Higgs results from the combination at ATLAS and at CMS.

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on behalf of the ATLAS and CMS collaborations

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Outline.

Talk focuses on the mass, cross sections and couplings measurements from the ATLAS Run-2 combination and the ATLAS+CMS Run-I combination

- Introduction
- Higgs boson mass combination
- Higgs boson signal strength, cross sections and couplings combination
- Conclusions and outlook

LHC and detector performance.

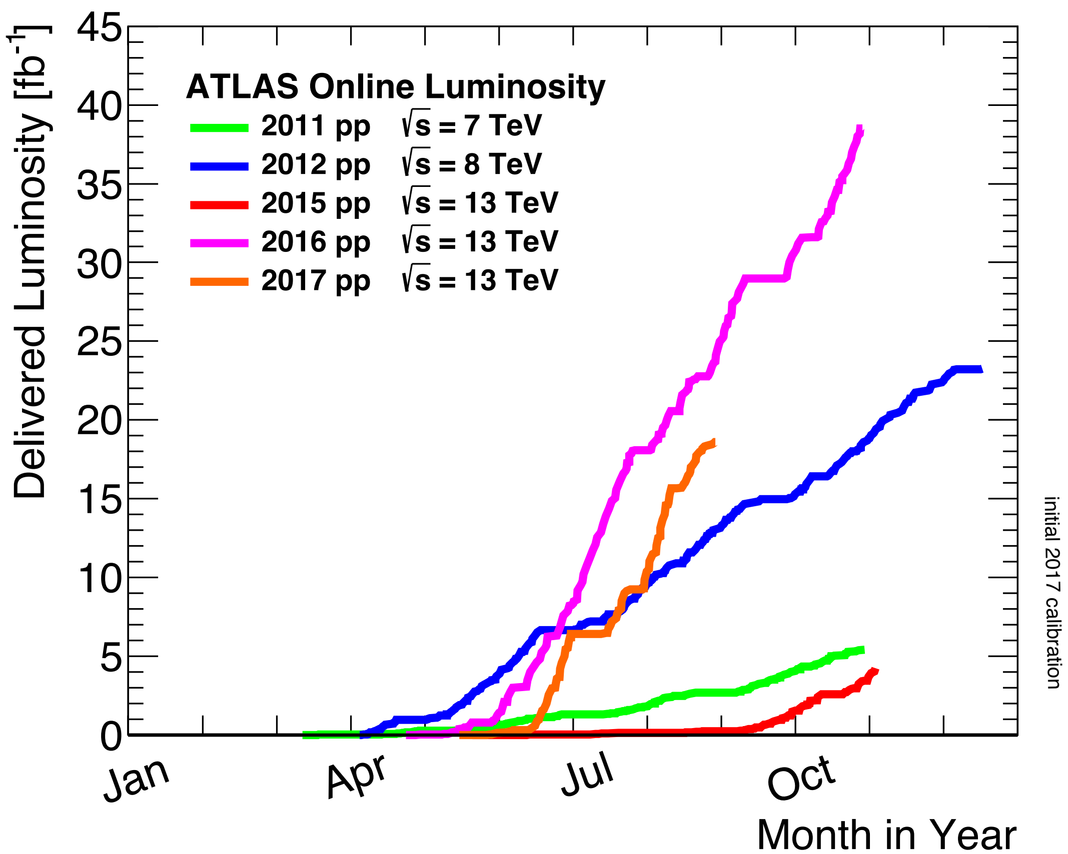
LHC performed very well during Run-1 and Run-2

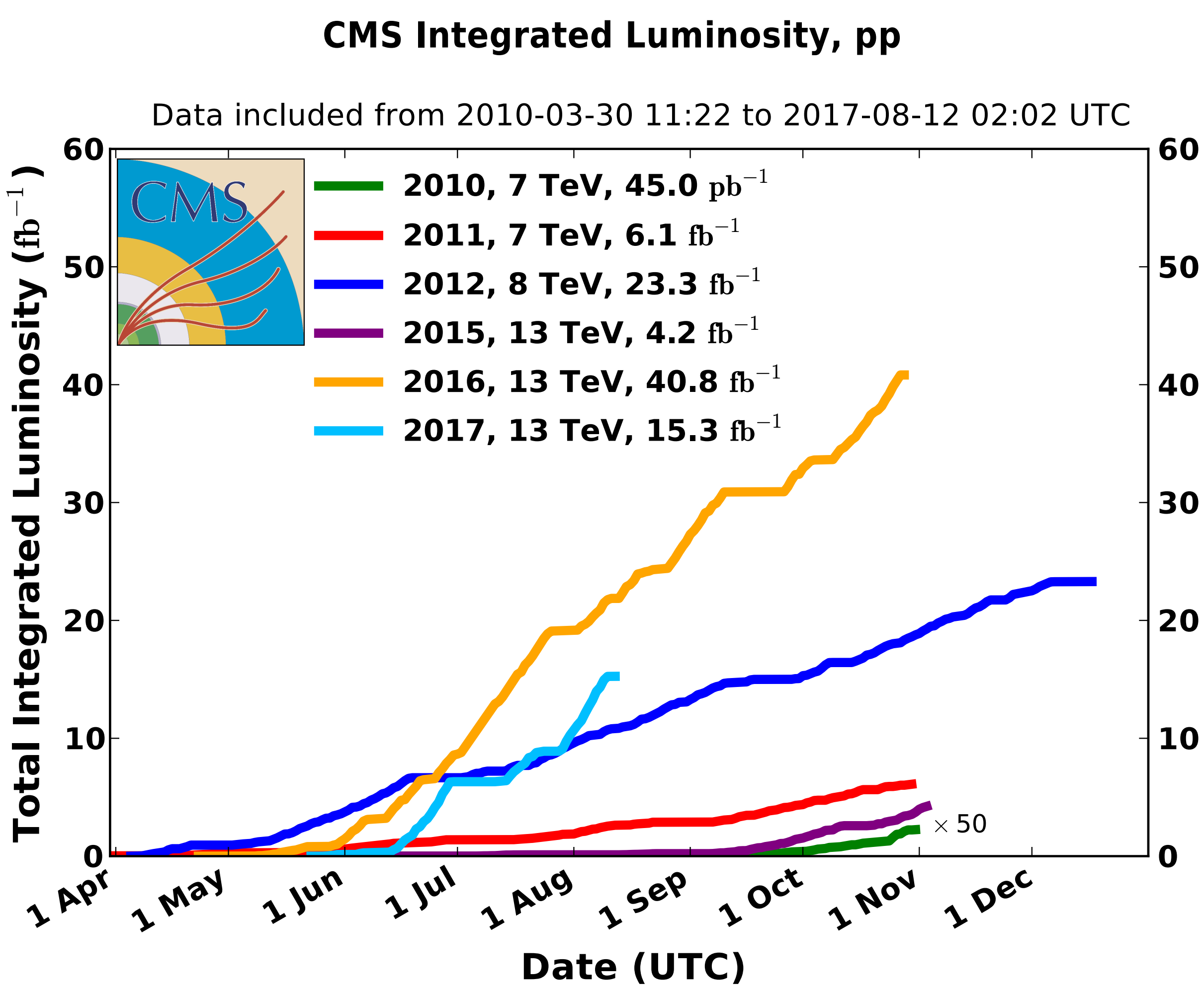
Both **ATLAS** and **CMS** experiments achieved very ***high data taking efficiencies***

~90% of data ready for physics

Data for analysis:

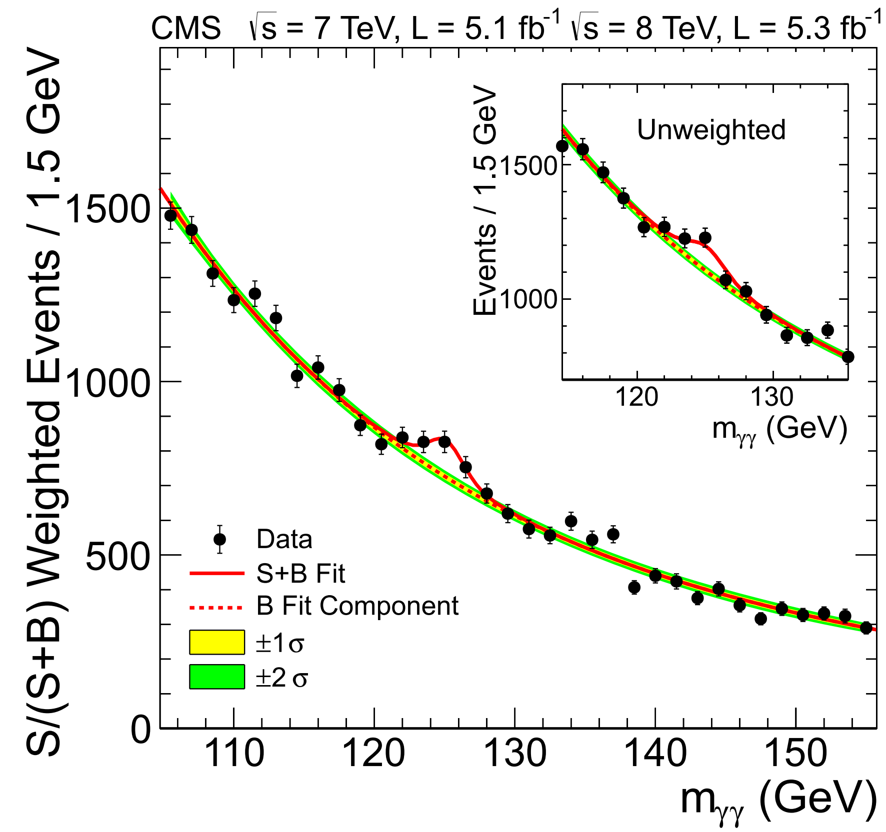
- 2011: **√s=7 TeV: ~5 fb-1**
- 2012: **√s=8 TeV: ~20 fb-1**
- 2015 & 2016: **√s=13 TeV: ~36 fb-1**

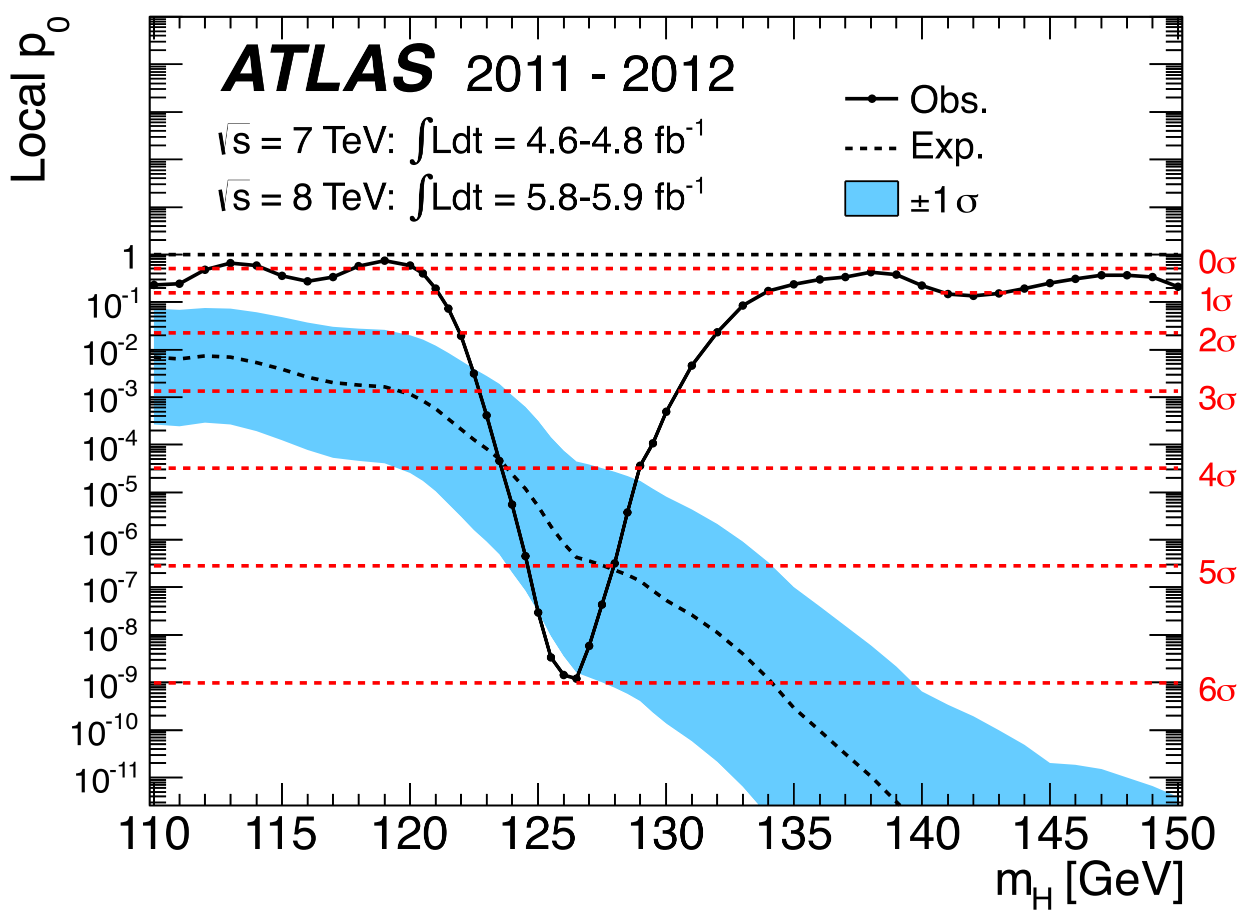


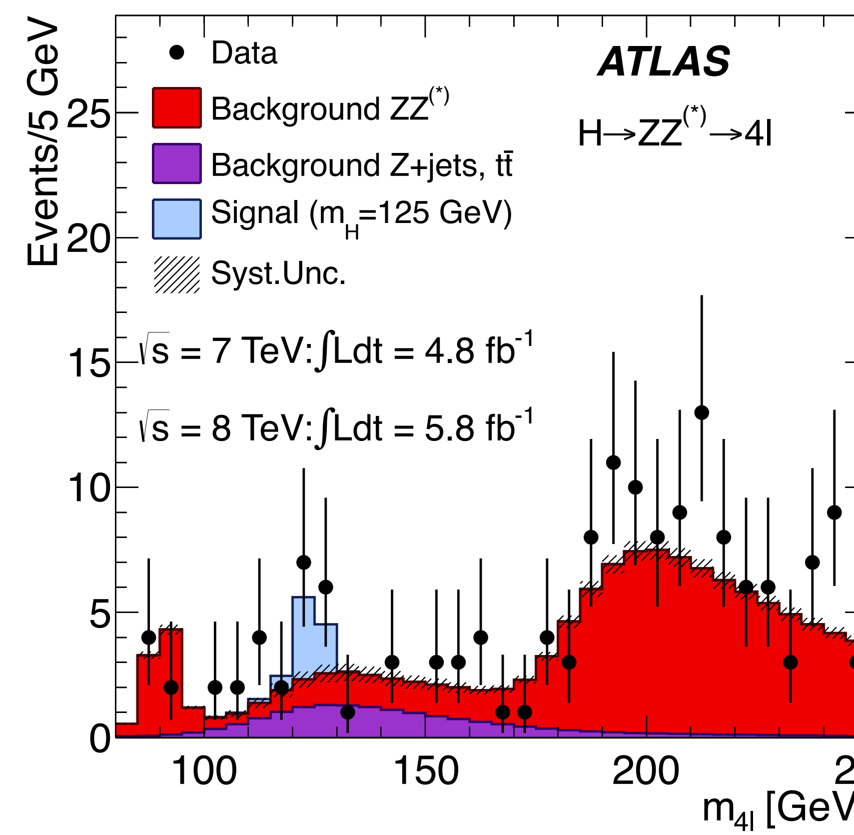


Higgs Discovery: July 2012.

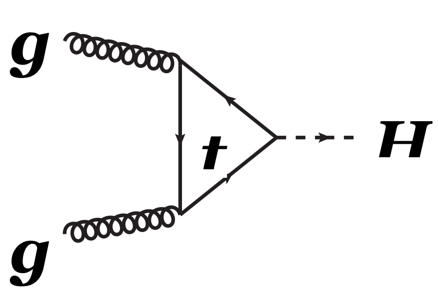
- Crowning achievement of Run 1
- To determine whether the discovered boson is ***fully compatible*** with the Standard Model Higgs, precise property measurements are required
    - Large effort towards studying its properties and searching for NP



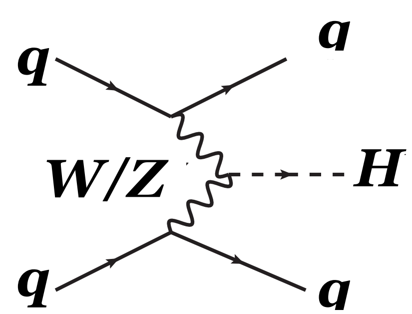




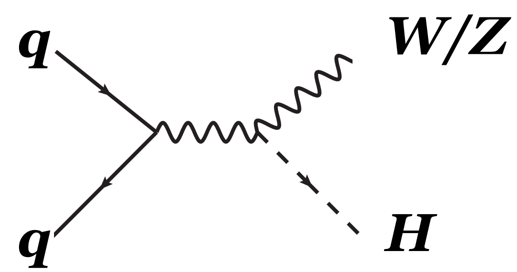
Higgs boson production & decay.



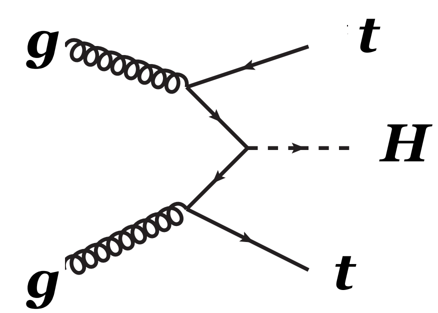
ggF: ~ 87%



VBF: ~ 7%



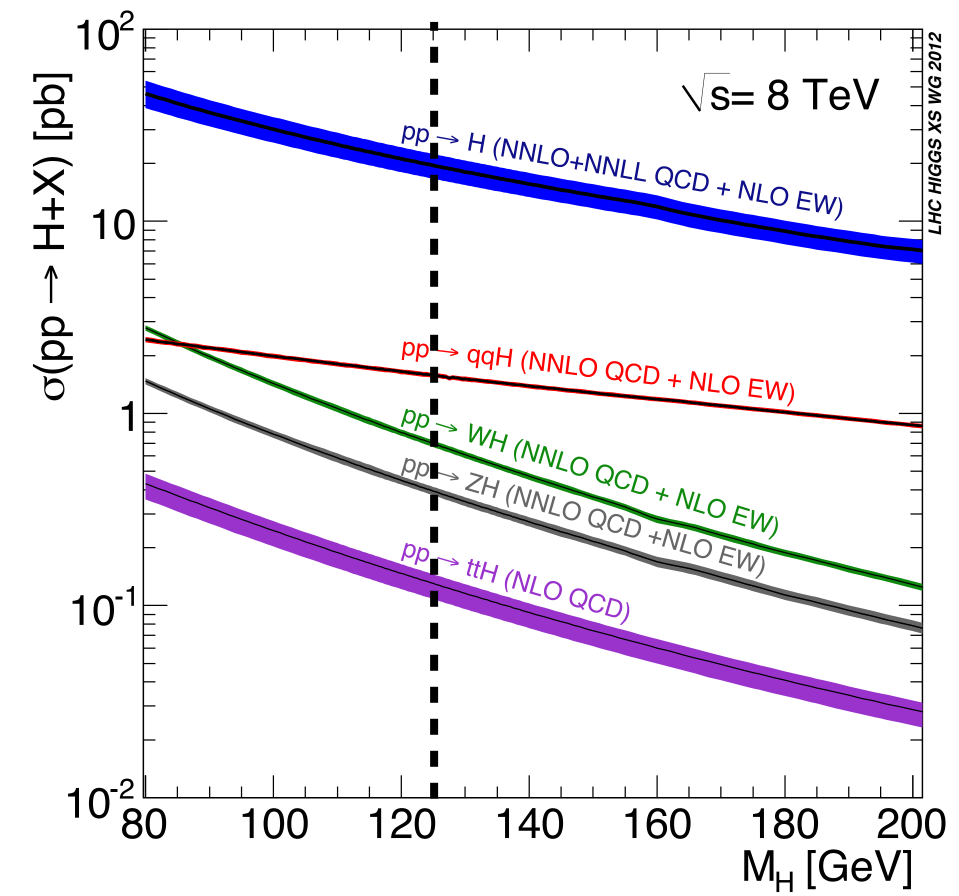
VH ≡ *WH* or *ZH*: ~4%

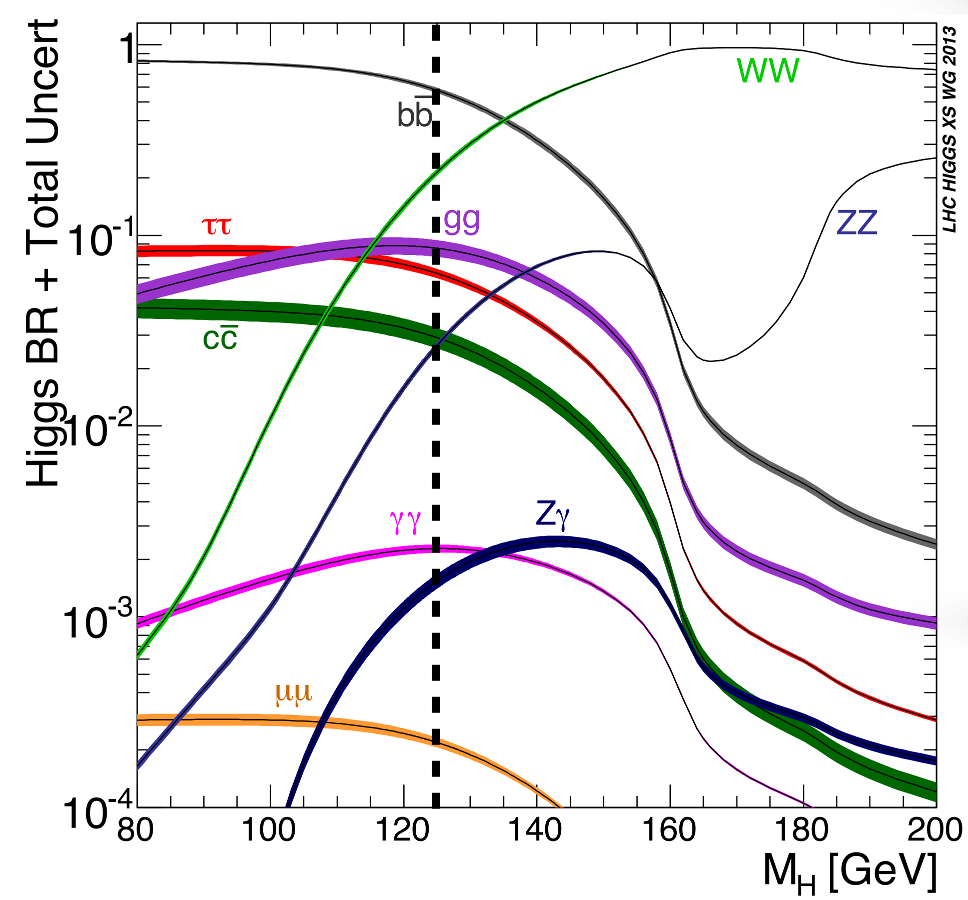


ttH: ~ 2%

bbH and gg→ZH not targeted by specific analysis categories

implemented in the fit model





No dedicated analyses for *H→cc* or *H→gg* (S/B too low)

Before making a ***statemen***t on the SM nature of the Higgs, we first need $\boldsymbol{m_H}$

Once the mass is determined then ***all other properties*** of the Higgs boson are ***set*** and ***calculable***

Combination: statistical methodology.

Combine measurements and fit for parameters of interest (POI) using a profile likelihood ratio:

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

- $\vec{\alpha}$: a vector of POI
- $\vec{\theta}$: nuisance parameters (NP), corresponding to systematic uncertainties
- $\hat{\vec{\alpha}}$, $\hat{\vec{\theta}}$ are the values of the POI and NP that maximize L
- $\hat{\hat{\vec{\theta}}}(\vec{\alpha})$ is the value of the NP that maximize L for a given $\vec{\alpha}$
- Assume asymptotic approximation to be valid: $f(\Lambda) = \chi^2(ndof)$

Theory uncertainties assumed ***uncorrelated between production modes*** (***except for VBF+VH***) and ***correlated*** between the two experiments

QCD, PDF, UEPS, B^f

Experimental uncertainties are ***correlated between analysis channels*** but ***uncorrelated*** *between the two experiments*, ***except for part of the luminosity***

Higgs boson mass

Mass combination.

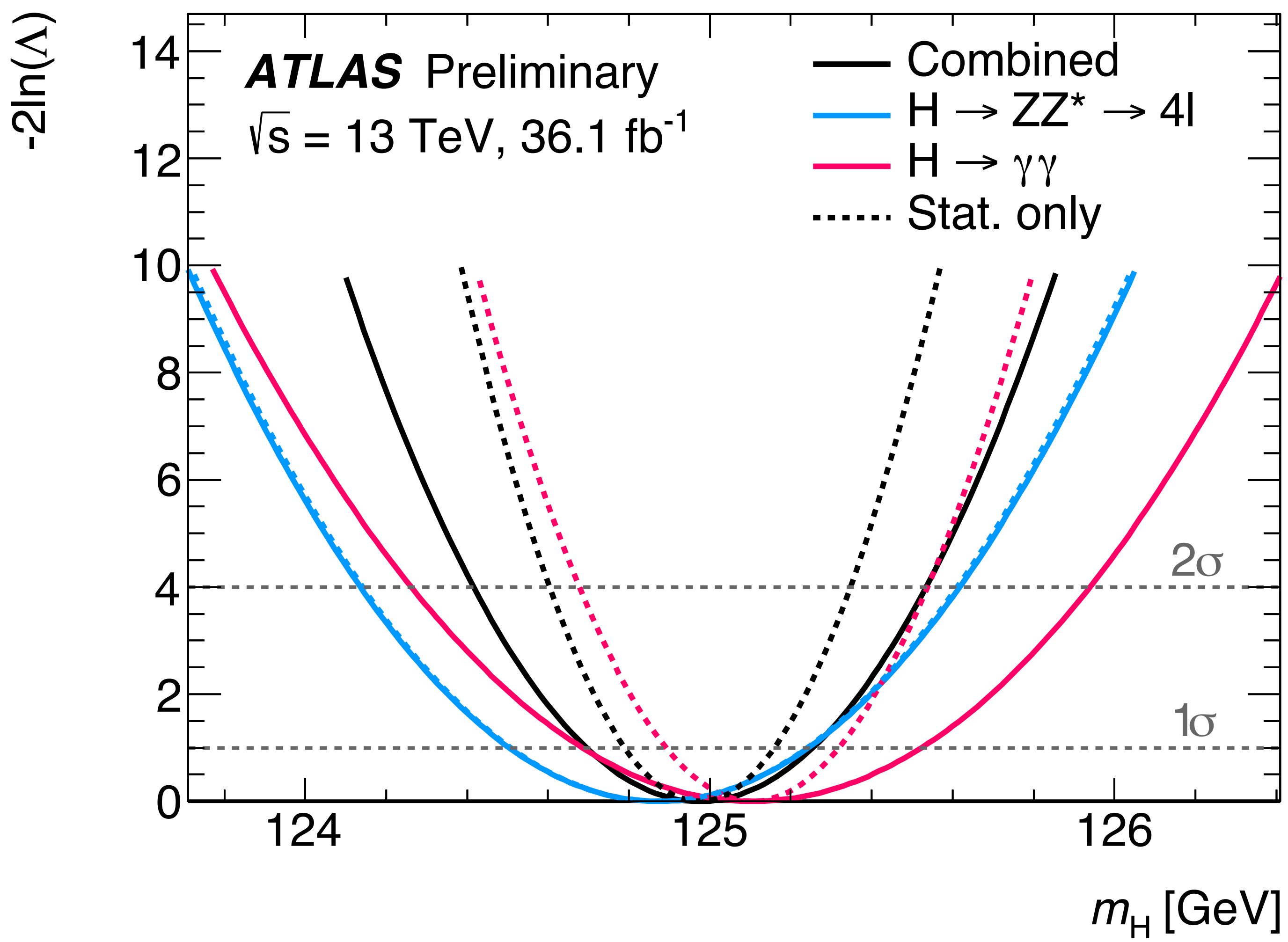
- Combining measurements in ***H→γγ*** and ***H→4l*** *decay* channels

  channels have the best mass resolution

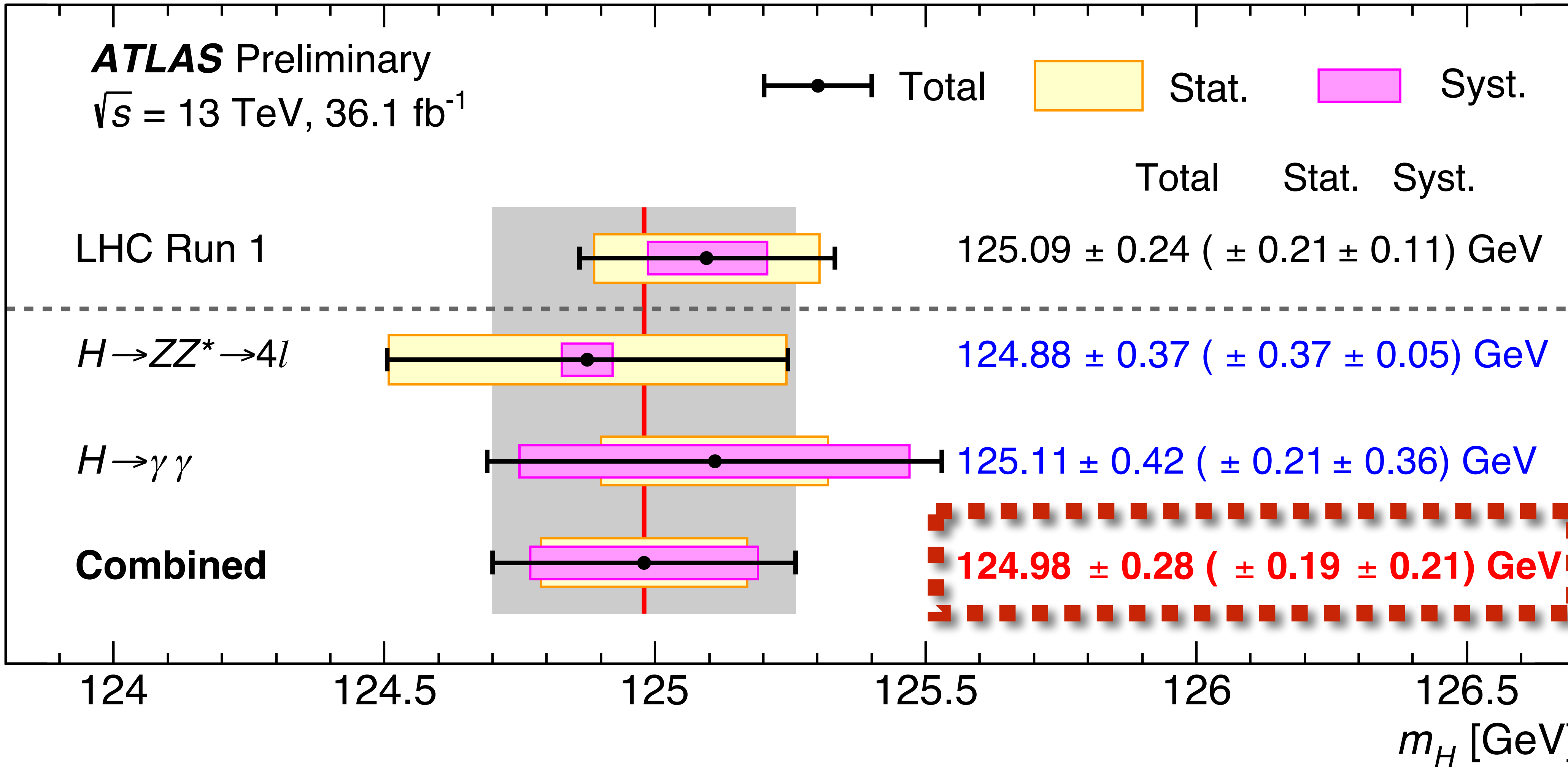
- ***Neglect interference*** between ***gg→γγ*** and ***gg→H→γγ*** :

  $\Delta m_{\gamma\gamma} = -35 \pm 9$ MeV (ATLAS)

- Use profile likelihood ratio



13 TeV ATLAS mass combination.

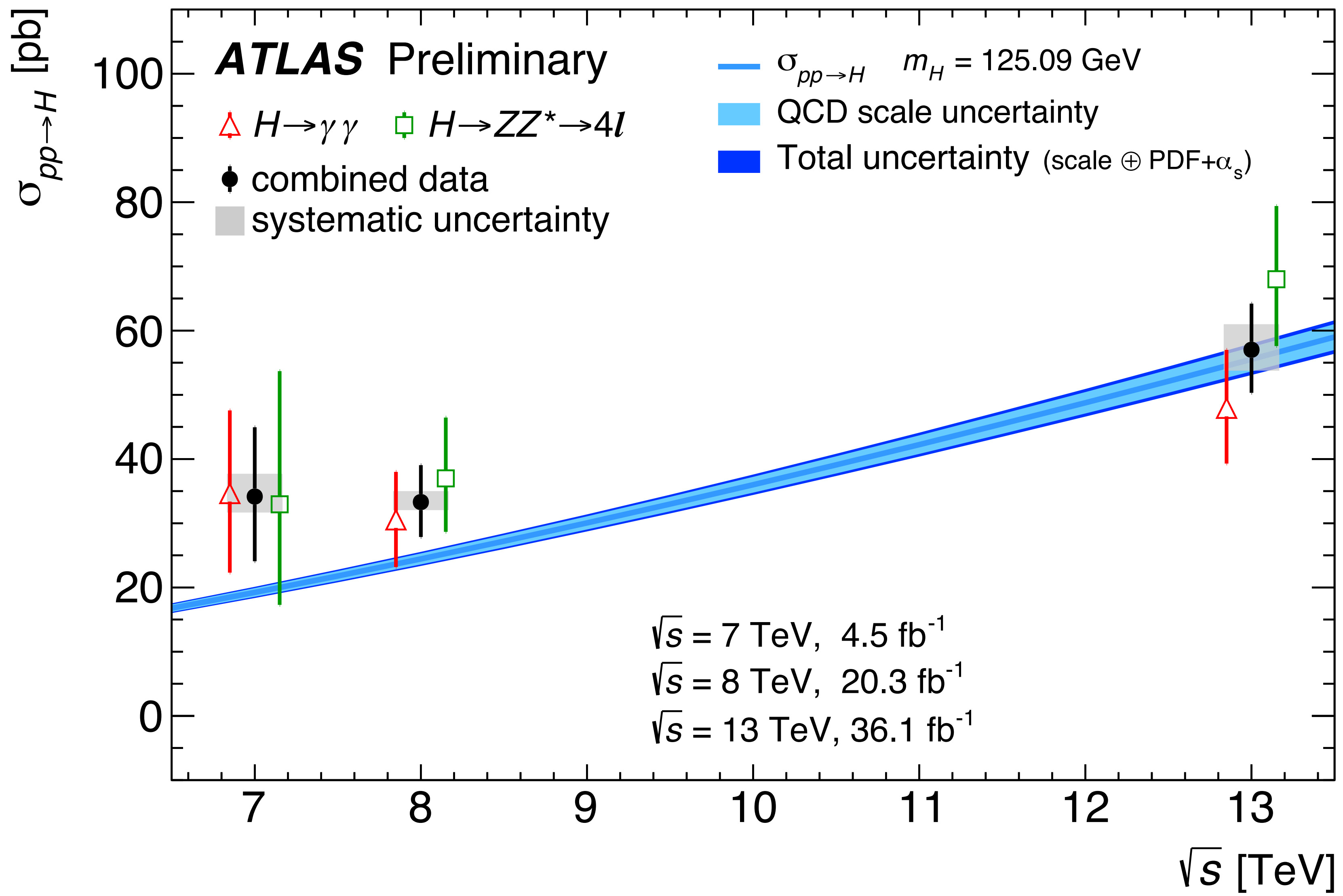


Source	Systematic uncertainty on m_H [MeV]
LAr cell non-linearity	90
LAr layer calibration	90
Non-ID material	60
ID material	50
Lateral shower shape	50
$Z \to ee$ calibration	30
Muon momentum scale	20
Conversion reconstruction	20

ATLAS combined mass in ***excellent agreement with the LHC Run-1 average***

Higgs boson cross sections, signal strengths and couplings

$H\to\gamma\gamma + H\to 4l$ total cross section.



Total cross section **based on inclusive yields in each decay channel**

- Yields extracted via a ***fit to the inclusive mass distributions*** ($\boldsymbol{m_{\gamma\gamma}}$ and $\boldsymbol{m_{4l}}$)
- Corrections for: detector effects, fiducial acceptances, BR

Individual channel compatibility: ***p-value = 29%***

Compatibility with ***SM***: ***p-value = 84%***

Production and decay combination inputs.

To increase sensitivity most analyses ***split datasets into categories***

- Categories have different S/B and background uncertainties
- Many categories provide ***sensitivity to different production modes***

Categories receive contributions from different productions and decay processes and encode information about different couplings

Run-1 ATLAS+CMS / *13 TeV ATLAS*	ggF	VBF	VH	ttH
$H\to\gamma\gamma$	✓ ✓	✓ ✓	✓ ✓	✓ ✓
$H\to ZZ^*\to 4l$	✓ ✓	✓ ✓	✓ ✓	✓ ✓
$H\to WW\to 2l2\nu$	✓ ✗	✓ ✗	✓ ✗	✓ ✗
$H\to\tau\tau$	✓ ✗	✓ ✗	✓ ✗	✓ ✗
$H\to bb$	✗ ✗	✗ ✗	✓ ✗	✓ ✗
$H\to\mu\mu$	✓ ✗	✓ ✗	✗ ✗	✗ ✗

S/B too low in ***gg→H→bb***

ATLAS+CMS Run-1

- VBF $H\to bb$ (CMS) not included
- ***H→μμ*** N_{sig} too low for ***VH ttH***

  $H\to\mu\mu$ used only in one model

ATLAS Run-2

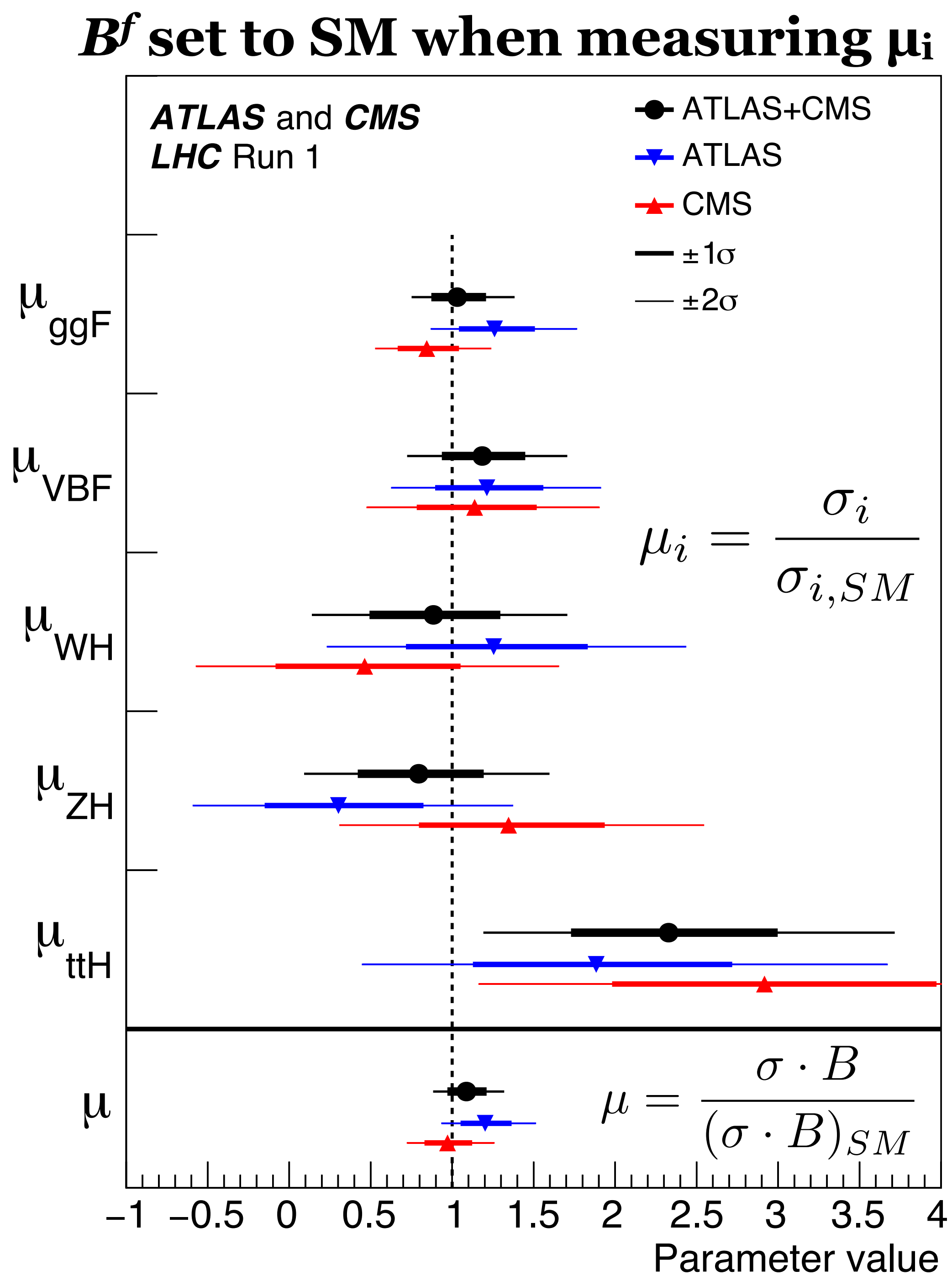
- *considering only* ***H→γγ*** *and* ***H→4l***

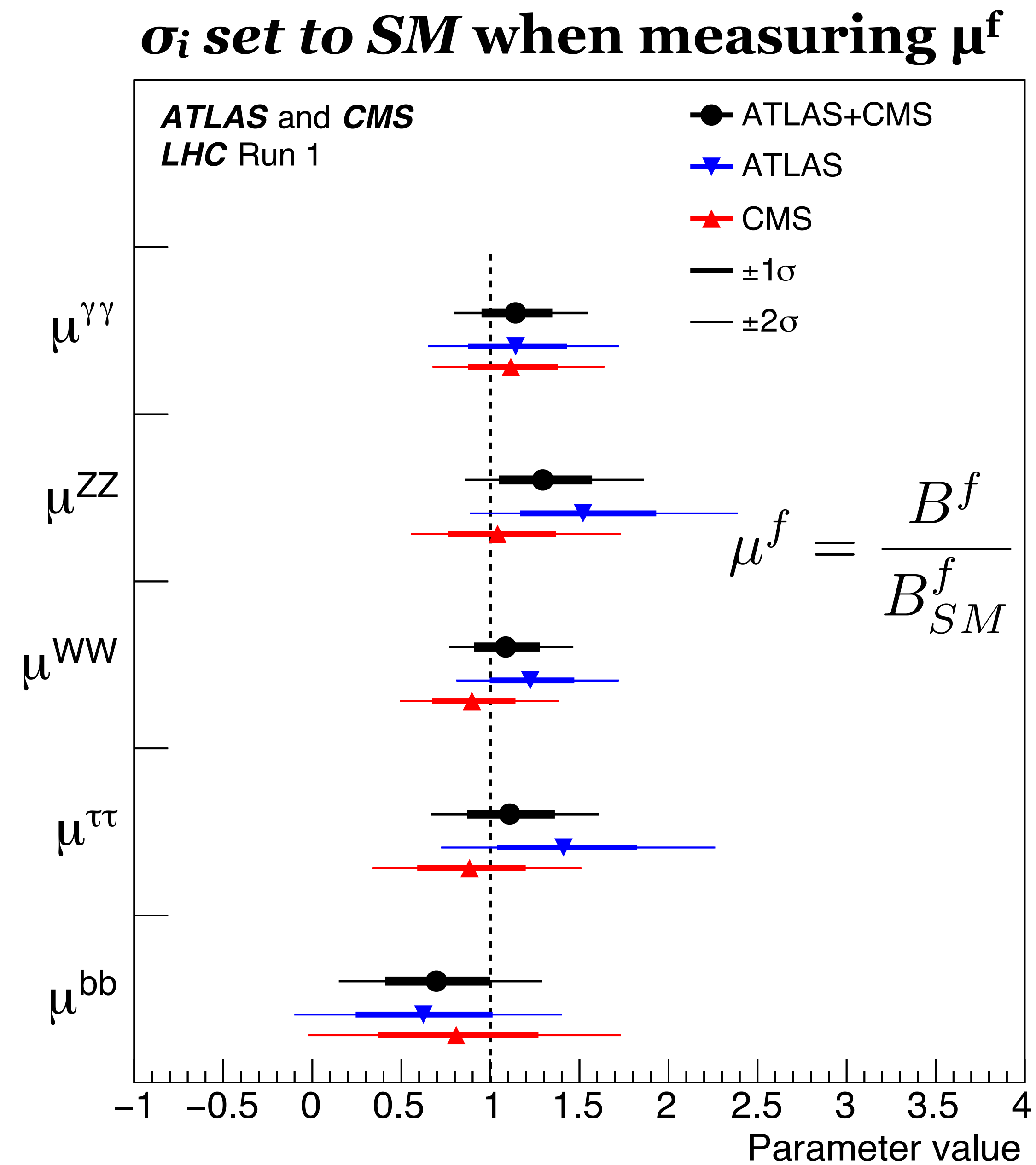
Assumptions:

- ***Single Higgs boson, CP-even, SM kinematics***
- ***Narrow Width Approximation (NWA: Γ_H ~4 MeV)***

$$\sigma\left(i\to H\to f\right)=\sigma_i\frac{\Gamma_f}{\Gamma_{tot}}$$

Signal strength measurements.



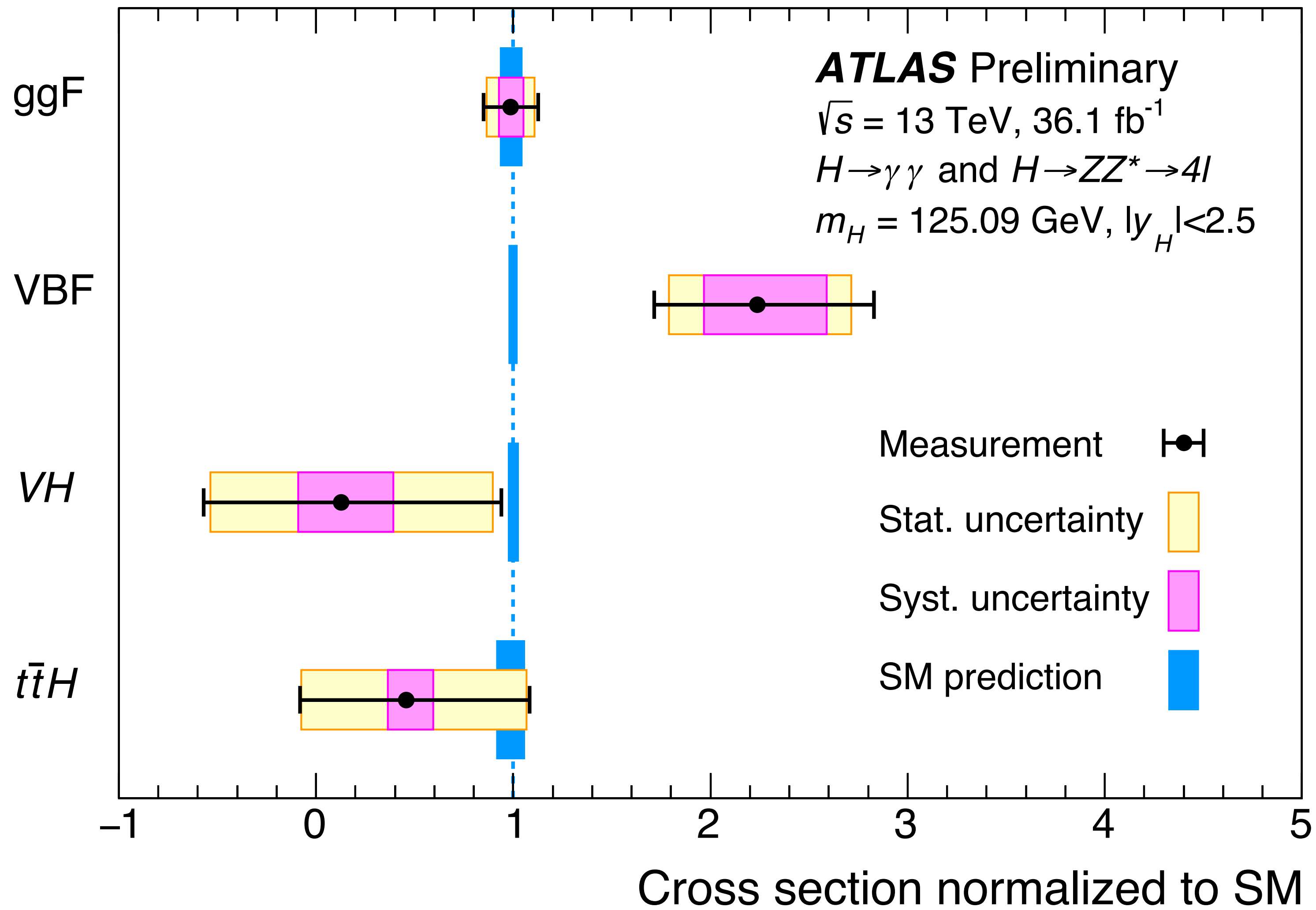


ATLAS+CMS Run-1: $\mu = 1.09 \pm 0.07(\textit{stat.}) \pm 0.05(\textit{exp.}) \pm 0.03(\textit{th. B}) \pm 0.07(\textit{th. S})$

ATLAS 13 TeV: $\mu = 1.09 \pm 0.09(\textit{stat.}) \pm 0.06(\textit{exp.}) \pm 0.06(\textit{th.})$

All ***production*** *and* ***decay signal strength*** measurements ***consistent with SM***

13 TeV $H\rightarrow\gamma\gamma+H\rightarrow 4l$ production cross sections.

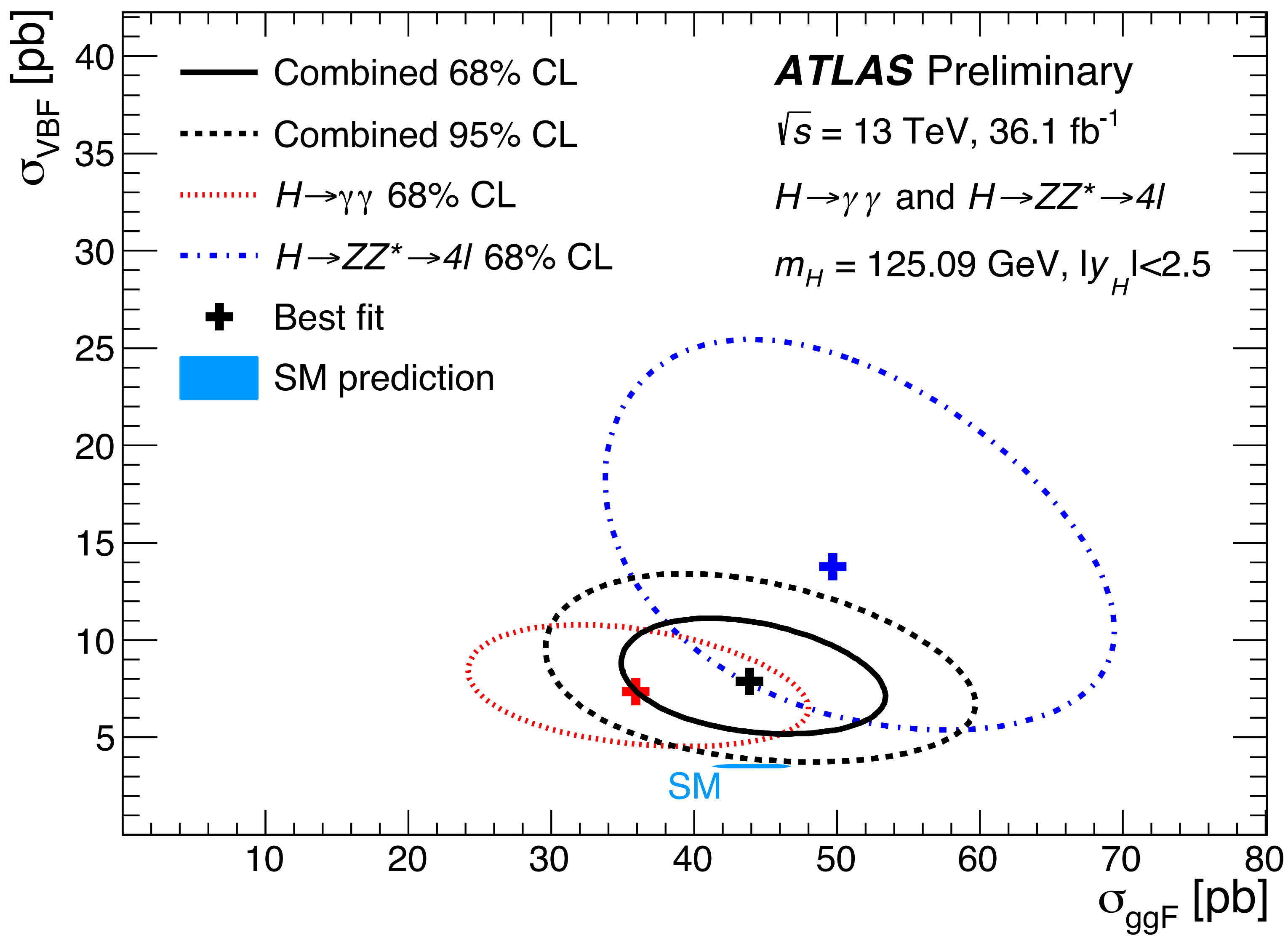


Higgs production is studied further by separating the production mechanism cross sections

- ***Assuming SM branching fractions***, a combined fit is performed, to extract the production cross sections (***ggF***, **VBF**, ***VH***, and ***ttH***) for **$|y_H|<2.5$**
- Measurements of ***ggF and ttH include bbH and tH***, ***respectively***
- Compatibility with SM predictions: ***p-value = 5%***

ggF and **VBF** cross sections measured with the best precision

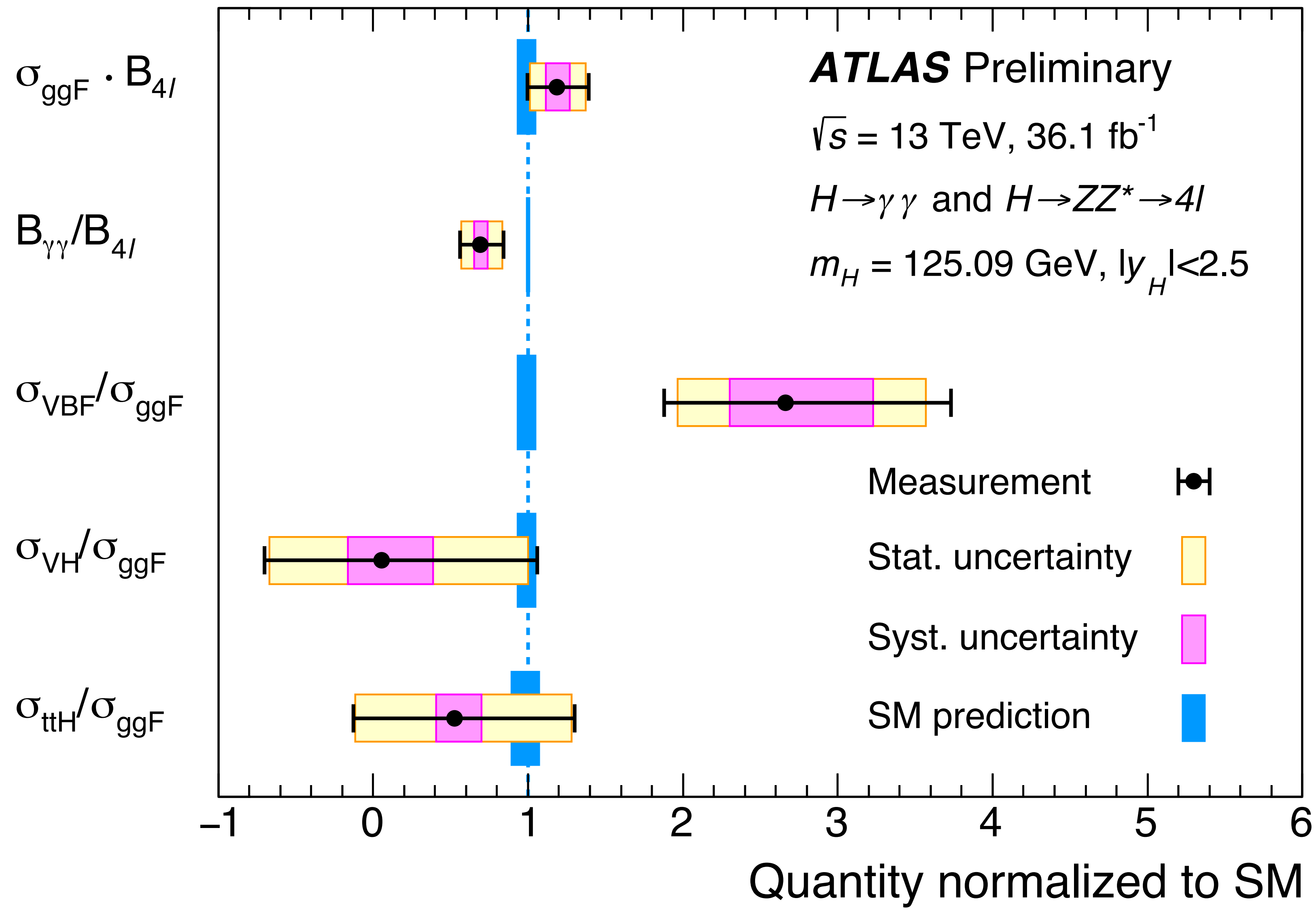
Anti-correlated since the **VBF** ***selection categories have significant contribution from ggF*** production



2D compatibility with SM predictions:

p-value = 3%

σ(VBF) vs. σ(ggF) likelihood contours for each analysis channel and their combination (***VH*** and ***ttH*** profiled with the data)



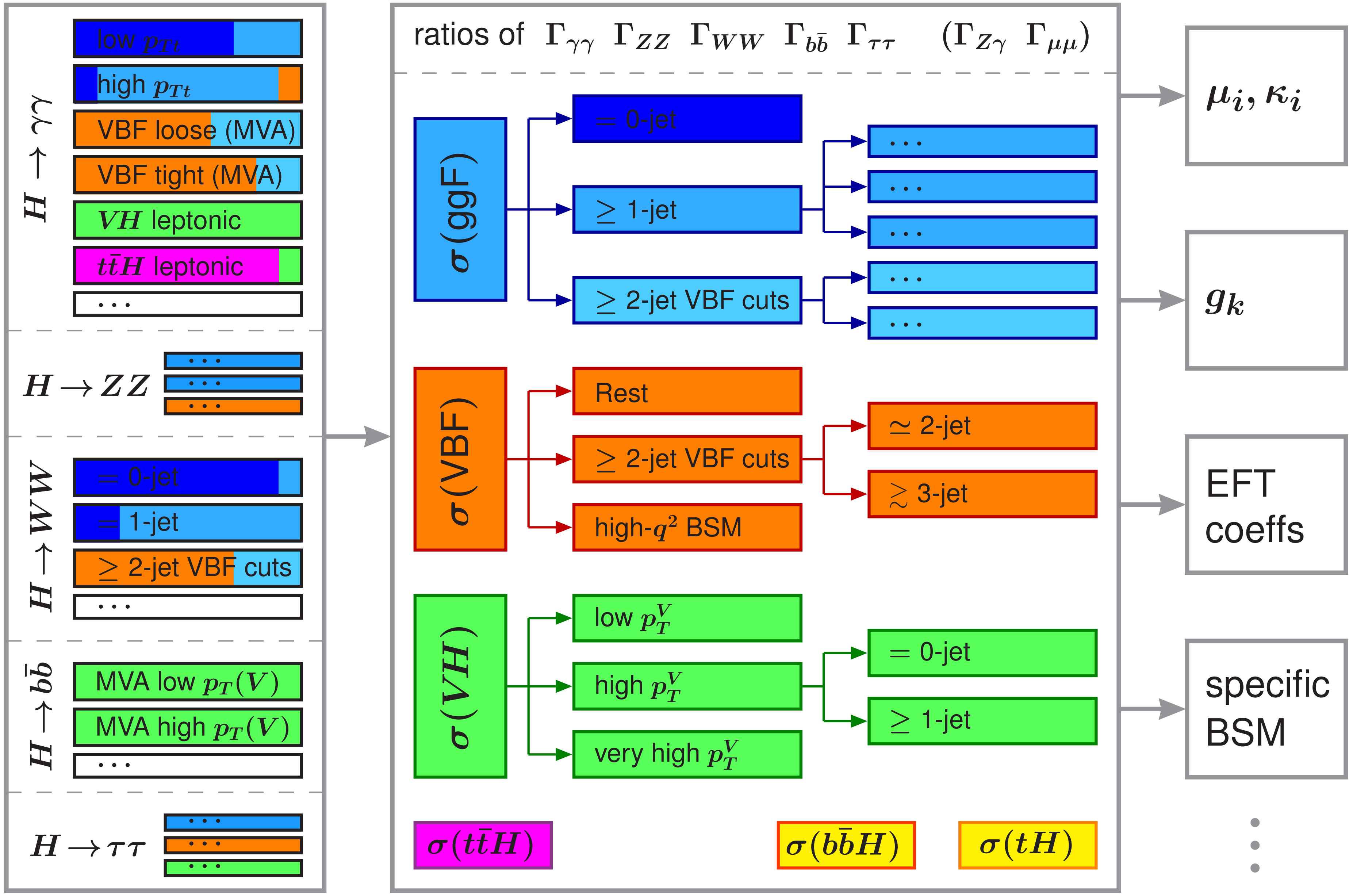
VBF, *VH*, and *ttH* normalized to *ggF* and $B^{\gamma\gamma}$ normalized to B^{ZZ}

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

Combined fit to extract the production and decay ratios for $|y_H| < 2.5$

Compatibility with SM predictions: ***p-value* = 3%**

STXS framework (|y_H|<2.5).

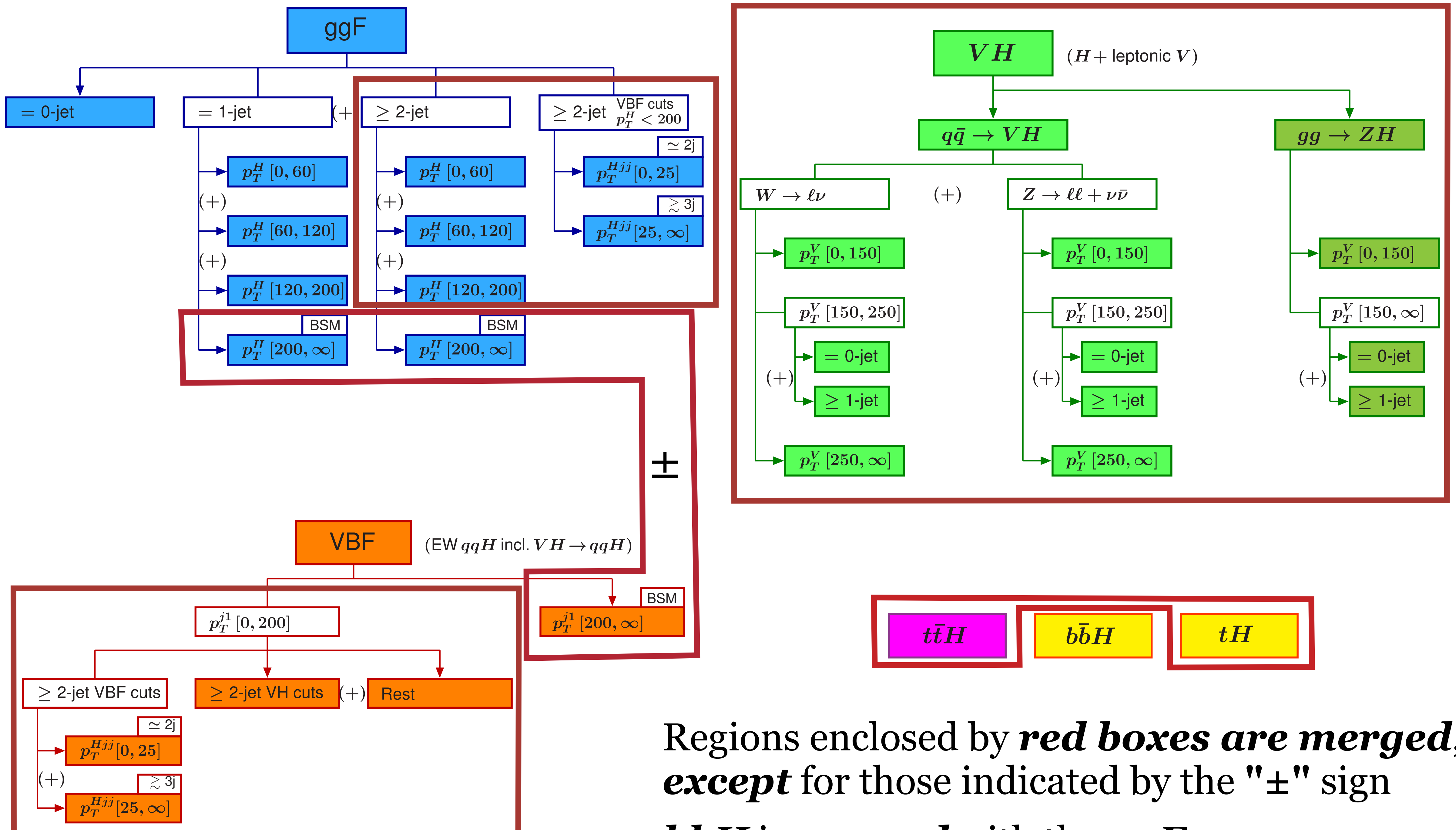


Simplified template cross sections (STXS) provide a *natural evolution of signal strength measurements*

Maximize sensitivity of the measurements *and* ***reduce the theory dependences*** *that get directly folded into measurements*

ATLAS preliminary

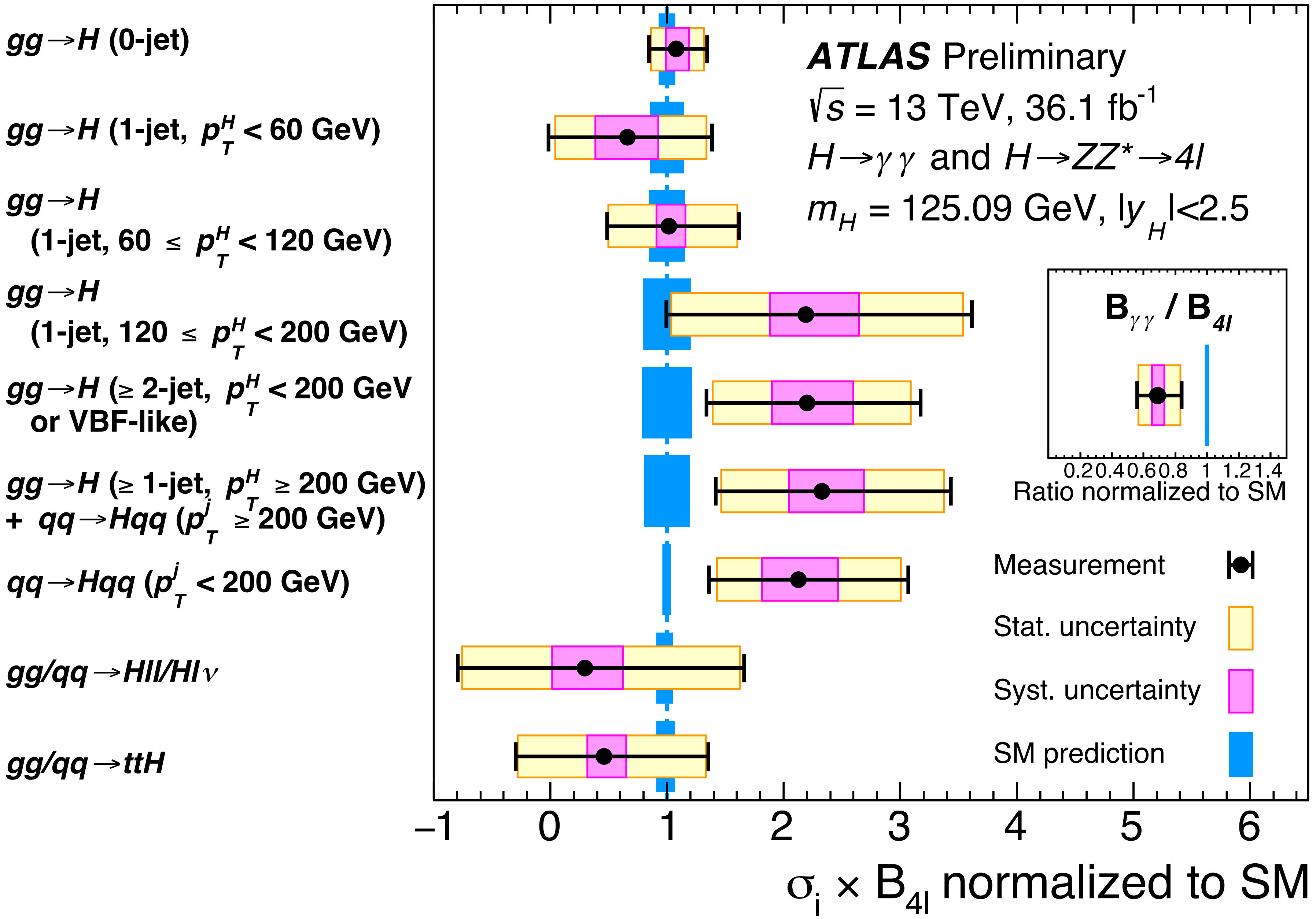
$$y_i = \sum_i A_{i,j} \cdot r_i \cdot (\sigma_i \cdot B_{4l})_{SM} \cdot r_f \cdot \left(\frac{B_f}{B_{4l}}\right) \cdot \mathcal{L}$$



Regions enclosed by ***red boxes are merged***, ***except*** for those indicated by the "±" sign

bbH is ***merged*** with the ***ggF***

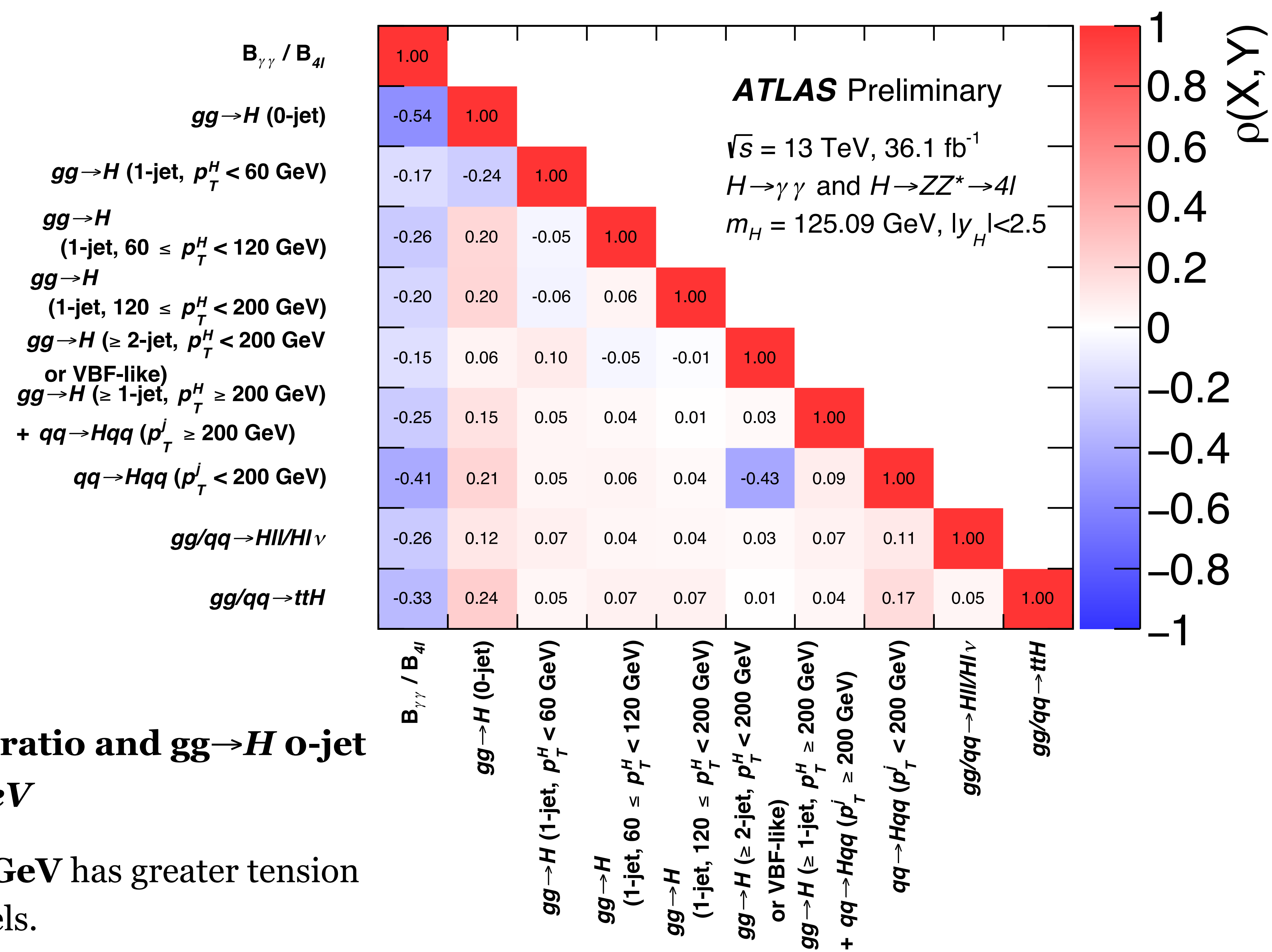
13 TeV STXS stage-1 combined measurements.



Results give a ***good overall agreement with SM predictions*** in a range of kinematic regions of Higgs boson production processes

The compatibility of the measurements with the SM expectation corresponds to a ***p-value of 9%***

STXS measurement correlations.



Correlations:

Largest between the **BR ratio and gg→*H* 0-jet** and ***qq→Hqq*** p_T^j ***<200GeV***

- ***qq→Hqq*** p_T^j **< 200 GeV** has greater tension between the two channels.

Significant between gg→H 0-jet and ***gg→H 1-jet*** p_T^H ***< 60 GeV***, due to migrations between experimental jet-bin categories

κ-framework.

$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

ATLAS EXPERIMENT CMS

- ***Leading-order (LO)*** *framework* ***(limited predictive power)*** *developed by the LHC Higgs Cross Section WG to study Higgs couplings*

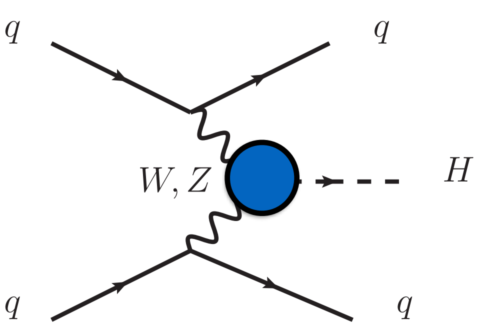
useful as long as the overall picture is SM-like

- ***Potential deviations from the SM predictions*** of the Higgs boson couplings to SM bosons and fermions ***encoded into*** a set of ***coupling modifiers***:

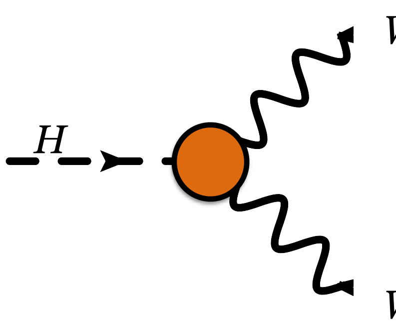
$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{B_f}{B_f^{SM}} \qquad \kappa_H^2 = \Sigma_j B_j^{SM} \kappa_j^2 \qquad \Gamma_H = \frac{\kappa_H^2 \Gamma_H^{SM}}{1 - B_{BSM}}$$

production **decay** **Total width**

- The ***same couplings*** are ***involved in production and decay modes***, hence the yield measurements need to be be projected onto the individual couplings



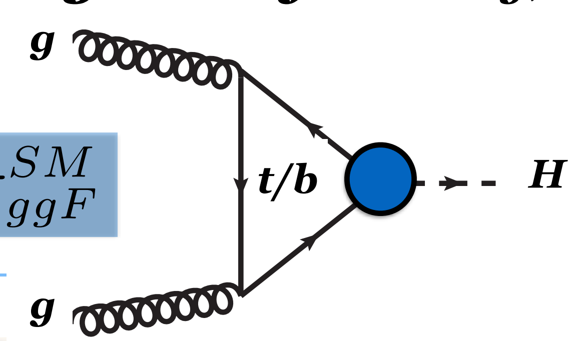
$$\sigma_{VBF} = (0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2) \cdot \sigma_{VBF}^{SM}$$



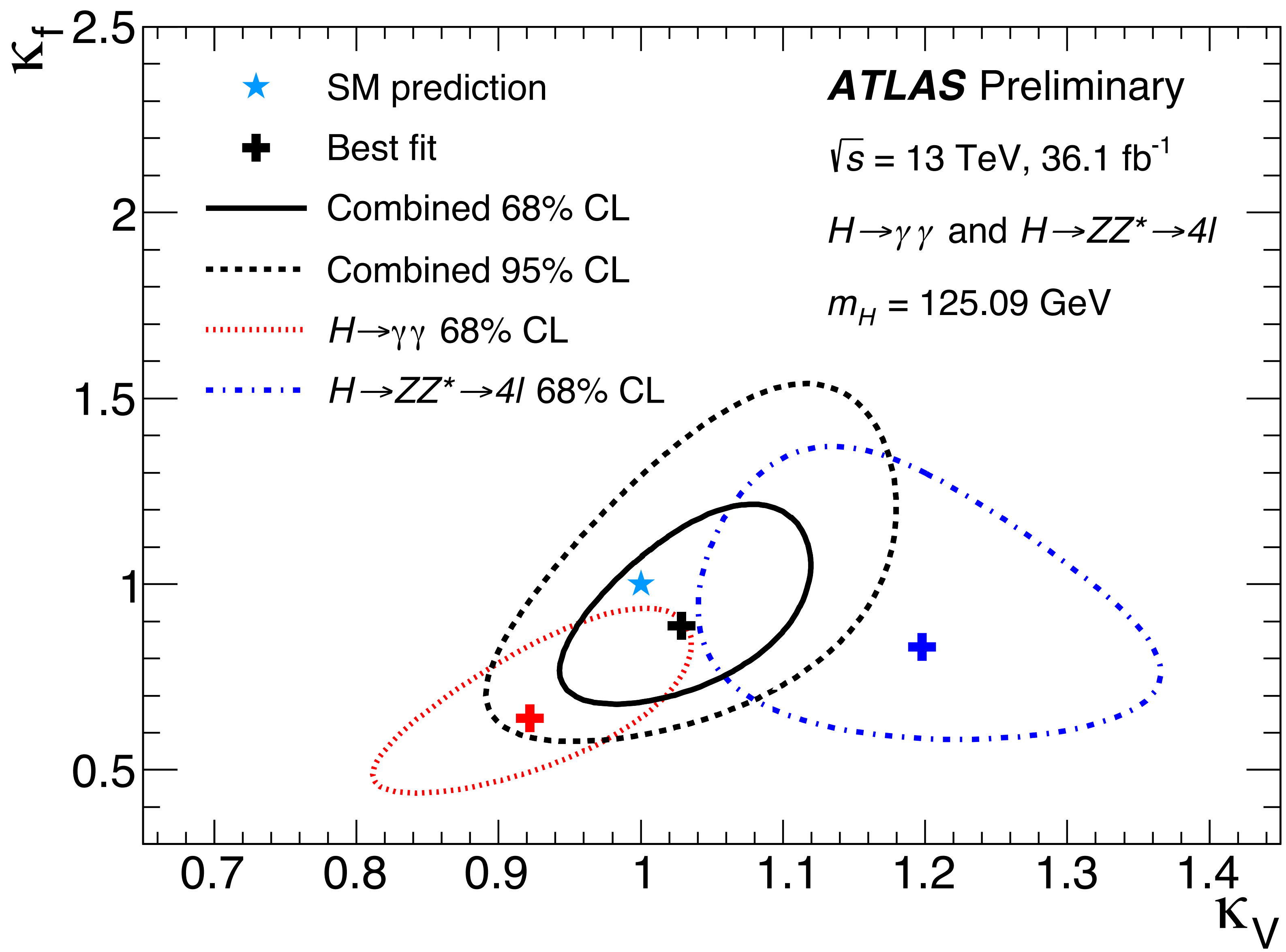
$$\kappa_{W,Z}^2 = \frac{\Gamma_{W,Z}}{\Gamma_{W,Z}^{SM}}$$

- Loops (***ggF***, ***H→γγ***) either expressed with ***effective coupling modifiers κ$_g$***, ***κ$_γ$***, or using more ***fundamental coupling modifiers κ$_x$***

$$\sigma_{ggF} = \kappa_g \cdot \sigma_{ggF}^{SM} = (1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b) \cdot \sigma_{ggF}^{SM}$$



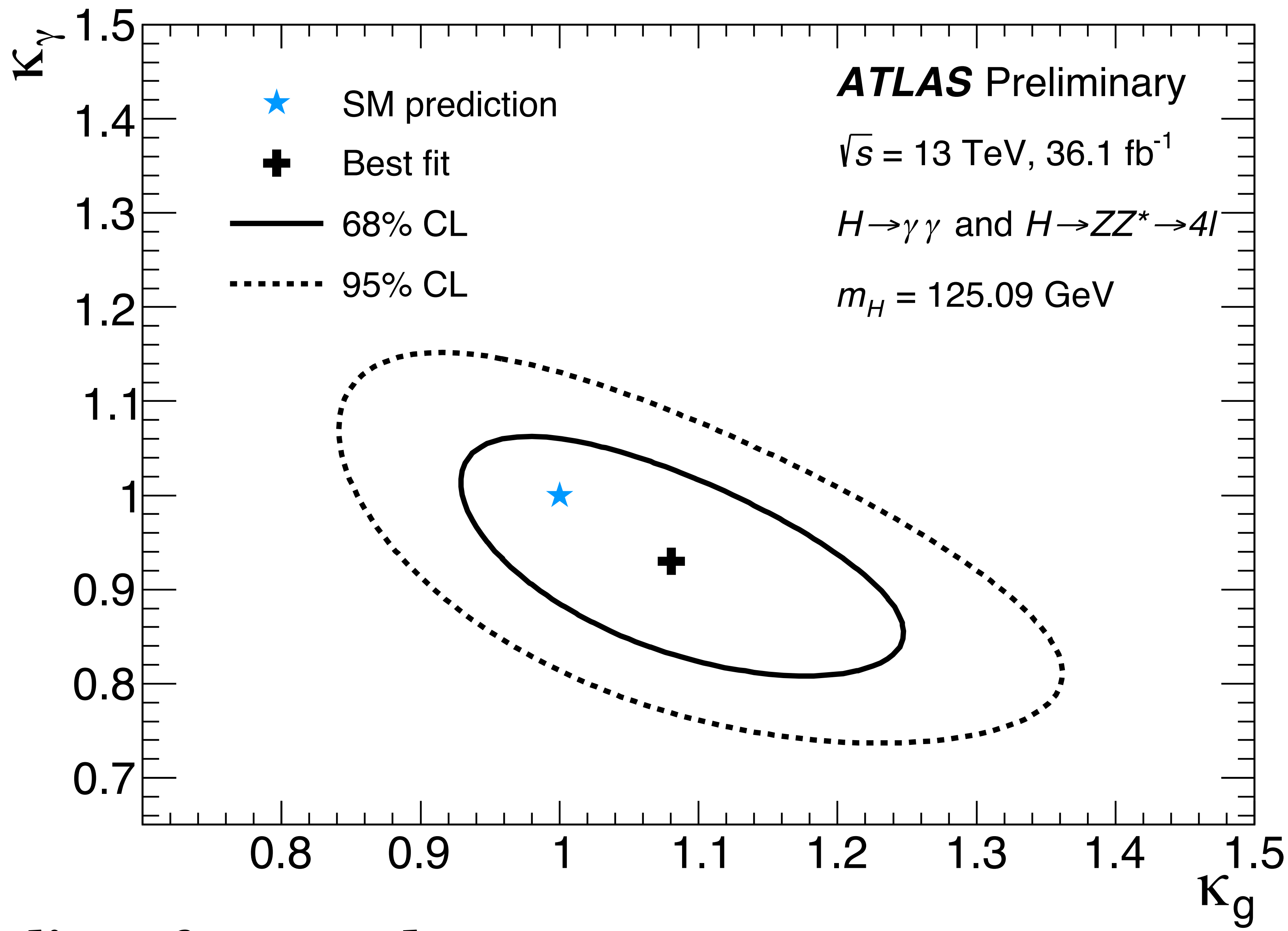
13 TeV ATLAS couplings modifier results.



Boson vs. fermion couplings

- SM Higgs couplings to fermions and boson very different (***Yukawa*** vs $\boldsymbol{D_\mu} \rightarrow \boldsymbol{\kappa_F}$ vs $\boldsymbol{\kappa_V}$)
- $\boldsymbol{\kappa_F}$, $\boldsymbol{\kappa_V}$ in agreement with SM
- $\boldsymbol{\kappa_F < 0}$ excluded at > 95% CL
- 2D compatibility with SM: ***p-value = 52%***

13 TeV ATLAS couplings modifier results.



Effective couplings for κ_γ and κ_g

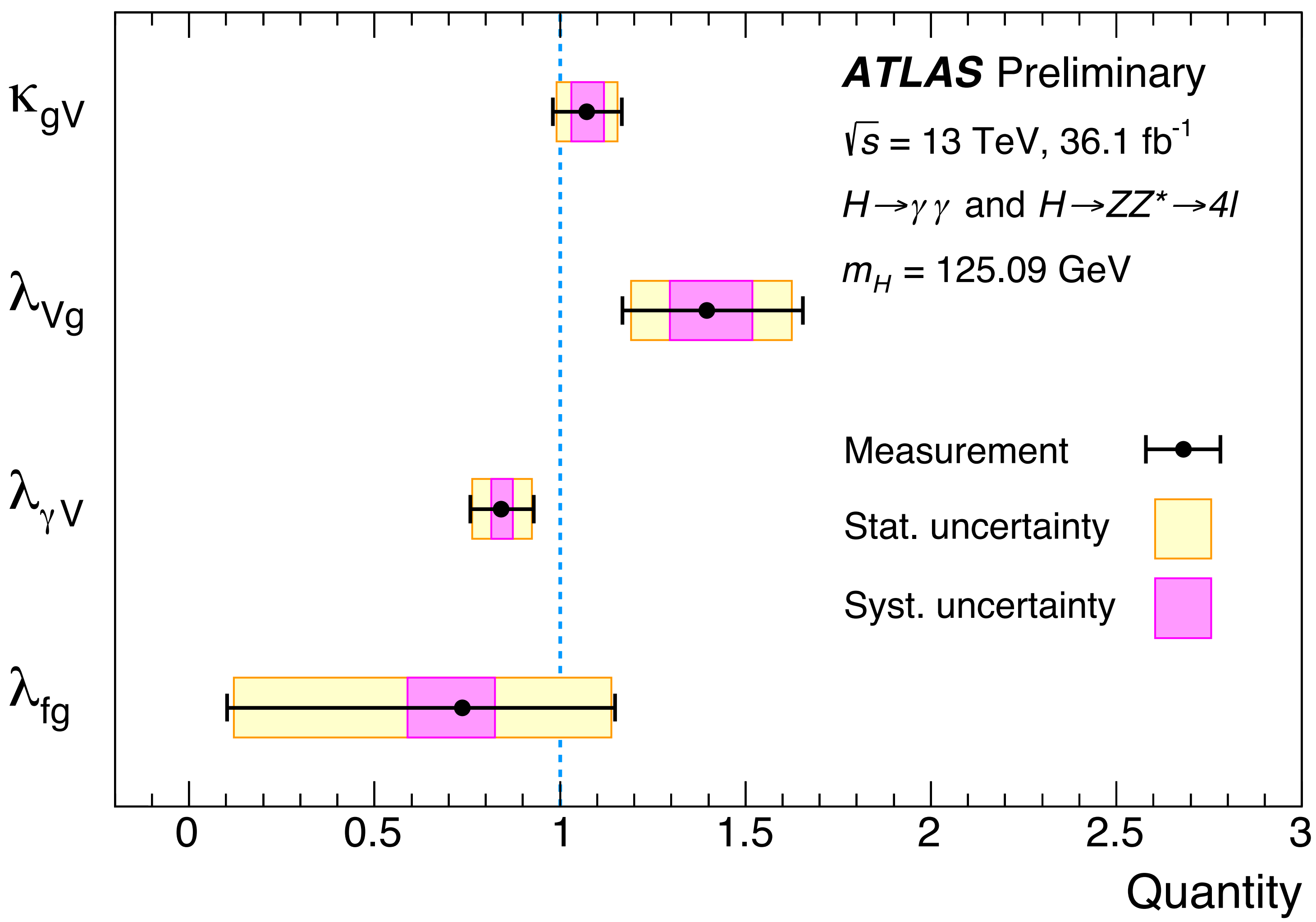
- No BSM decays (B_{BSM} = 0)
- ***ggF*** and ***Hγγ loops*** are ***allowed to be affected by contributions from additional particles***
- ***2 free parameters κ_γ, κ_g***, all other coupling modifiers fixed to their SM values
- 2D compatibility with SM: ***p-value = 68%***

13 TeV ATLAS couplings modifier ratios.

Conversion of signal strength ratios to the ***κ-framework*** using: $\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$

Four ratios constructed to probe loop vertices (**κ_g, κ_γ**), total width **κ_H** and fermion and vector couplings (**κ_f, κ_V**)

$$\kappa_{gV} = \frac{\kappa_g \kappa_V}{\kappa_H}, \quad \lambda_{Vg} = \frac{\kappa_V}{\kappa_g}, \quad \lambda_{fg} = \frac{\kappa_f}{\kappa_g}, \quad \lambda_{\gamma V} = \frac{\kappa_\gamma}{\kappa_V}$$



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

Negative ranges allowed for ***λ_{fg}*** to exploit the moderate sensitivity to the relative sign from ***tHX*** *and* ***ggZH***

- Best fit > 0, but limited sensitivity to interference terms

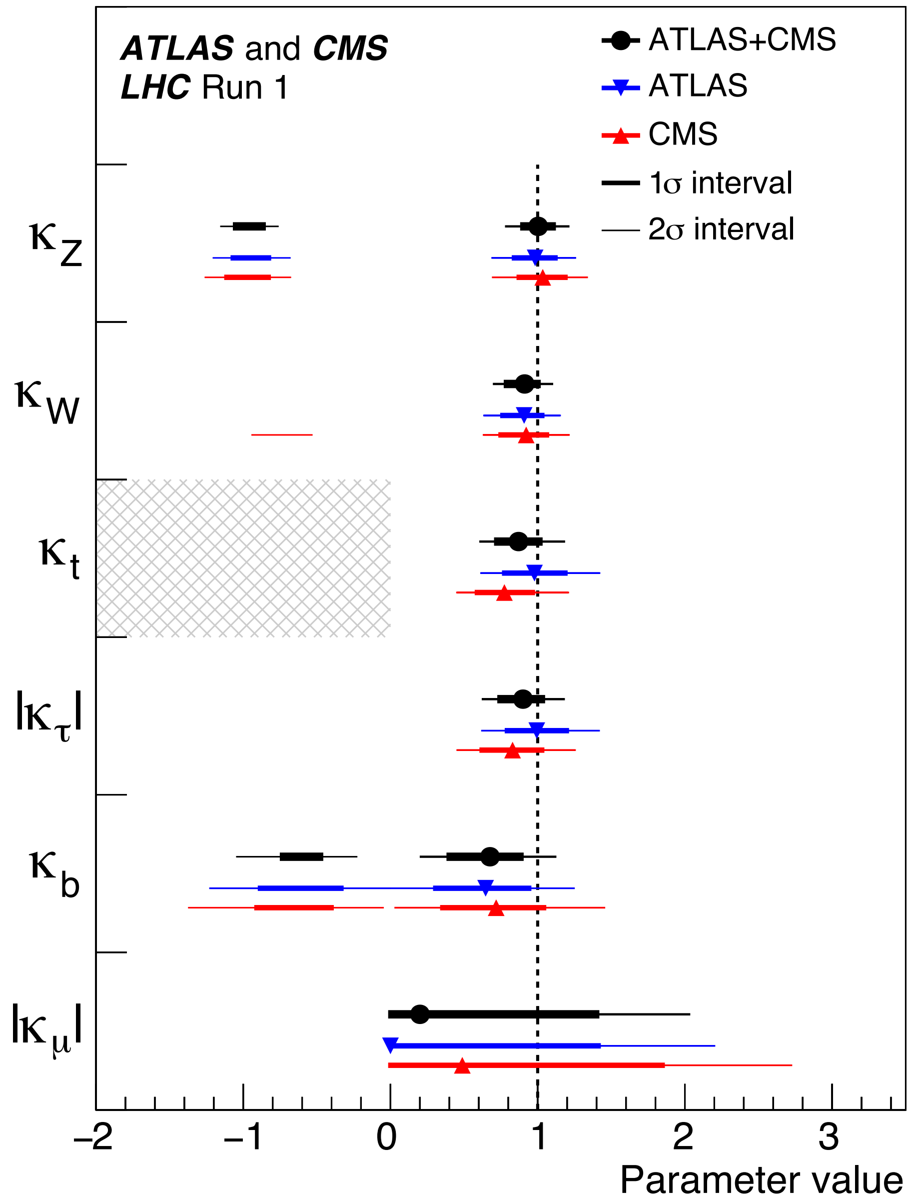
4D compatibility with SM:

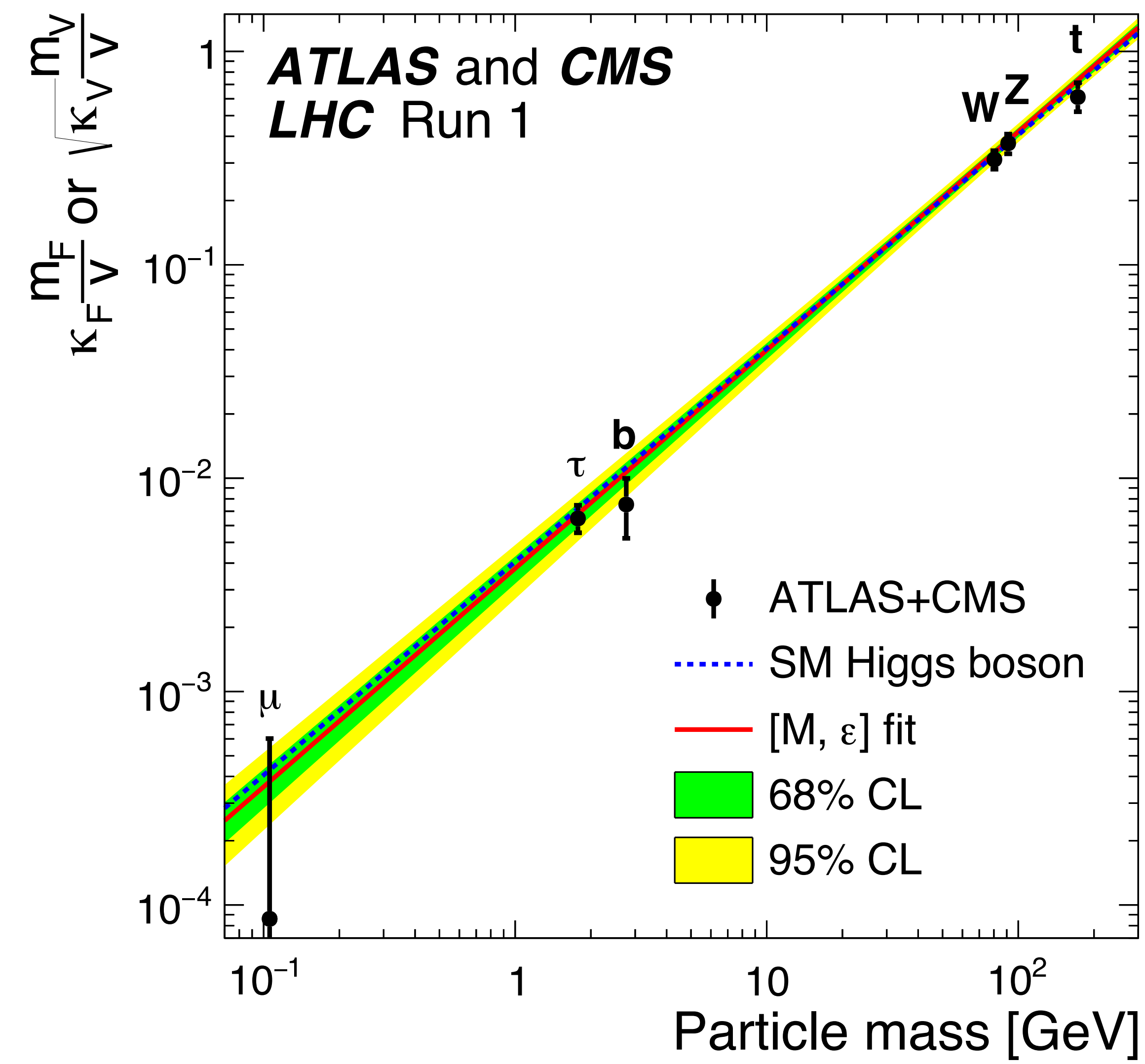
p-value = 15%

Run-1 Couplings modifiers (no BSM).

Express $\kappa_{g,H,\gamma}$ with other κs, $BR_{BSM} = 0$, $H \rightarrow \mu\mu$ also combined

Coupling modifiers lower than those predicted by the SM when compared to the global signal strength or the fit results of the decay signal strengths

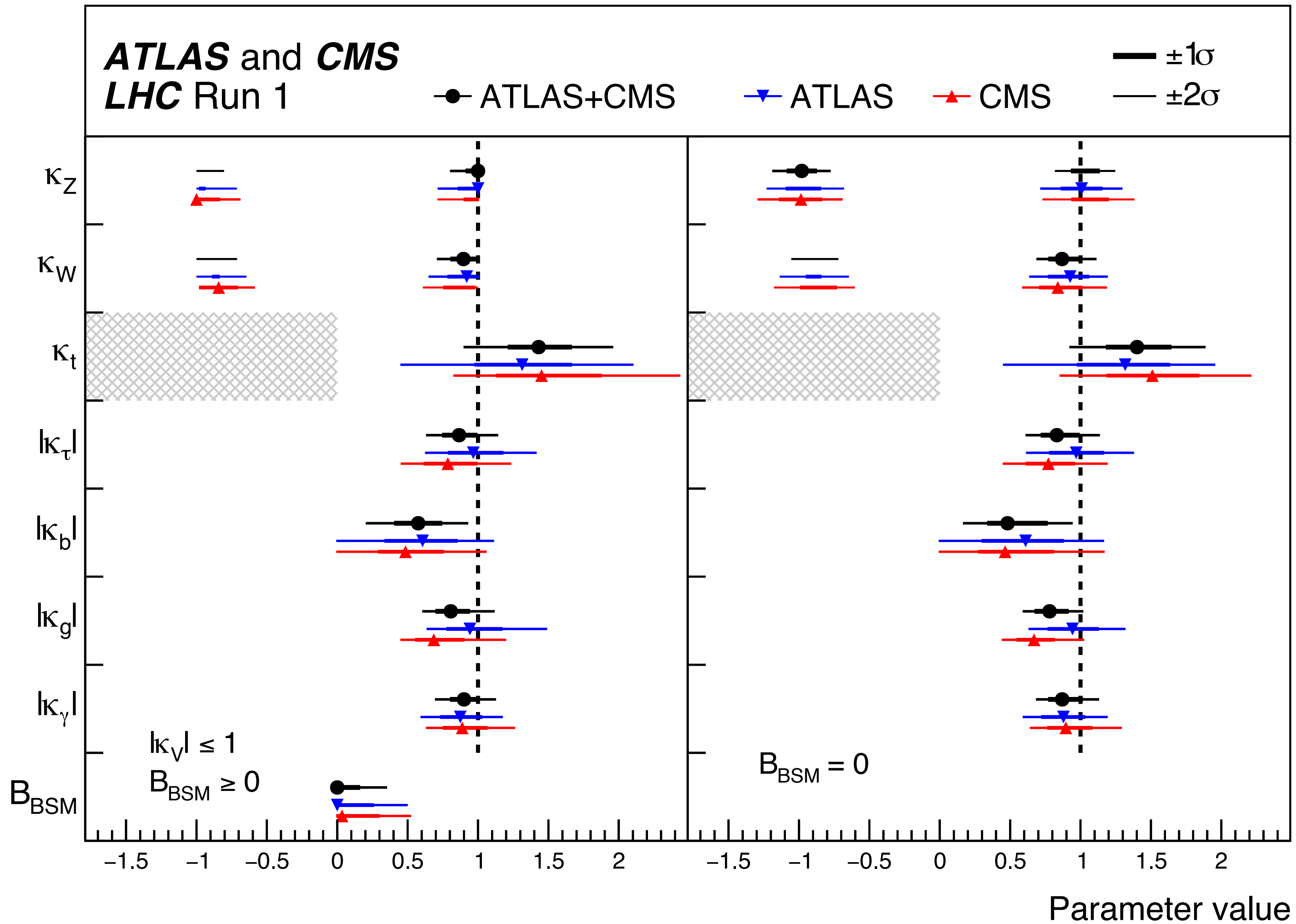




Parameterization derived from the coupling modifiers make the dependence on the particle masses explicit (as in the SM):

linear for the fermion Yukawa couplings and quadratic for the gauge couplings of the Higgs to the V-bosons

Run-1 couplings with BSM loops and new decays.



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

- Probe new decay channels: **NWA, B_{BSM}** > 0 and impose $|\boldsymbol{\kappa}_V|$< 1
- upper limit of **B_{BSM} = 0.34** at **95% CL** (*expected limit*: **0.39**)
- The ***p-value*** of the compatibility between the data and the SM predictions is **11%**, assuming that **B_{BSM}** = 0

Conclusion and outlook.

Run-1 (ATLAS+CMS)

- Mass measured at 0.2% level : m_H = 125.09 ± 0.24 GeV
- Various parameterization explored and were all found in agreement with SM (worst p-value of 11%)

Run-2 (ATLAS: $H \to \gamma\gamma$ & $H \to 4l$)

- **m_H = 124.98 ± 0.28 GeV, in agreement with ATLAS+CMS Run-1 result**
- Preliminary combination results for coupling modifiers, production mode and total cross sections
- **Possible improvements over the kappa-framework being investigated: preliminary results shown from STXS framework**, future considerations: EFT and PO

All measurements consistent with SM expectations

- Run-1 ATLAS+CMS combination provides the most accurate measurements in the Higgs sector, though the ATLAS Run-2 combination approaching the same accuracy
- **Increased statistics from the final Run-II dataset and improved theory predictions are already providing a significant increase in sensitivity**

References

Higgs boson discovery:

- **ATLAS:** *Phys. Lett. B 716 (2012) 1-29*
- **CMS:** *Phys. Lett. B 716 (2012) 30*

ATLAS+CMS combination:

- **Mass:** *Phys. Rev. Lett. 114, (2015)*
- **Couplings:** *JHEP 08 (2016) 045*

ATLAS and CMS individual combinations:

- **ATLAS:** *Eur. Phys. J. C76 (2016) 6*
- **CMS:** *Eur. Phys. J. C 75 (2015) 212*

ATLAS Hγγ Mass shift through interferometry: *ATL-PHYS-PUB-2016-009*

13 TeV ATLAS *H→γγ* & *H→4l* combination:

- **Mass:** *ATLAS-CONF-2017-046*
- **XS & couplings:** *ATLAS-CONF-2017-047*

13 TeV ATLAS combination inputs:

- ***H→γγ*:** *ATLAS-CONF-2017-045*
- ***H→4l*:** *ATLAS-CONF-2017-043*

ATLAS+CMS combination inputs:

H→γγ

- **ATLAS:** *Phys. Rev. D 90, 112015 (2014)*
- **CMS:** *EPJC 10.2014, 74:3076*

H→ZZ

- **ATLAS:** *Phys. Rev. D 91, 012006 (2015)*
- **CMS:** *Phys. Rev. D 89, 092007*

H→WW

- **ATLAS** *Phys. Rev. D 92, 012006 (2015)*, *JHEP 08.2015, 2015:137*
- **CMS:** *JHEP 01.2014, 2014:96*

H→ττ

- **ATLAS:** *JHEP April 2015, 2015:117*
- **CMS:** *JHEP 05 (2014) 104*

H→bb

- **ATLAS:** *JHEP 01.2015, 2015:69*
- **CMS:** *Phys. Rev. D 89 01.2014*

H→μμ

- **ATLAS:** *Physics Letters B 738 (2014) 68-86*
- **CMS:** *Physics Letters B V(744), 11.05.2015*

ttH

- **ATLAS:** *Eur. Phys. J. C (2015) 75:349*, *Phys. Letters B 749 (2015) 519-541*
- **CMS:** *JHEP 05.2013, 2013:145*, *JHEP 09 (2014) 087*

Additional material

Production and decay signal strengths.

Combine categories and ***fit*** for ***cross sections (σᵢ)*** or ***signal strength of*** different ***production processes (i)*** and ***final states (f)***

$$\mu_i = \frac{\sigma_i}{\sigma_{i,SM}} \qquad \mu^f = \frac{B^f}{B^f_{SM}} \qquad \mu_i^f = \frac{\sigma_i \cdot B^f}{(\sigma_i \cdot B^f)_{SM}}$$

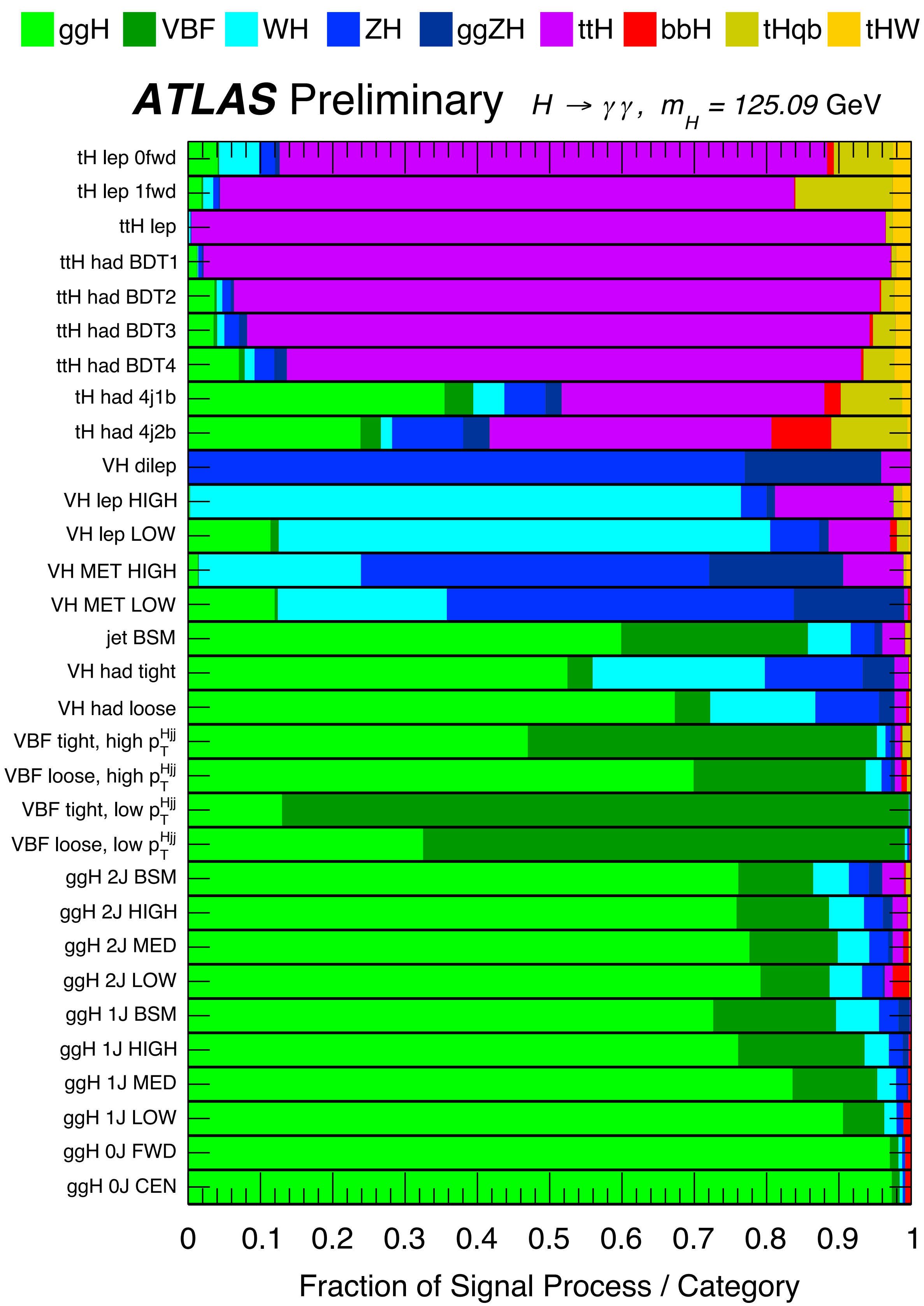
Analyses extract signal yields:

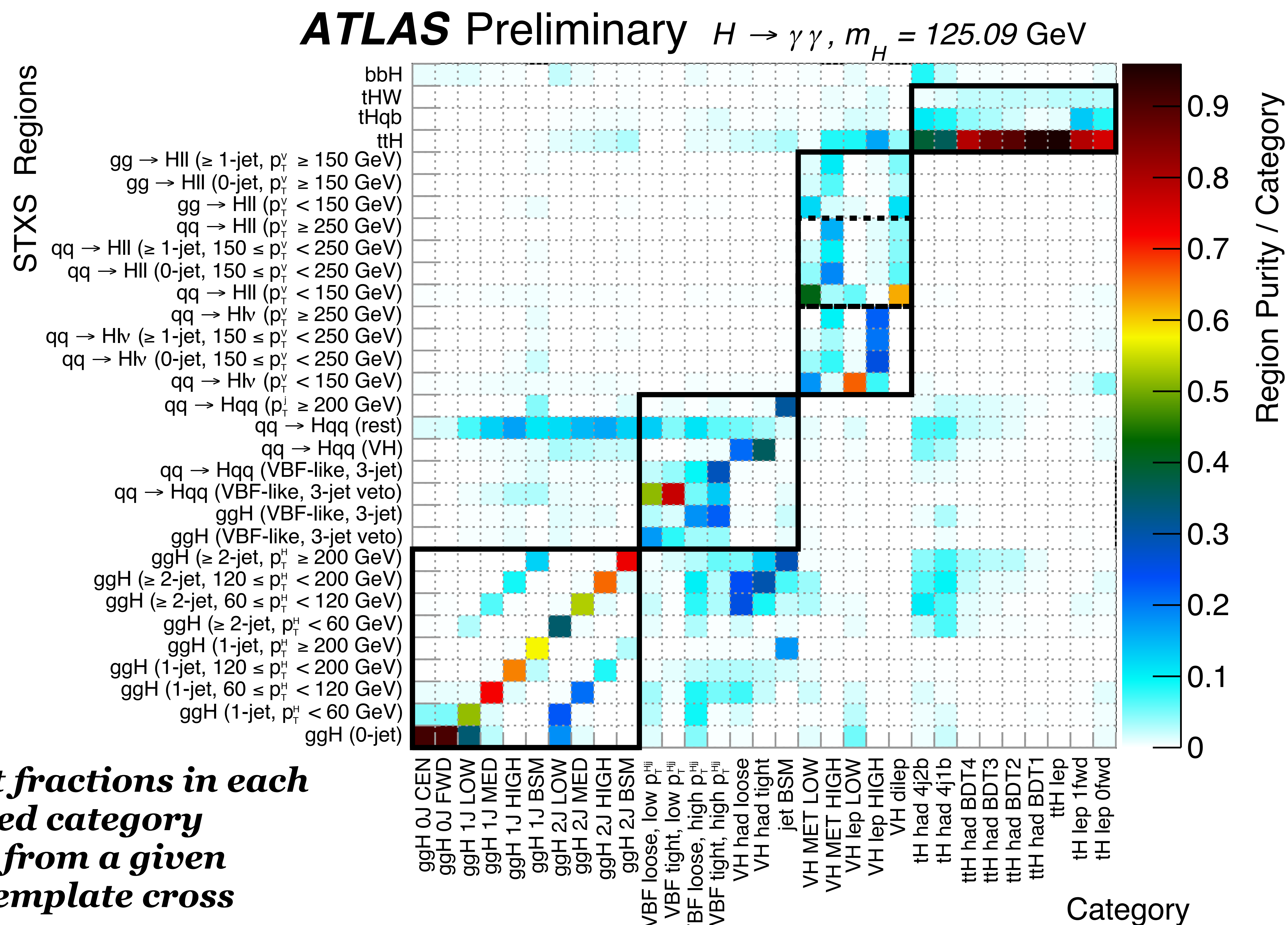
$$\begin{aligned}\nu^{\text{sig}} &= \mathcal{L}\Sigma_i\Sigma_f\left(\sigma_i A^f_{i,\text{SM}}\epsilon^f_{i,\text{SM}}B^f\right)\\ &= \mathcal{L}\Sigma_i\Sigma_f\left(\mu_i\sigma_{i,\text{SM}}A^f_{i,\text{SM}}\epsilon^f_{i,\text{SM}}\mu^f B^f_{\text{SM}}\right)\end{aligned}$$

where $\mathcal{L}$ is the luminosity, $\boldsymbol{\varepsilon}$ efficiencies, ***A*** the detector acceptance and $\boldsymbol{\mu_i}$, $\boldsymbol{\mu^f}$ are production and decay signal strengths

STXS signal composition by production mode

The expected composition of the selected Higgs boson events, in terms of the different production modes, for each reconstructed category





signal event fractions in each reconstructed category originating from a given simplified template cross section region

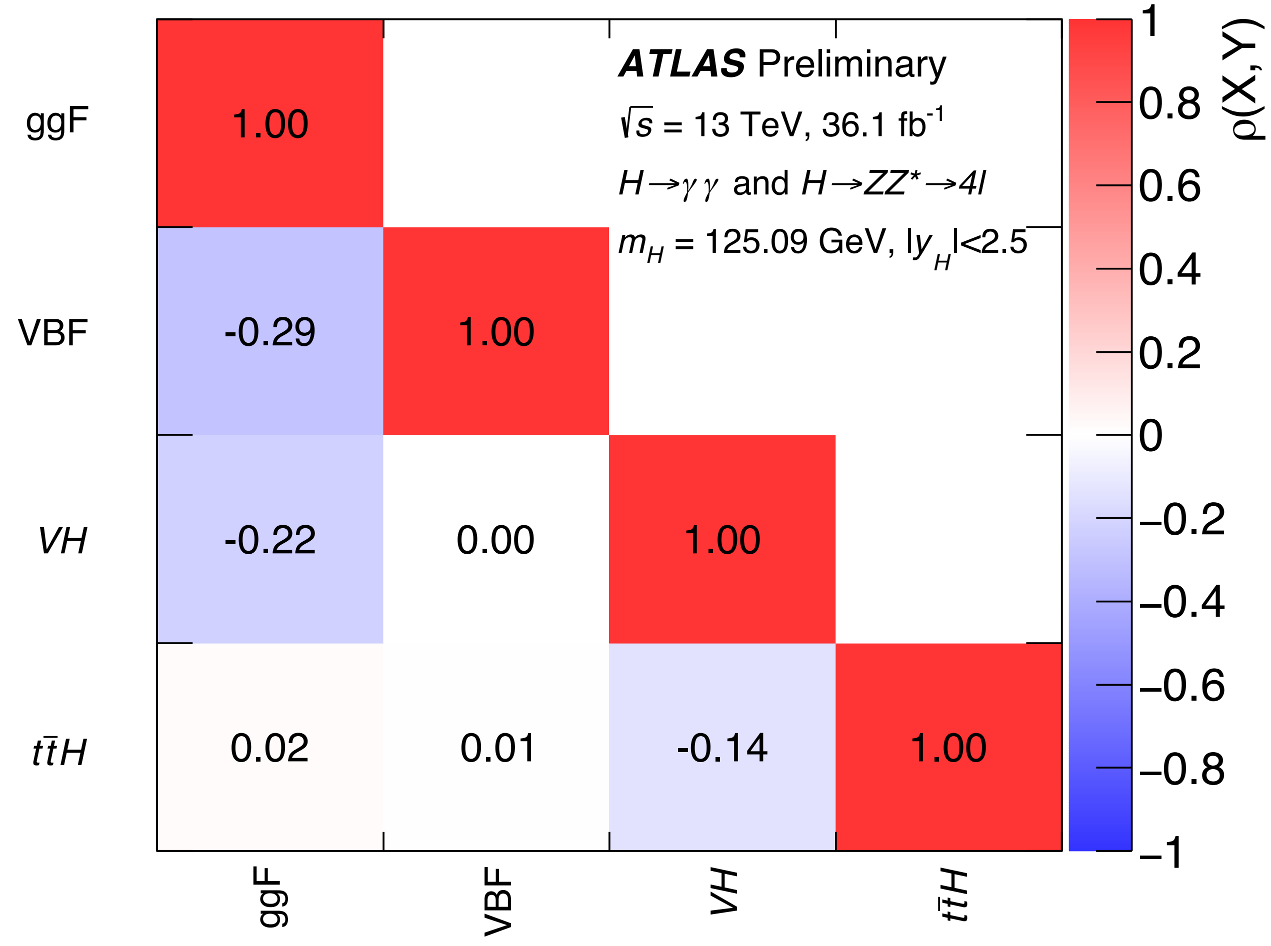
Analysis categories entering the combination.

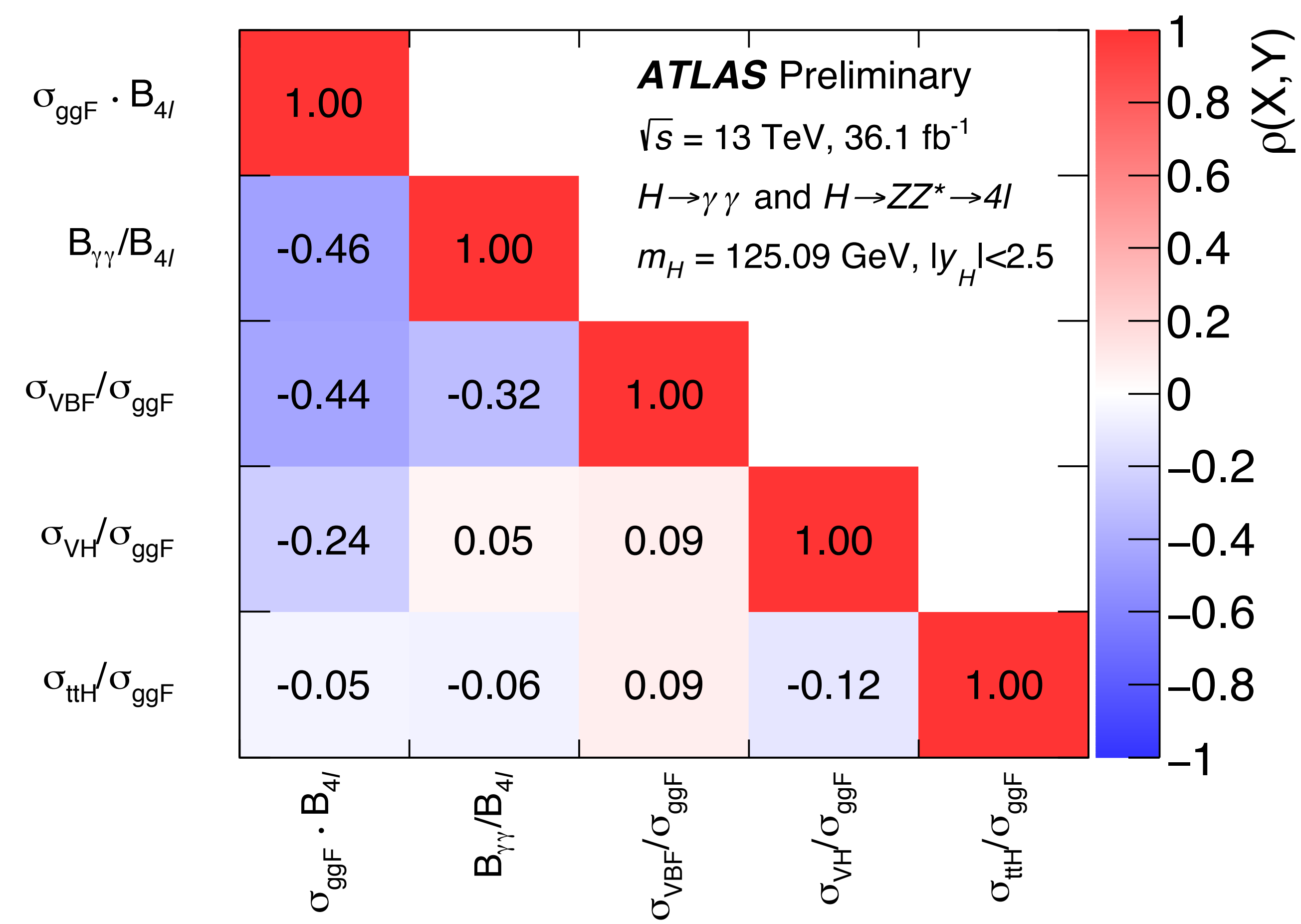
$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
$t\bar{t}H$+tH leptonic (two tHX and one $t\bar{t}H$ categories)	$t\bar{t}H$
$t\bar{t}H$+tH hadronic (two tHX and four BDT $t\bar{t}H$ categories)	VH leptonic
VH dilepton	2-jet VH
VH one-lepton, $p_{\mathrm{T}}^{\ell+\mathrm{MET}} \geq 150$ GeV	2-jet VBF, $p_{\mathrm{T}}^{j1} \geq 200$ GeV
VH one-lepton, $p_{\mathrm{T}}^{\ell+\mathrm{MET}}$¡150 GeV	2-jet VBF, p_{T}^{j1}¡200 GeV
VH $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}} \geq 150$ GeV	1-jet ggF, $p_{\mathrm{T}}^{4\ell} \geq 120$ GeV
VH $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ ¡150 GeV	1-jet ggF, 60 GeV¡$p_{\mathrm{T}}^{4\ell}$¡120 GeV
VH+VBF $p_{\mathrm{T}}^{j1} \geq 200$ GeV	1-jet ggF, $p_{\mathrm{T}}^{4\ell}$¡60 GeV
VH hadronic (BDT tight and loose categories)	0-jet ggF
VBF, $p_{\mathrm{T}}^{\gamma\gamma jj} \geq 25$ GeV (BDT tight and loose categories)	
VBF, $p_{\mathrm{T}}^{\gamma\gamma jj}$¡25 GeV (BDT tight and loose categories)	
ggF 2-jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV	
ggF 2-jet, 120 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡200 GeV	
ggF 2-jet, 60 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡120 GeV	
ggF 2-jet, $p_{\mathrm{T}}^{\gamma\gamma} < 60$ GeV	
ggF 1-jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV	
ggF 1-jet, 120 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡200 GeV	
ggF 1-jet, 60 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡120 GeV	
ggF 1-jet, $p_{\mathrm{T}}^{\gamma\gamma}$ ¡ 60 GeV	
ggF 0-jet (central and forward categories)	

ATLAS 13 TeV: STXS kinematic regions.

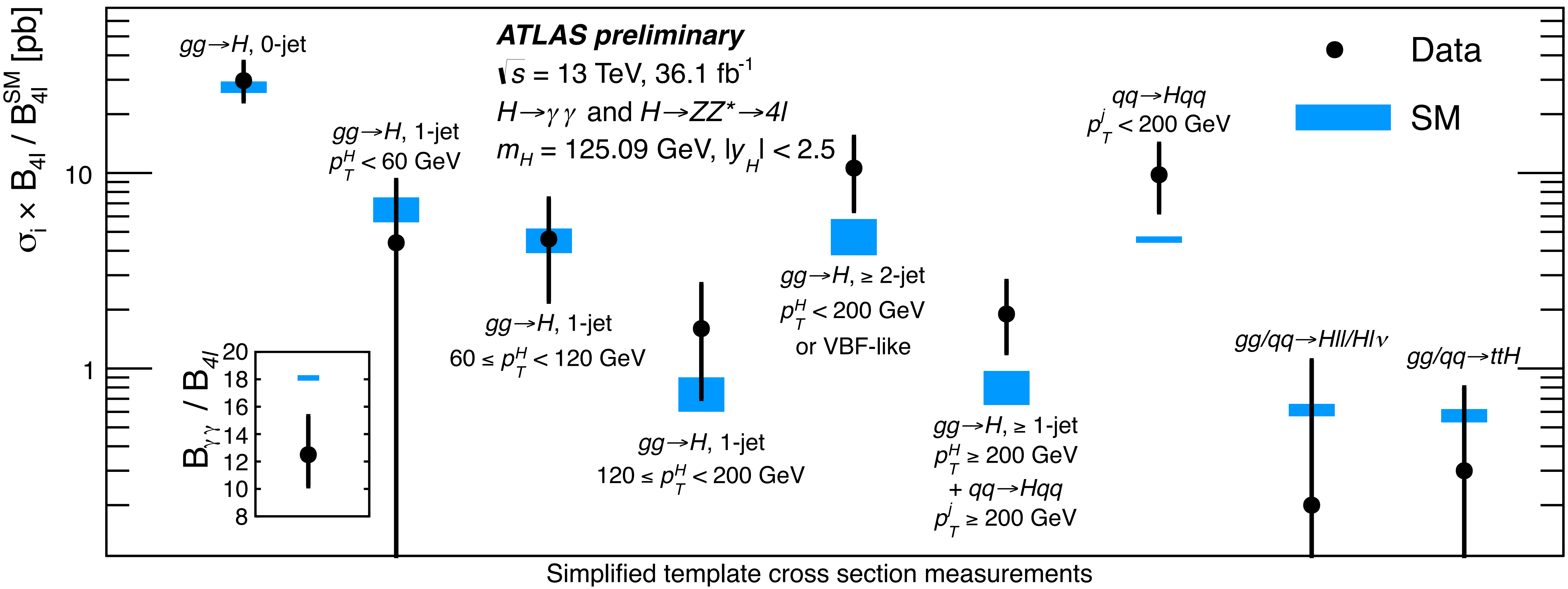
Stage 0 process	Measurement region	Stage 1 region
$gg \to H$	0-jet	0-jet
	1-jet, $p_{\mathrm{T}}^{H} < 60\,GeV$	1-jet, $p_{\mathrm{T}}^{H} < 60\,GeV$
	1-jet, $60 \leq p_{\mathrm{T}}^{H} < 120\,GeV$	1-jet, $60 \leq p_{\mathrm{T}}^{H} < 120\,GeV$
	1-jet, $120 \leq p_{\mathrm{T}}^{H} < 200\,GeV$	1-jet, $120 \leq p_{\mathrm{T}}^{H} < 200\,GeV$
	$\geq$ 1-jet, $p_{\mathrm{T}}^{H} > 200\,GeV$	1-jet, $p_{\mathrm{T}}^{H} > 200\,GeV$
		$\geq$ 2-jet, $p_{\mathrm{T}}^{H} > 200\,GeV$
	$\geq$ 2-jet, $p_{\mathrm{T}}^{H} < 200\,GeV$ or VBF-like	$\geq$ 2-jet, $p_{\mathrm{T}}^{H} < 60\,GeV$
		$\geq$ 2-jet, $60 \leq p_{\mathrm{T}}^{H} < 120\,GeV$
		$\geq$ 2-jet, $120 \leq p_{\mathrm{T}}^{H} < 200\,GeV$
		VBF-like, $p_{\mathrm{T}}^{Hjj} < 25\,GeV$
		VBF-like, $p_{\mathrm{T}}^{Hjj} \geq 25\,GeV$
$qq \to Hqq$	$p_{\mathrm{T}}^{j} \geq 200\,GeV$	$p_{\mathrm{T}}^{j} \geq 200\,GeV$
	$p_{\mathrm{T}}^{j} < 200\,GeV$	$p_{\mathrm{T}}^{j} < 200\,GeV$, VBF-like, $p_{\mathrm{T}}^{Hjj} < 25\,GeV$
		$p_{\mathrm{T}}^{j} < 200\,GeV$, VBF-like, $p_{\mathrm{T}}^{Hjj} \geq 25\,GeV$
		$p_{\mathrm{T}}^{j} < 200\,GeV$, VH-like
		$p_{\mathrm{T}}^{j} < 200\,GeV$, Rest

ATLAS Run-2 cross section correlations.

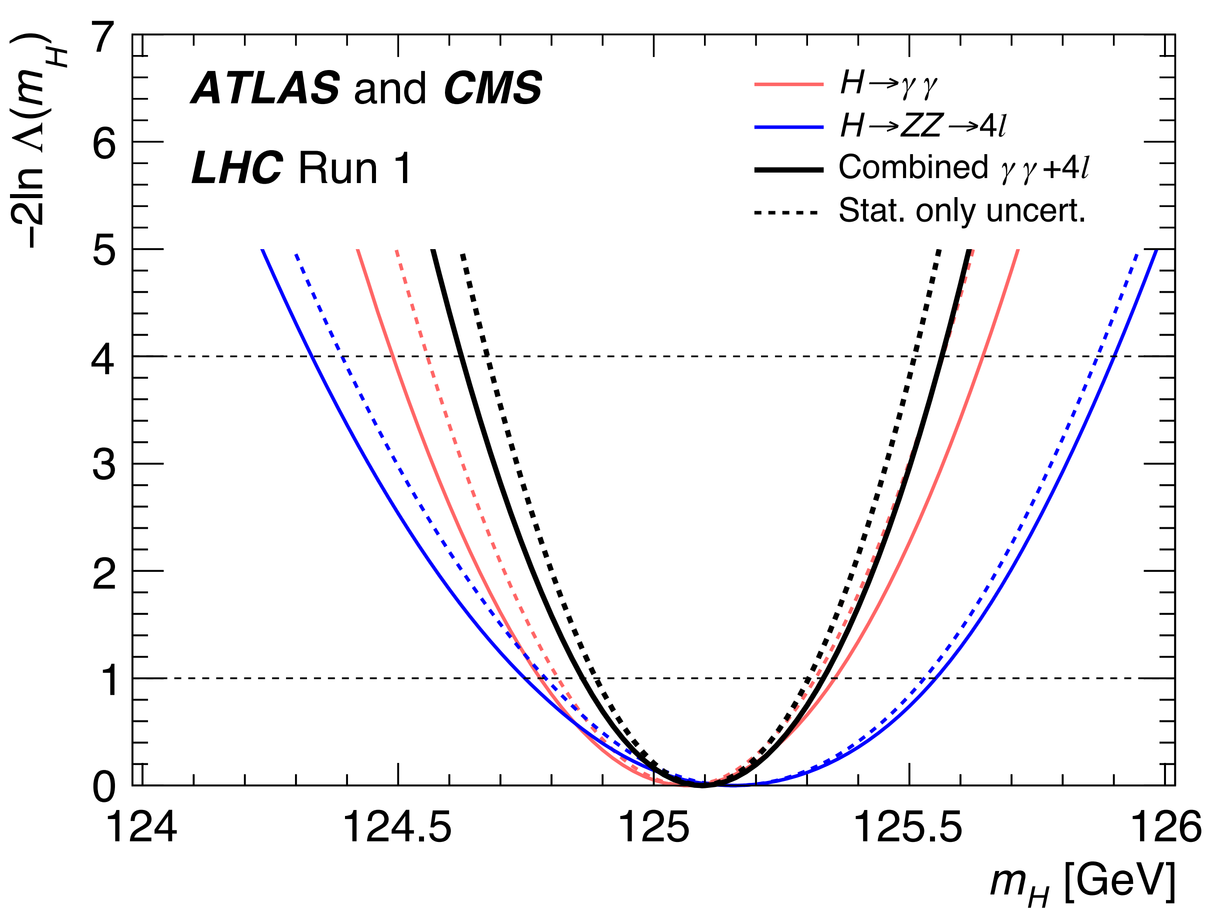




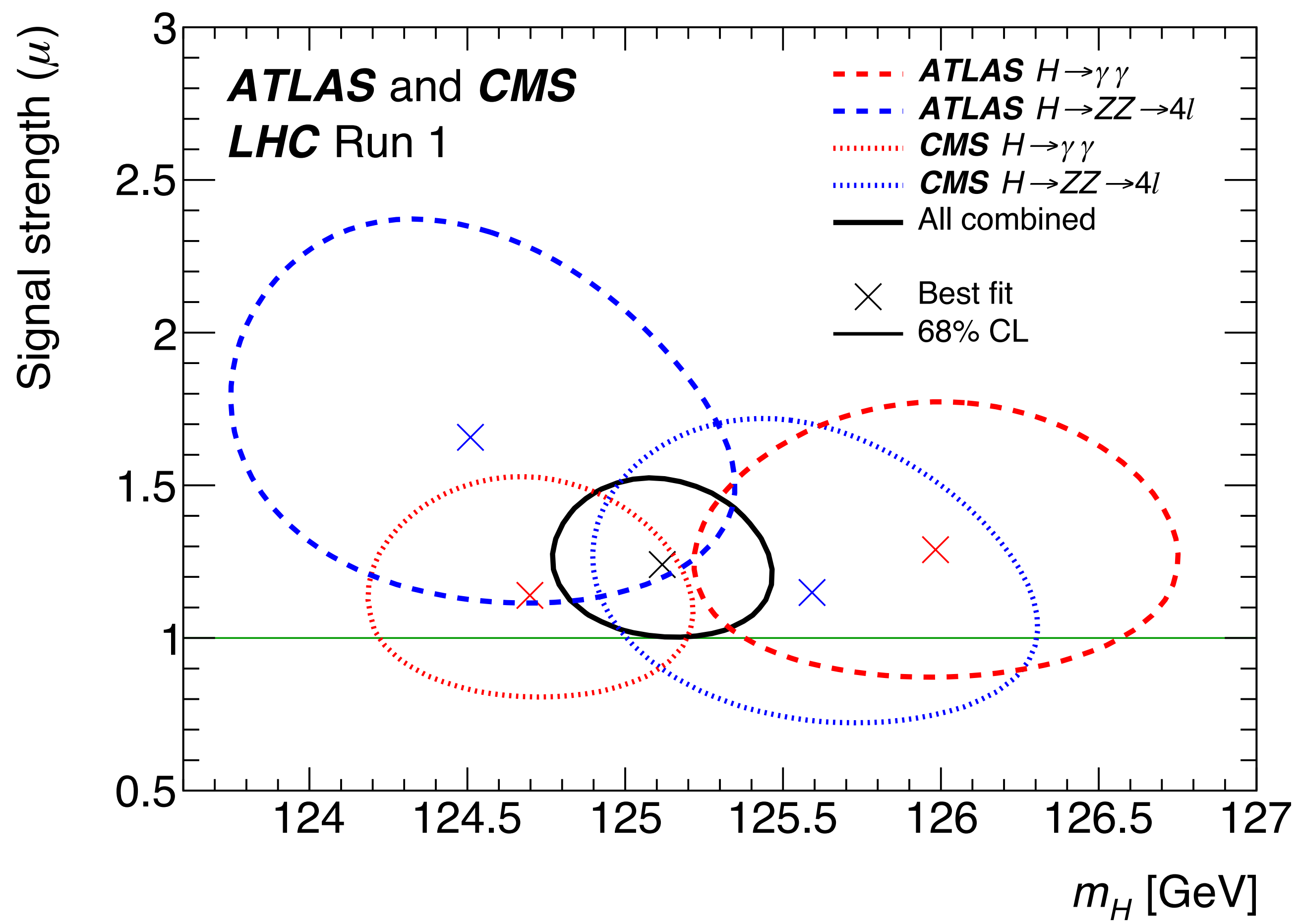
STXS stage-1 $\sigma_i \cdot B_{ZZ} / B^{SM}_{ZZ}$.



Mass vs. μ.

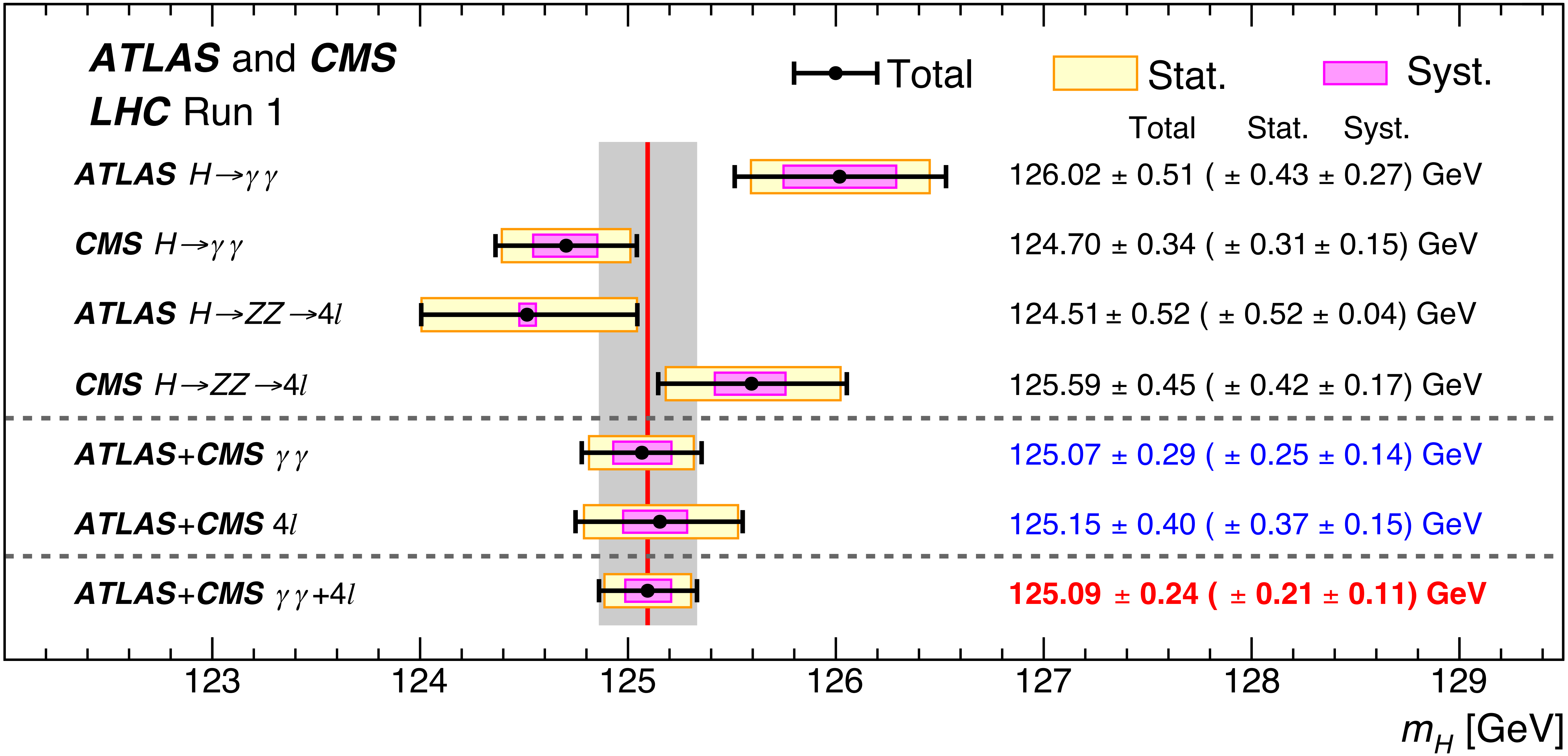


ATLAS and CMS
LHC Run 1
H→γγ
H→ZZ→4l
Combined γγ+4l
Stat. only uncert.
−2ln Λ(m_H)
m_H [GeV]



ATLAS and CMS
LHC Run 1
ATLAS H→γγ
ATLAS H→ZZ→4l
CMS H→γγ
CMS H→ZZ→4l
All combined
Best fit
68% CL
Signal strength (μ)
m_H [GeV]

Run-1 ATLAS+CMS mass combination.



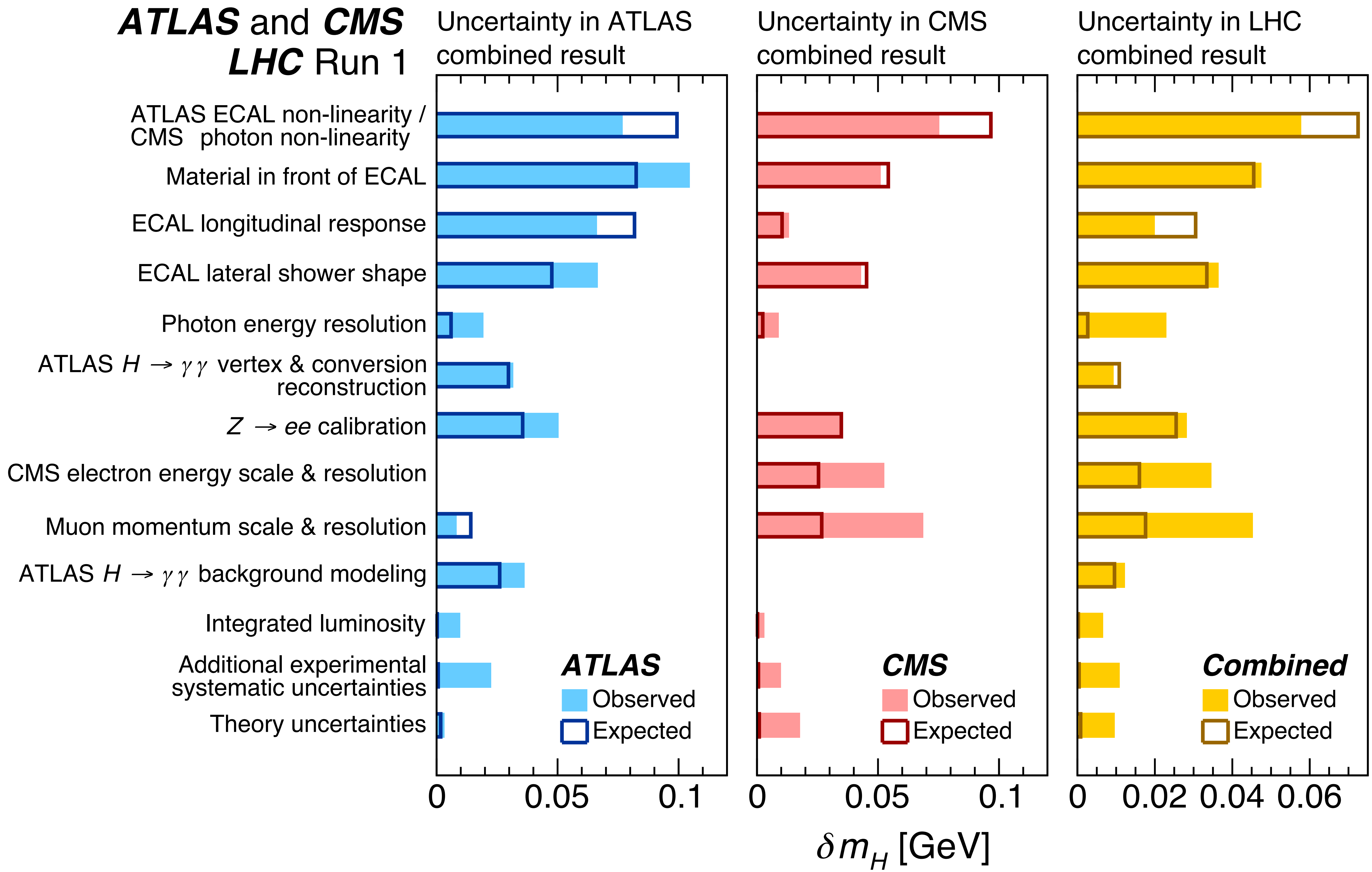
Results from the ***Run-1 ATLAS+CMS mass combination:***

Systematic uncertainty breakdown given in backup

Dominant uncertainties:

non-linearity, material in front of ECAL, muon calibration

Mass systematic uncertainties.



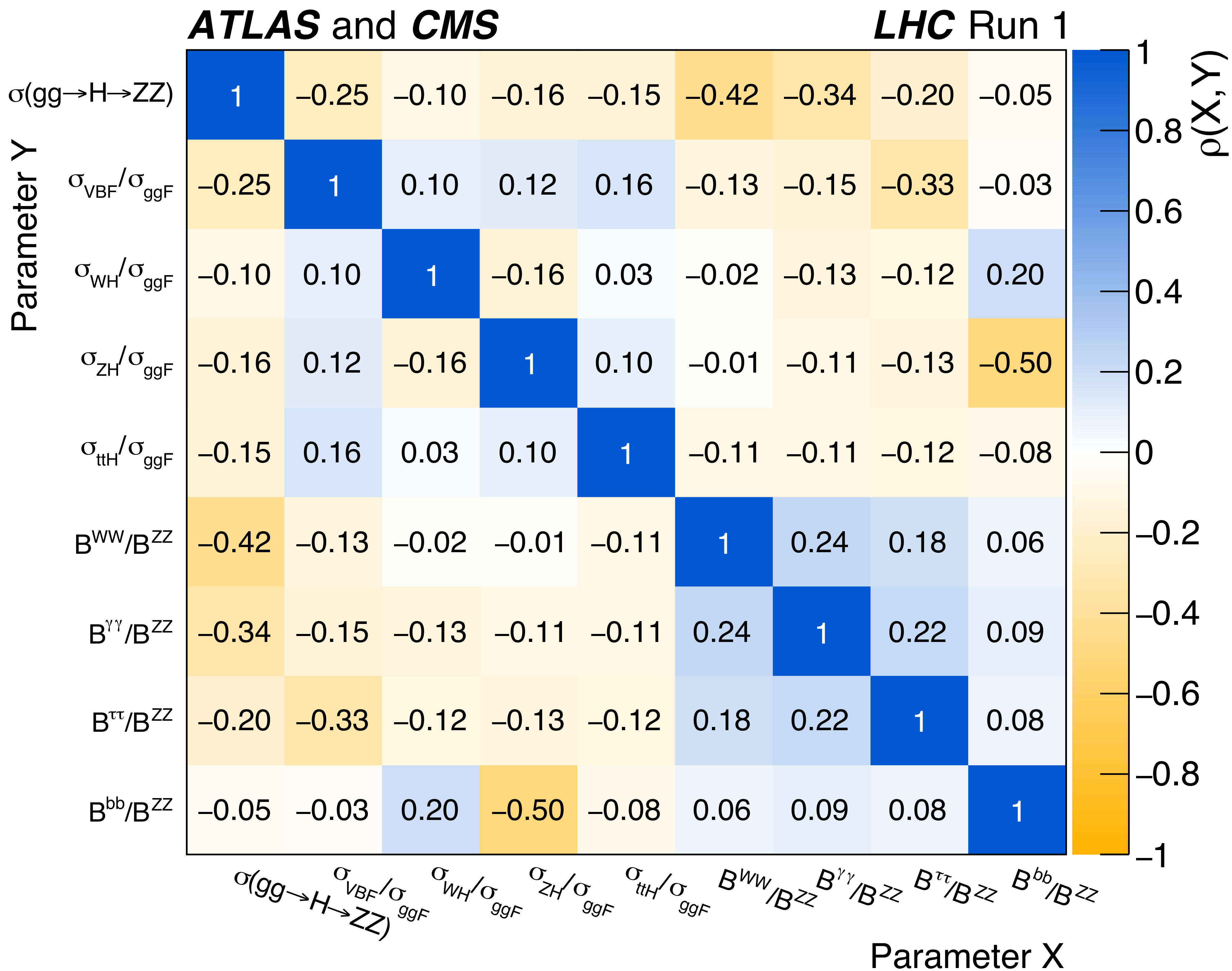
Couplings: compatibility with SM.

Parameterisation	p-value	DOF	Parameters
Global signal strength	40%	1	μ
Production processes	24%	5	$\mu_{ggF}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	65%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}$
Decay modes with $H \to \mu\mu$	75%	6	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}, \mu^{\mu\mu}$
μ_V and μ_F per decay	90%	10	$\mu_V^{\gamma\gamma}, \mu_V^{ZZ}, \mu_V^{WW}, \mu_V^{\tau\tau}, \mu_V^{bb}, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{bb}$
μ_V/μ_F ratio	75%	6	$\mu_V/\mu_F, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{bb}$
$\sigma_i \cdot \mathrm{B}^f$ product	20%	23	$(\sigma\cdot\mathrm{B})_{ggF}^{\gamma\gamma}, (\sigma\cdot\mathrm{B})_{ggF}^{ZZ}, (\sigma\cdot\mathrm{B})_{ggF}^{WW}, (\sigma\cdot\mathrm{B})_{ggF}^{\tau\tau}, (\sigma\cdot\mathrm{B})_{VBF}^{\gamma\gamma}, (\sigma\cdot\mathrm{B})_{VBF}^{ZZ}, (\sigma\cdot\mathrm{B})_{VBF}^{WW}, (\sigma\cdot\mathrm{B})_{VBF}^{\tau\tau}, (\sigma\cdot\mathrm{B})_{WH}^{\gamma\gamma}, (\sigma\cdot\mathrm{B})_{WH}^{ZZ}, (\sigma\cdot\mathrm{B})_{WH}^{WW}, (\sigma\cdot\mathrm{B})_{WH}^{\tau\tau}, (\sigma\cdot\mathrm{B})_{WH}^{bb}, (\sigma\cdot\mathrm{B})_{ZH}^{\gamma\gamma}, (\sigma\cdot\mathrm{B})_{ZH}^{ZZ}, (\sigma\cdot\mathrm{B})_{ZH}^{WW}, (\sigma\cdot\mathrm{B})_{ZH}^{\tau\tau}, (\sigma\cdot\mathrm{B})_{ZH}^{bb}, (\sigma\cdot\mathrm{B})_{ttH}^{\gamma\gamma}, (\sigma\cdot\mathrm{B})_{ttH}^{ZZ}, (\sigma\cdot\mathrm{B})_{ttH}^{WW}, (\sigma\cdot\mathrm{B})_{ttH}^{\tau\tau}, (\sigma\cdot\mathrm{B})_{ttH}^{bb}$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$	16%	9	$\sigma(gg \to H \to ZZ), \sigma_{VBF}/\sigma_{ggF}, \sigma_{WH}/\sigma_{ggF}, \sigma_{ZH}/\sigma_{ggF}, \sigma_{ttH}/\sigma_{ggF}, \mathrm{B}^{WW}/\mathrm{B}^{ZZ}, \mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}, \mathrm{B}^{\tau\tau}/\mathrm{B}^{ZZ}, \mathrm{B}^{bb}/\mathrm{B}^{ZZ}$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$ and 7/8 TeV	26%	14	$\sigma(gg \to H \to ZZ), \sigma_{VBF}/\sigma_{ggF}, \sigma_{WH}/\sigma_{ggF}, \sigma_{ZH}/\sigma_{ggF}, \sigma_{ttH}/\sigma_{ggF}, \mathrm{B}^{WW}/\mathrm{B}^{ZZ}, \mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}, \mathrm{B}^{\tau\tau}/\mathrm{B}^{ZZ}, \mathrm{B}^{bb}/\mathrm{B}^{ZZ}, \sigma_{ggF}^{7TeV}/\sigma_{ggF}^{8TeV}, \sigma_{VBF}^{7TeV}/\sigma_{VBF}^{8TeV}, \sigma_{WH}^{7TeV}/\sigma_{WH}^{8TeV}, \sigma_{ZH}^{7TeV}/\sigma_{ZH}^{8TeV}, \sigma_{ttH}^{7TeV}/\sigma_{ttH}^{8TeV}$
Coupling ratios	12%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	74%	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings vs mass	55%	2	M, ϵ
Couplings, BSM loops	11%	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_g, \kappa_\gamma$
BSM loops only	87%	2	κ_g, κ_γ
Fermion and vector couplings	64%	2	$\lambda_{FV}, \kappa_{VV}$
Up vs down couplings	72%	3	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$
Lepton vs quark couplings	79%	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$

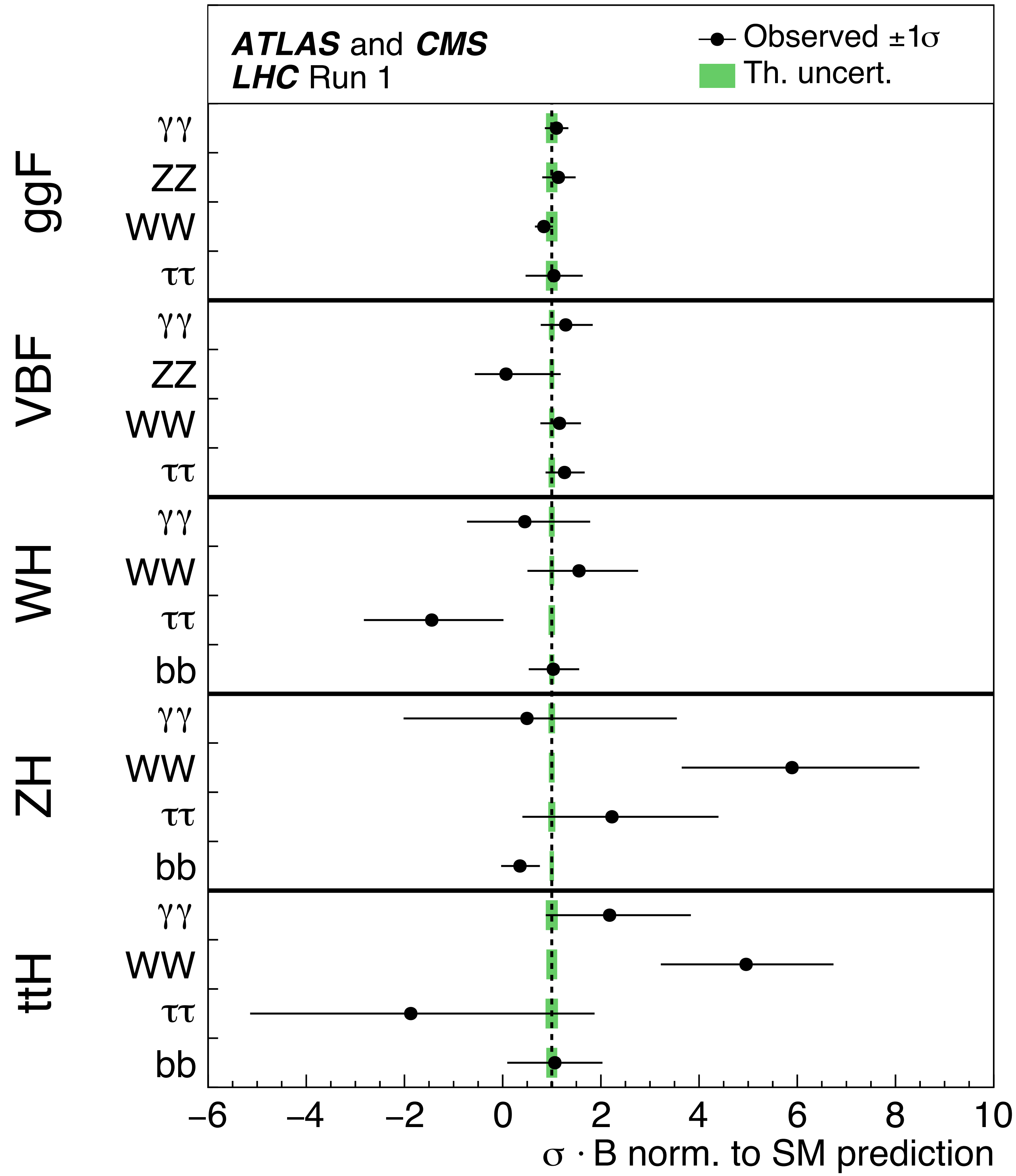
κ-framework parameterization.

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{\text{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Run-1 Cross section and BR ratio correlations.



$\sigma_i \cdot B^f$ for each channel ($i \to H \to f$).



The sensitivity of the Run-I combination allows six of the $\sigma_i \cdot B^f$ to be measured with a precision better than 40%

ggF

$H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$

VBF

$H \to \gamma\gamma$, $H \to WW$, $H \to \tau\tau$

Run-1 Production and decay significances.

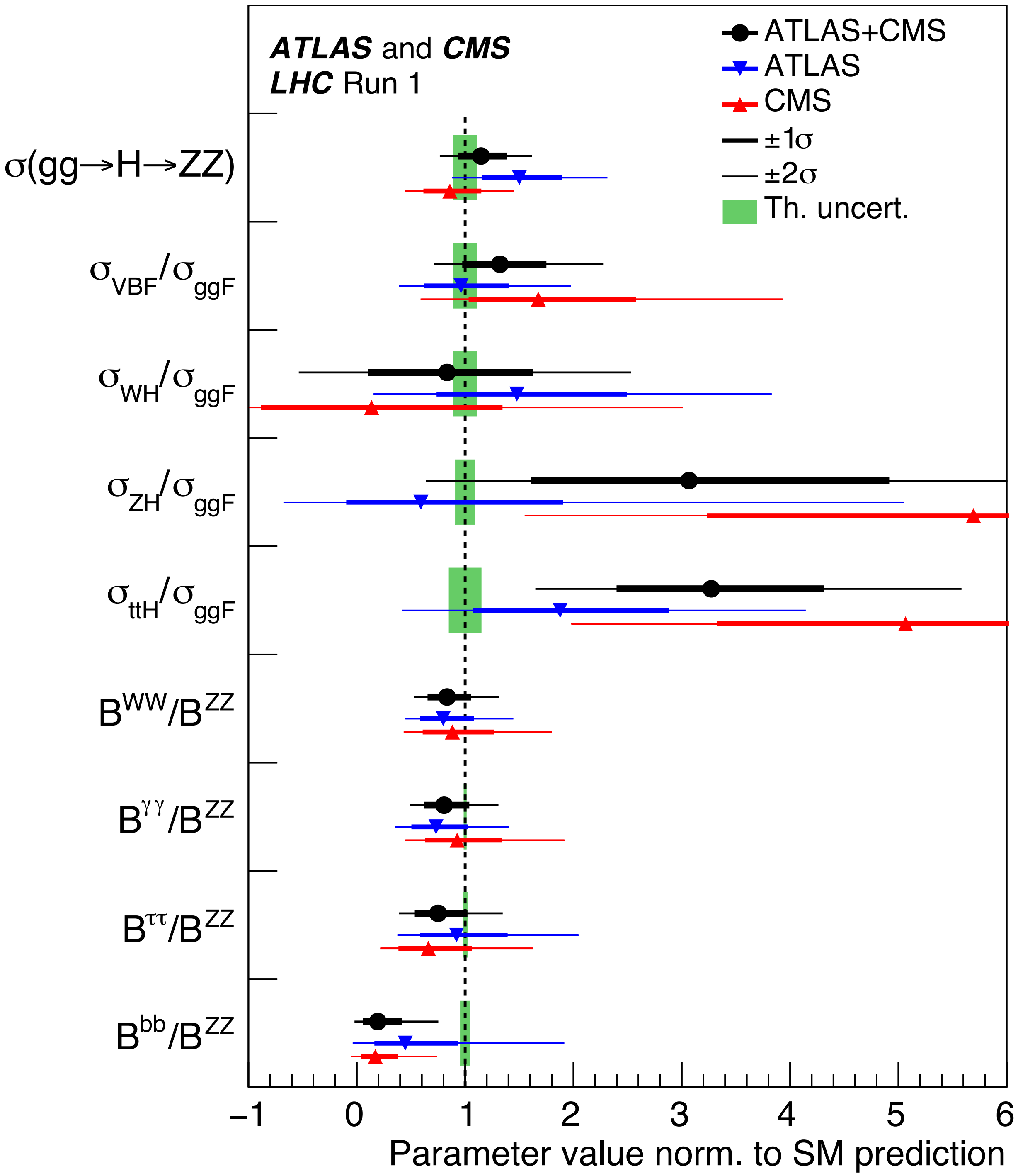
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Factor of √2 improvement in sensitivity from ATLAS+CMS combination

- Combined **>5σ** significance provides **observation of VBF production and *H*→*ττ* decay**
- **>3σ** significance for **VH production**
- **4.4σ** significance for ***ttH*** (**2.3σ excess** relative to SM)

Cross section and branching fraction ratios.

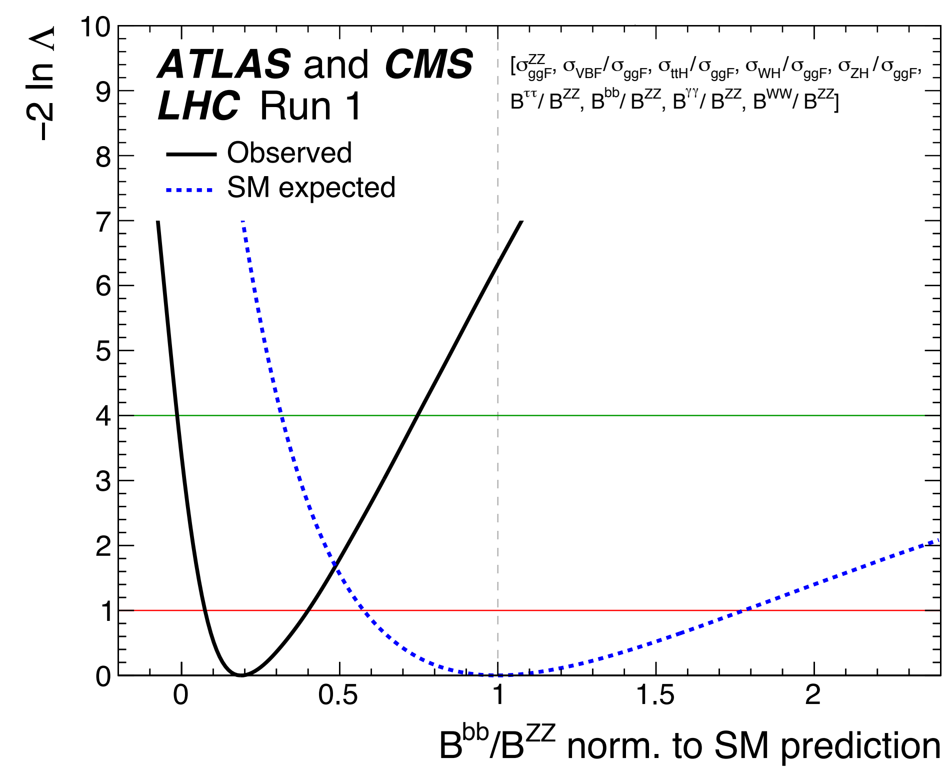
$$\sigma_i \cdot B^f = \sigma(gg \to H \to ZZ) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{B^f}{B^{ZZ}}\right)$$



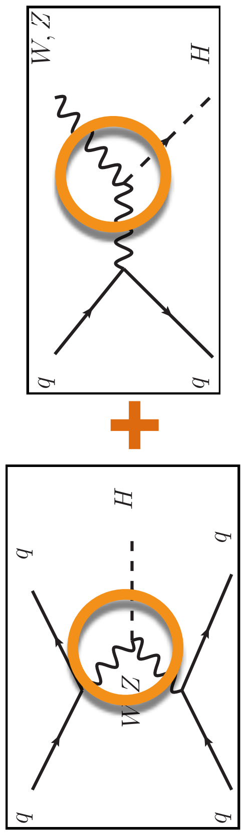
$\frac{\sigma_{ttH}}{\sigma_{ggF}}$ ratio of **3.3±1.0 (3σ excess)** relative to SM (mainly from multi-lepton)

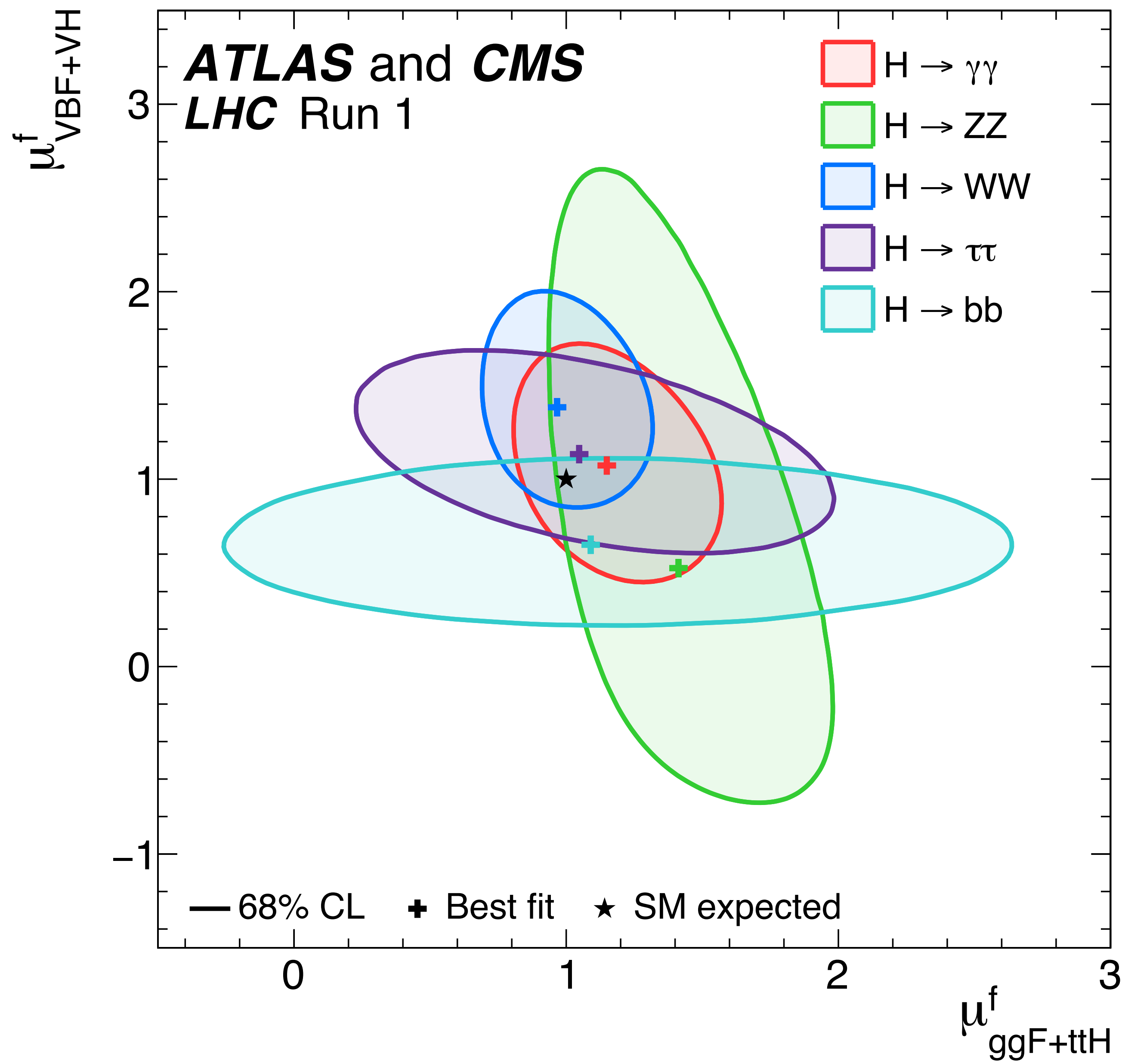
$\frac{\sigma_{ZH}}{\sigma_{ggF}}$ ratio of **3.2±1.7** relative to SM (slightly milder excess)

$\frac{B^{bb}}{B^{ZZ}}$ **~2.5σ** deficit relative to SM (in current parameterization, high values for $\boldsymbol{\sigma_{ttH}/\sigma_{ggF}}$ and $\boldsymbol{\sigma_{ZH}/\sigma_{ggF}}$ induce a low $\boldsymbol{H \to bb}$)



Production μ by decay channel.



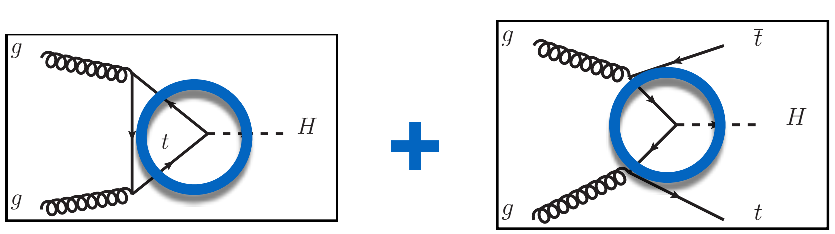


$$\mu_i^f = \frac{\sigma_i \cdot B^f}{\sigma_i^{SM} \cdot B^f_{SM}}$$

Parameterization using **two production signal strengths (*i*)**, one for **fermions** and one for **bosons**:

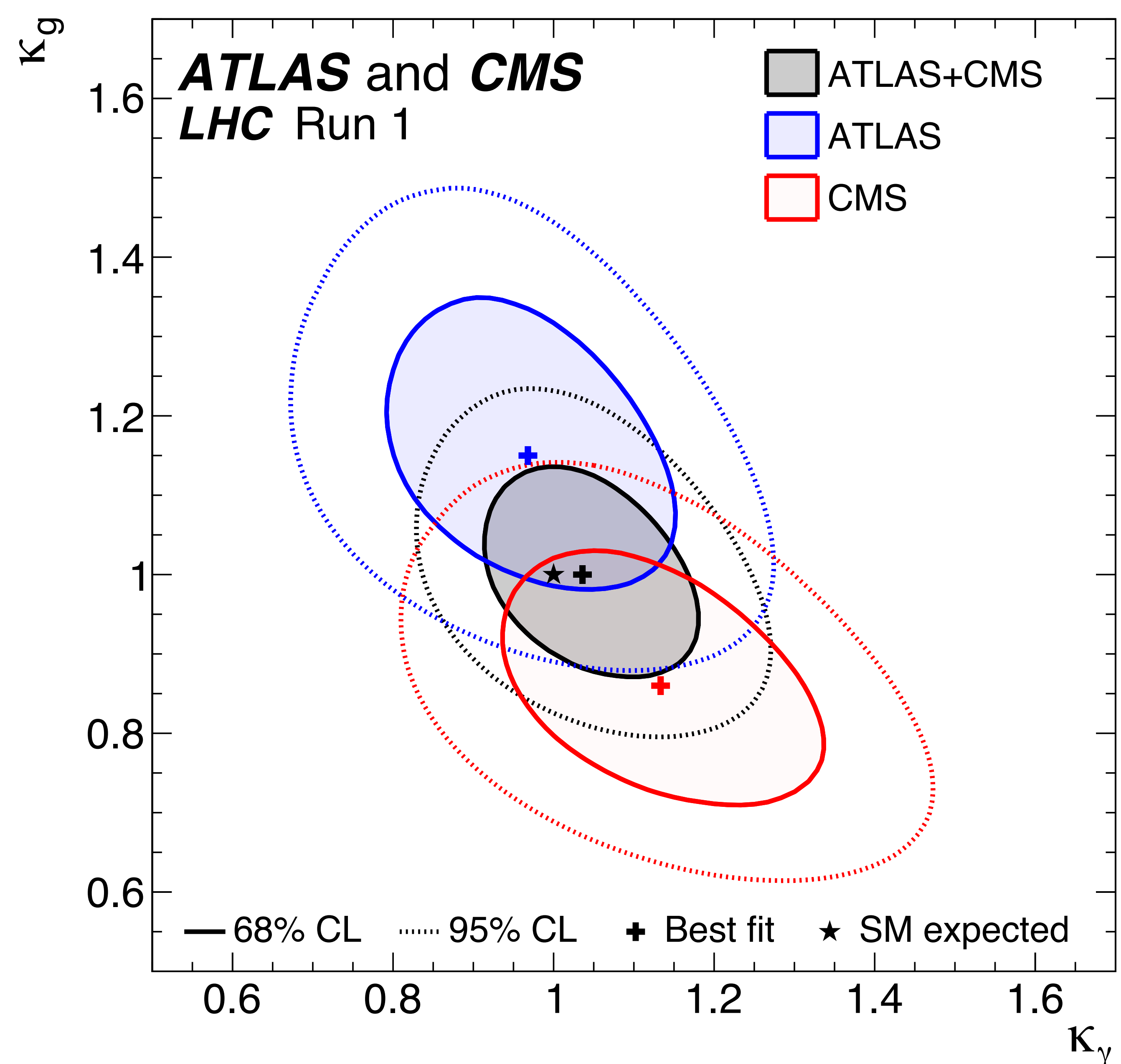
$\boldsymbol{\mu^f_{ggF+ttH}}$ vs. $\boldsymbol{\mu^f_{VBF+VH}}$

Good agreement with SM prediction for all decay channels



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

- No BSM decays (B_{BSM} = 0)
- All the couplings to SM particles are the same as in the SM
- Only the ***ggF*** production and ***γγ*** decay loops are allowed to be affected by the presence of additional particles
- Only free parameters κ_γ and κ_g, with all other coupling modifiers fixed to their SM values



p-value of the compatibility between the data and the SM predictions is 82%

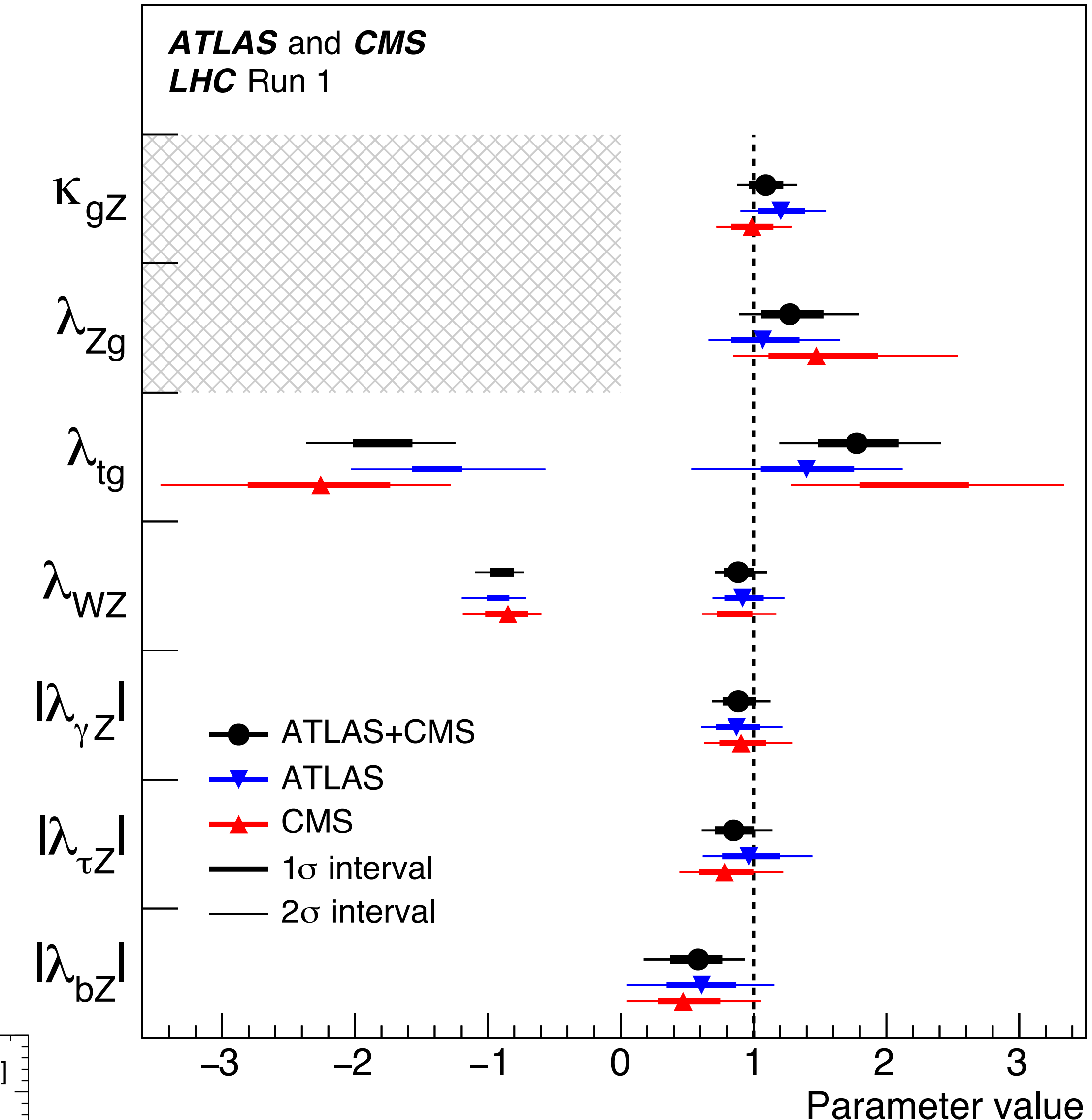
Conversion of signal strength ratios into κ-framework using:

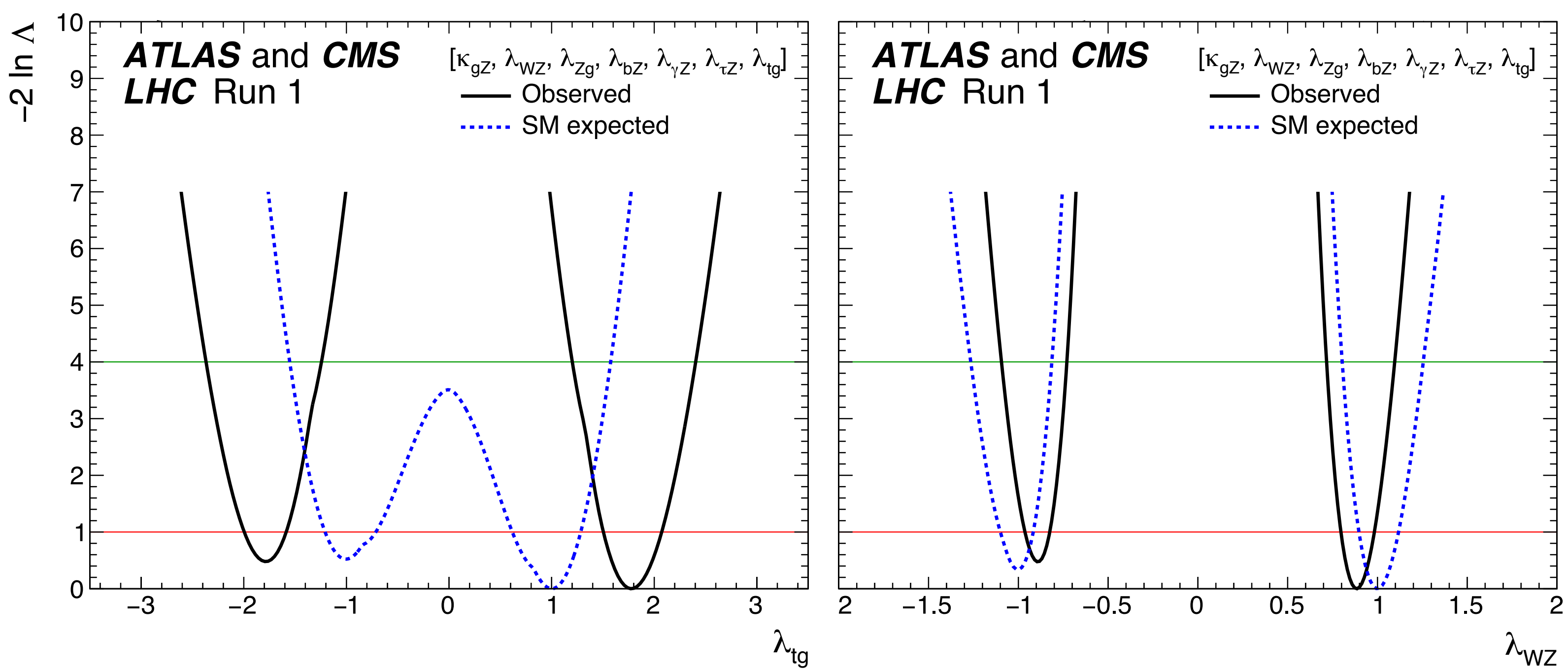
$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

Cross section times branching fraction for the ***gg→H→ZZ*** channel is parameterized as a function of:

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

then all other κ's can be determined

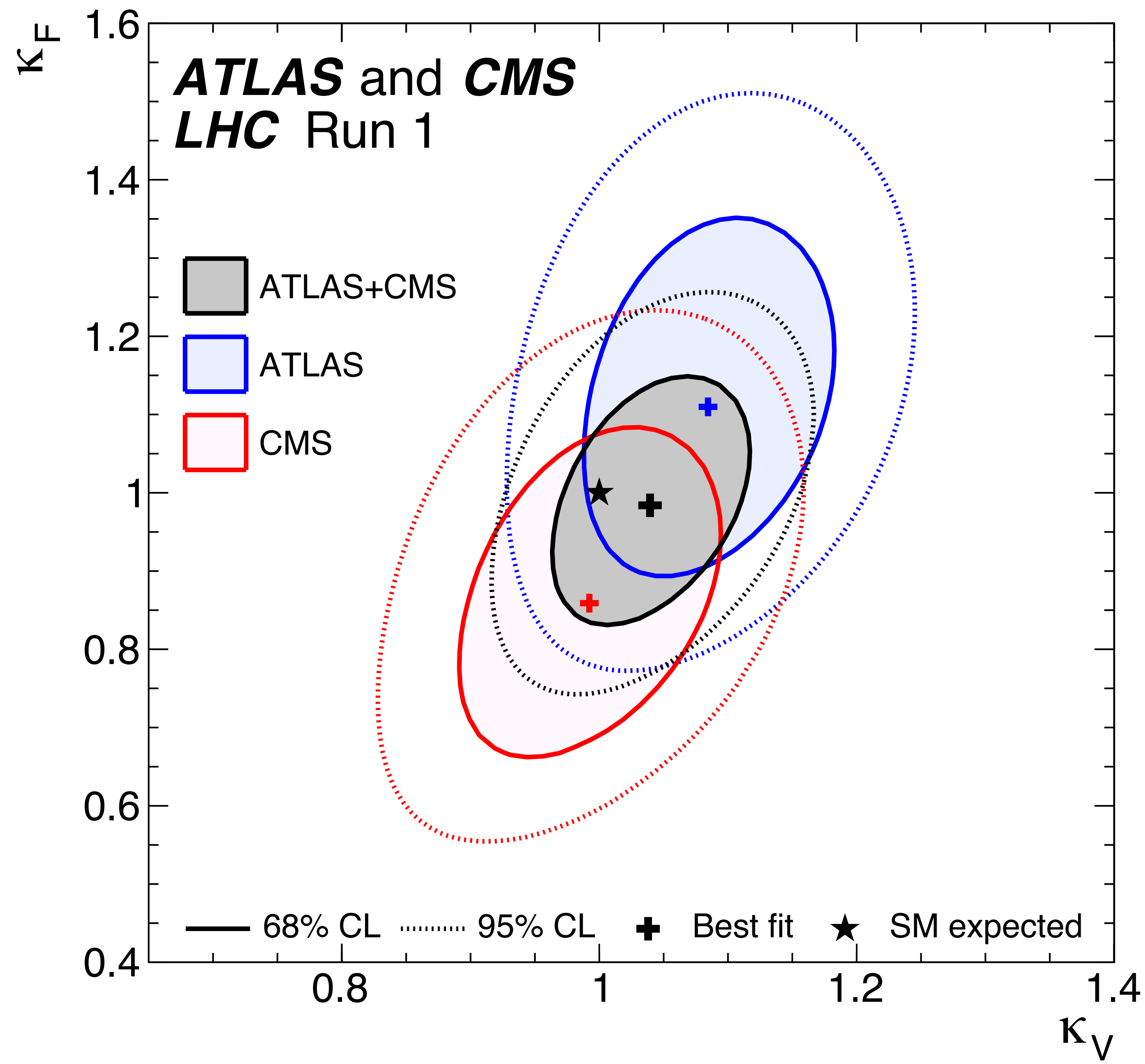




Negative ranges allowed for $\boldsymbol{\lambda_{WZ}}$ and $\boldsymbol{\lambda_{tg}}$ to illustrate possible interference effects due to ***ggZH*** or ***tH*** production

Best fit >0, but limited sensitivity to interference terms

Boson vs. fermion couplings.



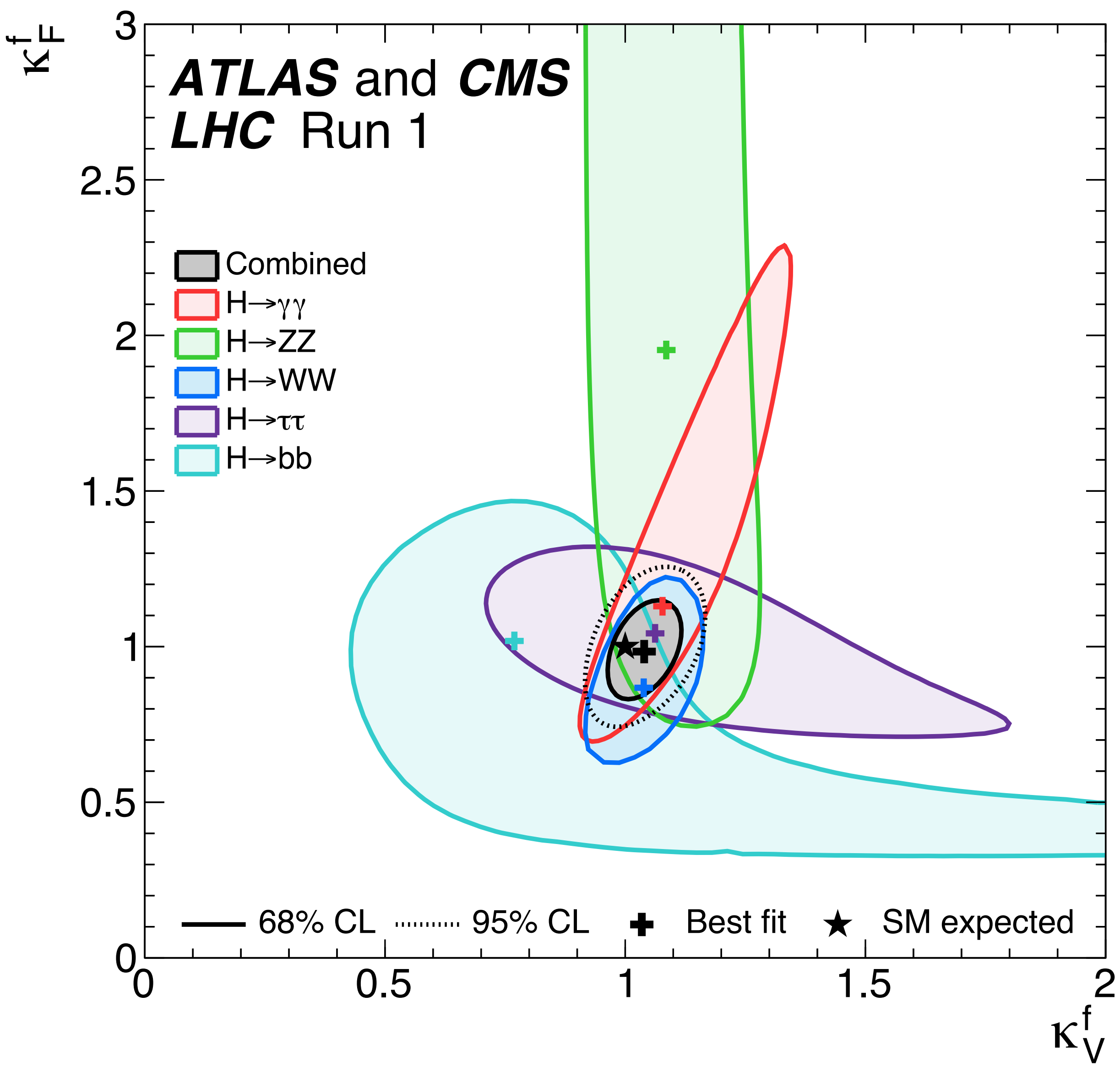
- SM Higgs couplings to fermions and boson very different

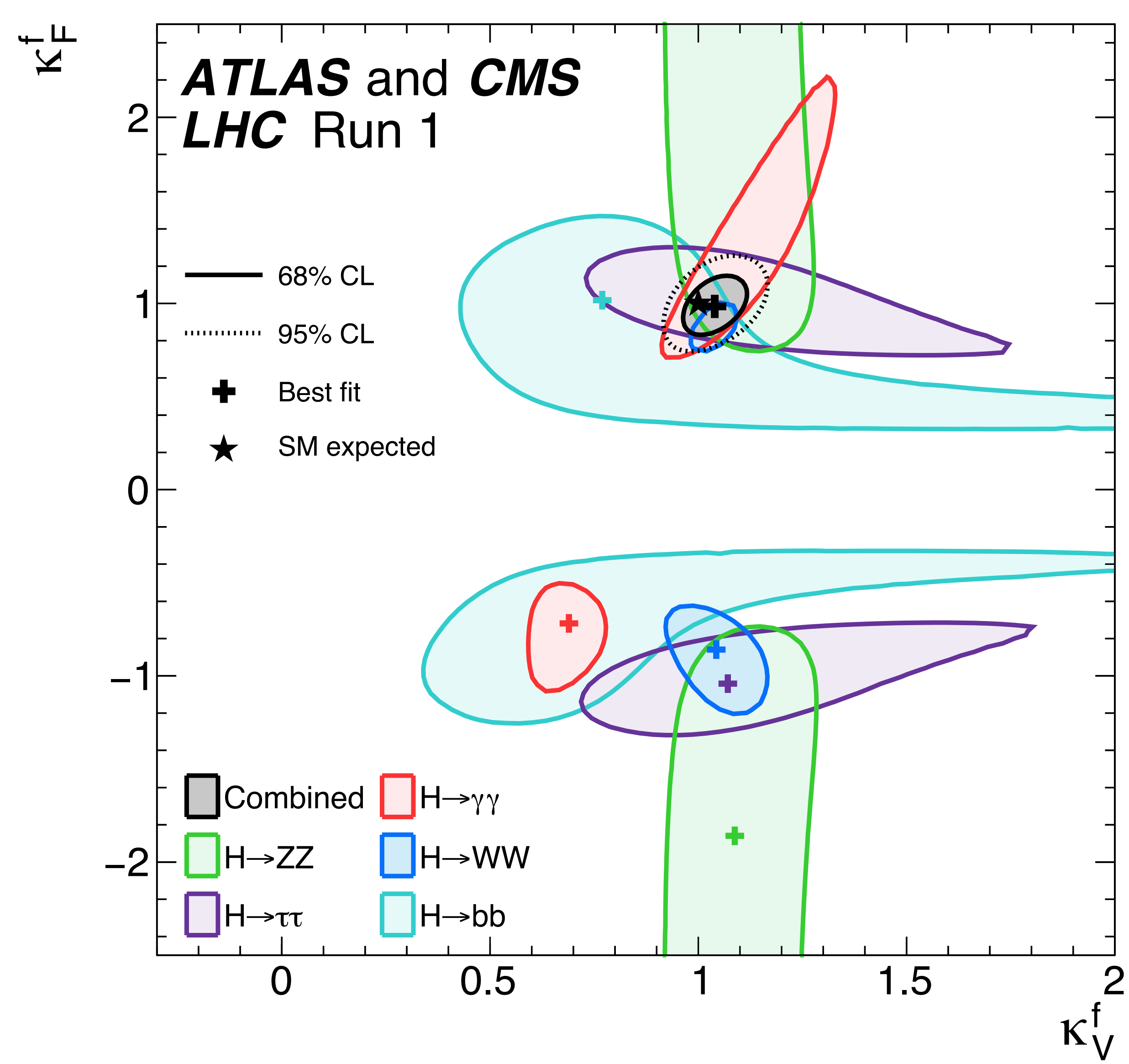
  Yukawa vs $\boldsymbol{D_\mu} \rightarrow \boldsymbol{\kappa_F}$ vs $\boldsymbol{\kappa_V}$

- $\boldsymbol{\kappa_F}$, $\boldsymbol{\kappa_V}$ in agreement with SM
- $\boldsymbol{\kappa_F} \times \boldsymbol{\kappa_V} < 0$ excluded at almost $\boldsymbol{5\sigma}$

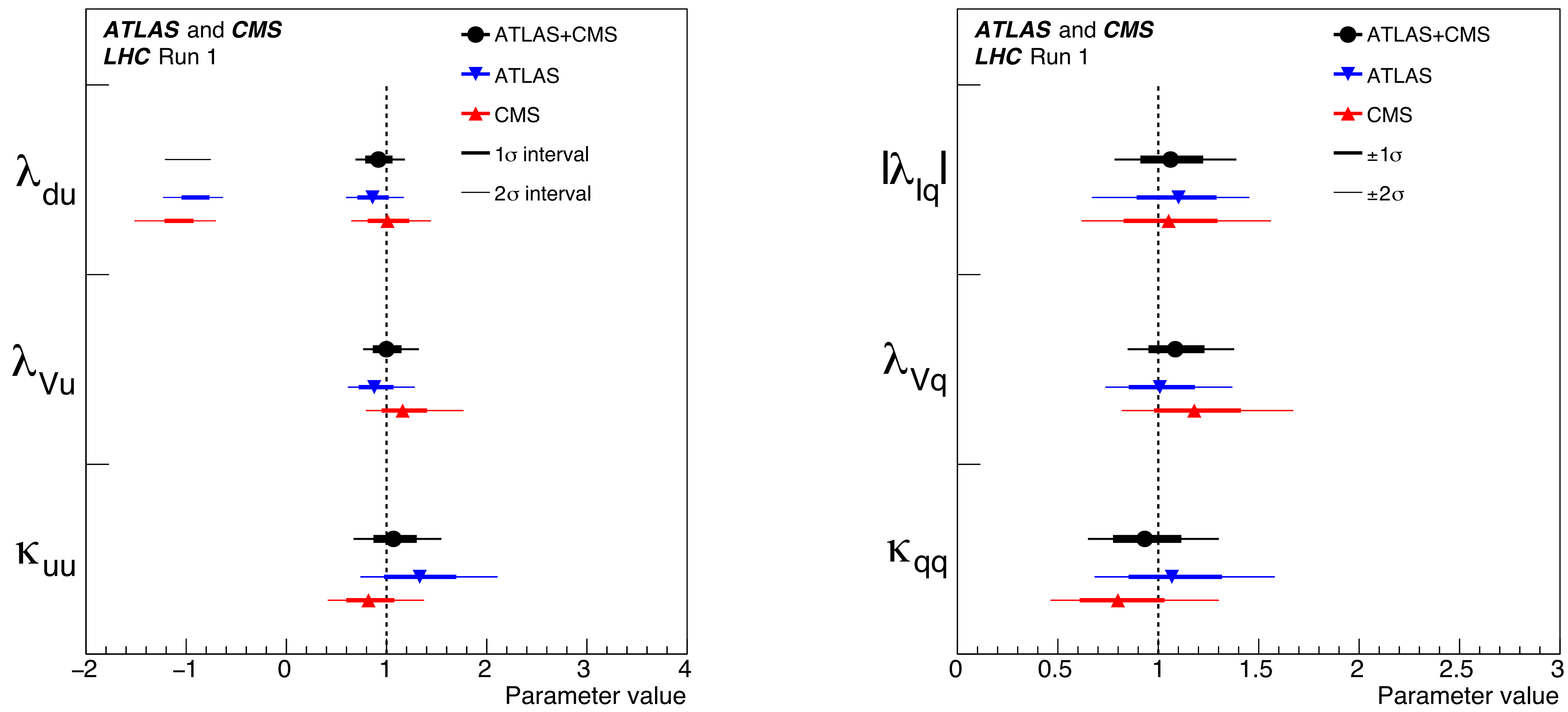
Likelihood contours at 68% CL in the (κ_F^f , κ_V^f) plane for the combination and for the individual decay channels as well as for their global combination, all κ's are assumed to positive

Likelihood contours at 68% and 95% CL in the (κ_F^f, κ_V^f) plane for the individual decay channels and also the combination, with no assumption about the sign of the coupling modifiers





Lepton-quark and up-down symmetry.



- ***u-type*** & ***d-type*** quarks could couple to different fields
- Test potential variations of $\lambda_{ud} = \frac{\kappa_d}{\kappa_u}$
- ***Charged leptons*** have same couplings as d-quarks for $\boldsymbol{\lambda_{ud}}$
- test the variation of coupling to leptons vs quarks $\lambda_{lq} = \frac{\kappa_l}{\kappa_q}$

All ratios consistent with unity

Couplings with BSM loops and new decays.