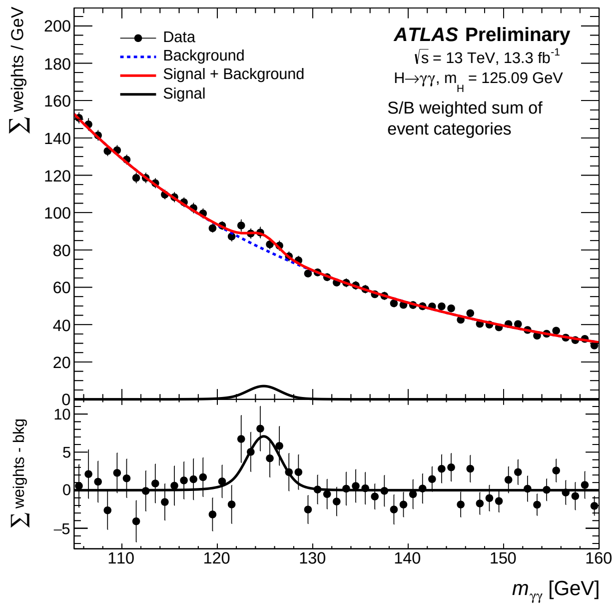
Higgs boson properties (ATLAS and CMS)

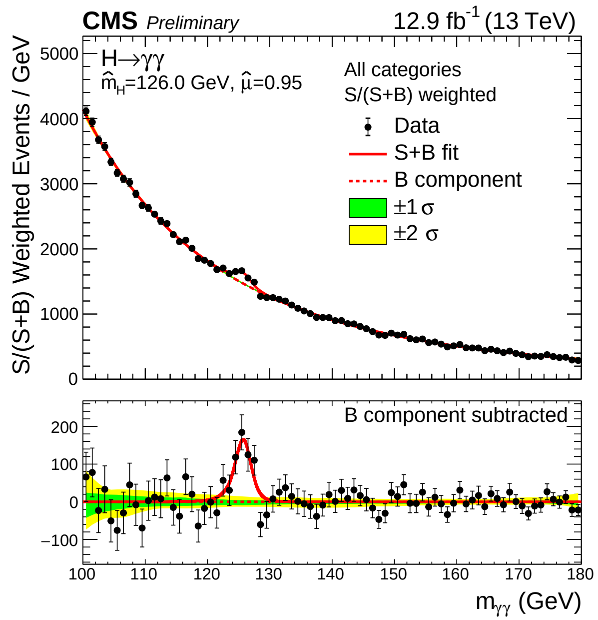
Marcello Fanti [University of Milano and INFN]

(on behalf of the ATLAS and CMS collaborations)

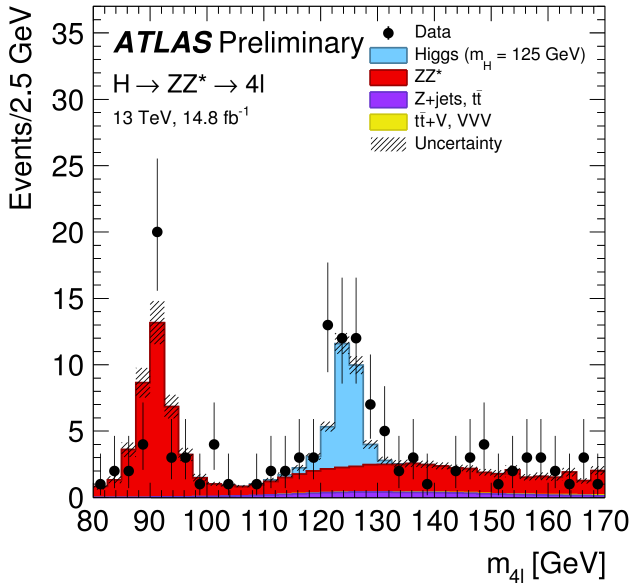
Run-II : Higgs boson strikes back!

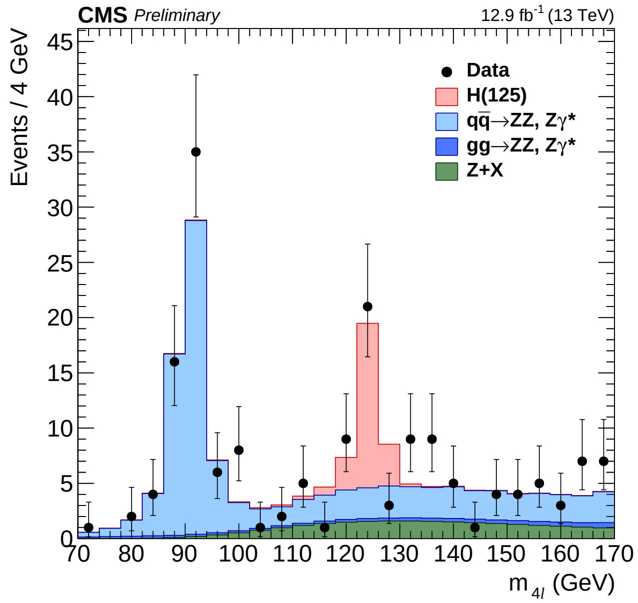
$H \to \gamma\gamma$



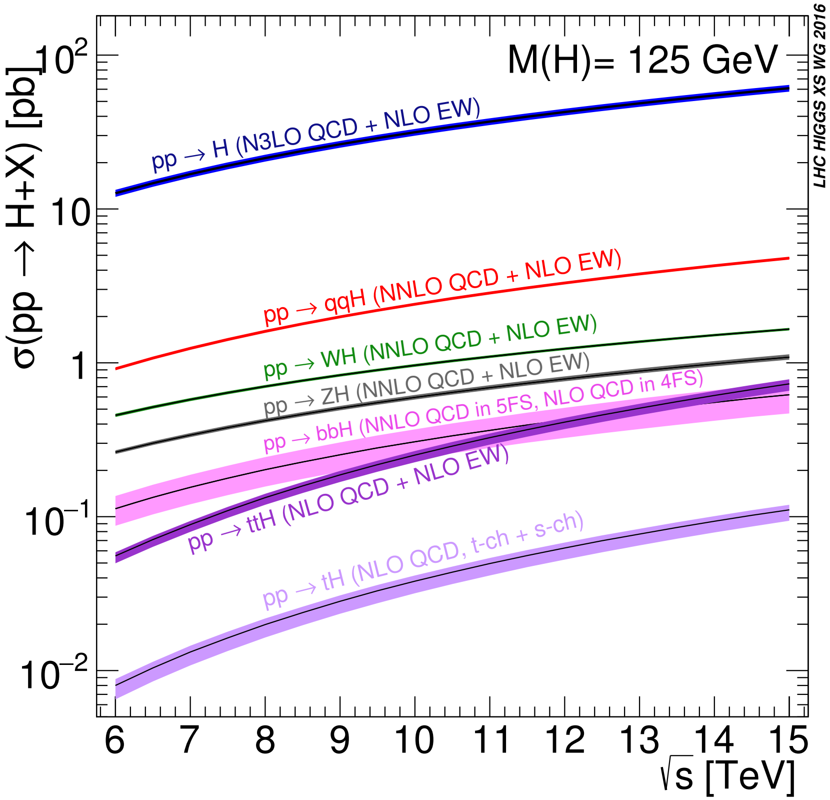


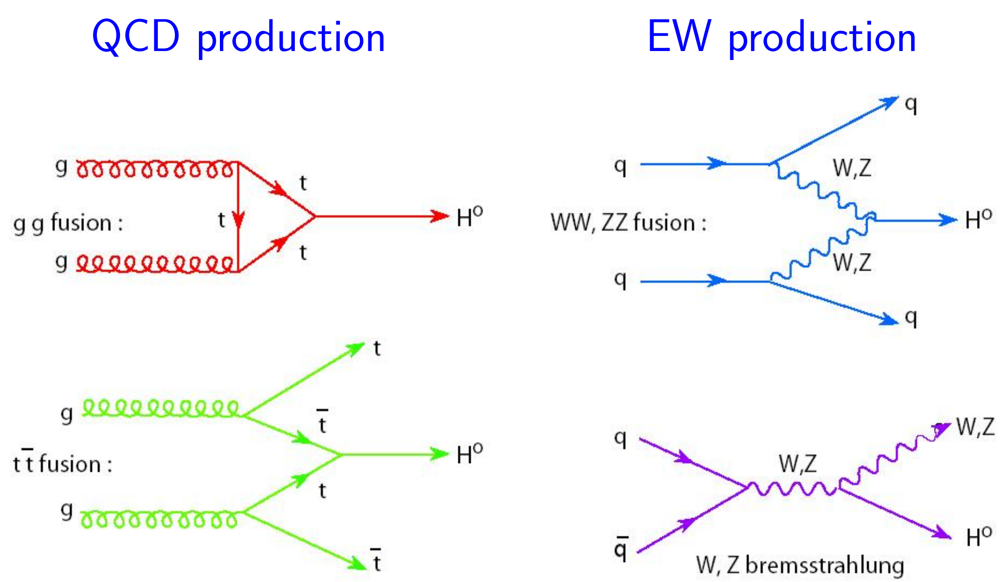
$H \to 4\ell$



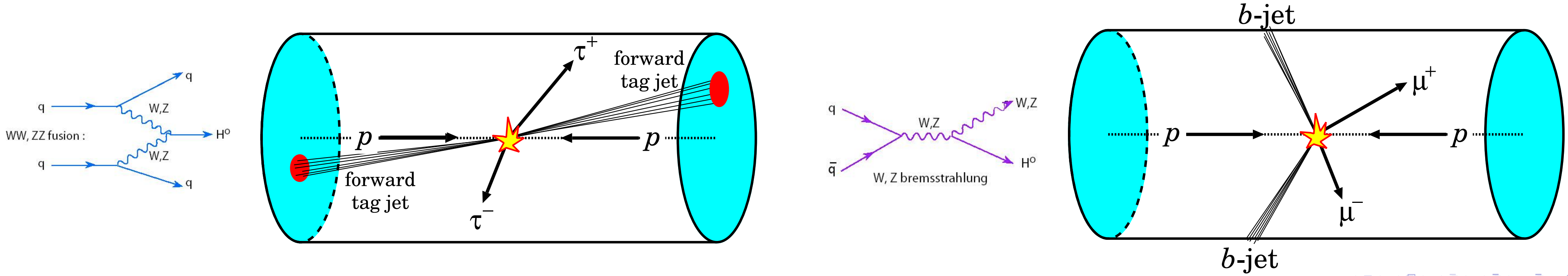


Higgs boson production at LHC





Experimental identification of VBF and VH productions ("tagging"):



Higgs at LHC : Run-I vs Run-II

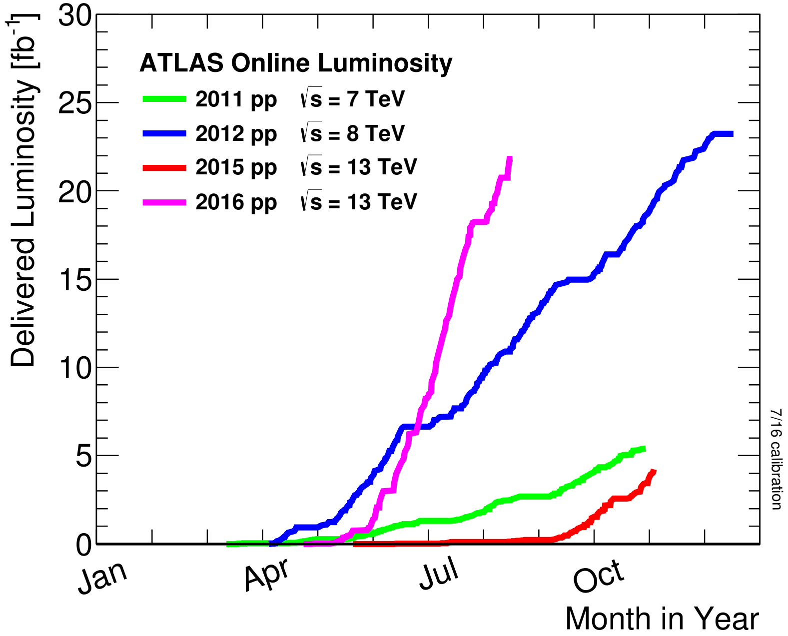
Cross-section vs $\sqrt{s}$

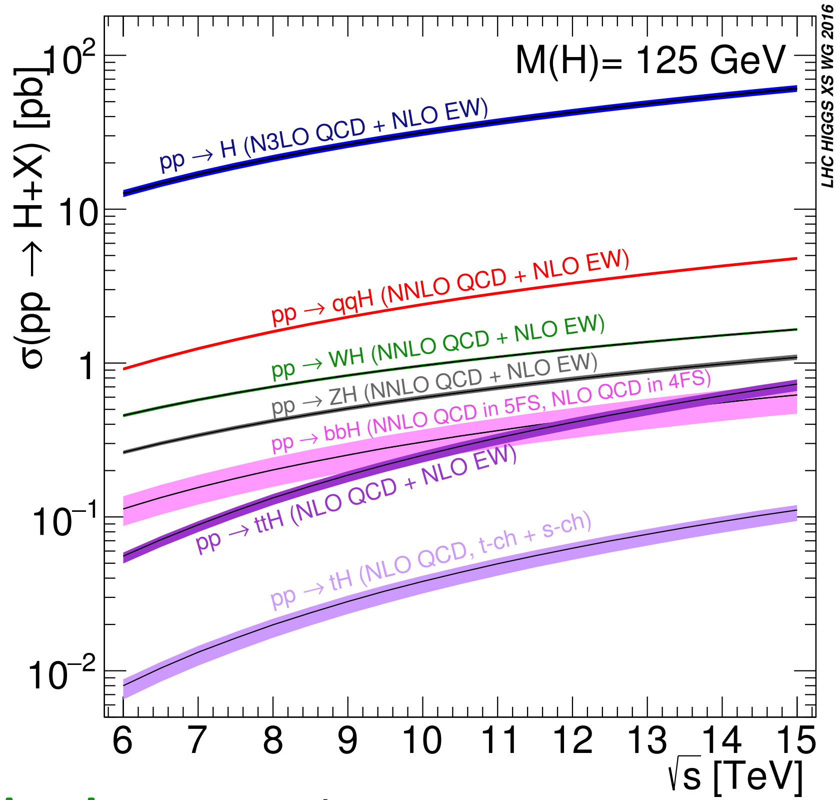
$\sqrt{s} = 8$ TeV $\longrightarrow$ 13 TeV

cross-sections increase:

ggF, VBF by 2.3 $\times$

ttH by 3.8 $\times$





Luminosity per experiment

In Run-I $\Rightarrow$ $\approx 25\ \mathrm{fb}^{-1}$

In 2015 $\Rightarrow$ $\approx 3\ \mathrm{fb}^{-1}$

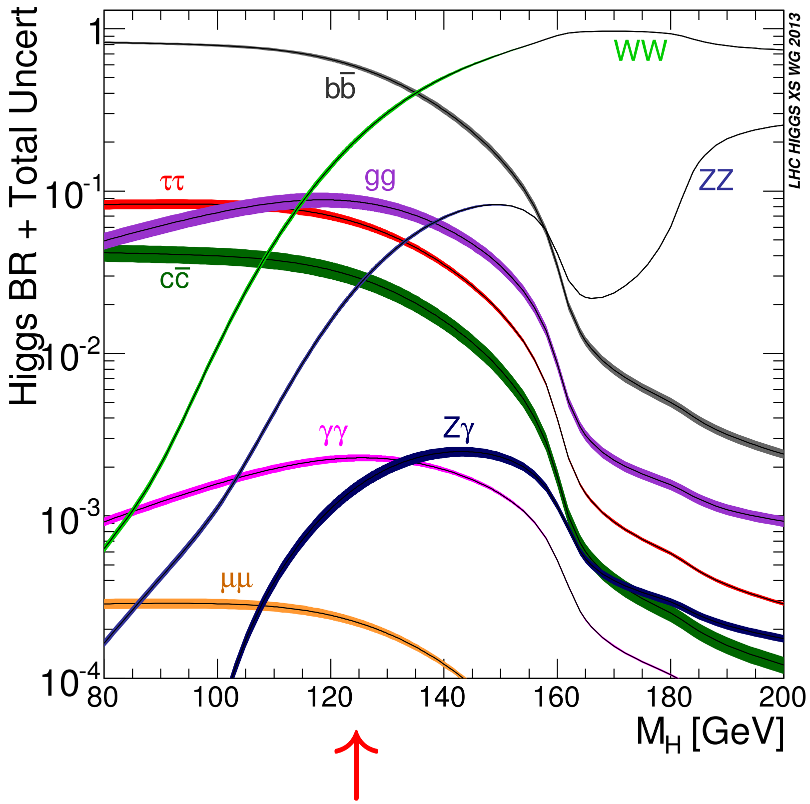
In 2016 $\Rightarrow$ $\approx 21\ \mathrm{fb}^{-1}$ and rising fast!

($\approx 9 - 15\ \mathrm{fb}^{-1}$ analysed)

Higgs boson decay modes

For a mass $m_H \simeq 125\ \mathrm{GeV}$, several decay modes are kinematically accessible

$\Rightarrow$ a thorough study of its properties is possible



If it is the Standard Model Higgs boson, its properties are:

- spin-parity : $J^{CP} = 0^{++}$
- couplings to vector bosons : $g_V = 2\dfrac{m_V^2}{v}$
- couplings to fermions : $g_f = \dfrac{m_f}{v}$

$\Rightarrow$ can probe several couplings and J^{CP} states

Observation of $H \to \gamma\gamma \Rightarrow C = +1$ and $J \neq 1$ (Landau-Yang theorem)

Higgs at LHC : Run-I vs Run-II

Mass measurement

From run-I, combined ATLAS+CMS measurement

Now repeated at Run-II

Cross-sections, Couplings

Fiducial and total cross-sections at 7, 8, 13 TeV

Couplings from run-I combined ATLAS+CMS measurement, and being repeated in Run-II

ttH production and $H \to b\bar{b}$

Spin and CP properties, width, differential cross-sections

From Run-I, being repeated in Run-II

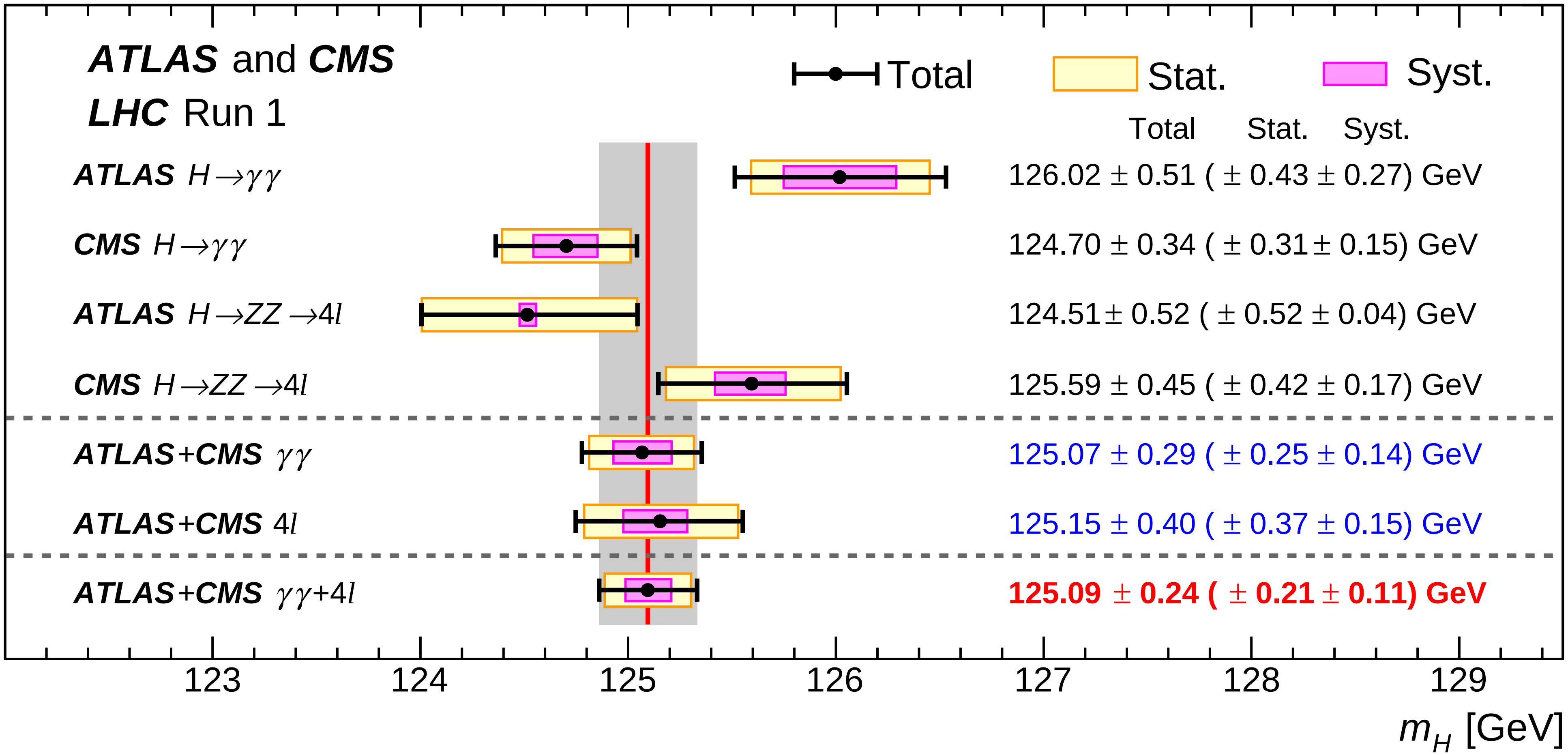
Mass measurement

[arXiv:1503.07589v1 [hep-ex] 26 Mar 2015   PRL 114 (2015) 191803]

Mass measurement

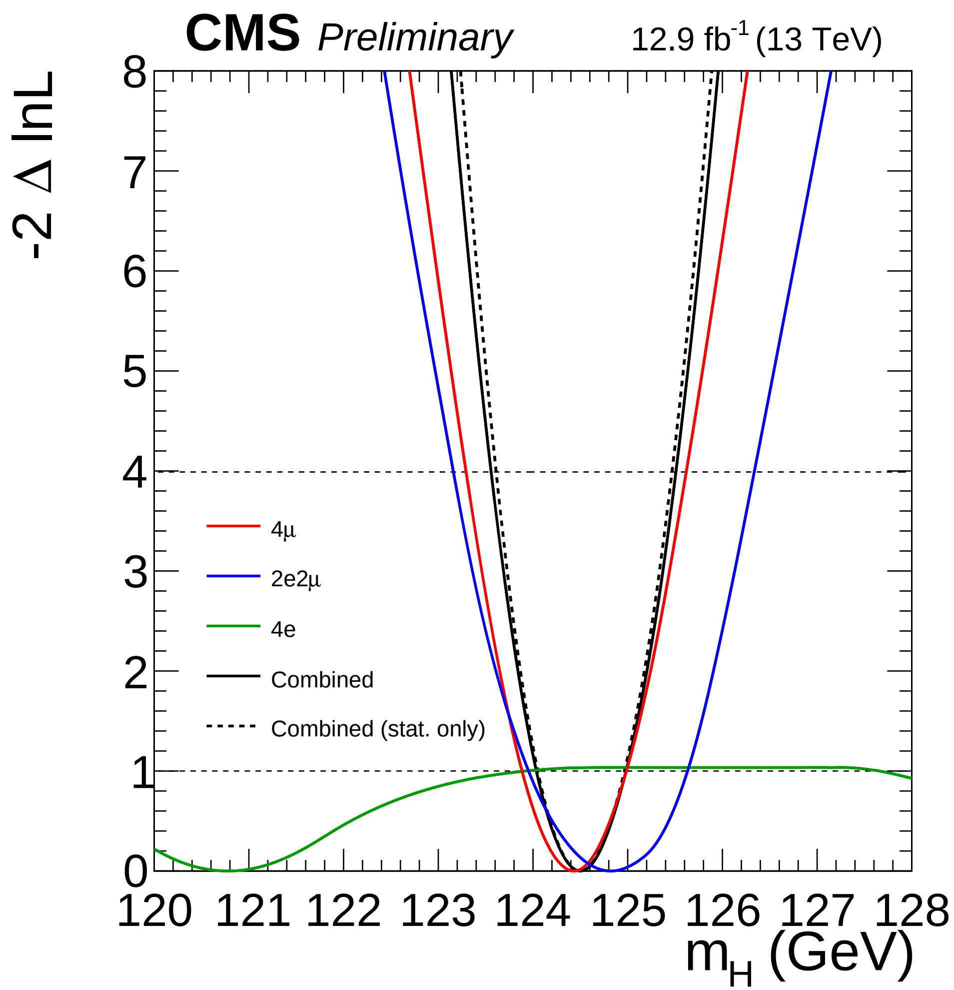
Using the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels
that allow a full kinematics reconstruction with good invariant mass resolution ($\mathcal{O}(1\ \mathrm{GeV})$)

(main source of systematic: energy scale)



$$\hat{m}_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\ \mathrm{GeV}$$

Mass measurement @ 13 TeV



CMS , $H \to 4\ell$ channel

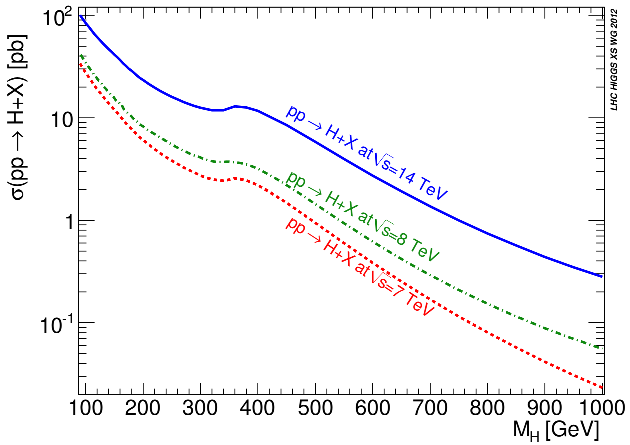
$$\hat{m}_H = 124.50^{+0.47}_{-0.45}(stat)^{+0.13}_{-0.15}(syst)\ \mathrm{GeV}$$

Importance of mass measurement

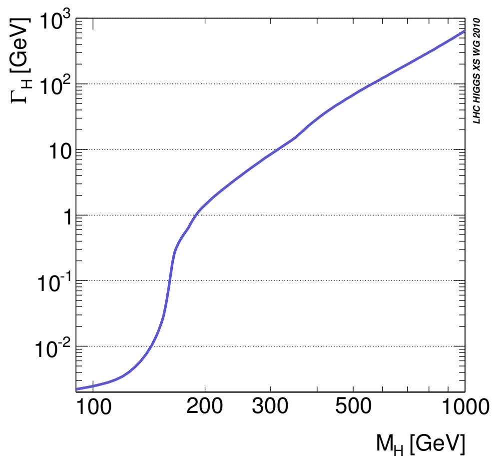
In the Standard Model, m_H is the only free parameter of the Higgs sector

The Higgs sector has two parameters: μ and λ related to the VEV υ and the Higgs mass m_H by: $\mu = \frac{m_H}{\sqrt{2}}$ and $\lambda = \frac{1}{2}\left(\frac{m_H}{\upsilon}\right)^2$. Since $\upsilon = \sqrt{\frac{1}{\sqrt{2}\,G_F}}$ is known, m_H is the only free parameter.

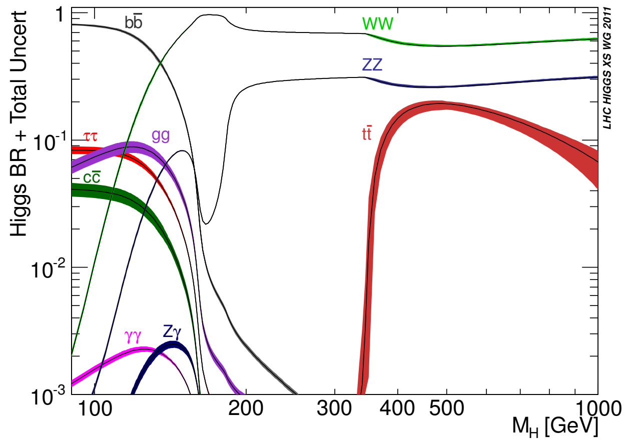
cross-section



decay width



branching ratios



$\Rightarrow$ everything else is calculable, once m_H is given.

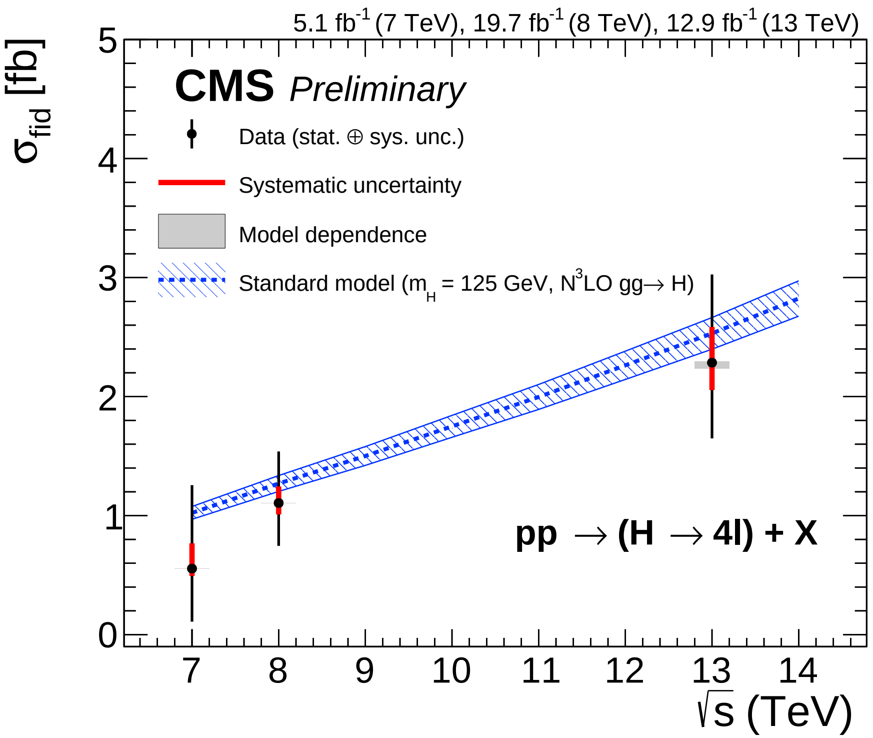
[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR]

Cross sections

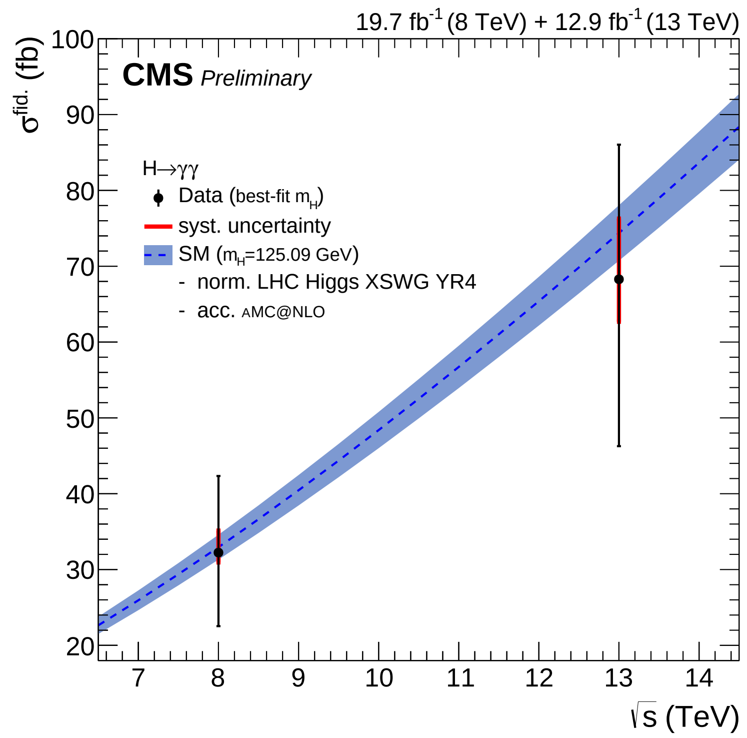
Cross-section from $\gamma\gamma$ and 4ℓ final states
[CMS-PAS-HIG-16-033 , CMS-PAS-HIG-16-020]

Fiducial cross-section vs $\sqrt{s}$

$H \to 4\ell$



$H \to \gamma\gamma$



Improved theory calculations for gluon fusion:

Run-I: NNLO+NNLL: $\pm 8\%$ from scale and $\pm 7\%$ from α_S+PDF

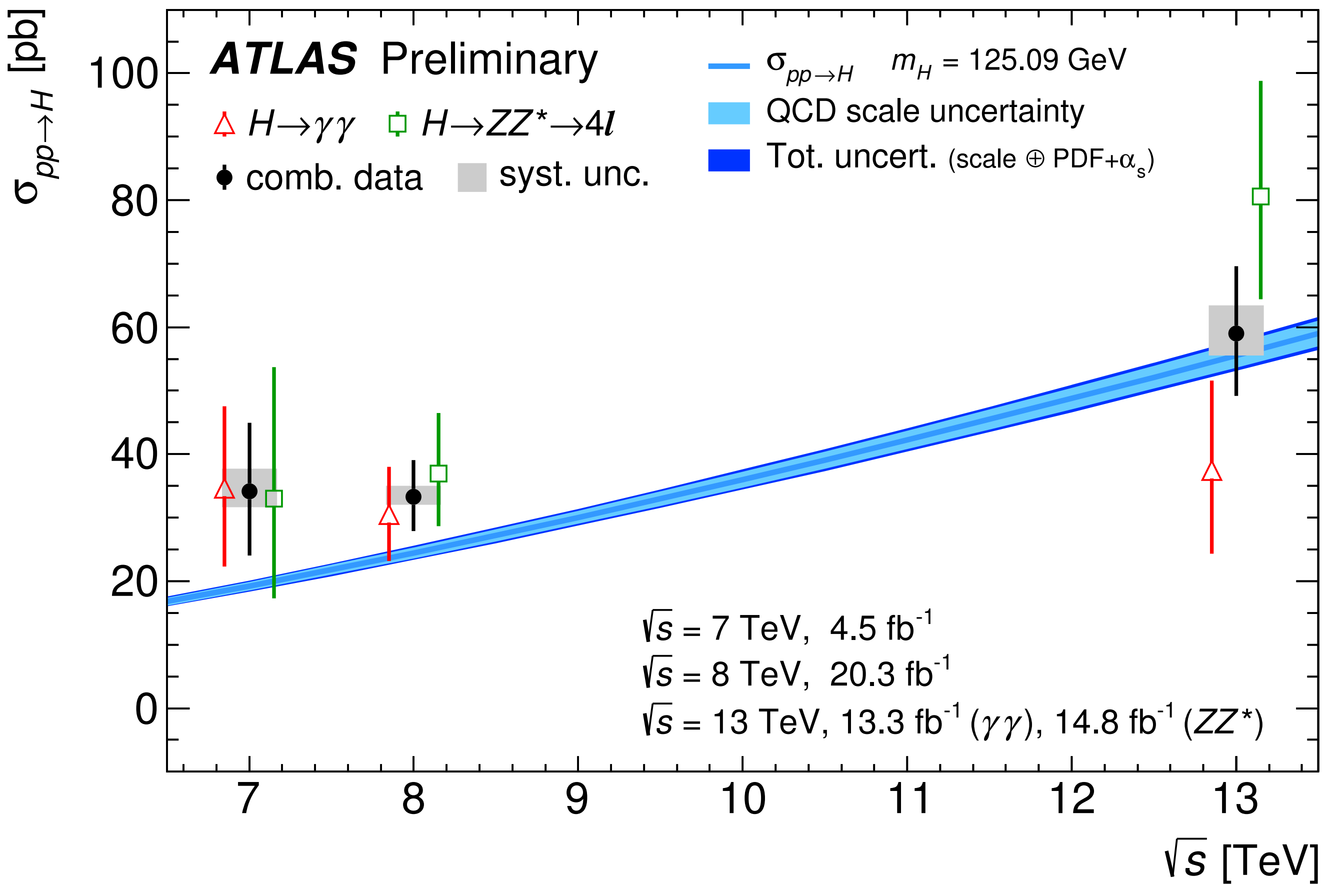
Run-II: N3LO: $\pm 4\%$ from scale and $\pm 3\%$ from α_S+PDF

. . . now experiments need to catch up!

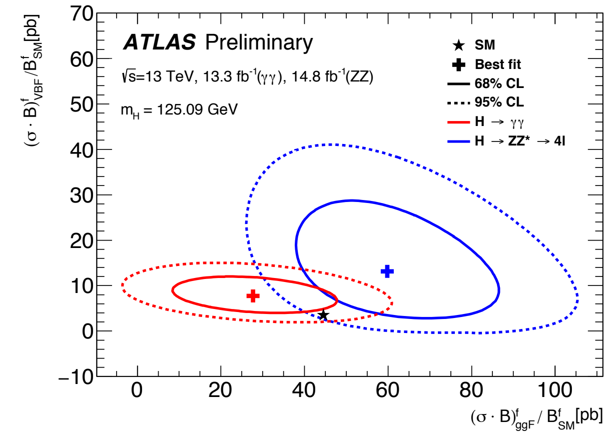
Cross-section from $\gamma\gamma$ and 4ℓ final states

[ATLAS-CONF-2016-081]

Total cross-section vs $\sqrt{s}$ ($\gamma\gamma$ and 4ℓ combined)



Cross-section for ggF vs VBF

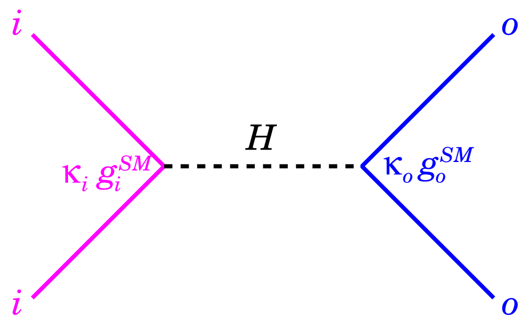


Measurements of couplings

[arXiv:1606.02266v1 [hep-ex] 7 Jun 2016   accepted by JHEP]

Couplings — the "κ-framework"

Reminder: in SM Higgs couplings are $g_f^{SM} = \dfrac{m_f}{v}$ and $g_V^{SM} = 2\dfrac{m_V^2}{v}$



Couplings are accessible through production ($ii \to H$) and decay ($H \to oo$)
Define "couplings modifiers" $\kappa_x = \dfrac{g_x}{g_x^{SM}}$

$$\Rightarrow \sigma_{ii\to H\to oo} = \sigma^{SM}_{ii\to H\to oo} \times \frac{\kappa_i^2\,\kappa_o^2}{\kappa_H^2}$$

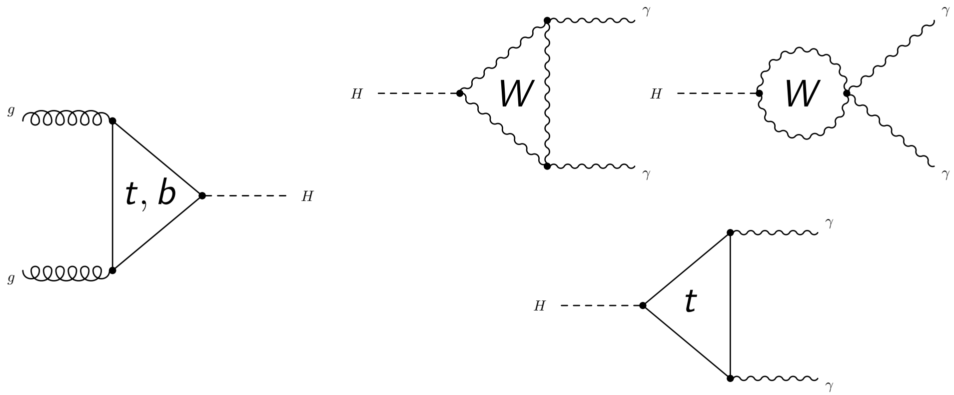
$$\left(\kappa_H^2 \stackrel{\text{def}}{=} \frac{\Gamma_H}{\Gamma_H^{SM}} \text{ — if no BSM decays, } \kappa_H^2 = \sum_o \kappa_o^2 BR^{SM}_{H\to oo}\right)$$

(... otherwise need to allow one extra free parameter, BR to new physics, B_{BSM} — see later on)

$\Rightarrow$ Several couplings: $\kappa_\mu,\ \kappa_\tau,\ \kappa_b,\ \kappa_W,\ \kappa_Z,\ \kappa_t\ \ldots$

$\Rightarrow$ effective couplings: $\kappa_g,\ \kappa_\gamma\ \ldots$

Assume weak gauge boson universality: $\kappa_W = \kappa_Z = \kappa_V$ and fermion universality: $\kappa_t = \kappa_b = \kappa_\tau = \kappa_f$

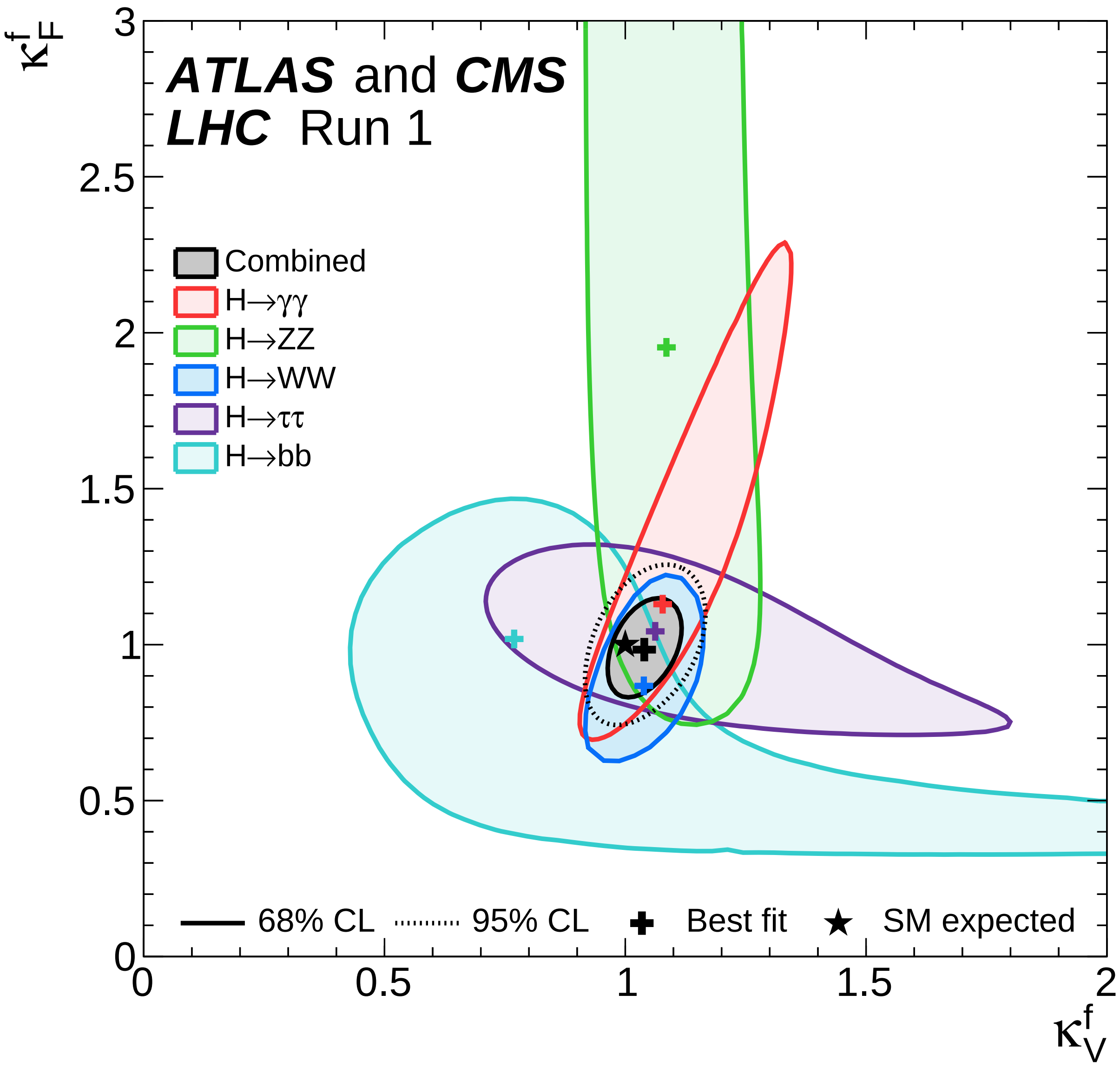


Loop-mediated interactions described as in SM:

$gg \to H$ (mainly) through top/bottom virtual loop
$\Rightarrow \kappa_g = \kappa_{t,b} = \kappa_f$

$H \to \gamma\gamma$ through top and W virtual loops
$\Rightarrow \kappa_\gamma^2 = (1.26\,\kappa_W - 0.26\,\kappa_t)^2 = (1.26\,\kappa_V - 0.26\,\kappa_f)^2$

(Universal) couplings to fermions and weak bosons



Exploit final state topologies (e.g. VBF, VH)

$\Rightarrow$ measure κ_V, κ_f for each decay channel

$\Rightarrow$ then combine decay channels

$\Rightarrow$ all measurements compatible with SM prediction ($\bigstar$)

$$(\kappa_V = 1, \ \kappa_f = 1)$$

Relaxing some assumptions

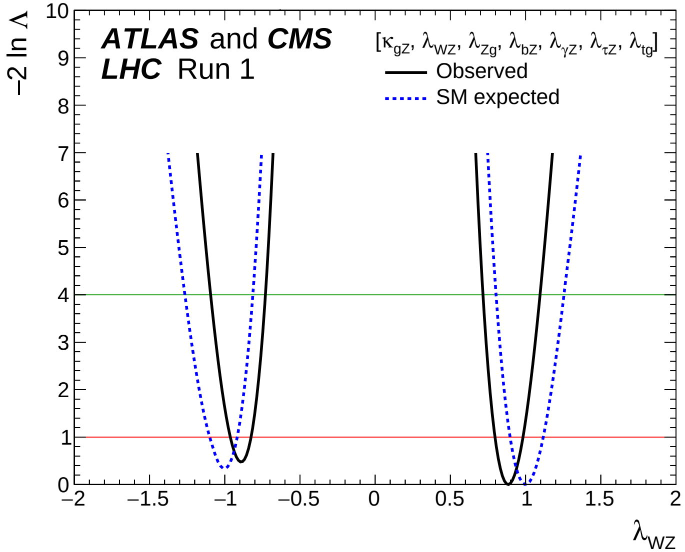
Testing the EW symmetry breaking:

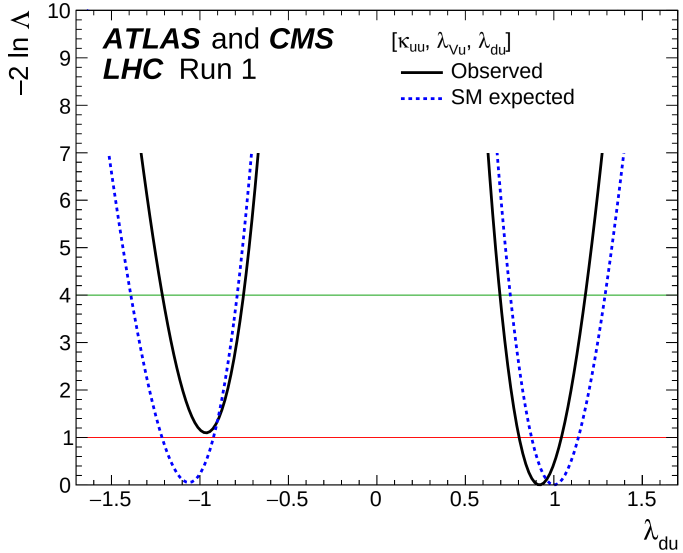
$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$

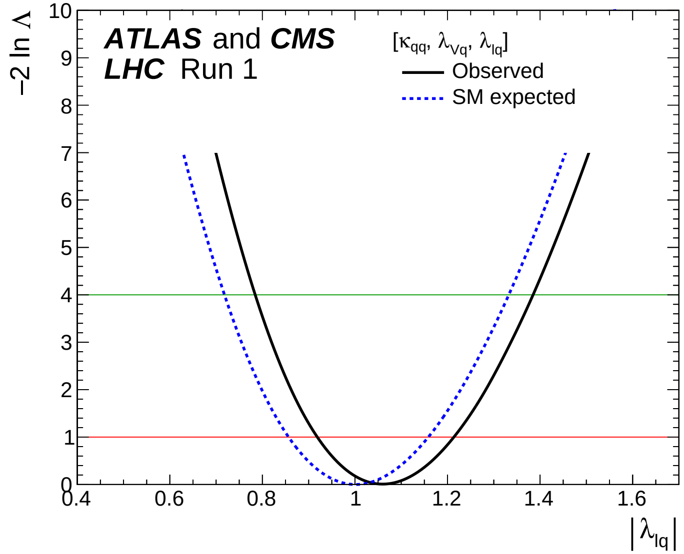
Testing up/down and lepton/quark universality
(would be broken in 2-Higgs-doublet models)

$$\lambda_{du} = \frac{\kappa_d}{\kappa_u}$$

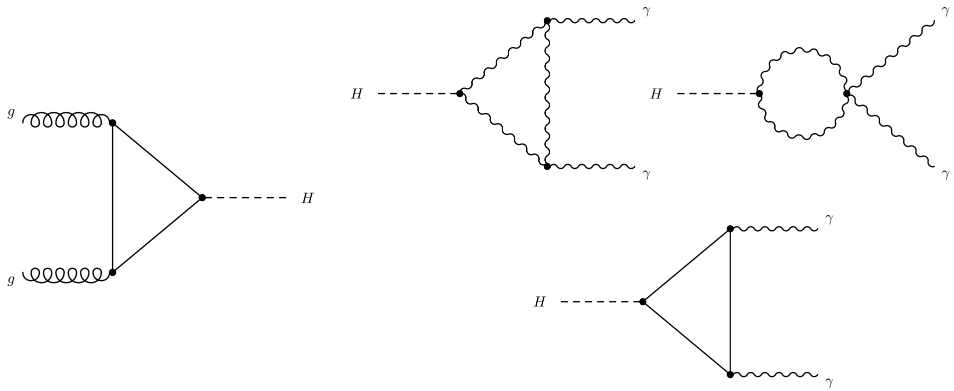
$$\lambda_{\ell q} = \frac{\kappa_\ell}{\kappa_q}$$



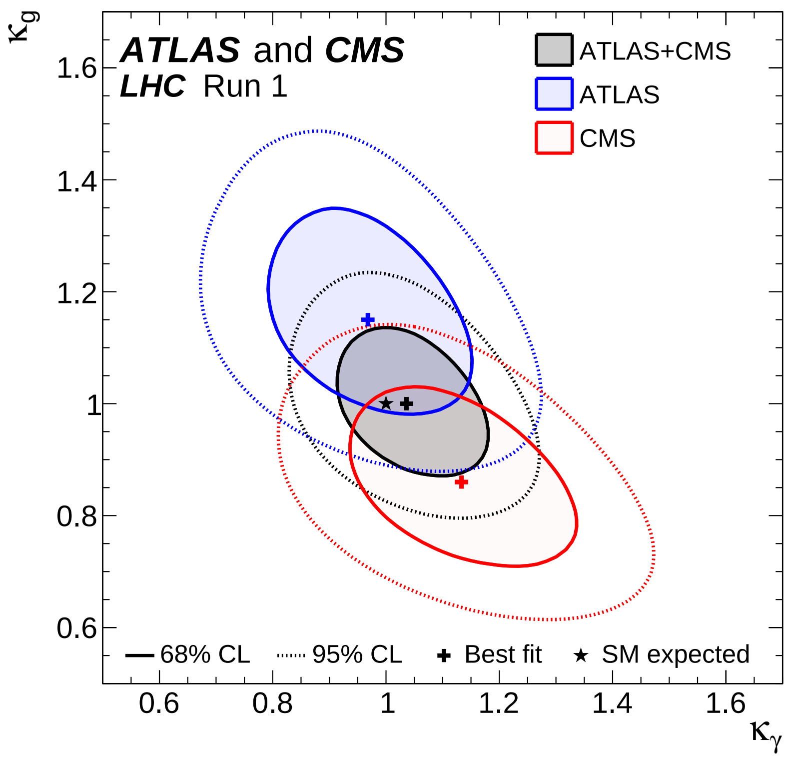




Testing the ggH and $H\gamma\gamma$ interactions



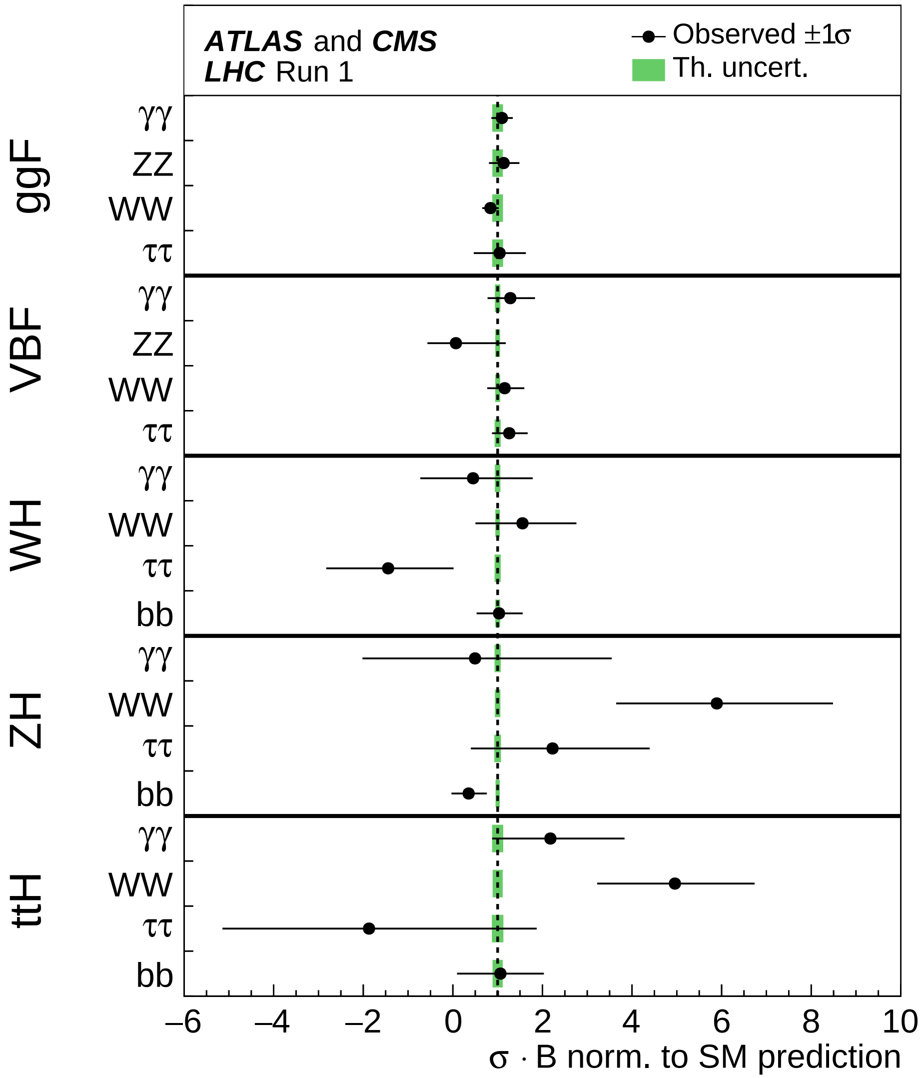
ggH and $H\gamma\gamma$ interactions in SM are mediated by loops
$\Rightarrow$ particularly sensitive to new particles in the loops

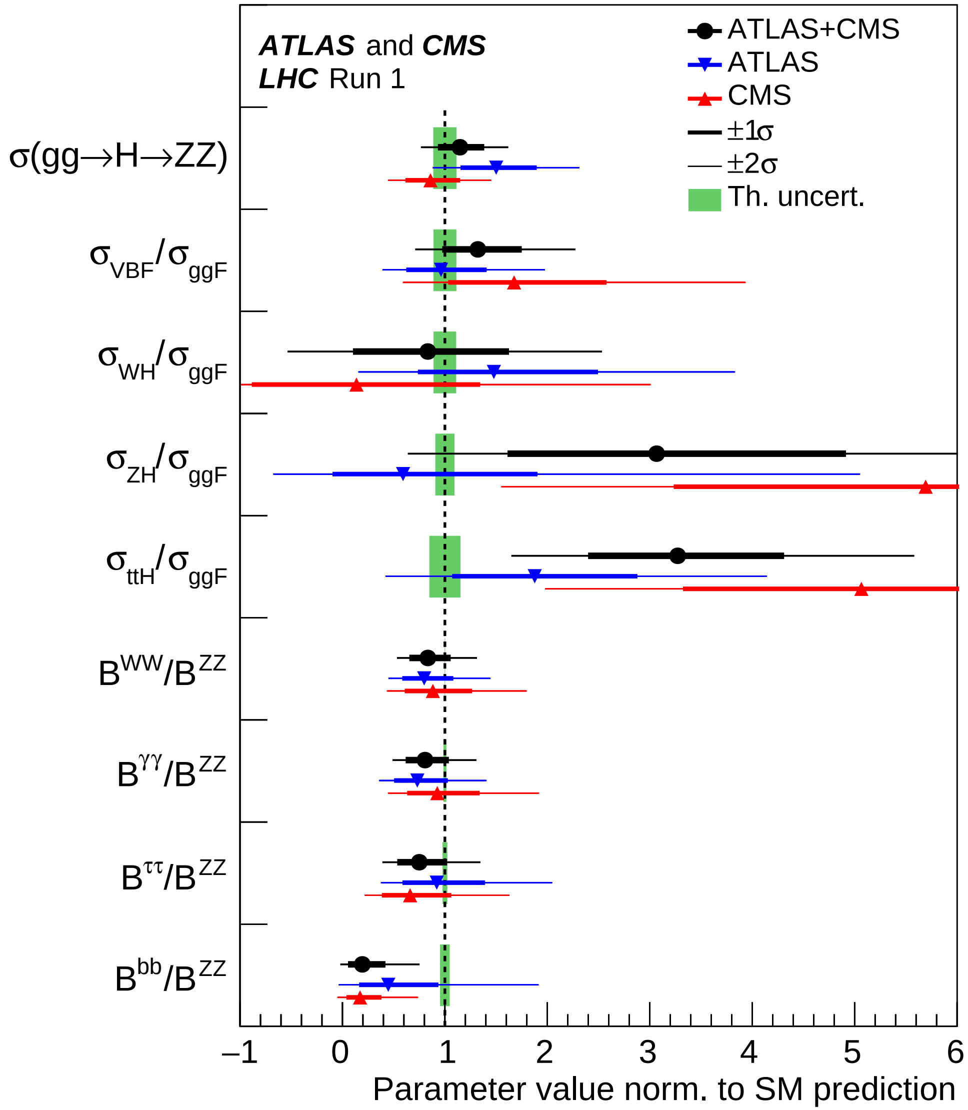


$\Rightarrow$ consider κ_g, κ_γ as free and profile others

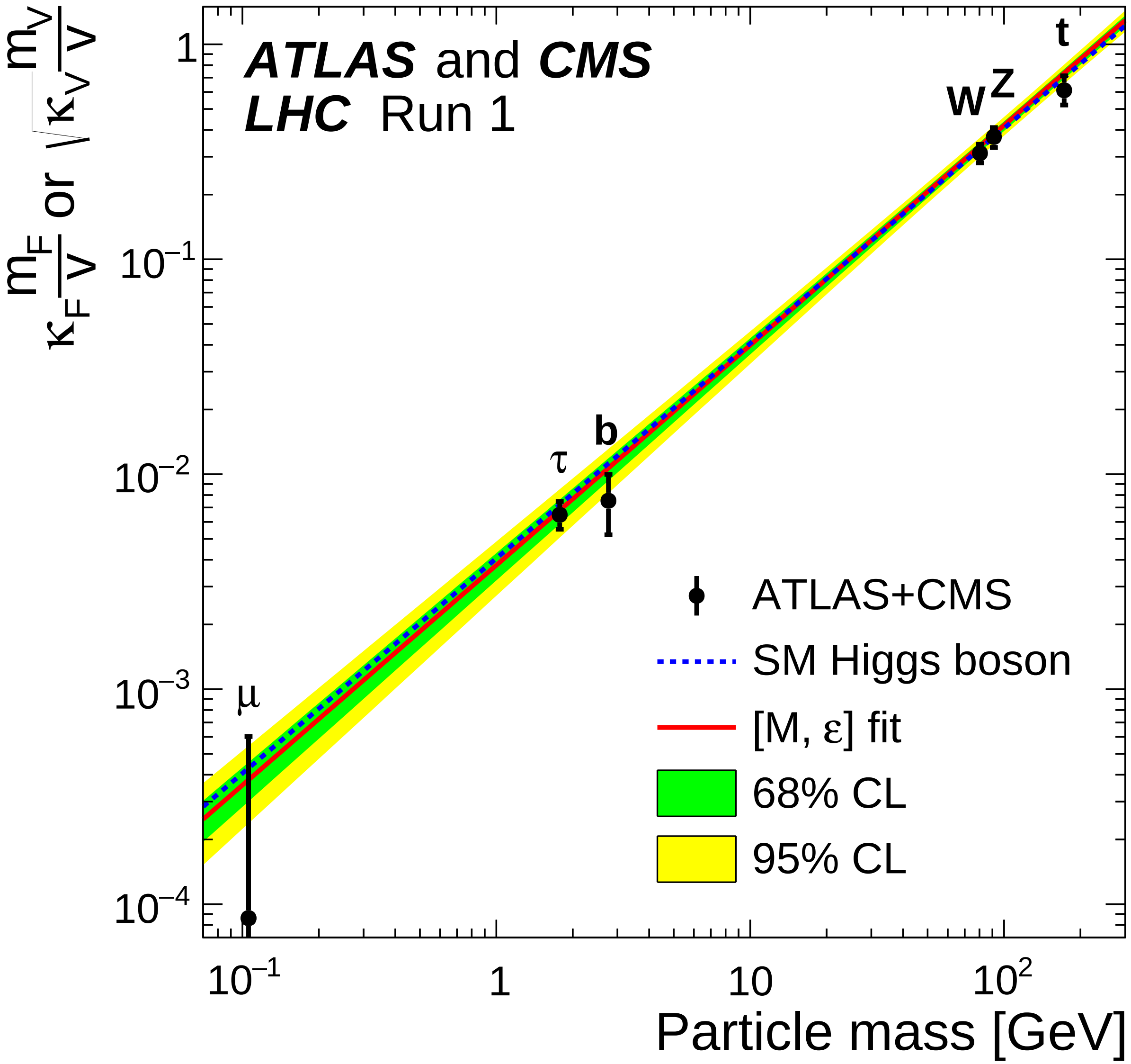
$\Rightarrow$ again, compatibility with SM ($\bigstar$)

Summary of the rates (wrt Standard Model predictions)





Summary of the couplings



Recall: in SM

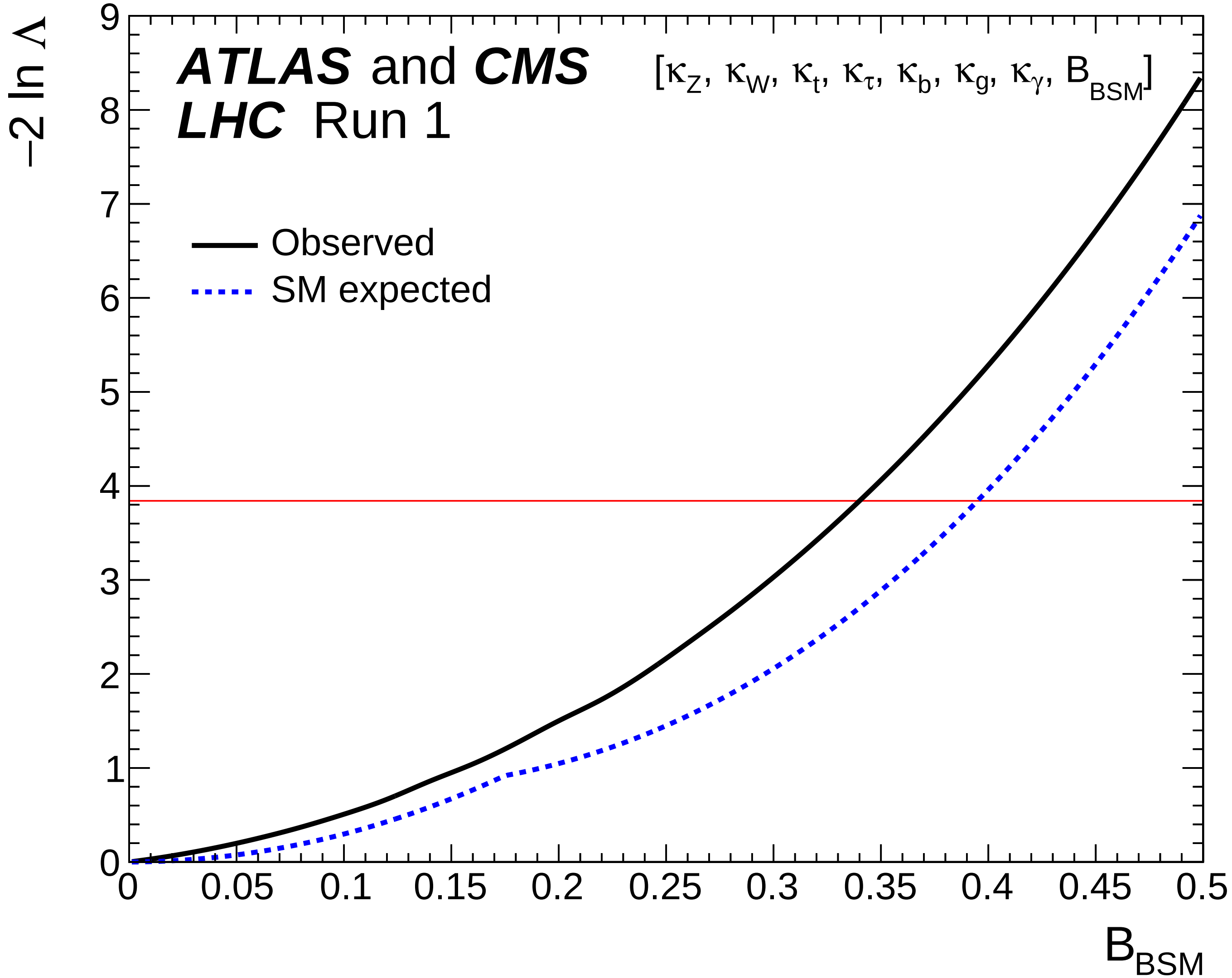
$g_f = \frac{m_f}{v}$ and $g_V = 2\frac{m_V^2}{v}$

$\Rightarrow$ plot measured g_f *vs* m_f and measured $\sqrt{\frac{g_V}{2v}}$ *vs* m_V

$\Rightarrow$ all scale like $\frac{m}{v}$ as expected, over more than 3 orders of magnitude!

$\Rightarrow$ Standard Model works pretty well

Testing decays to BSM particles



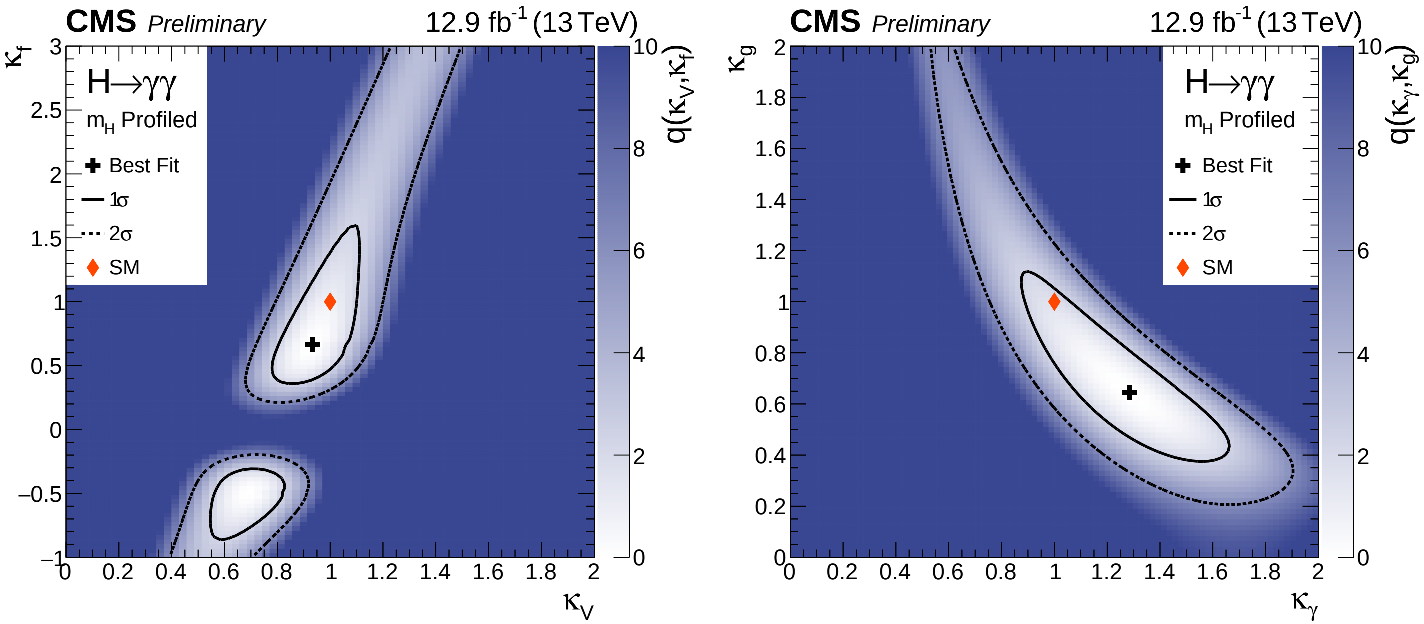
A branching ratio to BSM particles B_{BSM} is allowed as a free parameter

$\Rightarrow$ upper limit at 95% C.L. :

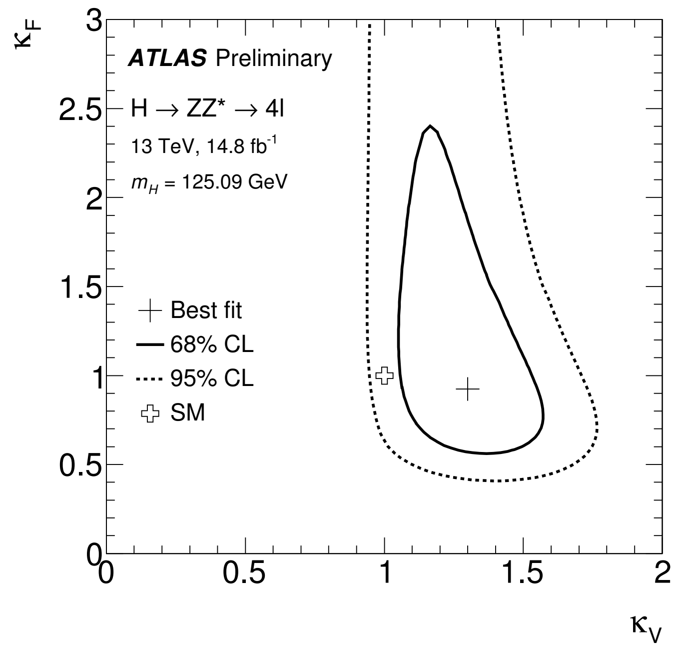
$$B_{BSM} < 0.34$$

(expected: $B_{BSM} < 0.39$)

$H \to \gamma\gamma$ channel

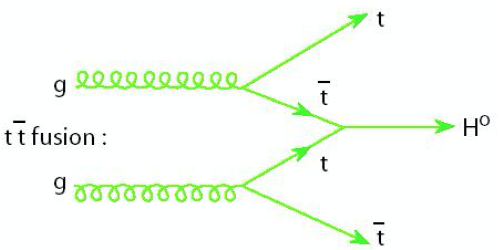


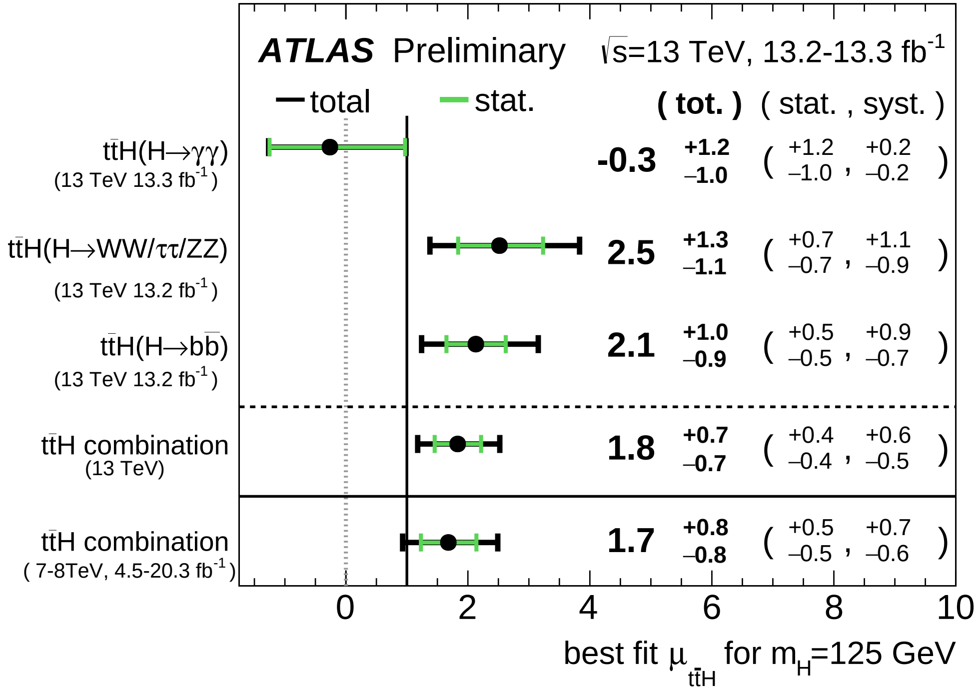
$H \to 4\ell$ channel



ttH production

[ATLAS-CONF-2016-068 , ATLAS-CONF-2016-080 , ATLAS-CONF-2016-058] , [HIG-16-022]





- important to probe directly the ttH Yukawa coupling
- cross-section 4× higher @ 13 TeV wrt 8 TeV

Table 2: Observed and expected asymptotic 95% CL upper limits on and best fit value of the signal strength parameter (μ).

Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit $\mu \pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

[CMS, 13 TeV, 12.9 fb^{-1}]

Significance wrt no-signal hypothesis: 3.2 σ (CMS) , 2.8 σ (ATLAS)

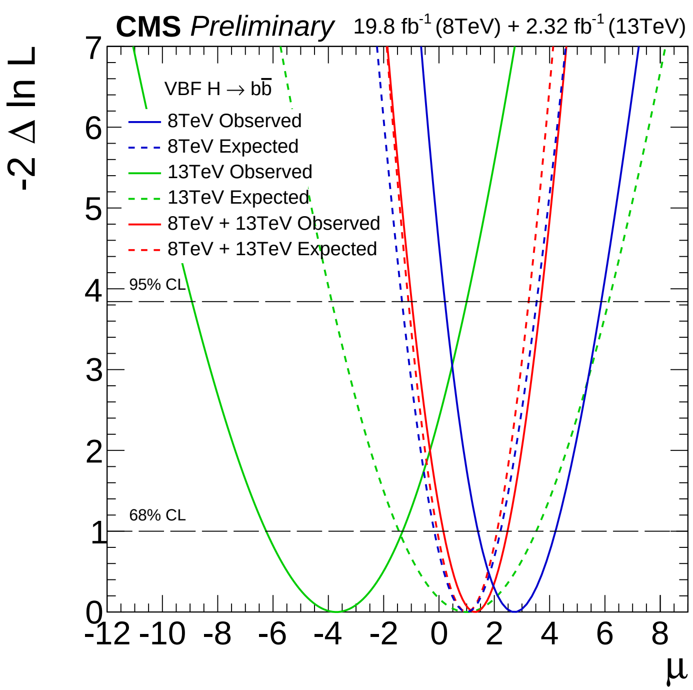
Search for $H \to b\bar{b}$

[CMS-PAS-HIG-16-003] , [JHEP01(2015)069 , ATLAS-CONF-2016-091]

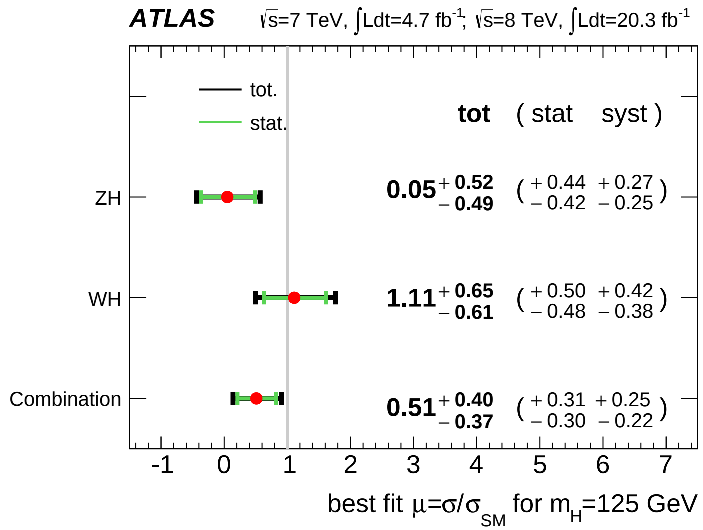
CMS: 8 TeV

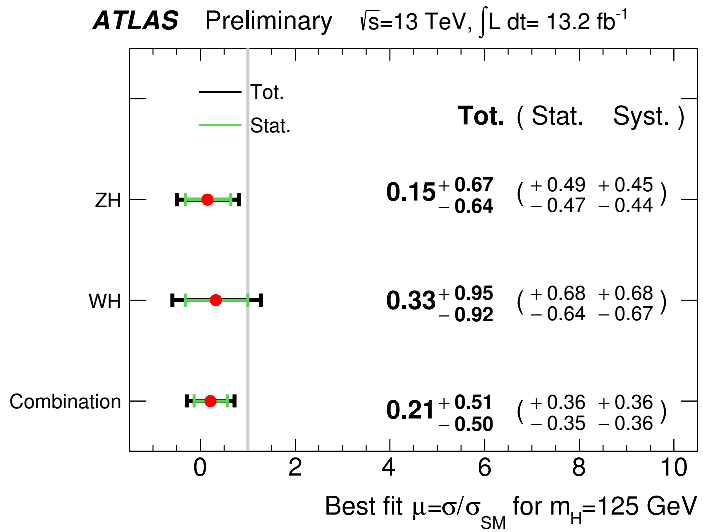
$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

CMS: 13 TeV (VBF production)



ATLAS: (VH production)





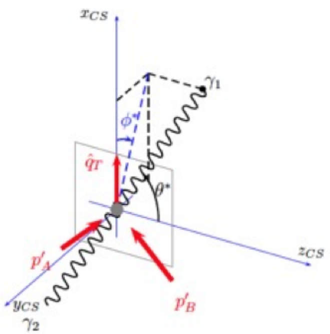
Spin hypothesis test

and parity measurements

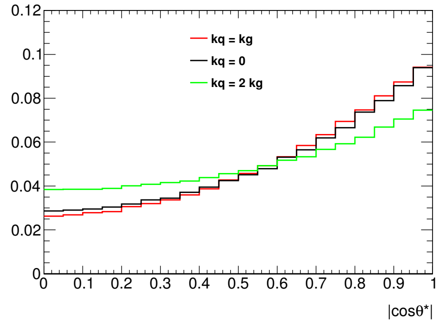
ATLAS: [Eur. Phys. J. C75 (2015) 476] , CMS: [PRD 92 (2015) 012004]

Spin/parity measurement

$H \to \gamma\gamma$: flat $|\cos\theta^*|$ for spin-0, sensitive to spin-2

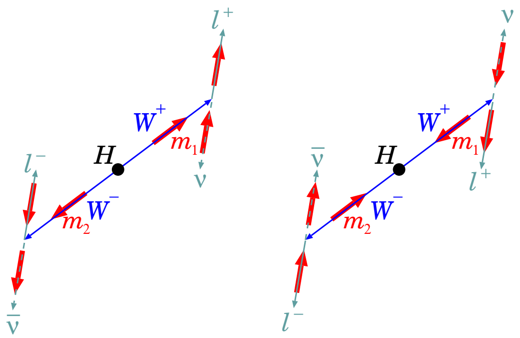


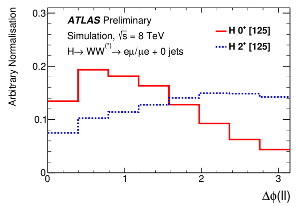
spin 2

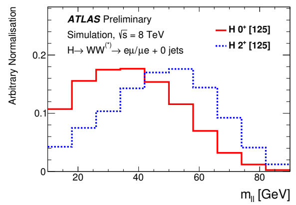


$H \to WW^* \to \ell\nu\ell\nu$: W^+/W^- spin correlation

spin 0

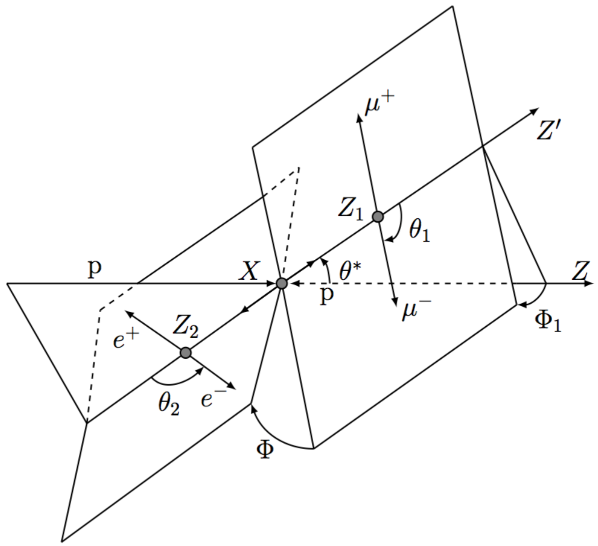






sensitive to spin and parity

$H \to ZZ^* \to 4\ell$:



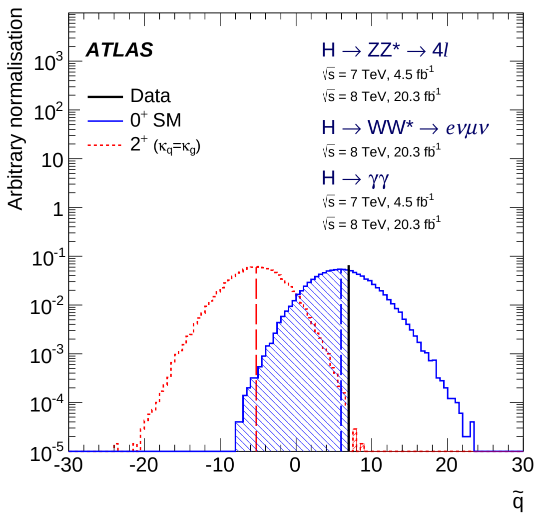
5 angular observables + m_{12}, m_{34}
can probe polarization of both H and Zs
sensitive to spin and parity

Spin-2 tests

effective lagrangian [HiggsCharacterization]

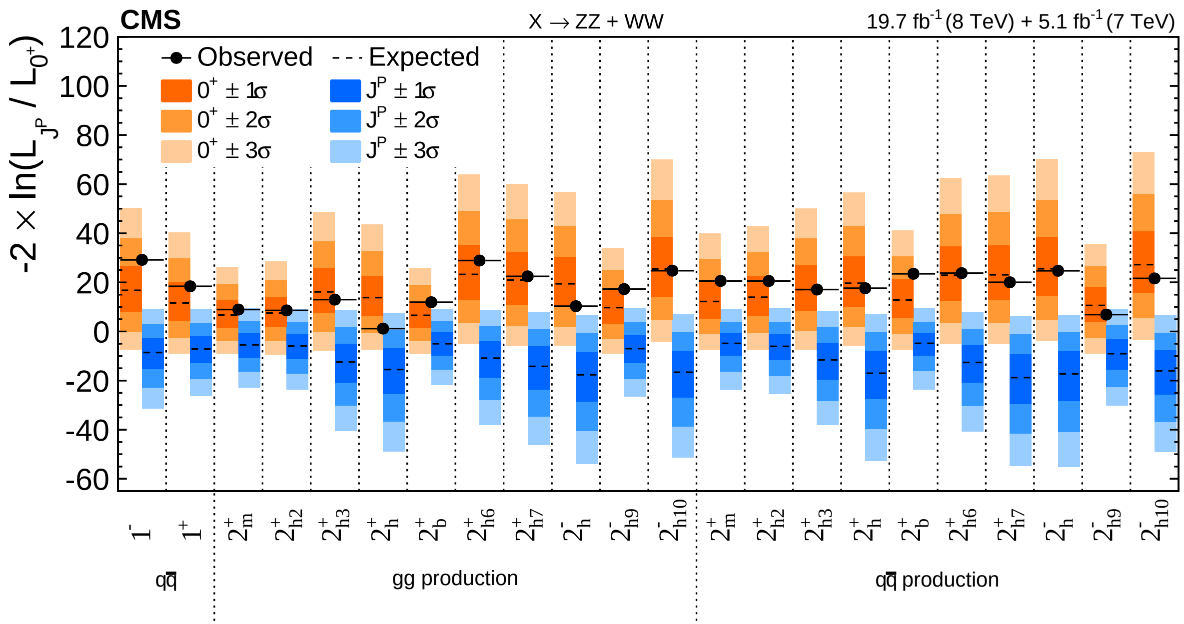
$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu}\mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu}\mathcal{T}^f_{\mu\nu}\right]$$

[below, $\tilde{q} \equiv -2\ln\left(\frac{L_{J^P}}{L_{0+}}\right)$]



effective transition amplitude [JHU]

$$A(X_{J=2}VV) \sim \Lambda^{-1}\Big[2c_1^{VV} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2^{VV} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta}$$
$$+c_3^{VV} t_{\beta\nu}\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}\left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}\right) + c_4^{VV} t_{\mu\nu}\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2} f^{*1,\alpha\beta} f^{*2}_{\alpha\beta}$$
$$+m_V^2\left(2c_5^{VV} t_{\mu\nu}\epsilon_{V1}^{*\mu}\epsilon_{V2}^{*\nu} + 2c_6^{VV} t_{\mu\nu}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}\left(\epsilon_{V1}^{*\nu}\epsilon_{V2}^{*\alpha} - \epsilon_{V1}^{*\alpha}\epsilon_{V2}^{*\nu}\right) + c_7^{VV} t_{\mu\nu}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}\epsilon_{V1}^*\epsilon_{V2}^*\right)$$
$$+c_8^{VV} t_{\mu\nu}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2} f^{*1,\alpha\beta}\tilde{f}^{*2}_{\alpha\beta}$$
$$+m_V^2\left(c_9^{VV} t^{\mu\alpha}\frac{\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon_{V1}^{*\nu}\epsilon_{V2}^{*\rho}q^\sigma}{\Lambda^2} + c_{10}^{VV} t^{\mu\alpha}\frac{\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma\left(\epsilon_{V1}^{*\nu}(q\epsilon_{V2}^*) + \epsilon_{V2}^{*\nu}(q\epsilon_{V1}^*)\right)}{\Lambda^4}\right)\Big]$$



⇒ **data favour spin-0**

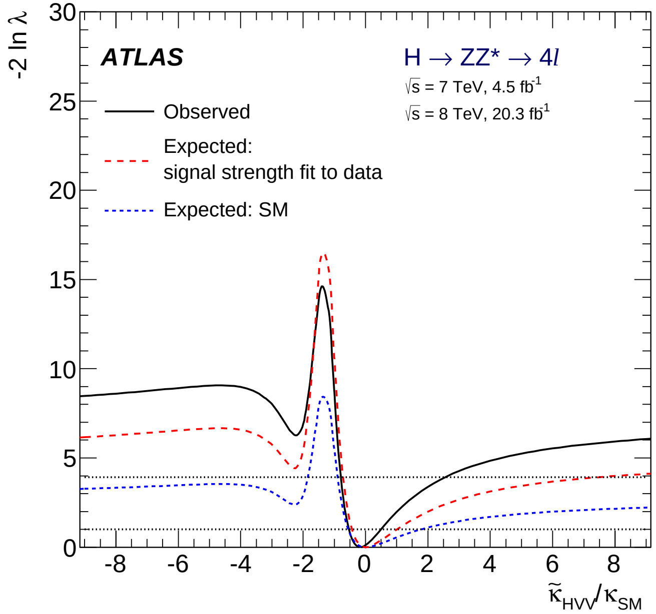
Parity and CP-mixing

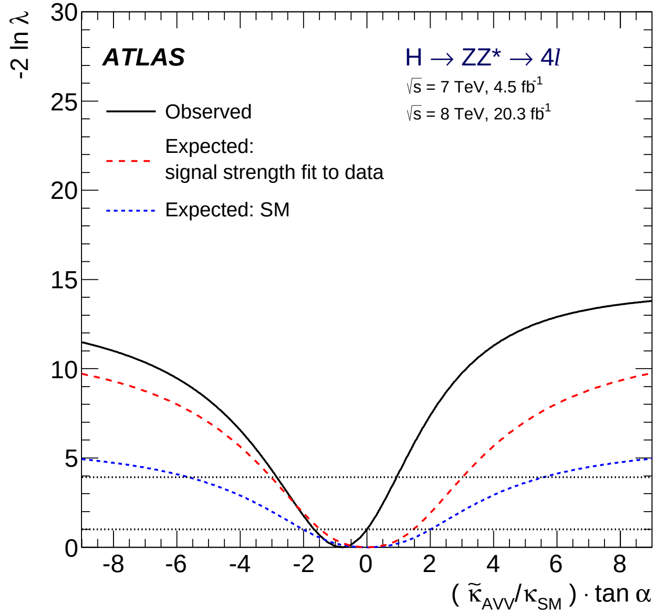
$$\mathcal{L}_0^V = X_0 \cdot \left\{ \cos\alpha\ \kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right.$$
$$- \frac{1}{4\Lambda} \left[\cos\alpha\ \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin\alpha\ \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right]$$
$$\left. - \frac{1}{2\Lambda} \left[\cos\alpha\ \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \sin\alpha\ \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \right\}$$

Standard Model : $\alpha = 0$, $\kappa_{HVV} = 0$, $\kappa_{AVV} = 0$

Beyond SM : $\kappa_{HVV} \Rightarrow CP$-even , $\kappa_{AVV} \Rightarrow CP$-odd

***CP*-mixing** for $\alpha \neq 0$ and $\alpha \neq \frac{\pi}{2}$

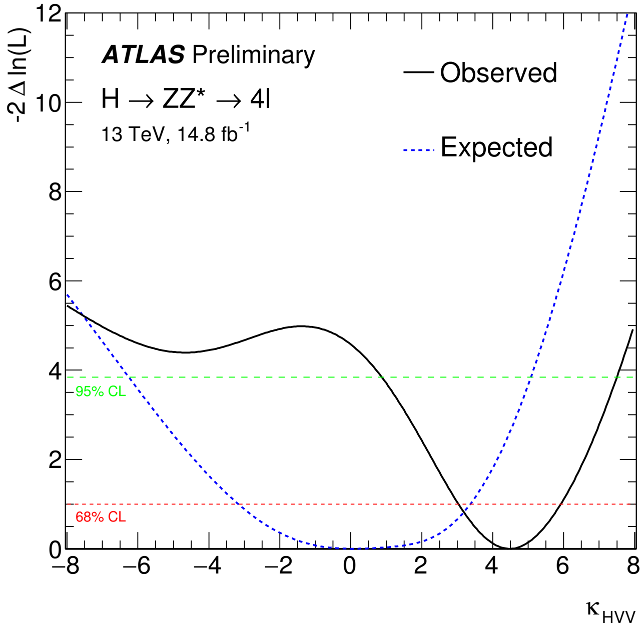


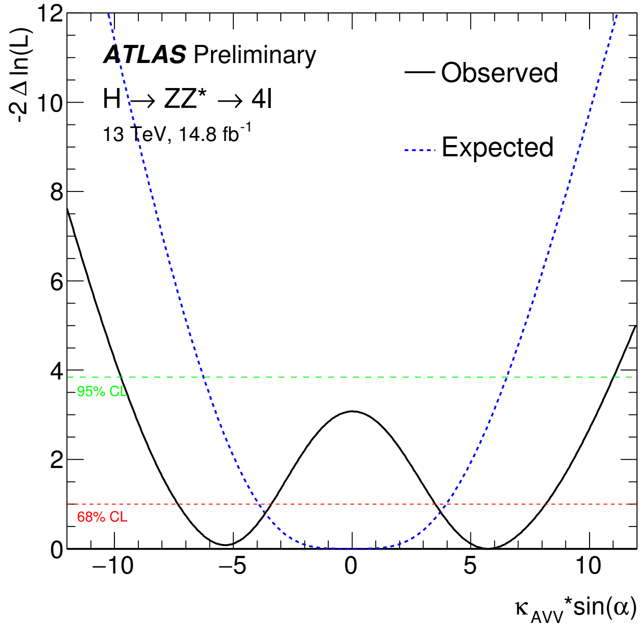


$$\tilde{\kappa}_{HVV} = \frac{v}{4\Lambda} \kappa_{HVV}$$
$$\tilde{\kappa}_{AVV} = \frac{v}{4\Lambda} \kappa_{AVV}$$

$\Rightarrow \tilde{\kappa}_{HVV},\ \tilde{\kappa}_{AVV}$ compatible with 0

CP-tests at 13 TeV [ATLAS-CONF-2016-079]





Some "tension" for κ_{HVV}, $\sim 2.1\sigma$
... not worrisome at this stage, though

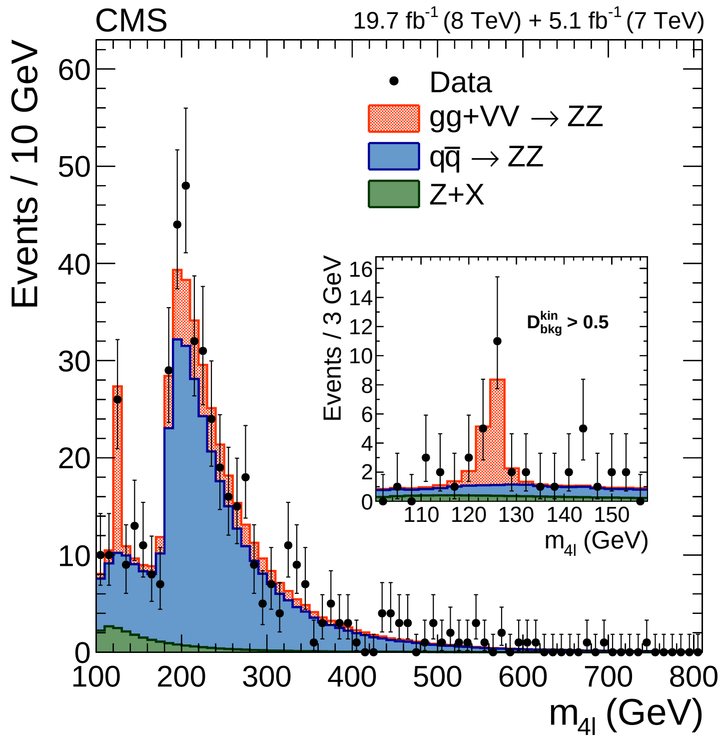
Width measurement

Width measurement [Phys. Lett. B 736 (2014) 64]

In Standard Model, the Higgs decay width is expected to be $\Gamma_H \simeq 4\ \mathrm{MeV}$
$\Rightarrow$ cannot measure it from the observed resonance width (experimental uncertainty $\mathcal{O}(\mathrm{GeV})$)

Use $H \to ZZ^{(*)} \to 4\ell$ decays.
Compare Higgs on-shell ($gg \to H \to ZZ^*$) and off-shell ($gg \to H^* \to ZZ$) production cross-sections:

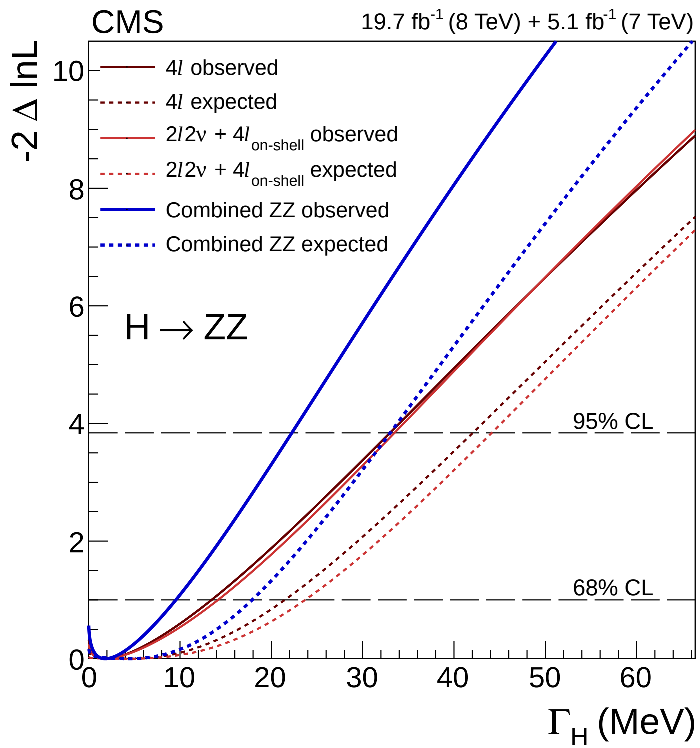
$$\sigma_{gg\to H\to ZZ^*} \propto \frac{g_{Hgg}\cdot g_{HZZ}}{\Gamma_H m_H} \quad ; \quad \sigma_{gg\to H^*\to ZZ} \propto \frac{g_{Hgg}\cdot g_{HZZ}}{(2m_Z)^2}$$



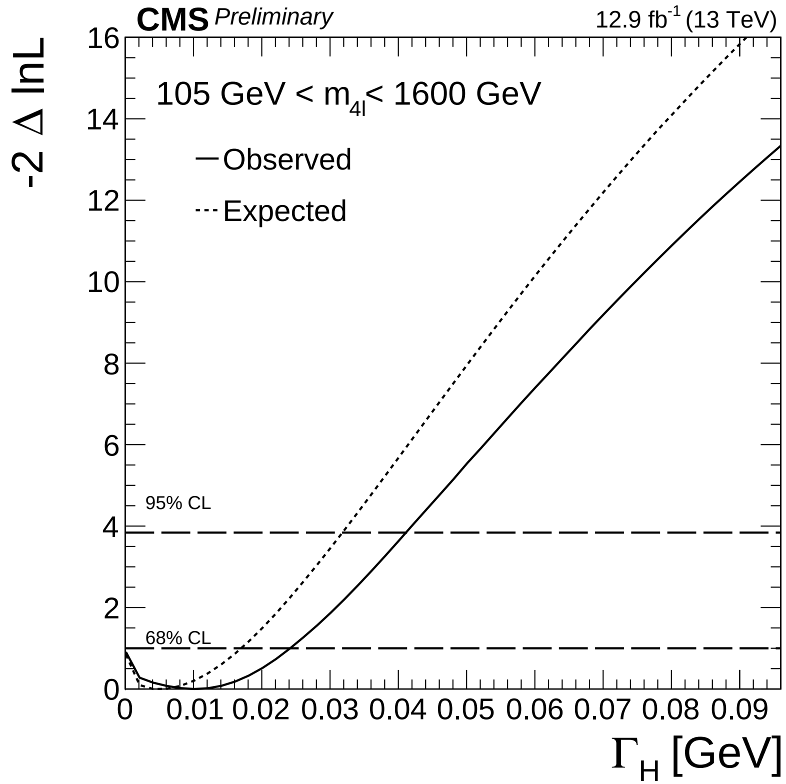
$\Rightarrow$ under specific assumptions on how g_{Hgg}, g_{HZZ} scale with $\hat{s}$, $\dfrac{\sigma_{gg\to H^*\to ZZ}}{\sigma_{gg\to H\to ZZ^*}}$ gives a measurement of Γ_H

Total width at 8 and 13 TeV [Phys. Lett. B 736 (2014) 64 , CMS-PAS-HIG-16-033]

8 TeV



13 TeV



$\Rightarrow$ $\Gamma_H < 22$ MeV (at 95% CL)

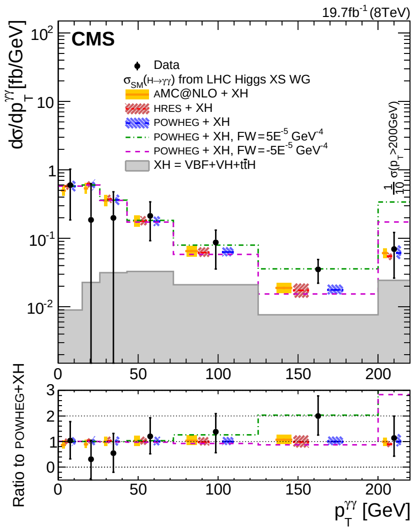
$\Rightarrow$ $\Gamma_H < 41$ MeV (at 95% CL)

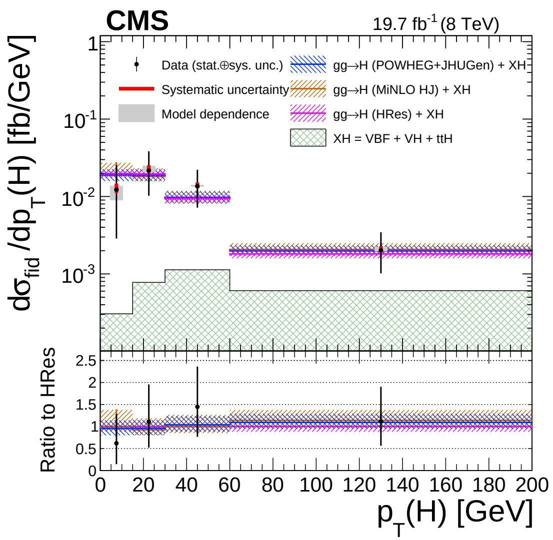
Differential cross-sections

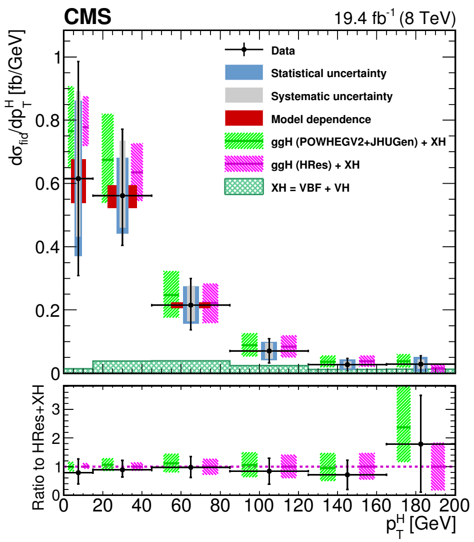
Differential cross-sections @ Run-I

[EPJC 76 (2016) 13 , JHEP 04 (2016) 005 , HIG-15-010] , [Phys. Rev. Lett. 115 (2015) 091801 , arXiv:1604.02997]

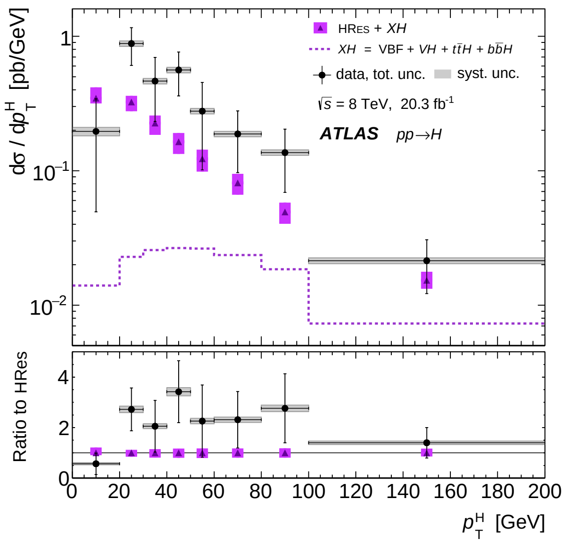
CMS: $H \to \gamma\gamma$, $H \to 4\ell$, $H \to WW^* \to e\nu\mu\nu$

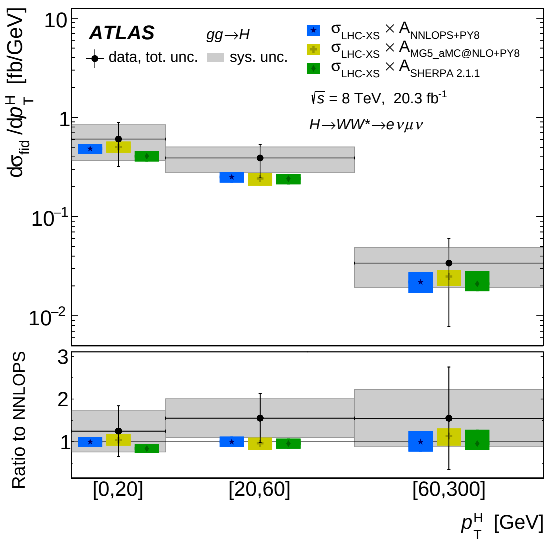






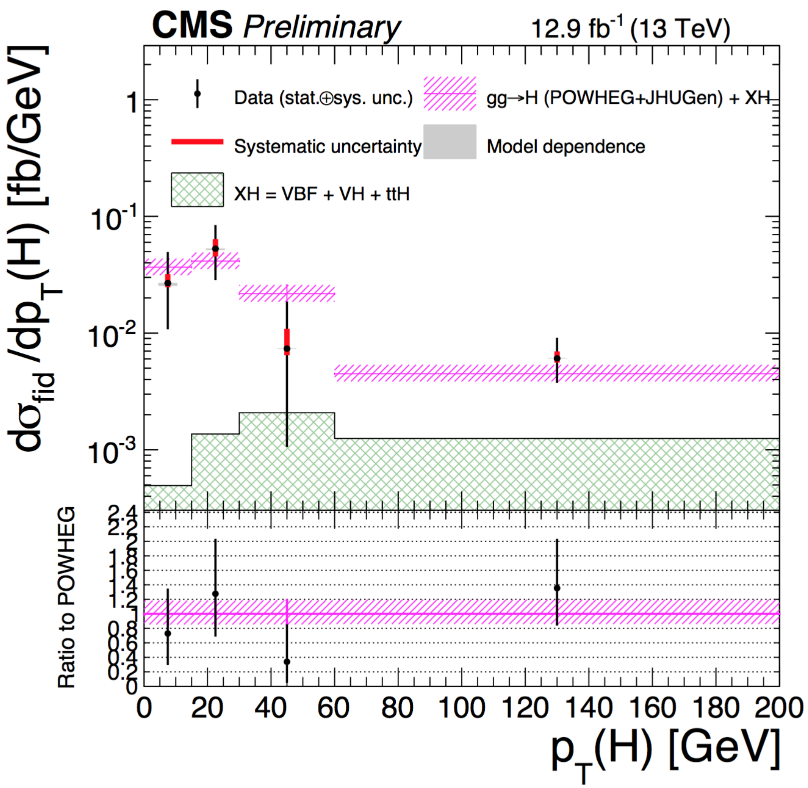
ATLAS: $H \to \gamma\gamma$, $H \to 4\ell$ combined, $H \to WW^* \to e\nu\mu\nu$



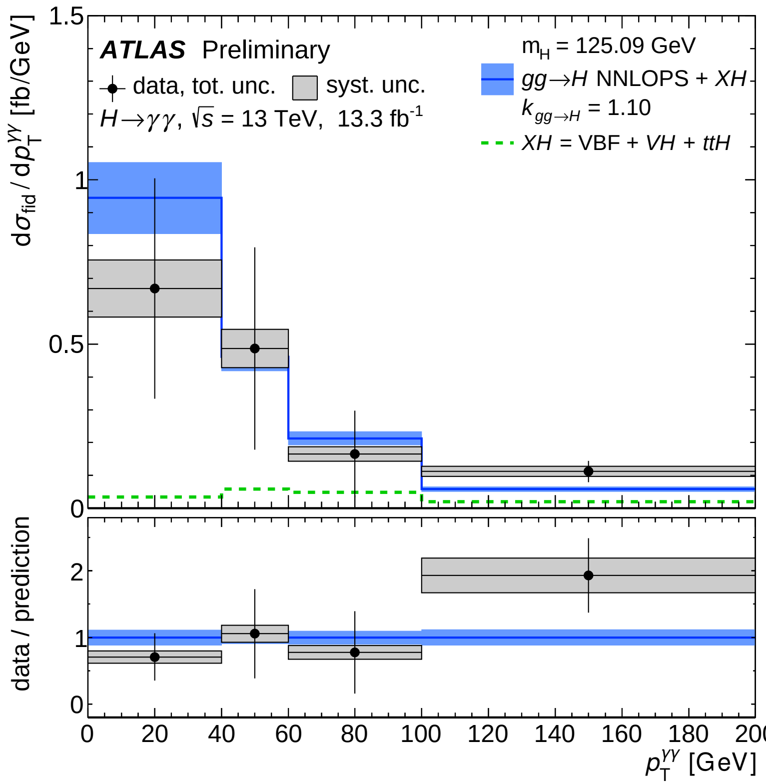


Differential cross-sections at 13 TeV

$H \to ZZ^* \to 4\ell$



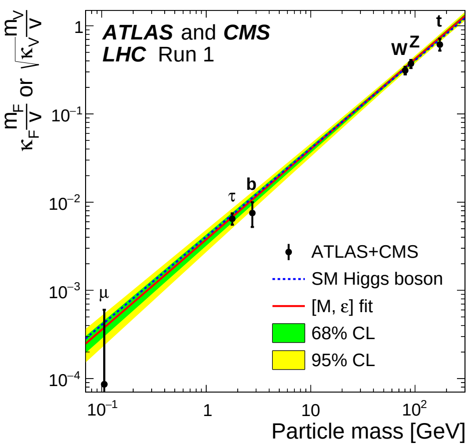
$H \to \gamma\gamma$

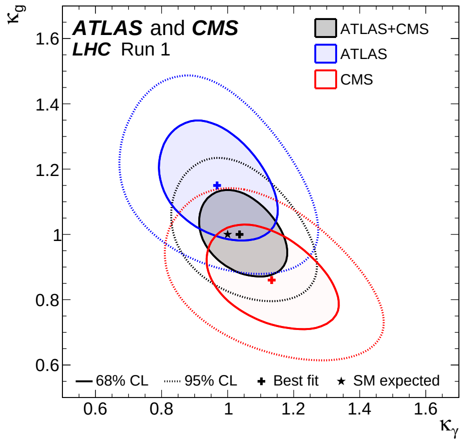


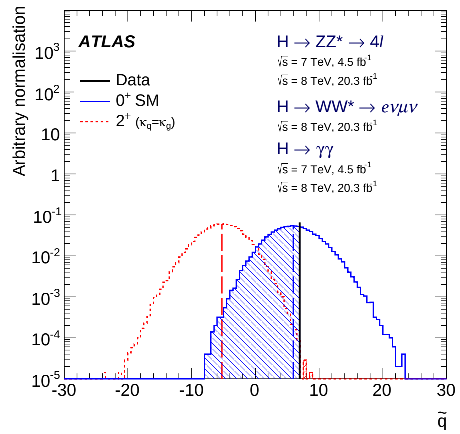
Conclusions

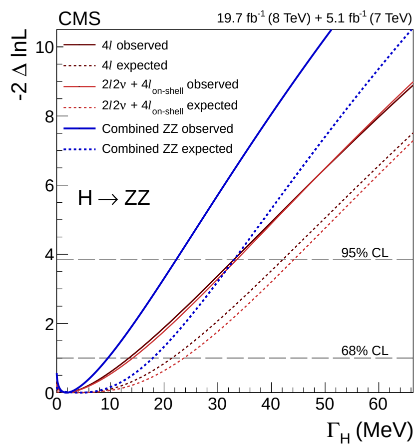
Conclusions

Run-I analyses well mature, ATLAS+CMS combined results available for mass and couplings:

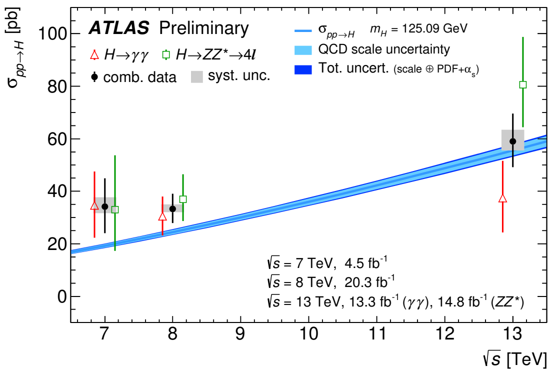


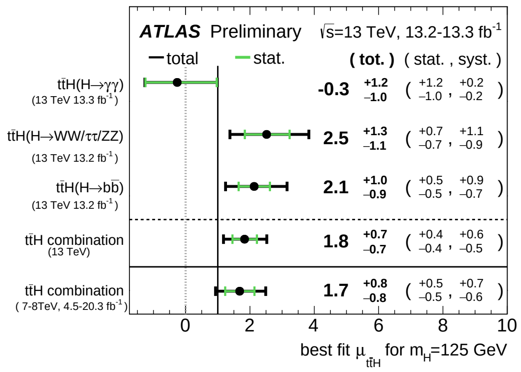


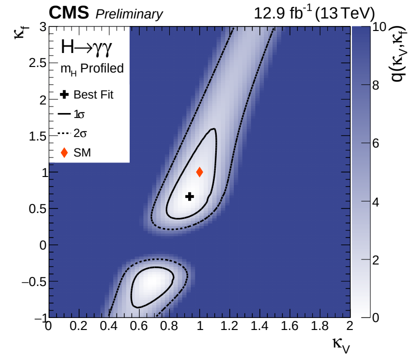


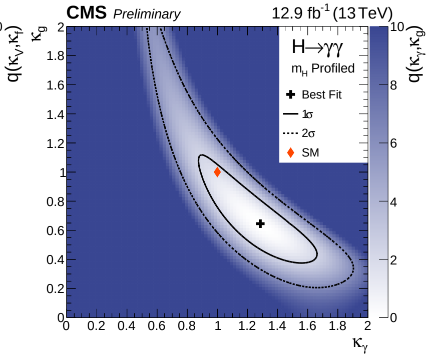


Run-II: efficient data-taking, analyses progressing fast, (cross-section)$\times$(luminosity) already beated Run-I









$\Rightarrow$ We are still compatible with Standard Model prediction ... but uncertainties are still large.

Theory uncertainties improved a lot. Important to pursue precision measurements in the Higgs sector, in Run-II and beyond, to investigate possible deviations from SM

Thanks for your attention

More material

Statistical models used in measurements

Extended likelihood function: $\mathcal{L}(\vec{\alpha};\vec{\nu})$:

$$-\ln\mathcal{L}(\vec{\alpha};\vec{\nu}) = (n_s+n_b) - \sum_e \left[\overbrace{n_s\cdot f_s\left(\vec{x}_e|\vec{\alpha},\vec{\nu}_s\right)}^{\text{signal pdf}} + \overbrace{n_b\cdot f_b\left(\vec{x}_e|\vec{\nu}_b\right)}^{\text{background pdf}} \right]$$
$$-\overbrace{\sum_k \ln\pi_k(\nu_k)}^{\text{ancillary pdfs}}$$

n_s, n_b: signal / background yields
$\vec{x}$: observables
f_s, f_b: signal / background pdfs
$\vec{\alpha}$: parameters of interest
(mass, cross-section, couplings, ...)
$\vec{\nu}$: "nuisance parameters"
(shape parameters, systematics, ...)
π_k: pdfs obtained from auxiliary measurements

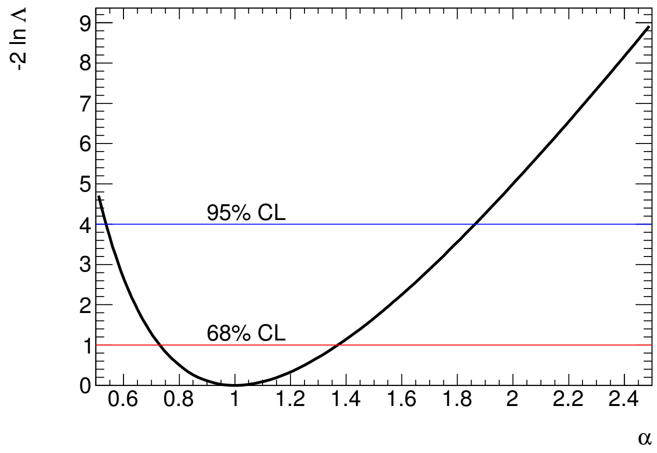
Test statistic: "Profiled Likelihood Ratio" (PLR)

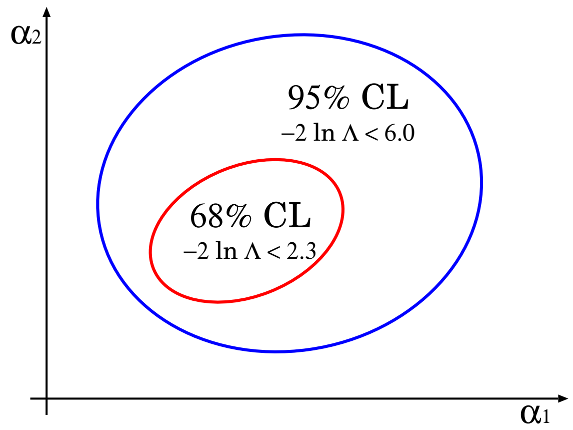
$$q_{\vec{\alpha}} = -2\ln\Lambda(\vec{\alpha}) = -2\ln\frac{\mathcal{L}(\vec{\alpha};\hat{\hat{\nu}}(\vec{\alpha}))}{\mathcal{L}(\hat{\alpha};\hat{\nu})}$$

$\leftarrow \mathcal{L}(\vec{\alpha};\hat{\hat{\nu}}(\vec{\alpha}))$: likelihood for fixed $\vec{\alpha}$ and "profiled" $\vec{\nu}$
$\leftarrow \mathcal{L}(\hat{\alpha};\hat{\nu})$: maximum likelihood for free $\vec{\alpha},\vec{\nu}$

Wilks' theorem : *if $\vec{\alpha}=\vec{\alpha}^{true}$, then $q_{\vec{\alpha}}$ follows a χ^2_D distribution, with D being the number of parameters of interest $\vec{\alpha}$*

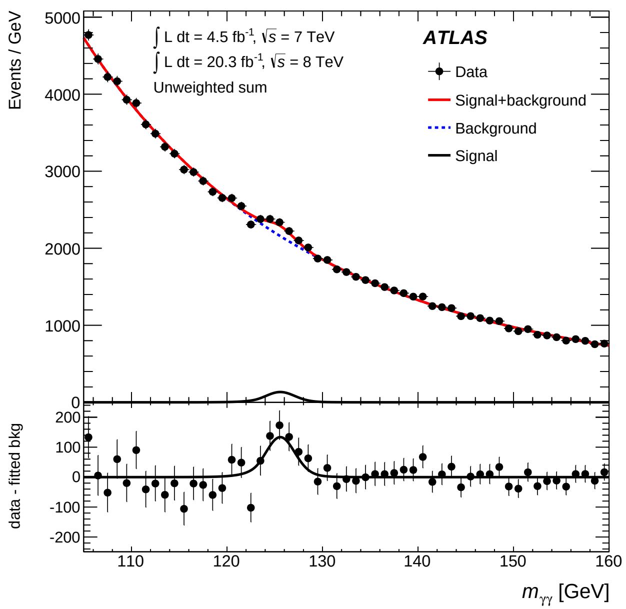
$\Rightarrow$ compute confidence intervals for $\vec{\alpha}$

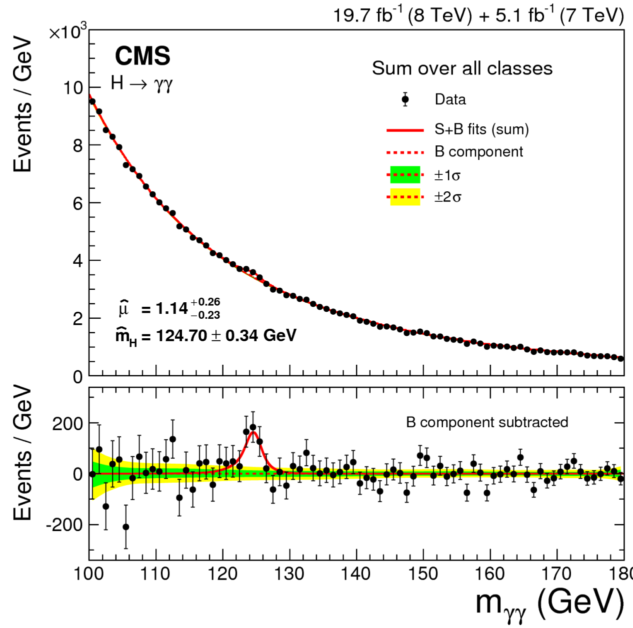




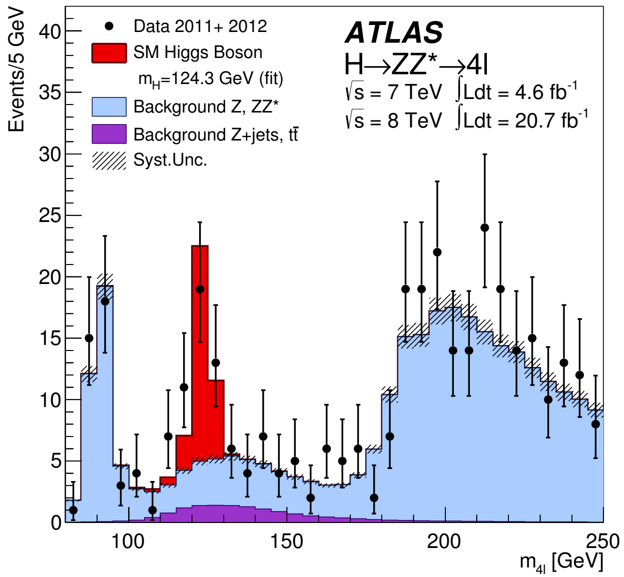
Higgs observation in Run-I : $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$

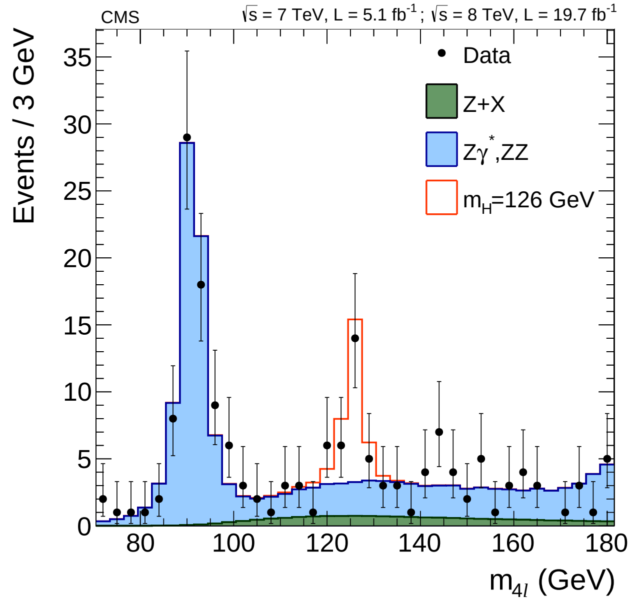
$H \to \gamma\gamma$





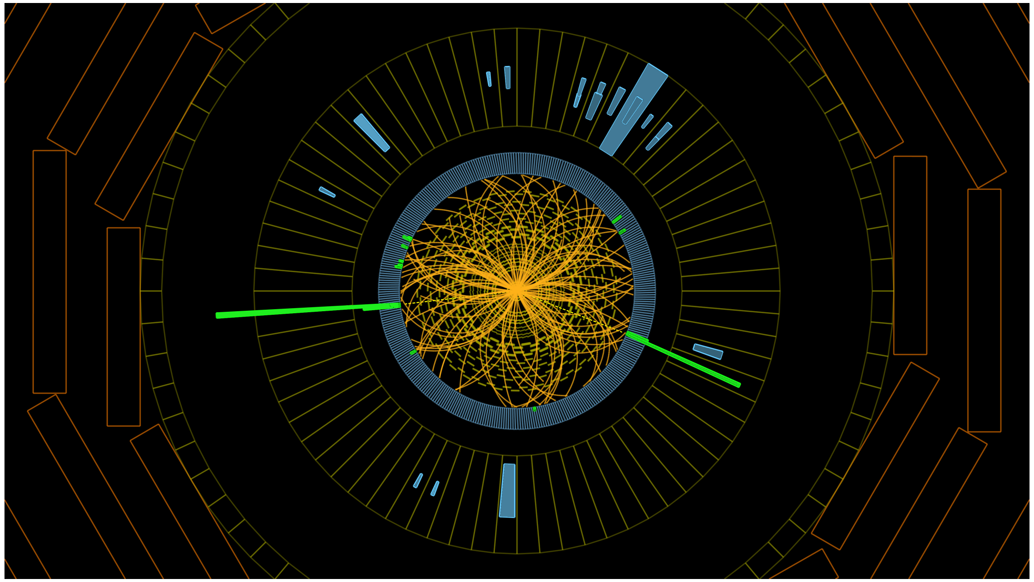
$H \to 4\ell$



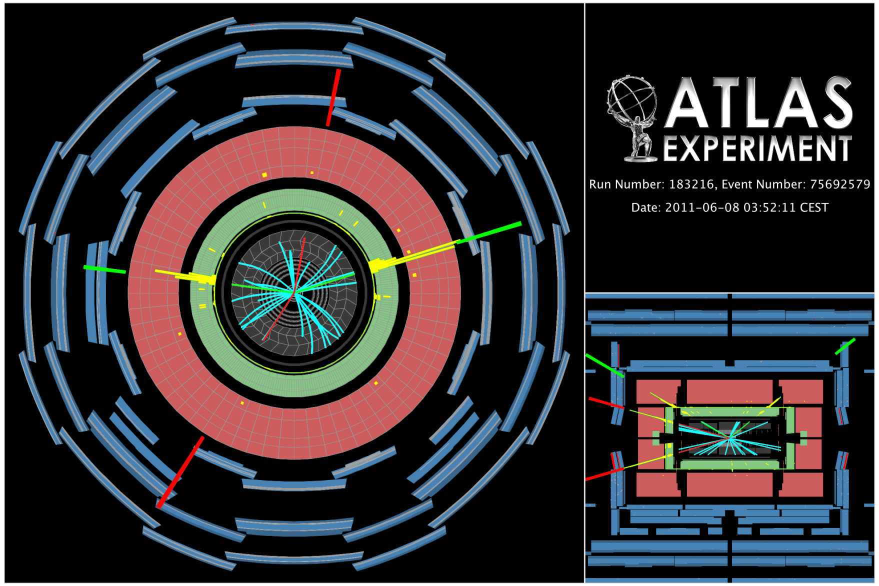


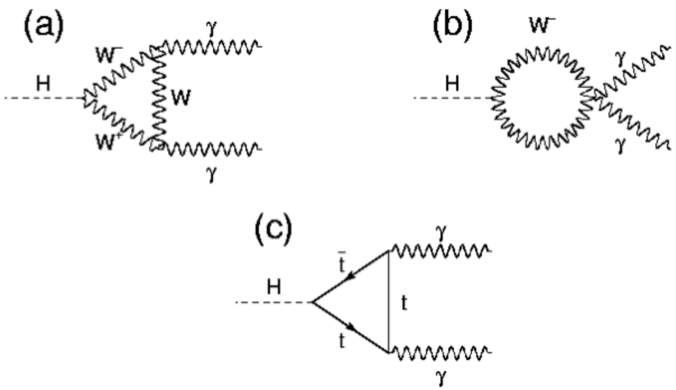
Higgs candidates : $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$

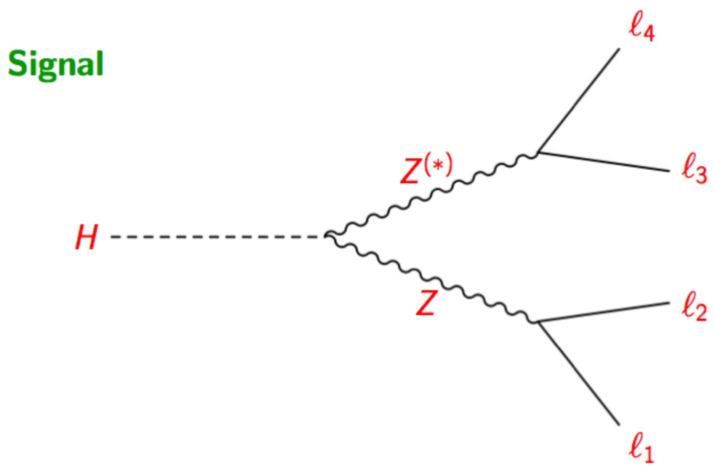
$H \to \gamma\gamma$ candidate at CMS



$H \to ZZ^* \to e^+e^-\mu^+\mu^-$ candidate at ATLAS



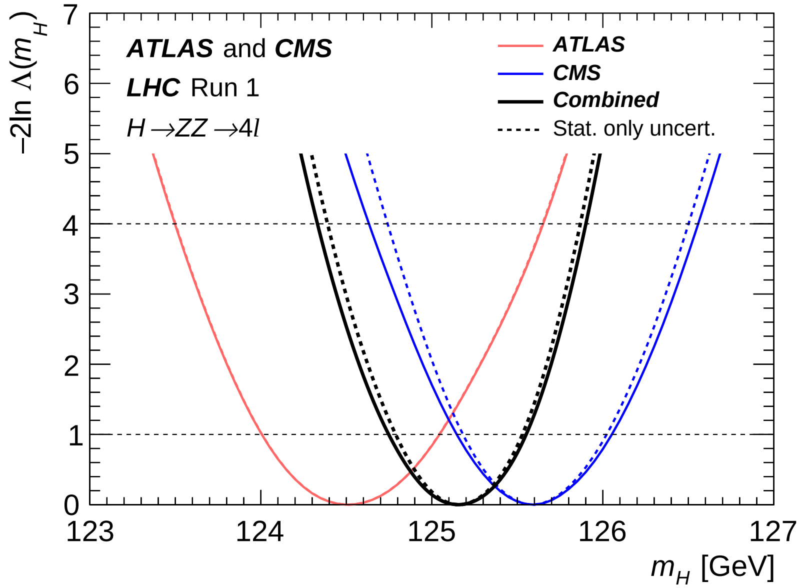




Mass measurement

Use the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels
that allow a full kinematics reconstruction with good invariant mass resolution ($\mathcal{O}(1\ \mathrm{GeV})$)

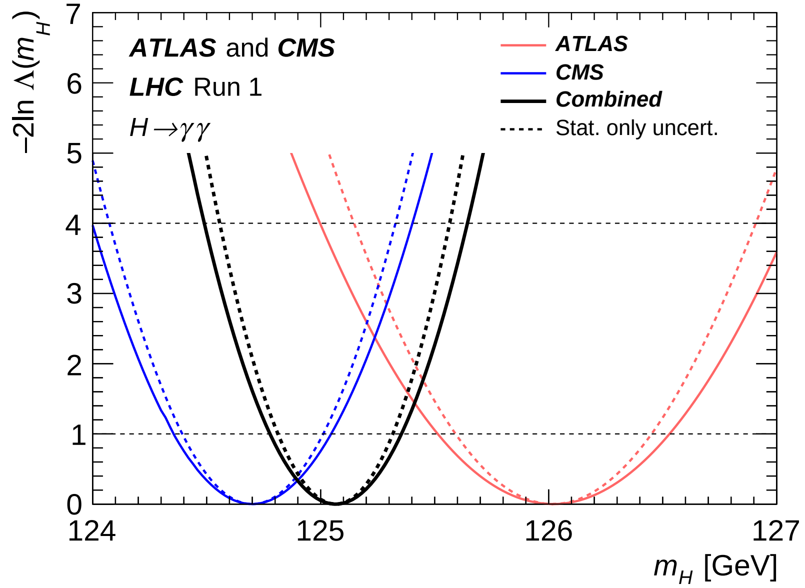
4ℓ channel



$$\hat{m}_H^{4\ell} = 125.15 \pm 0.37(stat) \pm 0.15(syst)\ \mathrm{GeV}$$

Good signal/background, low statistics
e, μ energy scales from $J/\psi, \Upsilon, Z \ \to \ \ell\ell$

$\gamma\gamma$ channel



$$\hat{m}_H^{\gamma\gamma} = 125.07 \pm 0.25(stat) \pm 0.14(syst)\ \mathrm{GeV}$$

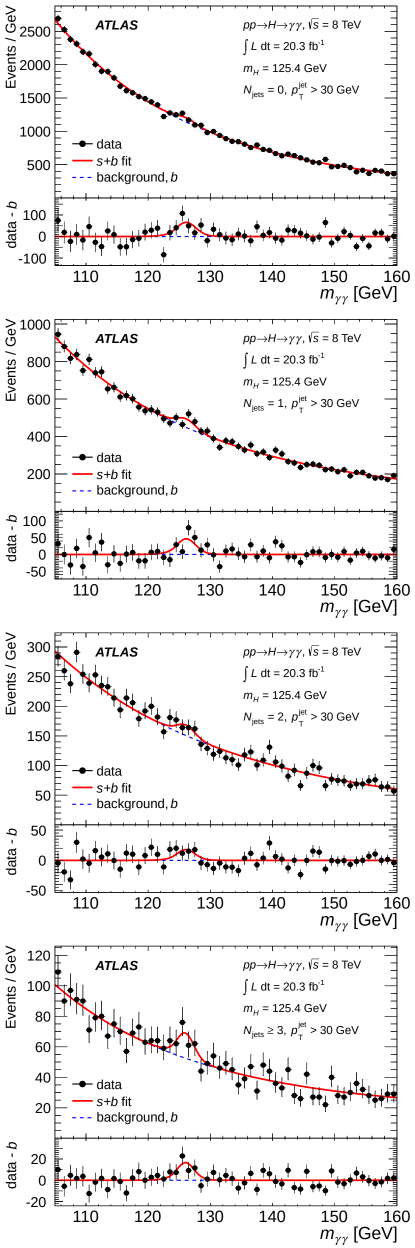
Large background, good statistics
γ energy scale from $Z \to e^+e^-$ and $e \to \gamma$ extrapolation

Comparison with SM expectations

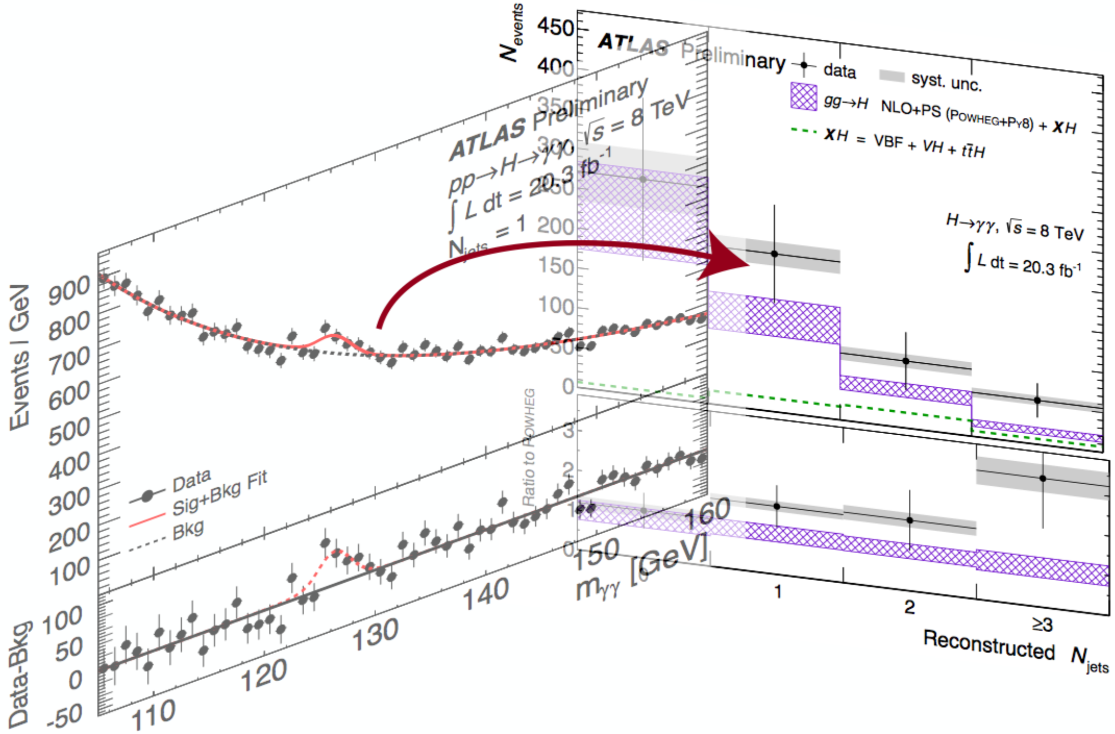
Parameterisation	p-value	DOF	Parameters
Global signal strength	40%	1	μ
Production processes	24%	5	$\mu_{ggF}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	65%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}$
Decay modes with $H \to \mu\mu$	75%	6	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}, \mu^{\mu\mu}$
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	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ggF}, (\sigma \cdot \mathrm{B})^{ZZ}_{ggF}, (\sigma \cdot \mathrm{B})^{WW}_{ggF}, (\sigma \cdot \mathrm{B})^{\tau\tau}_{ggF}, (\sigma \cdot \mathrm{B})^{\gamma\gamma}_{VBF}, (\sigma \cdot \mathrm{B})^{ZZ}_{VBF}, (\sigma \cdot \mathrm{B})^{WW}_{VBF}, (\sigma \cdot \mathrm{B})^{\tau\tau}_{VBF}, (\sigma \cdot \mathrm{B})^{\gamma\gamma}_{WH}, (\sigma \cdot \mathrm{B})^{ZZ}_{WH}, (\sigma \cdot \mathrm{B})^{WW}_{WH}, (\sigma \cdot \mathrm{B})^{\tau\tau}_{WH}, (\sigma \cdot \mathrm{B})^{bb}_{WH}, (\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ZH}, (\sigma \cdot \mathrm{B})^{ZZ}_{ZH}, (\sigma \cdot \mathrm{B})^{WW}_{ZH}, (\sigma \cdot \mathrm{B})^{\tau\tau}_{ZH}, (\sigma \cdot \mathrm{B})^{bb}_{ZH}, (\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ttH}, (\sigma \cdot \mathrm{B})^{ZZ}_{ttH}, (\sigma \cdot \mathrm{B})^{WW}_{ttH}, (\sigma \cdot \mathrm{B})^{\tau\tau}_{ttH}, (\sigma \cdot \mathrm{B})^{bb}_{ttH}$
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	$\sigma(gg \to H \to ZZ), \sigma_{VBF}/\sigma_{ggF}, \sigma_{WH}/\sigma_{ggF}, \sigma_{ZH}/\sigma_{ggF}, \sigma_{ttH}/\sigma_{ggF}, \mathrm{B}^{WW}/\mathrm{B}^{ZZ}, \mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}, \mathrm{B}^{\tau\tau}/\mathrm{B}^{ZZ}, \mathrm{B}^{bb}/\mathrm{B}^{ZZ}, \sigma^{7TeV}_{ggF}/\sigma^{8TeV}_{ggF}, \sigma^{7TeV}_{VBF}/\sigma^{8TeV}_{VBF}, \sigma^{7TeV}_{WH}/\sigma^{8TeV}_{WH}, \sigma^{7TeV}_{ZH}/\sigma^{8TeV}_{ZH}, \sigma^{7TeV}_{ttH}/\sigma^{8TeV}_{ttH}$
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	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$

"Compatibility with the SM prediction of fit results as a whole under the asymptotic approximation. For each parameterisation, the unconditional best fit is compared with the conditional fit where all parameters are set to their SM values. The conversion from $-2\ln\Lambda$ to the quoted p-value is performed assuming a two-sided distribution with the specified number of degrees of freedom (DOF). The quoted p-values are partially correlated between the different parameterisations."

Extraction of signal yield per category . . .



- divide events in categories (e.g. number of jets, bins of $p_{\rm T}^{\gamma\gamma}$, bins of $Y_{\gamma\gamma}$, etc . . .)
- from the invariant mass spectrum, extract the signal yield in each category / bin

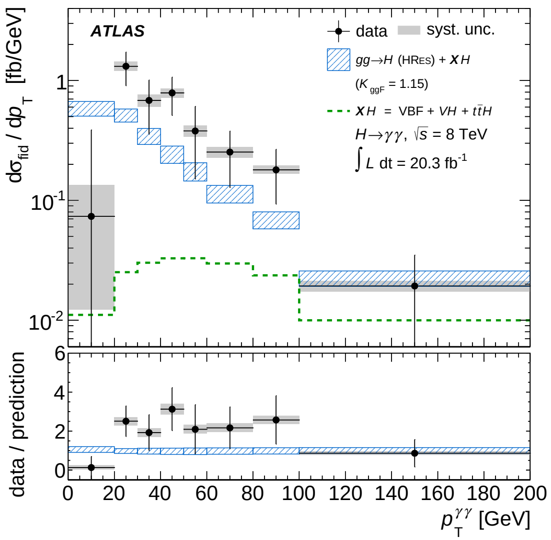


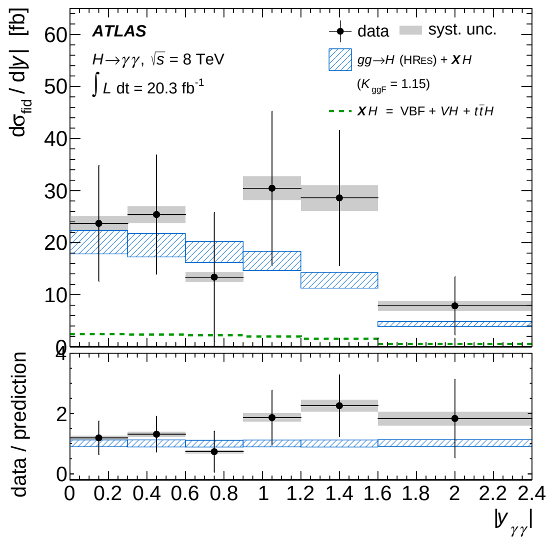
- then unfold the experimental effects (efficiencies, migrations, . . .)

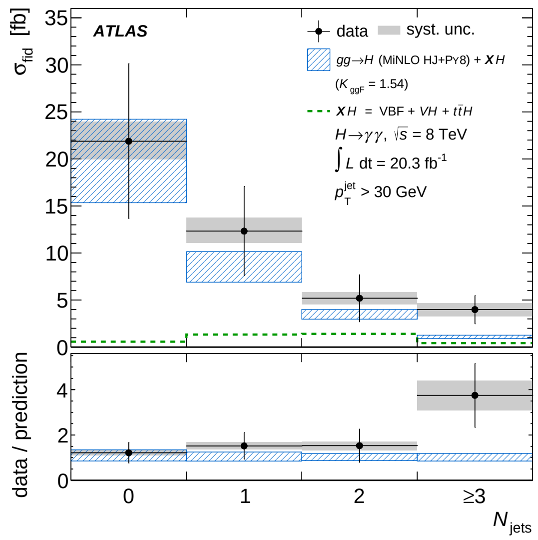
$\Rightarrow$ get the cross-section per category / bin

Differential cross-sections

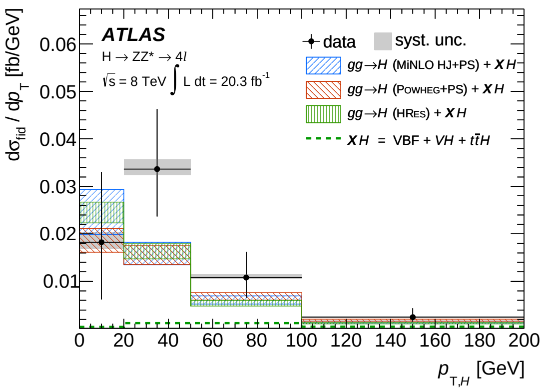
$H \to \gamma\gamma$

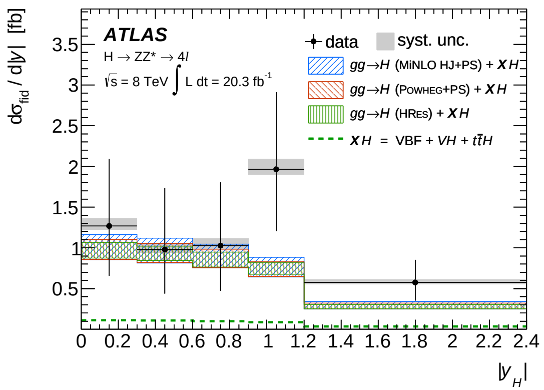


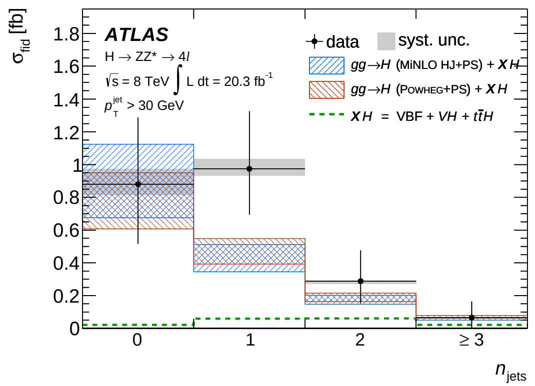




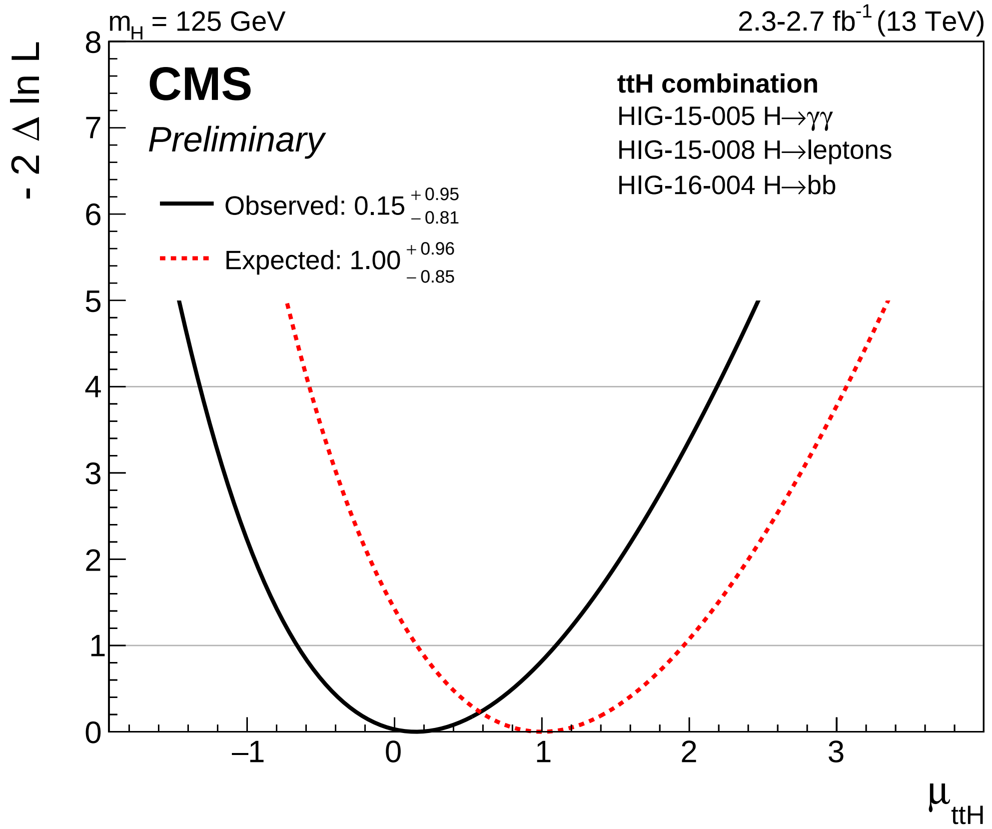
$H \to ZZ^* \to 4\ell$

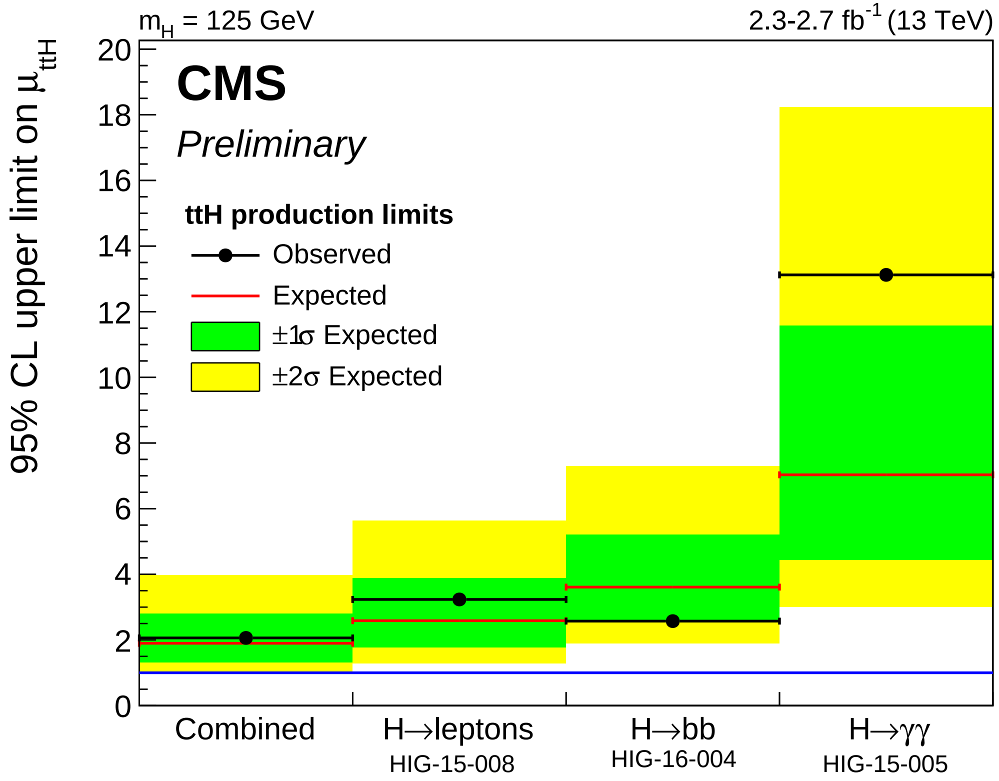






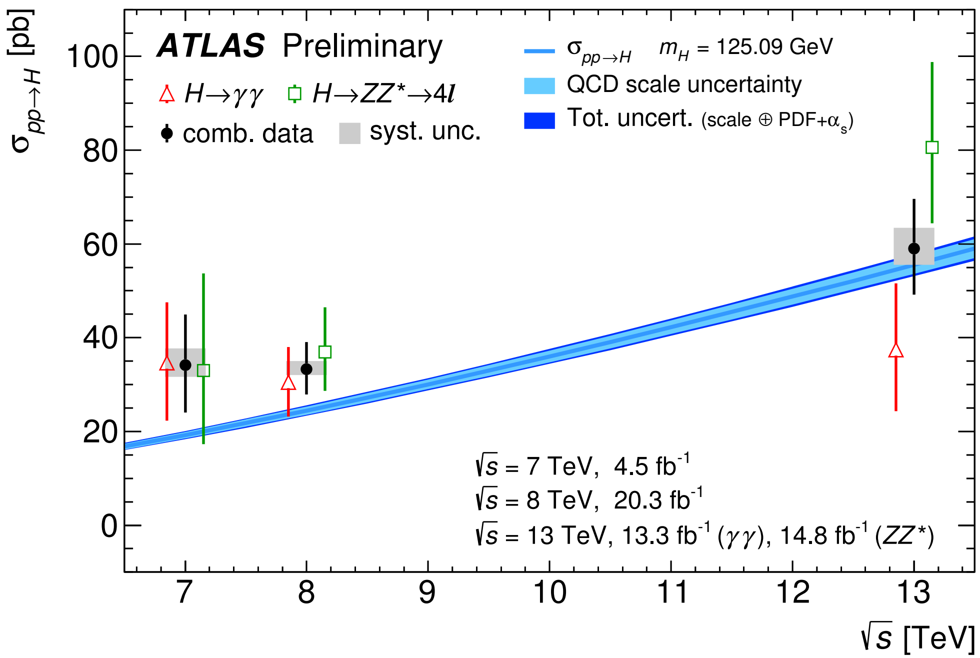
ttH production [HIG-15-008 , HIG-16-004 , HIG-15-005]

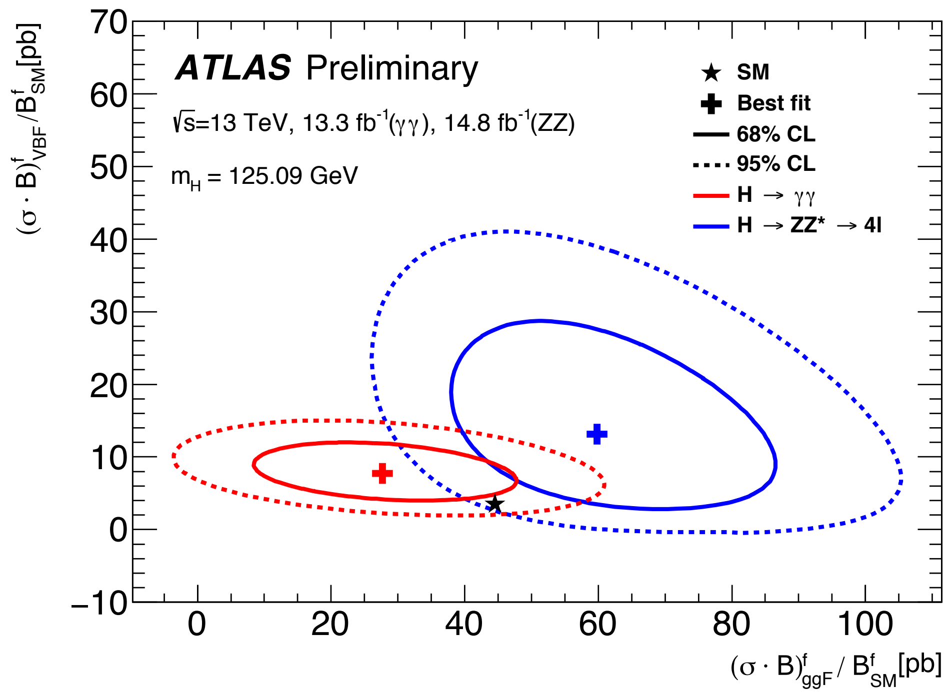




[to be updated if new results arrive from CMS 2016 data]

Total cross-section from $\gamma\gamma$ and 4ℓ final states
[ATLAS-CONF-2016-081]





Decay channel	Total cross section ($pp\to H+X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H\to\gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H\to ZZ^*\to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

Parameter	Best-fit value	SM prediction
$(\sigma\cdot B)^{ZZ}_{ggF}$ (pb)	$1.67\ ^{+0.41}_{-0.37}$	1.18 ± 0.07
$\sigma_{VBF}/\sigma_{ggF}$	$0.25\ ^{+0.15}_{-0.10}$	0.079 ± 0.004
$B^{\gamma\gamma}/B^{ZZ}$	$0.041\ ^{+0.015}_{-0.013}$	0.086 ± 0.003