Search for heavy resonances decaying into *VH* in semi-leptonic final states with ATLAS

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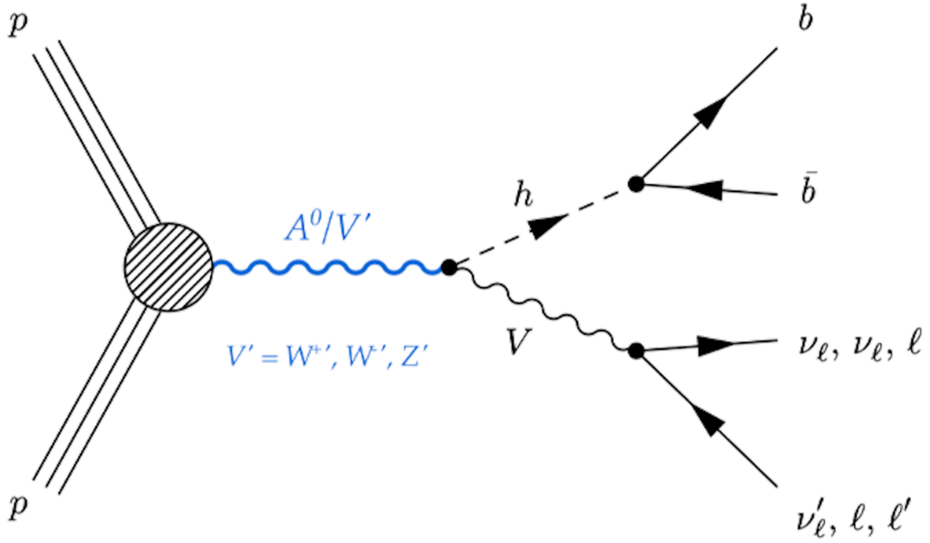
Outline

- ➢ Introduction
- ➢ Data and MC samples
- ➢ Event selection
- ➢ Background estimation
- ➢ Statistical analysis and results
- ➢ Summary



CONF Note

Introduction

Search for heavy resonances decaying into *ZH* or *WH*

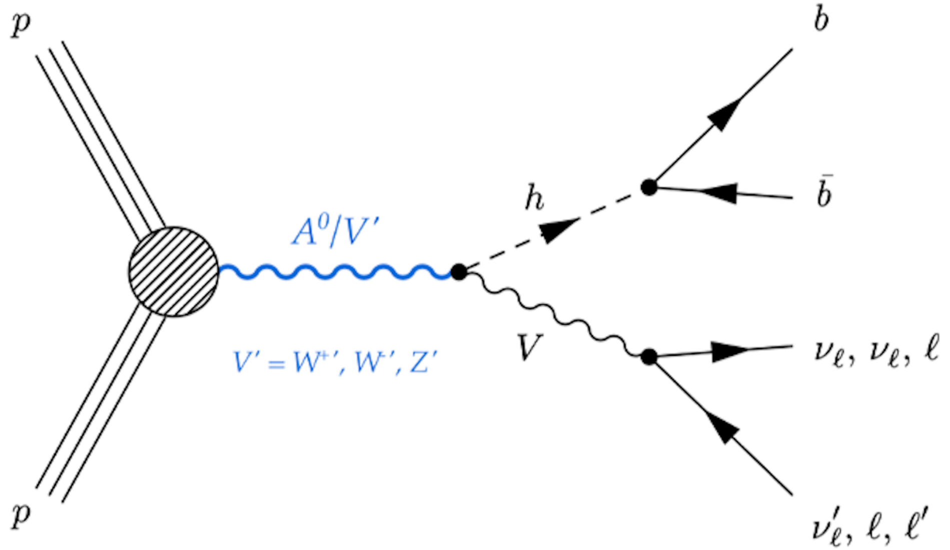
- Predicted by several BSM theories
- $H \rightarrow bb$ identified with observed SM Higgs boson (m_h=125GeV)

Two Higgs Doublet Model (2HDM)

- 5 Higgs bosons: H, h, $H^{\pm}$, A

Heavy Vector Triplet (HVT)

- Heavy vector bosons Z', W'
- Interpret of two benchmark models: Model A / Model B



Introduction

Three channels according to the number of leptons (*el* / *mu*)

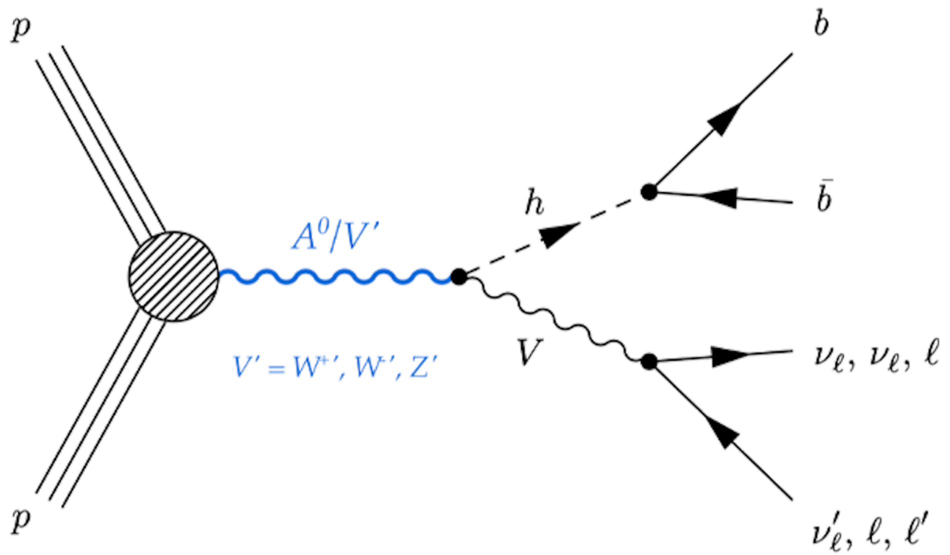
in the final state:

- 0-, 1- (HVT only) and 2- lepton channel

Two regimes for event categorization:

- resolved (two small-*R* jets)
- merged (one large-*R* jet)

"Priority Resolved SR" scheme was used



Data and MC samples

Full Run2 dataset collected by ATLAS used

Process	Generator	Prediction order of σ_{prod}
$W \to \ell\nu$, $Z \to \ell\ell$, $Z \to \nu\nu$	Sherpa 2.2.1	NNLO
$t\bar{t}$	Powheg + Pythia8	NNLO+NNLL
single top ($s/t/Wt$-channel)	Powheg + Pythia8	NLO
$t\bar{t} + h$	MG5_aMC@NLO + Pythia8	NLO (QCD) and NLO (EW)
$t\bar{t} + V$	MG5_aMC@NLO + Pythia8	NLO
$qg/q\bar{q} \to VV \to \ell\ell/\ell\nu/\nu\nu + q\bar{q}$	Sherpa 2.2.1	NLO
$gg \to VV \to \ell\ell/\ell\nu/\nu\nu + q\bar{q}$	Sherpa 2.2.2	NLO
$qg/q\bar{q} \to \ell\ell\nu\nu$	Sherpa 2.2.2	NLO
$qq \to Wh \to \ell\nu + b\bar{b}$	Powheg + Pythia8	NNLO (QCD) and NLO (EW)
$qq \to Zh \to \ell\ell/\nu\nu + b\bar{b}$	Powheg + Pythia8	NNLO (QCD) and NLO (EW)
$gg \to Zh \to \ell\ell/\nu\nu + b\bar{b}$	Powheg + Pythia8	NLO+NLL

Event selection

<table>
<tr><th>Variable</th><th>Resolved</th><th>Merged</th></tr>
<tr><td colspan="3">Common selection</td></tr>
<tr><td>Number of jets</td><td>$\geq$2 small-R jets (0, 2-lep.)
2 or 3 $R = 0.4$ jets (1-lep.)</td><td>$\geq$1 large-R jet</td></tr>
<tr><td>Leading jet p_{T} [GeV]</td><td>> 45</td><td>> 250</td></tr>
<tr><td>m_H [GeV]</td><td>110–140 (0,1-lep.), 100–145 (2-lep.)</td><td>75–145</td></tr>
<tr><td colspan="3">0-lepton selection</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]</td><td>> 150</td><td>> 200</td></tr>
<tr><td>H_T [GeV]</td><td>> 150 (120^{*})</td><td>–</td></tr>
<tr><td>$\Delta\phi_{bb}$</td><td>$< 7\pi/9$</td><td>–</td></tr>
<tr><td>$p_{\mathrm{T}}^{\mathrm{mis}}$ [GeV]</td><td colspan="2">$> 30^{\ddagger}$</td></tr>
<tr><td>$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{mis}}, \vec{p}_{\mathrm{T}}^{\mathrm{mis}})$</td><td colspan="2">$< \pi/2$</td></tr>
<tr><td>$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{mis}}, H)$</td><td colspan="2">$> 2\pi/3$</td></tr>
<tr><td>$\min\left[\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, R = 0.4\mathrm{jet})\right]$</td><td colspan="2">$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)</td></tr>
<tr><td>$N_{\tau_{\mathrm{had}}}$</td><td colspan="2">0^{**}</td></tr>
<tr><td colspan="3">1-lepton selection</td></tr>
<tr><td>Leading lepton p_{T} [GeV]</td><td>> 27</td><td>> 27</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]</td><td>> 40 $(80^{\dagger})$</td><td>> 100</td></tr>
<tr><td>$p_{\mathrm{T},W}$ [GeV]</td><td>$> \max\left[150,\ 710 - (3.3 \times 10^{5}\ \mathrm{GeV})/m_{Vh}\right]$</td><td>$> \max\left[150,\ 394 \cdot \ln(m_{Vh}/(1\ \mathrm{GeV})) - 2350\right]$</td></tr>
<tr><td>$m_{\mathrm{T},W}$ [GeV]</td><td colspan="2">< 300</td></tr>
<tr><td colspan="3">2-lepton selection</td></tr>
<tr><td>Leading lepton p_{T} [GeV]</td><td>> 27</td><td>> 27</td></tr>
<tr><td>Sub-leading lepton p_{T} [GeV]</td><td>> 20</td><td>> 25</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [$\sqrt{\mathrm{GeV}}$]</td><td colspan="2">$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}/(1\ \mathrm{GeV})$</td></tr>
<tr><td>$p_{\mathrm{T},\ell\ell}$ [GeV]</td><td colspan="2">$> 20 + 9 \cdot \sqrt{m_{Vh}/(1\ \mathrm{GeV}) - 320}^{\dagger\dagger}$</td></tr>
<tr><td>$m_{\ell\ell}$ [GeV]</td><td colspan="2">$[\max[40\ \mathrm{GeV},\ 87 - 0.030 \cdot m_{Vh}/(1\ \mathrm{GeV})],\ 97 + 0.013 \cdot m_{Vh}/(1\ \mathrm{GeV})]$</td></tr>
</table>

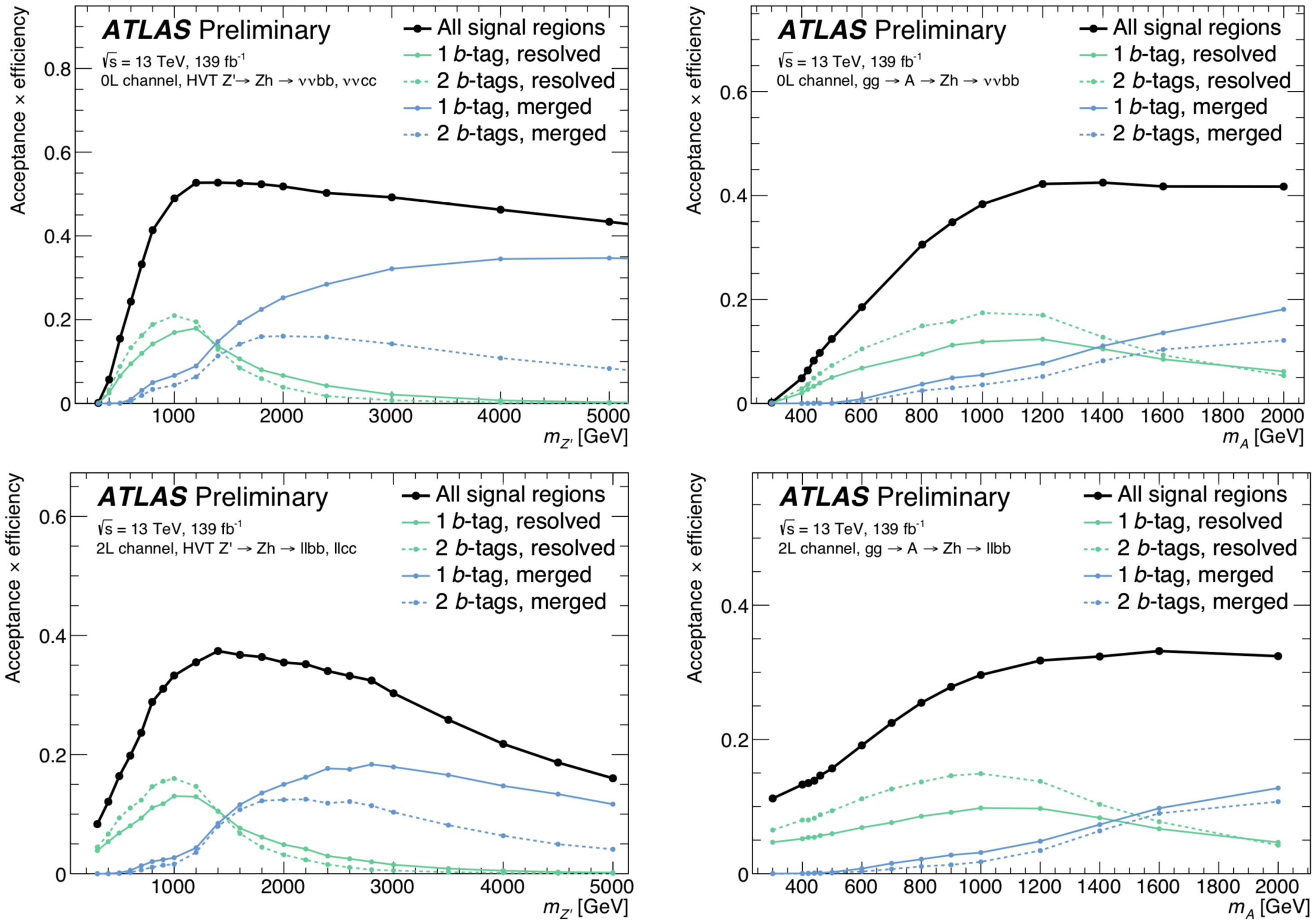
Event selections in 3 channels

Event selection

For 0-lepton, we used the transverse mass as the final discriminant:

$$m_{\mathrm{T},Vh} = \sqrt{\left(E_{h,\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{h,\mathrm{T}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$$

For 1- and 2- lepton, the final discriminant is the invariant mass of the *VH* system



Selection performance of signal in 0- and 2- lepton channel

QCD background in 1-lepton

Three different origins in the electron channel:

- At high momentum, non-prompt leptons from weak decays inside the jet parton shower dominate the multi-jet contribution
- At low momentum, the large number of light jets give rise to the possibility of jets mimicking the signature of electrons
- Photons from pion decays can fake the electron signature

The origin in the muon channel is dominated by non-prompt muons from weak decays of heavy-flavor quarks in the parton shower

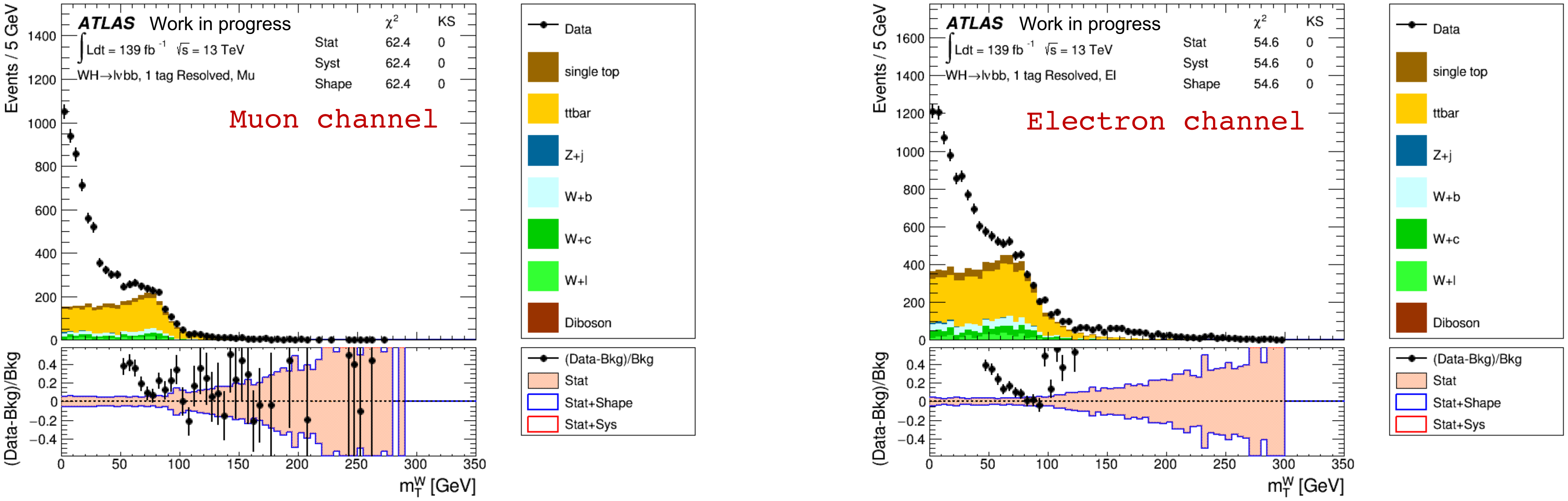
Data-driven template method

- The estimation is performed using data-driven method because MC samples suffer from limited statistics and difficult modeling
- Data-driven template method exploits the isolation of lepton to select a data sample enriched in multi-jet events
- Leptons from signal processes are expected to be well-isolated from hadronic activity while leptons in multi-jet events are located inside jets and thus not isolated from additional hadronic activity

	Criterion	isolated region	non-isolated region
Electron	ID	TightLH	TightLH
	Trk Isolation	ptvarcone20/pT < 0.06	ptvarcone20/pT < 0.06
	Calo Isolation	topoetcone20/pT < 0.06	topoetcone20/pT > 0.06
Muon	ID	TightLH	TightLH
	Trk Isolation	ptvarcone30/pT < 0.06	0.06 < ptvarcone30/pT < 0.15

Definition of isolated and non-isolated region

Multi-jet control region (MJCR)



mTW distributions in MJCR in muon and electron channel

- The MJ template is obtained by subtracting all EW backgrounds from data in MJCR, then fit the MJ template and EW background to data
- mTW was chosen as the discriminant variable
- Categories were separated into electron / muon channel and 1tag / 2tag region

Fit results and post-fit distributions

	Electron	Muon
MJ events	397.03 ± 476.44	3677.48 ± 435.72
MJ fraction	0.35% ± 0.42%	2.11% ± 0.25%

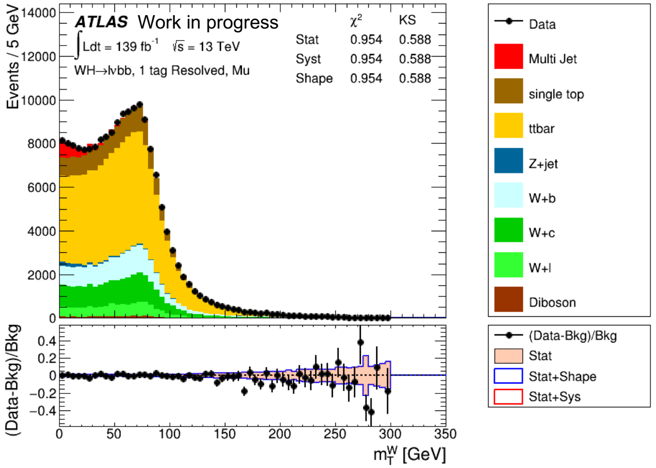
Fit 2 components to data:

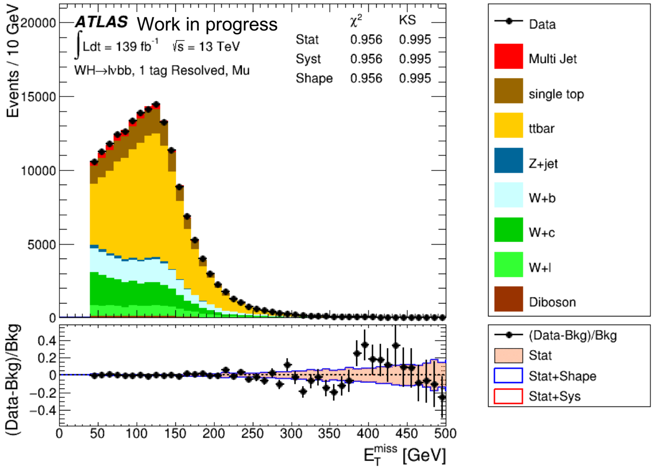
- ➢ MJ and sum of EW bkg
- ➢ both floating

Binning: 40 GeV / bin

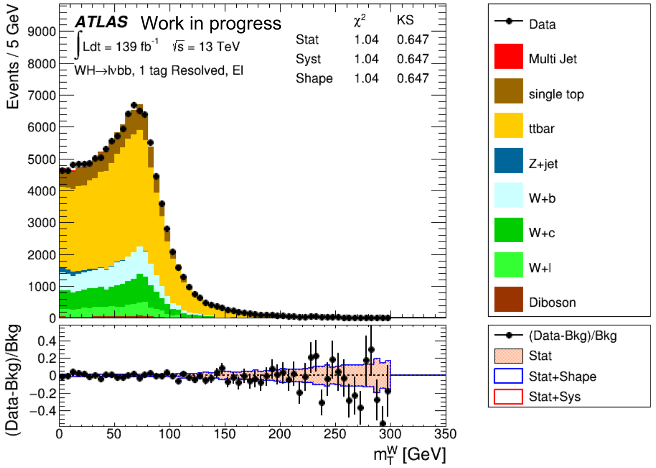
Fit range: 0 – 300 GeV

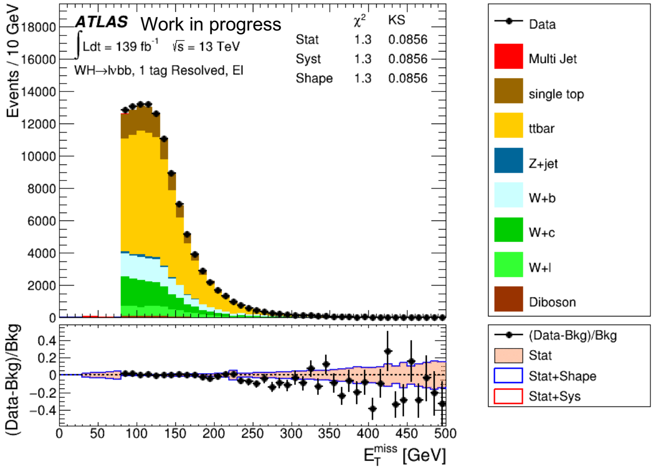
Stable fit has been gotten





Muon channel





Electron channel

Statistical analysis

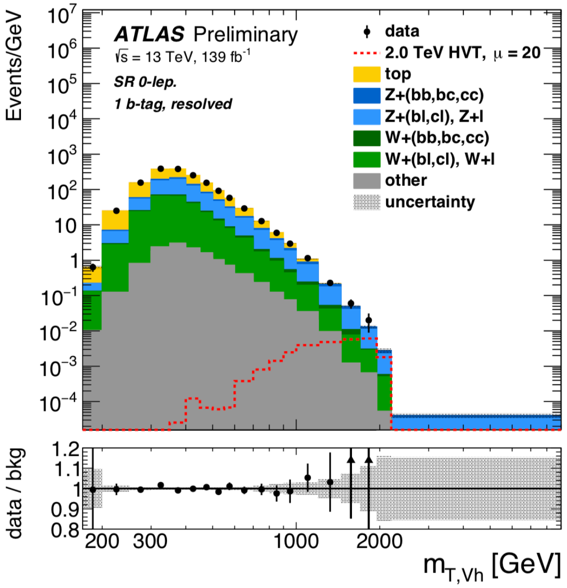
Fit	Channel	Resolved signal regions	Merged signal regions	Resolved control regions	Merged control regions
ggA, HVT	0-lepton	1, 2 b-tag	1, 2 b-tag	1, 2 b-tag m_{jj} sideband	1, 2 b-tag m_J sideband
	2-lepton	1, 2 b-tag	1, 2 b-tag	1+2 b-tag $e\mu$	–

- Control / signal regions and event yields for 0- and 2-lepton channel
- Statistical and systematic uncertainties are combined
- The uncertainties in the individual background are larger than the total due to correlations

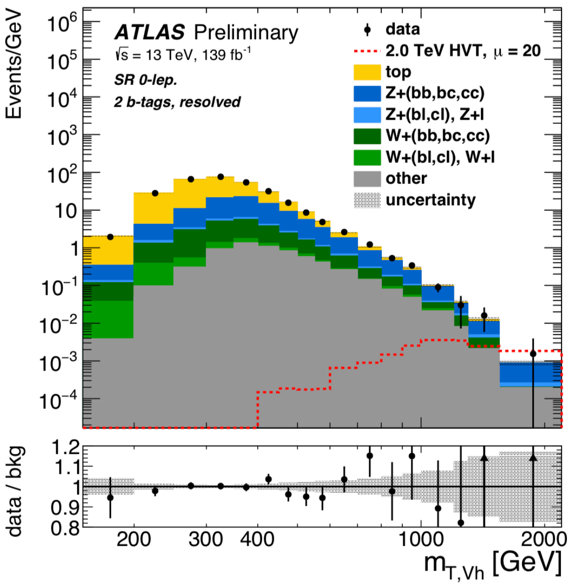
	Resolved		Merged	
0-lepton	1 b-tag	2 b-tag	1 b-tag	2 b-tag
Top	38000 ± 500	9700 ± 110	1440 ± 80	55.9 ± 2.8
Diboson	420 ± 40	62 ± 5	252 ± 30	69 ± 8
Zl	1950 ± 130	7.6 ± 1.6	453 ± 40	0.9 ± 0.2
Z+hl	23100 ± 900	149 ± 14	3210 ± 150	18.4 ± 1.7
Z+hf	4730 ± 160	3860 ± 110	810 ± 60	365 ± 18
Wl	2170 ± 160	19.2 ± 2.6	223 ± 33	0.2 ± 0.1
W+hl	9300 ± 1000	76 ± 7	760 ± 120	5.7 ± 1.1
W+hf	970 ± 50	720 ± 40	175 ± 26	68 ± 13
SM Vh	190 ± 20	252 ± 26	20.7 ± 2.8	12.7 ± 1.6
Total	80730 ± 180	14850 ± 70	7340 ± 60	596 ± 13
Data	80798	14839	7351	590
2-lepton	1 b-tag	2 b-tag	1 b-tag	2 b-tag
Top	7800 ± 40	5740 ± 60	34.3 ± 2.6	2.5 ± 0.3
Diboson	1820 ± 100	459 ± 29	115 ± 7	25.3 ± 1.7
Zl	9000 ± 700	17 ± 8	208 ± 15	0.5 ± 0.2
Z+hl	100700 ± 800	490 ± 28	724 ± 21	4.9 ± 0.3
Z+hf	23030 ± 300	17300 ± 110	225 ± 8	106 ± 4
Wl	0.8 ± 0.1	–	0.3 ± 0.0	–
W+hl	13 ± 1.8	0.2 ± 0.1	1.2 ± 0.2	–
W+hf	1.6 ± 0.5	1.0 ± 0.1	0.2 ± 0.0	0.1 ± 0.0
SM Vh	308 ± 14	367 ± 16	5.3 ± 0.3	2.7 ± 0.2
Total	142710 ± 260	24400 ± 100	1313 ± 16	142 ± 5
Data	142713	24379	1307	142

Resolved signal region

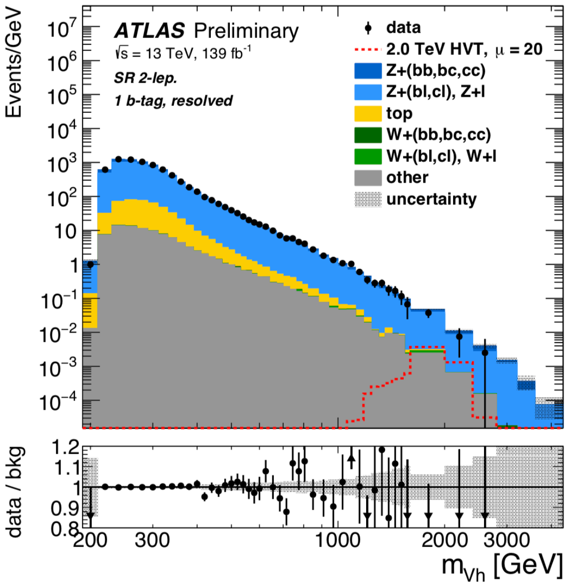
0lep 1tag



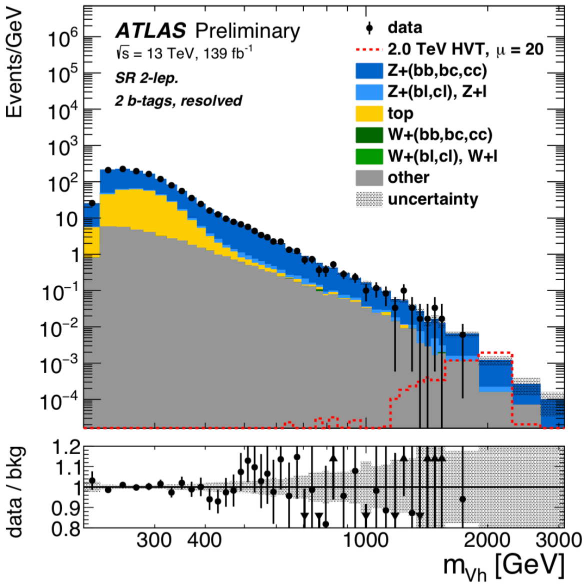
0lep 2tag



2lep 1tag



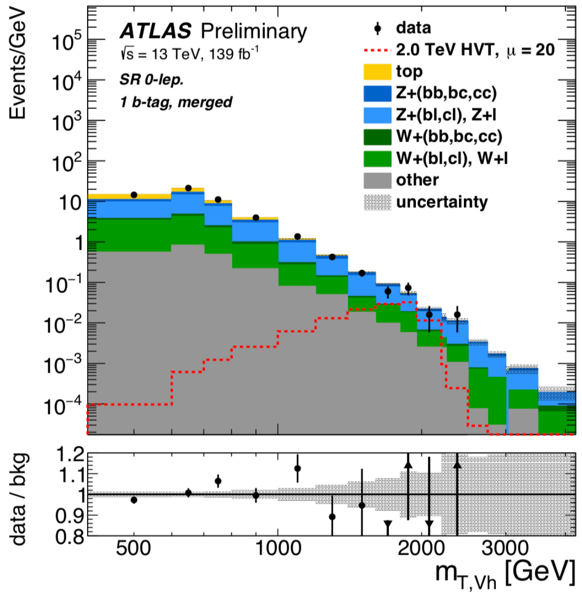
2lep 2tag



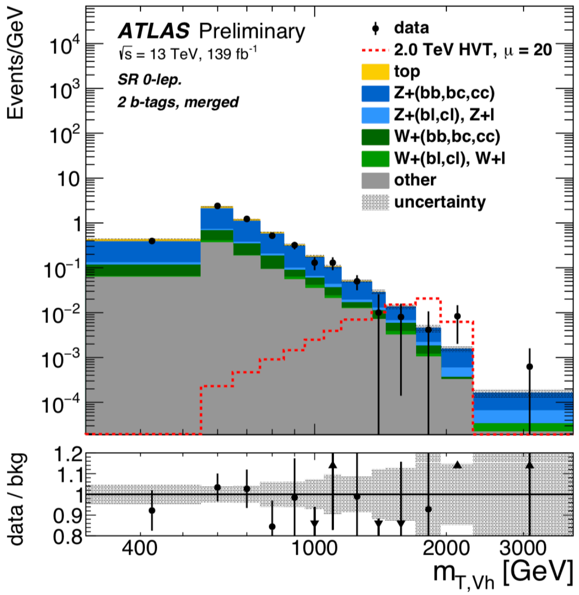
- Post-fit distributions for 0-lepton and 2-lepton in resolved signal regions
- The signal for HVT Model A with mass 2 TeV is shown as a dashed red line and normalized to 20 times
- Statistical and systematic uncertainties are considered

Merged signal region

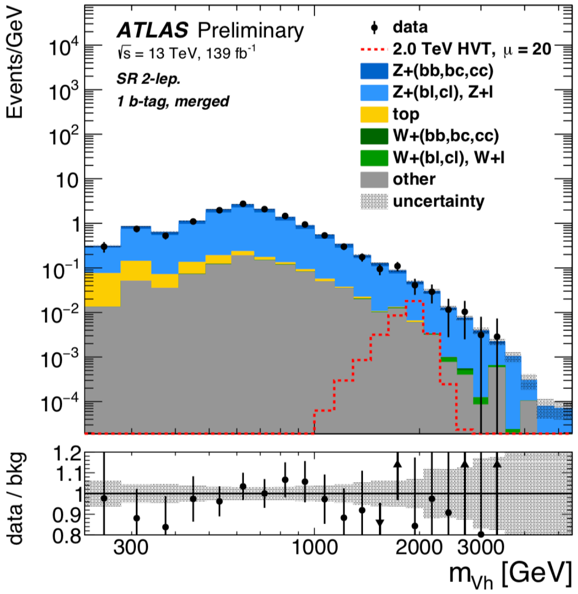
0lep 1tag



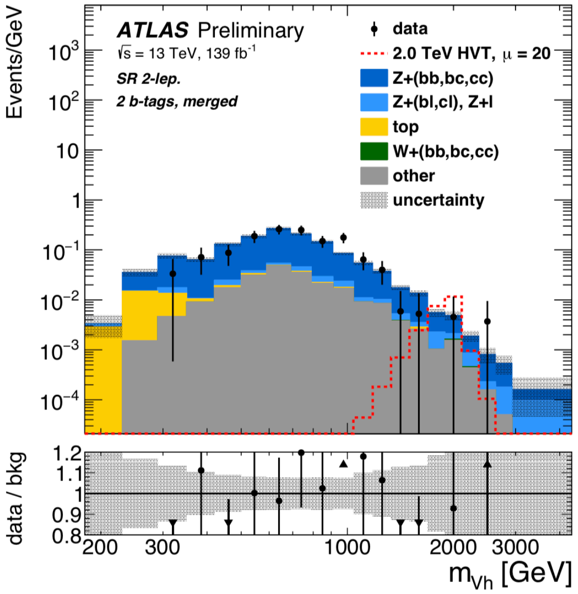
0lep 2tag



2lep 1tag

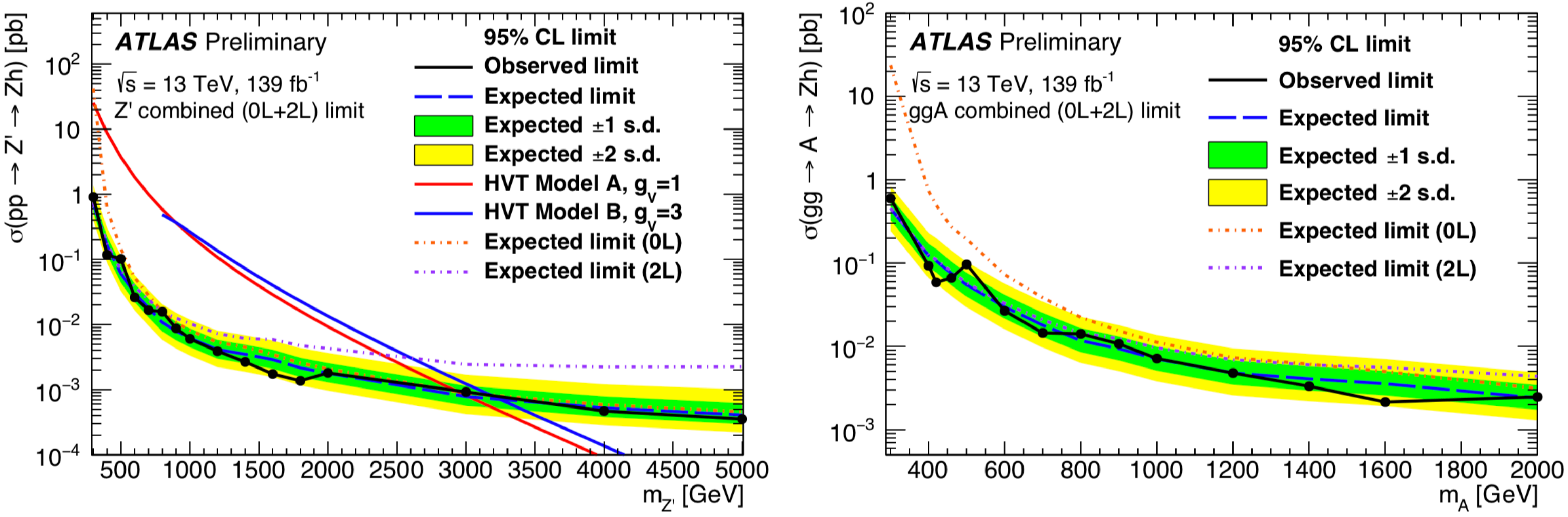


2lep 2tag



- Post-fit distributions for 0-lepton and 2-lepton in merged signal regions
- The signal for HVT Model A with mass 2 TeV is shown as a dashed red line and normalized to 20 times
- Statistical and systematic uncertainties are considered

Results



No significant excess observed above SM predictions. Upper limits set on the cross section

- Z' masses below 2.9 TeV excluded for HVT Model A and 3.2 TeV excluded for Model B

Summary

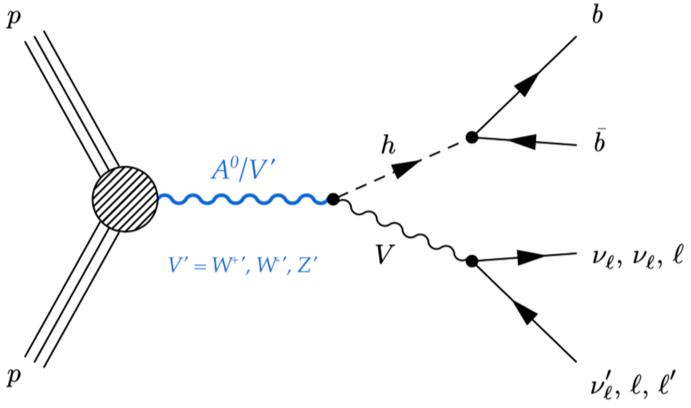
- Search for heavy vector boson *Z′* and CP-odd Higgs boson *A* in the semi-leptonic final states performed using full Run2 dataset collected by ATLAS

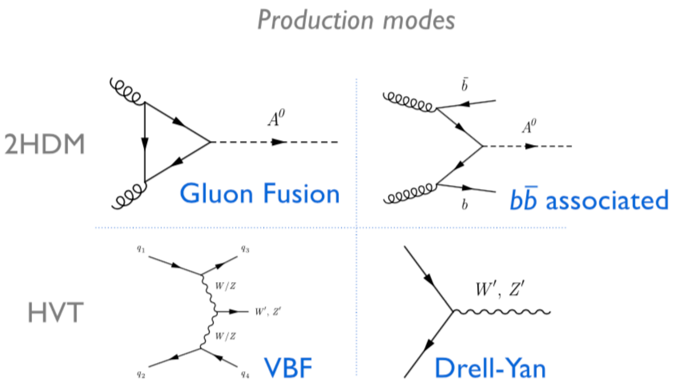
- No significant excess observed above the SM predictions. Upper limits set on production cross sections

- 1-lepton ($W' \to WH$, $W \to l\nu$, $H \to bb$) working towards unblinding approval

Back Up

Introduction





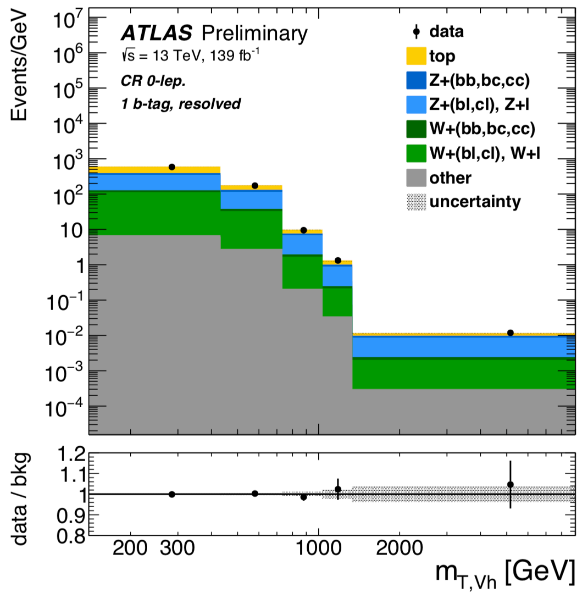
HVT search are interpreted in two benchmark models:

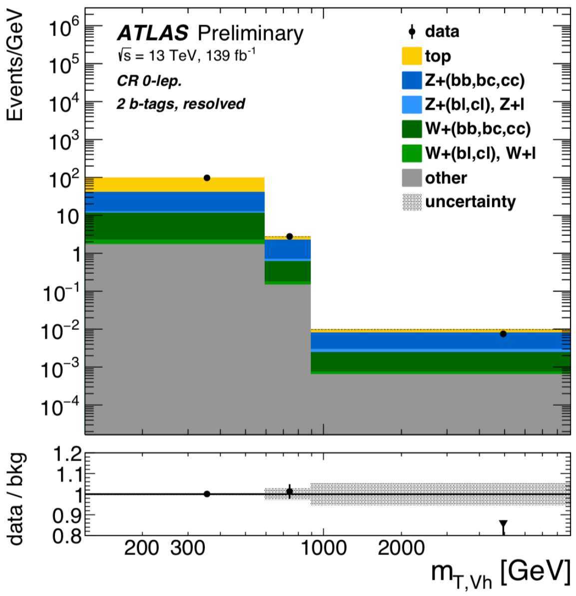
- Model A, the branching fractions to fermions and gauge bosons are comparable, as in some models with an extended gauge symmetry
- Model B, fermionic couplings are suppressed, as in strong dynamical models such as the minimal composite Higgs model

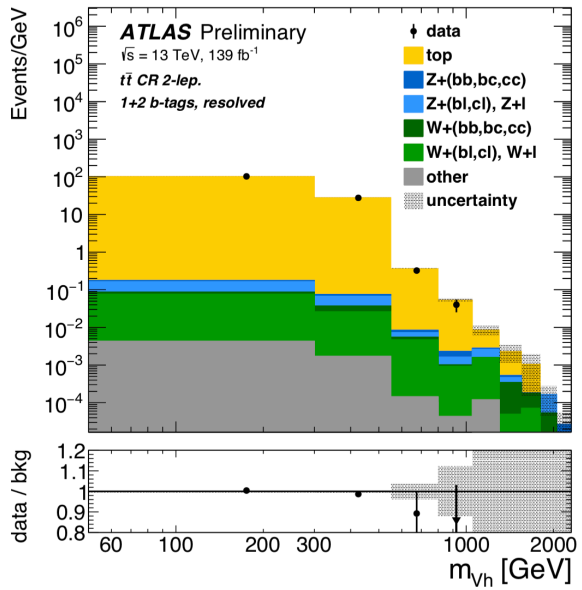
The search focuses on high resonance masses from 300 GeV up to 5 TeV

Search for A $\rightarrow$ Zh uses a smaller mass window from 300 GeV to 2 TeV, as in the models, Higgs potential becomes unstable for too large A boson masses

Resolved control region

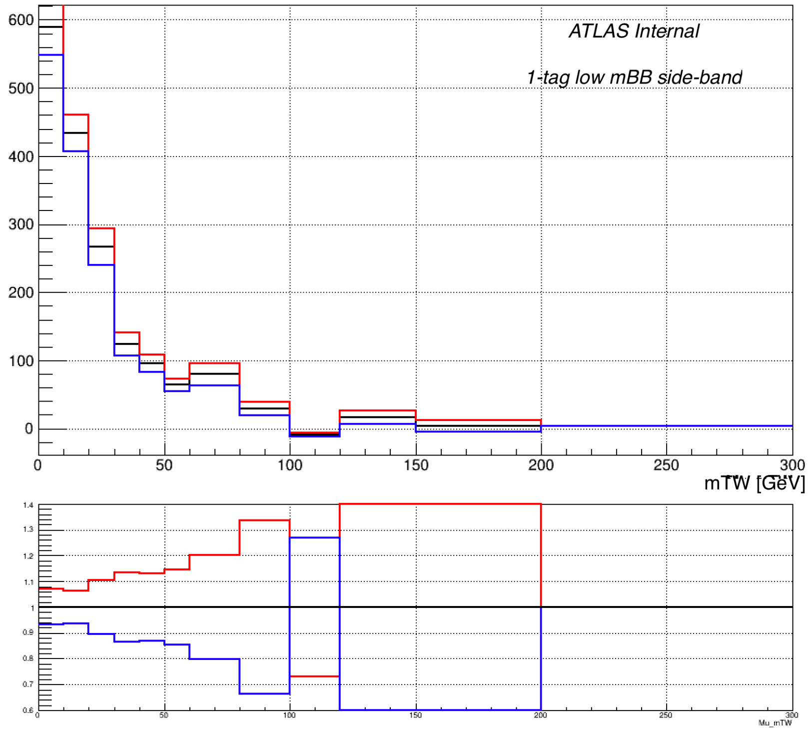


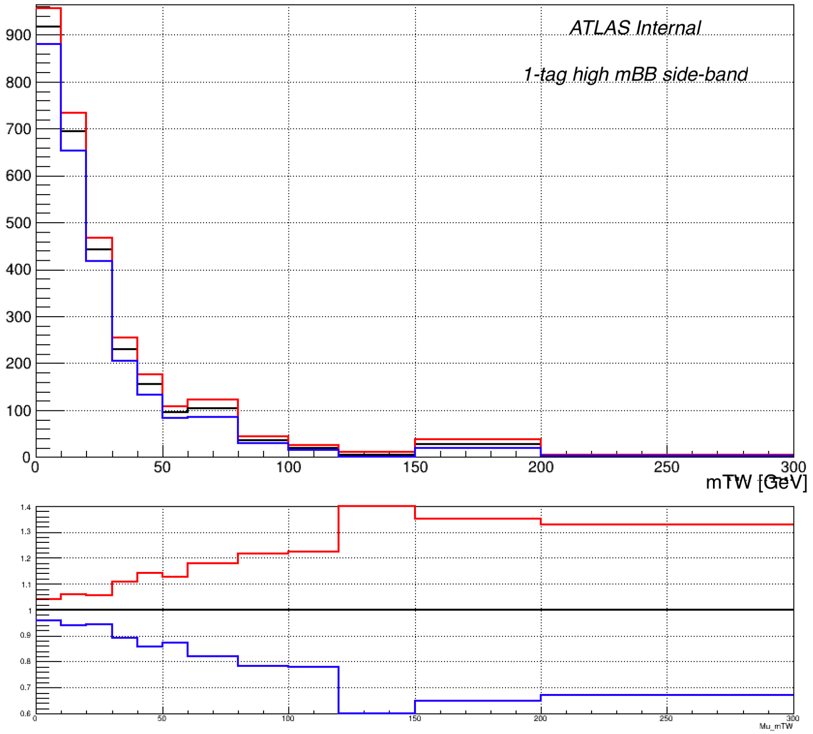




- Post-fit distributions of discriminant variable in mBB side-band for 0-lepton and ttbar CR for 2-lepton
- Wider bins are used here
- Both statistical and systematic uncertainties are included after the fit

Systematics of QCD estimation





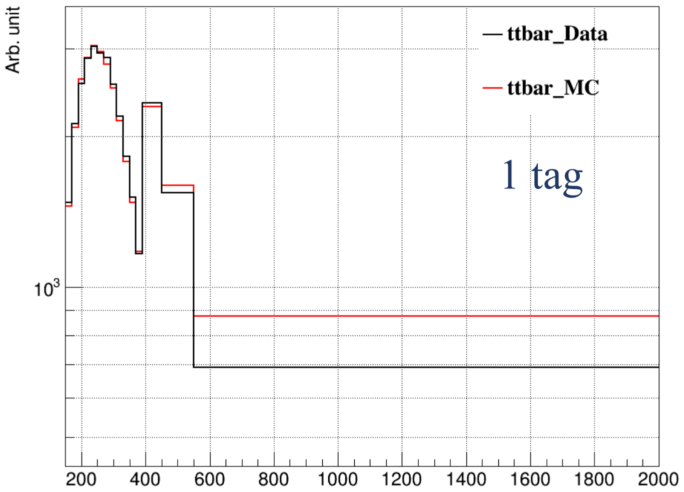
- Systematic uncertainties of QCD estimation were derived by varying the MJCR selections to re-extract the MJ template

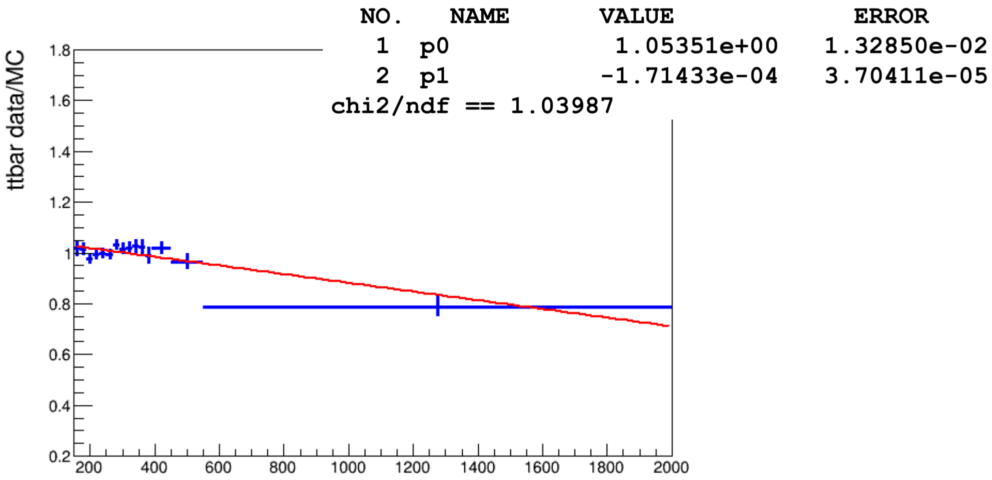
Systematic uncertainties

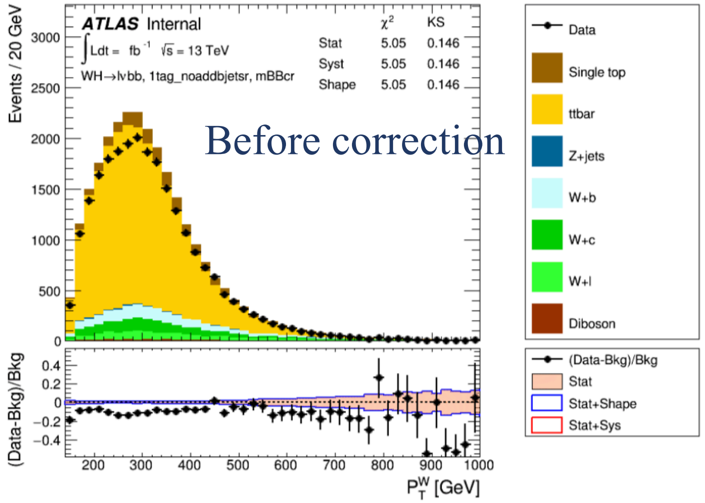
Process	Quantity/source	Value
Signal	acceptance	2-7%
	PS, ISR/FSR, PDF	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
$t\bar{t}$, single top	0-lep. norm.	float
	2-lep. norm.	float
	0-lep. resolved / merged	9–20%
	2-lep. resolved / merged	18%
	0-lep. m_{jj} SR / m_{jj} CR	2–12%
	2-lep. SR / $e\mu$ CR	1.2%
	PS, ISR/FSR, ME, PDF	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
Z+hf	norm.	float
	resolved / merged	10%
	0-lep. SR / m_{jj} CR	5–12%
	0-lep. / 2-lep.	15%
	generator, PDF, scale	S
	p_{T}^{bb} reweight.	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
Z+hl	norm.	float
	resolved / merged	20%
	0-lep. SR / m_{jj} CR	3–20%
	0-lep. / 2-lep.	12%
	generator, PDF, scale	S
	p_{T}^{bb} reweight.	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S

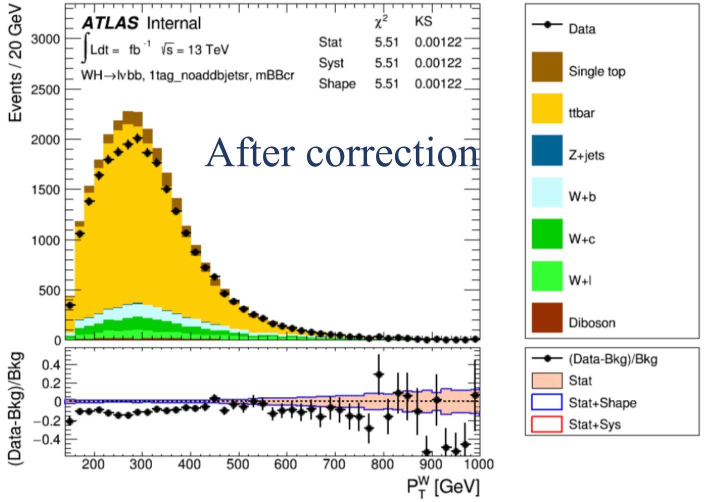
Process	Quantity/source	Value
Zl	norm.	19%
	resolved / merged	8%
	0-lep. SR / m_{jj} CR	5–20%
	0-lep. / 2-lep.	8 %
	generator, PDF, scale	S
	p_{T}^{bb} reweight.	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
W+hf	norm.	20%
	resolved / merged	46%
	0-lep. SR / m_{jj} CR	5–28%
	generator, PDF, scale	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
W+hl	norm.	30%
	resolved / merged	35%
	0-lep. SR / m_{jj} CR	2–20%
	generator, PDF, scale	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
Wl	norm.	30%
	resolved / merged	24%
	0-lep. SR / m_{jj} CR	4–20%
	generator, PDF, scale	S
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
SM Vh	0-lep norm.	32%
	2-lep norm.	32%
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S
Diboson	0-lep norm.	50%
	2-lep norm.	20%
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (0-lep.)	S

pTV mismodelling corrections





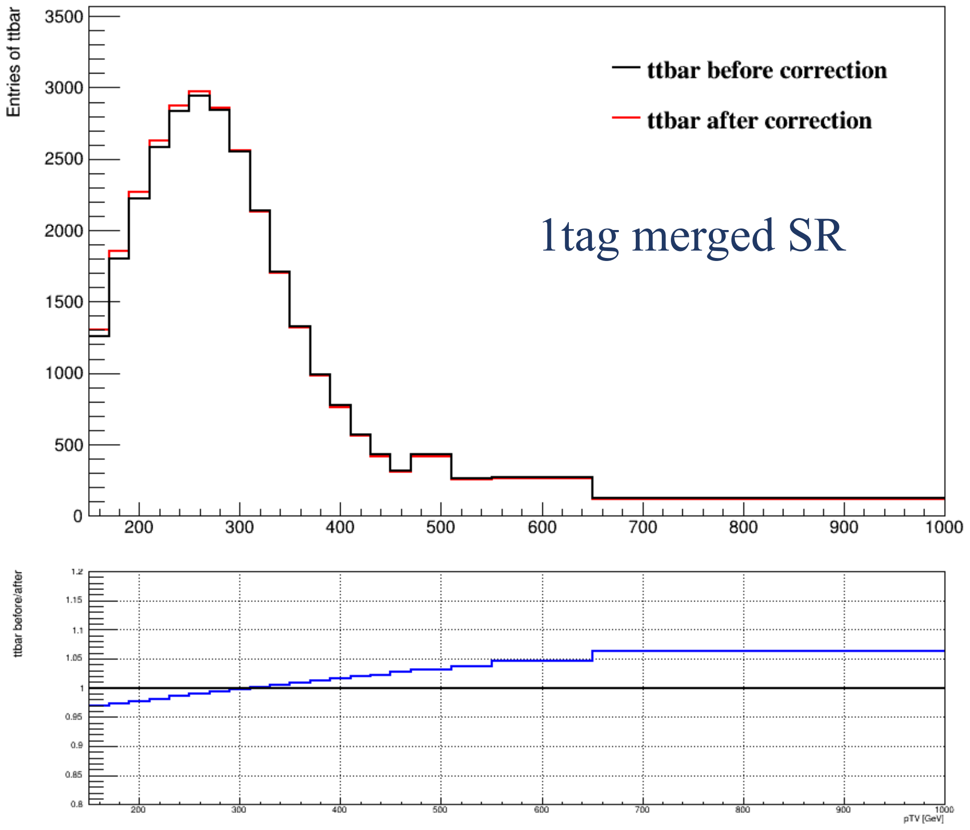


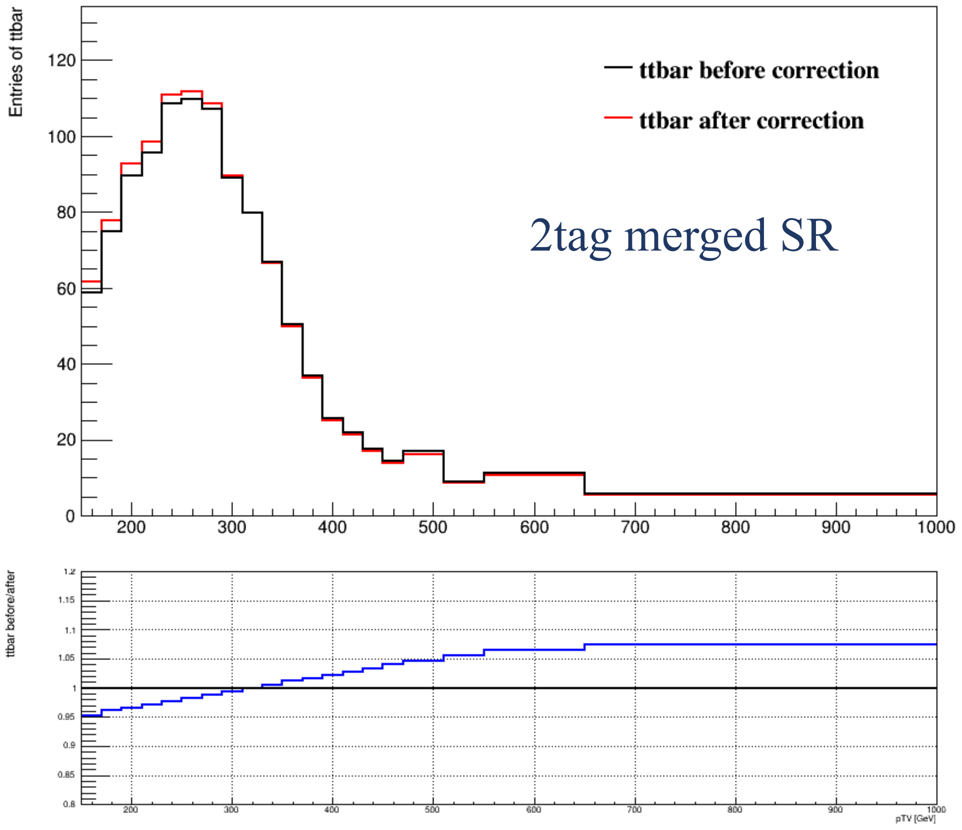


Slope of data/MC ratio was observed in merged region because of the ttbar mismodelling.

The mismodelling was considered as a systematic uncertainty "MODEL_ttbar_pTVReweight__1up".

Systematics





Comparisons of ttbar template in 1- / 2- tagged merged SRs before and after pTV correction.
The mismodelling was considered as a systematic uncertainty "MODEL_ttbar_pTVReweight__1up".

Object reconstruction

Electrons are reconstructed from ID tracks that are matched to clusters in the EM calorimeter

- "Tight" working point
- Isolated: `ptvarcone20/pt<0.06`

Muons are identified by matching tracks in ID to them reconstructed in MS ("combined muons"), or by stand-alone tracks in the MS

- "Tight" working point
- Isolated: `ptvarcone30/pt<0.06`

Electrons and muons are required to have a minimum p_T of 7 GeV and to lie within $|\eta| < 2.5$ for muons and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ for electrons

Object reconstruction

Small-R jets are reconstructed from topological clusters in calorimeter using R = 0.4

Large-R jets are used to reconstruct Higgs with high momenta for which the b-quarks are emitted close to each other. They are built using R = 1.0 and track-calo clusters (TCCs) as inputs

VR track jets are clustered from ID tracks using a variable radius (VR), they are used for tagging b-jets from boosted Higgs decays. In this analysis, only Large-R jets with at least two ghost-associated VR track jets are retained