Study of the production modes of the Higgs boson and EFT interpretations in the H->ZZ*->4l decay channel at 13 TeV center of mass energy with the ATLAS detector at LHC

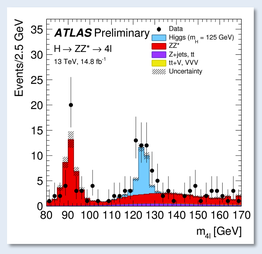
- Studies performed in order to pose limits on BSM couplings related to additional EFT contributions to the SM Lagrangian
- The VBF and VH production mechanisms shows a good sensitivity to BSM contributions to the HZZ vertex
- Measurements are therefore performed in reduced phase spaces enriched in each production mode (minimize the model dependence)
- Results are shown in the H -> ZZ* -> 4l decay channel with the 13 TeV data recorded by ATLAS at LHC

1) H->ZZ*->4l event selection

Higgs boson candidates are formed by selecting two same-flavour, opposite-sign lepton pairs (a lepton quadruplet) in an event.

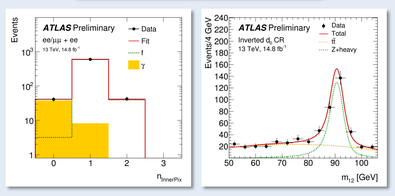
Leptons and Jets requirements	
Electrons	
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7GeV$ and $\|\eta\| < 2.47$	
Muons	
Loose identification $\|\eta\| < 2.7$	
Calo-tagged muons with $p_T > 15\,GeV$ and $\|\eta\| < 0.1$	
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5\,GeV$	
Jets	
anti-k_t jets with $p_T > 30GeV$, $\|\eta\| < 4.5$ and passing pile-up jet rejection requirements	
Event Selection	
Quadruplet Selection	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet - 20, 15 and $10GeV$ Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: $50\,GeV < m_{12} < 106\,GeV$ Sub-leading dilepton mass requirement: $12 < m_{34} < 115GeV$ Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5\,GeV$ $\Delta R(\ell,\ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
Isolation	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T/p_T < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/p_T < 0.30$ Electron track isolation ($\Delta R \leq 0.20$) : $\Sigma E_T/E_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $\|d_0/\sigma_{d_0}\| < 5$ For muons : $\|d_0/\sigma_{d_0}\| < 3$
Vertex Selection	Require a common vertex for the leptons χ^2/ndof < 6 for 4μ and < 9 for others.

- Muon p_T cut relaxed to 5 GeV improvement in the signal acceptance by ~5%
- Jet p_T cut tightened to 30 GeV to optimize the categories definition
- Vertex cut added to cope with the increasing bkg after relaxing muon p_T cut (Z+jet reduction ~ 25%)



Background estimates

- **ZZ* bkg**: from MC
- **Z+jets e ttbar:** from control regions enriched in bkg events (sub-leading lepton pair flavour)
  - Unbinned likelihood fit on discriminating variables to obtain the bkg composition
  - Transfer factors to extrapolate the yields to the signal region

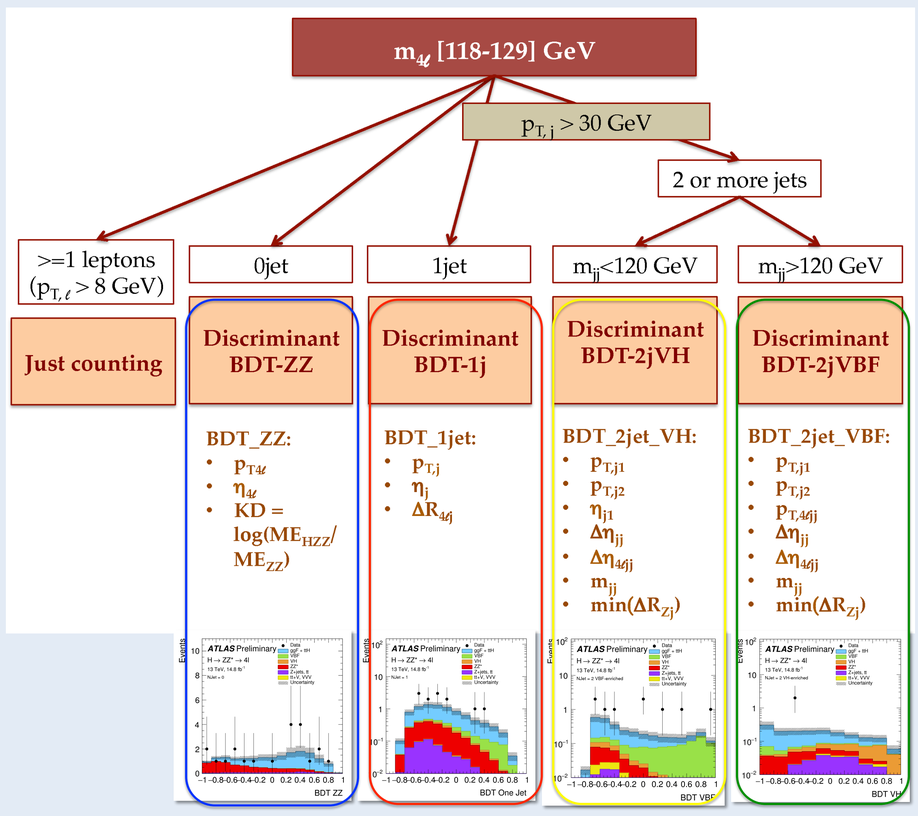


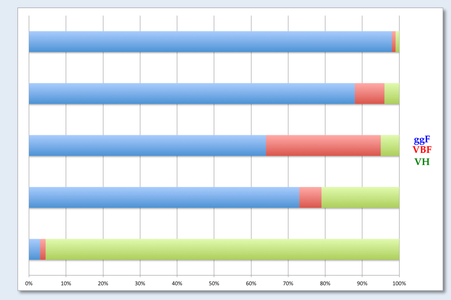
2) Event categorization and cross section per production mode

Measurements are performed splitting the events in categories built aiming for discrimination between production modes [1].

To gain sensitivity to different production modes a categorization of the Higgs candidate events:

- Exclusive categories: additional lepton and number of jets associated to the events
- Dedicated discriminants in each category
- Particular care for the 1jet category (~30% ggF events and ~30% VBF)





Signal extraction:

The observed number of events in each analysis categories (N^{obs}_k), can be expressed as:

$$\mathcal{N}_k^{\text{obs}} = \mathcal{L}_{\text{int}} \times \mathcal{BR}_{H\to ZZ^*\to 4\ell} \times \left(\sum_{i=1}^{\mathcal{N}^{prod}} \sum_{j=1}^{\mathcal{N}^{i}_{bin}} \mathcal{A}^i_{kj} \sigma^j_i \right)$$

- L_{int} (integrated luminosity)
- N^{prod} number of Higgs production mechanisms
- N^i_{bin} is the number of truth bins per Higgs production mechanism (i)
- A^i_{kj} detector response (trigger, reconstruction and identification efficiencies) for detecting the final state and the kinematic and geometric acceptance for the truth bin j of Higgs production mechanism i in the analysis category k.

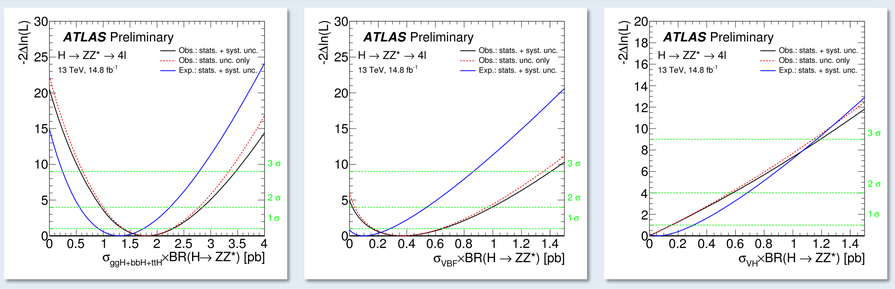
Analysis category	Signal: ggF + $b\bar{b}H + t\bar{t}H$	Signal: VBF	Signal: WH	Signal: ZH	Background: ZZ^*	Background: $Z+$jets, $t\bar{t}$	Total expected	Observed
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	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

Expected:

$$\sigma_{\text{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07 \text{ pb}$$
$$\sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003 \text{ pb}$$
$$\sigma_{\text{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002 \text{ pb}$$

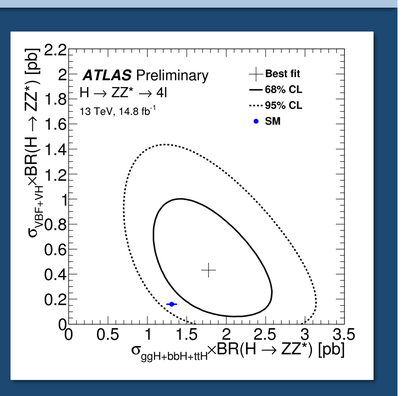
Observed:

$$\sigma_{\text{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44} \text{ pb}$$
$$\sigma_{\text{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21} \text{ pb}$$
$$\sigma_{\text{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15} \text{ pb}$$

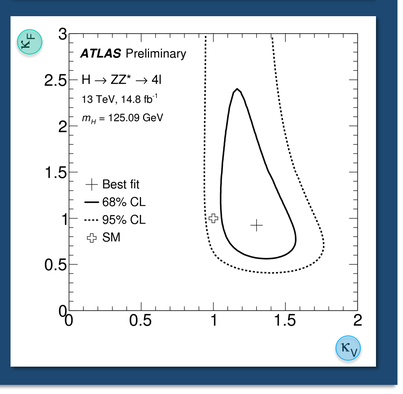


3) Cross section measurement and interpretation in the k-framework

- Agreement with the SM predictions:
  $\sigma_{\text{ggF+bbH+ttH}}$ B(H->ZZ*) @ 1.1σ
  σ_{VBF} B(H->ZZ*) @ 1.4σ
  The relative contribution of the VBF and VH production modes follows the SM prediction.



- The **same results** can be expressed in terms of **couplings with fermions (*ggF, bbH, ttH*)** or **vector bosons (*VBF, WH, ZH*)**:
  Potential deviations of this couplings from the SM can affect the coupling modifiers (k) :
  - k_F for the production mechanisms mediated by fermions
  - k_V for those mediated by vector bosons



Results obtained with the current statistic does not show significant deviations with respect to the SM

- Higgs mass fixed to m_H = 125.09 GeV
- Only the k_F>0 and k_V>0 quadrant is shown since the H->ZZ*->4l channel is not sensitive to the relative sign of the k

4) EFT terms in the SM Lagrangian

The possible presence of BSM terms in the Lagrangian describing the spin-0 resonance is investigated describing the HVV vertex interaction in terms of an effective BSM CP-odd and CP-even operators and deriving limits on the corresponding BSM couplings.

In the Higgs boson characterization model [2], the description of the spin-0 particle interaction with pairs of W and Z bosons is:

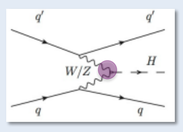
$$\mathcal{L}_0^V = \left\{ c_\alpha \kappa_{\text{SM}} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right] - \tfrac{1}{4}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \tfrac{1}{2}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \right\} X_0.$$

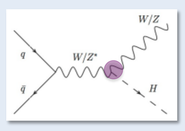
Contributo SM
k_{SM}=1, Λ=1 TeV
Contributo BSM
$k_{HZZ}=k_{HWW}=k_{HVV}$
$k_{AZZ}=k_{AWW}=k_{AVV}$

The κ^2_{SM}, κ^2_{HVV} and κ^2_{AVV} denote the coupling constants corresponding to the interaction of **Standard Model**, **BSM CP-even and BSM CP-odd spin-0 particles**, represented by the X_0 field, with ZZ or WW pairs.

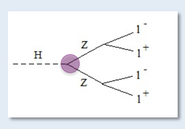
For large values of the BSM couplings, the VBF and VH production modes can have a significantly higher cross section due to the fact that the BSM couplings to W / Z bosons enter with the square power in the computation of the cross section.

Production:

VBF 

VH 

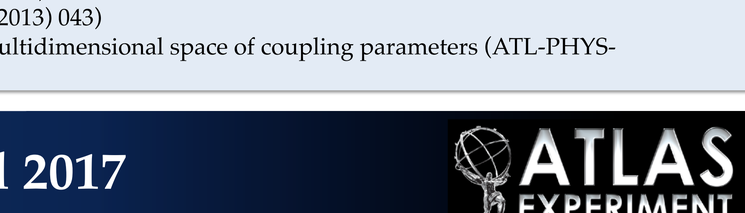
Decay:

H->ZZ* 

5) Limits on BSM couplings

The tensor couplings have been studied separately, fixing in the Lagrangian the SM component to its expectation ($\kappa_{SM} = 1$).
The likelihood expected distribution is symmetric since the cross section scales at the same rate for negative and positive values.
A small asymmetry arises from the correction to the total width, which is kept fixed to the SM value in generation, and a Γ_{BSM}/Γ_{SM} correction is then applied to the
$\sigma \cdot BR(H \to ZZ)$ for the samples with non-zero value for BSM.
Exclusion limits observed are less stringent than what expected due to the excess of events in the VBF 2jet enriched category.

Compatibility with the SM prediction:
k_{HVV}=0 compatible @ 2.1σ
k_{AVV}=0 compatible @ 1.8σ



- Only counting measurement in the categories (BSM discriminants and p_{Tj1},p_{TH} splitting for future)
- BSM samples have been generated using MadGraph5_aMC@NLO and Morphing techniques have been used in order to perform a continuous scan over the BSM couplings values [3]

Not excluded range at 95% CL	κ_{HVV} expected	κ_{HVV} observed	$\kappa_{AVV} \cdot \sin\alpha$ expected	$\kappa_{AVV} \cdot \sin\alpha$ observed
	$[-6.3, 5.1]$	$[0.9, 7.5]$	$[-6.3, 6.5]$	$[-9.7, 11.0]$

6) Conclusions

- Measurements performed up to now show results compatible with the SM predictions and with comparable sensitivity with respect to Run1
- Measurements are limited by the statistics available (errors statistically dominated)

References

[1] Study of the Higgs boson properties and search for high-mass scalar resonances in the H->ZZ*->4l decay channel at √s = 13 TeV with the ATLAS detector (ATLAS-CONF-2016-079)
[2] A framework for Higgs characterization (JHEP11 (2013) 043)
[3] A morphing technique for signal modelling in a multidimensional space of coupling parameters (ATL-PHYS-PUB-2015-047)

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IFAE - Trieste, 19 April 2017

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