High-mass resonances decaying to heavy particles with ATLAS

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Venugopal Ellajosyula

On behalf of the ATLAS collaboration

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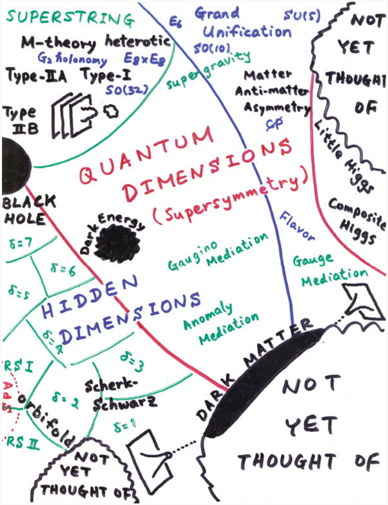
Uppsala University

UPPSALA UNIVERSITET

ATLAS EXPERIMENT

Introduction

Motivation



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A few of the issues SM cannot explain

- Neutrino masses
- Gravity
- Smallness of the Higgs mass
- Dark Matter

Many new models beyond the SM (BSM) that provide explanations for some of these issues.

Most of them predict new particles that can decay to heavy SM particles!

Contents

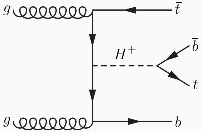
This talk is split into two main parts:

- **Heavy resonances decaying to heavy SM fermions**
    - Search for charged Higgs bosons decaying into a top-quark and a bottom-quark
    - Search for heavy Higgs bosons decaying into two τ leptons
    - Search for $t\bar{t}$ resonances
- **Heavy resonances decaying to heavy SM bosons**
    - Search for heavy diboson resonances in semi-leptonic final states
    - Search for resonances decaying into a weak vector boson and a Higgs boson
- **Bonus:** Dijet resonance search with weak supervision

This list is not exhaustive. A complete list of analyses with the full Run-2 data collected by ATLAS can be found here.

Heavy resonances decaying to fermions ($tb, \tau\tau, t\bar{t}$)

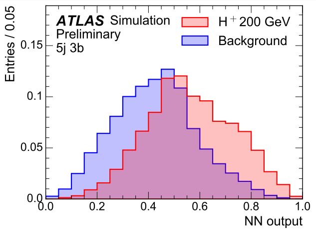
Search for charged Higgs bosons decaying into a top-quark and a bottom-quark ATLAS-CONF-2020-039

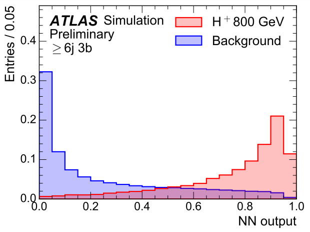


- Several models such as Two Higgs-Doublet Models (2HDM), Triplet extensions of the SM etc predict the existence of a charged Higgs in addition to scalar and pseudo-scalar neutral Higgs bosons.
- In 2HDMs which are a key feature of the minimal supersymmetric extension of the SM (MSSM), the properties of $H^{\pm}$ depend on
  - $M_{H^{\pm}}$
  - $\sin\alpha$ (angle of mixing between the neutral Higgs bosons)
  - $\tan\beta$ (ratio of the vacuum expectation values of the two doublets)
- This analysis considers final states with 1 lepton and at least 5 jets of which at least 2 are $b-$tagged jets.

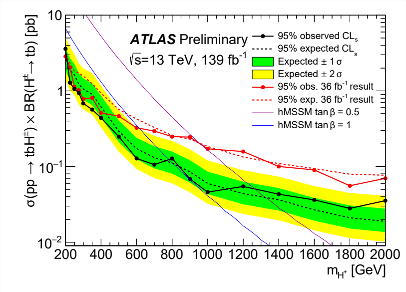
Signal region and source of background

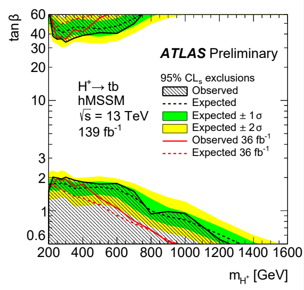
- Final states: 1 lepton, and at least 5 jets of which at least 2 are $b-$tagged jets.
- Different signal regions based on the number of jets and the number of $b-$tagged jets.
- Main source of background from $t\bar{t}$+jets.
- A multivariate neural network used to discriminate signal from background.
- Largest source of uncertainty from the modeling of $t\bar{t}$+jets.





Results





- Results expressed as a limit on cross-section (denoted by σ)$\times$BR as a function of $m_{H^\pm}$ as well as exclusions in the $\tan\beta$ vs $m_{H^\pm}$ plane.
- The observed (expected) limits on $\sigma \times$ BR range from **3.6** (**2.6**) **pb** at $\mathbf{m_{H^\pm}} =$ **200 GeV** to **0.035** (**0.019**) **pb** at $\mathbf{m_{H^\pm}} =$ **2 TeV**.
- Very low values of $\tan\beta$ (upto 2) and high values of $\tan\beta$ (between 35 and 60) are also excluded in some scenarios.

Search for heavy Higgs bosons decaying into two τ leptons

arXiv:2002.12223

- Similar to the charged Higgs bosons, BSM neutral Higgs bosons (ϕ) are predicted in several models with extended scalar sectors
- This analysis performs the search for $200 < m_\phi < 2500$ GeV.
- Production mode: gluon-gluon fusion (ggF) and production in association with a b quark.
- The final states are required to have at least one τ lepton decaying into hadrons, and are divided into two channels: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$.

Event selection:

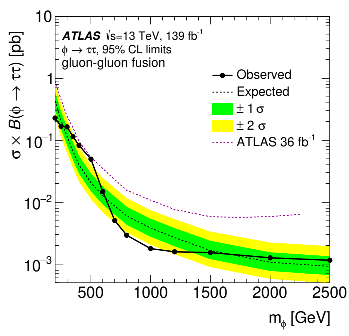
$\tau_{\mathbf{lep}}\tau_{\mathbf{had}}$

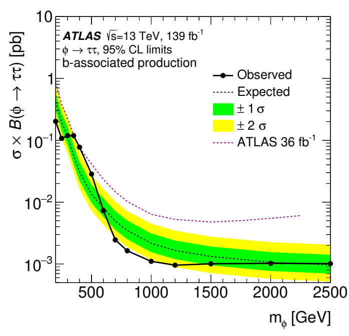
- Single electron/muon triggers
- Transverse mass, $m_T < 40$ GeV
- Invariant mass vetoed: $80 < m_{e^\pm e^\mp} < 110$ GeV

$\tau_{\mathbf{had}}\tau_{\mathbf{had}}$

- Single τ-lepton trigger
- Events with electrons/muons are vetoed
- The two τ leptons are required to have opposite charge, and be back-to-back.

Results





- Results for the ggF (left) and b-associated production (right) shown above.
- No significant excess over the expected SM backgrounds is found.
- The observed (expected) upper limits are **1.8 fb (3.8 fb) for ggF** and **1.1 fb (2.2 fb) for bbH production at $m_\phi = 1$**

Search for $t\bar{t}$ resonances in fully hadronic final states arXiv:2005.05138

- Being the heaviest known particle, the top quark could be a window into new physics.
- $t\bar{t}$ resonances are predicted by 2HDMs, Randall-Sundrum (RS) models with warped extra dimensions etc.
- This analysis is optimized for $m_{t\bar{t}} > 1.4$ TeV.
- Highly boosted tops, so difficult to reconstruct the $t\bar{t}$ system. A deep neural network (DNN) developed to solve this problem.

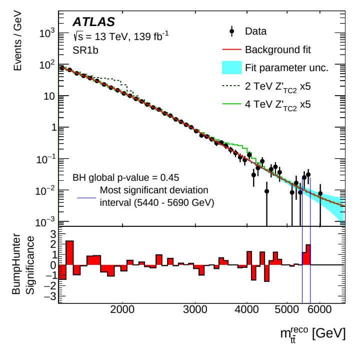
Event selection

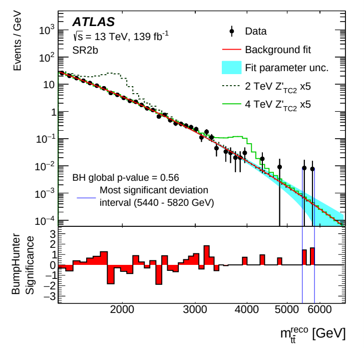
- Resonance (Z'_{TC2}) mass range considered in the RS model: 1.75 TeV − 5 TeV
- Signal region divided into two: 1 or 2 $b-$jets associated with the large-R(=1.0) jets.
- Model-independent results obtained by bump-hunting.

Selection cuts:

- At least two large-R jets (J) which are top-tagged using the DNN
- $p_T^{\text{leading jet}} > 500$ GeV
- $p_T^{\text{sub-leading jet}} > 350$ GeV
- $m_{JJ} > 1.4$TeV
- Leading and sub-leading jets required to be back-to-back in the transverse planes
- Rapidity distance required to be less than 1.8 to reject multijet background

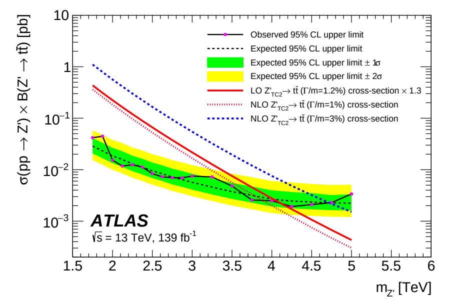
Results I





- Using a fully data driven background, with a global function fitted in the SR. The Functional form and uncertainties are estimated using a template built using an MC + Data driven mixture.
- Most significant deviation in **5.44 – 5.69 TeV for 1 b–jet** signal region and **5.44 – 5.82 TeV for 2b–jets** signal region with the corresponding **global p-values of 0.45 and 0.56**, respectively.

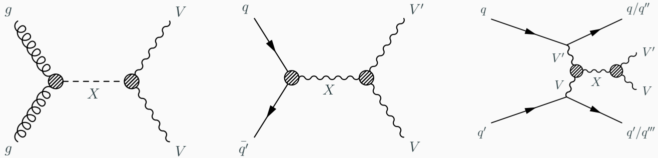
Results II



- For a Z' signal with a width $\Gamma/m = 1.2\%$, **masses up to 4.1 TeV are excluded at 95% CL**.
- Below 4.5 TeV, the expected sensitivity is limited by the statistical uncertainty of the background prediction.
- Above 4.5 TeV, systematic uncertainty dominates over the statistical uncertainty in the $2b-$jet channel.

Heavy resonances decaying to bosons (VV, VH, where $V = W^{\pm}, Z$)

Search for heavy diboson resonances in semi-leptonic final states arXiv:2004.14636



- Scalar, vector, and tensor diboson resonances are predicted in models such as 2HDM, composite Higgs models, extended gauge theories, RS models with warped extra dimensions.
- Search for VV ($V = W^{\pm}, Z$) where one V decays into leptons, the other decays to hadrons in the mass range $300 - 5000$ GeV.
- Production modes: gluon-gluon fusion (ggF), Drell-Yann (DY), vector-boson fusion (VBF)

Signal scenarios

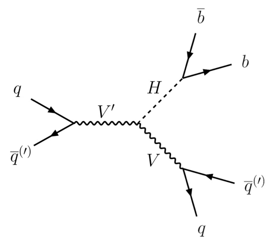
- Three scenarios:
  1) **Neutral scalar radion** decaying to WW or ZZ in R.S. models
  2) **Heavy vector bosons** as parametrized in Heavy Vector Triplet A (HVT bosons have comparable decay branching ratios into fermions and bosons) and HVT B (HVT boson couplings to fermions are suppressed) and decay through $W' \rightarrow WZ$ and $Z' \rightarrow ZZ$
  3) **Spin-2 graviton**, G_{KK}, of the first Kaluza-Klein excitation in a bulk RS model, decaying into WW or ZZ
- VBF distinguished from ggF/DY using a recurrent neural network.

Results

Production process	RS radion	HVT	W'	Z'	RS graviton
ggF/DY	3.2 (2.9)	Model A	3.9 (3.8)	3.5 (3.4)	2.0 (2.2)
		Model B	4.3 (4.0)	3.9 (3.7)	
VBF	–	Model C	–	–	0.76 (0.77)

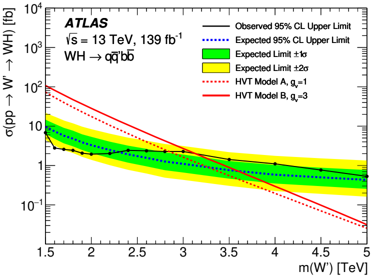
- Observed (expected) limits in TeV by combining WW, WZ, and ZZ channels shown above.
- **Improvement by a factor of 3 or more** compared to previous searches in the same final state which results from more data, new analysis techniques, as well as combing all semileptonic channels (WV and ZV).
- Similar analyses performed also for the all-hadronic final state (arxiv:1906.08589), and fully leptonic final states (HIGG-2018-09).

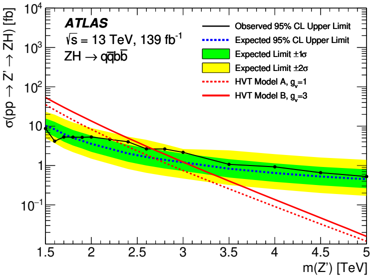
Search for resonances decaying into a weak vector boson and a Higgs boson arXiv:2007.05293



- The V' is assumed to decay into a weak vector boson, V, and the SM Higgs boson H.
- Only decays of V and H into hadrons is considered. This provides the best signal acceptance.
- The results are interpreted in the context of HVT model A and B.
- Resonance mass points between 1.5 and 5 TeV are considered.

Results

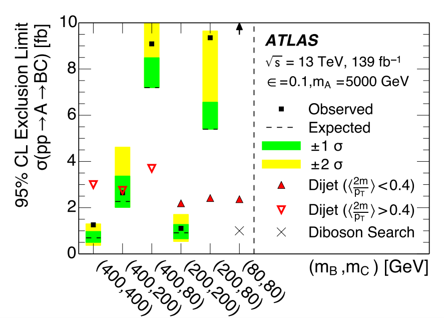




Excluded cross-sections		**Exclusion limits on W'(Z')**	
WH	ZH	HVT A	HVT B
6.8fb - 0.53fb	8.7 fb - 0.53 fb	2.9 TeV (2.20 TeV)	3.20 TeV (2.65 TeV)

- Similar analyses include resonances decaying to ZH in leptonic final states (ATLAS-CONF-2020-043), and resonances decaying to $H\gamma$ (arxiv:2008.05928).

Dijet resonance search with weak supervision arxiv:2005.02983



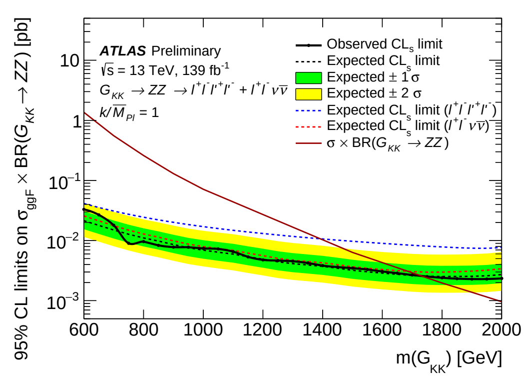
- Targeted topology: $A \to BC$, where B and C can both be BSM particles.
- Weakly supervised classification NNs are used to identify the presence of potential signals without training on simulations of any particular signal models.
  - Masses of the two leading large-R jets used for classification
- Mass range scanned: 2.28 TeV $< m_{JJ} <$ 6.81 TeV
- For $m_B = m_C =$ 400 GeV, the excluded cross-section is about 1 fb, a significant improvement over existing limits.

Summary

- Analysis shown here: $X \to VV, VH, t\bar{t}, tb, \tau\tau, jj$
  - Plenty more results including $HH \to 4b$ (arXiv:2001.05178), and $bb\tau\tau$ (arXiv:2007.14811)
- No significant excesses were observed. But most of these analyses have shown improvement over the previous searches.
- Major systematic uncertainties in most analyses arise from the modeling of data-driven backgrounds such as $t\bar{t}$+jets.
- Big improvements were made in background modeling and identification of large-R jets in boosted scenarios.
- Some of these analyses are limited by statistics and would benefit from Run 3.

Backup

Search for heavy resonances decaying into a pair of Z bosons



- Another analysis with heavy resonances decaying to two vector bosons (ZZ).
- Final states considered: 4 leptons or 2 leptons, 2 neutrinos.
- Production modes: ggF and VBF.
- Further details can be found here.