Higgs boson mass shift from interference effects in the $gg \to H \to \gamma\gamma$ channel at ATLAS

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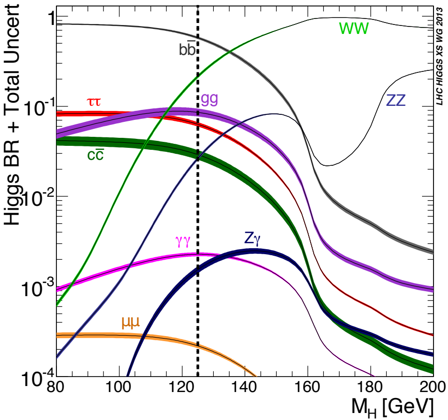
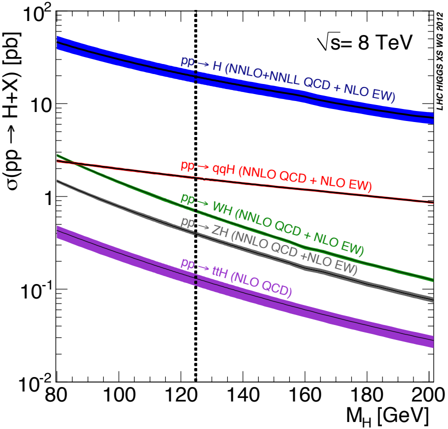
1. Motivations
2. Summary of the mass measurement in $h \to \gamma\gamma$
3. Description of the phenomenon
4. Estimate of Δm_H in the Standard Model
5. Δm_H for $\Gamma_H > \Gamma_H^{SM}$
6. Conclusion

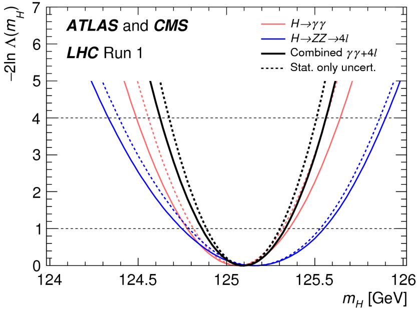
Higgs boson production & decay heavily depends on m_H $\rightarrow$ need to precisely measure it before searching for deviations w.r.t. SM

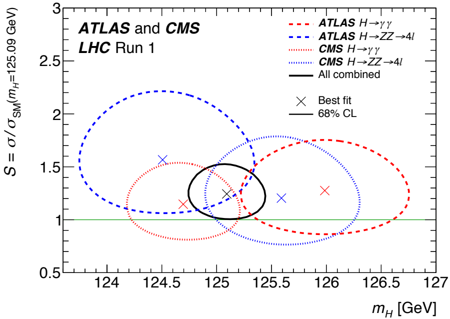




Precise determination of m_H Phys.Rev.Lett. 114 (2015) 191803

- Measured by ATLAS & CMS in $H \to \gamma\gamma$ & $H \to 4l$ (best resolution)
- 4 datasets combined to get most precise measurement



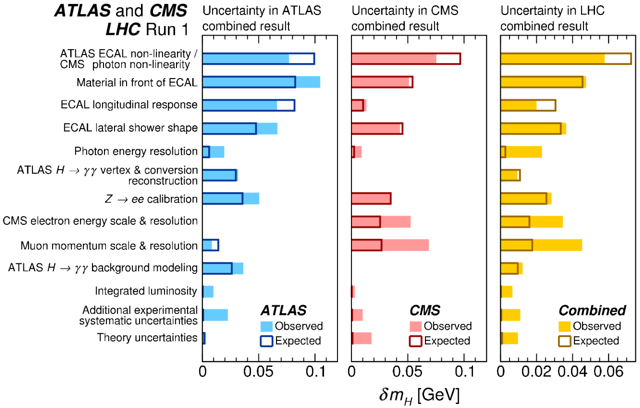


$m_H = 125.09 \pm\ 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV

Stat. limited $\rightarrow$ 70 MeV (stat.) after Run II !

More details on uncertainties

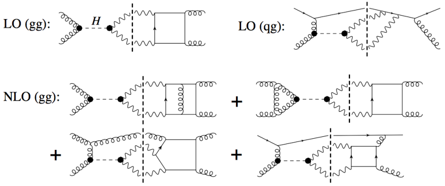
Most uncertainties on m_H linked to the energy scale

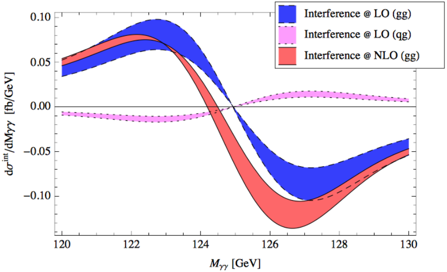


However neither of the $H \to \gamma\gamma$ considered interference between $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$

Initial theory estimate of the impact of interference

Impacts yield ($\approx 2\%$, taken into account), and the $m_{\gamma\gamma}$ lineshape





First estimate (LO) : $\Delta m_H = -100$ MeV arXiv:1208.1533

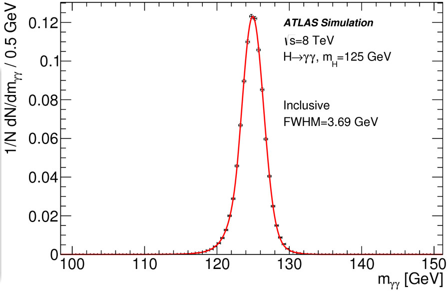
Best estimate (NLO) : $\Delta m_H = -70$ MeV arXiv:1305.3854

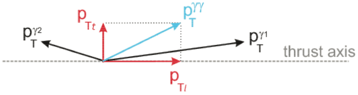
However these estimates were done in pure ggF production, without realistic detector simulation

Signal modelling

Define ten categories to decrease the uncertainty on m_H

- $\delta m_H \approx \sqrt{6}\sigma_{res}^{3/2}\frac{\sqrt{B/GeV}}{S}$
- Define categories as functions of conversion, η (σ_{res}) and p_{T_t} ($\frac{S}{B}$)
  - Signal model constructed separately for each category





Signal model : CB+Gaus

Parameters fitted on MC samples at different m_H^{MC} and interpolated

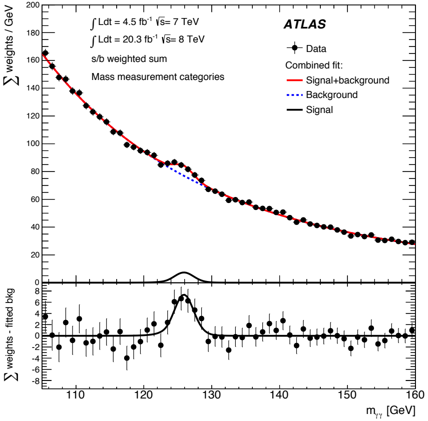
Background modelling

Background model : exponential (high-p_{T_t}) or exp. 2nd degree polynomial

- Shape determined on MC, parameters fitted to data

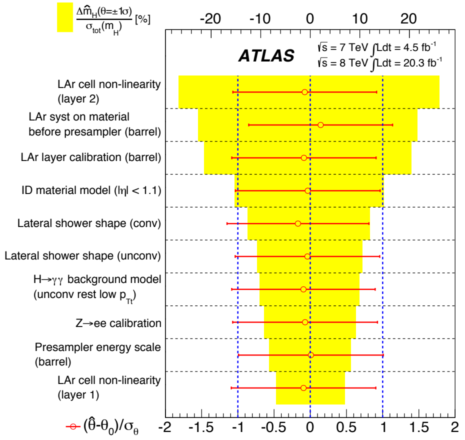
Uncertainty due to choice of shape

- Generate Asimov data with alternative bkg shape
- Fit it with the nominal model
- Variation of m_H corresponds to the uncertainty



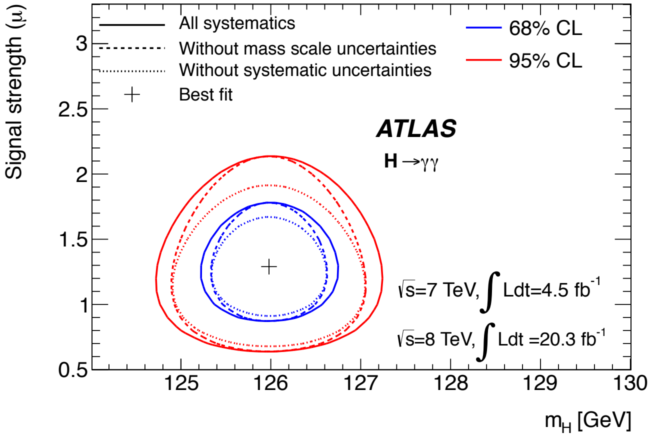
m_H determined by combined S+B unbinned likelihood fit to 10 categories

Main uncertainties



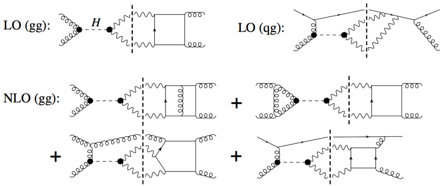
- All uncertainties implemented as additional nuisance parameters (NP) : $m_H \to m_H \times (1 + \delta\theta)$
  - θ : constrained by Gaussian (profiled in the fit)
  - δ = magnitude of the uncertainty
- Most relevant uncertainties linked to energy scale
  - Especially non-linearities
  - Then $e^\pm \to \gamma$ extrapolations
- Systematic uncertainty $\delta m_H^{\gamma\gamma} = \pm 280$ MeV → most uncertainties below 70 MeV

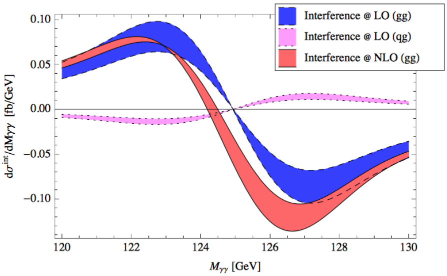
Results (Phys. Rev. D. 90, 052004 (2014))



$$m_H^{\gamma\gamma} = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$
$$\mu = 1.29 \pm 0.30$$

$$\mathcal{I} = -\frac{2}{(\hat{s}-m_h^2)^2+m_h^2\Gamma_h^2}\left((\hat{s}-m_h^2)Re(A^*_{cont}A_{h\to\gamma\gamma}A_{gg\to h}) + m_h\Gamma_h Im(A^*_{cont}A_{h\to\gamma\gamma}A_{gg\to h})\right)$$





- Assuming narrow peak everything but $\hat{s}$ is constant
  - *Im* part becomes non-zero at NLO (two-loops)
- *Re* part has 0 total XS *but* distorts the lineshape (non-zero $\frac{d\ \sigma}{d\ m_{\gamma\gamma}}$)

Current implementation

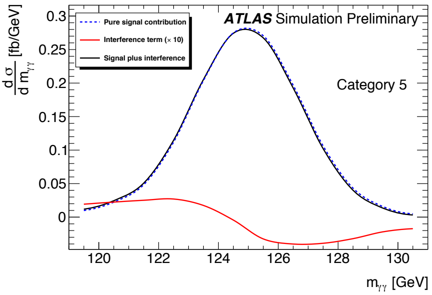
- Sherpa 2 implements a plug-in allowing studies of this effect, generating separately Signal, Background and Interference (weighted) events
- Uses the full NLO computation for the three terms, matched to a Parton-Shower (CSS, DiRe in future versions)

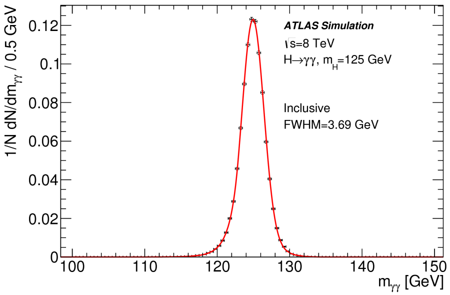
- Parton-shower tuned so that signal p_T distribution matches HRes 2.0 (NNLO+NNLL)
- Background p_T dist. checked against ResBos

- As the effect is small and given the weights distribution, need sizeable number of events to get precise estimate (use 400M)

Using FullSim was not possible given the large datasets needed

- Smear $m_{\gamma\gamma}$ using the signal model ($\approx$ mass resolution) for the current category
- Apply $\epsilon(p_T, \eta, \text{conv})$ as additional weight





Final mass distribution and yields in good agreement with previous analyses (m_H, cross-sections)

Main results

Background is taken from a fit to data (using official model)
Signal is rescaled to NNLO by $k_S = 1.45 \pm 0.1$ (PDF+α_S), interference term is rescaled by $\sqrt{k_S k_B}$ (nominal : $k_B = k_S$)
Fit $\mathcal{S}+\mathcal{B}+\mathcal{I}$ and $\mathcal{S}+\mathcal{B}$ only to get $\Delta m_H = m_H^{\mathcal{S}+\mathcal{B}+\mathcal{I}} - m_H^{\mathcal{S}+\mathcal{B}}$

With/out interf.	Quantity	Sample 1	Sample 2	Sample 3	Sample 4	Mean	RMS
S+B	m_H	124.998	124.998	124.997	124.997		
	μ	0.995	0.995	0.995	0.994		
S+B+I	m_H	124.963	124.962	124.962	124.962		
	μ	0.988	0.988	0.988	0.988		
Δm_H [MeV]		-35	-35	-35	-35	-35	0.3

Generate 4 different $\mathcal{S}$ and $\mathcal{I}$ datasets to estimate stat. uncertainty
$\Delta m_H = -35$ MeV with negligible variance (correcting would increase m_H)
Good closure on $m_H = 125.000$ GeV and $\mu = 1$

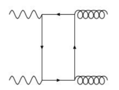
Theory uncertainties

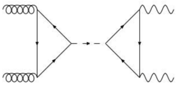
K-factor variations

	$K_S = 1.35$	$K_S = 1.45$	$K_S = 1.55$	Uncertainty
$K_B = 1$	-30 ± 0.2	-29 ± 0.2	-28 ± 0.2	
$K_B = k_S$	-35 ± 0.3	-35 ± 0.3	-35 ± 0.3	
Envelope	5	6	7	± 7

- Vary K_S by 0.1 $(PDF + \alpha_S)$
- Vary K_B from $1 \to K_S$
- Enveloppe as uncertainty

$$\frac{K_S}{K_B} = 1 + \frac{11}{2}\frac{\alpha_S}{\pi} \approx 1.2$$





Renorm. & fact. scale varied by $\frac{m_H}{2} \to 2m_H$, resum. $\frac{m_H}{4} \to 2m_H$

With/out interf.	Quantity	Nominal	μ_{Ren} up	μ_{Ren} down	μ_{Fac} up	μ_{Fac} down	μ_{Res} up	μ_{Res} down	All up	All down
no I	m_H	124.997	124.997	124.998	125.000	124.998	125.000	124.997	124.998	124.997
with I	m_H	124.962	124.961	124.963	124.960	124.967	124.962	124.961	124.959	124.967
Δm_H [MeV]		-35	-37	-35	-38	-31	-36	-36	-39	-31

Related uncertainty : ± 5 MeV

Method uncertainties

- Non-perfect closure for the fit of $m_H = 125.000$ GeV added as a systematics (3 MeV)

- Uncertainty from the choice of background shape (3 MeV)
  - Similar than for the measurement of m_H
- Vary background shape for template creation (poly. vs exp., vary order)
  - However correlate between all categories while mass analysis decorrelates $\rightarrow$ more conservative

- Other uncertainties (efficiency, ...) were considered and found to be negligible (< 1 MeV)

$$\Delta m_H = -35 \pm 8 \text{ (theo.) } \pm 4 \text{ (syst.) MeV} = -35 \pm 9 \text{ MeV}$$

Variation of the effect across categories

Δm_H has been determined separately in each category

Cat.	1	2	3	4	5	6	7	8	9	10
Nomin.	-41	-2	-54	-13	-59	-39	-1	-56	-11	-62
μ_{Ren}^{up}	-43	0	-55	-15	-59	-39	0	-59	-14	-65
μ_{Ren}^{down}	-41	-2	-55	-11	-59	-40	-2	-56	-10	-64
μ_{Fac}^{up}	-45	-2	-58	-14	-65	-41	-4	-61	-14	-69
μ_{Fac}^{down}	-36	-1	-49	-11	-55	-35	1	-49	-10	-57
μ_{Res}^{up}	-40	-15	-55	-24	-60	-40	-15	-57	-23	-62
μ_{Res}^{down}	-42	12	-55	3	-59	-40	11	-58	4	-67
all up	-44	-17	-58	-31	-67	-42	-17	-60	-29	-69
all down	-38	10	-51	1	-53	-35	10	-53	2	-55
$K_B = 1$	-34	-2	-45	-11	-49	-32	-1	-46	-9	-51

Factorization scale has dominating impact on low-p_{T_t} categories

Resummation scale dominating in high-p_{T_t} categories
(impact of LO(gg) strongly correlated with μ_{Res}, not LO(qg))
Cancels out in full fit to 10 categories (low stat in high-P_{T_t} + anti-correlated between high/low p_{T_t} categories)

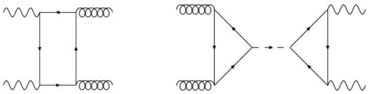
Δm_H for $\Gamma_H = 300$ and 600 MeV

Want to assess models that would keep μ constant but not Γ_H

Conserve observable rate $(\mathcal{S} + \mathcal{I})$:

$$(c_g c_\gamma)^2 \sigma_S(\Gamma) + (c_g c_\gamma)\sigma_I(\Gamma) = \sigma_S(\Gamma_{SM}) + \sigma_I(\Gamma_{SM})$$

Rescale $\mathcal{S}$ by $(c_g c_\gamma)^2$, $\mathcal{I}$ by $(c_g c_\gamma)$



	$\Gamma_H = 300$ MeV	$\Gamma_H = 600$ MeV
Δm_H [MeV]	-313 ± 72	-453 ± 106

Uncertainties determined in the same way than before

Verifies $\Delta m_H \propto \sqrt{\Gamma_H}$ for small enough widths

Conclusion

- Determined shift of m_H induced by signal-background interference effects in $H \to \gamma\gamma$ (ATL-PHYS-PUB-2016-009)
- $\Delta m_H = -35 \pm 9$ MeV
- Largely dominated by K-factor uncertainties
- For larger (but still narrow) widths, the shift scales as $\Delta m_H \propto \sqrt{\Gamma_H}$