LHC Run 1 results on the Higgs boson mass & couplings from ATLAS and CMS

Giovanni Petrucciani
CERN

Outline

- Mass measurement
- Cross sections and BRs
- Couplings
- Sumary & outlook

References:

- ATLAS + CMS combined mass measurement: PRL 114, 191803
- ATLAS + CMS combined Higgs cross sections, BRs, couplings: ATLAS-CONF-2015-044 & CMS-PAS-HIG-15-002

Higgs boson analyses

Qualitative picture to keep in mind when looking at fits of σ's, BR's, couplings:

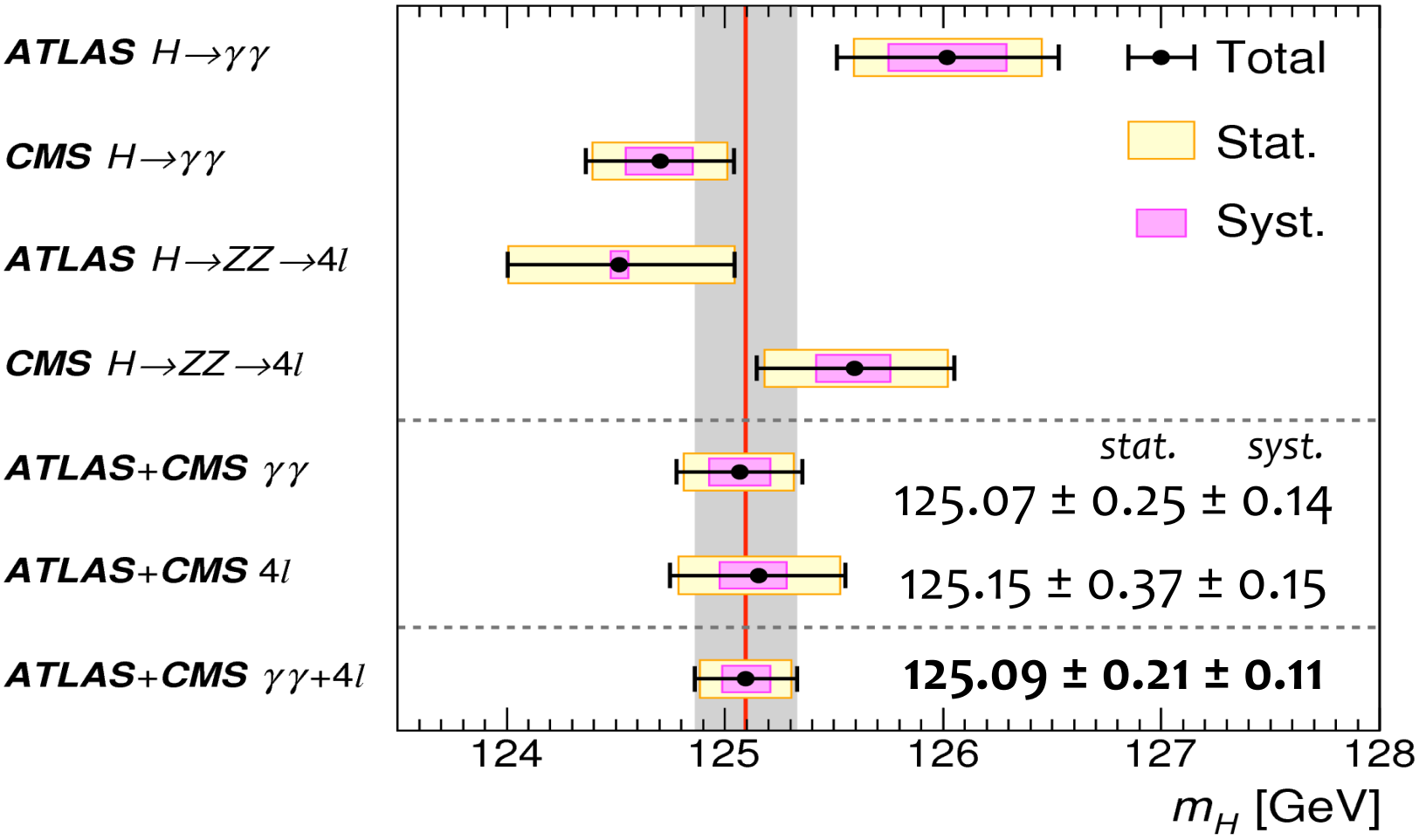
	ggH	VBF	VH	ttH
H → ZZ	✓	~	✗	✗
H → γγ	✓	✓	~	~
H → WW	✓	✓	~	~
H → ττ	✓	✓	~	✗
H → bb		~	✓	~

more bkgs & systematics

Mass measurement

- Extracted from the invariant mass of the decay products in the 4ℓ, $\gamma\gamma$ modes
- Clean measurement:
  - Sensitivity driven by statistical uncertainties
  - The only sizeable systematical uncertainties are from the energy scale calibrations, esp. for $\gamma\gamma$
  - Clear theoretical interpretation and negligible theory uncertainties (assuming narrow width)

LHC result


ATLAS $H\to\gamma\gamma$
CMS $H\to\gamma\gamma$
ATLAS $H\to ZZ\to 4l$
CMS $H\to ZZ\to 4l$
ATLAS+CMS $\gamma\gamma$
ATLAS+CMS $4l$
ATLAS+CMS $\gamma\gamma+4l$
Total
Stat.
Syst.
stat. syst.
125.07 ± 0.25 ± 0.14
125.15 ± 0.37 ± 0.15
125.09 ± 0.21 ± 0.11
124
125
126
127
128
m_H [GeV]

Cross sections, BRs, couplings

- From on-shell Higgs boson production, we can only measure products of σ × BR
  - And only some of them can be resolved
- Main approach used for properties in run 1:
  - Introduce some extra parameters in the model: signal strengths (μ), coupling modifiers (κ) or their ratios (λ)
  - Compute new σ's and BR's scaling the SM Higgs predictions as functions of those parameters
  - Fit those parameters from the data
- Recently, , as a first attempt to derive more model-independent measurements, also more direct fits of σ & BR ratios have been made

What we can't measure

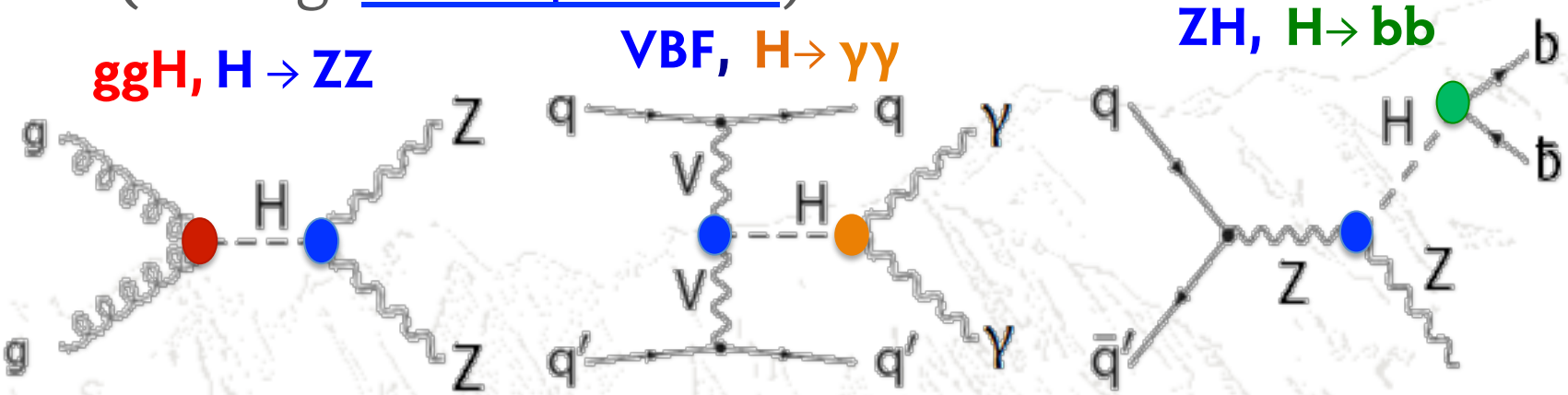
- Not all production and decay modes are accessible or measurable accurately
- Coupling modifier fits make assumptions:
  - non-measurable couplings, e.g. to charm quark, are related to measurable ones, e.g. top quark
- $\sigma \times BR$ ratio fits also need assumptions for quantities that can't be resolved:
  - $\sigma(gg \rightarrow ZH)$, $\sigma(tH)$, $\sigma(bbH)$, all σ's at $\sqrt{s} = 7$ TeV; $H \rightarrow cc, gg, Z\gamma$ decays (e.g. in $H \rightarrow bb$ search)

σ & BR ratio measurements

- ☑ Independent from theory predictions on Higgs boson inclusive cross sections and BRs
  - Results are not invalidated by a new more accurate computation of e.g. σ(ggH)
- ☑ Not limited to a neighbourhood of the SM
  - We are measuring physical observables
- ☒ Needs more degrees of freedom
- ☒ Assumptions on unmeasured quantities are necessarily more crude

Coupling deviation measurements

- ☑ Consistent physics across Higgs production and decay: e.g. κ_W, κ_Z give σ_{VBF}, σ_{WH}, $\sigma_{qq\to ZH}$, Γ_{WW}, Γ_{ZZ}
- ☑ Direct comparison with BSM physics scenarios compatible with the coupling assumptions used
- ☒ Experimental data is necessarily folded in with theory predictions in the results
  - Could try parametrizing fit results on theory inputs, (see e.g. arXiv:1401.0080)



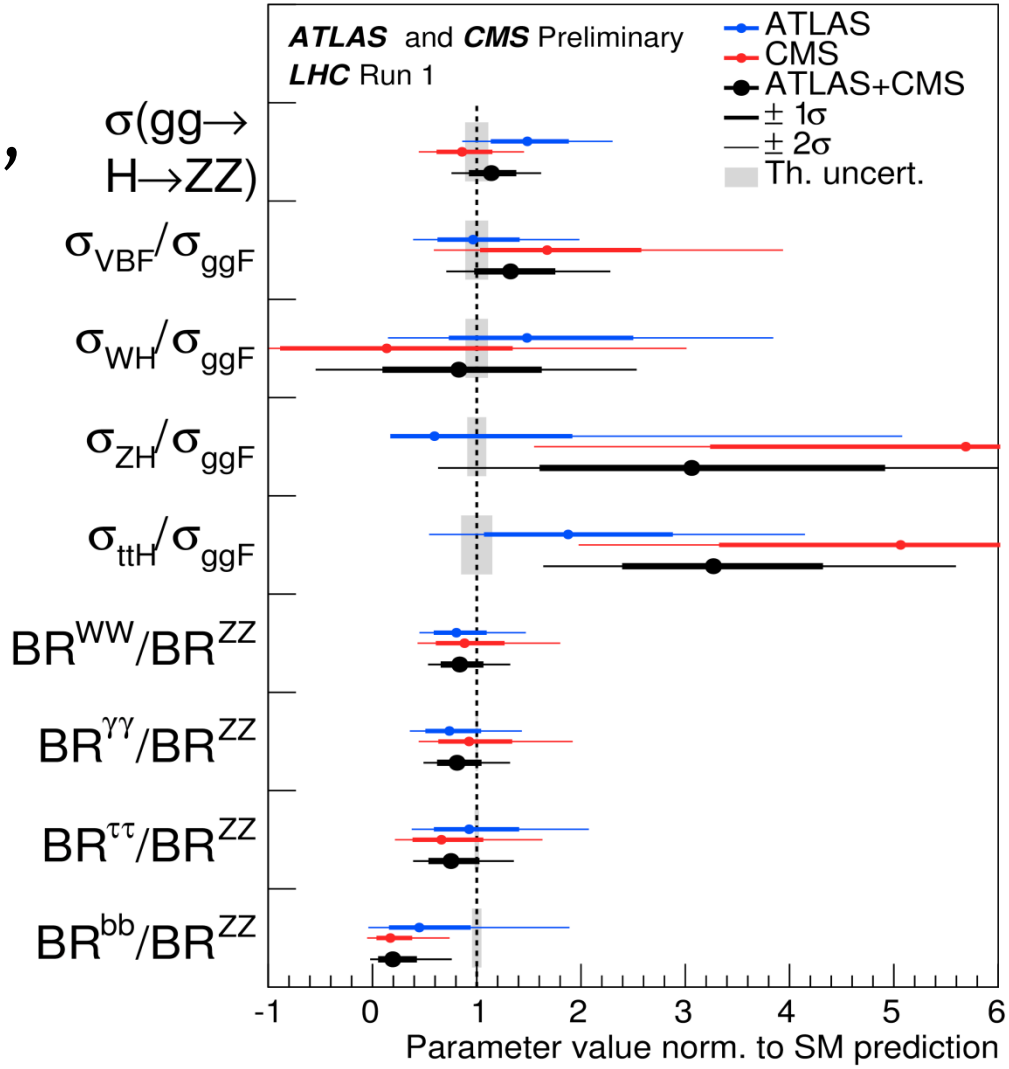
Common limitations

- Results fold in theory predictions of signal kinematic, and background predictions
  - could be solved by "template cross section" approach, and/or by parameterizing results as function of the input theory predictions
- New physics may affect SM backgrounds
  - e.g. yields and kinematics for diboson processes
  - could be addressed with joint Higgs+EWK fits
- Other BSM physics may spoil the picture
  - e.g. Higgs boson production from BSM decays

Fit results: σ & BR ratios

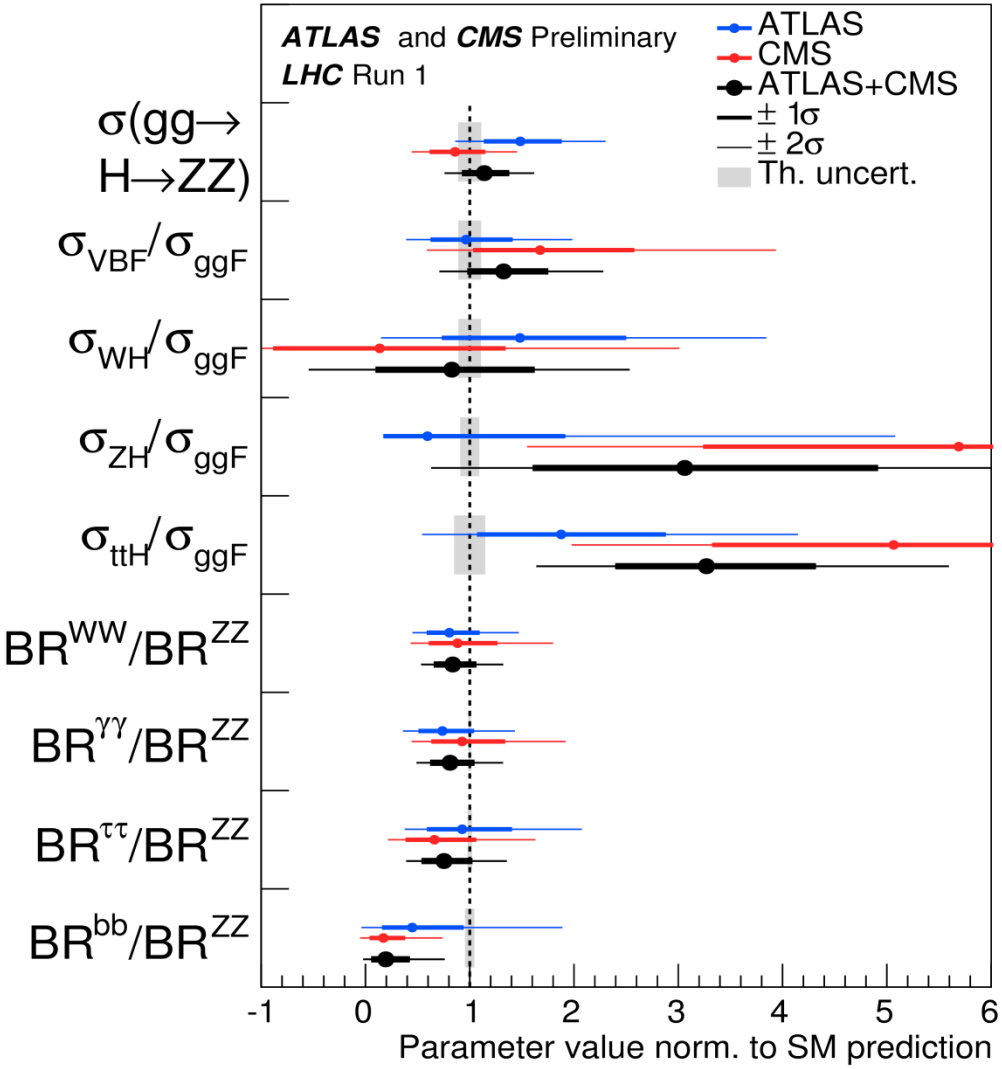
Sensitivity:

- reference cross section,
  $\sigma(gg \rightarrow H \rightarrow ZZ)$
  measured to ~ ±20%
- σ ratios to σ(ggF):
  - VBF ~ 30%
  - others ~ 50-70%
- BR ratios to ZZ:
  - WW, γγ ~25%
  - ττ ~35%
  - bb ~70%

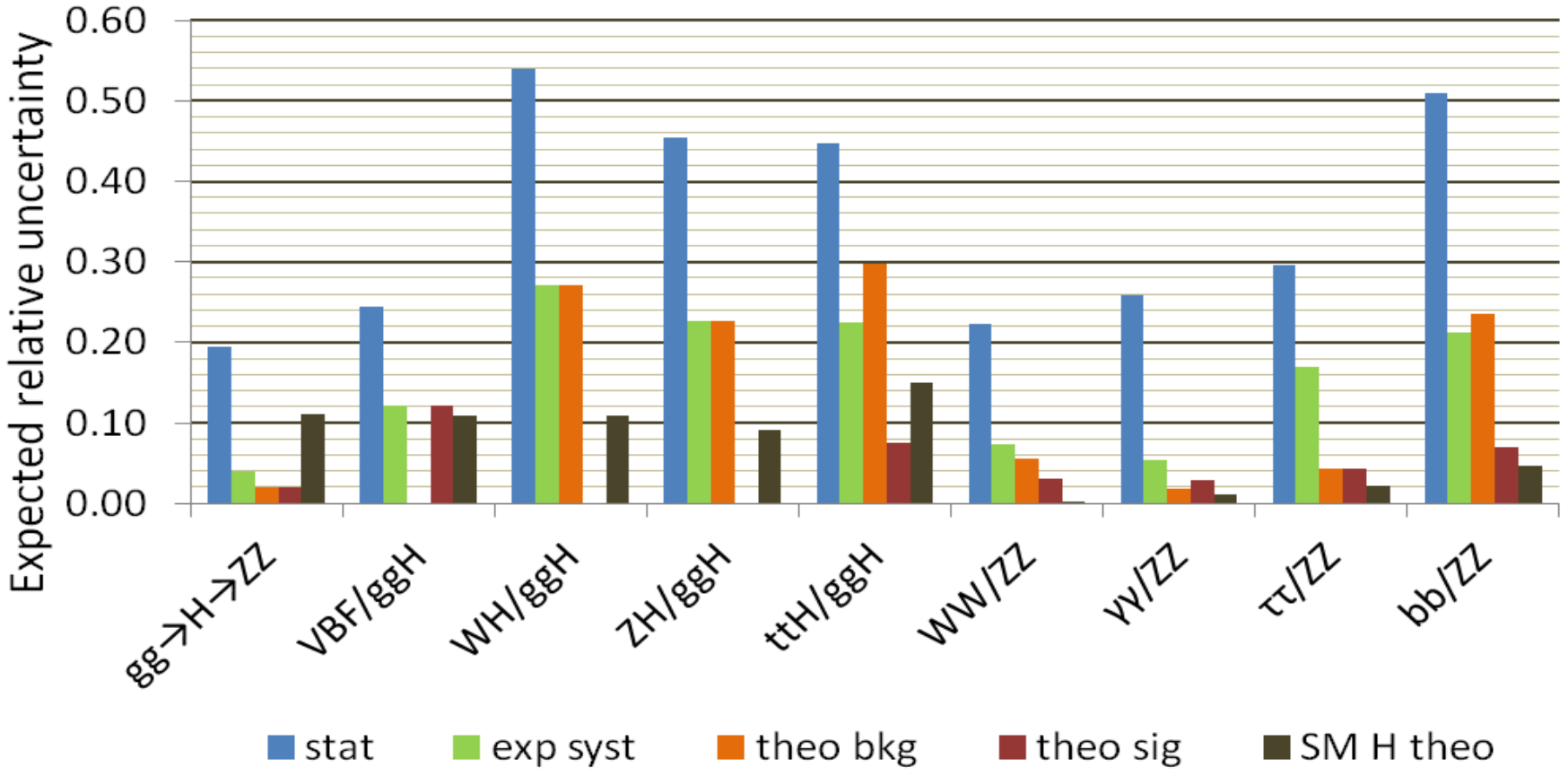


Fit results: σ & BR ratios

- Overall compatibility with SM Higgs: 16%
- Some tensions, at ~2σ :
  - Relative deficit in H→bb compared to other decays in VH and ttH modes makes BR^{bb}/BR^{ZZ} low
  - Large σ(ttH)/σ(ggH) mainly from multilepton and γγ final states
- Important correlations and near-degeneracies:
  - Some σ×BR much better measured than others



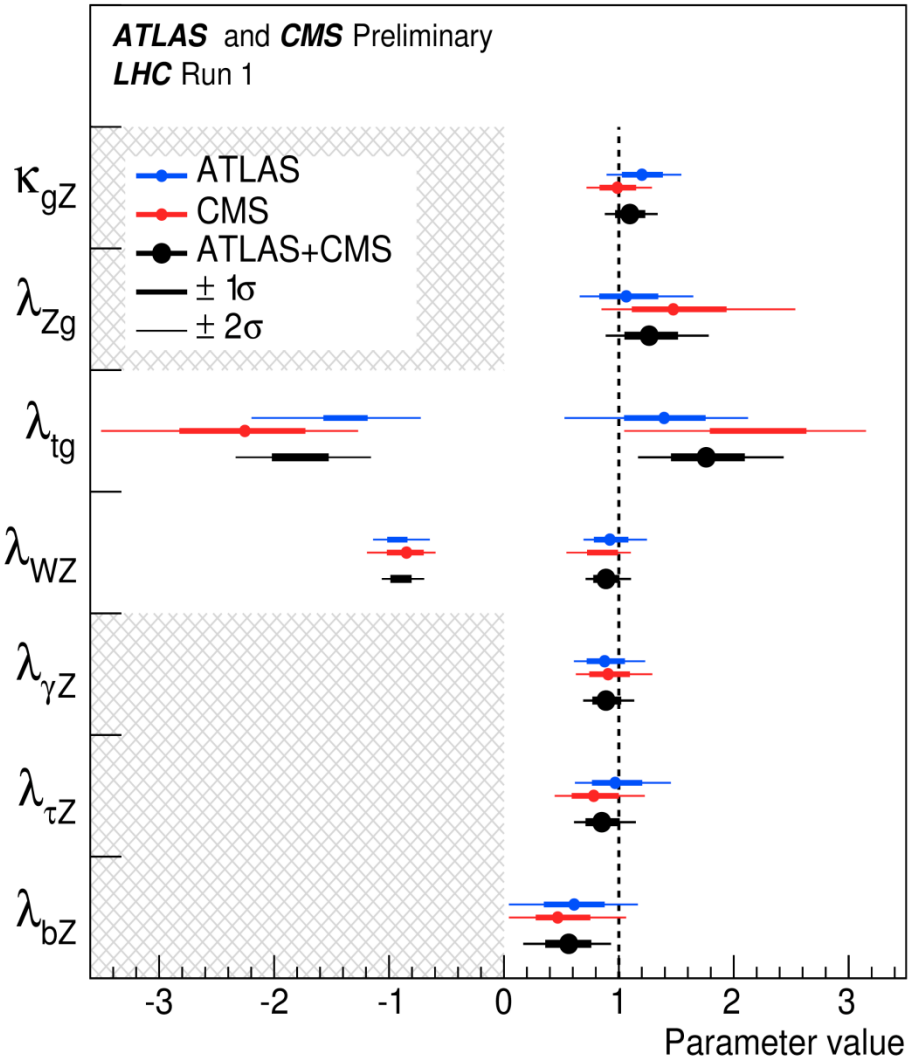
Uncertainty breakdown



SM H theo = uncertainties on inclusive SM Higgs σ & BRs
theo sig = all other signal theory uncertainties: acceptance, jet bins, p_T, …
zero uncertainty = too small wrt numerical accuracy of the fits.

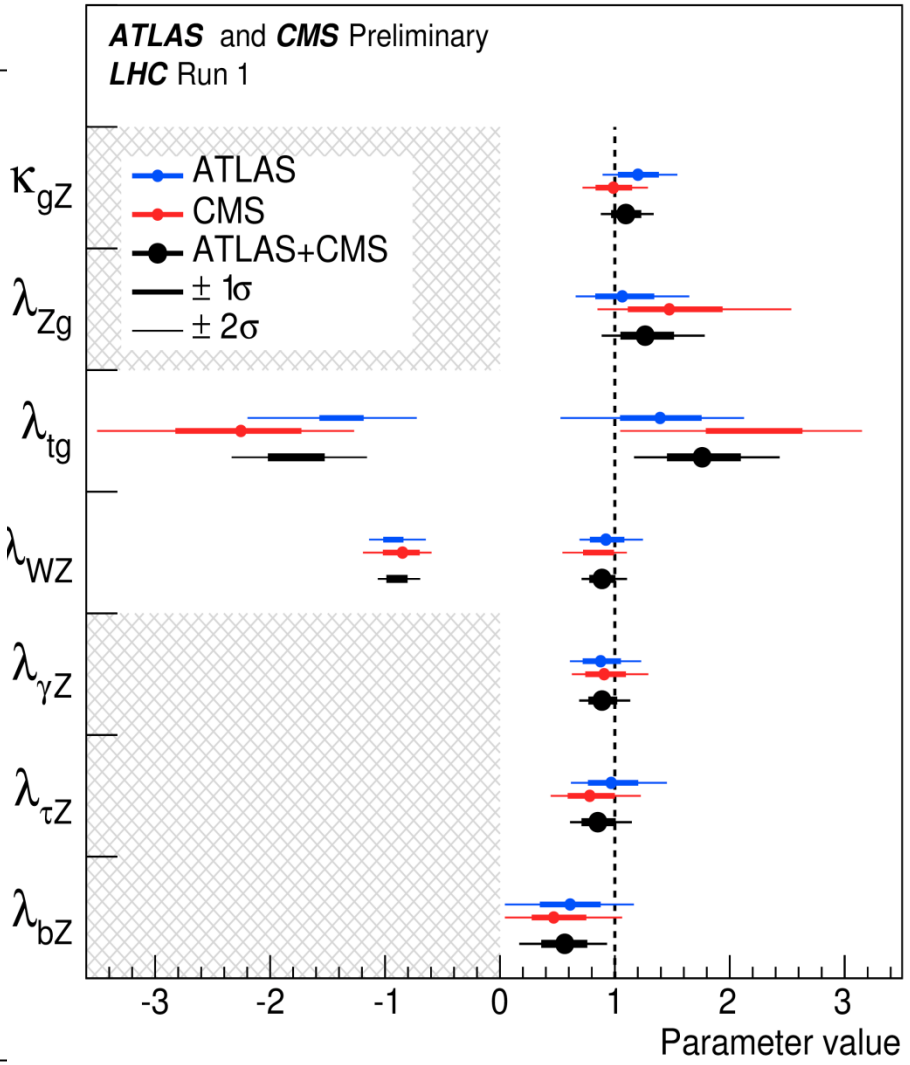
Fit results: coupling ratios

- As in previous model:
  - σ(ttH)/σ(ggH) excess visible, in this case in
    $\lambda_{tg} := \kappa_{top}/\kappa_{glu} = 1.8 \pm 0.3$
  - Relative deficit in H→bb
    $\lambda_{bZ} := \kappa_b/\kappa_Z = 0.6 \pm 0.2$
- Less free parameters: now production and decay are connected
  - so, σ(ZH)/σ(ggH) can't run wild anymore
- Overall compatibility with SM Higgs: 13%

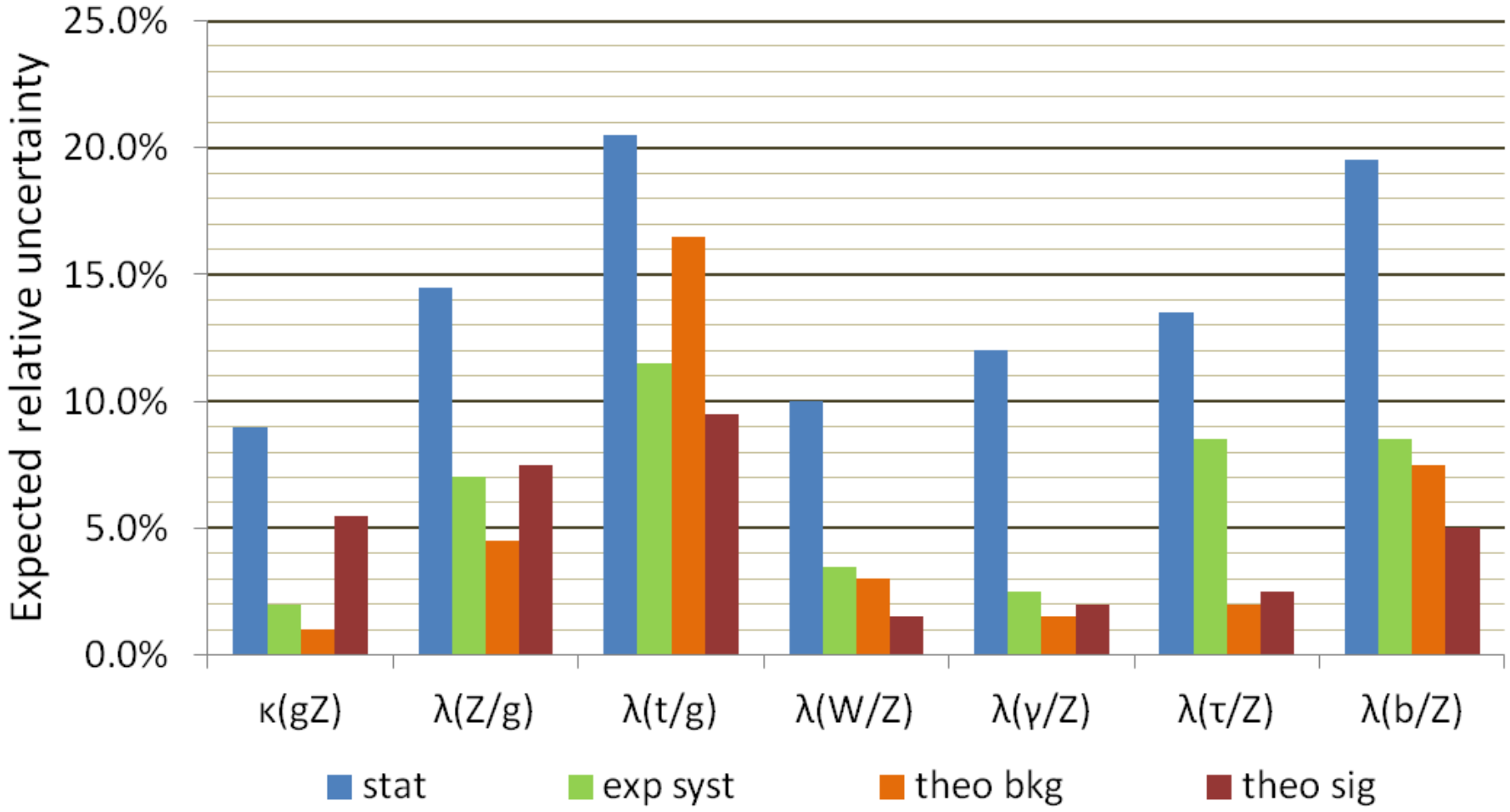


Fit results: coupling ratios

Parameter	Best-fit value	Uncertainty Stat	Uncertainty Syst
	ATLAS+CMS		
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	$1.10\ ^{+0.11}_{-0.11}$	$^{+0.09}_{-0.09}$	$^{+0.07}_{-0.06}$
	$(^{+0.11}_{-0.11})$	$(^{+0.09}_{-0.09})$	$(^{+0.06}_{-0.05})$
$\lambda_{Zg} = \kappa_Z / \kappa_g$	$1.26\ ^{+0.23}_{-0.19}$	$^{+0.18}_{-0.16}$	$^{+0.15}_{-0.12}$
	$(^{+0.20}_{-0.17})$	$(^{+0.15}_{-0.14})$	$(^{+0.12}_{-0.10})$
$\lambda_{tg} = \kappa_t / \kappa_g$	$1.76\ ^{+0.32}_{-0.29}$	$^{+0.21}_{-0.20}$	$^{+0.23}_{-0.20}$
	$(^{+0.29}_{-0.39})$	$(^{+0.20}_{-0.21})$	$(^{+0.21}_{-0.24})$
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$0.89\ ^{+0.10}_{-0.09}$	$^{+0.09}_{-0.08}$	$^{+0.04}_{-0.04}$
	$(^{+0.12}_{-0.10})$	$(^{+0.11}_{-0.09})$	$(^{+0.05}_{-0.04})$
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$	$0.89\ ^{+0.11}_{-0.10}$	$^{+0.11}_{-0.09}$	$^{+0.04}_{-0.03}$
	$(^{+0.13}_{-0.12})$	$(^{+0.13}_{-0.11})$	$(^{+0.04}_{-0.03})$
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$	$0.85\ ^{+0.14}_{-0.12}$	$^{+0.12}_{-0.10}$	$^{+0.07}_{-0.06}$
	$(^{+0.17}_{-0.15})$	$(^{+0.14}_{-0.13})$	$(^{+0.09}_{-0.08})$
$\lambda_{bZ} = \kappa_b / \kappa_Z$	$0.56\ ^{+0.18}_{-0.18}$	$^{+0.12}_{-0.11}$	$^{+0.10}_{-0.11}$
	$(^{+0.25}_{-0.22})$	$(^{+0.21}_{-0.18})$	$(^{+0.14}_{-0.11})$

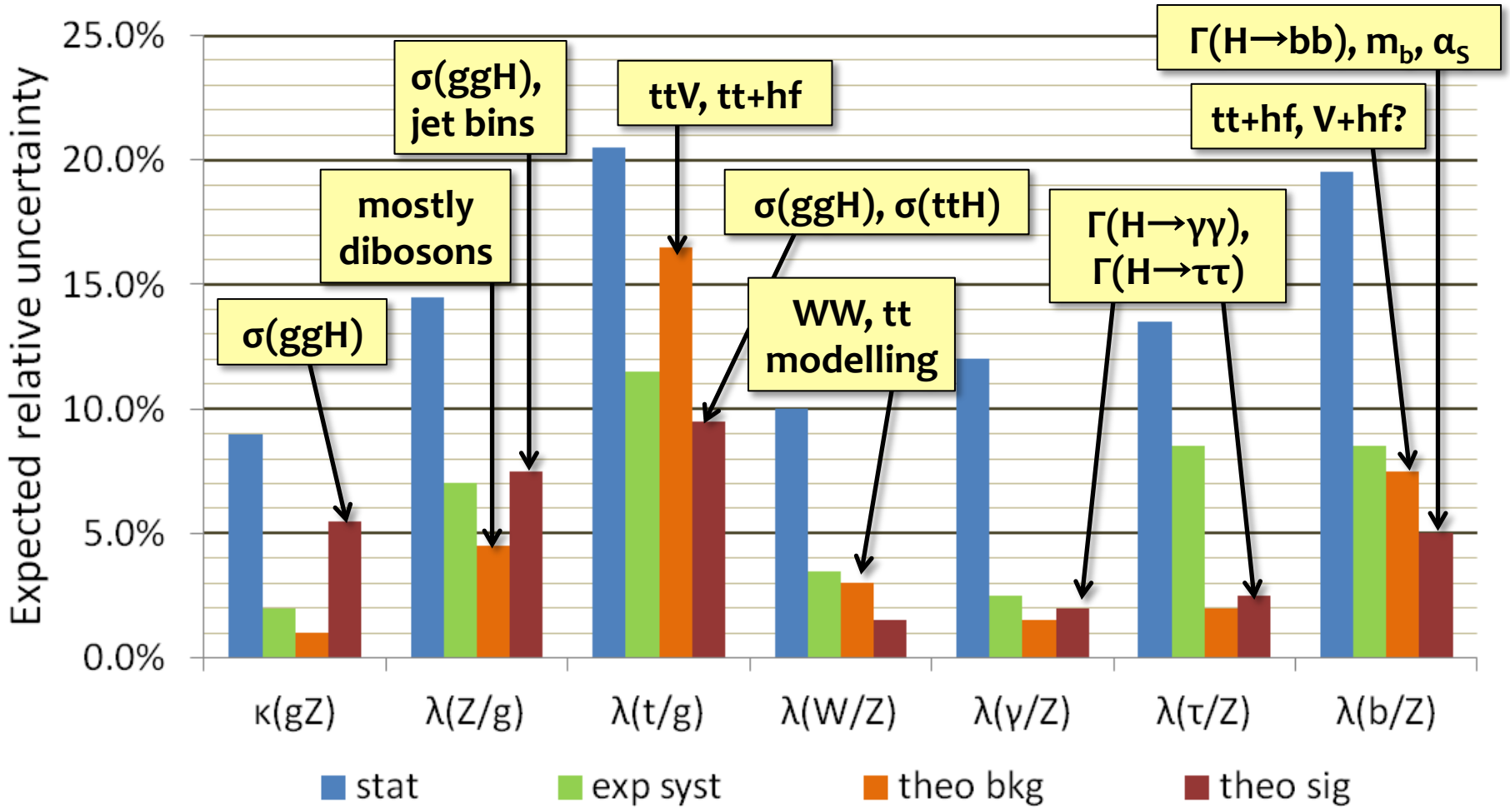


Uncertainty breakdown



note: here, as in all other fits of the couplings, the "theo sig" uncertainty contains also the theory uncertainty on the SM Higgs σ's & BR's

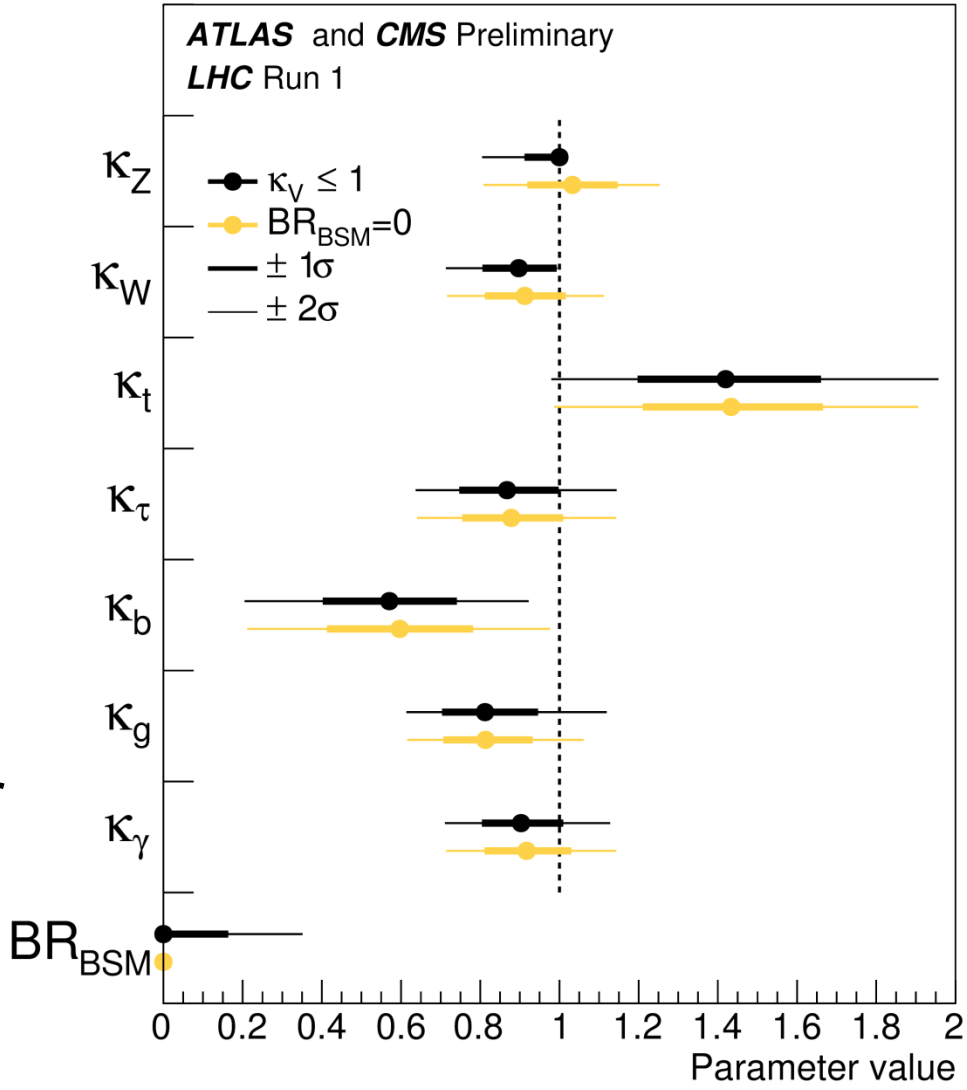
some sizeable theory uncertainties



A more quantitative breakdown of all sources of uncertainties may appear in the final LHC combination paper

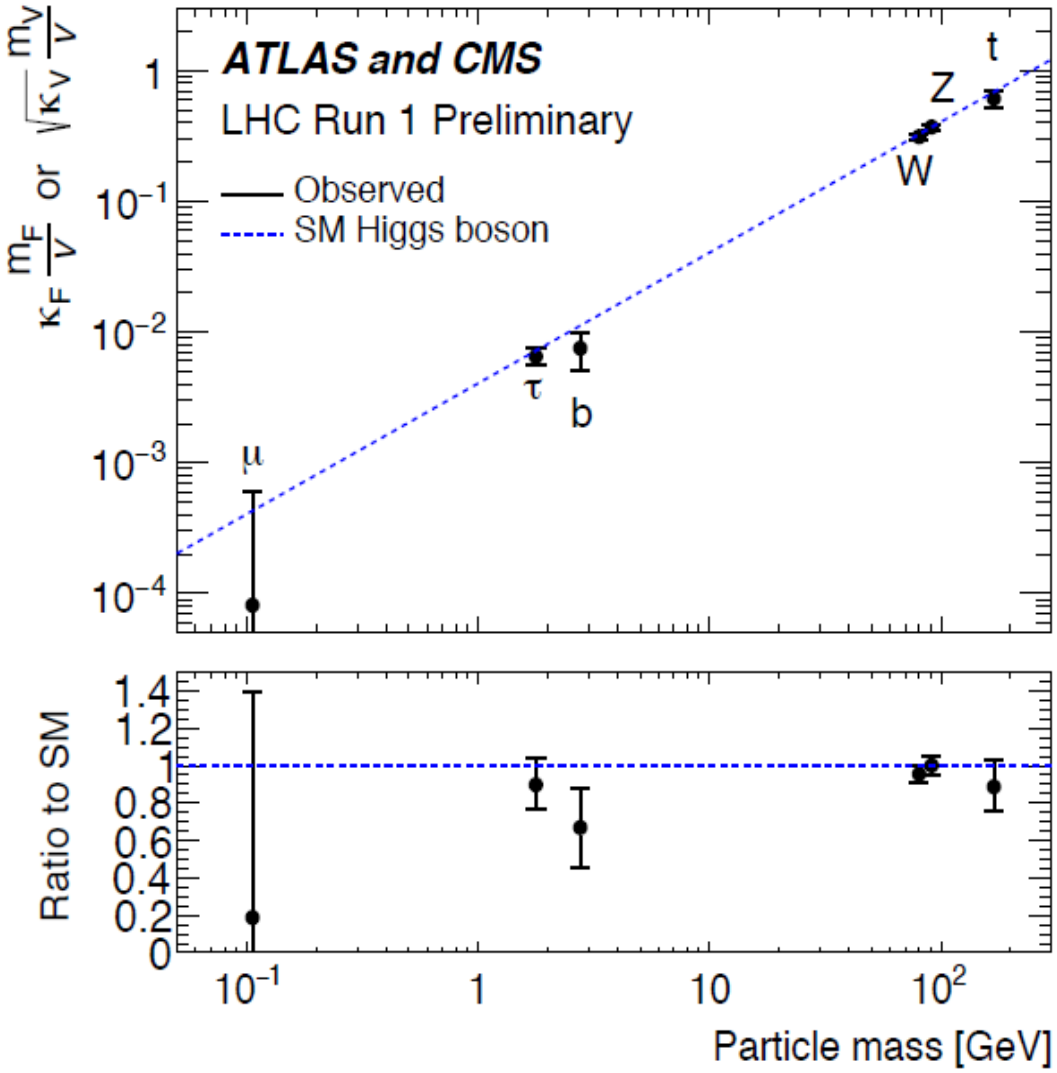
Fit results: couplings

- Absolute couplings fits need an assumption
- Two considered in the LHC combination:
  - Only SM Higgs decay modes: $\Gamma_{tot} = \Sigma \Gamma_{SM}(\kappa)$
  - An upper bound $\kappa \leq 1$ for W and Z couplings
- Most $\kappa_i < 1$, since a low fitted κ_b boosts all other decay BRs reducing Γ_{bb}
  - $\mu \sim \kappa_{prod}^2 \kappa_{decay}^2 / \kappa_b^2$ (very approximately)



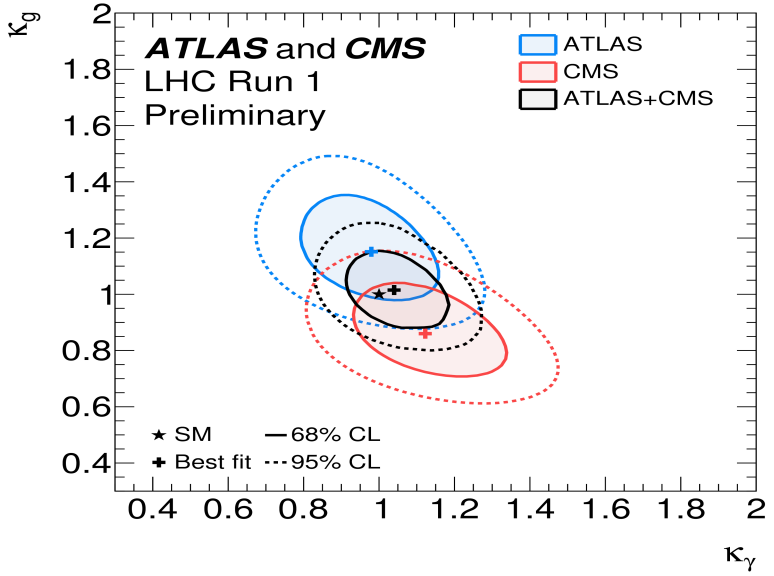
Fit results: tree-level couplings

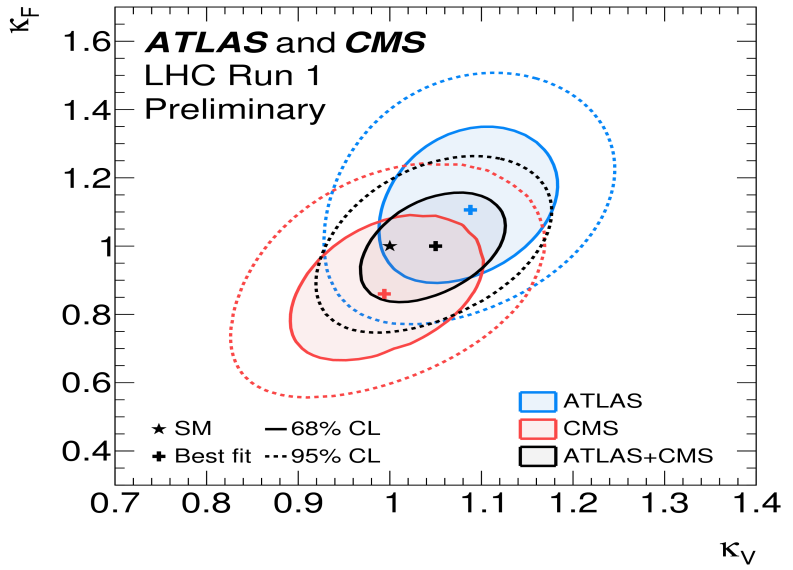
- Fit assuming only SM particles:
  - Resolve e.g. σ(ggH), H→γγ as function of the tree-level κ's
  - $\Gamma_{tot} = \Sigma \Gamma_{SM}(\kappa)$
- Display couplings vs particle mass
  - For W's & Z's, use $\sqrt{\kappa_V}$ instead of κ_V to keep it prop. to m_V
  - H → μμ included: $\kappa_\mu \sim O(1)$ is already a non-trivial result



Going narrower

- Couplings tested also in reduced models with less degrees of freedom
  - Target specific BSM scenarios, e.g. 2HDM
  - Uncertainties on the parameters ~10-15% (similar to those on the best couplings in the more general models)
- No indication of any deviation from SM





Going broader

- When interpreting the data in terms of Higgs couplings, or σ's & BR's, we make physics assumptions, e.g. of one Higgs, or one particle
- Those assumptions can be tested by comparing the quality of the fit in the tested model with that in a more generic model
  - e.g. comparing the κ & λ fit vs the σ & BR one we can see that σ_{VBF}/σ_{VH}, σ_{WH}/σ_{ZH} and BR_{WW}/BR_{ZZ} are consistent with just a single λ_{WZ}
  - in the CMS combination, a test was also done to check the compatibility with a a narrow resonance, i.e. that $\sigma(i \rightarrow H \rightarrow f)$ can factorize as $\sigma(i) \times BR(f)$

Summary

- The Higgs boson mass has been measured with 240 MeV uncertainty (0.2%)
- Cross section, BR & couplings were tested
  - Found agreement with SM predictions given the current uncertainties (10–30% on couplings)
  - The two largest individual deviations are an excess in ttH, H→ VV and a deficit in VH, H→bb
    - Neither particularly suggestive in terms of Higgs couplings
- The dominant uncertainties are still statistical, but theory uncertainties are already visible
  - Beyond σ(ggH), theory uncertainties seem to affect especially the tests of t and b couplings
- Run 2 has started, expect new results this year!

ATLAS & CMS Higgs analyses

- For the Higgs boson of mass ~125 GeV all the Standard Model production and decay modes accessible at LHC have been explored
  - I will present the combined results for the mass (final) and σ, BR, couplings (preliminary)
- Some modes where no significant signal is yet expected for a SM Higgs have also been studied (e.g. Zγ, μμ, tH), and similarly some non-SM decays (e.g. μτ via LFV, invisible)
  - These will not be covered in this talk, however

$H \rightarrow ZZ \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$

- The two cleanest, high resolution modes:
  - Excellent energy resolution allow for a precise measurement of the Higgs boson mass
  - Backgrounds are less of a challenge, allowing for measurements with smaller systematics
- $H \rightarrow \gamma\gamma$ larger signal yield allows categories targeting many different production modes

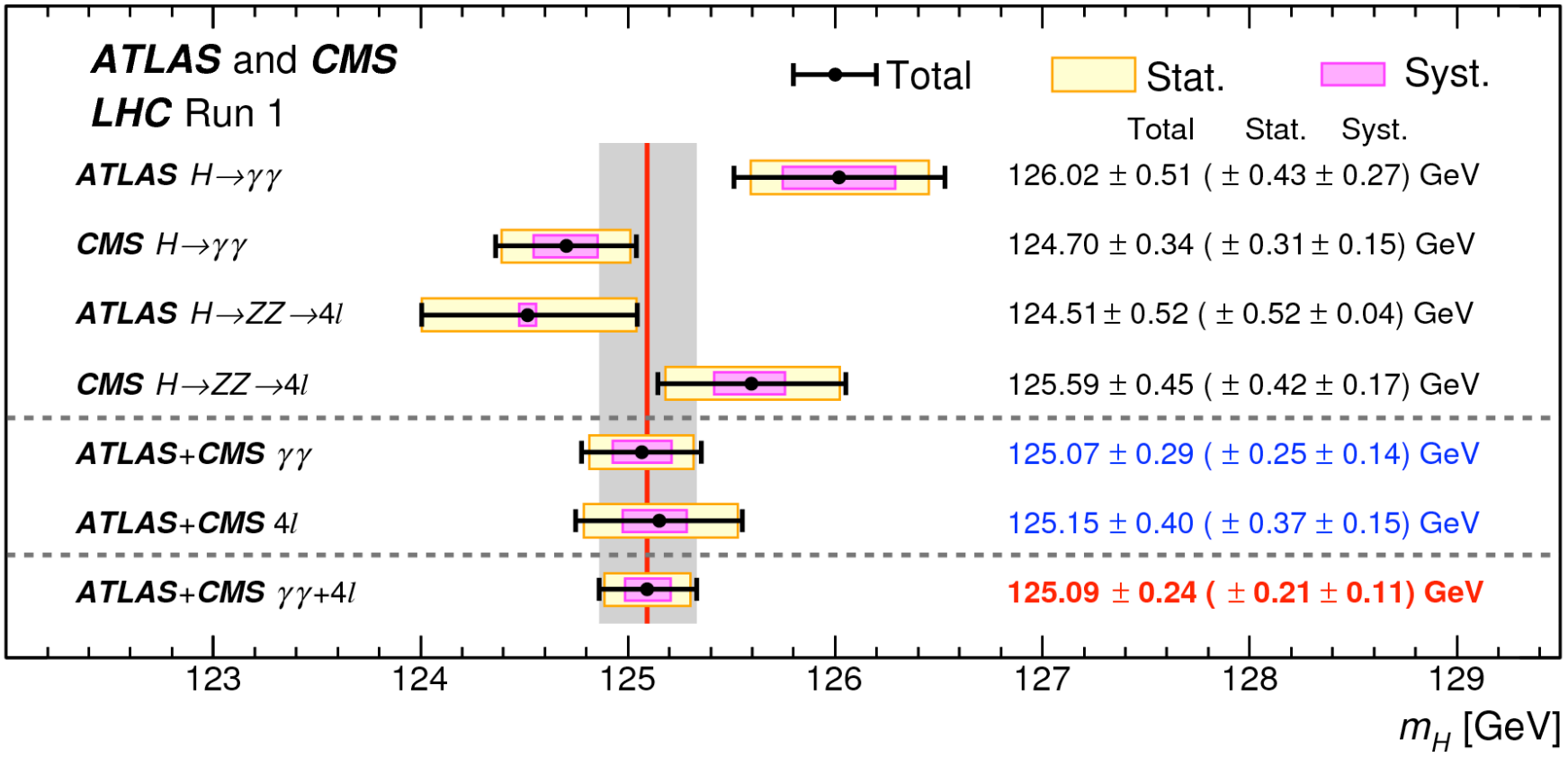
H → WW

- Large branching ratio, good S/B overall but worse kinematic separation between signal and background (no resonant peak):
  - Best statistical power in the measurement of the overall signal yield, but larger systematics:
    σ×BR(gg→ H→ WW): **±11%** (stat) **±10%** (syst)
    σ×BR(gg→ H→ ZZ): **±19%** (stat) **±4%** (syst)
- Good sensitivity also to VBF, especially with ATLAS's BDT-based analysis, and to ttH production in multilepton final states

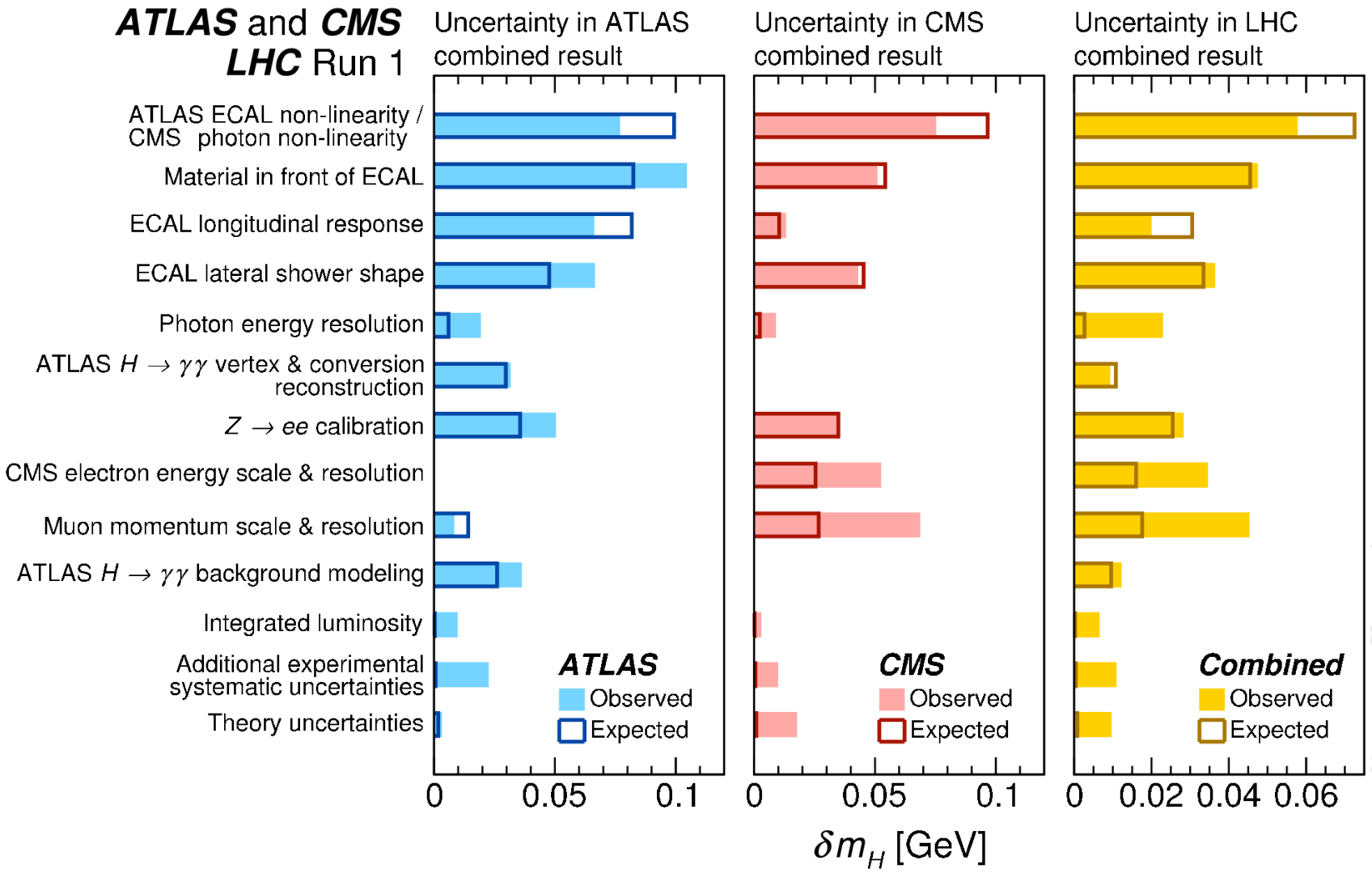
Fermionic modes

- H → ττ: most accessible fermion mode
  - Sensitivity mostly from VBF and high-p_T ggH production (boost helps trigger, reduces Z+jets and improves di-tau mass reconstruction using E_T^{miss})
- H → bb: BR ~60%, overwhelming background
  - best sensitivity in run 1 achieved in VH production, moderatetely boosted regime: $p_T(V) \sim 200$ GeV
  - ttH production: main challenge is tt+bb bckg., now less sensitive than VH, but will gain from √s
  - VBF quite more challenging (trigger!). Recent results exist, but are not included in the LHC combination.

Mass: numbers



Main systematical uncertainties

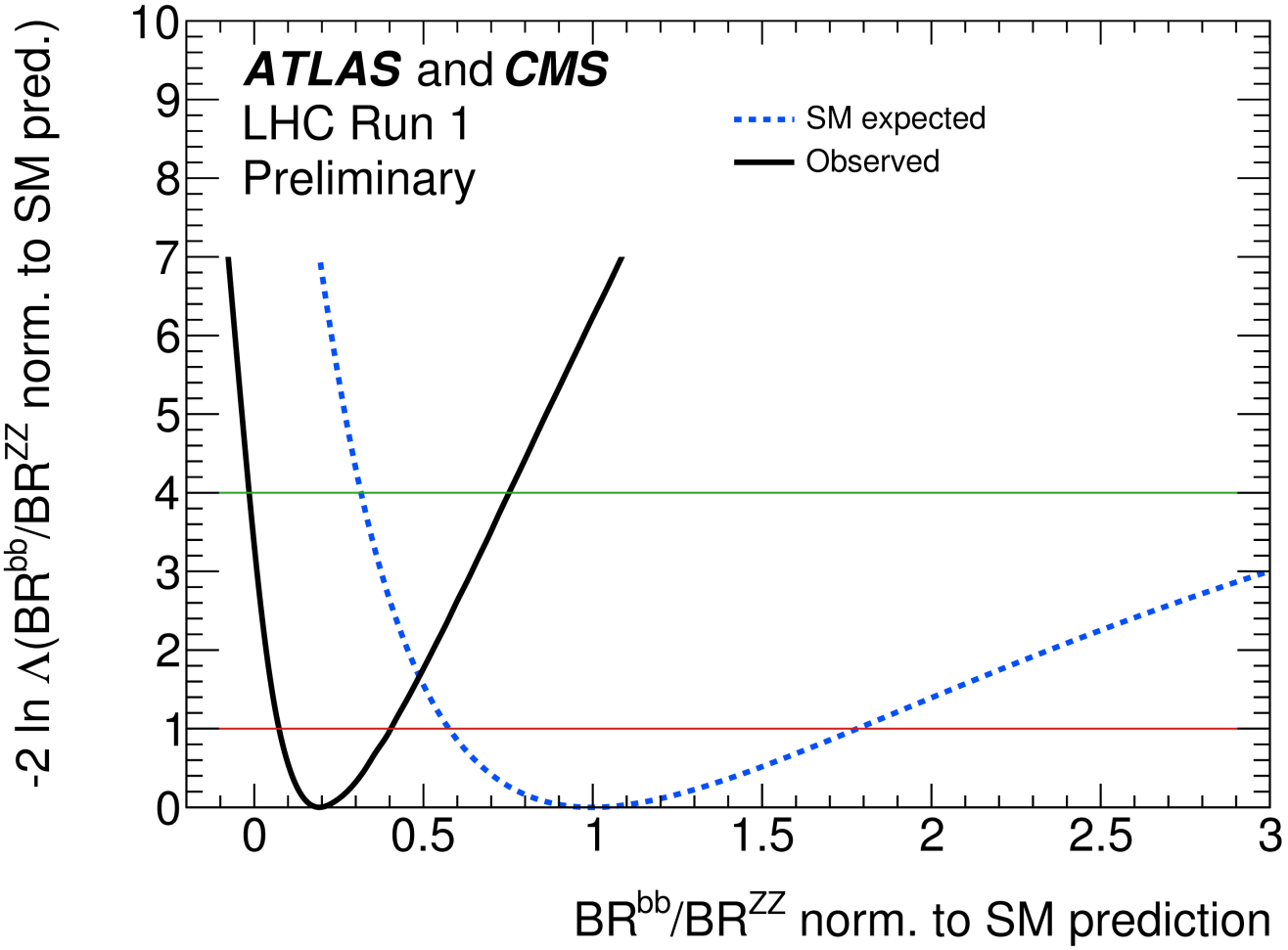


LHC combinations

When combining ATLAS+CMS Higgs analyses:

- all analyses are jointly reviewed to assess the consistency and any correlated uncertainties
- analyses may be updated to latest teory predictions for signals and backgrounds, or to allow studies not considered in the original papers (e.g. anomalous couplings)
- the full likelihood function is used, including all nuisance parameters (~4200 for run 1)
- thorough cross-checking of all numerical results between ATLAS and CMS using different codes

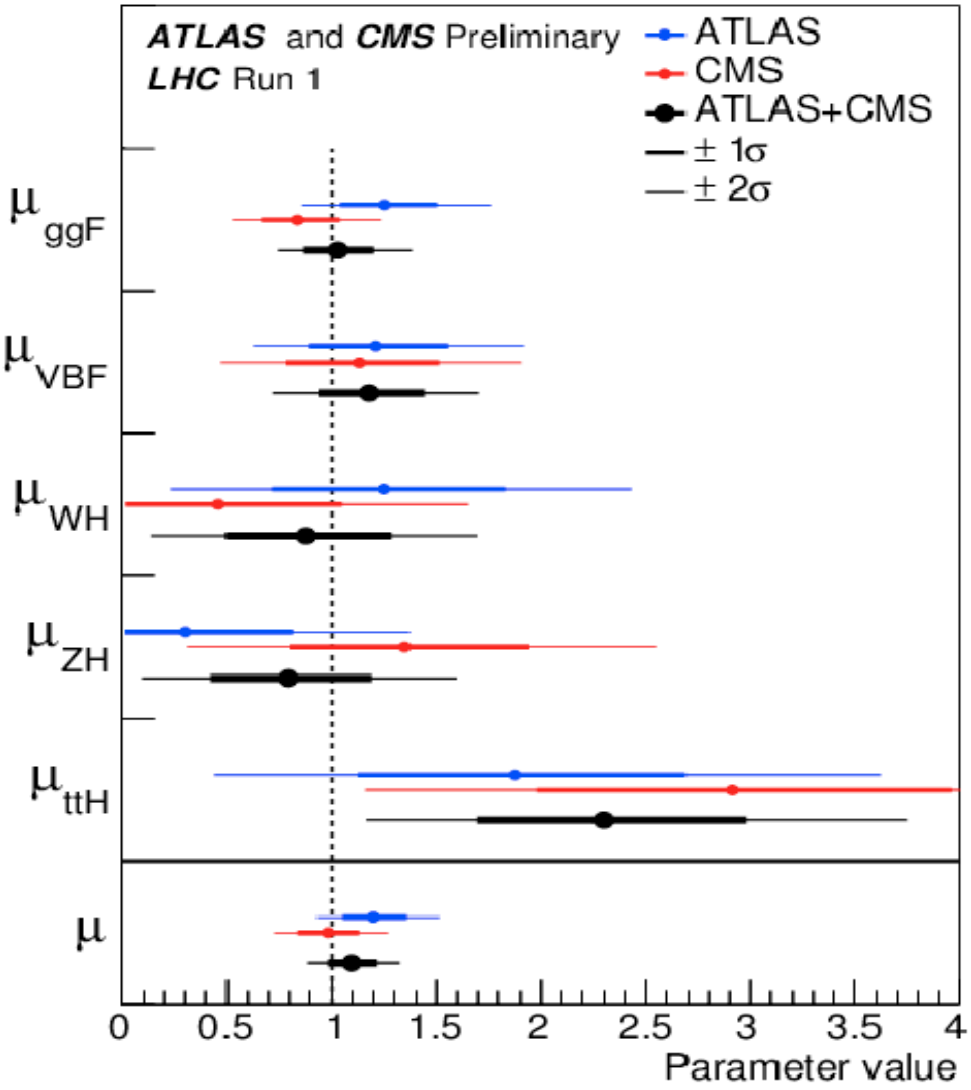
BR_{bb}/BR_{ZZ} likelihood scan



"Cross sections"

Signal strengths per production mode, assuming SM Higgs branching ratios

	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$



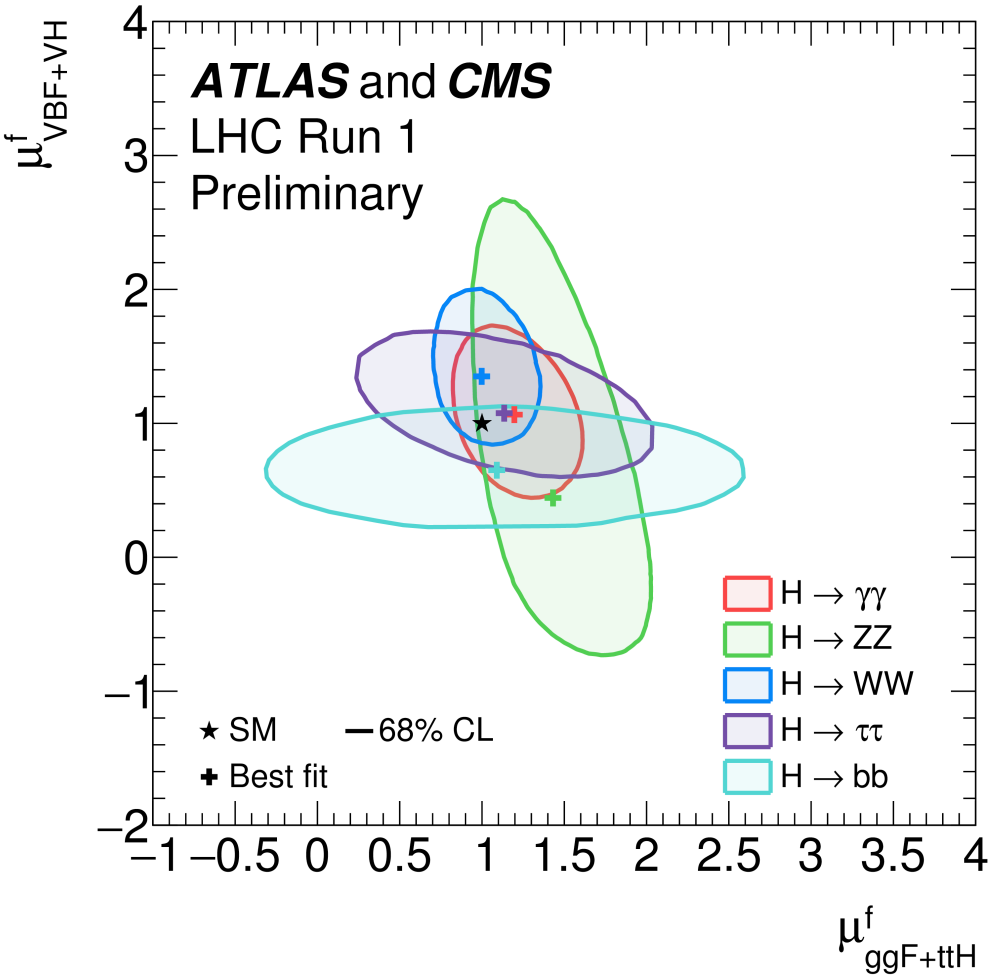
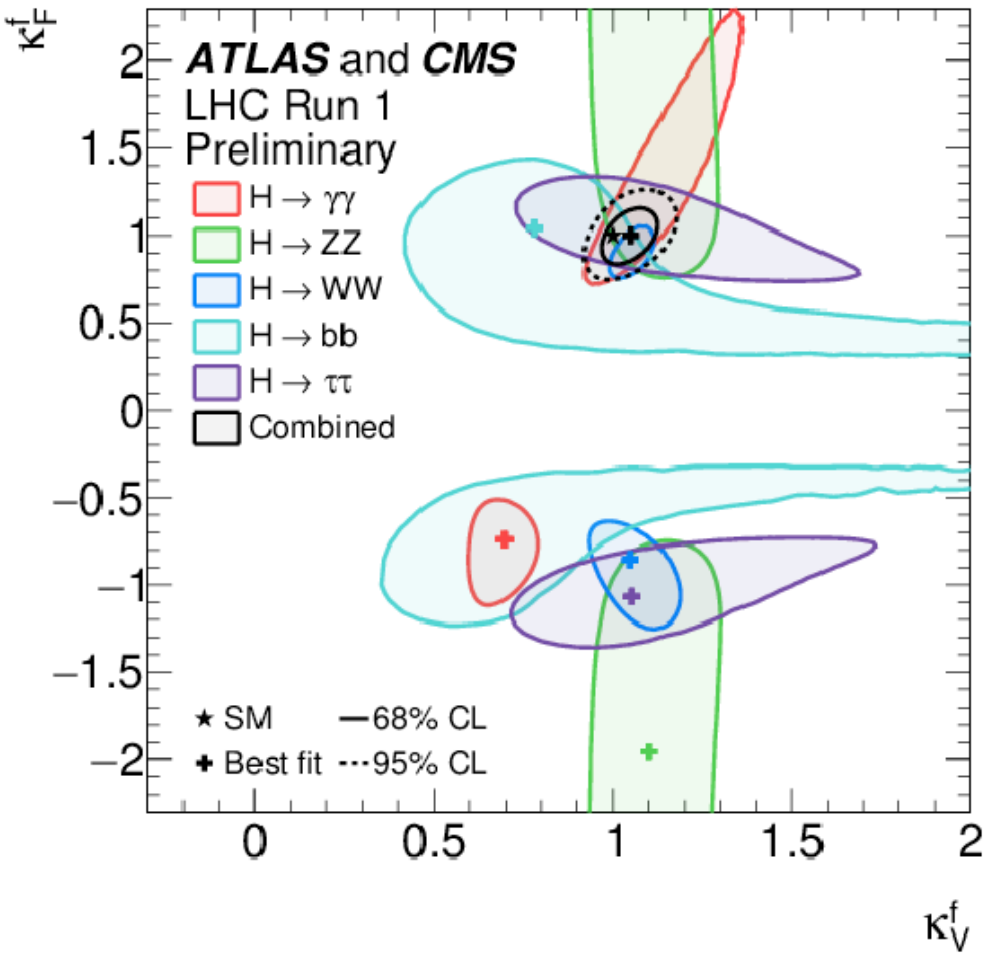
2HDM-like models

Parameter	ATLAS+CMS	
	Measured	Expected uncertainty
λ_{du}	$0.91^{+0.12}_{-0.11}$	$[-1.21, -0.92] \cup [0.87, 1.14]$
λ_{Vu}	$0.99^{+0.13}_{-0.12}$	$^{+0.20}_{-0.12}$
κ_{uu}	$1.09^{+0.22}_{-0.19}$	$^{+0.20}_{-0.27}$
$\lvert\lambda_{lq}\rvert$	$1.06^{+0.15}_{-0.14}$	$^{+0.16}_{-0.14}$
λ_{Vq}	$1.09^{+0.14}_{-0.13}$	$^{+0.13}_{-0.11}$
κ_{qq}	$0.94^{+0.17}_{-0.15}$	$^{+0.18}_{-0.16}$

SM Higgs compatibility

Model	p-value	DoF	Parameters
Global signal strength	34%	1	μ
Production processes	24%	5	$\mu_{\mathrm{ggF}}, \mu_{\mathrm{VBF}}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	60%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{b\bar{b}}$
μ_V and μ_F per decay	88%	10	$\mu_V^{\gamma\gamma}, \mu_V^{ZZ}, \mu_V^{WW}, \mu_V^{\tau\tau}, \mu_V^{b\bar{b}}, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
μ_V/μ_F ratio	72%	6	$\mu_V/\mu_F, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$	16%	9	$\sigma(gg \to H \to ZZ), \sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}, \sigma_{WH}/\sigma_{\mathrm{ggF}}, \sigma_{ZH}/\sigma_{\mathrm{ggF}}, \sigma_{ttH}/\sigma_{\mathrm{ggF}}, \mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}, \mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{ZZ}, \mathrm{BR}^{\tau\tau}/\mathrm{BR}^{ZZ}, \mathrm{BR}^{b\bar{b}}/\mathrm{BR}^{ZZ}$
Ratios of σ and BR relative to $\sigma(gg \to H \to WW)$	16%	9	$\sigma(gg \to H \to WW), \sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}, \sigma_{WH}/\sigma_{\mathrm{ggF}}, \sigma_{ZH}/\sigma_{\mathrm{ggF}}, \sigma_{ttH}/\sigma_{\mathrm{ggF}}, \mathrm{BR}^{ZZ}/\mathrm{BR}^{WW}, \mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{WW}, \mathrm{BR}^{\tau\tau}/\mathrm{BR}^{WW}, \mathrm{BR}^{b\bar{b}}/\mathrm{BR}^{WW}$
Coupling ratios	13%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	65%	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings, BSM loops	11%	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_g, \kappa_\gamma$
BSM loops only	82%	2	κ_g, κ_γ
Up vs down couplings	67%	3	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$
Lepton vs quark couplings	78%	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$
Fermion and vector couplings	59%	2	κ_V, κ_F

2D: signal strengths



2D: κ_V, κ_F