

*Measurement of
cross sections and couplings
of the Higgs Boson
using the ATLAS detector*

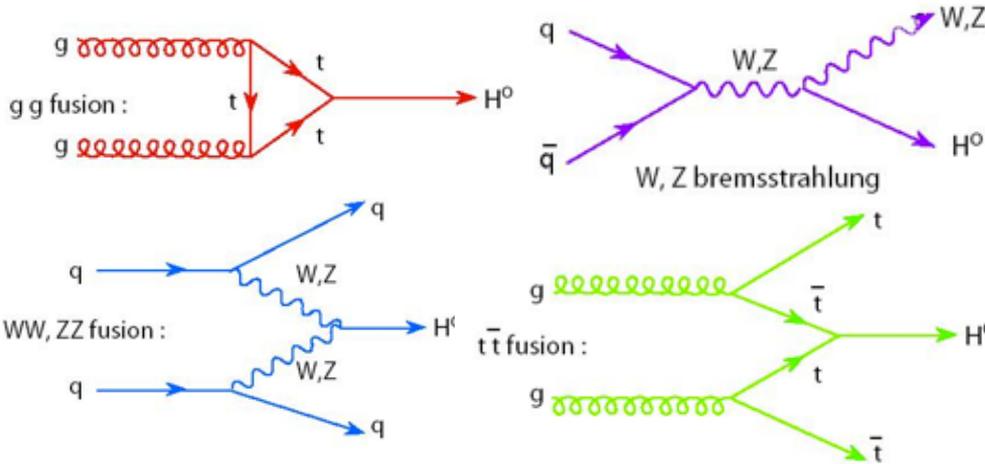
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29th Recontres de Blois 2017 (28th May – 2th June)

After Run1 discovery of the Higgs boson, it is crucial to investigate for possible deviations from the SM predictions in terms of Higgs couplings to SM particles and Xs.

This talk:

- **The Higgs at LHC:** production mechanisms and decays
- **Cross section and coupling measurements:**
 - Run 1 brief overview
 - Run 2 measurements at $\sqrt{s}=13$ TeV both in the bosonic and fermionic decay channels

The Higgs production at LHC can occur through the following mechanisms:

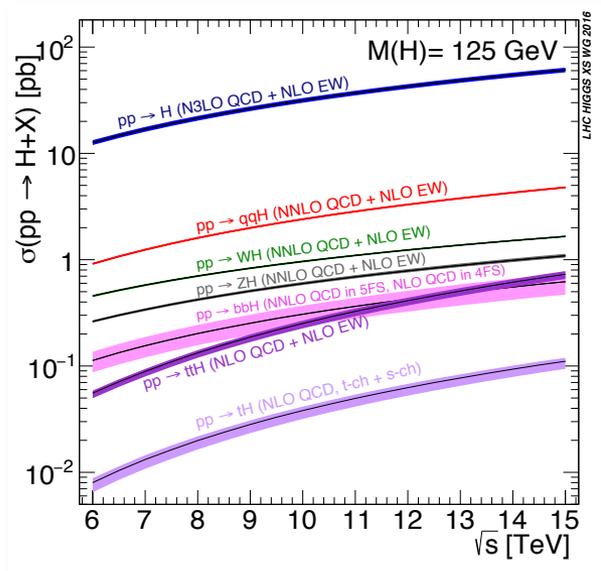


ggF: is the dominant production mode, $\sigma^{ggF}/\sigma^{TOT} = 87\% @ 13 \text{ TeV}$.

VBF: whose signature is characterized by H+2jet forward, $\sigma^{VBF}/\sigma^{TOT} = 7\% @ 13 \text{ TeV}$.

VH: whose signature is composed by a H associated to a W or a Z boson, $\sigma^{VH}/\sigma^{TOT} = 4\% @ 13 \text{ TeV}$.

ttH-bbH: in which the H is associated to tt-bar / bb-bar pairs, $\sigma^{ttH+bbH}/\sigma^{TOT} = 2\% @ 13 \text{ TeV}$.



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

Run1 analyses

The **first measurements of the properties** have shown that the observed boson was compatible, within the uncertainties, with the **Higgs predicted by the SM**



Measurements in terms of:

- **Signal strength** (more model dependent):

$$\mu = (\sigma BR)_{obs} / (\sigma BR)_{SM}$$

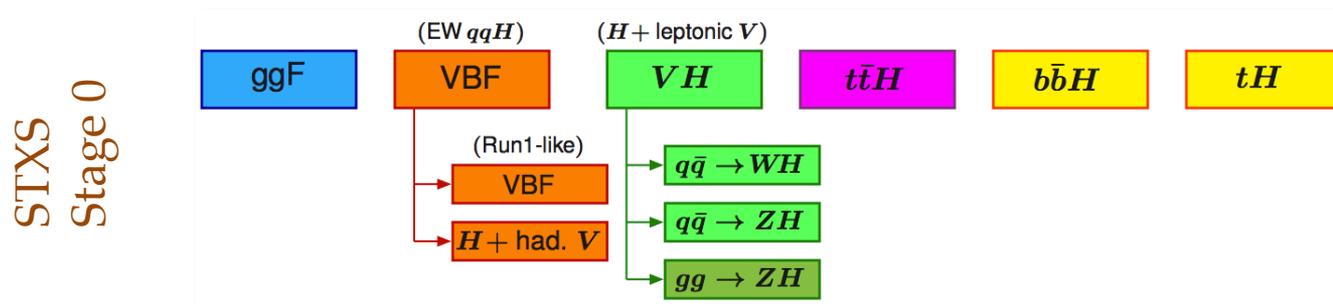
- **Coupling modifiers (κ_j)** added as **multiplying terms in the Higgs boson couplings to fermions and bosons in the SM Lagrangian** (take in account for NP effects both in production and decay)

$$\sigma_i \cdot \text{BR}^f = \frac{\sigma_i(\vec{k}) \cdot \Gamma^f(\vec{k})}{\Gamma_H} \quad \text{where} \quad \kappa_j^2 = \Gamma^j / \Gamma_{SM}^j, \quad \kappa_j^2 = \sigma_j / \sigma_j^{\text{SM}}$$

-> $\kappa_j=1$ refers to the Standard Model case (SM)

➔ Run2

- Production cross section increased by a factor ~ 2 (~ 4 for $t\bar{t}H$)
- Splitting the events in more restricted phase spaces to observe **exclusive production modes with small cross sections and channels which are difficult to probe**
- Aiming for better **precision on the coupling measurements**
- **STXS measurement performed:** to maximize the experimental sensitivity while minimizing the model dependency (measuring the XSs in exclusive regions of the phase-space)



H- $\gamma\gamma$

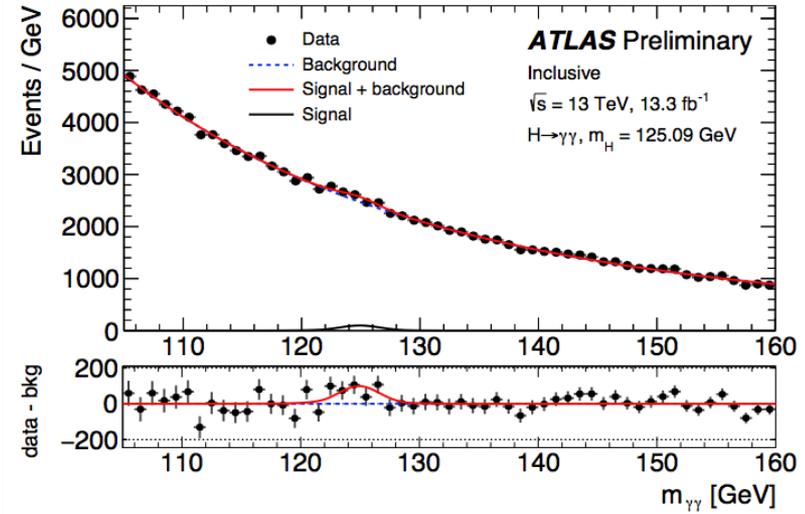
- two isolated photons
- $E_T/m_{\gamma\gamma} > 0.35$ (0.25)
- Maximum likelihood fit on the $m_{\gamma\gamma}$ spectrum

13.3 fb⁻¹ @ 13 TeV

Fiducial XS measured in phase space regions sensitive to the inclusive Higgs boson production, the VBF and the H production in association with a charged lepton:

$$\sigma_i = \frac{v_i^{\text{sig}}}{c_i \int L dt}$$

where c_i are taken from MC and take into account for detector efficiency and acceptance.



	diphoton baseline	VBF enhanced	single lepton
Photons	$ \eta < 1.37$ or $1.52 < \eta < 2.37$ $p_T^{\gamma 1} > 0.35 m_{\gamma\gamma}$ and $p_T^{\gamma 2} > 0.25 m_{\gamma\gamma}$		
Jets	-	$p_T > 30 \text{ GeV}$, $ y < 4.4$ $m_{jj} > 400 \text{ GeV}$, $ \Delta y_{jj} > 2.8$ $ \Delta\phi_{\gamma\gamma,jj} > 2.6$	-
Leptons	-	-	$p_T > 15 \text{ GeV}$ $ \eta < 2.47$

$m_H = 125.09 \pm 0.24 \text{ GeV}$

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	43.2 ± 14.9 (stat.) ± 4.9 (syst.)	$62.8^{+3.4}_{-4.4}$	[N ³ LO + XH]
VBF-enhanced	4.0 ± 1.4 (stat.) ± 0.7 (syst.)	2.04 ± 0.13	[NNLOPS + XH]
single lepton	1.5 ± 0.8 (stat.) ± 0.2 (syst.)	0.56 ± 0.03	[NNLOPS + XH]

- Categorization aiming for production modes separation by exploiting distinct event kinematics and topology from each of them

-> STXS

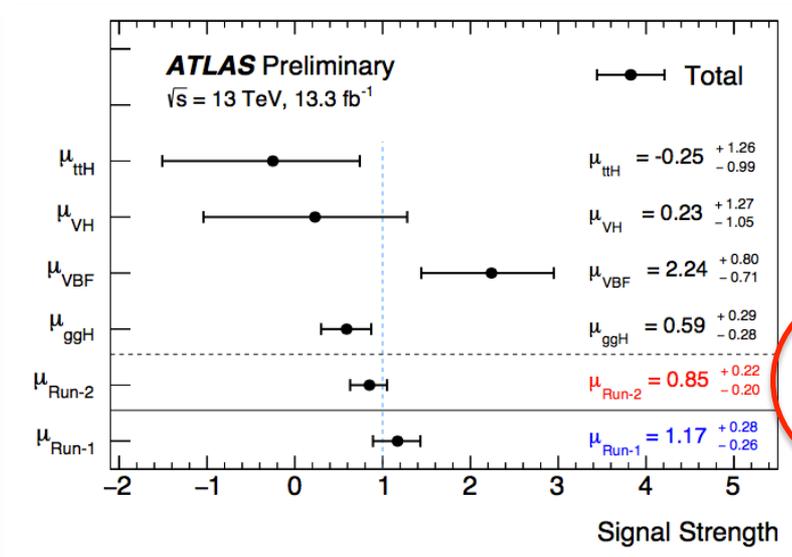
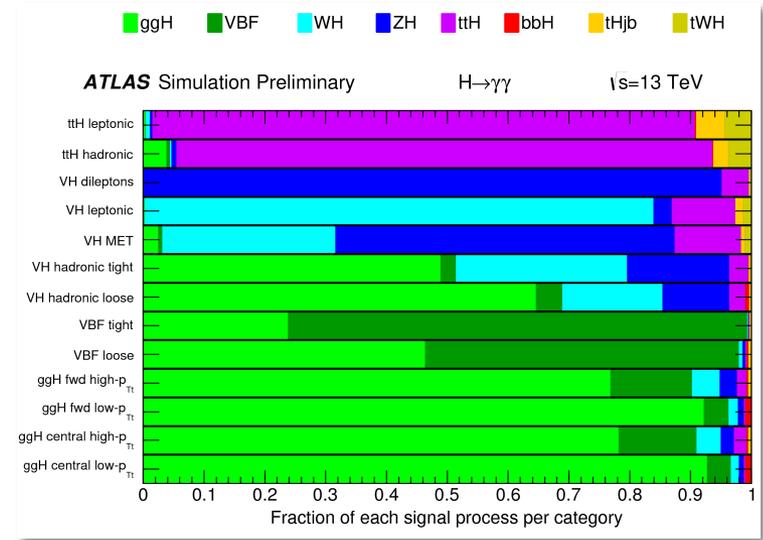
-> total production XS and μ

($b\bar{b}H$ and tH contributions fixed to SM)

- Maximum likelihood fit performed simultaneously on the $m_{\gamma\gamma}$ spectrum in each event category

XS per production mode:

$$\begin{aligned} \sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 65^{+32}_{-31} \text{ fb} \\ \sigma_{VBF} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 19.2^{+6.8}_{-6.1} \text{ fb} \\ \sigma_{VH} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 1.2^{+6.5}_{-5.4} \text{ fb} \\ \sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= -0.3^{+1.4}_{-1.1} \text{ fb} \end{aligned}$$



Significance Obs. 4.7σ (5.4σ Exp.)

H → ZZ* → 4l

- two isolated-lepton pairs (SFOS)
- $p_T > 5/7 \text{ GeV}$ for muons/electrons

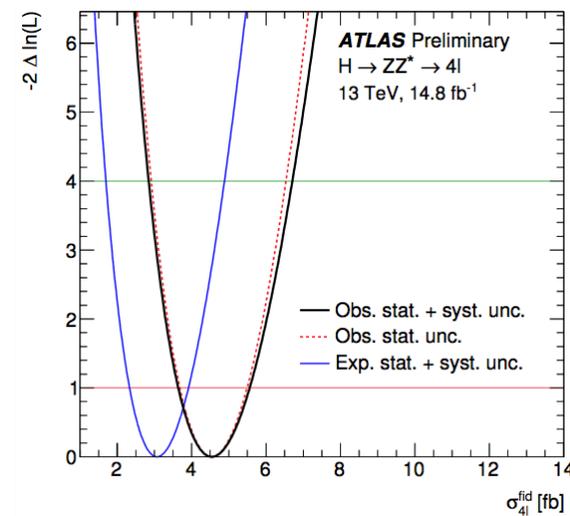
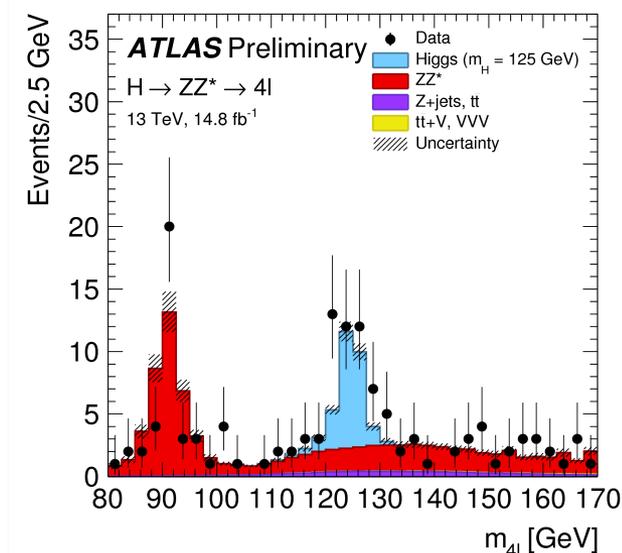
14.8 fb⁻¹ @ 13 TeV

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

- events extracted in the **mass region $115 < m_{4\ell} < 130 \text{ GeV}$** are analyzed to extract the **fiducial and total cross sections** (fiducial phase space to minimize the model dependence)
- **$m_{4\ell}$ distribution is used as a discriminant** to increase the sensitivity to the signal combining the sub-channels:

$$\sigma_{\text{fid,comb}}^{4\ell} = 4.54^{+1.02}_{-0.90} \text{ fb}$$

- total cross section contains **extrapolation factors to the full phase space**: $\sigma_{\text{tot}} = 81^{+18}_{-16} \text{ pb}$ $\sigma_{\text{tot,SM}} = 55.5^{+3.8}_{-4.4} \text{ pb}$



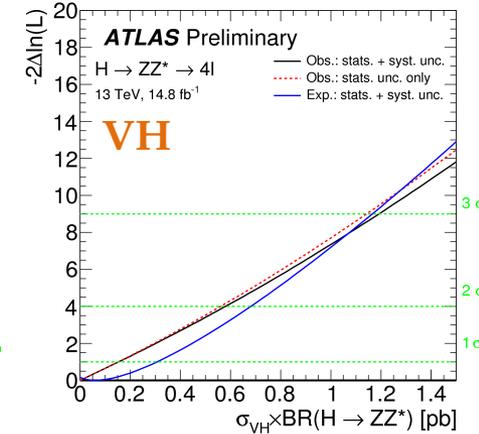
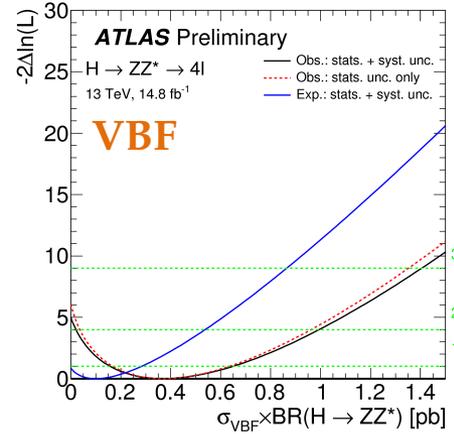
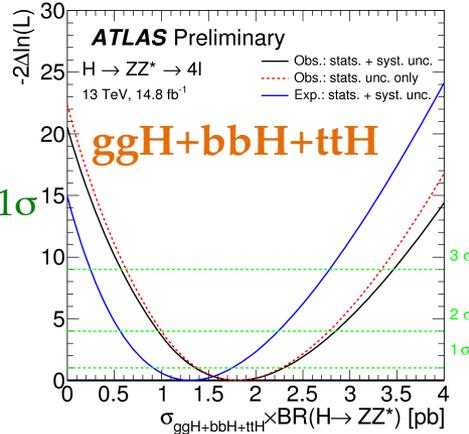
Categorization to extract the XS per production mode.

Signal extraction: Maximum Likelihood fit to the BDT discriminants distributions in each category (counting in VHlep)

Compatibility with the SM:

$$\sigma_{\text{ggF+bbH+ttH}} \mathcal{B}(H \rightarrow ZZ^*) @ 1.1\sigma$$

$$\sigma_{\text{VBF}} \mathcal{B}(H \rightarrow ZZ^*) @ 1.4\sigma$$



Cross section per production mode compared to the SM prediction:

Observed:

$$\sigma_{\text{ggF+bbH+ttH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.80^{+0.49}_{-0.44} \text{ pb}$$

$$\sigma_{\text{VBF}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.37^{+0.28}_{-0.21} \text{ pb}$$

$$\sigma_{\text{VH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0^{+0.15} \text{ pb}$$

Expected:

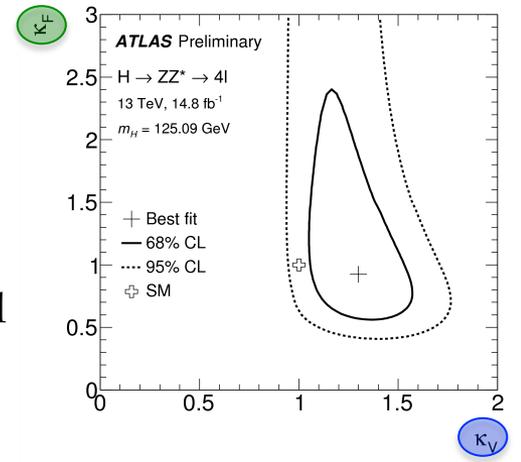
$$\sigma_{\text{SM,ggF+bbH+ttH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.31 \pm 0.07 \text{ pb}$$

$$\sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.100 \pm 0.003 \text{ pb}$$

$$\sigma_{\text{SM,VH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.059 \pm 0.002 \text{ pb}$$

Results can be expressed within the κ framework

- κ_F for the prod. modes mediated by fermions
- κ_V for those mediated by vector bosons



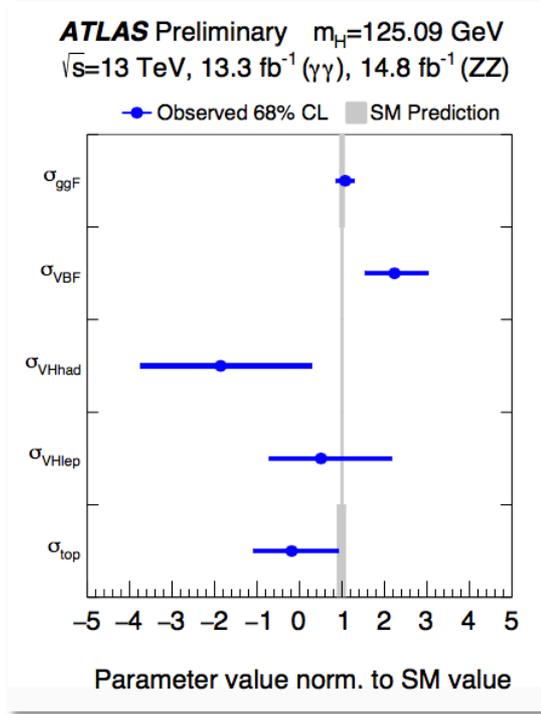
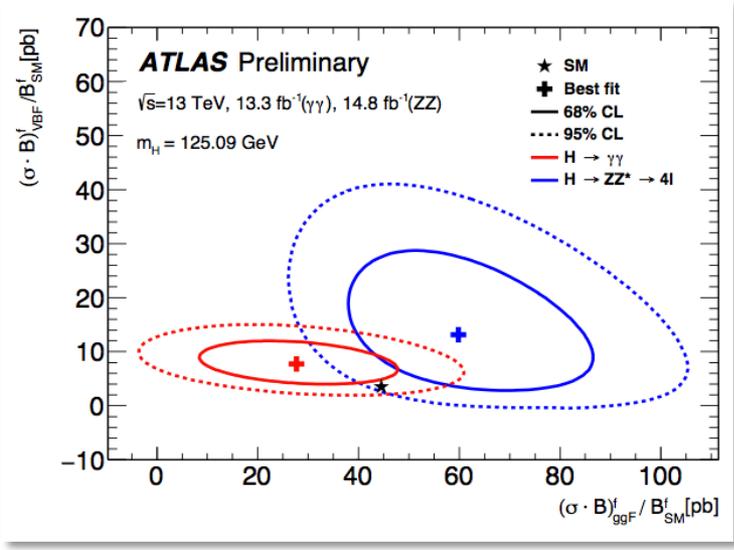
Combination of the 13 TeV results (ZZ* + γγ)

$m_H = 125.09 \pm 0.24 \text{ GeV}$

Decay mode	ggF +bbH	VBF	VHhad	VHlep	top ttH+tH
$H \rightarrow \gamma\gamma$	$(\sigma \cdot B)_{ggF}^{\gamma\gamma}$	$(\sigma \cdot B)_{VBF}^{\gamma\gamma}$	$(\sigma \cdot B)_{VHhad}^{\gamma\gamma}$	$(\sigma \cdot B)_{VHlep}^{\gamma\gamma}$	$(\sigma \cdot B)_{top}^{\gamma\gamma}$
$H \rightarrow ZZ^*$	$(\sigma \cdot B)_{ggF}^{ZZ}$	$(\sigma \cdot B)_{VBF}^{ZZ}$	fixed to SM	fixed to SM	fixed to SM

* Assuming SM BRs

- 5 independent σ_i ; BR^f assumed from SM
- Evidence for the the VBF with a local significance of 4.0 σ (1.9 σ exp.) (>5 σ Run1 ATLAS+CMS)



-> Global signal strength $\mu = 1.13^{+0.18}_{-0.17}$
 (compatibility with SM= 43%)

H->WW* (VBF and WH)

- **VBF analysis:** 2 leptons and ≥ 2 jets (large DY background $Z \rightarrow ee / \mu\mu$, only $e\mu / \mu e$ final states are taken into account)
- **WH analysis:** events with 3 leptons of a total electric charge of $\pm e$, in the presence of missing transverse momentum
- **Signal extraction:** Maximum likelihood fit in the SRs

5.8 fb⁻¹ @ 13 TeV
m_H = 125 GeV

SM predictions:

$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 1.4^{+0.8}_{-0.6}(\text{stat})^{+0.5}_{-0.4}(\text{sys}) \text{ pb}$$

$$0.808 \pm 0.021 \text{ pb}$$

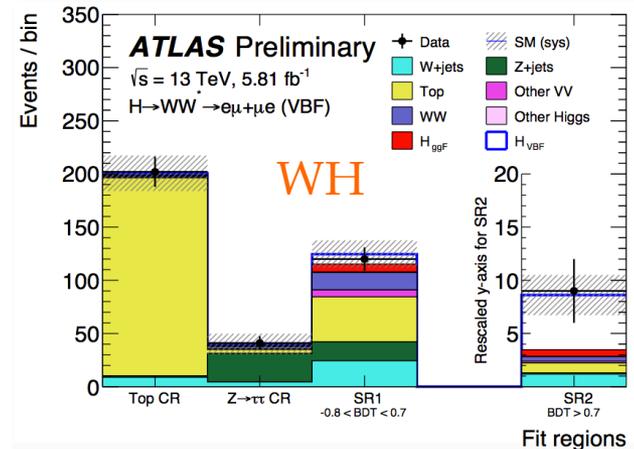
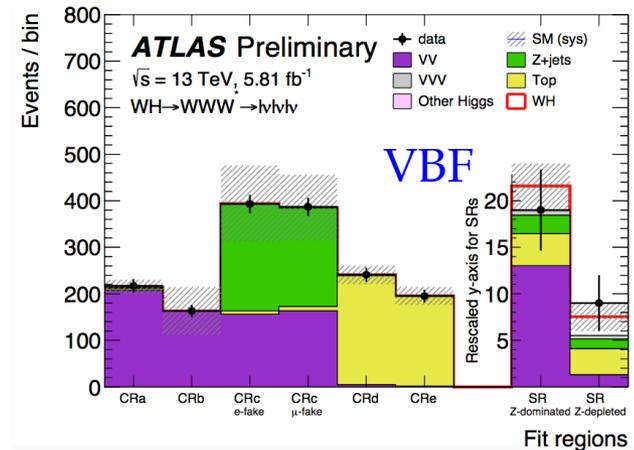
$$\sigma_{\text{WH}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.9^{+1.1}_{-0.9}(\text{stat})^{+0.7}_{-0.8}(\text{sys}) \text{ pb}$$

$$0.293 \pm 0.007 \text{ pb}$$

$$\mu_{\text{VBF}} = 1.7^{+1.0}_{-0.8}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$$

$$\mu_{\text{WH}} = 3.2^{+3.7}_{-3.2}(\text{stat})^{+2.3}_{-2.7}(\text{sys})$$

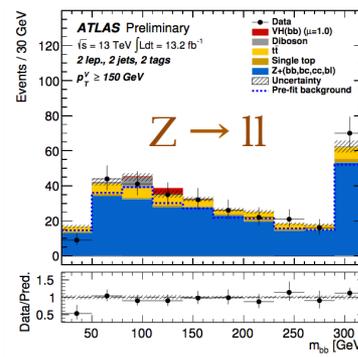
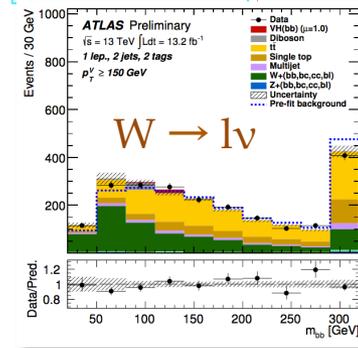
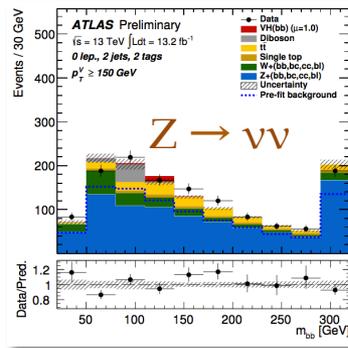
- The observed (expected) signal significance is 1.9 σ (1.2 σ) for VBF and 0.77 σ (0.24 σ) for WH
- Since observed significances of Xs are below 3 σ , 95% CL upper limits are given on the $(\sigma \mathcal{B})_{\text{VBF}}$ at 3.0 pb and on the $(\sigma \mathcal{B})_{\text{WH}}$ at 3.3 pb



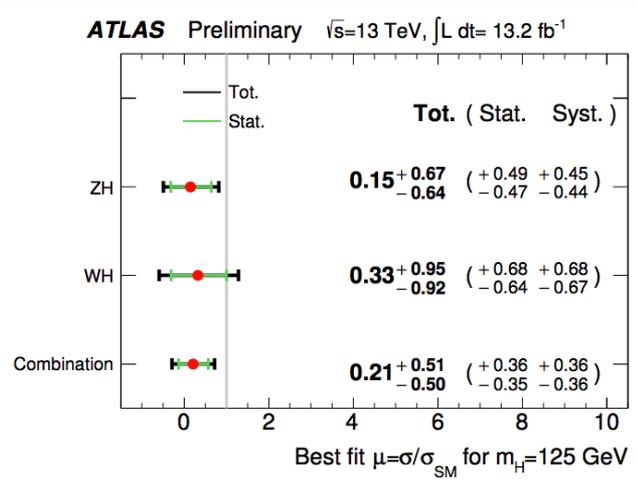
H->b \bar{b}

13.2 fb⁻¹ @ 13 TeV

- Huge bkg from multi-jet -> incl. search challenging
- Look at VH leptonic decays (lower XS than ggH)
- Event selection: 2 high-p_T b-tagged jets together with 0 (Z → νν), 1 (W → lv) or 2 (Z → ll) charged leptons (e,μ) (categories built using N_{jets}, N_{lep}, N_{b-tags})
- multivariate discriminants based on kinematics observables are used in each category
- Signal strength extraction: Maximum Likelihood fit



Signal strength results:



$\mu = 0.21^{+0.36}_{-0.35}(\text{stat.}) \pm 0.36(\text{syst})$

Observed combined limit on the ratio of the (σ B) with respect to the SM:

m_H = 125 GeV

Results already syst-dominated, Run1 deficit seems to persist.

Dataset	Limit		p ₀		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	1.4 ^{+0.6} _{-0.4}	2.0	0.07	0.15	1.45	1.02
1-lepton	2.0 ^{+0.8} _{-0.6}	2.1	0.15	0.46	1.04	0.10
2-lepton	1.8 ^{+0.7} _{-0.5}	1.7	0.13	0.57	1.14	-0.17
Combined	1.0 ^{+0.4} _{-0.3}	1.2	0.03	0.34	1.94	0.42

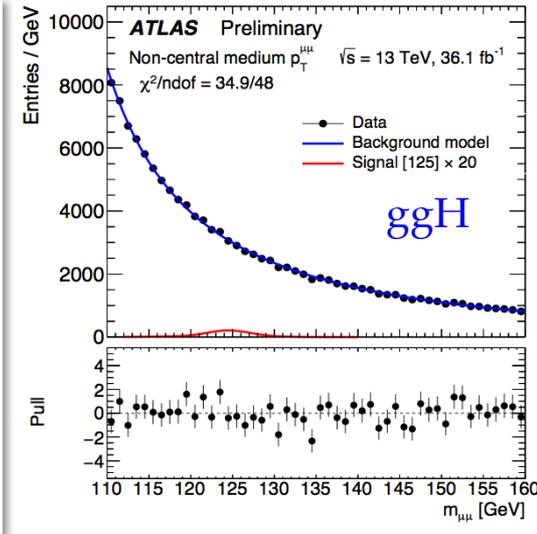
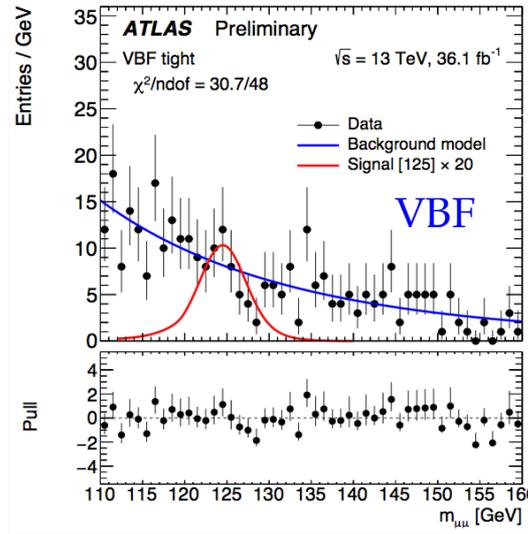
H → μμ

- Clean final state signature
- Irreducible DY bkg Z/γ* → μμ
- 2 VBF and 6 ggH enriched categories splitted relying on the event topology and kinematics
- BDT trained for the ≥ 2jet categories:

VBF_{tight} (BDT_{score} > 0.9),

VBF_{loose} (0.7 < BDT_{score} < 0.9)

36.1 fb⁻¹ @ 13 TeV

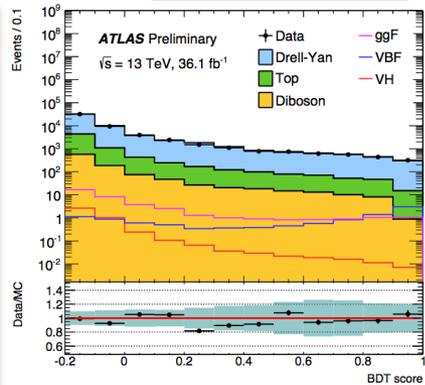
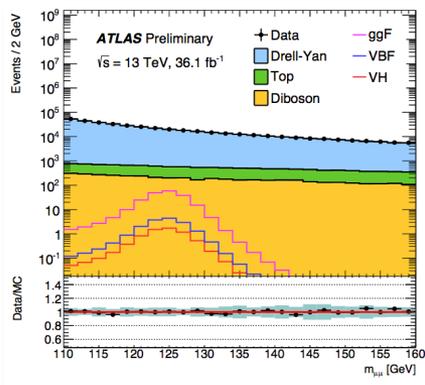


- Signal extraction: maximum likelihood fit to the observed m_{μμ} distributions simultaneously in all the categories

$$\mu_S = -0.1 \pm 1.5$$

- No significant excess observed in data
- The observed (expected) upper limit on μ_S at 95% is found to be 3.0 (3.1)

m_H = 125 GeV



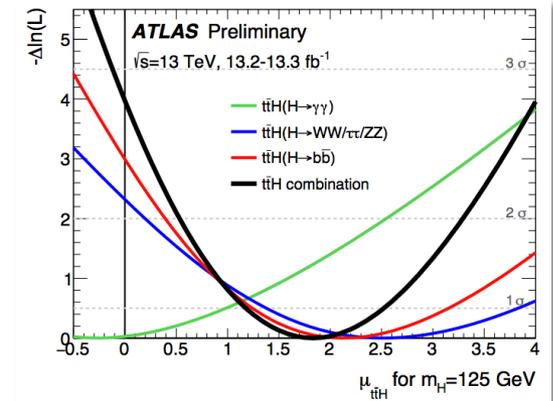
$t\bar{t}H$ production in the $\gamma\gamma$, multilepton, and $b\bar{b}$ final states

13.3 fb⁻¹ @ 13 TeV

$m_H = 125\text{GeV}$

- $\sigma_{t\bar{t}H} \propto (10^{-2}\sigma_{ggH})$
- Combination of final states to test the presence of a signal
- Signal strength extraction: Maximum likelihood fit (proper correlation of the syst. unc. among channels)

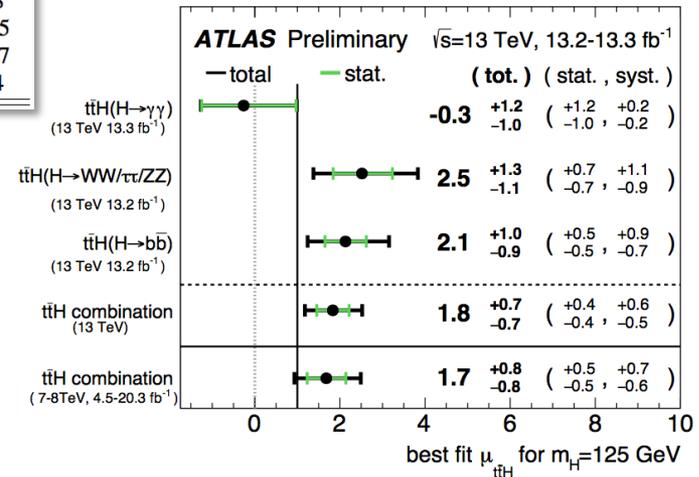
Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHj\bar{b} + WtH$	S/B	N _{Data}
$H \rightarrow \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2
$H \rightarrow (WW, \tau\tau, ZZ)$	2 ℓ SS ee	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09	26
	2 ℓ SS $e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13	59
	2 ℓ SS $\mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13	31
	2 ℓ SS + τ _{had}	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25	14
	3 ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16	46
	4 ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42	0
$H \rightarrow b\bar{b}$	ℓ +jets (≥ 6j, 3bj)	119 ± 16	11250 ± 240	6.2 ± 1.5	0.011	11561
	ℓ +jets (5j, ≥ 4bj)	11.8 ± 2.6	429 ± 28	0.91 ± 0.14	0.028	418
	ℓ +jets (≥ 6j, ≥ 4bj)	44.9 ± 9.4	1191 ± 55	2.10 ± 0.50	0.038	1285
	dilepton (≥ 4j, 3bj)	20.6 ± 4.2	1423 ± 45	0.71 ± 0.20	0.014	1467
	dilepton (≥ 4j, ≥ 4bj)	6.6 ± 2.0	133 ± 12	0.171 ± 0.053	0.050	154



The combined signal strength is:

$$\mu_{t\bar{t}H} = 1.8^{+0.4}_{-0.4} \text{ (stat.) } ^{+0.6}_{-0.5} \text{ (syst.)} = 1.8^{+0.7}_{-0.7}$$

-> observed (expected) significance of 2.8 σ (1.8 σ)



Conclusions

- Brief overview of the Run1 measurements presented
- Measurements of the cross sections and couplings of SM particles with the Higgs boson have been performed with 13 TeV p-p collisions
- No significant deviations with respect to the SM predictions has been observed
- Most measurements are statistically limited

-> Around 100 fb⁻¹ expected by the end of Run2!

Stay tuned!

Thanks for your attention!

Backup

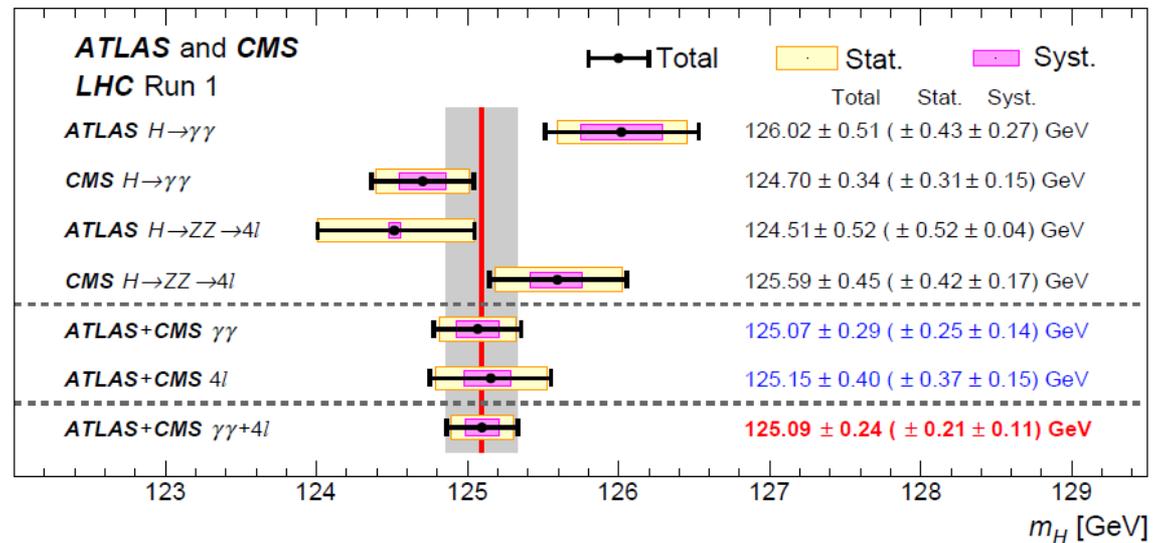
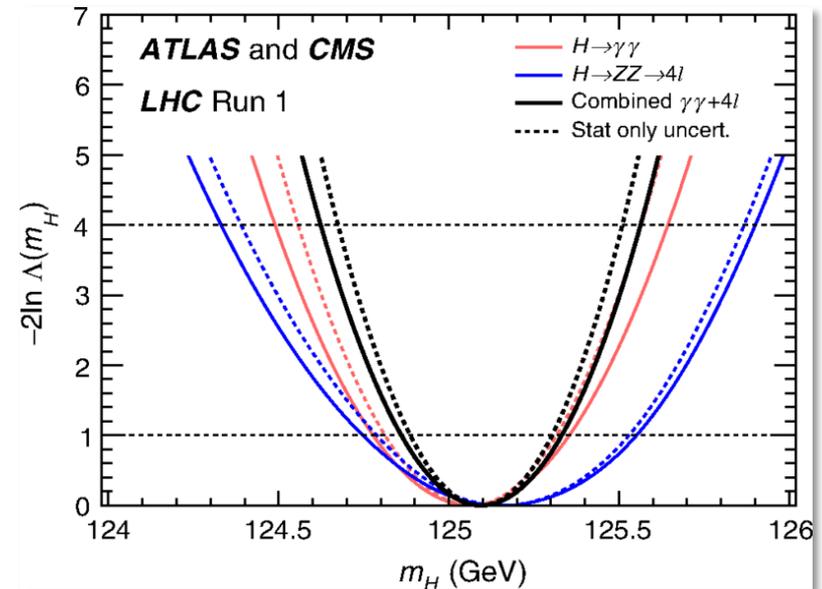
- **The Higgs at LHC:**

Production mechanisms at LHC and decays

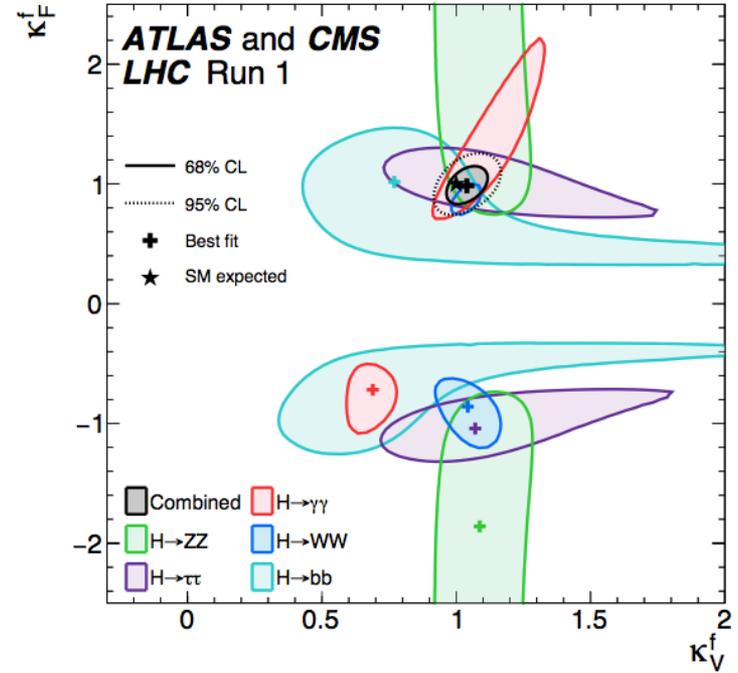
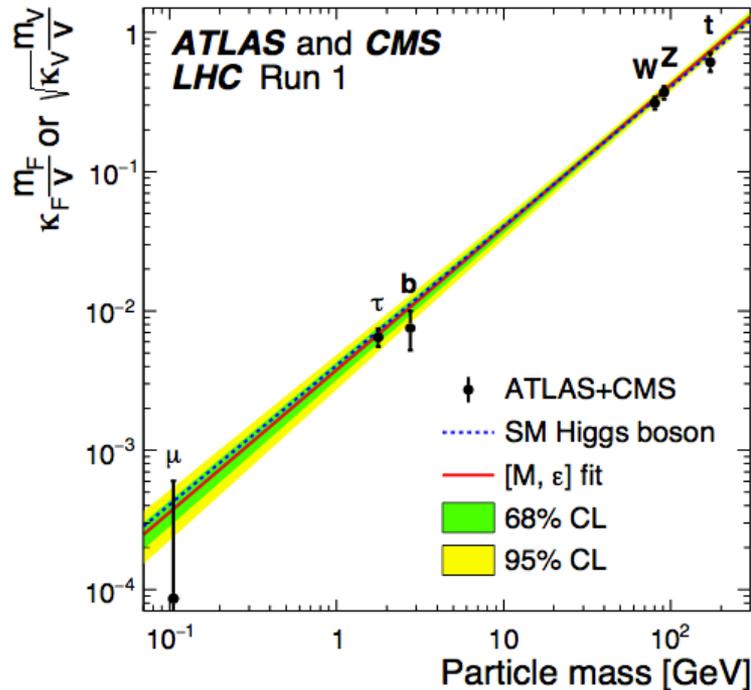
- **Cross section and coupling measurements:**

- Run 1 overview
- Run 2 measurements at $\sqrt{s}=13$ TeV

$m_H = 125.09 \pm 0.24 (\pm 0.21 \text{ stat.} \pm 0.11 \text{ syst.}) \text{ GeV}$



Interference effects (like in $H \rightarrow \gamma\gamma$) allow to test the relative sign between κ_V vs κ_F (universal coupling constant of the Higgs to vector bosons and fermions).



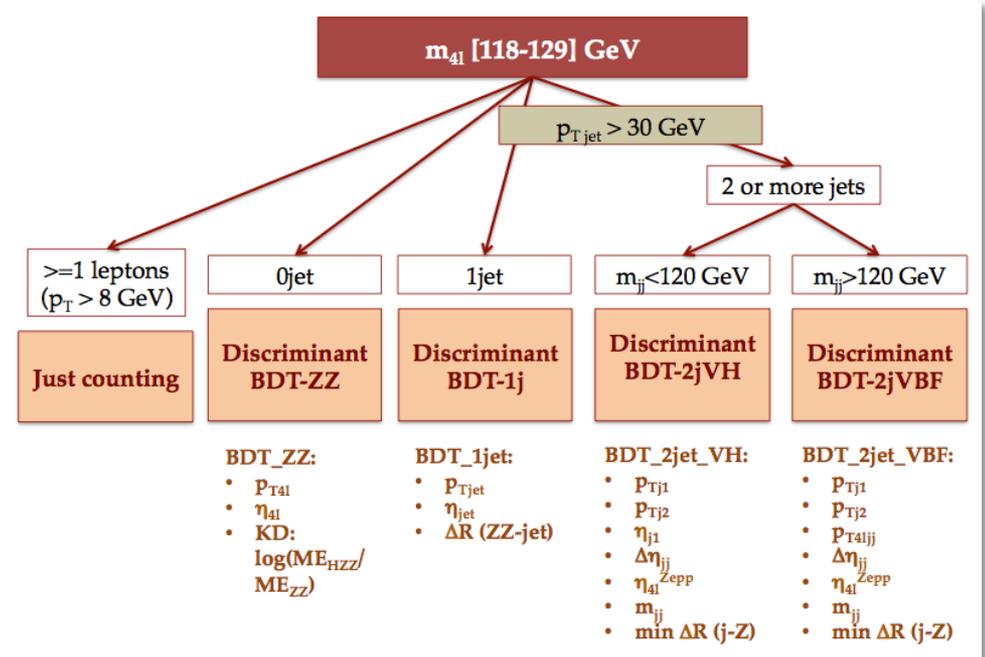
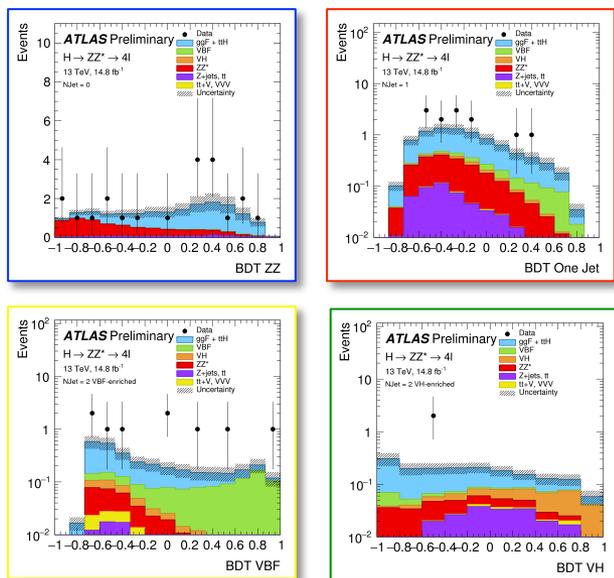
Reduced- κ can be defined:

$$y_{F,i} = \kappa_{F,i} \frac{m_{F,i}}{v} \quad e \quad y_{V,i} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{v}$$

where v is the vacuum expectation value of the Higgs field.

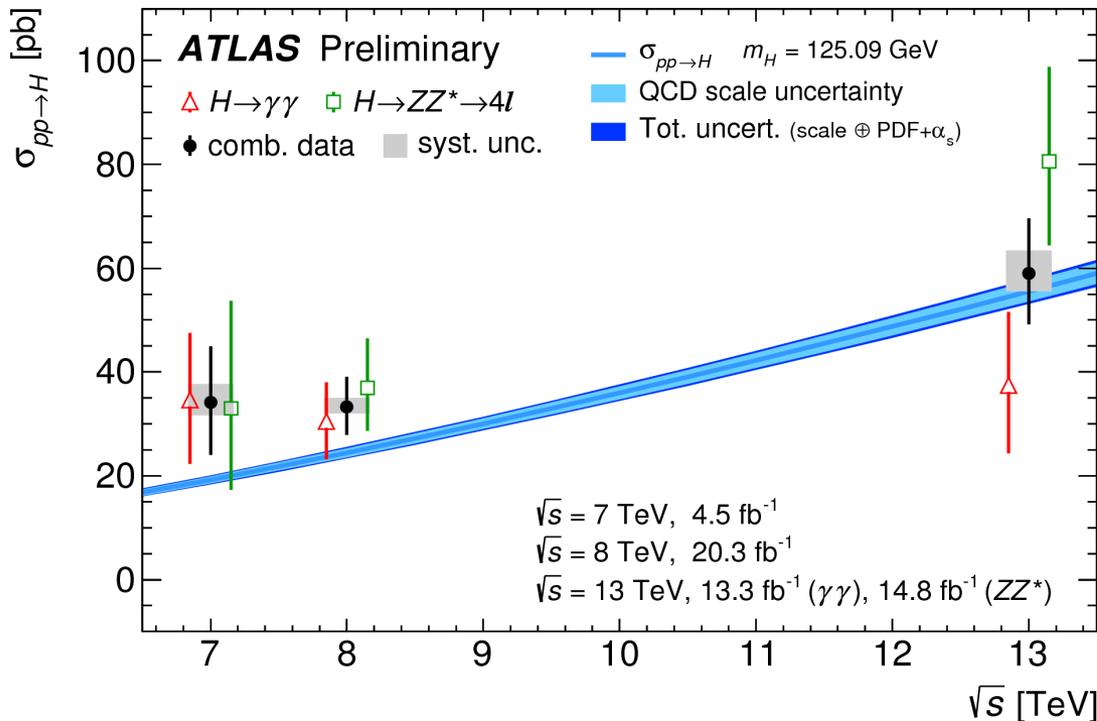
To illustrate / test the relation between mass and Higgs couplings in the SM

Categorization to extract the cross section per production mode.



Analysis category	Signal				Background		Total expected	Observed
	$ggF + b\bar{b}H + t\bar{t}H$	VBF	WH	ZH	ZZ^*	$Z + jets, t\bar{t}$		
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008	1.62 ± 0.21	0.44 ± 0.07	8.5 ± 2.4	12
2-jet VBF enriched	1.9 ± 0.9	0.92 ± 0.07	0.074 ± 0.007	0.052 ± 0.005	0.22 ± 0.05	0.24 ± 0.11	3.4 ± 0.9	9
2-jet VH enriched	1.1 ± 0.5	0.084 ± 0.009	0.143 ± 0.012	0.101 ± 0.009	0.166 ± 0.035	0.088 ± 0.011	1.6 ± 0.5	2
VH-leptonic	0.055 ± 0.004	< 0.01	0.067 ± 0.004	0.011 ± 0.001	0.016 ± 0.002	0.012 ± 0.010	0.16 ± 0.01	0
Total	20 ± 4	1.71 ± 0.14	0.47 ± 0.04	0.315 ± 0.027	8.2 ± 0.9	1.62 ± 0.07	32 ± 4	44

Total cross section measurements



Decay channel	Total cross section ($pp \rightarrow H + X$)		
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV
$H \rightarrow \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \rightarrow ZZ^* \rightarrow 4\ell$	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

