Global Analyses

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on behalf of the CMS Collaboration

Higgs Couplings, Heidelberg
7 November 2017

Overview

- Combined measurements of Higgs boson properties
- Signal strength and coupling fits
  - Providing model independent results for reinterpretation
  - Different assumptions in the kappa model
- Going beyond inclusive measurements
  - Simplified template cross sections and theoretical uncertainties
  - Differential distributions
- Interpretation in BSM scenarios

Progress in Run 2

- Coverage of main production & decay modes in CMS:

	Untagged	VBF	VH	ttH
H→ZZ→4l	🟩	🟩	🟩	🟩
H→γγ	🟩	🟩	🟩	🟩
H→WW	🟨	🟨	🟨	🟩
H→bb	🟩	🟨	🟩	🟨
H→ττ	🟩	🟩	🟥	🟩
H→μμ	🟩	🟩		
H→inv	🟩	🟨	🟩	

🟩 Full 2016 dataset

🟨 Partial 13 TeV dataset

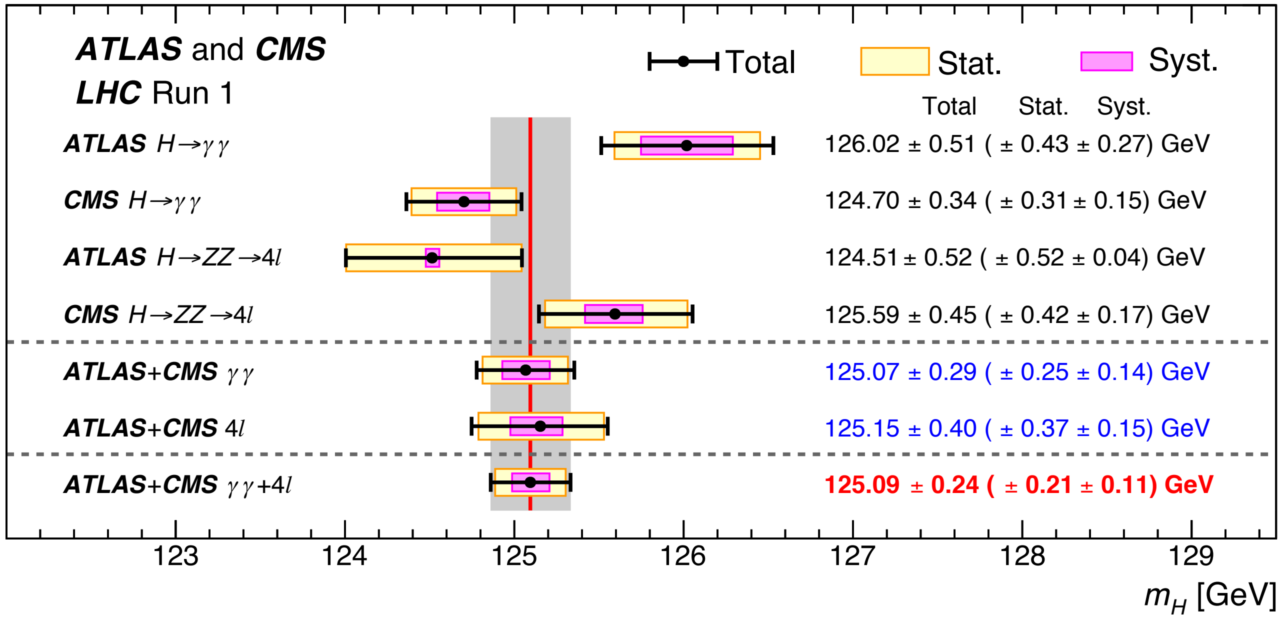
🟥 No 13 TeV update yet

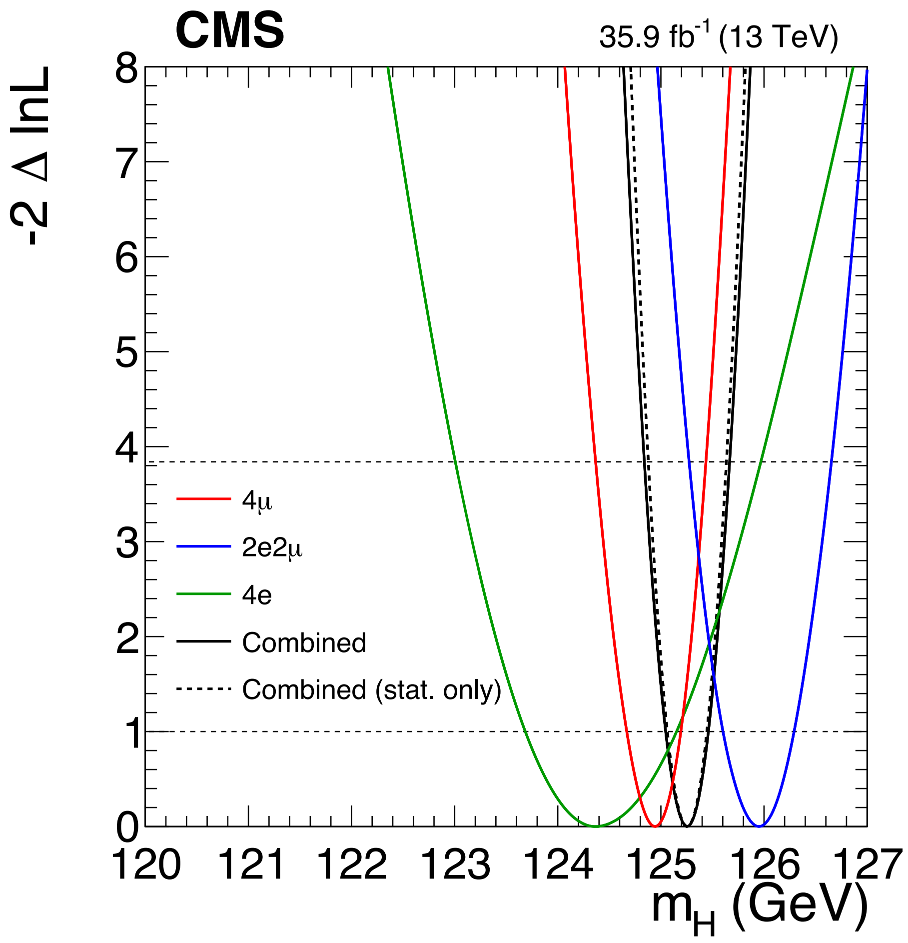
- For a combined coupling analysis, current state of the art is:
  - (1) Run 1 CMS combined measurements: Eur. Phys. J. C 75 (2015) 212
  - (2) The Run 1 CMS+ATLAS combination: J. High Energy Phys. 08 (2016) 045

Mass

- Using high resolution $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ\rightarrow 4l$ channels
- **Status from Run 1**: CMS+ATLAS combination
- Statistical uncertainty still dominates, main systematics related to energy or momentum scale of e, μ and γ
- **Status in Run 2:** measurements in individual channels
- **H→ZZ:** $m_H = 125.26 \pm 0.20\ \text{(stat)} \pm 0.08\ \text{(syst)}$ GeV
  - Kinematic fit with Z mass constraint to improve 4l res.
  - Already competitive with Run 1

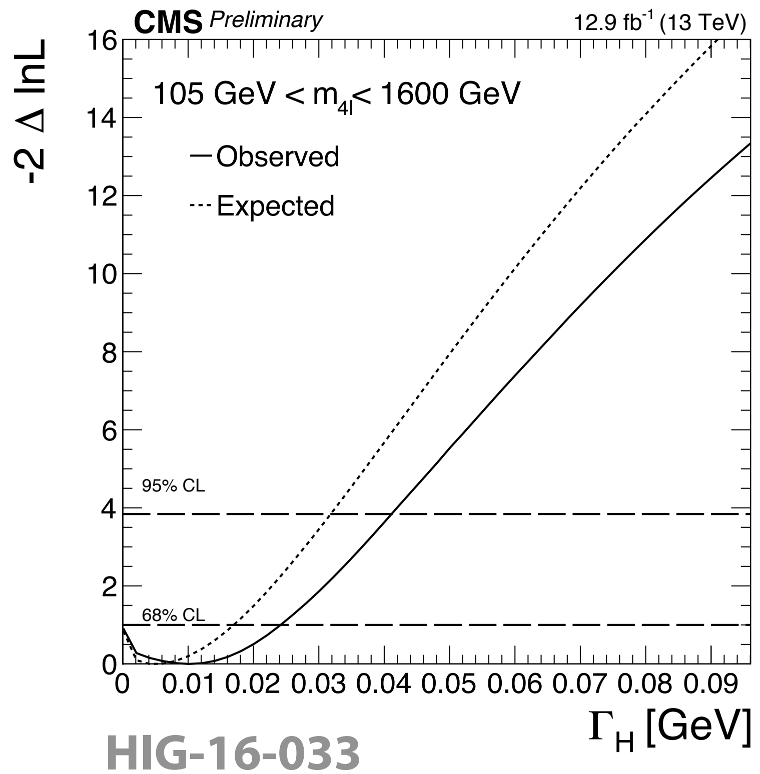
Phys. Rev. Lett. 114 (2015) 191803





Width

- Limits on Higgs width from the H→ZZ→4l channel using either on-shell or on-shell + off-shell regions



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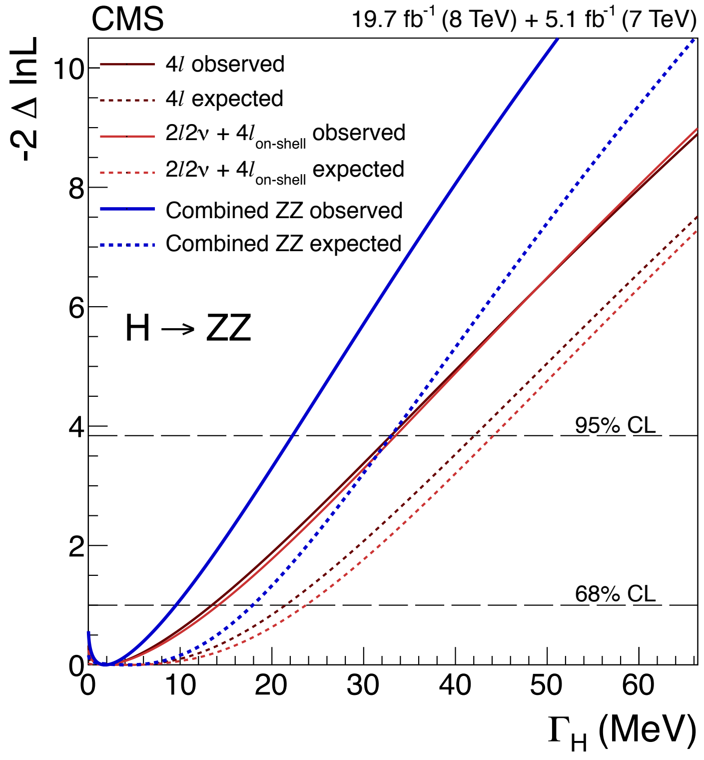
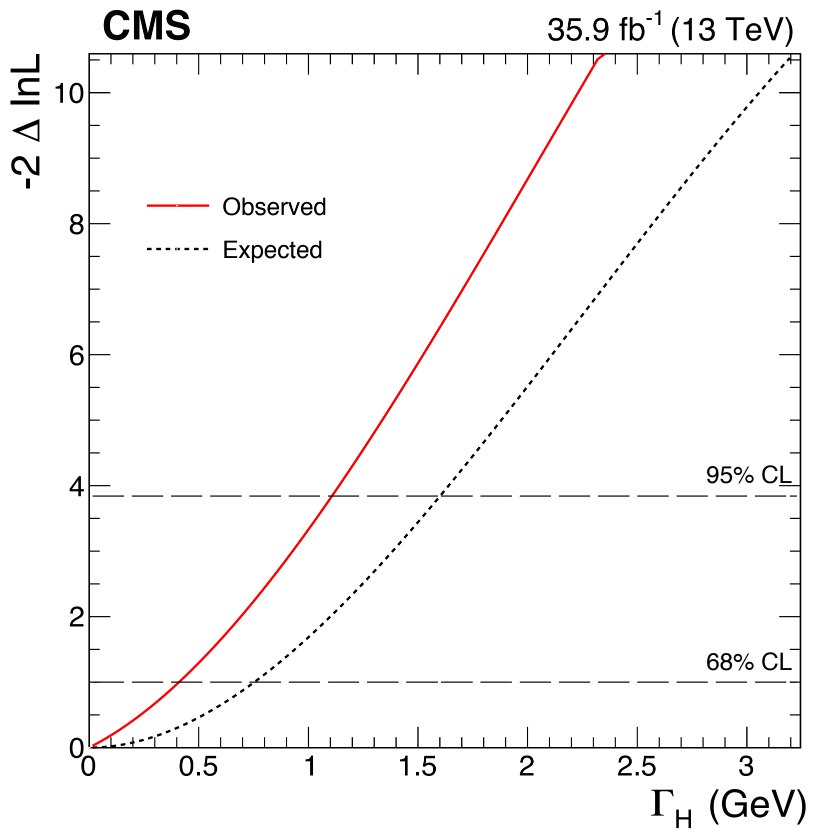


- Using both:
  - Indirect constraint on the width using ratio of off-shell to on-shell production in H→ZZ



Phys. Lett. B 736 (2014) 64

- Using on-shell only:
  - Direct measurement limited by the 4l mass resolution to ~ 1 GeV
  - $\Gamma_H <$ 1.10 GeV at 95% CL (c.f. Run 1 limit $\Gamma_H <$ 3.4 GeV)

Couplings: signal parameterisation

- Two main approaches used in combined coupling fits:

Signal strengths, μ

Parameters scale cross sections and BRs relative to SM

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

Scaling of generic i → H → f process

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

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

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

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\mathrm{H}}},$$

Total width determined as

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

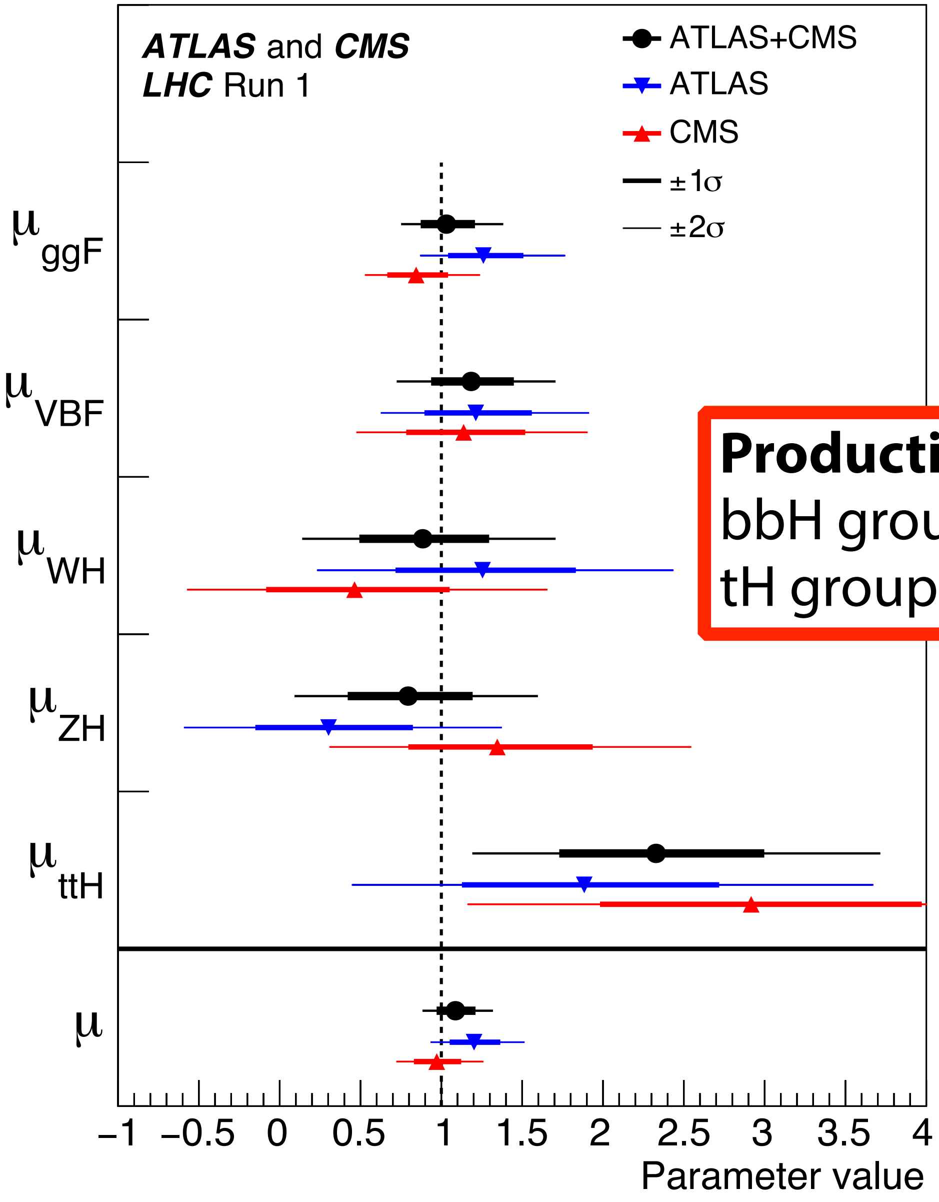
Where

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

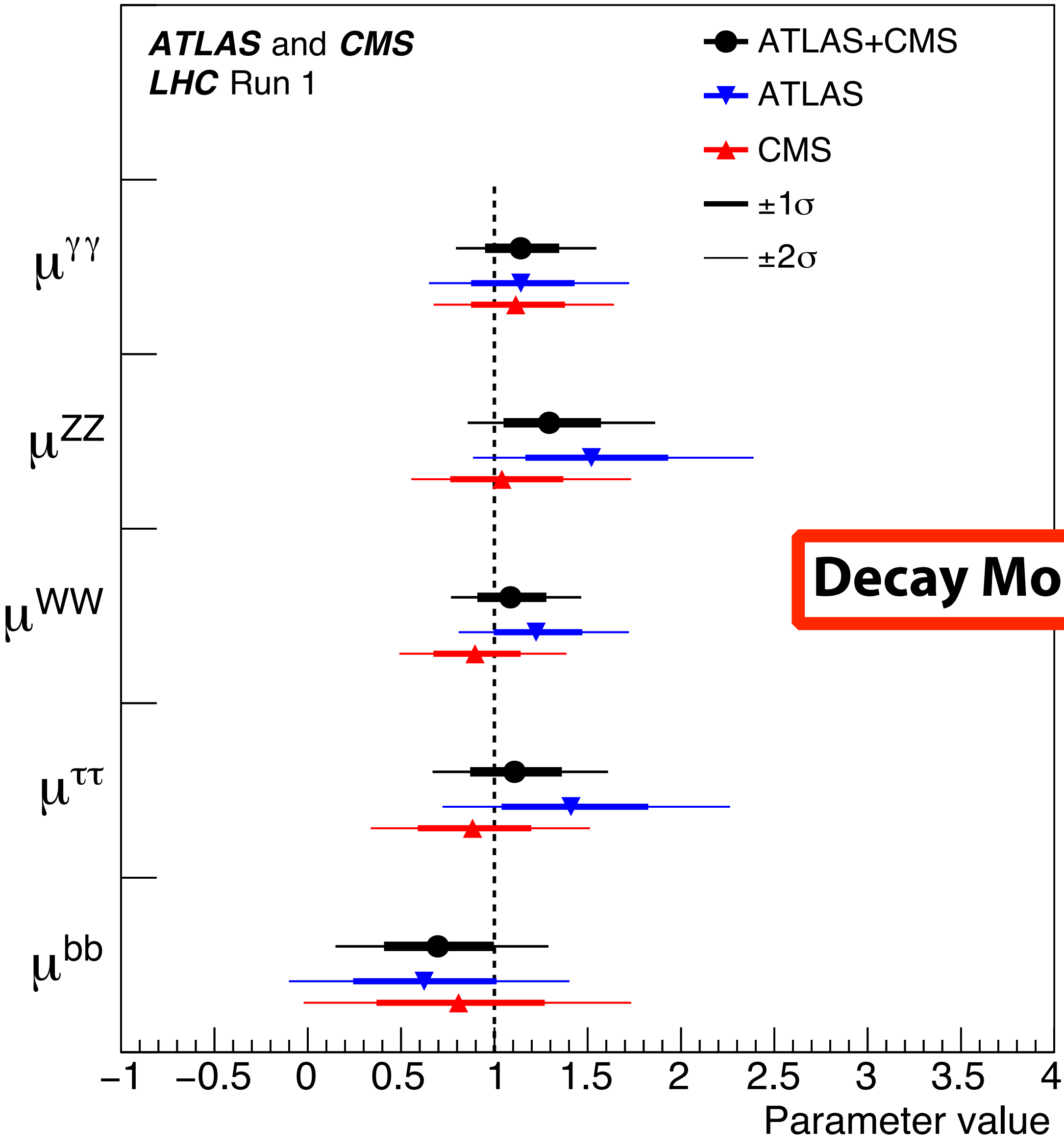
Signal strengths

- CMS+ATLAS:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig}),$$



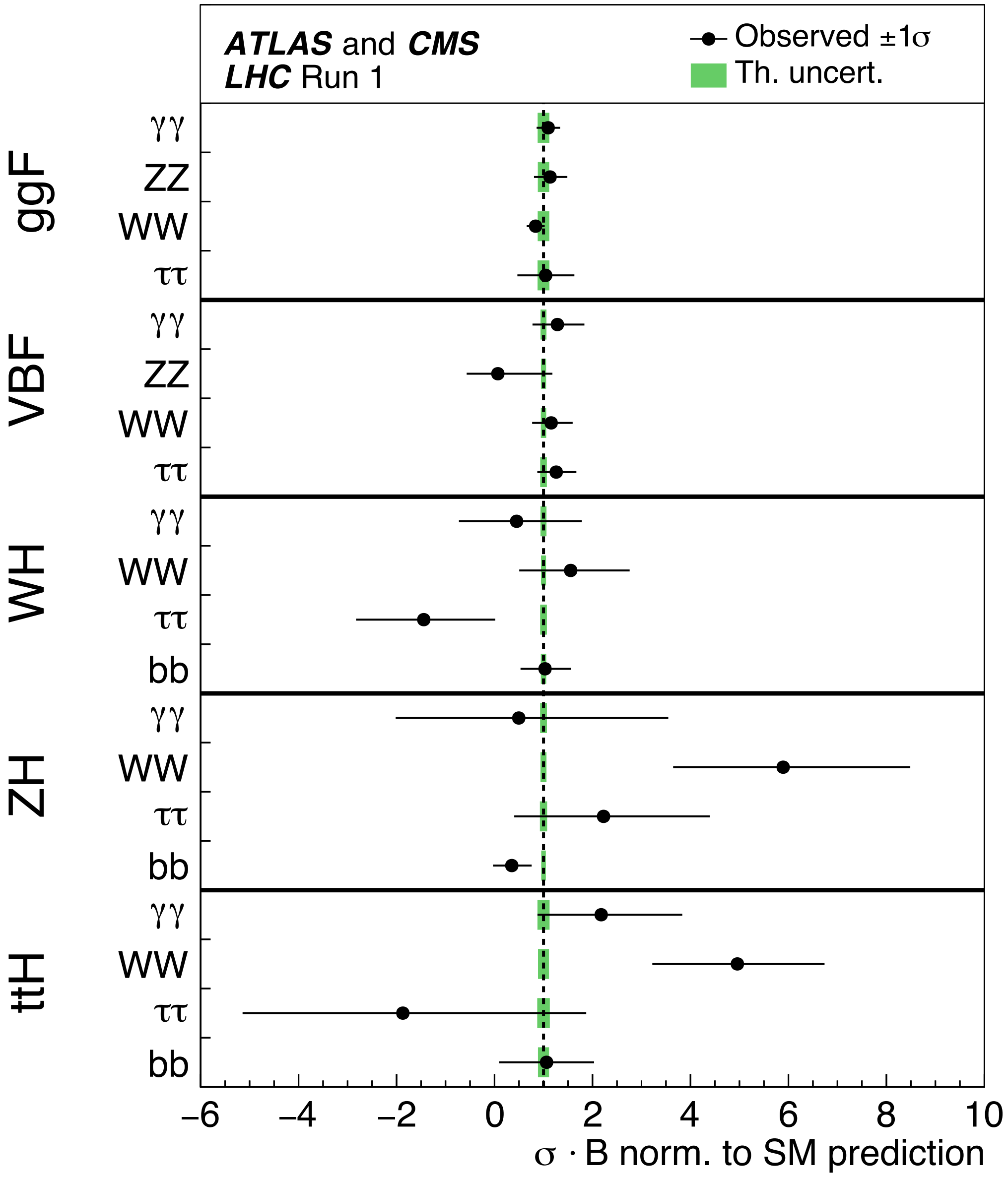
Production Modes
bbH grouped with ggF
tH grouped with ttH



Decay Modes

Generic signal strength results

- Most generic parametrisation: one μ per production x decay combination



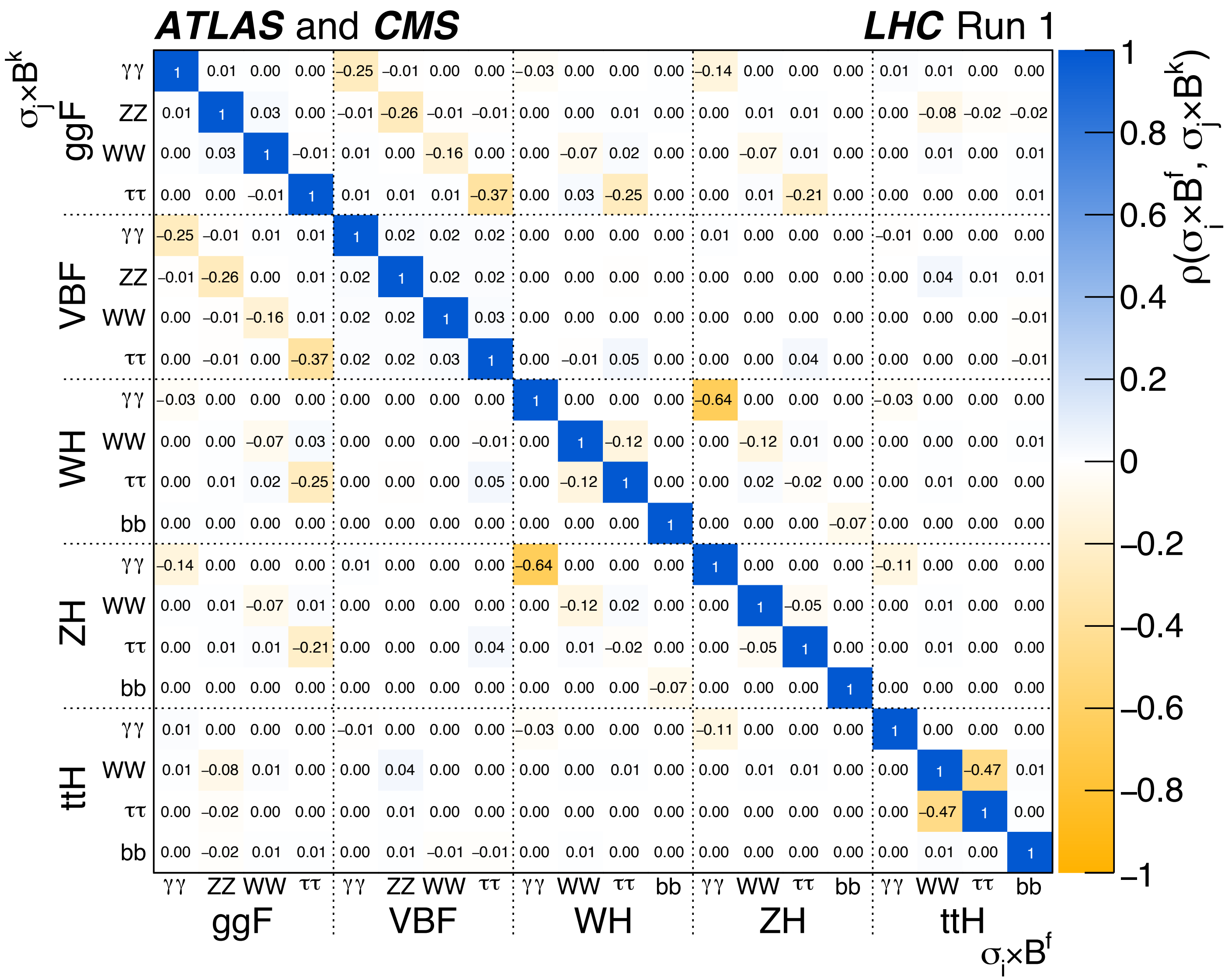
- Results given as σ x B measurement - inclusive theory uncertainties removed

- Uncertainty split into stat. and syst. sources

Production process		Decay mode														
		$H \to \gamma\gamma$ [fb]			$H \to ZZ$ [fb]			$H \to WW$ [pb]			$H \to \tau\tau$ [fb]			$H \to bb$ [pb]		
		Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst
ggF	Measured	$48.0^{+10.0}_{-9.7}$	$^{+9.4}_{-9.4}$	$^{+3.2}_{-2.3}$	580^{+170}_{-160}	$^{+170}_{-160}$	$^{+40}_{-40}$	$3.5^{+0.7}_{-0.7}$	$^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	1300^{+700}_{-700}	$^{+400}_{-400}$	$^{+500}_{-500}$	–		
		$\left(^{+9.7}_{-9.5}\right)$	$\left(^{+9.4}_{-9.4}\right)$	$\left(^{+2.5}_{-1.6}\right)$	$\left(^{+150}_{-130}\right)$	$\left(^{+140}_{-130}\right)$	$\left(^{+30}_{-20}\right)$	$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+700}_{-700}\right)$	$\left(^{+400}_{-400}\right)$	$\left(^{+500}_{-500}\right)$	–		
	Predicted	44 ±5			510 ±60			4.1 ±0.5			1210 ±140			11.0 ±1.2		
	Ratio	$1.10^{+0.23}_{-0.22}$	$^{+0.22}_{-0.21}$	$^{+0.07}_{-0.05}$	$1.13^{+0.34}_{-0.31}$	$^{+0.33}_{-0.30}$	$^{+0.09}_{-0.07}$	$0.84^{+0.17}_{-0.17}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	$1.0^{+0.6}_{-0.6}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.4}$	–		
VBF	Measured	$4.6^{+1.9}_{-1.8}$	$^{+1.8}_{-1.7}$	$^{+0.6}_{-0.5}$	3^{+46}_{-26}	$^{+46}_{-25}$	$^{+7}_{-7}$	$0.39^{+0.14}_{-0.13}$	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.05}$	125^{+39}_{-37}	$^{+34}_{-32}$	$^{+19}_{-18}$	–		
		$\left(^{+1.8}_{-1.6}\right)$	$\left(^{+1.7}_{-1.6}\right)$	$\left(^{+0.5}_{-0.4}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+8}_{-5}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+39}_{-37}\right)$	$\left(^{+34}_{-32}\right)$	$\left(^{+19}_{-18}\right)$	–		
	Predicted	3.60 ±0.20			42.2 ±2.0			0.341 ±0.017			100 ±6			0.91 ±0.04		
	Ratio	$1.3^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$^{+0.2}_{-0.1}$	$0.1^{+1.1}_{-0.6}$	$^{+1.1}_{-0.6}$	$^{+0.2}_{-0.2}$	$1.2^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+0.2}_{-0.2}$	$1.3^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$	–		
WH	Measured	$0.7^{+2.1}_{-1.9}$	$^{+2.1}_{-1.8}$	$^{+0.3}_{-0.3}$	–			$0.24^{+0.18}_{-0.16}$	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.08}$	-64^{+64}_{-61}	$^{+55}_{-50}$	$^{+32}_{-34}$	$0.42^{+0.21}_{-0.20}$	$^{+0.17}_{-0.16}$	$^{+0.12}_{-0.11}$
		$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.08}_{-0.07}\right)$	$\left(^{+67}_{-64}\right)$	$\left(^{+60}_{-54}\right)$	$\left(^{+30}_{-32}\right)$	$\left(^{+0.22}_{-0.21}\right)$	$\left(^{+0.18}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
	Predicted	1.60 ±0.09			18.8 ±0.9			0.152 ±0.007			44.3 ±2.8			0.404 ±0.017		
	Ratio	$0.5^{+1.3}_{-1.2}$	$^{+1.3}_{-1.1}$	$^{+0.2}_{-0.2}$	–			$1.6^{+1.2}_{-1.0}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$	$^{+1.2}_{-1.1}$	$^{+0.7}_{-0.8}$	$1.0^{+0.5}_{-0.5}$	$^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$
ZH	Measured	$0.5^{+2.9}_{-2.4}$	$^{+2.8}_{-2.3}$	$^{+0.5}_{-0.2}$	–			$0.53^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$^{+0.10}_{-0.07}$	58^{+56}_{-47}	$^{+52}_{-44}$	$^{+20}_{-16}$	$0.08^{+0.09}_{-0.09}$	$^{+0.08}_{-0.08}$	$^{+0.04}_{-0.04}$
		$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+49}_{-40}\right)$	$\left(^{+46}_{-38}\right)$	$\left(^{+16}_{-12}\right)$	$\left(^{+0.10}_{-0.09}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.05}_{-0.04}\right)$
	Predicted	0.94 ±0.06			11.1 ±0.6			0.089 ±0.005			26.1 ±1.8			0.238 ±0.012		
	Ratio	$0.5^{+3.0}_{-2.5}$	$^{+3.0}_{-2.5}$	$^{+0.5}_{-0.2}$	–			$5.9^{+2.6}_{-2.2}$	$^{+2.3}_{-2.1}$	$^{+1.1}_{-0.8}$	$2.2^{+2.2}_{-1.8}$	$^{+2.0}_{-1.7}$	$^{+0.8}_{-0.6}$	$0.4^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$
ttH	Measured	$0.64^{+0.48}_{-0.38}$	$^{+0.48}_{-0.38}$	$^{+0.07}_{-0.04}$	–			$0.14^{+0.05}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	-15^{+30}_{-26}	$^{+26}_{-22}$	$^{+15}_{-15}$	$0.08^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.06}_{-0.06}$
		$\left(^{+0.45}_{-0.34}\right)$	$\left(^{+0.44}_{-0.33}\right)$	$\left(^{+0.10}_{-0.05}\right)$	–			$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.02}_{-0.02}\right)$	$\left(^{+31}_{-26}\right)$	$\left(^{+26}_{-22}\right)$	$\left(^{+16}_{-13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.06}_{-0.05}\right)$
	Predicted	0.294 ±0.035			3.4 ±0.4			0.0279 ±0.0032			8.1 ±1.0			0.074 ±0.008		
	Ratio	$2.2^{+1.6}_{-1.3}$	$^{+1.6}_{-1.3}$	$^{+0.2}_{-0.1}$	–			$5.0^{+1.8}_{-1.7}$	$^{+1.5}_{-1.5}$	$^{+1.0}_{-0.9}$	$-1.9^{+3.7}_{-3.3}$	$^{+3.2}_{-2.7}$	$^{+1.9}_{-1.8}$	$1.1^{+1.0}_{-1.0}$	$^{+0.5}_{-0.5}$	$^{+0.8}_{-0.8}$

Recasting

- Correlation/covariance matrix also provided. Non-zero entries mostly due to experimental categories not perfectly able to distinguish certain processes
  - E.g. contamination of gluon-fusion in VBF targeting categories
  - V(had)H categories that select both WH and ZH production

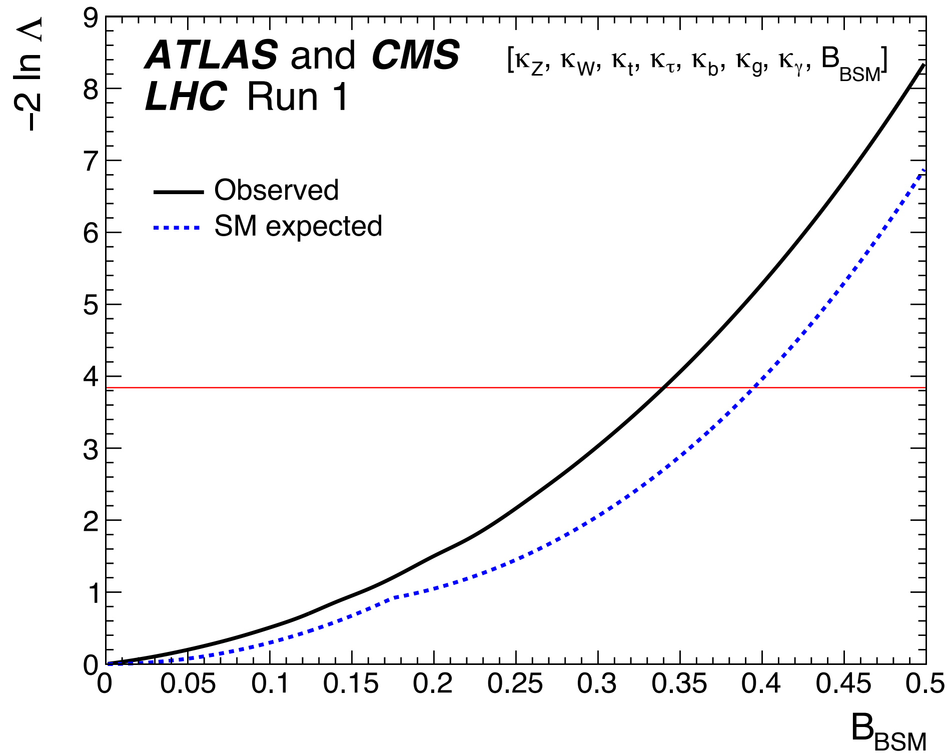


		ggF				VBF				WH				ZH				ttH			
		γγ	ZZ	WW	ττ	γγ	ZZ	WW	ττ	γγ	WW	ττ	bb	γγ	WW	ττ	bb	γγ	WW	ττ	bb
ggF	γγ	1	0.01	0.00	0.00	–0.25	–0.01	0.00	0.00	–0.03	0.00	0.00	0.00	–0.14	0.00	0.00	0.00	0.01	0.01	0.00	0.00
	ZZ	0.01	1	0.03	0.00	–0.01	–0.26	–0.01	–0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	–0.08	–0.02	–0.02
	WW	0.00	0.03	1	–0.01	0.01	0.00	–0.16	0.00	0.00	–0.07	0.02	0.00	0.00	–0.07	0.01	0.00	0.00	0.01	0.00	0.01
	ττ	0.00	0.00	–0.01	1	0.01	0.01	0.01	–0.37	0.00	0.03	–0.25	0.00	0.00	0.01	–0.21	0.00	0.00	0.00	0.00	0.01
VBF	γγ	–0.25	–0.01	0.01	0.01	1	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00
	ZZ	–0.01	–0.26	0.00	0.01	0.02	1	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01
	WW	0.00	–0.01	–0.16	0.01	0.02	0.02	1	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
	ττ	0.00	–0.01	0.00	–0.37	0.02	0.02	0.03	1	0.00	–0.01	0.05	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	–0.01
WH	γγ	–0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	–0.64	0.00	0.00	0.00	–0.03	0.00	0.00	0.00
	WW	0.00	0.00	–0.07	0.03	0.00	0.00	0.00	–0.01	0.00	1	–0.12	0.00	0.00	–0.12	0.01	0.00	0.00	0.00	0.00	0.01
	ττ	0.00	0.01	0.02	–0.25	0.00	0.00	0.00	0.05	0.00	–0.12	1	0.00	0.00	0.02	–0.02	0.00	0.00	0.01	0.00	0.00
	bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	–0.07	0.00	0.00	0.00	0.00
ZH	γγ	–0.14	0.00	0.00	0.00	0.01	0.00	0.00	0.00	–0.64	0.00	0.00	0.00	1	0.00	0.00	0.00	–0.11	0.00	0.00	0.00
	WW	0.00	0.01	–0.07	0.01	0.00	0.00	0.00	0.00	0.00	–0.12	0.02	0.00	0.00	1	–0.05	0.00	0.00	0.01	0.00	0.00
	ττ	0.00	0.01	0.01	–0.21	0.00	0.00	0.00	0.04	0.00	0.01	–0.02	0.00	0.00	–0.05	1	0.00	0.00	0.01	0.00	0.00
	bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.07	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00
ttH	γγ	0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00	–0.03	0.00	0.00	0.00	–0.11	0.00	0.00	0.00	1	0.00	0.00	0.00
	WW	0.01	–0.08	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	1	–0.47	0.01
	ττ	0.00	–0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.47	1	0.00
	bb	0.00	–0.02	0.01	0.01	0.00	0.01	–0.01	–0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	1

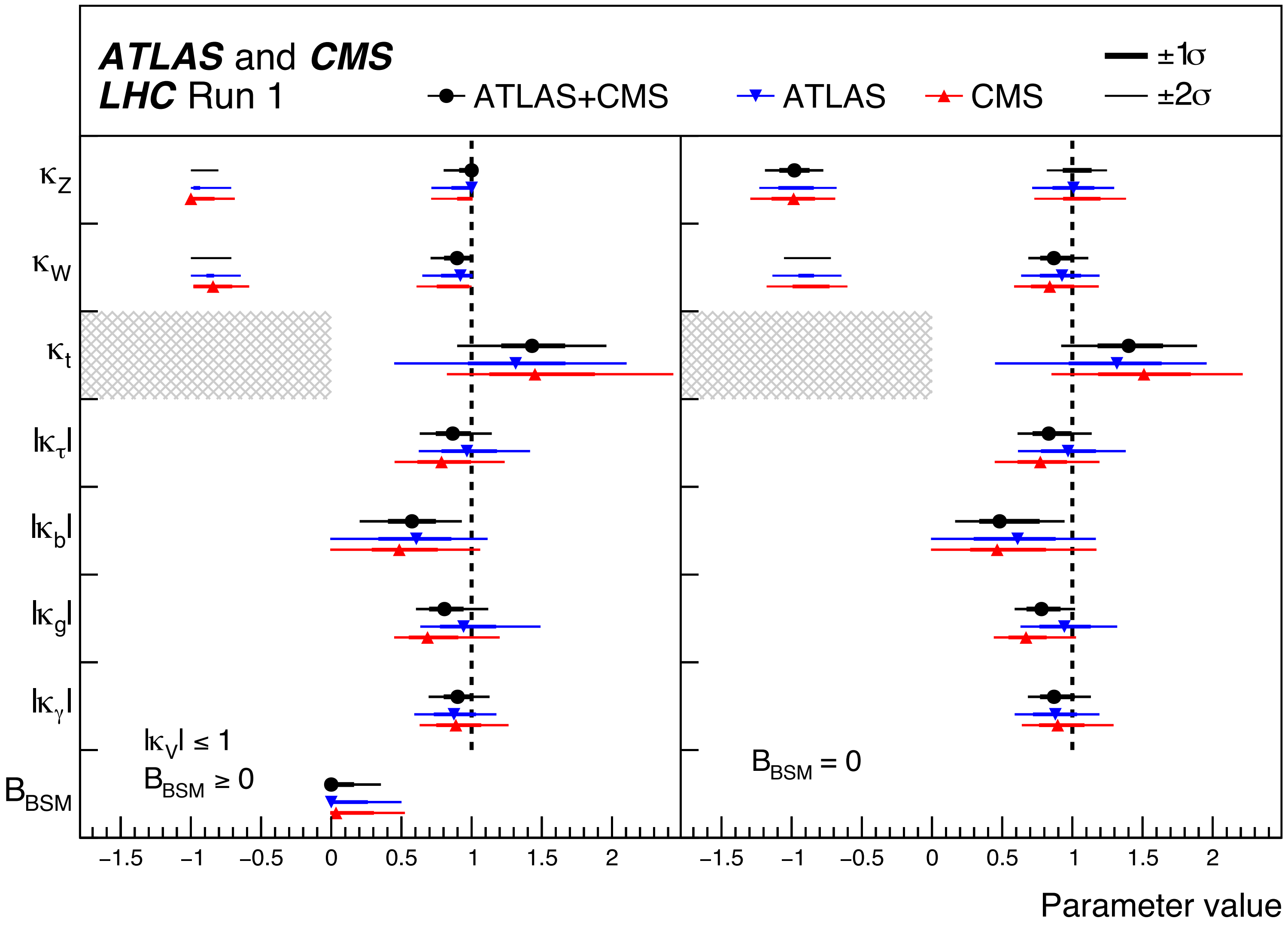
- Is this sufficient for the community or can we go further?
- More accurate NLL information required?
- More splitting of uncertainties into sources, e.g. theory uncertainties separately?
- Information on the impact of specific theory uncertainties on results?

Couplings: BSM loop/decay contributions

- Use effective couplings for ggH (κ_g) and H→γγ (κ_γ)
- Consider two scenarios: $BR_{BSM} = 0$ and BR_{BSM} floating, but $|\kappa_W|, |\kappa_Z| < 1$
- Sensitive to relative signs of κ_t, κ_W and κ_Z via interference in tH and ggZH production
- Care needed with BR_{BSM}: not just Higgs decays to new particles but also non-SM BRs to unmeasured final states, e.g. gg and cc

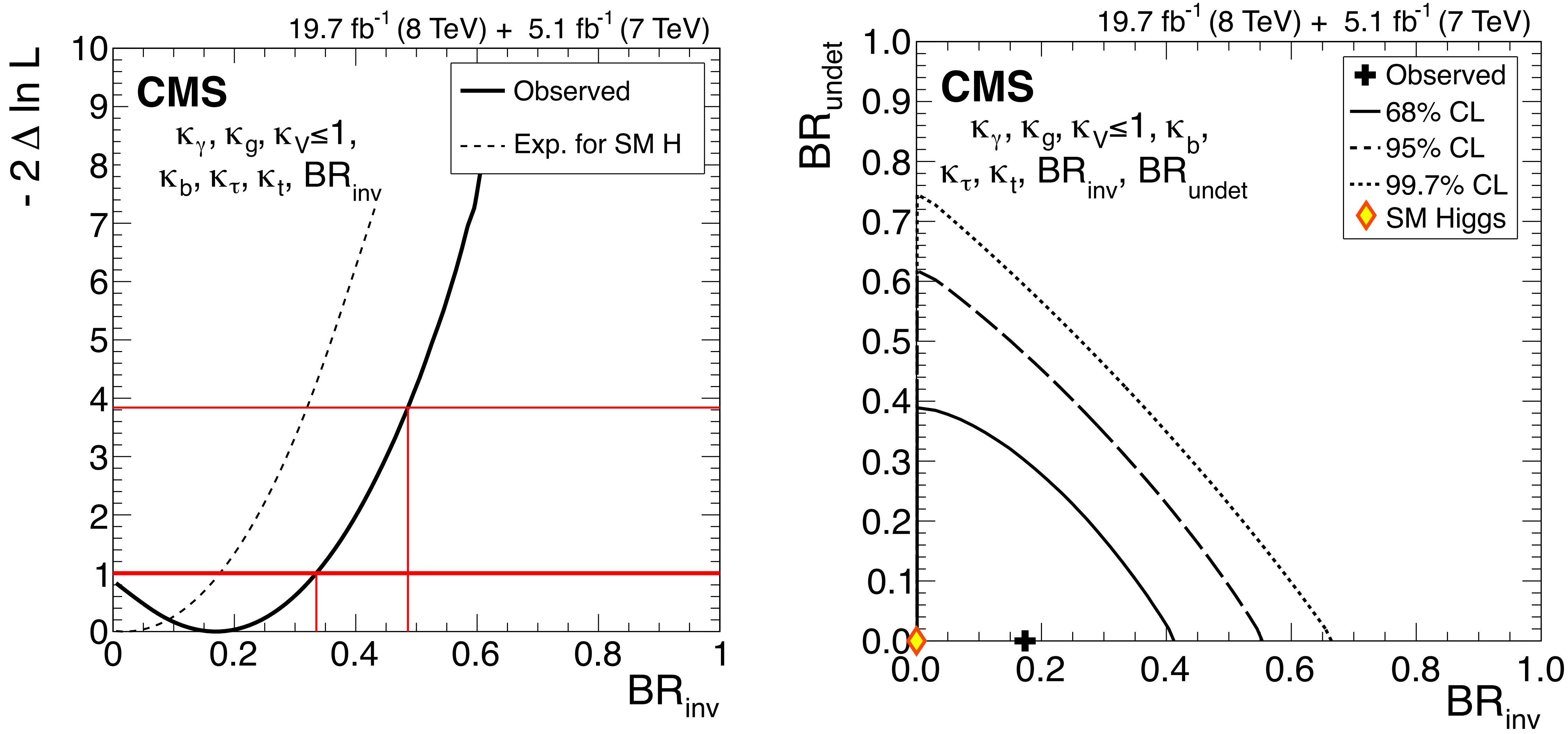


$BR_{BSM} < 0.34$ @ 95% CL



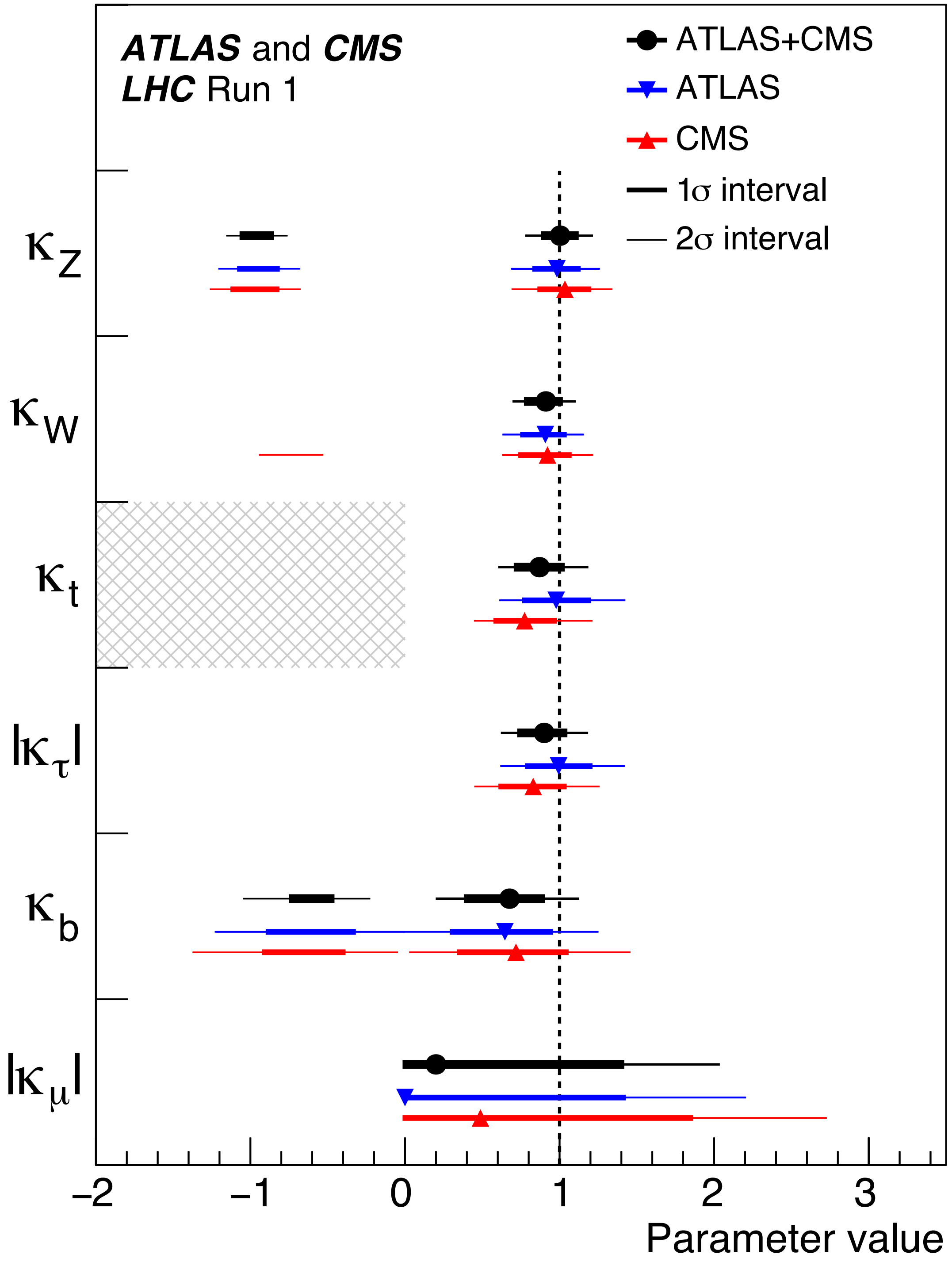
Couplings: BSM loop/decay contributions

- One step further: the CMS Run 1 combination also included the direct H→invisible searches (VBF, VH prod modes)
  - Define **BR_{BSM} = BR_{inv} + BR_{undet}**
- Assuming $BR_{undet} = 0$, improve on BR_{inv} sensitivity in 95 CL limits:
  - **Combination**: 0.49 obs. (0.32 exp.), **H→inv alone**: 0.58 obs. (0.44 exp)

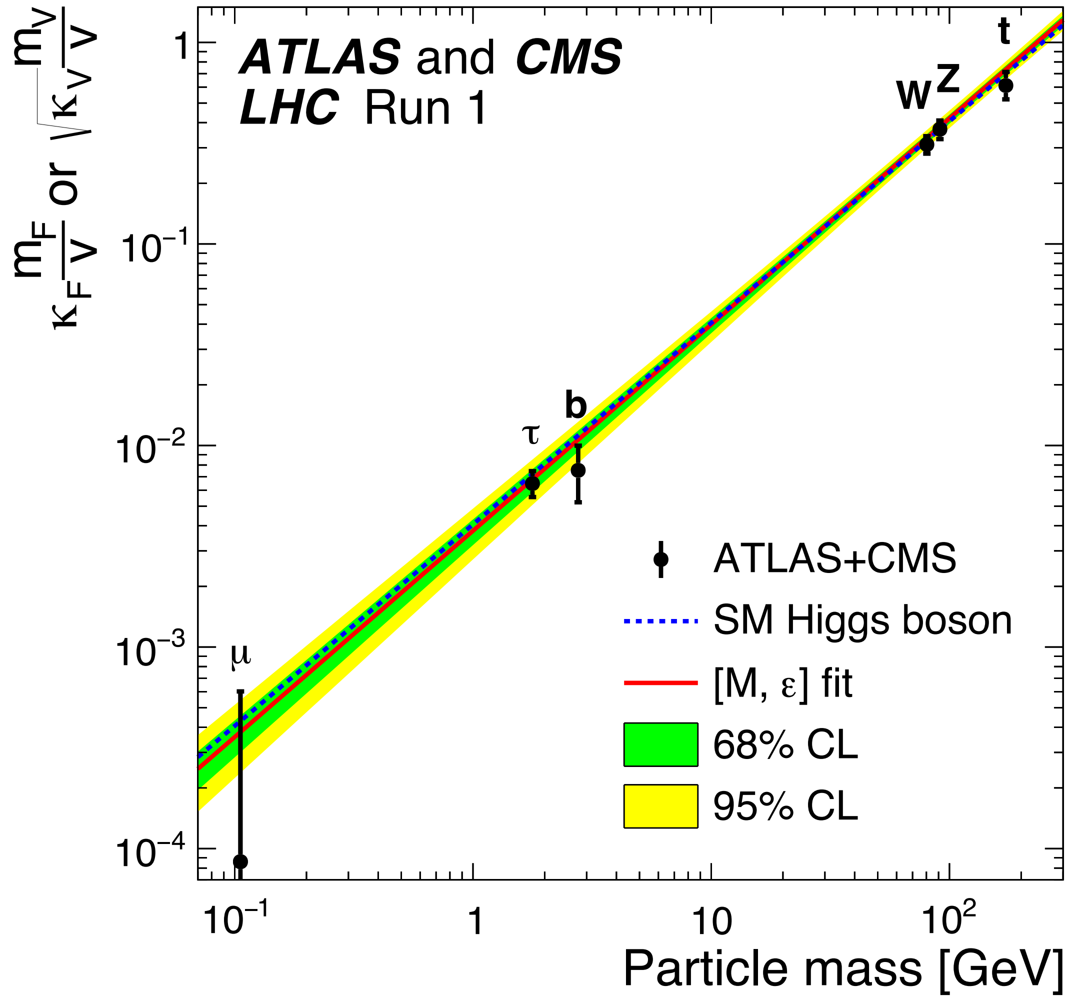


Couplings - no BSM loop/decay contributions

- Resolve ggH (κ_g) and H→γγ (κ_γ) loops



Includes H→μμ analyses for reduced coupling vs particle mass

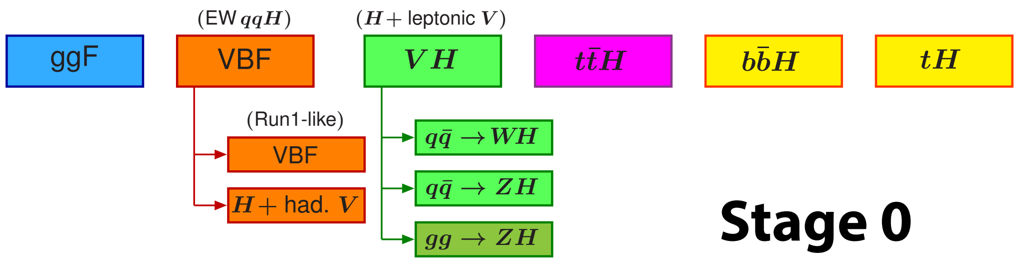


M, ε model:

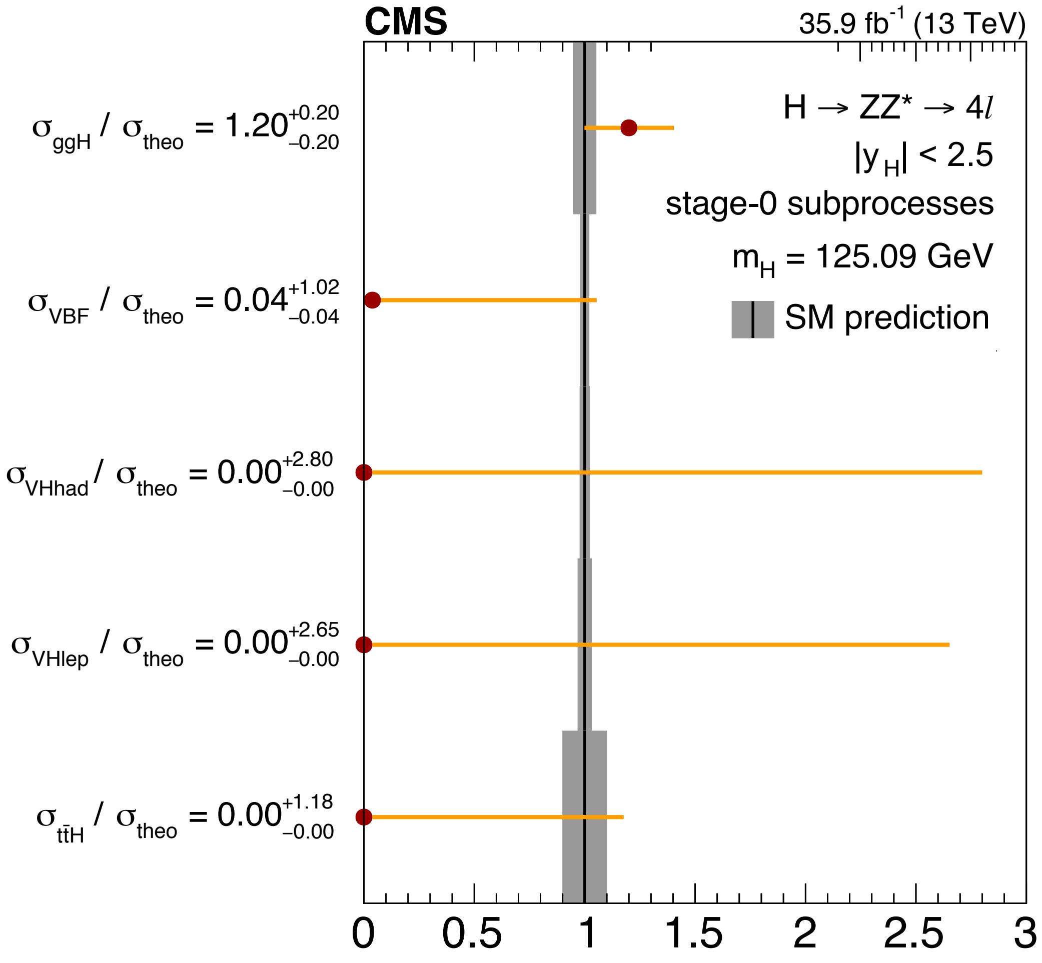
$$\kappa_{F,i} = v \cdot m_{F,i}^{\epsilon}/M^{1+\epsilon} \qquad \kappa_{V,i} = v \cdot m_{V,i}^{2\epsilon}/M^{1+2\epsilon}$$

Simplified template cross sections

- YR4 (arXiv:1610.07922) proposes simplified template cross sections
- Several stages proposed with increasing split of production modes by jet multiplicity, pT_H etc
- Possibility to connect to BSM models in different frameworks, e.g. kappa model, EFT coefficients

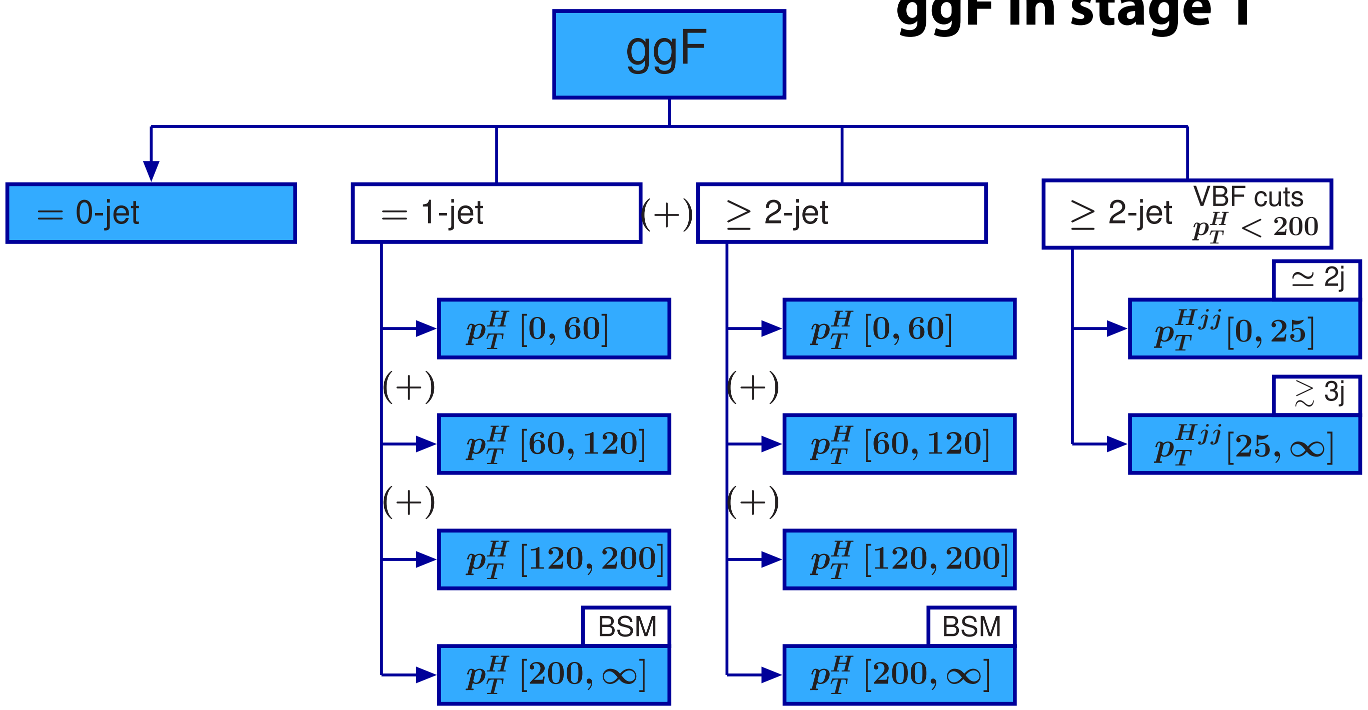


Stage 0



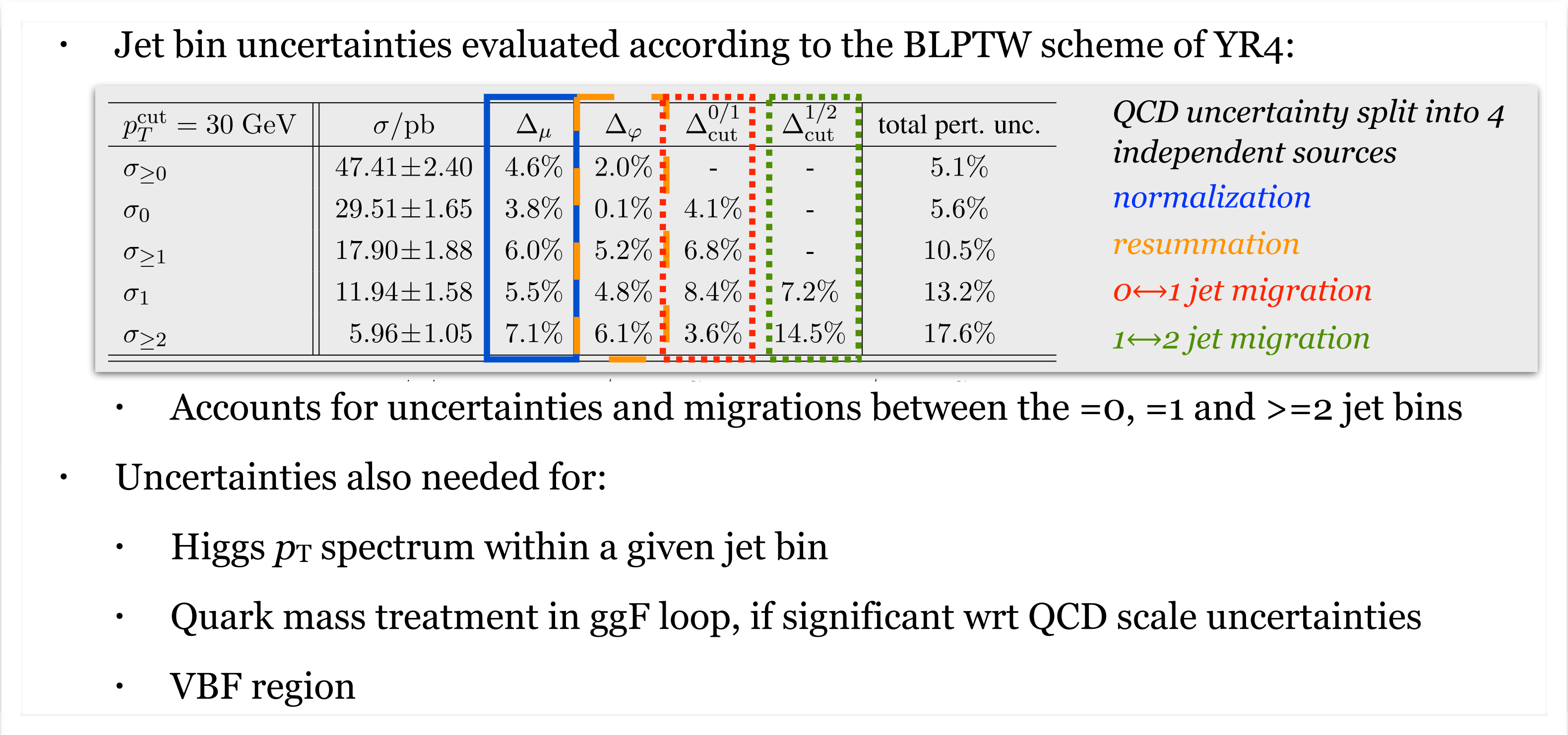
H→ZZ Run 2 results for Stage-0

ggF in stage 1



WG1 scheme for ggF uncertainties

- Along with STXS will adapt new scheme for ggF uncertainties:
  - Consistent treatment for all channels, makes combination more straightforward
  - Independent uncertainty sources targeted as migration uncertainty between bins, e.g. STXS



- Jet bin uncertainties evaluated according to the BLPTW scheme of YR4:

$p_T^{\text{cut}} = 30$ GeV	σ/pb	Δ_μ	Δ_φ	$\Delta_{\text{cut}}^{0/1}$	$\Delta_{\text{cut}}^{1/2}$	total pert. unc.
$\sigma_{\geq 0}$	47.41±2.40	4.6%	2.0%	-	-	5.1%
σ_0	29.51±1.65	3.8%	0.1%	4.1%	-	5.6%
$\sigma_{\geq 1}$	17.90±1.88	6.0%	5.2%	6.8%	-	10.5%
σ_1	11.94±1.58	5.5%	4.8%	8.4%	7.2%	13.2%
$\sigma_{\geq 2}$	5.96±1.05	7.1%	6.1%	3.6%	14.5%	17.6%

QCD uncertainty split into 4 independent sources

normalization

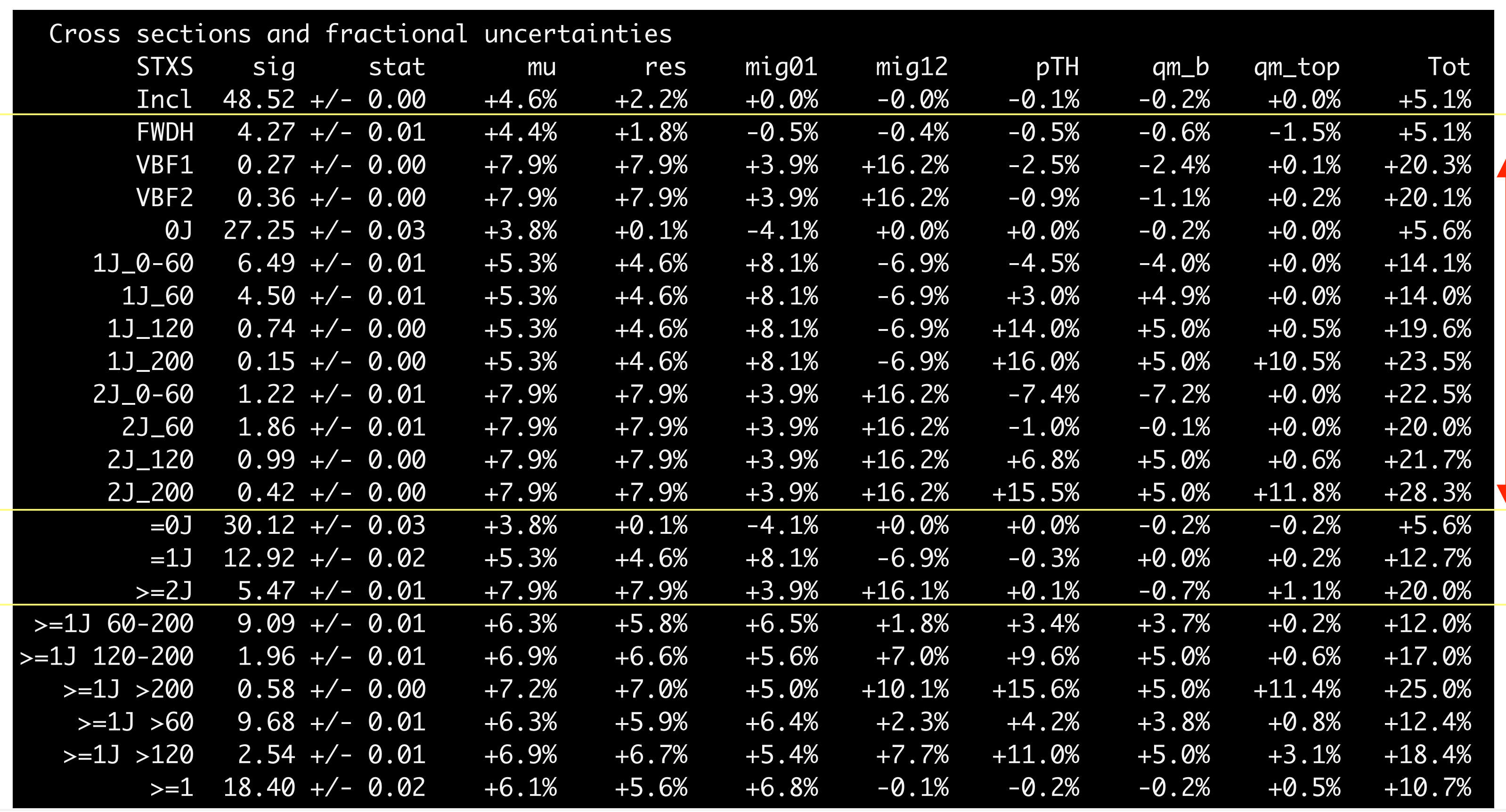
resummation

0⟷1 jet migration

1⟷2 jet migration

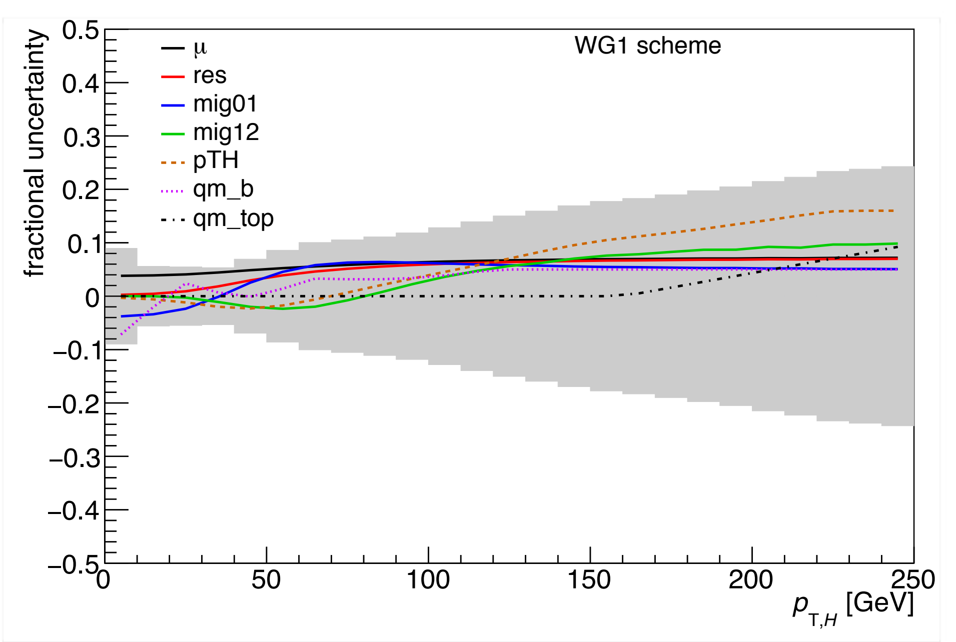
  - Accounts for uncertainties and migrations between the =0, =1 and >=2 jet bins
- Uncertainties also needed for:
  - Higgs p_T spectrum within a given jet bin
  - Quark mass treatment in ggF loop, if significant wrt QCD scale uncertainties
  - VBF region

F. Caola, D. Gillberg, A. Massironi, P. Monni



```
 Cross sections and fractional uncertainties
          STXS    sig       stat        mu       res     mig01     mig12       pTH      qm_b    qm_top       Tot
          Incl  48.52 +/- 0.00     +4.6%     +2.2%     +0.0%     -0.0%     -0.1%     -0.2%     +0.0%     +5.1%
          FWDH   4.27 +/- 0.01     +4.4%     +1.8%     -0.5%     -0.4%     -0.5%     -0.6%     -1.5%     +5.1%
          VBF1   0.27 +/- 0.00     +7.9%     +7.9%     +3.9%    +16.2%     -2.5%     -2.4%     +0.1%    +20.3%
          VBF2   0.36 +/- 0.00     +7.9%     +7.9%     +3.9%    +16.2%     -0.9%     -1.1%     +0.2%    +20.1%
            0J  27.25 +/- 0.03     +3.8%     +0.1%     -4.1%     +0.0%     +0.0%     -0.2%     +0.0%     +5.6%
       1J_0-60   6.49 +/- 0.01     +5.3%     +4.6%     +8.1%     -6.9%     -4.5%     -4.0%     +0.0%    +14.1%
         1J_60   4.50 +/- 0.01     +5.3%     +4.6%     +8.1%     -6.9%     +3.0%     +4.9%     +0.0%    +14.0%
        1J_120   0.74 +/- 0.00     +5.3%     +4.6%     +8.1%     -6.9%    +14.0%     +5.0%     +0.5%    +19.6%
        1J_200   0.15 +/- 0.00     +5.3%     +4.6%     +8.1%     -6.9%    +16.0%     +5.0%    +10.5%    +23.5%
       2J_0-60   1.22 +/- 0.01     +7.9%     +7.9%     +3.9%    +16.2%     -7.4%     -7.2%     +0.0%    +22.5%
         2J_60   1.86 +/- 0.01     +7.9%     +7.9%     +3.9%    +16.2%     -1.0%     -0.1%     +0.0%    +20.0%
        2J_120   0.99 +/- 0.00     +7.9%     +7.9%     +3.9%    +16.2%     +6.8%     +5.0%     +0.6%    +21.7%
        2J_200   0.42 +/- 0.00     +7.9%     +7.9%     +3.9%    +16.2%    +15.5%     +5.0%    +11.8%    +28.3%
           =0J  30.12 +/- 0.03     +3.8%     +0.1%     -4.1%     +0.0%     +0.0%     -0.2%     -0.2%     +5.6%
           =1J  12.92 +/- 0.02     +5.3%     +4.6%     +8.1%     -6.9%     -0.3%     +0.0%     +0.2%    +12.7%
          >=2J   5.47 +/- 0.01     +7.9%     +7.9%     +3.9%    +16.1%     +0.1%     -0.7%     +1.1%    +20.0%
  >=1J 60-200   9.09 +/- 0.01     +6.3%     +5.8%     +6.5%     +1.8%     +3.4%     +3.7%     +0.2%    +12.0%
 >=1J 120-200   1.96 +/- 0.01     +6.9%     +6.6%     +5.6%     +7.0%     +9.6%     +5.0%     +0.6%    +17.0%
    >=1J >200   0.58 +/- 0.00     +7.2%     +7.0%     +5.0%    +10.1%    +15.6%     +5.0%    +11.4%    +25.0%
     >=1J >60   9.68 +/- 0.01     +6.3%     +5.9%     +6.4%     +2.3%     +4.2%     +3.8%     +0.8%    +12.4%
    >=1J >120   2.54 +/- 0.01     +6.9%     +6.7%     +5.4%     +7.7%    +11.0%     +5.0%     +3.1%    +18.4%
          >=1  18.40 +/- 0.02     +6.1%     +5.6%     +6.8%     -0.1%     -0.2%     -0.2%     +0.5%    +10.7%
```

The 11 ggF STXS bins

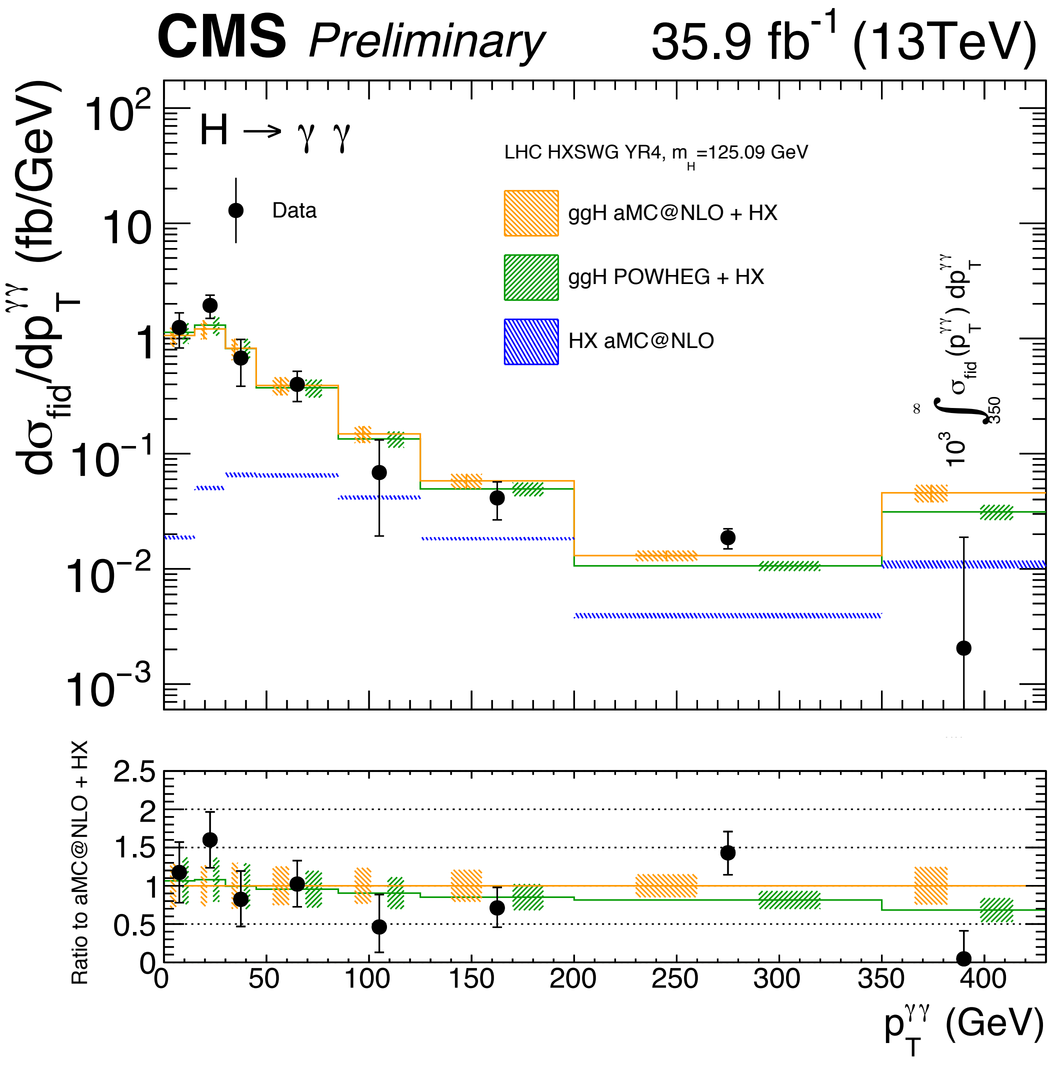


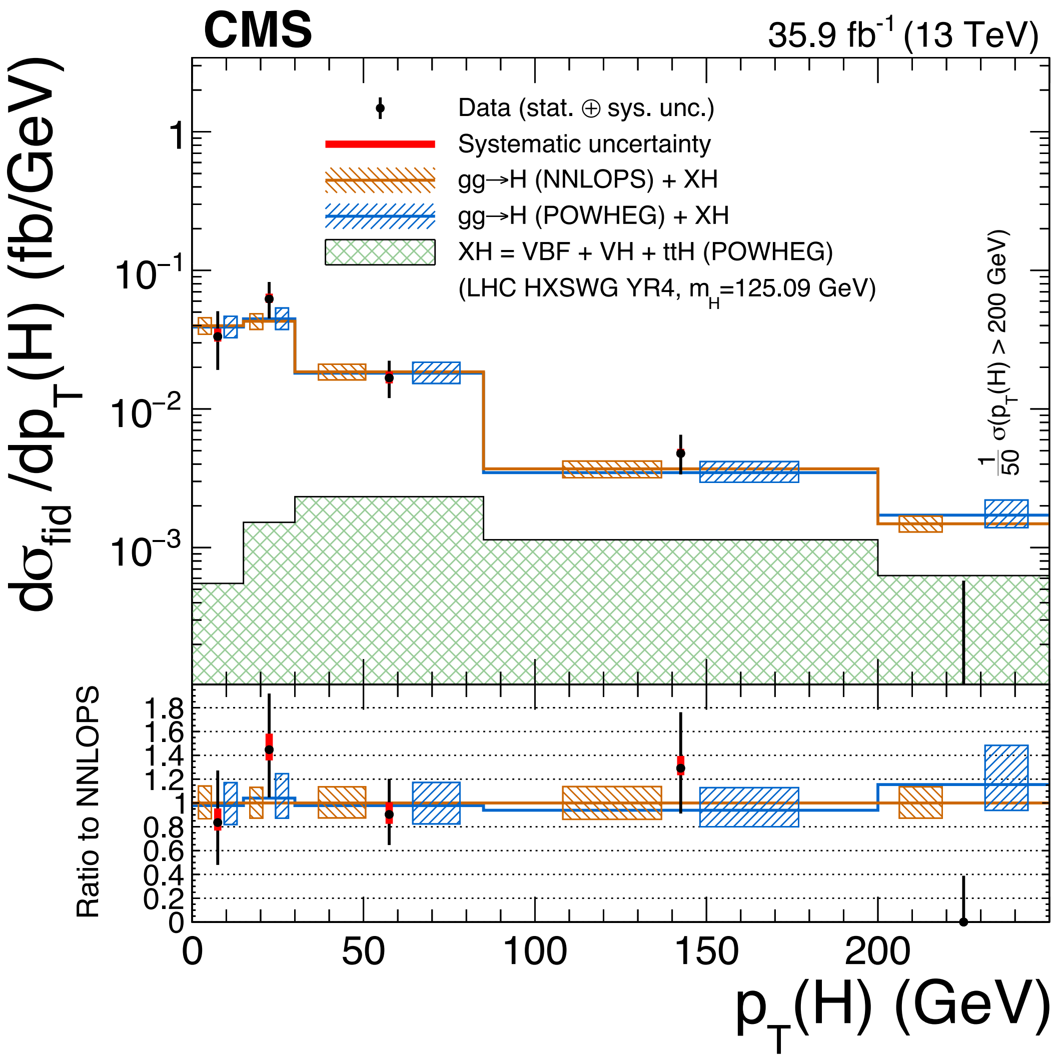
Differential measurements

- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels provide differential fiducial cross sections at particle level, chosen to match reco. selections closely

- Differential cross sections given for p_T^H and number of jets
  - High p_T^H tail sensitive to BSM effects, low p_T^H to lighter couplings, e.g. κ_c

- Combination of channels will be possible by unfolding to common phase-space



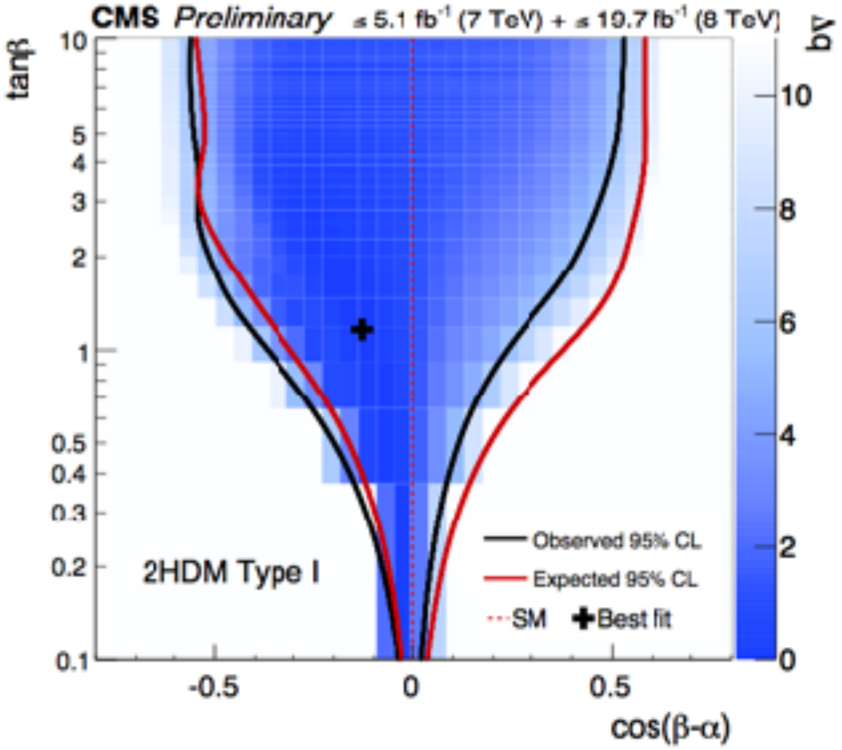


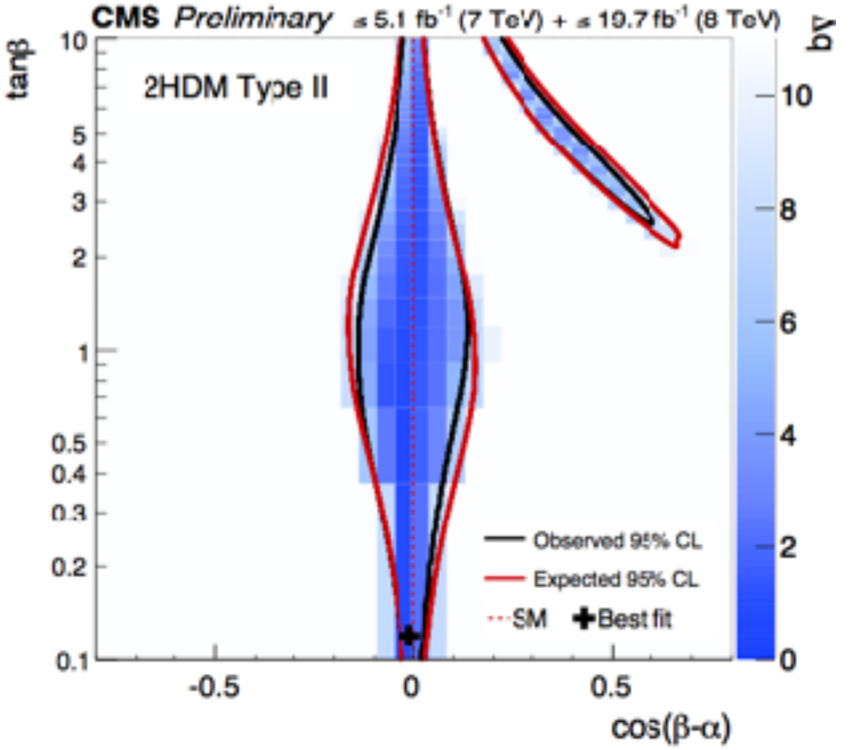
BSM interpretation

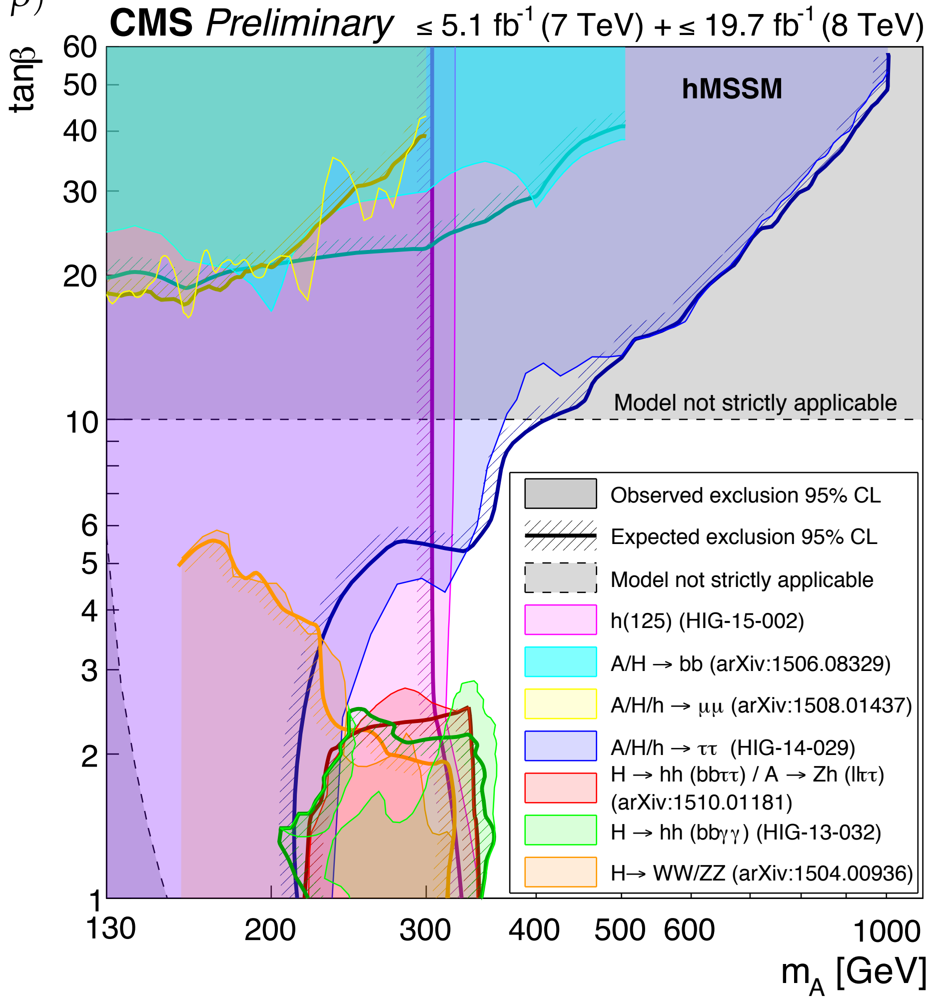
- Couplings constraints can be interpreted as constraints in 2HDM/MSSM models
- Uses the full likelihood with κ_V, κ_u and κ_d as parameters, related to cos(β-α)/tanβ or m_A/tanβ

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

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







Summary

- Large fraction of target analyses now covered with the full 2016 dataset
  - Up to factor 2 improvement over run 1

- Increasing focus on more granular measurements during run 2:
  - Fiducial/differential cross sections in H→ZZ and H→γγ
  - Simplified template cross section measurements
  - Currently stage-0 results, move to stage-1

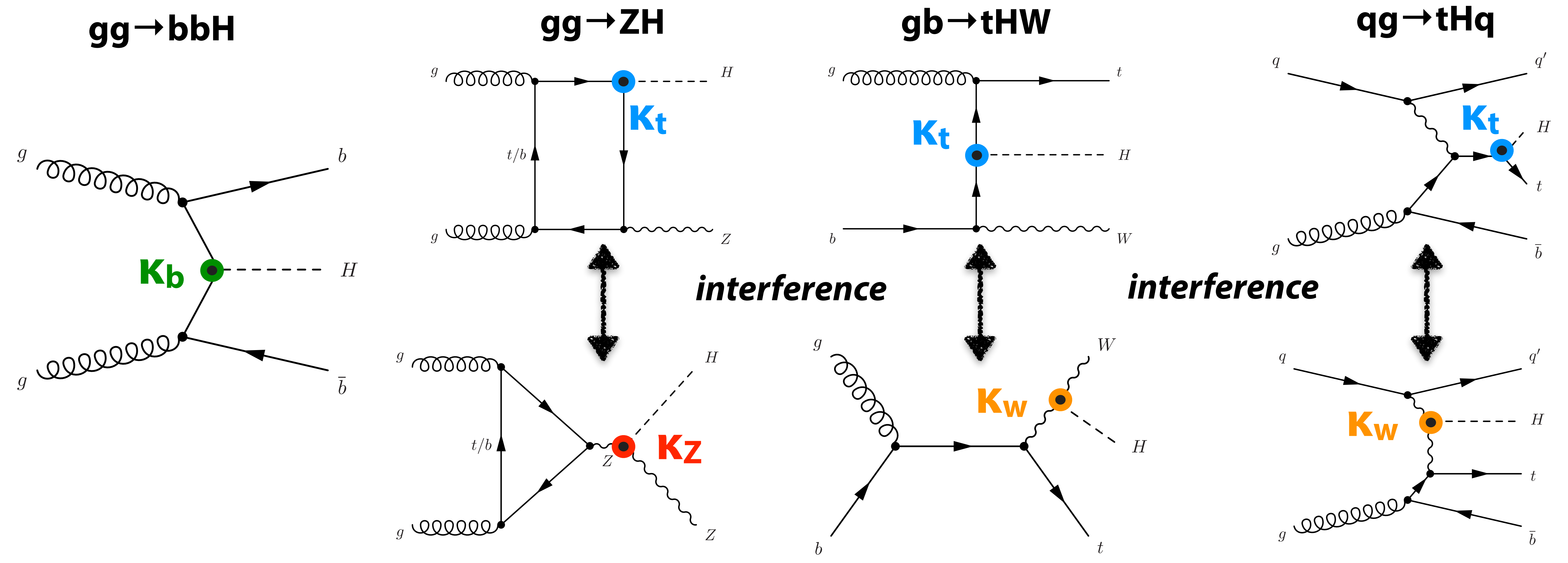
- Combined fits of all channels will give most coherent results on signal strengths / couplings - input from the theory community on new models/interpretations is appreciated

Backup

Decay processes

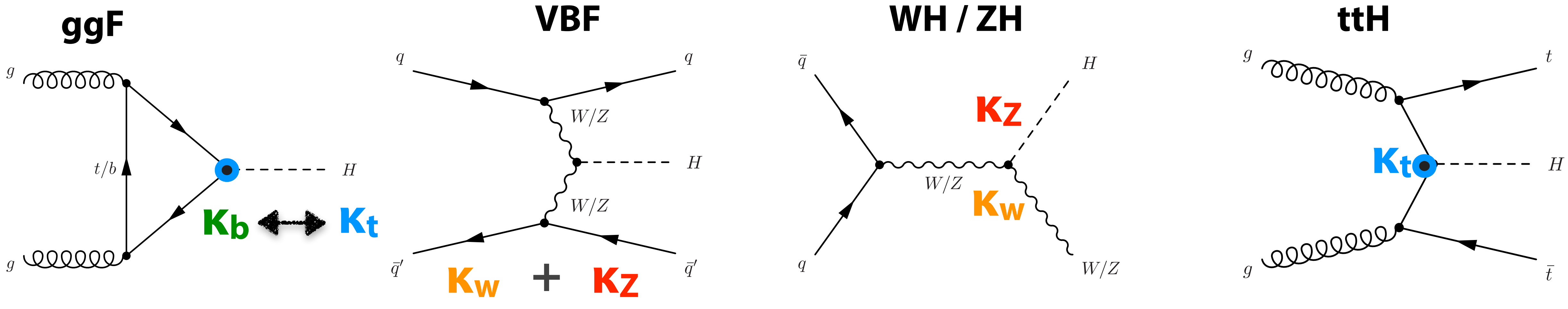
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

- **Rare processes:**



Production processes

- **Usual suspects:**



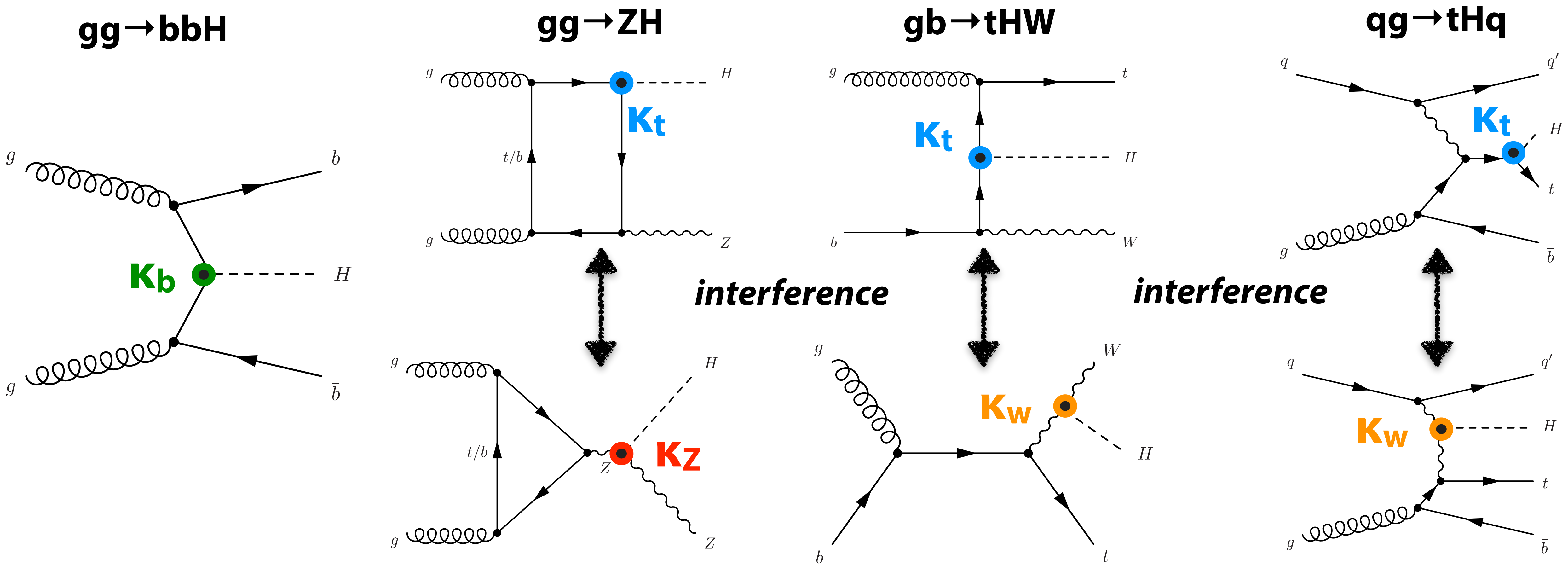
ggF

VBF

WH / ZH

ttH

- **Rare processes:**



gg→bbH

gg→ZH

gb→tHW

qg→tHq

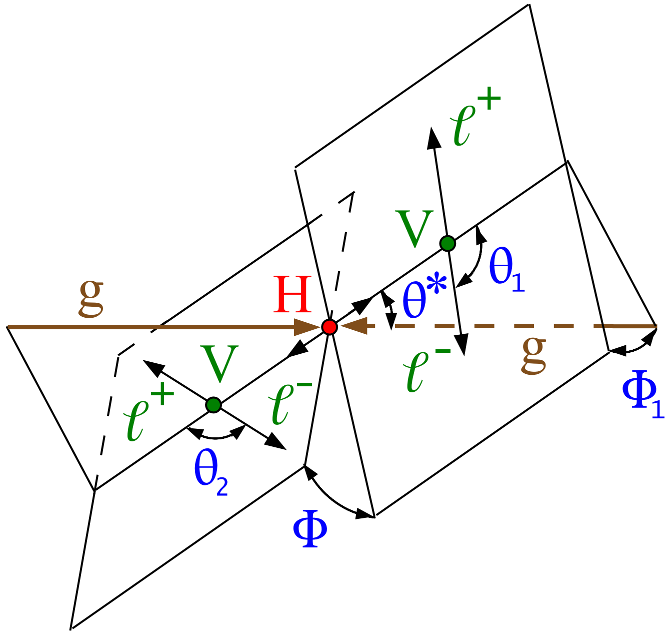
H→ZZ anomalous couplings

arXiv:1707.00541

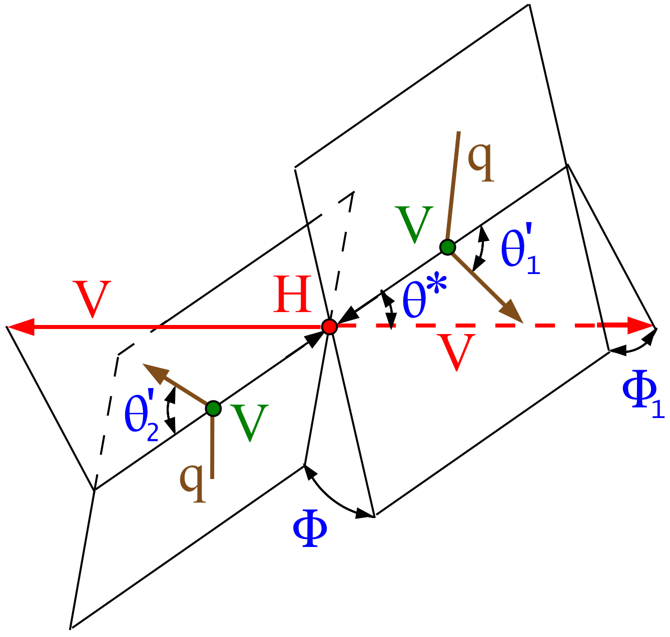
- Angular analysis of H→ZZ→4l events to search for anomalous spin-0 couplings
- New for 13 TeV: use kinematics of **production** H(VV) vertex in VBF and VH modes as well as in 4l **decay**
- Amplitude parametrised as:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

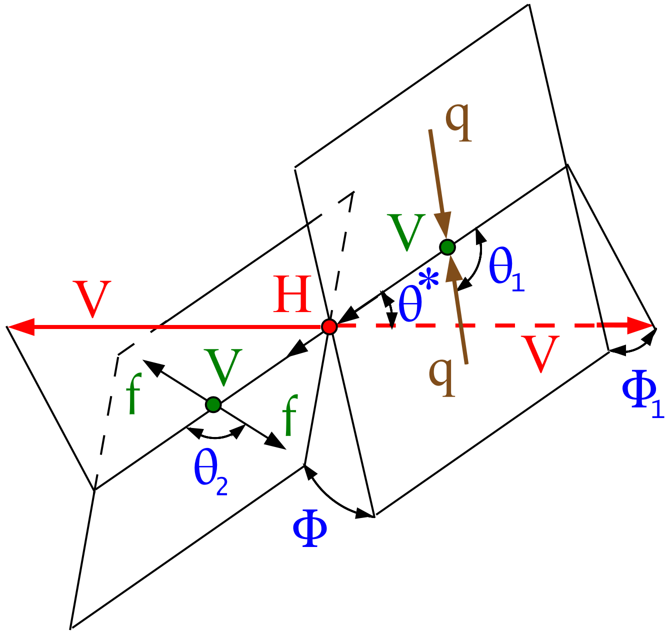
BSM CP-even **BSM CP-odd**



Gluon fusion (decay)



VBF production



VH production

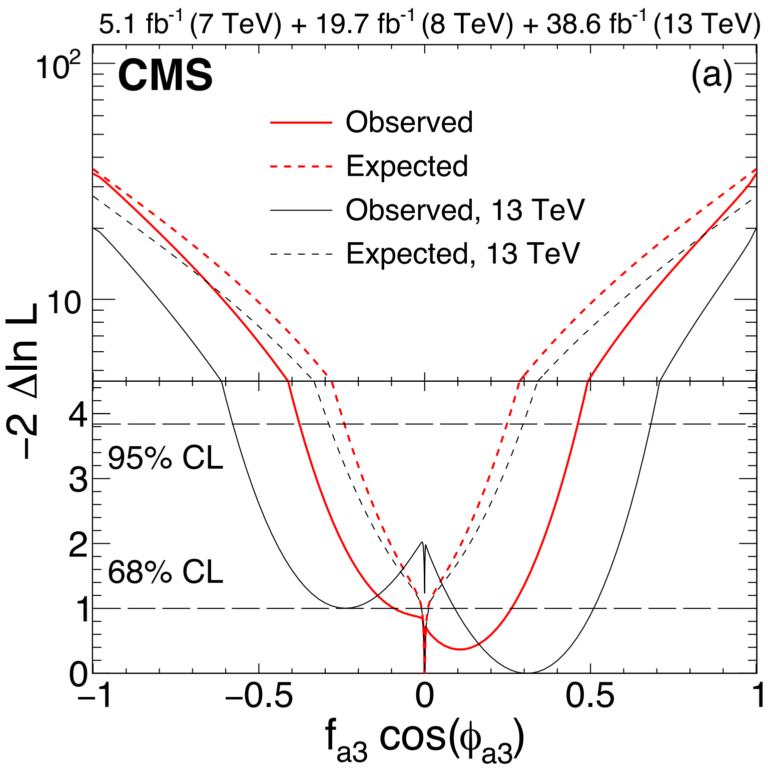
H→ZZ anomalous couplings

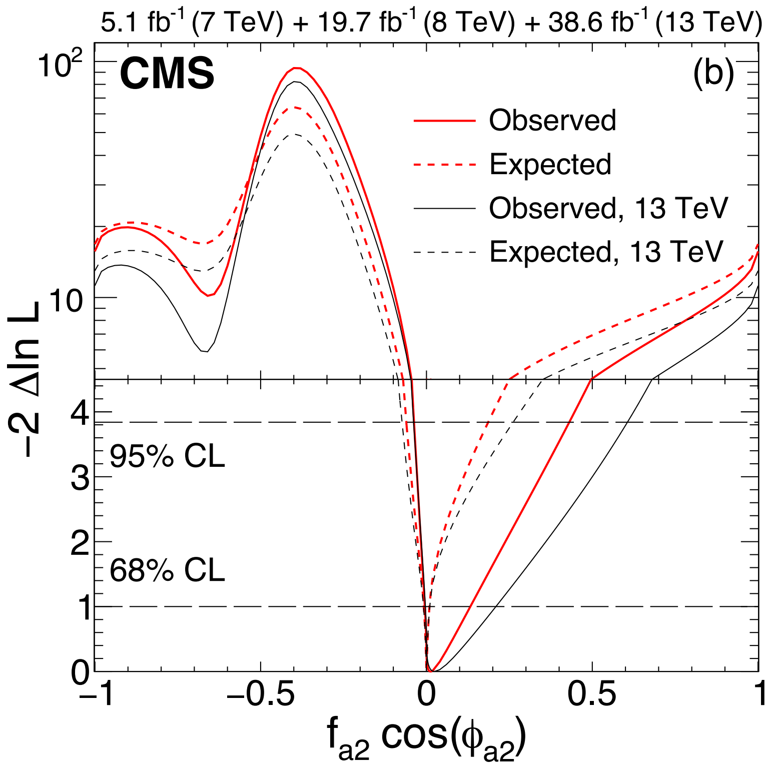
arXiv:1707.00541

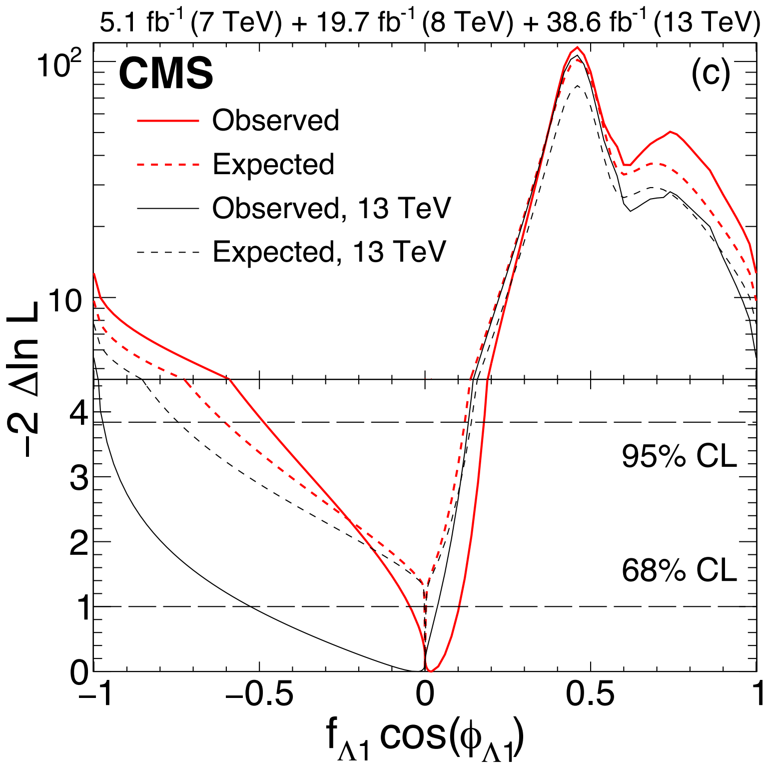
- Fits for anomalous coupling ratios f_{ai}: $f_{ai} = |a_i|^2\sigma_i \big/ \sum |a_j|^2\sigma_j$

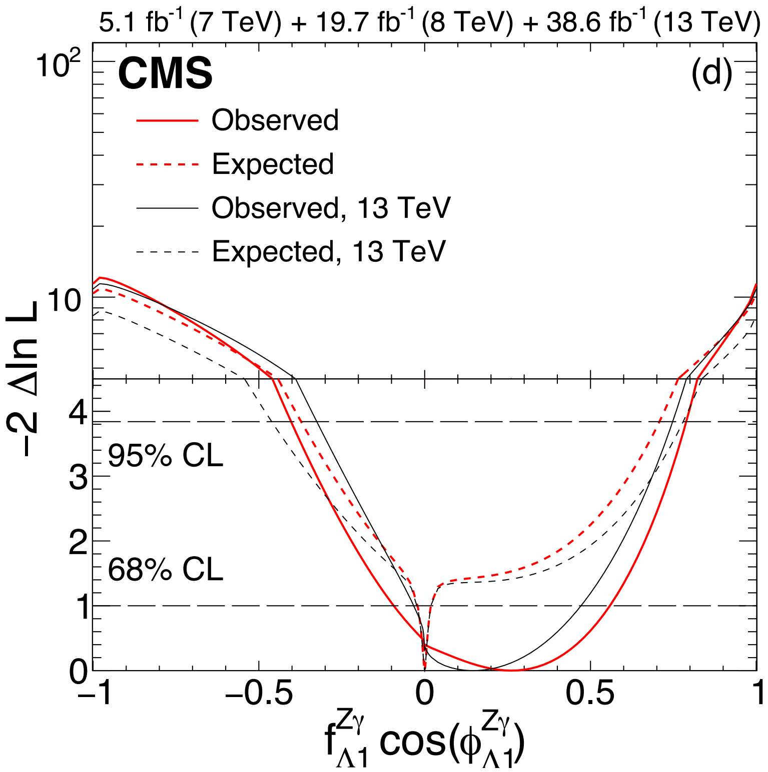
- Run 2 gives ~ factor 10 improvement in 68% CL sensitivity over run 1 due to addition of production information

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}\ [-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}\ [-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}\ [-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}\ [-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}\ [-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}\ [-0.60, 0.12]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}\ [-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}\ [-0.37, 0.71]$



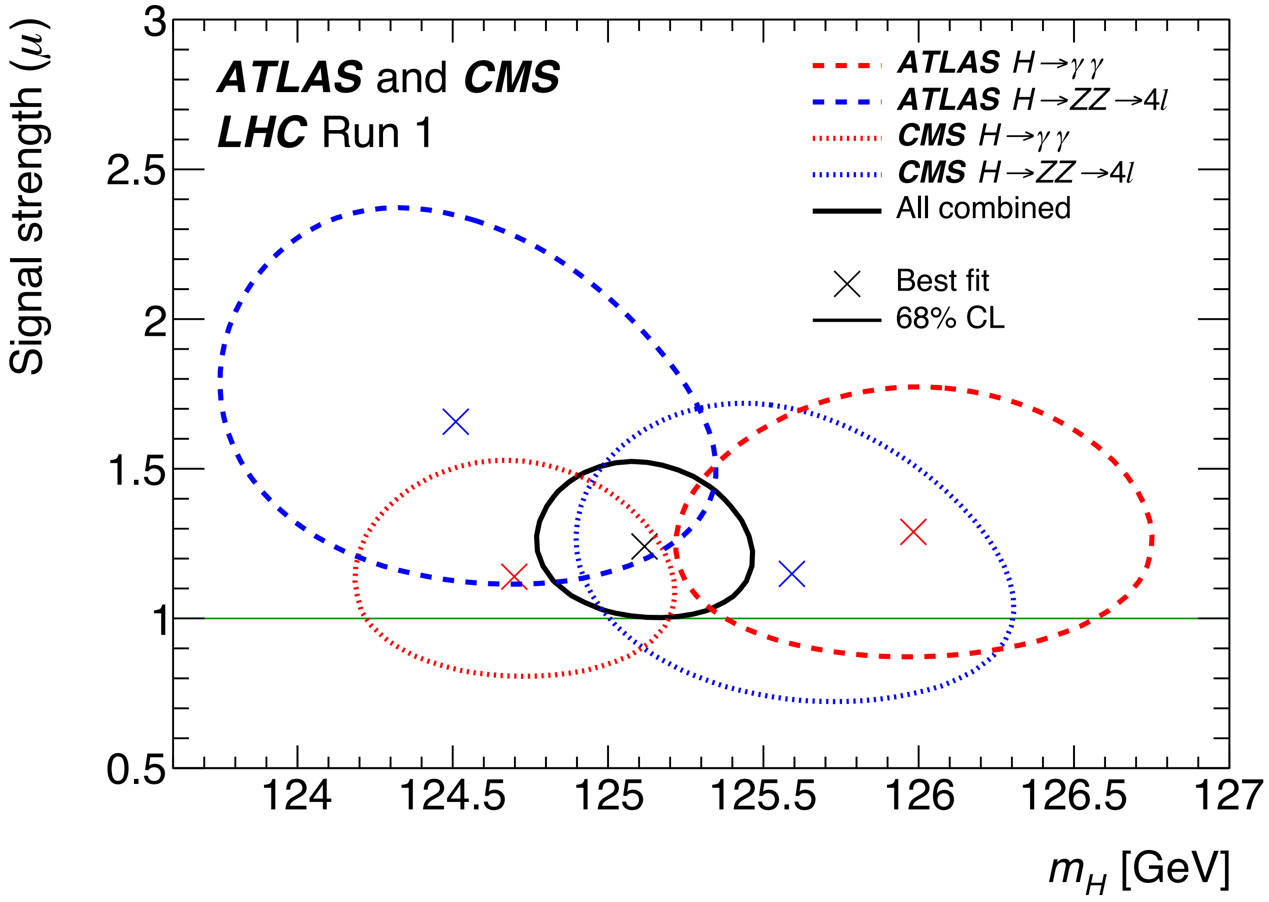


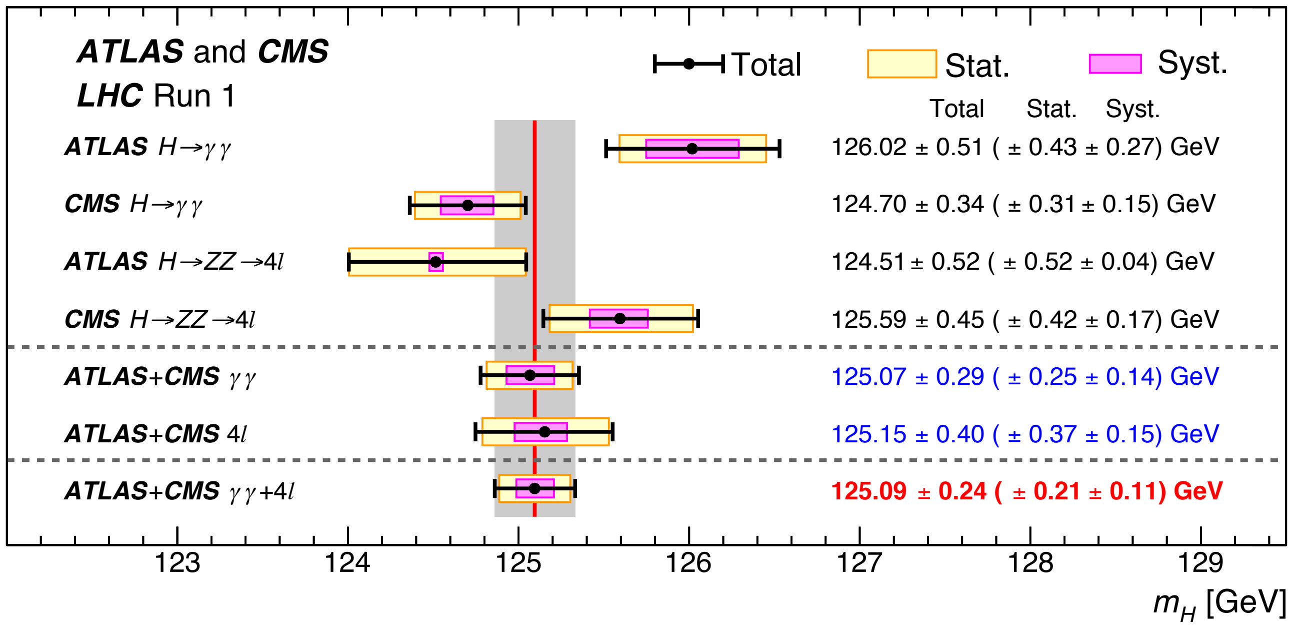




LHC Run 1 Combination Results

- Using high resolution H→γγ and H→ZZ→4l channels
- Important to establish the best measurement of m_H before attempting couplings
- Statistical uncertainty still dominates, main systematics related to energy or momentum scale of e, μ and γ





m_H = 125.09 ± 0.24 GeV = 125.09 ± 0.21 (stat.) ± 0.11 (syst) GeV

LHC Run 1 Combination Results

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}	$0.70^{+0.29}_{-0.27}$ $\left(^{+0.29}_{-0.28}\right)$	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$
$\mu^{\mu\mu}$	$0.1^{+2.5}_{-2.5}$ $\left(^{+2.4}_{-2.3}\right)$	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$

Production process	ATLAS+CMS	ATLAS	CMS
$\mu_{gg\mathrm{F}}$	$1.03^{+0.16}_{-0.14}$ $\left(^{+0.16}_{-0.14}\right)$	$1.26^{+0.23}_{-0.20}$ $\left(^{+0.21}_{-0.18}\right)$	$0.84^{+0.18}_{-0.16}$ $\left(^{+0.20}_{-0.17}\right)$
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}	$2.3^{+0.7}_{-0.6}$ $\left(^{+0.5}_{-0.5}\right)$	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$

LHC Run 1 Combination Results

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 [0.92, 1.00]	[−1.00, −0.89]∪ [0.89, 1.00]	1.00 [−0.97, −0.94]∪ [0.86, 1.00]	−1.00 [−1.00, −0.84]∪ [0.90, 1.00]
κ_W	0.90 [0.81, 0.99]	[−1.00, −0.90]∪ [0.89, 1.00]	0.92 [−0.88, −0.84]∪ [0.79, 1.00]	−0.84 [−1.00, −0.71]∪ [0.76, 0.98]
κ_t	$1.43^{+0.23}_{-0.22}$	${}^{+0.27}_{-0.32}$	$1.31^{+0.35}_{-0.33}$	$1.45^{+0.42}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.87^{+0.12}_{-0.11}$	${}^{+0.14}_{-0.15}$	$0.97^{+0.21}_{-0.17}$	$0.79^{+0.20}_{-0.16}$
$\lvert\kappa_b\rvert$	$0.57^{+0.16}_{-0.16}$	${}^{+0.19}_{-0.23}$	$0.61^{+0.24}_{-0.26}$	$0.49^{+0.26}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.81^{+0.13}_{-0.10}$	${}^{+0.17}_{-0.14}$	$0.94^{+0.23}_{-0.16}$	$0.69^{+0.21}_{-0.13}$
$\lvert\kappa_\gamma\rvert$	$0.90^{+0.10}_{-0.09}$	${}^{+0.10}_{-0.12}$	$0.87^{+0.15}_{-0.14}$	$0.89^{+0.17}_{-0.13}$
B_{BSM}	$0.00^{+0.16}$	${}^{+0.19}$	$0.00^{+0.25}$	$0.03^{+0.26}$
Parameterisation assuming $B_{BSM} = 0$				
κ_Z	−0.98 [−1.08, −0.88]∪ [0.94, 1.13]	[−1.01, −0.87]∪ [0.89, 1.11]	1.01 [−1.09, −0.85]∪ [0.87, 1.15]	−0.99 [−1.14, −0.84]∪ [0.94, 1.19]
κ_W	0.87 [0.78, 1.00]	[−1.08, −0.90]∪ [0.88, 1.11]	0.92 [−0.94, −0.85]∪ [0.78, 1.05]	0.84 [−0.99, −0.74]∪ [0.71, 1.01]
κ_t	$1.40^{+0.24}_{-0.21}$	${}^{+0.26}_{-0.39}$	$1.32^{+0.31}_{-0.33}$	$1.51^{+0.33}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$	${}^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.19}$	$0.77^{+0.18}_{-0.15}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$	${}^{+0.25}_{-0.28}$	$0.61^{+0.26}_{-0.31}$	$0.47^{+0.34}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$	${}^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.17}$	$0.67^{+0.14}_{-0.12}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$	${}^{+0.12}_{-0.13}$	$0.88^{+0.15}_{-0.15}$	$0.89^{+0.19}_{-0.13}$

LHC Run 1 Combination Results

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 $[-0.91, -0.40] \cup$ $[0.35, 1.04]$
$\lvert\kappa_\mu\rvert$	$0.2^{+1.2}$	${}^{+0.9}$	$0.0^{+1.4}$	$0.5^{+1.4}$