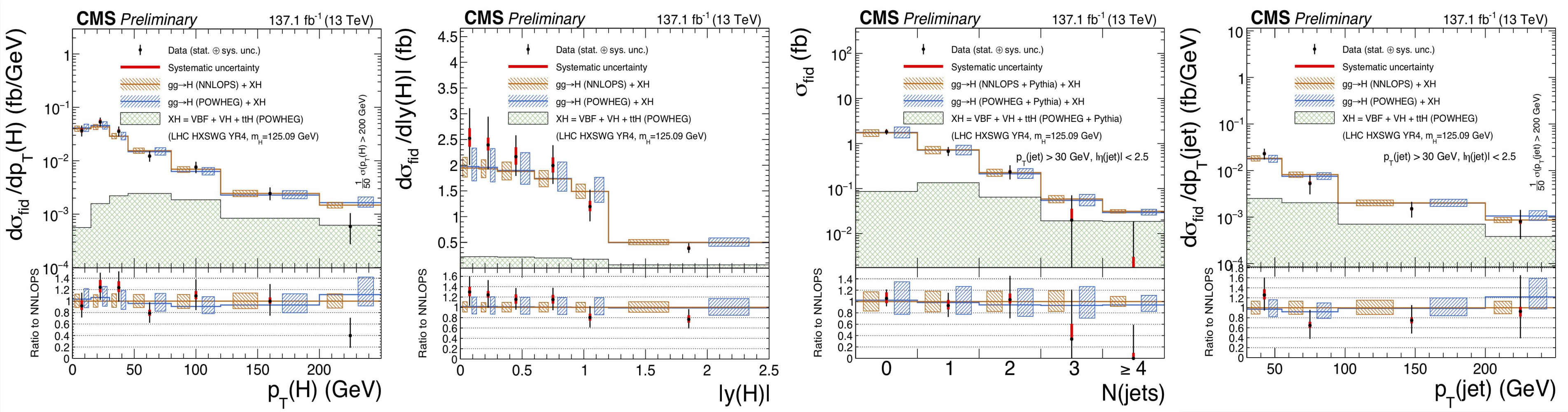
Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg→H (POWHEG)	0.402 ± 0.001	0.592 ± 0.002	0.053 ± 0.001	0.624 ± 0.002
VBF (POWHEG)	0.444 ± 0.002	0.605 ± 0.003	0.043 ± 0.001	0.631 ± 0.003
WH (POWHEG+MINLO)	0.325 ± 0.002	0.588 ± 0.003	0.075 ± 0.002	0.632 ± 0.004
ZH (POWHEG+MINLO)	0.340 ± 0.003	0.594 ± 0.005	0.081 ± 0.004	0.643 ± 0.006
ttH (POWHEG)	0.314 ± 0.003	0.585 ± 0.006	0.169 ± 0.006	0.684 ± 0.007





H→4l : Differential X-sec

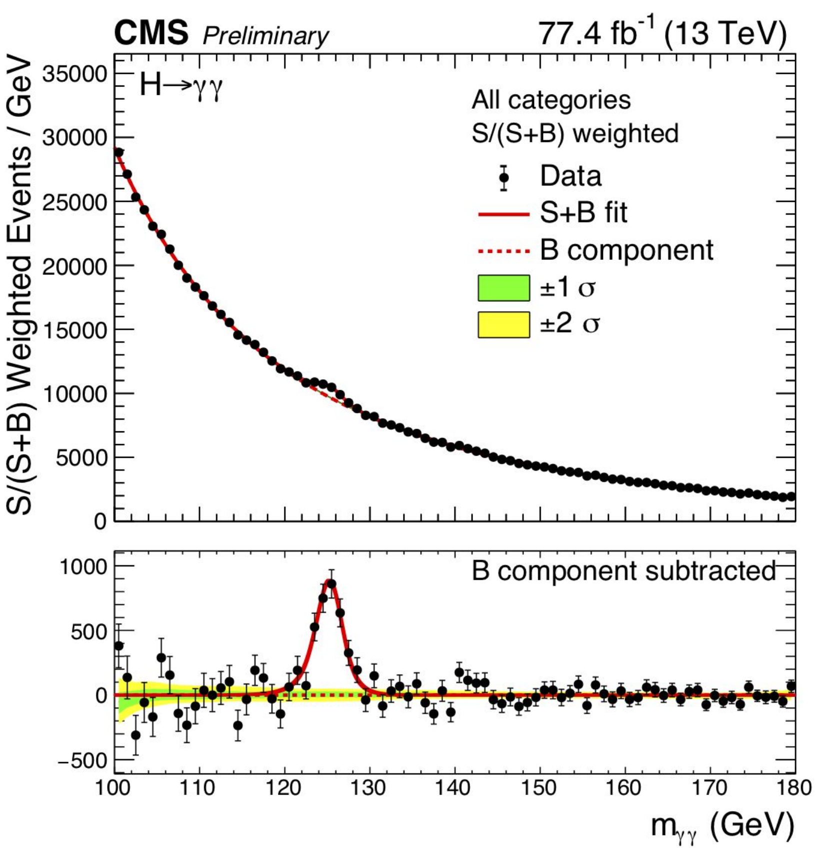
- ➔ Differential cross section measured for pT(H), |y(H)|, N(jet), pT(jet) with updated binning
- ➔ Unfolding performed by including response matrix in the likelihood
  - ◆ Unfolding is repeated with different response matrices created by varying the relative fraction of each SM production mode → to access model independence
- ➔ Compared to predictions from POWHEG and NNLOPS
- ➔ Dominant systematics are the experimental ones. Theoretical uncertainties are sub-dominant



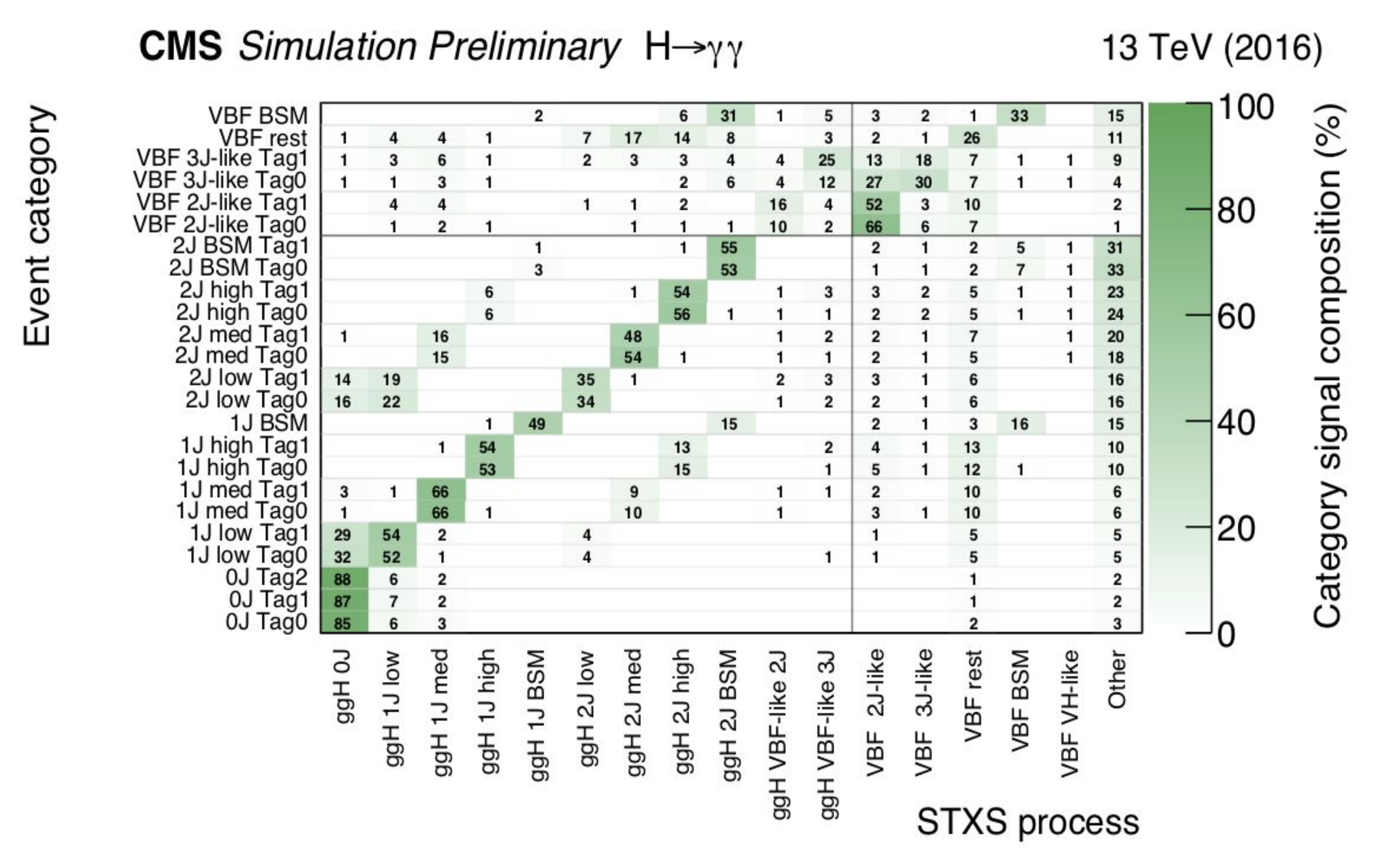
H→γγ : Overview

[HIG-18-029]

- High resolution channel with small branching ratio (~0.2%)
- Excellent energy resolution from lead tungstate crystals in ECAL
- Identify vertex using dedicated BDT
- 2016+2017 (77.4 fb-1) result with *STXS stage 1*
- The analysis is limited to ggF and VBF categories.
  - VH and ttH has limited sensitivity for stage 1
- ggH categories are defined with cuts on the equivalent reconstructed quantities of the defining generator level variables
  - background rejection using the diphoton BDT
- VBF categorisation based on the dijet BDT
- Some bins are merged in order to get enough statistics



H→γγ : STXS 1 (2016)

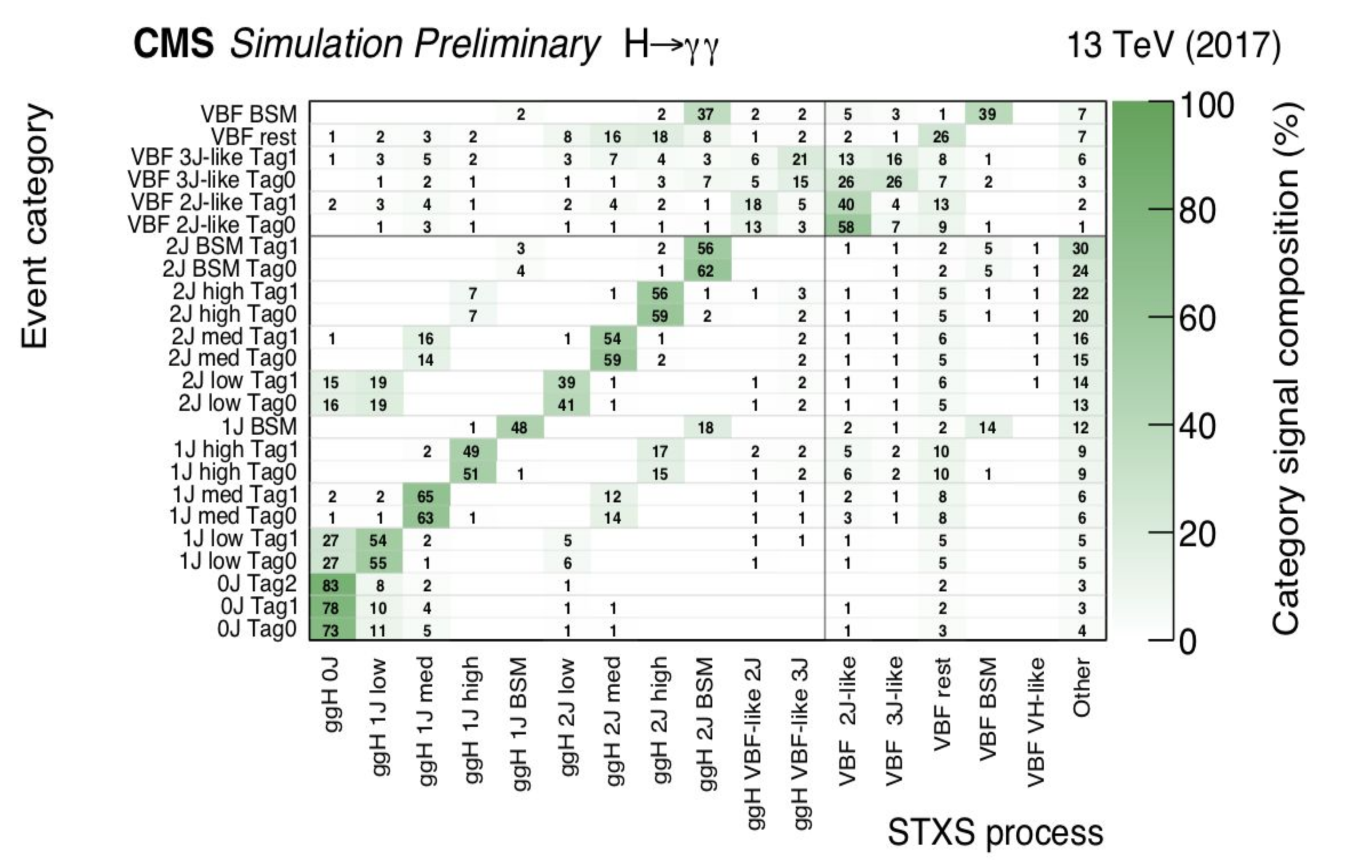


Colored scale corresponds to the fraction of each category (rows) accounted for by each stage 1 process (columns)

Each row sums up to 100%

Entries with less than 0.5% are now shown

H→γγ : STXS 1 (2017)

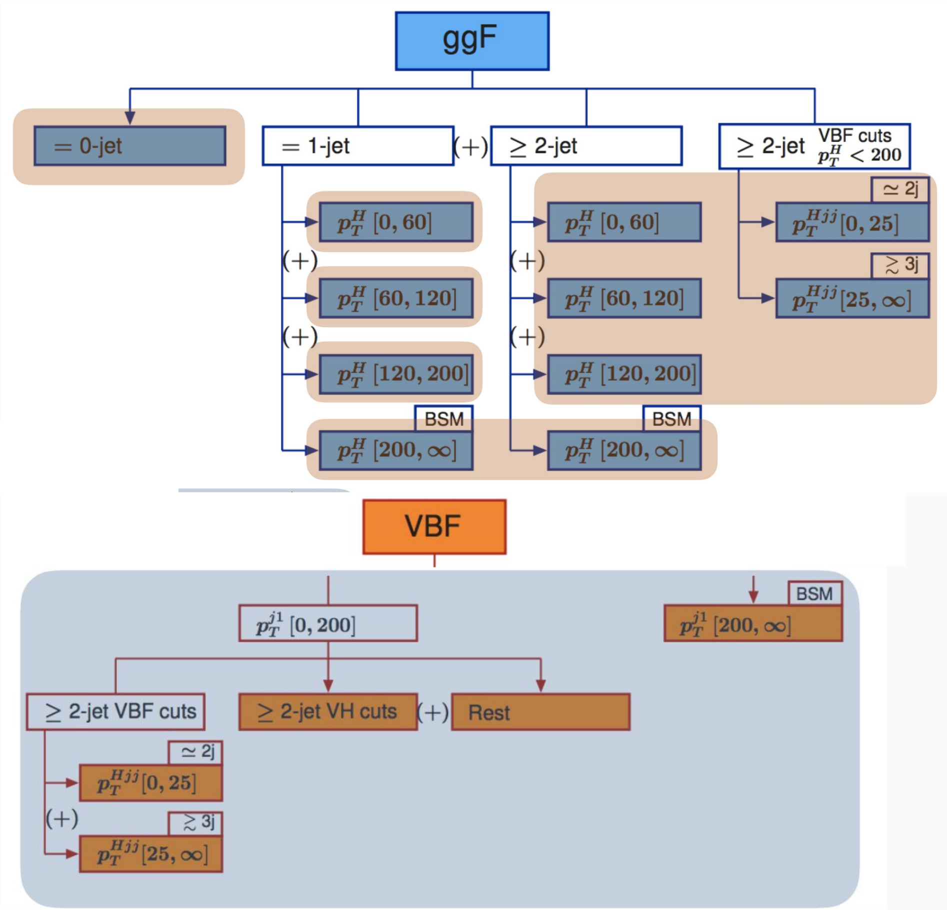


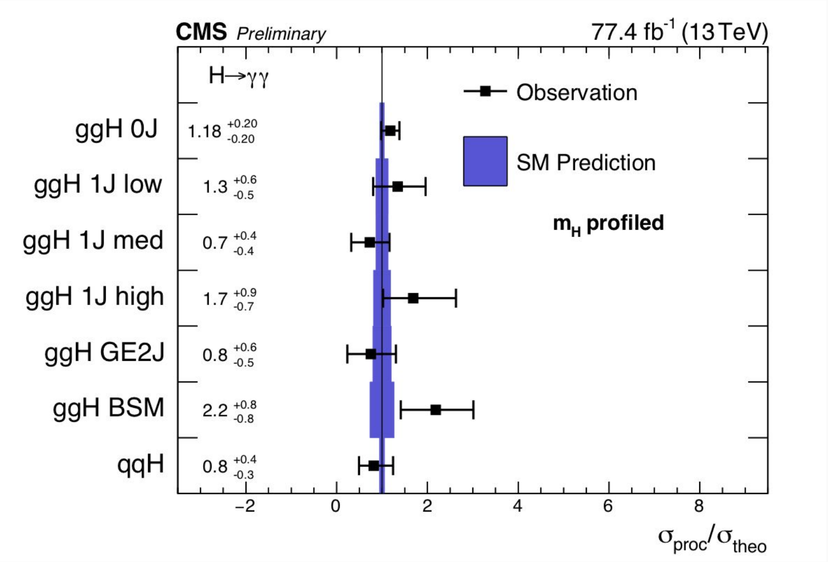
Colored scale corresponds to the fraction of each category (rows) accounted for by each stage 1 process (columns)

Each row sums up to 100%

Entries with less than 0.5% are now shown

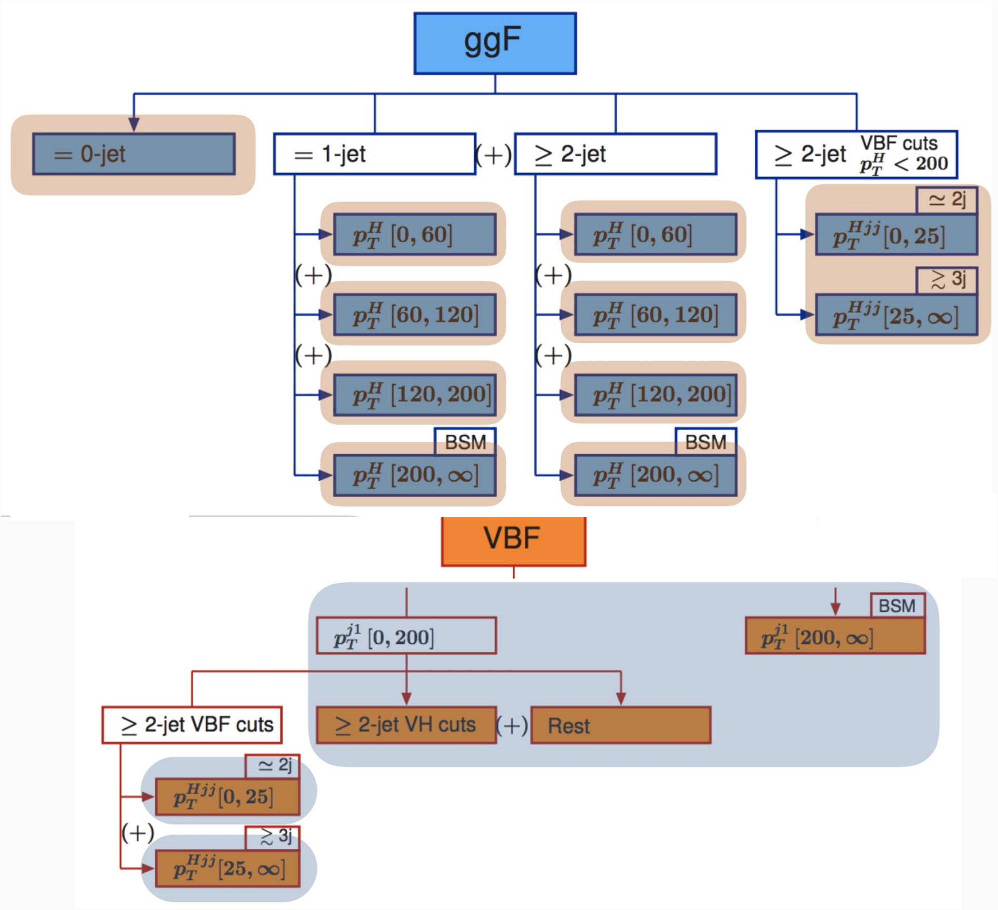
H→γγ : STXS 1 (Grouping 1)

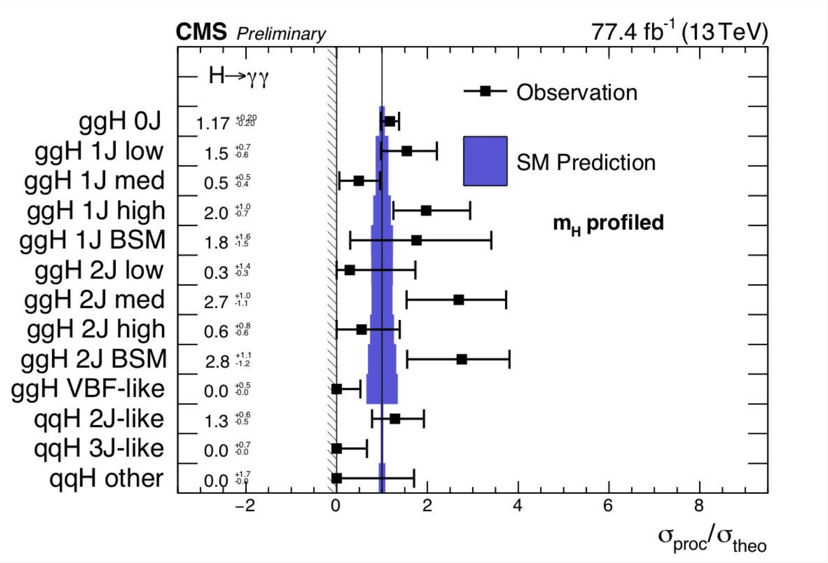




- Seven parameter fit, corresponding to the maximum granularity achievable whilst maintaining all uncertainties at ~±100% SM prediction
  - VBF all merged into 1 bin.

H→γγ : STXS 1 (Grouping 2)

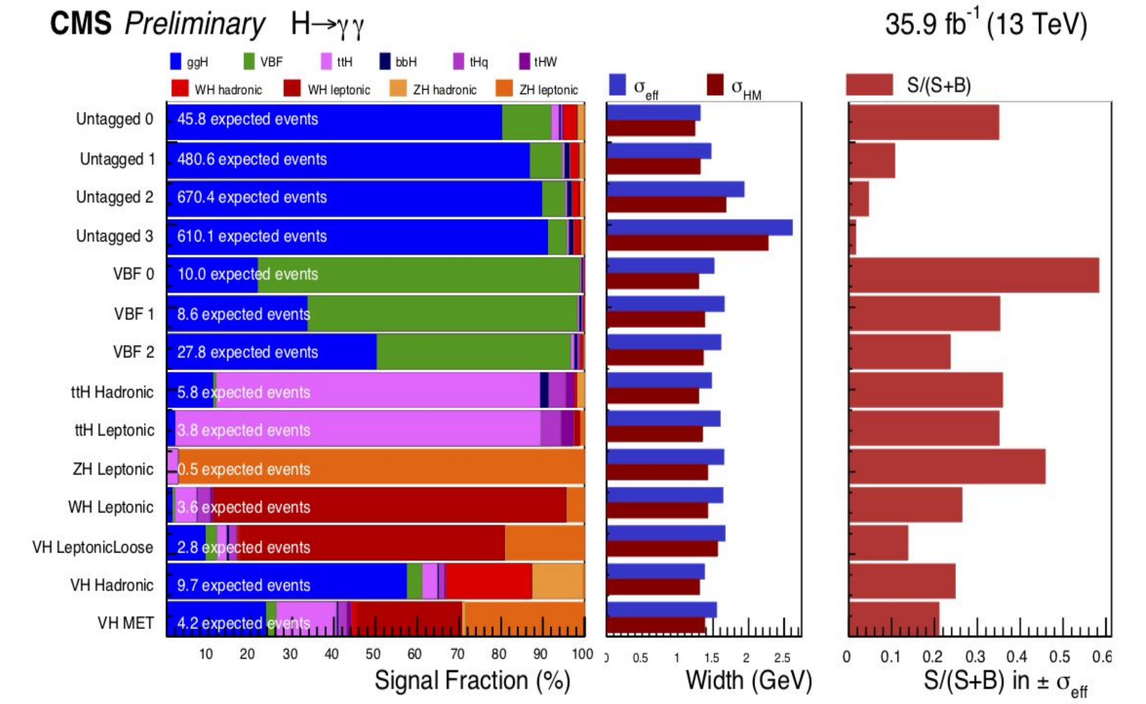




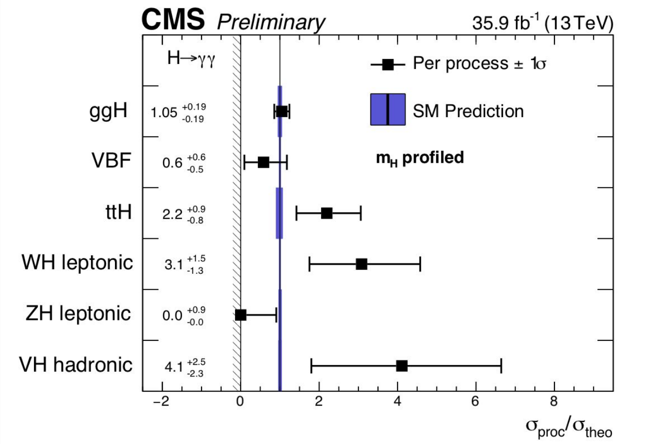
- Thirteen parameter fit, corresponding to the maximum granularity achievable
  - Only merged bins are ggH VBF-like and VBF-rest

H→γγ : 2016 result

HIG-16-040



- Untagged category dominated by ggH → defined using diphoton BDT
- VBF tags use dijet BDT to reduce ggH contamination
- Dedicated ttH hadronic BDT;
- VH tags cut-based

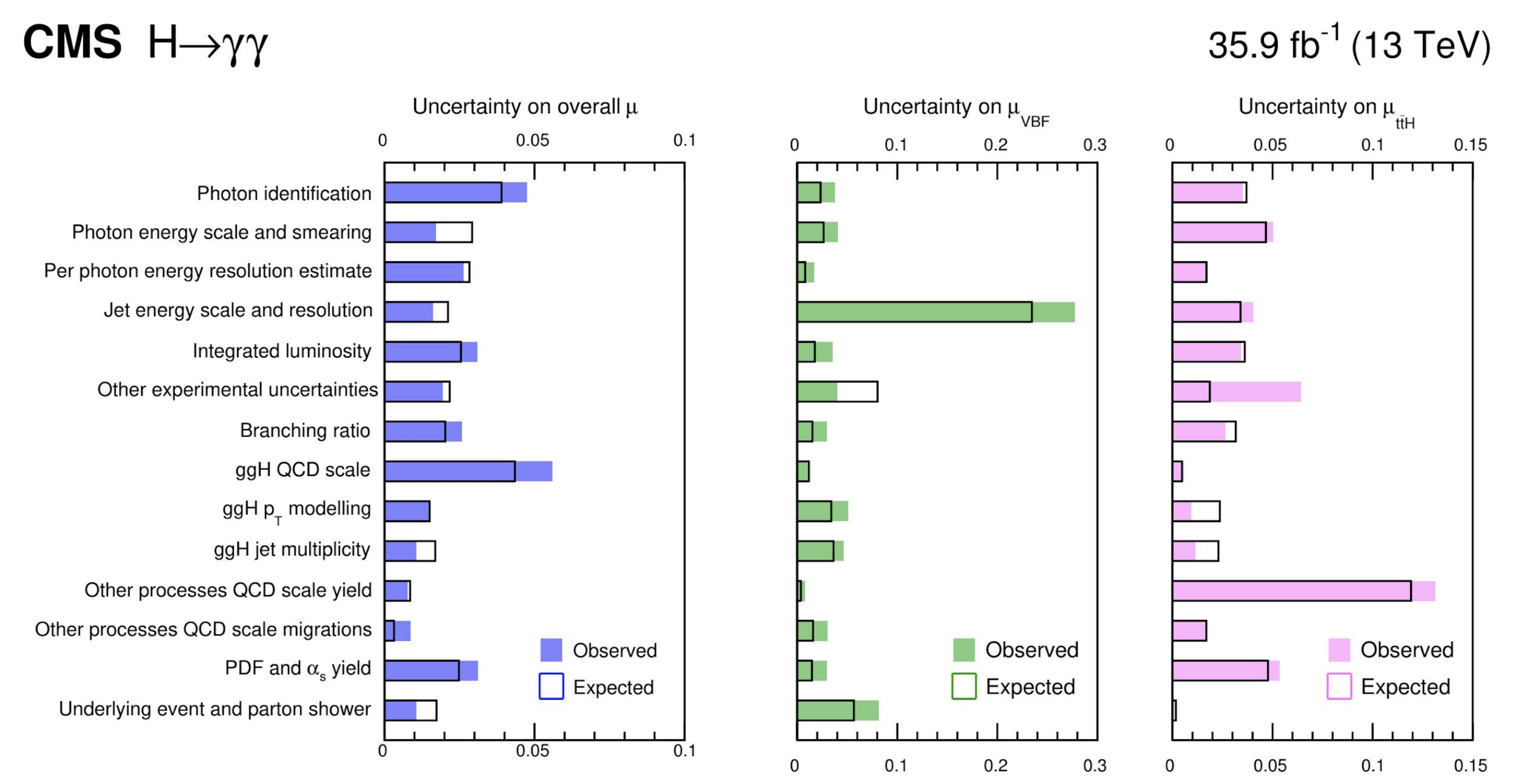


- Simultaneous fit to $m_{\gamma\gamma}$ is performed for each category

$$\widehat{\mu} = 1.18^{+0.17}_{-0.14} = 1.18\ ^{+0.12}_{-0.11}\,(\text{stat})^{+0.09}_{-0.07}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{theo})$$

H→γγ : Systematics

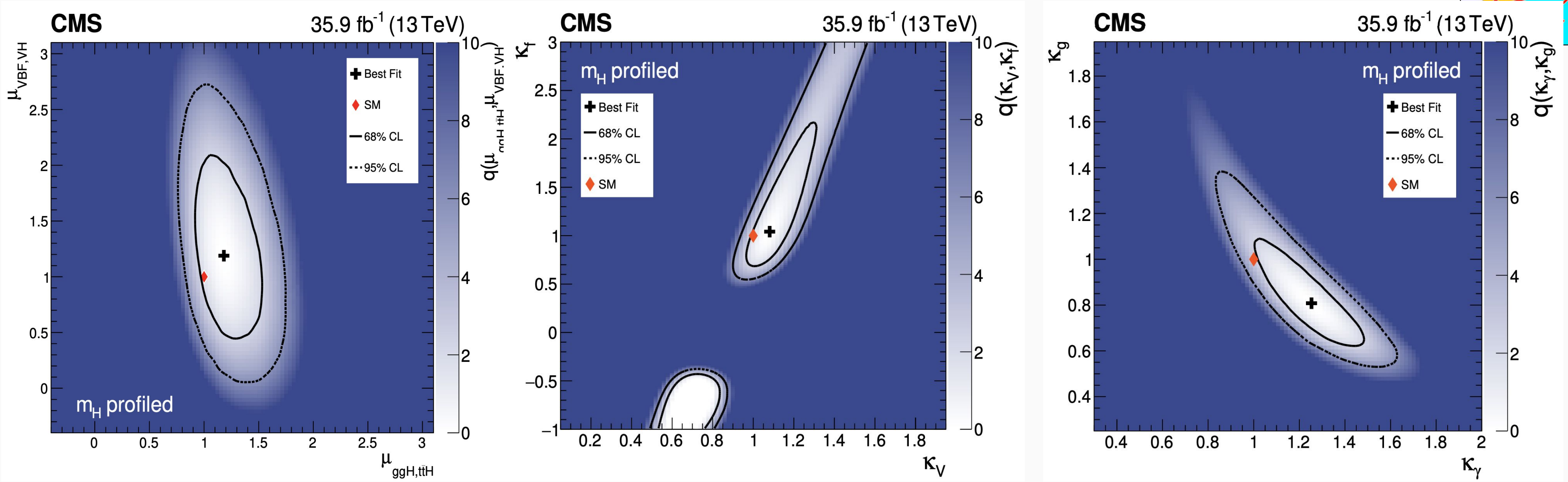
HIG-16-040



- Important contributions from both theoretical and experimental sources.

H→γγ : Couplings

HIG-16-040



- 2D likelihood scan is performed for fermionic and vector-boson production modes.

Best fit value :

$$\widehat{\mu}_{\mathrm{ggH,t\bar{t}H}} = 1.19^{+0.22}_{-0.18} \text{ and } \widehat{\mu}_{\mathrm{VBF,VH}} = 1.21^{+0.58}_{-0.51}$$

- Deviations from SM expectation in the couplings of the Higgs boson can be parameterized using coupling modifiers in the so-called κ framework
- All consistent with Standard Model.

H→4l + H→ττ : Anomalous Couplings

HIG-17-034

- ➔ 35.9 fb^{-1} data has been analyzed in H→ττ and results combined with those from the H→4l (with 80 fb^{-1}) targeting HVV anomalous coupling → also combined with Run-I
- ➔ Kinematic distributions for production modes (VBF+VH) and decay products (H→ττ & H→4l) has been used.

signal scattering amplitude describing the interaction between a spin-0 Higgs boson and two spin-one gauge bosons VV :

$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} - \frac{\kappa_3^{VV} (q_1 + q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}.$$

- a_1, a_2 : CP-even interaction
- a_3 : CP-odd interaction (pseudoscalar)
- Λ1 : leading momentum expansion

➔ HVV amplitude parameterised as fractional cross section :

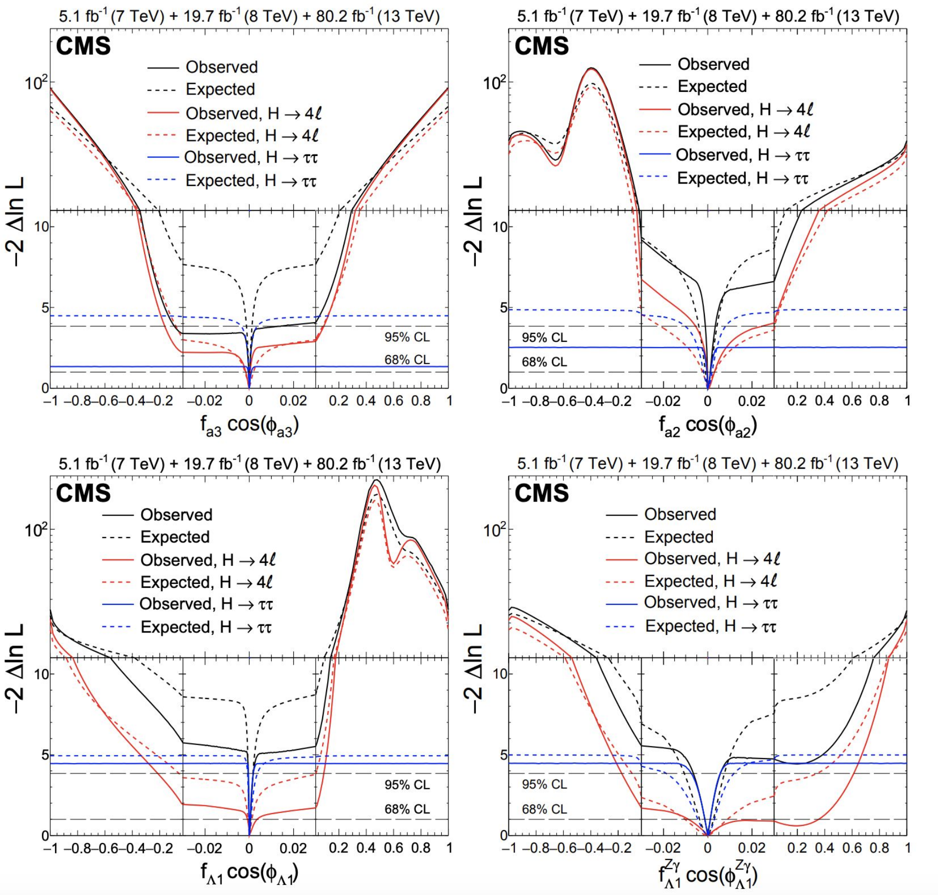
$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\Sigma_j |a_j|^2 \sigma_j}$$

and relative phase :

$$\phi_{ai} = \arg\left(\frac{a_i}{a_1}\right)$$

Anomalous Couplings : Results

HIG-17-034



- ➔ large confidence levels and large values of f_{ai} are predominantly constrained by the decay information in the H→VV analysis,
- ➔ the constraints in the narrow range of f_{ai} are dominated by the production information where the H→ττ channel dominates over the H → 4l
- ➔ Combination of these results in the most stringent limits on anomalous HVV couplings

Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
	68% CL	95% CL	68% CL	95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$

H→WW Overview

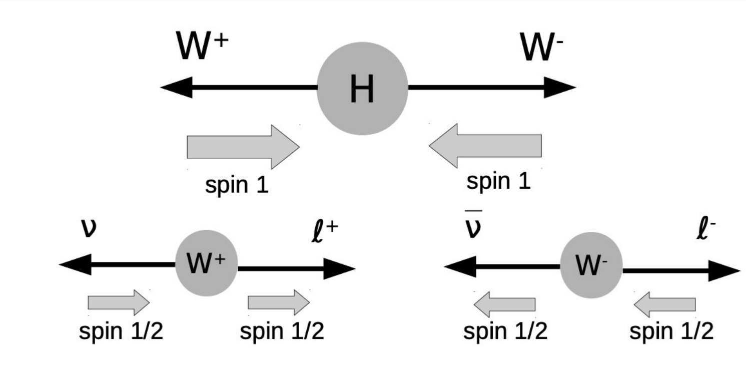
PLB (HIG-16-042)

★ With second Highest B.R. for Higgs at 125 GeV, H→WW is an important channel for measurement of Higgs boson properties.

★ With 2016 → enough statistics to tackle all the main production modes.

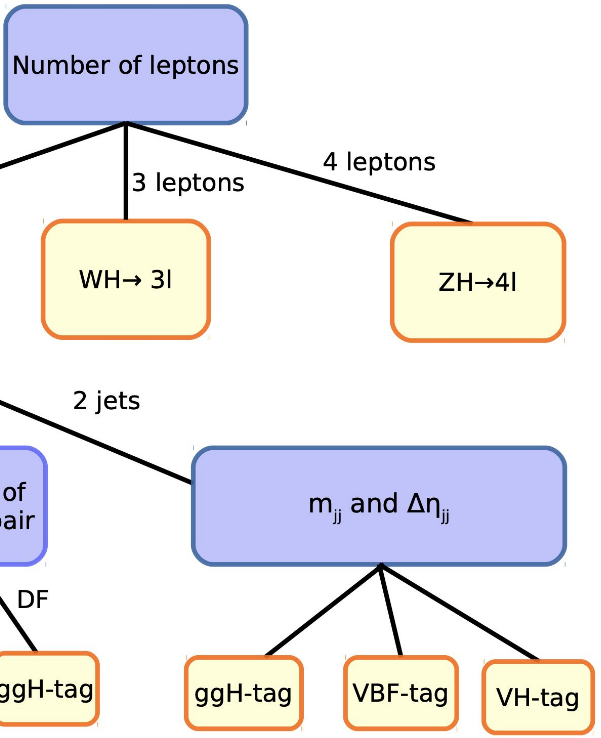
★ **Signature** :
- 2 opposite sign leptons with moderate missing energy

★ Tag production mechanisms using the number of jets and additional leptons

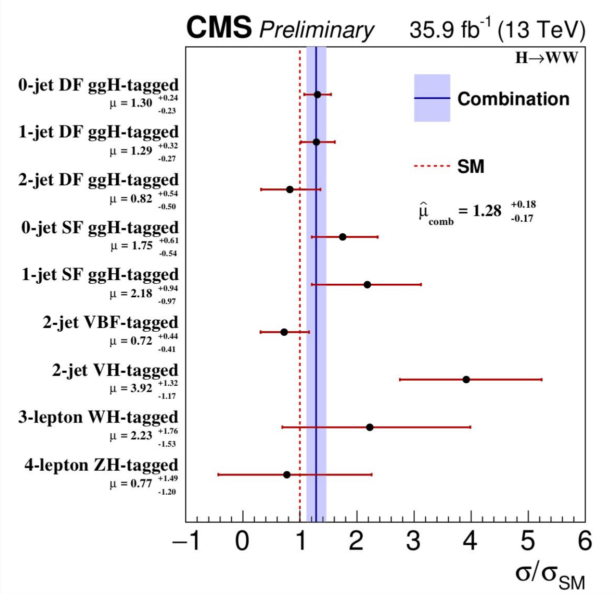


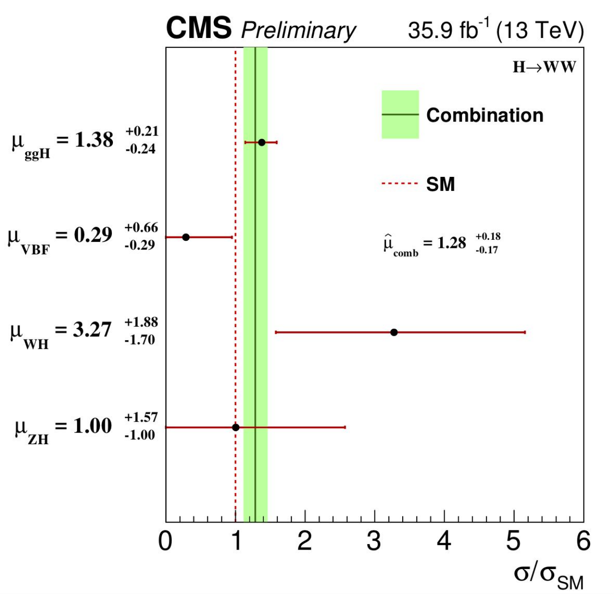
Higgs Spin 0 → leptons are closer → low m_{ll}

SF: Same Flavour (ee/μμ)
DF: Different Flavour (eμ)

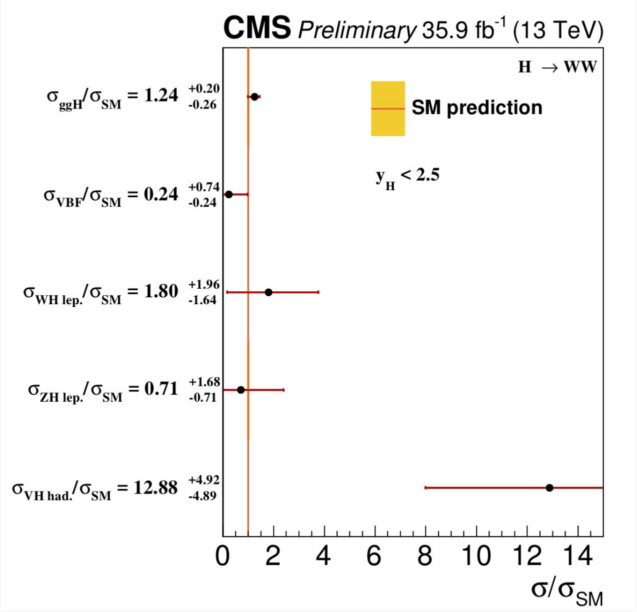


H→WW : Signal Strengths





- Stage-0 STXS with $|y_H| < 2.5$
- H→ $\tau\tau$ is considered as background in fit.



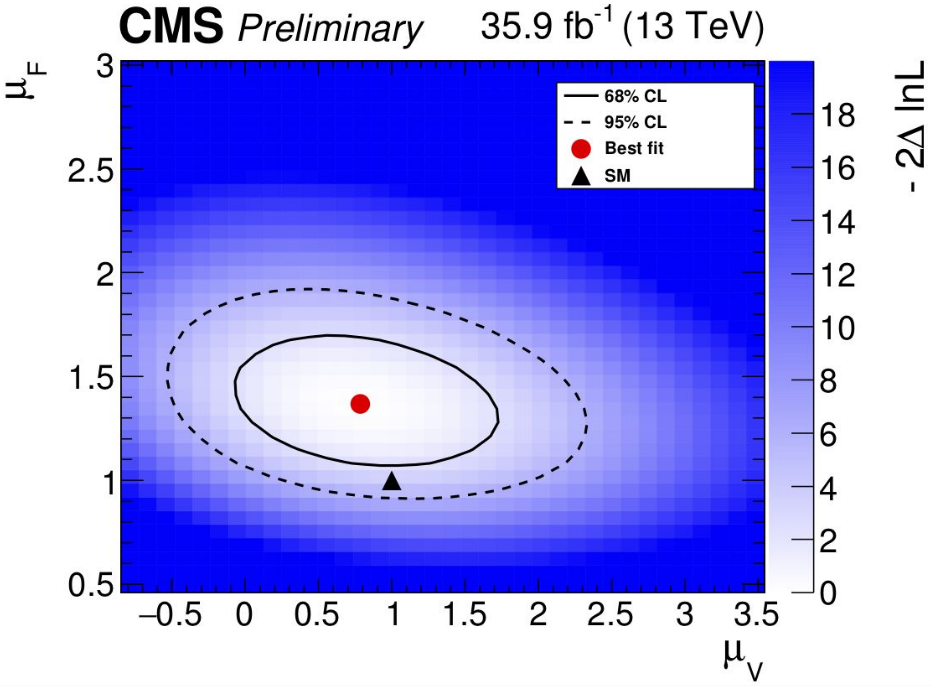
- ggH measurement is systematically limited

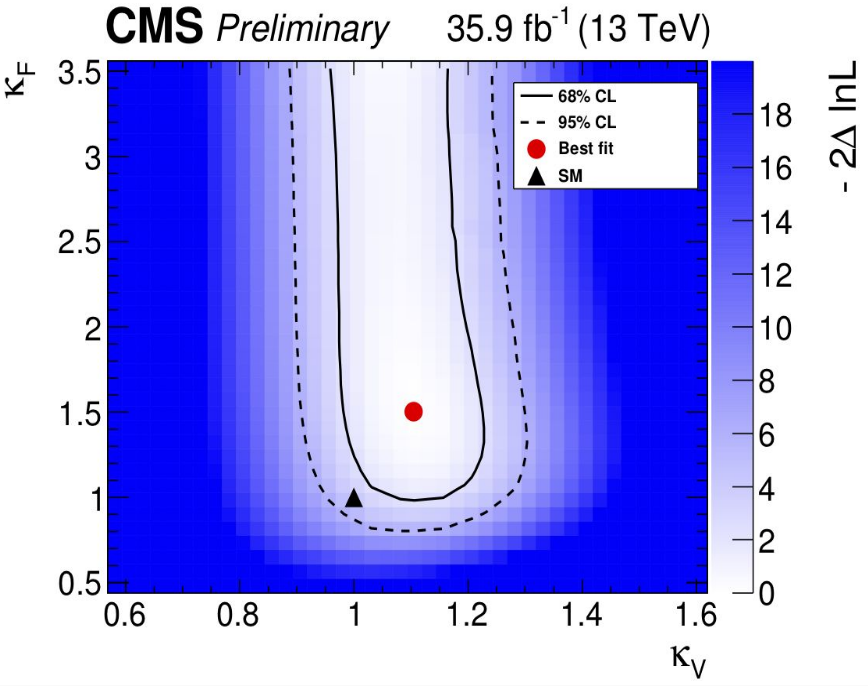
$$\mu = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10\,(\text{stat}) \pm 0.11\,(\text{syst})^{+0.10}_{-0.07}\,(\text{theo})$$

$$\text{Significance} = 9.1\sigma (7.1\sigma\ \text{exp})$$

First observation of H→WW in CMS

H→WW : Couplings





- μ_V *and* μ_F *: signal strengths associated to ggH and VBF/VH*
- K_V *and* K_F *: coupling constants associated to fermionic and bosonic processes, as defined in the "kappa" framework.*

Summary & Outlook

➔ Higgs Physics is in precision measurement "era".

➔ Most of the inclusive measurements are already systematic limited with partial Run-II dataset.

➔ H→4l has been presented with full Run-2 dataset (signal strength, STXS1.1, fiducial & differential Xsec)

$$\mu = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

➔ Some important results were not included here because of lack of time :

- HIG-16-041 (JHEP) (35.9 fb^{-1}) : Mass measurement with H→4l : 125.26 ± 0.21 GeV
- HIG-18-002 (PRD) (80.2 fb^{-1}@13TeV + Run-I) : Off-shell Higgs width with H→4l : $3.2^{+2.8}_{-2.2}$ MeV
- HIG-17-025 (JHEP) (35.9 fb^{-1}) : Inclusive and Fiducial & differential fiducial X-sec in H→γγ
- HIG-18-018 (41.5 fb-1) : ttH (H→γγ) with 2017 data → see M.Peruzzi talk tomorrow !

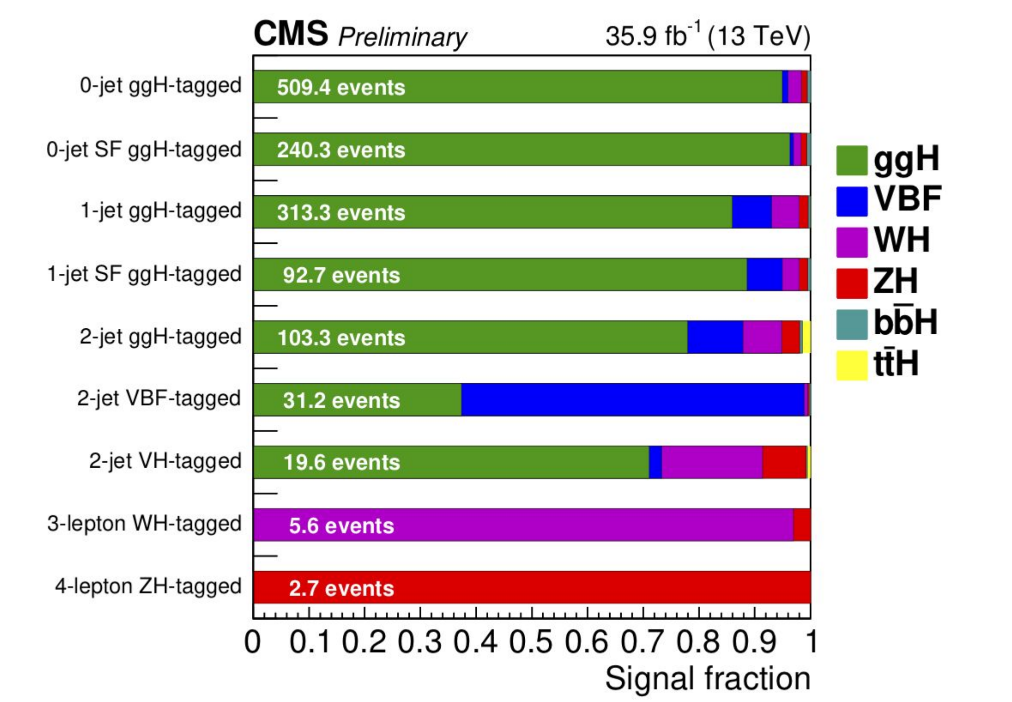
➔ All analyses are being updated with full Run-II luminosity → Stay Tuned !!

Thank you for your attention !

Back up

H→WW : categories

PLB (HIG-16-042)



★ More finer categories are defined by lepton flavour and sub-leading lepton p_T.

$$m_T = \sqrt{2 p_T^{\ell\ell} p_T^{miss} [1 - \cos \Delta\phi(\ell\ell, \vec{p}_T^{miss})]},$$

➔ Most categories are shape-based :

- ◆ ggH DF → 2D in m_{ll} and m_T
- ◆ ggH SF → cut-and-count with a BDT to reject DY
- ◆ 2jet VBF and VH → 1D m_{ll} shape
- ◆ 3 lepton WH → $\min(\Delta R_{ll})$
- ◆ 4 lepton ZH → cut-and-count

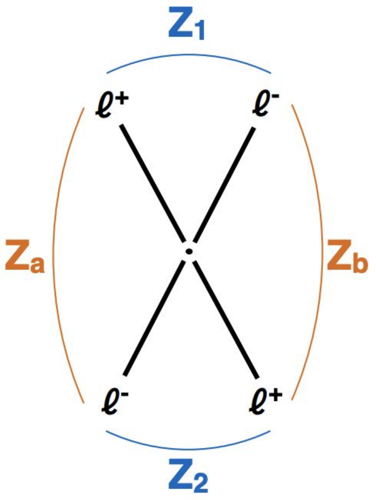
Main Systematics : lepton reconstruction, background data driven estimation and ggH theoretical uncertainties

ZZ candidate selection

Z candidate = any OS-SF pair that satisfy $12 < m_{ll(\gamma)} < 120$ GeV

Build all possible ZZ candidates, define Z_1 candidate with $m_{ll(\gamma)}$ closest to the PDG m(Z) mass

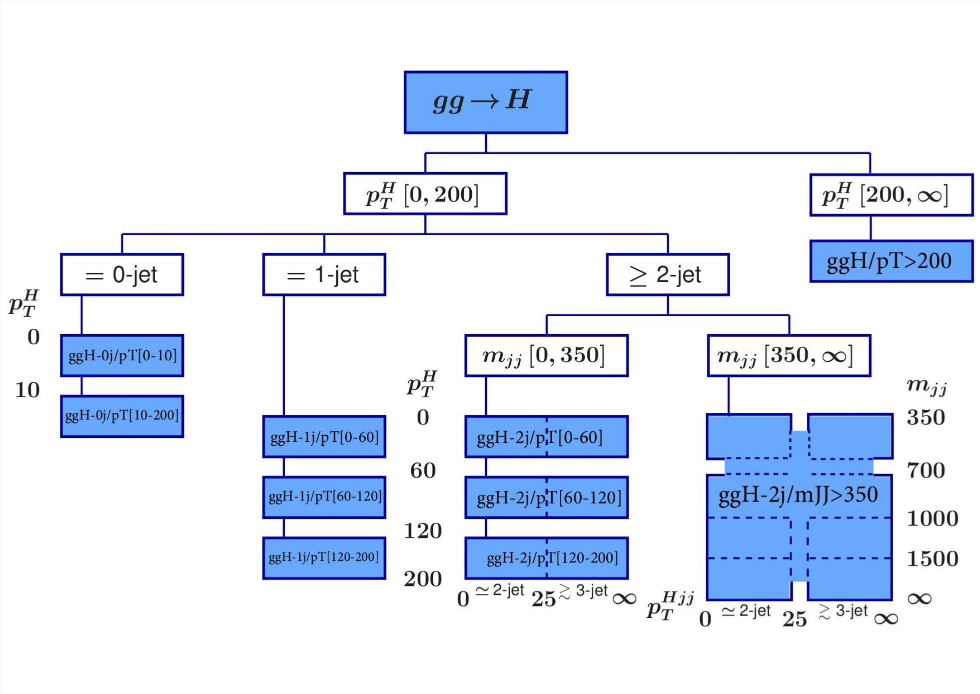
- $m_{Z1} > 40$ GeV, $p_T(l1) > 20$ GeV, $p_T(l2) > 10$ GeV
- $\Delta R > 0.02$ between each of the four leptons
- $m_{ll} > 4$ GeV for OS pairs (regardless of flavour)
- reject 4μ and 4e candidates where the alternate pairing Z_aZ_b satisfies $|m(Z_a)-m(Z)|<|m(Z_1)-m(Z)|$ and $m(Z_b)<12$ GeV
- $m_{4l} > 70$ GeV

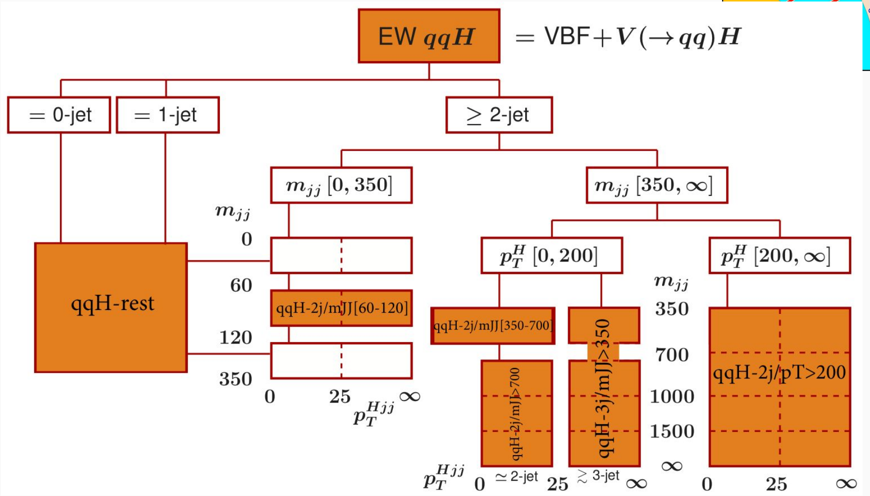


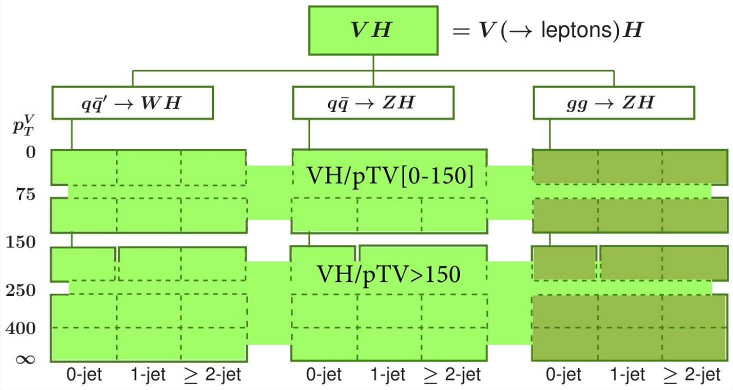
If more than one ZZ candidate is left, choose the one of highest $\mathcal{D}_{\rm bkg}^{\rm kin}$
If $\mathcal{D}_{\rm bkg}^{\rm kin}$ is the same, take the one with Z_1 mass closest to m(Z)*

*For fiducial measurements take the one with Z_1 mass closest to m(Z)

STXS 1.1

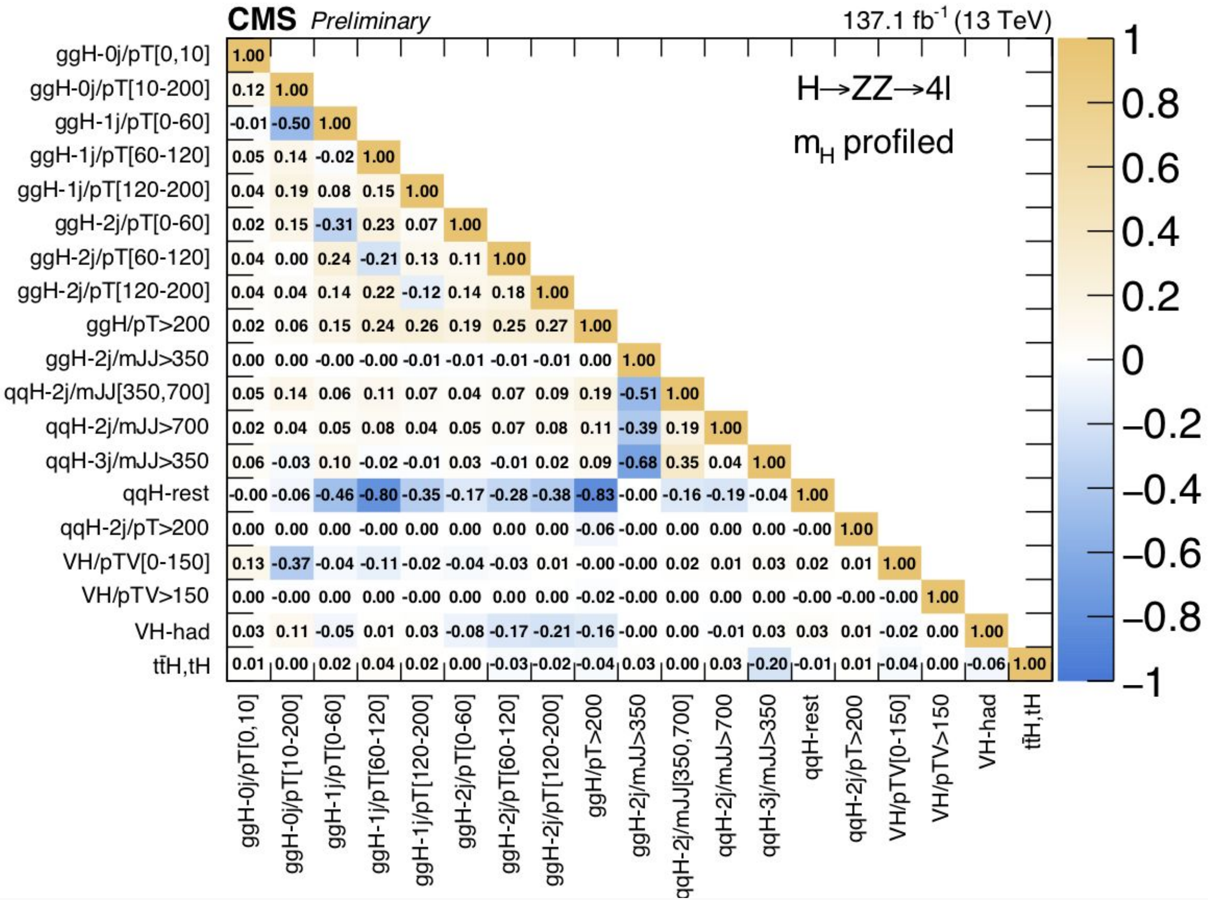

$gg \to H$
p_T^H [0, 200]
p_T^H [200, ∞]
ggH/pT>200
= 0-jet
= 1-jet
≥ 2-jet
p_T^H
0
10
ggH-0j/pT[0-10]
ggH-0j/pT[10-200]
ggH-1j/pT[0-60]
ggH-1j/pT[60-120]
ggH-1j/pT[120-200]
m_{jj} [0, 350]
m_{jj} [350, ∞]
p_T^H
0
60
120
200
ggH-2j/pT[0-60]
ggH-2j/pT[60-120]
ggH-2j/pT[120-200]
0 ≃ 2-jet 25 ≳ 3-jet ∞
ggH-2j/mJJ>350
m_{jj}
350
700
1000
1500
∞
p_T^{Hjj}
0 ≃ 2-jet 25 ≳ 3-jet ∞


EW qqH
= VBF + $V(\to qq)H$
= 0-jet
= 1-jet
≥ 2-jet
m_{jj} [0, 350]
m_{jj} [350, ∞]
qqH-rest
m_{jj}
0
60
120
350
qqH-2j/mJJ[60-120]
0 25 ∞
p_T^{Hjj}
p_T^H [0, 200]
p_T^H [200, ∞]
qqH-2j/mJJ[350-700]
qqH-2j/mJJ>700
qqH-3j/mJJ>350
m_{jj}
350
700
1000
1500
∞
qqH-2j/pT>200
p_T^{Hjj} 0 ≃ 2-jet 25 ≳ 3-jet ∞
0 25 ∞


VH
= $V(\to$ leptons$)H$
$q\bar{q}' \to WH$
$q\bar{q} \to ZH$
$gg \to ZH$
p_T^V
0
75
150
250
400
∞
VH/pTV[0-150]
VH/pTV>150
0-jet 1-jet ≥ 2-jet
0-jet 1-jet ≥ 2-jet
0-jet 1-jet ≥ 2-jet

H→4l : STXS 1.1 (correlation matrix)

The dominant experimental sources of systematic uncertainty are from lepton eff and luminosity, while the dominant theoretical source is the uncertainty in the category migration for the ggH process.

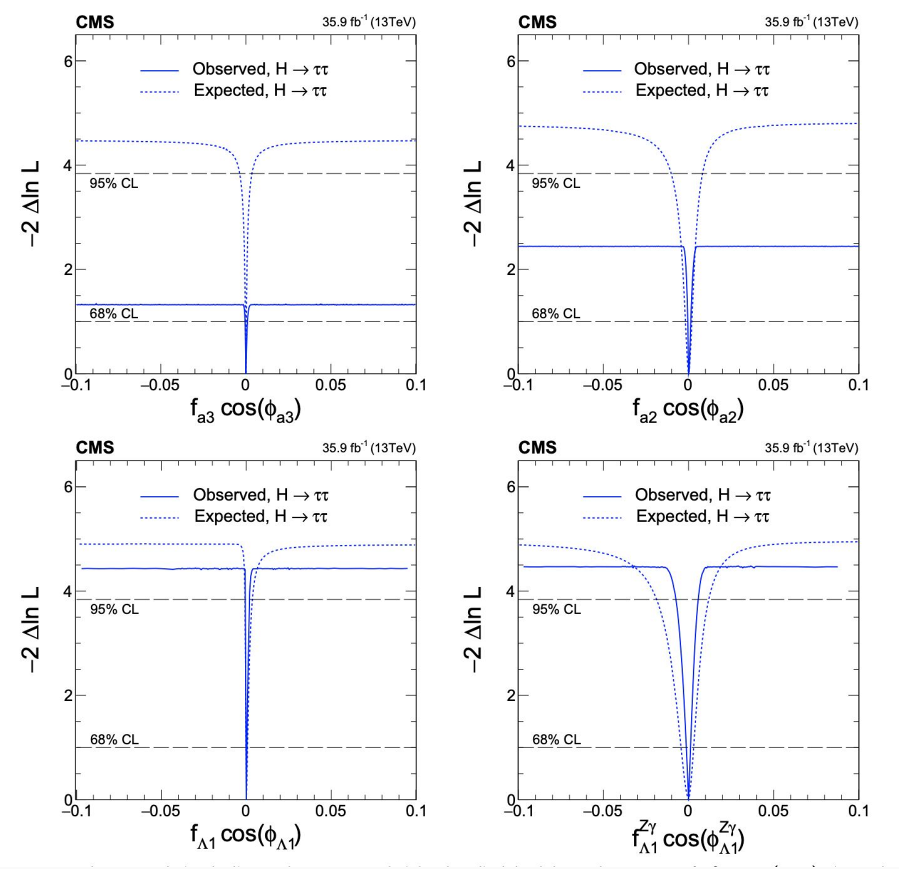


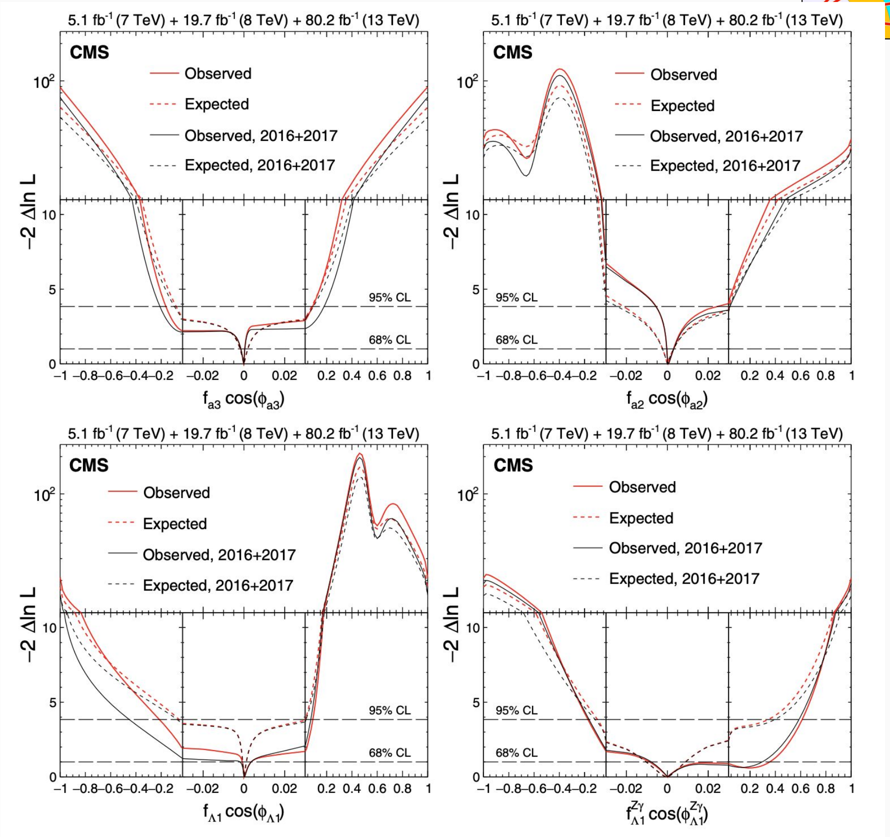
H→4l : Fiducial X-sec

Requirements for the H $\rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\text{GeV} < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12\,\text{GeV} < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$

$$N^{f,i}_{obs}(m_{4\ell}) = N^{f,i}_{fid}(m_{4\ell}) + N^{f,i}_{nonfid}(m_{4\ell}) + N^{f,i}_{nonres}(m_{4\ell}) + N^{f,i}_{bkg}(m_{4\ell})$$
$$= \epsilon^{f}_{i,j} \cdot \left(1 + f^{f,i}_{nonfid}\right) \cdot \sigma^{f,j}_{fid} \cdot \mathcal{L} \cdot \mathcal{P}_{res}(m_{4\ell})$$
$$+ N^{f,i}_{nonres} \cdot \mathcal{P}_{nonres}(m_{4\ell}) + N^{f,i}_{bkg} \cdot \mathcal{P}_{bkg}(m_{4\ell}),$$

Anomalous coupling





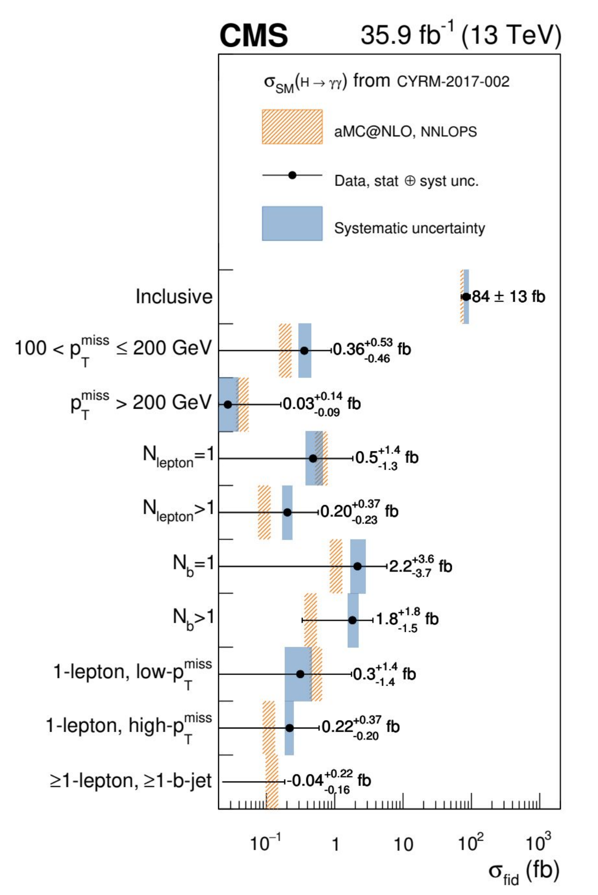
Anomalous coupling

Table 4: Summary of the allowed 95% CL intervals for the anomalous HVV couplings using the results in Table 3. The coupling ratios are assumed to be real and include the factor $\cos(\phi_{\Lambda1})$ or $\cos(\phi_{\Lambda1}^{Z\gamma}) = \pm1$.

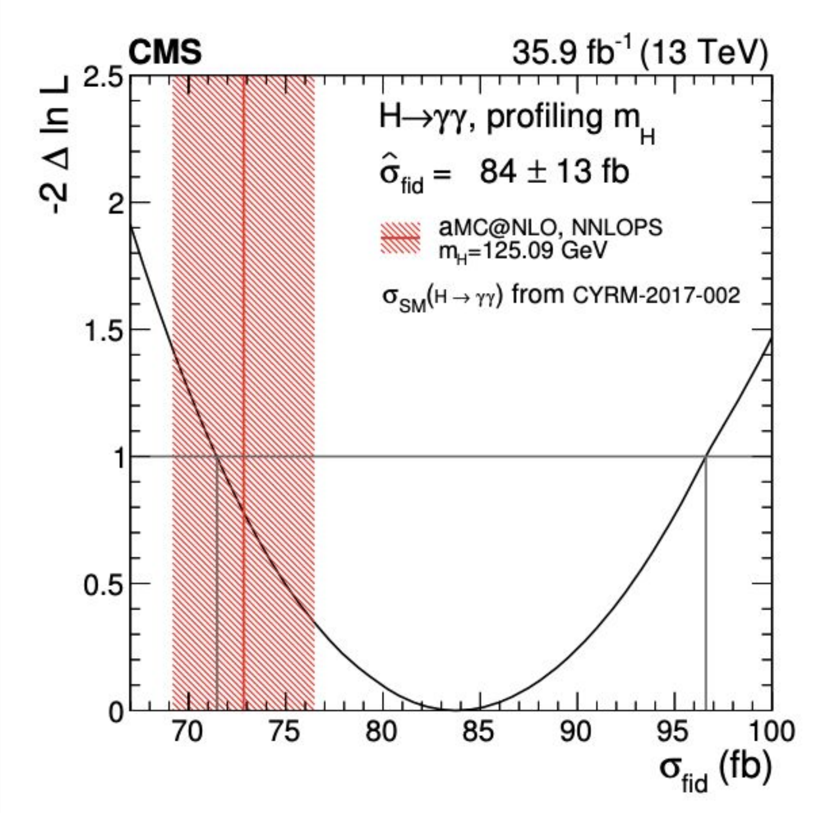
Parameter	Observed	Expected
a_3/a_1	$[-0.81, 0.31]$	$[-0.090, 0.090]$
a_2/a_1	$[-0.055, 0.097]$	$[-0.11, 0.11]$
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda1})$ (GeV)	$[-\infty, -650] \cup [440, \infty]$	$[-\infty, -610] \cup [450, \infty]$
$(\Lambda_1^{Z\gamma}\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda1}^{Z\gamma})$ (GeV)	$[-\infty, -400] \cup [420, \infty]$	$[-\infty, -360] \cup [390, \infty]$

H→γγ : Fiducial differential Xsec

Phase space region	Observable	Bin boundaries								
	$p_T^{\gamma\gamma}$ (GeV)	0	15	30	45	80	120	200	350	∞
Baseline	N_{jet}	0	1	2	3	4	∞			
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$	$\lvert y^{\gamma\gamma}\rvert$	0	0.15	0.3	0.6	0.9	2.5			
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$\lvert\cos(\theta^*)\rvert$	0	0.1	0.25	0.35	0.55	1			
$\lvert\eta^{\gamma}\rvert < 2.5$	$p_T^{\gamma\gamma}$ (GeV), $N_{jet} = 0$	0	20	60	∞					
$\text{Iso}_{gen}^{\gamma} < 10$ GeV	$p_T^{\gamma\gamma}$ (GeV), $N_{jet} = 1$	0	60	120	∞					
	$p_T^{\gamma\gamma}$ (GeV), $N_{jet} > 1$	0	150	300	∞					
	N_{jet}^{b}	0	1	2	∞					
	N_{lepton}	0	1	2	∞					
	p_T^{miss} (GeV)	0	100	200	∞					
1-jet	$p_T^{j_1}$ (GeV)	0	45	70	110	200	∞			
Baseline + $\geq$1 jet	$\lvert y^{j_1}\rvert$	0	0.5	1.2	2	2.5				
$p_T^{j} > 30$ GeV, $\lvert\eta^{j}\rvert < 2.5$	$\lvert\Delta\phi^{\gamma\gamma,j_1}\rvert$	0	2.6	2.9	3.03	π				
	$\lvert\Delta y^{\gamma\gamma,j_1}\rvert$	0	0.6	1.2	1.9	∞				
	$p_T^{j_2}$ (GeV)	0	45	90	∞					
2-jets	$\lvert y^{j_2}\rvert$	0	1.2	2.5	4.7					
Baseline + $\geq$2 jets	$\lvert\Delta\phi^{j_1,j_2}\rvert$	0	0.9	1.8	π					
$p_T^{j} > 30$ GeV, $\lvert\eta^{j}\rvert < 4.7$	$\lvert\Delta\phi^{\gamma\gamma,j_1j_2}\rvert$	0	2.9	3.05	π					
	$\lvert\overline{\eta}_{j_1j_2} - \eta_{\gamma\gamma}\rvert$	0	0.5	1.2	∞					
	$m^{j_1j_2}$ (GeV)	0	100	150	450	1000	∞			
	$\lvert\Delta\eta^{j_1,j_2}\rvert$	0	1.6	4.3	∞					
VBF-enriched	$p_T^{j_2}$ (GeV)	0	45	90	∞					
2-jets + $\lvert\Delta\eta^{j_1,j_2}\rvert > 3.5$, $m^{j_1j_2} > 200$ GeV	$\lvert\Delta\phi^{j_1,j_2}\rvert$	0	0.9	1.8	π					
	$\lvert\Delta\phi^{\gamma\gamma,j_1j_2}\rvert$	0	2.9	3.05	π					



H→γγ : Fiducial differential Xsec



$$\hat{\sigma}_{\text{fiducial}} = 84 \pm 11\,(\text{stat}) \pm 7\,(\text{syst})\,\text{fb} = 84 \pm 13\ (\text{stat+syst})\,\text{fb}\,.$$

$$\sigma^{\text{theory}}_{\text{fiducial}} = 73 \pm 4\,\text{fb}.$$