Higgs boson couplings measurements in ATLAS and CMS

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on behalf of the ATLAS and CMS Collaboration

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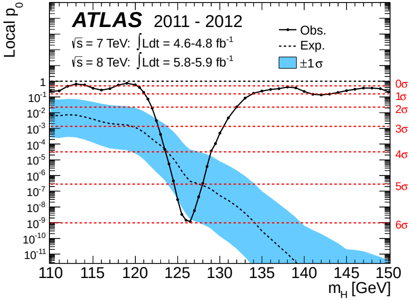
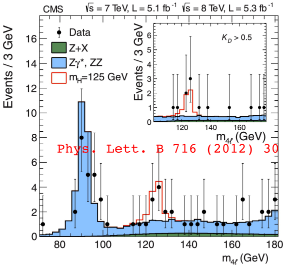
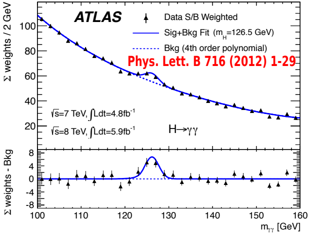
Discovery of a Higgs-like boson (July 2012)

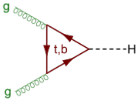




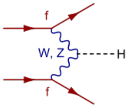


- Greatest achievement of Run 1
- Sizable efforts spent studying its properties, searching for NP
- Magnitude of its couplings to other particles is of utmost importance

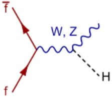
Higgs boson production modes



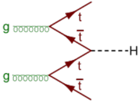
ggF



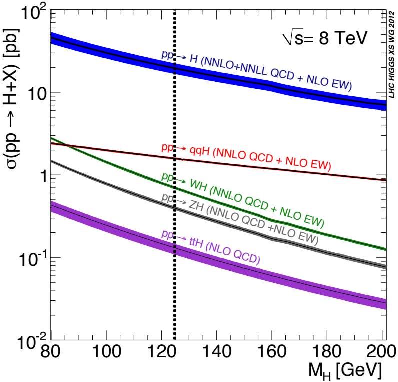
VBF



VH



ttH

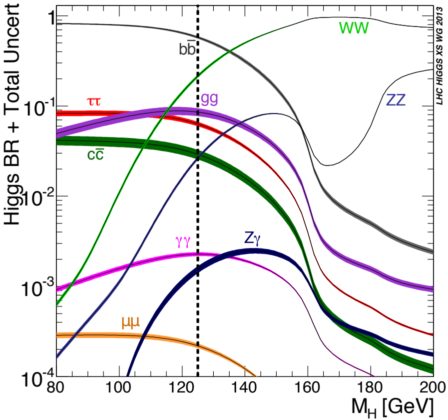


Other production mechanisms

$b\bar{b}H$, $gg \to ZH$ (box) and single-top+Higgs contributions not targetted by specific categories, but implemented in the fit model

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

Higgs boson decay channels



SM Branching ratios at $m_H = 125.09 \pm 0.24$ GeV

Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

$BR(VV^*)$ vary by $\approx 2\%$ in 1 $\sigma(m_H)$

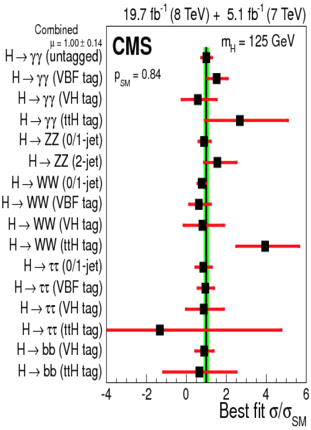
No analysis dedicated to $H \to c\bar{c}$ or $H \to gg$ (very low $\frac{S}{B}$)

Both production & decay depend on $m_H \to$ measure m_H first and every other property will be measured at this mass

Individual combination by each collaboration

Each experiment already published its combination, with different inputs

Results from 7 TeV (5 fb^{-1}) + 8 TeV (20 fb^{-1}) datasets from 2011-2012



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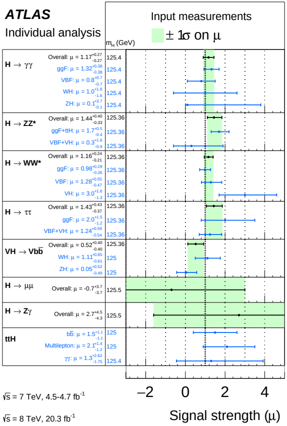

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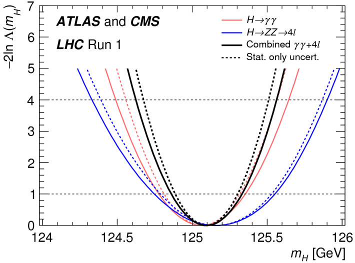
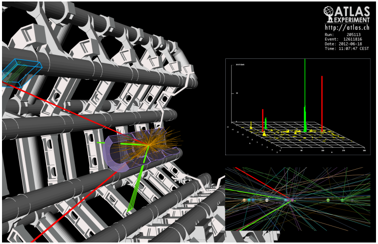
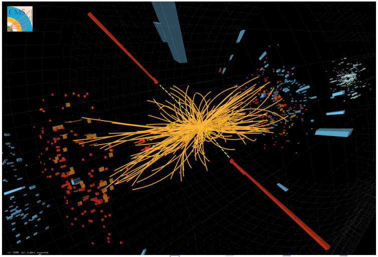
- Measured in $\gamma\gamma$ and $4l$ channels (best mass resolution)
- $m_H = 125.09 \pm 0.21(stat)$ $\pm 0.11(syst)$ GeV
- Neglects interference between $gg \to \gamma\gamma$ and $gg \to H \to \gamma\gamma$:
  $\Delta m_H^{\gamma\gamma} = -35 \pm 9$ MeV (ATLAS)







Inputs to the ATLAS-CMS couplings combination

- Most of the analyses split datasets into categories
  - Different $\frac{S}{B}$ and background uncertainties
  - Increases discovery sensitivity
  - Provides sensitivity to different production modes
- $\approx$ 600 categories total
- Each can receive contributions from different processes
- Each can bring information about different couplings

Many categories target specific production and decay processes

	ggF	VBF	VH	$t\bar{t}H$
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to ZZ^* \to 4l$	✓	✓	✓	✓
$H \to WW^* \to 2l2\nu$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to b\bar{b}$	✗	✗	✓	✓
$H \to \mu\mu$	✓	✓	✗	✗

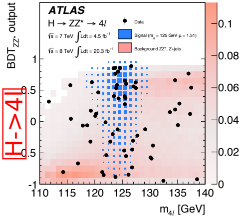
$\frac{S}{B}$ too low in $gg \to H \to b\bar{b}$
VBF $H \to b\bar{b}$ (CMS) not combined
Signal yield too low in VH and $t\bar{t}H$, $H \to \mu\mu$
$H \to \mu\mu$ used only in one model

Assume SM tensor structure ($\to$ SM kinematics)
and Narrow Width Approximation ($\sigma(i \to H \to f) = \sigma_i \frac{\Gamma_f}{\Gamma_{tot}}$)
See talks by K. Whalen (differential XS), A.-M. Magnan (spin/CP)

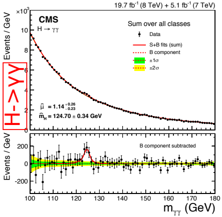
Every analysis extracts the signal yield :

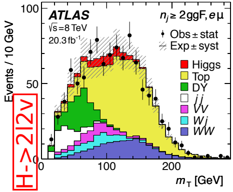
$$n_s = \mathcal{L} \sum_i \sum_f (\sigma_i A_i^{f,SM} \epsilon_i^{f,SM} BR^f) = \mathcal{L} \sum_i \sum_f (\mu_i \sigma_i^{SM} A_i^{f,SM} \epsilon_i^{f,SM} \mu^f BR^f_{SM})$$

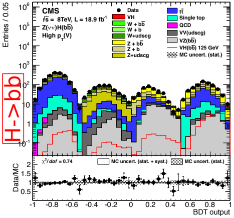
with $\mathcal{L}$ the luminosity, ϵ efficiencies, A the detector acceptance and μ_i, μ^f are signal strengths

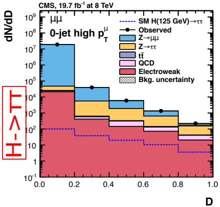


The discriminating variables used are very different depending on the analyses









Statistical procedure

Test-statistic definition

Use profile log-likelihood ratio $t_\alpha = -2\ ln\ \frac{L(\vec{\alpha}; \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}; \hat{\vec{\theta}})}$

- $\vec{\alpha}$ represents the parameters of interest (POI)
- $\vec{\theta}$ are nuisance parameters (NP), representing systematic uncertainties
- $\hat{\vec{\alpha}}$, $\hat{\vec{\theta}}$ are the values of the POI and NP that maximise L
- $\hat{\hat{\vec{\theta}}}(\vec{\alpha})$ is the value of the NP that maximise L for a given $\vec{\alpha}$

Assume the large-sample limit to be valid ($f(t_\alpha) = \chi^2(n.\ dof)$)

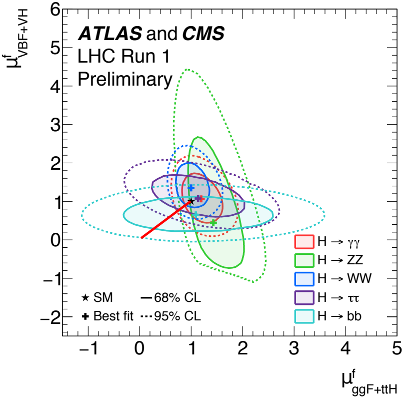
- Full combination uses $\approx$ 4200 nuisance parameters
  - Many nuisance parameters correspond to Monte Carlo Statistical Uncertainty

Correlation scheme

- Theory uncertainties correlated between the two experiments (e.g. QCD scales, PDF)
- Most experimental uncertainties are uncorrelated (except part of the luminosity)

Production signal-strength by decay channel

Good agreement between all the decay channels for the measurement of $\mu_{ggF+ttH}$ vs μ_{VBF+VH} ($\mu_{prod}^{decay} = \frac{\sigma_{prod}}{\sigma_{prod}^{SM}} \frac{BR^{decay}}{BR_{SM}^{decay}}$)



Following results based on higher-dimensional versions (4 μ) of this plot

Significances of the various channels

Quantifies probability for the current observation under hypothesis there is no signal in a given production/decay channel

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
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

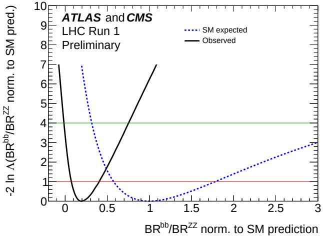
- Observation of VBF production, $H \to \tau\tau$ decay channels
- Evidence for VH and $t\bar{t}H$ production modes (see $t\bar{t}H$ talk by V. Kostyukhin)

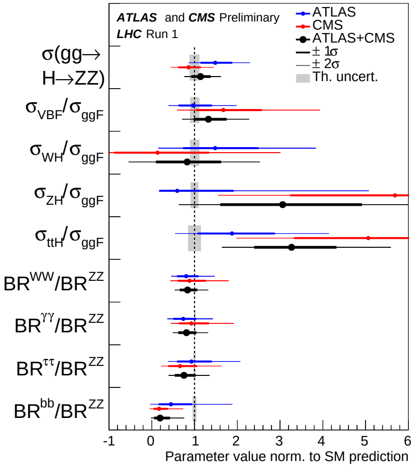
Ratio of cross-sections and branching fractions

Use ratios of μ^f (μ_i) (= ratios of BR (σ)) for more general parametrization

$$\sigma(i \to H \to f) = \sigma(gg \to H \to ZZ^*) \times \left(\frac{BR_f}{BR_{ZZ^*}}\right) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right)$$

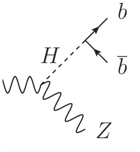
- Excess in $\frac{\sigma_{ttH}}{\sigma_{ggF}}$
- Milder $\frac{\sigma_{ZH}}{\sigma_{ggF}}$ excess
- 2.4σ deficit in $\frac{BR_{b\bar{b}}}{BR_{ZZ}}$ (ZH & $t\bar{t}H$ excess not shared by $H \to b\bar{b}$)





The κ-framework

Leading-order inspired framework to study couplings developed by the LHC Higgs Cross Section WG



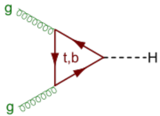
$\propto \frac{\kappa_Z \kappa_b}{\kappa_H}$

Each coupling scaled by κ, gives :

$\kappa_i^2 = \sigma_i/\sigma_i^{SM}$; $\kappa_f^2 = BR_f/BR_f^{SM}$

Loops (ggF, $H \to \gamma\gamma$) either expressed with κ_g, κ_γ or broken down into fundamental κs

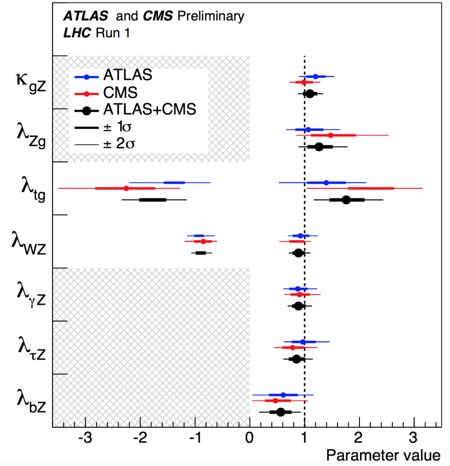
VBF depends on both κ_Z and κ_W



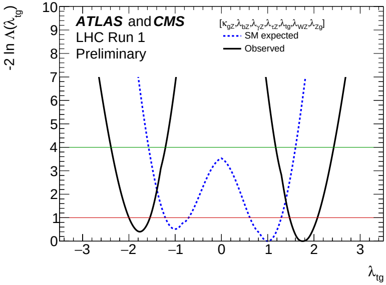
Width also modified by $\kappa_H^2 = \sum_j BR_j^{SM} \kappa_j^2$, or to accomodate for new (or enhanced un-measured) decay channel $\Gamma_H = \frac{\kappa_H^2 \Gamma_H^{SM}}{1 - BR_{BSM}}$

Sign of some κs unconstrained, e.g. sensitivity to sign of $\kappa_F \times \kappa_V$ through interference terms (single-top+Higgs, $gg \to ZH$, $h \to \gamma\gamma$)

Conversion of ratios of μs into κ-framework using $\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$

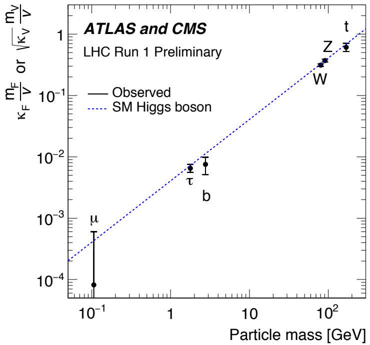


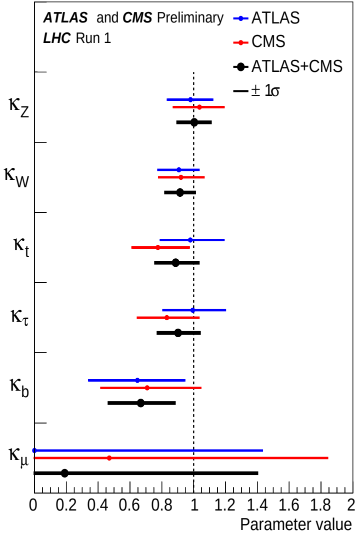
- Only assumption on Γ_H : NWA
  - $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$
- Then all the other $\kappa_{i,j}$ can be determined



Results for couplings modifiers (no BSM loops or decays)

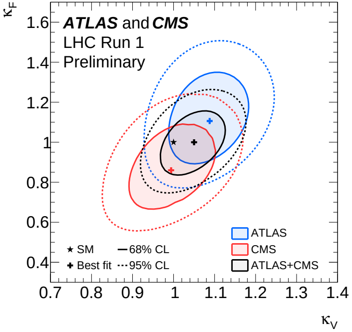
Here $H \to \mu\mu$ is combined too





- Express $\kappa_{g,H,\gamma}$ with other κs
- Consider $BR_{BSM} = 0$
- Couplings scale perfectly with mass, as expected in SM

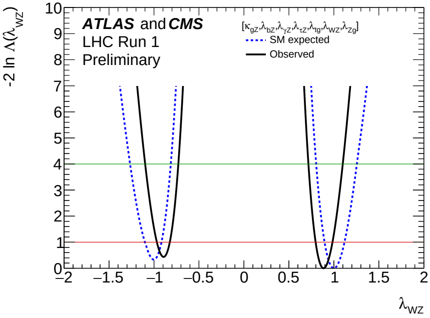
Boson-fermion and custodial symmetry



- Custodial symmetry : same couplings deviation for W & Z bosons, well tested by EWPM $\rightarrow \lambda_{WZ} = \frac{\kappa_Z}{\kappa_W}$
- Good agreement with $\lambda_{WZ} = 1$

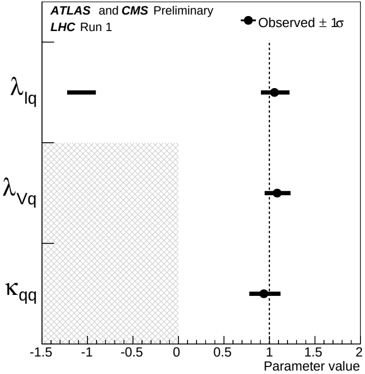
- SM Higgs couplings to fermions and boson very different (Yukawa vs D_μ) $\rightarrow \kappa_V$ vs κ_F
- κ_F, κ_V in agreement with SM

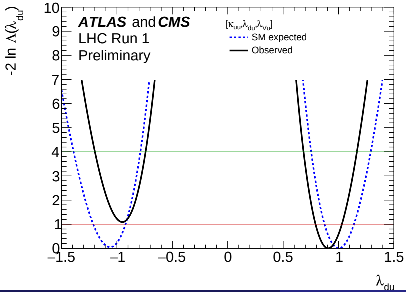
  ($\kappa_F \times \kappa_V < 0$ excluded at almost 5σ)



up-down and lepton-quark symmetries

- u-type & d-type quarks may couple to different fields → test potential variations of λ_{ud}
- Charged leptons have same couplings as d quarks for λ_{ud}



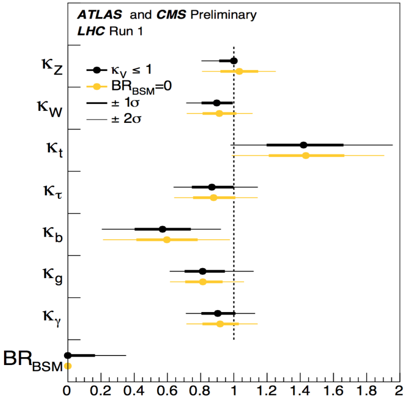


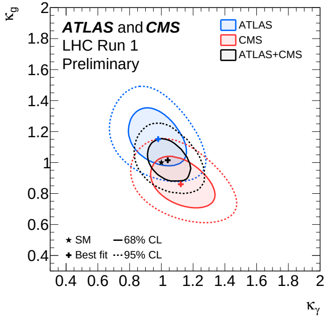
- Also test the variation of coupling to leptons vs quarks λ_{lq}
- All ratios compatible with 1

Couplings with BSM in loops/new decays

$gg \to H$ and $H \to \gamma\gamma$
loop-induced : sensitive to NP
(even above m_H)

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





2 scenarios to break degeneracy

- Probe new decay channels, impose $\kappa_V < 1$ (N-HDM) $\to$ $BR_{BSM} < 0.34$ 95%C.L. (left)
- Impose $BR_{BSM} = 0$ (up, $p_0 = 11\%$)

Conclusion

ATLAS+CMS combination gives the most accurate picture of the Higgs sector

- Mass measured at 0.2% level : $m_H = 125.09 \pm 0.24$ GeV

- VBF Higgs Production mechanism and $H \to \tau\tau$ observed (5σ)
- Evidence for VH and ttH

- Various parametrizations have been tried and were all found in agreement with SM (worst p-value of 11%)

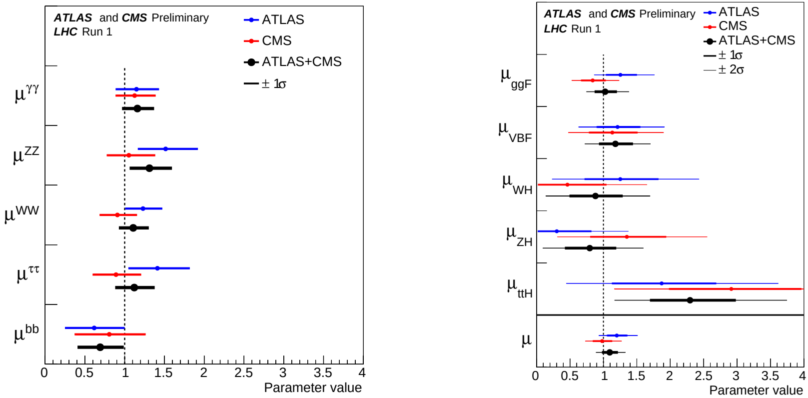
Still lot of room for surprises in Run 2, thanks to the coming improved precision (increased statistics and predictions)

BACKUP

Measurement of signal strength (μ)

$$\text{Reminder}: \mu_i = \frac{\sigma_i^{obs}}{\sigma_i^{SM}} \text{ and } \mu^f = \frac{BR_f^{obs}}{BR_f^{SM}}$$

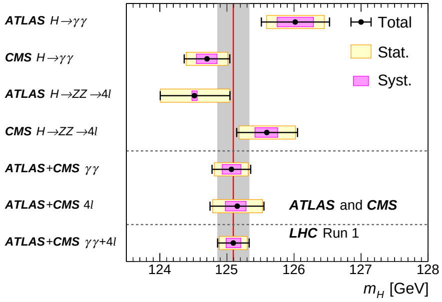
Set all $\mu^i = 1$ to measure μ_f — Set all $\mu^f = 1$ to measure μ_i

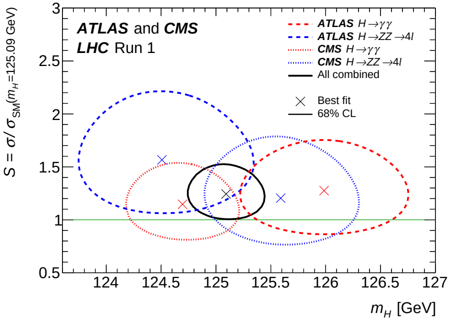


$\mu = 1.09 \pm 0.07(stat.) \pm 0.05(exp.) \pm 0.03(th.bkg.) \pm 0.07(th.sig.)$

Theory uncertainties can be improved (Talks by P. Nadolsky (PDFs), E. Furlan (XS & BR))

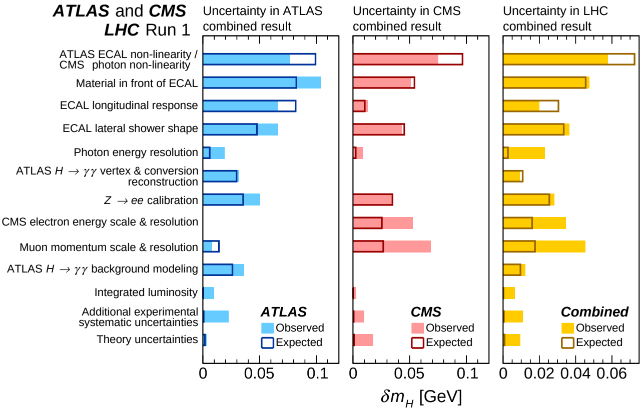
μ vs m_H and separate m_H measurement





Uncertainties for m_H measurement

Dominated by statistical uncertainty



Main systematics uncertainties linked to photon energy-scale (especially non-linearities)

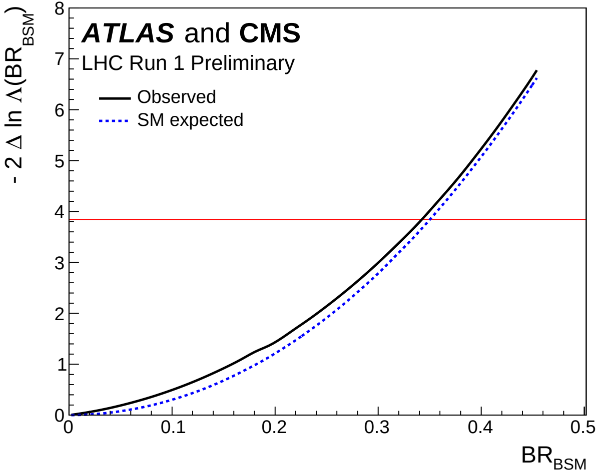
p-value of the Standard-Model within the various parametrisations

Model	p-value	DoF	Parameters
Global signal strength	34%	1	μ
Production processes	24%	5	μ_{ggF}, μ_{VBF}, μ_{WH}, μ_{ZH}, μ_{ttH}
Decay modes	60%	5	$\mu^{\gamma\gamma}$, μ^{ZZ}, μ^{WW}, $\mu^{\tau\tau}$, $\mu^{b\bar{b}}$
μ_V and μ_F per decay	88%	10	$\mu_V^{\gamma\gamma}$, μ_V^{ZZ}, μ_V^{WW}, $\mu_V^{\tau\tau}$, $\mu_V^{b\bar{b}}$, $\mu_F^{\gamma\gamma}$, μ_F^{ZZ}, μ_F^{WW}, $\mu_F^{\tau\tau}$, $\mu_F^{b\bar{b}}$
μ_V/μ_F ratio	72%	6	μ_V/μ_F, $\mu_F^{\gamma\gamma}$, μ_F^{ZZ}, μ_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	κ_{gZ}, λ_{Zg}, λ_{tg}, λ_{WZ}, $\lambda_{\gamma Z}$, $\lambda_{\tau Z}$, λ_{bZ}
Couplings, SM loops	65%	6	κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_μ
Couplings, BSM loops	11%	7	κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_g, κ_γ
BSM loops only	82%	2	κ_g, κ_γ
Up vs down couplings	67%	3	λ_{du}, λ_{Vu}, κ_{uu}
Lepton vs quark couplings	78%	3	λ_{lq}, λ_{Vq}, κ_{qq}
Fermion and vector couplings	59%	2	κ_V, κ_F

Expression of σs, BRs with κ

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

Scan of $-2\ ln\lambda(BR_{BSM})$



Confidence interval of κ_F vs κ_V (full range)