Measurements of Higgs boson production by gluon-gluon fusion and vector-boson fusion using $H \to WW^* \to e\nu\mu\nu$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Phys. Rev. D 108 (2023) 032005

Badr-eddine Ngair (obo the group **B**)

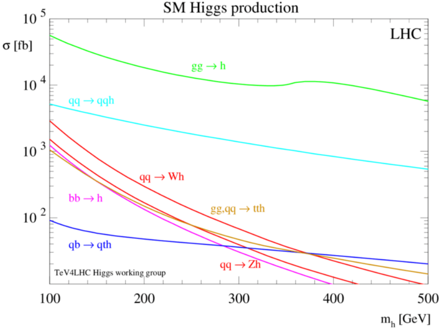
ASIA EUROPE PACIFIC SCHOOL OF HIGH-ENERGY PHYSICS-2024

23-June-2024

1. Introduction
2. Measurements of Higgs boson production
3. Results

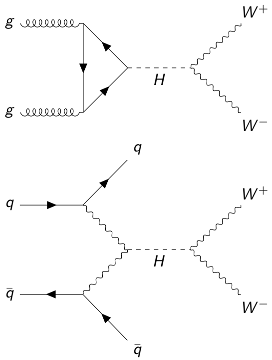
Motivation

Measurements of the Higgs **properties** are a powerful test of the **SM** and can be used to constrain theories of physics beyond the SM **(BSM)**.

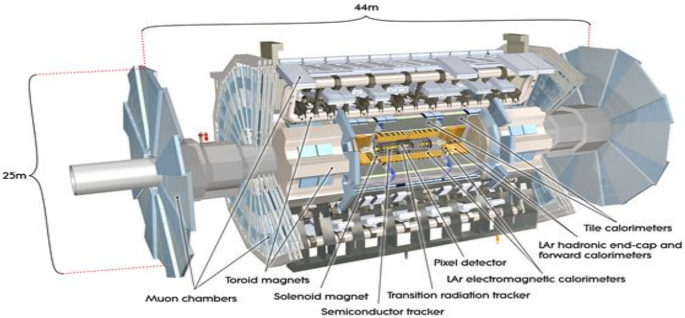


Introduction

1. Measurement of Higgs boson production by gluon-gluon fusion **(ggF)** and vector-boson fusion **(VBF)**
2. The decay H $\rightarrow WW^* \rightarrow e\nu\mu\nu$
   - Large branching ratio
   - Low-level backgrounds: different flavor of charged leptons in final state
3. Previous measurements
   - ATLAS [**PLB 789 (2019) 508**], $\sqrt{s} = 13$ TeV, $\mathcal{L} = 36\ fb^{-1}$
   - CMS [**JHEP 03 (2021) 003**] $\sqrt{s} = 13$ TeV, $\mathcal{L} = 137\ fb^{-1}$
4. Additions for full **Run 2** Analysis (relative to the 36 fb^{-1} Analysis)
   - Include of ggF **Njets** ≥ 2 region
   - VBF signal tagging with a **ML** technique (DNN).
   - **Simplified Template Cross Section** (STXS) stage 1.2



ATLAS Detector



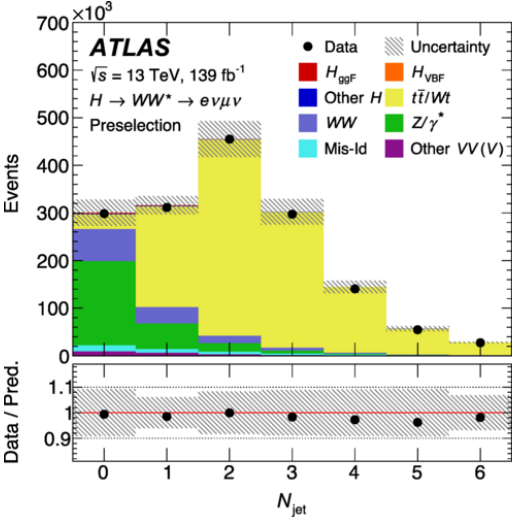
1. Data taken from pp collision at $\sqrt{s} = 13$ TeV, using the full Run2 dataset with $\mathcal{L} = 139\ fb^{-1}$
2. MC simulation for signal and backgrounds generated via standard generators like POWHEG, Pythia, MadGraph and Sherpa

Event Reconstuction

1. Tracks $p_T > 500$ MeV
2. $\geq$ one primary vertex with $\geq$ two associated tracks
3. Electrons
    - Excluding the transition region between the barrel and end caps of the LAr calorimeter
4. Muons
    - Inner tracker and muon spectrometer
5. Trigger objects must be matched to at least one of offline reconstructed leptons

Event Selection

- Two isolated leptons with opposite charge and different flavour $\alpha = (e, \mu)$
- $p_T(l_1) > 22$ GeV
- $p_T(l_2) > 15$ GeV
- $\tau\tau$ Background reduction
  - $m_{ll} > 10$ GeV
  - $p_T^{miss} > 20$ GeV (only ggF)



Event Categorization

N$_j$=0

- Sensitive to ggF
- discriminant for bkg: $\Delta\phi_{\ell\ell} < 0.8$ and $\Delta m_{\ell\ell} < 55$ GeV

N$_j$=1

- Sensitive to ggF
- discriminant for the bkg: max $(m_T^{\ell_i}) > 50$ GeV
  $m_T^{\ell_i} = \sqrt{2p_T^{\ell_i}E_T^{miss}(1 - cos\Delta\phi(\ell_i, E_T^{miss}))}$

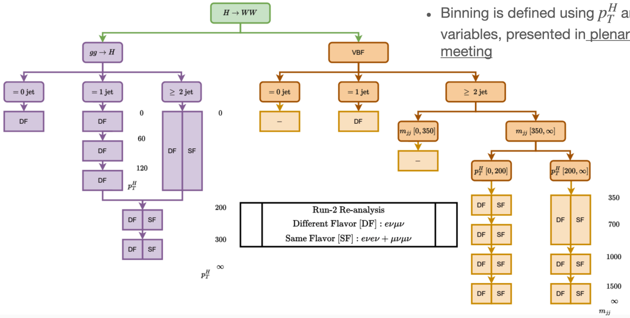
$N_j \geq 2$

- Sensitive to ggF and VBF
- For ggF : $|m_{jj} - 85| < 15$ GeV, $\Delta y_{jj} < 1.2$, $\Delta\phi_{\ell\ell} < 0.8$ and $\Delta m_{\ell\ell} < 55$ GeV
- For VBF: Deep Neural Network (DNN) trained on 15 variables

$\rightarrow$ Dominant bkg includes WW,$t\bar{t}$/Wt,Z/γ^* in above categories

STXS (Stage 1.2)

Simplified template cross sections (STXS) are an approach to categorise the Higgs-boson candidate events according to the properties associated with the Higgs production mode. This allows physicists to characterise the Higgs boson independently of its decay channel.



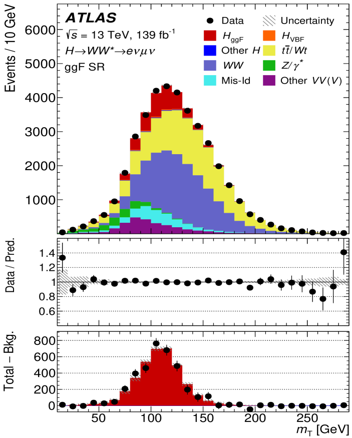
- Binning is defined using p_T^H and m_{jj} variables, presented in plenary meeting

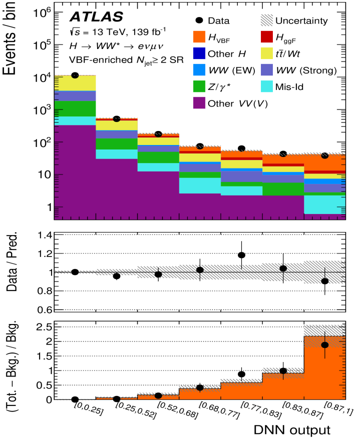
Systematic uncertainties

Source	$\frac{\Delta\sigma_{\mathrm{ggF+VBF}} \cdot B_{H\to WW*}}{\sigma_{\mathrm{ggF+VBF}} \cdot B_{H\to WW*}}$ [%]	$\frac{\Delta\sigma_{\mathrm{ggF}} \cdot B_{H\to WW*}}{\sigma_{\mathrm{ggF}} \cdot B_{H\to WW*}}$ [%]	$\frac{\Delta\sigma_{\mathrm{VBF}} \cdot B_{H\to WW*}}{\sigma_{\mathrm{VBF}} \cdot B_{H\to WW*}}$ [%]
Data **stat** uncertainties	4.6	5.1	15
Total **sys** uncertainties	9.5	11	18
Total	10	12	23

ggF signal: measurement of exclusive jet multiplicities
VBF signal: different generators for the matrix-element matching
Background: theoretical uncertainties in the WW and top-quark

Post-fit m_T and DNN distributions





Post-fit SR yields

Process	$N_{jet} = 0$ ggF	$N_{jet} = 1$ ggF	$N_{jet} \geq 2$ ggF	$N_{jet} \geq 2$ VBF Inclusive	$N_{jet} \geq 2$ VBF DNN: [0.87, 1.0]
H_{ggF}	2100 ± 220	1100 ± 130	440 ± 90	209 ± 40	2.6 ± 0.9
H_{VBF}	23 ± 9	103 ± 30	46 ± 12	180 ± 40	28.8 ± 5.5
Other Higgs	40 ± 20	55 ± 28	55 ± 27	29 ± 15	0.04 ± 0.02
WW	9700 ± 350	3500 ± 410	1500 ± 470	2100 ± 340	4.6 ± 1.2
$t\bar{t}/Wt$	2200 ± 210	5300 ± 340	6100 ± 500	7600 ± 370	2.6 ± 0.8
Z/γ^*	140 ± 50	280 ± 40	930 ± 70	1300 ± 300	0.6 ± 0.1
Other VV	1400 ± 130	840 ± 100	470 ± 90	380 ± 80	0.6 ± 0.1
Mis-Id	1200 ± 130	720 ± 90	470 ± 50	330 ± 40	1.7 ± 0.2
Total	$16\,770 \pm 130$	$11\,940 \pm 110$	$10\,030 \pm 100$	$12\,200 \pm 180$	42.0 ± 5.1
Observed	16 726	11 917	9 982	12 189	38

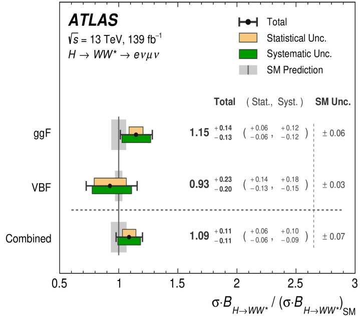
Inclusive cross-section

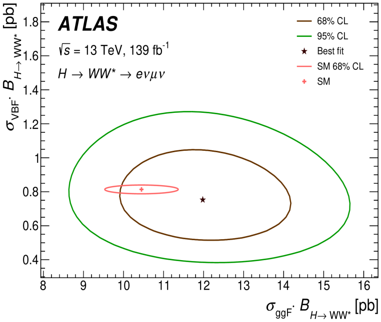
$\sigma_{\mathbf{ggF}} . \mathcal{B}_{H \to WW^*} = 12.0 \pm 1.4$ **pb**

$(\sigma_{\mathrm{ggF}} . \mathcal{B}_{H \to WW^*})^{SM} = 10.4 \pm 0.5$ pb

$\sigma_{\mathbf{VBF}} . \mathcal{B}_{H \to WW^*} = 0.75^{+0.19}_{-0.16}$ **pb**

$(\sigma_{\mathrm{VBF}} . \mathcal{B}_{H \to WW^*})^{SM} = 0.81 \pm 0.02$ pb

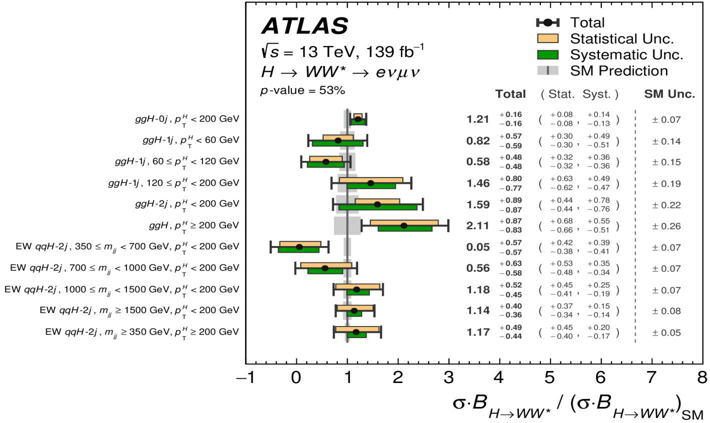




$\sigma_{\mathrm{ggF+VBF}} . \mathcal{B}_{H \to WW^*} = 12.3 \pm 1.3$ pb

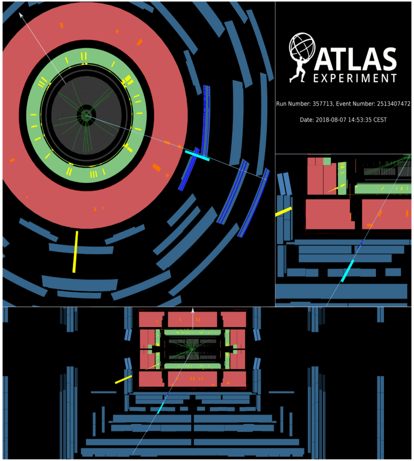
$(\sigma_{\mathrm{ggF+VBF}} . \mathcal{B}_{H \to WW^*})^{SM} = 11.3 \pm 0.5$ pb

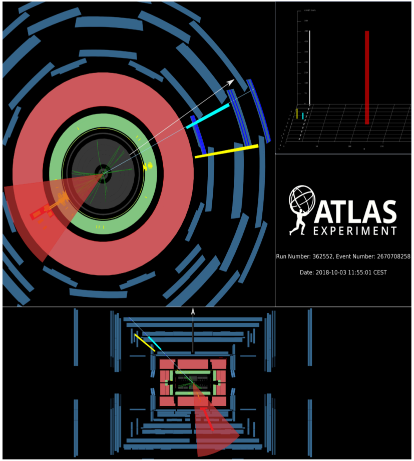
STXS results



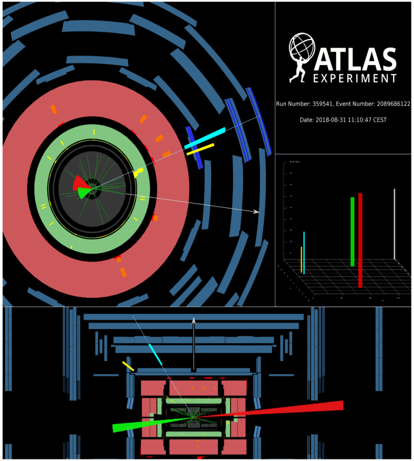
- The analysis is extended to include measurements of production cross-sections in **11 kinematic fiducial regions** (STXS) for the first time in this decay channel.
- Agreement with the SM with a p-value of **53%**

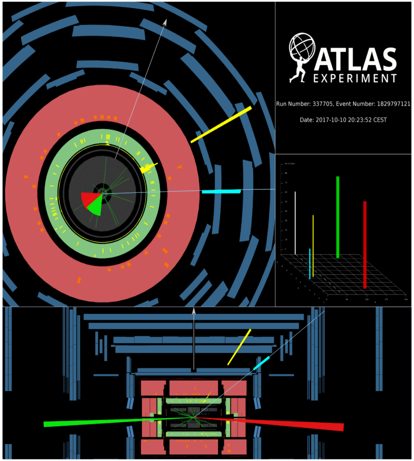
Event display - ggF $N_j = 0$ (left) and 1 (right)





Event display - ggF $N_j \geq 2$ (left) and VBF (right)





Summary

1. This paper constitutes the first full Run 2 cross section measurements of ggF+VBF H $\rightarrow$ WW^* in ATLAS
2. H $\rightarrow$ WW^* cross section measured in each of the STXS bins, normalized to the corresponding SM prediction are done.
3. Looking forward to use run3 data and combine run2+run3.

Thank you for your attention!

Back-Up

Systematic uncertainties (2)

Experimental uncertainties

1. Uncertainties arise from the jet energy scale (JES) and resolution (JER), JVT, and the jet ID
2. Uncertainties due to the trigger selection
3. Uncertainties for the soft term in the reconstruction od MET
4. combined 2015–2018 integrated luminosity is 1.7%
5. Uncertainty in the modeling of pileup
6. uncertainty on the electron (muon) ranging from 10% (12%) at low pt to 35% (75%) at high pt.

Theoretical uncertainties

1. For signal, top, and Z/Γ
   - parton shower and the matrix-element
2. qqWW and of WZ, ZZ and $V\gamma^*$
   - variations of the matching scale and nonperturbative effects
3. For signal processes
   - variations of the matching scale and nonperturbative effects

   factorization and renormalization scales.
4. The ggWW process:
   - conservative $50\%/+100\%$ normalization uncertainty

Simulation tools

Process	Matrix element	PDF set	UEPS model	Prediction for total cross section
ggF H	Powheg Box v2 NNLOPS (MG5_aMC@NLO)	PDF4LHC15nnlo	Pythia 8 (Herwig 7)	N3LO QCD + NLO EW
VBF H	Powheg Box v2 (MG5_aMC@NLO)	PDF4LHC15nlo	Pythia 8 (Herwig 7)	NNLO QCD + NLO EW
VH excluding $gg \to ZH$	Powheg Box v2	PDF4LHC15nlo	Pythia 8	NNLO QCD + NLO EW
$t\bar{t}H$	Powheg Box v2	NNPDF3.0nlo	Pythia 8	NLO
$gg \to ZH$	Powheg Box v2	PDF4LHC15nlo	Pythia 8	NNLO QCD + NLO EW
$qq \to WW$	Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.2	NLO
$qq \to WWqq$	MG5_aMC@NLO	NNPDF3.0nlo	Pythia 8 (Herwig 7)	LO
$gg \to WW/ZZ$	Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.2	NLO
$WZ/V\gamma^*/ZZ$	Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.2	NLO
$V\gamma$	Sherpa 2.2.8	NNPDF3.0nnlo	Sherpa 2.2.8	NLO
VVV	Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.2	NLO
$t\bar{t}$	Powheg Box v2 (MG5_aMC@NLO)	NNPDF3.0nlo	Pythia 8 (Herwig 7)	NNLO+NNLL
Wt	Powheg Box v2 (MG5_aMC@NLO)	NNPDF3.0nlo	Pythia 8 (Herwig 7)	NNLO
Z/γ^*	Sherpa 2.2.1 (MG5_aMC@NLO)	NNPDF3.0nnlo	Sherpa 2.2.1	NNLO

Systematic uncertainties

Uncertainties from both experimental and theoretical sources affect the results of the analysis

Source	$\frac{\Delta\sigma_{\text{ggF+VBF}} \cdot B_{H\to WW^*}}{\sigma_{\text{ggF+VBF}} \cdot B_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{ggF}} \cdot B_{H\to WW^*}}{\sigma_{\text{ggF}} \cdot B_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{VBF}} \cdot B_{H\to WW^*}}{\sigma_{\text{VBF}} \cdot B_{H\to WW^*}}$ [%]
Data statistical uncertainties	4.6	5.1	15
Total systematic uncertainties	9.5	11	18
MC statistical uncertainties	3.0	3.8	4.9
Experimental uncertainties	5.2	6.3	6.7
Flavor tagging	2.3	2.7	1.0
Jet energy scale	0.9	1.1	3.7
Jet energy resolution	2.0	2.4	2.1
$E_{\text{miss}}\ T$	0.7	2.2	4.9
Muons	1.8	2.1	0.8
Electrons	1.3	1.6	0.4
Mis-Id extrapolation factors	2.1	2.4	0.8
Pileup	2.4	2.5	1.3
Luminosity	2.1	2.0	2.2
Theoretical uncertainties	6.8	7.8	16
ggF	3.8	4.3	4.6
VBF	3.2	0.7	12
WW	3.5	4.2	5.5
Top	2.9	3.8	6.4
$Z\tau\tau$	1.8	2.3	1.0
Other VV	2.3	2.9	1.5
Other Higgs	0.9	0.4	0.4
Background normalizations	3.6	4.5	4.9
WW	2.2	2.8	0.6
Top	1.9	2.3	3.4
$Z\tau\tau$	2.7	3.1	3.4
Total	10	12	23

Event selection and categorization

<table>
<tr><th>Category</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF</th></tr>
<tr><td rowspan="2">Preselection</td><td colspan="4">Two isolated, different-flavor leptons ($\ell = e, \mu$) with opposite charge
$p_T^{\text{lead}} > 22$ GeV , $p_T^{\text{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="3">$p_T^{\text{miss}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="4">$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$</td></tr>
<tr><td rowspan="2">$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$
$p_T^{\ell\ell} > 30$ GeV</td><td colspan="3">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>max $(m_T^{\ell}) > 50$ GeV</td><td colspan="2"></td></tr>
<tr><td rowspan="3">$H \to WW^* \to e\nu\mu\nu$
topology</td><td colspan="3">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td rowspan="3">central jet veto
outside lepton veto
$m_{jj} > 120$ GeV</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>fail central jet veto
or
fail outside lepton veto</td></tr>
<tr><td>$|m_{jj} - 85| > 15$ GeV
or
$\Delta y_{jj} > 1.2$</td></tr>
<tr><td>Discriminating fit variable</td><td colspan="3">m_T</td><td>DNN</td></tr>
</table>

Analysis Overview

1. Event Characterization
   - two leptons + two neutrinos (MET)
2. Background composition varies with jet count Njet.
   - ggF: Njet = 0, 1, and >= 2 (targeted by Dilepton Transverse Mass m_T)
     $m_T = \sqrt{(E_{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_{T,\ell\ell} + E_T^{\text{miss}}|^2}$
   - VBF: Njet $\geq$ 2 (targeted by a Deep Neural Network (DNN) trained on 15 variables using lepton, jet and E_T^{miss} information)
3. STXS framework is conducted to measure the cross-section
   - ggF: higher-order QCD and EW corrections
   - VBF: (V$\rightarrow$ $q\bar{q}$)H topology