Karlsruhe Institute of Technology

Measurements of the ~125 GeV Higgs boson and EFT interpretations

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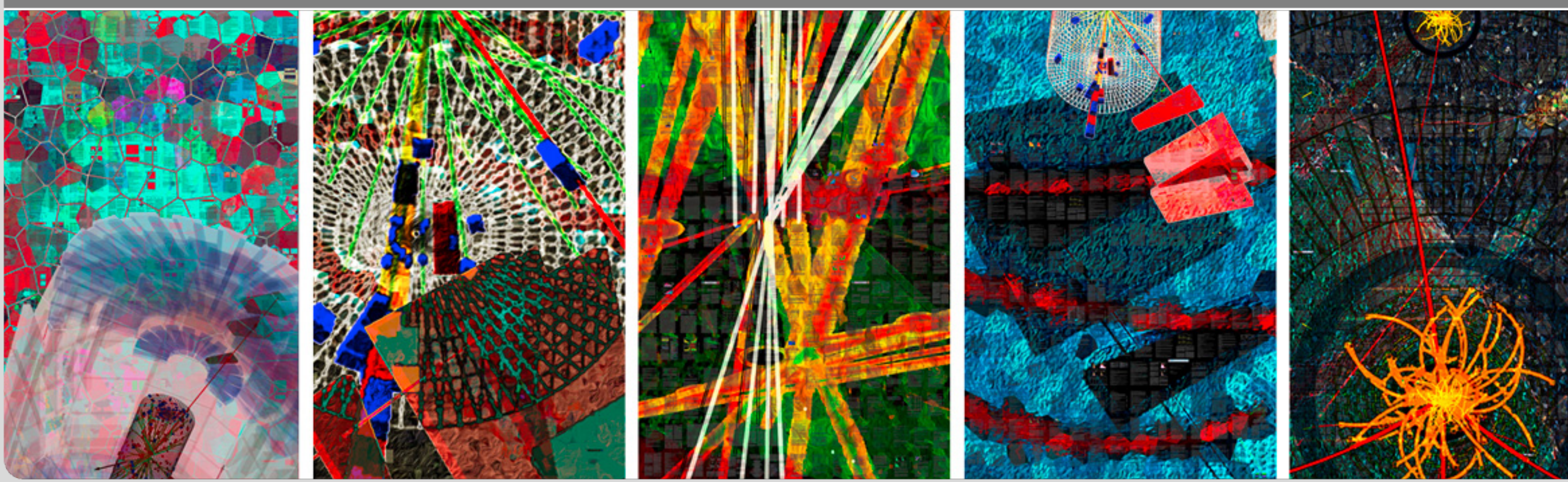


Overview

- **Run 1**
  - Extensively discussed already - will focus on CMS+ATLAS combined results
  - Properties: mass, width, spin/parity, couplings

- **Run 2**
  - Rediscovery of H(125), first results in many channels now
  - Broad and growing range of measurements:

signal strengths (μ)

Fiducial cross sections

EFT interpretations

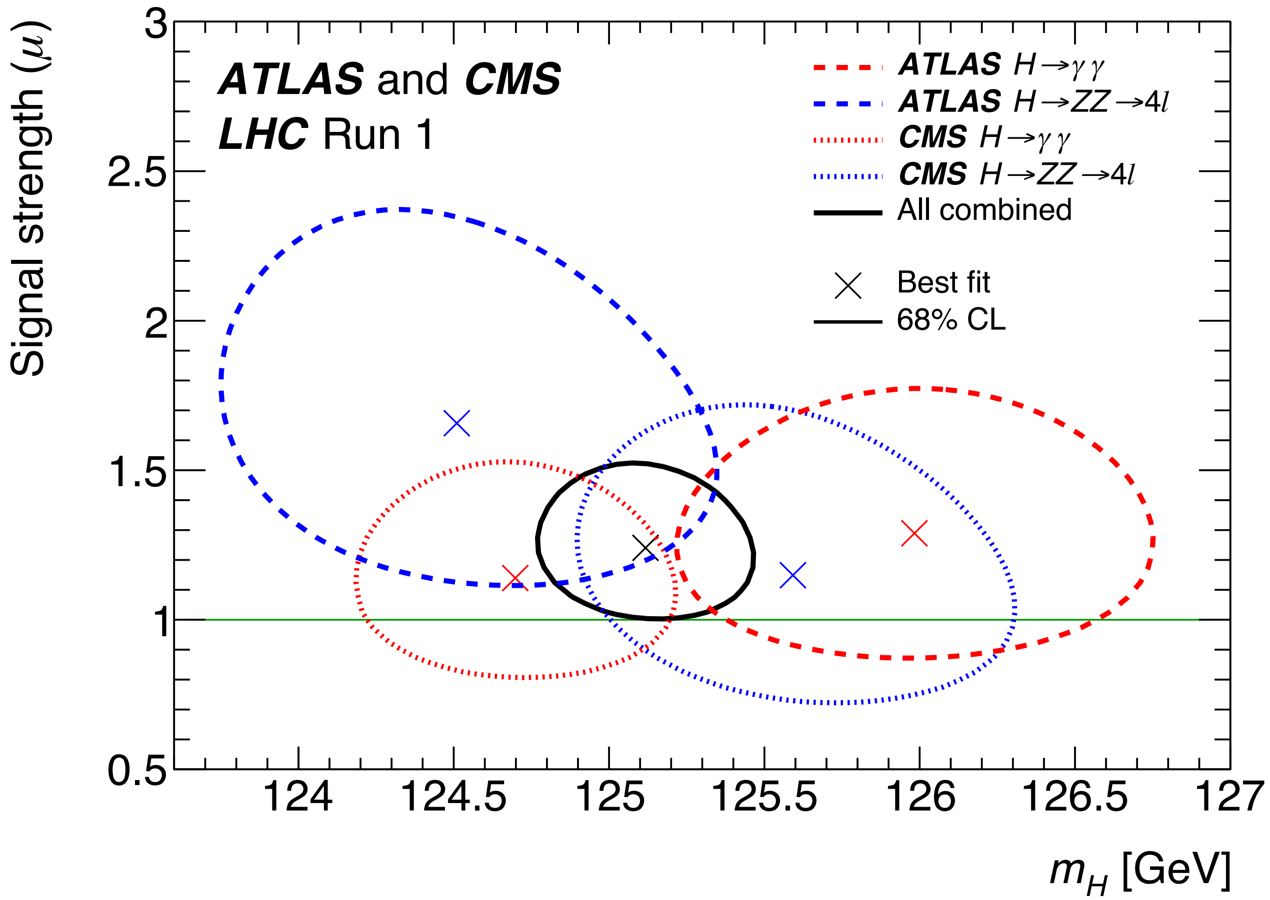
couplings (κ framework)

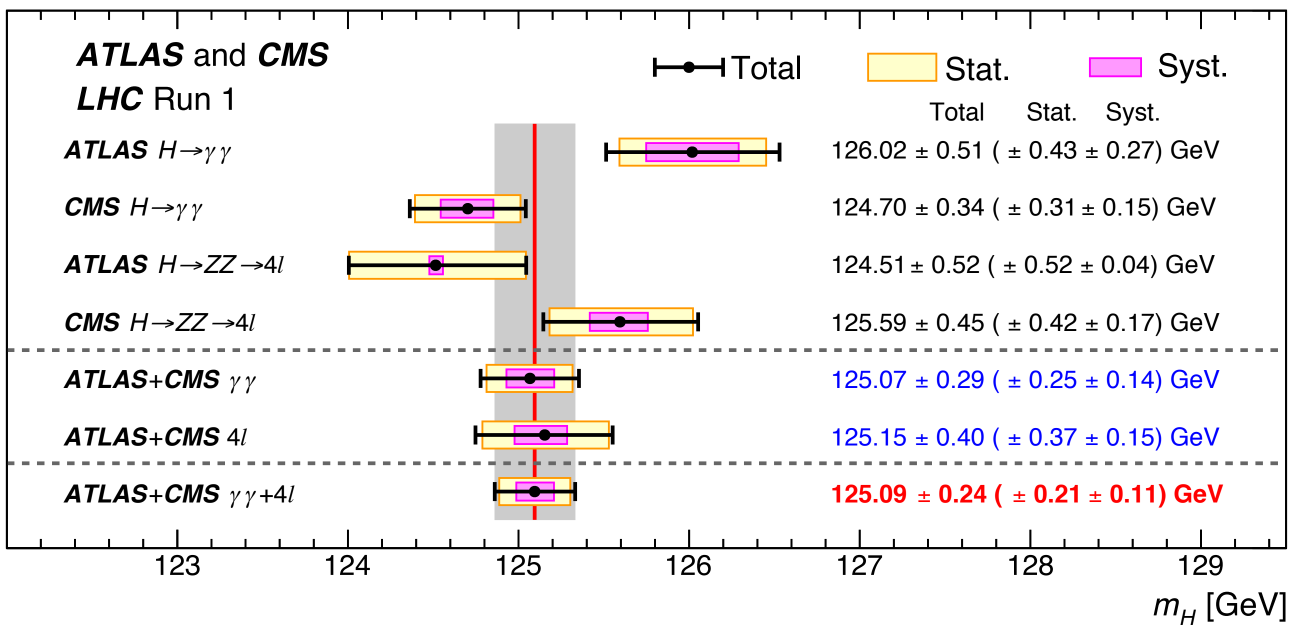
Differential cross sections

Template cross sections

Run 1 Mass Combination

- 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





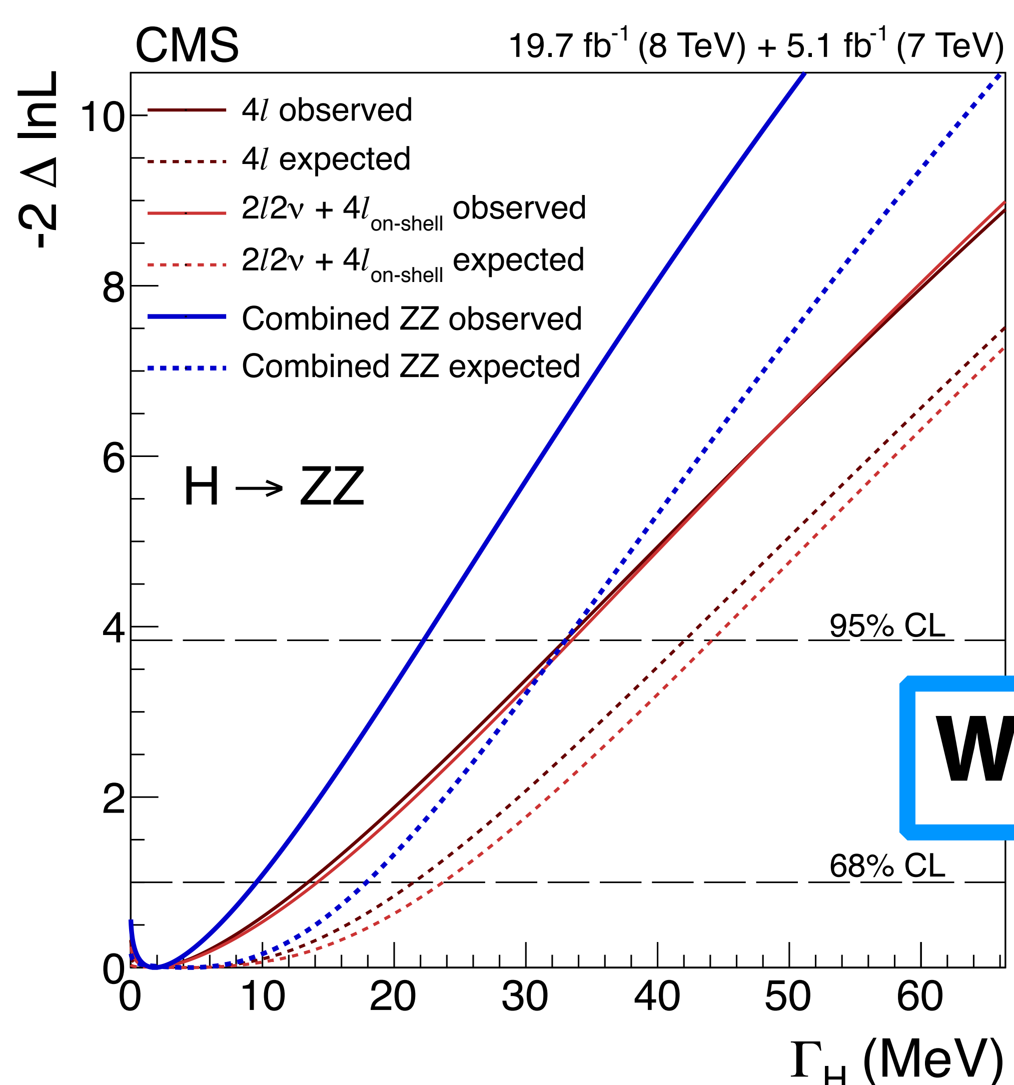
$m_H = 125.09 \pm 0.24$ GeV $= 125.09 \pm 0.21$ (stat.) ± 0.11 (syst) GeV

Properties

Spin/Parity

Eur. Phys. J. C75 (2015) 476

- Indirect constraint on the width using ratio of off-shell to on-shell production in H→ZZ
- SM predicts Γ ~ 4 MeV
- ATLAS and CMS find limits on Γ/Γ_{SM} ~ 4-8
- Also measured with H→WW but less sensitive



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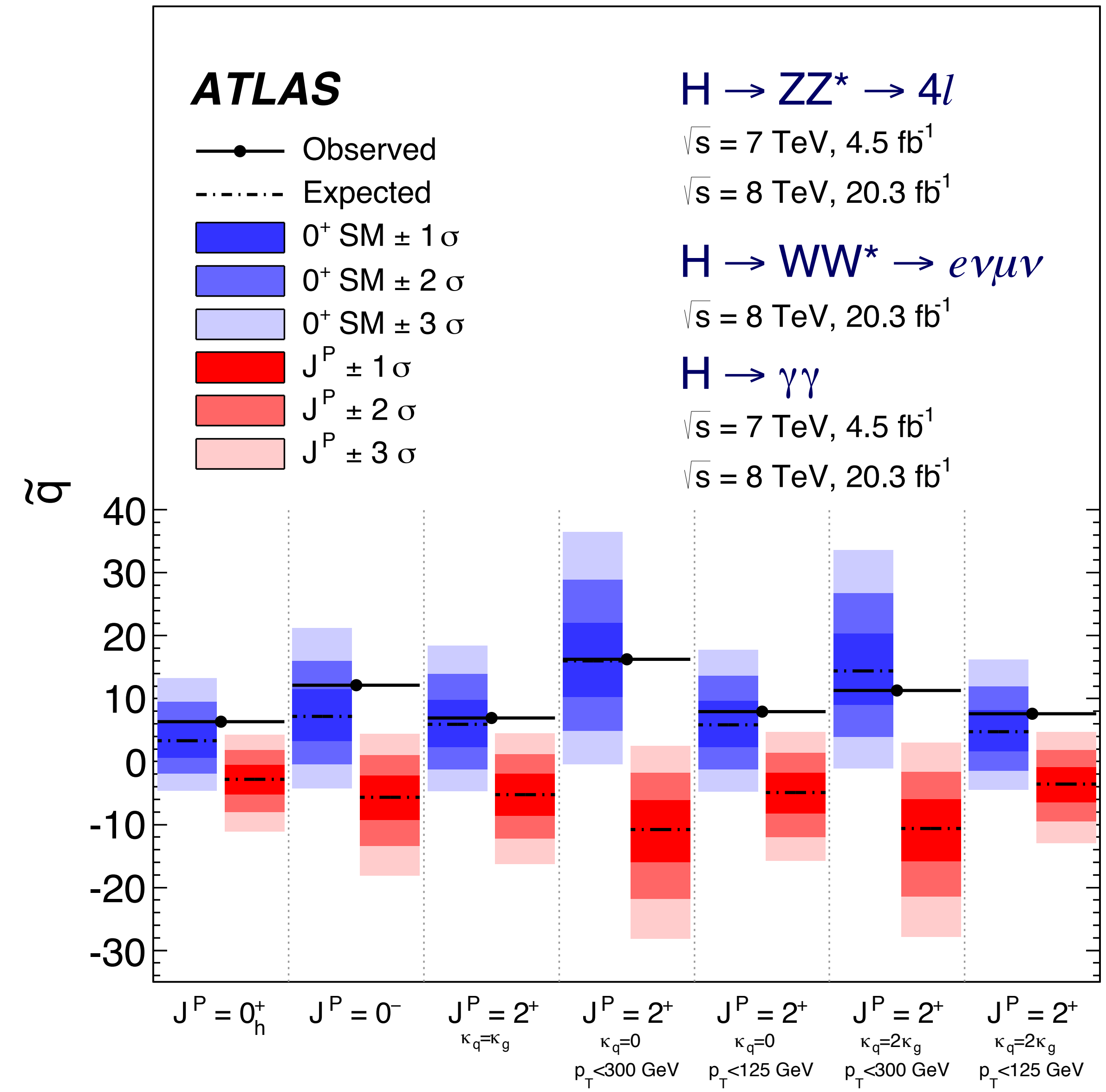


- Test many alternative hypotheses against SM CP-even scalar, $J^P = 0^+$, e.g. pseudoscalar, spin-2
- All rejected at 99.9% CL

Couplings Combination

- Based on the inputs to the separate CMS and ATLAS combinations: the main five decay channels + ttH analyses

	Untagged	VBF	VH	ttH
H→γγ	✓	✓	✓	✓
H→ZZ→4l	✓	✓	✓	✓
H→WW→2l2ν	✓	✓	✓	✓
H→ττ	✓	✓	✓	✓
H→bb			✓	✓
H→μμ	✓	✓		

- **Not included as not in both CMS and ATLAS combination results:**
  - H→Zγ search
  - Off-shell measurements
  - H→invisible searches
  - VBF H→bb

- H→μμ only included for one particular result
- Each analysis targeting a particular production/decay mode may also include contributions from other processes that are not specifically targeted, e.g. **H→WW entering H→ττ analysis**, **single-top + Higgs production in ttH**

Signal Parameterisation

- Both parametrisations based on scaling full phase-space cross sections:

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

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

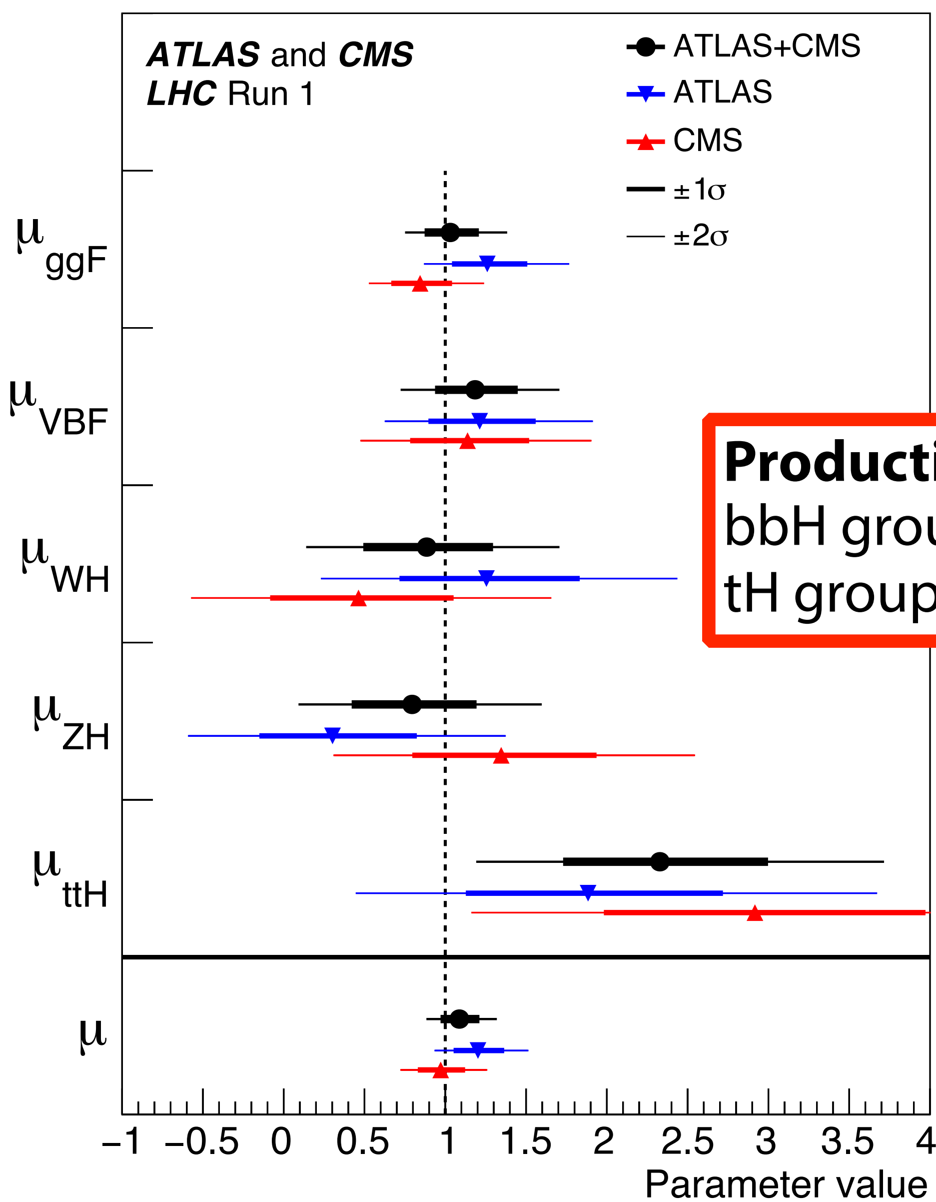
Where

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

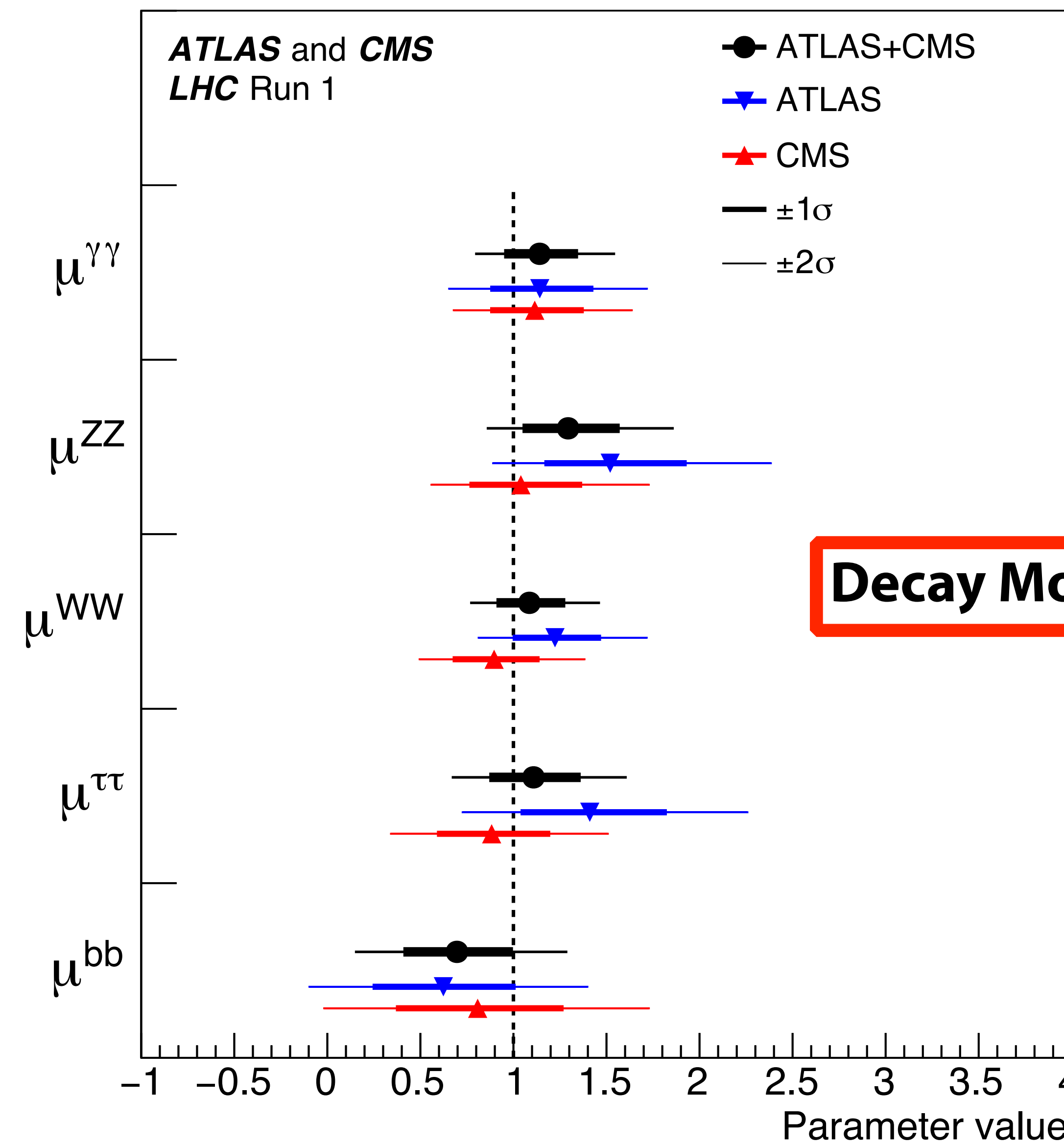
Signal strengths

Assumptions
- SM ratios of BRs **or** cross sections

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



Production Modes
bbH grouped with ggF
tH grouped with ttH

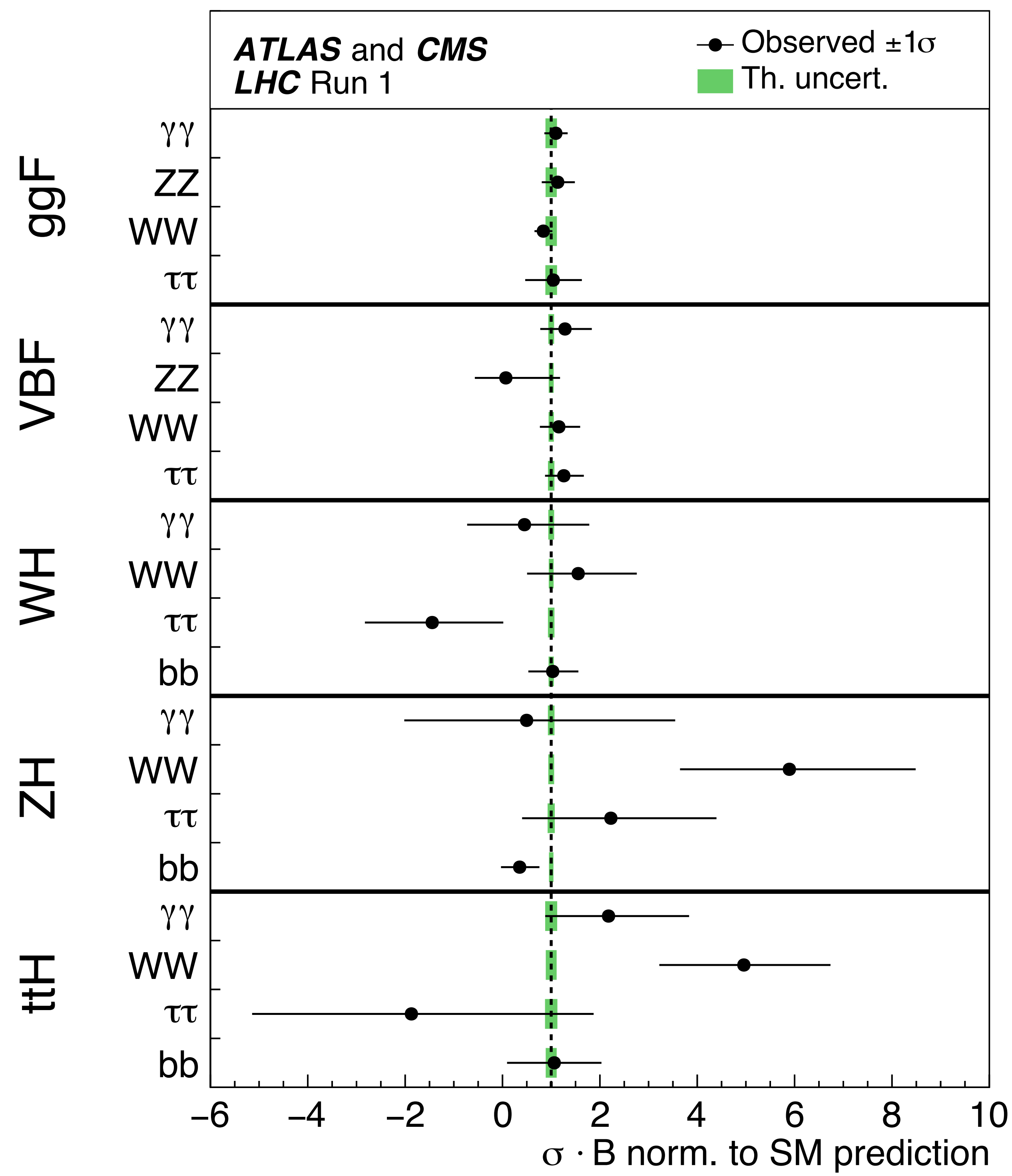


Decay Modes

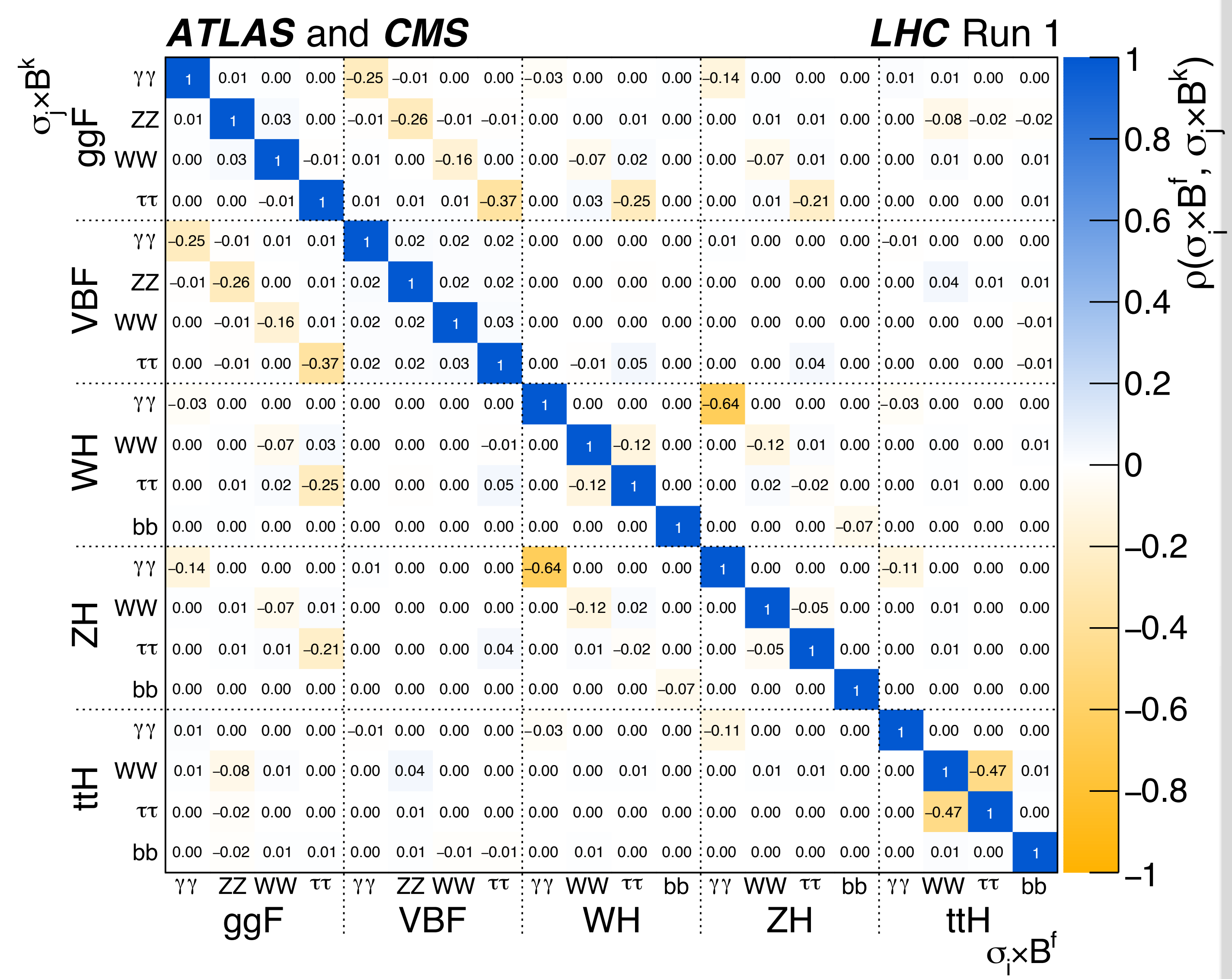
- Most significant deviation from μ=1 is ttH (2.3σ)

Generic signal strength results

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



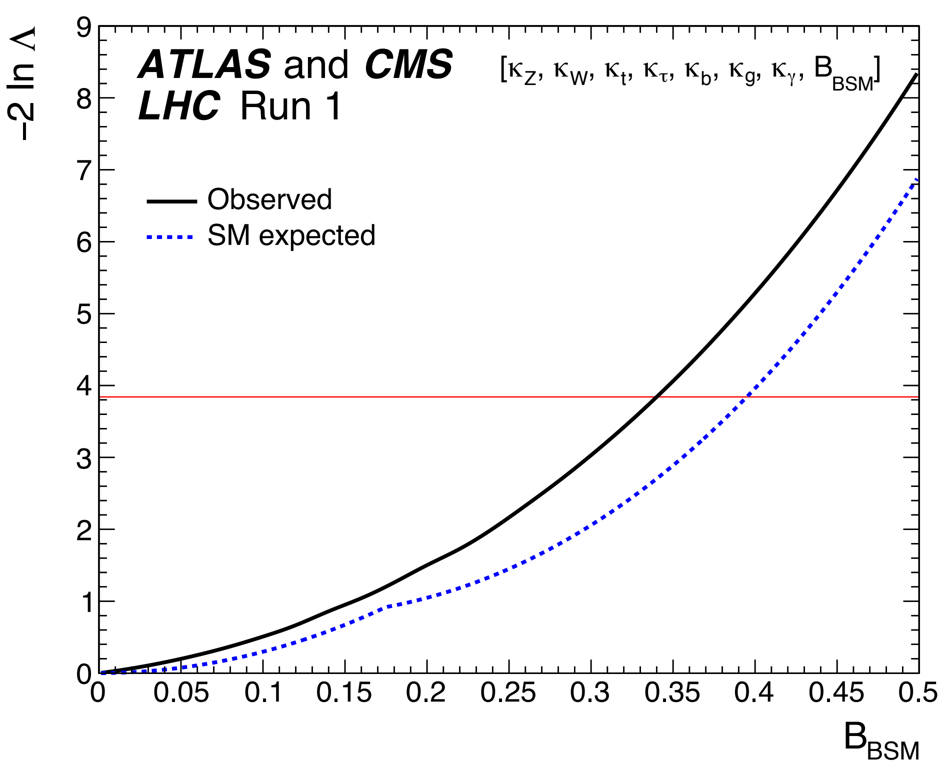
- Measurements mostly uncorrelated, except where multiple processes contribute to same categories, e.g. H→γγ WH and ZH

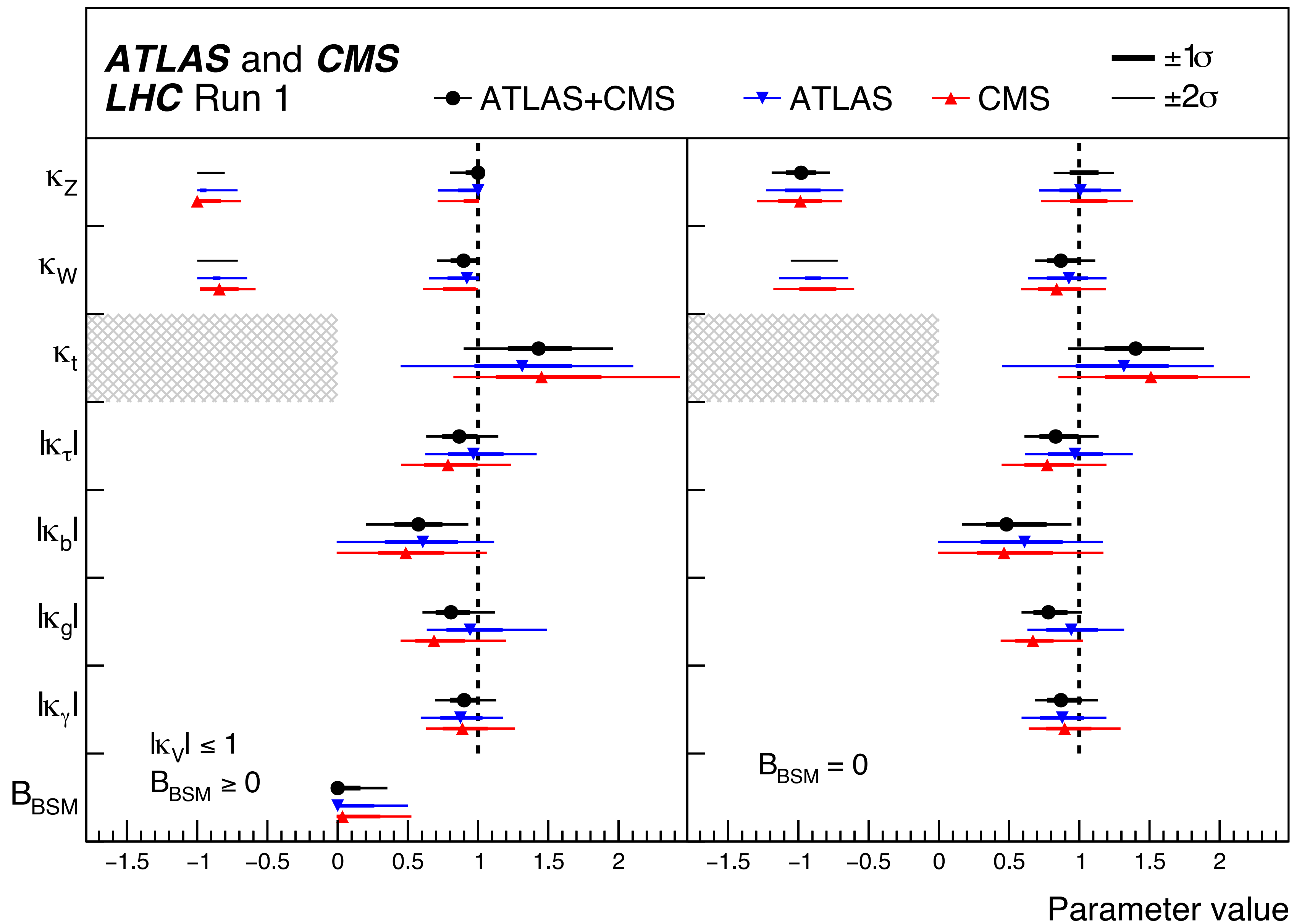


Couplings - allowing for BSM loop/decay contributions

- Use effective couplings for ggH (κ_g) and $H \rightarrow \gamma\gamma$ (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

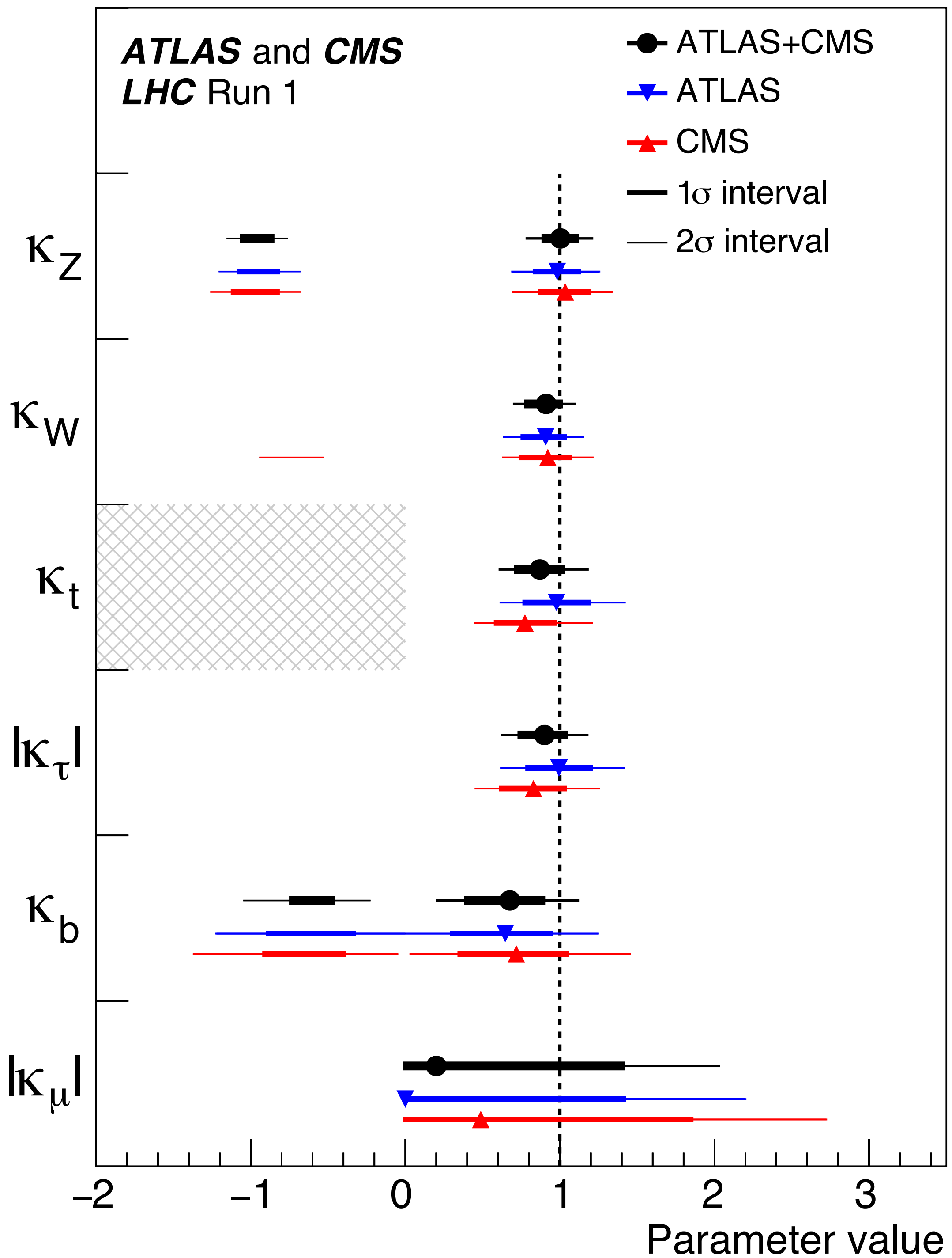
- Care needed with BR_{BSM}: not just Higgs decays to new particles but also non-SM BRs to unmeasured final states, e.g. gg and cc



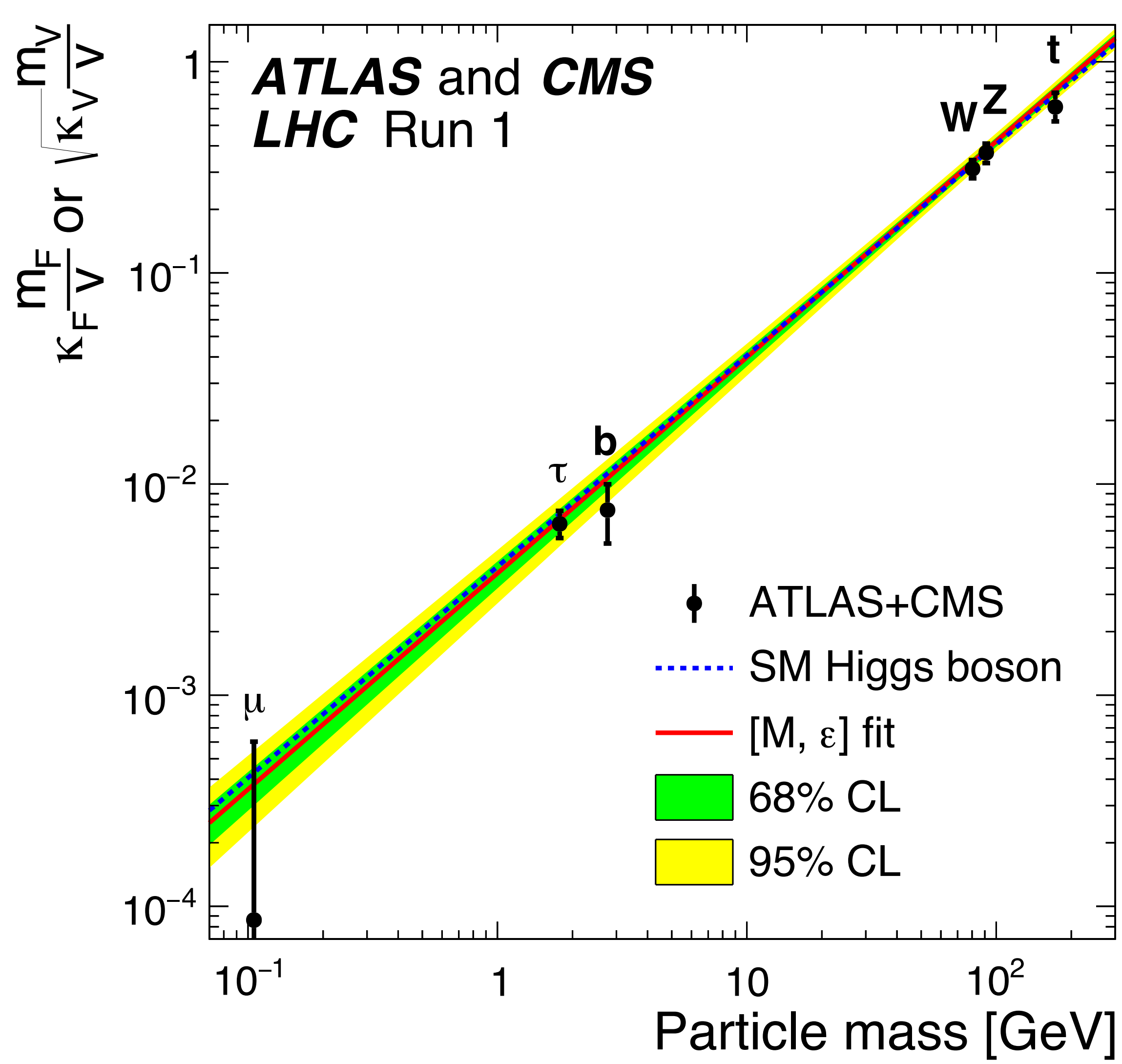


$BR_{BSM} < 0.34$ @ 95% CL

Couplings - 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

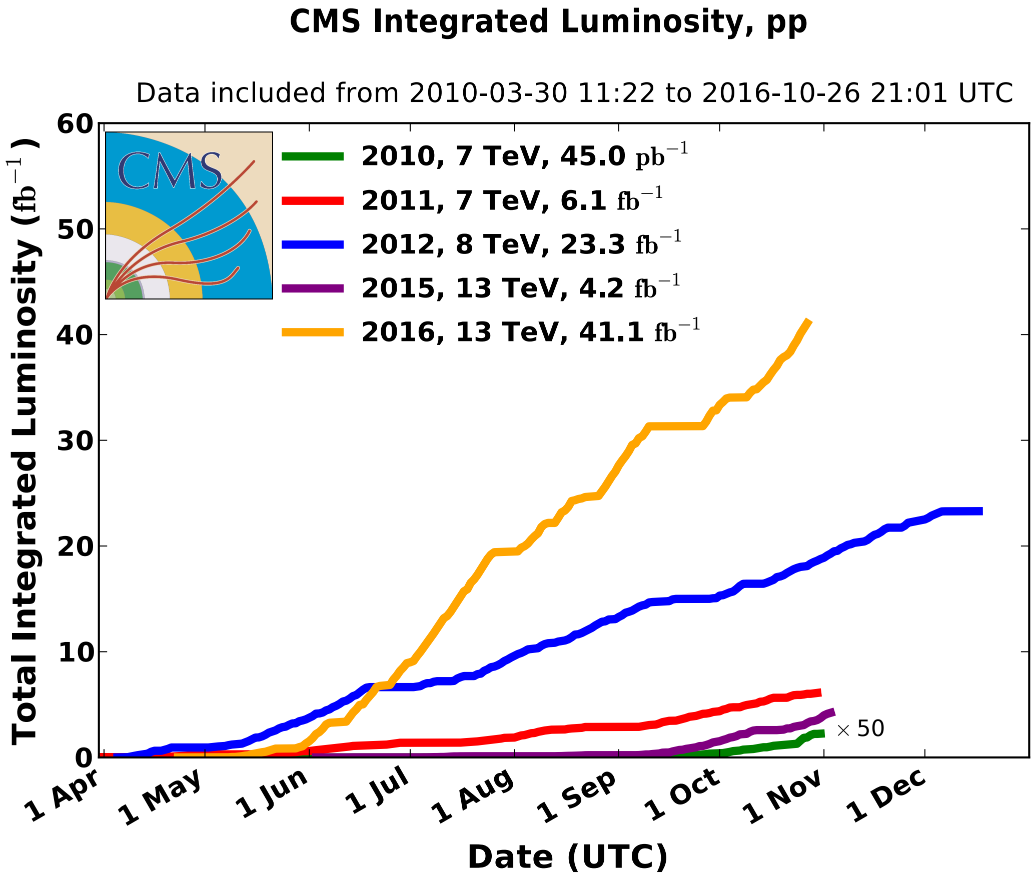


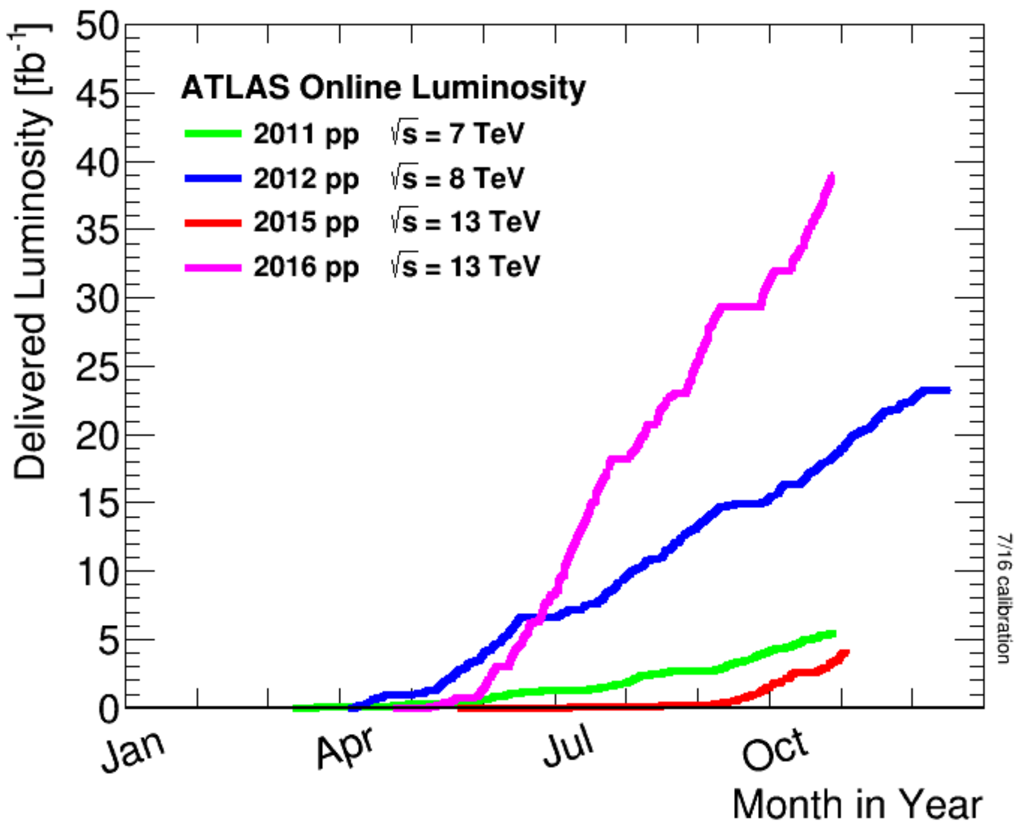
M, ε model:

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

Run 2

- Excellent LHC performance this year has delivered ~ 40 fb^{-1} of 13 TeV collision data to CMS and ATLAS

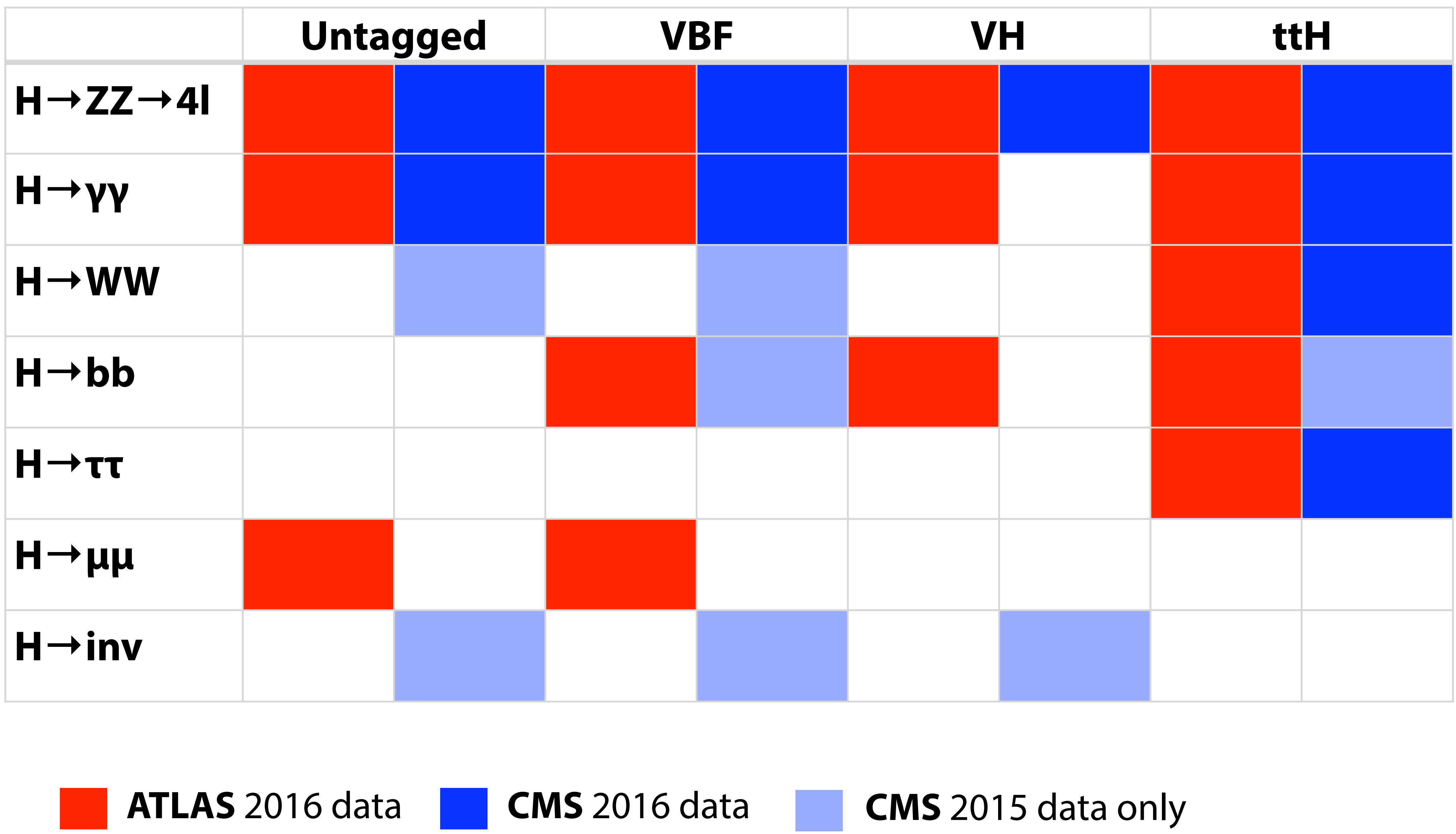




- Compared to run 1: higher instantaneous luminosity, 50 → 25 ns bunch spacing and increased pileup
- Detectors have been (and are being) upgraded, e.g. ATLAS insertable pixel b-layer during LS1, CMS pixel upgrade coming in extended technical stop
- Despite these challenges already a wide array of Higgs boson measurements

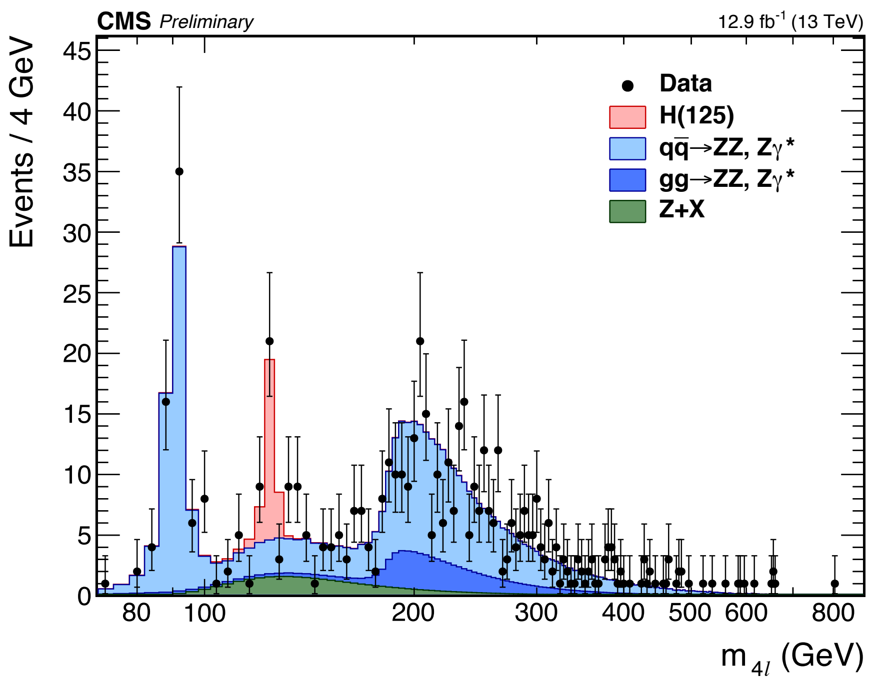
Run 2 - Results

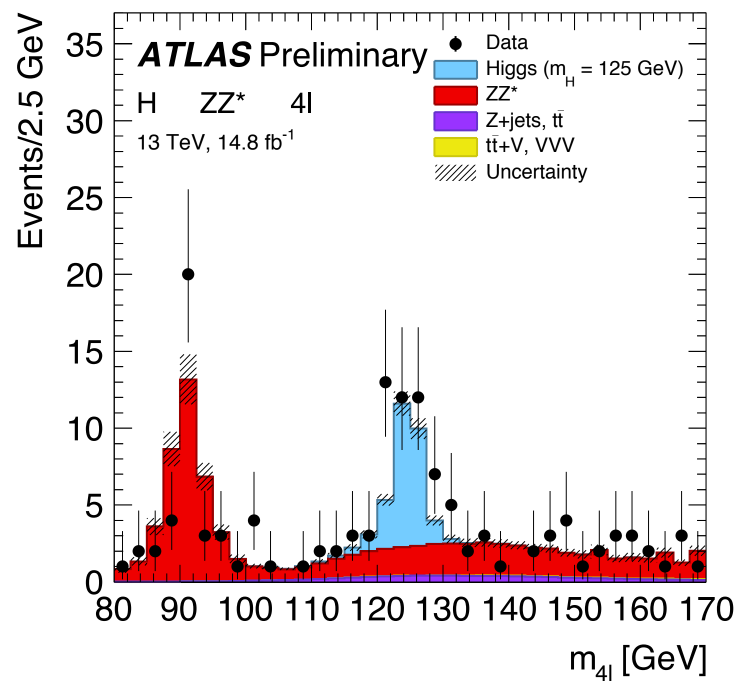
- Already good coverage of major production and decay channels at 13 TeV
- Many preliminary results on the partial 2016 dataset (~ 13 fb^{-1}) and others only on 2015 (~ 2-3 fb^{-1})

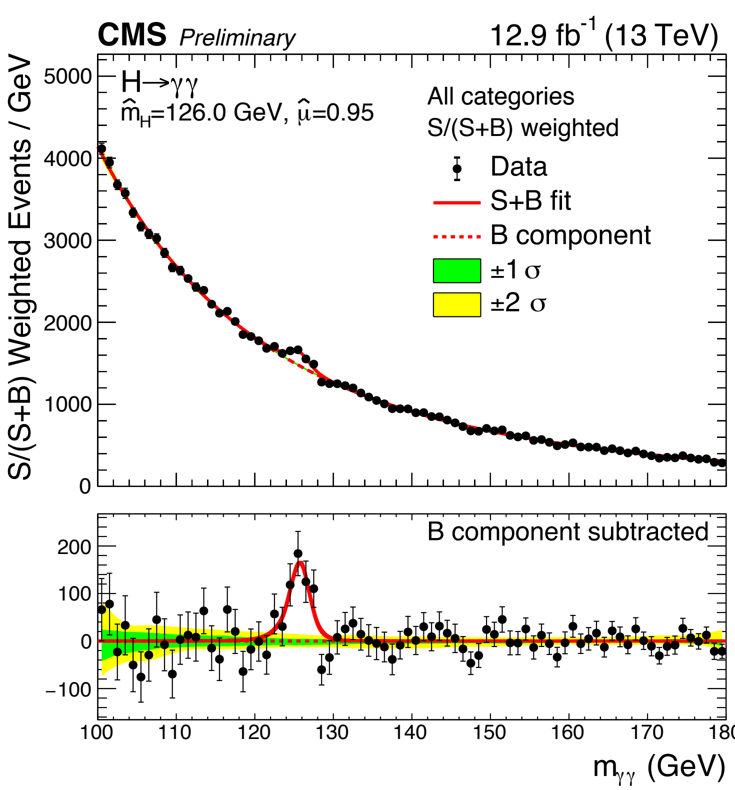


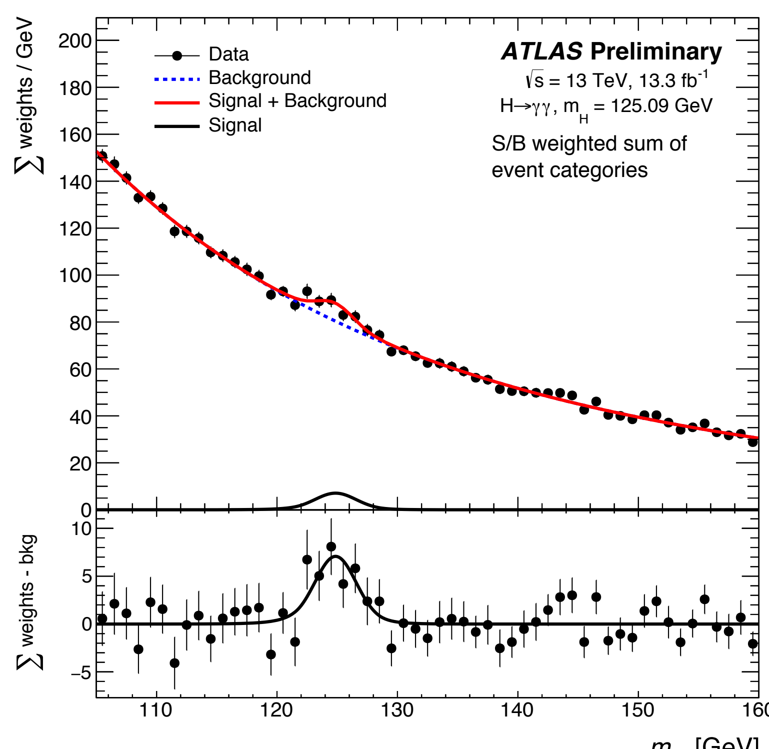
Rediscovering H(125) at 13 TeV

- Signal re-established in H→ZZ and H→γγ with > 5σ significance





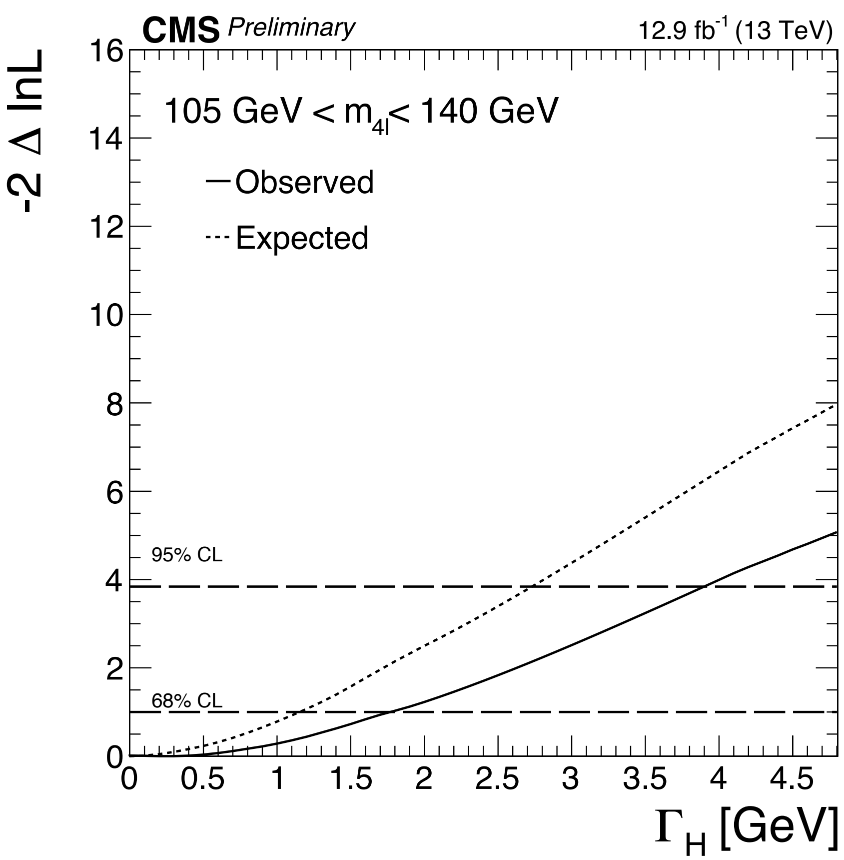


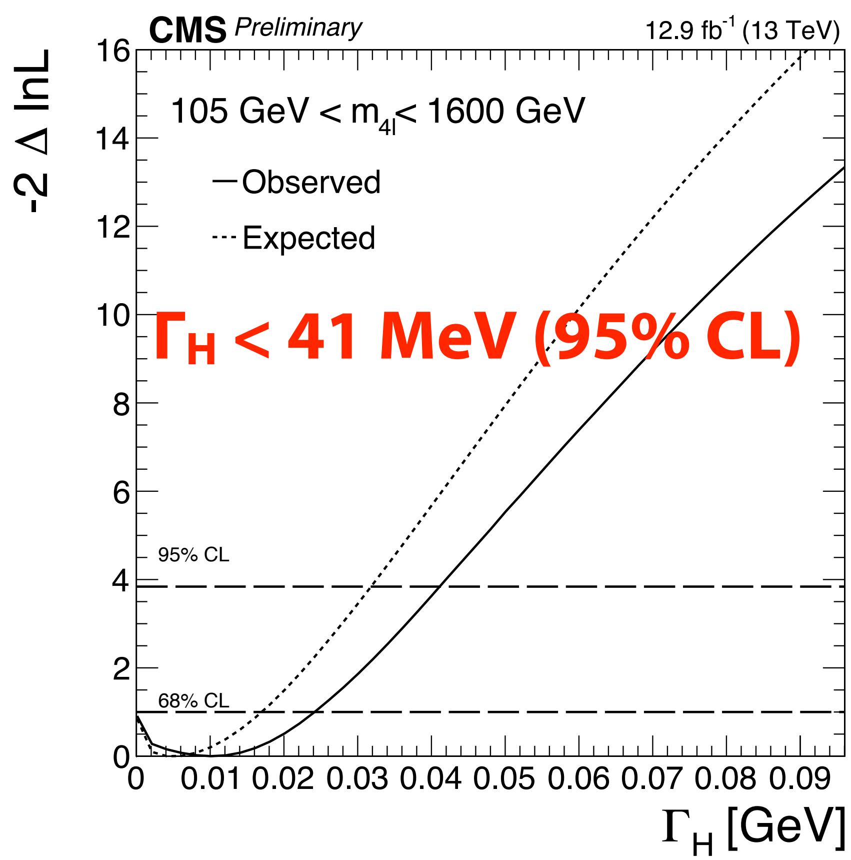


- **Best-fit μ / σ @ 125.09 GeV**
- **H→ZZ**
  - CMS: $\hat{\mu} = 0.99^{+0.33}_{-0.26}$
  - ATLAS: σ = 81 ± 16 pb (σ_{SM} = 55.5 ± 4.1 pb exp.)
- **H→γγ**
  - ATLAS: $\hat{\mu} = 0.85 \pm 0.21$
  - CMS: $\hat{\mu} = 0.91 \pm 0.20$
- Signal strengths also measured per production mode via dedicated event categories ⇒ see backup

Measuring properties

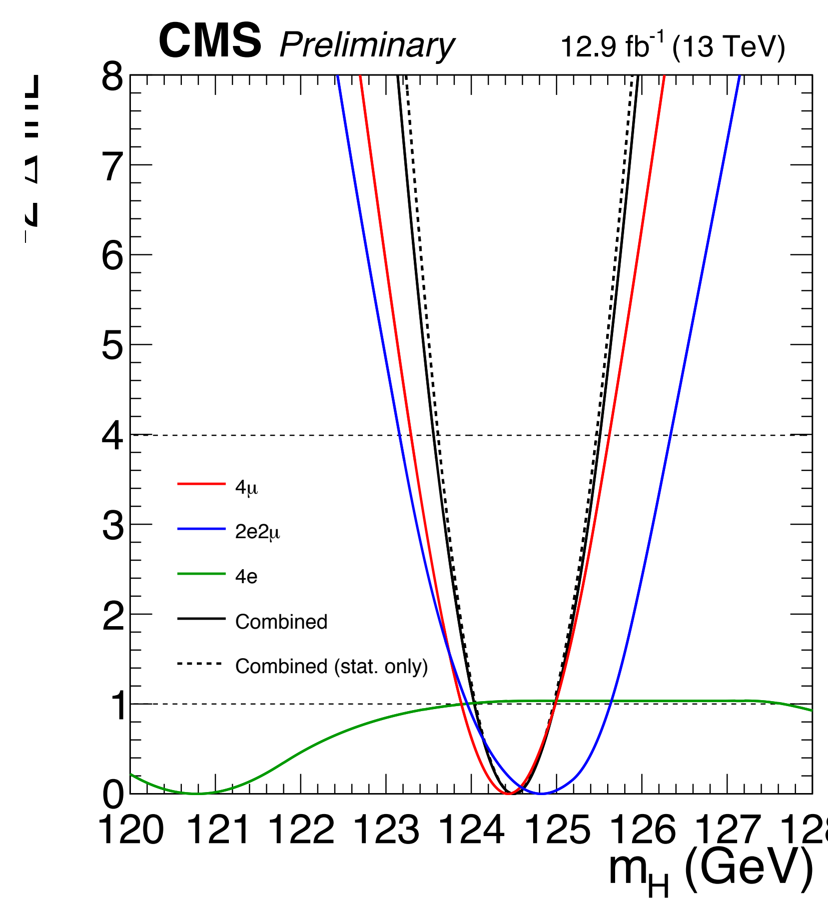
- CMS measured the mass and width in the H→ZZ→4l final state: both compatible with SM expectation & Run 1 results
- Width measured using only on-shell region ($105 < m_{4l} < 140$ GeV) and the combination with the off-shell region ($105 < m_{4l} < 1600$ GeV) which greatly enhances sensitivity





$\Gamma_H < 41$ MeV (95% CL)

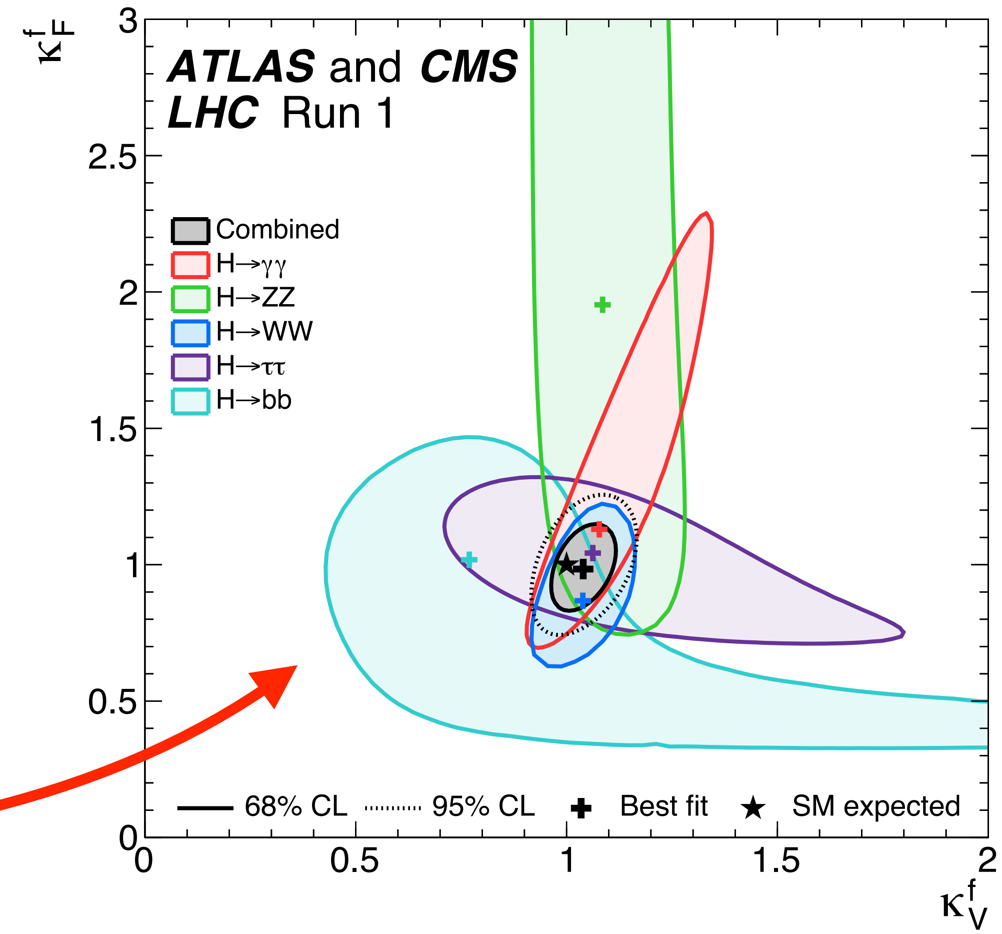
$m_H = 124.5 \pm 0.48$ GeV

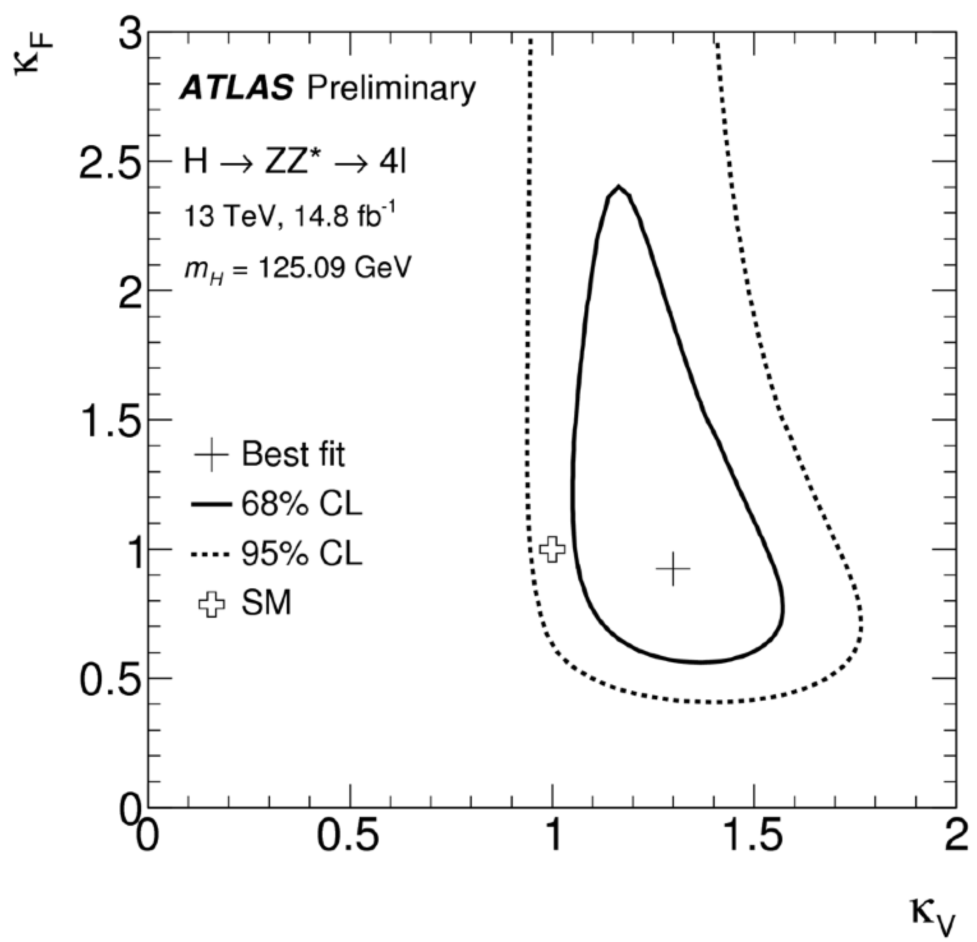


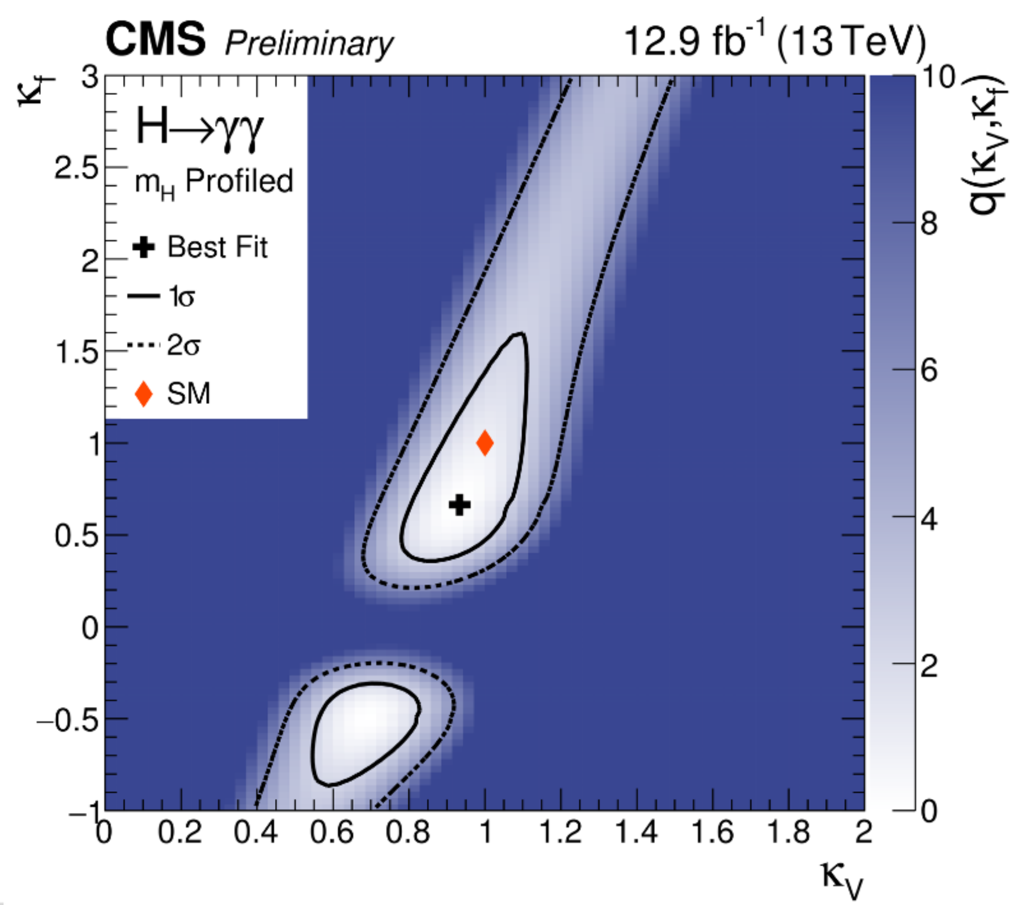
Parameter	$m_{4\ell}$ range	Observed	Expected
Γ_H (GeV)	$[100, 1600]$	$0.010^{+0.014}_{-0.010}$ $[0.000, 0.041]$	$0.004^{+0.013}_{-0.004}$ $[0.000, 0.032]$
Γ_H (GeV)	$[105, 140]$	$0.3^{+1.4}_{-0.0}$ $[0.0, 3.9]$	$0.0^{+1.1}_{-0.0}$ $[0.0, 2.7]$

Kappa framework

- Remains a useful model for testing for deviations from the SM expectation
- 2D κ_V-κ_F scans produced for H→ZZ and H→γγ decay modes
- Eventually combination of all final states will provide the strongest constraint due to complementary regions of sensitivity, i.e. ATLAS+CMS Run 1 combination

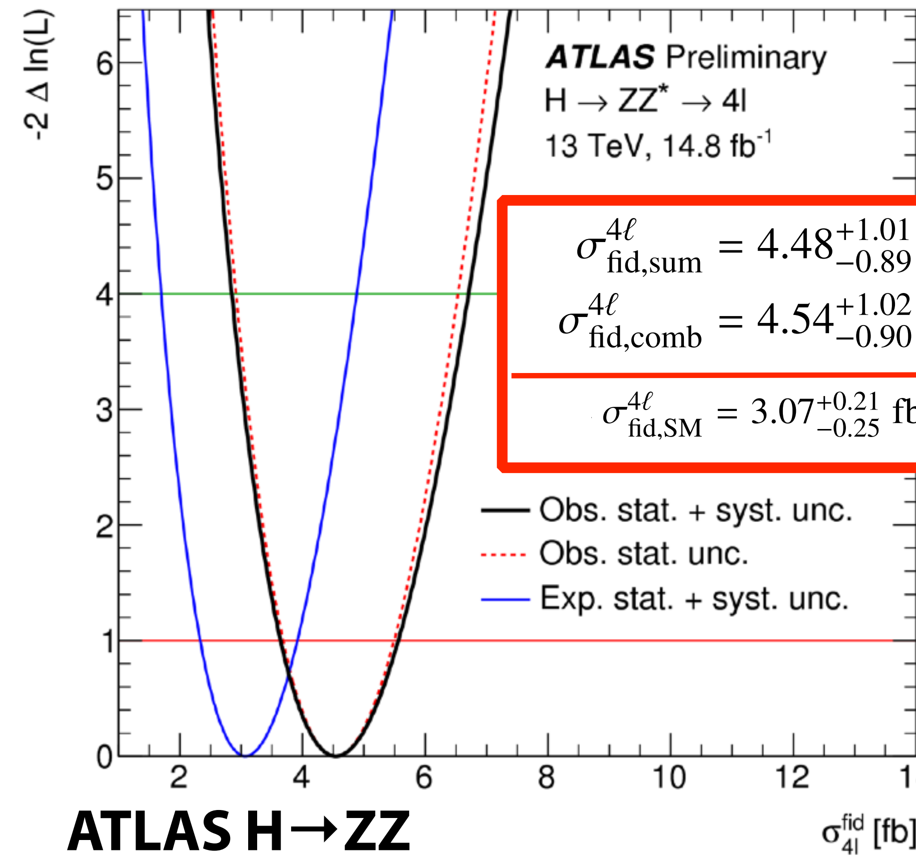






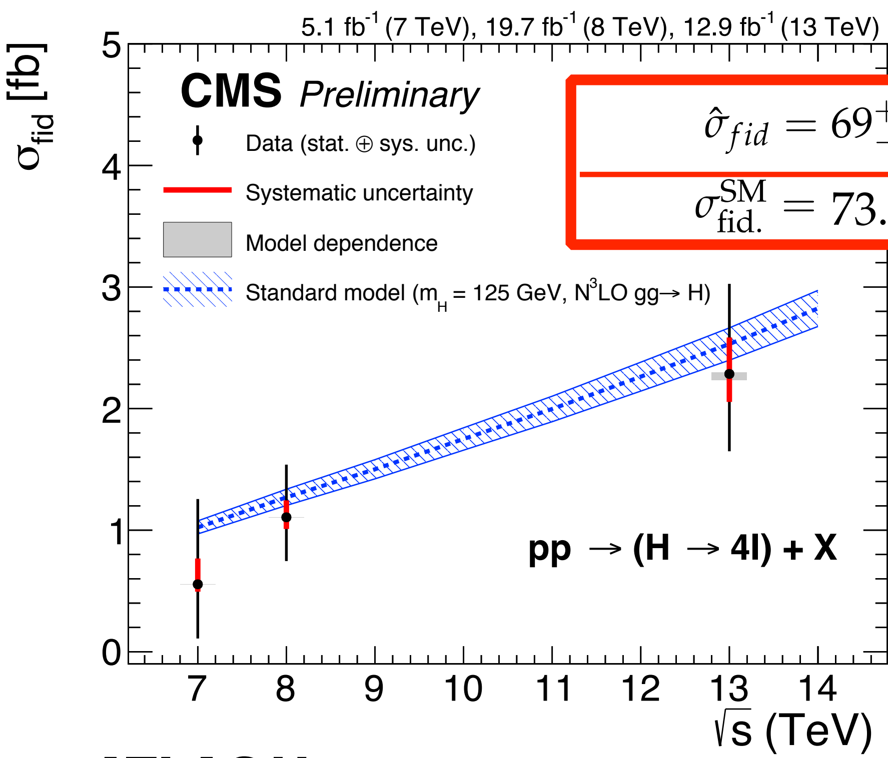
Fiducial cross sections

- Fiducial volumes chosen to match experimental acceptance as closely as possible
- Minimises extrapolation which depends on theoretical modelling and assumptions on relative production mode rates
- Measured values compared to latest N³LO ggH prediction



$$\sigma^{4\ell}_{\rm fid,sum} = 4.48^{+1.01}_{-0.89}\ \text{fb}$$
$$\sigma^{4\ell}_{\rm fid,comb} = 4.54^{+1.02}_{-0.90}\ \text{fb}$$
$$\sigma^{4\ell}_{\rm fid,SM} = 3.07^{+0.21}_{-0.25}\ \text{fb.}$$

ATLAS H→ZZ

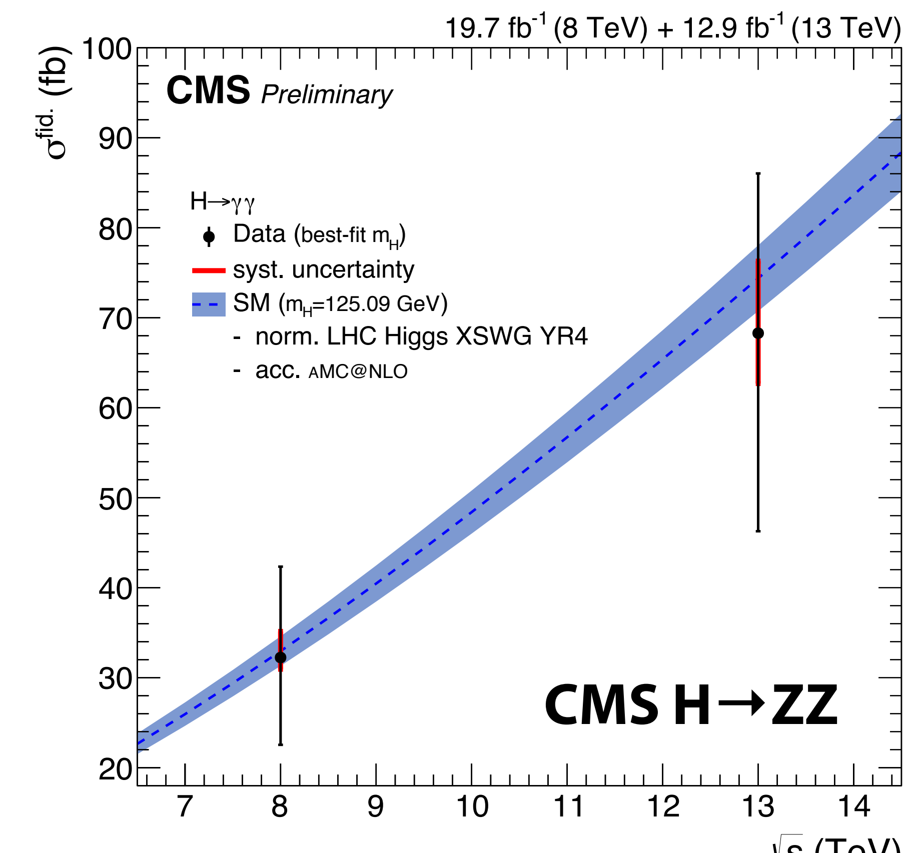


$$\hat{\sigma}_{fid} = 69^{+18}_{-22}\text{fb} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$
$$\sigma^{\rm SM}_{\rm fid.} = 73.8 \pm 3.8\ \text{fb}$$

CMS H→γγ

ATLAS H→γγ

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8^{+3.4}_{-4.4}$	[N³LO + XH]
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	[NNLOPS + XH]

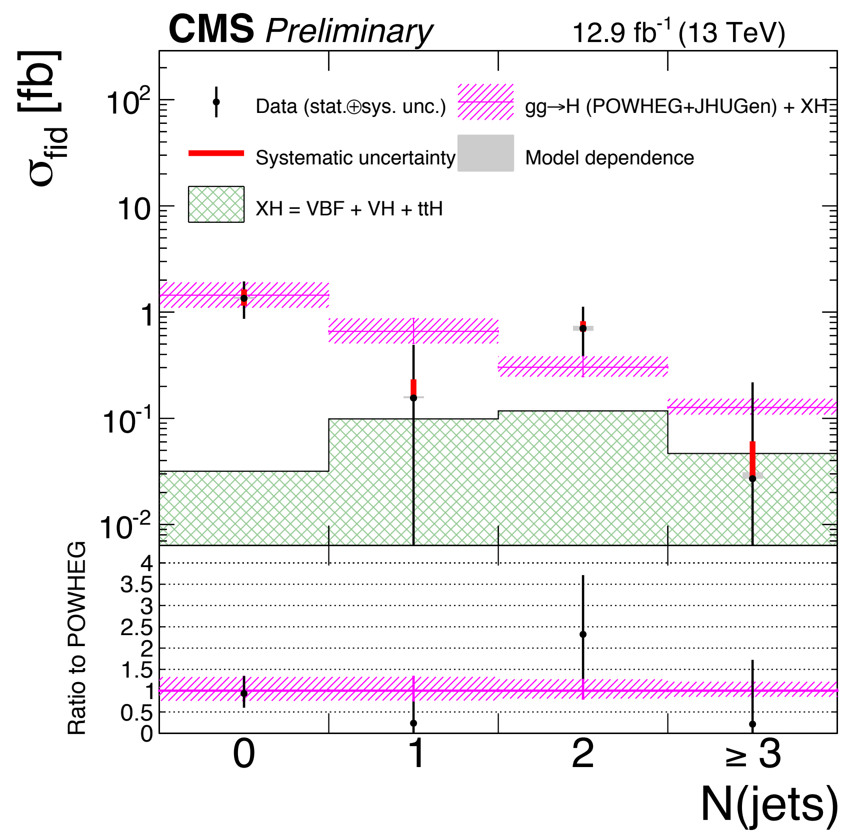


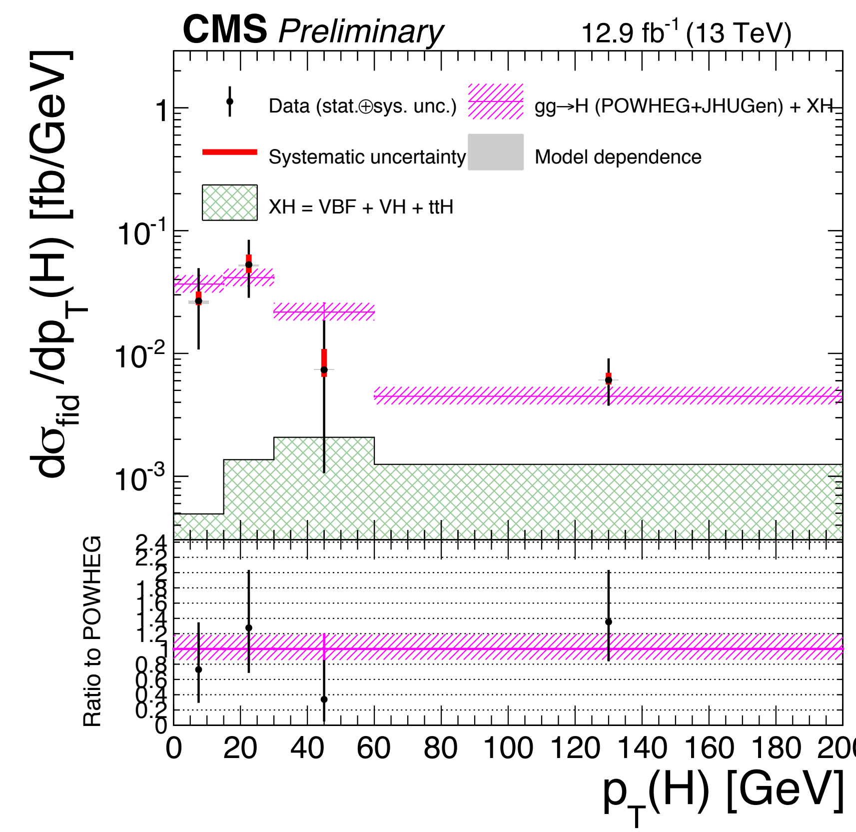
CMS H→ZZ

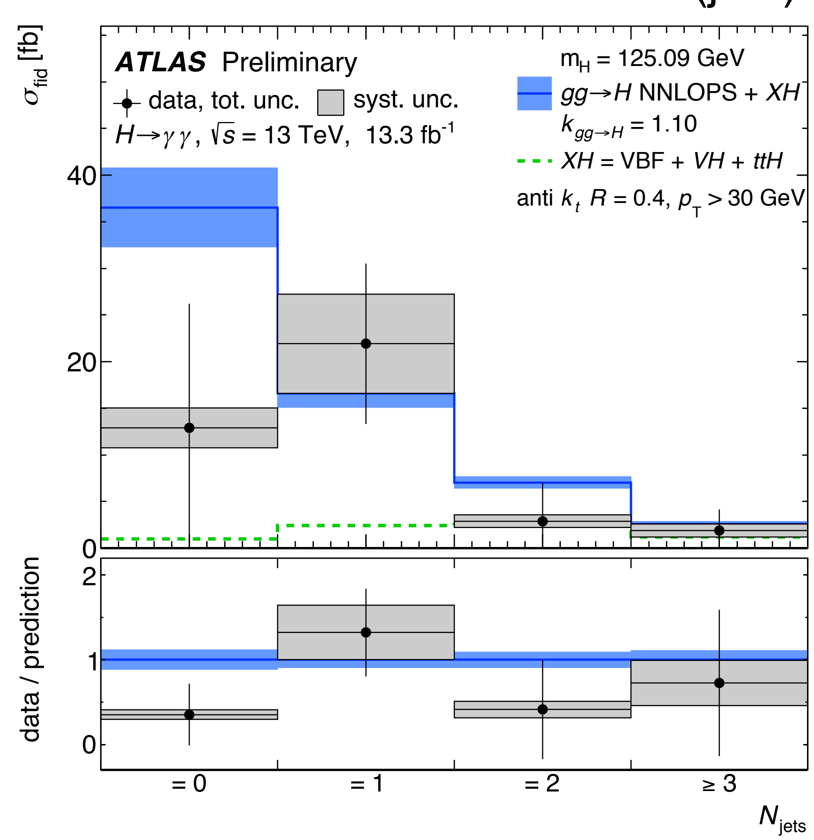
$$\sigma_{\rm fid.} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb}$$
$$\sigma^{\rm SM}_{\rm fid.} = 2.53 \pm 0.13\ \text{fb.}$$

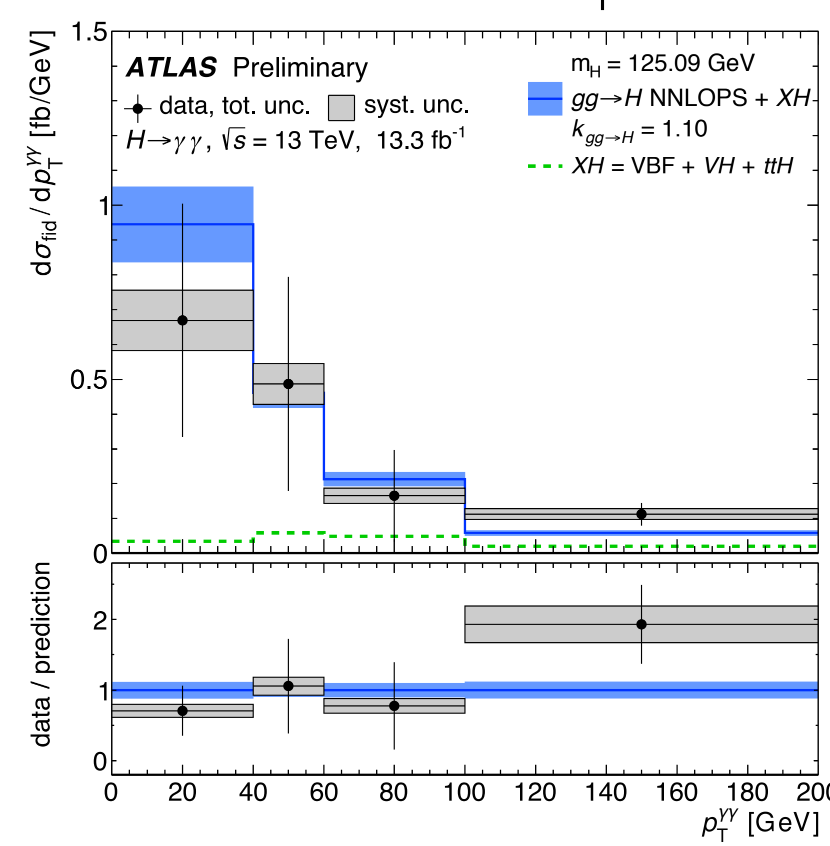
Fiducial differential cross sections

- Differential cross sections give even more model-independent information on the Higgs boson properties
- H→γγ and H→ZZ at 13 TeV given for several variable including p_T^H and N_{jets}
- Can be compared to different generator predictions
- Also possible to use as probe of BSM contributions that appear in the tails of distributions



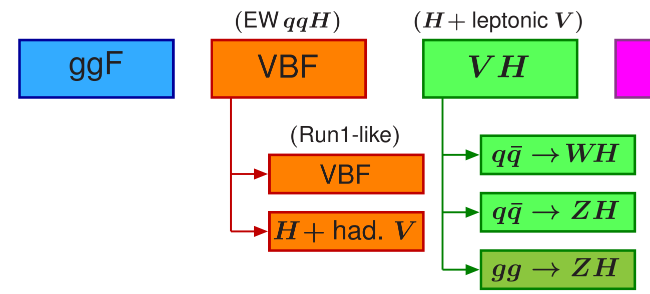




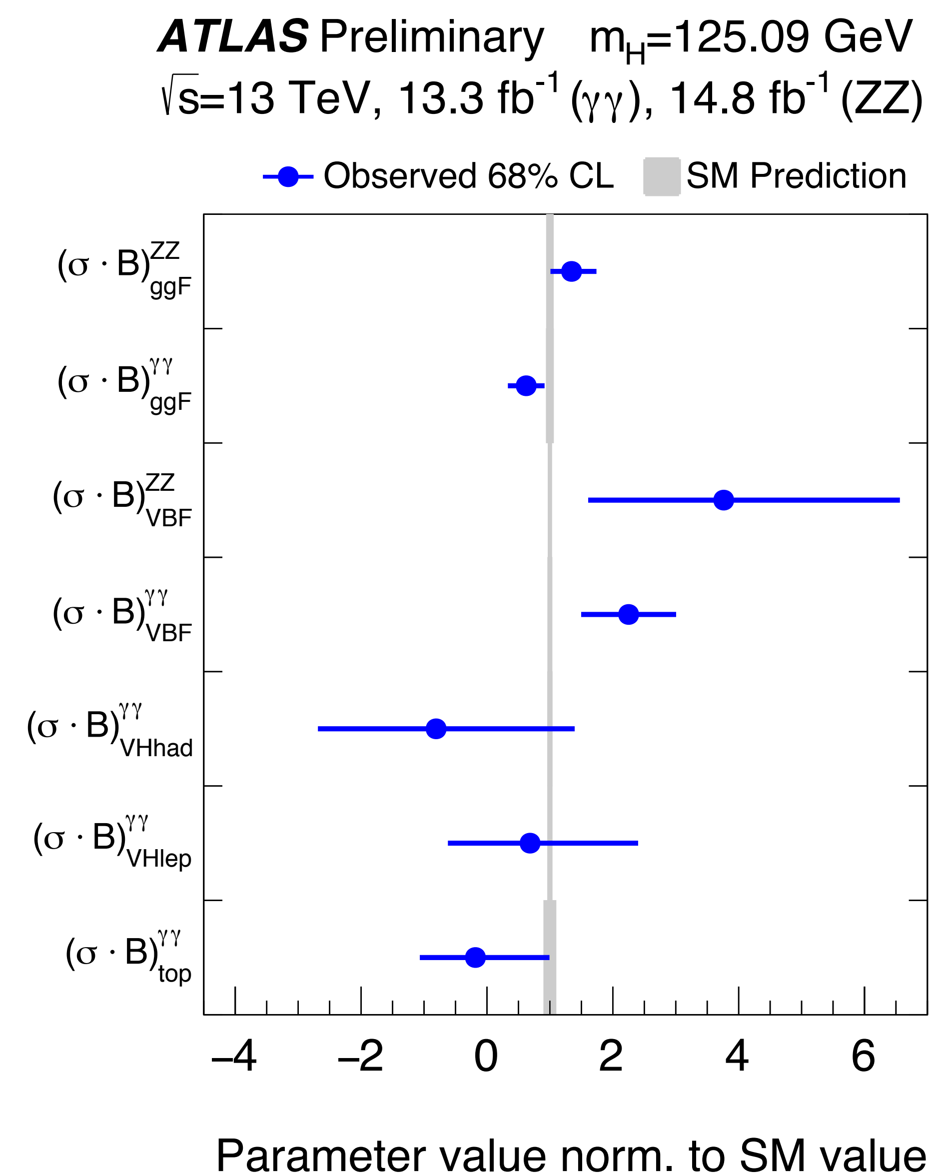


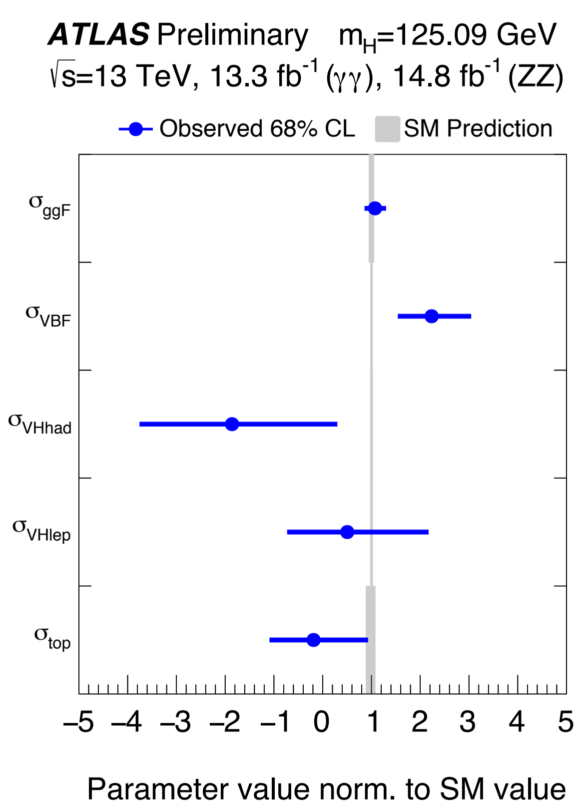
Simplified template cross sections

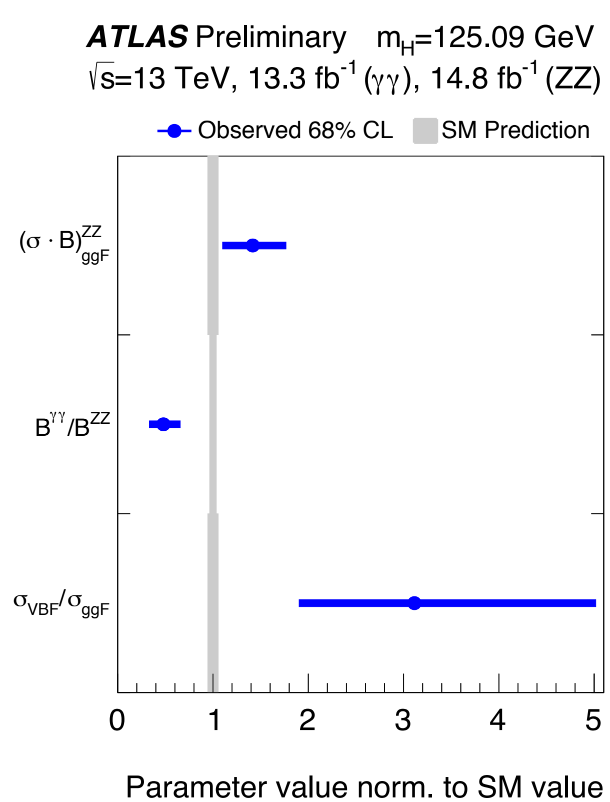
- YR4 (arXiv:1610.07922) proposes simplified template cross sections
- Several stages proposed with increasing split of production modes by jet multiplicity, p_T^H etc
- Possibility to connect to BSM models in different frameworks, e.g. kappa model, EFT coefficients
- First results from ATLAS combining H→γγ and H→ZZ



Stage 0

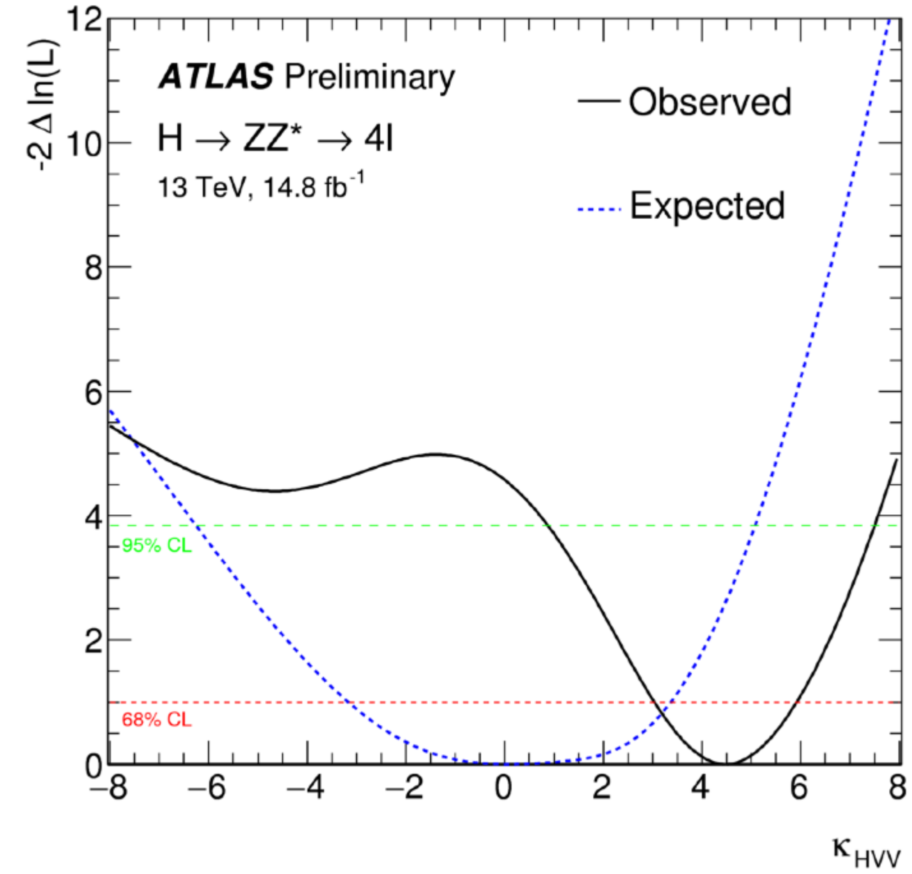




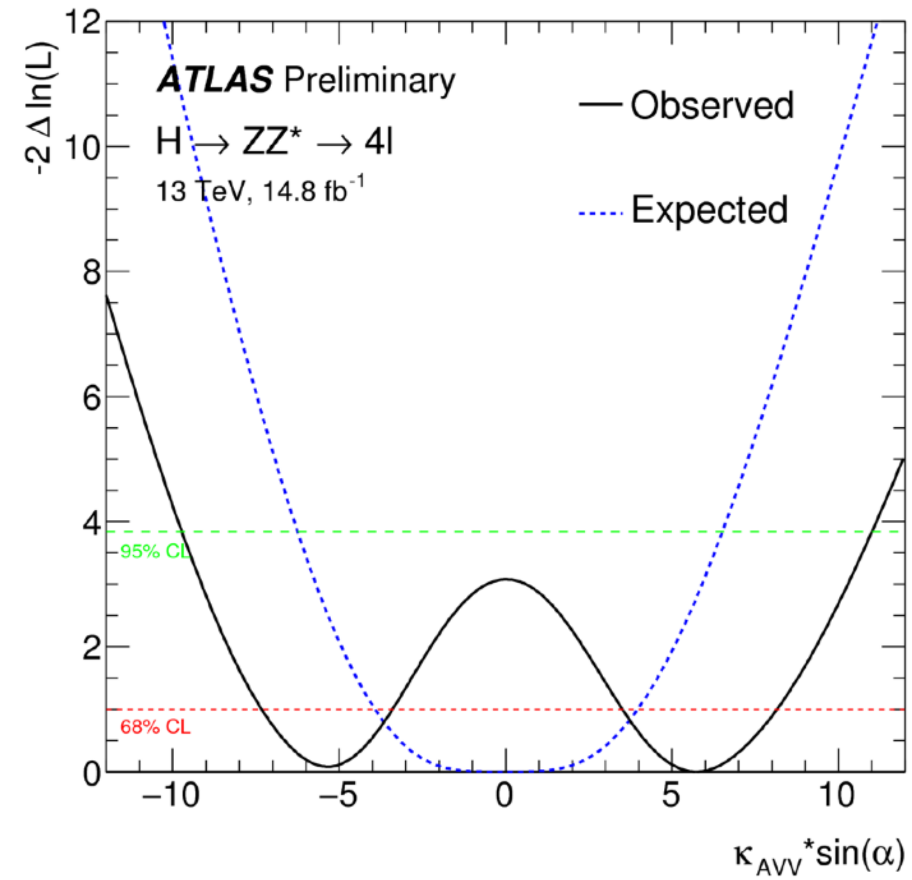


Effective Lagrangian interpretation

- Use Higgs Characterisation model to probe for anomalous couplings in H→ZZ→4l:
  - BSM scalar - **κ_{HVV}**
  - BSM pseudo-scalar - **κ_{AVV}*sin(α)**
- Split events into categories sensitive to different Higgs production modes
- Fix SM contribution **cos(α)*κ_{SM}** to 1
- Presence of BSM interactions modifies signal yields



$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\mathrm{SM}} \left[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu} \right] \\
& - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu} \right] \\
& - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \left(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c. \right) \right] \Big\} X_0 \,,
\end{aligned}
$$



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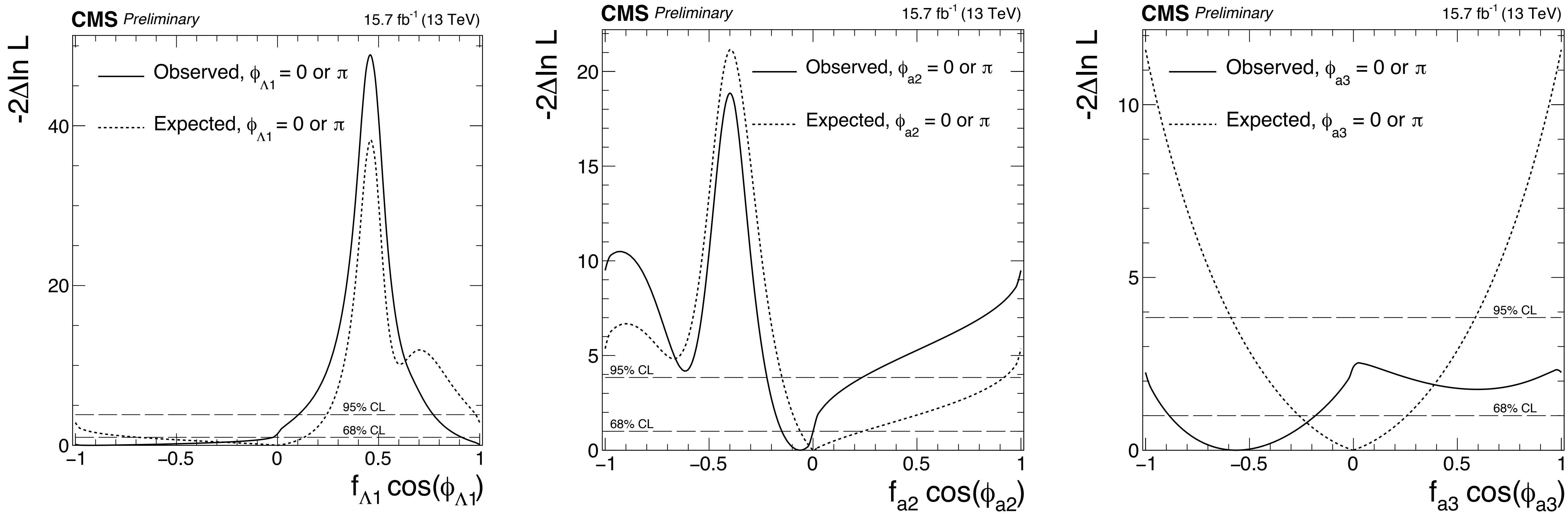
Anomalous couplings

- CMS updated constraints on anomalous spin-0 couplings in $H \rightarrow ZZ \rightarrow 4l$ using decay kinematics
- All results compatible with SM expectation so far
- CMS and ATLAS parametrisations are related (⇒ see backup)

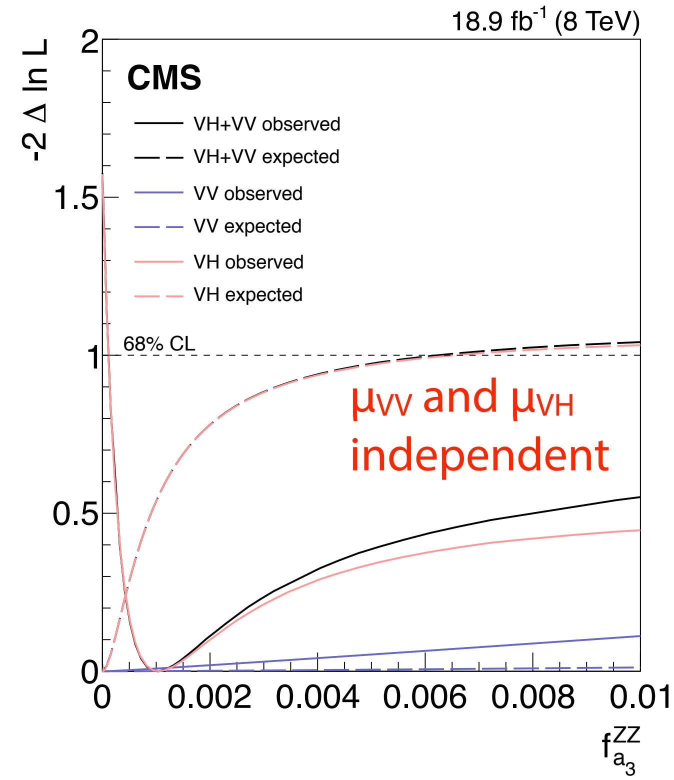


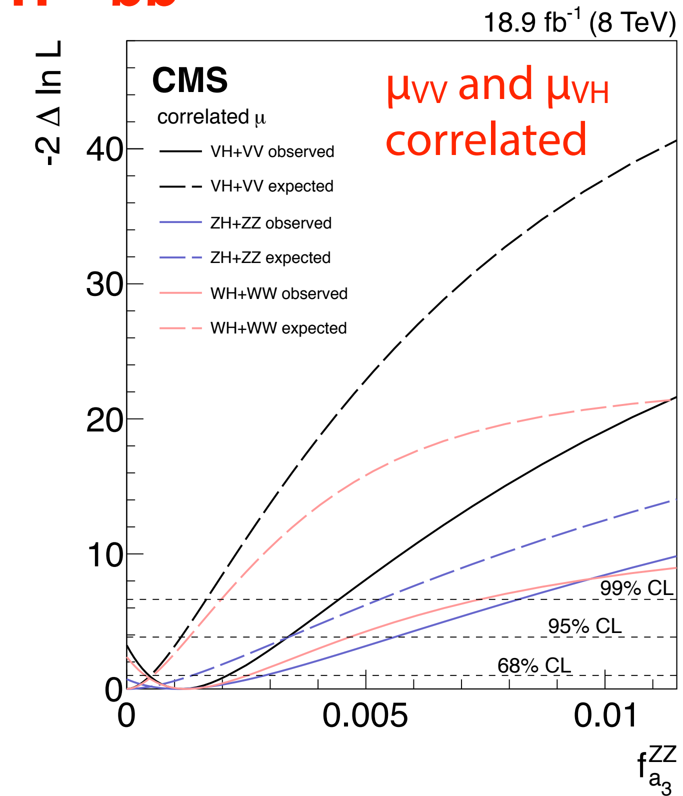
Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$-0.56^{+0.38}_{-0.32}$ $[-1.00, 1.00]$	$0.00^{+0.26}_{-0.26}$ $[-0.59, 0.59]$
$f_{a2}\cos(\phi_{a2})$	$-0.06^{+0.06}_{-0.09}$ $[-0.22, 0.24]$	$0.00^{+0.24}_{-0.06}$ $[-0.15, 0.92]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$-0.93^{+0.90}_{-0.16}$ $[-1.00, 0.10] \cup [0.77, 1.00]$	$0.00^{+0.13}_{-0.69}$ $[-1.00, 0.24] \cup [0.98, 1.00]$

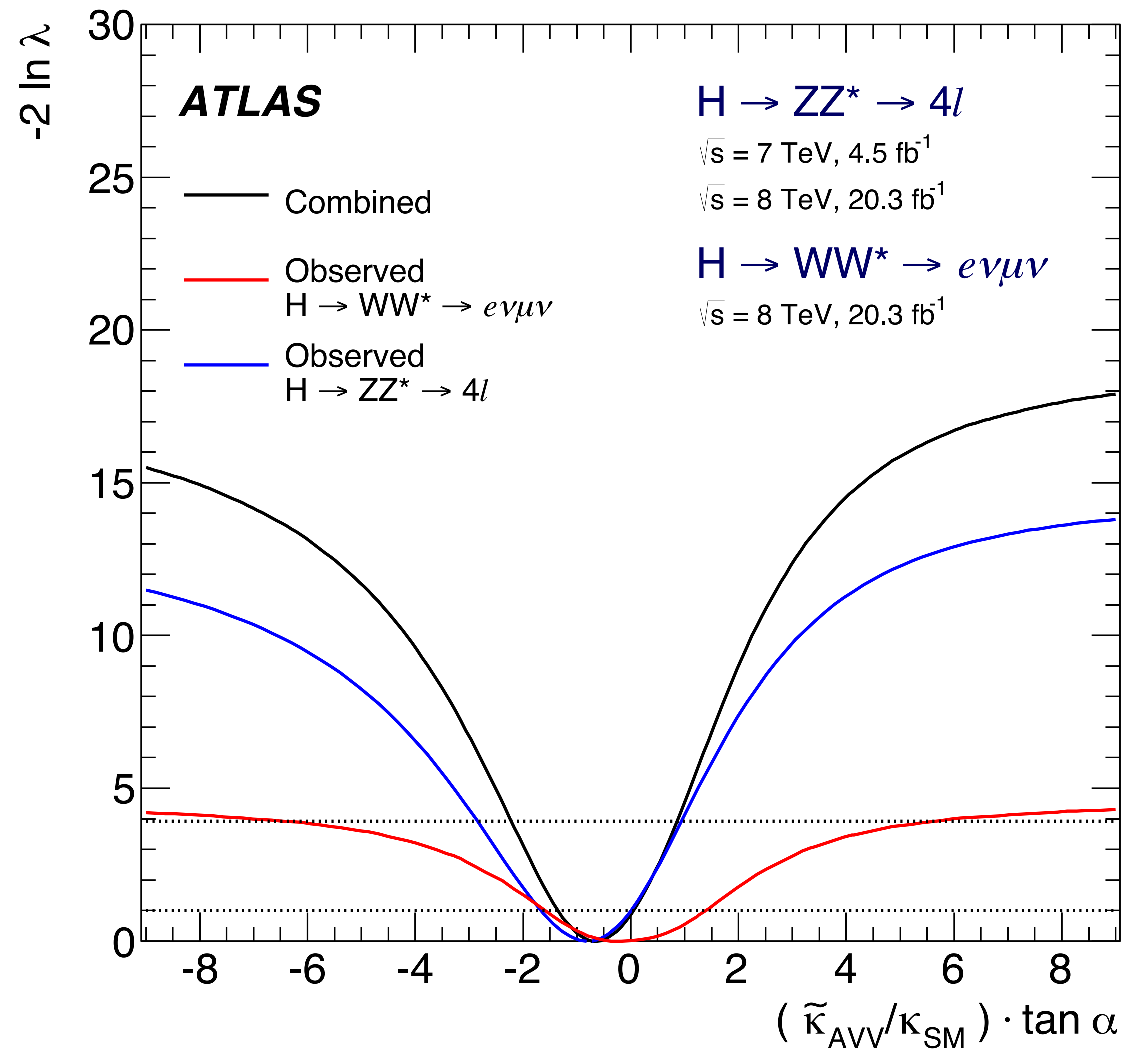
Anomalous couplings combinations

- **Results from Run 1:** stronger constraints possible by combining channels but results depend on exact assumptions made

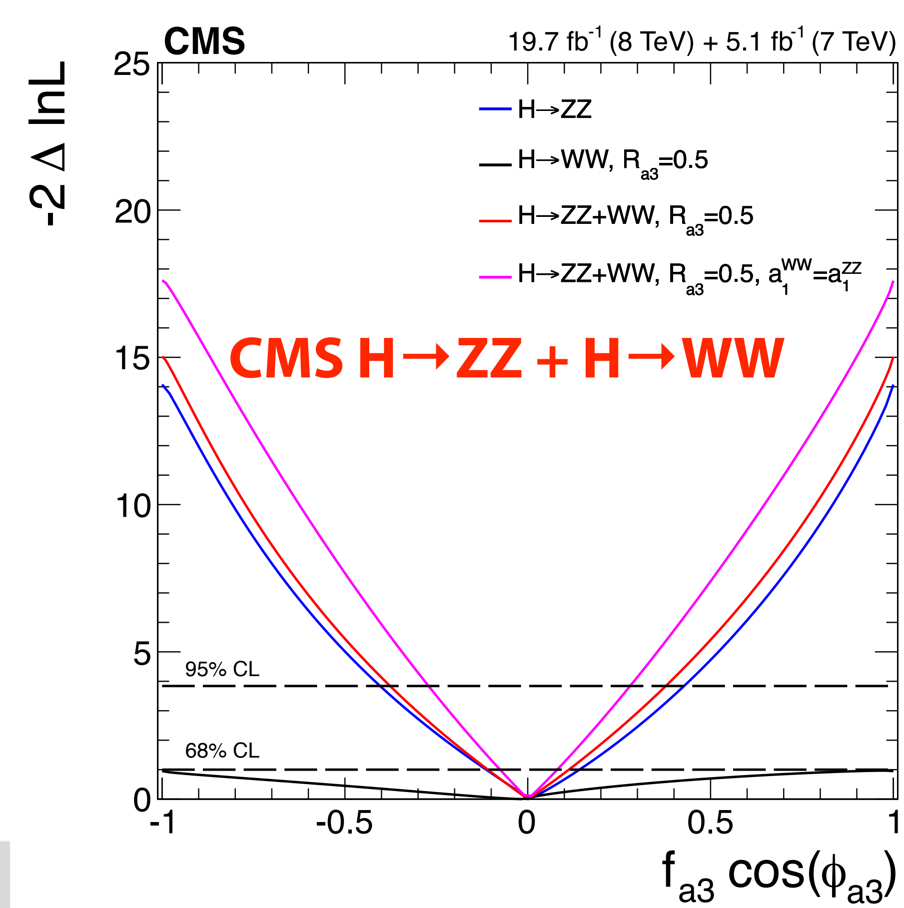
CMS H→VV + VH→bb







ATLAS H→ZZ + H→WW



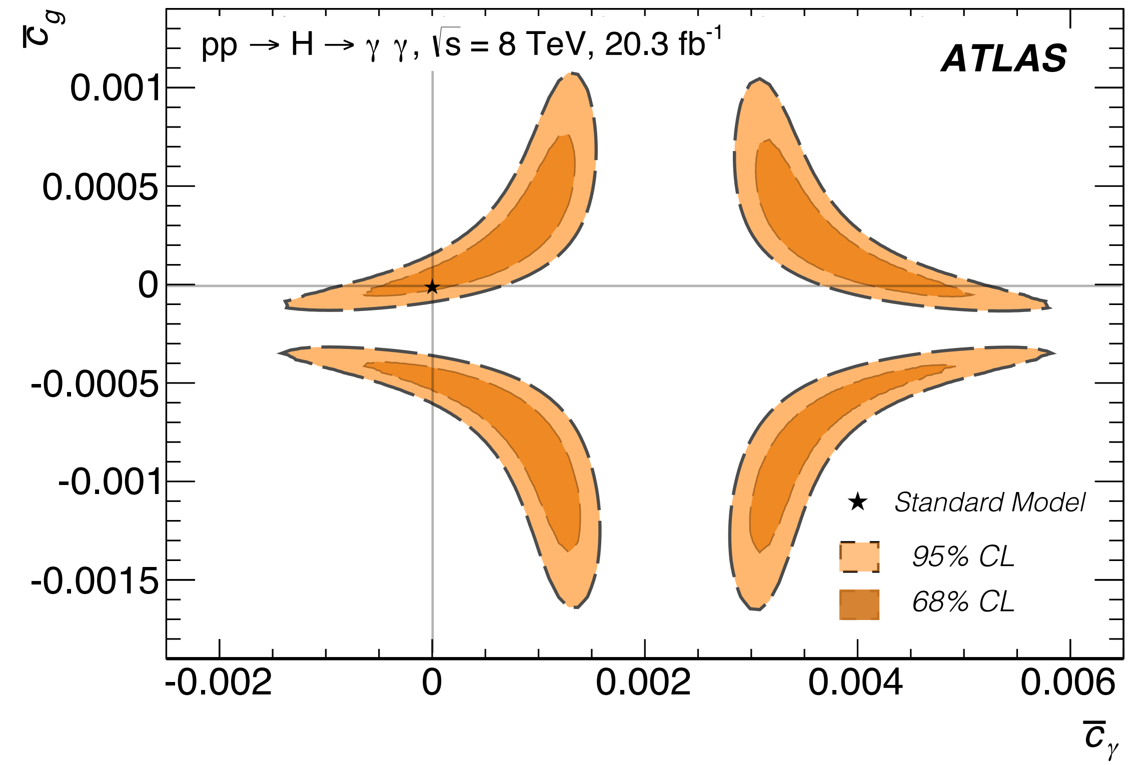
CMS H→ZZ + H→WW

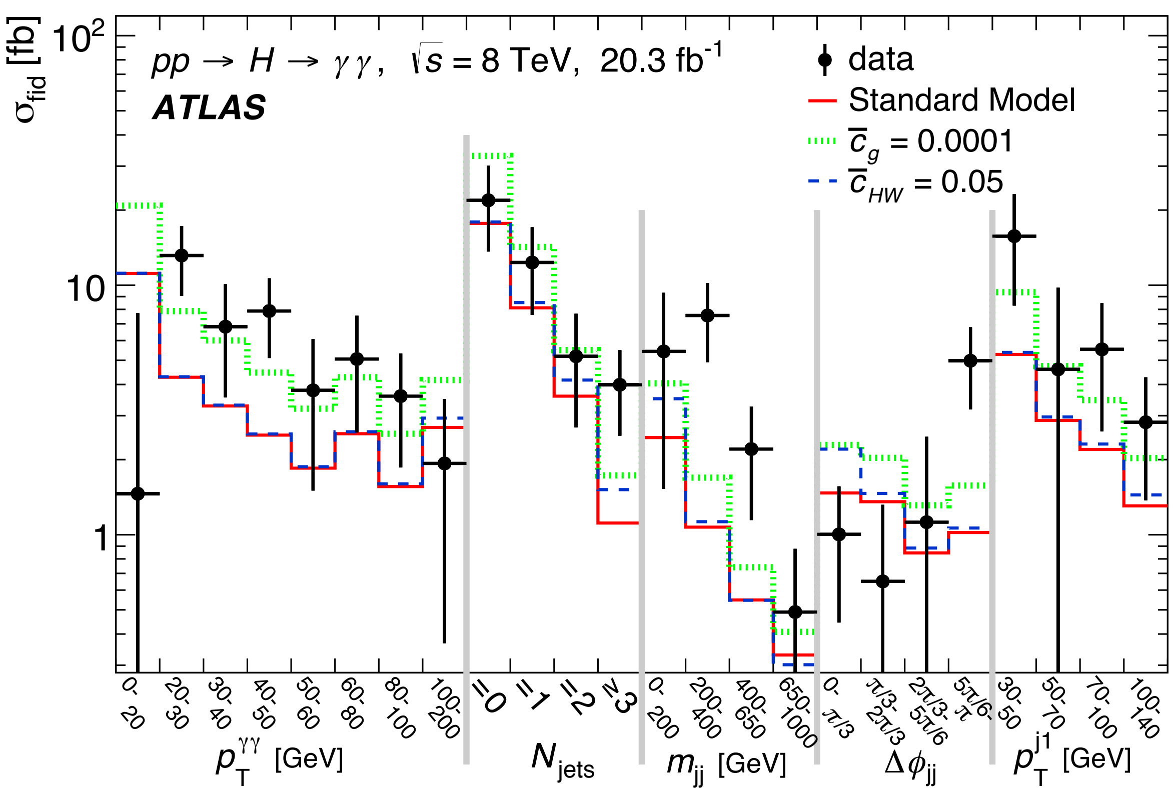
Reinterpretation of differential cross sections

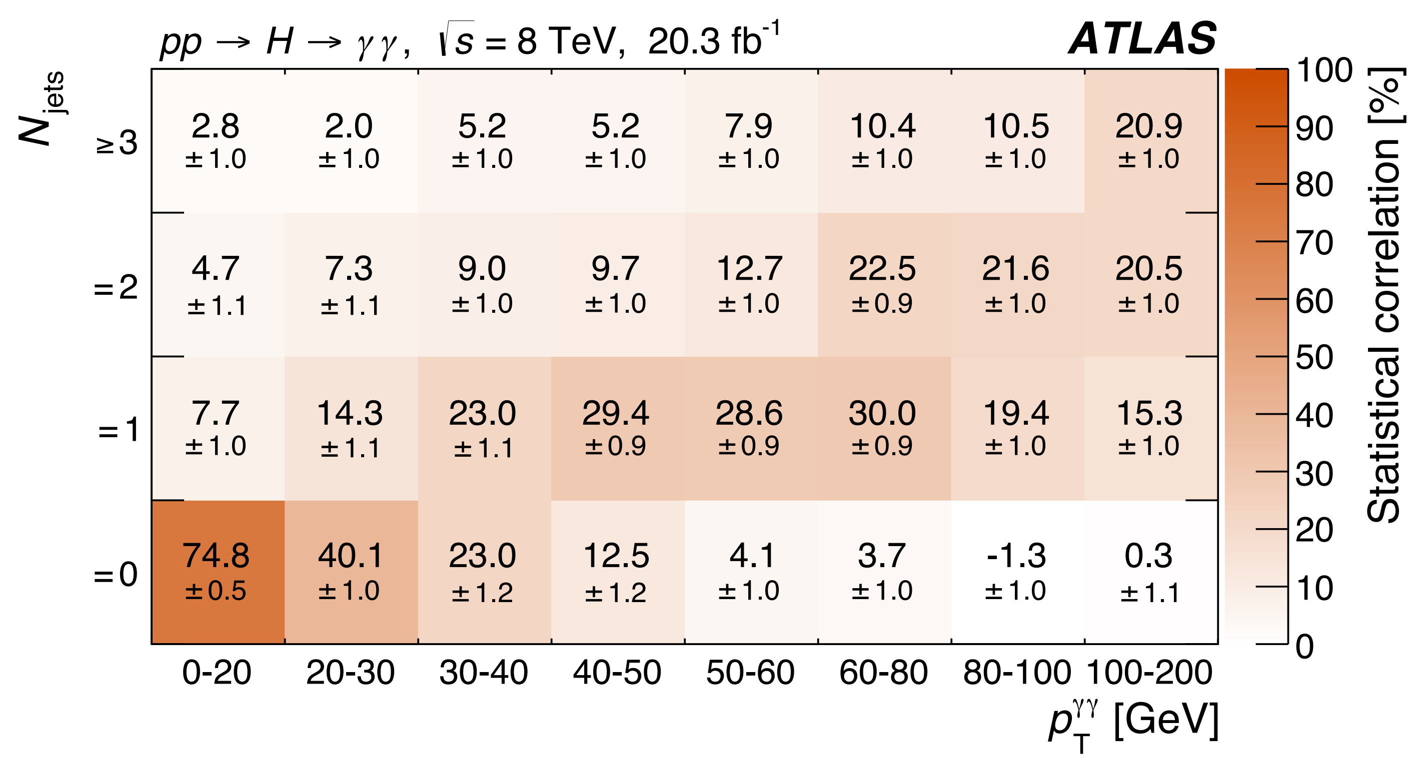
PLB 753 (2016) 69-85

- **Results from Run 1:** ATLAS reinterpret H→γγ differential cross sections using an effective Lagrangian approach
- Statistical correlation matrix between bins of different observables provided - allows for further reinterpretation
- Likelihood scans performed for coefficients of new CP-even and CP-odd interactions

$$\mathcal{L}_{\text{eff}} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

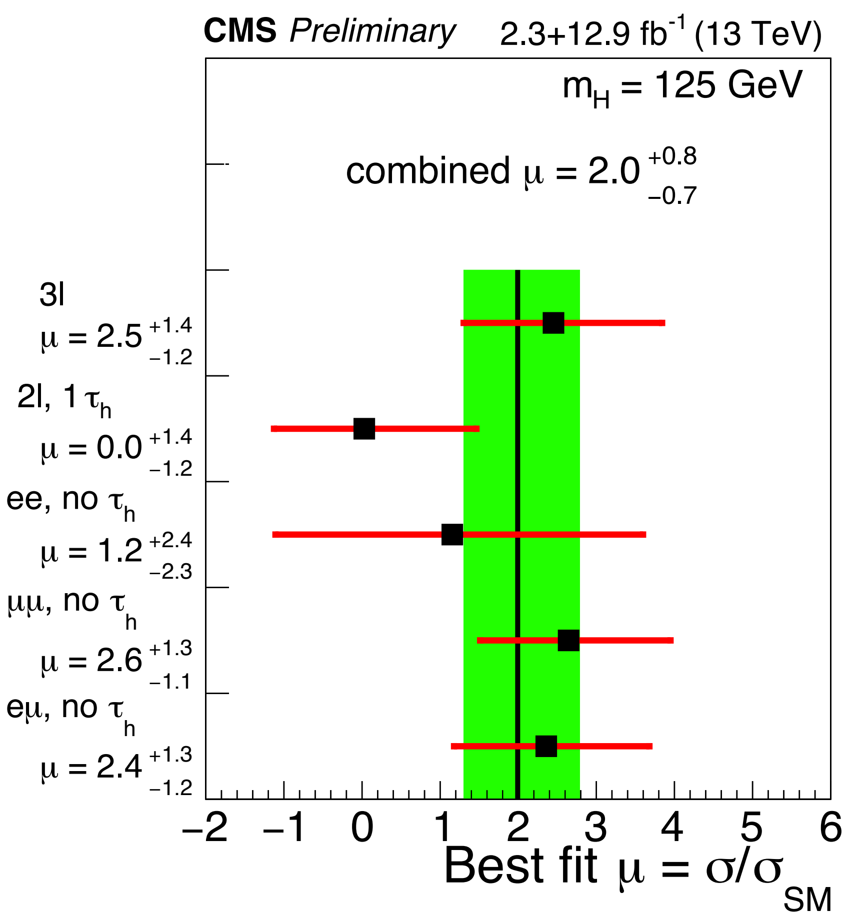


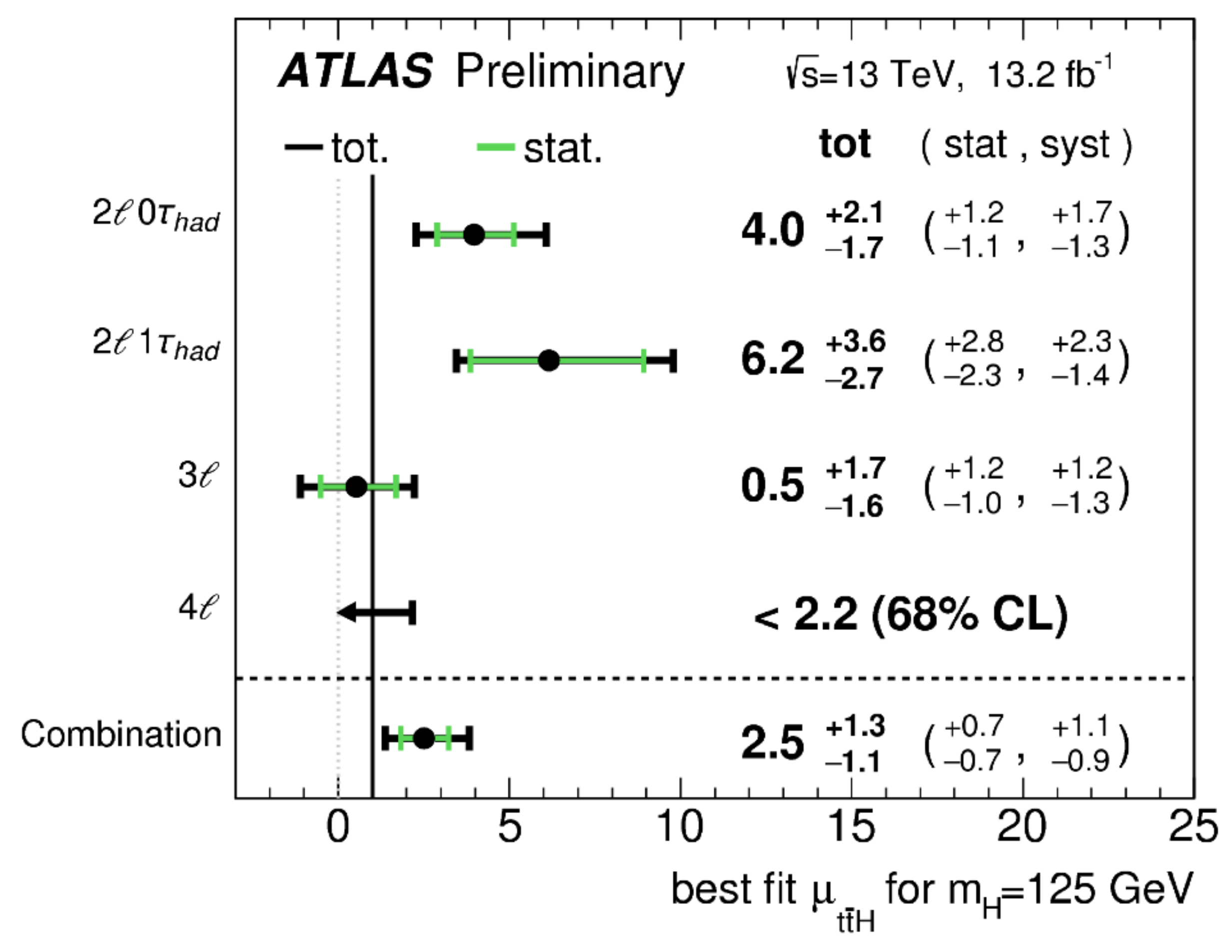




ttH → multileptons

- ttH cross section σ(13 TeV)/σ(8 TeV) ~ 4: improves sensitivity (though backgrounds also increase)
- Heightened interest due to moderate excess in the Run 1 combination:
  - $\mu_{ttH} = 2.3 \pm 0.7$
- Both CMS and ATLAS continue to see this excess at 13 TeV - stay tuned!



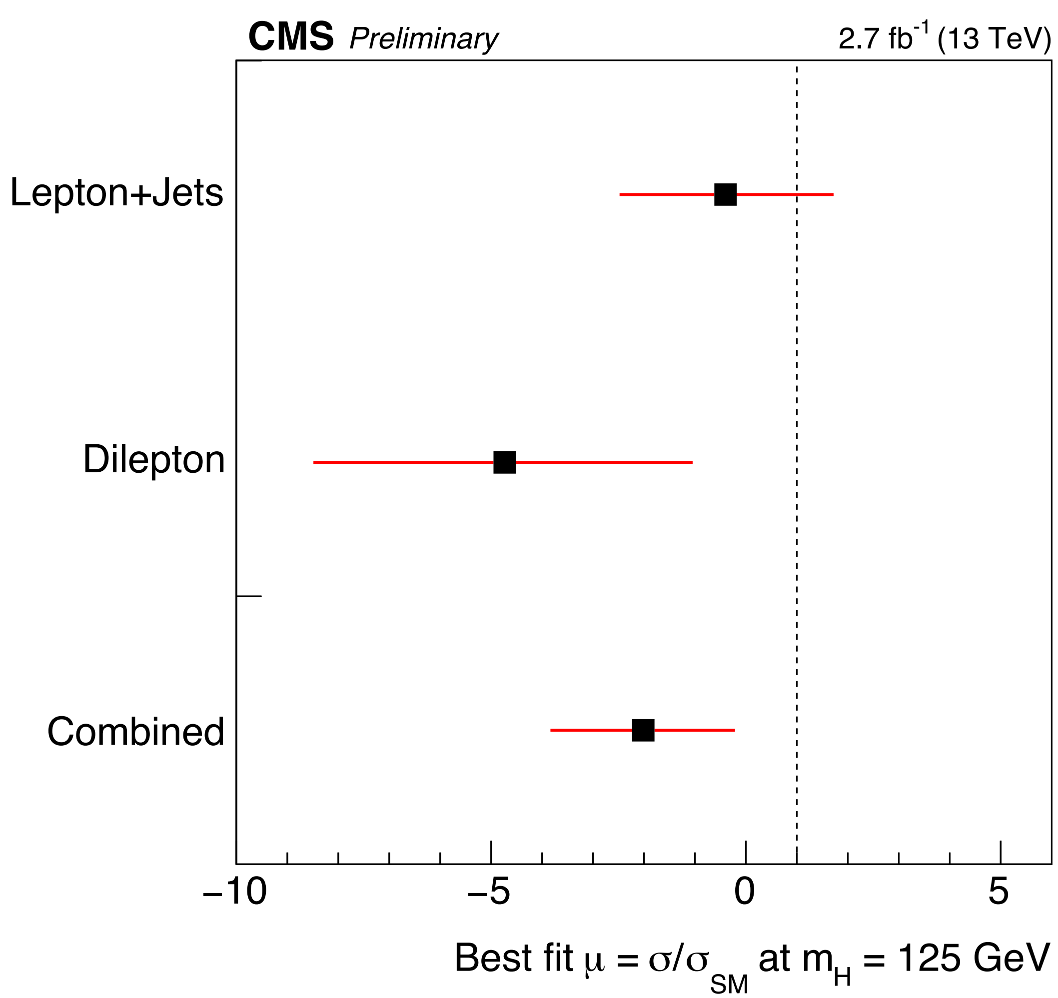


ttH→bb

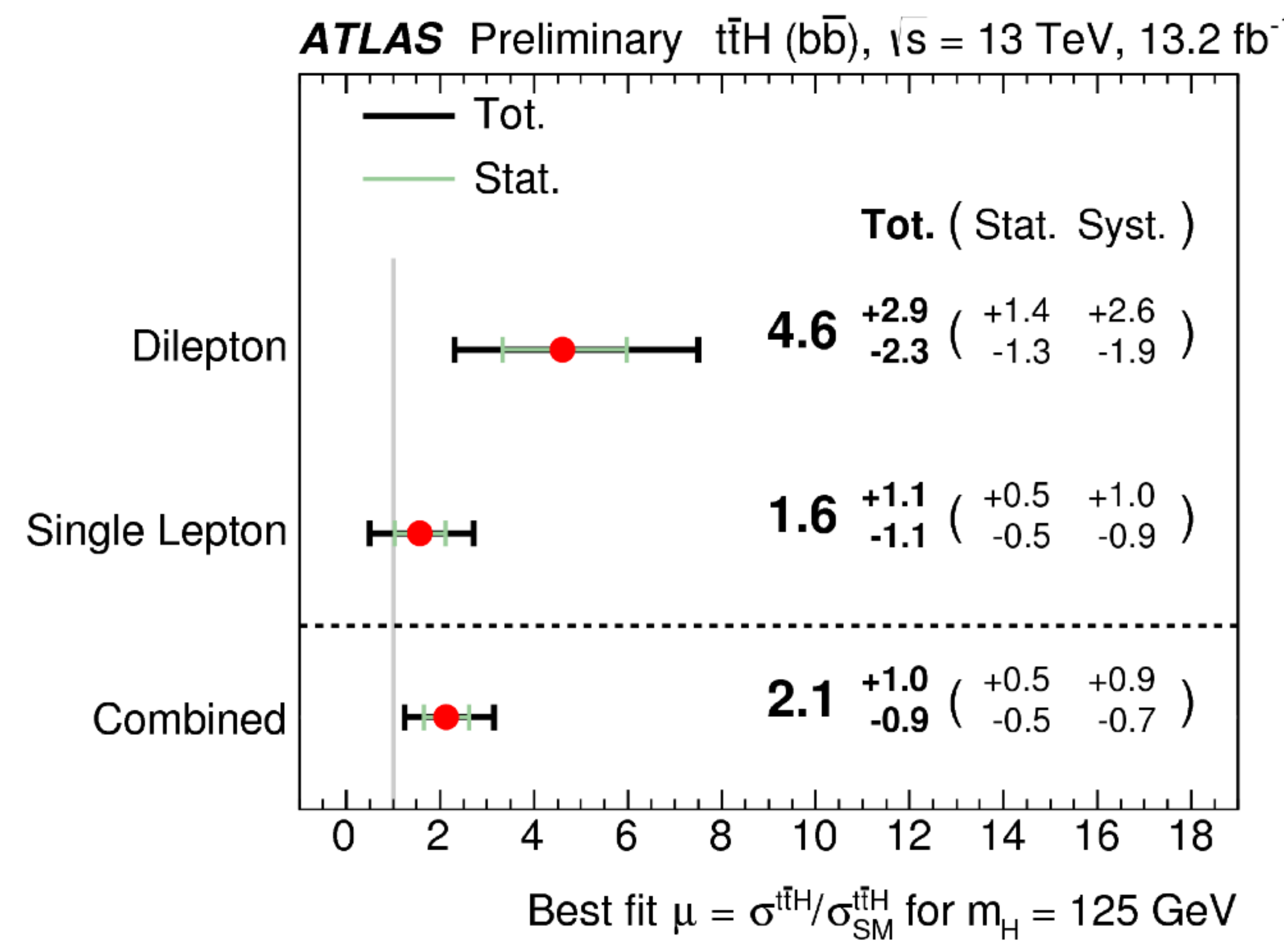
ATLAS-CONF-2016-080
CMS-PAS-HIG-16-004

- ATLAS results for 13.2 fb^{-1} show a moderate excess
  - Systematic uncertainties already important, in particular the modelling of the tt+b(b) background
- CMS results for 2.7 fb^{-1} show a deficit

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89



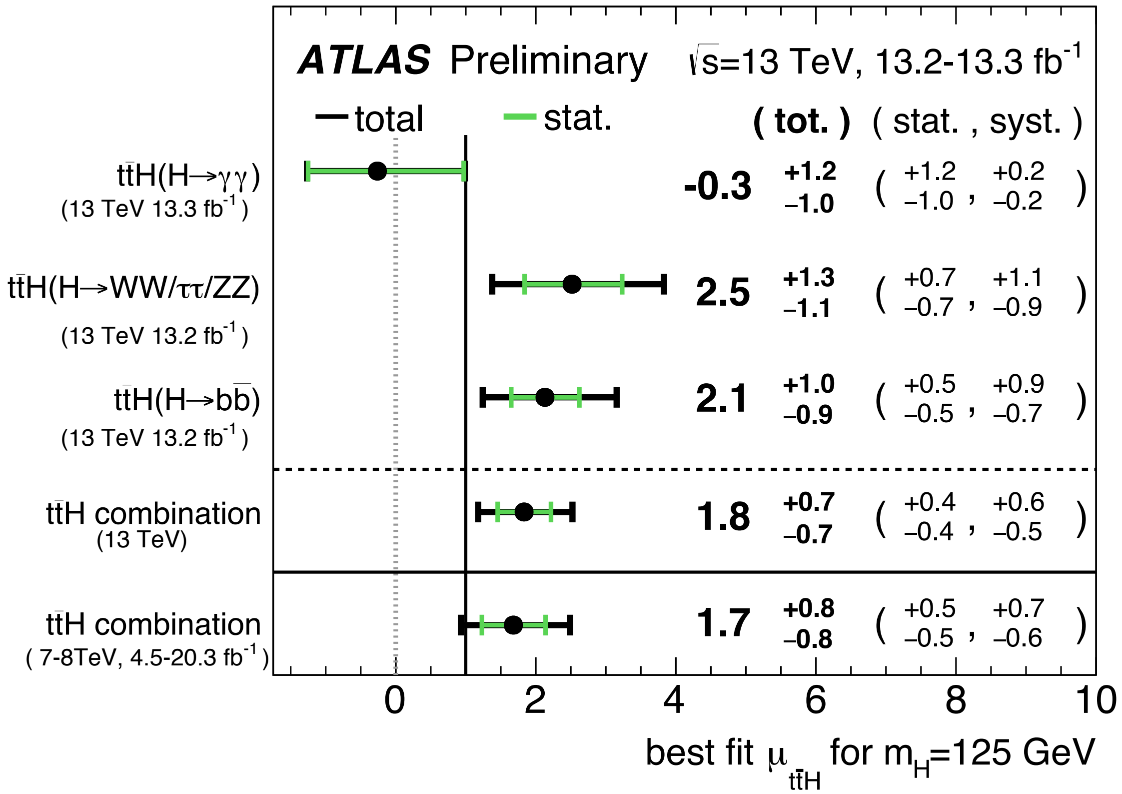
CMS

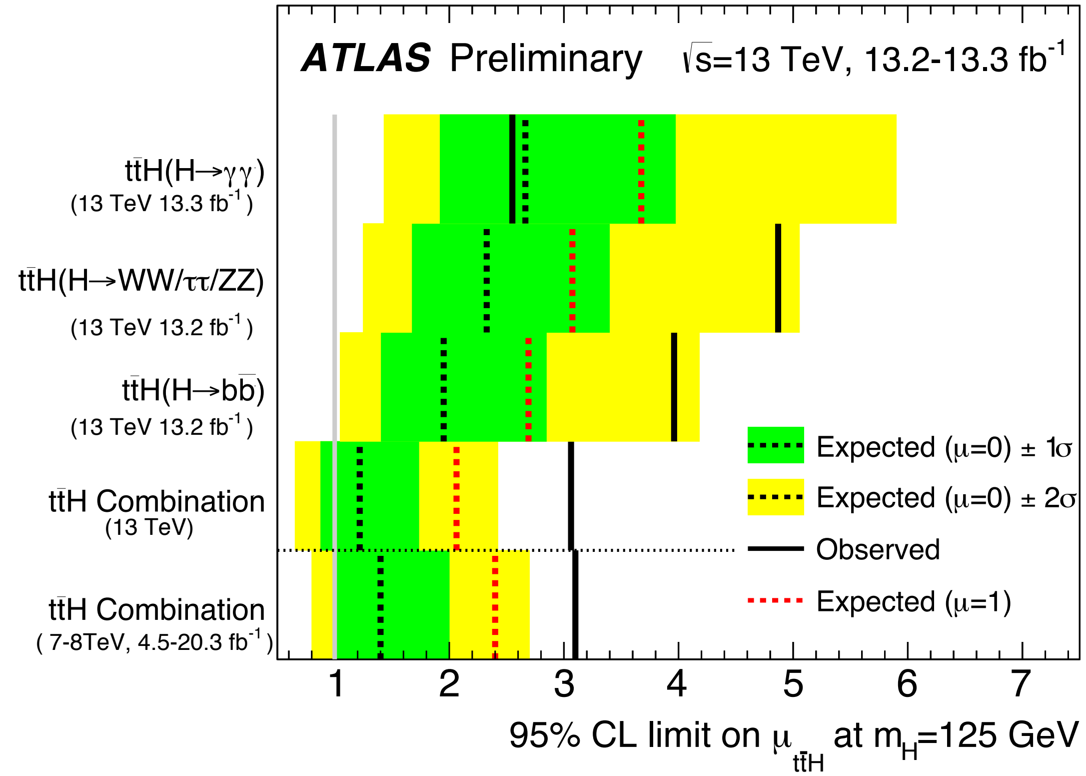


ATLAS

ttH - combination

- Combination of γγ, multilepton and bb analyses from ATLAS gives a consistent picture with Run 1 results





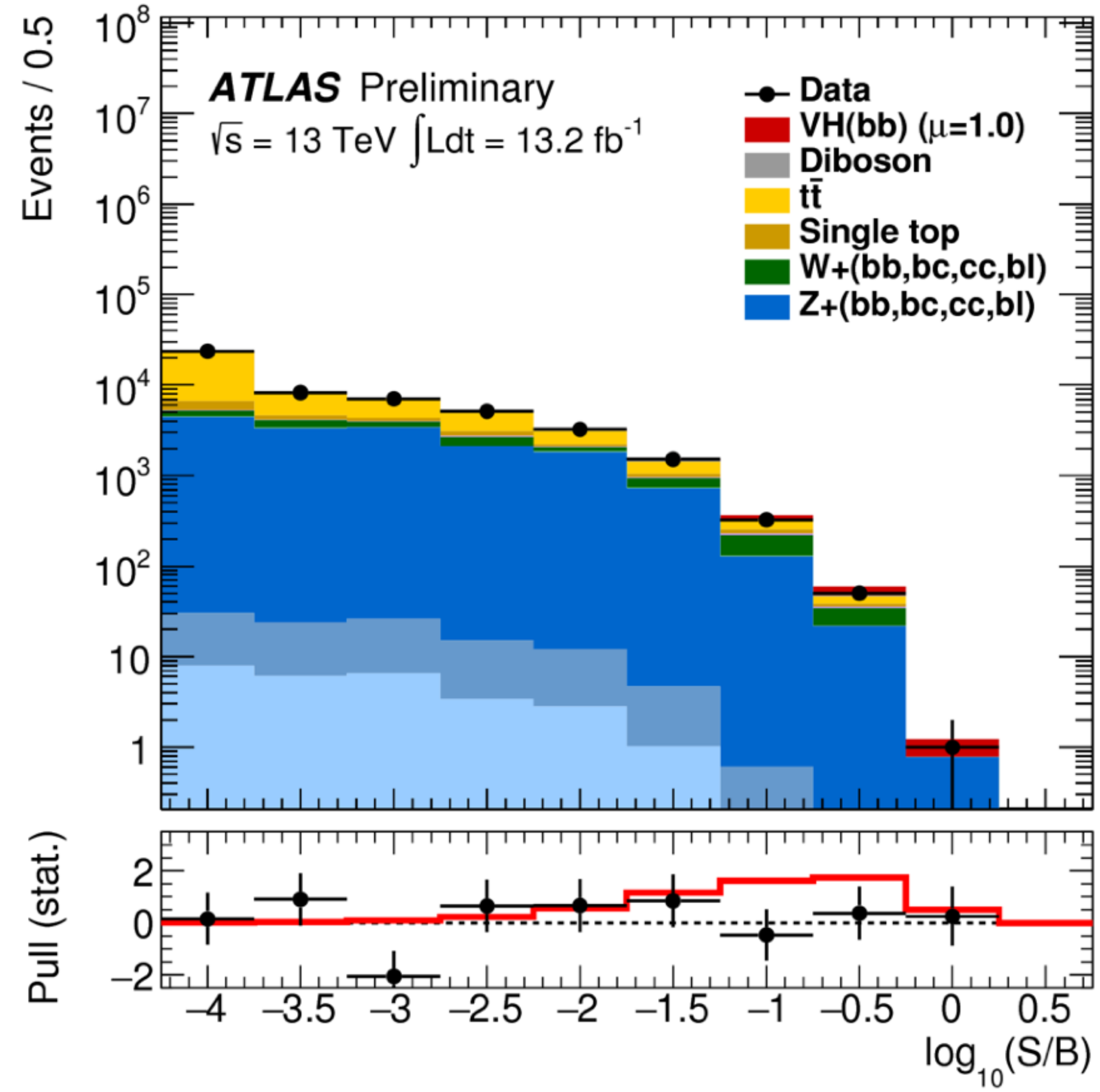
- Run 2 combination gives 2.8σ observed significance (1.8σ expected)
- Already exceeds Run 1 sensitivity (1.5σ expected)
- Some tensions between individual channels in CMS and ATLAS to be resolved with further data and (hopefully) reduction of systematic uncertainties

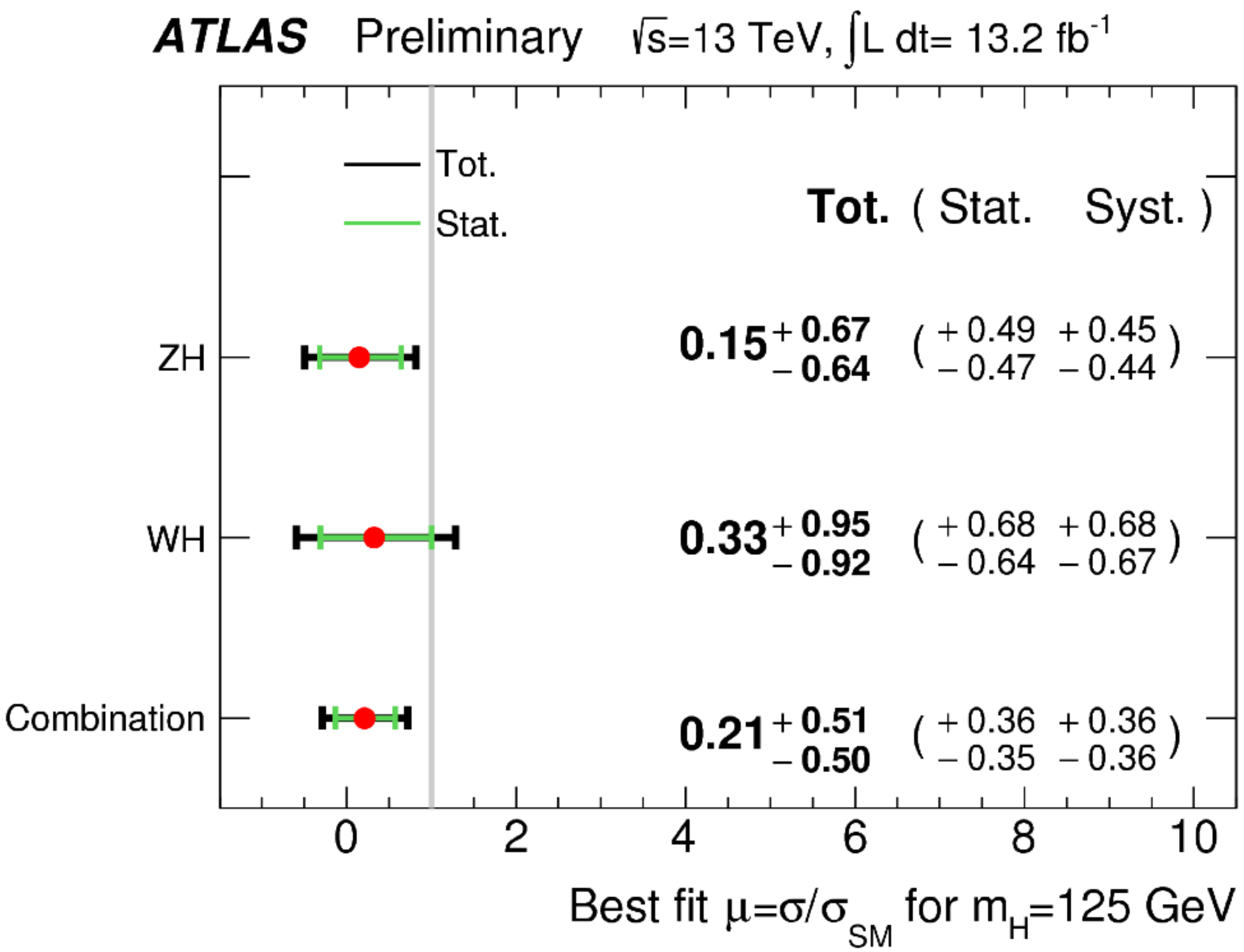
CMS ttH→γγ (13 TeV, 12.9 fb^{-1})**:** $\mathbf{1.9^{+1.5}_{-1.2}}$

VH→bb

ATLAS-CONF-2016-091

- Updated result with 13.2 fb^{-1} from ATLAS
- Analysis makes use of BDTs trained to separate signal in categories based on the number of jets and $p_T(V)$
- Validated by extracting VZ→bb as signal instead: $\mu_{VZ} = 0.91 \pm 0.17$ (stat) ± 0.30 (syst)



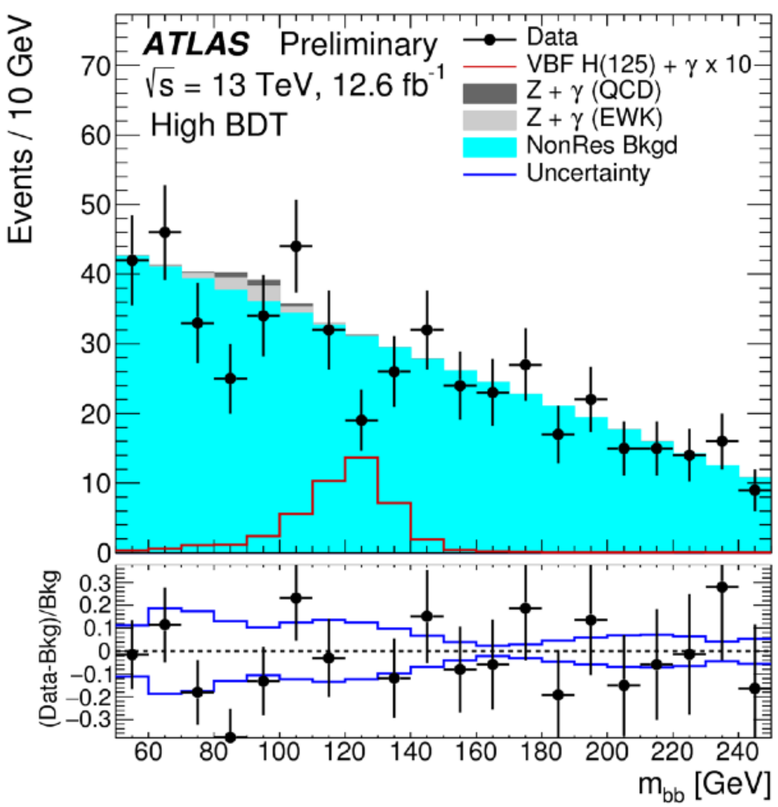


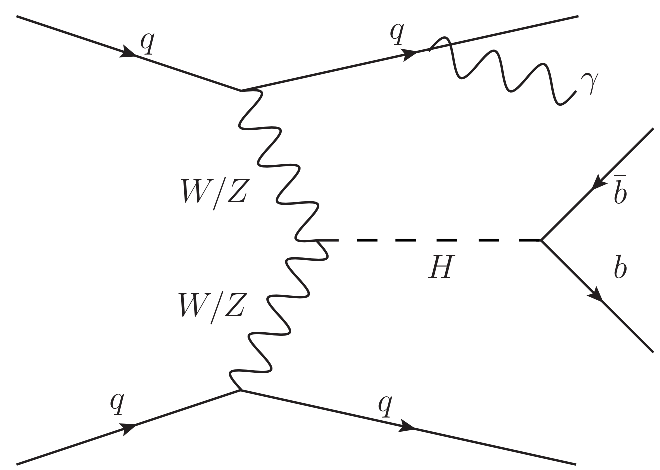
- Slight deficit in measured signal strength, similar to run 1

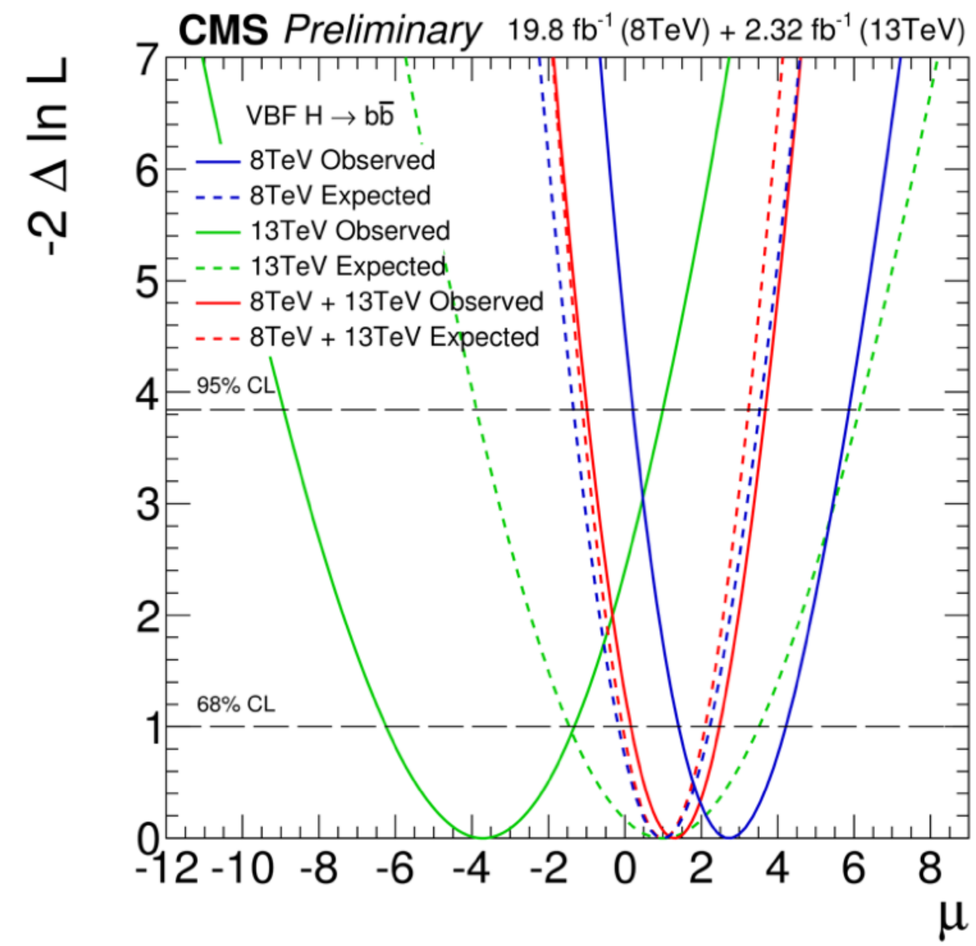
Run 1 CMS+ATLAS	$\hat{\mu}$
WH→bb	1.0 ± 0.4 (stat) ± 0.3(syst)
ZH→bb	0.4 ± 0.3 (stat) ± 0.2 (syst)

VBF H→bb

- **CMS**: 2.3 fb^{-1} of 13 TeV data - similar strategy to Run 1
- **ATLAS**: novel approach requiring high p_T γ in the final state - more efficient triggering and reduced non-resonant background







CMS Run1 + Run2 combined

	$\hat{\mu}$
CMS Run 1 + Run 2 (2.3 fb^{-1})	**$1.3^{+1.2}_{-1.1}$**
ATLAS Run 1	**-0.8 ± 2.3**
ATLAS Run 2 (VBF + γ)	**$-0.39^{+2.8}_{-2.7}$**

- Both measurements with relatively large uncertainties and compatible with SM

Summary

- Currently the best global picture of Higgs boson couplings from the Run 1 ATLAS+CMS combination
- There is good progress on moving beyond the signal strength and kappa framework results:
  - Fiducial inclusive and differential measurements
  - Direct EFT interpretations
  - Template cross sections
- With a large 13 TeV dataset now in hand will significantly improve sensitivity in new results by early next year

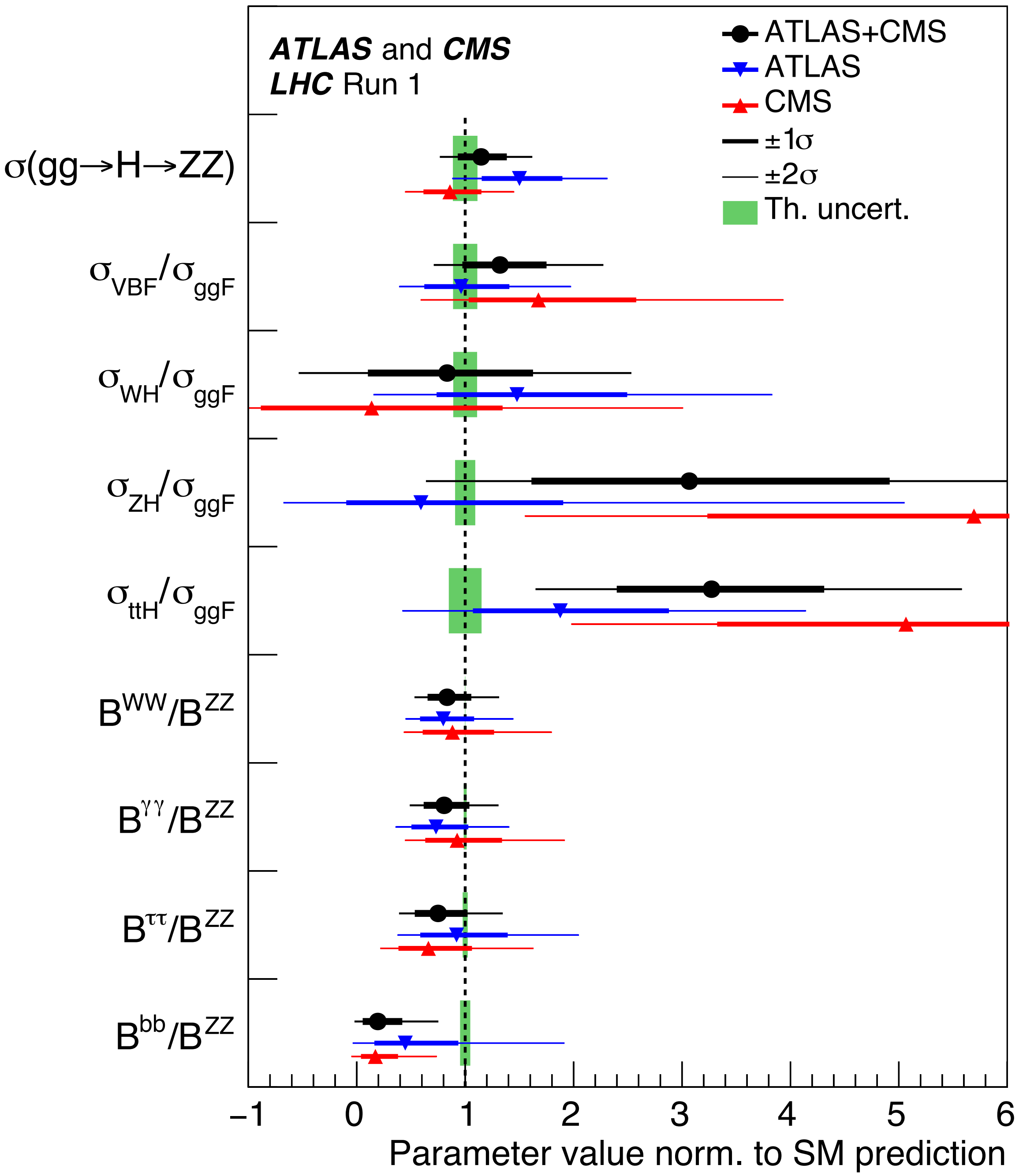
Backup

Signal strength ratios

Assumptions
- Only the 7/8 TeV ratios

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

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

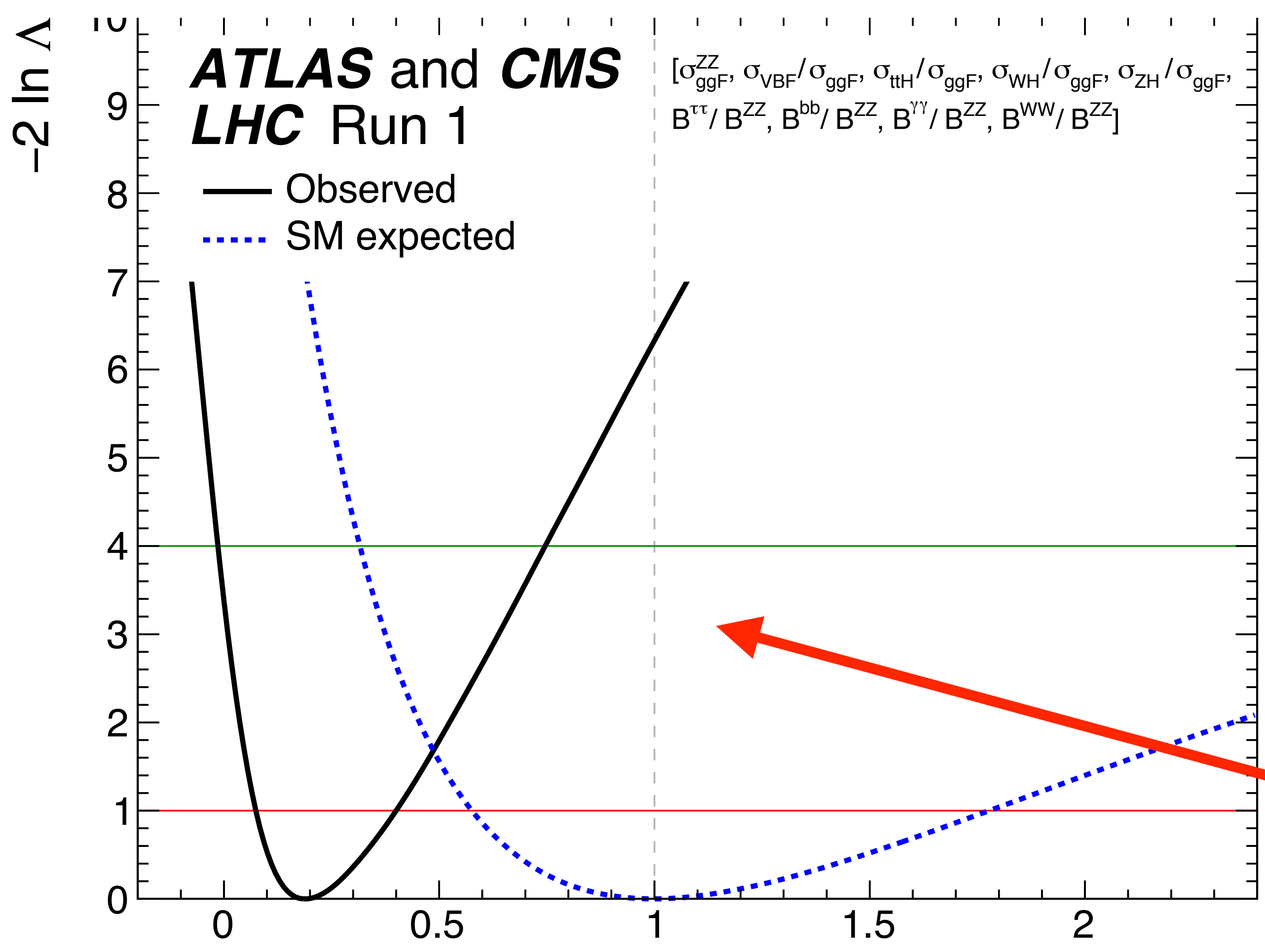


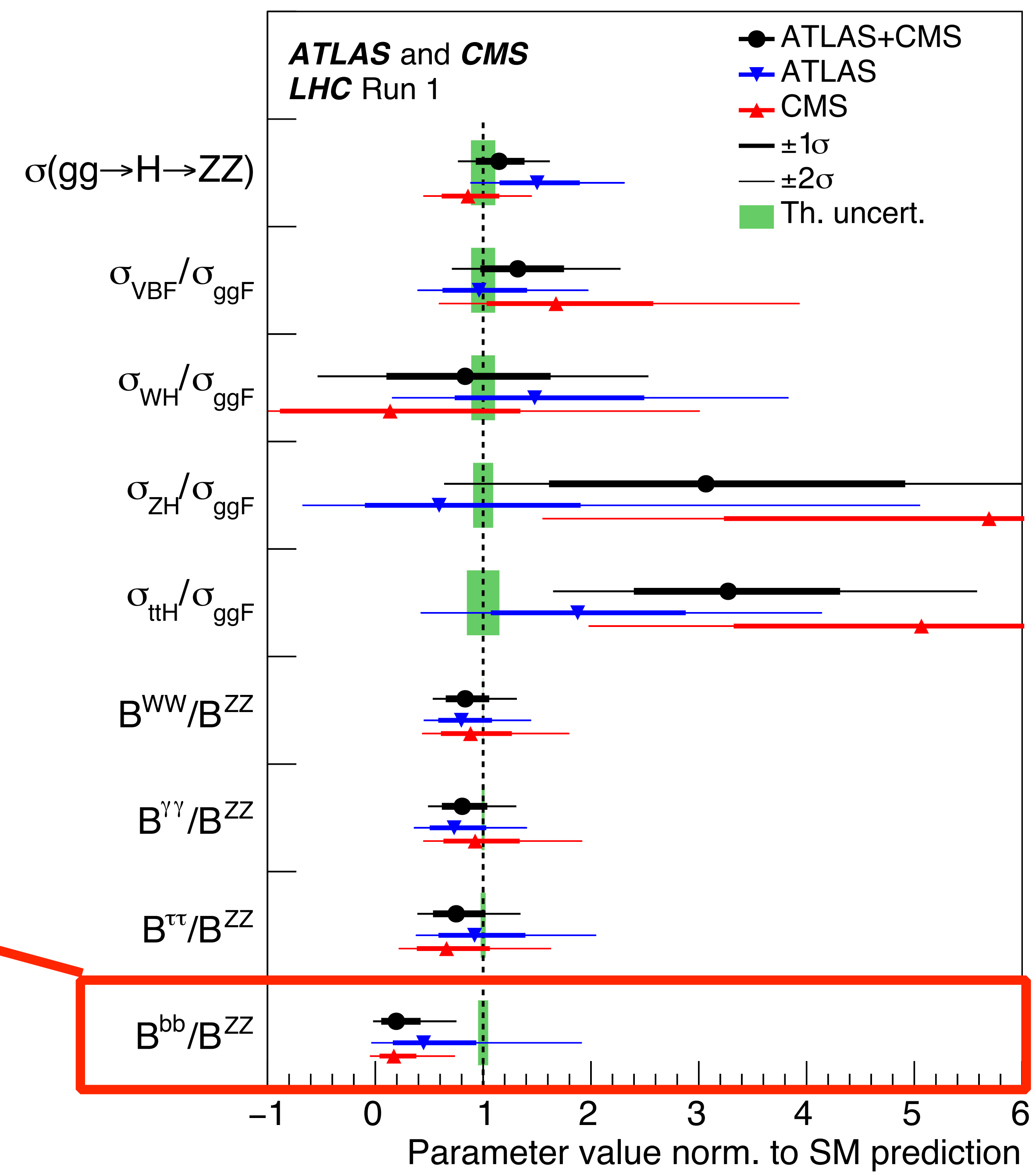
Signal strength ratios

- Largest disagreement in BR^{bb}/BR^{ZZ} (2.4σ)

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

- Though some care needed with the uncertainties on ratios ⇒ non-Gaussian behaviour

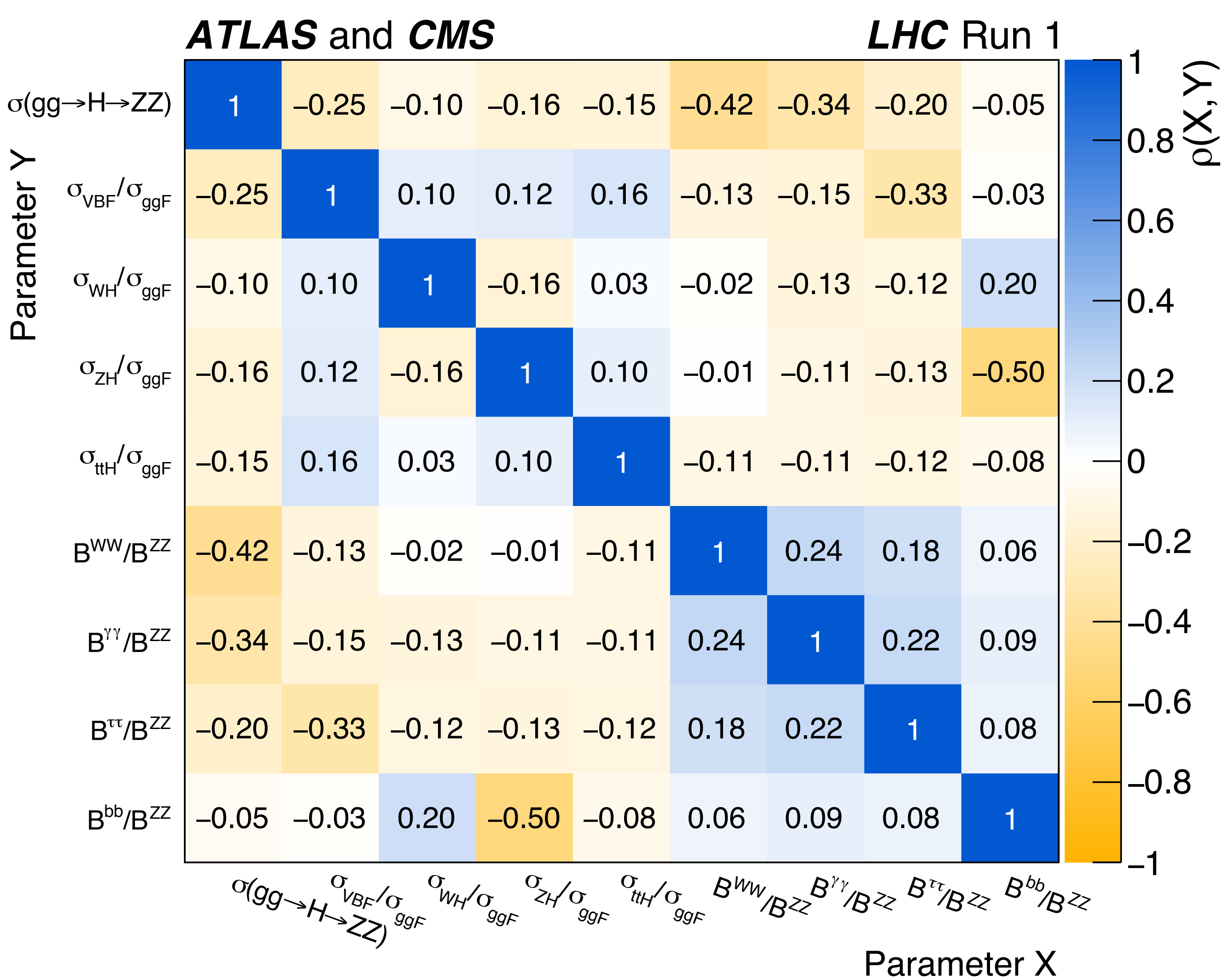


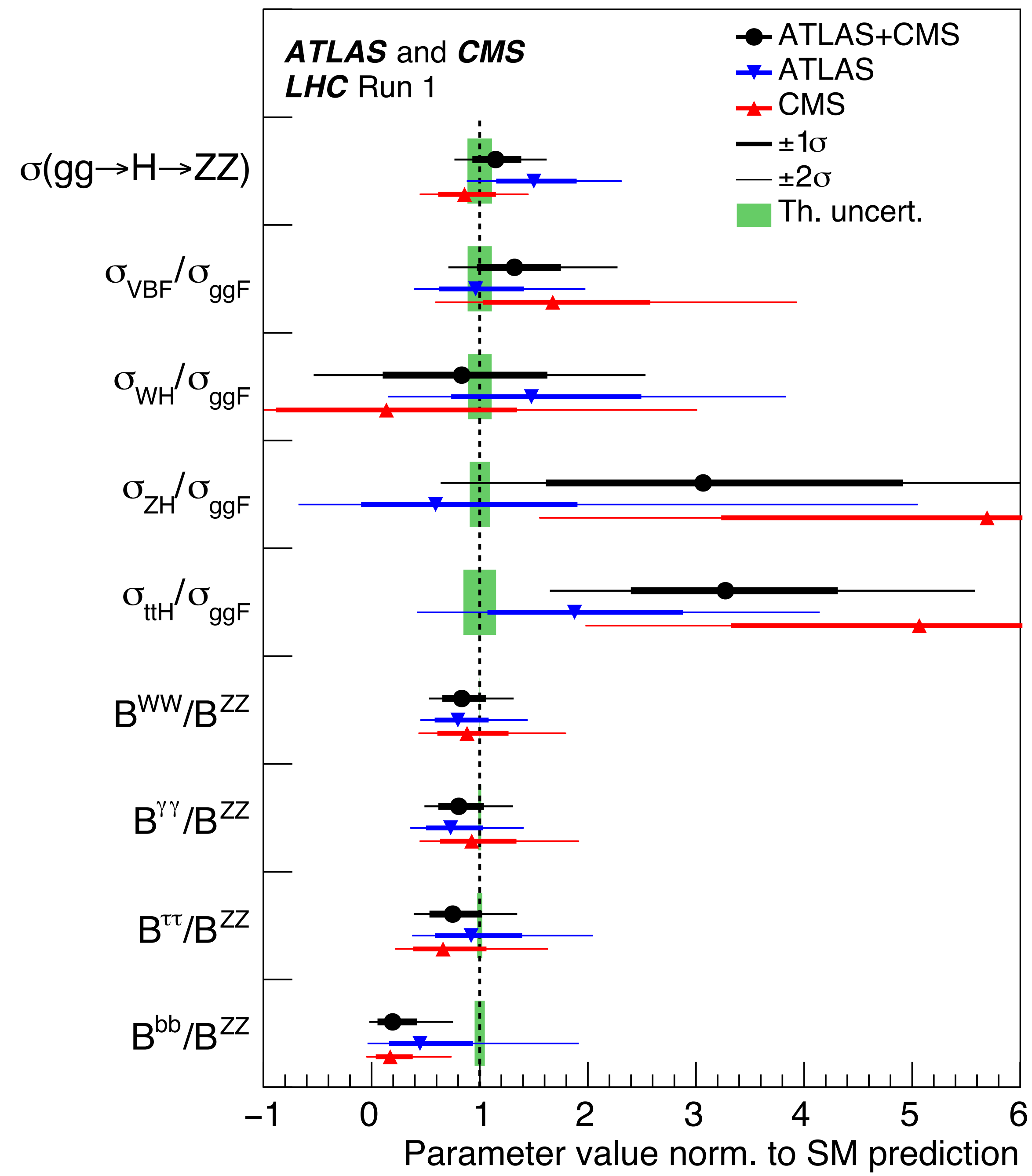


Signal strength ratios

- Correlation matrix also provided
- Non-zero correlations due to use of ratios which explicitly relate different processes

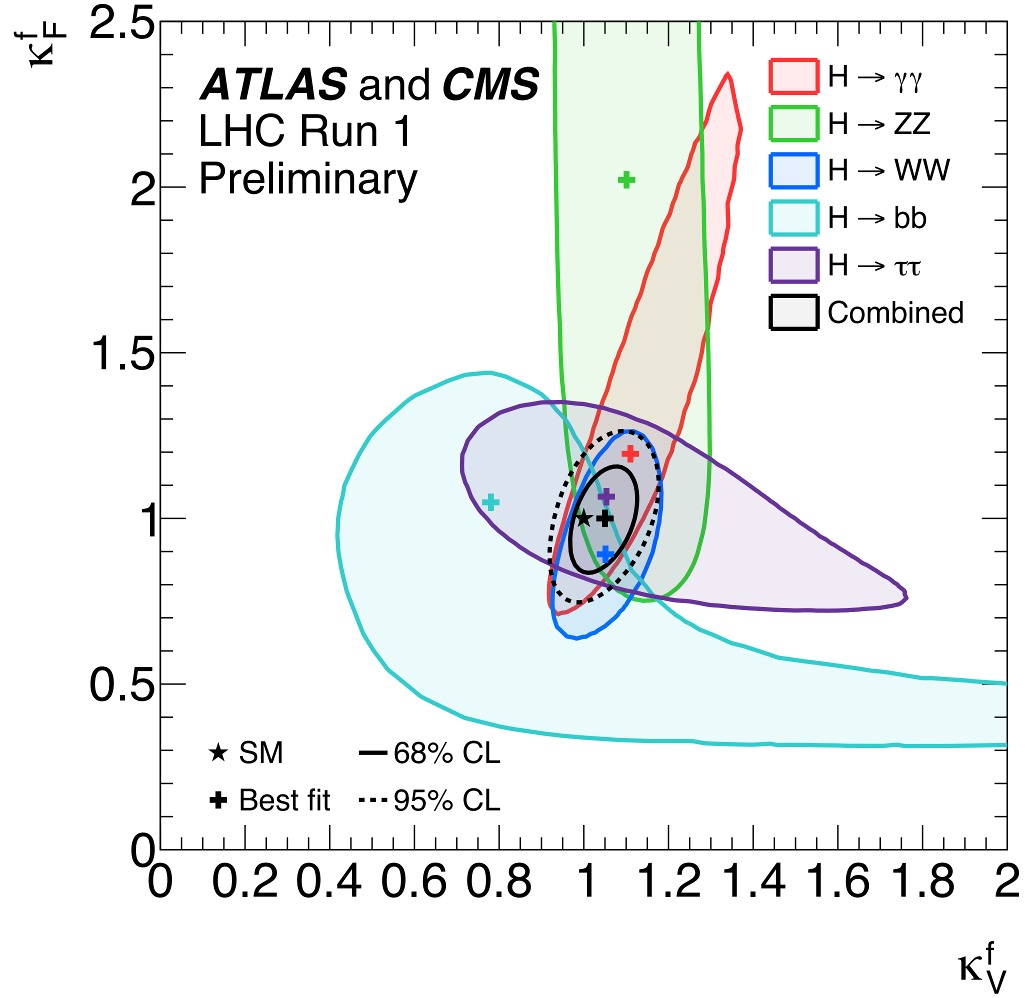
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

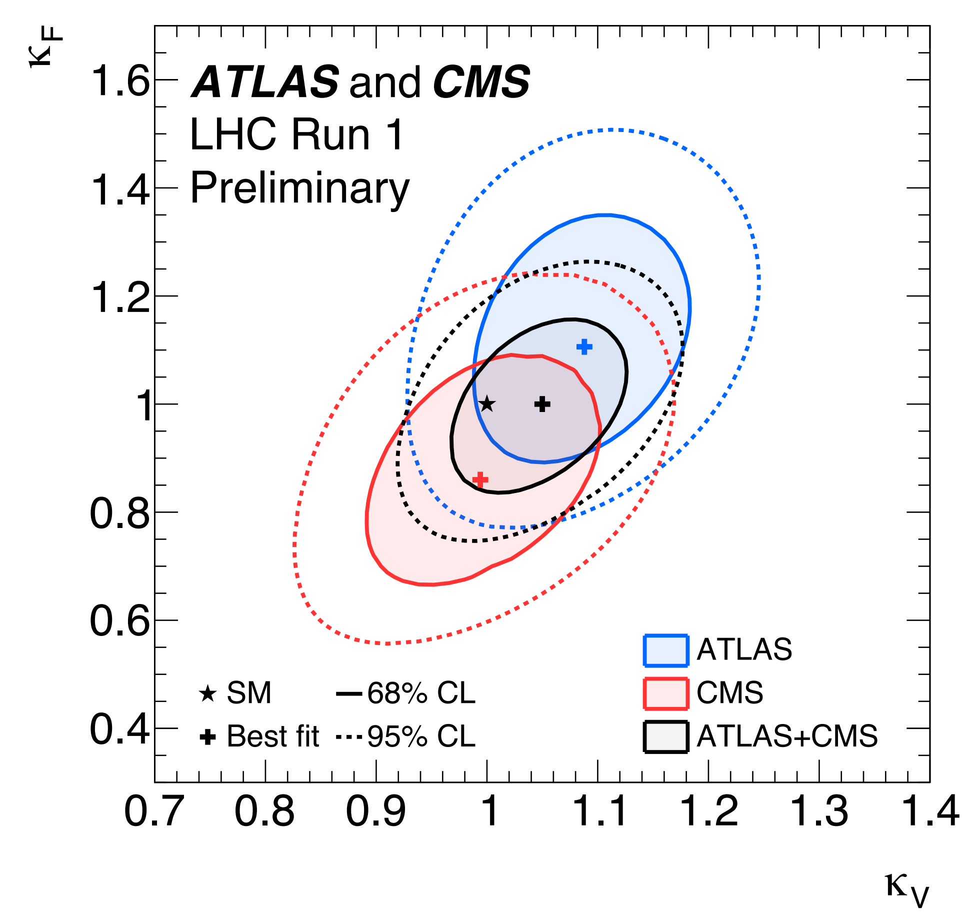




2D scans of κ_V, κ_F

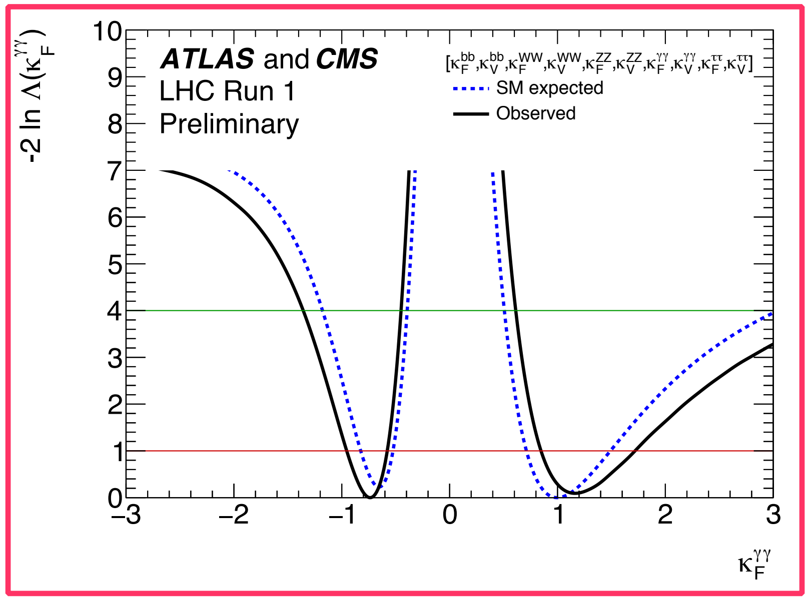
- Commonly-presented model in which
  - $\boldsymbol{\kappa_V} = \kappa_W = \kappa_Z$
  - $\boldsymbol{\kappa_F} = \kappa_t = \kappa_b = \kappa_\tau$
- Perform additional scans in a model with separate κ_V^f, κ_F^f per decay-mode
  - In contrast to previous CMS combinations this is a 10 parameter fit instead of 5 x 2 parameter fits
- Here the best-fit is restricted to quadrant where $\kappa_V>0$, $\kappa_F>0$
- All channels compatible with $\kappa_V=\kappa_F=1$

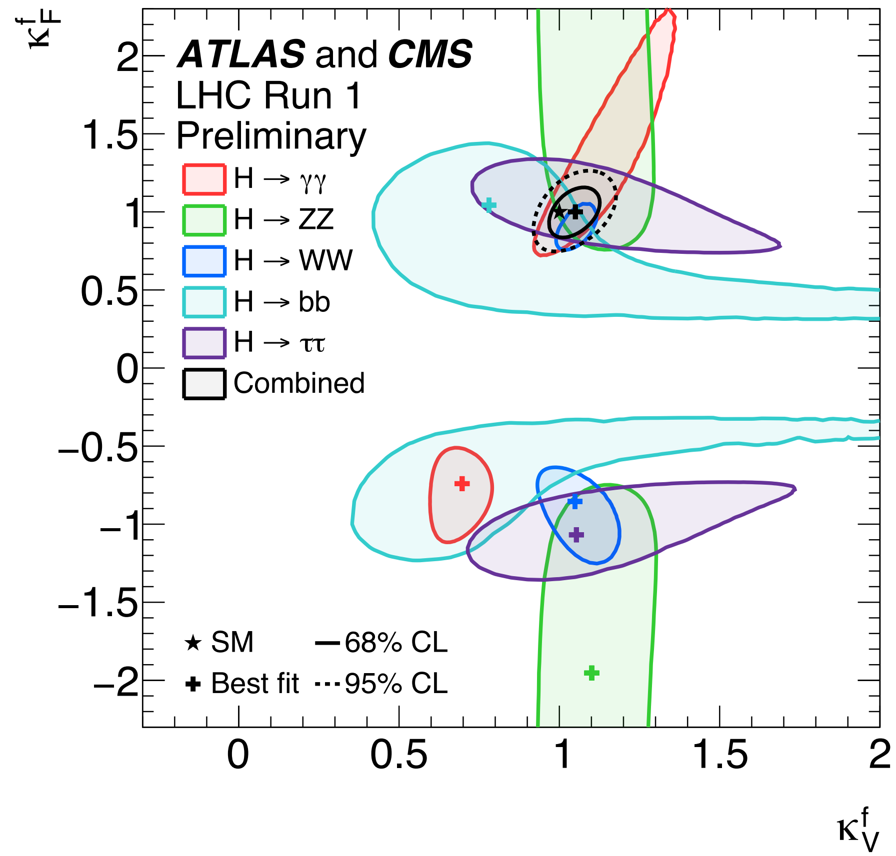


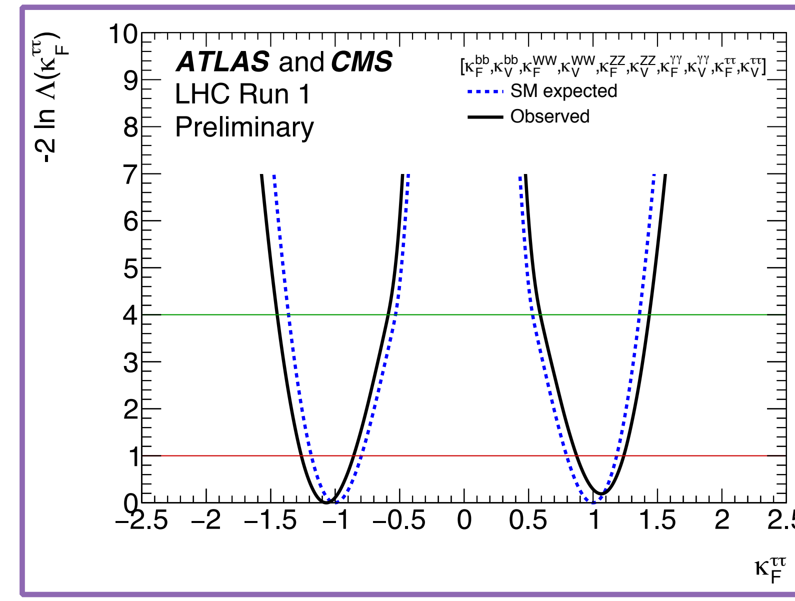


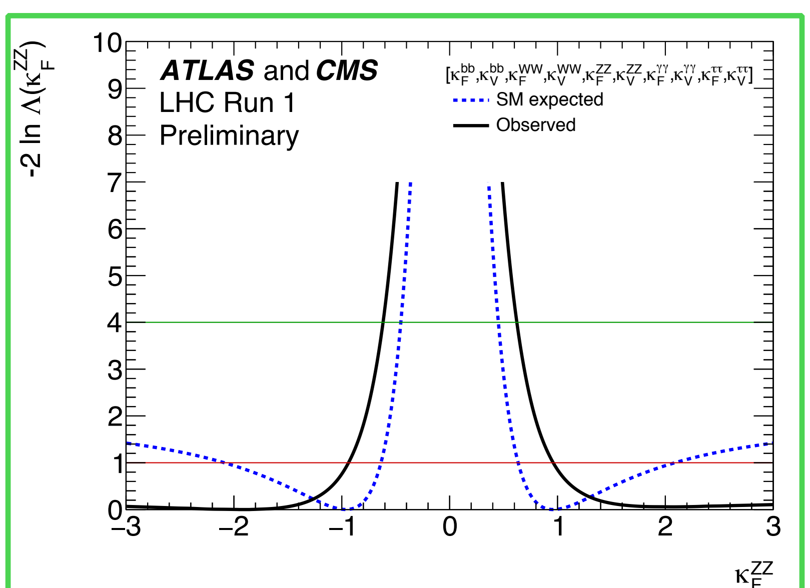
2D scans of κV, κF

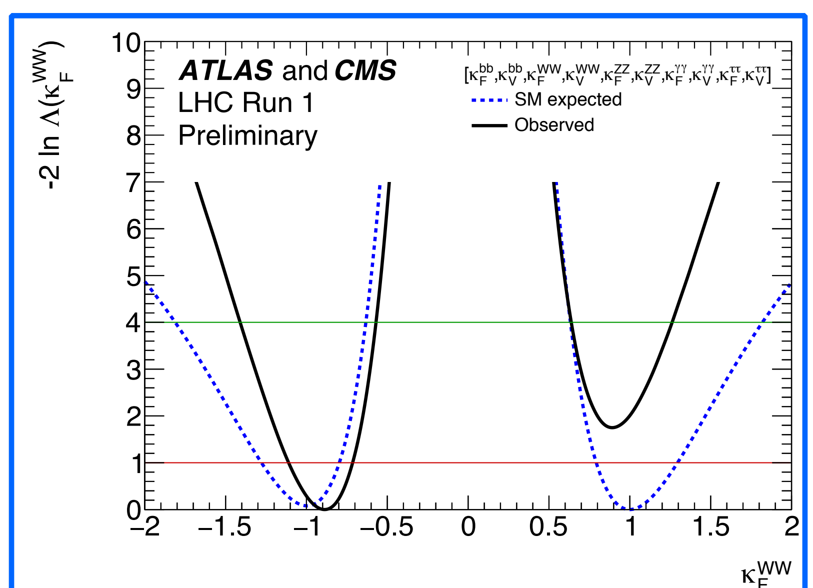
- Most channels nearly degenerate in relative sign of κV and κF

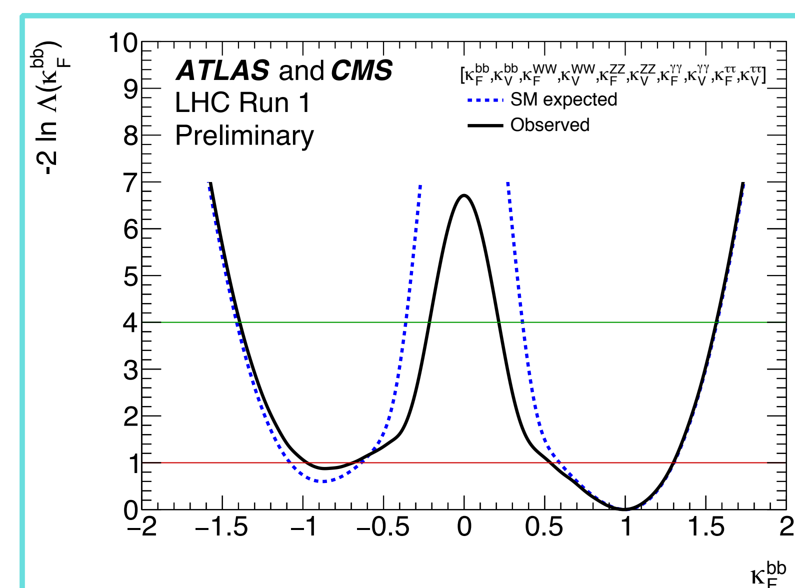






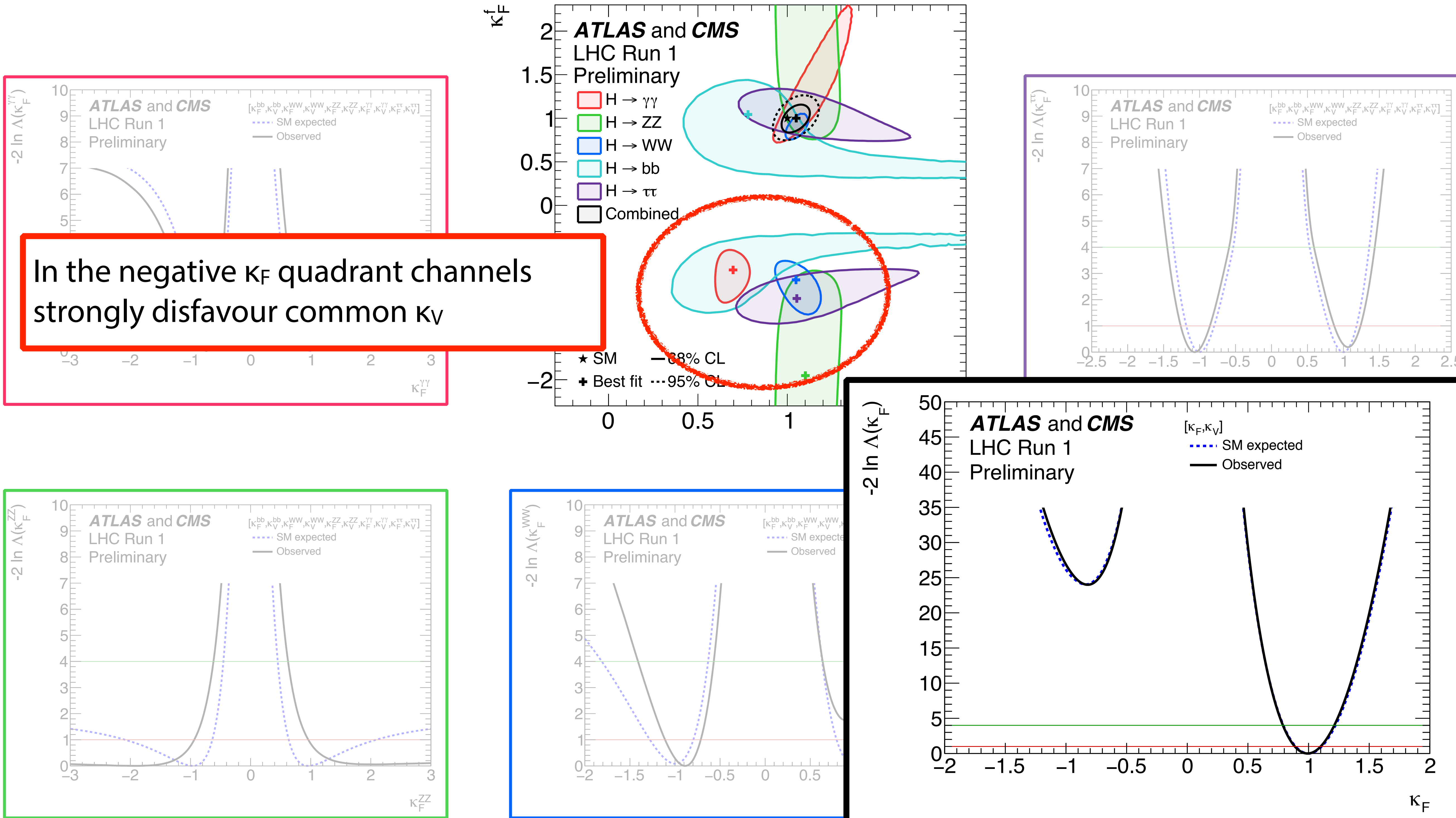






2D scans of κV, κF

- Most channels nearly degenerate in relative sign of κV and κF

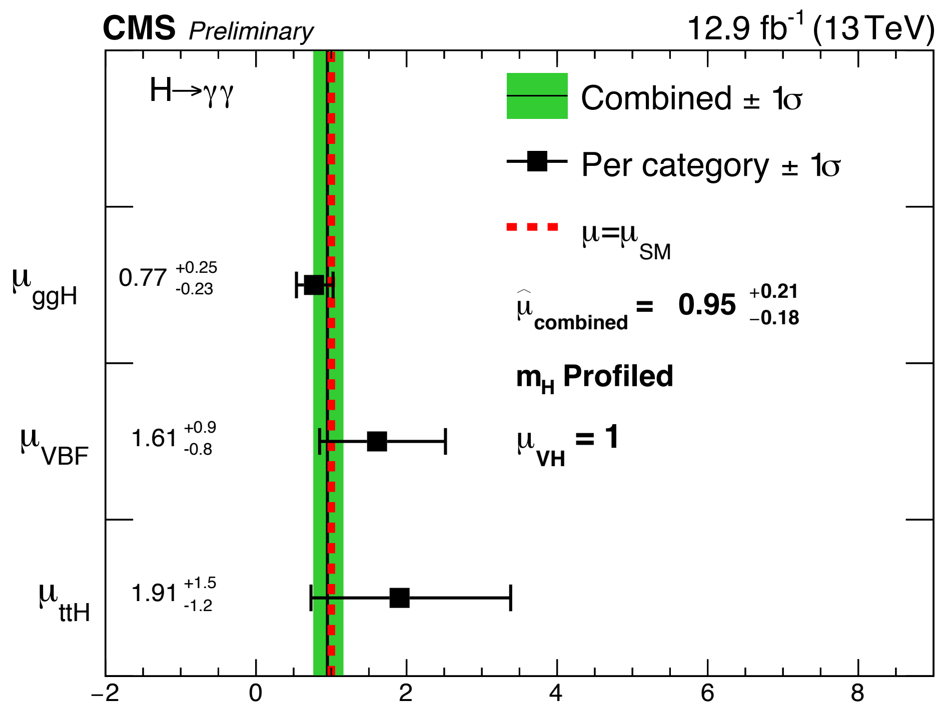


In the negative κF quadrant channels strongly disfavour common κV

Signal Processes - Summary

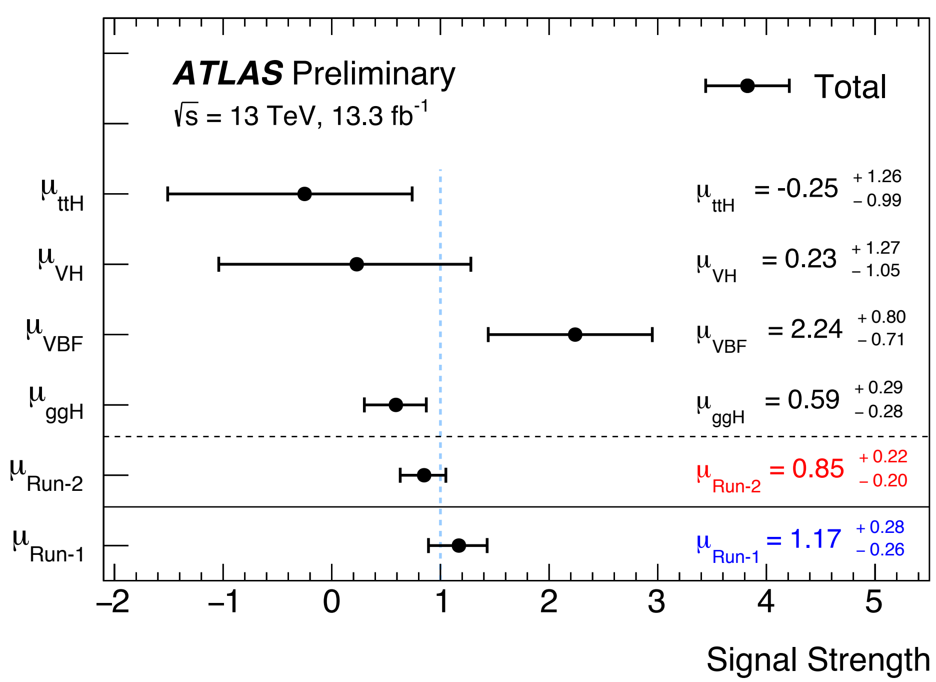
Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

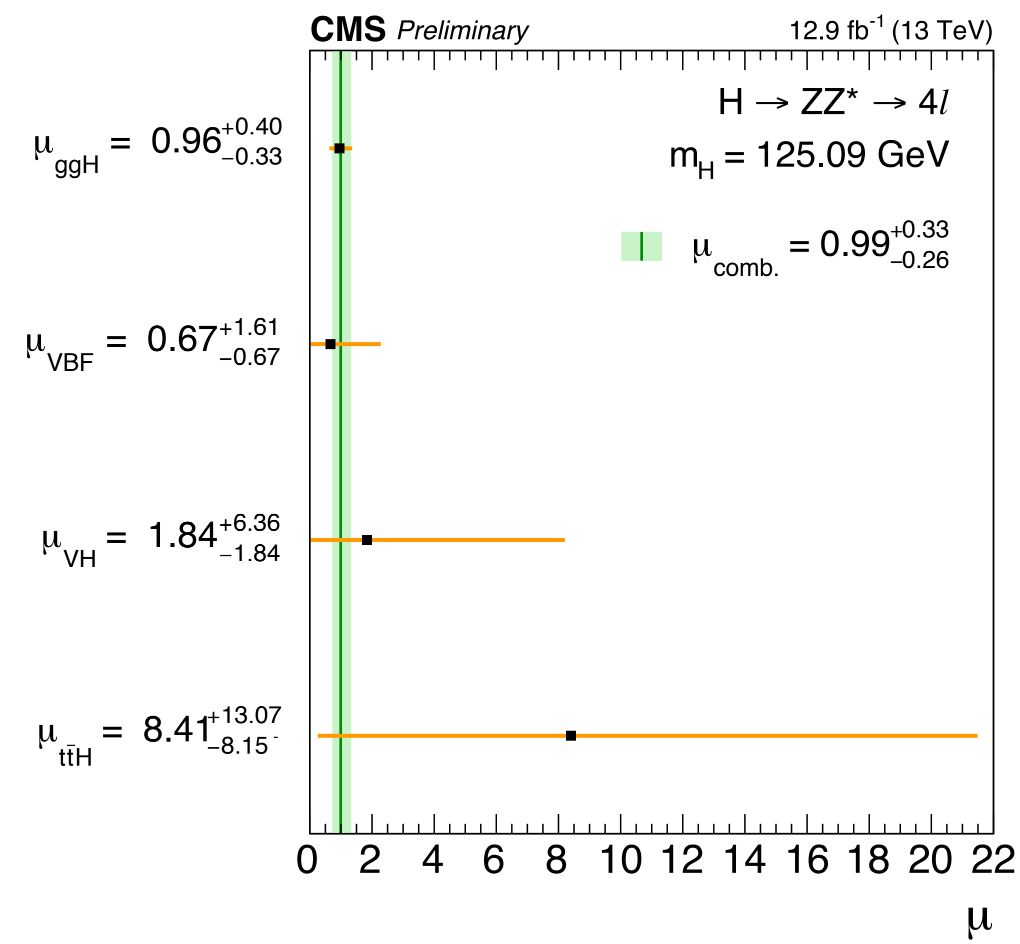
13 TeV signal strengths by production mode



CMS H→γγ

ATLAS H→γγ





CMS H→ZZ

ATLAS H→ZZ

$$\sigma_{\text{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \text{pb} \qquad \sigma_{\text{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \text{pb}$$

$$\sigma_{\text{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \text{pb} \qquad \sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \text{pb}$$

$$\sigma_{\text{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \text{pb} \qquad \sigma_{\text{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \text{pb} \tag{8}$$

Anomalous coupling approaches

- **CMS:**

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{HVV}} + \frac{\kappa_1^{\mathrm{HVV}} q_{\mathrm{V}_1}^2 + \kappa_2^{\mathrm{HVV}} q_{\mathrm{V}_2}^2}{\left(\Lambda_1^{\mathrm{HVV}}\right)^2}\right] m_{\mathrm{V}_1}^2 \epsilon_{\mathrm{V}_1}^* \epsilon_{\mathrm{V}_2}^* + a_2^{\mathrm{HVV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{HVV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

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

- Define cross section fractions:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

- **ATLAS:**

$$\begin{aligned}\mathcal{L}_0^V = \; & \Big\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\} X_0.\end{aligned}$$

- ATLAS coupling ratios can be related CMS cross sections:

$$f_{gi} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}, \; \phi_i = \arg\left(\frac{g_i}{g_1}\right).$$

$$r_{21}^2 = \frac{\sigma_{HVV}}{\sigma_{\mathrm{SM}}}\left(\frac{\tilde{k}_{HVV}}{k_{\mathrm{SM}}}\right)^2, \quad \text{and} \quad r_{41}^2 = \frac{\sigma_{AVV}}{\sigma_{\mathrm{SM}}}\left(\frac{\tilde{k}_{AVV}}{k_{\mathrm{SM}}}\right)^2 \tan^2\alpha.$$

$$f_{g_i} = \frac{r_{i1}^2}{1 + r_{i1}^2}; \quad (i = 2, 4),$$

Fiducial cross sections

Requirements for the $\mathrm{H} \rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_{T}	$p_{\mathrm{T}} > 20$ GeV
Next-to-leading lepton p_{T}	$p_{\mathrm{T}} > 10$ GeV
Additional electrons (muons) p_{T}	$p_{\mathrm{T}} > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
Sum of scalar p_{T} of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 \cdot p_{\mathrm{T}}$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\mathrm{GeV} < m_{\mathrm{Z}_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12\,\mathrm{GeV} < m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$

CMS H→ZZ fiducial definition

Lepton definition	
Muons: $p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$	Electrons: $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading leptons $p_{\mathrm{T}} > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV

ATLAS H→ZZ fiducial definition

Fiducial cross sections

- $\frac{p_{T,gen}^{\gamma_{1,(2)}}}{m_{\gamma\gamma}} > \frac{1}{3}(\frac{1}{4})$ for the generator-level transverse momentum of the leading (subleading) photon,
- $|\eta_{gen}^{\gamma}| < 2.5$ for the generator-level pseudorapidities of both photon
- the generator-level isolation of the photons, calculated as the sum of the transverse momenta of all stable particles inside a cone of aperture $R = 0.3$ around the photon, is required to be smaller than 10 GeV.

CMS H→γγ fiducial definition

	diphoton baseline	VBF enhanced	single lepton
Photons	$\vert\eta\vert < 1.37$ or $1.52 < \vert\eta\vert < 2.37$ $p_{\mathrm{T}}^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_{\mathrm{T}}^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\vert y\vert < 4.4$ $m_{jj} > 400\,\mathrm{GeV}$, $\vert\Delta y_{jj}\vert > 2.8$ $\vert\Delta\phi_{\gamma\gamma,jj}\vert > 2.6$	- - -
Leptons	-	-	$p_{\mathrm{T}} > 15\,\mathrm{GeV}$ $\vert\eta\vert < 2.47$

ATLAS H→γγ fiducial definition