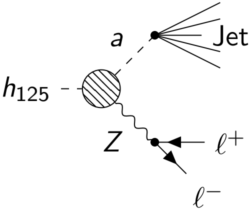
Higgs Boson Decays to Light Scalars at ATLAS

University of Birmingham, 22nd April 2020

Elliot Reynolds

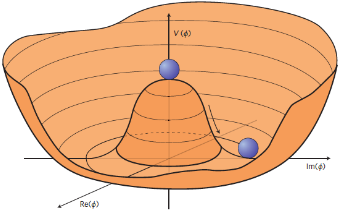


This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

Ways to Extend the Higgs Sector

Standard Model Higgs Sector

Higgs Doublet field introduces gauge invariant mass terms to the Standard Model (SM), facilitates electroweak (EW) symmetry breaking (EWSB), and preserves the unitarity of $W_L W_L \to W_L W_L$



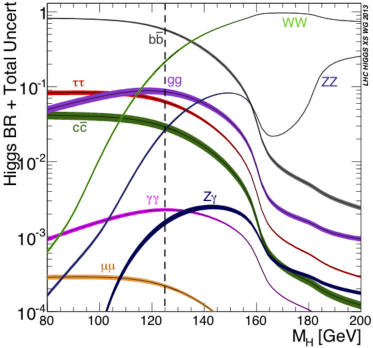
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ \phi_3(x) + i\phi_4(x) \end{pmatrix} \longrightarrow$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$m_W = \frac{1}{2} g_W v$$

$$m_Z = \frac{1}{2} v \sqrt{g_W^2 + g'^2}$$

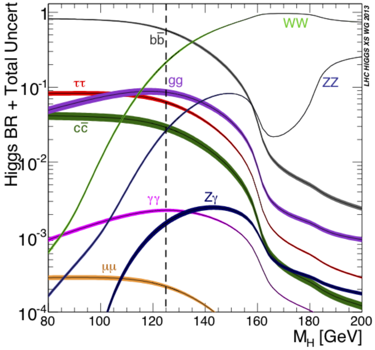
Observed Higgs Boson



arXiv:1307.1347

Observed Higgs Boson

Single neutral Higgs boson (h_{125}) with a mass of 125 GeV discovered in 2012 by ATLAS and CMS



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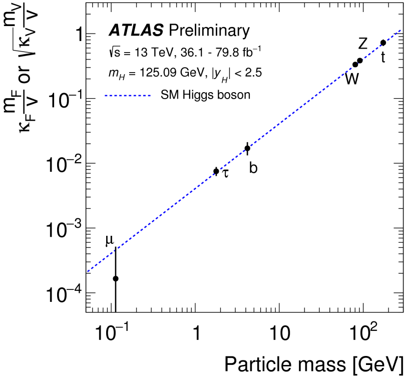

ATLAS-CONF-2018-031

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  - Higgs doublet with one or more additional scalar singlets
  - Two Higgs doublet model (2HDM)
  - 2HDM with an additional singlet (2HDM+S)

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  - 2HDM with an additional singlet (2HDM+S)
- More complex scalar sectors (including involving triplets) are possible, leading to exotic signatures such as doubly charged Higgs bosons

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Two Higgs Doublet Model

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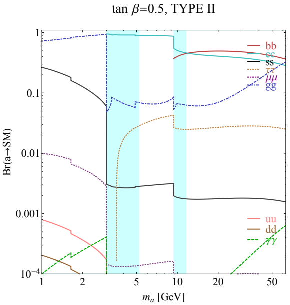
- Physical Higgs bosons: h and H (CP-even), a (CP-odd), and $H^{\pm}$
- $\tan\beta = v_2/v_1$
- To avoid tree-level flavour changing neutral currents, all fermions of a given charge and quantum numbers couple to one doublet (arXiv:1207.1083)

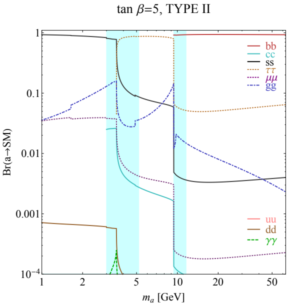
2HDM Type	First Doublet	Second Doublet
Type-I	All fermions	
Type-II (Supersymmetry)	Up-type fermions	Down-type fermions
Type-III	Quarks	Leptons
Type-IV	Up-type quarks	Down-type quarks
	Down-type leptons	Up-type leptons

Two Higgs Doublet Model with an Additional Singlet

- The 2HDM+S extends the 2HDM by one singlet field
- This extends the scalar sector of the 2HDM by one neutral CP-even boson and one neutral CP-odd boson
- The Type-II 2HDM+S is featured in Supersymmetric models, where it solves a naturalness problem in the Higgs mass scale
- The 2HDM+S is less constrained that the 2HDM



arXiv:1312.4992



Heavy or Light?

The new scalars can be heavy...

- Many active search channels:
  - $H \rightarrow \tau\tau$ (arXiv:2002.12223)
  - $H \rightarrow \mu\mu$ (arXiv:1901.08144)
  - $H \rightarrow WW$ (arXiv:1710.01123)
  - $H \rightarrow \gamma\gamma$ (arXiv:1707.04147)
  - $bH \rightarrow bbb$ (arXiv:1907.02749)
  - $H^{\pm} \rightarrow tb$ (arXiv:1808.03599)
  - $H^{\pm} \rightarrow \tau\nu$ (arXiv:1807.07915)
  - $H^{\pm} \rightarrow ZW$ (arXiv:1806.01532)
  - $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ (arXiv:1808.01899)
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Or they can be light

- Previous experiments would not have discovered them if their only large coupling is to h_{125}
- $h_{125} \to aa$ and $h_{125} \to Za$ possible
- Subject of what follows (specifically: $m < 4$ GeV)
- Small natural width of h_{125} means even small couplings to new light resonances would lead to large BRs

Heavy or Light?

$$\Gamma_{h_{125}} \approx 4.07 \text{ MeV}$$

$$\Gamma_{h_{125}}/m_{h_{125}} \approx 3.3 \times 10^{-5}$$

$H \to bb, \tau\tau$ suppressed by $y_{b,\tau} < \mathcal{O}(10^{-2})$

$H \to \gamma\gamma, gg, Z\gamma$ suppressed by loop factors

$H \to WW^*, ZZ^*, t\bar{t}$ suppressed by phase space

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Current ATLAS Search Programme

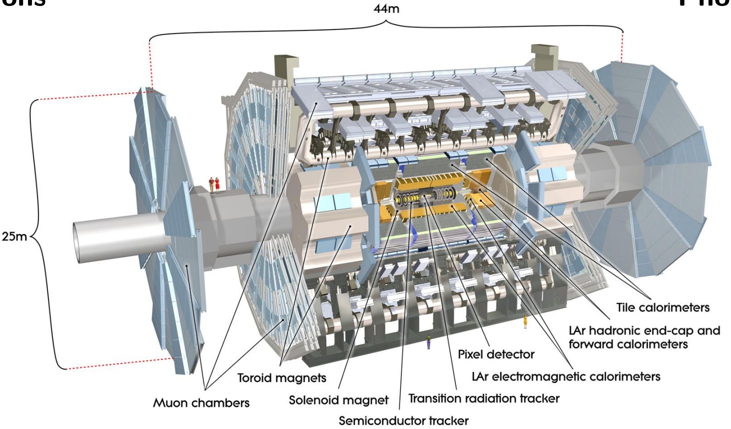
(Selection of Searches)

LHC: 13 TeV *pp* collisions

Run 2: $\mathcal{L}_{\text{int}} = 139\ \text{fb}^{-1}$ to date

Hadrons

Photons



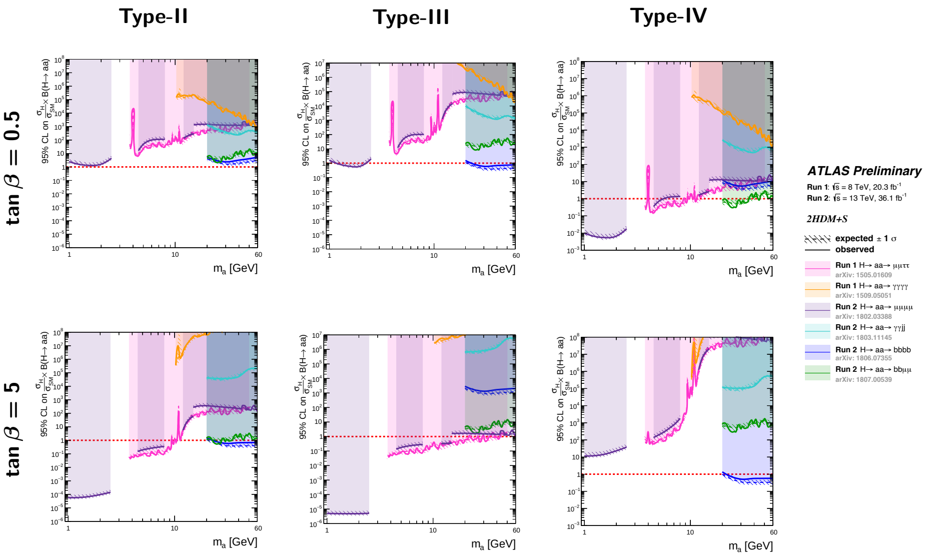
Electrons+Muons

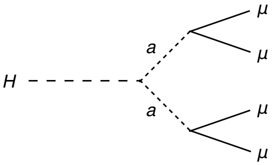
Neutrinos

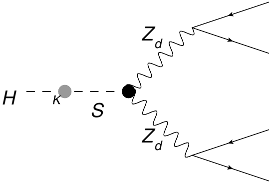
arXiv:1011.6665

ATLAS 2HDM+S $H \to aa$ Summary Plots

HDBS-2018-46



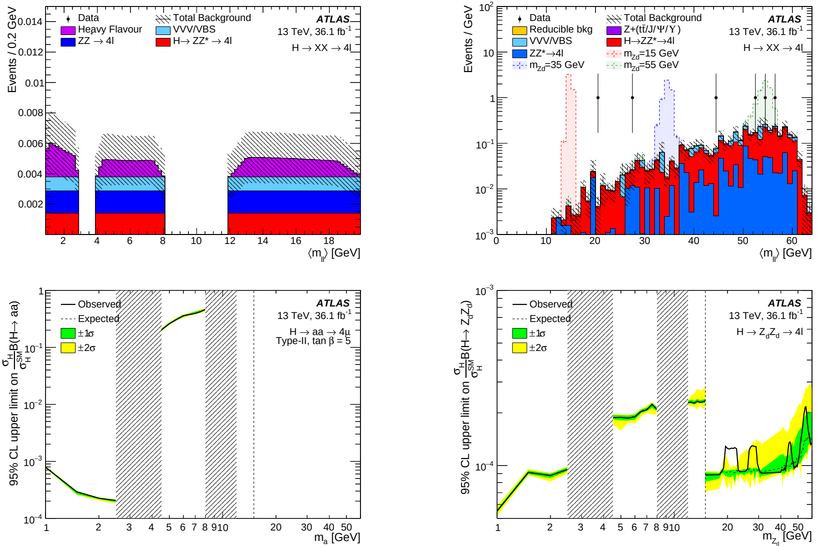




- $\mathcal{L}_{\text{int}} = 36.1\ \text{fb}^{-1}$
- Dual-interpretation analysis:
  - Pseudoscalar a from 2HDM+S[†], 4μ only
  - Vector Z_D from Hidden Abelian Higgs Model[‡]
- Dual-range analysis:
  - Low mass: $1\ \text{GeV} < m_a < 15\ \text{GeV}$, 4μ only
  - High mass: $15\ \text{GeV} < m_a < 60\ \text{GeV}$, $4\mu + 2\mu 2e + 4e$
- Select quadruplet with min: $\Delta m = |m_{12} - m_{34}|$
- Observable: $\langle m \rangle = (m_{12} + m_{34})/2$
- Dominant background EW, with additional fake lepton background

[†] arXiv:1002.1956 [‡] arXiv:1412.0018

$H \to aa \to \ell\ell\ell\ell$ - Results



Gaps in the Search Programme

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- When $h_{125} \to aa$ decays are suppressed
  - $\mathrm{BR}(h_{125} \to aa)$ and $\mathrm{BR}(h_{125} \to Za)$ can be adjusted independently (arXiv:1312.4992, arXiv:1606.09177)

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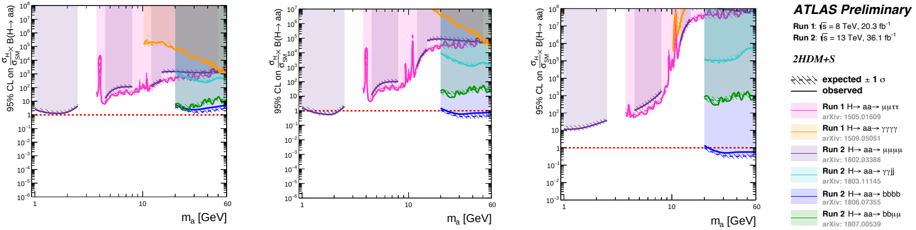
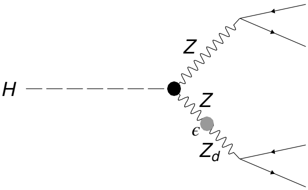
Type-II, tan β = 0.5 **Type-III, tan β = 0.5** **Type-IV, tan β = 5** HDBS-2018-46



$H \to ZZ_D \to \ell\ell\ell\ell$ - Overview

- $\mathcal{L}_{\text{int}} = 36.1\ \text{fb}^{-1}$
- Z_D arises from kinetic mixing to $Z^\dagger$
- Search range: 15 GeV $< m_{Z_D} <$ 55 GeV
- Quadruplet with dilepton mass closest to m_Z selected
- Observable: m_{34}
- Dominant backgrounds: ZZ^* and $H \to ZZ^*$
  - Estimated in MC
- Small fake lepton background
  - Estimated using data-driven method



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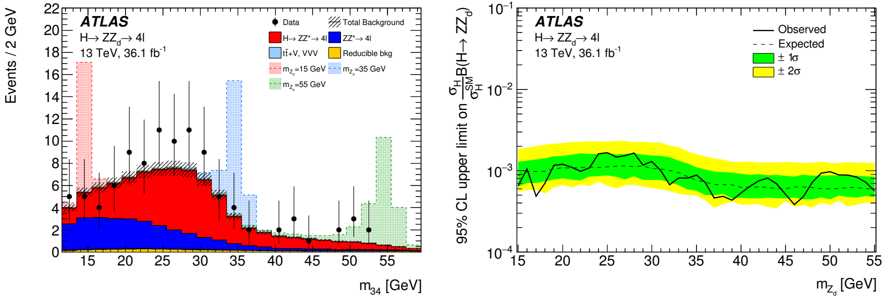
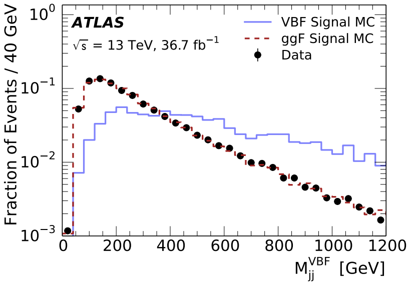


$H \to aa \to \gamma\gamma jj$ - Overview

- Sensitive to models where down-type fermionic decays are suppressed
  - Jets are gluon-induced
- Search range: $20\text{ GeV} < m_a < 60\text{ GeV}$
- VBF production mode targeted:
  - $m_{jj}^{\max} > 500$ GeV
- $100\text{ GeV} < m_{jj\gamma\gamma} < 150\text{ GeV}$
- Main backgrounds: $\gamma\gamma$jj and jjjj

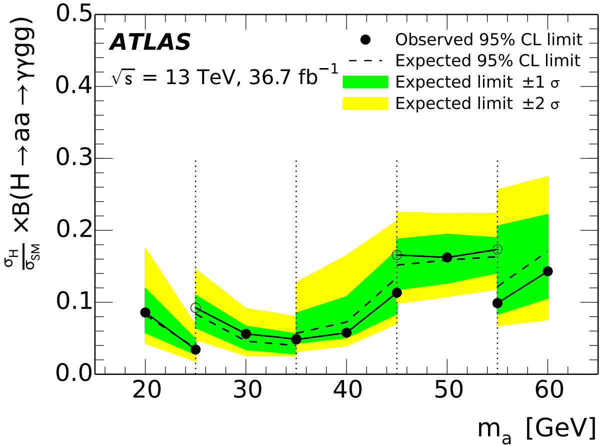


		Photon requirements: TightLoose	Photon requirements: TightTight
$\lvert m_{jj} - m_{\gamma\gamma}\rvert$	$> x_R$	A	C
	$\leq x_R$	B	D

$m_{\gamma\gamma}$ regime	Definition	Range of m_a values	x_R [GeV]
1	$17.5\text{ GeV} < m_{\gamma\gamma} < 27.5\text{ GeV}$	$20\text{ GeV} \leq m_a \leq 25\text{ GeV}$	12
2	$22.5\text{ GeV} < m_{\gamma\gamma} < 37.5\text{ GeV}$	$25\text{ GeV} \leq m_a \leq 35\text{ GeV}$	12
3	$32.5\text{ GeV} < m_{\gamma\gamma} < 47.5\text{ GeV}$	$35\text{ GeV} \leq m_a \leq 45\text{ GeV}$	16
4	$42.5\text{ GeV} < m_{\gamma\gamma} < 57.5\text{ GeV}$	$45\text{ GeV} \leq m_a \leq 55\text{ GeV}$	20
5	$52.5\text{ GeV} < m_{\gamma\gamma} < 65.0\text{ GeV}$	$55\text{ GeV} \leq m_a \leq 60\text{ GeV}$	24

$H \to aa \to \gamma\gamma jj$ - Results

- Likelihood fit to various mass regions and ABCD categories
- No significant excess is observed



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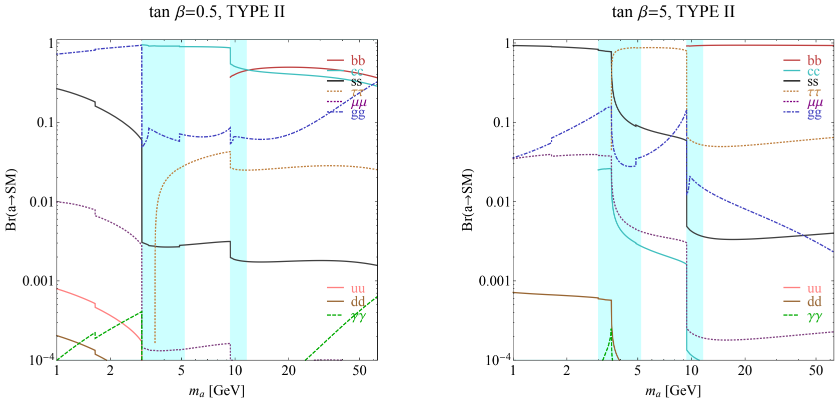

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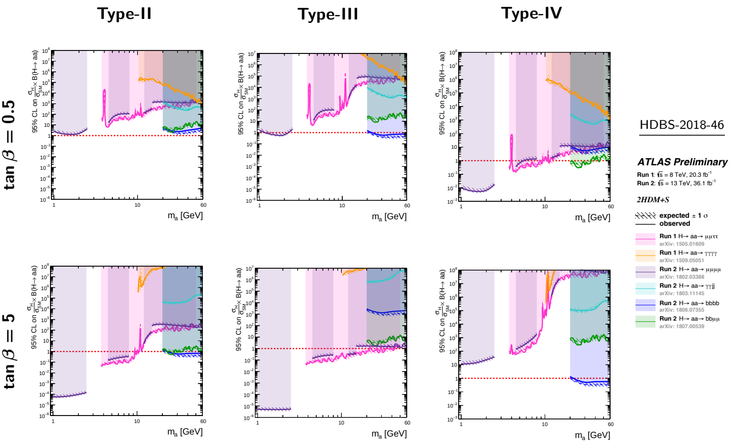


New Ideas Required!

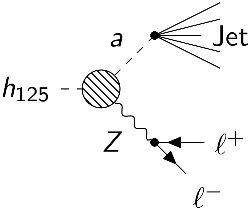
- Very few searches for $H \to Za$
- Almost all searches use decays of a to down-type fermions
- Both of these gaps can be filled with a search for $\boldsymbol{h_{125} \to Za \to \ell\ell j}$
- Huge challenge from overwhelming $Z+$ jets background!
- New ideas required to address this challenge

$$h_{\mathbf{125}} \to Za \to \ell\ell\mathbf{j}$$

arXiv:2004.01678 and Auxiliary Material

Aims

- Use full ATLAS Run II dataset (139 fb^{-1}) to perform first search for $\boldsymbol{h_{125} \to Z(\ell^+\ell^-)a/\mathcal{Q}(\mathrm{had})}$, $\ell = e$ *or* μ
- Interpret resonance as $\boldsymbol{J/\psi}$ or $\boldsymbol{\eta_c}$ ($\mathcal{Q}$), or $\boldsymbol{a}$ (BSM) with $\boldsymbol{m_a}$ **<4 GeV**



Charmonium Motivation

- Higgs boson decay to Z + light resonances unconstrained
- Potential limits on charm Yukawa coupling

BSM Motivation

- **Fills both of the aforementioned gaps in the search programme**

Physics Processes and Simulation

Physics Processes

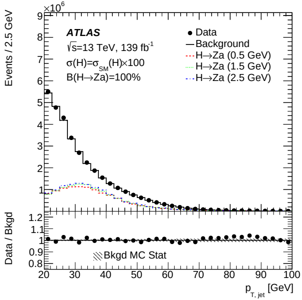
- Focus on low mass ($<$ **4 GeV**) signals, as higher BR and unique decay kinematics of a lead to higher sensitivity
- Search for signals from inclusive Higgs boson production
- The dominant background is $\boldsymbol{Z+}$ **jets**, with small contributions from $t\bar{t}$ and diboson

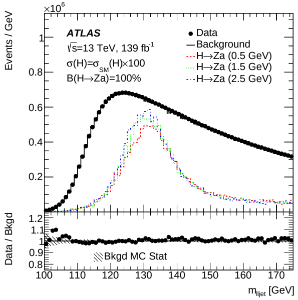
Simulation

- Signals modelled using Powheg, Pythia8 and EvtGen
- $Z+$ jets modelled using Sherpa 2.2.1
- Full Geant4 simulation of the ATLAS detector

Event-Level Kinematics and Selection

Selection	Details
Triggers	Single lepton triggers $p_{\mathrm{T},\ lead} > 27$ GeV
Leptons	$N_\ell \geq 2$ with $p_{\mathrm{T}} > 18$ GeV
Z boson	2 SF OS leptons, with $\lvert m_{ll} - m_Z \rvert < 10$ GeV
Jet (a)	Anti-k_T jet, with radius parameter (R) 0.4, formed of topological clusters at the EM scale with $p_{\mathrm{T},\ \mathrm{jet}} > 20$ GeV
Pre-Higgs	$m_{\ell^+\ell^-\mathrm{j}} < 250$ GeV
Select highest p_{T} jet as a-candidate	
≥ 2 tracks	≥ 2 tracks ghost associated to the calo jet
Higgs SR	120 GeV $< m_{\ell^+\ell^-j} <$ 135 GeV





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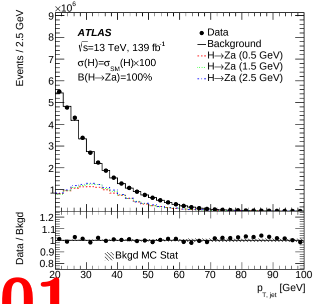
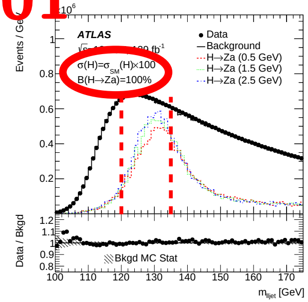
$S/B < 0.01$





Hadronic Resonance Tagger (1/6)

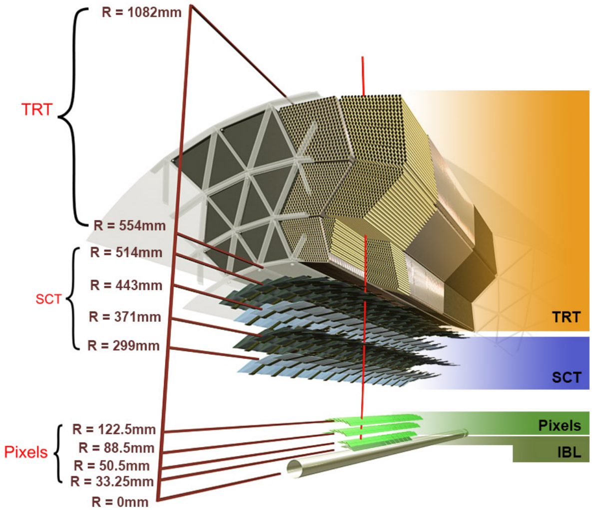
- Subtle differences in substructure of a-induced and QCD-induced jets
- Substructure techniques commonplace for high-mass resonances, using $R = 1$ jets and calorimeter information
- **Can similar techniques be applied to $R = 0.4$ jets?**

Pixel resolution

$\sim 12\mu m$ in $R - \phi$ and ~ 66 (~ 77) μm in z (R) in the barrel (disks)

SCT resolution

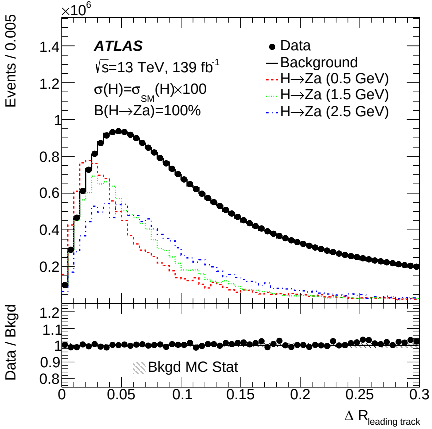
$\sim 16\mu m$ in $R - \phi$ and $\sim 580\mu m$ in z (R) in the barrel (disks)



arXiv:1011.6665

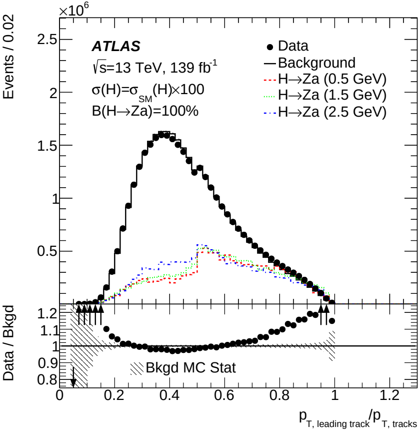
Hadronic Resonance Tagger (3/6) - Substructure Variables

- Input variables:
  1. $\Delta R_{\text{lead track}}$



Hadronic Resonance Tagger (3/6) - Substructure Variables

- Input variables:
  1. $\Delta R_{\text{lead track}}$
  2. $p_{\text{T, lead track}} / p_{\text{T, tracks}}$



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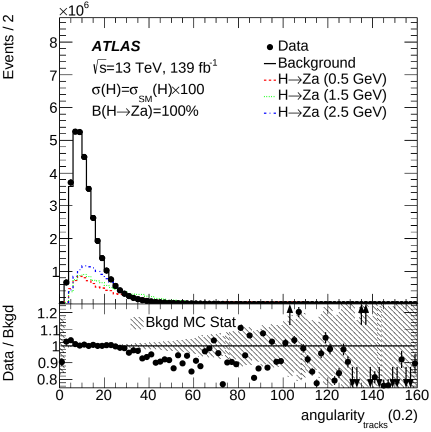
  3. angularity(2)†



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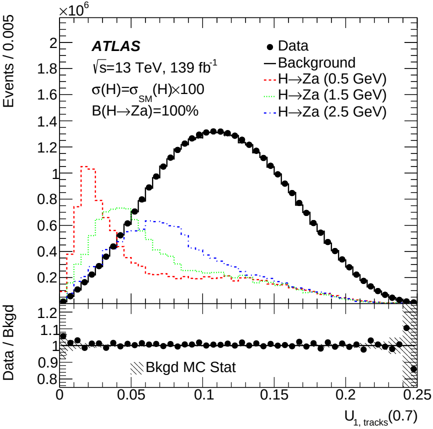
  4. $U1(0.7)$[‡]



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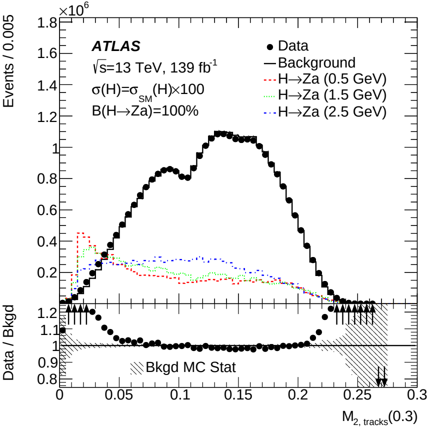
  5. $M2(0.3)$[‡]



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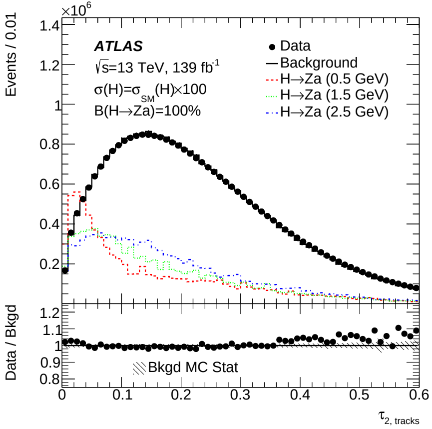
  5. $M2(0.3)$‡
  6. τ_2§
- All dimensionless to minimise correlation between substructure and event-level variables

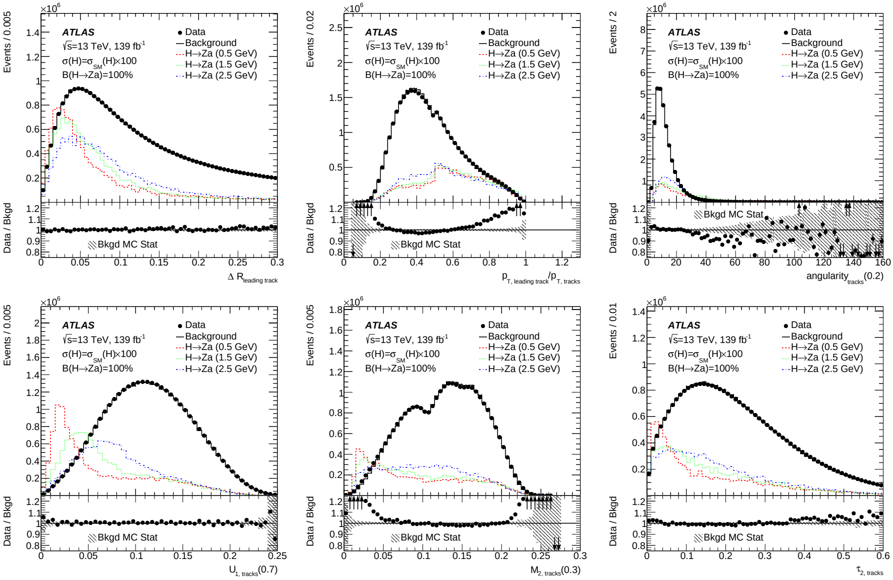


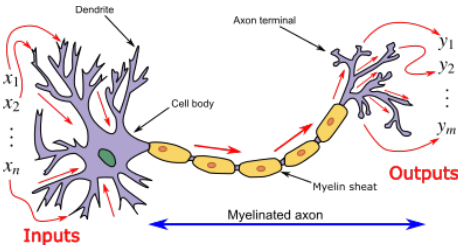
† arXiv:0807.0234

‡ arXiv:1609.07483

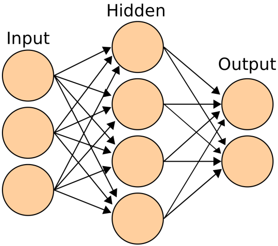
§ arXiv:1011.2268

Hadronic Resonance Tagger (3/6) - Substructure Variables





Wikipedia

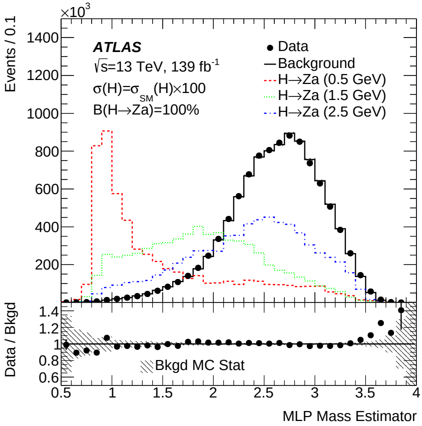


Wikipedia

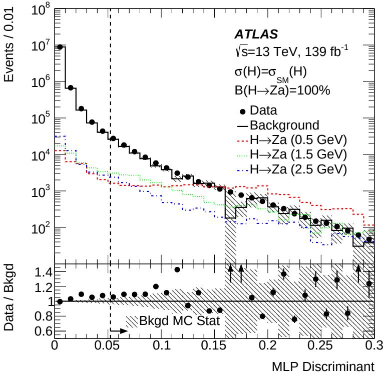
- **A Multi-Layer-Perceptron (MLP) is a function**, with many free parameters, which are "trained" on a dataset
- They are usually used for regression or classification

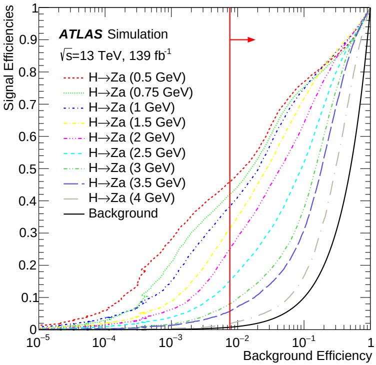
Hadronic Resonance Tagger (5/6) - Regression

- A Multi-Layer-Perceptron is used to classify signal resonances against background jets
- Not a standard classification problem, due to the spectrum of signals
- This is solved by training a regression MLP to predict m_a
- The mass hypothesis informs the classifier which part of the phase space to consider
- This results in $\sim$ **13%** improvement in the expected $S/\sqrt{B}$

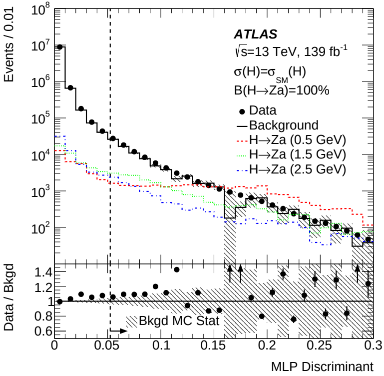


Hadronic Resonance Tagger (6/6) - Classification





Hadronic Resonance Tagger (6/6) - Classification



- Bkgd eff $= \mathbf{0.761\%}$ (MLP)
- Cut chosen to optimise the expected $S/\sqrt{B}$, assuming all values of a mass equally likely: $MLP > 0.052$

a mass / GeV	0.5	0.75	1	1.5	2	2.5	3	3.5	4
MLP Eff (%)	45.9	42.1	38.2	31.5	25.1	15.4	8.06	5.70	1.88
MLP $S/\sqrt{B}$ Change	5.3	4.8	4.4	3.6	2.9	1.8	0.92	0.65	0.22
MLP S/B Change	60	55	50	41	33	20	11	7.5	2.5

Background Estimate

- MC is reweighted to data in: p_{T}, N_{tracks} & $U1(0.7)$

Background Estimate

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- Four regions are defined in the $m_{\ell^+\ell^-\mathrm{j}} - MLP$ plane:
  - **A**: $120 < m_{\ell^+\ell^-\mathrm{j}} < 135$ GeV and $0.052 < MLP$
  - **B**: $155 < m_{\ell^+\ell^-\mathrm{j}} < 175$ GeV and $0.052 < MLP$
  - **C**: $120 < m_{\ell^+\ell^-\mathrm{j}} < 135$ GeV and $0.011 < MLP < 0.052$
  - **D**: $155 < m_{\ell^+\ell^-\mathrm{j}} < 175$ GeV and $0.011 < MLP < 0.052$
- Background estimate:

$$A_{\mathrm{SR}}^{\mathrm{ABCD\ Est.}} = \underbrace{\frac{B_{\mathrm{data}} C_{\mathrm{data}}}{D_{\mathrm{data}}}}_{\text{Data-driven ABCD Estimate}}$$

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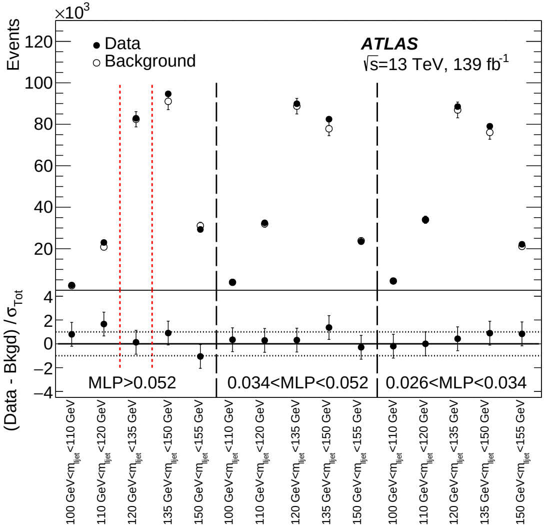
$$A_{\mathrm{SR}}^{\mathrm{ABCD\ Est.}} = \underbrace{\frac{B_{\mathrm{data}} C_{\mathrm{data}}}{D_{\mathrm{data}}}}_{\text{Data-driven ABCD Estimate}} \times \underbrace{\frac{A_{\mathrm{MC}}}{\frac{B_{\mathrm{MC}} C_{\mathrm{MC}}}{D_{\mathrm{MC}}}}}_{\text{MC-based ABCD Correction Factor}}$$

- MC-based correction factor accounts for **13%** correlation between $m_{\ell^+\ell^-\mathrm{j}}$ and MLP
- Background estimate of **82400**, with **3.5%** stat uncertainty

Validation of Background Estimate



Cut-and-Count Analysis Strategy

- Single-bin **cut-and-count** analysis strategy adopted
- Expected background:
  - Efficiency: $(8.45 \pm 0.22) \times 10^{-5}$
  - Yield: 82400 ± 2900

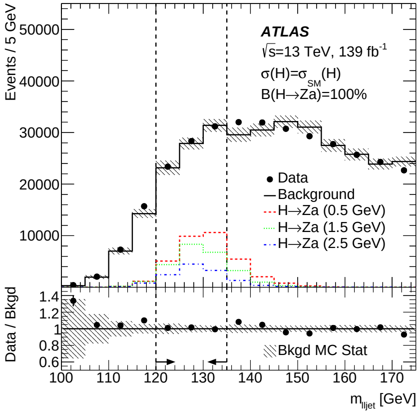
Expected Signal Efficiencies and Yields (Assuming $BR(h_{125} \to Za) = 100\%$, and Pythia8 a BRs with $\tan\beta = 1$)

a mass / GeV	0.5	0.75	1	1.5	2	2.5	3	3.5	4
Efficiency (%)	3.3	2.8	2.9	2.5	2.0	1.3	0.69	0.51	0.14
Yield ($\times$1000)	26	22	22	20	16	10	5.4	4.0	1.1

Results

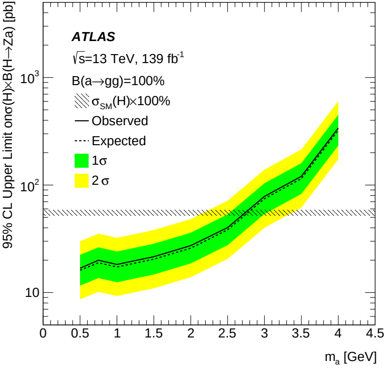
- Signal region ($MLP > 0.052$ & $120 < m_{\ell^+\ell^-j} < 135$ GeV):
  - Background estimate: **82400 ± 3700**
  - Observed: **82908**
- The results are **consistent with the background-only SM expectation**

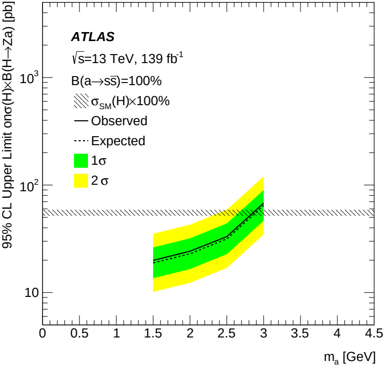
$MLP > 0.052$



Model-Independent Limits

- Fits to observed yield used to set 95% CL_s upper limits on, and measurements of, $\sigma(h_{125})BR(h_{125} \to Za)$
- $\sigma(h_{125})BR(h_{125} \to Z\eta_c) <$ **110 pb**
- $\sigma(h_{125})BR(h_{125} \to ZJ/\psi) <$ **100 pb**
- Limits calculated assuming BR of a to gluons/quarks of 100%





Conclusions and Outlook

$h_{125} \to Za$ Uncertainty Breakdown

Impact of uncertainties on $\sigma(pp \to h_{125})\mathrm{BR}(h_{125} \to Za)/\mathrm{pb}$ for three signal hypotheses

a mass	0.5 GeV	1.5 GeV	2.5 GeV
Total Uncertainty	8.3	10.7	20.3
Total Statistical Uncertainty	0.6	0.8	1.6
Total Systematic Uncertainty	8.2	10.7	20.2
Signal Systematic Uncertainties			
Jet Energy Scale	1.3	1.5	1.5
Parton Shower	1.4	1.4	1.4
Luminosity, Pileup, Trigger, Leptons, & JVT	0.2	0.3	0.5
MC Statistics	0.2	0.2	0.6
Renormalization Scale	0.1	< 0.1	0.2
Acceptance	0.1	< 0.1	0.2
Background Systematic Uncertainties			
MC Statistics	6.4	8.4	15.8
Parton Shower and ME	3.9	5.1	9.6
Renormalization Scale	3.4	4.4	8.3

What Could be Achieved?

Not ATLAS work

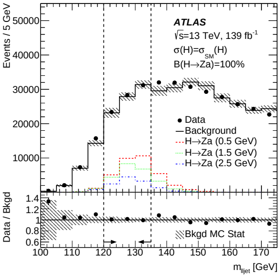
Relevant uncertainties combined in quadrature, and limits on $\sigma(pp \to h_{125})\mathrm{BR}(h_{125} \to Za)/\mathrm{pb}$ ($\sigma(pp \to h_{125})\mathrm{BR}(h_{125} \to Za)/\sigma_{\mathrm{SM}}(pp \to h_{125})$) scaled down linearly, assuming $\mathrm{BR}(a \to gg) = 100\%$

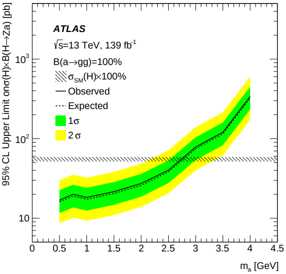
MC Stat	Modelling	0.5 GeV	1.5 GeV	2.5 GeV
✓	✓	17 (31%)	22 (39%)	40 (72%)
✗	✓	11 (20%)	15 (26%)	26 (46%)
✗	✗	4.2 (7.5%)	4.6 (8.3%)	5.4 (9.7%)

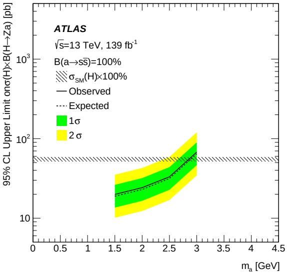
How to Generate Enough MC?

- **Generator more MC?**
- **Fully data-driven background model?**
- Using a **Generative Adversarial Network** (GAN), data can be simulated from a baseline sample (arXiv:1406.2661)
- The GAN consists of two parts:
  - The **generator**, which generates data based on random numbers
  - The **discriminator**, which attempts to tell the difference between the generated data and the baseline sample
- Each 'event' takes ∼ms, as opposed to ∼mins

Summary







- First search performed for $h_{125} \to Za \to \ell^+\ell^-$j
- Made possible by first use of track-based substructure in dual-stage MLP for light resonance identification
- Limits set, starting at BRs of **31%**
- This fills in two gaps in the previous search programme: suppression of a decays to down-type fermions, and small BR($H \to Za$)

Backup Slides

Hadronic Resonance Tagger - Track Selection

Ghost-Association[†]

- Tracks are associated to the calorimeter jet using ghost-association
- The anti-k_T ($R = 0.4$) clustering algorithm is rerun on the calorimeter clusters, including the tracks
- The tracks are treated as having very low p_{T} so they do not influence the calorimeter jet

Track Selection[‡]

- Track quality requirements: ≥ 7 silicon hits, ≤ 1 shared pixel cluster, ≤ 2 shared SCT clusters on same layer, ≤ 1 pixel hole & ≤ 2 silicon holes
- Vertexing requirements: $|d_0| < 2$ mm & $|\Delta z_0 \sin\theta| < 3$ mm
- Jets are required to have ≥ 2 tracks surviving these requirements

[†] arXiv:0707.1378

[†] arXiv:1704.07983