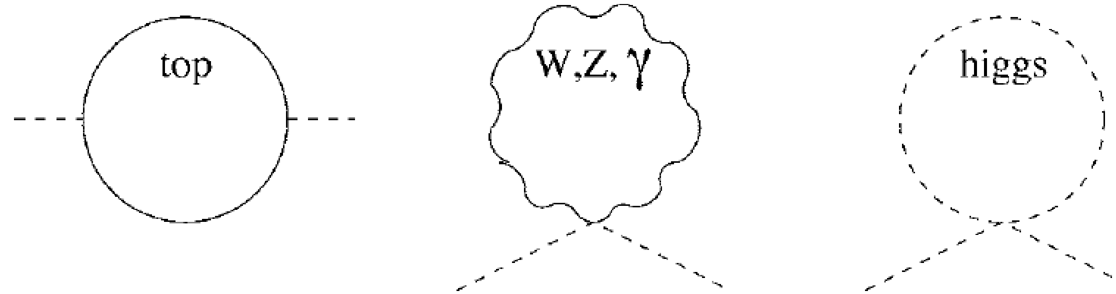
Present and Future of Higgs Couplings Measurements At the LHC in CMS

FNAL Topic of the Week Seminar
30th October 2018

David Sperka (Boston University)

Why Measure the Higgs Couplings?

- The discovery of the 125 GeV Higgs boson was the triumph of Run 1
- The Higgs is special:
  - ➔ First fundamental scalar particle (?)
  - ➔ First example of non-Gauge interactions (?)
- The Higgs sector is the least tested portion of the SM and also the most problematic:
  - ➔ Hierarchy Problem
  - ➔ Flavor Puzzle



$\Lambda_{top} \lesssim 2$ TeV $\quad \Lambda_{gauge} \lesssim 5$ TeV $\quad \Lambda_{Higgs} \lesssim 10$ TeV

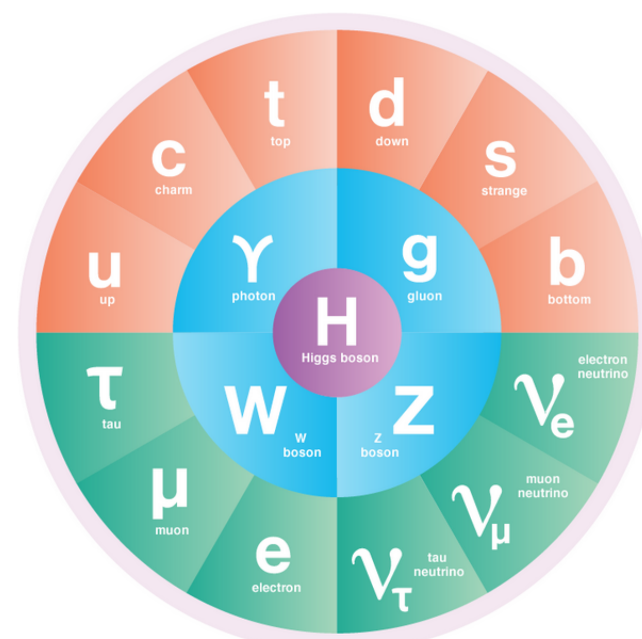
$$y_f^{SM} = \sqrt{2} m_f / v$$

$$y_t^{SM} \approx 0.99$$

$$y_b^{SM} \approx 0.02$$

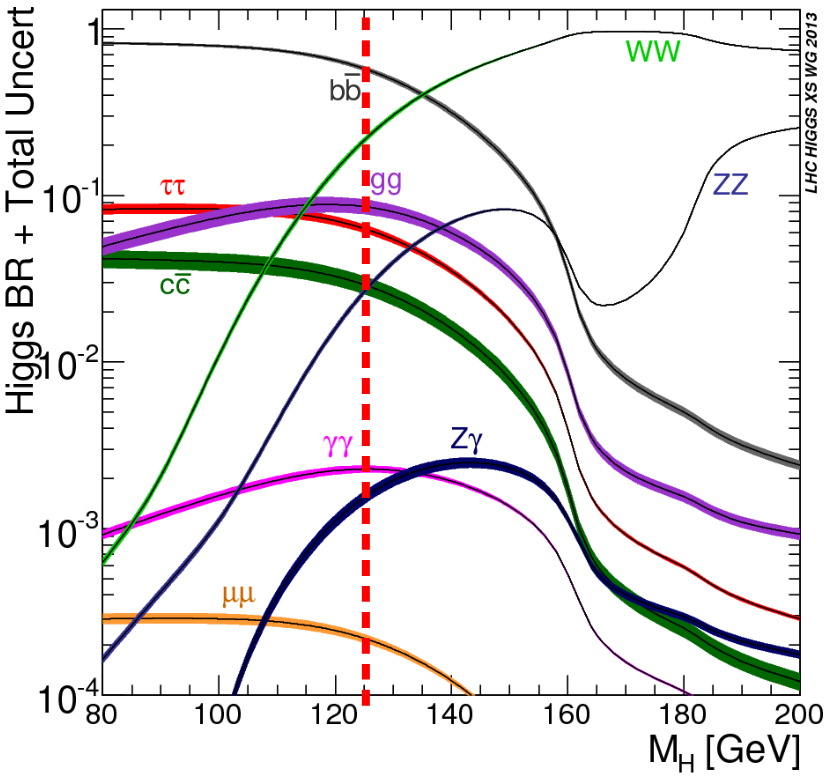
$$y_\tau^{SM} \approx 0.01$$

$$y_\mu^{SM} \approx 0.0006$$



Why measure Higgs couplings?

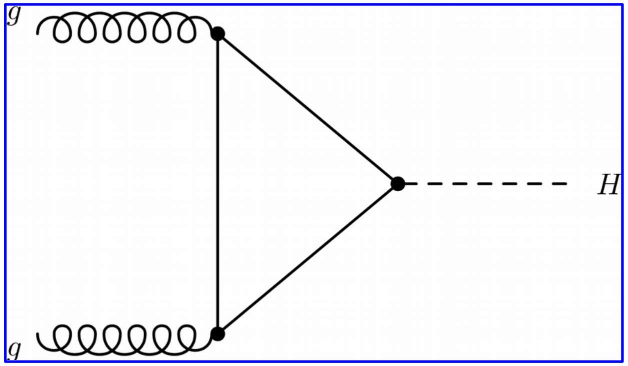
- No direct evidence so far for new physics at the LHC
- Indirect measurements are complementary to searches
- Want to measure couplings to O(1%) level to indirectly test BSM theories
- For observed m(H), (nearly) all couplings are accessible



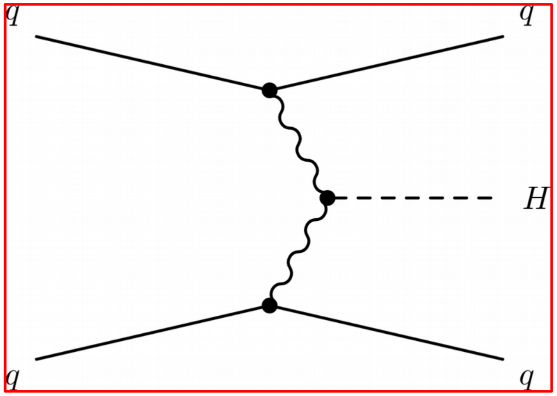
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arxiv:1310.8361

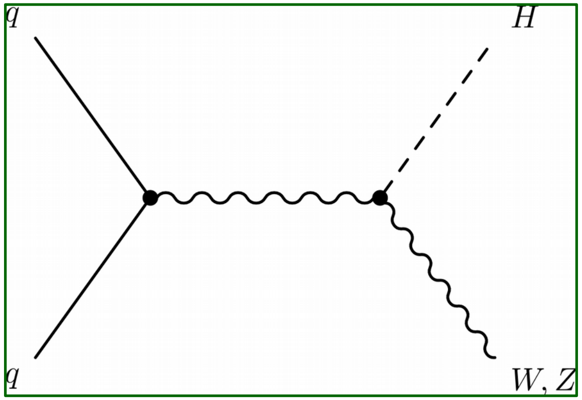
Higgs Production Mechanisms



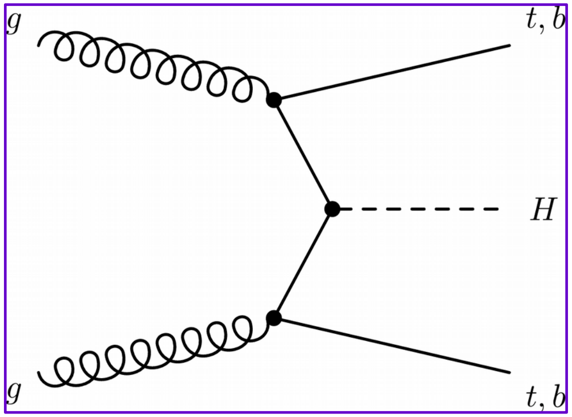
σ(gg→H) = 48.52 pb ±3.9% (th.) ±3.2% (pdf)
(N^3LO QCD + NLO EW)



σ(VBF) = 3.779 pb ±0.4% (th.) ±2.1% (pdf)
(NNLO QCD + NLO EW)



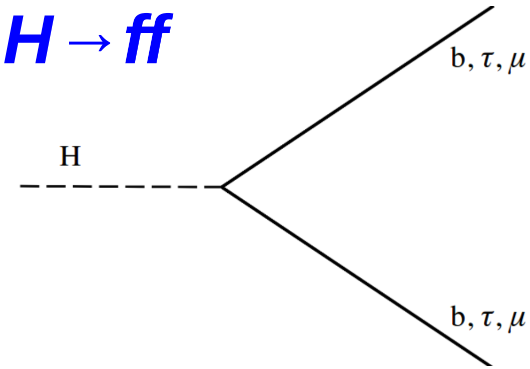
σ(pp→WH) = 1.369 pb ±0.7% (th.) ±1.9% (pdf)
σ(pp→ZH) = 0.8824 pb ±3.8% (th.) ±1.9% (pdf)
(NNLO QCD + NLO EW)



σ(ttH) =0.5065 pb $\pm^{5.8}_{9.2}$% (th.) ±3.6% (pdf)
(NLO QCD + NLO EW)

Higgs Decay Modes

H → ff



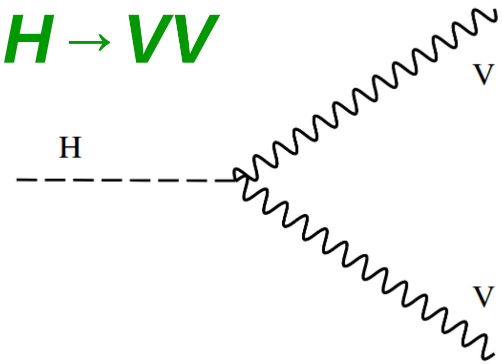
$B(H \rightarrow bb)_{SM} = 0.58$ (largest B, down-type yukawa)

$B(H \rightarrow \tau\tau)_{SM} = 0.06$ (leptonic coupling)

$B(H \rightarrow cc)_{SM} = 0.03$ (second generation yukawa)

$B(H \rightarrow \mu\mu)_{SM} = 0.0002$ (second generation yukawa)

H → VV

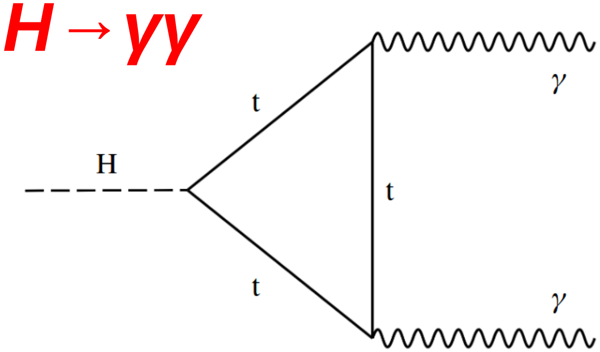


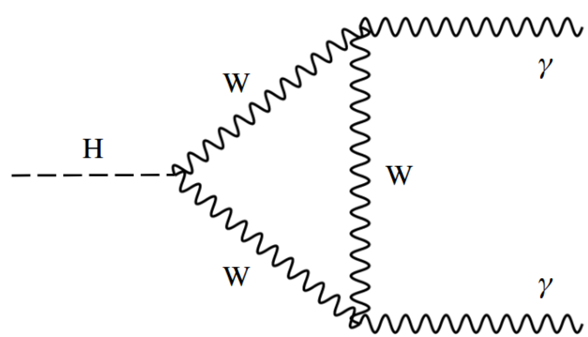
$B(H \rightarrow WW)_{SM} = 0.22$

$B(H \rightarrow ZZ)_{SM} = 0.026$

(HVV couplings, electroweak symmetry breaking)

H → γγ



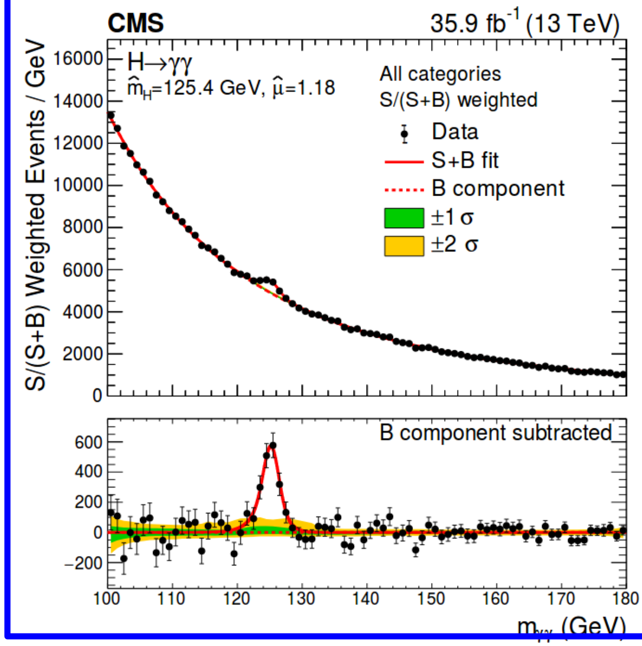


$B(H \rightarrow \gamma\gamma)_{SM} = 0.0023$

(best compromise of resolution and BR, loop induced, sensitive to new physics)

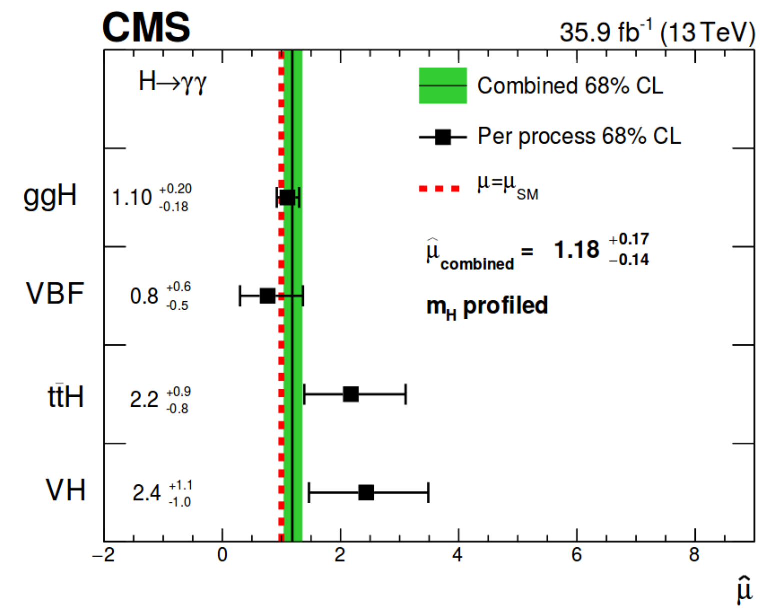
CMS Higgs Measurements with 35.9 fb^{-1} of 13 TeV data

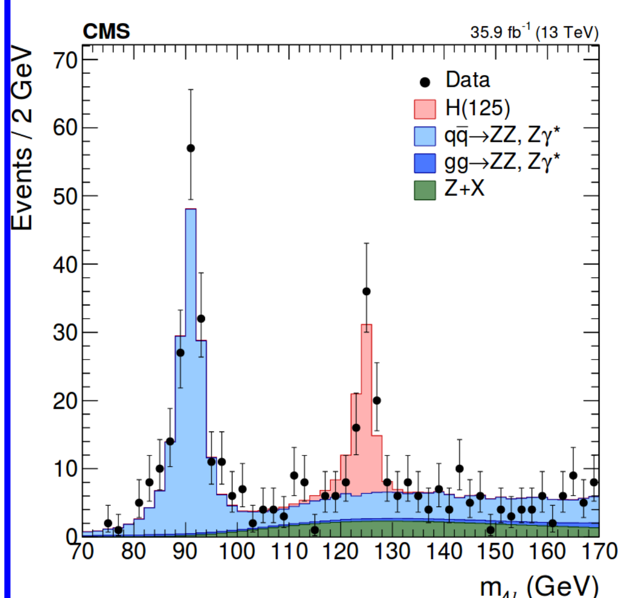
H → γγ, ZZ



arxiv:1804.02716

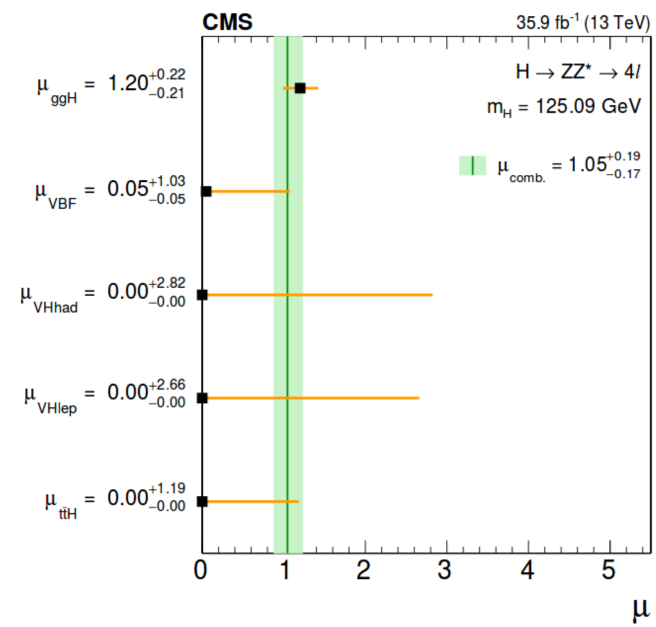
- Fit to $m_{\gamma\gamma}$ distribution
- Sensitive to all production modes
- Main systematics: ggH th. unc. and photon ID eff. and energy scale





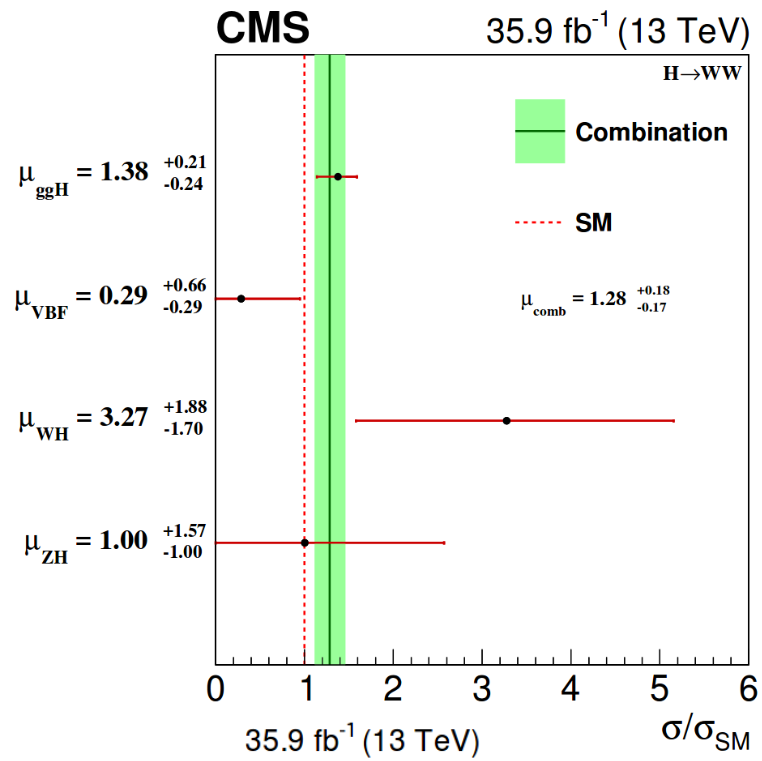
arxiv:1706.09936

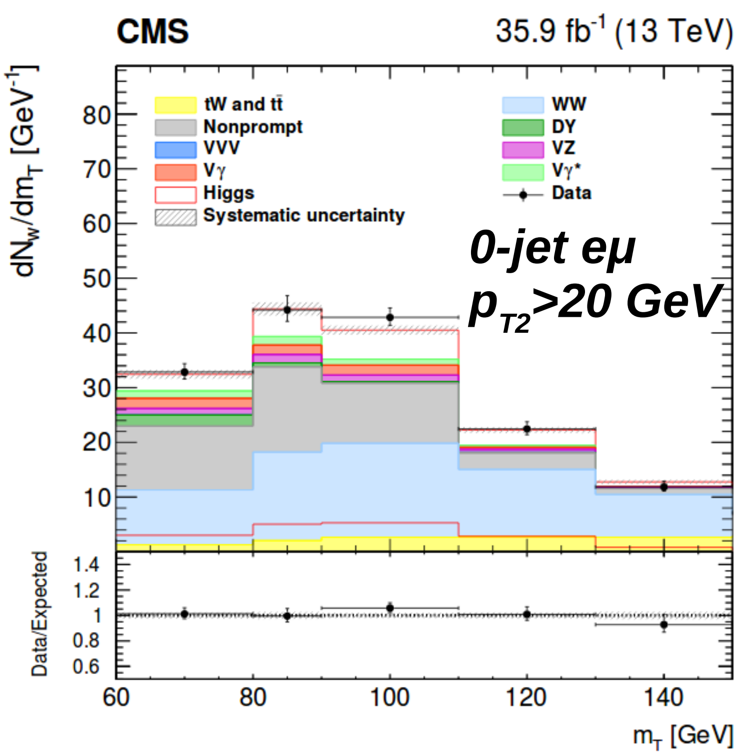
- 2D fit of $m_{4\ell}$ and ME distributions
- Precise measurement of ggH
- Main systematics: ggH th. unc. and lepton ID eff.

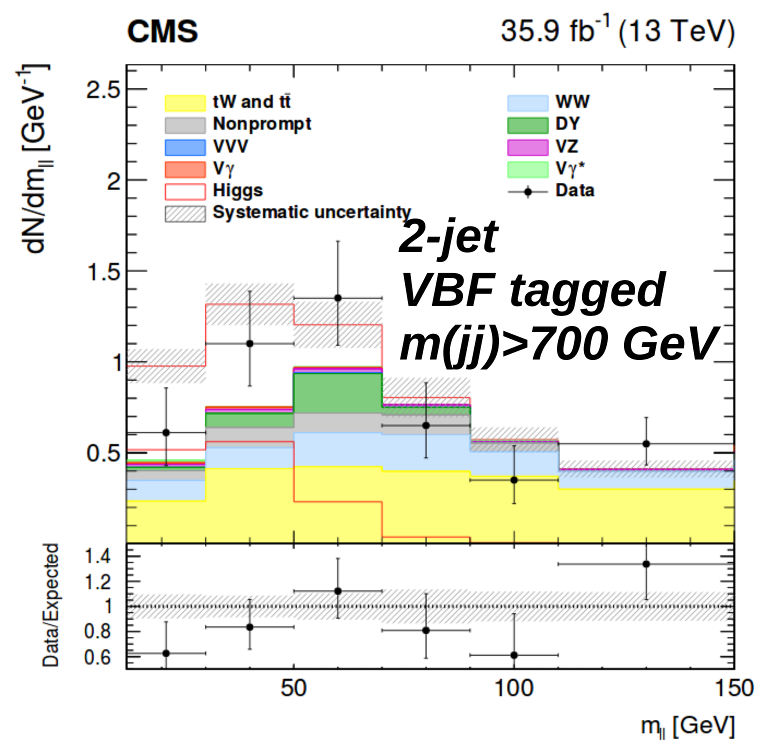


H→WW *arxiv:1806.05246*

- Total of 30 signal regions target ggH, VBF, WH, and ZH production modes
- Signal extracted from different sensitive observables depending on the category
- Main systematics: bkg. estimation, th. unc. on signal norm. and migration

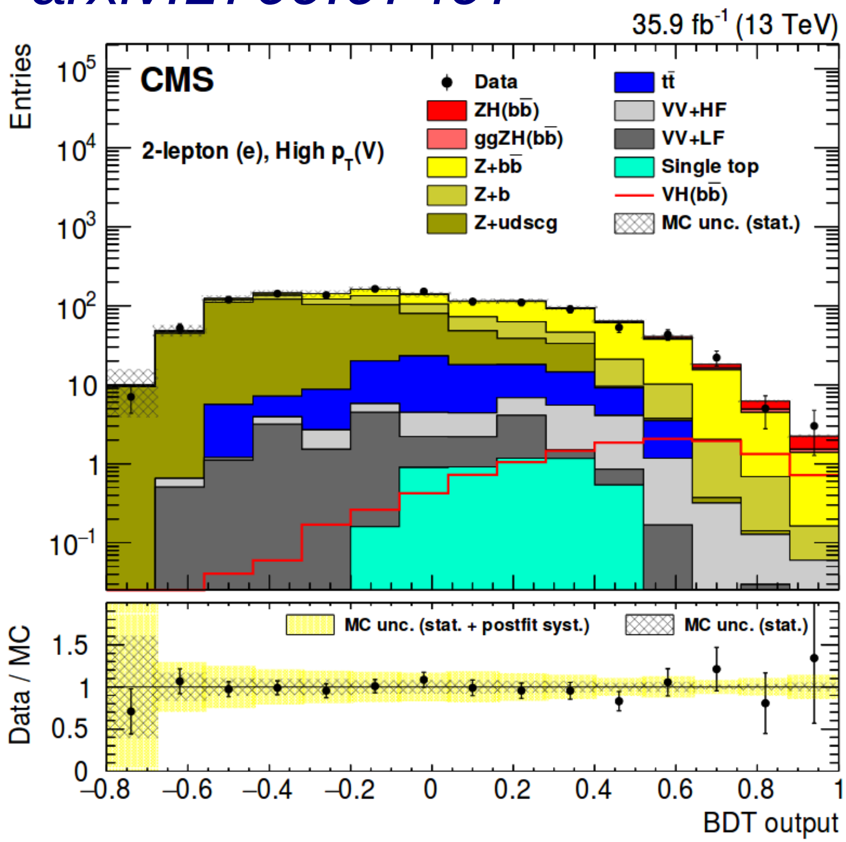






VH(bb), ggH(bb)

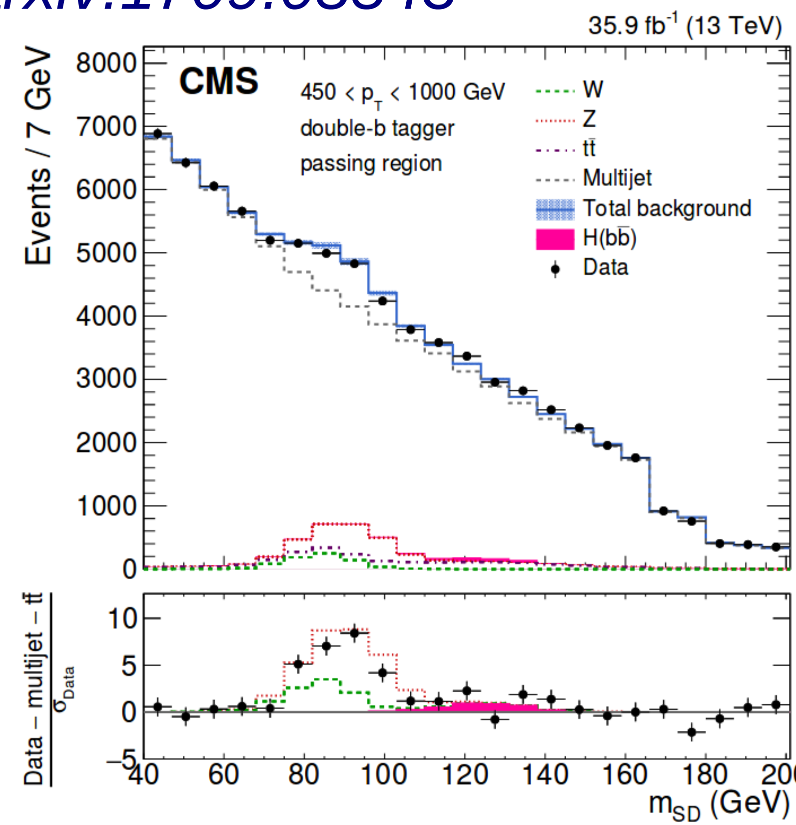
arxiv:1709.07497



- 0, 1, 2 lepton categories particularly sensitive to high $p_T(V)$ phase space
- Main systematics: bkg. norm and modeling, MC stats, b-tag eff.

$$\mu = 1.2 \pm 0.4$$

arxiv:1709.05543

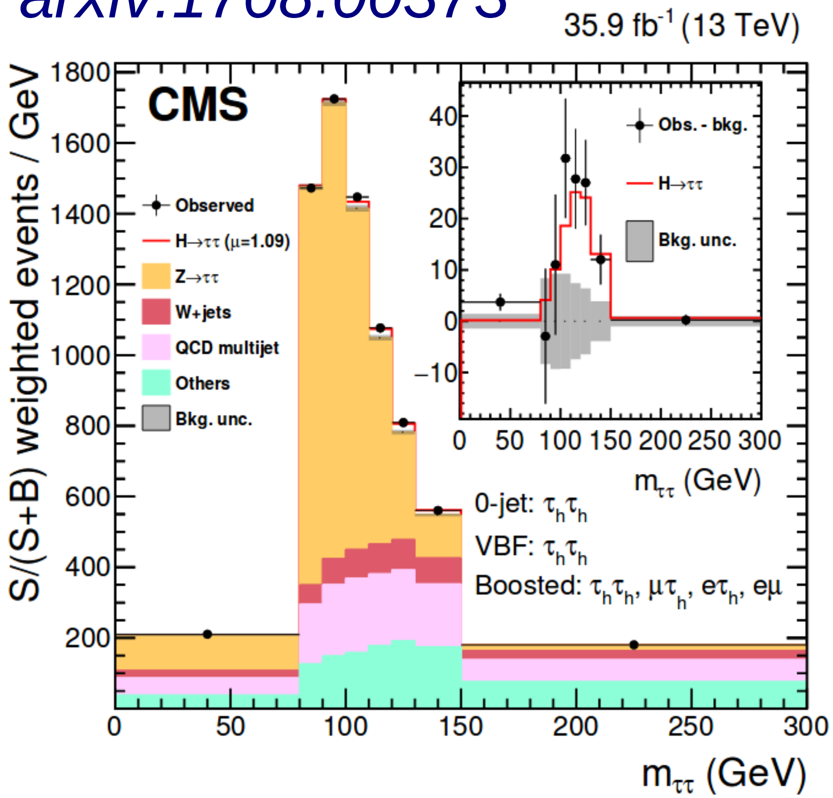


- Look for single boosted jet with p_T > 450 GeV, using substructure
- Dominant QCD background estimated from data

$$\mu_H = 2.3 \pm 1.5\,(\mathrm{stat})^{+1.0}_{-0.4}\,(\mathrm{syst})$$

H → ττ, μμ

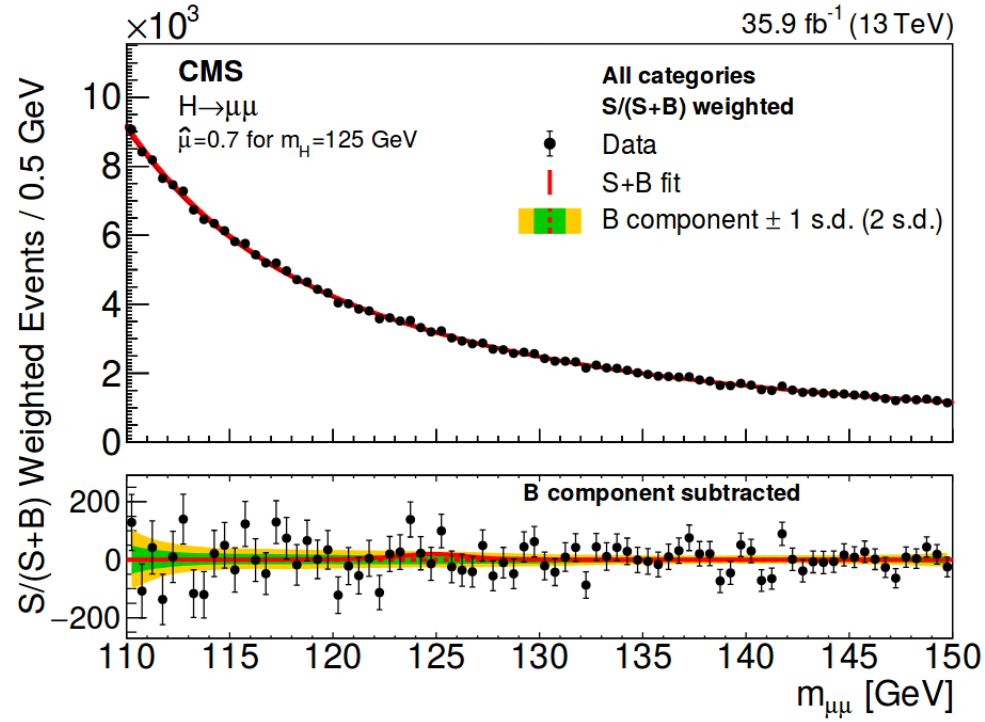
arxiv:1708.00373



- 0 jet, boosted, and VBF cats. to measure ggH and VBF
- Main sys τ_h and p_T(miss) scales, bkg. norm., ggH th. unc. on norm. and migration

$$\hat{\mu} = 1.09^{+0.27}_{-0.26}$$

arxiv:1807.06325



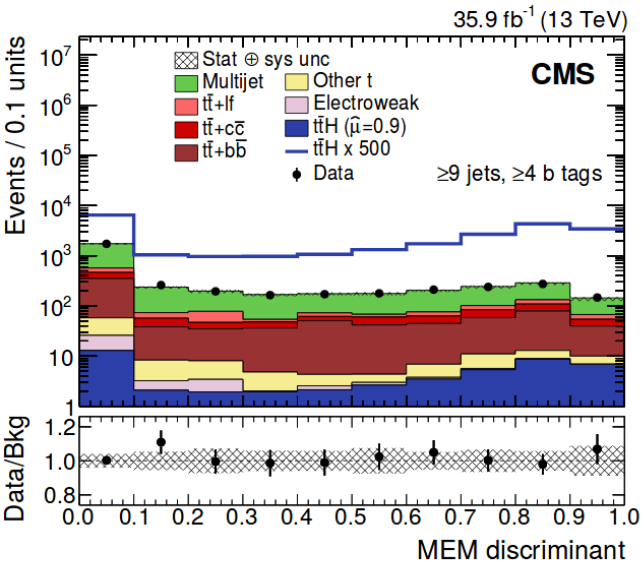
- 15 event categories based on mass resolution and expected signal and background comp.
- Extract signal from fit to $m_{\mu\mu}$ distribution

$$\mu = 0.7 \pm 1.0$$

ttH(bb), ttH(multilepton)

ttH(bb), 0ℓ

arxiv:1803.06986

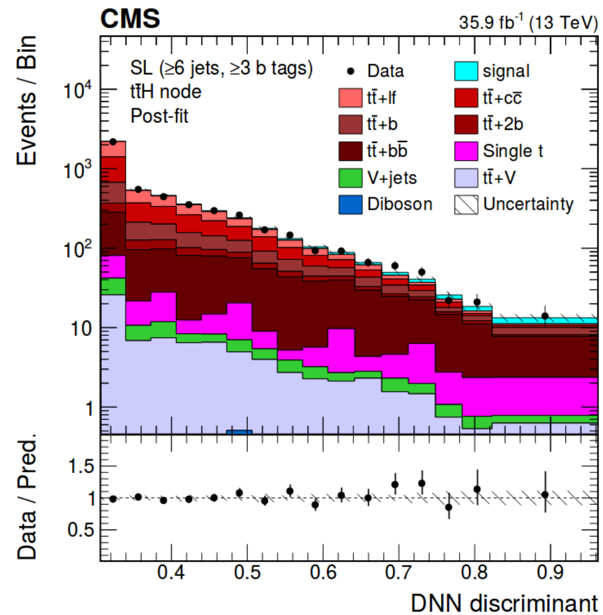


- Large QCD multijet background, mitigated with quark-gluon discrimination
- Signal extracted with multivariate discr.

$$\hat{\mu} = 0.9 \;{}^{+1.5}_{-1.5} \left({}^{+0.7}_{-0.7} \;\; {}^{+1.3}_{-1.3} \right)$$

ttH(bb), 1ℓ / 2ℓ

arxiv:1804.03682

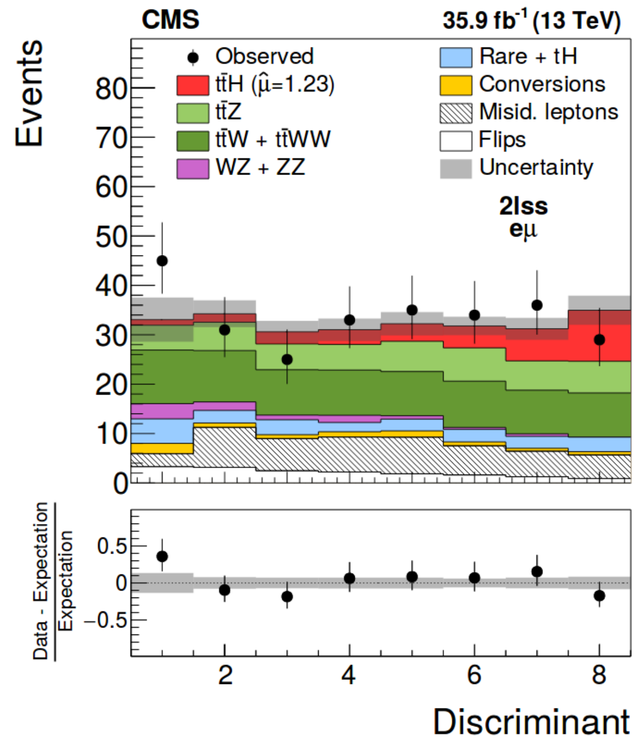


- Signal extracted with multivariate discr.
- Main sys. B-tag eff. MC stats, tt+HF model

$$\hat{\mu} = 0.72 \;{}^{+0.45}_{-0.45} \;\; {}^{+0.24}_{-0.24} \;\; {}^{+0.38}_{-0.38}$$

ttH, 2ℓss / 3ℓ / 4ℓ

arxiv:1803.05485

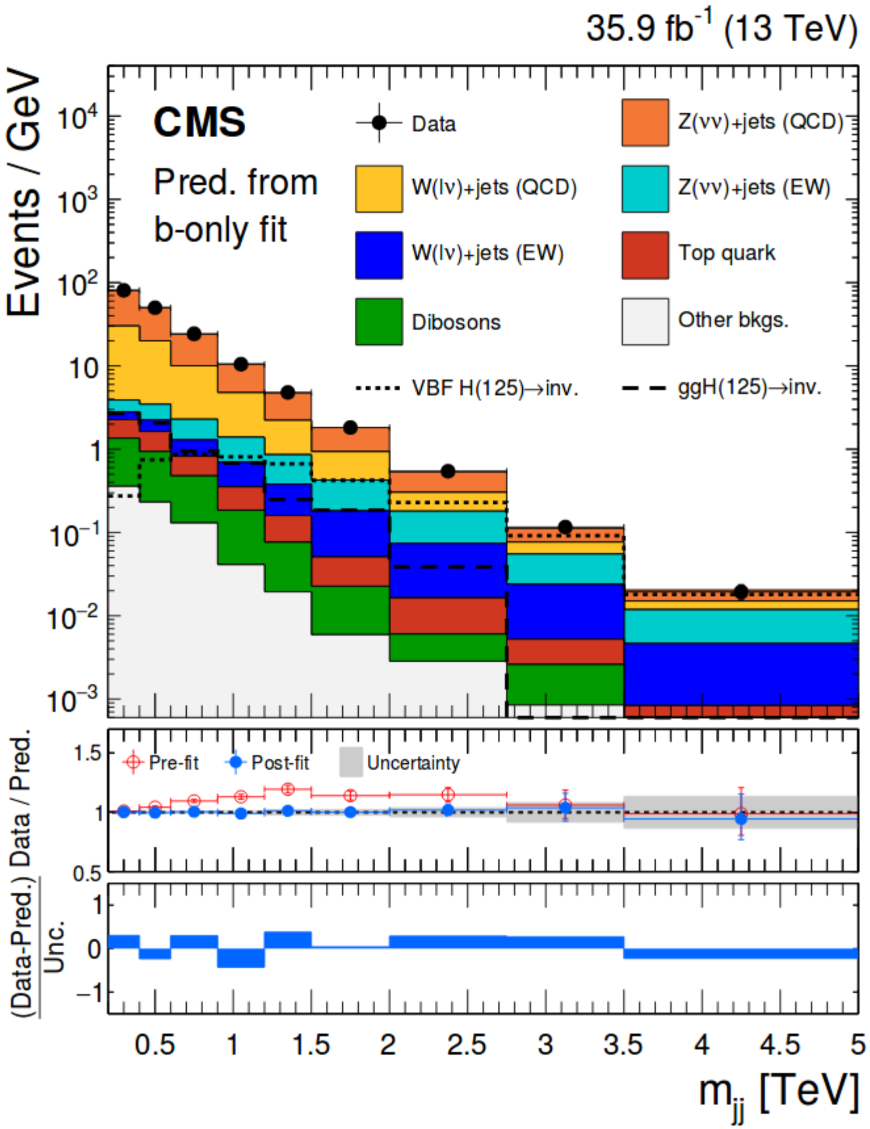


- Signal extracted with multivariate discr.
- Main sys. lepton ID eff., irr. bkg. norms

$$\mu = \mathbf{1.23} \;{}^{\mathbf{+0.45}}_{\mathbf{-0.43}} \left[{}^{+0.26}_{-0.25}(\text{stat.}) \;\; {}^{+0.37}_{-0.35}(\text{syst.}) \right]$$

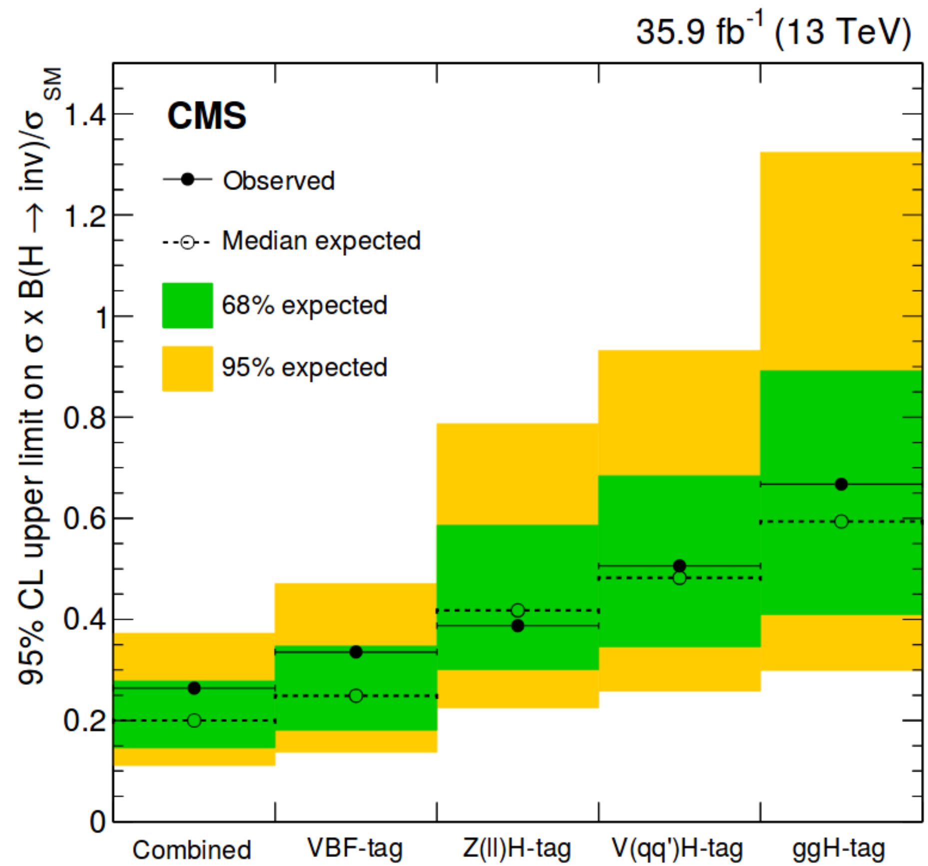
H → Invisible

arxiv:1809.05937



$$\mathcal{B}(\mathrm{H} \to \mathrm{inv}) < 0.26\,(0.20)$$

- Direct search for invisible decays of the 125 GeV Higgs included in the combination
- 4 production mode categories, VBF channel has the best sensitivity
- Combined assuming SM production cross sections



The “Grand Combination”

The "Grand Combination"

arxiv:1809.10733

Combined measurements of Higgs boson couplings in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration

(Submitted on 27 Sep 2018)

Combined measurements of the production and decay rates of the Higgs boson, as well as its couplings to vector bosons and fermions, are presented. The analysis uses the LHC proton-proton collision data set recorded with the CMS detector in 2016 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. The combination is based on analyses targeting the five main Higgs boson production mechanisms (gluon fusion, vector boson fusion, and associated production with a W or Z boson, or a top quark-antiquark pair) and the following decay modes: H→ $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, and $\mu\mu$. Searches for invisible Higgs boson decays are also considered. The best-fit ratio of the signal yield to the standard model expectation is measured to be $\mu = 1.17 \pm 0.10$, assuming a Higgs boson mass of 125.09 GeV. Additional results are given for parametrizations with varying assumptions on the scaling behavior of the different production and decay modes, including generic ones based on ratios of cross sections and branching fractions or coupling modifiers. The results are compatible with the standard model predictions in all parametrizations considered. In addition, constraints are placed on various two Higgs doublet models.

Comments:	Submitted to EPJC. All figures and tables can be found at this http URL (CMS Public Pages)
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	CMS-HIG-17-031, CERN-EP-2018-263
Cite as:	**arXiv:1809.10733 [hep-ex]**
	(or **arXiv:1809.10733v1 [hep-ex]** for this version)

Submission history

From: The CMS Collaboration [view email]

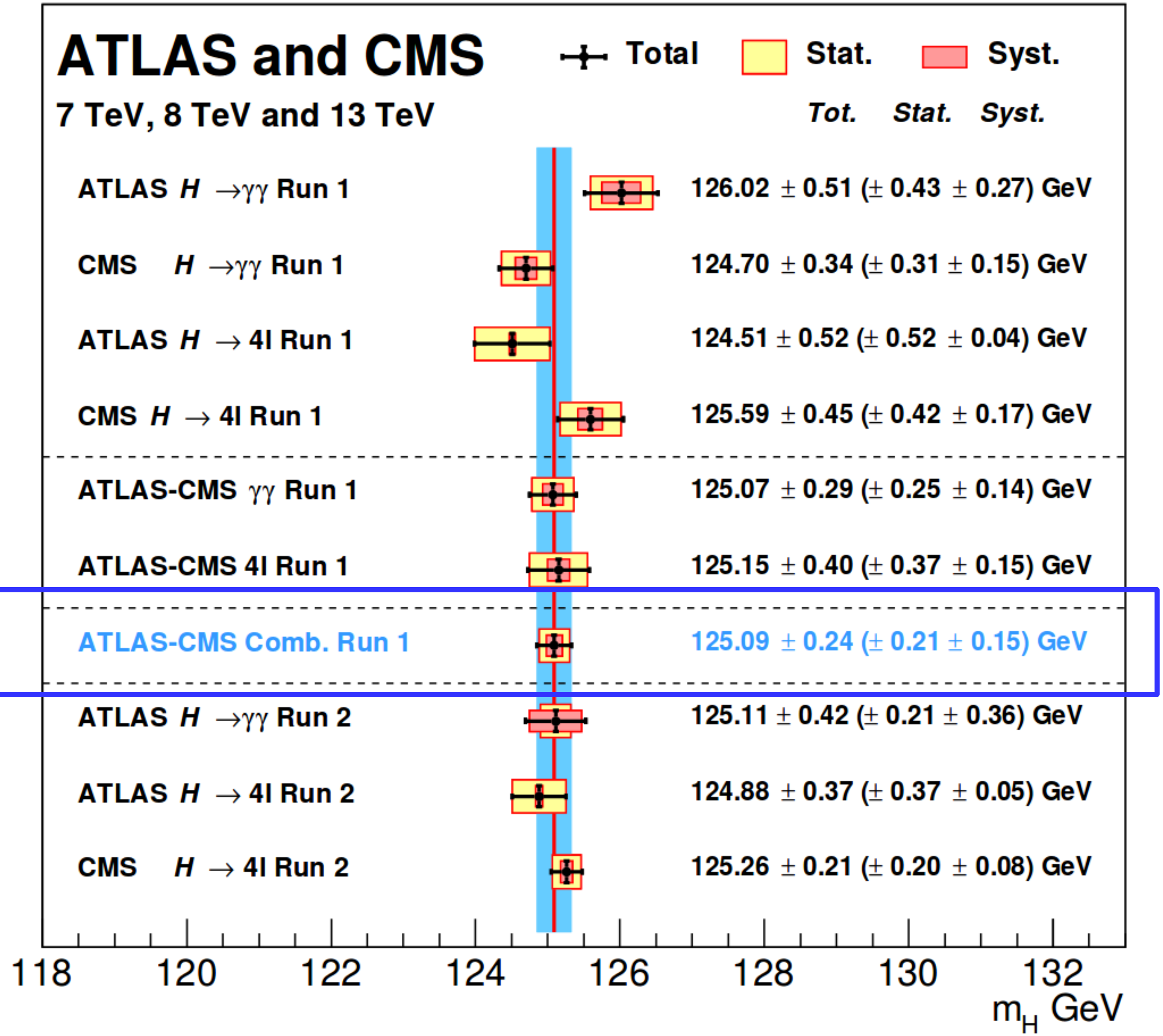
[v1] Thu, 27 Sep 2018 19:28:22 UTC (1,543 KB)

The “Grand Combination”

- In total up to 265 event categories and over 5500 nuisance parameters
- Correlation scheme studied in detail
- Gluon fusion modeling updated in certain analyses (reweight to NNLOPS, 9 parameter unc. scheme) to ensure consistency amongst channels

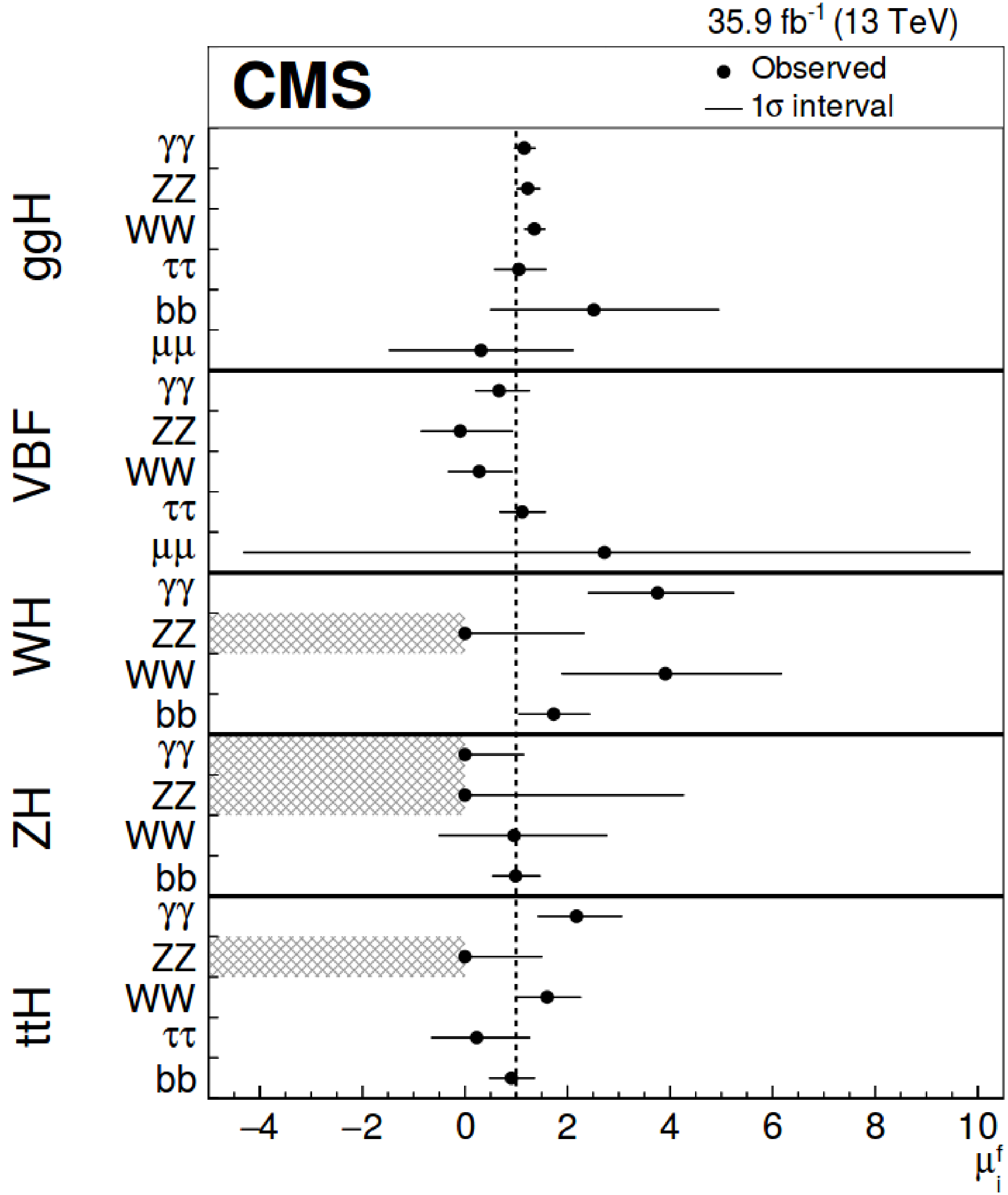
Production and decay tags		Expected signal composition	Number of categories	Mass resolution
$H \to \gamma\gamma$, Section 3.1				
$\gamma\gamma$	Untagged	74–91% ggH	4	≈1–2%
	VBF	51–80% VBF	3	
	VH hadronic	25% WH, 15% ZH	1	
	WH leptonic	64–83% WH	2	
	ZH leptonic	98% ZH	1	
	VH p_T^{miss}	59% VH	1	
	ttH	80–89% ttH, ≈8% tH	2	
$H \to ZZ^{(*)} \to 4\ell$, Section 3.2				
$4\mu, 2e2\mu/2\mu 2e, 4e$	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 + $\geq$ 1 jet	80% ggH, 9% VBF	1	
	VH hadronic	54% VH, 39% ggH	1	
	ZH leptonic	≈100% ZH, of which 21% ggZH	1	

m(H) measurement



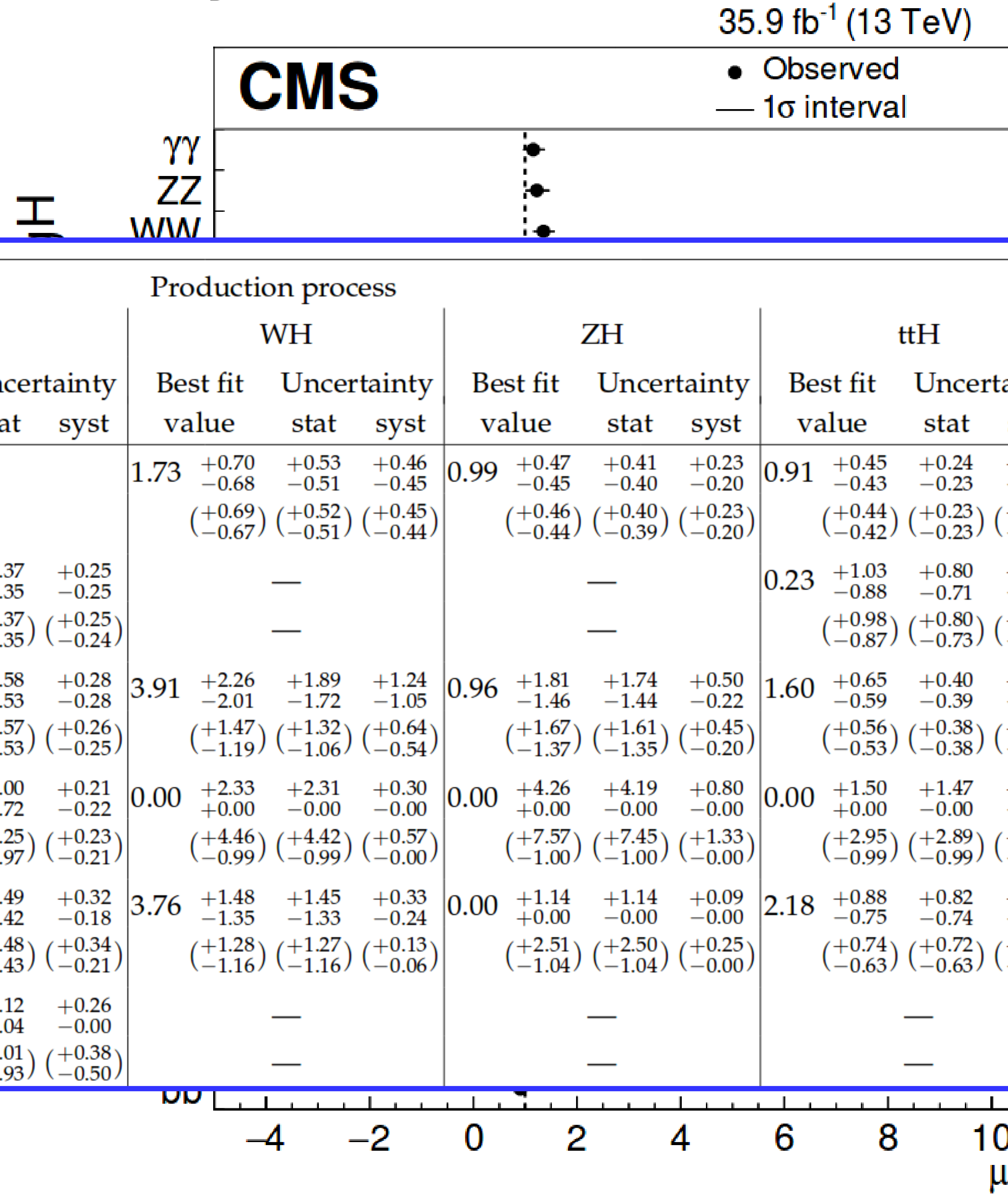
Per Production x Decay Mode

- 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



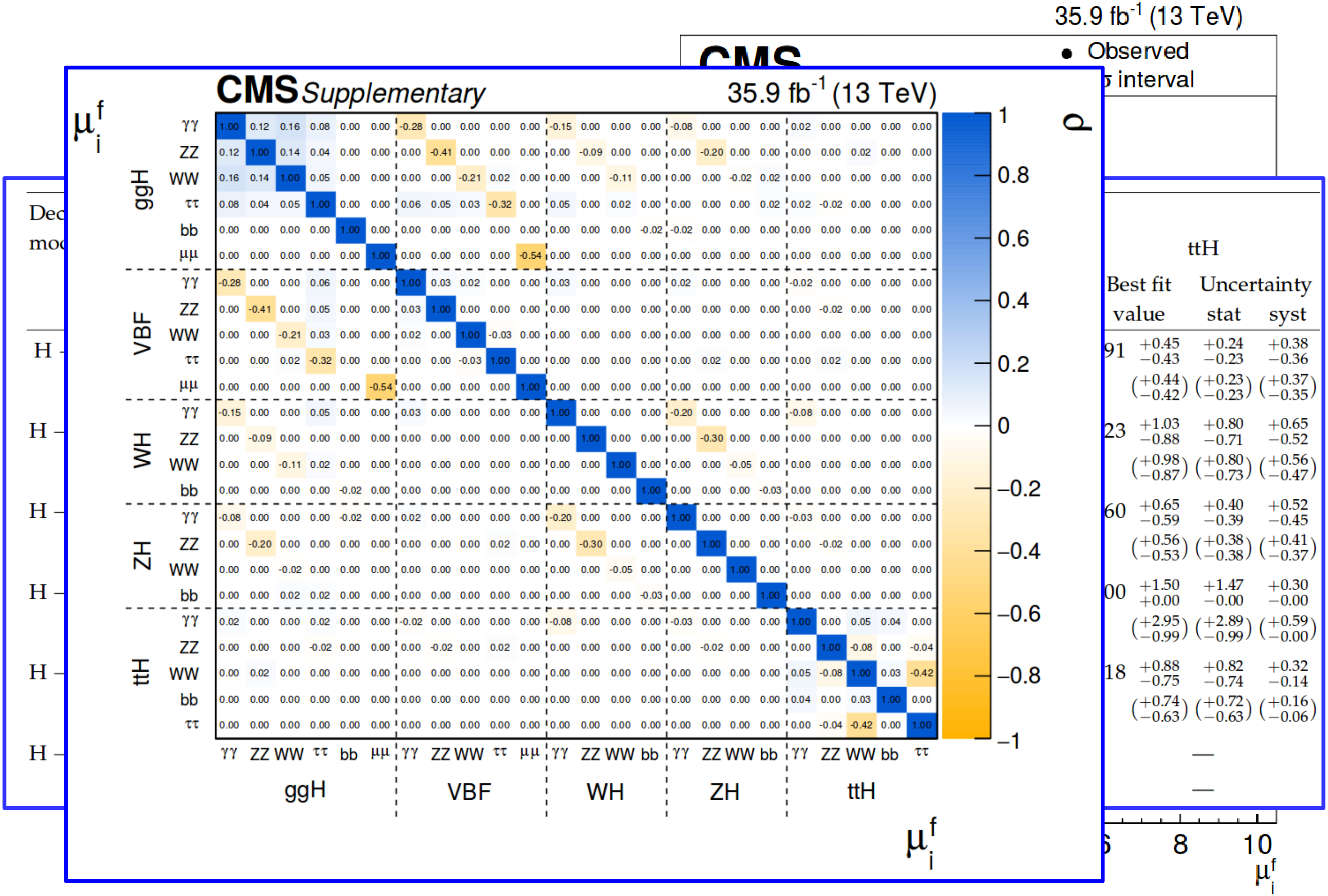
Per Production x Decay Mode

- Most generic parametrization

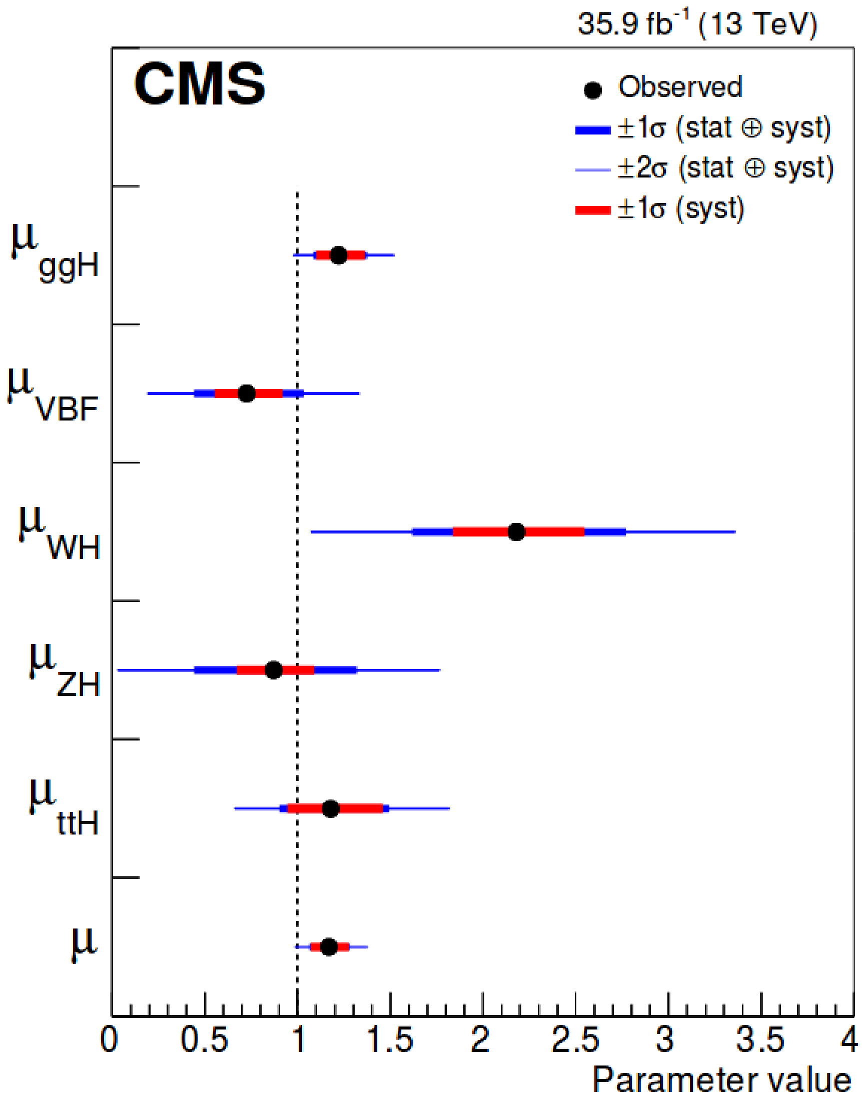


Decay mode	ggH Best fit value	ggH stat	ggH syst	VBF Best fit value	VBF stat	VBF syst	WH Best fit value	WH stat	WH syst	ZH Best fit value	ZH stat	ZH syst	ttH Best fit value	ttH stat	ttH syst
H → bb	2.51 $^{+2.43}_{-2.01}$ ($^{+2.06}_{-1.86}$)	$^{+1.96}_{-1.92}$ ($^{+1.85}_{-1.83}$)	$^{+1.44}_{-0.59}$ ($^{+0.89}_{-0.33}$)	— (—)			1.73 $^{+0.70}_{-0.68}$ ($^{+0.69}_{-0.67}$)	$^{+0.53}_{-0.51}$ ($^{+0.52}_{-0.51}$)	$^{+0.46}_{-0.45}$ ($^{+0.45}_{-0.44}$)	0.99 $^{+0.47}_{-0.45}$ ($^{+0.46}_{-0.44}$)	$^{+0.41}_{-0.40}$ ($^{+0.40}_{-0.39}$)	$^{+0.23}_{-0.20}$ ($^{+0.23}_{-0.20}$)	0.91 $^{+0.45}_{-0.43}$ ($^{+0.44}_{-0.42}$)	$^{+0.24}_{-0.23}$ ($^{+0.23}_{-0.23}$)	$^{+0.38}_{-0.36}$ ($^{+0.37}_{-0.35}$)
H → $\tau\tau$	1.05 $^{+0.53}_{-0.47}$ ($^{+0.45}_{-0.41}$)	$^{+0.25}_{-0.25}$ ($^{+0.23}_{-0.23}$)	$^{+0.46}_{-0.40}$ ($^{+0.38}_{-0.34}$)	1.12 $^{+0.45}_{-0.43}$ ($^{+0.45}_{-0.43}$)	$^{+0.37}_{-0.35}$ ($^{+0.37}_{-0.35}$)	$^{+0.25}_{-0.25}$ ($^{+0.25}_{-0.24}$)	— (—)			— (—)			0.23 $^{+1.03}_{-0.88}$ ($^{+0.98}_{-0.87}$)	$^{+0.80}_{-0.71}$ ($^{+0.80}_{-0.73}$)	$^{+0.65}_{-0.52}$ ($^{+0.56}_{-0.47}$)
H → WW	1.35 $^{+0.21}_{-0.19}$ ($^{+0.17}_{-0.16}$)	$^{+0.12}_{-0.12}$ ($^{+0.10}_{-0.10}$)	$^{+0.17}_{-0.15}$ ($^{+0.13}_{-0.12}$)	0.28 $^{+0.64}_{-0.60}$ ($^{+0.62}_{-0.58}$)	$^{+0.58}_{-0.53}$ ($^{+0.57}_{-0.53}$)	$^{+0.28}_{-0.28}$ ($^{+0.26}_{-0.25}$)	3.91 $^{+2.26}_{-2.01}$ ($^{+1.47}_{-1.19}$)	$^{+1.89}_{-1.72}$ ($^{+1.32}_{-1.06}$)	$^{+1.24}_{-1.05}$ ($^{+0.64}_{-0.54}$)	0.96 $^{+1.81}_{-1.46}$ ($^{+1.67}_{-1.37}$)	$^{+1.74}_{-1.44}$ ($^{+1.61}_{-1.35}$)	$^{+0.50}_{-0.22}$ ($^{+0.45}_{-0.20}$)	1.60 $^{+0.65}_{-0.59}$ ($^{+0.56}_{-0.53}$)	$^{+0.40}_{-0.39}$ ($^{+0.38}_{-0.38}$)	$^{+0.52}_{-0.45}$ ($^{+0.41}_{-0.37}$)
H → ZZ	1.22 $^{+0.23}_{-0.21}$ ($^{+0.22}_{-0.20}$)	$^{+0.20}_{-0.19}$ ($^{+0.20}_{-0.19}$)	$^{+0.12}_{-0.10}$ ($^{+0.10}_{-0.07}$)	−0.09 $^{+1.02}_{-0.76}$ ($^{+1.27}_{-0.99}$)	$^{+1.00}_{-0.72}$ ($^{+1.25}_{-0.97}$)	$^{+0.21}_{-0.22}$ ($^{+0.23}_{-0.21}$)	0.00 $^{+2.33}_{+0.00}$ ($^{+4.46}_{-0.99}$)	$^{+2.31}_{-0.00}$ ($^{+4.42}_{-0.99}$)	$^{+0.30}_{-0.00}$ ($^{+0.57}_{-0.00}$)	0.00 $^{+4.26}_{+0.00}$ ($^{+7.57}_{-1.00}$)	$^{+4.19}_{-0.00}$ ($^{+7.45}_{-1.00}$)	$^{+0.80}_{-0.00}$ ($^{+1.33}_{-0.00}$)	0.00 $^{+1.50}_{+0.00}$ ($^{+2.95}_{-0.99}$)	$^{+1.47}_{-0.00}$ ($^{+2.89}_{-0.99}$)	$^{+0.30}_{-0.00}$ ($^{+0.59}_{-0.00}$)
H → $\gamma\gamma$	1.16 $^{+0.21}_{-0.18}$ ($^{+0.17}_{-0.16}$)	$^{+0.17}_{-0.15}$ ($^{+0.14}_{-0.14}$)	$^{+0.13}_{-0.10}$ ($^{+0.11}_{-0.08}$)	0.67 $^{+0.59}_{-0.46}$ ($^{+0.59}_{-0.48}$)	$^{+0.49}_{-0.42}$ ($^{+0.48}_{-0.43}$)	$^{+0.32}_{-0.18}$ ($^{+0.34}_{-0.21}$)	3.76 $^{+1.48}_{-1.35}$ ($^{+1.28}_{-1.16}$)	$^{+1.45}_{-1.33}$ ($^{+1.27}_{-1.16}$)	$^{+0.33}_{-0.24}$ ($^{+0.13}_{-0.06}$)	0.00 $^{+1.14}_{+0.00}$ ($^{+2.51}_{-1.04}$)	$^{+1.14}_{-0.00}$ ($^{+2.50}_{-1.04}$)	$^{+0.09}_{-0.00}$ ($^{+0.25}_{-0.00}$)	2.18 $^{+0.88}_{-0.75}$ ($^{+0.74}_{-0.63}$)	$^{+0.82}_{-0.74}$ ($^{+0.72}_{-0.63}$)	$^{+0.32}_{-0.14}$ ($^{+0.16}_{-0.06}$)
H → $\mu\mu$	0.31 $^{+1.80}_{-1.79}$ ($^{+1.69}_{-1.65}$)	$^{+1.79}_{-1.78}$ ($^{+1.67}_{-1.67}$)	$^{+0.19}_{-0.19}$ ($^{+0.28}_{-0.00}$)	2.72 $^{+7.12}_{-7.03}$ ($^{+7.02}_{-6.94}$)	$^{+7.12}_{-7.04}$ ($^{+7.01}_{-6.93}$)	$^{+0.26}_{-0.00}$ ($^{+0.38}_{-0.50}$)	— (—)			— (—)			— (—)		

Per Production x Decay Mode



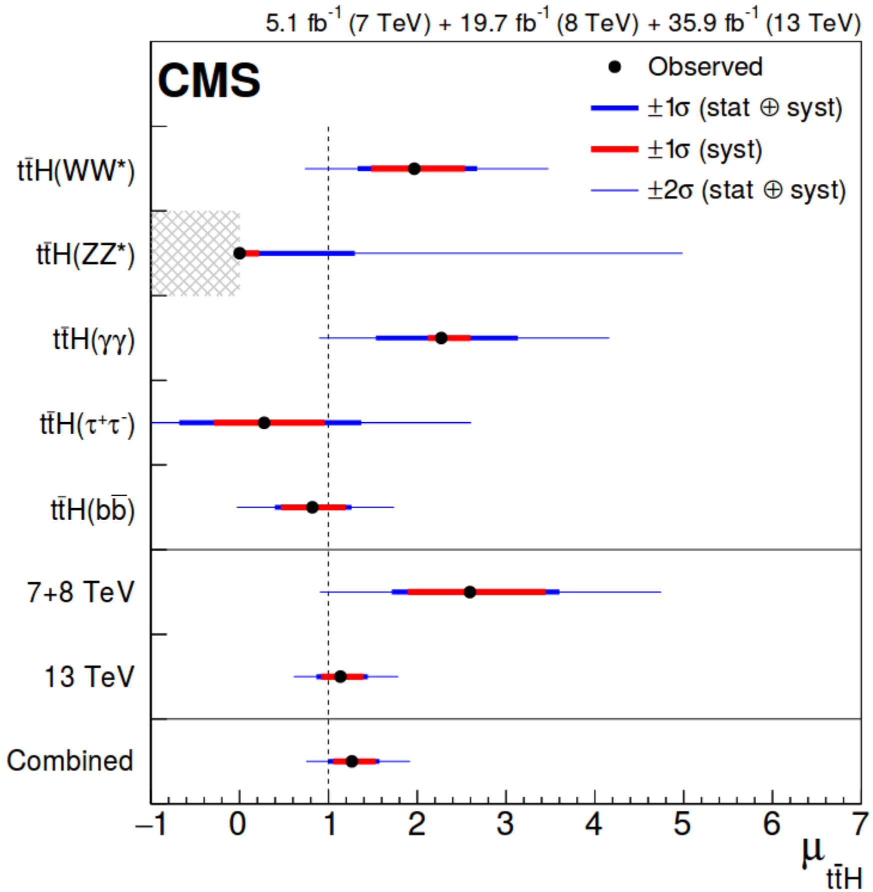
Assume SM Branching Ratios...

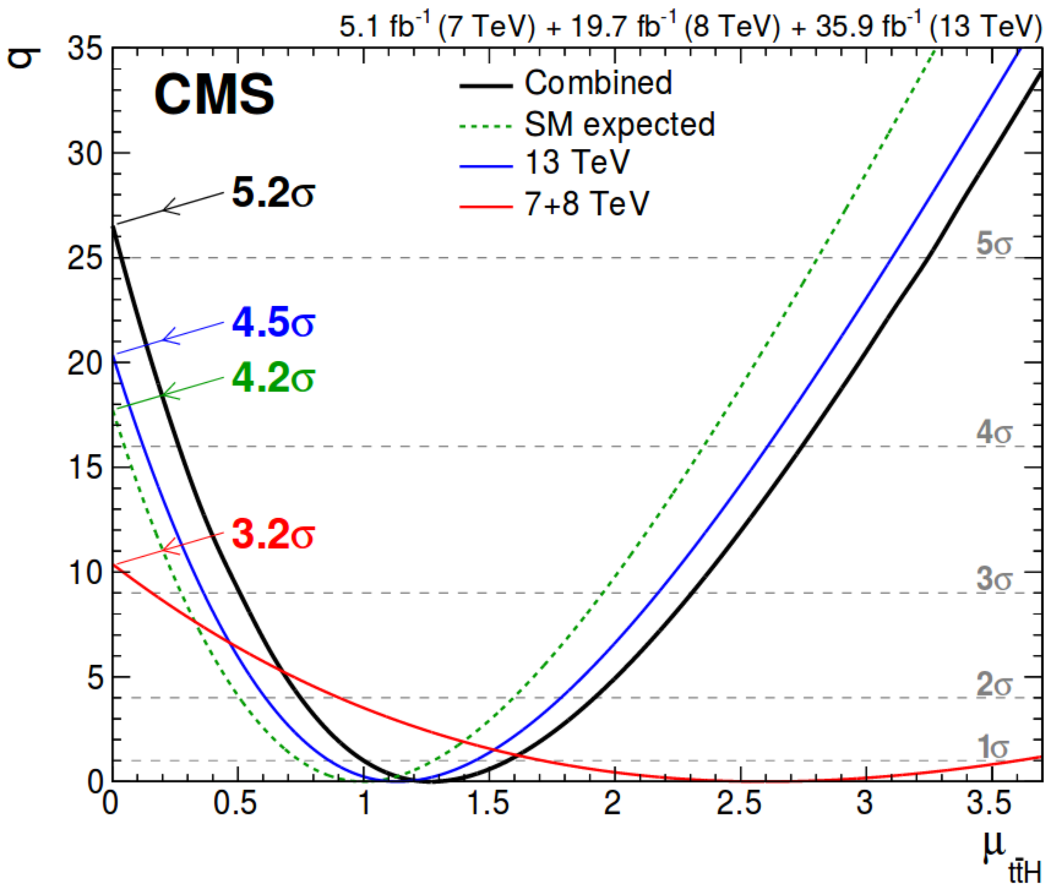


Production process	Best fit value	Uncertainty	stat.	syst.
ggH	1.22	$^{+0.14}_{-0.12}$	$^{+0.08}_{-0.08}$	$^{+0.12}_{-0.10}$
		$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.09}_{-0.08}\right)$
VBF	0.73	$^{+0.30}_{-0.27}$	$^{+0.24}_{-0.23}$	$^{+0.17}_{-0.15}$
		$\left(^{+0.29}_{-0.27}\right)$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

An aside: Observation of ttH

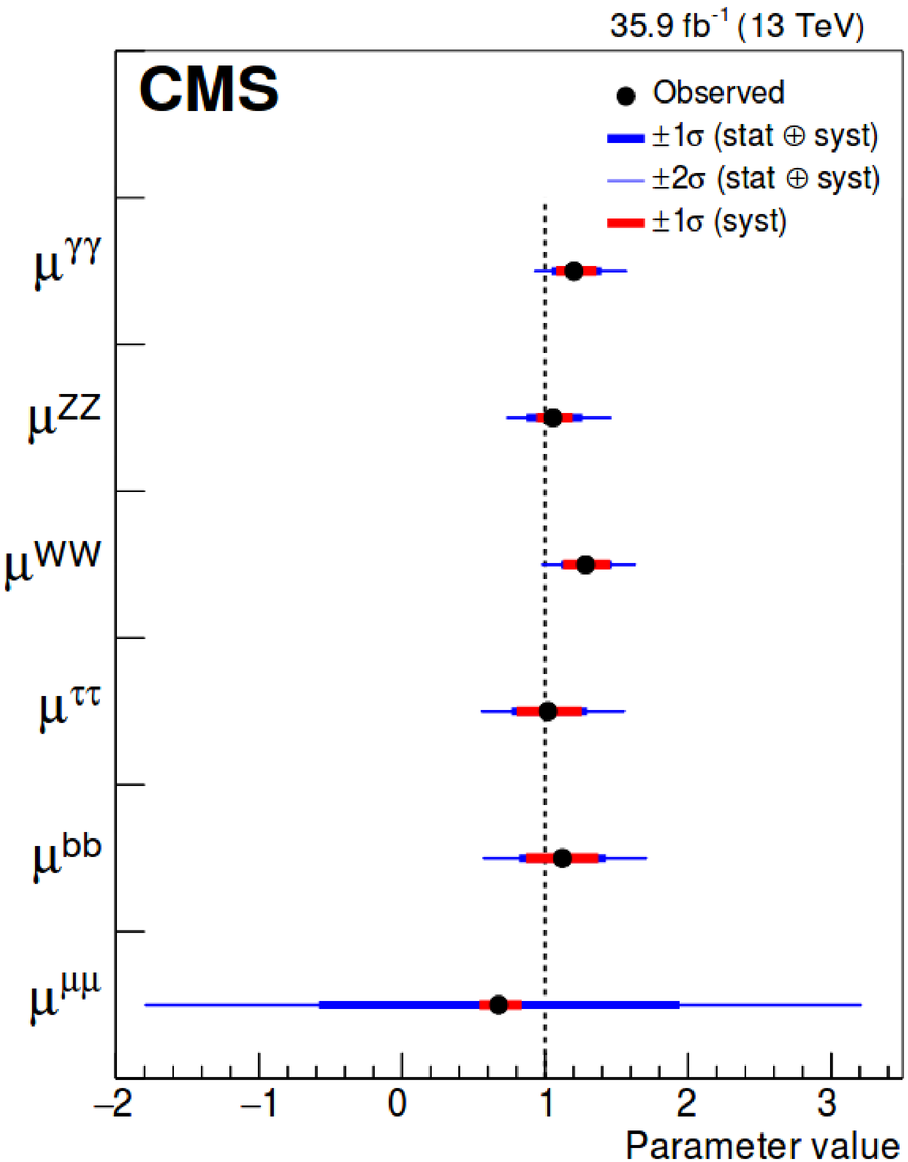
arxiv:1804.02610





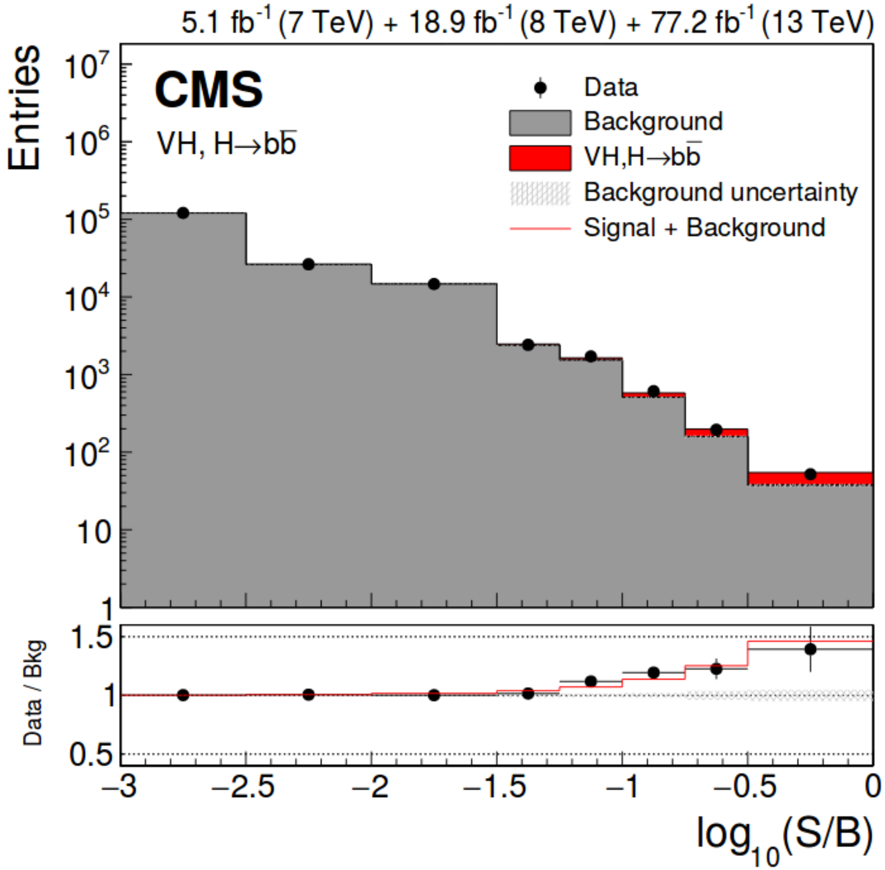
		Uncertainty			
Parameter	Best fit	Stat	Expt	Thbgd	Thsig
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.15}_{-0.15}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.15}_{-0.07}$ $\left(^{+0.11}_{-0.05}\right)$

Assume SM Relative Cross Sections...

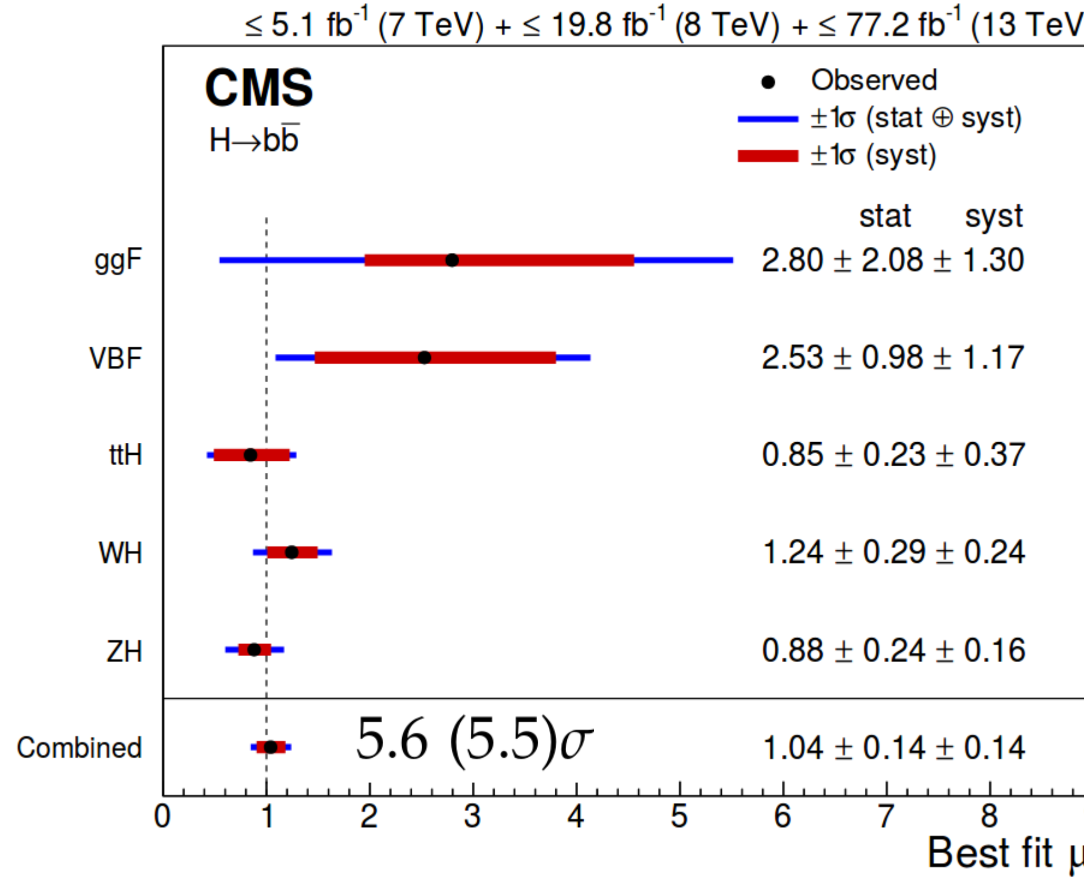


Decay mode	Best fit value	Uncertainty	stat.	syst.
$H \to bb$	1.12	$^{+0.29}_{-0.29}$ $\left(^{+0.28}_{-0.27}\right)$	$^{+0.19}_{-0.18}$ $\left(^{+0.18}_{-0.18}\right)$	$^{+0.22}_{-0.22}$ $\left(^{+0.21}_{-0.20}\right)$
$H \to \tau\tau$	1.02	$^{+0.26}_{-0.24}$ $\left(^{+0.24}_{-0.22}\right)$	$^{+0.15}_{-0.15}$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

An aside: Observation of H→bb



[arxiv:1808.08242](https://arxiv.org/abs/1808.08242)



	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.22

Assume SM Branching Ratios *and* Relative Production Cross Sections

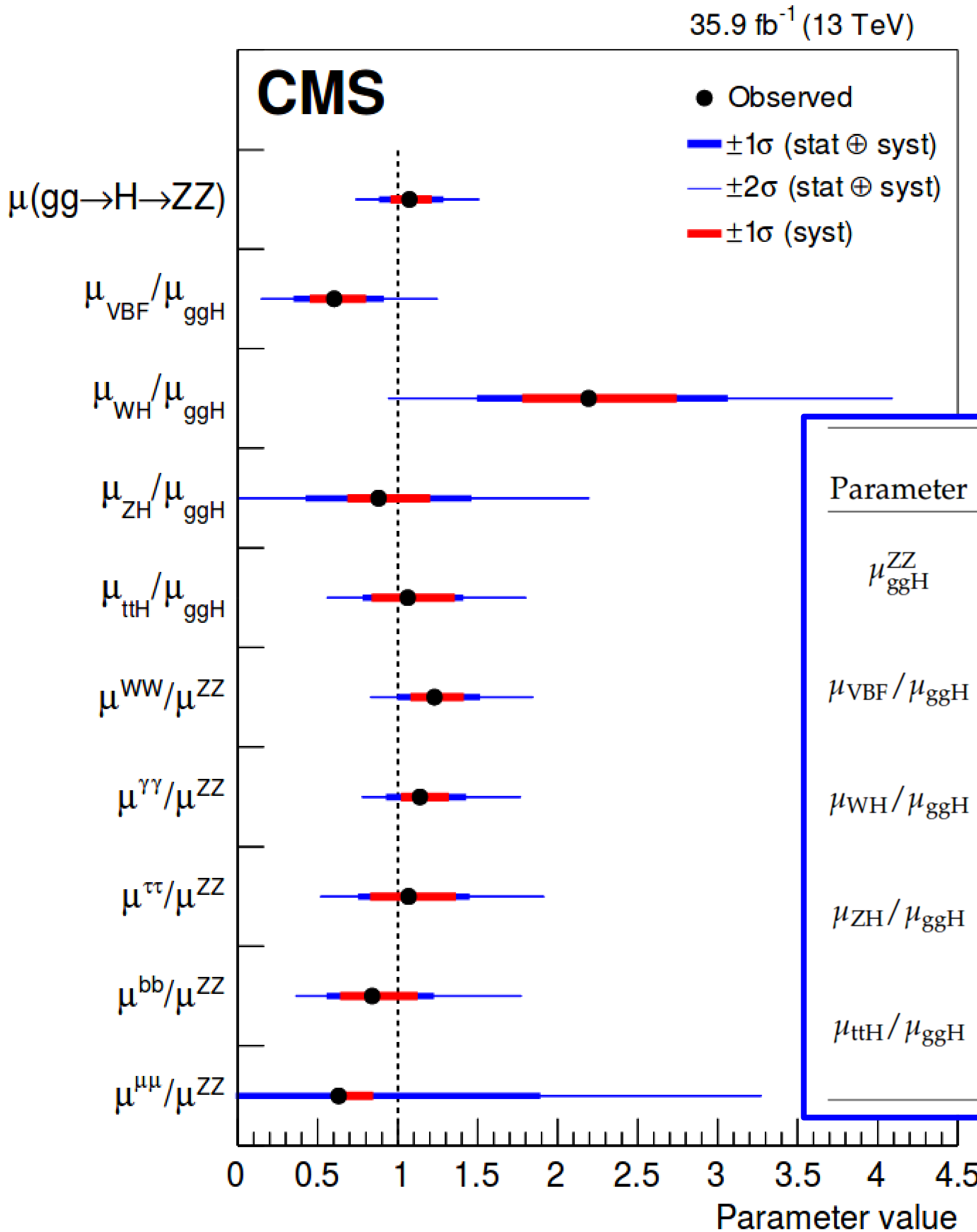
- Most constrained interpretation: single signal strength modifier which scales all prod. and decay modes assuming SM relative composition

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

- Systematically dominated, similar weight of theoretical and experimental uncertainties

- ~2σ agreement with respect to SM prediction

Another Generic Parametrization

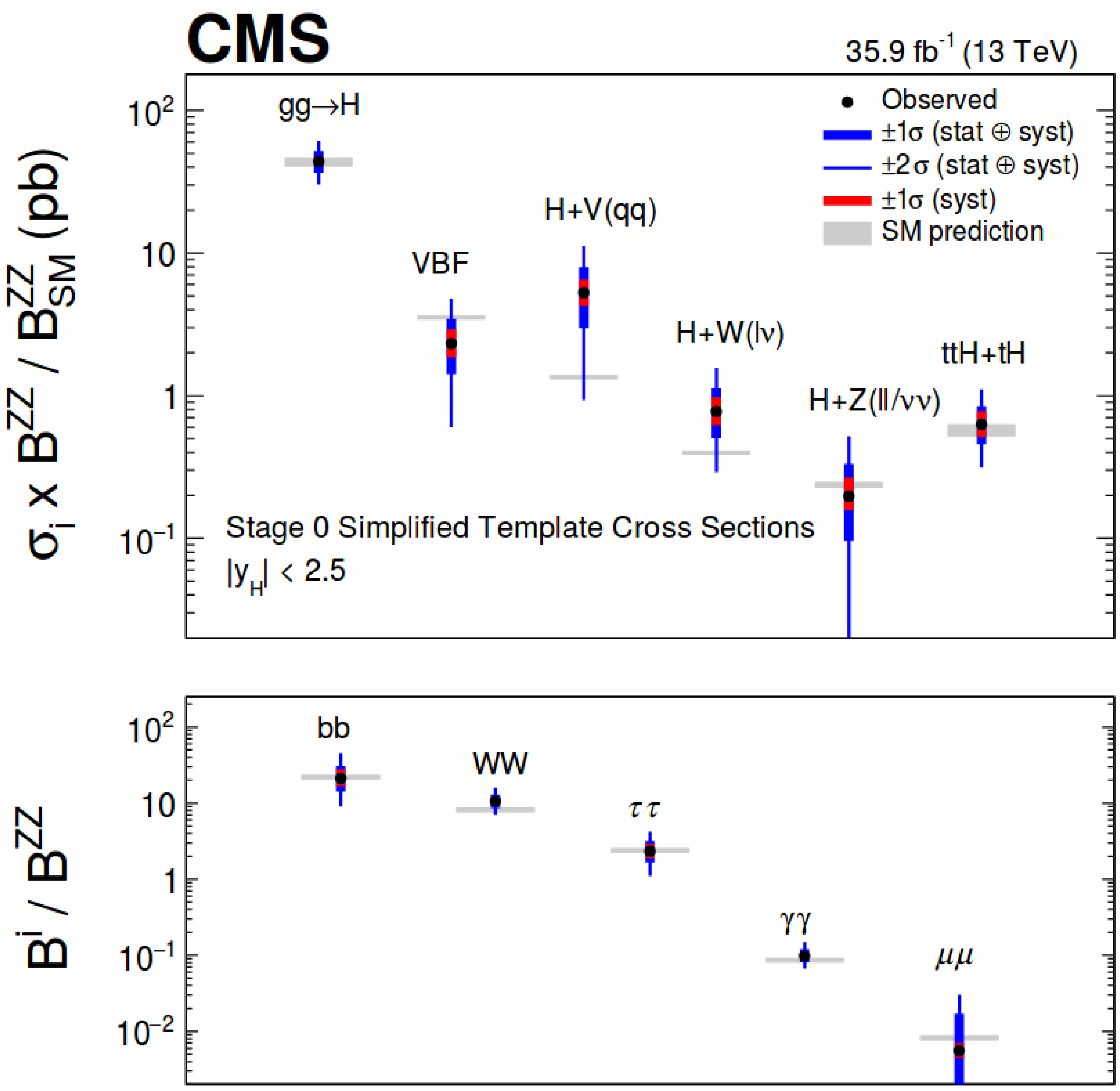


- Correlate production modes using one process as normalization and ratios of cross sections and BRs
- Some uncs. cancel in ratios

Parameter	Best fit	Uncertainty stat	Uncertainty syst	Parameter	Best fit	Uncertainty stat	Uncertainty syst
μ^{ZZ}_{ggH}	$1.07\,^{+0.20}_{-0.18}$ $\left(^{+0.19}_{-0.16}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.15}_{-0.14}\right)$	$^{+0.11}_{-0.09}$ $\left(^{+0.11}_{-0.08}\right)$	$\mathcal{B}^{bb}/\mathcal{B}^{ZZ}$	$0.84\,^{+0.37}_{-0.27}$ $\left(^{+0.56}_{-0.37}\right)$	$^{+0.27}_{-0.21}$ $\left(^{+0.38}_{-0.28}\right)$	$^{+0.26}_{-0.17}$ $\left(^{+0.40}_{-0.25}\right)$
μ_{VBF}/μ_{ggH}	$0.60\,^{+0.30}_{-0.24}$ $\left(^{+0.40}_{-0.32}\right)$	$^{+0.24}_{-0.21}$ $\left(^{+0.31}_{-0.27}\right)$	$^{+0.17}_{-0.13}$ $\left(^{+0.24}_{-0.17}\right)$	$\mathcal{B}^{\tau\tau}/\mathcal{B}^{ZZ}$	$1.07\,^{+0.37}_{-0.30}$ $\left(^{+0.35}_{-0.28}\right)$	$^{+0.25}_{-0.21}$ $\left(^{+0.25}_{-0.20}\right)$	$^{+0.27}_{-0.22}$ $\left(^{+0.25}_{-0.19}\right)$
μ_{WH}/μ_{ggH}	$2.19\,^{+0.86}_{-0.69}$ $\left(^{+0.65}_{-0.52}\right)$	$^{+0.68}_{-0.56}$ $\left(^{+0.53}_{-0.44}\right)$	$^{+0.52}_{-0.39}$ $\left(^{+0.39}_{-0.29}\right)$	$\mathcal{B}^{WW}/\mathcal{B}^{ZZ}$	$1.23\,^{+0.27}_{-0.22}$ $\left(^{+0.24}_{-0.19}\right)$	$^{+0.22}_{-0.18}$ $\left(^{+0.19}_{-0.16}\right)$	$^{+0.16}_{-0.13}$ $\left(^{+0.14}_{-0.11}\right)$
μ_{ZH}/μ_{ggH}	$0.88\,^{+0.57}_{-0.44}$ $\left(^{+0.68}_{-0.47}\right)$	$^{+0.49}_{-0.41}$ $\left(^{+0.53}_{-0.41}\right)$	$^{+0.30}_{-0.17}$ $\left(^{+0.43}_{-0.23}\right)$	$\mathcal{B}^{\gamma\gamma}/\mathcal{B}^{ZZ}$	$1.14\,^{+0.28}_{-0.20}$ $\left(^{+0.23}_{-0.18}\right)$	$^{+0.23}_{-0.18}$ $\left(^{+0.20}_{-0.16}\right)$	$^{+0.16}_{-0.09}$ $\left(^{+0.11}_{-0.08}\right)$
μ_{ttH}/μ_{ggH}	$1.06\,^{+0.34}_{-0.27}$ $\left(^{+0.36}_{-0.30}\right)$	$^{+0.20}_{-0.18}$ $\left(^{+0.23}_{-0.21}\right)$	$^{+0.27}_{-0.20}$ $\left(^{+0.27}_{-0.21}\right)$	$\mathcal{B}^{\mu\mu}/\mathcal{B}^{ZZ}$	$0.63\,^{+1.24}_{-1.21}$ $\left(^{+1.26}_{-1.19}\right)$	$^{+1.24}_{-1.20}$ $\left(^{+1.25}_{-1.19}\right)$	$^{+0.15}_{-0.11}$ $\left(^{+0.20}_{-0.03}\right)$

“Simplified Template Cross Sections”

- Can also separate th. uncs. in SM predictions (grey bands) from exp. and th. uncs. in the measurements
- Results quoted for a common simplified fiducial volume
- Results quoted for the usual production modes
  - VH split into V(ℓℓ) and V(qq)
- More on this later



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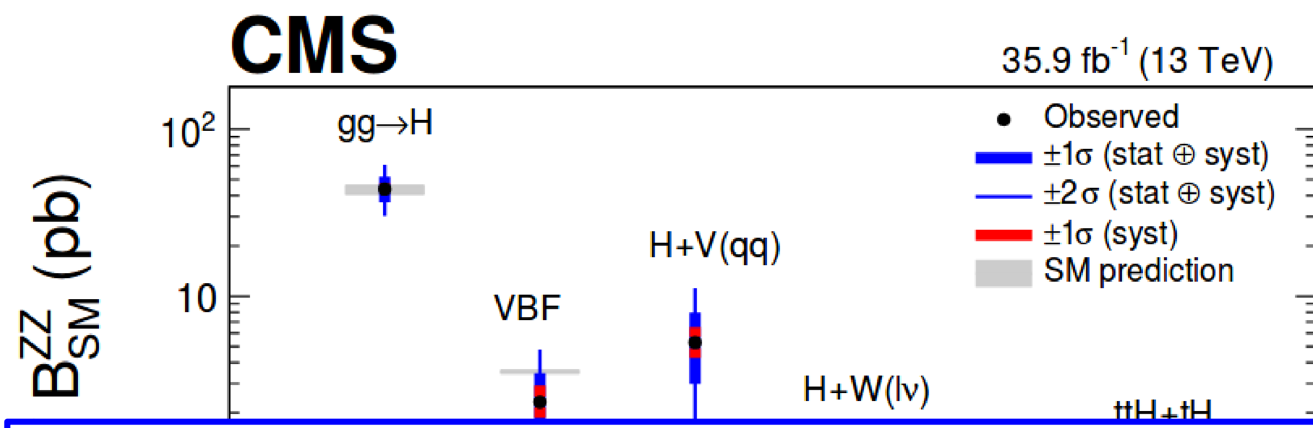
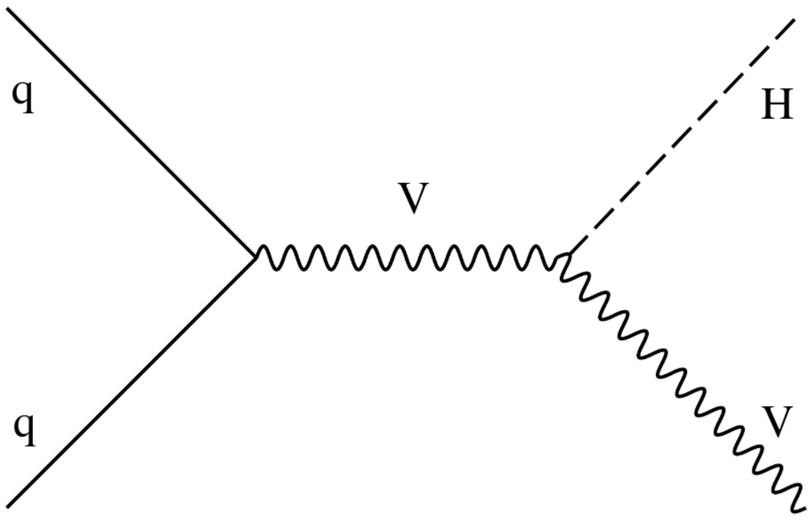
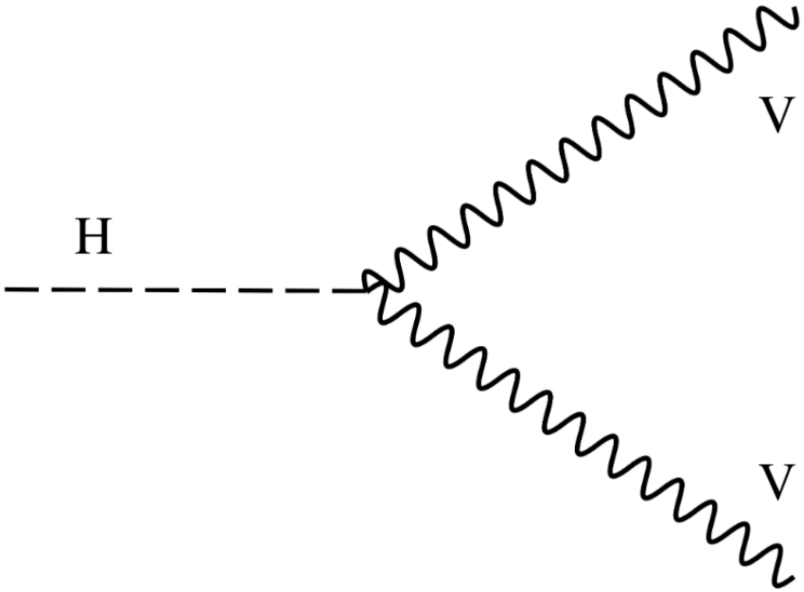


Parameter	Best fit	Uncertainty stat	Uncertainty syst	Parameter	Best fit	Uncertainty stat	Uncertainty syst
$\sigma_{\mathrm{ggH}}\mathcal{B}^{ZZ}$	$1.00\ ^{+0.19}_{-0.16}\ (^{+0.18}_{-0.16})$	$^{+0.16}_{-0.15}\ (^{+0.16}_{-0.15})$	$^{+0.09}_{-0.07}\ (^{+0.09}_{-0.07})$	$\mathcal{B}^{bb}/\mathcal{B}^{ZZ}$	$0.96\ ^{+0.44}_{-0.31}\ (^{+0.57}_{-0.38})$	$^{+0.32}_{-0.24}\ (^{+0.40}_{-0.29})$	$^{+0.30}_{-0.20}\ (^{+0.41}_{-0.25})$
$\sigma_{\mathrm{VBF}}\mathcal{B}^{ZZ}$	$0.66\ ^{+0.32}_{-0.26}\ (^{+0.40}_{-0.32})$	$^{+0.27}_{-0.22}\ (^{+0.33}_{-0.27})$	$^{+0.17}_{-0.13}\ (^{+0.22}_{-0.16})$	$\mathcal{B}^{\tau\tau}/\mathcal{B}^{ZZ}$	$0.98\ ^{+0.35}_{-0.28}\ (^{+0.36}_{-0.29})$	$^{+0.24}_{-0.20}\ (^{+0.26}_{-0.21})$	$^{+0.25}_{-0.20}\ (^{+0.25}_{-0.19})$
$\sigma_{\mathrm{H+V(qq)}}\mathcal{B}^{ZZ}$	$3.93\ ^{+2.00}_{-1.71}\ (^{+1.66}_{-1.05})$	$^{+1.77}_{-1.53}\ (^{+1.49}_{-1.05})$	$^{+0.93}_{-0.75}\ (^{+0.72}_{-0.00})$	$\mathcal{B}^{WW}/\mathcal{B}^{ZZ}$	$1.30\ ^{+0.29}_{-0.24}\ (^{+0.24}_{-0.20})$	$^{+0.24}_{-0.20}\ (^{+0.20}_{-0.16})$	$^{+0.17}_{-0.13}\ (^{+0.14}_{-0.11})$
$\sigma_{\mathrm{H+W}(\ell\nu)}\mathcal{B}^{ZZ}$	$1.95\ ^{+0.88}_{-0.68}\ (^{+0.69}_{-0.52})$	$^{+0.72}_{-0.57}\ (^{+0.56}_{-0.44})$	$^{+0.51}_{-0.38}\ (^{+0.40}_{-0.29})$	$\mathcal{B}^{\gamma\gamma}/\mathcal{B}^{ZZ}$	$1.14\ ^{+0.26}_{-0.20}\ (^{+0.23}_{-0.19})$	$^{+0.23}_{-0.18}\ (^{+0.21}_{-0.17})$	$^{+0.13}_{-0.09}\ (^{+0.11}_{-0.08})$
$\sigma_{\mathrm{H+Z}(\ell\ell/\nu\nu)}\mathcal{B}^{ZZ}$	$0.84\ ^{+0.57}_{-0.43}\ (^{+0.71}_{-0.46})$	$^{+0.49}_{-0.40}\ (^{+0.56}_{-0.41})$	$^{+0.29}_{-0.17}\ (^{+0.44}_{-0.22})$	$\mathcal{B}^{\mu\mu}/\mathcal{B}^{ZZ}$	$0.67\ ^{+1.40}_{-1.36}\ (^{+1.35}_{-1.28})$	$^{+1.39}_{-1.35}\ (^{+1.34}_{-1.28})$	$^{+0.18}_{-0.13}\ (^{+0.17}_{-0.05})$
$\sigma_{\mathrm{ttH}}\mathcal{B}^{ZZ}$	$1.08\ ^{+0.37}_{-0.30}\ (^{+0.38}_{-0.31})$	$^{+0.26}_{-0.22}\ (^{+0.28}_{-0.23})$	$^{+0.26}_{-0.19}\ (^{+0.26}_{-0.20})$				

Correlating Production and Decay





???

Coupling Modifier Model

- We interpret the results using the LO coupling modifier or "kappa" framework
- Introduce parameters which coherently scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}} \implies \sigma_i \mathcal{B}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}(\vec{\kappa})}$$

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \frac{\kappa_{\mathrm{H}}^2}{1 - (\mathcal{B}_{\mathrm{undet}} + \mathcal{B}_{\mathrm{inv}})}, \qquad \kappa_{\mathrm{H}}^2 = \begin{array}{l} 0.58\kappa_{\mathrm{b}}^2 + 0.22\kappa_{\mathrm{W}}^2 + 0.08\kappa_{\mathrm{g}}^2 + \\ + 0.06\kappa_{\tau}^2 + 0.026\kappa_{\mathrm{Z}}^2 + 0.029\kappa_{\mathrm{c}}^2 + \\ + 0.0023\kappa_{\gamma}^2 + 0.0015\kappa_{\mathrm{Z}\gamma}^2 + \\ + 0.00025\kappa_{\mathrm{s}}^2 + 0.00022\kappa_{\mu}^2 \end{array}$$

- Two parameters account for BSM contributions to total width:
  - → B_{inv} : Decays to invisible particles (direct search included in comb.)
  - → B_{undet} : Other BSM decays, direct searches not included in comb.

Couplings: Assumptions (1)

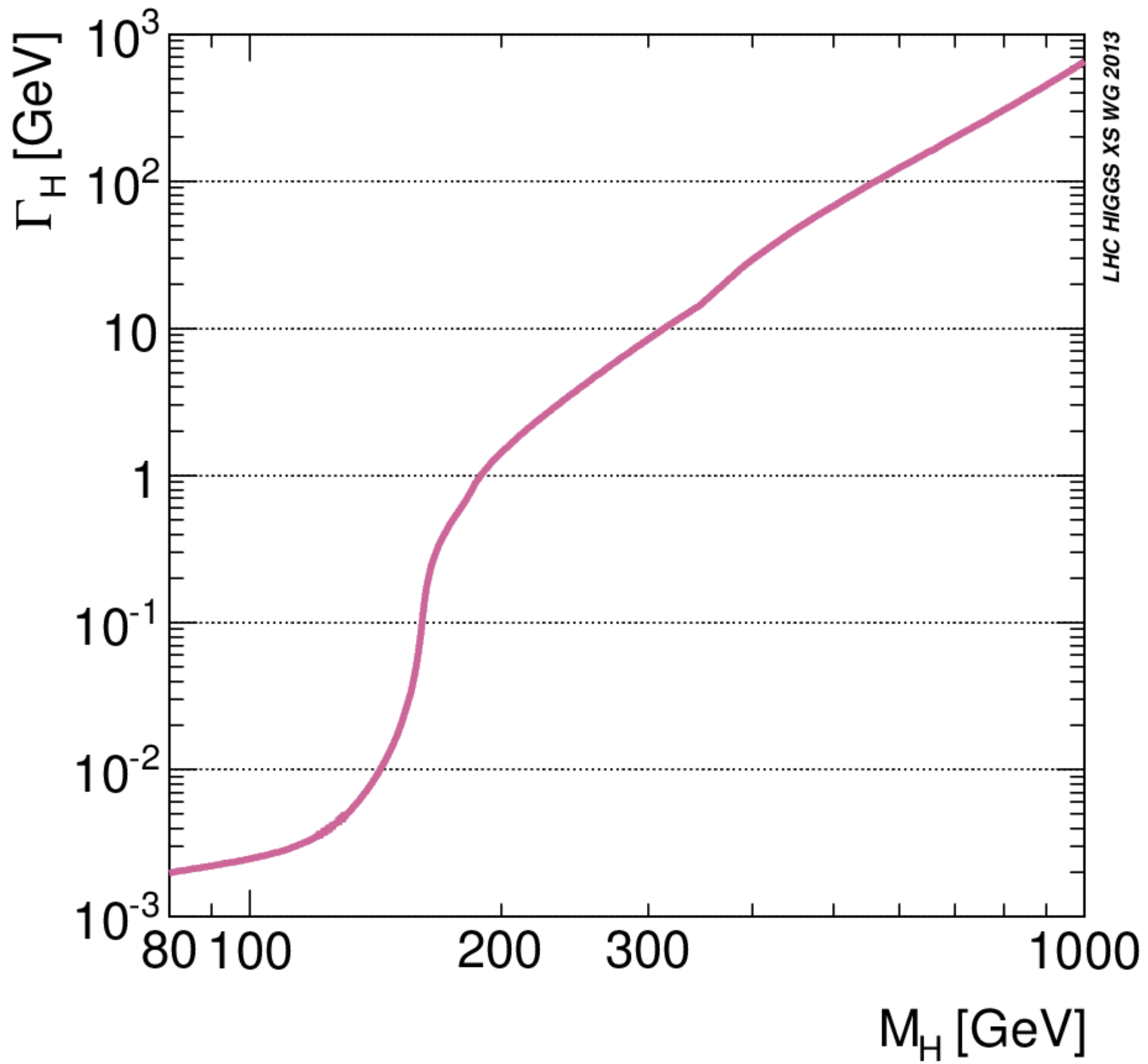
- There is an ambiguity in the model:
  - If we scale all SM couplings by a common factor the production cross sections increase
  - Branching ratios stay the same if $B_{BSM} = 0$, rate increases
  - But we can keep the rates the same if we increase B_{BSM} to compensate for the increase in cross section

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \frac{\kappa_{\mathrm{H}}^2}{1 - (\mathcal{B}_{\mathrm{undet}} + \mathcal{B}_{\mathrm{inv}})},$$

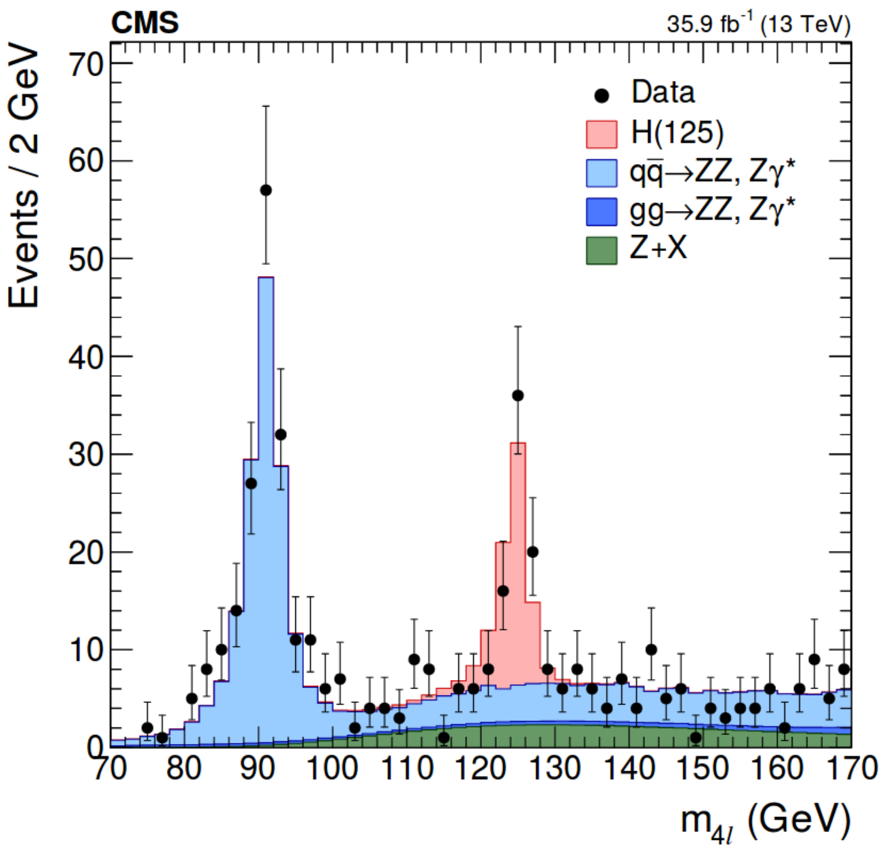
$$\kappa_{\mathrm{H}}^2 = \begin{array}{l} 0.58\kappa_{\mathrm{b}}^2 + 0.22\kappa_{\mathrm{W}}^2 + 0.08\kappa_{\mathrm{g}}^2 + \\ + 0.06\kappa_{\tau}^2 + 0.026\kappa_{\mathrm{Z}}^2 + 0.029\kappa_{\mathrm{c}}^2 + \\ + 0.0023\kappa_{\gamma}^2 + 0.0015\kappa_{\mathrm{Z}\gamma}^2 + \\ + 0.00025\kappa_{\mathrm{s}}^2 + 0.00022\kappa_{\mu}^2 \end{array}$$

An Aside: The Total Higgs Width (1)

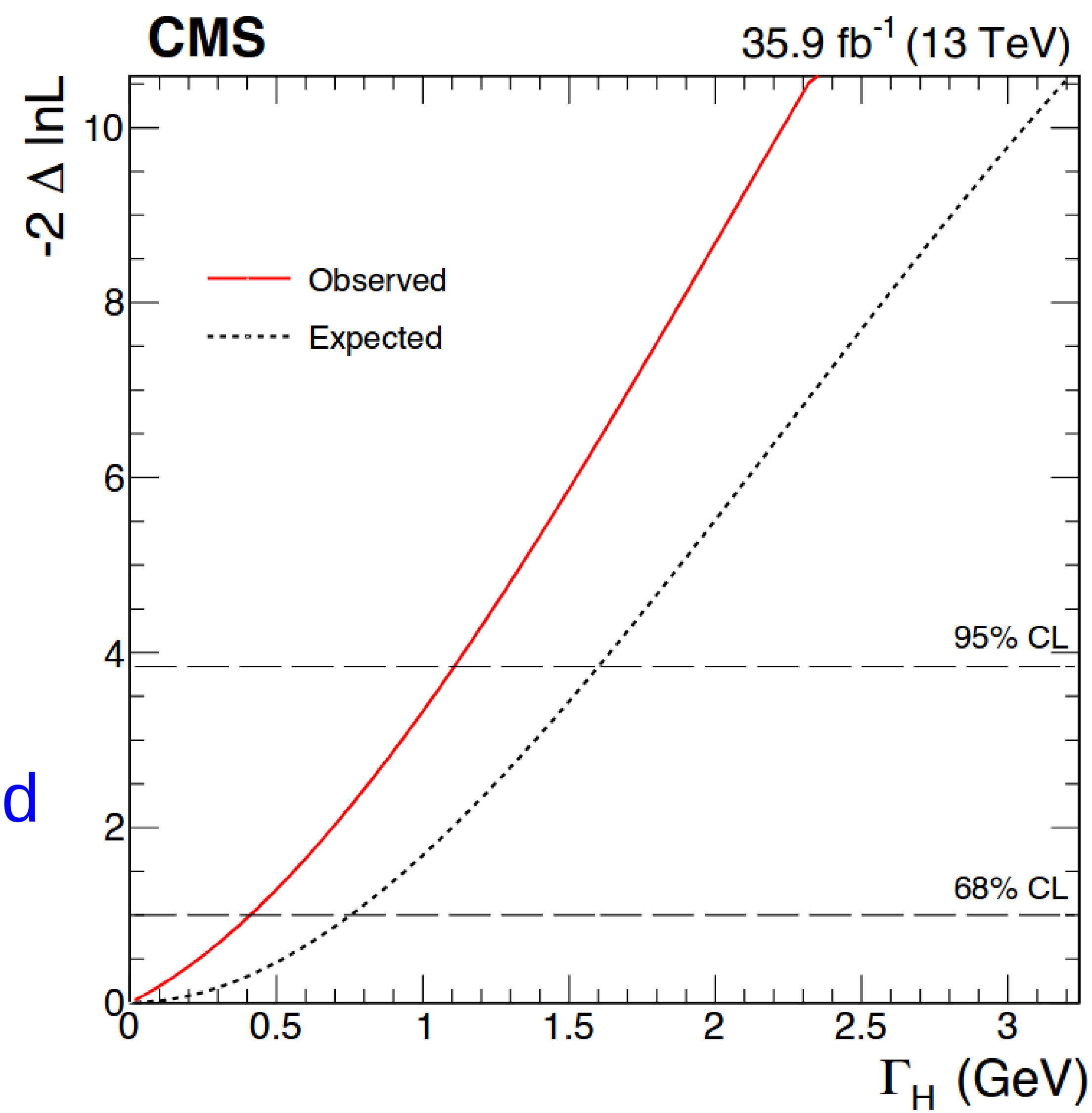
- The Higgs width at 125 GeV in the SM is tiny: ~4 MeV
- The Higgs wants to decay to massive particles but it is too light!
- Partial widths in SM are all suppressed by phase space factors or small yukawa couplings
- BSM with small couplings can still have quite large BR



An Aside: The Total Higgs Width (2)



arxiv:1706.09936



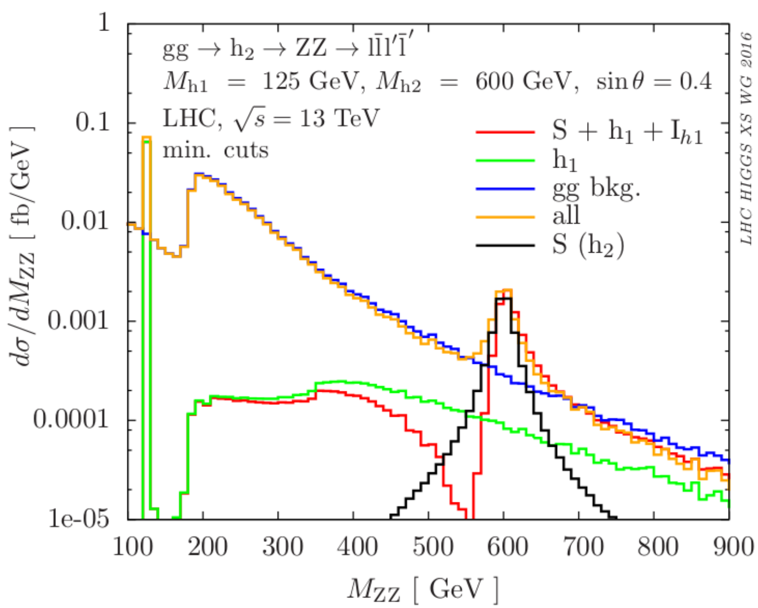
- Direct measurement limited by detector resolution
- $\Gamma_H <\sim 1$ GeV @ 95% CL

An Aside: The Total Higgs Width (3)

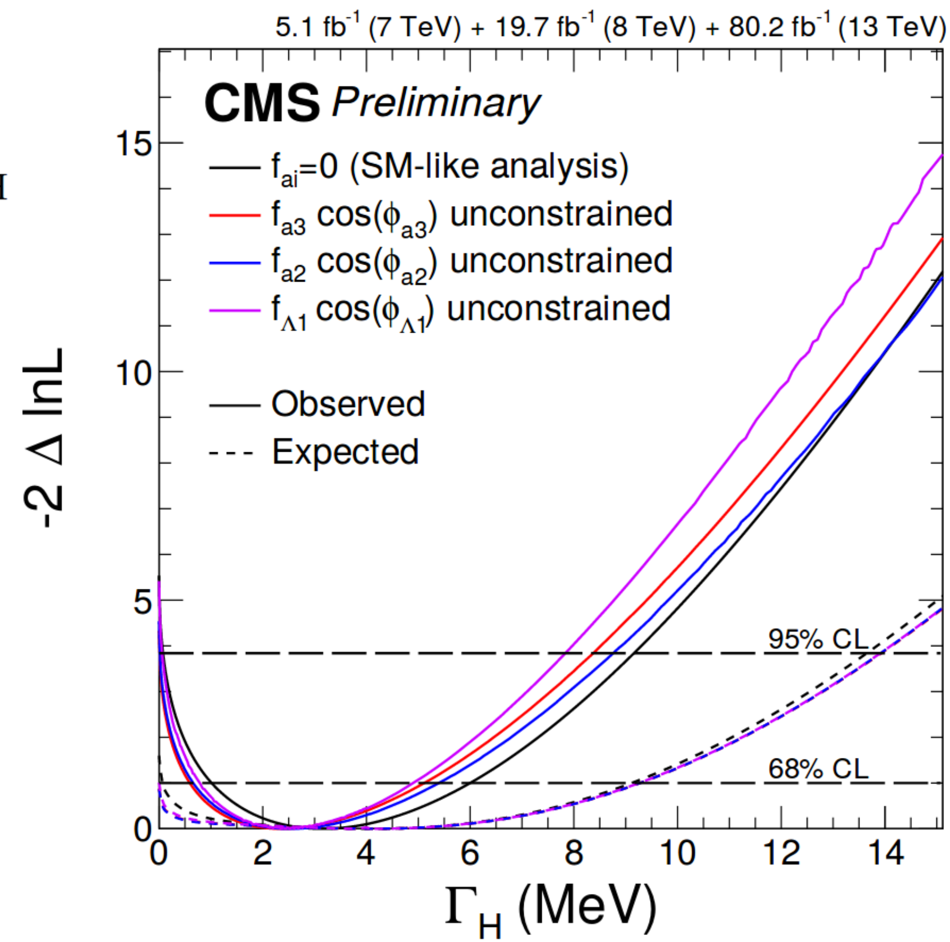
- Indirect measurement from ratio of off-shell and on-shell signal strength

$$\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}} \text{ and } \sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}} \cdot \Gamma_{\text{H}}$$

- Assumes no new physics in ggH loop or at high m(ZZ)



CMS-PAS-HIG-18-002



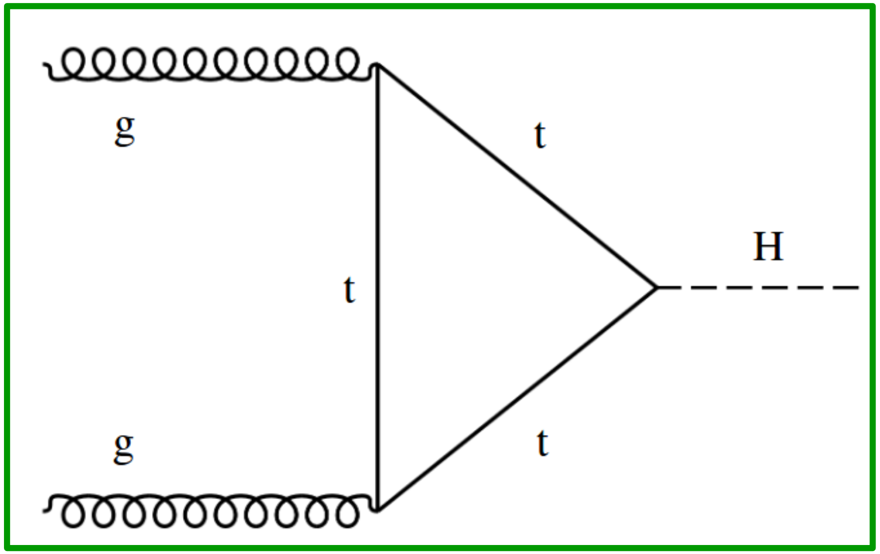
$\Gamma_H < \sim 8$ MeV @ 95% CL

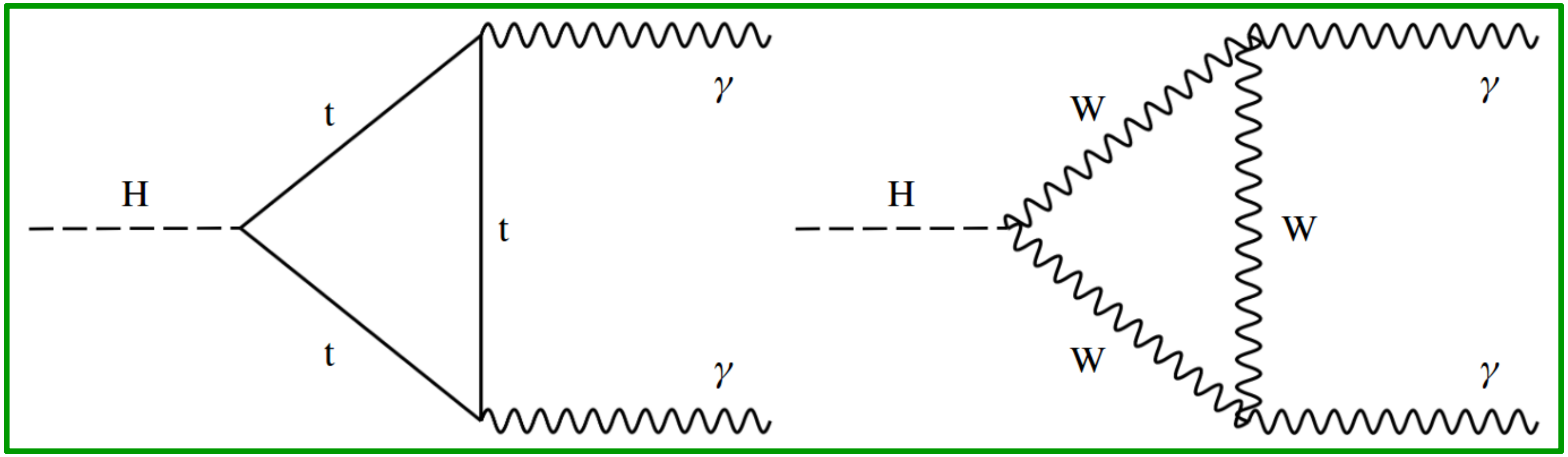
Nevertheless, we proceed….

- We make three different assumptions to resolve the ambiguity in the total Higgs width:
  - ➔ Don't measure absolute couplings, only ratios of couplings
  - ➔ $B_{BSM} = 0$ (Big assumption!)
  - ➔ Restrict $\kappa_V < 1$ (Motivated by unitarity, true in many BSM models, but not all)

Couplings: Assumptions (2)

Can assume we know what is happening inside loop processes, or not

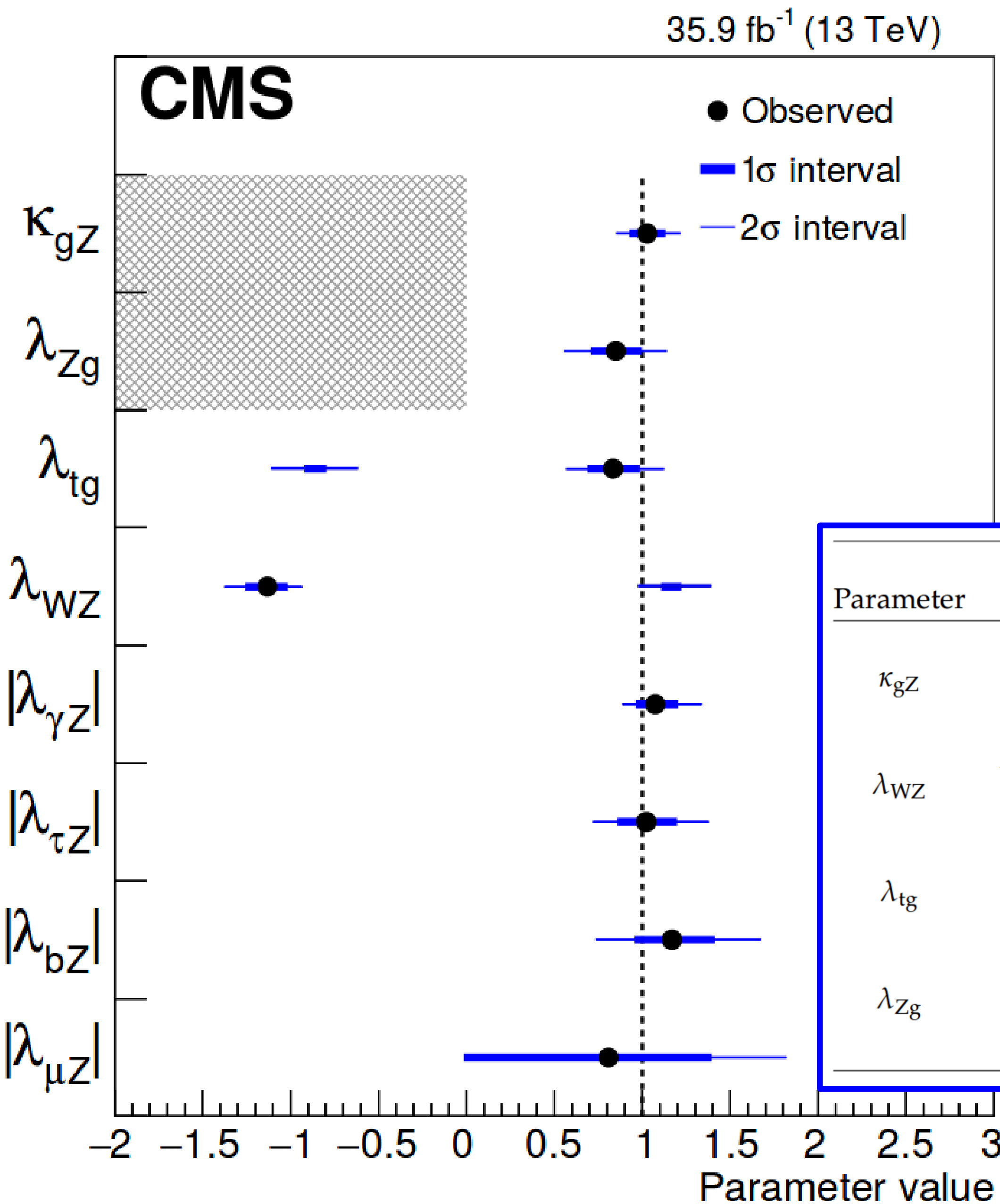




Coupling Modifier Model

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\text{ggH})$	✓	b-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\text{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\text{WH})$	—	—		κ_W^2
$\sigma(\text{qq/qg} \to \text{ZH})$	—	—		κ_Z^2
$\sigma(\text{gg} \to \text{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\text{ttH})$	—	—		κ_t^2
$\sigma(\text{gb} \to \text{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(\text{qb} \to \text{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\text{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{\text{BSM}} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 + 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$

Coupling Modifier Ratio Model

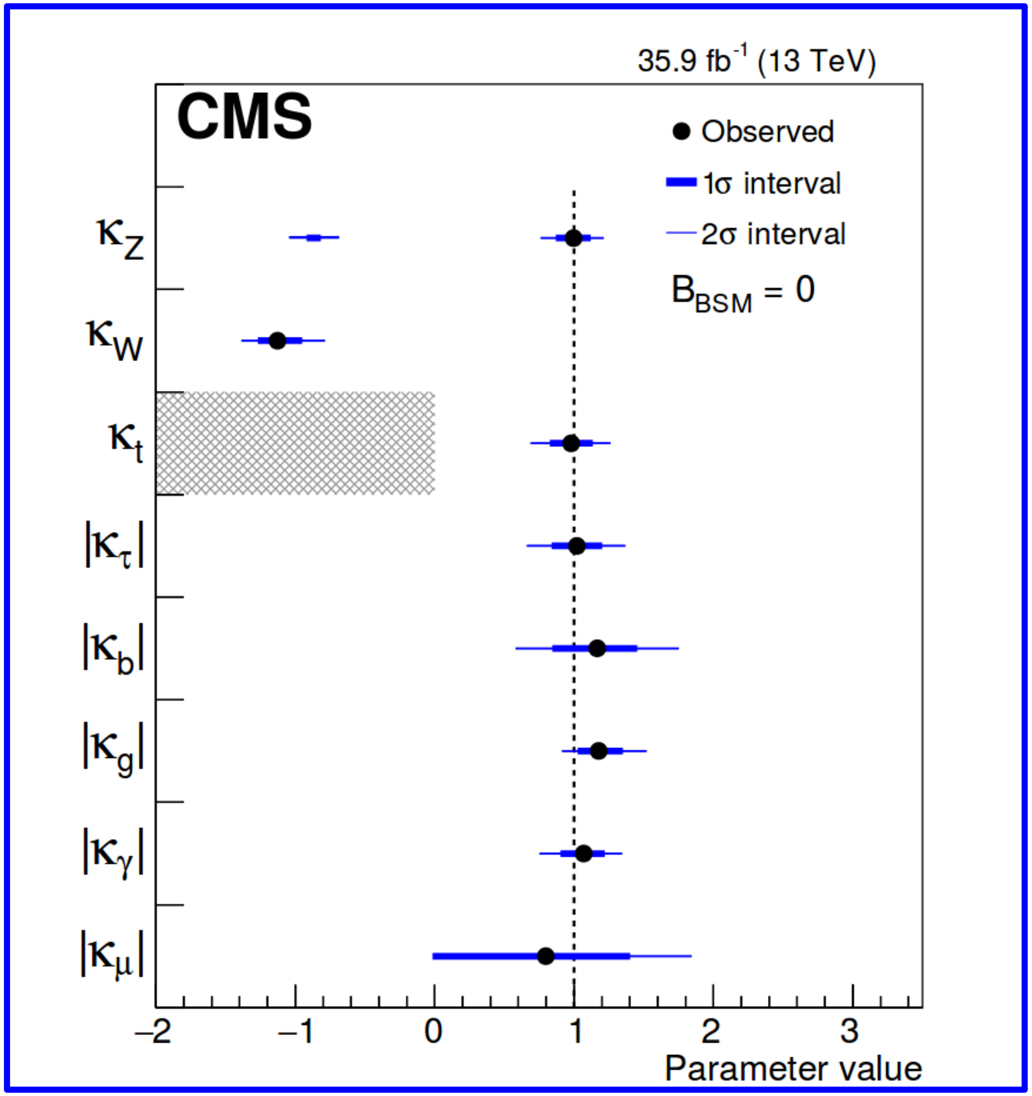


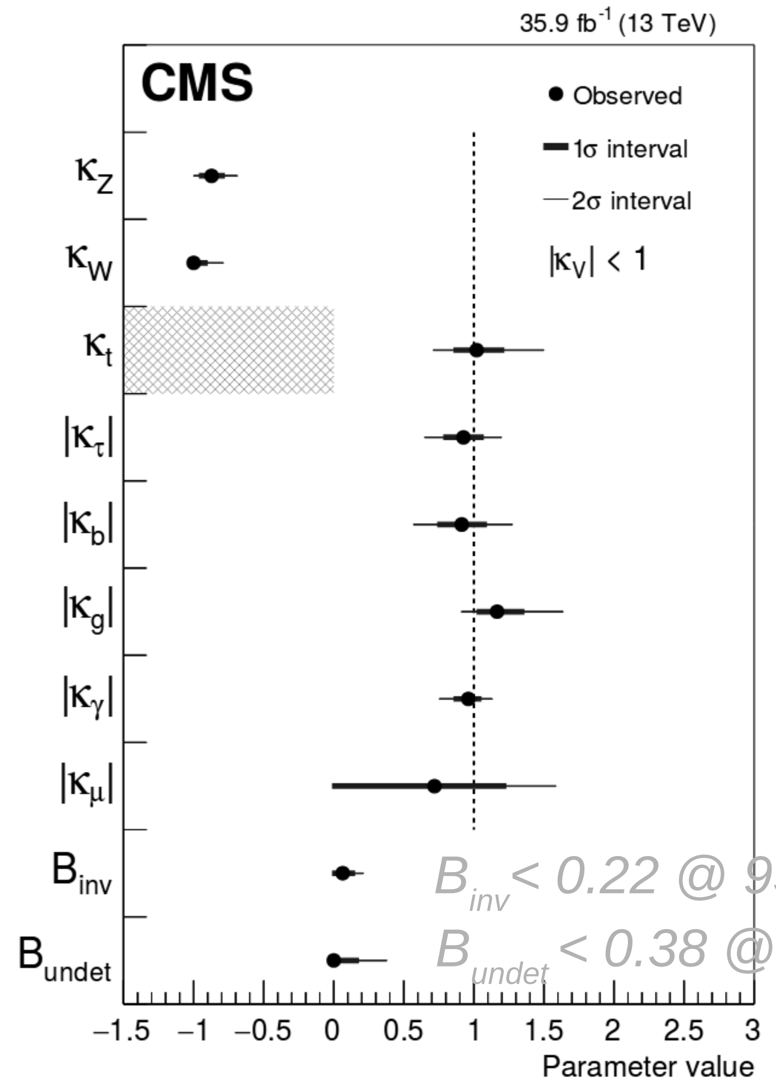
- Take gg→H→ZZ as normalization mode
- Don't measure absolute couplings, only ratios of couplings

Parameter	Best fit	Uncertainty stat	Uncertainty syst	Parameter	Best fit	Uncertainty stat	Uncertainty syst
κ_{gZ}	$1.03\ ^{+0.09}_{-0.09}\ \left(^{+0.09}_{-0.09}\right)$	$^{+0.07}_{-0.07}\ \left(^{+0.07}_{-0.07}\right)$	$^{+0.05}_{-0.05}\ \left(^{+0.05}_{-0.05}\right)$	$\lambda_{\gamma Z}$	$1.07\ ^{+0.12}_{-0.10}\ \left(^{+0.11}_{-0.09}\right)$	$^{+0.10}_{-0.08}\ \left(^{+0.09}_{-0.08}\right)$	$^{+0.06}_{-0.05}\ \left(^{+0.05}_{-0.04}\right)$
λ_{WZ}	$-1.13\ ^{+0.10}_{-0.11}\ \left(^{+0.11}_{-0.09}\right)$	$^{+0.08}_{-0.09}\ \left(^{+0.09}_{-0.08}\right)$	$^{+0.06}_{-0.06}\ \left(^{+0.06}_{-0.05}\right)$	λ_{bZ}	$1.17\ ^{+0.23}_{-0.20}\ \left(^{+0.22}_{-0.19}\right)$	$^{+0.16}_{-0.14}\ \left(^{+0.16}_{-0.14}\right)$	$^{+0.16}_{-0.14}\ \left(^{+0.15}_{-0.13}\right)$
λ_{tg}	$0.83\ ^{+0.14}_{-0.13}\ \left(^{+0.17}_{-0.16}\right)$	$^{+0.08}_{-0.08}\ \left(^{+0.11}_{-0.11}\right)$	$^{+0.11}_{-0.10}\ \left(^{+0.12}_{-0.12}\right)$	$\lambda_{\tau Z}$	$1.02\ ^{+0.16}_{-0.15}\ \left(^{+0.16}_{-0.14}\right)$	$^{+0.11}_{-0.10}\ \left(^{+0.11}_{-0.10}\right)$	$^{+0.12}_{-0.11}\ \left(^{+0.11}_{-0.10}\right)$
λ_{Zg}	$0.85\ ^{+0.14}_{-0.13}\ \left(^{+0.17}_{-0.16}\right)$	$^{+0.10}_{-0.12}\ \left(^{+0.13}_{-0.13}\right)$	$^{+0.09}_{-0.05}\ \left(^{+0.11}_{-0.09}\right)$	$\lambda_{\mu Z}$	$0.81\ ^{+0.57}_{-0.81}\ \left(^{+0.50}_{-1.01}\right)$	$^{+0.56}_{-0.82}\ \left(^{+0.49}_{-1.01}\right)$	$^{+0.11}_{-0.00}\ \left(^{+0.07}_{-0.07}\right)$

Couplings: Effective Loops

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



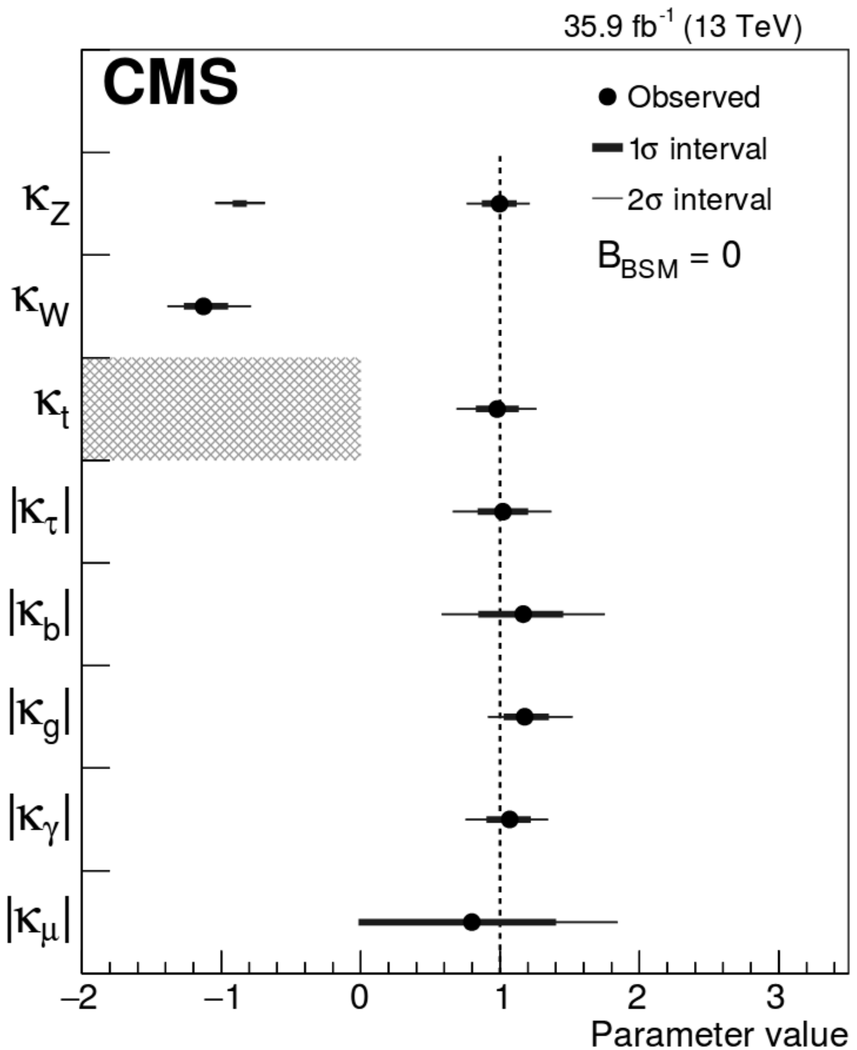


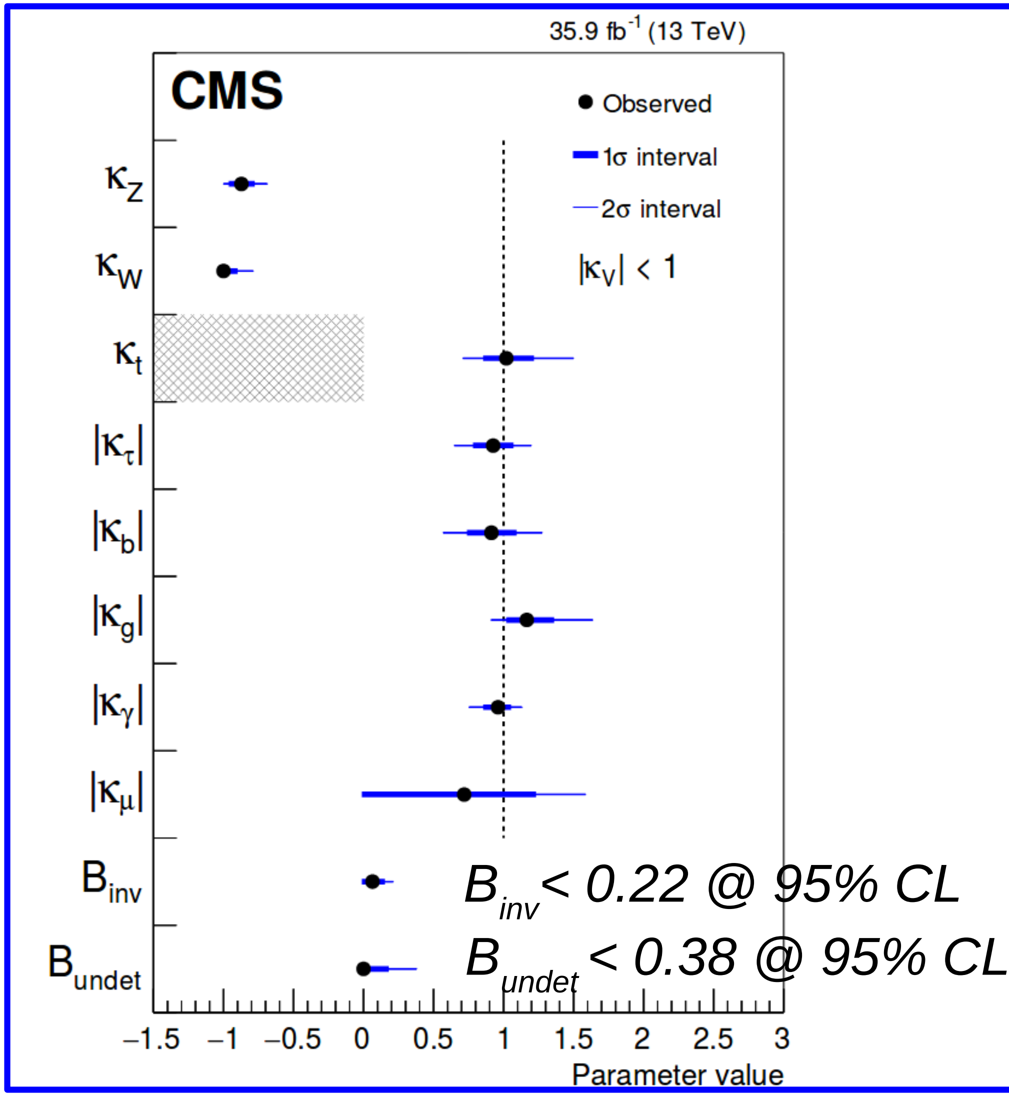
$B_{inv} < 0.22$ @ 95% CL

$B_{undet} < 0.38$ @ 95% CL

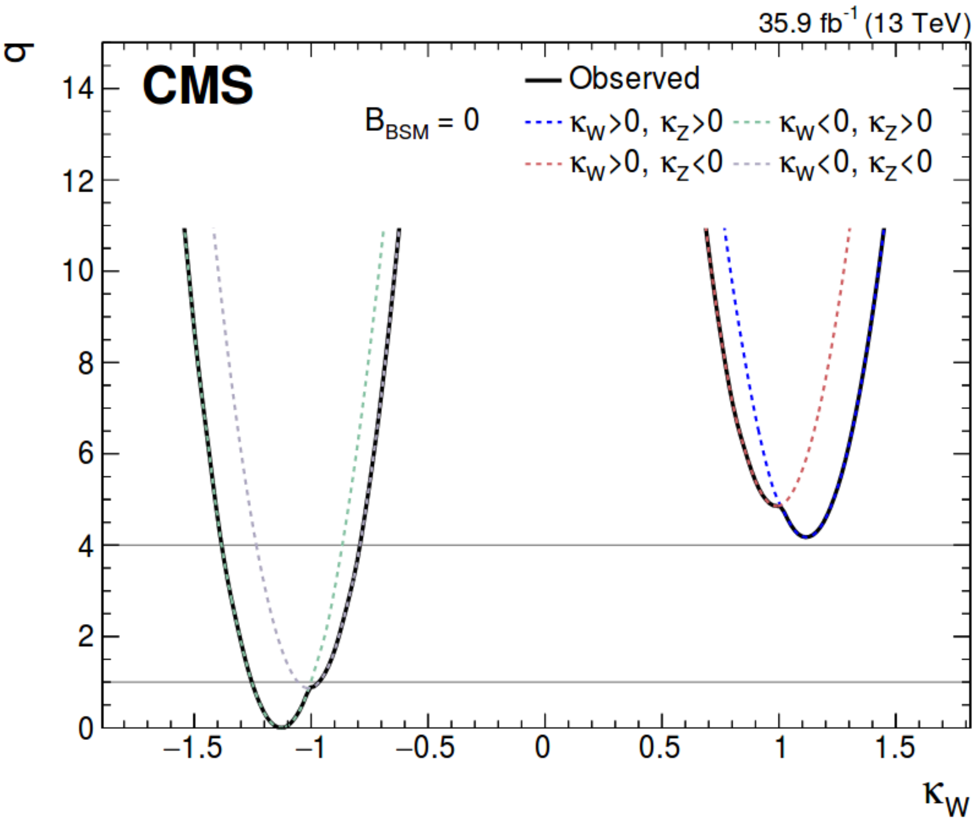
Couplings: Effective Loops

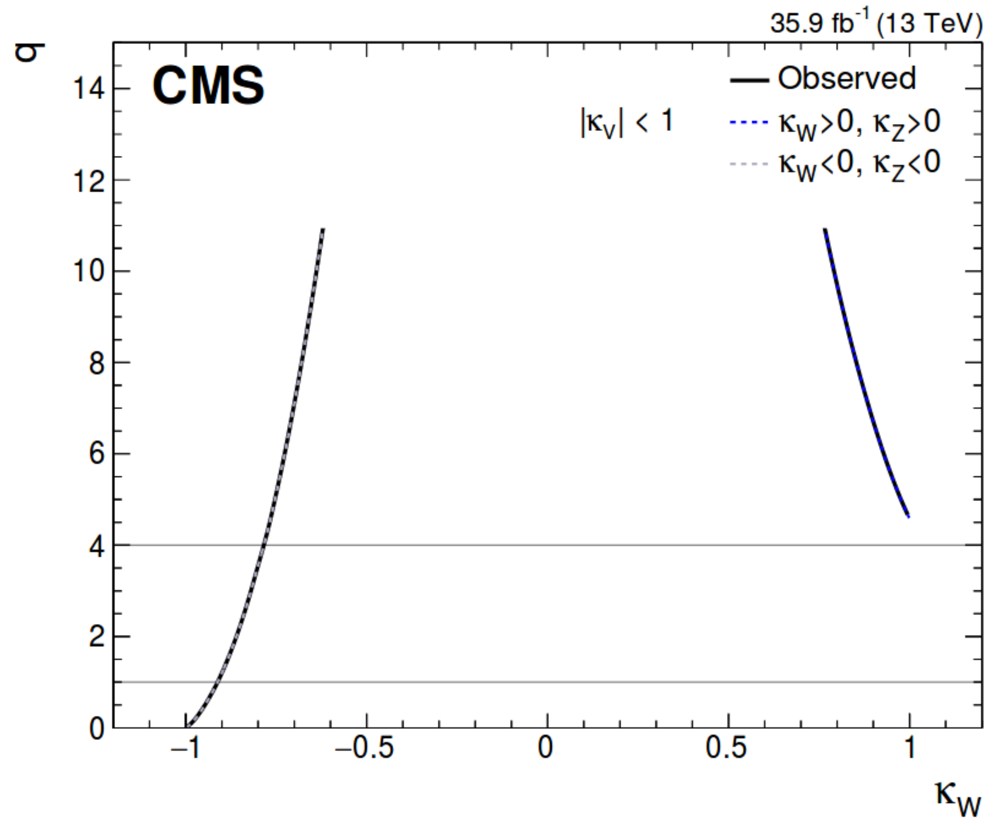
- No assumptions about loops (k_g and k_γ free parameters)
- Assumption about total width: $k_V < 1$





Couplings: Relative Sign of k_t and k_W

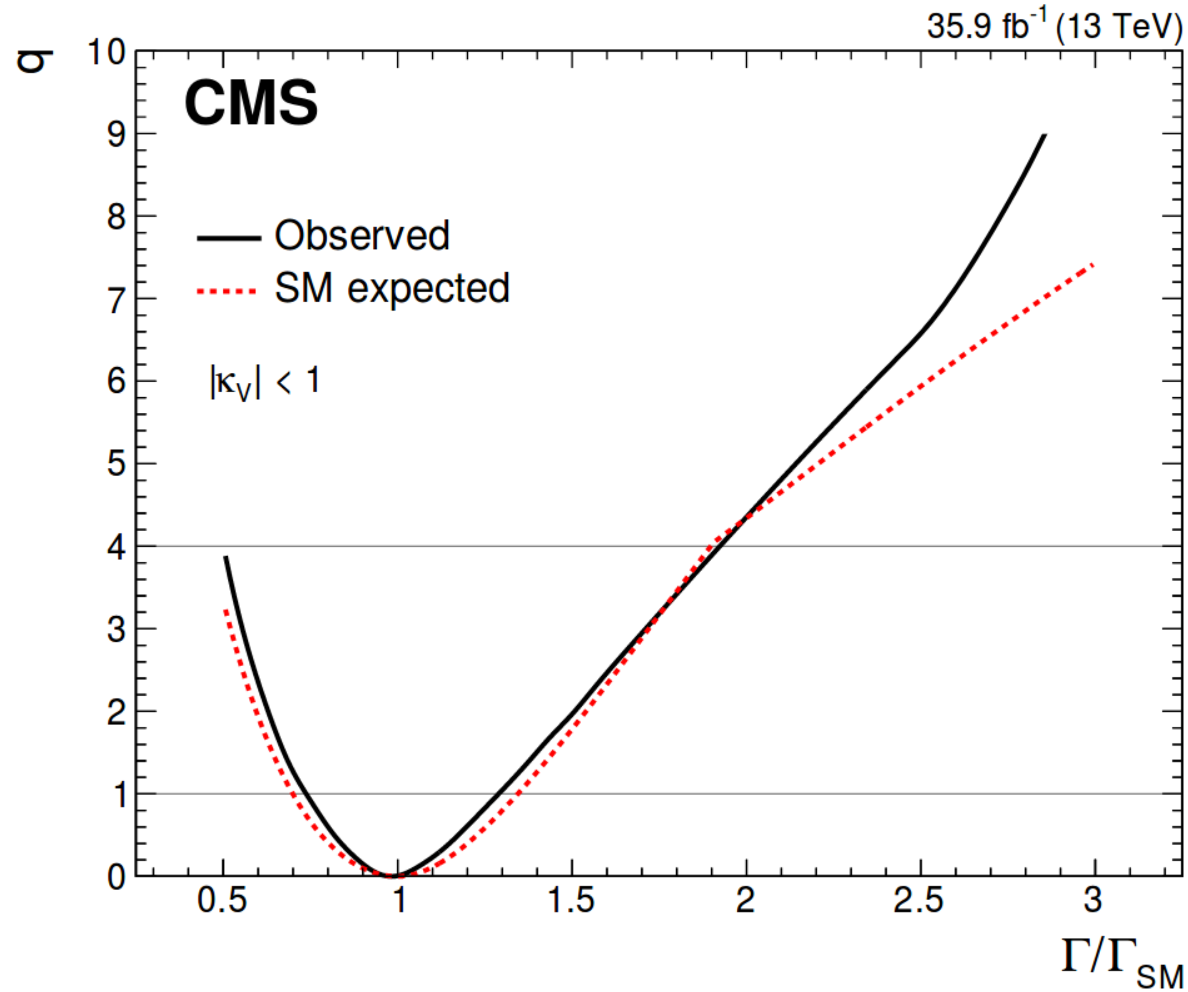




- Mild preference (~2σ) for $k_t k_W < 0$, which enhances tH prod.
- Driven by excess in ttH categories of H→γγ analyis
- Dedicated tH categories not included, will be resolved w/ full Run 2 dataset (include these categories in the combination)

Constraint on Total Width

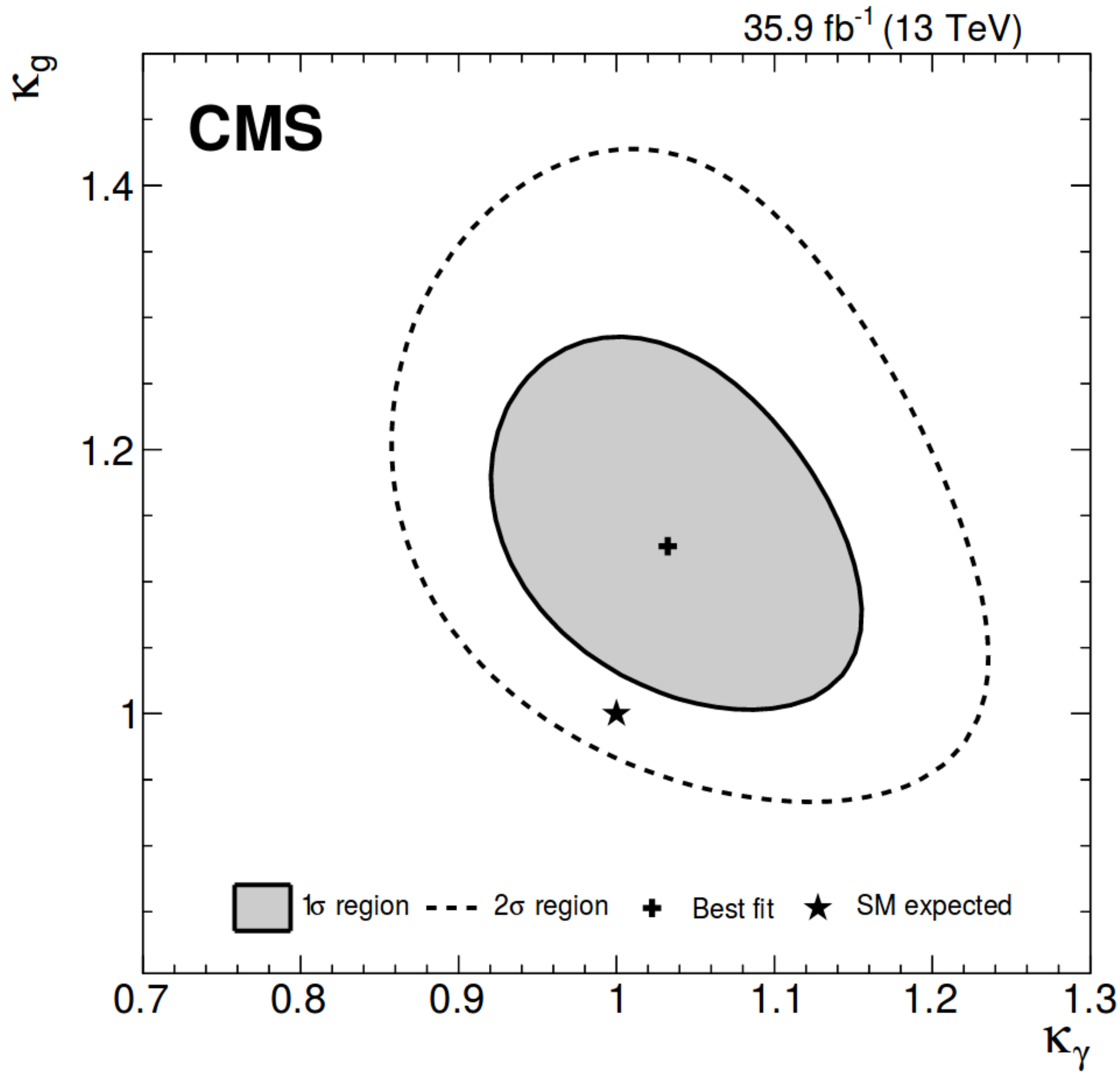
- Assuming $k_V < 1$, but allowing for BSM decays, set constraint on total Higgs width
- Performed by making total width a parameter of the model (instead of a function of other k's), and making k_b a function of other k's and total width



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

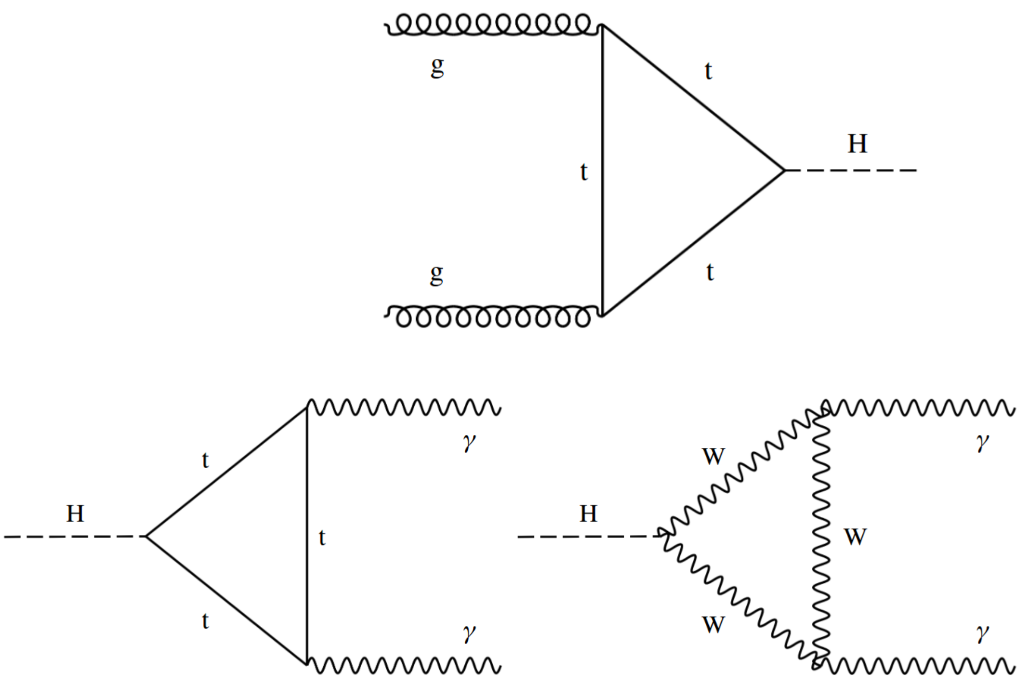
Looking Only at Loop Processes

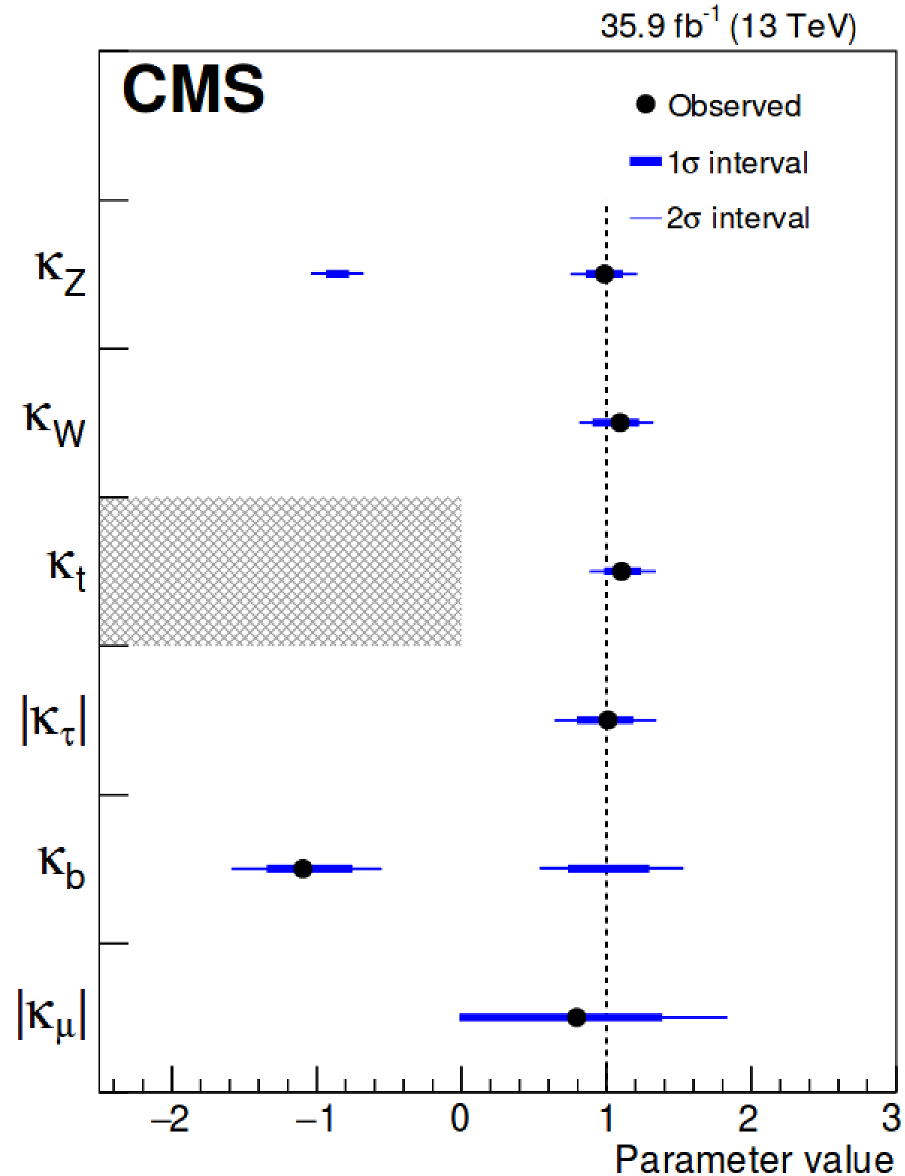
- Test for new physics in loop processes gg→H and H→γγ
- Allow for the presence of BSM decays
- All other k's fixed to SM value



Couplings: Resolved Loops

- Assume no new physics in loop processes
- Assume no BSM decays

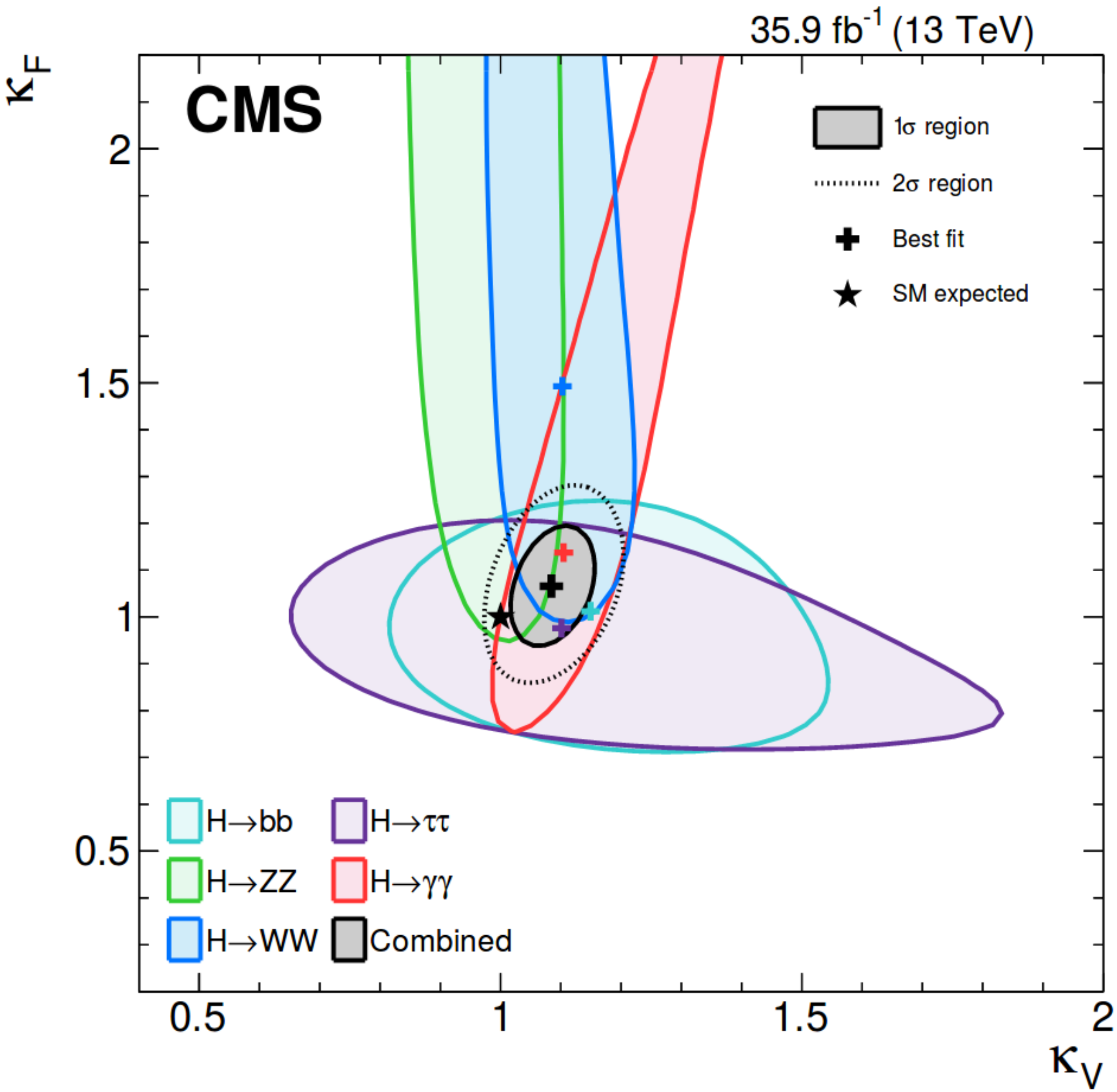




- $k_t\,k_W < 0$ strongly disfavored
- Very weak preference for $k_b<0$

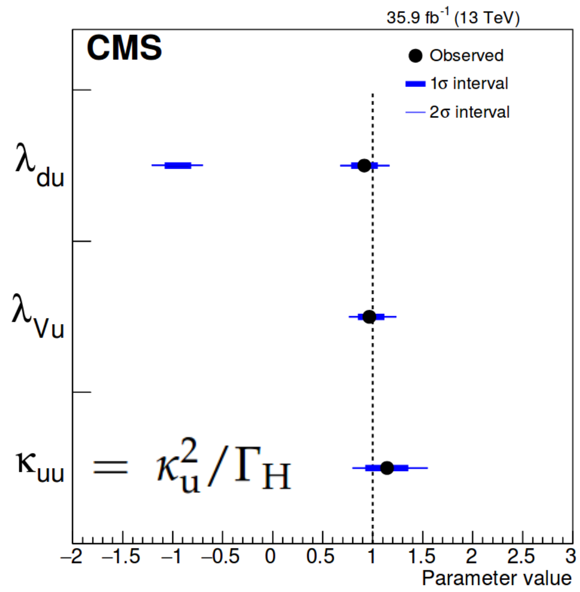
Couplings: Vector Bosons vs. Fermions

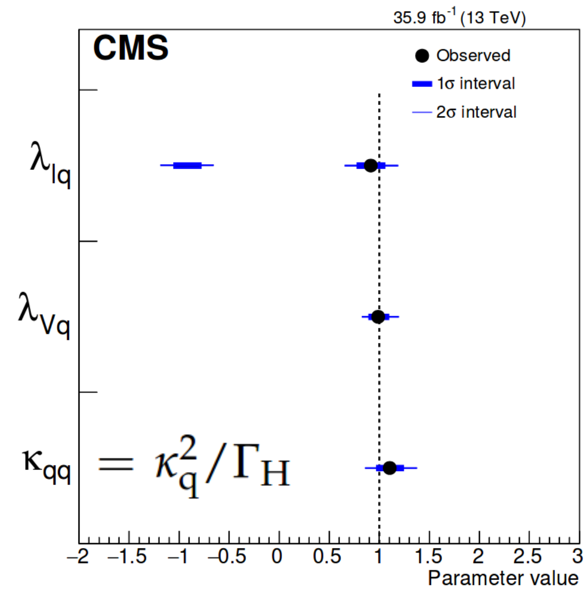
- Assume two separate modifiers: for vector bosons and fermions
- Assume no BSM decays and knowledge of loop processes
- Input from all decay modes needed to obtain strong constraints



Testing Symmetry of Fermion Couplings

- Build different models to test symmetry of up type vs. down type fermion couplings, and quarks vs. leptons
- Can be used to constrain BSM models, such as 2HDM and MSSM...

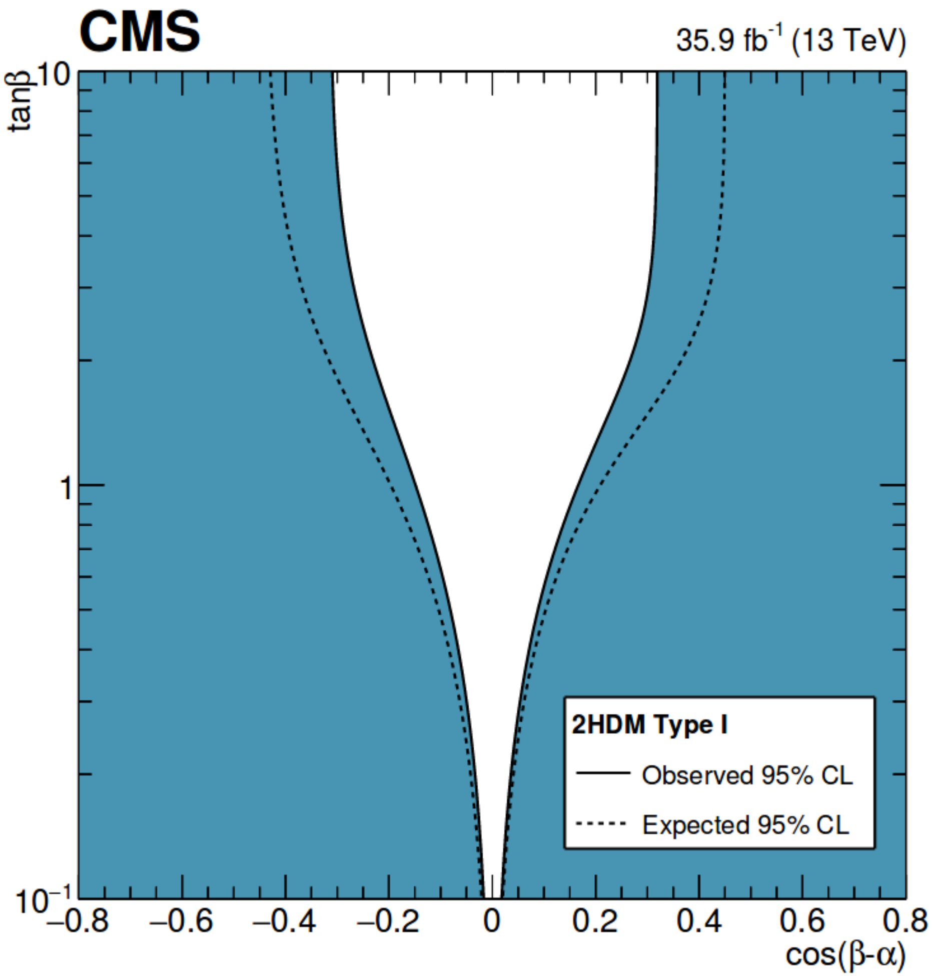


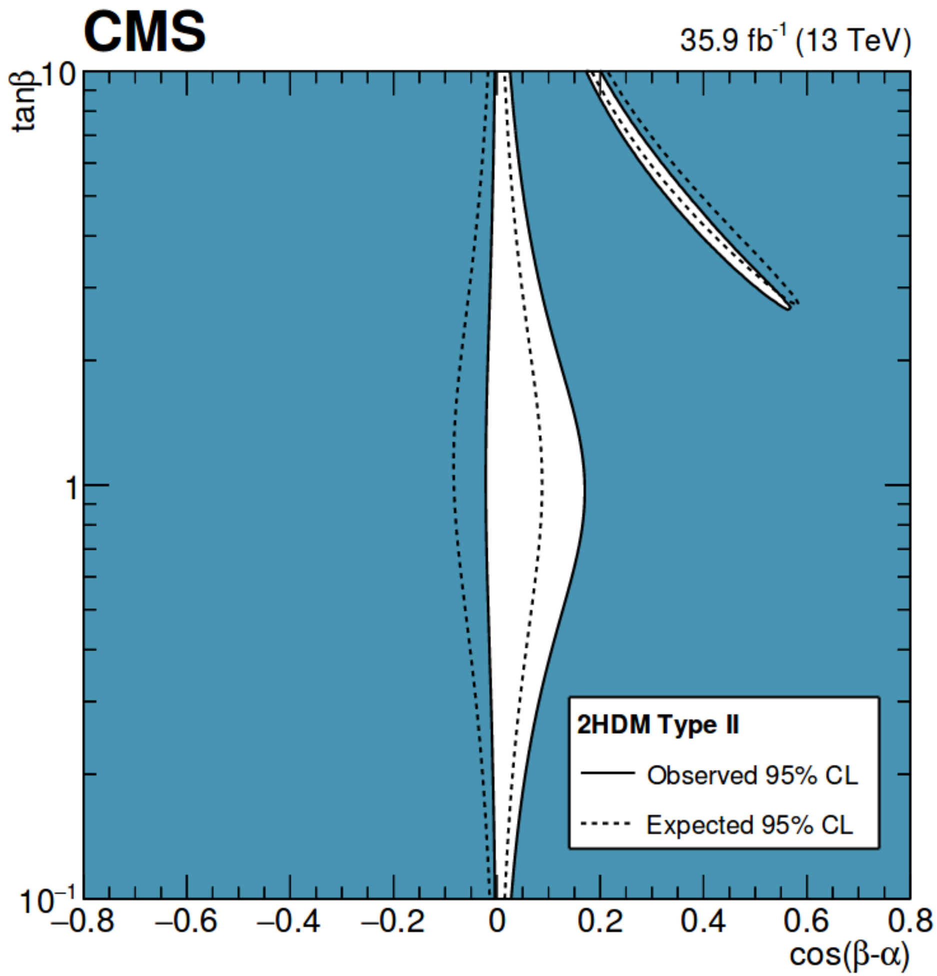


	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$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

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

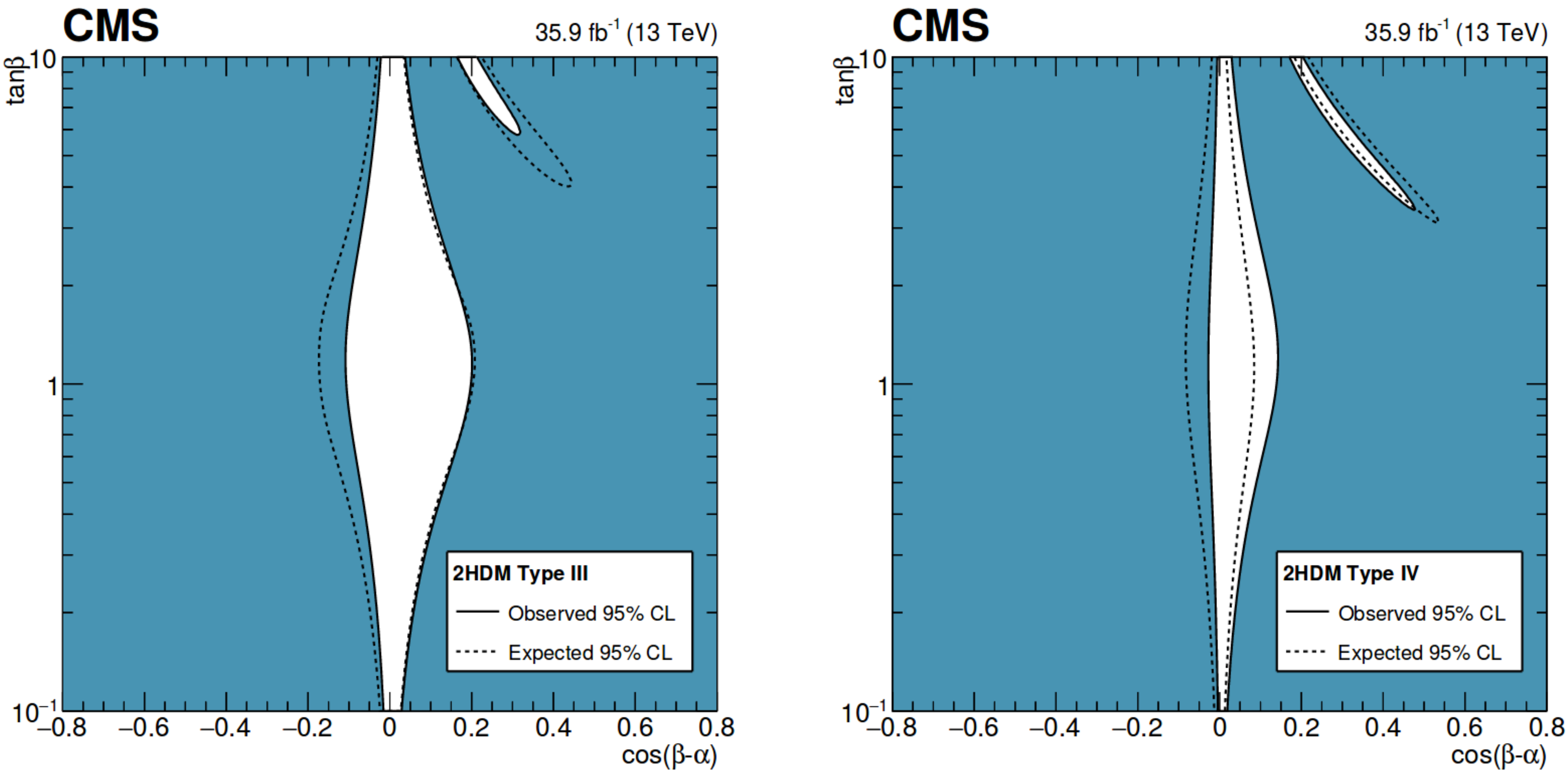
As promised: Constraints on BSM models





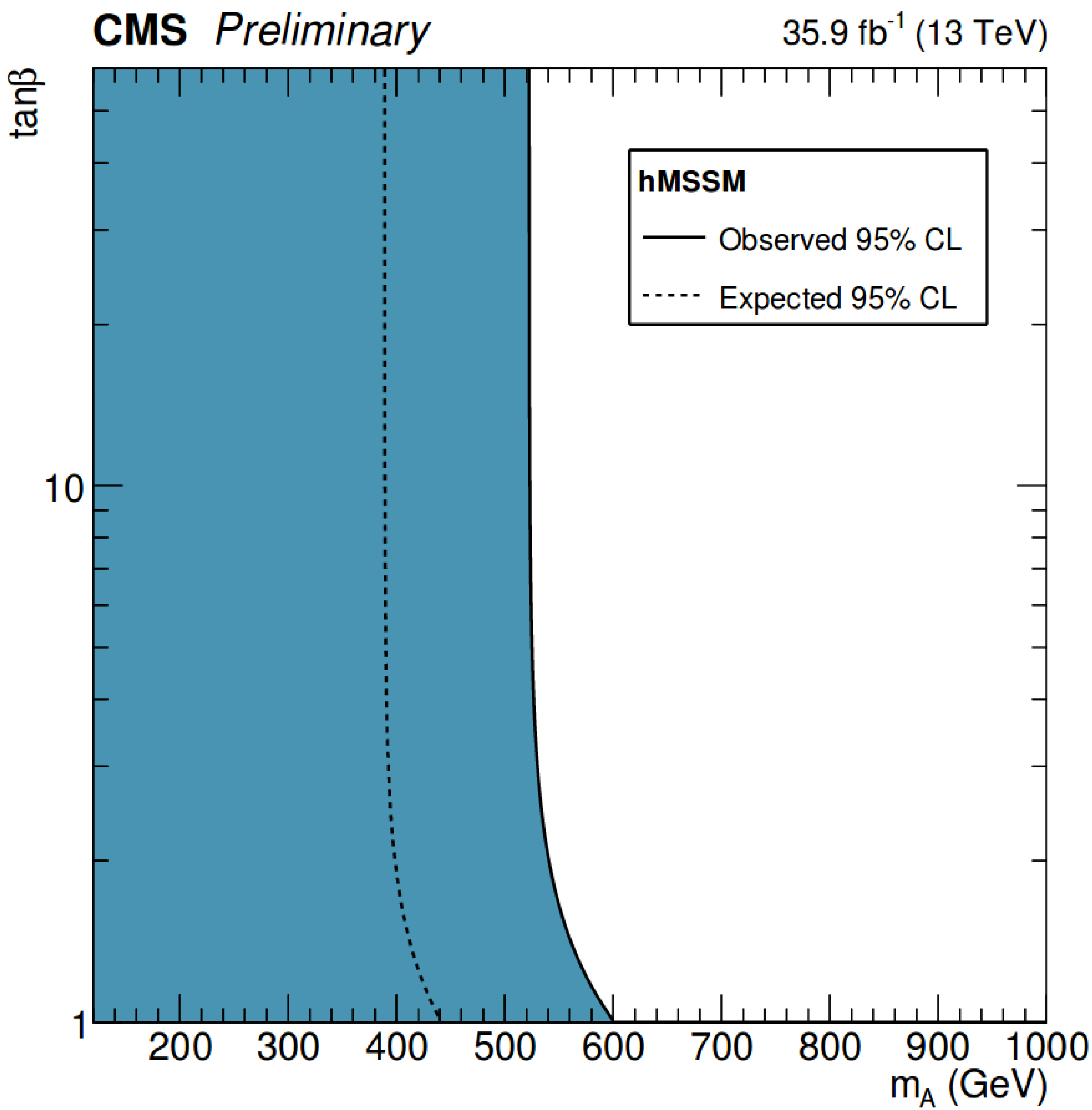
	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$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

As promised: Constraints on BSM models

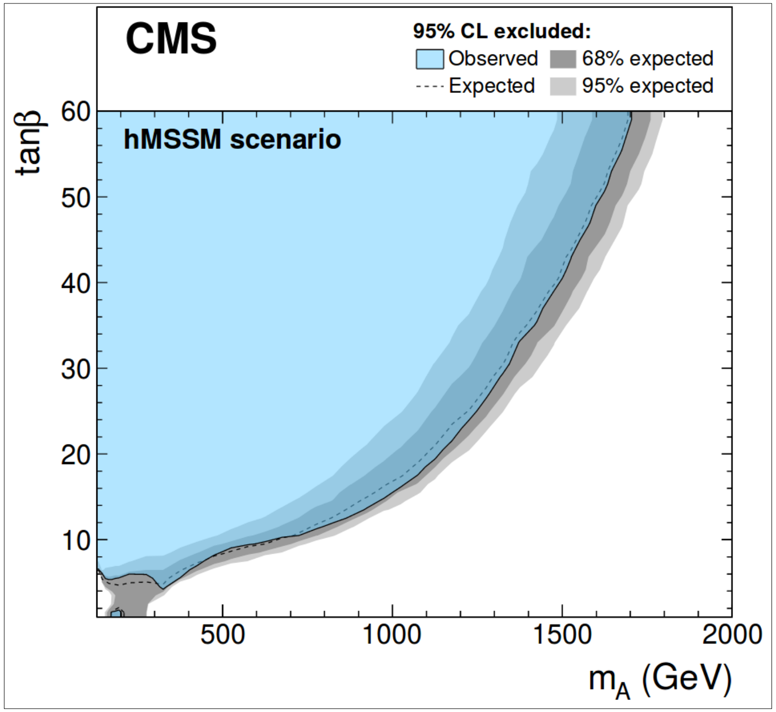


	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$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

As promised: Constraints on BSM models



- Indirect constraints provide complementary information compared to direct searches

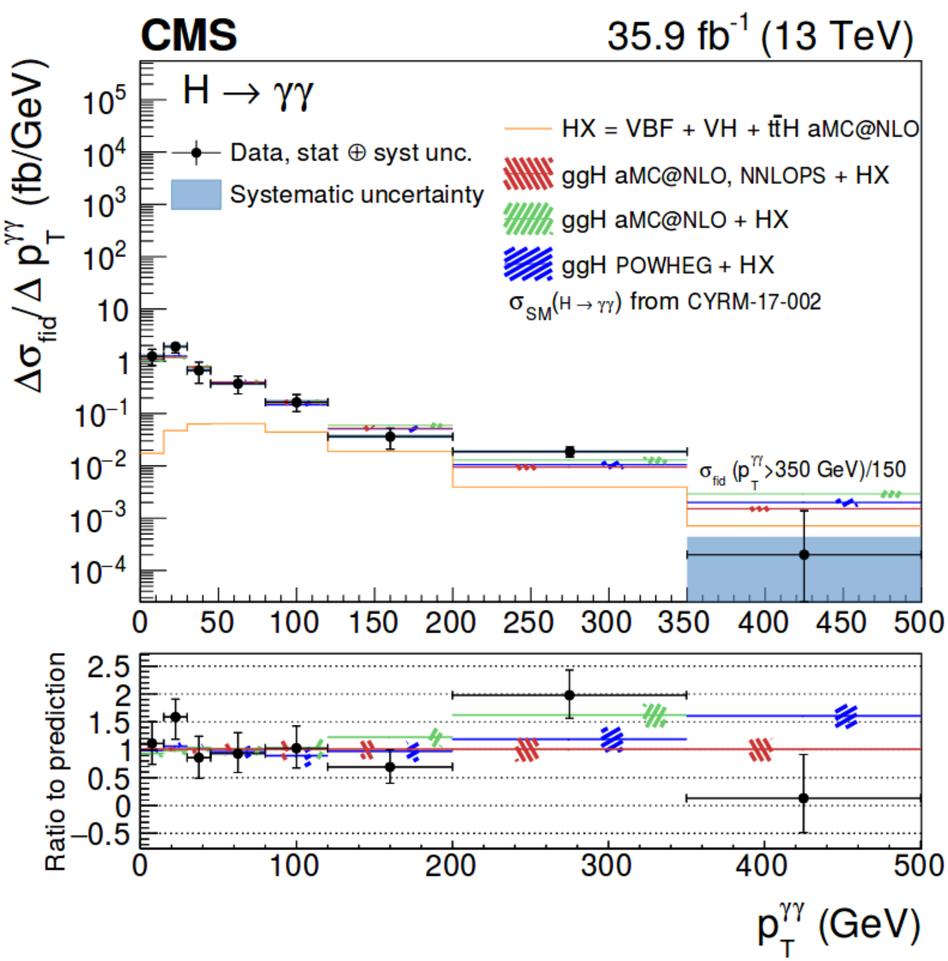


Where do we go from here?

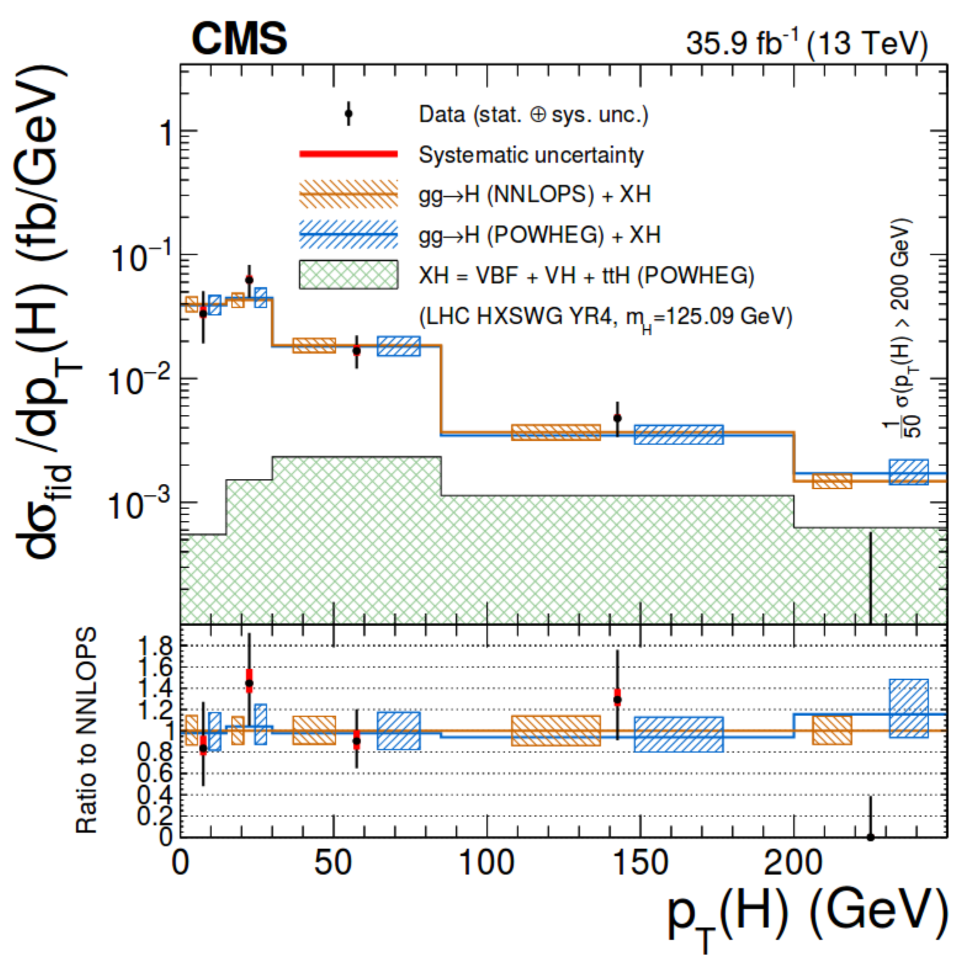
Going Differential

- BSM effects which are small (or zero) inclusively can be better constrained by looking at kinematic distributions
- Such measurements already performed in $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$

arxiv:1807.03825



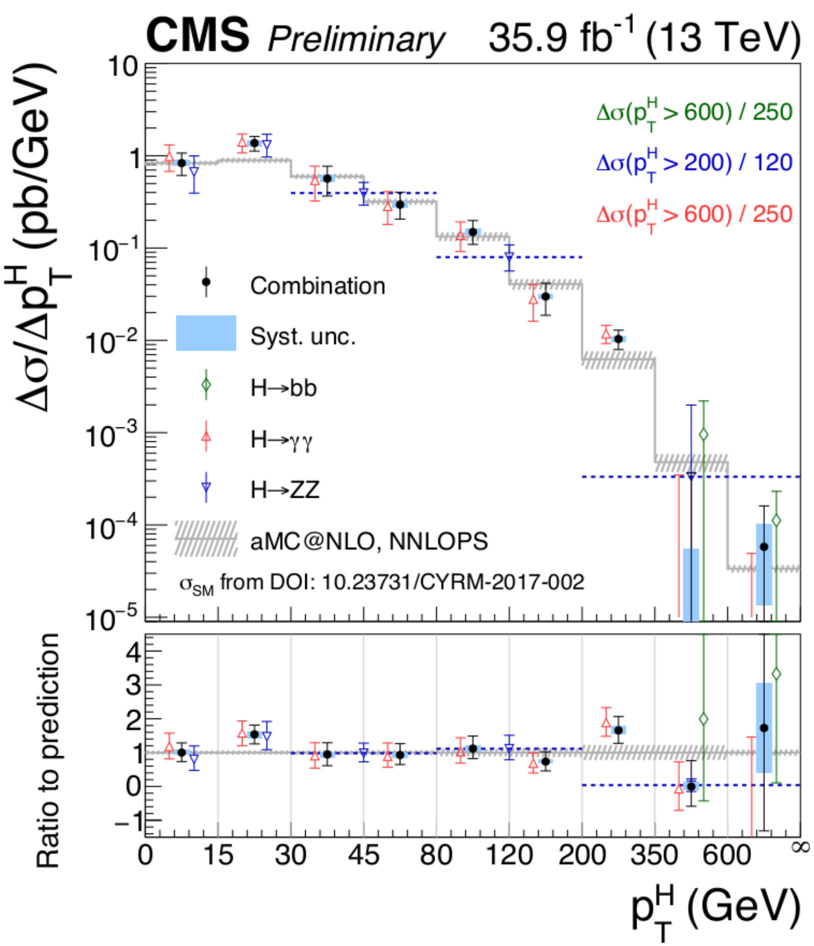
arxiv:1804.02716

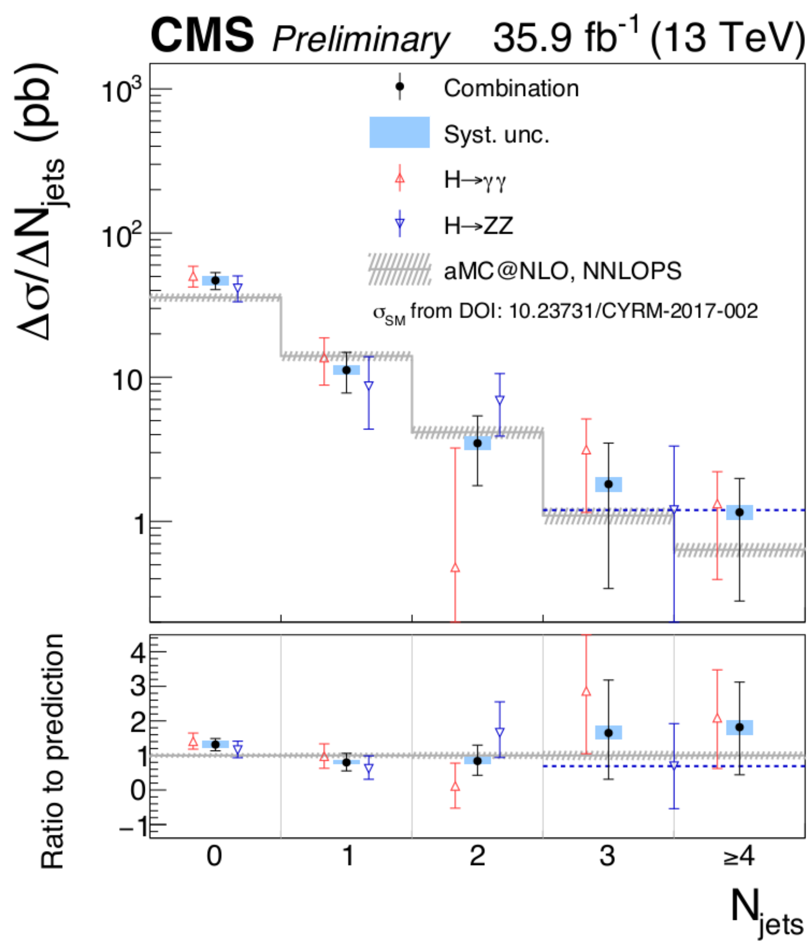


Combination of Differential Spectra

- Assuming SM for acceptance corrections, can combine spectra measured from different decay channels
- Also includes boosted H → bb at high $p_T(H)$

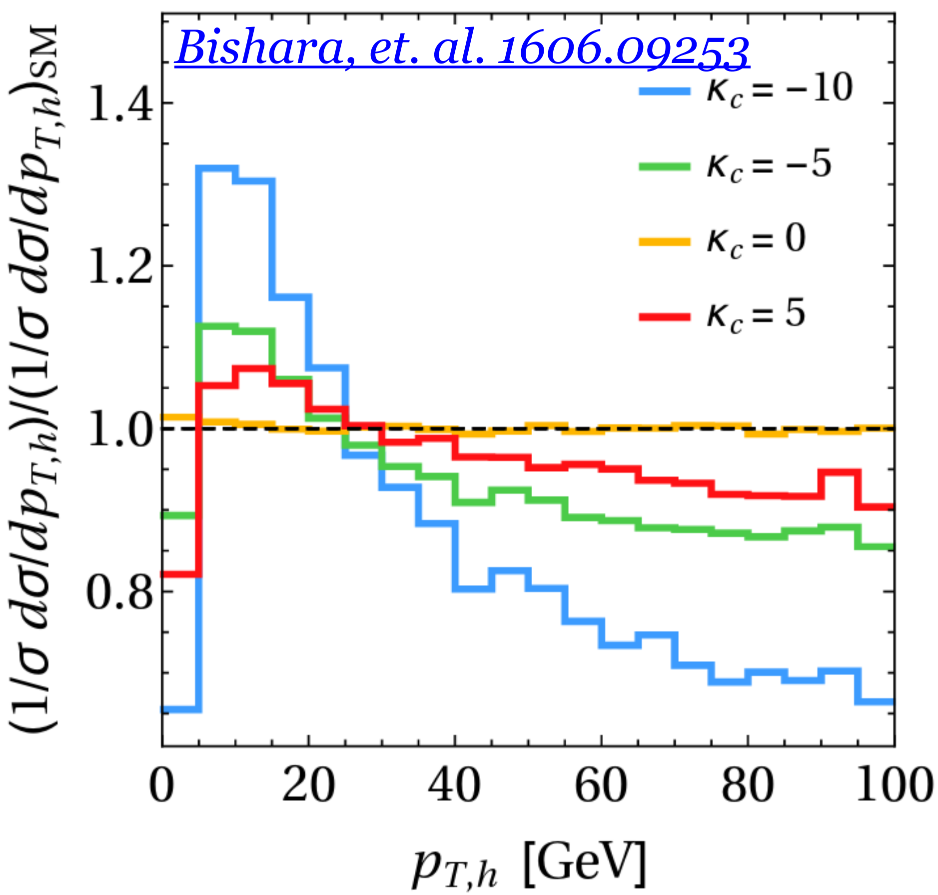
CMS-PAS-HIG-17-028

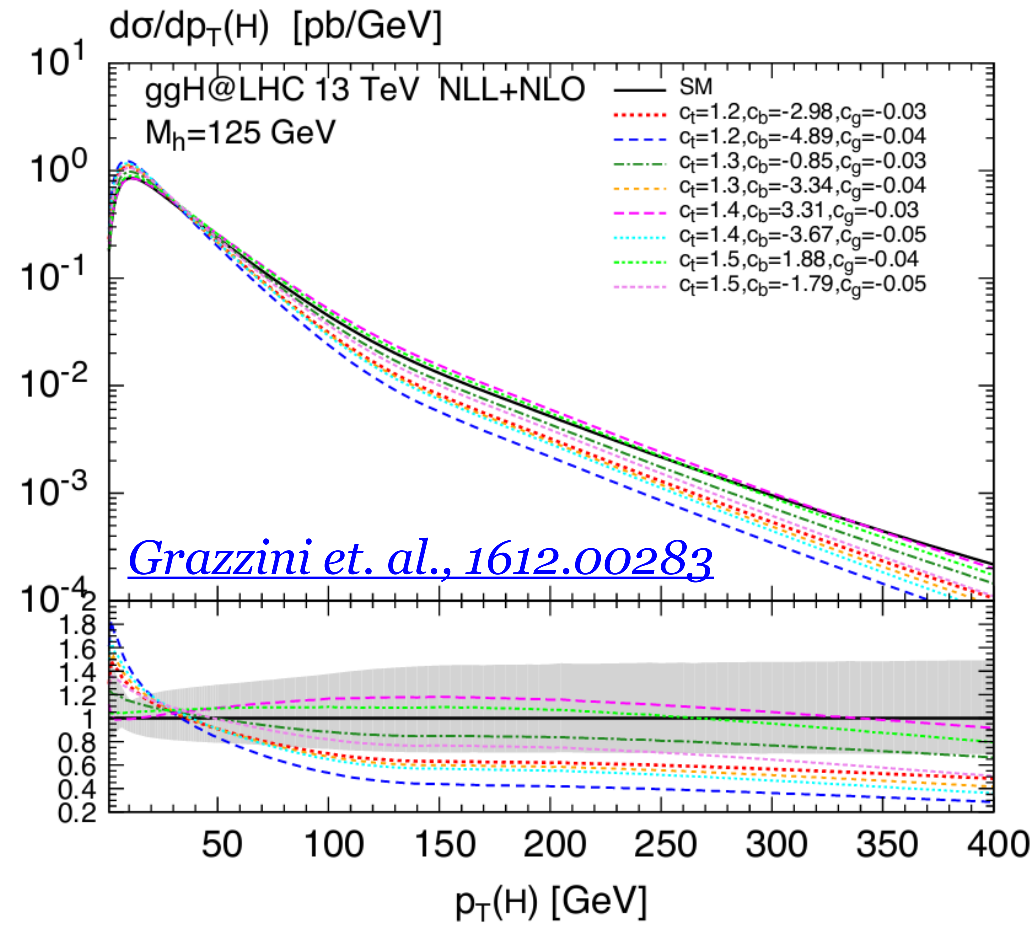




Interpretation of p_T(H) spectra

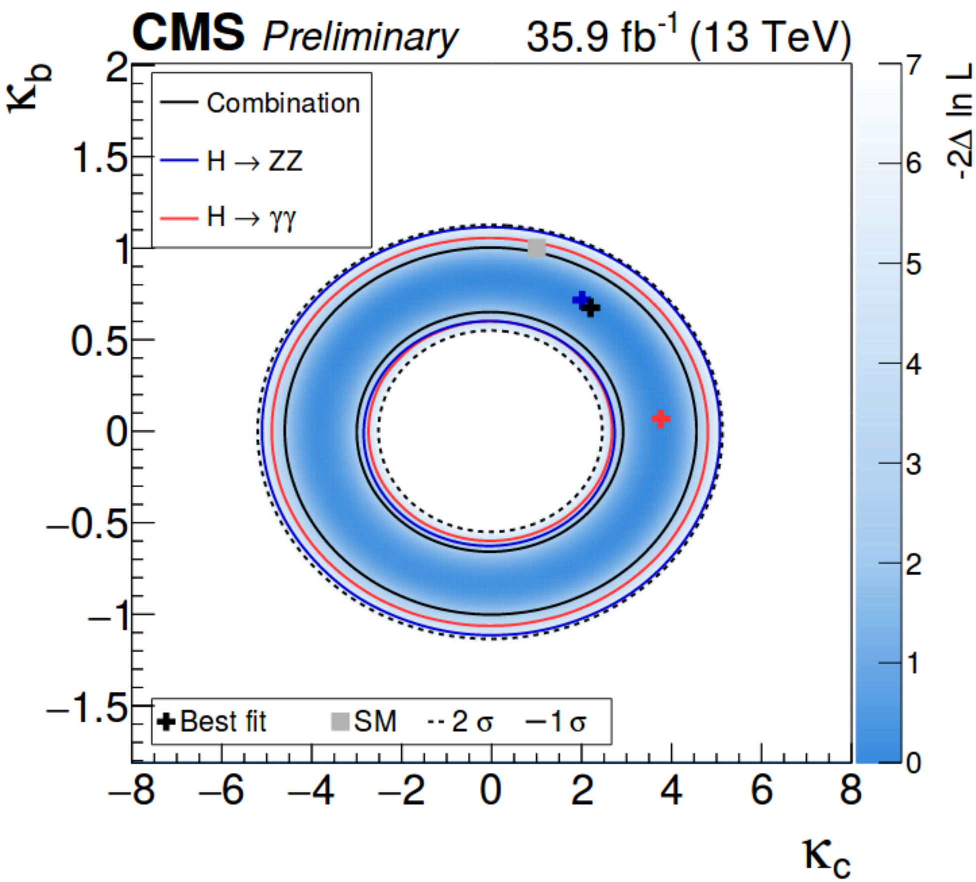
- Higgs p_T spectrum one of the most important differential observables
  - Difficult theoretically due to matching of fixed order and resummed calculations, inclusion of finite top and bottom quark masses
  - Also sensitive to BSM effects, even for the same total cross section



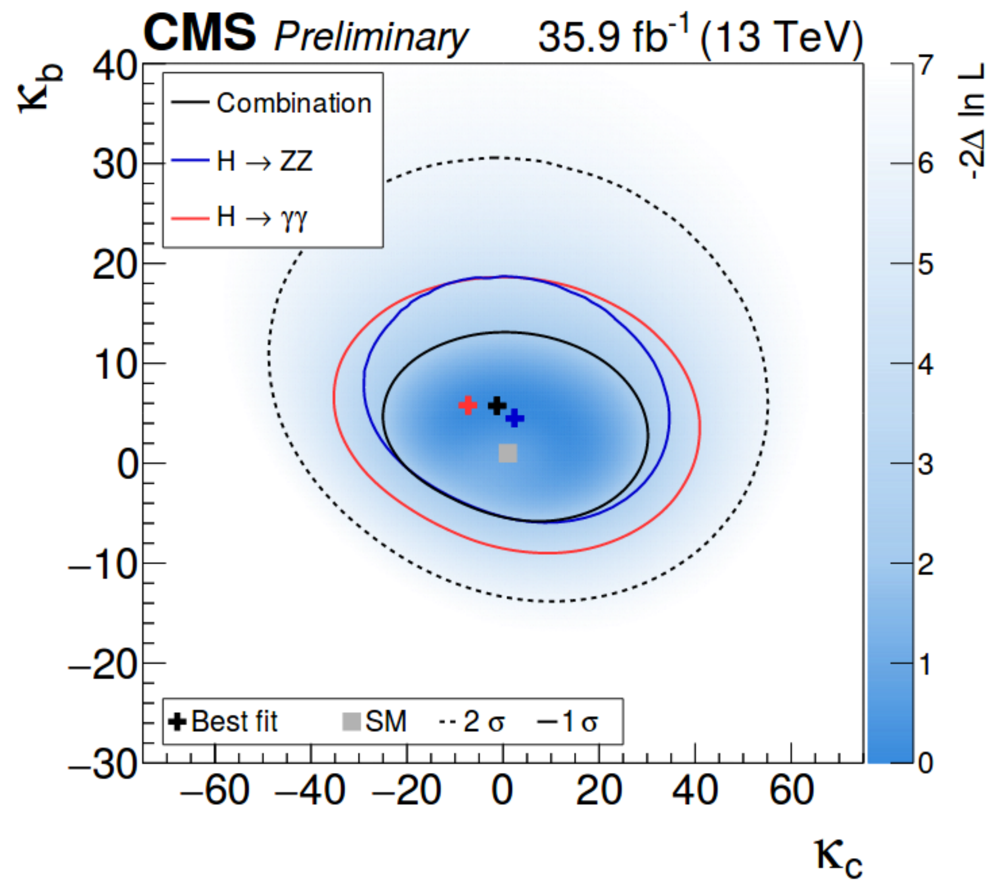


Interpretation of $p_T(H)$ spectra

SM Dependence of BRs and total Higgs width on coupling modifiers



Shape information only, no assumptions on coupling dependence of BR's and total Higgs Width



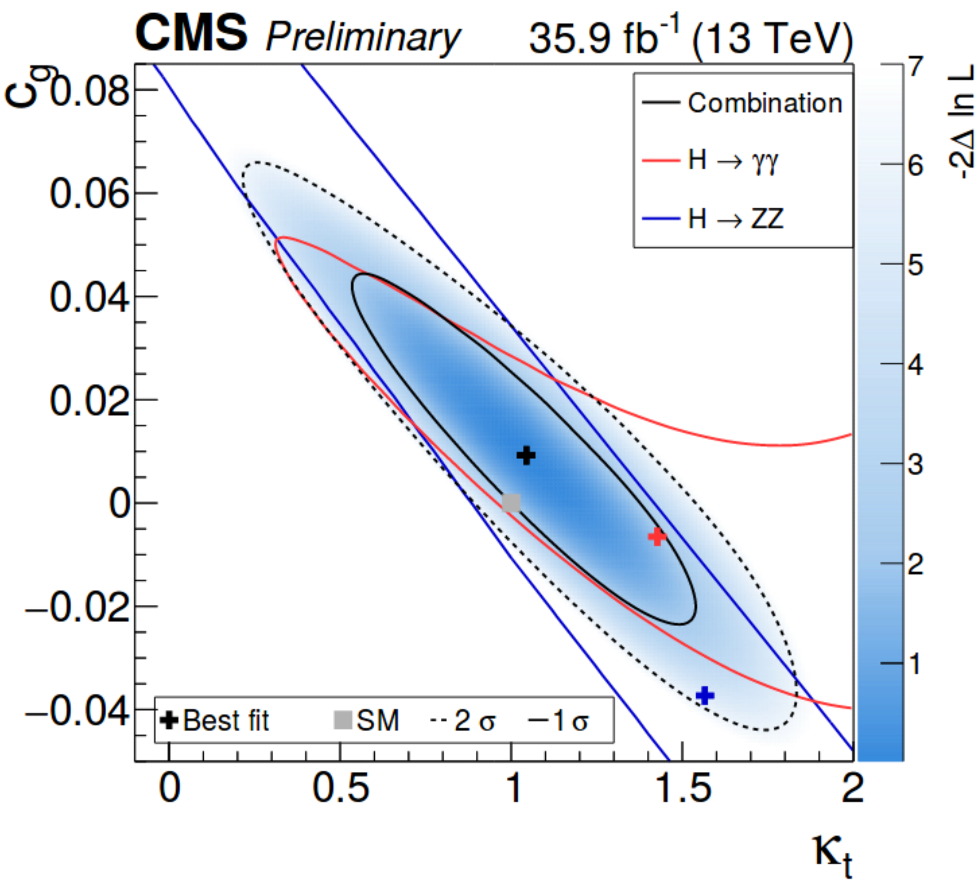
CMS-PAS-HIG-17-028

$$-2.8 < \kappa_b < 9.9 \quad (-3.7 < \kappa_b < 7.3 \ \text{expected}),$$

$$-18.0 < \kappa_c < 22.9 \quad (-15.7 < \kappa_c < 19.3 \ \text{expected}),$$

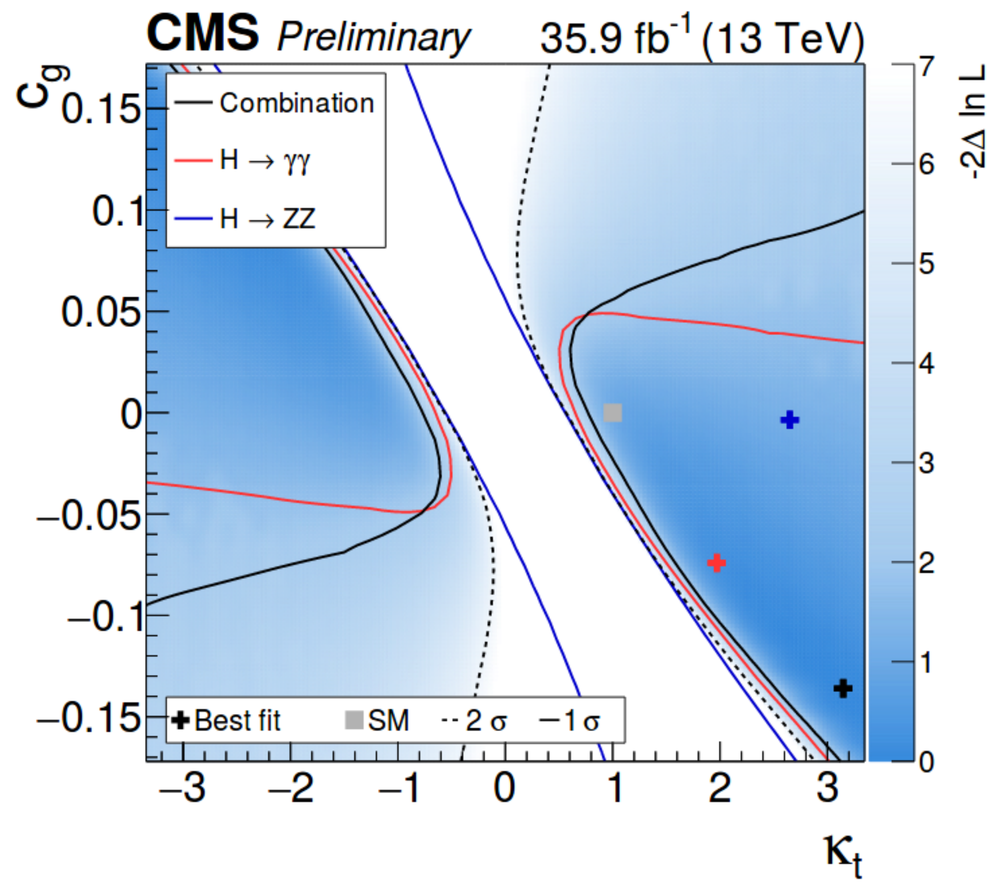
Interpretation of $p_T(H)$ spectra

SM Dependence of BRs and total Higgs width on coupling modifiers



CMS-PAS-HIG-17-028

Shape information only, no assumptions on coupling dependence of BR's and total Higgs Width



$$\sigma \simeq \left|12c_g + \kappa_t\right|^2 \sigma^{SM}$$

Interpretation of $p_T(H)$ spectra

$$O_6 = -\lambda \left(H^\dagger H\right)^3 \implies \mathcal{L} \supset -\lambda c_3 v h^3 = -\lambda \left(1 + \bar{c}_6 - \frac{3\bar{c}_H}{2}\right) v h^3$$

arxiv:1610.05771

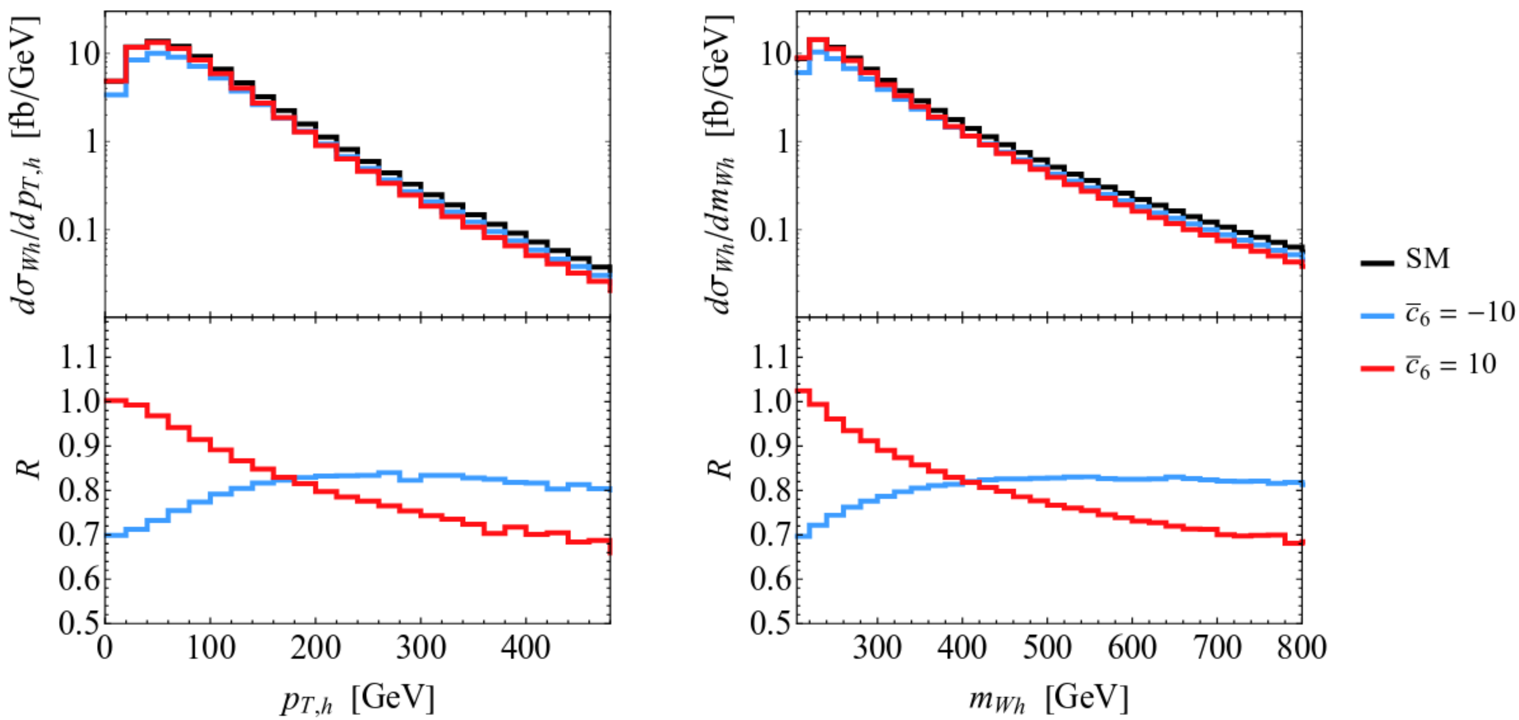
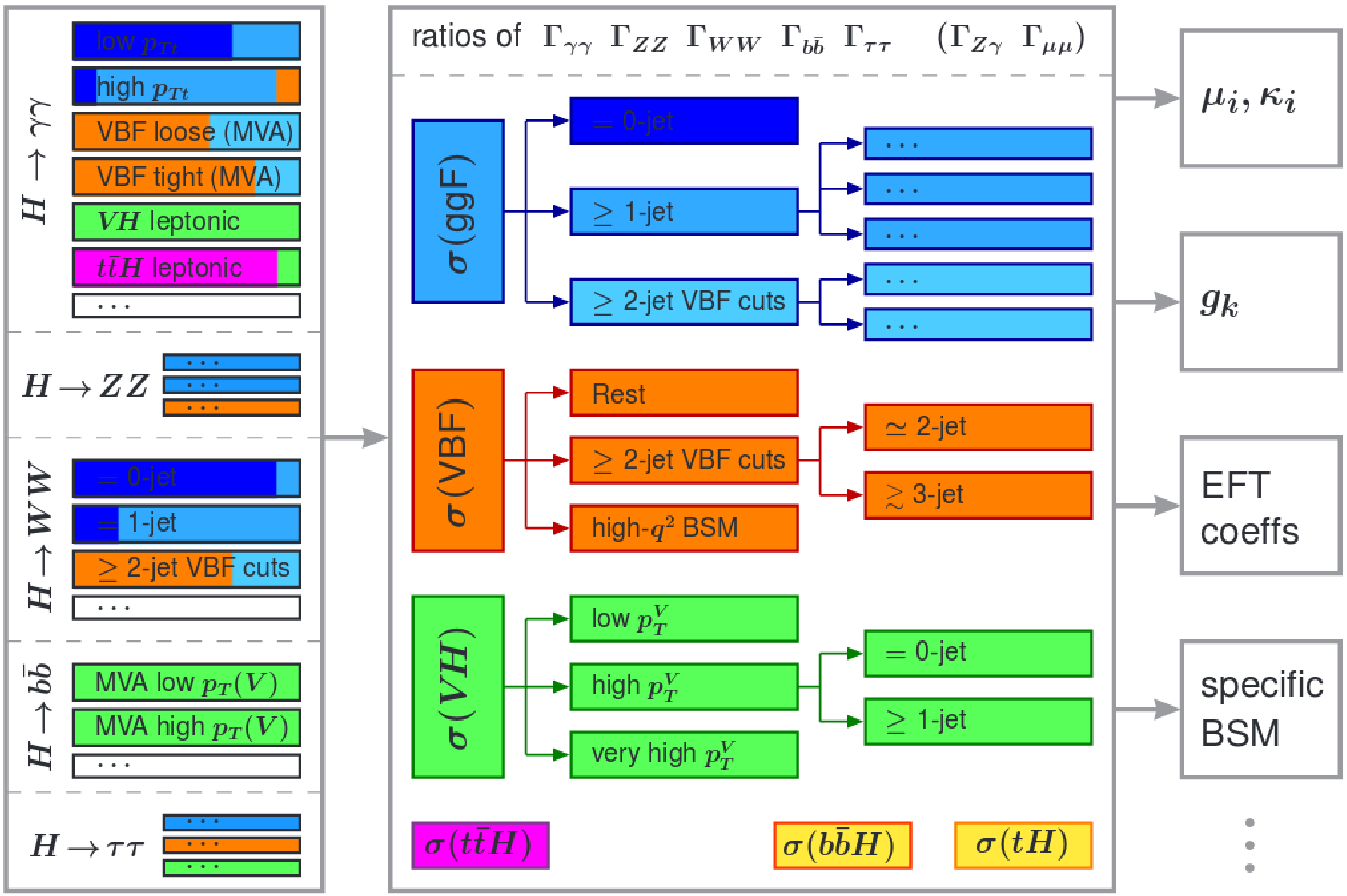
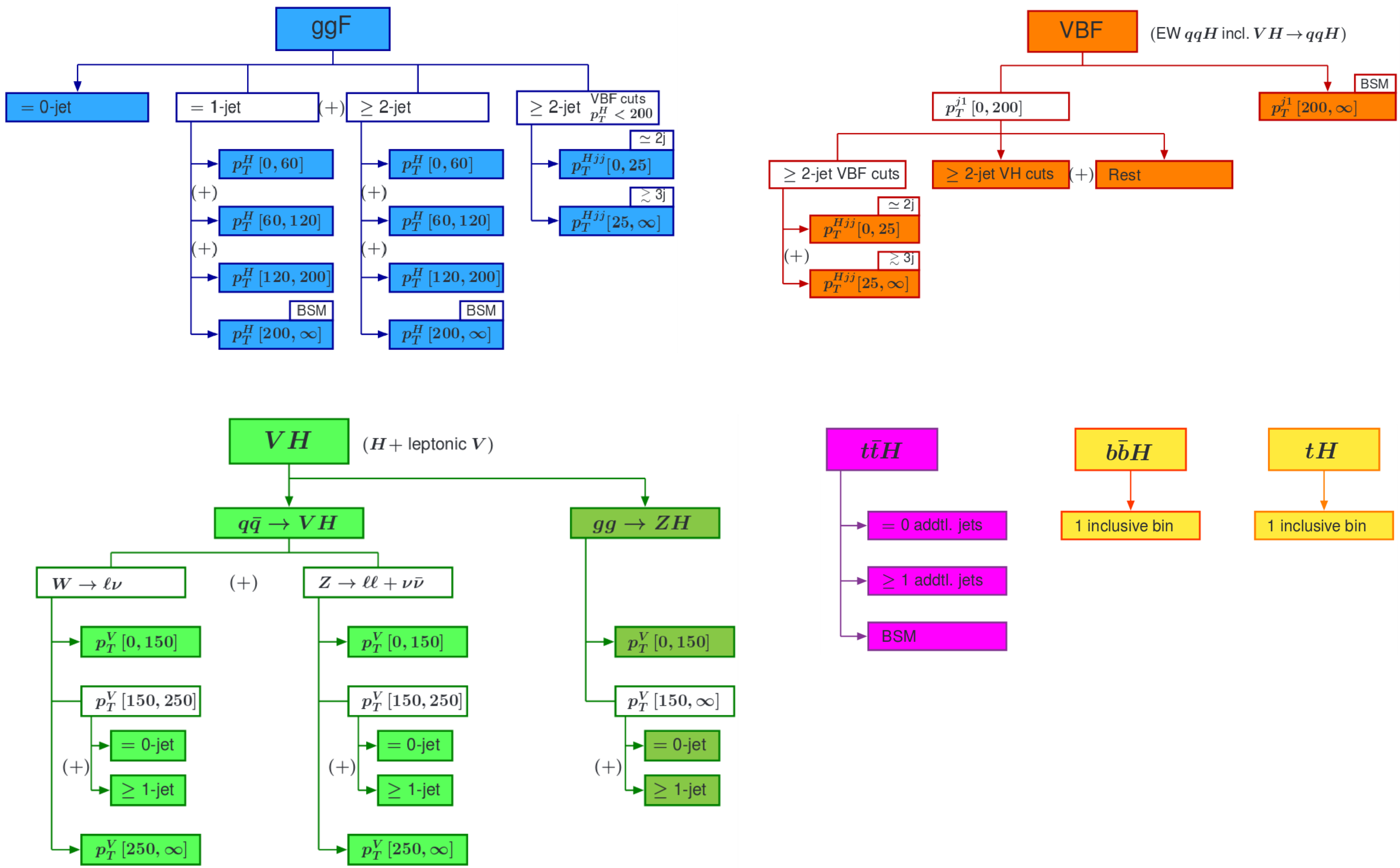


Figure 6. Comparison of the $p_{T,h}$ (left) and m_{Wh} (right) spectrum in Wh production. The upper panels show the SM predictions (black) as well as the cases $\bar{c}_6 = -10$ (blue) and $\bar{c}_6 = 10$ (red). The ratios between the case $\bar{c}_6 = -10$ and the SM (blue) and the case $\bar{c}_6 = 10$ and the SM (red) are displayed in the lower panels. All results correspond to pp collisions at $\sqrt{s} = 13\,\text{TeV}$.

“Simplified Template Cross Sections”

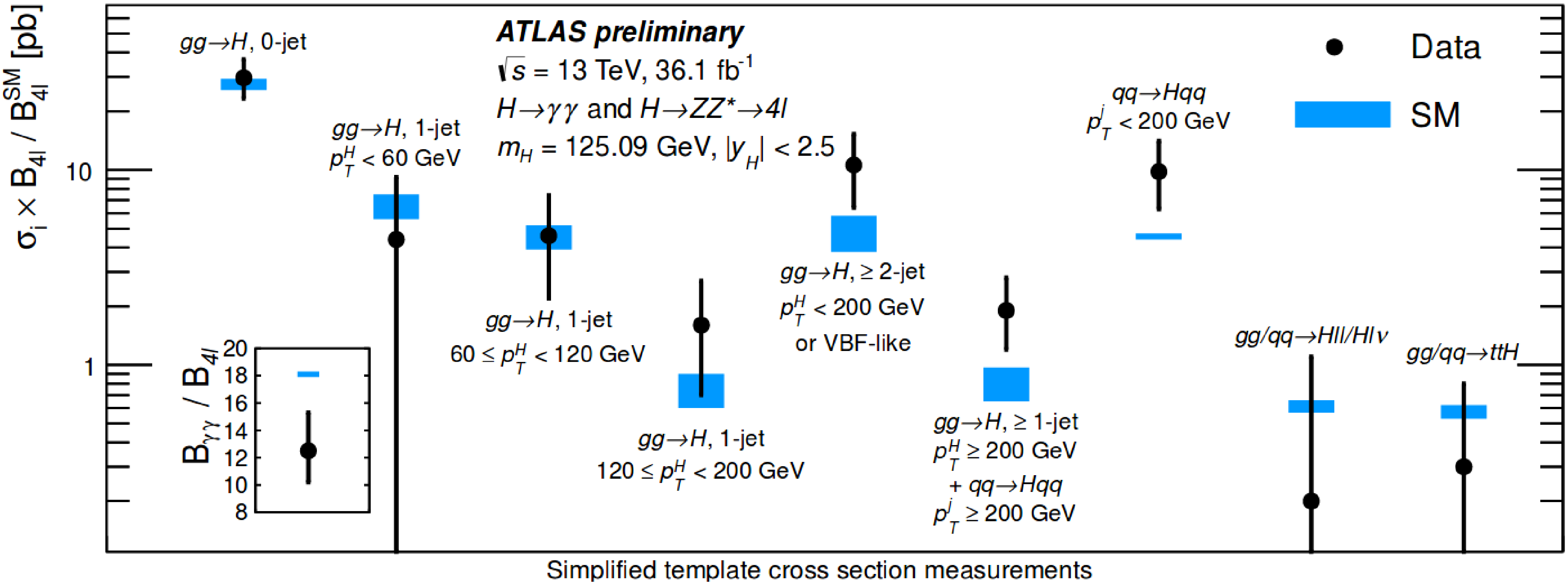


“Simplified Template Cross Sections”



"Simplified Template Cross Sections"

ATLAS-CONF-2017-047



Summary & Outlook

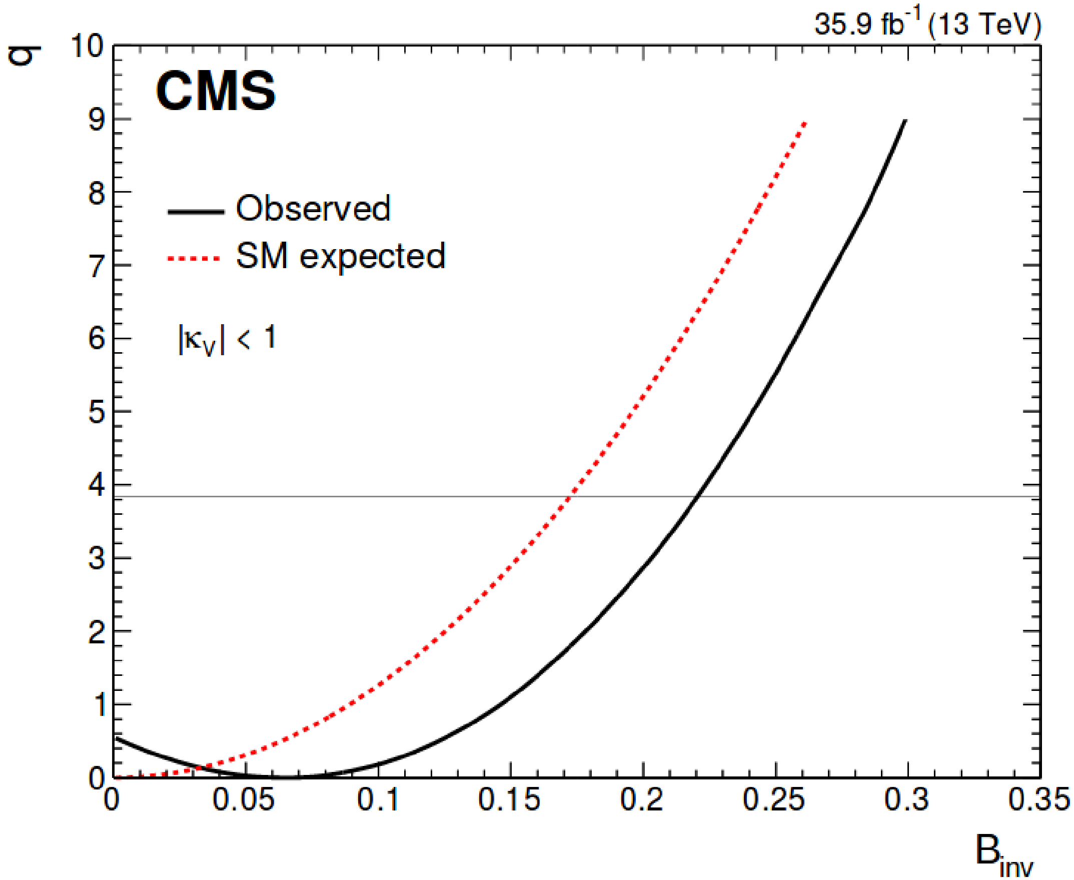
- The Higgs is a special particle and the Higgs sector is the least tested part of the Standard Model
- Extracting Higgs couplings requires a combination of all possible production and decay channels (as well as many assumptions)
- We are moving past the “observation” phase and are now testing for subtle deviations predicted by BSM models, and already placing constraints that are complementary to direct searches
- We need to move towards more fine grained study of the kinematics of each production process (and possibly decay processes as well!)

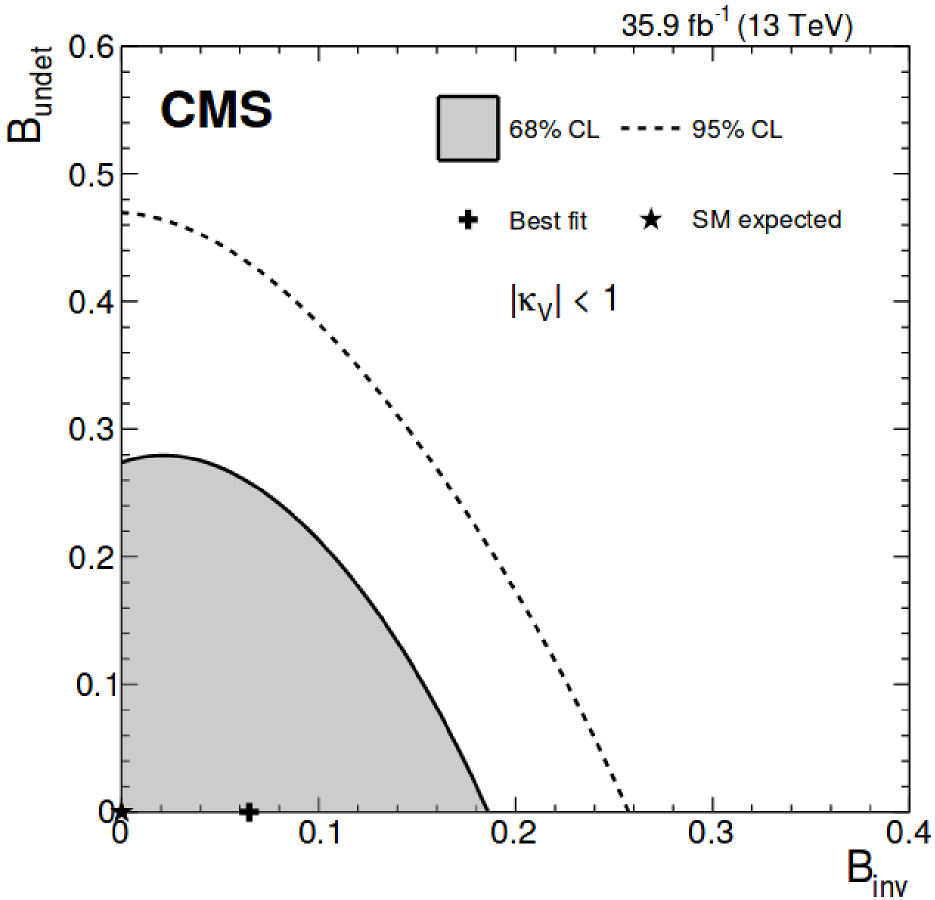
Backup

Unfortunately, It's all Compatible...

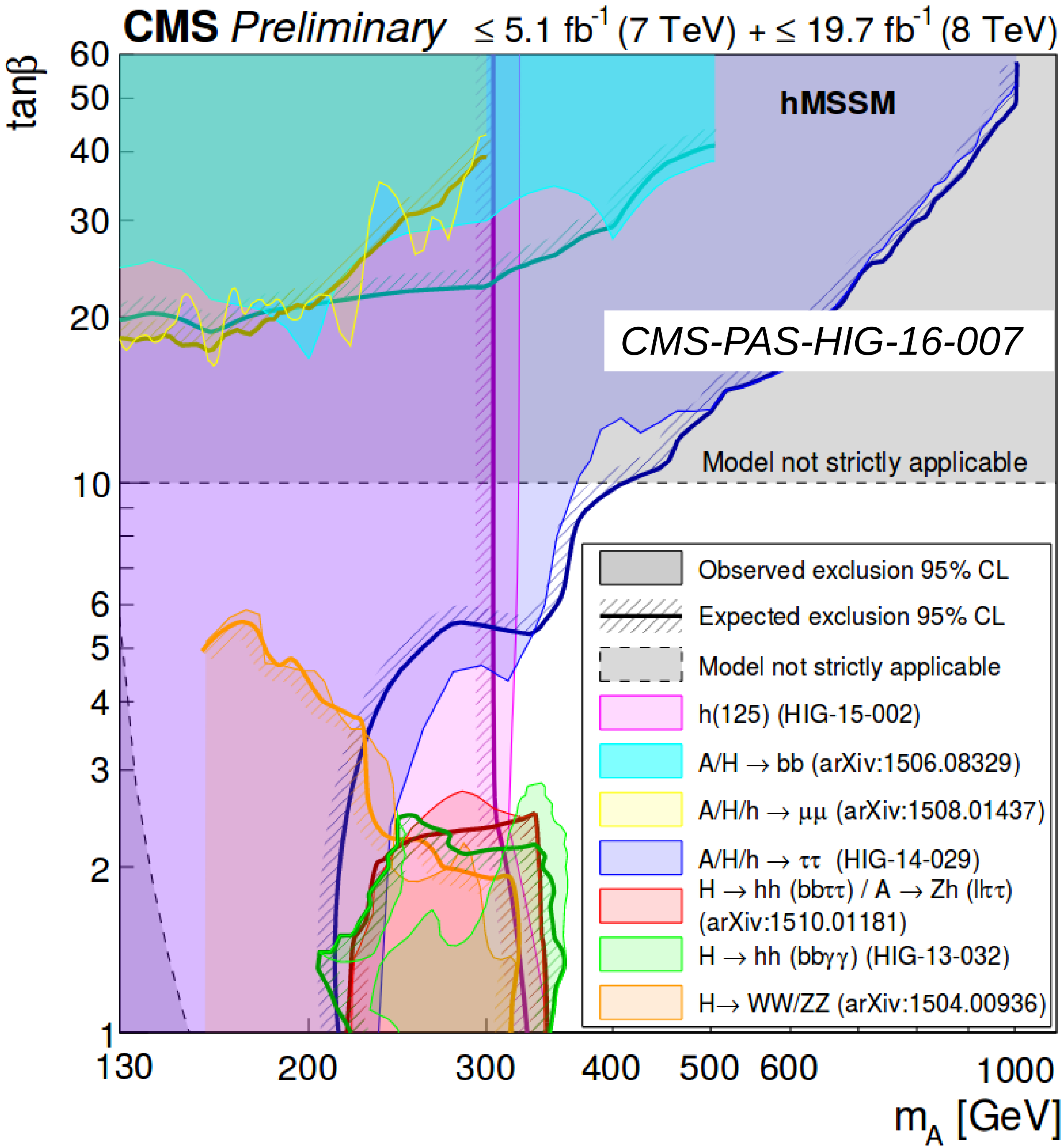
Parameterization	p-value (q_{SM})	DOF	Parameters of interest
Global signal strength	6.28% (3.46)	1	μ
Production processes	9.87% (9.27)	5	$\mu_{ggH}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	53.8% (5.05)	6	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}, \mu^{\mu\mu}$
$\sigma_i \mathcal{B}^f$ 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 $\rightarrow$ H $\rightarrow$ ZZ	32.3% (11.5)	10	$\mu^{ZZ}_{ggH}, \mu_{VBF}/\mu_{ggH}, \mu_{WH}/\mu_{ggH}, \mu_{ZH}/\mu_{ggH}, \mu_{ttH}/\mu_{ggH}$, $\mu^{WW}/\mu^{ZZ}, \mu^{\gamma\gamma}/\mu^{ZZ}, \mu^{\tau\tau}/\mu^{ZZ}, \mu^{bb}/\mu^{ZZ}, \mu^{bb}/\mu^{\mu\mu}$
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 $\rightarrow$ 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	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$

Constraints on BSM Decays





Constraints on benchmark BSM models

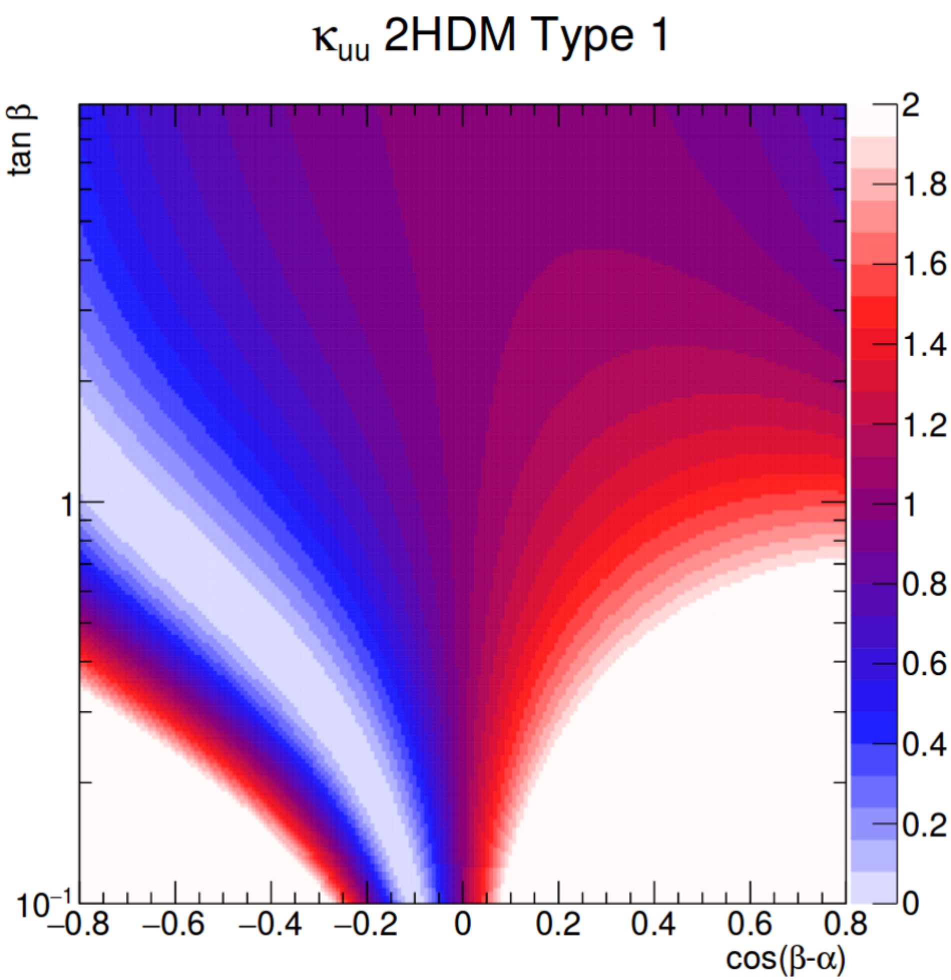


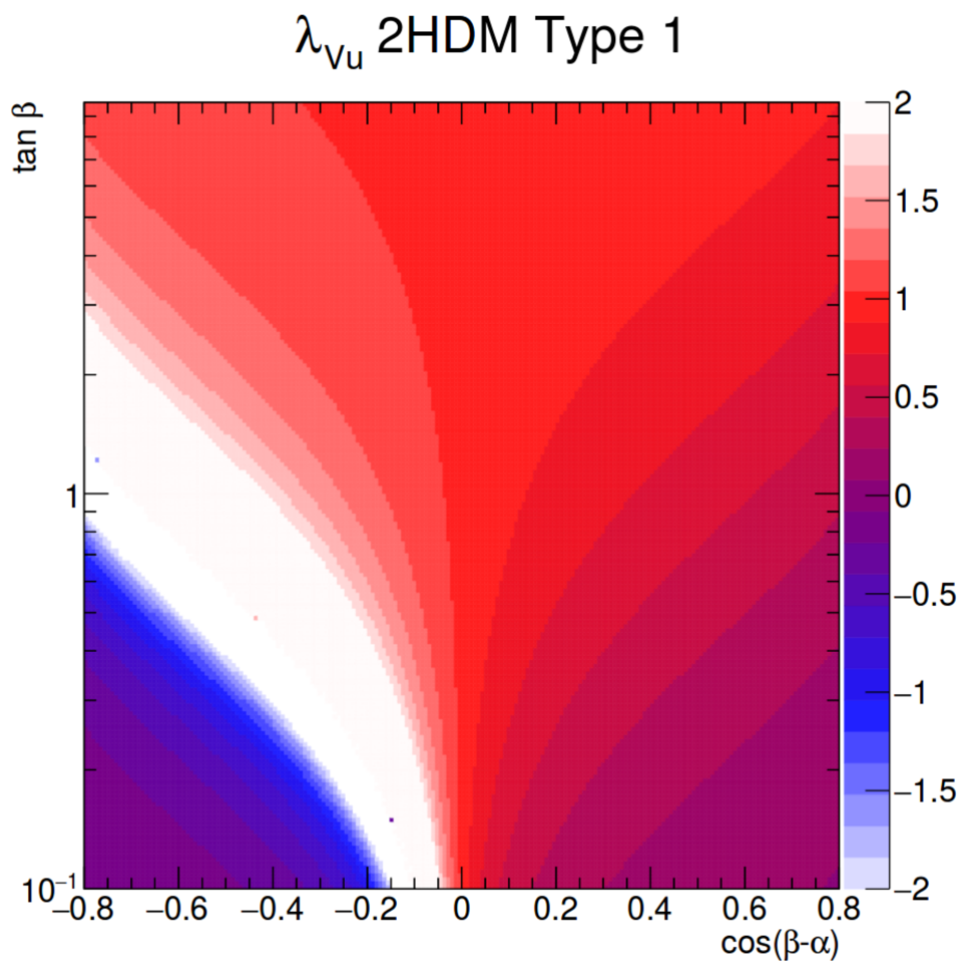
Constraints on benchmark BSM models

arxiv:1401.0152

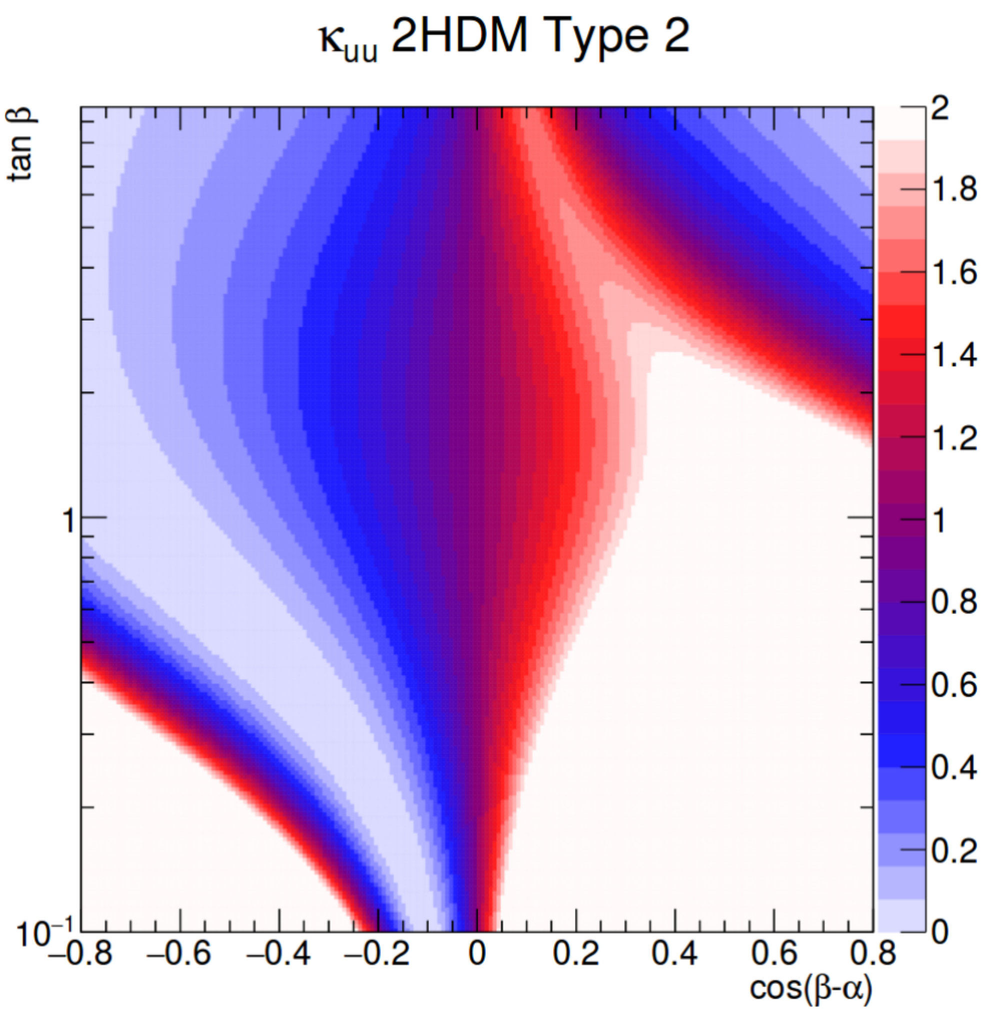
Higgs interaction	2HDM coupling	decoupling limit
hVV	$\sin(\beta-\alpha)$	$1-\frac{1}{2}\cos^2(\beta-\alpha)$
hhh	see eq. (61) of Ref. [26]	$1+2(Z_6/Z_1)\cos(\beta-\alpha)$
$hhhh$	see eq. (62) of Ref. [26]	$1+3(Z_6/Z_1)\cos(\beta-\alpha)$
$h\overline{D}D$ [Type-I] , $h\overline{U}U$ [Types-I and II]	$\frac{\cos\alpha}{\sin\beta}=\sin(\beta-\alpha)+\cos(\beta-\alpha)\cot\beta$	$1+\cos(\beta-\alpha)\cot\beta$
$h\overline{D}D$ [Type-II]	$-\frac{\sin\alpha}{\cos\beta}=\sin(\beta-\alpha)-\cos(\beta-\alpha)\tan\beta$	$1-\cos(\beta-\alpha)\tan\beta$

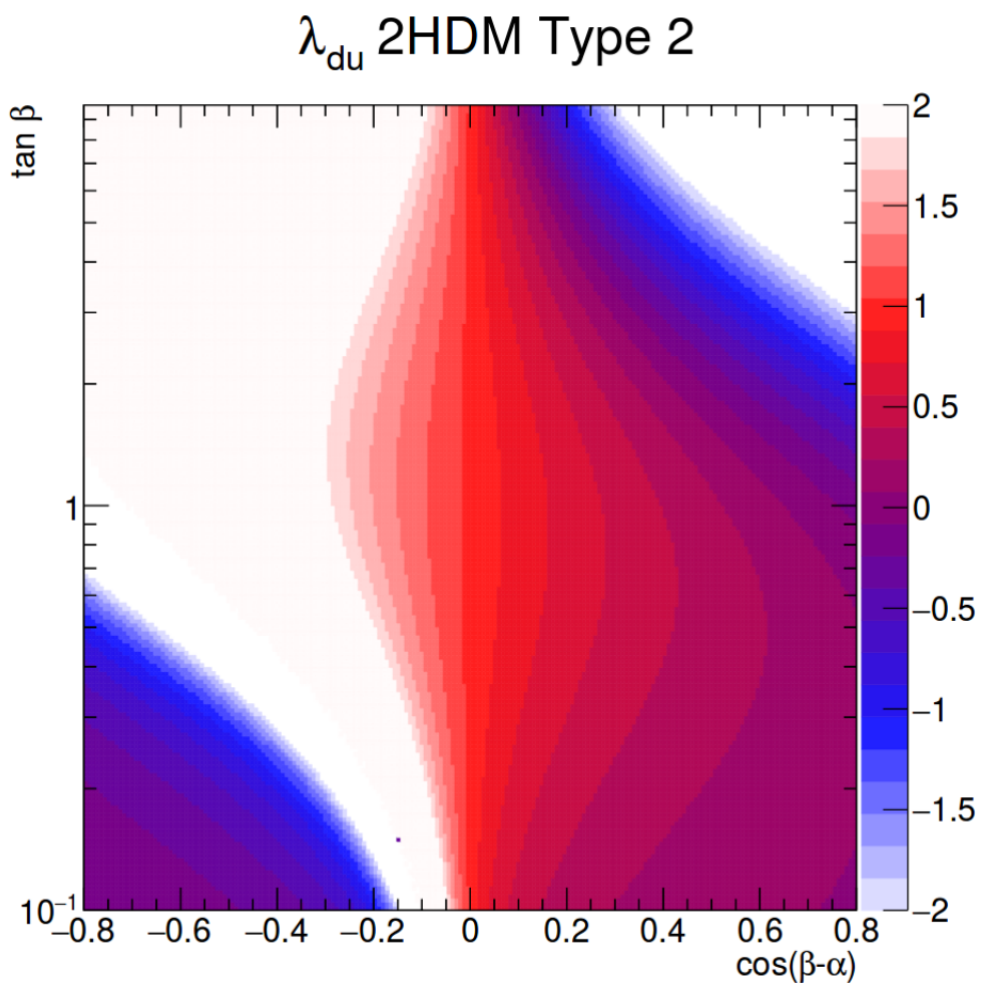
Constraints on benchmark BSM models



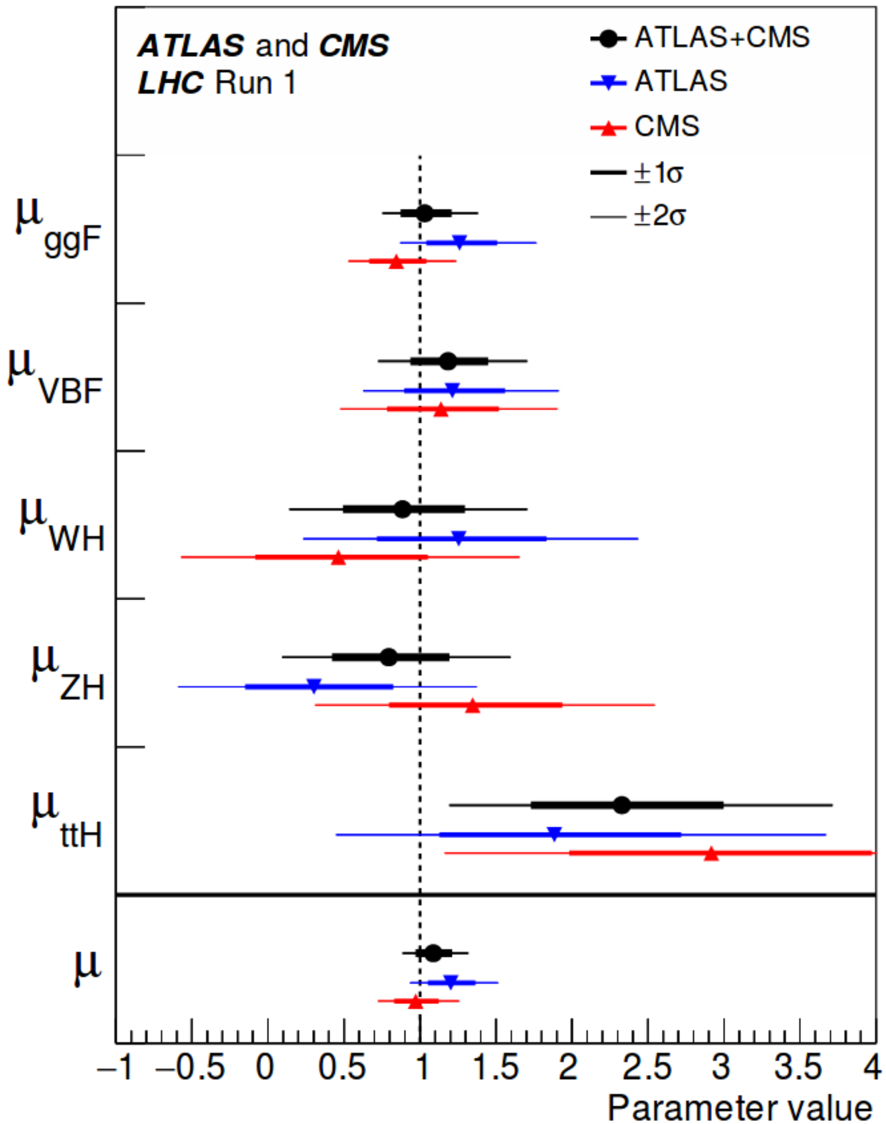


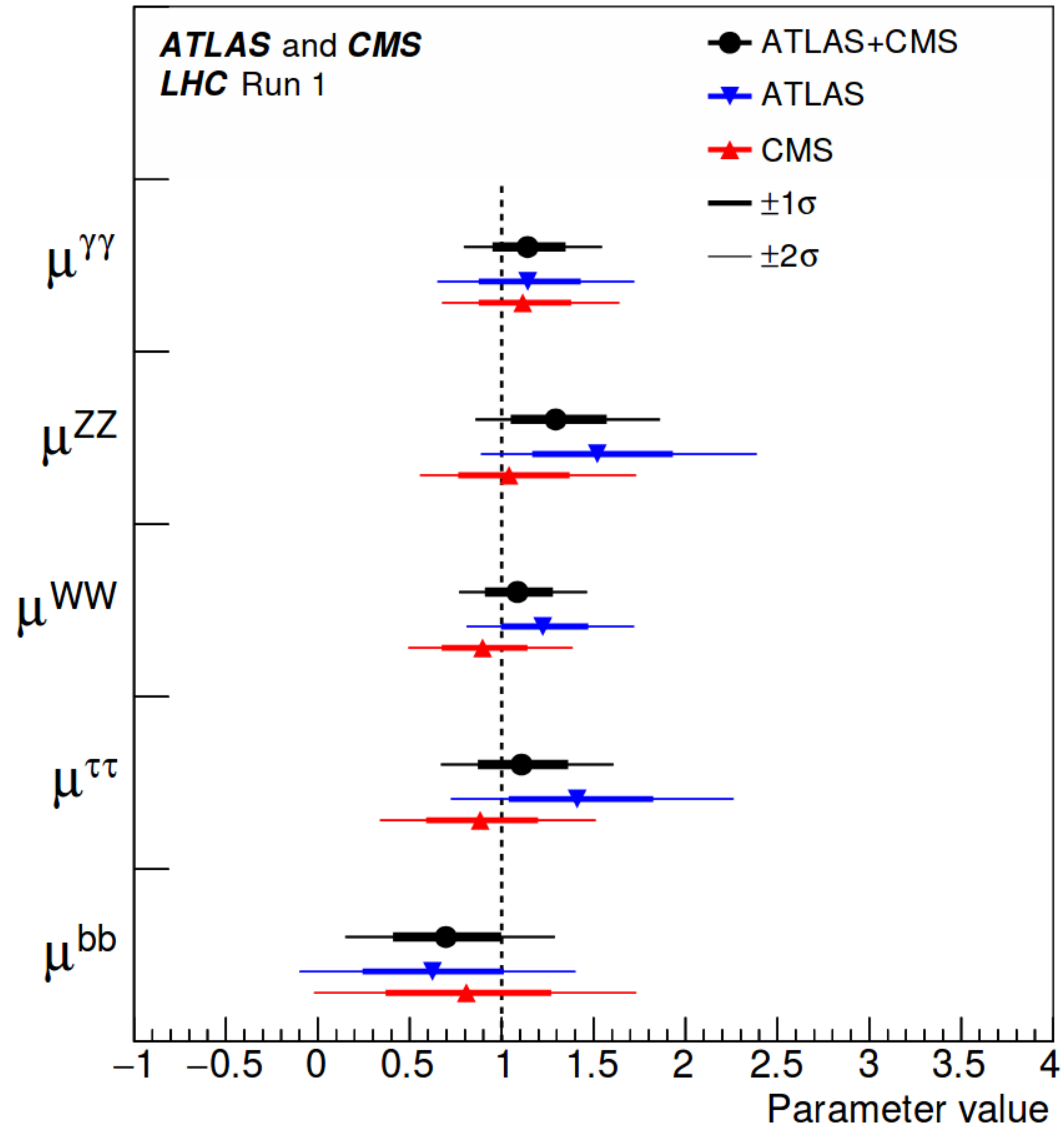
Constraints on benchmark BSM models





ATLAS+CMS Combination





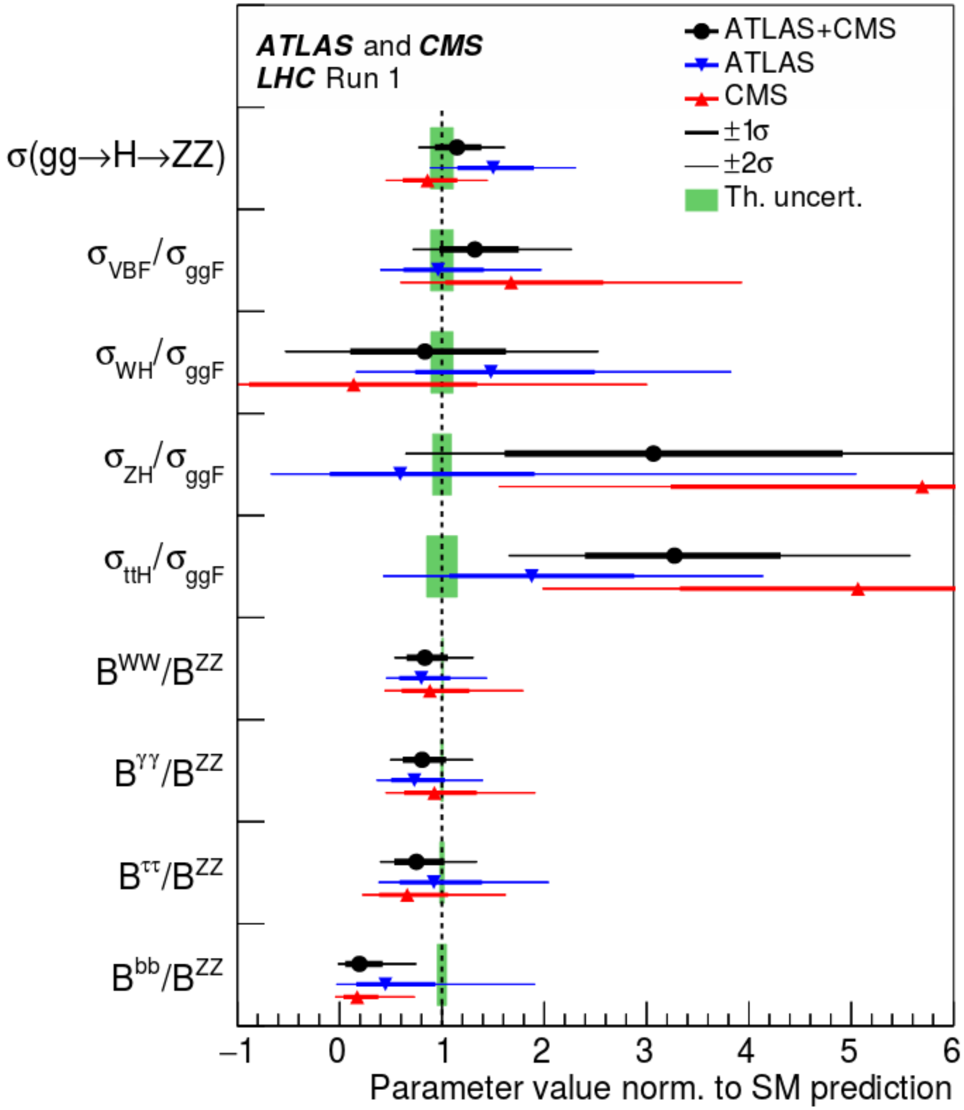
ATLAS+CMS Combination

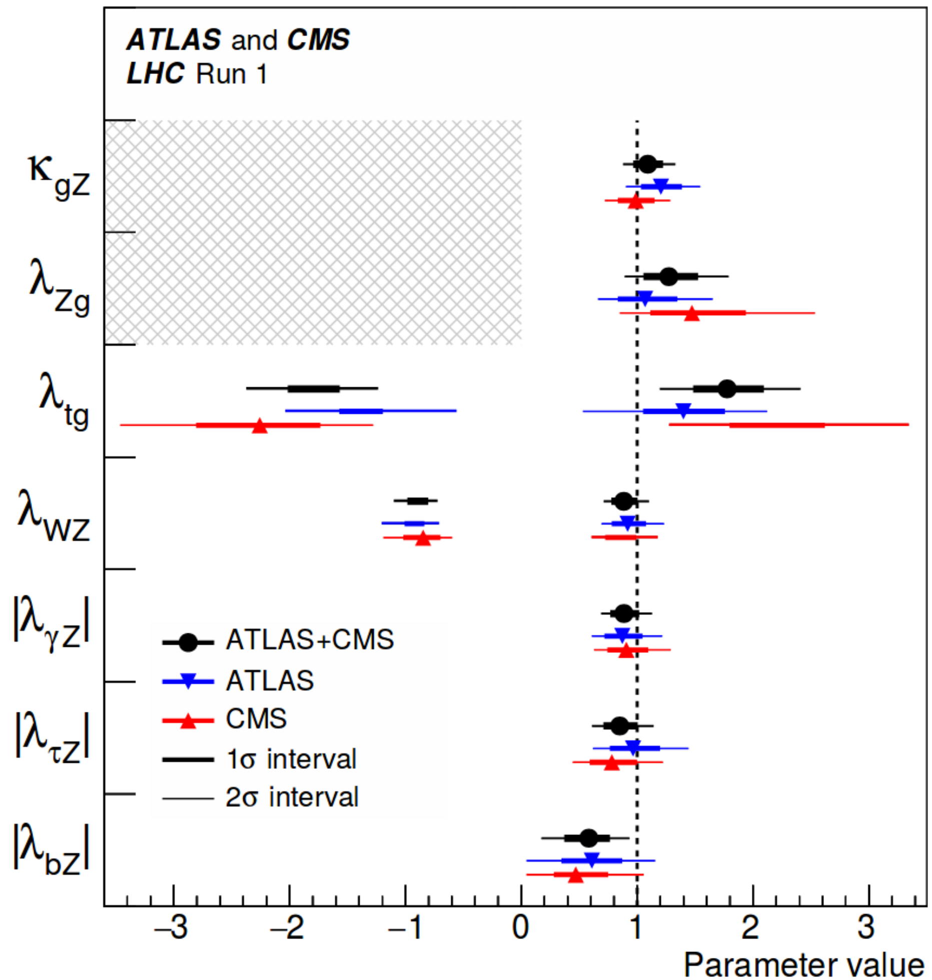
Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03\,^{+0.16}_{-0.14}$ $\left(^{+0.16}_{-0.14}\right)$	$1.26\,^{+0.23}_{-0.20}$ $\left(^{+0.21}_{-0.18}\right)$	$0.84\,^{+0.18}_{-0.16}$ $\left(^{+0.20}_{-0.17}\right)$
μ_{VBF}	$1.18\,^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$1.21\,^{+0.33}_{-0.30}$ $\left(^{+0.32}_{-0.29}\right)$	$1.14\,^{+0.37}_{-0.34}$ $\left(^{+0.36}_{-0.34}\right)$
μ_{WH}	$0.89\,^{+0.40}_{-0.38}$ $\left(^{+0.41}_{-0.39}\right)$	$1.25\,^{+0.56}_{-0.52}$ $\left(^{+0.56}_{-0.53}\right)$	$0.46\,^{+0.57}_{-0.53}$ $\left(^{+0.60}_{-0.57}\right)$
μ_{ZH}	$0.79\,^{+0.38}_{-0.36}$ $\left(^{+0.39}_{-0.36}\right)$	$0.30\,^{+0.51}_{-0.45}$ $\left(^{+0.55}_{-0.51}\right)$	$1.35\,^{+0.58}_{-0.54}$ $\left(^{+0.55}_{-0.51}\right)$
μ_{ttH}	$2.3\,^{+0.7}_{-0.6}$ $\left(^{+0.5}_{-0.5}\right)$	$1.9\,^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9\,^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.14\,^{+0.19}_{-0.18}$ $\left(^{+0.18}_{-0.17}\right)$	$1.14\,^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11\,^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$
μ^{ZZ}	$1.29\,^{+0.26}_{-0.23}$ $\left(^{+0.23}_{-0.20}\right)$	$1.52\,^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04\,^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$
μ^{WW}	$1.09\,^{+0.18}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$	$1.22\,^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90\,^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$
$\mu^{\tau\tau}$	$1.11\,^{+0.24}_{-0.22}$ $\left(^{+0.24}_{-0.22}\right)$	$1.41\,^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88\,^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$
μ^{bb}	$0.70\,^{+0.29}_{-0.27}$ $\left(^{+0.29}_{-0.28}\right)$	$0.62\,^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81\,^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$
$\mu^{\mu\mu}$	$0.1\,^{+2.5}_{-2.5}$ $\left(^{+2.4}_{-2.3}\right)$	$-0.6\,^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9\,^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$

Run 1 Results:

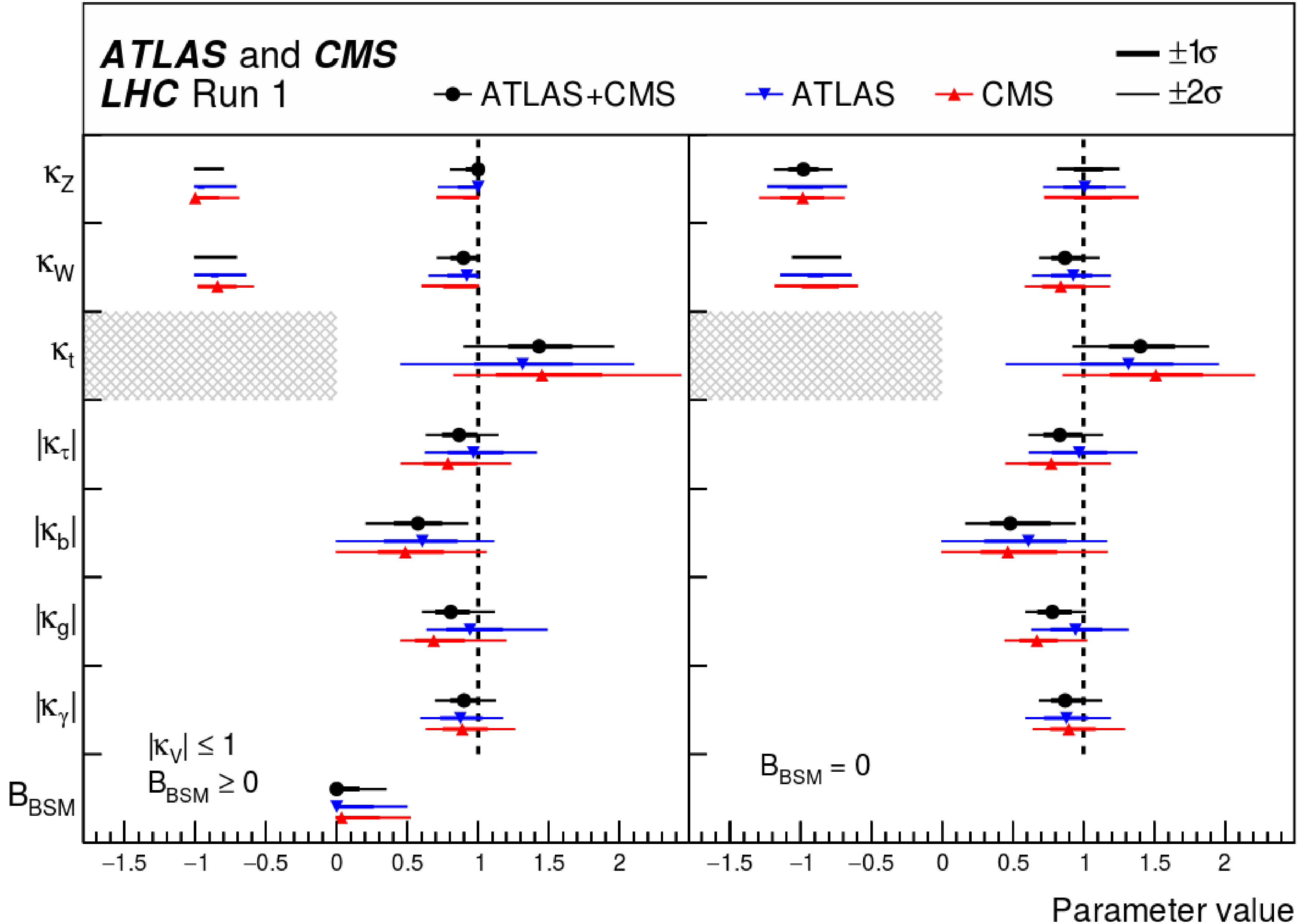
ATLAS+CMS Combination





Run 1 Results:

ATLAS+CMS Combination



ATLAS+CMS Combination

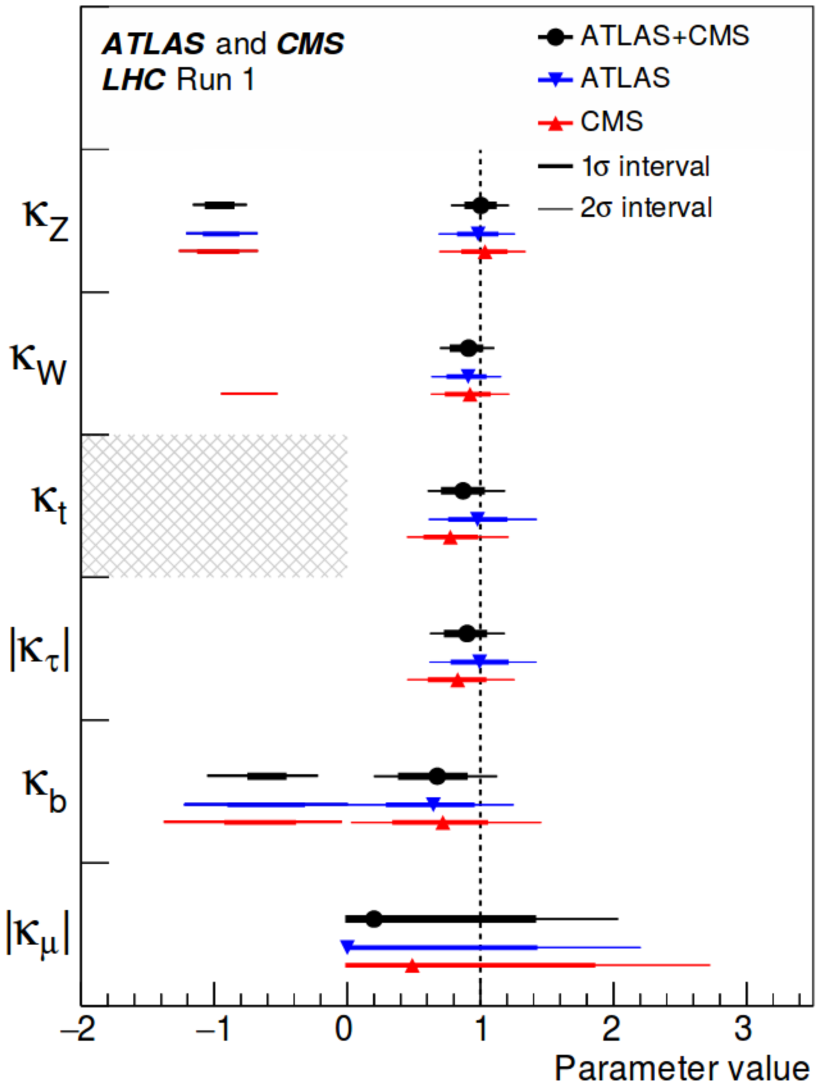
Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $B_{BSM} = 0$				
κ_Z	-0.98 $[-1.08, -0.88] \cup [0.94, 1.13]$	$[-1.01, -0.87] \cup [0.89, 1.11]$	1.01 $[-1.09, -0.85] \cup [0.87, 1.15]$	-0.99 $[-1.14, -0.84] \cup [0.94, 1.19]$
κ_W	0.87 $[0.78, 1.00]$	$[-1.08, -0.90] \cup [0.88, 1.11]$	0.92 $[-0.94, -0.85] \cup [0.78, 1.05]$	0.84 $[-0.99, -0.74] \cup [0.71, 1.01]$
κ_t	$1.40^{+0.24}_{-0.21}$	${}^{+0.26}_{-0.39}$	$1.32^{+0.31}_{-0.33}$	$1.51^{+0.33}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$	${}^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.19}$	$0.77^{+0.18}_{-0.15}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$	${}^{+0.25}_{-0.28}$	$0.61^{+0.26}_{-0.31}$	$0.47^{+0.34}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$	${}^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.17}$	$0.67^{+0.14}_{-0.12}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$	${}^{+0.12}_{-0.13}$	$0.88^{+0.15}_{-0.15}$	$0.89^{+0.19}_{-0.13}$

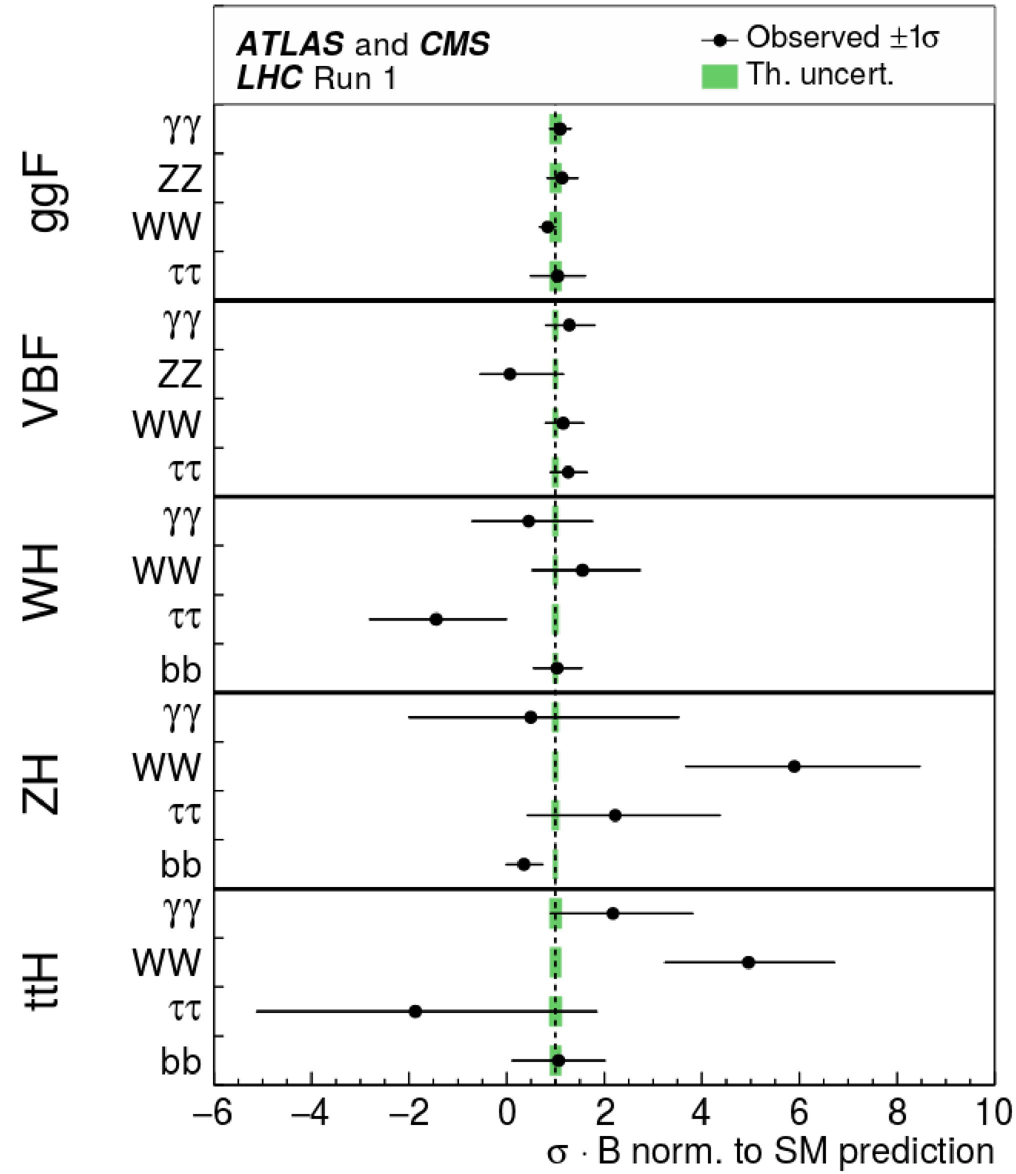
ATLAS+CMS Combination

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $\lvert\kappa_V\rvert \leq 1$ and $B_{BSM} \geq 0$				
κ_Z	1.00		1.00	−1.00
	[0.92, 1.00]	[−1.00, −0.89]∪	[−0.97, −0.94]∪	[−1.00, −0.84]∪
		[0.89, 1.00]	[0.86, 1.00]	[0.90, 1.00]
κ_W	0.90		0.92	−0.84
	[0.81, 0.99]	[−1.00, −0.90]∪	[−0.88, −0.84]∪	[−1.00, −0.71]∪
		[0.89, 1.00]	[0.79, 1.00]	[0.76, 0.98]
κ_t	$1.43^{+0.23}_{-0.22}$	$^{+0.27}_{-0.32}$	$1.31^{+0.35}_{-0.33}$	$1.45^{+0.42}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.87^{+0.12}_{-0.11}$	$^{+0.14}_{-0.15}$	$0.97^{+0.21}_{-0.17}$	$0.79^{+0.20}_{-0.16}$
$\lvert\kappa_b\rvert$	$0.57^{+0.16}_{-0.16}$	$^{+0.19}_{-0.23}$	$0.61^{+0.24}_{-0.26}$	$0.49^{+0.26}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.81^{+0.13}_{-0.10}$	$^{+0.17}_{-0.14}$	$0.94^{+0.23}_{-0.16}$	$0.69^{+0.21}_{-0.13}$
$\lvert\kappa_\gamma\rvert$	$0.90^{+0.10}_{-0.09}$	$^{+0.10}_{-0.12}$	$0.87^{+0.15}_{-0.14}$	$0.89^{+0.17}_{-0.13}$

Run 1 Results:

ATLAS+CMS Combination





Run 1 Results:

ATLAS+CMS Combination

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
κ_Z	1.00 $[-1.05, -0.86] \cup$ $[0.90, 1.11]$	$[-1.00, -0.88] \cup$ $[0.90, 1.10]$	0.98 $[-1.07, -0.83] \cup$ $[0.84, 1.12]$	1.03 $[-1.11, -0.83] \cup$ $[0.87, 1.19]$
κ_W	$0.91^{+0.10}_{-0.12}$	$^{+0.10}_{-0.11}$	$0.91^{+0.12}_{-0.15}$	$0.92^{+0.14}_{-0.17}$
κ_t	$0.87^{+0.15}_{-0.15}$	$^{+0.15}_{-0.18}$	$0.98^{+0.21}_{-0.20}$	$0.77^{+0.20}_{-0.18}$
$\lvert\kappa_\tau\rvert$	$0.90^{+0.14}_{-0.16}$	$^{+0.15}_{-0.14}$	$0.99^{+0.20}_{-0.20}$	$0.83^{+0.20}_{-0.21}$
κ_b	0.67 $[-0.73, -0.47] \cup$ $[0.40, 0.89]$	$[-1.24, -0.76] \cup$ $[0.74, 1.24]$	0.64 $[-0.89, -0.33] \cup$ $[0.30, 0.94]$	0.71 $[-0.91, -0.40] \cup$ $[0.35, 1.04]$
$\lvert\kappa_\mu\rvert$	$0.2^{+1.2}$	$^{+0.9}$	$0.0^{+1.4}$	$0.5^{+1.4}$

Run 1 Results:

ATLAS+CMS Combination