Search for heavy Vh resonances with the ATLAS detector in the final state with boosted $h \to b\bar{b}$ decays

Andreas Hönle
supervised by Dominik Duda

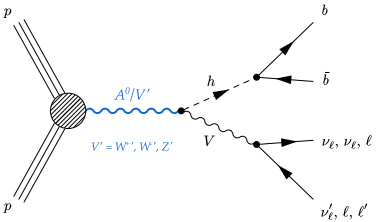
Max Planck Institute for Physics
(Werner-Heisenberg-Institut)

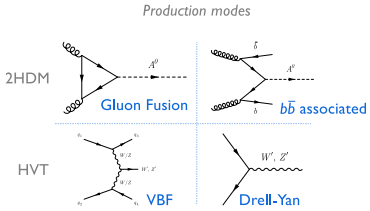
DPG 2019, Aachen
T53.2, 27 Mar 2019

ATLAS EXPERIMENT

MAX-PLANCK-GESELLSCHAFT

Analysis motivation





- Search for **heavy resonances** decaying into Zh or Wh
  - Predicted by several BSM theories
  - Interpreted in minimal extensions / simplified models
  - $h \to b\bar{b}$ identified with observed SM-like Higgs boson, $m_h = 125$ GeV

- **Two Higgs Doublet Model (2HDM)**
  - CP conserved $\to$ 5 higgs bosons H, h, $H^{\pm}$, A

- **Heavy Vector Triplet (HVT)**
  - Heavy vector bosons Z', W'
  - Simplified model with additional **SU(2) triplet**
  - Interpret in framework of two benchmark models: **Model A/B**

Model parameters

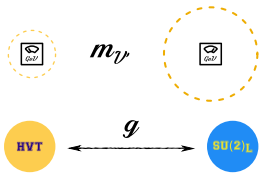
Model A

BR to all SM particles on same scale.

Model B

Decay into boson pairs preferred.

HVT

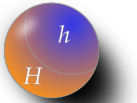


$$\frac{g^2 c_F}{g_V}, \; g_V c_H$$

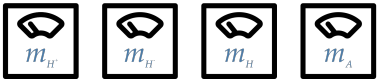
2HDM

$$\tan\beta = \frac{v_1}{v_2}$$

h, H mixing angle α



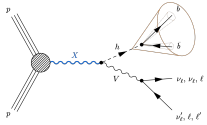
Masses



Resonance mass and coupling strengths are model parameters.
Benchmark models chosen to **maximise** $\sigma \times \mathcal{B}$ for given process.

Search for Vh resonances — overview

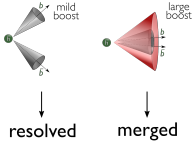
3 channels



- 0 lepton
- 1 lepton (HVT only)
- 2 lepton

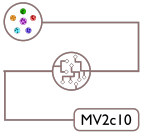
- (Transverse) invariant mass
  - **2HDM**: 0.2 – 2 TeV
  - **HVT**: 0.5 – 5 TeV

2 regimes



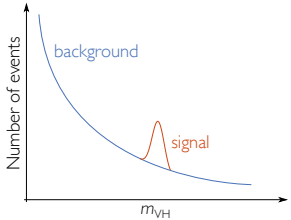
- **Resolved**
  - Two small-*R* (0.4) calo jets
- **Merged**
  - One large-*R* (1.0) calo jet with at least one associated track jet (R = 0.2)

b tagging



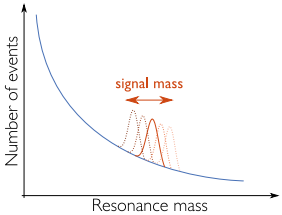
- To identify **Higgs** candidate
  - 1 or 2 *b*-tagged small-*R* jets / tracks jet(s) associated to large-*R* jet
- ***b*-associated** production
  - 0 or 1+ additional *b*-tagged small-*R* jet(s) / track jet(s) *not* associated to large-*R* jet
- **mass window** cut applied on higgs candidate mass

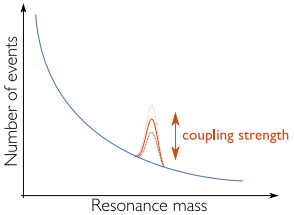
Bump hunting

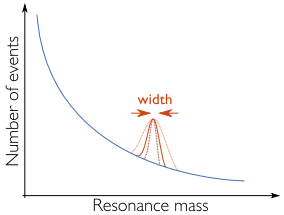


- **Localised bump** on top of a "smoothly" falling background
  - Background estimated with **Monte-Carlo** simulated samples
- **Binned maximum likelihood fit** to determine significance of the bump
- If no bump observable: **Constrain possible parameter space** of underlying signal model

Bump hunting







- **Localised bump** on top of a "smoothly" falling background
  - Background estimated with **Monte-Carlo** simulated samples
- **Binned maximum likelihood fit** to determine significance of the bump
- If no bump observable: **Constrain possible parameter space** of underlying signal model
- Position and characteristics depend on **model parameters**

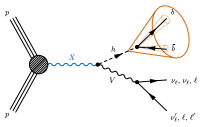
Event selection from JHEP03(2018)174

Variable	Resolved 	Merged 
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_j [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi$(j,j)	$> 7\pi$ / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	$> \pi$ / 2	
$\Delta\phi(E_T^{miss}, h)$	$> 2\pi/3$	
min[$\Delta\phi(E_T^{miss}$, small-R jet)]	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{had}}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	max[150, 710 - (3.3 × 10^5 GeV)/m_{Vh}]	max[150, 394 · ln(m_{Vh}/GeV) - 2350]
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}$/GeV	
$p_{T,\ell\ell}$[GeV]	$< 20 + 9 \cdot \sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	max[40 GeV, 87 - 0.030 · m_{Vh}/GeV] < $m_{\ell\ell}$ < 97 + 0.013 · m_{Vh}/GeV	

Event selection from JHEP03(2018)174

Variable	Resolved	Merged
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi$(j,j)	$> 7\pi$ / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	$> \pi$ / 2	
$\Delta\phi(E_T^{miss}, h)$	$> 2\pi/3$	
min[$\Delta\phi(E_T^{miss}$, small-R jet)]	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau,had}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	max[150, 710 - (3.3 × 10^5 GeV)/m_{Vh}]	max[150, 394 · ln(m_{Vh}/GeV) - 2350]
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}$/GeV	
$p_{T,\ell\ell}$[GeV]	$< 20 + 9 \cdot \sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	max[40 GeV, 87 - 0.030 · m_{Vh}/GeV] < $m_{\ell\ell}$ < 97 + 0.013 · m_{Vh}/GeV	

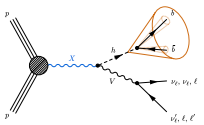
Topology
Kinematics



Event selection from JHEP03(2018)174

Variable	Resolved	Merged
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_j [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi$(j,j)	$> 7\pi$ / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	$> \pi$ / 2	
$\Delta\phi(E_T^{miss}, h)$	$> 2\pi/3$	
min[$\Delta\phi(E_T^{miss}$, small-R jet)]	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{had}}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	max[150, 710 - (3.3 × 10^5 GeV)/m_{Vh}]	max[150, 394 · ln(m_{Vh}/GeV) - 2350]
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}$/GeV	
$p_{T,\ell\ell}$[GeV]	$< 20 + 9 \cdot \sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	max[40 GeV, 87 - 0.030 · m_{Vh}/GeV] < $m_{\ell\ell}$ < 97 + 0.013 · m_{Vh}/GeV	

Topology
Kinematics

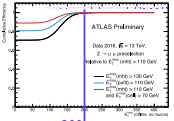


Event selection from JHEP03(2018)174

Variable	Resolved	Merged
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi(j,j)$	$> 7\pi$ / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	$> \pi$ / 2	
$\Delta\phi(E_T^{miss}, h)$	$> 2\pi/3$	
min[$\Delta\phi(E_T^{miss}$, small-R jet)]	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau,had}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	max[150, 710 - (3.3 × 10^5 GeV)/m_{Vh}]	max[150, 394 · ln(m_{Vh}/GeV) - 2350]
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}$/GeV	
$p_{T,\ell\ell}$[GeV]	$< 20 + 9 \cdot \sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	max[40 GeV, 87 - 0.030 · m_{Vh}/GeV] < $m_{\ell\ell}$ < 97 + 0.013 · m_{Vh}/GeV	

Trigger efficiency

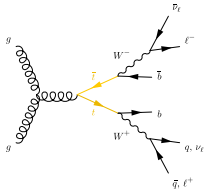
fully efficient > 200 GeV,
dedicated scale factors below



Event selection from JHEP03(2018)174

Variable	Resolved	Merged
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi(j,j)$	> 7π / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	> π / 2	
$\Delta\phi(E_T^{miss}, h)$	> 2π/3	
min[$\Delta\phi(E_T^{miss}$, small-R jet)]	> π/9 (2 or 3 jets), > π/6 (≥ 4 jets)	
$N_{\tau_{had}}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	max[150, 710 - (3.3 × 10^5 GeV)/m_{Vh}]	max[150, 394 · ln(m_{Vh}/GeV) - 2350]
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	< 1.15 + 8 × 10^{-3} · m_{Vh}/GeV	
$p_{T,\ell\ell}$[GeV]	< 20 + 9 · $\sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	max[40 GeV, 87 - 0.030 · m_{Vh}/GeV] < $m_{\ell\ell}$ < 97 + 0.013 · m_{Vh}/GeV	

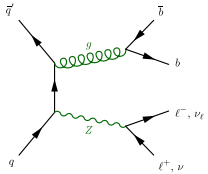
suppress ttbar



Event selection from JHEP03(2018)174

Variable	Resolved	Merged
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi(j,j)$	> 7π / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	> π / 2	
$\Delta\phi(E_T^{miss}, h)$	> 2π/3	
min[$\Delta\phi(E_T^{miss}$, small-R jet)]	> π/9 (2 or 3 jets), > π/6 (≥ 4 jets)	
$N_{\tau_{had}}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	max[150, 710 - (3.3 × 10^5 GeV)/m_{Vh}]	max[150, 394 · ln(m_{Vh}/GeV) - 2350]
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	< 1.15 + 8 × 10^{-3} · m_{Vh}/GeV	
$p_{T,\ell\ell}$[GeV]	< 20 + 9 · $\sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	max[40 GeV, 87 - 0.030 · m_{Vh}/GeV] < $m_{\ell\ell}$ < 97 + 0.013 · m_{Vh}/GeV	

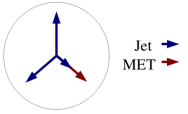
suppress V+jets



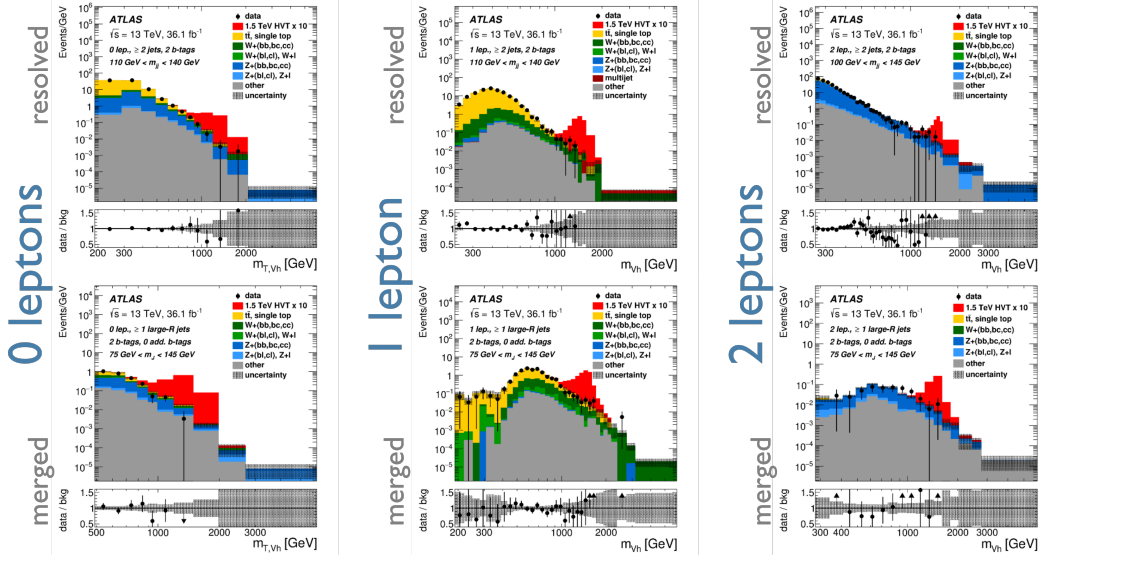
Event selection from JHEP03(2018)174

Variable	Resolved	Merged
Common selection		
Number of jets	2 or 3 small-R (1 lepton), ≥ 2 (else)	≥ 1 large-R
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110 - 140 (0, 1 lep.), 100 - 145 (2 lep.)	75 - 145
0 lepton selection—bbνν		
E_T^{miss} [GeV]	> 150	> 200
$\Sigma\, p_T^{jet,i}$ [GeV]	> 120 (2 central jets), > 150 (else)	–
$\Delta\phi(j,j)$	$> 7\pi$ / 9	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(E_T^{miss}, p_T^{miss})$	$> \pi$ / 2	
$\Delta\phi(E_T^{miss}, h)$	$> 2\pi/3$	
$\min[\Delta\phi(E_T^{miss}, \text{small-}R\text{ jet})]$	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{had}}$	0 (only for $A \to Zh$)	
1 lepton selection—bbℓν		
leading lepton p_T [GeV]	> 27	
E_T^{miss} [GeV]	> 40 (μν), > 80 (eν)	> 100
$p_{T,W}$ [GeV]	$\max[150, 710 - (3.3 \times 10^5\ \text{GeV})/m_{Vh}]$	$\max[150, 394 \cdot \ln(m_{Vh}/\text{GeV}) - 2350]$
$m_{T,W}$ [GeV]	< 300	
2 lepton selection—bbℓℓ		
leading lepton p_T [GeV]	> 27	
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [√GeV]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}/\text{GeV}$	
$p_{T,\ell\ell}$[GeV]	$< 20 + 9 \cdot \sqrt{m_{VH}/\text{GeV} - 320}$ (not in resolved 2, 3+ b-tag)	
$m_{T,\ell\ell}$ [GeV]	$\max[40\ \text{GeV}, 87 - 0.030 \cdot m_{Vh}/\text{GeV}] < m_{\ell\ell} < 97 + 0.013 \cdot m_{Vh}/\text{GeV}$	

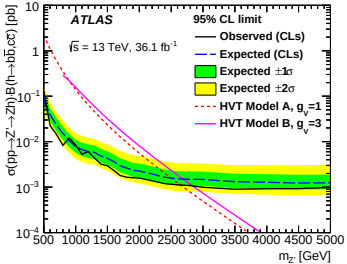
suppress QCD/Multi-jet



Latest results – JHEP03(2018)174 – $\int \mathcal{L} dt = 36.1\,\text{fb}^{-1}$



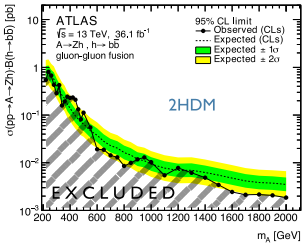
Exclusion limits with $\int \mathcal{L} dt = 36.1\,\text{fb}^{-1}$ (JHEP03(2018)174)



Exclusion limits with $\int \mathcal{L} dt = 36.1\,\text{fb}^{-1}$ (JHEP03(2018)174)

Exclusion limits with $\int \mathcal{L} dt = 36.1\,\text{fb}^{-1}$ (JHEP03(2018)174)

fig_05a_overlay.png



Exclusion limits with $\int \mathcal{L} dt = 36.1\,\text{fb}^{-1}$ (JHEP03(2018)174)

fig_05a_overlay.png

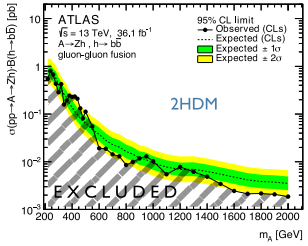
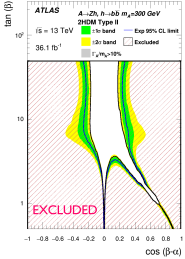


fig_04d_overlay.png

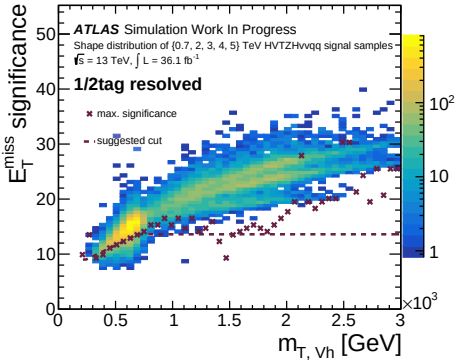


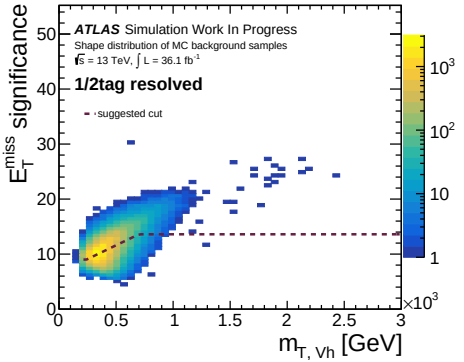
Mass fixed

Width fixed

Couplings fixed to "Type II" scenario

$E_{\mathrm{T}}^{\mathrm{miss}}$ significance—reduce fake $E_{\mathrm{T}}^{\mathrm{miss}}$ events

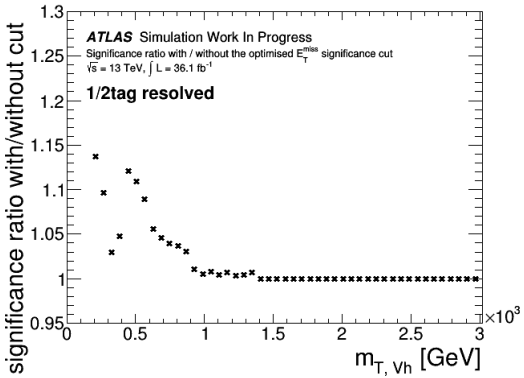




$$Z = \begin{cases} +\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n \geqslant b \\ -\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n < b. \end{cases}$$

- Calculate **maximum significance** in every m_{Vh} bin
- Fit maximum significance
- $\max[9.0, 6.6 + 0.01 \cdot \min(m_{\mathrm{Vh}}/\mathrm{GeV}, 700)]$

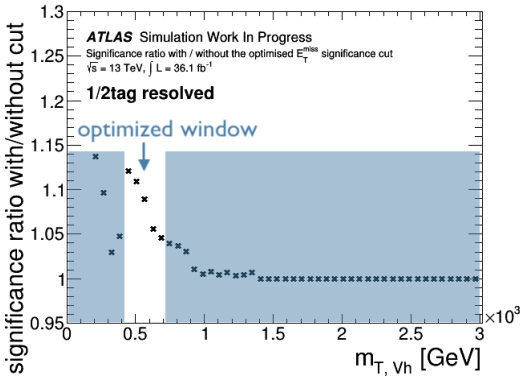
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance—reduce fake $E_{\mathrm{T}}^{\mathrm{miss}}$ events



$$Z = \begin{cases} +\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n \geqslant b \\ -\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n < b. \end{cases}$$

- Calculate **maximum significance** in every m_{Vh} bin
- Fit maximum significance
- $\max[9.0, 6.6 + 0.01 \cdot \min(m_{\mathrm{Vh}}/\mathrm{GeV}, 700)]$

$E_{\mathrm{T}}^{\mathrm{miss}}$ significance—reduce fake $E_{\mathrm{T}}^{\mathrm{miss}}$ events



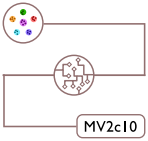
$$Z = \begin{cases} +\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n \geqslant b \\ -\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n < b. \end{cases}$$

- Calculate **maximum significance** in every m_{Vh} bin
- Fit maximum significance
- $\max[9.0, 6.6 + 0.01 \cdot \min(m_{\mathrm{Vh}}/\mathrm{GeV}, 700)]$

Improved limits with variable radius track jets

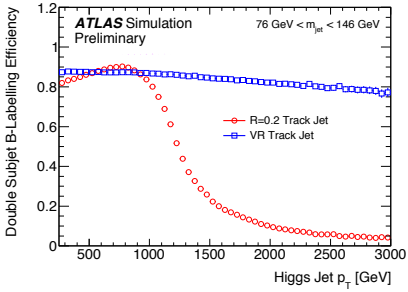
b labelling

Matching truth b jets to reconstructed jets (Monte Carlo)

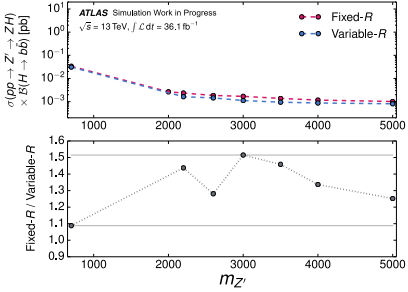


b tagging

Identifying a reconstructed jet as a b jet (data and Monte Carlo).



Expect more events in two tag category at high p_{T} [ATL-PHYS-PUB-2017-010] .



Expected limits improve up to 50 %.

Summary

- Search for new **heavy resonances** with $b\bar{b}$ final states published with $\int \mathcal{L}dt = 36.1\,\text{fb}^{-1}$
- Improved **exlusion limits** for HVT and 2HDM model parameters
- **Full Run 2 analysis** with $\int \mathcal{L}dt \sim 150\,\text{fb}^{-1}$ in preparation
- Lots of analysis **improvements** will be included

Thank you.