ATLAS H(125) bosonic decays results

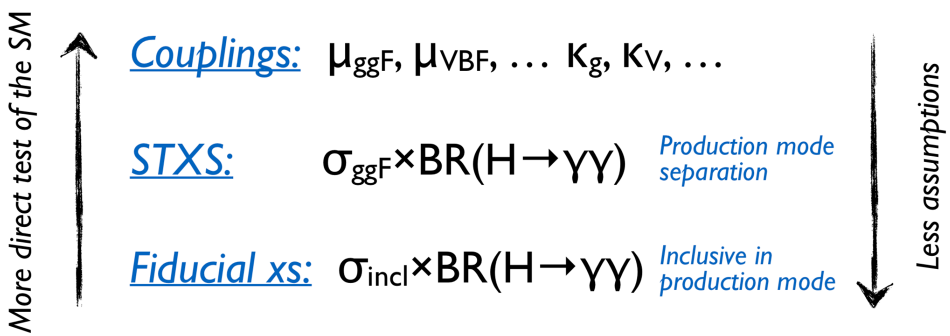
Higgs Hunting

29th – 31st July 2019

Giada Mancini LNF INFN

In this presentation:

- **Run2: Higgs boson property measurements**
  - Mass and Higgs Width
  - Couplings and cross section per production mode in the bosonic decay channels



  - Summary and perspectives
- **Conclusions**

In BSM theories, the Higgs boson properties may not be determined only via a simple scaling of couplings: kinematic distributions in production and decay modes may be sensitively modified by BSM (incl. EFT) effects.

Simplified template cross sections (STXS) developed to:

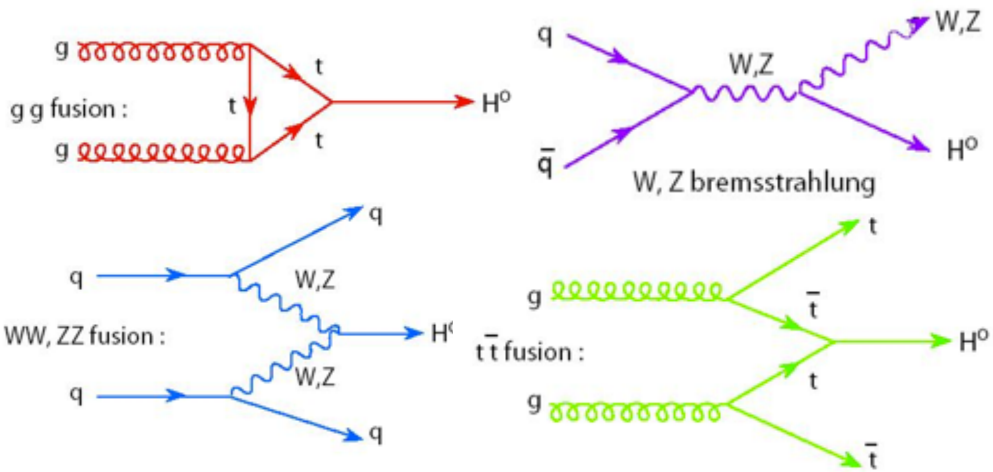
- separate measurement and interpretation steps to reduce in a systematic fashion the theory dependencies folded into the measurements (dependence on theoretical uncertainties and on the underlying physics model)
- provide more finely-grained measurements (and hence more information for theoretical interpretations) while at the same time allowing and benefiting from the global combination of the measurements in all decay channels

Fiducial cross sections, i.e. cross sections for specific states within the phase space defined by experimental selection and acceptance cuts, provide:

- largely model-independent way to test for deviations in kinematic distributions
- differential fiducial XS are a powerful for scrutinizing the SM Lagrangian structure of the Higgs boson interactions (dedicated talk by Lailin)

Production and decay modes

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



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

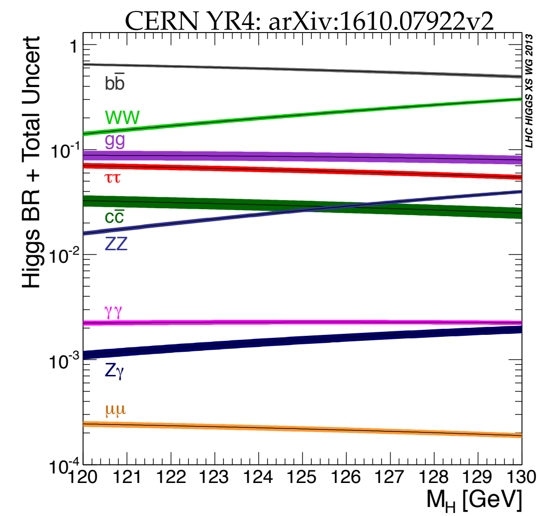
VBF: whose signature is characterized by H+2jet forward, $\sigma^{VBF}/\sigma^{TOT}$ = 7% @ 13 TeV.

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

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

Decay channels:

- H->ZZ*->4l: pure channel but very low statistics ($BR_{H\to ZZ^*\to 4l} \sim 2 \cdot 10^{-4}$)
- H->γγ : simple final state but low BR and large background
- H->WW*->lνlν: good sensitivity but low mass resolution
- H->bb-bar: huge bkg, best accesible via VH production
- H->ττ: very large bkg, best accesible via VBF and boosted H production
- H->Zγ & H->μμ: low BR

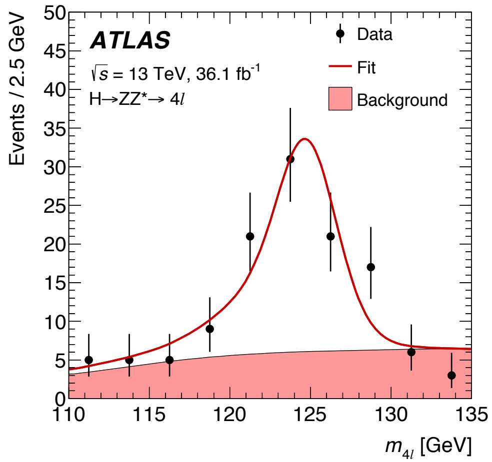


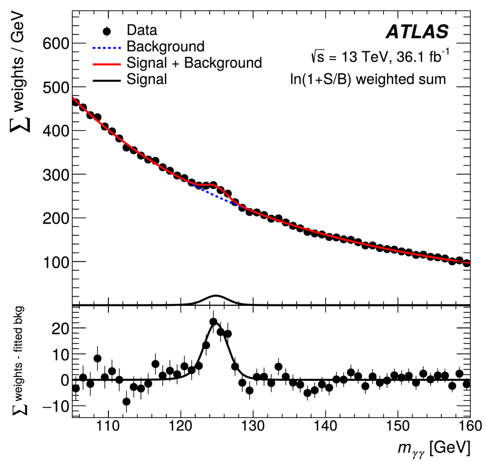
Higgs mass and off-shell couplings

H->ZZ* and H->γγ are the most sensitive channels

Resolution on mass few permill

Low BR but clean signature





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$m_{ZZ^*} = 124.79 \pm 0.37$ GeV $m_{\gamma\gamma} = 124.93 \pm 0.40$ GeV

Run1+2 ATLAS Comb. $m_H = 124.97 \pm 0.24$ GeV

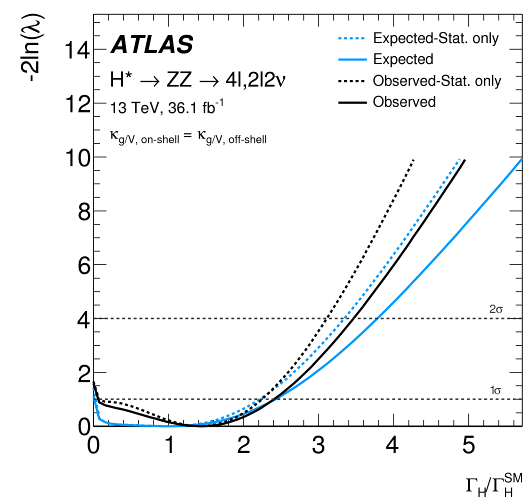
Higgs width (no direct measurement dominated by detector resolution)

$\sigma_{off\text{-}shell} \sim k^2_{g,off\text{-}shell}\, k^2_{Z,off\text{-}shell}$

$\sigma_{on\text{-}shell} \sim k^2_{g,on\text{-}shell}\, k^2_{Z,on\text{-}shell} / (\Gamma_H / \Gamma_H^{SM})$

Measurements from H->ZZ* improved expected limits by a factor 2 wrt Run1

$\Gamma_H < 3.8\ (3.4)\ \Gamma_H^{SM}$ @ 95% CL



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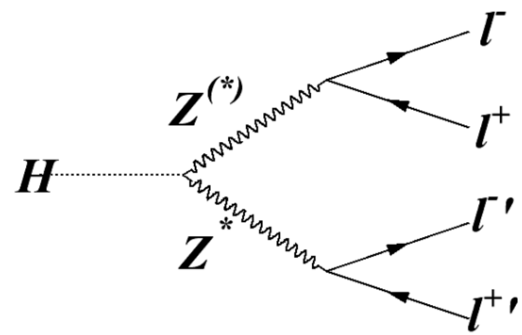
$H \rightarrow ZZ^* \rightarrow 4l$

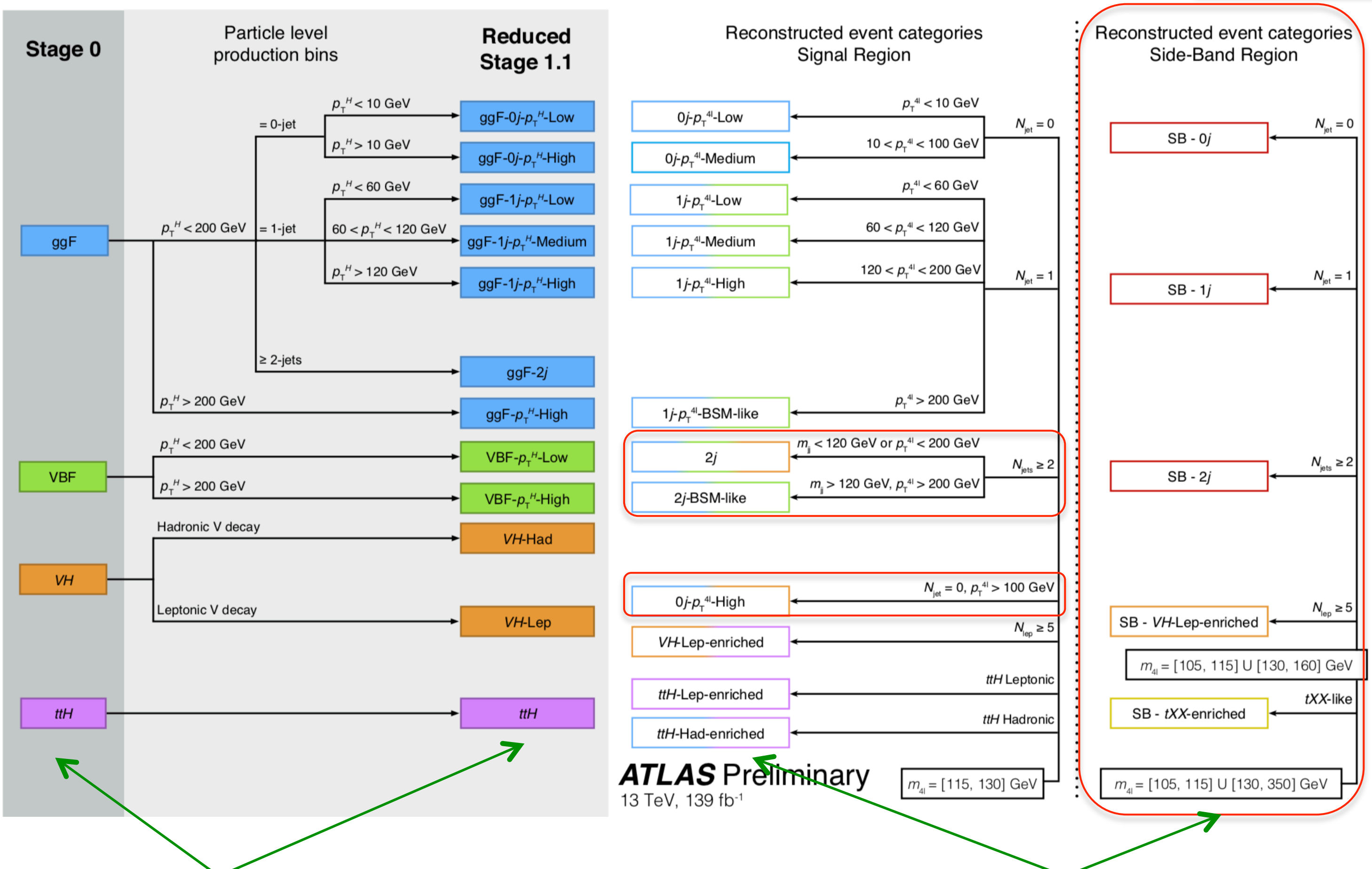
New results with full Run2 stat 139 fb^{-1}:



- Improved lepton isolation to mitigate the impact of pileup
- Constrain the major non-resonant ZZ^* background and the tXX background from dedicated side-bands/control regions respectively
- Additional reconstructed event categories and new discriminants to enhance the sensitivity to the various production modes

Event selection (at most one quadruplet per event)	
Mass requirements	$50\ \text{GeV} < m_{12} < 106\ \text{GeV}$ and $12\ \text{GeV} < m_{34} < 115\ \text{GeV}$
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5\ \text{GeV}$ for all SFOS lepton pairs
Mass window	$115\ \text{GeV} < m_{4\ell} < 130\ \text{GeV}$
If extra leptons with $p_T > 12\ \text{GeV}$	Quadruplet with the largest ME

H-> ZZ*



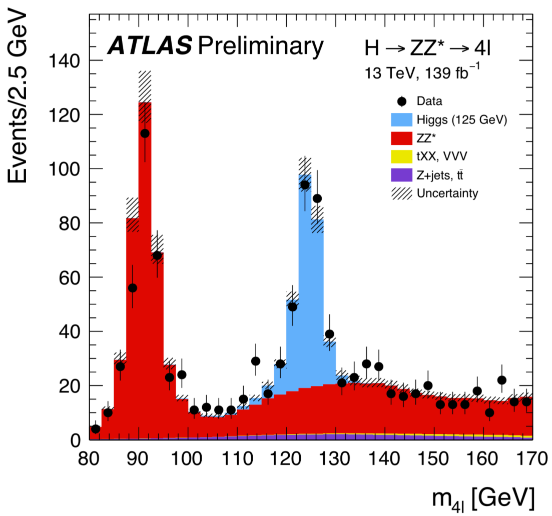
Production bins are defined at particle level for Stage 0 and Stage 1.1

Corresponding reco categories, NN discriminants used to separate between prod modes, new side band category for bkg

- 2jet (p_T^{4l}>200 GeV) category -> BSM enriched
- 0jet high p_T^{4l} cat for VH (Z->νν, W->lν where l is missing)

Signal extraction:

- Combined fit of the m_{4l} invariant mass distribution ([115,130] GeV for STXS)
- Results with |y|< 2.5
- Bkg estimation from sidebands



Many of systematic uncertainties have decreased

- Luminosity 2.8% → 1.7%
- Electron/muon reconstruction and identification efficiency and pileup uncertainties, still dominant among syst. unc. but reduced
- ZZ* bkg (data driven: reduction of the syst. by removing both theoretical and lumi unc.)

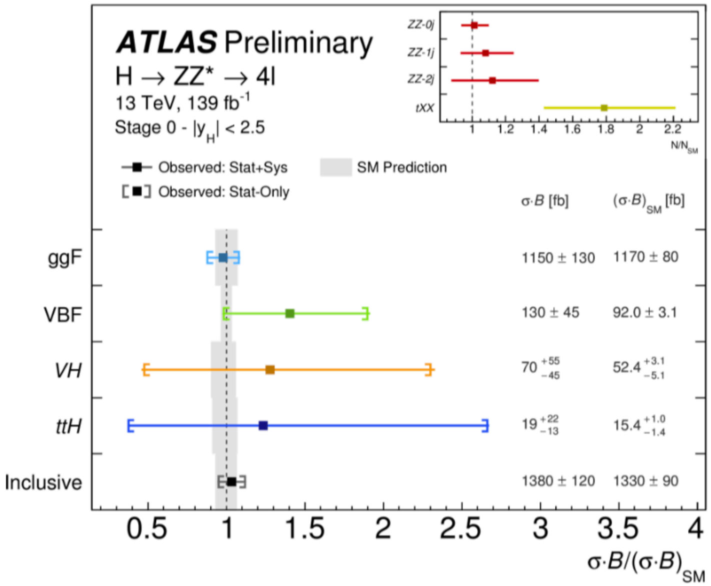
Final state	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
4μ	78 ± 5	38.1 ± 2.2	2.87 ± 0.18	119 ± 5	118
$2e2\mu$	52.8 ± 3.1	26.1 ± 1.4	3.01 ± 0.19	81.9 ± 3.4	98
$2\mu 2e$	40.0 ± 2.9	17.4 ± 1.3	3.5 ± 0.5	60.9 ± 3.2	57
$4e$	35.3 ± 2.6	15.1 ± 1.5	2.9 ± 0.4	53.3 ± 3.1	43
Total	206 ± 13	97 ± 6	12.3 ± 0.9	315 ± 14	316

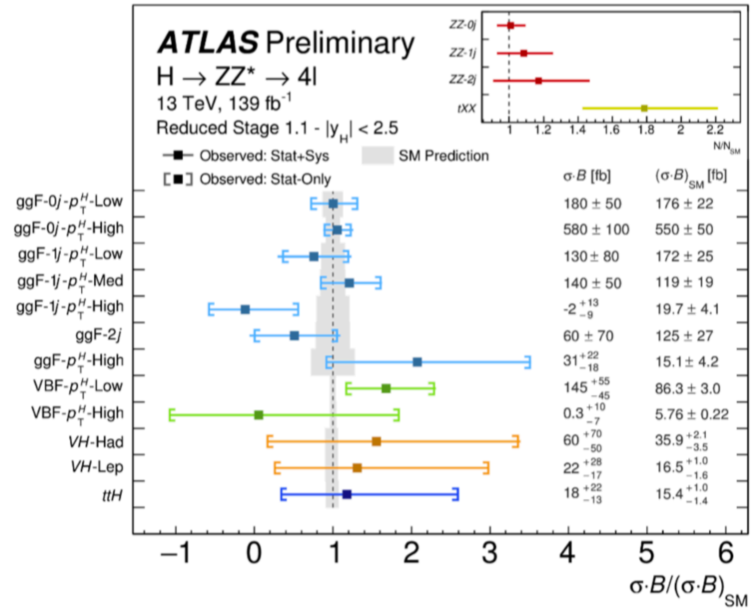
$$\sigma \cdot \mathcal{B} \equiv \sigma \cdot \mathcal{B}(H \to ZZ^*) = 1.38 \pm 0.11(\text{stat.})^{+0.05}_{-0.03}(\text{exp.}) \pm 0.03(\text{th.})\text{ pb} = 1.38 \pm 0.12\text{ pb}.$$

$$(\sigma \cdot \mathcal{B})_{\text{SM}} \equiv (\sigma \cdot \mathcal{B}(H \to ZZ^*))_{\text{SM}} = 1.33 \pm 0.09\text{ pb}.$$

$$\mu = 1.04^{+0.09}_{-0.08}(\text{stat.})^{+0.04}_{-0.03}(\text{exp.})^{+0.06}_{-0.05}(\text{th.}) = 1.04^{+0.12}_{-0.10}.$$

H-> ZZ*

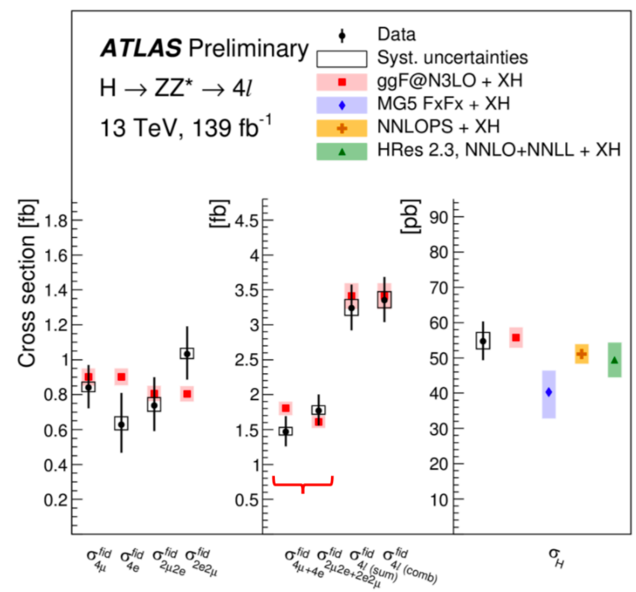




All Stage0 and Reduced Stage 1.1 ggF measurements agree with the SM predictions for the Higgs boson within 1.5 σ

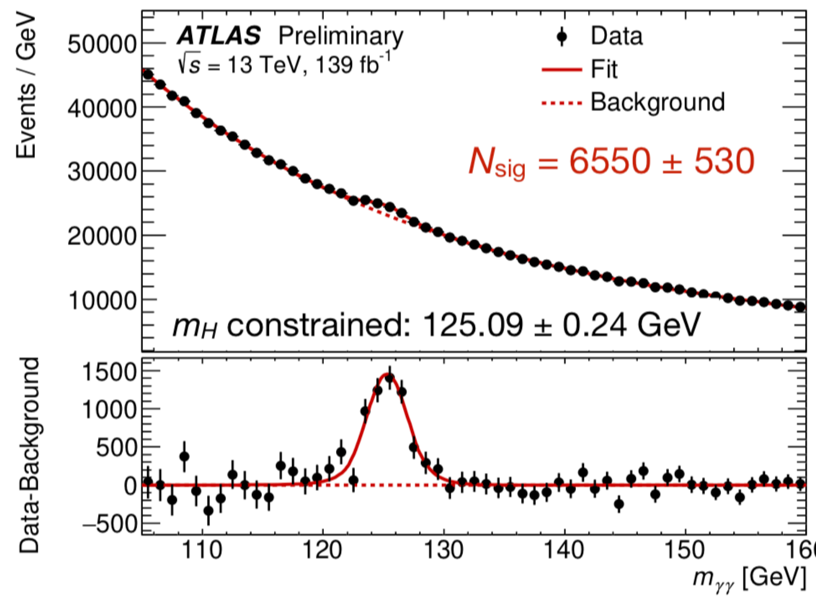
The fiducial XS is extrapolated to the total phase space (no categorization):

Cross section [fb]	Data (± (stat.) ± (syst.))			Standard Model prediction		*p*-value [%]
σ_{tot} [pb]	54.7	±4.9	±2.3	55.7	± 2.8	85



H -> $\gamma\gamma$

Fiducial XS results with 139 fb^{-1}



Selection:

- Photon isolation at reconstruction and particle level
- $E_{T,1}>0.35m_{\gamma\gamma}$, $E_{T,2}>0.25m_{\gamma\gamma}$
- $|\eta^{\gamma}| <1.37$ or $1.52<|\eta^{\gamma}| <2.37$

Signal extraction:

- Continuous bkg with a mass fit
  - Bkg estimation from data using analytical functions
- Yields unfolded to a fiducial volume matching the experimental acceptance

$$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 0.3\,(\text{theo.})\,\text{fb}$$

SM prediction: σ_{fid} = 63.3 +- 3.3 fb

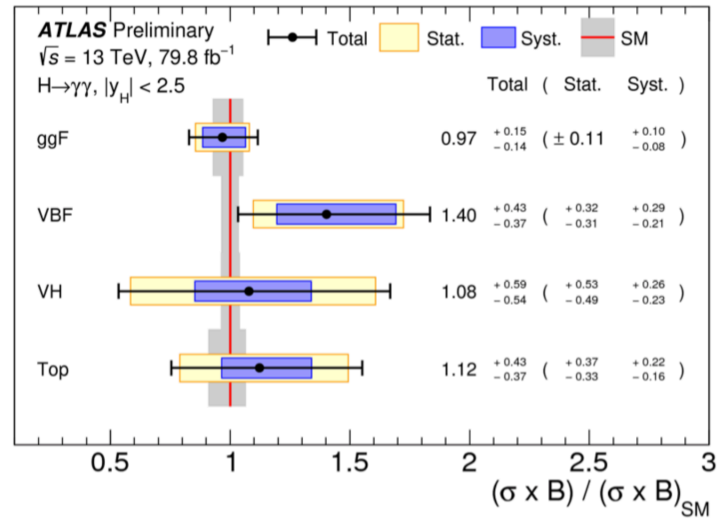
Experimental unc. dominate:

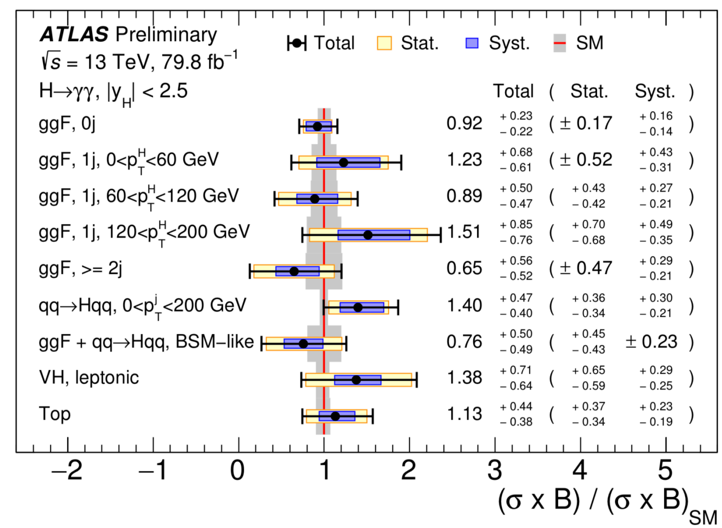
- Photon energy resolution
- Bkg modelling

STXS results with 80 fb^{-1}

Events are divided into 29 categories based on the reconstructed event properties, to target the different production modes and the different STXS regions.

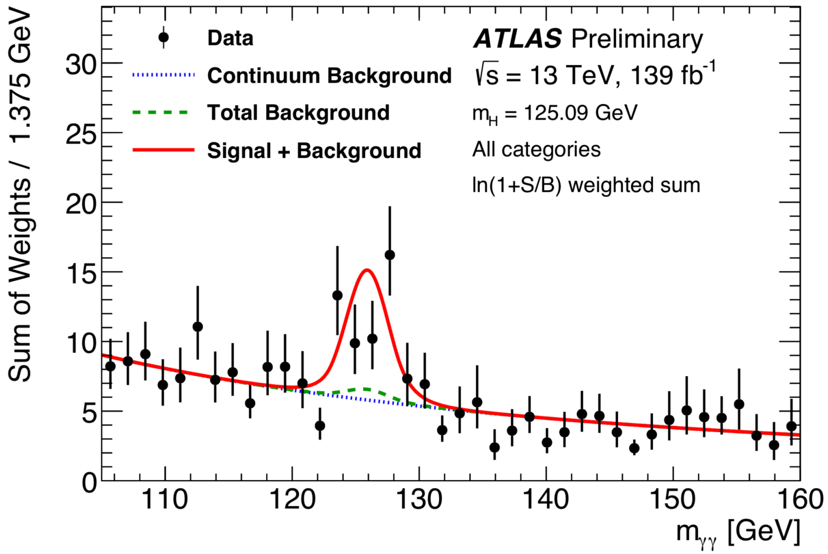
- Stage0: truth level splitting of the Higgs production processes
- Stage1-reduced: Additional splitting based on Higgs kinematics and associated particles to be measured when the experimental sensitivity allows -> 9 XSs are measured





ttH measurement with 139 fb^{-1}:

- Additional $t\bar{t}$H selection imposed in conjunction with the di-photon selection
- Simultaneous fit in 7 signal-enriched event categories
- Lep categories: $t\bar{t}$ decays 1 isolated lepton (W->lv) + 1jet with $p_T > 25$ GeV (b-tagged)
- Had categories: 1jet with $p_T > 25$ GeV (b-tagged), as well as contain at least two additional jets with $p_T > 25$ GeV and no reconstructed leptons
- BDT dedicated to Lep and Had selection
- **4.9 σ observation (4.2 σ expected)**



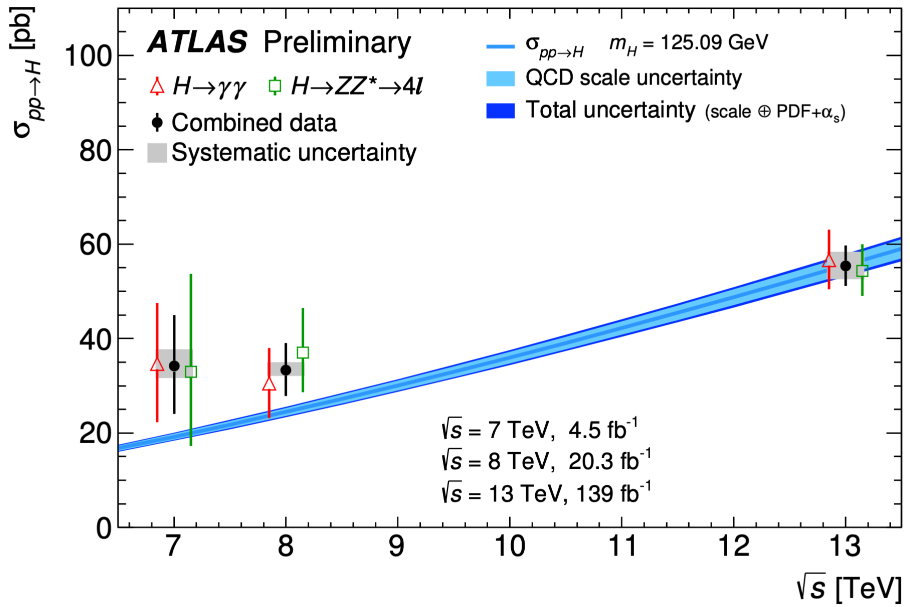
$$\mu_{t\bar{t}H} = 1.38 \,{}^{+0.41}_{-0.36}$$

$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39} \text{ fb}$$

$$\text{(SM pred.)} = 1.15^{+0.09}_{-0.12} \text{ fb}$$

XS: H->γγ and H->ZZ*->4l combination

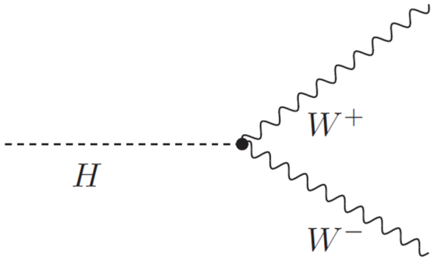
- Results with 139 fb^{-1} @ 13 TeV
- m_H=125.09 GeV
- The cross sections are obtained from the measured event yields, combined accounting for luminosity, detector effects, acceptances, and branching fractions (SM assumptions)



- The measured total Higgs boson production cross section is: $55.4^{+4.3}_{-4.2}$ pb (± 3.1(stat.) $^{+3.0}_{-2.8}$(sys.))
- Agreement with the Standard Model prediction: 55.6 ± 2.5 pb

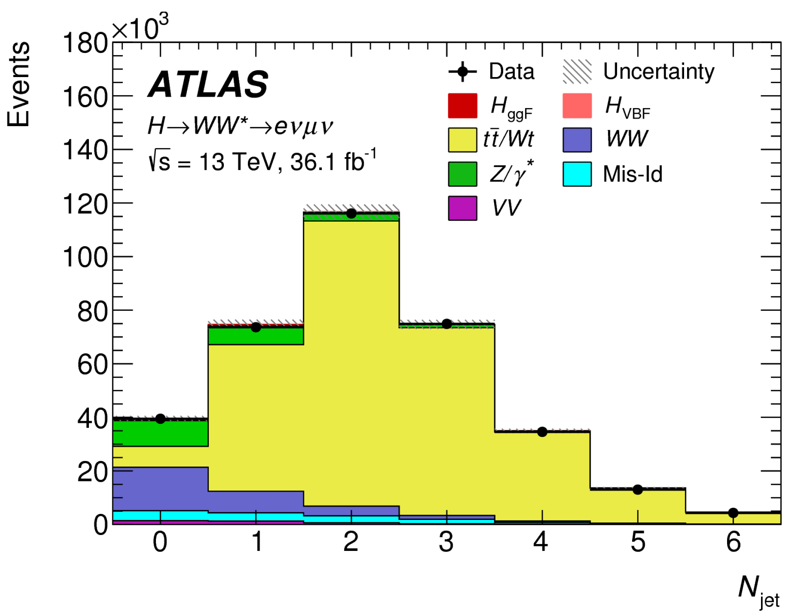
H -> WW*

The H->WW*->lνlν decay (1.5% of the overall final states) more abundant than ZZ* and γγ



Characterized by:

- the presence of 2 leptons with small opening angle
- requiring different flavor leptons helps reducing further the backgrounds:
  1 e +1 μ opposite sign ($p_T > 22/15$ GeV)
- the presence of 2 neutrinos (MET) that prevent a full reconstruction of the Higgs mass, contrary to the ZZ* and $\gamma\gamma$ final states



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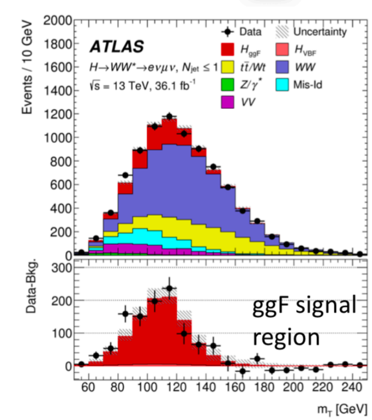
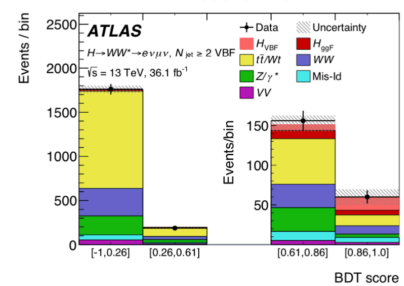
ggF and VBF

- 3 Signal Regions further split by leading lepton flavor, m_{ll}, and subleading lepton p_T
- BDT used for VBF analysis to disentangle signal and bkgs
- Normalization of main backgrounds constrained via Control Regions: tt+Wt, WW and Z/γ^*, W+jets and multi jet events (fake lepton bkgs) are estimated from data
- Signal extraction: Simultaneous fit of the SRs and CRs



VBF BDT score in SR



Measurements

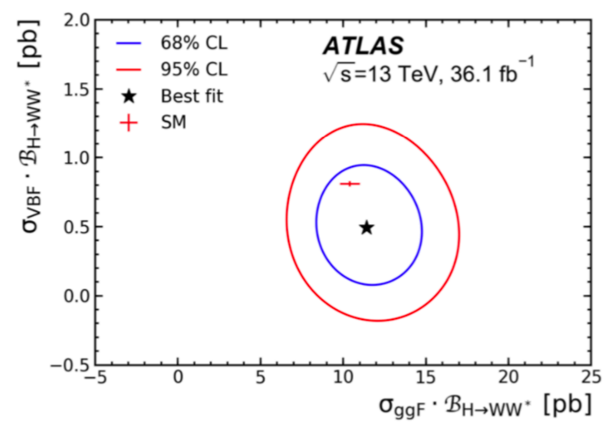
$$\sigma_{\rm ggF}\cdot\mathcal{B}_{H\to WW^*} = 11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.2}_{-1.1}(\text{theo syst.})^{+1.4}_{-1.3}(\text{exp syst.})\ \text{pb} = 11.4^{+2.2}_{-2.1}\ \text{pb}$$

$$\sigma_{\rm VBF}\cdot\mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.10(\text{theo syst.})^{+0.12}_{-0.13}(\text{exp syst.})\ \text{pb} = 0.50^{+0.29}_{-0.28}\ \text{pb}.$$

Predictions

10.4 ± 0.6 pb
0.81 ± 0.02 pb

Significances:
6.3 (5.2) σ for ggF
1.9 (2.7) σ for VBF
SM expectations agree within 1 σ

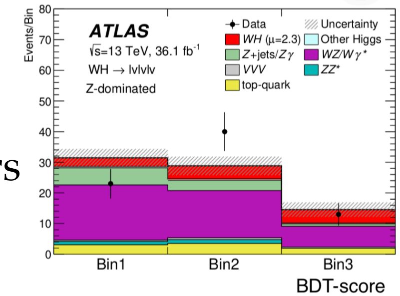


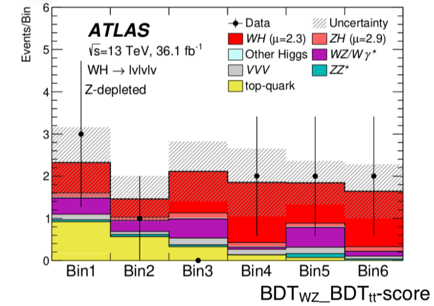
WH main selection cuts, 2 categories:

- 3 leptons (e/μ) total charge±1 (p_T>15 GeV):

  2 cat depending on the number of SFOS lepton pairs
- BDT vs main bkgs: diboson & top quark (ttV or tt)
- CR for WZ/Wγ*, top, misidentified leptons Data Driven

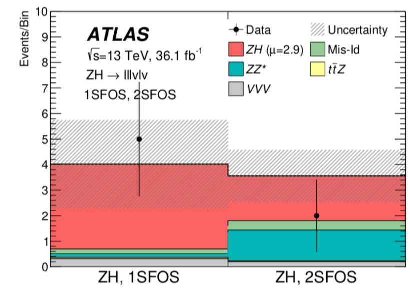
  method for Z+jets/Zγ



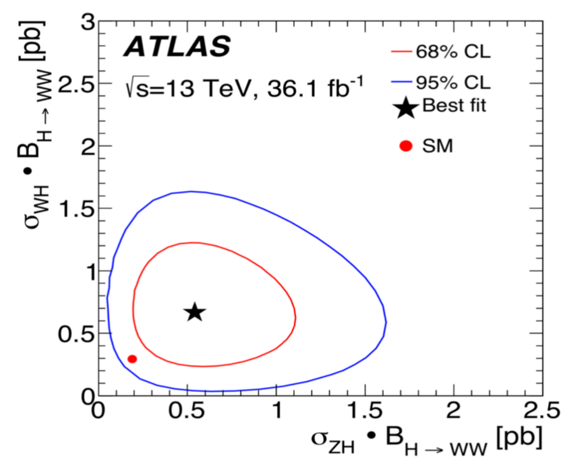


ZH main selection cuts:

- 4 leptons (e/μ) total charge 0 (p_T>10 GeV)
- Main bkgs: ZZ* and ttZ from CR, Data Driven for Z+jets/Zγ



$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.67^{+0.31}_{-0.27}(\text{stat.})^{+0.11}_{-0.09}(\text{theo syst.})^{+0.14}_{-0.11}(\text{exp syst.})\ \text{pb},$$
$$\sigma_{ZH} \cdot \mathcal{B}_{H\to WW^*} = 0.54^{+0.31}_{-0.24}(\text{stat.})^{+0.11}_{-0.05}(\text{theo syst.})^{+0.10}_{-0.05}(\text{exp syst.})\ \text{pb}.$$



SM predictions:

$\sigma_{WH}\,B = 0.293 \pm 0.007$ pb

$\sigma_{ZH}\,B = 0.189 \pm 0.007$ pb

Significances:

WH 2.6 obs (1.3 exp)

ZH 2.8 obs (1.2 exp)

Combined 4.1 obs (1.9 exp)

Consistent with the SM predictions within 1.3σ for *WH* and 1.5σ for *ZH*.

Conclusions

- We are studying the main production processes of the Higgs boson decays to bosons with precision up to the level of 10%
- Results from Run1+Run2 with up to 139 fb^{-1} indicate that measurements of the properties of the H(125) show consistency with the Higgs Boson predicted by the SM
- Most of our measurements are still statistically dominated in the most sensitive channels

We are entering the precision era:

looking for possible hints of New Physics behind the corner!

Thanks for your attention!

Backup

From Run1 on

Analyses in RunI have been optimized for the discovery

- Observed boson compatible, within the uncertainties, with the Higgs predicted by the SM -> deviations are small

Measurements of:

- **Fiducial Cross Sections and Differential Cross Sections** in variables sensitive to the quantum numbers of the Higgs boson (spin, CP), production modes, proton PDFs and perturbative QCD effects

Interpretations in terms of:

- **Signal strenght**: defined as the ratio of the XS • BR with respect to the SM (more model dependent): $\mu = (\sigma\, BR)_{obs} / (\sigma\, BR)_{SM}$
- **Coupling modifiers (k_j)**: parametrizing production and decay, coupling modifiers as multiplicative factors, narrow width approximation

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

where $\kappa_j^2 = \Gamma^j / \Gamma^j_\mathrm{SM}$, $\kappa_j^2 = \sigma_j / \sigma_j^\mathrm{SM}$

-> k_j=1 refers to the Standard Model case (SM)

Observation of VH production

- **VH takes ~ 4%** of the total Higgs boson production modes at the LHC
- **Observation combining Run2 results:** H->bb-bar , H-> γγ, H->ZZ*
- Assuming SM Higgs boson BR
- **Significance 5.3 σ (4.8 expected) -> Dominant contribution is from bb-bar channel**
- Direct observation of the Higgs boson being produced in association with a vector boson
- Results still statistically dominated

Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

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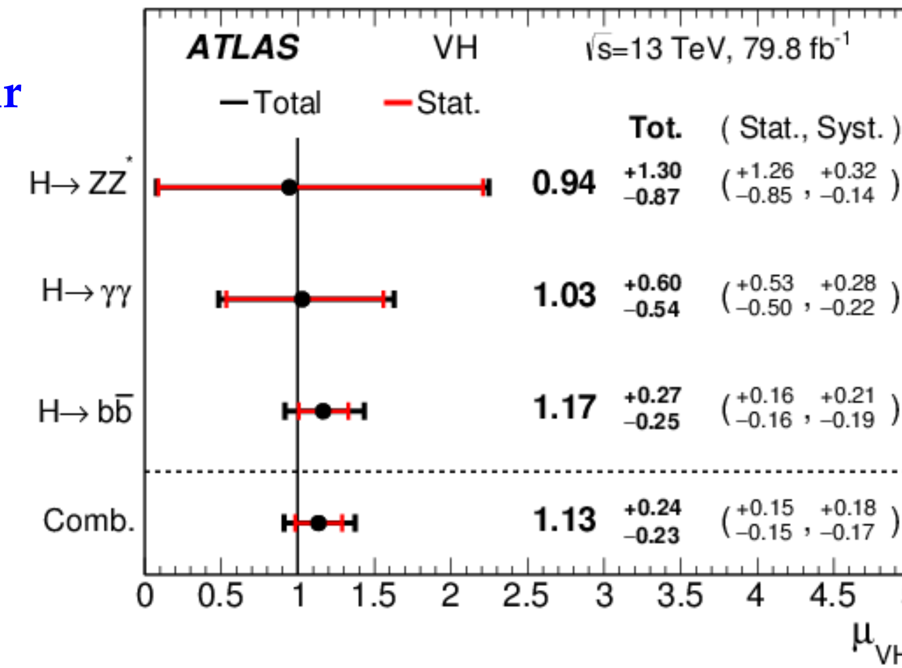
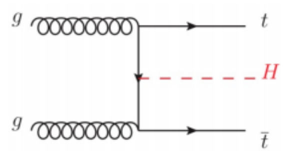
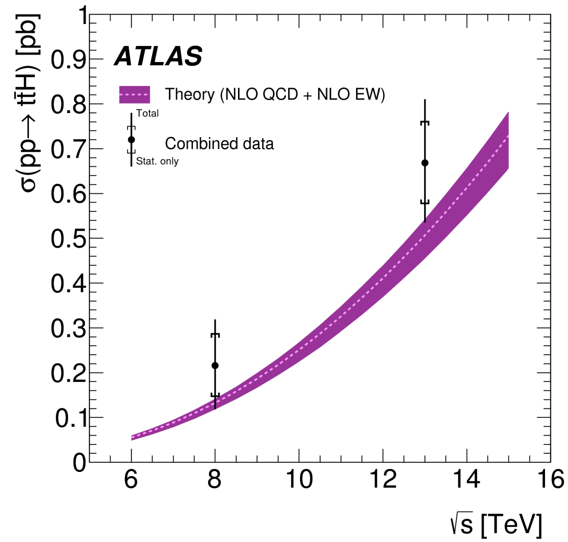


- **Direct Higgs coupling to top quark, largest Yukawa coupling**





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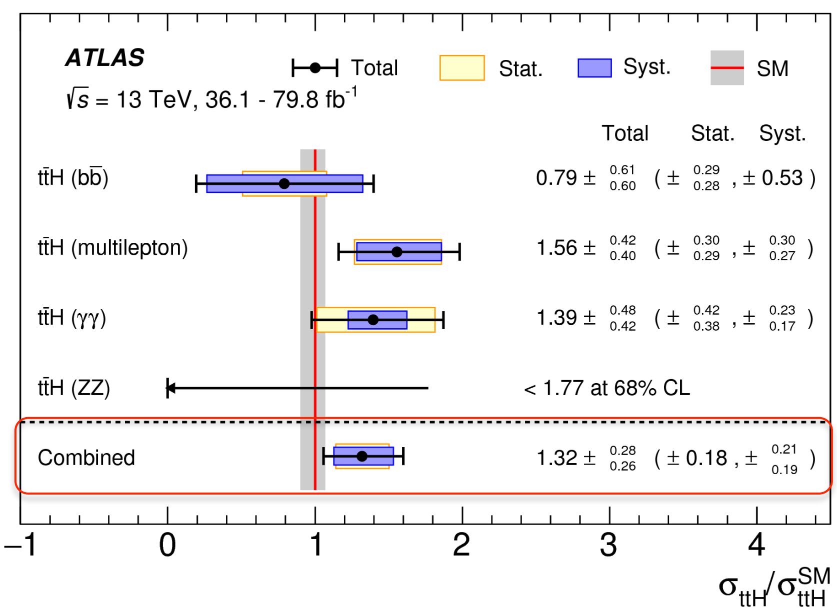
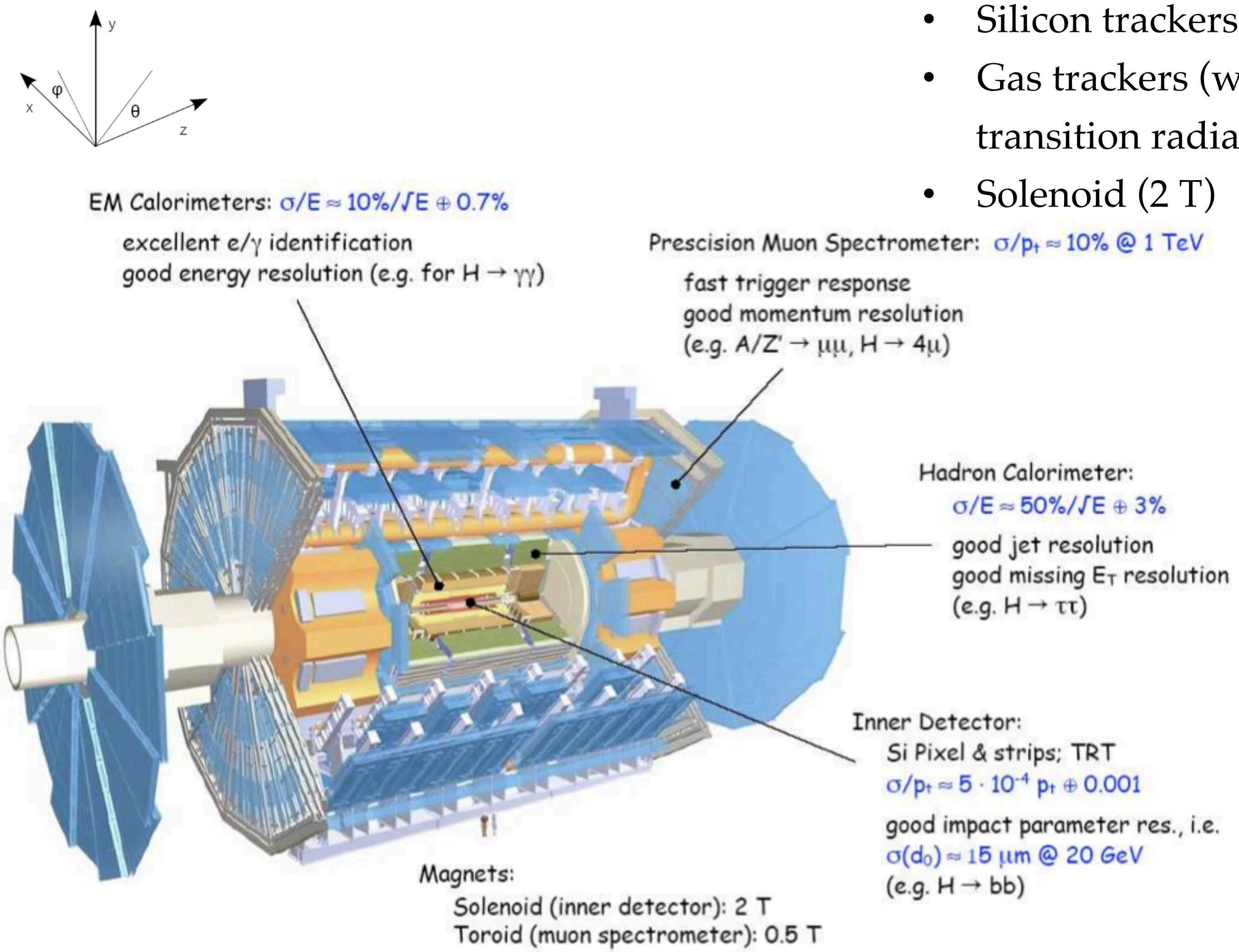
- Deviation of couplings -> sensitive to new physics!
- **Challenging to detect σ_{ttH}~0.5 pb @ 13 TeV**
- Complex final state and huge bkgs
- Combination of results from different decay modes
- Results still stat. dominated

- **<u>Run2 (up to 80 fb-1):</u>**
  5.8 σ (obs.) 4.9 σ (exp.)
  -> driven by γγ and multileptons
- **<u>Run1+2:</u> 6.3 σ (obs.) 5.1 σ (exp.)**



A Thoroidal LHC ApparatuS



Inner Detector:

- Silicon trackers (pixel and microstrip)
- Gas trackers (with measurement of the transition radiation, TRT)
- Solenoid (2 T)

Electromagnetic Calorimeter:

- Sampling Pb+LAr

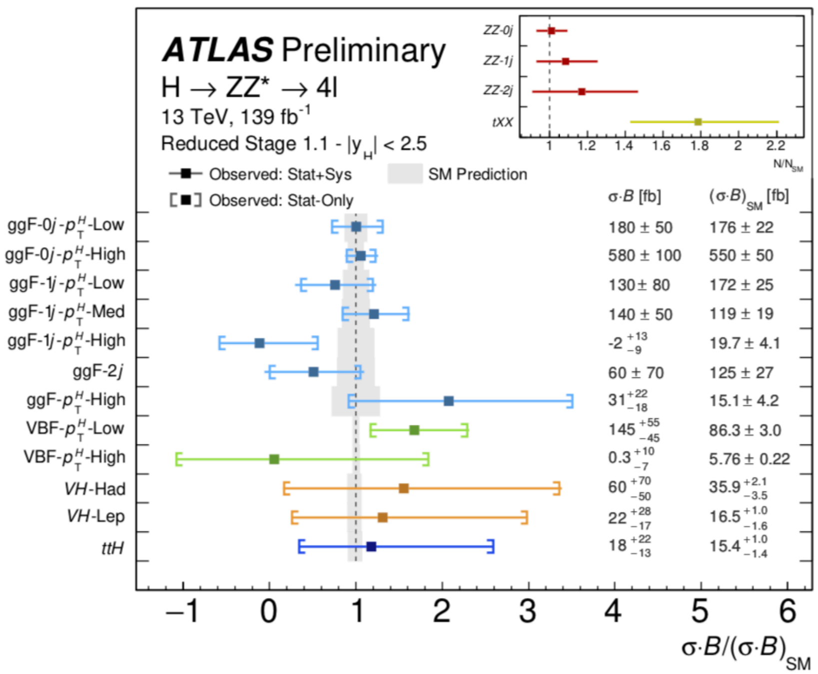
Hadronic Calorimeter:

- Fe+scintillator
- LAr technology

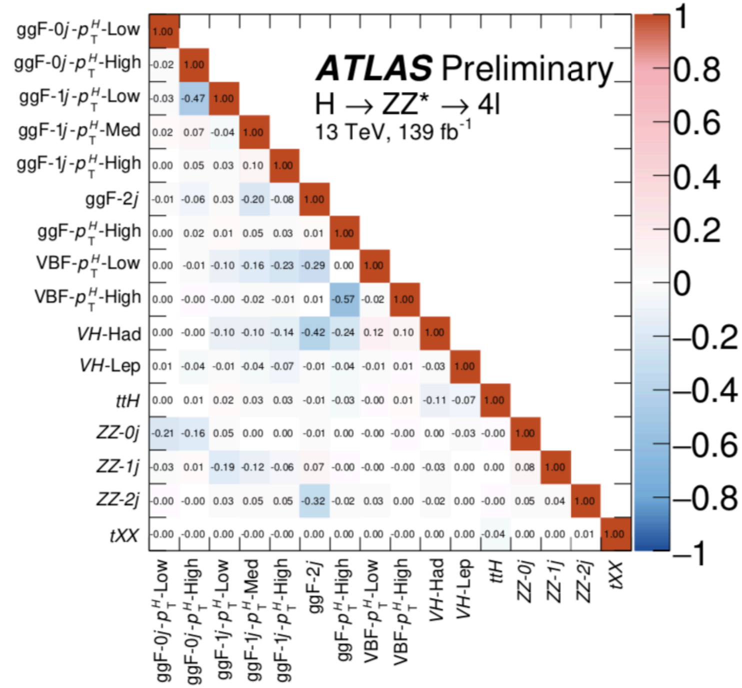
Muon System:

- Superconducting thoroids
- Precision tracking chambers
- Trigger chambers

ZZ* correlation matrix



(c)



(d)

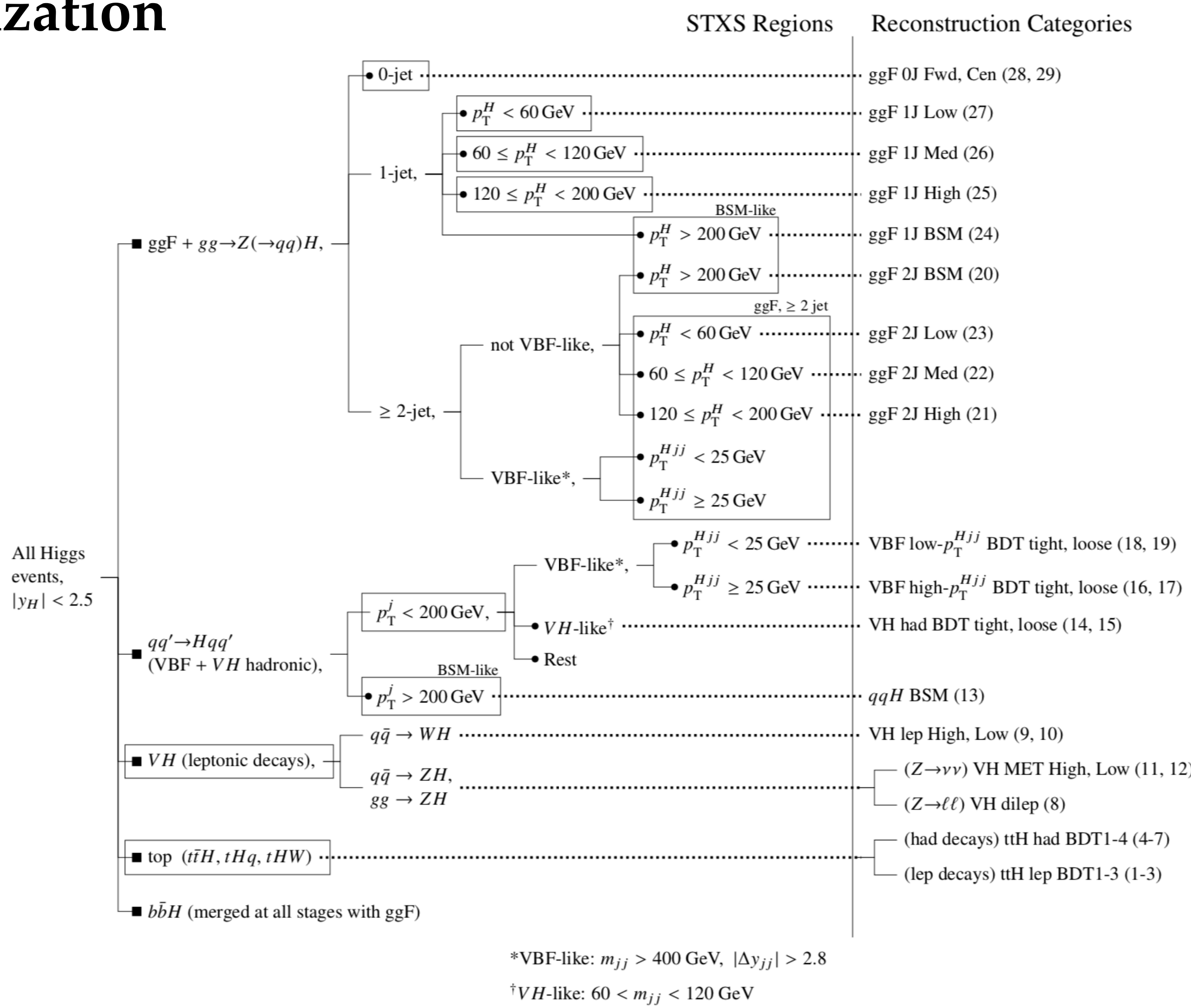
Figure 12: The observed and expected SM values of the cross section ratios $\sigma \cdot \mathcal{B}$ normalised by the SM expectation $(\sigma \cdot \mathcal{B})_{SM}$ for (a) the inclusive production and in the Stage-0 and (c) the reduced Stage-1.1 production bins for an integrated luminosity of 139 fb^{-1}at $\sqrt{s}$ = 13 TeV. The fitted normalisation factors for the the ZZ and tXX background are shown in the inserts. Different colours indicate different Higgs boson production modes (or background sources). The grey vertical band represents the theory uncertainty in the signal prediction. The correlation matrices between the measured cross-sections and the ZZ and tXX normalisation factors are shown for (b) Stage-0 and (d) reduced Stage-1.1.

ZZ^* systematics

Table 5: The impact of the dominant systematic uncertainties (in percent) on the measured inclusive fiducial cross section, and on the Stage-0 production mode cross sections. Similar sources of systematic uncertainties are grouped together - Luminosity (Lum.), electron/muon reconstruction and identification efficiencies and pile-up modelling (e, μ, pile-up), jet energy scale/resolution and b-tagging efficiencies (Jets, flavour tagging), uncertainties on reducible background (Reducible backgr.), theoretical uncertainties on ZZ^* background (ZZ^* backgr.) and tXX background (tXX backgr.), and theoretical uncertainties on the signal due to parton density function (PDF), QCD scale and showering algorithm (Parton shower). The uncertainties on correction factor due to the relative contribution of each Higgs boson production mechanism (Signal composition) are only applicable to fiducial cross section measurements. The uncertainties have been rounded to the nearest 0.5%, except for the luminosity uncertainty which has been measured to be 1.7% and can increase for a measurement due to simulated background.

Measurement	Experimental uncertainties [%]				Theory uncertainties [%]					
	Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	ZZ^* backgr	tXX backgr.	PDF	QCD scale	Parton Shower	Signal Composition
Fiducial cross section										
σ_{comb}	1.7	2.5	–	< 0.5	1	< 0.5	< 0.5	2	1	< 0.5
Per decay final state fiducial cross sections										
4μ	1.7	2.5	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
$4e$	1.7	7	–	0.5	1.5	< 0.5	< 0.5	2	0.5	< 0.5
$2\mu2e$	1.7	5.5	–	0.5	1	< 0.5	< 0.5	2	1.5	< 0.5
$2e2\mu$	1.7	2.0	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
Stage-0 production bin cross sections										
ggF	1.7	1.5	1	0.5	1.5	< 0.5	0.5	1	2	–
VBF	1.7	1	4.5	0.5	2	0.5	1.5	8	6	–
VH	1.8	1.5	3.5	1	5	0.5	2	12	8	–
ttH	1.7	1	4.5	1	1	0.5	0.5	8	4	–

$\gamma\gamma$ categorization



$\gamma\gamma$ systematics

Table 3: The breakdown of uncertainties on the inclusive diphoton fiducial cross section measurement. The uncertainties from the statistics of the data and the systematic sources affecting the signal extraction are shown. The remaining uncertainties are associated with the unfolding correction factor and luminosity.

Source	Uncertainty (%)
Statistics	6.9
Signal extraction syst.	7.9
Photon energy scale & resolution	4.6
Background modelling (spurious signal)	6.4
Correction factor	2.6
Pile-up modelling	2.0
Photon identification efficiency	1.2
Photon isolation efficiency	1.1
Trigger efficiency	0.5
Theoretical modelling	0.5
Photon energy scale & resolution	0.1
Luminosity	1.7
Total	11.0

WW* systematics (ggF+VBF)

Breakdown of the main contributions to the total uncertainty in $\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*}$ and $\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*}$. The individual sources of systematic uncertainties are grouped together. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components.

Source	$\Delta\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*}$ [%]	$\Delta\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*}$ [%]
Data statistics	10	46
CR statistics	7	9
MC statistics	6	21
Theoretical uncertainties	10	19
ggF signal	5	13
VBF signal	<1	4
WW	6	12
Top-quark	5	5
Experimental uncertainties	8	9
b-tagging	4	6
Modelling of pile-up	5	2
Jet	2	2
Lepton	3	<1
Misidentified leptons	6	9
Luminosity	3	3
TOTAL	18	57

WW* systematics (VH)

Table 6: Breakdown of the main contributions to the total uncertainty in $\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*}$ (left) and $\sigma_{ZH} \cdot \mathcal{B}_{H\to WW^*}$ (right). The individual sources of systematic uncertainties are grouped together. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components. Systematic uncertainties that affect the shape of the fitted distribution are indicated by an asterix.

Source	$\Delta\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*}$ [%]
Data statistics in SR	43
Data statistics in CR	6
Theoretical uncertainties	16
$WZ/W\gamma^*$(*)	12
Top-quark(*)	8
WH signal(*)	4
ZZ^*	2
Experimental uncertainties	12
Impact parameter mismodelling	8
Misidentified leptons	8
b-tagging	1
MC statistics	9
Luminosity	3
TOTAL	49

Source	$\Delta\sigma_{ZH} \cdot \mathcal{B}_{H\to WW^*}$ [%]
Data statistics in SR	50
Data statistics in CR	< 1
Theoretical uncertainties	15
ZH signal	14
Top-quark	1
$WZ/W\gamma^*$	< 1
ZZ^*	< 1
Experimental uncertainties	7
Misidentified leptons	3
b-tagging	1
MC statistics	11
Luminosity	2
TOTAL	54