Some materials for discussion on Higgs

Mingshui Chen (IHEP)

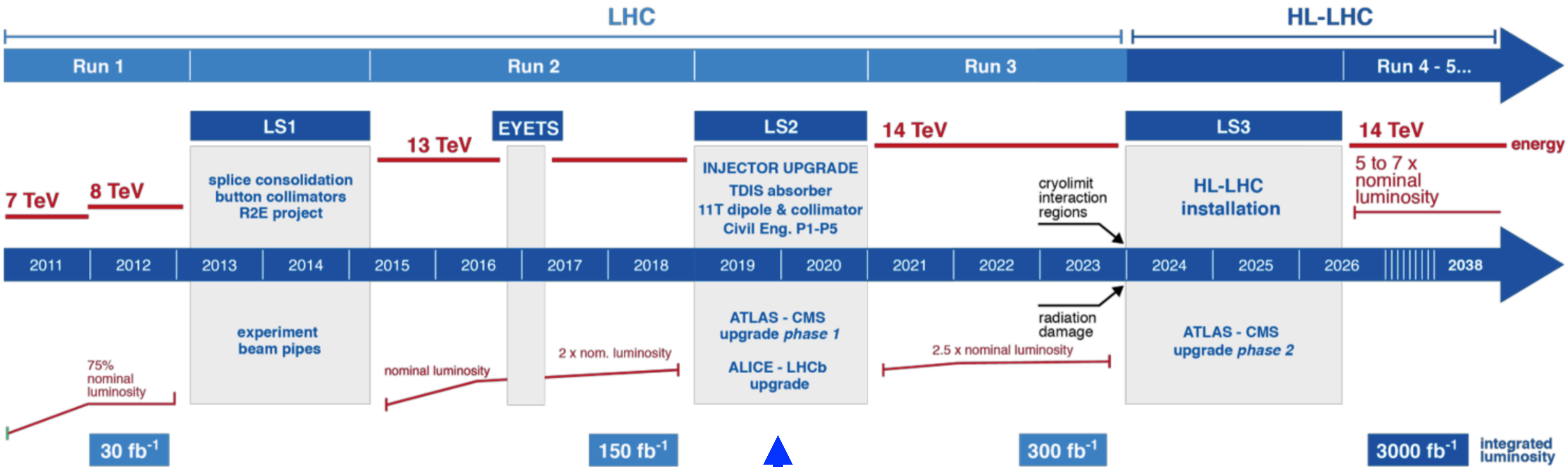
LHC mini-workshop, Chongqing Univ.

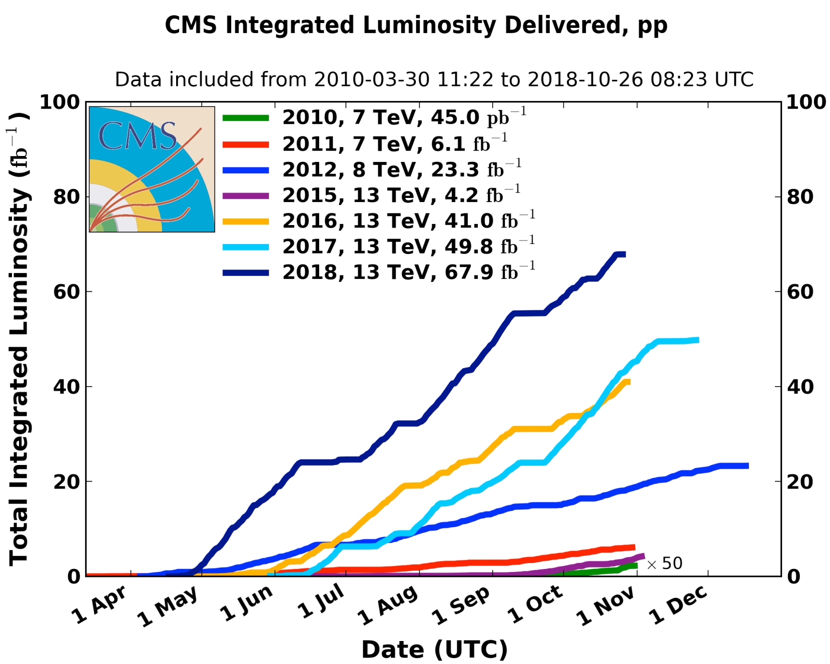
2019.05.18-20

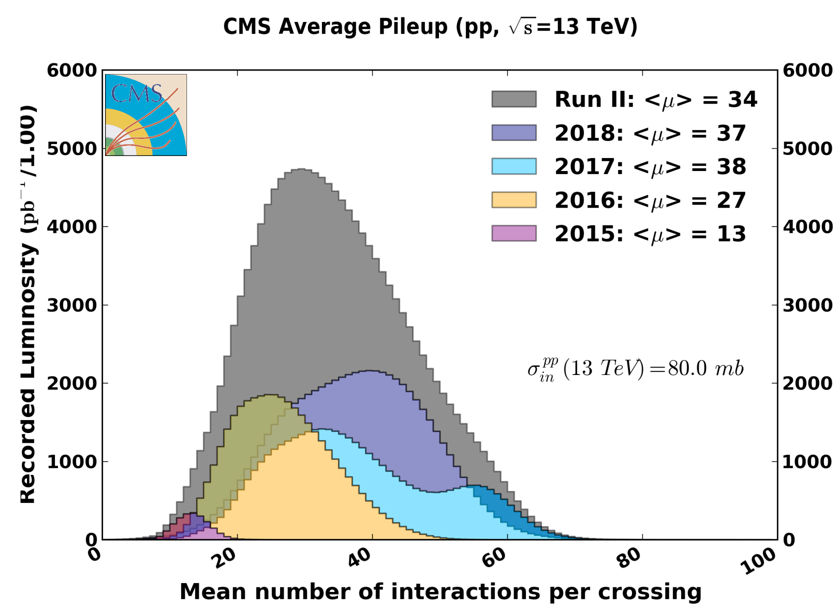
Notes

- Selected Run 2 results (still mostly based on partial dataset)
  - Differential XS, STXS, Width, Couplings
- Next Challenges for Run 3 and beyond
- Projection for HL-LHC

Where do we stand ?







Run 2 Higgs Milestones -> 3rd generation

Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

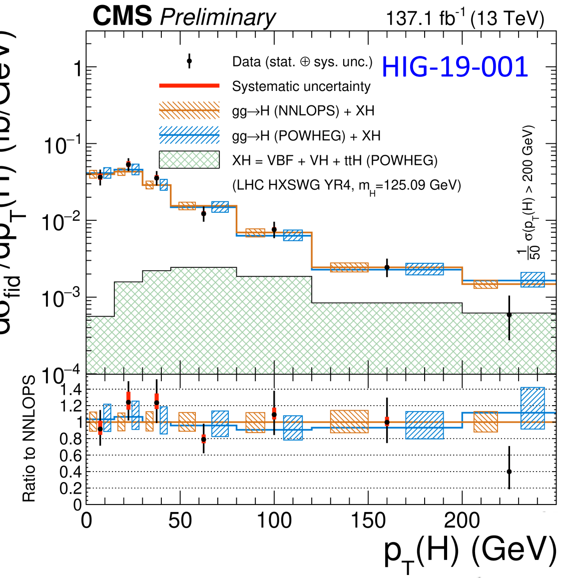
* 13 TeV only derived from cross section measurements

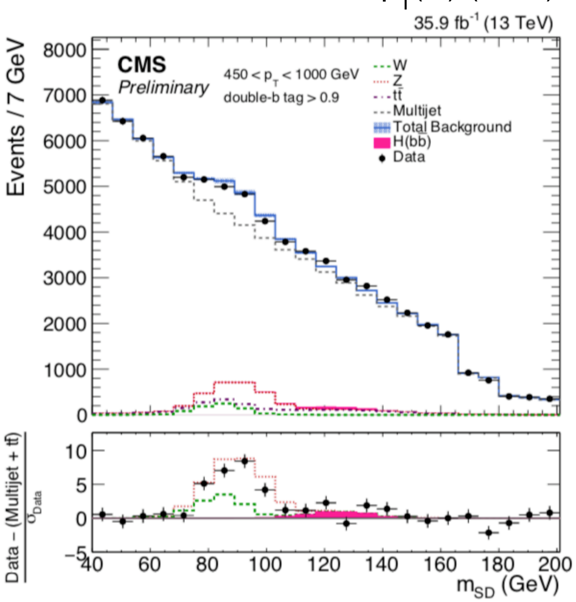
** Lower uncertainty (upper uncertainty 31)

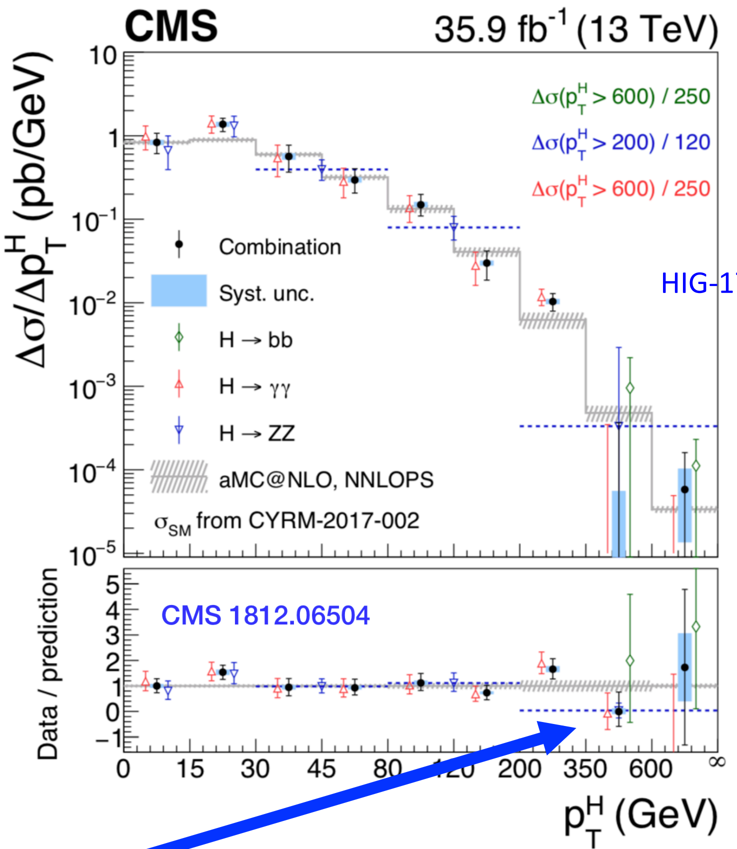
Recently, observation of ttH in single channel H->γγ

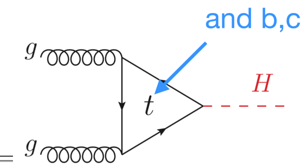
- Still room for improvement
  - Larger statistics will allow to focus on more specific regions of phase space
  - Make ancillary measurements for a better control of the backgrounds

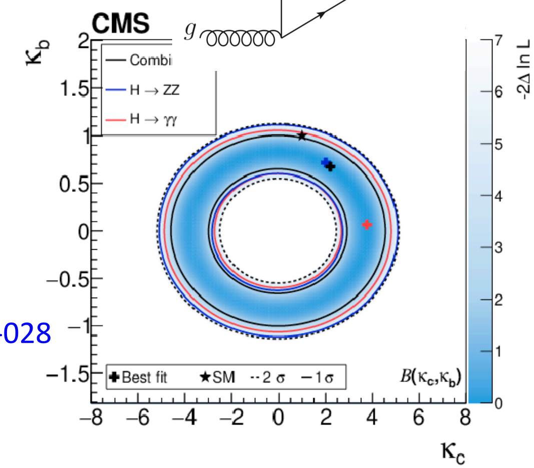
Differential Cross Sections

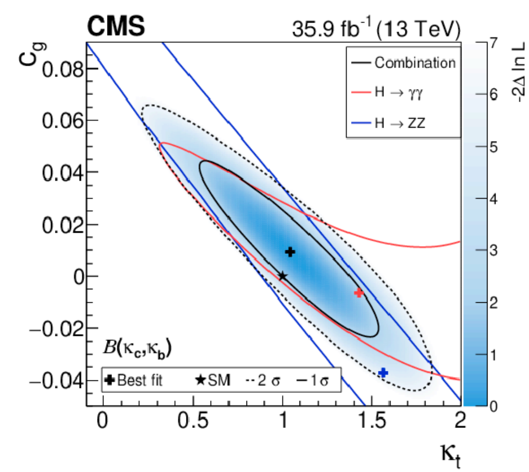












Boosted analysis in bb to reach highest pT

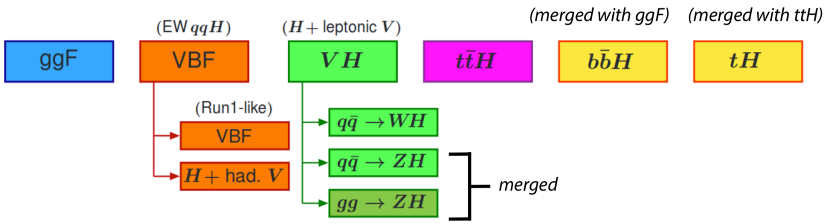
- At least one AK8 jet and 450 GeV
  (For ATLAS, AK1-trimmed jet of 480 GeV)
- One or two b-tags (double b-tagging efficiency pT dependent)

- More observables, double differential XS in pipeline

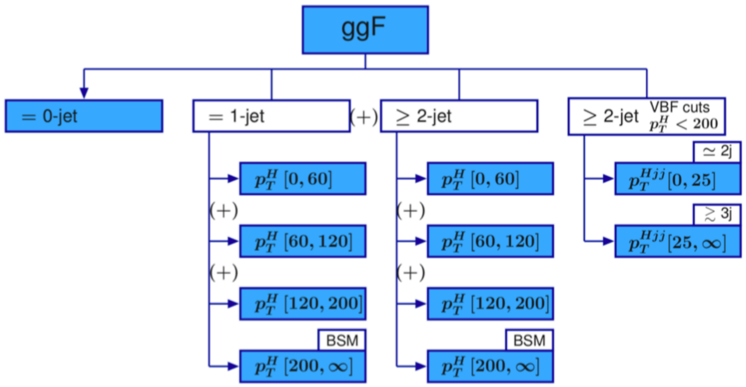
Simplified Template Cross Sections

- **To measure as precisely as possible individual production processes (ggF, VBF, VH and ttH) in different regions of phase space**
  - Integrate over the decay products of the Higgs.
  - Define fiducial cuts at truth particle level on the Higgs production (eta, pT, number and kinematics of the additional jets or leptons in the events).
  - Define (as much as possible) reconstruction level cuts corresponding to the fiducial volume of interest (as much as possible).
  - Fit the defined partially fiducial defined cross sections in all regions simultaneously.
- Advantage possibility to **combine decay channels** and use **multivariate techniques** in specific channels. **Compromise** as both aspects increase the extrapolation.

Stage 0

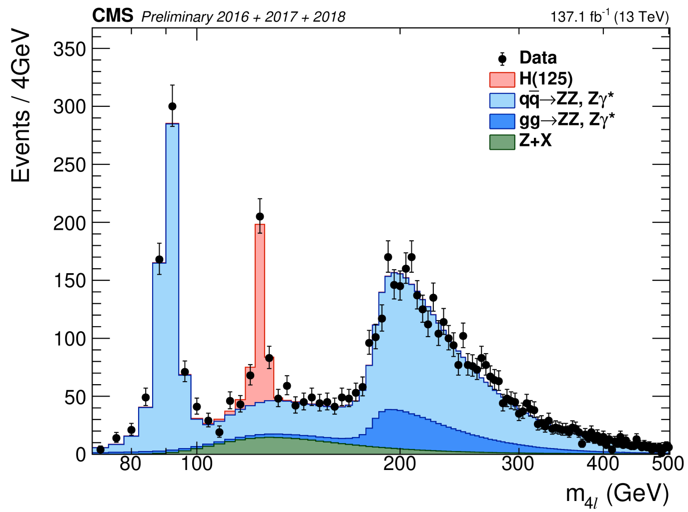


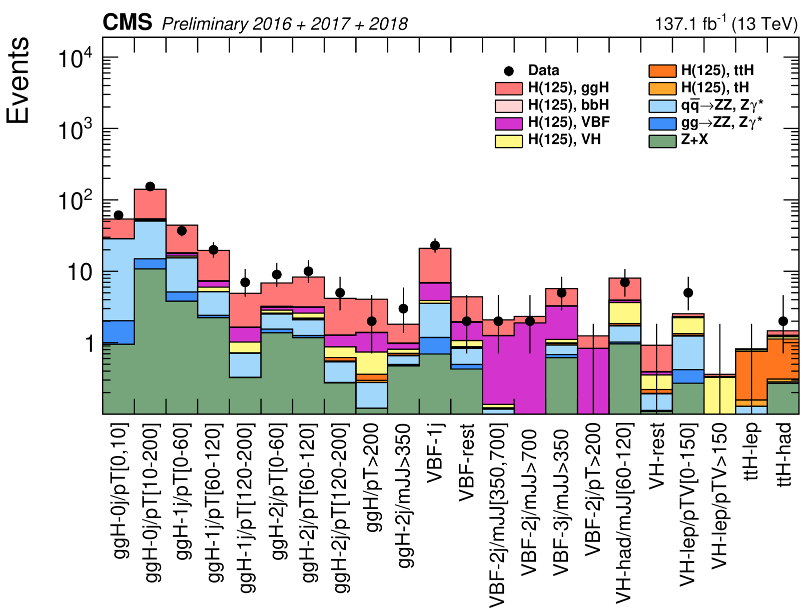
Stage 1 - ggF

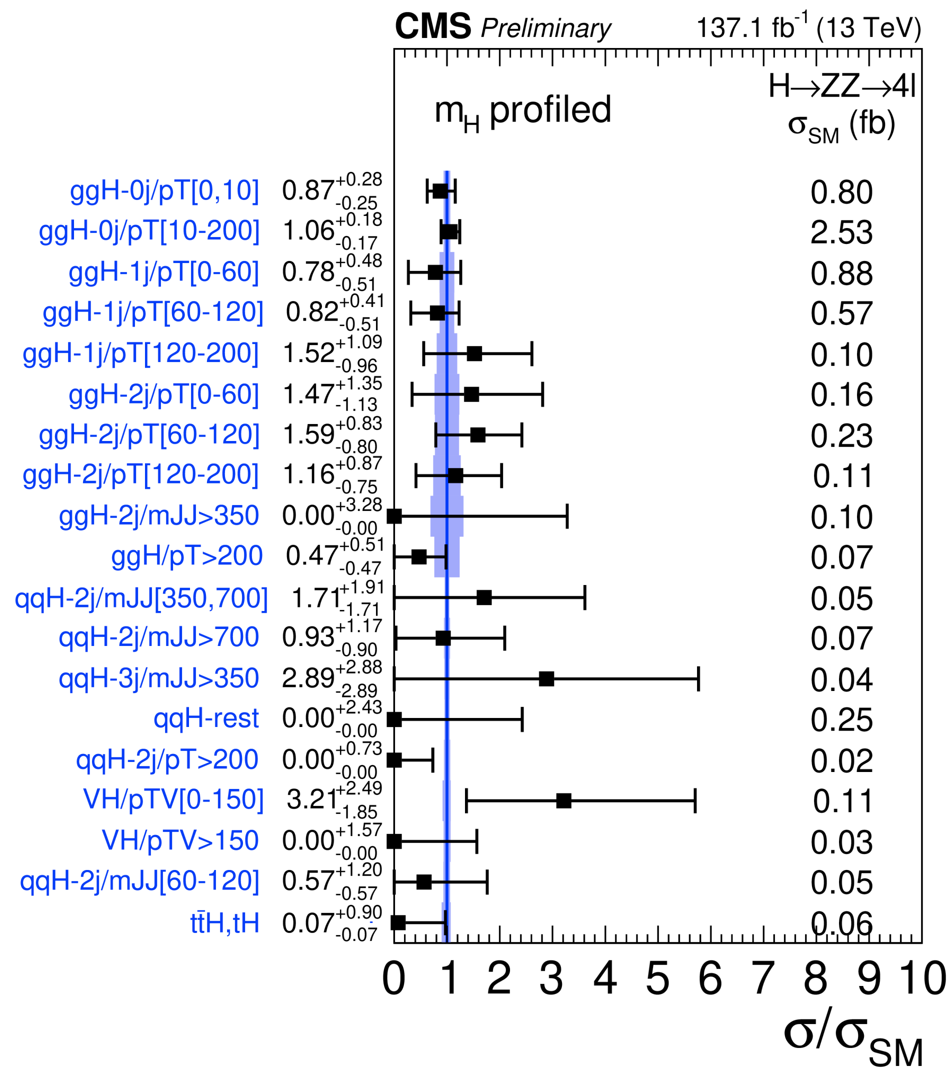


Simplified Template Cross Sections

CMS-PAS-HIG-19-001





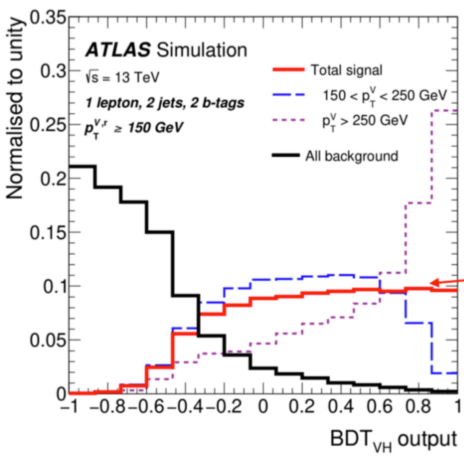


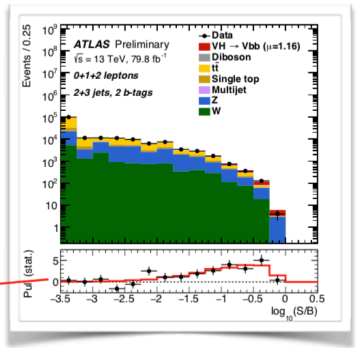
- 22 signal regions aiming at stage 1.1 STXS

STXS Stage 1 – VH

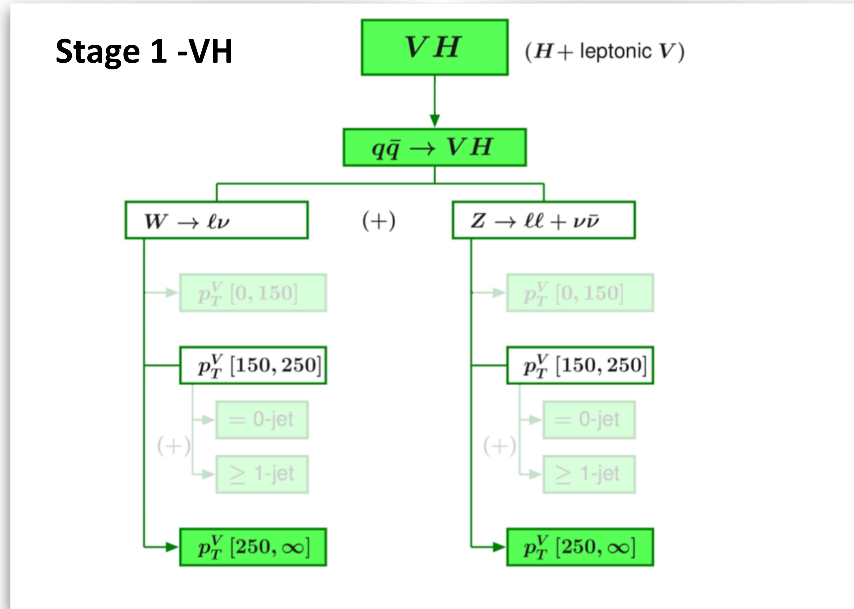
VH(bb)

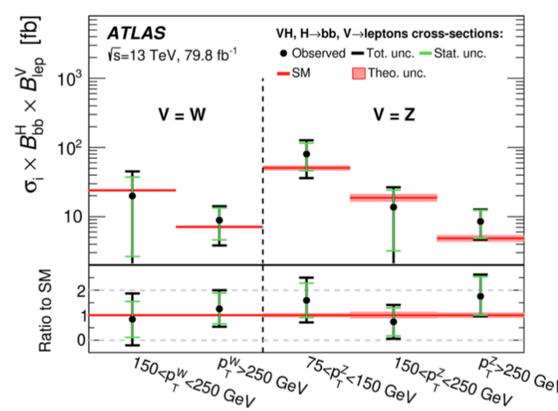
ATLAS 1903.04618





Observation analysis





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Analysis based on three main channels targeting WH and ZH production, based on the W or Z decays:

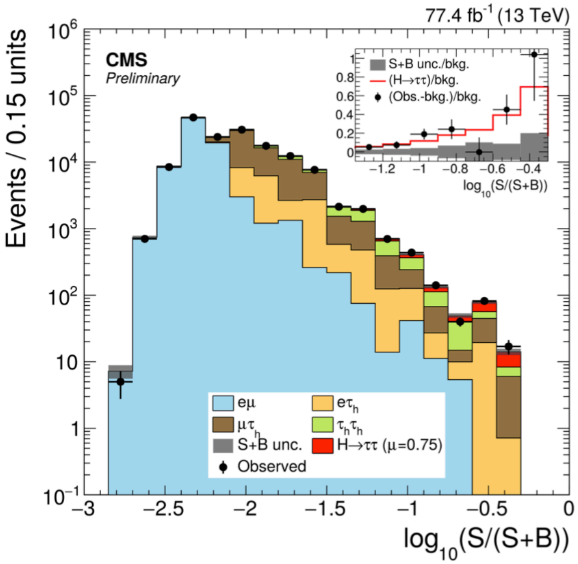
- 0 « leptons » (for neutrino decays of the Z)
- 1-lepton (W decaying to an electron or a muon)
- 2-leptons (Z decaying to electrons or muons)

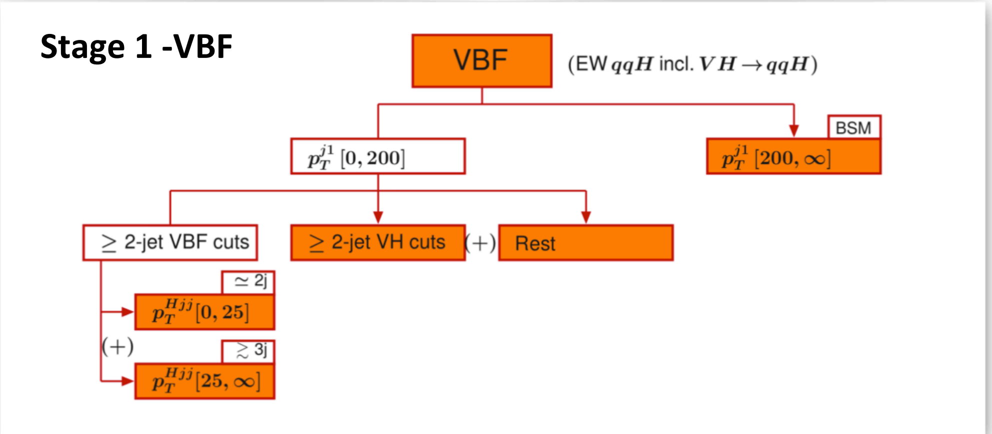
Main background is V+jets (in particular b-jets), relies on a good simulation, but is controlled in the mass side-bands!

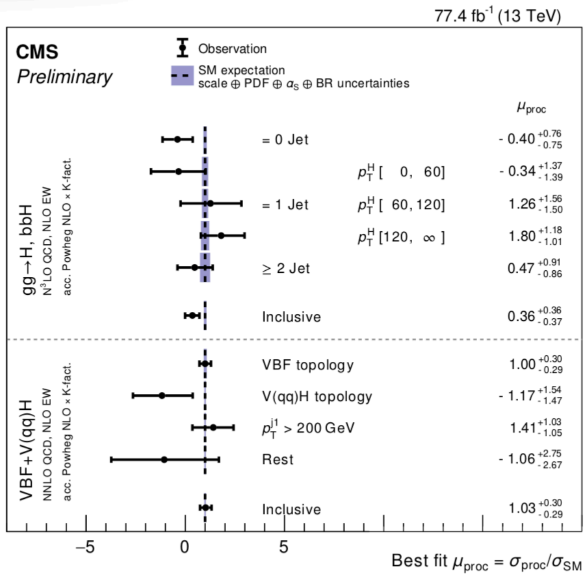
STXS Stage 1 – VBF

qqH(ττ)

CMS-PAS-HIG-18-032







Main background Z-jets estimated using embedding technique. Other backgrounds estimated using MC and fake factors.

Classification using a Multi-Class NN technique with 8 categories (ggH, qqH,Z-jets, diboson (dilepton), single top, tt, qcd, and misc other.

Simultaneous fit of the ggF STXSs (which have a non negligible impact in the specific fiducial regions.

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Interpretation based on STXS

ATLAS 1903.04618

Interpretation: interpret ATLAS VH(bb) STXSs in an EFT framework, in this case the high energy parametrization is important.

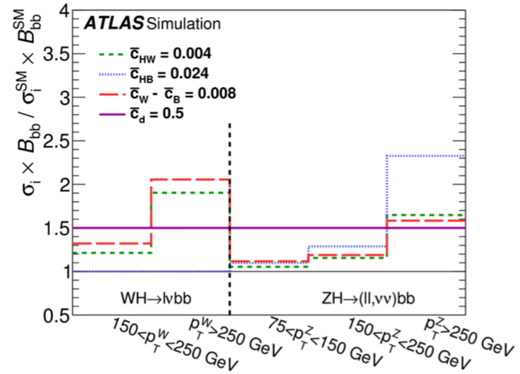
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots$$

- Reduction of the (2499 baryon number preserving dim-6 Wilson coefficients) keeping only universal and CP-invariant operators reduces to 8 Higgs production operators and 9 operators affecting EW observables.

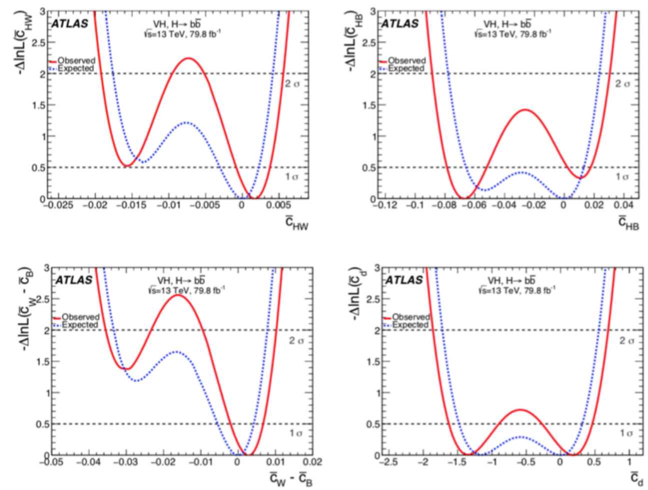
- **SILH**: Strongly interacting light Higgs basis, with universal couplings in which new physics couples only to the Higgs captures best the low energy effects.

  - $\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu},$
  - $\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu},$
  - $\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu},$
  - $\mathcal{O}_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}.$

Linear terms for SM-BSM interference and quadratic terms taken into account.



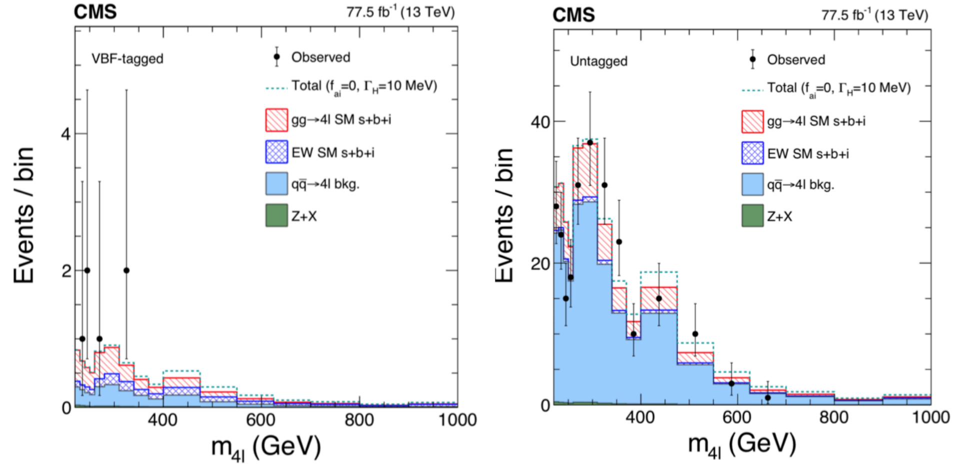
$$\bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2}, \quad \bar{c}_d = v^2\frac{c_d}{\Lambda^2}$$



Constraints on Higgs Width

SM width (small i.e. potentially large relative variations from BSM couplings)

$$\Gamma^{H}_{SM} = 4.07 \pm 0.16 \text{ MeV}$$



Width from Lineshape measurements

- Current constraints from the measurement of the higgs line shape from 4-leptons and diphoton channels:

$$\Gamma^{H}_{SM} < 1.10 \text{ GeV at } 95\% \text{ CL}$$

(CMS-PAS-HIG-16-041 with 4l only and 36 fb-1)

Using ggF, VBF and VH production (and WW decays at Run 1)

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma^{SM}_{H}$$

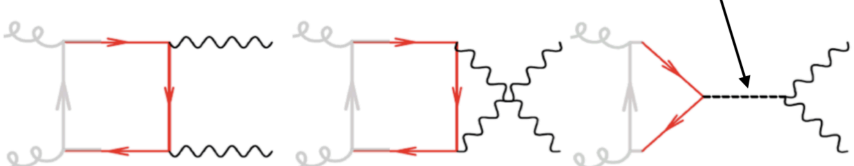
Assuming running of the SM running of the couplings and that

Offshell Higgs measurements

CMS 1901.00174

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

Study the 4-leptons spectrum in high mass regime where the Higgs boson acts as **propagator**



$aE^2 + (b+c)m_t E$ $\quad -aE^2 + (d-c)m_t E$ $\quad -(b+d)m_t E$

Courtesy J. Campbell

Impressively strong constraints with still room for improvements with higher statistics.

Careful to systematics from ggZZ (including interference term).

HL-LHC projection: ~ 1 MeV unc.

Higgs combination inputs

arXiv:1809.10733

- All main production and decay modes, based on 2016 13 TeV dataset (35.9 fb-1) @ CMS

Analysis	Reference
$H\to ZZ\to 4l$	JHEP 11 (2017) 047
$H\to\gamma\gamma$	arXiv:1804.02716
$H\to WW$	arXiv:1806.05246
$VH\to bb$	PLB 780 (2018) 501
$H\to\tau\tau$	PLB 779 (2018) 283
$H\to\mu\mu$	arXiv:1807.06325
Boosted $H\to bb$	PRL 120 (2018) 071802
$ttH\to WW/ZZ/\tau\tau$	arXiv:1803.05485
$ttH\to bb$ (leptonic)	arXiv:1804.03682
$ttH\to bb$ (hadronic)	arXiv:1803.06986
$H\to$invisible (*)	arXiv:1809.05937

	ggF	VBF	VH	ttH
$H\to ZZ\to 4l$	●	●	●	●
$H\to\gamma\gamma$	●	●	●	●
$H\to WW$	●	●	●	●
$H\to bb$	●		●	●
$H\to\tau\tau$	●	●		●
$H\to\mu\mu$	●	●		
$H\to$inv	●	●	●	

Couplings – κ framework

- LO coupling modifier/kappa framework to probe deviations from SM
  - Assumptions: only **one CP-even** Higgs state with m_H=125 GeV and **negligible width**
- Parameter scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\mathrm{SM}}$$

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}$$

Total width determined as

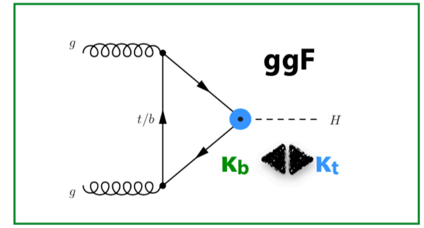
$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

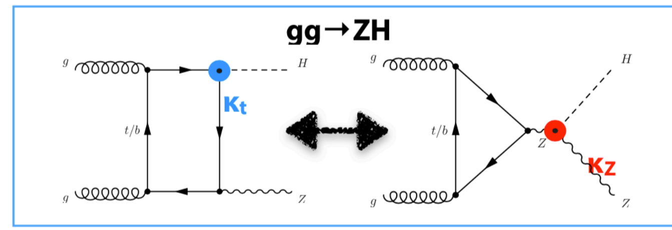
Where

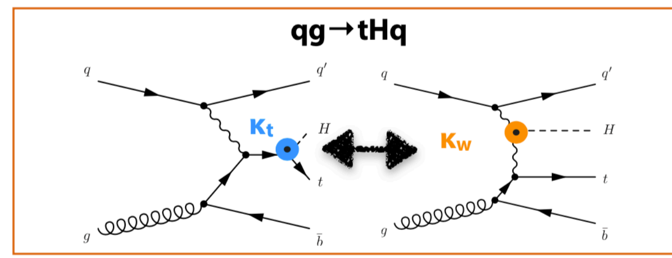
$$\kappa_H^2 = \sum_j \mathrm{BR}_{\mathrm{SM}}^j \kappa_j^2$$

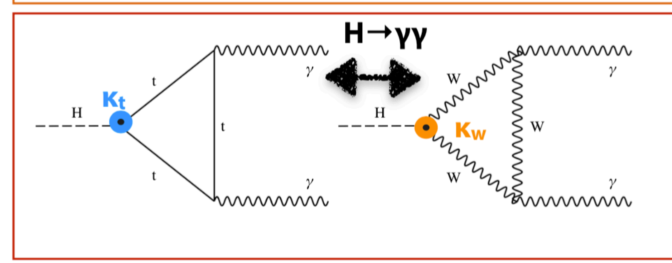
Coupling Parameterization

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\text{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t\kappa_b$
$\sigma(\text{VBF})$	–	–		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\text{WH})$	–	–		κ_W^2
$\sigma(\text{qq/qg} \to \text{ZH})$	–	–		κ_Z^2
$\sigma(\text{gg} \to \text{ZH})$	✓	Z − t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z\kappa_t$
$\sigma(\text{ttH})$	–	–		κ_t^2
$\sigma(\text{gb} \to \text{WtH})$	–	W − t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t\kappa_W$
$\sigma(\text{qb} \to \text{tHq})$	–	W − t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t\kappa_W$
$\sigma(\text{bbH})$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $\text{BR}_{\text{BSM}} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



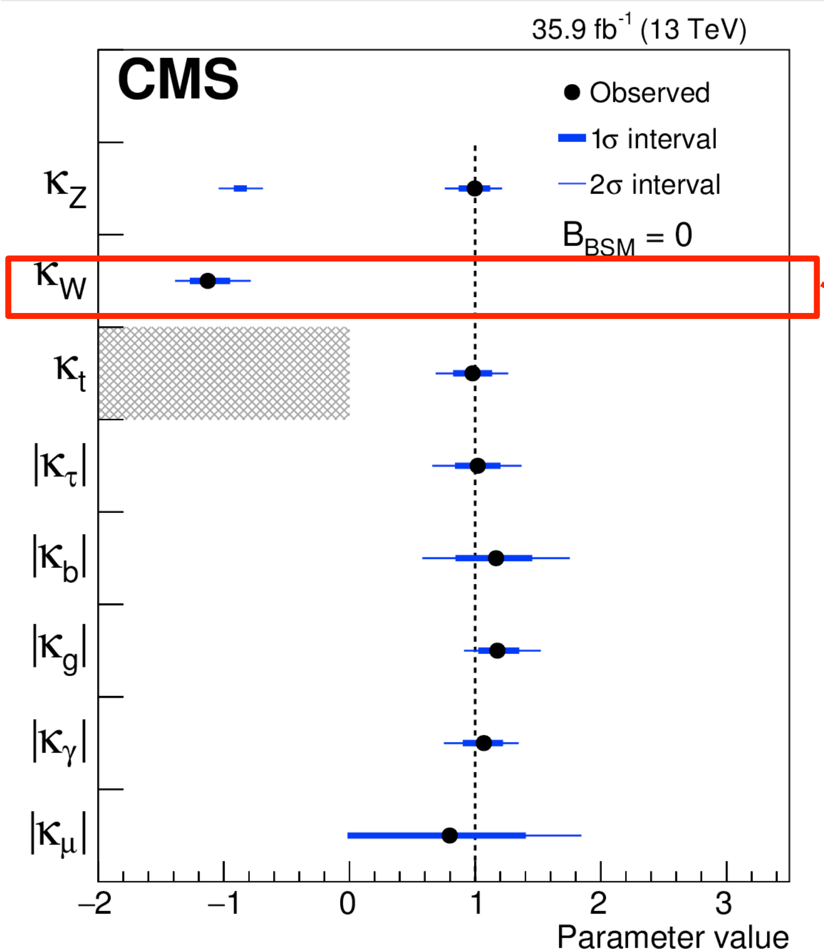


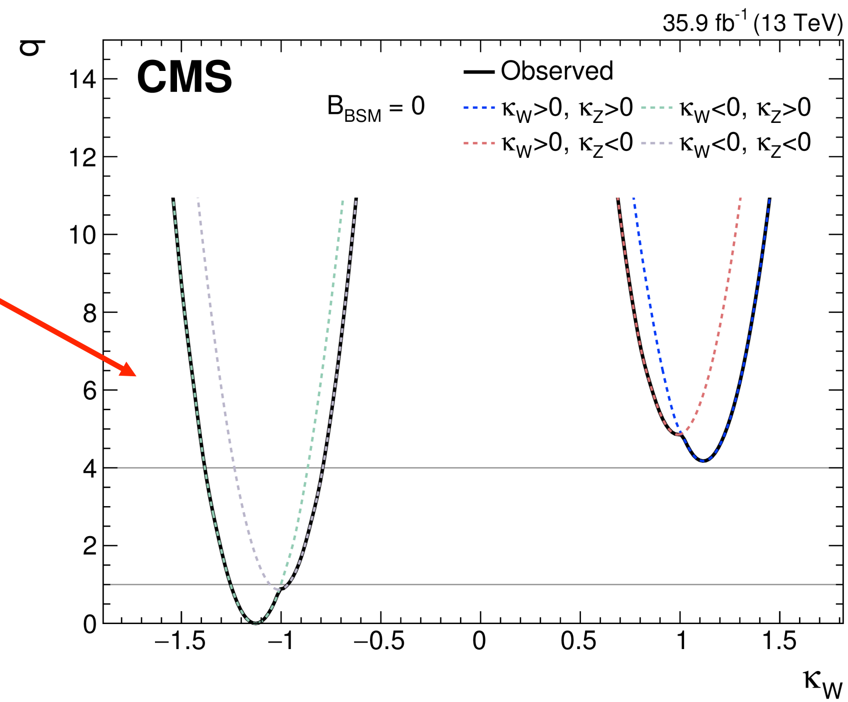




Couplings: Effective Loops

- No assumptions about loops (κ_g and κ_γ free parameters)
- Assumption about total width: No BSM decays

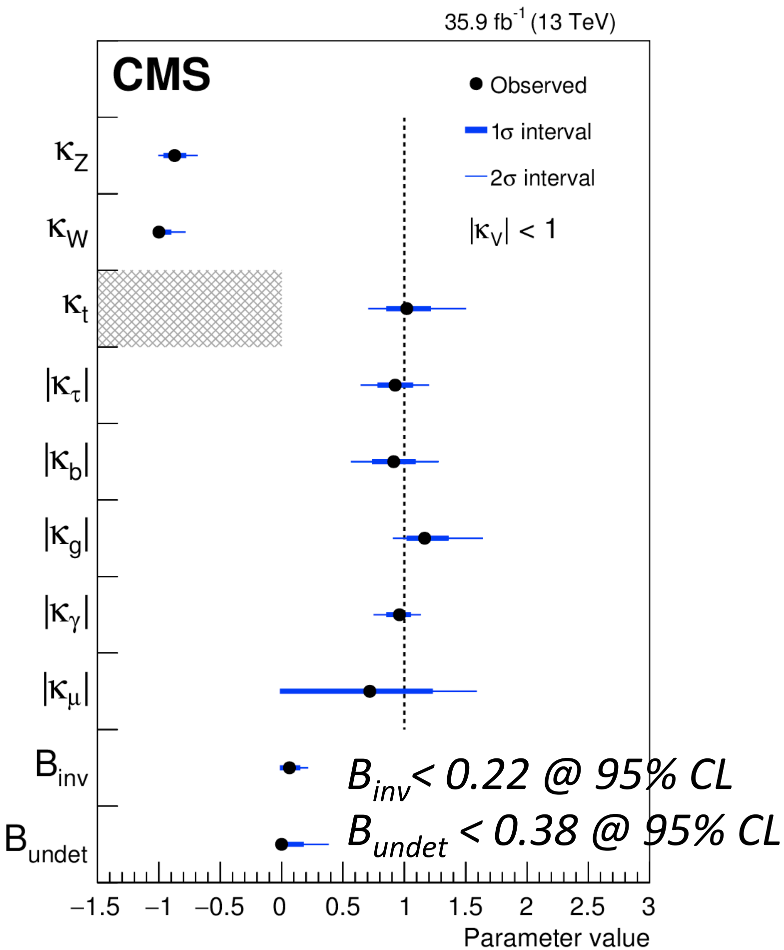




Positive κ_W disfavoured at just over 2σ, partly driven by moderate excess in ttH-tag H→γγ categories, compensated by enhanced tHq when $\kappa_W \cdot \kappa_t < 1$

Couplings: Effective Loops

- No assumptions about loops (κ_g and κ_γ free parameters)
- Assumption about total width: $|\kappa_V| < 1$



$|\kappa_V| < 1$ imposed - typically the case in BSM models that affect Higgs couplings

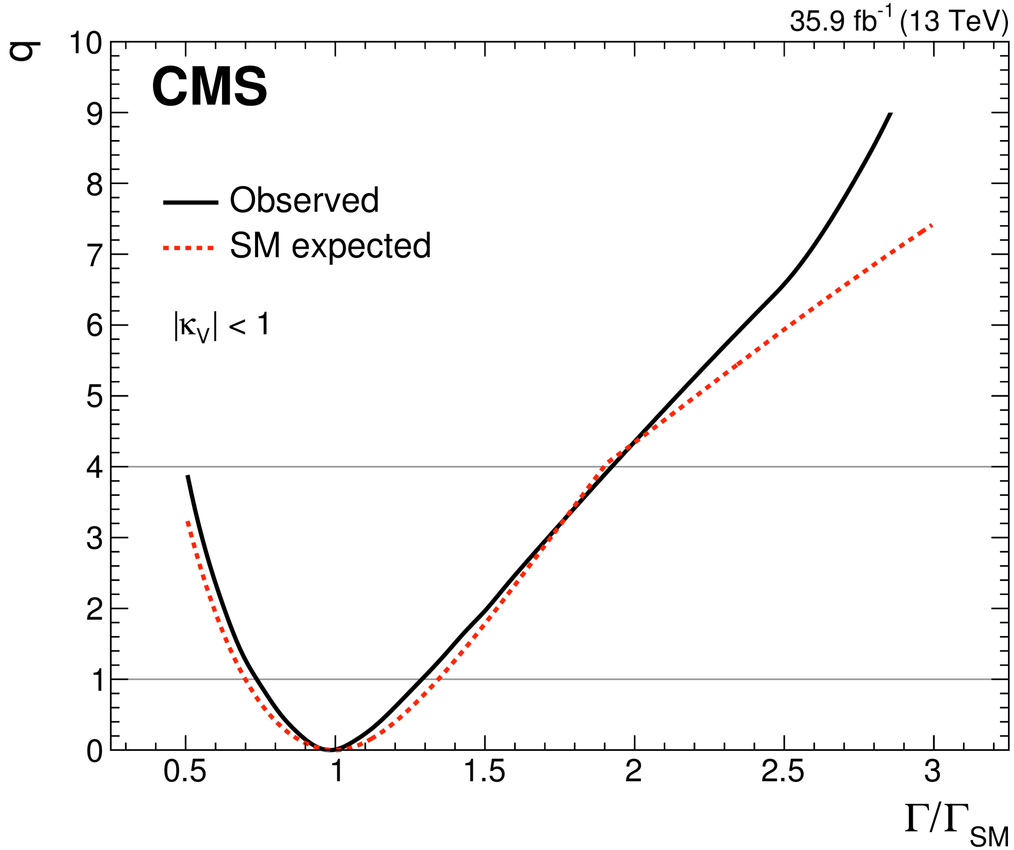
$BR_{inv} > 0$, $BR_{undet} > 0$

BR_{inv}: Scales signal normalisation in direct H→invisible searches

BR_{undet}: Represents branching ratio to any final state not directly detected by analyses

Constraint on Total Width

- Assuming $\kappa_V < 1$, but allowing for BSM decays, set constraint on total Higgs width
- Performed by making total width a parameter of the model (instead of a function of other κ's), and making κ_b a function of other κ's and total width



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

$$\kappa_H^2 = 0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 + 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_u^2$$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = 0.98^{+0.31}_{-0.25}$$

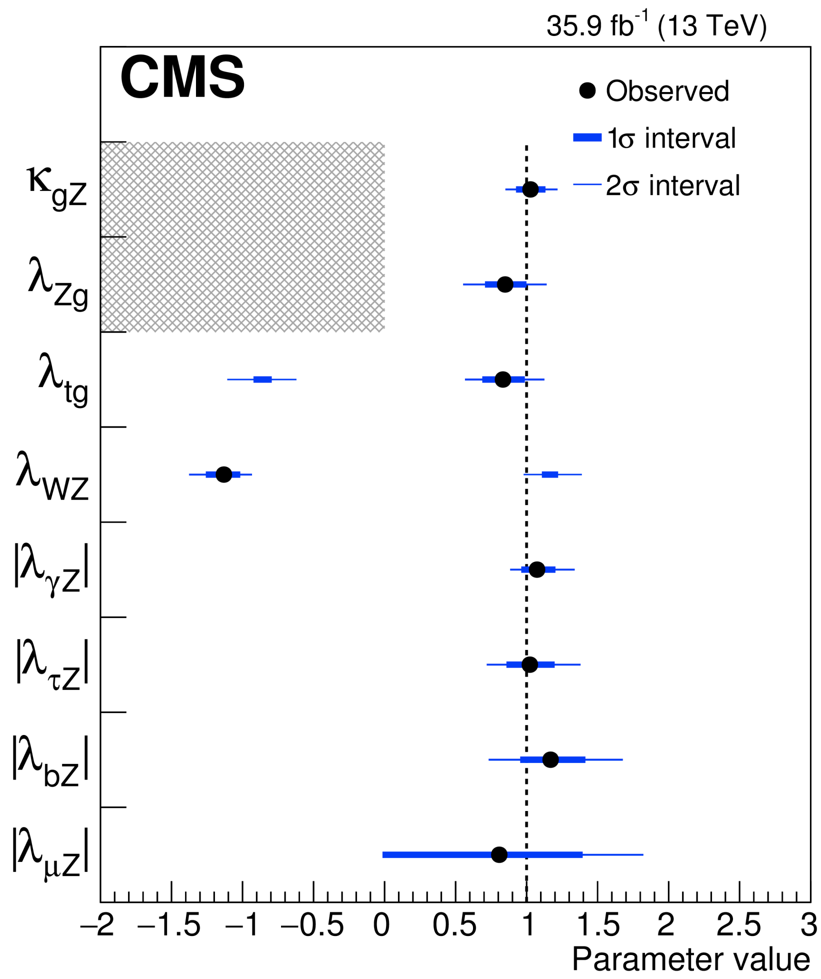
Couplings modifier ratios

- Analogous to signal strength ratios, measure ratios of coupling modifiers given a reference κ:

$$\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$$

- Assume $\kappa_{gZ}>0$ and $\lambda_{Zg}>0$ without loss of generality
- Evaluate λ_{tg} and $\lambda_{WZ}<0$ subject to constraint $\lambda_{tg}\,\lambda_{WZ}>0$, to probe interference in ggZH production but not tH

No assumption on total width

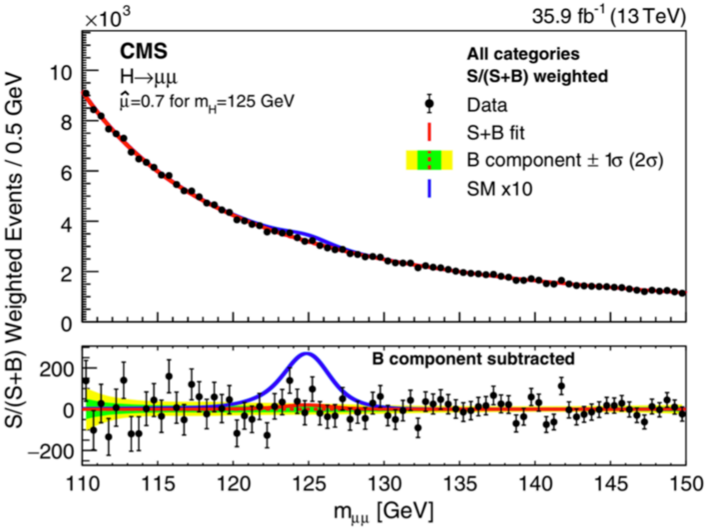


Next Challenges: H->μμ, H->Zγ

CMS dimuon search

Phys. Rev. Lett. 122 (2019) 021801

- Very low s/b, search for peak in $m_{\mu\mu}$ spectrum over smooth background (requiring accurate background description)
- BDT separating ggF, VBF and VH signatures.



Current limits at

$$\mu < 2.92\ (2.16\ \text{exp.})\ \text{at}\ 95\%\ \text{CL}$$

Coupling precision reach at HL-LHC*

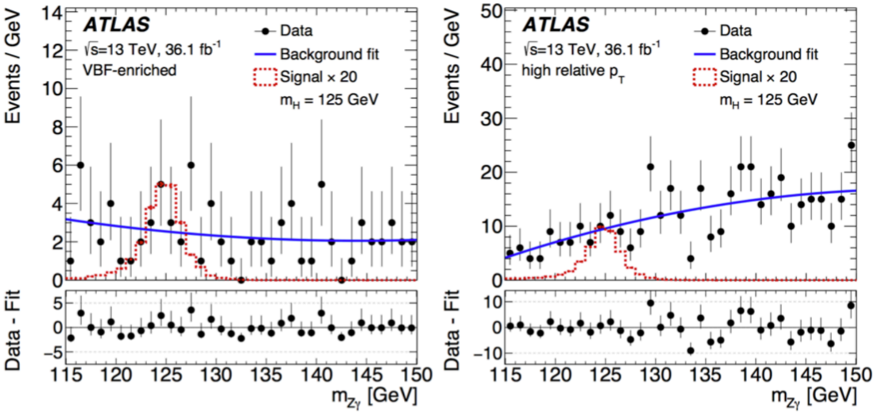
~5% HL-LHC YR 1902.00134

* With the kappa model assuming no BSM in the decay

ATLAS $Z\gamma$ search

Not so small branching fraction of 1.5 10-3 however search for leptonic decays of the Z boson.

Categorised in main production modes gluon fusion (at high pT) and VBF (with the typical VBF topology). Improved mass reconstruction with FS correction for muons.



95% CL limits at **6.6** (obs) and **5.2** (exp), no significant signal observed.

Precision reach at HL-LHC*

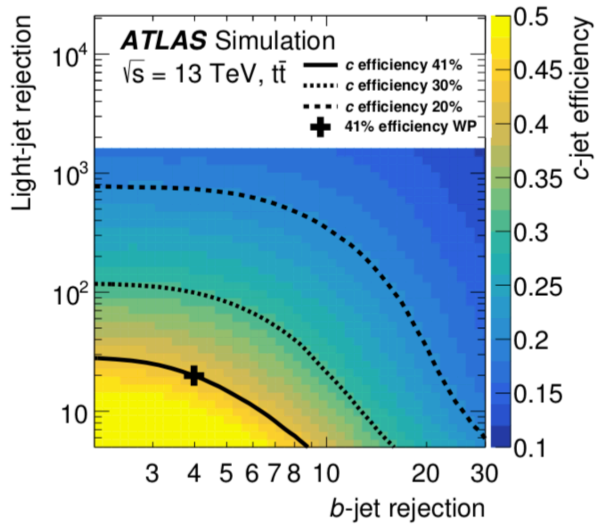
~10% HL-LHC YR 1902.00134

* With the kappa model assuming no BSM in the decay

Next Challenges: Charm Yukawa Couplings

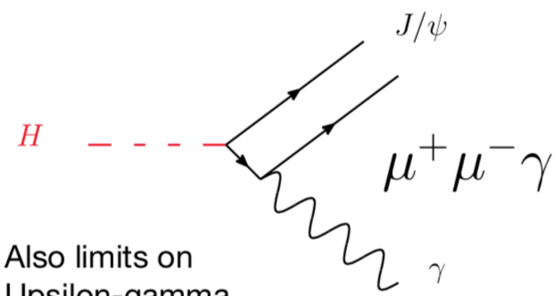
Very challenging but various approaches and new ideas emerging!

- VH(cc) direct detection (relies on ability to distinguish b and c jets)
- Differential cross sections
- Charmonium-photon exclusive decays
- WH production charge asymmetry (PDFs)
- Total width from the couplings fit



Run 2	HL-LHC	
<100xSM	**<6xSM**	HL-LHC YR 1902.00134

Potentially sensitive to charm Yukawa



Also limits on Upsilon-gamma

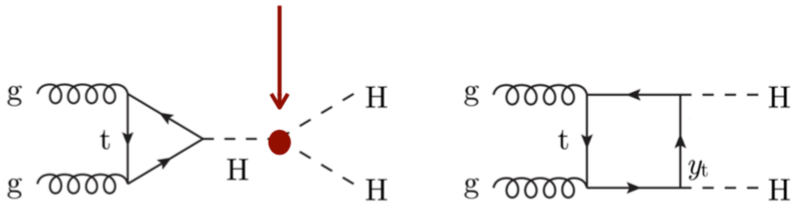
Sensitivity to gamma-gamma* (top loop) and interference

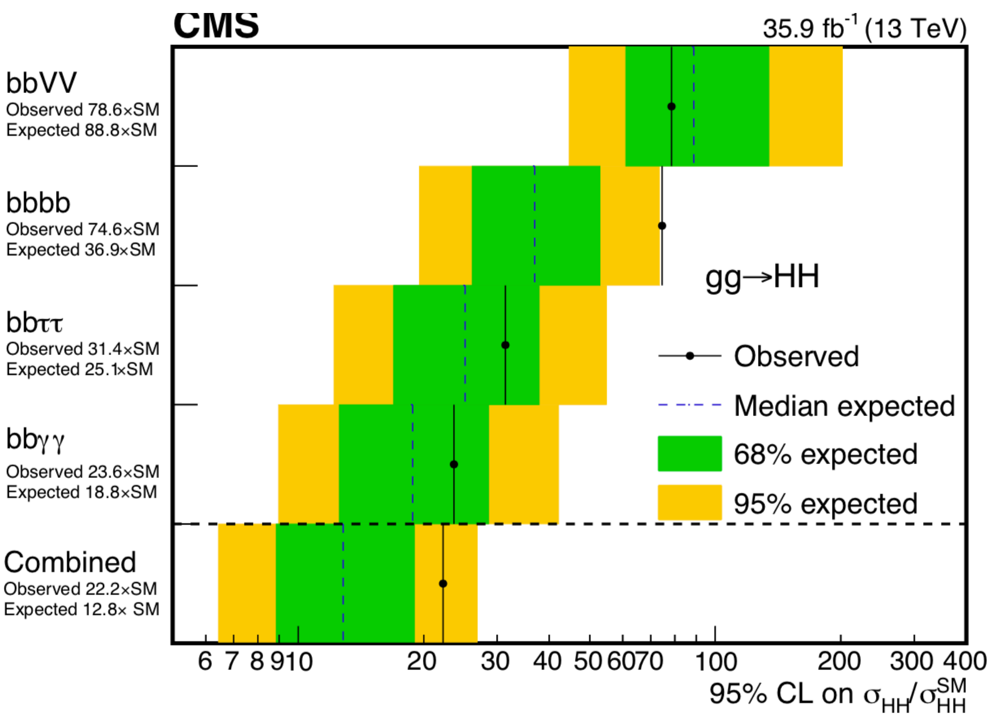
HE-LHC	
<50xSM	HL-LHC YR 1902.00134

Next Challenges: Higgs self-coupling

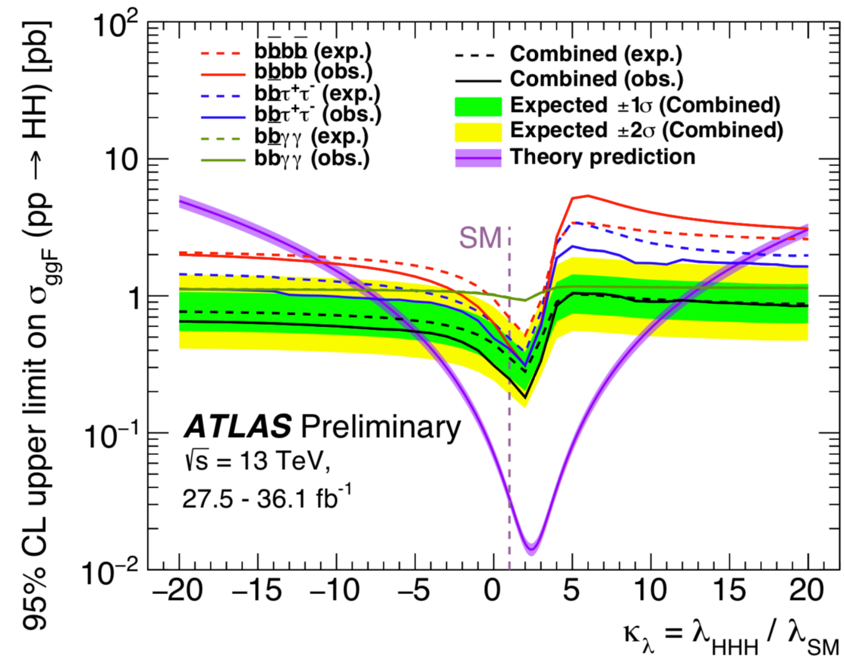
HH production allows to probe the self-coupling

$$\lambda = \frac{m_{\rm H}^2}{2v^2} = 0.13$$





Constraints on k_λ

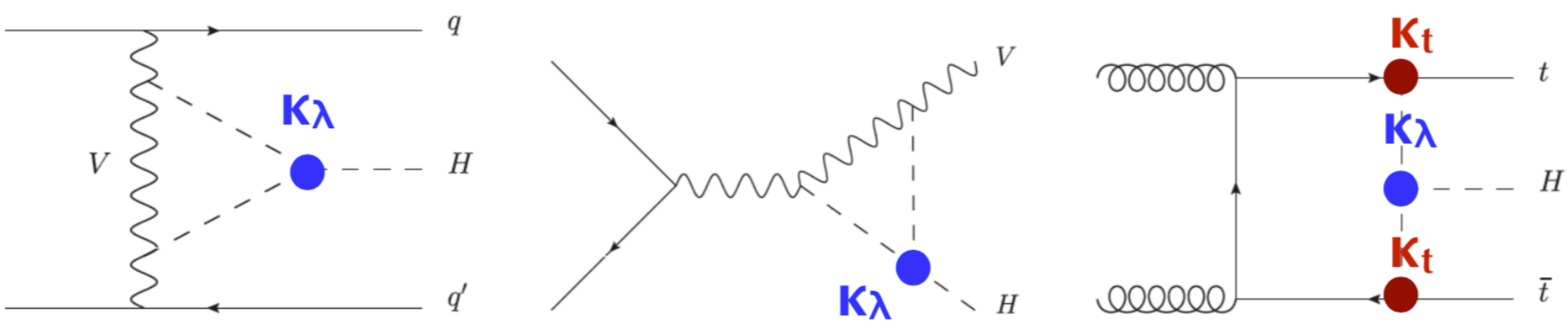


$\kappa_\lambda \in$ [-5.8, 12.1] ATLAS / [-11.8, 18.8] CMS assuming SM top-H coupling

The combination probes ~**10 times the SM prediction**

Next Challenges: Higgs self-coupling

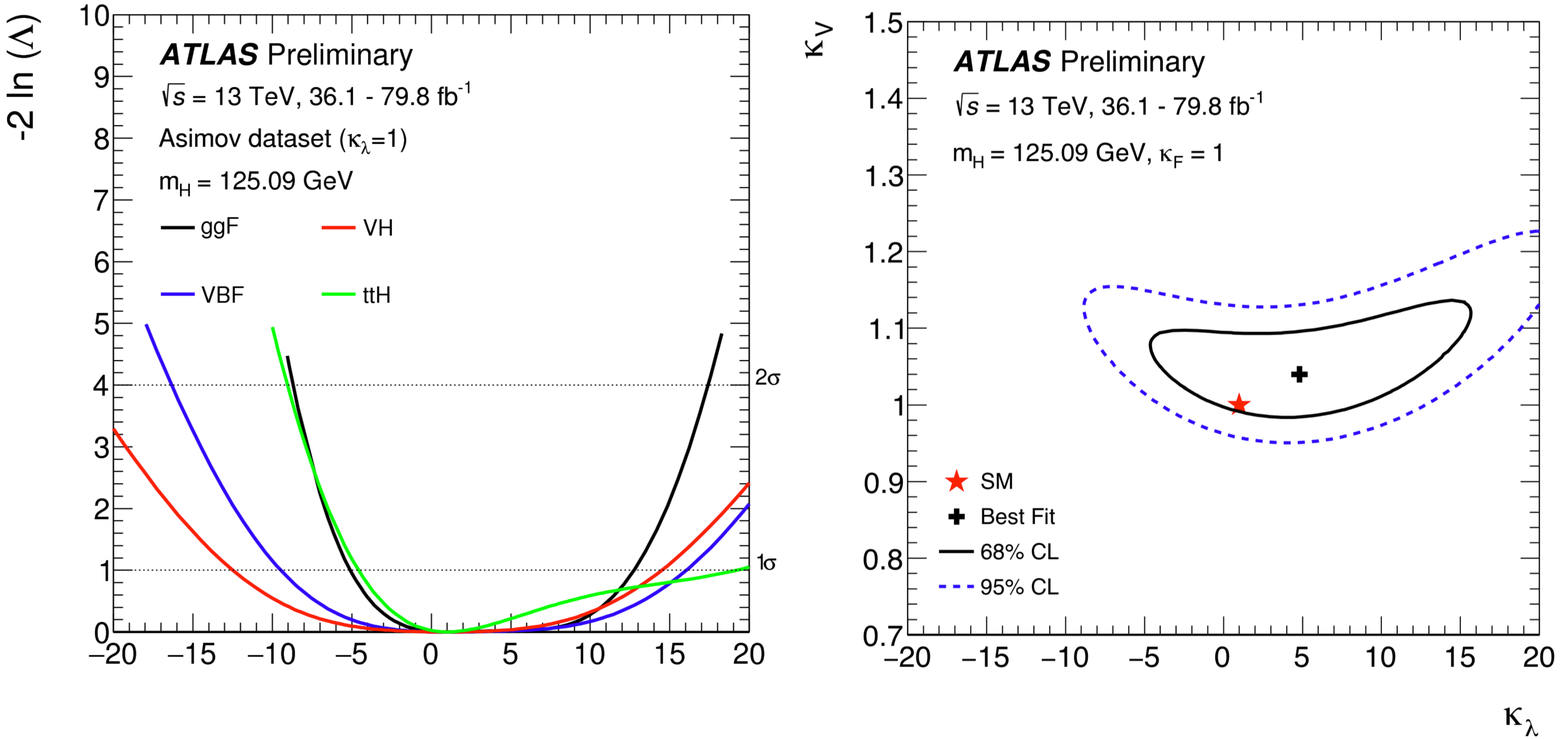
- Single Higgs processes are sensitive to λ via **loop corrections**
- NLO EW κ_λ-dependent corrections to
  - cross-sections (**ttH, ggF, VH, VBF**)
  - Higgs boson decay rates
  - kinematics properties of the event (differential distributions)



JHEP 12 (2016) 080,
Eur. Phys. J. C77 (2017) 887

ATLAS PHYS-PUB-2019-009

Next Challenges: Higgs self-coupling



$$\kappa_\lambda = 4.0^{+4.3}_{-4.1}$$

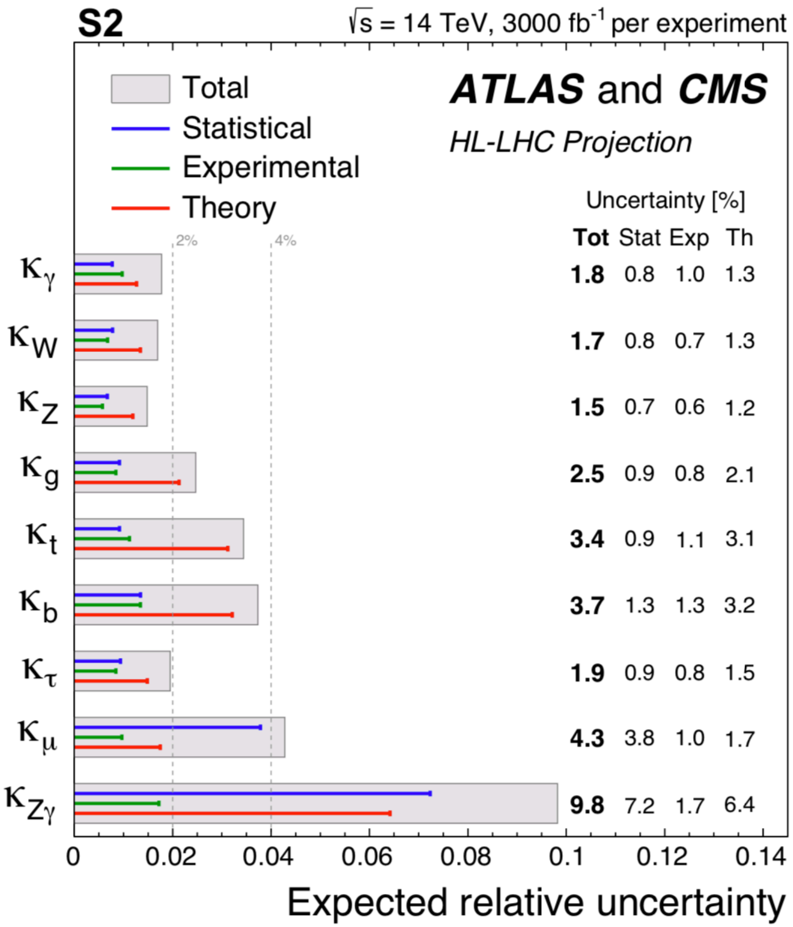
$\kappa_\lambda \in$ **[-3.2,11.9] @95%CL ($\kappa_F = \kappa_V = 1$)** [-6.2,14.4] exp.

Projections for HL-LHC

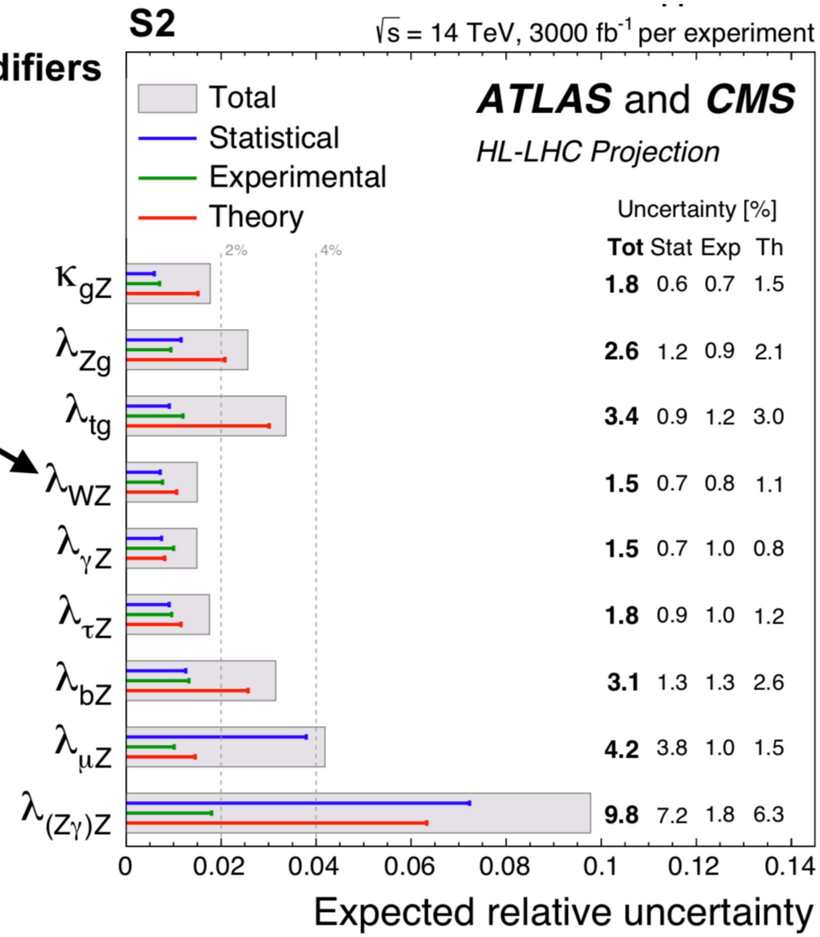
- **Analysis of simulated samples with HL-LHC conditions and detectors**
  - Generally for new, or significantly improved, analyses
- **Extrapolations from Run 2 data to 3 ab^{-1}**
  - Analyses that were already performed in Run 2
  - Efficiencies, resolutions, fake rates assumed unchanged from the Run 2 values
  - Main scenario **YR18 systematic uncertainties (S2)**:
    - **Most theoretical uncertainties scaled down by a factor 1/2, experimental uncertainties scaled down by $\sqrt{L}$ until they reach a defined lower limit.**
  - Scenario for comparison: using Run 2 systematic uncertainties (S1)
  - **In all cases uncertainties due to the finite number of simulated events are neglected**

Projections for HL-LHC

Coupling modifiers



Ratios of coupling modifiers



Uncertainties on the κ's 2-5%, apart from Zγ
Mostly limited by theoretical uncertainties

Uncertainties on the ratios of k's 1.5-4%,
With $\lambda_{\gamma Z}$ and λ_{WZ} most precisely measured

To summarize

- Full Run 2 Higgs results are on their way
- Lumi will not increased rapidly in next few years
  - New ideas, technique, etc. to be explored for Run 2 and 3 data
- Still very promising program ahead @ HL-LHC

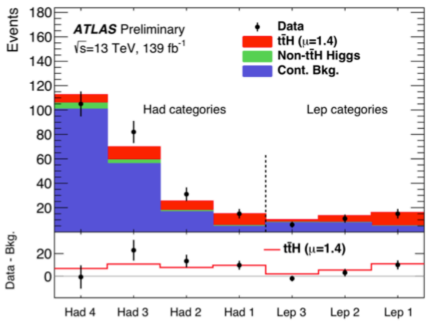
backup

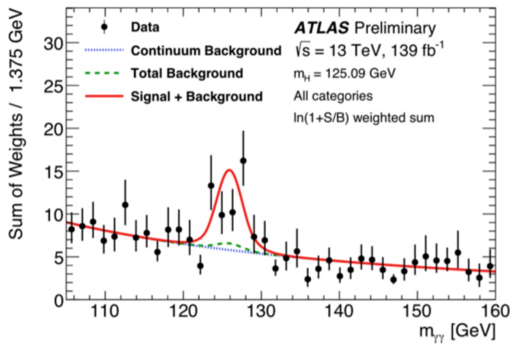
Observation of ttH in single channel H->γγ

ATLAS Full dataset!!

Observation and measurement of ttH production in the diphoton channel with 139 fb-1 of data at Run 2

ATLAS-CONF-2019-04





Analysis in two separate main channels **0L** and **1L** using a BDT based on low level variables:

- 3-vector of photons (normalised to Myy)
- 4-vectors of jets (up to 6 leading jets)
- 4-vectors of leptons (up to 2 leading leptons)

Background and signal modelled using analytic functions.

Observed	Expected
4.9σ	(4.2σ)

Measurement dominated by statistical uncertainties:

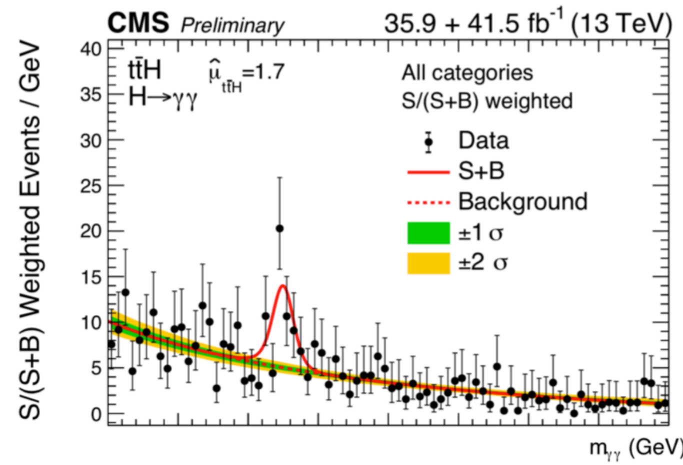
$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.38}_{-0.36}\ \text{(stat.)}\ ^{+0.15}_{-0.12}\ \text{(exp.)}\ ^{+0.15}_{-0.11}\ \text{(theo.) fb}$$

CMS CMS-PAS-HIG-18-018

Similarly CMS analysis with 35.9 fb-1 (2016) + 41.5 fb-1 (2017).

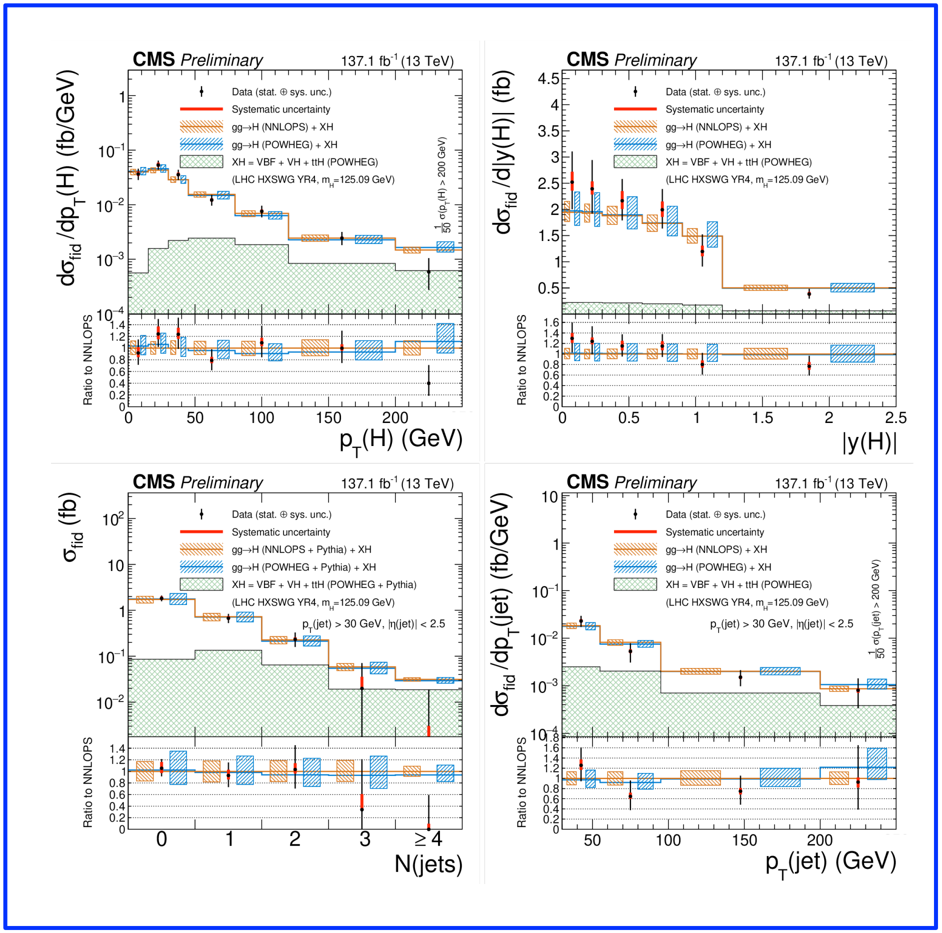
BDTs also with low level variables (and additional and modelling backgrounds and signals using analytic functions.

Similar analysis with similar performance, difference in sensitivity largely due to difference in dataset.

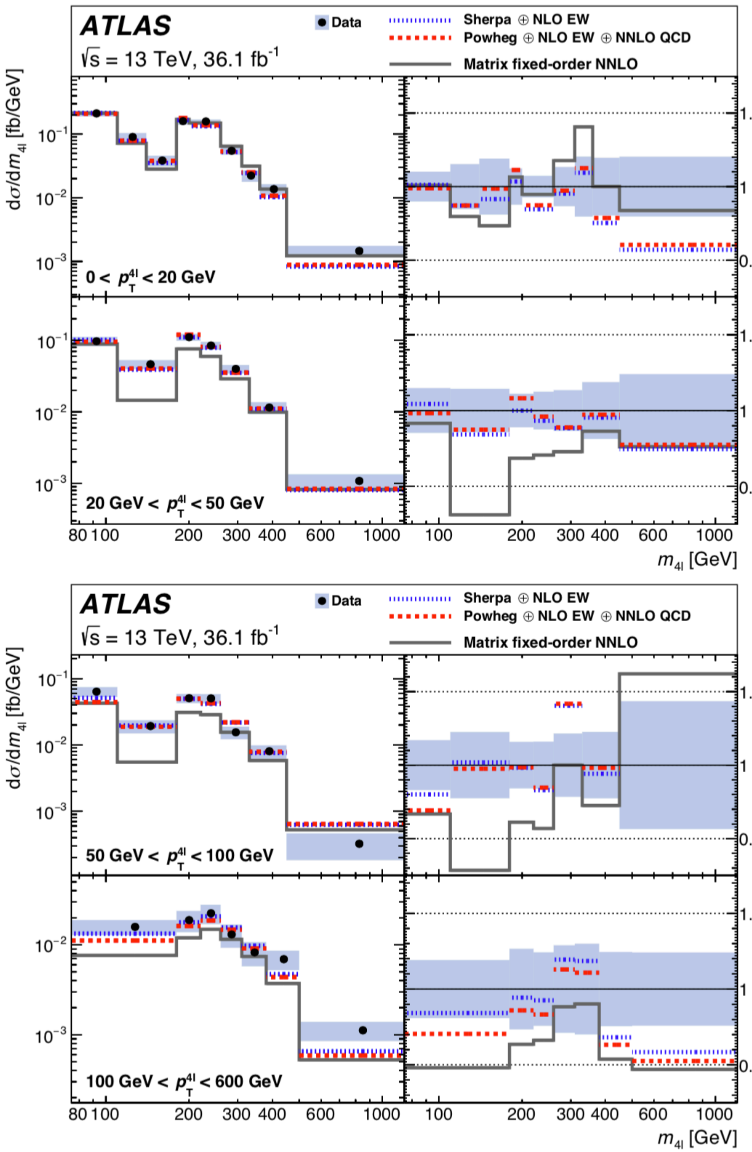


Observed	Expected	Signal strength
4.1σ	(2.7σ)	$\mu_{ttH} = 1.7^{+0.6}_{-0.5}$

Differential XS in 4l channel



CMS-PAS-HIG-19-001

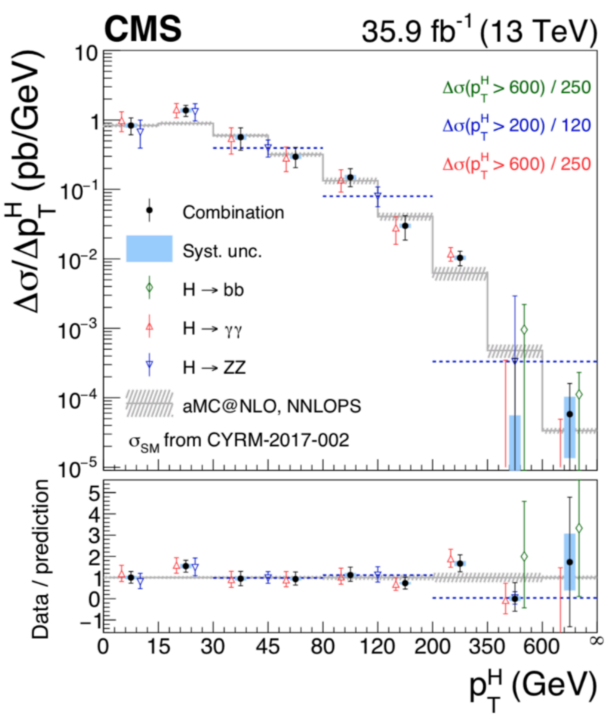


arXiv:1902.05892

double differential, off-shell Higgs region

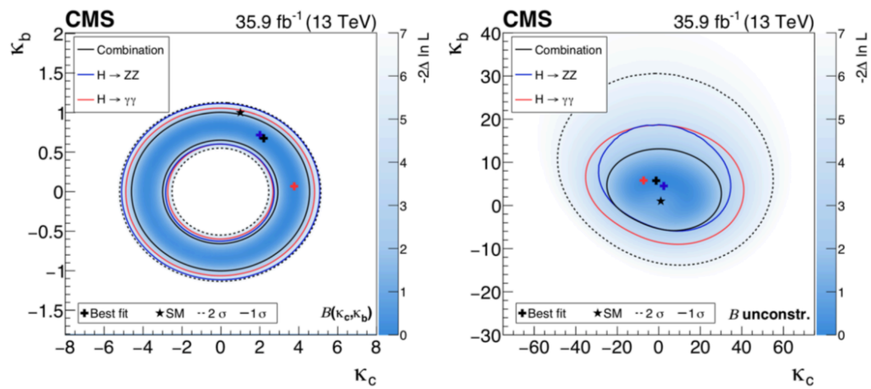
Couplings from differential XS

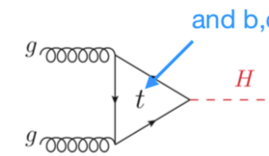
CMS 1812.06504



Diphoton, 4-lepton and bb differential cross section

Branching fractions w/ couplings dependency

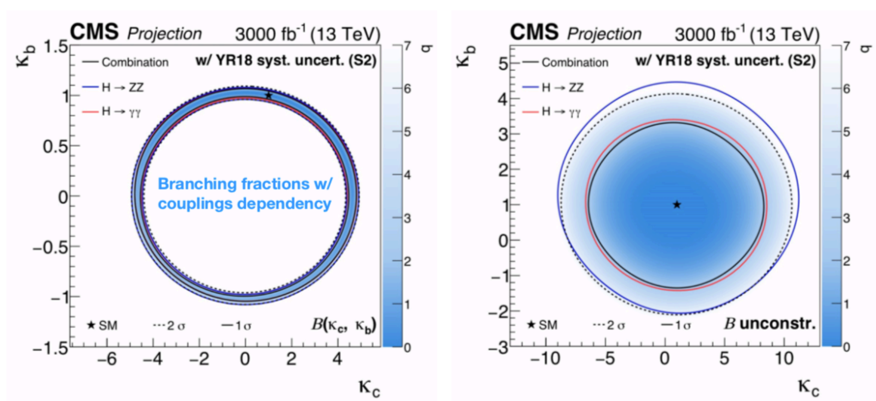




Limits on Kc at Run 2

XS x Br **~5 x SM**

Shape only **~33 x SM**



HL-LHC YR 1902.00134

Limits on Kc at HL-LHC

XS x Br **~4 x SM**

Shape only **~8 x SM**

STXS Combination

STXS Combination

NEW

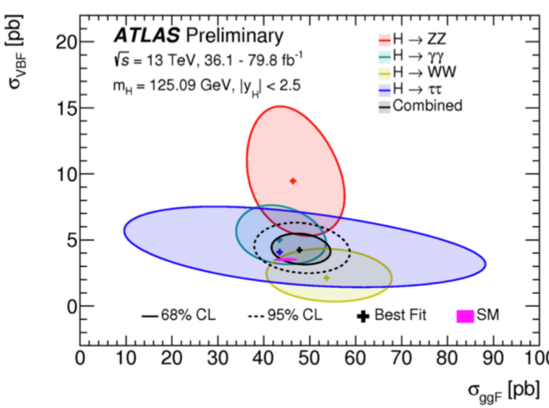
ATLAS Combination of STXS results

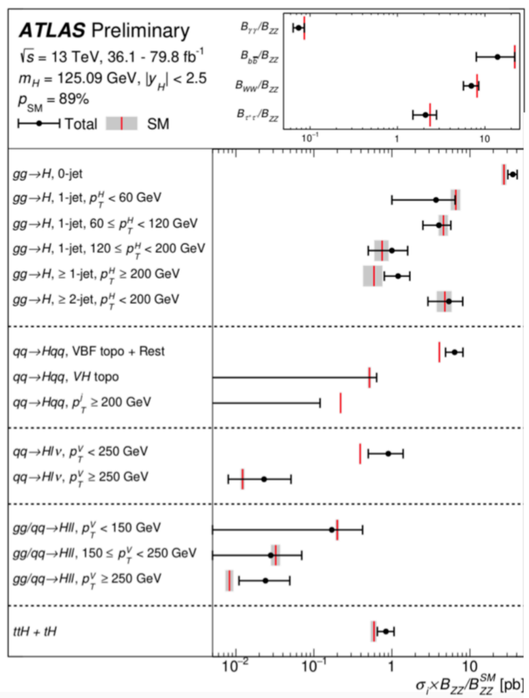
ATLAS-CONF-2019-04

Combination of all channels including STXSs (ATLAS), presented last week.

All main channels entering the combination (diphoton, ZZ*, WW*, bb, tautau, ttH).

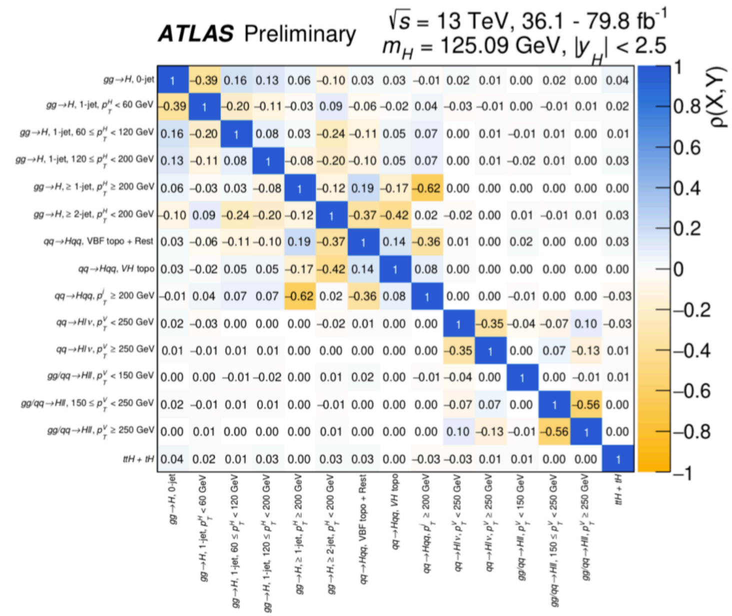
With a dataset corresponding to an integrated luminosity of up to ~80 fb-1.





Ratios of branching fractions to the ZZ branching left floating in the fit.

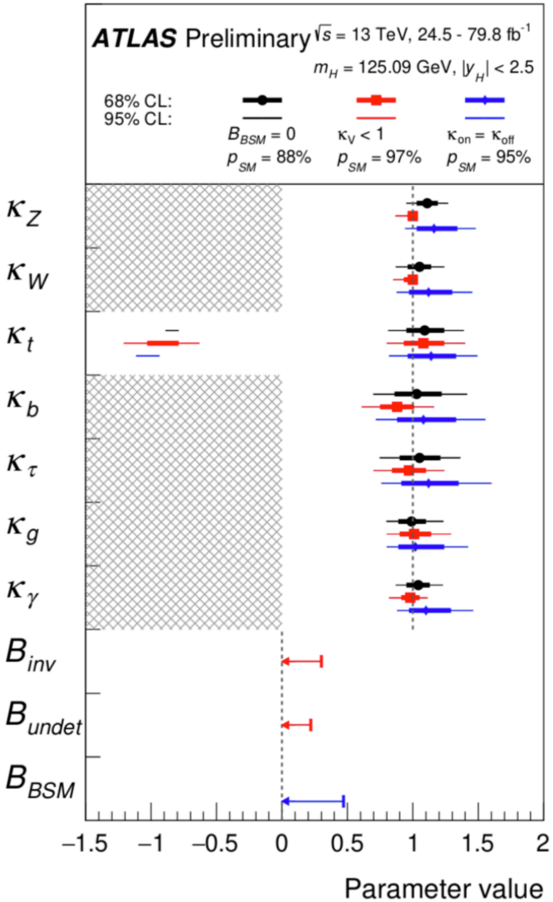
Correlation matrix indicating the level of degeneracy of different SXSs and the resolution effects from one bin to the other.



This version of the correlation matrix is from the fit with fixed branching fractions for simplicity.

New ATLAS Combination

ATLAS-CONF-2019-04



Parameter	(a) $B_{inv} = B_{undet} = 0$	(b) B_{inv} free, $B_{undet} \geq 0$, $\kappa_{W,Z} \leq 1$	(c) $B_{BSM} \geq 0$, $\kappa_{off} = \kappa_{on}$
κ_Z	1.11 ± 0.08	> 0.87 at 95% CL	$1.16^{+0.18}_{-0.13}$
κ_W	1.05 ± 0.09	> 0.85 at 95% CL	$1.12^{+0.18}_{-0.15}$
κ_b	$1.03^{+0.19}_{-0.17}$	0.88 ± 0.13	$1.08^{+0.25}_{-0.20}$
κ_t	$1.09^{+0.15}_{-0.14}$	$[-1.03, -0.79] \cup [0.93, 1.24]$ at 68% CL	$1.14^{+0.19}_{-0.18}$
κ_τ	$1.05^{+0.16}_{-0.15}$	0.97 ± 0.13	$1.12^{+0.23}_{-0.21}$
κ_γ	1.05 ± 0.09	0.98 ± 0.07	$1.10^{+0.19}_{-0.13}$
κ_g	$0.99^{+0.11}_{-0.10}$	$1.01^{+0.13}_{-0.11}$	$1.02^{+0.22}_{-0.13}$
B_{inv}	-	< 0.30 at 95% CL	-
B_{undet}	-	< 0.22 at 95% CL	-
B_{BSM}	-	-	< 0.47 at 95% CL

Precision on main couplings to bosons to better than 10% !

Precision on 3d generation Yukawas to better than 20% !!

Assuming kV<1 allows to set a limit on Br(BSM) with Run 2 data of **~22%** (ATLAS only with generic model)

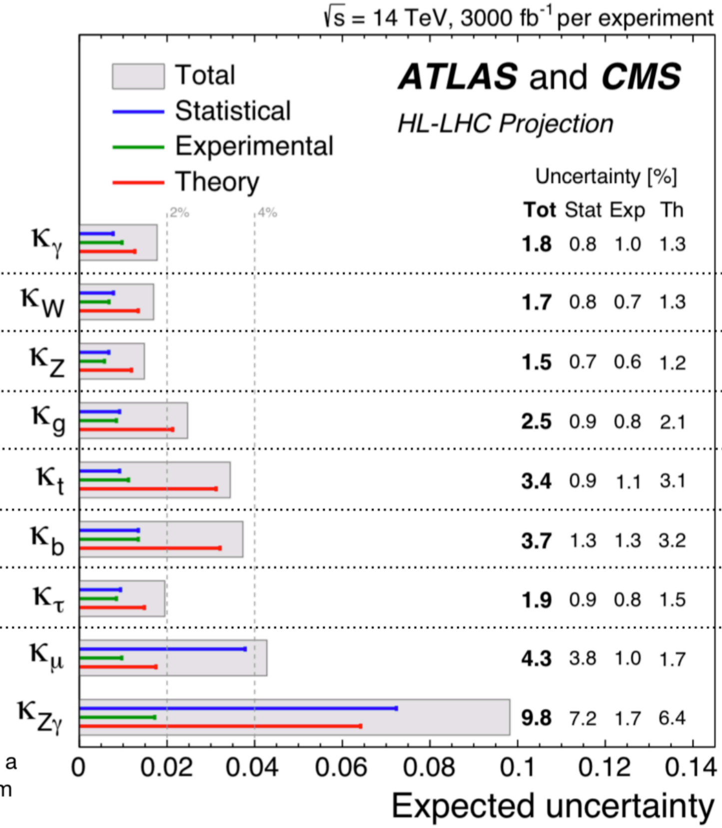
At HL-LHC **Br(BSM) < 5%** (95% CL) HL-LHC YR 1902.00134

New ATLAS Combination

NEW Measurement of the couplings properties of the Higgs boson - in this case assuming no BSM in the Higgs width

	ATLAS - CMS Run 1 combination	ATLAS Run 2	HL-LHC
κ_γ	13%	9%	1.8%
κ_W	11%	8.6%	1.7%
κ_Z	11%	7.2%	1.5%
κ_g	14%	11%	2.5%
κ_t	30%	14%	3.4%
κ_b	26%	18%	3.7%
κ_τ	15%	14%	1.9%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	HL-LHC YR 1902.00134

Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)



Experimental systematics non negligible

17

Projection assumptions

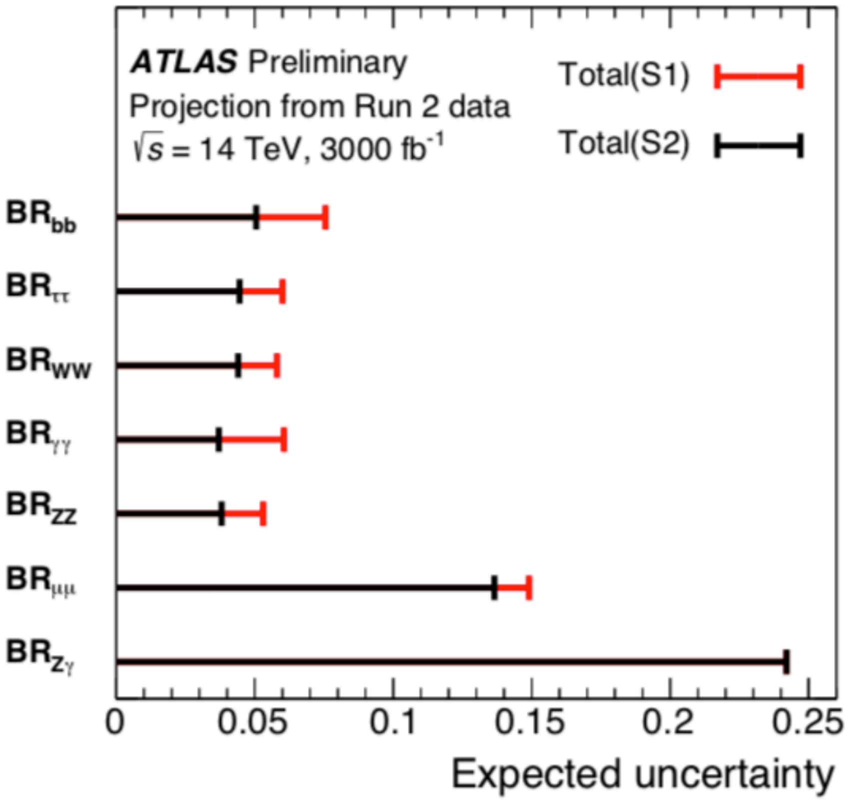
S1 is a conservative scenario using the uncertainties of the current Run II measurements.

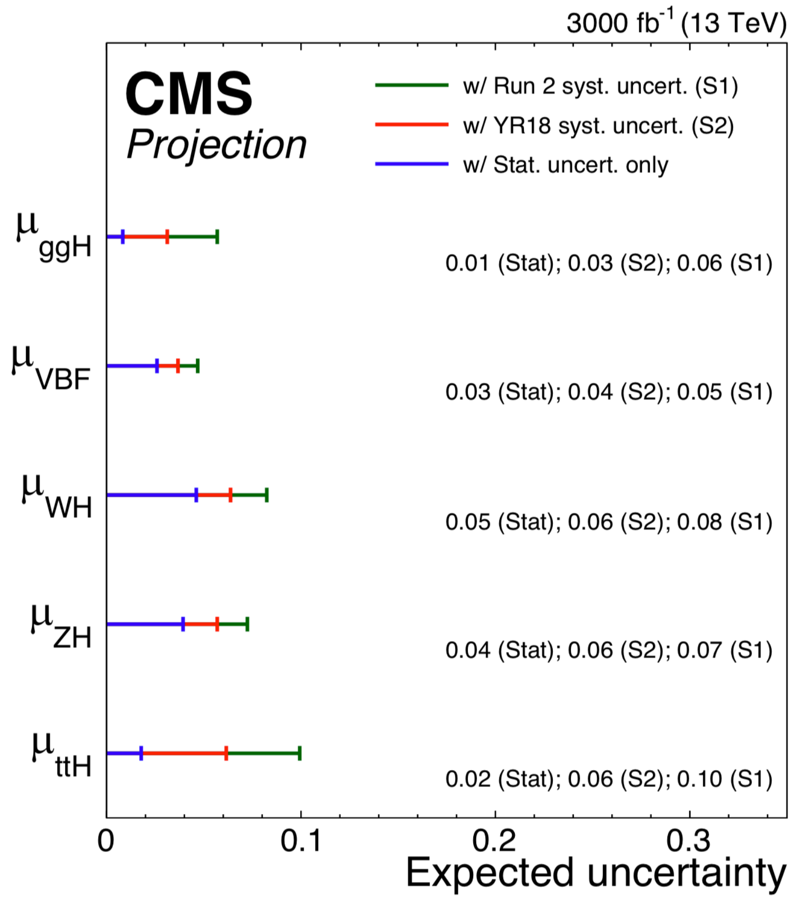
S2 assumes improvements due to detector upgrades and reduced uncertainties on the methods. For many sources the Run II uncertainty is **half** as shown in the table below. The luminosity uncertainty is 1% and the uncertainty due to size of simulation samples is negligible

Table 1: The sources of systematic uncertainty for which minimum values are applied in S2.

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Projection on signal strengths

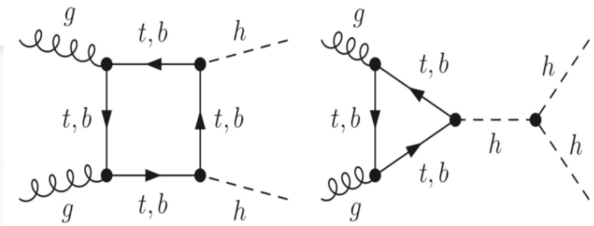


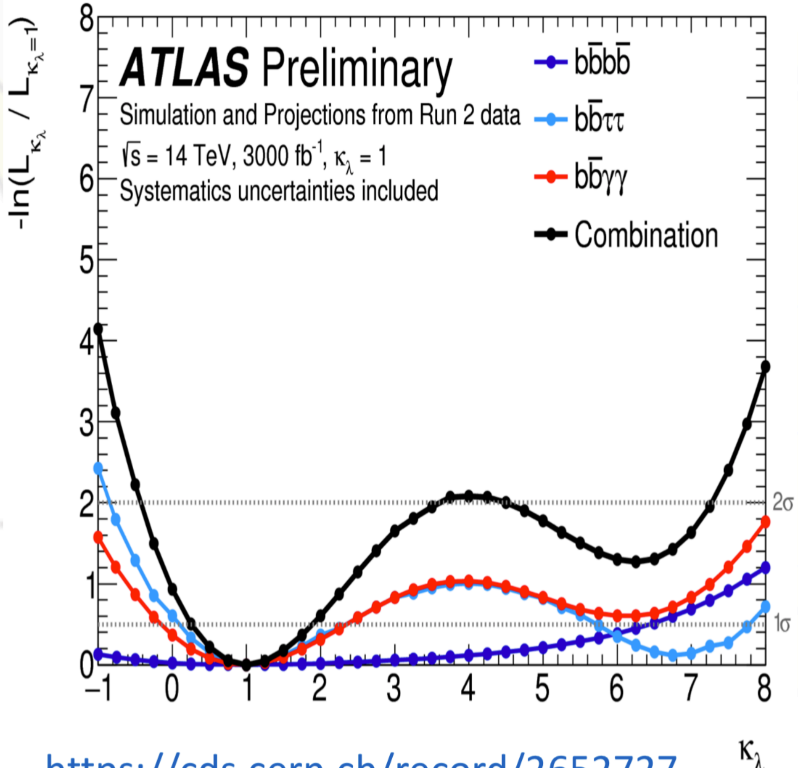


Projections on Higgs self-coupling

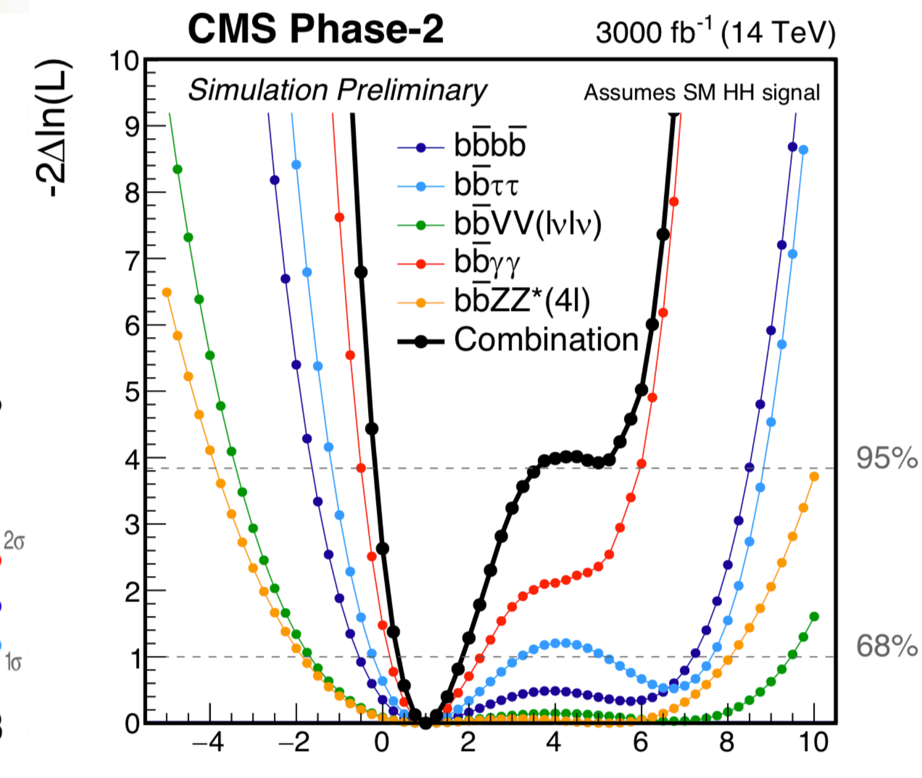
Di-Higgs production

- Sensitive to Higgs self-coupling (λ_{HHH}), but small cross-section (~36 fb).
- A significance of 2.6 (3.0) sigma expected by CMS (ATLAS) for evidence of HH.





https://cds.cern.ch/record/2652727



https://cds.cern.ch/record/2652549

arXiv:1809.10733

CMS Higgs Combination

Higgs combination inputs

- All main production and decay modes, based on 2016 13 TeV dataset (35.9 fb-1) @ CMS

Analysis	Reference
$H\to ZZ\to 4l$	JHEP 11 (2017) 047
$H\to\gamma\gamma$	arXiv:1804.02716
$H\to WW$	arXiv:1806.05246
$VH\to bb$	PLB 780 (2018) 501
$H\to\tau\tau$	PLB 779 (2018) 283
$H\to\mu\mu$	arXiv:1807.06325
Boosted $H\to bb$	PRL 120 (2018) 071802
$ttH\to WW/ZZ/\tau\tau$	arXiv:1803.05485
$ttH\to bb$ (leptonic)	arXiv:1804.03682
$ttH\to bb$ (hadronic)	arXiv:1803.06986
$H\to$invisible (*)	arXiv:1809.05937

	ggF	VBF	VH	ttH
$H\to ZZ\to 4l$	•	•	•	•
$H\to\gamma\gamma$	•	•	•	•
$H\to WW$	•	•	•	•
$H\to bb$	•		•	•
$H\to\tau\tau$	•	•		•
$H\to\mu\mu$	•	•		
$H\to$inv	•	•	•	

Higgs combination inputs

- In total up to 265 event categories and over 5500 nuisance parameters
- Correlation scheme studied in detail
- Consistency on signal modeling ensured among channels

Production and decay tags		Expected signal composition	Number of categories	Mass resolution
$H \to \gamma\gamma$, Section 3.1				
$\gamma\gamma$	Untagged	74–91% ggH	4	≈1–2%
	VBF	51–80% VBF	3	
	VH hadronic	25% WH, 15% ZH	1	
	WH leptonic	64–83% WH	2	
	ZH leptonic	98% ZH	1	
	VH p_T^{miss}	59% VH	1	
	ttH	80–89% ttH, ≈8% tH	2	
$H \to ZZ^{(*)} \to 4\ell$, Section 3.2				
4μ, $2e2\mu/2\mu2e$, $4e$	Untagged	≈95% ggH	3	≈1–2%
	VBF 1, 2-jet	≈11–47% VBF	6	
	VH hadronic	≈13% WH, ≈10% ZH	3	
	VH leptonic	≈46% WH	3	
	VH p_T^{miss}	≈56% ZH	3	
	ttH	≈71% ttH	3	
$H \to WW^{(*)} \to \ell\nu\ell\nu$, Section 3.3				
$e\mu/\mu e$	ggH 0, 1, 2-jet	≈55–92% ggH, up to ≈15% $H \to \tau\tau$	17	≈20%
	VBF 2-jet	≈47% VBF, up to ≈25% $H \to \tau\tau$	2	
$ee+\mu\mu$	ggH 0, 1-jet	≈84–94% ggH	6	
$e\mu$+jj	VH 2-jet	22% VH, 21% $H \to \tau\tau$	1	
3ℓ	WH leptonic	≈80% WH, up to 19% $H \to \tau\tau$	2	
4ℓ	ZH leptonic	85–90% ZH, up to 14% $H \to \tau\tau$	2	
$H \to \tau\tau$, Section 3.4				
$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	0-jet	≈70–98% ggH, 29% $H \to WW$ in $e\mu$	4	≈10–20%
	VBF	≈35–60% VBF, 42% $H \to WW$ in $e\mu$	4	
	Boosted	≈48–83% ggH, 43% $H \to WW$ in $e\mu$	4	
VH production with $H \to bb$, Section 3.5				
$Z(\nu\nu)bb$	ZH leptonic	≈100% VH, 85% ZH	1	≈10%
$W(\ell\nu)bb$	WH leptonic	≈100% VH, ≈97% WH	2	
$Z(\ell\ell)bb$	Low-$p_T(V)$ ZH leptonic	≈100% ZH, of which ≈20% ggZH	2	
	High-$p_T(V)$ ZH leptonic	≈100% ZH, of which ≈36% ggZH	2	
Boosted H Production with $H \to bb$, Section 3.6				
$H \to bb$	$p_T(H)$ bins	≈72–79% ggH	6	≈10%
ttH production with $H \to$ leptons, Section 3.7.1				
$H \to WW, \tau\tau, ZZ$	$2\ell ss$	$WW/\tau\tau \approx 4.5$, ≈5% tH	10	
	3ℓ	$WW : \tau\tau : ZZ \approx 15 : 4 : 1$, ≈5% tH	4	
	4ℓ	$WW : \tau\tau : ZZ \approx 6 : 1 : 1$, ≈3% tH	1	
	$1\ell+2\tau_h$	96% ttH with $H \to \tau\tau$, ≈6% tH	1	
	$2\ell ss+1\tau_h$	$\tau\tau : WW \approx 5 : 4$, ≈5% tH	2	
	$3\ell+1\tau_h$	$\tau\tau : WW : ZZ \approx 11 : 7 : 1$, ≈3% tH	1	
ttH production with $H \to bb$, Section 3.7.2				
$H \to bb$	$t\bar{t} \to$ jets	≈83–97% ttH with $H \to bb$	6	
	$t\bar{t} \to 1\ell$+jets	≈65–95% ttH with $H \to bb$, up to 20% $H \to WW$	18	
	$t\bar{t} \to 2\ell$+jets	≈84–96% ttH with $H \to bb$	3	
Search for $H \to \mu\mu$, Section 3.8				
$\mu\mu$	S/B bins	56–96% ggH, 1–42% VBF	15	≈1–2%
Search for invisible H decays, Section 3.9				
$H \to$ invisible	VBF	52% VBF, 48% ggH	1	
	ggH + ≥ 1 jet	80% ggH, 9% VBF	1	
	VH hadronic	54% VH, 39% ggH	1	
	ZH leptonic	≈100% ZH, of which 21% ggZH	1	

Combination Results

- **Signal strengths & cross sections**
- Couplings in kappa framework
- Constraints on BSM models

Signal strength measurements

- The number of signal events in each analysis category ***k*** is expressed as

$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma \times \mathrm{B})_{if} (\epsilon \times A)_k^{if}$$

Integrated luminosity

Efficiency x Acceptance

- Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \qquad \mu^f = \frac{\text{BR}^f}{\text{BR}^f_{\text{SM}}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

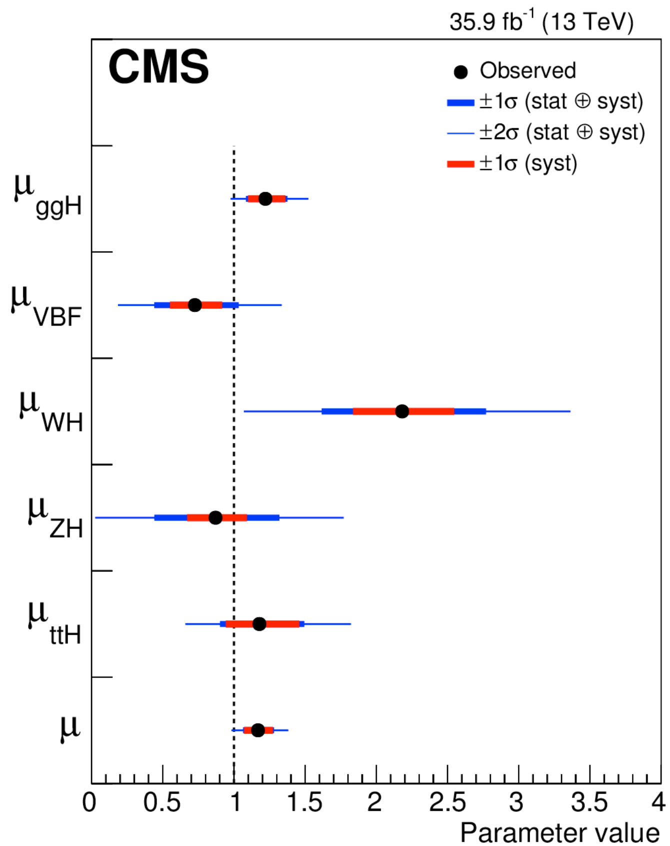
Overall signal strength
Assume SM BR and Relative Production XS

- Most constrained interpretation: single signal strength modifier which scales all prod. and decay modes assuming SM relative composition

$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\;^{+0.06}_{-0.05}\,(\text{sig. th.})\;^{+0.06}_{-0.06}\,(\text{other sys.})$$

- Systematically dominated, similar weight of theoretical and experimental uncertainties
- ~2σ agreement with respect to SM prediction

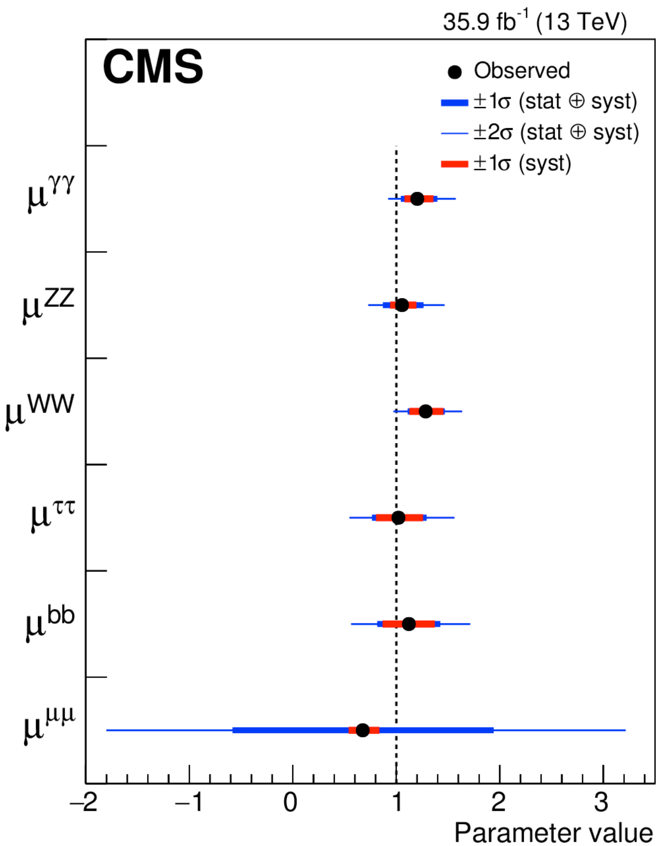
Production Signal Strengths



Production process	Best fit value		Uncertainty stat.	Uncertainty syst.
ggH	1.22	$^{+0.14}_{-0.12}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.12}_{-0.10}$ $\left(^{+0.09}_{-0.08}\right)$
VBF	0.73	$^{+0.30}_{-0.27}$ $\left(^{+0.29}_{-0.27}\right)$	$^{+0.24}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$
WH	2.18	$^{+0.58}_{-0.55}$ $\left(^{+0.53}_{-0.51}\right)$	$^{+0.46}_{-0.45}$ $\left(^{+0.43}_{-0.42}\right)$	$^{+0.34}_{-0.32}$ $\left(^{+0.30}_{-0.29}\right)$
ZH	0.87	$^{+0.44}_{-0.42}$ $\left(^{+0.43}_{-0.41}\right)$	$^{+0.39}_{-0.38}$ $\left(^{+0.38}_{-0.37}\right)$	$^{+0.20}_{-0.18}$ $\left(^{+0.19}_{-0.17}\right)$
ttH	1.18	$^{+0.30}_{-0.27}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.26}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$

- Most or all inclusive production mode signal strengths will be systematically limited with full Run2 dataset

Decay Signal Strengths

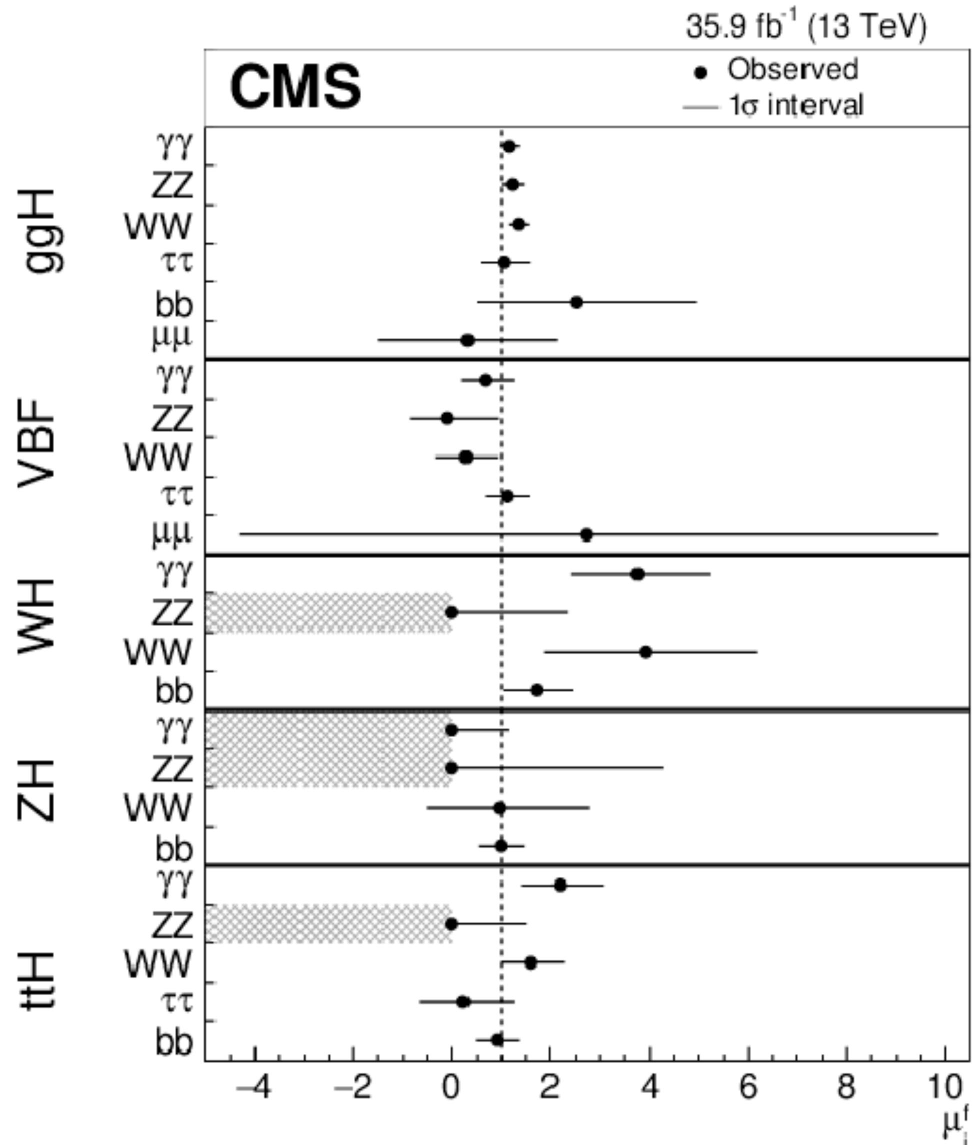


Decay mode	Best fit value		Uncertainty stat.	Uncertainty syst.
$H \to bb$	1.12	$^{+0.29}_{-0.29}$ $\left(^{+0.28}_{-0.27}\right)$	$^{+0.19}_{-0.18}$ $\left(^{+0.18}_{-0.18}\right)$	$^{+0.22}_{-0.22}$ $\left(^{+0.21}_{-0.20}\right)$
$H \to \tau\tau$	1.02	$^{+0.26}_{-0.24}$ $\left(^{+0.24}_{-0.22}\right)$	$^{+0.15}_{-0.15}$ $\left(^{+0.15}_{-0.14}\right)$	$^{+0.21}_{-0.19}$ $\left(^{+0.19}_{-0.17}\right)$
$H \to WW$	1.28	$^{+0.17}_{-0.16}$ $\left(^{+0.14}_{-0.13}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.11}_{-0.10}\right)$
$H \to ZZ$	1.06	$^{+0.19}_{-0.17}$ $\left(^{+0.18}_{-0.16}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.15}_{-0.14}\right)$	$^{+0.11}_{-0.08}$ $\left(^{+0.10}_{-0.08}\right)$
$H \to \gamma\gamma$	1.20	$^{+0.18}_{-0.14}$ $\left(^{+0.14}_{-0.12}\right)$	$^{+0.13}_{-0.11}$ $\left(^{+0.10}_{-0.10}\right)$	$^{+0.12}_{-0.09}$ $\left(^{+0.09}_{-0.07}\right)$
$H \to \mu\mu$	0.68	$^{+1.25}_{-1.24}$ $\left(^{+1.20}_{-1.17}\right)$	$^{+1.24}_{-1.24}$ $\left(^{+1.18}_{-1.17}\right)$	$^{+0.13}_{-0.11}$ $\left(^{+0.19}_{-0.03}\right)$

- All inclusive decay mode signal strengths except H->μμ will be systematically limited with full Run2 dataset

Per Production x Decay Mode

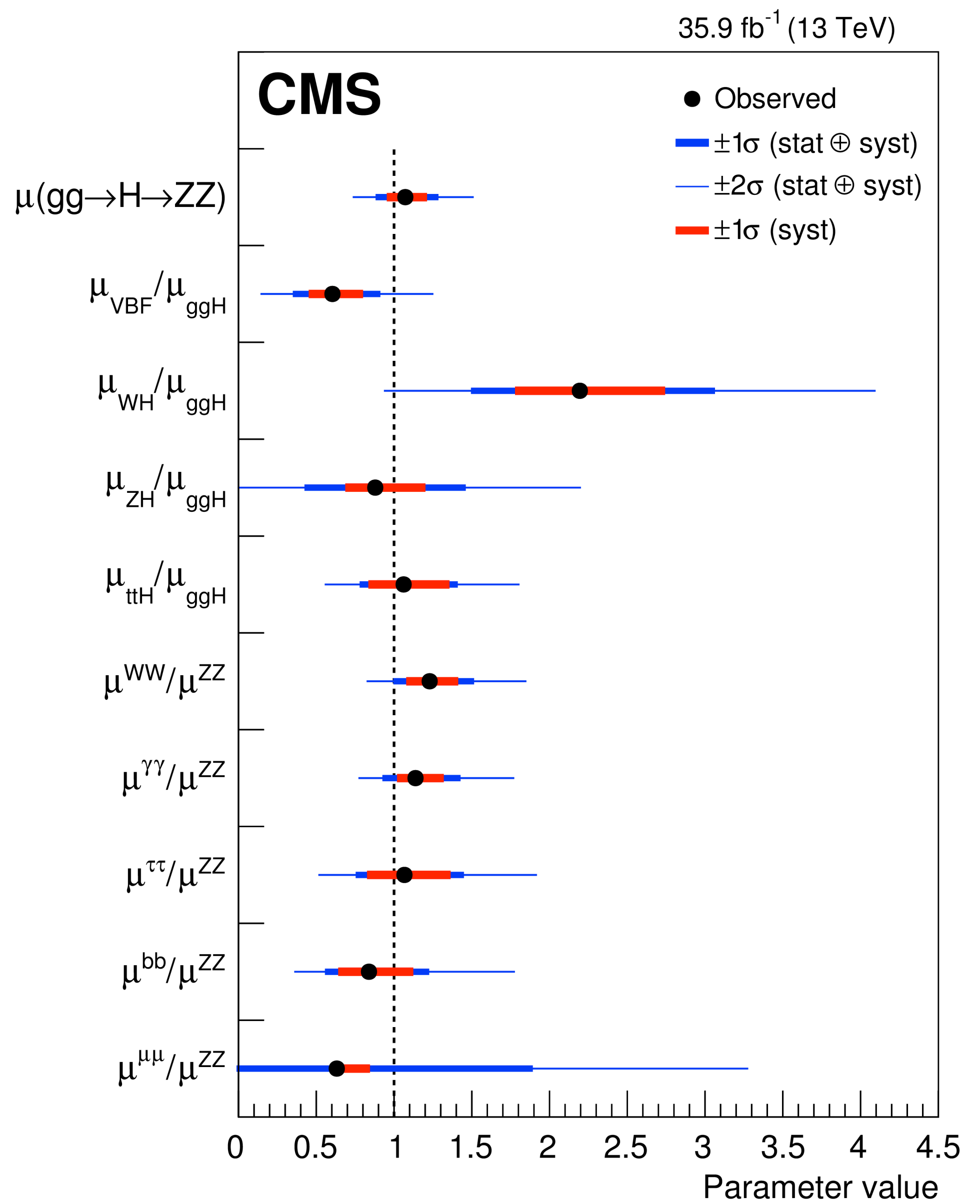
- Most generic parametrization giving different signal strength to each prod. and decay combination
- Certain signal strengths restricted due to low background expectation
- Suitable for reinterpretation



Signal strength ratios

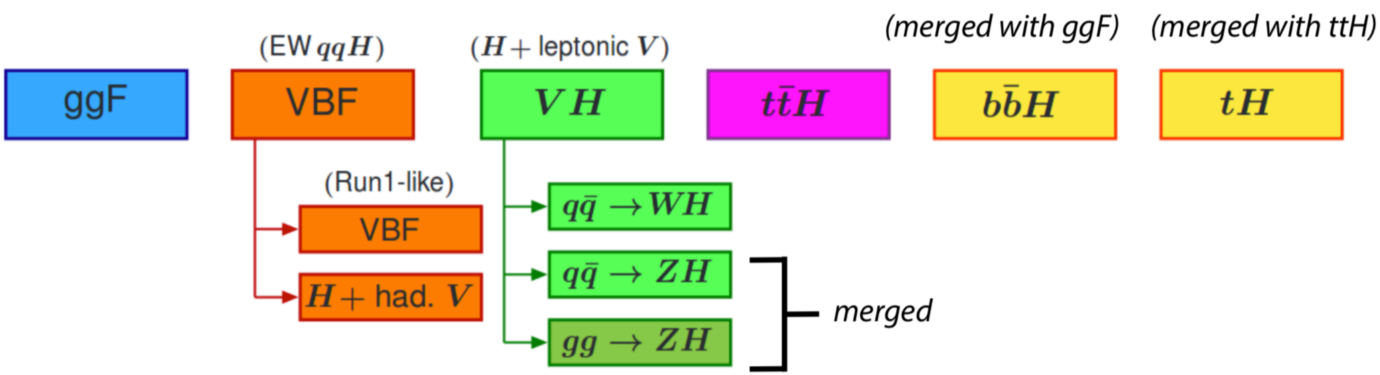
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$

- Normalize the rate for any particular channel to a reference process using ratios of cross sections and branching ratios
- Motivation:
  - No assumptions on relative cross sections or BRs
  - Measured values independent of SM prediction and inclusive theory uncertainties
  - **Cancellation of common systematic uncertainties in ratios**
- Choose reference process as one measured with the **smallest systematic uncertainty: gg→H→ZZ**



Simplified Template Cross Sections

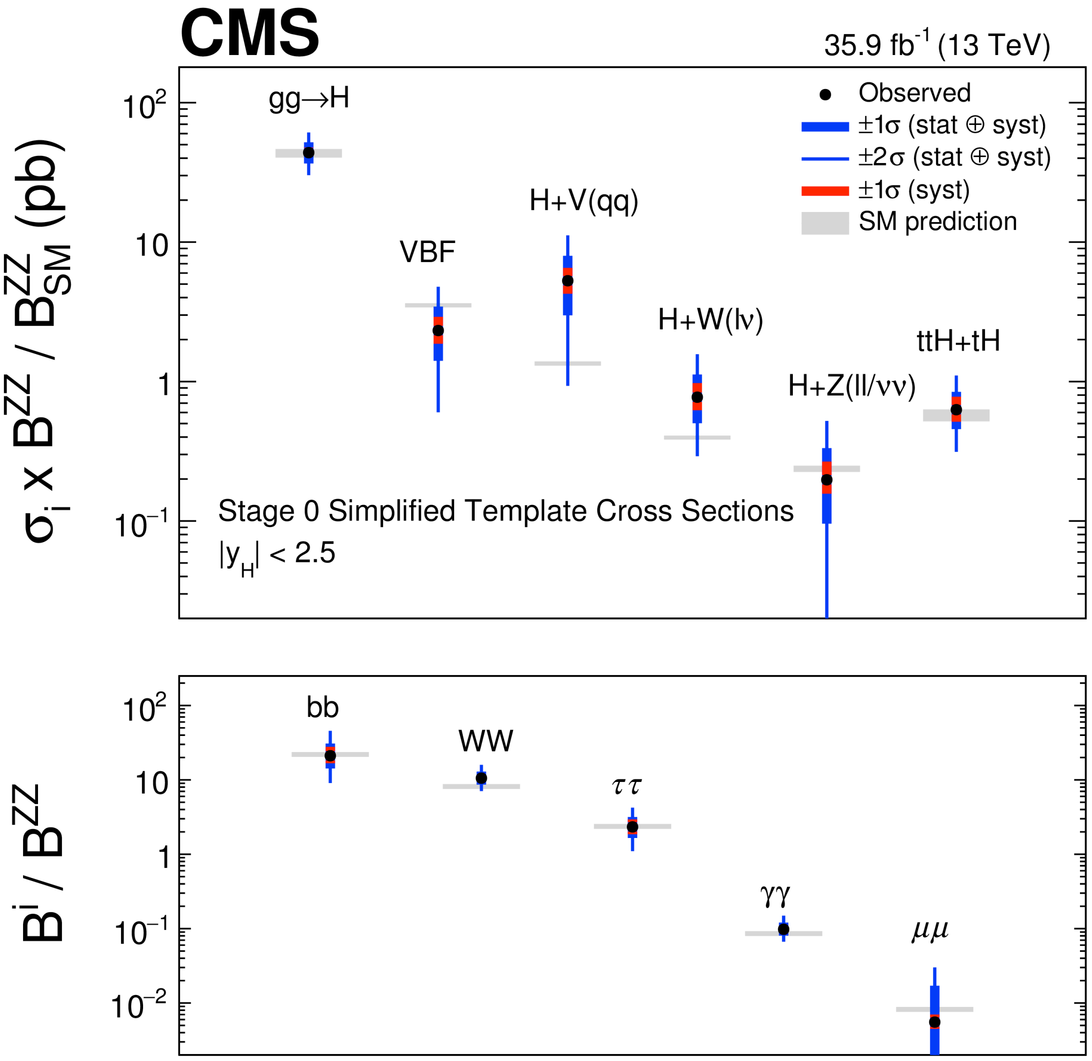
- A common framework recommended by *LHCHXSWG (arXiv:1610.07922)*
- Maximize sensitivity at the cost of some theory dependence, all analysis techniques maintained
- Can serve as input to BSM interpretations, e.g. for determining Wilson coefficients, etc.
- Several stages proposed



Stage-0 example: VH split into V(ll) and V(qq)

Simplified Template Cross Sections

- Separate th. uncs. in SM predictions from exp. and th. uncs. in the measurements
- Results quoted for a common simplified fiducial volume
- One parameter for each cross section, with floating ratios of the decay BRs



Combination Results

- Signal strengths & cross sections
- **Couplings in kappa framework**
- Constraints on BSM models

Couplings – κ framework

- LO coupling modifier/kappa framework to probe deviations from SM
  - Assumptions: only **one CP-even** Higgs state with m_H=125 GeV and **negligible width**
- Parameter scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\mathrm{SM}}$$

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}$$

Total width determined as

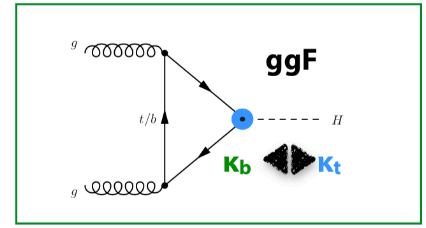
$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

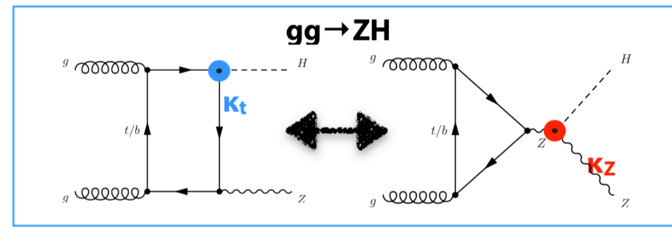
Where

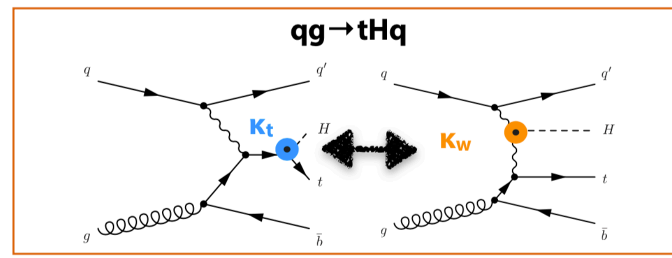
$$\kappa_H^2 = \sum_j \mathrm{BR}_{\mathrm{SM}}^j \kappa_j^2$$

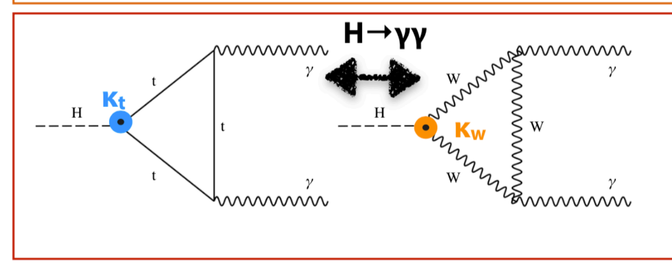
Coupling Parameterization

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\mathrm{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\mathrm{WH})$	–	–		κ_W^2
$\sigma(qq/qg \to \mathrm{ZH})$	–	–		κ_Z^2
$\sigma(gg \to \mathrm{ZH})$	✓	Z − t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z \kappa_t$
$\sigma(\mathrm{ttH})$	–	–		κ_t^2
$\sigma(gb \to \mathrm{WtH})$	–	W − t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t \kappa_W$
$\sigma(qb \to \mathrm{tHq})$	–	W − t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t \kappa_W$
$\sigma(\mathrm{bbH})$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 + 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



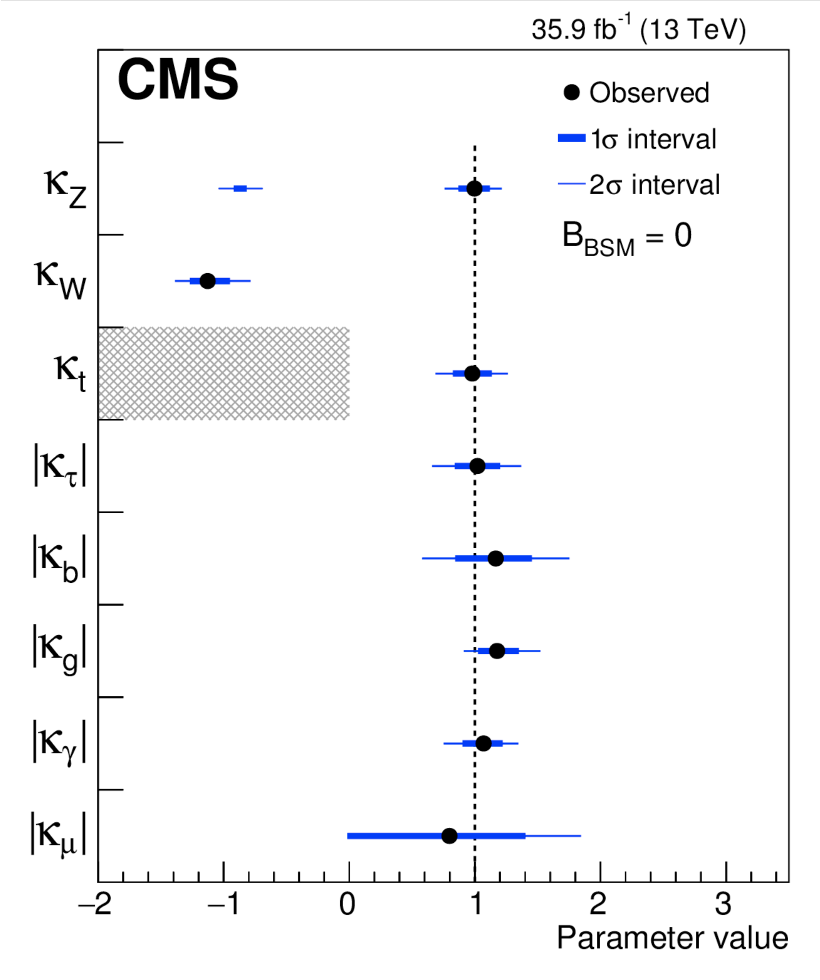






Couplings: Effective Loops

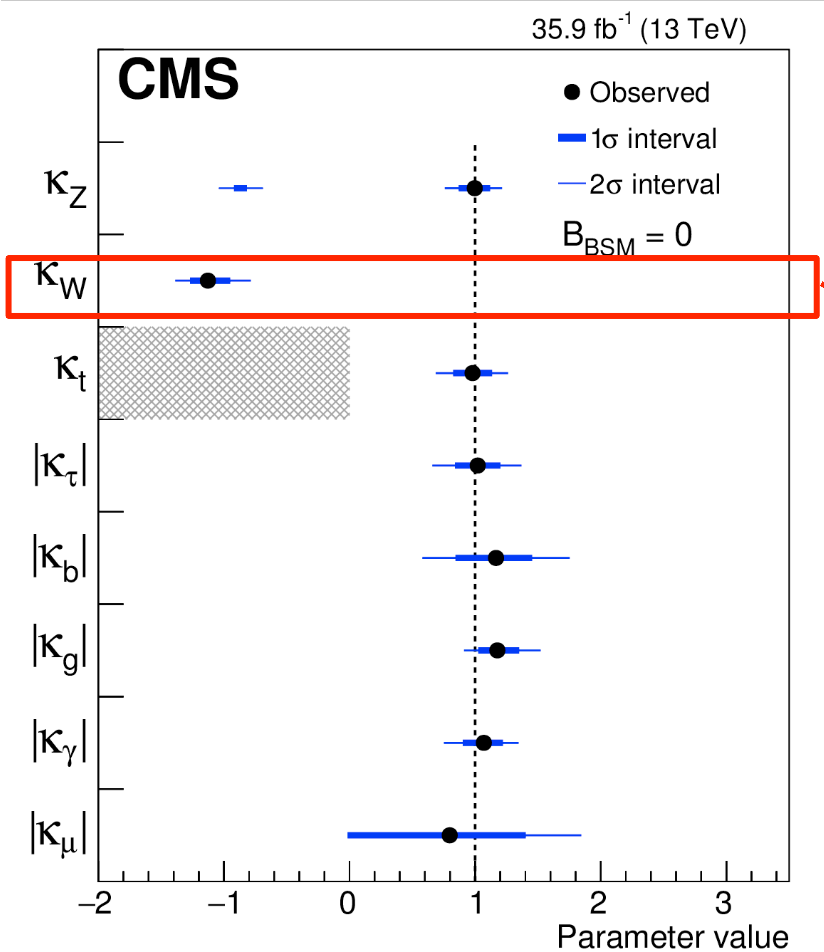
- No assumptions about loops (κ_g and κ_γ free parameters)
- Assumption about total width: No BSM decays

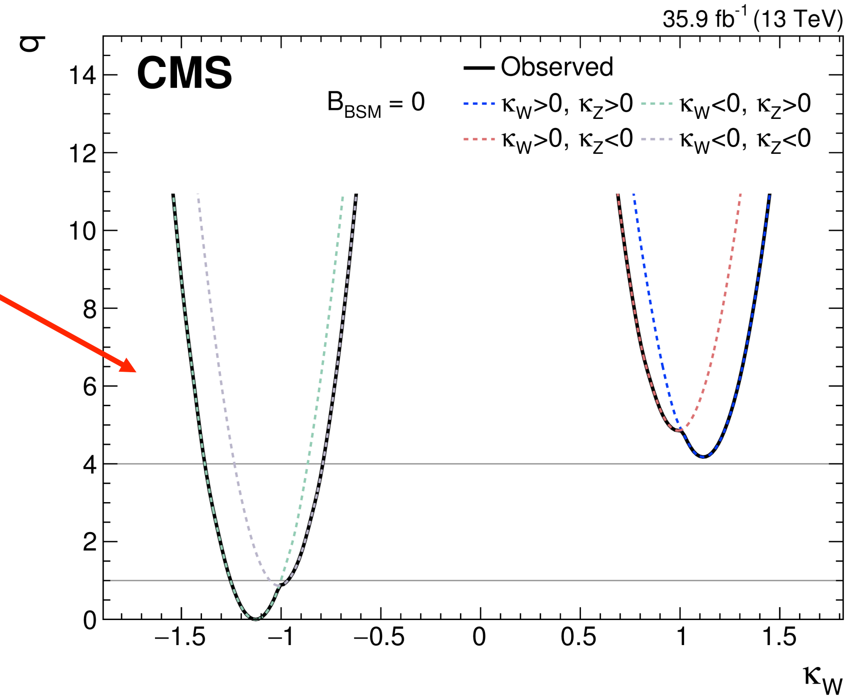


Gluon fusion and H->$\gamma\gamma$ scaled by κ_g and κ_γ

Couplings: Effective Loops

- No assumptions about loops (κ_g and κ_γ free parameters)
- Assumption about total width: No BSM decays

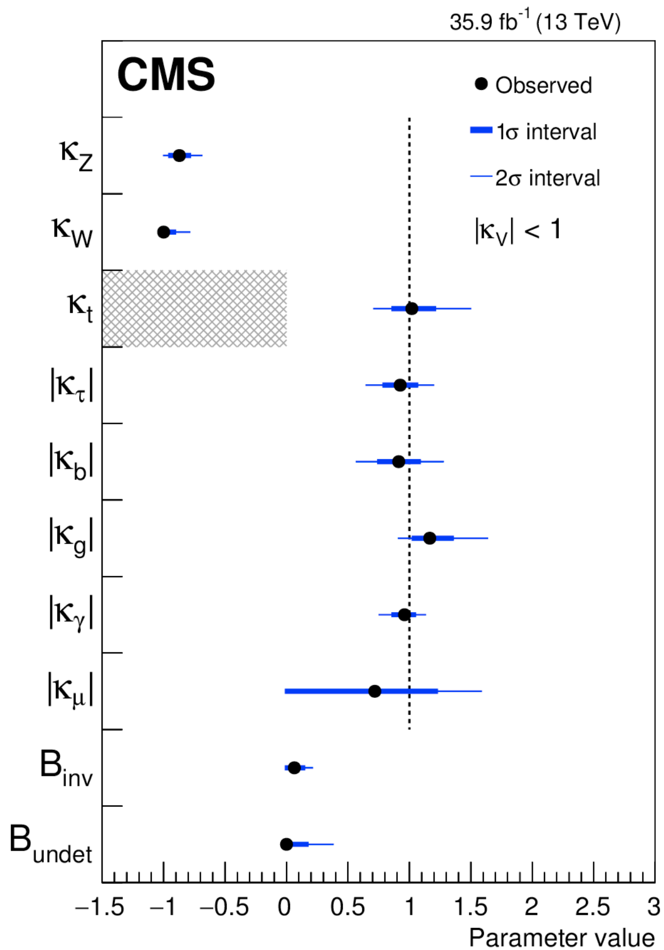




Positive κ_W disfavoured at just over 2σ, partly driven by moderate excess in ttH-tag H→γγ categories, compensated by enhanced tHq when $\kappa_W \bullet \kappa_t < 1$

Couplings: Effective Loops

- No assumptions about loops (κ_g and κ_γ free parameters)
- Assumption about total width: $|\kappa_V| < 1$



$|\kappa_V| < 1$ imposed - typically the case in BSM models that affect Higgs couplings

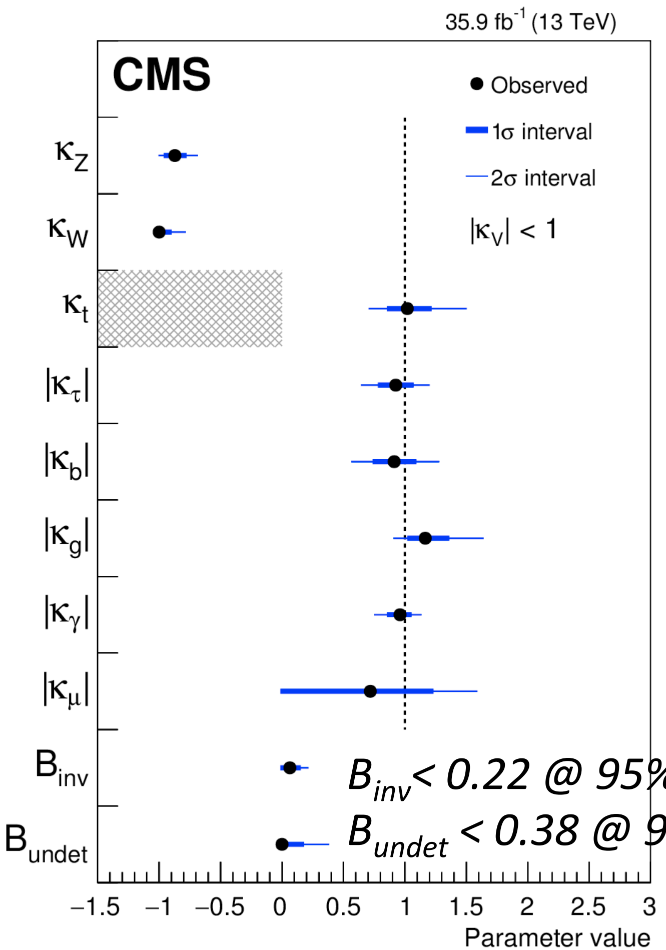
$BR_{inv} > 0$, $BR_{undet} > 0$

BR_{inv}: Scales signal normalisation in direct H→invisible searches

BR_{undet}: Represents branching ratio to any final state not directly detected by analyses

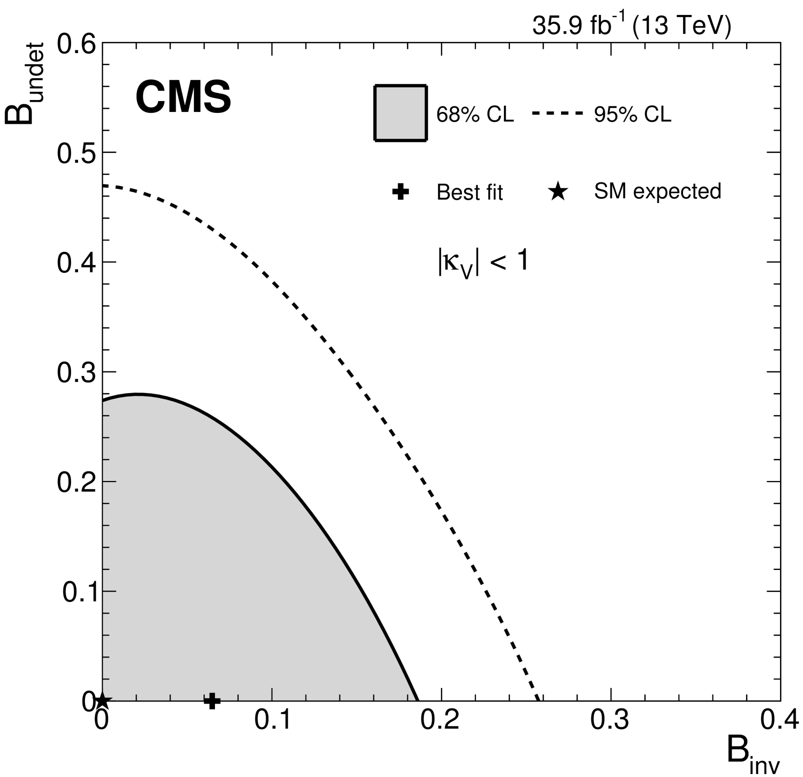
Couplings: Effective Loops

- No assumptions about loops (κ_g and κ_γ free parameters)
- Assumption about total width: $|\kappa_V| < 1$



B_{inv}< 0.22 @ 95% CL

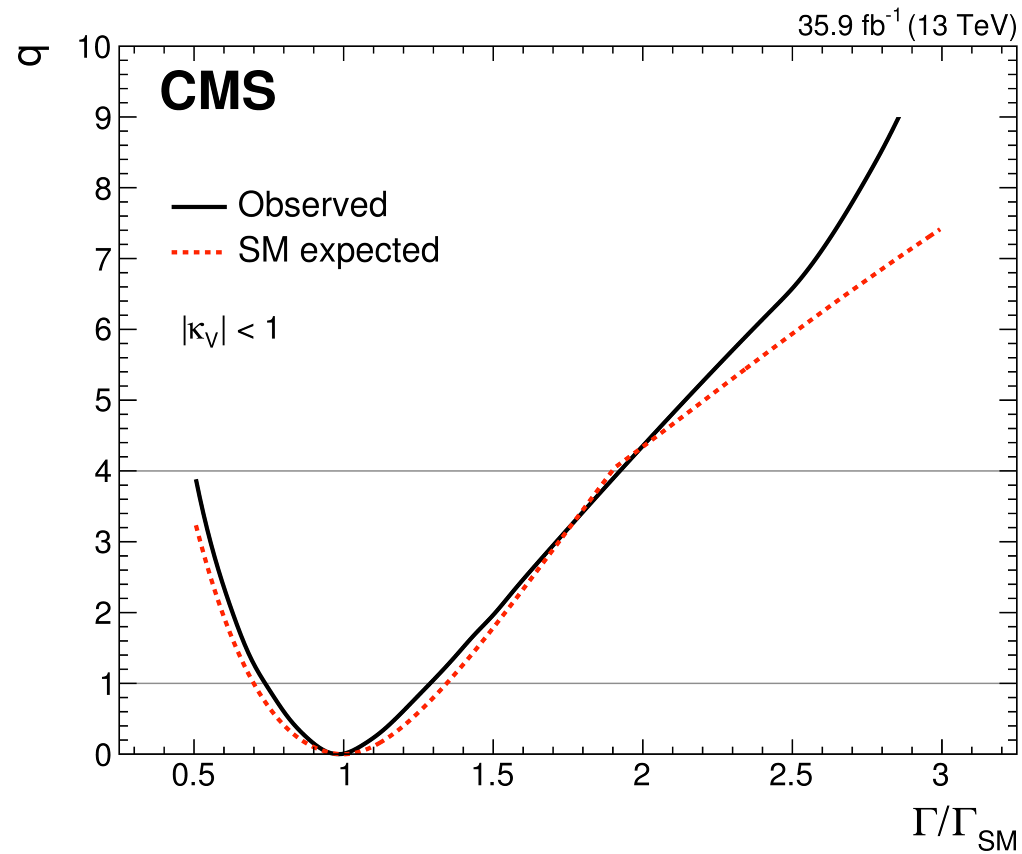
B_{undet} < 0.38 @ 95% CL



moderate anti-correlated between measurements

Constraint on Total Width

- Assuming $\kappa_V < 1$, but allowing for BSM decays, set constraint on total Higgs width
- Performed by making total width a parameter of the model (instead of a function of other κ's), and making κ_b a function of other κ's and total width



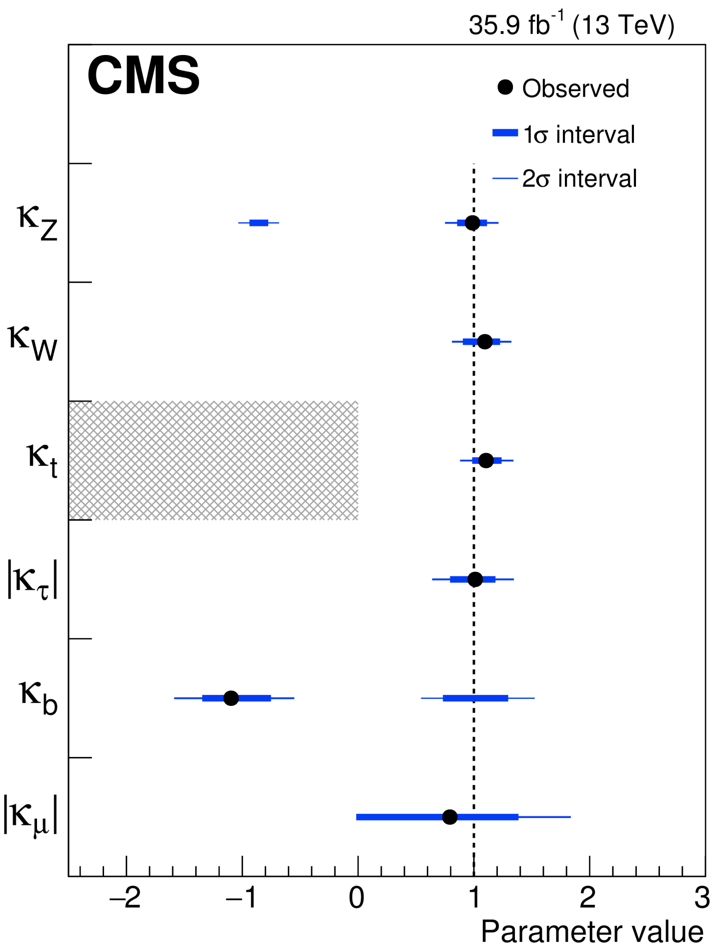
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{1 - (BR_{undet.} + BR_{inv.})}$$

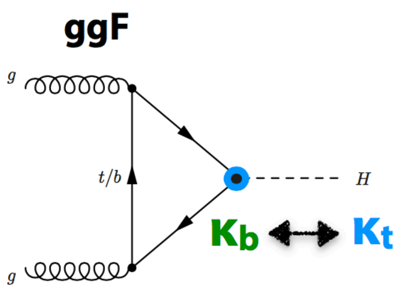
$$\kappa_H^2 = 0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 + 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_u^2$$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = 0.98^{+0.31}_{-0.25}$$

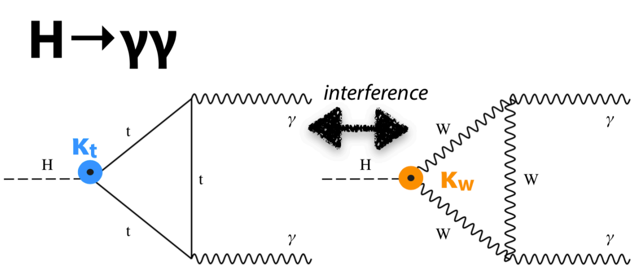
Couplings: Resolved loops

- Assume SM structure in ggH and Hγγ loops, i.e. no contribution from new particles





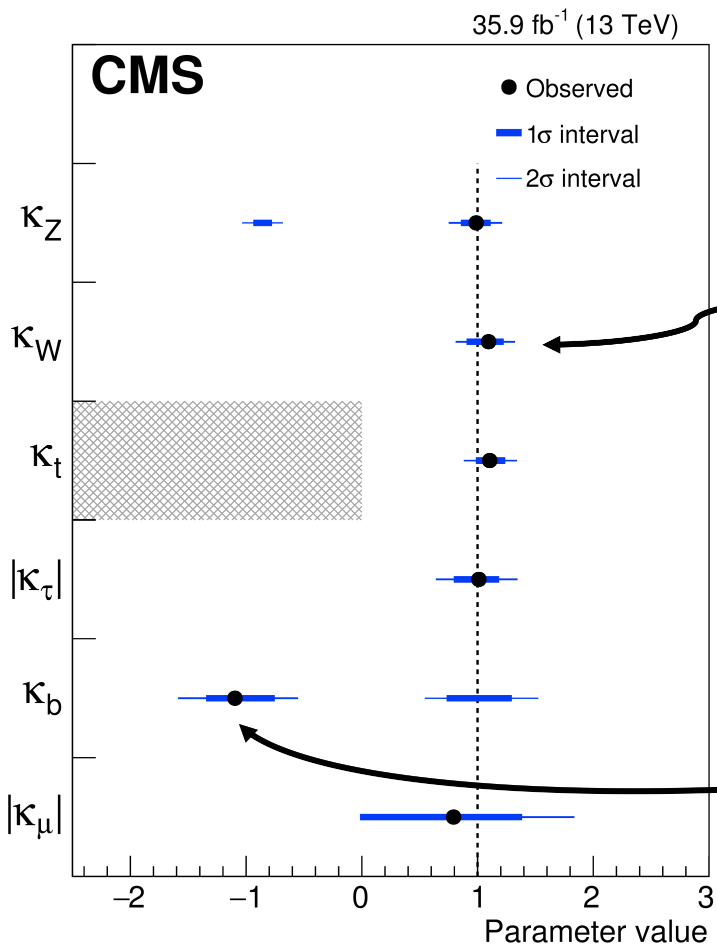
$$\kappa_g{}^2 = 1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$$



$$\kappa_\gamma{}^2 = 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$$

Couplings: Resolved loops

- Assume SM structure in ggH and Hγγ loops, i.e. no contribution from new particles



Negative κ_W strongly disfavoured when H→γγ loop resolved

Mild preference for $\kappa_b < 0$ from b-t interference in gluon fusion production

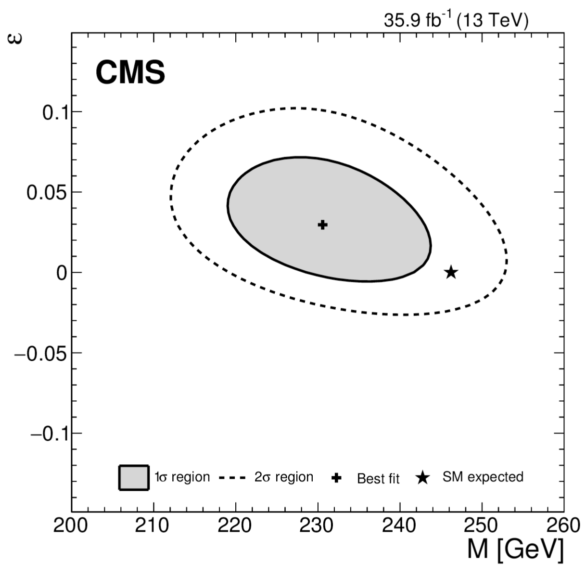
Couplings vs. mass

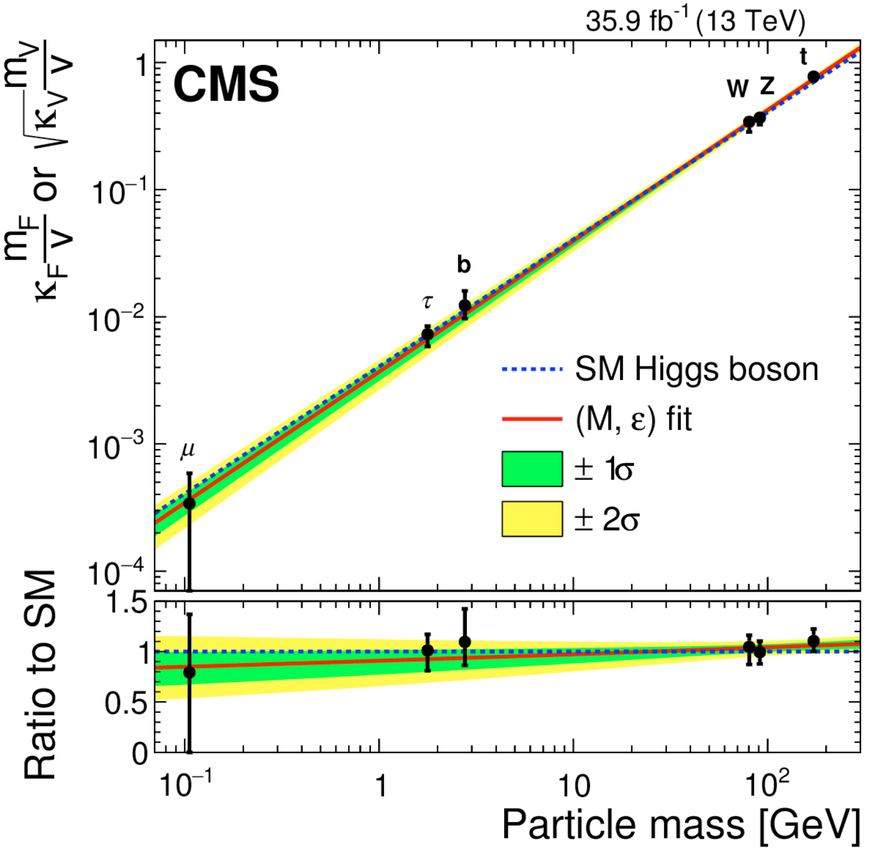
- Perform two parameter (M, ε) fit where

$$\kappa_{F,i} = v\frac{m_{F,i}^{\epsilon}}{M^{1+\epsilon}} \qquad \kappa_{V,i} = v\frac{m_{V,i}^{2\epsilon}}{M^{1+2\epsilon}}$$

SM given by: **M=v=246 GeV, ε=0**

- Can visualize result in terms of absolute coupling modifiers vs particle mass



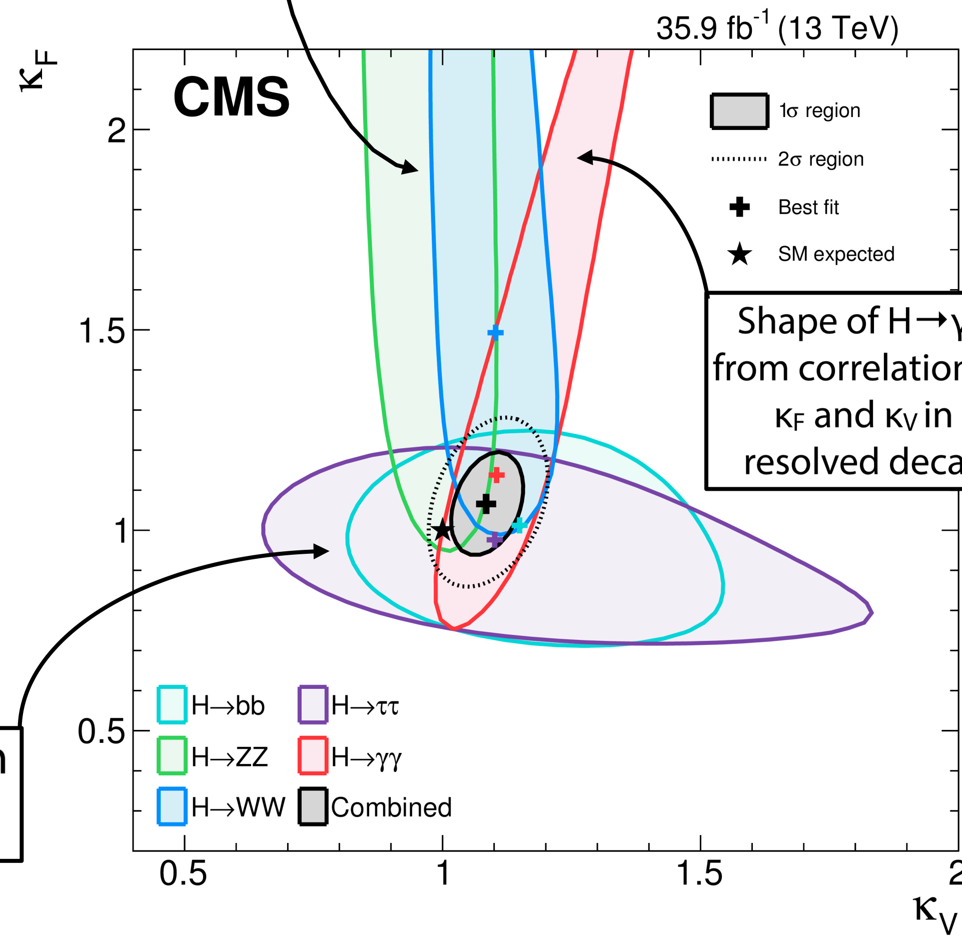


Higgs boson couplings follow closely SM predictions over the full explored mass range

Vector boson vs. fermion couplings

- Scale all **fermionic couplings** and all **bosonic couplings** to the Higgs boson by the same modifier
- Only consider $\kappa_F\kappa_V>0$ (negative relative sign already strongly disfavored since run 1 at ~5σ
- Per-channel model shows complementary constraints from the different analyses

H→ZZ/WW sensitivity to high κ_F limited. Scaling of ggH→VV goes as: $\kappa_F^2 \bullet \kappa_V^2 / (0.75\kappa_F^2 + 0.25\kappa_V^2) \rightarrow \kappa_V^2$ as $\kappa_F \rightarrow \infty$

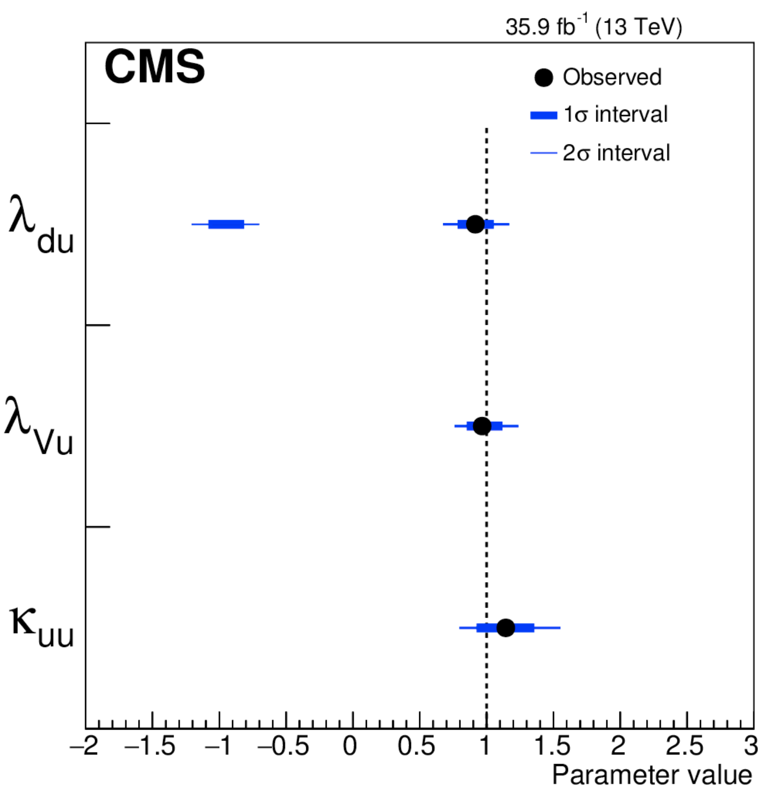


Shape of H→γγ from correlation of κ_F and κ_V in resolved decay

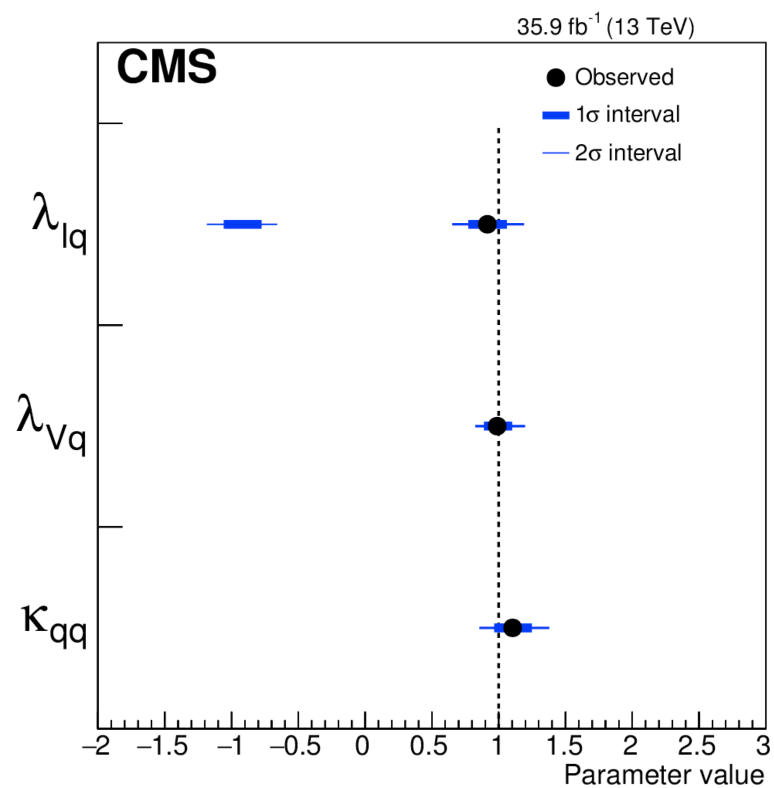
Sensitivity to κ_F predominantly from H→fermions channels

Test symmetry of fermion couplings

- In MSSM / 2HDM Type II [κ_V, κ_d, κ_u], ratio of down-type (b, τ, μ) and up-type (t) fermion couplings is tested with ~10% precision
- No enhancement observed wrt SM, i.e. consistent with alignment limit



- In 2HDM Lepton-Specific [κ_V, κ_l, κ_q], ratio of lepton (τ, μ) and quark couplings (t, b) would be enhanced at large tan β
- Also good agreement with SM



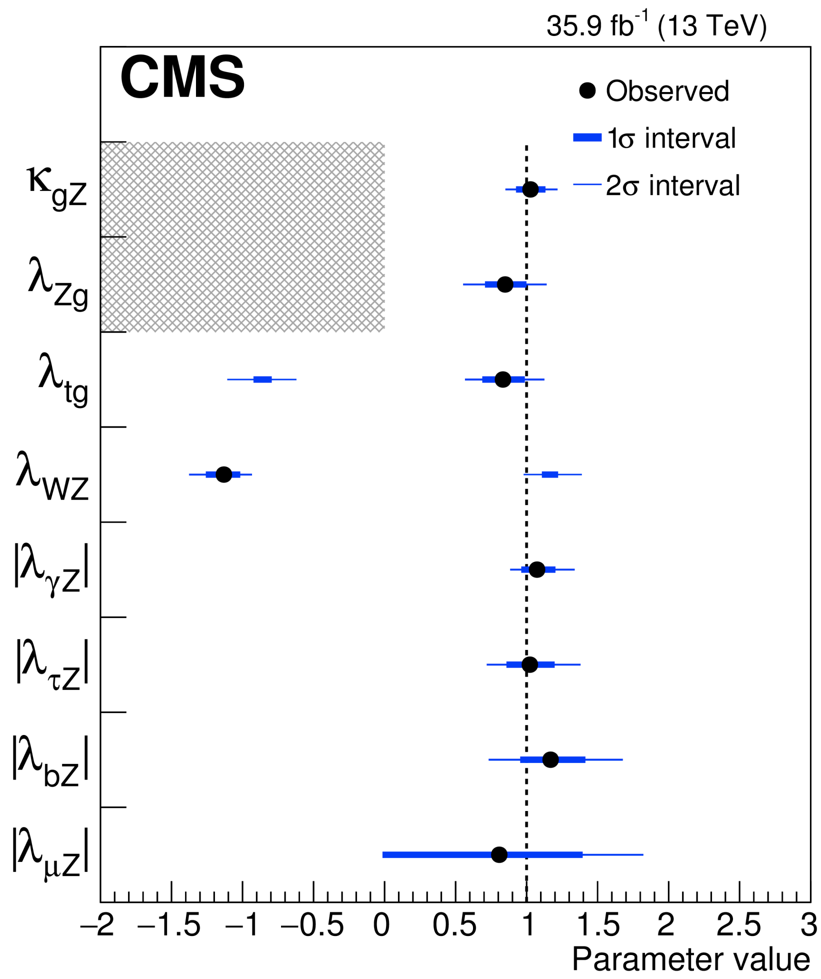
Couplings modifier ratios

- Analogous to signal strength ratios, measure ratios of coupling modifiers given a reference κ:

$$\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$$

- Assume $\kappa_{gZ}>0$ and $\lambda_{Zg}>0$ without loss of generality
- Evaluate λ_{tg} and $\lambda_{WZ}<0$ subject to constraint $\lambda_{tg}\,\lambda_{WZ}>0$, to probe interference in ggZH production but not tH

No assumption on total width



Combination Results

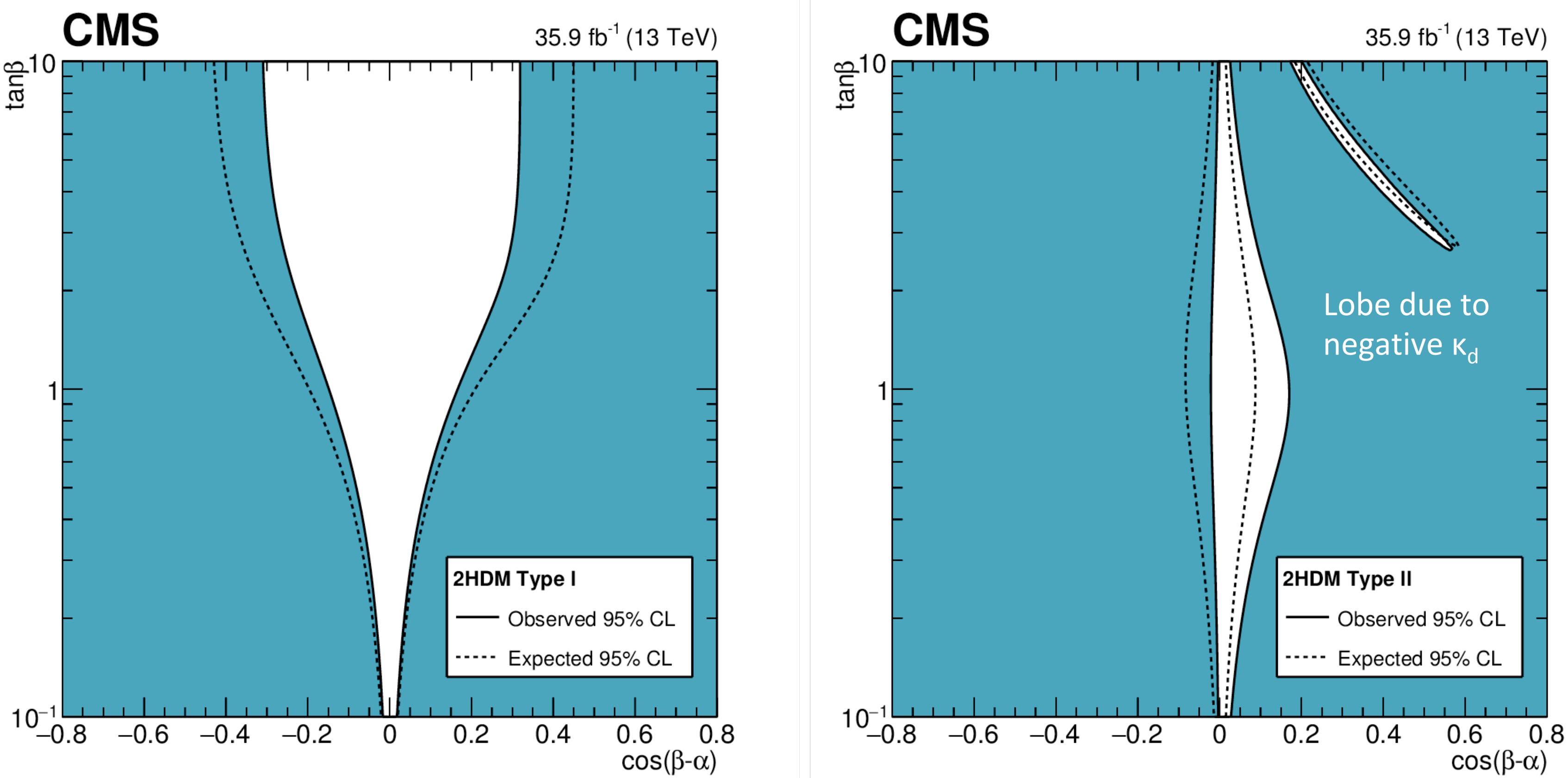
- Signal strengths & cross sections
- Couplings in kappa framework
- **Constraints on BSM models**

Constraints on BSM models

- Interpret Higgs coupling strength results in terms of BSM model parameters
  - Complementary to the limits obtained from direct searches for new physics
- Consider different types of 2HDMs and the hMSSM under certain assumptions
  - Higgs boson identified as the light CP-even neutral scalar, exhibiting only SM production and decay modes
  - Neglect corrections of the ggF production and diphoton decay rates from SUSY partners as well as effects breaking the universality of down-type fermion coupling

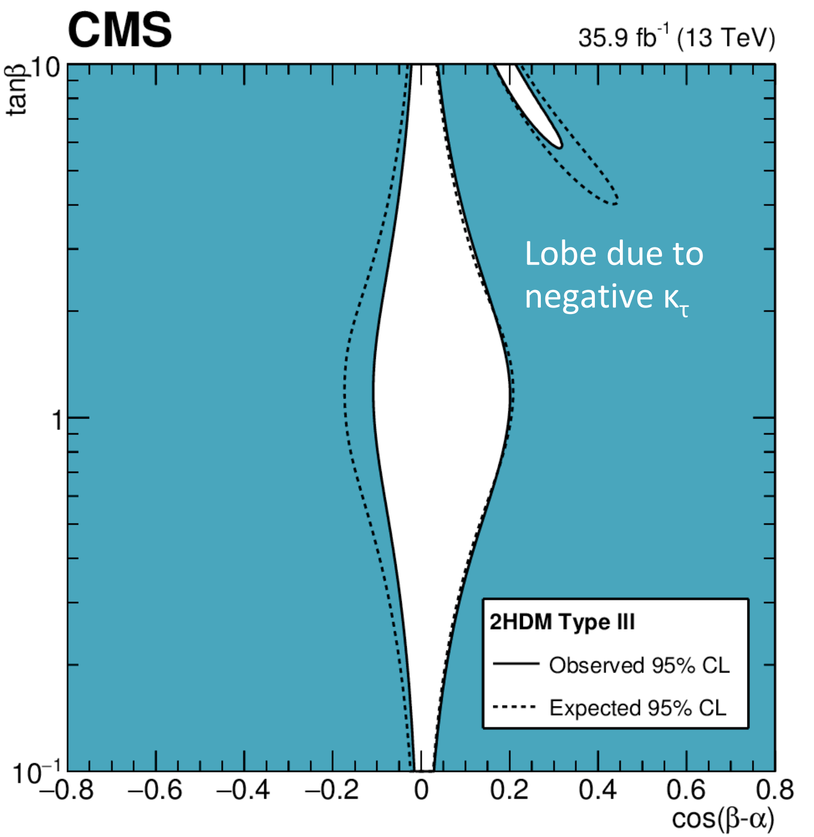
	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$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

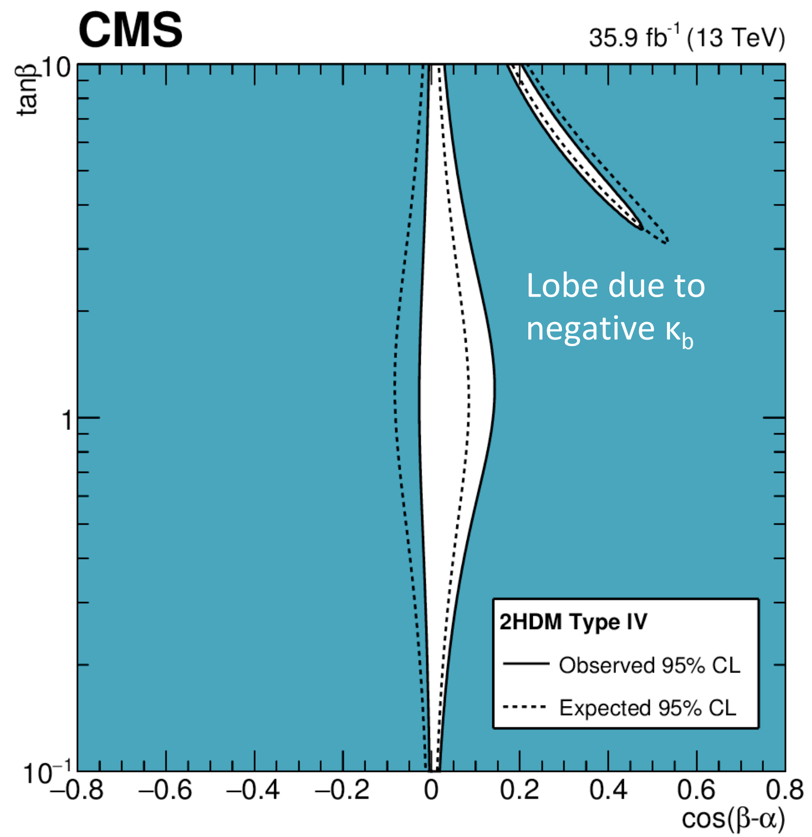
Constraints on BSM models



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

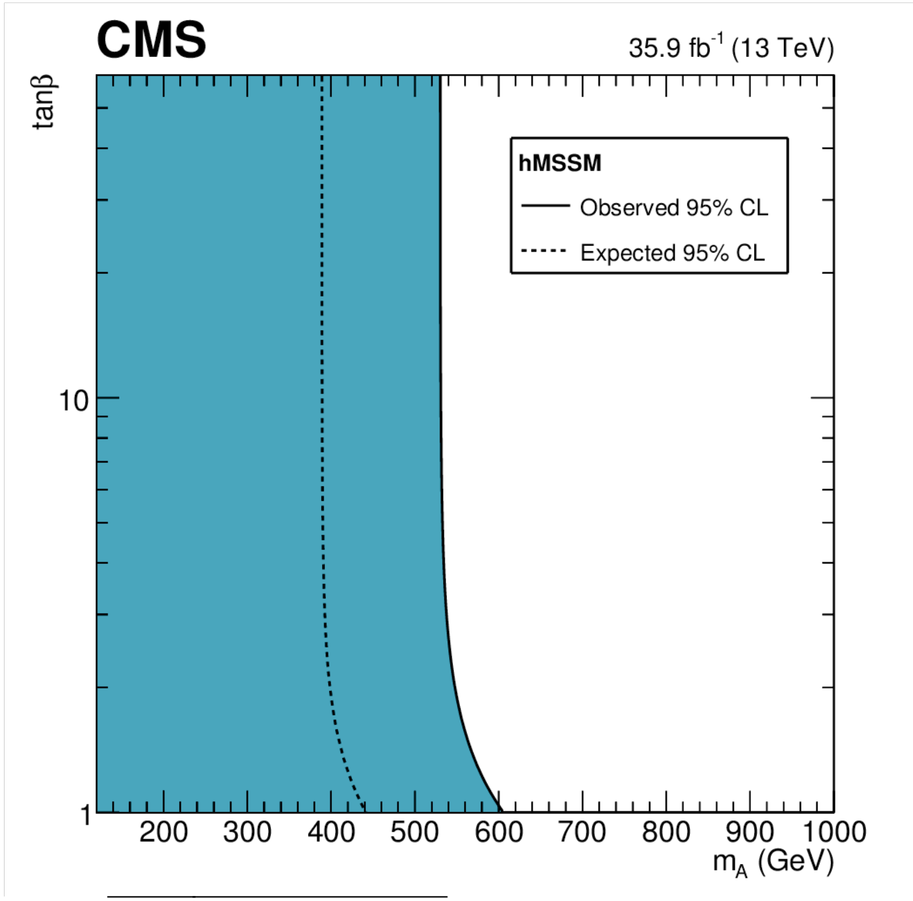
Constraints on BSM models





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

Constraints on BSM models

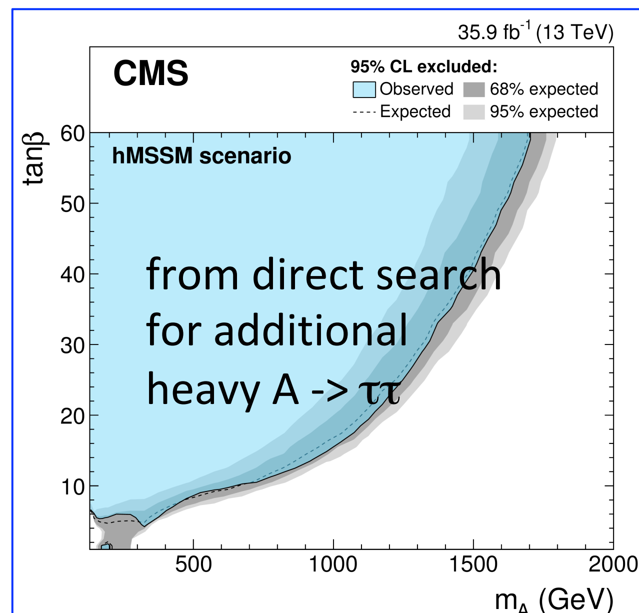


	hMSSM
κ_V	$\frac{s_d + s_u \tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$s_u \frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$s_d \sqrt{1+\tan^2\beta}$
κ_l	$s_d \sqrt{1+\tan^2\beta}$

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

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

- Indirect constraints provide complementary information compared to direct searches
- Possible to interpret in other MSSM benchmark models

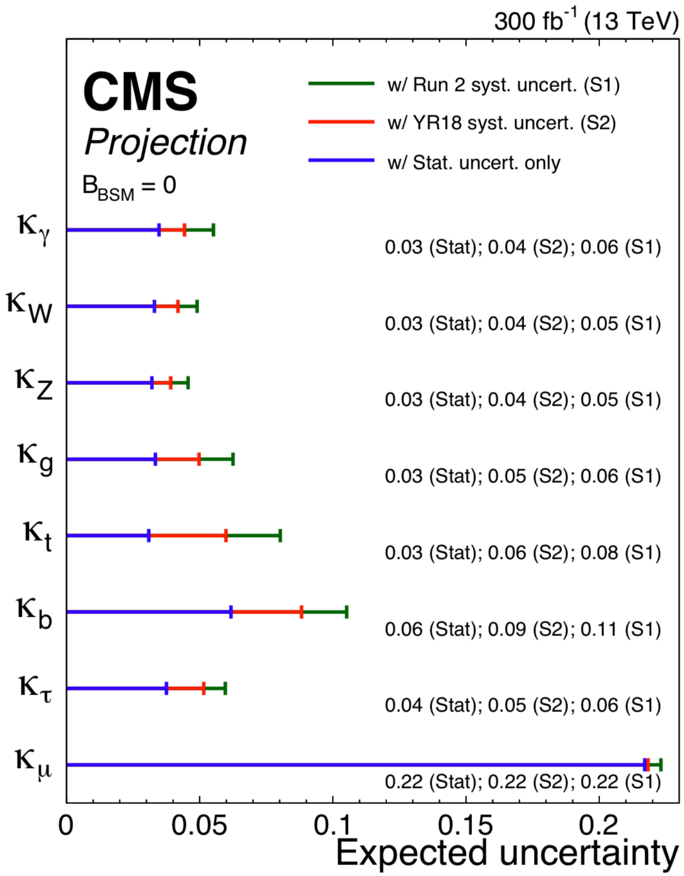


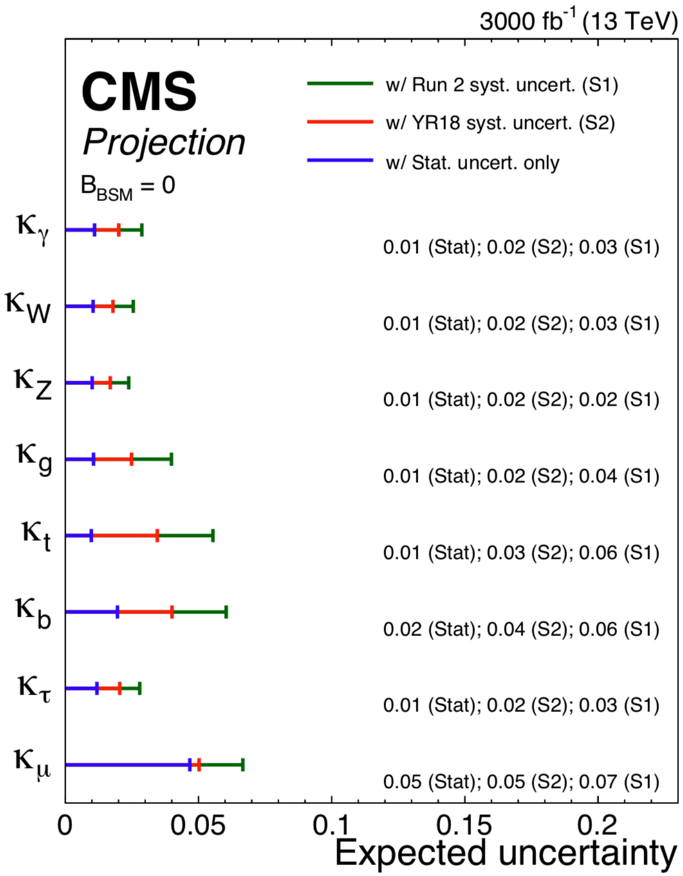
Summary

- Wide range of combination results with 36/fb 13 TeV CMS data
- Direct observation of **all main production and decay modes**
- Direct confirmation of **coupling to all 3rd generation quarks and charged leptons**
- Higgs physics is an important indirect probe for BSM physics: so far **no deviations from SM** observed
- Much more data ahead, stay tuned

Future sensitivity (CMS-PAS-FTR-18-011)

- Most coupling uncertainties will reach ~4-6% precision with 300/fb and 2-4% after 3000/fb





Backup

Coupling Deviations in BSM

- How well do we need to measure Higgs couplings ?
- Typical effect on coupling from heavy particle M or new physics at scale M:

$$\Delta \sim \left(\frac{v}{M}\right)^2 \sim 5\% \text{ @ } M \sim 1 \text{ TeV}$$

*Han et al., hep-ph/*0302188
*Gupta et al., arXiv:*1206.3560
……

Typical sizes of coupling modifications: arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Statistics

- Workhorse of the combination is the **profile likelihood ratio, Λ**

$\vec{\alpha}$ = Set of POIs at some fixed values to be tested

$\vec{\theta}$ = Nuisance parameters

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}\,,\ \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

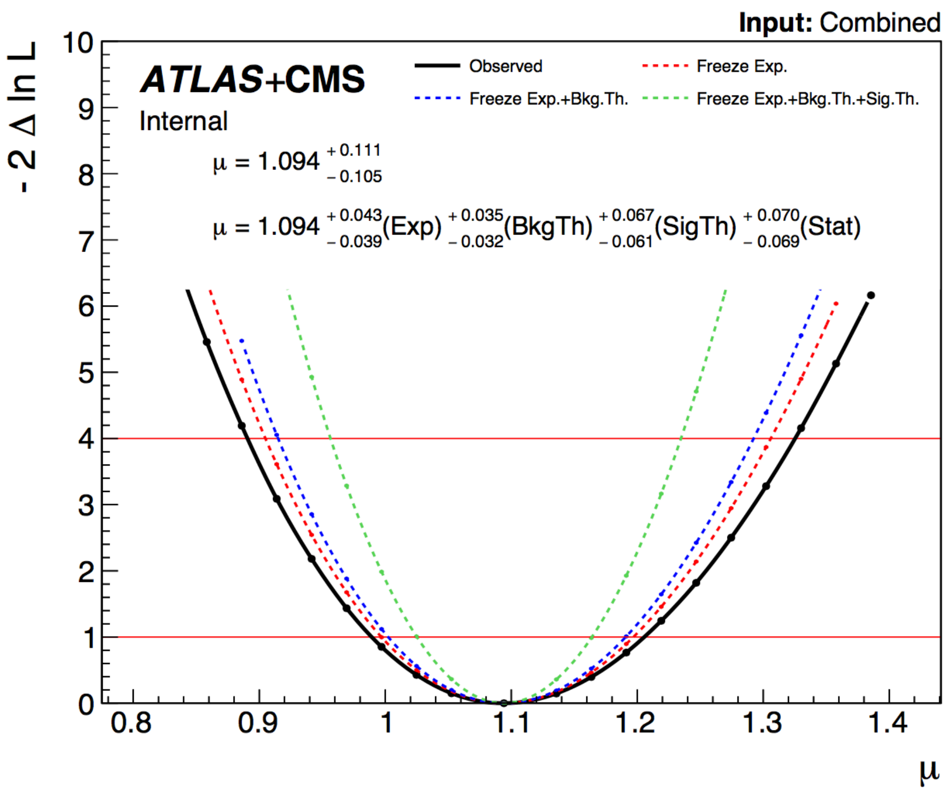
Values of $\vec{\theta}$ that maximise the likelihood given the fixed values of $\vec{\alpha}$ being tested (conditional estimate)

Values of $\vec{\alpha}$ and $\vec{\theta}$ that globally maximise the likelihood (unconditional estimate)

- Exploit the **asymptotic limit**:
  - Test statistics $q(\vec{\alpha}) = -2\ln(\Lambda(\vec{\alpha}))$ is assumed to follow a χ^2 distribution with $\vec{\alpha}$ degrees of freedom
  - To determine a confidence-level (CL) interval for a single parameter α, we only need to find the values of α where $q(\alpha)$ = the χ^2 critical value for that CL, e.g. 1D 68% CL at $q(\alpha) = 1.00$

An example of breaking down of uncertainties

- For this, and other key measurements, break uncertainty down into 4 components:
  - statistical, experimental, background theory, signal theory
- All ~4300 NPs assigned to one of these groups
- Each component determined by fixing successive group of NPs to best-fit values $\hat{\theta}$ and repeating NLL scan



Higgs rates & couplings

- Signal parameterization

Signal strengths, μ

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu^f = \frac{BR^f}{BR^f_{SM}}.$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} = \mu_i \times \mu^f$$

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

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

$$\sigma_i \cdot BR^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H},$$

Total width determined as

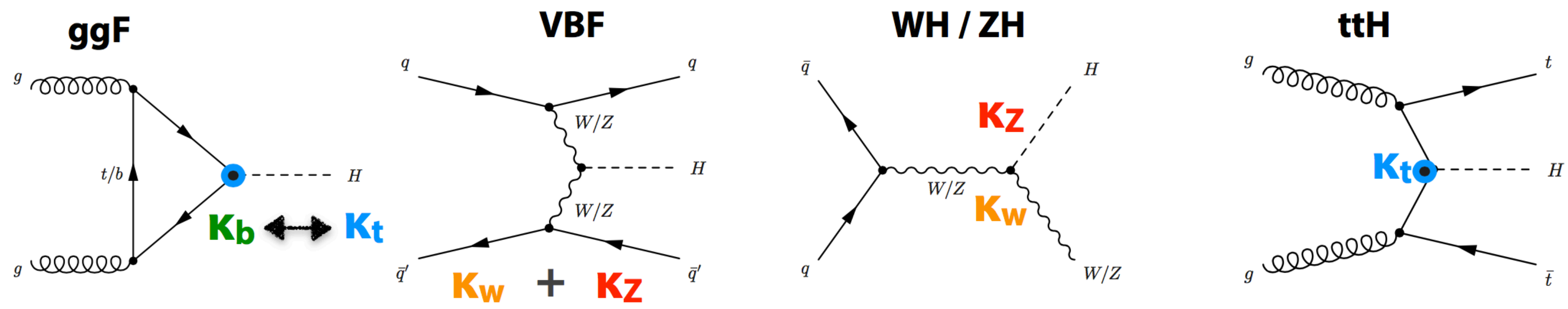
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

Where

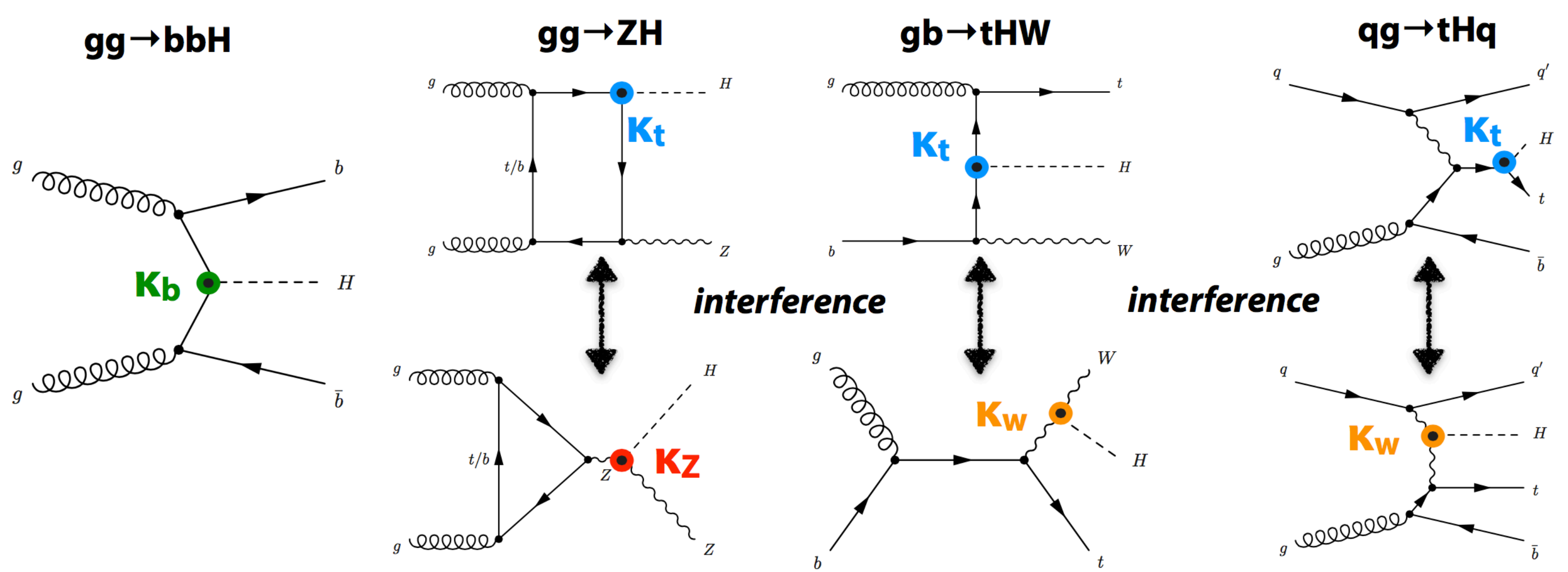
$$\kappa_H^2 = \sum_j BR^j_{SM} \kappa_j^2$$

Higgs production processes

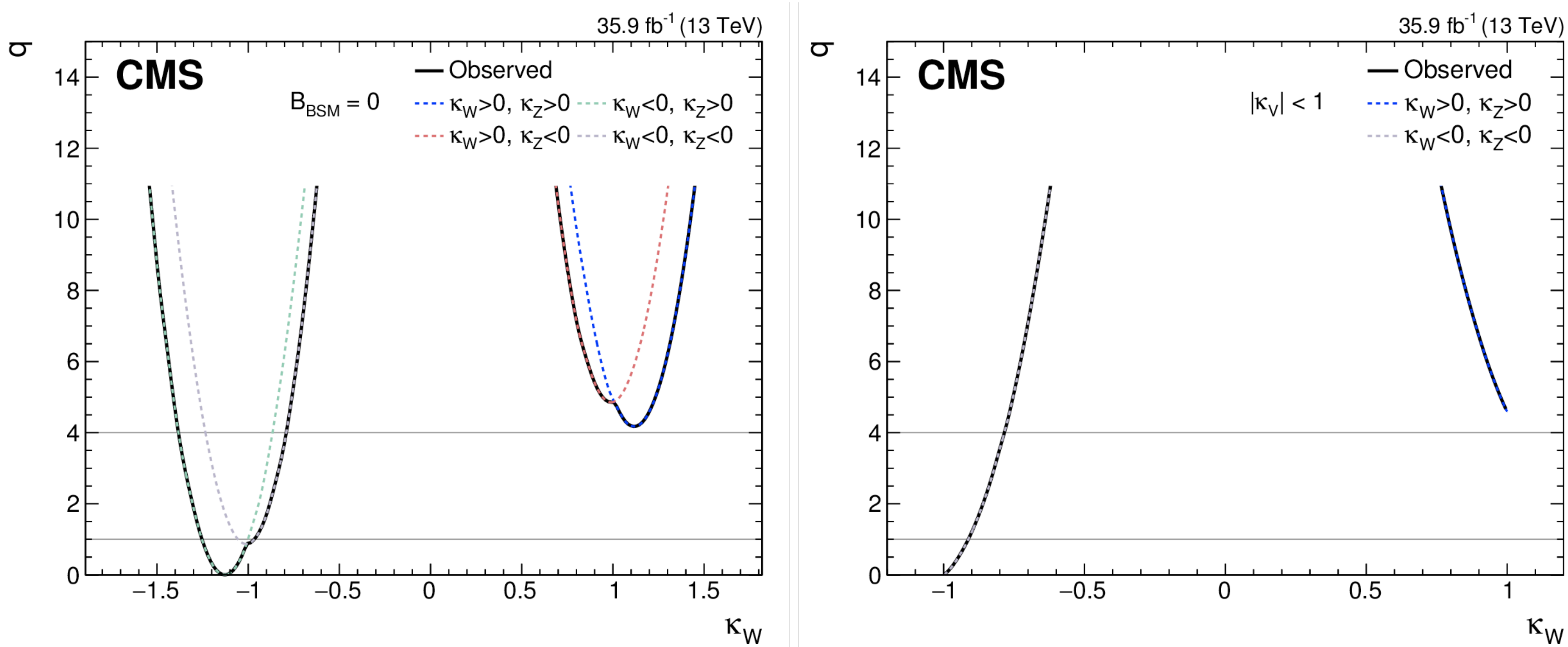
- Usual suspects:



- Rare processes:



Couplings: Relative Sign of κ_t and κ_W

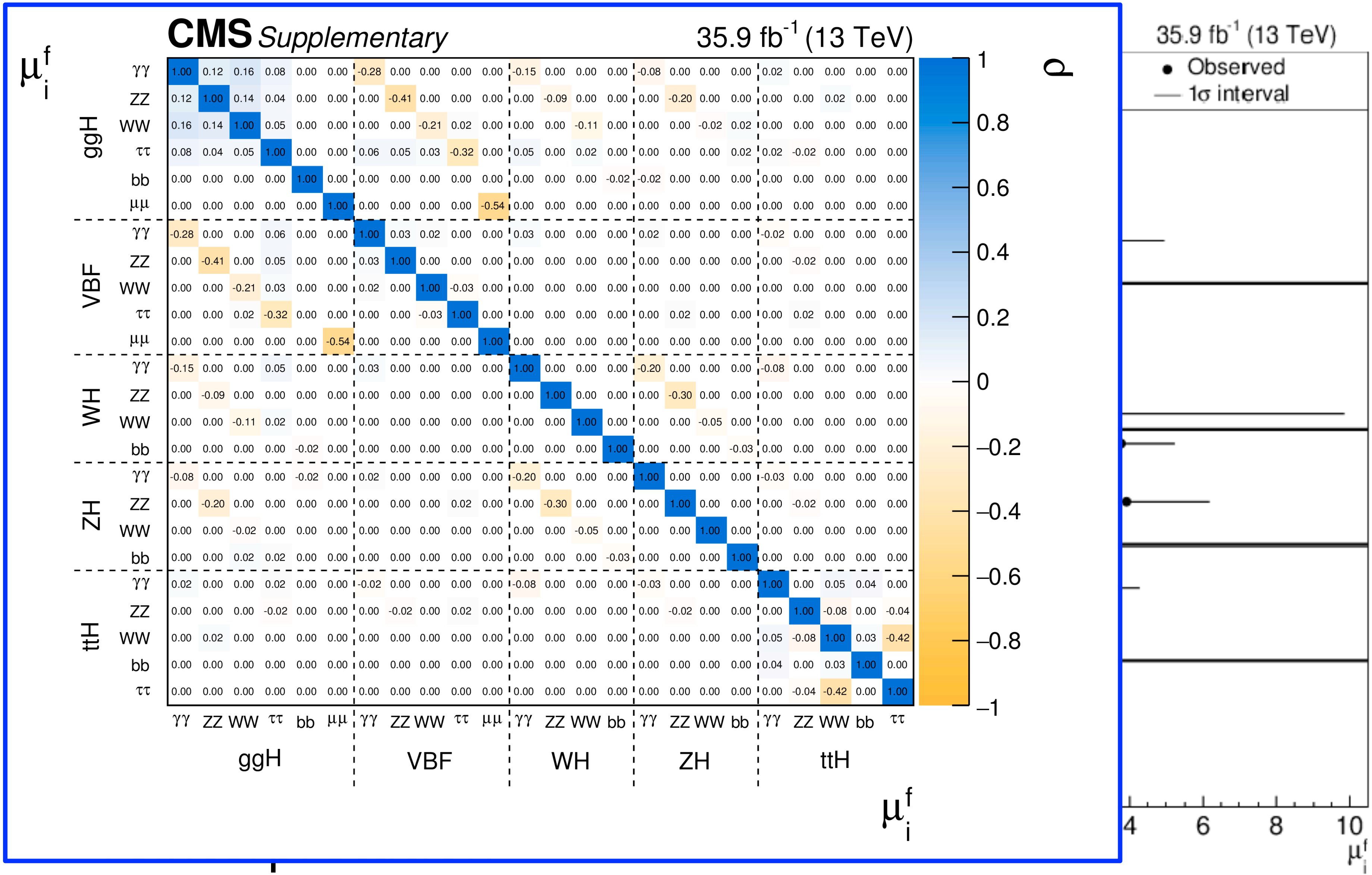


- Mild preference (~2σ) for $\kappa_t \kappa_W < 0$, which enhances tH prod.
- Driven by excess in ttH categories of H->γγanalysis

Compatibility of the fit results with SM

Parameterization	p-value (q_{SM})	DOF	Parameters of interest
Global signal strength	6.28% (3.46)	1	μ
Production processes	9.87% (9.27)	5	$\mu_{ggH}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	53.8% (5.05)	6	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}, \mu^{\mu\mu}$
$\sigma_i \mathcal{B}^f$ products	61.2% (21.5)	24	$\sigma_{ggH}\mathcal{B}^{bb}$, $\sigma_{ggH}\mathcal{B}^{\tau\tau}$, $\sigma_{ggH}\mathcal{B}^{\mu\mu}$, $\sigma_{ggH}\mathcal{B}^{WW}$, $\sigma_{ggH}\mathcal{B}^{ZZ}$, $\sigma_{ggH}\mathcal{B}^{\gamma\gamma}$, $\sigma_{VBF}\mathcal{B}^{\tau\tau}$, $\sigma_{VBF}\mathcal{B}^{\mu\mu}$, $\sigma_{VBF}\mathcal{B}^{WW}$, $\sigma_{VBF}\mathcal{B}^{ZZ}$, $\sigma_{VBF}\mathcal{B}^{\gamma\gamma}$, $\sigma_{WH}\mathcal{B}^{bb}$, $\sigma_{WH}\mathcal{B}^{WW}$, $\sigma_{WH}\mathcal{B}^{ZZ}$, $\sigma_{WH}\mathcal{B}^{\gamma\gamma}$, $\sigma_{ZH}\mathcal{B}^{bb}$, $\sigma_{ZH}\mathcal{B}^{WW}$, $\sigma_{ZH}\mathcal{B}^{ZZ}$, $\sigma_{ZH}\mathcal{B}^{\gamma\gamma}$, $\sigma_{ttH}\mathcal{B}^{\tau\tau}$, $\sigma_{ttH}\mathcal{B}^{WW}$, $\sigma_{ttH}\mathcal{B}^{ZZ}$, $\sigma_{ttH}\mathcal{B}^{\gamma\gamma}$, $\sigma_{ttH}\mathcal{B}^{bb}$
Ratios of σ and $\mathcal{B}$ relative to $gg \to H \to ZZ$	32.3% (11.5)	10	μ^{ZZ}_{ggH}, μ_{VBF}/μ_{ggH}, μ_{WH}/μ_{ggH}, μ_{ZH}/μ_{ggH}, μ_{ttH}/μ_{ggH}, μ^{WW}/μ^{ZZ}, $\mu^{\gamma\gamma}/\mu^{ZZ}$, $\mu^{\tau\tau}/\mu^{ZZ}$, μ^{bb}/μ^{ZZ}, $\mu^{bb}/\mu^{\mu\mu}$
Simplified template cross sections with branching fractions relative to $\mathcal{B}^{ZZ}$	21.2% (14.4)	11	$\sigma_{ggH}\mathcal{B}^{ZZ}$, $\sigma_{VBF}\mathcal{B}^{ZZ}$, $\sigma_{H+V(qq)}\mathcal{B}^{ZZ}$, $\sigma_{H+W(\ell\nu)}\mathcal{B}^{ZZ}$, $\sigma_{H+Z(\ell\ell/\nu\nu)}\mathcal{B}^{ZZ}$, $\sigma_{ttH}\mathcal{B}^{ZZ}$, $\mathcal{B}^{bb}/\mathcal{B}^{ZZ}$, $\mathcal{B}^{\tau\tau}/\mathcal{B}^{ZZ}$, $\mathcal{B}^{\mu\mu}/\mathcal{B}^{ZZ}$, $\mathcal{B}^{WW}/\mathcal{B}^{ZZ}$, $\mathcal{B}^{\gamma\gamma}/\mathcal{B}^{ZZ}$
Couplings, SM loops	45.6% (5.71)	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings vs. mass	16.8% (3.57)	2	M, ϵ
Couplings, BSM loops	18.5% (11.3)	8	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu, \kappa_\gamma, \kappa_g$
Couplings, BSM loops and decays including $H \to$ invisible channels	32.4% (11.5)	10	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu, \kappa_\gamma, \kappa_g, \mathcal{B}_{inv}, \mathcal{B}_{undet}$
Ratios of coupling modifiers	18.1% (11.4)	8	$\kappa_{gZ}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{tg}, \lambda_{bZ}, \lambda_{\tau Z}, \lambda_{\mu Z}, \lambda_{Zg}$
Fermion and vector couplings	16.9% (3.55)	2	κ_F, κ_V
Fermion and vector couplings, per decay mode	76.7% (8.2)	12	$\kappa_F^{bb}, \kappa_F^{\tau\tau}, \kappa_F^{\mu\mu}, \kappa_F^{WW}, \kappa_F^{ZZ}, \kappa_F^{\gamma\gamma}, \kappa_V^{bb}, \kappa_V^{\tau\tau}, \kappa_V^{\mu\mu}, \kappa_V^{WW}, \kappa_V^{ZZ}, \kappa_V^{\gamma\gamma}$
Up vs. down-type couplings	25.5% (4.06)	3	$\lambda_{Vu}, \lambda_{du}, \kappa_{uu}$
Lepton vs. quark couplings	27.2% (3.91)	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$

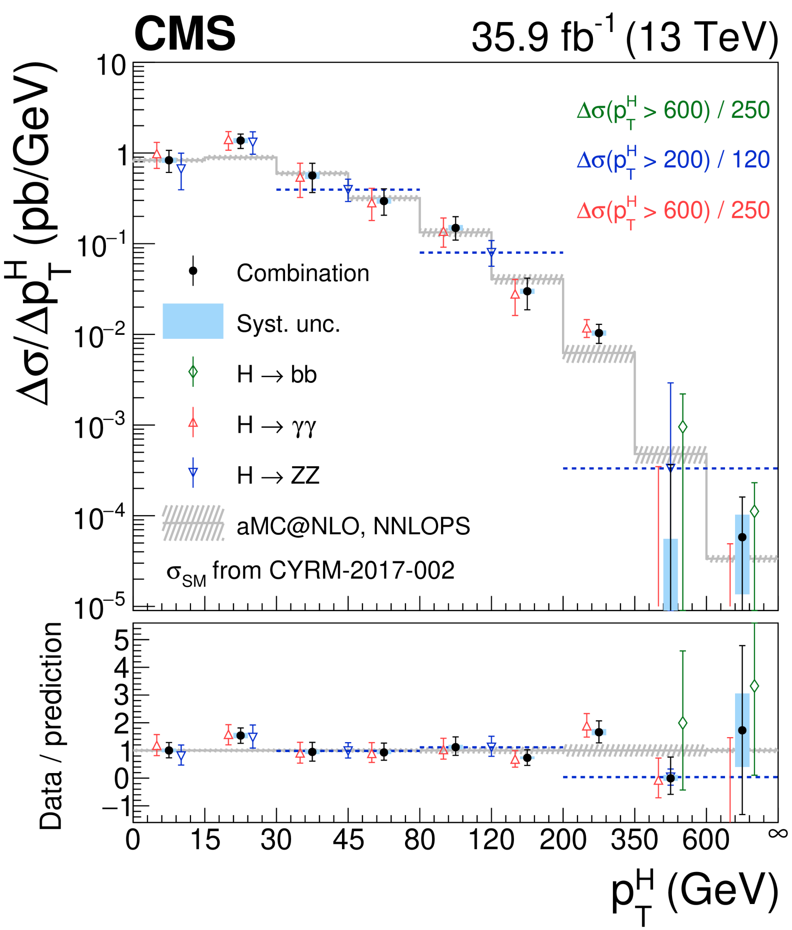
Per Production x Decay Mode

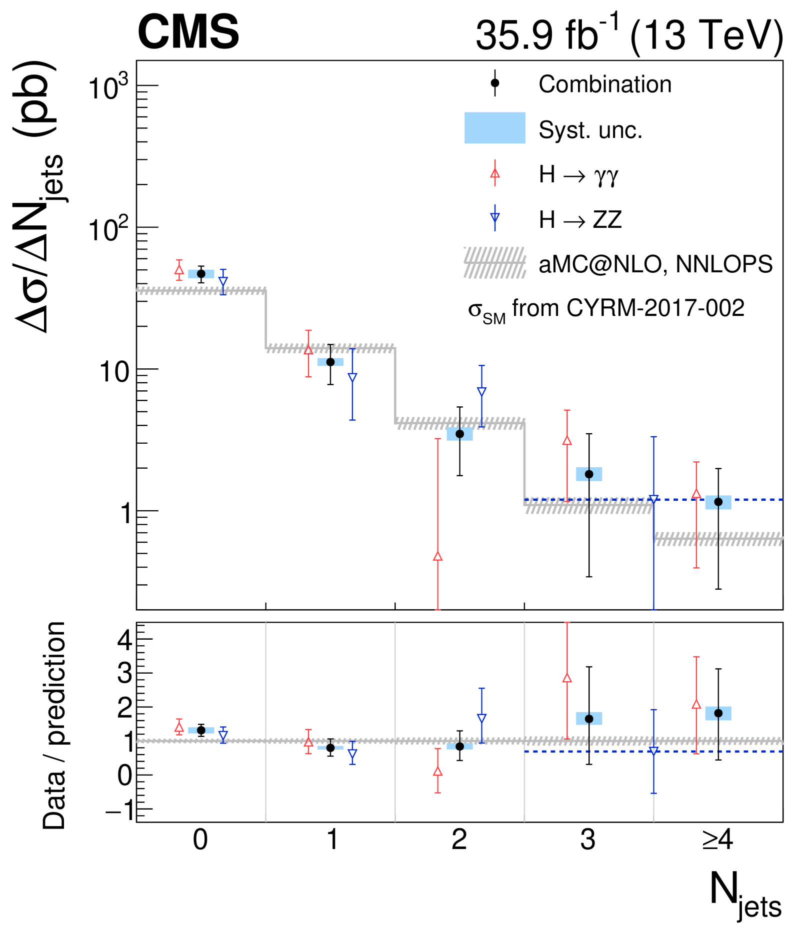


Coupling from differential cross sections

- Combined differential cross sections using H->γγ, H4l and boosted H->bb

arXiv:1812.06504

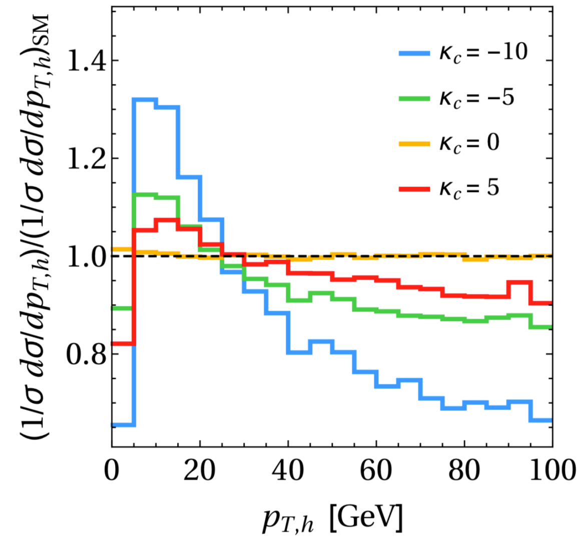


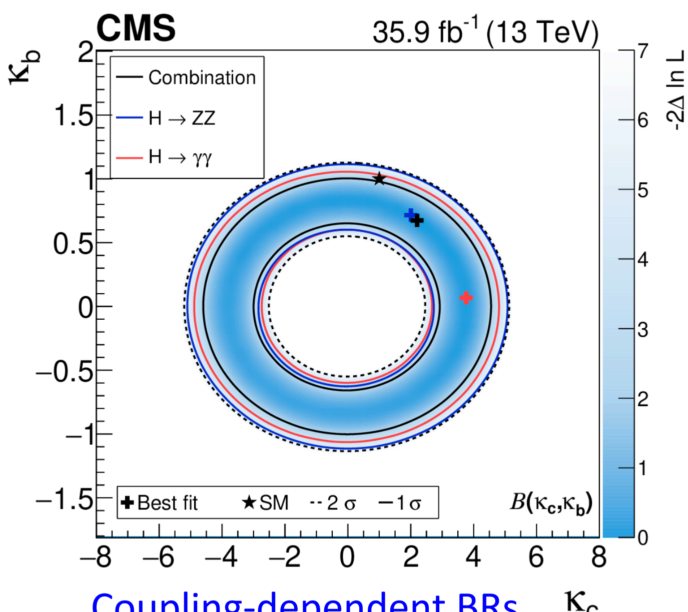


Coupling from differential cross sections

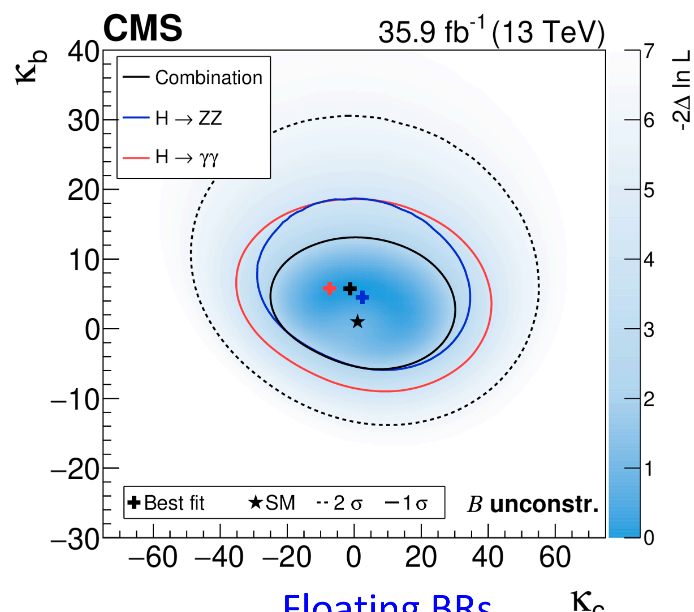
- Higgs pT distribution is sensitive to couplings, in particular, low pT region sensitive to k_b-k_c deviations

arXiv:1606.09253





Coupling-dependent BRs
assuming no Binv, resolved loops

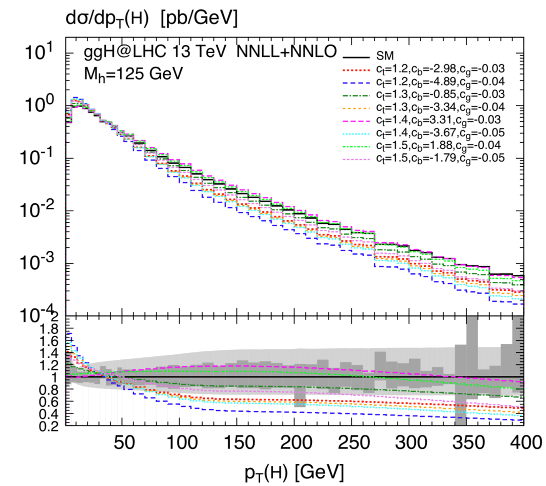


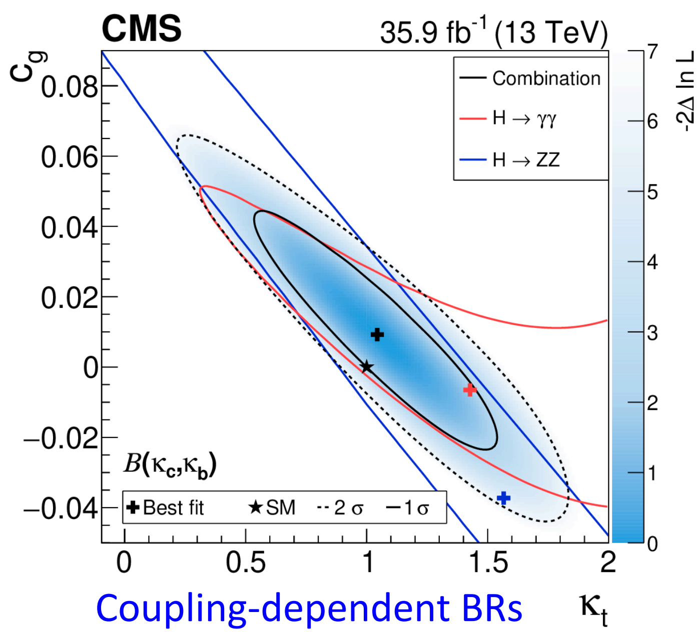
Floating BRs
i.e. constraint from "shape" only

Coupling from differential cross sections

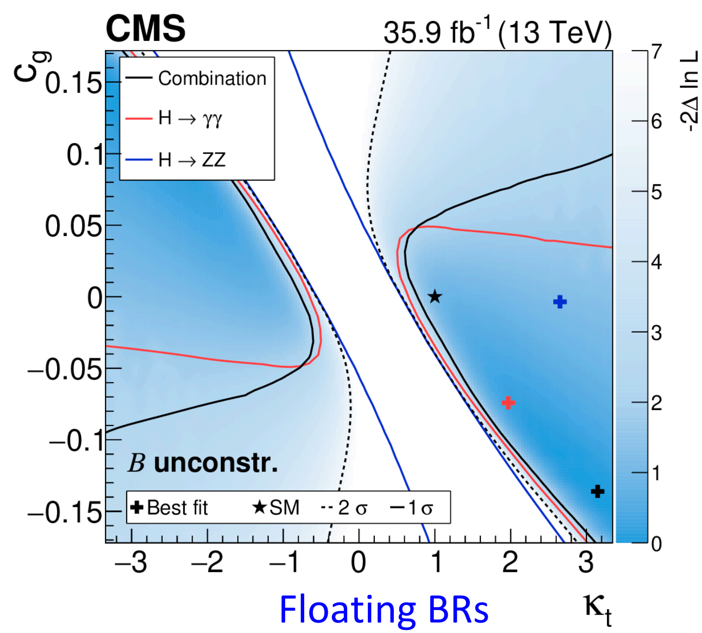
- EFT-based parametrisation in κ_b, κ_t and c_g, where c_g is direct Higgs-gluon coupling in heavy top limit.

arXiv:1705.05143





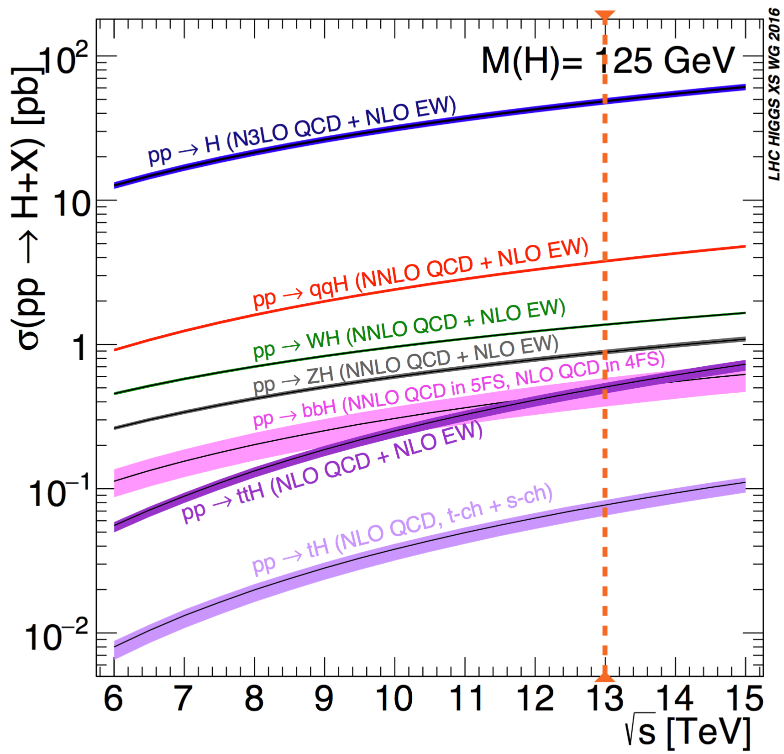
Coupling-dependent BRs
assuming no Binv, resolved loops

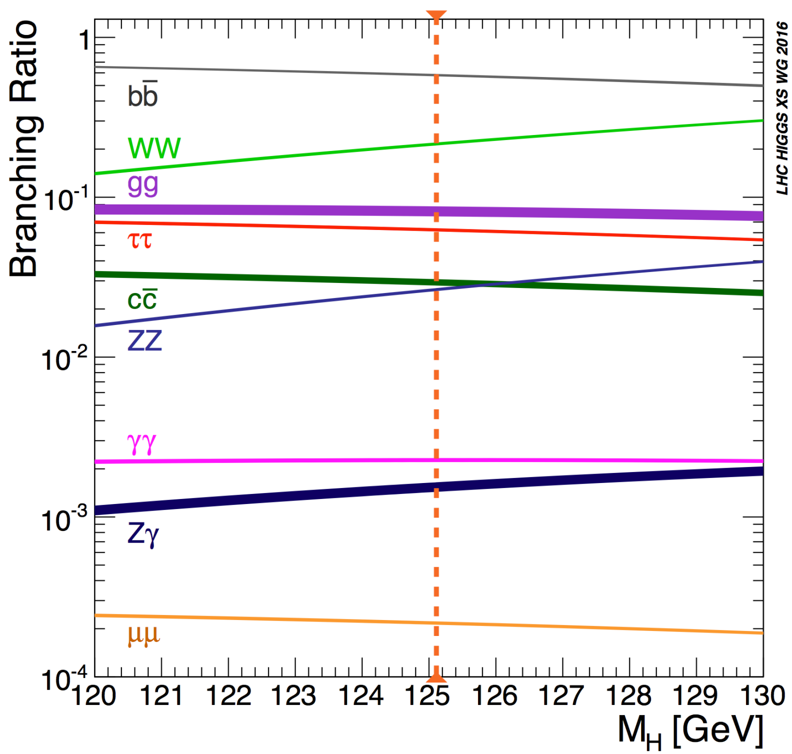


Floating BRs
i.e. constraint from "shape" only

Higgs @ LHC

- Very rich program thanks to m_H~125 GeV





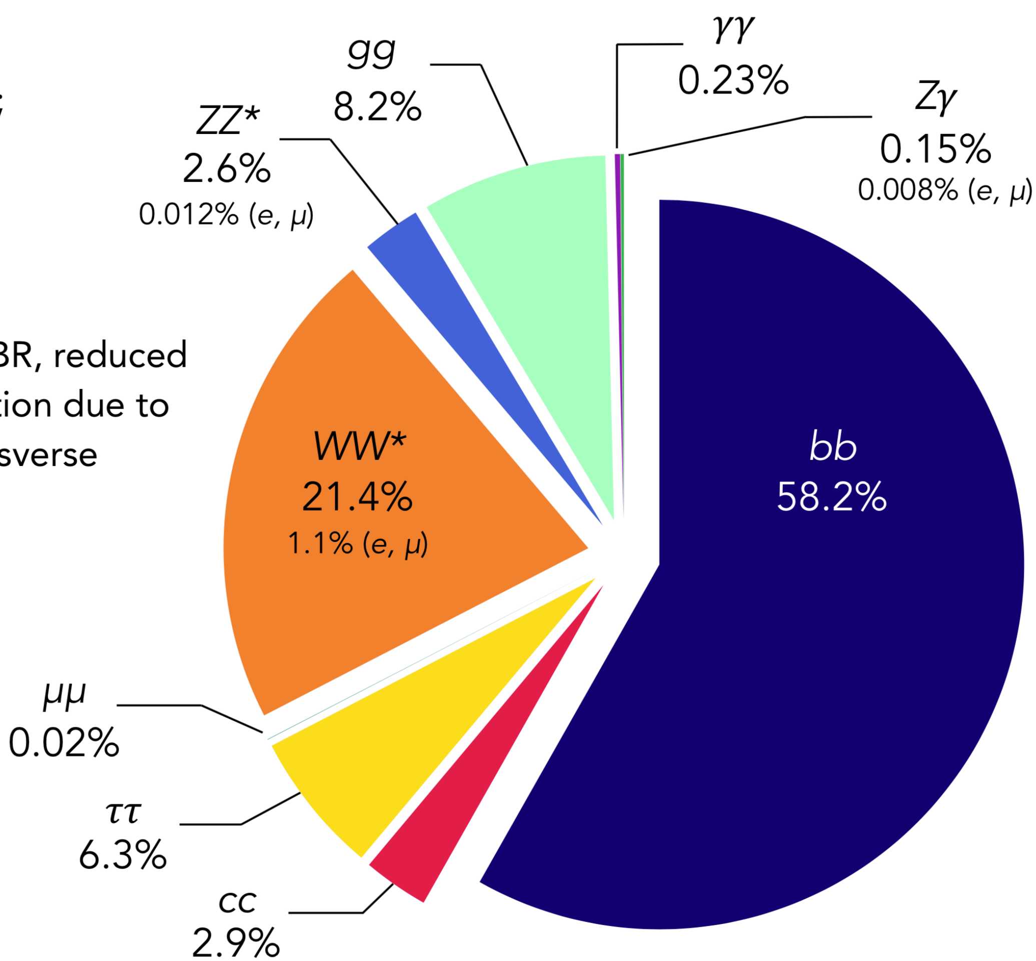
Because couplings affect both Higgs boson production and decay, the best constraints come only from a combined analysis of all accessible channels.

Higgs decay modes

ZZ^*, $\gamma\gamma$: high mass resolution channels; mass and precise differential measurements

WW^*: high BR, reduced mass resolution due to missing transverse energy

μμ: very small BR, access to coupling to 2nd generation fermions



bb, $\tau\tau$: high BR, but low s/b, important to probe Higgs to fermion couplings