Recent results in the search for resonant $W^{\pm} Z \rightarrow l\nu ll$ production in Run-2 with the ATLAS detector

On behalf of the ATLAS X->WZ->lvll analysis team

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16/06/2022 , HEP2022 Conference

Ευρωπαϊκή Ένωση
European Social Fund

Operational Programme
Human Resources Development, Education and Lifelong Learning

Co-financed by Greece and the European Union

ΕΣΠΑ 2014-2020
ανάπτυξη - εργασία - αλληλεγγύη

«This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project "Strengthening Human Resources Research Potential via Doctorate Research" (MIS-5000432), implemented by the State Scholarships Foundation (IKY)»

Support Documents

- Paper: https://cds.cern.ch/record/2808353
- Analysis framework: framework migrated from the 36.1fb^{-1} analysis AODNtupleUtility
  Xchecked with ELCore framework using EventLoop package
- Statistical Framework: Resonance Finder (RooFit and RooStats based)

ATLAS Paper

HDBS-2018-19

3rd May 2022

Journal: Phys. Lett. B.

Draft version 2.0

Search for Resonant $WZ \rightarrow \ell\nu\ell'\ell'$ Production in Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector

The ATLAS Collaboration

Overview

1. Introduction and Motivation

- **Hierarchy** and **naturalness problems** due to the low mass of the SM Higgs boson.
- Need beyond SM physics to explain such problems.
- Resonance searches: the simplest way to discover new particles.
- These searches are Model-independent probe to new physics.

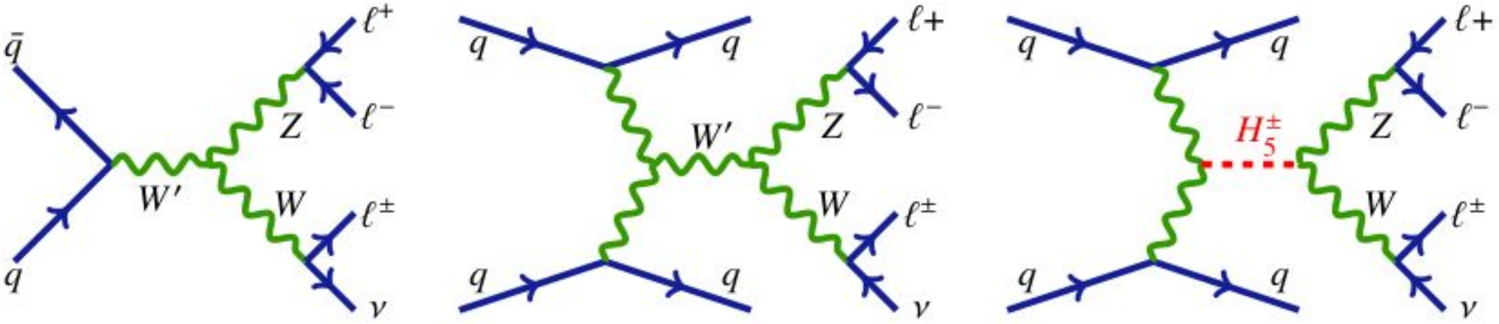


Fig: LO Feynman diagram for resonant WZ process at the LHC

- Resonance benchmark:
  - Heavy vector Triplets (simplified Lagrangian) produced either by qqF (Drell-Yan category) or VBF
  - Georgi - Machacek (GM) Higgs Triplet Model produced via VBF
    (fermiophobic fiveplet H5 that couples nearly exclusively with vector bosons)

1. Introduction and Analysis strategy

- The present analysis extends the search for resonant WZ production in the lvll (l = e, μ) decay using 139.7± 1.7 % fb^{-1} of data. Previous results with 36fb^{-1} can be found here

- We look into fully leptonic decay mode:
  - Small branching fractions
  - Clean signature, low background
  - Good sensitivity to low mass

Experimental signature:

  - 3 hight p_T isolated leptons
  - Missing transverse energy (E_T^{miss})

Two models used as benchmarks

- HVT produced via qq fusion or Vector Boson Fusion
- Charged Higgs $H_5^{\pm}$ from GM model produced via VBF

Analysis strategy

1) **VBF Artificial Neural Network signal region:** A cut on the Artificial Neural Network discriminant trained using H5 signals is used to define the signal. This signal region is used to compare H5/VBF HVT signals with data & set limits.
2) **VBF cut-based signal region:** Defined using the typical VBF topology cuts -> as a cross-check for the ANN analysis of VBF HVT and used to produce limits with alternative variables
3) **Drell-Yan signal region:** compare data with the W' produced via quark-antiquark annihilation predicted by HVT & set limits

2. Background and Signal samples

a. SM Monte Carlo background Samples

Derivation: DAOD_STDM5

DSID	Process	Generators	PDF
364253	$WZ \to \ell\nu\ell\ell$	Sherpa 2.2.2	NNPDF30NNLO
361292	$WZ \to \ell\nu\ell\ell$	Madgraph+Pythia8	A14NNPDF23LO
361293	$WZ \to \ell\nu\ell\ell$	Madgraph+Pythia8	A14NNPDF23LO
361601	$WZ \to \ell\nu\ell\ell$	Powheg+Pythia8	NLO CT10
364739	WZjj + tZ: $WZ \to e^-\nu\mu\mu$, $WZ \to \mu^-\nu ee$	MadGraph+Pythia8	NNPDF30NNLO
364740	WZjj + tZ: $WZ \to e^+\nu\mu\mu$, $WZ \to \mu^+\nu ee$	MadGraph+Pythia8	NNPDF30NNLO
364741	WZjj + tZ: $WZ \to \mu^-\nu\mu\mu$, $WZ \to e^-\nu ee$	MadGraph+Pythia8	NNPDF30NNLO
364742	WZ EW: $WZ \to \mu^+\nu\mu\mu$, $WZ \to e^+\nu ee$	MadGraph+Pythia8	NNPDF30NNLO
364250	ZZ QCD: $\ell\ell\ell\ell$	Sherpa 2.2.2	NNPDF30NNLO
364254	ZZ QCD: $\ell\ell\nu\nu$	Sherpa 2.2.2	NNPDF30NNLO
364283	ZZ EWK: $\ell\ell\ell\ell$	Sherpa 2.2.2	NNPDF30NNLO
345705	$gg \to \ell\ell\ell\ell$ ($m_{4\ell}$ < 130)	Sherpa 2.2.2	NNPDF30NNLO
345706	$gg \to \ell\ell\ell\ell$ ($m_{4\ell}$ > 130)	Sherpa 2.2.2	NNPDF30NNLO
361603	$q\bar{q} \to ZZ \to \ell\ell\ell\ell$	Powheg+Pythia8	NLO CT10
361604	$q\bar{q} \to ZZ \to \ell\ell\nu\nu$	Powheg+Pythia8	NLO CT10
364100-364141	Z+jets	Sherpa 2.2.1	NNPDF30NNLO
361106	$Z \to ee$	Powheg+Pythia8	CTEQ6L1
361107	$Z \to \mu\mu$	Powheg+Pythia8	CTEQ6L1
361108	$Z \to \tau\tau$	Powheg+Pythia8	CTEQ6L1
364500-364509	NLO $Z\gamma$	Sherpa 2.2.2	NNPDF30NNLO
366140-364149	LO $Z\gamma$	Sherpa 2.2.4	NNPDF30NNLO
361600	W^+W^-	Powheg+Pythia8	NLO CT10
361100	$W^+ \to e\nu$	Powheg+Pythia8	CTEQ6L1
361101	$W^+ \to \mu\nu$	Powheg+Pythia8	CTEQ6L1
361102	$W^+ \to \tau\nu$	Powheg+Pythia8	CTEQ6L1
361103	$W^- \to e\nu$	Powheg+Pythia8	CTEQ6L1
361104	$W^- \to \mu\nu$	Powheg+Pythia8	CTEQ6L1
361105	$W^- \to \tau\nu$	Powheg+Pythia8	CTEQ6L1
410470	$t\bar{t}$ ($\geqslant 1\ell$)	Powheg+Pythia6	A14NNPDF23LO
410155	$t\bar{t}W$	Madgraph+Pythia8	NNPDF23LO
410218	$t\bar{t}Z(ee)$	Madgraph+Pythia8	NNPDF23LO
410219	$t\bar{t}Z(\mu\mu)$	Madgraph+Pythia8	NNPDF23LO
364242	$WWW \to 3\ell 3\nu$	Sherpa 2.2.2	NNPDF30NNLO
364243	$WWZ \to 4\ell 2\nu$	Sherpa 2.2.2	NNPDF30NNLO
364244	$WWZ \to 2\ell 4\nu$	Sherpa 2.2.2	NNPDF30NNLO
364245	$WZZ \to 5\ell 1\nu$	Sherpa 2.2.2	NNPDF30NNLO
364246	$WZZ \to 3\ell 3\nu$	Sherpa 2.2.2	NNPDF30NNLO
364247	$ZZZ \to 6\ell 0\nu$	Sherpa 2.2.2	NNPDF30NNLO
364248	$ZZZ \to 4\ell 2\nu$	Sherpa 2.2.2	NNPDF30NNLO
364249	$ZZZ \to 2\ell 4\nu$	Sherpa 2.2.2	NNPDF30NNLO

- WZ QCD main background: 2 different generators available and compared for uncertainties
- Z+jets, Zγ, ttbar, WW: All MC backgrounds that include at least one miss-identified lepton are only used to validate data driven method

2. Background and Signal samples

b. Signals

LO

DSID	qqHVT Mass
307376	250
307377	300
307378	400
302266	500
302267	600
302268	700
302269	800
302270	900
302271	1000
302272	1100
302273	1200
302274	1300
302275	1400
302276	1500
302277	1600
302278	1700
302279	1800
302280	1900
302281	2000
302282	2200
302283	2400
302284	2600
302285	2800
302286	3000
302287	3500
302288	4000
302289	4500
302290	5000

VBF HVT

307730	250
313538	275
307731	300
313539	325
313540	350
313541	375
307732	400
313542	425
313543	450
313544	475
307733	500
313545	525
313546	550
307734	600
307735	700
307736	800
307737	900
307738	1000
307739	1100
307740	1200
307741	1300
307742	1400
307743	1500
307744	1600
307745	1700
307746	1800
307747	1900
307748	2000

NLO

VBF GM

450765	200
450766	250
450767	300
450768	350
450769	400
450770	450
450771	500
502511	225
502512	275
502513	325
502514	375
502515	425
502516	475
502517	525
502518	550
502519	600
502520	700
502521	800
502522	900
502523	1000

3. Object Reconstruction

- Four lepton categories:
  - Baseline leptons used for 4-lepton veto
  - Loose leptons used for the “fake” background estimation
  - Tighter cuts for the Z, and W leptons
- VBF jets have a tighter selection than baseline analysis jets

Muon object selection

Selection	*baseline*	*loose*	*tight(Z)*	*tight(W)*
$p_T > 5$ GeV (15 GeV for CT muons)	✓	✓	✓	✓
$p_T > 25$ GeV		✓	✓	✓
$\|\eta\| < 2.7$	✓	✓	✓	✓
|z0sinθ| < 0.5 mm	✓	✓	✓	✓
cosmic cut ($\|d_0\| < 1$ mm)	✓	✓	✓	✓
$\|d_0/\sigma(d_0)\| < 3$[3]		✓	✓	✓
Loose quality (if p_T >300 GeV HighPt quality)	✓	✓	✓	✓
FCLoose isolation	✓	✓	✓	✓
μ-jet overlap removal		✓	✓	✓
Medium quality (if p_T >300 GeV HighPt quality)			✓	
FCTight isolation			✓	
Tight quality (if p_T >300 GeV HighPt quality)				✓
FCTight isolation				✓

Electron object selection

Selection	*baseline*	*loose*	*tight(Z)*	*tight(W)*
$p_T > 7$ GeV	✓	✓	✓	✓
$p_T > 25$ GeV		✓	✓	✓
$\|\eta^{\text{cluster}}\| < 2.47$	✓	✓	✓	✓
Exclude $1.37 < \|\eta^{\text{cluster}}\| < 1.52$		✓	✓	✓
Electron object quality	✓	✓	✓	✓
|z0sinθ| < 0.5 mm	✓	✓	✓	✓
$\|d_0/\sigma(d_0)\| < 5$[4]		✓	✓	✓
LooseLH+BLayer identification	✓	✓	✓	✓
FCLoose isolation	✓	✓	✓	✓
e-μ and e-e overlap removal		✓	✓	✓
e-jets overlap removal		✓	✓	✓
MediumLH identification			✓	
FCTight isolation			✓	
TightLH identification				✓
FCTight isolation				✓

Jet object selection

Selection	*baseline*	VBS
$p_T > 30$ GeV	✓	✓
$\|\eta\| < 4.5$	✓	✓
Pile-up Removal		✓
veto b-Tagging		✓
μ-jet overlap removal		✓
e-jets overlap removal		✓

4. Event Selection and Analysis strategy

a. Inclusive Region Event Selection

Good Run List

data15_13TeV.periodAllYear_DetStatus-v89-pro21-02_Unknown_PHYS_StandardGRL_All_Good_25ns
data16_13TeV.periodAllYear_DetStatus-v89-pro21-01_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns
data17_13TeV.periodAllYear_DetStatus-v97-pro21-17_Unknown_PHYS_StandardGRL_All_Good_25ns_Triggerno17e33prim
data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_Unknown_PHYS_StandardGRL_All_Good_25ns_Triggerno17e33prim

Single lepton HLT triggers

	2015	2016-2018
Single muon	HLT_mu20_iloose_L1MU15 HLT_mu50	HLT_mu26_ivarmedium HLT_mu50
Single electron	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_e24_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0

High Efficiency 3 leptons in final state, possibility to use dilepton and MET triggers was studied and no gain was found

WZ inclusive selection

Inclusive event selection	
Event cleaning	Reject LAr, Tile and SCT corrupted events and incomplete events
Primary vertex	Hard scattering vertex with at least two tracks
Trigger	Single lepton (electron or muon) trigger
Jet cleaning	pass DFCommonJetseventCleanLooseBad
ZZ veto	veto events with additional *Baseline* leptons
N leptons	Exactly three leptons passing the "loose^{-}" lepton selection with $p_T > 25$ GeV ($p_T > 27$ GeV for the trigger-matched lepton)
Z candidate	built from Same-Flavor-Opposite-Sign (SFOS) lepton pair with $M_{\ell\ell}$ closest to Z PDG mass
W candidate	built from the third lepton and E_T^{miss}
W, Z selection	Z leptons passing "tight(Z) "lepton selection W leptons passing "tight(W) "lepton selection.
Mass window	$\|M_{\ell\ell} - M_Z\| < 20$ GeV
Missing Energy	$E_T^{miss} > 25$ GeV

Designed to select good W and Z pairs decaying leptonically

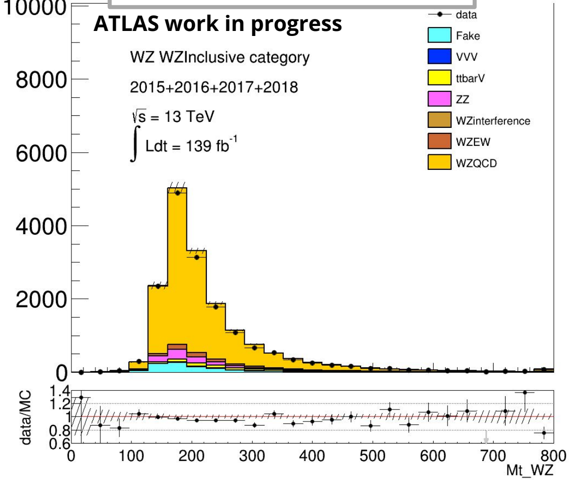
→ on top of this region the Drell-Yan and VBF signal regions are built

4. Event Selection and Analysis Strategy

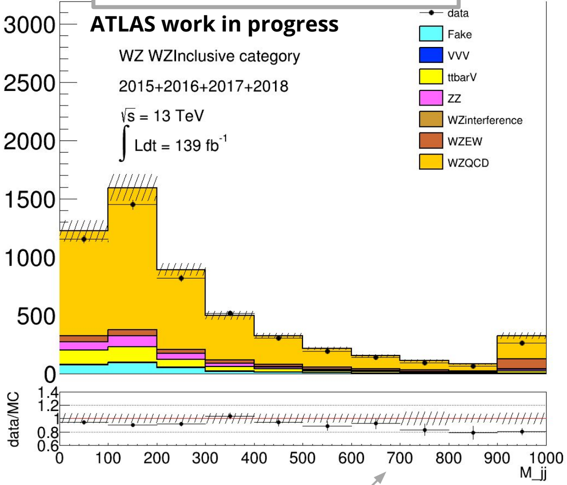
b. Control distributions of selected $W^{\pm}Z$ events in inclusive region

- Validation distributions in the inclusive region
  - Only MC backgrounds used in here and only experimental syst. unc. included

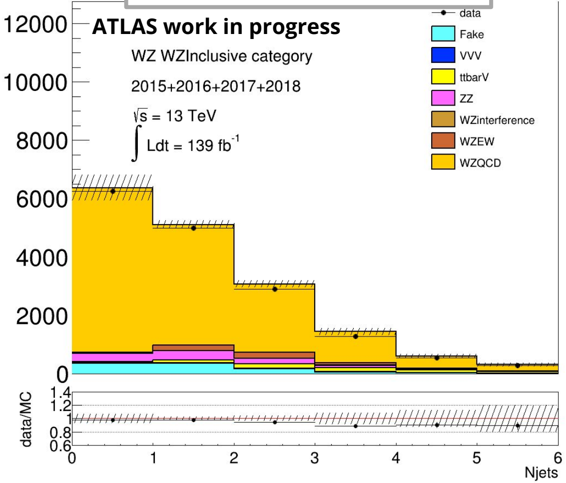
WZ transverse mass



Dijet invariant mass



Jet multiplicity



Know high Mjj miss-modelling of WZ QCD

Good data/MC agreement in inclusive region the signal regions are built on top of this selection

4. Event Selection and Analysis Strategy

c. Signal and Control Regions

- $p_T^{Z/W}$: strongly correlated with HVT resonance mass *
- $p_T^{Z} / M_{WZ} > 0.35$ and $p_T^{W} / M_{WZ} > 0.35$ ➩ Clear separation between signal & SM background

Baseline *WZ* selection		
Event cleaning and primary vertex Single-electron or single-muon trigger Exactly 3 *Loose* leptons (e or μ) with p_T >25 GeV (p_T >27 GeV for the trigger-matched lepton) *ZZ* veto: veto events with additional *Baseline* leptons *Z* candidate: A *Tight Z* Same-Flavour-Opposite-Sign lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV *W* candidate: *Tight W* lepton requirements on "non-*Z* leptons" and $E_T^{miss} > 25$ GeV		
Selection	**Drell-Yan**	**VBF**
Signal region	$p_T(V)/m(WZ) > 0.35$	At least 2 *VBF jets* $m_{jj} > 100$ GeV Veto events with b-tagged jets ANN Output > 0.82
WZ-QCD control region	$p_T(W)/m(WZ) \leq 0.35$ or $p_T(Z)/m(WZ) \leq 0.35$ $p_T(V)/m(WZ) > 0.1$	At least 2 *VBF jets* $m_{jj} > 500$ GeV Veto events with b-tagged jets ANN Output < 0.82
ZZ control region	Additional *Baseline* lepton No E_T^{miss} requirement	Additional *Baseline* lepton No E_T^{miss} requirement At least 2 *VBF jets*

* for heavy resonances produced at rest at s-channel, the $p_T(W, Z) \sim 50\%$ of M_{wz}

4. Event Selection and Analysis Strategy

c. Signal and Control Regions

- Enriched in vbf-category events
- VBF cut-based as cross-check :

at least 2 VBS jets
b-jet veto
$M_{jj} > 500$ GeV
$|\Delta Y jj| > 3.5$

Baseline *WZ* selection		
Event cleaning and primary vertex Single-electron or single-muon trigger Exactly 3 *Loose* leptons (e or μ) with p_T >25 GeV (p_T >27 GeV for the trigger-matched lepton) *ZZ* veto: veto events with additional *Baseline* leptons *Z* candidate: A *Tight Z* Same-Flavour-Opposite-Sign lepton pair with $\lvert m_{\ell\ell} - m_Z\rvert < 20$ GeV *W* candidate: *Tight W* lepton requirements on "non-*Z* leptons" and $E_T^{miss} > 25$ GeV		
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4. Event Selection and Analysis Strategy

c. Signal and Control Regions

Baseline *WZ* selection		
Event cleaning and primary vertex Single-electron or single-muon trigger Exactly 3 *Loose* leptons (e or μ) with p_T >25 GeV (p_T >27 GeV for the trigger-matched lepton) *ZZ* veto: veto events with additional *Baseline* leptons Z candidate: A *Tight* Z Same-Flavour-Opposite-Sign lepton pair with $\|m_{\ell\ell} - m_Z\| < 20$ GeV W candidate: *Tight* W lepton requirements on "non-Z leptons" and $E_T^{miss} > 25$ GeV		
Selection	**Drell-Yan**	**VBF**
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WZ-QCD control region	$p_T(W)/m(WZ) \leq 0.35$ or $p_T(Z)/m(WZ) \leq 0.35$ $p_T(V)/m(WZ) > 0.1$	At least 2 *VBF jets* $m_{jj} > 500$ GeV Veto events with b-tagged jets ANN Output < 0.82
ZZ control region	Additional *Baseline* lepton No E_T^{miss} requirement	Additional *Baseline* lepton No E_T^{miss} requirement At least 2 *VBF jets*

-> to constrain the main background contributions in SRs using data
-> orthogonal to the SRs

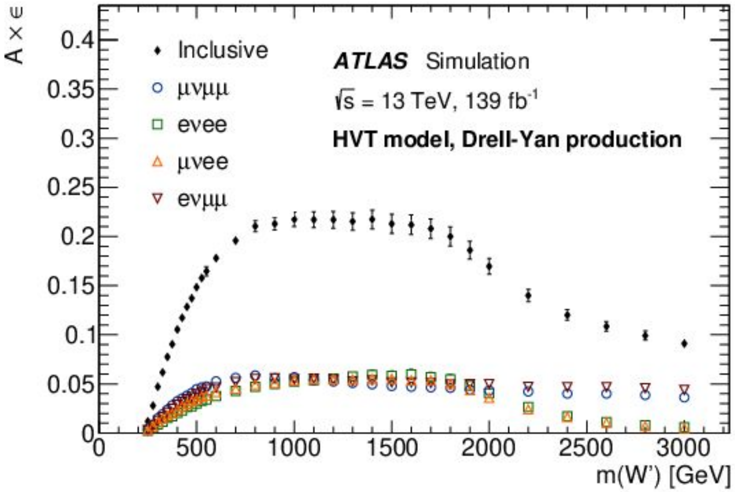
5. Signal Optimization

a. Drell-Yan selection

- Use the $p_T^{Z/W}/M_{WZ} > 0.35$ as optimized for the 36fb^{-1} analysis -> to reduce the contribution of not resonant WZ

- Acceptance x Efficiency calculated for the HVT model:

  - Increases steadily as increasing mass at low mass values, but starts to decrease for **m > 2 TeV**, particularly in the electron channel.
    - Z bosons from the heavy HVT decays are highly boosted → 2 lep from the Z boson decays are very close together
    - Limited spatial resolution of the ATLAS calorimeter → 2 e cannot be efficiently
    - reconstructed and identified separately → loss in efficiency



5. Signal Optimization

b. Artificial Neural Network (ANN) VBF selection

Hyperparameter	Value
Epochs	100
Number of Layers	2
Neurons per layer	45
Learning rate	0.028
Patience	0 (no early stopping)
Dropout	0.2
Momentum	0.7
Folds	4

Table 14: Hyperparameters used for MVA selection of GM signals.

- Training done using simultaneously all the NLO H_5 GM MC signals as “signal” and the SM WZ QCD and EWK events as “background” (same ANN used for HVT VBF)
- Training is performed using events passing a very loose VBF selection:
  - Inclusive region selection
  - Number of jets >=2
  - Dijet invariant mass >100 GeV & b-jet veto
- For training of each mass individually, mass window ~ 40% of input signal mass (~2.5 σ) was used
- Optimal value for the cut on ANN output significance Z :

$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)}$$

Where n: observed events
b : predicted bkg events
σ : variance + Gaussian approximation for syst. Unc.

Variables for ANN training

M_{jj}	Invariant mass of 2 leading pT jets
$\Delta\varphi_{jj}$	Difference in φ of the leading pT jets
η_W, η_Z	Pseudorapidities of the reconstructed gauge bosons
η_{j1}	Leading jet pseudorapidity
$\zeta_{1,\ lep}$	Event centrality
E_T^{miss}	Missing transverse energy
H_T	Scalar sum of the transverse moments of visible objects (jets & leptons)

- After training -> ntuples decorated with the ANN output → cut on this output to maximize signal significance

5. Signal Optimization

b. Artificial Neural Network (ANN) VBF selection

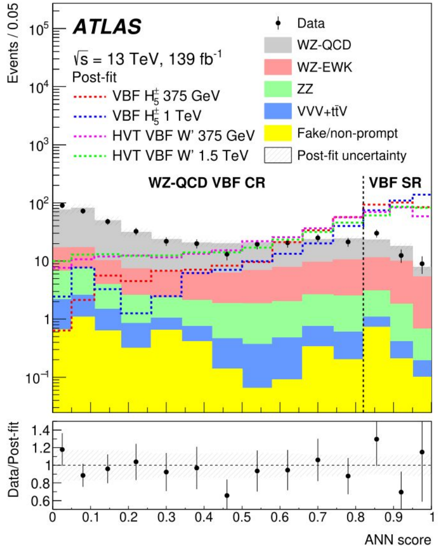
- ANN cut is defined by maximizing the Z for the 200 GeV mass point for GM and

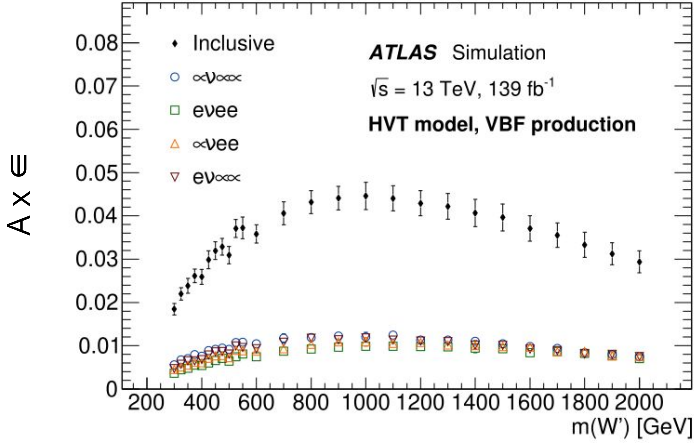
  (one ANN training for each mass point : not improving significantly the performance)

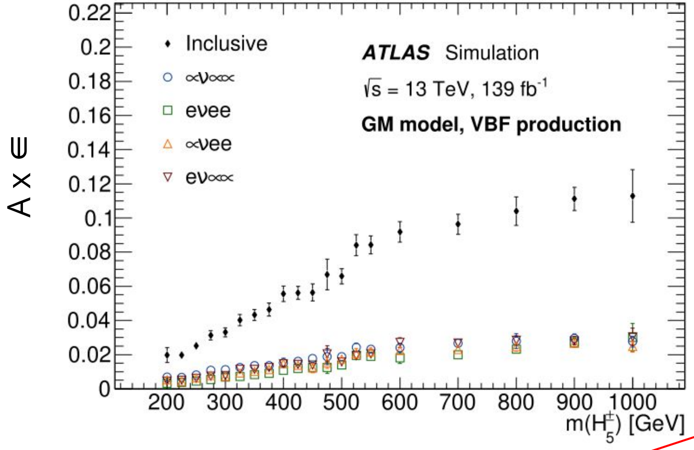
  ANN output = 0.82

- ANN output applied to both GM and HVT vbf signals

  > **85**% (**70 %**)drop in SM background events when comparing to VBF cut-based selection while maximum **30%** (**50%**) signal loss for **VBF GM** (**VBF HVT**) signals







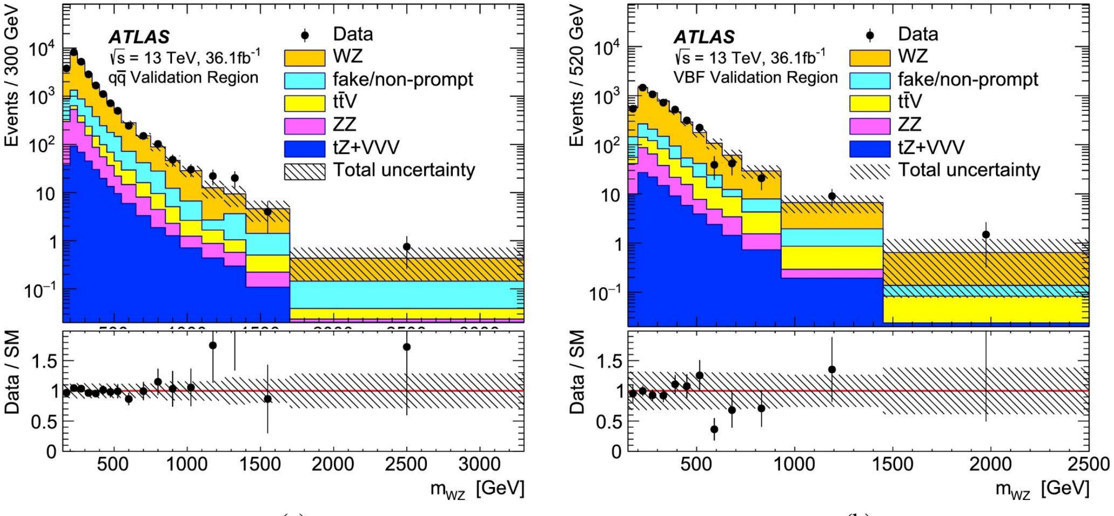
Masses 200-1000 GeV : 2-5 % **&** **2-12 %**

Generator level selections
&
Diff. angular distributions of products

6. Background Estimation

From the 36fb^{-1} paper

Drell-Yan SR　　　VBF SR



(a)　　　(b)

- Matrix method for **reducible backgrounds** (jets or photons mis-iden. as leptons) -> **Z+jets, Z+gamma, ttbar, Wt & WW**
- Dedicated control regions included in the fit for **irreducible backgrounds** (**WZ and ZZ**) -> to constrain it
- MC estimation for the other backgrounds (**ttbarV, VV, VVV**)

7. Statistical Treatment

a. Limit setting strategy & yields

- A binned maximum-likelihood fit using the reconstructed $W^{\pm}Z$ invariant mass spectrum (M_{WZ})
- Histogram templates of the signal and backgrounds are fitted using the ResonanceFinder package.
- All the decay channels (electron and muon) are merged together
- *Simultaneous fit* of the signal regions together with their respective WZ and ZZ control regions.

Inputs to the fit

- The $W^{\pm}Z$ invariant mass histograms for signal and backgrounds in the signal region to fit.
- The $W^{\pm}Z$ invariant mass histograms in the $W^{\pm}Z$ and ZZ of the control regions (each SR has their respective $W^{\pm}Z$ CR & the ZZ CR).
- The number of fake-lepton events in each region is obtained with the data-driven method
- The number of events predicted by the simulation in each region for the other backgrounds: ttbar+ V and VVV.

Free parameters

- Normalisation for the $W^{\pm}Z$ QCD and ZZ background (all other backgrounds allowed to vary within its uncertainties)
- Signal normalization
- Decorrelated theory uncertainties between CR and SR

Nuisance parameters

1. MC stat. Unc.
2. Object & event syst. Unc. + correlations
3. PDF, Scale & PS unc.
4. Fake uncertainty → from the Matrix Method
5. ttbar+ V and VVV → X-sec theory unc.

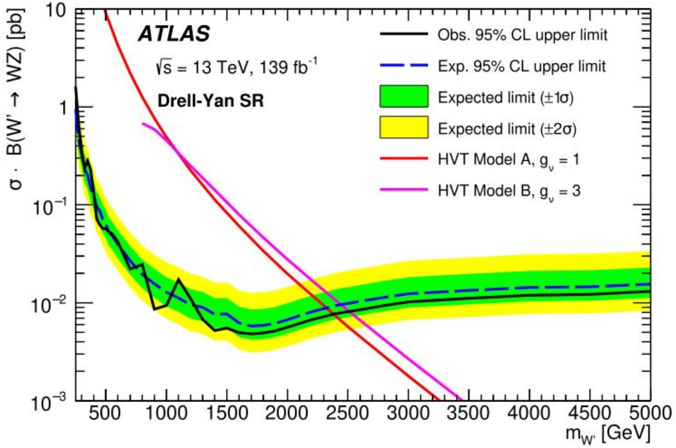
Postfit Yields

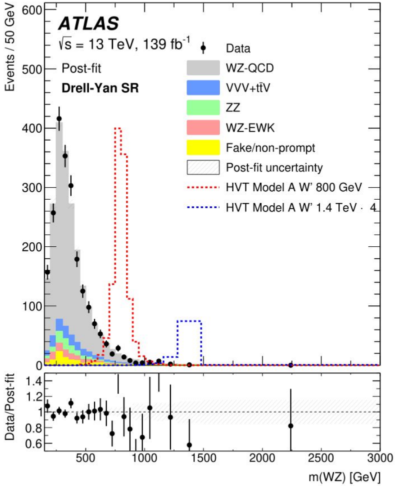
	Drell-Yan signal region	VBF signal region
WZ-QCD	1734 ± 77	29 ± 4
WZ-EWK	89 ± 10	26 ± 3
$VVV + t\bar{t}V$	148 ± 27	0.9 ± 0.2
ZZ	95 ± 5	5 ± 1
Fakes/non-prompt leptons	88 ± 49	0.3 ± 0.8
Total background	2155 ± 71	61 ± 6
Observed	2155	66

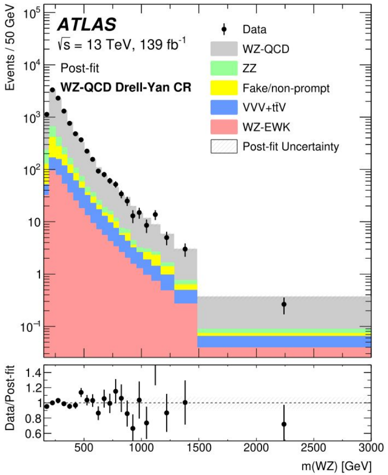
7. Statistical Treatment

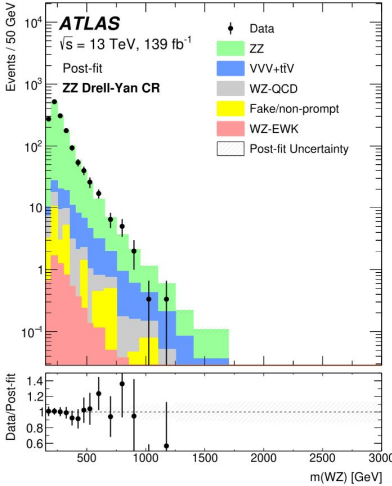
b. Drell-Yan 95% CL Limits

- Limits improve as expected with increased luminosity
- Currently expected limits are for **HVT Model-A : at ~2.4 TeV** **HVT Model-B : at ~2.5 TeV**





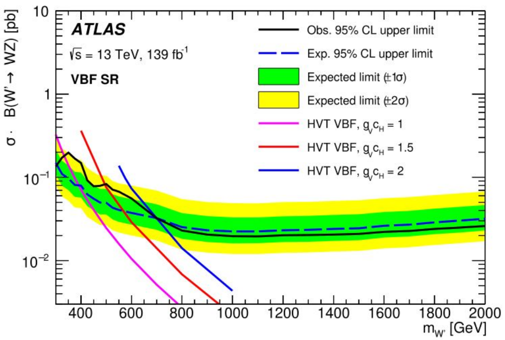


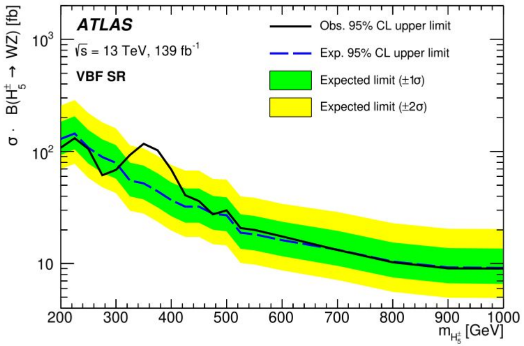


- Largest observed excess ~1.1TeV
- local significance 1.2σ

7. Statistical Treatment

c. VBF ANN 95% CL Limits

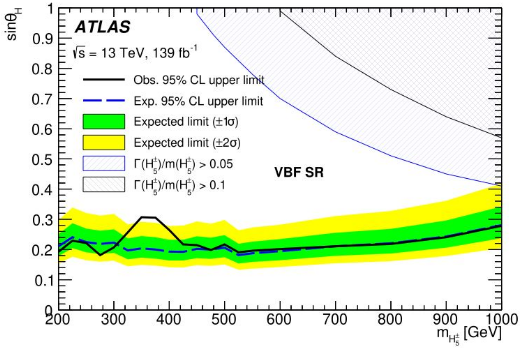


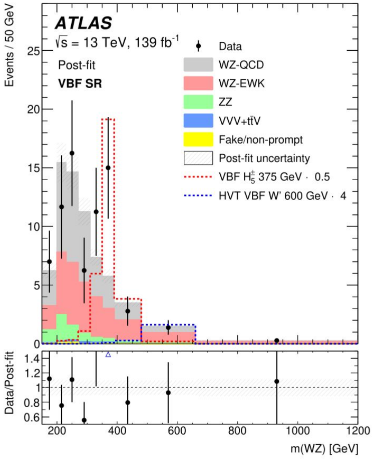


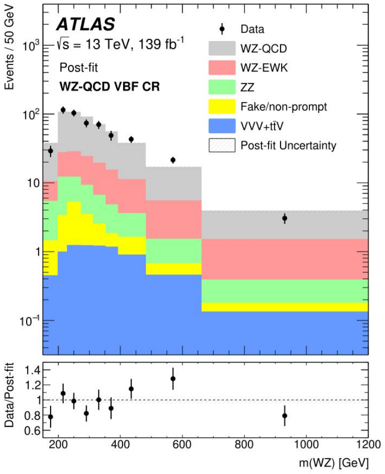
- Limits improve as expected with increased luminosity
- Currently expected limits are for
  HVT VBF at 340 GeV, 500 GeV & 700 GeV

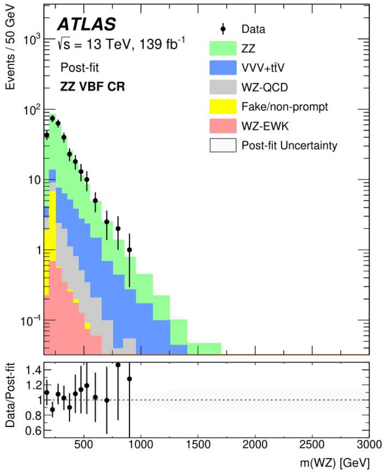
$$sin(\theta_H) = \sqrt{\frac{\sigma \times BR(H_5^{\pm} \to W^{\pm}Z)}{\sigma_1^{NNLO}(H_5^{+}) + \sigma_1^{NNLO}(H_5^{-})}} = (2 \sqrt{2}\, \upsilon_{\chi}) / 2$$

vacuum expectation value contribution of the complex bi-triplet of GM model





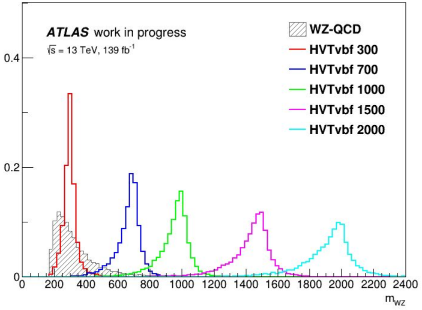


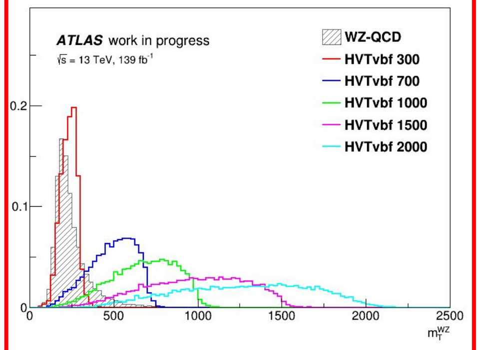


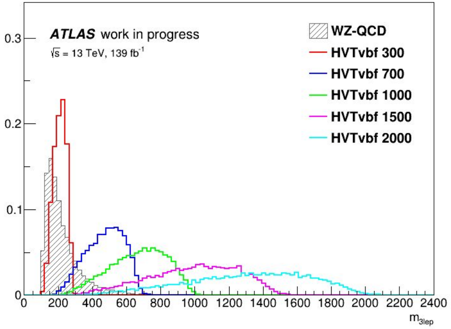
- Largest observed excess ~375GeV
- local significances 2.8σ for H5
  and 2.5σ for HVT W' (1.6 & 1.7 global sign.)

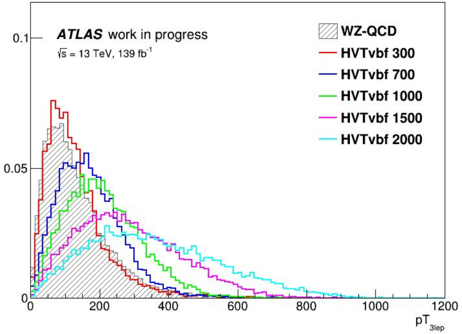
8. Alternative variables

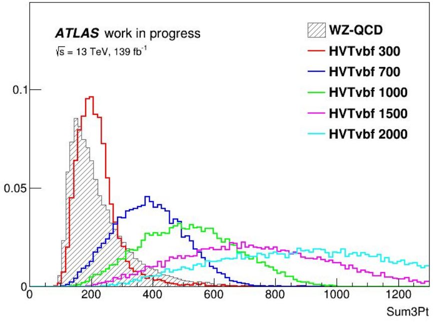
- Sensitive variables that are going to be used in the limits setting procedure => search for new particles in the direction of the extension of the SM
- Clear signal peaks and good discriminating power between different signal models
- **Mjj** : effective in discriminating between all non-VBS processes and the signal => VBS/VBF topologies : large values for the mJJ









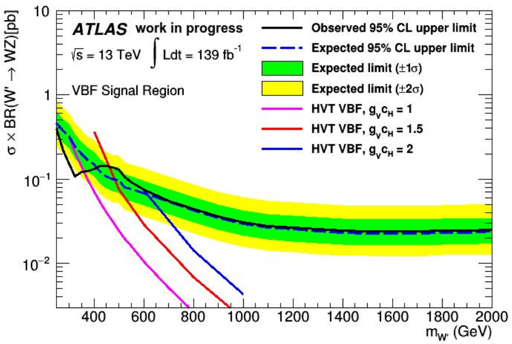


=> check correlations in order to put 2 dim limits

=>Lowest correlation obtained for mTWZ& mjj

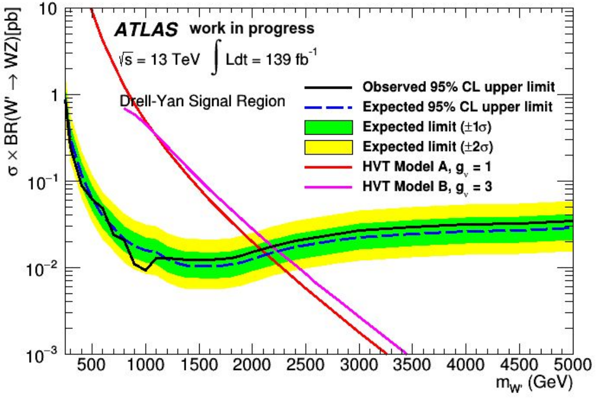
9. Setting limits with m_T^{WZ}

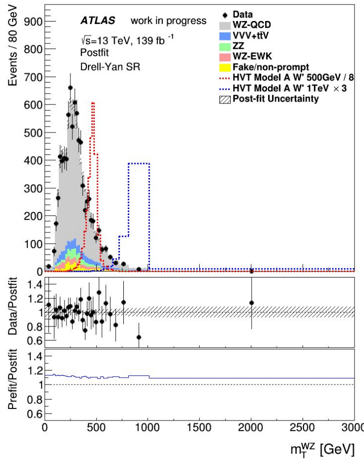
VBF HVT at 380 GeV, 480 GeV & 640 GeV



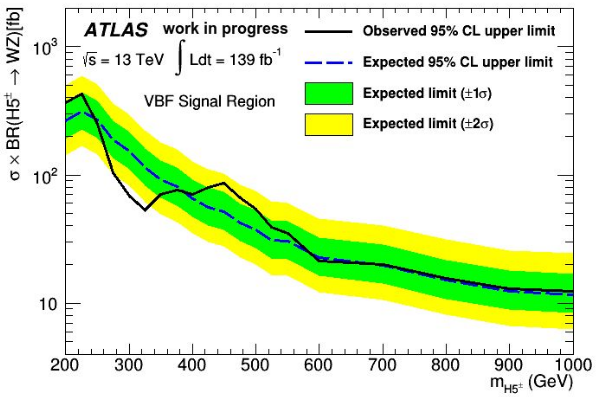
Drell-Yan Model-A : at ~2.1 TeV

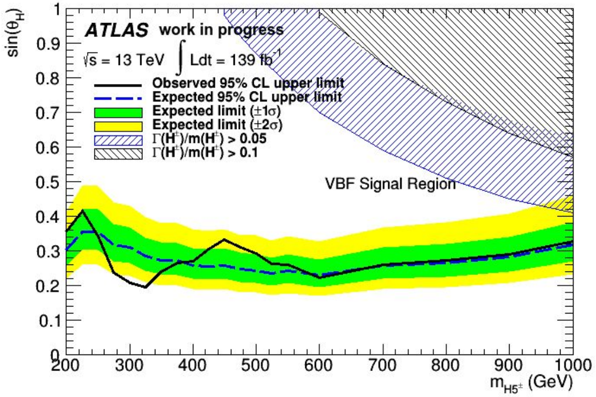
Model-B : at ~2.25 TeV

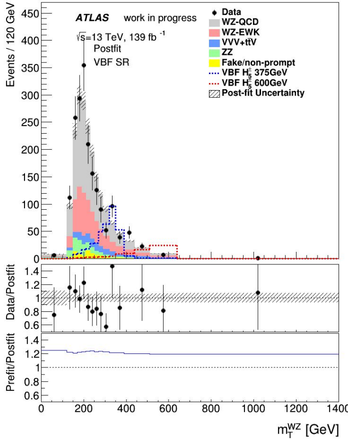




VBF GM (H5)

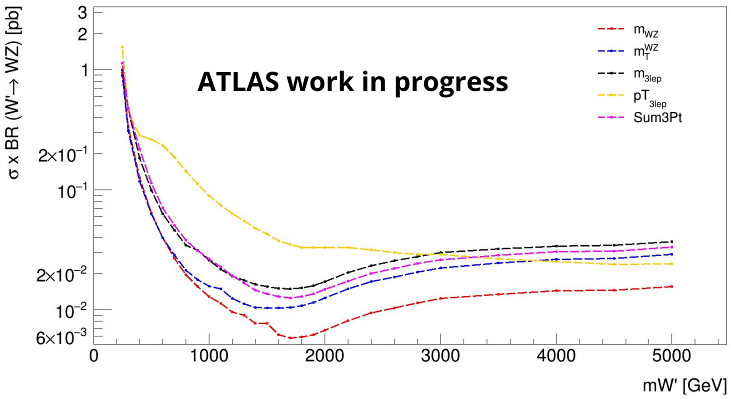




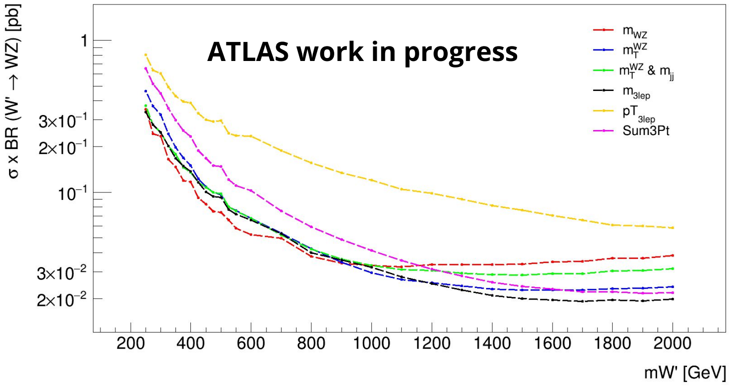


10. Comparison plots for limits with alternative variables (expected)

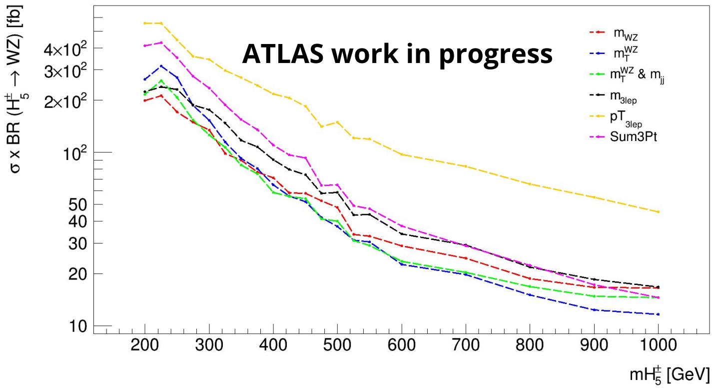
Drell-Yan

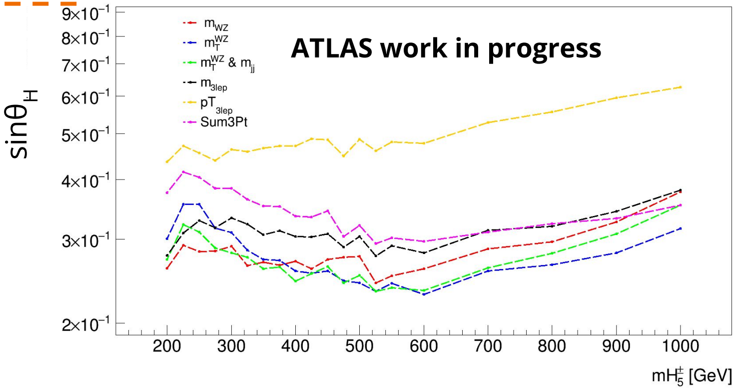


VBF HVT



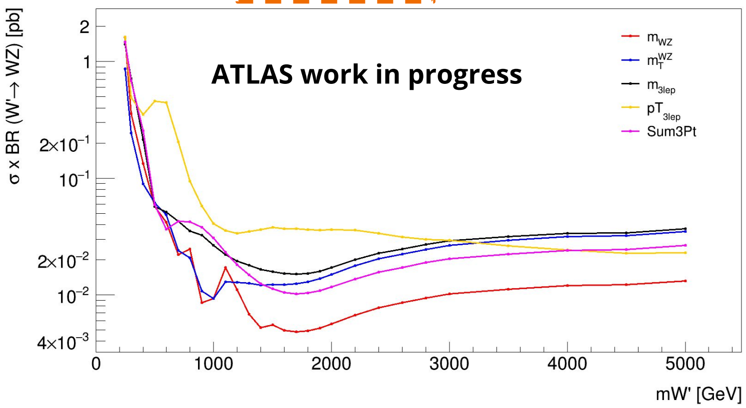
VBF GM (H5)



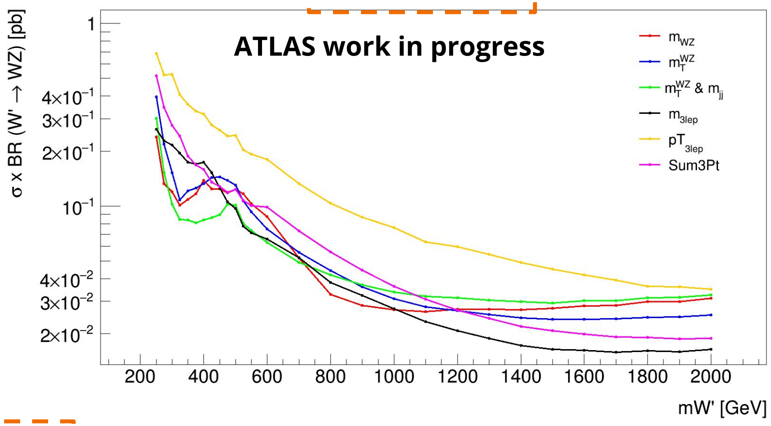


10. Comparison plots for limits with alternative variables (observed)

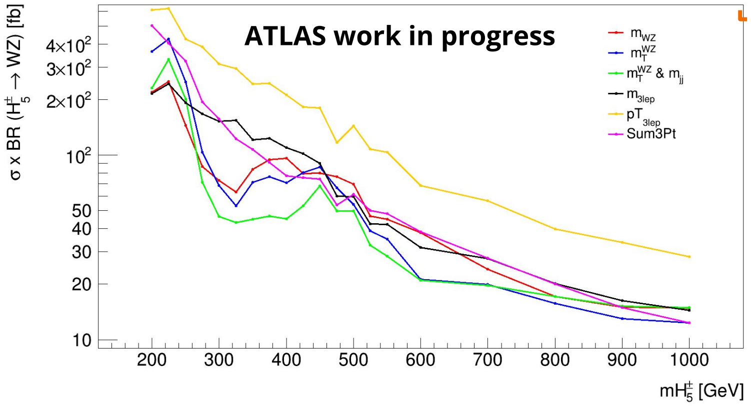
Drell-Yan

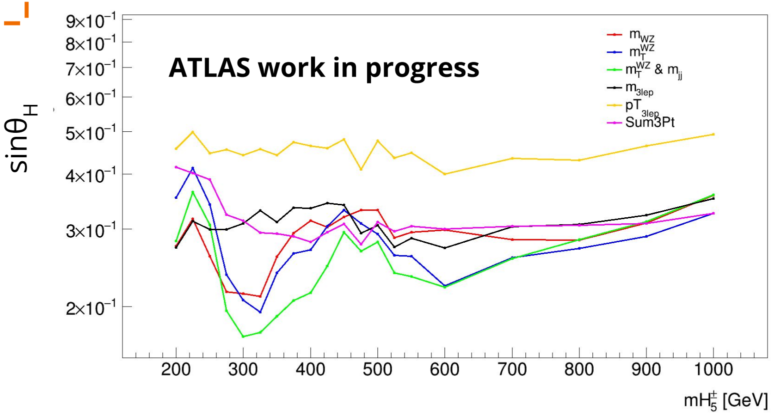


VBF HVT



VBF GM (H5)



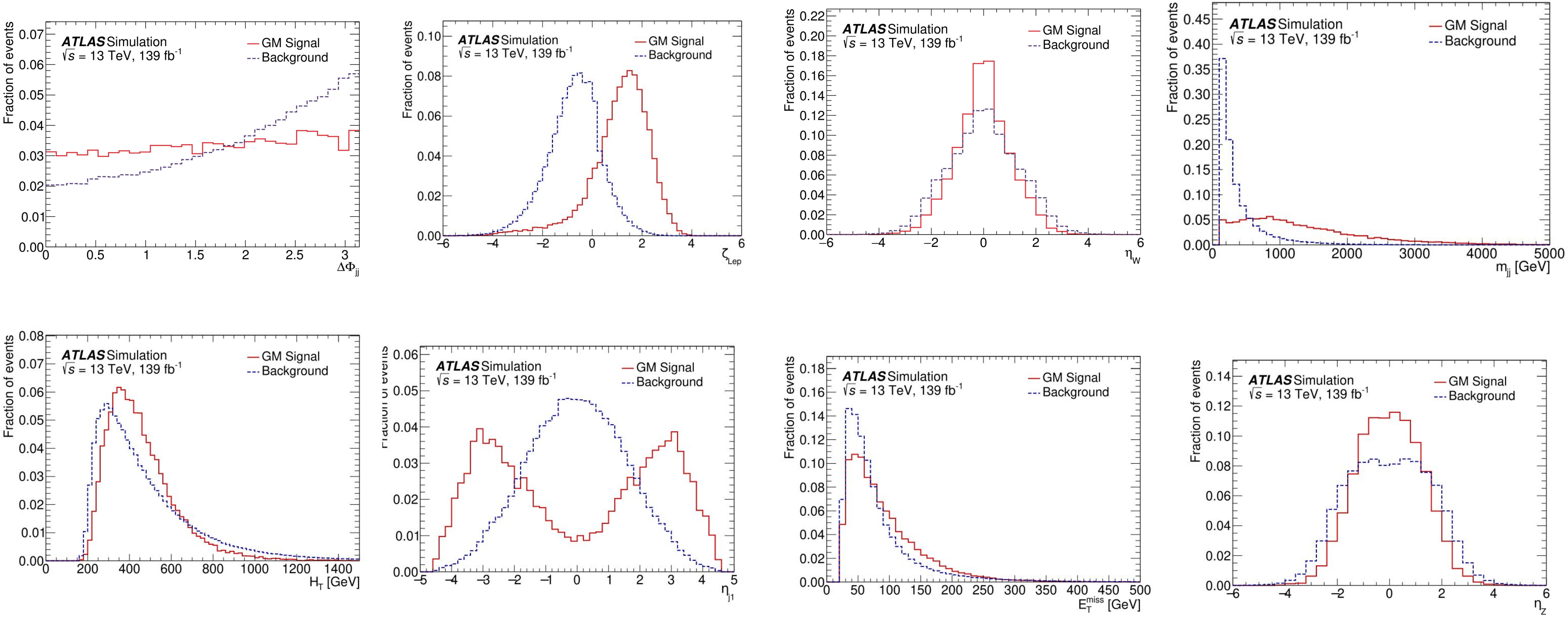


Conclusions

- ❖ Search for resonant WZ -> lvll (electron/muons) production in pp collisions by ATLAS at sqrt(s) = 13TeV with an integrated luminosity 139fb-1 => Drell-Yan & VBF processes
- ❖ No significant deviation from SM is observed
- ❖ Limits are set on the production xsection times branching ratio as a function of resonance mass
- ❖ Some alternative variables (mTWZ, mTWZ&mjj, m3lep,Sum3pt) seem to produce stricter limits for specific mass ranges (work in progress)

Backup slides

5. Signal Optimization
ANN training variables



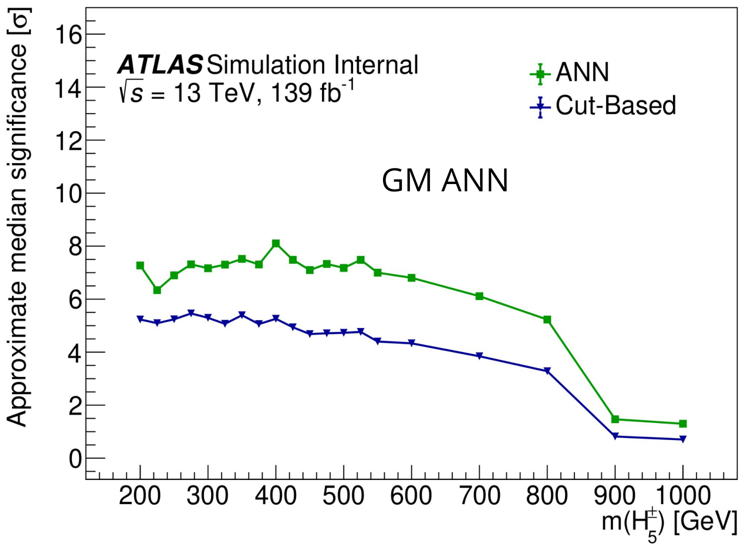
Red curve : distribution corresponding to summed mass points in GM signal simulation
Blue curve : SM WZ background

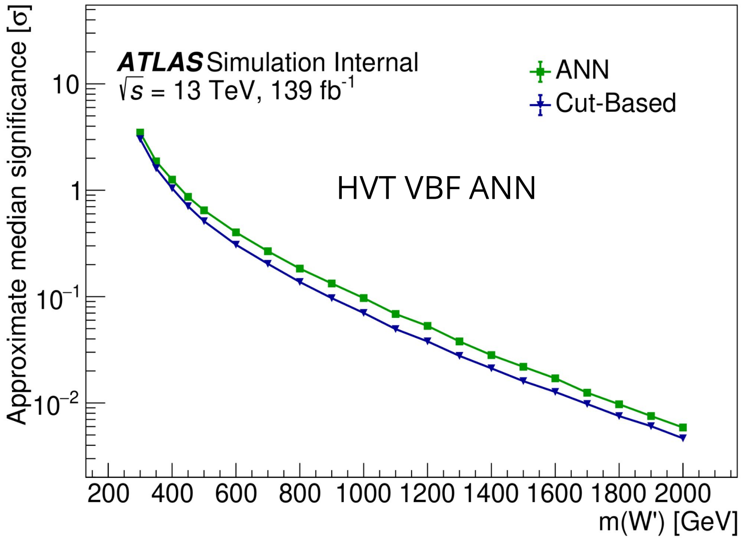
5. Signal Optimization
Artificial Neural Network (ANN) VBF selection

centrality = min{ [min(η_{l1} , η_{l2} , η_{l3}) − min(η_{j1} , η_{j2})], [max(η_{j1} , η_{j2})− max(η_{l1} , η_{l2} , η_{l3})] }

- After the training, the ntuples are "decorated" with the ANN output of each event.
- ANN output = 0.82

Measurement of the smaller pseudorapidity difference between the Most forward jet + lepton, in either hemisphere



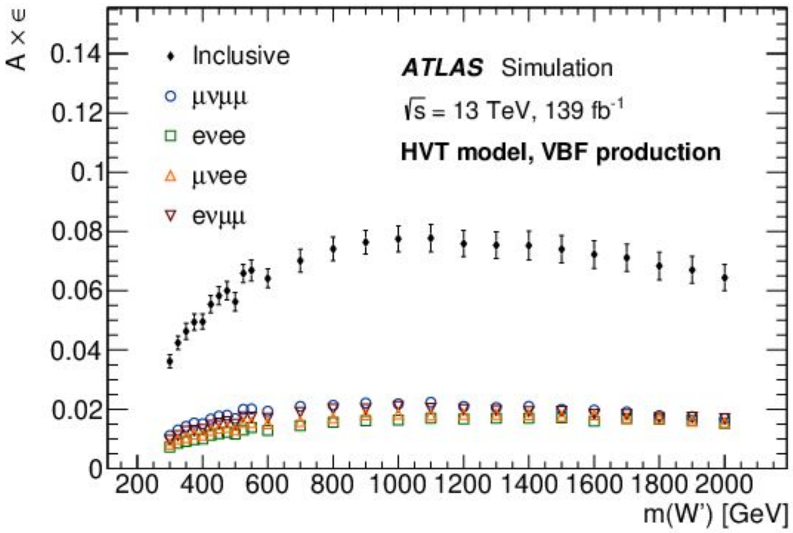


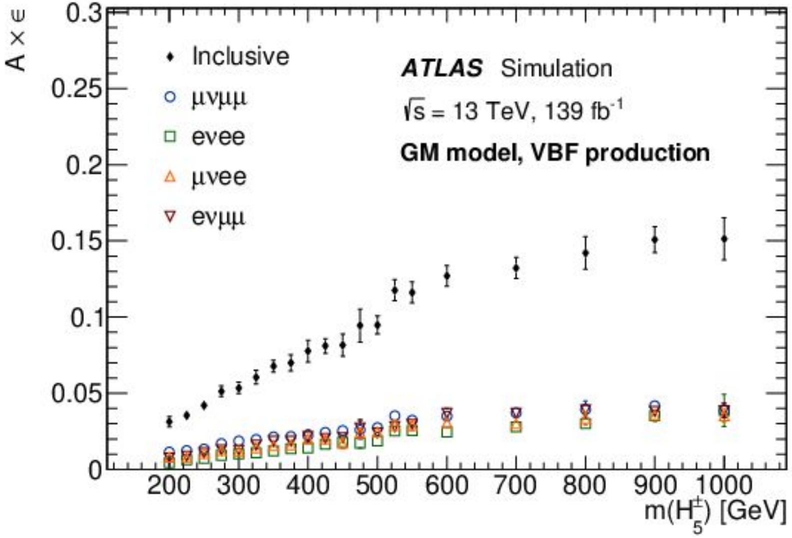
> **85**% drop in SM background events when comparing to VBF cut-based selection while maximum 30% signal loss

~ **70**% drop in SM background events and maximum 50% for the lowest mass point

5. Signal Optimization

Cutbased VBF selection

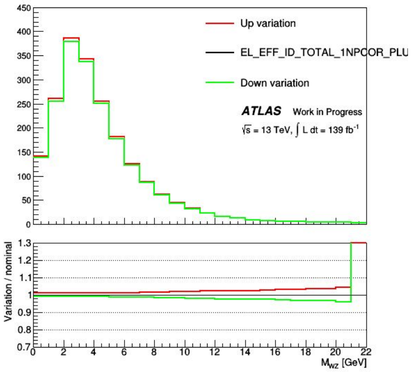




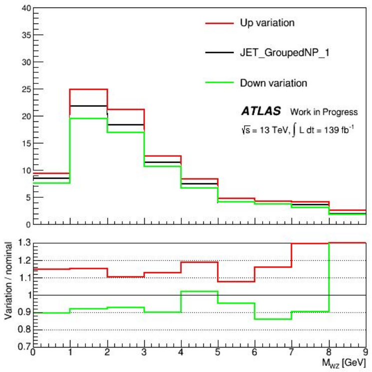
7. Systematic Uncertainties

- Complete set of objects uncertainties included :
  - Electron systematics (important in qqF)
  - Muon systematics (important in qqF)
  - Missing Et systematics
  - PRW systematics (important in qqF and VBF fits)
  - Jet systematics (using R4_SR_Scenario1_SimpleJER → will update to GlobalReduction_SimpleJER)
  - Flavor tagging systematics
  - Matrix method systematics
- Shapes are smoothed for the fit

qqF: Electron ID efficiency



VBF HVT: JET calibration uncertainties



electron systematics

EG_RESOLUTION_ALL	0.01074%
EG_SCALE_AF2	0.00000%
EG_SCALE_ALL	0.17909%
EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR	1.03462%
EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR	0.13293%
EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR	0.17624%

missing Et systematics

MET_SoftTrk_ResoPara	0.36243%
MET_SoftTrk_ResoPerp	0.29816%
MET_SoftTrk_ScaleDown	0.36701%

PRW systematics

PRW_DATASF	1.48271%

muon systematics

MUON_EFF_ISO_STAT	0.03322%
MUON_EFF_ISO_SYS	0.42996%
MUON_EFF_RECO_STAT	0.14751%
MUON_EFF_RECO_STAT_LOWPT	0.00000%
MUON_EFF_RECO_SYS	0.56604%
MUON_EFF_RECO_SYS_LOWPT	0.00000%
MUON_EFF_TTVA_STAT	0.04483%
MUON_EFF_TTVA_SYS	0.05624%
MUON_ID	0.02327%
MUON_MS	0.01655%
MUON_SAGITTA_RESBIAS	0.00642%
MUON_SAGITTA_RHO	0.00662%
MUON_SCALE	0.24776%

jet systematics

JET_EtaIntercalibration_NonClosure_highE	0.00001%
JET_EtaIntercalibration_NonClosure_negEta	0.00631%
JET_EtaIntercalibration_NonClosure_posEta	0.00319%
JET_Flavor_Response	0.13921%
JET_GroupedNP_1	0.23703%
JET_GroupedNP_2	0.22260%
JET_GroupedNP_3	0.01573%
JET_JER_EffectiveNP_1	0.00001%
JET_JER_EffectiveNP_2	0.00000%
JET_JER_EffectiveNP_3	0.00001%
JET_JER_EffectiveNP_4	0.00000%
JET_JER_EffectiveNP_5	0.00000%
JET_JER_EffectiveNP_6	0.00000%
JET_JER_EffectiveNP_7restTerm	0.00001%
JET_JvtEfficiency	0.07487%
JET_fJvtEfficiency	0.31240%

(results here are at the level of the WZ inclusive Validation region)

flavor tagging systematics

FT_EFF_Eigen_B_0	0.02674%
FT_EFF_Eigen_B_1	0.00604%
FT_EFF_Eigen_B_2	0.00434%
FT_EFF_Eigen_B_3	0.00158%
FT_EFF_Eigen_B_4	0.00014%
FT_EFF_Eigen_B_5	0.00002%
FT_EFF_Eigen_B_6	0.00002%
FT_EFF_Eigen_B_7	0.00000%
FT_EFF_Eigen_B_8	0.00000%
FT_EFF_Eigen_C_0	0.04878%
FT_EFF_Eigen_C_1	0.00381%
FT_EFF_Eigen_C_2	0.00318%
FT_EFF_Eigen_C_3	0.00048%
FT_EFF_Eigen_Light_0	0.04676%
FT_EFF_Eigen_Light_1	0.00179%
FT_EFF_Eigen_Light_2	0.00492%
FT_EFF_Eigen_Light_3	0.00036%
FT_EFF_extrapolation	0.00336%
FT_EFF_extrapolation_from_charm	0.01013%

8. Theoretical Uncertainties

On Signals

- PDF and scale uncertainties calculated for each mass model and signal / control region
  - **qqF / vbf HVT pdf envelope**: standard deviation of 100 MC replicas of NNPDF (nominal))and comparison with CT14 and MMHT
  - **GM pdf envelope**: standard deviation of 100 MC replicas
  - **Renormalization & factorization Uncertainties * :** using 7 point variations a combining them using PMG recommendations

W±Z QCD

Pdf unc. Drell-Yan/ VBF SR : ~5 %

Scale unc. In Drell-Yan (VBF) SR : ~ 15 % (~20 %)

PS +Mod. Unc. in Drell-Yan/VBF SR : up to 5 %

W±Z EWK

Pdf unc. Drell-Yan/ VBF SR : ~10 %

Scale unc. In Drell-Yan / VBF SR : ~ 5%

PS Unc. in Drell-Yan/VBF SR : up to 5 %

Other SM bkg

20 % for VVV, 13% for ttV

ZZ : pdf ~ 10 %

scale ~ 15/25 %

DSID	mass [GeV]	pdf (%)	scale (%)
502511	225	± 24.30	± 12.99
502512	275	± 24.24	± 13.15
502513	325	± 24.66	± 13.72
502514	375	± 26.75	± 13.46
502515	425	± 25.74	± 13.83
502516	475	± 24.99	± 14.17
502517	525	± 25.94	± 13.63
502518	550	± 26.27	± 13.63
502519	600	± 25.85	± 13.80
502520	700	± 26.59	± 14.04
502521	800	± 26.60	± 14.58
502522	900	± 27.21	± 14.66
502523	1000	± 27.75	± 15.20

VBF GM

mass [GeV]	pdf (%)	scale (%)
250	± 13.35	± 7.31
300	± 13.41	± 7.72
350	± 13.51	± 8.02
400	± 13.68	± 8.44
450	± 13.78	± 8.72
500	± 13.75	± 9.11
600	± 13.82	± 9.8
700	± 13.83	± 10.58
800	± 13.89	± 11.23
900	± 13.98	± 11.81
1000	± 13.86	± 12.44
1100	± 13.95	± 13.1
1200	± 14.07	± 13.72
1300	± 14.06	± 14.24
1400	± 14.06	± 14.76
1500	± 14.01	± 15.37
1600	± 14.12	± 15.87
1700	± 14.08	± 16.36
1800	± 14.24	± 16.91
1900	± 14.13	± 17.39
2000	± 14.31	± 17.84

VBF hvt

mass [GeV]	pdf (%)	scale (%)
250	± 10.39	± 3.96
300	± 10.45	± 3.17
400	± 10.18	± 1.50
500	± 9.94	± 0.99
600	± 9.75	± 1.63
700	± 9.70	± 2.33
800	± 9.98	± 2.95
900	± 10.56	± 3.53
1000	± 11.09	± 4.06
1100	± 11.73	± 4.57
1200	± 12.36	± 5.03
1300	± 13.06	± 5.45
1400	± 13.76	± 5.84
1500	± 14.45	± 6.22
1600	± 15.12	± 6.57
1700	± 15.72	± 6.90
1800	± 16.33	± 7.20
1900	± 16.90	± 7.51
2000	± 17.39	± 7.79
2200	± 18.29	± 8.32
2400	± 19.03	± 8.85
2600	± 19.63	± 9.34
2800	± 20.22	± 9.82
3000	± 20.50	± 10.28
3500	± 21.21	± 11.40
4000	± 21.65	± 12.41
4500	± 23.60	± 13.45
5000	± 25.03	± 13.94

qq hvt

8. Theoretical Uncertainties

b. On SM WZ background

(i) Cut-Based

- Calculated at reco level for both qqF/ VBF SRs and CRs

$W^{\pm}Z$ QCD theory Uncertainties
➢ Nominal: Sherpa 2.2.2 used as nominal generator (364253) 0,1j@NLO, 2,3j@LO + PS
➢ Alternative: Madgraph+Pythia8 (361293) 0,1j@NLO, FxFx

Sherpa QCD pdf envelope: standard deviation of NNPDF100 MC replicas, and comparison
of NNPDF30nloas0118 (nominal) with CT14nnlo and MMHT2014nlo68cl sets
Madgraph QCD pdf envelope: standard deviation of NNPDF100 MC replicas

QCD Scale Uncertainties : using 7 point variations
Compare different variations with nominal $\mu_R = \mu_F = 1$ and creating the envelope with maximum downwards & upwards deviations

Pdf unc. in qqF/ VBF SR : ~5 %

Scale unc. in qqF SR : ~ 15 %
Scale unc. VBF SR ~20 %

$W^{\pm}Z$ EWK theory Uncertainties
➢ Nominal: Madgraph+Pythia8 (364739-364742) LO
➢ Alternative: none
Madgraph EWK pdf envelope: standard deviation of NNPDF100 MC replicas &
Asymmetric Hessian Errors from the 56 eigenvectors of CT14nnlo set

EWK Scale Uncertainties : using 8 point variations and combining them using PMG recom.
Compare different variations with nominal $\mu_R = \mu_F = 1$ and creating the envelope by getting maximum downwards & upwards deviations

Pdf unc. in qqF/ VBF SR : ~10 %

Scale unc. in qqF/ VBF SR : ~ 5%

Parton Shower Unc.
Rel. uncertainty -> difference between the mass distributions of Madgraph+Py8 and Sherpa for QCD (Madgraph+Py8/ Madgraph+Herwig for EWK) and dividing by a factor of 2

PS +Mod. Unc. in qqF SR : up to 5 %
PS +Mod. Unc. in VBF SR : up to 5 %

PS Unc. in qqF SR : up to 5 %
PS Unc. in VBF SR : up to 4 %

8. Theoretical Uncertainties

b. On SM WZ background

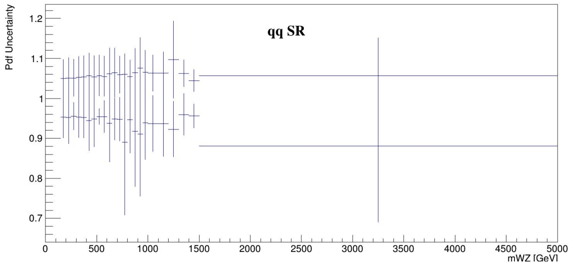
(ii) ANN

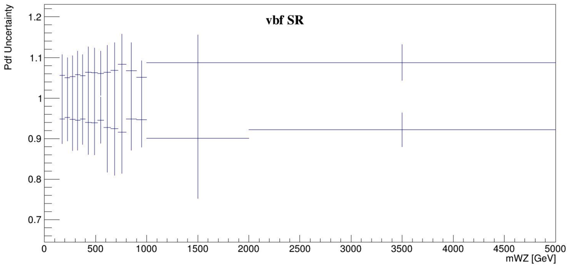
QCD	EWK
Pdf unc. in ann SR : ~5 %	Pdf unc. in ann SR : ~10 %
Scale unc. in ann SR : ~ 20 %	Scale unc. in ann SR : ~ 15 %
PS unc. in ann SR : up to 5 %	PS unc. in ann SR : up to 5 %

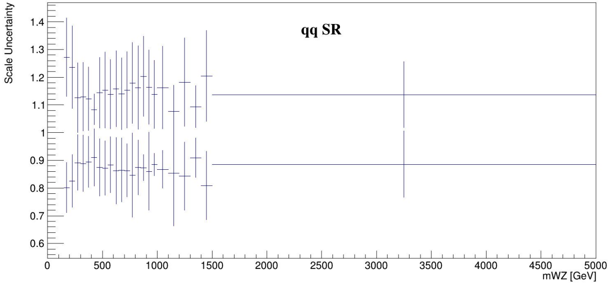
- Calculated at reco level for both VBF SRs and CRs

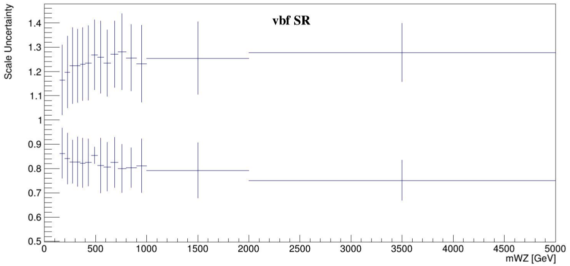
c. On other SM backgrounds

- 20 % for VVV, 13% for ttV
- For ZZ : pdf and scale unc. envelopes







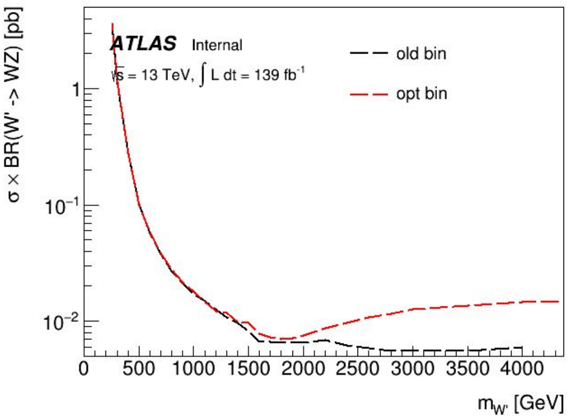


9. Statistical Treatment

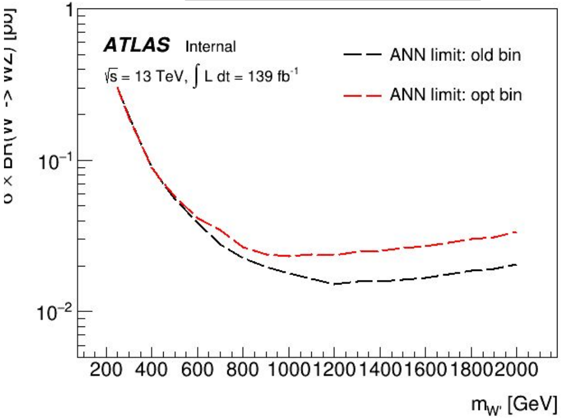
b. Binning Optimization

1. **Defined a simple algorithm to define which binning configurations to test:**
   a. Minimum total background per bin (default = 10, 5 for high mass region): For the asymptotic approximation to work
   b. Maximum relative bkg MC uncertainty (default = 0.3): To avoid bins with large MC uncertainties
2. **Compare the limits extracted using stat only fit. Two possibilities tried:**
   a. Published binning, almost the same as the 36fb^{-1}
   b. Optimal binning, from the algorithm described previously

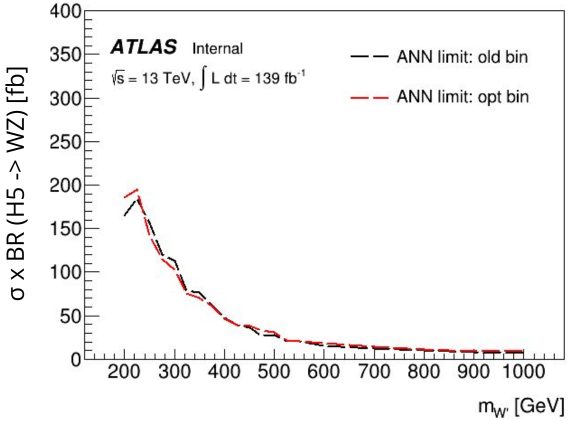
limits for qq HVT



limits for VBF HVT



limits for VBF GM

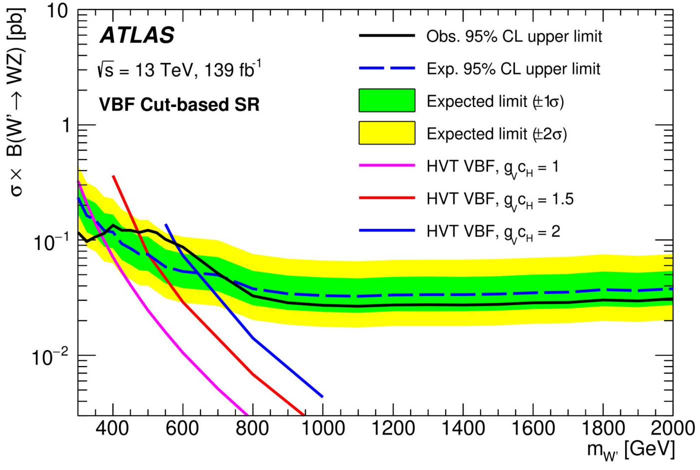


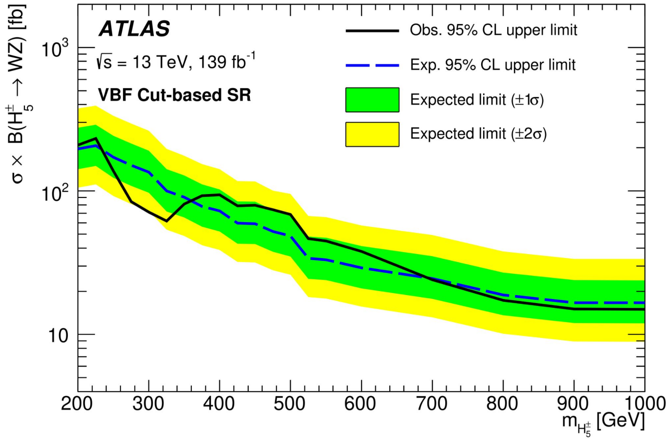
GM VBF ANN signal region (9 bins): [150,200,230,270,300,340,390,480,660,5000]
HVT VBF ANN signal region (9 bins): [150,200,250,300,350,400,450,520,650,5000]

mH5 [GeV]

HVT qqF signal region (22bins):[150,200,250,300,350,400,450,500,550,600,650,700,750,800,850,900,950,1010,1080,1160,1280,1480,5000]

Limits for mwz VBF cutbased





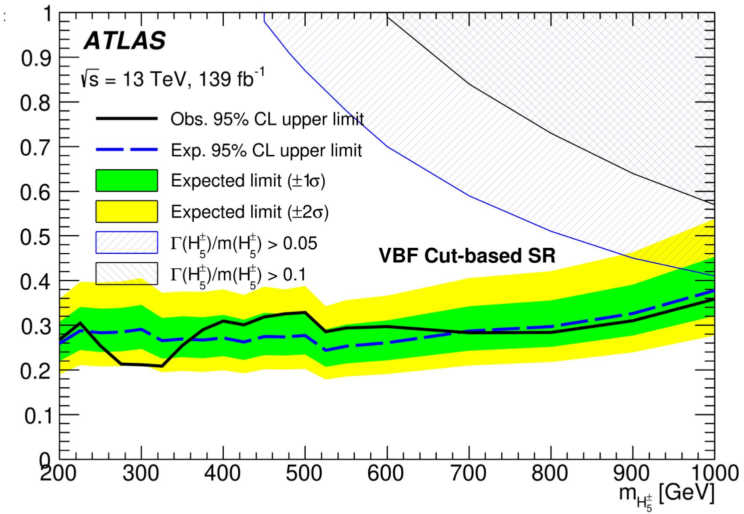
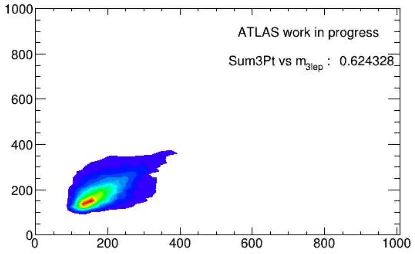
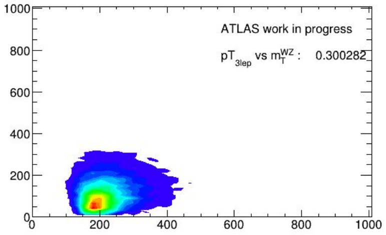


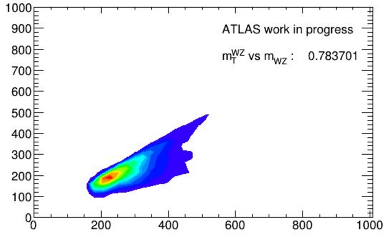
Table 4: Dominant relative uncertainties in the best-fit signal-strength parameter (μ) for a hypothetical HVT signal of mass $m(W') = 1\,100$ GeV in the Drell-Yan signal region and a GM signal of mass $m(H_5^{\pm}) = 375$ GeV in the VBF signal region. For this study, the production cross-section of the signals is set to the expected median upper limits at these two mass values. Uncertainties with smaller contributions are not included.

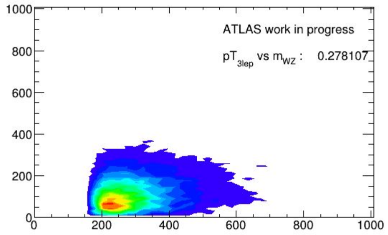
Source of uncertainty	$\Delta\mu/\mu$ [%]	
	Drell-Yan signal region $m(W') = 1100$ GeV	VBF signal region $m(H_5^{\pm}) = 375$ GeV
WZ-QCD+ZZ normalization	2	11
WZ background: parton shower	6	1
WZ background: scale, PDF	5	8
Fake/non-prompt background	3	1
ZZ background: scale, PDF	0.2	<0.1
$VVV + t\bar{t}V$ modelling	3	1
Electron identification	6	3
Muon identification	1	4
Jet uncertainty	0.8	16
Flavour tagging	0	1
Missing transverse energy	0.2	0.5
MC statistical uncertainty	10	5
Luminosity	2	8
Pileup	0.1	8
Total systematic uncertainty	16	22
Data statistical uncertainty	54	55
Total	56	59

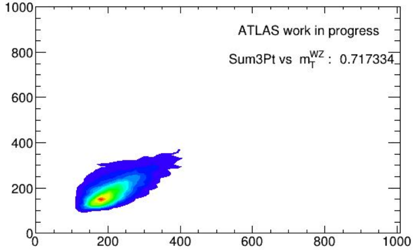
10. Alternative variables correlation plots

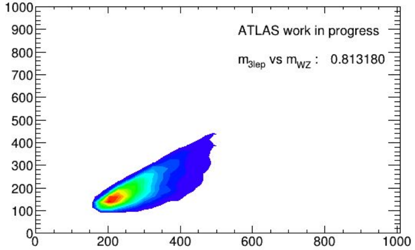


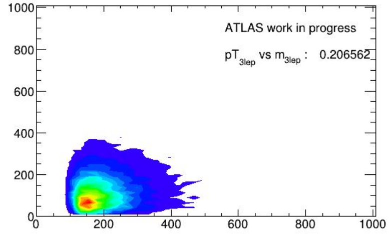


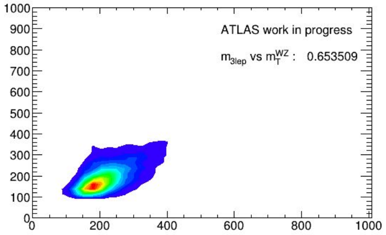


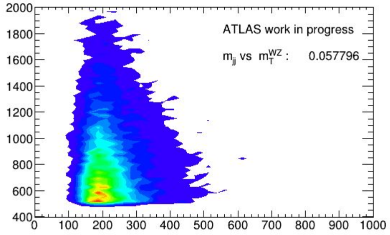


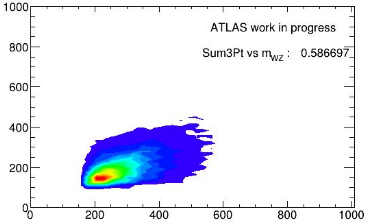












Binning for alternative variables

Variable	Binning
m_{WZ}	vbfHVT=[0,150,200,250,300,350,400,460,520,650,5000] vbfGM=[0,150,200,230,270,310,350,390,480,660,5000] Drell-Yan=[0,150,200,250,300,350,400,450,500,550,600,650,700,750,800,850,900,950, 1010,1080,1160,1280,1480,5000]
m_T^{WZ}	vbf=[0, 120, 150, 170, 190, 210, 230, 250, 270, 290, 320, 350, 390, 440, 510, 640, 3000] Drell-Yan=[0, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 510, 540, 570, 610, 660, 720, 810, 1010, 3000]
m_{jj} & m_T^{WZ}	[500,1500] , medium m_T^{WZ}=[0, 130, 150, 170, 190, 210, 230, 250, 270, 300, 330, 370, 420, 490, 640,3000] [1500,∞] , high m_T^{WZ}=[0, 160, 200, 240, 300, 400, 3000]
m_{3lep}	vbf=[0, 110, 130, 150, 170, 190, 210, 230, 250, 270, 300, 330, 370, 410, 470, 560, 790, 3000] Drell-Yan=[0, 110, 130, 150, 170, 190, 210, 230, 250, 270, 290, 310, 330, 350, 370, 390, 420,450, 490, 540, 610, 730, 3000]
pT_{3lep}	vbf=[0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 230, 260, 300, 360, 480, 3000] Drell-Yan=[0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 330, 360, 400, 450, 530, 740, 3000]
$Sum3Pt$	vbf=[0, 120, 140, 160, 180, 200, 220, 240, 260, 280, 310, 340, 380, 430, 500, 660, 3000] Drell-Yan=[0, 130, 150, 170, 190, 210, 230, 250, 270, 290, 310, 330, 350, 370, 390, 410, 440, 470, 500, 540, 590, 660, 800,3000]

36 fb-1 Results