Search for an Invisibly Decaying Higgs Produced via Weak Boson Fusion

[ATLAS-CONF-2015-004]

https://cds.cern.ch/record/2002121

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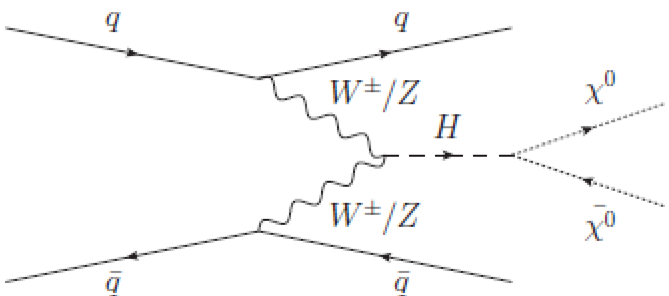
Introduction

- Dark matter or long-lived particles not interacting with the detector can couple to the Higgs sector due to their mass, while interacting weakly with the SM particles → invisible decay of the Higgs boson
- We are looking for the VBF Higgs production channel, with the Higgs decaying to invisible products.
  - VBF decay: associated with two jets with a large angular separation

    → signature: two jets + high missing transverse energy
- The limit on the Higgs boson width can be interpreted as a limit on the branching fraction to invisible particles and other unmeasured decays of the Higgs boson to SM or non-SM particles ("undetected" decays)
- *No excess in the Higgs boson decaying to invisible particles searches would point toward other undetected decays or incorrect model assumptions*



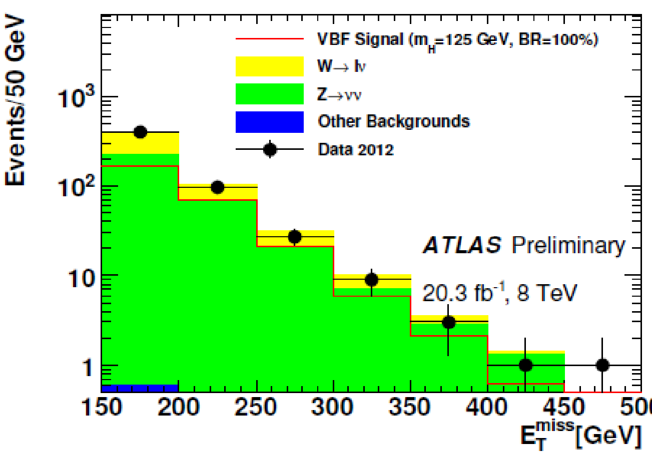
Backgrounds

- Largest: Z(vv) + jets → real Missing Transverse Energy (MET)
  - Estimated using W/Z+jets data control regions
- W(lv)+jets, when the lepton is out of acceptance, or is not reconstructed
  - Estimated using W+jets data control regions with good leptons
- Small contributions, when a jet is mis-reconstructed or a lepton is mis-identified:
  - QCD multi-jet background (mainly in the low MET), estimated using multi-jet enhanced data control regions
  - ttbar (simulation-based)
  - Di-Boson (simulation-based)

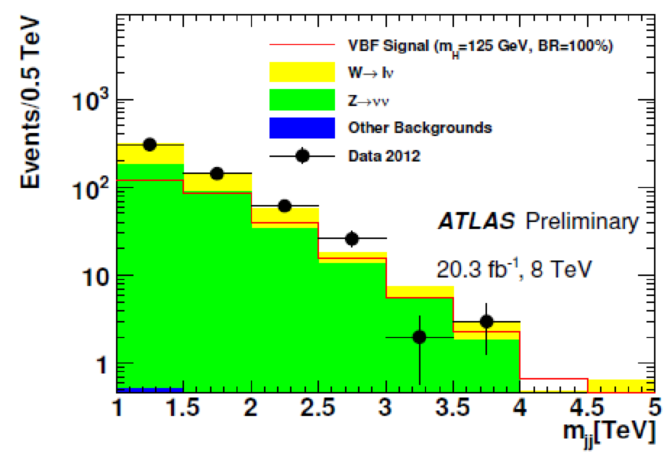
Event selection

- Using 20 fb-1 of 2012 ATLAS data, MET trigger
- Two jets with $p_T > 75\,GeV$ for the leading jet and $p_T > 50\,GeV$ for the sub-leading jet
- b-jet veto (to suppress the top background), electron/muon veto
- MET > 150 GeV
  - To suppress the multi-jet background, and to have a fully efficient MET trigger
- $\Delta\varphi_{jj} < 2.5$ and $\Delta\varphi_{j,MET} < 1.6$
  - To suppress the multi-jet background
- To focus on the VBF decay channel:
  - $\Delta\eta_{jj} > 4.8$, be in opposite hemispheres, and $m_{jj} > 1\,TeV$
- No third jet with $p_T > 30\,GeV$ and $|\eta| < 4.5$ in the event

Signal & BG are MC only.
Signal is normalized to the SM inclusive Higgs boson production cross-section
With BR(H → invisible)=100%.



(a) E_T^{miss} distribution



(b) m_{jj} distribution

Electroweak background estimation

- The W/Z+jets data **control regions** are constructed to match the signal selection as closely as possible, only differing in the lepton selection
  - Leptons in these control regions are required to be isolated, with the associated track being compatible with the primary vertex
- The Monte Carlo predictions for these two backgrounds (W and Z) are then scaled by a common factor k which is determined in a simultaneous fit to the signal region and the two control regions.
- Significant reduction in the large uncertainties of MC predictions due to the use of ratios of data to Monte Carlo in the two control regions to scale the background expectations in the signal region

Z(ll)+jets control region

- Lepton triggers
- Two same-flavor, oppositely-charged leptons with $p_T > 30\,GeV$ and $p_T > 20\,GeV$
- $|m_{ee/\mu\mu} - m_Z| < 25\,GeV$
- To model the boson pT (offline MET) of the signal region:
  - The electron or muon momenta are added vectorially to the MET
    → *emulated MET*
- All other signal region cuts on jets and (emulated) MET are the same as those in the signal region

Errors are statistical only

Background	$Z \to ee$	$Z \to \mu\mu$
QCD $Z \to \ell\ell$	10.4±1.5	14.0±1.5
EW $Z \to \ell\ell$	7.4±0.8	8.2±0.8
Other Backgrounds	0.3±0.2	0.2±0.1
Total	18.1±1.7	22.4±1.7
Data	22	25

W(lnu)+jets control region

- One lepton with $p_T > 30\,GeV$, and no additional leptons with $p_T > 20\,GeV$
- MET is emulated as in the Z(ll)+jets control region to get the boson pT
- All other signal region cuts on jets and (emulated) MET are the same as those in the signal region
- Multi-jet background in this control region is due to a misidentified jet as a lepton

$$m_{\mathrm{T}} = \sqrt{2E_{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos(\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}}))}$$

  - Multi-jet events tend to have a lower mT, as it has a lower MET value, with the direction along the direction of the jet that has been misidentified as a lepton.
  - A fit is performed to the transverse mass, using regions with reversed lepton cuts
  - Shape templates for real leptons are taken from W/Z MC samples
  - Shape templates for multi-jet are taken from regions with reversed lepton cuts

Errors are statistical only

Background	$W^+ \to e\nu$	$W^- \to e\nu$	$W^+ \to \mu\nu$	$W^- \to \mu\nu$
$Z \to \ell\ell$+jets	6±1	7±1	9±1	8±1
QCD W	92±7	55±5	86±7	44±5
EW W	99±4	53±3	82±4	39±3
Multijet	28±7	28±7	2±3	2±3
Other Backgrounds	4±1	2±0.4	3±1	1±0.3
Total	230±11	145±9	181±8	94±6
Data	225	141	182	98

Estimation of QCD multi-jet in the signal region

- Data control regions based on inverting the $\Delta\varphi_{j,MET}$ cut are defined, dominated by QCD events
- The efficiency method:
  - starts from a data sample which passes the leading and subleading jet pT cuts, the MET trigger requirement, and the inverted $\Delta\varphi_{j,MET}$
  - Efficiency of each subsequent cut is calculated in this sample and assumed to apply to the signal region
  - This yields an estimate of 2 ± 2
- The jet pT extrapolation method:
  - starts with a sample with the full signal region selection applied except that an additional jet is required and the $\Delta\varphi_{j,MET}$ cut is inverted
  - This control region consists of events with one extra jet in the event and the MET pointing along any of the 3 jets
  - The pT of the jet nearest the MET is then extrapolated using a polynomial fit to the region below the jet $p_T > 30\,GeV$ threshold

Validation regions

- In order to validate the data-driven background estimations, three validation regions are defined:
  - One by reversing the $\Delta\eta_{jj}$ cut: $\Delta\eta_{jj} < 3.8$ (*small dEta*)
  - One by reversing the jet veto, by requiring a 3rd jet with $p_T > 40\,GeV$ (*3-jet)*
  - One by reversing both these cuts simultaneously (*3-jet-small-dEta*)
- Using control regions analogous to those used for the main signal region, good agreement between expectation and observation is found in all three of these regions

Errors are statistical only

Process	3-jet	Small-$\Delta\eta_{jj}$	3-jet Small-$\Delta\eta_{jj}$
ggH Signal	6±3	-	-
VBF Signal	20±1	12±1	5±1
$Z \rightarrow \nu\nu$+jets	97±10	114±9	111±10
$W \rightarrow \ell\nu$+jets	79±7	72±12	73±1
Mulijets	20±22	-	-
Other Backgrounds	2±0.3	0.1±0.1	1±0.1
Total	198±25	186±16	185±14
Data	212	185	195

Main systematic uncertainties

- Jet energy scale
  - ~ 3-5% on the ratios
- Lepton-related uncertainties : negligible
- Theoretical uncertainties:
  - Factorisation & renormalisation scales (4-5% on the ratios)
  - PDFs evaluated with CT10 (1-2%)
- Combined theoretical uncertainty on VBF signal efficiency, using the MCFM event generator: 4.4%

Results

[ATLAS-CONF-2015-004]

- The limit on the branching fraction of H → invisible is computed using a maximum likelihood fit to the yields in the signal region and W/Z control samples
- An upper limit on the H → invisible branching fraction is set, assuming the SM Higgs boson production cross section.
- **Expected limit on BR at 95% CL : 35% (±1σ range: 25% to 49%)**
- **Observed limit on BR at 95% CL: 29%**
  - *https://cds.cern.ch/record/2002121/*
- CMS limit: 58%
  - They only used Zll to estimate Znunu background
  - *http://arxiv.org/abs/1404.1344*

Process	Yield ± Stat ± Syst
ggH Signal	20 ± 6 ± 10
VBF Signal	286 ± 5 ± 49
$Z \rightarrow \nu\nu$+jets	339 ± 22 ± 13
$W \rightarrow \ell\nu$+jets	237 ± 17 ± 18
Multijet	2 ± 2
Other Backgrounds	0.7 ± 0.2 ± 0.3
Total Background	578 ± 38 ± 30
Data	539